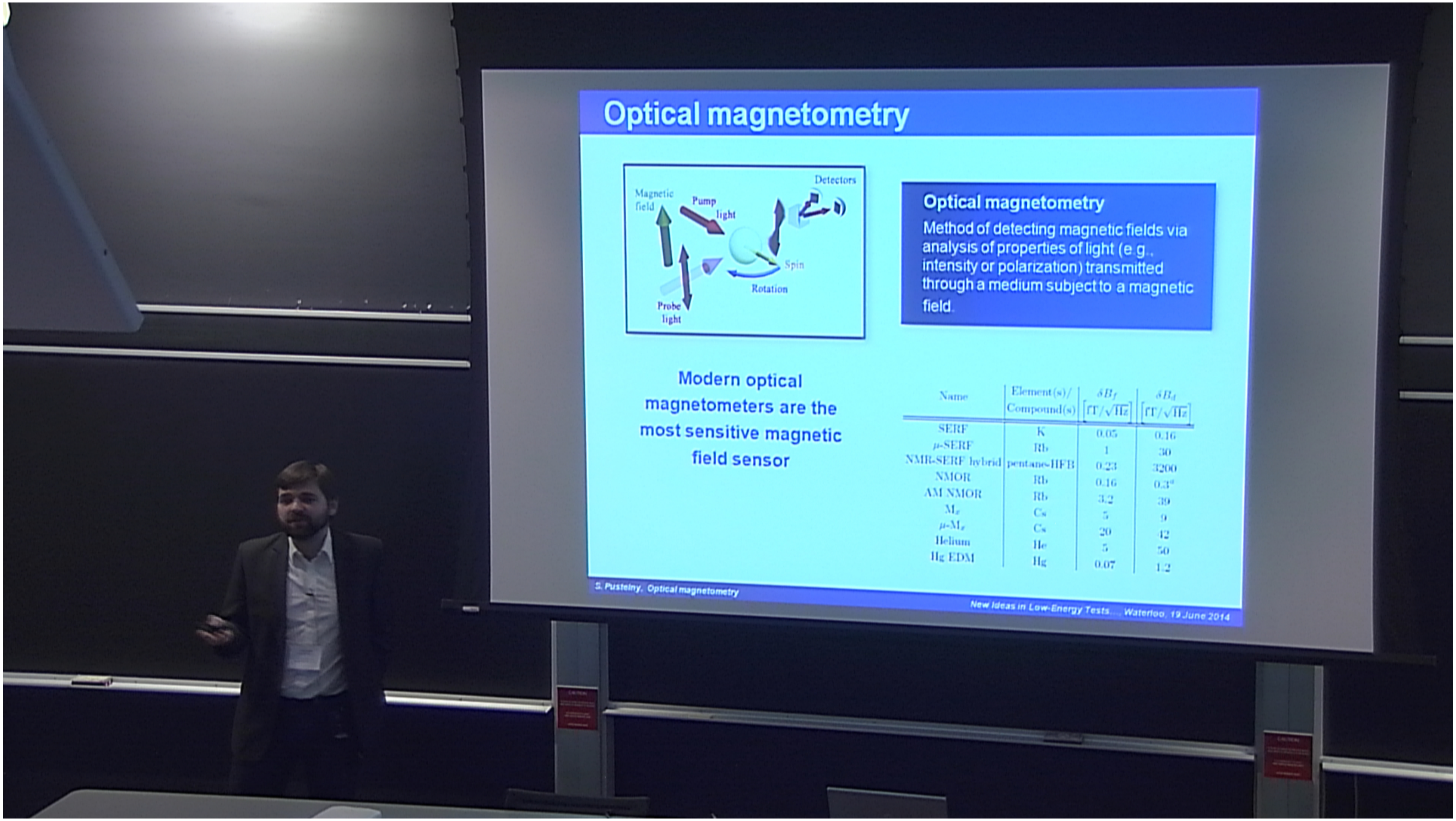
Title: Optical magnetometry - From basics to Global Network of Optical Magnetometer for Exotic physics

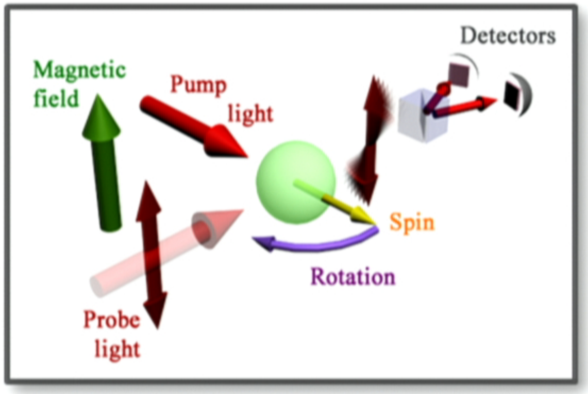
Date: Jun 19, 2014 09:00 AM

URL: http://pirsa.org/14060032

Abstract: In our talk we seek to present a broad overview of the field of optical magnetometers, starting from basic principles to fundamental limitations to the variety of applications in which they have already found use. We will end with a report on the development of a new worldwide network of synchronized magnetometers that can be used to search for a variety of new physical phenomena (many of which are discussed at this conference!).


Optical magnetometry
Magnetic field
Pump light
Detectors
Spin
Rotation
Probe light
Optical magnetometry
Method of detecting magnetic fields via analysis of properties of light (e.g., intensity or polarization) transmitted through a medium subject to a magnetic field.
Modern optical magnetometers are the most sensitive magnetic field sensor
Name | Element(s)/Compound(s) | δB_f [fT/√Hz] | δB_d [fT/√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
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
S. Pustelny, Optical magnetometry
New Ideas in Low-Energy Tests..., Waterloo, 19 June 2014

Optical magnetometry



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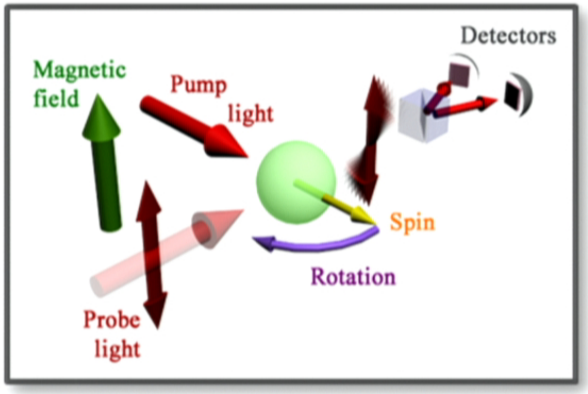
μ-SERF	Rb	1	30
NMR-SERF hybrid	pentane-HFB	0.23	3200
NMOR	Rb	0.16	0.3[a]
AM NMOR	Rb	3.2	39
M_x	Cs	5	9
μ-M_x	Cs	20	42
Helium	He	5	50
Hg EDM	Hg	0.07	1.2

Optical magnetometry



Optical magnetometry

Method of detecting magnetic fields via analysis of properties of light (e.g., intensity or polarization) transmitted through a medium subject to a magnetic field.

How do they work?

mos

What are they good for?

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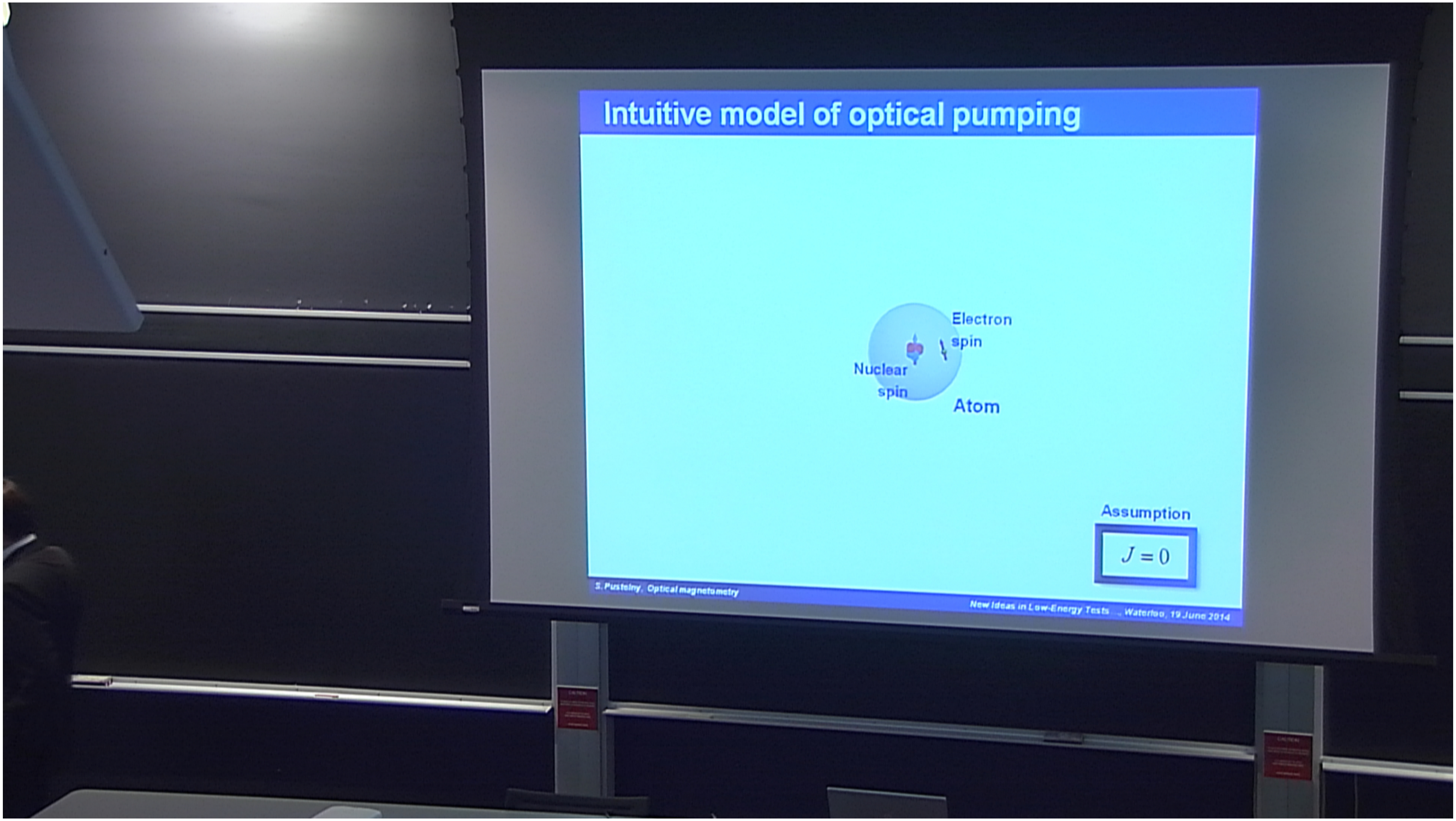
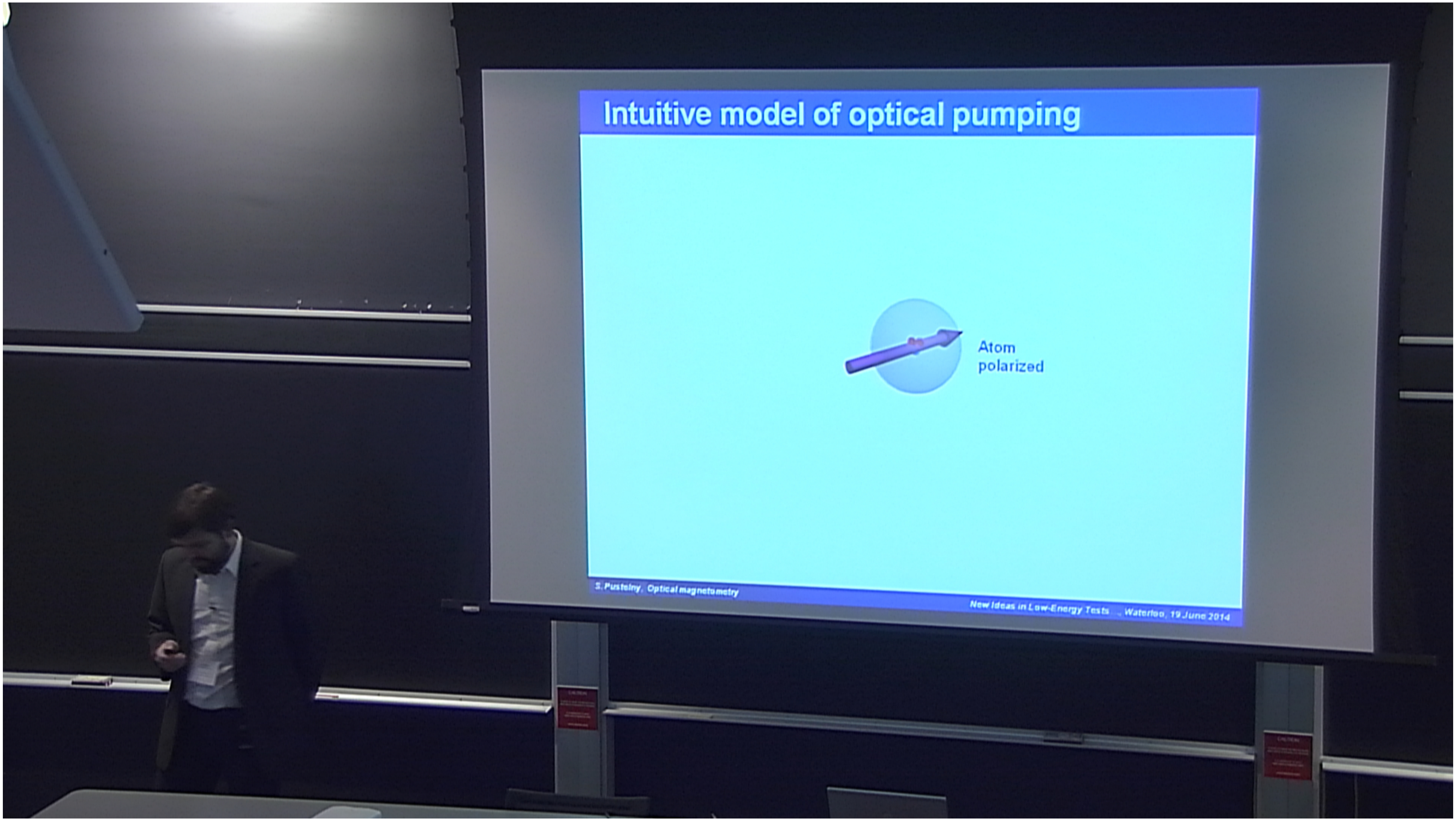
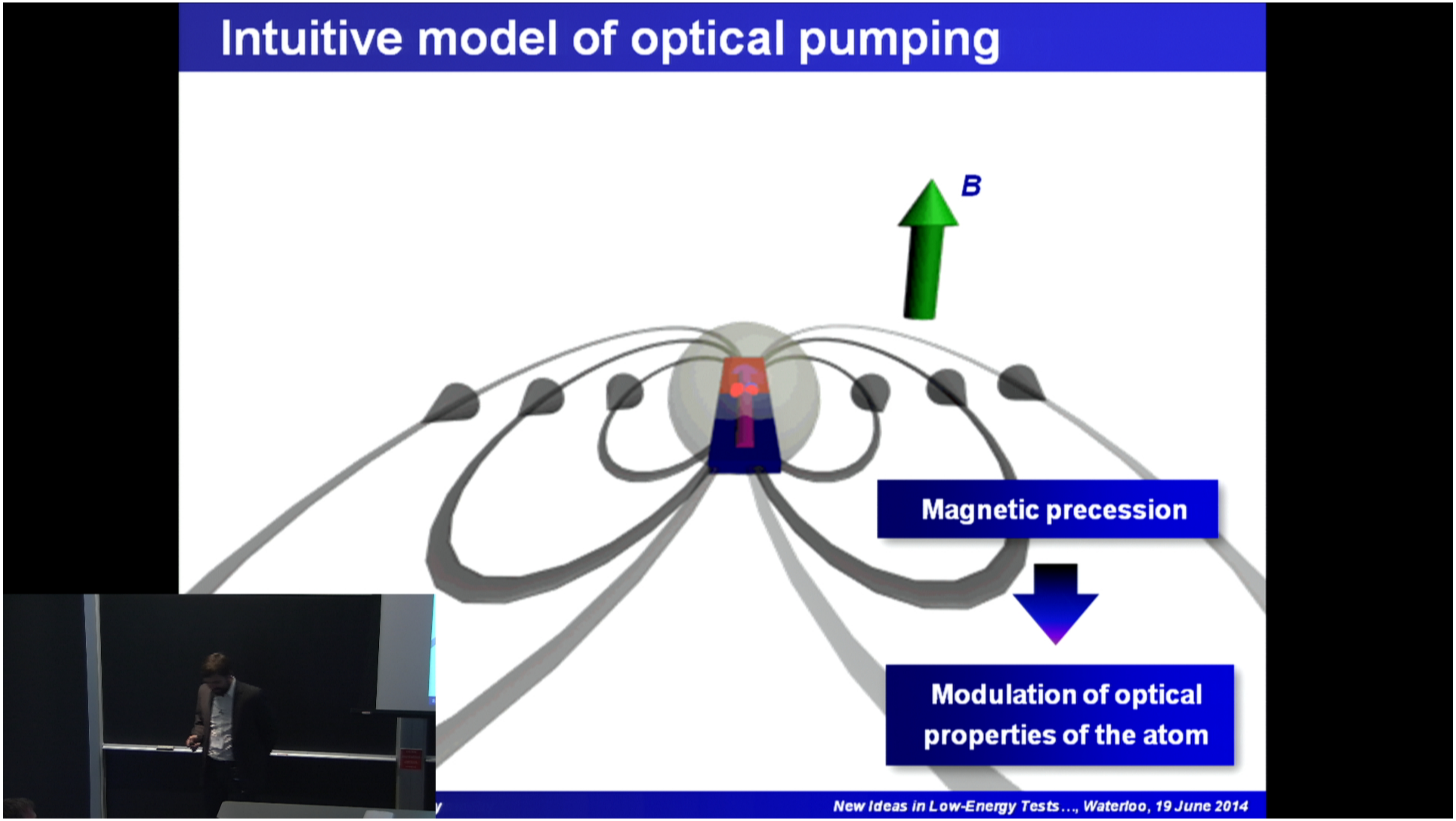
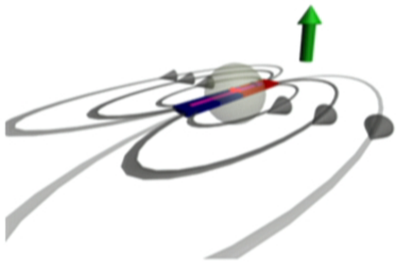

Intuitive model of optical pumping
Electron
spin
Nuclear
spin
Atom
Assumption
$J = 0$
S. Pustelny, Optical magnetometry
New Ideas in Low-Energy Tests ..., Waterloo, 19 June 2014


Intuitive model of optical pumping
Atom
polarized
S. Pustelny, Optical magnetometry
New Ideas in Low-Energy Tests ..., Waterloo, 19 June 2014

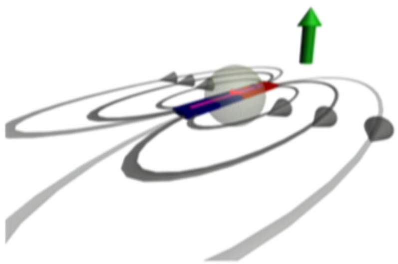

Intuitive model of optical pumping
B
Magnetic precession
Modulation of optical properties of the atom
New Ideas in Low-Energy Tests..., Waterloo, 19 June 2014

General observations



Evolution of the optical properties of the atom is determined by the spin-magnetic field coupling

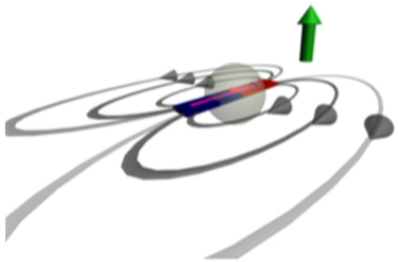
General observations



Evolution of the optical properties of the atom is determined by the spin-magnetic field coupling

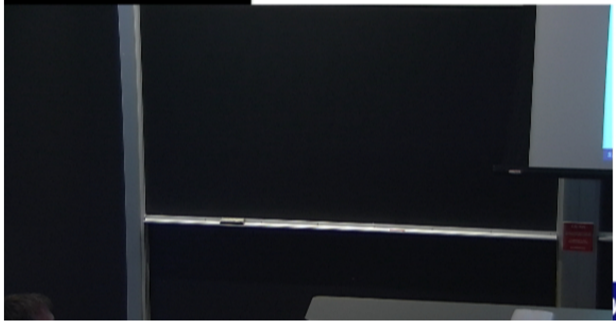
Simple, „pictorial” representation

General observations



Evolution of the optical properties of the atom is determined by the spin-magnetic field coupling

Simple, „pictorial" representation → Real media consists of more than 10^9 atoms



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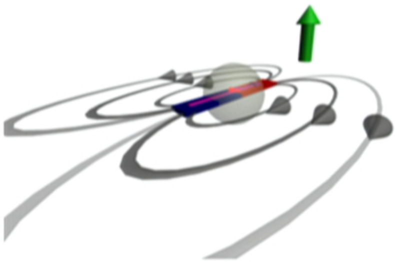

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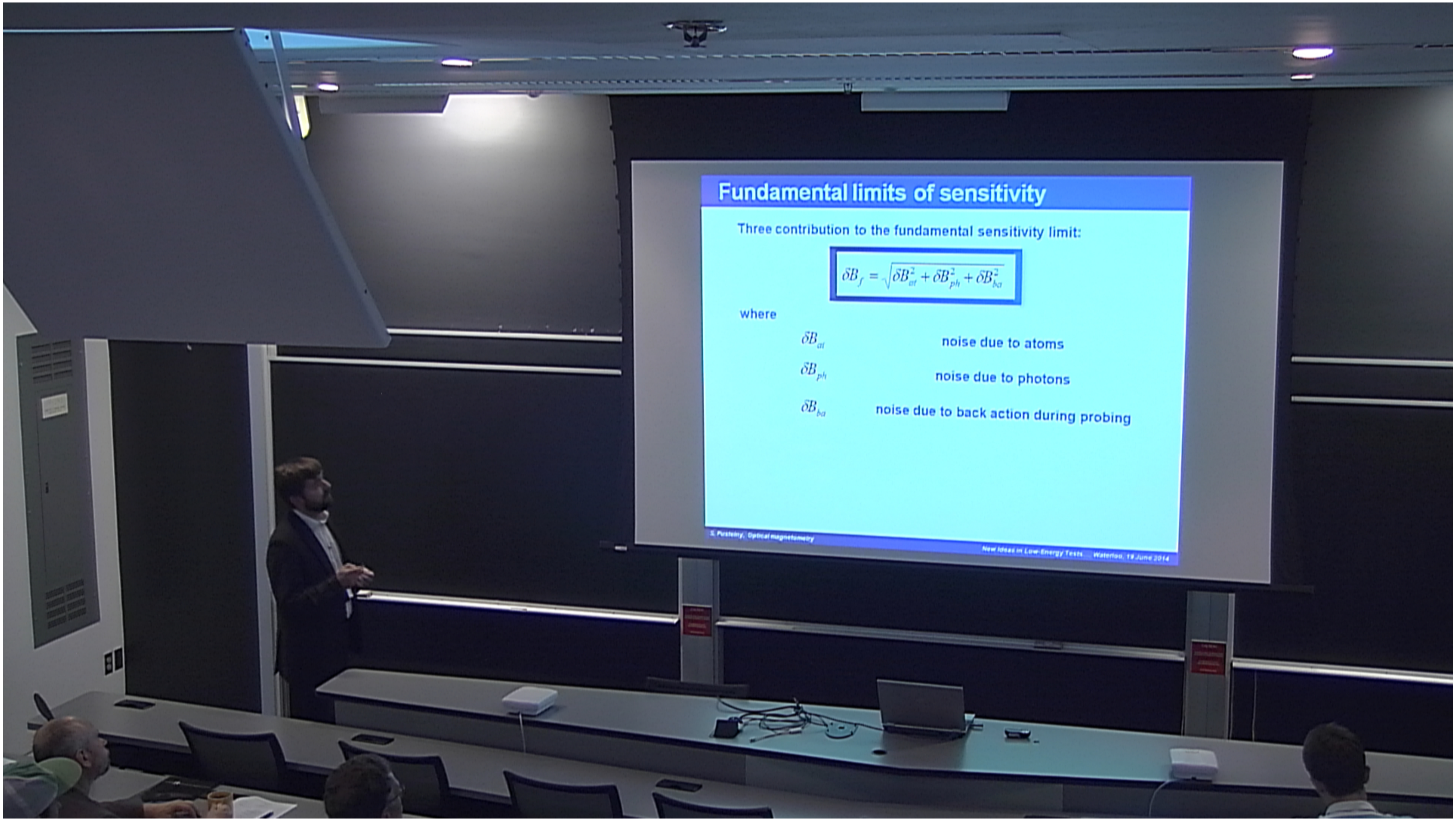
Sensitivity determined by the ability to determine orientation or precession frequency of spins


Fundamental limits of sensitivity
Three contribution to the fundamental sensitivity limit:
$\delta B_f = \sqrt{\delta B_{at}^2 + \delta B_{ph}^2 + \delta B_{ba}^2}$
where
δB_{at} noise due to atoms
δB_{ph} noise due to photons
δB_{ba} noise due to back action during probing

Photon shot-noise limit

Photon contribution

Photon shot noise

Fluctuation in the number of photons due to their Poissonian statistics

New Ideas in Low-Energy Tests…, Waterloo, 19 June 2014

Photon shot-noise limit

Photon contribution

Photon shot noise

Fluctuation in the number of photons due to their Poissonian statistics

Optical properties of light (e.g., intensity, polarization state) can be determined with the finite precission

Limit on the determination of the spin orientation

N_{ph} – the number of probing photons

Signal

$$S \propto N_{ph}$$

Noise

$$\delta B_{ph} \propto \sqrt{N_{ph}}$$


Back-action limit
Back-action contribution
ac Stark shift
Electric field of light can modify the precession of spins via ac Stark effect
S. Pustelny, Optical magnetometry
New Ideas in Low-Energy Tests ... Waterloo, 19 June 2014

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Photon shot noise

Fluctuation in photon number

Uncertainty in determination of spin precession

ac Stark shift

$$\Delta E_{St} \propto N_{ph}$$

Back-action limit

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$$\Delta E_{St} \propto N_{ph}$$

Back-action limit

$$\delta B_{ba} \propto \sqrt{N_{ph}}$$

Operation at weak probe-light power

Atomic projection-noise limit

Atomic contribution

Spin projection noise

$$\delta F_i^2 \delta F_j^2 \geq \frac{\hbar^2 \langle F_k \rangle^2}{4}$$

F_i – the spatial component of the total angular momentum F in i-th direction,
<F> - the mean (macroscopic) value of spin projection

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Equation (1)

$$\delta B_{at} = \frac{\hbar}{g\mu_B}\sqrt{\frac{1}{N_{at} t \tau}}$$

N_{at} – the number of spins, t – time of measure, τ – the transverse spin polarization lifetime

g – the Lande factor, $\hbar$ - the Planck constant, μ_B – the Bohr magneton

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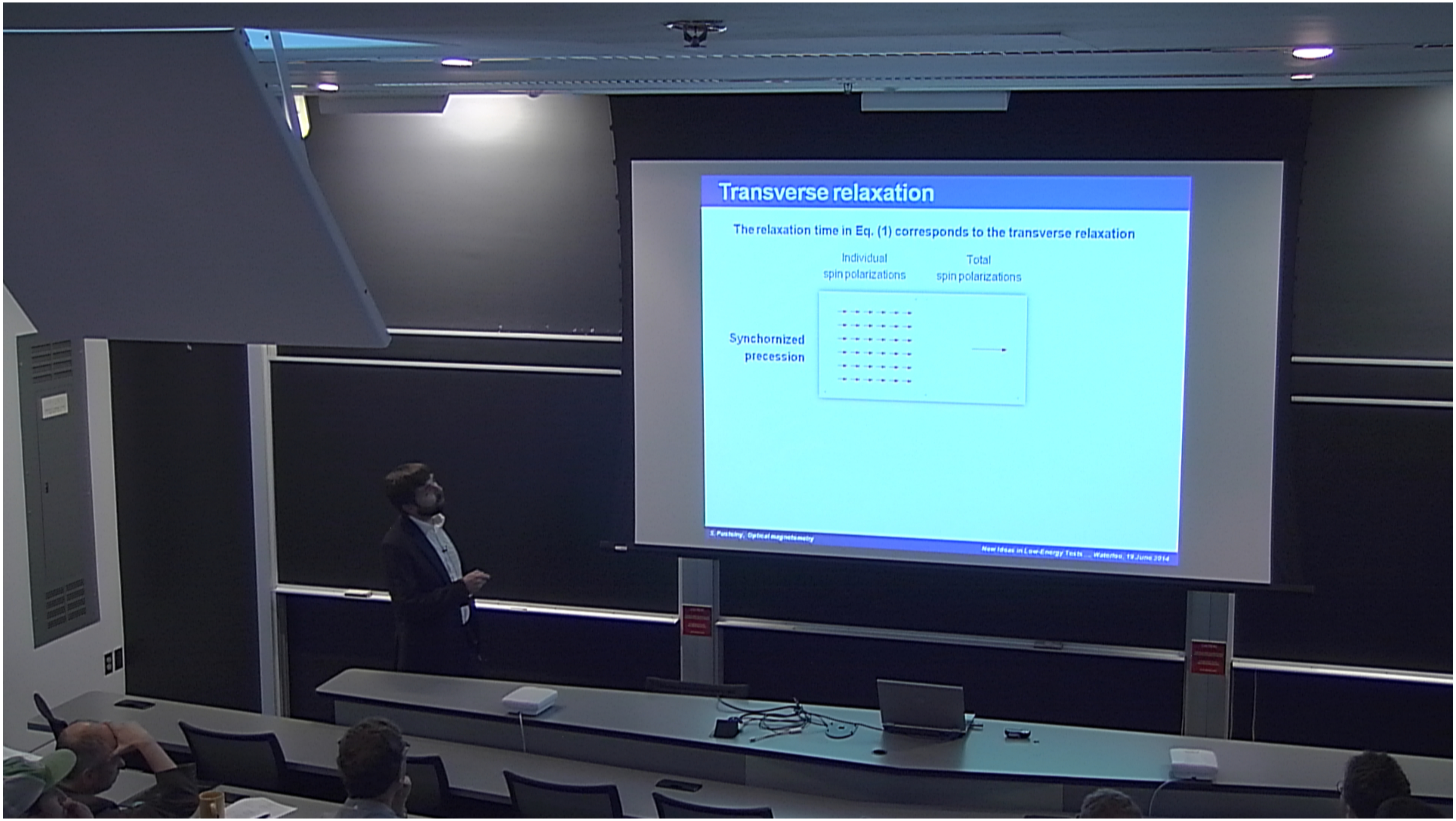
Means of reducing atomic projection-noise limit:

- prolonging a measurement,


Transverse relaxation
The relaxation time in Eq. (1) corresponds to the transverse relaxation
Individual
spin polarizations
Total
spin polarizations
Synchornized
precession
S. Pustelny, Optical magnetometry
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Transverse relaxation

Sources of transverse relaxation:

- inhomogeneity/local fields:
  - **magnetic field (Zeeman effect),**
  - **electric field (ac/dc Stark effect).**

Solid states (dense media) typically possess very short transeverse (coherence) relaxation lifetimes

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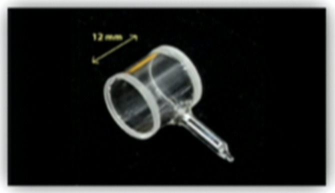
Dilute gases are great candidates for magneto-optical media



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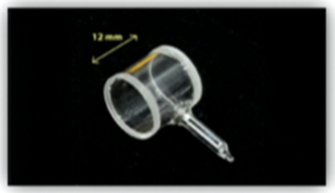

Properties of alkali-metal vapor:

- concentration of **10^9-10^{10}** atoms /cm^3 at room temperature,

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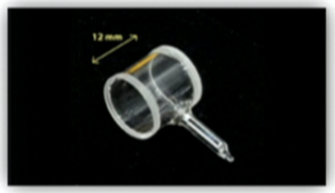
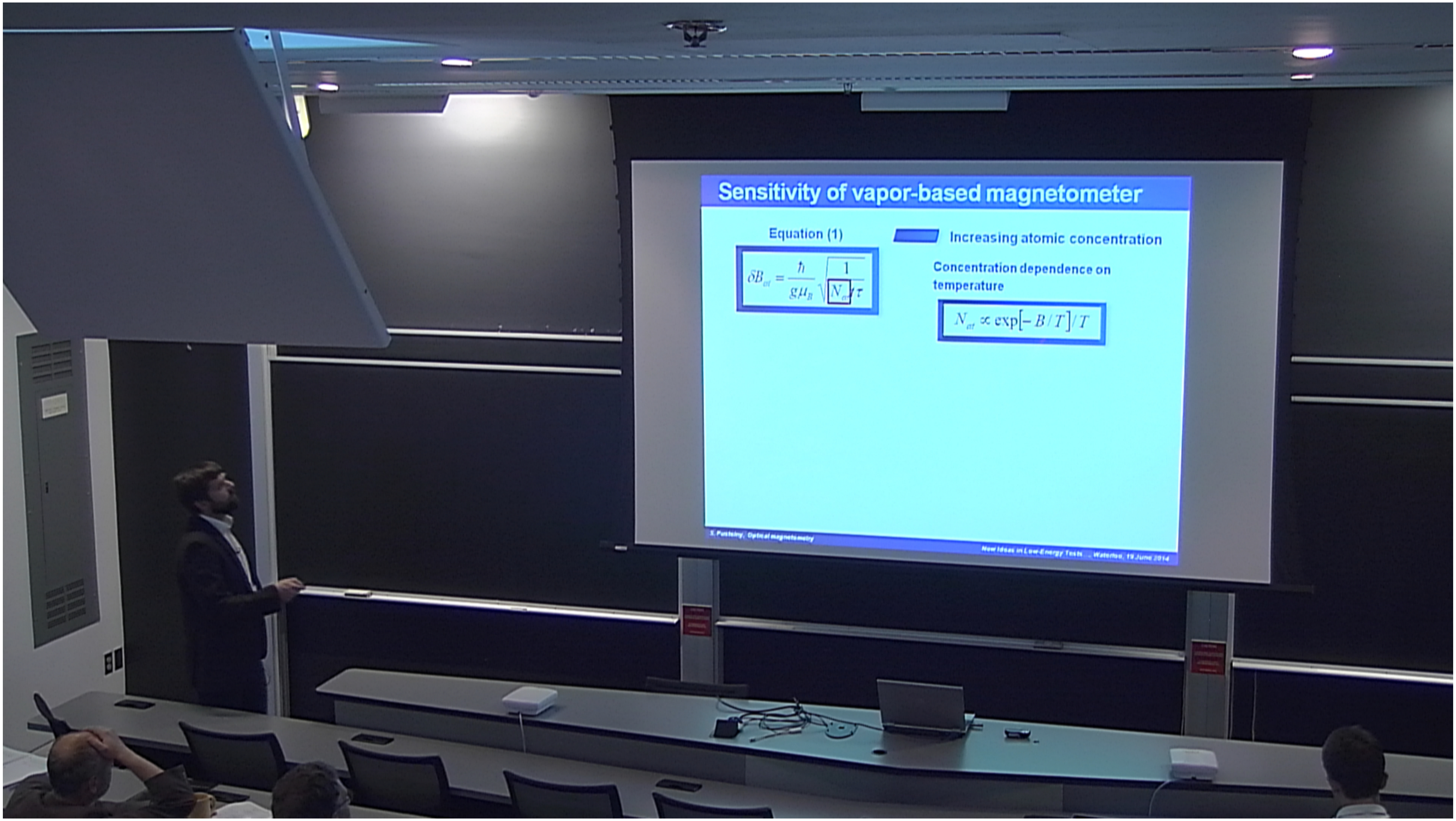
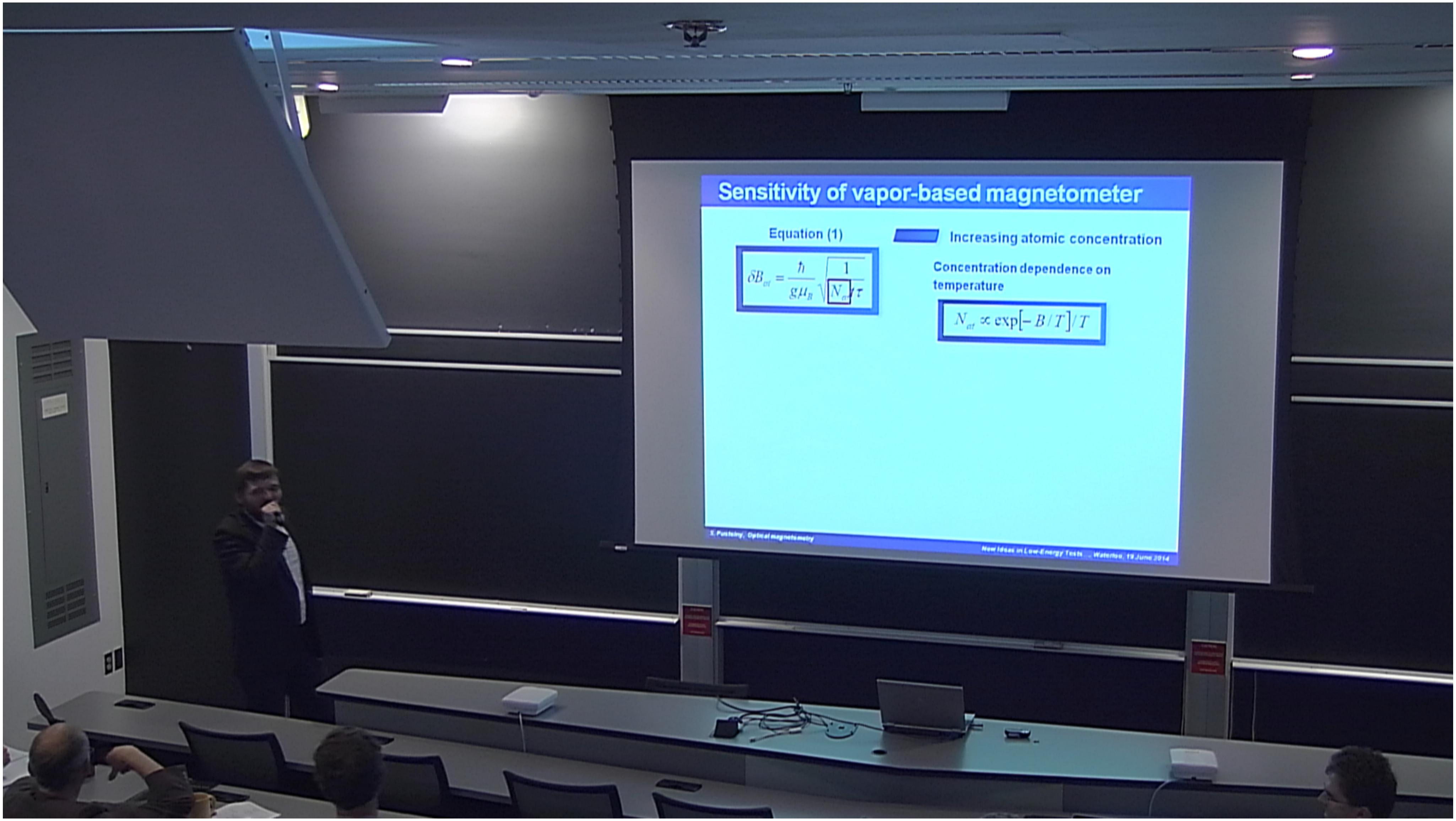


Properties of alkali-metal vapor:

- concentration of **10^9-10^{10}** atoms /cm^3 at room temperature,
- vapor pressure of **10^{-6}-10^{-5} Torr** at room temperature,

Mean free path ~100 m


Sensitivity of vapor-based magnetometer
Equation (1)
$\delta B_{at} = \frac{\hbar}{g\mu_B}\sqrt{\frac{1}{N_{at}\tau}}$
Increasing atomic concentration
Concentration dependence on temperature
$N_{at} \propto \exp[-B/T]/T$



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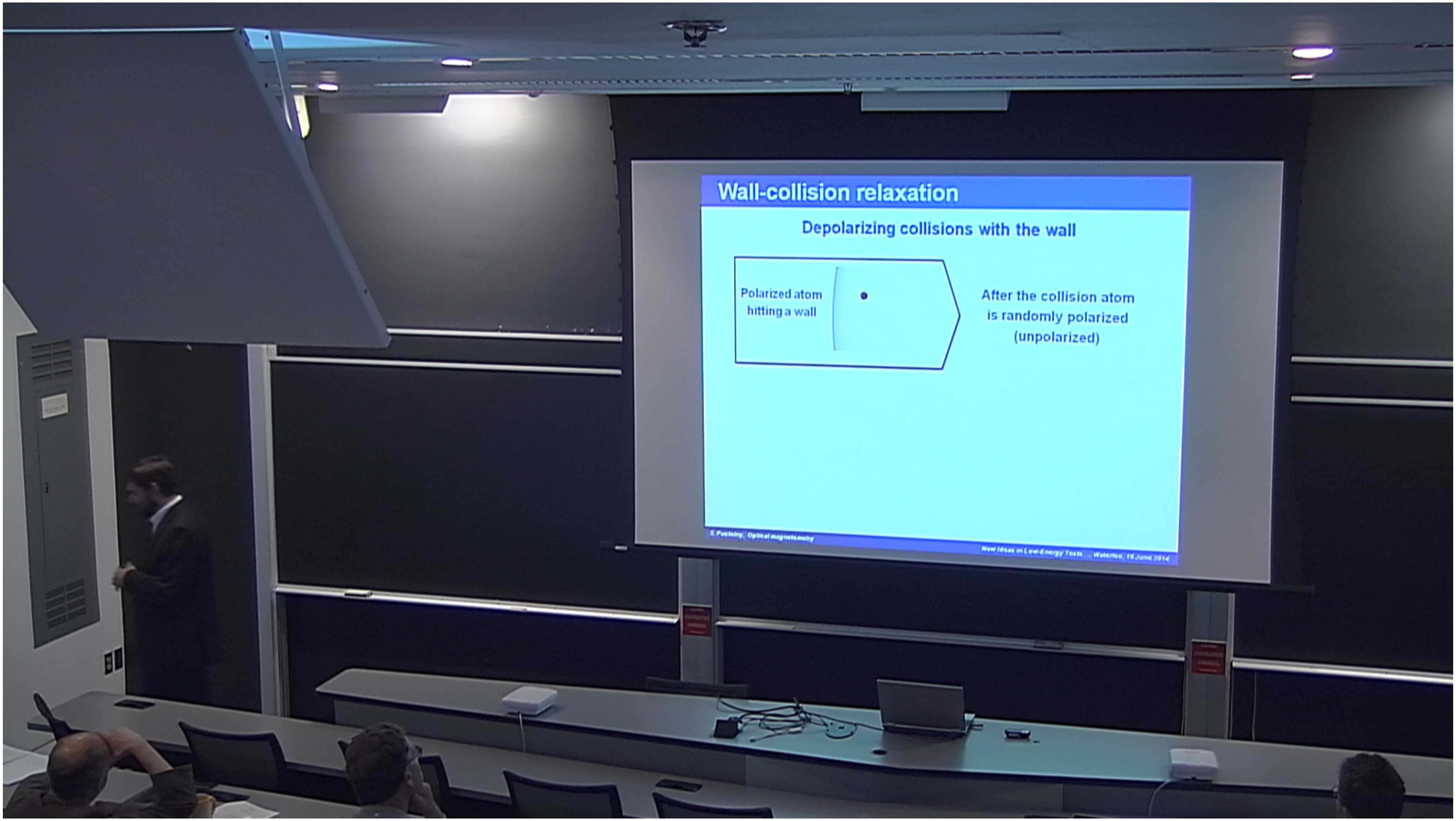
Wall-collision relaxation

Depolarizing collisions with the wall

Polarized atom
hitting a wall


Wall-collision relaxation
Depolarizing collisions with the wall
Polarized atom
hitting a wall
After the collision atom
is randomly polarized
(unpolarized)
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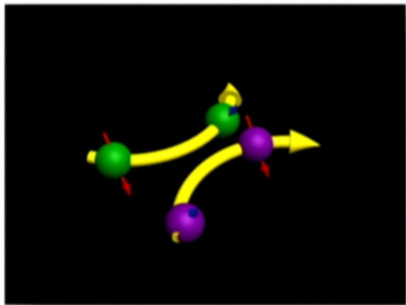
Spin-exchange relaxation

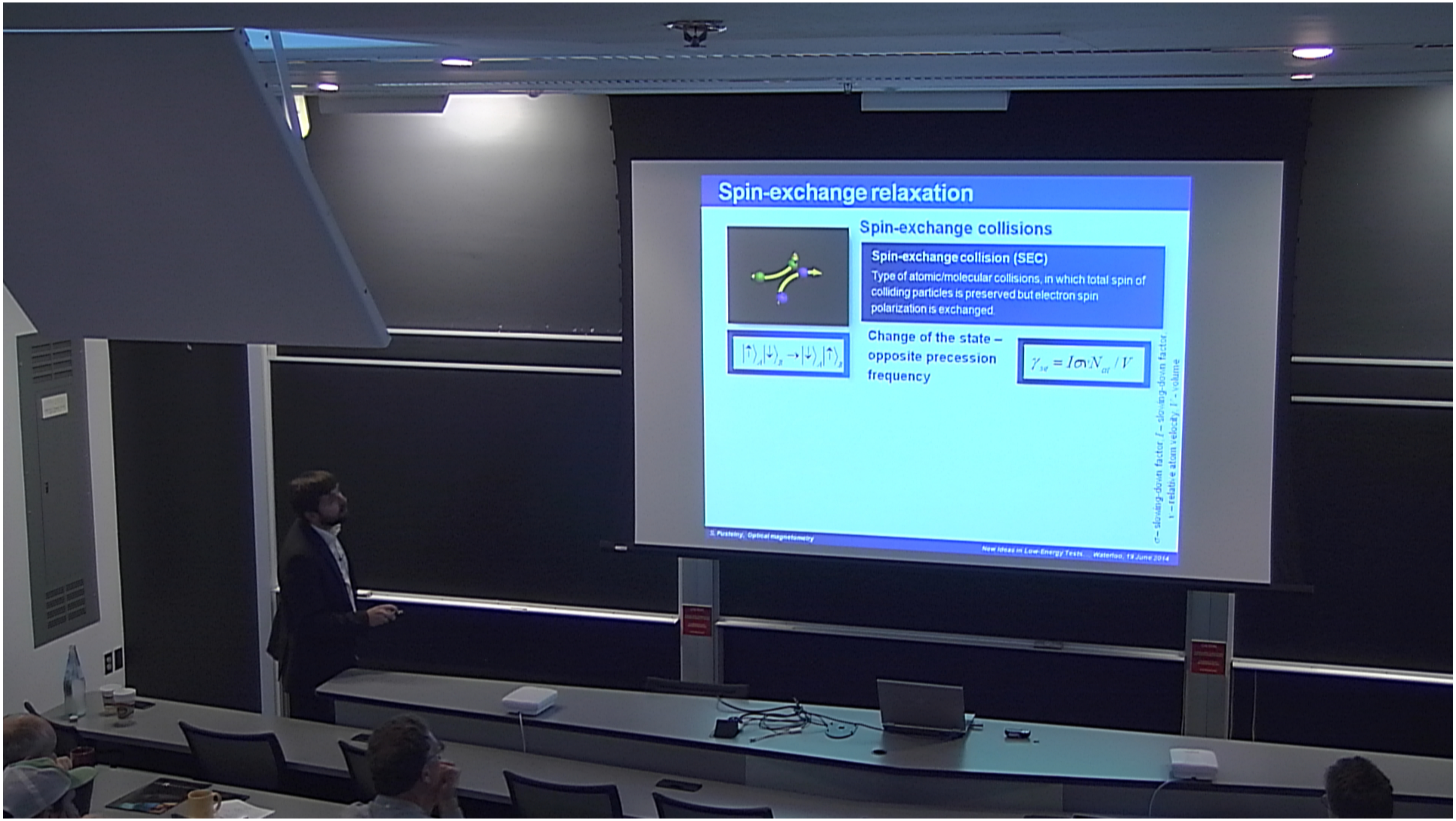


$$|\uparrow\rangle_A|\downarrow\rangle_B \rightarrow |\downarrow\rangle_A|\uparrow\rangle_B$$

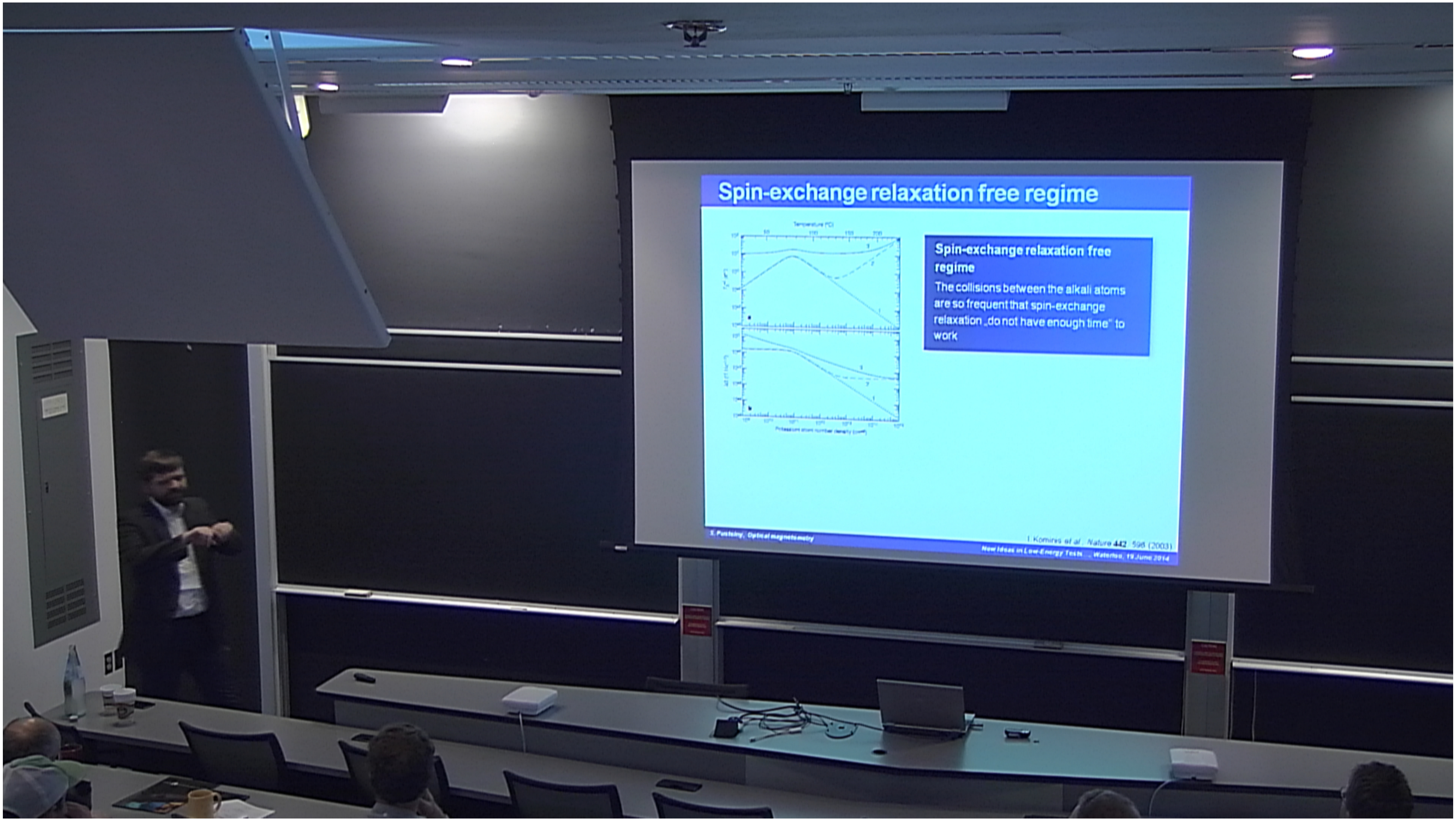
Spin-exchange collisions

Spin-exchange collision (SEC)

Type of atomic/molecular collisions, in which total spin of colliding particles is preserved but electron spin polarization is exchanged.



Spin-exchange relaxation
Spin-exchange collisions
Spin-exchange collision (SEC)
Type of atomic/molecular collisions, in which total spin of colliding particles is preserved but electron spin polarization is exchanged.
$|\uparrow\rangle_A|\downarrow\rangle_B \rightarrow |\downarrow\rangle_A|\uparrow\rangle_B$
Change of the state – opposite precession frequency
$\gamma_{se} = I\sigma v N_{at} / V$
σ – slowing-down factor, I – slowing-down factor, v – relative atom velocity, V – volume
S. Pustelny, Optical magnetometry
New ideas in Low-Energy Tests... Waterloo, 18 June 2014



Spin-exchange relaxation free regime
Spin-exchange relaxation free regime
The collisions between the alkali atoms are so frequent that spin-exchange relaxation „do not have enough time" to work
I. Komiros et al., Nature 442, 596 (2003)
S. Pustelny, Optical magnetometry
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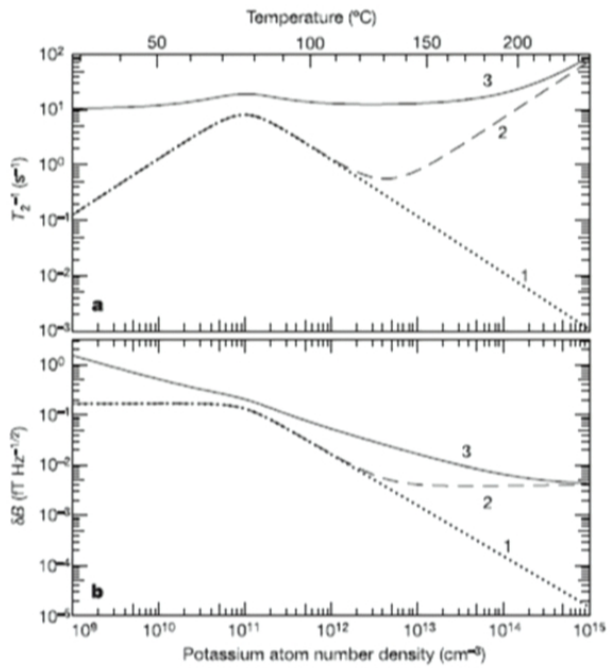
Spin-exchange relaxation free regime



Spin-exchange relaxation free regime

The collisions between the alkali atoms are so frequent that spin-exchange relaxation „do not have enough time" to work

Slow relaxation at high concentration

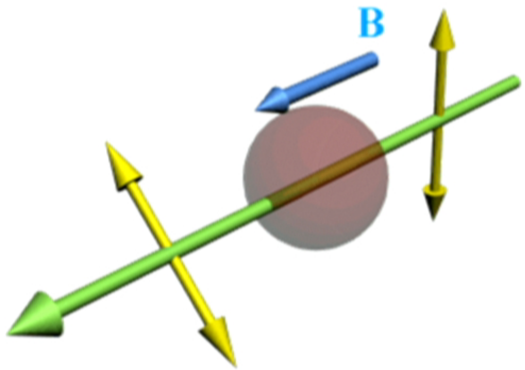
$$\delta B_d = 1.6\times10^{-16}\ \mathrm{T/Hz^{1/2}}$$

H. Dang *et al.*, *Appl. Phys. Lett.* **97**, 151110 (2010).

I. Kominis *et al.*, *Nature* **442**, 596 (2003).

Nonlinear magneto-optical rotation

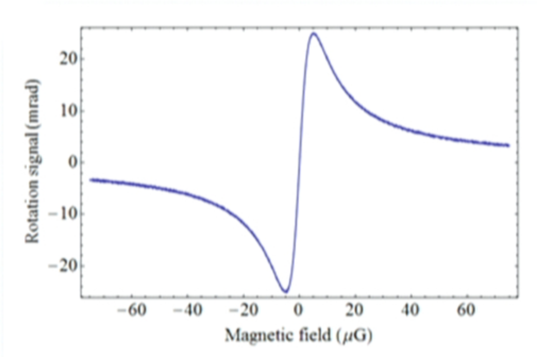
Nonlinear magneto-optical rotation



Nonlinear magneto–optical rotation (NMOR)

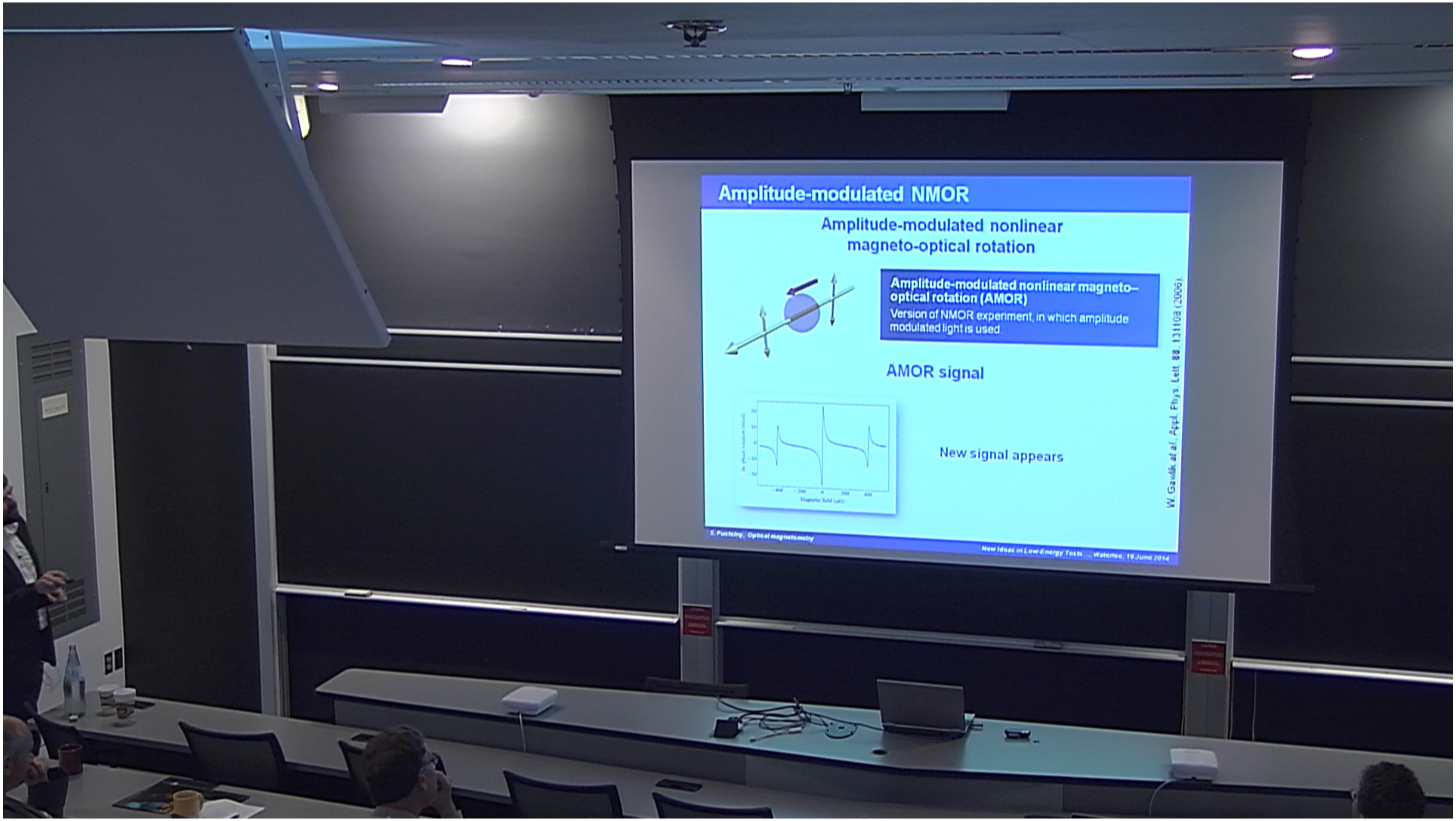
Light-intensity dependent rotation of polarization plane of linearly polarized light upon its propagation through a medium subjected to the magnetic field.

NMOR signal



Linear part in the center enabling magnetic field measurements


Amplitude-modulated NMOR
Amplitude-modulated nonlinear magneto-optical rotation
Amplitude-modulated nonlinear magneto–optical rotation (AMOR)
Version of NMOR experiment, in which amplitude modulated light is used
W. Gawlik at al. Appl. Phys. Lett. 88, 131108 (2006).


Amplitude-modulated NMOR
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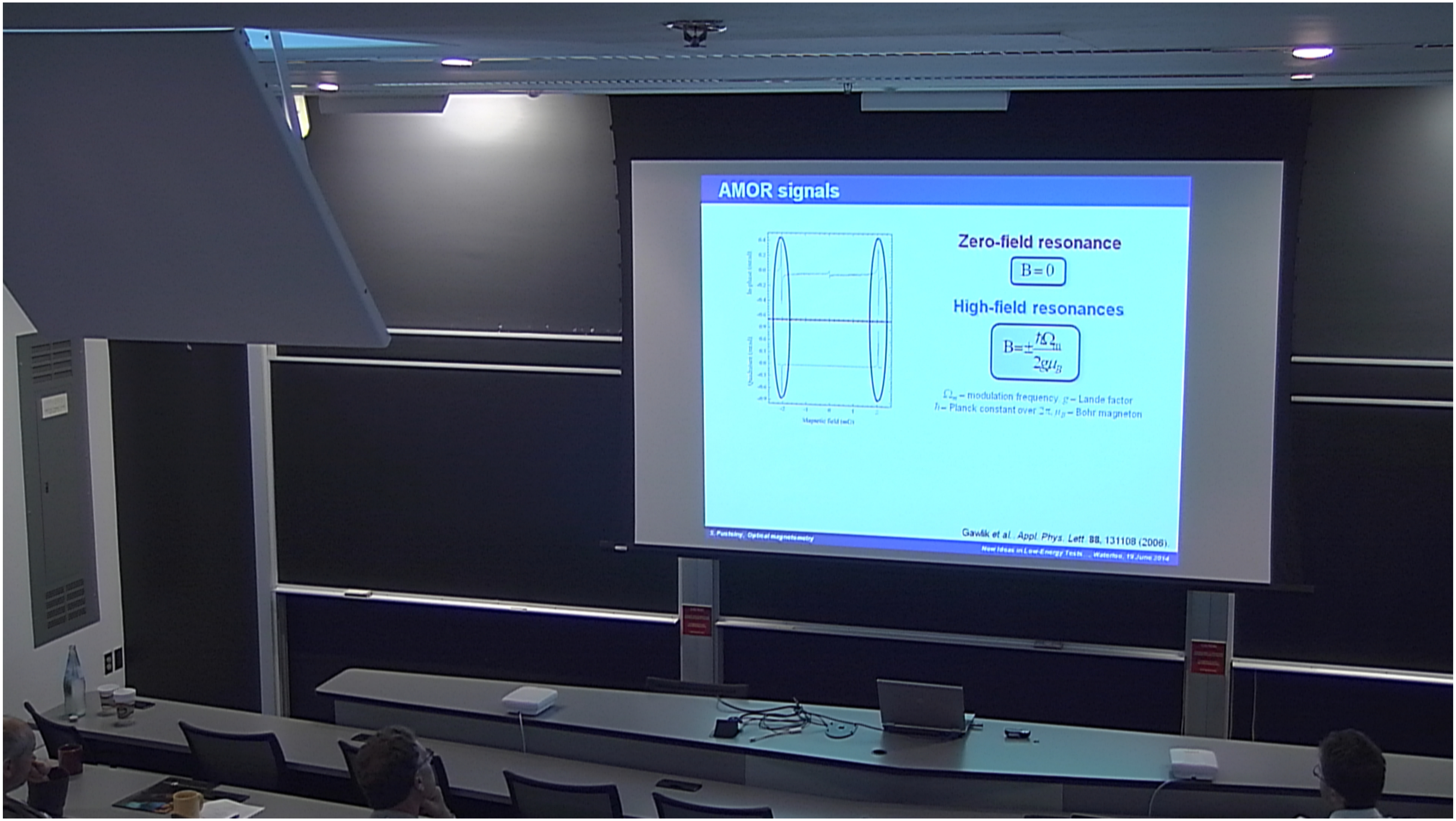
Version of NMOR experiment, in which amplitude modulated light is used
AMOR signal
New signal appears
W. Gawlik at al., Appl. Phys. Lett 88, 131108 (2006).


AMOR signals
Zero-field resonance
B=0
High-field resonances
$B=\pm\frac{\hbar\Omega_m}{2g\mu_B}$
Ω_m – modulation frequency, g – Lande factor
$\hbar$ – Planck constant over 2π, μ_B – Bohr magneton
Gawlik et al., Appl. Phys. Lett. 88, 131108 (2006).
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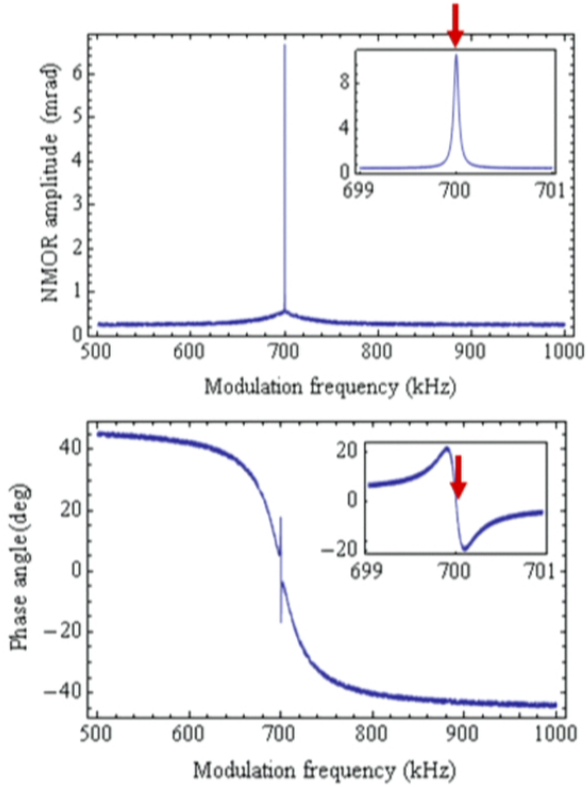
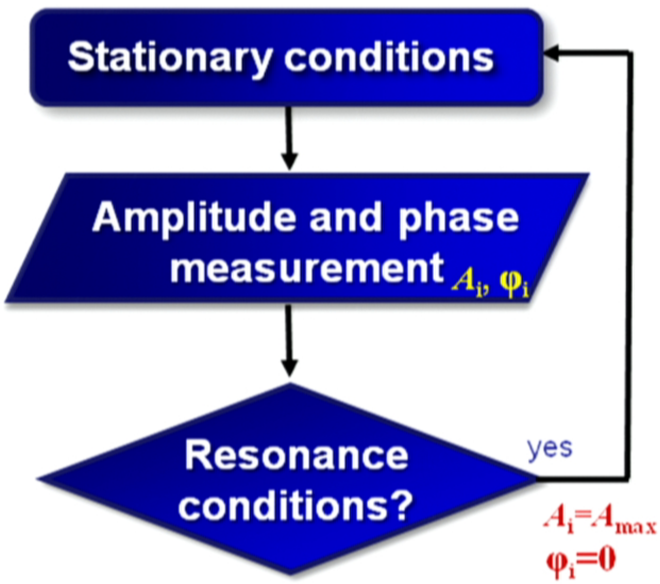
Optical magnetometry



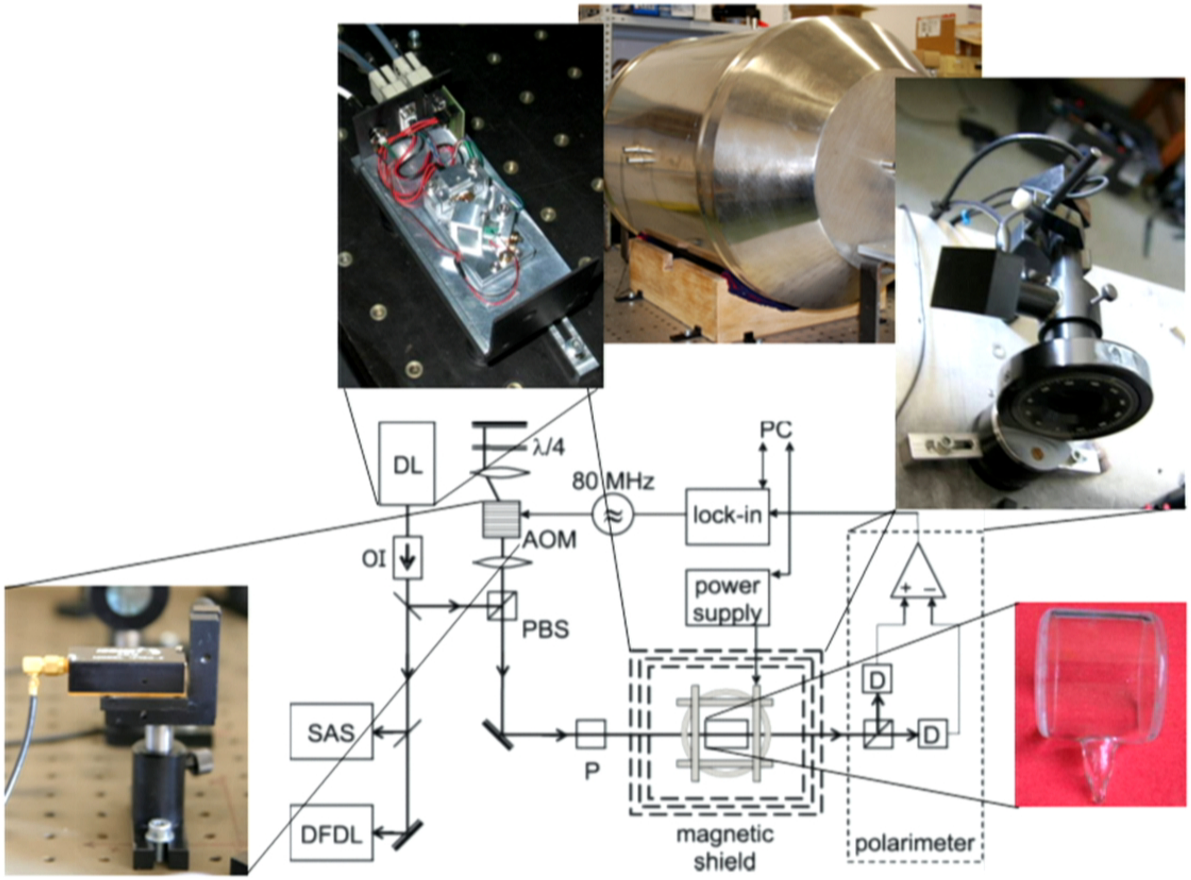
Position of the resonance vs. the modulation frequency depends on the magnetic field

Tracking algorithm



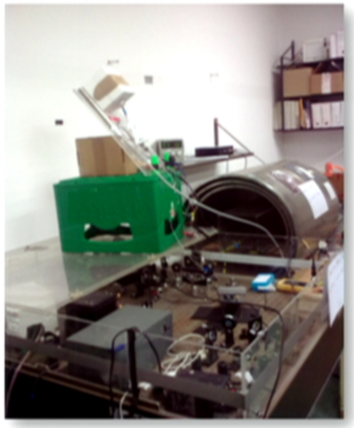
J Appl. Phys. **103**, 063108 (2008).

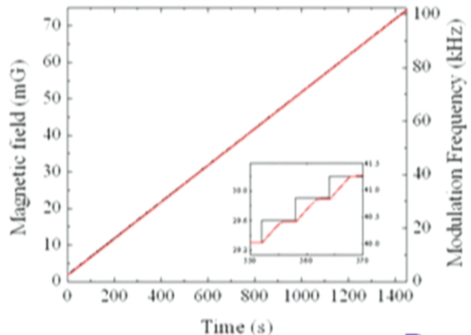
Novel magnetic-field sensor

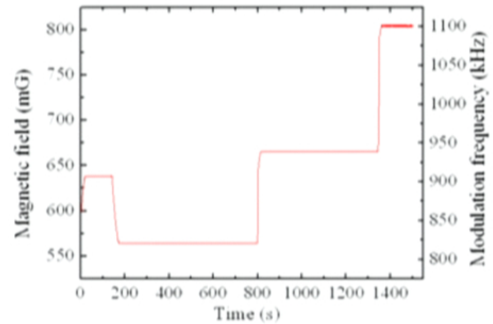


Magnetometer parameters

Dynamic range

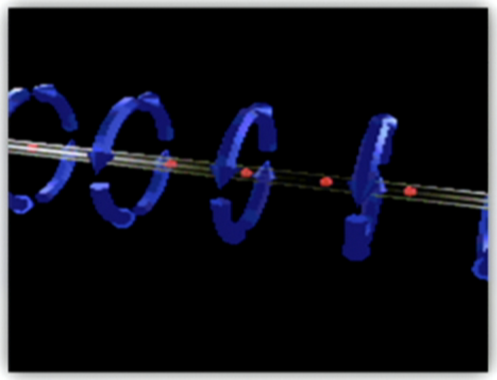




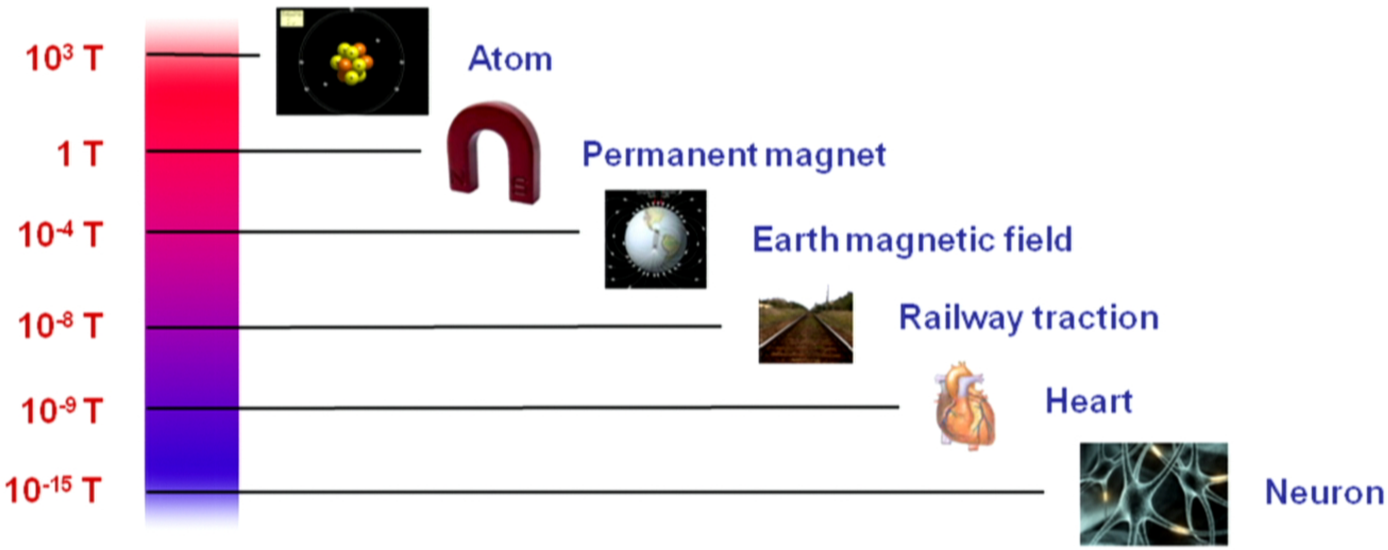


Demonstrated dynamic range **0-10^{-5} T**

Magnetic field



Magnetic field
One of the most fundamental and easily accessible physical observables providing information about surrounding Universe




Applications
Scientific
Testing of existing theories
Verification of scientific hypothesis
Astronomy
Paleomagnetism
Archeology
Practical
Natural–resource surveys
Electronics
Military
Medicine


Biomagnetism
Body can be considered as
complex electromagnetic system
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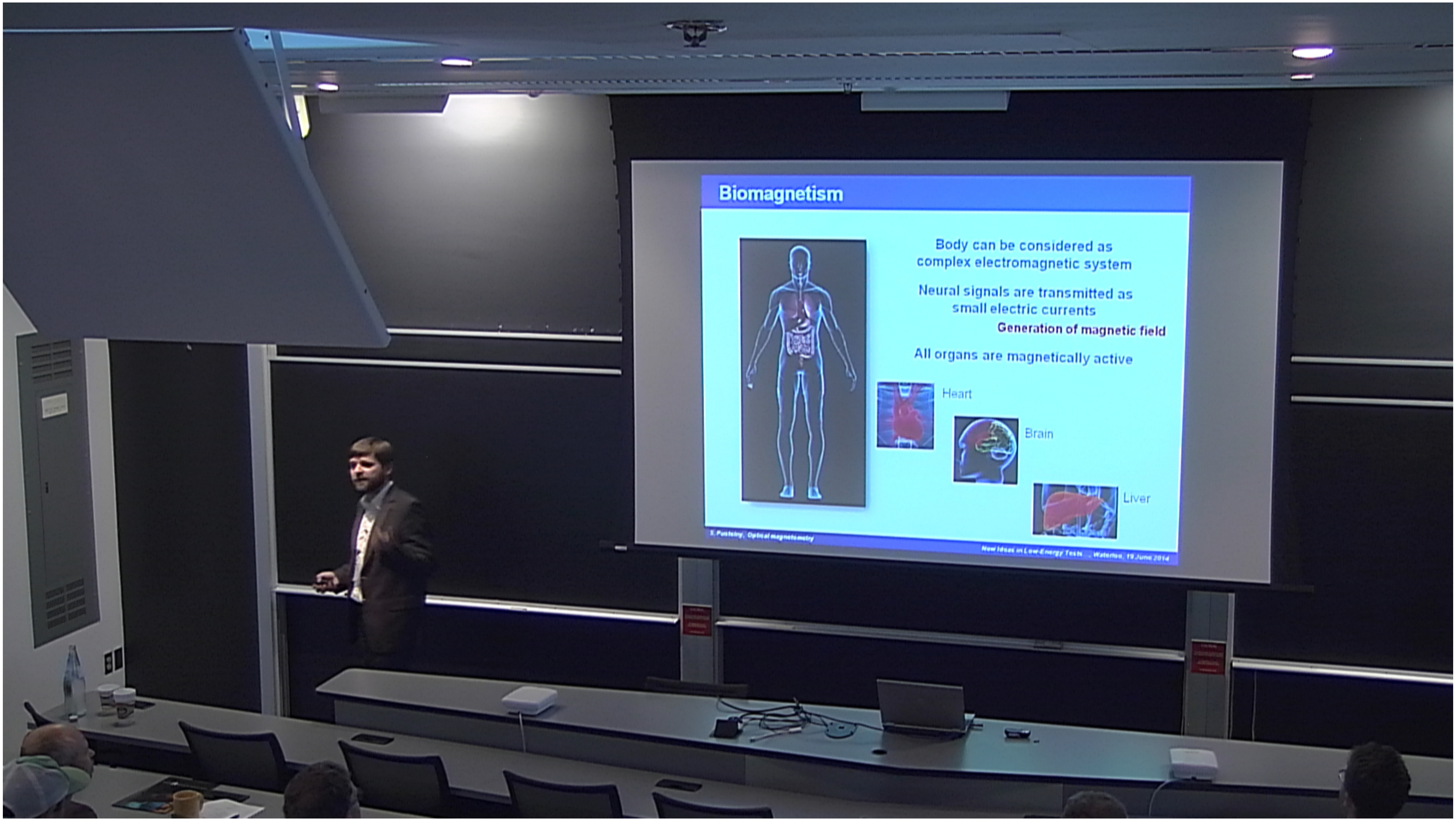
Biomagnetism
Body can be considered as
complex electromagnetic system
Neural signals are transmitted as
small electric currents
Generation of magnetic field
All organs are magnetically active
Heart
Brain
Liver
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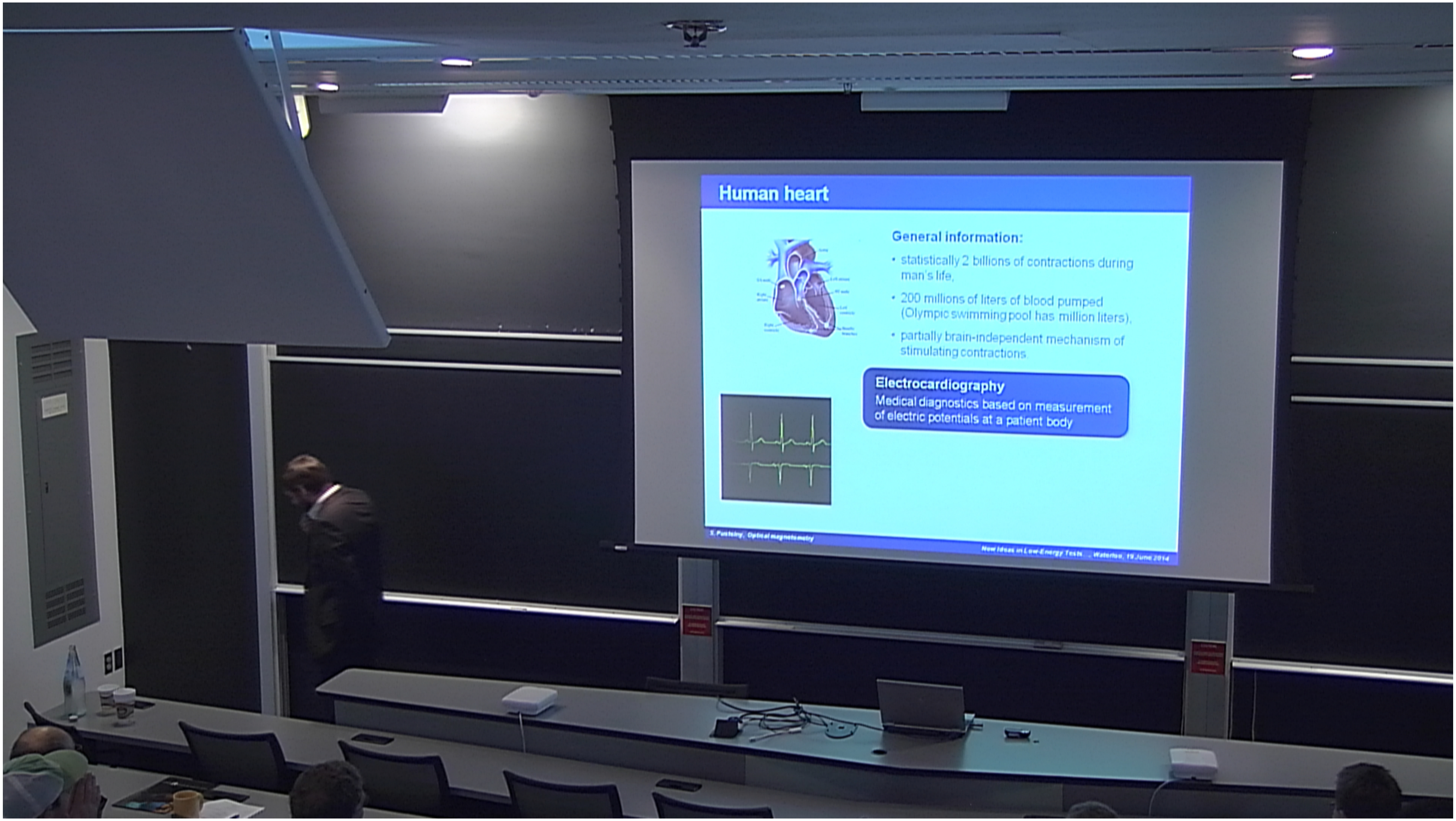
Human heart
General information:
• statistically 2 billions of contractions during man's life,
• 200 millions of liters of blood pumped (Olympic swimming pool has million liters),
• partially brain-independent mechanism of stimulating contractions
Electrocardiography
Medical diagnostics based on measurement of electric potentials at a patient body
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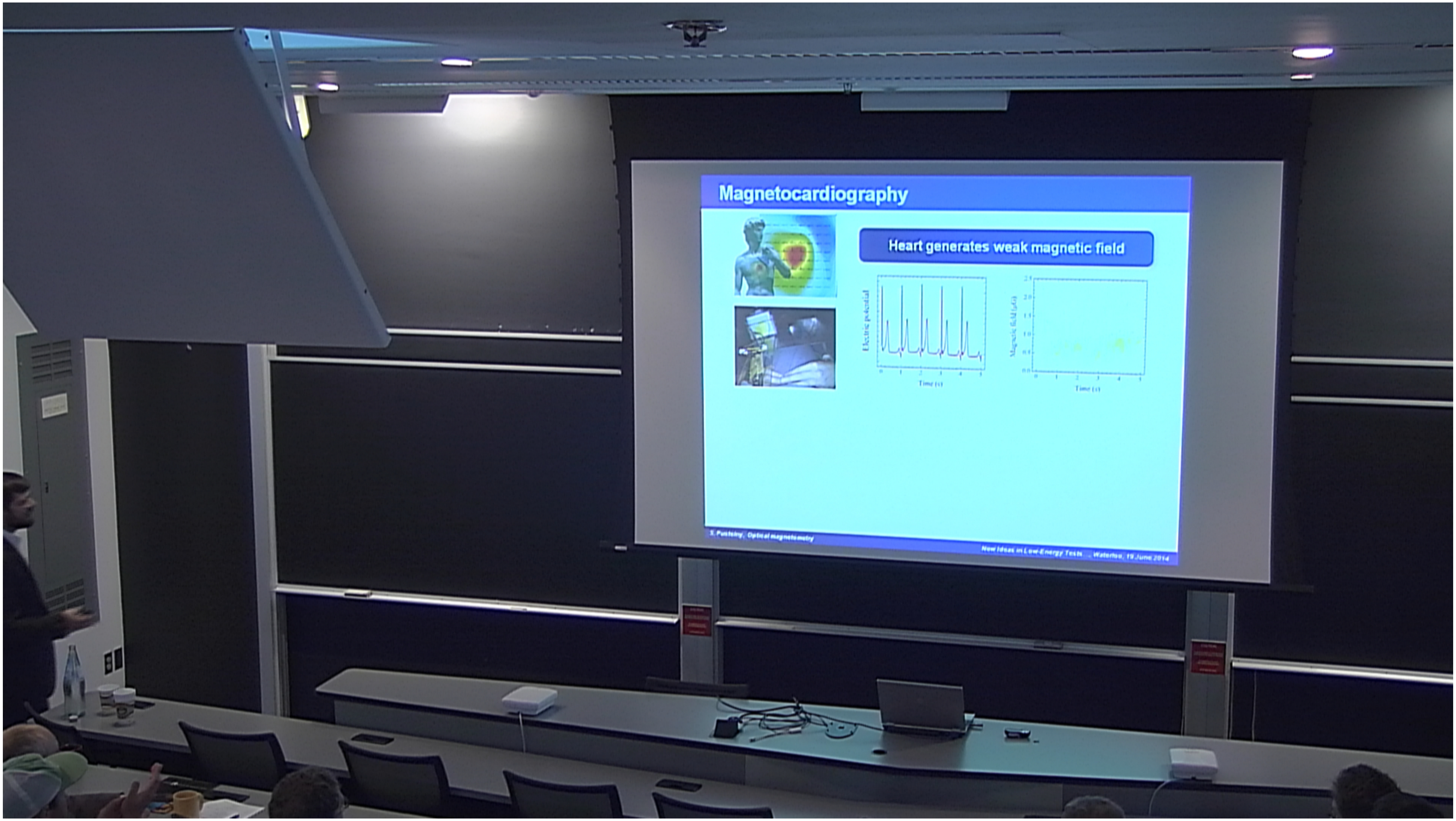
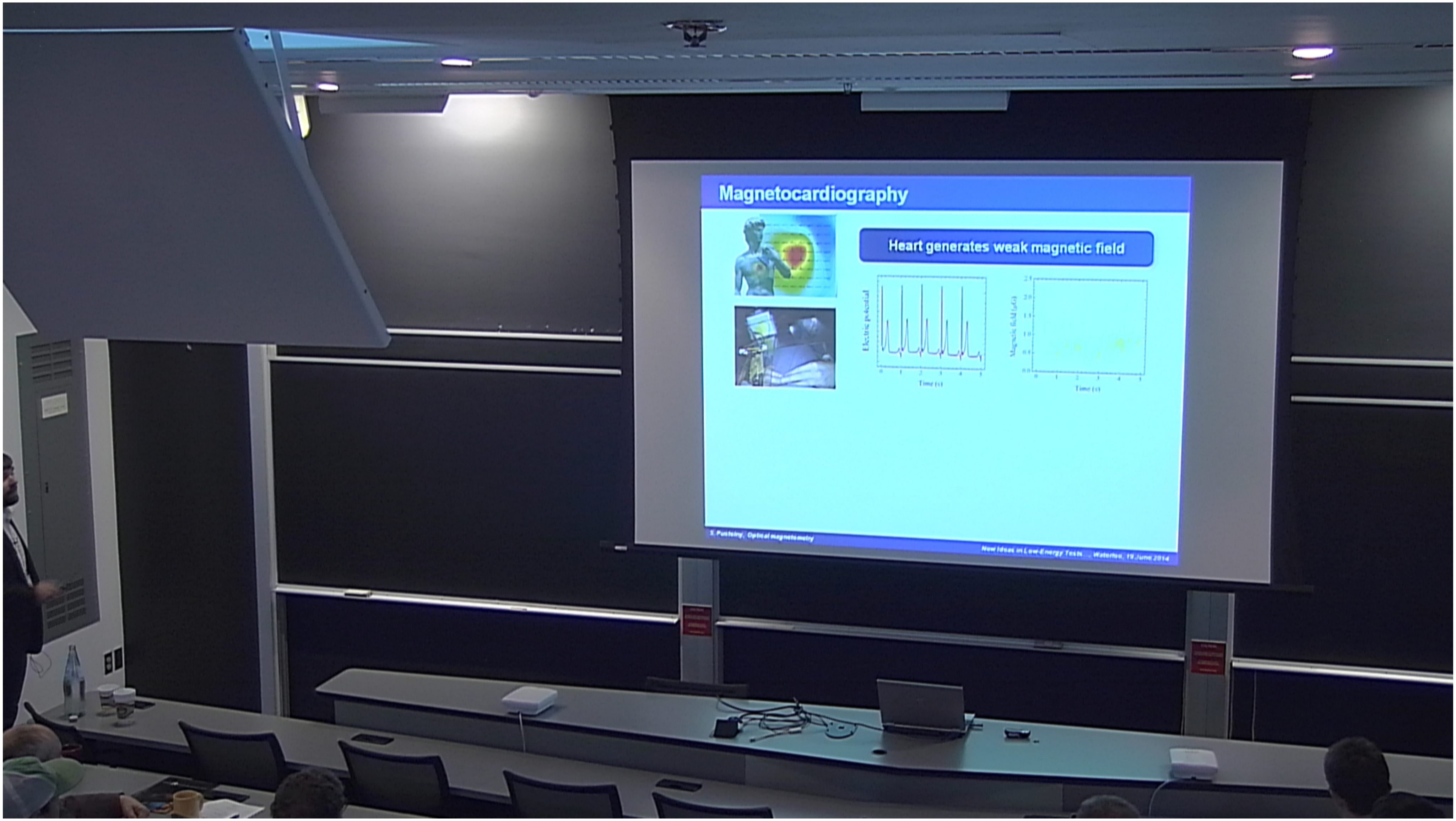


Magnetocardiography
Heart generates weak magnetic field
Electric potential
Time (s)
Time (s)
S. Pustelny, Optical magnetometry
New Ideas in Low-Energy Tests ... Waterloo, 19 June 2014


Magnetocardiography
Heart generates weak magnetic field
Electric potential
Time (s)
Magnetic field (pG)
Time (s)
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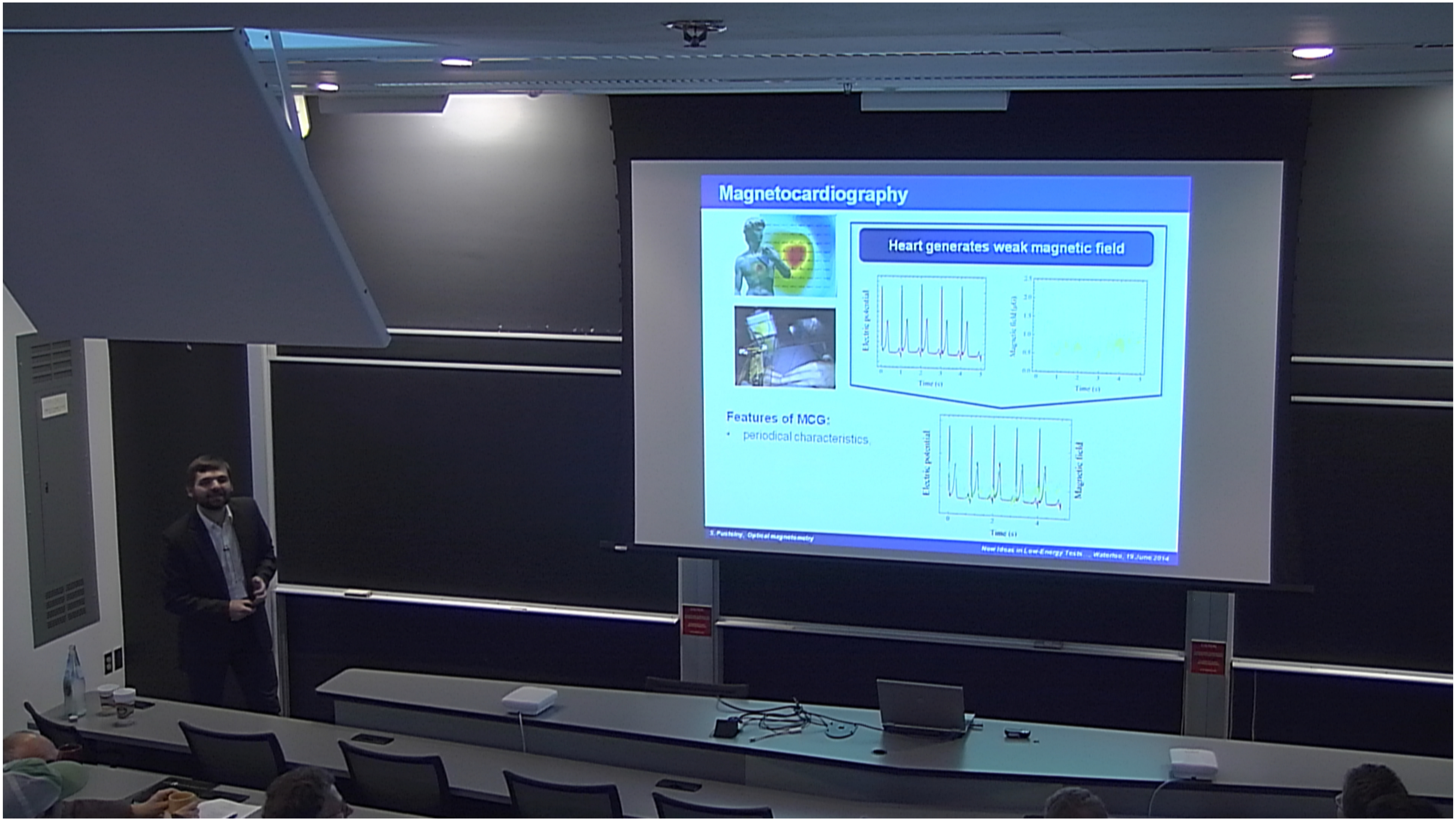
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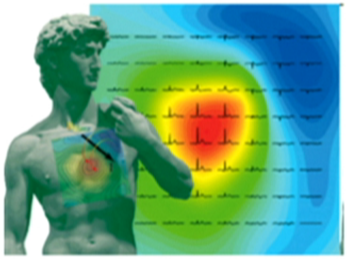
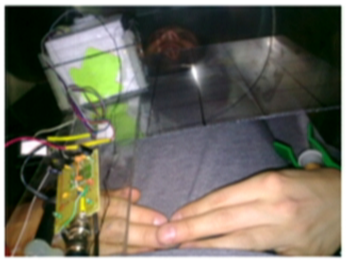
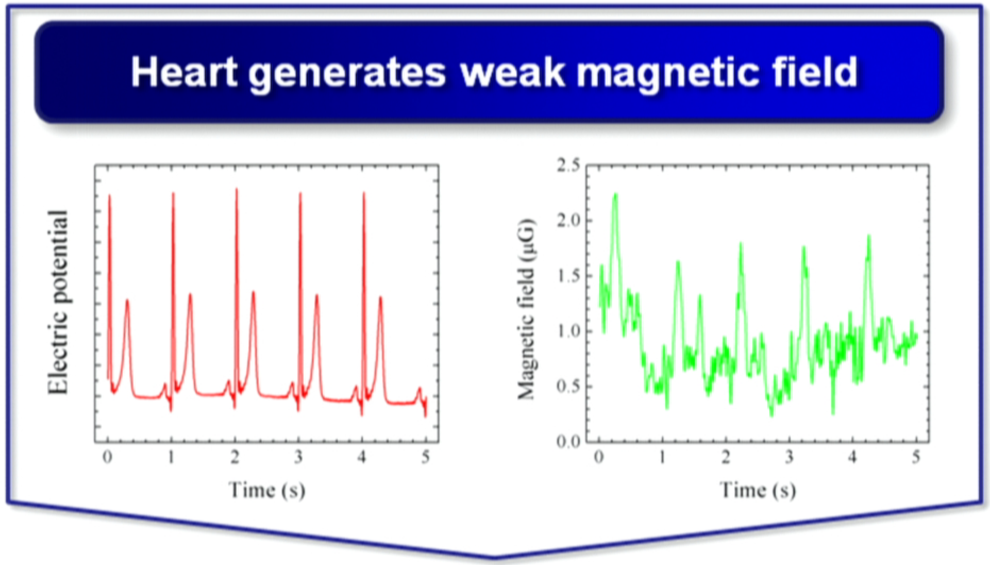
Heart generates weak magnetic field
Electric potential
Time (s)
Magnetic field
Features of MCG:
• periodical characteristics,
Electric potential
Magnetic field
Time (s)

Magnetocardiography

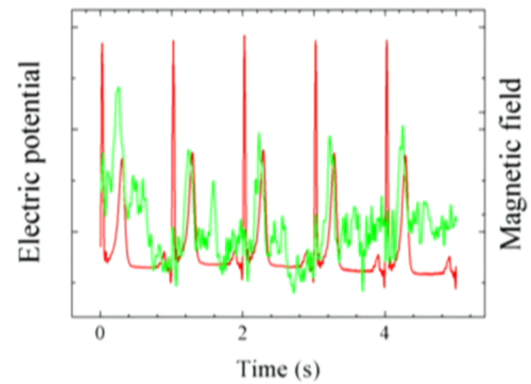




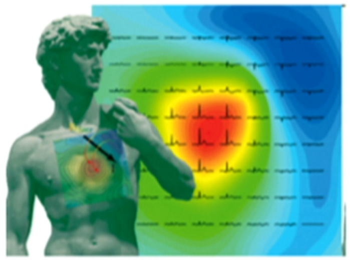


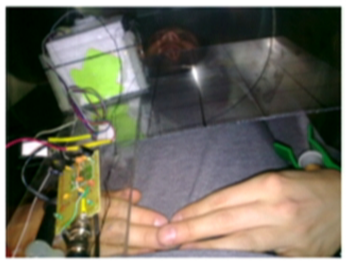
Features of MCG:

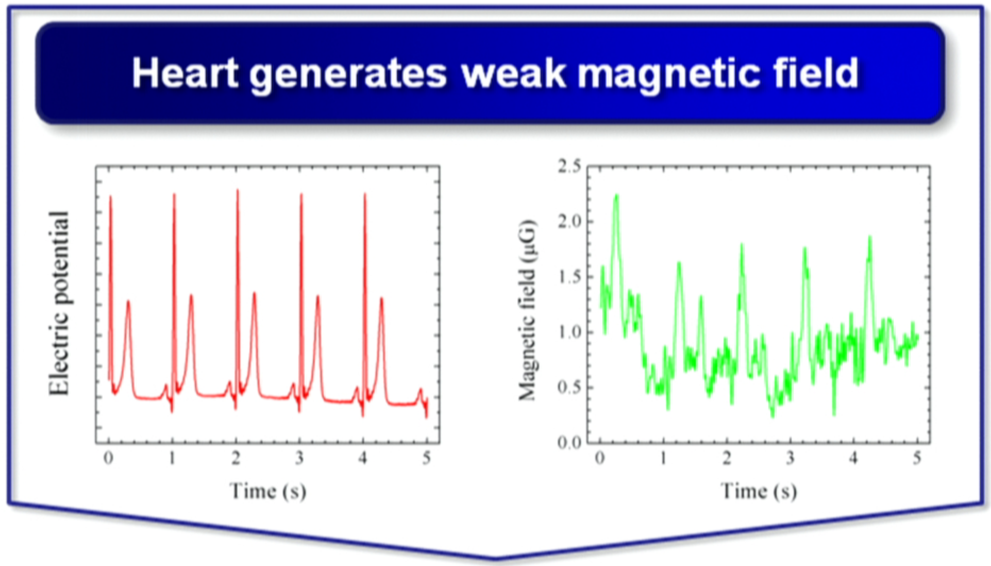
- periodical characteristics,



Magnetocardiography

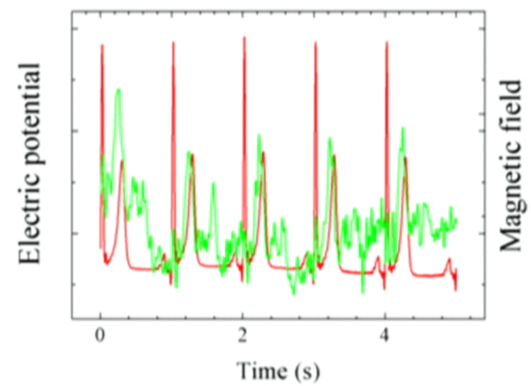


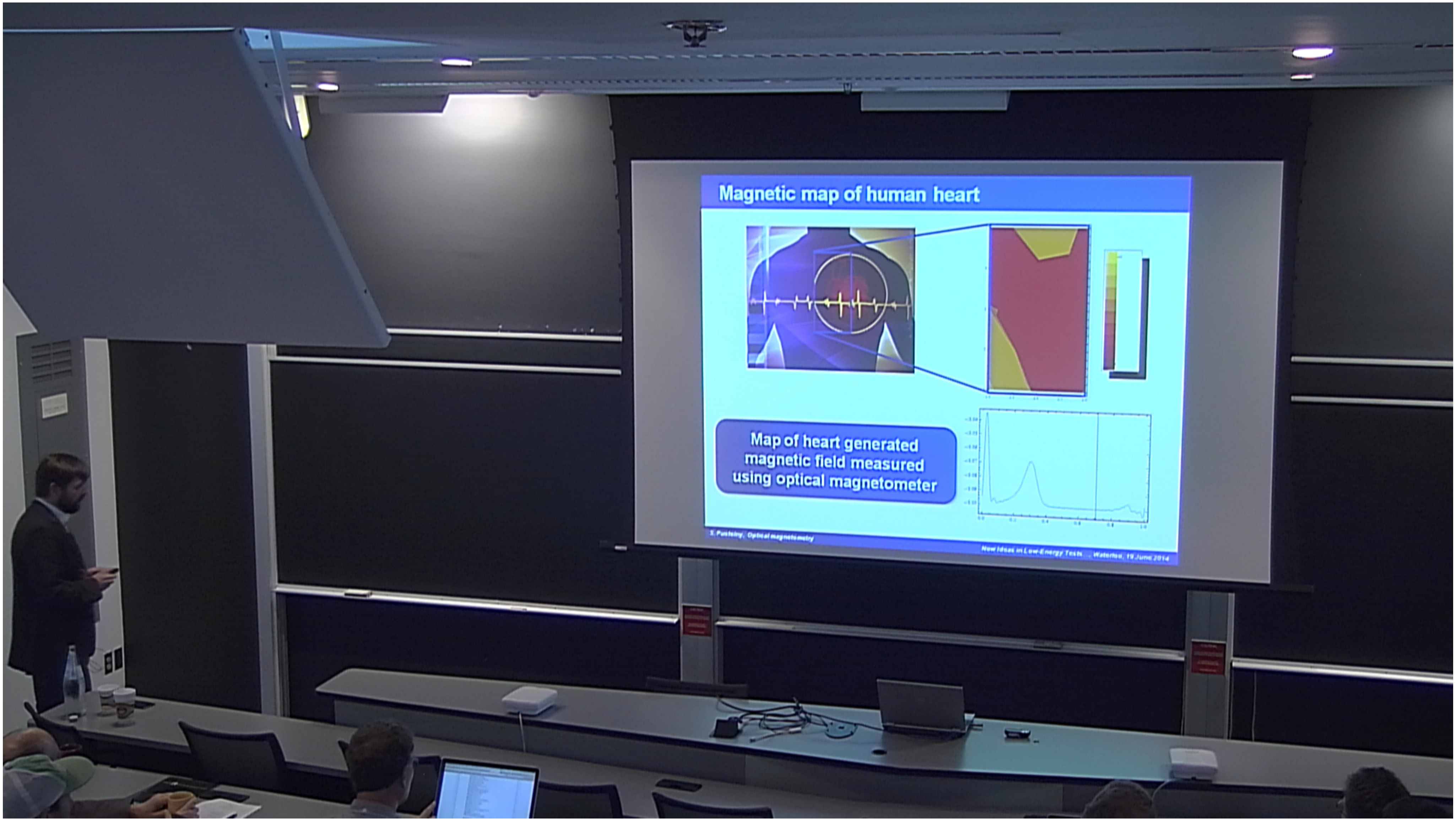




Features of MCG:

- periodical characteristics,
- complementary information to ECG (magnetic pre-initiation),
- 3D information,
- noninvasive,

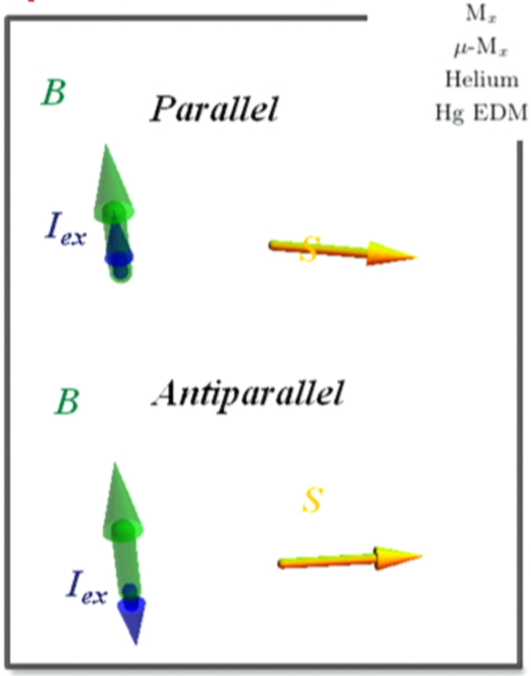




Magnetic map of human heart
Map of heart generated magnetic field measured using optical magnetometer

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

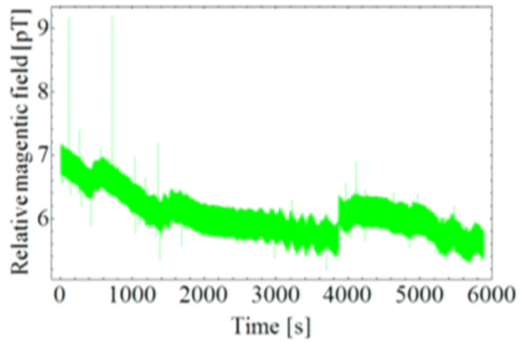
Exotic spin coupling

The spin precession is modified

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

Noise vs transient signals

Experimental signals



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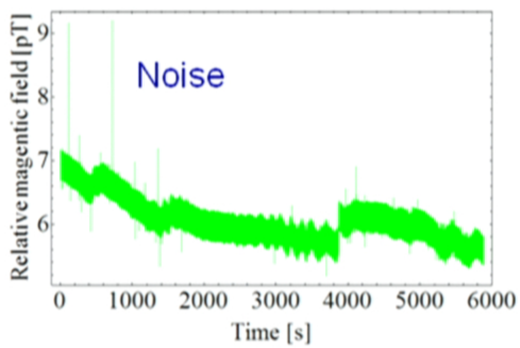


Noise source:

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

Elimination of the noise

Transient spin couplings

If it is transverse coupling

It is very difficult to be identified in normal scheme

Particular challenges:

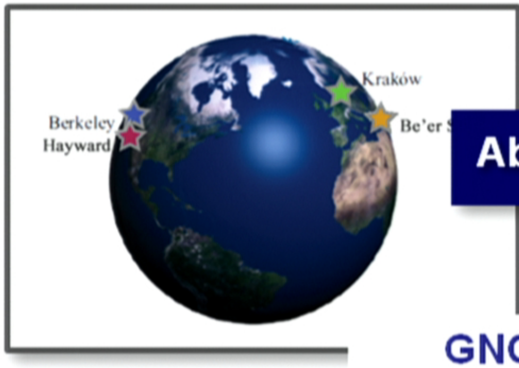
- short duration of the signals (**high bandwidth and sensitivity**)
- problems with shielding spins against magnetic fields in broad frequency range(**noise**)
- difficult/impossible modulation of the interaction (**noise**)

GNOME

Most important GNOME features:

- ability to suppress local noise (**correlations**)

GNOME



Most important GNOME features:

- ability to suppress local noise (**correlations**)

Ability to identify global transient disturbances

- spatio-temporal resolution (**spatial identification of the coupling source**).

GNOME crucial ingredients

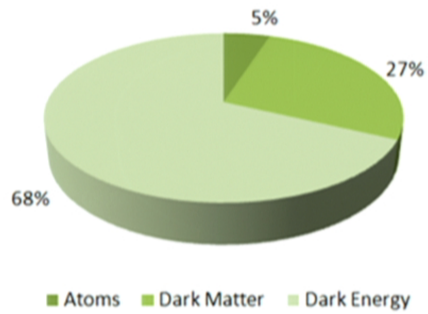
Sensitive OMAGs

Global timing

Data exchange

Data analysis

Dark matter and Axions



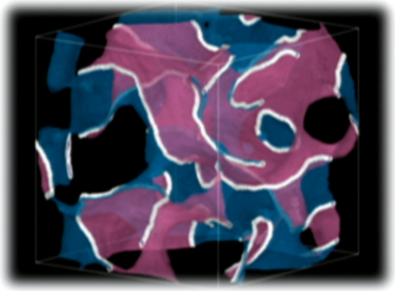
Dark matter

27% of total Universe's energy is dark matter, which does not emit, absorb, or scatter light.

Dark-matter candidates:

- Weakly Interacting Massive Particles (WIMPs),
- supersymmetric particles,
- neutrino,
- axions,
- …

Axion-field domain structure



Axion-field domain structure

Initial random distribution of axion-like field resulted in formation of the domain structure during the Universe expansion and cool down – different energy vacua of the field in different places

Crossing through the domain wall of the axion-like field generates detectable spin coupling

$$H_{DW} = \frac{\vec{S}\cdot\vec{\nabla}a}{S\, f_{eff}} \neq 0$$

$$B_{eff} < 0.4\,\mathrm{pT}\ \text{at}\ \ t_c = 1\ \mathrm{ms}$$

Specific conditions

OMAGs can be used to probe axion-like fields with domain structure

M. Pospelov *et al.*, *Phys. Rev. Lett.* **110**, 021803 (2013).

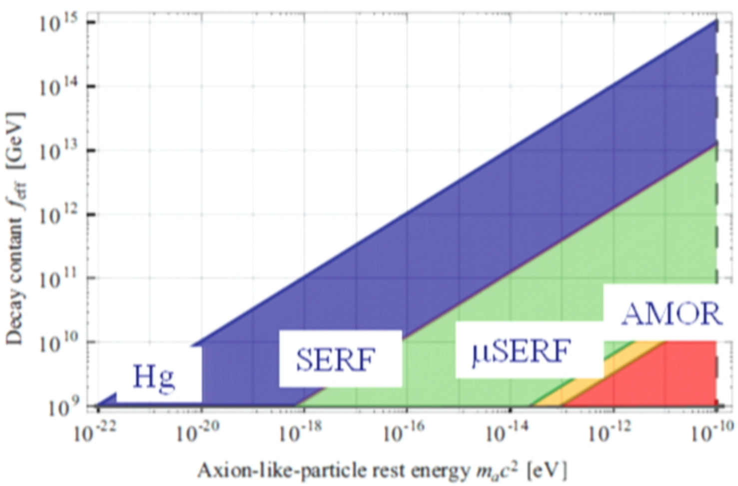
Probeable parameter space

Space of parameters

Decay constant

$$f_{\exp} = \hbar c^2 \sqrt{\frac{\rho_{DW} L_D m_a}{\delta E_d}} \cos\phi$$

L_D – domain size, ρ_{DW} – axion-wall energy density, ϕ – the transition angle



Assumption

Domain-wall size: $L_D = 0.01$ ly

Wall energy densuty: $\rho_{DW} \leq 0.4\,\mathrm{GeV/cm^3}$

Comments

Vertical line 10^{-10} eV – **magnetometer bandwidth**

Horizontal line 10^9 GeV – **astronomical limit**

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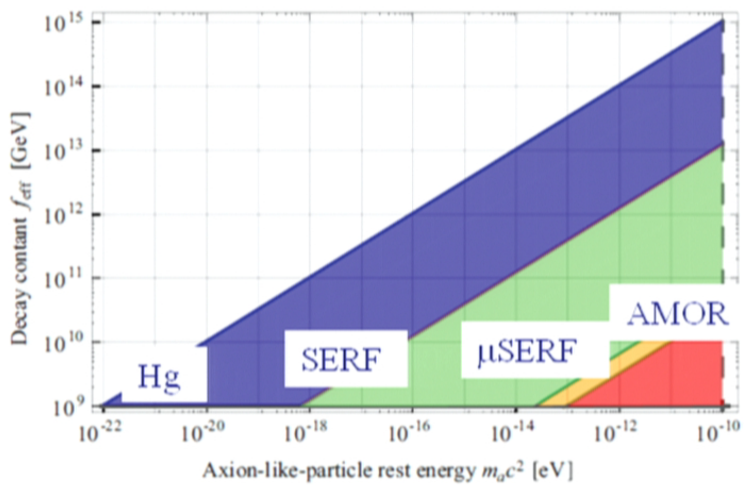

The ability to probe yet unconstrained parameter space

M. Pospelov *et al.*, *Phys. Rev. Lett.* **110**, 021803 (2013).

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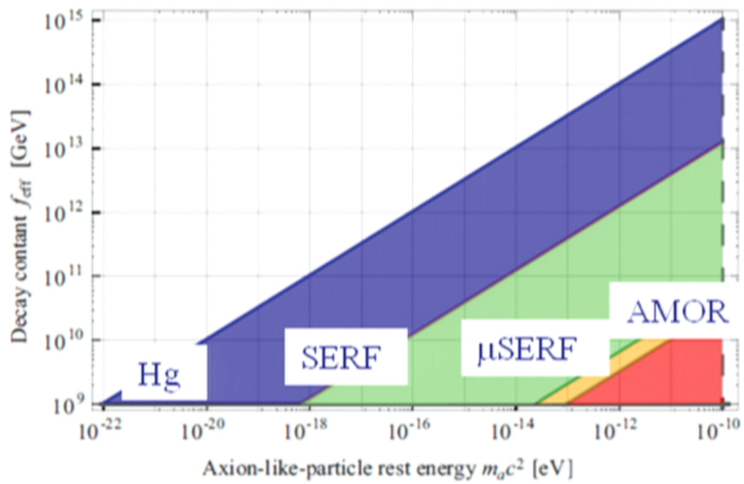


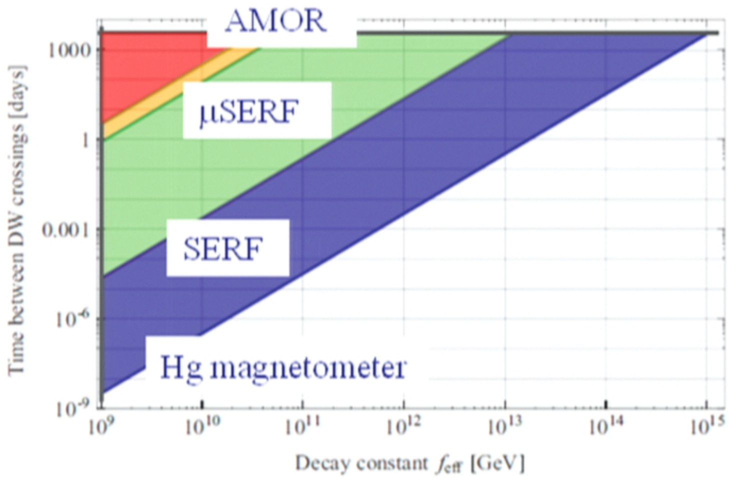
The ability to probe yet unconstrained parameter space

M. Pospelov *et al.*, *Phys. Rev. Lett.* **110**, 021803 (2013).

Duration of the experiment

Length of the experiment

- **There is no natural scale in the model**
- Rational limits on the length of the experiment



Already within a day one we will probe unconstraned parameter space

Assumption

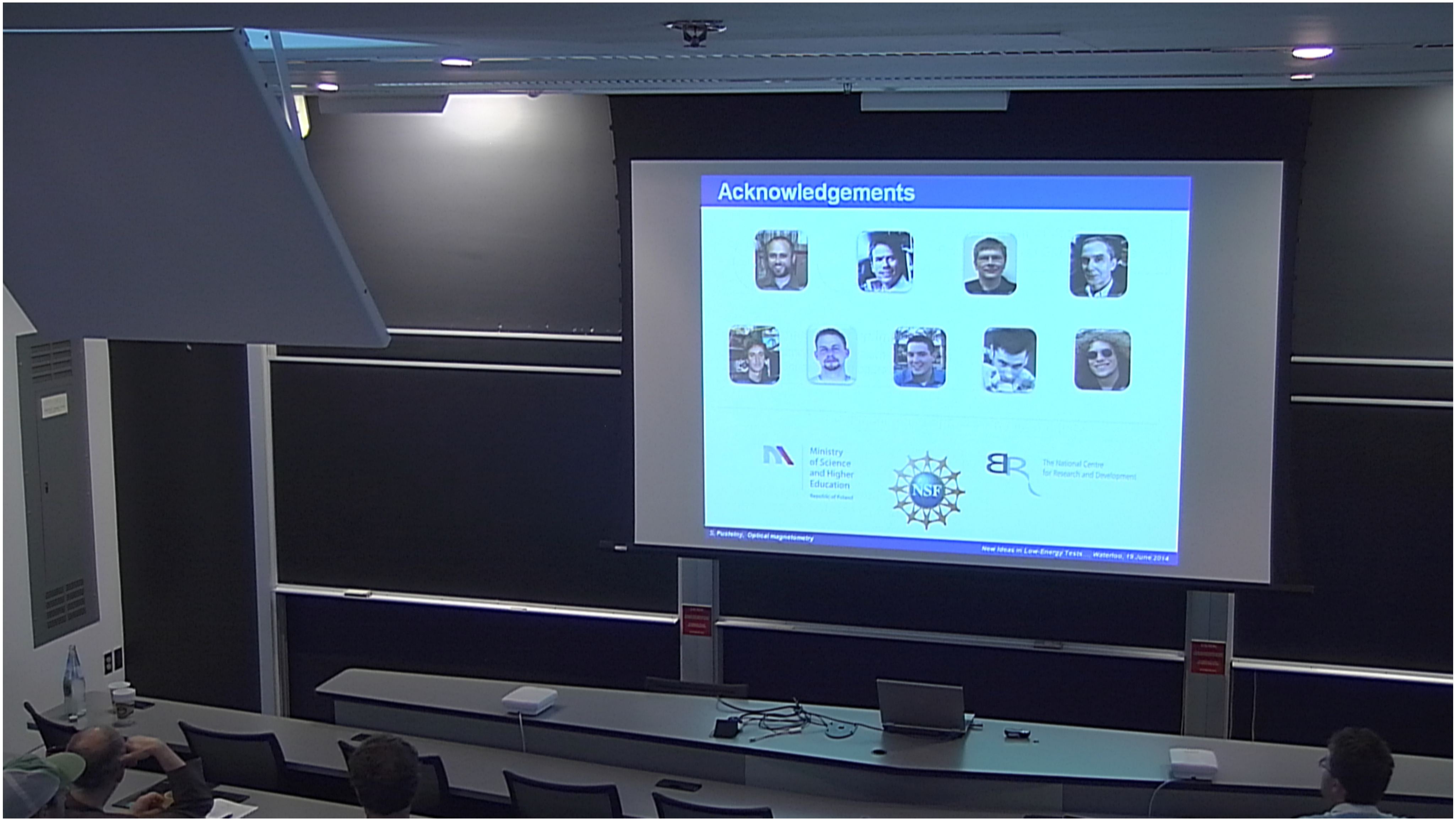
Domain wall energy density: $\rho_{DW} = 0.4\,\mathrm{GeV/cm^3}$

$\rho_{DW} = \rho_{DM}$

Axion mass: $m_a c^2 = 10^{-10}\,\mathrm{eV}$

Time of transition: $\tau = 13\,\mathrm{ms}$


Outlook and Conclusions
Development of the GNOME


Acknowledgements
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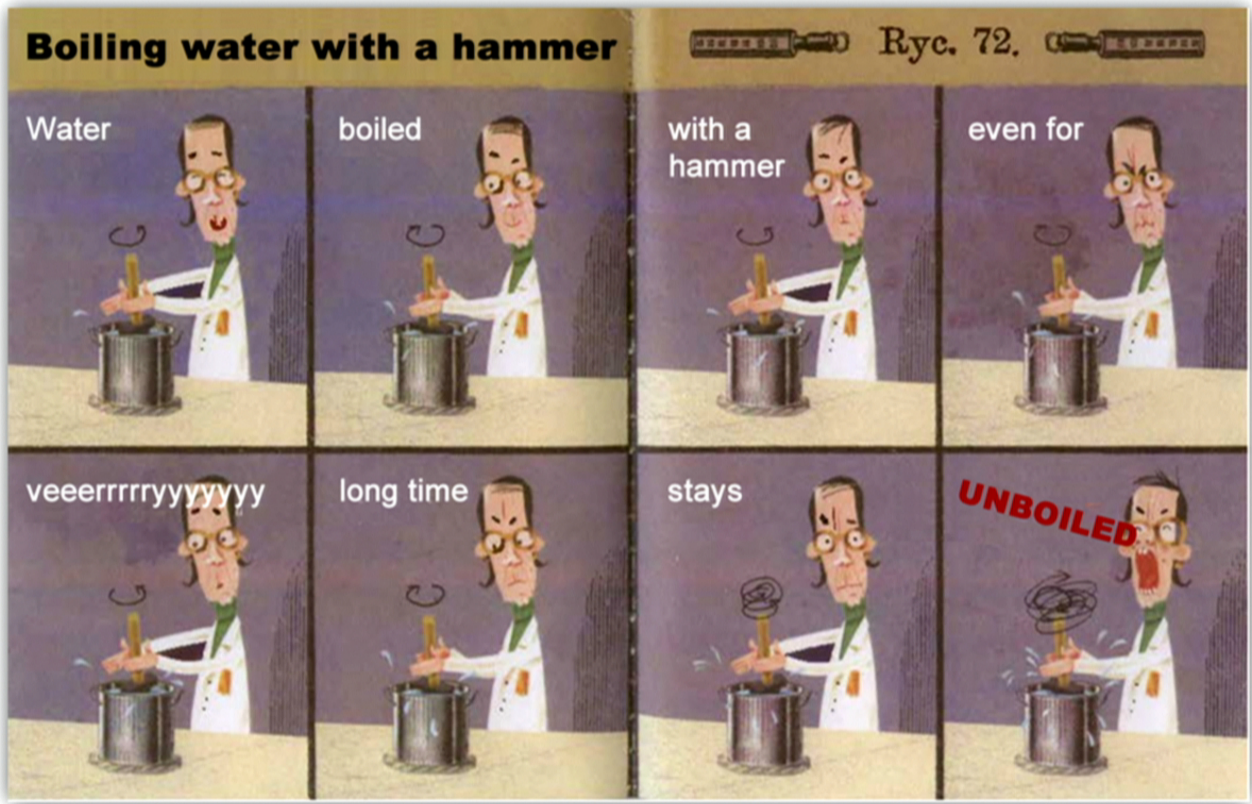
What the community things about us?



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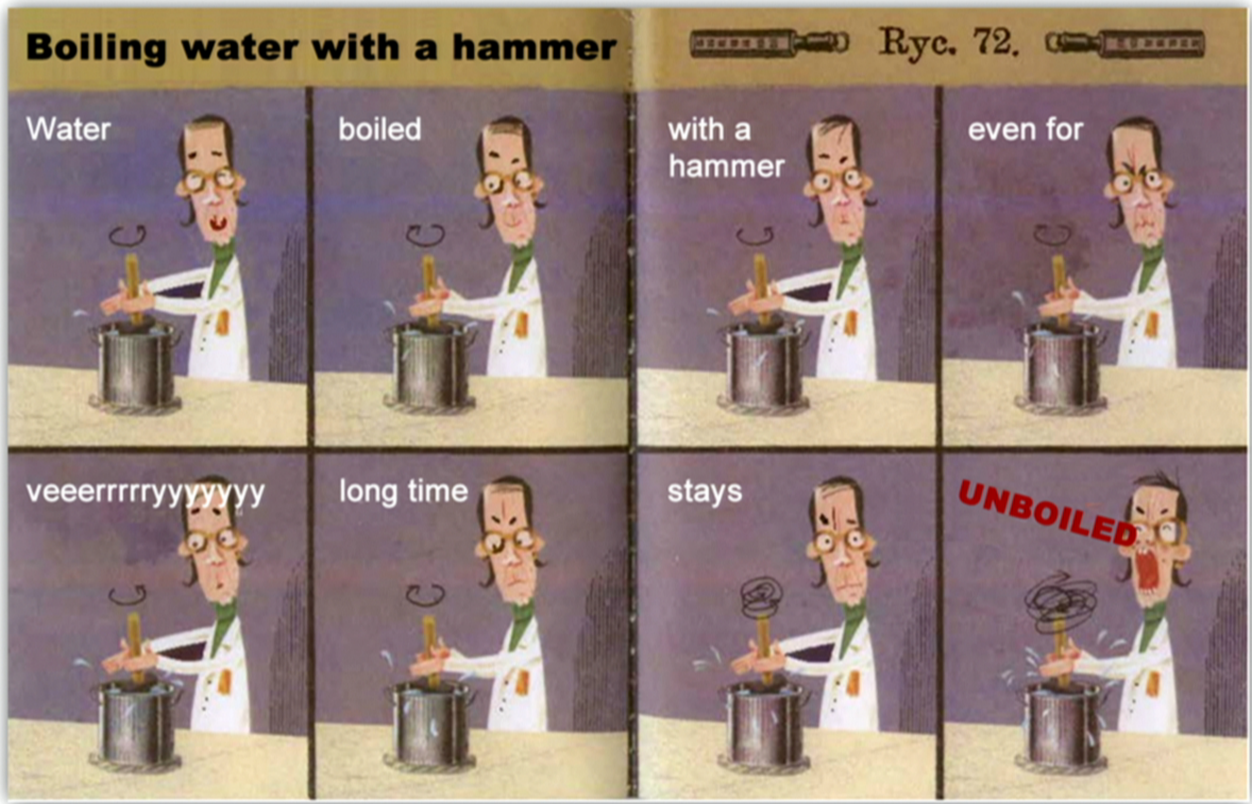

Even if it is true… **<u>IT MAY STILL BE VERY INTERESTING</u>**