The search for an electric dipole moment of the neutron at PSI

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KU Leuven

PSI2016

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Speaking on behalf of the nEDM collaboration

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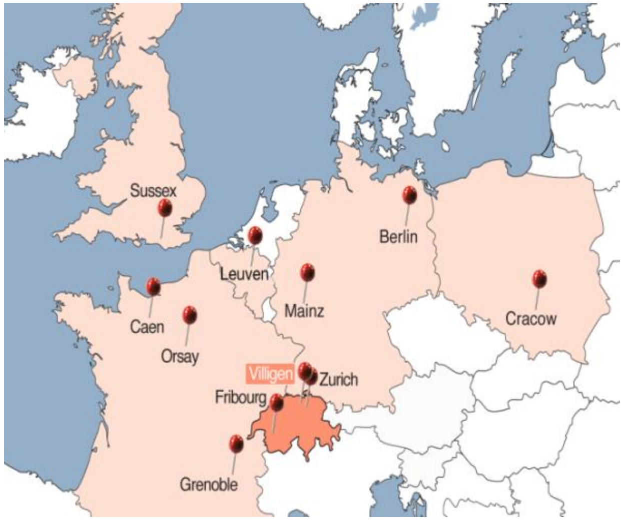
The collaboration

- 13 Institutions
- 7 Countries
- 48 Members
- 10 PhD students



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Contents

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Motivation

CP violation

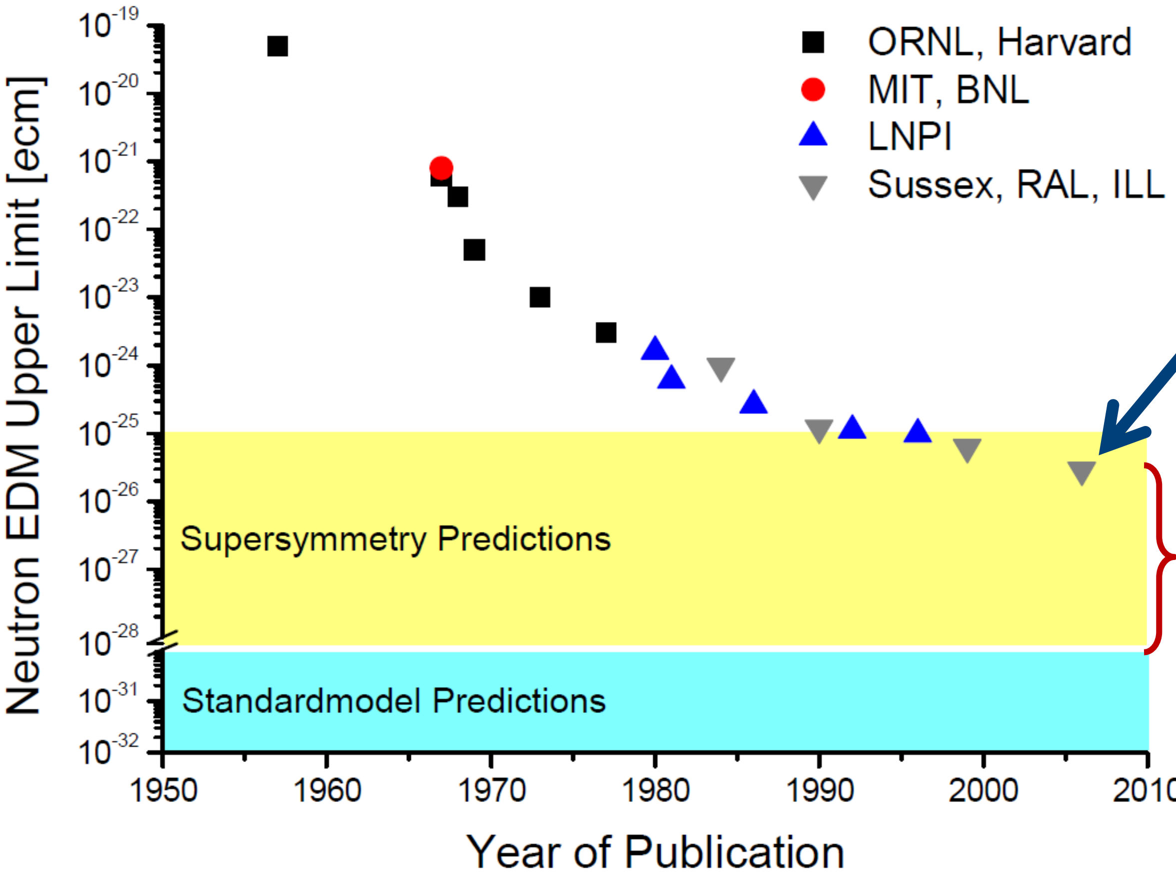
Permanent Electric Dipole Moment (EDM) of a particle violates CP symmetry if CPT symmetry is conserved

$$\boxed{\mathcal{H} = -\mu \cdot \frac{\vec{S}}{|\vec{S}|} \cdot \vec{B} - d \cdot \frac{\vec{S}}{|\vec{S}|} \cdot \vec{E}}$$

(non-relativistic interaction Hamiltonian)

Motivation

Constrain BSM physics



B $d_n < 2.9 \times 10^{-26}\ e \cdot \mathrm{cm}$

$3.0 \times 10^{-26}\ e\,\mathrm{cm}$

(90% C.L.)

Excellent observable to constrain non-SM physics!

Standard Model prediction:

$$d_n \approx 10^{-32} \ldots 10^{-30}\ e \cdot \mathrm{cm}$$

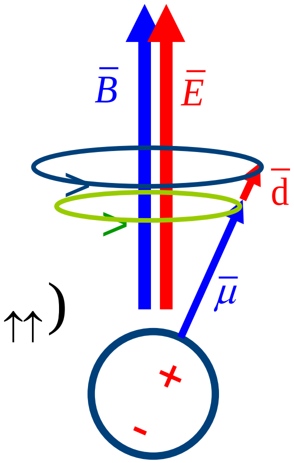
(without QCD θ-term)

Experimental method & setup

General idea:

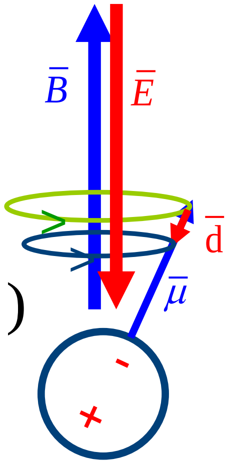
1. Measure Larmor precession frequency with parallel E and B

$$\hbar\omega_{\uparrow\uparrow} = 2(\mu_n B_{\uparrow\uparrow} + d_n E_{\uparrow\uparrow})$$



2. Measure Larmor precession frequency with antiparallel E and B

$$\hbar\omega_{\uparrow\downarrow} = 2(\mu_n B_{\uparrow\downarrow} - d_n E_{\uparrow\downarrow})$$



3. Take the difference!

$$d_n = \frac{\hbar\Delta\omega - 2\mu_n(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}{2(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})} = \frac{\hbar\Delta\omega}{4|E|}$$

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Experimental method & setup

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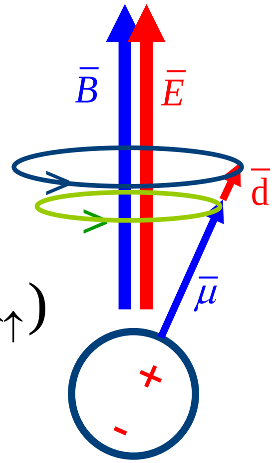

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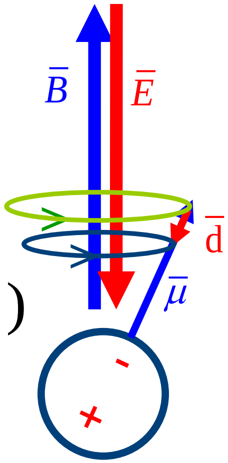

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$$d_n = \frac{\hbar\Delta\omega - 2\mu_n \boxed{(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}}{2(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})} =$$

Knowledge of magnetic field is important!!!

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Experimental method & setup

We use ultra cold neutrons (UCNs)

- UCNs have very low energies: ~100neV
- Speed less than 7m/s
- Full reflection at certain surfaces
- Can be guided and stored in a vessel!

Setup was moved from ILL to PSI where they built a dedicated UCN source

For more info on the UCN source, see the poster of Nicolas Hild!

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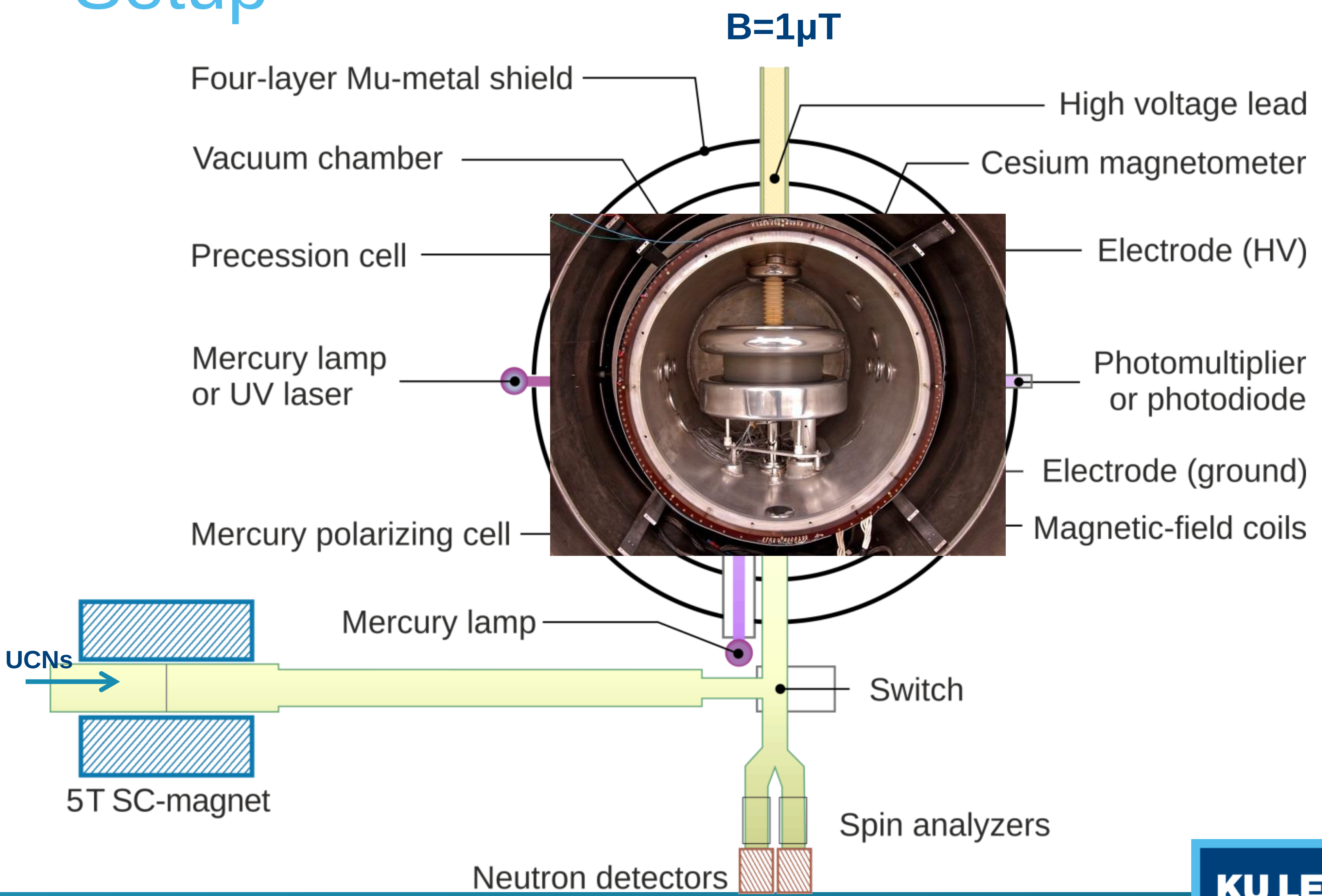
Setup



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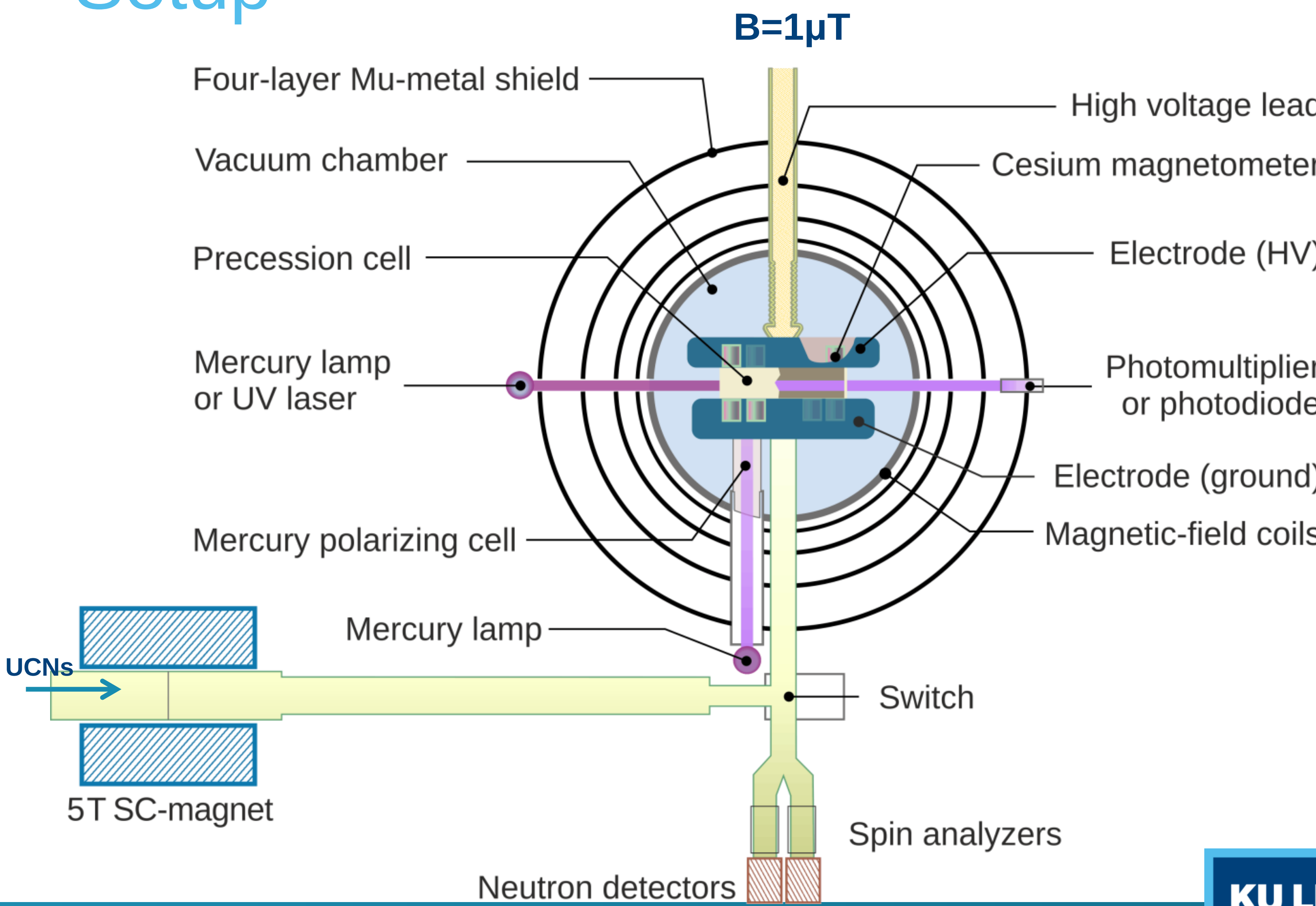
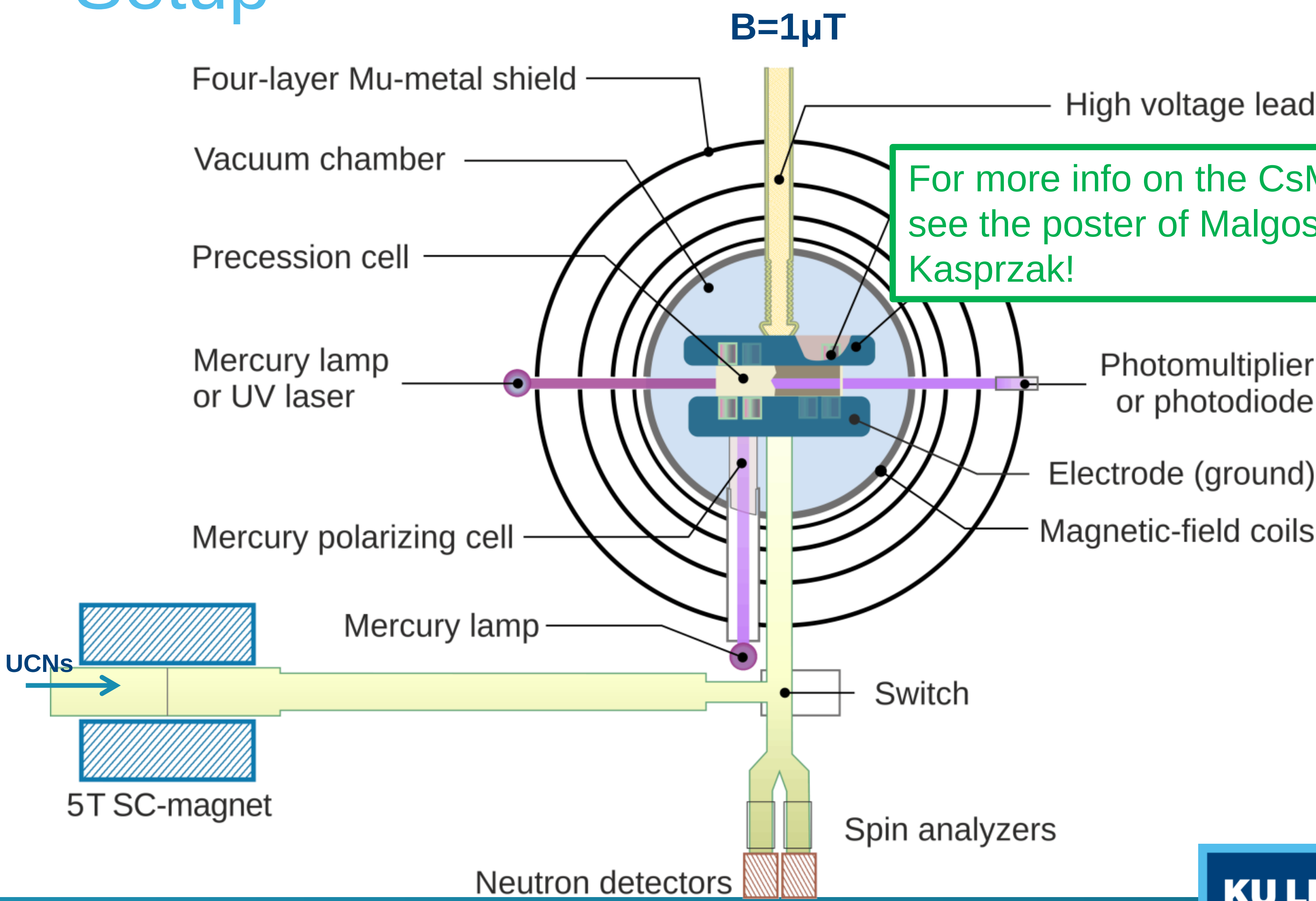
Setup


B=1µT
Four-layer Mu-metal shield
Vacuum chamber
Precession cell
Mercury lamp or UV laser
Mercury polarizing cell
Mercury lamp
High voltage lead
Cesium magnetometer
Electrode (HV)
Photomultiplier or photodiode
Electrode (ground)
Magnetic-field coils
UCNs
Switch
5T SC-magnet
Spin analyzers
Neutron detectors

Setup



For more info on the CsMs, see the poster of Malgosia Kasprzak!

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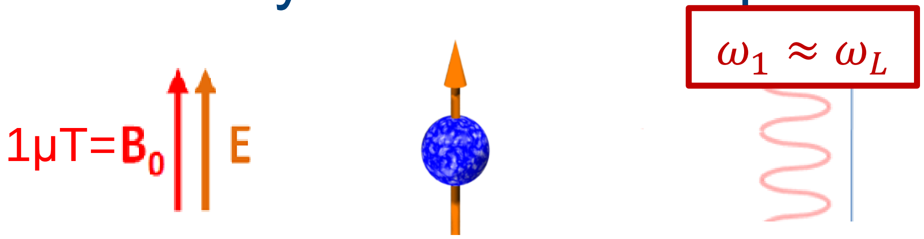
Experimental method

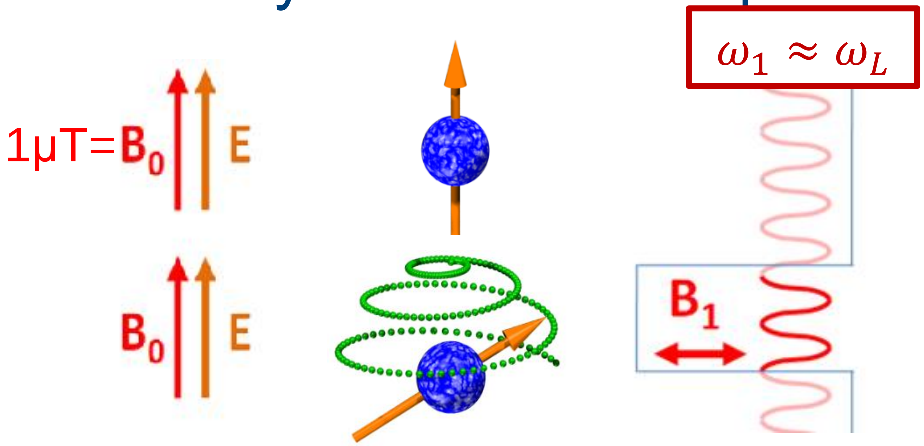
Ramsey’s method of separated oscillatory fields:



1. Polarize neutrons in direction of B_0.
Choose frequency ω_1 of external clock.

Experimental method

Ramsey's method of separated oscillatory fields:



1. Polarize neutrons in direction of B_0. Choose frequency ω_1 of external clock.

2. Apply rotating (ω_1) magnetic field B_1 perpendicular to B_0 for 2s. Neutron spin is flipped.

Experimental method

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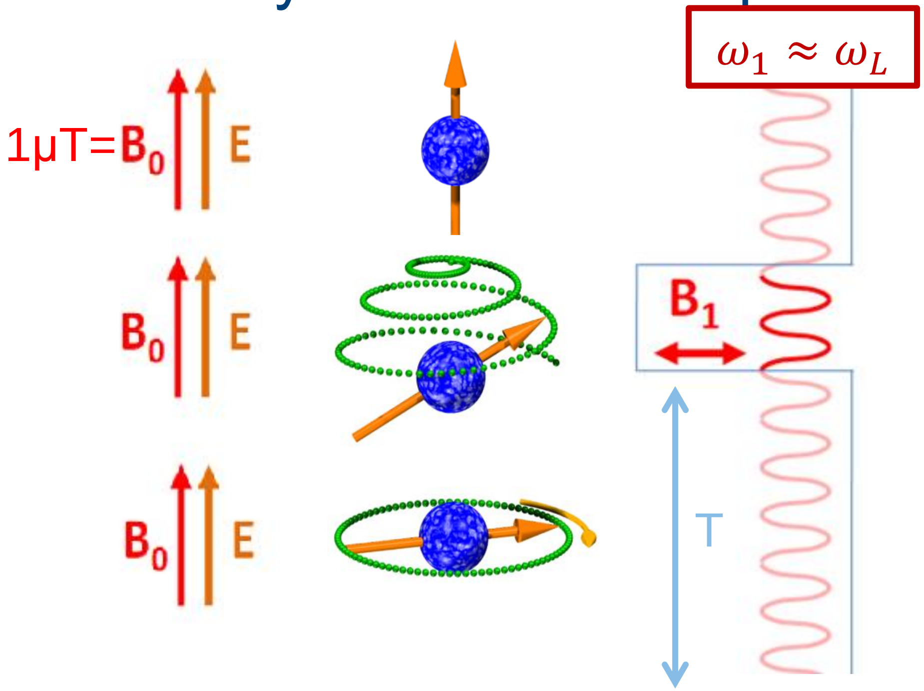

1. Polarize neutrons in direction of B_0. Choose frequency ω_1 of external clock.

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3. Neutrons precess freely during T, typically 180s.

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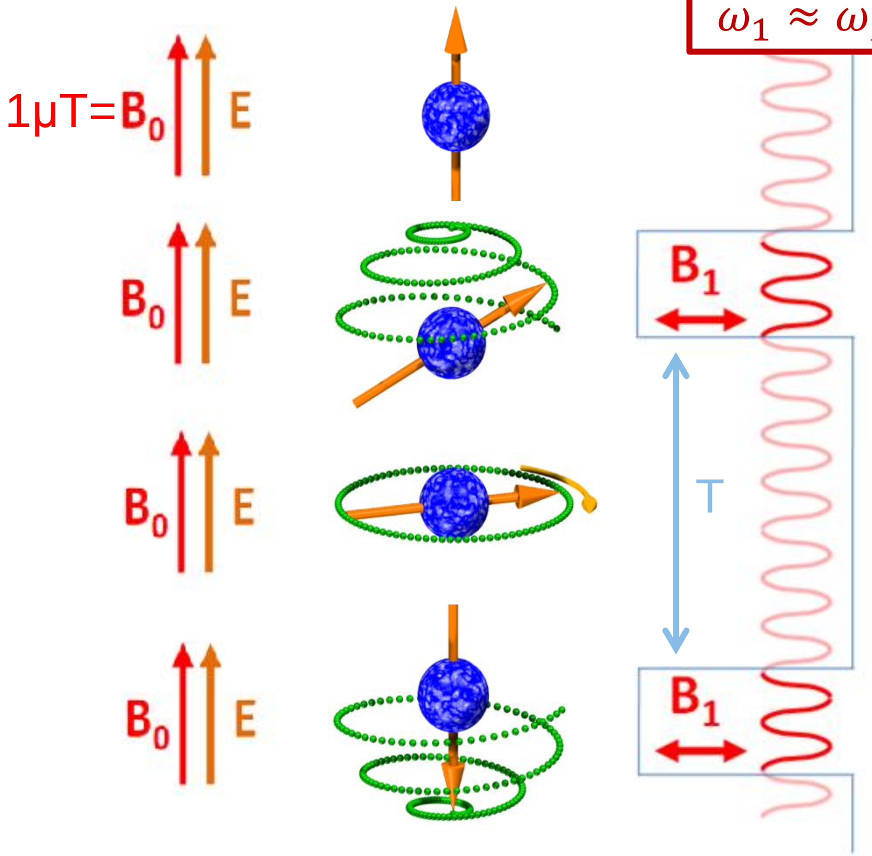

$\boxed{\omega_1 \approx \omega_L}$

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2. Apply rotating (ω_1) magnetic field B_1 perpendicular to B_0 for 2s. Neutron spin is flipped.

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4. Second spin flip pulse. Direction & amplitude of flip depend on phase built up between neutron spin and ω_1.

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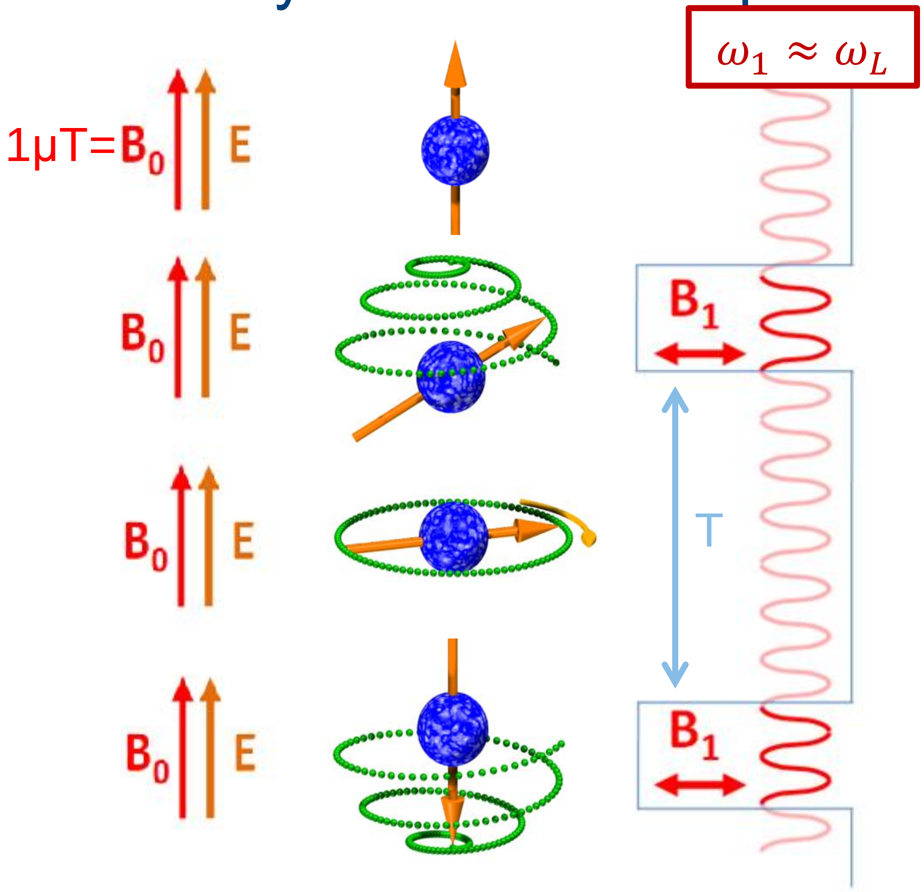

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5. Count spin up/down neutrons in function of ω_1

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Experimental method

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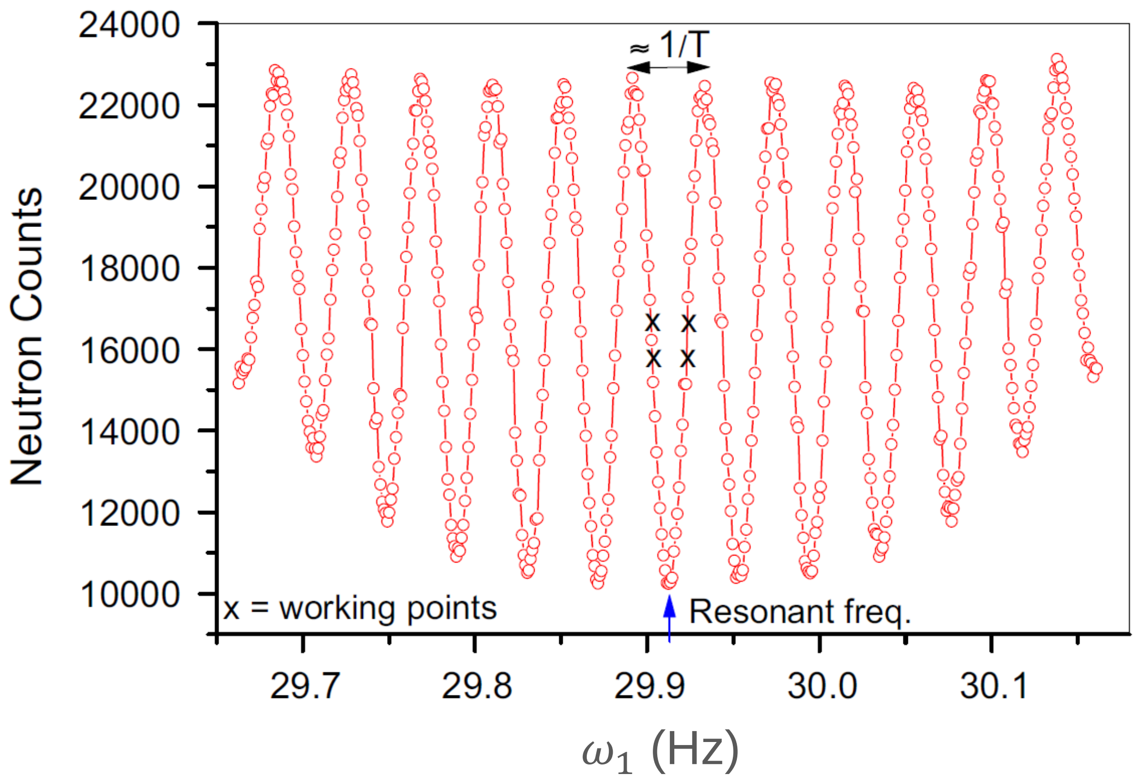

B=1μT

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Experimental method

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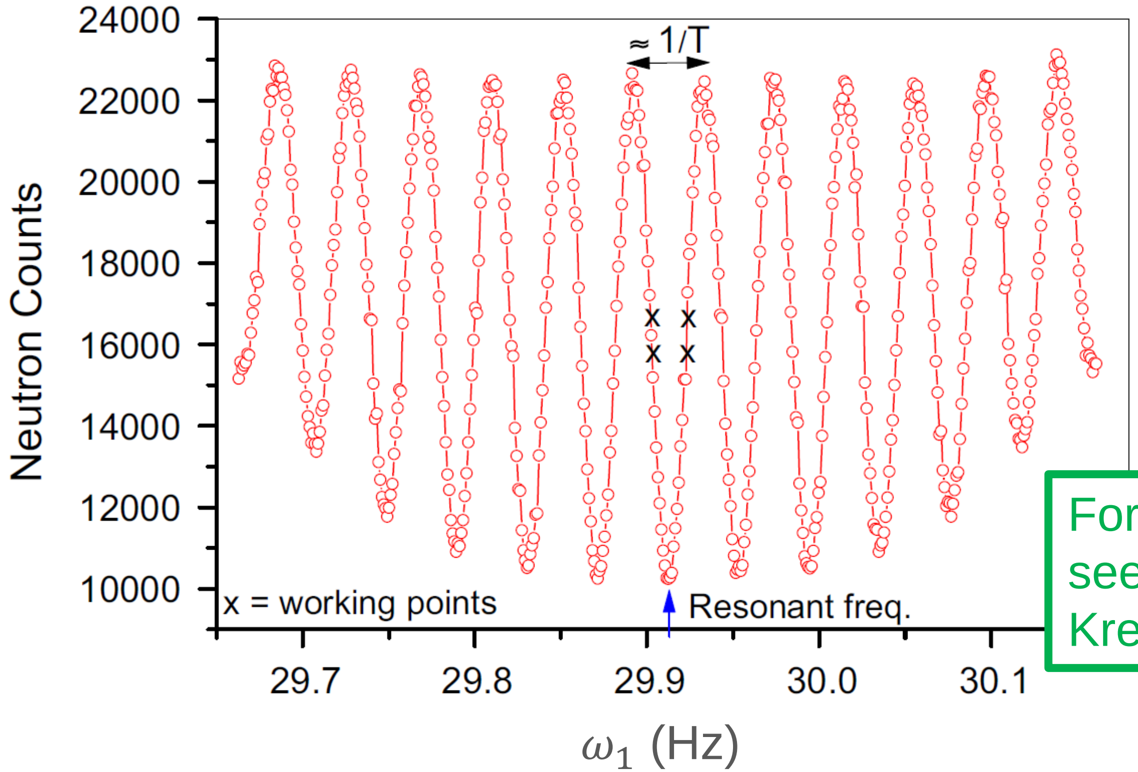


B=1μT

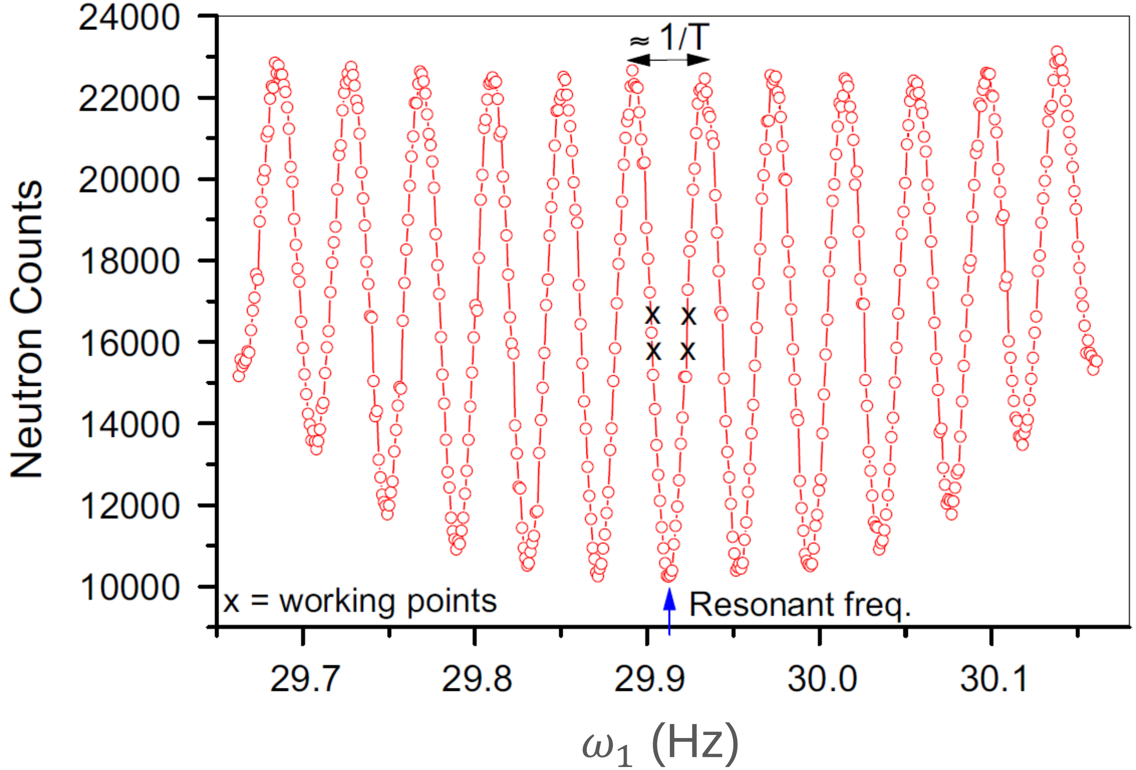
Blinding

We have introduced an artificial nEDM offset, i.e. a shift of the resonance frequency ifo E, B, …

For more info on blinding, see the poster of Jochen Krempel!

Experimental method

Ramsey's method of separated oscillatory fields:



B=1μT

Uncertainty on d_n due to counting statistics:

$$\sigma_{d_n} = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

E: electric field
α: visibility (polarization)
T: free precession time
N: neutron counts

Statistical sensitivity

Statistical uncertainty: $\sigma(d_n) = \dfrac{\hbar}{2\alpha E T \sqrt{N}}$

How did we improve the sensitivity in the last years?

Parameter	2014	2015	2016
N	6000	10000	**18000**
E	10kV/cm	11kV/cm	11kV/cm
T	180s	180s	180s
α	0.55-0.65	0.75-0.80	0.75-0.80

UCN source improvements

Statistical sensitivity

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UCN source improvements

New magnetic field optimisation procedure, see the poster of Elise Wursten!

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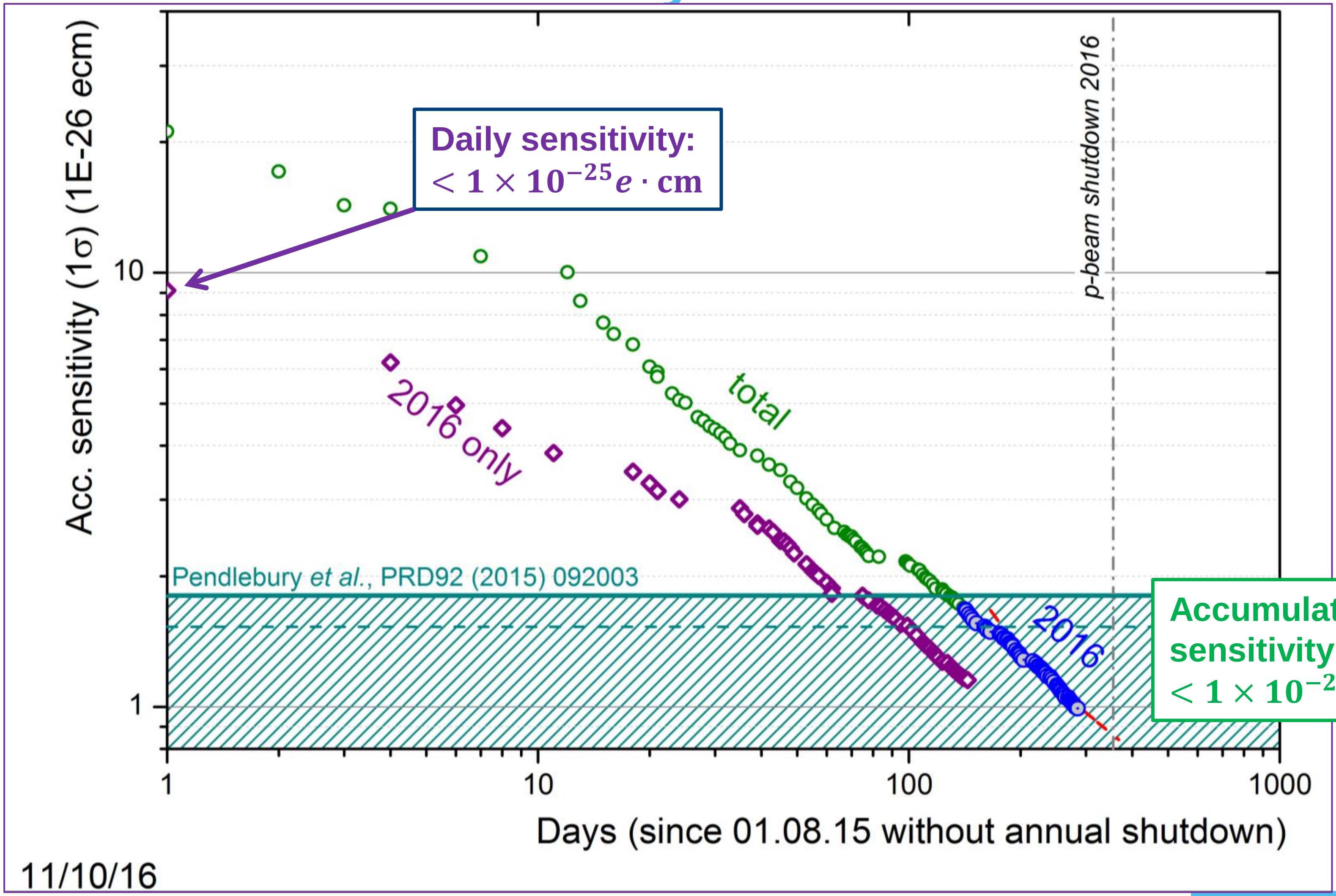
Statistical sensitivity



Accumulated sensitivity:
$< 1 \times 10^{-26} e \cdot \mathrm{cm}$

Systematic effects

Knowledge of magnetic field is important:

$$d_n = \frac{\hbar\Delta\omega - 2\mu_n \boxed{(B_{\uparrow\uparrow} - B_{\uparrow\downarrow})}}{2(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})}$$

We have a co-habiting Hg magnetometer to monitor drifts

=> introduces systematic effects

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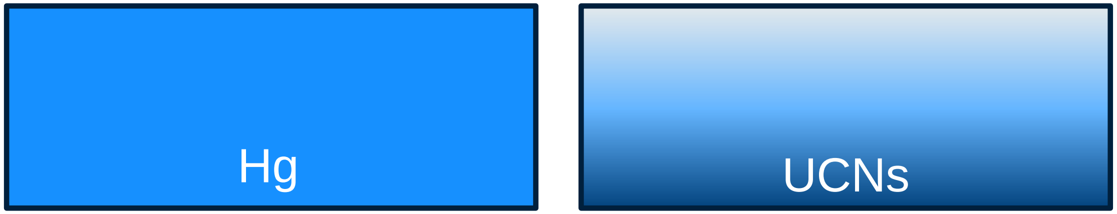
Systematic effects

Effects due to the Hg magnetometer

1. Difference in **density**, UCNs are sensitive to **vertical gradients**



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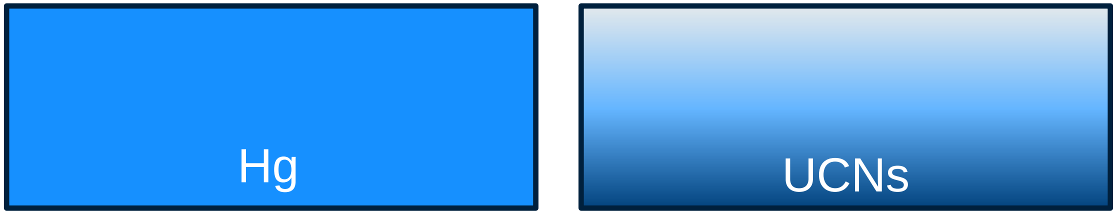
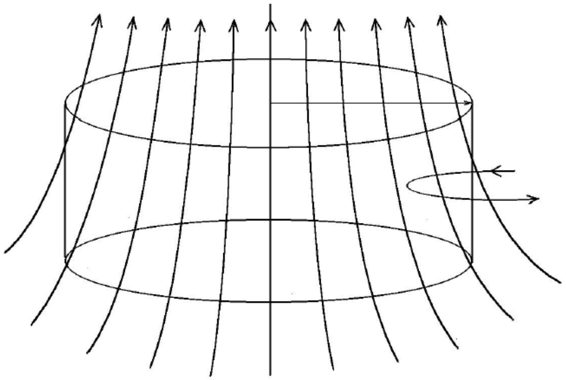


2. **Geometric phase effect**: interplay between motional magnetic field and magnetic field gradients

$$B_v = \frac{1}{c^2} E \times v$$



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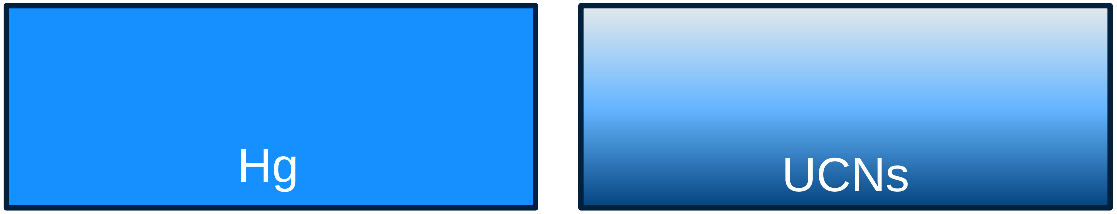

2. **Geometric phase effect**: interplay between motional magnetic field and magnetic field gradients

3. Difference in **adiabaticity**, UCNs are sensitive to **transverse field gradients**

Crossing point analysis (RAL-Sussex) to take these effects into account

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Systematic effects

Crossing point analysis:

1. Density difference => Shift of center of gravity:

$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \pm \frac{h}{|B|} \frac{\partial B_z}{\partial z} \right)$$ for B_0 up/down

Systematic effects

Crossing point analysis:

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2. Geometric Phase effect: :

$$\Delta f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}^2 D^2}{32\pi c^2}\frac{\partial B_z}{\partial z}E$$

which translates into a false nEDM:

$$d^{\mathrm{false}} = \frac{\partial B_z}{\partial z} 1.150 \times 10^{-27} e \cdot \mathrm{cm}/(\mathrm{pT}/\mathrm{cm})$$

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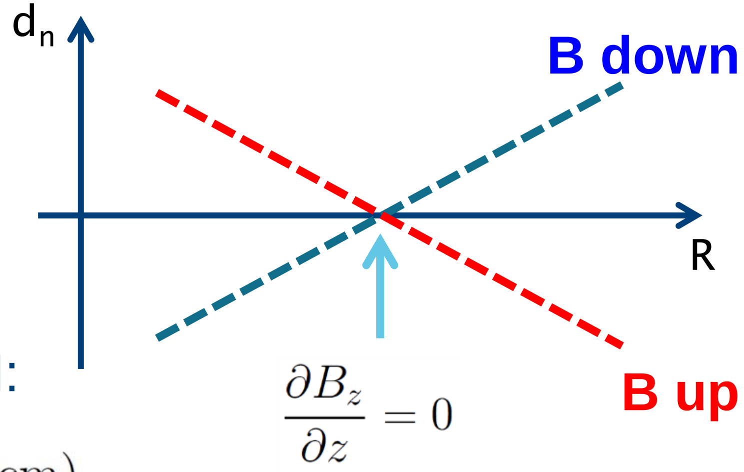

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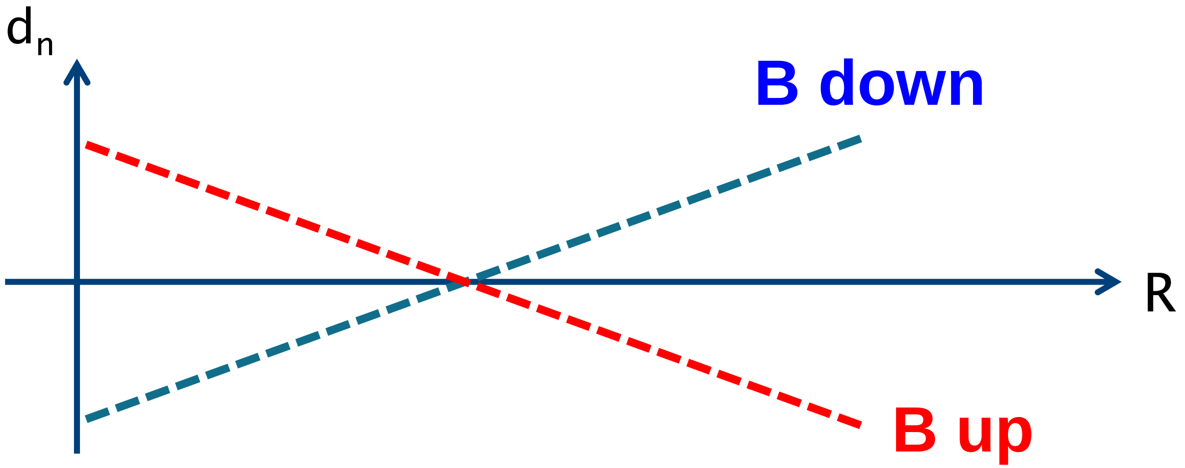


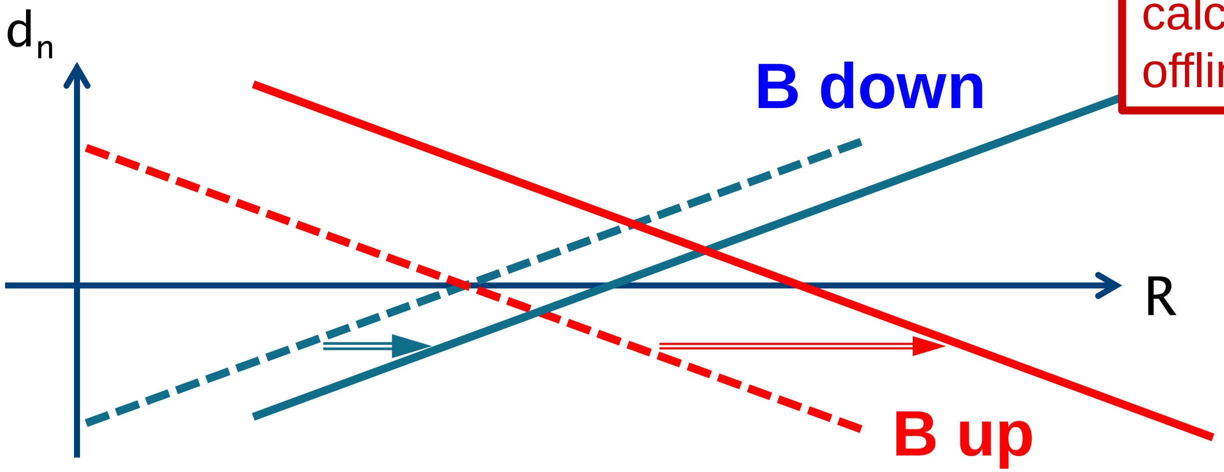
Systematic effects

Crossing point analysis:

3. Adiabaticity difference: Hg atoms sample the field non-adiabatically $\|\langle\vec{B}\rangle\|$, whereas neutrons are adiabatic $\langle\|\vec{B}\|\rangle$

$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(1 \pm \frac{h}{|B|}\frac{\partial B_z}{\partial z} + \boxed{\frac{\langle B_T^2\rangle}{2B^2}}\right)$$

Can change per magnetic field configuration, is calculated from offline maps



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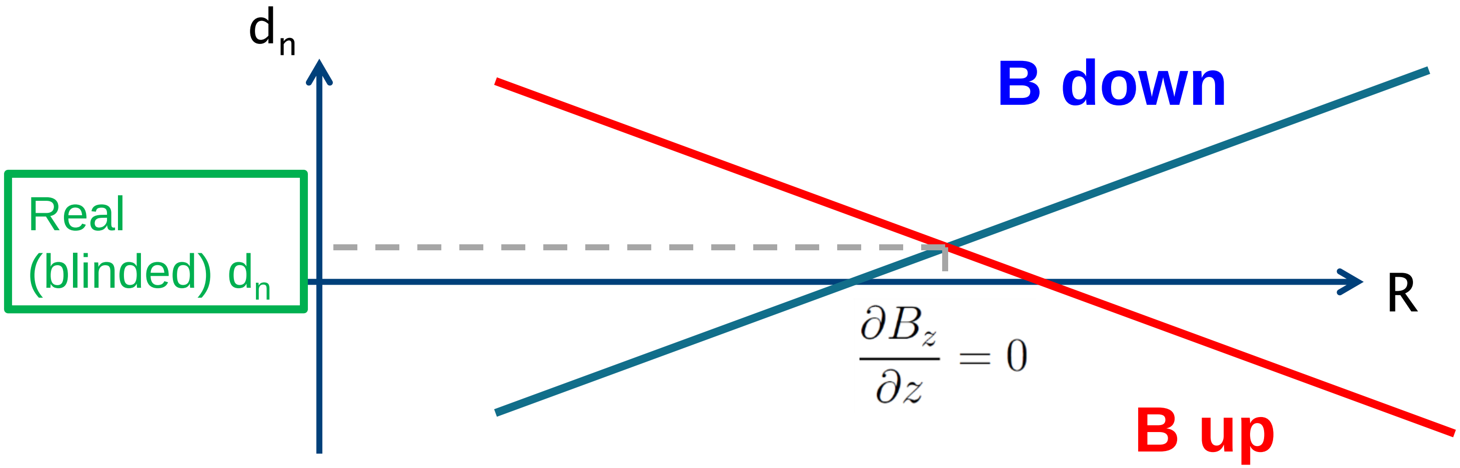

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n/Hg magnetic moment ratio

$$R = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \boxed{\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}}(1 + \delta_{\mathrm{Grav}} + \delta_{\mathrm{T}} + \delta_{\mathrm{Light}} + \delta_{\mathrm{Earth}})$$

Systematic effects:

1. Gravitational shift
2. Transverse components
3. HgM light shift
4. Earth's rotation

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Systematic effects:

1. Gravitational shift

$$\delta_{\mathrm{Grav}}^{\uparrow/\downarrow} = \pm \frac{h}{B_0} \frac{\partial B}{\partial z}$$

Due to difference (*h*) in center of mass for neutrons and mercury atoms combined with the presence of vertical magnetic field gradients.

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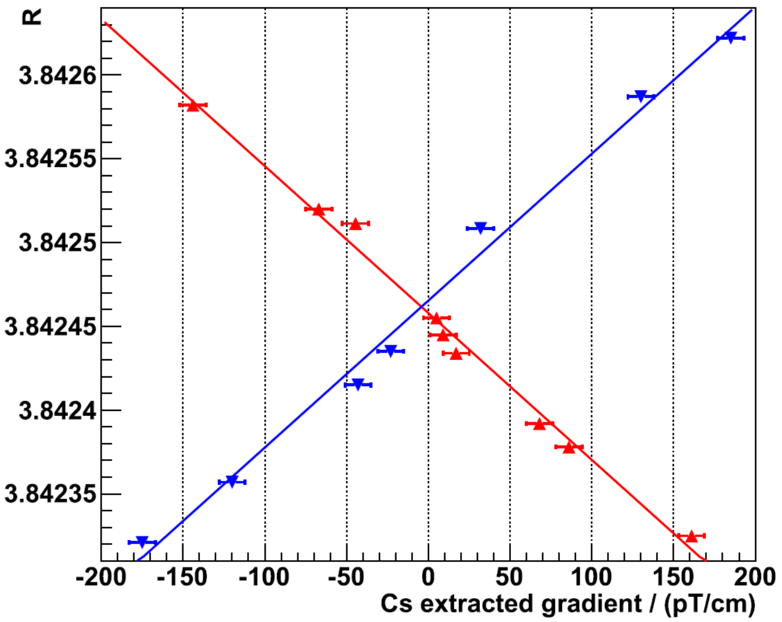

Measure at

- different magnetic field gradients
- B_0 up and B_0 down

Extract R-value at 0 gradient

n/Hg magnetic moment ratio

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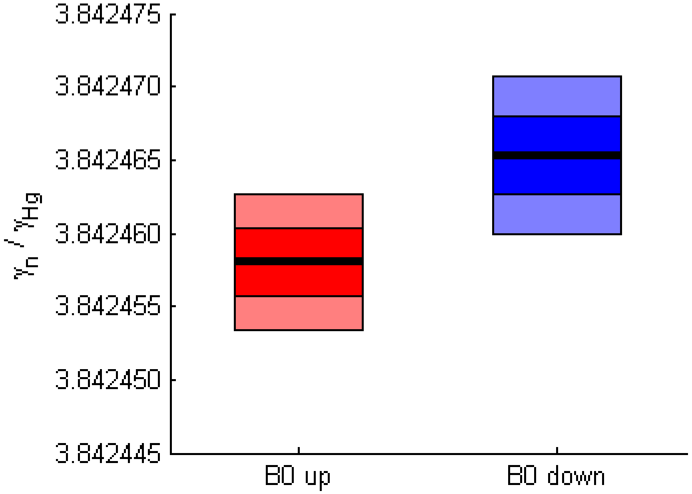

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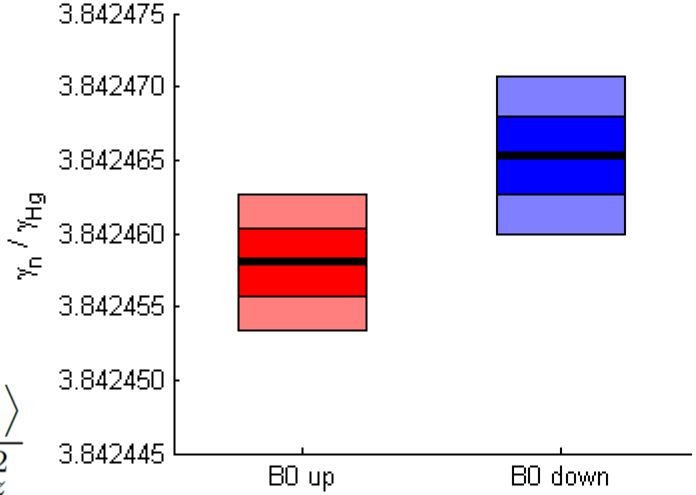
Systematic effects:

1. Gravitational shift
2. Transverse components

Neutrons:
Mercury:

$$\frac{\left\langle |\vec{B}| \right\rangle}{\left| \langle \vec{B} \rangle \right|} \simeq \frac{\left\langle \sqrt{B_x^2 + B_y^2 + B_z^2} \right\rangle}{B_z} \simeq 1 + \frac{\langle B_T^2 \rangle}{2B_z^2}$$



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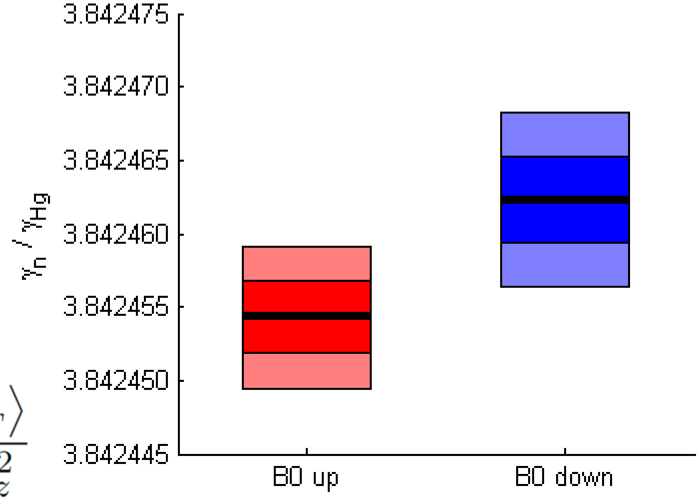

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Field maps provide $\langle {B_T}^2 \rangle$ for B_0 up and down

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n/Hg magnetic moment ratio

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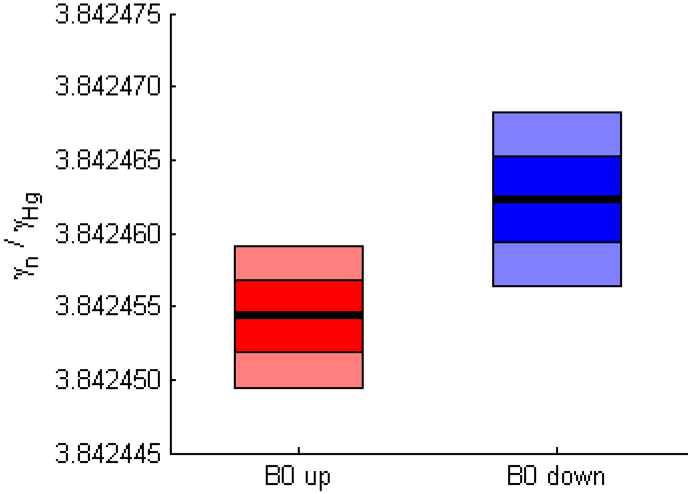
Systematic effects:

1. Gravitational shift
2. Transverse components
3. HgM light shift



f_{Hg} depends on UV light intensity and possibly on the angle between $\vec{k}$ and $\vec{B}$.

n/Hg magnetic moment ratio

$$R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}(1 + \delta_{Grav} + \delta_T + \delta_{Light} + \delta_{Earth})$$

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2. Transverse components
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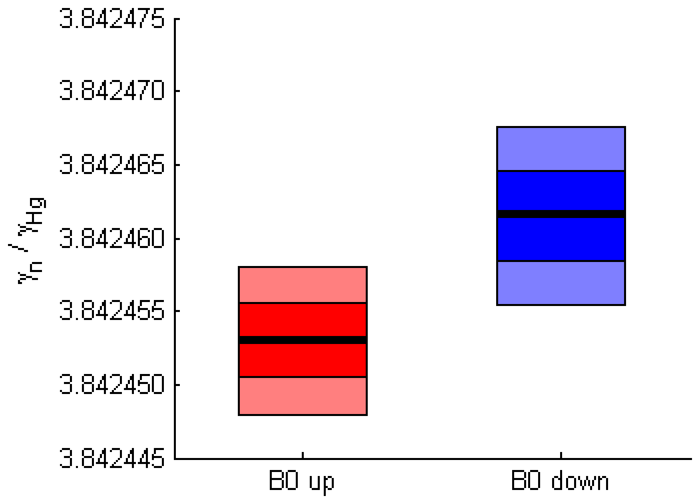

f_{Hg} depends on UV light intensity and possibly on the angle between $\vec{k}$ and $\vec{B}$.

Dedicated measurements have been done in May 2014 to investigate this effect.

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n/Hg magnetic moment ratio

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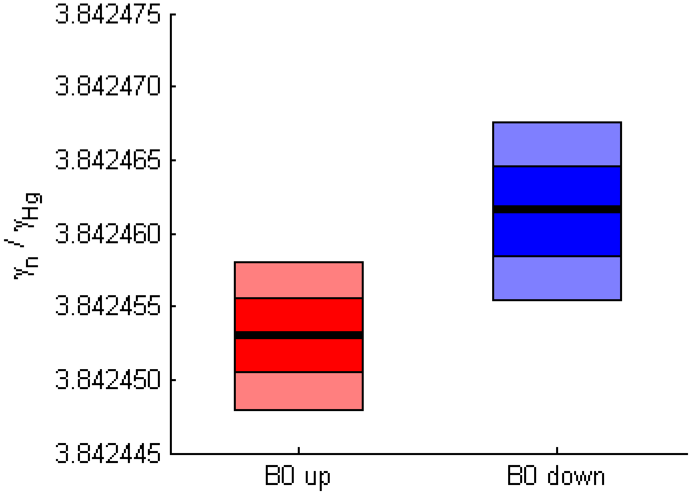
4. Earth’s rotation



Frequency shift due to rotation of the earth

n/Hg magnetic moment ratio

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Systematic effects:

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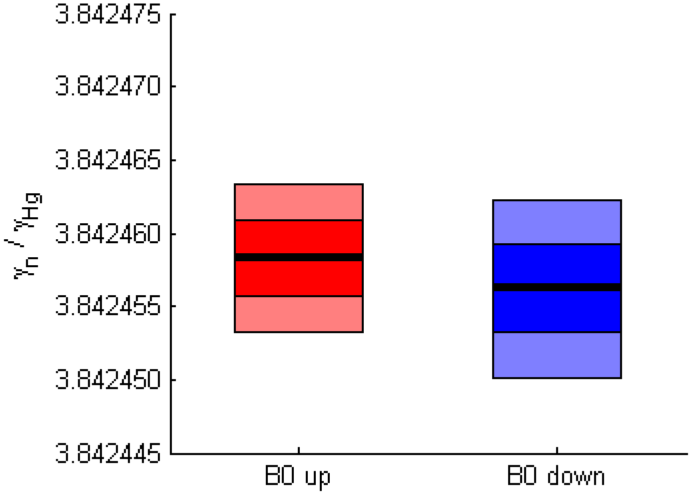
3. HgM light shift
4. Earth's rotation



Frequency shift due to rotation of the earth

$$\delta_\mathrm{Earth}^{\uparrow/\downarrow} = \mp\left(\frac{f_\mathrm{Earth}}{f_\mathrm{n}} + \frac{f_\mathrm{Earth}}{f_\mathrm{Hg}}\right)\sin(\lambda) = \mp 1.4 \times 10^{-6}$$

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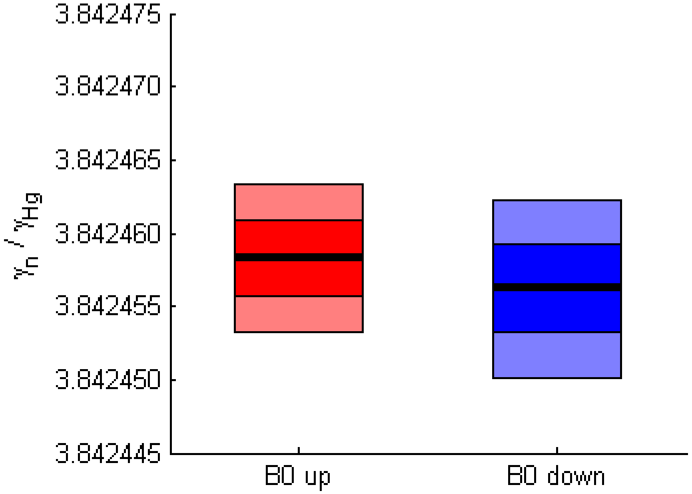
n/Hg magnetic moment ratio

$$R = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}(1 + \delta_\mathrm{Grav} + \delta_\mathrm{T} + \delta_\mathrm{Light} + \delta_\mathrm{Earth})$$

Systematic effects:

1. Gravitational shift
2. Transverse components
3. HgM light shift
4. Earth's rotation



Final result:

$$\gamma_\mathrm{n}/\gamma_\mathrm{Hg} = 3.8424574(30) \quad [0.78\ \mathrm{ppm}].$$

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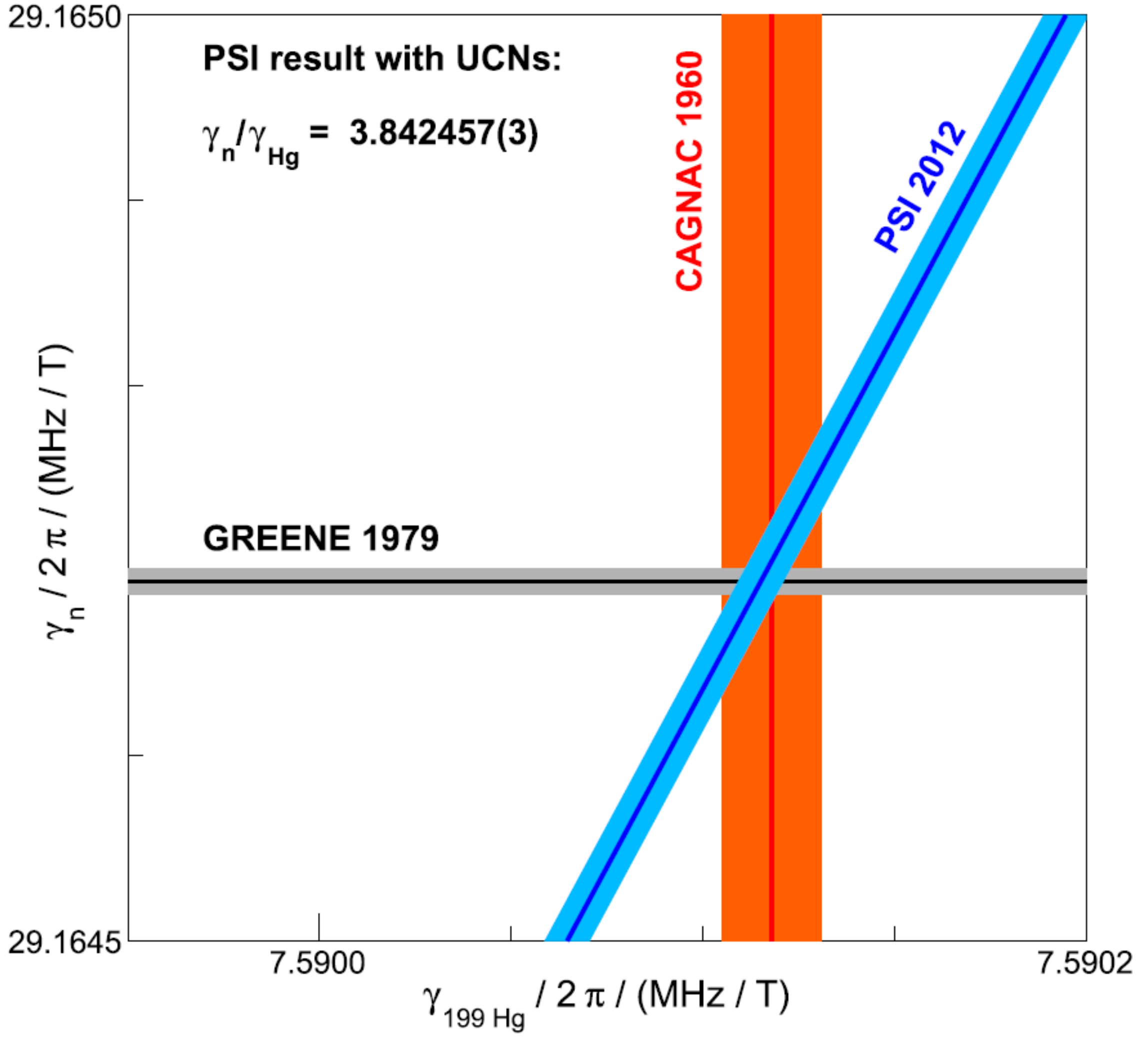
n/Hg magnetic moment ratio



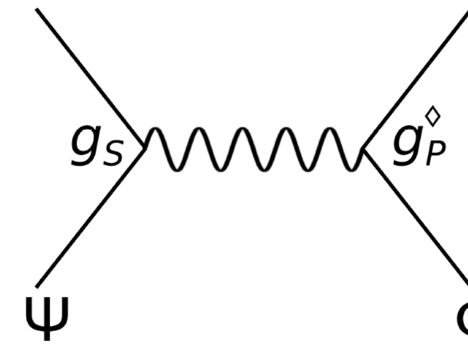
Constraints on axion-like particles

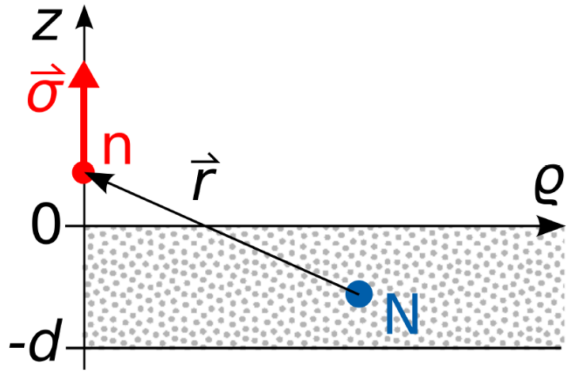
How can you test for axion-like particles?

- Short range spin-dependent interaction could be mediated by an axion or ALP.
- For example: Interaction between unpolarized particle Ψ and a polarized particle Φ. Potential caused by $g_s g_p$-coupling is

$$V(\boldsymbol{r}) = g_S\, g_P^{\diamond} \frac{(\hbar c)^2}{8\pi m^{\diamond} c^2} (\hat{\boldsymbol{\sigma}}^{\diamond} \cdot \hat{\boldsymbol{r}}) \left(\frac{1}{r\lambda} + \frac{1}{r^2} \right) e^{-r/\lambda}$$

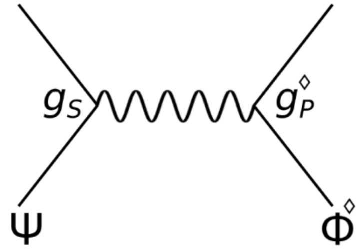
  with interaction range λ.
- Gives rise to a **pseudomagnetic field *b*** in case of a polarised neutron interacting with an unpolarised bulk material.





Constraints on axion-like particles

How can you test for axion-like particles?

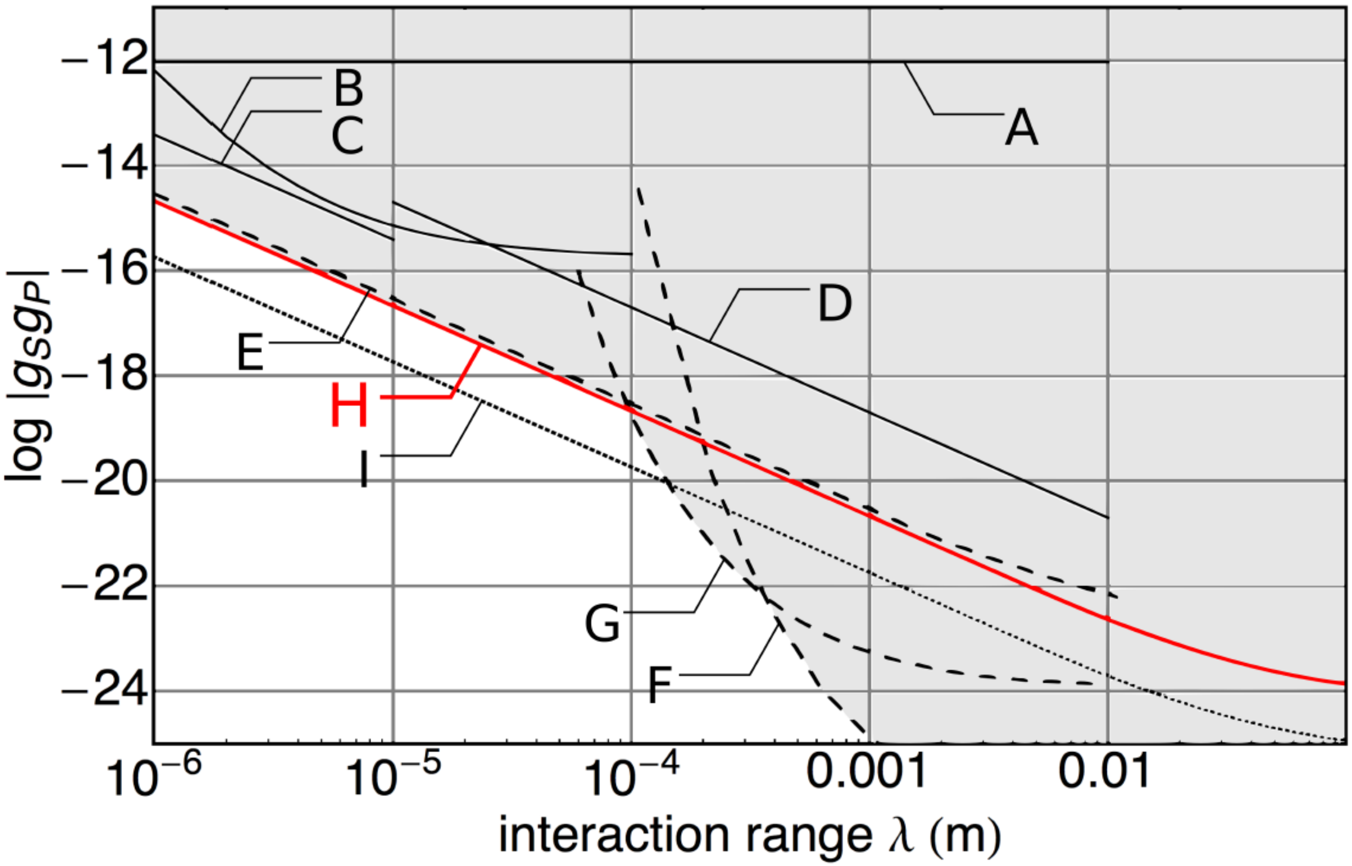


The field pseudomagnetic field *b* at the vessel surfaces points in opposite directions.

- **No shift** in Larmor frequency for the Hg atoms.
- UCN density increases towards the bottom, so depending on the sign on the main field, the Larmor precession frequency will increase of decrease.
- Hence R will be shifted: $R^{\uparrow\downarrow} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(1 \pm \frac{b}{B_0}\right)$

Luckily, we already measured R for B_0 up and down!

Constraints on axion-like particles



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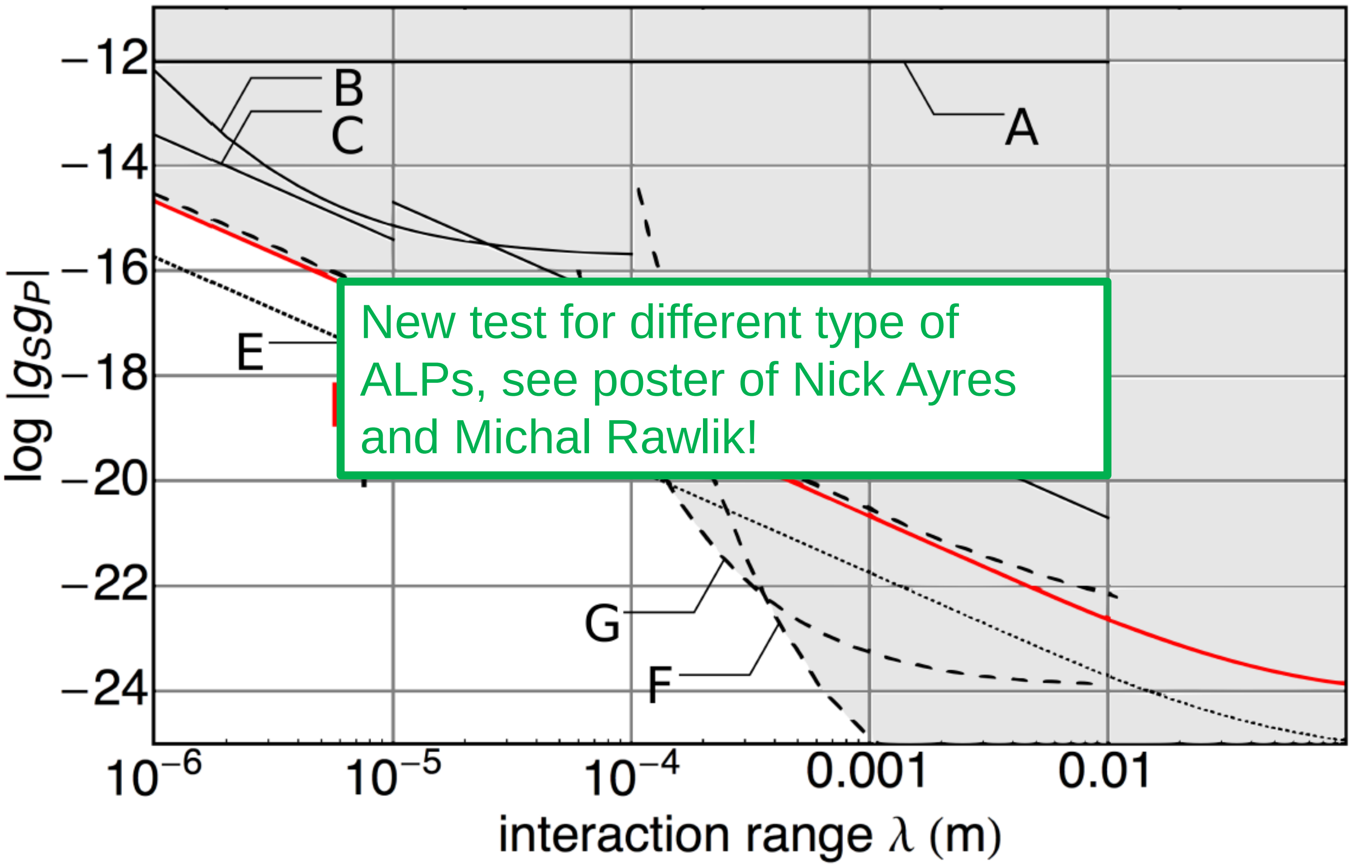
Constraints on axion-like particles



New test for different type of ALPs, see poster of Nick Ayres and Michal Rawlik!

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Conclusion

We have introduced blinding since September 2015

Our apparatus is functioning well:

- Sensitivity is excellent:
  - Current per day $1 \times 10^{-25} e \cdot \mathrm{cm}$
  - Accumulated below $1 \times 10^{-26} e \cdot \mathrm{cm}$
- Systematic effect are under control $< 5 \times 10^{-27} e \cdot \mathrm{cm}$

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Outlook

nEDM operation will come to an end in 2017

n2EDM will be installed and commissioned in 2018/19

n2EDM will start data taking in 2020

n2EDM sensitivity will intrinsically be more than 5 times better than that of nEDM and will cut into the low $10^{-27} e \cdot \mathrm{cm}$ region

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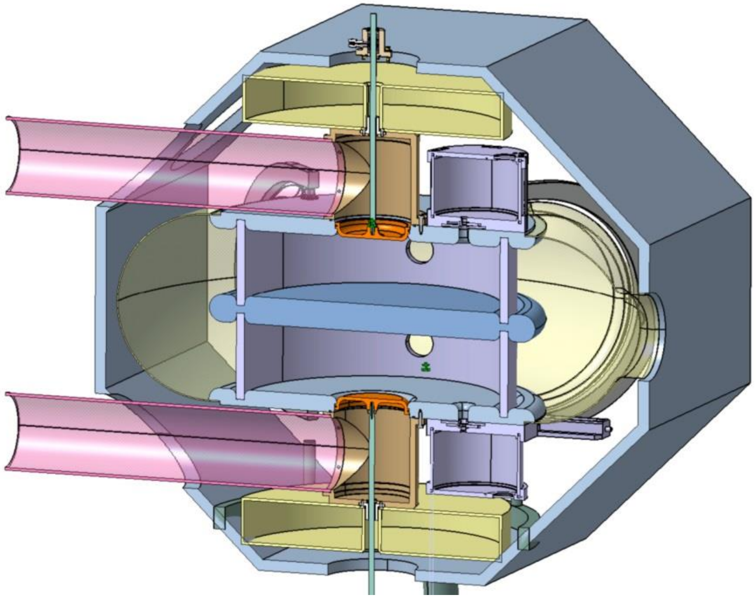
Outlook

For more information about n2EDM, see the following posters:

- HgM laser: Sybille Komposch
- Magnetometry: Georg Bison
- DAQ: Jochen Krempel
- KM current source: Peter Koss
- E-field studies: Jacob Thorne



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Thank you for your attention!