Opportunities for Fundamental Symmetries Experiments with Neutrons and Nuclei

A. R. Young

North Carolina State University
Triangle Universities Nuclear Laboratory

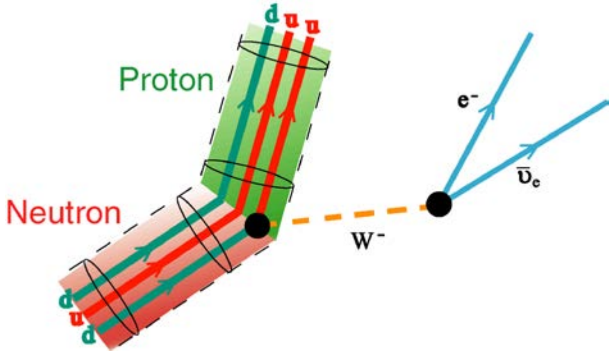
Outline

- Beta Decay
  - ^{19}Ne and nuclear mirror decays
  - The β-asymmetry with UCN
  - Other experiments?
- Spin precession with neutrons
  - n-n’ precession experiments
  - SR spin-dependent force

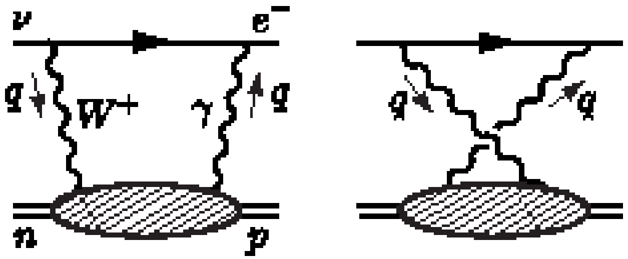
Two Drivers for High Precision Measurements with Mirror Decays

i) Progress on limiting uncertainties of the electroweak corrections

ii) Nuclear mirror decay analysis problem identified and solved



Precision of hadronic component of inner radiative corrections
~ factor of two improvement!



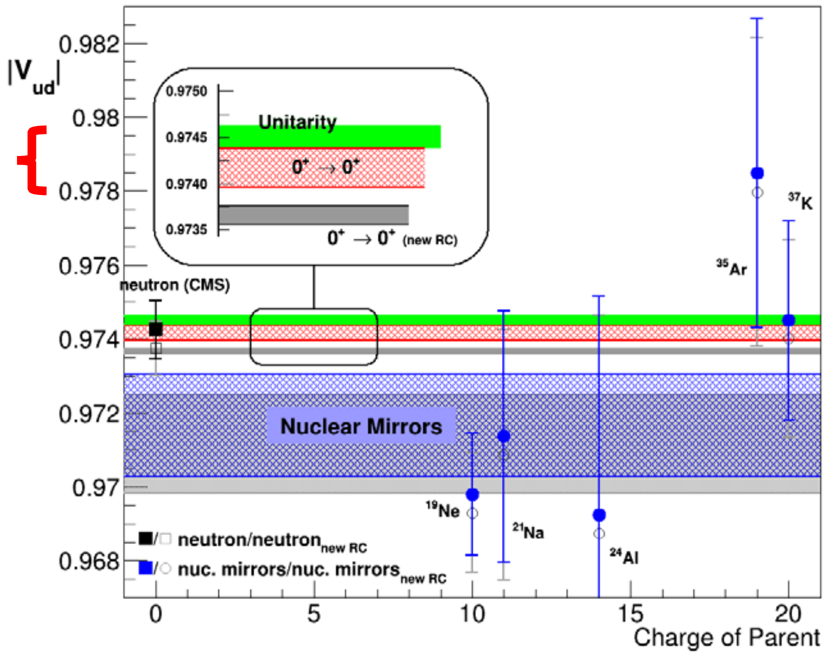
Seng, Gorchtein, Patel, Ramsey-Musolf, PRL **121,** 241804 (2018)

IMPACT: $|V_{us}|$ now nominally provides limiting uncertainty for unitarity

4σ shift in EWRC correction –
~0.1% in unitarity sum!

Current status of CKM Unitarity

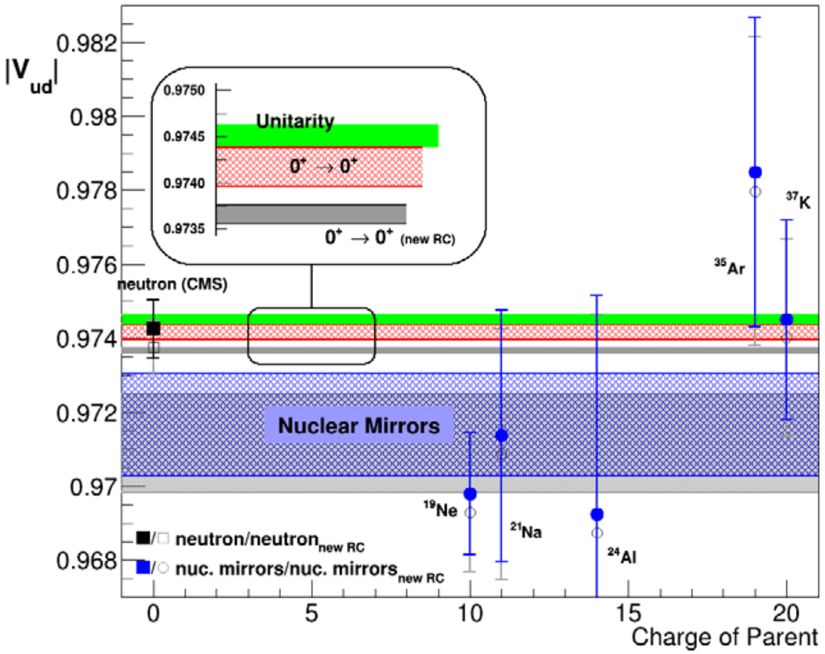
Deviation 1.5 - 3σ

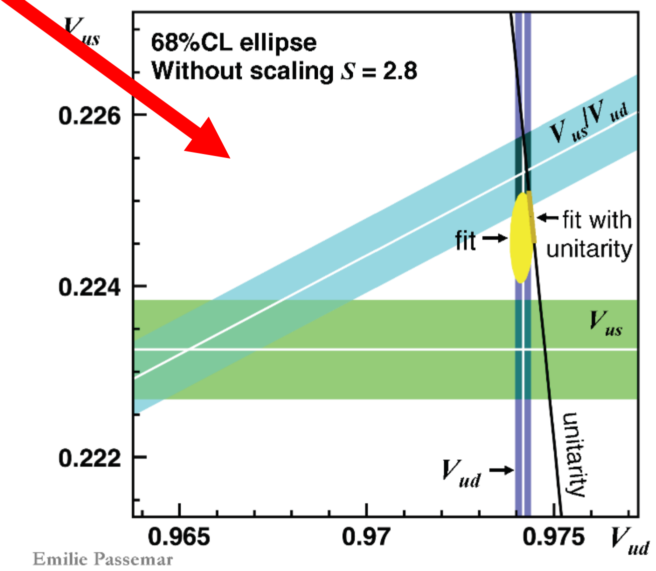


Current status of CKM Unitarity

Sources of Discrepancy?

V_{us}?





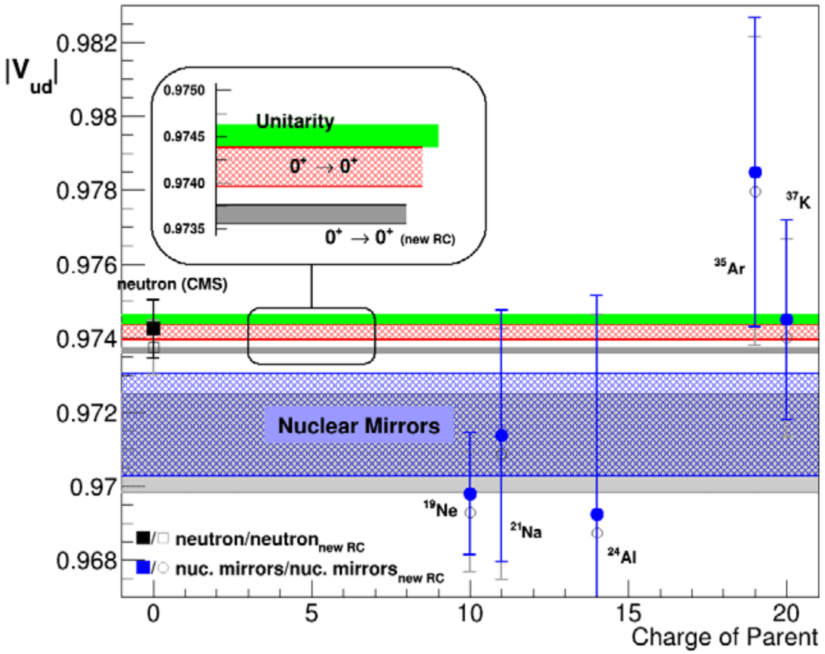
3-5σ discrepancy between Kℓ2 and Kℓ3

Current status of CKM Unitarity

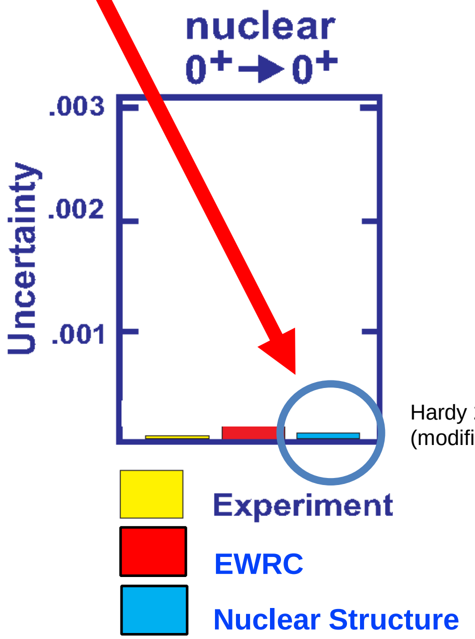
Sources of Discrepancy?

V_{us}?

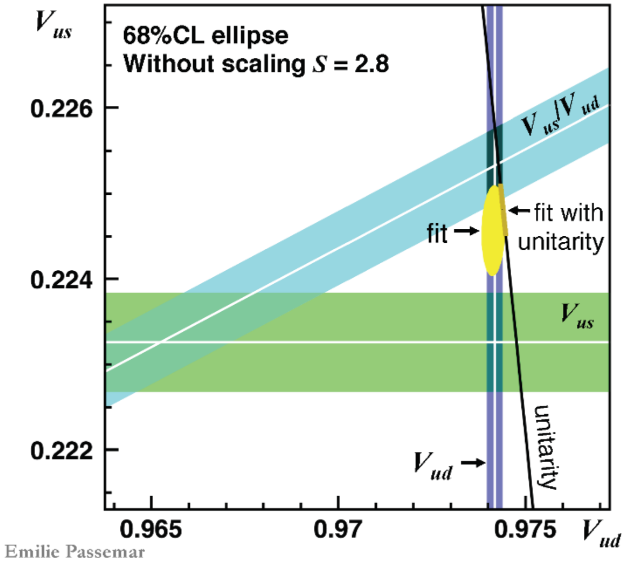
Nuclear Structure?



Superallowed nuclear structure uncertainty ~ 0.01% -- optimistic?



Hardy 2015 (modified)



3-5σ discrepancy between $K\ell2$ and $K\ell3$

Current status of CKM Unitarity

Sources of Discrepancy?

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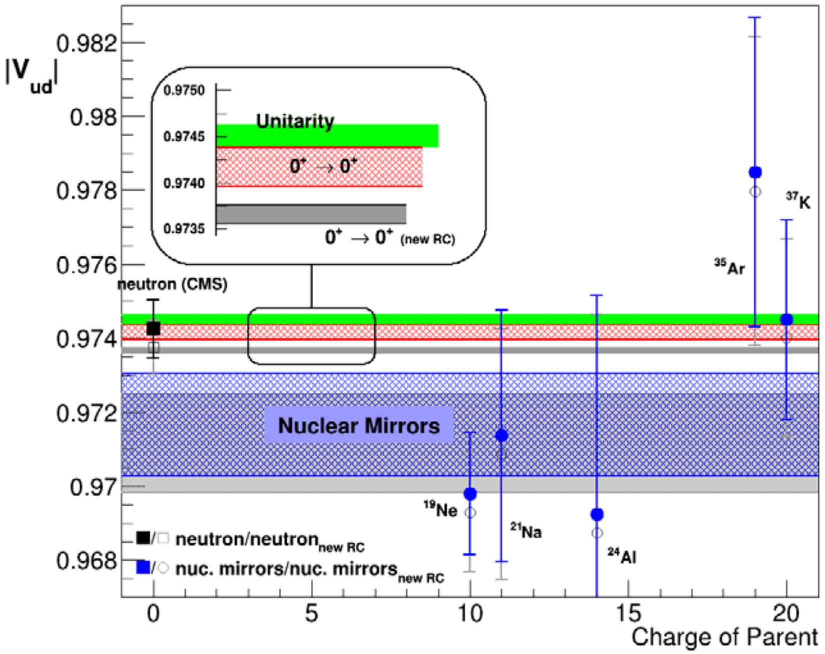
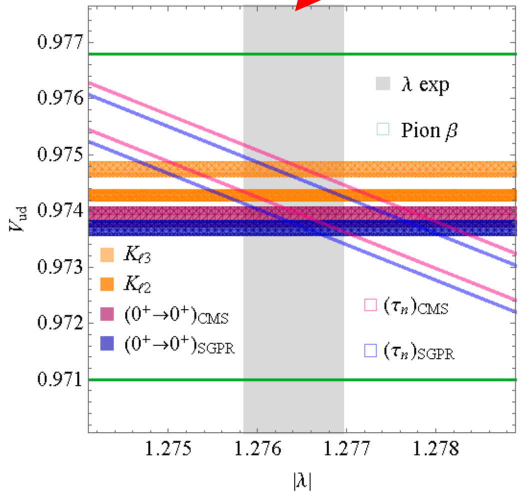
Nuclear Structure?

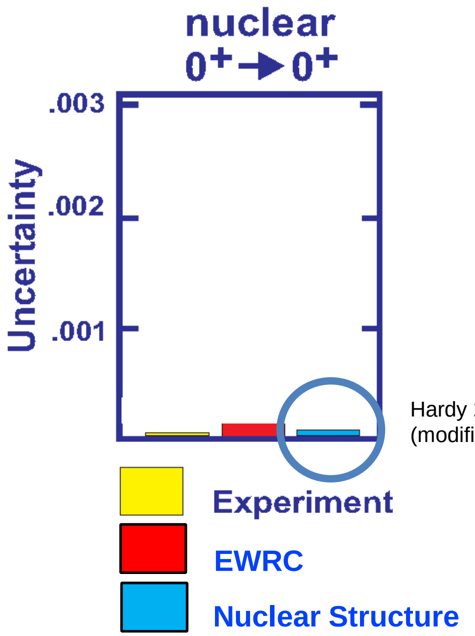
BSM?





Lepton Flavor Universality

Crivellin and Hoferichter, 2002.07184



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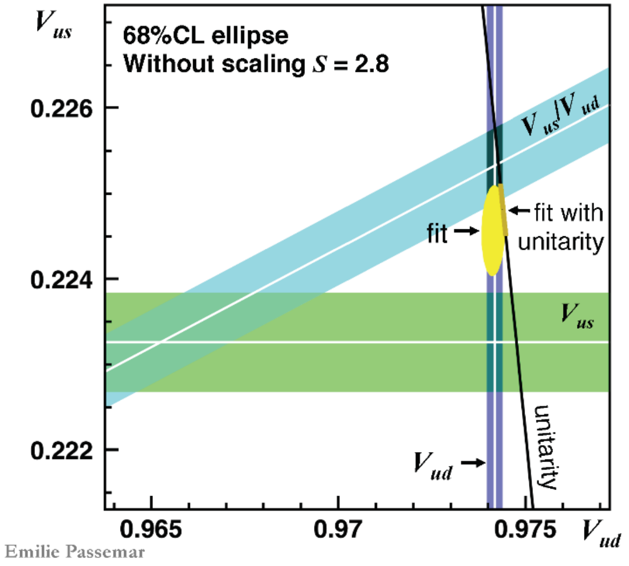


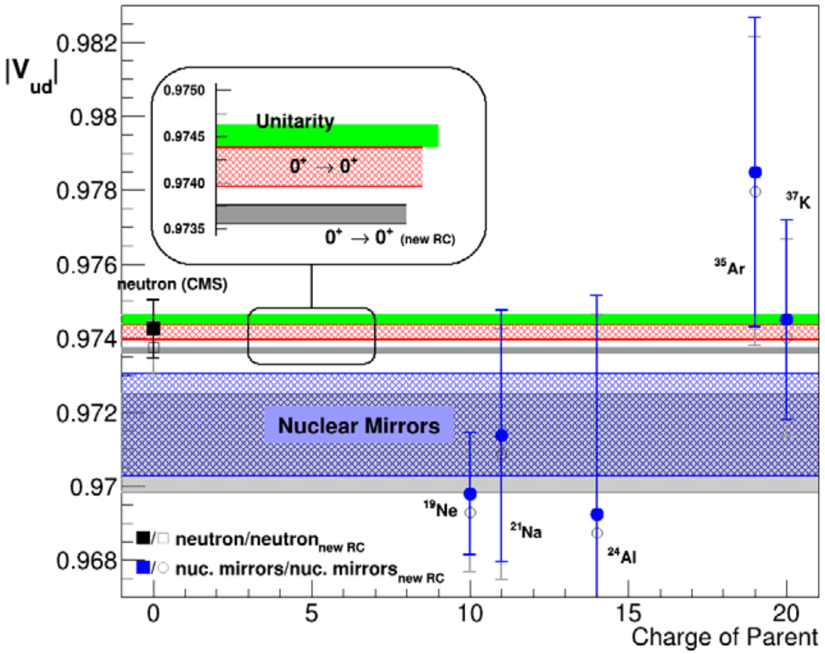
3-5σ discrepancy between $K\ell 2$ and $K\ell 3$

Current status of CKM Unitarity

Opportunities for Progress

V_{us}?

Nuclear Structure?



Marciano (INT 2019)

$$R_A=\Gamma(K\to\mu\nu(\gamma))/\Gamma(\pi\to\mu\nu(\gamma))$$

vs

$$R_V=\Gamma(K_L\to\pi e\nu(\gamma))/\Gamma(\pi^+\to\pi^0 e^+\nu(\gamma))$$

Improve lattice constraints with improved K/π ratio for $K\ell 3$ with improved measurement of $\pi^+ \to \pi^0 e^+ \nu$

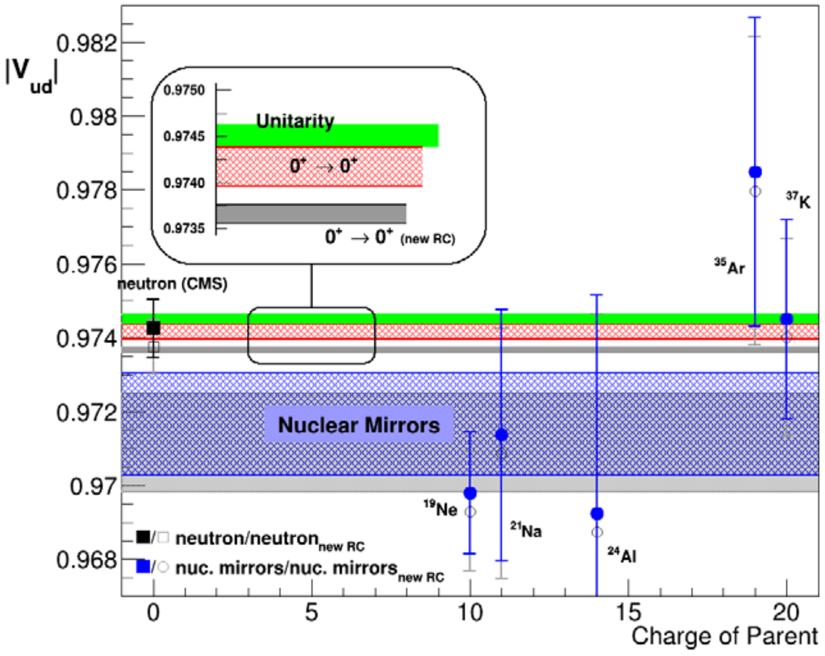
Current status of CKM Unitarity

Opportunities for Progress

V_{us}?

Nuclear Structure?

- Neutron lifetime and angular corr (no nuclear structure)
- Improved measurements of mirror nuclei
  - target ≤ 0.1% precision (probe effects at scale of EWRC shift)
  - A=10 to A =20 multiple theory approaches, few superallowed cases



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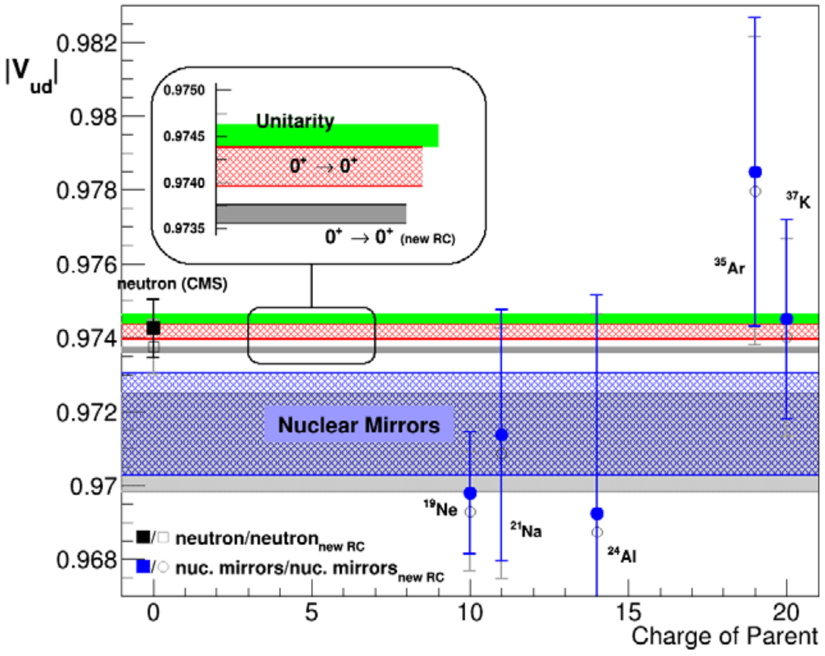

- e/μ K, π decay ratios
- High precision neutron and mirror decay measurements:
  - can provide excellent broad band sensitivity to BSM
  - in some cases not limited by EWRC corr. (**will provide example!**)

- Neutron lifetime and angular corr (no nuclear structure)
- Improved measurements of mirror nuclei
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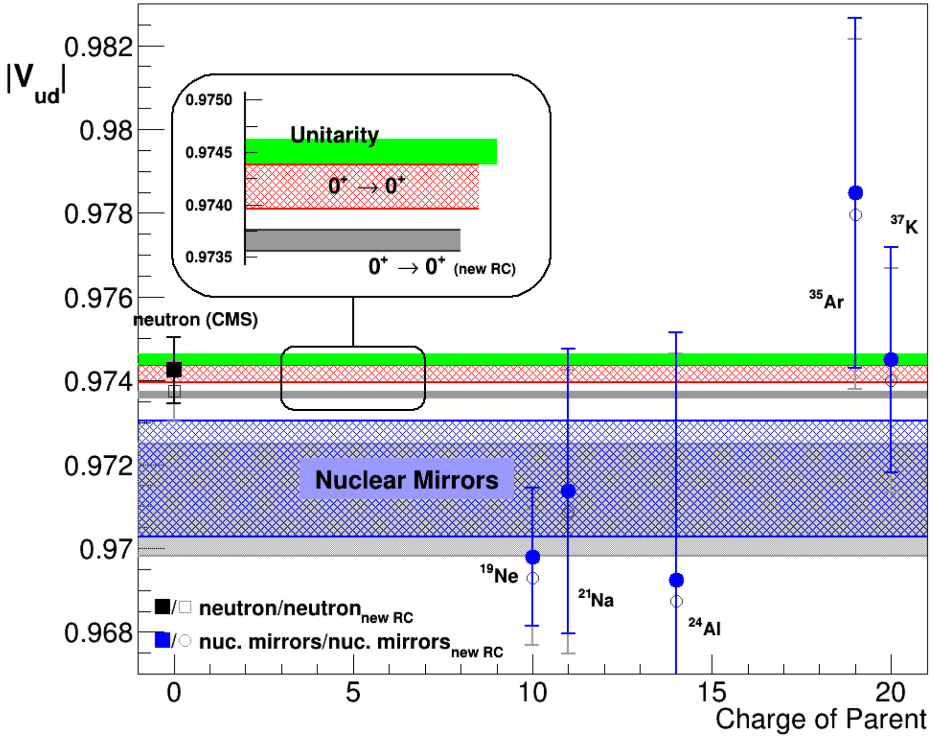
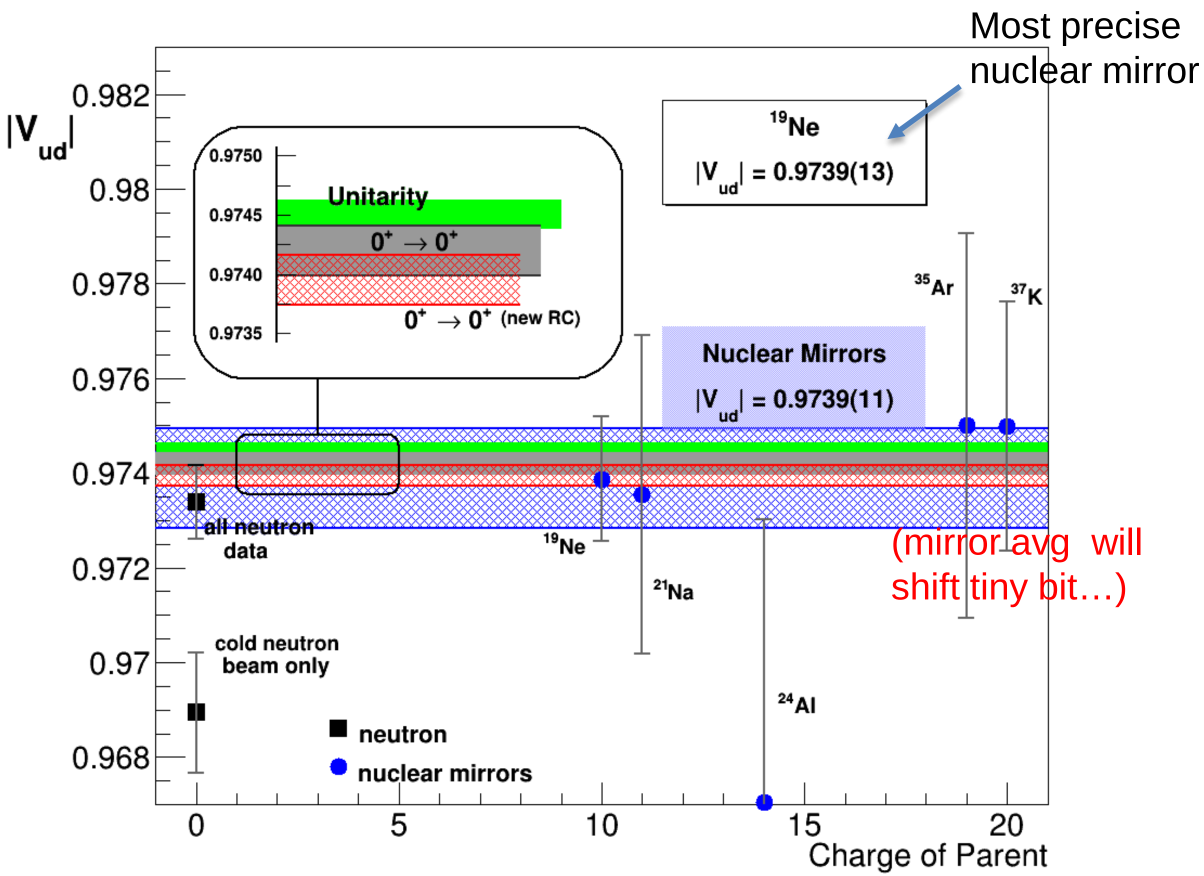
Status of Mirror Decays, Issues Resolved!



June 2019: 3σ from unitarity

Nuclear mirrors in good shape!



L. M. Hayen: GT recoil order effects and radiative corrections
1906.09870

$$|V_{ud}|_{0^+\to 0^+} = 0.97370(21)$$
$$|V_{ud}|_{n} = 0.97399(78)$$
$$|V_{ud}|_{n+mir} = 0.97396(63)$$

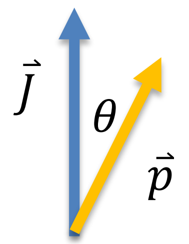
Current status sets stage for drive to higher precision!

TRIUMF is wonderfully positioned to have a major impact on the status of the charged current

How to proceed?

Optimizing impact:

- Identify opportunities to push to 0.01% (superallowed) precision
- “Modest” technical advances,building on local expertise
- Areas where competition “thin” –only 2 actually “on the books” at 0.2% sensitivity or below



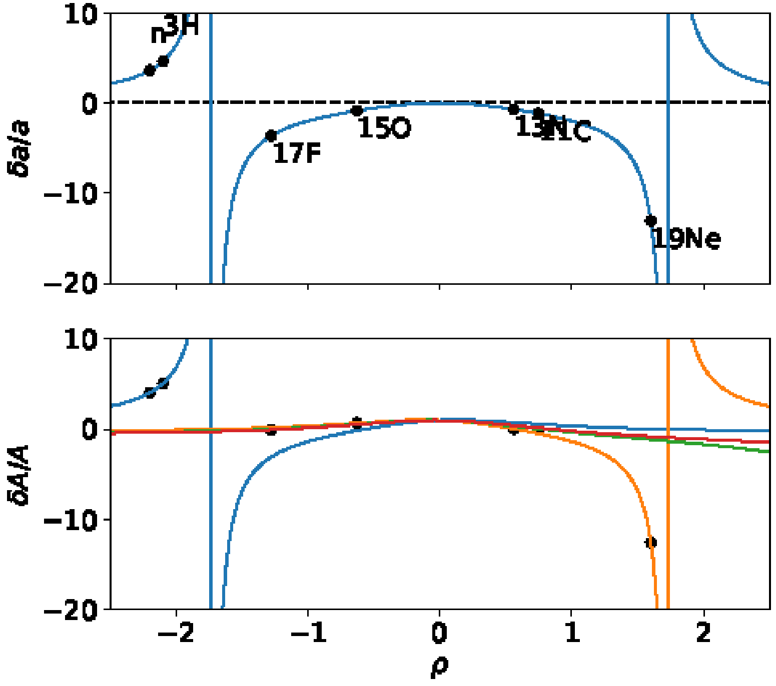
$$\Gamma = 1 + A(E)\langle J\rangle\beta\cos\theta$$

Angular correlation measurements with polarized nuclei

Large enhancements of sensitivity to coupling to ratio of F to GT decay amplitudes ρ for n (~4) and ^{19}Ne (~13) due to accidental cancellations in asymmetry

To reach current precision of superallowed with asymmetry measurement :

- neutron ~0.1%
- **^{19}Ne ~0.3%**



LH, A. Young, 2009.11364

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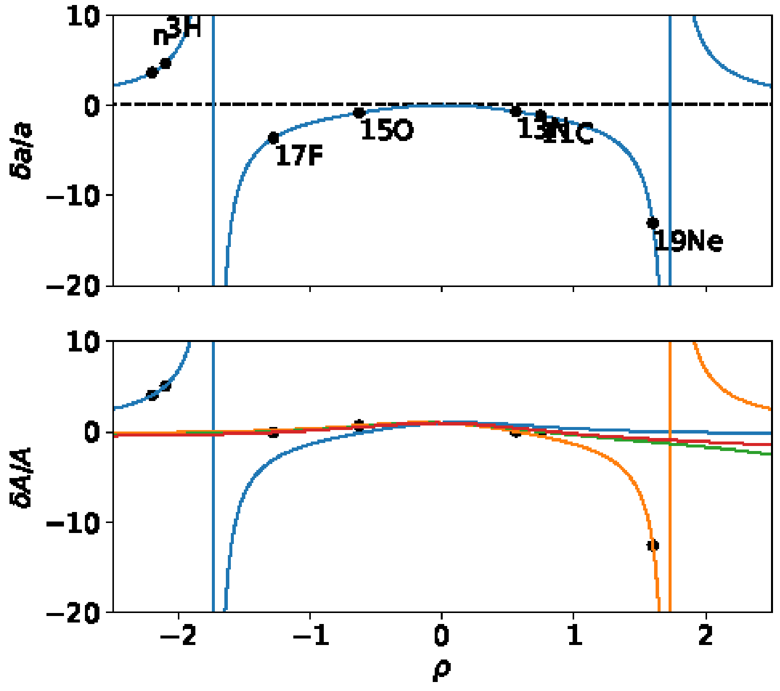
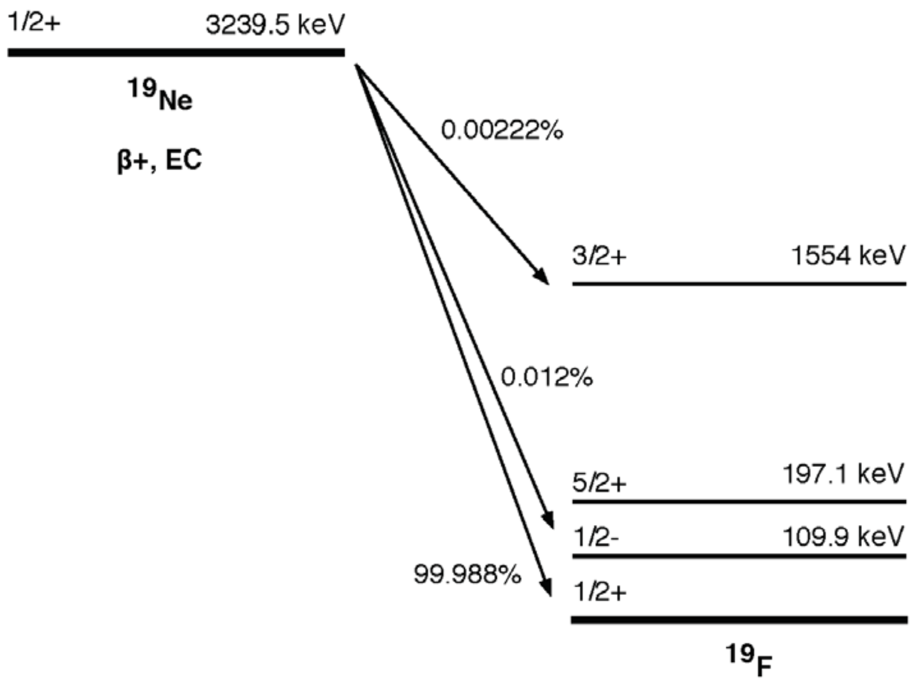
Already Achieved by TRINAT group!



LH, A. Young, 2009.11364

Decay Scheme and Advantages of ^{19}Ne



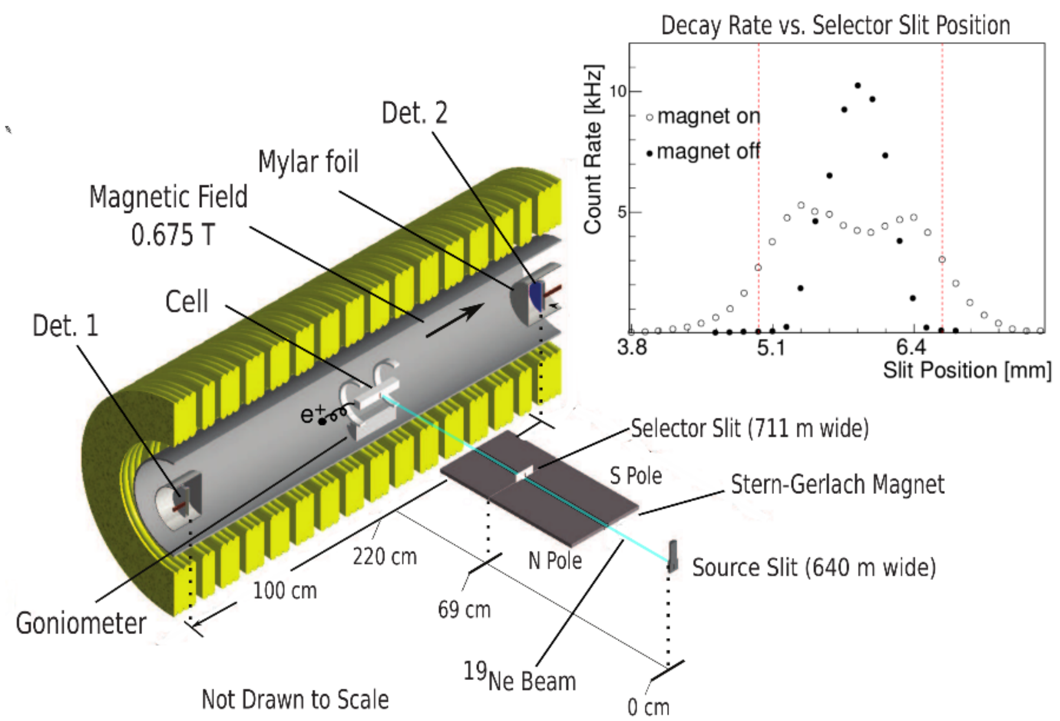
- Decay scheme ~100% to G.S
- All decay properties adequately known for 0.02% measurement except ρ
- Optically trappable

Table 2: Parameters used to calculate $\mathcal{F}t_0$ and A_0.

Constant	Value	Units	Reference
$K/(\hbar c)^6$	$8120.278(4) \times 10^{-10}$	$\mathrm{GeV}^{-4}\mathrm{s}$	*(44)*
$G_F/(\hbar c)^3$	$1.16637(1) \times 10^{-5}$	GeV^{-2}	*(44)*
Δ_R^V	$2.467(22) \times 10^{-2}$		*(11)*
Q_{EC}	3.23949(16)	MeV	*(45)*
f_V	98.648(31)		*(46)*
f_A/f_V	1.0012(2)		*(47)*
$\delta_C^V - \delta_{NS}^V$	$0.52(4) \times 10^{-2}$		*(25)*
BR	0.999878(7)		*(22)*
P_{EC}	0.00101(1)		*(25)*
$t_{1/2}$	17.2578(34)	s	*(48, 49)*
F_σ^V	-148.5605(26)		*(24, 50)*
W_0	2.72850(16)	MeV	*(45)*
m_e	0.510998910(13)	MeV	*(51)*
M	19.00188090(17)	amu	*(45)*

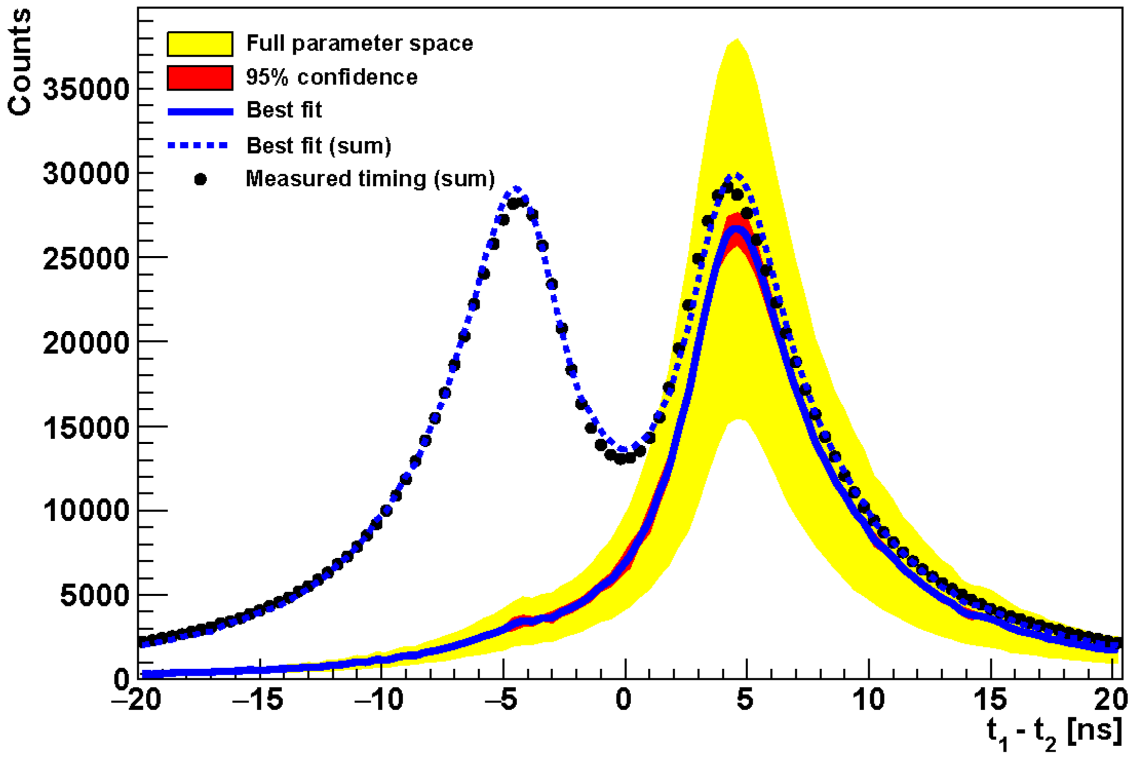
TRIUMF groups made significant contributions

Most Precise Experiment to Date…



(featured Stern-Gerlach polarizer)

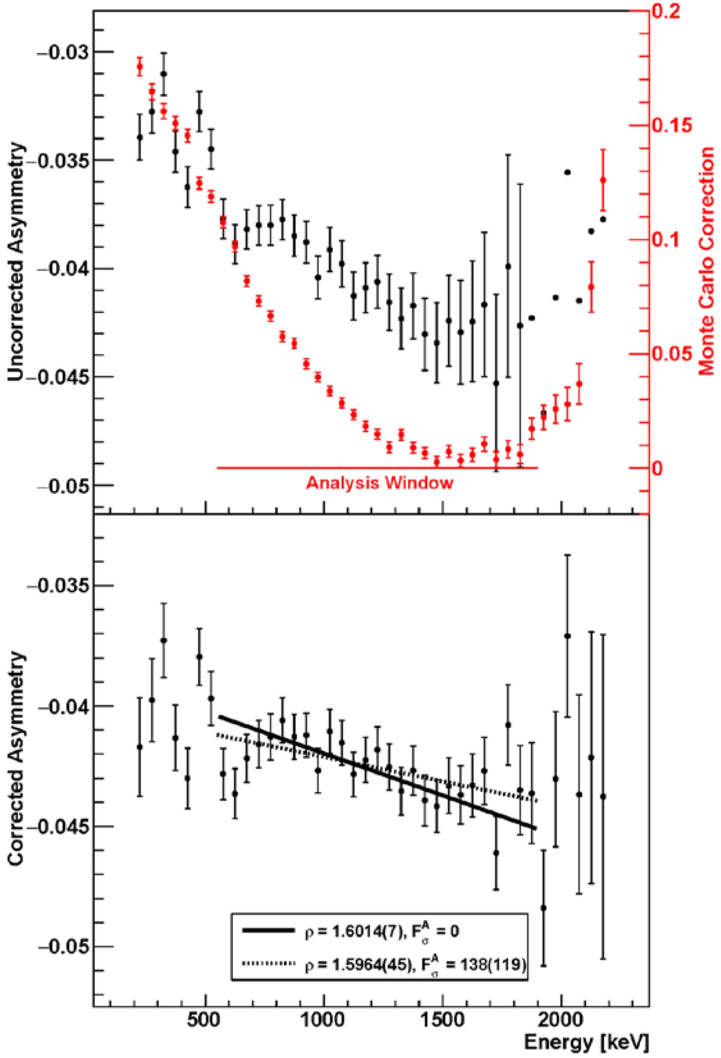
In 1993-95, Young participated in the thesis experiment of G. Jones at Princeton, a measurement of the beta asymmetry of ^{19}Ne



Successfully developed a model of Si(Li) detector response and detailed simulation of decay and calibration data to produce consistent analysis (thesis D. Combs)

^{19}Ne Beta Decay Results

Result: no evidence for 2nd class currents,
a roughly 0.15% measurement of ρ



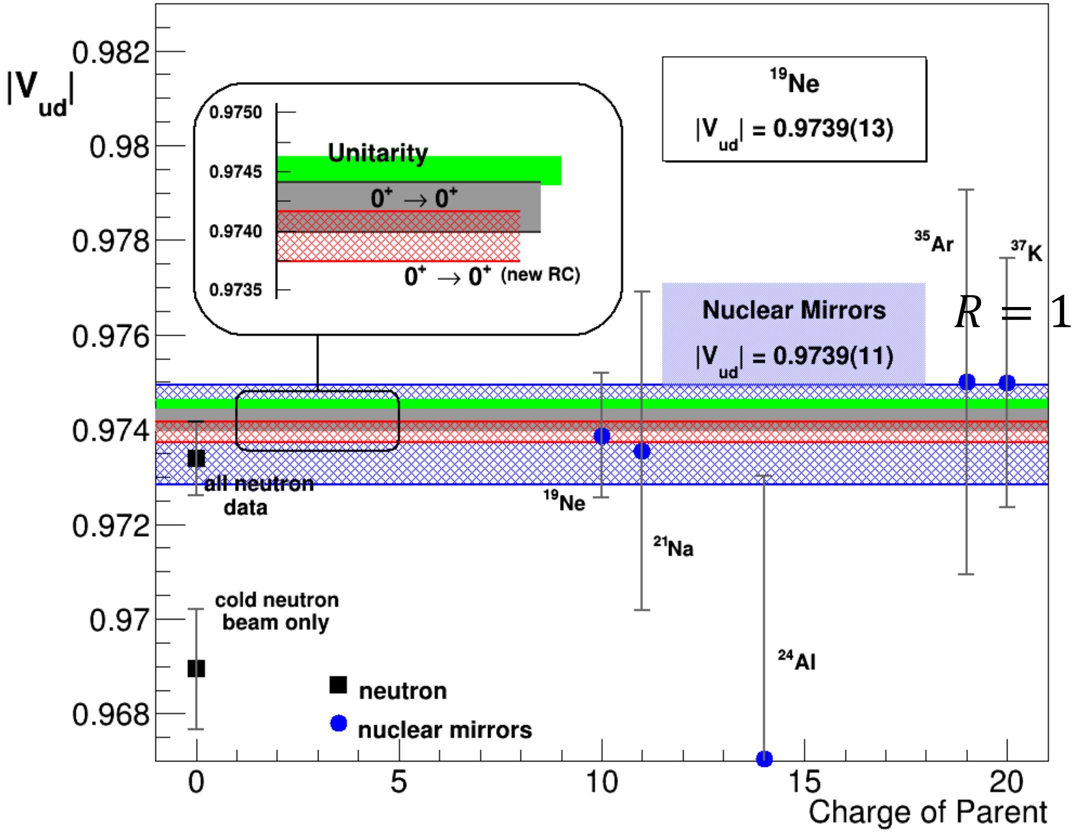
Systematic	Correction (10^{-4})	Uncertainty (10^{-4})
Monte Carlo Corrections:		
Above threshold in both detectors:		
Backscatter correction	+14.5	±3.6
Energy loss correction	-2.0	±0.5
Above threshold in a single detector:		
Backscatter correction	+3.1	±0.8
Energy loss correction	-0.9	±0.2
Below threshold in both detectors:	-0.5	±0.1
Polarization	–	+5.7 -0.0
Spin relaxation	+5.3	±5.3
Energy non-linearity	–	±0.5
Dead time	-0.5	±0.4
Pileup	+0.6	±0.4
Background subtraction	+0.2	±0.2
Statistical	–	±2.6
Total	**+19.8**	+6.5, −8.7

$$A_0 = -0.03872(65/-87)_{sys}(26)_{stat}$$

$$\rho = 1.6014(+21/-28)_{sys}(8)_{stat}$$

Impact

Mirror decays now fully consistent with neutron and superallowed (n and mirrors now make an impressive crosscheck of superallowed



$R = 1$

Ratio of ^{19}Ne to n Ft_0 has impressive sensitivity to tensor Fierz terms:

$$R = 1 + 0.051\epsilon_S - 6.1\epsilon_T$$

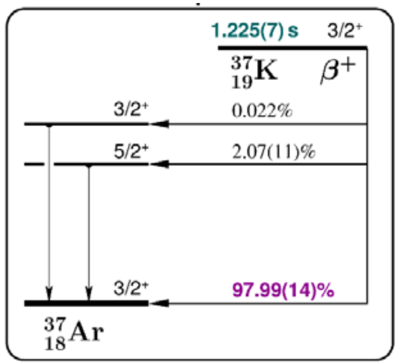
$$\Lambda_T > 5.5\ TeV$$

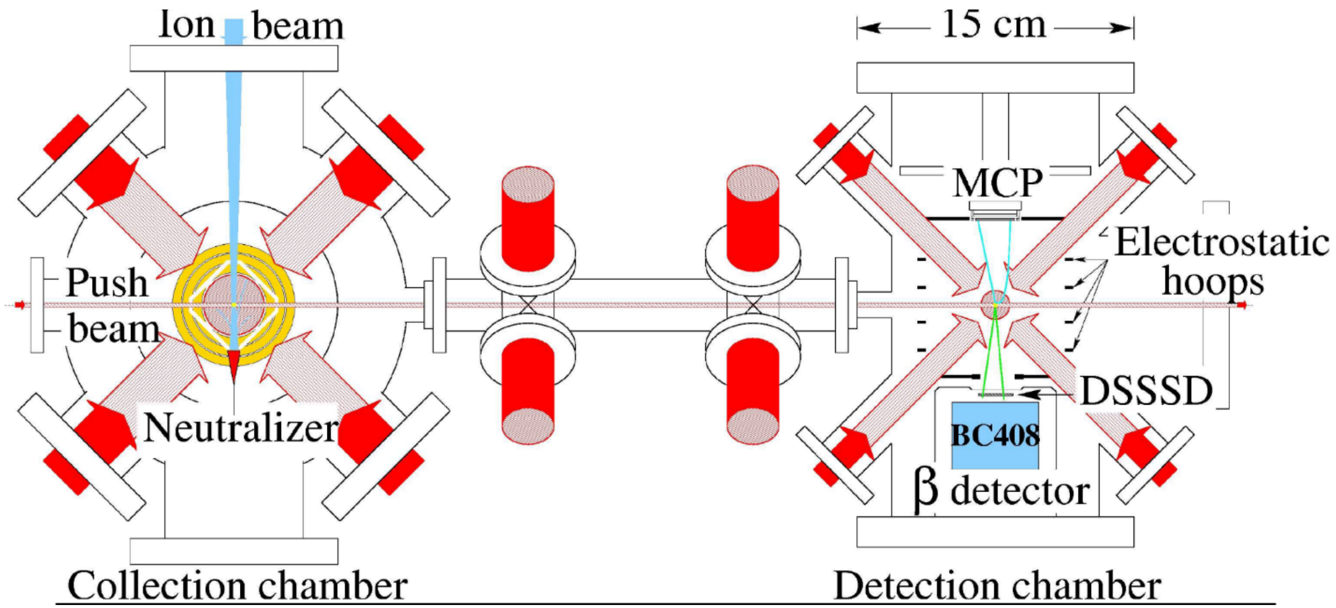
Over 20 TeV with 0.02% precision!

Note: Fierz term changes sign from beta to positron decays! Also handy for other measurements

Ongoing Research…

Laser-trapped species include Alkali metals (^{37}K) and meta-stable & noble gas atoms (^{19}Ne)



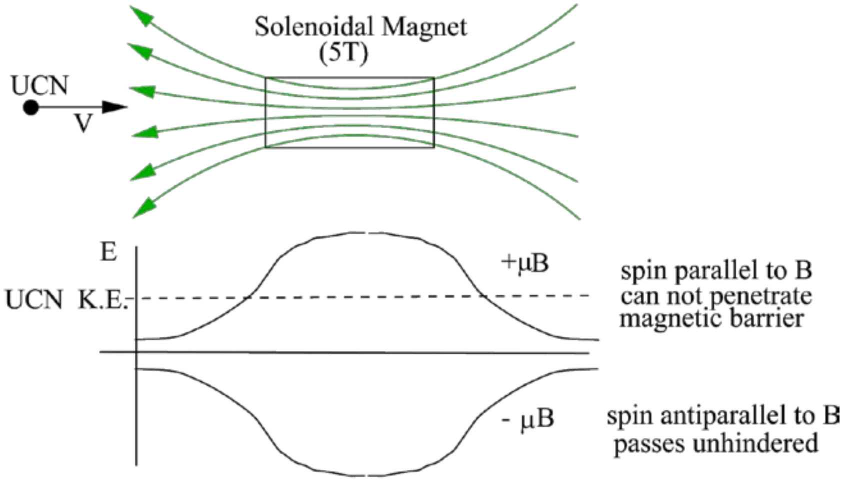


TRINAT measurement improves all major sources of uncertainty in Princeton measurement by factor of 10, improvements on the way…

Options for improvement may exist for neutrons too!

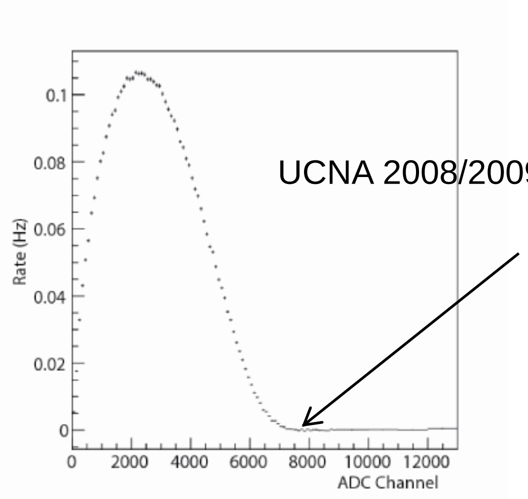
Motivation for Measurement of Beta Asymmetry with UCN

Polarization: "Potential barrier" polarization demonstrated effective alternative to supermirror/^{3}He cell technology with P ≥ 99.5% and ultimate uncertainties at or below 0.1% level

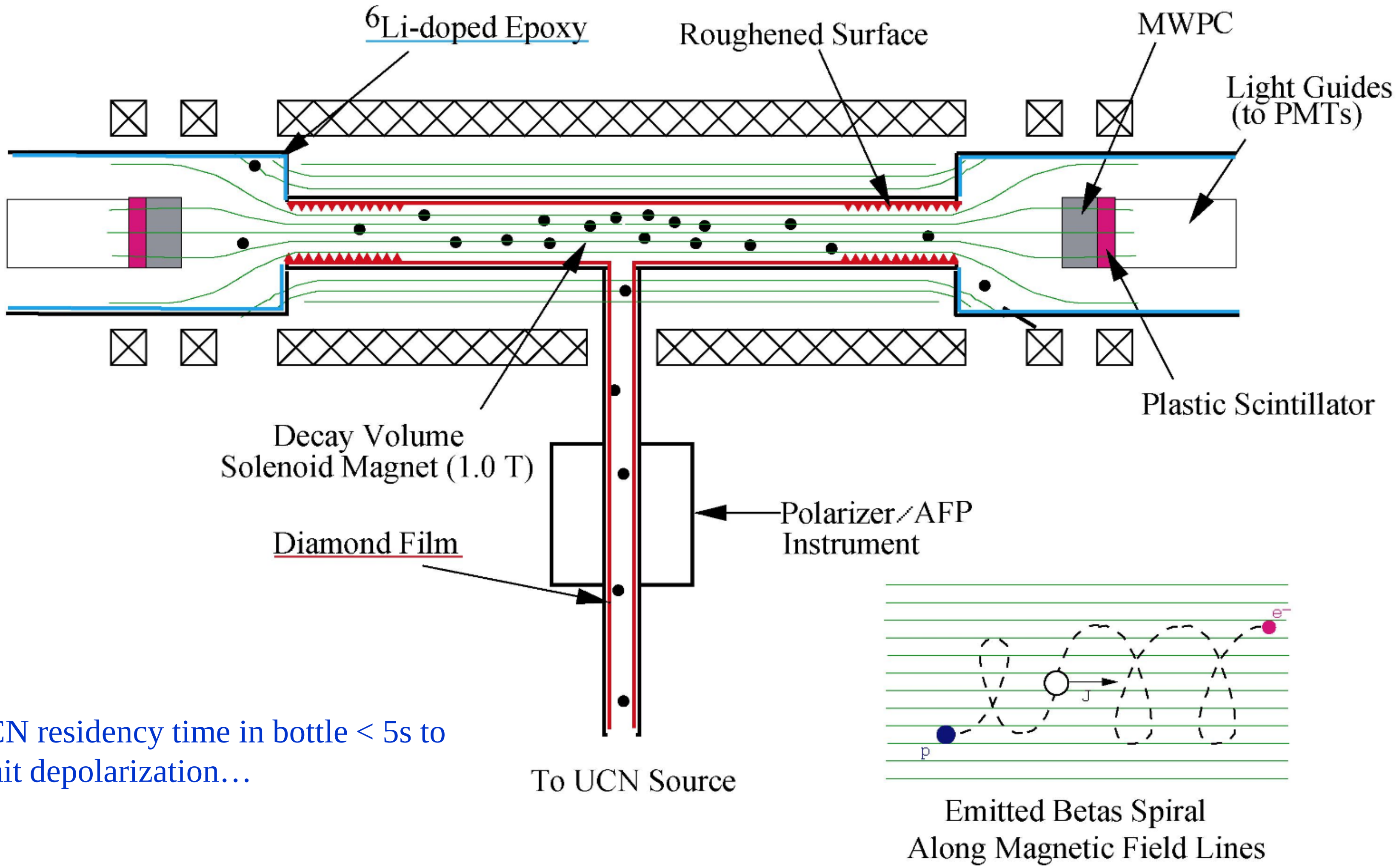


(note: neutron magnetic moment is negative)

Neutron generated backgrounds: small number of neutrons and low capture probability (long residency time) lead to order of magnitude improvement relative to (then) current cold neutron beams experiments



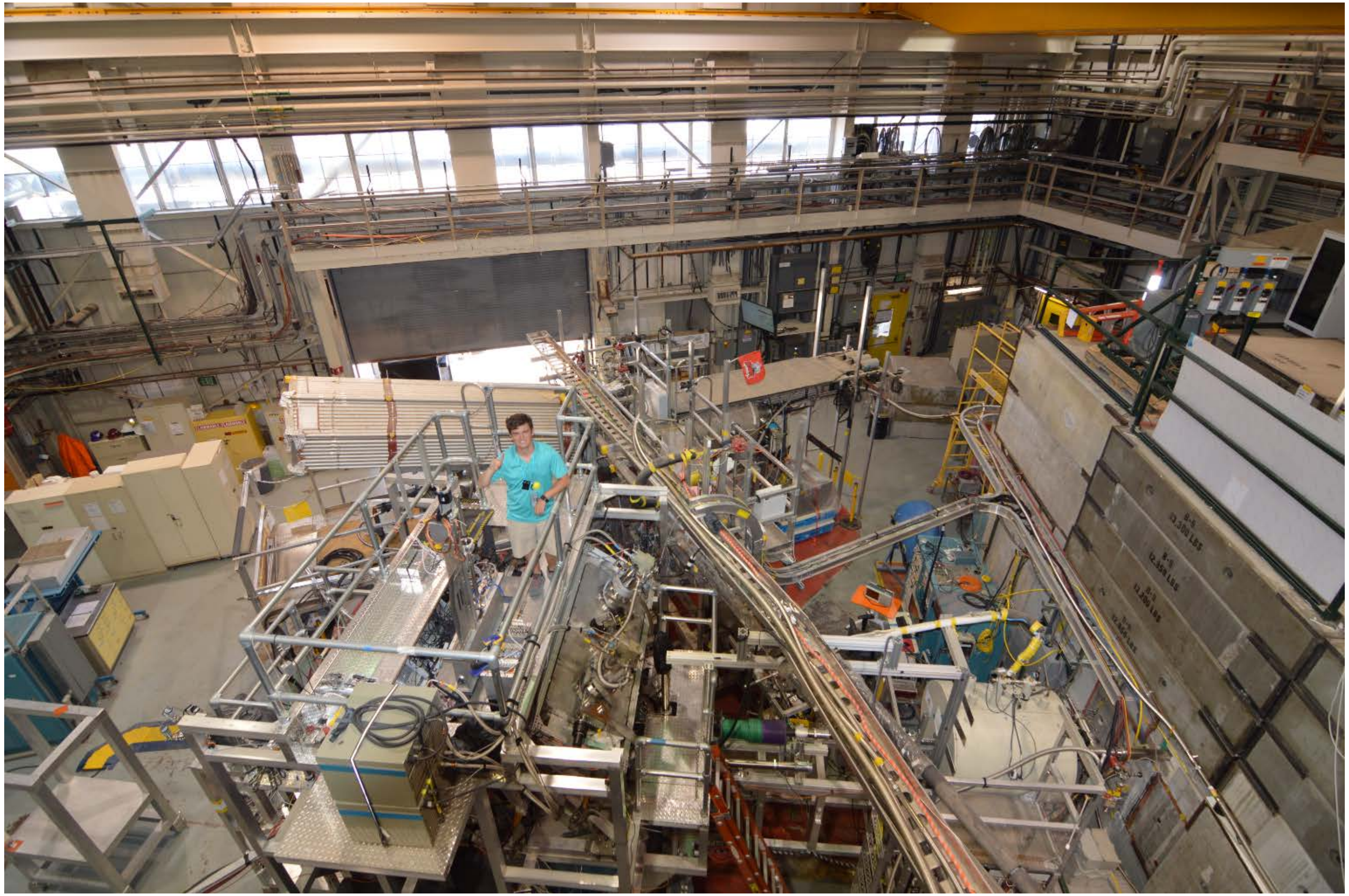
The Original Concept for UCNA



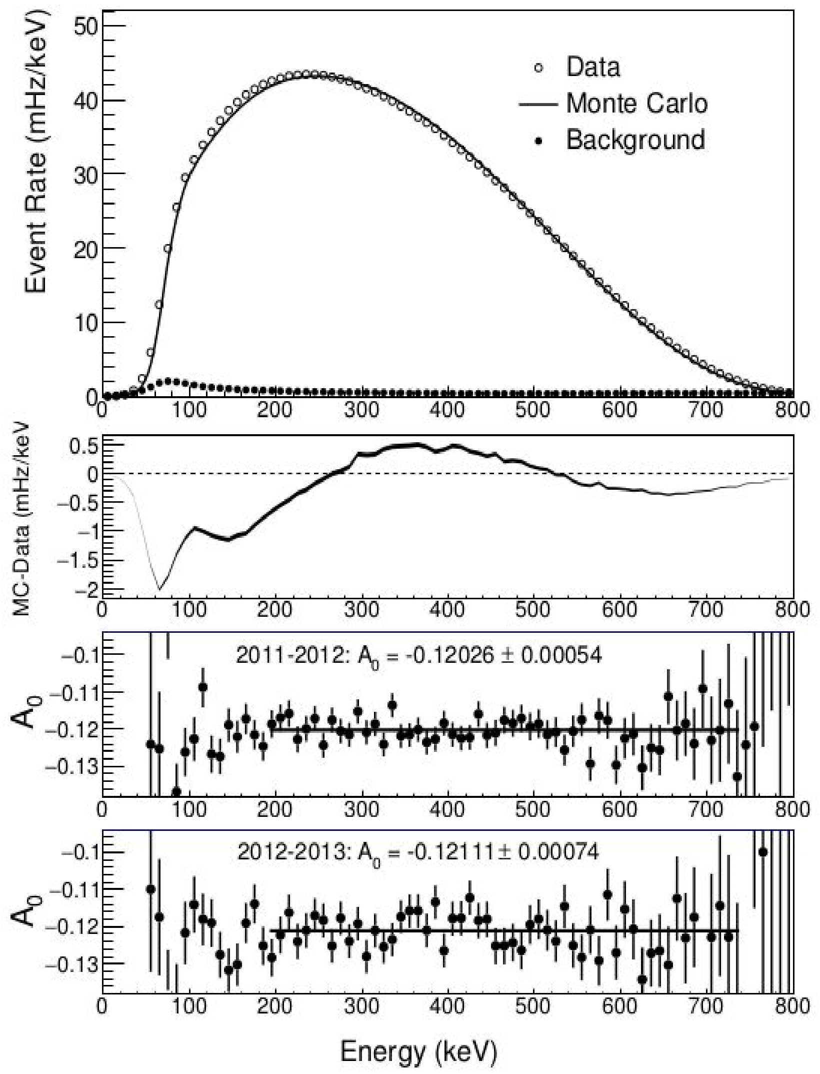
UCN residency time in bottle < 5s to limit depolarization…

With **116 dps in an open trap:**
uncertainty in $\delta A_o/A_o$ < 0.2% in ~1 year

Obtained between 1 and 2 UCN/cm^3



Results



$$A_0 = -0.12054(44)_{\mathrm{stat}}(68)_{\mathrm{syst}}$$

$$\lambda \equiv \frac{g_A}{g_V} = -1.2783(22)$$

2011-2012

$$A_0 = -0.12026(54)_{\mathrm{stat}}(67)_{\mathrm{syst}}$$

2012-2013

$$A_0 = -0.12111(74)_{\mathrm{stat}}(69)_{\mathrm{syst}}$$

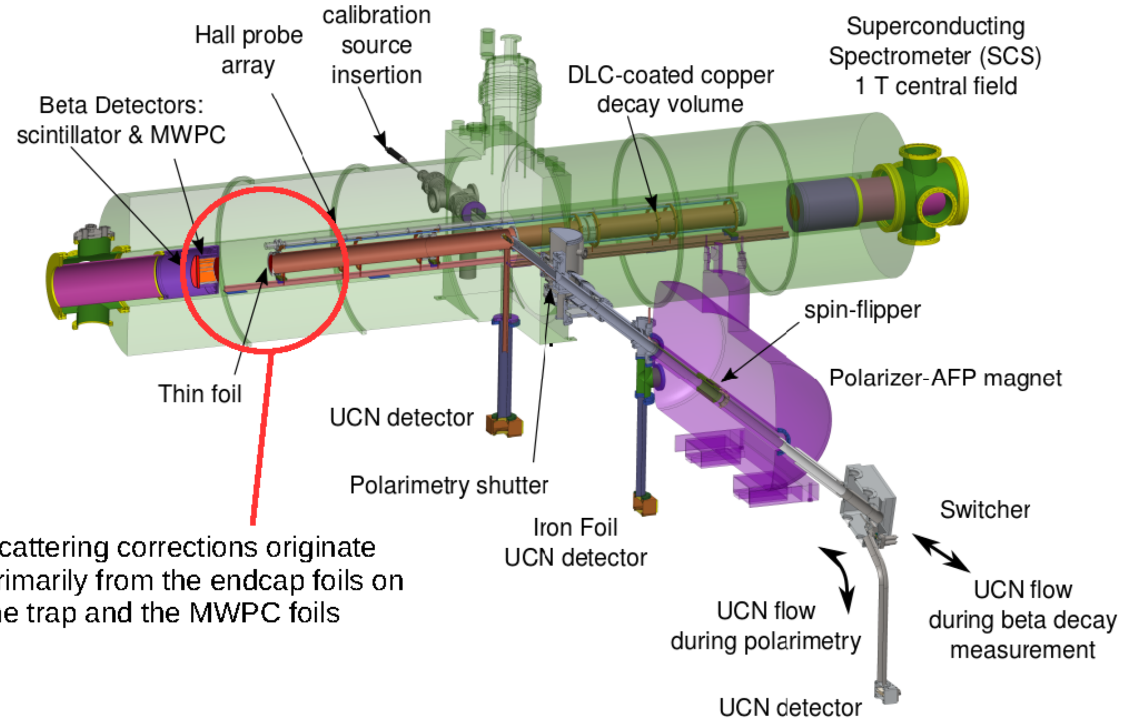
Critical Issue: scattering corrections

$$A_0 = -0.12054(44)_{\mathrm{stat}}(68)_{\mathrm{syst}}$$ **0.67%**

$$\lambda \equiv \frac{g_A}{g_V} = -1.2783(22)$$ **0.17%**

	% Corr. 2011-2012	% Corr. 2012-2013	% Unc.	2010 Unc.
$\Delta_{\cos\theta}$	-1.53	-1.51	0.33	0.30
$\Delta_{\mathrm{backscattering}}$	1.08	0.88	0.30	0.34
Energy Recon.			0.20	0.31
Depolarization	0.45	0.34	0.17	0.56
Gain			0.16	
Field Nonunif.			0.11	
Muon Veto			0.03	
UCN Background	0.01	0.01	0.02	
MWPC Efficiency	0.13	0.11	0.01	
Statistics			0.36	
Theory Corrections [9, 10, 24–27]				
Recoil Order	-1.68	-1.67	0.03	
Radiative	-0.12	-0.12	0.05	

Most dramatic improvement, from shutter!



Scattering corrections originate primarily from the endcap foils on the trap and the MWPC foils

(originally not in design, but required to obtain sufficient decay rate)

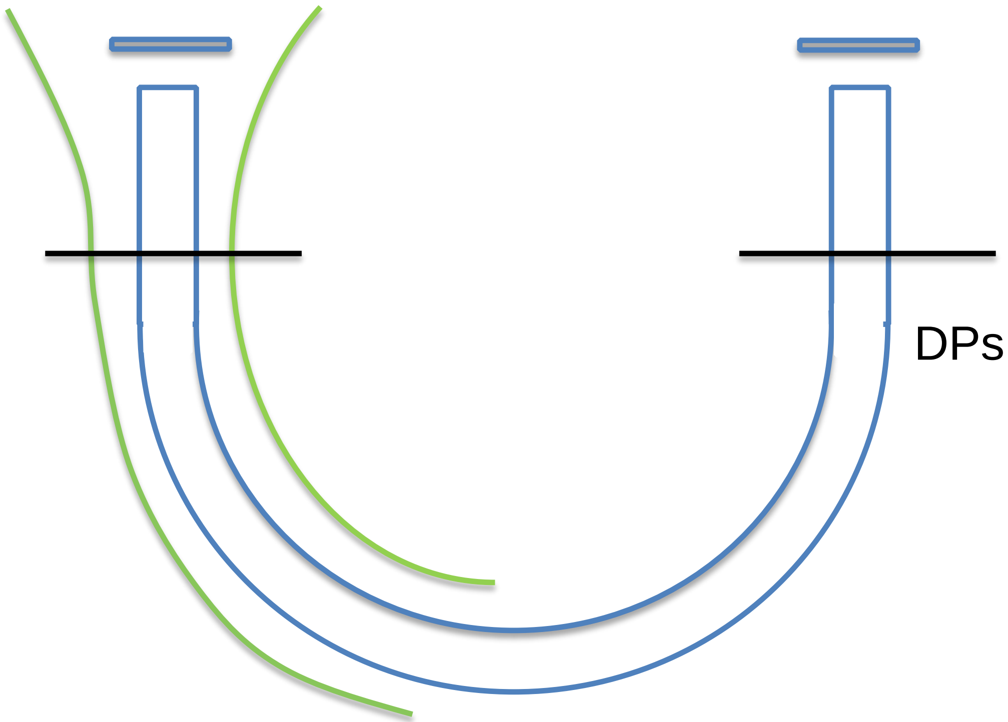
If it is possible to load a 10 liter volume (5cm x 200cm) to ~100 UCN/cm^3 both issues can be addressed:

Overall geometry fairly compact (vertical)
Fields ~ 1T

Optimized, shielded detector geometry

Decay ensures competitiveness with most sensitive measurements (Perc)

Max UCN height provides windowless break



DPs wall coatings (depol < 1×10^{-6})

S. Lamoreaux suggested this in early discussions concerning UCNA

Fill through split coil gaps at bottom

Extending the Reach of neutron EDM Experiments with Precession Searches

- EDM apparatus are use successfully to place limits Lorentz invariance violation scenarios, axions and other dark matter and short-ranged interactions
- EDM experiments must be optimized for long storage time and the application of strong electric fields, often limiting their flexibility
- As more EDM experiments come on line and densities increase, planning capability for different cell configurations, inner surface topologies and field orientations may have a significant impact on the physics delivered by the experiment
- Two cases as examples: mirror neutron searches and ALPs

TRIUMF is wonderfully positioned to have a major impact on future precession limits

Neutron-Mirror Neutron Searches

- Motivated by fact that spin-conserving mirror world interaction breaks into two, coupled two state problems when fields are along the quantization axis in respective universes

- Expect generically that eigenstates are effected quadratically by perturbations, precession measurements generically possible!

Berezhiani, Eur. Phys. J. C **64**, 421-431 (2009)

- Started considering possible experiments with small working group (B. Franke, C. Swank, G. Pignol, S. Roccia)

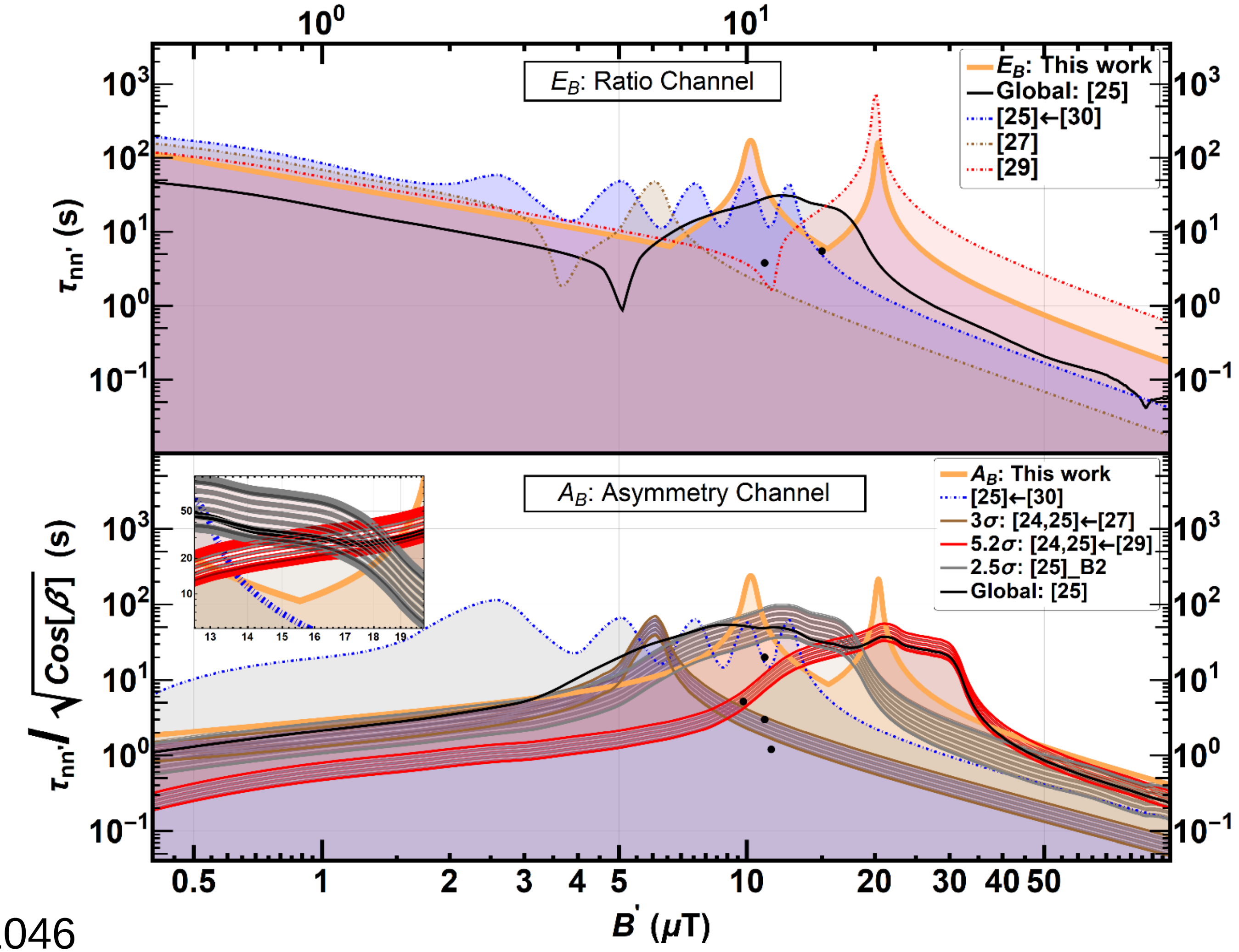
still effectively sharing my notes...

Conducted to monitor magnetic field dependent oscillations with interaction

$$\mathcal{H} = \begin{bmatrix} -\mu_n \boldsymbol{B}\cdot\boldsymbol{\sigma} & 1/\tau_{nn'} \\ 1/\tau_{nn'} & -\mu_n \boldsymbol{B'}\cdot\boldsymbol{\sigma} \end{bmatrix},$$

Results in field dependent oscillations

$$P^{nn'}_{BB'}(t) = \frac{\sin^2[(\omega-\omega')t]}{2\tau^2_{nn'}(\omega-\omega')^2} + \frac{\sin^2[(\omega+\omega')t]}{2\tau^2_{nn'}(\omega+\omega')^2} + \left(\frac{\sin^2[(\omega-\omega')t]}{2\tau^2_{nn'}(\omega-\omega')^2} - \frac{\sin^2[(\omega+\omega')t]}{2\tau^2_{nn'}(\omega+\omega')^2}\right)\cos\beta \quad (2)$$



Latest limits from PSI, Abel et al 2009.11046

Strongest limits come from storage expts (Serebrov)

But…can cause precession too!

A spin-dependent Hamiltonian is presented in Berezhiani et al, Eur. Phys. J. C 72:1974 (2012) for a spin-independent n-n' coupling:

$$H = \begin{bmatrix} \mu B \sigma & \epsilon \\ \epsilon & \mu' B' \sigma \end{bmatrix} \tag{1}$$

which can be expanded to

$$H = \begin{bmatrix} \frac{\mu}{2}B & 0 & \epsilon & 0 \\ 0 & -\frac{\mu}{2}B & 0 & \epsilon \\ \epsilon & 0 & \frac{\mu'}{2}B' & 0 \\ 0 & \epsilon & 0 & -\frac{\mu'}{2}B' \end{bmatrix} \tag{2}$$

For fields along the z and z' axis

for the wavefunction

$$\Psi = \begin{bmatrix} \psi_{n+} \\ \psi_{n-} \\ \psi_{n'+} \\ \psi_{n'-} \end{bmatrix}, \tag{3}$$

neutron: spin up, spin down

mirror neutron: spin up, spin down

Mirror neutrons have same mass, opposite magnetic moment

Splitting depends on magnitude of earth and mirror magnetic fields!

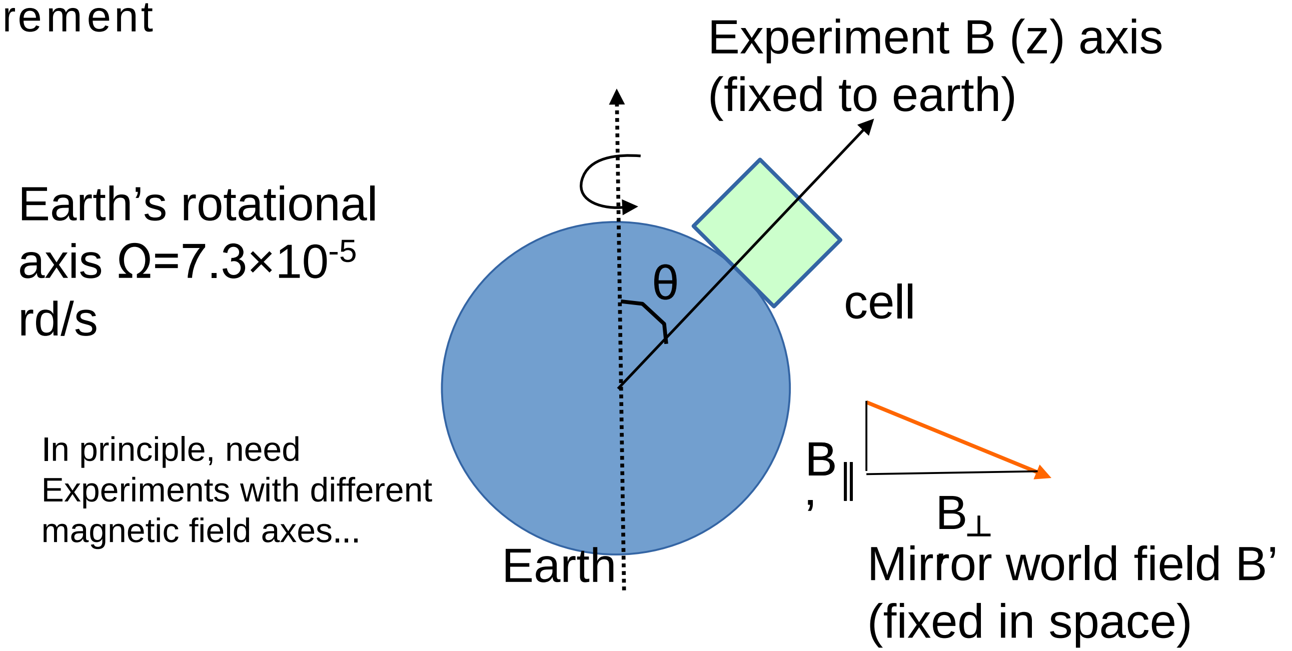
- Fields in both neutron and mirror neutron frames have very small spatial variations (true for normal fields for precession experiments)

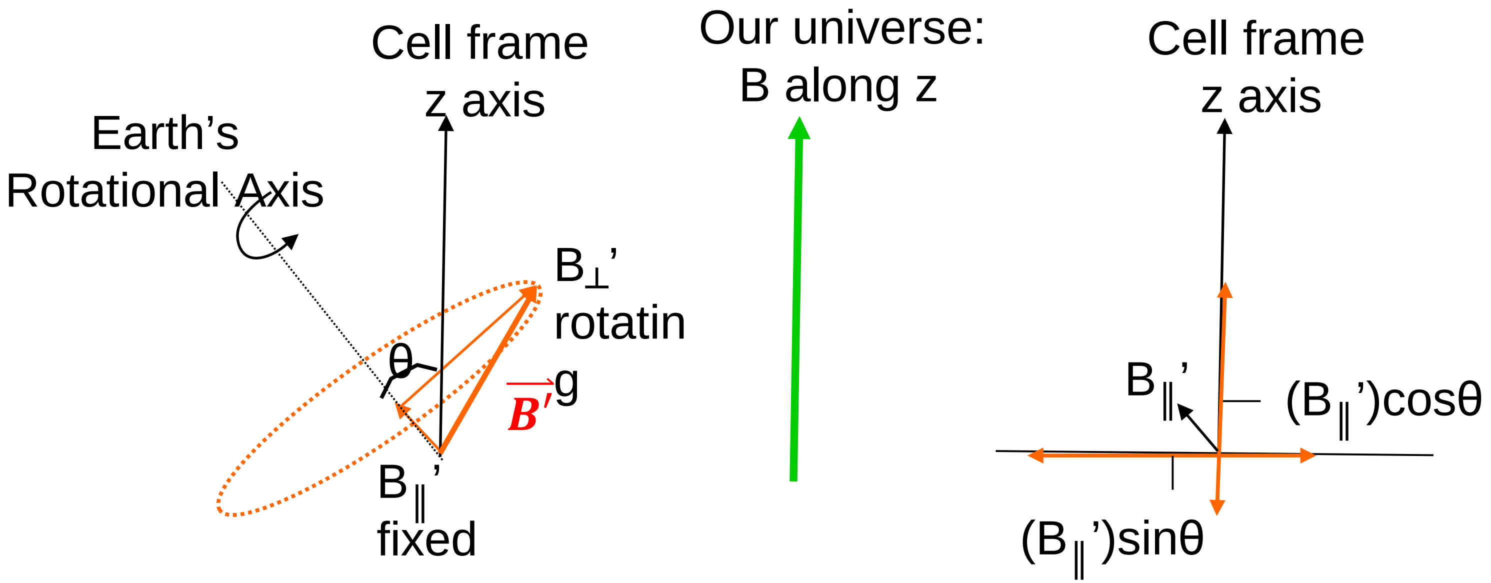
- Mirror neutrons are not confined by cell walls

- Magnetic field arranged along the z axis in our universe (the experiment)

- Each precession measurement takes ~100-300 s (T_2 or storage time limit)

- Negligible n’ amplitude before first spin flip (flip in guide with very short collision time, short times between collisions compared to precession measurement





The cell sweeps out a trajectory, where $B_\parallel'$ is constant, and $B_\perp$' rotates at freqency Ω

Average field: ($B_\parallel$')cosθ along z
($B_\parallel$')sinθ along x

Fluctuating field: ($B_\perp$')cosθ along z

Non-zero mirror field produces a diurnal variation in the coupling to n' and the precession frequency independent secular equation, $H\Psi = E\Psi$, can be written:

$$\begin{bmatrix} f-E & 0 & \epsilon & 0 \\ 0 & f-E & 0 & \epsilon \\ \epsilon & 0 & d-E & 0 \\ 0 & \epsilon & 0 & d-E \end{bmatrix} \begin{bmatrix} \psi_{n+} \\ \psi_{n-} \\ \psi_{n'+} \\ \psi_{n'-} \end{bmatrix} = 0 \qquad (4)$$

The eigenvalue equation for this system is (with $f = \frac{\mu}{2}B$ and $d = -\frac{\mu'}{2}B'$:

$$(E^2 - f^2)(E^2 - d^2) - 2\epsilon^2 \left(E^2 + fd\right) + \epsilon^4 = 0 \qquad (5)$$

With solutions (letting $\Gamma = \sqrt{(f-d)^2 + 4\epsilon^2}$):

$$\begin{aligned} E_{n\pm} &= \pm\frac{1}{2}\left(\Gamma + (f+d)\right) \quad \Big\} \text{ Neutron in limit } \varepsilon \to 0 \\ E_{n'\pm} &= \mp\frac{1}{2}\left(\Gamma - (f+d)\right) \quad \Big\} \text{ Mirror neutron in limit } \varepsilon \to 0 \end{aligned} \qquad (6)$$

Expected result! Precession energies depend on coupling to mirror sector and mirror magnetic fields!

Experimental signal

$$|a(t_f)|^2 = \left[|b|^2 sin^2\frac{\omega_1}{2}t_f - |a||b| sin\Delta\phi sin\omega_1 t_f + |a|^2 cos^2\frac{\omega_1}{2}t_f\right]$$
$$= \frac{\alpha^2 M^2}{2}\left[1 - sin\left(2\left(\phi_o + \gamma\right) + \boxed{\left(E_2 - E_1\right)t_p/\hbar} + \pi/2\right)\right]$$

The part of the phase that evolves with the total storage time is:

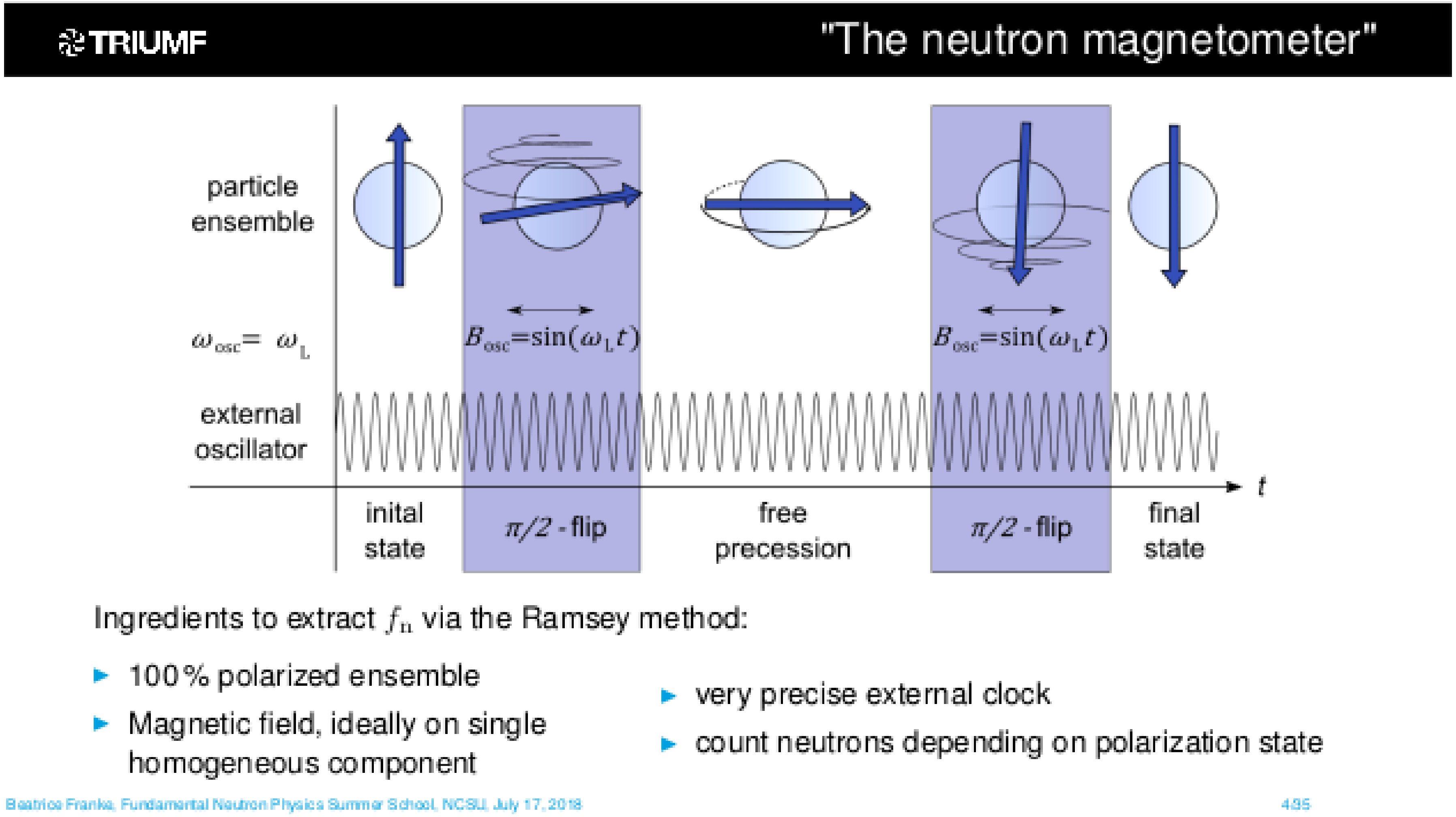
$$E_1 - E_2 = 2(f+d+\sqrt{4\varepsilon^2 + (f-d)^2})$$

$$E_2 - E_1 \approx -2f\left(1 + \frac{\epsilon^2}{(f-d)^2}\right),$$

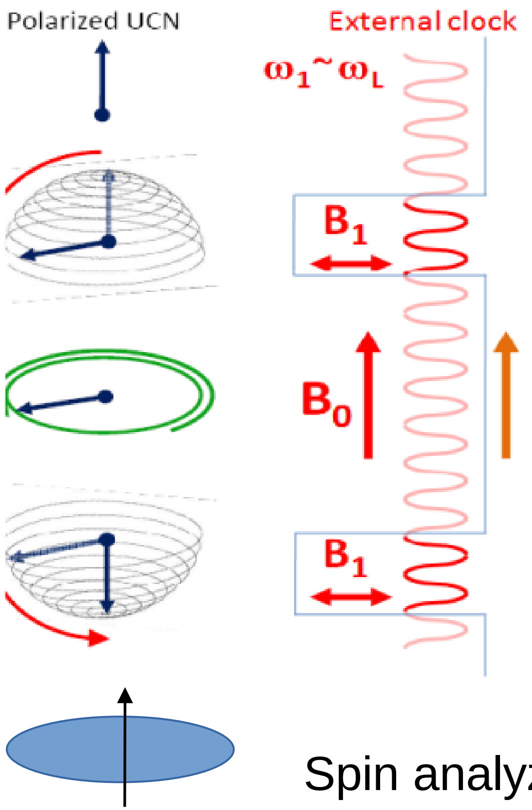
The effect of coupling to the mirror world is to change the effective size of the magnetic field! Effect is quadratic in couplings away from resonance, like n-n' oscillation

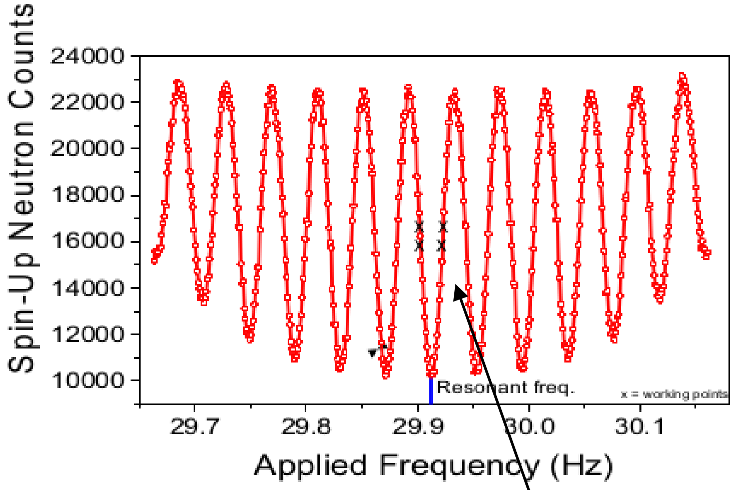
A Precession Experiment with Polarized Neutrons

From B. Franke, “By-products of nEDM Searches”, Neutron Summer School 2018, Raleigh NC (2018):



The Ramsey's method of separated oscillating fields





$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

Pick good points to
Measure slope is large...

Spin analyzer (depending on point in precession, spin somewhere between parallel and antiparallel spin analyzer axis)

We have considered 3 kinds of experiments so far

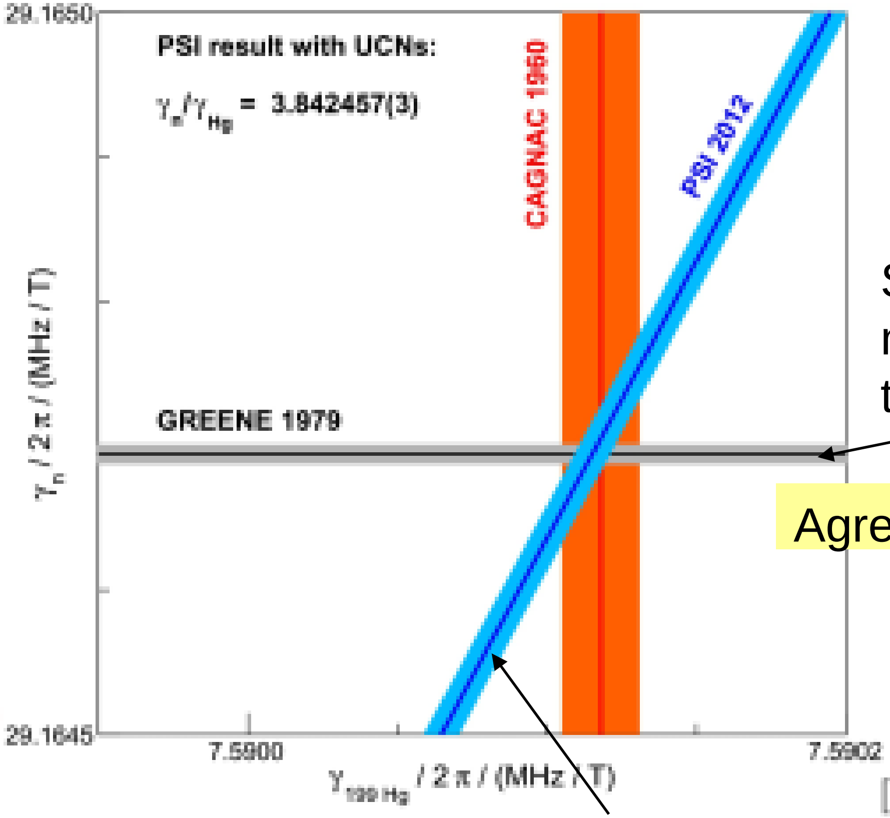
- Absolute average change in measured effective magnetic field due to “pseudo-magnetic field” from mirror couplings (expect deviation, especially if B’ on scales of few ~10^{-6} T where EDM experiments are performed with high precision)
- B-scaling measurements (look for non-linearity in B)
- Time varying fields

All three rely on the presence of **atomic co-magnetometer,** which can be used as a reference, and which is not affected by coupling to the mirror world (checked with Z. Berezhiani, this appears to be reasonable), experiment measures R:

$$R = \frac{\gamma_n}{\gamma_{Hg}}$$

with $\omega=\gamma B$

Results from a clock comparison



Super precise measurement of magnetic moment of neutron relative to proton by Geoff Greene

Agreement of extracted field: 0.28 ± 0.53 pT !

[Afach et.al., PLB **739**, 128 (2015)]

Measurement of relative to mercury (correct for gravitational effect + gradients)

A Limit from Pseudomagnetic Field Constraints

The precession phase is parametrized in terms of energy differences for the energy states:

$$\Delta E = E_2 - E_1 = -\mu_n B_z - (\mu_n B_z) = 2|\mu_n|(B + b) = 2f(1 + \delta)$$

Spin down Spin up

Mirror field

$\delta = \varepsilon^2/(f - d)^2$

Given limits on a pseudomagnetic field of $b < 5\times10^{-13}$ T with $B = 1\times10^{-6}$ T so $f = 6\times10^{-14}$ eV

$\varepsilon < 4.2\times10^{-17}$ eV

$T > 15$ s

For mirror fields significantly larger than 1 μT, these limits will be less stringent

- Changing magnetic fields is difficult for nEDM experiments – they are carefully optimized for these fields (for PSI they are about 1 μT)
- If several measurements were made of precession at the current precision of nEDMs, then for mirror fields near 1 μT or lower, the limit will be at the uncertainty in determinations of R, equivalent to the relative uncertainty of the precession frequency (or the energy of the precessing state):

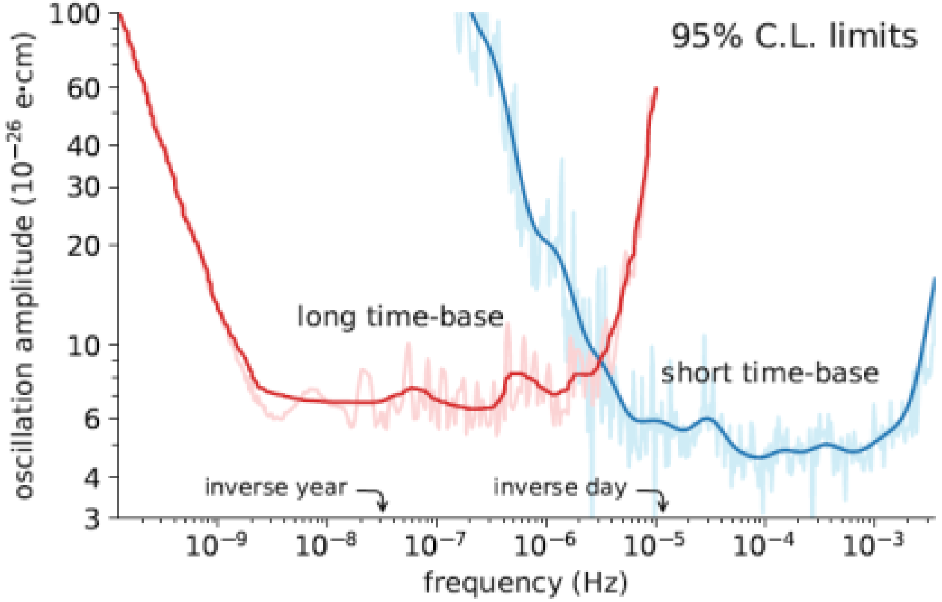
Convert EDM limit to effective magnetic splitting ($\Delta E = 2f + 2d_nE$):

$$\Delta E/2f = 2(\sim 1\times10^{-26}\ \text{ecm} * 10^{4}\ \text{V/cm})/(2*6\times10^{-14}\ \text{eV}) = 1.7\times10^{-9}$$

$$\varepsilon < 2.4\times10^{-18}\ \text{eV}$$

$$\tau > 260\ \text{s}$$

Abel et al., Phys. Rev. X 7, 041034 (2017)



Analysis of precession data (but not organized into EDM sets, just daily variations) could make interesting limits!

$\varepsilon < \sim 4.2 \times 10^{-18}$ eV

$\tau > \sim 149$ s

- We want to add the transverse fields in the mirror dimension. This has already been done by Berezhiani, but in a basis that confused me – I think that this will result in small changes, including producing a new source of T_1 and T_2 losses (needs to be checked – in some scenarios may produce observable signature for mirror fields

- Precession measurements may add a new tool (if this is right!) to probe interactions with a mirror universe. The sensivitivity seems comparable to beam and UCN disappearance measurements.

  - New observables of precession phase and depolarization, simultaneously accessible with oscillations

  - Some data already taken can probably be cast into interesting limits (based on rough estimates)!

- Resonance scenarios may offer more sensitivity, but complicated (beat frequency effects) developing 4x4 matrix approach – C. Swank observed that can scan through resonace and adjust width of resonance independent from field using dressed fields!

- Large range of field orientations, dressed fields, etc…useful for these studies – must be planned in advance!

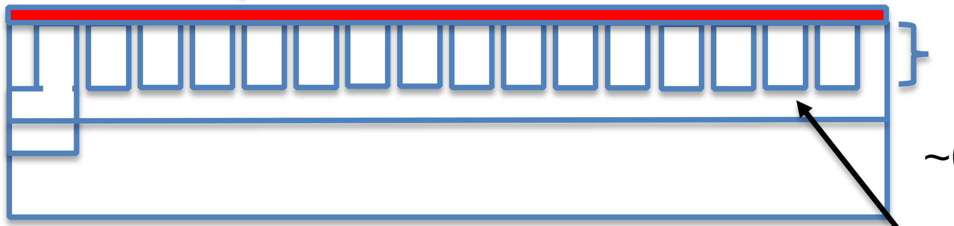
Another concept

- Another opportunity – SR forces!
- Very difficult to arrange experiments with different materials without disrupting experiments
- Also difficult to develop very large ratios of near-scale densities, attractor materials
- If precession cell designed appropriately can incorporate a microfluidic substrate which can increase the density ratios of probed materials by 1 to 2 orders of magnitude, and permit relative measurements (on reasonable time scales) without changing the measurement fields, and provides a control for effects!

Tuned to probe ranges ($i.e. V_5 = \alpha \frac{e^{-r/\lambda}}{r}$) near micron scale

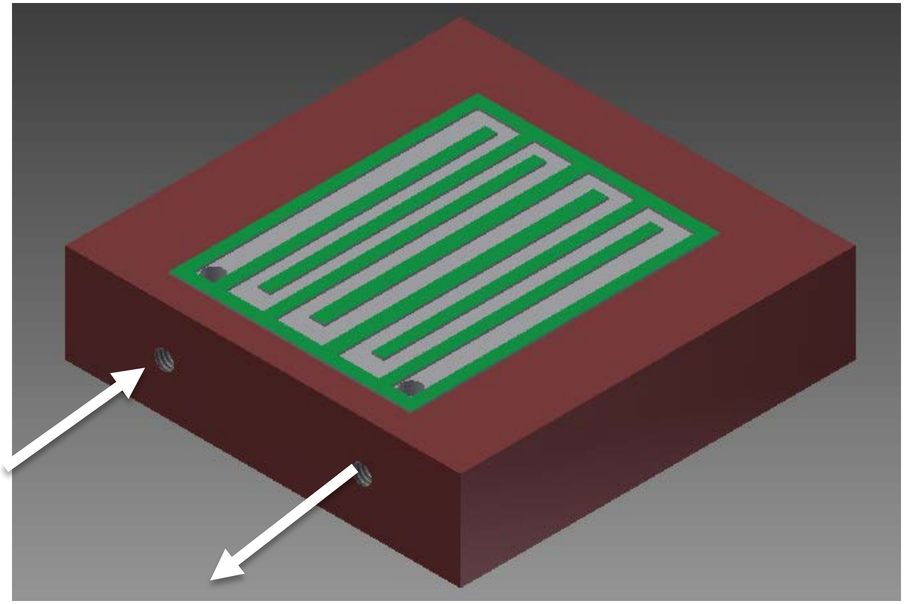
Membrane (SiN – coated with dPb?)

0.5 – 2 μm thickness



Channel depth

~0.1 - 1 mm



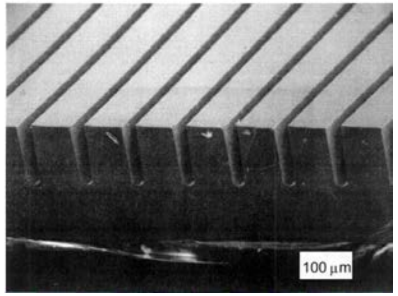
quartz block (10 cm x 10 cm, 2.5 cm thick)

Channel volume filling factor 90-95%
Minimum density at few microns -> .015 g/cm^3
Maximum density 12.6 g/cm^3 (95% Hg)

Si wafer
PDMS bonding

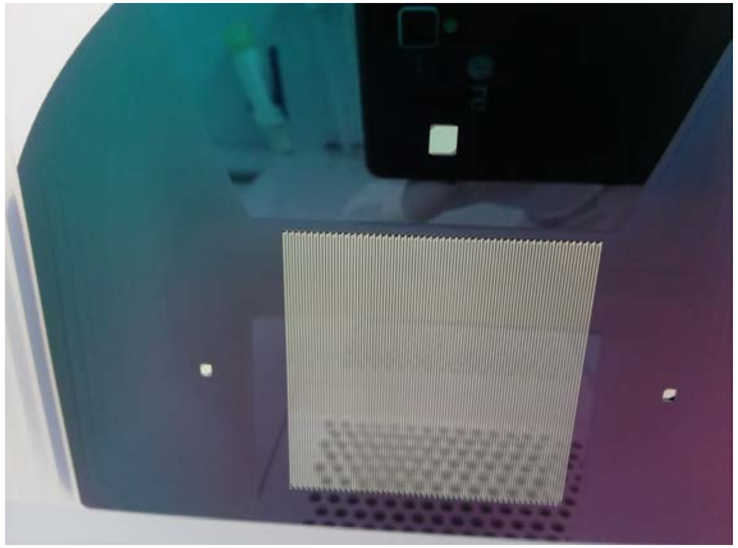
Realization

Mercury flowing through array!



Si wafer wet-etch

No opportunity to use!



90% channel filling, 1 micron membrane
5cm x 5cm area, use non-wetting fluids
(mercury, ethanol)

Assemblies non-magnetic
(PSI flux-gate study)

Neutron Friendly

1 micron waviness, much
smaller roughness

Summary

The availability of

(1) Production capability of radioactive nuclei and neutrons
(2) Expertise on fundamental symmetries measurments of laser trapped nuclei

Creates some very interesting opportunities (especially if densities near 100 UCN/cm^3 are achieved) for next generation asymmetries experiments with reach comparable to superallowed decays and new BSM constraints

Having both ^{19}Ne and UCNs adds some interesting long term possibilities for other experiments (CRES?), see Brent Graner's talk..

The room temperature EDM might be ideally suited for the flexibility required to take a dvantage of physics opportunities for new limits from precession experiments!

Planning for flexibility in field range, orientation, rf field production and cell configurations with an external vacuum chamber and access for fluidic ports/control may permit new physics reach on dark sector and short-ranged force limits!