# A direct experimental limit on neutron - mirror neutron oscillations


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for the nEDM collaboration

# Motivation

- Parity violation proposed and observed in weak interactions

  - Lee and Yang, Phys. Rev. **104** (1956)
  - Wu et al, Phys. Rev. **105** (1957)

- Assumption:
  Parity is an unbroken symmetry!

  → Add mirror particles with complementary transformation (V+A)

> «If such asymmetry is indeed found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry.»

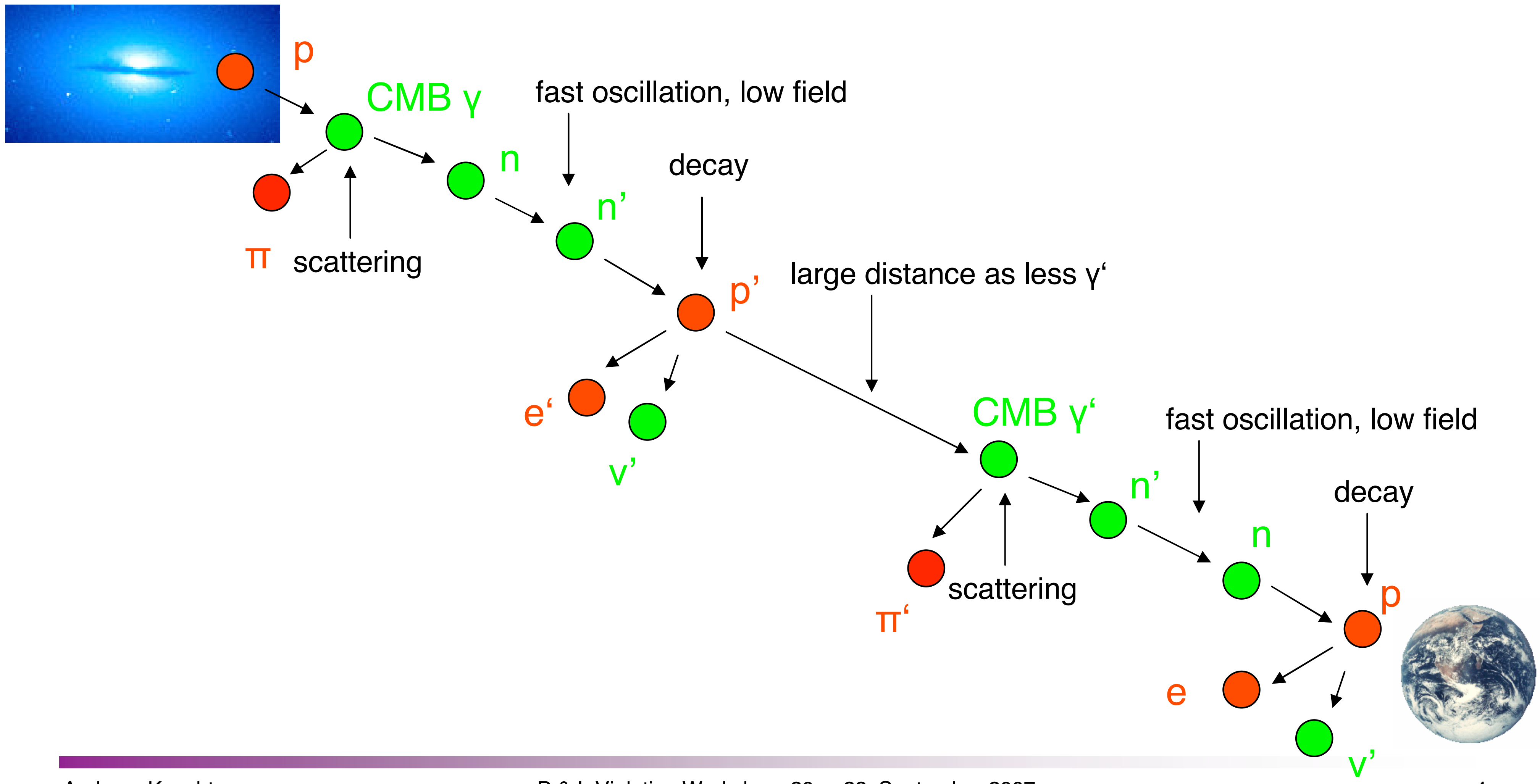
Lee and Yang, 1956

# Anomalies explained…

- Dark Matter, mirror stars/planets
  - Kobzarev, Sov. J. Nucl. Phys. **3** (1966)
  - Foot, Phys. Lett. B **452** (1999)
  - Foot, Phys. Lett. B **471** (1999)
  - Berezhiani, Int. J. Mod. Phys. A **19** (2004)
  - Foot, Int. J. Mod. Phys. A **19** (2004)
- Violation of GZK-cutoff
  - Mohaptra et al, Phys. Lett. B **627** (2005)
  - Berezhiani and Bento, Phys. Lett. B **635** (2006)
  - Berezhiani and Bento, Phys. Rev. Lett. **96** (2006)
  - Pokotilovski, Phys. Lett. B **639** (2006)
- Orthopositronium lifetime anomaly
  - Atoyan, Phys. Lett. B **220** (1989)
  - Mitsui et al, Phys. Rev. Lett. **70** (1993)
  - Badertscher et al., Phys. Rev. D **75** (2007)
- Neutrino anomalies
  - Berezhiani and Mohapatra, Phys. Rev. D **52** (1995)
  - Foot and Volkas , Phys. Rev. D **61** (2000)
  - Mohapatra and Nasri, Phys. Rev. D **71** (2005)
- Pioneer spacecraft anomaly
  - Foot and Vokas, Phys. Lett. B **517** (2001)
- Anomalous impacts

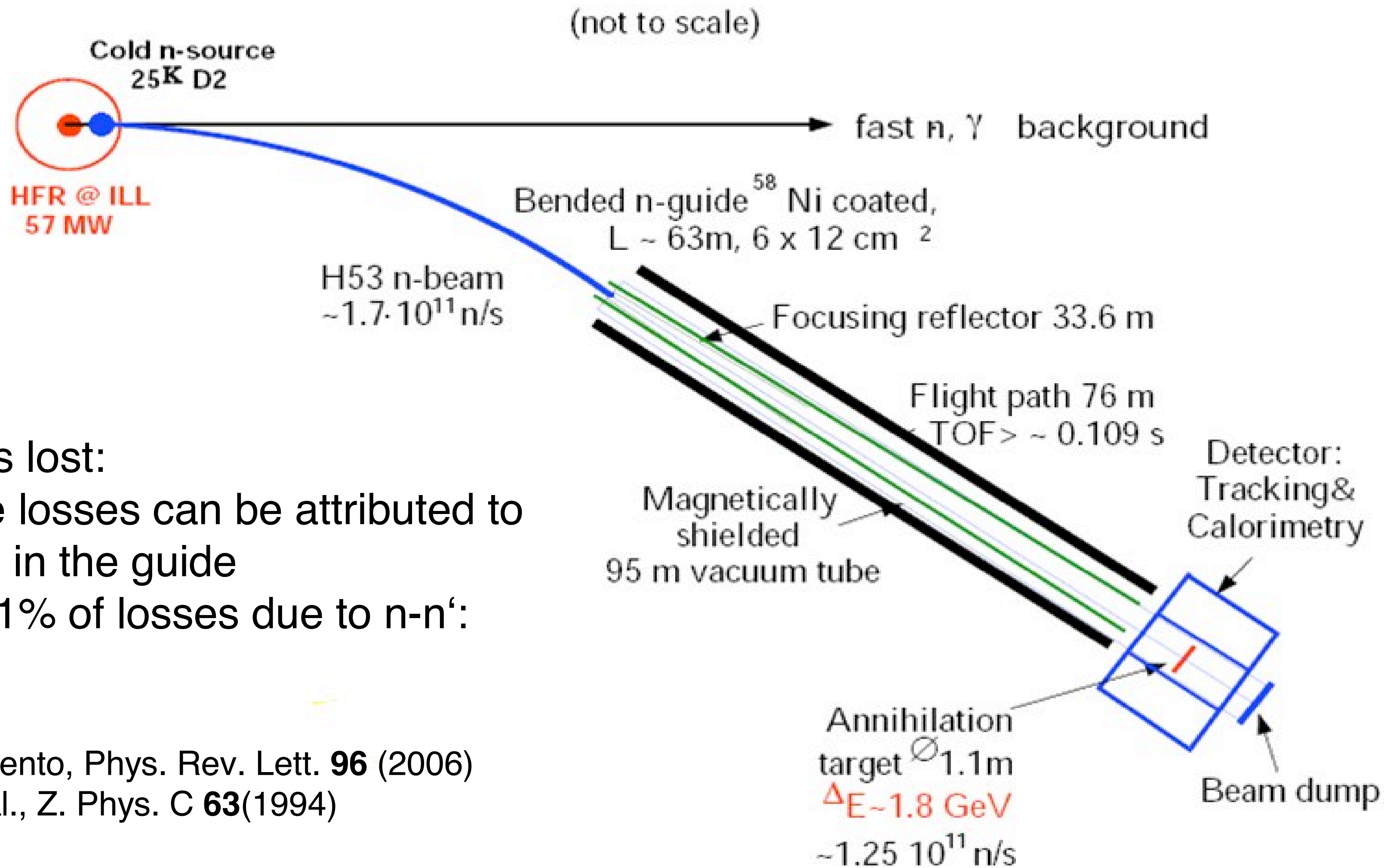
# Violation of GZK-cutoff

Explanation with fast ($\tau_{osc} << \tau_n$) neutron – mirror neutron oscillations



# Existing limit

Indirect limit on n-n' oscillations extracted from the neutron-antineutron oscillation measurement




5% of neutrons lost:

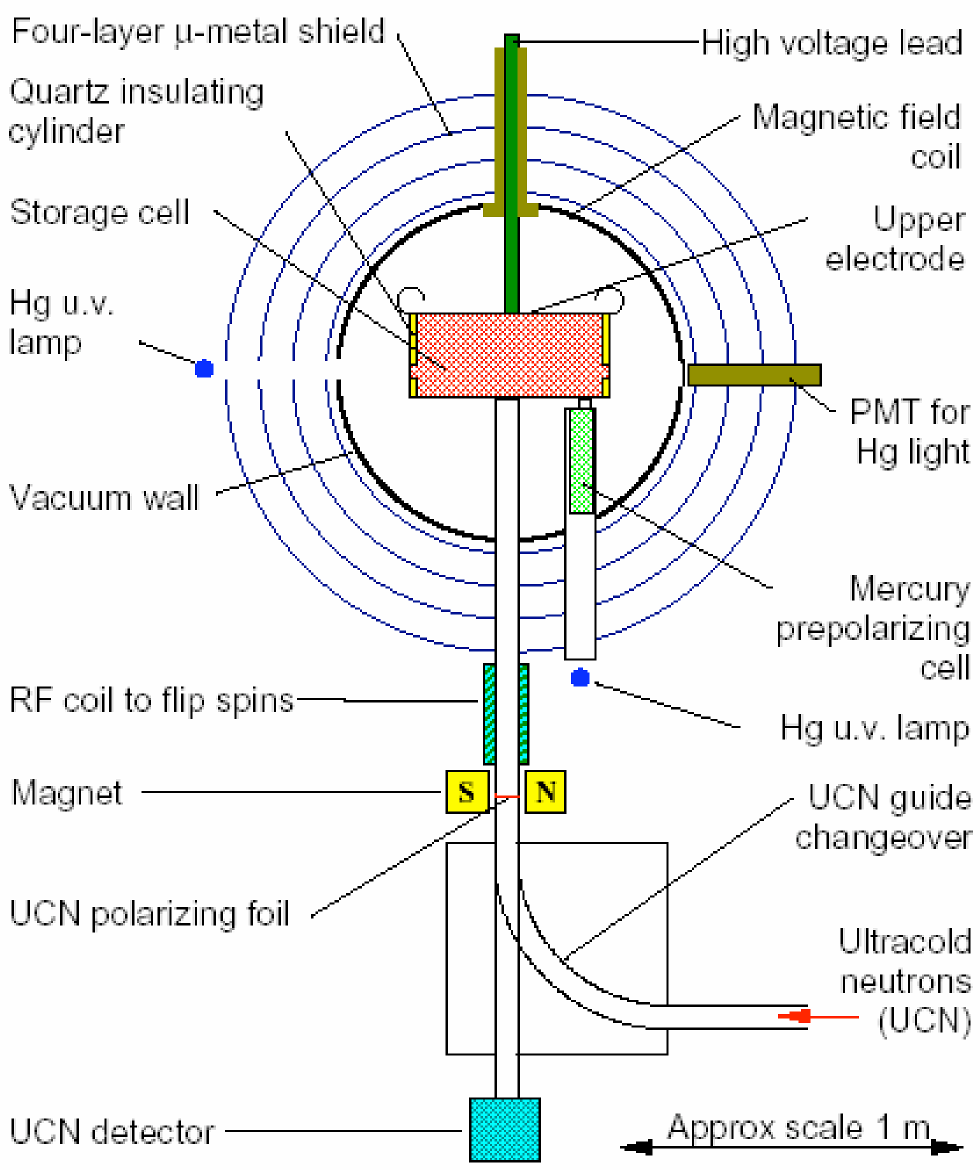
→ Most of the losses can be attributed to scatterings in the guide

→ Assuming 1% of losses due to n-n‘:

$\tau_{nn'} > 1\text{s}$

- Berezhiani and Bento, Phys. Rev. Lett. **96** (2006)
- Baldo-Ceolin et al., Z. Phys. C **63**(1994)

# nEDM experiment

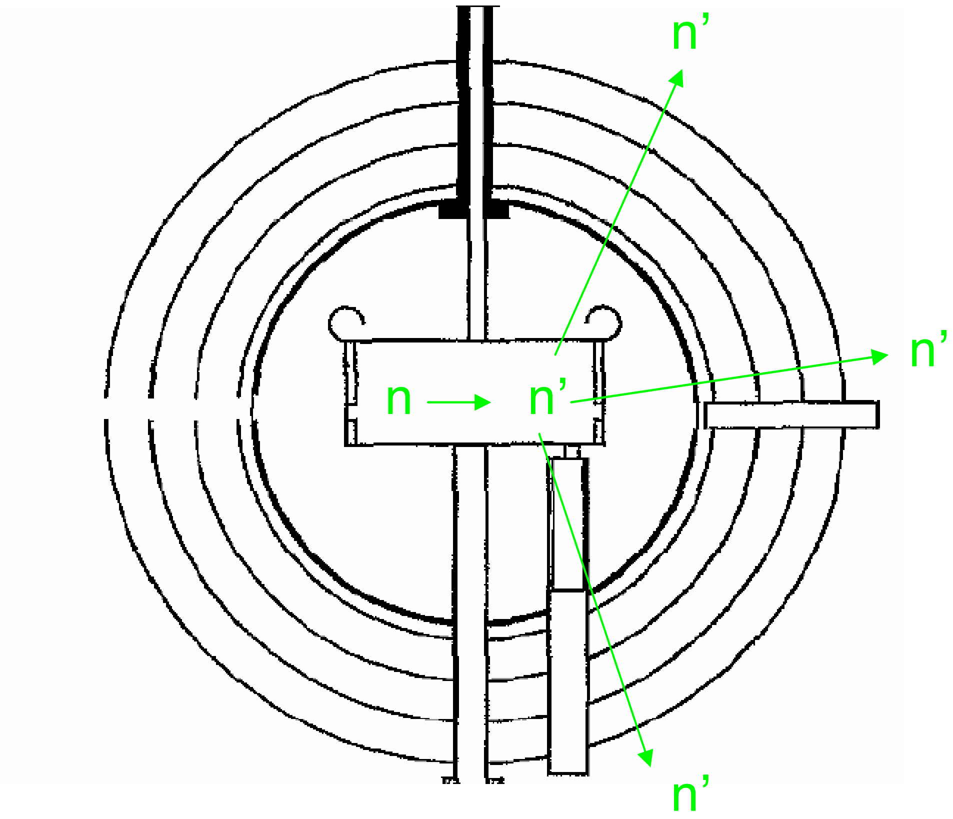



- Experiment to search for the P and T violating electric dipole moment of the neutron

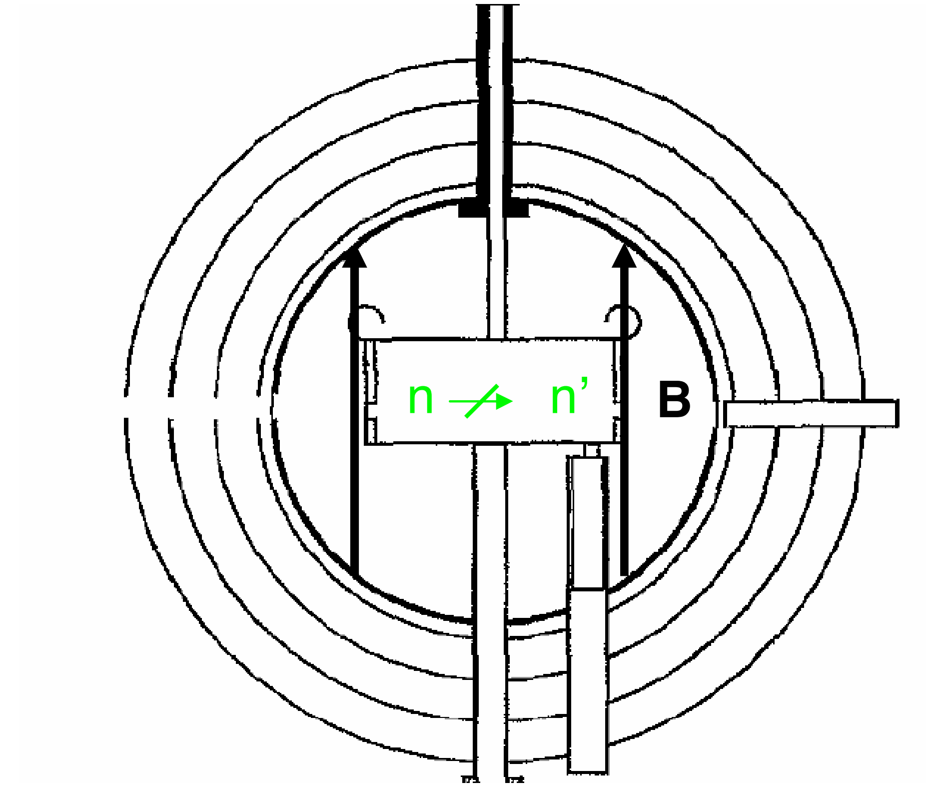
- Current limit: $d_n < 2.9 \times 10^{-26}$ *e* cm
  - Baker et al, PRL **97** (2006)

- The EDM limit directly constrains theories beyond the standard model such as SUSY

# nEDM goes n'




demagnetised shields, coils off



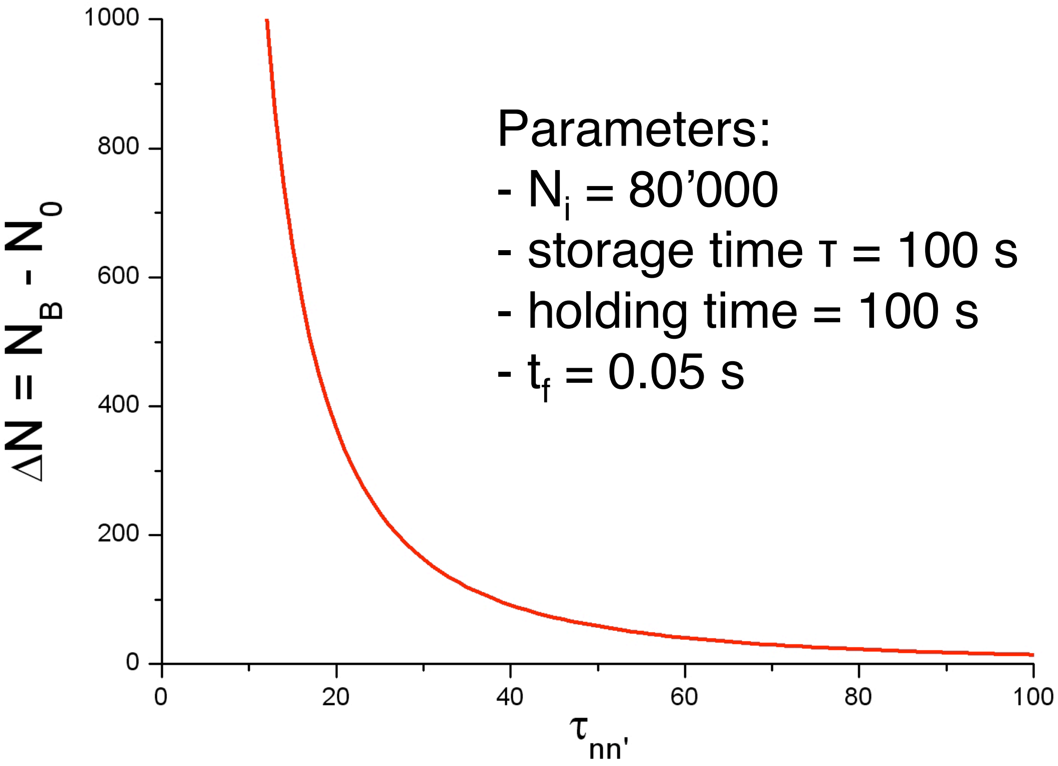

magnetic field, different energy levels

→ additional loss channel due to nn' oscillations
→ relevant time scale: free flight time $t_f$ between wall collisions

# nEDM goes n'

- Count UCNs after a certain holding time for magnetic field on and off

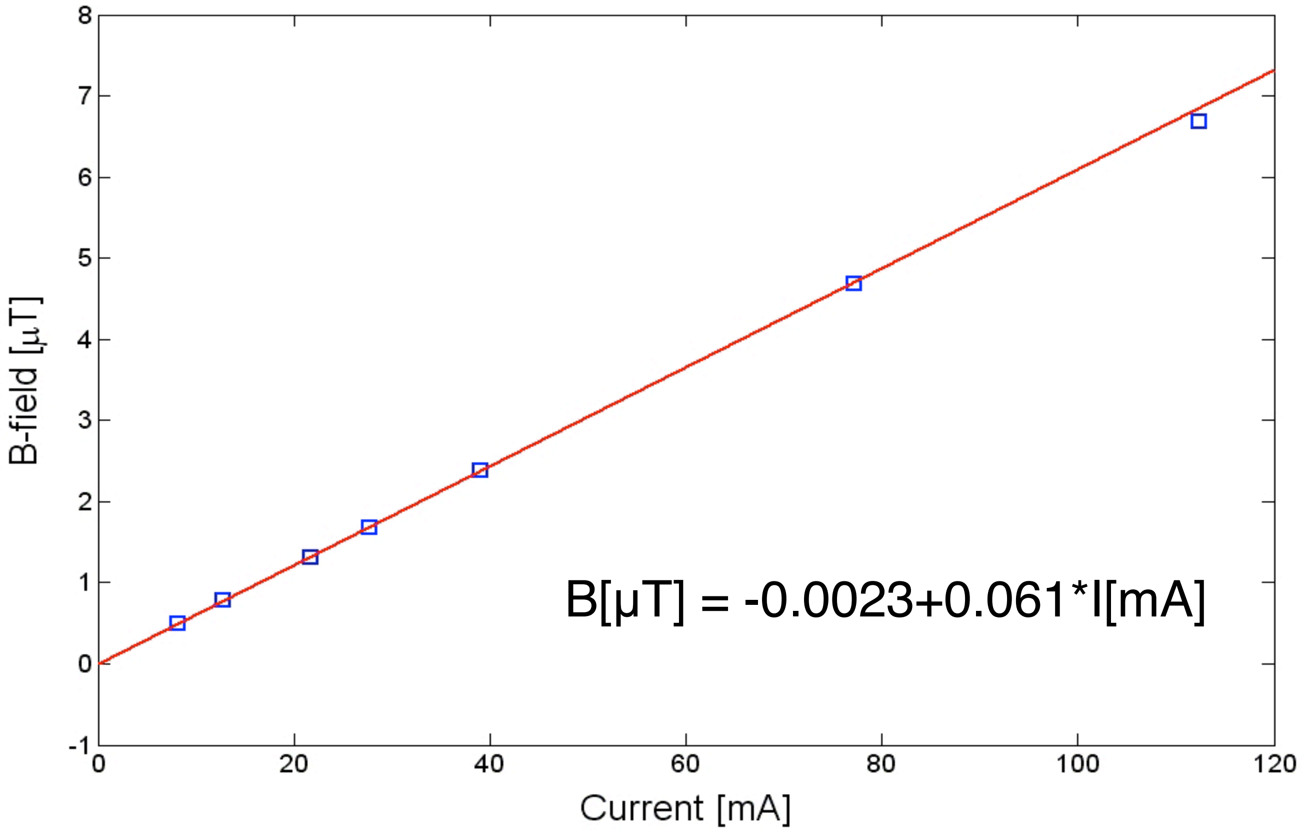
- Additional loss channel due to oscillations
  → Loss rate:
  $R = 1/t_f * P_{n \to n'}(t_f)$



# High/Low B-fields



**Measurements with $^{199}$Hg co-magnetometer**




- We can produce high fields
- Extrapolating to I=0: Low field below 13 nT (95% CL)
- Low field measured with fluxgates < 50 nT

# nEDM goes n′

**Measurements:**

- ~ 80’000 unpolarised UCNs filled
- Change of magnetic field: 0 / $B_\uparrow$ / $B_\downarrow$ / 0 / 0 / $B_\downarrow$ / 0 / $B_\uparrow$ and repeat
  - Always demagnetised before a low field run
  - Each run consists of 4x100s, 4x50s, 4x175s and 4x100s holding time (roughly 1.5h)

**Necessary assumption:**

- No mirror magnetic field at experimental site!
  (only weak bound of ~ $10^{-3}$ on mirror matter inside earth)
  - Ignatiev and Volkas, Phys Rev D **62** (2000)

# Analysis

**Oscillation probability:**

$$p(t) = \frac{\sin^2(\sqrt{1+(\omega\tau_{\mathrm{nn'}})^2} \times t/\tau_{\mathrm{nn'}})}{1+(\omega\tau_{\mathrm{nn'}})^2} \to \frac{t^2}{\tau_{nn'}^2} \quad \text{low field, < 50 nT}$$

$$\to \frac{1}{2(\omega_{\uparrow\downarrow}\,\tau_{\mathrm{nn'}})^2} \quad \text{high field, > 5 µT}$$

Def.: ω = µB/2ħ

**Transition rates:** $R_s = \frac{1}{\langle t_f \rangle_{t_s}} \langle p(t_f) \rangle_{t_s}$

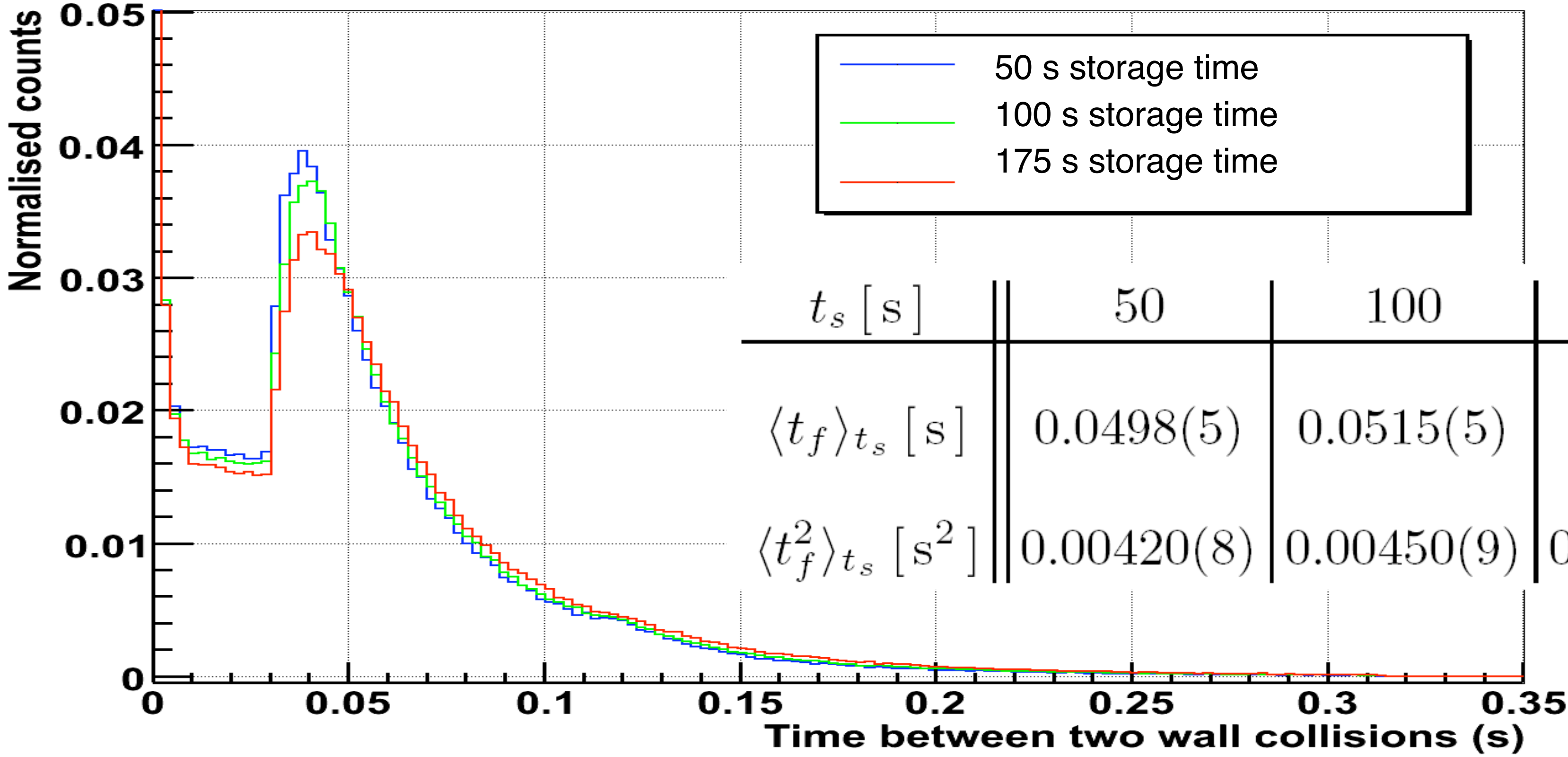
- Low field: $R_{s,0} = \frac{1}{\langle t_f \rangle_{t_s}} \frac{\langle t_f^2 \rangle_{t_s}}{\tau_{\mathrm{nn'}}^2}$
- High field: $R_{s,\uparrow\downarrow} = \frac{1}{\langle t_f \rangle_{t_s}} \frac{1}{2(\omega_{\uparrow\downarrow}\,\tau_{\mathrm{nn'}})^2}$

Ratio of measured UCN counts:

$$N_{0/\uparrow\downarrow} \equiv \frac{n_0(t_s)}{n_{\uparrow\downarrow}(t_s)} = \exp[(R_{s,\uparrow\downarrow} - R_{s,0})\, t_s]$$

# Free flight times






| $t_s$ [s] | 50 | 100 | 175 |
|---|---|---|---|
| $\langle t_f \rangle_{t_s}$ [s] | 0.0498(5) | 0.0515(5) | 0.0543(5) |
| $\langle t_f^2 \rangle_{t_s}$ [$s^2$] | 0.00420(8) | 0.00450(9) | 0.00505(10) |

- Geant4UCN calculation of apparatus tuned to experimental data
- Systematic errors obtained by varying simulation parameters

# Results

| $t_s$ [s] / $t_s^*$ [s] | 50 (a) / 73 ± 3 | 50 (b) / 73 ± 3 | 100 / 123 ± 3 | 175 / 198 ± 3 |
|---|---|---|---|---|
| $n(B_0)$ | 44’317 ± 40 | 44’363 ± 53 | 28’635 ± 21 | 17’015 ± 22 |
| $n(B_\uparrow)$ | 44’197 ± 53 | 44’443 ± 53 | 28’671 ± 30 | 17’047 ± 31 |
| $n(B_\downarrow)$ | 44’128 ± 53 | 44’316 ± 46 | 28’596 ± 30 | 16’974 ± 31 |
| $n(B_{\uparrow\downarrow})$ | 44’163 ± 38 | 44’371 ± 35 | 28’633 ± 22 | 17’011 ± 22 |
| $N_{0/\uparrow\downarrow}$ | 1.0035(13) | 0.9998(15) | | |
| $N_{0/\uparrow\downarrow}$ | **1.0019(10)** | | **1.0001(11)** | **1.0002(18)** |

- $t_s^*$: corrected storage time by adding 2x the emptying/filling constant
- 50s measured a second time (b) after switch repair

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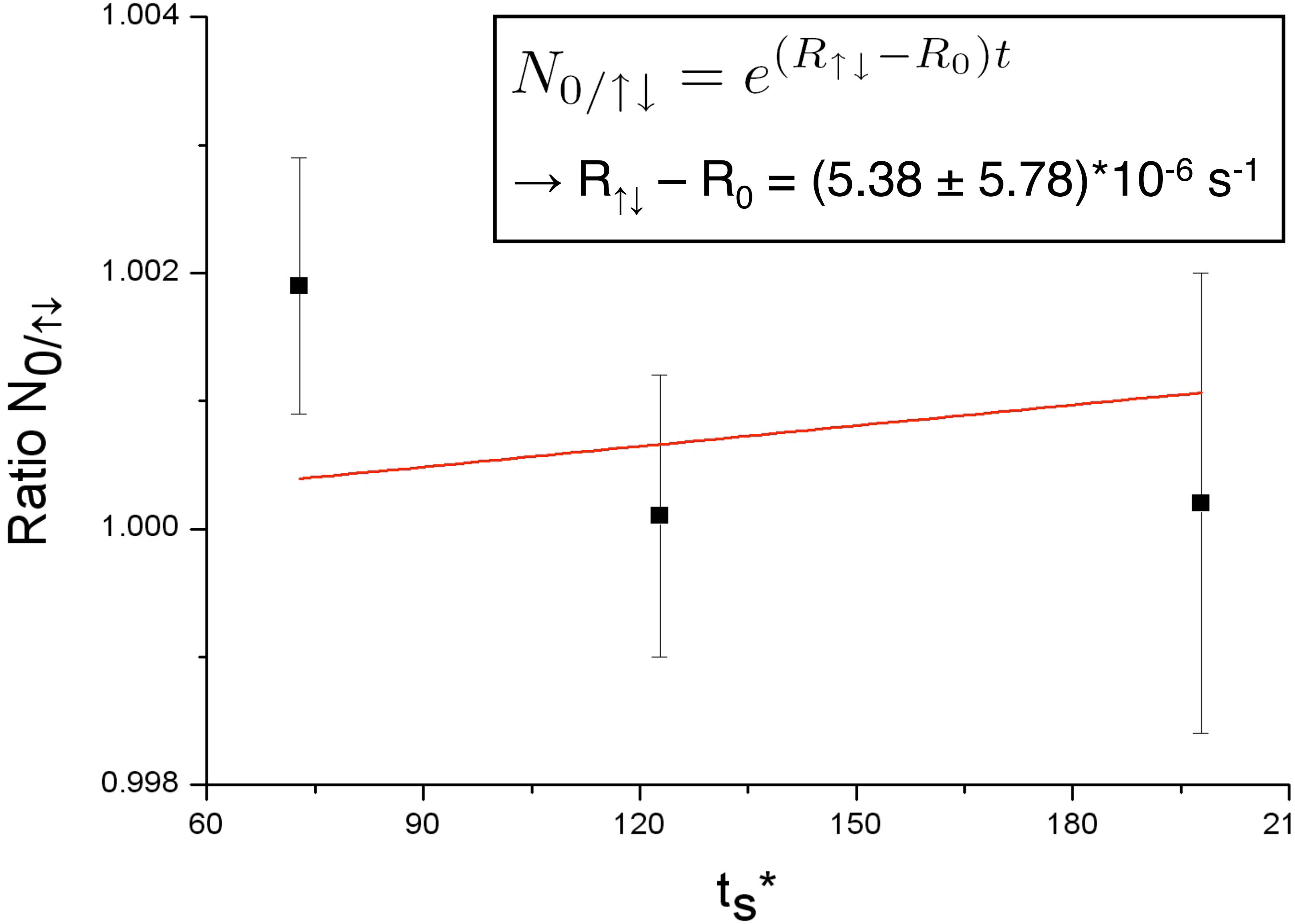
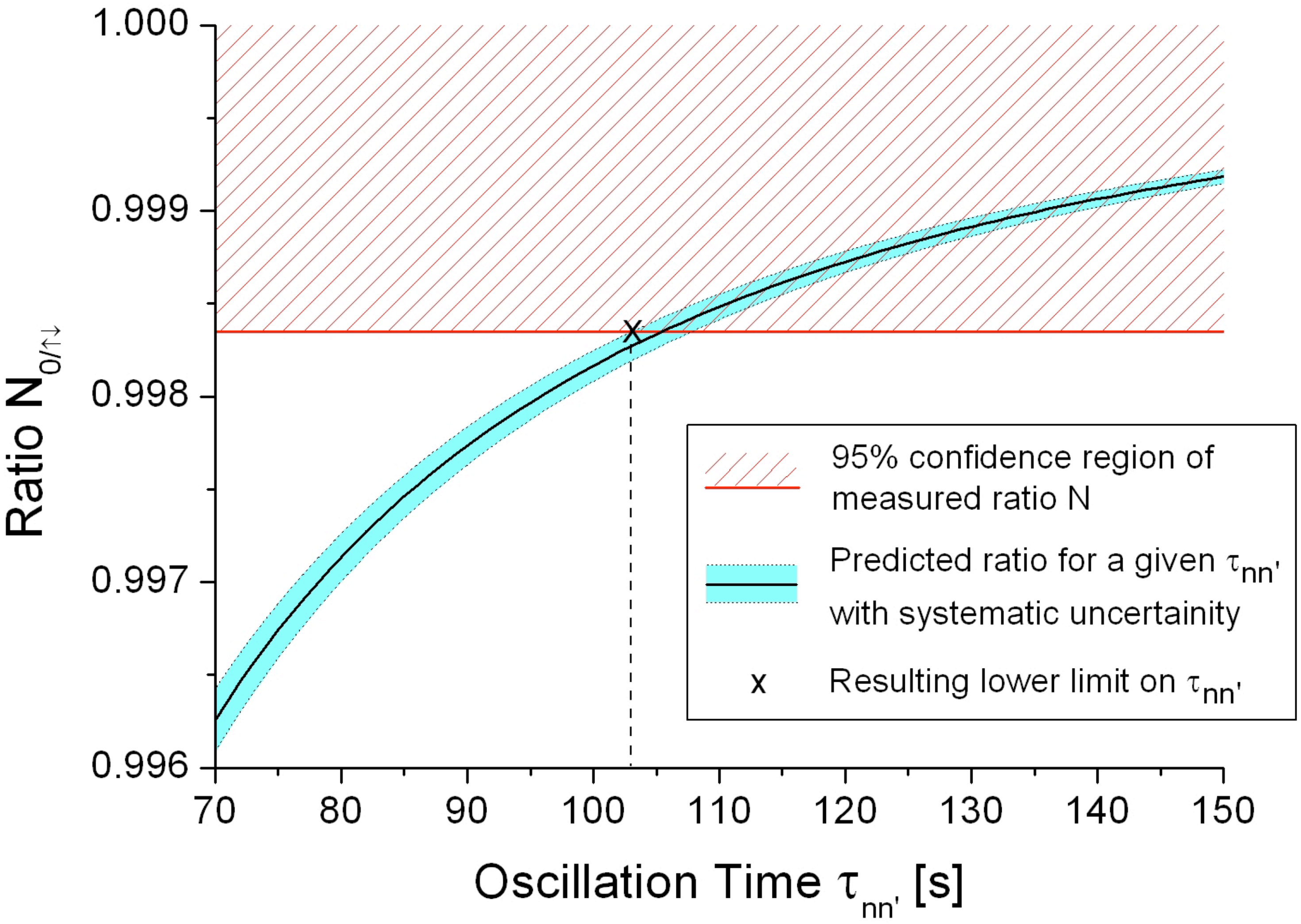
# Results

Ultra Cold Neutron Source




$\rightarrow$ from the fit: **$N_{0/\uparrow\downarrow}(t_s{}^*=198s) = 1.00106 \pm 0.00114$**

# Obtaining the Limit




→ $\tau_{nn'} > 103$ s (95% C.L.)

# Conclusion

- First direct measurement on neutron – mirror neutron oscillations

- No oscillation observed: **$\tau_{nn'} > 103$ s (95% C.L.)**

  - Ban et al, accepted for publication in PRL (arXiv:0705.2336)

- This improves the present indirect limit by two orders of magnitude but cannot rule out the nn'-explanation for UHECR above the GZK-cutoff

- Possible improvements:
  - Straightforward: $\tau_{nn'} > O(1'000\text{ s})$
  - Dedicated effort: $\tau_{nn'} > O(10'000\text{ s})$

# Backup

# Beam vs. Storage

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Ultra Cold Neutron Source

**Beam:**

- Ratio: $N = 1 - \frac{t_f^2}{\tau_{nn'}^2}$ Limit: $\tau_{nn'} > \sqrt{\frac{t_f^2}{1 - N + 1.65\Delta N}}$
- N=1, $t_f^2 \sim 0.05^2\ s^2$ (VCN), $\Delta N \sim 10^{-7} \rightarrow$ **$\tau_{nn'} > 100$ s**
- # of counts needed ~ **$10^{13}$**

**Storage:**

- Ratio: $N = 1 - \frac{t_f t_s}{\tau_{nn'}^2} = 1 - \frac{t_f^2}{\tau_{nn'}^2}\frac{t_s}{t_f}$ Limit: $\tau_{nn'} > \sqrt{\frac{t_s t_f}{1 - N + 1.65\Delta N}}$
- N=1, $t_f t_s \sim 0.1 * 150\ s^2$, $\Delta N \sim 10^{-3} \rightarrow$ **$\tau_{nn'} > 100$ s**
- # of counts needed ~ **$10^{6}$**

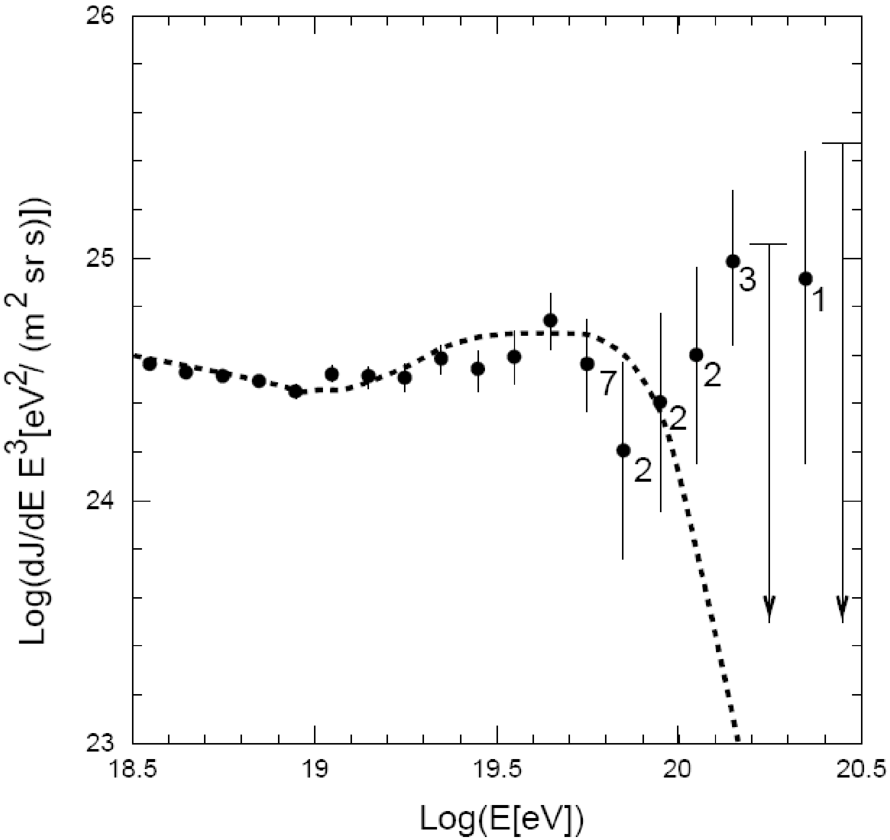
# GZK-cutoff



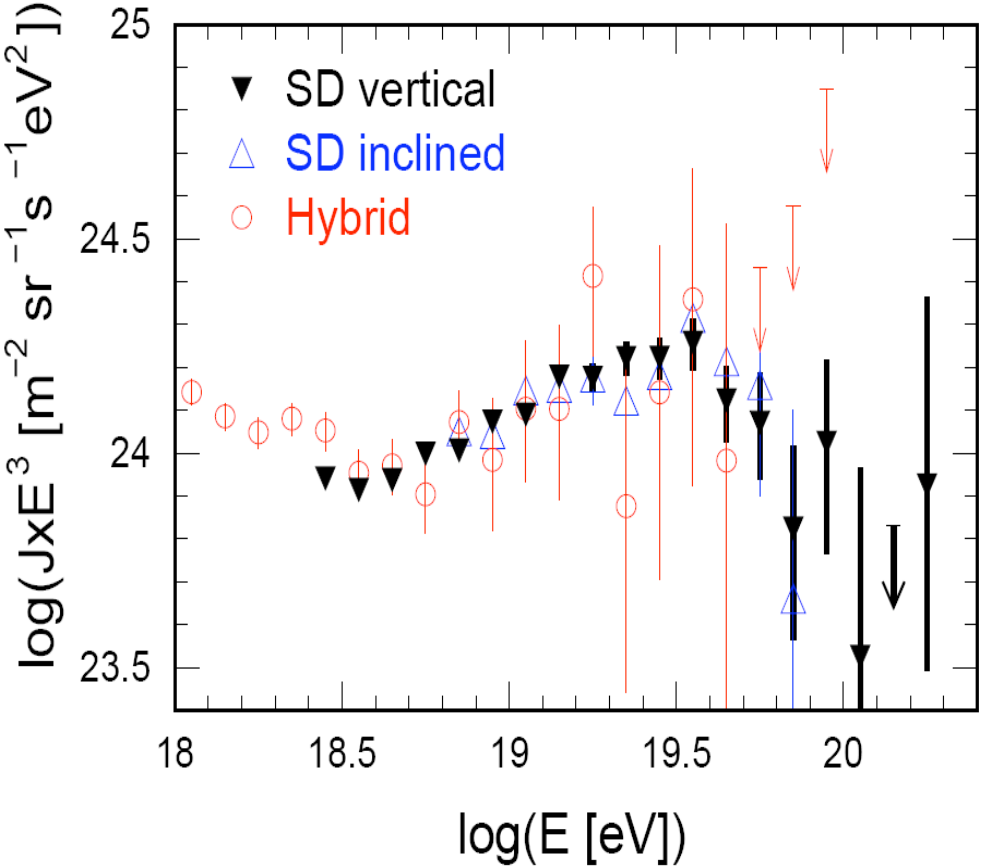
- Greisen, Zatsepin, Kuzmin
  - Greisen, Phys. Rev. Lett. (1966)
  - Zatsepin and Kuzmin, JETP Lett. (1966)

- Threshold for pion production by protons on CMB: $10^{20}$ eV
  → No high energy cosmic rays (above $10^{20}$ eV) from sources more than mean free path (5 Mpc) away

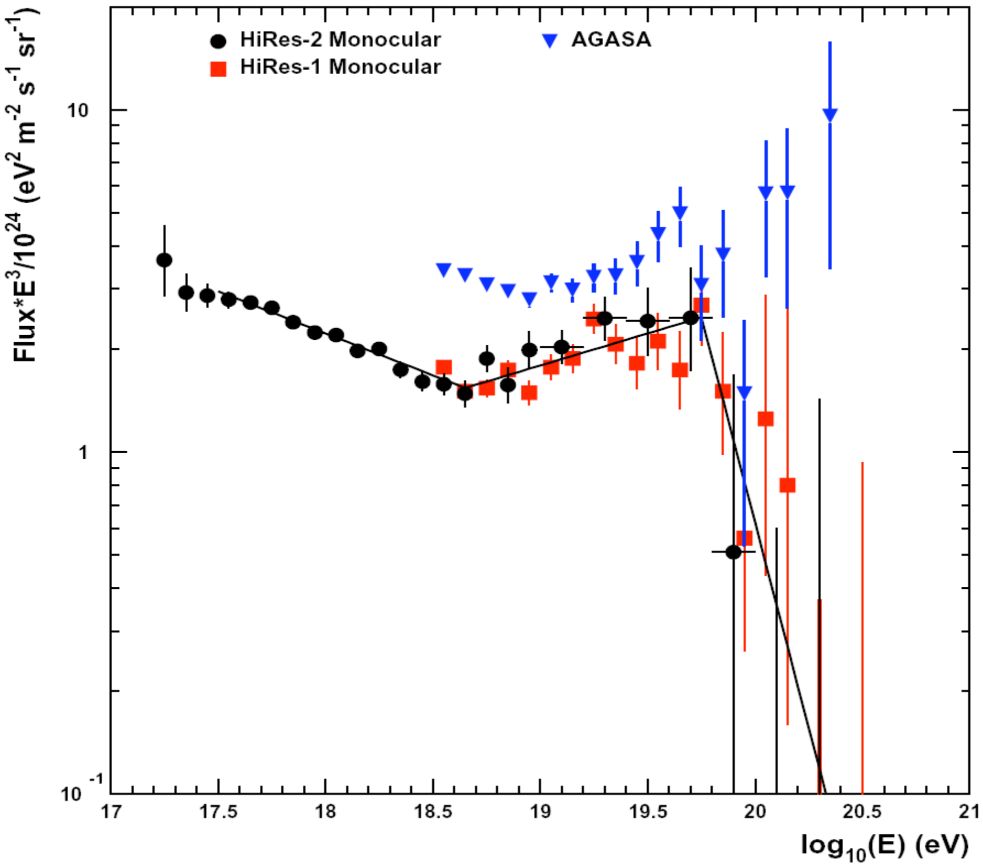
- Highest energy protons observed from far sources by AGASA detectors.
  - Takeda et al, Phys. Rev. Lett. (1998)
  - Tinjakov and Tkachev, JETP Lett. (2001)
  - Tinjakov and Tkachev, Astropart. Phys. (2002)



# New Data on UHECR



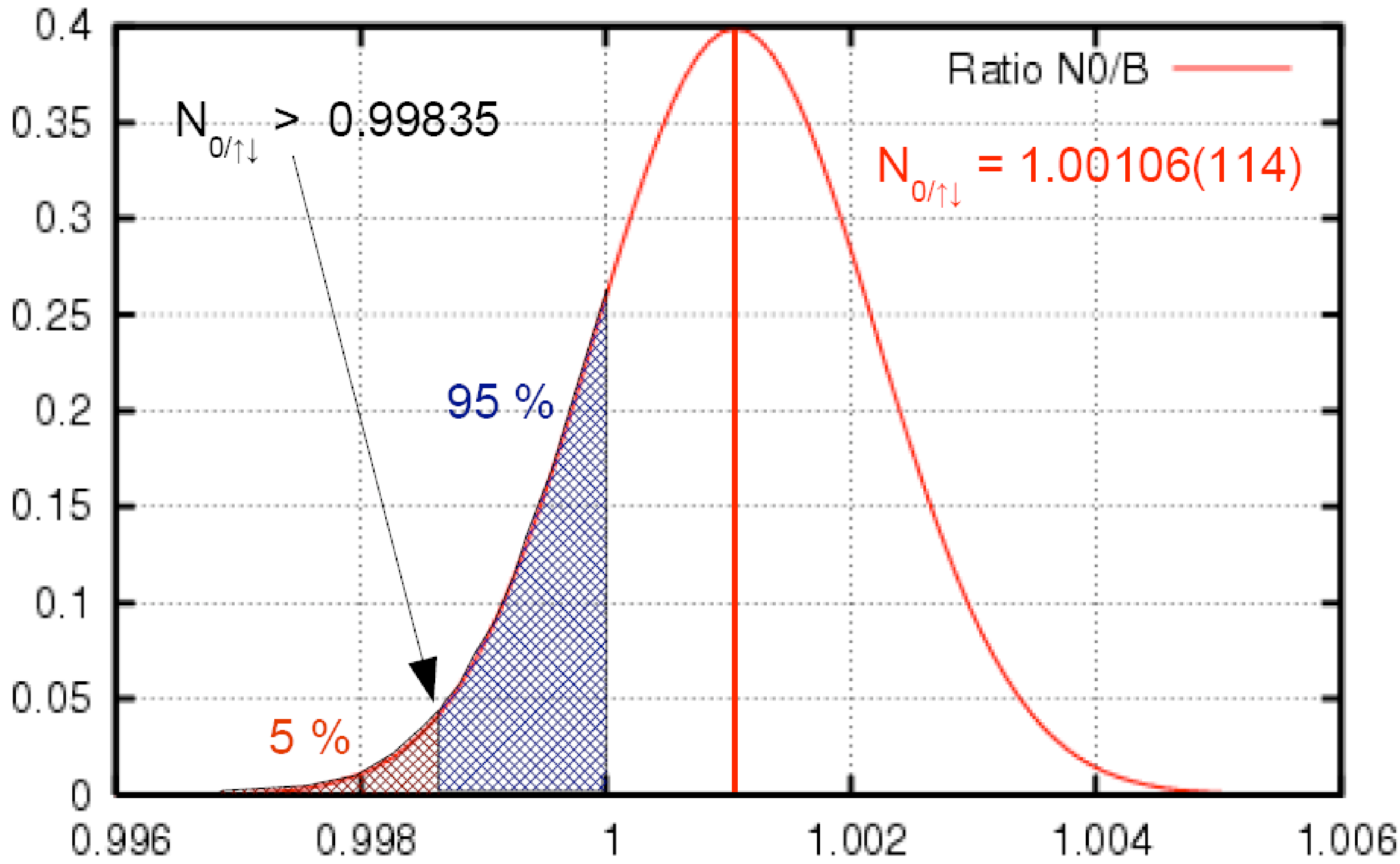

**Pierre Auger Observatory**
- Yamamoto et al., arXiv:0707.2638 (2007)




**High Resolution Fly's Eye detector**
- Bergman et al., Nucl. Phys B **165** (2007)

→ Newest data on UHECR seem to confirm existence of GZK-cutoff.

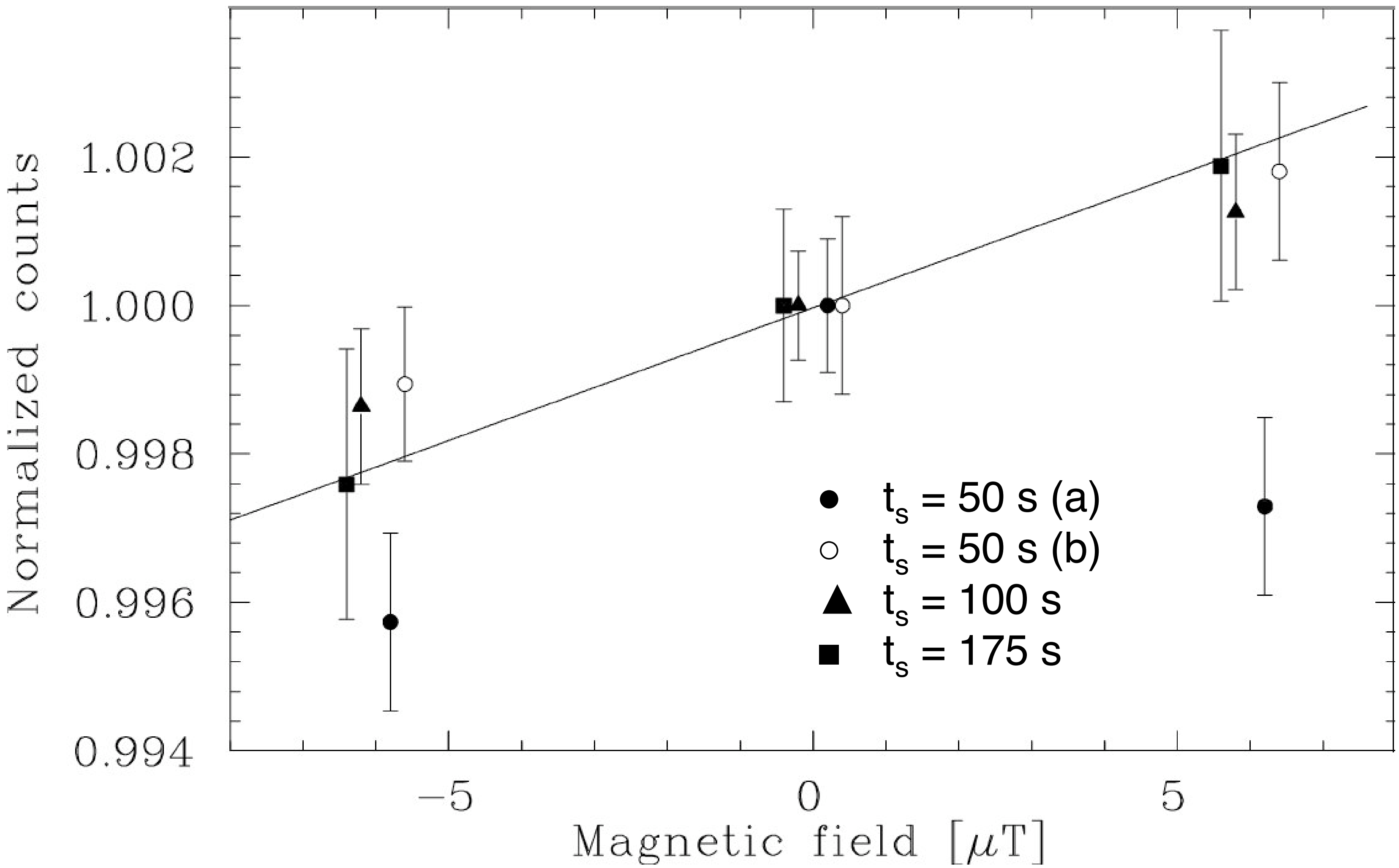
# Obtaining the Limit




Bayesian approach as values above 1 unphysical within nn' analysis

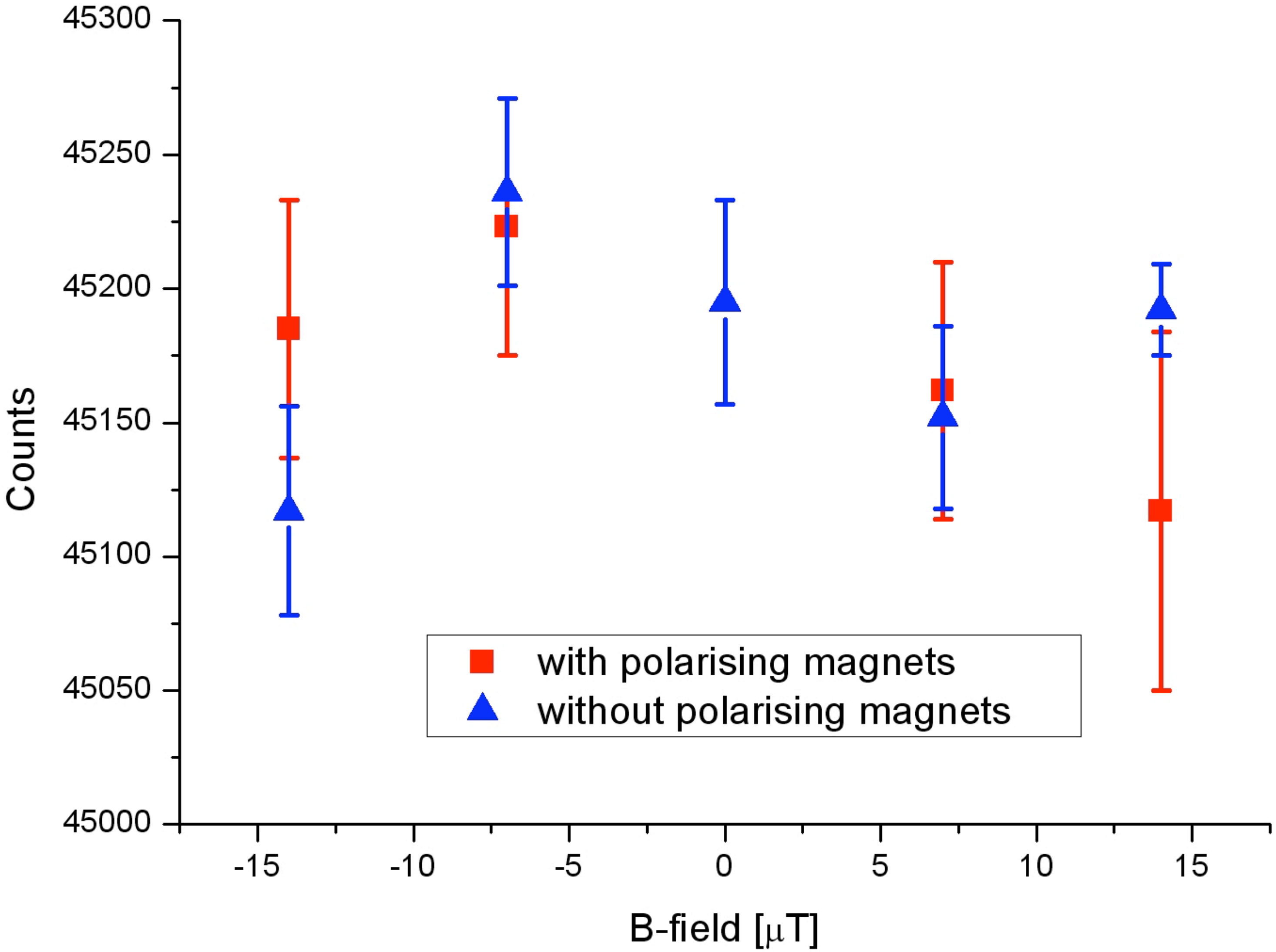
- W.-M. Yao et al., J. Phys. G 33, 1, p. 305 (2006)

# Counts vs B-field (nn')



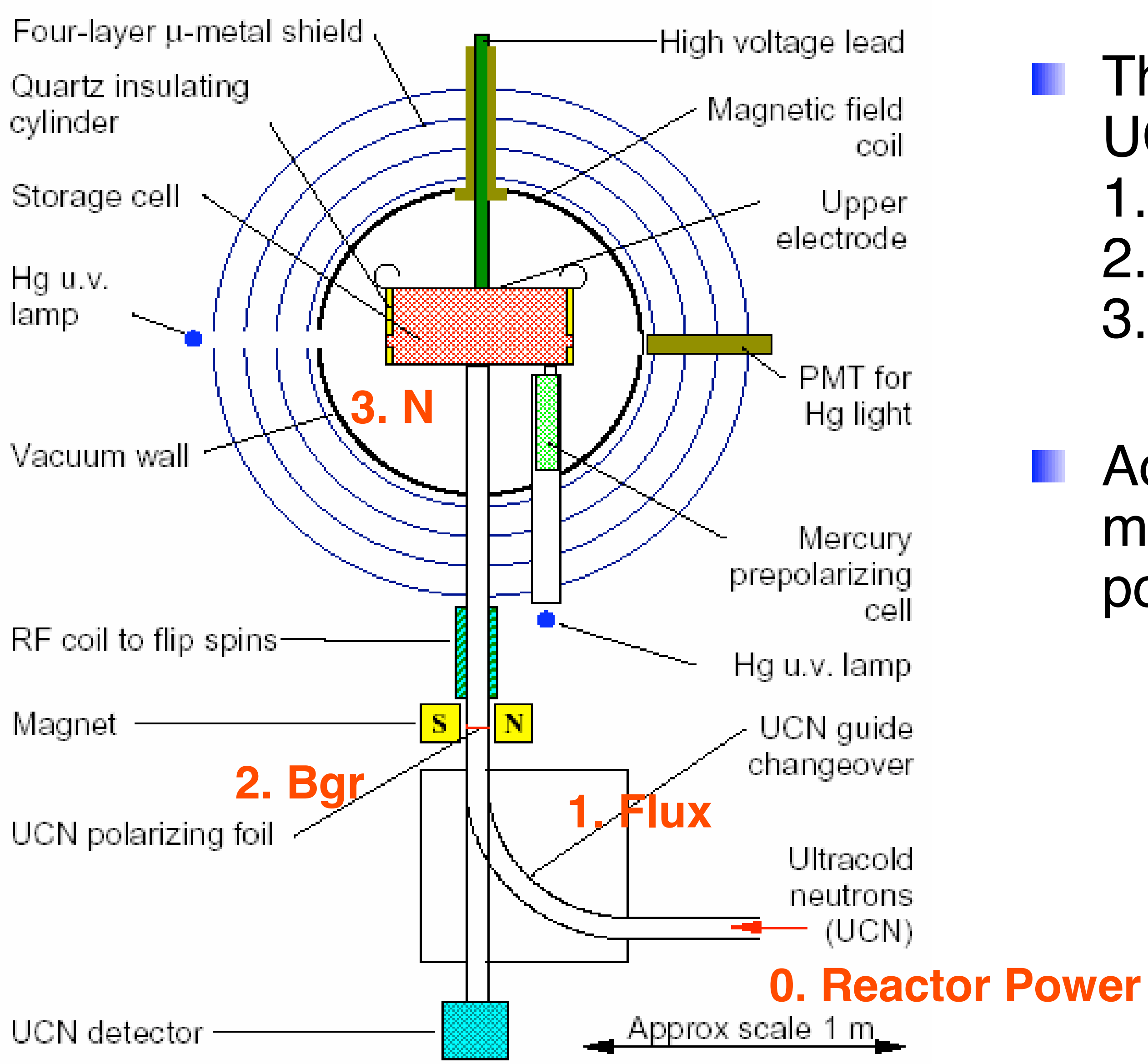

Possible dependency?
→ Does not affect nn' analysis as nn'-signature depends on $B^2$!

# Counts vs. B-field (remeas.)



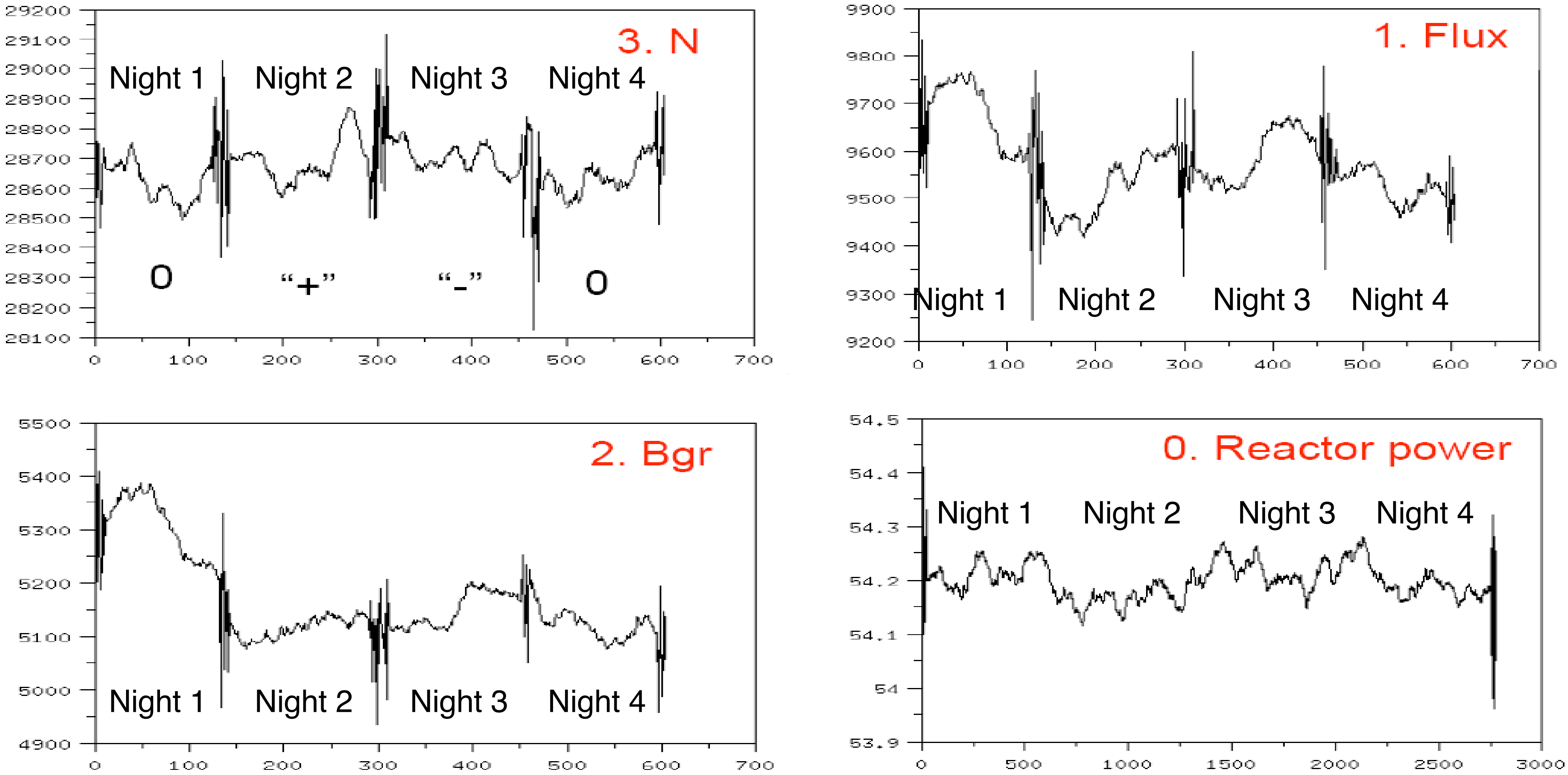

→ No dependency observed!

# Counters




- Three time windows for UCN detector:
  1. Filling
  2. Storage
  3. Counting
- Additionally log file of 1 min average reactor power available

# Normalisation




Normalisation due to non-reliable switch position not possible

→ Night runs not included in analysis

→ Drifts on the order of several hours: averaged out during the day