Title: Nuclear spin precession of noble gases in ultra low magnetic fields

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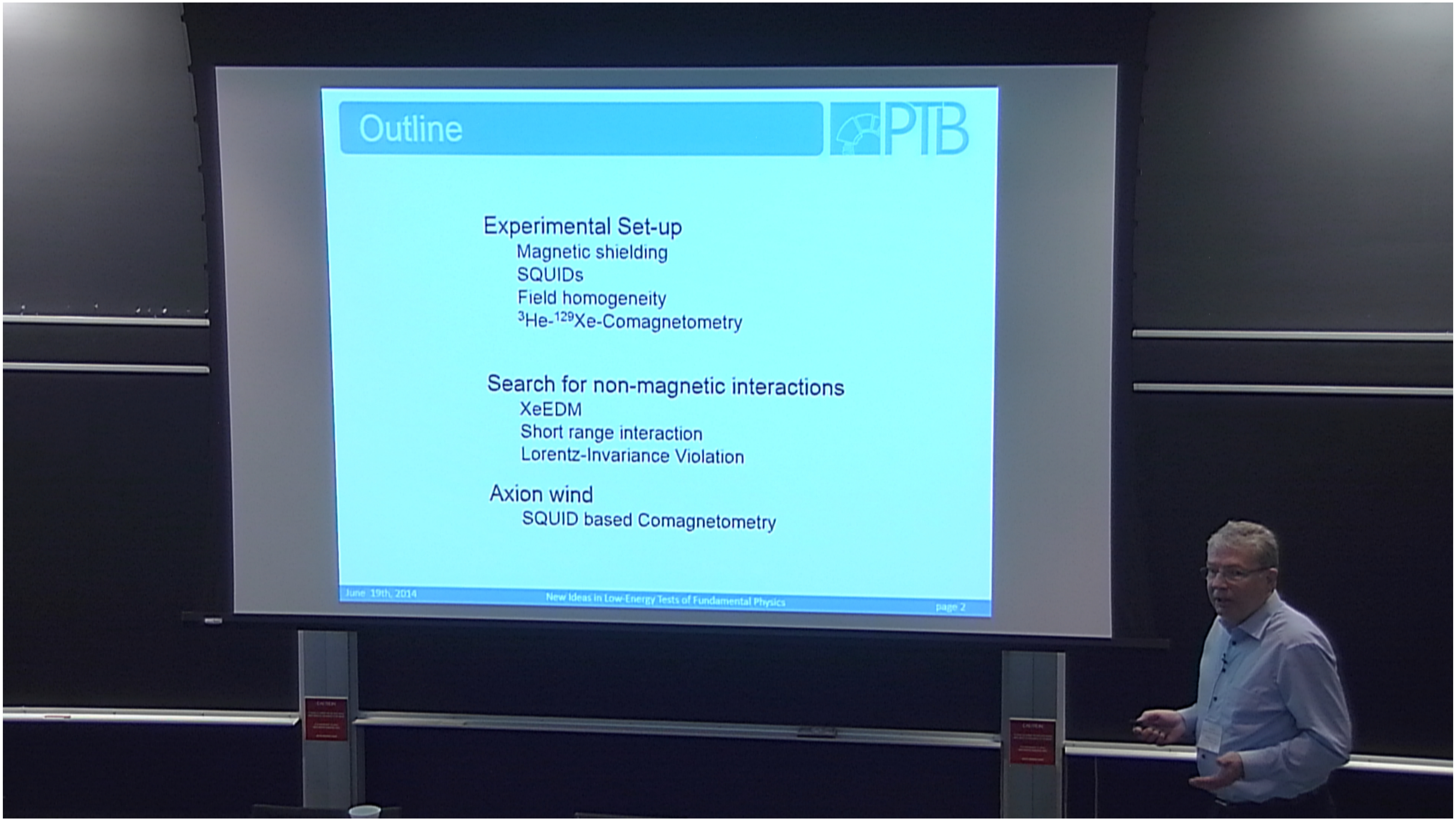
Abstract: In the low energy reÂ¬gime, precision measurements of spin precession have gained increased attention as an alternative pathway to physics beyond the standard model. These measurements aim at the detection of minute frequency changes superimposed on low Larmor frequencies at extremely weak magnetic fields. Such measurements require an effective shielding against the magnetic field of the Earth and other perturbations. For measuring the precession frequency with high precision, a long lifetime of the precessing nuclear magnetization is required, thus the homogeneity of the applied field is a crucial parameter. In addition, criteria are needed that unambiguously distinguish magnetic artifacts from the non-magnetic exotic interactions that we search for. This can be accomplished by the concept of co-magnetometry, i.e., by simultaneous measuring the precession of two nuclear species such as 3He and 129Xe. Yet another kind of co-magnetometry is the use of SQUIDs for monitoring the spin precession. SQUIDs are magnetic field detectors of their own kind, which can measure the oscillating magnetic field generated by the precessing nuclear magnetic moment as well as the magnetic dc background field. In this presentation, I will report on the current state of the art in our lab in measurements of nuclear spin precession of noble gases.


Outline
PTB
Experimental Set-up
Magnetic shielding
SQUIDs
Field homogeneity
3He-129Xe-Comagnetometry
Search for non-magnetic interactions
XeEDM
Short range interaction
Lorentz-Invariance Violation
Axion wind
SQUID based Comagnetometry
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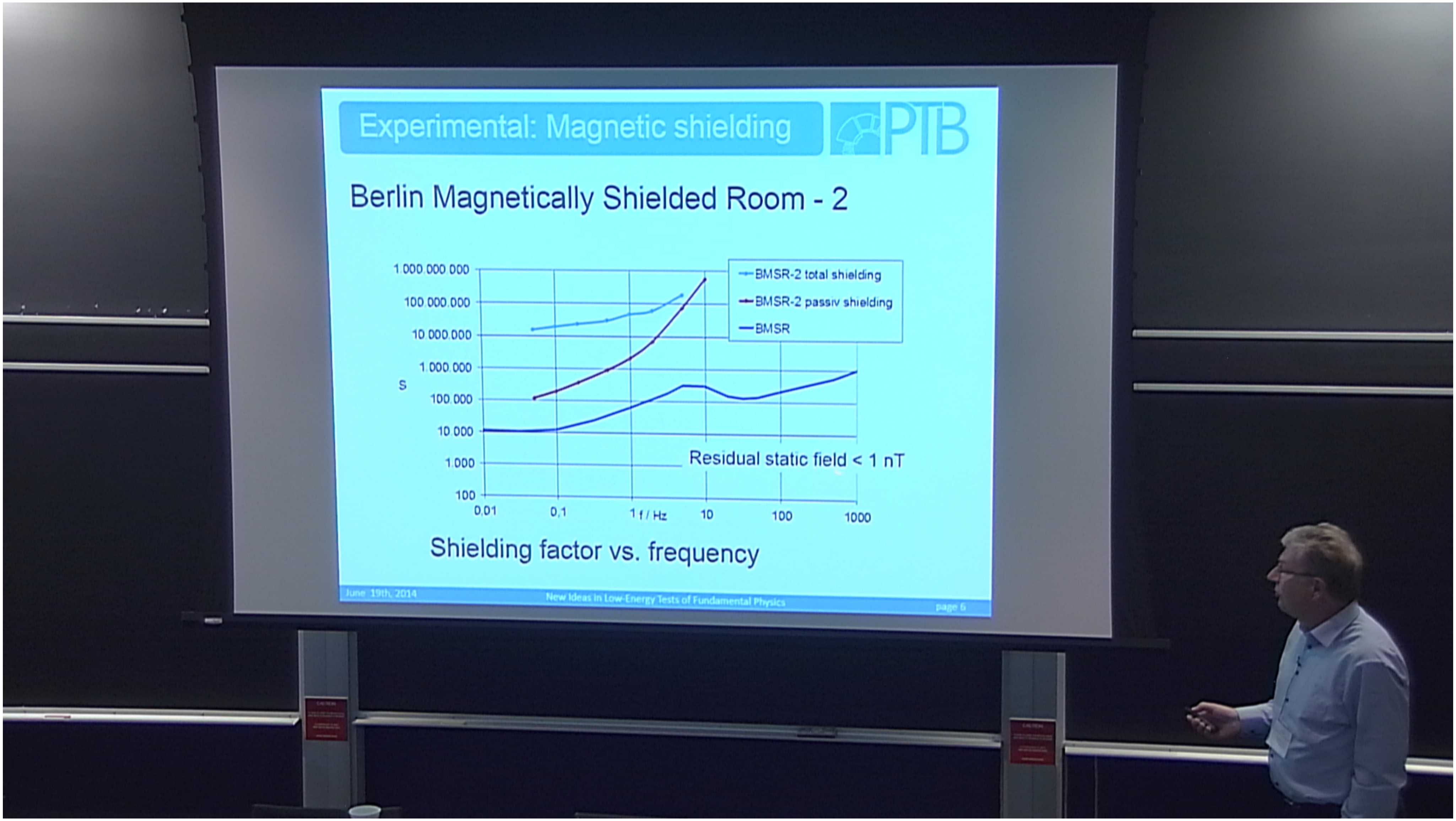
Experimental: Magnetic shielding
PTB
Berlin Magnetically Shielded Room - 2
1.000.000.000
100.000.000
10.000.000
1.000.000
S
100.000
10.000
1.000
100
0,01
0,1
1 f / Hz
10
100
1000
BMSR-2 total shielding
BMSR-2 passiv shielding
BMSR
Residual static field < 1 nT
Shielding factor vs. frequency
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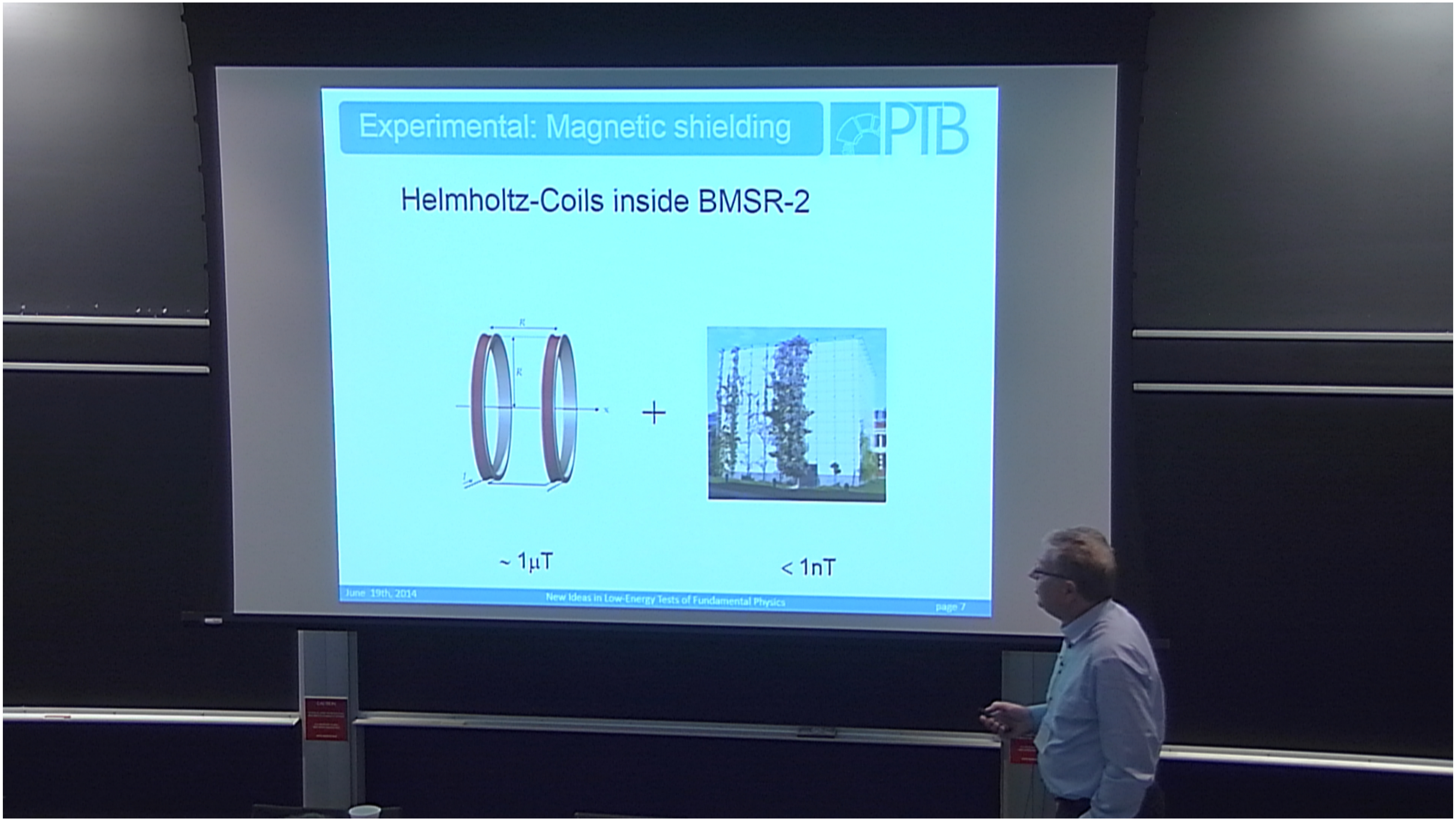
Experimental: Magnetic shielding
PTB
Helmholtz-Coils inside BMSR-2
~ 1μT
< 1nT
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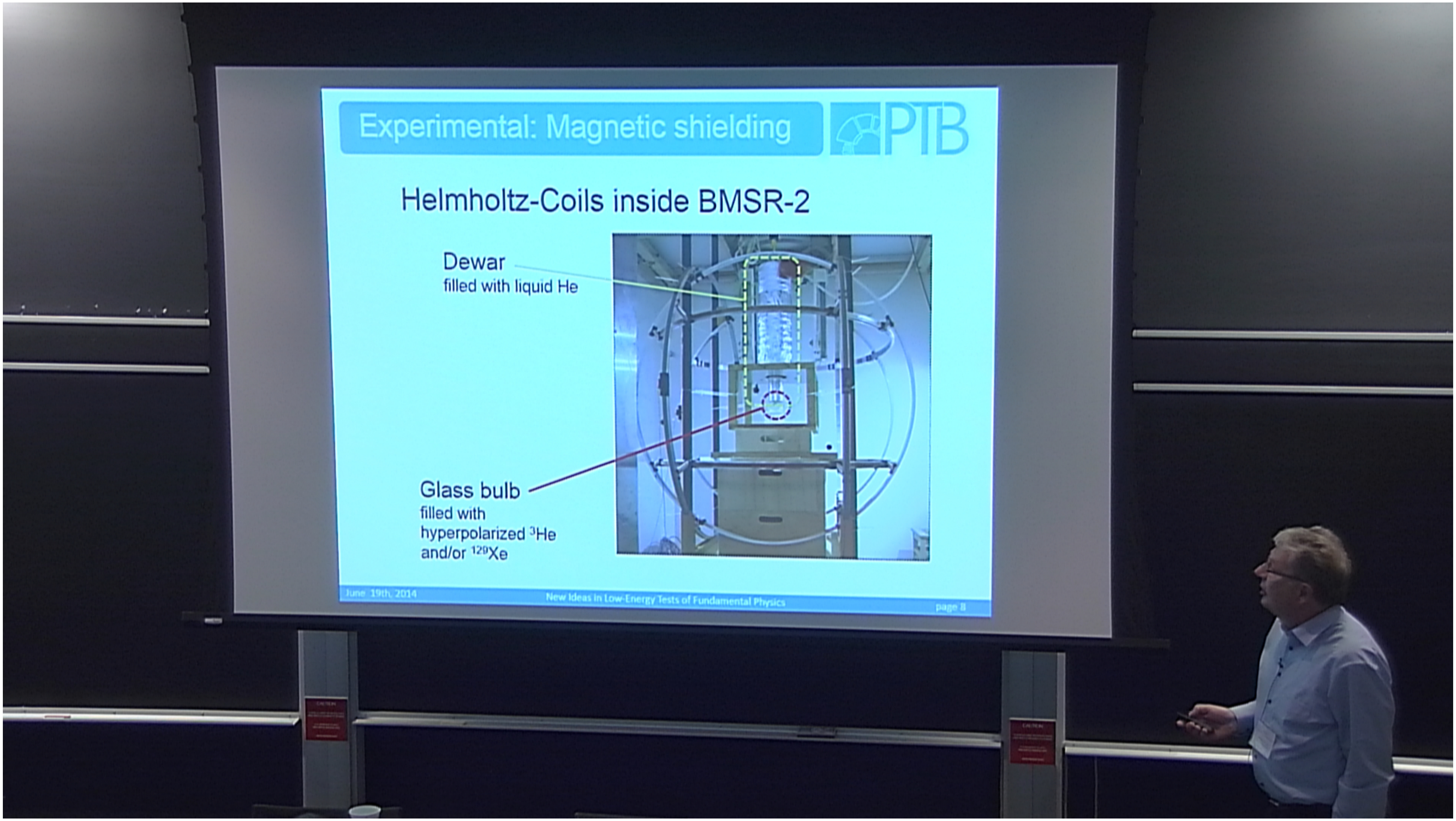
Experimental: Magnetic shielding
PTB
Helmholtz-Coils inside BMSR-2
Dewar
filled with liquid He
Glass bulb
filled with
hyperpolarized ³He
and/or ¹²⁹Xe
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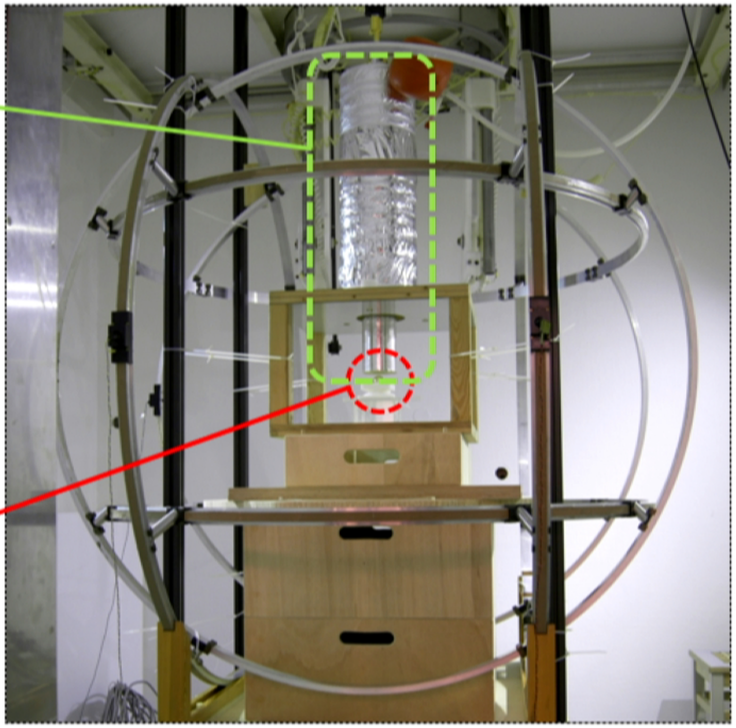
Experimental: Magnetic shielding

Helmholtz-Coils inside BMSR-2

Dewar
filled with liquid He



Glass bulb
filled with
hyperpolarized ^{3}He
and/or ^{129}Xe


Experimental: Field homogeneity
PTB
3He precession as measured by SQUID
B(t)/pT
time [s]
SQUIDs
^{3}He
B
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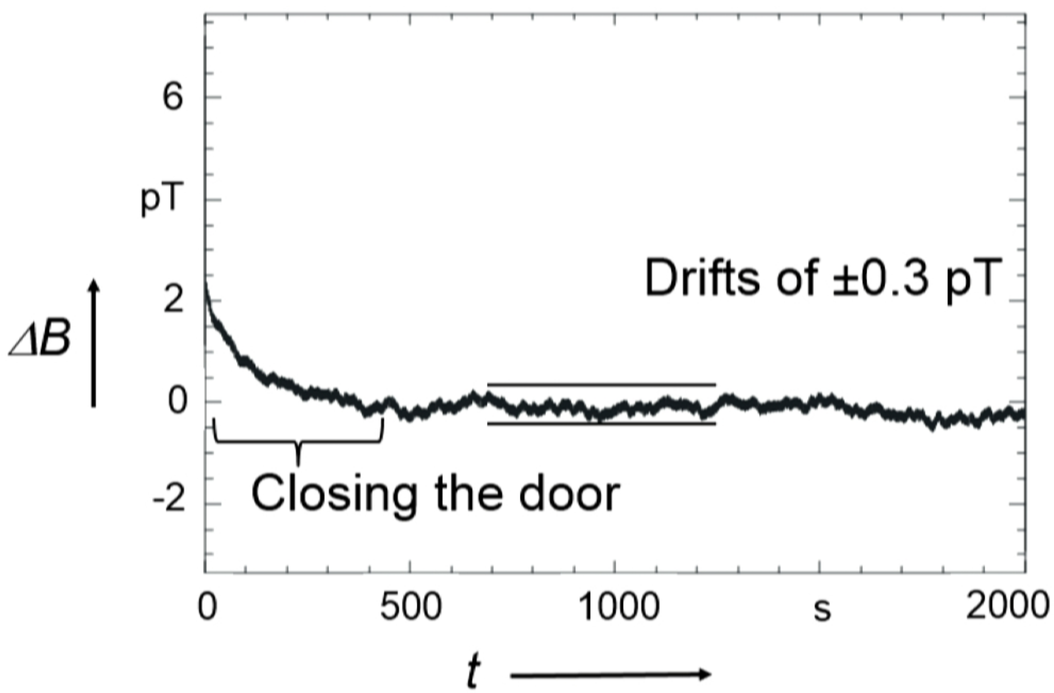
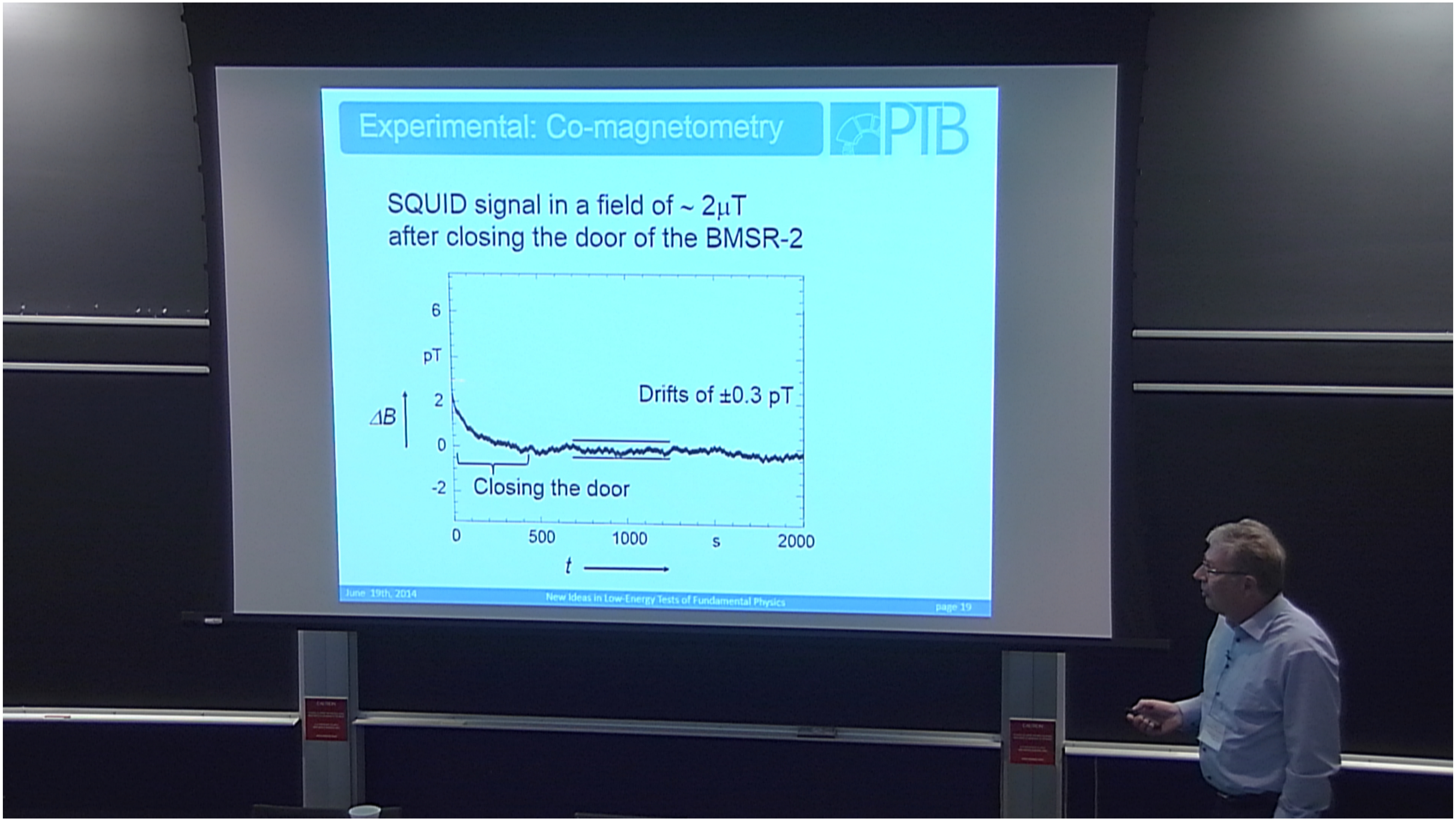
Experimental: Co-magnetometry

SQUID signal in a field of ~ 2μT
after closing the door of the BMSR-2





Experimental: Co-magnetometry
PTB
SQUID signal in a field of ~ 2μT
after closing the door of the BMSR-2
6
pT
2
ΔB
0
-2
Drifts of ±0.3 pT
Closing the door
0
500
1000
s
2000
t
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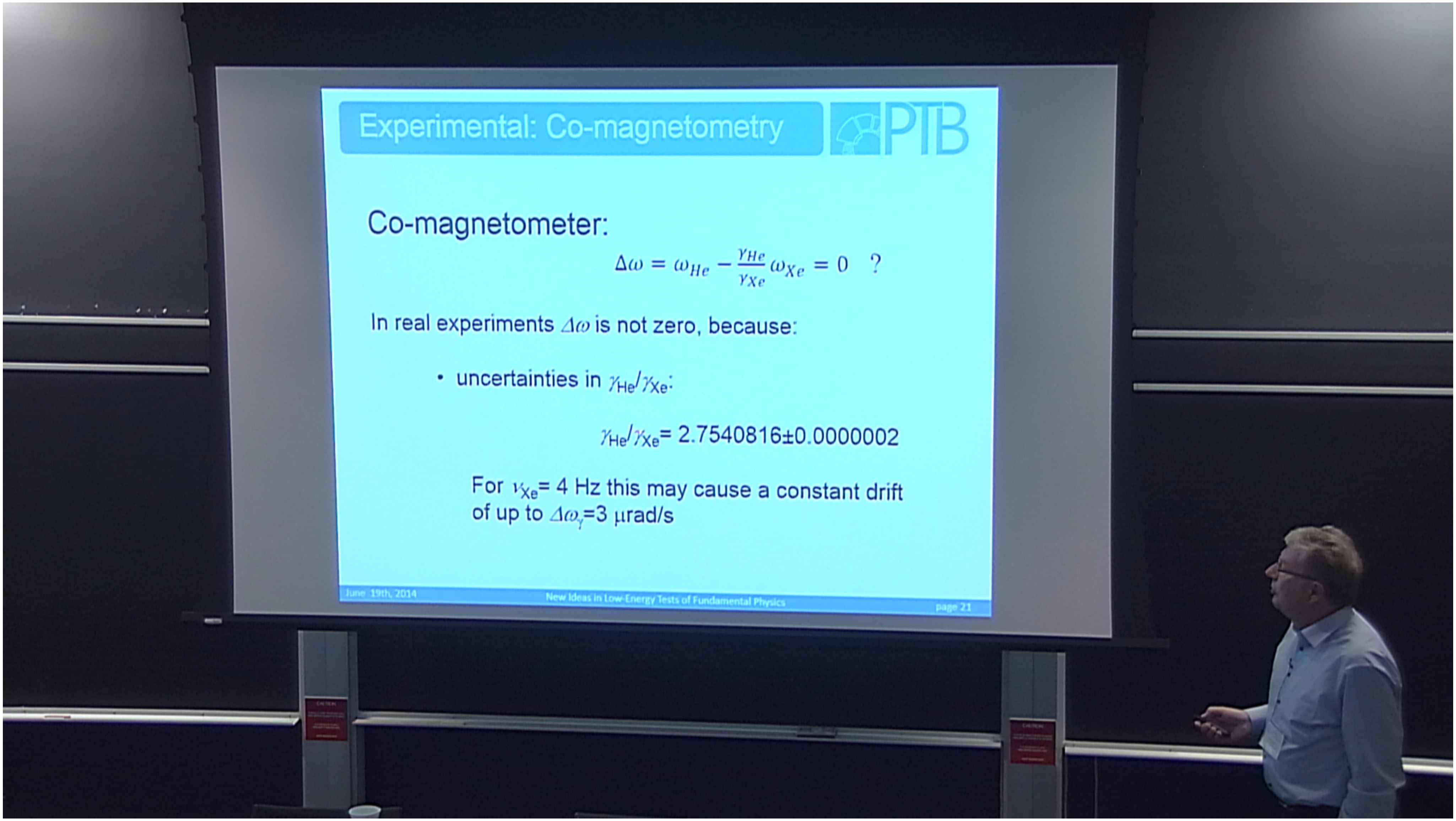
Experimental: Co-magnetometry
PTB
Co-magnetometer:
$\Delta\omega = \omega_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \omega_{Xe} = 0$?
In real experiments $\Delta\omega$ is not zero, because:
• uncertainties in γ_{He}/γ_{Xe}:
γ_{He}/γ_{Xe}= 2.7540816±0.0000002
For ν_{Xe}= 4 Hz this may cause a constant drift of up to $\Delta\omega_{\gamma}$=3 μrad/s
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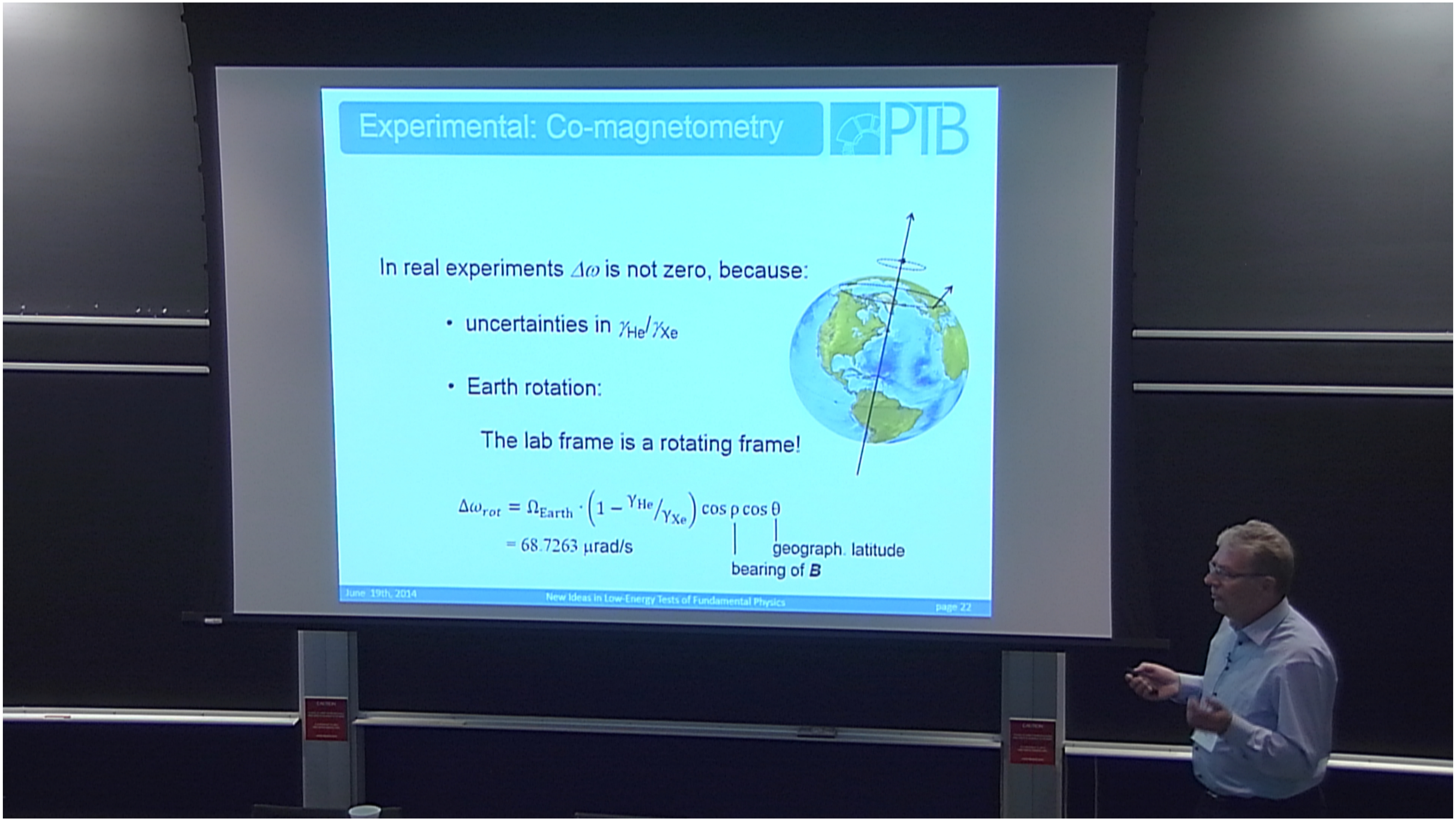
Experimental: Co-magnetometry
PTB
In real experiments Δω is not zero, because:
• uncertainties in γHe/γXe
• Earth rotation:
The lab frame is a rotating frame!
Δωrot = ΩEarth · (1 − γHe/γXe) cos ρ cos θ
= 68.7263 µrad/s
geograph. latitude
bearing of B
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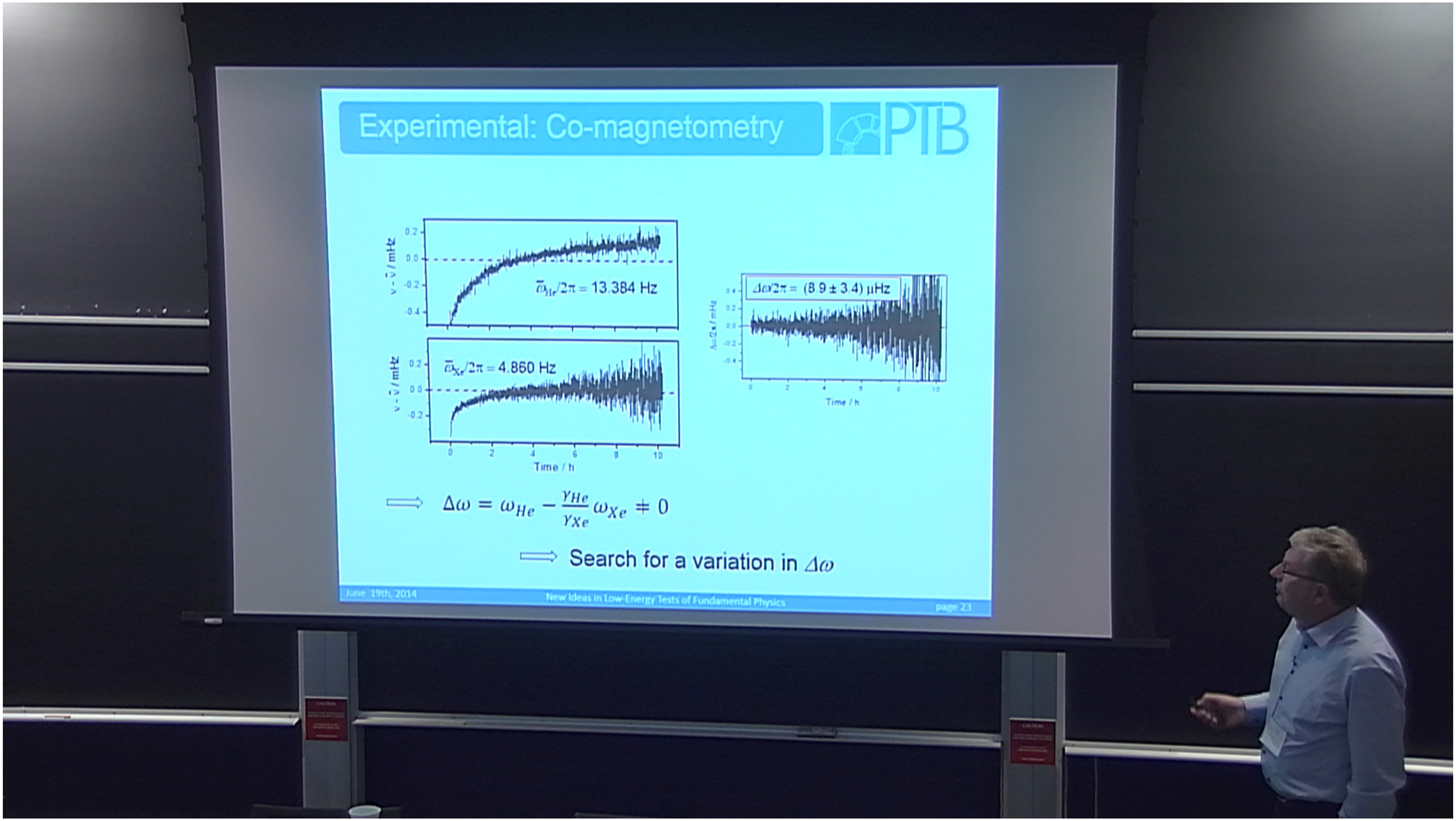

Experimental: Co-magnetometry
PTB
$\bar{\omega}_{He}/2\pi$ = 13.384 Hz
$\bar{\omega}_{Xe}/2\pi$ = 4.860 Hz
$\Delta\omega/2\pi$ = (8.9 ± 3.4) μHz
Time / h
$\Delta\omega = \omega_{He} - \frac{\gamma_{He}}{\gamma_{Xe}}\omega_{Xe} \neq 0$
Search for a variation in $\Delta\omega$
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Search for exotic interactions
PTB
Experimental Set-up
Magnetic shielding
SQUIDs
Field homgeneity
^{3}He-^{129}Xe-Comagnetometry
Search for non-magnetic interactions
XeEDM
Short range interaction
Lorentz-Invariance Violation
Axion wind
SQUID based Comagnetometry
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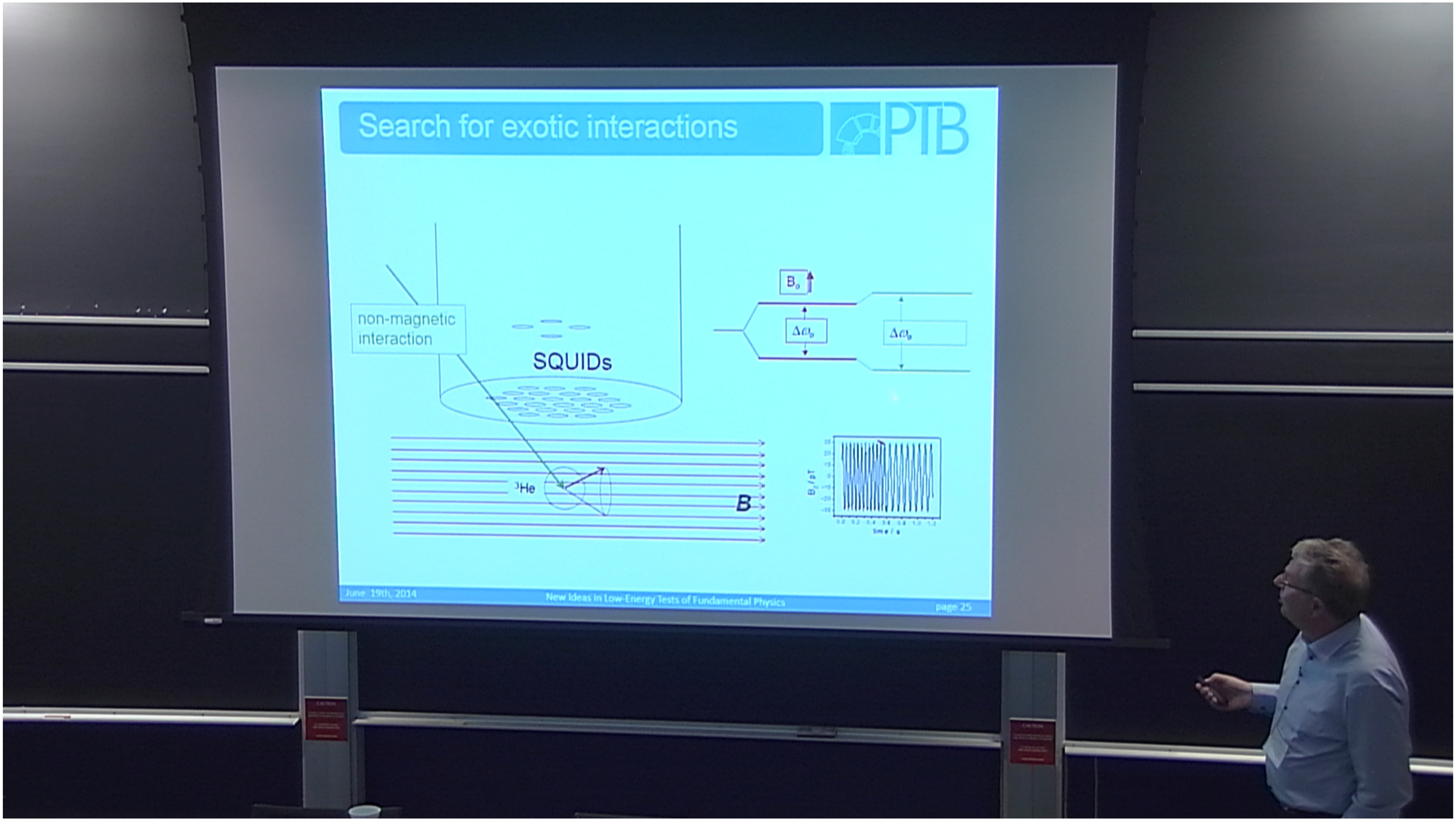
Search for exotic interactions
PTB
non-magnetic
interaction
SQUIDs
^{3}He
B
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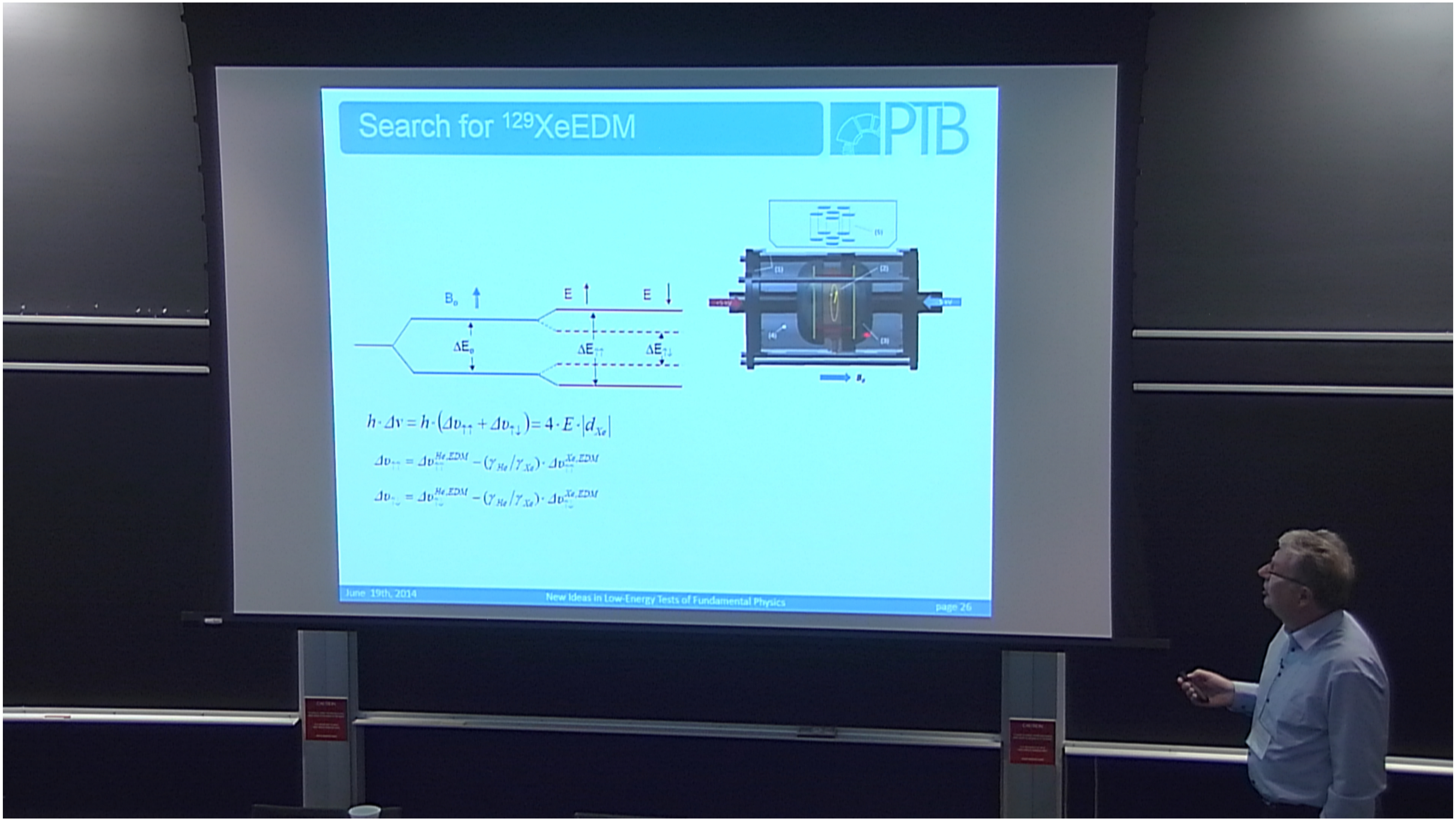
Search for 129XeEDM
B0
E
E
ΔE0
ΔE↑↑
ΔE↑↓
h·Δν = h·(Δν↑↑ + Δν↑↓) = 4·E·|dXe|
Δν↑↑ = Δν↑↑He,EDM − (γHe/γXe)·Δν↑↑Xe,EDM
Δν↑↓ = Δν↑↓He,EDM − (γHe/γXe)·Δν↑↓Xe,EDM
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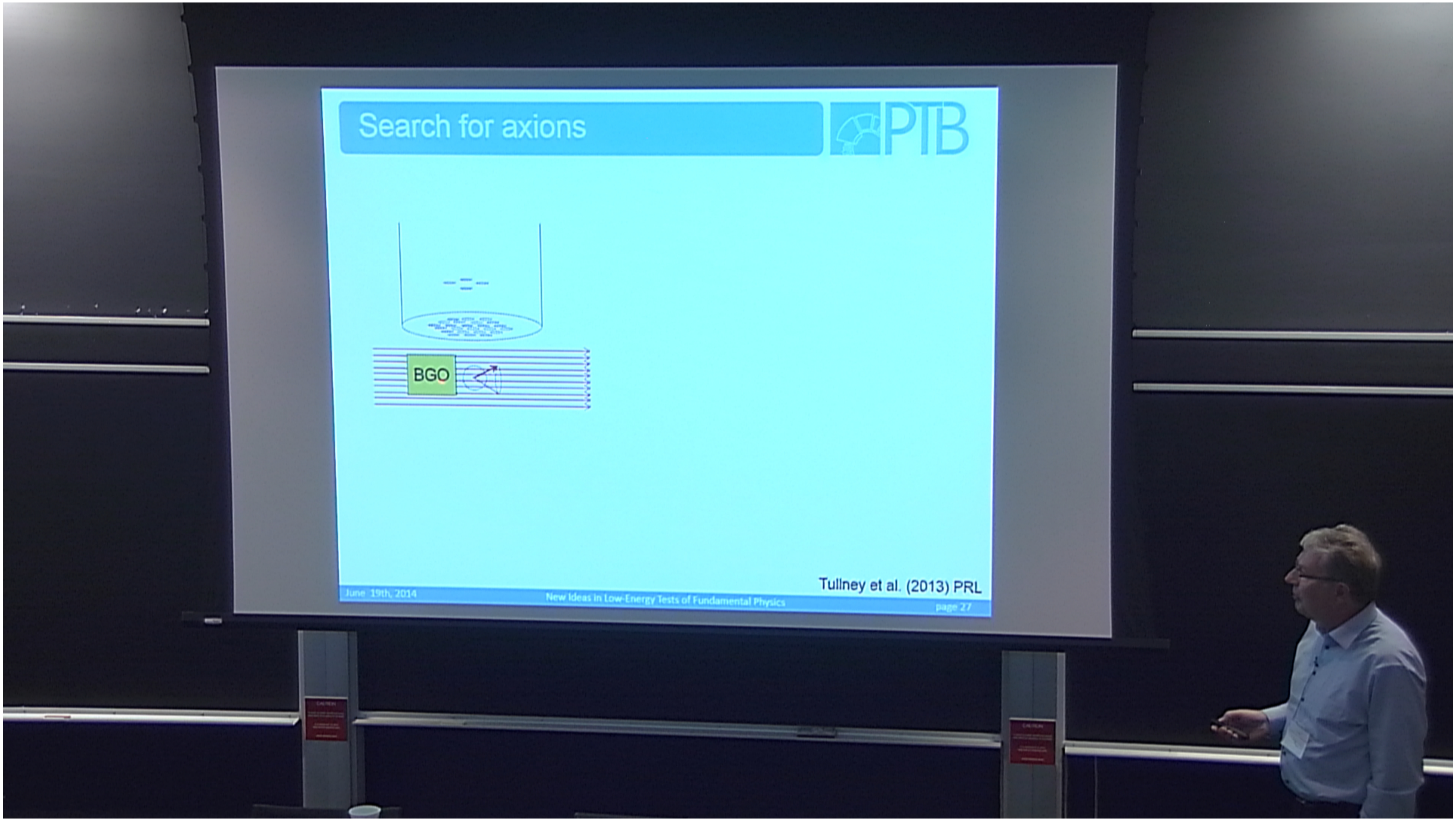

Search for axions
PTB
BGO
Tullney et al. (2013) PRL
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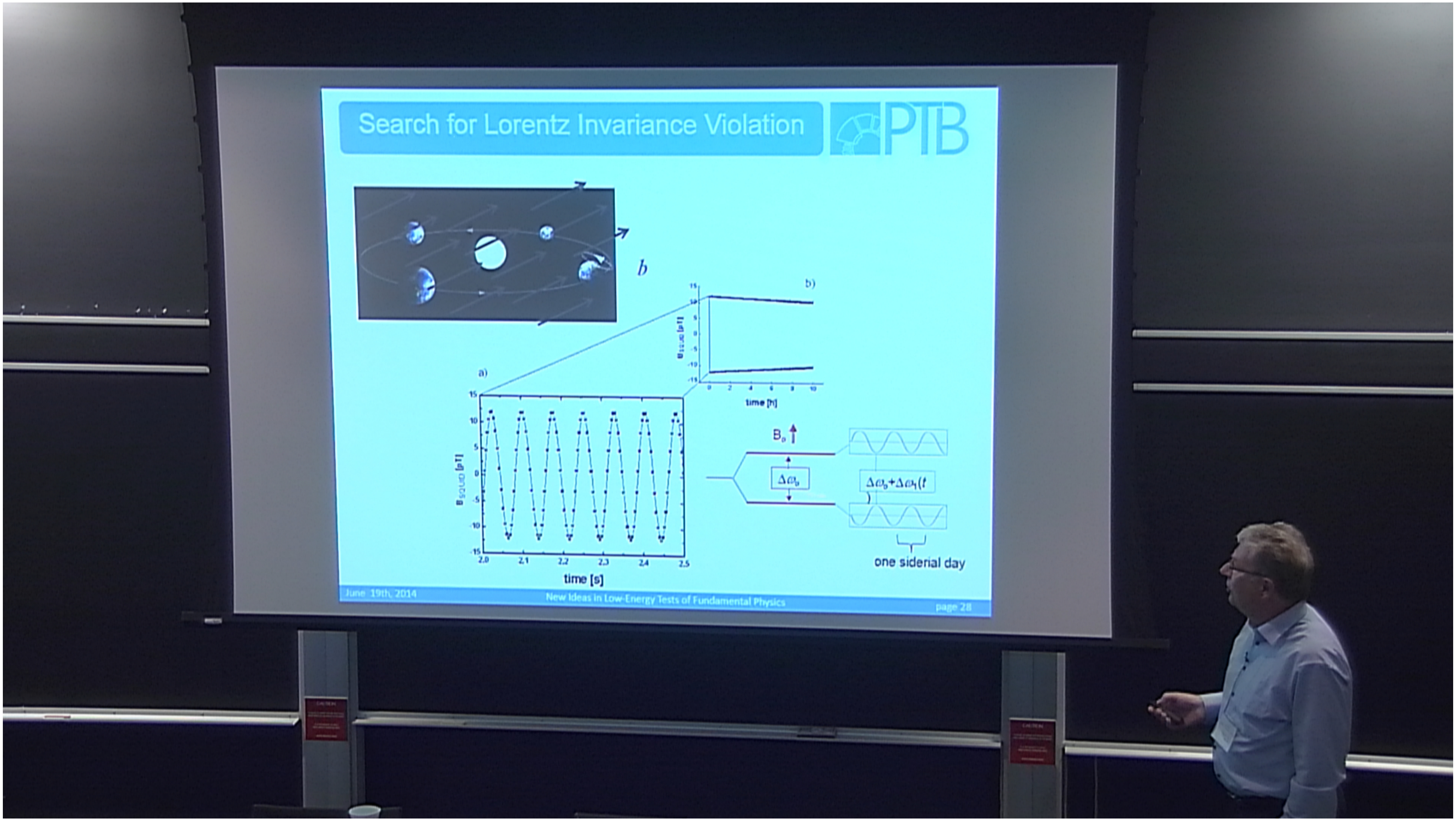

Search for Lorentz Invariance Violation
PTB
b
b)
a)
time [h]
time [s]
B₀
Δω₀
Δω₀+Δω₁(t)
one siderial day
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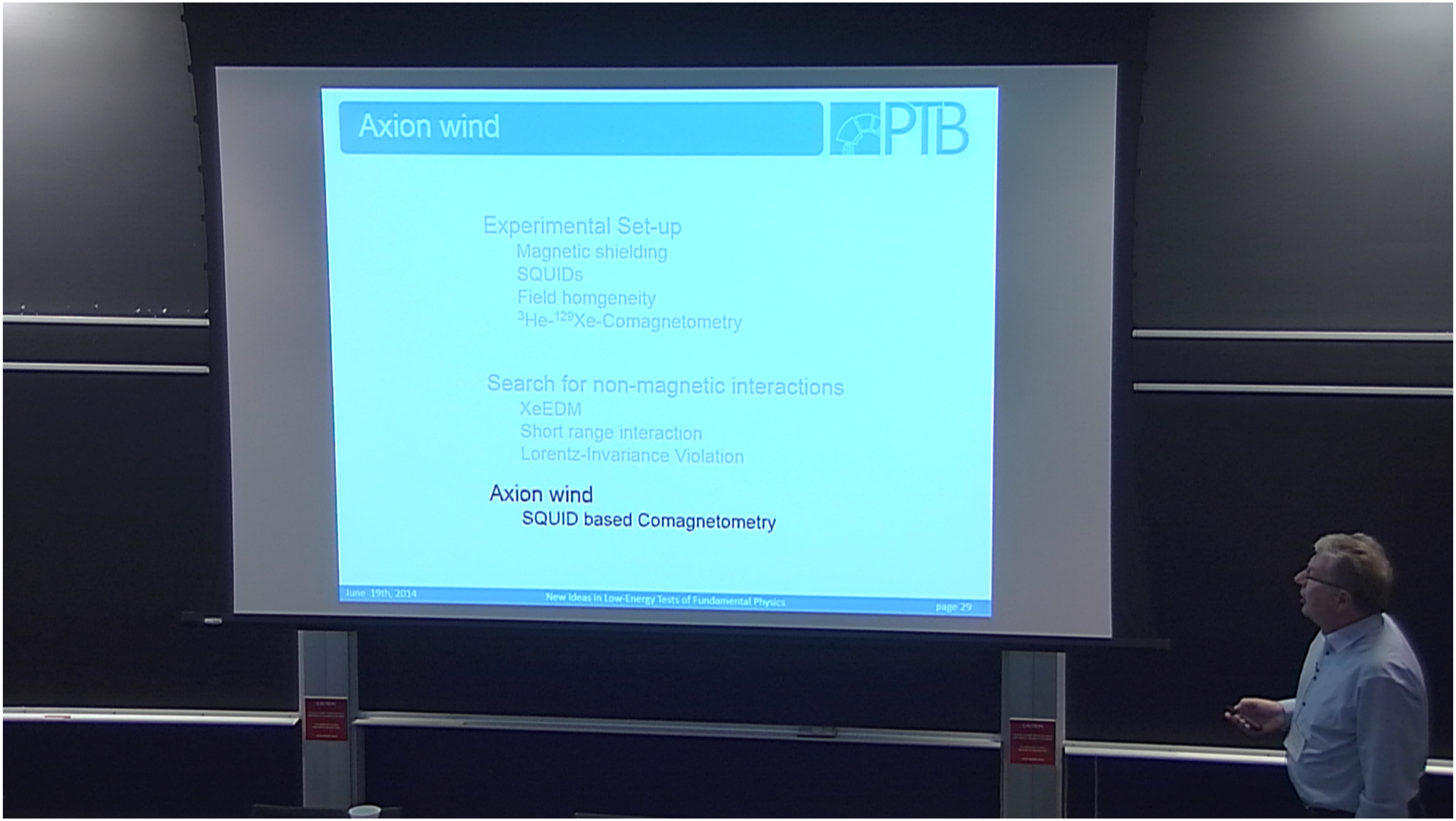
Axion wind
PTB
Experimental Set-up
Magnetic shielding
SQUIDs
Field homgeneity
3He-129Xe-Comagnetometry
Search for non-magnetic interactions
XeEDM
Short range interaction
Lorentz-Invariance Violation
Axion wind
SQUID based Comagnetometry
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Axion wind

Experimental Set-up

- Magnetic shielding
- SQUIDs
- Field homgeneity
- ^{3}He-^{129}Xe-Comagnetometry

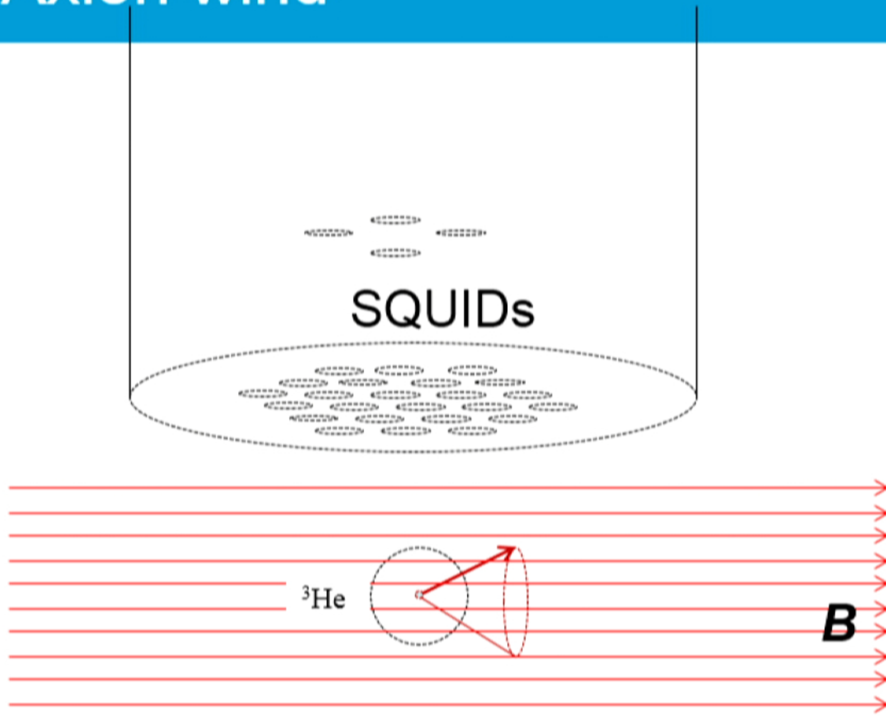
Search for non-magnetic interactions

- XeEDM
- Short range interaction
- Lorentz-Invariance Violation

Axion wind

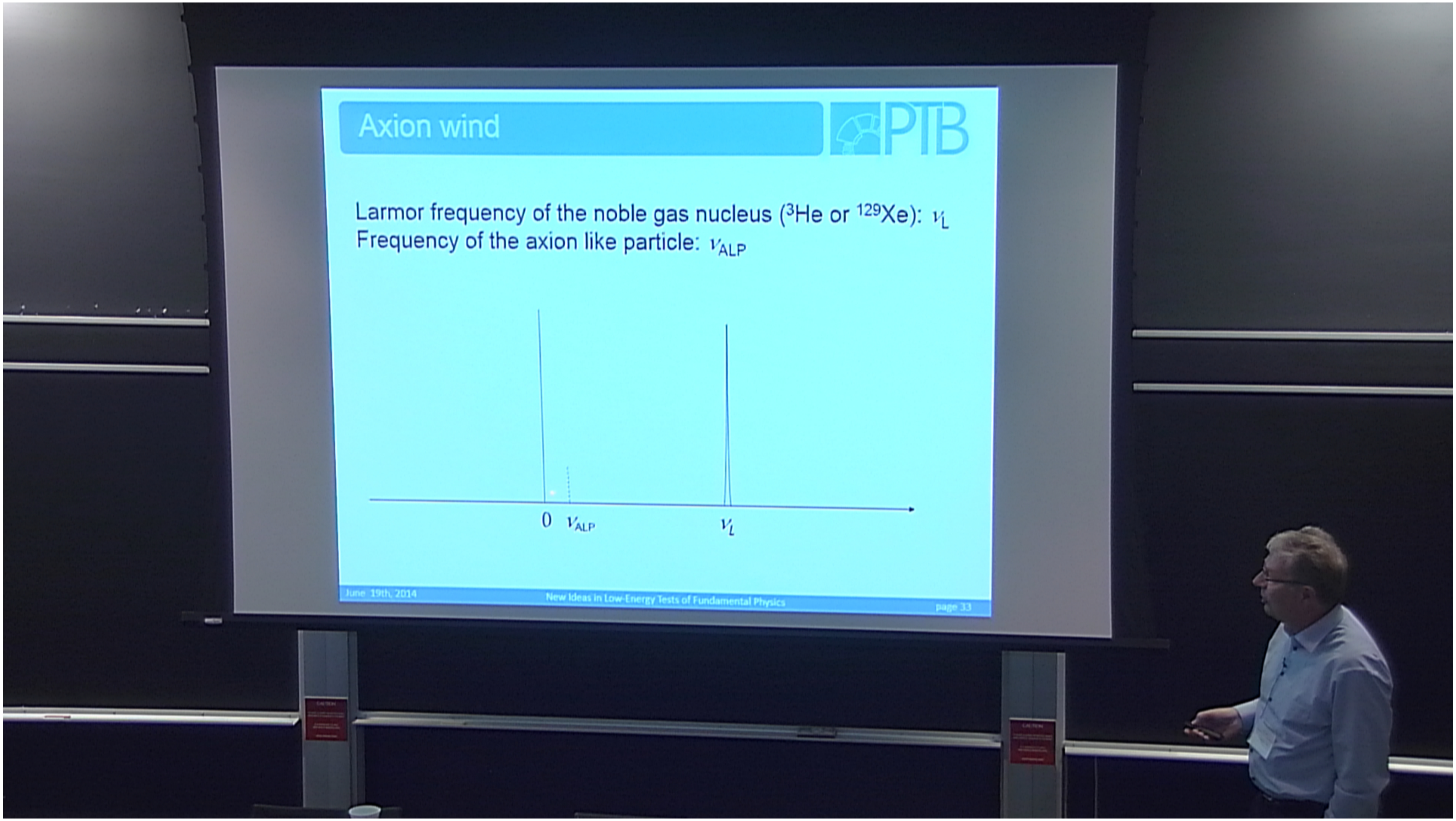
- **SQUID based Comagnetometry**

Axion wind



$$\nu = \nu_{\text{Larmor}}$$

P. Graham and S. Rajendran, PRD 2011, 2013


Axion wind
PTB
Larmor frequency of the noble gas nucleus (3He or 129Xe): νL
Frequency of the axion like particle: νALP
0
νALP
νL
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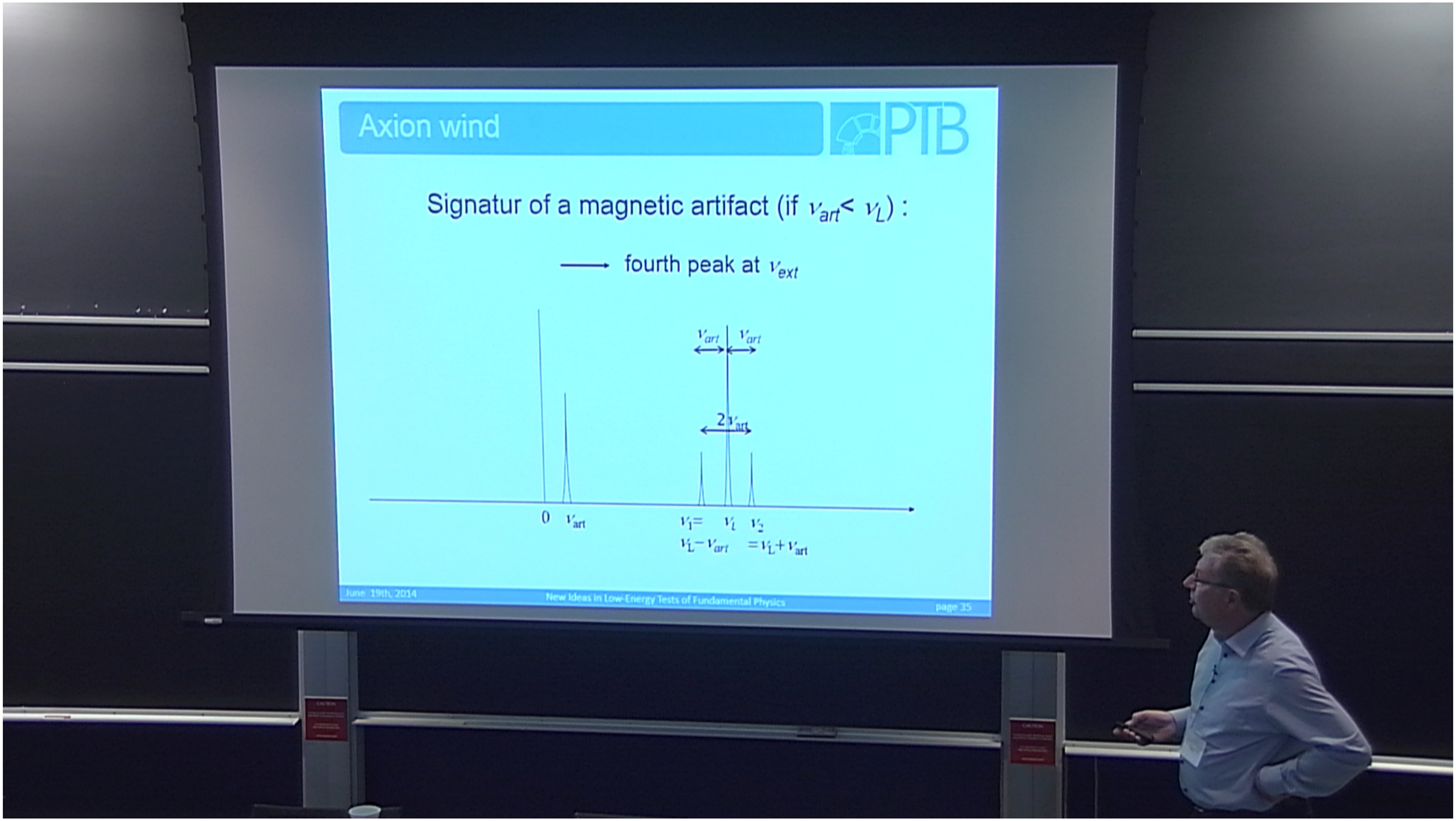

Axion wind
PTB
Signatur of a magnetic artifact (if $\nu_{art} < \nu_L$) :
fourth peak at ν_{ext}
ν_{art}
ν_{art}
$2\nu_{art}$
0
ν_{art}
$\nu_1 = \nu_L - \nu_{art}$
ν_L
$\nu_2 = \nu_L + \nu_{art}$
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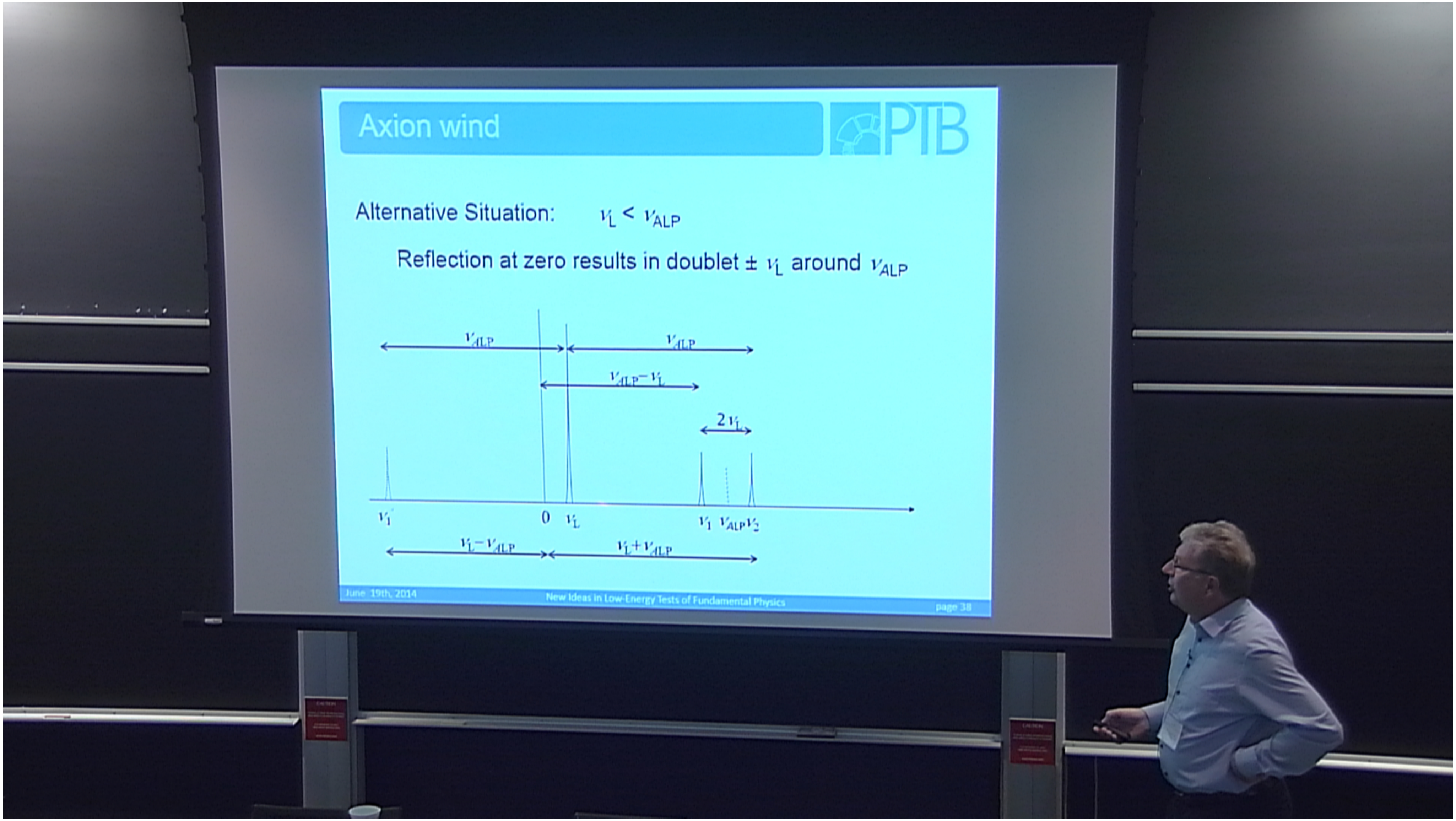
Axion wind
PTB
Alternative Situation: $\nu_L < \nu_{ALP}$
Reflection at zero results in doublet $\pm\ \nu_L$ around ν_{ALP}
ν_{ALP}
ν_{ALP}
$\nu_{ALP} - \nu_L$
$2\nu_L$
ν_1'
0
ν_L
ν_1 ν_{ALP} ν_2
$\nu_L - \nu_{ALP}$
$\nu_L + \nu_{ALP}$
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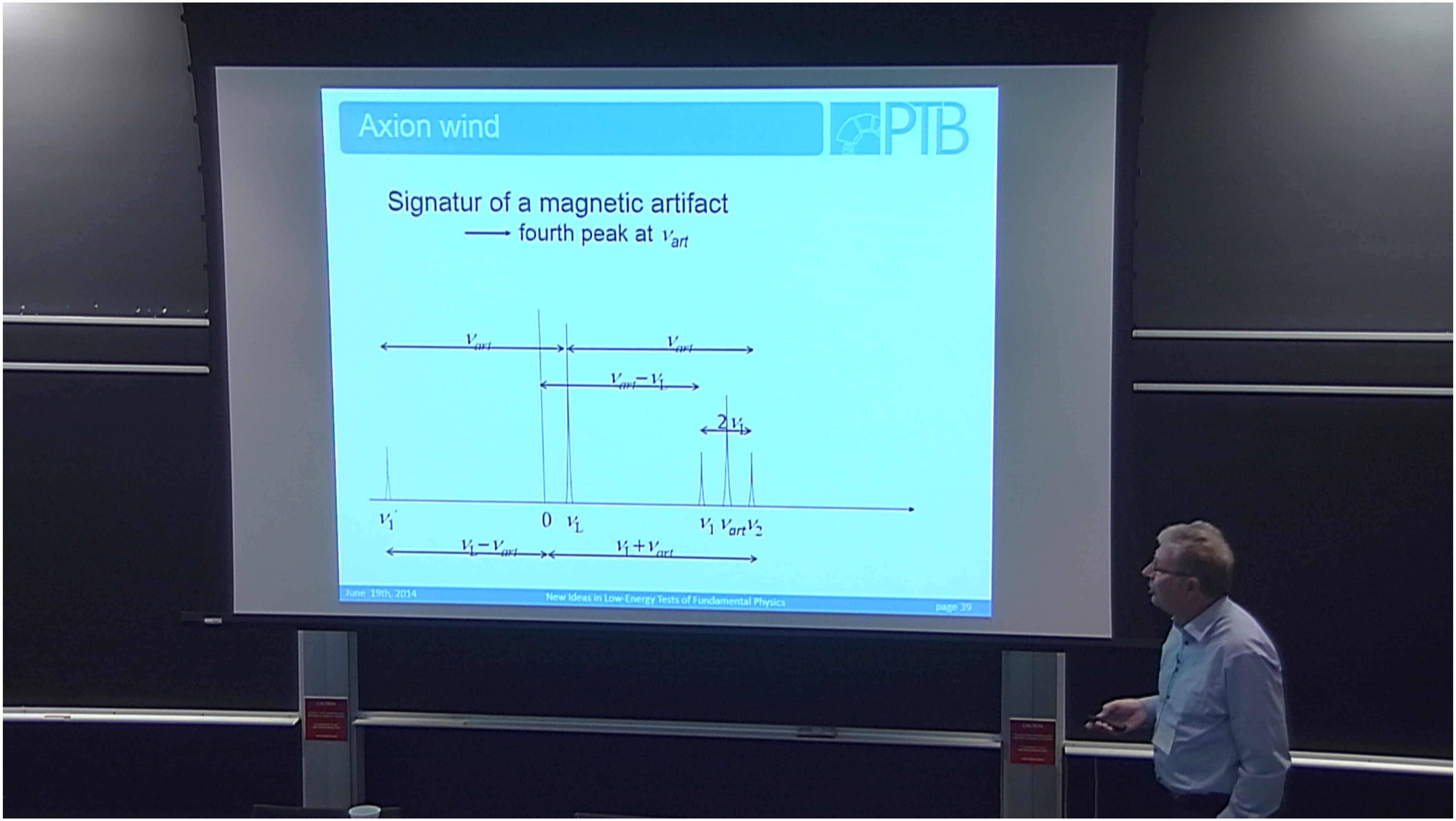

Axion wind
PTB
Signatur of a magnetic artifact
→ fourth peak at ν_{art}
ν_{art}
ν_{art}
$\nu_{art} - \nu_L$
$2\nu_L$
ν_1'
0
ν_L
ν_1 ν_{art} ν_2
$\nu_L - \nu_{art}$
$\nu_L + \nu_{art}$
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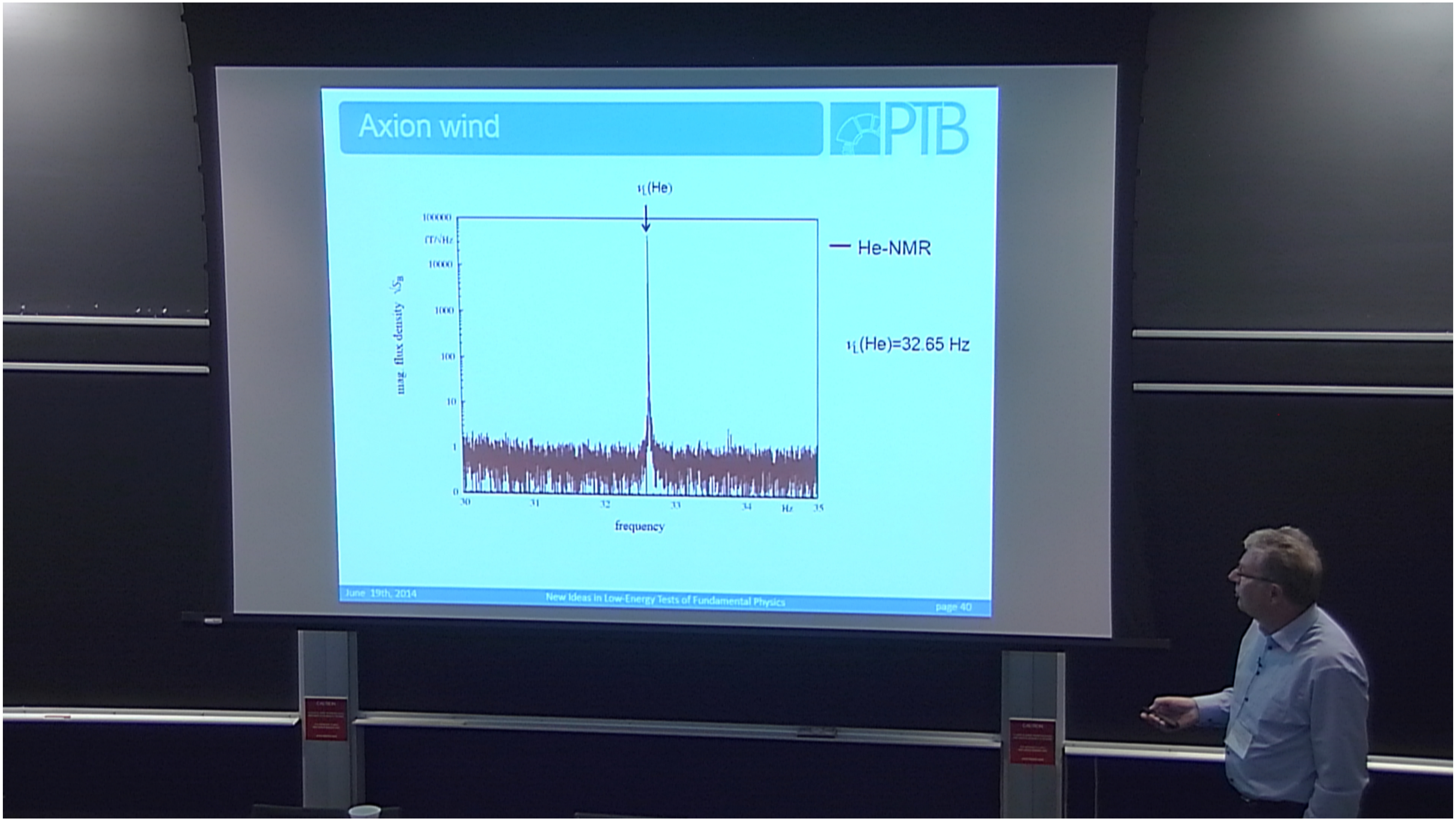

Axion wind
PTB
ν(He)
He-NMR
ν(He)=32.65 Hz
mag. flux density
frequency
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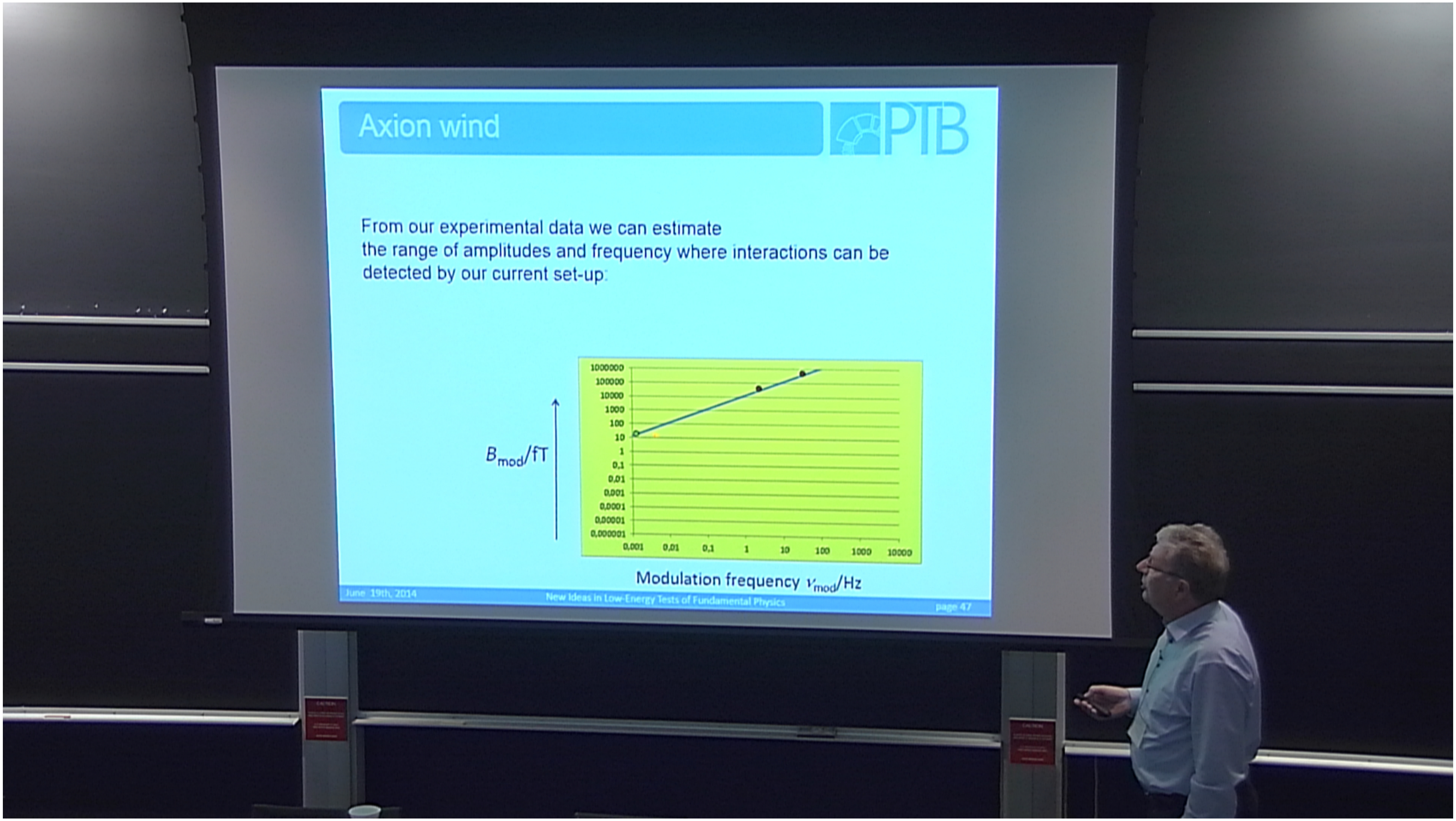
Axion wind
PTB
From our experimental data we can estimate
the range of amplitudes and frequency where interactions can be
detected by our current set-up:
B_{mod}/fT
Modulation frequency ν_{mod}/Hz
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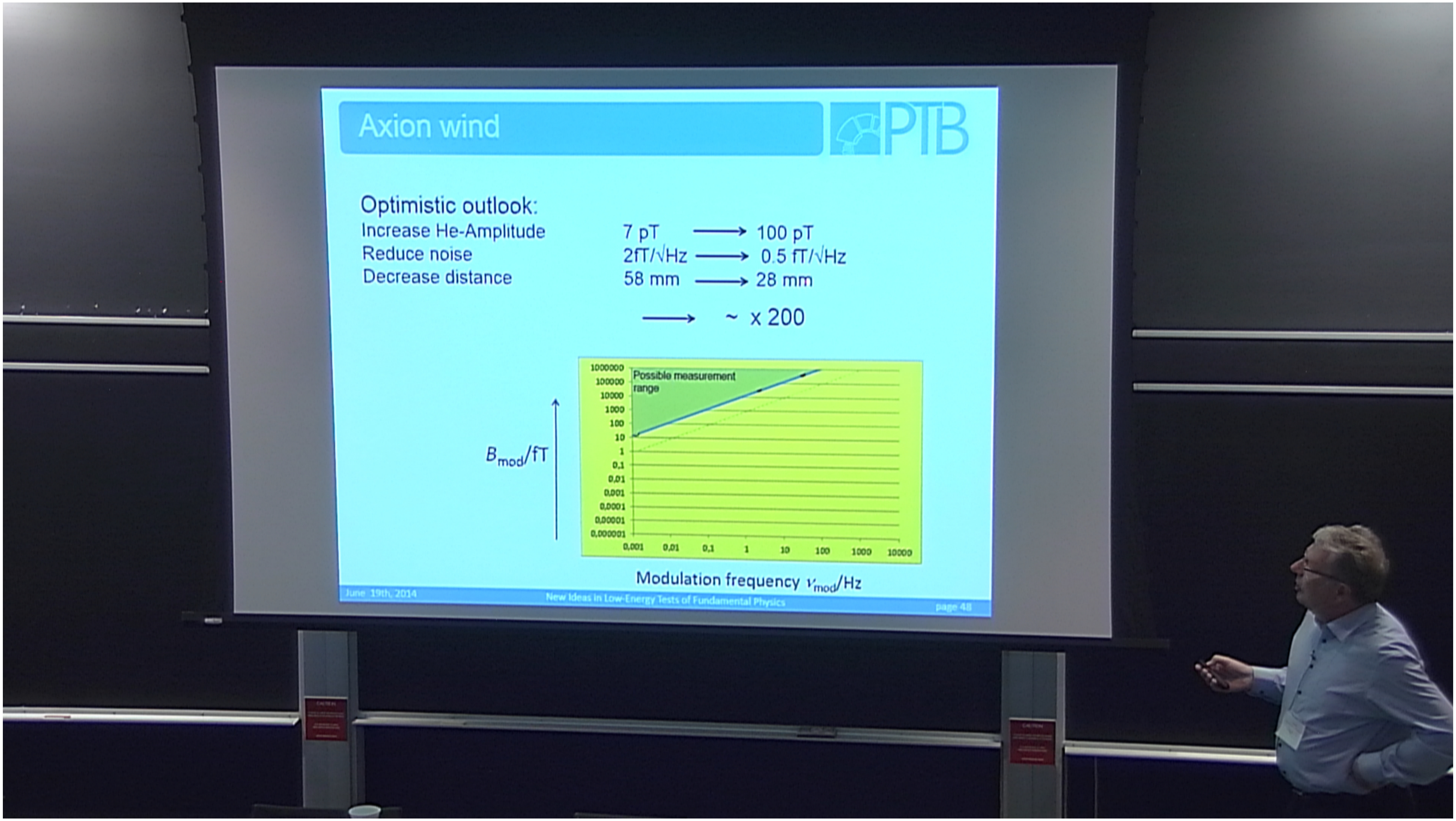
Axion wind
Optimistic outlook:
Increase He-Amplitude 7 pT ⟶ 100 pT
Reduce noise 2fT/√Hz ⟶ 0.5 fT/√Hz
Decrease distance 58 mm ⟶ 28 mm
⟶ ~ x 200
Possible measurement range
1000000
100000
10000
1000
100
10
1
0,1
0,01
0,001
0,0001
0,00001
0,000001
0,001 0,01 0,1 1 10 100 1000 10000
B_{mod}/fT
Modulation frequency ν_{mod}/Hz
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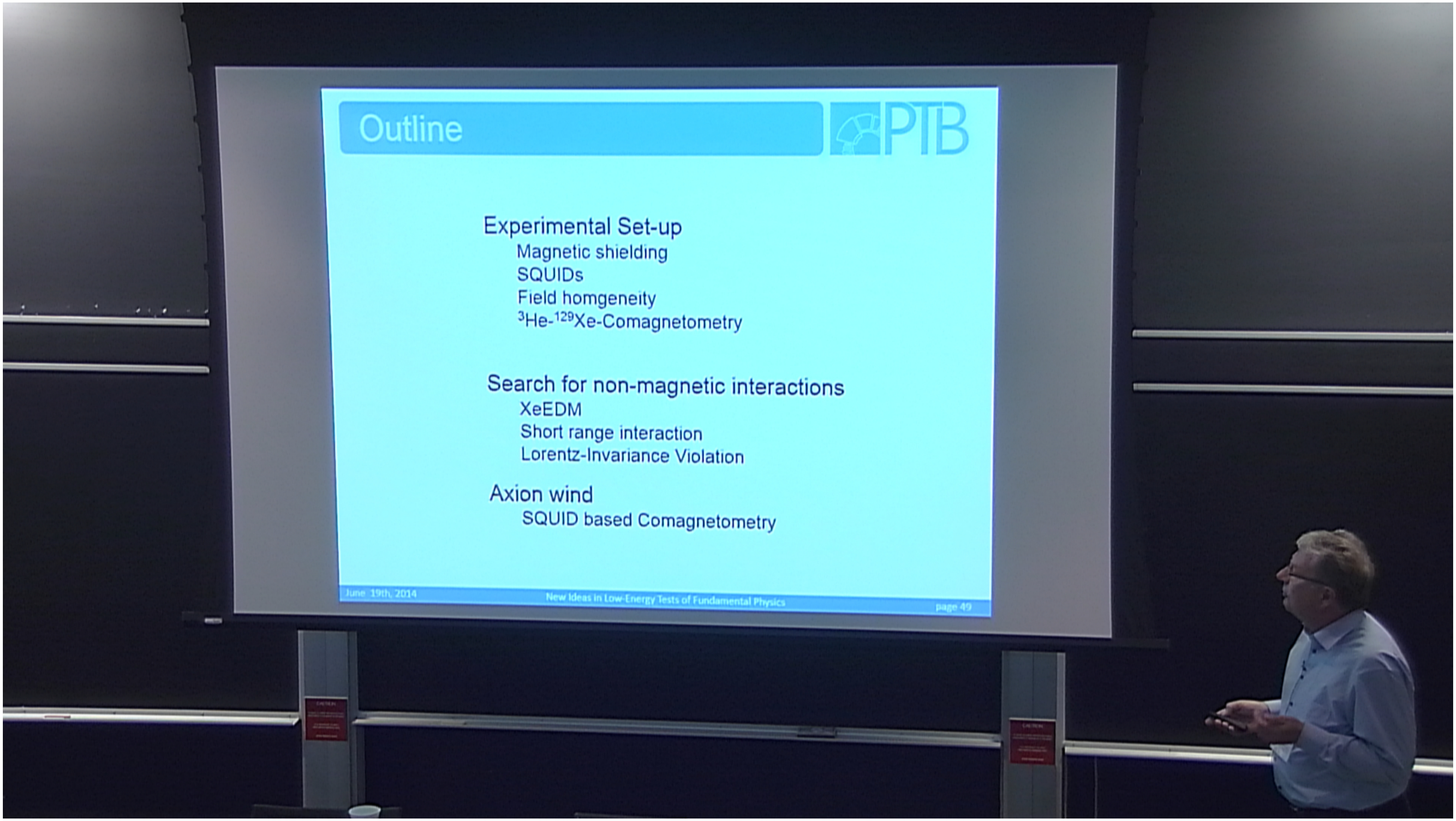
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