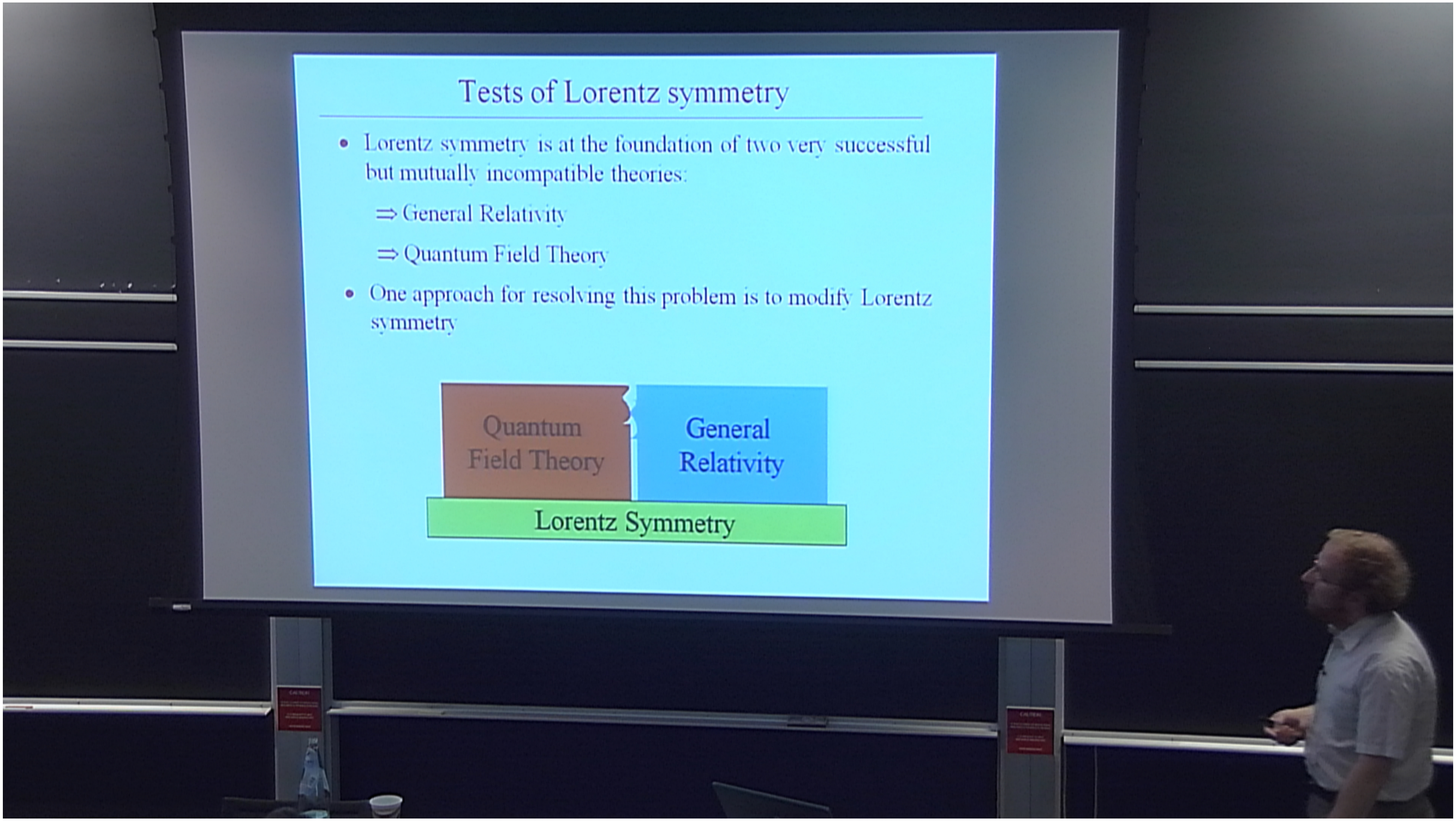
Title: Atomic magnetometers for precision measurements

Date: Jun 19, 2014 10:30 AM

URL: http://pirsa.org/14060034

Abstract: Atomic magnetometers have a long history in tests of Standard Model since they provide sensitive constraints on new spin interactions. I will review recent progress in magnetometry using electron and nuclear spins, describe some of the limits set on new physics and discuss ideas for future experiments.



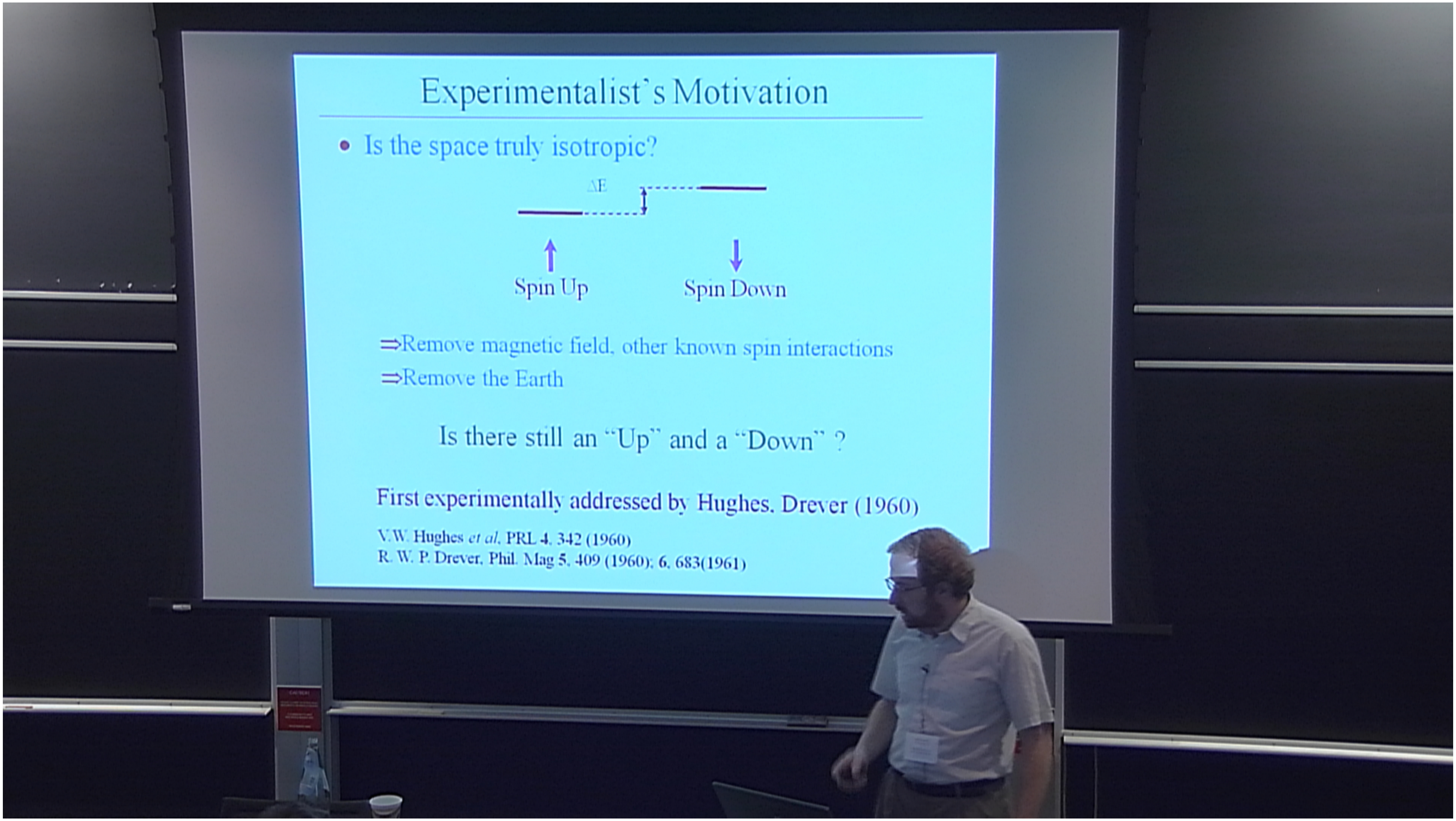
Tests of Lorentz symmetry

- Lorentz symmetry is at the foundation of two very successful but mutually incompatible theories:
  - ⇒ General Relativity
  - ⇒ Quantum Field Theory
- One approach for resolving this problem is to modify Lorentz symmetry

Quantum Field Theory

General Relativity

Lorentz Symmetry



Experimentalist's Motivation

- Is the space truly isotropic?

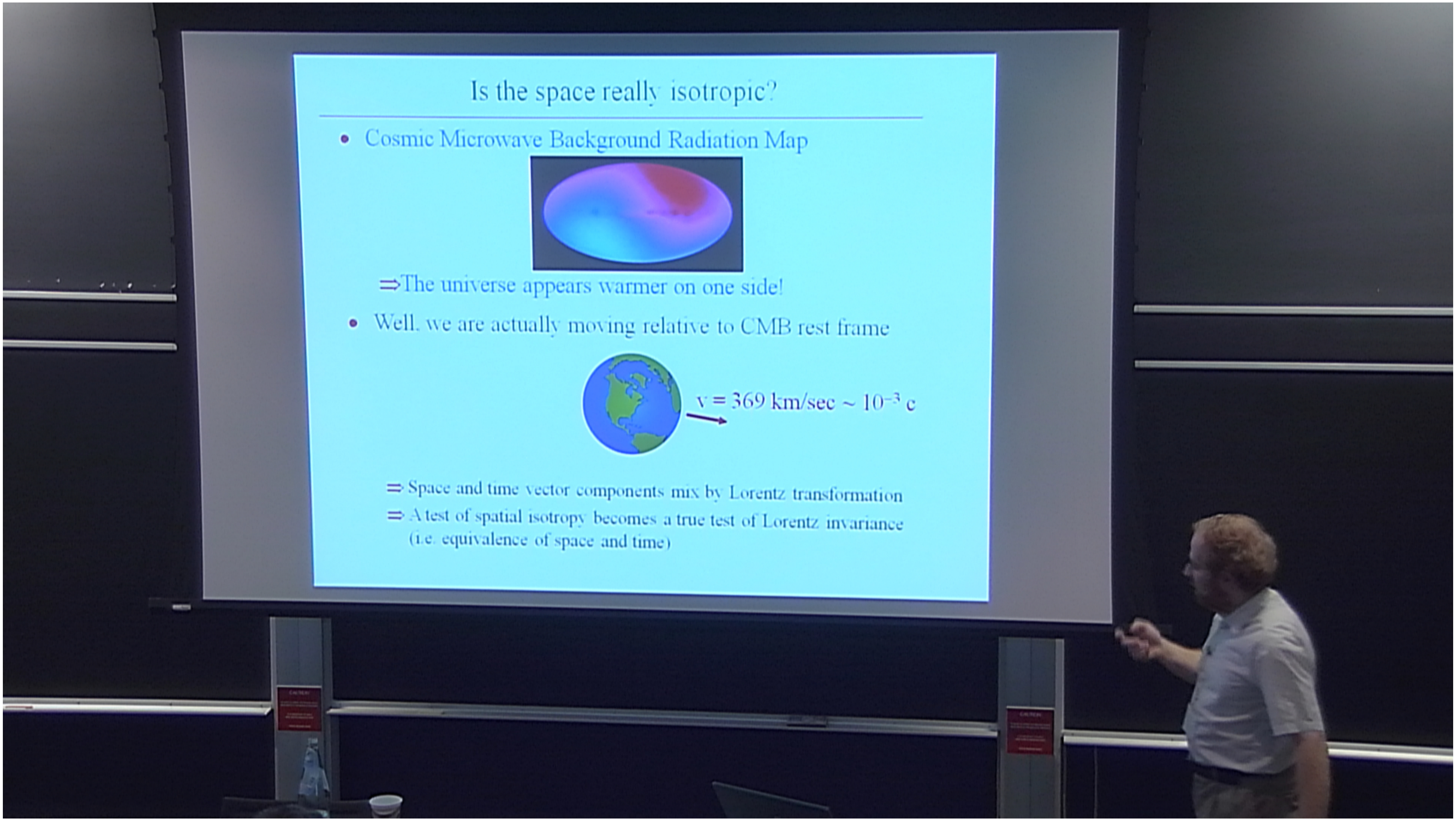
⇒Remove magnetic field, other known spin interactions

⇒Remove the Earth

Is there still an "Up" and a "Down" ?

First experimentally addressed by Hughes, Drever (1960)

V.W. Hughes *et al*, PRL 4, 342 (1960)
R. W. P. Drever, Phil. Mag 5, 409 (1960); 6, 683(1961)



Is the space really isotropic?

- Cosmic Microwave Background Radiation Map

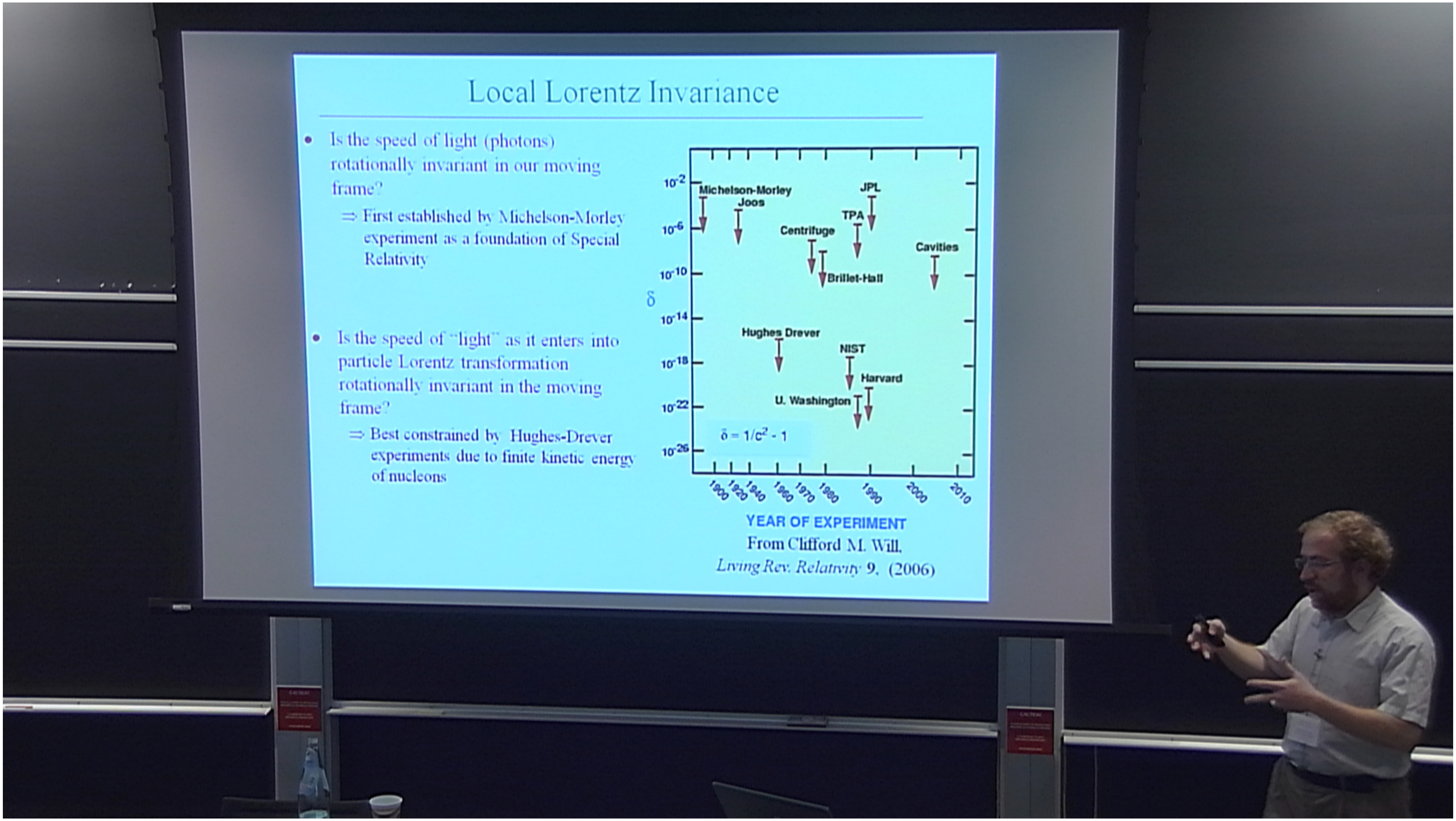
⇒The universe appears warmer on one side!

- Well, we are actually moving relative to CMB rest frame

$v = 369$ km/sec ~ 10^{-3} c

⇒ Space and time vector components mix by Lorentz transformation

⇒ A test of spatial isotropy becomes a true test of Lorentz invariance (i.e. equivalence of space and time)

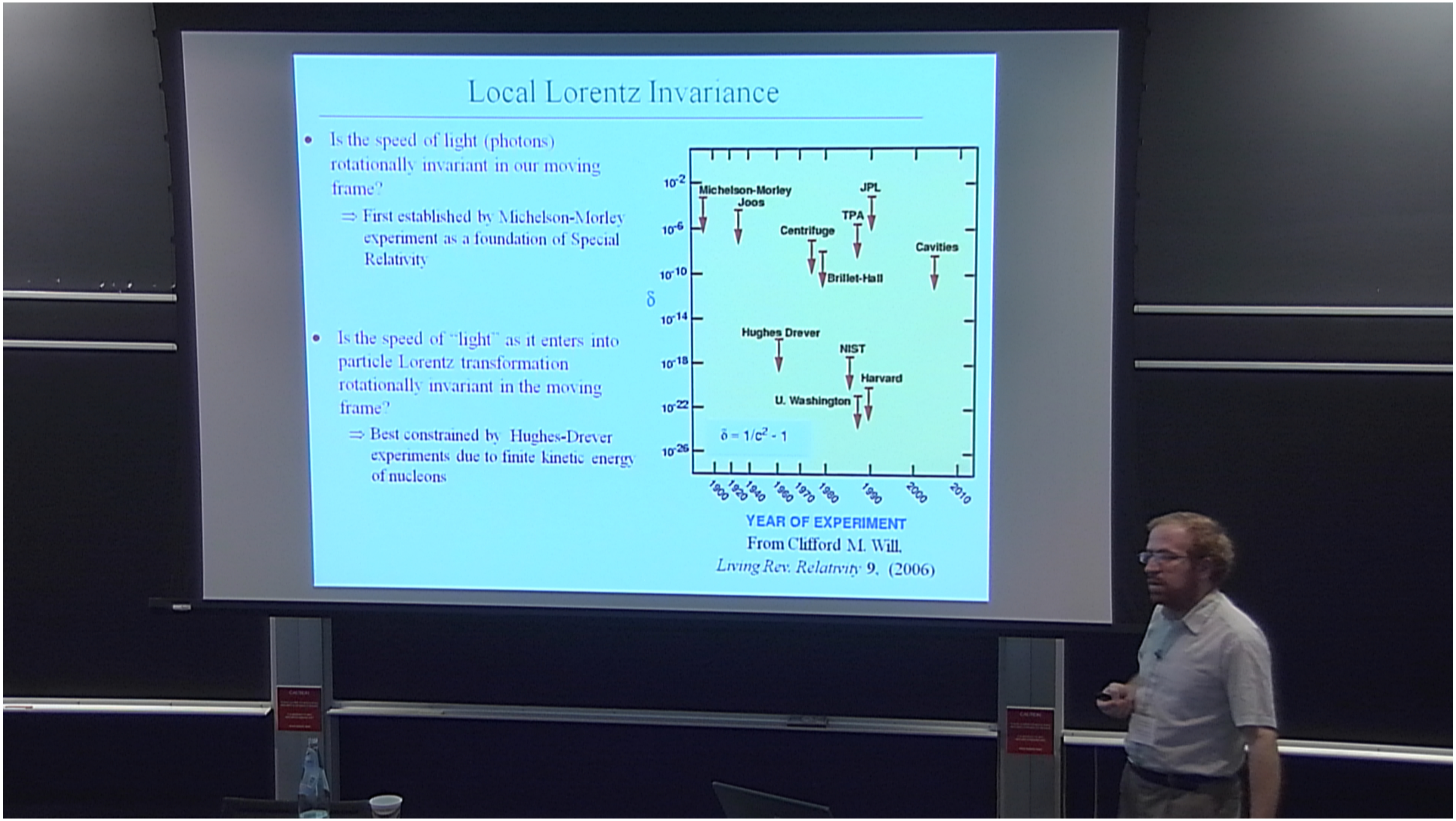


Local Lorentz Invariance

- Is the speed of light (photons) rotationally invariant in our moving frame?
  - ⇒ First established by Michelson-Morley experiment as a foundation of Special Relativity

- Is the speed of "light" as it enters into particle Lorentz transformation rotationally invariant in the moving frame?
  - ⇒ Best constrained by Hughes-Drever experiments due to finite kinetic energy of nucleons

From Clifford M. Will, *Living Rev. Relativity* 9, (2006)



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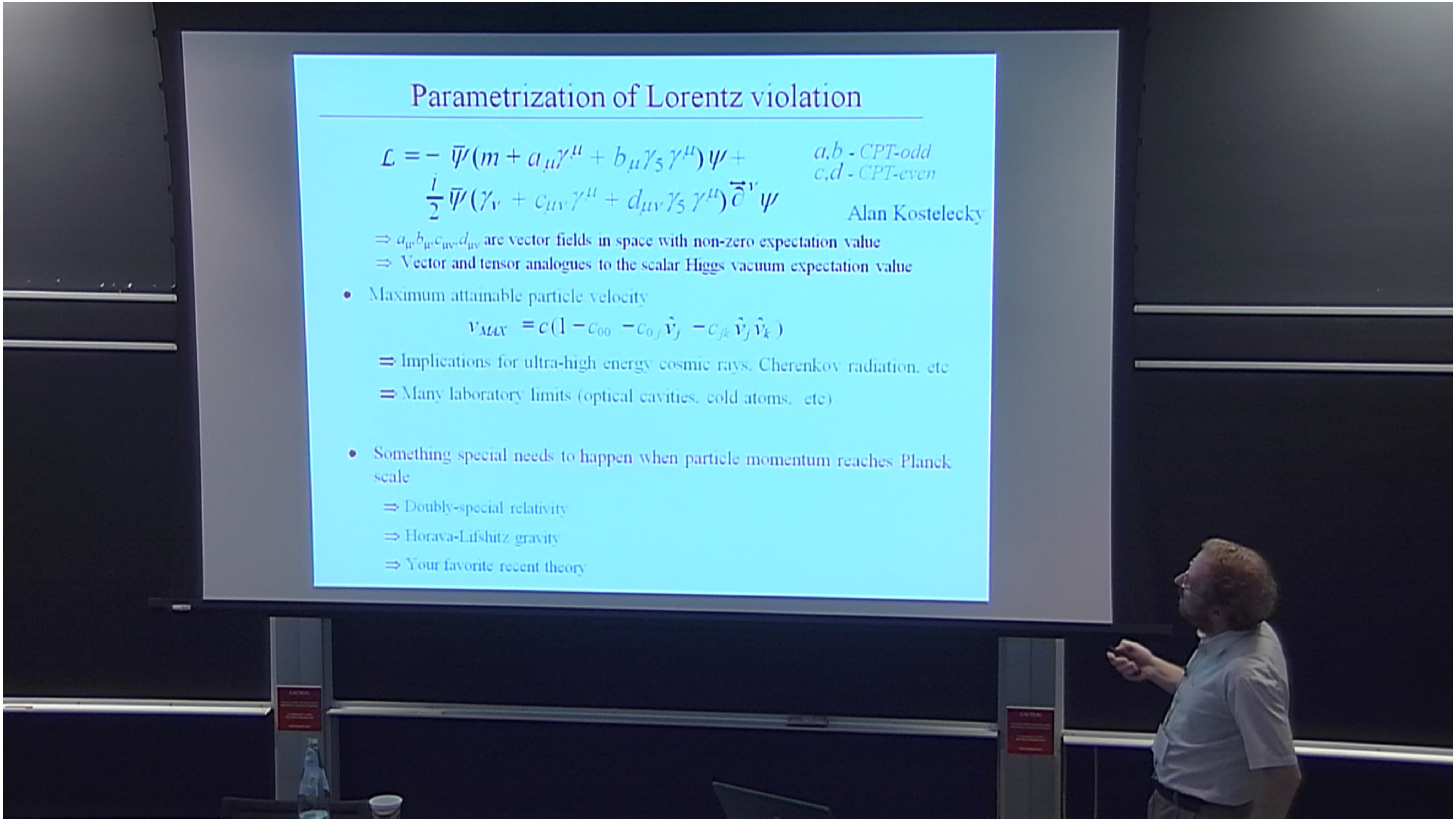

Parametrization of Lorentz violation

$$\mathcal{L} = -\bar{\psi}(m + a_\mu \gamma^\mu + b_\mu \gamma_5 \gamma^\mu)\psi + \frac{i}{2}\bar{\psi}(\gamma_\nu + c_{\mu\nu}\gamma^\mu + d_{\mu\nu}\gamma_5\gamma^\mu)\overleftrightarrow{\partial}^\nu \psi$$

a, b - *CPT-odd*
c, d - *CPT-even*

Alan Kostelecky

⇒ $a_\mu, b_\mu, c_{\mu\nu}, d_{\mu\nu}$ are vector fields in space with non-zero expectation value
⇒ Vector and tensor analogues to the scalar Higgs vacuum expectation value

- Maximum attainable particle velocity

$$v_{MAX} = c(1 - c_{00} - c_{0j}\hat{v}_j - c_{jk}\hat{v}_j\hat{v}_k)$$

⇒ Implications for ultra-high energy cosmic rays, Cherenkov radiation, etc
⇒ Many laboratory limits (optical cavities, cold atoms, etc)

- Something special needs to happen when particle momentum reaches Planck scale

⇒ Doubly-special relativity
⇒ Horava-Lifshitz gravity
⇒ Your favorite recent theory

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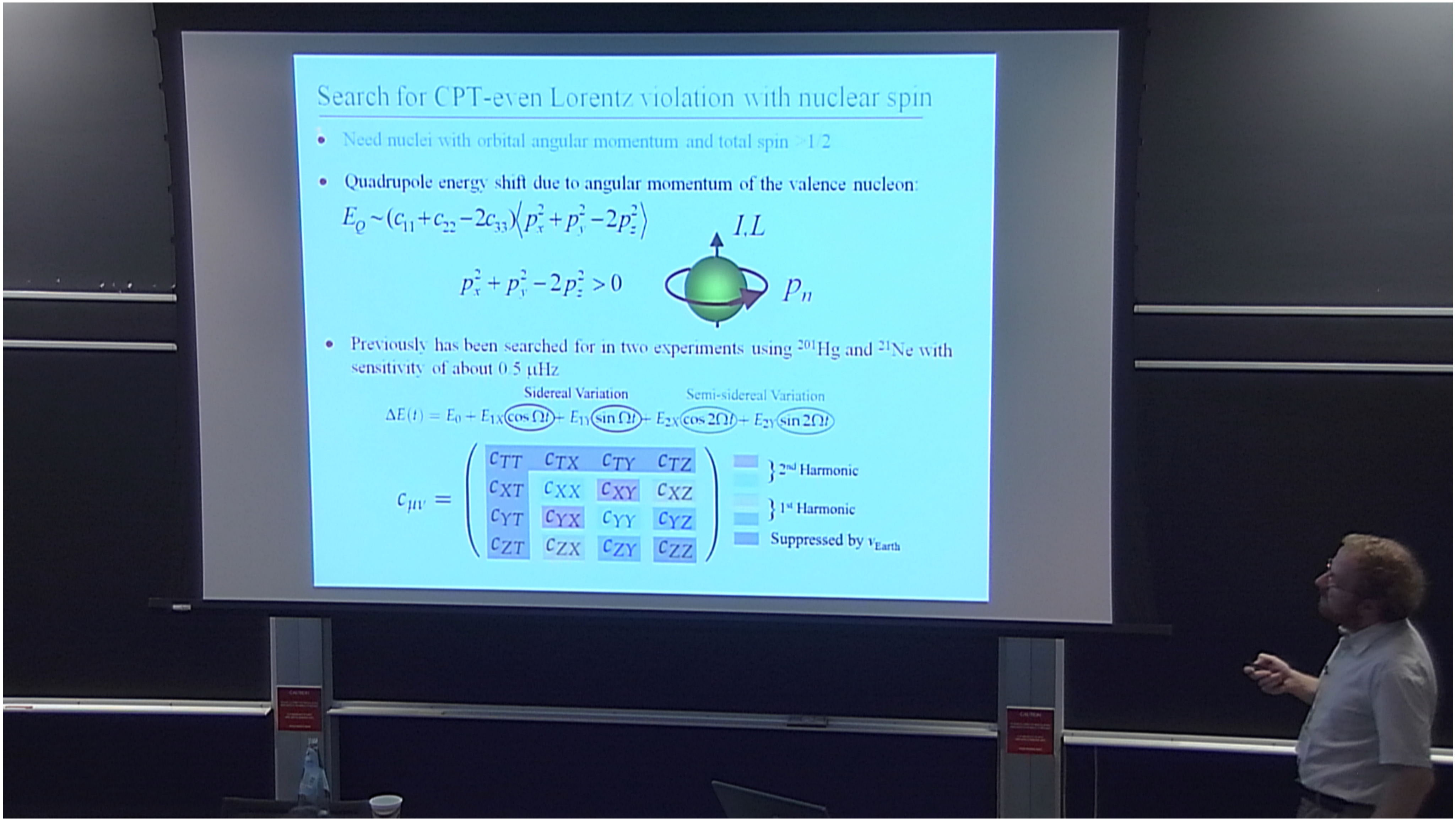


Search for CPT-even Lorentz violation with nuclear spin

- Need nuclei with orbital angular momentum and total spin >1/2
- Quadrupole energy shift due to angular momentum of the valence nucleon:

$$E_Q \sim (c_{11} + c_{22} - 2c_{33})\langle p_x^2 + p_y^2 - 2p_z^2 \rangle$$

$$p_x^2 + p_y^2 - 2p_z^2 > 0$$

- Previously has been searched for in two experiments using ^{201}Hg and ^{21}Ne with sensitivity of about 0.5 μHz

Sidereal Variation　　　Semi-sidereal Variation

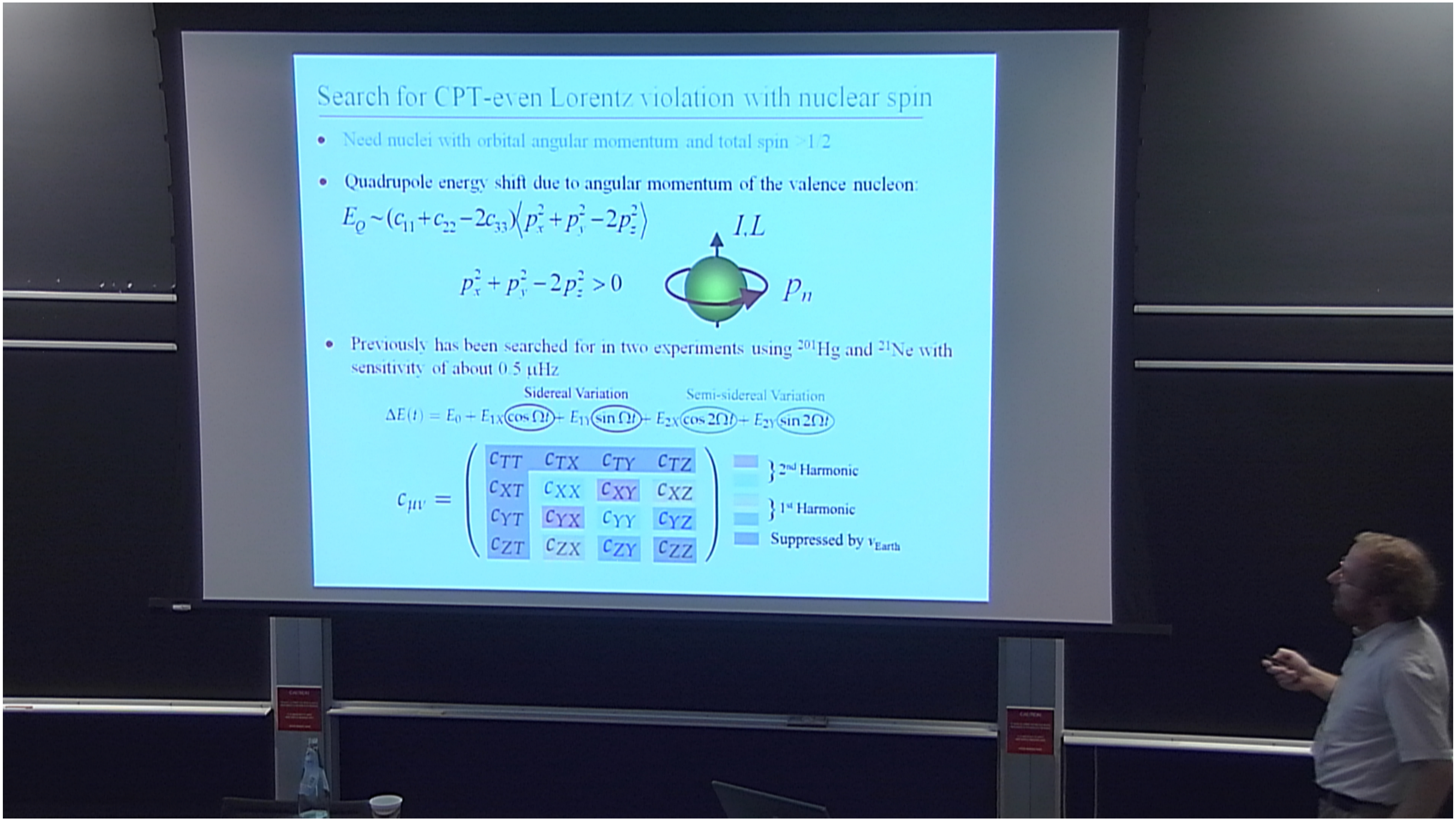
$$\Delta E(t) = E_0 + E_{1X}\boxed{\cos\Omega t} + E_{1Y}\boxed{\sin\Omega t} + E_{2X}\boxed{\cos 2\Omega t} + E_{2Y}\boxed{\sin 2\Omega t}$$

$$c_{\mu\nu} = \begin{pmatrix} c_{TT} & c_{TX} & c_{TY} & c_{TZ} \\ c_{XT} & c_{XX} & c_{XY} & c_{XZ} \\ c_{YT} & c_{YX} & c_{YY} & c_{YZ} \\ c_{ZT} & c_{ZX} & c_{ZY} & c_{ZZ} \end{pmatrix}$$

▨ ▨ } 2nd Harmonic

▨ ▨ } 1st Harmonic

▨ Suppressed by v_{Earth}



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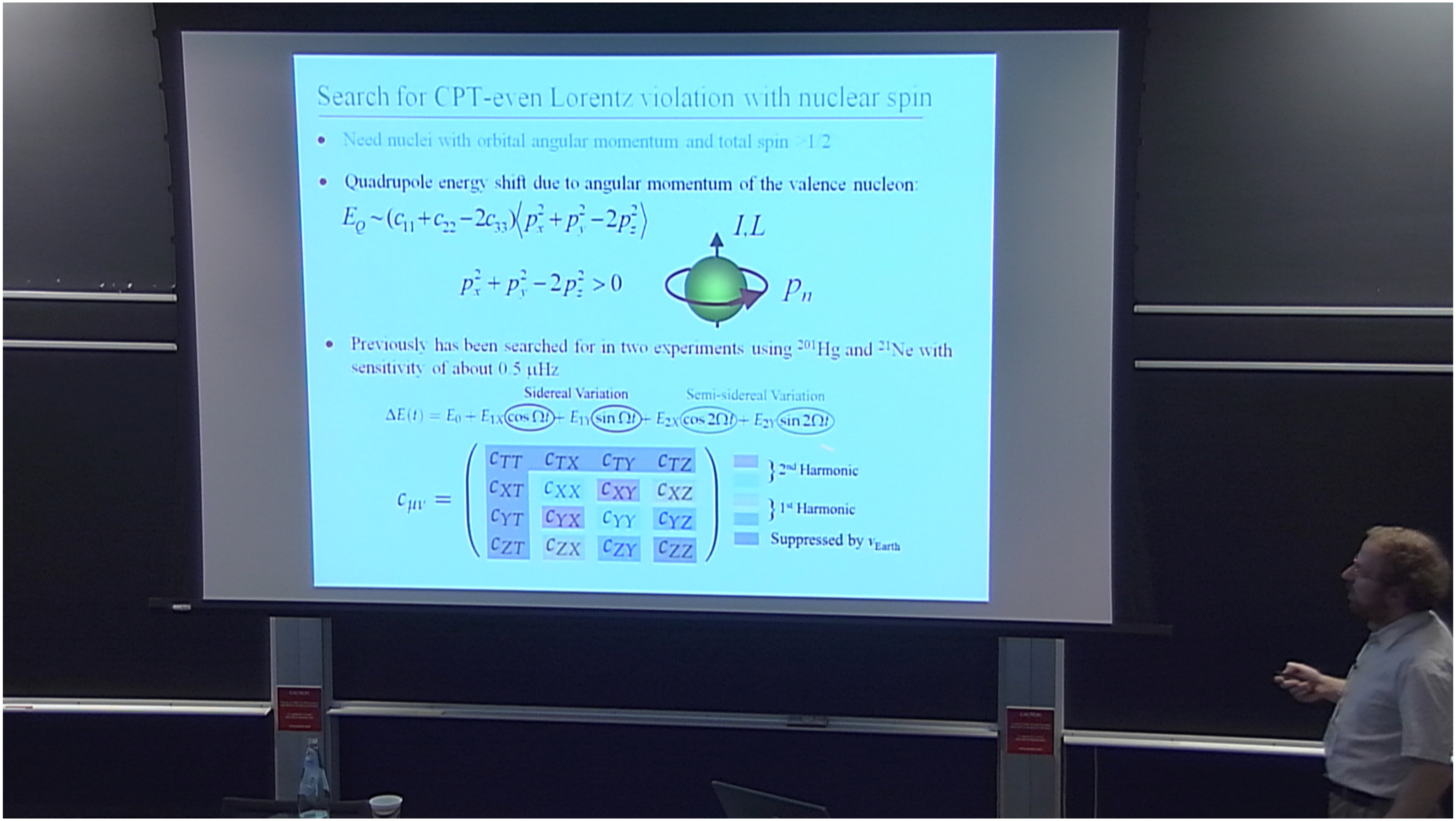

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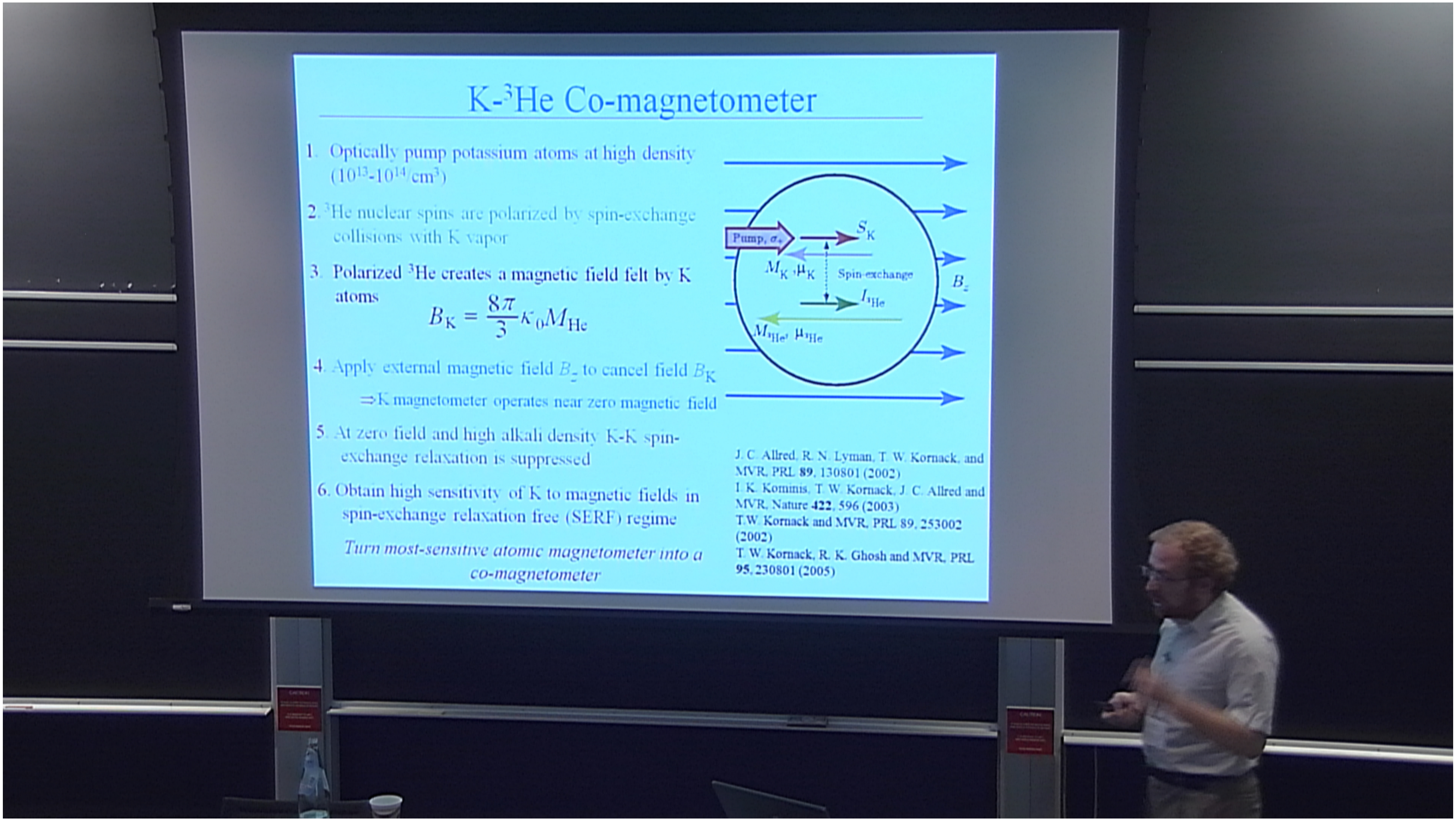

K-^{3}He Co-magnetometer

1. Optically pump potassium atoms at high density (10^{13}-10^{14}/cm^3)
2. ^{3}He nuclear spins are polarized by spin-exchange collisions with K vapor
3. Polarized ^{3}He creates a magnetic field felt by K atoms
$$B_K = \frac{8\pi}{3}\kappa_0 M_{He}$$
4. Apply external magnetic field B_z to cancel field B_K
⇒K magnetometer operates near zero magnetic field
5. At zero field and high alkali density K-K spin-exchange relaxation is suppressed
6. Obtain high sensitivity of K to magnetic fields in spin-exchange relaxation free (SERF) regime

Turn most-sensitive atomic magnetometer into a co-magnetometer

J. C. Allred, R. N. Lyman, T. W. Kornack, and MVR, PRL **89**, 130801 (2002)
I. K. Kominis, T. W. Kornack, J. C. Allred and MVR, Nature **422**, 596 (2003)
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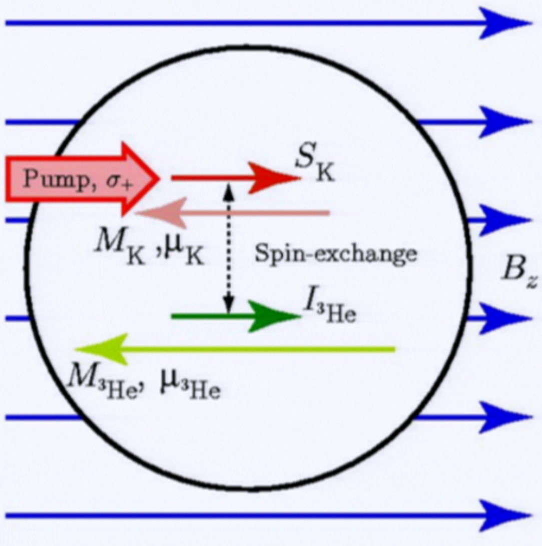

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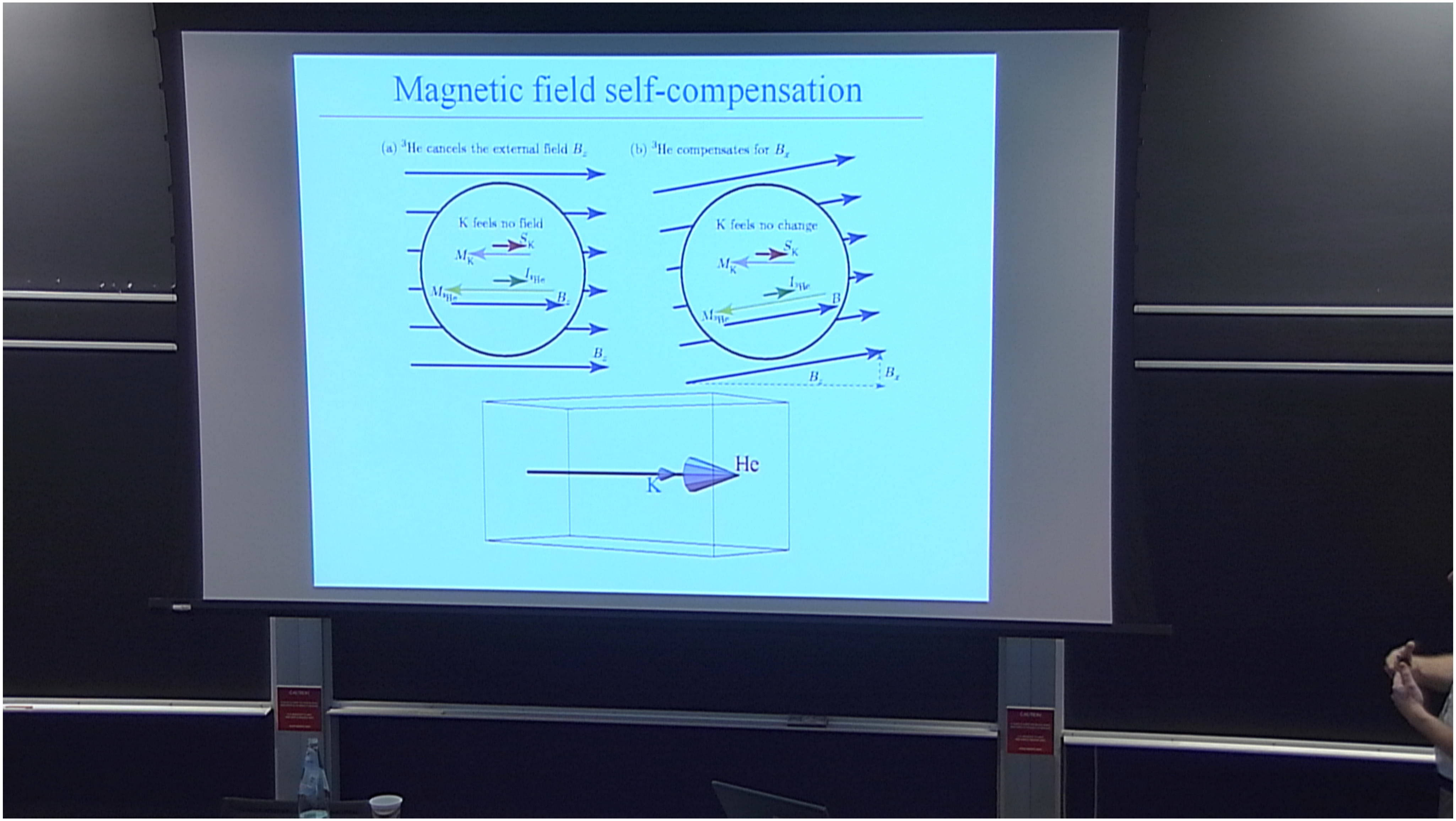
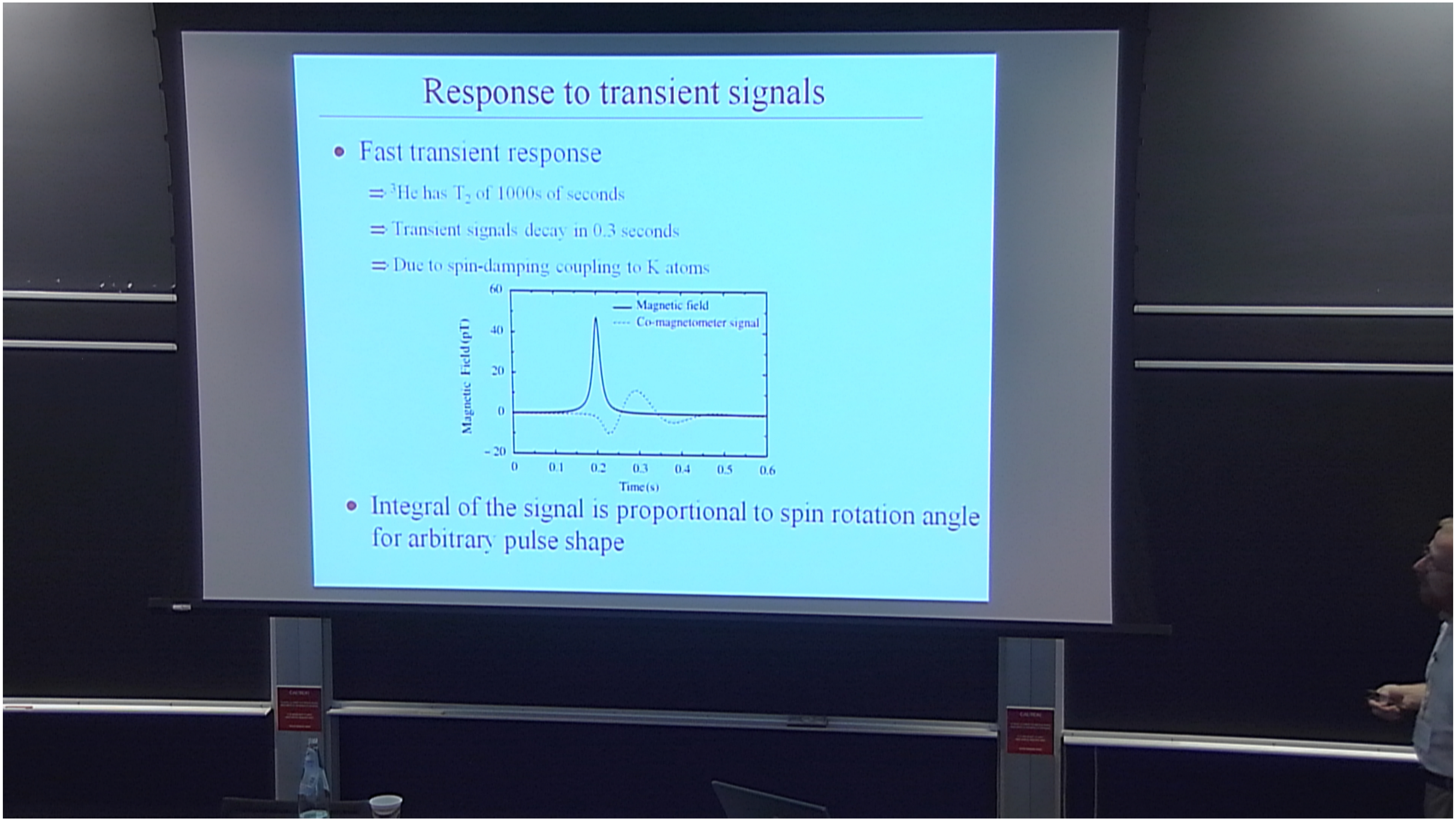


Magnetic field self-compensation

(a) ^{3}He cancels the external field B_z

(b) ^{3}He compensates for B_x



Response to transient signals

- Fast transient response
  - ⇒ ^{3}He has T_2 of 1000s of seconds
  - ⇒ Transient signals decay in 0.3 seconds
  - ⇒ Due to spin-damping coupling to K atoms

- Integral of the signal is proportional to spin rotation angle for arbitrary pulse shape

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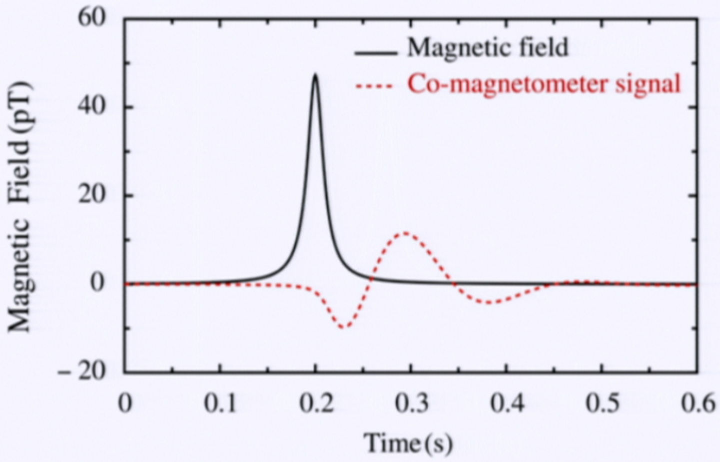

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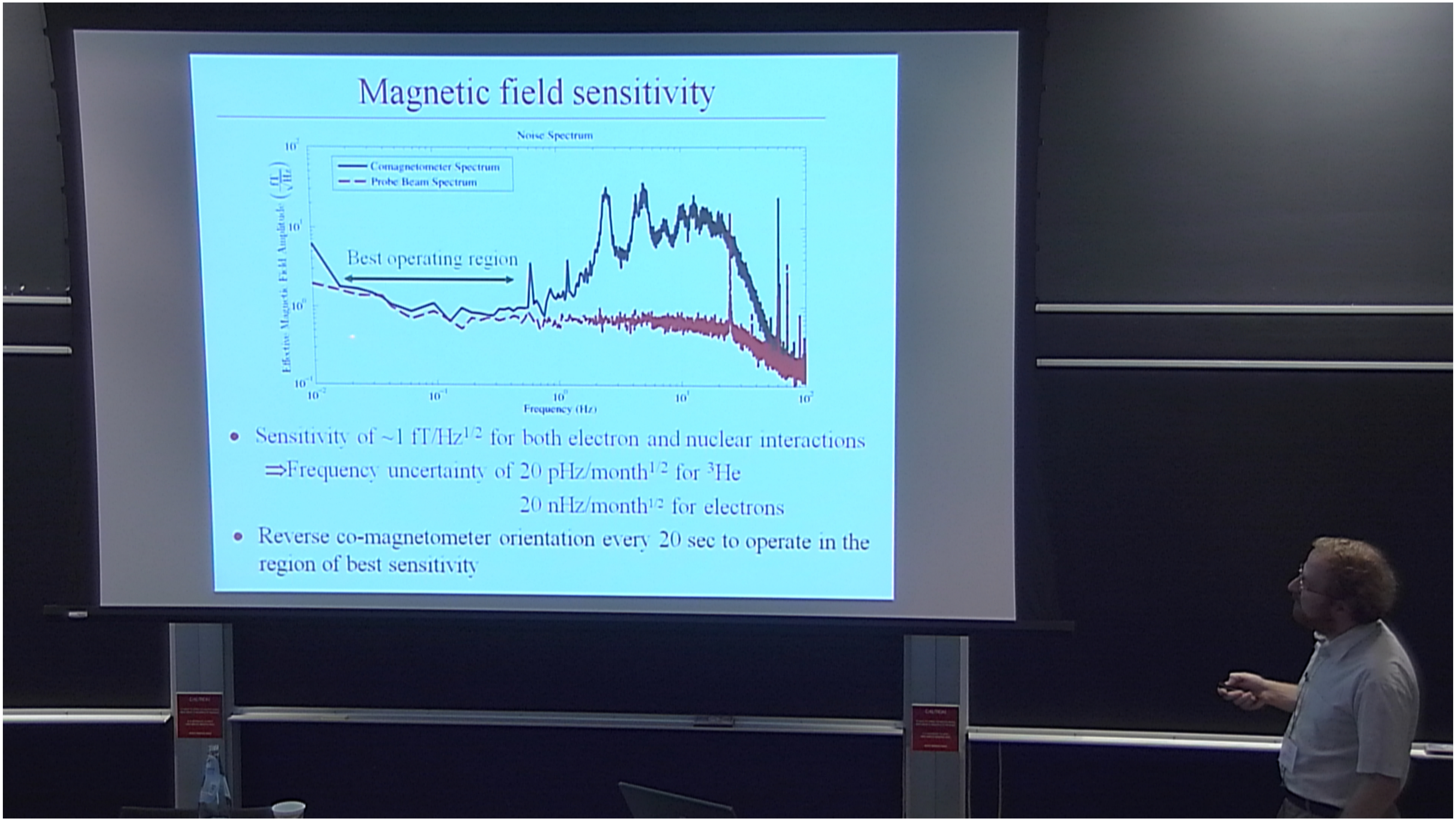
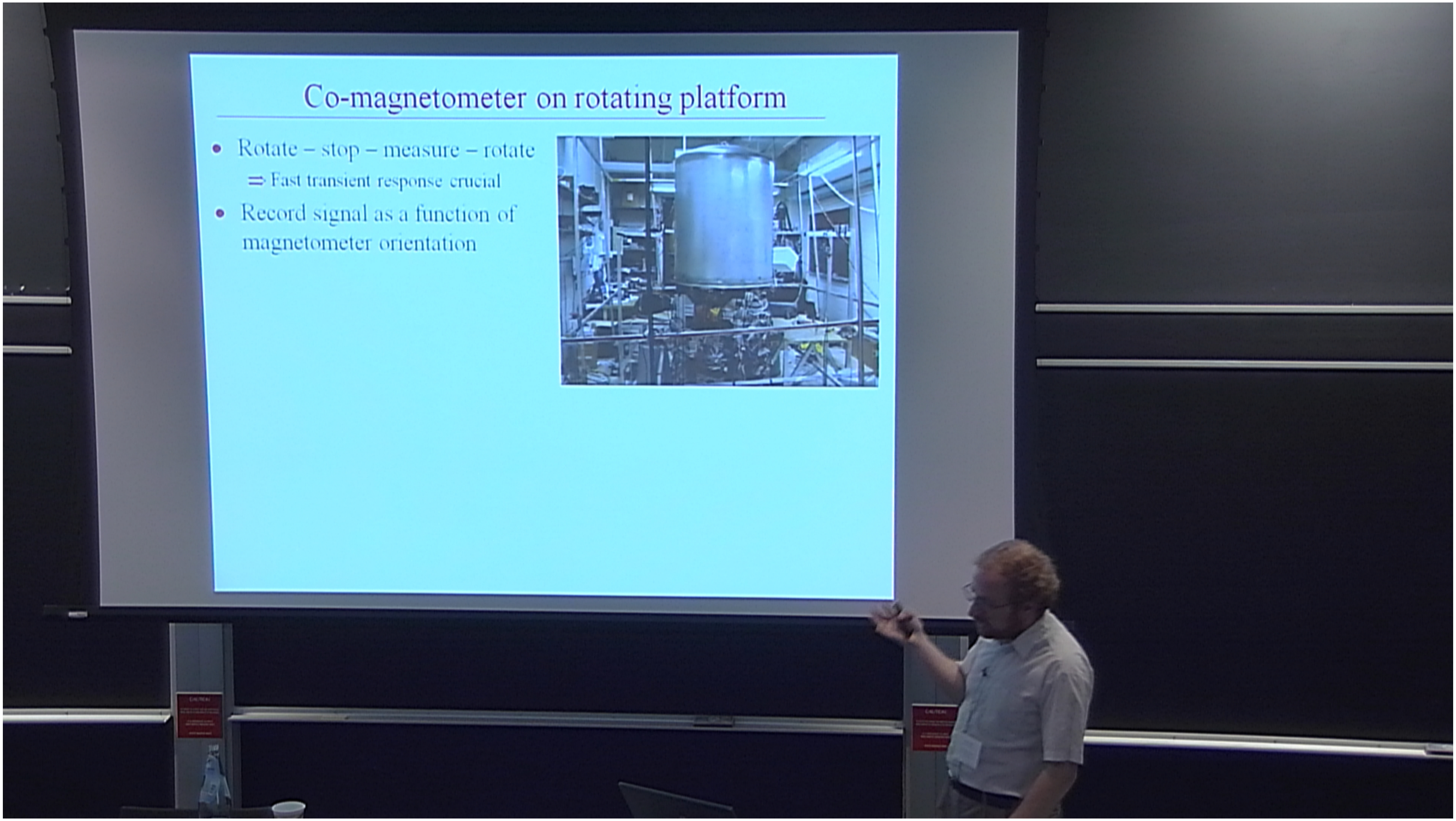


Magnetic field sensitivity

- Sensitivity of $\sim$1 fT/Hz$^{1/2}$ for both electron and nuclear interactions

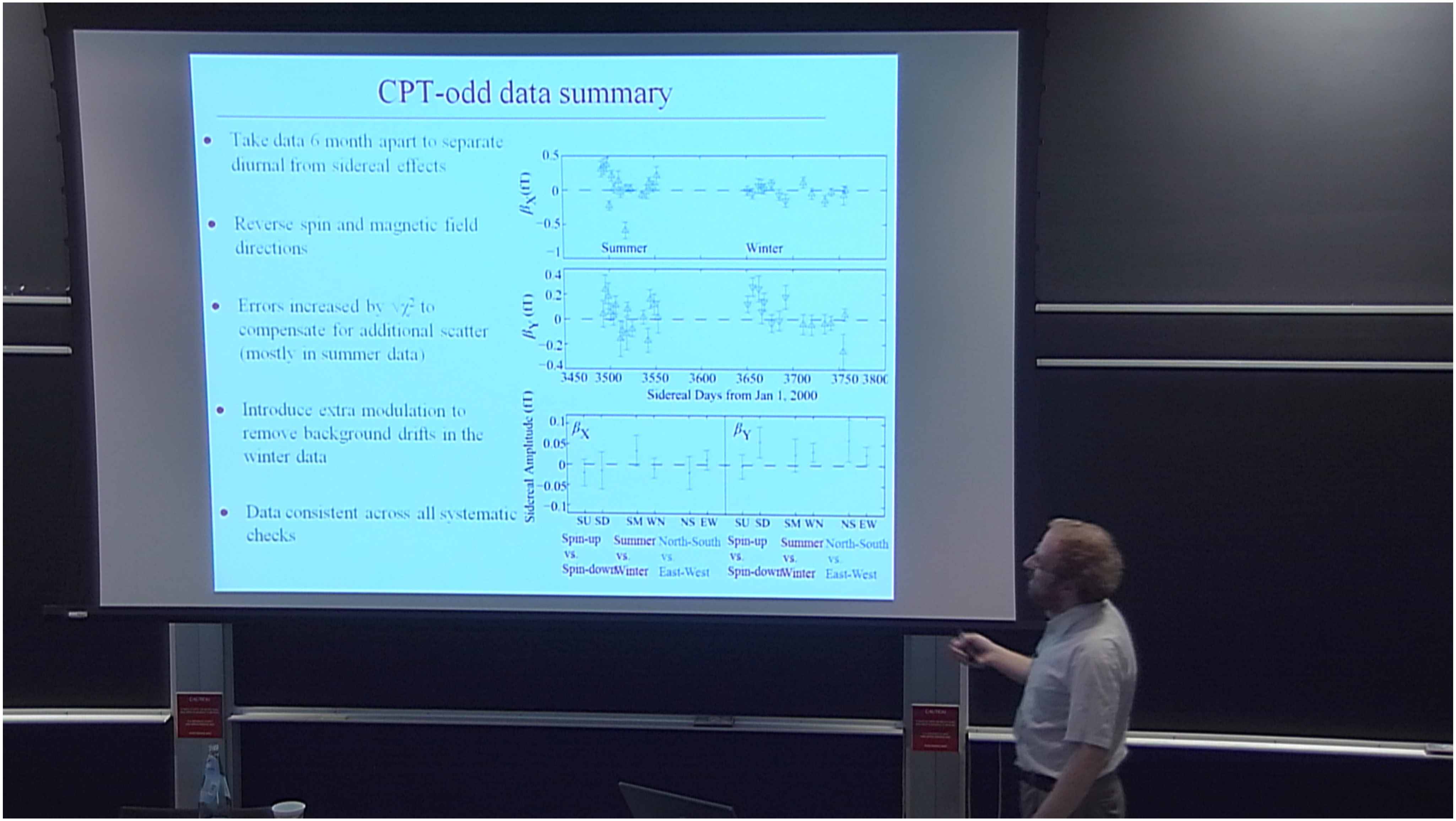
  ⇒Frequency uncertainty of 20 pHz/month$^{1/2}$ for ^{3}He

  20 nHz/month$^{1/2}$ for electrons
- Reverse co-magnetometer orientation every 20 sec to operate in the region of best sensitivity



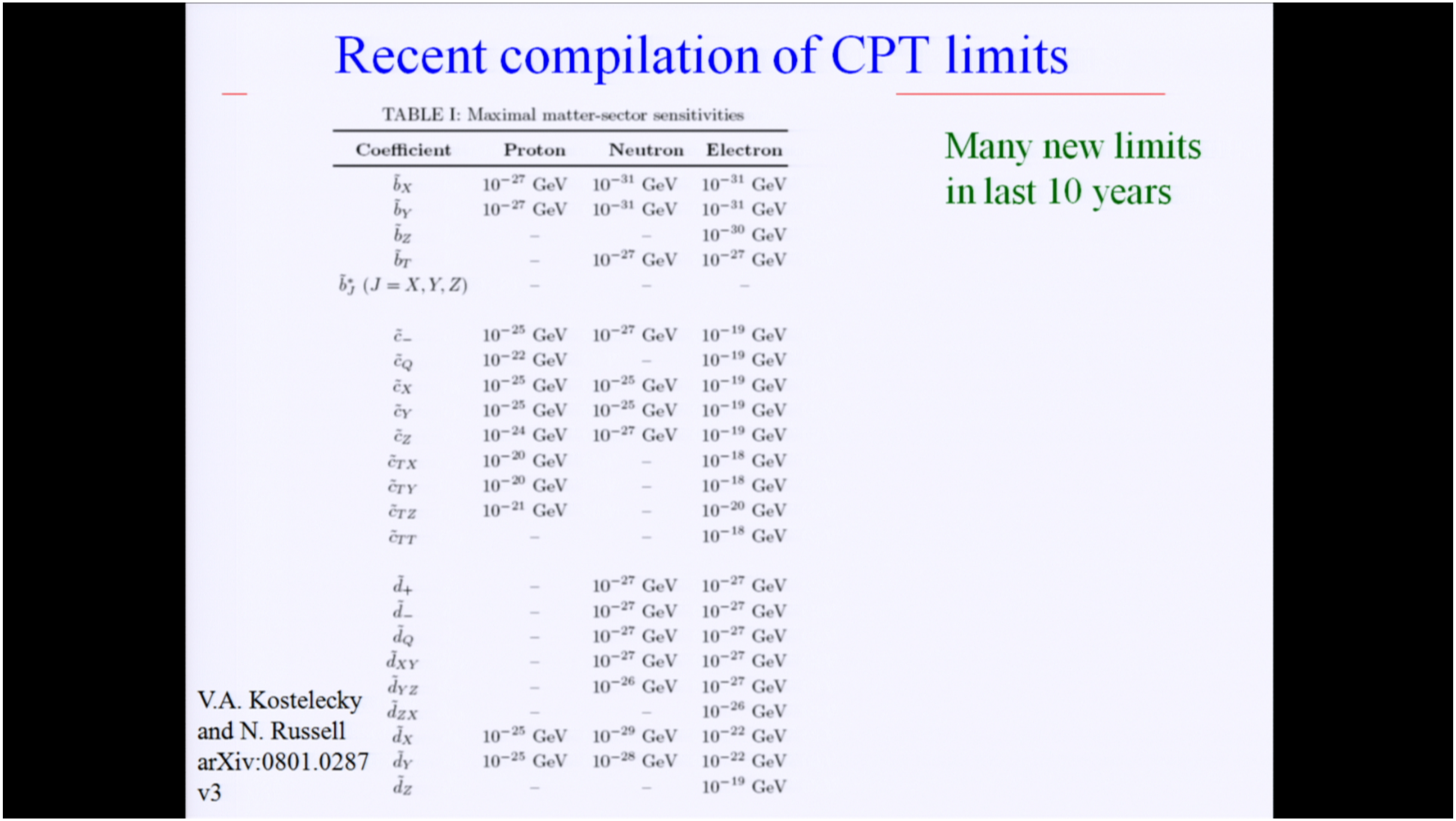
Co-magnetometer on rotating platform

- Rotate – stop – measure – rotate
  - ⇒ Fast transient response crucial
- Record signal as a function of magnetometer orientation



CPT-odd data summary

- Take data 6 month apart to separate diurnal from sidereal effects
- Reverse spin and magnetic field directions
- Errors increased by $\sqrt{\chi^2}$ to compensate for additional scatter (mostly in summer data)
- Introduce extra modulation to remove background drifts in the winter data
- Data consistent across all systematic checks



Recent compilation of CPT limits

TABLE I: Maximal matter-sector sensitivities

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$\tilde{b}_Z$	–	–	10^{-30} GeV
$\tilde{b}_T$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{b}_J^* \ (J = X, Y, Z)$	–	–	–
$\tilde{c}_-$	10^{-25} GeV	10^{-27} GeV	10^{-19} GeV
$\tilde{c}_Q$	10^{-22} GeV	–	10^{-19} GeV
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$\tilde{c}_{TY}$	10^{-20} GeV	–	10^{-18} GeV
$\tilde{c}_{TZ}$	10^{-21} GeV	–	10^{-20} GeV
$\tilde{c}_{TT}$	–	–	10^{-18} GeV
$\tilde{d}_+$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_-$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_Q$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_{XY}$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_{YZ}$	–	10^{-26} GeV	10^{-27} GeV
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Many new limits
in last 10 years

V.A. Kostelecky
and N. Russell
arXiv:0801.0287
v3

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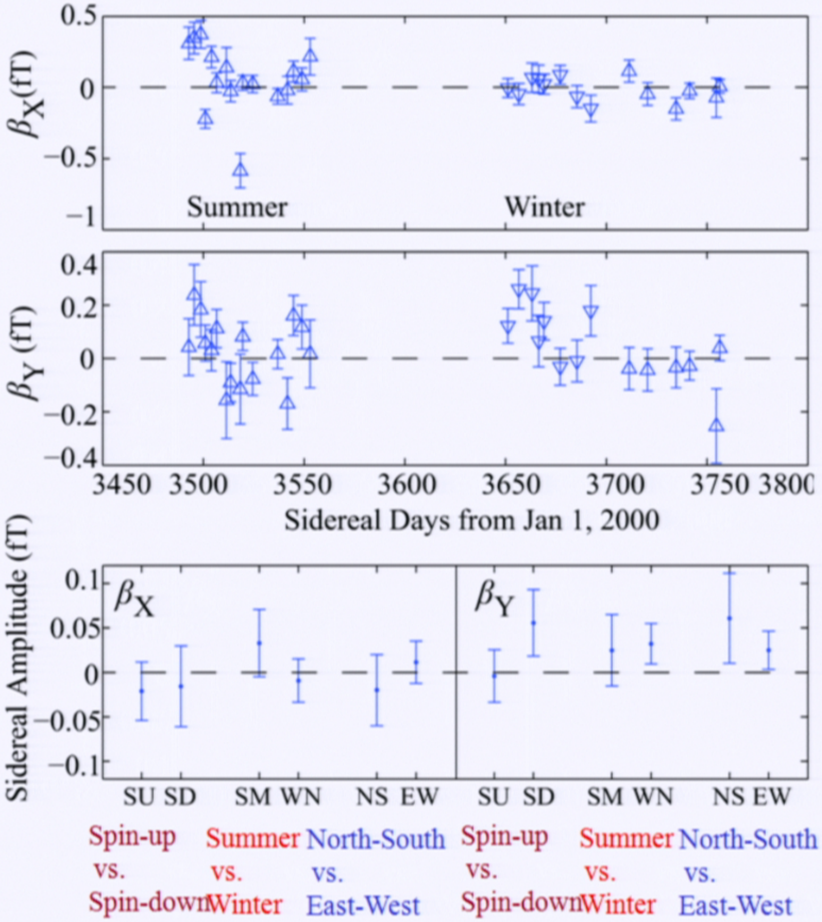

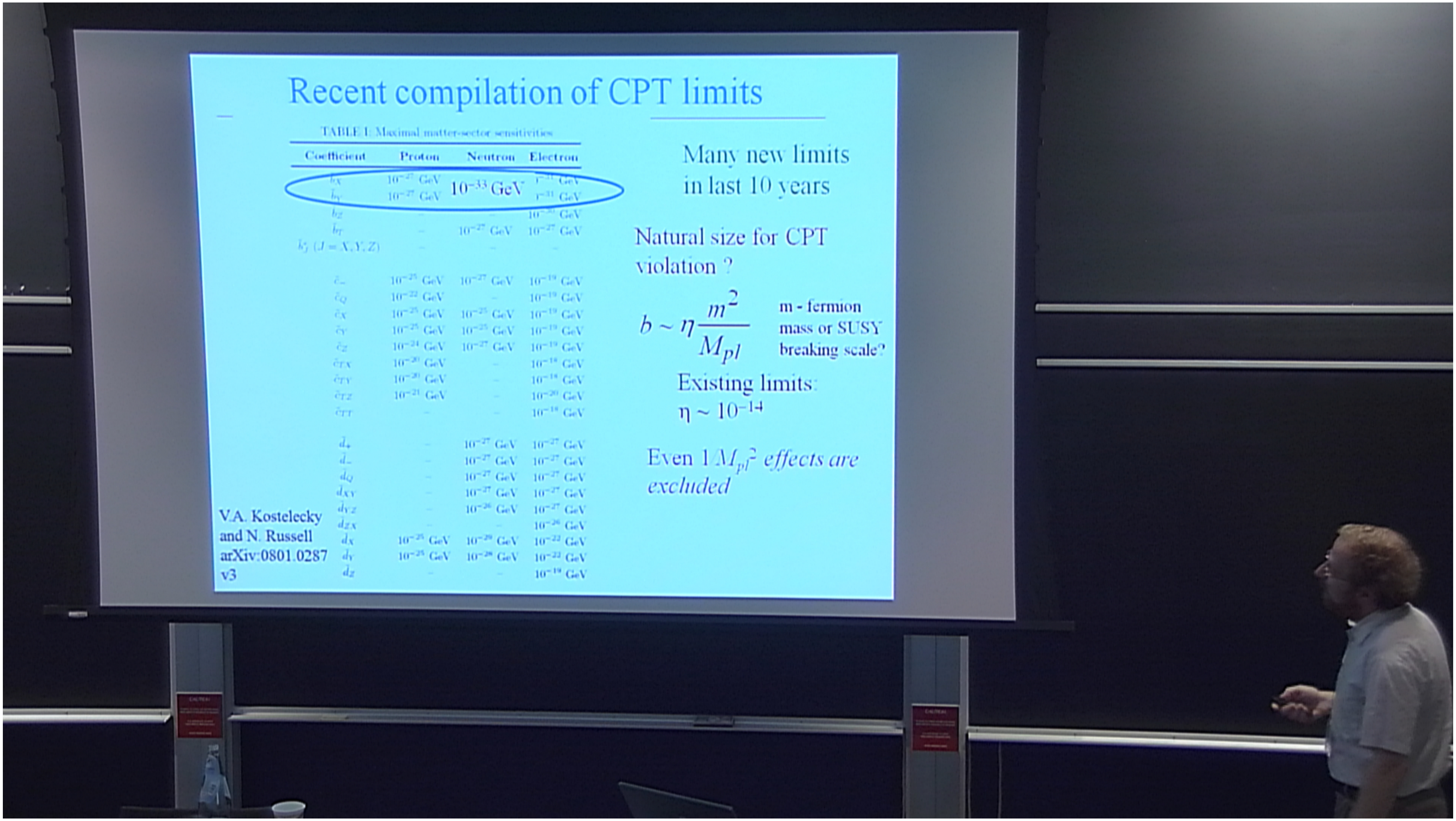

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in last 10 years

Natural size for CPT
violation ?

$$b \sim \eta \frac{m^2}{M_{pl}}$$

m - fermion
mass or SUSY
breaking scale?

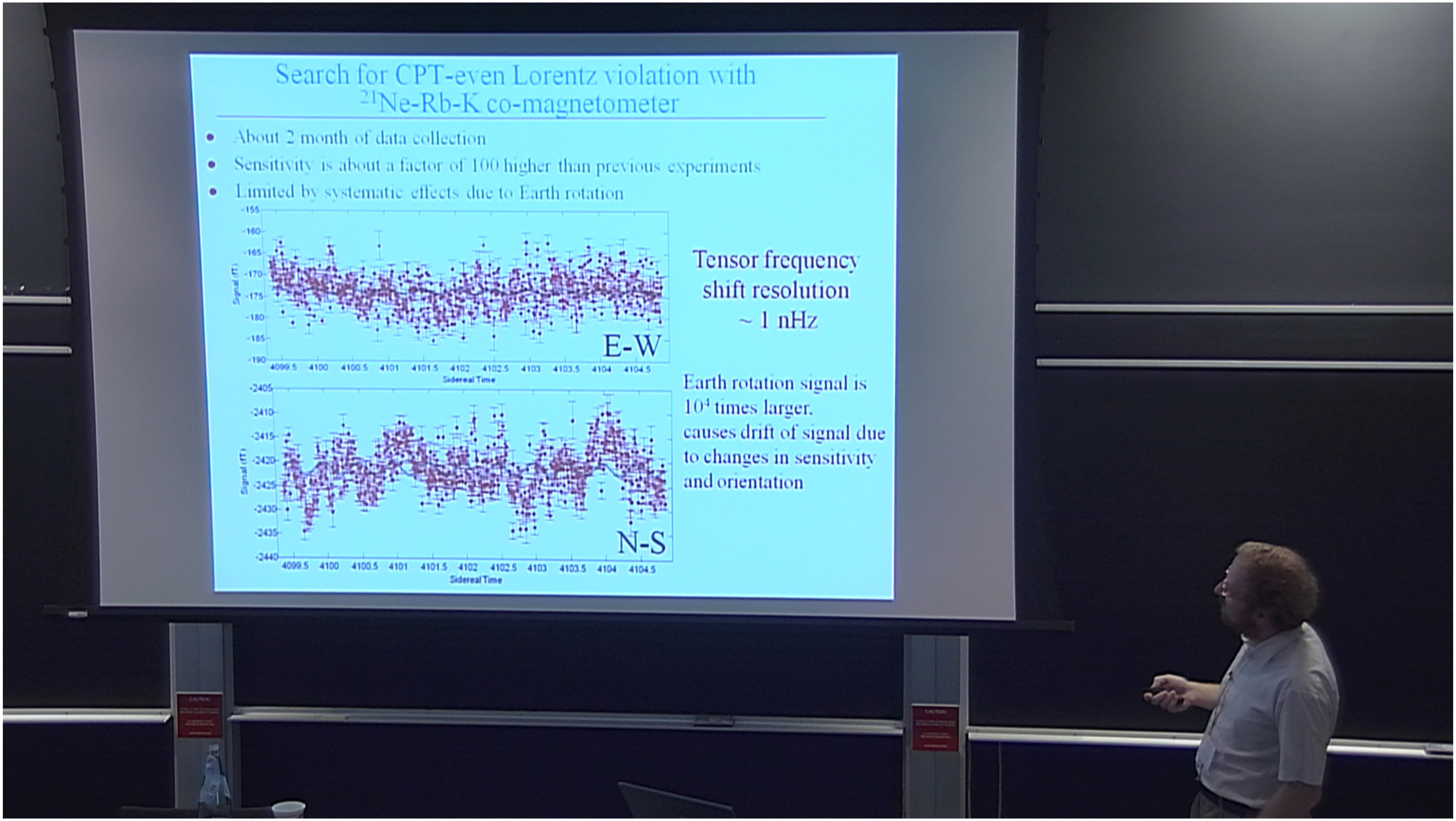
Existing limits:
$\eta \sim 10^{-14}$

Even $1/M_{pl}^2$ *effects are excluded*

^{21}Ne-Rb-Cs co-magnetometer

- Replace ^{3}He with ^{21}Ne
  - ⇒ A factor of 10 smaller gyromagnetic ratio of ^{21}Ne gives the co-magnetometer 10 times better energy resolution for anomalous interactions
- Use hybrid optical pumping Cs→Rb→^{21}Ne
  - ⇒ Small concentration of Cs is optically-thin, allows uniform pump light illumination
  - ⇒ Rb is polarized by fast spin-exchange with Cs
  - ⇒ ^{21}Ne is polarized by spin-exchange with high density Rb vapor
  - ⇒ Probe laser is tuned near Rb D1 line
  - ⇒ Allows operation with 10 times higher Rb density, lower ^{21}Ne pressure.
  - ⇒ Overcomes faster quadrupole spin relaxation of ^{21}Ne

M. V. Romalis, Phys. Rev. Lett. **105**, 243001 (2010)



Search for CPT-even Lorentz violation with ^{21}Ne-Rb-K co-magnetometer

- About 2 month of data collection
- Sensitivity is about a factor of 100 higher than previous experiments
- Limited by systematic effects due to Earth rotation

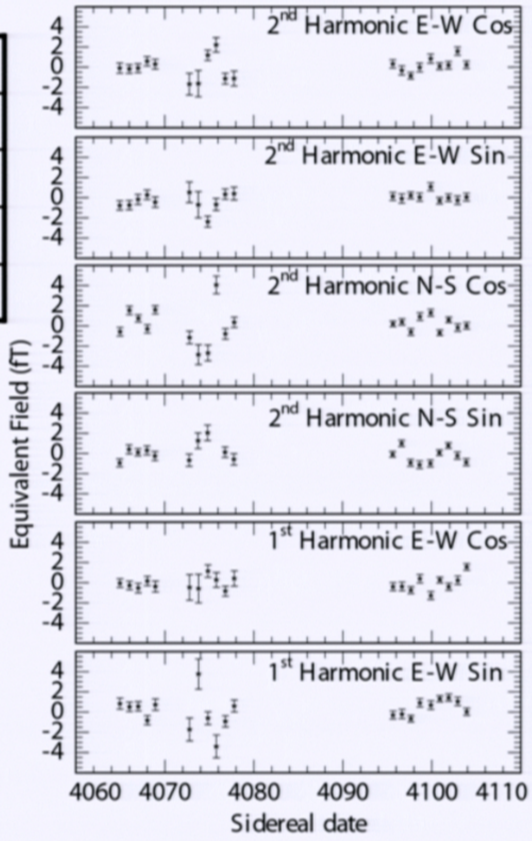
Tensor frequency
shift resolution
~ 1 nHz

Earth rotation signal is 10^4 times larger, causes drift of signal due to changes in sensitivity and orientation

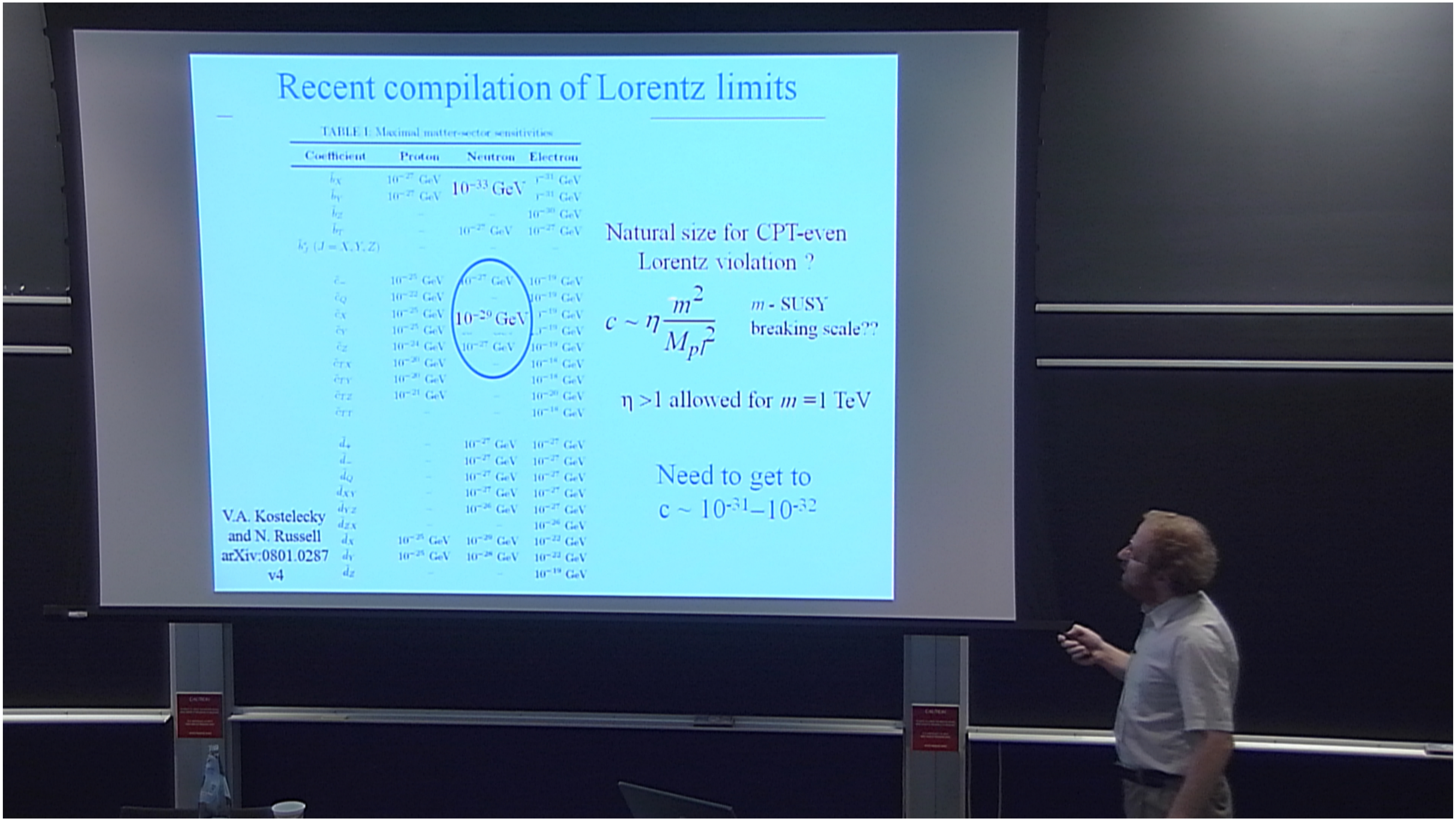
Results of Tensor Lorentz-Violation Search

	$\times 10^{-29}$	East-West	North-South	Comb.
2 ω	$c_{xx}-c_{yy}$	0.86 ±1.1 ±0.56	3.6 ±2.8 ±1.6	1.2 ±1.1
	$c_{xx}+c_{yy}$	0.14 ±1.1 ±0.56	0.57 ±2.8 ±1.6	0.19 ±1.1
1 ω	$c_{yz}+c_{zy}$	5.2 ±3.9 ±2.1	−4.2 ±15 ±18	4.8 ±4.3
	$c_{xz}+c_{zx}$	−4.1 ±2.2 ±2.4	17 ±14 ±13	−3.5 ±3.2

- Constrain 4 out of 5 spatial tensor components of $c_{\mu\nu}$ at 10^{-29} level
- Improve previous limits by 2 to 3 orders of magnitude
- Most stringent constrains on CPT-even Lorentz violation!
- Assume Schmidt nucleon wavefunction – not a good approximation for ^{21}Ne –better wavefunction calculations in progress with Alex Brown (MSU)
- Assume kinetic energy of valence nucleon ~ 5 MeV



M. Smiciklas, J. M. Brown, L.W. Cheuk, S. Smullin, M. V. R., Phys. Rev. Lett. **107**, 171604 (2011)



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$\tilde{c}_Y$	10^{-25} GeV	–	10^{-19} GeV
$\tilde{c}_Z$	10^{-24} GeV	10^{-27} GeV	10^{-19} GeV
$\tilde{c}_{TX}$	10^{-20} GeV	–	10^{-18} GeV
$\tilde{c}_{TY}$	10^{-20} GeV		10^{-18} GeV
$\tilde{c}_{TZ}$	10^{-21} GeV	–	10^{-20} GeV
$\tilde{c}_{TT}$	–	–	10^{-18} GeV
$\tilde{d}_+$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_-$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_Q$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_{XY}$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{d}_{YZ}$	–	10^{-26} GeV	10^{-27} GeV
$\tilde{d}_{ZX}$	–	–	10^{-26} GeV
$\tilde{d}_X$	10^{-25} GeV	10^{-29} GeV	10^{-22} GeV
$\tilde{d}_Y$	10^{-25} GeV	10^{-28} GeV	10^{-22} GeV
$\tilde{d}_Z$	–	–	10^{-19} GeV

V.A. Kostelecky
and N. Russell
arXiv:0801.0287
v4

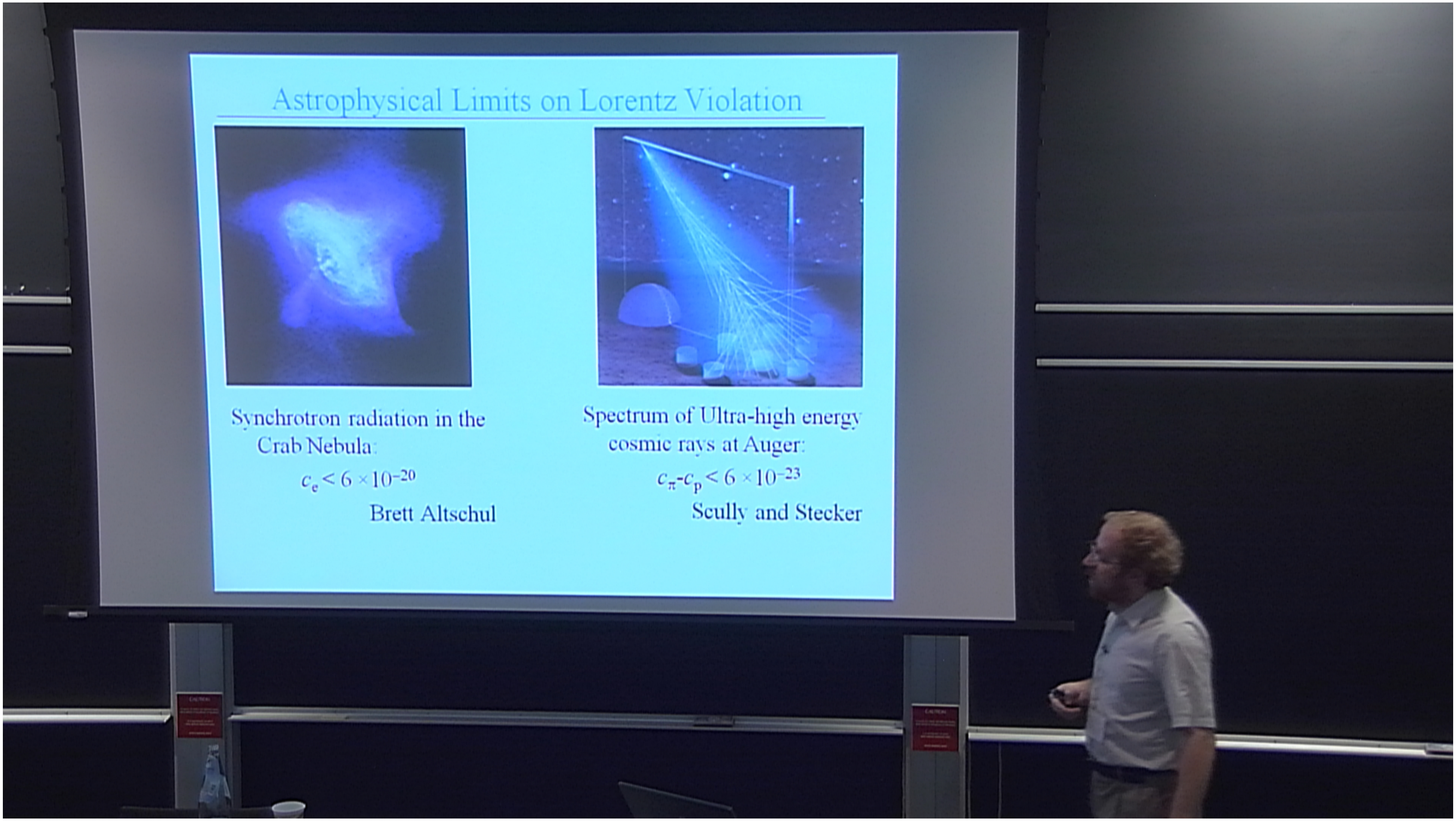
Natural size for CPT-even
Lorentz violation ?

$$c \sim \eta \frac{m^2}{M_{Pl}^2}$$

m - SUSY
breaking scale??

$\eta > 1$ allowed for $m = 1$ TeV

Need to get to
$c \sim 10^{-31} – 10^{-32}$



Astrophysical Limits on Lorentz Violation

Synchrotron radiation in the Crab Nebula:

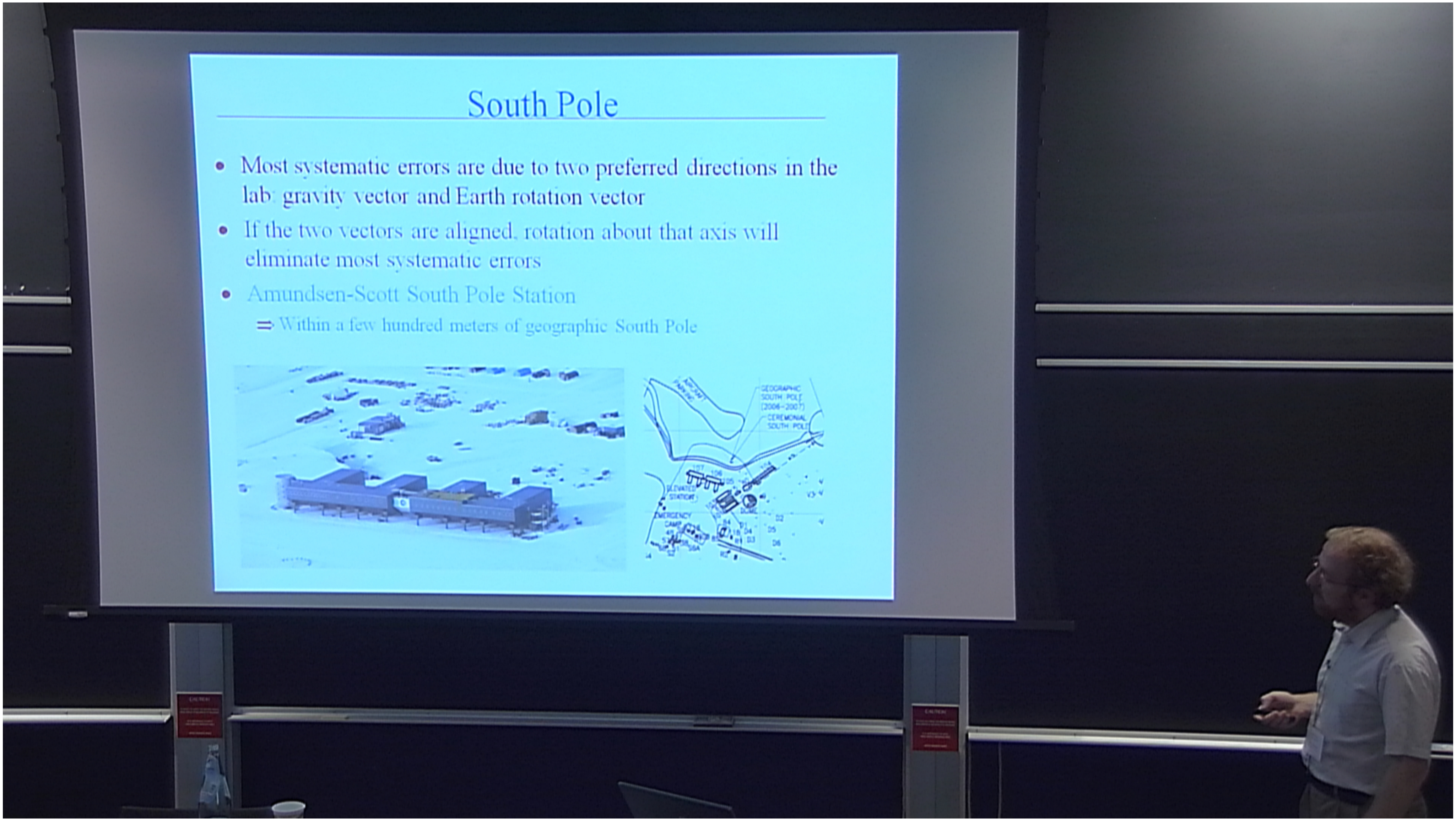
$c_e < 6 \times 10^{-20}$

Brett Altschul

Spectrum of Ultra-high energy cosmic rays at Auger:

$c_\pi - c_p < 6 \times 10^{-23}$

Scully and Stecker



South Pole

- Most systematic errors are due to two preferred directions in the lab: gravity vector and Earth rotation vector
- If the two vectors are aligned, rotation about that axis will eliminate most systematic errors
- Amundsen-Scott South Pole Station
  - ⇒ Within a few hundred meters of geographic South Pole

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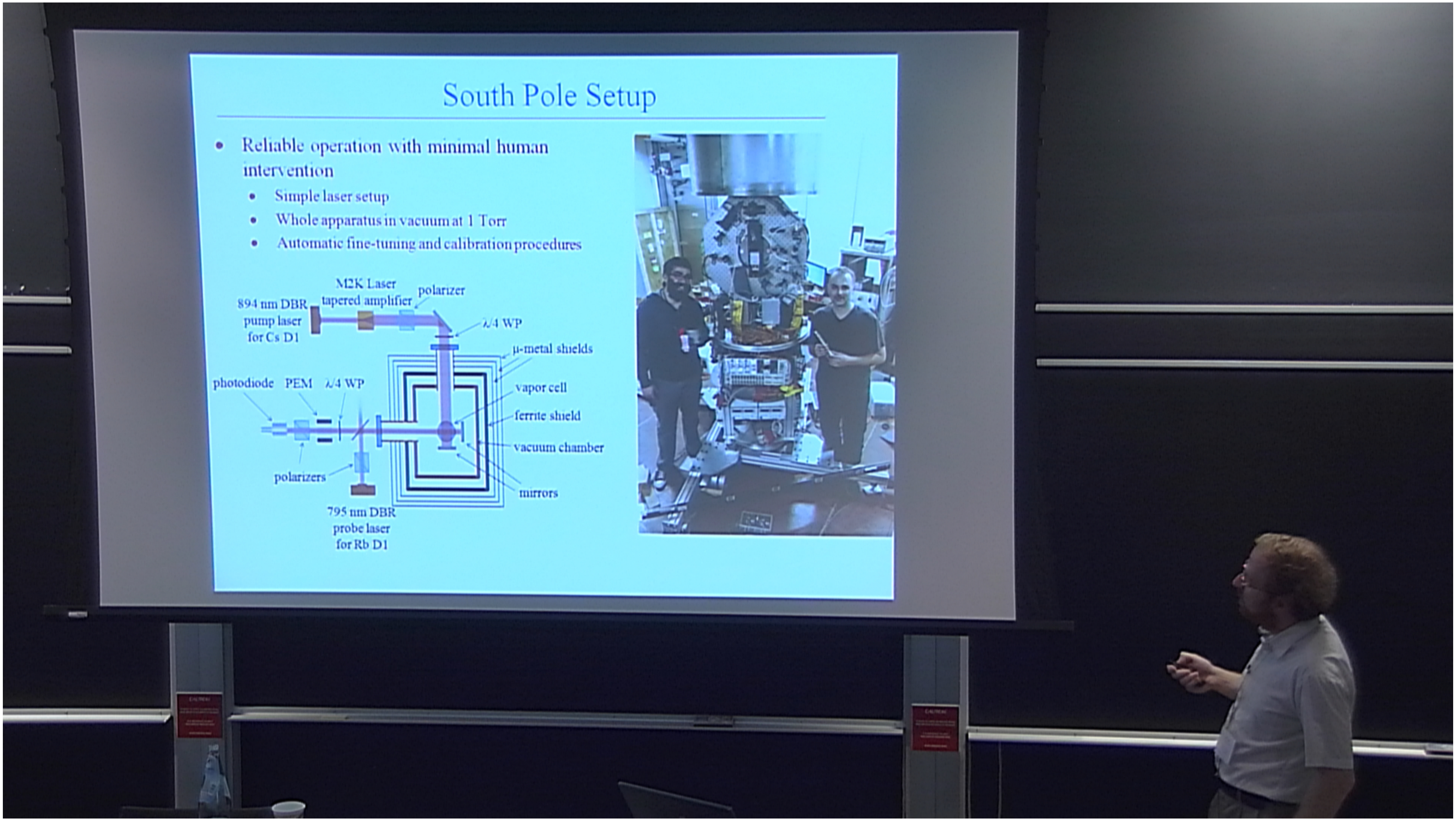
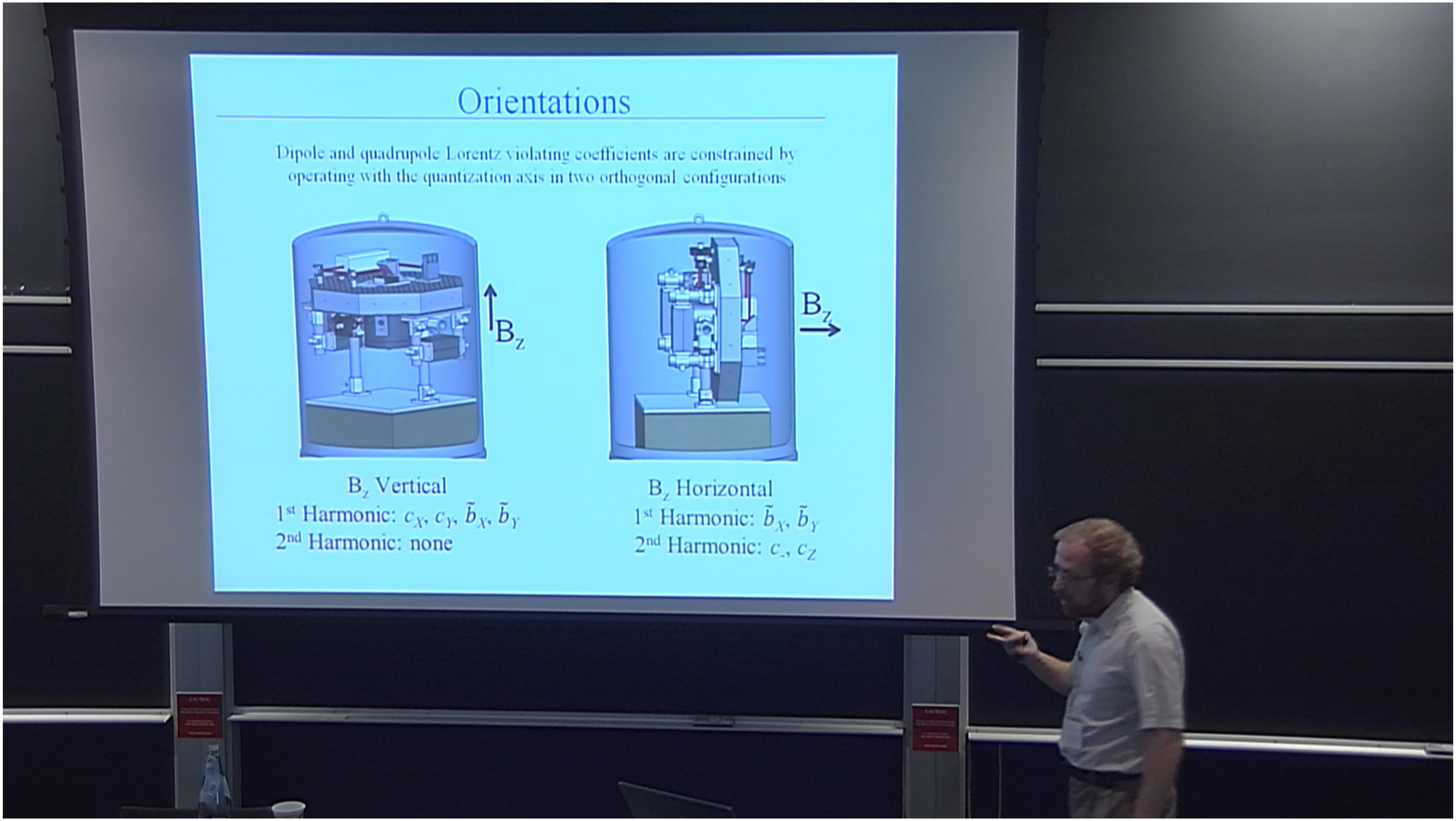


South Pole Setup

- Reliable operation with minimal human intervention
  - Simple laser setup
  - Whole apparatus in vacuum at 1 Torr
  - Automatic fine-tuning and calibration procedures

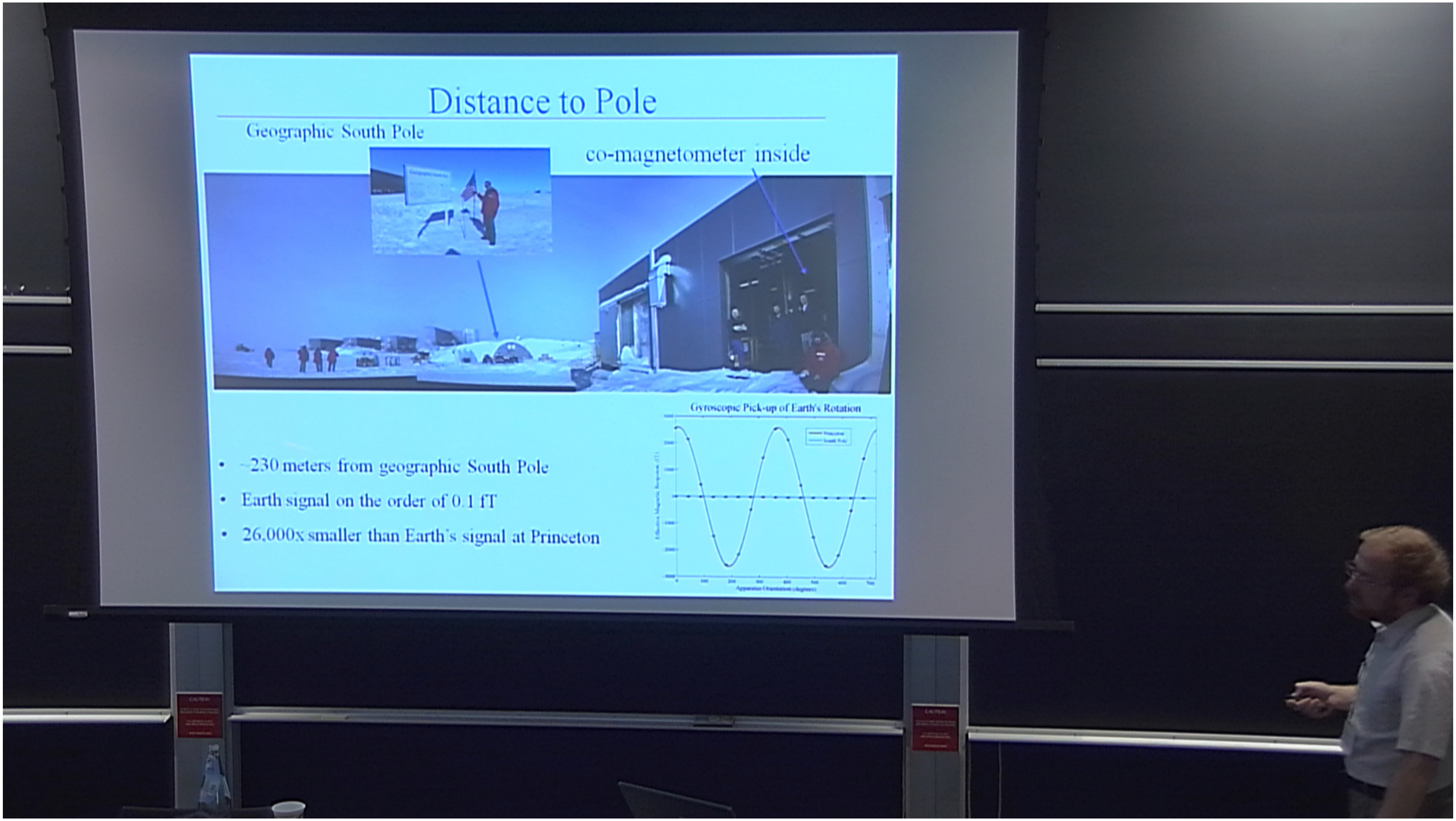


Orientations

Dipole and quadrupole Lorentz violating coefficients are constrained by operating with the quantization axis in two orthogonal configurations

B_z Vertical
1st Harmonic: c_X, c_Y, $\tilde{b}_X$, $\tilde{b}_Y$
2nd Harmonic: none

B_z Horizontal
1st Harmonic: $\tilde{b}_X$, $\tilde{b}_Y$
2nd Harmonic: c_{-}, c_Z



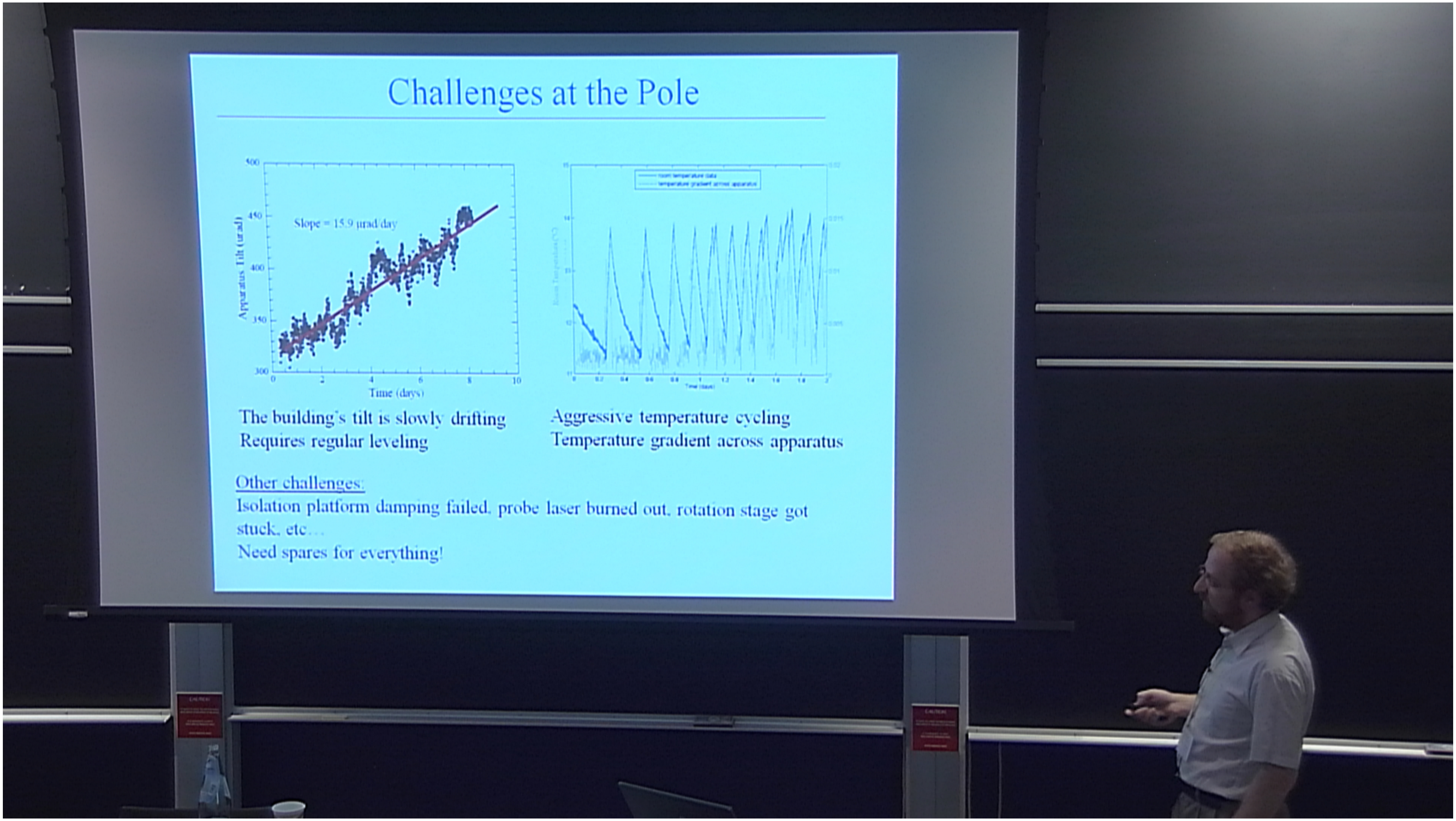
Distance to Pole

Geographic South Pole

co-magnetometer inside

Gyroscopic Pick-up of Earth's Rotation

- ~230 meters from geographic South Pole
- Earth signal on the order of 0.1 fT
- 26,000x smaller than Earth's signal at Princeton



Challenges at the Pole

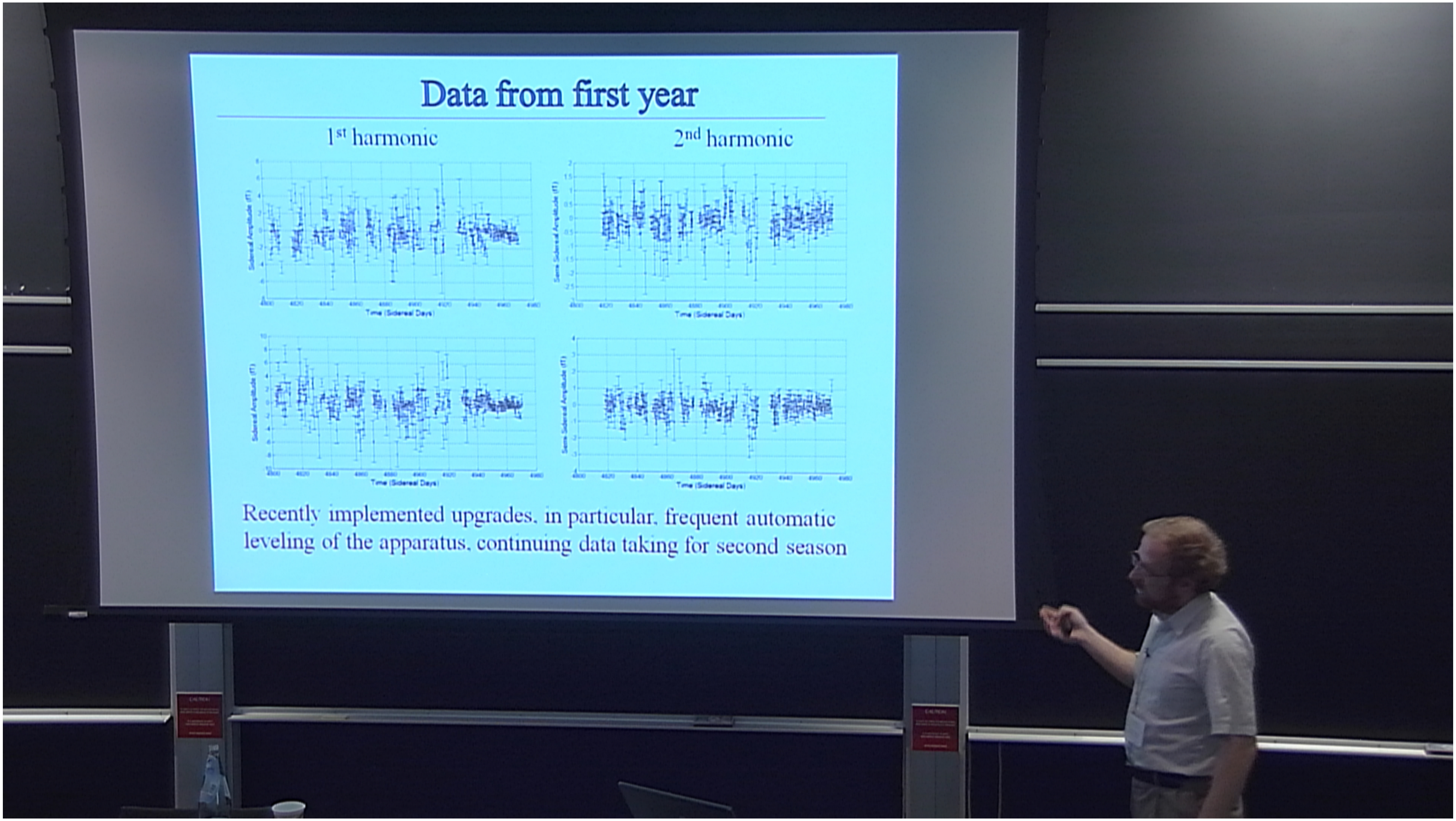
The building's tilt is slowly drifting
Requires regular leveling

Aggressive temperature cycling
Temperature gradient across apparatus

Other challenges:

Isolation platform damping failed, probe laser burned out, rotation stage got stuck, etc…

Need spares for everything!

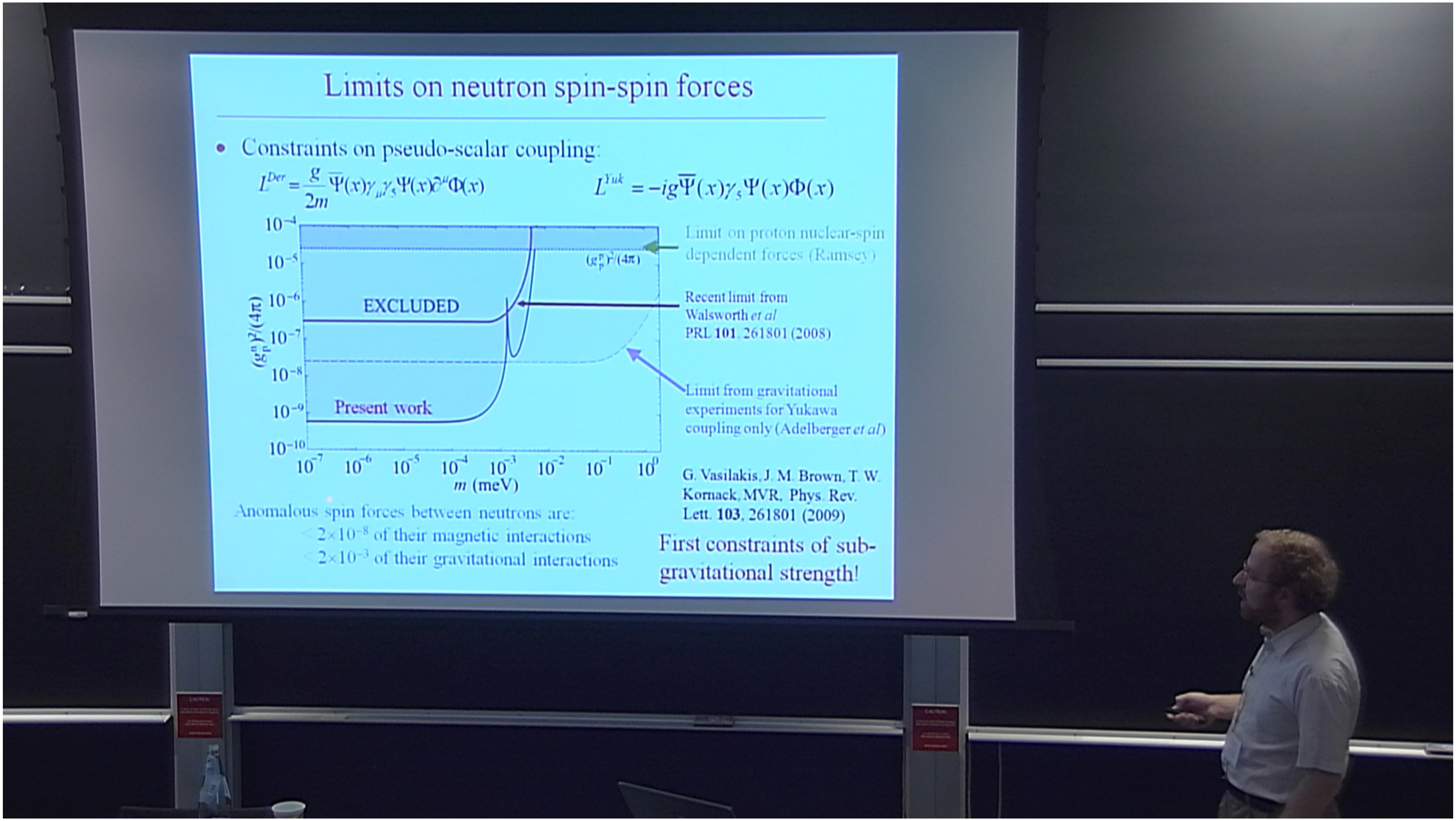


Data from first year

1st harmonic

2nd harmonic

Recently implemented upgrades, in particular, frequent automatic leveling of the apparatus, continuing data taking for second season



Limits on neutron spin-spin forces

- Constraints on pseudo-scalar coupling:

$$L^{Der} = \frac{g}{2m}\overline{\Psi}(x)\gamma_\mu\gamma_5\Psi(x)\partial^\mu\Phi(x) \qquad L^{Yuk} = -ig\overline{\Psi}(x)\gamma_5\Psi(x)\Phi(x)$$

Limit on proton nuclear-spin dependent forces (Ramsey)

Recent limit from Walsworth *et al* PRL **101**, 261801 (2008)

Limit from gravitational experiments for Yukawa coupling only (Adelberger *et al*)

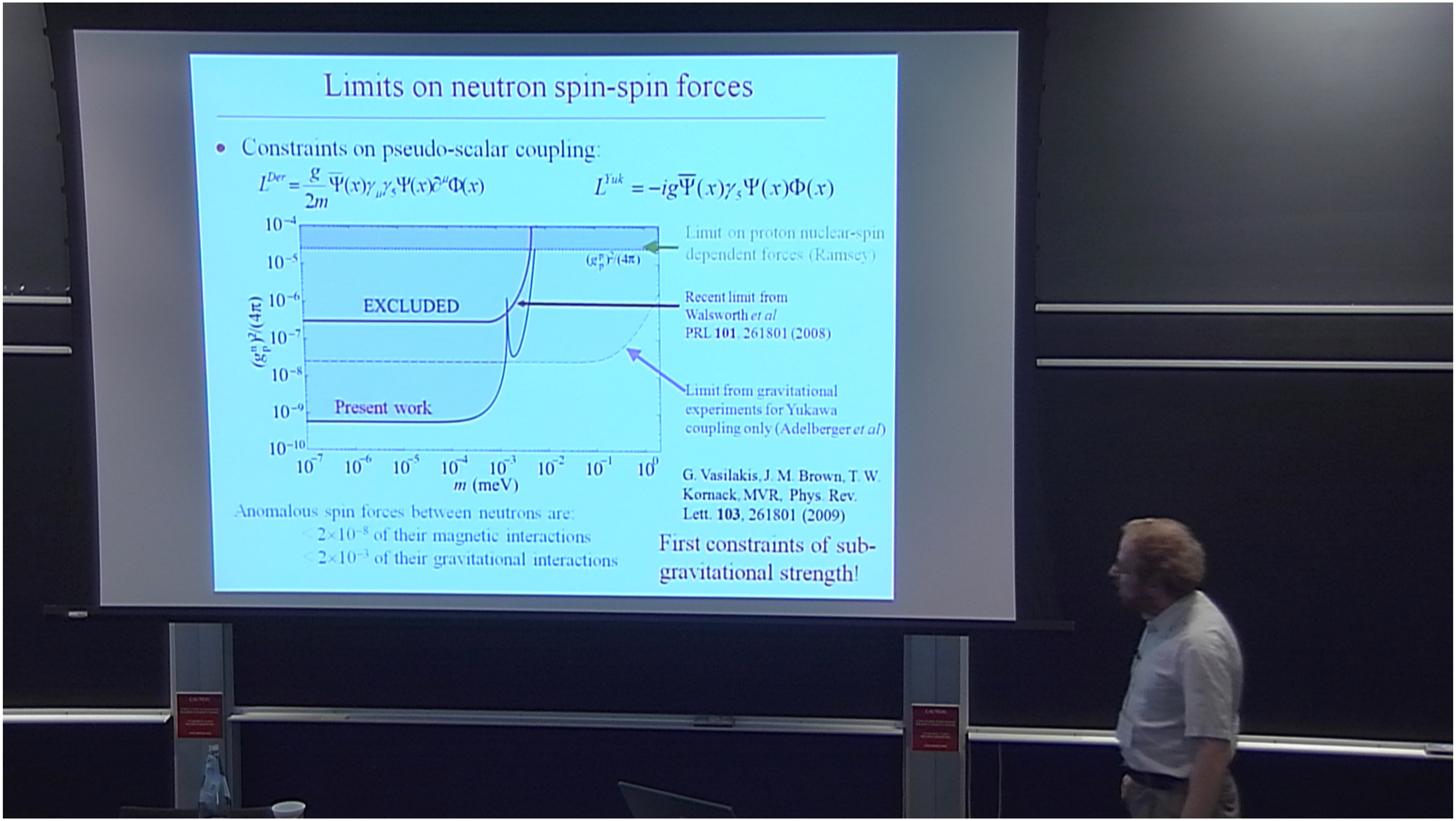
G. Vasilakis, J. M. Brown, T. W. Kornack, MVR, Phys. Rev. Lett. **103**, 261801 (2009)

Anomalous spin forces between neutrons are:

$< 2\times10^{-8}$ of their magnetic interactions

$< 2\times10^{-3}$ of their gravitational interactions

First constraints of sub-gravitational strength!



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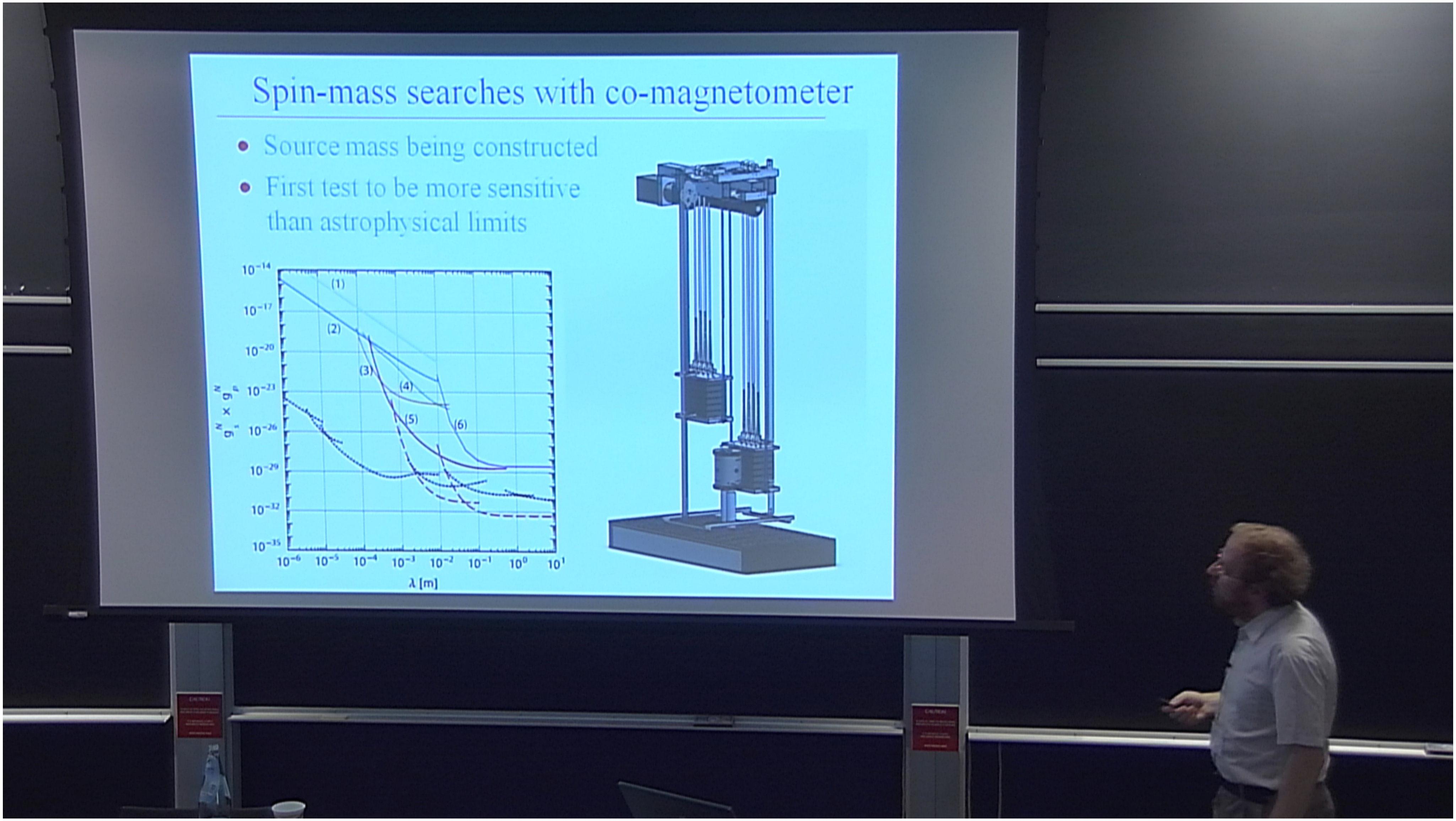
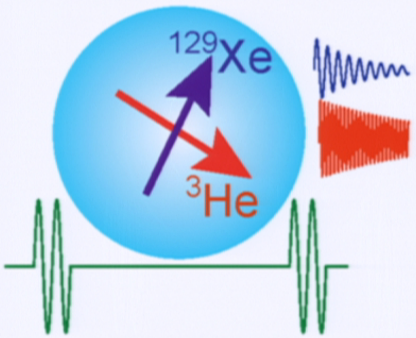


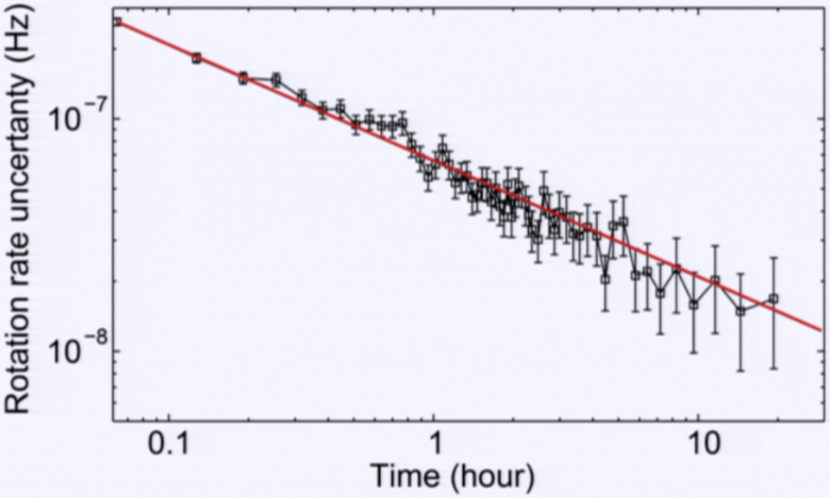
Spin-mass searches with co-magnetometer

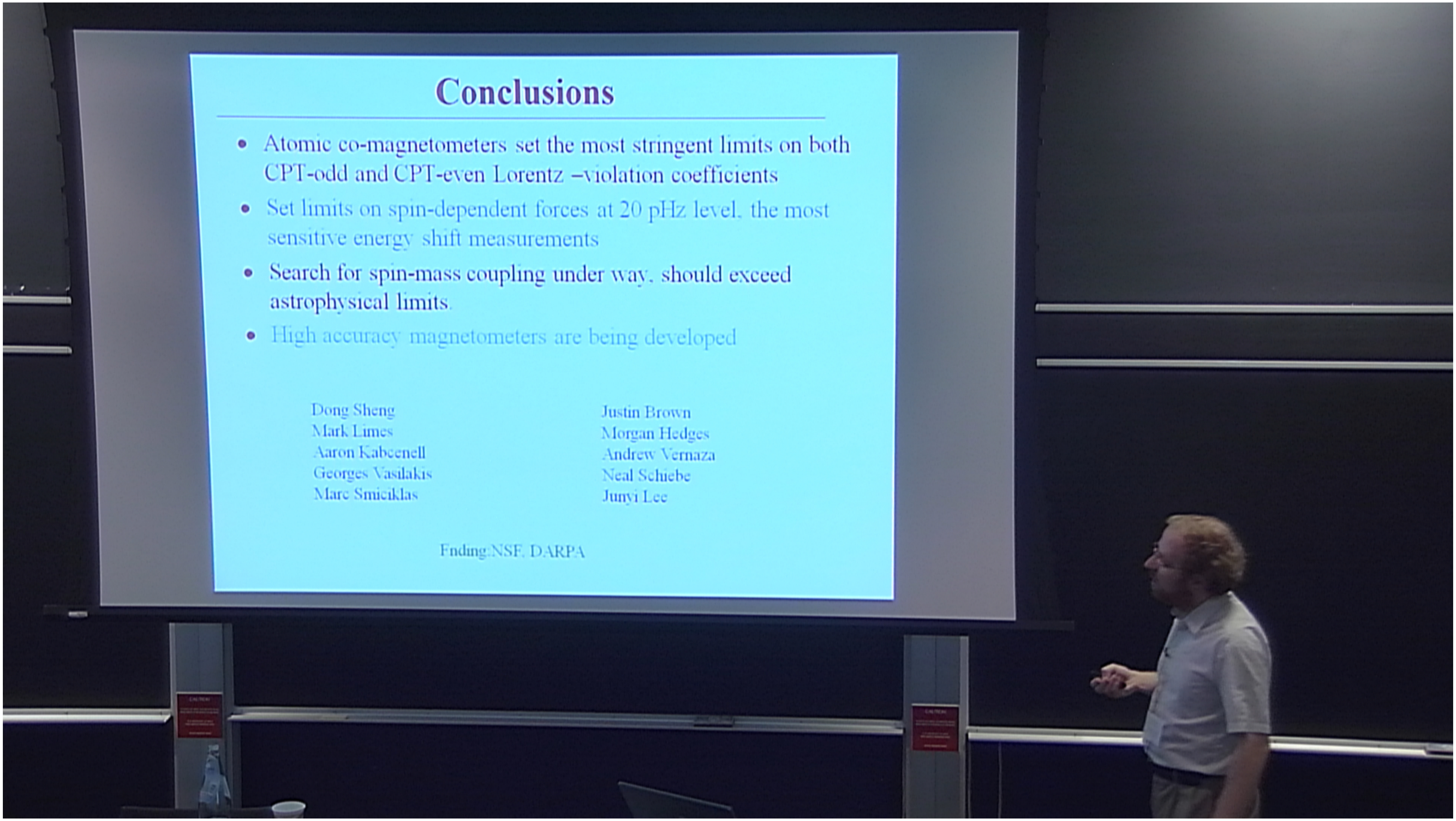
- Source mass being constructed
- First test to be more sensitive than astrophysical limits

Next-generation co-magnetometer

- Developing a co-magnetometer using ^{3}He and ^{129}Xe atoms in free precession (scalar) mode
- Rb is used as sensor, but is "turned off" for nuclear spin precession "in the dark"
- Minimize frequency shifts to achieve clock-like stability
- Short-term sensitivity is not very good yet, but is being improved.
- Much better long-term stability
- Allows to search for spin interactions that are difficult to reverse, such as Earth's gravity







Conclusions

- Atomic co-magnetometers set the most stringent limits on both CPT-odd and CPT-even Lorentz –violation coefficients
- Set limits on spin-dependent forces at 20 pHz level, the most sensitive energy shift measurements
- Search for spin-mass coupling under way, should exceed astrophysical limits.
- High accuracy magnetometers are being developed

Dong Sheng	Justin Brown
Mark Limes	Morgan Hedges
Aaron Kabcenell	Andrew Vernaza
Georges Vasilakis	Neal Schiebe
Marc Smiciklas	Junyi Lee

Fnding:NSF, DARPA