Global Network of Optical Magnetometers for Exotic physics

Current Status and Future Perspectives

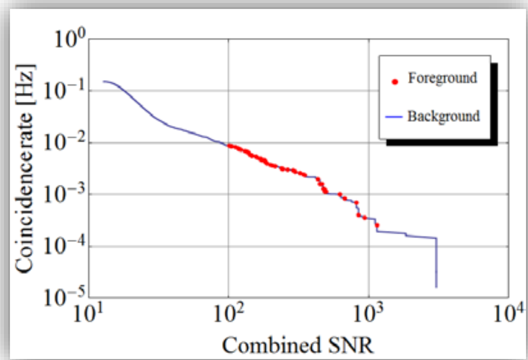
Szymon Pustelny

JAGIELLONIAN UNIVERSITY
since 1364

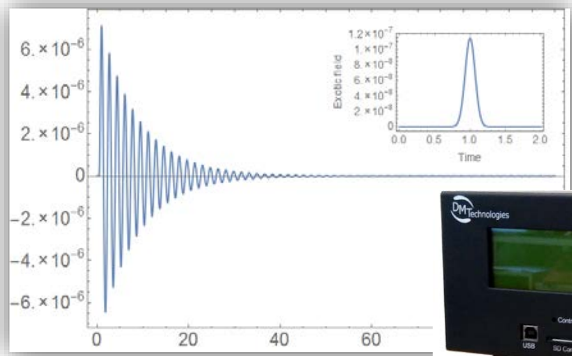
Mainz, 17 June 2015

Outline

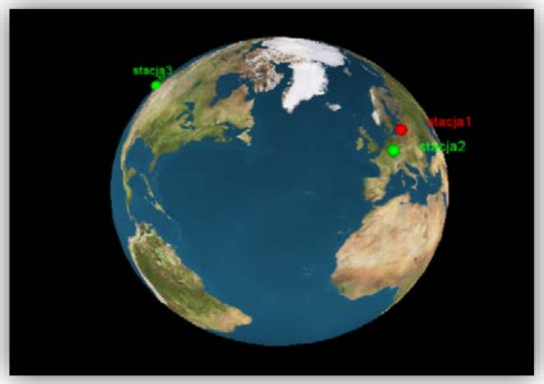
Introduction



Proof-of-principle experiment

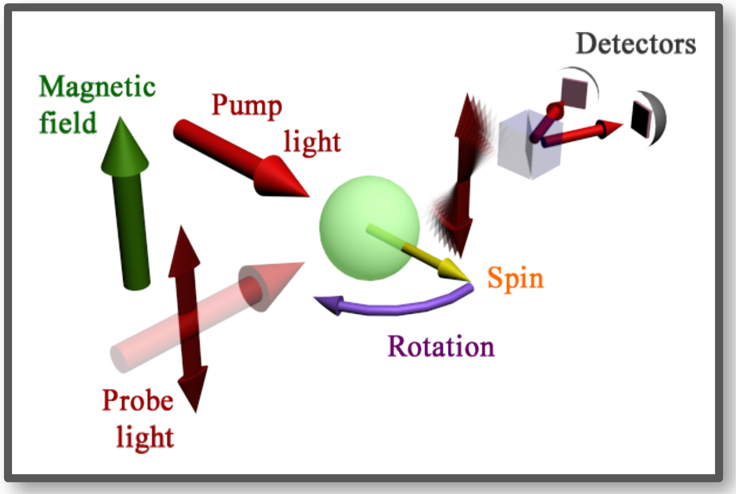


Current status



Outlook

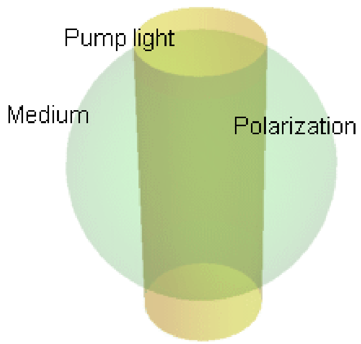
Optical magnetometry



Optical magnetometry

Method of detecting magnetic fields via detection of properties of light propagating through magneto-optically active medium

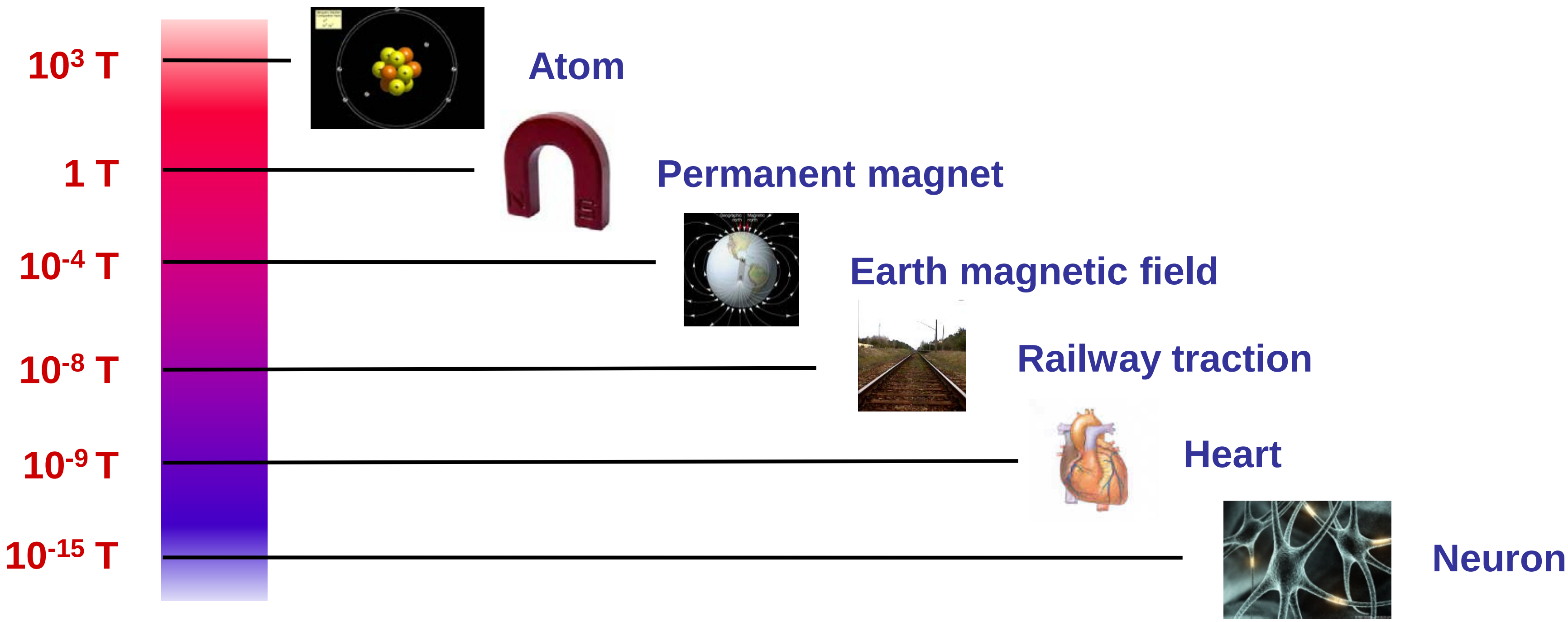
Principles of operation



Magnetic field

Name	Element(s)/ Compound(s)	δB_f [$\mathrm{fT}/\sqrt{\mathrm{Hz}}$]	δB_d [$\mathrm{fT}/\sqrt{\mathrm{Hz}}$]
SERF	K	0.05	0.16
μ-SERF	Rb	1	30
NMR-SERF hybrid	pentane-HFB	0.23	3200
NMOR	Rb	0.16	0.3^a
AM NMOR	Rb	3.2	39
M_x	Cs	5	9
μ-M_x	Cs	20	42
Helium	He	5	50
Hg EDM	Hg	0.07	1.2

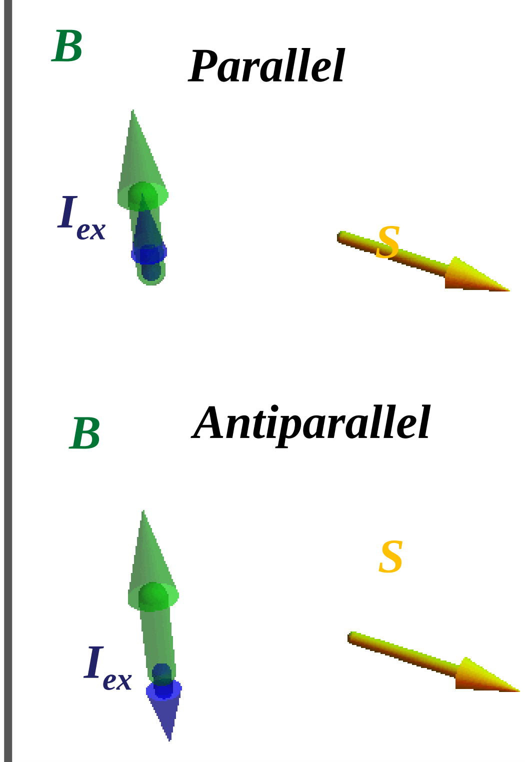
Optical magnetometers are **the most sensitive** magnetic-field sensors



Exotic spin-coupling detection

OMAGs are ideally suited for detection of non-magnetic spin interactions

Name	Element(s)/ Compound(s)	δB_f $[\mathrm{fT}/\sqrt{\mathrm{Hz}}]$	δB_d $[\mathrm{fT}/\sqrt{\mathrm{Hz}}]$	δE_f $[10^{-20}\mathrm{eV}/\sqrt{\mathrm{Hz}}]$	δE_d $[10^{-20}\mathrm{eV}/\sqrt{\mathrm{Hz}}]$
SERF	^{3}He	0.002	0.75	3×10^{-5}	0.01
μ-SERF	Rb	1	30	1.9	58
NMR-SERF hybrid	pentane-HFB	0.23	3200	0.004	55
NMOR	Rb	0.16	0.3[a]	0.31	0.58
AM NMOR	Rb	3.2	39	9	110[a]
M_x	Cs	5	9	7	13
μ-M_x	Cs	20	42	29	61
Helium	He	5	50	54	540
Hg EDM	Hg	6×10^{-4}[b]	320	2×10^{-6}	1



Exotic spin coupling

The spin precession is modified

$$\vec{I}_{ex}\cdot\vec{S}\neq 0 \;\Rightarrow\; \omega_{\uparrow\downarrow}\neq\omega_{\uparrow\uparrow}$$

Exotic spin-coupling detection

Many experiments use this approach

- Searches for EDM
- Searches for GDM
- Lorentz symmetry violation
- Searches for long-range spin couplings
- CPT symmetry violation
- …

All these give null results

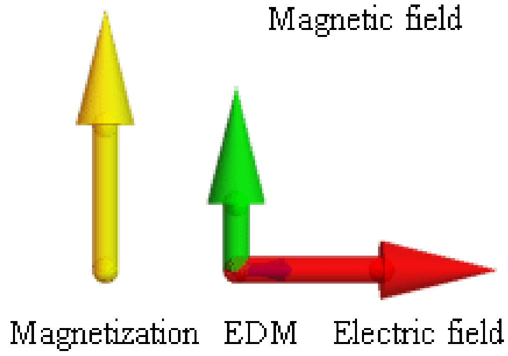
Why?

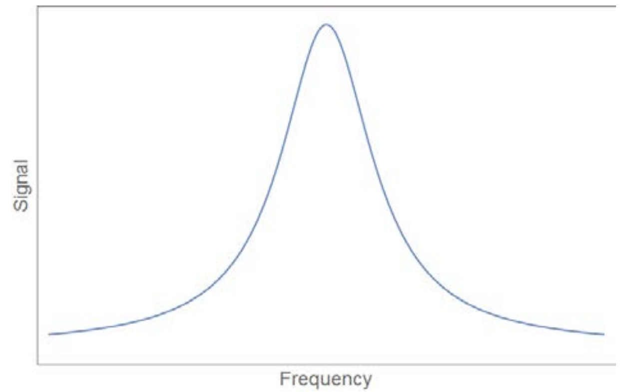
We are (still) not sensitive enough

We are looking in a wrong way

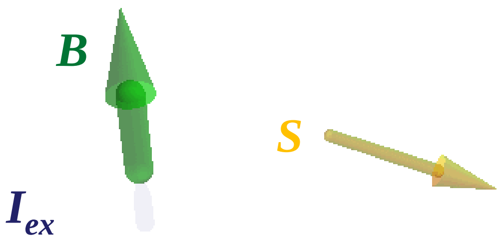
Oscillating field and transients

Oscillating exotic spin coupling

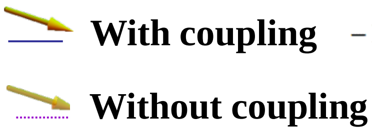


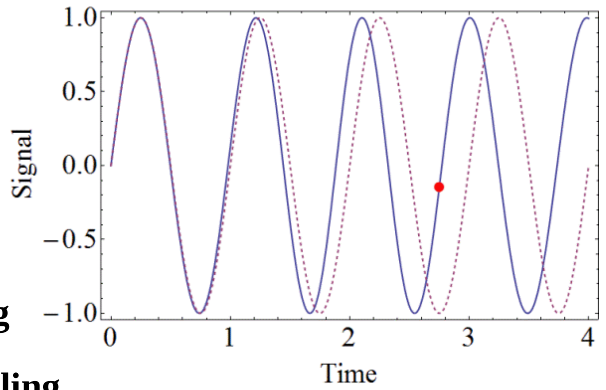


Transient exotic spin coupling



Transient coupling

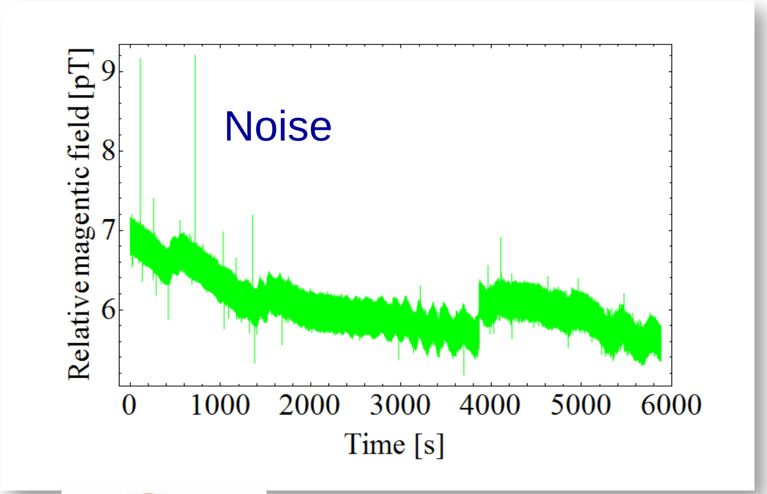




Transient spin couplings

Global Network of Optical Magnetometers for Exotic physics (GNOME)

A network of optical magnetometers operating synchronously in distant locations, which by correlating readouts if the magnetometers enables detection of global disturbances of spin dynamics

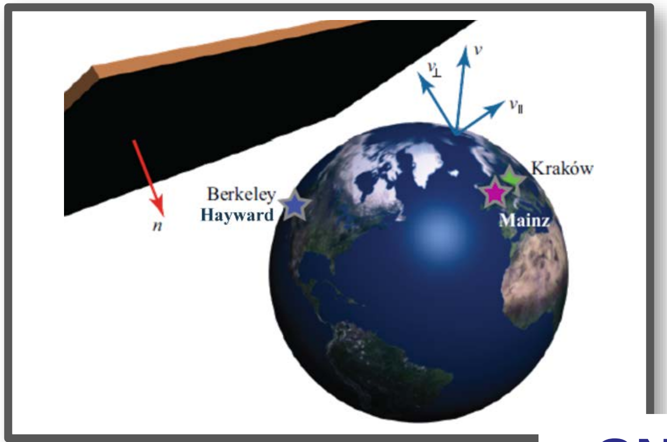


Experimental signal:

- leakage of the magnetic field into the shield,
- change of laser properties,
- electrical disturbances,
- …

How to differentiate real signal from noise?

GNOME



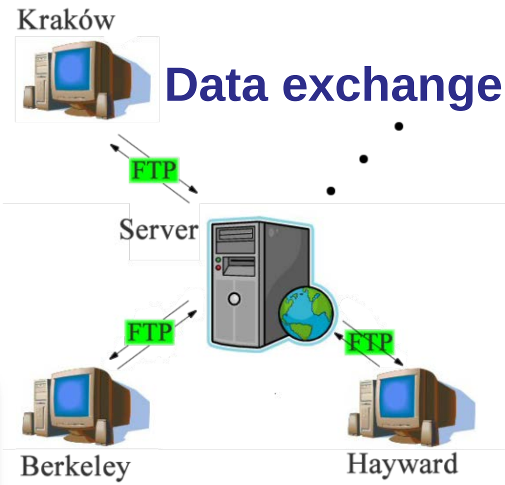
Correlating signals

Ability to suppress local noise (**correlations**)
Spatio-temporal resolution (**spatial identification of the coupling source**).

GNOME crucial ingredients

Sensitive OMAGs

Data exchange



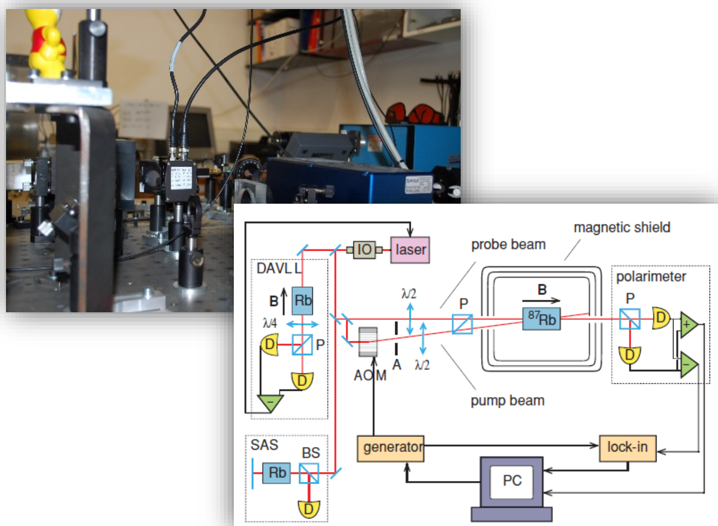
Global timing

Data analysis

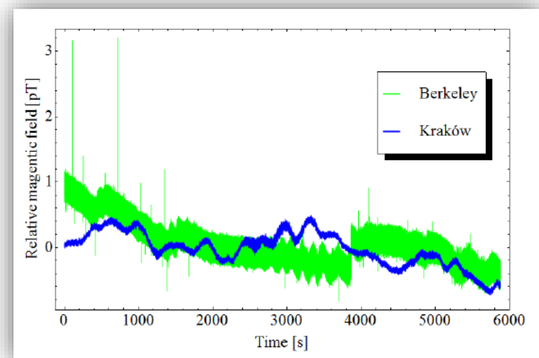
Proof-of-principle experiment

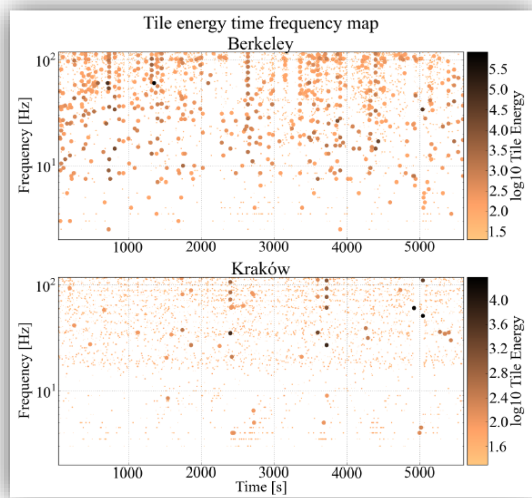
Proof-of-principle GNOME

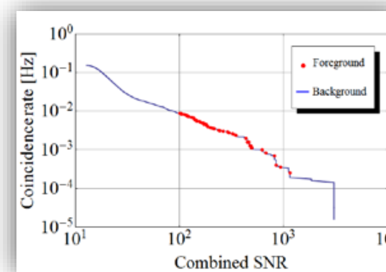
Experimental setup



Experimental results





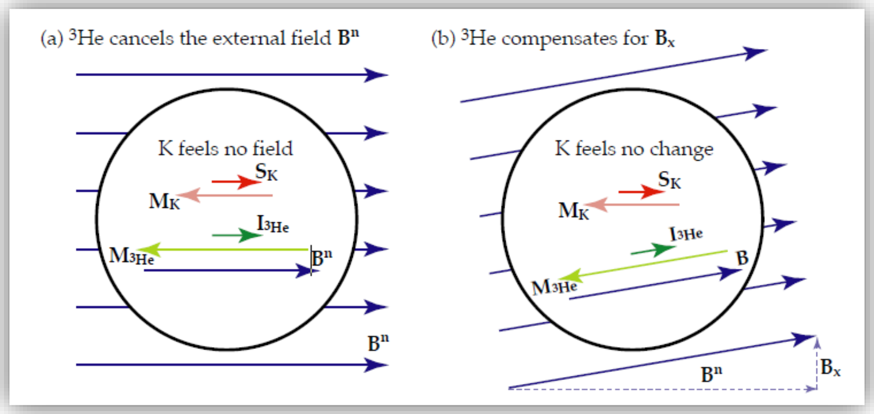


No correlations

Consequences:

- primarily sensitive to the magnetic fields,
- unoptimized for the detection of the magnetic field.

Self-compensating magnetometer – Setup



Romalis's self-compensating magnetometer

Crucial elements

mixture of gases

- alkali(s) vapor (potassium or rubidium)
- noble gas (helium or xenon) – ~5 amg

Compansating magnetic field

High temperaturę operation

- temperature – 150°C-200°C

Spin-exchange relaxation free regime

Dynamics of the system

Equation of motion of electron (alkali) polarization:

$$\frac{\partial \mathbf{P^e}}{\partial t} = \frac{\gamma_e}{Q(P^e)}(\mathbf{B} + \lambda M^n \mathbf{P^n} + \mathbf{L} + \mathbf{b^e}) \times \mathbf{P^e} + \mathbf{\Omega} \times \mathbf{P^e} + (R_p \mathbf{s_p} + R_{se}^{en} \mathbf{P^n} + R_m \mathbf{s_m} - R_{tot} \mathbf{P^e})/Q(P^e)$$

Polarization precession

Gyroscopic effect

Polarization relaxation/generation

Polarization-precession term:

$$(\mathbf{B} + \lambda M^n \mathbf{P^n} + \mathbf{L} + \mathbf{b^e}) \times \mathbf{P^e}$$

- $\mathbf{B}$: Magnetic field
- $\lambda M^n \mathbf{P^n}$: Magnetic-field due to polarized helium
- $\mathbf{L}$: Light shifts
- $\mathbf{b^e}$: Exotic spin coupling

Relaxation/generation term:

$$(R_p \mathbf{s_p} + R_{se}^{en} \mathbf{P^n} + R_m \mathbf{s_m} - R_{tot} \mathbf{P^e})$$

- $R_p \mathbf{s_p}$: Optical polarization
- $R_{se}^{en} \mathbf{P^n}$: SEC polarization in helium collisions
- $R_m \mathbf{s_m}$: Probe-light pumping
- $R_{tot} \mathbf{P^e}$: Polarization relaxation

Equation of motion of helium (neuron) polarization:

$$\frac{\partial \mathbf{P^n}}{\partial t} = \gamma_n(\mathbf{B} + \lambda M^e \mathbf{P^e} + \mathbf{b^n}) \times \mathbf{P^n} + \mathbf{\Omega} \times \mathbf{P^n} + R_{se}^{ne}(\mathbf{P^e} - \mathbf{P^n}) - R_{tot}^{n} \mathbf{P^n}$$

Dynamics of the system

Equations of motion:

$$\frac{\partial \mathbf{P^e}}{\partial t} = \frac{\gamma_e}{Q(P^e)}\left(\mathbf{B} + \lambda M^n \mathbf{P^n} + \mathbf{L} + \mathbf{b^e}\right) \times \mathbf{P^e} + \mathbf{\Omega} \times \mathbf{P^e} + \left(R_p \mathbf{s_p} + R_{se}^{en} \mathbf{P^n} + R_m \mathbf{s_m} - R_{tot} \mathbf{P^e}\right)/Q(P^e)$$

$$\frac{\partial \mathbf{P^n}}{\partial t} = \gamma_n\left(\mathbf{B} + \lambda M^e \mathbf{P^e} + \mathbf{b^n}\right) \times \mathbf{P^n} + \mathbf{\Omega} \times \mathbf{P^n} + R_{se}^{ne}\left(\mathbf{P^e} - \mathbf{P^n}\right) - R_{tot}^{n} \mathbf{P^n}$$

Observations:

- The ability to compensate the polarization of a given species with an external magnetic field…
- but this is possible only for one species,
- Different than magnetic coupling to hypothetical exotic field.

The ability to simulate response of the „magnetometer"

General simulation simplifications:

- Negligence of pump-light action on spin precession (no light shift) $\boldsymbol{L} = 0$
- Negligence of Earth rotation $\boldsymbol{\Omega} = 0$
- Negligence of optical pumping with probe $\boldsymbol{s_m} = 0$

Dynamics of the system - Pumping

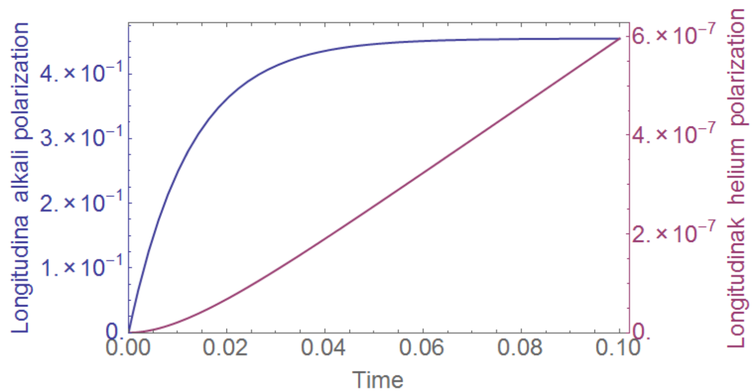
Simulation parameters:

- Large optical pumping rate
- Relaxation rate of alkali polarization
- Relaxation rate of helium polarization
- No magnetic field

$$R_p = 180\ 1/s$$
$$R_{tot} = 400\ 1/s$$
$$R^n_{tot} = 10^{-3}\ 1/s$$
$$\boldsymbol{B} = 0$$

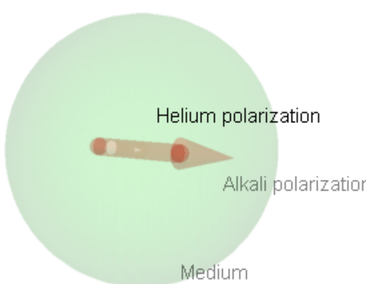
Short time scale

t=0.

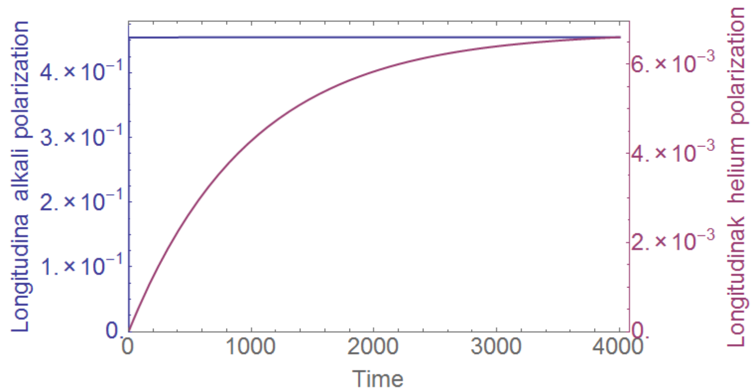


Optical pumping

Long time scale



t=10



SEC pumping

Dynamics of the system – Transverse field

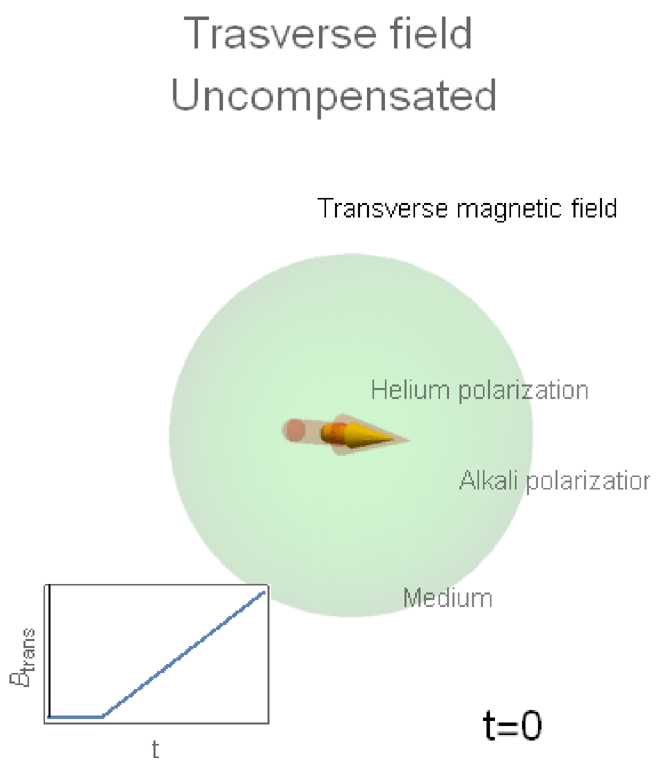
Simulation parameters:

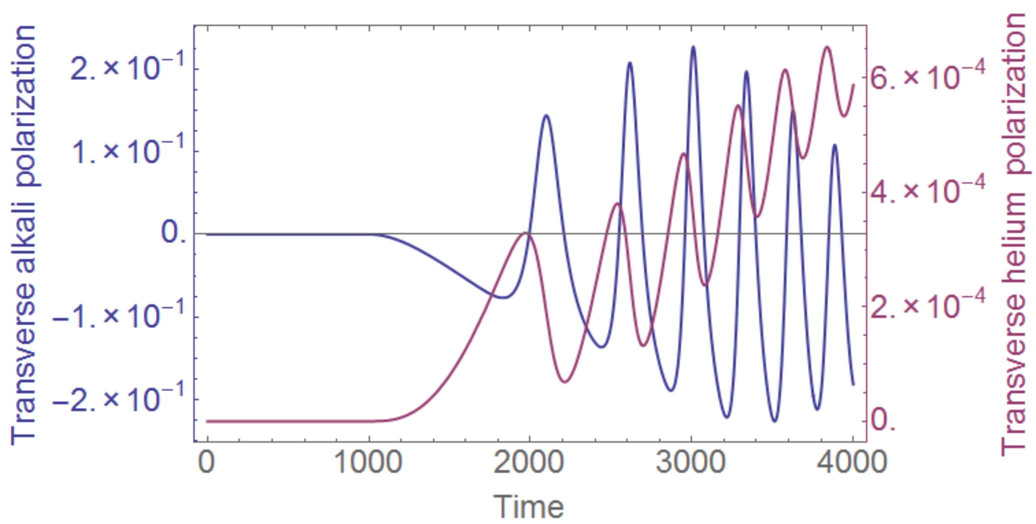
- Old parameters
- Varying magnetic field

$$R_p = 180\ 1/s \quad R_{tot} = 400\ 1/s \quad R_{tot}^n = 10^{-3}\ 1/s$$

$$B = \begin{cases} 0, & 0 \text{ for } t \le \frac{t_f}{4} \\ \frac{B_{comp}}{100}\left(t - \frac{t_f}{4}\right) \text{ for } t \le \frac{t_f}{4}, 0 \end{cases}$$

Uncompensated field





Transverse magnetic field causes rotation of both polarization

Dynamics of the system – Transverse field

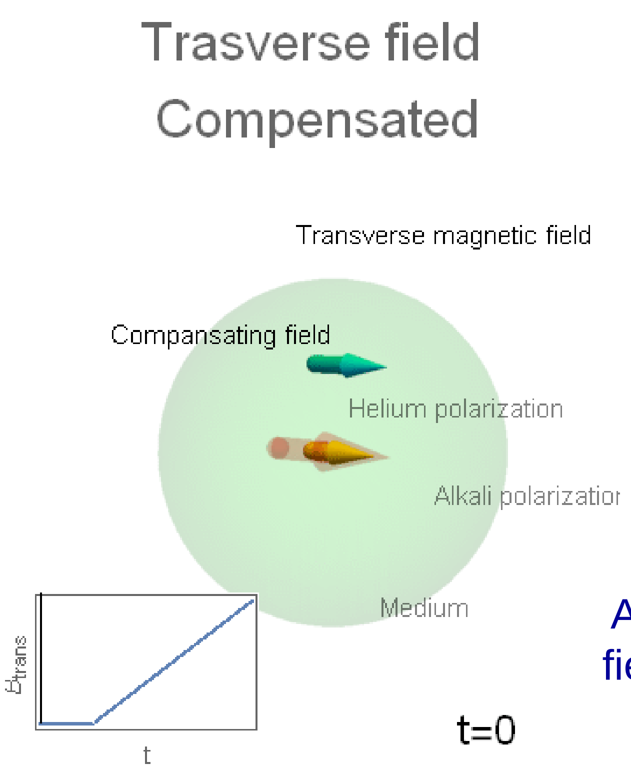
Simulation parameters:

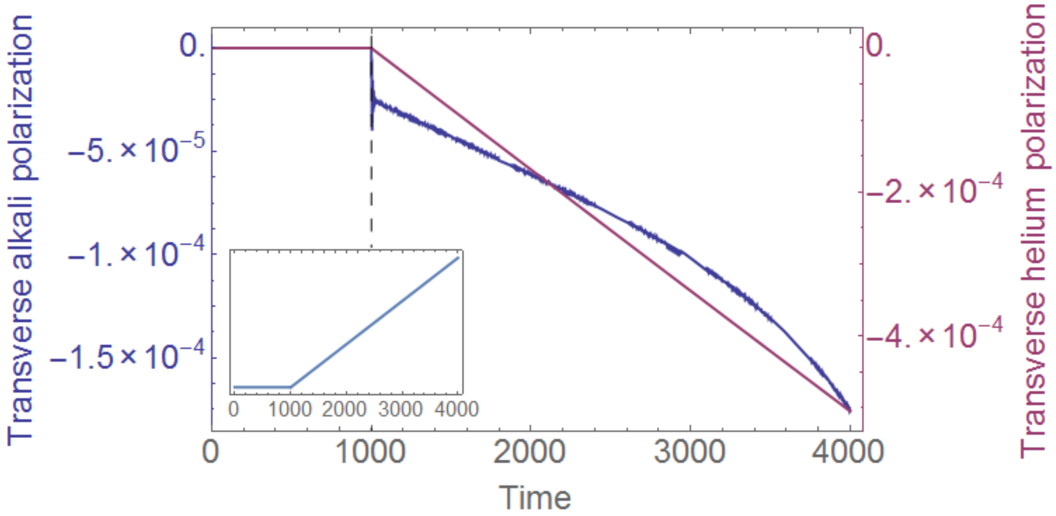
- Old parameters
- Varying magnetic field

$$R_p = 180\ 1/s \quad R_{tot} = 400\ 1/s \quad R_{tot}^n = 10^{-3}\ 1/s$$

$$B = \left\{ 0, \begin{matrix} 0 \text{ for } t \le \frac{t_f}{4} \\ \frac{B_{comp}}{100}\left(t - \frac{t_f}{4}\right) \text{ for } t \le \frac{t_f}{4} \end{matrix}, B_{comp} \right\}$$

Magnetic field compensating helium magnetization





Application of a magnetic field compensating helium magnetization

1000-fold decrease of alkali response

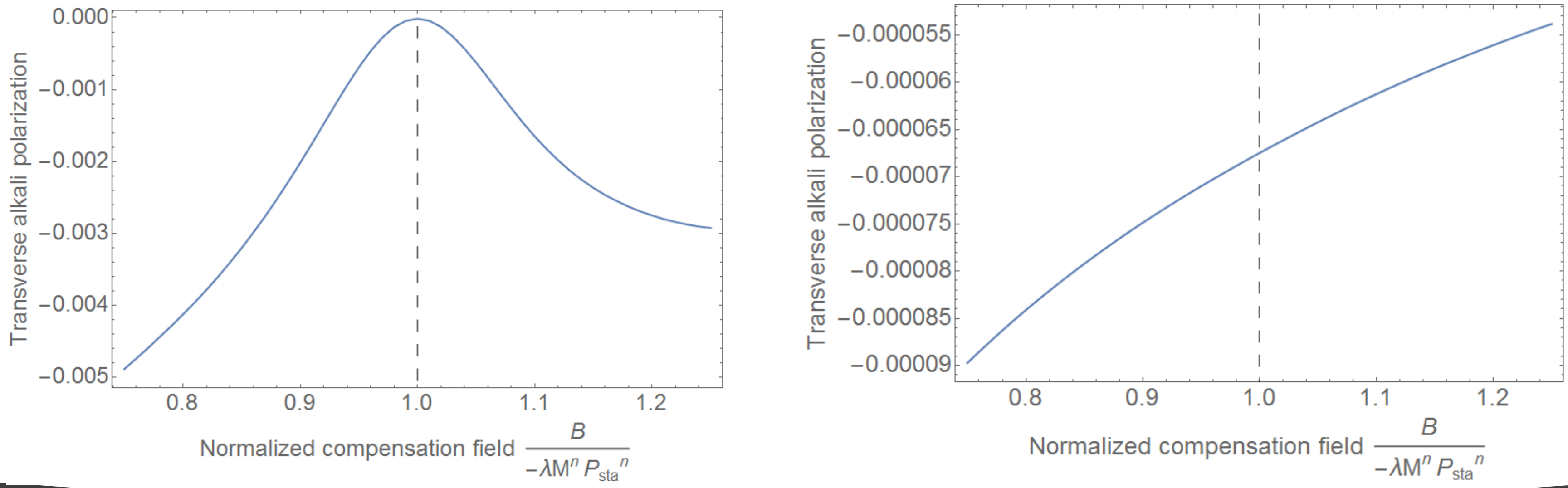
Dynamics of the system – Transverse field

Alkali polarization dynamics

$$\frac{\partial \mathbf{P^e}}{\partial t} = \frac{\gamma_e}{Q(P^e)}(\mathbf{B} + \lambda M^n \mathbf{P^n} + \mathbf{L} + \mathbf{b^e}) \times \mathbf{P^e} + \mathbf{\Omega} \times \mathbf{P^e} + (R_p \mathbf{s_p} + R_{se}^{en} \mathbf{P^n} + R_m \mathbf{s_m} - R_{tot} \mathbf{P^e})/Q(P^e)$$

How good the compensation have to be?

Alkali polarization dynamics



Remarks:

- The efficiency of self-compensation depends strongly on the compensation field,
- The compensation field depends on the actual experimental parameters.

Dynamics of the system – Transverse exotic

Alkali polarization dynamics

$$\frac{\partial \mathbf{P^e}}{\partial t} = \frac{\gamma_e}{Q(P^e)}\left(\mathbf{B} + \lambda M^n \mathbf{P^n} + \mathbf{L} + \mathbf{b^e}\right) \times \mathbf{P^e} + \mathbf{\Omega} \times \mathbf{P^e} + \left(R_p \mathbf{s_p} + R_{se}^{en}\mathbf{P^n} + R_m \mathbf{s_m} - R_{tot}\mathbf{P^e}\right)/Q(P^e)$$

Zeroed

Nonzero exotic coupling to electrons

Simulation parameters:

- Old parameters $R_p = 180\ 1/s \quad R_{tot} = 400\ 1/s \quad R_{tot}^n = 10^{-3}\ 1/s \quad \boldsymbol{B} = \{0,0,B_{comp}\}$
- Electron exotic-field coupling

$$b^e = \left\{0,0, \begin{matrix} 0\ for\ t < \frac{t_f}{8} \\ \frac{B_{comp}}{100}\left(t - \frac{t_f}{8}\right) for\ t > t_f/8 \end{matrix}\right\}$$

Helium dynamics

$$\frac{\partial \mathbf{P^n}}{\partial t} = \gamma_n\left(\mathbf{B} + \lambda M^e \mathbf{P^e} + \mathbf{b^n}\right) \times \mathbf{P^n} + \mathbf{\Omega} \times \mathbf{P^n} + R_{se}^{ne}\left(\mathbf{P^e} - \mathbf{P^n}\right) - R_{tot}^n \mathbf{P^n}$$

Nonzero

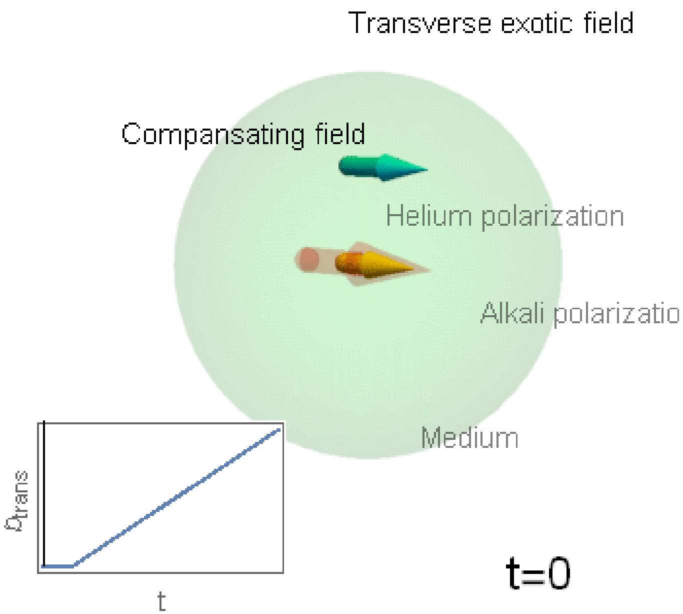
Zero exotic coupling to neutrons

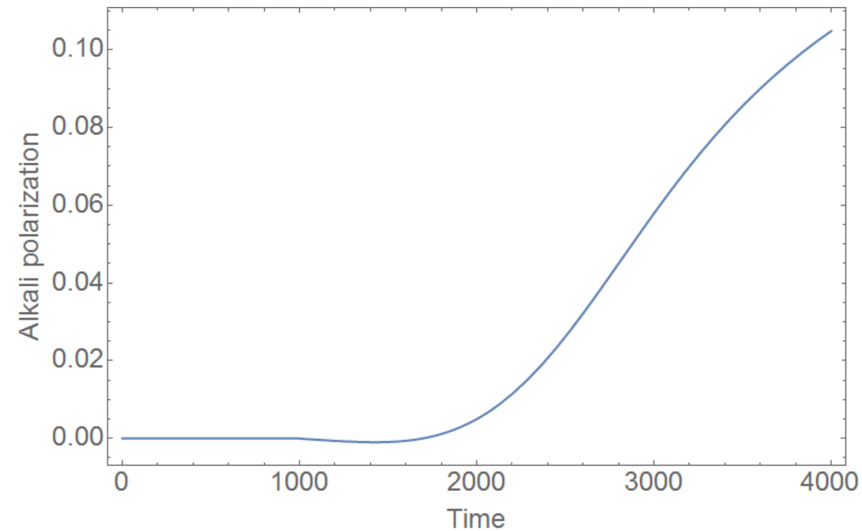
Simulation parameters:

- No neutron spin coupling $\quad b^n = \{0,0,0\}$

Dynamics of the system – Transverse exotic

Transverse exotic field

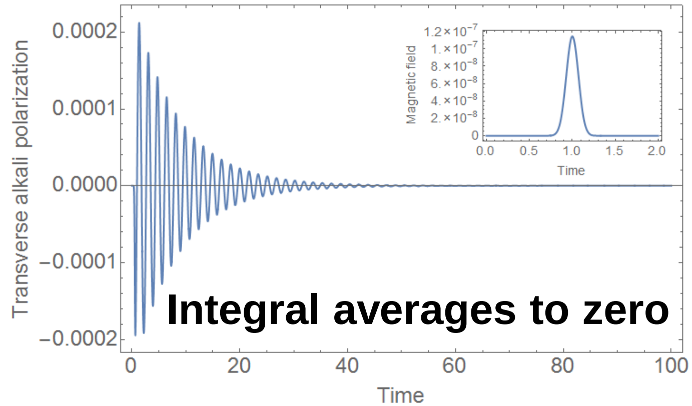


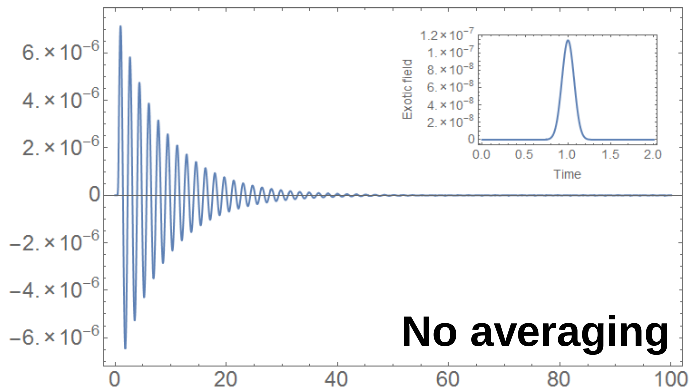


Transverse exotic fields are not compansated

Dynamics of the system – Pulsed response

Response to the pulse





Pulse causes reorientation of the spins

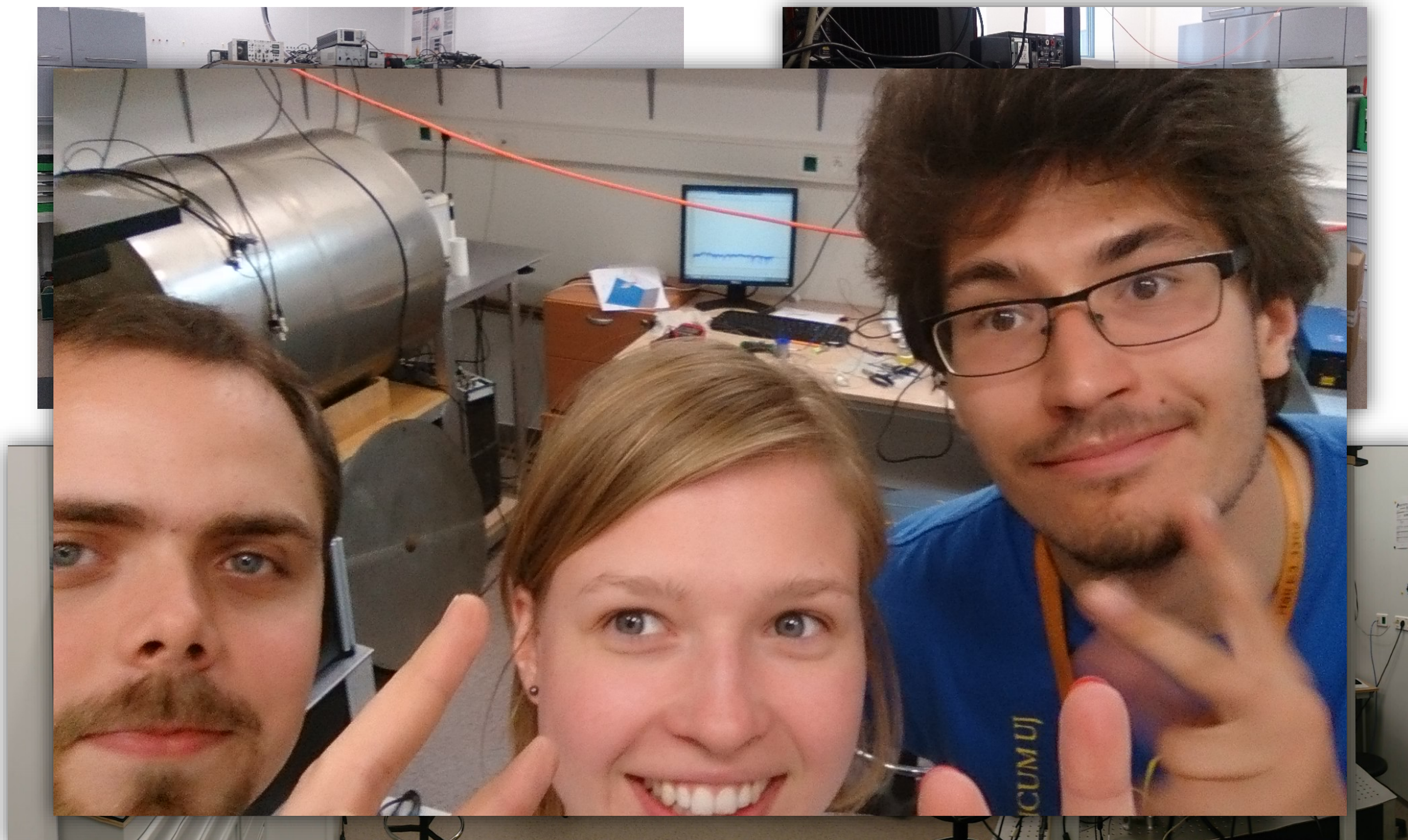
Ringing in the transverse polarization

The ability to shield magnetic fields and to be sensitive to transverse signal

Shy isn’t the system ready?

Six months later…

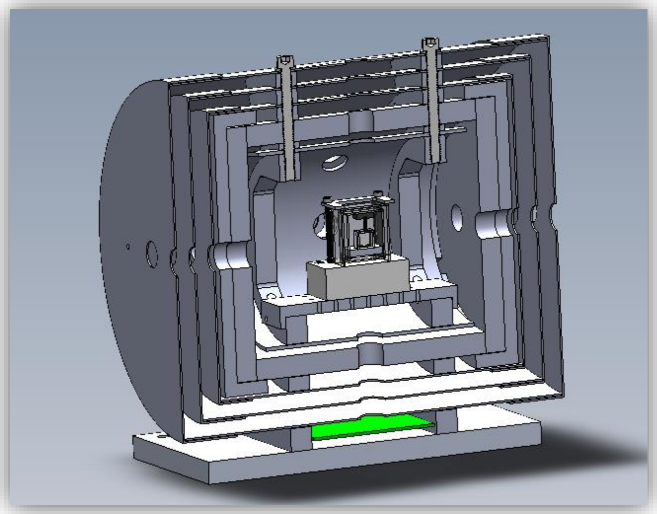
Shy isn't the system ready?



We are ready…

Construction of the GNOME station

Kraków station status update

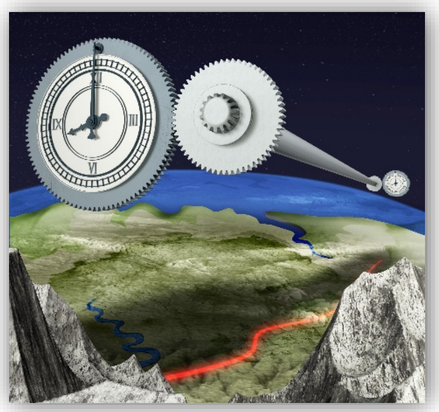


Experiment is under construction

Global time synchronization

Techniques of time synchronization

- Internet time servers (NTP, PTP, etc.)
- Radio-broadcast clock time
- Fiber systems
- Satellite
  - **GPS,**
  - Geostationary satellites
  - TWSTFT



Pros & Cons

Cheap $\delta t > 10\ \mathrm{ms}$

Uncontrollable fluctuations of propagation time

Limited reception range

$\delta t \sim 1\ \mathrm{ms}$

Absolutely highest precision

$\delta t < 1\ \mathrm{ps}$

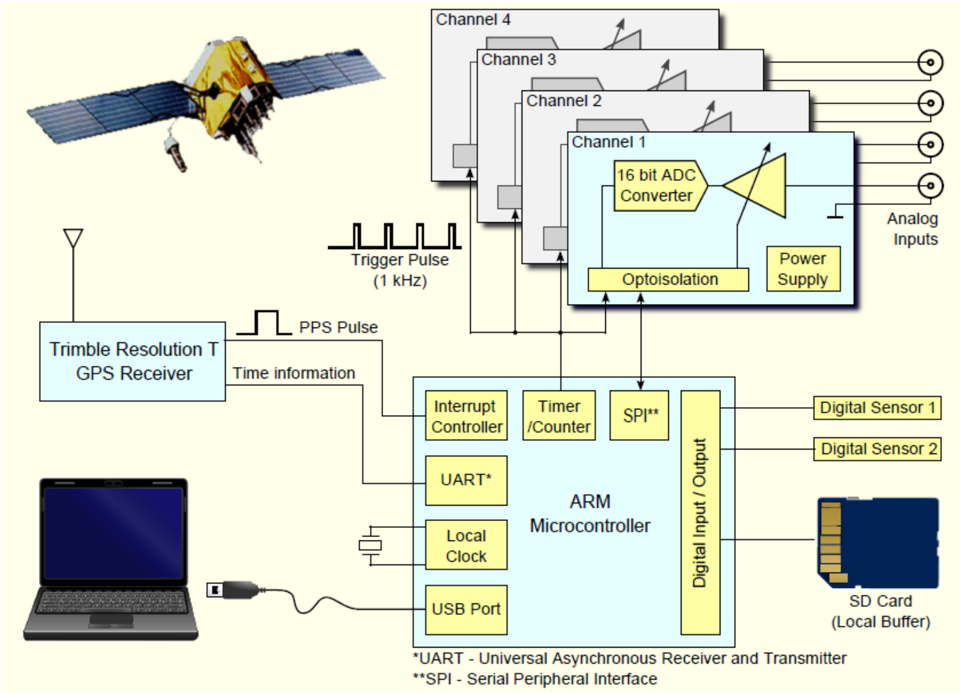
Limited applicability

$\delta t < 100\ \mathrm{ns}$

Global available

Requires construction of dedicated equipment

Global time synchronization



System parameters:

- 4 analog channels
  - Time precision: <1 μs
  - Sampling rate: 1 – 1000 S/s
  - Resolution: 16 bits
  - Input ranges: ±1.25 V, ±2.5 V, ±5 V, ±10 V
- Additional sensors (50 S/s)
  - Temperature
  - Magnetic field (GMR)
- Communication:
  - USB
  - Internal memory (20 h data)

GPS data logger

DMTechnologies

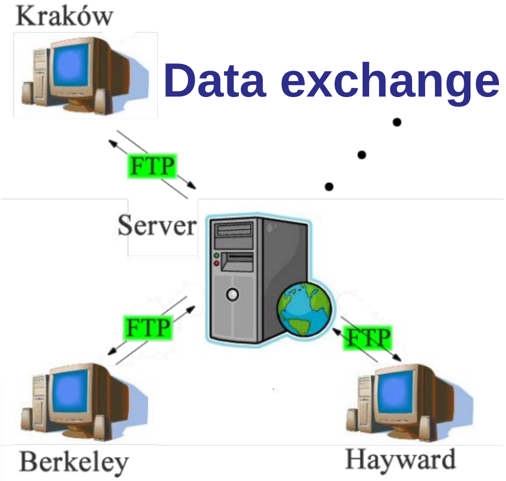
Global time synchronization

GNOME crucial ingredients

Sensitive OMAGs

Global timing

Data exchange



Automatic data exchange

Data analysis

The ability to compare different devices and identify signals

Outlook for future GNOME collaboration

Core collaboration:

- D. Budker (Mainz, Germany/Berkeley, USA)
- D. F. Jackson Kimball (California State University – East Bay, USA)
- S. Pustelny (Jagiellonian University, Poland)

People who expressed interest:

- M. Romalis (Princeton, USA),
- Z.-T. Lu (Hefei, China),
- P. Firlinger (University Cluster – Munchen, Germany),
- Y. Semertzidis (Institute for Basic Science, Korea)
- S. Rangwala (Raman Research Institute, India)
- B. Heckel (U. Seattle, USA)
- M. Larsen (Northrop Grumman, USA)
- I. Novikova (William and Mary Collage, USA)
- J. Stalnaker (Oberlin Collage, USA),
- R. Folman (Ben-Gurion University, Israel)

Other ideas:

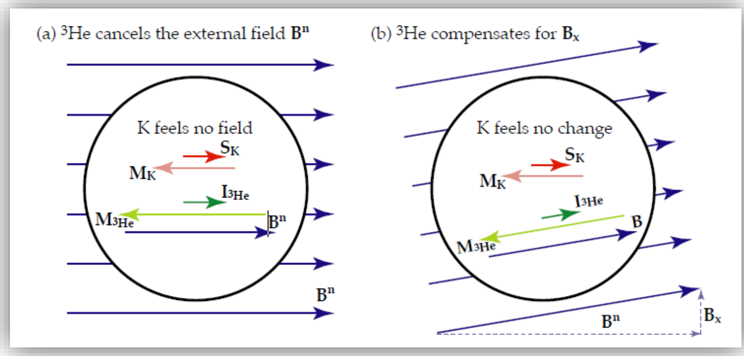
- A. Derevianko (U. Nevada, USA)
- M. Pospelov (Perimiter Institute, Canada)

Clocks

- H. Muller (Berkeley, USA)
- P. Hamilton (Los Angeles, USA)

Atomic interferometers

Outlook

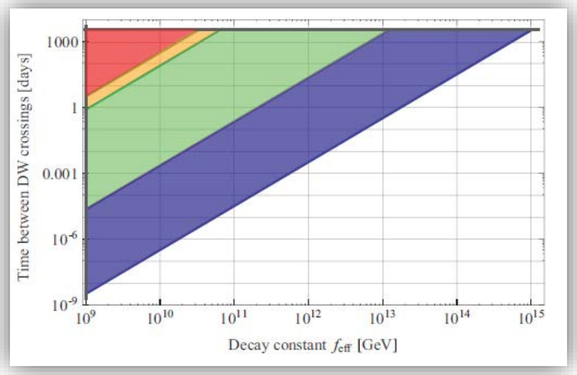


Development of the GNOME

System optimization

Development of data processing techniques

Development of data exchange protocols



Identification of theoretical problems that can be address with the GNOME

Acknowledgements









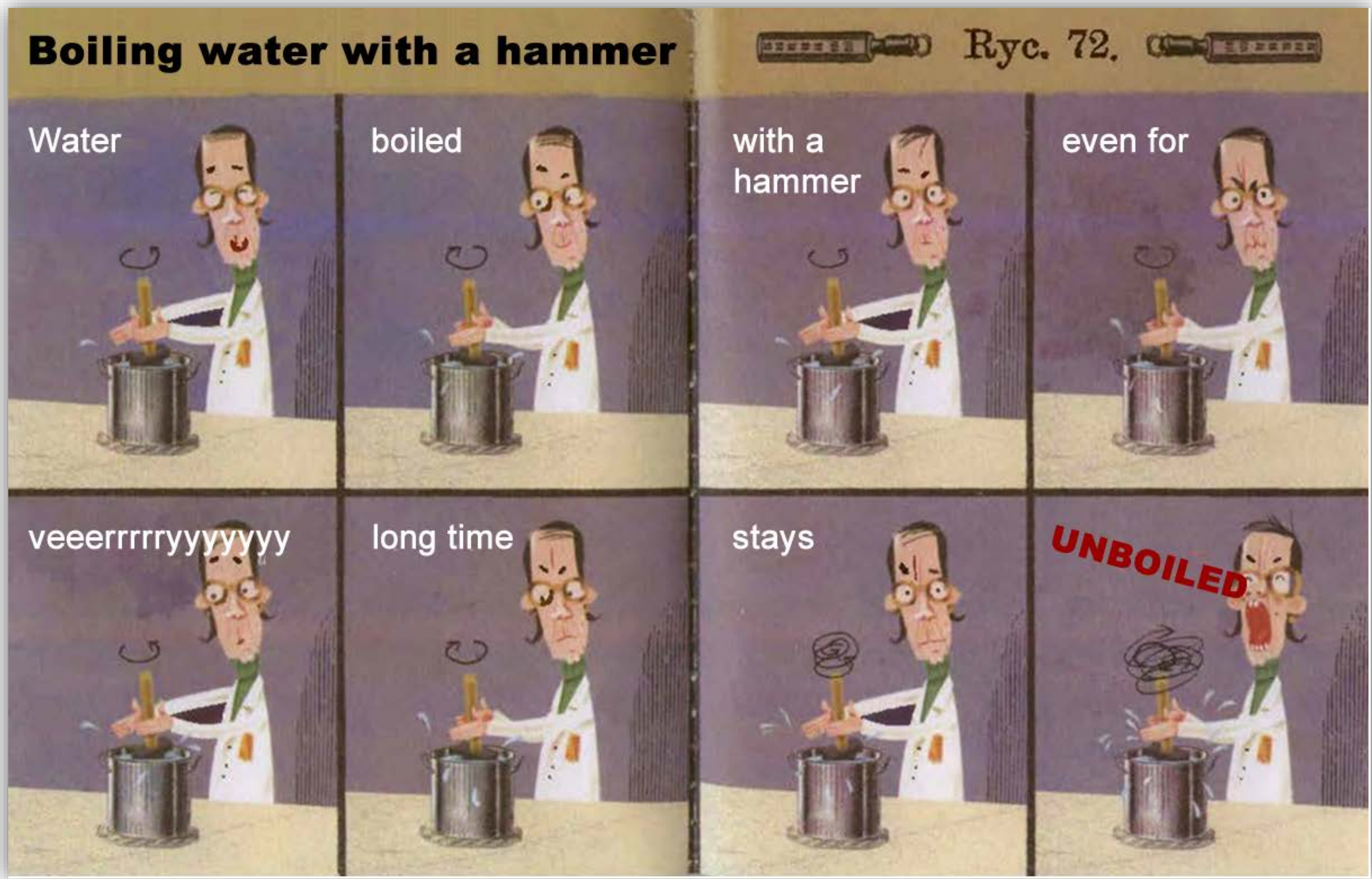


Ministry
of Science
and Higher
Education
Republic of Poland

NSF

The National Centre
for Research and Development

What the community things about us?



Even if it is true… **IT MAY STILL BE VERY INTERESTING**