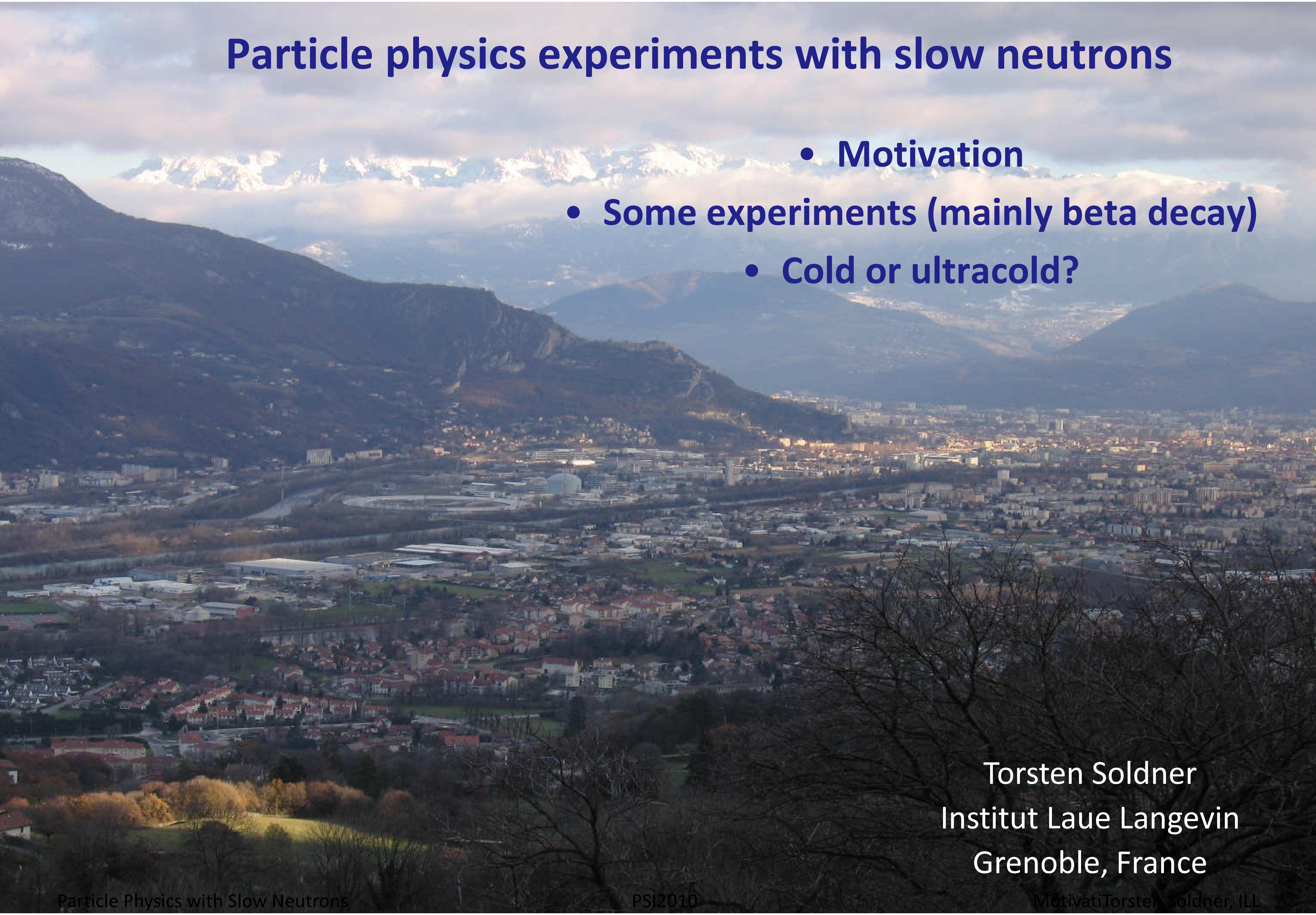


Particle physics experiments with slow neutrons

- Motivation
- Some experiments (mainly beta decay)
- Cold or ultracold?

Torsten Soldner
Institut Laue Langevin
Grenoble, France

Neutron and known interactions

Strong

- Nuclear force (n,γ), (n,p)...
- Neutron optical potential
- Neutron polarisibility
  →Potential of quark confinement

Electromagnetic

- Magnetic moment
  ↔quark magnetic moment
- Neutron neutrality
  →Charge quantisation (SM++, GUTs, magnetic monopoles?)

Weak

- Neutron beta decay
- Weak hadronic processes
  →$p(n_{pol},\gamma)d$, $^{6}Li(n_{pol},t)\alpha$ ...
  →neutron weak spin rotation

Gravitation

- Newton: $V = -G\frac{m_n M}{r}$

but: Falling quantum object

Neutron and unknown interactions

GUTs?

\+ favourable symmetry breaking:

→ observable n$\underline{n}$

SUSY? Additional higgs fields?...

- New CP violating phases

→ EDM

→ CP violation in decay

Additional heavy bosons?

- Right-handed, leptoquark, exotics

→ Modification of V—A weak interaction

→ New CP violation

Short range forces?

- Light bosons (axions...)?
- Extra dimensions?

→ $V \propto \frac{\alpha e^{-r/\lambda}}{r}$

→ Spin-dependent interactions

Neutron beta decay

$n \rightarrow p\, e\, \bar{\nu}_e$ 99.7%

- Next slide

$n \rightarrow p\, e\, \bar{\nu}_e\, \gamma$ 3.13(35) · 10^{-3}

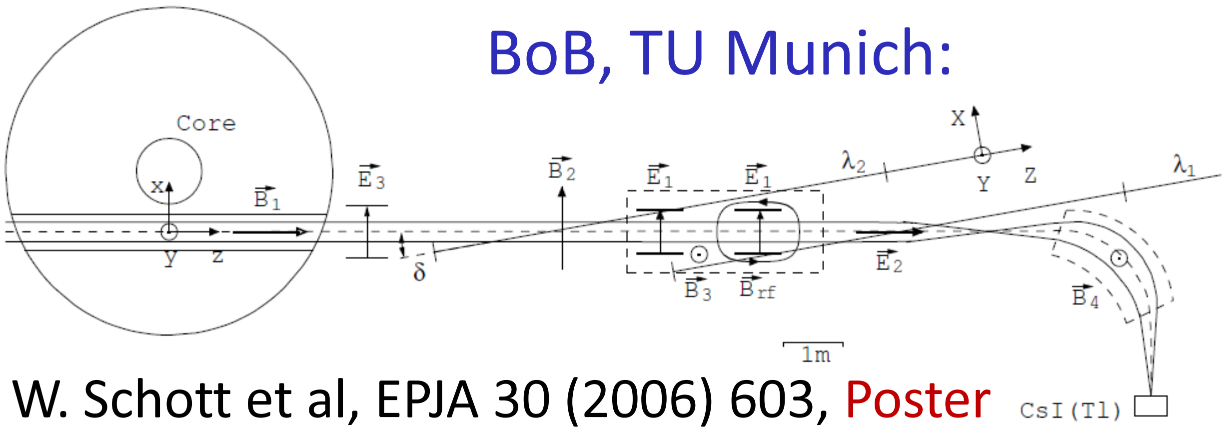
- Precise branching ratio?
- Photon spectrum?
- Angular correlations?
- Talk S. Gardner, Tuesday

$n \rightarrow H\, \bar{\nu}_e$ 4 · 10^{-6} (predicted)

- Signature: T_H = 326 eV
- First detection?
- Occupation of hyperfine states?

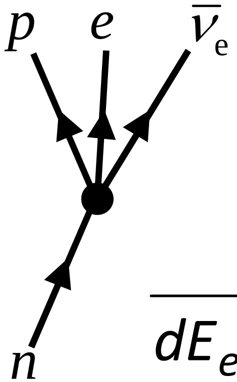
ν_e	n	p	e	$\|m_S m_l\rangle$	*W* [%]
←	←	←	→	|+->	44.14(5)
←	←	→	←	|-+>	55.24(4)
←	→	→	→	|++>	0.622(11)
→	←	←	←	|-->	0
→	→	→	←	|-+>	0
→	→	←	→	|+->	0

BoB, TU Munich:



W. Schott et al, EPJA 30 (2006) 603, Poster

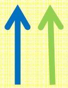
Neutron beta decay and weak interaction



$$H = \frac{G_W}{2\sqrt{2}} \sum_{i=V,A,S,T} \left\{ L_i \left(\bar{p}\boldsymbol{O}_i n\right)\left(\bar{e}\boldsymbol{O}_i\left(1-\gamma_5\right)\nu\right) + R_i\left(\bar{p}\boldsymbol{O}_i n\right)\left(\bar{e}\boldsymbol{O}_i\left(1+\gamma_5\right)\nu\right)\right\}$$

$$\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto G_e(E_e)\left\{1 + a\frac{\boldsymbol{p}_e\boldsymbol{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \boldsymbol{P}\left(A\frac{\boldsymbol{p_e}}{E_e} + B\frac{\boldsymbol{p_\nu}}{E_\nu} + D\frac{\boldsymbol{p_e}\times\boldsymbol{p_\nu}}{E_e E_\nu}\right)\right\}$$

$$a = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}$$

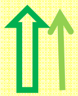


$$= \frac{|L_V|^2 - |L_A|^2 - |L_S|^2 + |L_T|^2 + |R_V|^2 - |R_A|^2 - |R_S|^2 + |R_T|^2}{|L_V|^2 + 3|L_A|^2 + |L_S|^2 + 3|L_T|^2 + |R_V|^2 + 3|R_A|^2 + |R_S|^2 + 3|R_T|^2}$$

$$A = \frac{N_{\Uparrow\uparrow} - N_{\Uparrow\downarrow}}{N_{\Uparrow\uparrow} + N_{\Uparrow\downarrow}}$$

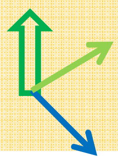
$$= A\left(L_V, L_A, L_S, L_T, R_V, R_A, R_S, R_T\right)$$

B



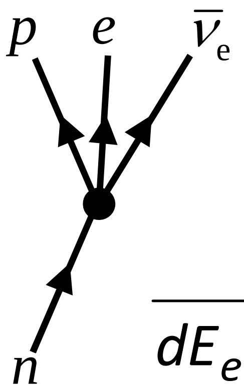
$$= B\left(L_V, L_A, L_S, L_T, R_V, R_A, R_S, R_T\right)$$

D



$$= D\left(L_V, L_A, L_S, L_T, R_V, R_A, R_S, R_T\right)$$

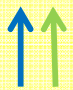
Neutron beta decay and V—A theory



$$H = \frac{G_W}{2\sqrt{2}} \sum_{i=V,A} L_i \left(\bar{p}\,\boldsymbol{O}_i n\right)\left(\bar{e}\,\boldsymbol{O}_i\left(1-\gamma_5\right)\nu\right) \qquad \lambda = \frac{L_A}{L_V}$$

$$\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto G_e(E_e)\left\{1 + a\frac{\boldsymbol{p}_e\boldsymbol{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \boldsymbol{P}\left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_\nu}{E_\nu} + D\frac{\boldsymbol{p}_e \times \boldsymbol{p}_\nu}{E_e E_\nu}\right)\right\}$$

$$a = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}$$



$$= a\left(L_V, L_A, L_S, L_T, R_V, R_A, R_S, R_T\right) \qquad a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$$

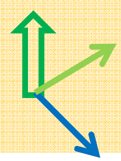
$$A = \frac{N_{\Uparrow\uparrow} - N_{\Uparrow\downarrow}}{N_{\Uparrow\uparrow} + N_{\Uparrow\downarrow}}$$

$$= A\left(L_V, L_A, L_S, L_T, R_V, R_A, R_S, R_T\right) \qquad A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$

B

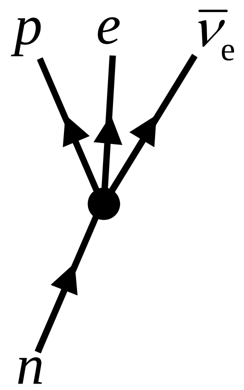
$$= B\left(L_V, L_A, L_S, L_T, R_V, R_A, R_S, R_T\right) \qquad B = 2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$

D

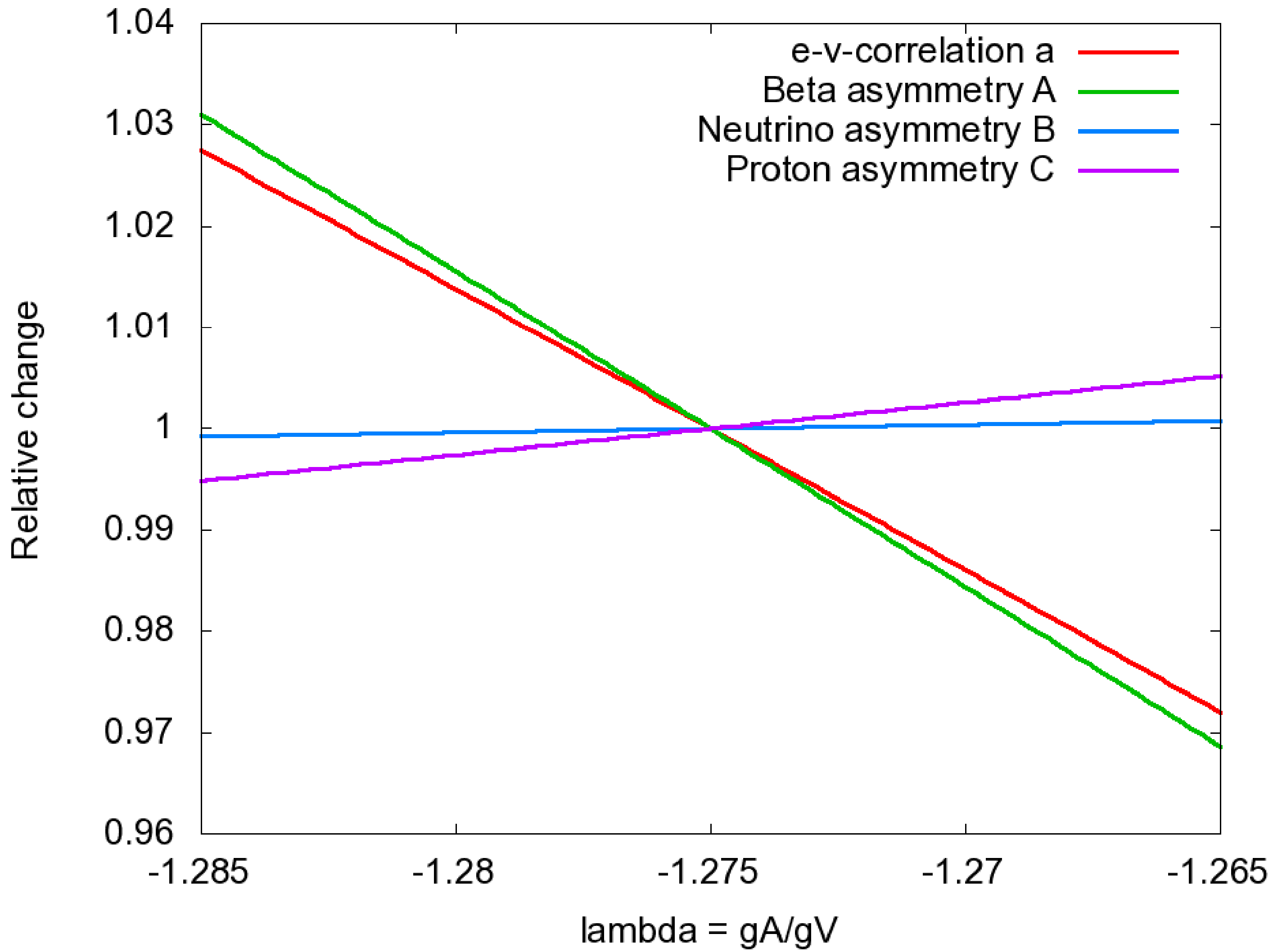


$$= D\left(L_V, L_A, L_S, L_T, R_V, R_A, R_S, R_T\right) \qquad D = 2\frac{\mathrm{Im}(\lambda)}{1+3|\lambda|^2}$$

Neutron beta decay and V—A theory



$$H = \frac{G_W}{2\sqrt{2}} \sum_{i=V,A} L_i \left(\bar{p}\,\mathbf{O}_i n\right)\left(\bar{e}\,\mathbf{O}_i \left(1-\gamma_5\right)\nu\right) \qquad \lambda = \frac{L_A}{L_V}$$



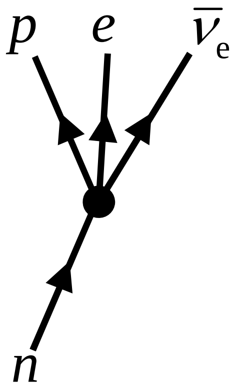
$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$$

$$A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$

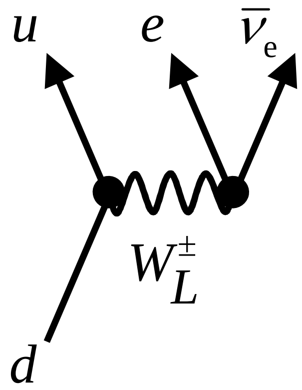
$$B = 2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$

$$C = -x_C \frac{4\,\mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$

Neutron beta decay and the Standard Model



$$H = \frac{G_F}{\sqrt{2}} V_{ud} \bar{p} \gamma^{\mu} (1 + \lambda \gamma_5) n \; \bar{e} \gamma_{\mu} (1 - \gamma_5) \nu$$



$$H = \frac{G_F}{\sqrt{2}} V_{ud} \bar{u} \gamma^{\mu} (1 - \gamma_5) d \; \bar{e} \gamma_{\mu} (1 - \gamma_5) \nu$$

$$\tau = \frac{4908.7(1.9)\,\mathrm{s}}{|V_{ud}|^2 (1 + 3\lambda^2)}$$

$$A = -2 \frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2}$$

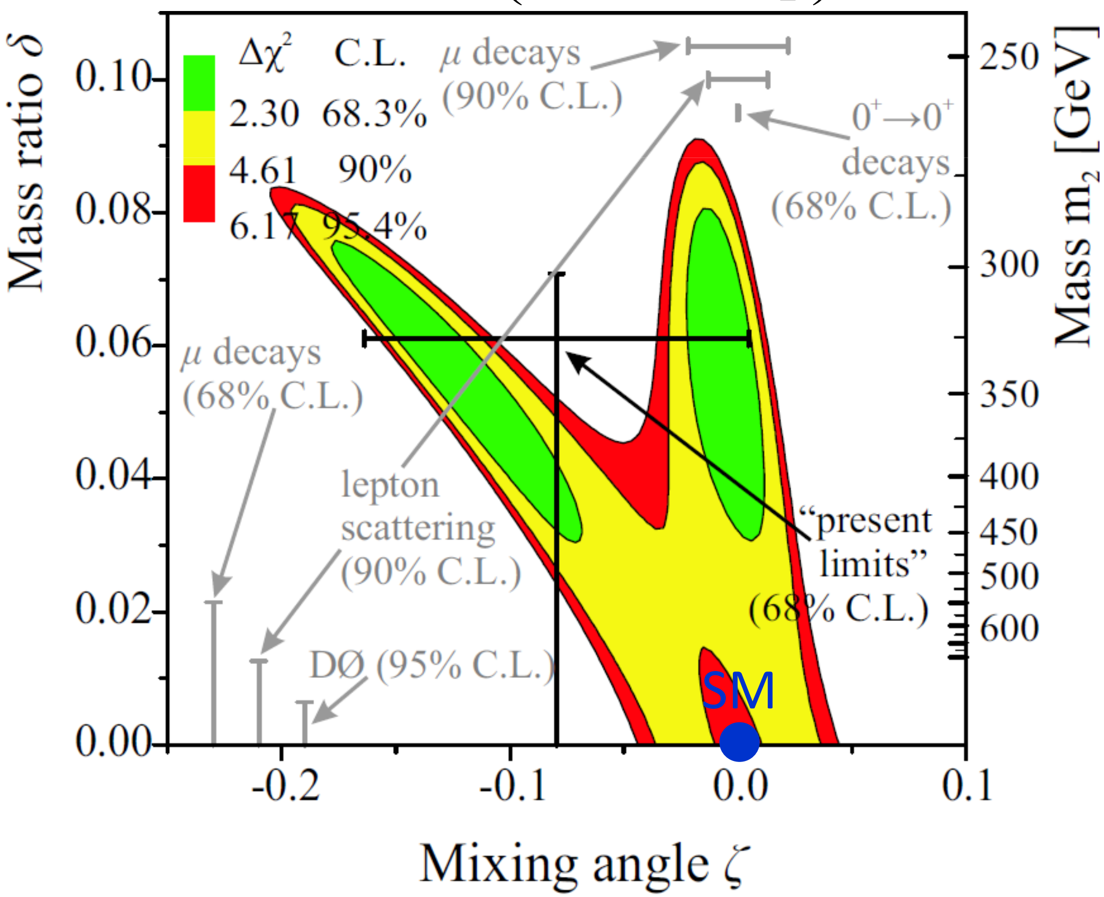
$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} e_L \\ \nu_{eL} \end{pmatrix}$$

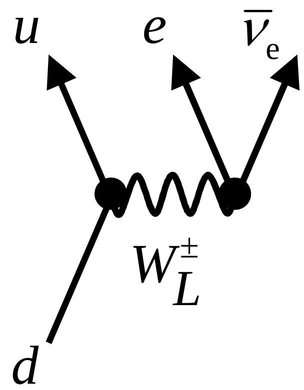
New Physics?

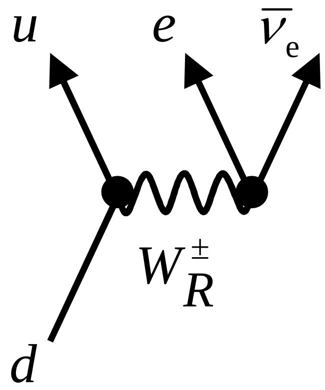
Right-handed interactions (V+A)

$$\begin{pmatrix} W_L \\ W_R \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1 \\ W_2 \end{pmatrix}$$

$$(a, A, B, \tau) \rightarrow \left(\lambda', \zeta, \delta = \frac{m_1^2}{m_2^2} \right)$$







(broken) $SU(2)_L \times SU(2)_R$

→deviation from maximal parity violation (V+A)

→also: additional phases for CP violation

Other analyses:

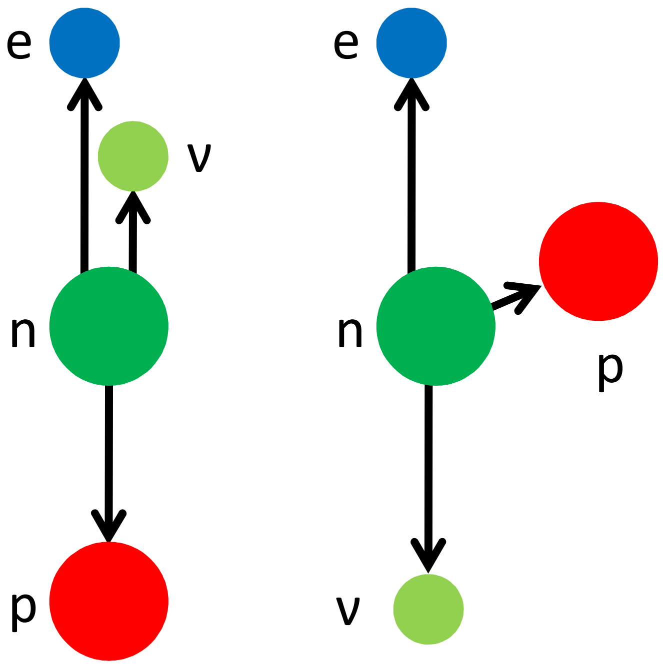
- Left-handed scalar and tensor
- Right-handed scalar and tensor

G. Konrad et al, arxiv:1007.3027

Electron-neutrino correlation *a*

$$dW \propto 1 + a \frac{\boldsymbol{p}_e \boldsymbol{p}_\nu}{E_e E_\nu}$$

$$a = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}}$$

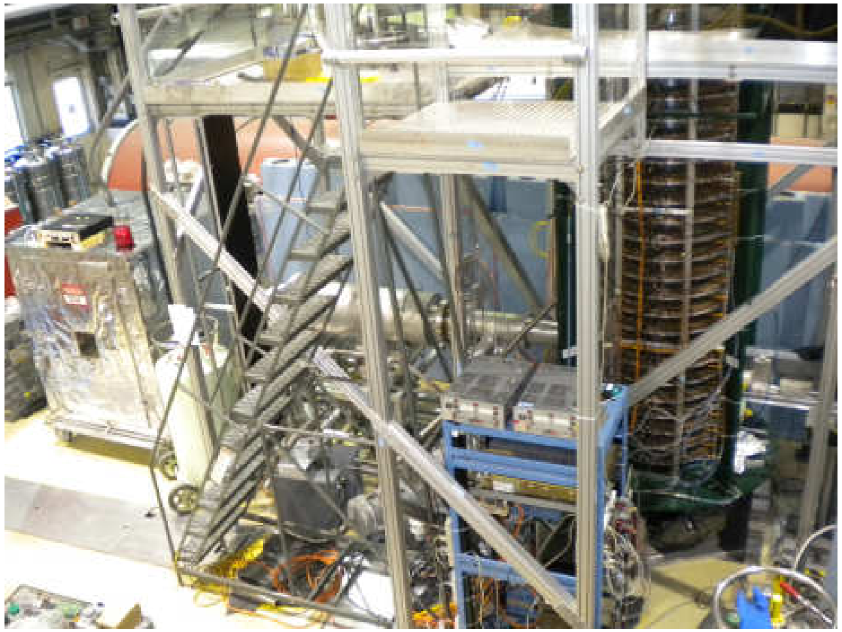


[PDG10] a = -0.103 ± 0.004 (4%)

Methods

Goal: Δa/a=O(10^{-3})

- **Proton spectrum 0...751 eV**
  aSPECT (Mainz, Munich, ILL)
  Talk G. Konrad, Tuesday
- **Correlation e-p, proton TOF**
  aCORN, running at NIST
  Nab, in progress

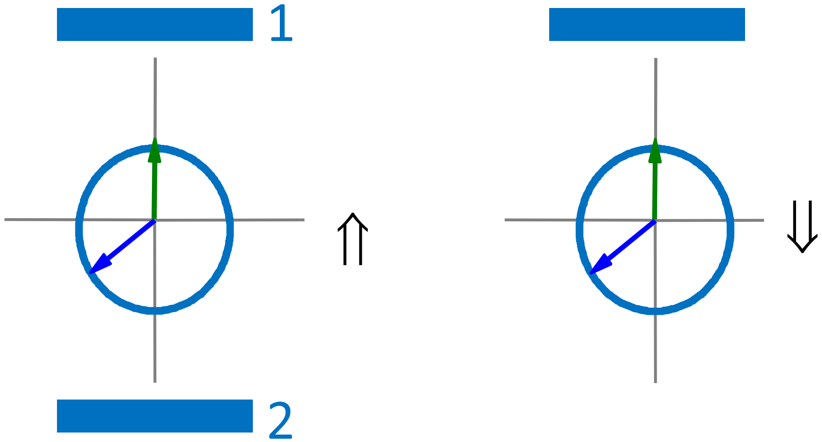


aCORN@NG6 (NIST)
Courtesy F.E. Wietfeldt

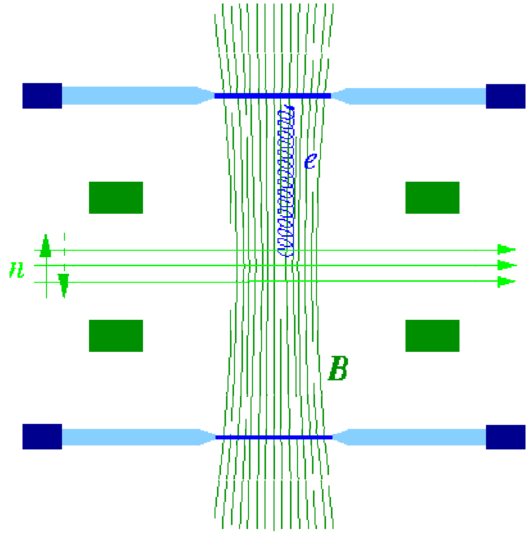
Beta asymmetry A

$$dW \propto 1 + AP\frac{\boldsymbol{p}_e}{E_e}$$

$$A = \frac{N_{\Uparrow\uparrow} - N_{\Uparrow\downarrow}}{N_{\Uparrow\uparrow} + N_{\Uparrow\downarrow}}$$



$$Ak\beta = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \qquad kA\beta = \frac{N_{\Uparrow} - N_{\Downarrow}}{N_{\Uparrow} + N_{\Downarrow}}$$



2×2π solid angle with Magnetic field

$$k = \left\langle FP\frac{\boldsymbol{p}_e}{E_e} \right\rangle$$

Requirements

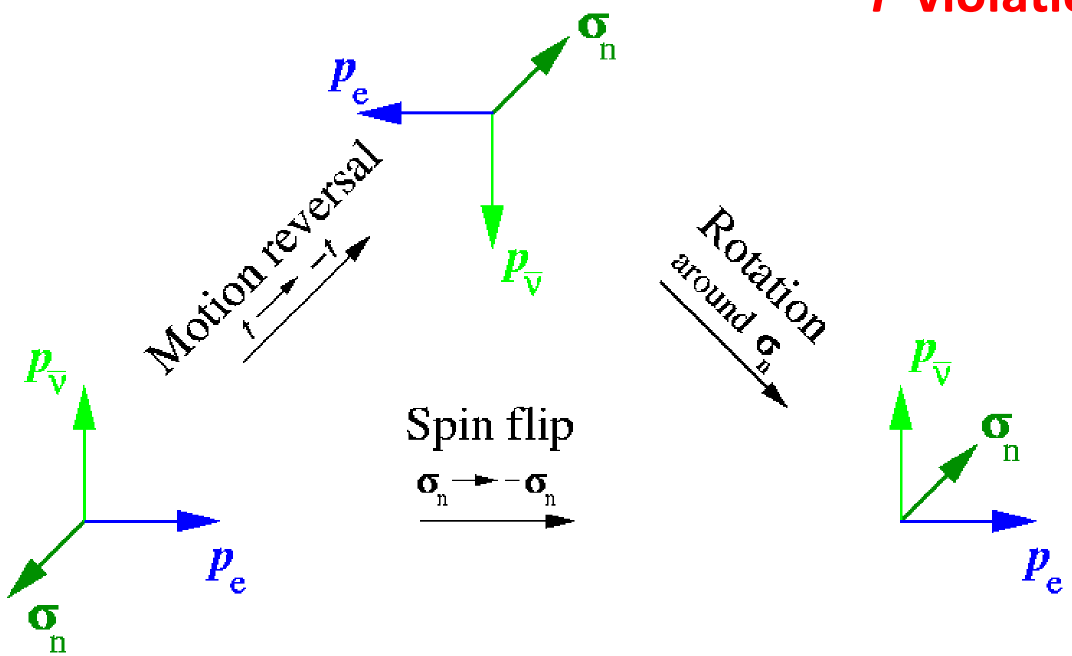
- Solid angle
- Statistics
- Polarisation / Flipping
- Background
- Energy calibration

Time reversal violationg correlation *D*

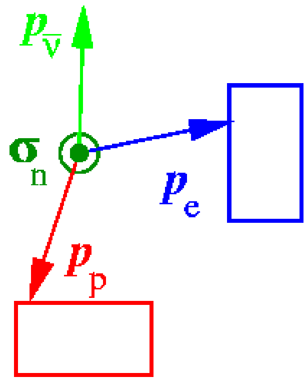
$D = 0$ in SM

$$\frac{\mathrm{d}W}{\mathrm{d}E_\mathrm{e}\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_{\bar{\nu}}} \propto G_\mathrm{e}(E_\mathrm{e}) \cdot \left\{ 1 + a\frac{\boldsymbol{p}_\mathrm{e}\boldsymbol{p}_{\bar{\nu}}}{E_\mathrm{e}E_{\bar{\nu}}} + b\frac{m_\mathrm{e}}{E_\mathrm{e}} + \frac{\boldsymbol{\sigma}_\mathrm{n}}{\sigma_\mathrm{n}}\left(A\frac{\boldsymbol{p}_\mathrm{e}}{E_\mathrm{e}} + B\frac{\boldsymbol{p}_{\bar{\nu}}}{E_{\bar{\nu}}} \right). + D\frac{\boldsymbol{\sigma}_\mathrm{n}}{\sigma_\mathrm{n}} \cdot \frac{\boldsymbol{p}_\mathrm{e} \times \boldsymbol{p}_{\bar{\nu}}}{E_\mathrm{e}E_{\bar{\nu}}} \right\}$$

***P* violation ⇔ Asymmetry with spin-flip**



Principle Set-Up



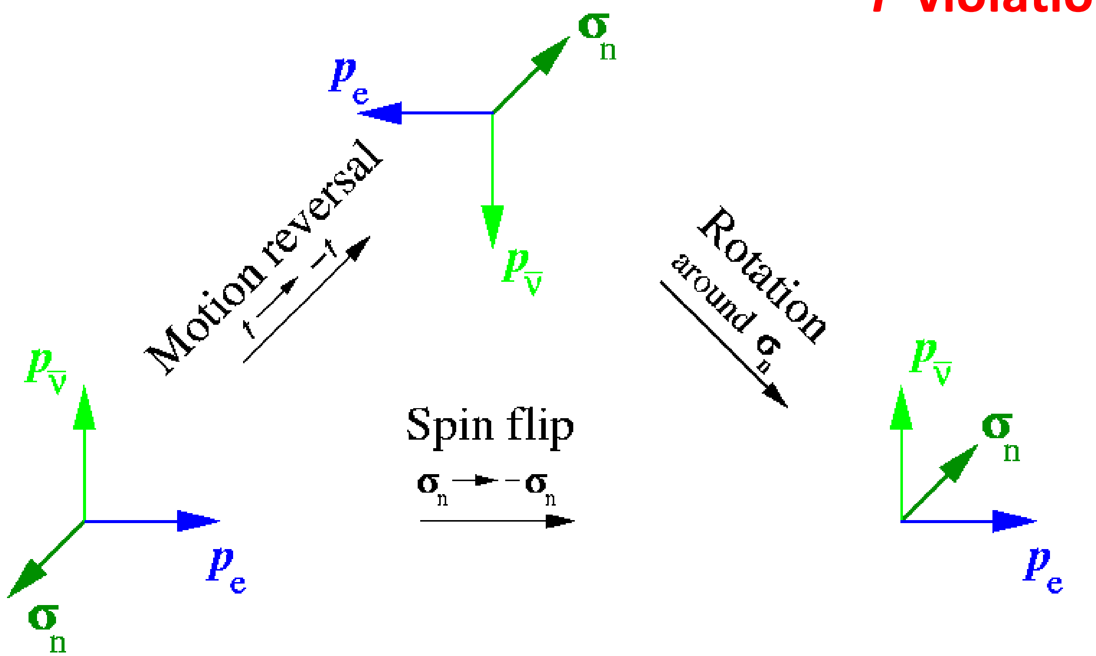
$$\alpha = \frac{N_{\mathrm{ep}}^{\uparrow} - N_{\mathrm{ep}}^{\downarrow}}{N_{\mathrm{ep}}^{\uparrow} + N_{\mathrm{ep}}^{\downarrow}} = DP\kappa_D + AP\kappa_A + BP\kappa_B$$

Time reversal violationg correlation *D*

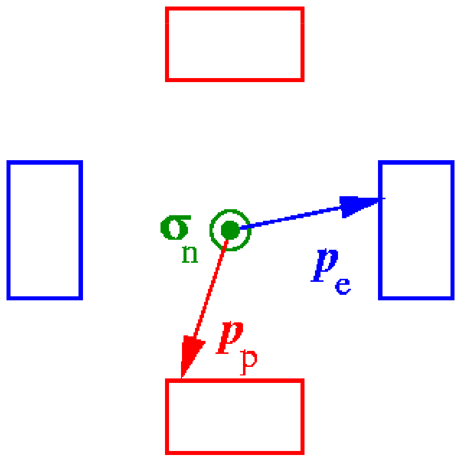
$D = 0$ in SM

$$\frac{\mathrm{d}W}{\mathrm{d}E_e \mathrm{d}\Omega_e \mathrm{d}\Omega_{\bar{\nu}}} \propto G_e(E_e) \cdot \left\{ 1 + a\frac{\boldsymbol{p}_e \boldsymbol{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}} + b\frac{m_e}{E_e} + \frac{\boldsymbol{\sigma}_n}{\sigma_n}\left(A\frac{\boldsymbol{p}_e}{E_e} + B\frac{\boldsymbol{p}_{\bar{\nu}}}{E_{\bar{\nu}}} \right) . + D\frac{\boldsymbol{\sigma}_n}{\sigma_n} \cdot \frac{\boldsymbol{p}_e \times \boldsymbol{p}_{\bar{\nu}}}{E_e E_{\bar{\nu}}} \right\}$$

***P* violation ⇔ Asymmetry with spin-flip**



Principle Set-Up

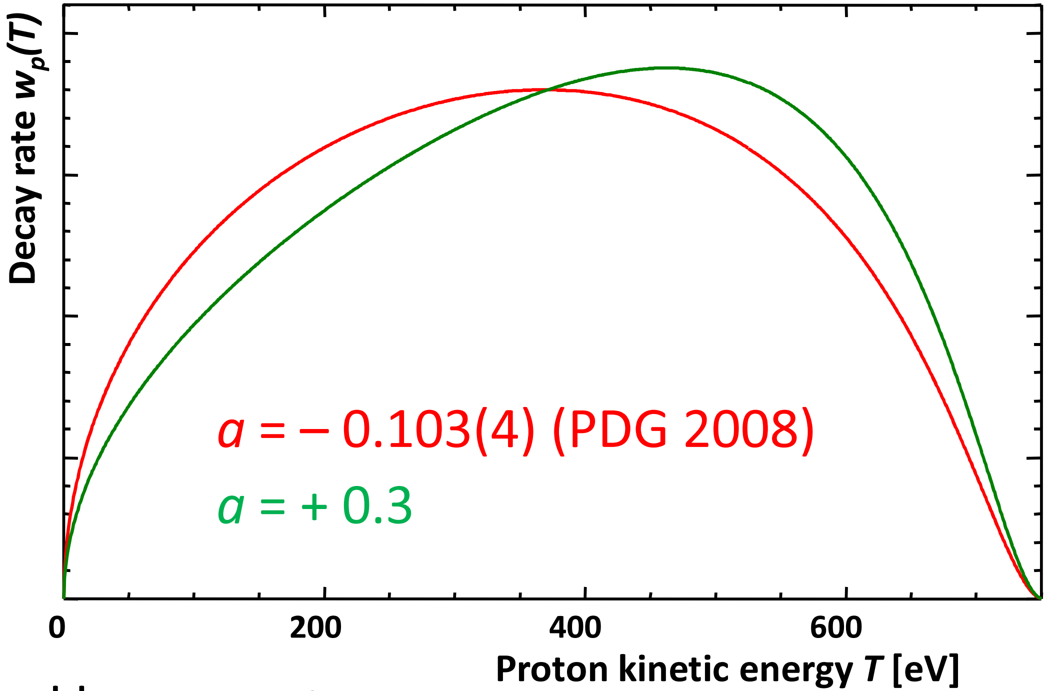


Breaking of detector symmetry
⇒Systematic effects

$$D = \frac{\alpha^{00} - \alpha^{01} - \alpha^{10} + \alpha^{11}}{4P\kappa_D^{00}}$$

Cold or ultracold? Velocity!

	Cold		Ultracold	
Velocity		**800 m/s**		**5 m/s**
Doppler eff.	E_p = 751 eV +	**4 eV**	E_p = 751 eV +	**0.02 eV**

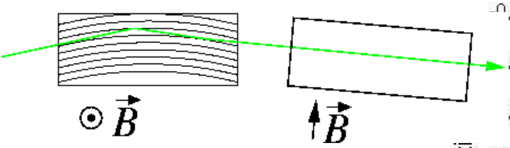


Compensated by geometry
and 4π proton detection

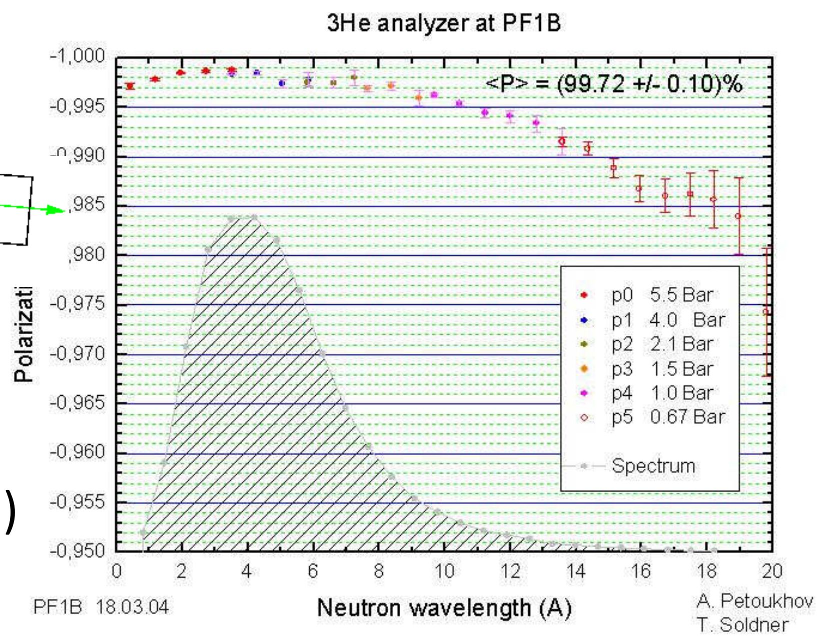
$v \times E$		**large**		**small**

Cold or ultracold? Statistics! Polarisation!

	Cold	Ultracold
Statistics – Density	In guide: **10^5/cm³** Polarised 98%: **10^4/cm³** Polarised 99.7%, background optimised: **$3\cdot10^2$/cm³**	Demonstrated: 100/cm³ Promised: **10^3...10^5/cm³** Polarised 90% PF2 EDM: **1/cm³** Polarisation losses should be small
Polarisation	**99.7(1)%**	Believed: **100%** Demonstrated (UCNA): **>99.5%**



$$P_{12} = \frac{P_1 + P_2}{1 + P_1 P_2} = 1 - \frac{1}{2}(1 - P_1)(1 - P_2)$$



PSI EDM magnet
Photo stolen from P. Fierlinger

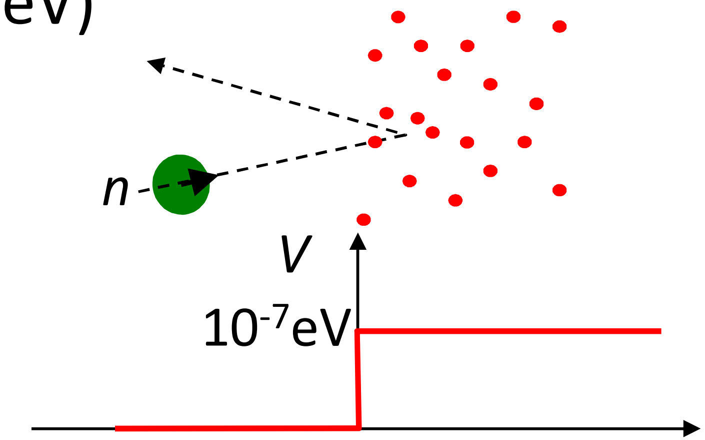
UCN – the magic 100 neV

Kinetic energy

- 100 neV for 4 m/s

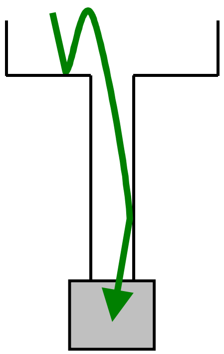
Neutron optical potential

- O(100 neV)



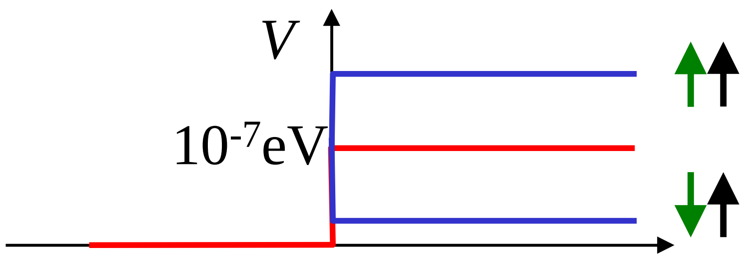
Gravitation

- 100 neV / m



Magnetic interaction

- 100 neV / 1.7 T



Cold or ultracold? Symmetry!

	Cold (3 meV, 800 m/s)	Ultracold (100 neV, 5 m/s)
Magnetic field 1 T	Spin-dependent focussing or de-focussing (Perkeo II): **0.2%**	Spin-dependent loading efficiencies (UCNA): **30%***
Gravitation	Vertical gradient: **small**	Vertical gradient: **few%/10 cm**

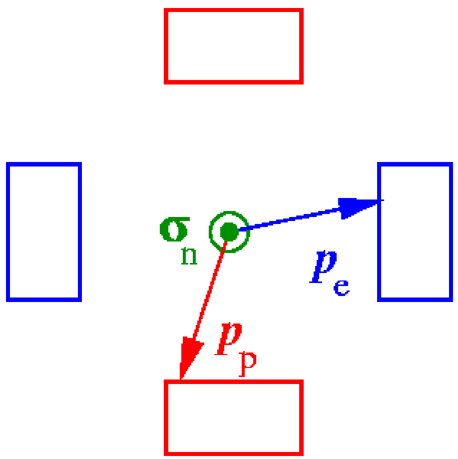
Example: *height difference for ^{199}Hg and UCN (EDM)*

Require storage

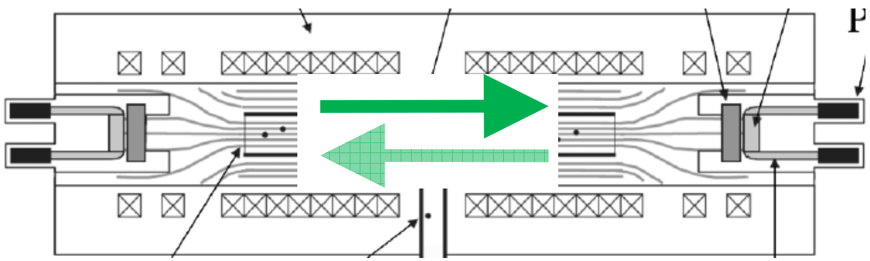
→energy loss electrons

→proton detection??

Spatial Symmetry



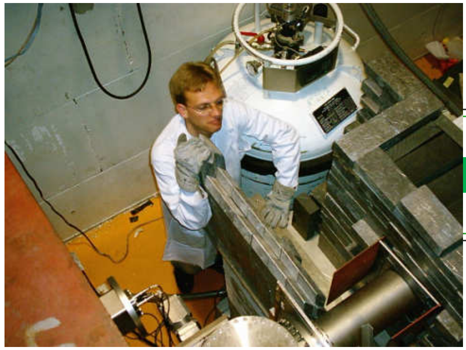
Spin symmetry

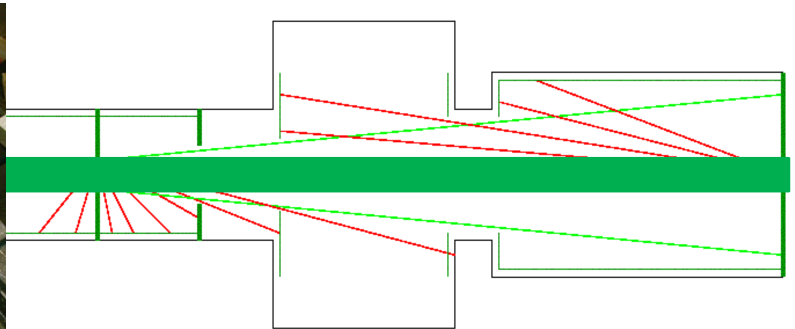


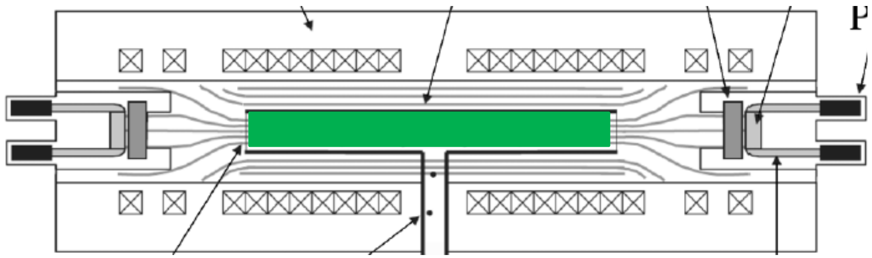
* Thanks to A. Young for info

Cold or ultracold? Background!

	Cold (800 m/s)		Ultracold (5 m/s)	
Obs.time		10^{-3}s/m		**0.2s/m**
Sg/beamBG Decay: **10^{-3}/s**	Observation time (1m): **Decay/absorption:** ***Decay & absorption separate!*** Sg/BG Perkeo II: (SCI only)	10^{-3}s 10^{-6} **10^3**	Collisions: Loss/collision: **Decay/absorption:** ***Decay & absorption close!*** Sg/BG UCNA: (MWPC+SCI)	30/s $3 \cdot 10^{-5}$ **1** **$5 \cdot 10^3$**

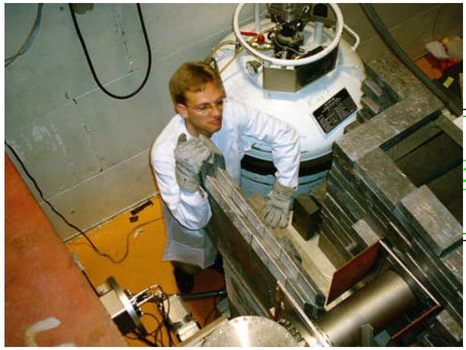


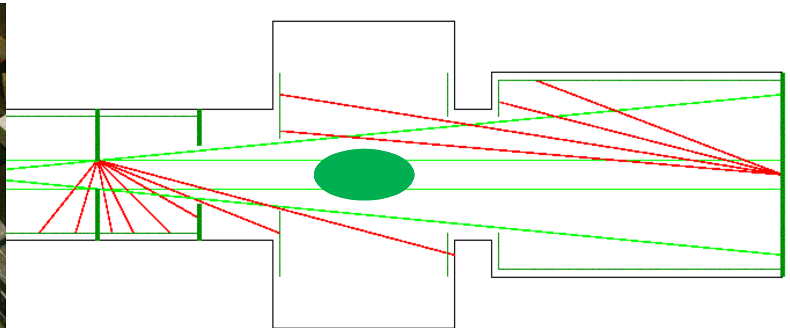


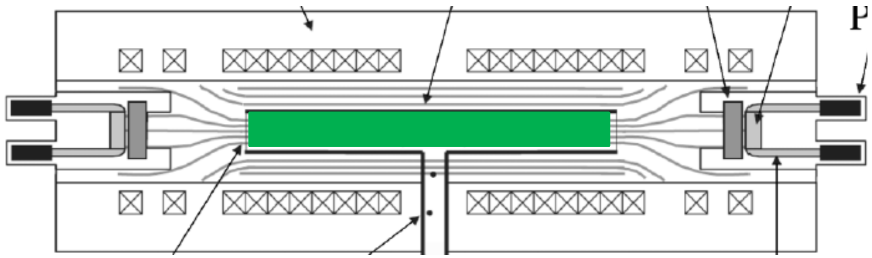


Cold or ultracold? Background!

	Cold (800 m/s)		Ultracold (5 m/s)	
Obs.time		10^{-3}s/m		**0.2s/m**
Sg/beamBG	Observation time (1m):	10^{-3}s	Collisions:	30/s
Decay:			Loss/collision:	$3\cdot10^{-5}$
10^{-3}/s	**Decay/absorption:**	10^{-6}	**Decay/absorption:**	**1**
	Decay & absorption separate!		***Decay & absorption close!***	
	Sg/BG Perkeo II:	**10^3**	Sg/BG UCNA:	**$5\cdot10^3$**
	(SCI only)		(MWPC+SCI)	



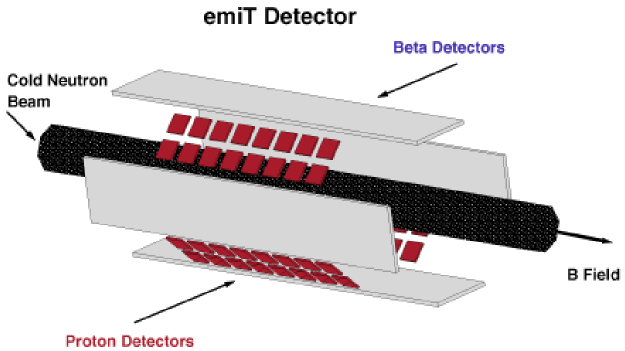


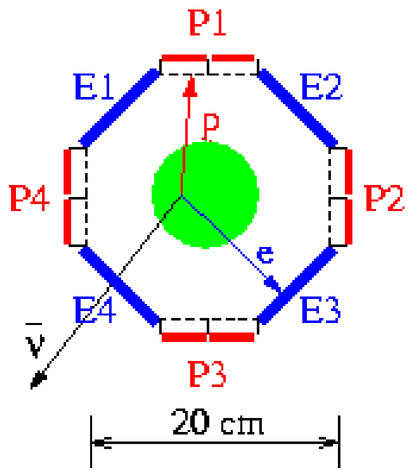


Or use pulsed beam!

D – Status

emiT





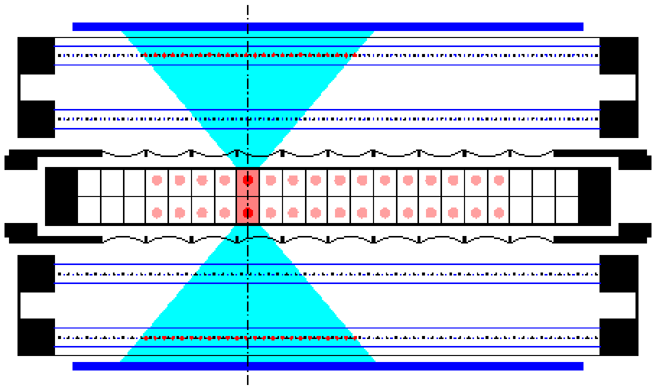
$D = (-6 \pm 12^{stat} \pm 5^{syst}) \cdot 10^{-4}$

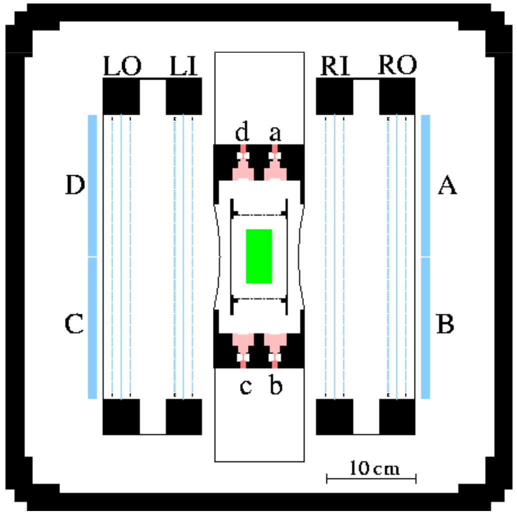
L.J. Lising et al, PRC 62 (2000) 055501.

and ongoing analysis

Talk on R coefficient K. Bodek, Tuesday

Trine

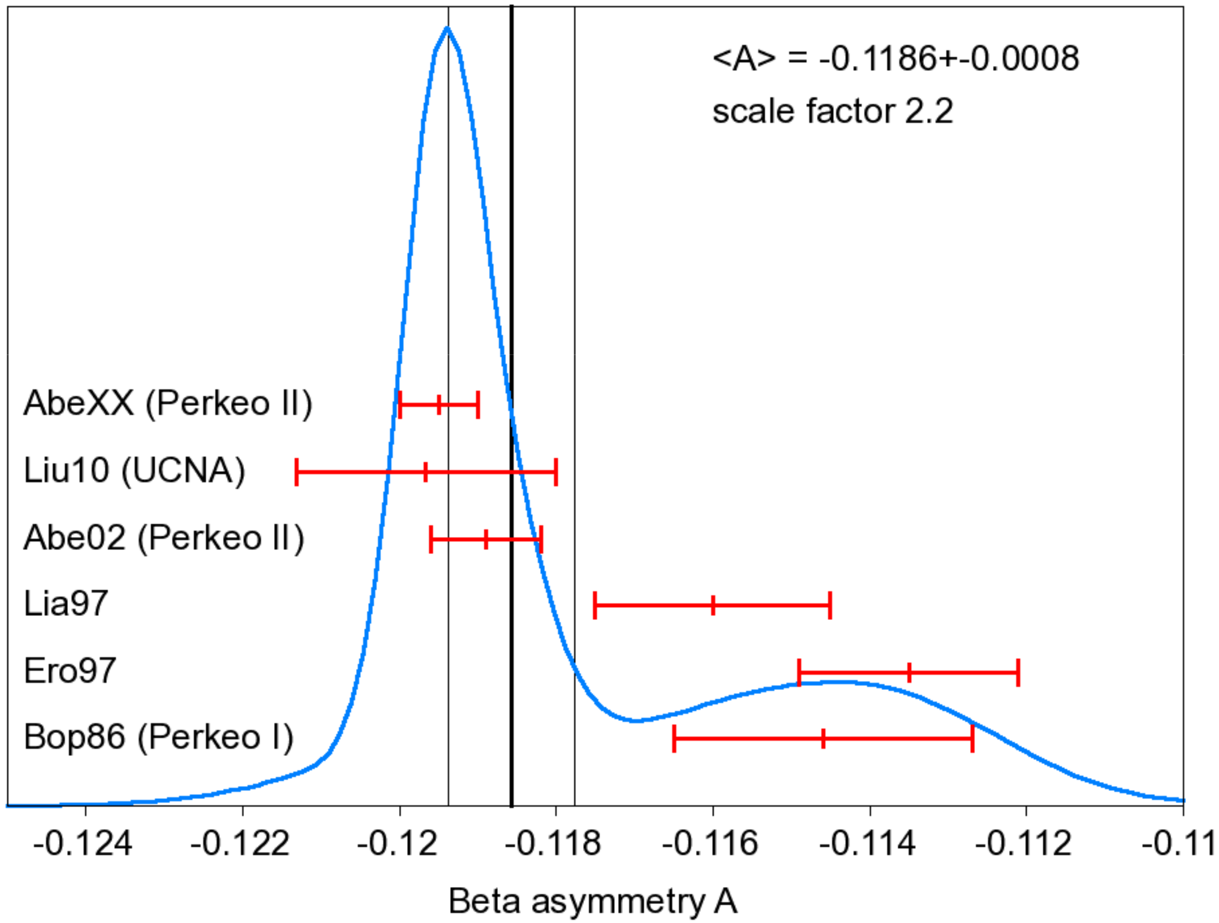




$D = (-2.8 \pm 6.4^{stat} \pm 3.0^{syst}) \cdot 10^{-4}$

T. S. et al, Phys. Lett. B 581 (2004) 49.

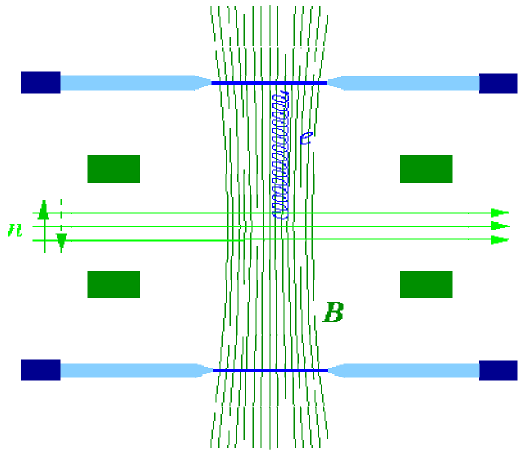
Beta asymmetry *A* –Status



Experiments

- Perkeo II
  Final publication soon
- Perkeo III
  Analysis in progress
  Talk B. Märkisch, Tuesday
- UCNA
  First results (2009, 10)
  Talk A. Young, Tuesday
- PERC
  funded
- abBA
  farer future

Limitations in cold neutron beam experiments

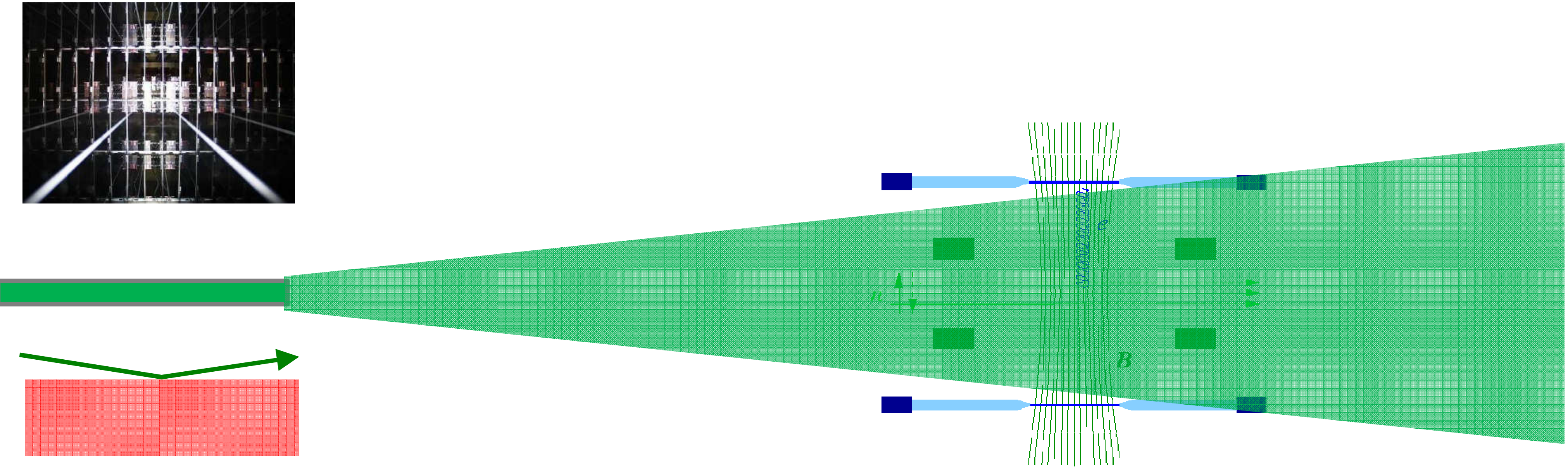


10^6 /s m

10^5 /s m polarised

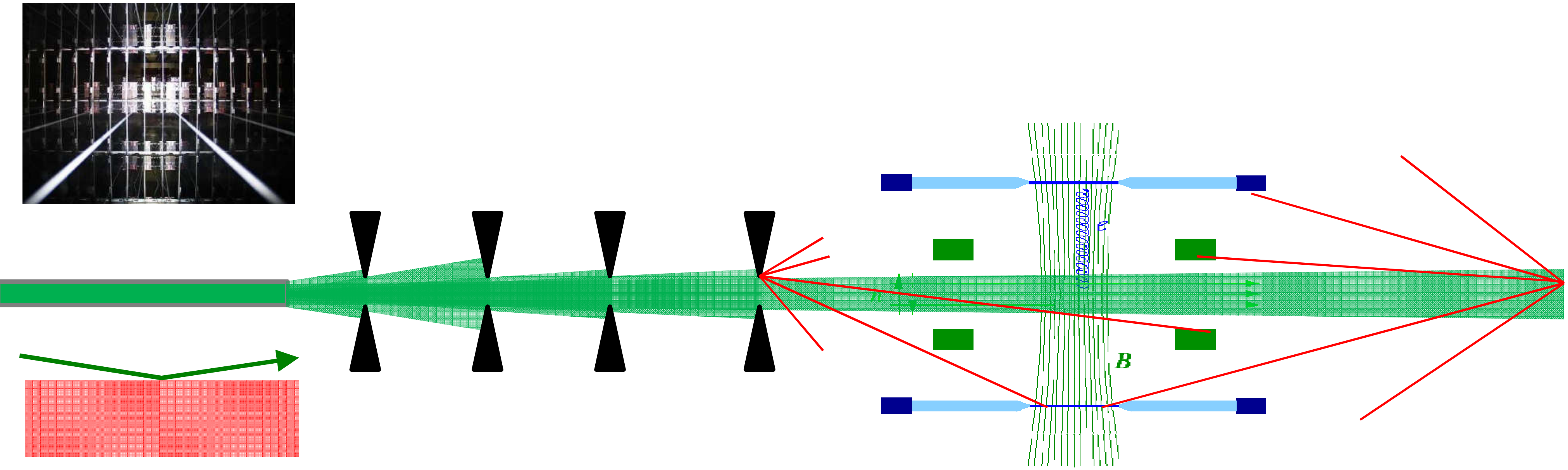
10^3 /s m

Limitations in cold neutron beam experiments



10^6 /s m 10^5 /s m polarised 10^3 /s m

Limitations in cold neutron beam experiments



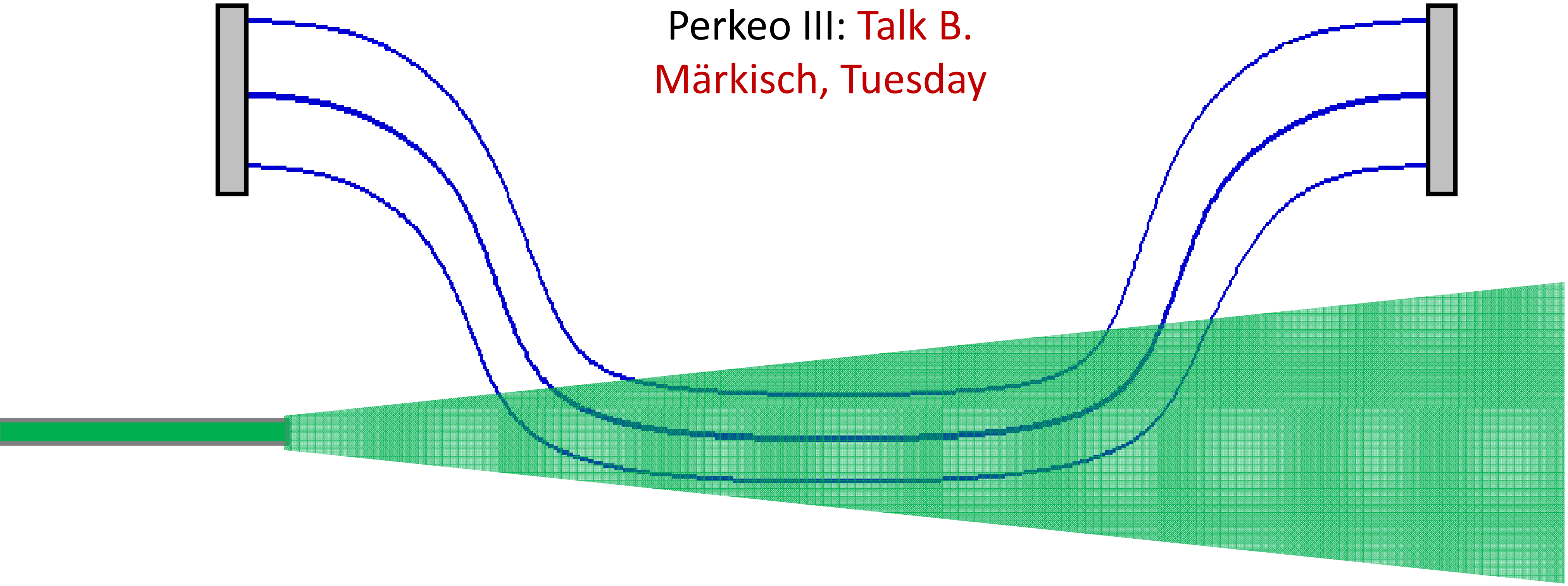
10^6 /s m

10^5 /s m polarised

10^3 /s m

Limitations in cold neutron beam experiments

Perkeo III: Talk B. Märkisch, Tuesday

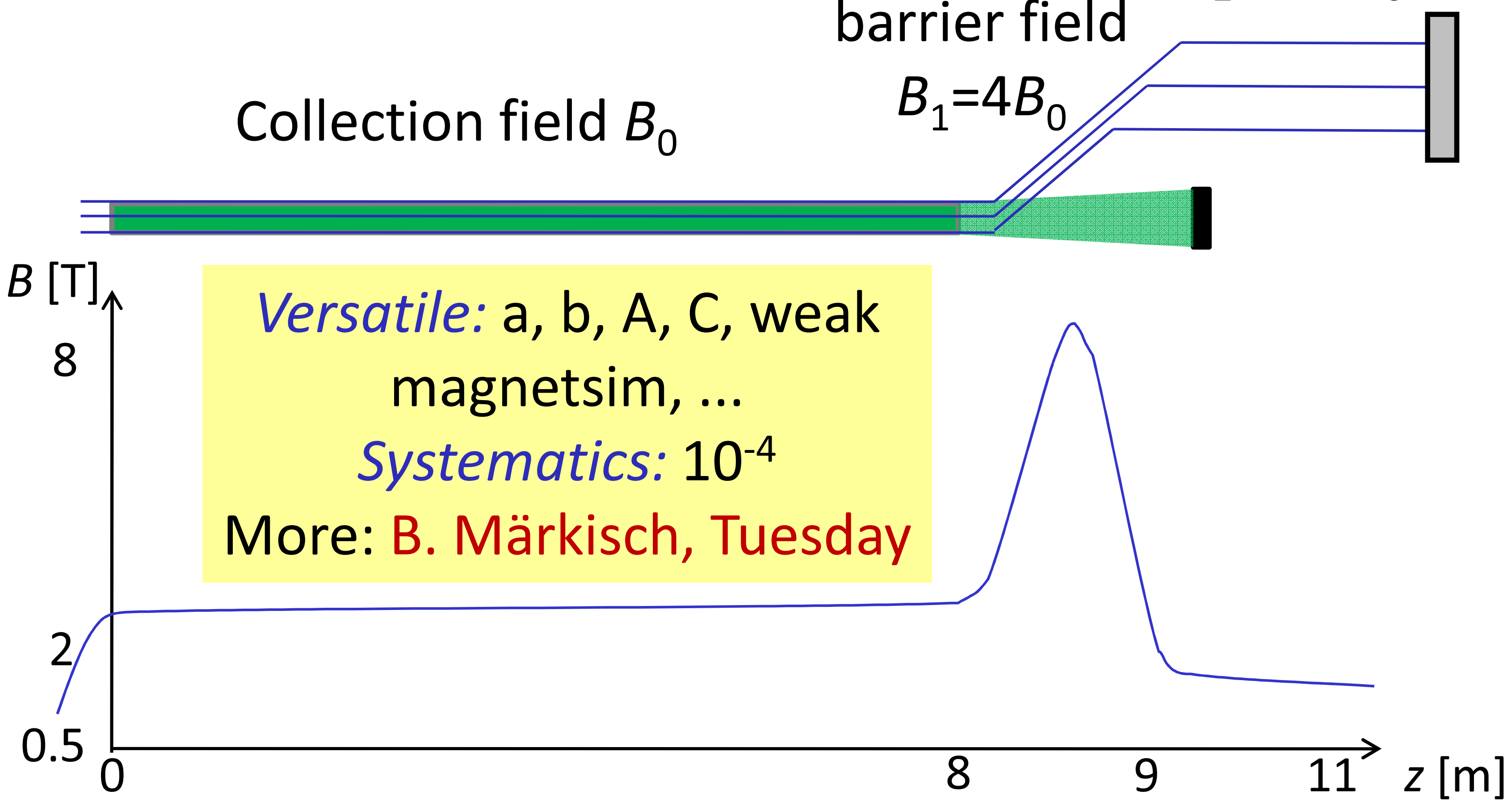


10^6 /s m 10^5 /s m polarised

Solution – PERC

Magnetic barrier: treat systematics against statistics

$$\frac{\sin\theta}{\sin\theta_0} = \sqrt{\frac{B}{B_0}}$$



Versatile: a, b, A, C, weak magnetsim, ...

Systematics: 10^{-4}

More: B. Märkisch, Tuesday

D. Dubbers et al., NIMA 596 (2008) 238 and arXiv:0709.4440

Cold or ultracold? $n\bar{n}$?

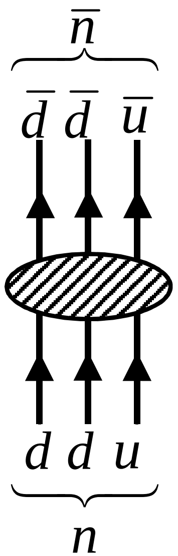
	Cold (800 m/s)	Ultracold (5 m/s)
Free flight	0.1 s	1 s

$\tau_{n\bar{n}} \geq 0.86 \cdot 10^{8}\,\mathrm{s}$ (90%c.l.)

M. Baldo-Ceolin et al: Z. Phys. C 63 (1994) 409

$$P_{\bar{n}}(t) \approx \left(\frac{t}{\tau_{n\bar{n}}}\right)^2$$

$$P_{\bar{n}}(t) = \left(\frac{t_{\text{free}}}{\tau_{n\bar{n}}}\right)^2 \quad N = \frac{t_{\text{free}}\, t_{\text{storage}}}{\tau_{n\bar{n}}^{\;2}}$$



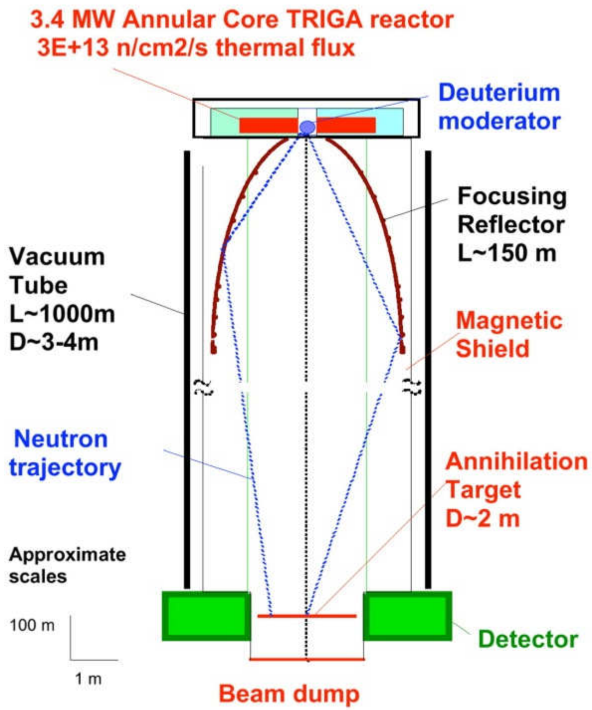
$|\Delta B| = 2$

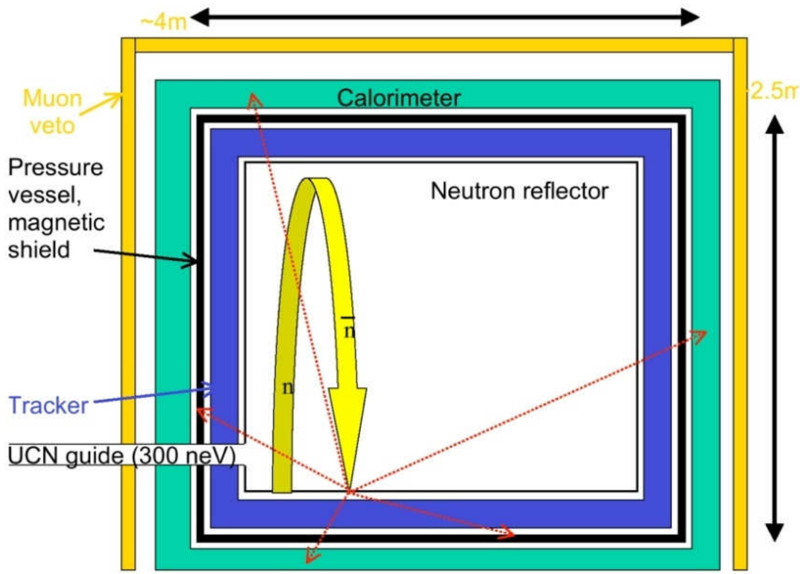
$$H \sim \frac{\lambda}{M_\mathrm{I}^5}(ddu\, ddu)$$

limit from $\tau_{n\bar{n}}$, τ_{nucleons}:

$$M_\mathrm{I} \geq 10^5\ \mathrm{GeV}$$

Intermediate scales (GUT breaking, SUSY seesaw, extradim)



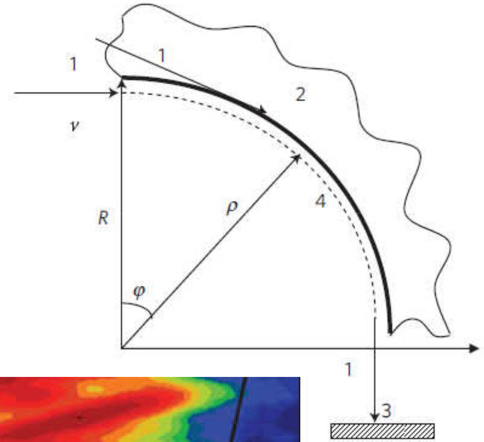


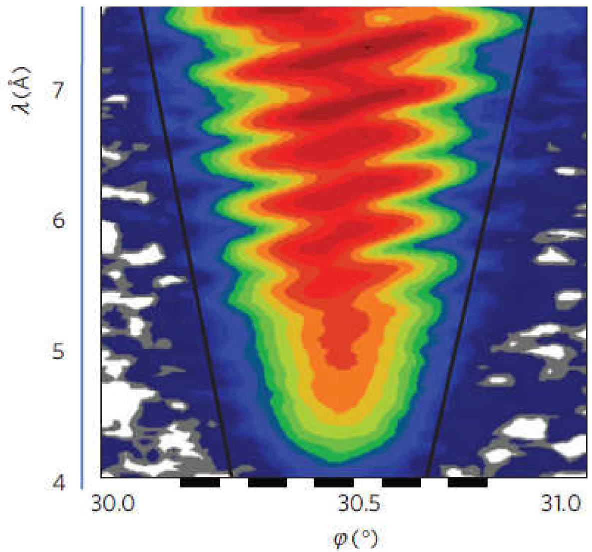
Factor 30 W. Snow, NIMA 611 (2009) 144 **Factor 7**

Cold or ultracold? Gravitational quantum states!

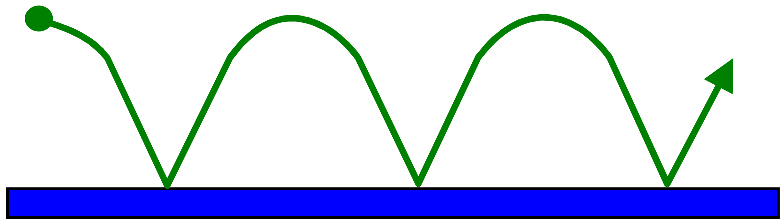
	Cold (800 m/s)	Ultracold (5 m/s)
Observ. time	10^{-3}s/m	0.2s/m

Zentrifugal quantum states





V. Nesvizhevsky et al, Nature Physics 6 (2010) 114



n	E_n [peV]	z_n [μm]
1	1.41	13.7
2	2.46	24.0
3	3.32	32.4

$$\Delta E\ \Delta t > \hbar \quad \Delta E = 0.12\text{peV} \Rightarrow \Delta t > 5\text{ms}$$

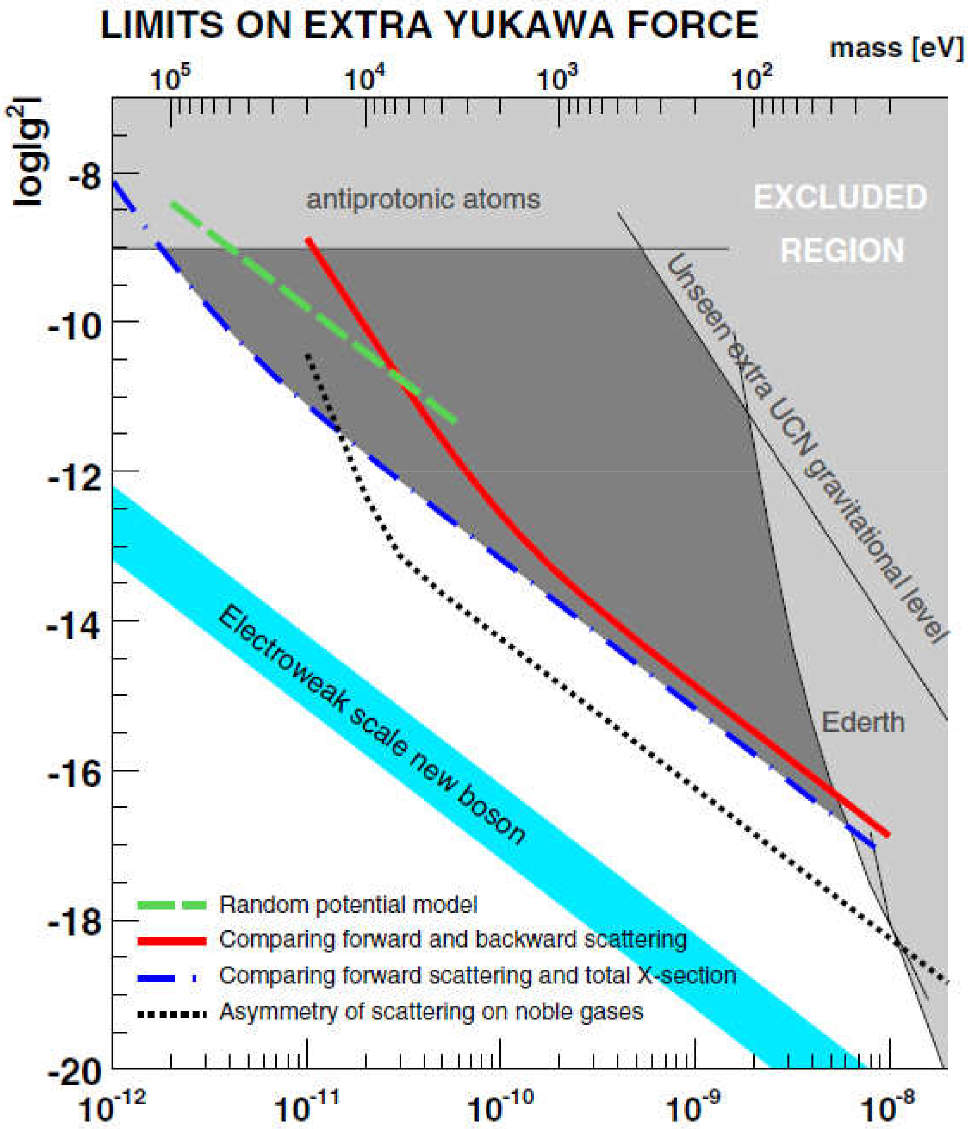
Manageable mirror size: ~ 10cm

$v_x < 20$m/s → *VCN or UCN*

Quantum states and short range forces?

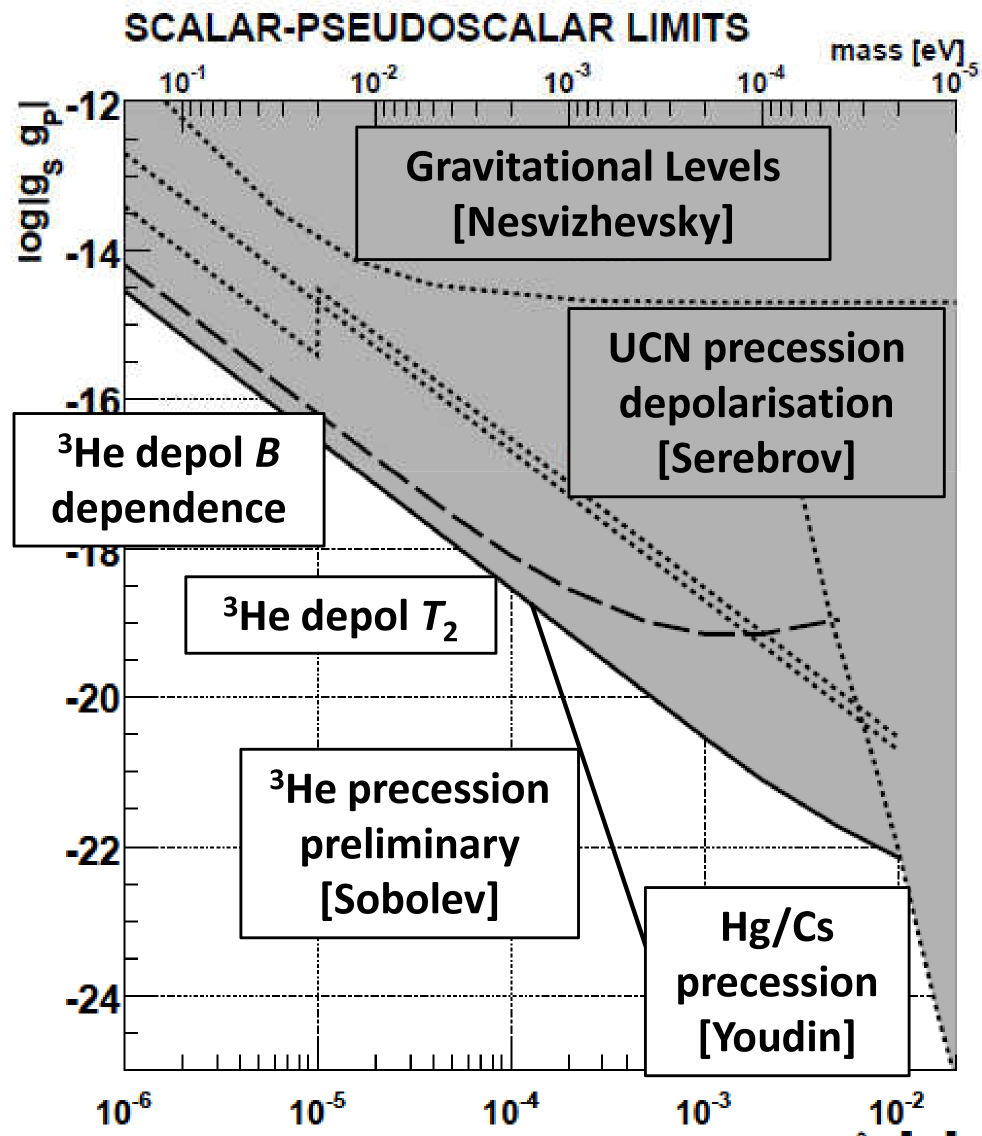
Merci á G. Pignol for discussions

Spin-indepenent



V. Nesvizhevsky et al, PRD 77 (2008) 034020

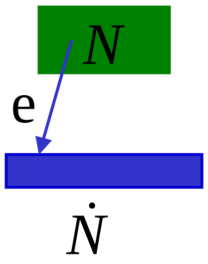
Spin-dependent



A. Petoukhov et al, arxiv:1009.3434

Cold and Ultracold! Neutron lifetime! $N(t) = N_0 \exp\left(-\frac{t}{\tau_n}\right)$

Beam experiments

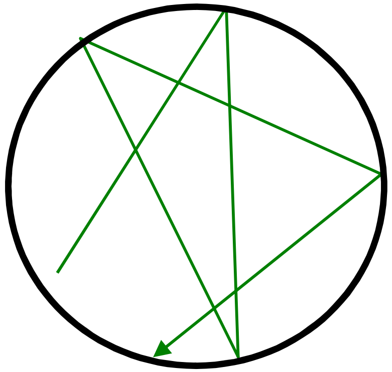


$$\tau_n = \frac{N}{-\dot{N}}$$

- Two absolute measurements:
  ? Solid angle
  ? Thresholds
  ? Backscattering
  ...

- Stated precision $4 \cdot 10^{-3}$

Storage experiments



$$\tau_n = \frac{t}{\ln \frac{N(t)}{N_0}}$$

- Counting survivors after storage
- Relative measurement (?)
- Losses → extrapolation techniques

- Stated precision $9 \cdot 10^{-4}$

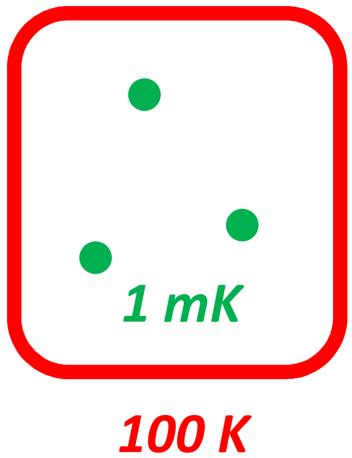
Storage experiment – Spectrum changes

Obvious

- Faster neutrons
  → More collisions
  → Faster losses

Also obvious

- Thermal non-equilibrium
  → Heating



→ Spectrum changes somehow predictable

Talk A. Fomin

Storage experiment – Spectrum changes

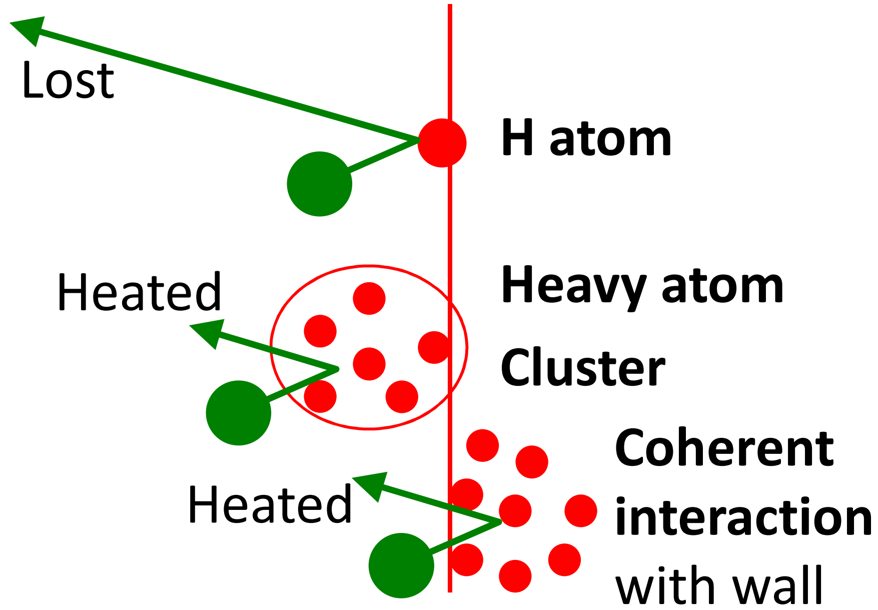
Obvious

- Faster neutrons
  → More collisions
  → Faster losses

→ Spectrum changes somehow predictable

Also obvious

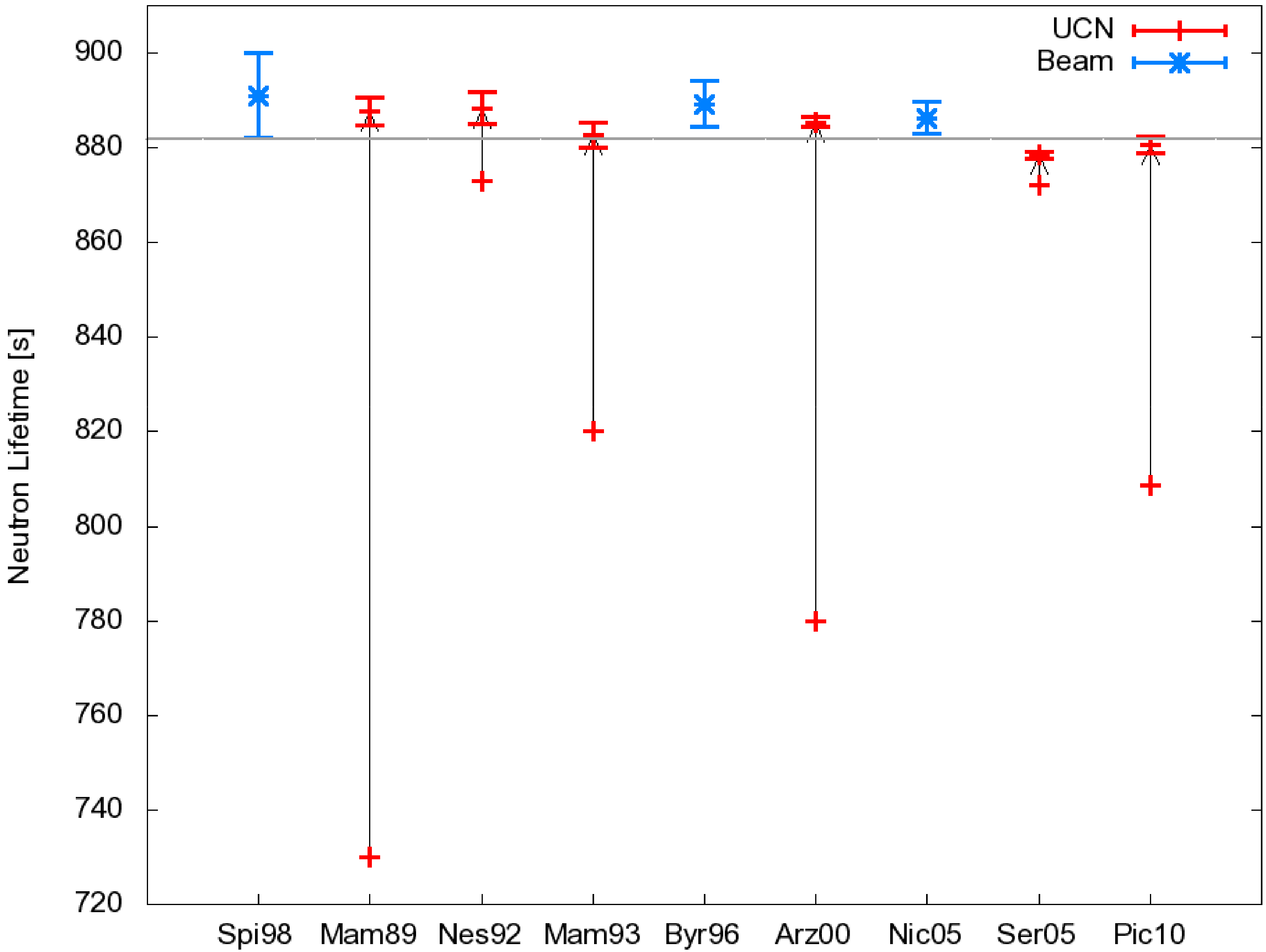
- Thermal non-equilibrium
  → Heating



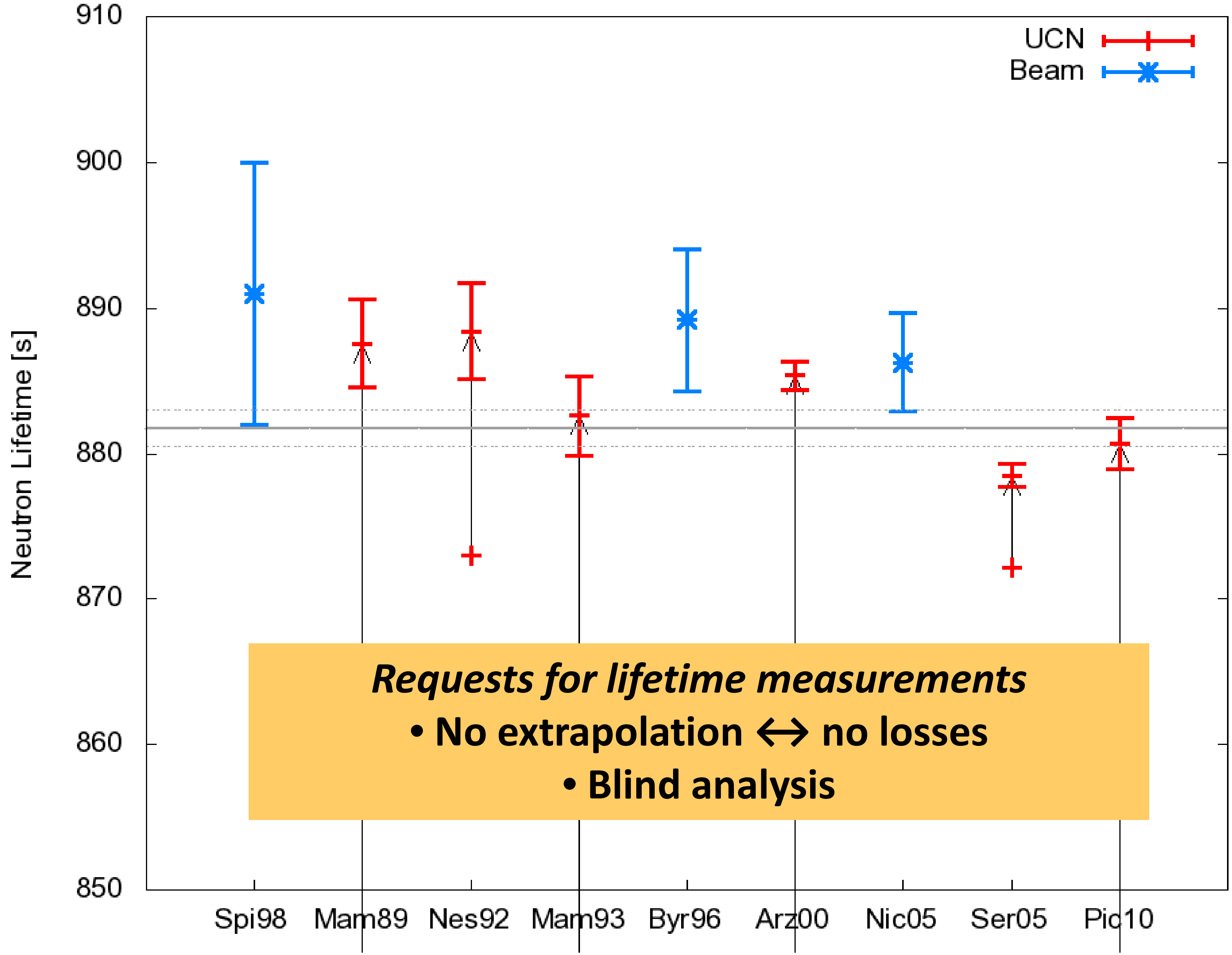
→ Unpredictable spectrum change

→ Concept of storage time constant invalid

Neutron lifetime – Status



Neutron lifetime – Status

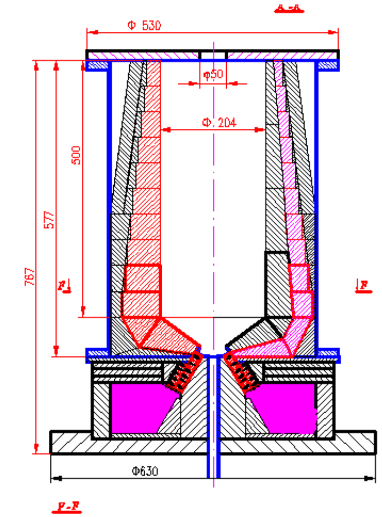


Requests for lifetime measurements

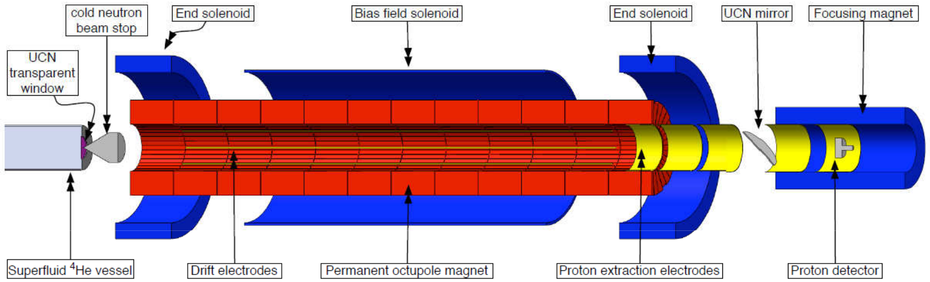
• No extrapolation ↔ no losses

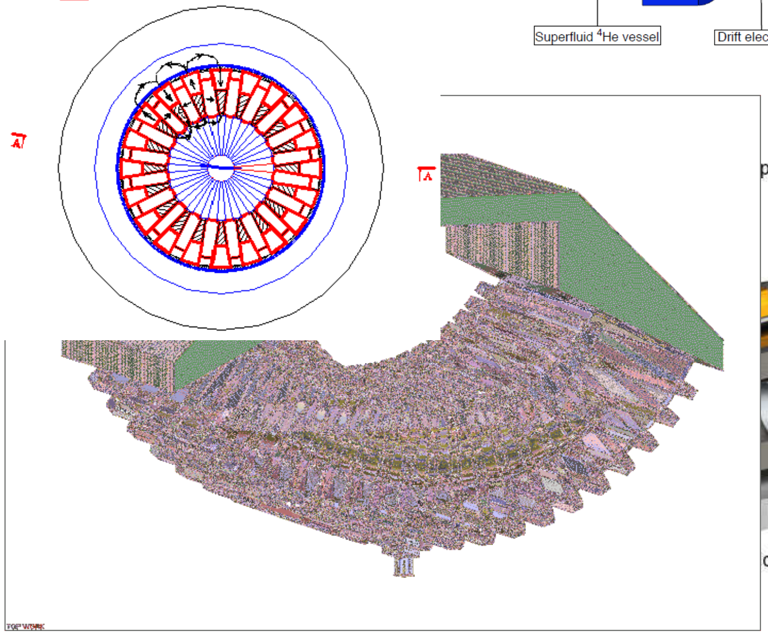
• Blind analysis

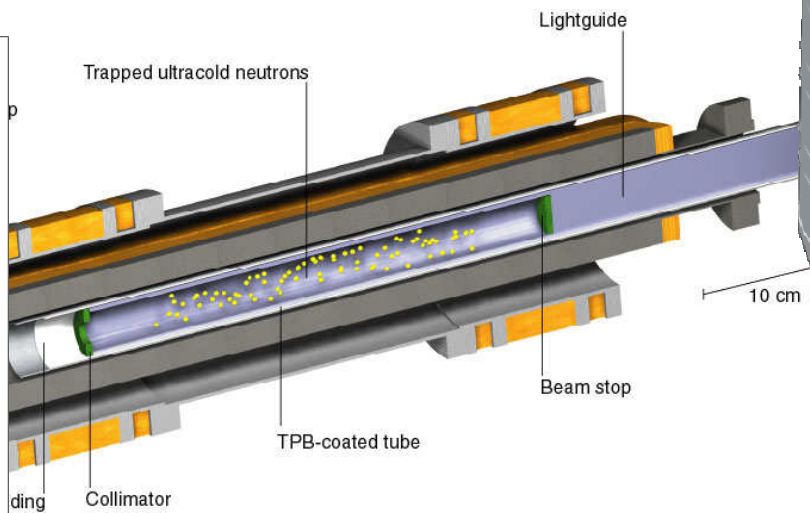
A possible solution? Magnetic trapping

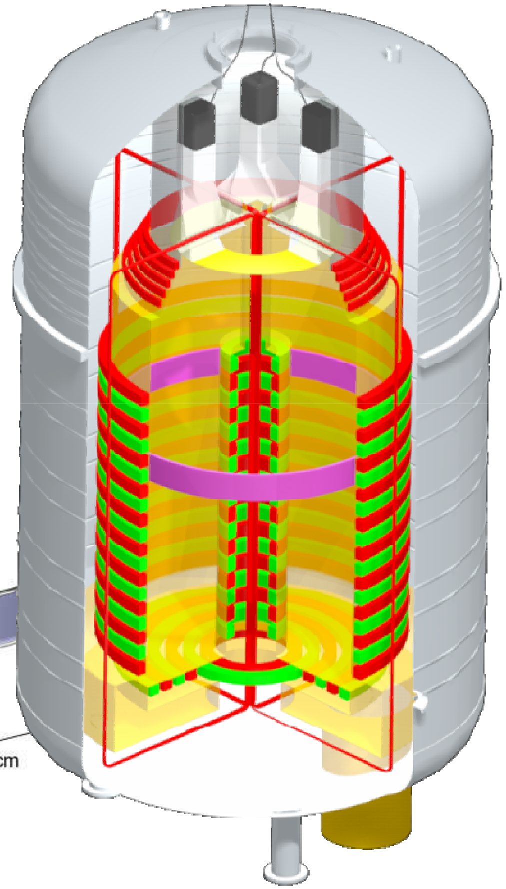


Talk V. Ezhov









Talk R. Picker

Summary

- Neutron particle physics:
  - Precision measurements & theory (*A*, *B*, *C*, τ, gravitational states, occupation of bob states)
  - Search deviations from 0 (*D*, d_n, *q*, |--> state)
  - Search for the forbidden (n$\underline{\text{n}}$)
  - *Very active field*
- Cold or ultracold neutrons?
  - Doppler effect, $v \times E$, statistics, polarisation, symmetry (space, spin), background, observation time
  - Choose the best for **you**!
- Neutron lifetime: **No** losses, please!

The Neutron Guide to the Universe