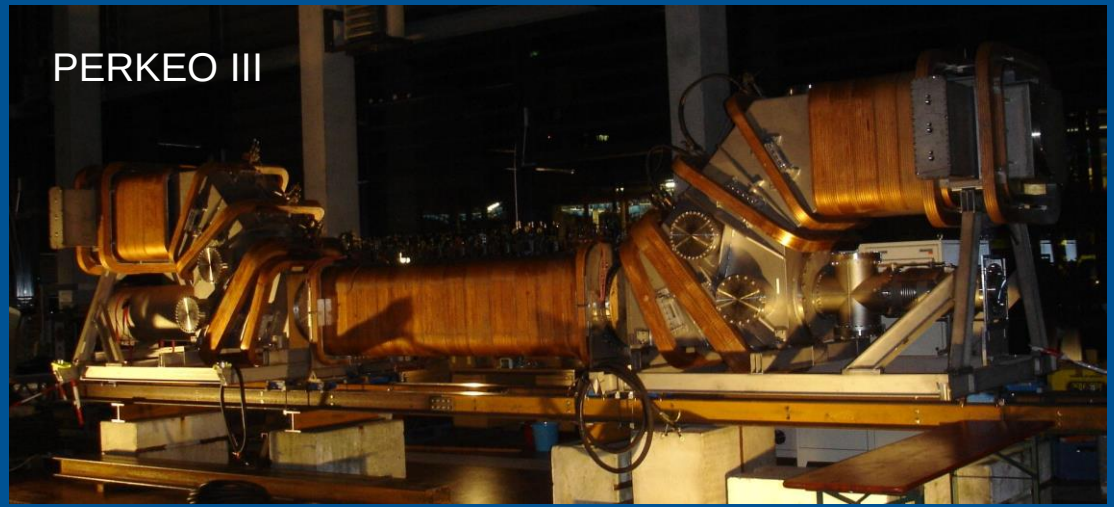
# $V_{ud}$ from Neutron Decay

Bastian Märkisch
Physik-Department
Technische Universität München




CKM2021, Melbourne

# Two Experimental Inputs

$V_{ud}$ from neutron decay requires only very few inputs: Many new results!

Updated „master formula“ with **radiative corrections** $\Delta_R$

$$V_{ud} = \left(\frac{5099.34s}{\tau_n(1+3\lambda^2)(1+\Delta_R)}\right)^{\frac{1}{2}}$$

C.-Y. Seng, M. Gorchtein, M.J. Ramsey-Musolf
Phys. Rev. Lett.121, 241804 (2018) and
Phys. Rev. D 100, 013001 (2019)

See talk by Mikhail Gorchtein

**Neutron lifetime $\tau$**

Material storage of UCN,
Magnetical storage of UCN,
In-beam (cold neutrons)

F. M. Gonzalez *et al.,*
Phys. Rev. Lett. 127, 162501 (2021)

See talk by Chen-Yu Liu

**Ratio of axial-vector and vector-couplings** $\lambda = g_A/g_V$

Beta-Asymmetry *A*
Electron-Neutrino-Correlation *a*
Others

BM *et al.,* Phys. Rev. Lett. 122, 242501 (2019)
Saul *et al.*, Phys. Rev. Lett. 125, 112501 (2020)
Beck *et al.*, Phys. Rev. C 101, 055506 (2020)
Hassan *et al.*, Phys. Rev. C 103, 045502 (2021)

This talk

Also: percent level LQCD results on $g_A$, many theory articles: Czarnecki *et al.*, Hayen *et al.*, Ivanov *et al.*, Falkowski *et al.*

# Status of Neutron Lifetime

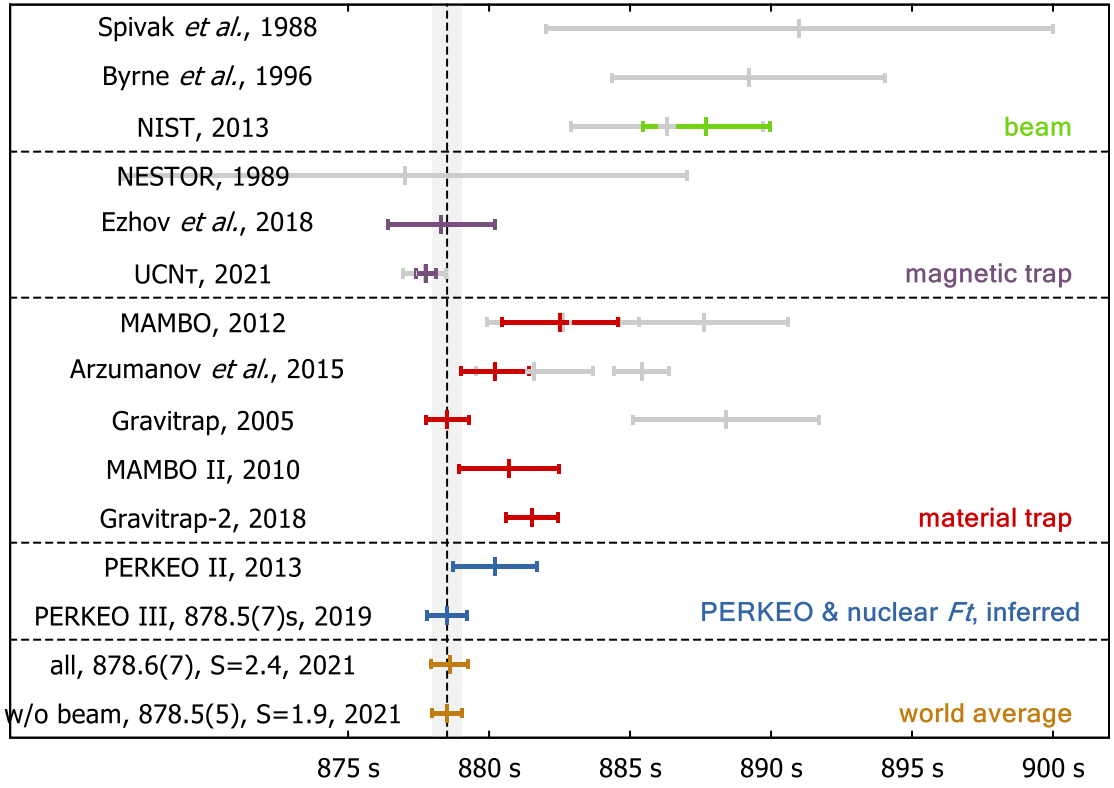
Most precise experimental results using material traps or magnetic traps consistent.

Grey data are *not* included in world-average. Some re-analyzed, updated, or retracted older measurements.

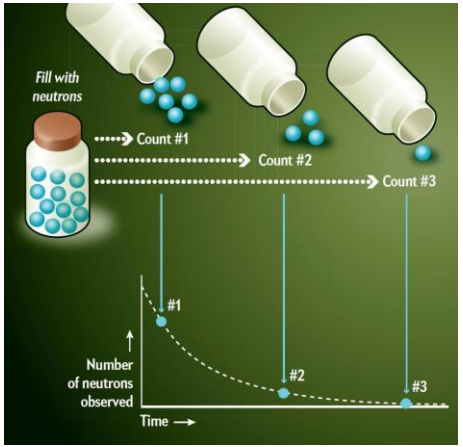
Magnetic and material bottle measurements in agreement with SM prediction based on nuclear *Ft* values and λ: mostly excludes exotic new decay channels.

Dubbers, *et al.*, Phys. Lett. B 791, 6-10 (2019)
Czarnecki, *et al.*, Phys. Rev. Lett. 120 (2018) and Phys. Rev. D 100, 073008 (2019)

PDG avg. currently does not consider beam.



# Neutron Lifetime: Material Storage; Bottle Method




*Picture: G.L. Greene, P. Geltenbort: The Neutron Enigma, Sci. Am. 314, 36 (2016).*

„Fill-and-empty“

**Measurement of the neutron lifetime using a gravitational trap and a low-temperature Fomblin coating**
A. Serebrov *et al.*, Phys. Lett. B 605 (2005) 72-78

$$\tau = (878.5 \pm 0.8)\ \mathrm{s}$$

Measure lifetime by **relative** comparison of number of stored neutrons N after different storage times t

$$\frac{1}{\tau_m} = \frac{1}{t_2 - t_1} \cdot \ln \frac{N(t_1)}{N(t_2)}$$

*Measured* storage time is (potentially) modified by systematic effects: wall-losses, UCN-leaks, rest gas interaction, …

$$\frac{1}{\tau_m} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\mathrm{wall}}} + \frac{1}{\tau_{\mathrm{leak}}} + \frac{1}{\tau_{\mathrm{vacuum}}} + \ldots$$

Minimize wall losses by choice of material and/or low temperature (since $E_{UCN} \ll k_B T$).
Variation of trap size and neutron spectrum.

# Neutron Lifetime: *Magnetic Storage*

## UCNτ at LANL, USA

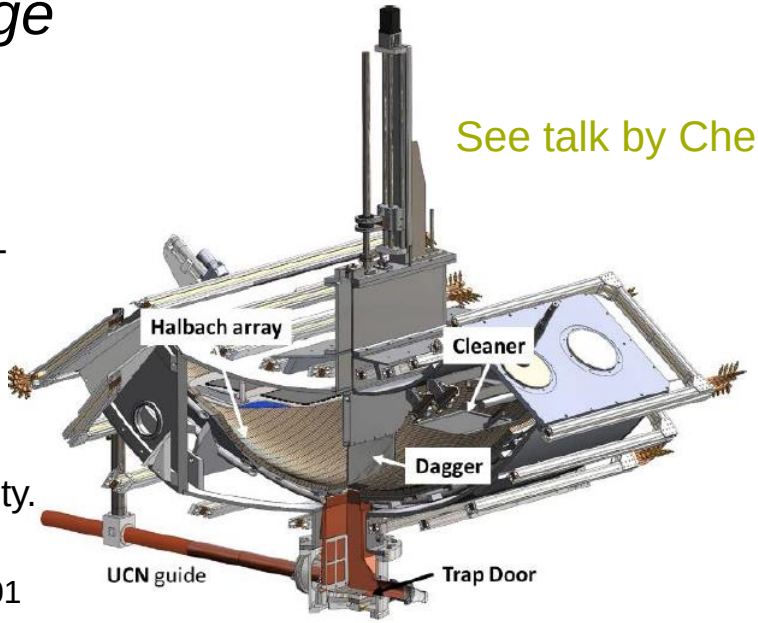
See talk by Chen-Yu Liu

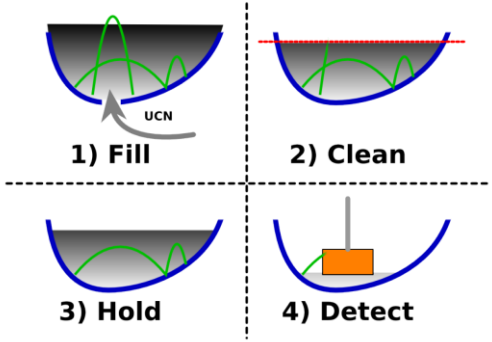
Measurement of the neutron lifetime using a magneto-gravitational trap. This avoids material interaction and associated losses.

$$877.75 \pm 0.33\ \mathrm{s}$$

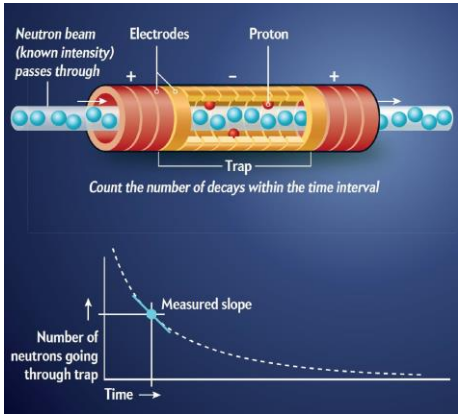
Largest correction to raw result smaller than uncertainty.
Most precise result.

F. M. Gonzalez *et al.,* Phys. Rev. Lett. 127 (2021) 162501
R.W. Pattie Jr. *et al.*, Science 360, 6389 (2018) 627-632



# Neutron Lifetime: *Beam Method*



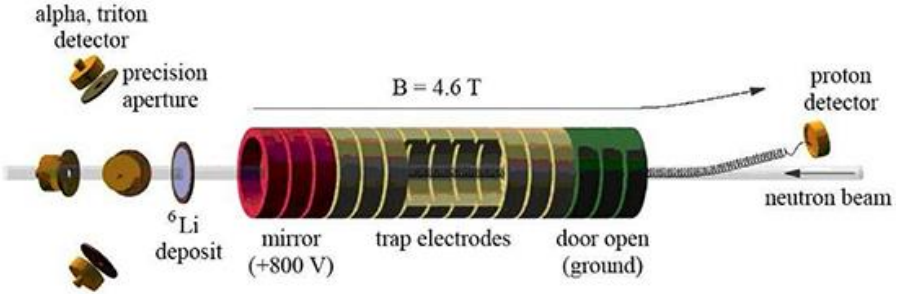

*Picture: G.L. Greene, P. Geltenbort: The Neutron Enigma, Sci. Am. 314, 36 (2016).*

Measure lifetime by **absolute** determination of neutron flux and neutron decay rate: slope!

$$n_\beta = \frac{\mathrm{d}N}{\mathrm{d}t} = -\frac{N_0}{\tau_n} e^{-\frac{l}{v \cdot \tau_n}}$$

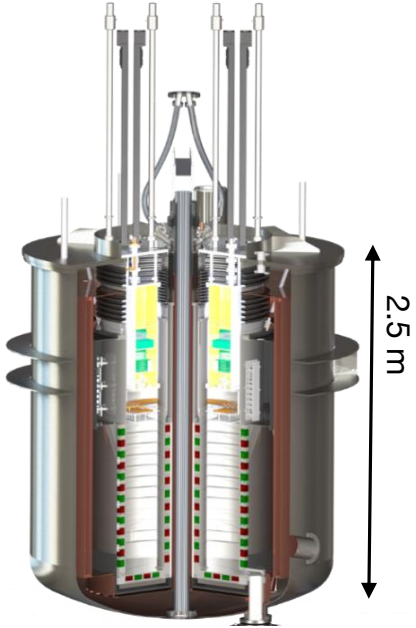
**Improved Determination of the Neutron Lifetime**
A. T. Yue *et al.*, Phys. Rev. Lett. 111, 222501

$$\tau = (877.7 \pm 2.2)\ \mathrm{s}$$




BL-2: improved detector, electrostatic trap, electronics, statistics; measurement recommences with availability of neutrons at NIST.
Successor BL-3 funded.

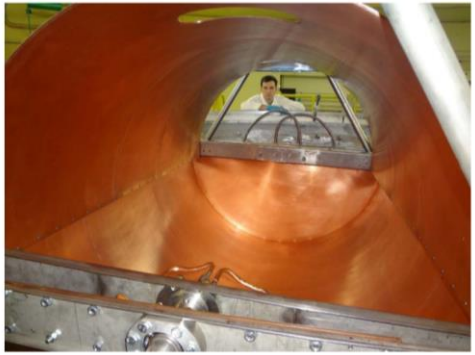
# Lifetime Projects




PENeLOPE, TUM

superconducting multipole **magnet**, **in-situ** decay detection

R. Picker, *et al.*, J. Res. NIST 110, 357 (2005)

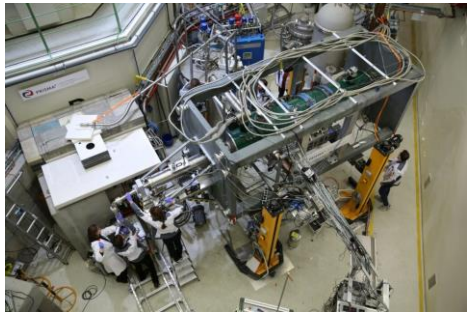


Gravitrap-2, ILL

**material**, giant size

**first result**: $\tau_n = 880.7(7)_{\mathrm{stat}}(6)_{\mathrm{sys}}$

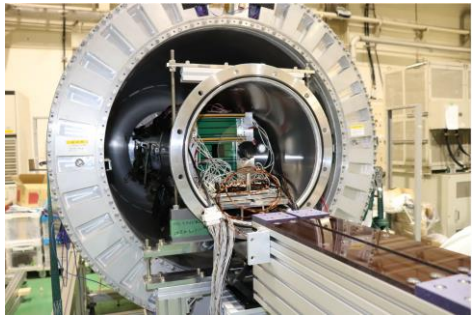
Serebrov, *et al.*, Phys. Rev. C 97, 055503 (2018)



tauSPECT, Mainz

permanent **magnet** multipole, s uperconducting magnet, horizontal

Kahlenberg 10.25358/openscience-5455



LiNA, J-PARC

cold, pulsed beam; TPC with $^4$He and He admixture in magnetic field

Yano *et al.*, JPS Conf. Proc. , 011117 (2021)

Predecessor: Hirota et al., Prog. Theor. Exp. Phys. 12, 123C02 (2020)

HOPE, ILL

permanent **magnets**, vertical **in-situ** decay detection

Leung, *et al.*, Phys Rev C 94, 045502 (2016)

*Successors to UCNtau (Tau2), Ezhov bottle, BL3, …*

# Status of $\lambda = g_A/g_V$ from Decay Correlations

All 4 results by PERKEO II, 4 results by UCNA, and the PERKEO III result are consistent - since 1997! (Not pre-2002…)

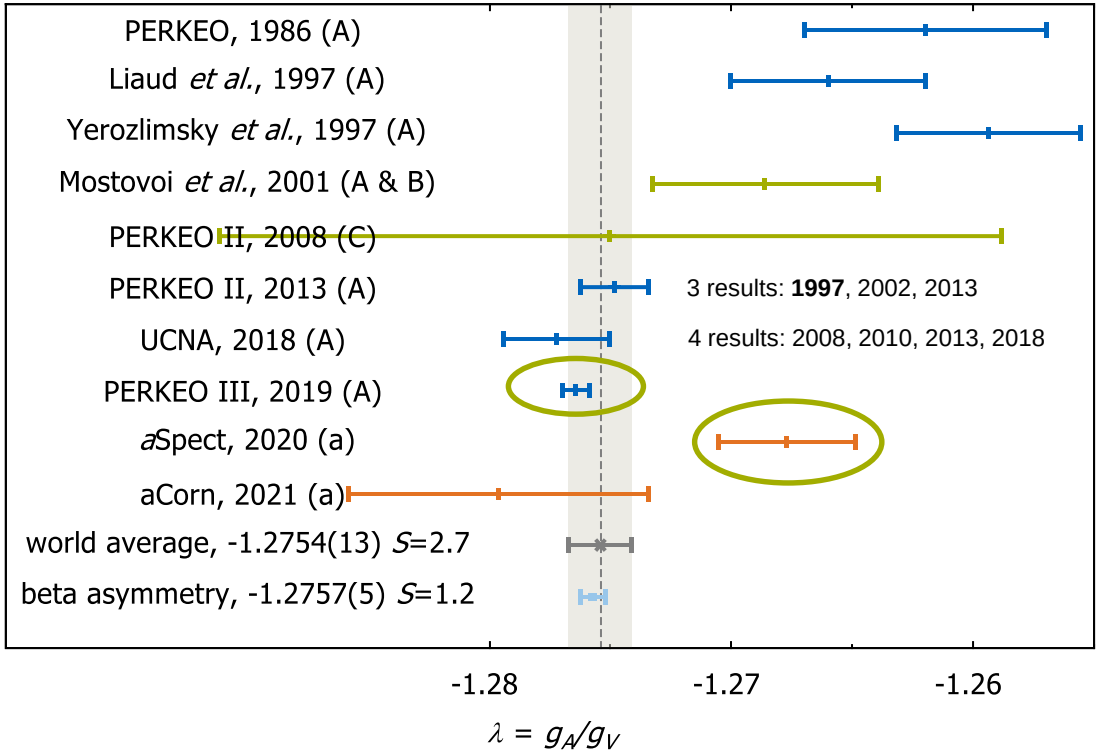
But disagree with older measurements of beta asymmetry $A$ and new *a*Spect electron-neutrino correlation $a$ result.

$$A_{avg} = -0.11958(21), \qquad S = 1.2$$

Newer measurements of *A* have order of magnitude **smaller corrections**.

UCNA, PERKEO III, aCorn, aSpect: **blinded analysis**.

(Newer results of UCNA & PERKEO II include older results)



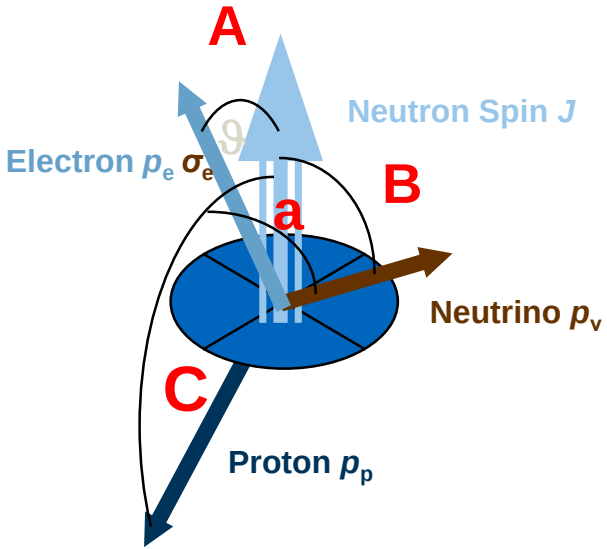

UCNA: A. Saunders, CKM2018

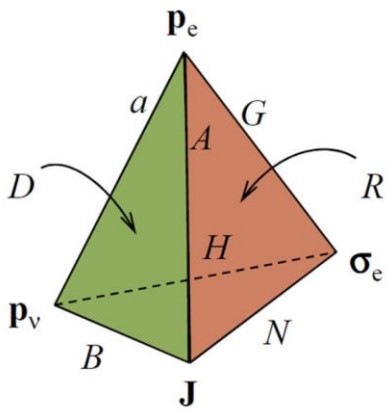
Brown et al., Phys. Rev. C 97, 035505 (2018)

# Correlations in Neutron Decay

Determination of $\lambda = g_A/g_V$ from neutron decay via angular **correlations**; (typically) **beta asymmetry *A***, or **electron-neutrino correlation *a***:

$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2} \qquad a = \frac{1-\lambda^2}{1+3\lambda^2}$$



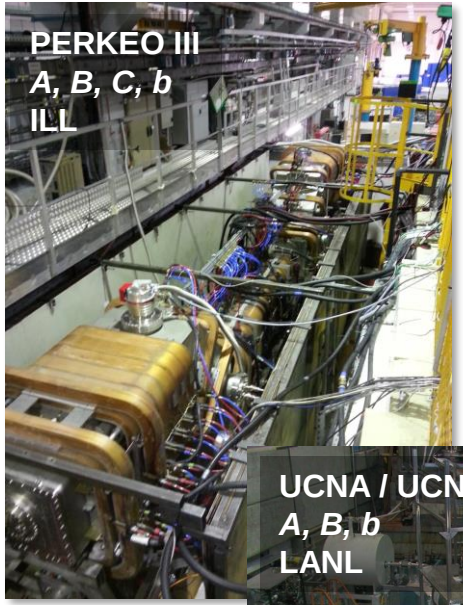




O. Naviliat-Cuncic and M. Gonzalez-Alonso, Ann. Phys. 525, 8–9, 600–619 (2013)
Dubbers and Schmidt, Rev. Mod. Phys (2012)

Typically, **specialised** instruments / setups required for different observables.

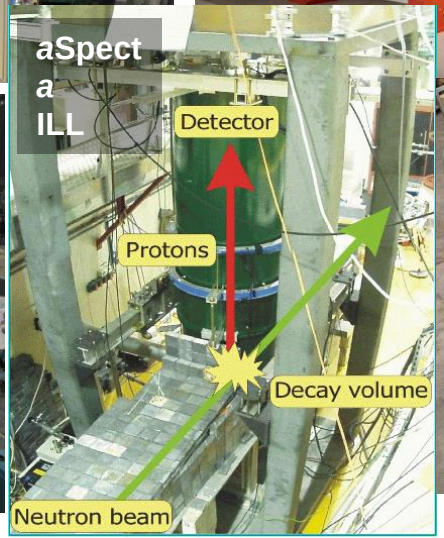
More on neutron beta decay: Falkowski, *et al.*, J. High Energ. Phys. 2021, 126 (2021)
Dubbers & BM, Ann. Rev. Nucl. Part. Sci. 71, 139-163 (2021)

# Current Neutron Decay Correlation Experiments

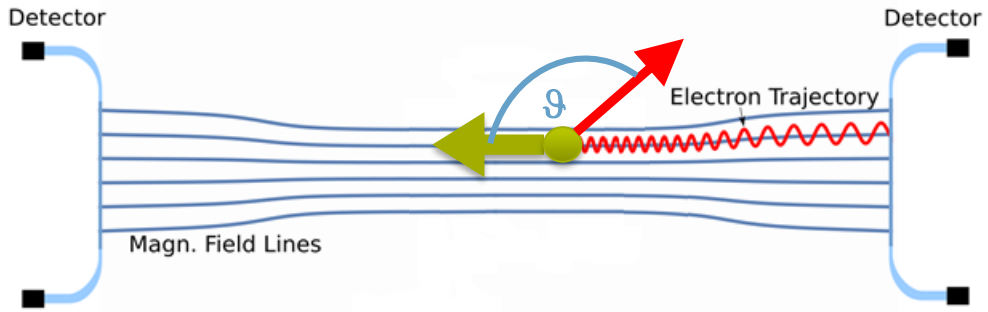









# PERKEO: Measuring Beta Asymmetry – **Symmetric Layout**




electron angular distribution:

$$W(\vartheta, E) = 1 + \frac{v}{c} A \cos\vartheta$$

within Standard Model:

$$A = -2\,\frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \qquad \lambda = \frac{g_A}{g_V}$$

magnetic field for spin alignment

integration over hemispheres:
2 × 2 π detection

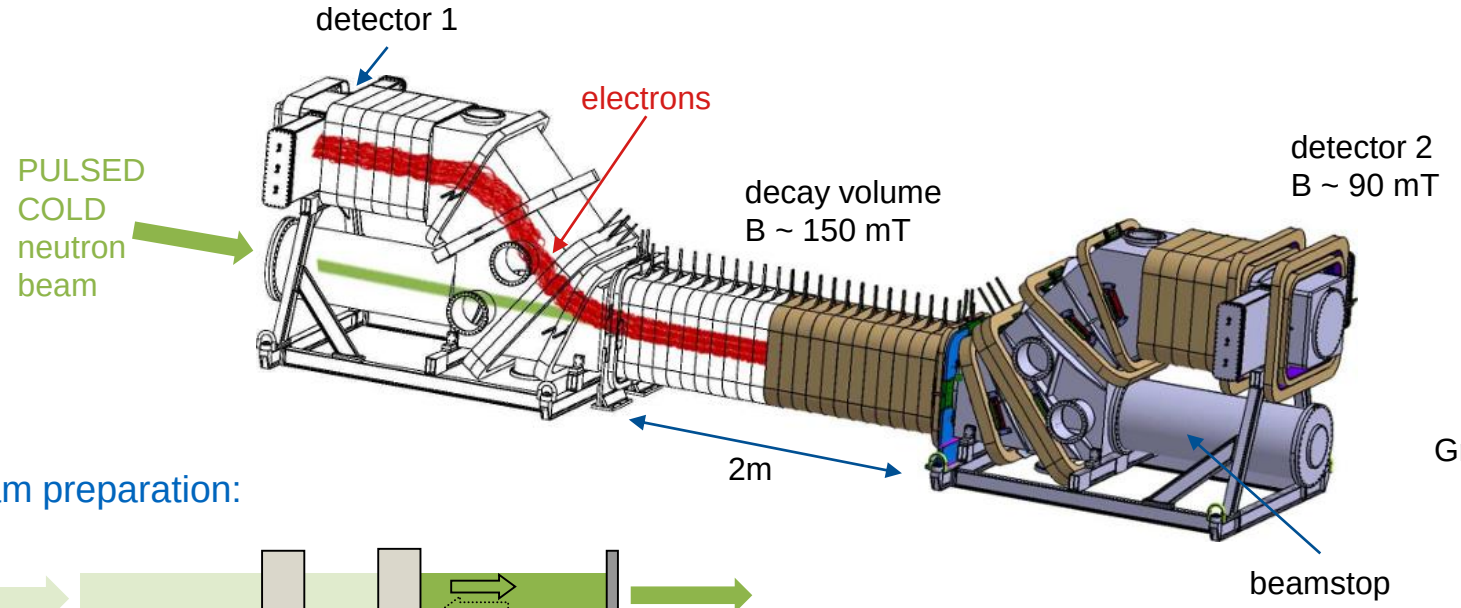
$$\cos\vartheta \rightarrow 1/2$$

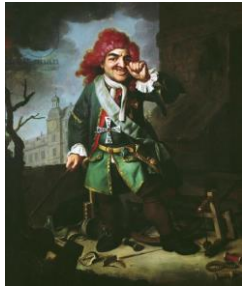
experimental asymmetry, polarisation *P*

$$A_{\text{exp}} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}} = \frac{1}{2}\frac{v}{c} P A$$

symmetric layout enables detection of backscattered electrons

# Spectrometer PERKEO III

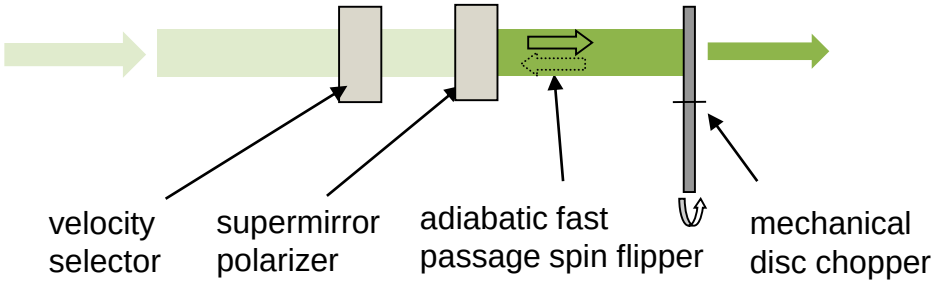


Perkeo

guardian of the
Great Heidelberg Tun

Beam preparation:




~50.000 decays/s in polarised *continuous* beam;
time avg. :~200 $s^{-1}$ in polarised pulsed mode,
~800 $s^{-1}$ in unpolarised pulsed mode

# Background Subtraction with Pulsed Neutron Beam

Free neutron pulse does not interact with matter during measurement.

Same background condition in *signal* and *background time window.*

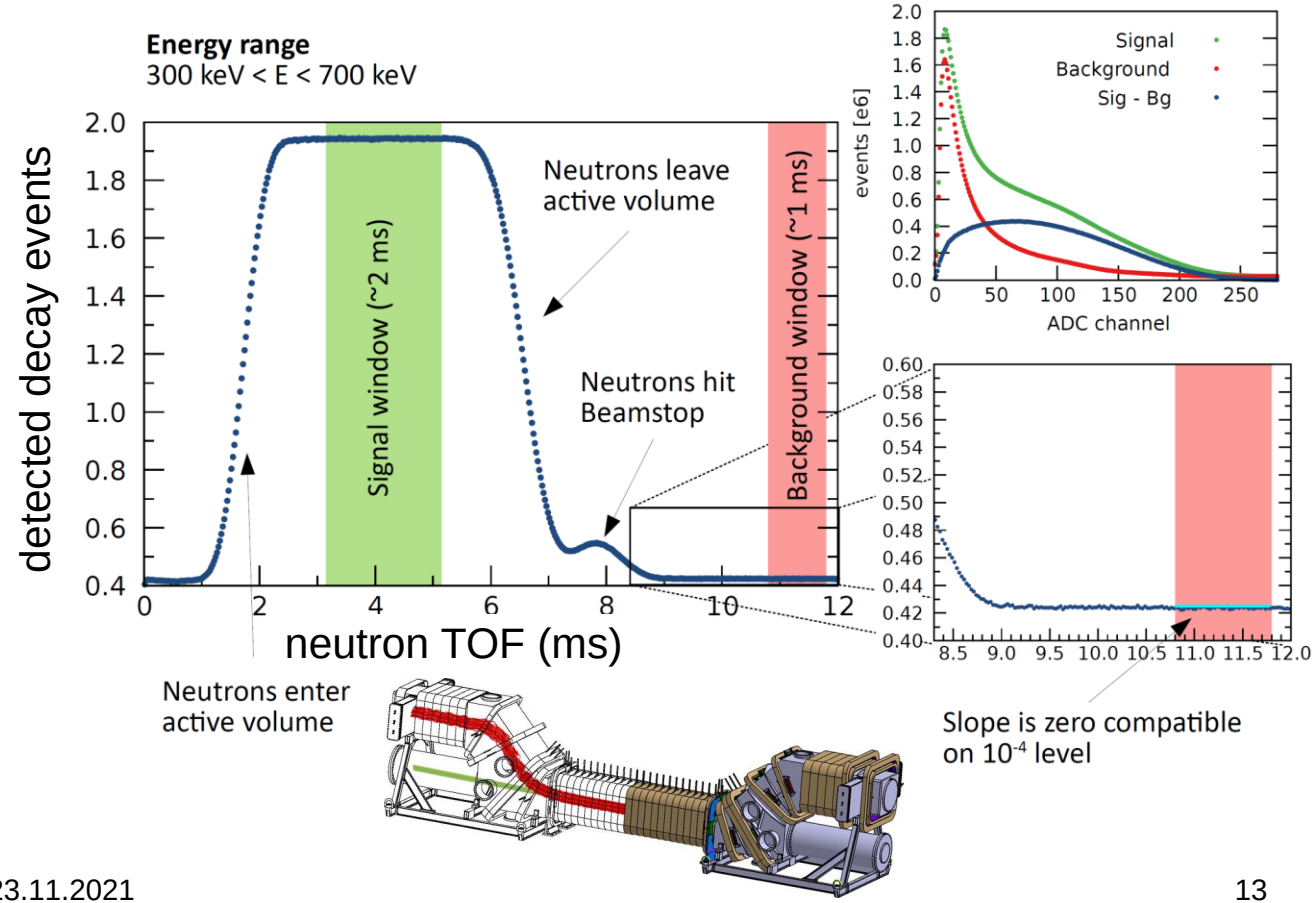
**Related Uncertainties:**

Time dependence

$$\Delta A/A = 0.8\times10^{-4}$$

Chopper disc uniformity

$$\Delta A/A = 0.7\times10^{-4}$$



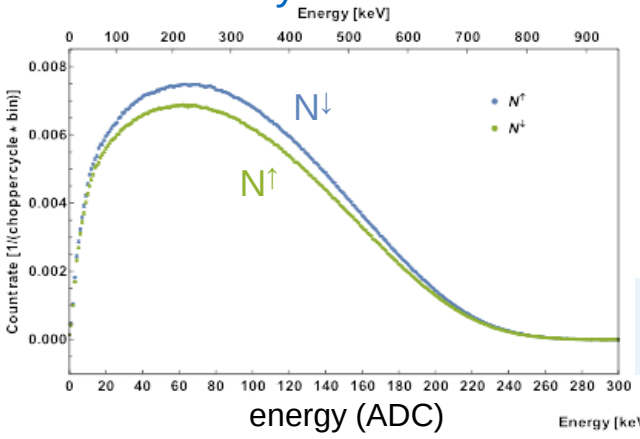
# Summary of Corrections and Result

**Corrections** to the „raw“ fit result on the $10^{-3}$ – $10^{-4}$ level only.

**Analysis blinded** to remove potential bias.

Separate analyses by independent teams :

- electron and background measurements,
- neutron polarisation: opaque $^3$He spin filters,
- magnetic mirror effect.

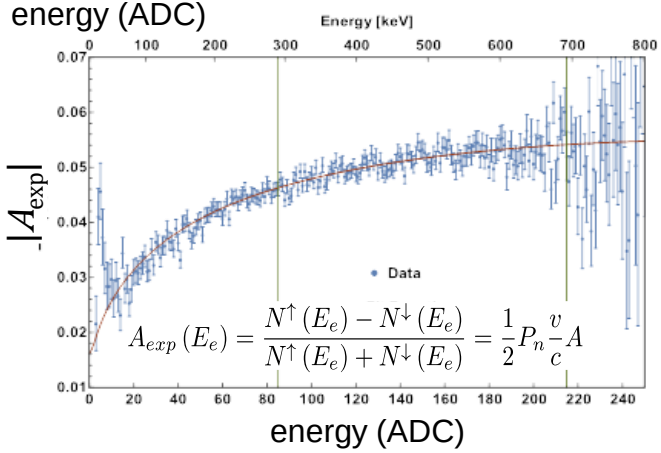



$6\times10^8$ events,
$(\Delta A/A)_{\text{stat}} = 14 \times 10^{-4}$

$$\lambda = -1.27641(45)_{\text{stat}}(33)_{\text{sys}}$$
$$= -1.27641(56)$$
$$A = -0.11985(17)_{\text{stat}}(12)_{\text{sys}}$$
$$= -0.11985(21).$$

$$\frac{\Delta\lambda}{\lambda} = 4.4 \times 10^{-4}$$

Phys. Rev. Lett. 122, 222503 (2019)




BSM analysis including scalar & tensor couplings (Fierz term):

PERKEO III: Saul, *et al.*, Phys. Rev. Lett. 125, 112501 (2020)

UCNA: Sun, *et al.*, Phys. Rev. C 101, 035503 (2020)

# *a*SPECT at ILL

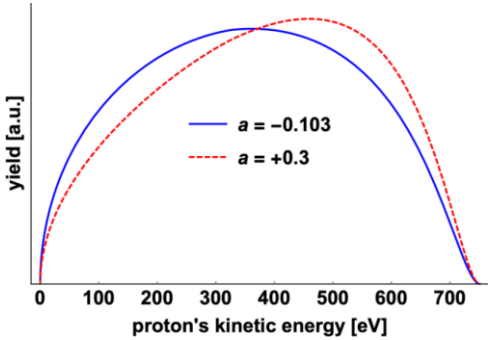
MAC-E type spectrometer to derive electron-neutrino correlation from proton spectrum

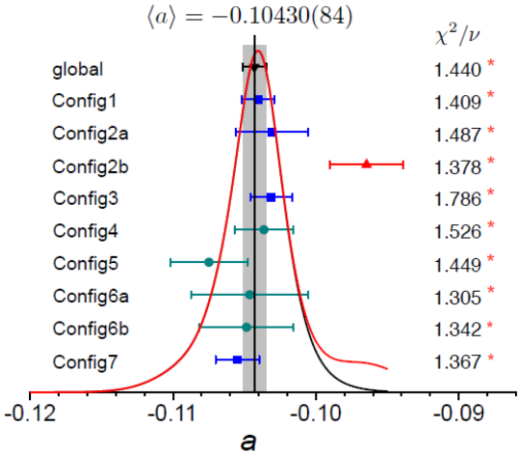
**Multiple configurations**: runs with changes of measurement configuration from optimum:
Total $10^9$ events in analysis

**Multidimensional fit** to determine instrument parameters:
144 data points int. proton spectrum, 192 auxiliary measurements & MC results;
68 fit parameters.
Scale error to account for red. $\chi^2$

$$a = -0.10430(84)\,,\ \Delta a/a = 0.8\%$$
$$\lambda = -1.2677 \pm 0.0028$$

Beck, *et al.*, Phys. Rev. C 101, 055506 (2020)




PF1b at ILL. Grenoble

# Nab at SNS

## Running at the Spallation Neutron Source, Oak Ridge, TN

Determine a from slope of cuts through Dalitz plot. Determine electron energy from Si detector, proton energy from time-of-flight.

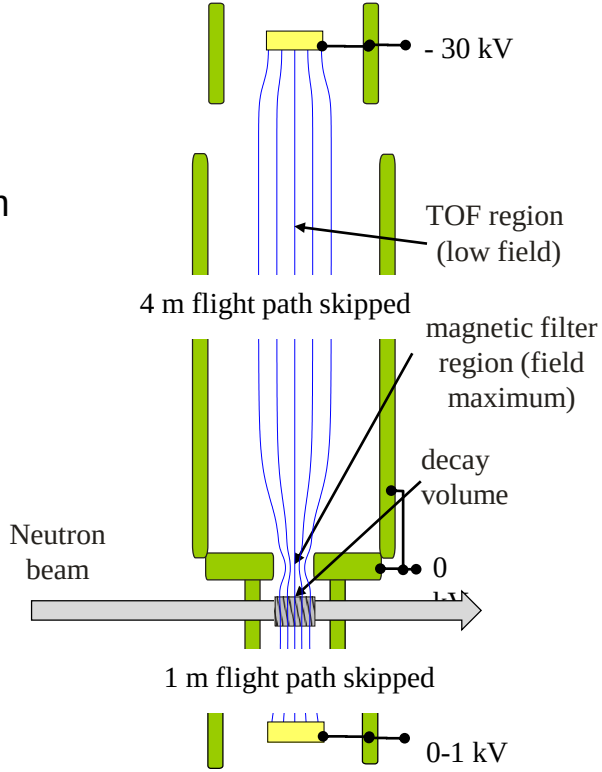
Goal of current measurement run

$$(\Delta a/a) = 2 \cdot 10^{-3}$$
$$(\Delta \lambda/\lambda) = 5 \cdot 10^{-4}$$

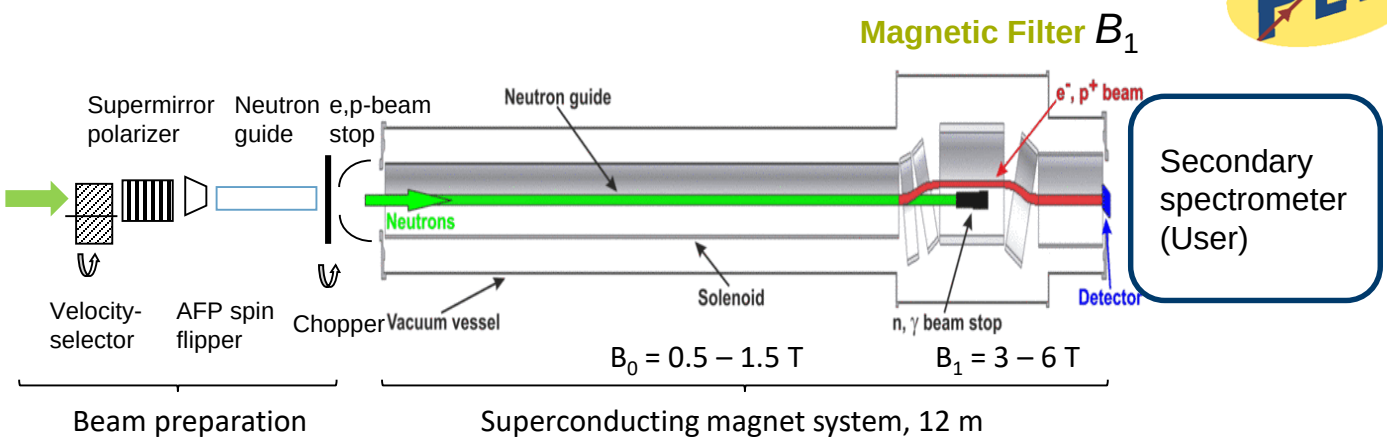
pNab proposal:

$$(\Delta A/A)_{\text{stat}} = 8 \cdot 10^{-4}$$
$$(\Delta \lambda/\lambda)_{\text{stat}} = 2 \cdot 10^{-4}$$

Fry et al., EPJ Web Conf. 219, 04002 (2019)
Počanić et al., NIM A 611, 211 (2009)




# PERC Facility at MLZ




Secondary spectrometer (User)

**Innovative concept**

- Cold (pulsed) neutron beam (MEPHISTO / hall east)
- Non-depolarising neutron guide as **active volume**
- **Magnetic filter** ($B_1$= 3 - 6T) to enhance systematics
- Source of electrons and protons to user-spectrometers

$$\frac{B_1}{B_0} = 2 \dots 12$$

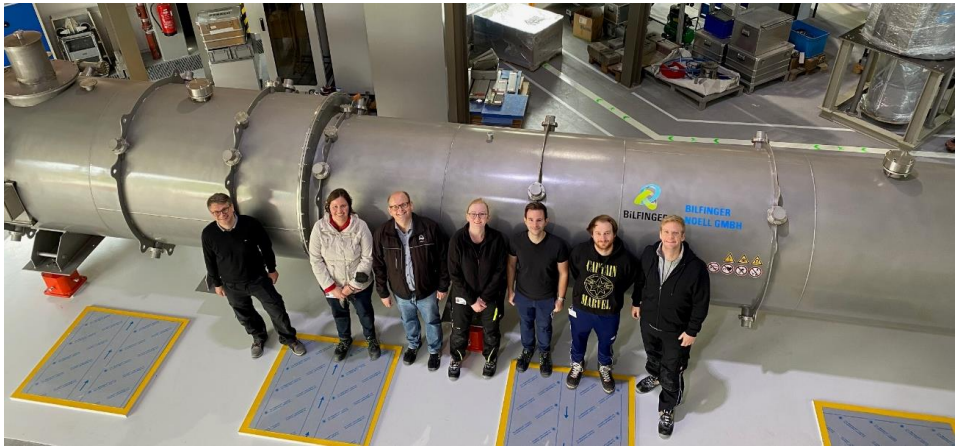
Goal:

$$\Delta A/A = 5 \cdot 10^{-4}$$
$$\Delta\lambda/\lambda = 1 \cdot 10^{-4}$$

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

# PERC Magnet Delivered!






PERC‘s main component, a 12m long superconducting magnet system, arrived at FRM II, Garching.

# Proposed Cold Beamline for Particle Physics at ESS

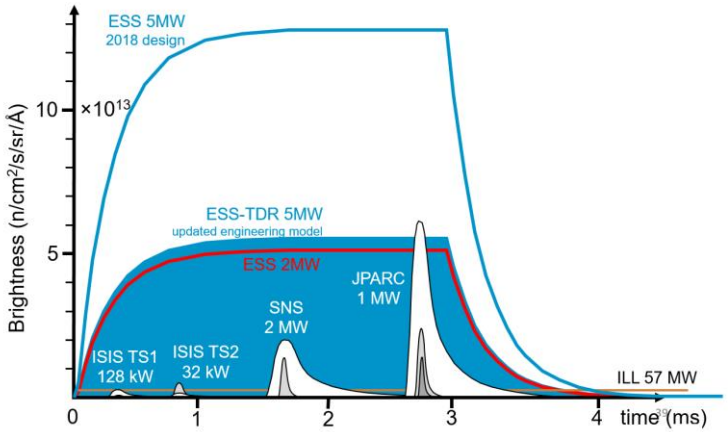
## Particle Physics Beamline at the European Spallation Source

ESS design goal is same time average neutron flux as ILL. Peak brightness in pulse: 30 × ILL

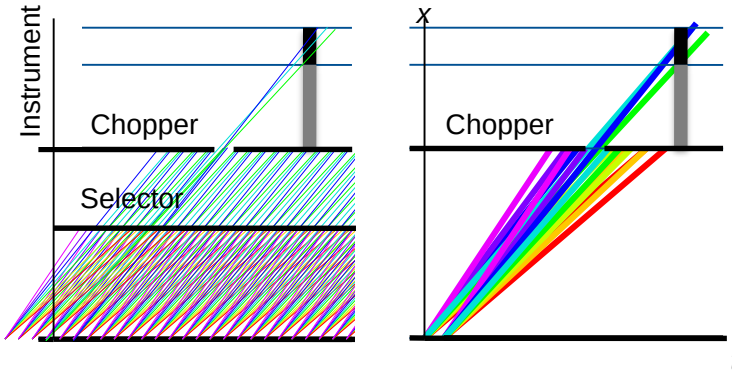
Using pulsed beam for particle physics already at reactor sources!

## Statistics gain factor for a PERC-like system: x 15 !

*ANNI – A pulsed cold neutron beam facility for particle physics at the ESS*
T. Soldner, *et al.*, EPJ Web Conf. 219, 10003 (2019)




**Reactor** **ESS: Peak brightness = 30 × ILL**




## General purpose particle physics beam line:

Neutron beta decay, EDM, hadronic weak interaction, Baryon number violation, …

# Neutron and $V_{ud}$ Summary and Outlook

## Breakthrough result in neutron lifetime

UCNτ halves the error on neutron lifetime: $\tau_n = 877.75(33)s$

Bottle measurements (magnetic and material) mostly consistent: $\tau_n = 878.5(5)s,\ S = 1.9$

Tension with beam measurement remains: improved BL-2 measurement ongoing

## Ratio of axial-vector and vector coupling

PERKEO III result improves world-average of beta asymmetry by factor 5,

$$A = -0.11958(21),\ S = 1.2 \quad \lambda_A = -1.2757(5)$$

Tension in particular with *a*SPECT result on electron-neutrino correlation:

$$\lambda_{\mathrm{avg}} = -1.2754(13),\ S = 2.7$$

## Matrix element $V_{ud}$ from neutrons competitive!

Beta asymmetry: $V_{ud} = 0.97408(11)_{RC}(28)_{\tau}(32)_{\lambda} = 0.97408(44)$

All data: $V_{ud} = 0.97427(11)_{RC}(28)_{\tau}(82)_{\lambda} = 0.97427(88)$

Nuclear decays $V_{ud} = 0.97373(31)$ Hardy & Towner, Phys. Rev. C 102, 045501 (2020)

Improved experiments running or under construction,