The (Neutron) Lifetime Problem

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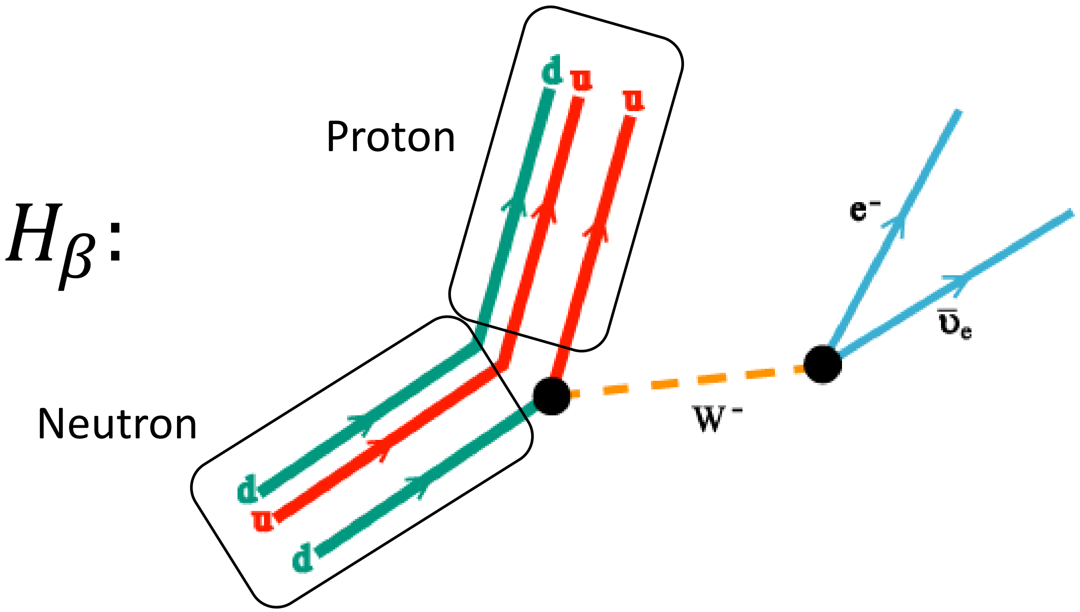
Outline

- Why Measure the Neutron Lifetime?
- The Neutron Lifetime Problem
  - Ultracold Neutron Storage Measurements through 2005-2013
  - Beam Measurements 2005-2013
- What to do?
  - Confirm experimental findings (probe systematic error budgets)
  - Search for evidence of alternative physics scenarios
- Current status

Why Measure the Neutron Lifetime?

Neutron beta decay basics

H_β:



Feynman diagram depicts the quantum mechanical amplitude for decay, H_β

Total decay rate ∝ H_β^2

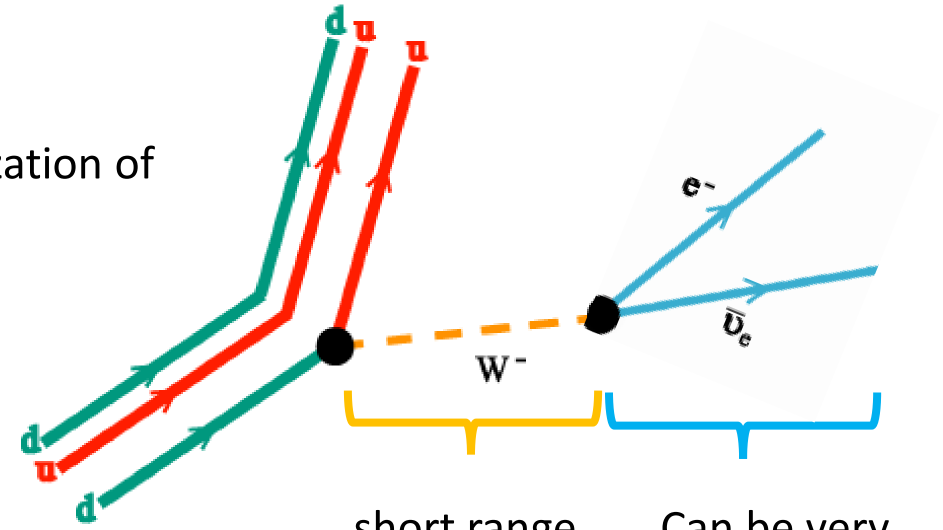
Neutron → proton + electron + anti-neutrino

Interaction mediated by exchange of W^- particle

Neutron beta decay basics

Appeal:

Permits very precise characterization of the weak interaction!



short range
($\lesssim 10^{-18}$ m)

Can be very precisely determined!

Switch off the strong force binding quarks in the neutron ➡ d quark → u quark + electron + anti-neutrino

Neutron beta decay basics

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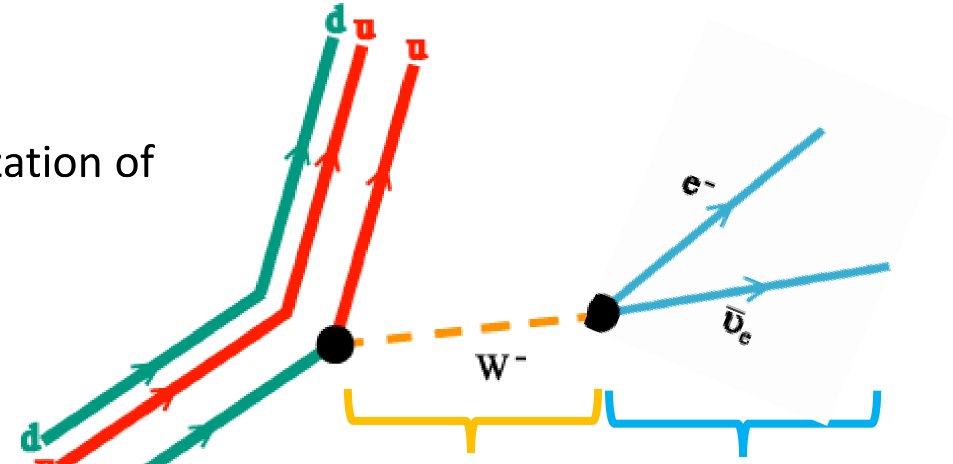
Permits very precise characterization of the weak interaction!



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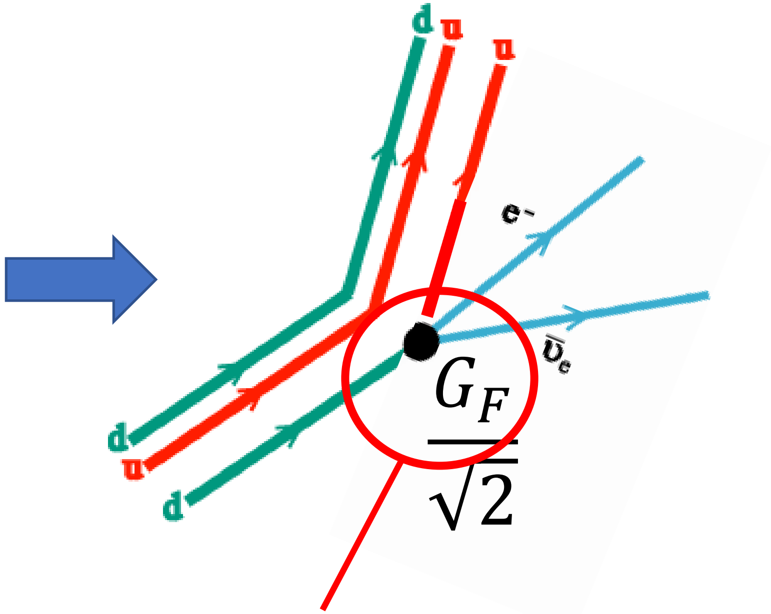


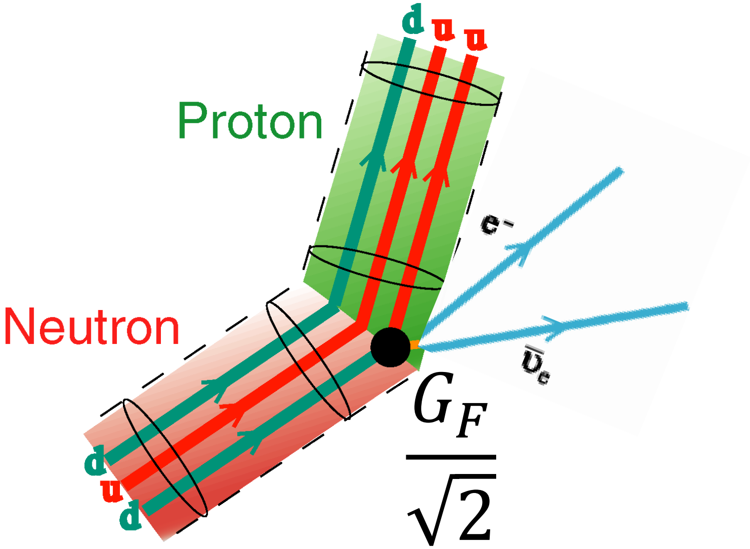
Fermi constant:
W- exchange"strength"

Switch off the strong force binding quarks in the neutron

d quark → u quark + electron + anti-neutrino

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

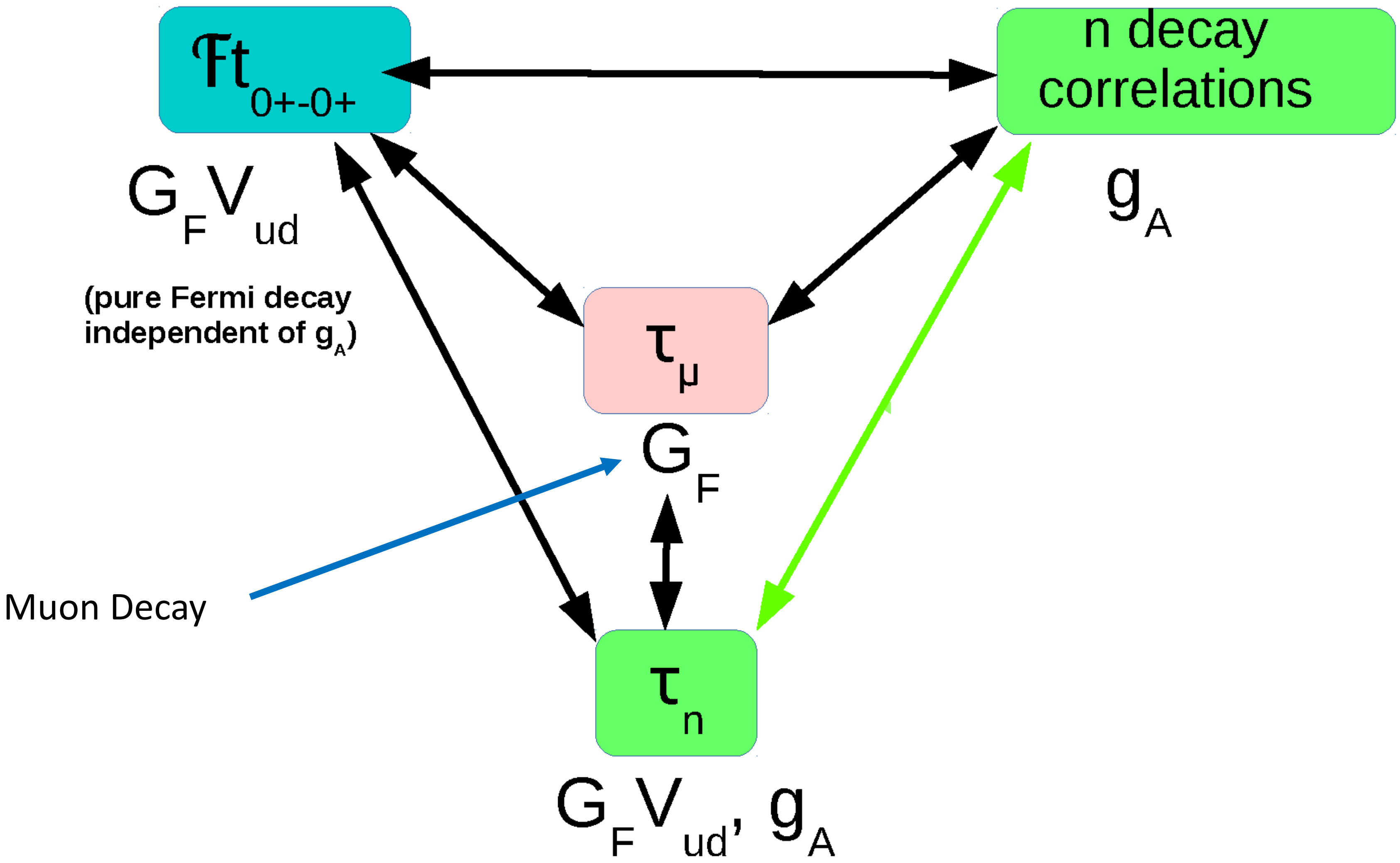
V

A

Axial matrix element

Vector matrix element specified by CVC

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

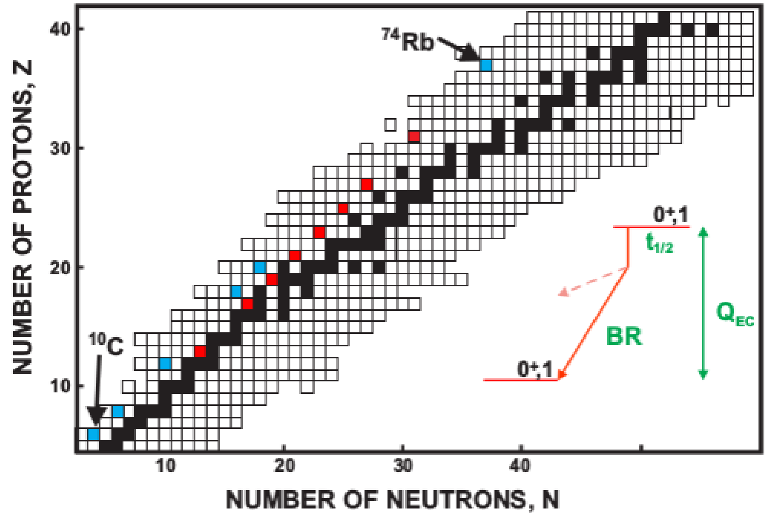


Super-allowed Nuclear Decays

Isobaric analog decays with initial and final spin,parity = 0^+

$$0^+ \rightarrow 0^+$$

- Parent & product nuclear states almost identical
- Spin selection rules ensure only G_V contributes
- Hundreds of measurements lead to incredible experimental data precision < 10^{-4}

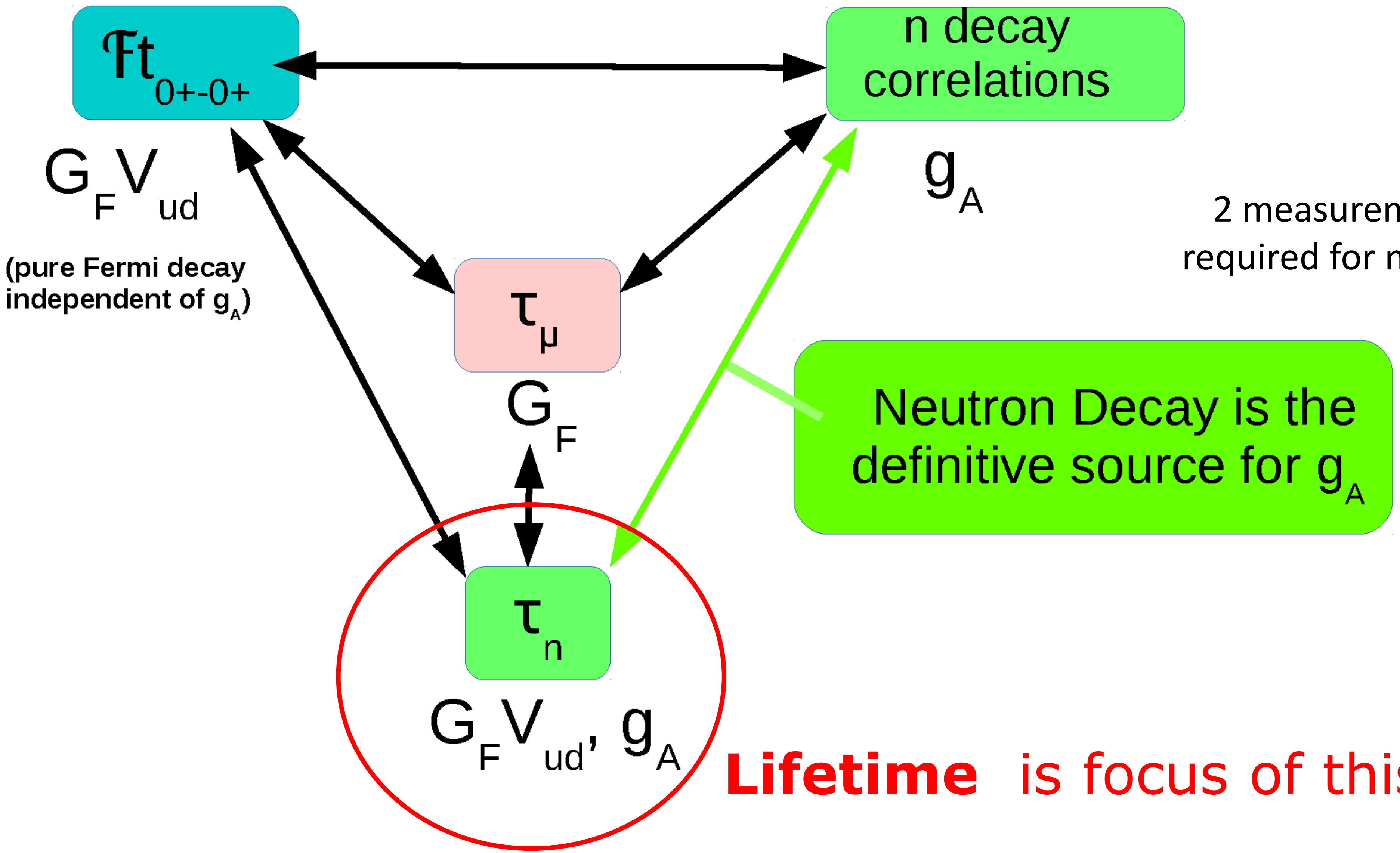


- 8 cases with *ft*-values measured to <0.05% precision; 6 more cases with 0.05-0.3% precision.
- ~220 individual measurements with compatible precision

But nuclear structure corrections very challenging!

J. Hardy and I. Towner, PRC **91**, 023501 (2015)
J. Hardy and I. Towner, PRC **102**, 045501 (2020)

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



2 measurements required for neutron

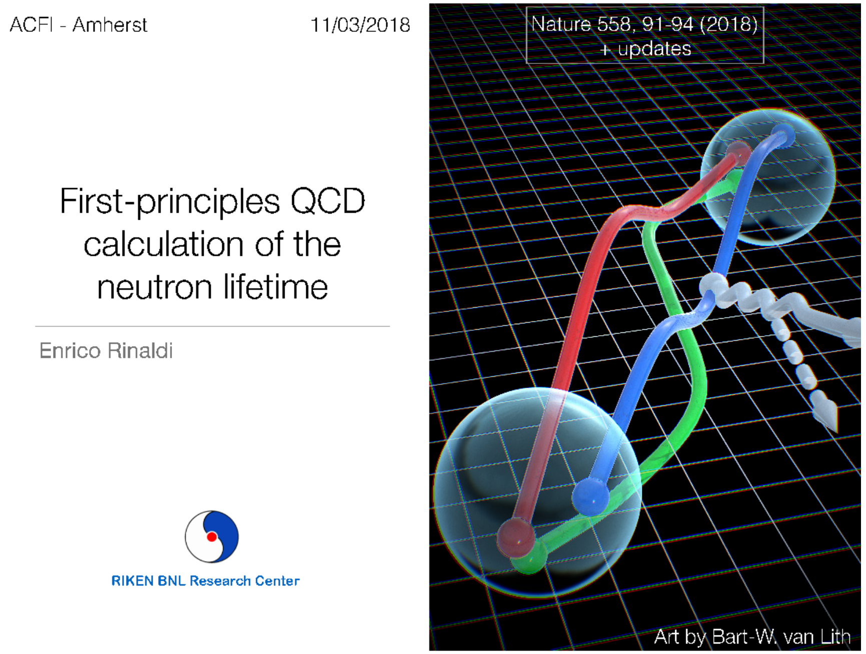
Lifetime is focus of this talk

Neutron Data Impact

- **Lifetime** input important (with sub-1% precision) for
  - Big bang nucleosynthesis (0.1% pred. of ^{4}He/H !)
  - Solar fusion rates
  - Reactor neutrino anomaly
  - High precision target for lattice nucleon couplings possible, e.g. at < 1% level in g_A!

LANL theory group
& Callat collaboration

Pushing precision envelope for QCD



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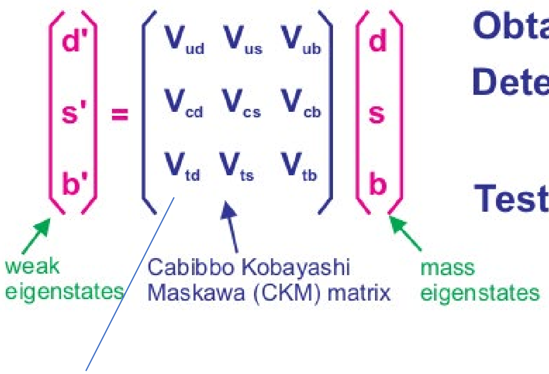
- **New Physics** Constraints
  - Input for CKM unitarity test
  - Direct test for BSM Axial couplings (combine with lattice)
  - Model independent constraints on exotic (S,T) interaction
  - Variety of models (leptoquarks, MSSM, charged Higgs)

Unitarity Tests

In SM, u quark must couple to a linear combination of either d, s or b quarks!



Obtain precise value of $G_V^2(1 + \Delta_R)$

Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2$$

G_F from μ decay

Test CKM unitarity

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

Mixing coefficients are fundamental inputs
To the SM (should be the same for all processes)

(only possibilities: u couples to either d, s, or b!)

Concept introduced for 3 generations of quarks by Kobayashi and Maskawa!

Kobayashi, M.; Maskawa, T. (1973), *Progress of Theoretical Physics*. **49** (2): 652–657.

Cabibbo, N. (1963), *Physical Review Letters*. **10** (12): 531–533.

Unitarity Tests

In SM, u quark must couple to either d, s or b!

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates — Cabibbo Kobayashi Maskawa (CKM) matrix — mass eigenstates

Obtain precise value of $G_V^2(1 + \Delta_R)$

Determine V_{ud}^2

$$V_{ud}^2 = G_V^2/G_\mu^2$$

Test CKM unitarity

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

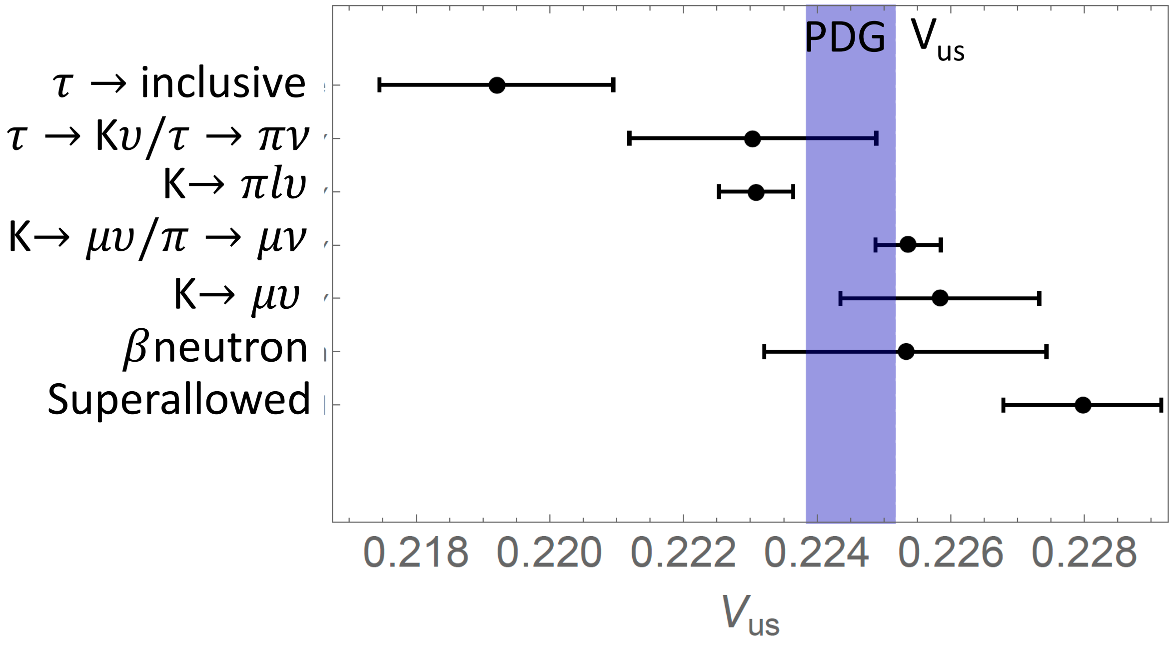
Sensitive to BSM V,A couplings!

High precision value for V_{ud} required! -- **LHC can not provide**! SM "backgrounds" too large (precision limited to ~ %)

Current status: compare measured values of V_{us} with unitarity prediction (should be consistent!)

$$|V_{ub}|^2 \ll 1 \Longrightarrow |V_{ud}|^2 + |V_{us}|^2 \overset{?}{=} 1$$

The Cabbibo Anomaly: Unitarity Issues



decays involving strange quarks

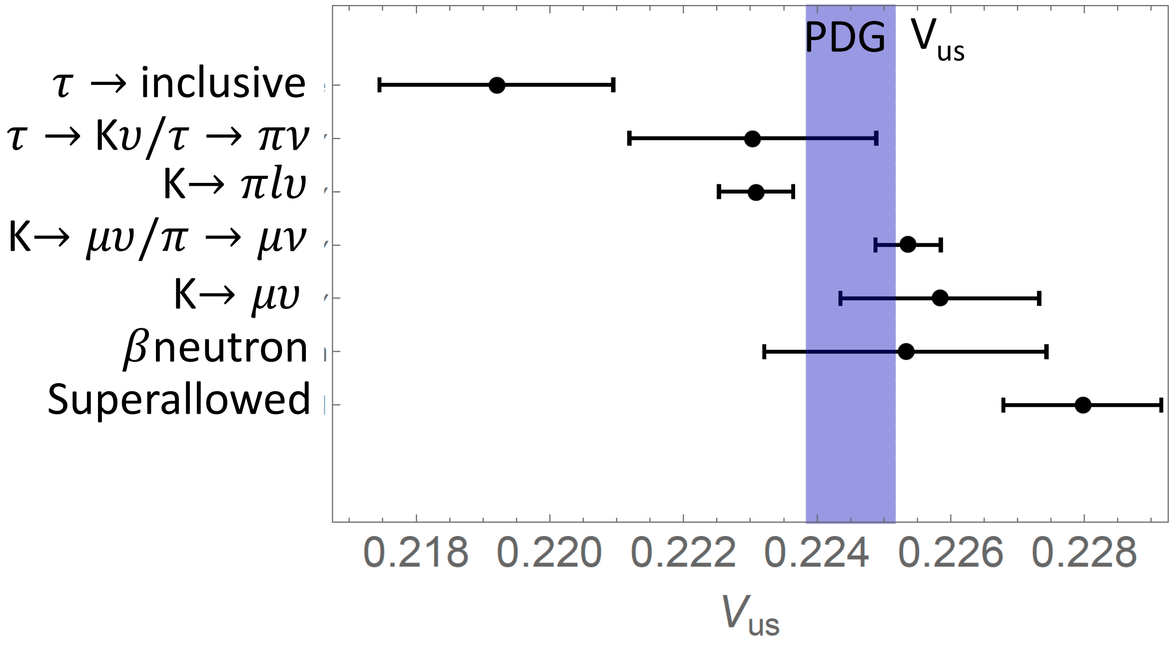
neutron

V_{us} predicted **from unitarity**

Should all provide the **same** value!

[Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, 2112.02087]

The Cabbibo Anomaly: Unitarity Issues



use $0^+ \to 0^+$ currently

[Cirigliano, Díaz-Calderón, Falkowski, MGA & Rodríguez-Sánchez, 2112.02087]

1 operator at a time: [10^-3 units]

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
L	-0.79(25)	-0.6(1.2)	0.40(87)	0.5(1.2)	5.0(2.5)	-18.2(6.2)
R	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)
S	1.40(65)	-1.6(3.2)	x	-0.51(43)	-6(16)	-270(100)
P	0.00018(17)	-0.00044(36)	-0.015(32)	-0.032(64)	1.7(2.5)	10.4(5.5)
$\hat{T}$	0.29(82)	0.035(70)	x	2(18)	28(10)	-55(27)

At least two **separate** sources of BSM physics required, with both > 3σ

Lepton “non-universality” a possibility…

Neutron and nuclear decays

Cabbibo Anomaly!

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
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Neutron uncertainty targets: lifetime – 0.25 s (current most precise, UCNtau with 0.36 s)
g_A ~ 0.025% (current most precise, PERKEO III with 0.044%)

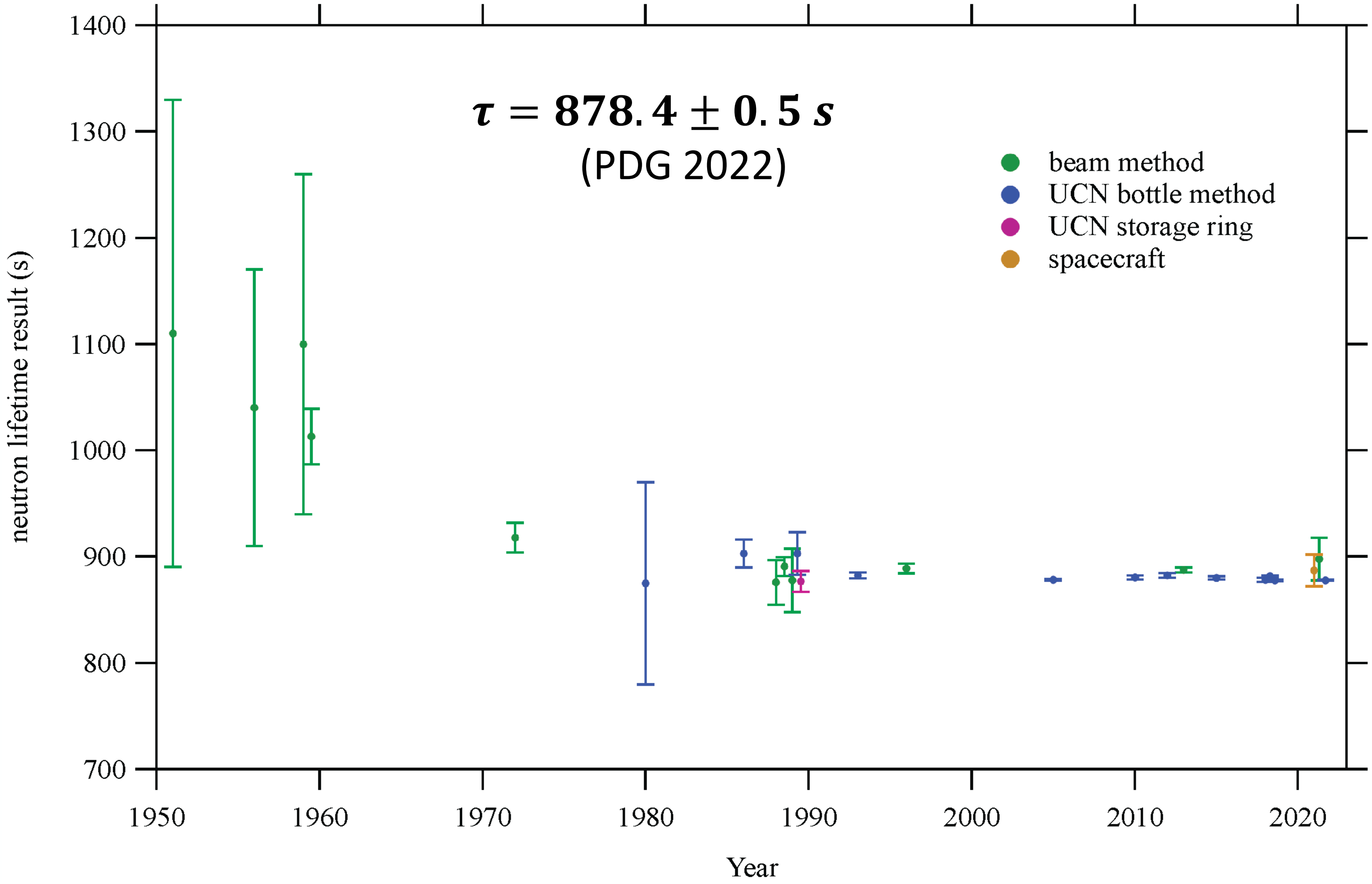
Neutron can probe an important possible source of discrepancy: the nuclear structure corrections required to interpret $0^+ \rightarrow 0^+$ decays!

The Neutron Lifetime Puzzle

(A personal perspective)

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)

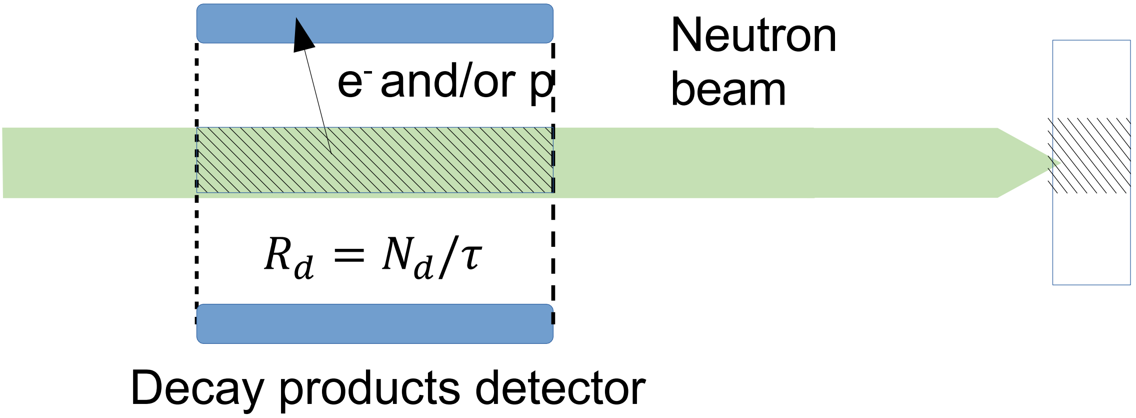
Lifetime measurements: two varieties

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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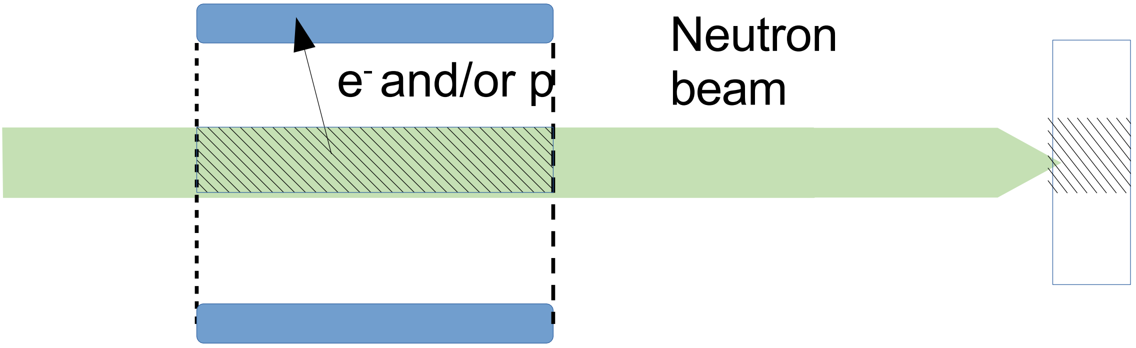

Requires precisely known:

i) decay volume
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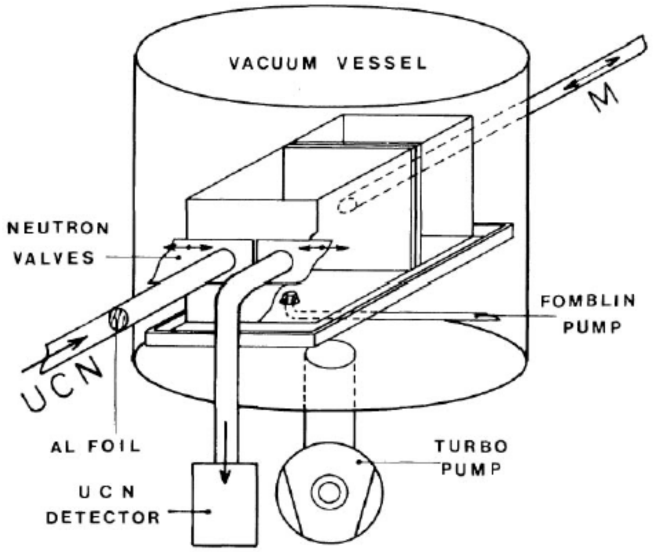
Pre-2013: neutron density was dominant source of uncertainty

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



Actually measures total loss rate from trap…

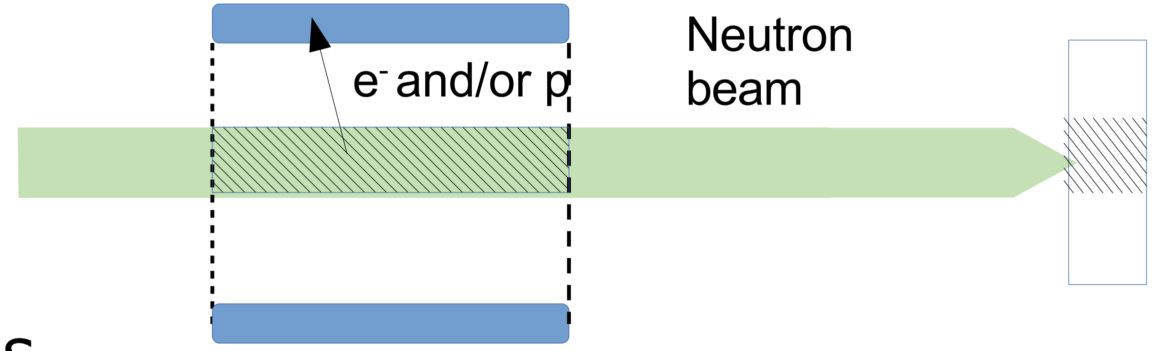
$$\frac{N(t_o + t_s)}{N(t_o)}$$

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

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

Lifetime measurements: two varieties

Historically, shown reasonable agreement, but since 2013:

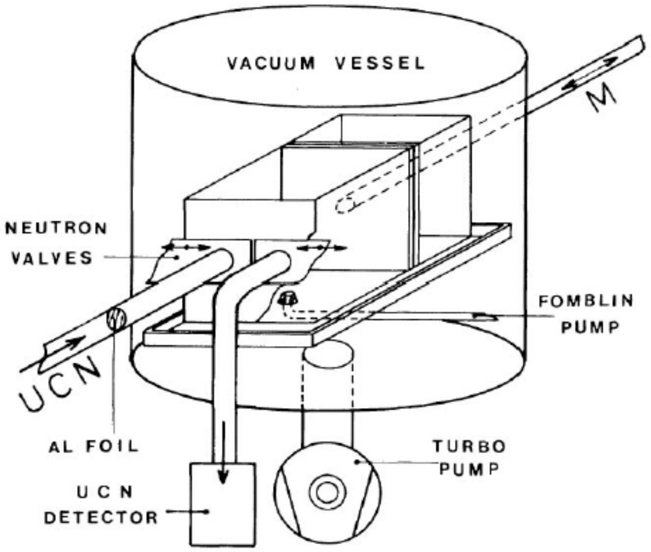


Decay products detector

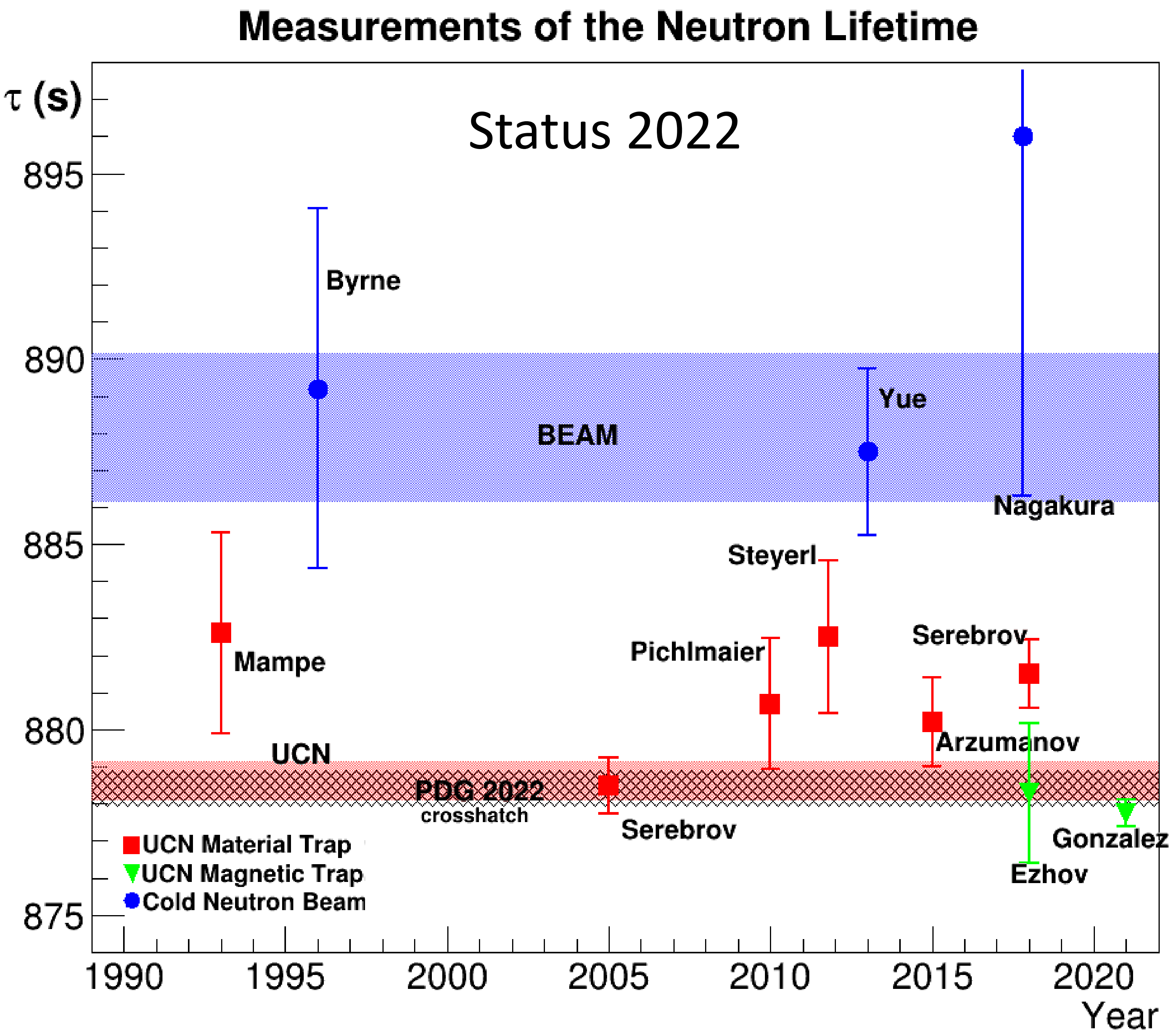
Cold neutron beams: τ = 888.0(2.0) s

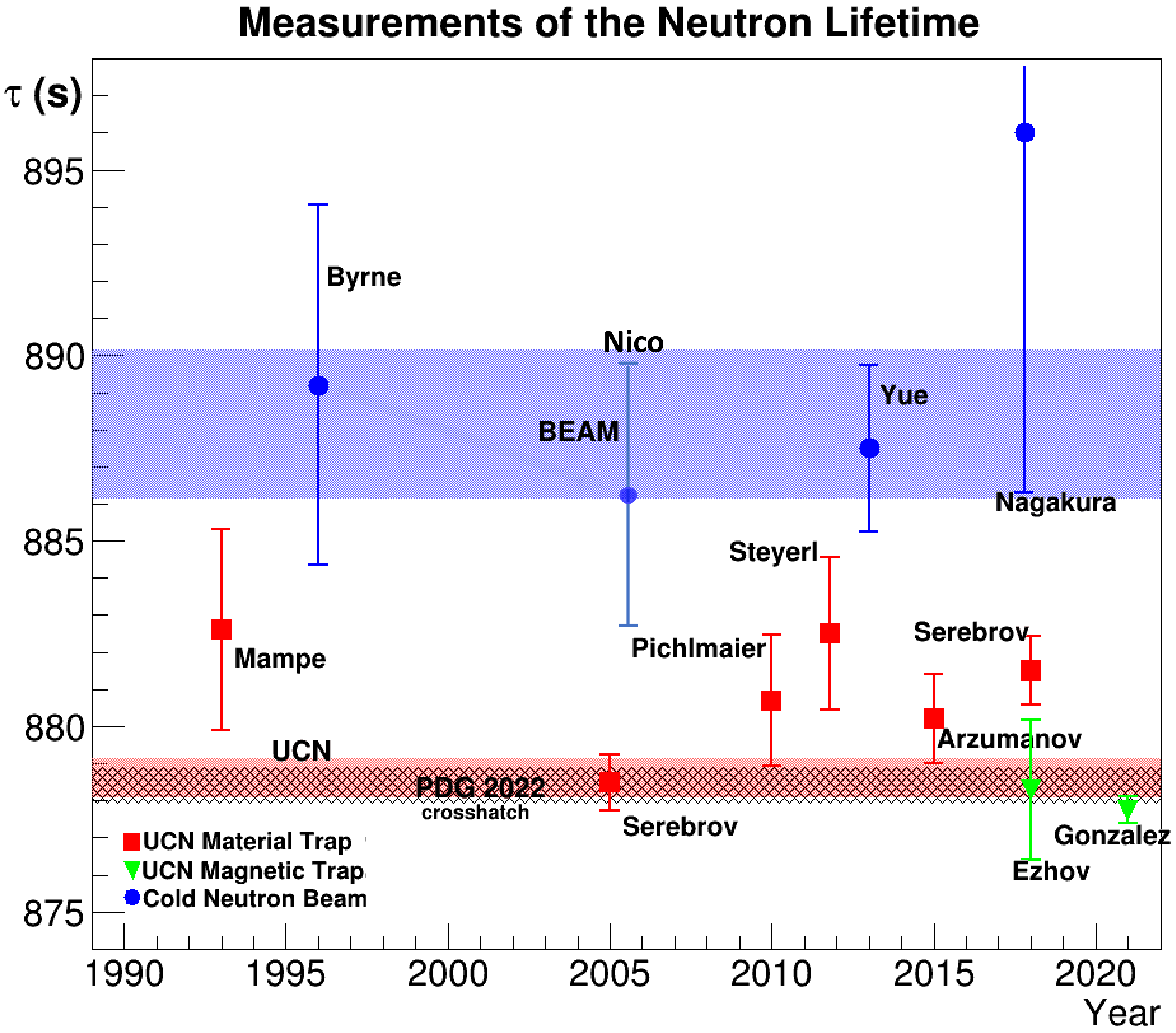
Differ by 4σ

UCN storage experiments in material traps:
τ = 878.4(5) s



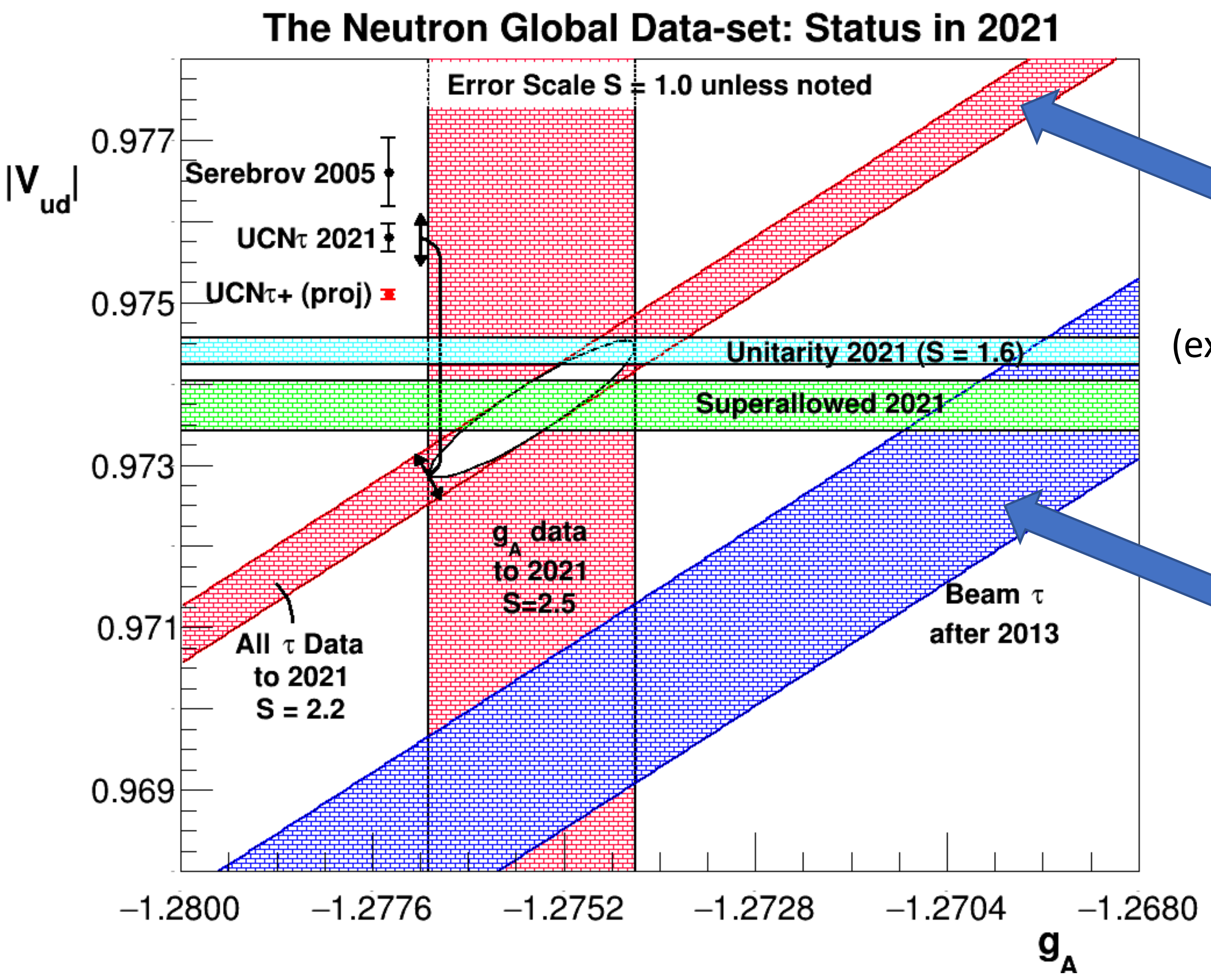
Latest/most
Sensitive Results
for all groups





Conclusion: 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 and the Gravitrap Experiment

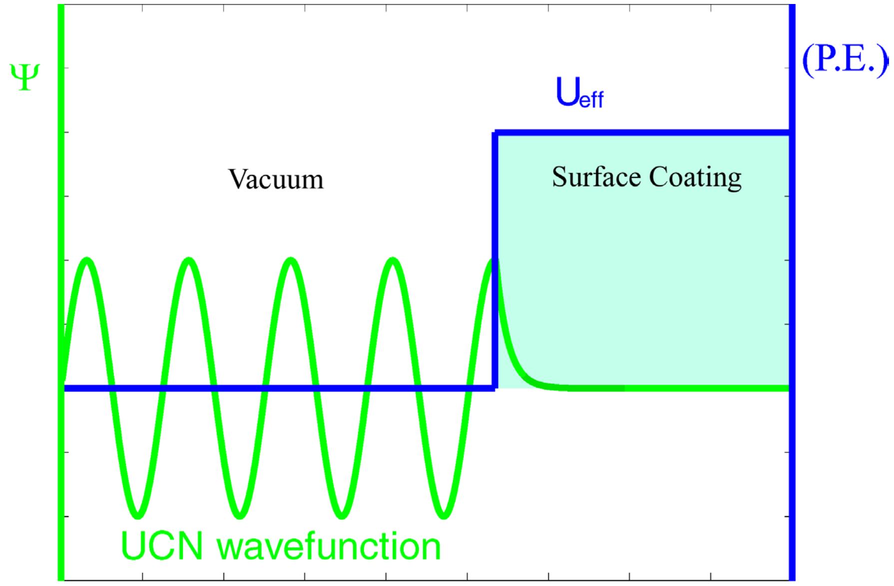
(one way to solve the problem of manipulating these neutral particles is to slow them down!)

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

What is an Ultracold Neutron?

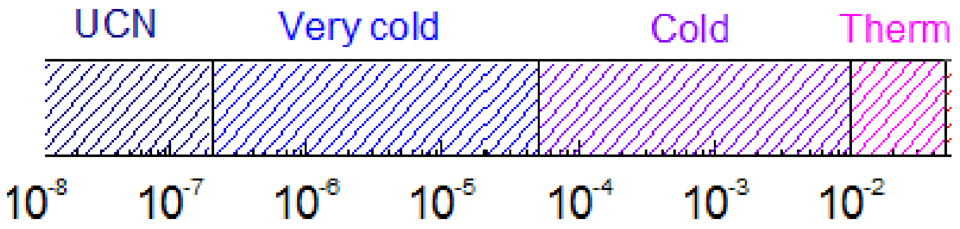
For a neutron "wave", coherent interaction with many nuclear sites makes an effective potential, U_{eff} for neutrons incident on a material surface

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



Case where $E < U_{eff}$

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



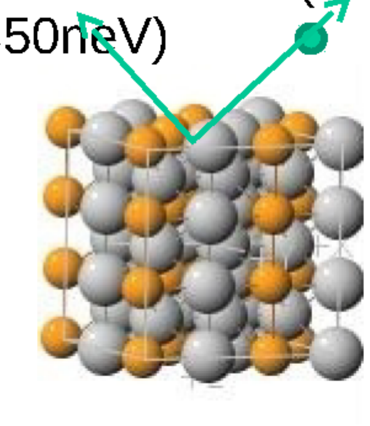
UCN can be stored for 100's of seconds
In material and magnetic traps!

Different ways to manipulate UCN

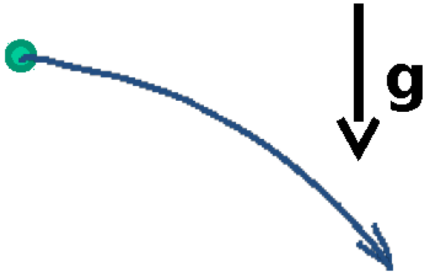
UCN energies so low, they reflect from some material surfaces for any angle of incidence!

- Nuclear force (max: 350neV)

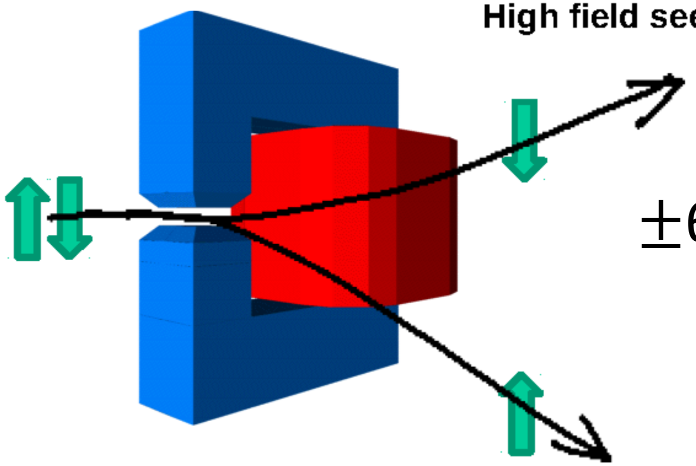
Store them in bottles!



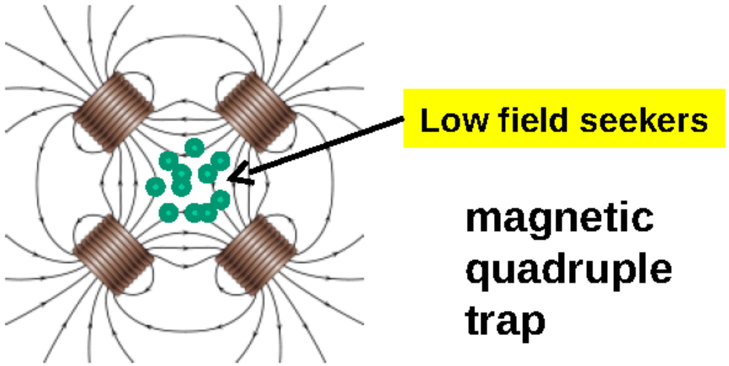
- Gravitational force (100neV/m)



- Magnetic force



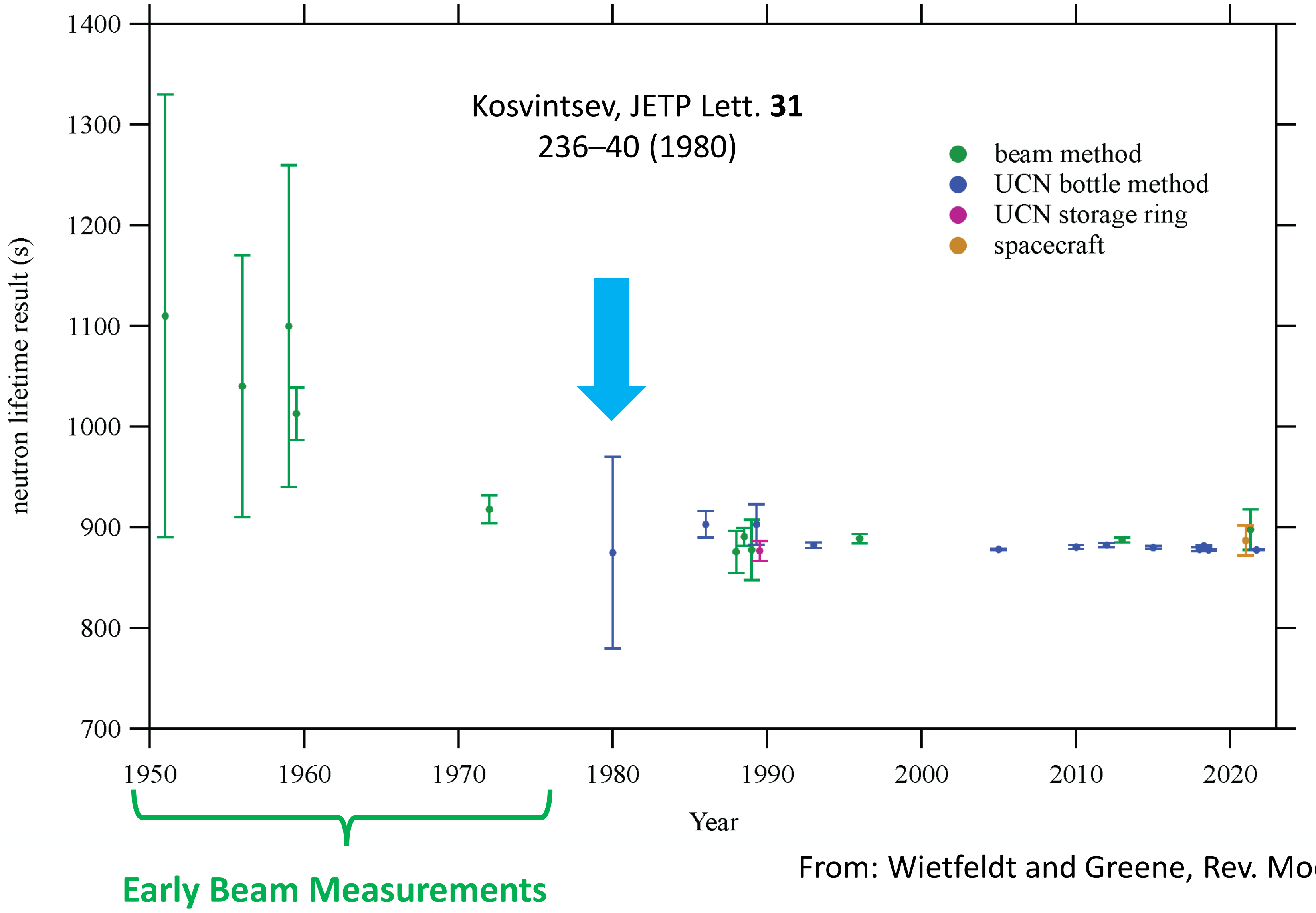
± 60 neV/T



magnetic quadruple trap

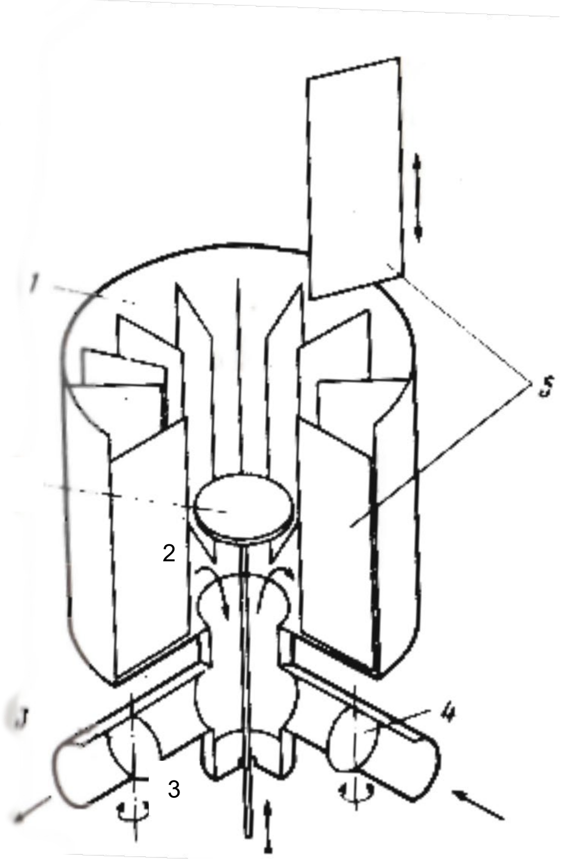
C.-Y. Liu

Neutron Lifetime Measurements



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

Storage experiments with UCN



As early as 1980: Kosvintsev reported regarding beam measurements:

"The experimental values of the lifetime of the neutron, which were obtained by recording the products of its β decay, differ in the case of each author by a value that exceeds the measurement error. In view of this, the development of new methods of measuring this value are of interest."

The use of ultracold neutrons for measurement of the neutron lifetime," Yu. Yu. Kosvintsev, Yu. A. Kushnir, V. I. Morozov, and G. I. Terekhov,
JETP Lett. **31**, 237 (1980).

Scatter due to poorly characterized systematic uncertainty in beam measurements motivated measurements using very different technique: **UCN storage**

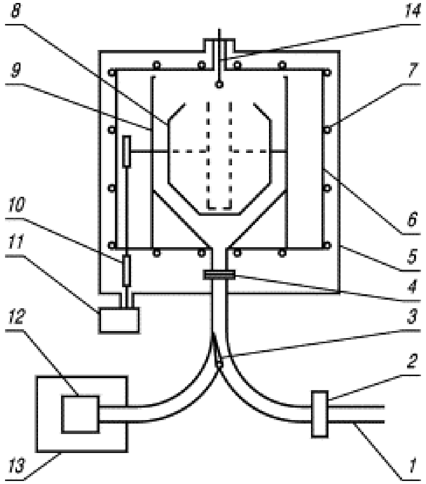
But...losses on the walls can produce large corrections!

Extrapolation Procedures

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

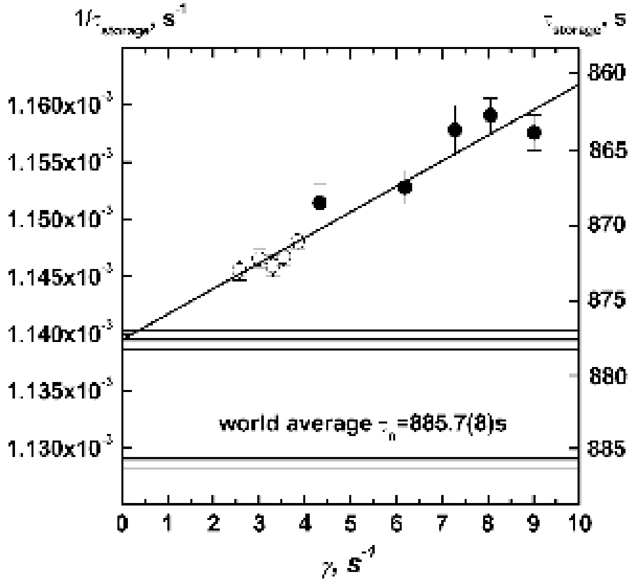
trap losses set scale for corrections

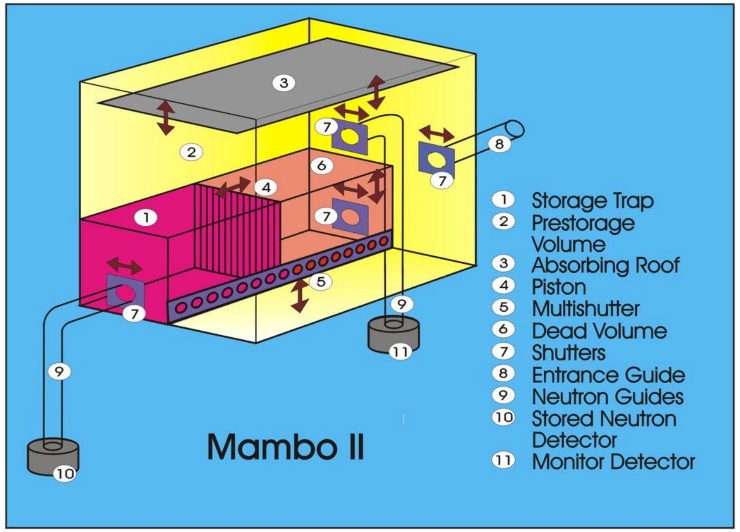
Strategy: vary A/V to characterize wall losses! (Kosvintsev inserts...)



2005 Gravitrap

Most successful, small corrections needed





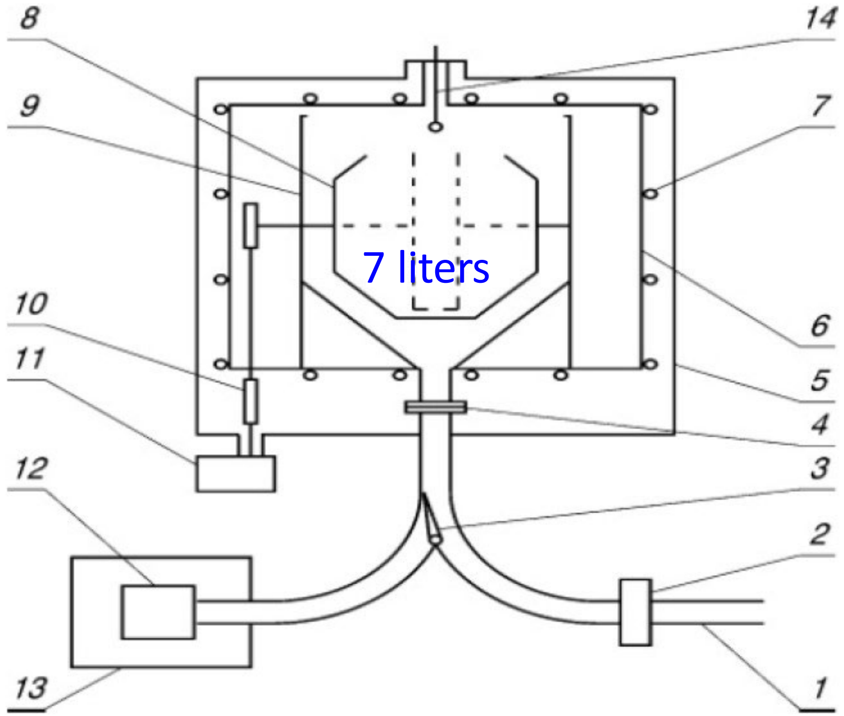
Mambo II

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

The Gravitrap Experiment

PHYSICAL REVIEW C **78**, 035505 (2008)

A. P. SEREBROV *et al.*



Gravitrap experiment

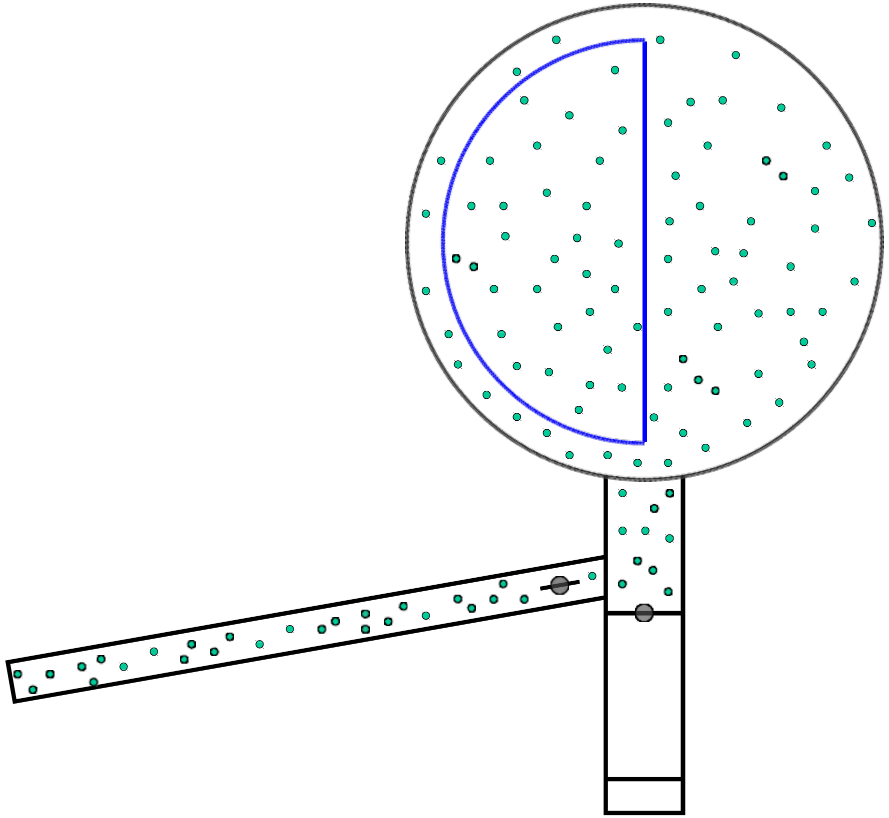
A.Serebrov et al. , Phys Lett B 605, (2005) 72-78

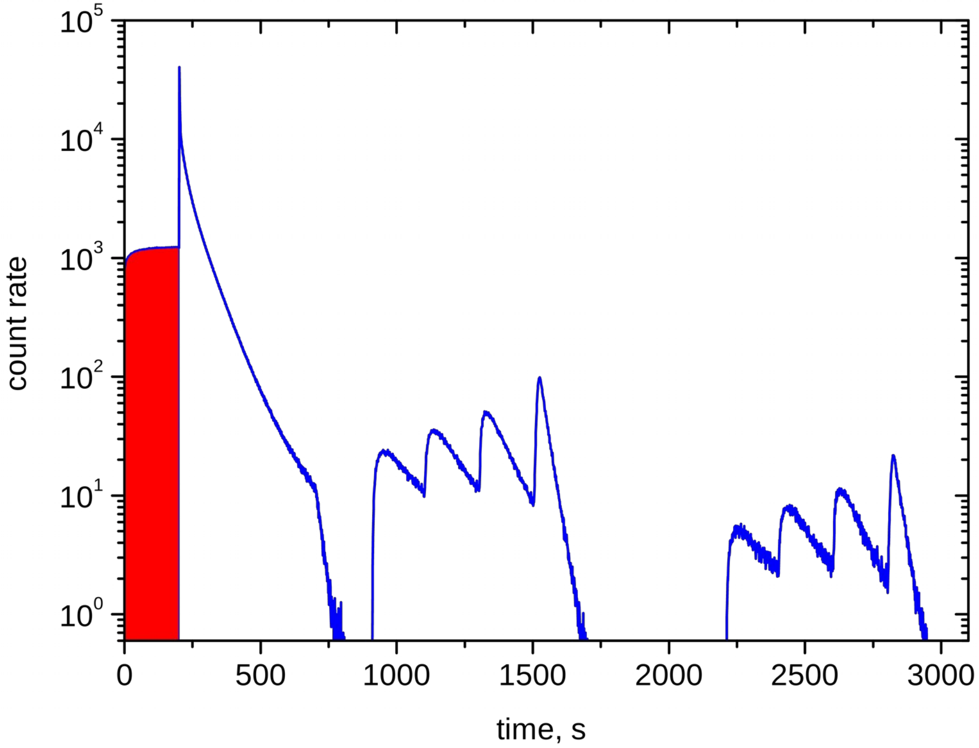
878.5 ± 0.8 s

2002-2004 (PNPI-JINR-ILL), ILL reactor, Grenoble

3

Generic Measurement Scheme:
(1) Fill





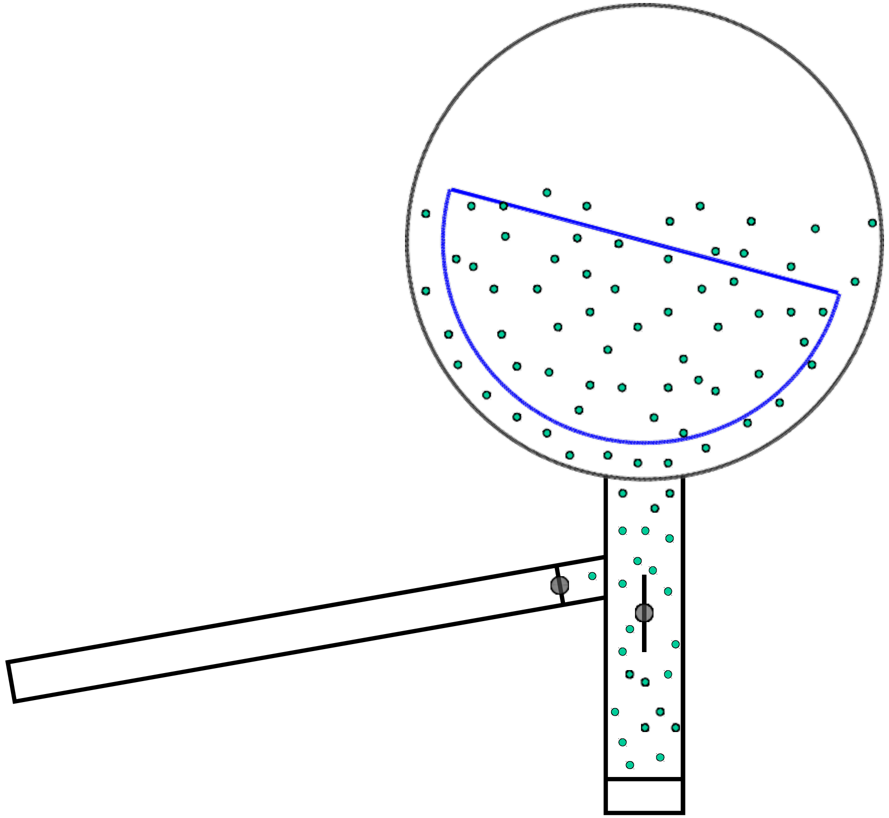
Filling of the trap with UCN: =90

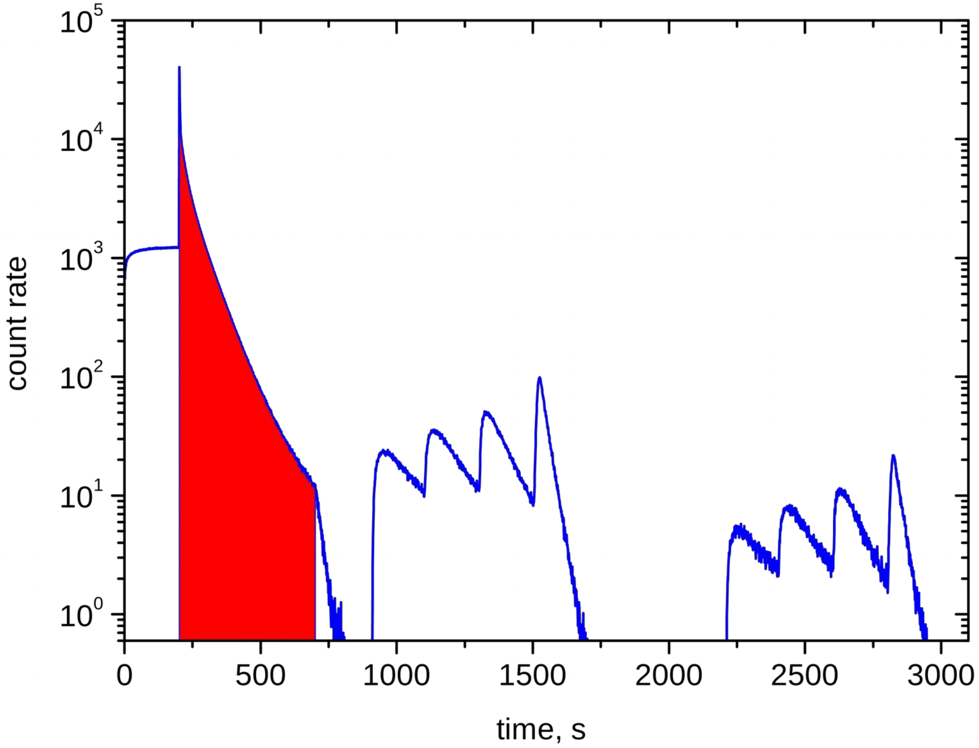
3
4

Generic Measurement Scheme:

(1) Fill

(2) Clean – (remove high E
UCN not trapped)





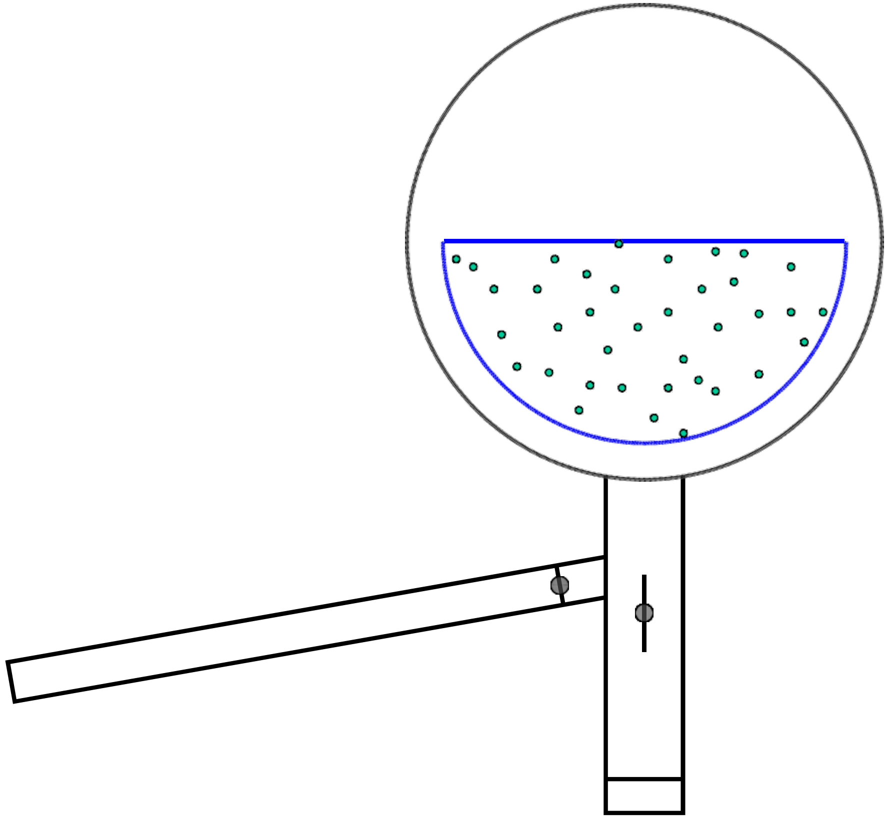
Monitoring: =15

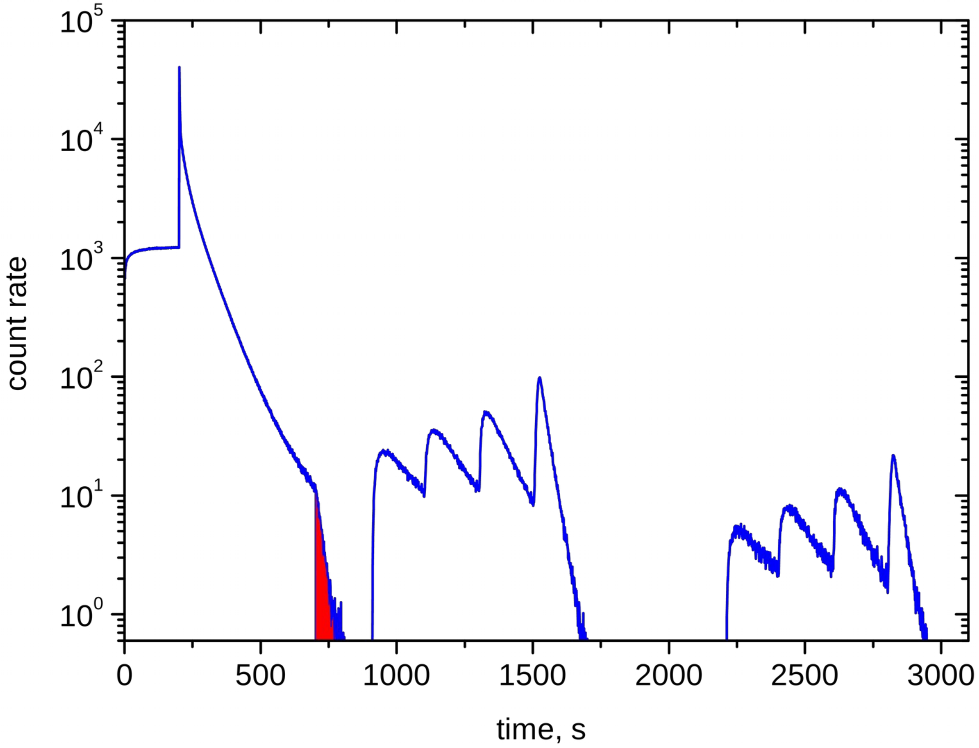
Generic Measurement Scheme:

(1) Fill

(2) Clean

(3) Store for time Δt_1

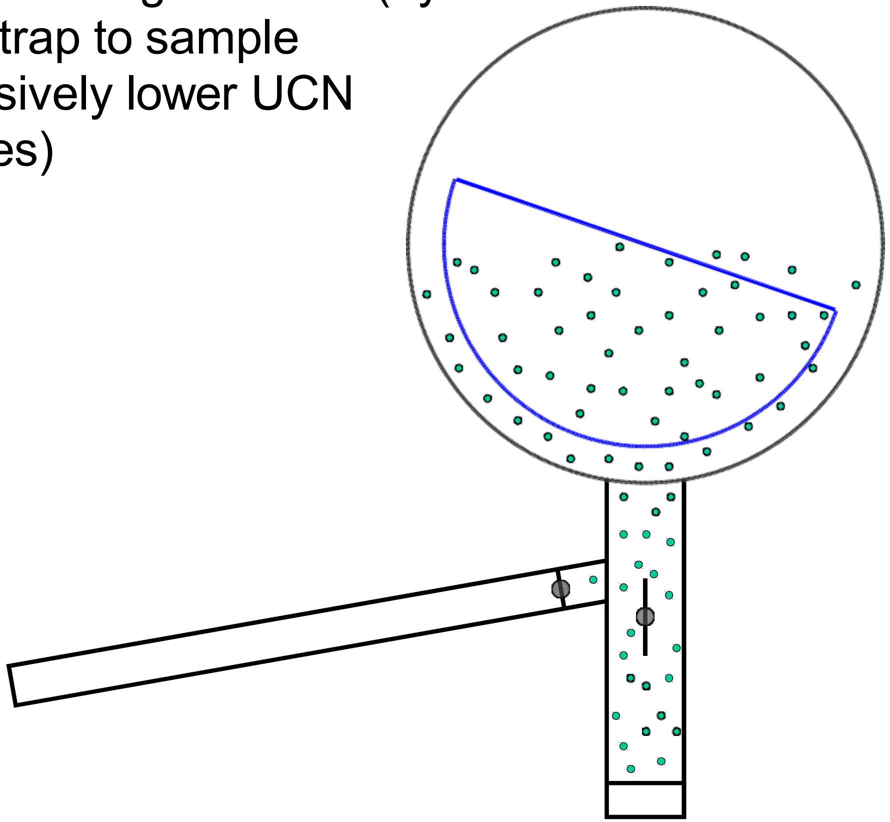


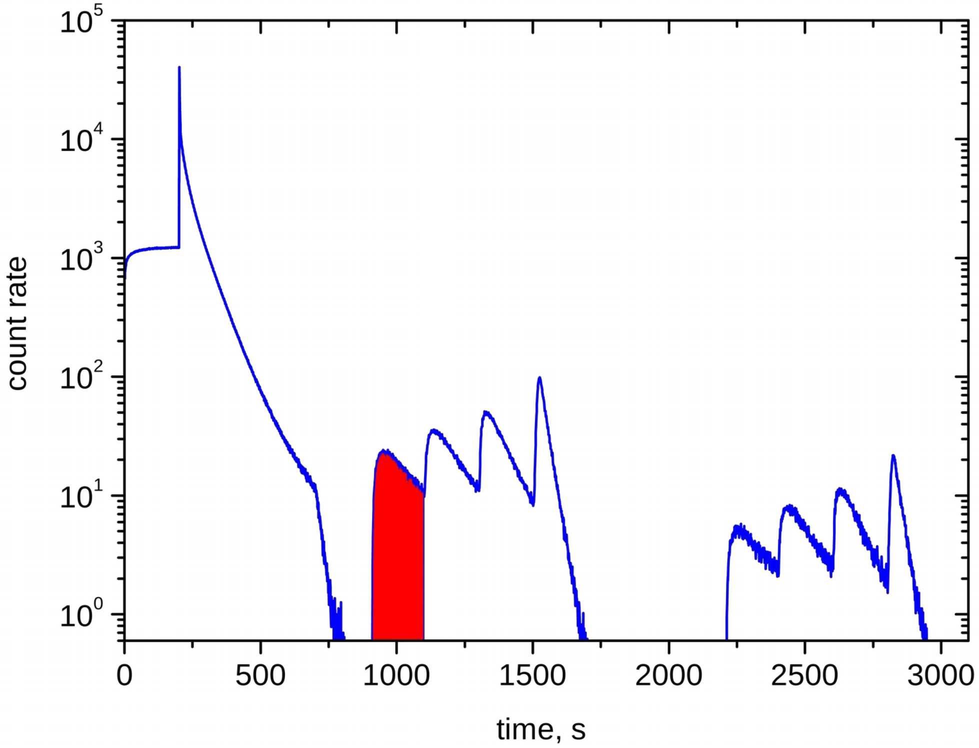


Holding: =0

Generic Measurement Scheme:

(1) Fill
(2) Clean
(3) Store for time Δt_1
(4) Count surviving neutrons (by tipping trap to sample successively lower UCN velocities)

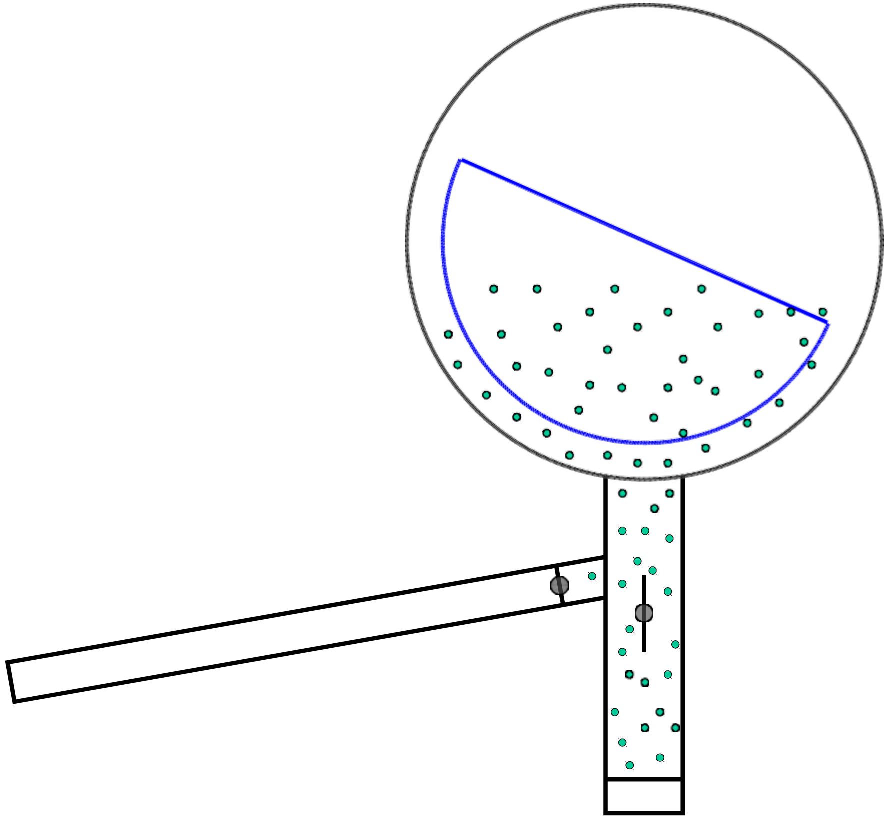


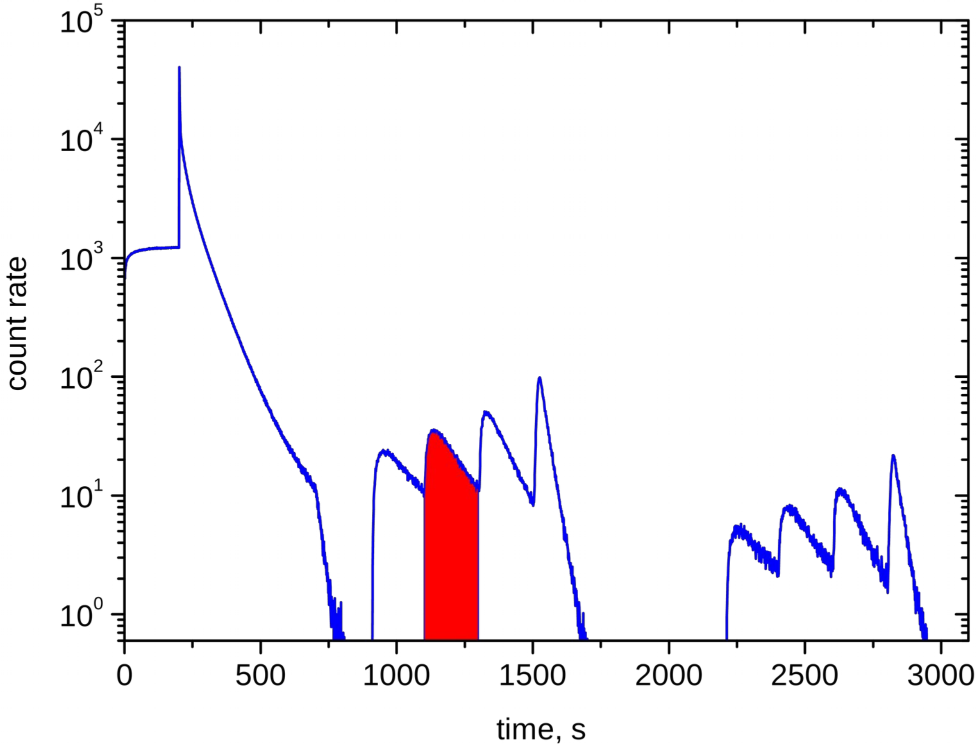


Registration of UCN 1: =19

Generic Measurement Scheme:

(1) Fill
(2) Clean
(3) Store for time Δt_1
(4) Measure





Registration of UCN 2: �=24�

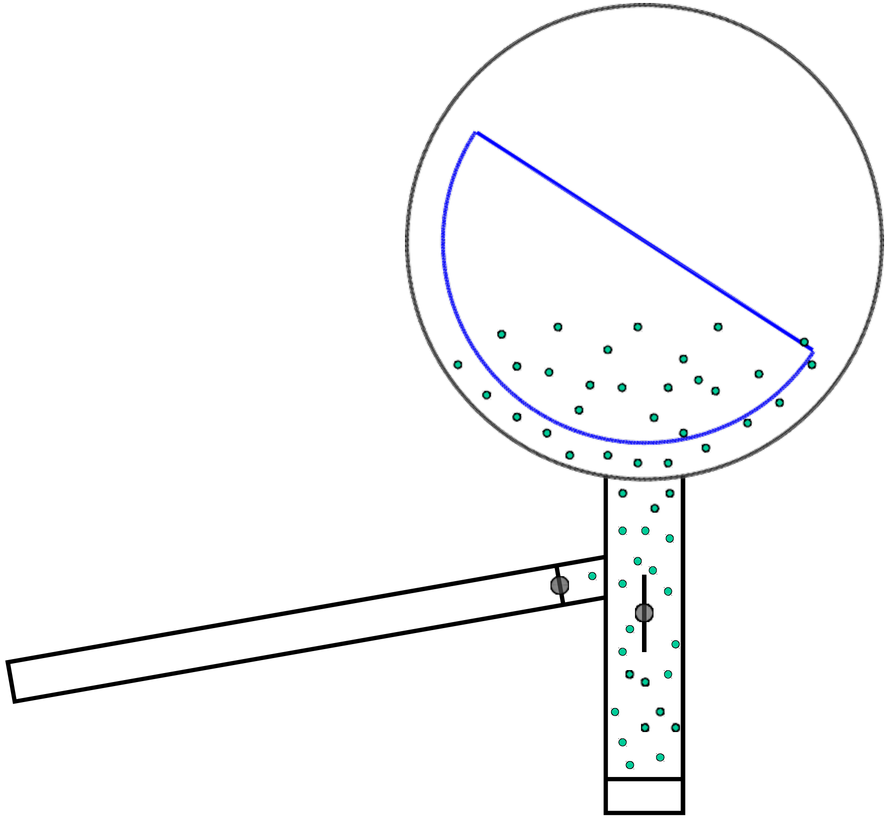
Generic Measurement Scheme:

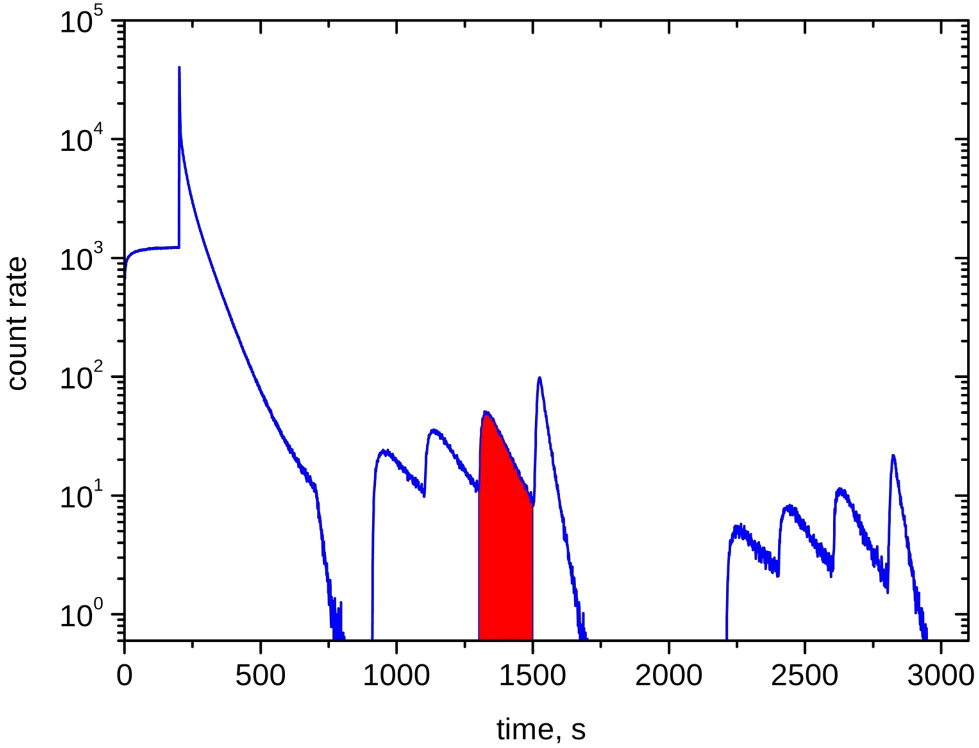
(1) Fill

(2) Clean

(3) Store for time Δt_1

(4) Measure





Registration of UCN 3: [illegible]=33[illegible]

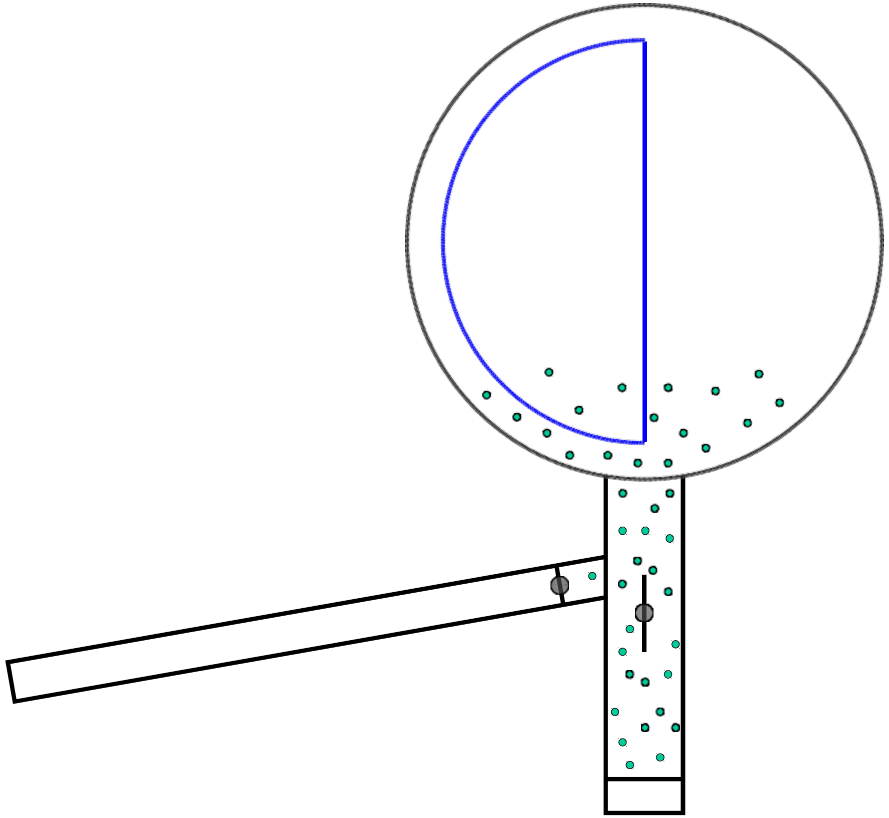
Generic Measurement Scheme:

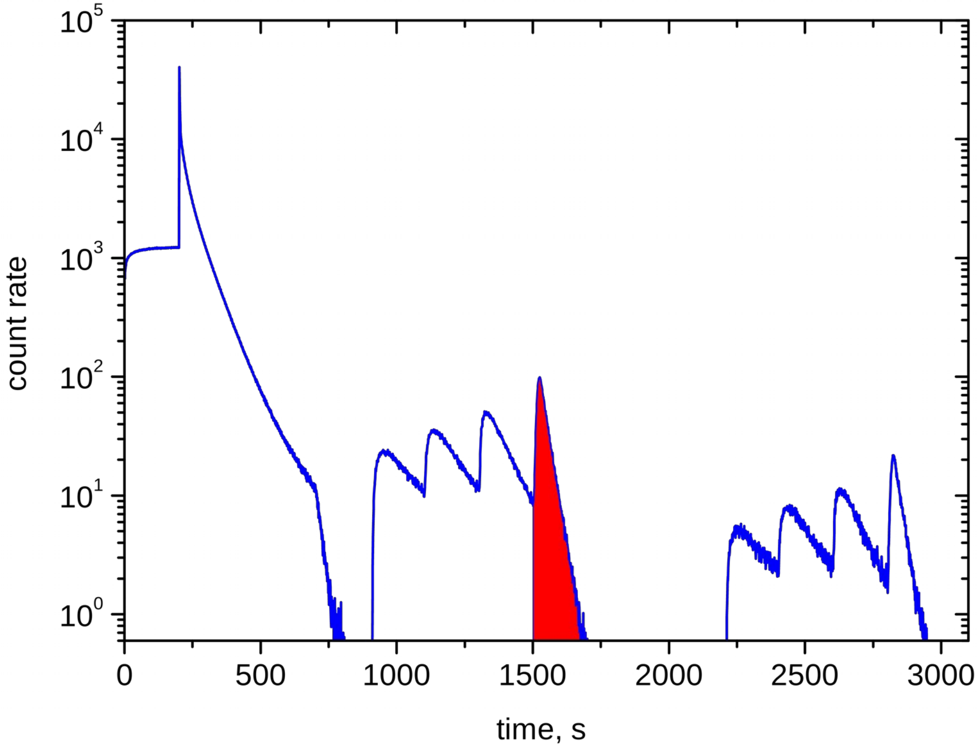
(1) Fill

(2) Clean

(3) Store for time Δt_1

(4) Measure

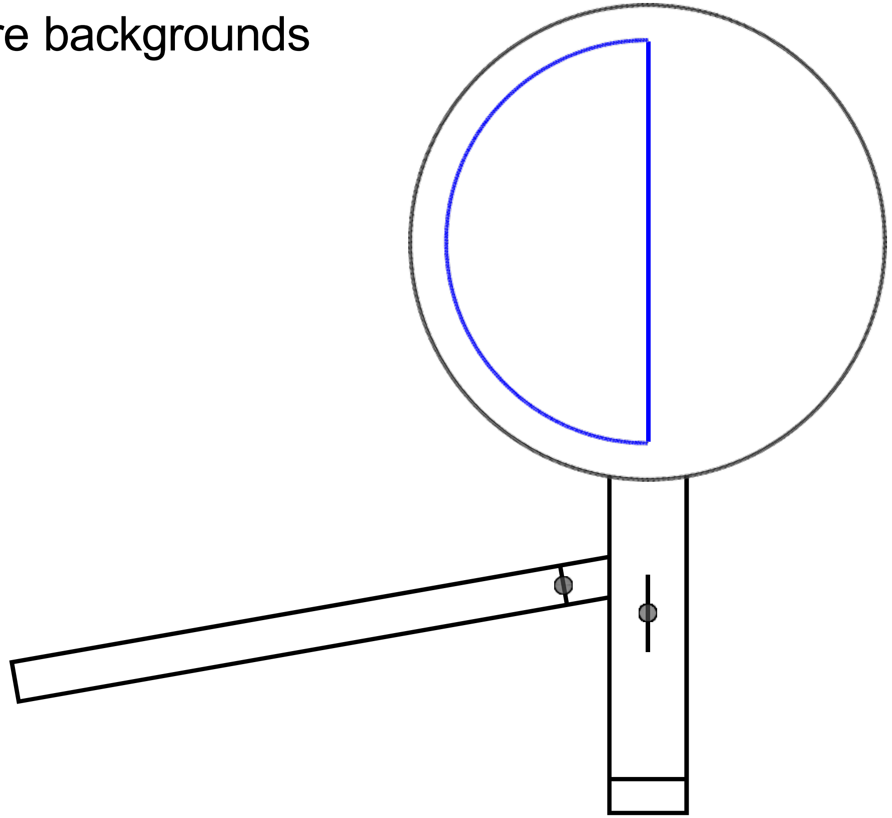


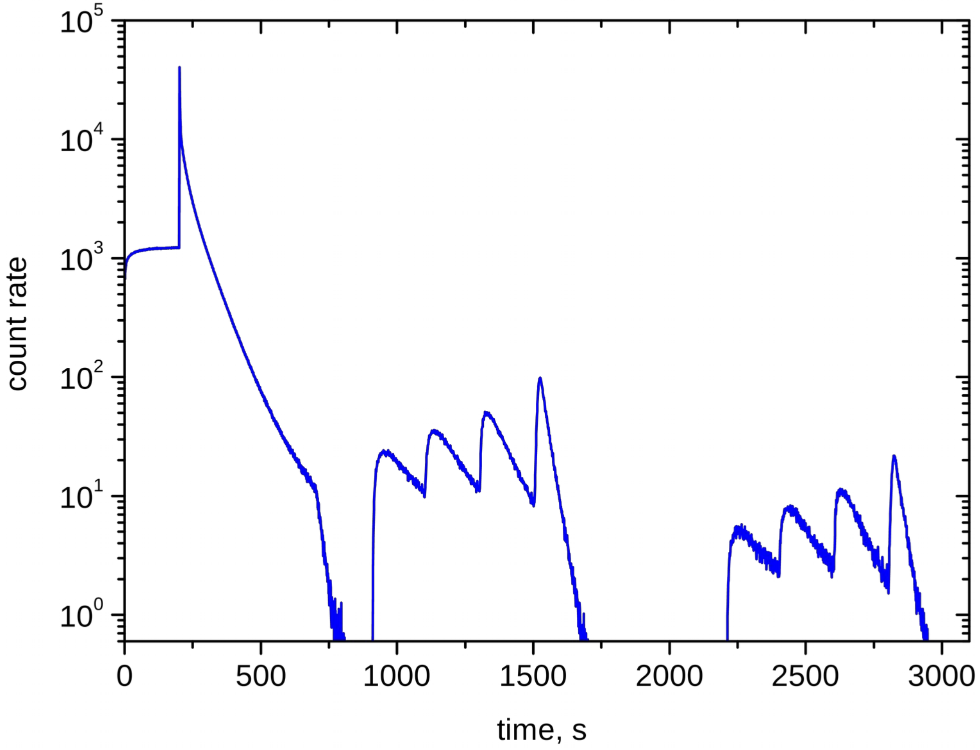


Registration of UCN 4: ?=90?

Generic Measurement Scheme:

(1) Fill
(2) Clean
(3) Store for time Δt_1
(4) Measure
(5) Measure backgrounds





Background: =9.0

Measurement Method

Generic Measurement Scheme:
(1) Fill
(2) Clean – (remove high E UCN not trapped)
(3) Store for time Δt_1
(4) Count surviving neutrons
(5) Measure backgrounds

Repeat for storage time Δt_2

$$N(t) = N_o e^{-\Delta t/\tau}$$

$$\tau = (\Delta t_2 - \Delta t_1)/\ln(N_1/N_2)$$

Relative measurement! Counting efficiency not important..

Losses **are** important

Influence of model for losses due to wall bounces

Only correction due to residual gas

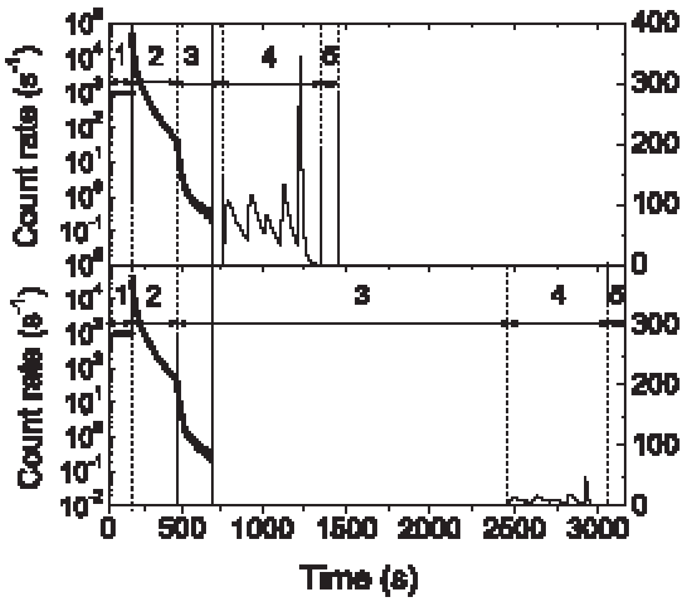
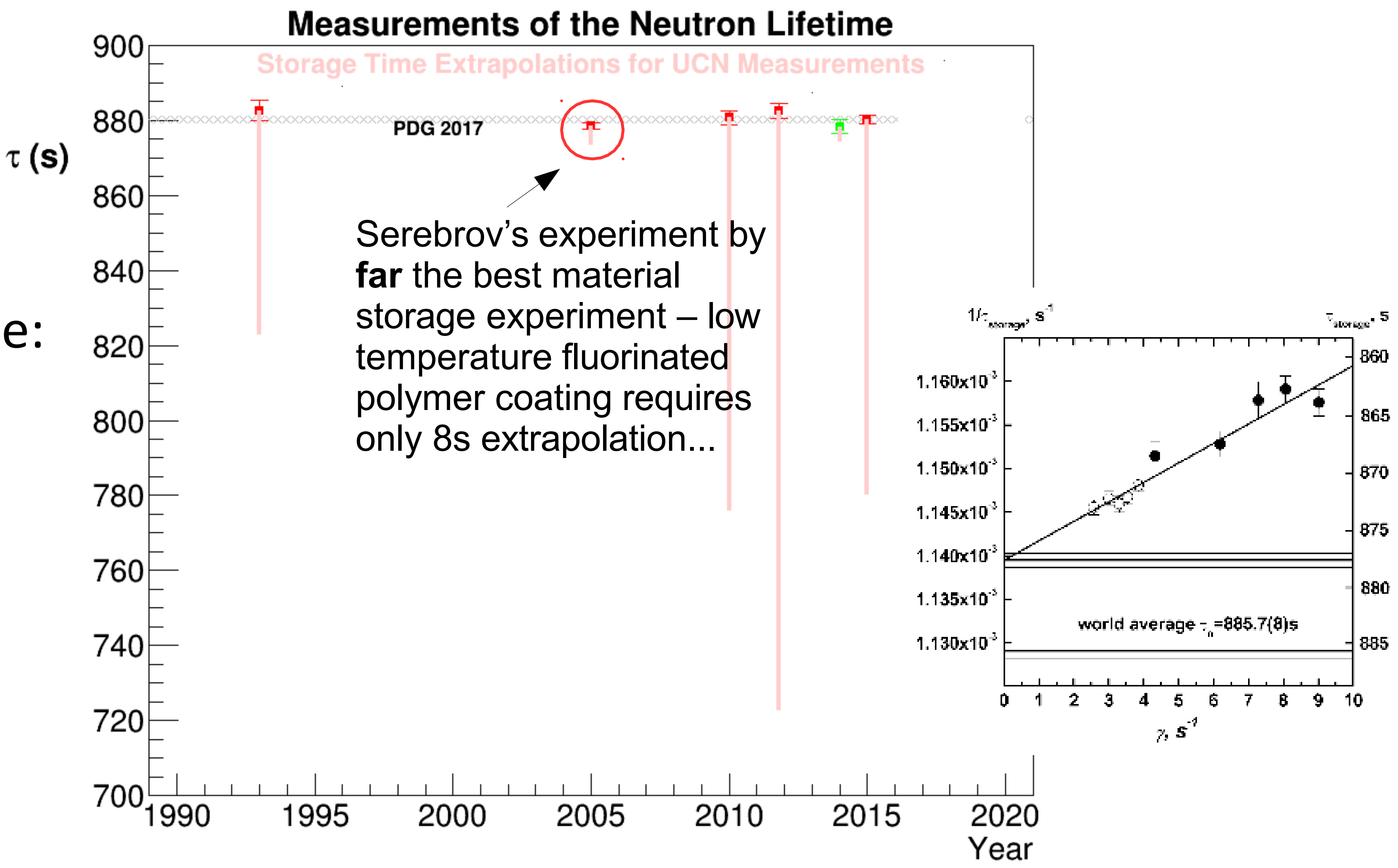


TABLE I. Systematic effects and their uncertainties.

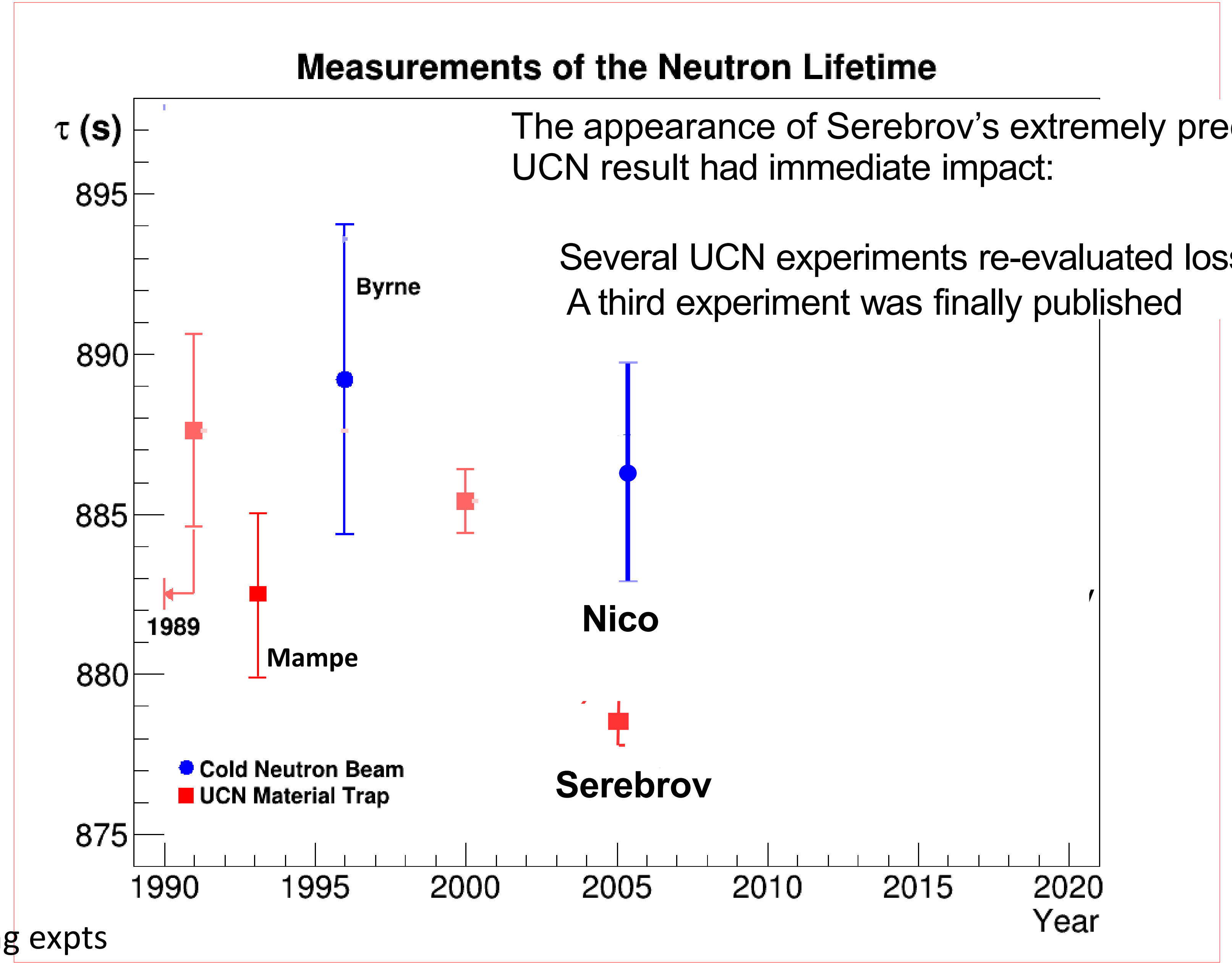
Systematic effect	Magnitude (s)	Uncertainty (s)
Method of calculating γ	0	0.236
Influence of shape of function $\mu(E)$	0	0.144
UCN spectrum uncertainty	0	0.104
Uncertainty of trap dimensions (1 mm)	0	0.058
Residual gas effect	0.4	0.024
Uncertainty in PFPE critical energy (20 neV)	0	0.004
Total systematic correction	0.4	0.3

The big difference:



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

What’s missing with this picture is how many of these experiments evolved!

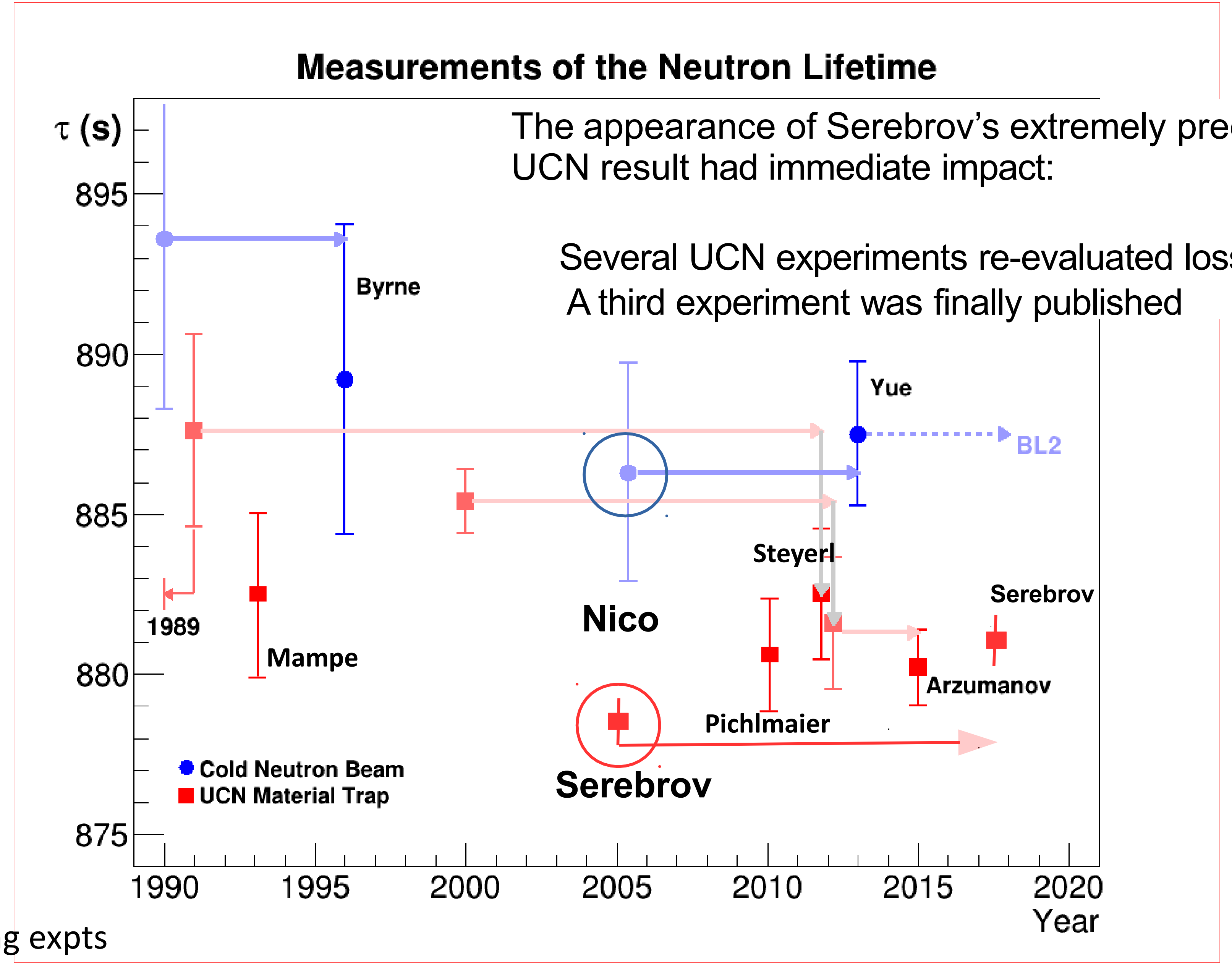


The appearance of Serebrov’s extremely precise UCN result had immediate impact:

Several UCN experiments re-evaluated losses
A third experiment was finally published

Horizonal arrows:
Refinement of existing expts

What's missing with this picture is how many of these experiments evolved!



The appearance of Serebrov's extremely precise UCN result had immediate impact:

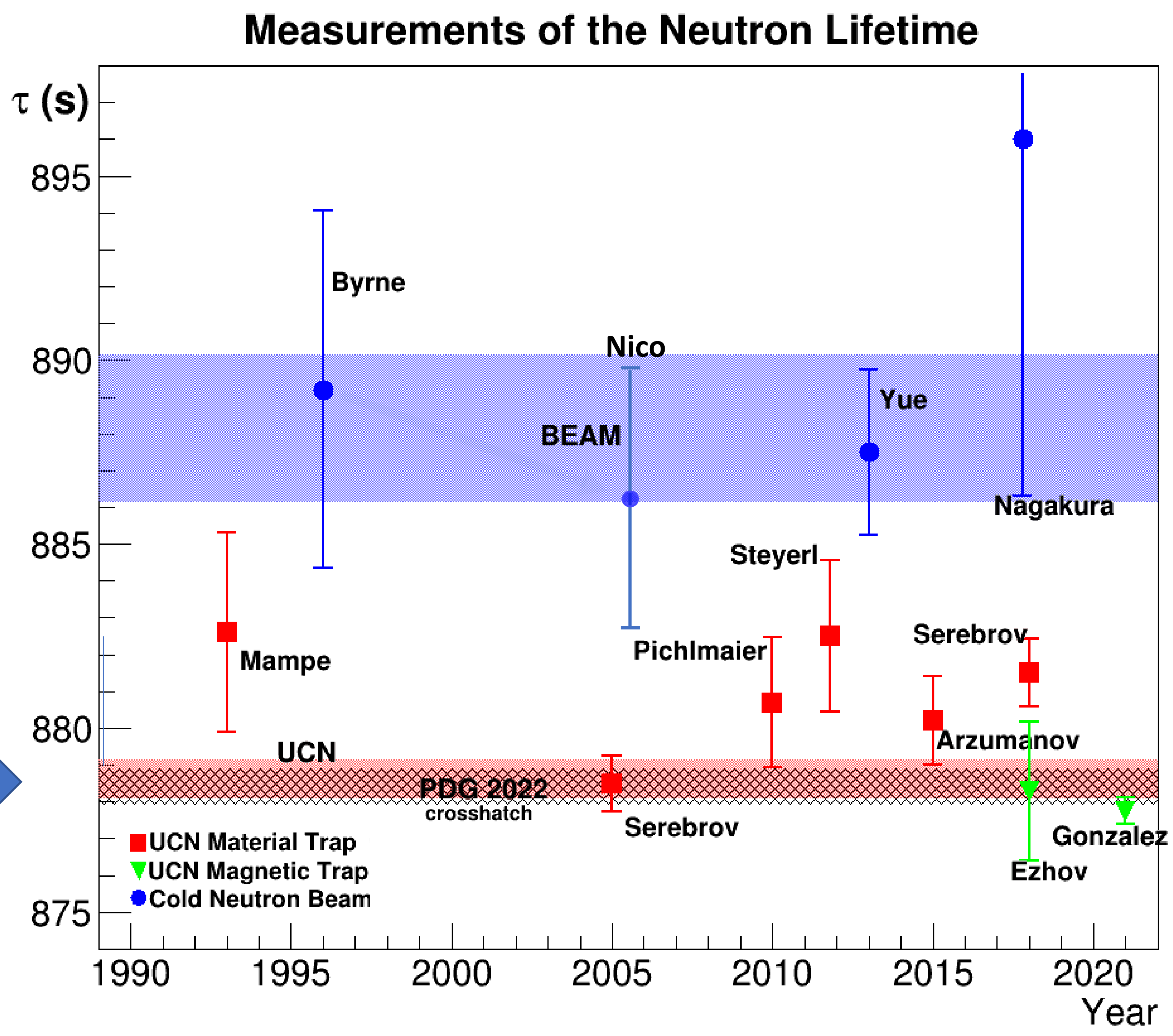
Several UCN experiments re-evaluated losses
A third experiment was finally published

Horizonal arrows:
Refinement of existing expts

Latest/most
Sensitive Results
for all groups

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

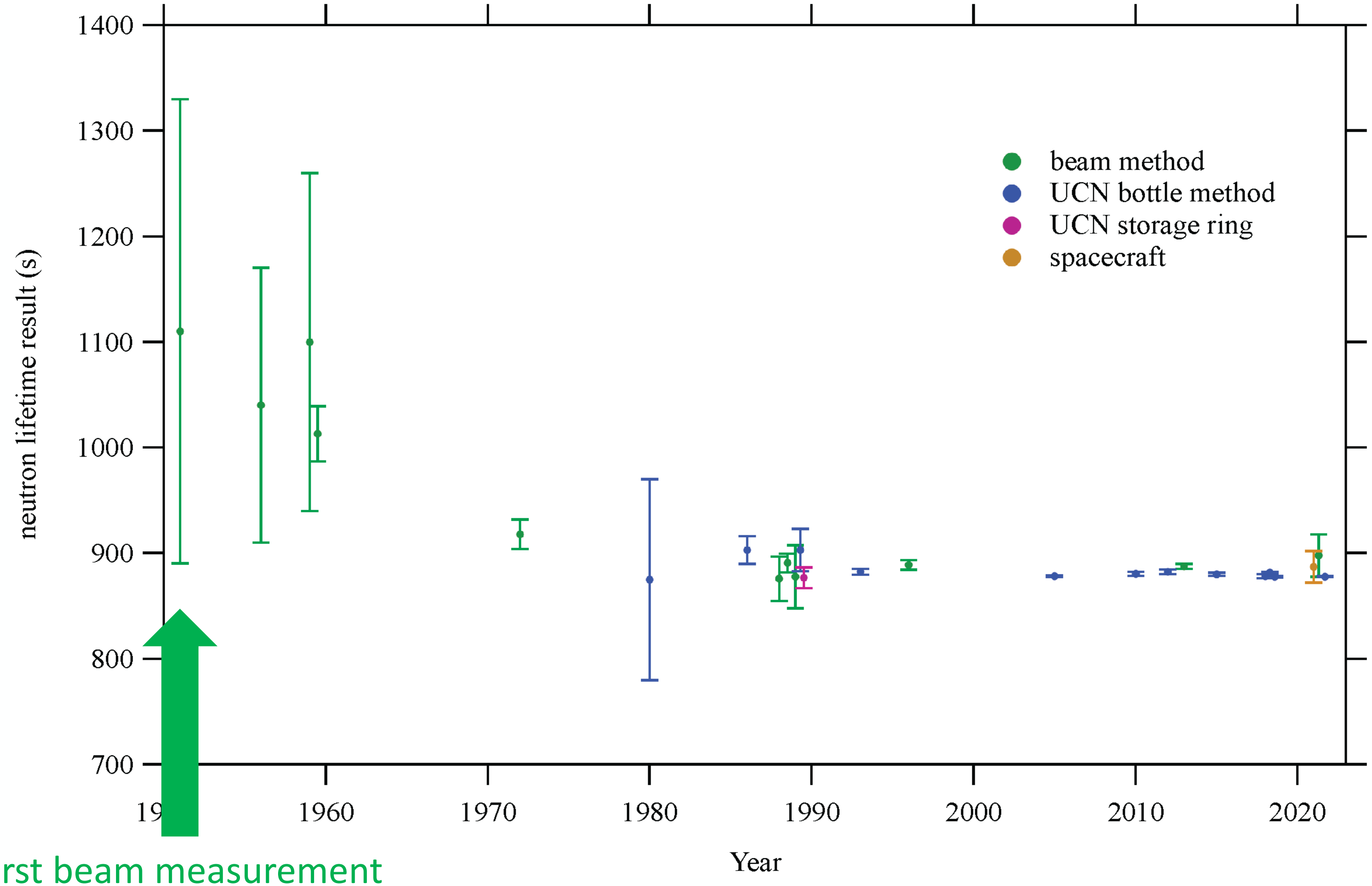
(underestimated
Systematic unc…)



Beam Measurements

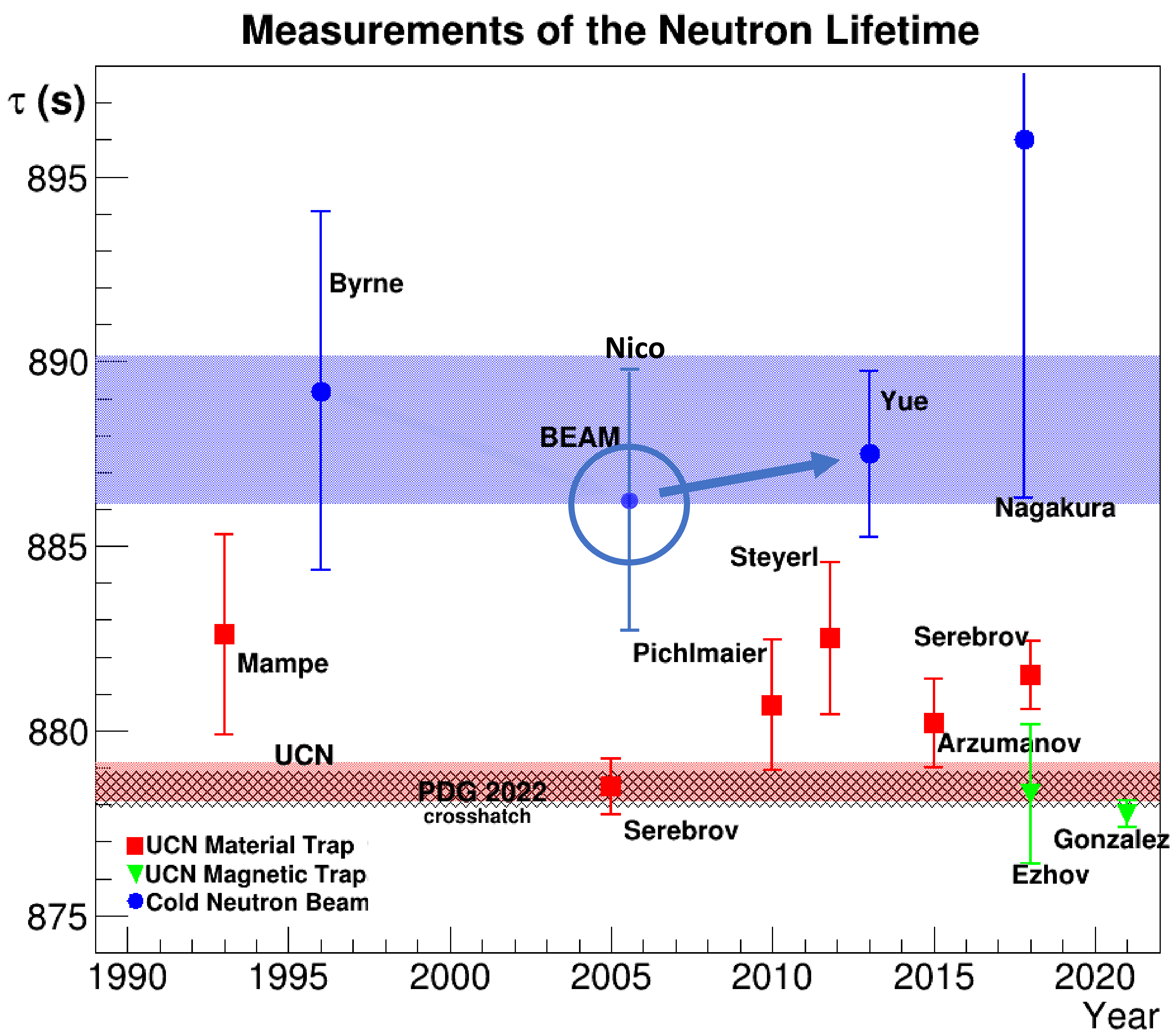
Special thanks to D. Salvat, C.-Y Liu, F. Wietfeldt for slides

Neutron Lifetime Measurements



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

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

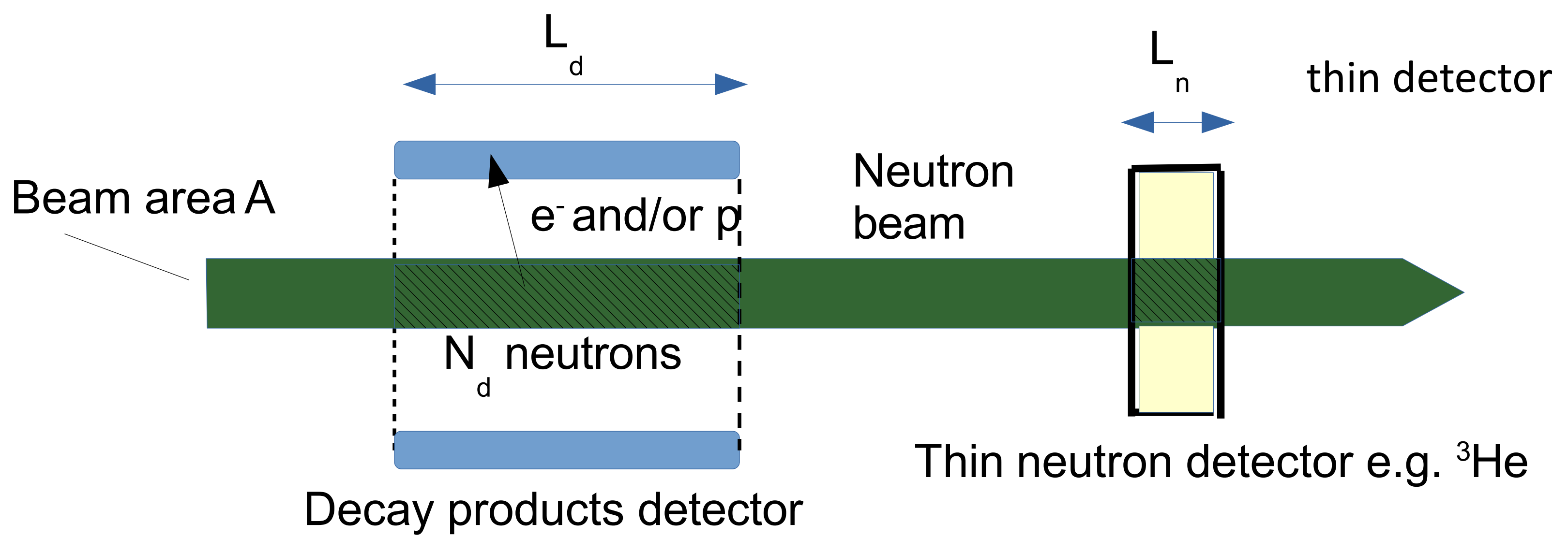

Measurements of the Neutron Lifetime
τ (s)
895
890
885
880
875
1990
1995
2000
2005
2010
2015
2020
Year
Byrne
Nico
BEAM
Yue
Nagakura
Steyerl
Mampe
Pichlmaier
Serebrov
Arzumanov
UCN
PDG 2022
crosshatch
Serebrov
Gonzalez
Ezhov
UCN Material Trap
UCN Magnetic Trap
Cold Neutron Beam

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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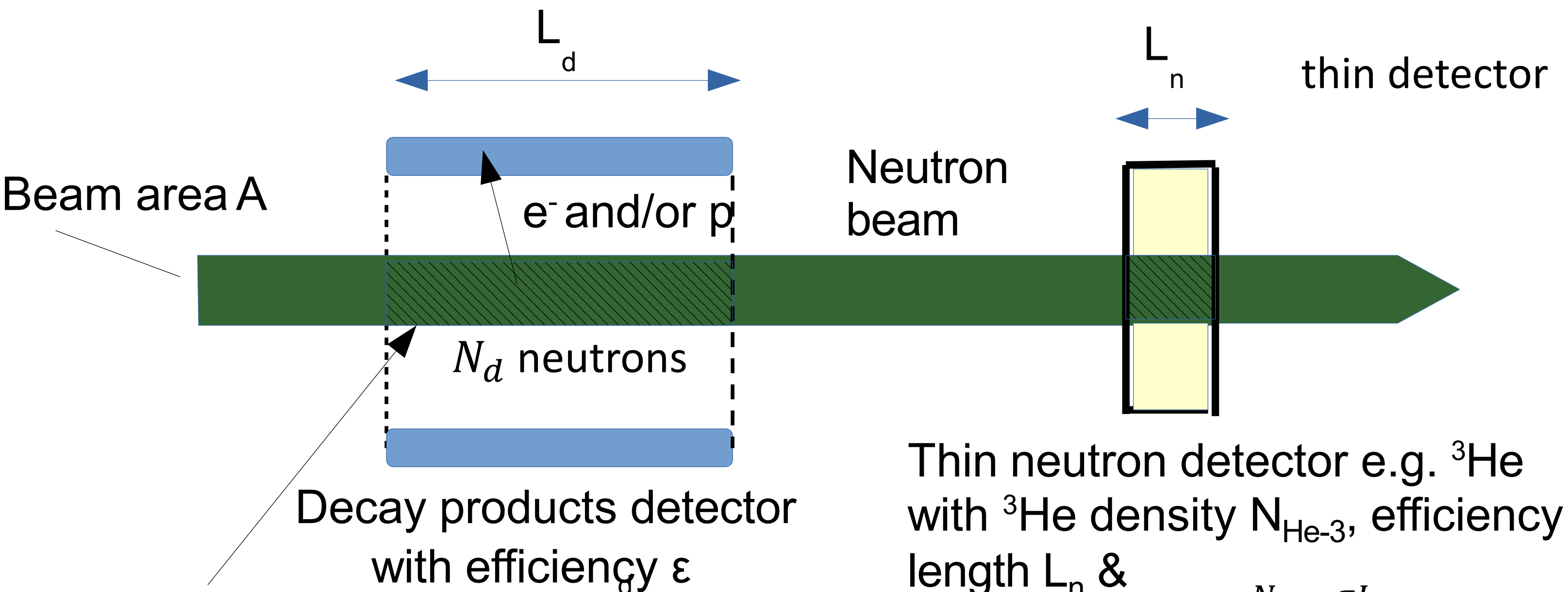


Decay products detector with efficiency ε_d

Thin neutron detector e.g. ^3He with ^3He 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:

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

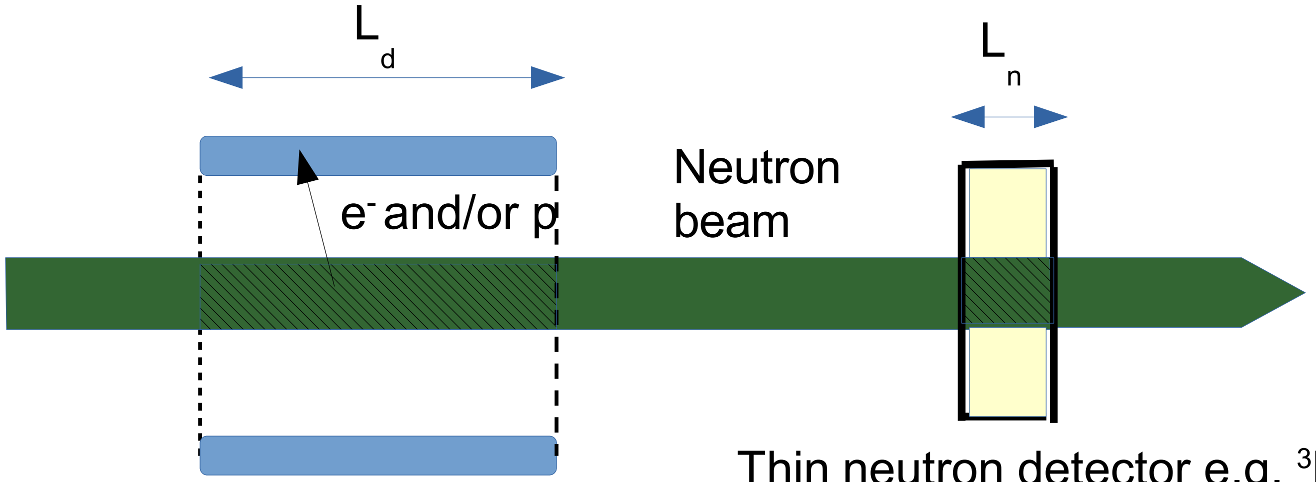
Same 1/v dependence appears in particle detection rate and neutron rate (in one case, we need a density, in the other it arises from the cross-section!)

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 $1/v = \sigma_{th} v_{th}/v$

Neutron beam with cross-sectional area A



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

Use measured rates to solve for τ

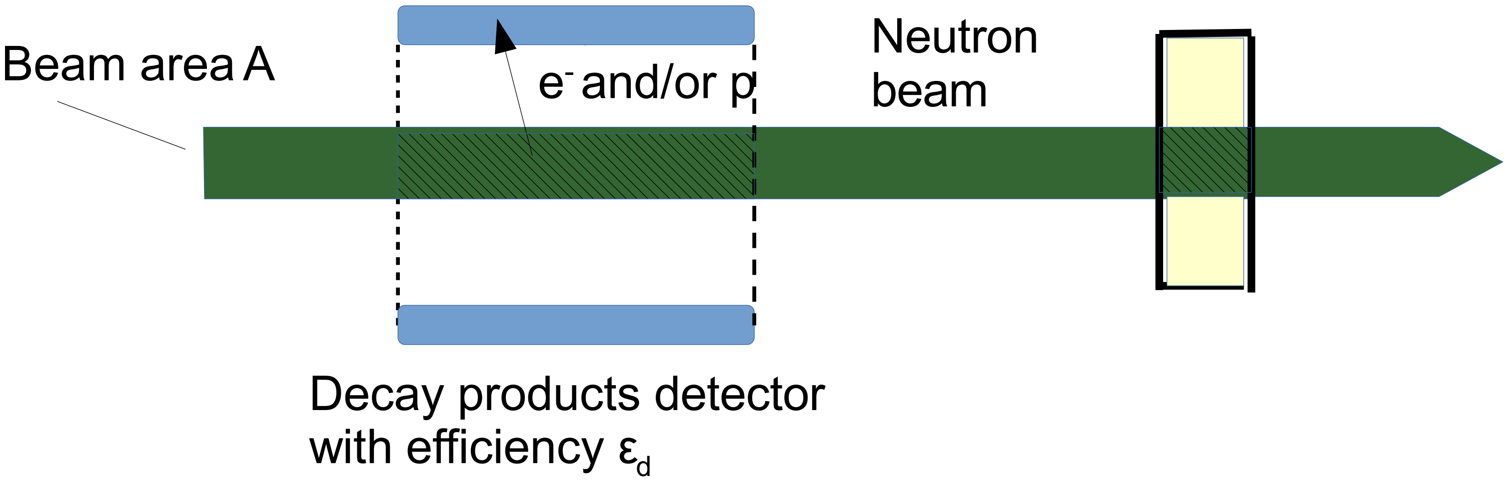
$$\frac{S_d/\varepsilon_d}{S_n/\varepsilon_n} = \frac{(\Phi/v)AL_d}{(\Phi/v)AL_n\sigma_{th}v_{th}}\,\frac{1}{\tau} \quad\Rightarrow\quad \tau = \frac{S_n\varepsilon_d\, L_d}{S_d\varepsilon_n L_n\sigma_{th}v_{th}}$$

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

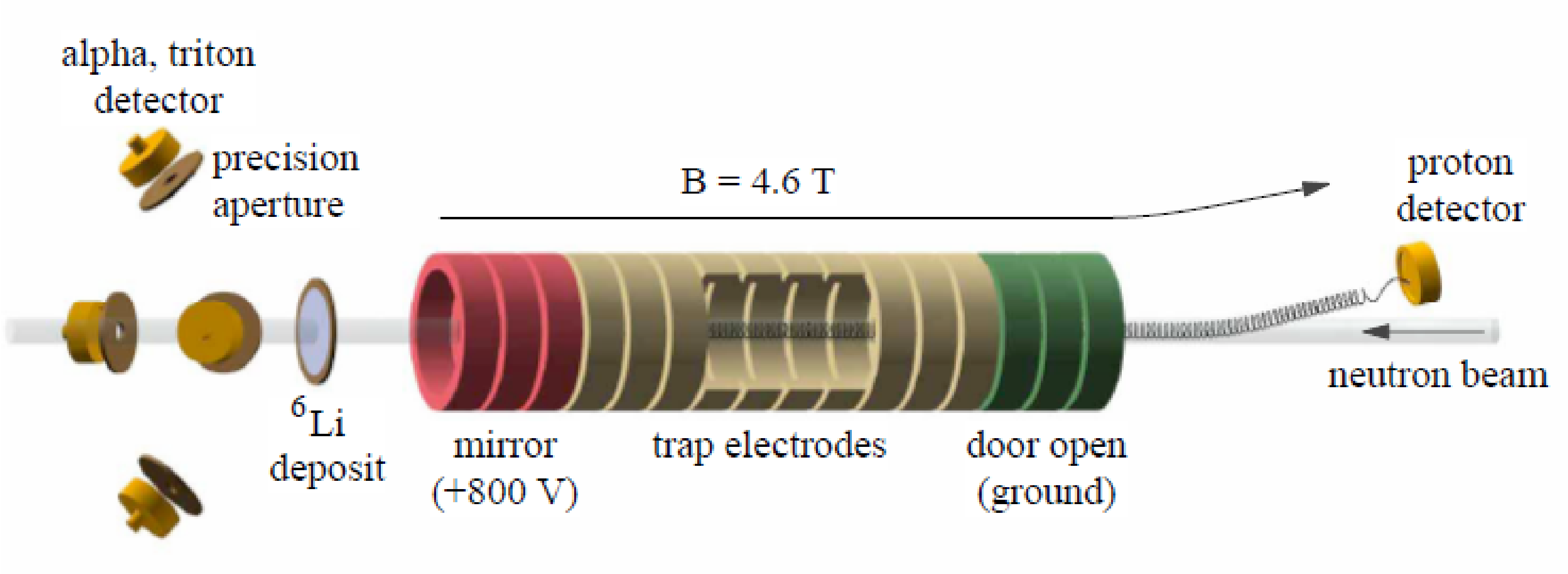
(2) neutron detector cross section proportional to $1/v = \sigma_{th} v_{th}/v$



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

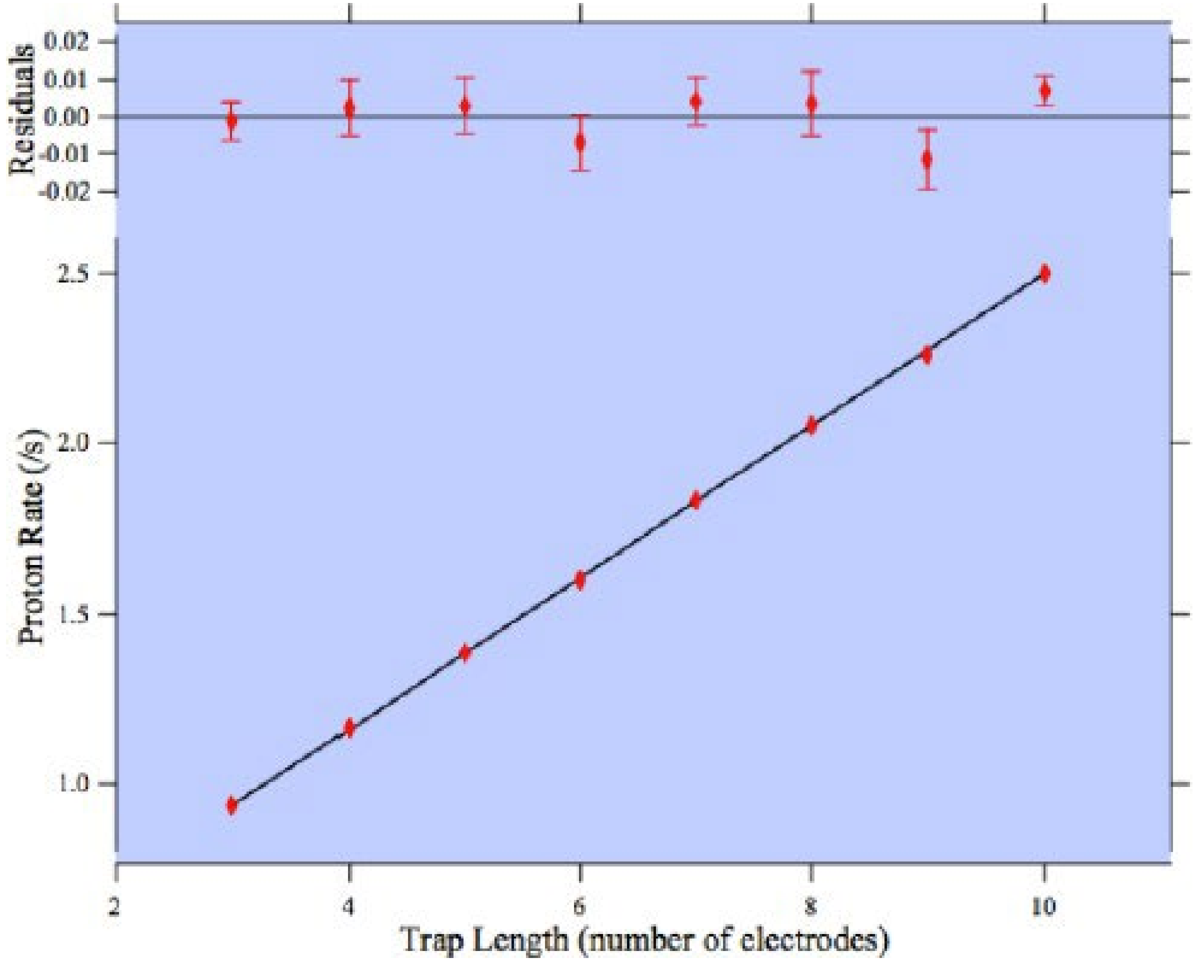
So...with knowledge of absolute efficiencies, the length of the decay and neutron detection regions, and the neutron absorption cross-section, you can determine the neutron beta decay lifetime!

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+^{6}Li$\rightarrow$ ^{3}He+α

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



Vary trap length to characterize edge effects

NIST Lifetime (pre-BL1)

30 years of experience developing the CN beam lifetime method utilizing the incredible metrology capability at NIST

1. physical dimensions of trap determined at micron level
2. mass and physical dimensions of Li absorber characterized to parts per 10^4
3. proton backscattering determined from experimental data to parts per 10^4

Systematic uncertainty of 3.2 s was **dominated by neutron counting efficiency–** limited by uncertainty in ^{6}Li cross section

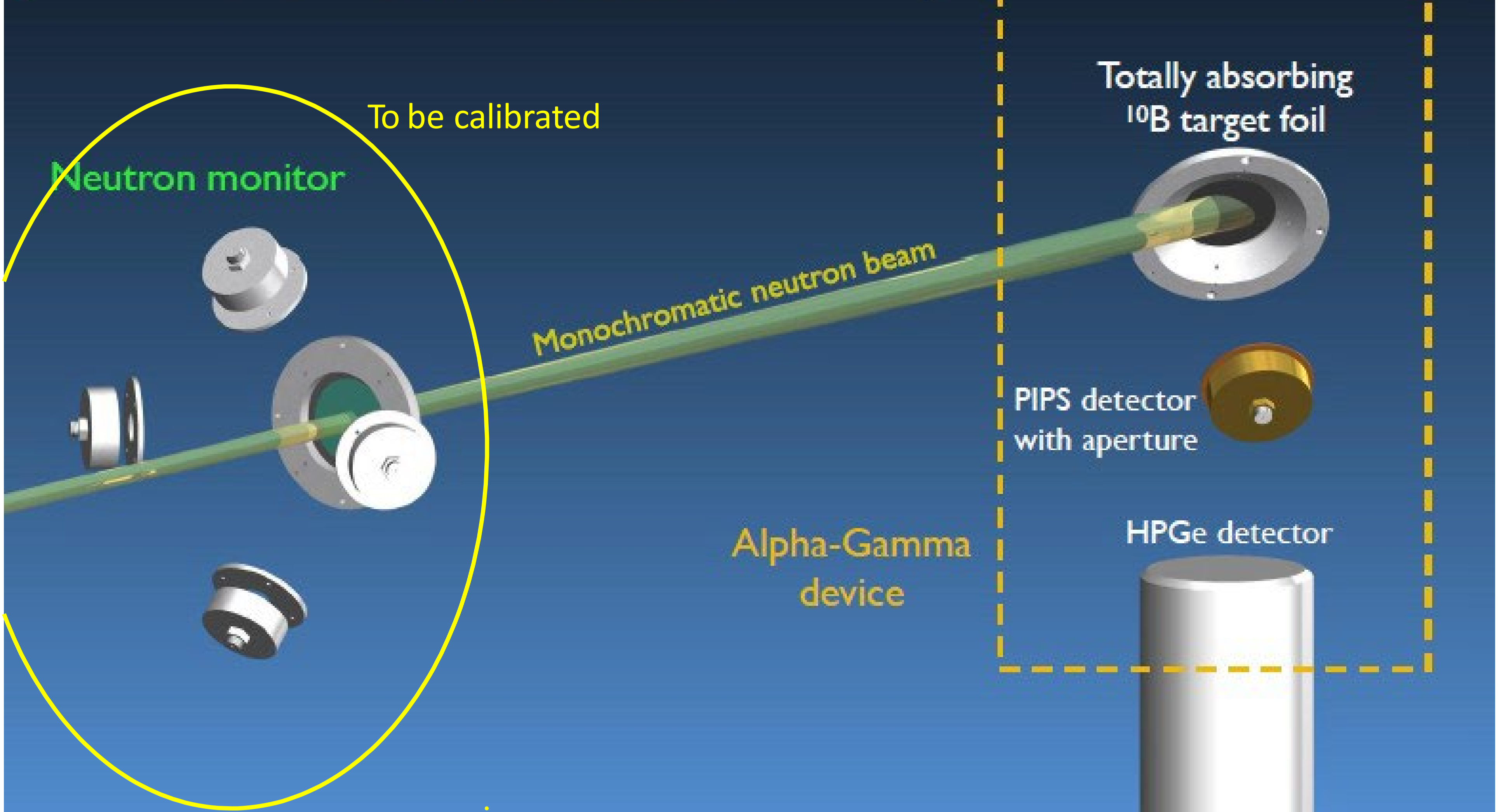
$$\tau = 886.3(1.2)_{stat}(3.2)_{sys}$$

Nico *et al.*, Phys. Rev. C **71**, 055502 (2005)

The Alpha-Gamma device

Andrew Yue, UT Ph.D. thesis (2013), Advisor: Geoff Greene

R_n determined by absolute γ counting from $^{10}B(n,\gamma)^{7}Li$ reaction

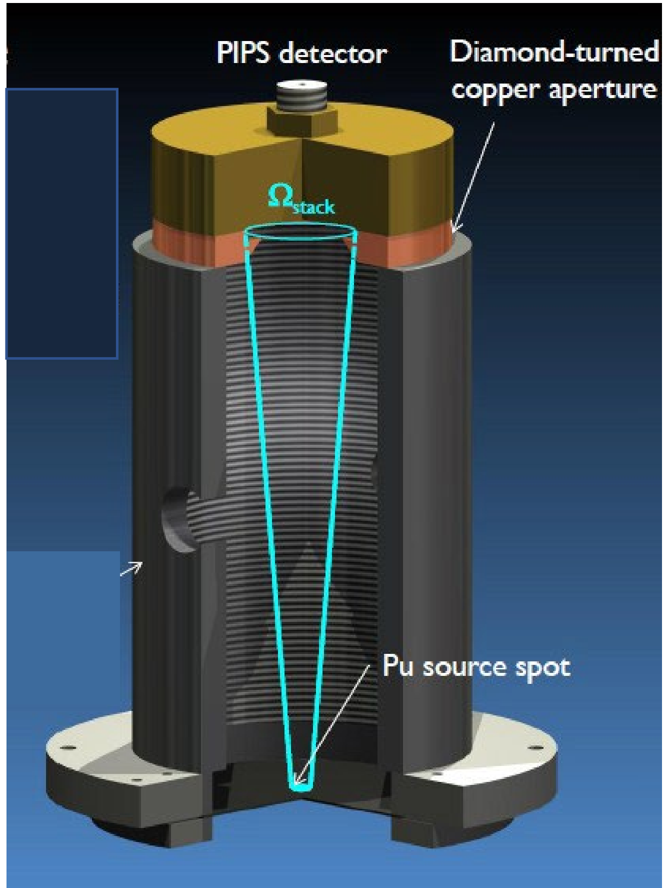


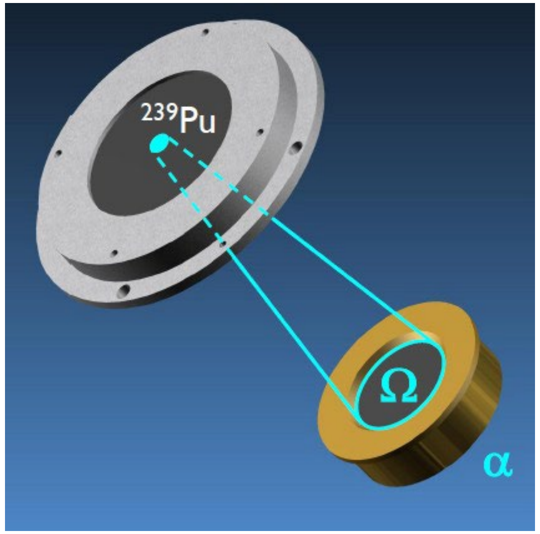
1 Measure the absolute activity of an alpha source

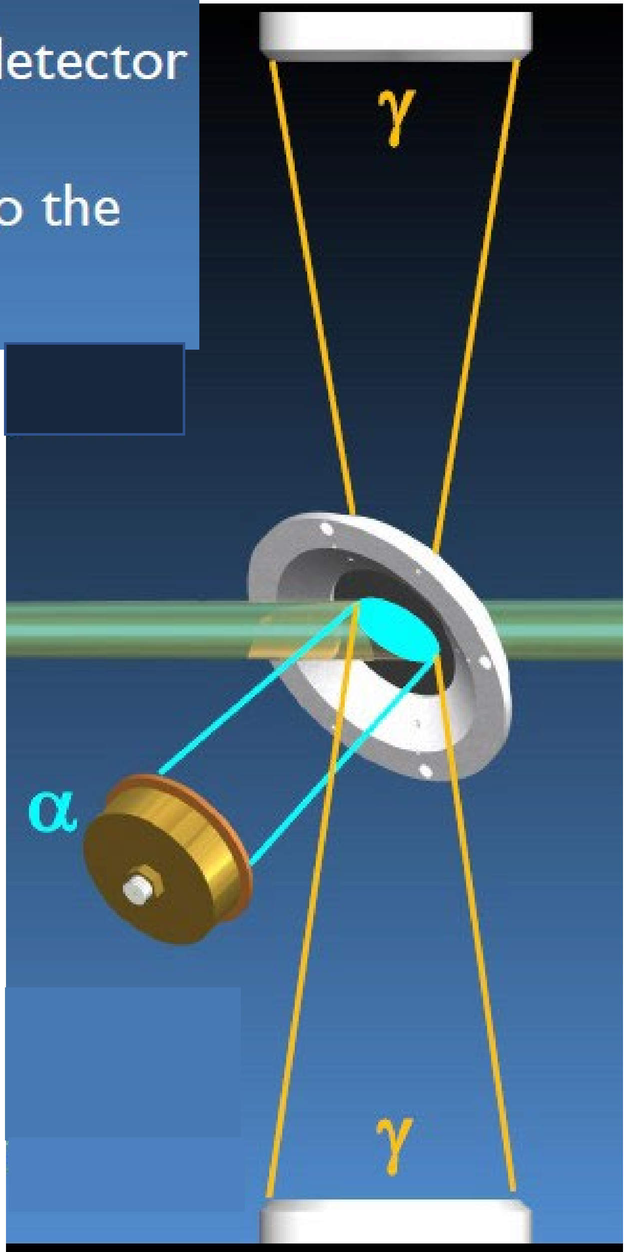
This is only absolute efficiency required

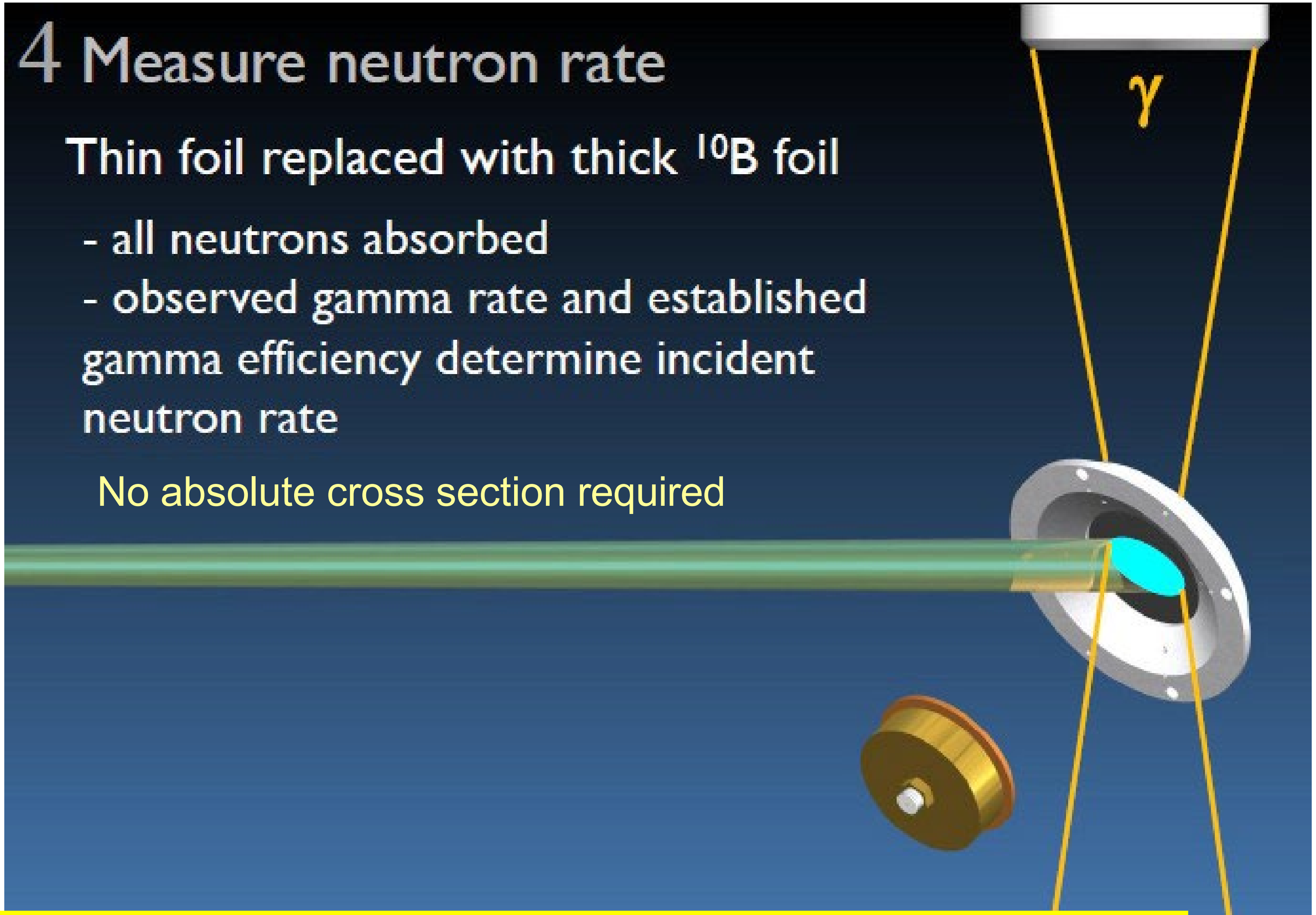
2 Use this source to determine solid angle of alpha detector

3 Use an (n,αγ) reaction to transfer the calibration to the gamma detectors









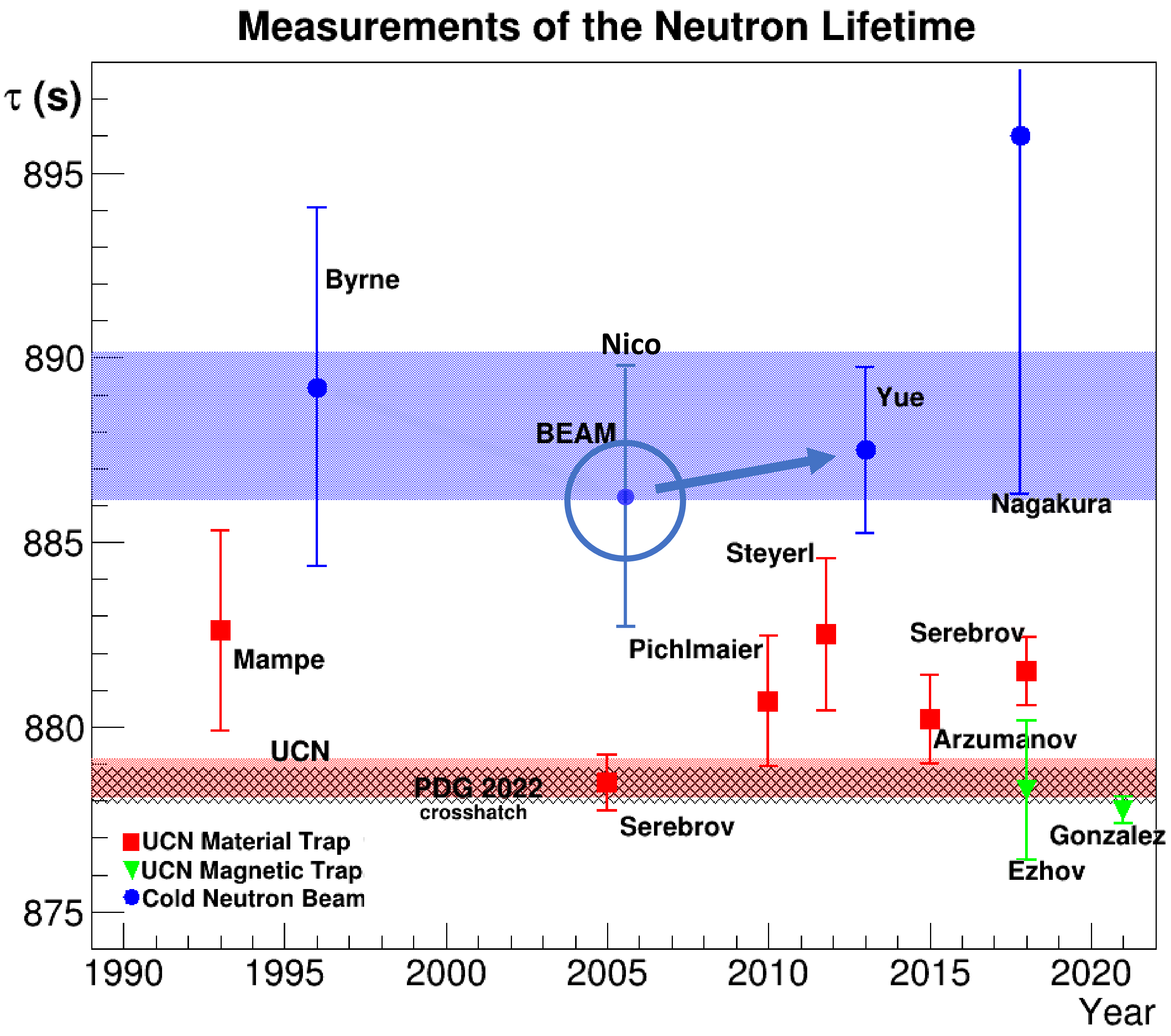
886.3 ± 1.2 [stat] ± 3.4 [sys] seconds   Nico et al 2005

887.7 ± 1.2 [stat] ± 1.9 [sys] seconds   Yue et al 2013

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

Information provided by N. Fomin



Conclusion:
Decay rate from
beam experiment
1% slower!

Why the Kerfuffle?

- NIST experiment has been continuously refined for roughly 30 years – not a "one"-off
- Serebrov's measurement drove a re-assessment of effectively all storage experiments (material storage expt at that time) leading to a new consensus among those experiments
- The magnitude of the discrepancy suggests it is not "just" statistics. There is very likely a real problem either with the systematic error budget(s) or the standard model (although the precedent of the "kaon miracle" suggests caution in drawing conclusions about the SM)
- The value neutron lifetime is important!

The Path Forward (since 2013):

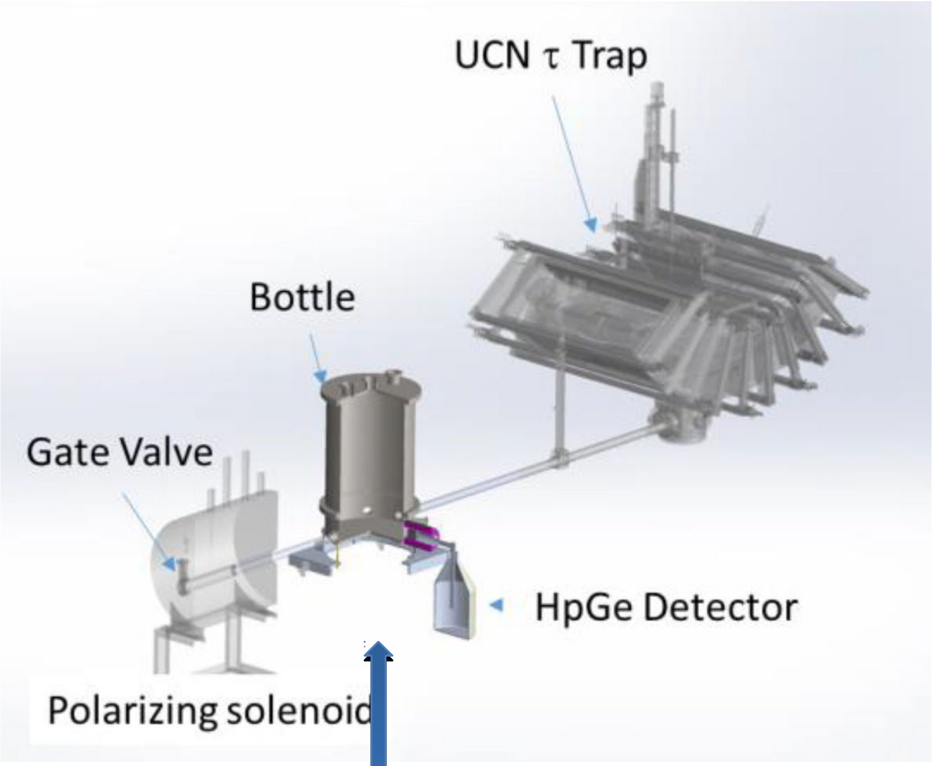
- Explore possible indications of **new** (BSM) physics
  - Is the total neutron decay rate greater than the beta decay rate?

    Decay to Dark Particles & UCNProβe
  - Is the neutron oscillating to a state which is not observable in the beam expts?

    Neutron-mirror neutron (N-N') oscillations

Decay into Dark Particles?

Fornal & Grinstein, Phys. Rev. Lett. 120, 191801 (2018)

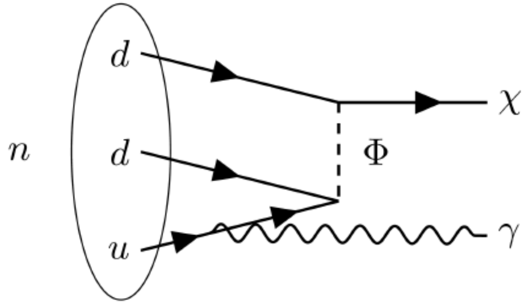


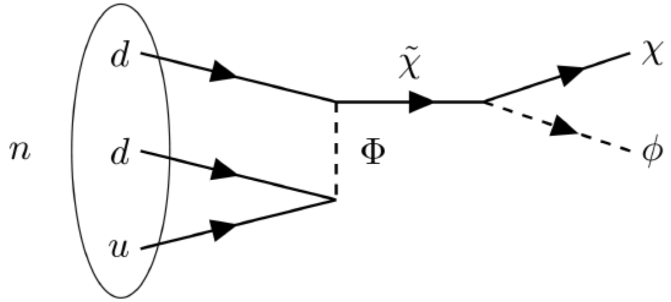
$$(A)\ n \to \chi\gamma$$
$$(B)\ n \to \chi e^+e^-$$
$$(C)\ n \to \chi\phi$$

0.782 < γ < 1.664 MeV

BR ~ 1% to explain issue

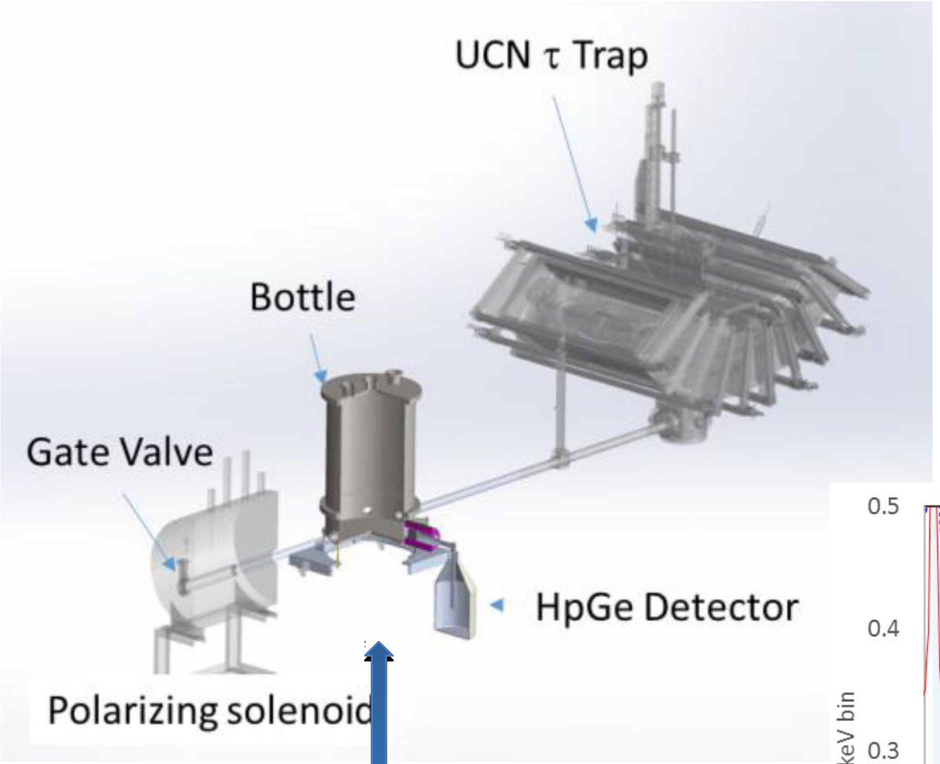
A buffer volume installed (2018) to smooth out the pulse response for more stable normalization.





Decay into dark matter?

Fornal & Grinstein,
Phys. Rev. Lett. 120,
191801 (2018)

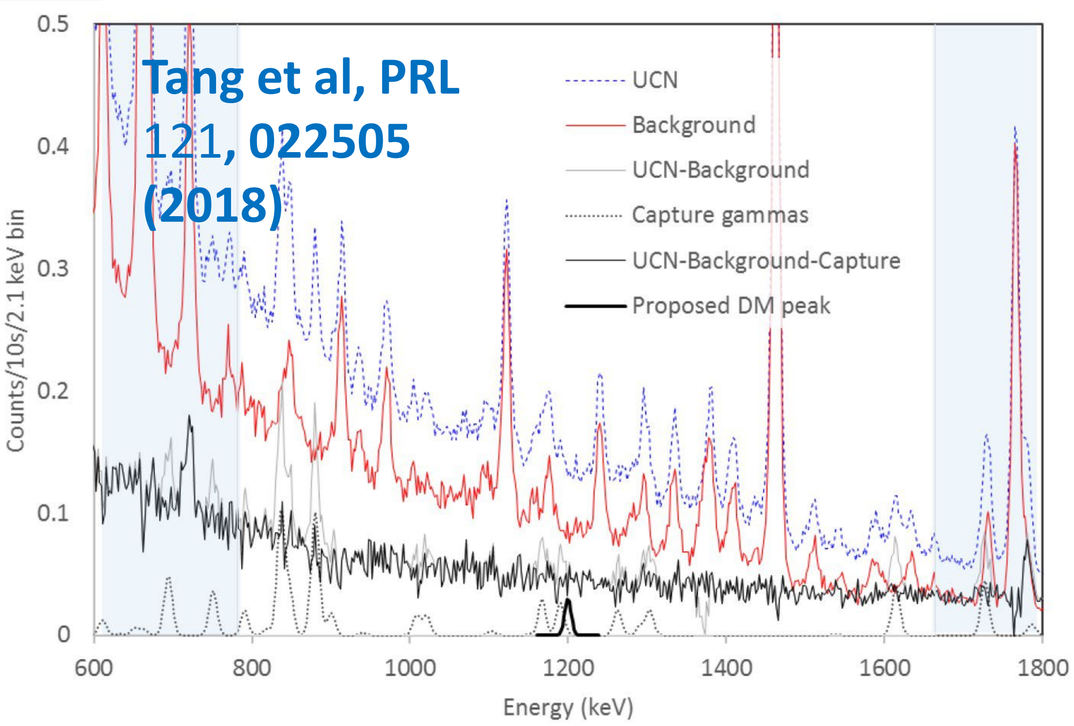


(A) $n \to \chi\gamma$ — Tang et al, PRL **121**, 022505 (2018)

(B) $n \to \chi e^+e^-$ — Sun et al, PRC **97**, 052501 (2018)
Saul et al., ArXiv:1911.01766 (2019)

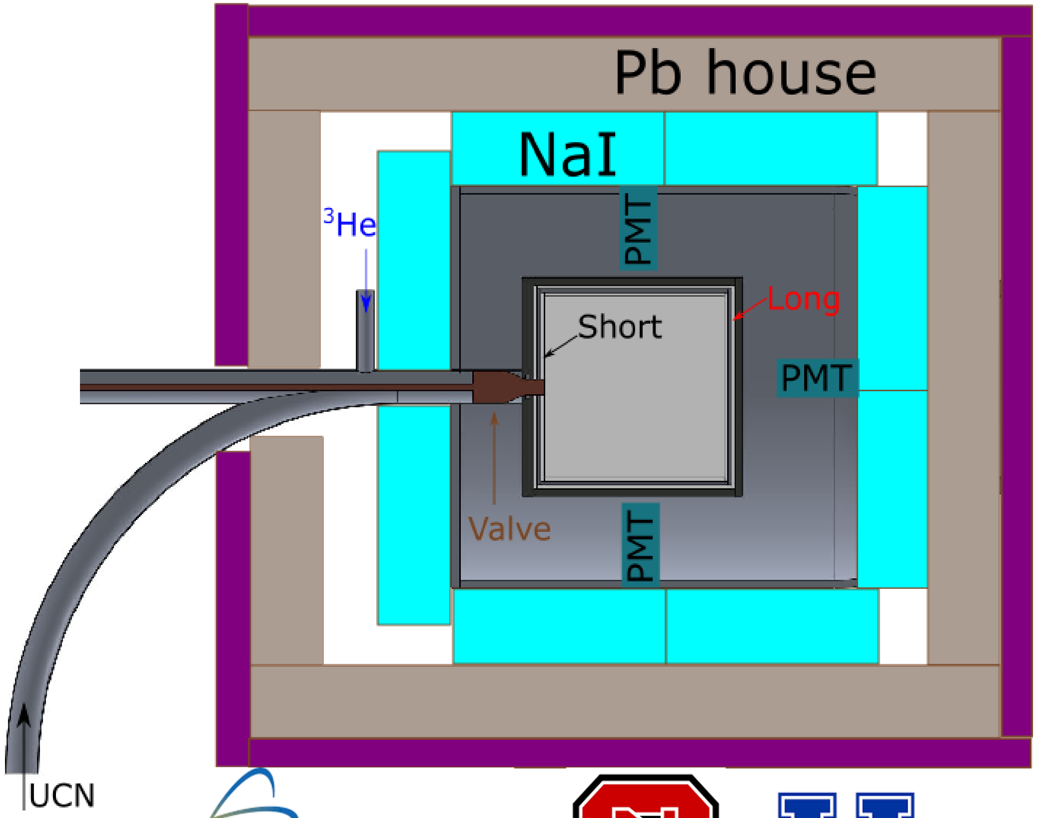
(C) $n \to \chi\phi$ — Nuclear decays

A buffer volume installed (2018) to smooth out the pulse response for more stable normalization.



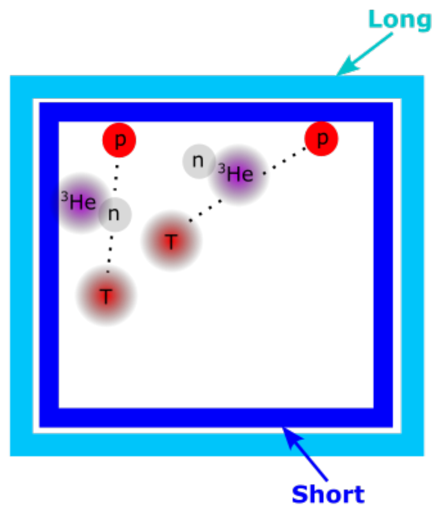
UCNProbe is a new "beam" method experiment using UCN

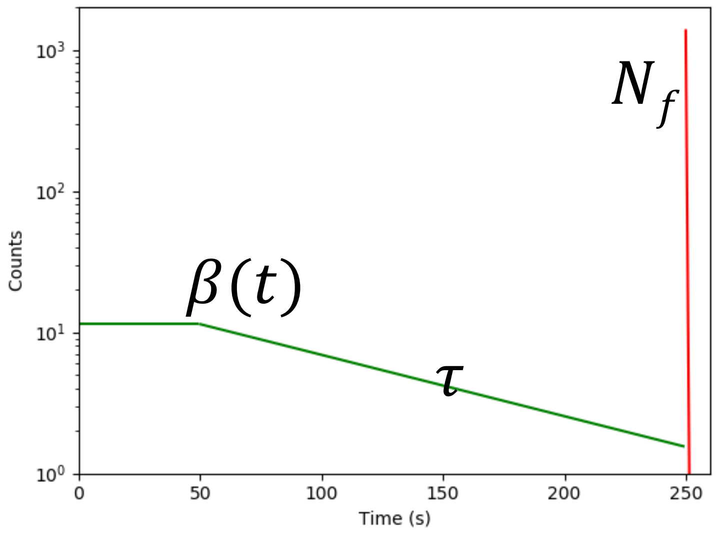
- **Goal is to measure τ_β using UCN with a total error of 1-2 seconds with totally different systematic effects compared to past "beam" experiments.**
- Requires absolute measurements of two quantities to 0.1%
    - Number of neutrons in the trap
    - Number of neutrons that decayed (measurement of charged particles)
- The collaboration is completing prototype detector this year
- Plans to start commissioning run with UCN in 2025.
- 4 weeks real time of data taking for 0.14% statistics.
- Funded by DOE early career award (2023-2027), previously funded by LANL LDRD-ER (2019-2022)



Two-layer scintillator box allows for further reduction in background

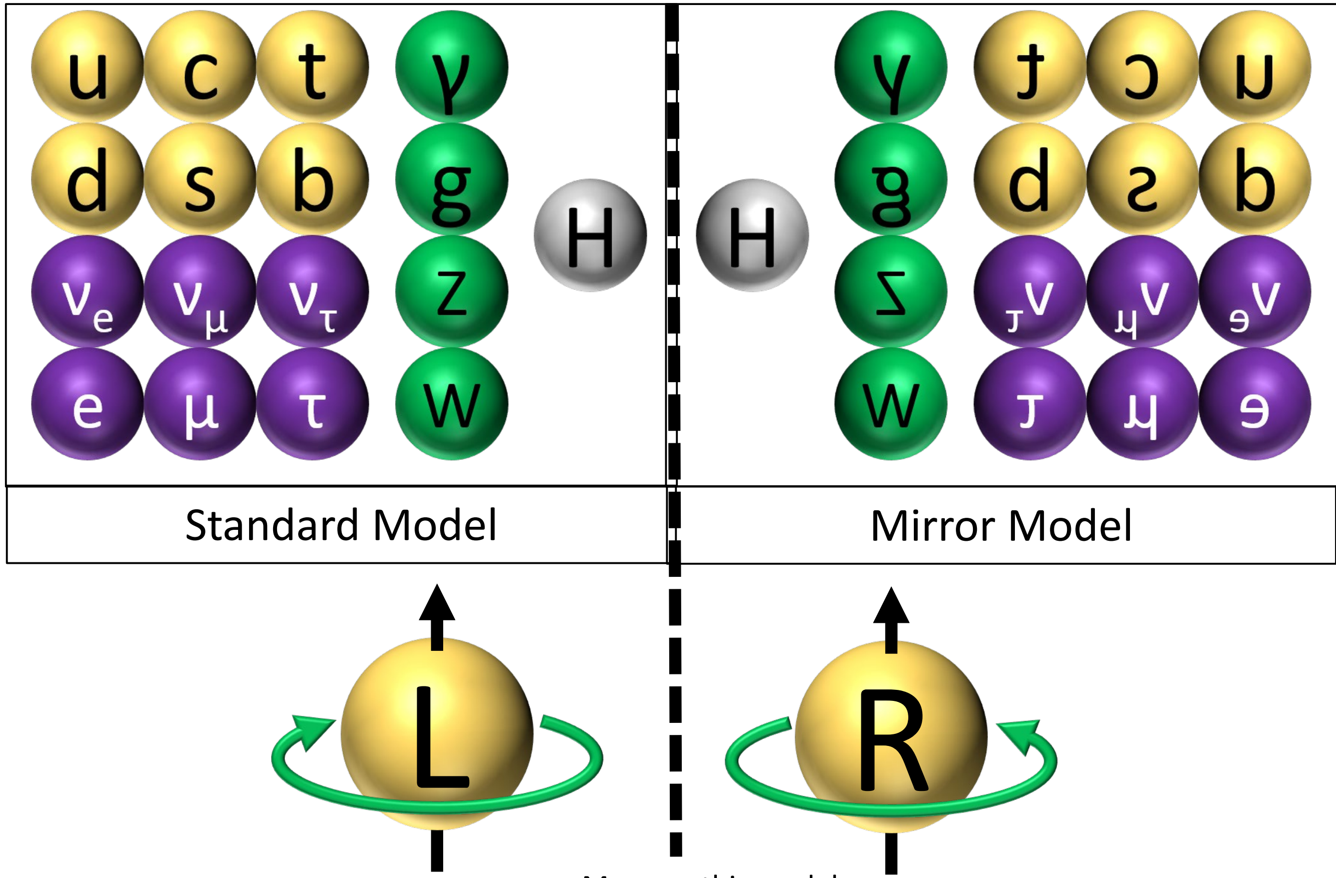
- Using deuterated polystyrene as both a UCN trap and as the in-situ detector, Fermi potential measured at 168 neV.
- Light collection
  - Using 4 PMTs to collect light from scintillator boxes
  - Vacuum chamber lined with Teflon for diffusive light reflection (>95%)
  - Outer layer of scintillator has a long decay time so that background and data can be collected separately
- Using electrons for charged particle detection.
- Neutron detection using ^3He gas, n + ^3He = p + T+ 764 keV.
- Detector efficiencies will be determined using gamma tagged source (^{134}Cs and ^{210m}Bi)
- Extraction of $\frac{1}{\tau_\beta} = \frac{\beta(t)}{N(t)}$ using $N(t) = N_f e^{(t_f - t)/\tau}$





Standard Model Extension: Mirror Matter

- Introduce a new hidden sector SM copy
  - Restore global parity with right-handed weak interactions
  - Mirror composite particles (p', n')
  - Interaction through gravity
- Normal and Mirror Model mixing
  - $i\frac{d}{dt}|\Psi(t)\rangle = \begin{pmatrix} \Delta E(\Delta m, B, B', V) & \epsilon_{nn'} \\ \epsilon_{nn'} & 0 \end{pmatrix} |\Psi(t)\rangle$
    - Δm from different Higgs VEV
- In lab can control fields (B) and materials (V)
  - Look for resonance at $\Delta E = 0$

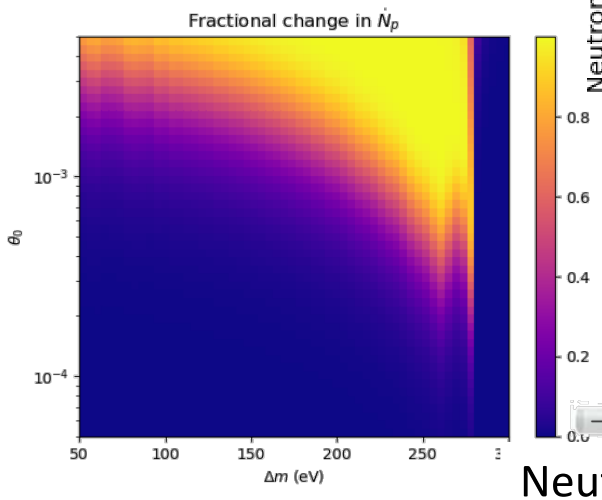


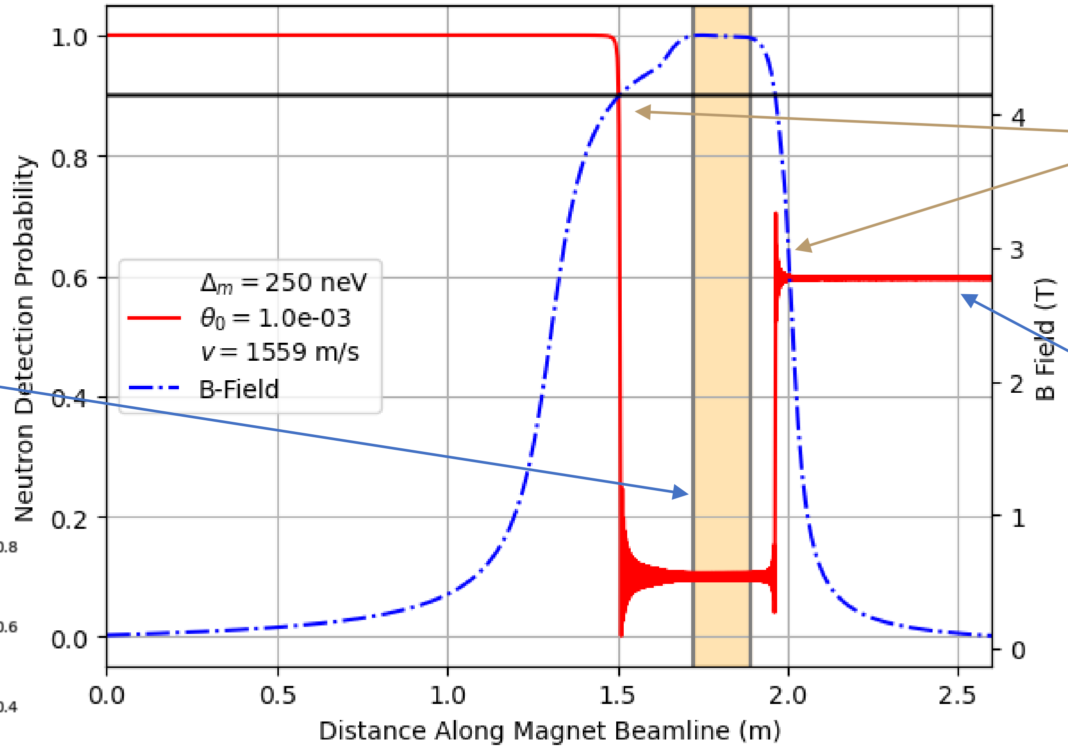
More on this model:
- Berezhiani, Z., and Bento, L., PRL 96 081801 (2006)

$n \rightarrow n'$ in the Beam Lifetime

$$\tau_{meas} = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

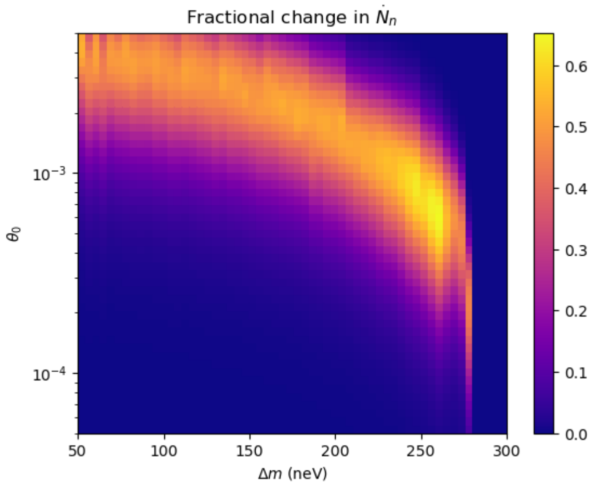
p^+ counted in this region

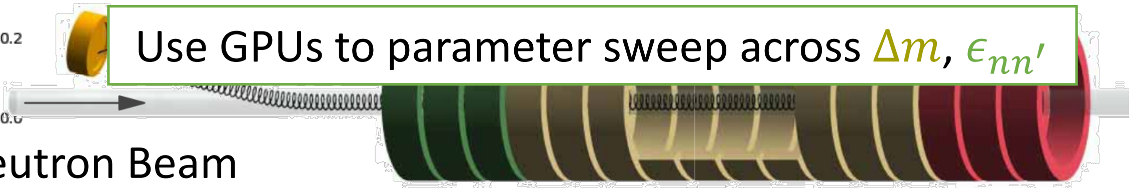




Landau-Zener Transitions when $\Delta\text{E} = 0$

n counted after magnet



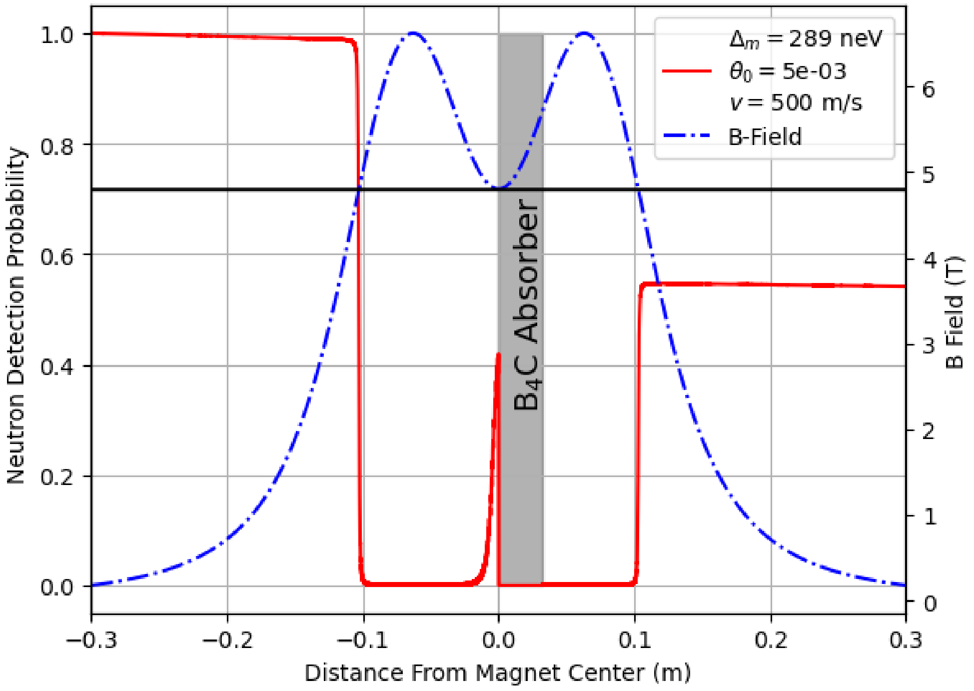


Use GPUs to parameter sweep across Δm, $\epsilon_{nn'}$

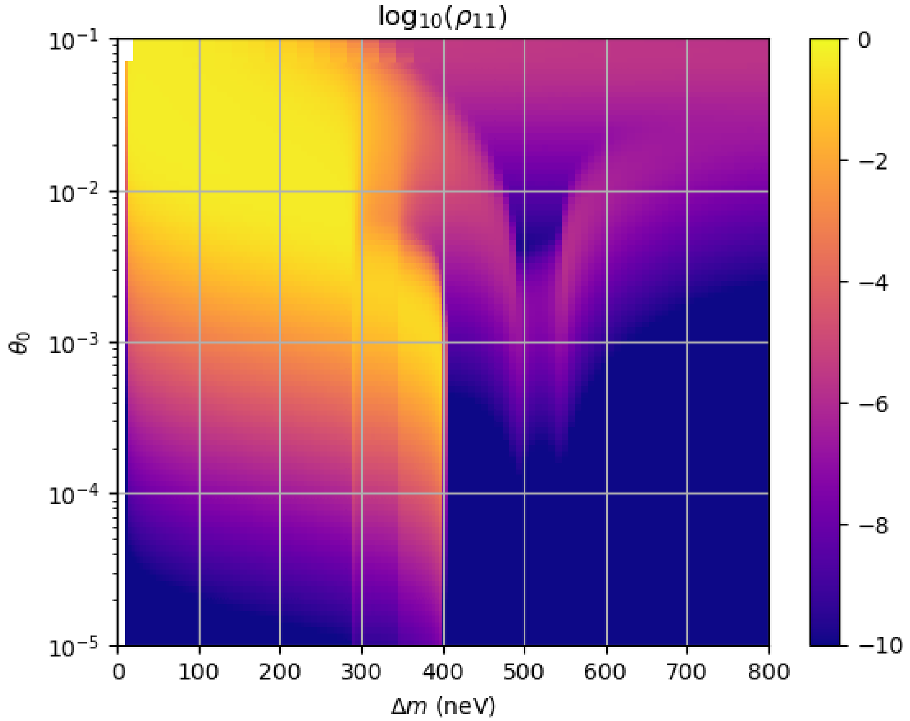
Neutron Beam

Searching for $n \to n'$ at ORNL

- Double solenoid with B_4C absorber inside
  - Absorber blocks transmission of n
  - Doesn't block n'!



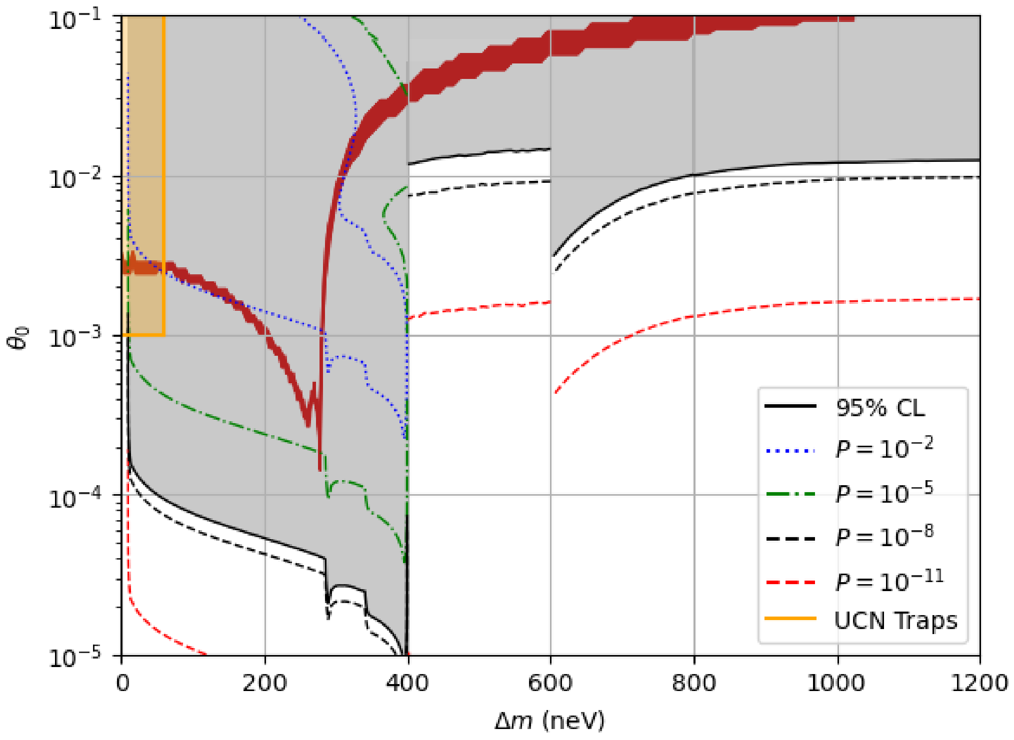
- Calculate the probability of n':
  - Use GPU codes to parameter sweep Δm and θ
  - Exclude regions without enough transmission



Does $n \to n'$ Explain the Neutron Lifetime Discrepancy?

NO!

- No counts observed above background!
  - No transmission $< 2.5 \times 10^{-8}$ (95% CL)
  - Excludes gray parameter space
- Difference between Beam Lifetime and τ_n (red band)
- Mirror neutrons do NOT explain the lifetime shift
  - [Broussard, L.J. *et al.* Phys. Rev. Lett. 128, 212503 (2022).]



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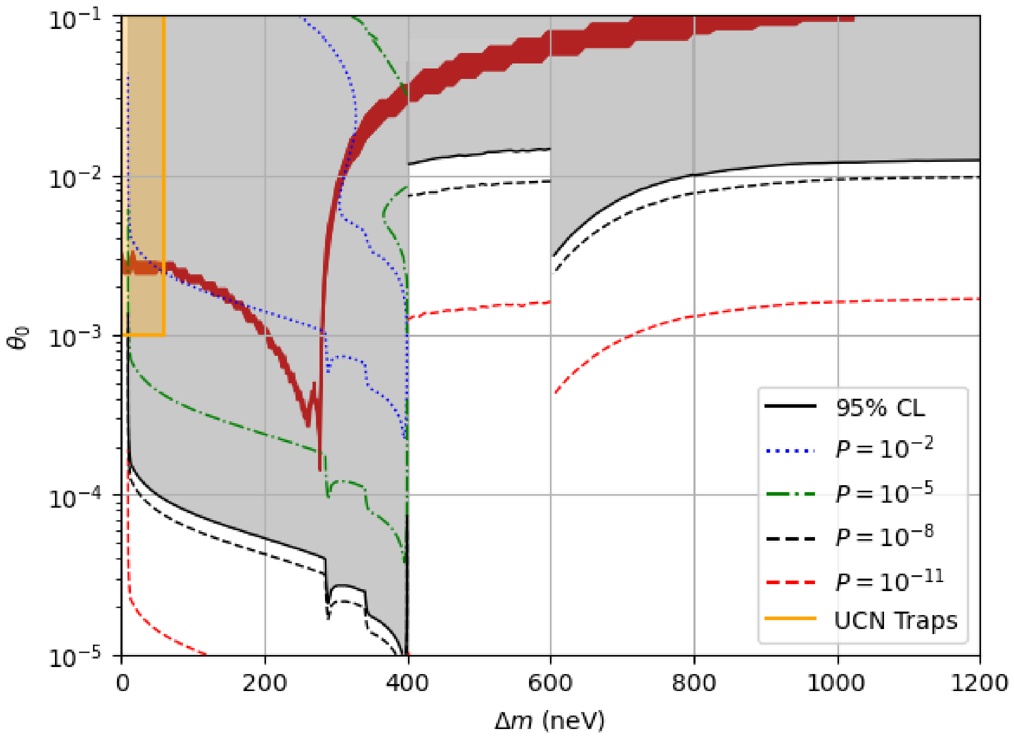

$n \to n'$ Collaboration

V. Santoro European Spallation Source

K. Bailey, W.B. Bailey, K. Berry, L. Broussard, L. DeBeer-Schmitt, M. Frost, A. Galindo-Uribarri, F. Gallmeier, F. Gonzalez, E. Iverson, S. Penttila, A. Saunders Oak Ridge National Laboratory

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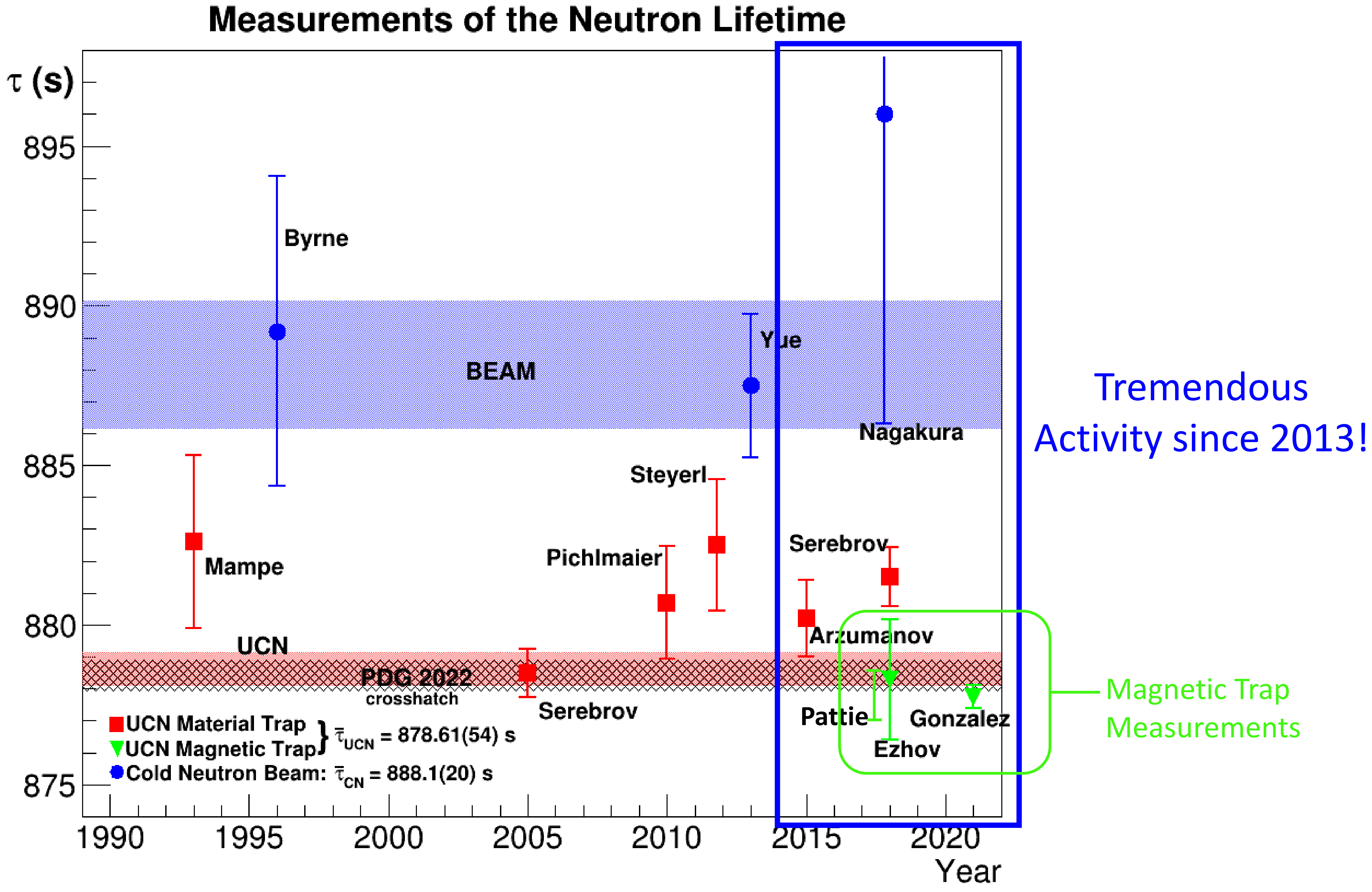
We gratefully acknowledge the LDRD program of ORNL, the DOE OS NP, and the NSF

The Path Forward (since 2013):

- Explore possible indications of **new** (BSM) physics
  - Decay to Dark Particles & UCNProβe
  - Neutron-mirror neutron (N-N’) oscillations
- **Confirm** beam and storage measurement results
  - Develop experiments with alternative measurement techniques
  - Improve control of the sources of systematic uncertainty on existing techniques



$\Delta\tau = 9.6 \pm 2.1$ s

4.6 σ

Beam Experiments: NIST BL2, BL3 and the J-PARC lifetime expt

Systematic Effects for the NIST Beam Lifetime (BL) Experiments

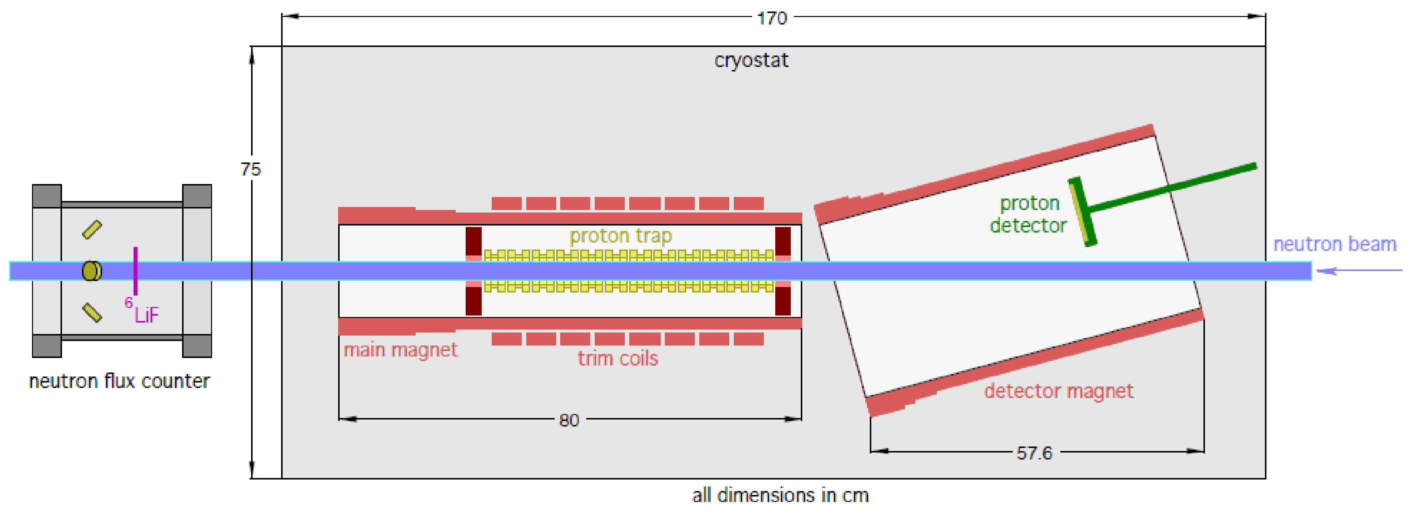
Source of uncertainty	2013 BL1 [s]	BL2 projected [s]	BL3 projected [s]
Neutron flux monitor efficiency	0.5	0.5	0.2
Absorption of neutrons by ^{6}Li	0.9	0.1	< 0.1
Neutron beam profile and detector solid angle	0.1	0.1	< 0.1
Neutron beam profile and ^{6}Li deposit shape	0.1	0.1	< 0.1
Neutron beam halo	1.0	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

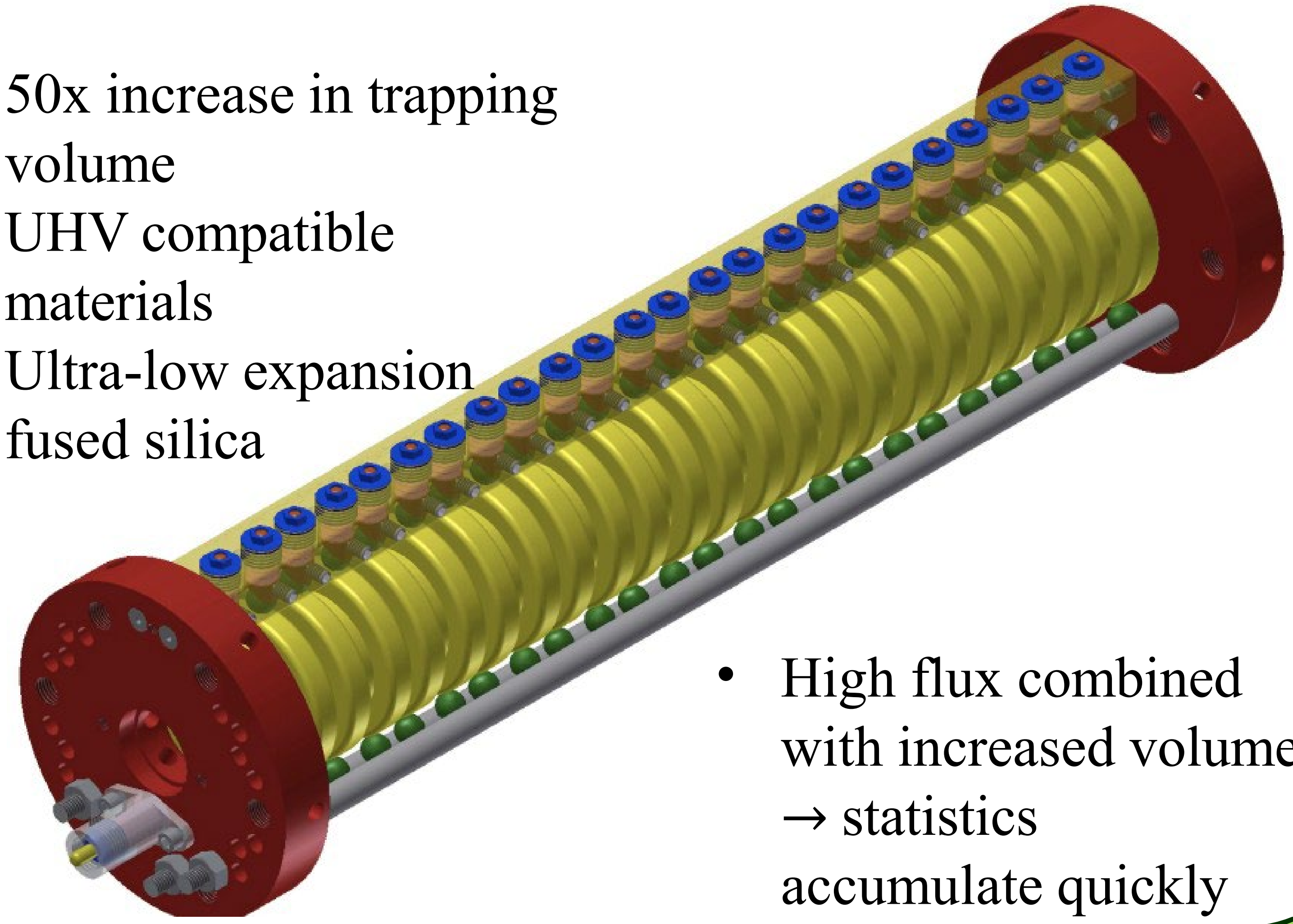
BL3: Bigger!

- 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
- 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!

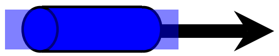
Principle of J-PARC Beam Lifetime experiment

Cold neutrons are injected into a TPC.
The neutron β-decay and the $^3He(n,p)^3H$ reaction are measured simultaneously.

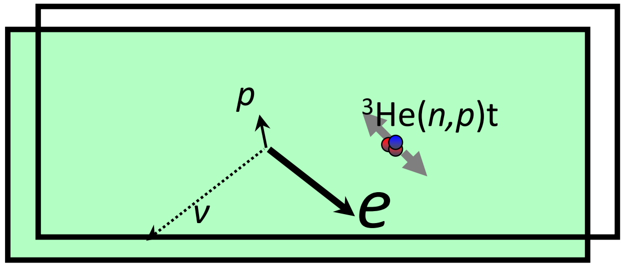
Experiment contact:
Kenji Mishima

Principle （Kossakowski,1989）

Neutron bunch
shorter than TPC



Count events during time of
bunch in the TPC



Neutron bunch

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta}\right)$$

β-decay $S_\beta = \epsilon_e N \frac{L}{\tau_n v}$

$^3He(n,p)^3H$ $S_n = \epsilon_n N \rho \sigma L$

τ_n : lifetime of neutron
v : velocity of neutron
ε_e : detection efficiency of electron

ε_n : detection efficiency of ^3He reaction
ρ : density of ^3He
σ : cross section of ^3He reaction

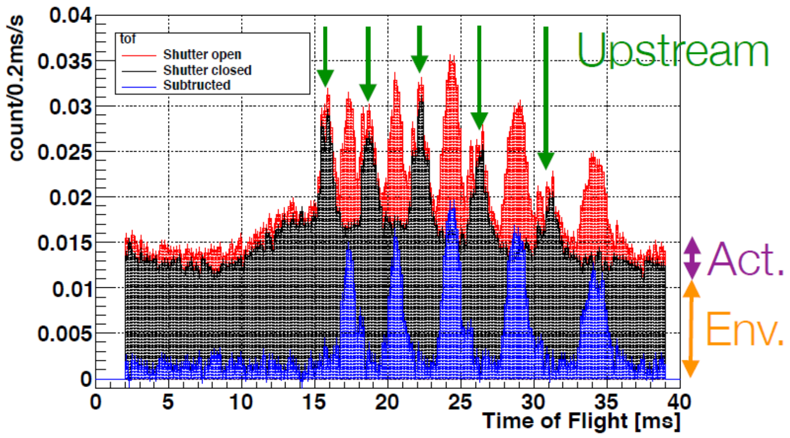
$$\sigma v = \sigma_0 v_0$$

σ_0=cross section@v_0, v_0=2200[m/s]

This method is free from the uncertainties due to external flux monitor, wall loss, depolarization, etc.

The goal is the experiment is accuracy of 1 sec.

Background against beta decay

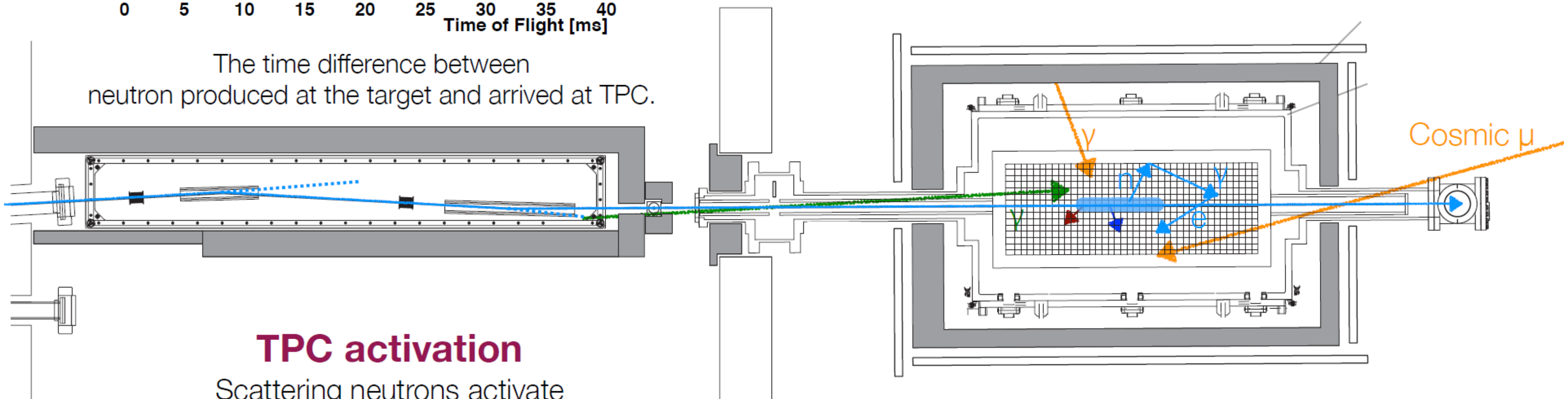


The time difference between neutron produced at the target and arrived at TPC.

Cut & Simulation

Gas induced

Neutrons produce γ rays in the TPC gas.



TPC activation

Scattering neutrons activate TPC inner wall.

Upstream

γ rays from SFC produce electrons in the TPC via Compton scattering

Environment

Cosmic rays
Radioisotopes in the shields

CO_2 capture

^{3}He capture

$$^{3}\mathrm{He} + n \to t + p + 764\ \mathrm{keV}$$

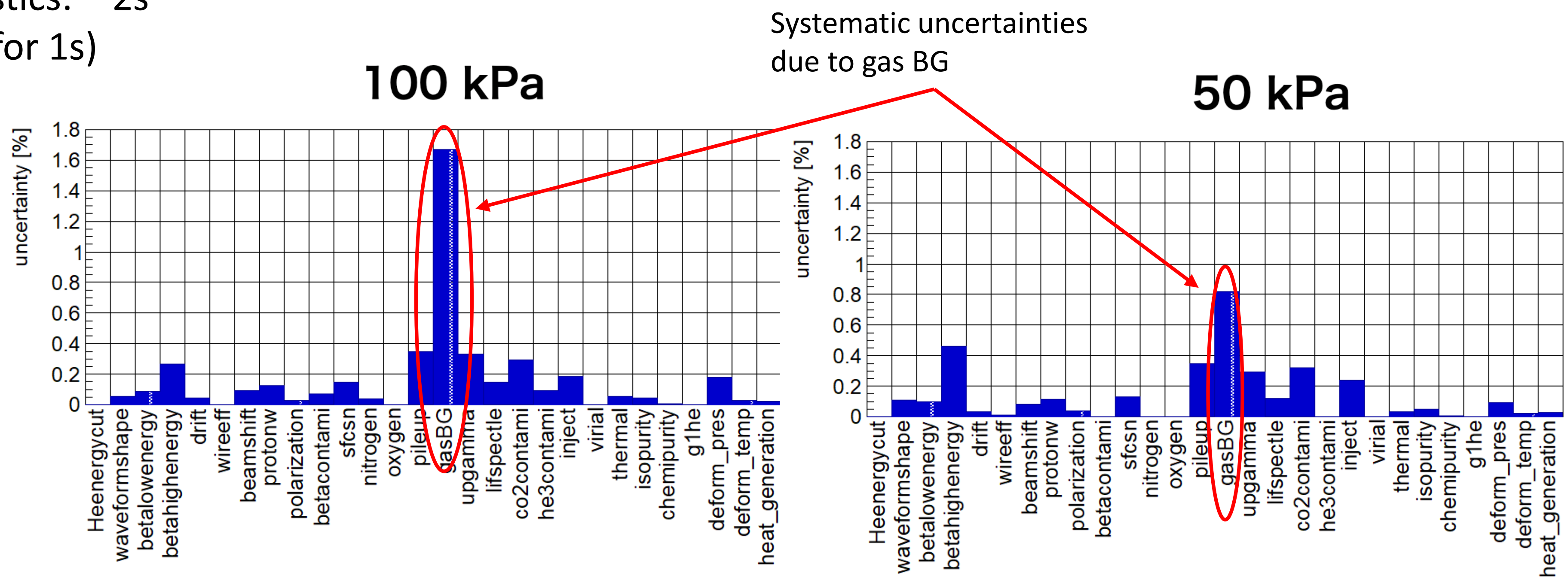
$$^{12}\mathrm{C} + \mathrm{n} \to ^{13}\mathrm{C}(1\,\mathrm{keV}) + \gamma$$

Time of Flight

Energy and Range cut

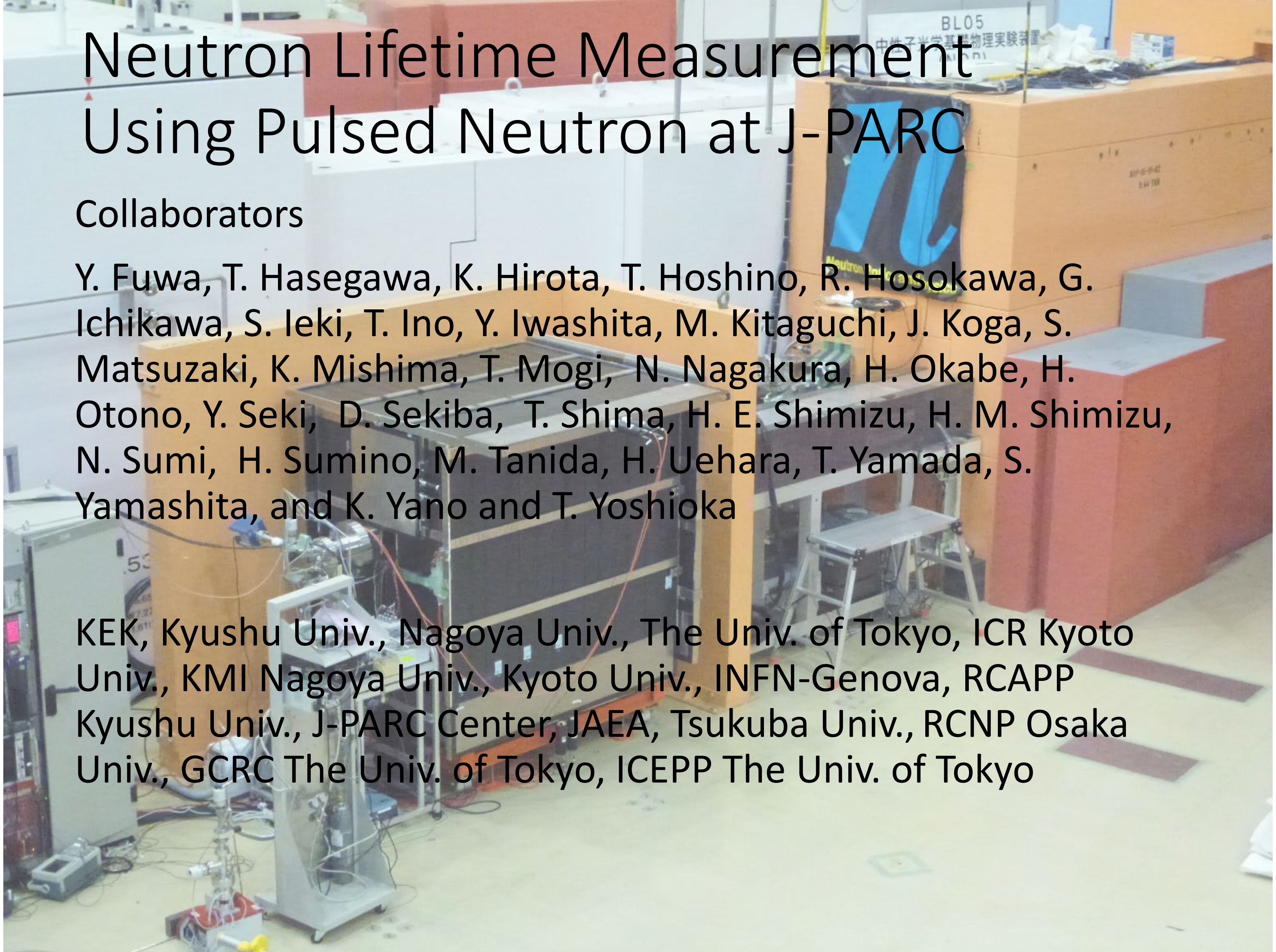
Systematics

Current statistics: ~ 2s
(need 110 d for 1s)



- Gas induced background events are major source of systematic uncertainties of our experiment
  - Uncertainty on lifetime: +2/-14 s for 100 kPa
  - Low pressure runs can reduce the uncertainty to +1/-7 s

- Other systematics are also under improving

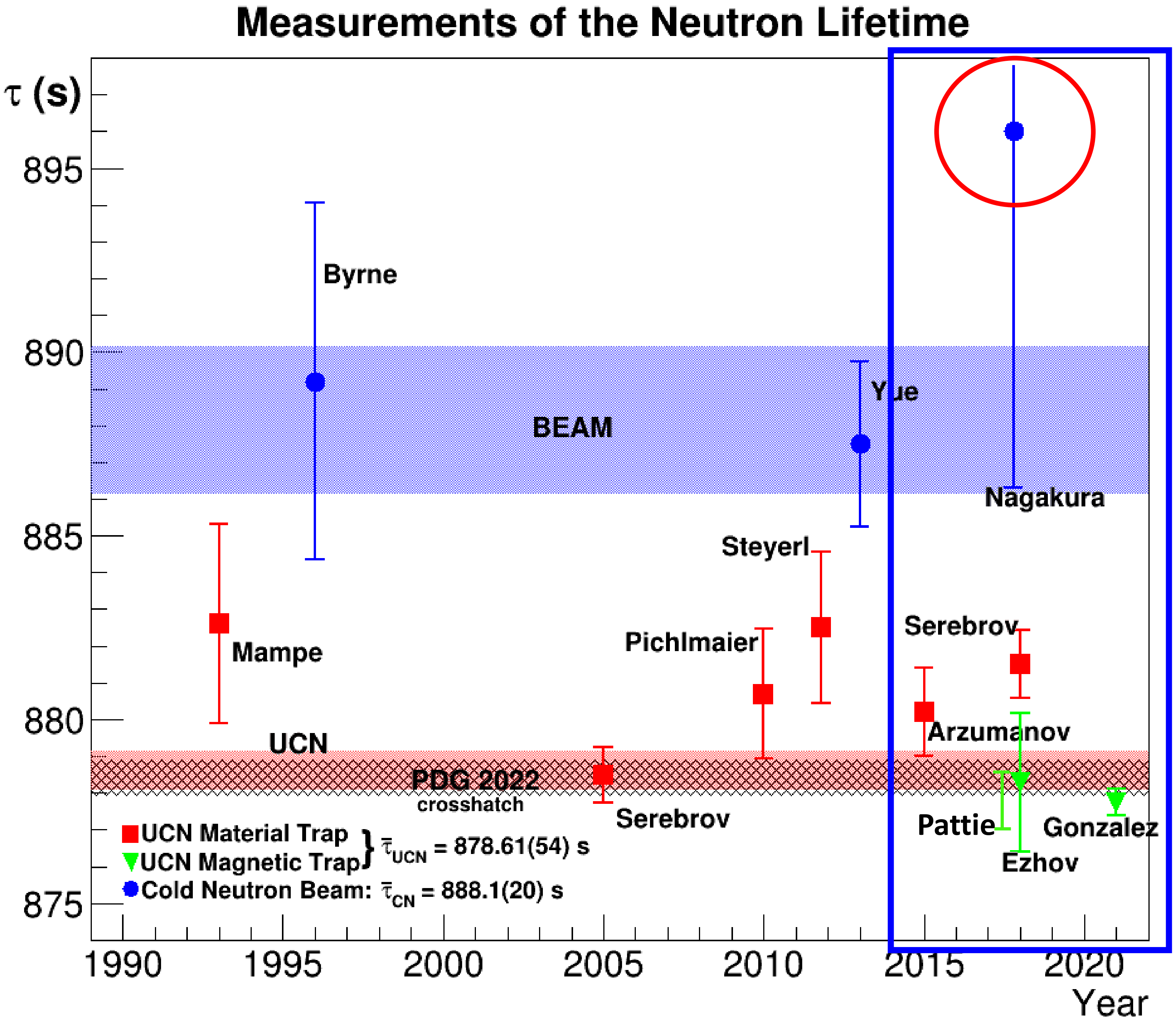


Neutron Lifetime Measurement Using Pulsed Neutron at J-PARC

Collaborators

Y. Fuwa, T. Hasegawa, K. Hirota, T. Hoshino, R. Hosokawa, G. Ichikawa, S. Ieki, T. Ino, Y. Iwashita, M. Kitaguchi, J. Koga, S. Matsuzaki, K. Mishima, T. Mogi, N. Nagakura, H. Okabe, H. Otono, Y. Seki, D. Sekiba, T. Shima, H. E. Shimizu, H. M. Shimizu, N. Sumi, H. Sumino, M. Tanida, H. Uehara, T. Yamada, S. Yamashita, and K. Yano and T. Yoshioka

KEK, Kyushu Univ., Nagoya Univ., The Univ. of Tokyo, ICR Kyoto Univ., KMI Nagoya Univ., Kyoto Univ., INFN-Genova, RCAPP Kyushu Univ., J-PARC Center, JAEA, Tsukuba Univ., RCNP Osaka Univ., GCRC The Univ. of Tokyo, ICEPP The Univ. of Tokyo



Almost factor 2 precision improvement already in hand!

Activity since 2013!

Not shown: a new measurement using satellite data!

UCN Experiments: Magnetically Trapped UCN

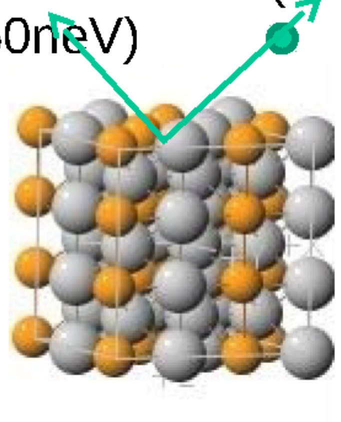
(using magnetic repulsion to eliminate wall losses!)

Different ways to manipulate UCN

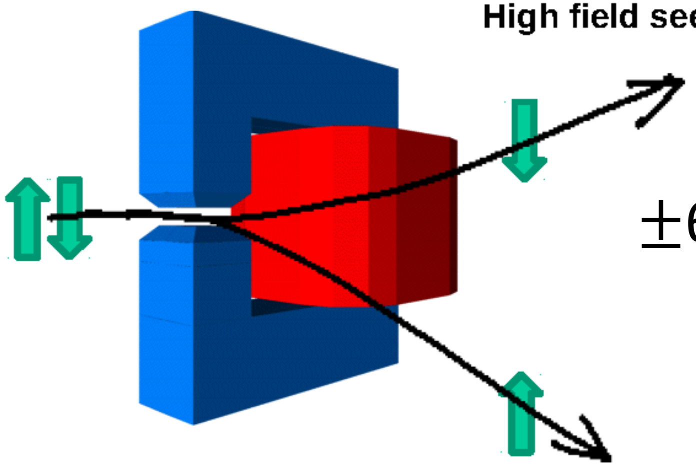
UCN energies so low, they reflect from some material surfaces for any angle of incidence!

- Nuclear force (max: 350neV)

Store them in bottles!



- Magnetic force

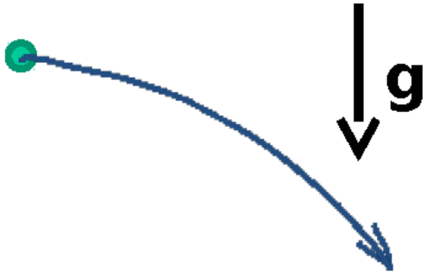


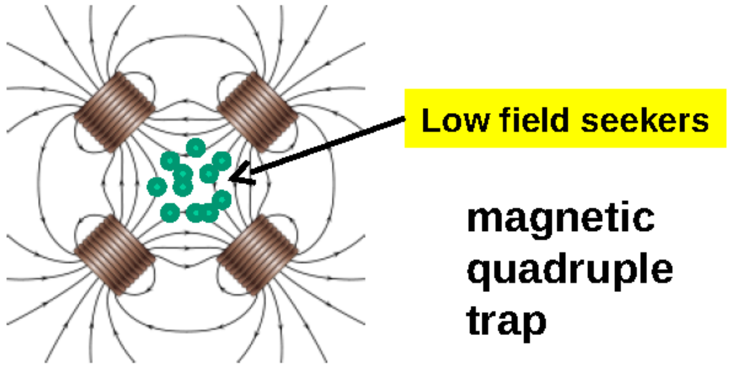
$\pm$60 neV/T

Old idea: use repulsive magnetic forces to trap UCN!

Vladimirskii, Zhur. i. Teoret Fiz., 1960

- Gravitational force (100neV/m)



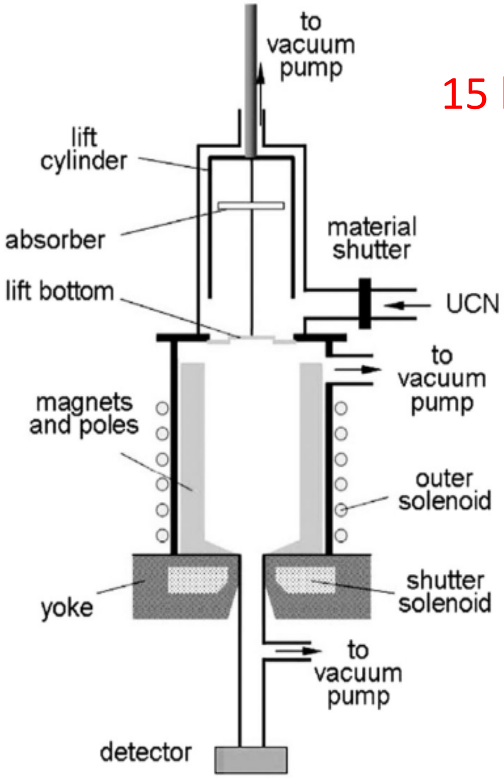


magnetic quadruple trap

C.-Y. Liu

Magnetic Bottles: Many in Progress

15 l

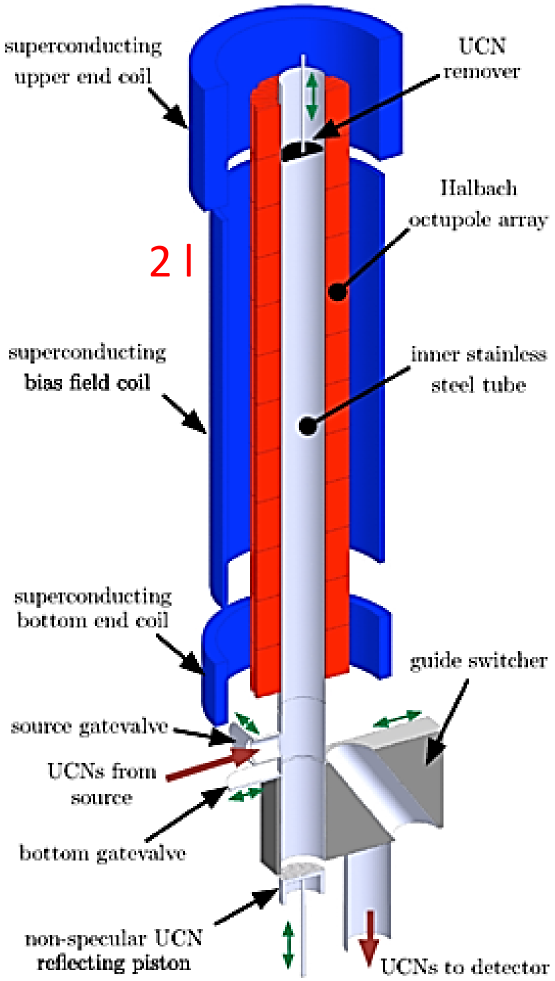


V. Ezhov *et al.*, NIMA, 611, 167 (2009)

$\tau_n = 878.3 \pm 1.9$ s

HOPE

2 l



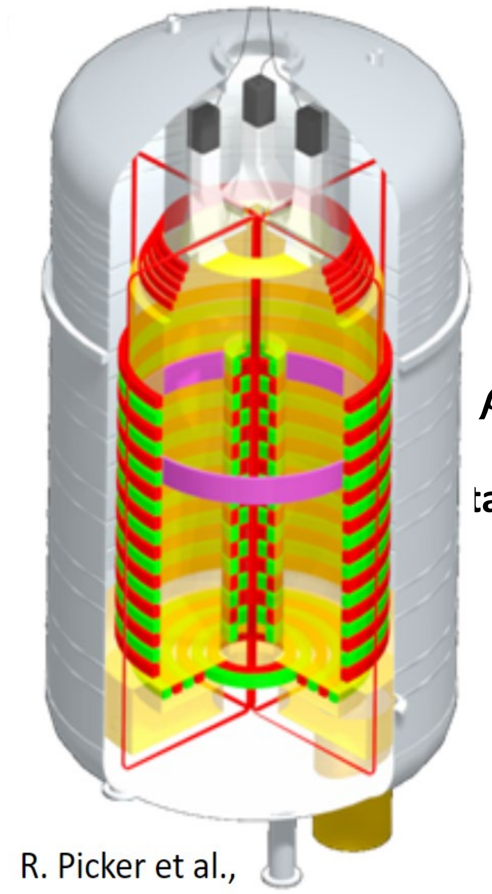
τ_n =(887±39)s

Leung, et al, PRC 94, 045502 (2016)

TU Munich

PENeLOPE

700 l



$\rho_{UCN} = 10^3 – 10^4\ cm^{-3}$

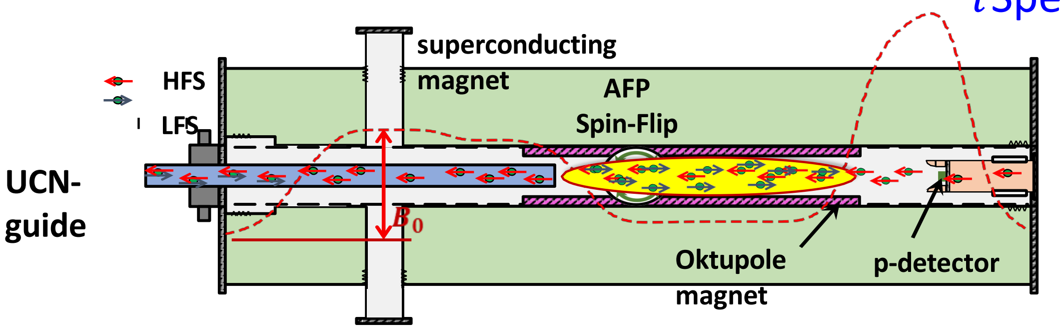
(FRM II)

tat $\delta\tau_n$ ~ 0.1 s in 2-4 days

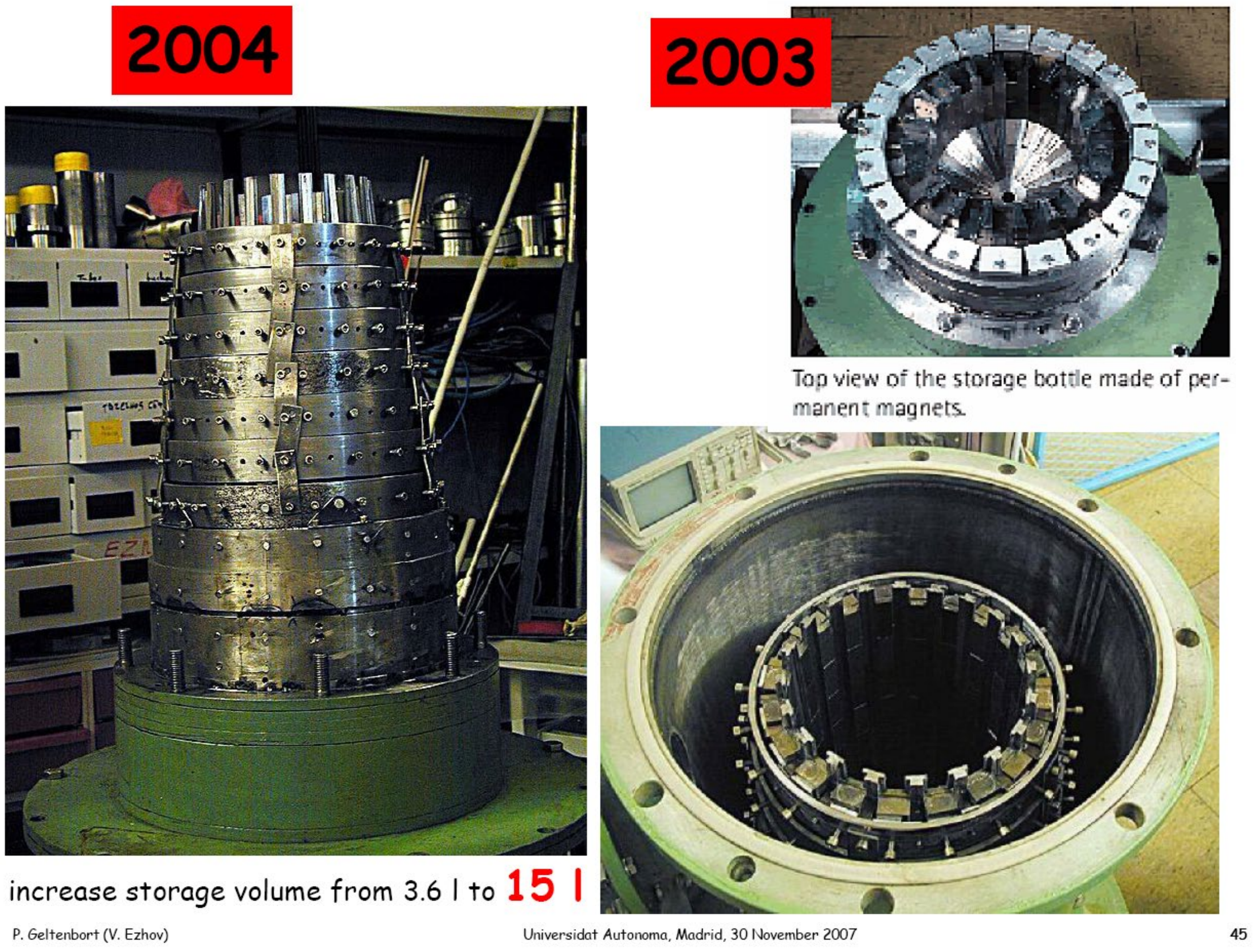
R. Picker et al.,

J. Res. NIST 110 (2005) 357

τSpect



UCN Lifetime Experiment at the ILL



- Neutrons from the ILL turbine.
- Trapped with permanent magnets and gravity.
- Surviving neutrons counted.

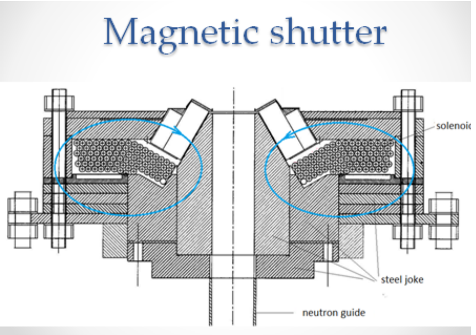
Analysis unpublished

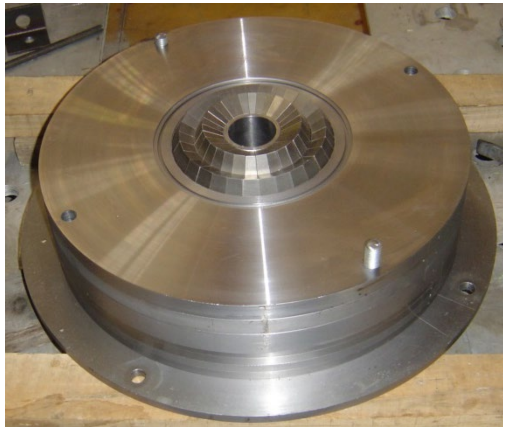
V. Ezhov *et al.*, J. Res. NIST 110 (2005) 345

V.F. Ezhov et. al. *JETP Letters, 2018, Vol. 107, No. 11, pp. 671–675*

$\tau_n = (878.3 \pm 1.6 \pm 1.0)$ s

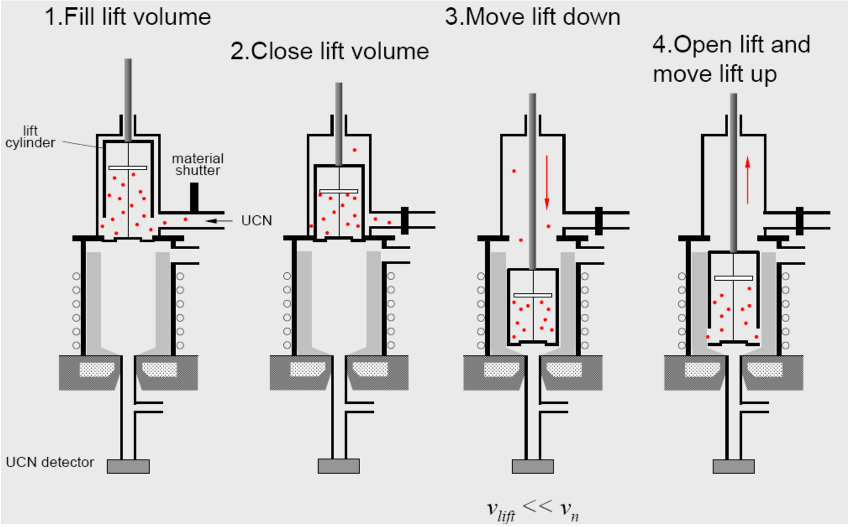
Magnetic shutter in lower part of trap permits to collect depolarized UCN during storage time





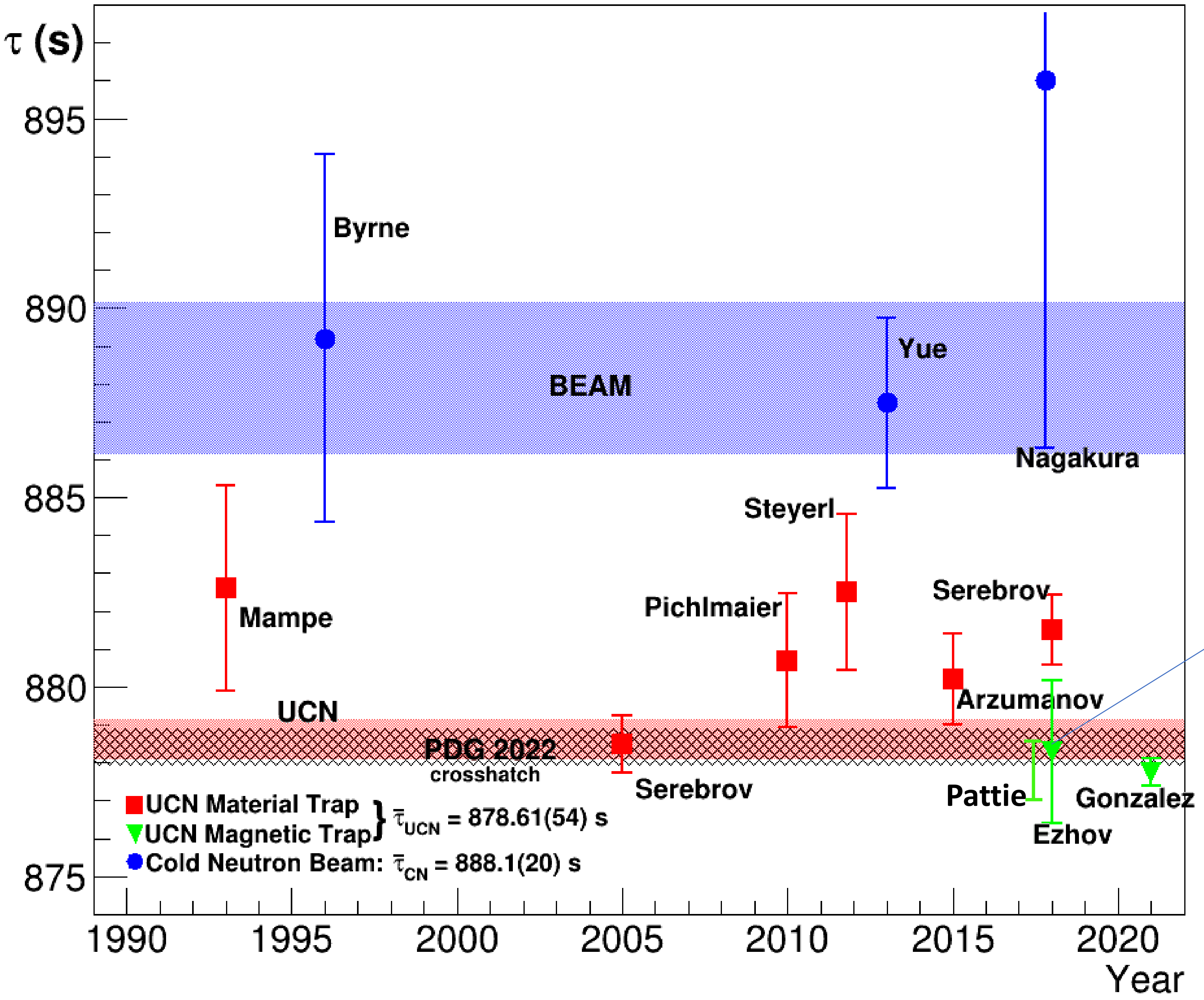
V.F. Ezhov, et al, Technical Physics Letters, Vol. 44, No. 7, pp. 602–604, 2018.

Trap is filled using elevator in upper part of trap. There are an absorber inside elevator for preliminary preparation of UCN spectrum. Final cleaning proceeds inside the trap throw magnetic shutter in lower part of trap



Trap is filled with unpolarized UCN. In this case half of neutrons are leaking during trap filling and they will be detected just during the filling. So before each run real quantity of UCN in trap is measured.

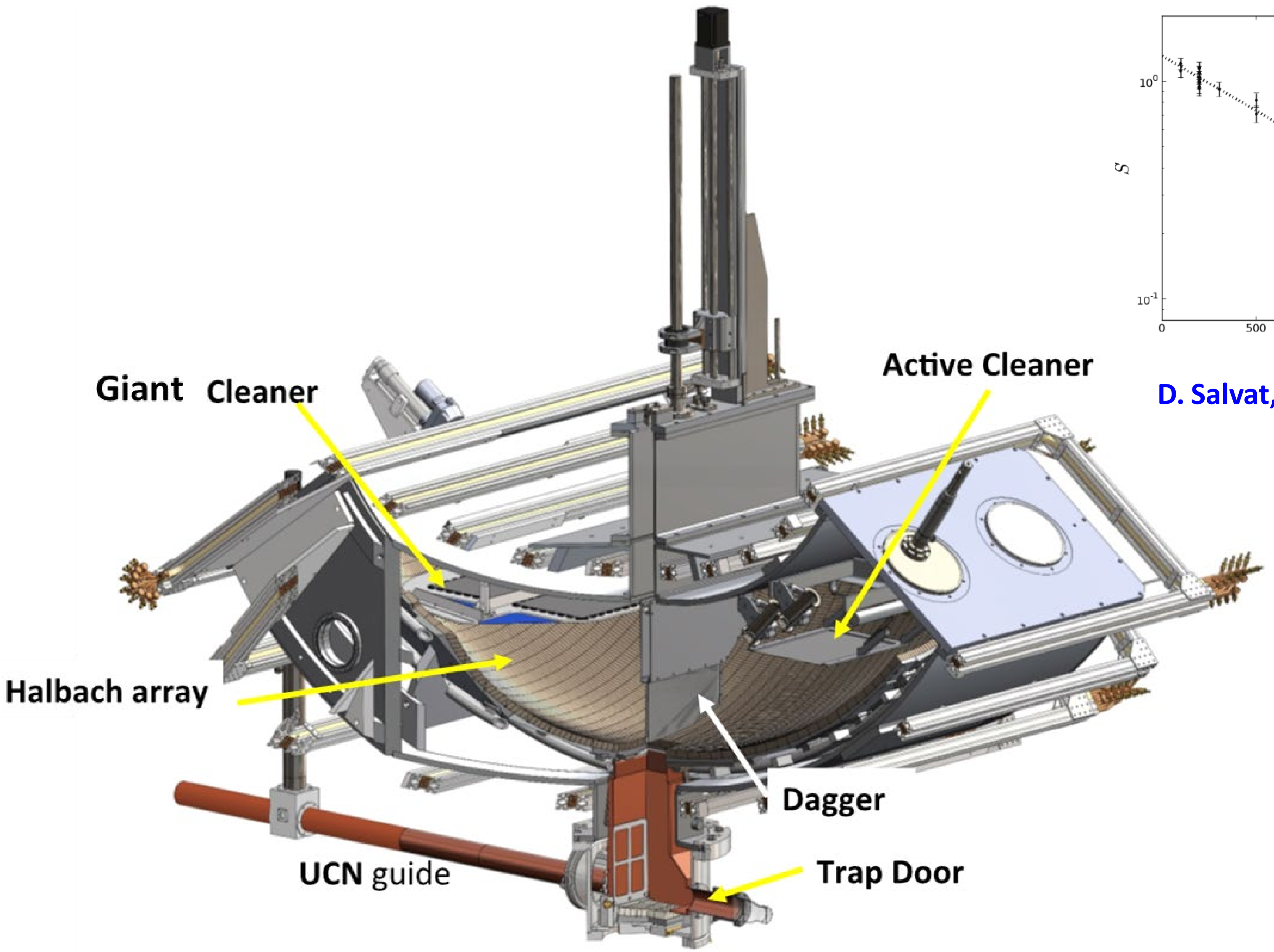
Measurements of the Neutron Lifetime



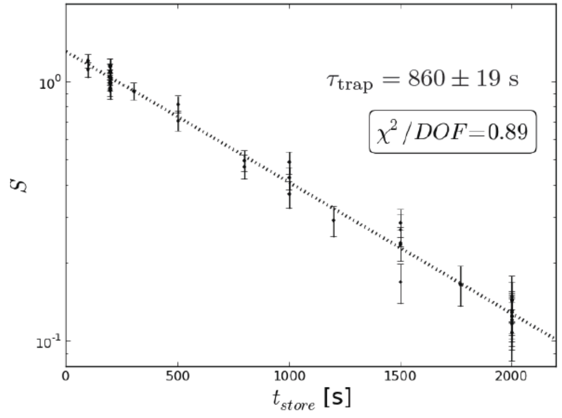
Ezhov

Storage time correction
~few seconds (depol)

The UCNτ Experiment



1st measurement

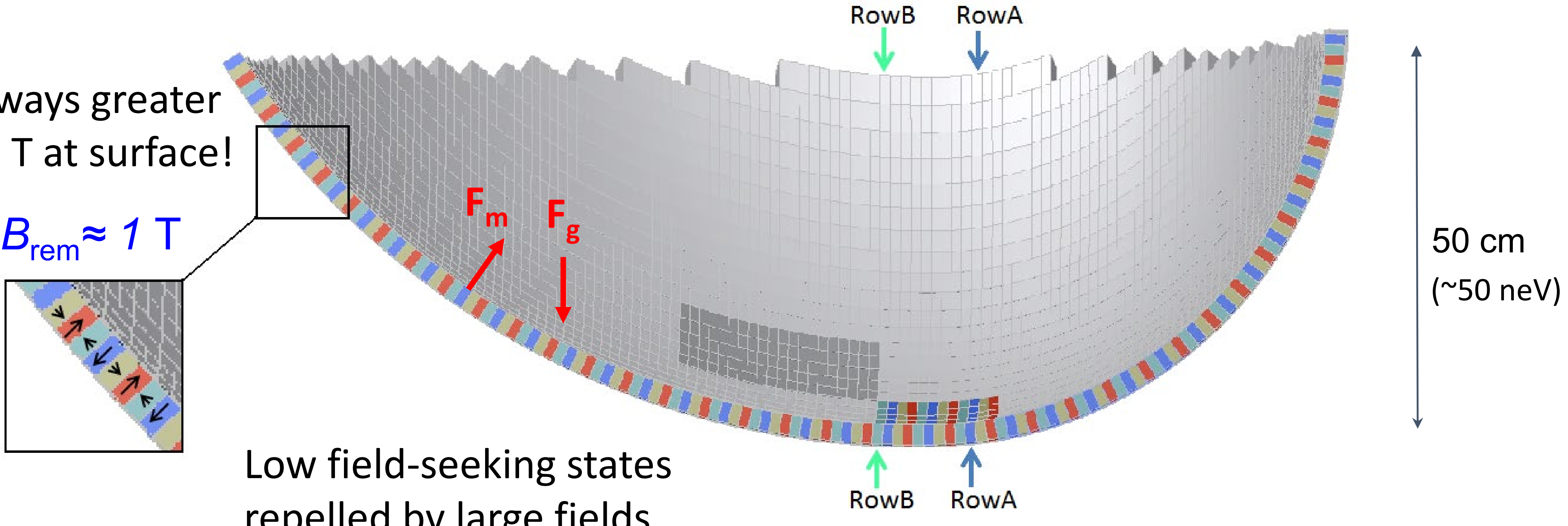


D. Salvat, PRC 89, 052501 (2014)

UCNτ

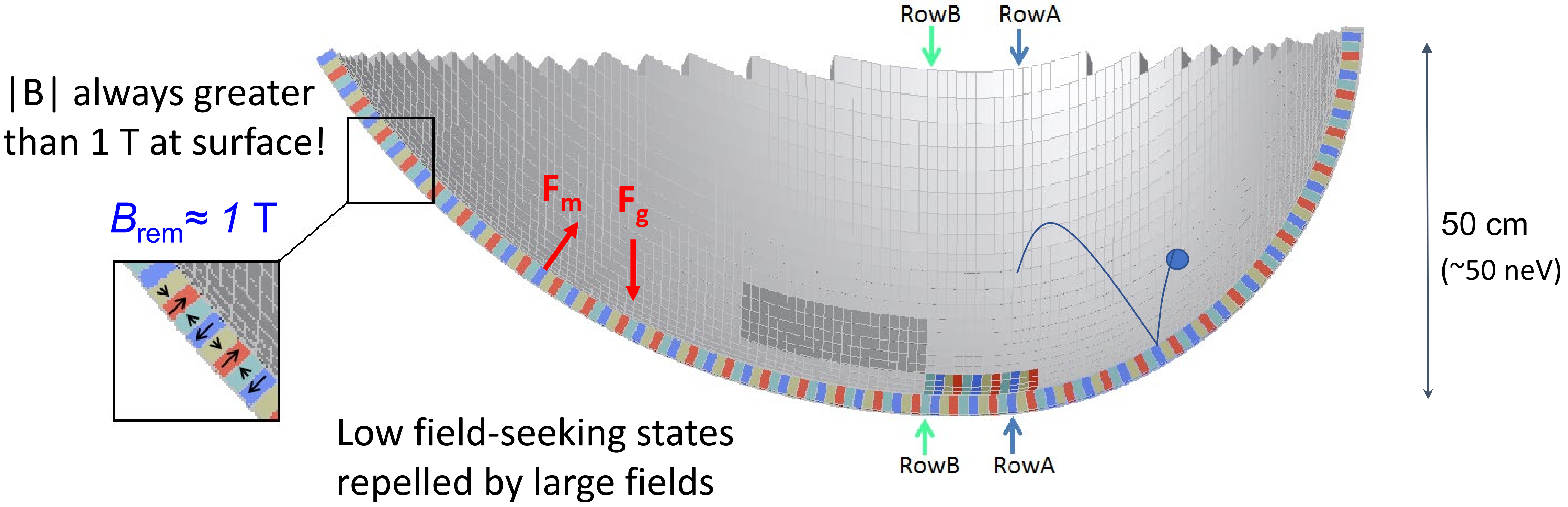
|B| always greater than 1 T at surface!

$B_{rem} \approx 1$ T



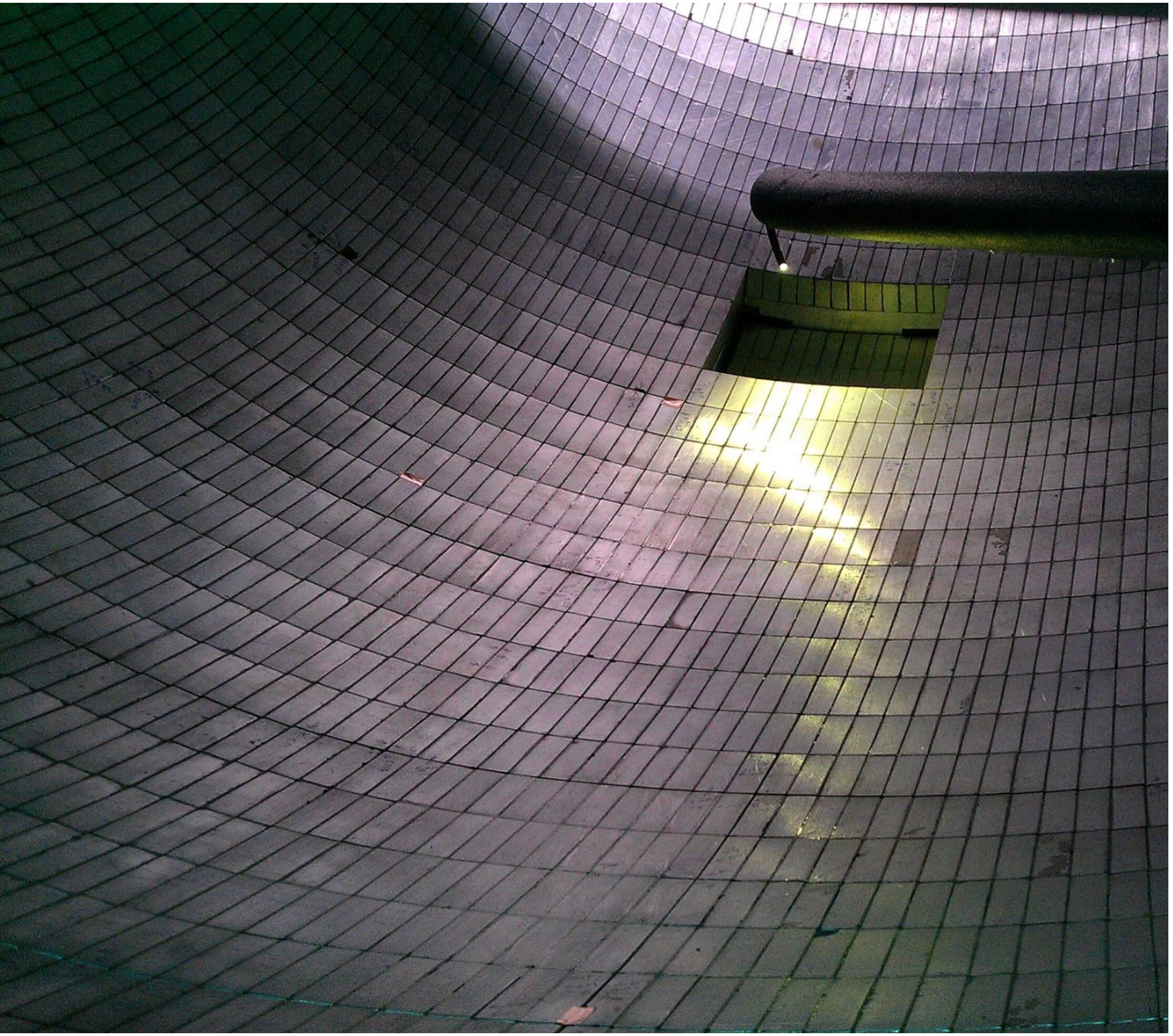
Low field-seeking states repelled by large fields

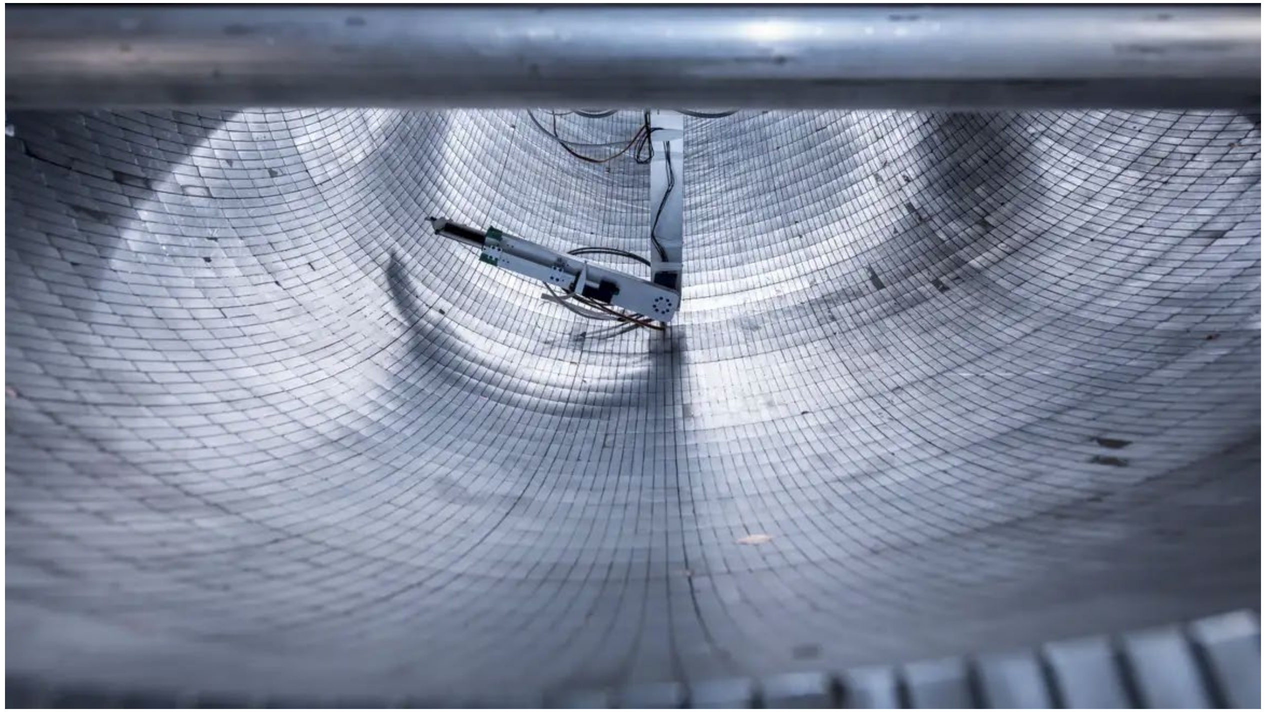
UCNτ



UCNτ Design Features

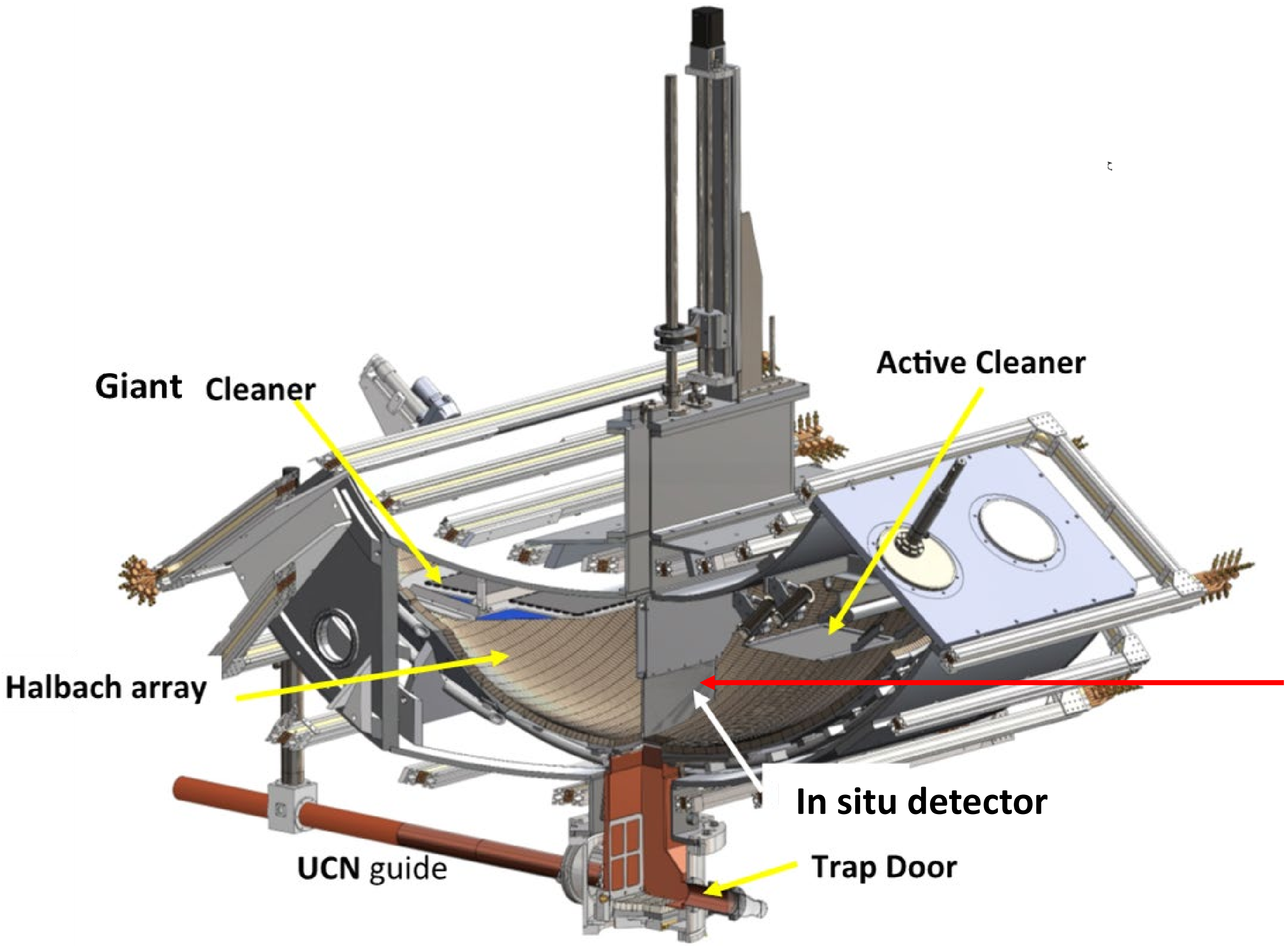
1) Magnetic barrier eliminates interaction with materials
2) Very large volume (~400 l UCN storage)
3) Asymmetrical construction to ensure rapid emptying/detection





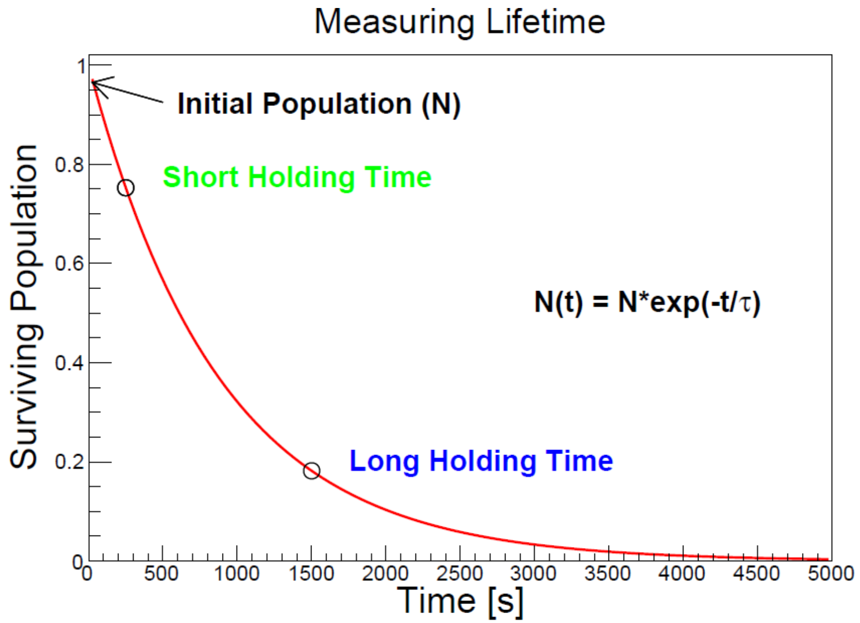
D. Salvat

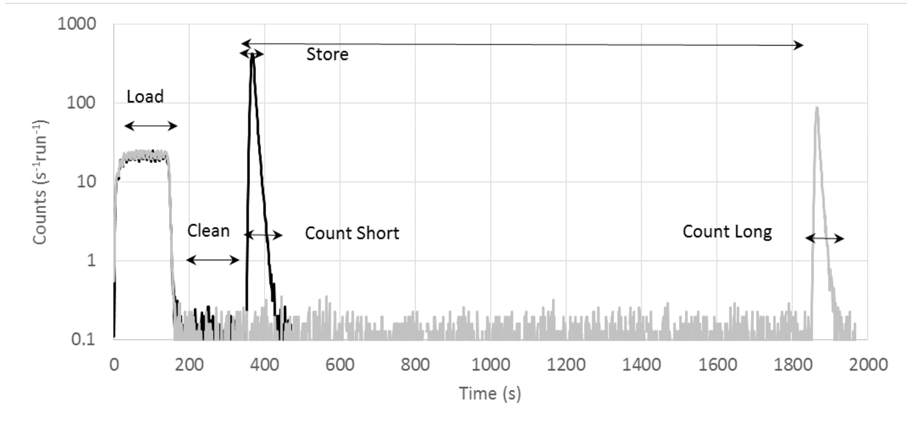
The UCNτ apparatus



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

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

$$\frac{1}{\tau_{\text{trap}}} = \frac{1}{\tau_{\text{n}}} + \frac{1}{\tau_{\text{escape}}} + \frac{1}{\tau_{\text{heating}}} + \frac{1}{\tau_{\text{depol}}} + \ldots$$

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

UCNτ Progress: the 2017-2018 Data Set

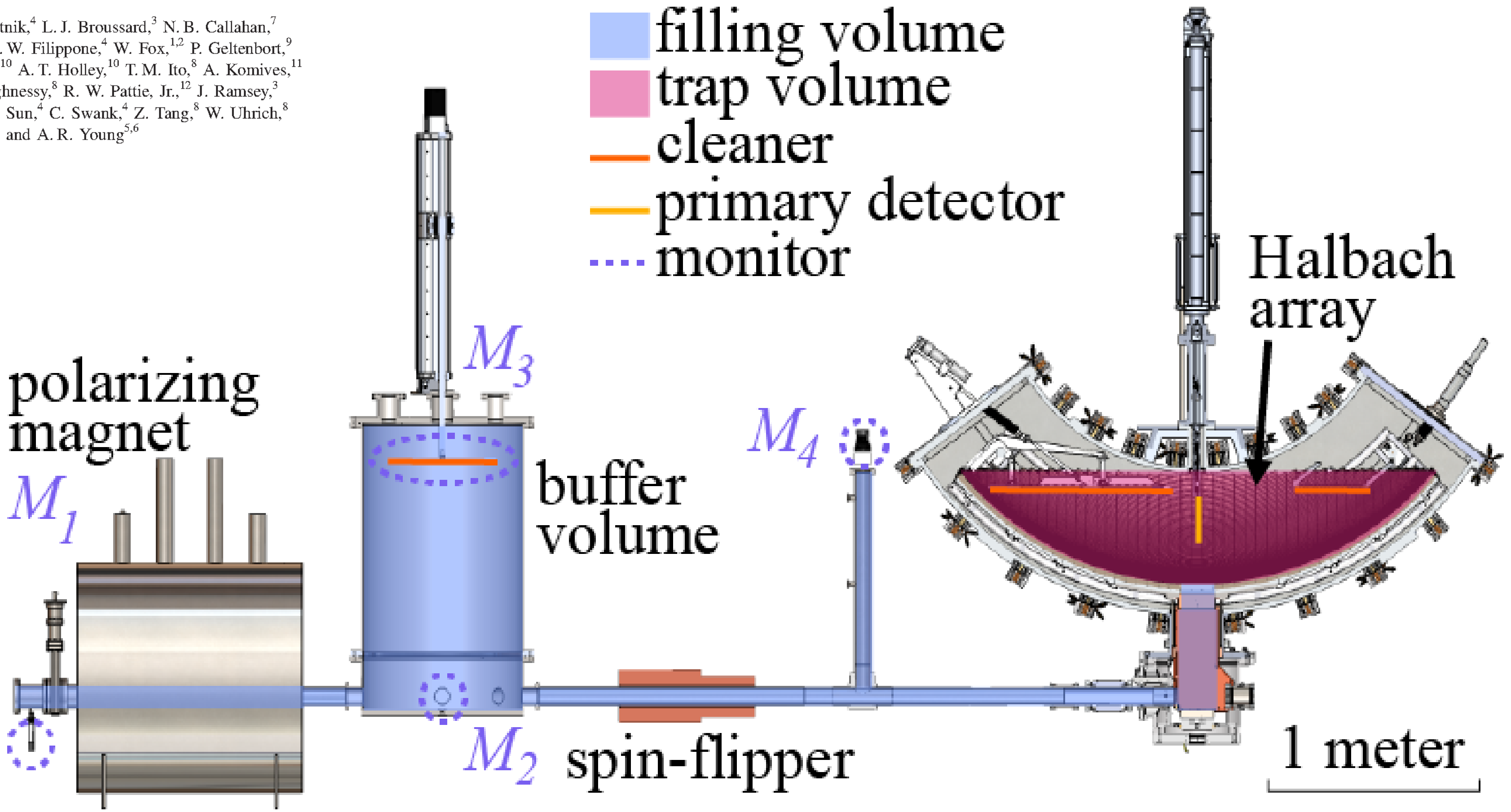
PHYSICAL REVIEW LETTERS 127, 162501 (2021)

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



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

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

D. Salvat

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

Most precise value for τ_n to date!

D. Salvat

UCNτ 2022 and beyond

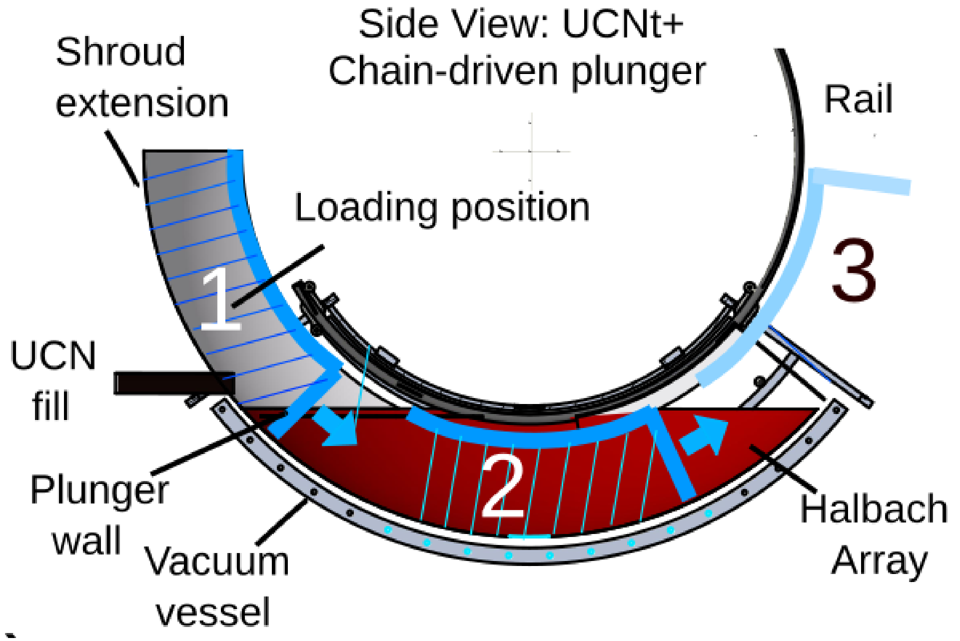
- LDRD-funded upgrade of UCNτ underway: $UCN\tau^{+}$
- Longer term: Tau2 (larger trap/ increased UCN production)

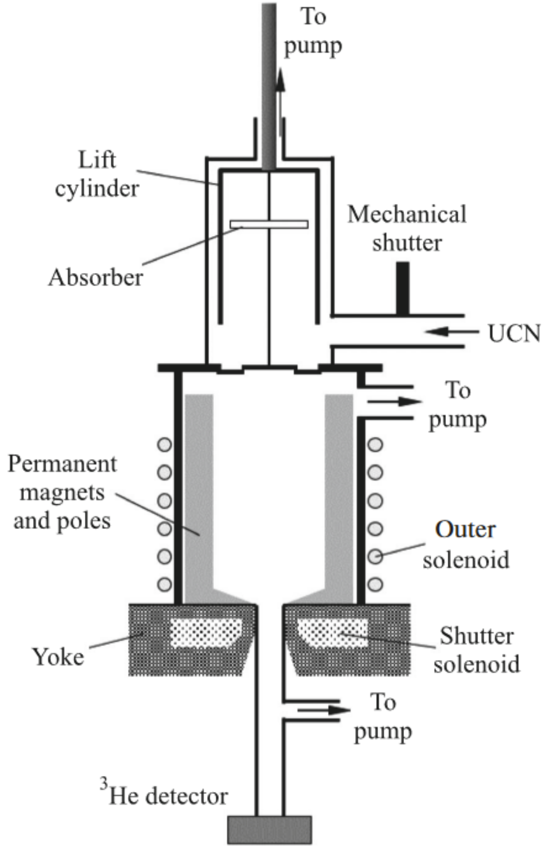
ISSN 0021-3640, JETP Letters, 2018, Vol. 107, No. 11, pp. 671–675. © Pleiades Publishing, Inc., 2018.

A neutron elevator: UCNτ+

New Loading Mechanisms to maximize statistics

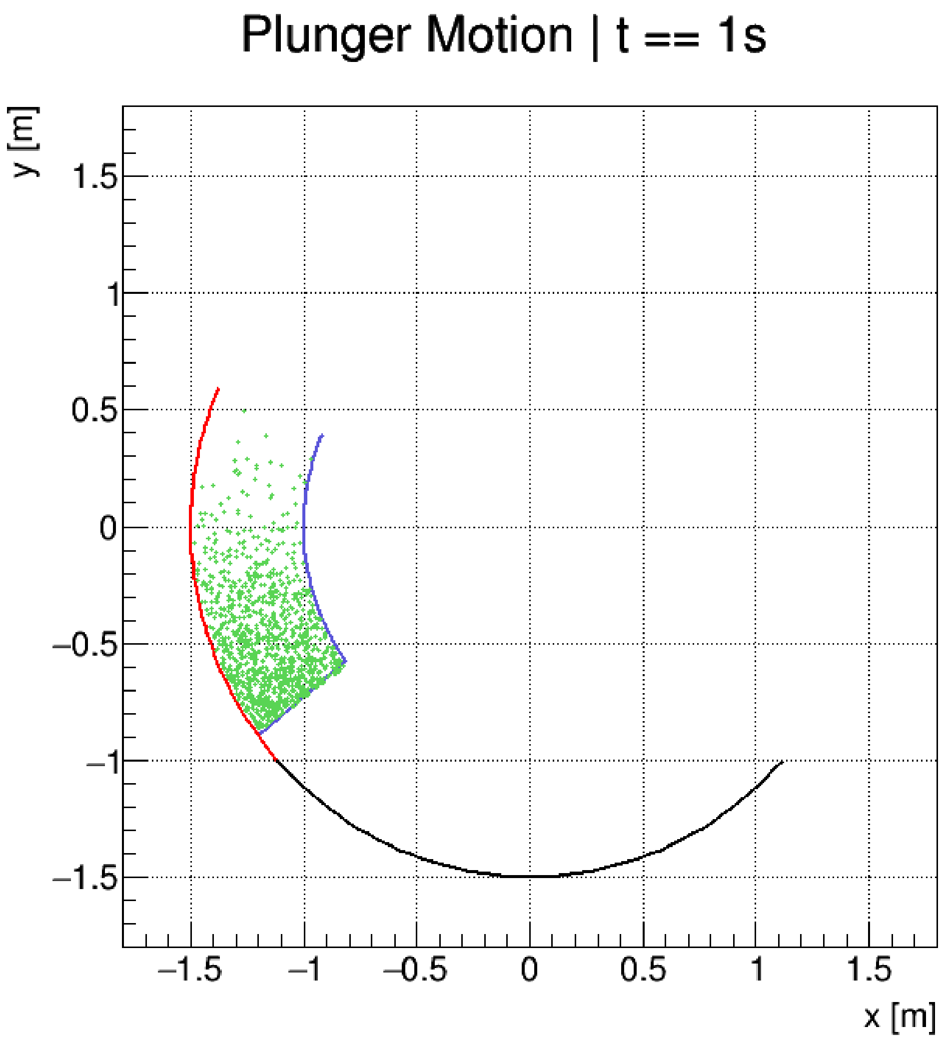
- Funded by LANL LDRD
- Anticipate ~10× counts



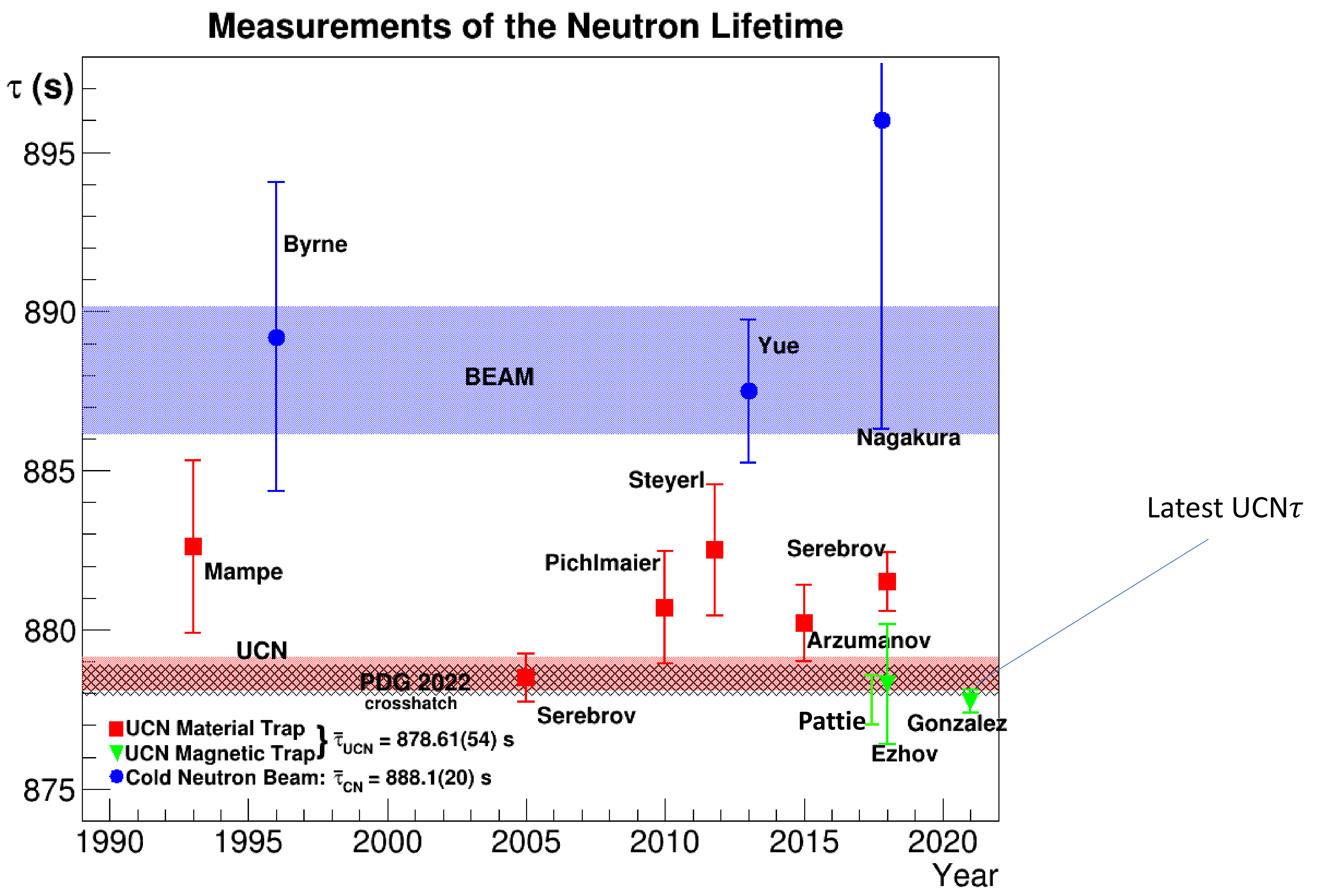


Shooting for < 0.15 s sensitivity!

Simulation of a cylindrical trap geometry: UCN Loading



Modeling: thesis R. Musedinovic



Measurements of the Neutron Lifetime
τ (s)
895
890
885
880
875
1990
1995
2000
2005
2010
2015
2020
Year
Byrne
BEAM
Yue
Nagakura
Steyerl
Mampe
Pichlmaier
Serebrov
Arzumanov
UCN
PDG 2022
crosshatch
Serebrov
Pattie
Gonzalez
Ezhov
UCN Material Trap
UCN Magnetic Trap
$\bar{\tau}_{UCN}$ = 878.61(54) s
Cold Neutron Beam: $\bar{\tau}_{CN}$ = 888.1(20) s
Latest UCNτ

Conclusions

- Motivation for measurements of τ_n for BSM constraints is strong
- The neutron lifetime problem emerged as neutron beam and UCN storage experiments evolved, driven by key results from A. Serebrov's group and the NIST beam experiment. The problem is still with us in 2022.
- Since 2013, much has been accomplished, and much is underway

  BL3: NIST upgrade with ~ order of magnitude smaller uncertainties

  J-PARC beam expt: independent cross check of the NIST 2013 result

  UCNτ: already effectively confirmed the 2005, Serebrov experiment!

  And many other projects!

  Now a 4.6σ discrepancy!

- The community has not yet identified new physics which can explain this issue, but the work is being done to provide a robust investigation of the tension between these two measurements in the next five years!

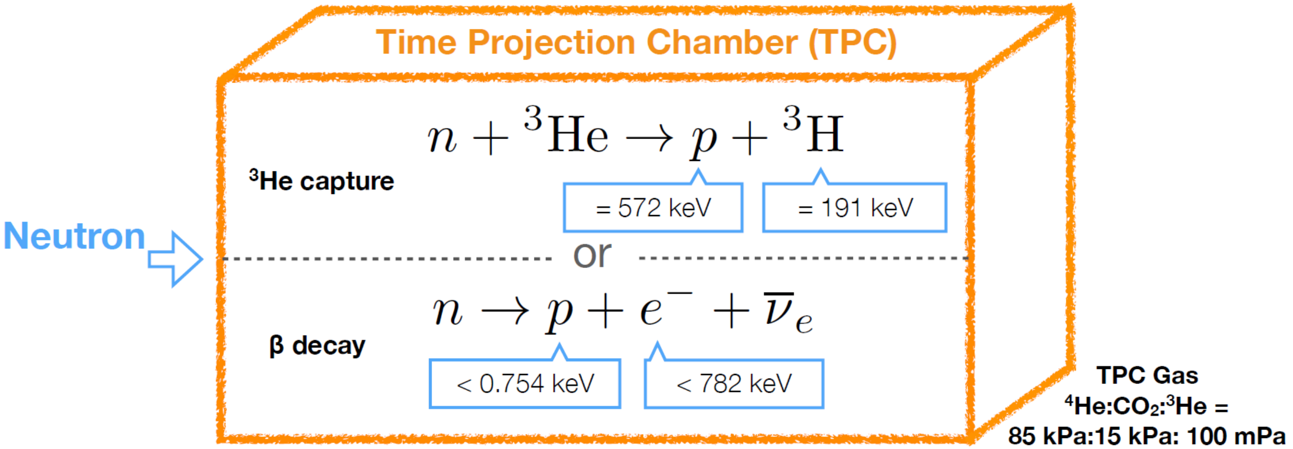
Jparc Beam Experiment

The method of neutron lifetime measurement

- **Electron-Counting method**
  Neutron lifetime is obtained from neutron β decay and flux (^3He capture).

$$\tau_n = \frac{1}{\rho\sigma v}\left(\frac{S_{\mathrm{He}}/\varepsilon_{\mathrm{He}}}{S_\beta/\varepsilon_\beta}\right)$$

τ_n	Neutron Lifetime		
ρ	^3He density (Blind)	S_β	Number of β decay signal
σ	^3He neutron capture cross section	S_{He}	Number of ^3He capture signal
v	Neutron velocity	ε	Cut efficiency

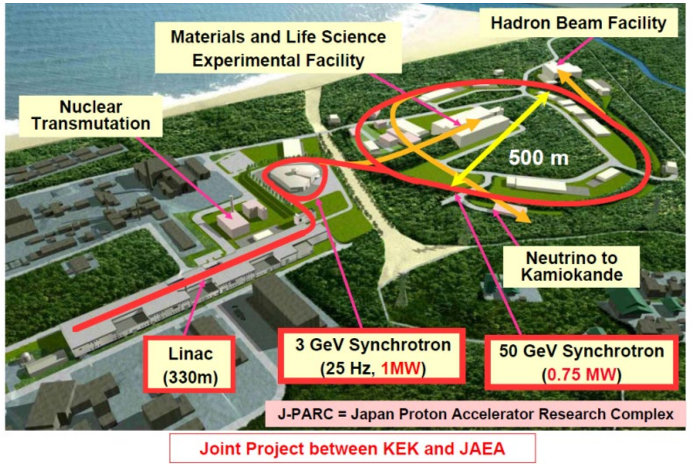


The only experiment underway which can directly cross check the NIST experiment!

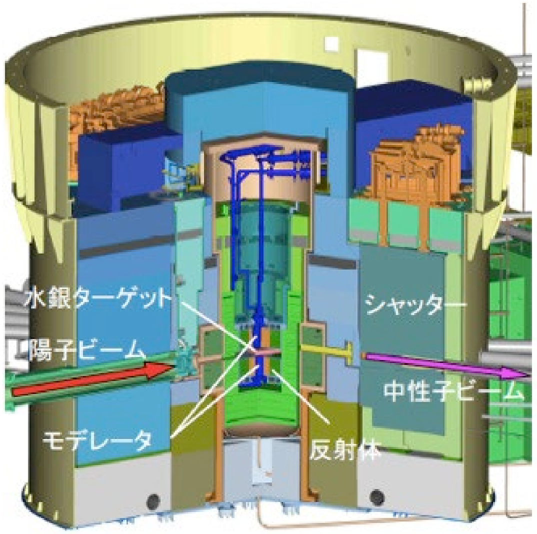
First result : O(10) sec accuracy
⇒ Final goal : 1 sec accuracy

J-PARC / MLF / BL05

J-PARC
Materials and Life Science
Experimental Facility(MLF)

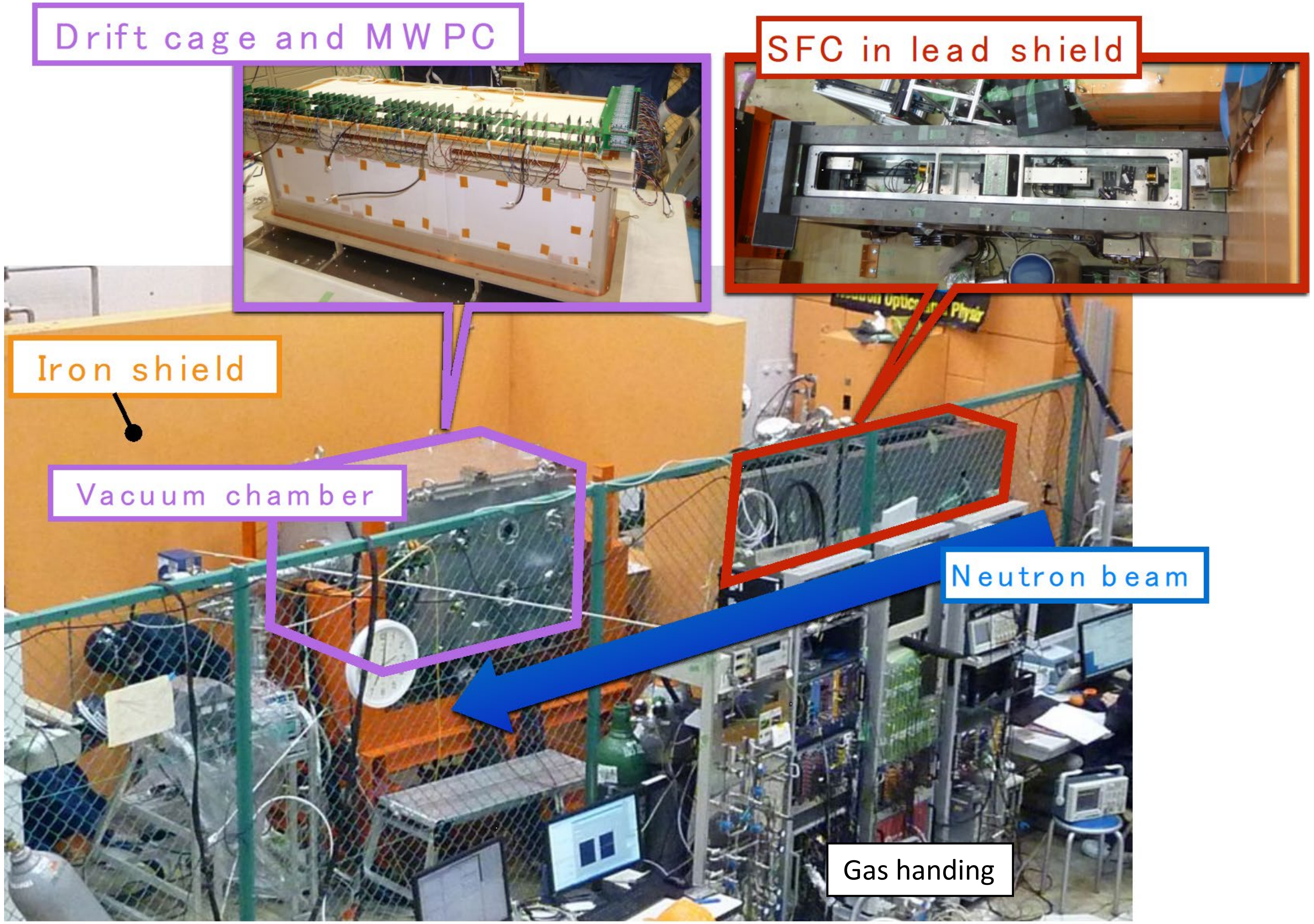


Spallation neutron target (designed for 1MW)



Pulsed neutron Beam line BL05
Neutron optics and physics(NOP)

Experimental Setup

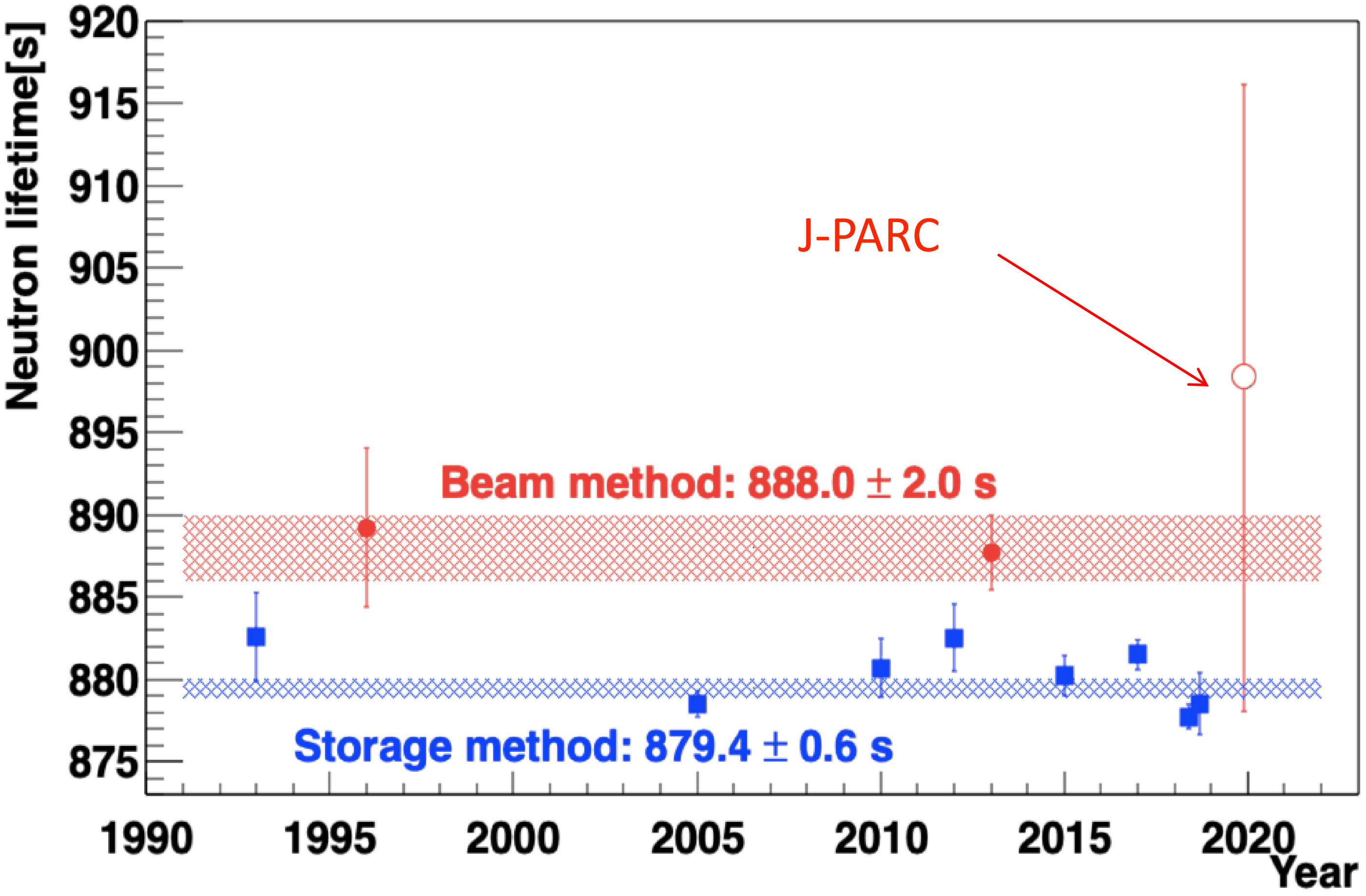


The first result from J-PARC

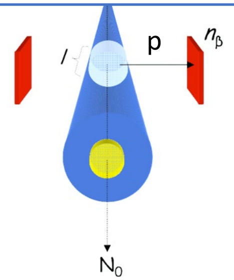
The published result by using data using 2014-2016 was

$$\tau_n = 898 \pm 10(stat.)^{+15}_{-18}\,(sys.) = 898^{+18}_{-20}\ \mathrm{s}$$

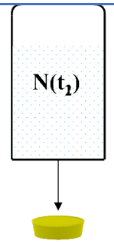
[K. Hirota et al., Prog. Theor. Exp. Phys. **2020**, 123C02]



In-beam method
Count the dead



Storage method
Count the living



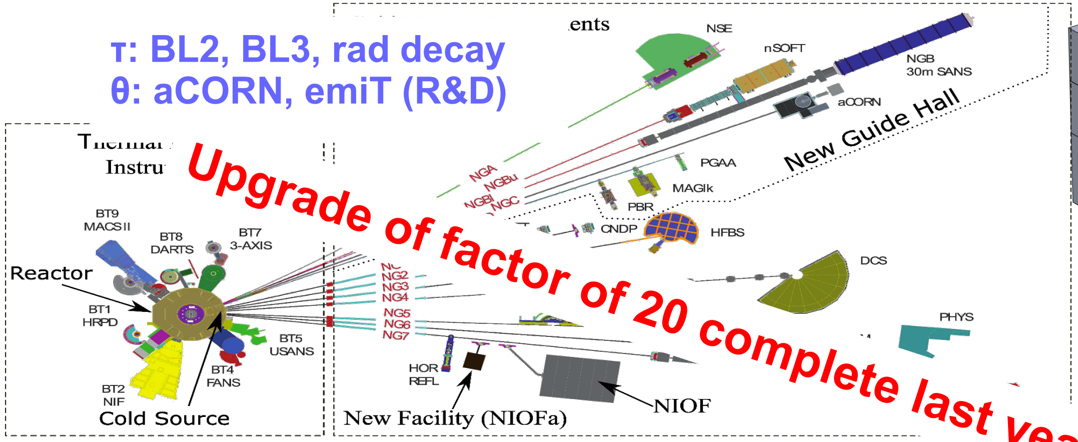
U.S. Facilities

Spallation Neutron Source Fundamental Neutron Physics Beamline (FNPB)

θ: Nab

Cold Neutron Beams

τ: BL2, BL3, rad decay
θ: aCORN, emiT (R&D)



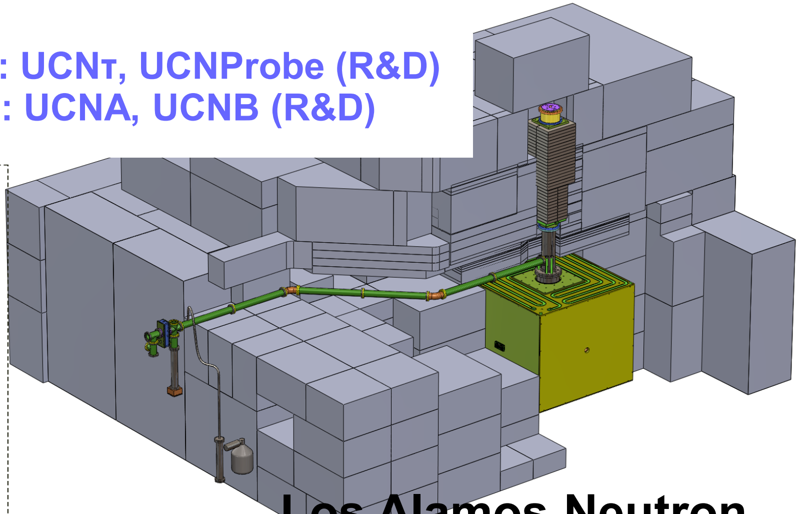
Upgrade of factor of 20 complete last year!

National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR)

UCN

Upgrade in 2016 successful!

τ: UCNτ, UCNProbe (R&D)
θ: UCNA, UCNB (R&D)



Los Alamos Neutron Science Center (LANSCE) Area B Source

Magnetic Fields of Trap

- For "low-field seeking" polarized neutrons

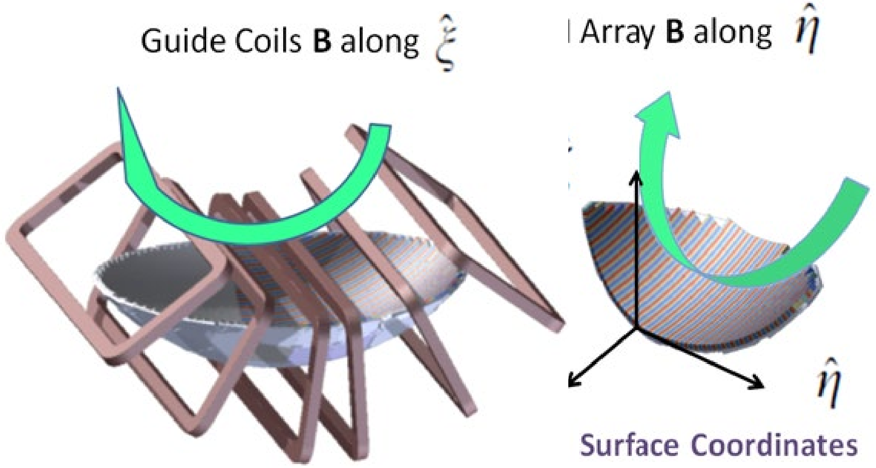
$$\vec{F} = \vec{\mu} \cdot (\nabla \vec{B})$$

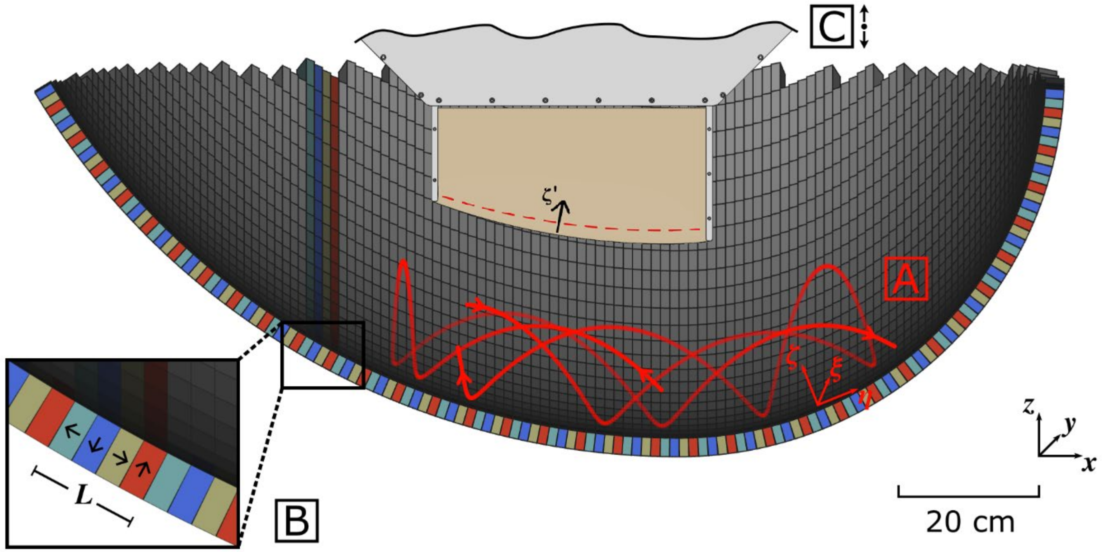
Permanent Magnet Halbach Array:

$$\boldsymbol{B} = \frac{4B_{rem}}{\pi\sqrt{2}} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{4n-3} \left(1 - e^{-k_n d}\right) e^{-k_n \zeta} \left(\sin k_n \eta\, \hat{\boldsymbol{\eta}} + \cos k_n \eta\, \hat{\boldsymbol{\zeta}}\right)$$

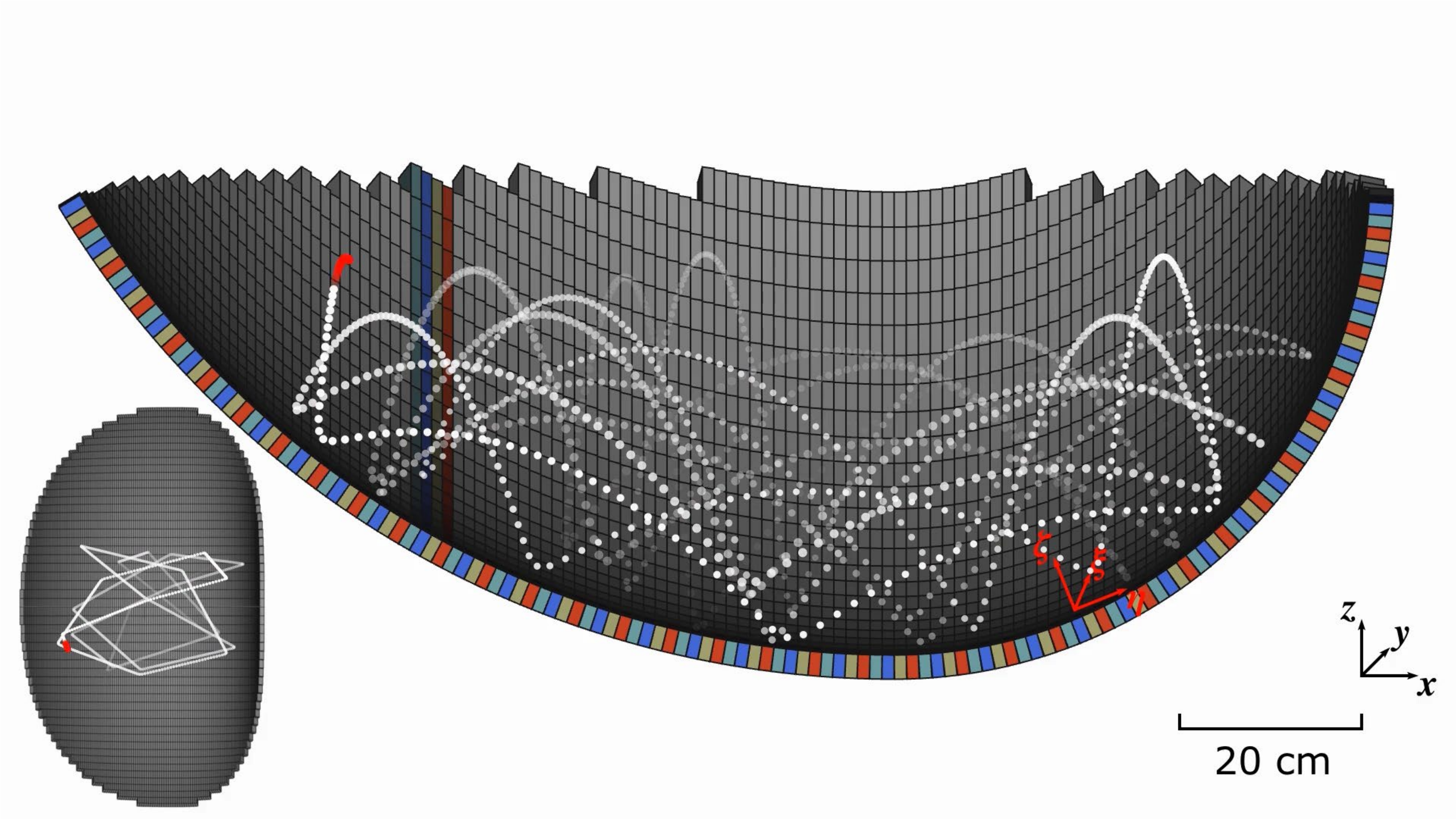
Guide field coils along axis:

$$B_\xi = \frac{B_0 (r+R)}{\sqrt{x^2+y^2}}\, \hat{\boldsymbol{\xi}}$$

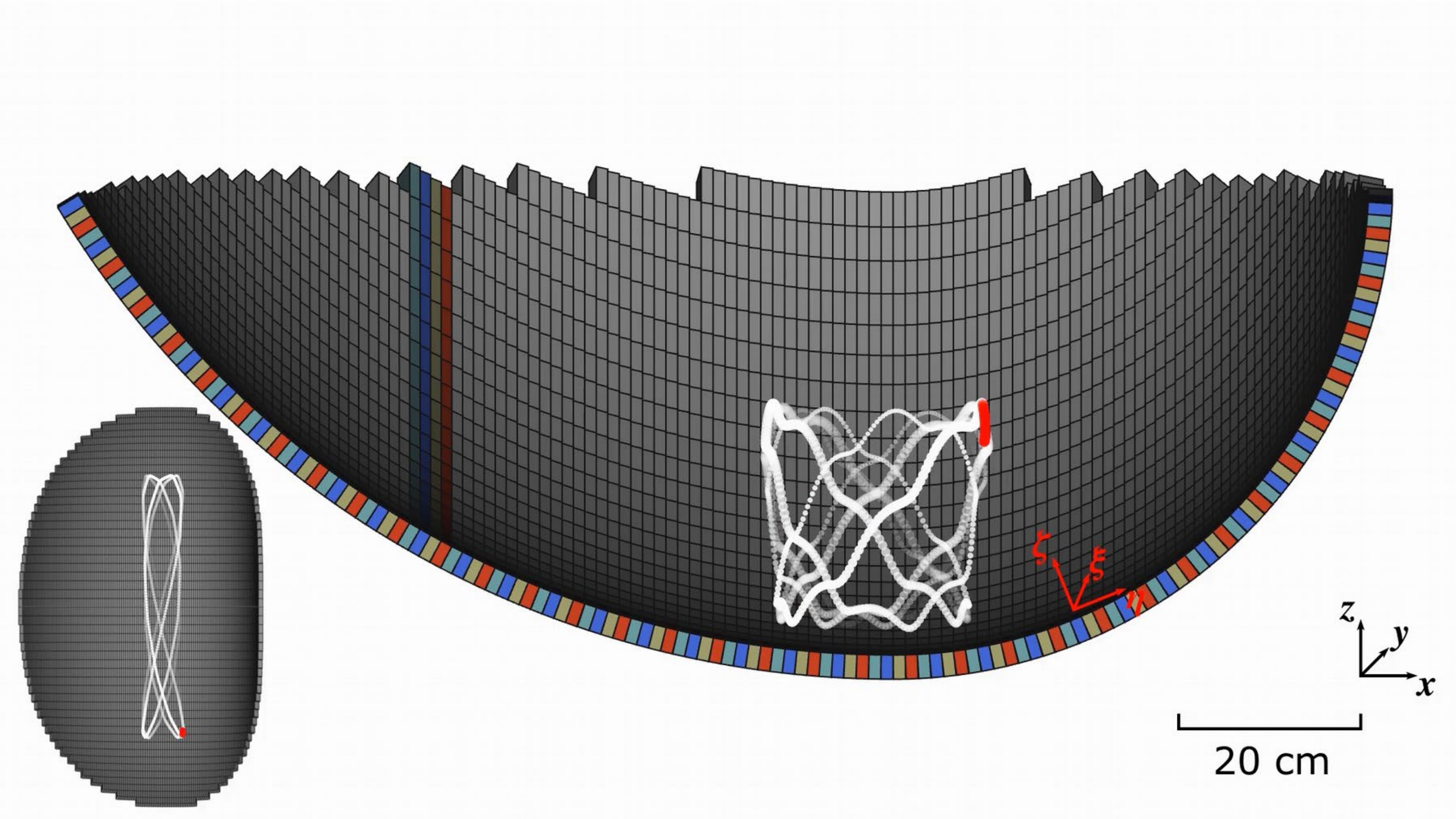




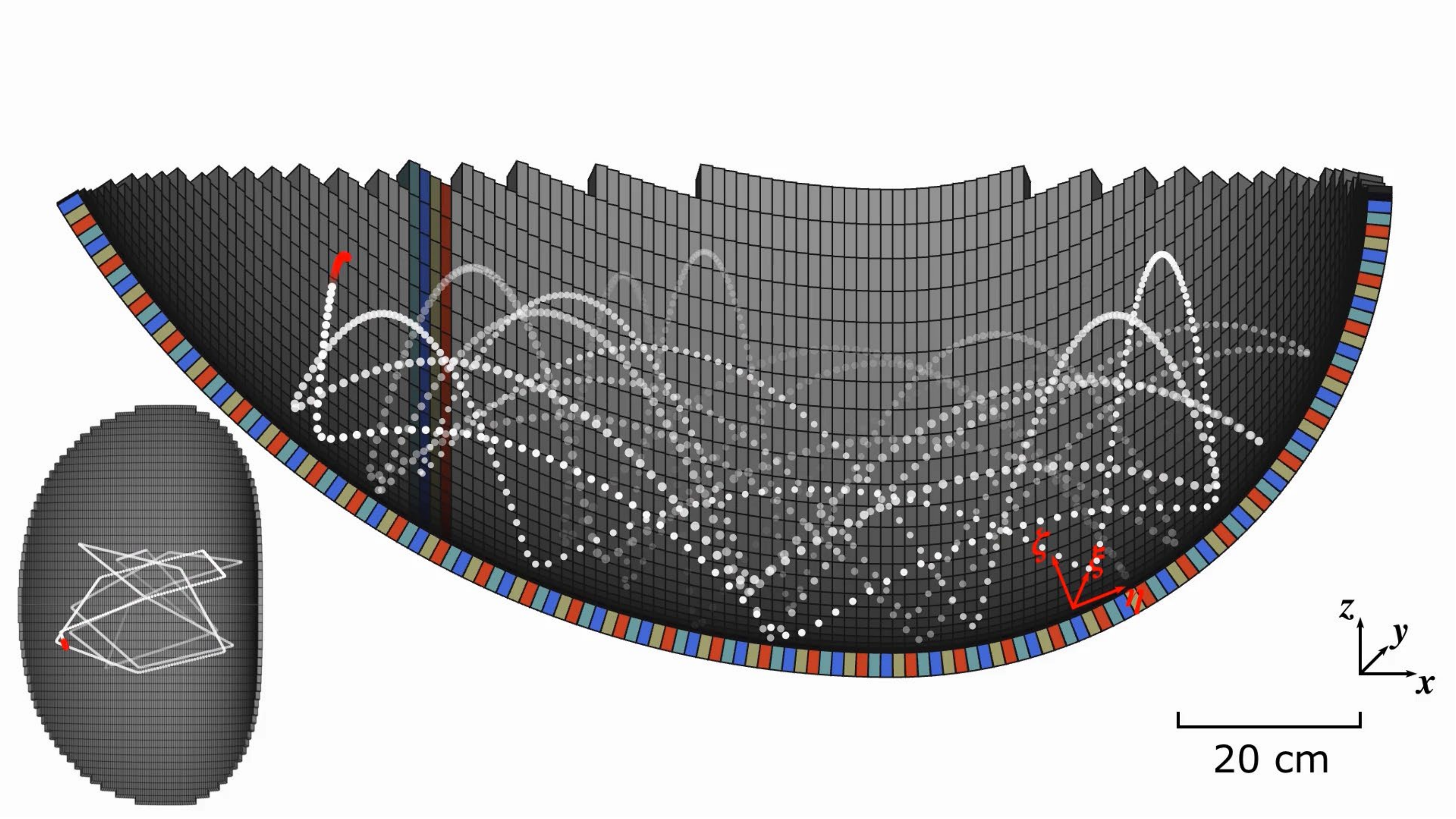
D. Salvat



N. Callahan



N. Callahan

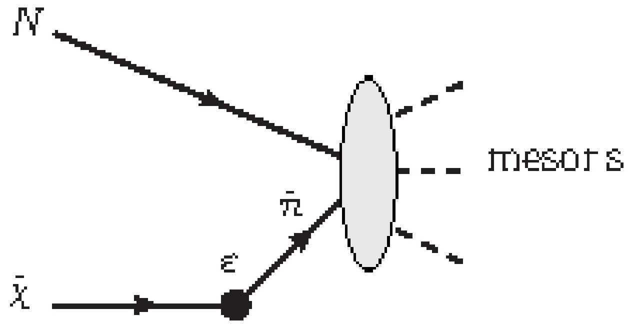


D. Salvat

Reference	Neutron lifetime (s)	Uncertainty (s)
Beam Experiments		
Robson, 1951	1110	220
Spivak *et al.*, 1956	1040	130
D'Angelo, 1959	1100	160
Sosnovsky *et al.*, 1959	1013	26
Christensen *et al.*, 1972	918	14
Last *et al.*, 1988	876	21
Spivak, 1988*	891	9
Kossakowski *et al.*, 1989	878	30
Byrne *et al.*, 1996*	889.2	4.8
Nico *et al.*, 2005*	886.3	3.4
Bottle Experiments		
Kosvintsev *et al.*, 1980	875	95
Kosvintsev, Morozov, and Terekhov, 1986	903	13
Morozov, 1989	893	20
Mampe *et al.*, 1989*	887.6	3.0
Alfimenkov *et al.*, 1992	888.4	3.3
Mampe *et al.*, 1993*	882.6	2.7
Arzumanov *et al.*, 2000	885.4	0.98
Serebrov *et al.*, 2005*	878.5	0.76
Pichlmaier *et al.*, 2010*	880.7	1.8
Magnetic Trap Experiments		
Paul *et al.*, 1989*	877	10
Ezhov *et al.*, 2009	878.2	1.9

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

Another constraint...from underground physics...on decays to DM?

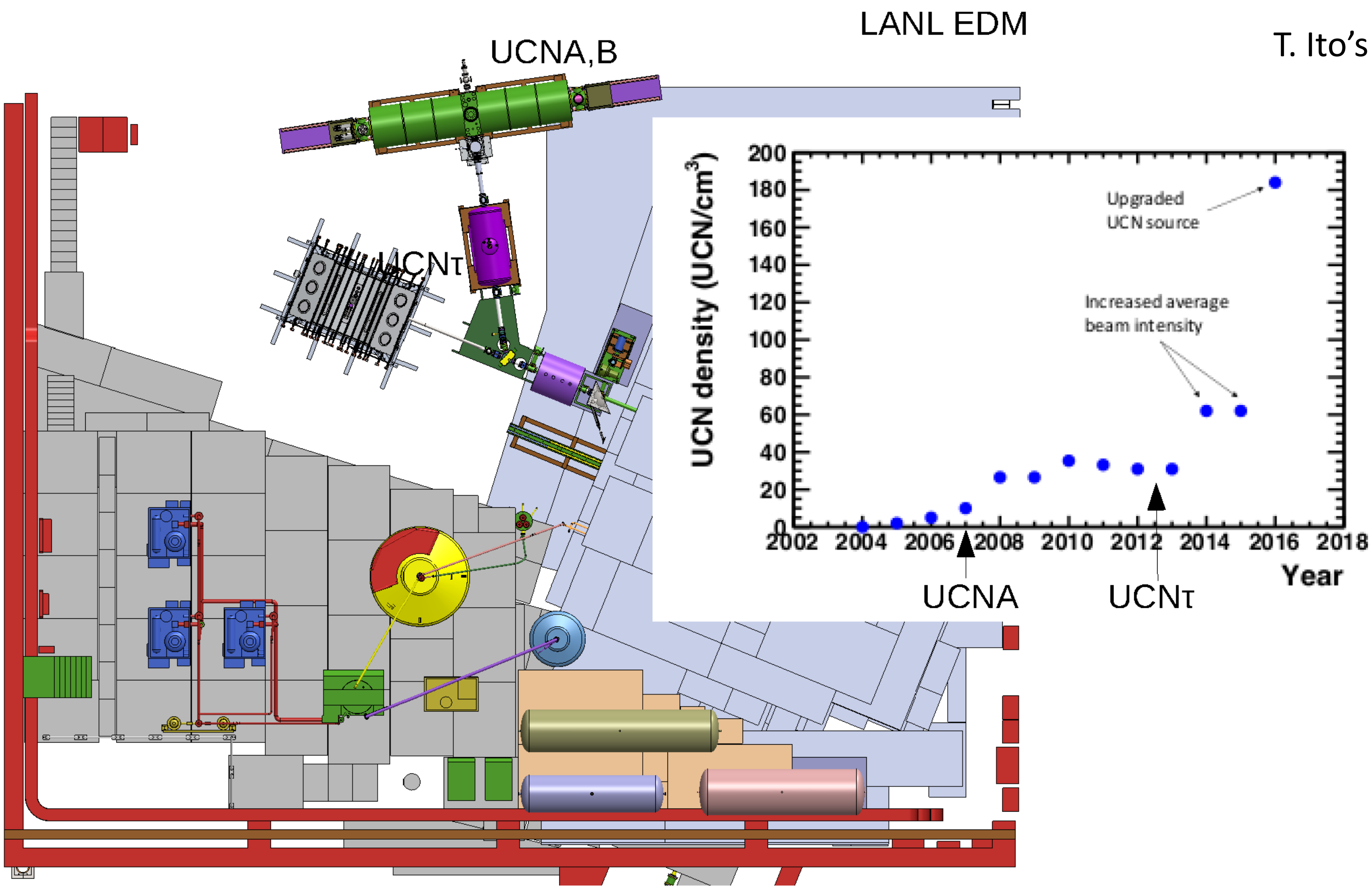


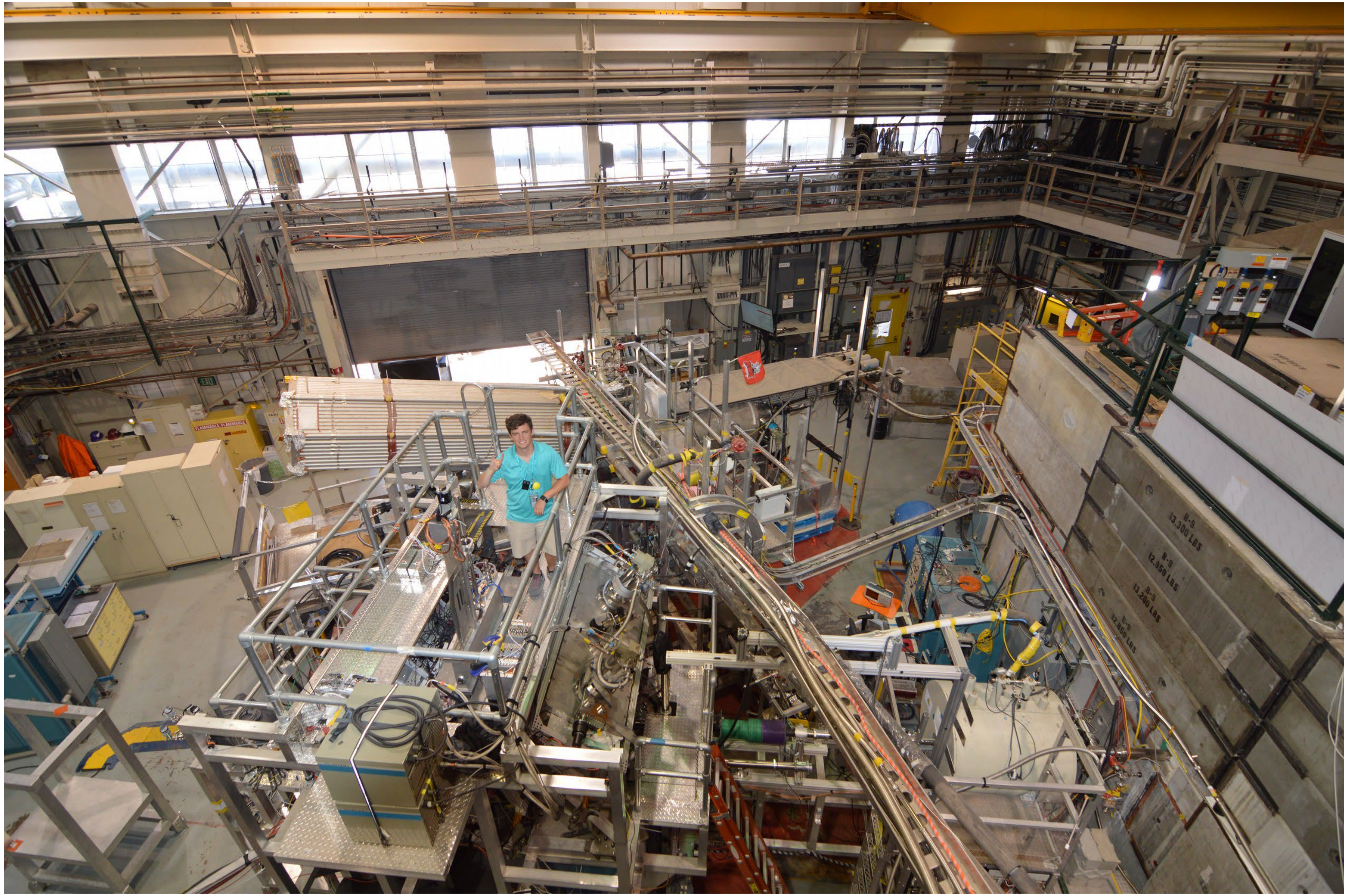
Min et al, ArXiv:1808.10644

Interactions with DM cause nucleons to decay into mesons! Can use nnbar limits to set scale for mediator at 10^7 GeV (about 4 orders of magnitude higher than is consistent with lifetime issues…) – need for very little of this DM to be around!

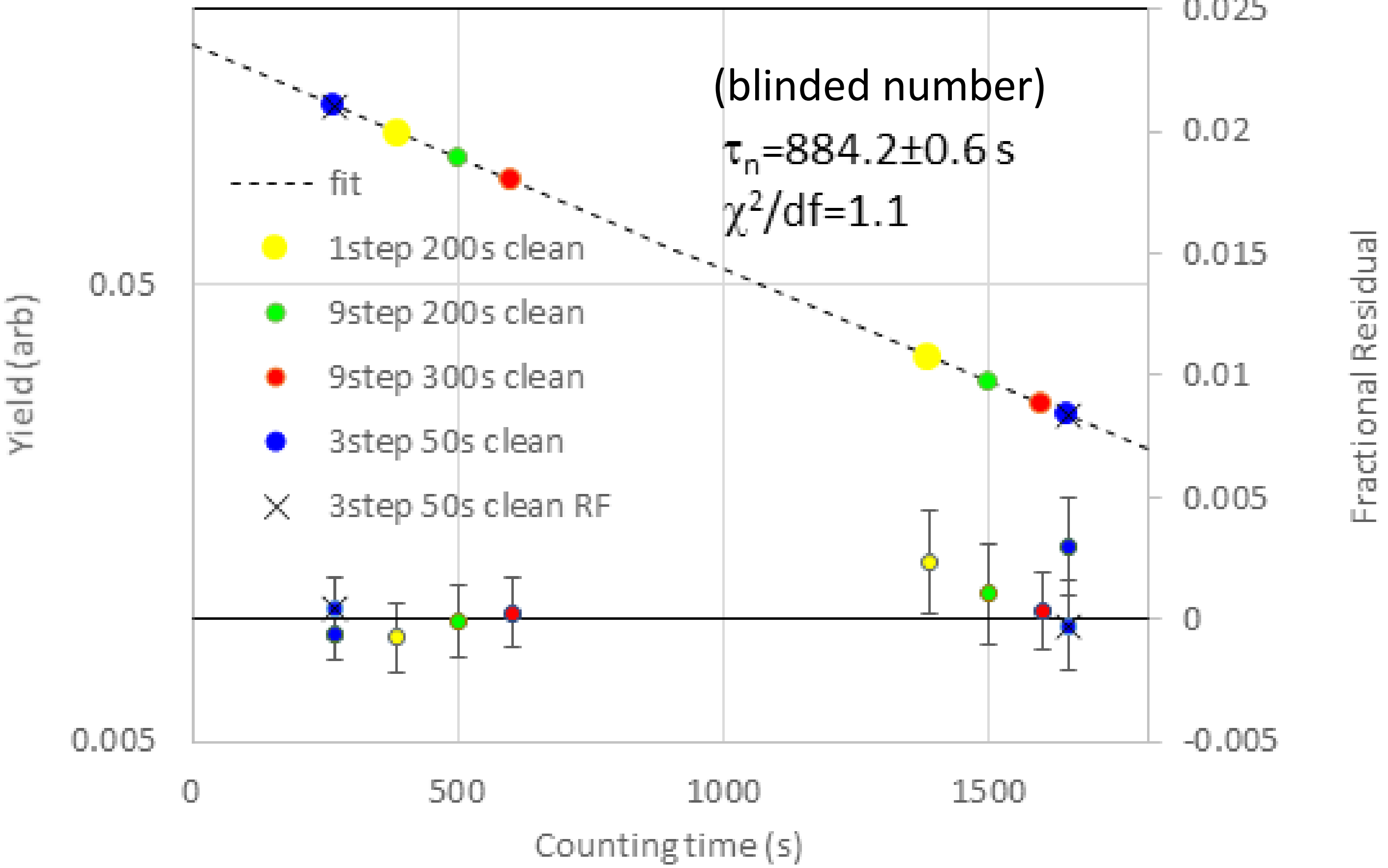
The LANSCE UCN Facility in 2017

T. Ito's talk on Thurs.





Global fit into a single exponential function

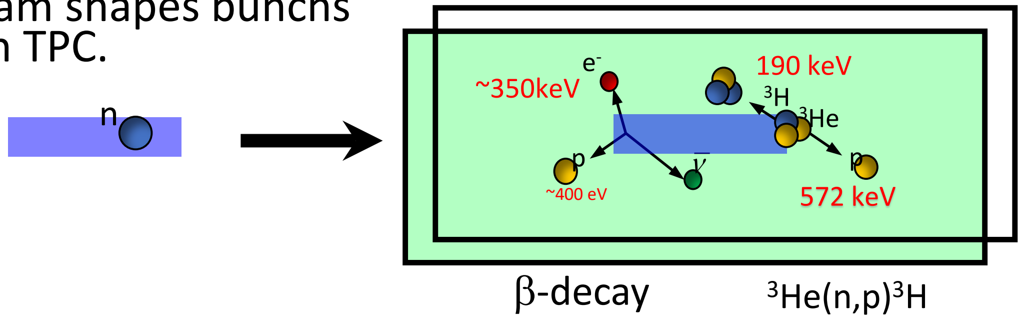


Short Description: works like a charm! UCN storage time greater than a month!

Neutron lifetime measurement at J-PARC BL05

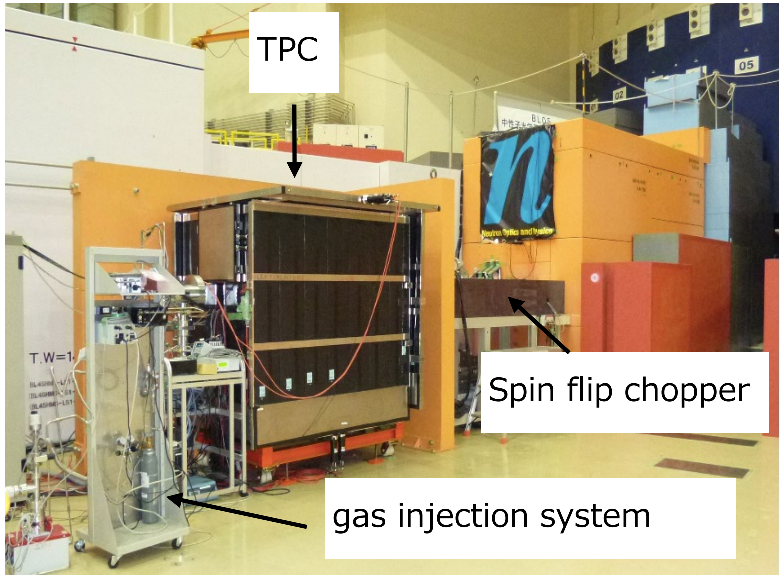
Neutron beam shapes bunchs shorter than TPC.

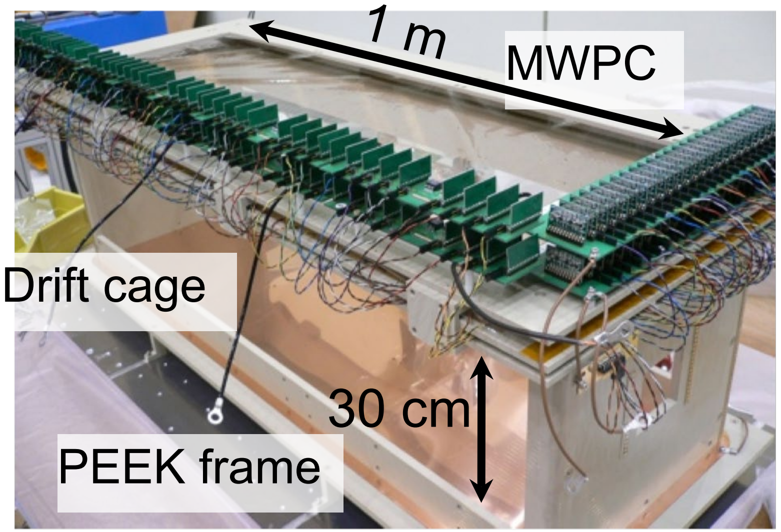
Count events during time of bunch in the TPC doped ~100 mPa of ^3He.



Ratio of Neutron beta decay and Count events during time of bunch in the TPC.

$$\tau = \frac{1}{\rho\sigma_0 v_0}\frac{S_{3He}}{S_\beta}$$





The goal of this experiment is 1 sec (0.1%) accuracy.

- Present statistics is ~2 s.
- Present systematics is estimated as < 10 s.