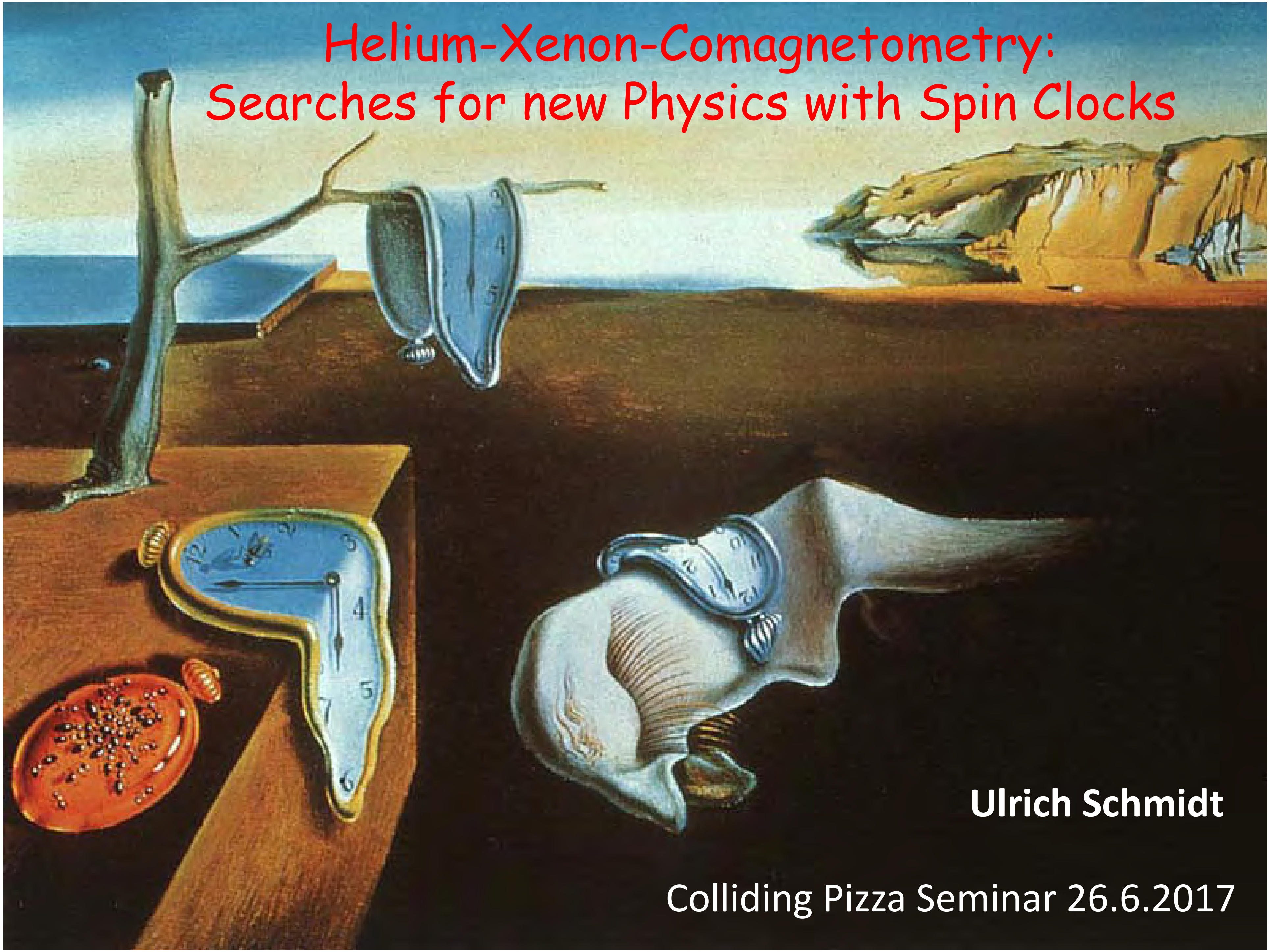
Helium-Xenon-Comagnetometry: Searches for new Physics with Spin Clocks



Ulrich Schmidt

Colliding Pizza Seminar 26.6.2017

Helium-Xenon-Comagnetometry: Searches for new Physics with Spin Clocks

Introduction:

- For what are spin clocks good for ?
- Search for new Physics with Spin Clocks: the classical example: EDMs

He-Xe-Comagnetomtry:

- **Setup and operating conditions**
- **Search for axion like spin-dependent short-range interactions**
- **Search for an ^{129}Xe EDM**

Conclusion:

Outlook:

- **HeXeniA**

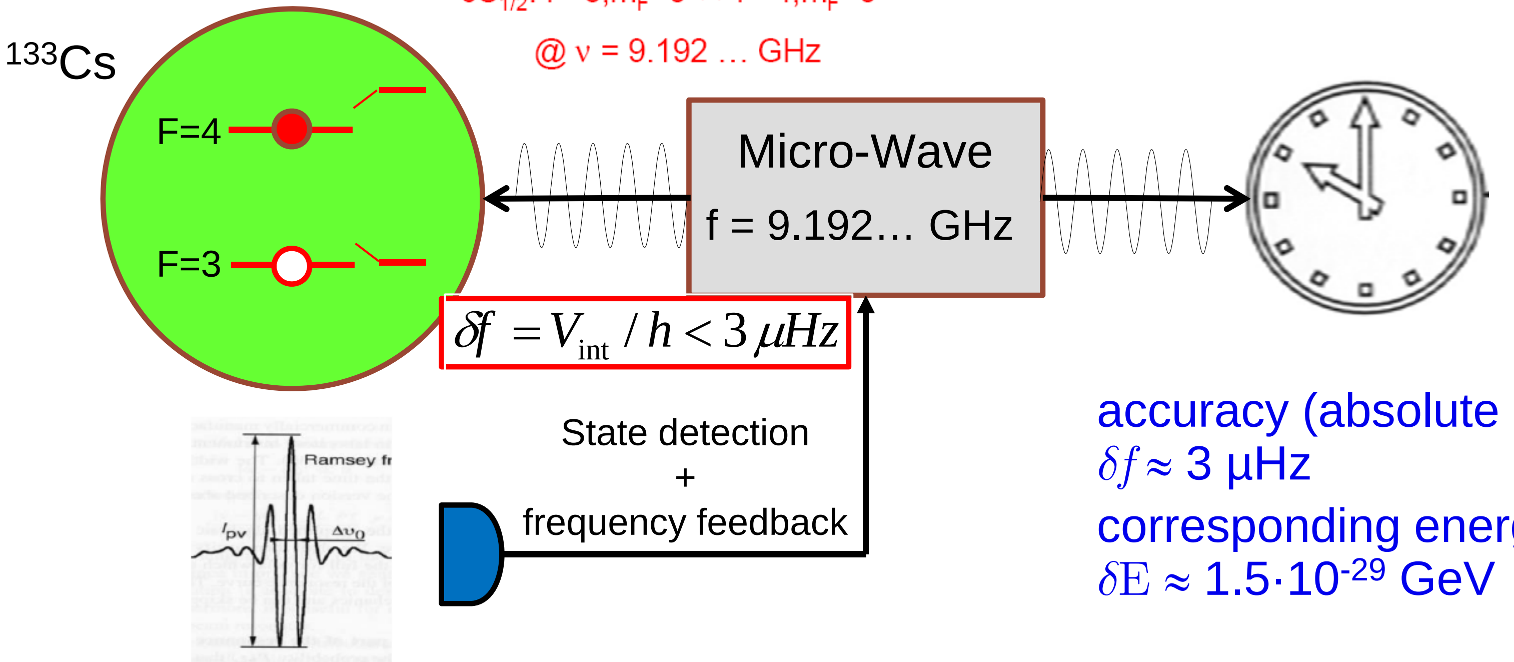
Introduction: Features of $^{3}He/^{129}Xe$ spin-clocks

Atomic clock ⟷ Spin clock

Oscillator + Frequency divider + Counter

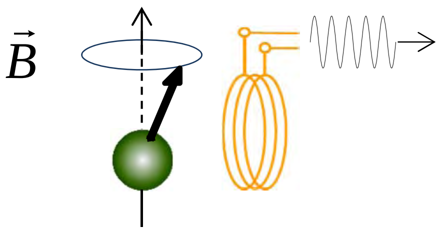
$6S_{1/2}$: $F=3, m_F=0 \leftrightarrow F=4, m_F=0$

@ ν = 9.192 … GHz



accuracy (absolute scale):
$\delta f \approx$ 3 μHz
corresponding energy shift
$\delta E \approx 1.5 \cdot 10^{-29}$ GeV

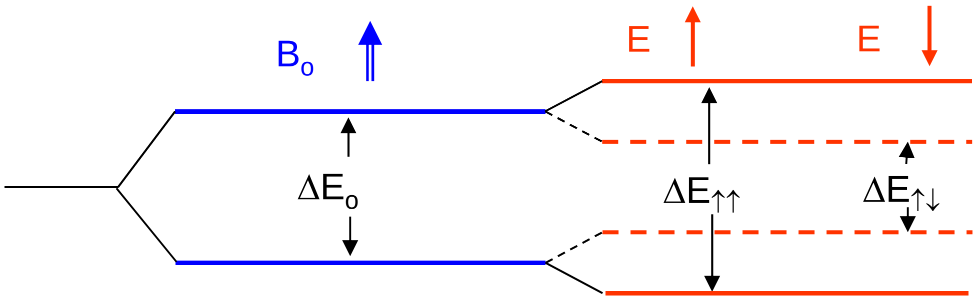
Spin clock :



reference transition at $f \approx$ 10 Hz
with $\delta f / f \approx 10^{-13}$
accuracy (absolute scale):
$\delta f \approx$ 1 pHz → $\delta E \approx 4 \cdot 10^{-36}$ GeV

→ accuracy to trace tiny frequency shifts ≈ 6 orders of magnitude higher

Measurement sensitivity: ^{129}Xe electric dipole moment



$$h \cdot \Delta \nu = h \cdot \left(\Delta \upsilon_{\uparrow\uparrow} - \Delta \upsilon_{\uparrow\downarrow} \right) = 4 \cdot E \cdot \left| d_{Xe} \right|$$

$$4 \cdot 10^{-15}\,\mathrm{eVs} \times 1\,\mathrm{pHz} =$$

$$4 \times 1 \cdot 10^{3}\,\frac{\mathrm{V}}{\mathrm{cm}} \times 1 \cdot 10^{-30}\,\mathrm{e\,cm}$$

The **C**ramer-**R**ao **L**ower **B**ound (CRLB) sets the lower limit on the variance

$$\sigma_f^2 \geq \frac{12}{(2\pi)^2 \cdot (SNR)^2 \cdot f_{BW} \cdot T_\sigma^3} \times C(T_2^*)$$

Correction for T_2-relaxation

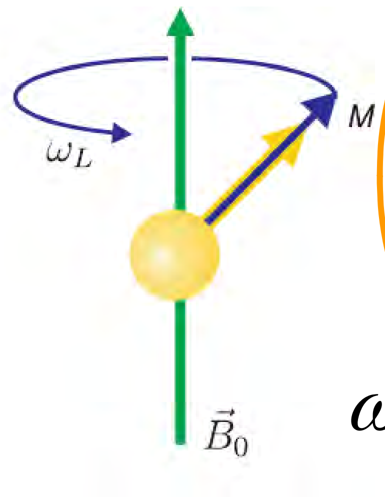
$$\sigma_f \propto \left[\begin{matrix} \text{Fourier} \\ \text{width} \end{matrix} \propto \frac{1}{T} \right] \times \frac{1}{[\#\,\text{data points} \propto \mathrm{T}]^{\frac{1}{2}}} \propto \frac{1}{T^{\frac{3}{2}}}$$

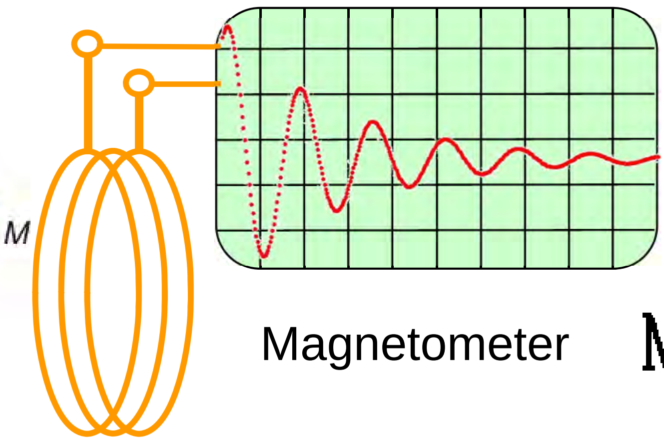
$$\sigma_\phi \propto 1 / \sqrt{T}$$

example: SNR = 10000:1 , f_{BW} = 1 Hz , T= 1 day $\Rightarrow \sqrt{\sigma_f^2} \approx pHz$

Free induction decay

Polarized nuclear spins generate a macroscopic magnetic moment which precesses around a static B-field B_0

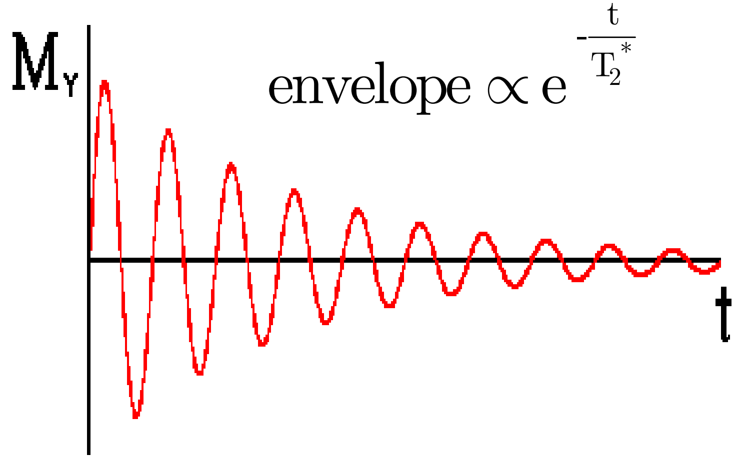




Magnetometer

$$\omega_L = 2\pi\nu_L = \gamma\left|\vec{B}\right|$$

Example:
Nuclear **M**agnetic **R**esonance



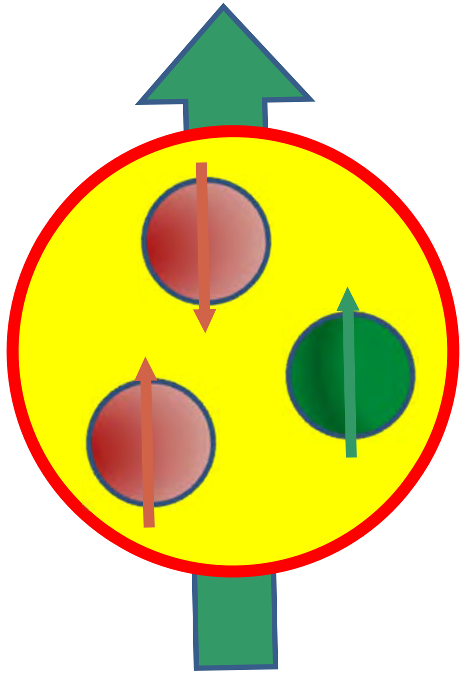
(G. D. Cates, et al., Phys. Rev. A 37, 2877)

$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{1}{T_{2,\,\mathrm{field}}}$$

$$\frac{1}{T_{2,\,\mathrm{field}}} \approx \frac{4R^4\gamma^2}{175D}\left(\left|\vec{\nabla}B_{1,\,z}\right|^2 + \left|\vec{\nabla}B_{1,\,y}\right|^2 + 2\left|\vec{\nabla}B_{1,\,x}\right|^2\right) \propto R^4 \cdot p \cdot \left|\vec{\nabla}B\right|^2$$

Nuclear spin properties:

"First order" nuclear structure:
Both nuclei have one unpaired neutron,
which accounts for the nuclear spin.
All other nucleons are paired with
antiparallel spins $\rightarrow \quad J = \frac{1}{2}$



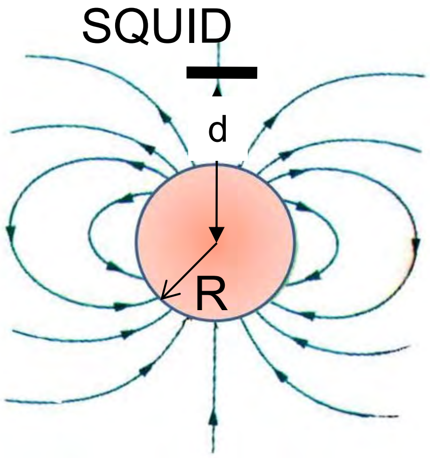
$$\mu_n = -1.913\mu_N$$
$$\mu_{^3He} = -2.1276\mu_N$$
$$\mu_{^{129}Xe} = -0.7779\mu_N$$

^{3}He polarization
Optical pumping of metastable ^{3}He*-atoms (MEOP)

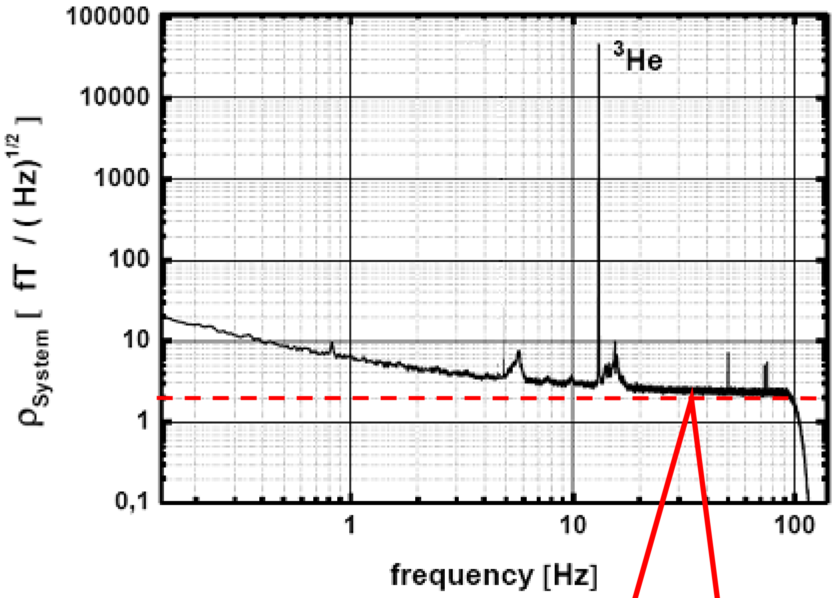
^{3}He and ^{129}Xe polarization
Spin exchange with optically pumped Rb-vapour (SEOP)

^{3}He free spin-precession signal

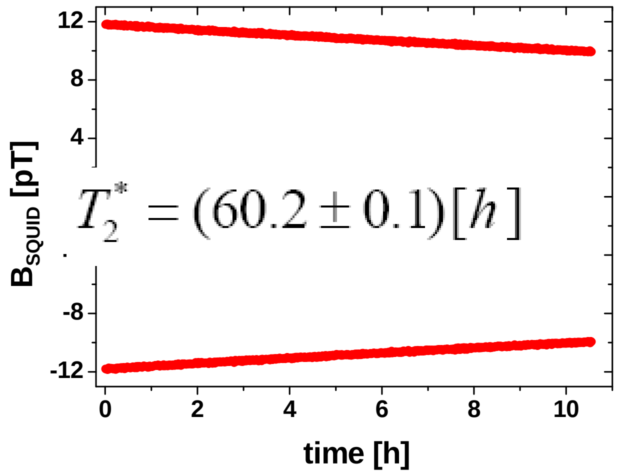
Eur. Phys. J. D 57, 303–320 (2010)



parameters:
p_{He}= 1-3 mbar
P = 10-50%
R =2.9 cm; d = 6cm
→ ΔB = 10-30 pT

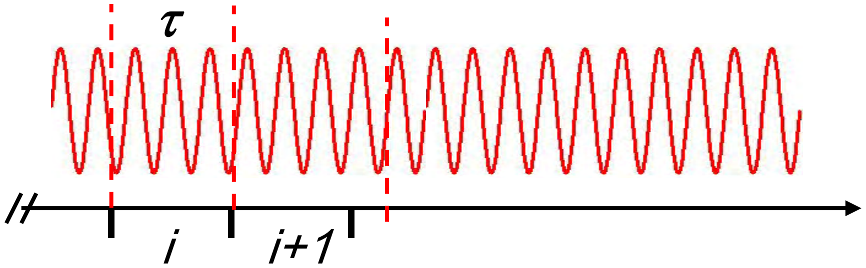


Signal: $\Delta B[pT] \approx 220 \cdot p[mbar] \cdot P \cdot \left(\frac{R}{d}\right)^3$

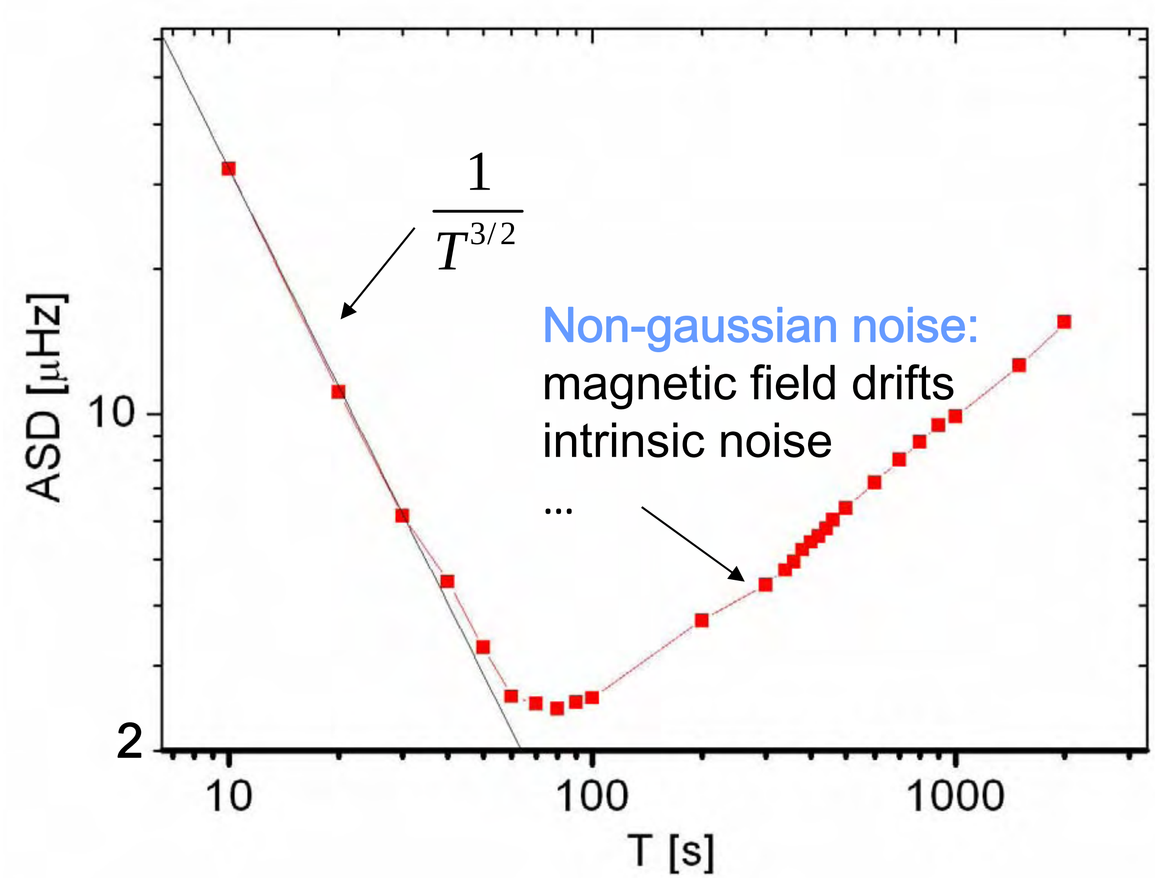


system noise
inside BMSR-2
~ 2 fT/√Hz

Test of CRLB via Allan Standard Deviation (ASD)



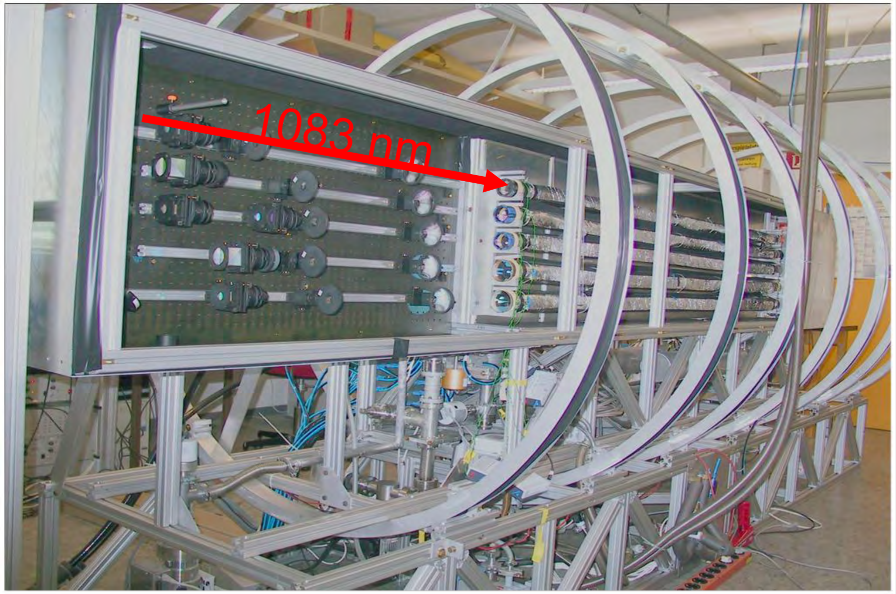
$$\sigma_{\upsilon}(\tau)=\sqrt{\frac{1}{2}\frac{\sum_{i=1}^{N-1}\left(\overline{\upsilon}_{i+1}(\tau)-\overline{\upsilon}_{i}(\tau)\right)^2}{N-1}}$$

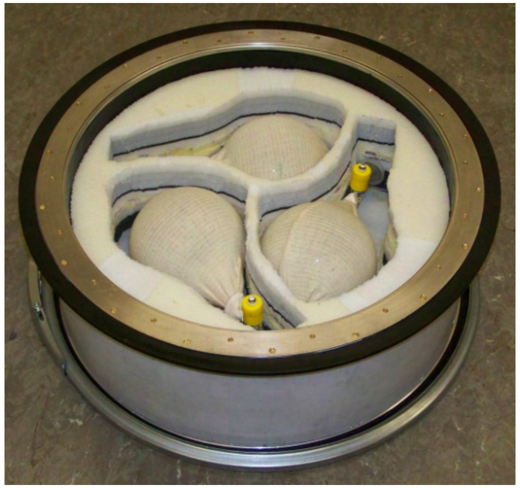


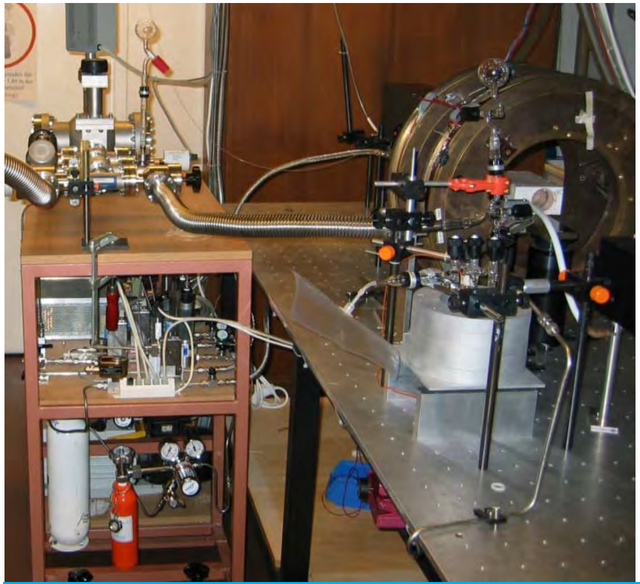
Limit: 60s

only for T < 60s
σ_{υ} reaches CRLB

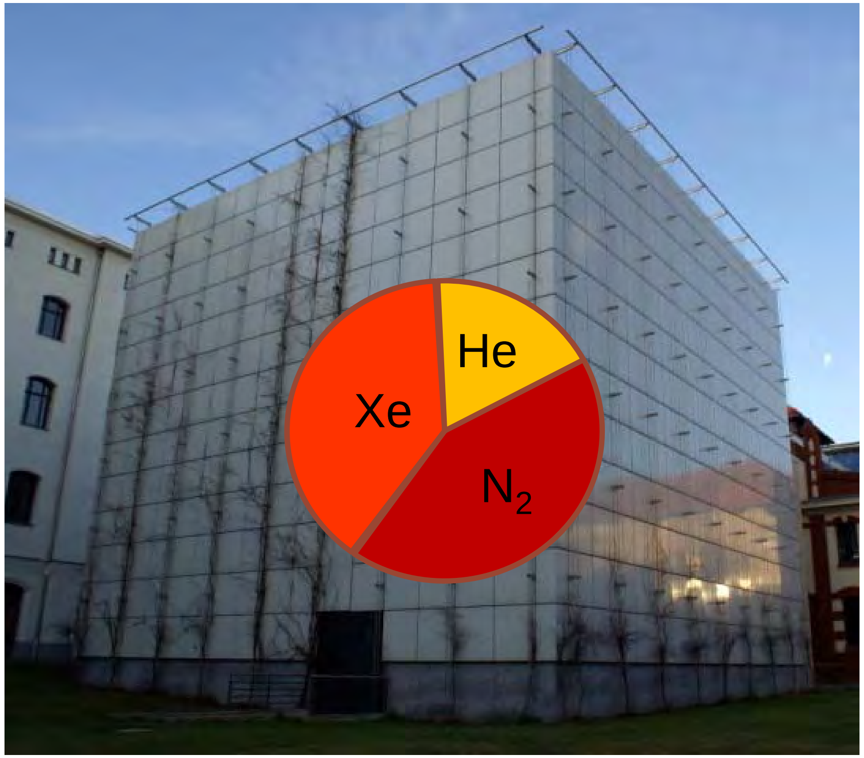
MEOP Polarizer Mainz: ^{3}He





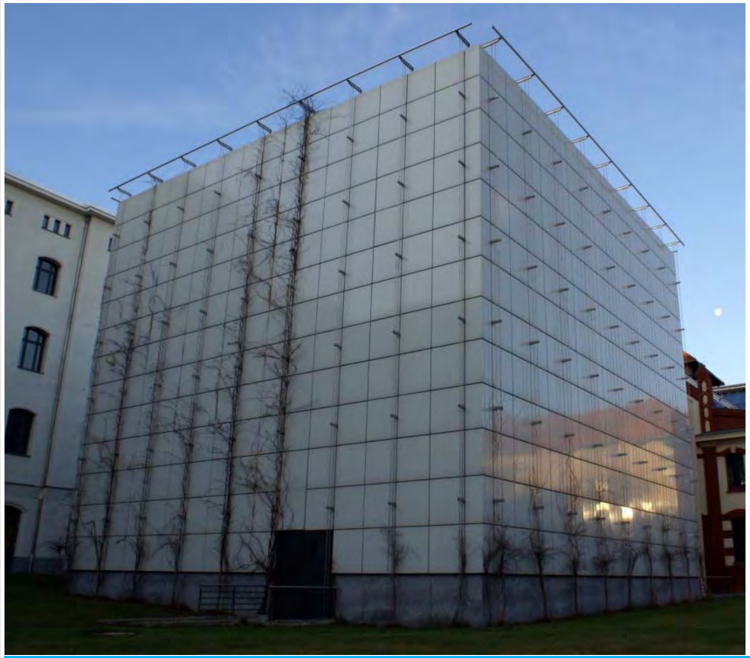


SEOP
Polarizer
PTB: ^{129}Xe

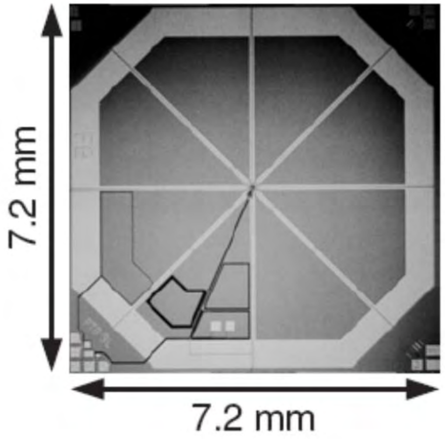


BMSR 2, PTB Berlin

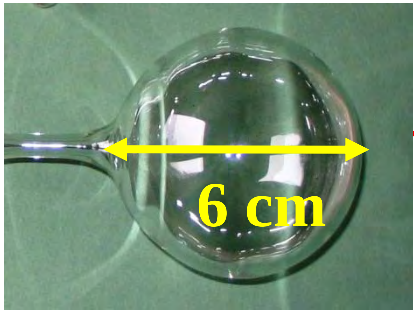
The 7-layered magnetically shielded room
(residual field < 2 nT)



LT_c- SQUID



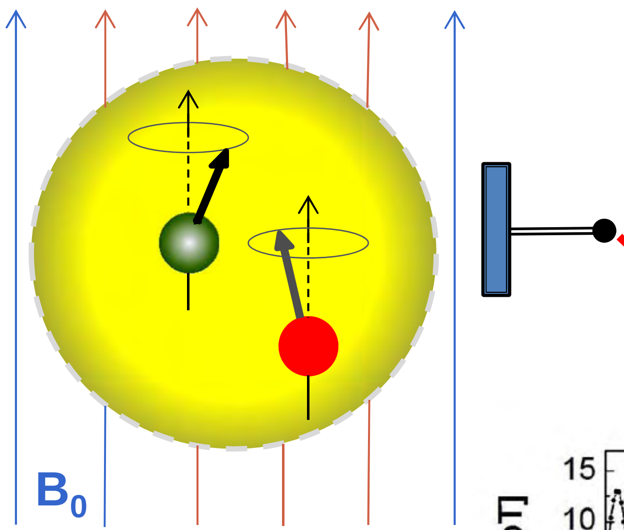
^{3}He (4.5 mbar)

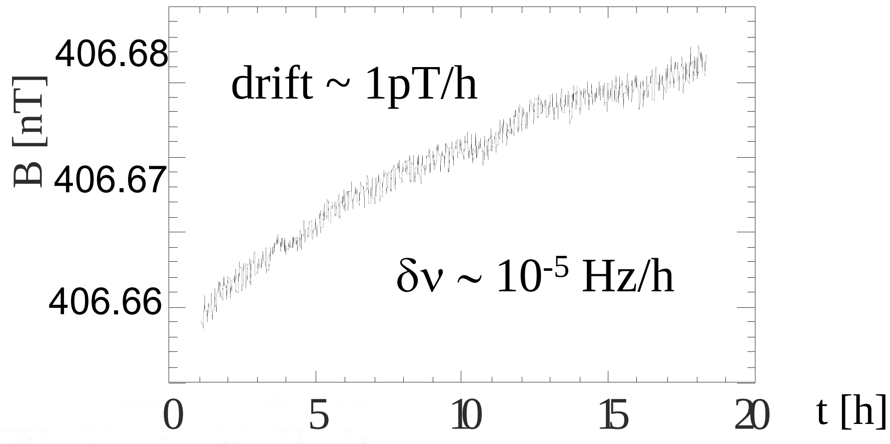


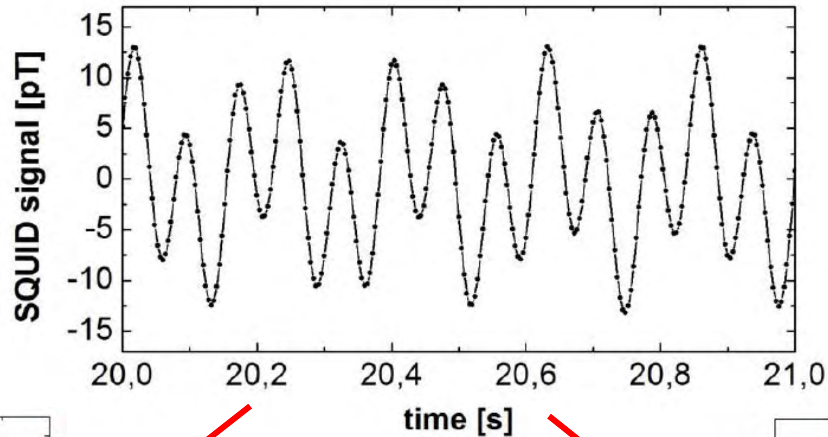
$B_0 \approx 0.4\ \mu T$
(Helmholtz-coils)

$\left|\vec{\nabla} B_{x,y,z}\right| \approx 20\ pT/cm$

^{3}He / ^{129}Xe clock comparison to get rid of magnetic field drifts



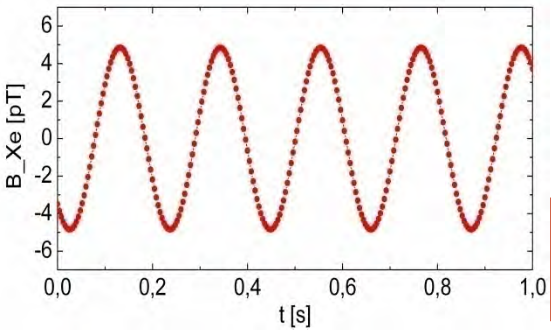




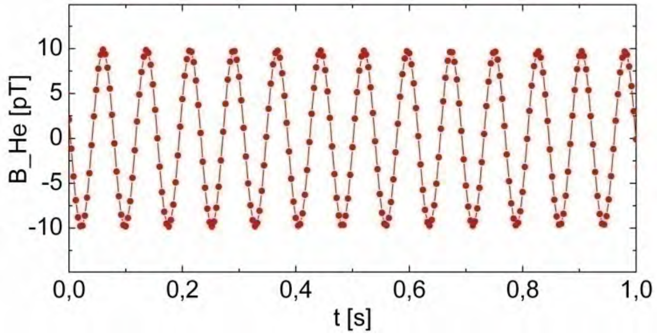
$$\omega_L = 2\pi\nu_L = \gamma\left|\vec{B}\right|$$

^{129}Xe **(4,7 Hz)**

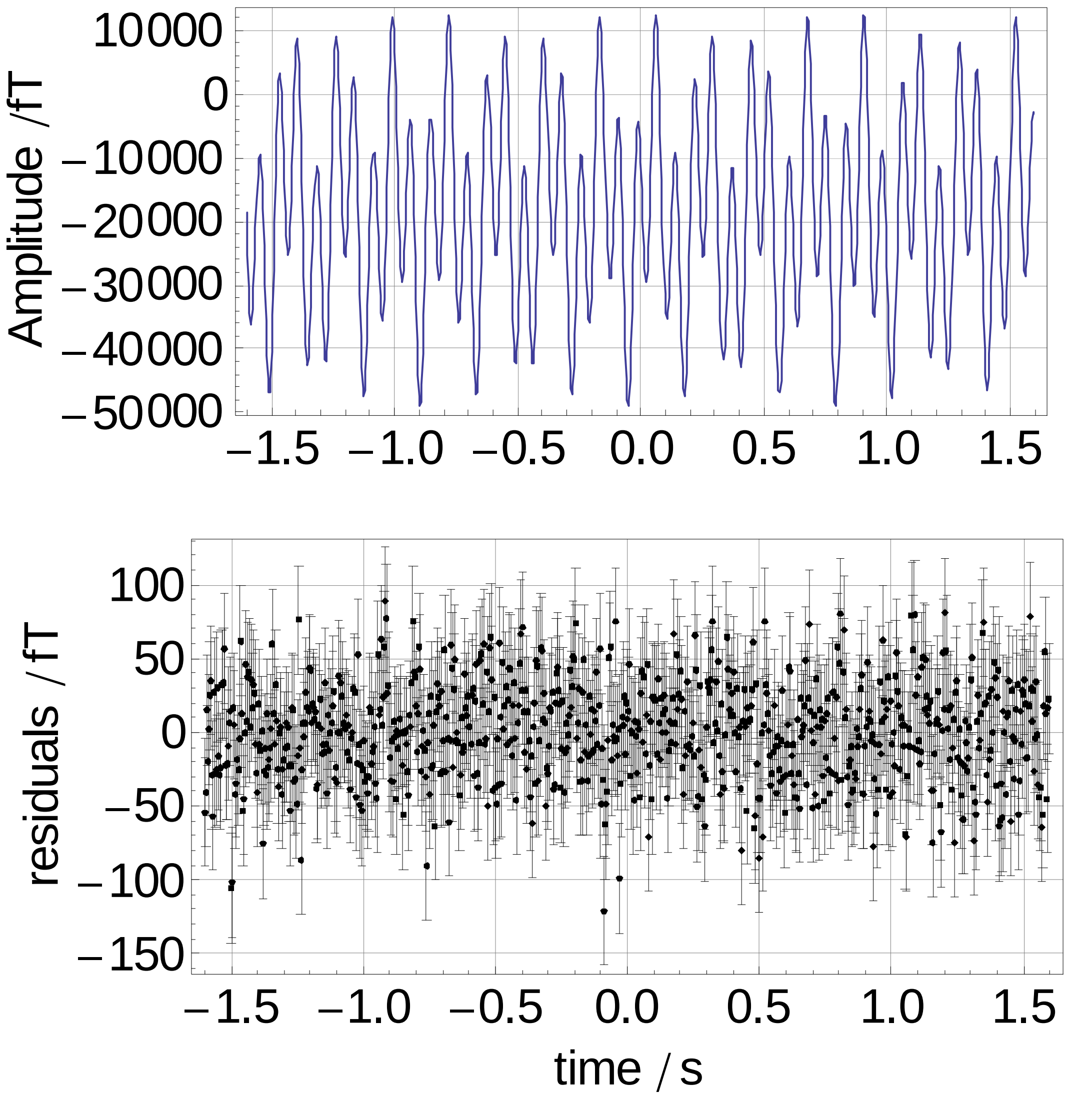
^{3}He **(13 Hz)**



$$\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe} = const\ .$$



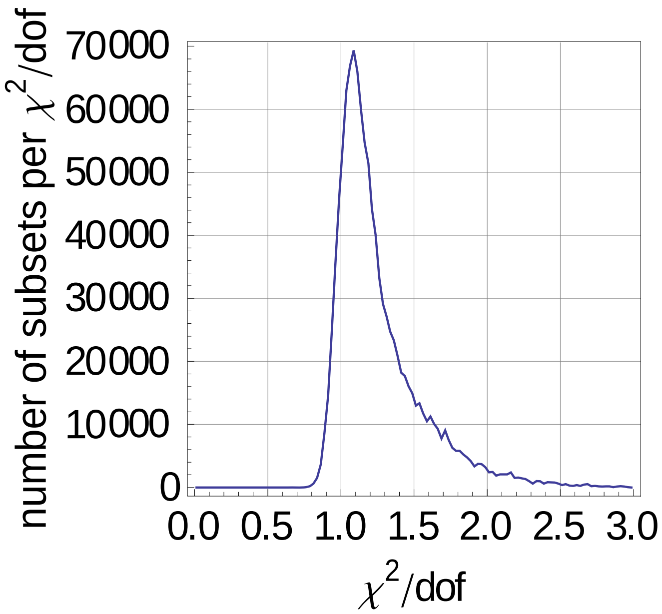
$$B_S(t) = c_{He} \cdot \cos(\omega_{He} t) + s_{He} \cdot \sin(\omega_{He} t) + c_{Xe} \cdot \cos(\omega_{Xe} t) + s_{Xe} \cdot \sin(\omega_{Xe} t) + c_{lin} \cdot t + c_{const}$$



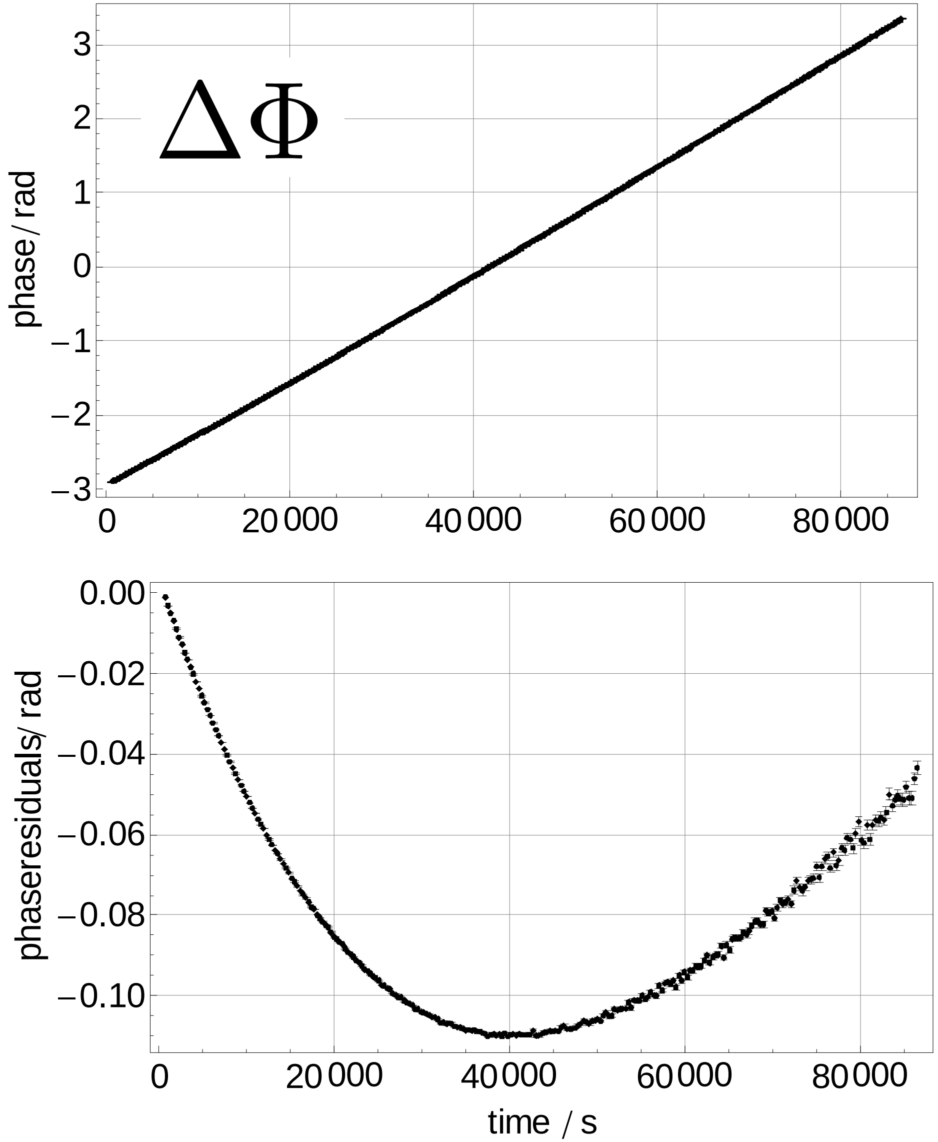
Fitting subset

subset left:

χ^2/dof = 1.03



Subtraction of deterministic phase shifts



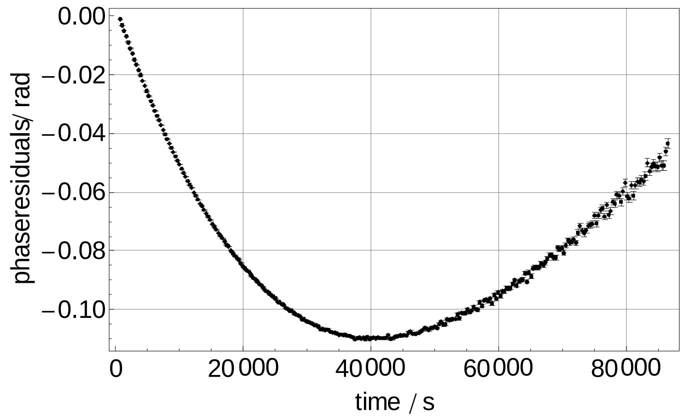
$$\Phi_{He} = 2\pi \cdot 12\text{Hz} \cdot 1\text{day} = 6.5 \cdot 10^6$$

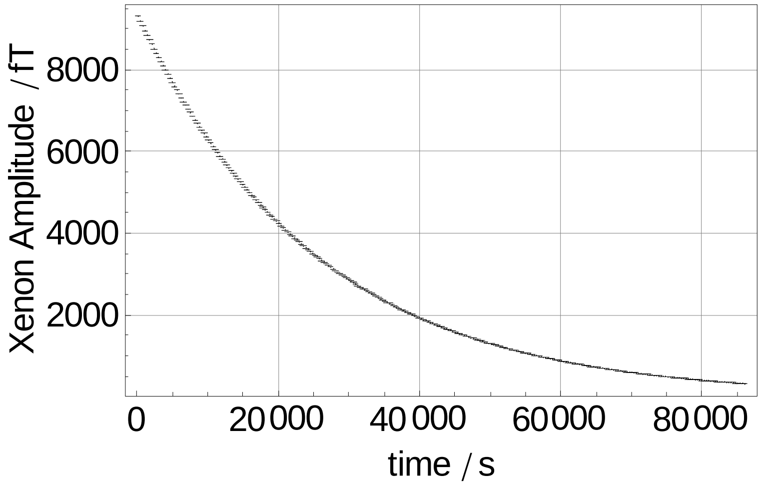
$$\Delta\Phi = \Phi_{He} - \gamma_{He} / \gamma_{Xe} \Phi_{Xe}$$

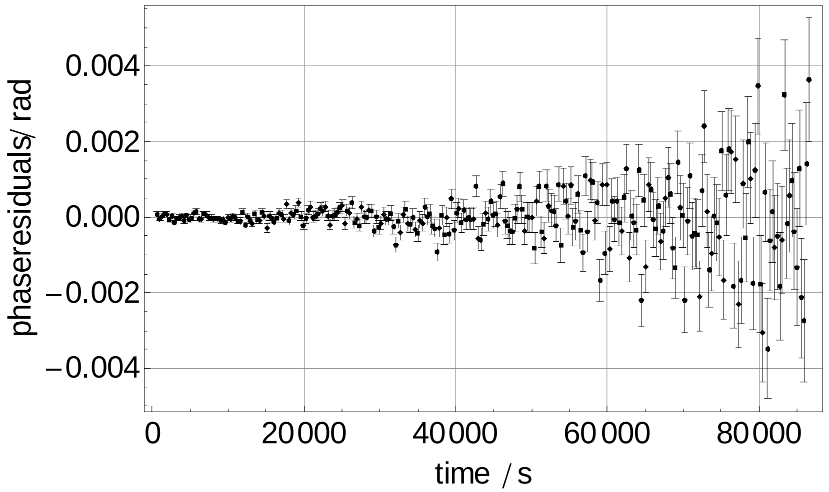
$$\Delta\Phi = c + a_{lin} \cdot t$$

a_{lin}: earth rotation and chemical shift

Subtraction of deterministic phase shifts





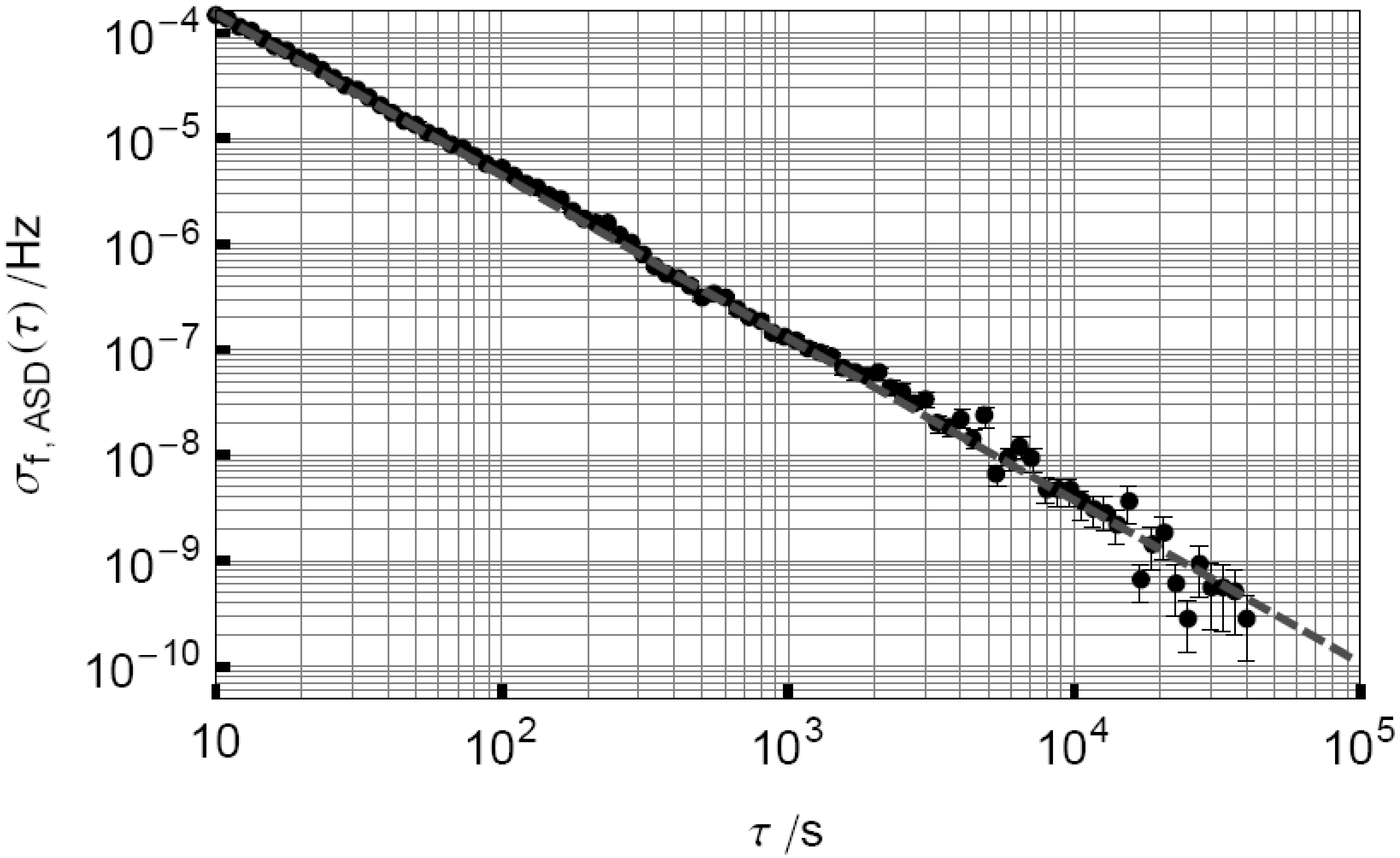


$$\Delta\Phi = c + a_{lin} \cdot t$$
$$+ a_{He} \cdot e^{-t/T^*_{2,He}} + a_{Xe} \cdot e^{-t/T^*_{2,Xe}}$$
$$+ b_{He} \cdot e^{-t/(2T^*_{2,He})} + b_{Xe} \cdot e^{-t/(2T^*_{2,Xe})}$$
$$+ \Phi(t)_{spin\text{-}coupling}$$

a: generalized Ramsey-Bloch-Siegert-Shift $\propto$ Magnetisation

b: Bloch-Siegert-Shift $\propto$ Magnetisation^2 of other spin species

ASD of frequency residuals



The detection of the free precession of co-located $^{3}He/^{129}Xe$ sample spins can be used as ultra-sensitive probe for

non-magnetic spin interactions of type:

$$V_{non-magn.} = \vec{a} \cdot \vec{\sigma}$$

- Search for a Lorentz violating sidereal modulation of the Larmor frequency

$$V(r)/\hbar = \langle \tilde{b} \rangle \hat{\varepsilon} \cdot \vec{\sigma} / \hbar$$

- Search for spin-dependent short-range interactions Axion like particles

$$V(r)/\hbar = c\, \vec{\sigma} \cdot \hat{n} / \hbar$$

- Search for EDM of Xenon

$$V(r)/\hbar = -|d_n|\, \vec{\sigma} \cdot \vec{E} / \hbar$$

- …

Observable:

$$\Delta\omega = \omega_{L,He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \omega_{L,Xe} \neq 0$$

Search for axion like particles with ^{3}He - ^{129}Xe spin clocks

Institut für Physik, Universität Mainz:
C. Gemmel, W. Heil, H.Hofsetz, S. Karpuk,
Y. Sobolev, K. Tullney

Physikalisch-Technische-Bundesanstalt, Berlin:
M. Burghoff, W. Kilian, S. Knappe-Grüneberg,
W. Müller, A. Schnabel, F. Seifert, L. Trahms

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg:
F. Allmendinger, U. Schmidt

Search for a new pseudoscalar boson (Axion-like particle)

Gerardus 't Hooft,: QCD has a non-trivial vacuum structure that in principle permits CP-violation

from neutron EDM we get: $d_n \approx 10^{-16} \cdot \overline{\theta} < 3 \cdot 10^{-26} \; e \cdot cm$

Original proposal for Axion (R. Peccei, H.Quinn PRL 38(1977),1440) as possible solution to the „Strong CP Problem“ that cancels the CP violating term in the QCD Lagrangian

Modern interest: Dark Matter candidate. All couplings to matter are weak

Axions, if they exist, it will be very light and will mediate a macroscopic CP violating force

$$m_a \approx \frac{m_\pi \cdot f_\pi}{f_a} \approx 6\mu eV \cdot \left(\frac{10^{12}\, GeV}{f_a} \right)$$

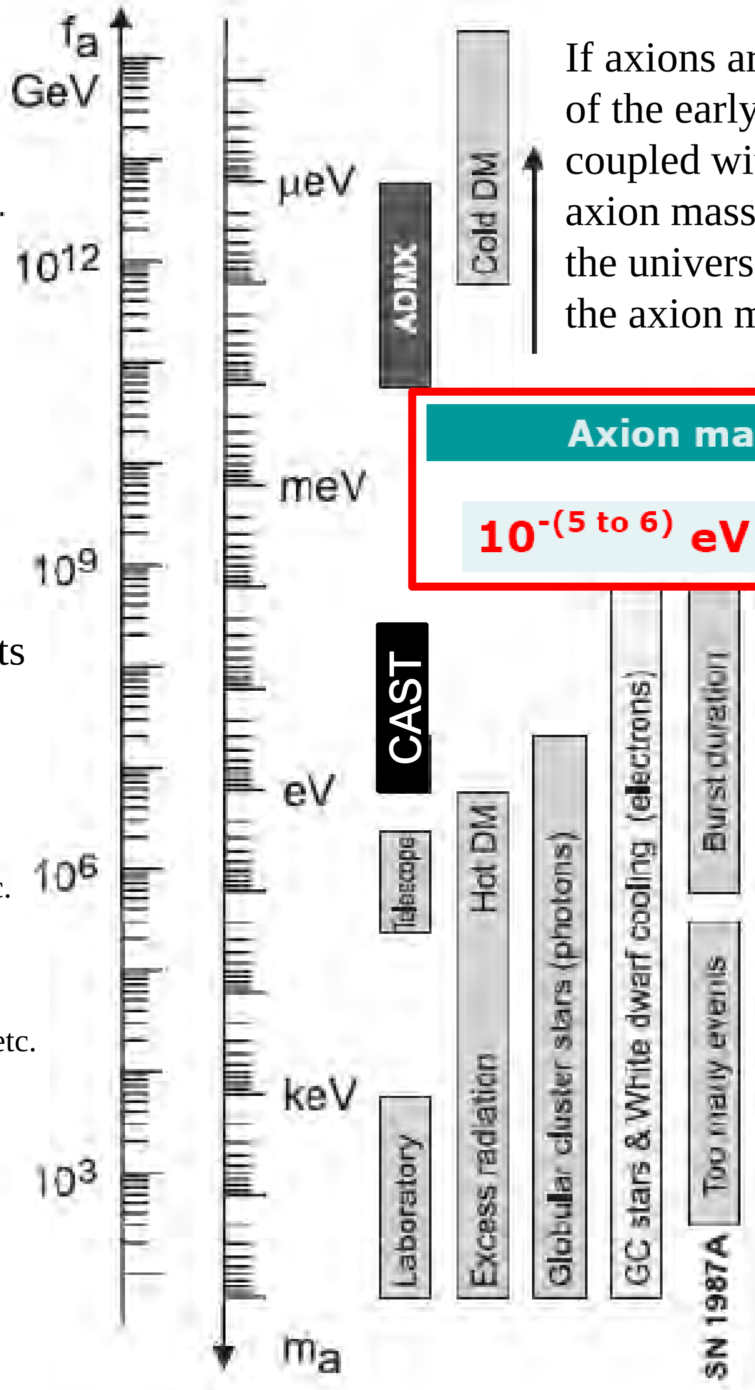
f_a : energy scale P.Q.-symmetry is spontaneously broken

THE CURRENT BOUNDS

C. Hagmann, H. Murayama, G.G. Raffelt, L.J. Rosenberger, and K. van Bibber
2008 Rev. Part. Physics.
Phys. Lett. B 667,1 (2008).

Current Axion Search Experiments

- Solar Axion Telescope – „CAST“
- Dark Matter Axion Search – „ADMX“
- Vacuum Optical Properties –“PVLAS“ etc.
- Photon Disappearance Experiments
- New Force Search – Torsion Pendulums, etc.



If axions are dark matter, they are a relic of the early universe. A particular scenario coupled with the requirement that the axion mass density not severely over close the universe results in a lower bound to the axion mass.

Axion mass window

$10^{-(5\ \text{to}\ 6)}$ eV $< m_a <$ $10^{-(2\ \text{to}\ 3)}$ eV

Short range interaction of the axion

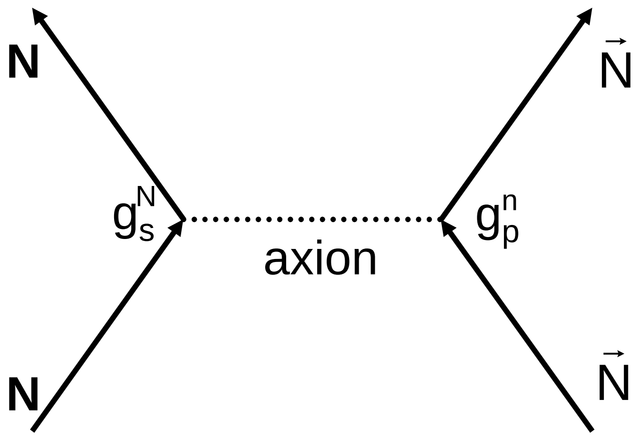
Yukawa-type potential with monopole-dipole coupling:

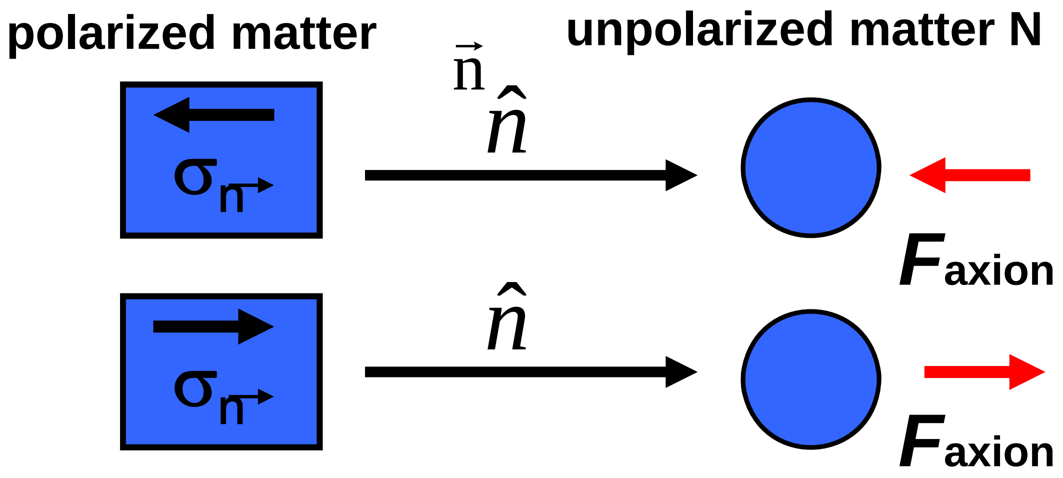
$$V(r) = \kappa \hat{n} \cdot \vec{\sigma} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda}$$

*(Moody and Wilczek PRD **30** 130 (1984))*

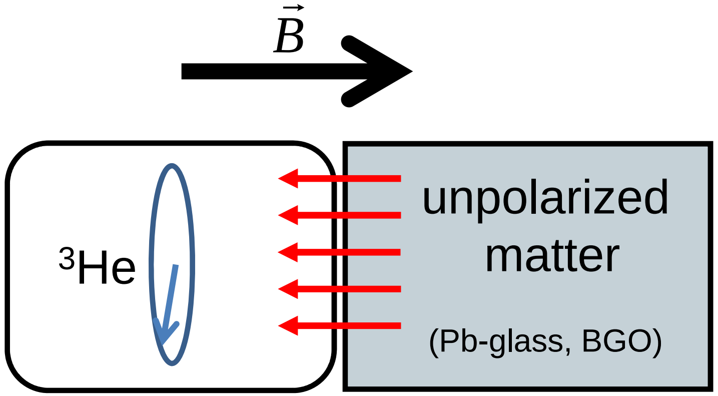
with: $\kappa = \frac{\hbar^2 g_s g_p}{8\pi m_n}$, $\lambda = \frac{\hbar}{m_a c}$

$$\begin{pmatrix} 10^{-6}\,\text{eV} < m_a < 10^{-2}\,\text{eV} \\ 10^{-5}\,\text{m} < \lambda < 10^{-1}\,\text{m} \end{pmatrix}$$





How to measure?



$$\omega_{\text{L,He}}(t) = \gamma_{\text{He}} \cdot B(t)$$

$$\omega_{\text{Close}}(t) = \omega_{\text{L,He}}(t) + \Delta\omega$$

$$\left(\text{with:} \quad \Delta\omega = 2\pi \cdot \delta\nu = \bar{V} / \hbar\right)$$

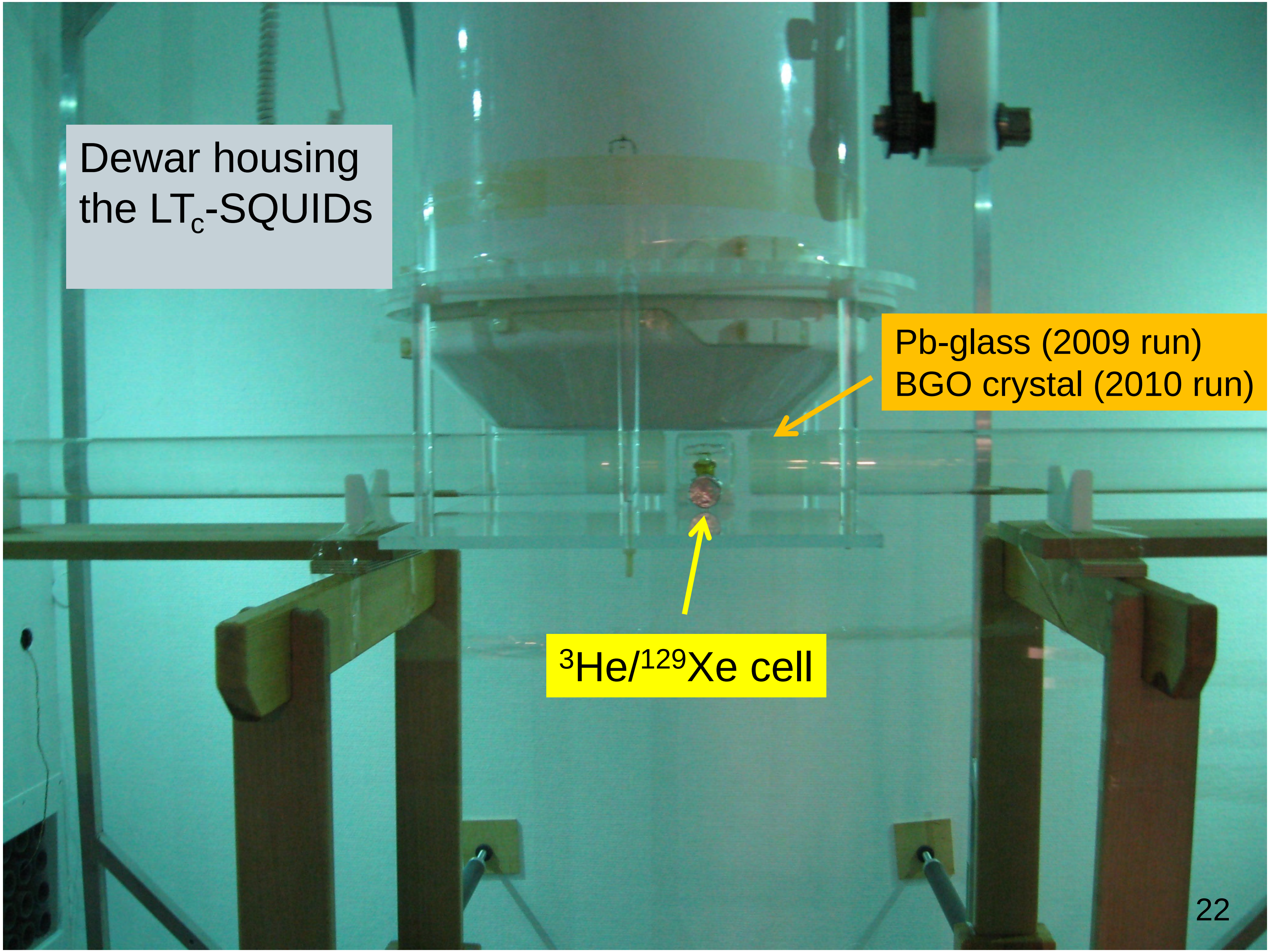
Position: Close

$$\omega_{\text{Far}}(t) = \omega_{\text{L,He}}(t)$$

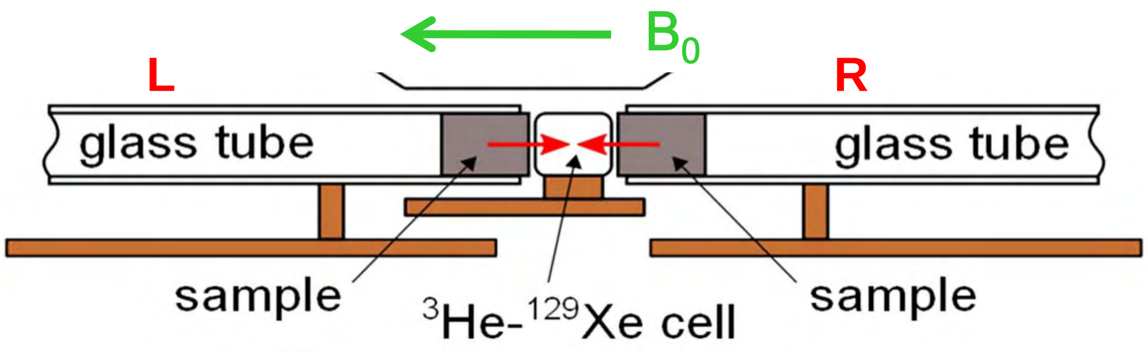
Position: Far

$$\Rightarrow \boxed{\Delta\omega = \omega_{\text{Close}} - \omega_{\text{Far}}}$$

<u>Requirement:</u> $\omega_{\text{L,He}}(t) = const.$


Dewar housing the LT$_c$-SQUIDs
Pb-glass (2009 run)
BGO crystal (2010 run)
^{3}He/^{129}Xe cell

Results



September 2010:

6 runs (each ~9 hours)

gap = 2.2 mm

Mass sample: BGO crystal with density ρ=7.13 g/cm³

=> $\Delta\nu_{SR}$ = (-2.9 ± 6.9 ± 0.4) nHz (95% C.L.)

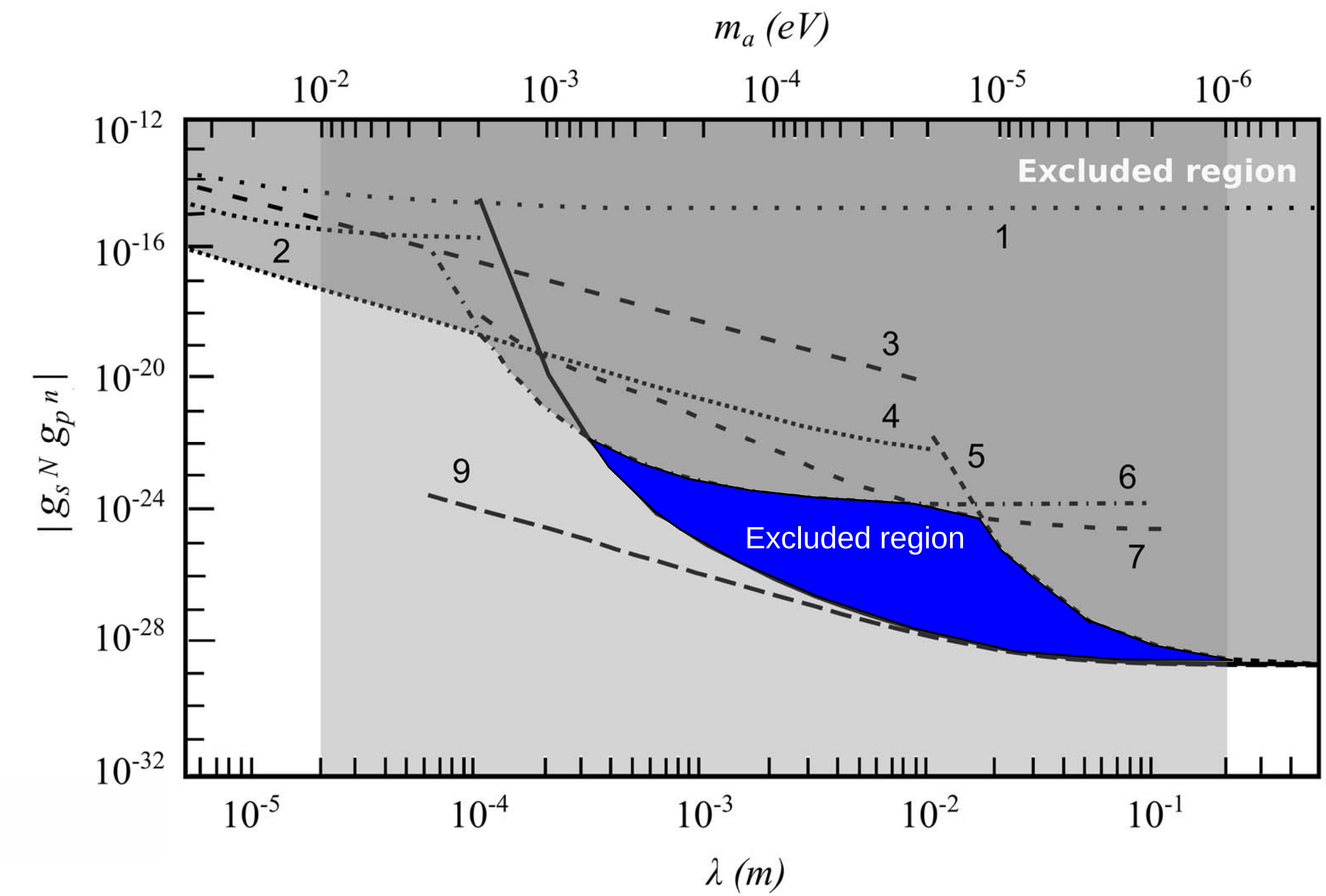
Analysis: $$V_{SP}(\vec{r}) = \frac{\hbar^2 g_S g_P}{8\pi m}\left(\frac{\vec{r}}{r}\cdot\vec{\sigma}\right)\left(\frac{1}{r\lambda}+\frac{1}{r^2}\right)\cdot e^{-r/\lambda}$$

Average potential $\langle V^*(\lambda)\rangle$ was calculated numerically for our cells (Ø= 6 cm, l = 6 cm), a gap of 2.2 mm between cell inner volume and BGO crystal (Ø= 57 mm, l = 81 mm). Due to the inequation $\langle V^*(\lambda)\rangle/h < \Delta(\delta\nu)$ the sensitivity level of $g_S g_P$ can be determined by:

$$g_S\, g_P < 4\,(2\pi)^2\, m_n\, \delta(\Delta\nu)_{corr} \,/\, (NV\, \hbar\, \langle V^*(\lambda)\rangle)$$

Exclusion Plot for new spin-dependent forces (axion like particles)

direct search: Phys.Rev.Let. **111**, 100801 (2013)



1: S. Baeßler et al. Phys. Rev. D, 75, 075006 (2007).

2:T. Jenke et al. Phys. Rev. Let. **112** 151105 (2014)

3: A.P. Serebrov et al. JETP Letters, 91, 6 (2010).

4: A.K.Petukhov et al. Phys. Rev. Lett., 105, 170401 (2010).

5: A.N. Youdin et al. Phys. Rev. Lett., 77, 2170 (1996).

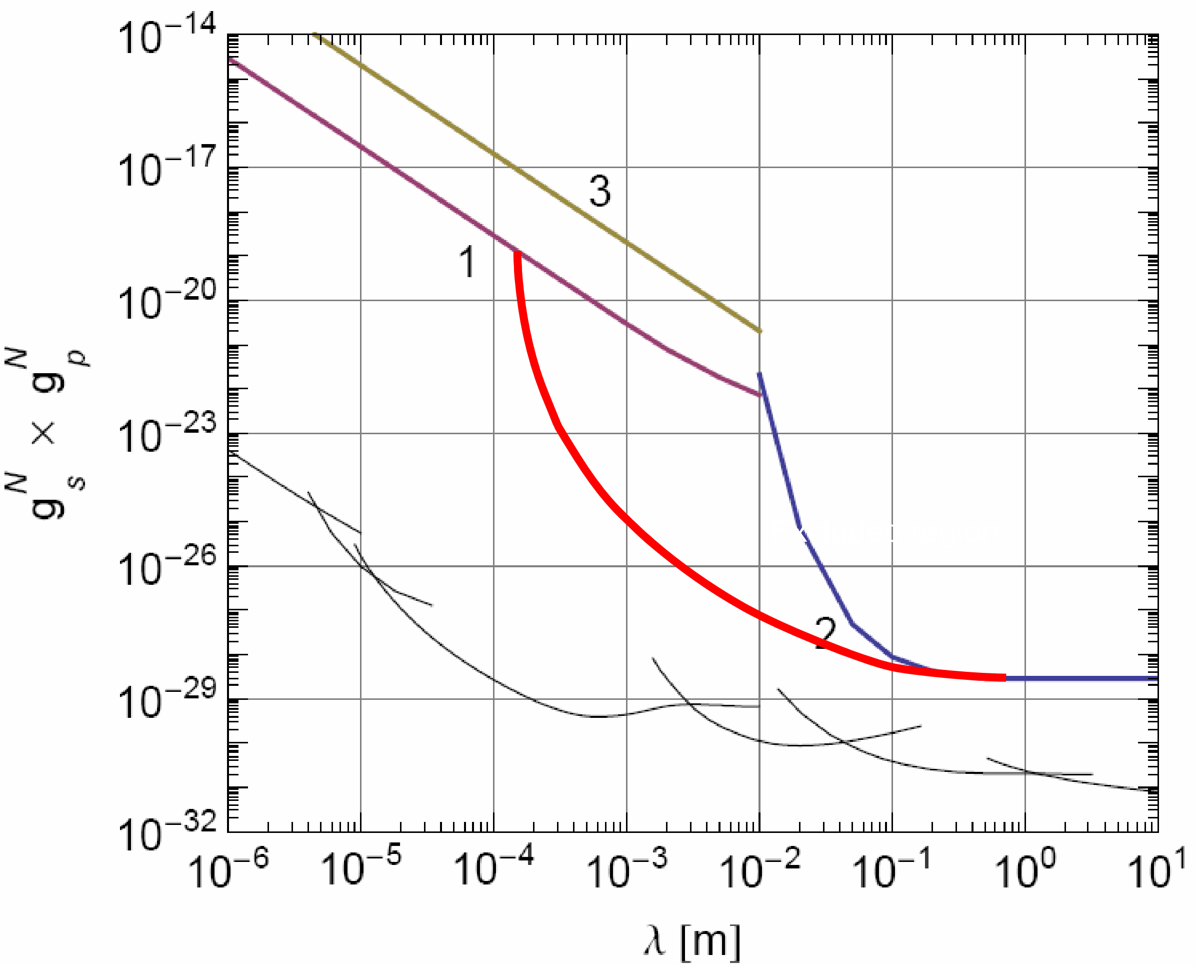
6: arXiv:submit/0534993 [hep-ex] 18 Aug 2012C.

7: P.-H. Chu et al. Phys. Rev. D, 87, 011105(R) (2013).

9: He/Xe for $\Delta x \approx 0$mm

Exclusion Plot for new spin-dependent forces (axion like particles)

arXiv:1205.1776v2 [hep-ph] 29 Jul 2012: Georg Raffelt limits from combining stellar energy-loss arguments with results from Newton's inverse square law tests



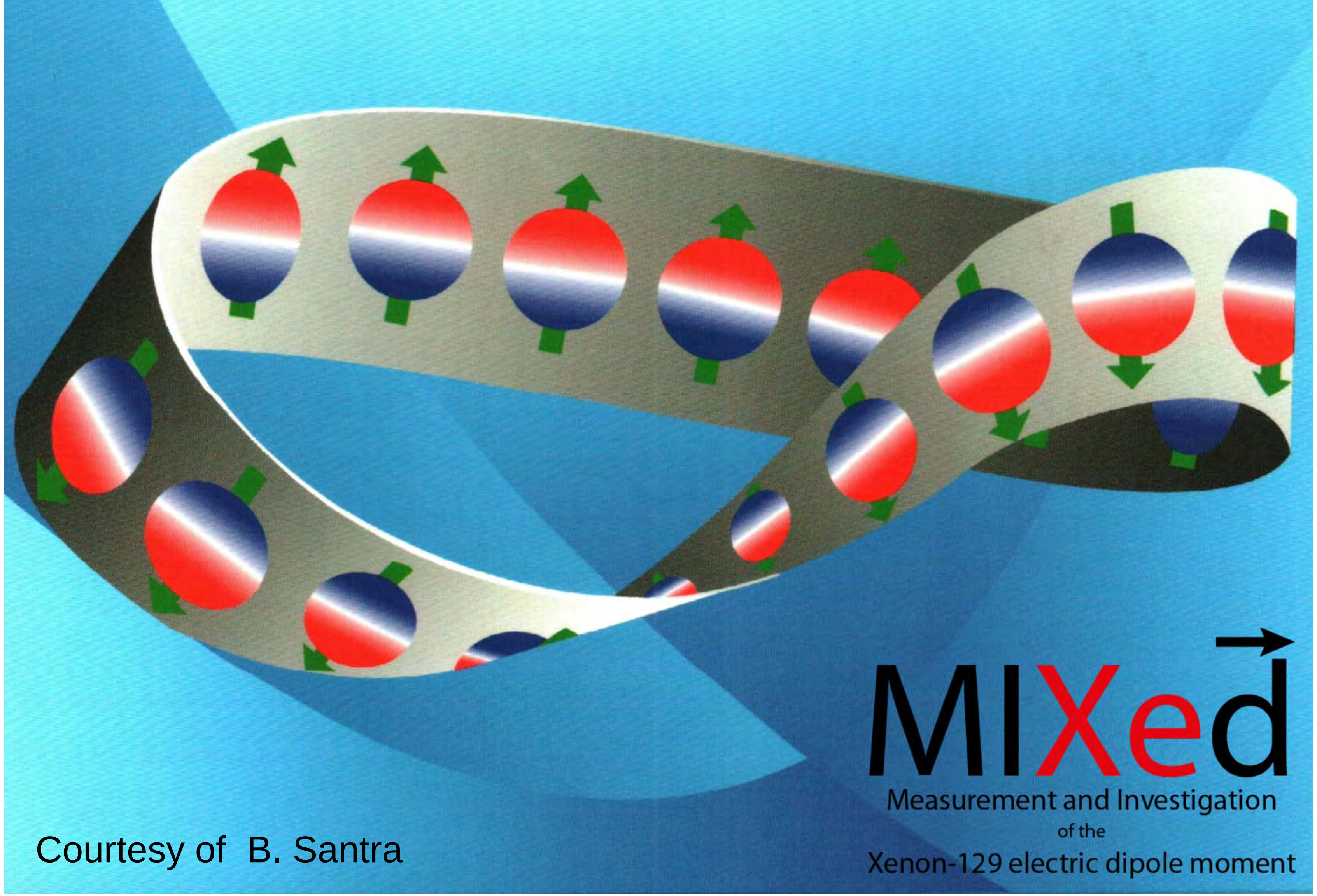
3 (3): A.P. Serebrov et al. JETP Letters, 91, 6 (2010).

1 (4): A.K.Petukhov et al. Phys. Rev. Lett., 105, 170401 (2010).

2 (5): A.N. Youdin et al. Phys. Rev. Lett., 77, 2170 (1996).

He-Xe limit not in the original plot of Raffelt

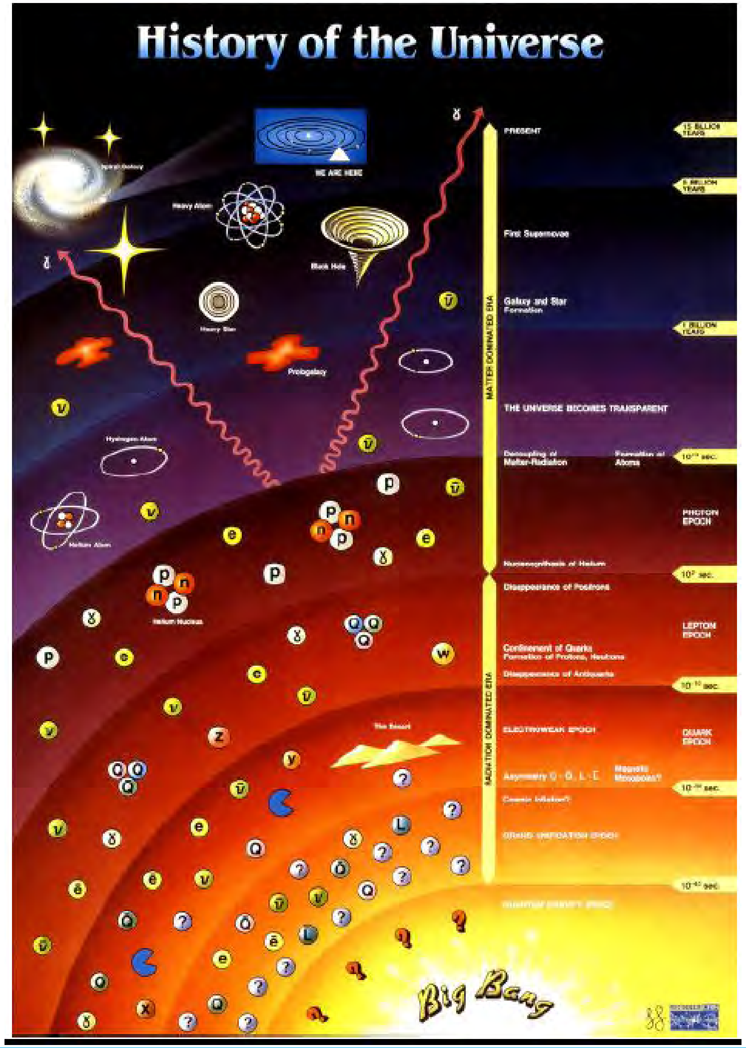
Towards the Xe EDM

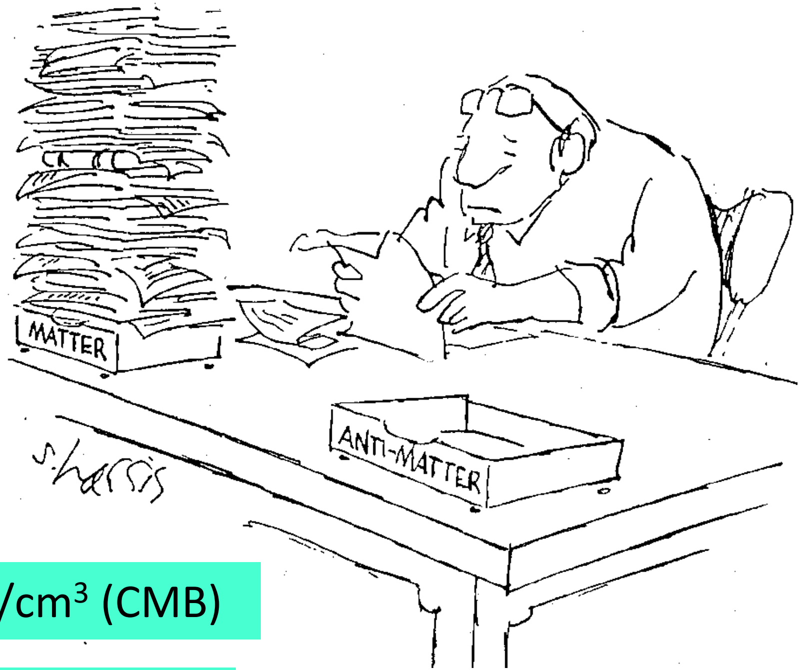


Courtesy of B. Santra

Our world is composed of matter

... and not antimatter





$n_\gamma \approx 400/cm^3$ (CMB)

$n_b \approx 0.2$ protons/m^3

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 6 \times 10^{-10}$$

SM prediction based on observed flavor-changing CP-violation (CKM-matrix)

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 10^{-18}$$

Motivation for EDM searches

Unsolved puzzle :

Why is there much more matter than antimatter in the universe ?

"Sakharov conditions" are:

Baryon number violation, CP-symmetry violation and out of thermal equilibrium.

CP violation within the Standard Model is to small to generate observed baryon asymmetry

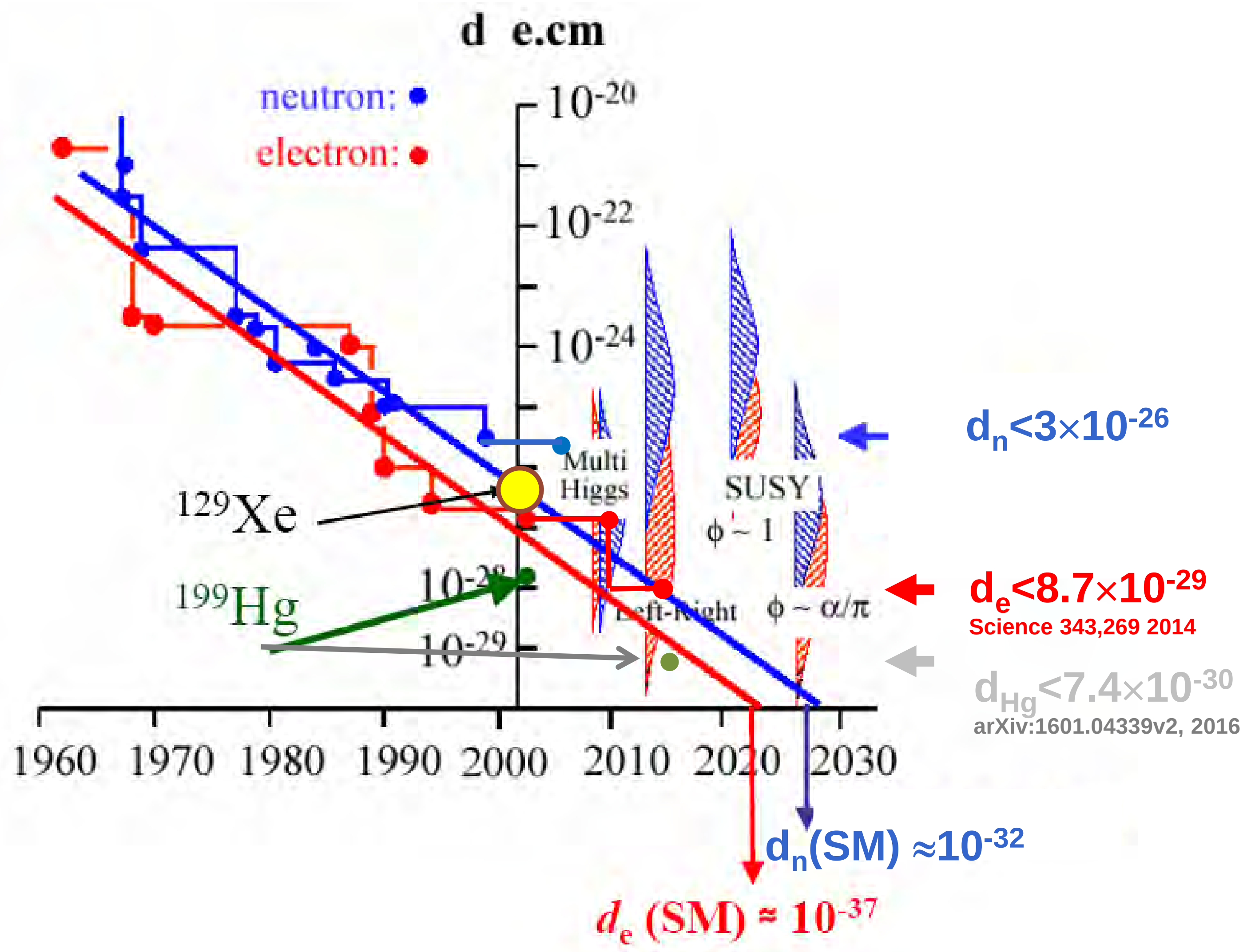
$\Rightarrow$ search for CP violation bigger than predicted by the Standard Model.

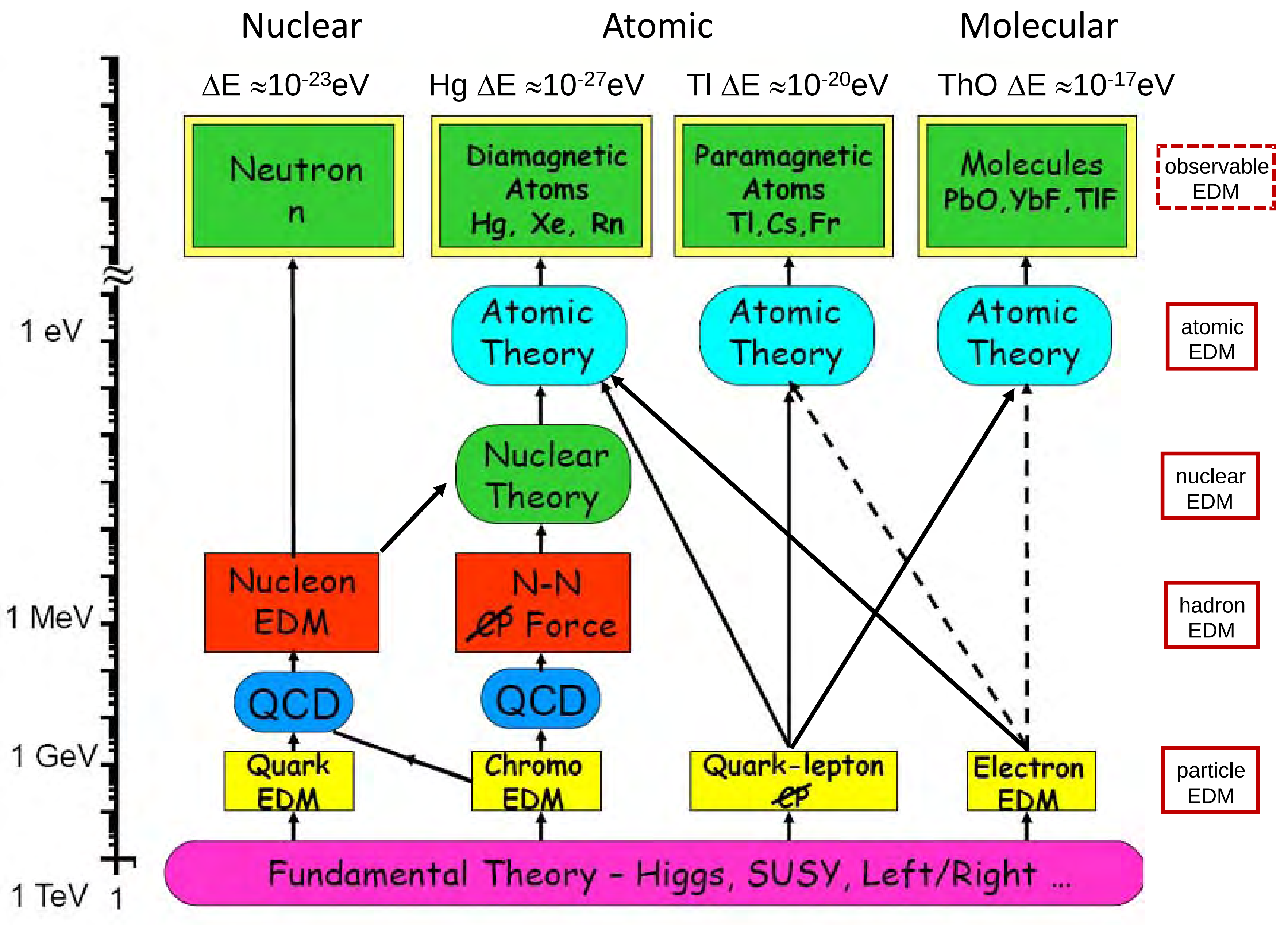
$\Rightarrow$ Good candidates: EDM of electron, neutron and nuclei

If no EDM is found

=> strong constrains for Models beyond the SM or method to rule Model out

Search for a particle EDM

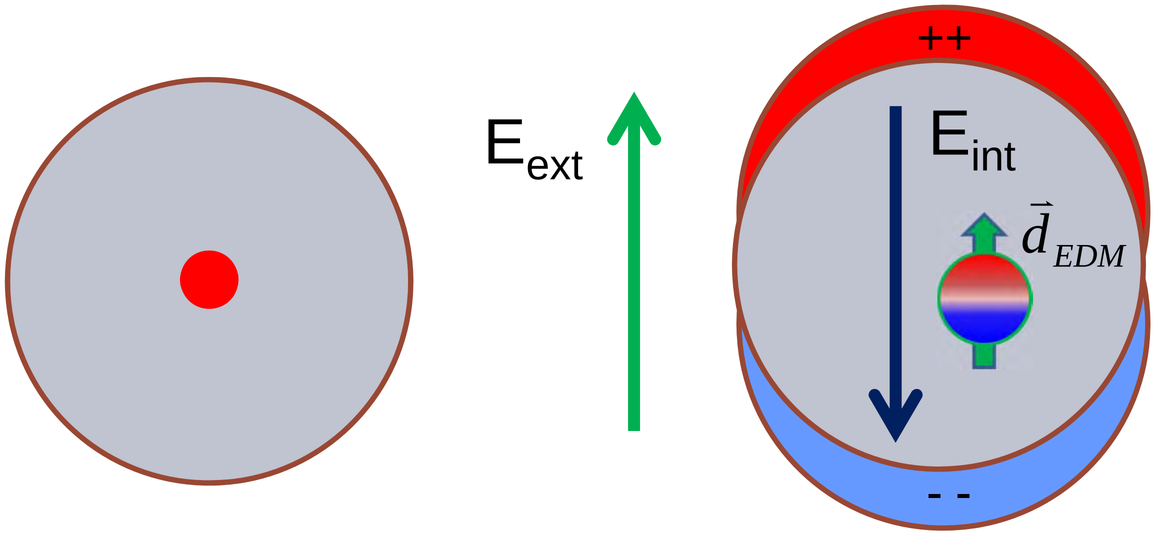




Nuclear
Atomic
Molecular
ΔE ≈10^-23 eV
Hg ΔE ≈10^-27 eV
Tl ΔE ≈10^-20 eV
ThO ΔE ≈10^-17 eV
Neutron n
Diamagnetic Atoms Hg, Xe, Rn
Paramagnetic Atoms Tl, Cs, Fr
Molecules PbO, YbF, TlF
observable EDM
Atomic Theory
Atomic Theory
Atomic Theory
atomic EDM
1 eV
Nuclear Theory
nuclear EDM
Nucleon EDM
N-N CP Force
1 MeV
hadron EDM
QCD
QCD
1 GeV
Quark EDM
Chromo EDM
Quark-lepton CP
Electron EDM
particle EDM
Fundamental Theory - Higgs, SUSY, Left/Right ...
1 TeV
1

Atomic EDM's

$$E_{eff} = E_{ext} + E_{\text{int}} = \varepsilon \cdot E_{ext} = 0$$



$$\Delta E_{EDM} = -\vec{d}_{atom} \cdot \vec{E}_{ext}$$
$$= -\vec{d}_{EDM} \cdot \varepsilon \cdot \vec{E}_{ext}$$
$$= 0$$

- L.I.Schiff (*PR **132** 2194,1963)*:

  System of non-relativistic charged point particles that interact electrostatically can not have an EDM

Atomic and Molecular EDMs

Schiff's screening theorem:

For a non relativistic system made up of point like charged particles which interact electrostatically and an arbitrary external field, the shielding is complete

For the measurement of an EDM search for exceptions:

- Heavy paramagnetic atoms and molecules
  the relativistic effect of the electromagnetic interaction between electrons and the nucleus enhances effectively the external field.

YbF	E_{eff} = 14.5 GV/cm
ThO	E_{eff} = 84 GV/cm

- Heavy diamagnetic Atoms (closed electron (sub-)shell)
  finite size effect: Schiff's screening is not perfect, but suppresses EDM-coupling by 1 to 3 orders of magnitude

– $d_e \neq 0 \rightarrow d_{atom} \neq 0$ $\sim Z^3\alpha^2 d_e$

– P,T-odd eN interaction

Tensor-Pseudotensor $\sim Z^2 G_F C_T$

Scalar- Pseudoscalar $\sim Z^3 G_F C_S$

– Nuclear EDM – finite size
  Schiff moment induced by P,T-odd N-N interaction $\sim 10^{-25}\ \eta$ [ecm]

Parameter	^{199}Hg	Best alternate limit
d_e / (e ·cm)	3.0×10^{-27}	ThO: 8.6×10^{-29}
$d_{n/}$ / (e ·cm)	1.6×10^{-26}	n: 2.9×10^{-26}
d_p/ (e ·cm)	2.0×10^{-25}	TlF: 5.4×10^{-23}
θ_{QCD}	8.5×10^{-11}	n: 2.4×10^{-10}
C_S	1.3×10^{-8}	Tl: 2.4×10^{-7}
C_T	1.5×10^{-10}	TlF: 4.5×10^{-7}
C_{PS}	1.2×10^{-7}	TiF: 3×10^{-4}
η	8.0×10^{-5}	Xe: 5×10^{-2}

$$d\left({}^{199}\mathrm{Hg}\right) \le 7.4\cdot10^{-30}\,\mathrm{e}\cdot\mathrm{cm}$$

Reduced Limit on the Permanent Electric Dipole Moment of ^{199}Hg
B. Graner, Y. Chen, E. G. Lindahl, and B. R. Heckel
arXiv:1601.04339v2 [physics.atom-ph] 20 Jan 2016

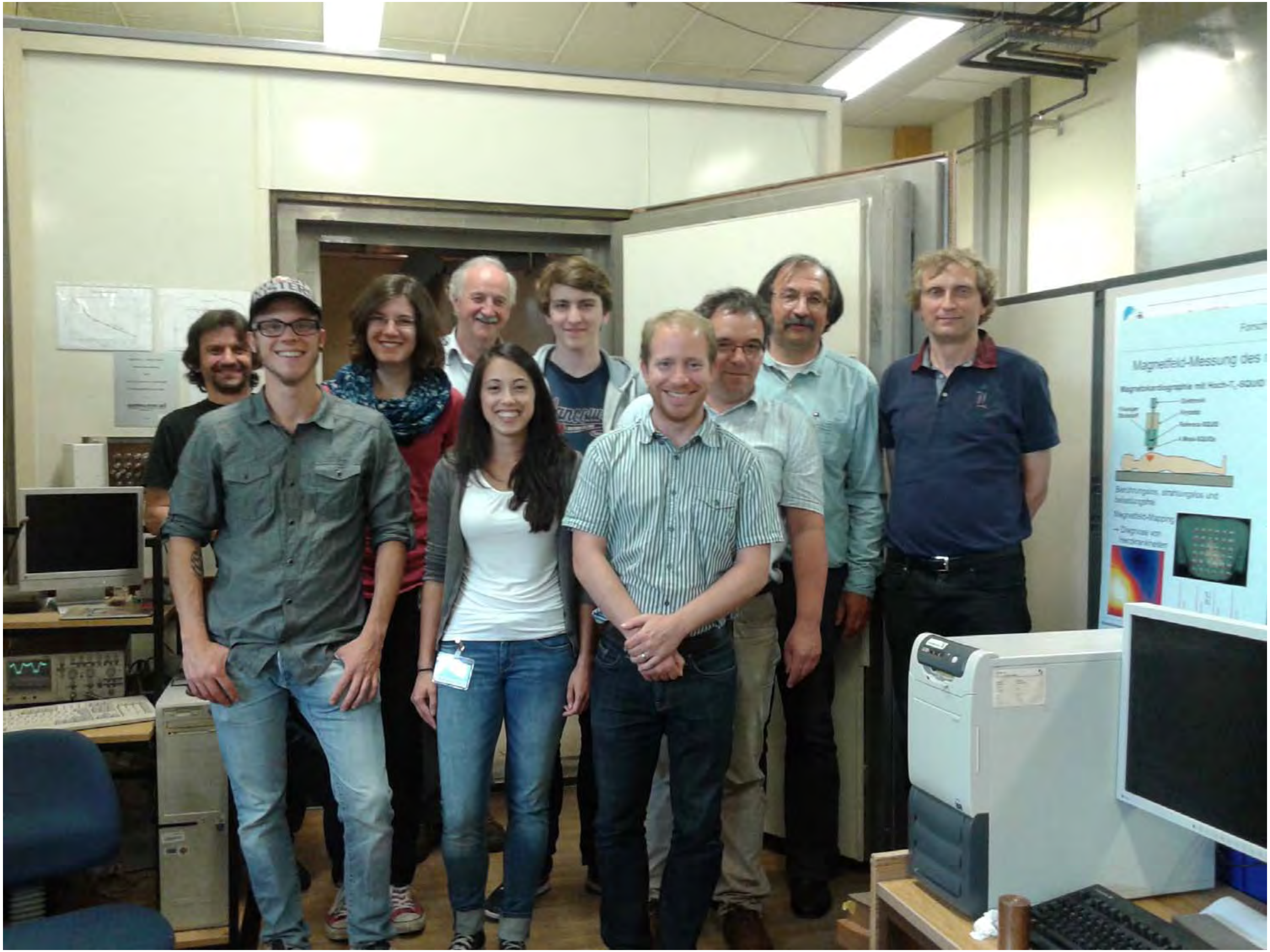
$$d\left({}^{199}\mathrm{Hg}\right) = 10^{-2}d_e + (2.0\times10^{-20}C_T + 5.9\times10^{-22}C_S + 6\times10^{-23}C_{PS} + 3.9\times10^{-25}\eta)\,\mathrm{e}\cdot\mathrm{cm}$$

$$d\left({}^{129}\mathrm{Xe}\right) = 10^{-3}d_e + (5.2\times10^{-21}C_T + 5.6\times10^{-23}C_S + 1.2\times10^{-23}C_{PS} + 6.7\times10^{-26}\eta)\,\mathrm{e}\cdot\mathrm{cm}$$

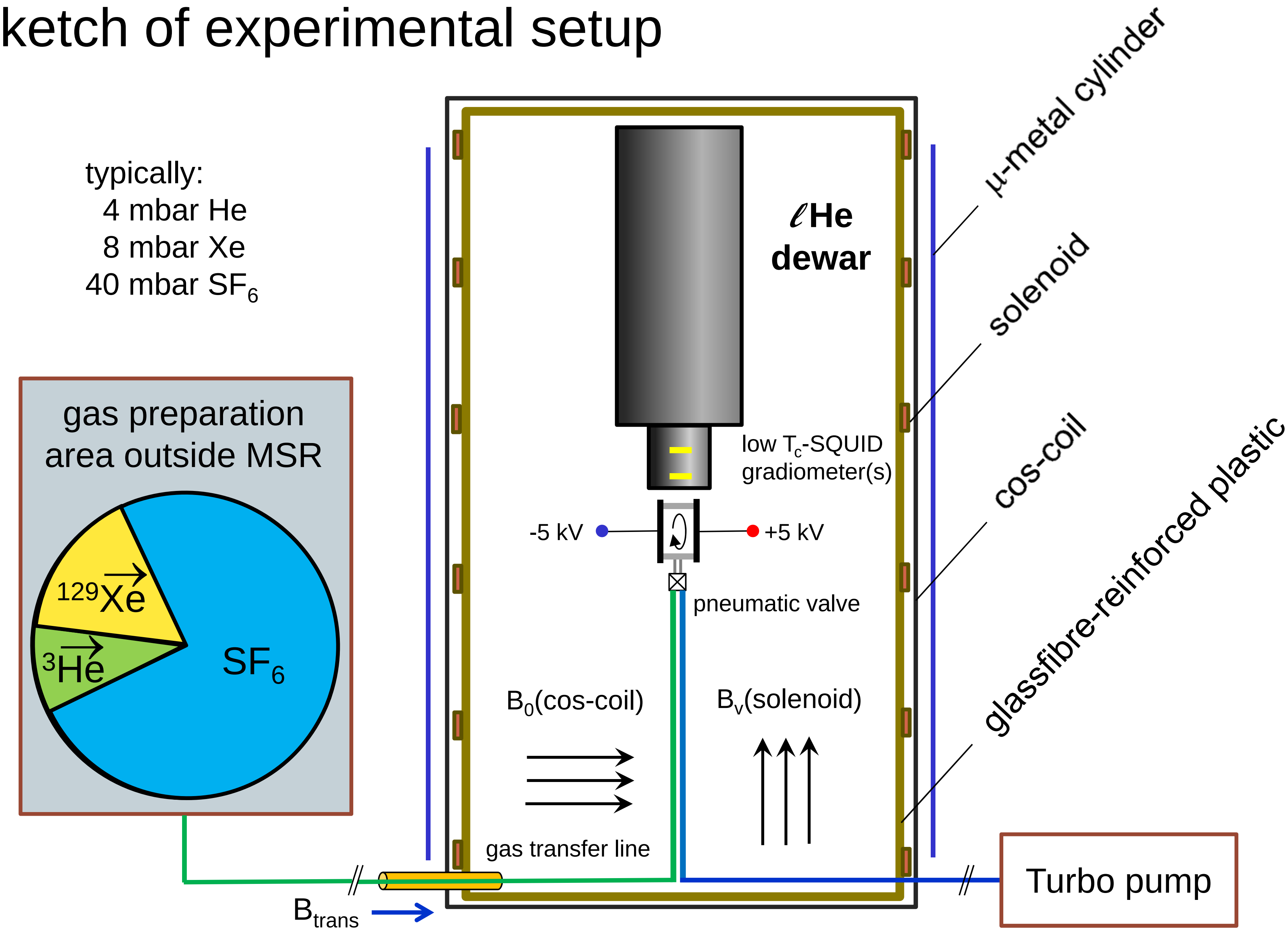
$$d\left({}^{129}\mathrm{Xe}\right) \le 3.3\cdot10^{-27}\,\mathrm{e}\cdot\mathrm{cm}$$

6× less sensitive to CP violating interactions

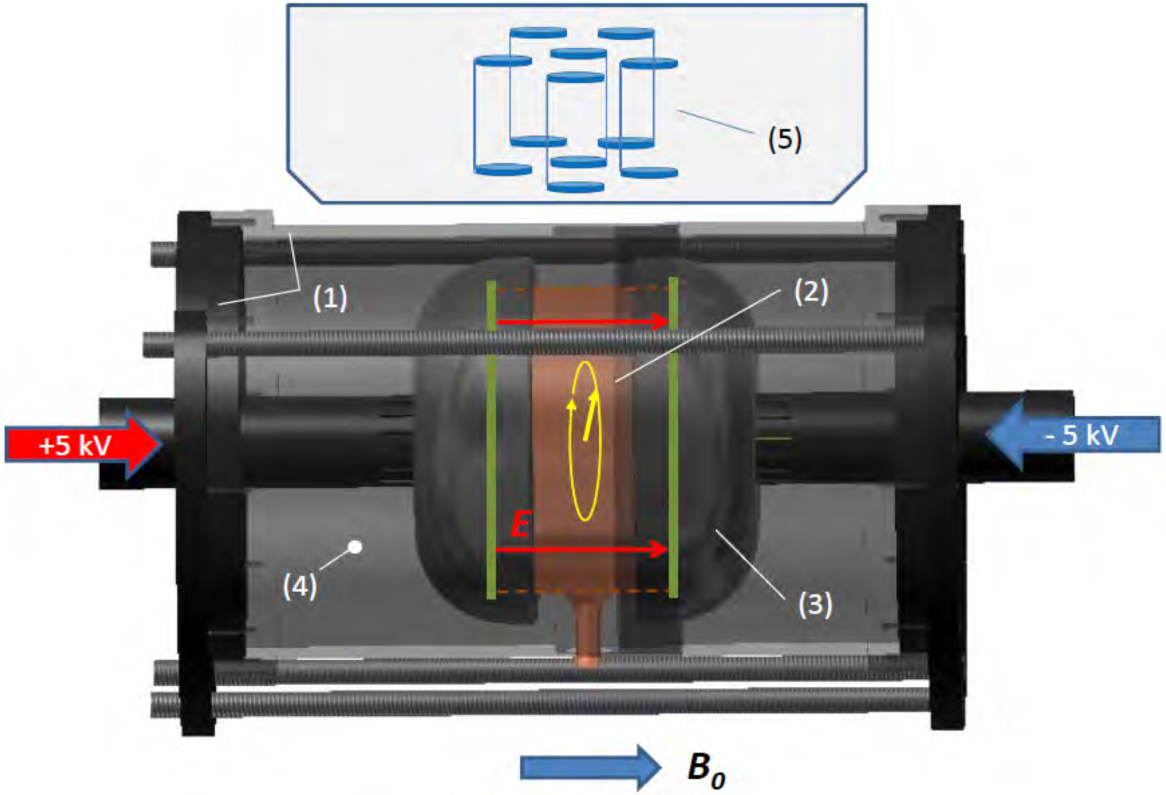
Magnetically shielded room (MSR) at Jülich Research Center


Magnetfeld-Messung des

Sketch of experimental setup



Scheme inner setup of the ^{129}Xe-EDM experiment



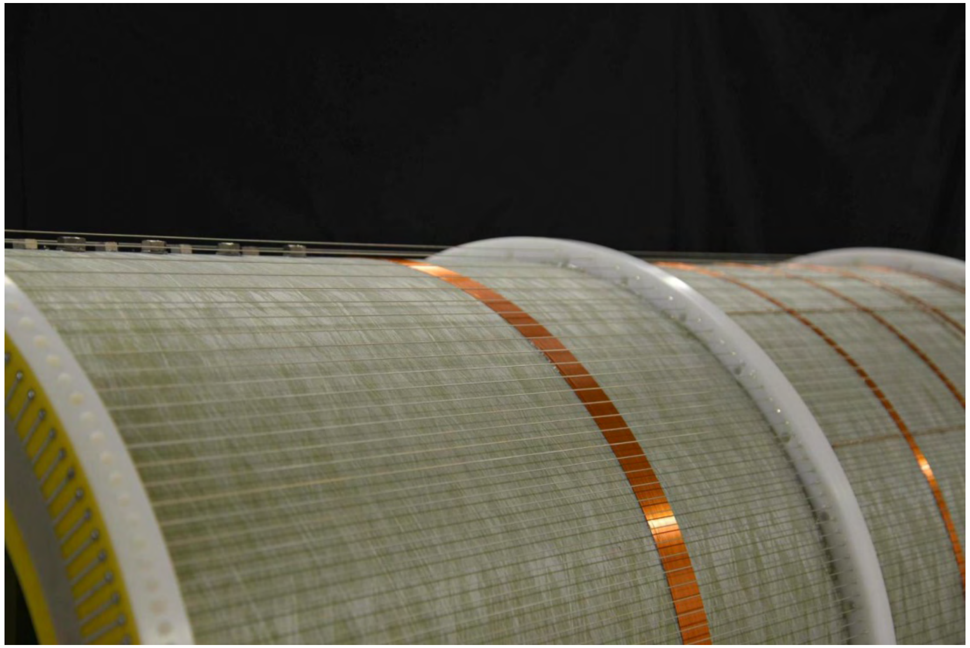
(1) Conductive Plastic housing

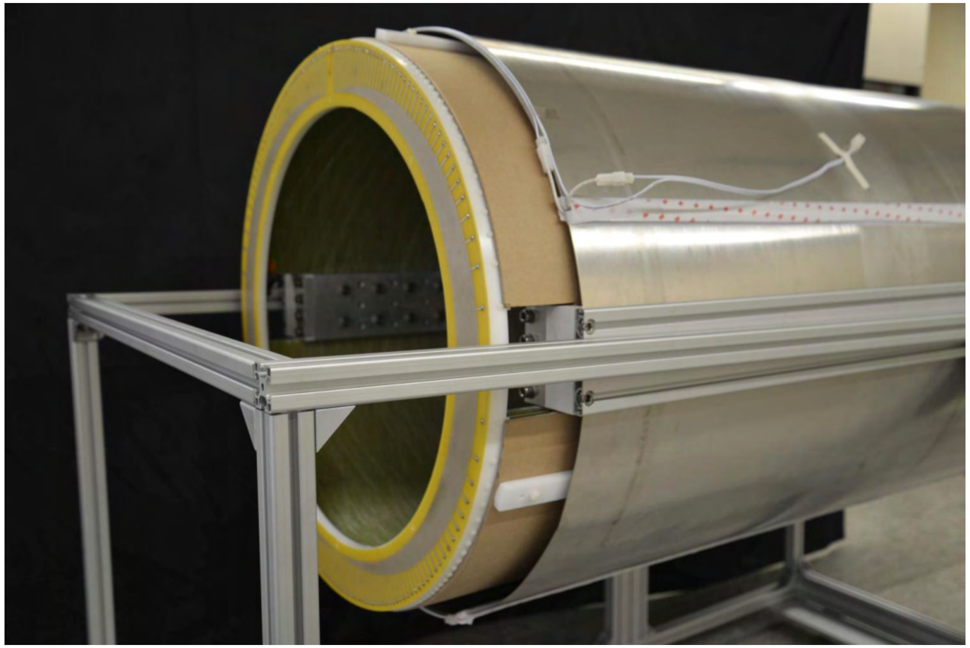
(2) Glass cell with silicon lids

(3) High voltage electrodes with cabling

(4) Filled with SF_6

(5) Cryostat made of carbon fiber, inside special low temperature SQUID Gradiometers

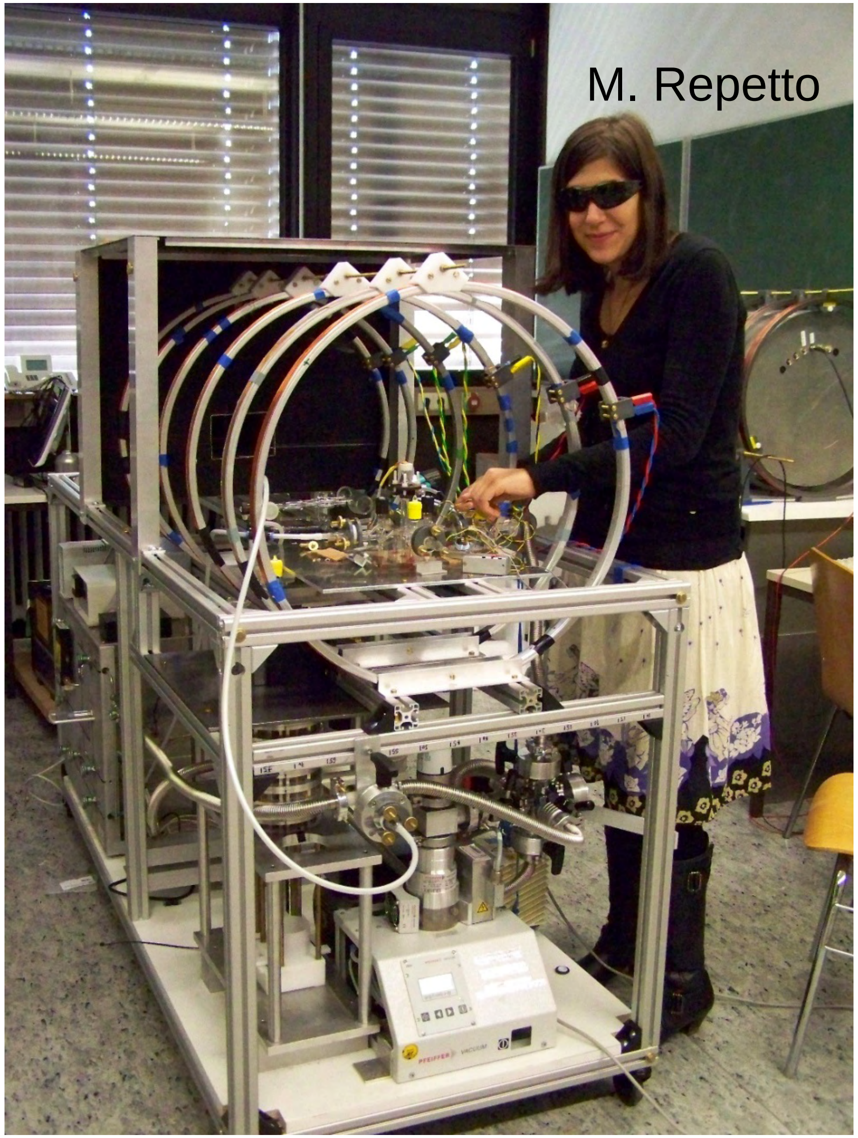




Mounting of the Cosin-coil and the µ-metal cylinder at Mainz

Fiber glass cryostat inside
are 3 SQUID gradiometers

Hyperpolarized gases



Xe-Polarizer (^{129}Xe: 91%)

3He-Polarizer

Contents lists available at ScienceDirect

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JMR

Communication

HP-Xe to go: Storage and transportation of hyperpolarized ^{129}Xenon

M. Repetto[a], S. Zimmer[a], F. Allmendinger[b], P. Blümler[a,*], M. Doll[a], J.O. Grasdijk[c], W. Heil[a], K. Jungmann[c], S. Karpuk[a], H.-J. Krause[d], A. Offenhäusser[d], U. Schmidt[b], Y. Sobolev[a], L. Willmann[c]

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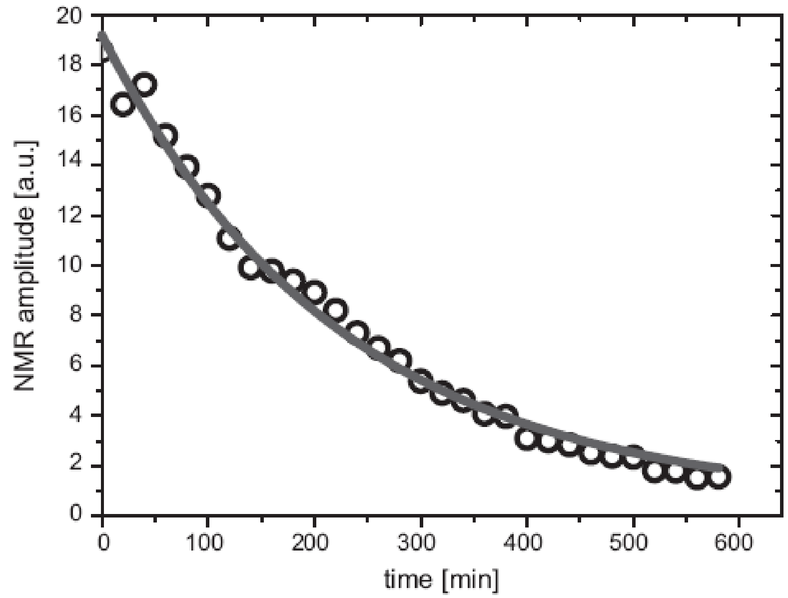
[d] Peter Grünberg Institut (PGI-8), Forschungszentrum Jülich, 52425 Jülich, Germany



MIXed collaboration

Status of the ^{129}Xe EDM

Best limit of EDM ^{129}Xe: $(0.7 \pm 2.8)\cdot 10^{-27}$ e·cm
by M. A. Rosenberry and T. E. Chupp (2001)

- Apparatus is setup and running
- 3 weeks of data taking July 2016
- Best run same statistical limit as Rosenberry and Chupp within 6 hours
- discovery a „new“ systematic effect: „magnetization“ field of polarized nuclear spins in a cylindrical cell causes additional frequency/phase-shifts
- remodeling of the apparatus for use of a spherical cell
- 2 weeks of data taking July 2017
- Goal: EDM ^{129}Xe < $1.0\cdot 10^{-27}$ e·cm
- Data evaluation finished autumn 2017

MIXed collaboration

Institut für Physik, Universität Mainz:

W. Heil, M. Repetto, P. Blümeler, M. Doll,
S. Karpuk, Y. Sobolev, St. Zimmer

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg:

F. Allmendinger, U. Schmidt

KVI-Groningen

Olivier Grasdijk K. Jungmann, L.Willmann

Forschungszentrum Jülich

H.-J. Krause, A. Offenhäusser

Conclusion

He-Xe-comagnetometry: spin clocks are a very powerful method to search for very tiny spin dependent effects

Best limits for new physics obtained with He-Xe spin clocks:

Short range pseudoscalar spin coupling: direct search for ALPs improved by more than 4 order of magnitude over half of the range of the axion window

Not discussed: best limit for Lorenz violating coupling of the nucleon spin to a relic background field; preferred direction

Xe-EDM is on the way for best limit

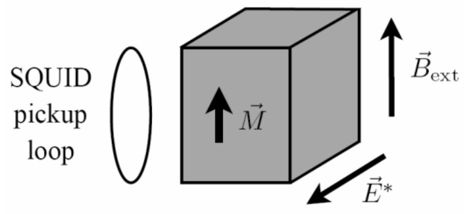
Still new ideas to use HeXe spin clocks ->

Outlook He-Xe Spin Clocks

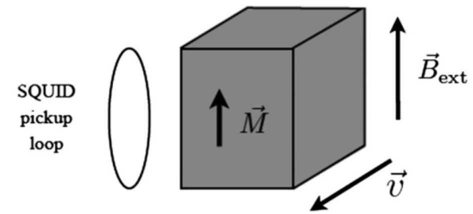
Peter W. Graham and Surjeet Rajendran
DOI: 10.1103/PhysRevD.88.035023 (2013) → Cosmic Axion Spin Precession Experiment (CASPEr)

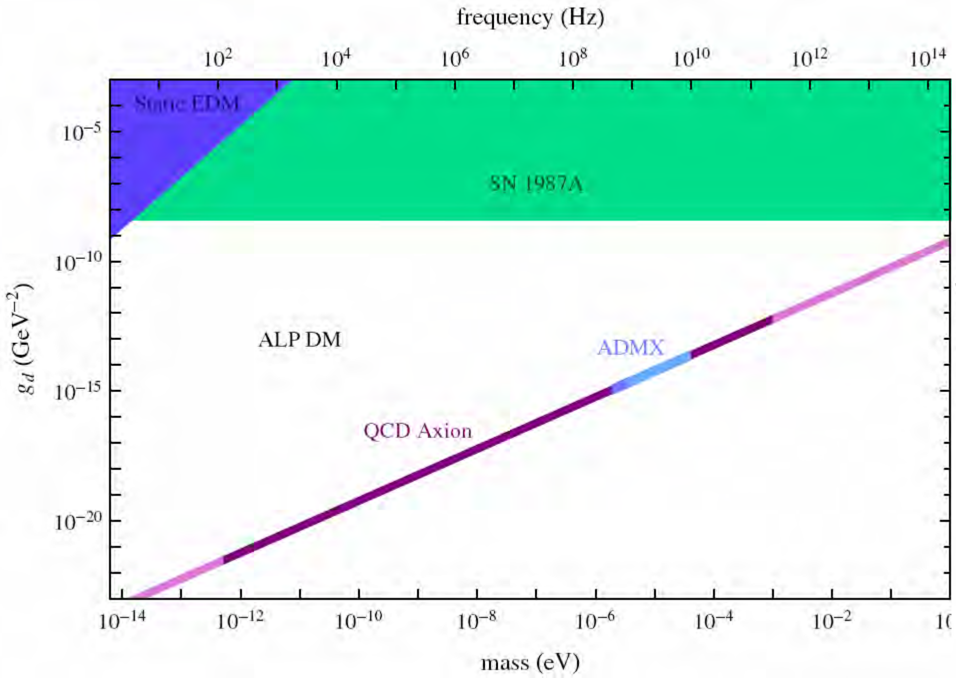
Interaction of nuclei with back ground axion (like) dark matter field leads to:

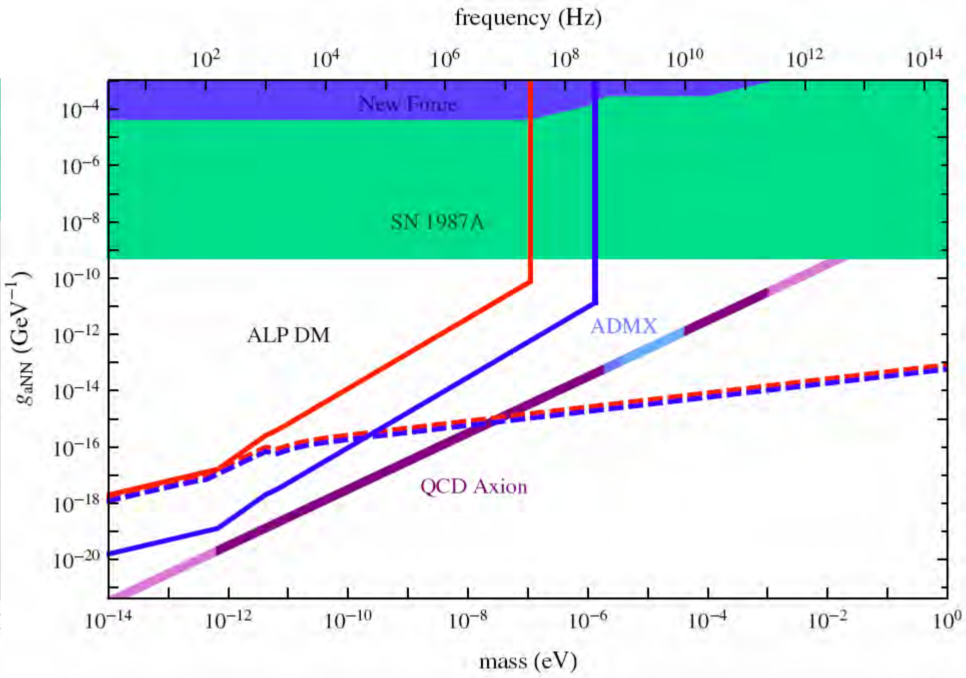
oscillating EDM
in resonance with
Larmor precession
→ transversal magnetization



Axion wind;
gradient of
axion field
→ transversal magnetization



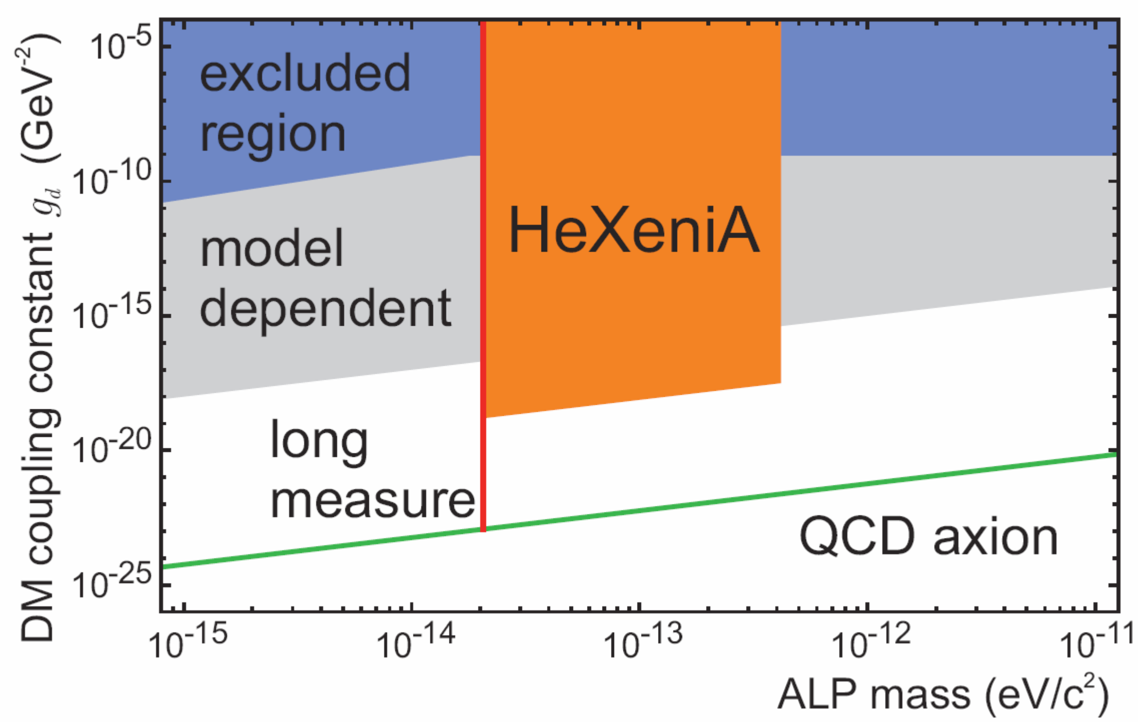




Outlook He-Xe Spin Clocks

New Project HeXeniA (**He Xe n**uclei **i**nteract with **a**xions)
(embedded within the “exploring dark matter” proposal for a cluster of excellence)

5Hz Larmor frequency is in resonance with axion/ALP mass of $2 \cdot 10^{-14}$ eV



$$m_{ALP} \approx 5 \cdot 10^{-13} eV \cdot \left(\frac{1.2 \cdot 10^{19}\, GeV}{f_{ALP}} \right)$$

f_{ALP} energy scale of spontaneously broken symmetry

WISPy Cold Dark Matter

INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

J. Jaeckel[**]

S. Abel[†], J. Berges[**], B. Doebrich[z], L. Gastaldo[**], M. Goodsell[xx],
H. Gies[0], F. Kahlhoefer[*], S. Knirck[**],
V. Khoze[†], A. Lobanov[y], J. Redondo[x],
A. Ringwald[*], U. Schmidt[**], K. Schmidt-Hoberg[*]
and The FUNK Collaboration

[**]Heidelberg University, [z]CERN, [†]IPPP Durham, [*]DESY,
[y]MPIfR Bonn, [x]U. Zaragoza, [xx]Paris LPTHE, [0]ITP Jena

New couplings:
A spin experiment

Looking for oscillating dipoles

- Remember:

  Axion field controls electric dipole moment:

$$d_e \sim \theta \sim \frac{a}{f_a}$$

- Dipole moments follow the oscillating axion field
  - → Tiny oscillating electric dipole

$$d_e \sim 10^{-35} e\,\mathrm{cm}\cos(m_a t)$$

New Observables for Direct Detection of Axion Dark Matter
Peter W. Graham, Surjeet Rajendran (Stanford U., ITP). Jun 25, 2013. 13 pp.
Published in **Phys.Rev. D88 (2013) 035023**
DOI: 10.1103/PhysRevD.88.035023
e-Print: arXiv:1306.6088 **[hep-ph]** | PDF

ITP INSTITUT FÜR THEORETISCHE PHYSIK
Heidelberg University

Sensitivity (¤8¤– ¨!