Neutron Beta Decay: Status and Prospects

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Outline

- Neutron Beta Decay input to the Standard Model (SM) and Beyond Standard Model (BSM) Physics
- Lifetime experiments:
  - UCN storage experiments
  - Measurements with Cold Neutron beams
- Angular correlations
  - Beta asymmetry measurements (A)
  - beta-neutrino correlation (a)

see Hitesh Rahangdale's talk

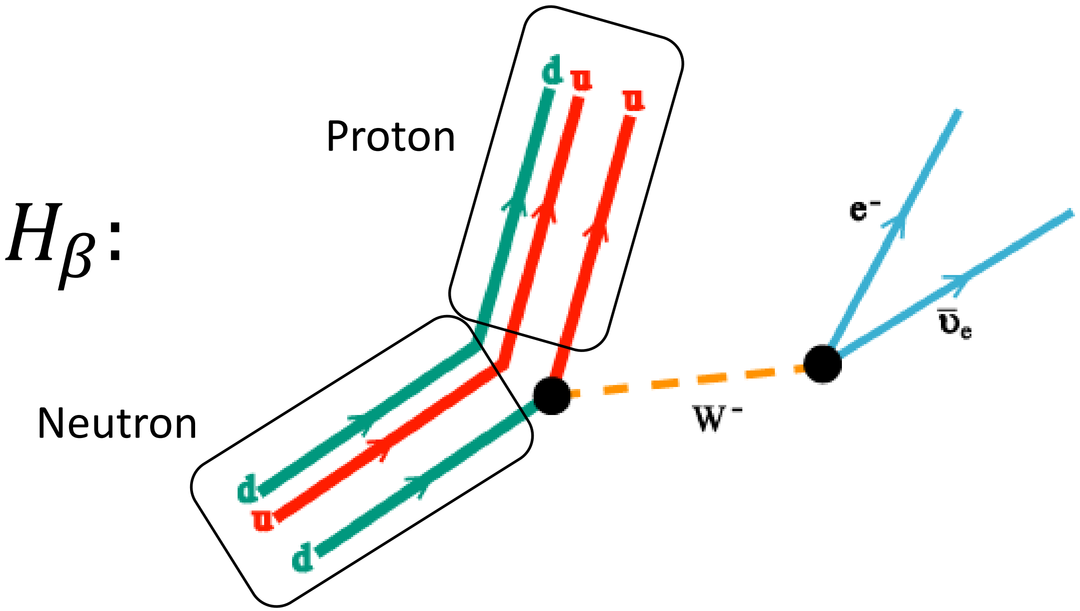
- Conclusions

(I started out with a much broader list of subtopics!)

Neutron Beta Decay Input to the SM and BSM Physics

Neutron → proton + electron + anti-neutrino

H_β:

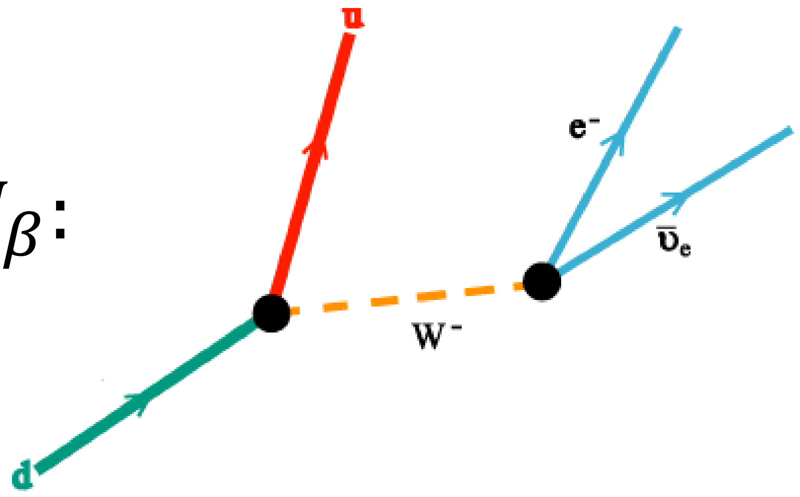


Neutron Beta Decay Input to the SM and BSM Physics

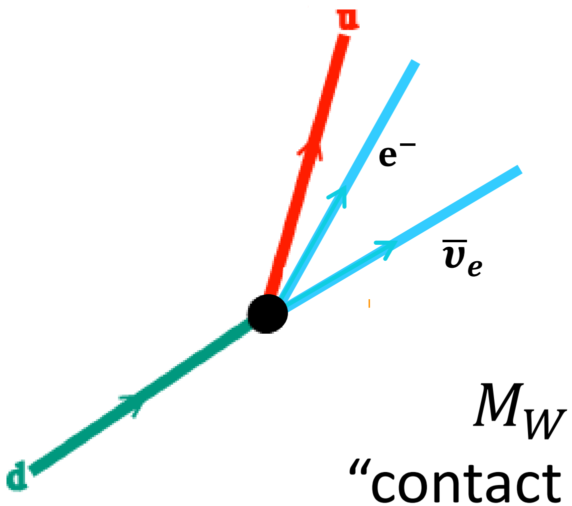
(switch off strong Interaction)

d-quark → u-quark + electron + anti-neutrino

H_β:



$\approx$

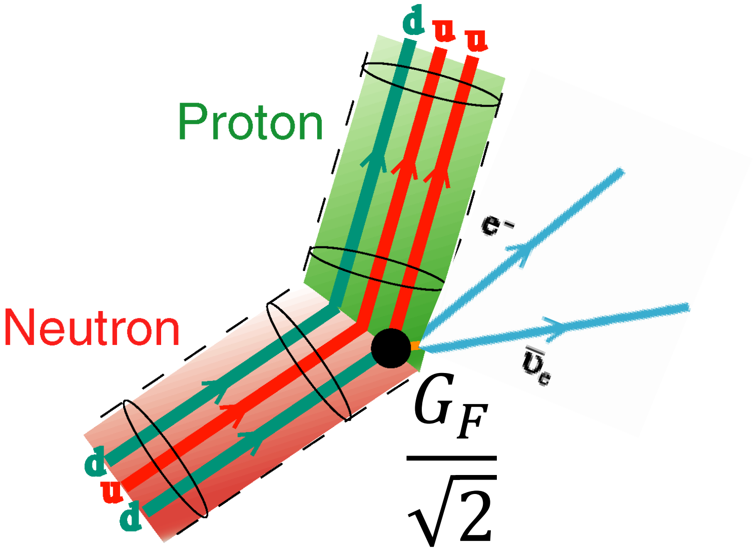


$M_W \gg E_o$

"contact interaction"

The Standard Model for β Decay

Three input parameters required:



$$\frac{G_F}{\sqrt{2}}$$

Fermi constant:
W⁻ exchange“strength”

$\sqrt{2}$

(Precisely calculable)

$$J_\mu^{(quarks)} = \bar{u}\left[\gamma_\mu - \gamma_\mu \gamma_5\right] V_{ud}\, d \;+\; h.c.$$

CKM matrix: flavor mixing in SM

V-A helicity structure

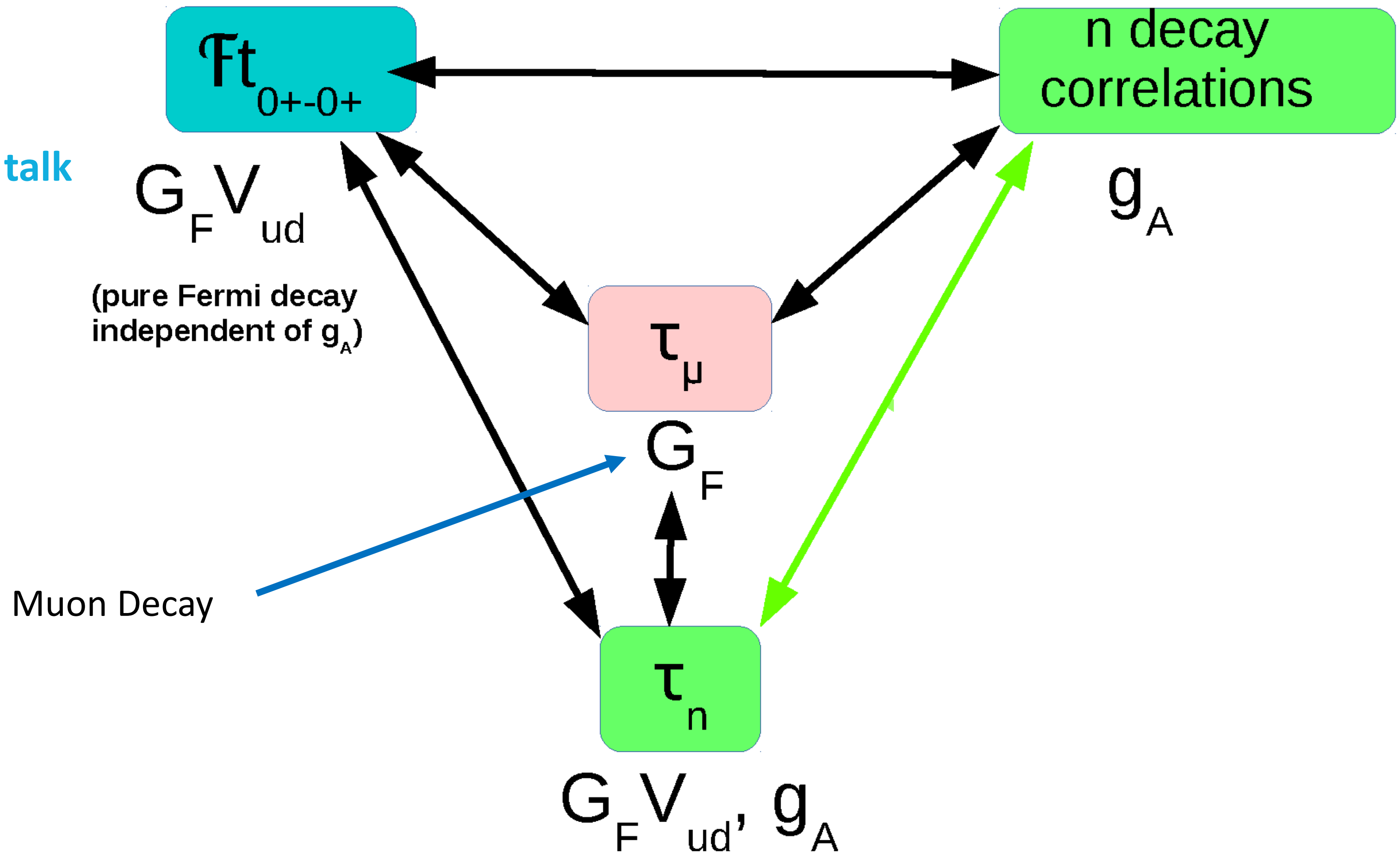
V

A

Axial matrix element

Vector matrix element specified by CVC

SM parameters: G_F, V_{ud}, g_A – most precise experimental inputs



Melconian talk

$\mathcal{F}t_{0+\text{-}0+}$

$G_F V_{ud}$

(pure Fermi decay independent of g_A)

n decay correlations

g_A

τ_μ

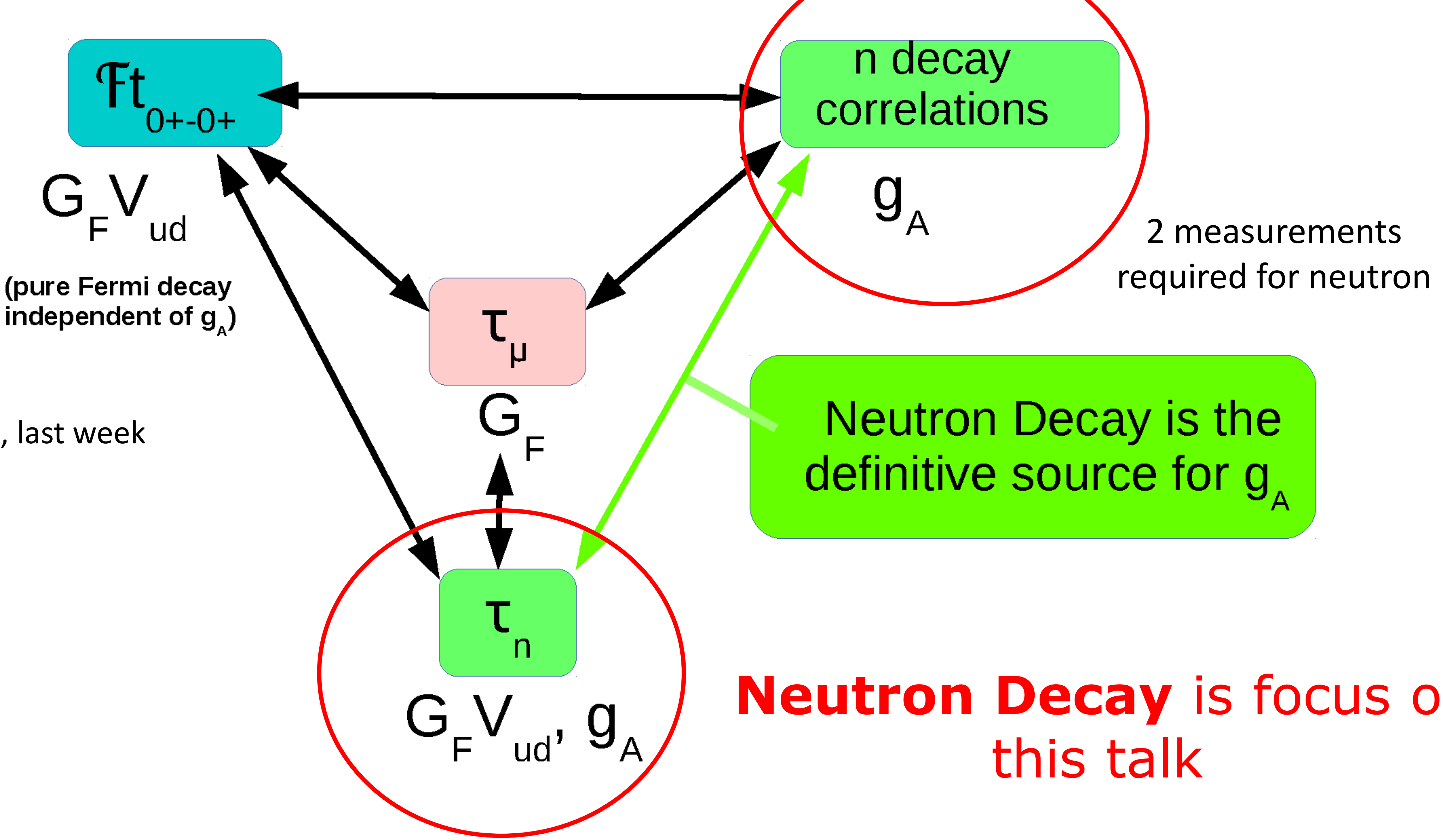
G_F

Muon Decay

τ_n

$G_F V_{ud}$, g_A

SM parameters: G_F, V_{ud}, g_A – most precise experimental inputs



$\mathcal{F}t_{0+-0+}$

$G_F V_{ud}$

(pure Fermi decay independent of g_A)

n decay correlations

g_A

2 measurements required for neutron

τ_μ

G_F

τ_n

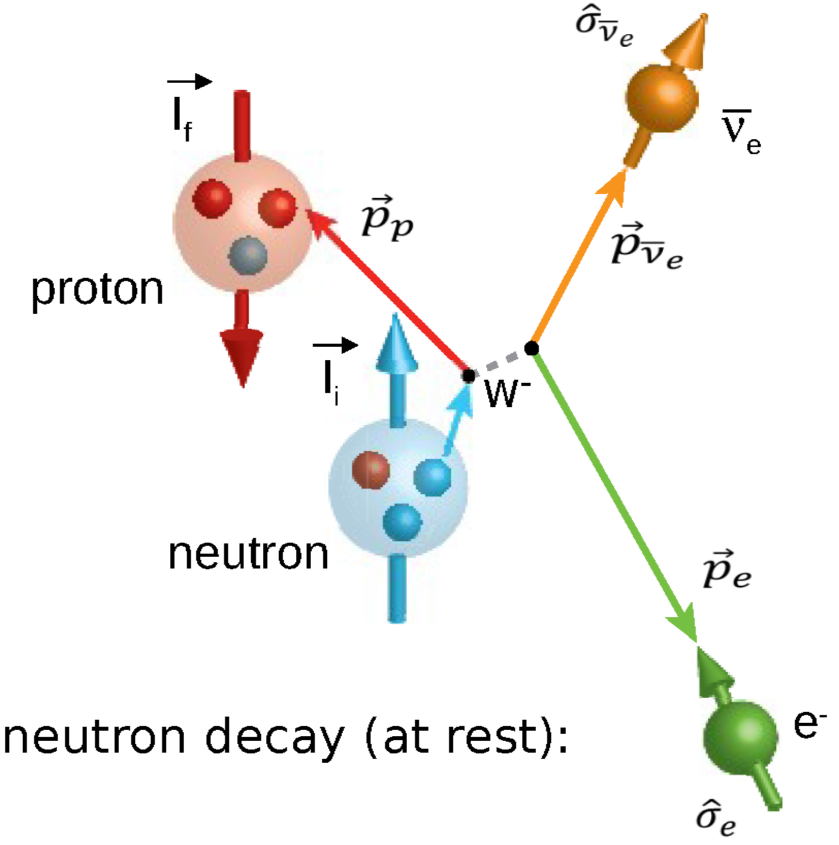
$G_F V_{ud}$, g_A

Neutron Decay is the definitive source for g_A

Melconian talk, last week

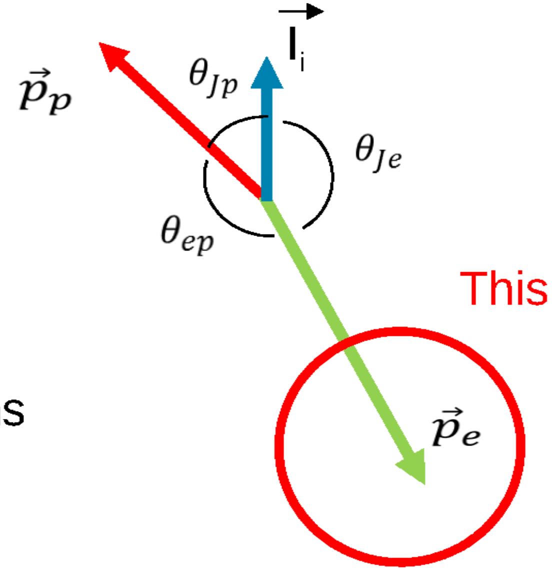
Neutron Decay is focus of this talk

Beta Decay Observables



neutron decay (at rest):

Don't observe
final state spins
or neutrino



This talk

- **Decay rate**
- **Energy spectrum**: p, e
- Directional distribution (**angular correlations**)

Many accessible observables

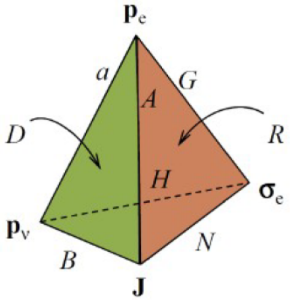
$\{\vec{I}_i, \vec{I}_f, \vec{p}_p, E_p, \hat{\sigma}_e, \vec{p}_e, E_e\}$

Use momentum consv: $\vec{p}_{\overline{\nu}_e} = -\vec{p}_p - \vec{p}_e$

Beta Decay Parameters

Jackson, Treiman and Wyld (Phys. Rev. **106** and Nucl. Phys. **4**, 1957)

$$\frac{d^5W}{dE_e\,d\Omega_e\,d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|V_{ud}|^2}{(2\pi)^5}\,p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu\ \text{correlation}} + \overbrace{b\frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} + \frac{\langle\vec{I}\rangle}{I}\cdot\left[\underbrace{A_\beta\frac{\vec{p}_e}{E_e}}_{\beta\ \text{asym}} + \underbrace{B_\nu\frac{\vec{p}_\nu}{E_\nu}}_{\nu\ \text{asym}} + \underbrace{D\frac{\vec{p}_e\times\vec{p}_\nu}{E_e E_\nu}}_{T-\text{violating}}\right]\right) + \ldots$$



On-going or planned efforts to measure:

(1) **Decay rates and β-spectra** ($G_F V_{ud}, \xi, b$)

(2) **Unpolarized angular correlations** ($a_{\beta\nu}, b$)

(3) **Polarized angular correlations** (A_β, B_ν, b, b_ν)

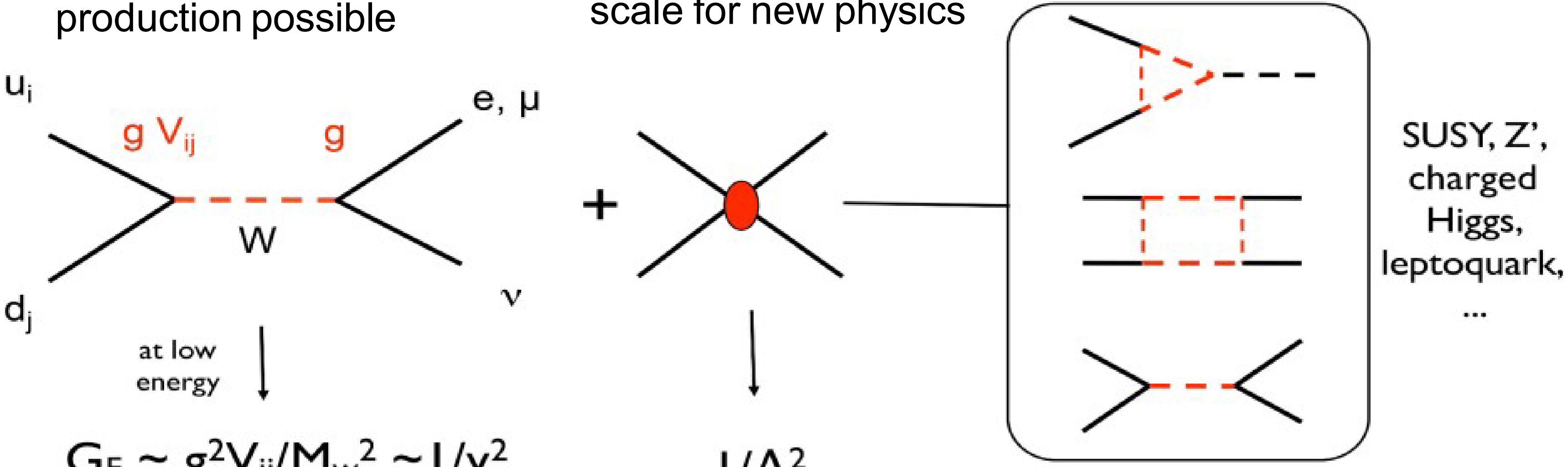
Note: to specify both C_V and C_A, 2 meas. needed

EFT Model Independent Analysis

At high energy, direct W production possible

Assume below prod scale for new physics

Cirigliano, 2013



$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

$1/\Lambda^2$

V = 170 GeV

Contact interaction
Similar to G_F at low E

\+ Build in appropriate helicity dependence

Permits “broad-band” comparison between sensitivity of high energy probes and beta decay, for example through the CKM unitarity test

Need τ to ~0.25 s and asymmetry to ~0.1% for competitive extraction of V_{ud} from neutron with the superallowed decays.

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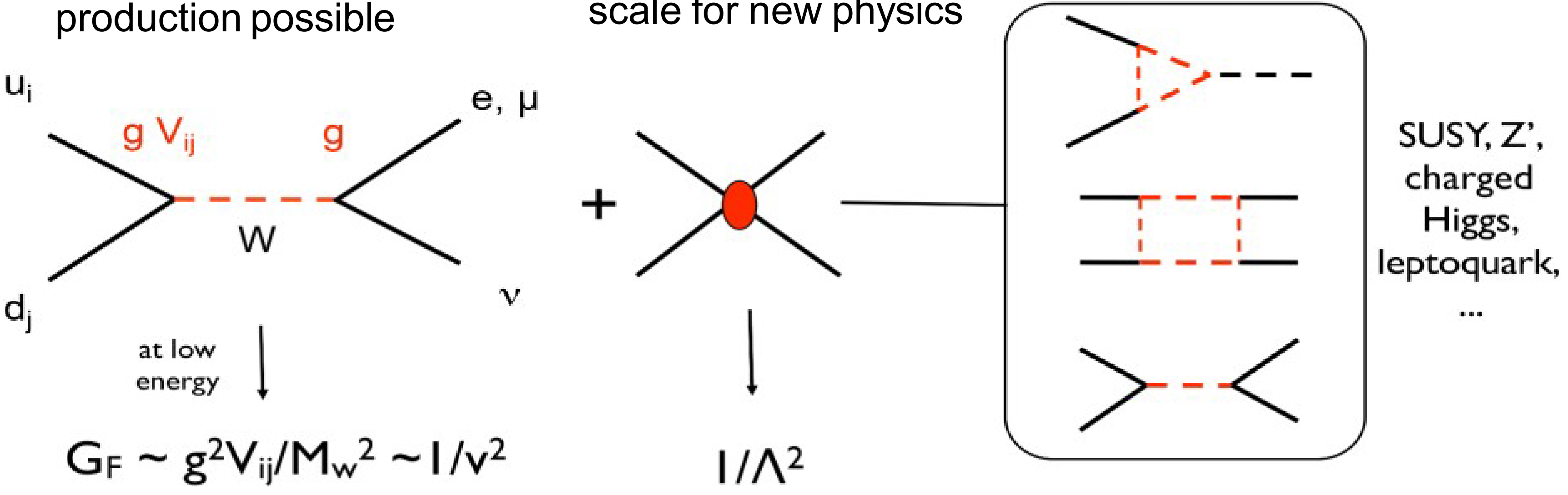

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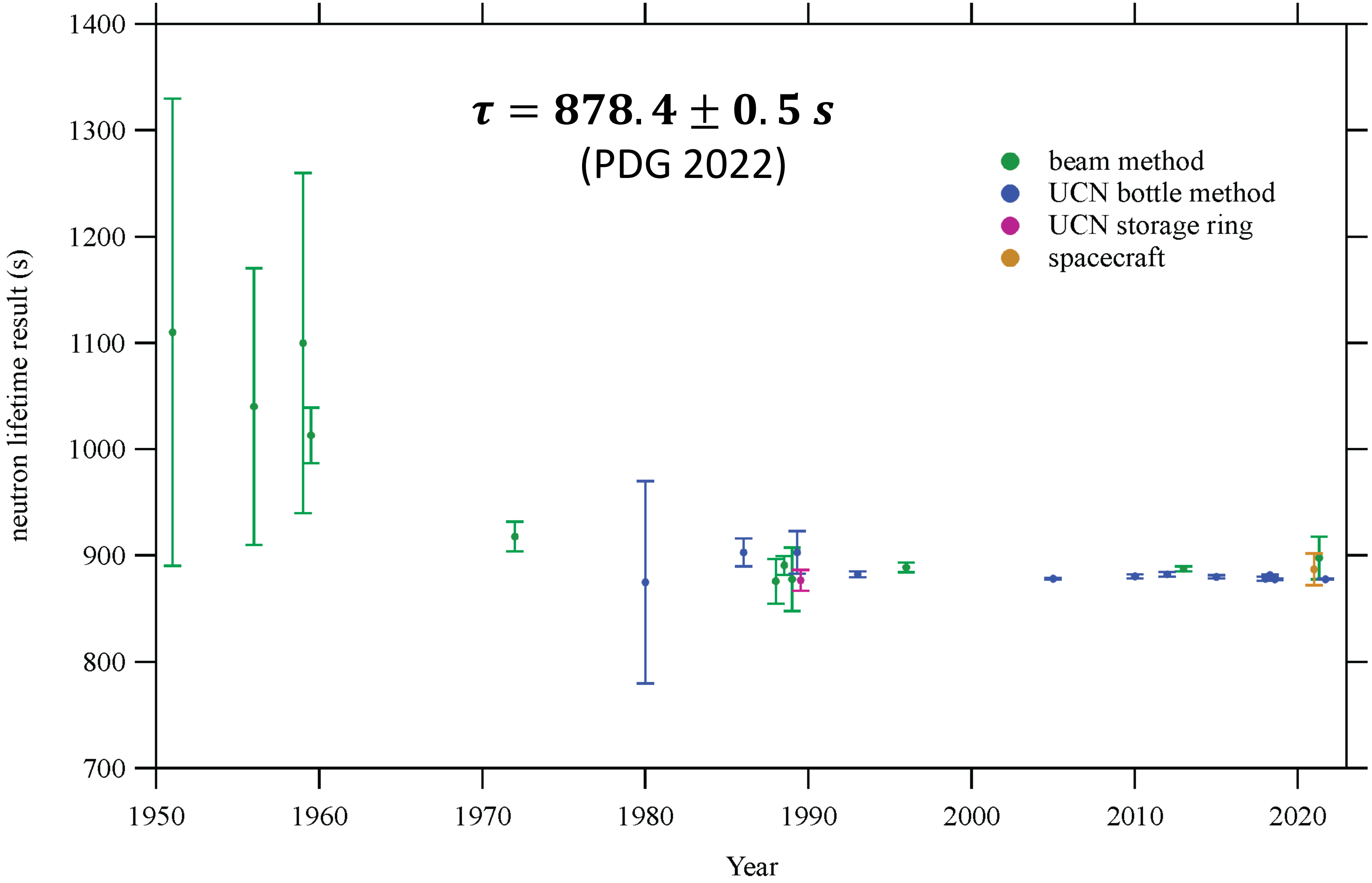
What are the prospects to achieve this?

The Neutron Lifetime

Bottles and Beams!

Special thanks to D. Salvat, C.-Y Liu, F. Wietfeldt for slides

Neutron Lifetime Measurements (quite a history!)

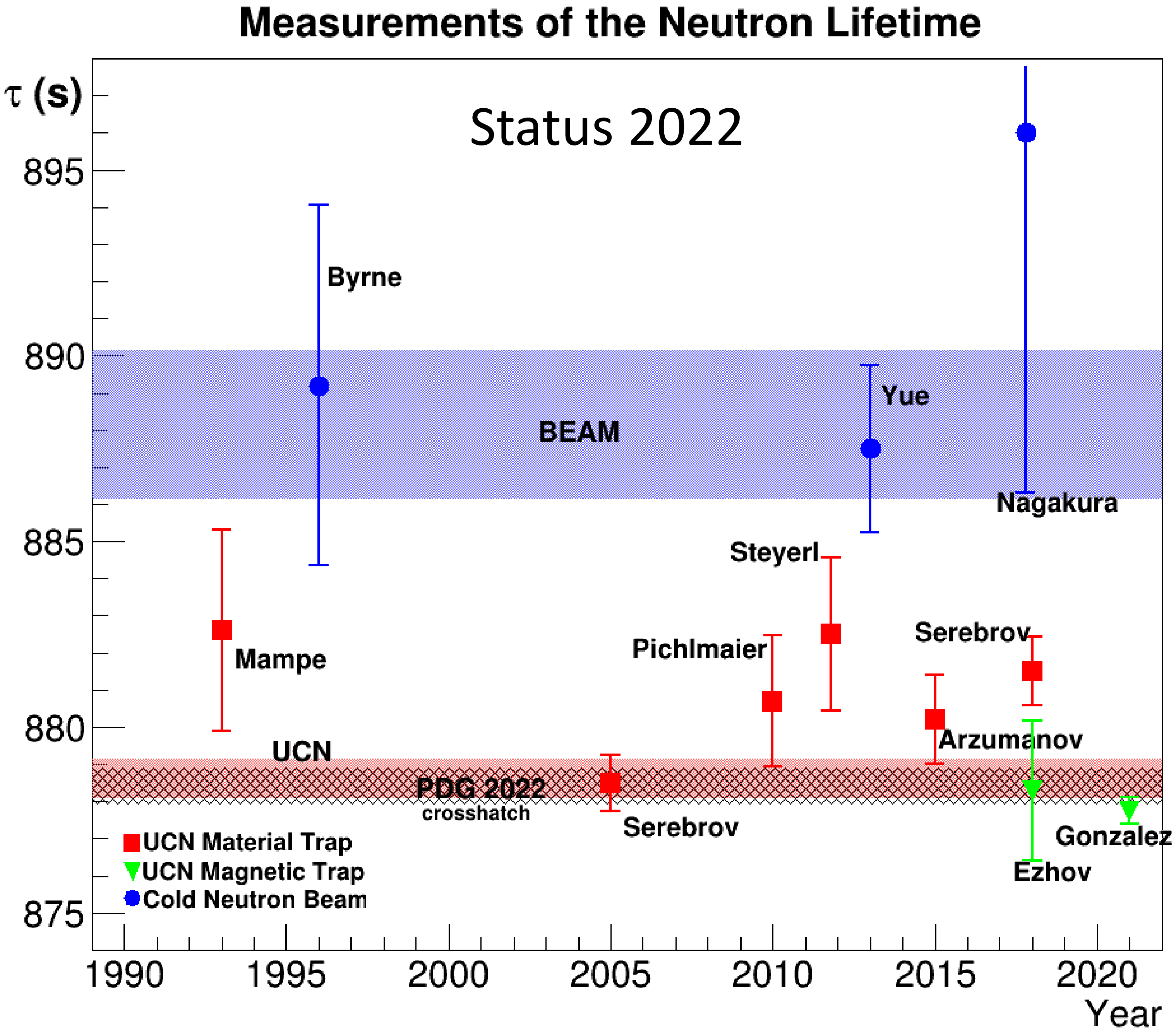


Challenging:

- Neutral Particle
- Absorbed by ~ all materials
- Relatively long-lived

From: Wietfeldt and Greene, Rev. Mod. Phys. **83**, p. 1173 (2011)

Latest/most Sensitive Results for all groups in PDG + Nagakura



PDG

878.4±0.5 s (S=1.8)

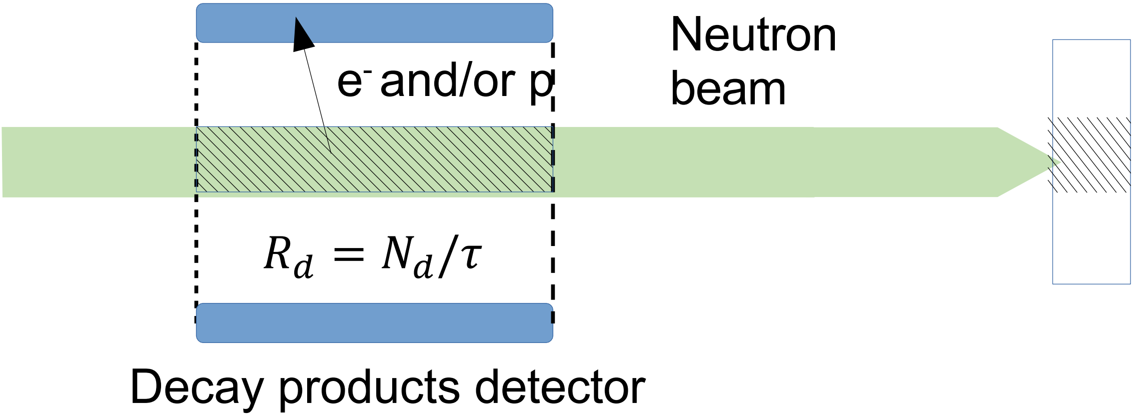
Lifetime measurements: two varieties

Beam lifetimes: count neutron beta **decay** products

Requires precisely known:

- i) decay volume
- ii) absolute neutron density
- iii) decay product detection efficiency

Pre-2013: neutron density was dominant source of uncertainty



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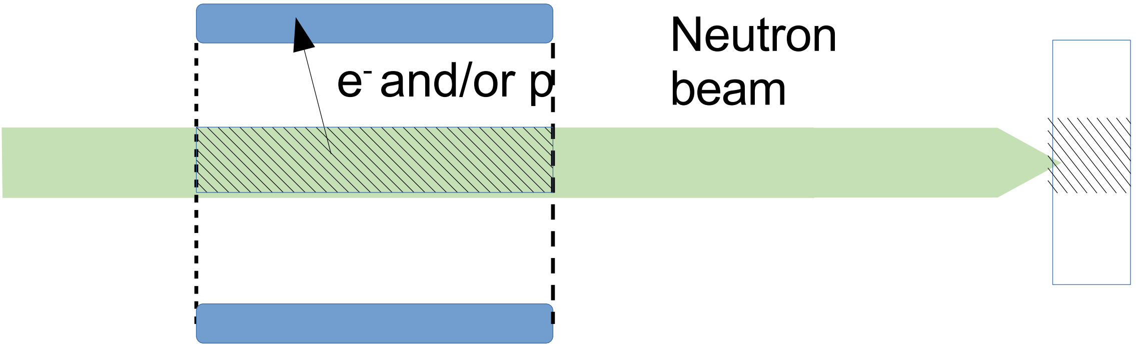


Decay products detector

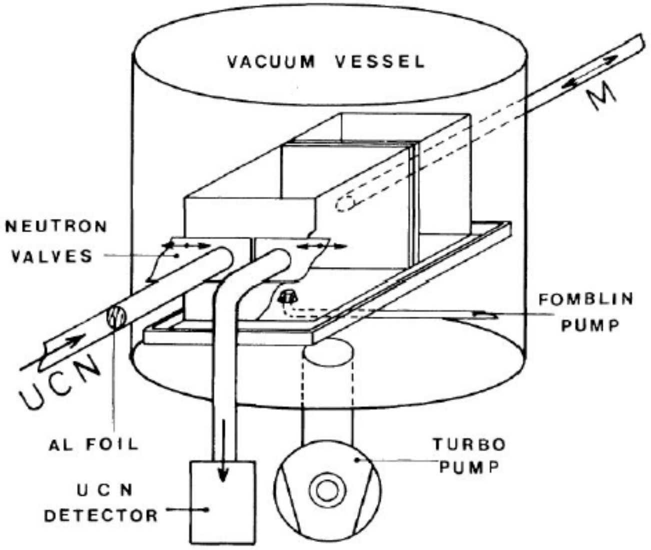
UCN storage experiments: count neutrons which **survive** after well defined storage time t_s

Actually measures total loss rate from trap…

$$\frac{N(t_o + t_s)}{N(t_o)}$$

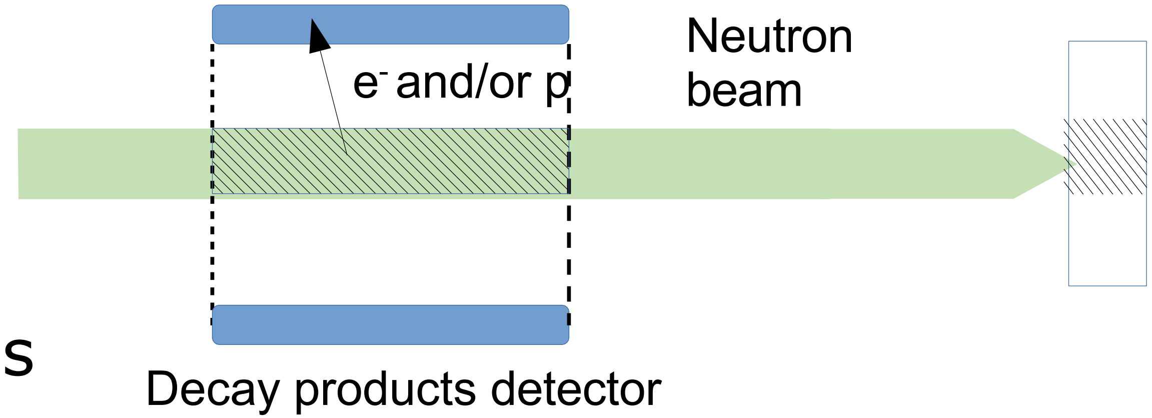
$$\frac{1}{\tau_{mea}} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{heat}} + \frac{1}{\tau_{qb}} + \ \ldots$$

Pre-2018: **losses** due to collisions with material surfaces were dominant source of uncertainty



Lifetime measurements: two varieties

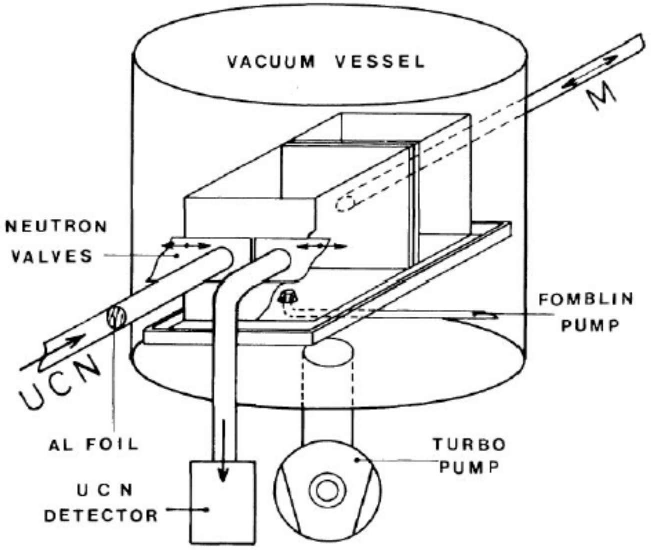
Historically, shown reasonable agreement, but since 2013:

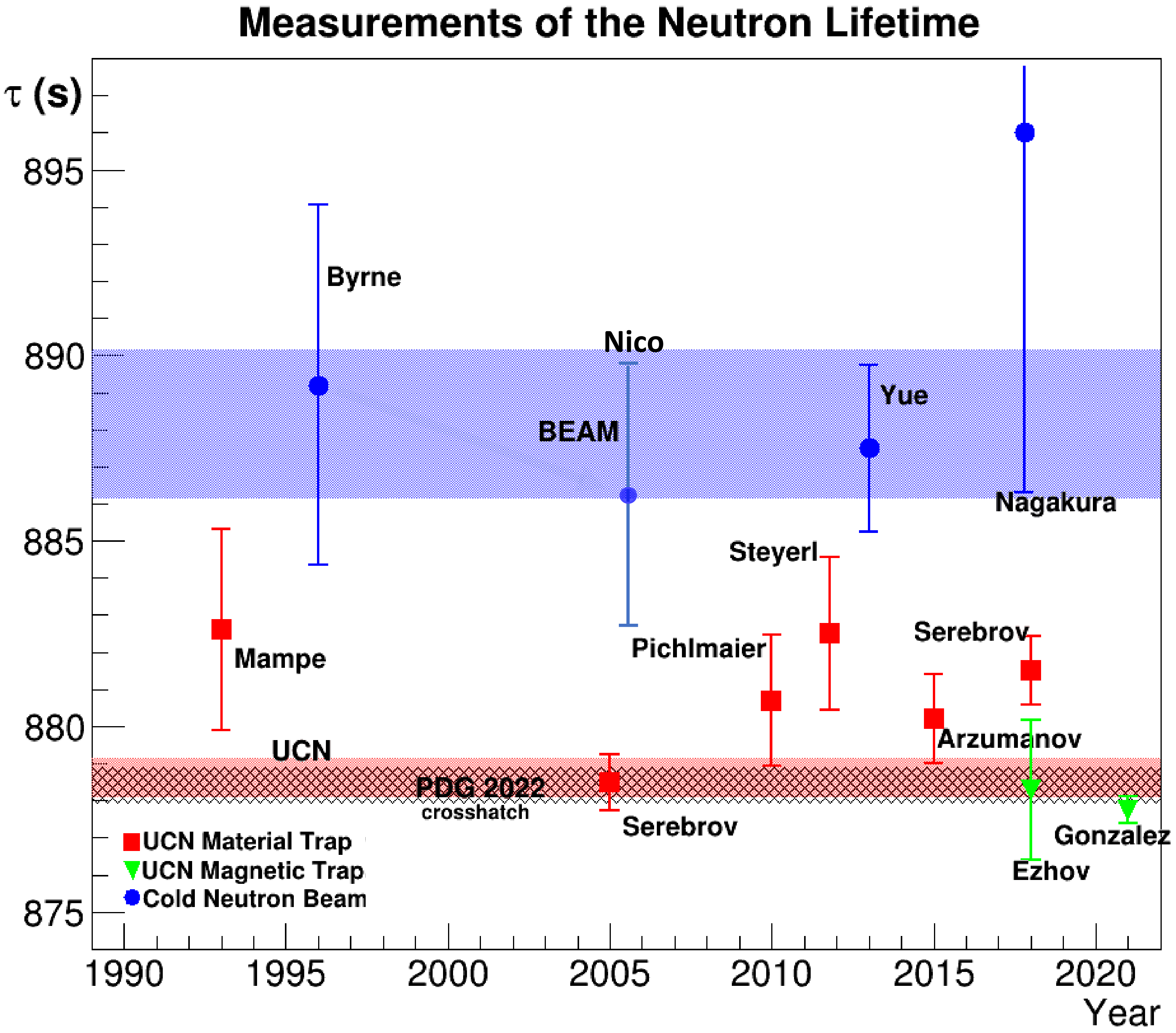


Cold neutron beams: $\tau = 888.0(2.0)$ s

Differ by 4σ

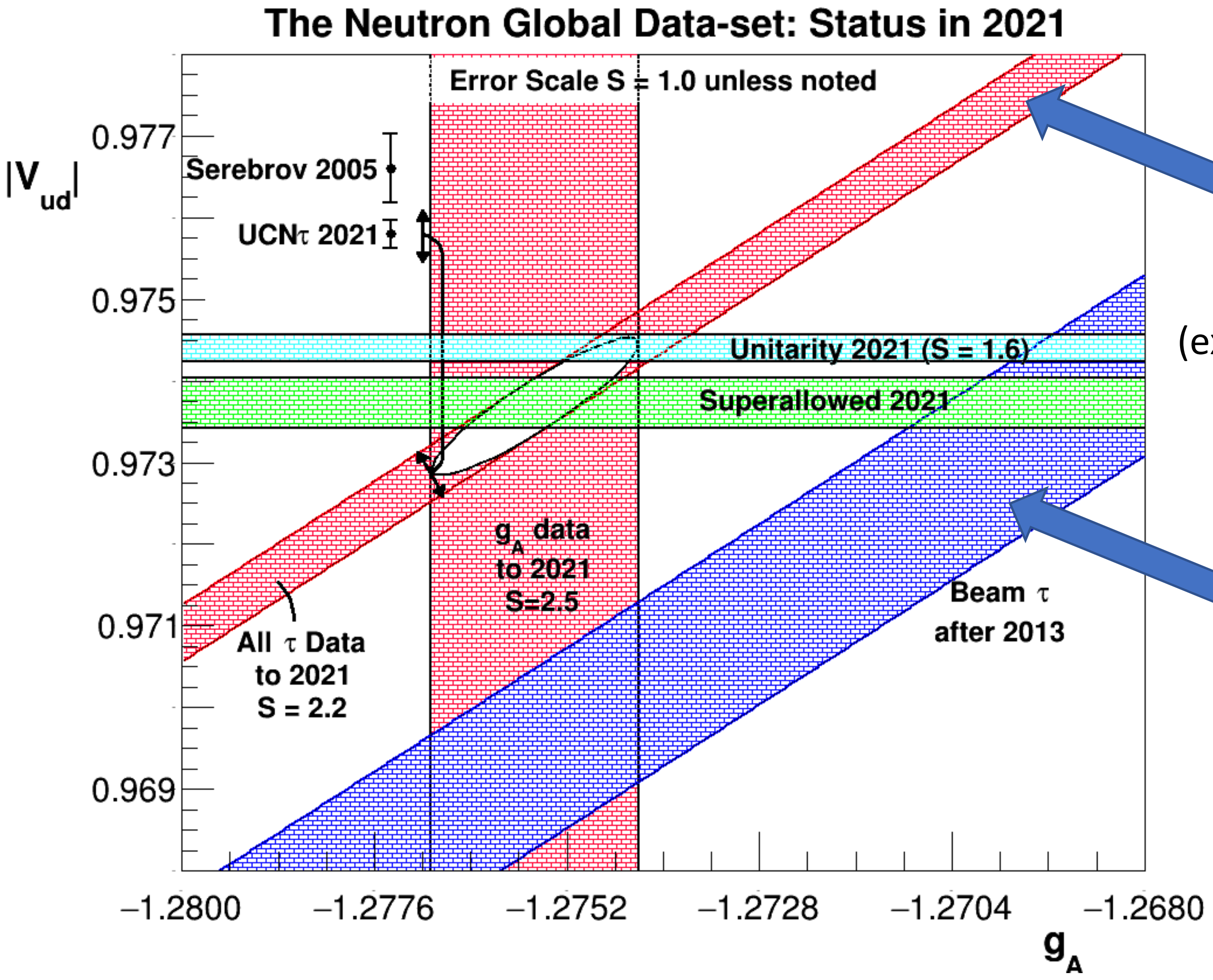
UCN storage experiments in material traps:
$\tau = 878.4(5)$ s





As of 2013:
decay rate from
beam experiment
1% slower!

More Motivation: Status of the Neutron Lifetime



Dominated by UCN storage expts

(expanded V_{us} error bar)

Most precise beam lifetime (BL1)
BL2 and BL3 ongoing!

$$\tau_{beam} - \tau_{UCN} = 9.6(2.1)\ s \sim 1\%$$

^{4}He abundance…

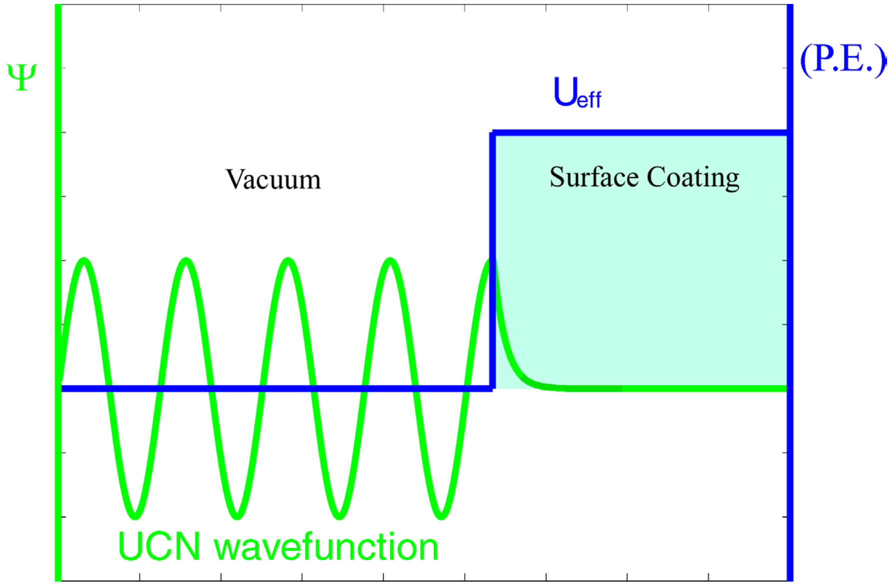
Ultracold Neutron Storage Measurements

“neutron disappearance” measurements

Special thanks to F. Gonzalez, C.-Y Liu, D. Salvat, F. Wietfeldt for slides

What is an Ultracold Neutron?

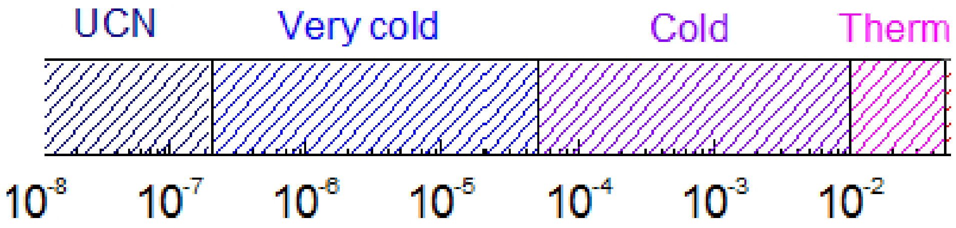
For a neutron “wave”, coherent interaction with many nuclear sites makes an effective potential, U_{eff} for neutrons incident on a material surface



Case where $E < U_{eff}$

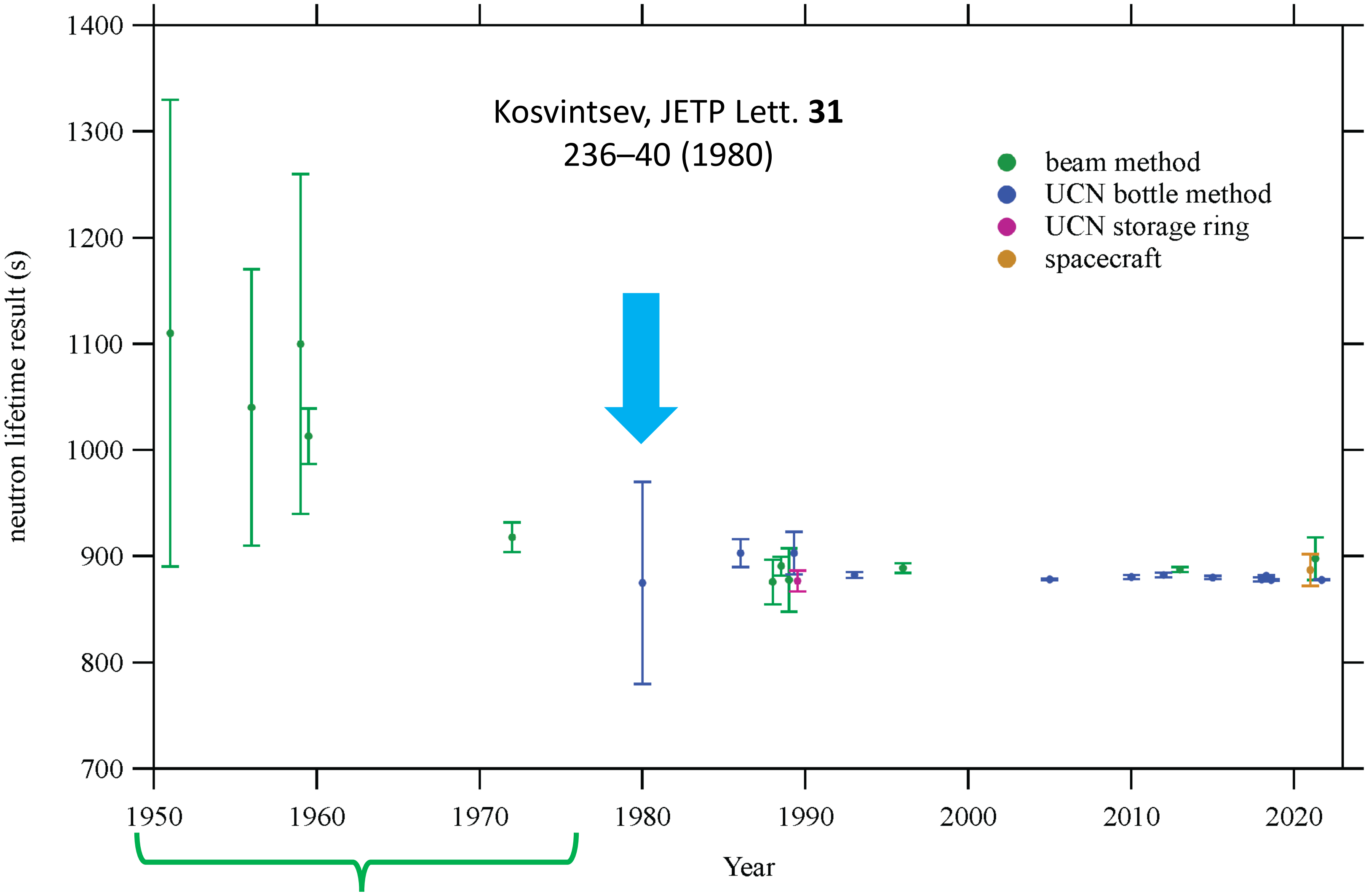
Reflection: $E_{\perp} < U_{eff}$

Ultracold Neutrons (UCN) are neutrons moving slow enough that the can be reflected for **any** angle of incidence, typically $E_{UCN} <$ ~340 neV (about 3 mK)



UCN can be stored for 100’s of seconds In material and magnetic traps!

Neutron Lifetime Measurements



Kosvintsev, JETP Lett. **31**
236–40 (1980)

Early Beam Measurements

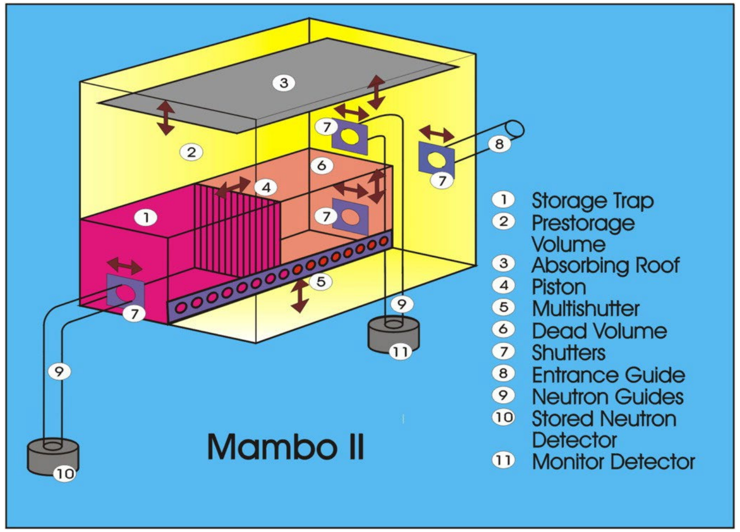
From: Wietfeldt and Greene, Rev. Mod. Phys. **83**, p. 1173 (2011)

Losses: Extrapolation Procedures

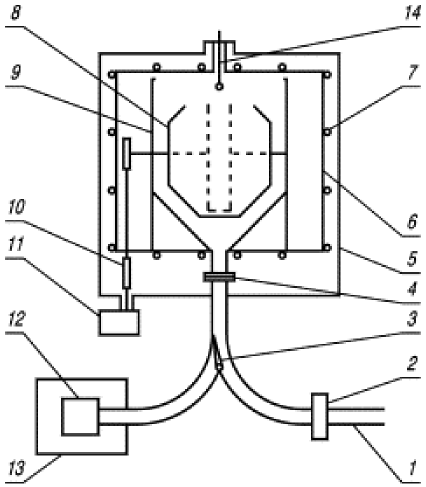
$$\frac{1}{\tau_{mea}} = \frac{1}{\tau_{\beta}} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{heat}} + \frac{1}{\tau_{qb}} + \ldots$$

Trap losses on walls set scale for corrections

Strategy: vary A/V to characterize wall losses! (Kosvintsev inserts…)

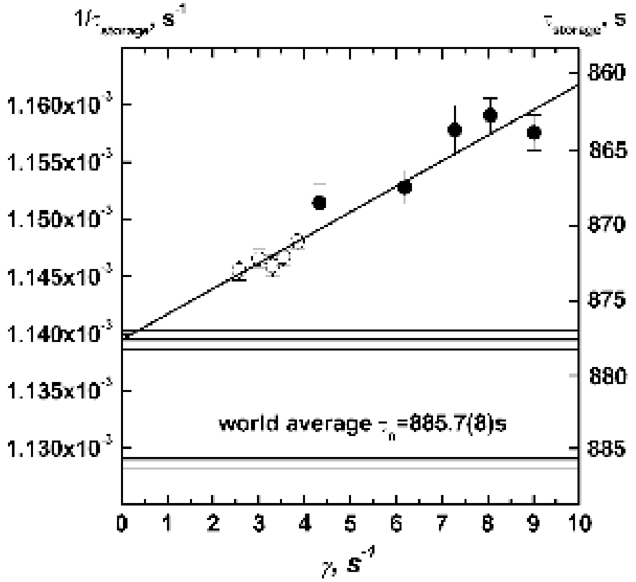


Mambo II



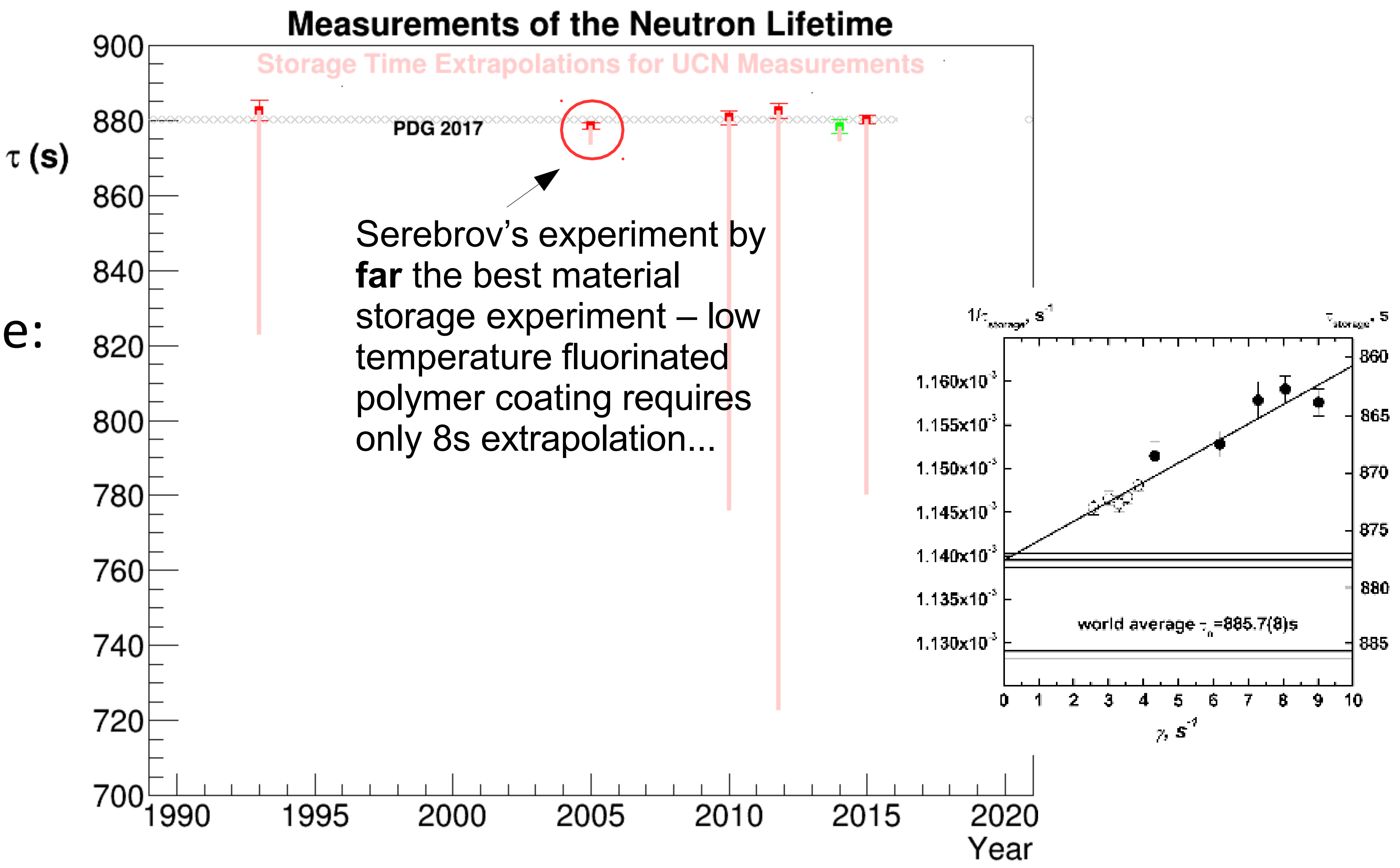
2005 Gravitrap

Most successful, small corrections needed



Scale to collision rate with walls: velocity Groups and different A/V

The big difference:



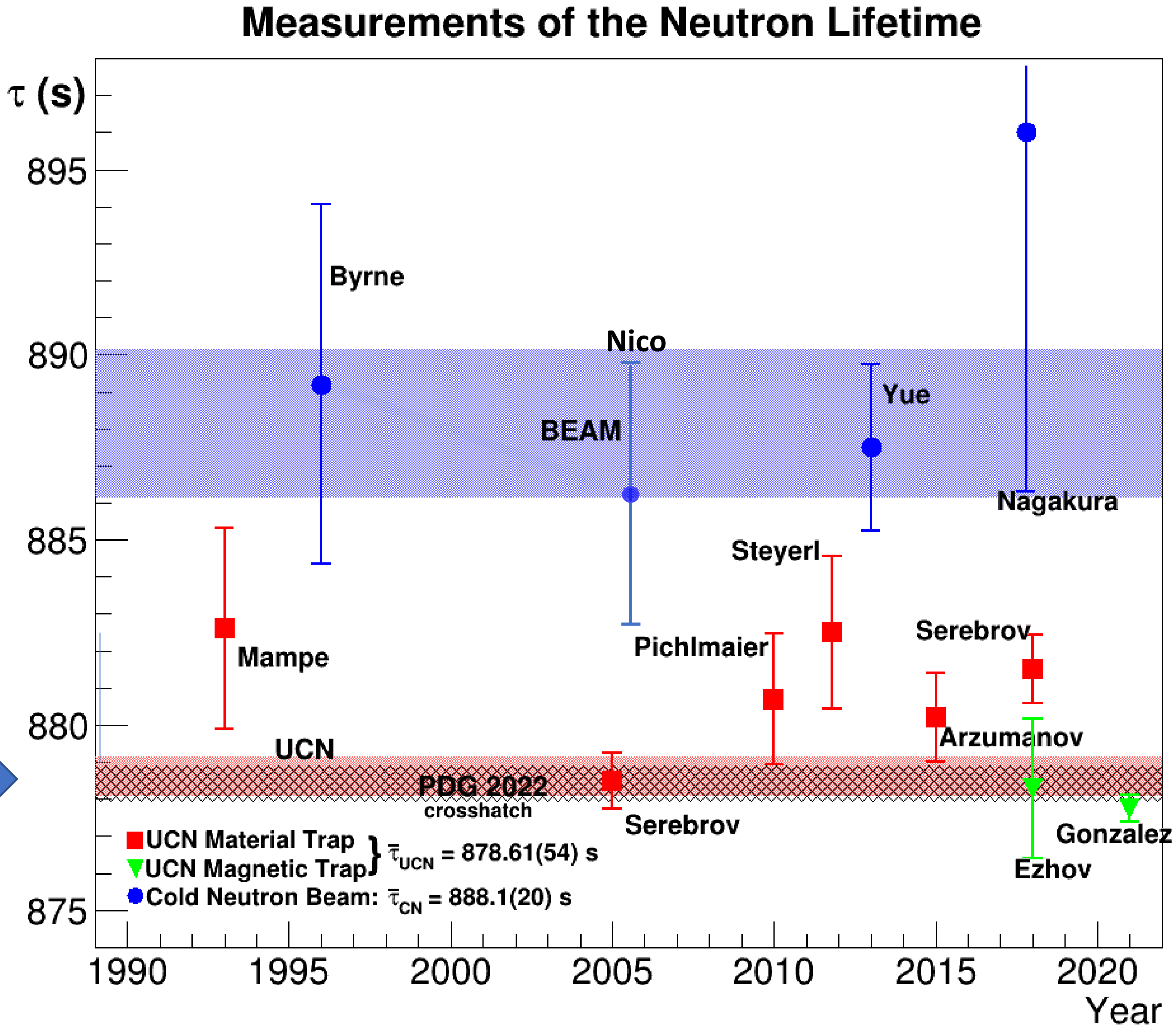
Serebrov's experiment by **far** the best material storage experiment – low temperature fluorinated polymer coating requires only 8s extrapolation...

Corrections for UCN storage experiments in material traps due to losses are typically large!

Latest/most
Sensitive Results
for all groups

PDG assigns
scale factor of 1.8
for **scatter**

(under-estimated
systematic unc…)

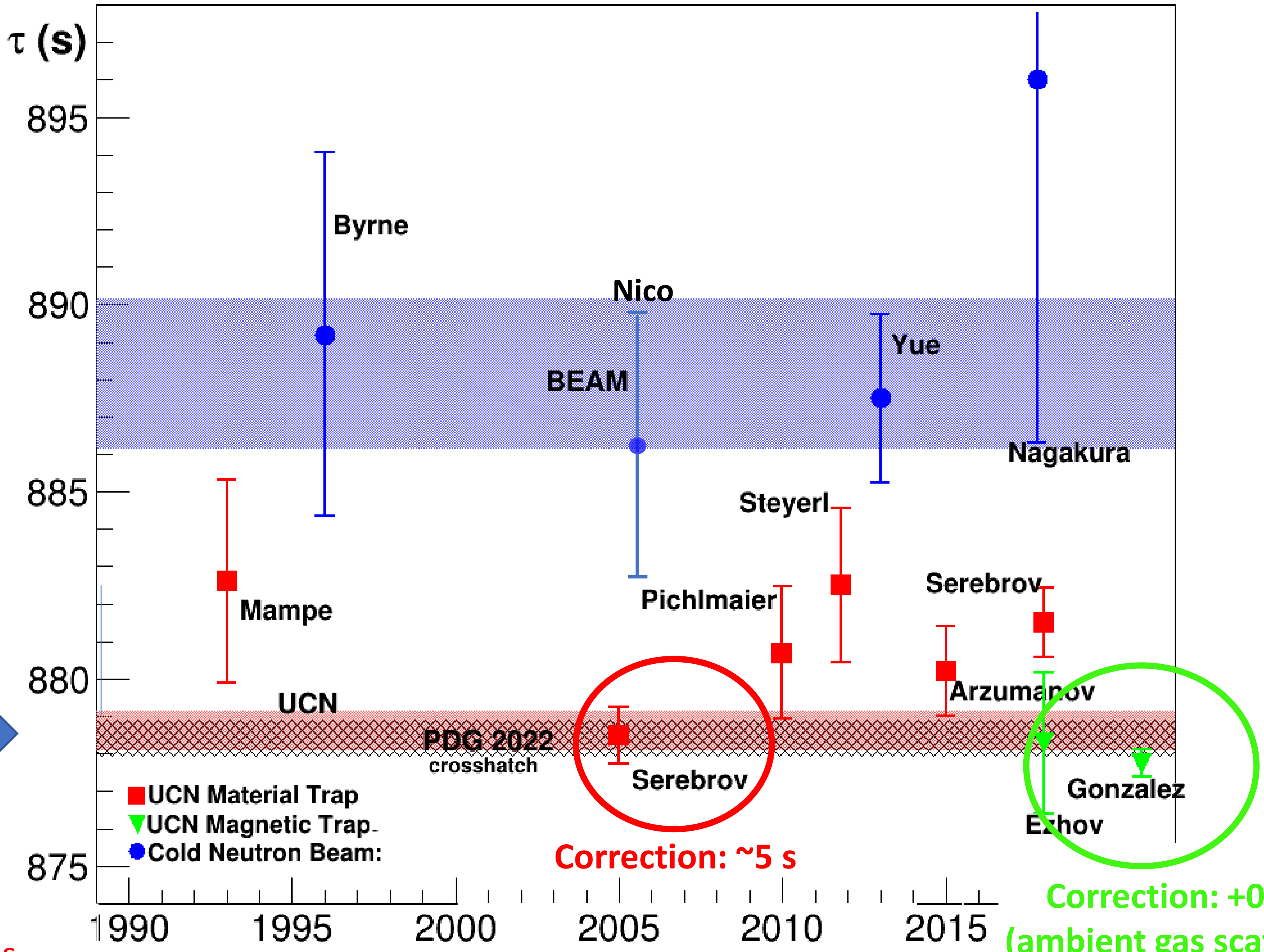


PDG

878.4±0.5 s (S=1.8)

Measurements of the Neutron Lifetime

Latest/most
Sensitive Results
for all groups



PDG assigns
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(under-estimated
systematic unc…)

Correction: ~5 s

Correction: +0.06 s
(ambient gas scattering)

PDG

878.4±0.5 s (S=1.8)

Min. Correction: ~6 s

General Considerations:

- UCN storage experiments were first reported by Kosvintsev at the CM-2 reactor in Dubna

  Y. Kosvintsev et al., *JETP Lett.* **31**, p. 236, 1980

- The experiment by Serebrov in 2005 at the Institut Laue Langevin (ILL) produced a significant shift in the world average for storage experiments, motivating a number of groups to re-investigate or constrain losses

  A. Serebrov et al., *Phys.Lett.B* **605**, p. 72-75, 2005

- The first neutron storage experiment was performed using VCN (velocity ~ 15 m/s) in a toroidal storage ring at the ILL (877 ± 10 s)

  U. Paul et al, Z. Phys. C **45**, p. 25, 1989

- A scheme to trap UCN using an assembly of permanent magnets was reported in 2001 by Ezhov (V. Ezhov et al, Tech. Phys. Lett. 27, 105, 2001) with a results published in 2018 (Ezhov et al., *JETP Lett.* **107**, 671-675 , 2018)

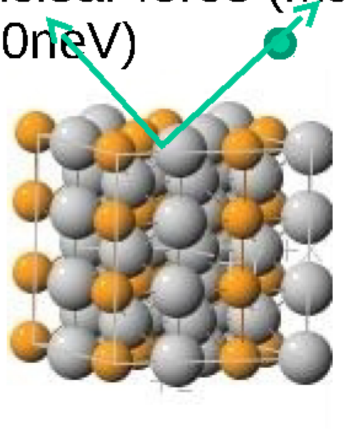
- Currently, most precise is UCNτ -- have a look at this experiment!

Different ways to manipulate UCN

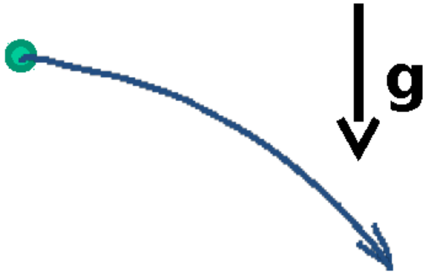
UCN energies so low, they reflect from some material surfaces for any angle of incidence!

- Nuclear force (max: 350neV)

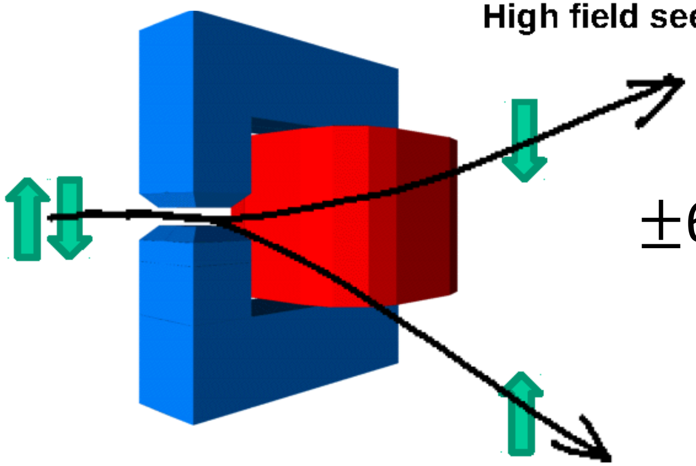
Store them in bottles!



- Gravitational force (100neV/m)



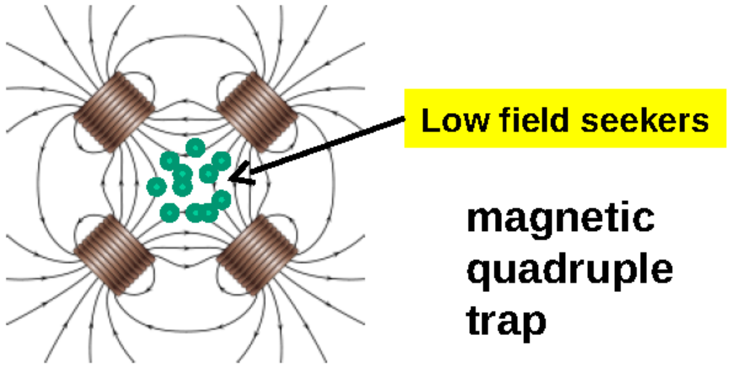
- Magnetic force



± 60 neV/T

Old idea: use repulsive magnetic forces to trap UCN!

Vladimirskii, Zhur. i. Teoret Fiz., 1960

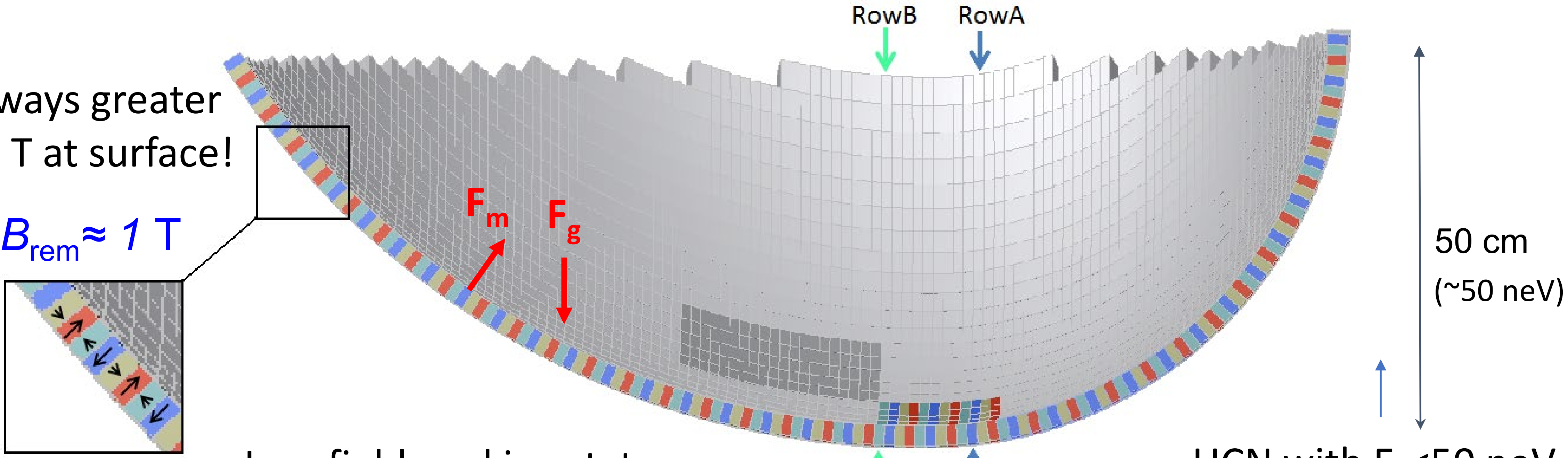


C.-Y. Liu

UCNτ

|B| always greater than 1 T at surface!

$B_{rem} \approx 1$ T

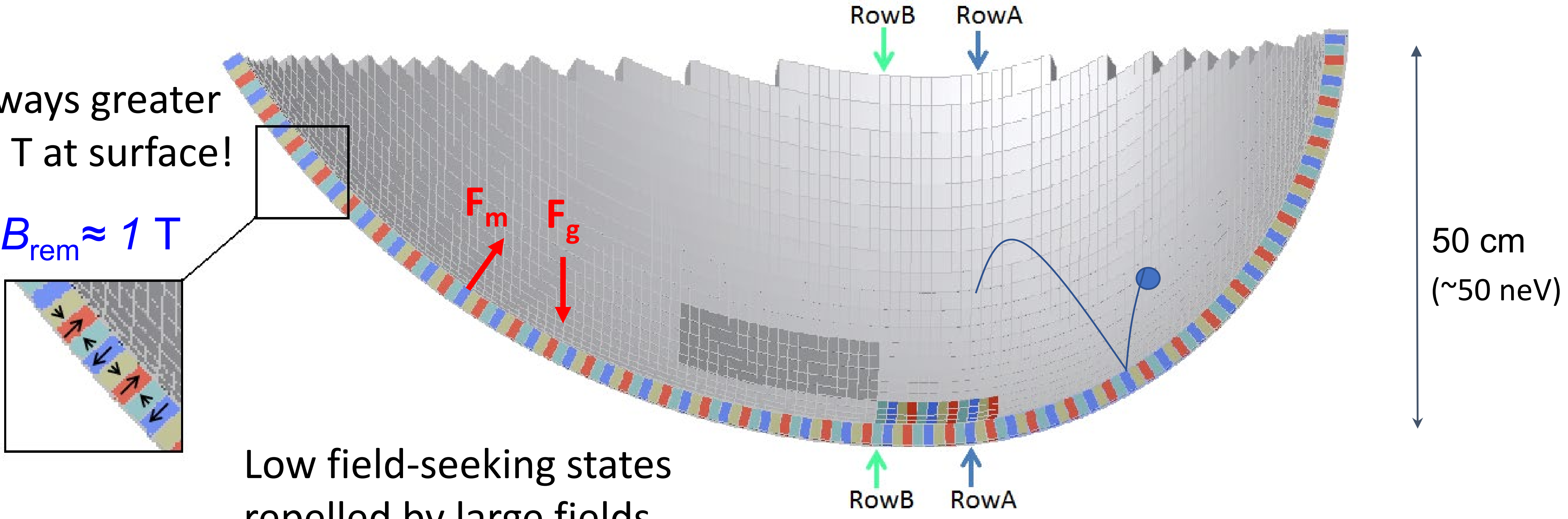


Low field-seeking states repelled by large fields

UCN with E_k<50 neV at bottom are trapped!

Strategy: eliminate wall losses by avoiding contact with material surfaces – use magnetic repulsion and gravity to confine UCN!

UCNτ



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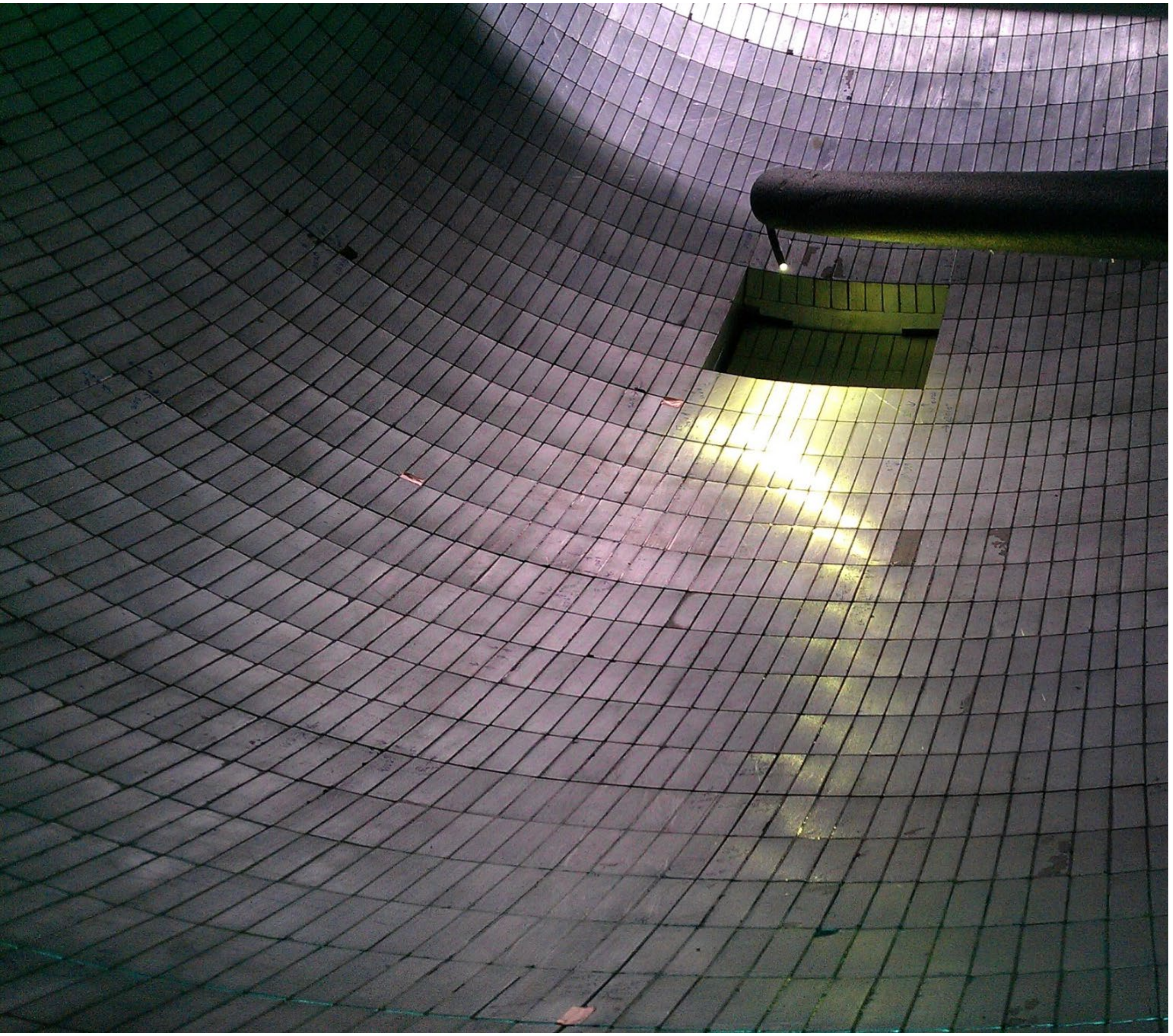
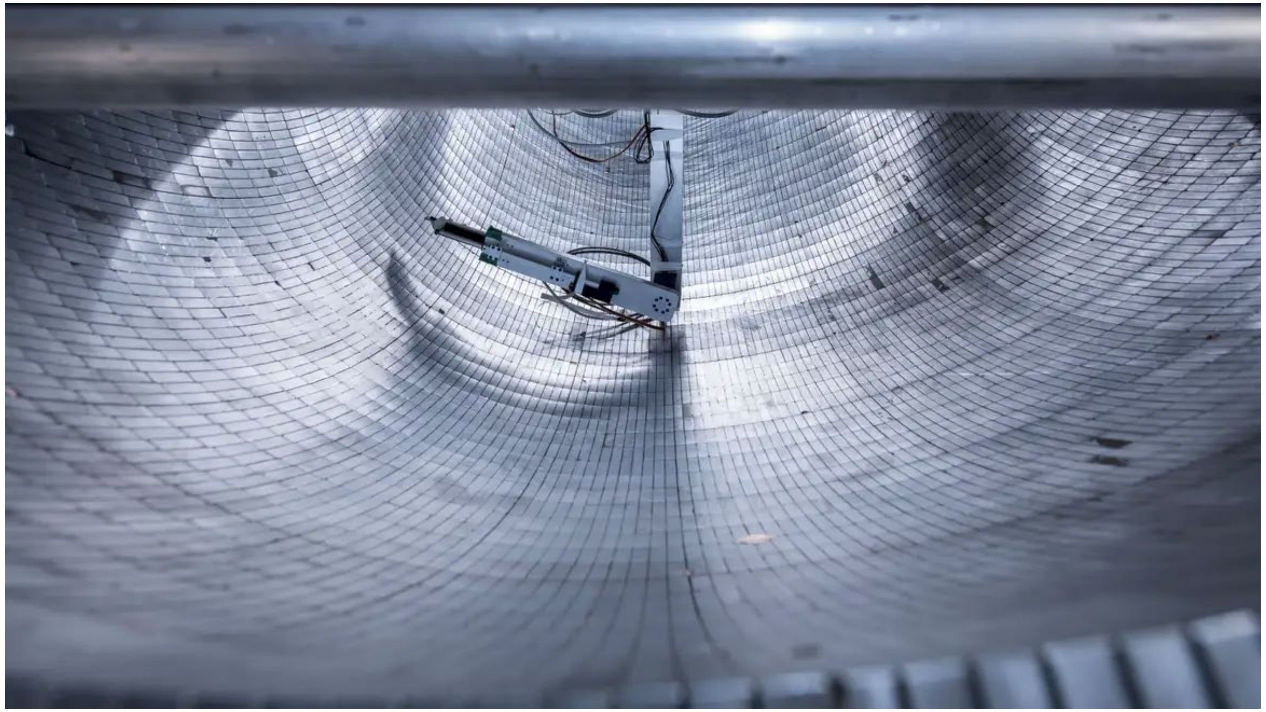
Low field-seeking states repelled by large fields

UCNτ Design Features

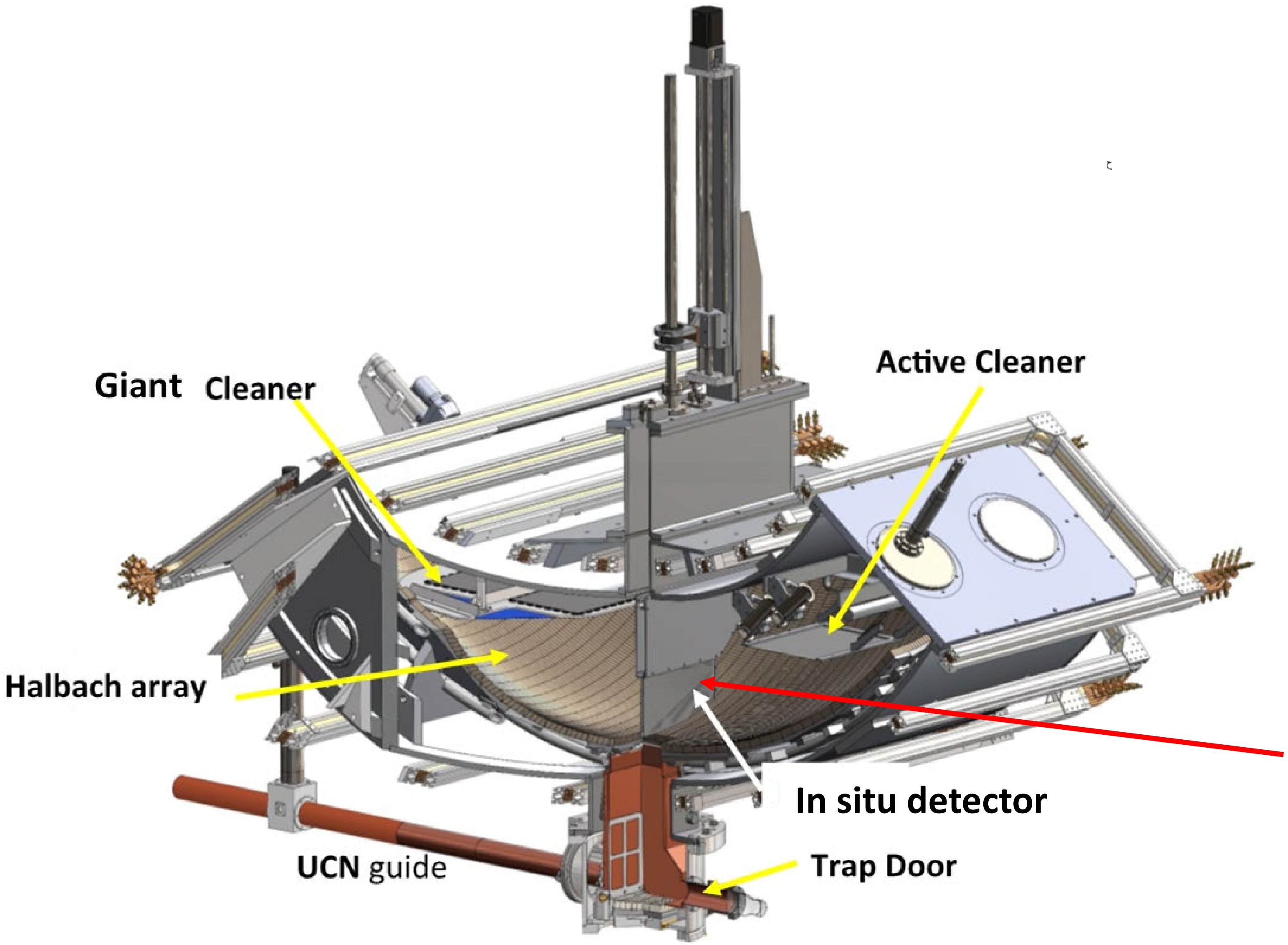
1) Halbach array (B field) eliminates interaction with materials
2) Very large volume (~400 l UCN storage)
3) Asymmetrical construction to ensure rapid emptying/detection





D. Salvat

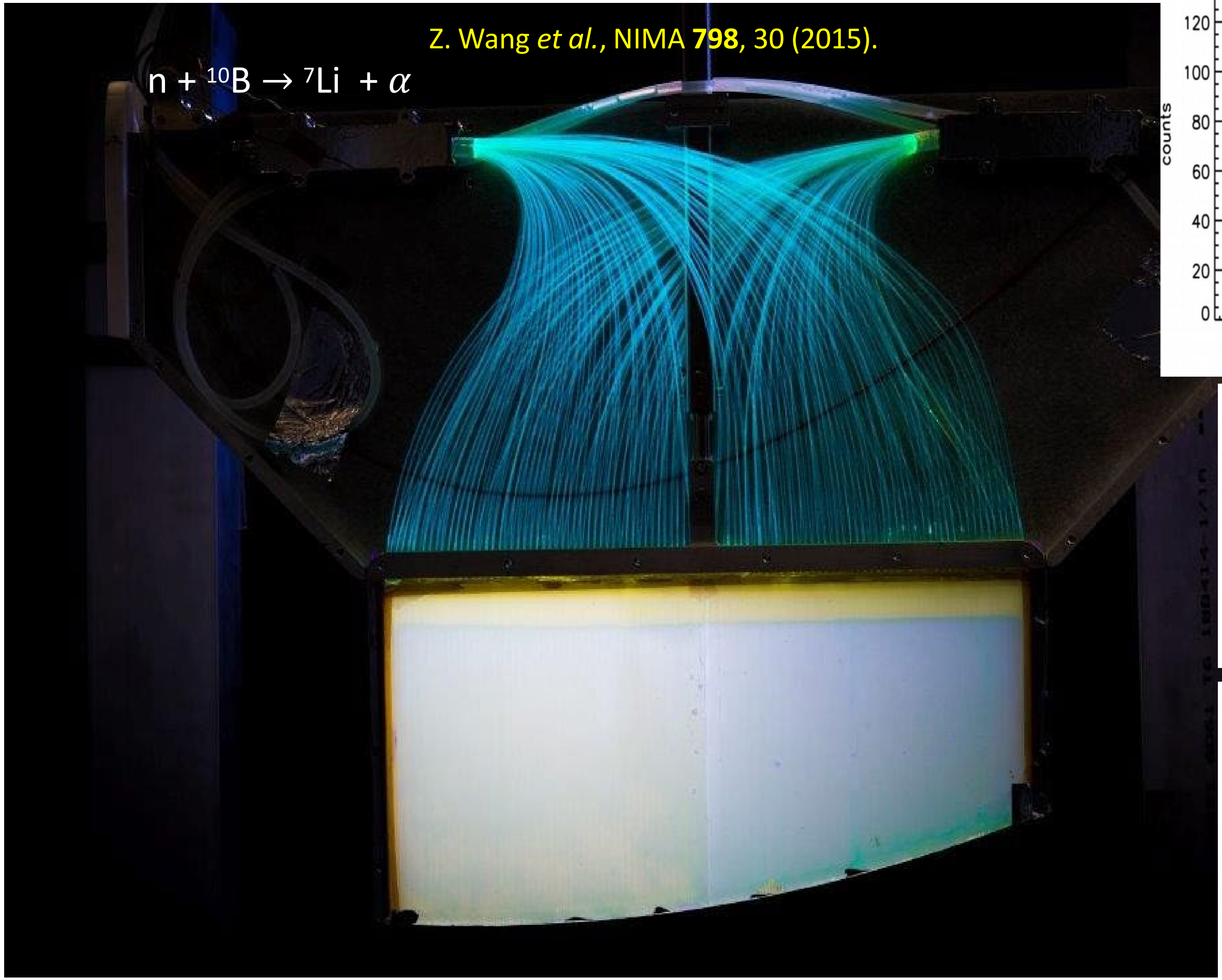
The UCNτ apparatus



Detector enters trap from top, permits studies of "quasi-bound" neutrons

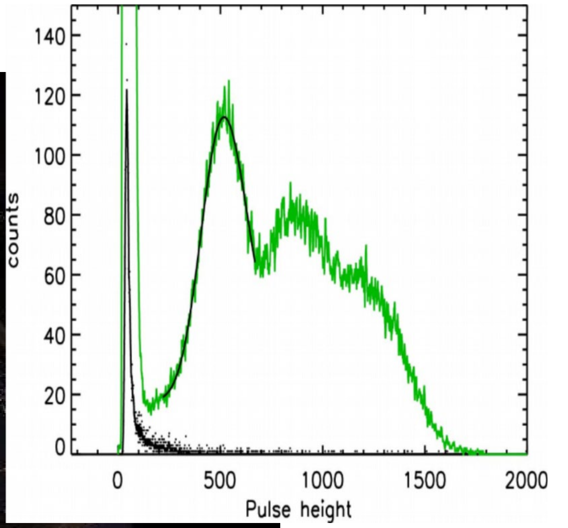
Measures counts at several heights, P1, P2, etc…

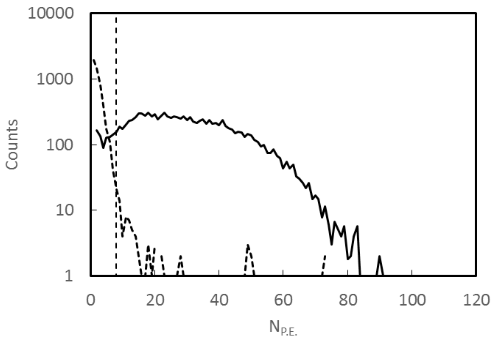
In situ “Dagger” Detector

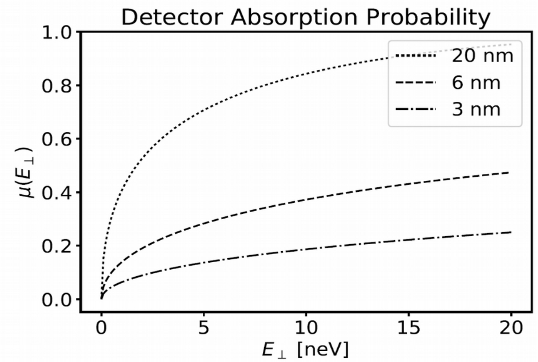


Z. Wang *et al.*, NIMA **798**, 30 (2015).

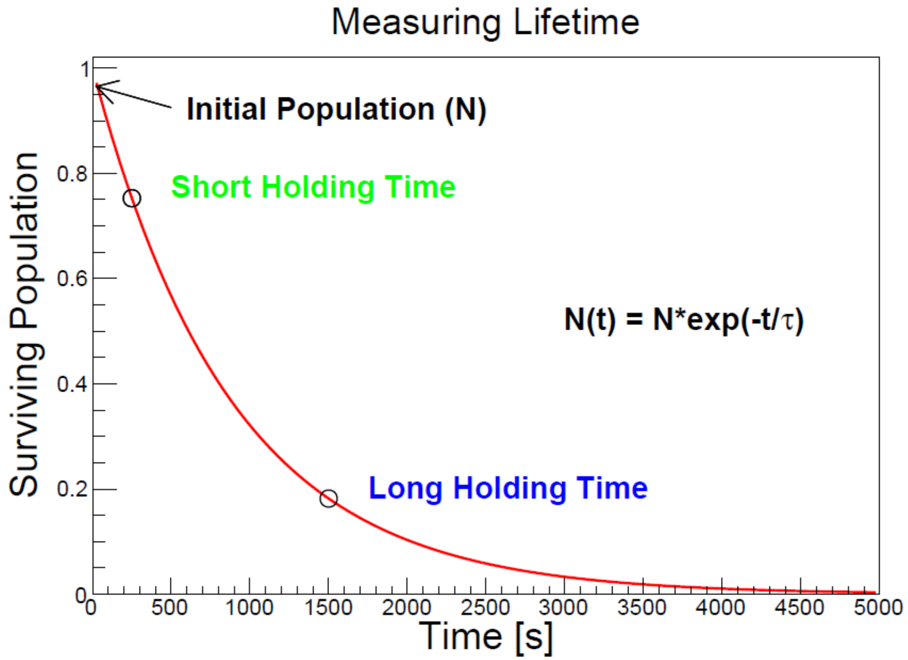
$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$

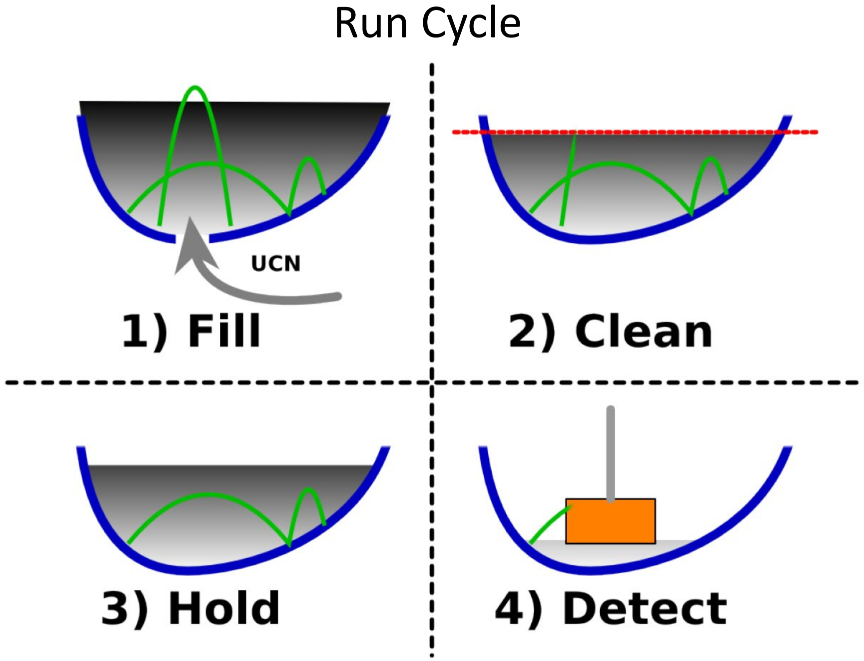






Pairs of short-long storage times



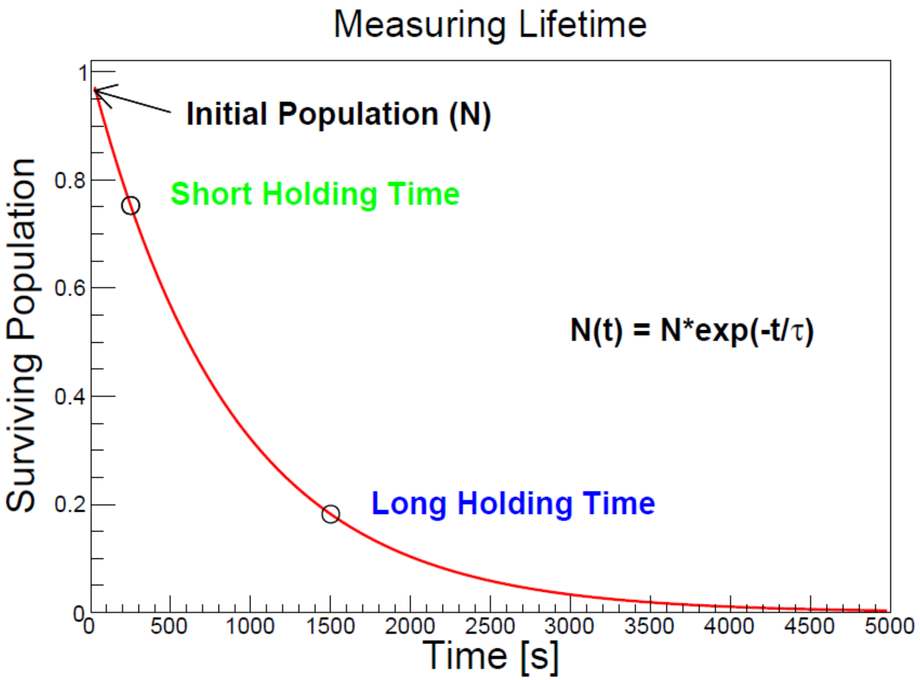


$$\tau_{trap} = \frac{\Delta t}{\log\left(\frac{N_{short}}{N_{long}}\right) - \log\left(\frac{M_{short}}{M_{long}}\right)}$$

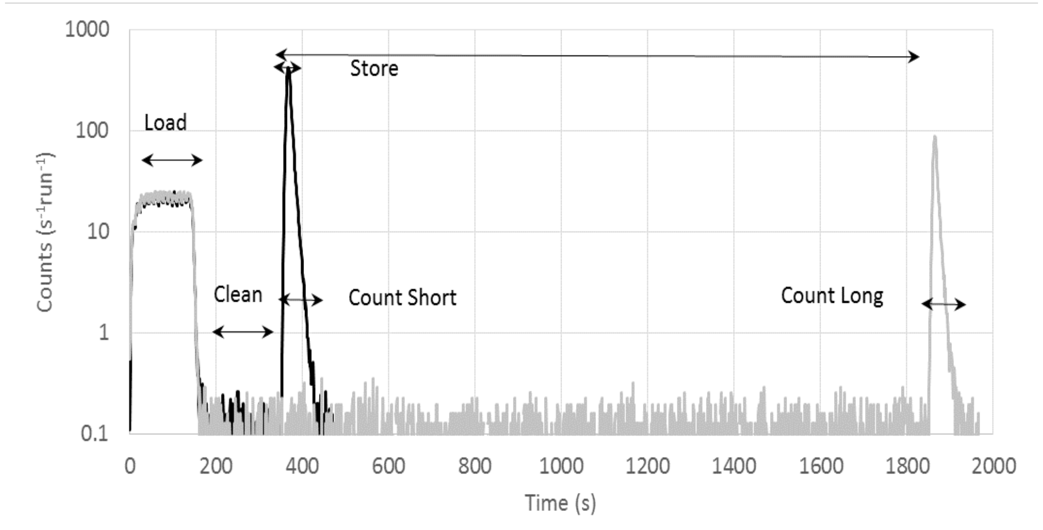
N: UCN counts
M: Monitor counts

(Detector lowered in “steps”)

Pairs of short-long storage times



Run Cycle



$$\tau_{trap} = \frac{\Delta t}{\log\left(\frac{N_{short}}{N_{long}}\right) - \log\left(\frac{M_{short}}{M_{long}}\right)}$$

N: UCN counts
M: Monitor counts

The *UCNτ* Collaboration

Argonne National Laboratory N. B. Callahan

California Institute of Technology M. Blatnik, B. Filippone, E. M. Fries, K. P. Hickerson, S. Slutsky, V. Su, X. Sun, C. Swank, W. Wei

DePauw University A. Komives

East Tennessee State University R. W. Pattie, Jr.

Indiana University/CEEM M. Dawid, W. Fox, C.-Y. Liu, F. Gonzalez, D. J. Salvat, J. Vanderwerp

Institut Laue-Langevin P. Geltenbort

Joint Institute for Nuclear Research E. I. Sharapov

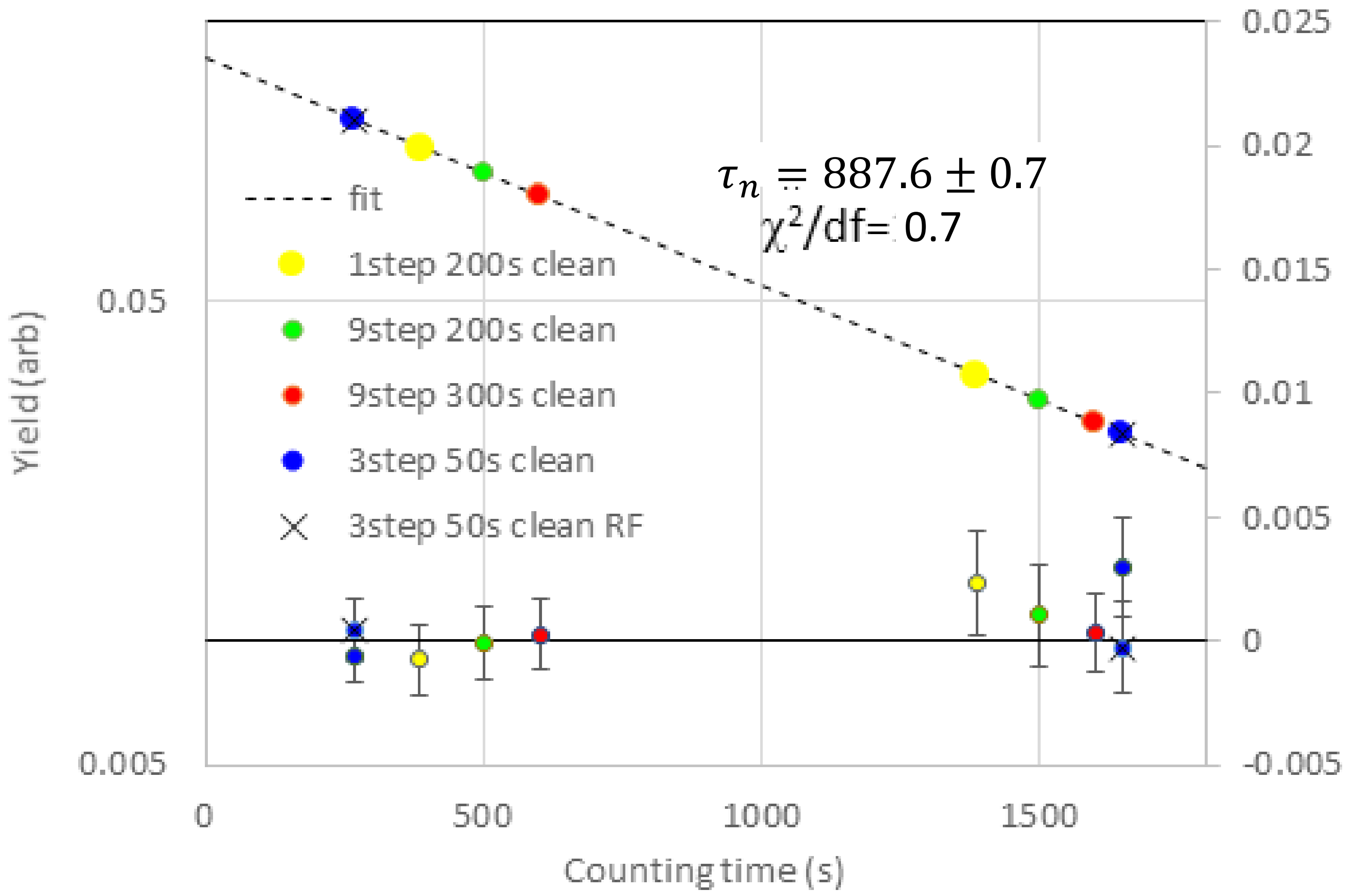
Los Alamos National Laboratory S. M. Clayton (co-spokesperson), S. A. Curry, M. A. Hoffbauer, T. M. Ito, M. Makela C. L. Morris, C. O'Shaughnessy, Z. Tang, W. Uhrich, P. L. Walstrom, Z. Wang

North Carolina State University T. Bailey, J. H. Choi, C. Cude-Woods, E. B. Dees, L. Hayen, R. Musedinovic, A. R. Young

Oak Ridge National Laboratory L. J. Broussard, J. Ramsey, A. Saunders

Tennessee Technological University R. Colon, D. Dinger, J. Ginder, A. T. Holley (co-spokesperson), M. Kemp, C. Swindell

Fit to all data (different cleaning and storage times) to a single exponential decay:

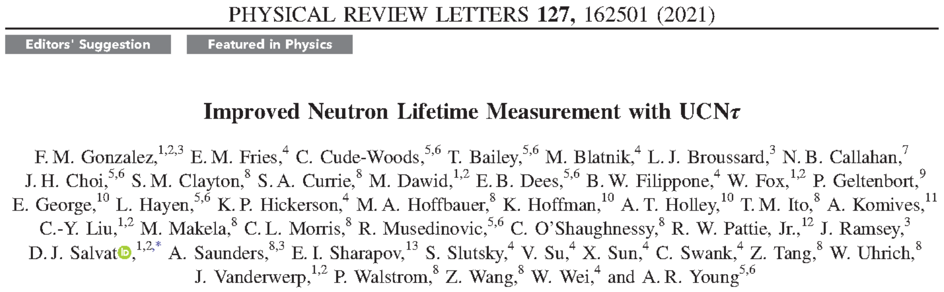


Note: still must correct for ambient gas scattering

Short Description: works like a charm! UCN storage time greater than a month!

Useful test for quasi-bound neutrons and phase space evolution

UCNτ Progress: the 2017-2018 Data Set

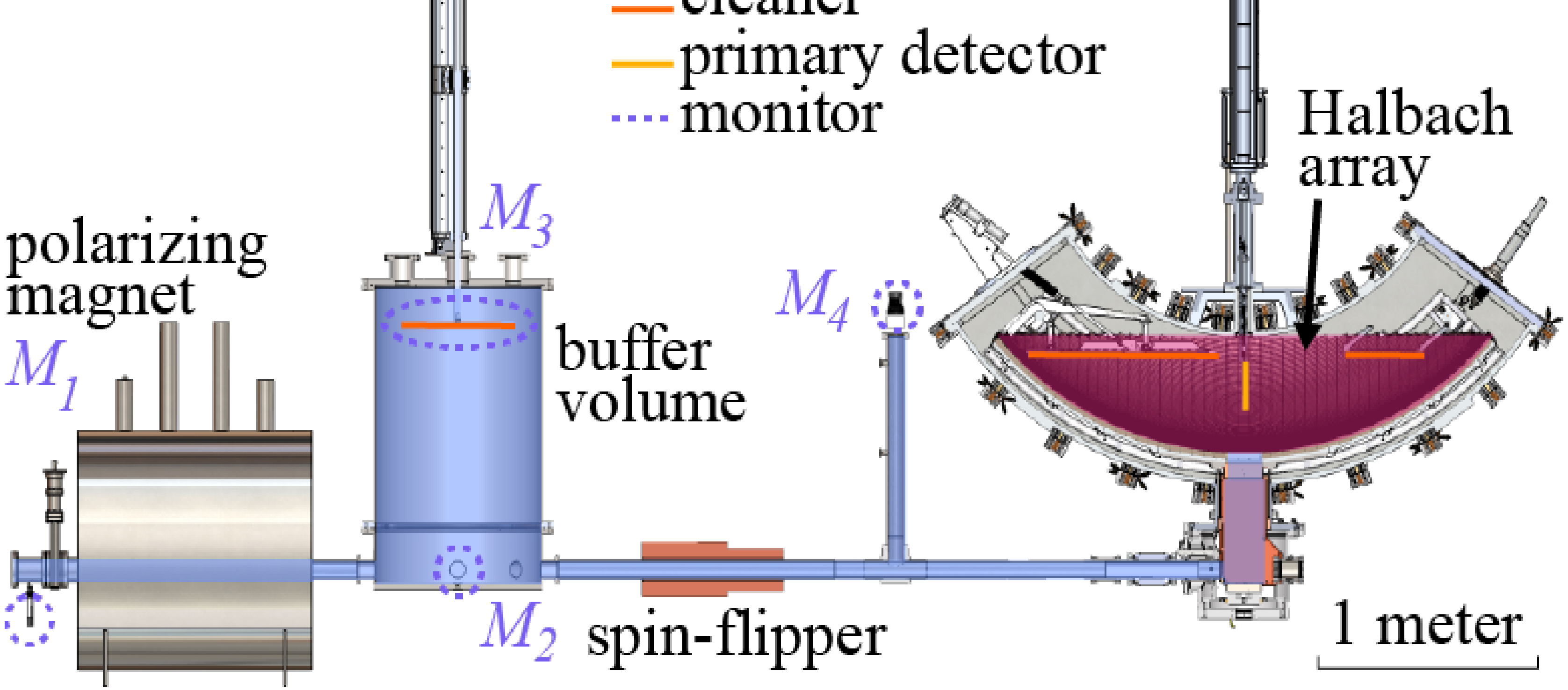


PHYSICAL REVIEW LETTERS **127**, 162501 (2021)

Editors' Suggestion | Featured in Physics

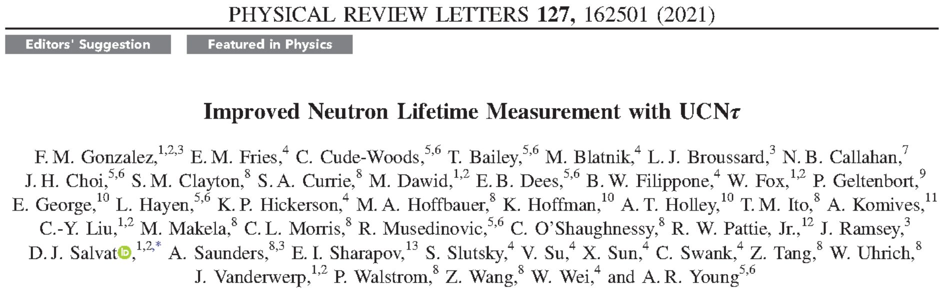
Improved Neutron Lifetime Measurement with UCNτ

F. M. Gonzalez,[1,2,3] E. M. Fries,[4] C. Cude-Woods,[5,6] T. Bailey,[5,6] M. Blatnik,[4] L. J. Broussard,[3] N. B. Callahan,[7] J. H. Choi,[5,6] S. M. Clayton,[8] S. A. Currie,[8] M. Dawid,[1,2] E. B. Dees,[5,6] B. W. Filippone,[4] W. Fox,[1,2] P. Geltenbort,[9] E. George,[10] L. Hayen,[5,6] K. P. Hickerson,[4] M. A. Hoffbauer,[8] K. Hoffman,[10] A. T. Holley,[10] T. M. Ito,[8] A. Komives,[11] C.-Y. Liu,[1,2] M. Makela,[8] C. L. Morris,[8] R. Musedinovic,[5,6] C. O'Shaughnessy,[8] R. W. Pattie, Jr.,[12] J. Ramsey,[3] D. J. Salvat,[1,2,*] A. Saunders,[8,3] E. I. Sharapov,[13] S. Slutsky,[4] V. Su,[4] X. Sun,[4] C. Swank,[4] Z. Tang,[8] W. Uhrich,[8] J. Vanderwerp,[1,2] P. Walstrom,[8] Z. Wang,[8] W. Wei,[4] and A. R. Young[5,6]



Thesis:
F. Gonalez
E. Fries

UCNτ Progress: the 2017-2018 Data Set



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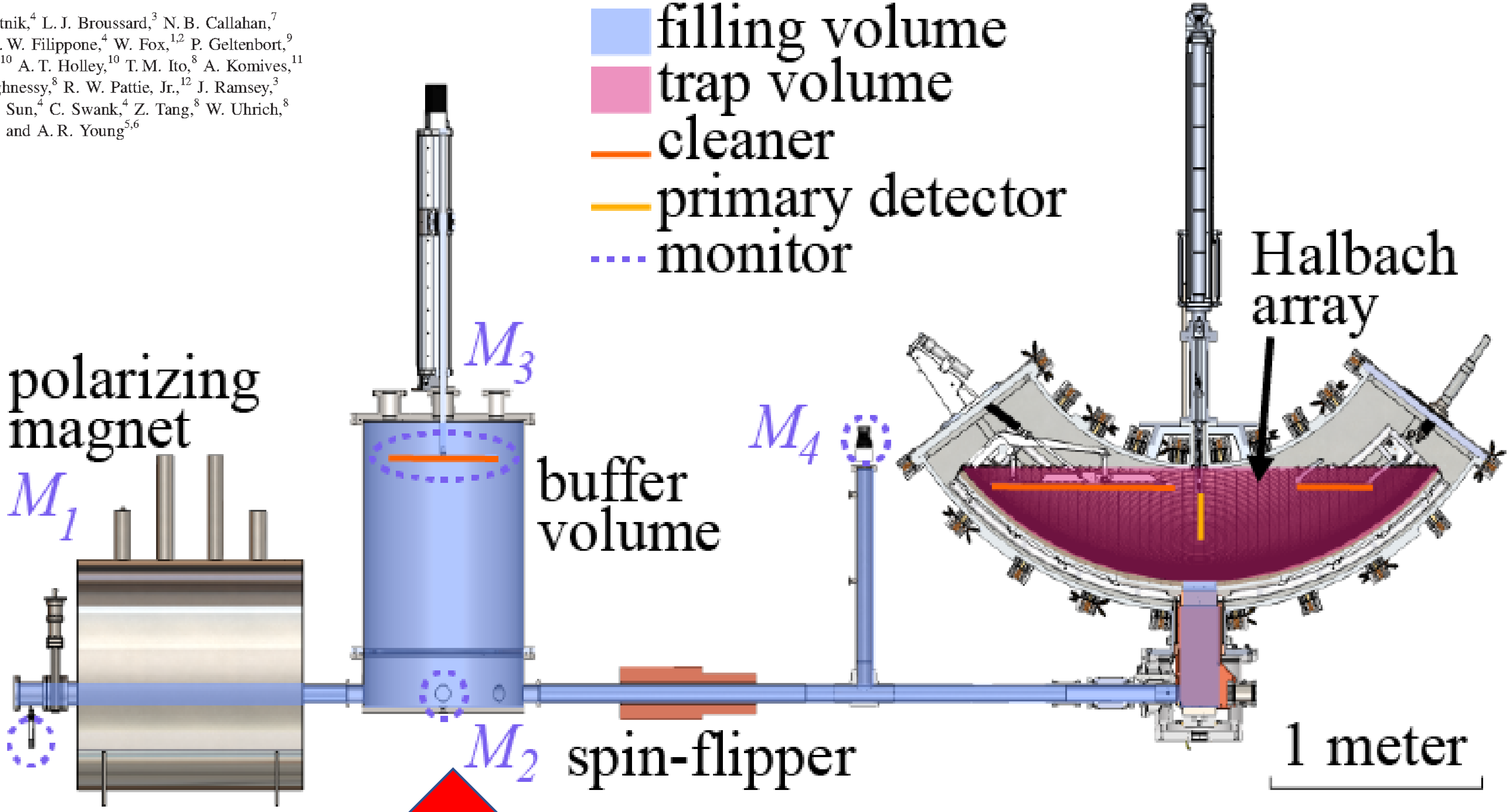

Significant improvement – ~500l buffer volume
(impacts normalization and UCN spectral control)

The error budget

Effect	Previous Reported Value (s)	New Reported Value (s)	Notes
τ_{meas}	877.5 ± 0.7	877.58 ± 0.28	Uncorrected Value!
UCN Event Definition	0 ± 0.04	0 ± 0.13	Single photon analysis vs. Coincidence analysis
Normalization Weighting	--	0 ± 0.06	Previously unable to estimate
Depolarization	$0 + 0.07$	$0 + 0.07$	
Uncleaned UCN	$0 + 0.07$	$0 + 0.11$	
Heated UCN	$0 + 0.24$	$0 + 0.08$	
Phase Space Evolution	0 ± 0.10	--	Now included in stat. uncertainty
Al Block	--	0.06 ± 0.05	Accidentally dropped into trap...
Residual Gas Scattering	0.16 ± 0.03	0.11 ± 0.06	
Sys. Total	$\mathbf{0.16^{+0.4}_{-0.2}}$	$\mathbf{0.17^{+0.22}_{-0.16}}$	
TOTAL	$\mathbf{877.7 \pm 0.7^{+0.4}_{-0.2}}$	$\boxed{\mathbf{877.75 \pm 0.28^{+0.22}_{-0.16}}}$	

Most precise value for τ_n to date!

D. Salvat

The error budget

Effect	Previous Reported Value (s)	New Reported Value (s)	Notes
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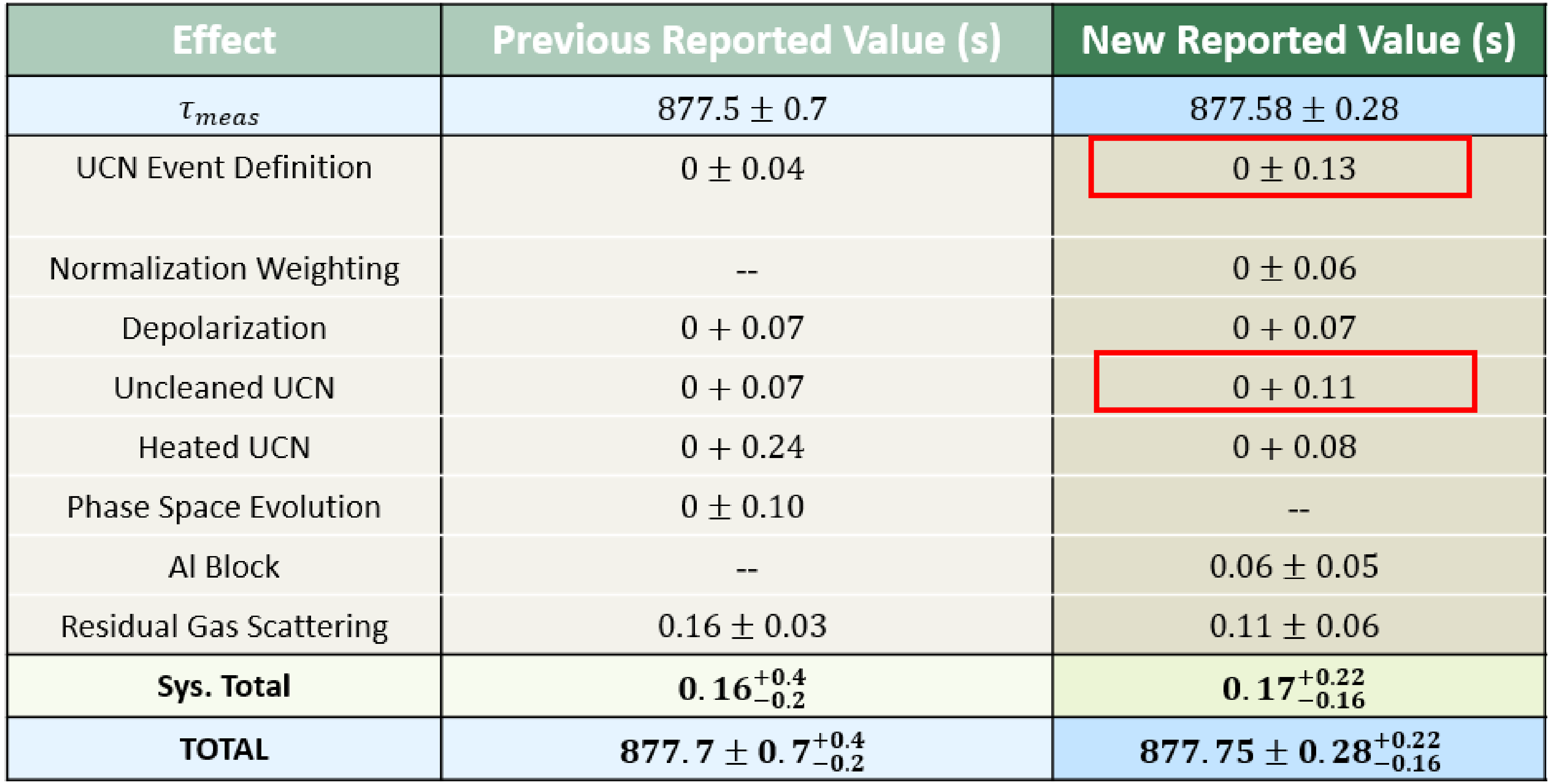
D. Salvat

Losses small compared to statistical unc!
(huge step from most material traps)

The error budget

Key Sources of Uncertainty



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TOTAL	$\mathbf{877.7 \pm 0.7^{+0.4}_{-0.2}}$	$\mathbf{877.75 \pm 0.28^{+0.22}_{-0.16}}$

Long timing “tails” for ZnS scintillator together with relatively high rates (overlapping events)

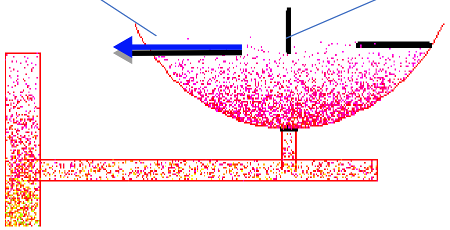
Limits from loading “uncleaned” UCN

MC indicates negligible losses due to UCN expected

D. Salvat

Normal cleaning

Measure
(1) P1 signal ($P1_c$)
(2) τ_c -- lifetime when trap cleaned



Cleaner absorbs UCN above 38 cm

Dagger

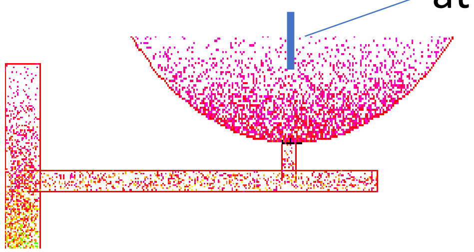
50 cm

No cleaning!

Measure
(1) P1 signal ($P1_u$)
(2) τ_u -- lifetime when trap not cleaned

Calibrate!

UCN hit dagger at P1 position



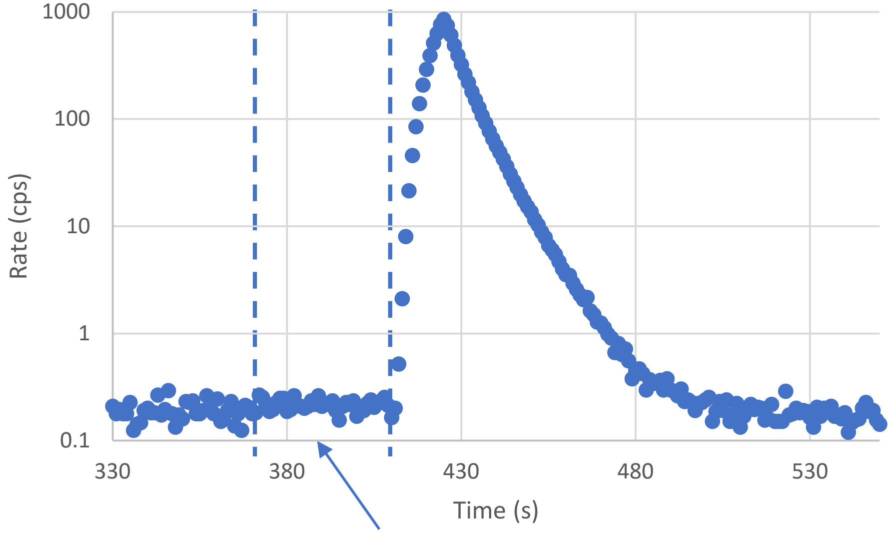
Correction to τ_n:

$$\Delta\tau_n = (\tau_c - \tau_u)\frac{P1_c}{P1_u}$$

$$< 0.11\ s$$

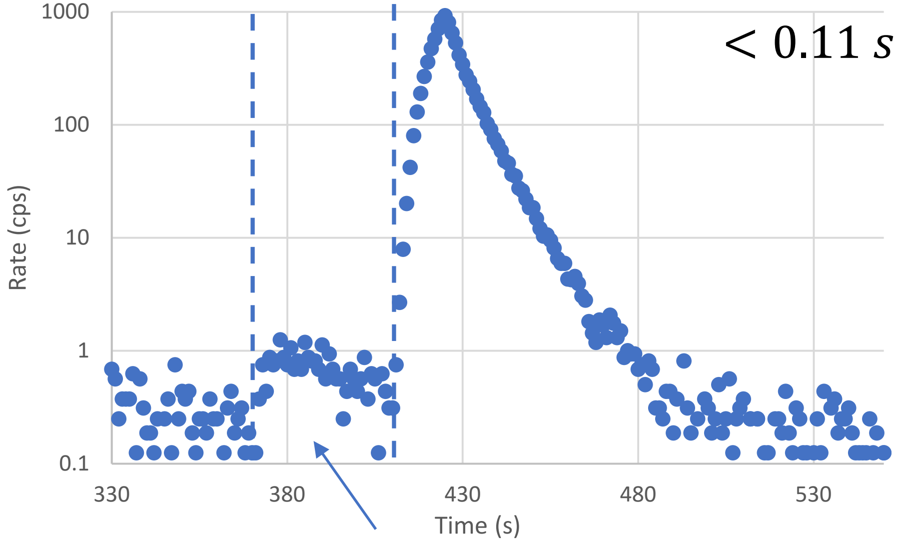
20 s unload

Position 1



$P1_c$ signal consistent with background…
(**upper bound** on uncleaned UCN)

Position 1



$P1_u$ signal present from population not cleaned!

UCNτ: 2023 and beyond

- UCNτ running now complete – another data set comparable to 2021 update available, with a number of new systematic studies as well
- LDRD-funded upgrade of UCNτ underway with goal 0.12 s: UCNτ$^+$

  prototype installation planned at LANL during 2023 run cycle

  with (projected) order of magnitude greater UCN densities

Some potential issues are already addressed for UCNτ$^+$:

(1) Rate dependent effects will be reduced using higher granularity for "dagger" read-out and possibly faster scintillator

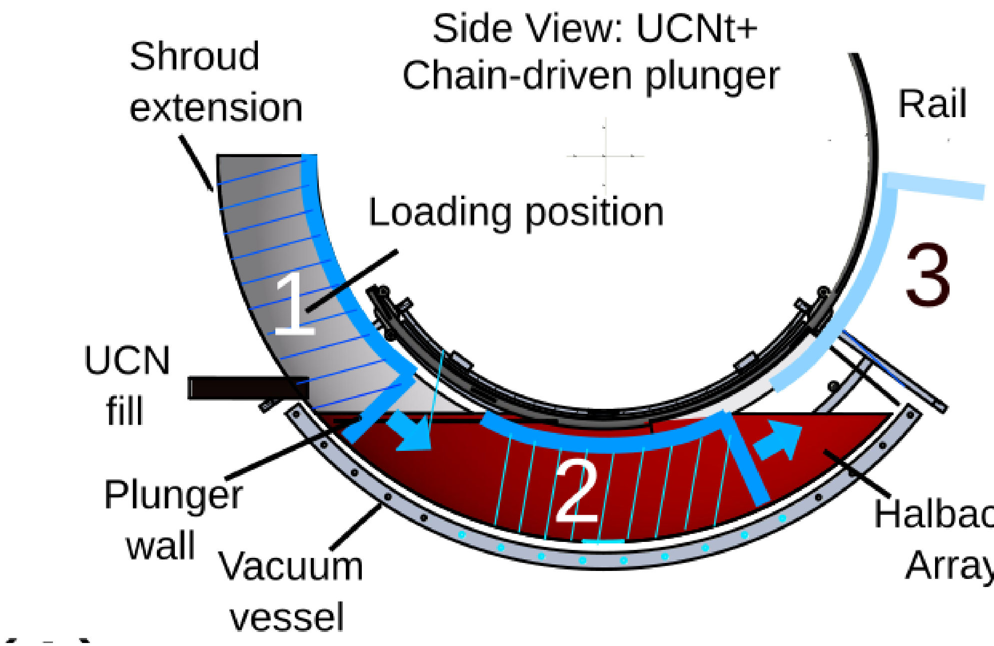
(2) Higher statistics will permit corresponding improvement in statistical constraint for quasi-bound (not cleaned) UCN

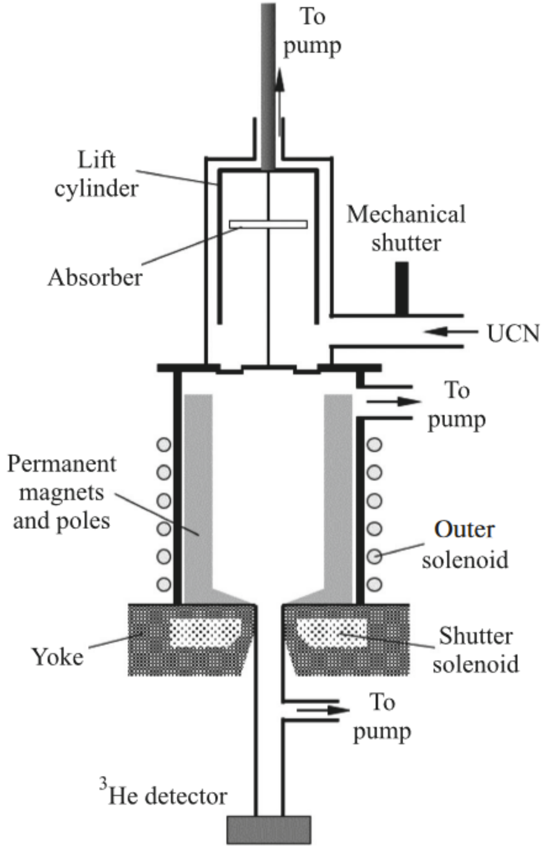
ISSN 0021-3640, JETP Letters, 2018, Vol. 107, No. 11, pp. 671–675. © Pleiades Publishing, Inc., 2018.

A neutron elevator: UCNτ+

New Loading Mechanisms to maximize statistics

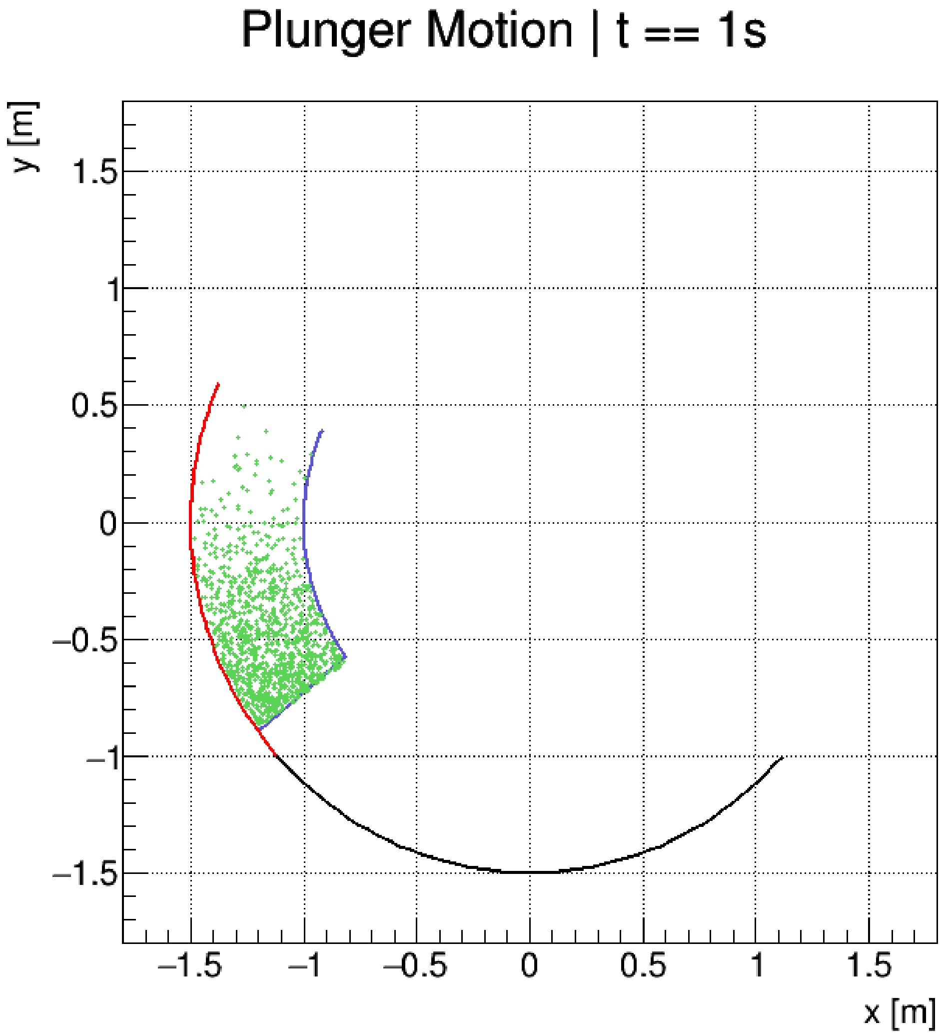
- Funded by LANL LDRD
- Anticipate ~10× counts





Shooting for < 0.15 s sensitivity!

Simulation of a cylindrical trap geometry: UCN Loading

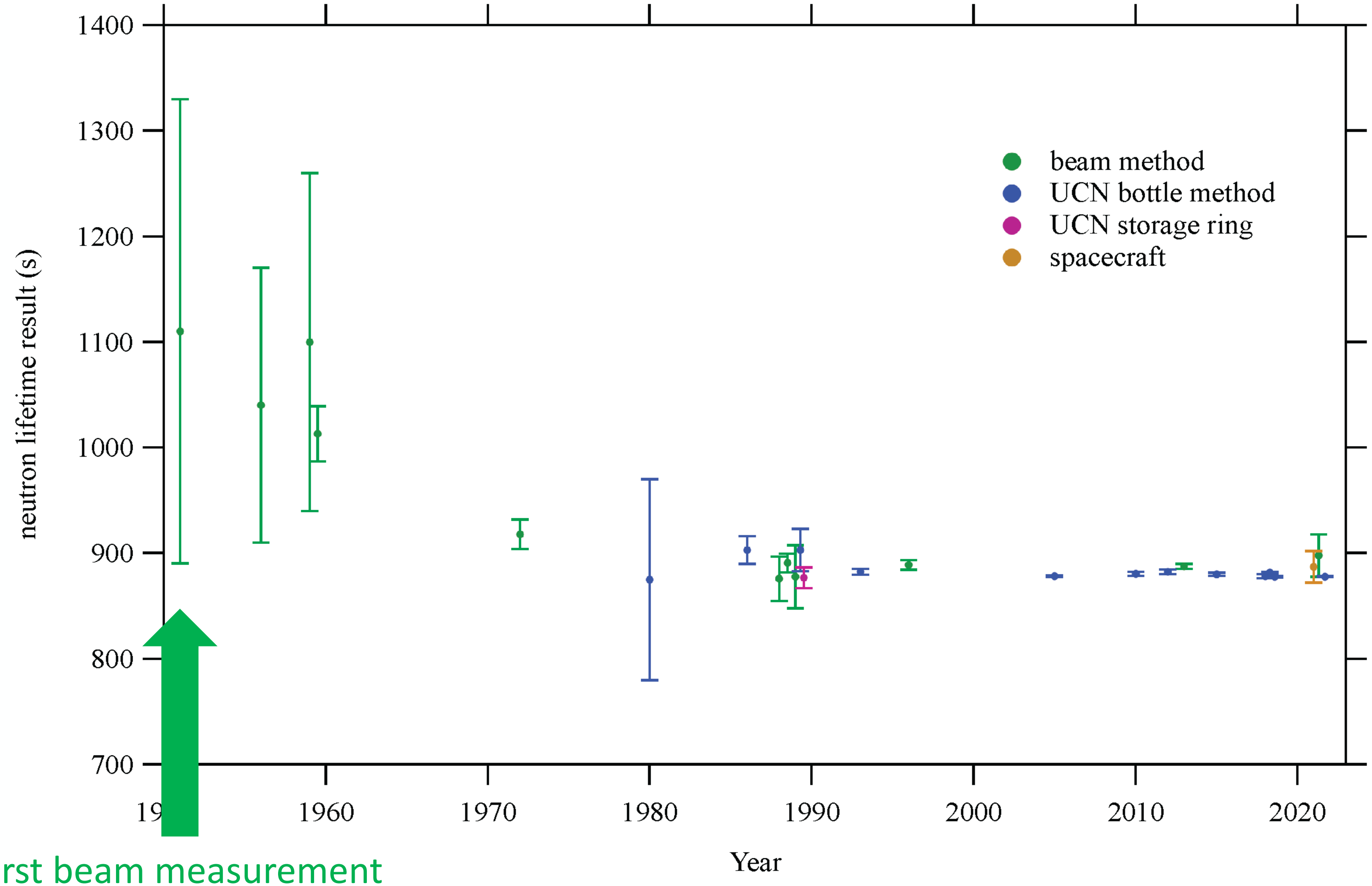


Modeling: thesis R. Musedinovic

Beam Measurements

Special thanks to D. Salvat, C.-Y Liu, F. Wietfeldt for slides

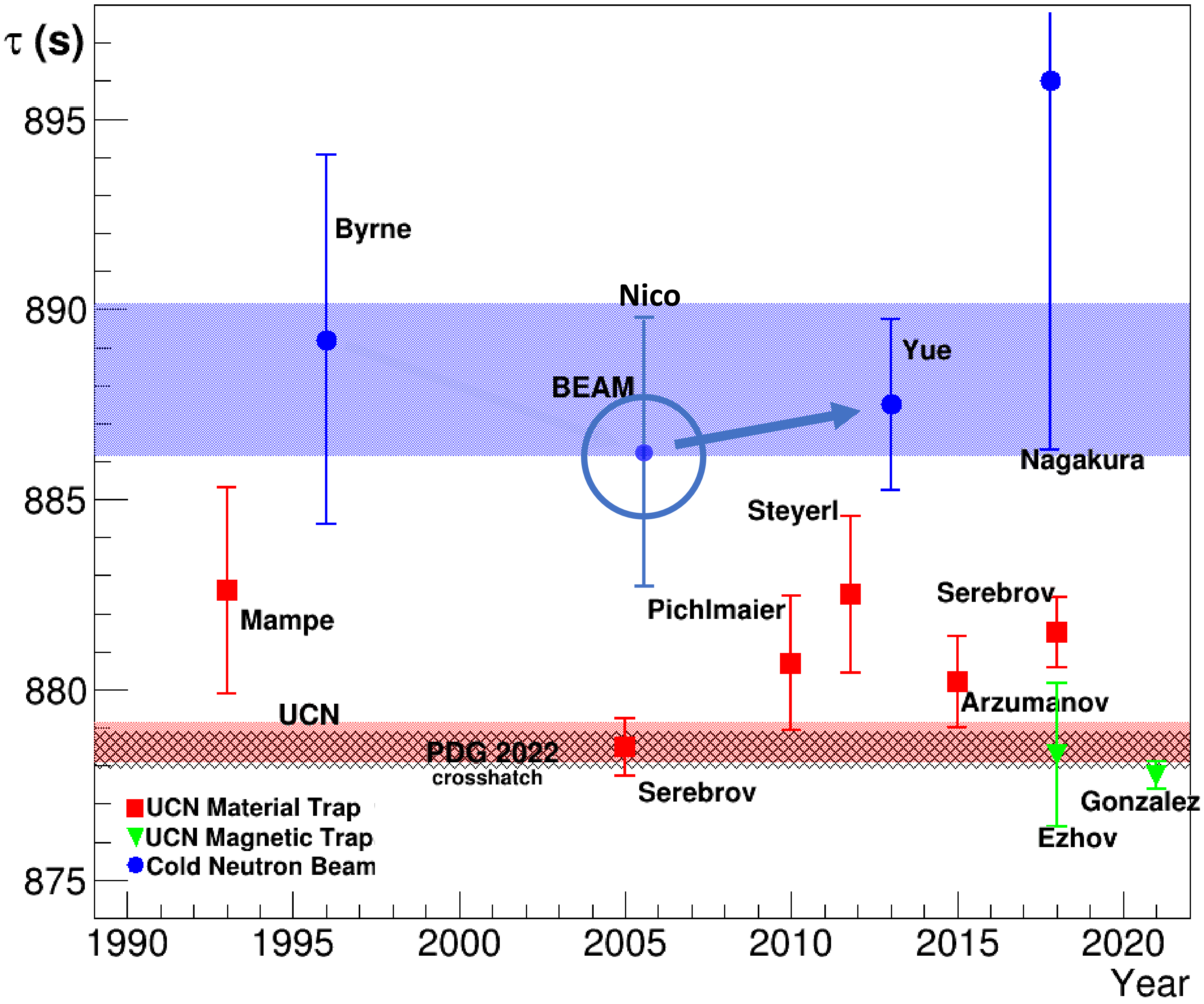
Neutron Lifetime Measurements



First beam measurement
(Robson, Phys. Rev. **83**, 349 (1951)

From: Wietfeldt and Greene, Rev. Mod. Phys. **83**, p. 1173 (2011)

Measurements of the Neutron Lifetime

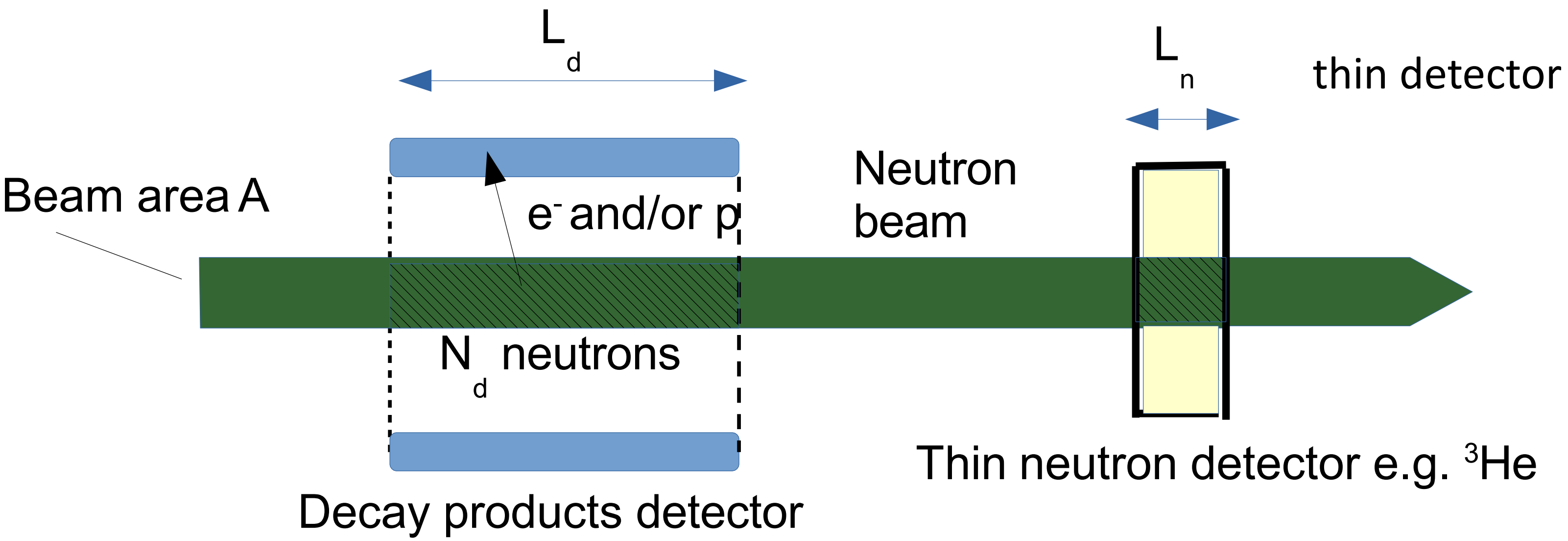


Lifetime measurements with cold neutron beams

State of the art as of 2005…

Assume (1) mono-energetic neutron beam (with speed v), density ρ_n, flux $\Phi_n = \rho_n v$

(2) neutron detector cross section proportional to $1/v = \sigma_{th} v_{th}/v$



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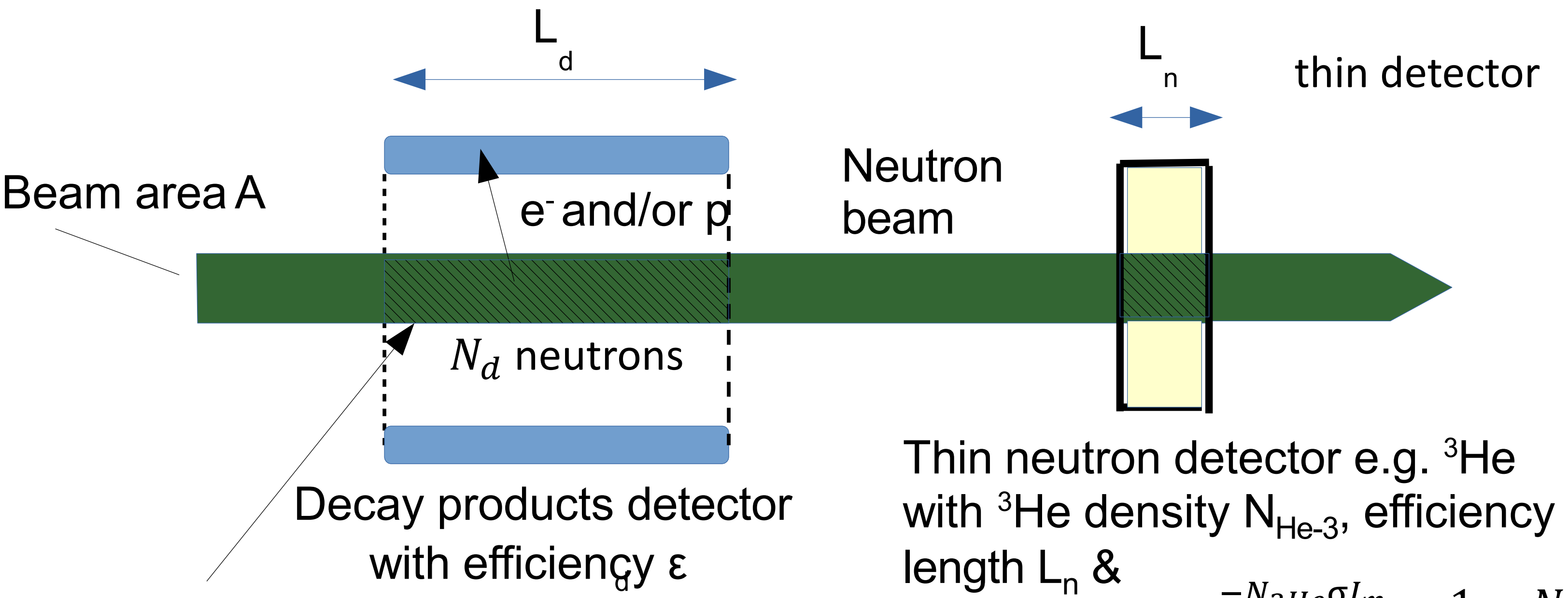


Decay products detector with efficiency ε_d

Thin neutron detector e.g. ^{3}He with ^{3}He density $N_{He\text{-}3}$, efficiency ε and length L_n &

$$e^{-N_{3He}\sigma L_n} \approx 1 - N_{3He}\sigma L_n$$

True decay rate in detector:

$$R_d = N_d/\tau = \boldsymbol{\rho_n} A L_d/\tau = (\Phi/v) A L_d/\tau$$

Neutron absorption rate:

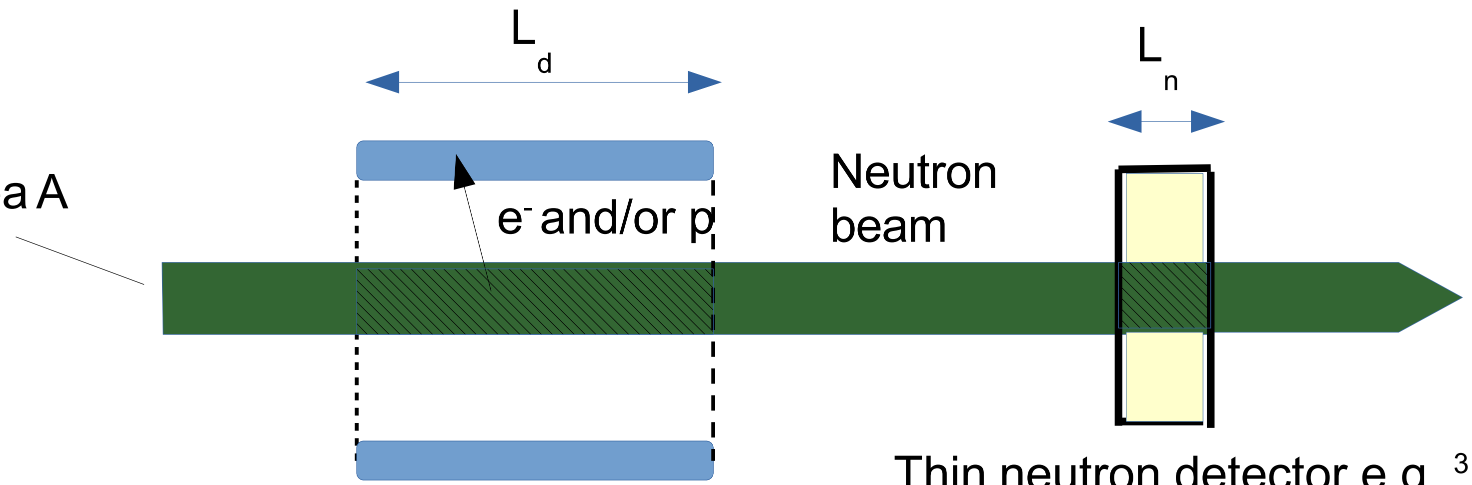
$$R_n = \Phi A N_{3He} L_n \sigma = \Phi A N_{3He} L_n \boldsymbol{\sigma_{th} v_{th}/v}$$

Same 1/v dependence appears in particle detection rate and neutron rate
(in one case, we need a density, in the other it arises from the cross-section!)

Lifetime measurements with cold neutron beams

Assume (1) mono-energetic neutron beam (v_n) with flux Φ_n and density ρ_n

(2) neutron detector cross section proportional to $1/v = \sigma_{th} v_{th}/v$



L_d

L_n

Neutron beam with cross-sectional area A

e^- and/or p

Neutron beam

Decay products detector with efficiency ε_d

Thin neutron detector e.g. ^{3}He with ^{3}He density N_{3He}, efficiency ε and length L_n

Measured $S_d = R_d\,\varepsilon_d$ $S_n = R_n\,\varepsilon_n$

Use measured rates to solve for τ

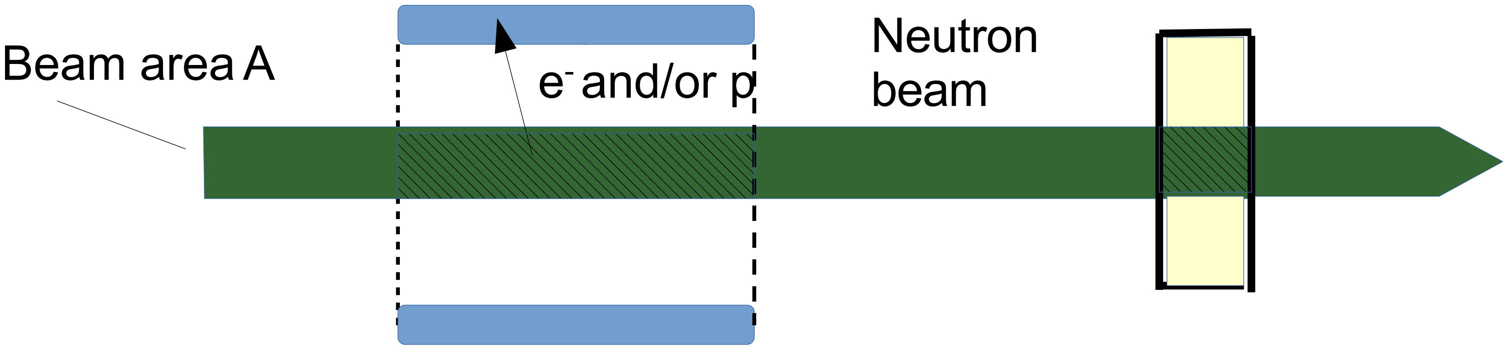
$$\frac{S_d/\varepsilon_d}{S_n/\varepsilon_n} = \frac{(\Phi/v)AL_d}{(\Phi/v)AL_n\sigma_{th}v_{th}}\,\frac{1}{\tau} \Longrightarrow \boxed{\tau = \frac{S_n\varepsilon_d\,L_d}{S_d\varepsilon_n L_n\sigma_{th}v_{th}}}$$

The flux and velocity factors drop out!
(makes high precision measurement possible)!

Lifetime measurements with cold neutron beams

Assume (1) mono-energetic neutron beam (v_n) with flux Φ_n and density ρ_n

(2) neutron detector cross section proportional to $1/v = \sigma_{th} v_{th}/v$



Beam area A

e

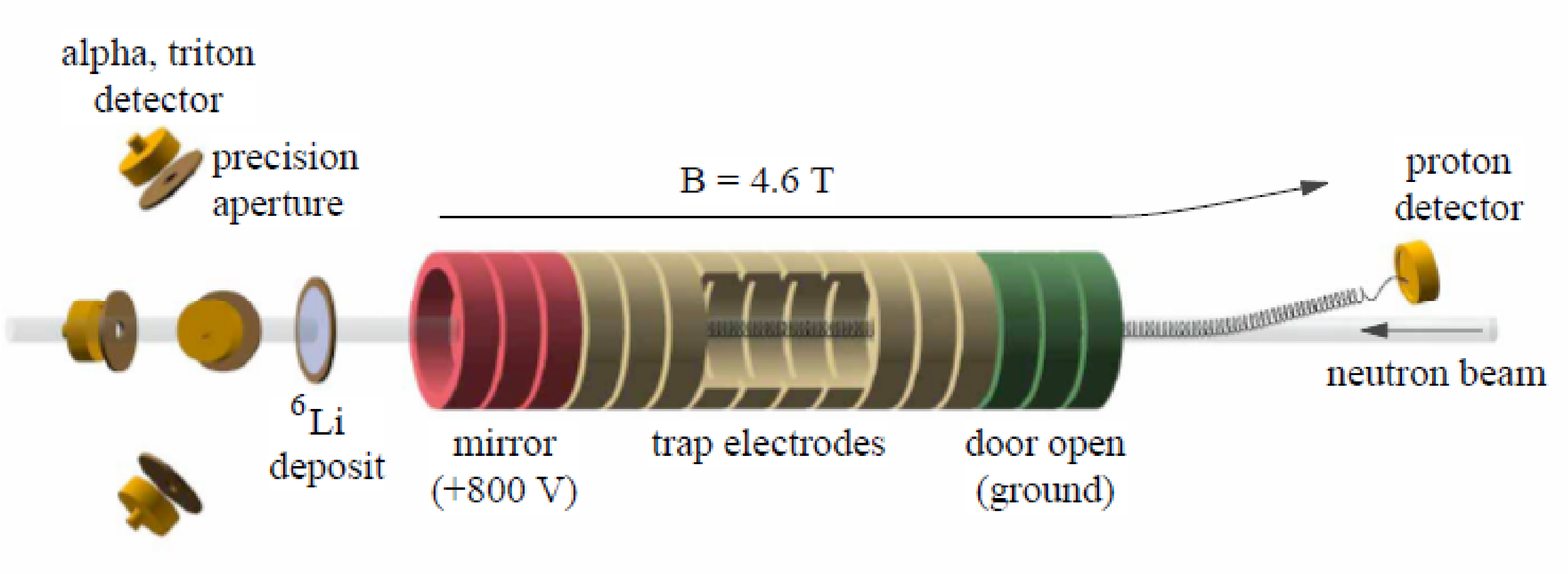
Neutron beam

Decay products detector with efficiency ε_d

$$\frac{S_d}{S_n} = \frac{\varepsilon_n (\Phi/v) A L_d}{\varepsilon_d (\Phi/v) A L_n \sigma_{th} v_{th}} \frac{1}{\tau} \Longrightarrow \boxed{\tau = \frac{S_n \varepsilon_d L_d}{S_d \varepsilon_n L_n \sigma_{th} v_{th}}}$$

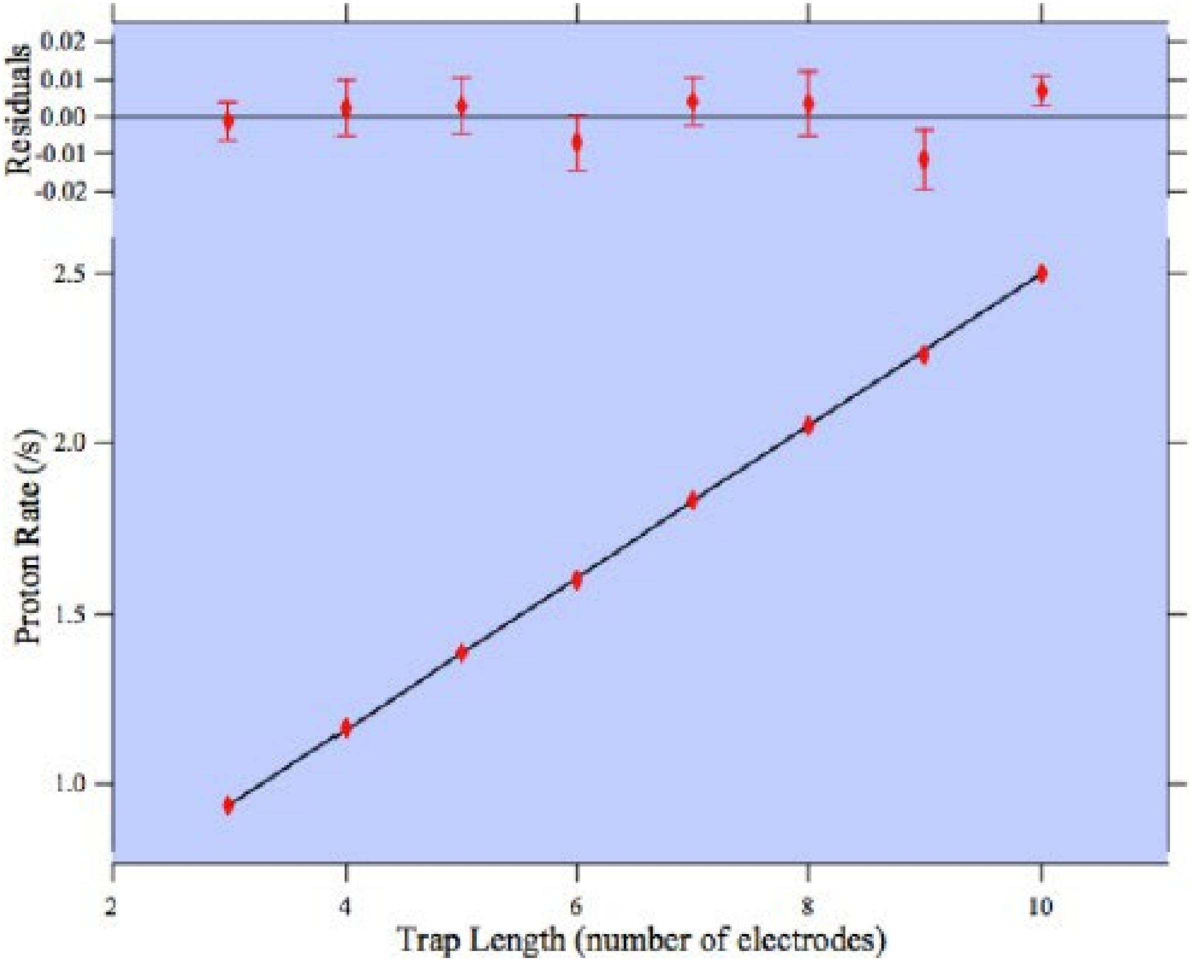
So...with knowledge of absolute efficiencies, the length of the decay and neutron detection regions, and the neutron absorption cross-section, you can determine the neutron beta decay lifetime!

The most precise beam experiment is at the National Institute of Standards and Technology (NIST)



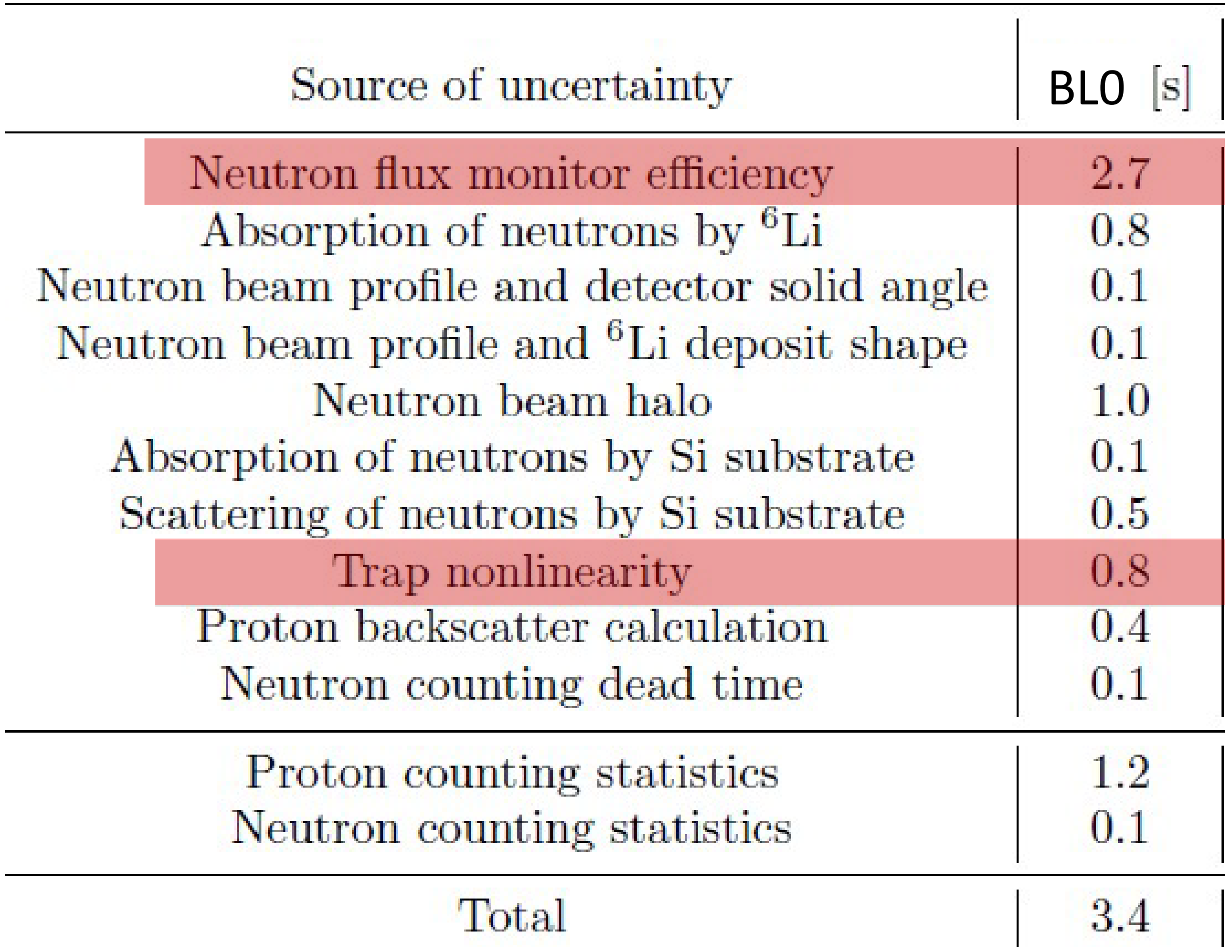
- Cold neutron beam, collimated to 2 mm
- A quasi-penning trap electrostatically traps beta-decay protons. When the door electrodes are set to ground, the protons are guided by a B field to an external detector (surface barrier Si detector).
- Neutron monitor measures the incident neutron flux by counting $n+{}^6Li \rightarrow {}^3He+\alpha$

$$\dot{N}_p = \dot{N}_{\alpha+t} \left(\frac{L}{\tau_n} \right) \frac{\epsilon_p}{R_D L_D \epsilon_D}$$



Vary trap length to characterize edge effects

Systematic Effects for the NIST Beam Lifetime (BL) Experiments

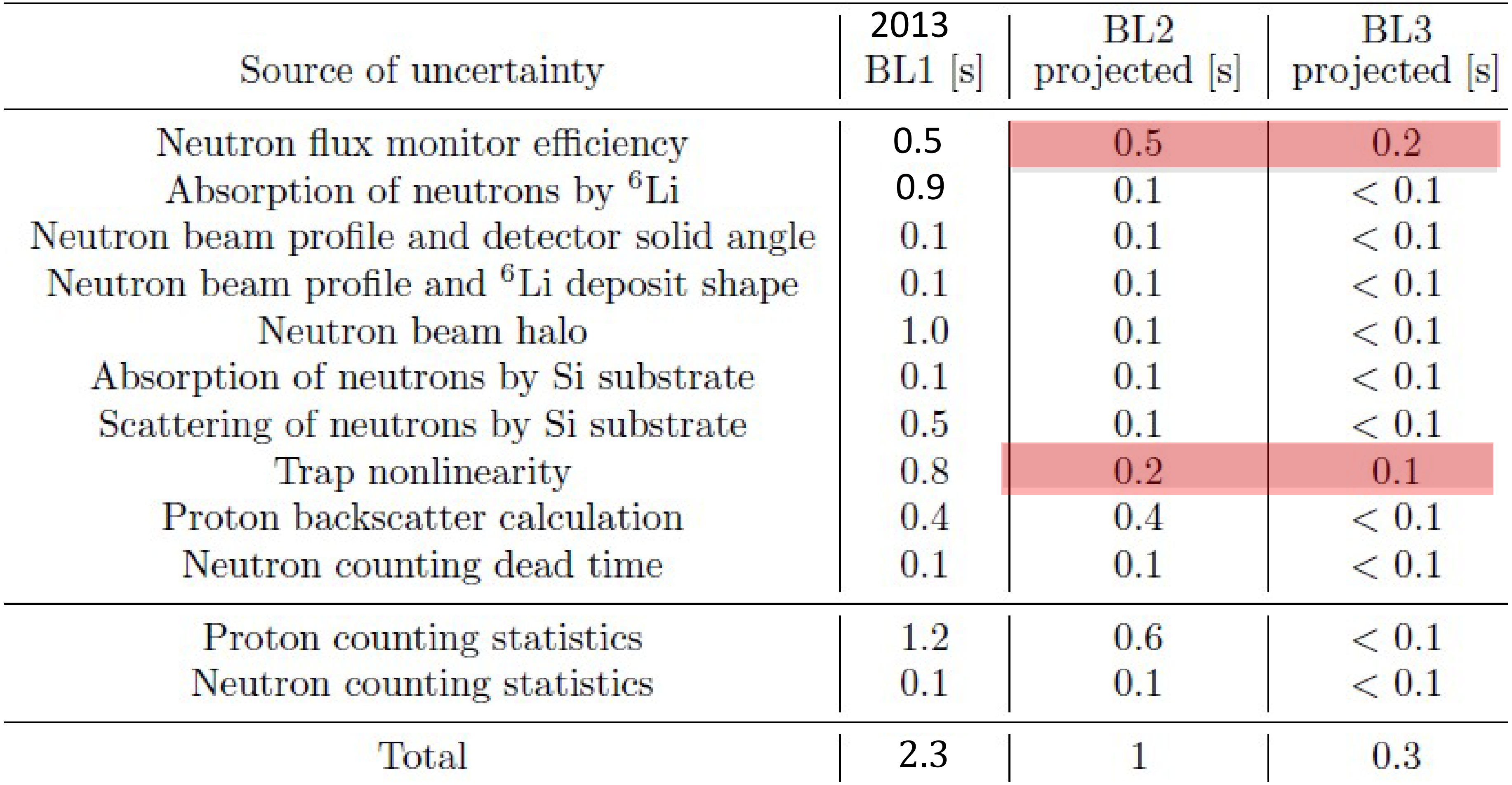


Source of uncertainty	BL0 [s]	BL1
Neutron flux monitor efficiency	2.7	→0.5
Absorption of neutrons by ^{6}Li	0.8	→0.9
Neutron beam profile and detector solid angle	0.1	
Neutron beam profile and ^{6}Li deposit shape	0.1	
Neutron beam halo	1.0	
Absorption of neutrons by Si substrate	0.1	
Scattering of neutrons by Si substrate	0.5	
Trap nonlinearity	0.8	
Proton backscatter calculation	0.4	
Neutron counting dead time	0.1	
Proton counting statistics	1.2	
Neutron counting statistics	0.1	
Total	3.4	→ 2.3

Use absolute alpha counting to calibrate efficiency for a thick absorber monitoring gamma decays!

Information provided by N. Fomin

Systematic Effects for the NIST Beam Lifetime (BL) Experiments



Source of uncertainty	2013 BL1 [s]	BL2 projected [s]	BL3 projected [s]
Neutron flux monitor efficiency	0.5	0.5	0.2
Absorption of neutrons by ^{6}Li	0.9	0.1	< 0.1
Neutron beam profile and detector solid angle	0.1	0.1	< 0.1
Neutron beam profile and ^{6}Li deposit shape	0.1	0.1	< 0.1
Neutron beam halo	1.0	0.1	< 0.1
Absorption of neutrons by Si substrate	0.1	0.1	< 0.1
Scattering of neutrons by Si substrate	0.5	0.1	< 0.1
Trap nonlinearity	0.8	0.2	0.1
Proton backscatter calculation	0.4	0.4	< 0.1
Neutron counting dead time	0.1	0.1	< 0.1
Proton counting statistics	1.2	0.6	< 0.1
Neutron counting statistics	0.1	0.1	< 0.1
Total	2.3	1	0.3

BL2: on-going data-taking; expect to finish in 2023.

Information provided by N. Fomin

BL2 – providing new insight and assessment of NIST experiment

A recent concern: proton lifetime in trap!

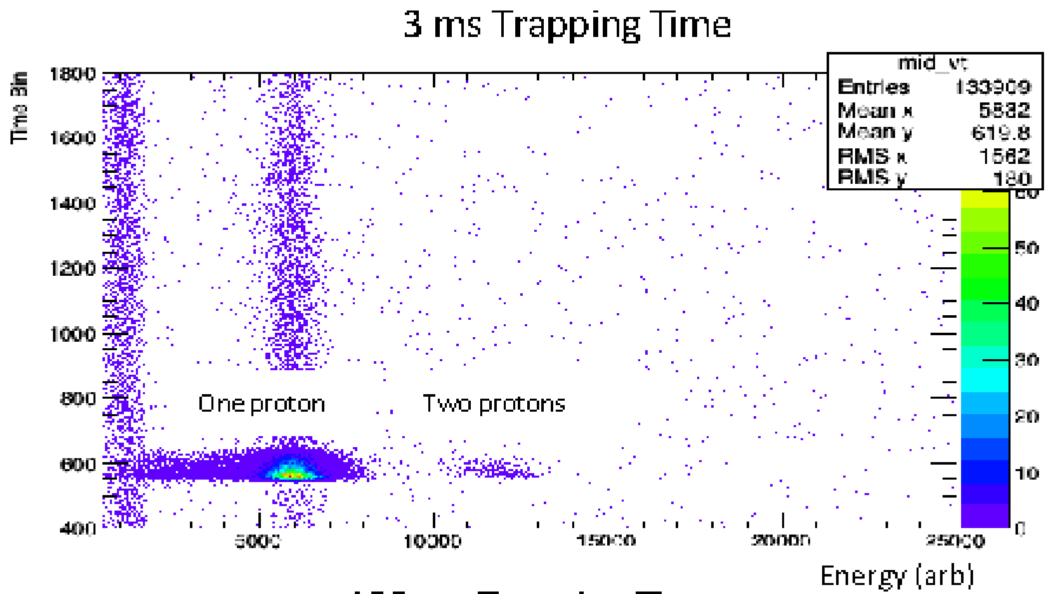
Protons lost from trap due to charge exchange or scattering would reduce proton yield and increase effective lifetime (discussion at Solvay workshop "Beta-Decay Weak Interaction Studies in the Era of the LHC" in 2014)

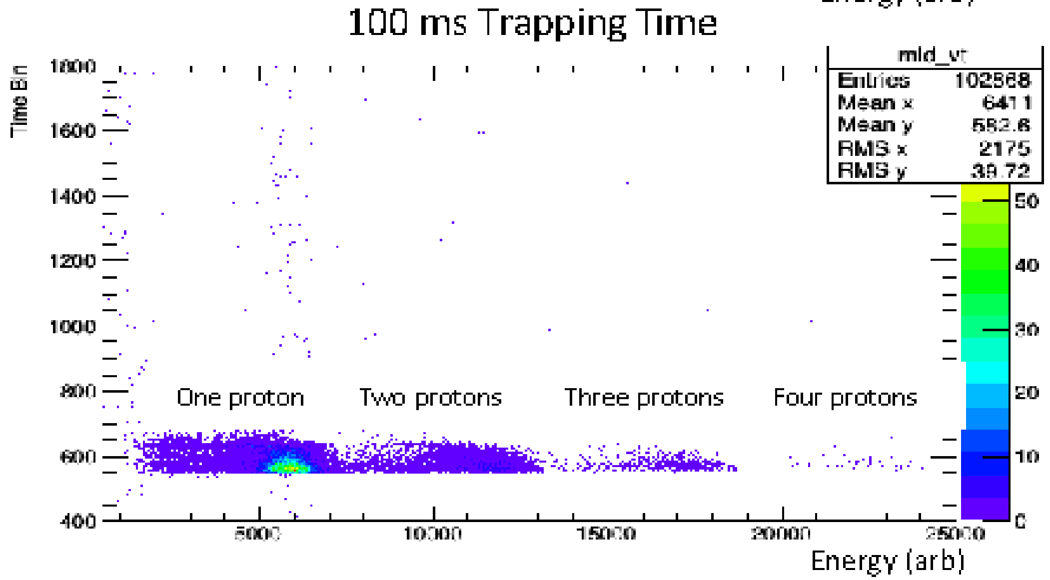
Byrne and Worcester, J. Phys. G: Nucl. Part. Phys. **46**, 085001 (2019)

A. Serebrov et al., Phys. Rev. D **103**, 074010 (2021)

Almost all data taken with 10 ms trapping time for BL1 (no correction in BL1)

Losses quantified in BL2
(need for significant correction not clear yet)





BL2 Collaboration

R. Biswas, J. Caylor, B. Crawford, M. S. Dewey, N. Fomin, K. Grammer, G. L. Greene, S. F. Hoogerheide, H. P. Mumm, J. S. Nico, H. Rahangdale, E. M. Scott, W. M. Snow, F. E. Wietfeldt , and J. D. Zuchegno

Thanks to collaboration for some slides, images, and figures

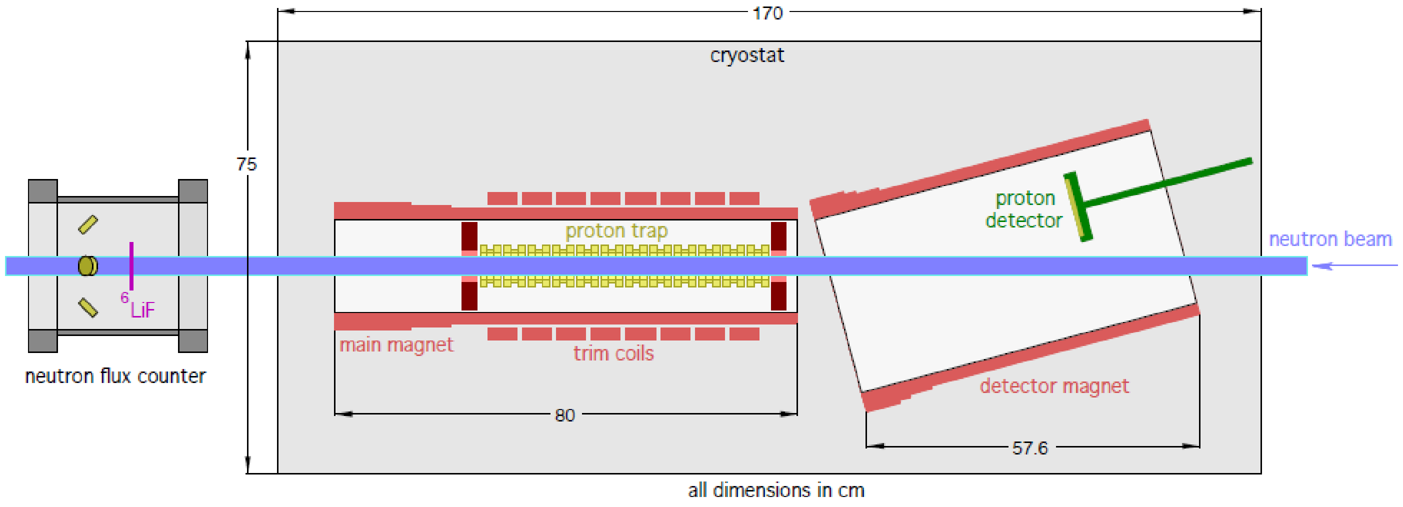
Supported by:

Interagency Agreement 89243019SSC000025
DE-FG02-03ER41258

PHY-2012395

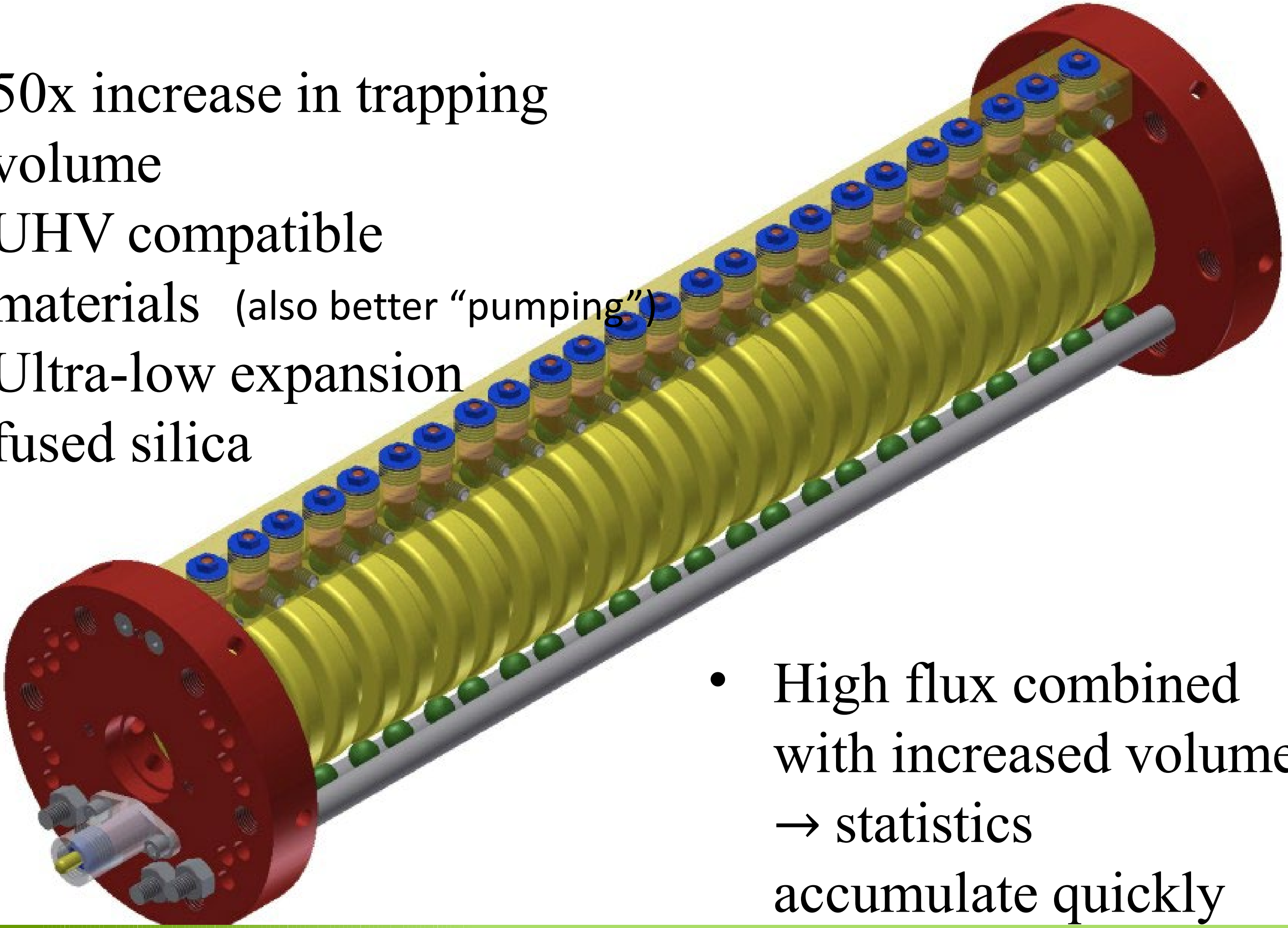
BL3: Bigger!

- Increased neutron beam diameter
  7 mm → 35 mm
- Uniformity requirements:
  $\Delta B/B < 10^{-3}$ (in proton trap)
- 50x increase in trapping volume



New Quasi-PenningTrap

- 50x increase in trapping volume
- UHV compatible materials (also better "pumping")
- Ultra-low expansion fused silica



- High flux combined with increased volume → statistics accumulate quickly

Scheduled to begin data-taking in ~2026, sensitivity goal 0.3 s!

Lifetime Prospects

Next 5 years plans include:

- UCN storage measurements
  1. **UCNτ** (magnetic trapping): running complete, with 2020-2022 data set to analyze
  2. **UCNτ+** (magnetic trapping): target precision 0.12 s
  3. **TauSpect** (magnetic trapping): commissioning this year at PSI, with target precision 0.3 s <Spokesperson D. Ries>
  4. **PeNELOPE** (magnetic trapping): commissioning planned at ILL within a few years, with target precision 0.1 s <Spokesperson R. Picker>

Inactive? (Need update for **Serebrov, Ezhov** and **HOPE**)

- Beam measurements
  1. **BL2** (clarifying some sources of systematic uncertainty for BL1) and **BL3** starting in 2026, with target precision 0.3 s
  2. **J-PARC** pulsed beam experiment (TPC) at J-PARC, ongoing, with target precision 1 s <Spokesperson K. Mishima>
- **UCNProbe**: <Spokesperson Z. Tang> branching ratio for beta decay to roughly 1 s level

Prospects not clear (to me) for satellite-based measurements

Lifetime Prospects

A LOT of Activity

In next 5 years plans include:

- UCN storage measurements
  1. **(1) UCNτ** (magnetic trapping): running complete, with 2020-2022 data set to analyze
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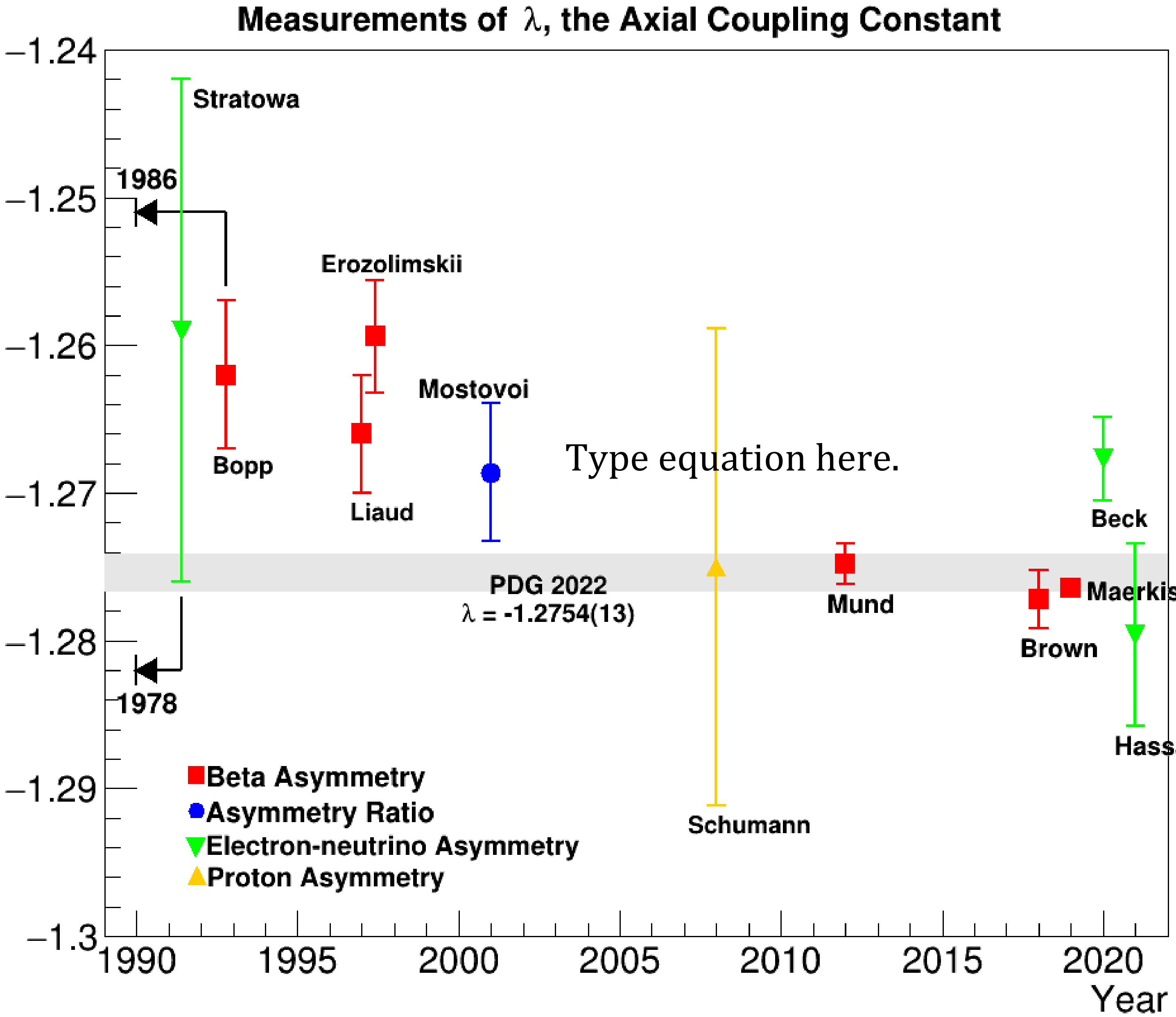
Prospects not clear (to me) for satellite-based measurements

Angular Correlation Measurements:
Beta Asymmetry

Thanks to B. Maerkisch for slides

Latest/most
Sensitive Results
for all groups


Measurements of λ, the Axial Coupling Constant

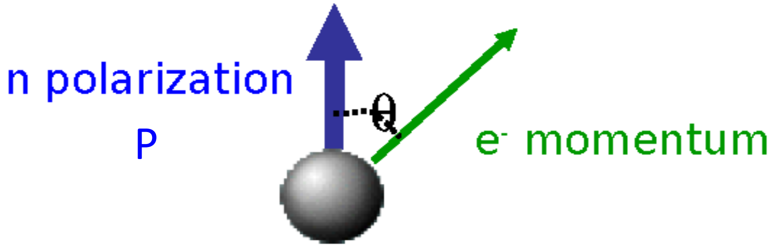
Type equation here.

PDG 2023

$\lambda = -1.2754(13), S = 2.6$

What is the Beta Asymmetry?

The directional angular correlation between emitted beta momentum and the neutron spin



$$R = R_o(1 + (v/c)\, P\, A(E) \cos\theta)$$

β-asymmetry = A(E) in angular distribution of β

$$A_\beta(0) = \frac{\rho^2 - 2\rho\sqrt{J(J+1)}}{(1+\rho^2)(J+1)}$$

(ρ is the mixing ratio M_{GT}/M_F & J_f=J_i)

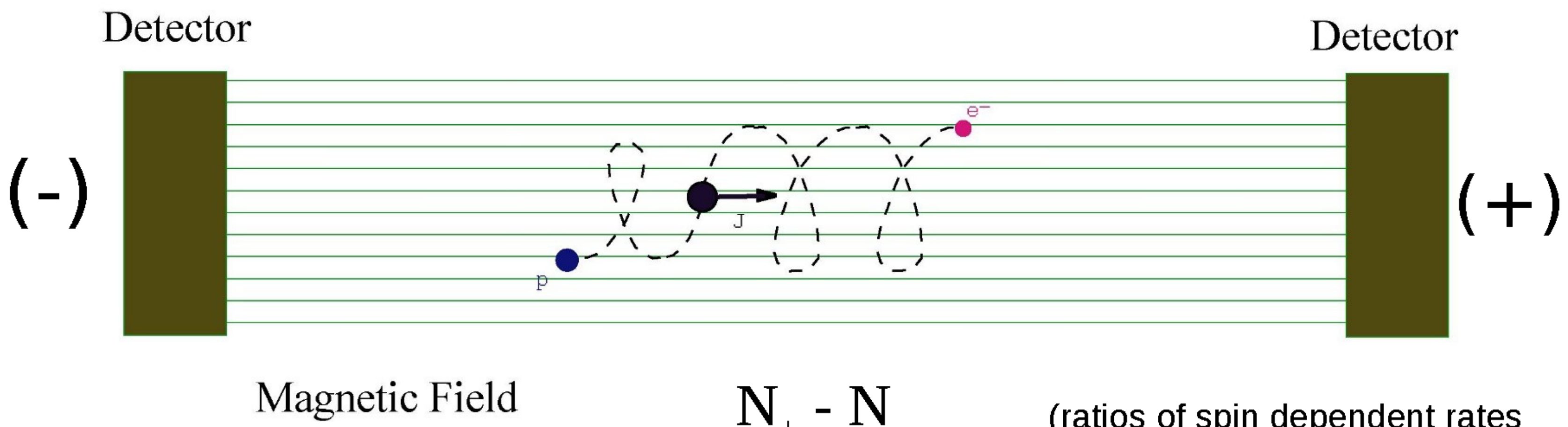
Ignoring recoil order terms – just a function of $\lambda = (C_A/C_V) = \rho/\sqrt{3}$

PDG for neutron: A_o=-0.11958(21), S (1.2)

$$\left|\frac{\delta\lambda}{\lambda}\right| \approx 0.25 \left|\frac{\delta A}{A}\right|$$

Measurement Challenges

β directional distribution: $1 + P\frac{v}{c}A(E)\cos\theta$
(polarized neutrons)



$$A(E) \propto \frac{N_+ - N_-}{N_+ + N_-}$$

(ratios of spin dependent rates are used to cancel efficiencies)

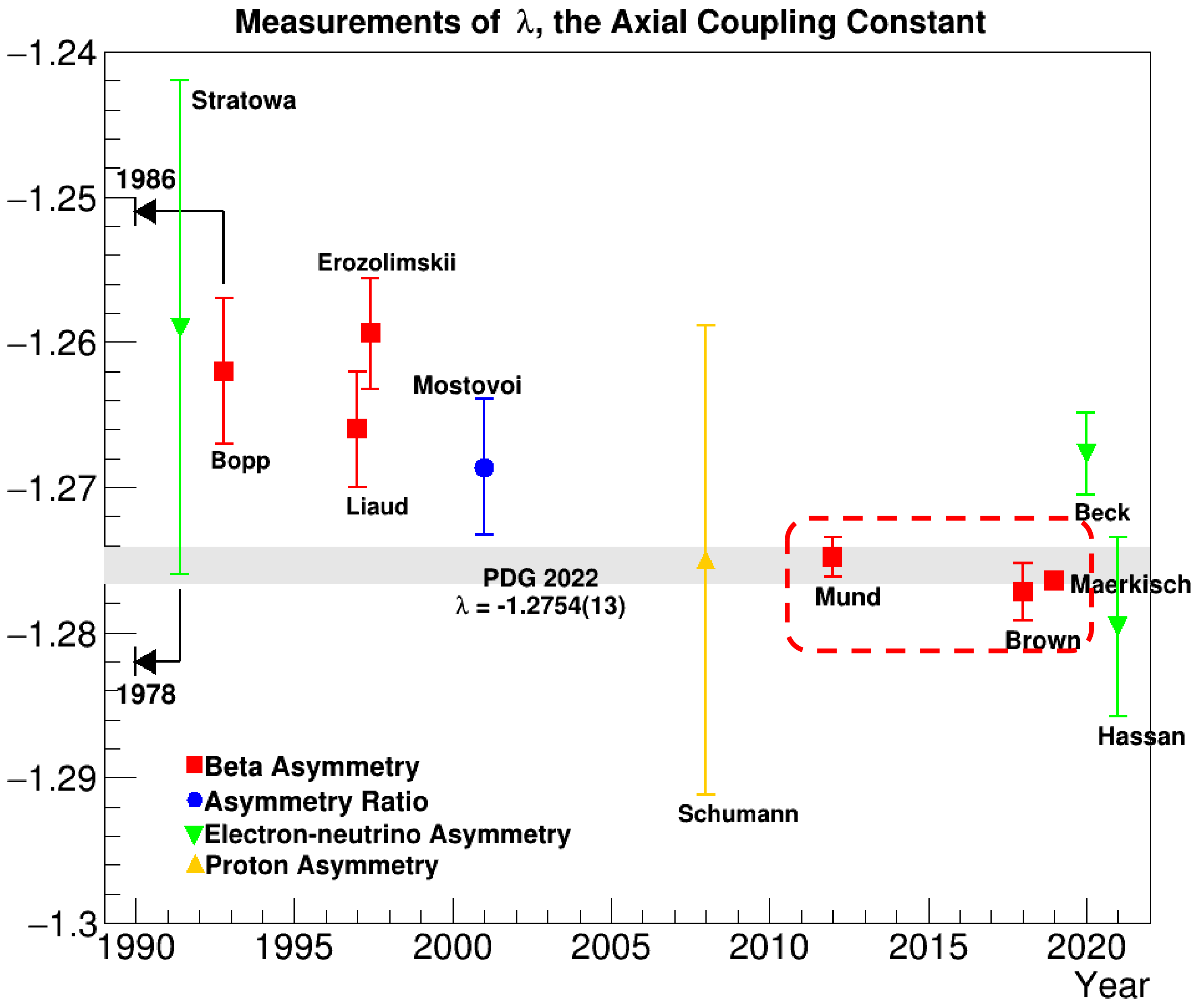
Must determine:

Systematic effects:

- Beta rates → Backgrounds
- Beta spectra → Calibration/Linearity
- <cosθ> → Scattering (esp. backscattering)
- Polarization → Absolute polarization required!

Systematic uncertainties drive limits in most cases! ⇨

Latest/most Sensitive Results for all groups



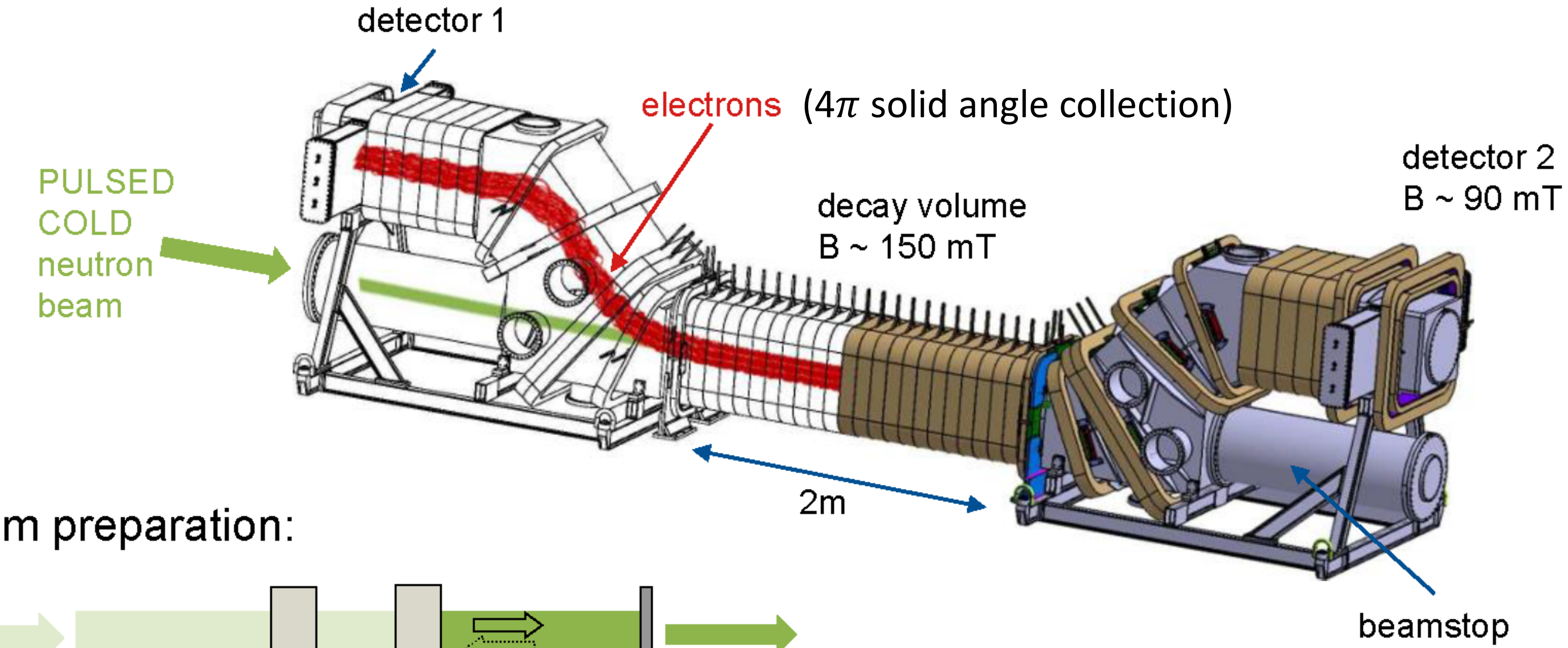
Recent measurements of A(E) for neutron agree, with most precise PERKEO III

Using only beta asym:

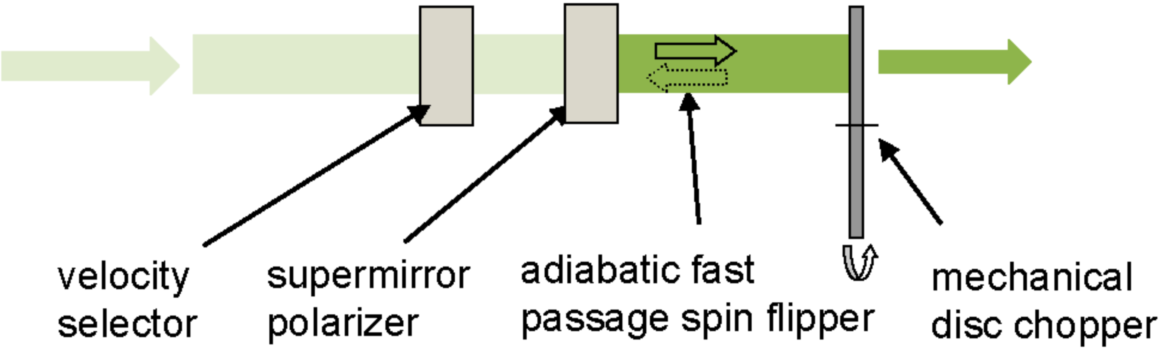
$$\lambda = -1.2757(5),\ S{=}1.2$$

Spectrometer PERKEO III

(The most sensitive angular correlation expt for neutrons)

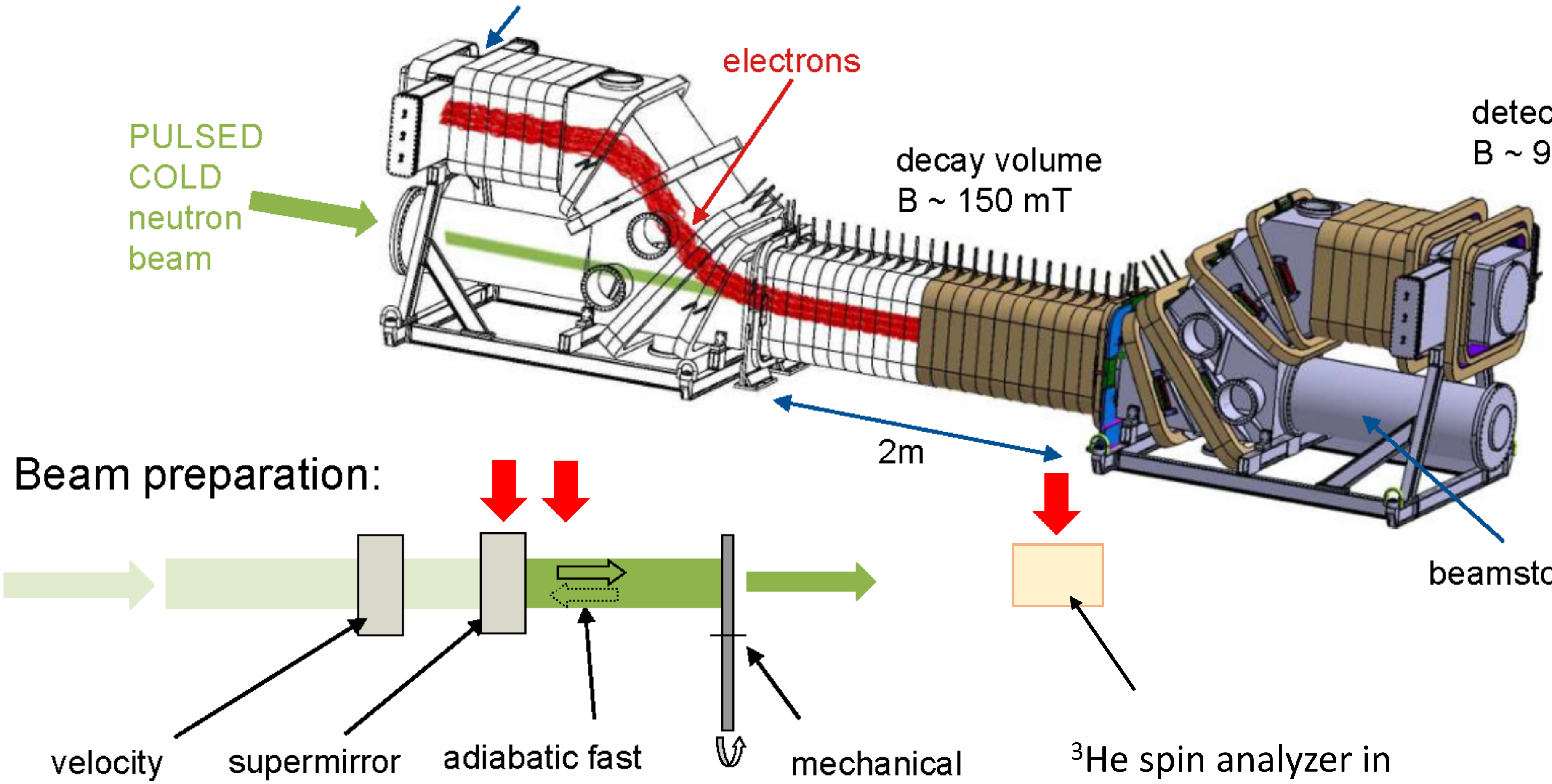


Beam preparation:



~50.000 decays/s in *continuous* beam
time avg. ~200 s^{-1} in pulsed mode

Spectrometer PERKEO III (Beam Polarization)



detector 1

electrons

PULSED COLD neutron beam

decay volume
B ~ 150 mT

detector 2
B ~ 90 mT

2m

beamstop

Beam preparation:

velocity selector

supermirror polarizer

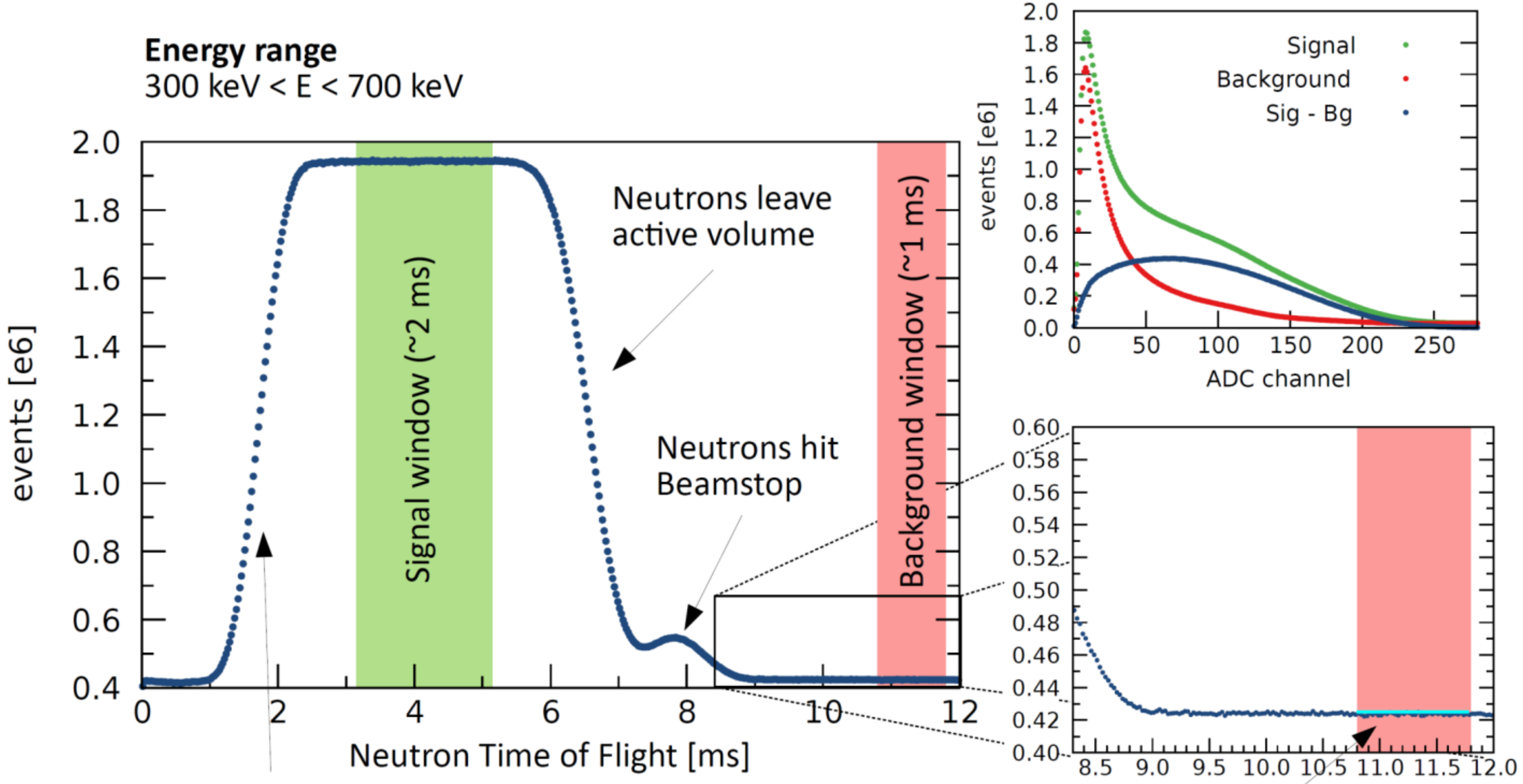
adiabatic fast passage spin flipper

mechanical disc chopper

^{3}He spin analyzer in beamstop position

PERKEO III: Pulsed Neutron Beam

Energy range
300 keV < E < 700 keV



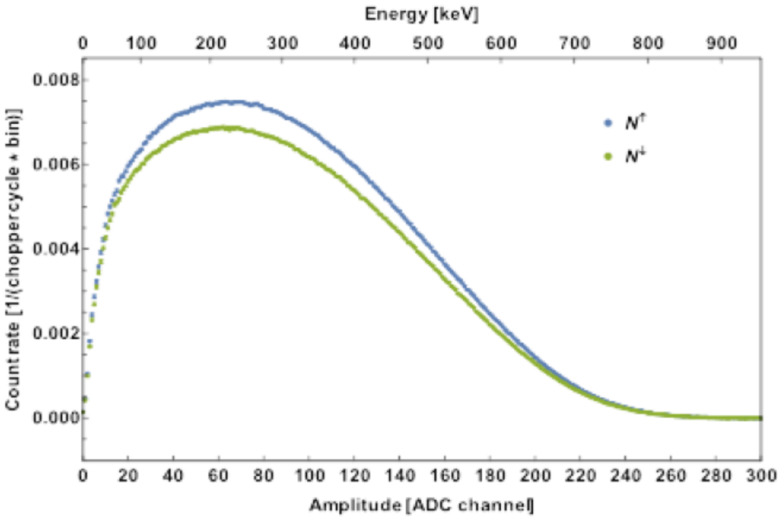
Neutrons leave active volume

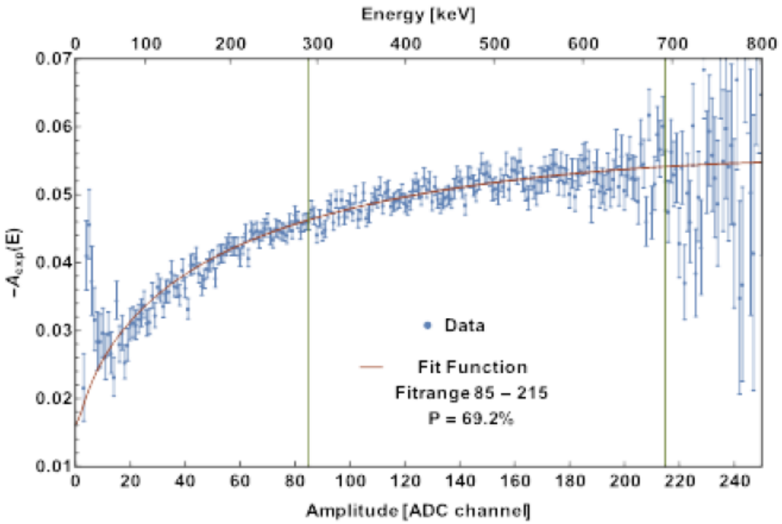
Neutrons hit Beamstop

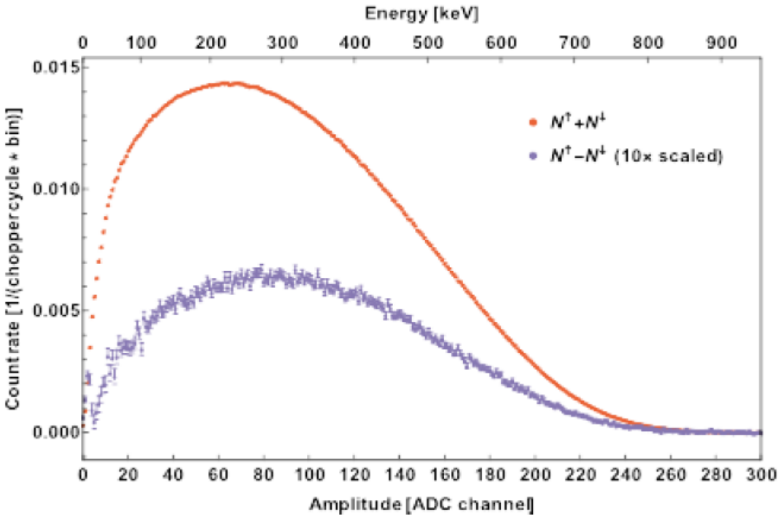
Neutrons enter active volume

Slope is zero compatible on 10^{-4} level

Asymmetry Extraction







$$A_{exp}(E_e) = \frac{N^\uparrow(E_e) - N^\downarrow(E_e)}{N^\uparrow(E_e) + N^\downarrow(E_e)} = \frac{1}{2} P_n \frac{v}{c} A$$

Largest neutron decay data set

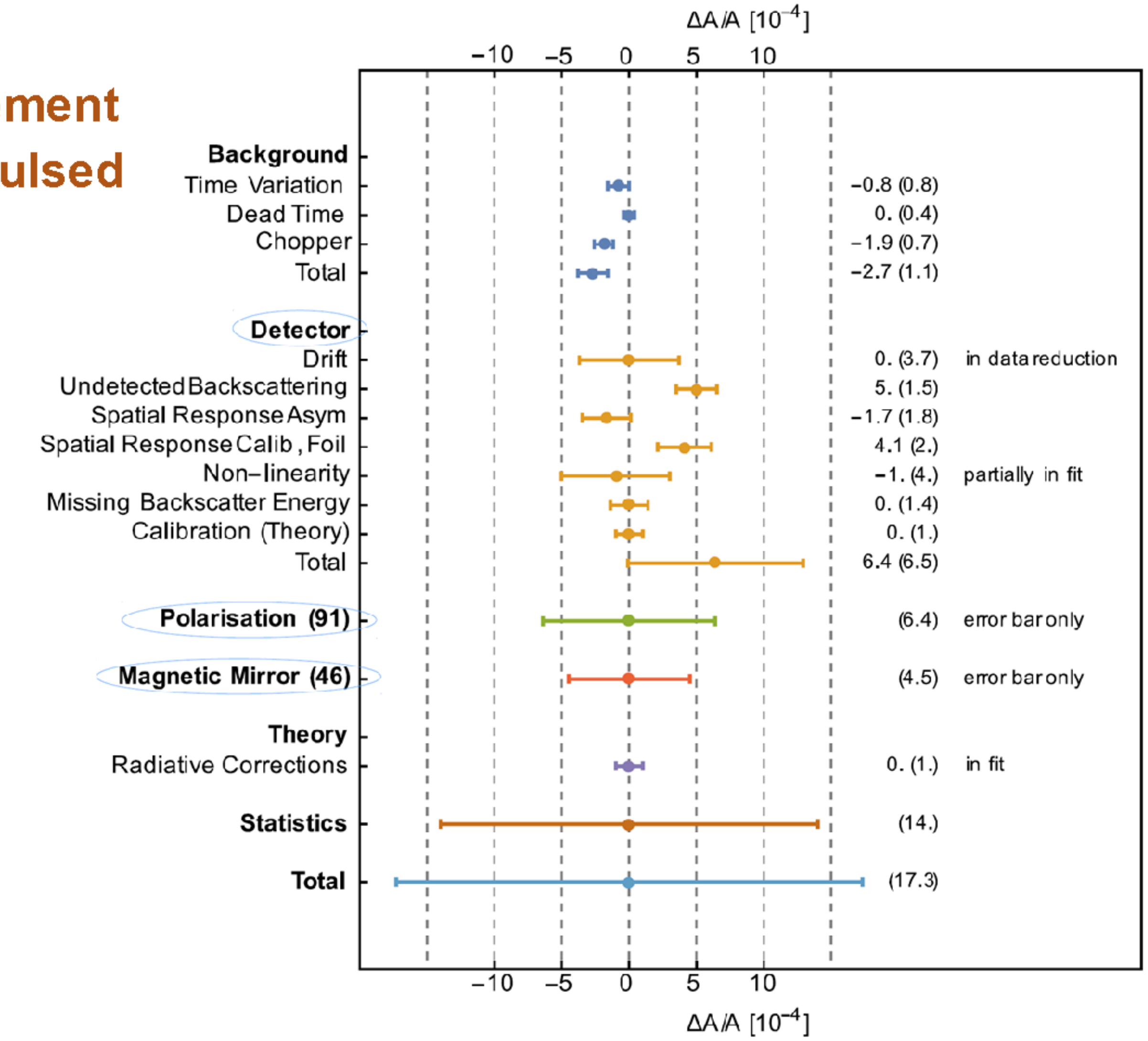
1 of 4 subsets shown

6×10^8 events in analysis

Statistical Uncertainty: $\Delta A/A = 14 \times 10^{-4}$

Summary of Corrections and Uncertainties

First measurement of λ using a pulsed beam



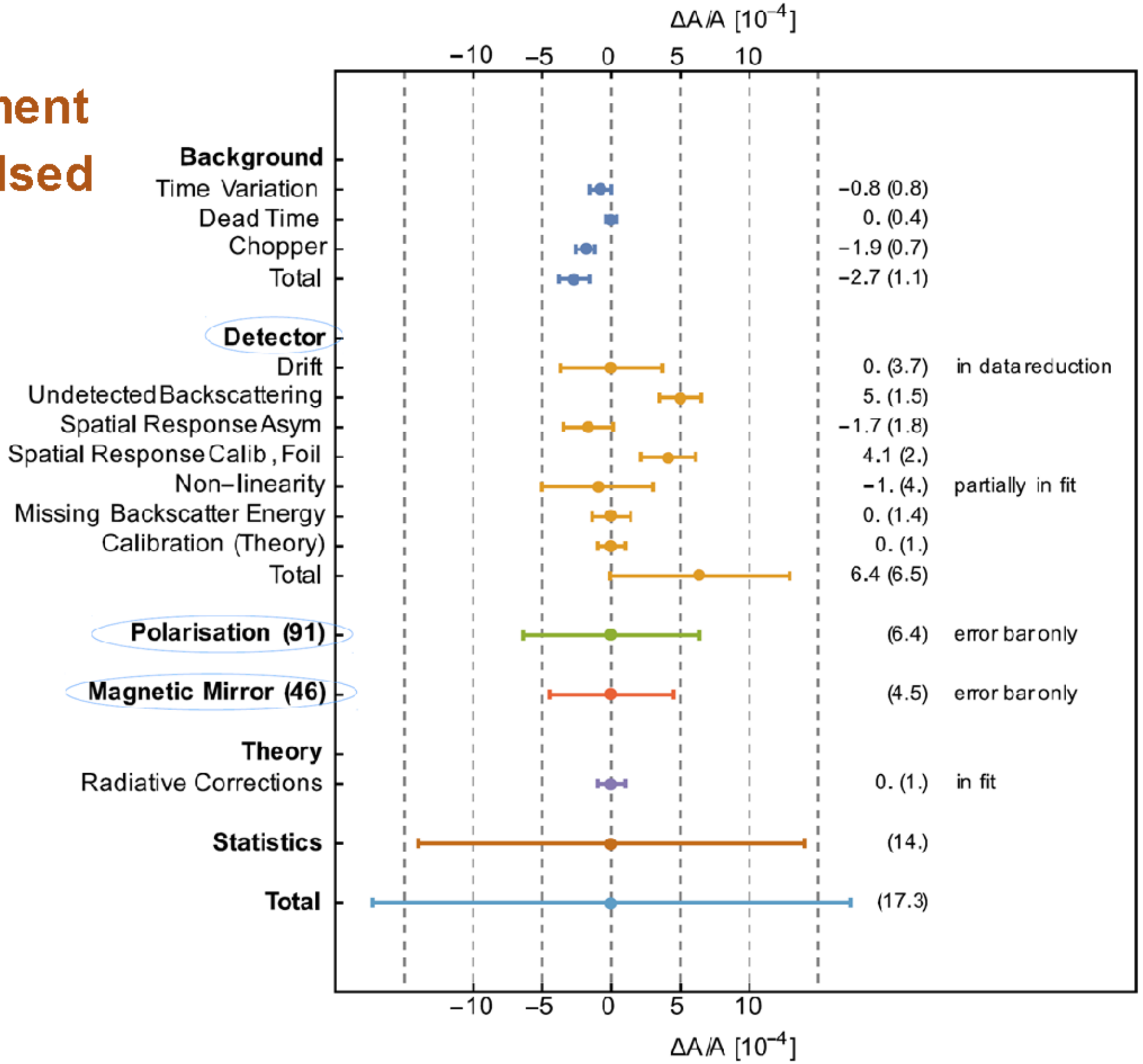
B. Markisch et al., Phys. Rev. Lett **122**, 242501 (2019)

λ = −1.27641(56),
Δλ/λ = 4.4 × 10 −4

see also
Undetected Electron Backscattering in PERKEO III
C. Roick, H. Saul, H. Abele, B. Märkisch
arXiv:1905.10189

Summary of Corrections and Uncertainties

First measurement of λ using a pulsed beam



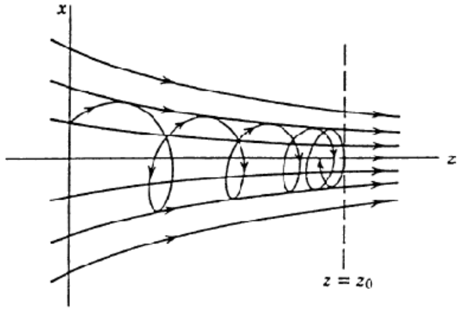
Important Sources of Systematic Uncertainty

Detector Effects

Polarization

Magnetic Mirror

Magnetic Mirror Effect



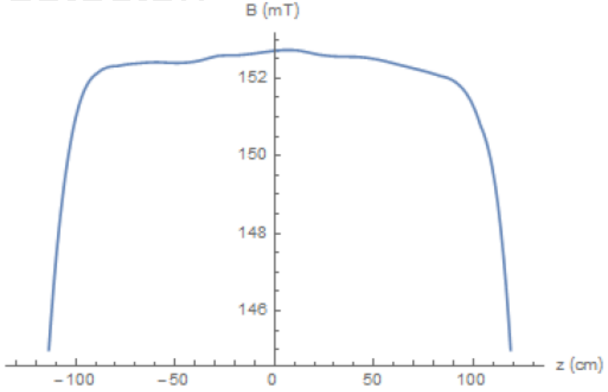
Flux through cross section of gyration is *adiabatic invariant*

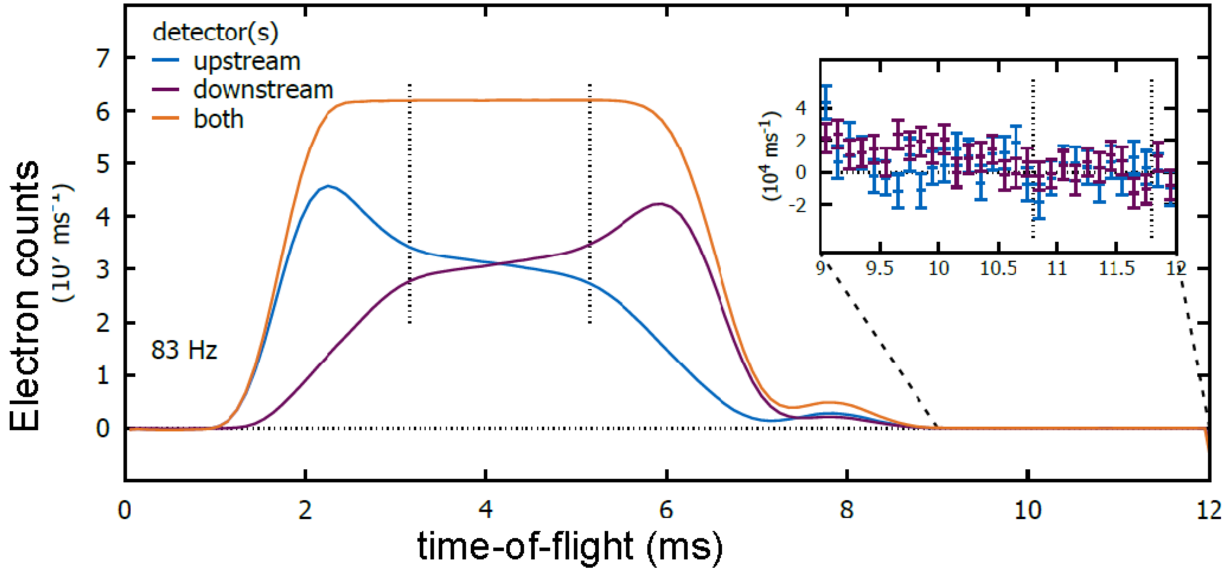
$$B_0 \times r_0^2 = B_1 \times r_1^2$$

Critical angle for reflection

$$\Theta_c = \arcsin\sqrt{\frac{B_1}{B_0}}$$

Magnetic field curvature leads to significant rate change on **single** detector:





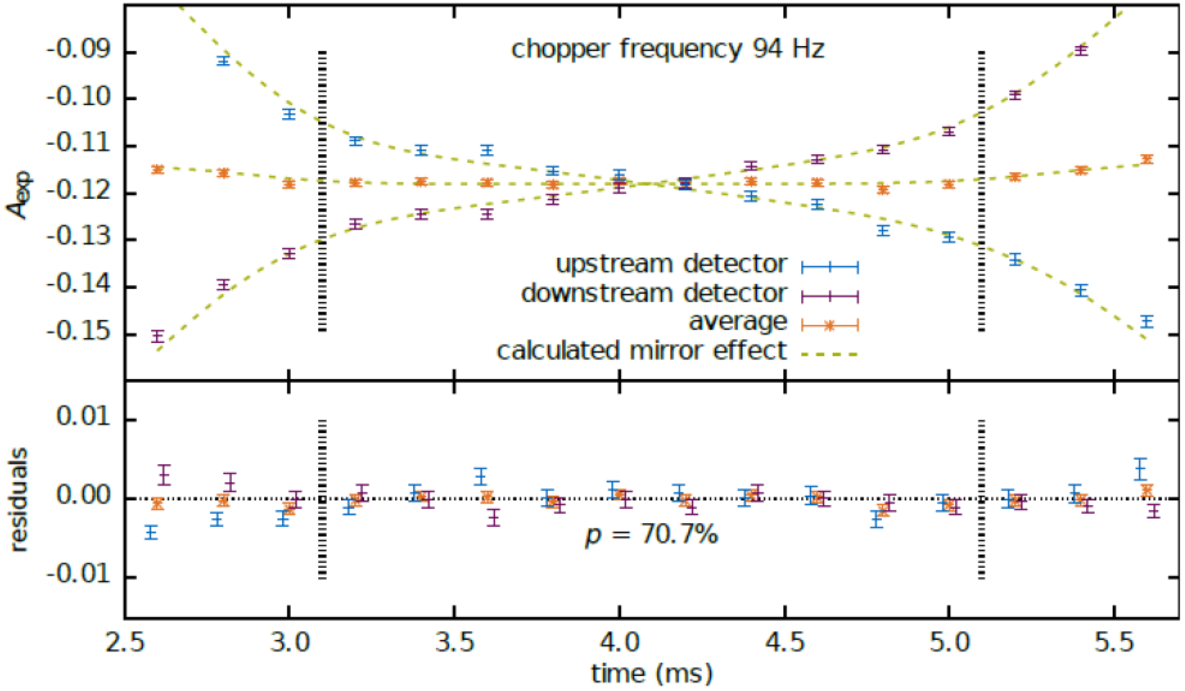
Magnetic Mirror Effect

(field magnitude decreases away from center)

Most of the effect cancels by **averaging** detectors. **(Symmetry)**

Calculate **correction** from *measurements* of the magnetic field and neutron pulse:
Interpolation in space and time based on models of the beam optics and magnet.

Result reproduces time-of-flight behavior of asymmetry. No fit!



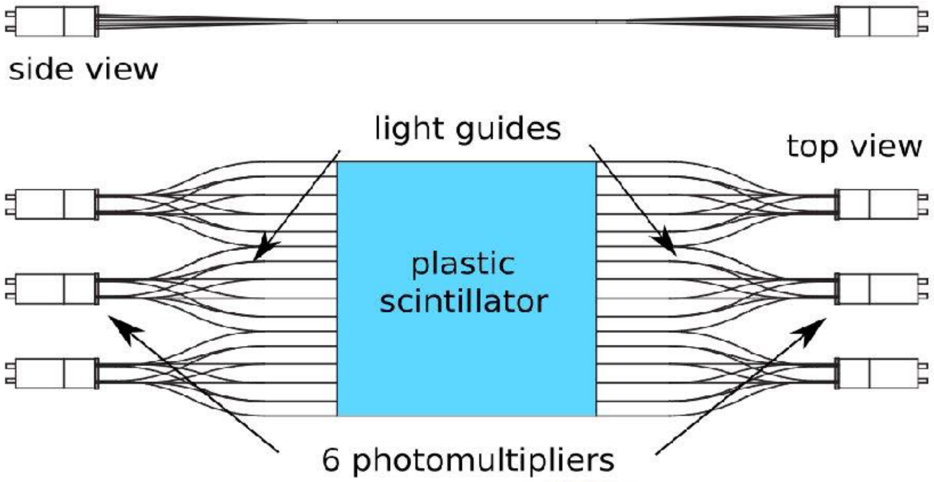
downstream

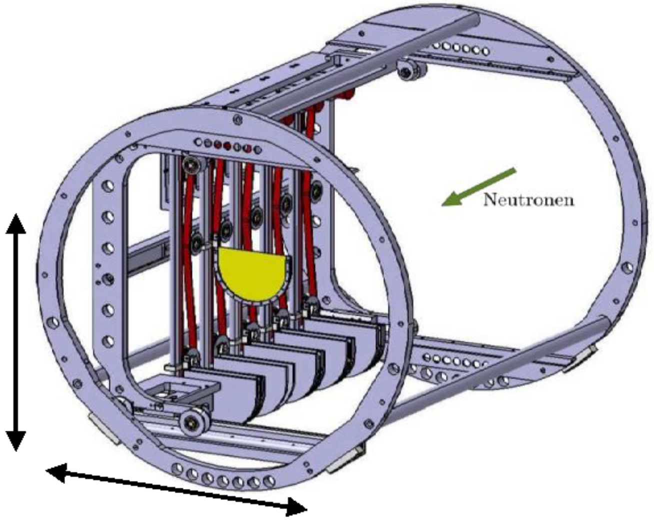
average

upstream

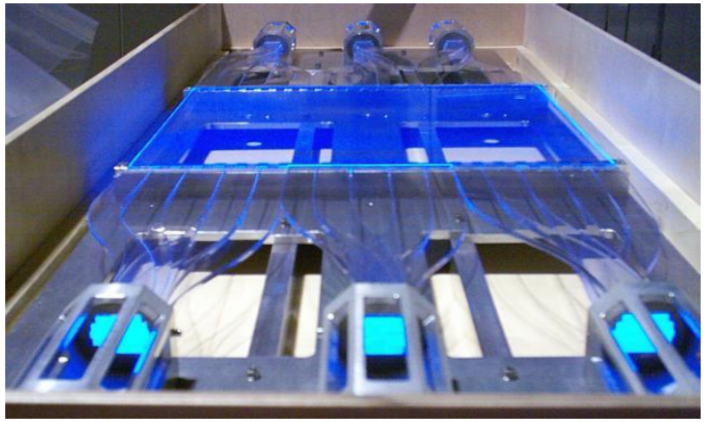
Correction:
$\Delta A/A = 46.1(4.5) \times 10^{-4}$

Electron Detector





Size ~ 40 x 40 cm²
Light output ~ 250 PE/MeV



Calibration with electron conversion sources:

^{207}Bi – 500 keV, 1.06 MeV, 2 Auger

^{137}Cs – 630 keV, 2 Beta Spectra
^{113}Sn – 370 keV, Auger

^{139}Ce – 130 keV

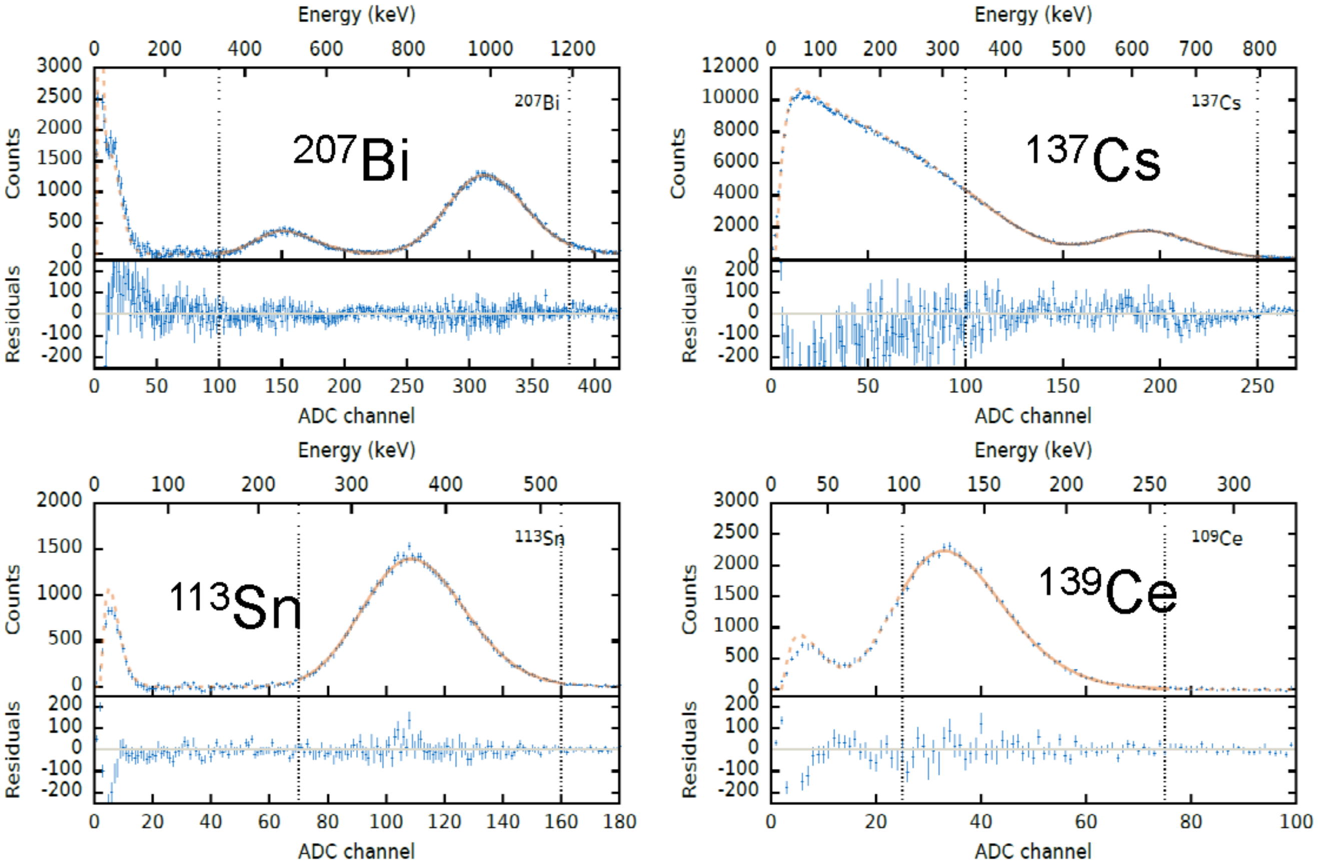
Hourly calibration

Full calibration set twice a day

Every few days complete 2D scan

Detector Calibration Fit

Calibration, drift monitoring and uniformity scans using electron-conversion sources



(+ hourly drift measurements + weekly uniformity scans)

114 full calibration sets measured in ~60 days

Simultaneous fit, **free parameters:**

non-linearity, gain, photo-electrons, norms

X^2/NDF = 1.0 – 1.3

Related Uncertainties

Sources: $\Delta A/A = 1\times10^{-4}$

Statistics: $\Delta A/A = 0.1\times10^{-4}$

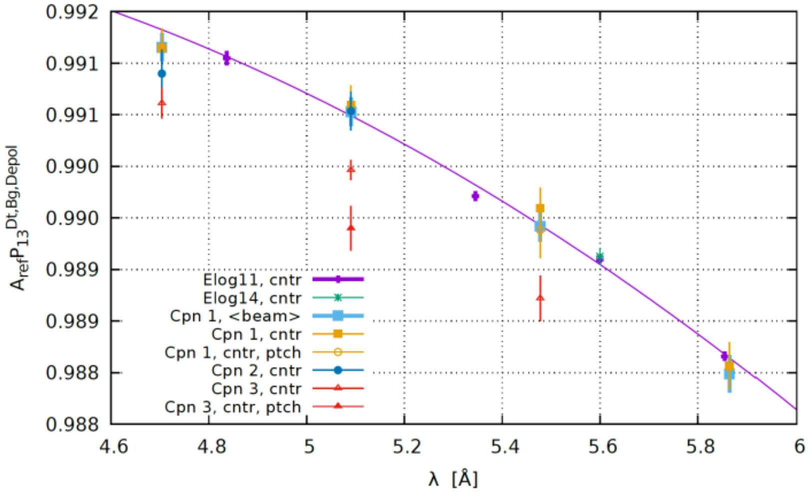
Non-linearity: $\Delta A/A = 4\times10^{-4}$

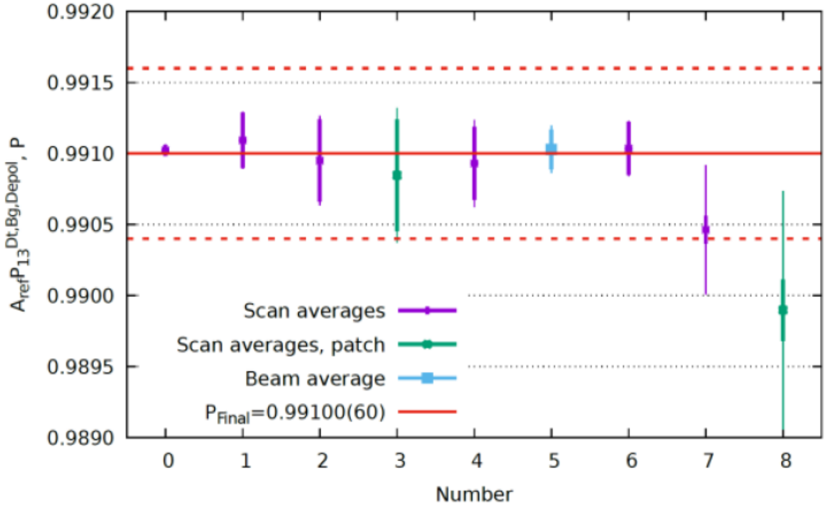
Stability: $\Delta A/A = 3.7\times10^{-4}$

Polarisation

Measurement of beam polarisation with ^{3}He cells (T. Soldner, A. Petoukhov):

- in front of and behind instrument
- at three different times during measurement
- scan over beam cross section and wavelength





Polarisation: P = 0.9910(6)

Spin Flip Efficiency: F > 0.99964 (68% C.L.)

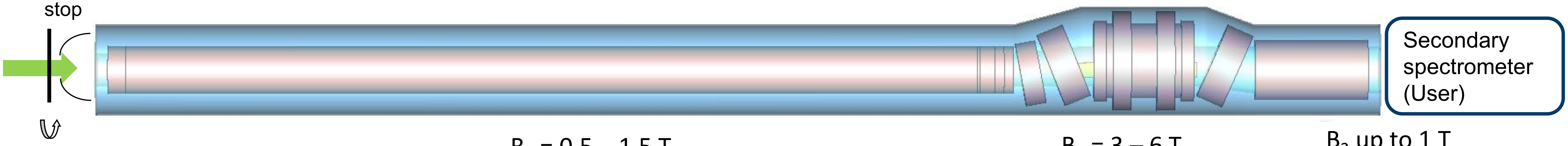
The next generation:
PERC (Proton Electron Radiation Channel) at MLZ / FRM II, Garching

Goal: Order of magnitude improvement.
New observables.

SLOW NEUTRONS
DFG SPP 1491

Priority Programme SPP1491 of the
German Research Foundation (DFG)

PERC (Proton Electron Radiation channel) Facility at MLZ



e,p-beam stop

Active volume – 8m !

Magnetic filter

Detector region

Secondary spectrometer (User)

Mechanical Chopper

$B_0 = 0.5 – 1.5$ T

$B_1 = 3 – 6$ T

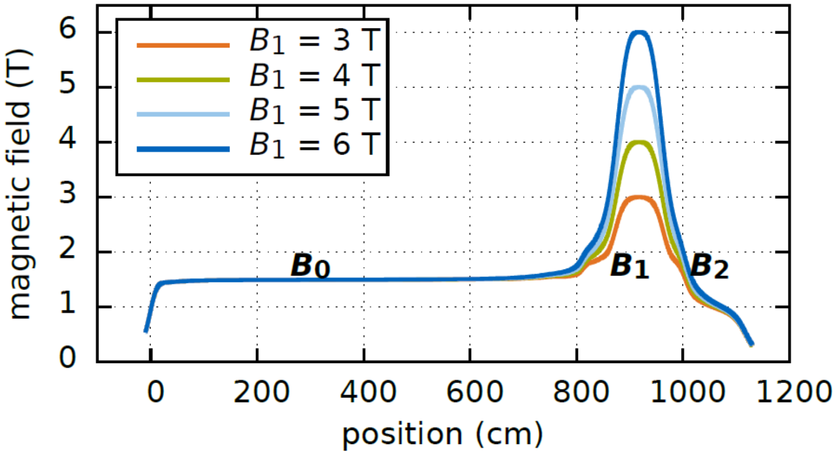
B_2 up to 1 T

Raw decay rate ~ ~30 kHz/m…

- (*pulsed, polarised*) cold **neutron beam** (6x6cm²)
- 8m long non-depolarising neutron guide as **active volume, $B_0 \sim 1.5$T**
- **Magnetic filter** $(B_1 = 3 \text{ - } 6\text{T})$ to enhance systematics $^{B_1}/_{B_0} = 2 \ldots 12$

  separates e/p from neutrons, contains neutron beam stop,

  limits max. angle of electrons / protons
- Source of electrons and protons to user-spectrometers:
  Observables: A, B, C, b, a



X. Wang, C. Ziener *et al*. (PERC Collaboration), EPJ Web Conf. 219, 04007 (2019)

D. Dubbers *et al*., Nucl. Instr. Meth. A **596**, 238 (2008) and arXiv:0709.4440

Observables and Statistics

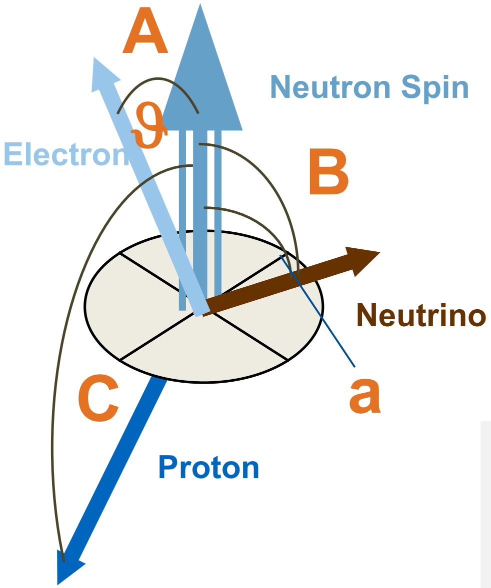
Focus on *non-coincident* measurements due to high count rates:

Polarised neutrons

β-asymmetry ***A***	***$\Delta A \sim 5 \cdot 10^{-4}$***
Proton asymmetry ***C***	***$\Delta C \sim 3 \cdot 10^{-4}$***
Neutrino asymmetry ***B***	***$\Delta B \sim 1 \cdot 10^{-3}$***
Weak magnetism f_{WM} from β-asymmetry or polarised spectra	***$> 3\sigma$***

Unpolarised neutrons

Correlation ***a*** from proton spectrum	***$\Delta a \sim 5 \cdot 10^{-3}$***
Fierz coefficient ***b*** from electron spectrum or β-asymmetry	***$\Delta b \sim 1 \cdot 10^{-3}$***



Time for 10^9 events

- 5 hours (unpolarised)
- 1 day polarised 98%
- 2 days polarised 99.7%
- ×25 for pulsed mode

Observables and Statistics

Focus on *non-coincident* measurements due to high count rates:

$$\frac{\Delta\lambda}{\lambda} \sim 1.25 \times 10^{-4}$$

Polarised neutrons	
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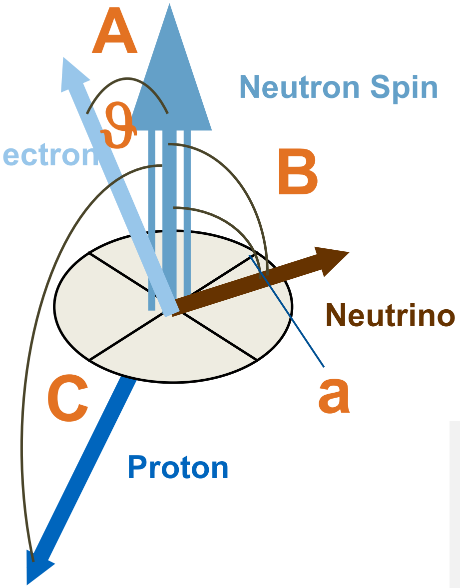


Time for 10^9 events

- 5 hours (unpolarised)
- 1 day polarised 98%
- 2 days polarised 99.7%
- ×25 for pulsed mode

Systematic Error Budget (must improve over PERKEO III!)

Source of error	Correction	Error	Comment
Non-uniform n-flux Φ	2.5×10^{-4}	5×10^{-5}	For $\Delta\Phi/\Phi$=10% over 1cm width
Other edge effects on e/p-window	4×10^{-4}	1×10^{-4}	For max. gyration radius = worst case
Magn. mirror effect for cont's n-beam Magn. mirror effect for pulsed n-beam	2×10^{-2} 5×10^{-5}	4×10^{-4} $< 10^{-5}$	For $\Delta B/B$=10% over 7m length
Non-adiabatic e/p-transport	5×10^{-5}	5×10^{-5}	
Background from n-guide	2×10^{-3}	1×10^{-4}	is separately measurable
Background from n-beam stop	2×10^{-4}	1×10^{-5}	is separately measurable
Backscattering off e/p-beam dump	5×10^{-5}	1×10^{-5}	
Backscattering off e/p-window	2×10^{-5}	1×10^{-5}	
Backscattering off organic scintillator ... with active e/p-beam dump	2×10^{-3} -	4×10^{-4} 1×10^{-4}	worst case worst case
Neutron polarisation	3×10^{-3}	1×10^{-4}	C. Klauser, T. Soldner et al. A. Petoukhov et al.

R&D solutions exist for most issues…

Concern over detector-related effects driving development of Si dets…(will get back to this)

Note: not every error source contributes to all measurements

All errors O(10^{-4}) or smaller

Nucl. Instr. Meth. A **596** (2008) 238 and arXiv:0709.4440 a

Angular Correlation Measurements:
Beta-neutrino angular correlation

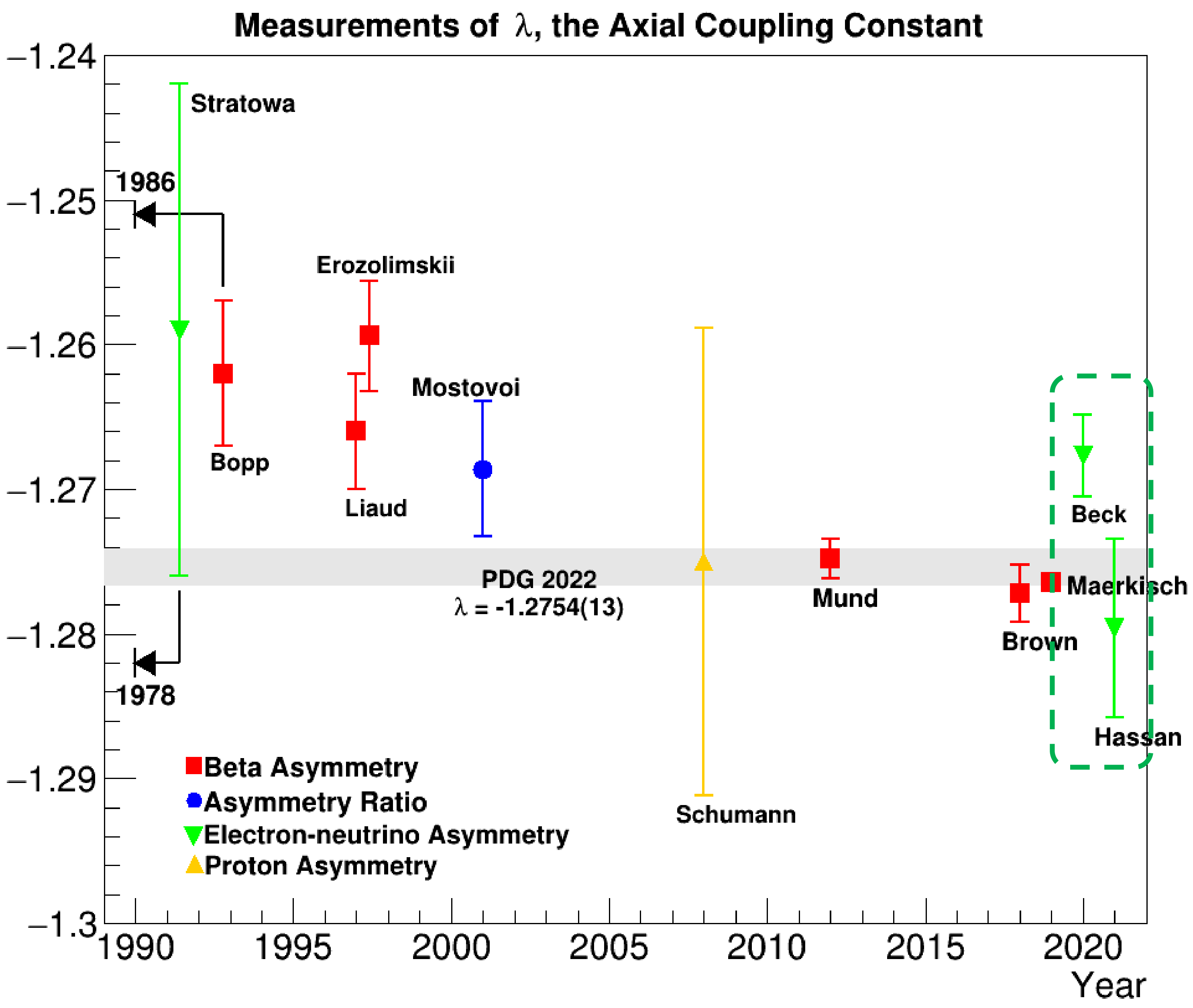
$$\frac{d^5W}{dE_e\,d\Omega_e\,d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2|\boldsymbol{V_{ud}}|^2}{(2\pi)^5}p_eE_e(A_\circ - E_e)^2\xi}^{\text{basic decay rate}}\left(1 + \overbrace{\boldsymbol{a_{\beta\nu}}\frac{\vec{p}_e\cdot\vec{p}_{\nu_e}}{E_eE_{\nu_e}}}^{\beta-\nu\ \text{correlation}} + \overbrace{\boldsymbol{b}\frac{\Gamma m_e}{E_e}}^{\text{Fierz term}}\right)$$

The angular correlation between the emitted beta momentum and the neutrino momentum

Similar sensitivity to λ as the beta asymmetry

Subject of Hitesh’s talk!

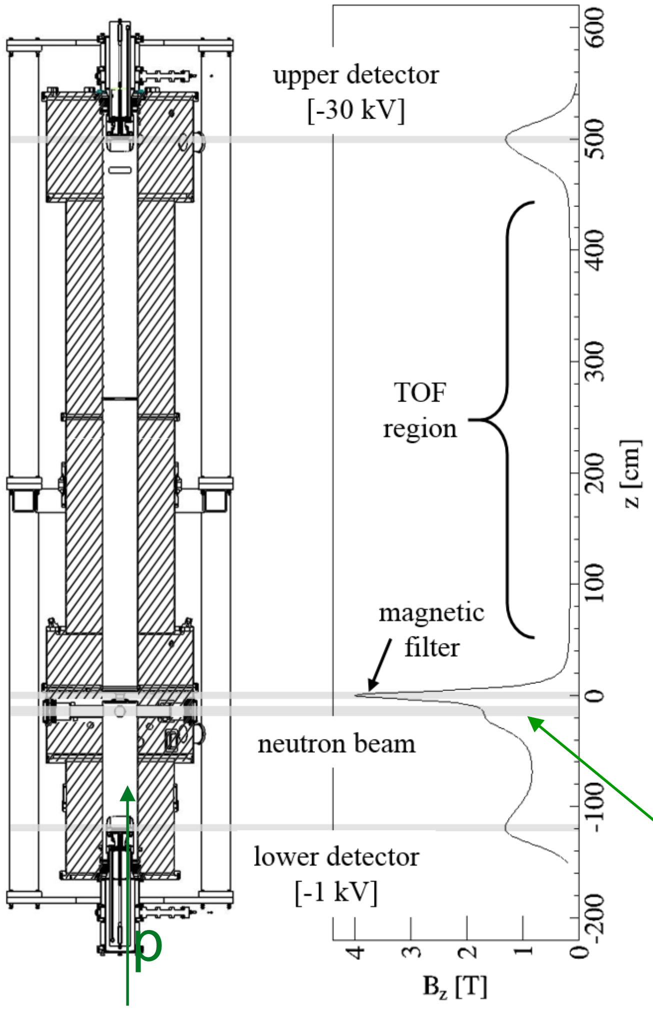
Latest/most
Sensitive
Results
for all groups



Note: although not as precise, one recent measurement of a is impacting scatter for λ

To properly address, develop a more sensitive measurement of a…

Nab



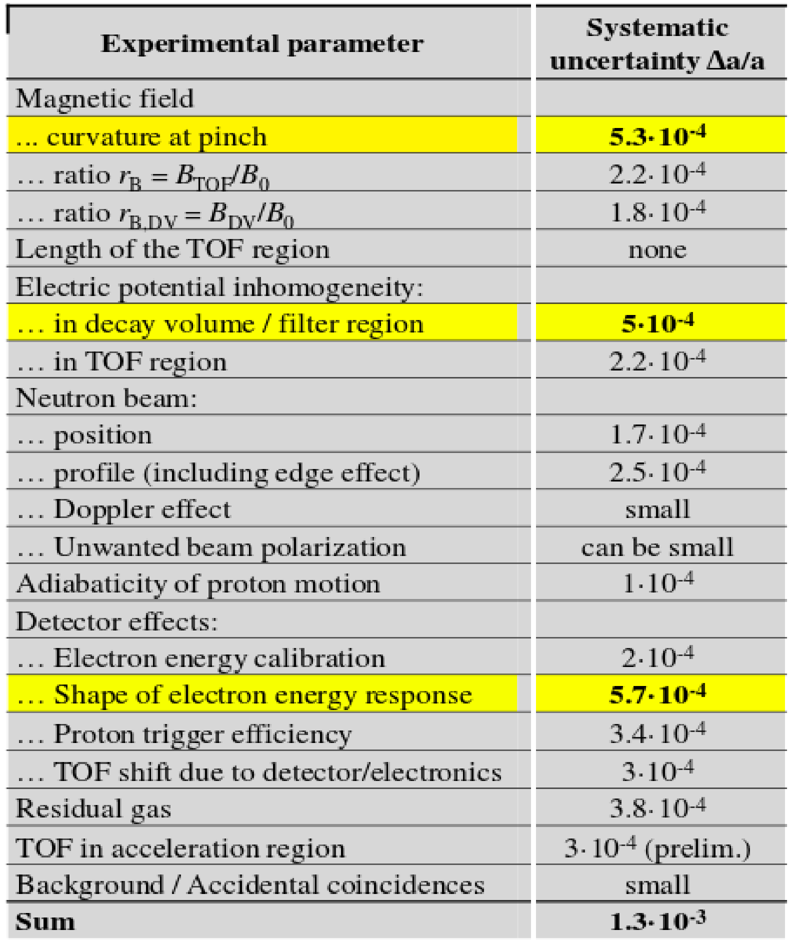
Measure momentum of protons through time of flight, then use conservation of momentum to relate to $a_{\beta\nu}$

$$P_p(p_{\mathrm{p}}^2) = \begin{cases} 1 + a\beta\frac{p_{\mathrm{p}}^2 - p_{\mathrm{e}}^2 - p_\nu^2}{2p_{\mathrm{e}}p_\nu} & \text{where } \left|\frac{p_{\mathrm{p}}^2 - p_{\mathrm{e}}^2 - p_\nu^2}{2p_{\mathrm{e}}p_\nu}\right| < 1 \\ 0 & \text{otherwise} \end{cases}$$

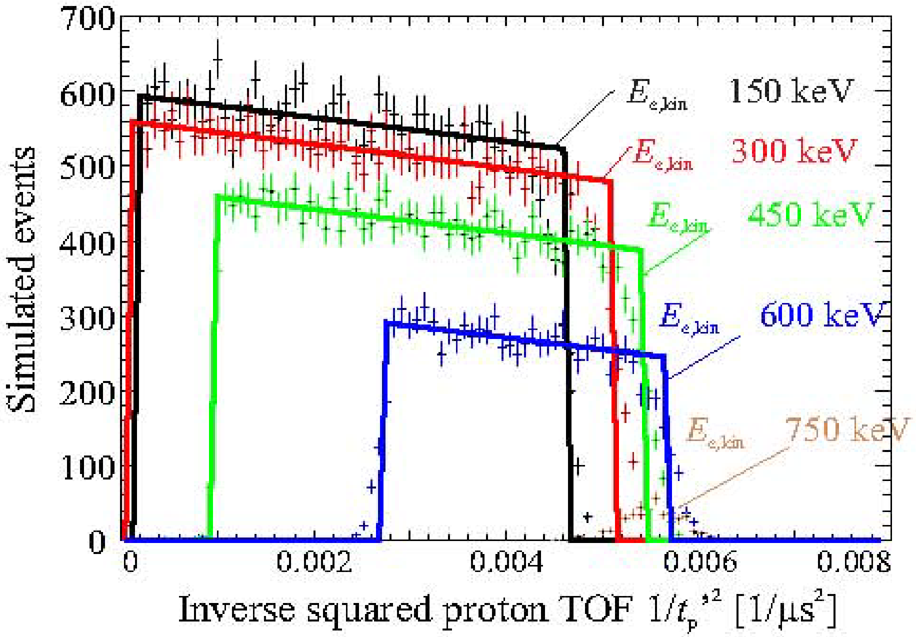
Thin dead-layer, segmented Si detectors record electron “start” in either detector, proton “stop” in upper detector

Magnetic field “pinch”, long, low field TOF region optimize sensitivity to TOF

Nab



Experimental parameter	Systematic uncertainty Δa/a
Magnetic field	
… curvature at pinch	**$5.3\cdot10^{-4}$**
… ratio $r_B = B_{TOF}/B_0$	$2.2\cdot10^{-4}$
… ratio $r_{B,DV} = B_{DV}/B_0$	$1.8\cdot10^{-4}$
Length of the TOF region	none
Electric potential inhomogeneity:	
… in decay volume / filter region	**$5\cdot10^{-4}$**
… in TOF region	$2.2\cdot10^{-4}$
Neutron beam:	
… position	$1.7\cdot10^{-4}$
… profile (including edge effect)	$2.5\cdot10^{-4}$
… Doppler effect	small
… Unwanted beam polarization	can be small
Adiabaticity of proton motion	$1\cdot10^{-4}$
Detector effects:	
… Electron energy calibration	$2\cdot10^{-4}$
… Shape of electron energy response	**$5.7\cdot10^{-4}$**
… Proton trigger efficiency	$3.4\cdot10^{-4}$
… TOF shift due to detector/electronics	$3\cdot10^{-4}$
Residual gas	$3.8\cdot10^{-4}$
TOF in acceleration region	$3\cdot10^{-4}$ (prelim.)
Background / Accidental coincidences	small
Sum	**$1.3\cdot10^{-3}$**



Significant input
To global data set!

$$\frac{\Delta\lambda}{\lambda} \sim 0.04\%$$

Uncertainty target: 0.15%

- Use central part of $P_t(1/t_p^2)$ ($\sim$ 70%) to extract **a**.
- Use edges to determine and verify shape of detection function $\Phi(1/t_p^2, p_p^2)$;

Angular Correlation Prospects

Next 5 years plans include:

Beta asymmetry measurements

1. **Perc**: should start operation, with target precision for λ of 0.013%
   significant R&D may still be required (schedule still a bit uncertain)

Beta-neutrino correlation measurements

1. **Nab**, nominally complete in 2025, target precision of 0.04%

Note: Nab can also potentially resolve the current tension in the beta-neutrino correlation data (or substantiate it!)
Nab also has a significantly different experimental approach to the beta asymmetry measurements, ensuring different systematic uncertainty budget

Angular Correlation Prospects

Next 5 years plans include:

Beta asymmetry measurements

(1) Perc: should start operation, with target precision for λ of 0.013%
significant R&D may still be required (schedule still a bit uncertain)

Beta-neutrino correlation measurements

(1) **Nab**, nominally complete in 2025, target precision of 0.04%

Note: Nab can also potentially resolve the current tension in the beta-neutrino correlation data (or substantiate it!)
Nab also has a significantly different experimental approach to the beta asymmetry measurements, ensuring
different systematic uncertainty budget

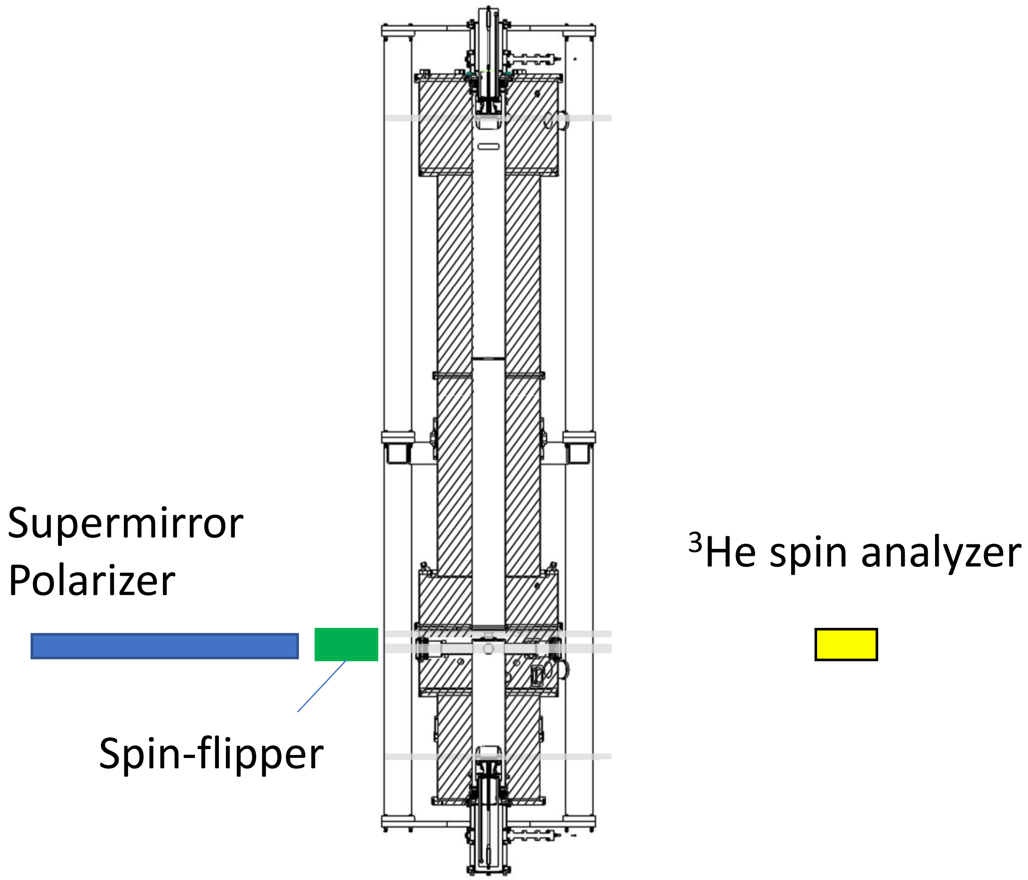
Not quite the same situation as the lifetime! The scatter in the current data set is larger, the number of potentially contributing experiments is smaller, and the timeline less certain

Some possibilities might be…

pNab

Upgrade of Nab to perform measurements of polarized angular correlations

- Measurements of several angular correlations possible
- Systematic uncertainties controllable through super-ratios
- Simultaneous measurement of beta and proton asymmetries can sensitivity to the absolute polarization (tricky though)



Target uncertainty: A_β, B_ν : 0.1% & λ : 0.025%

Follow up to Nab:

i) Requires implementation of supermirror polarizer, high efficiency spin-flipper and ^{3}He analyzer

ii) Requires beam-time after Nab

UCNA+ :an upgrade of UCNA could reach A_β,< 0.2%, building on the already successful experiment

Conclusions

- UCNτ+ and BL2/BL3 are on track to anchor a global data set for the neutron lifetime at an appropriate sensitivity to compete with the superallowed decays

- The Perc beta asymmetry experiment and Nab can potentially provide the needed precision for the axial coupling constant, but the existing scatter in the global data set for the axial coupling constant is larger than for the lifetime, and the number of potentially contributing experiments less – certainly making room for ideas that can push the field forward.

- The current neutron beta decay research program has the potential, in any case, to provide powerful input to our understanding of the Cabibbo Anomaly, and add constraints to a number of BSM scenarios as well.