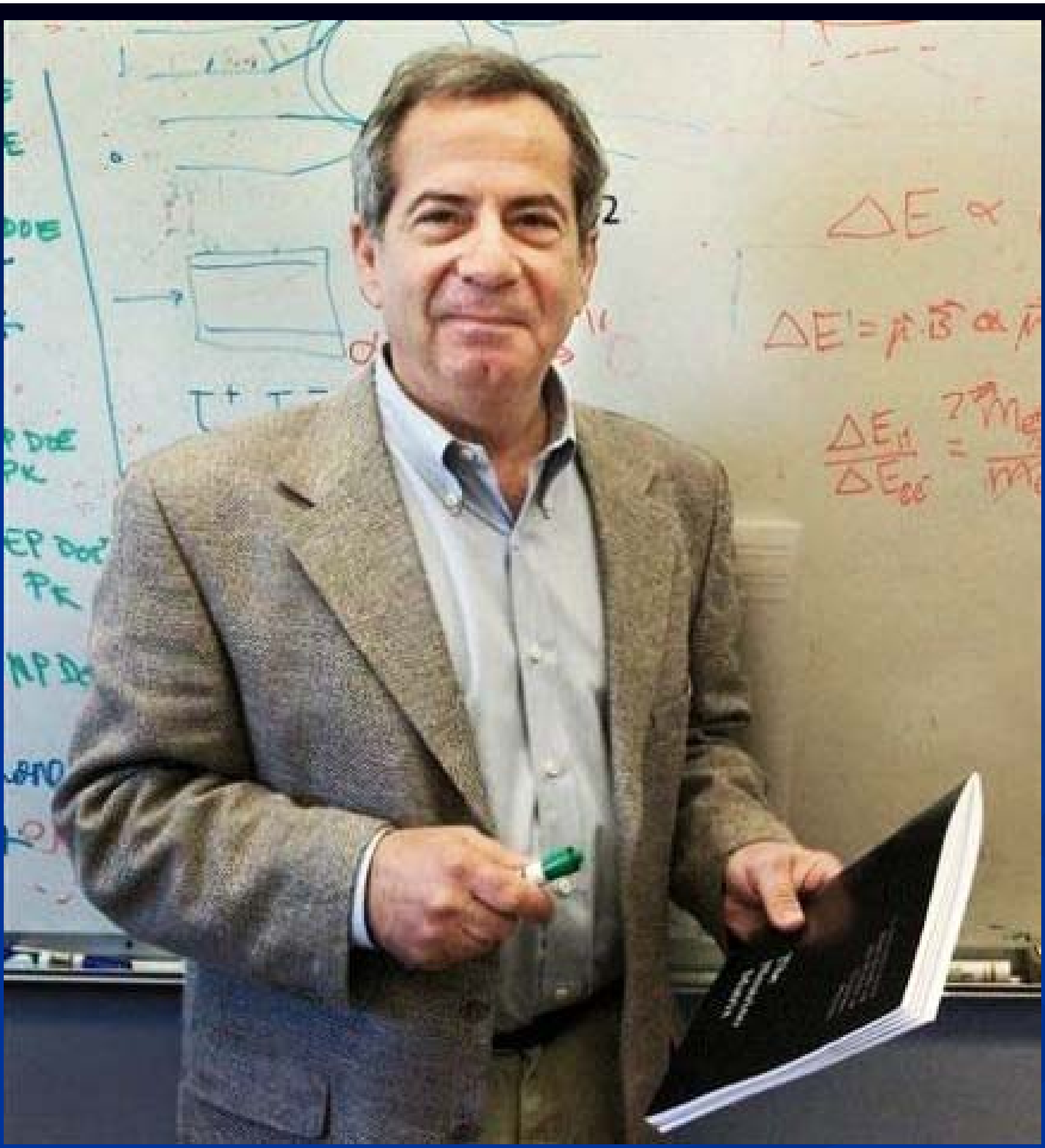
EDM, Axions, Axion-Like Particles, and The Dark Side

Dmitry Budker

UC Berkeley, and LBNL

CP violation workshop

Mahabaleshwar India, February 2013

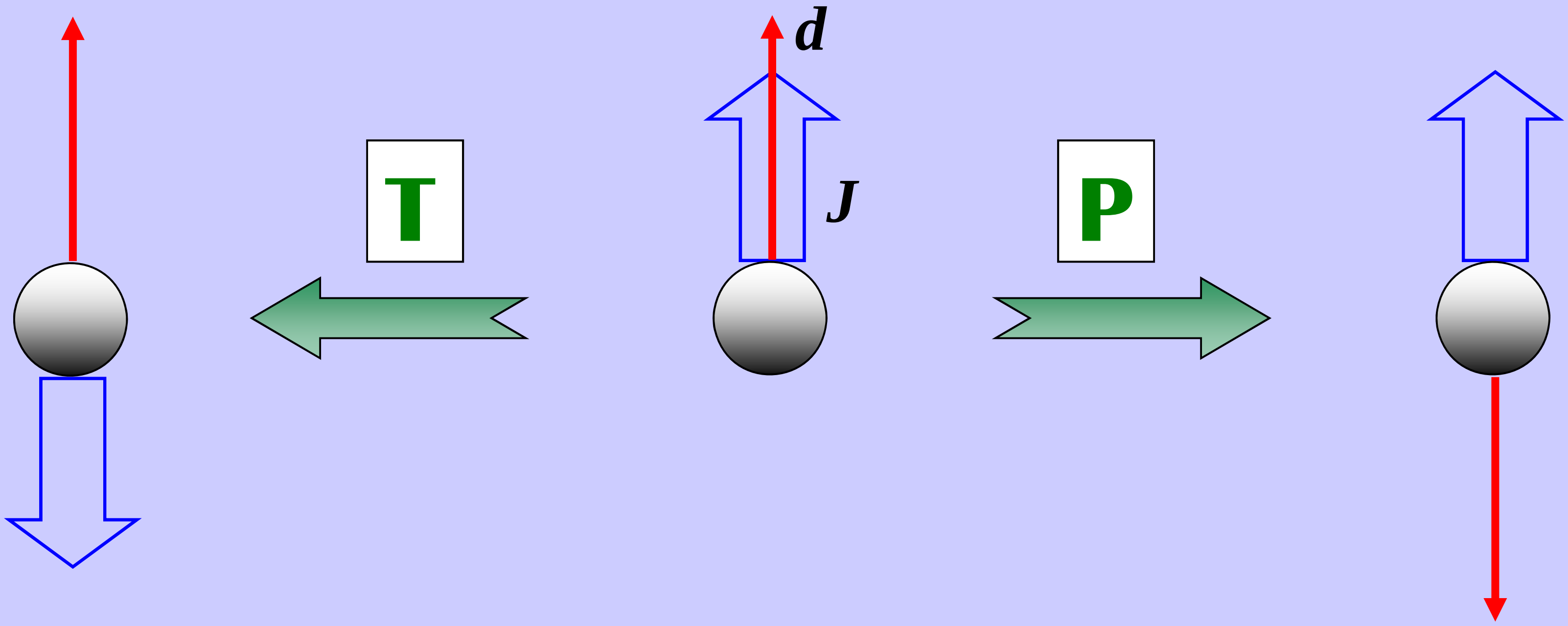


Stuart J. Freedman
1944-2012

Outline:

- General introduction to EDMs
- Proposed search for **oscillating** EDM
- Proposed search for cosmic domains of **A**xion **L**ike **P**articles

Permanent EDM of a particle contradicts <u>both</u> P- and T-invariance

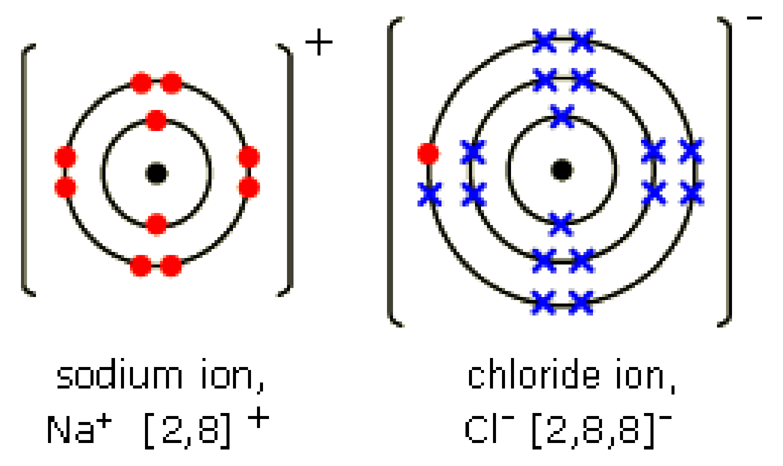


T violation was not understood
in the first EDM experiments!

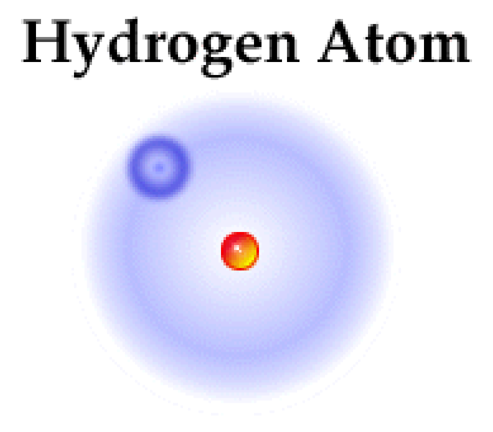
Prof. Norman F. Ramsey
(1915–2011)

“What if we see an EDM?”

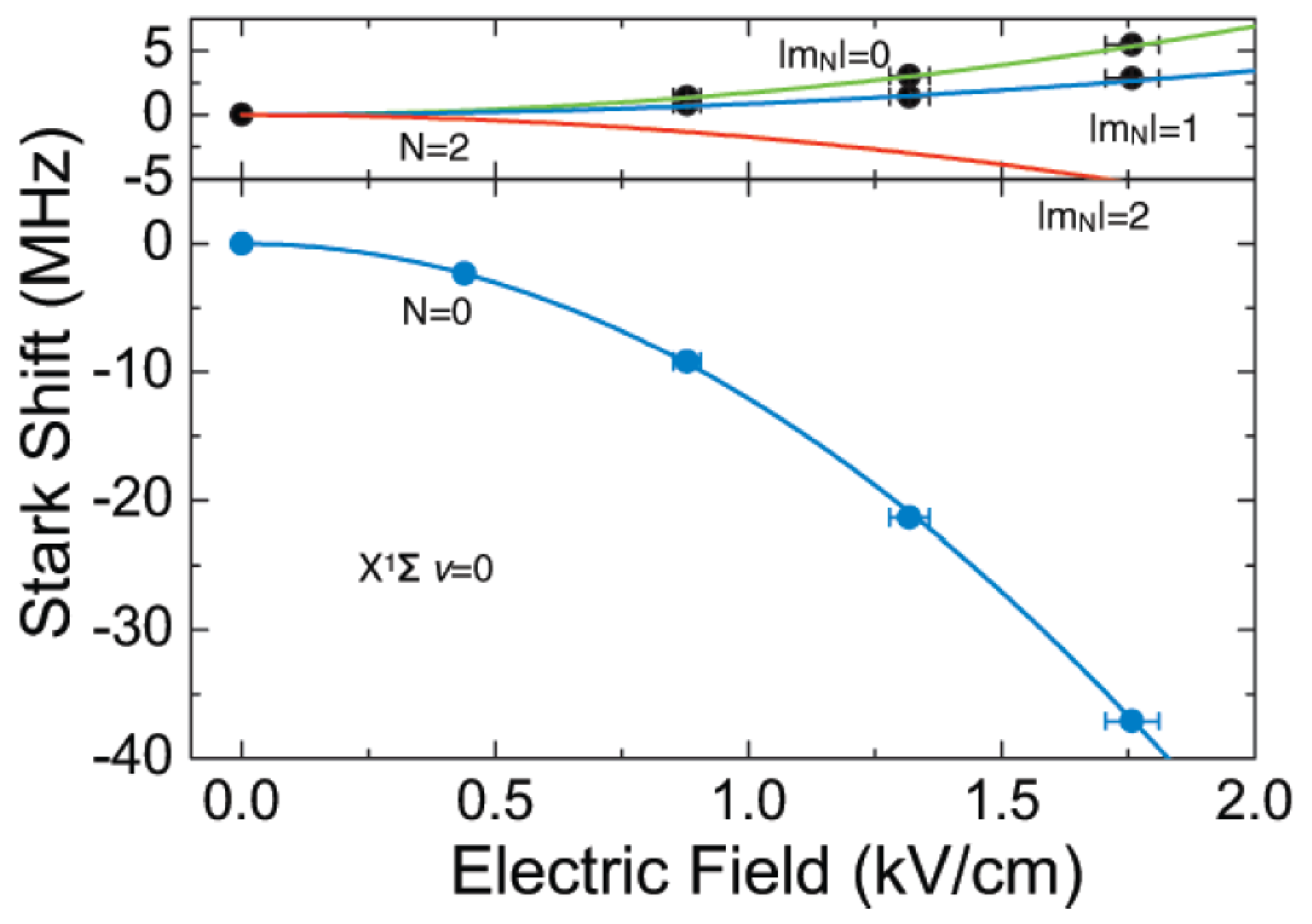
But what about polar molecules?



No EDM in a state with a well defined rotational quantum number!



“Permanent” EDM of KRb

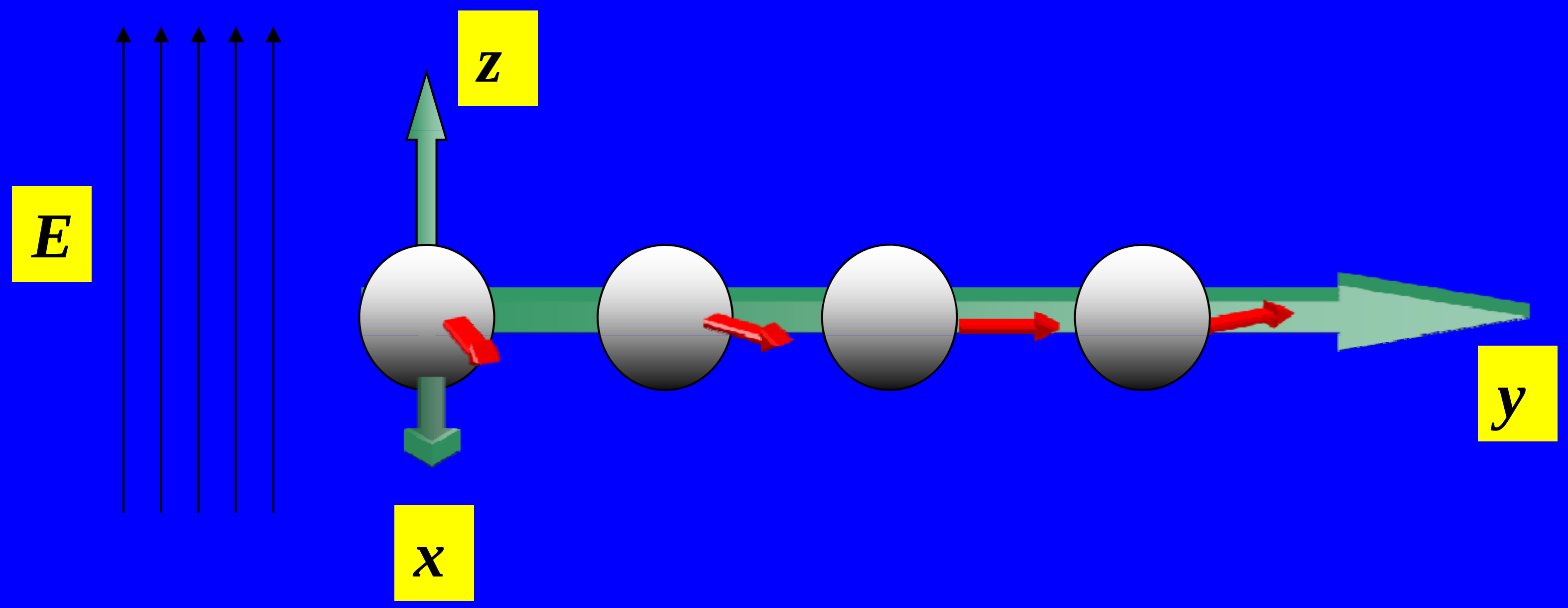


“Given the measured B, the fit of the Stark shift (line in lower panel) gives a permanent electric dipole moment of 0.566(17) D.” K.-K. Ni, et al. Science **322** (2008) 231.

T violation and EDM

- Existence of particle EDM implies T reversal invariance violation
- T reversal violation implies CP violation if CPT symmetry preserved
- Std. model $\Longrightarrow$ immeasurably small EDM
- EDMs are good to look beyond Std. model

EDM causes spin to precess in an electric field



Universal Statistical Sensitivity Formula (“**Equation One**”)

$$\delta d \approx \frac{\hbar}{E}\cdot\frac{1}{\sqrt{N\tau T}}$$

Electric field

Number of Particles

Coherence Time

Lifetime of Experimentalist

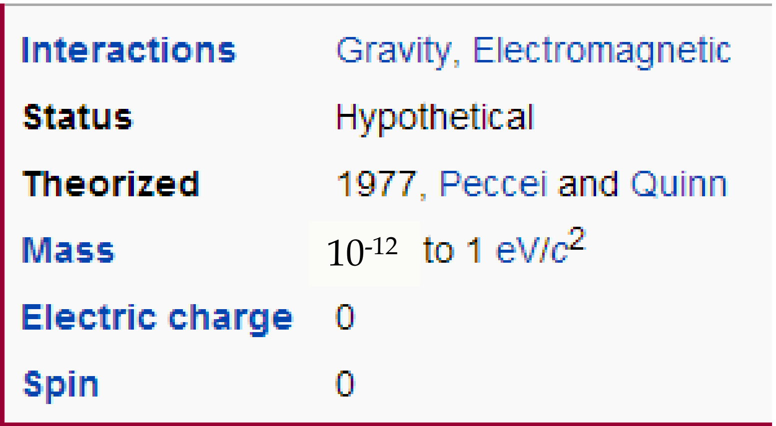
OSCILLATING AXIONS AND "EDM NMR"

Theory: **Peter Graham and Surjeet Rajendran (Stanford)**

Experimental dreams: **Micah Ledbetter and D. Budker**
(UC Berkeley&LBNL); **Alex Sushkov (Harvard)**

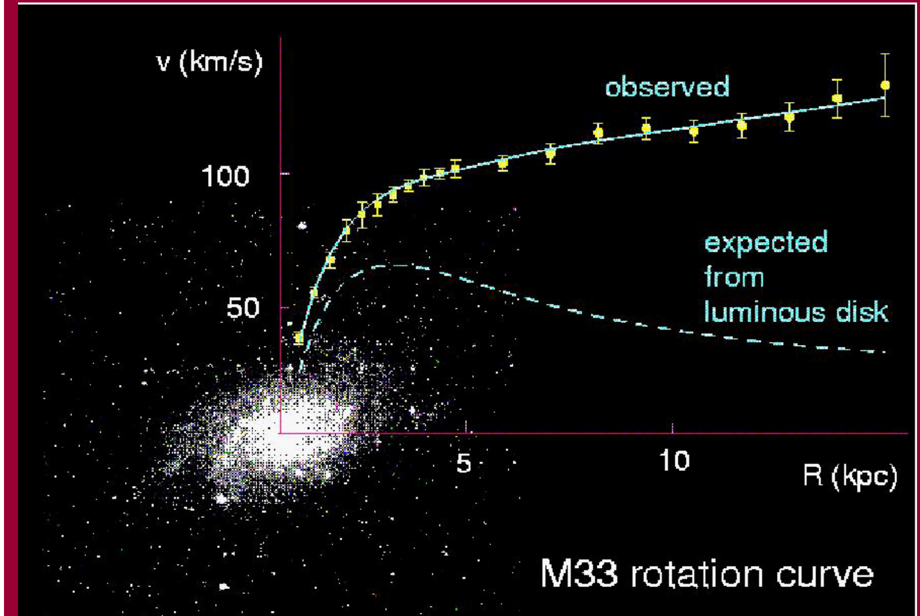
CP Violation Workshop, Mahabaleshwar,
Maharashtra, India, February 2013

AXIONS

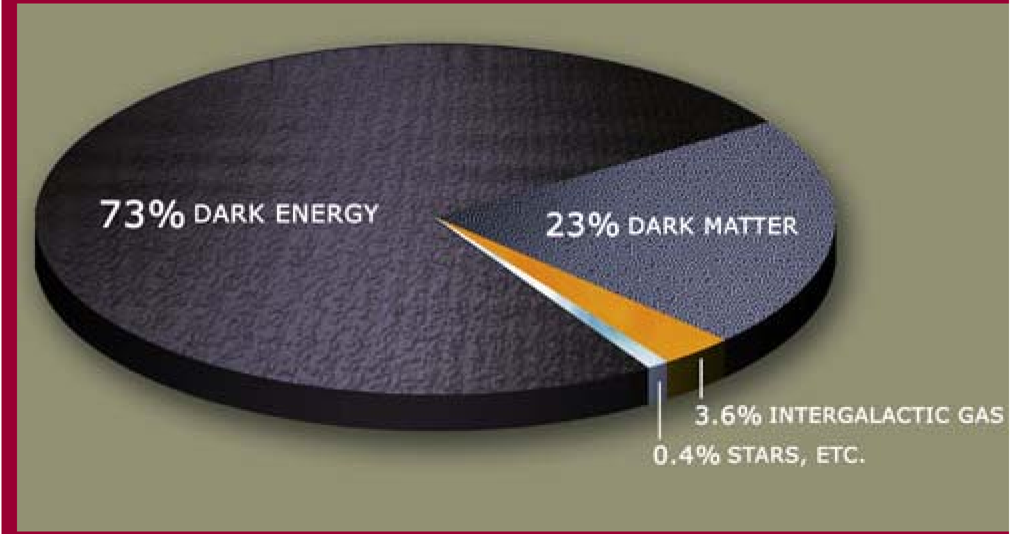


Interactions	Gravity, Electromagnetic
Status	Hypothetical
Theorized	1977, Peccei and Quinn
Mass	10^{-12} to 1 eV/c^2
Electric charge	0
Spin	0

- Introduced to solve strong CP problem in QCD:
- why is n-EDM so small?
- Axions may also solve the **Dark Matter** problem



http://scienceblogs.com/startswithabang/files/2012/04/rotationCurve.jpeg

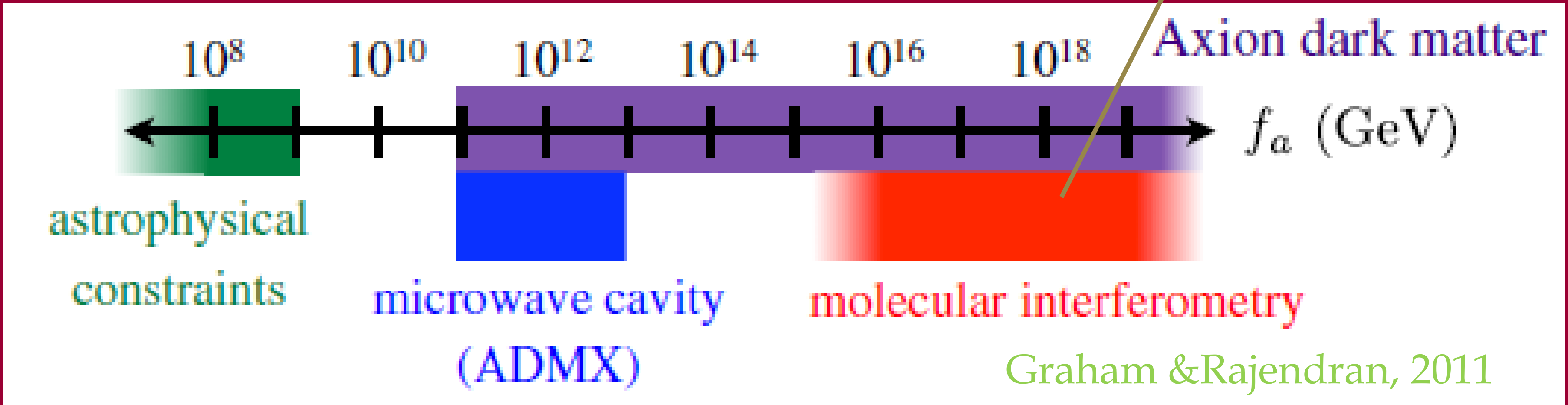


http://earthsky.org/space/

AXION SEARCHES

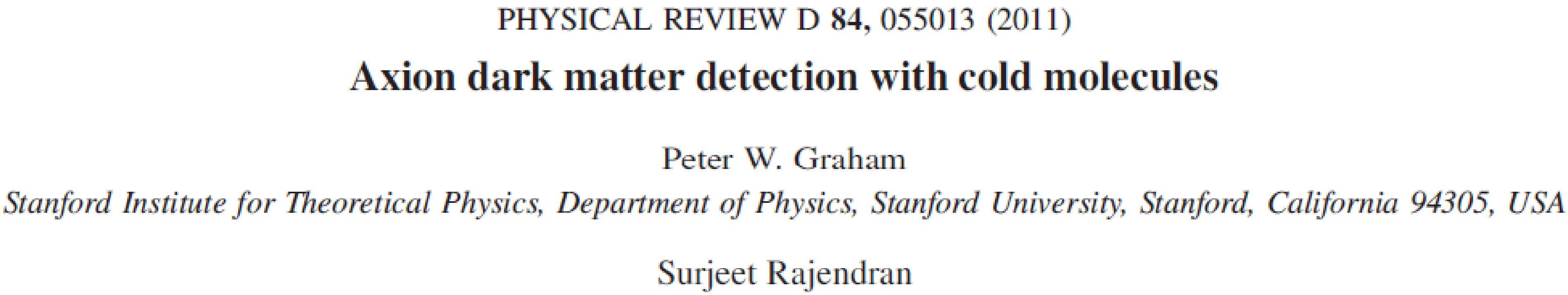
- f_a - axion decay constant
- expected to be around $M_{\mathrm{GUT}}(\sim 10^{16}\,\mathrm{GeV}) - M_{\mathrm{Pl}}(\sim 10^{19}\,\mathrm{GeV})$
- $\Lambda_{\mathrm{QCD}} \sim 200$ MeV is the QCD confinement scale
- $$m_a \sim \frac{\Lambda_{\mathrm{QCD}}^2}{f_a}$$
- Axion parameter space:

Theoretically “natural” range



Graham &Rajendran, 2011

NEW IDEAS



PHYSICAL REVIEW D **84**, 055013 (2011)

Axion dark matter detection with cold molecules

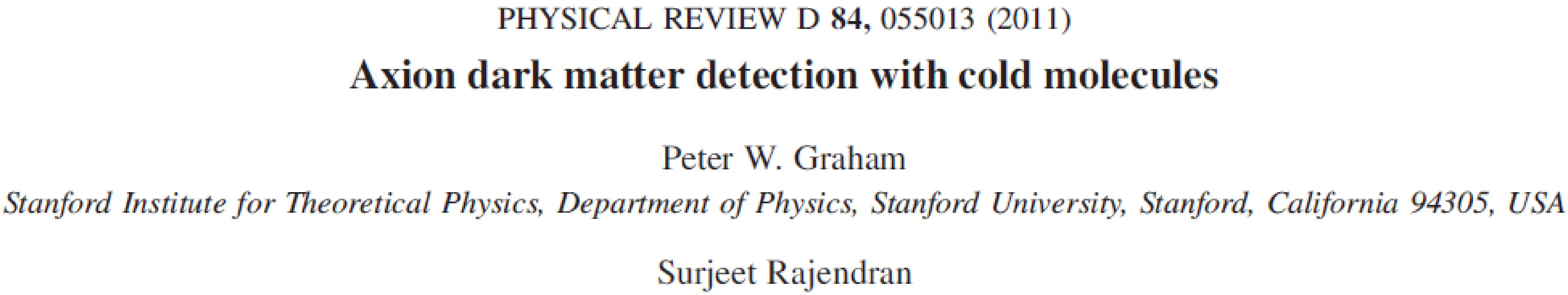
Peter W. Graham

Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305, USA

Surjeet Rajendran

- Axion field oscillates
- at a frequency equal to its mass
- $\Longrightarrow$ time varying CP-odd nuclear moments:
- nEDM, Schiff, …

NEW IDEAS



PHYSICAL REVIEW D **84**, 055013 (2011)

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- Existing searches rely on axion-photon conversion
- via the coupling $\mathcal{L} \supset g_{a\gamma} \frac{a}{f_a} F\tilde{F} = g_{a\gamma} \frac{a}{f_a} \vec{E} \cdot \vec{B}$

$$\boxed{\mathcal{L} \supset \frac{g_s^2}{32\pi^2} \frac{a}{f_a} \mathrm{tr} G\tilde{G}}$$

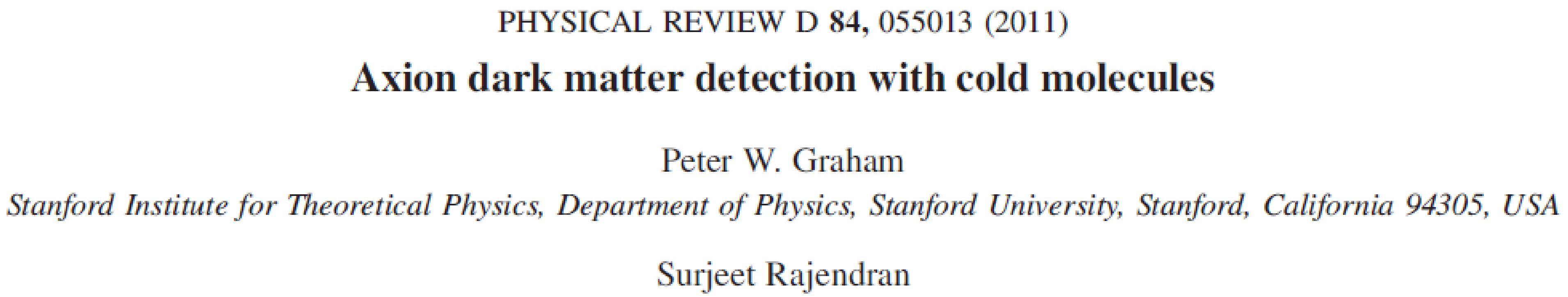
- Graham & Ragendran: use coupling to gluons instead
- $\Longrightarrow$ background axions generate nucleon EDM:

$$d_n = 1.2 \times 10^{-16} \theta_{\mathrm{QCD}} \; \mathrm{e} \cdot \mathrm{cm}.$$

$$\boxed{d_n = 1.2 \times 10^{-16} \frac{a}{f_a} \; \mathrm{e} \cdot \mathrm{cm}}$$

- in analogy to QCD

NEW IDEAS



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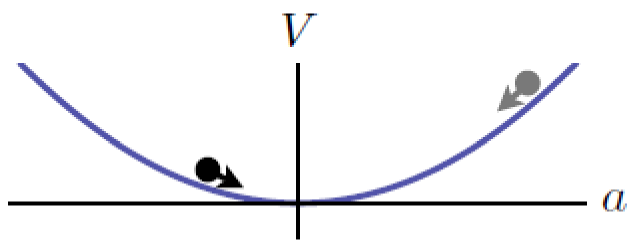
Surjeet Rajendran

- What is the local density of axion dark-matter field?
- Nearly constant value everywhere after inflation
- Subsequent evolution governed by the mass term

$$\mathcal{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}\mathrm{tr}G\tilde{G} + m_a^2 a^2 \qquad m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$$

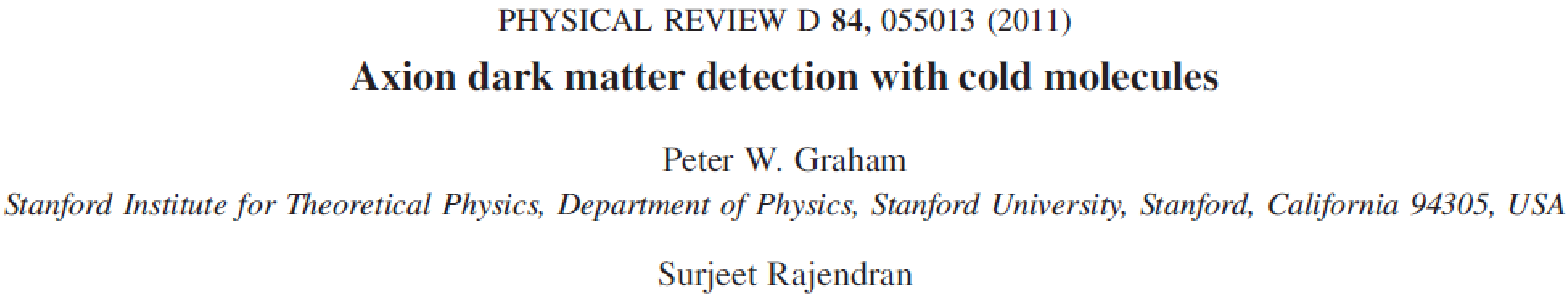
GUT scale

- Oscillating solution: $a(t) = a_0 \cos(m_a t)$
- All axion interactions suppressed → no thermalization
- Good cold dark matter candidate



Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

NEW IDEAS



PHYSICAL REVIEW D **84**, 055013 (2011)

Axion dark matter detection with cold molecules

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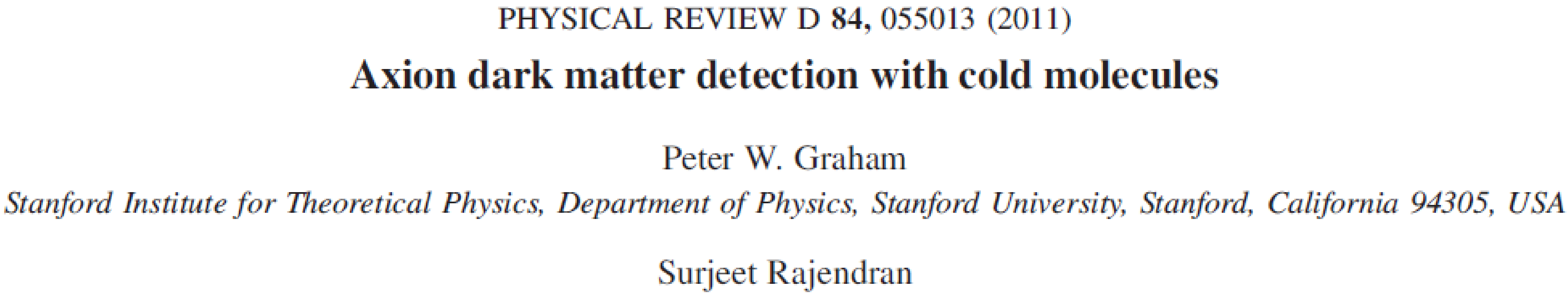
Surjeet Rajendran

- Axion field affected by gravitation → galactic speed
- $v/c \sim 10^{-3} \Longrightarrow$ finite coherence length $\sim h/mv$ $\sim 500\ \mathrm{km}(\frac{f_a}{M_{\mathrm{GUT}}})$
- and coherence time $\sim h/mv^2$
- $\rightarrow \sim 10^6 \times$ field oscillation period

NEW IDEAS


PHYSICAL REVIEW D **84**, 055013 (2011)

Axion dark matter detection with cold molecules

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- Assuming that axions are the dark matter
- and taking $m_a \sim 10^{-19}$ GeV(M_{GUT}/f_a) $\Longrightarrow$

$$\theta_a = \frac{a_0}{f_a} \sim \frac{\sqrt{\rho_{\rm DM}}}{\Lambda_{\rm QCD}^2} \sim 3 \times 10^{-19}.$$

- This generates oscillating EDM:

$$d_n \approx 4 \times 10^{-35} \cos(m_a t) \text{ e} \cdot \text{cm}$$

- Independent of f_a

$$m_a \approx 1 \text{ kHz}\left(\frac{M_{\rm Pl}}{f_a}\right) \approx 1 \text{ MHz}\left(\frac{M_{\rm GUT}}{f_a}\right)$$

- Nucleons radiate (but no problem)
- "Classic" EDM searches are insensitive to oscil. EDM

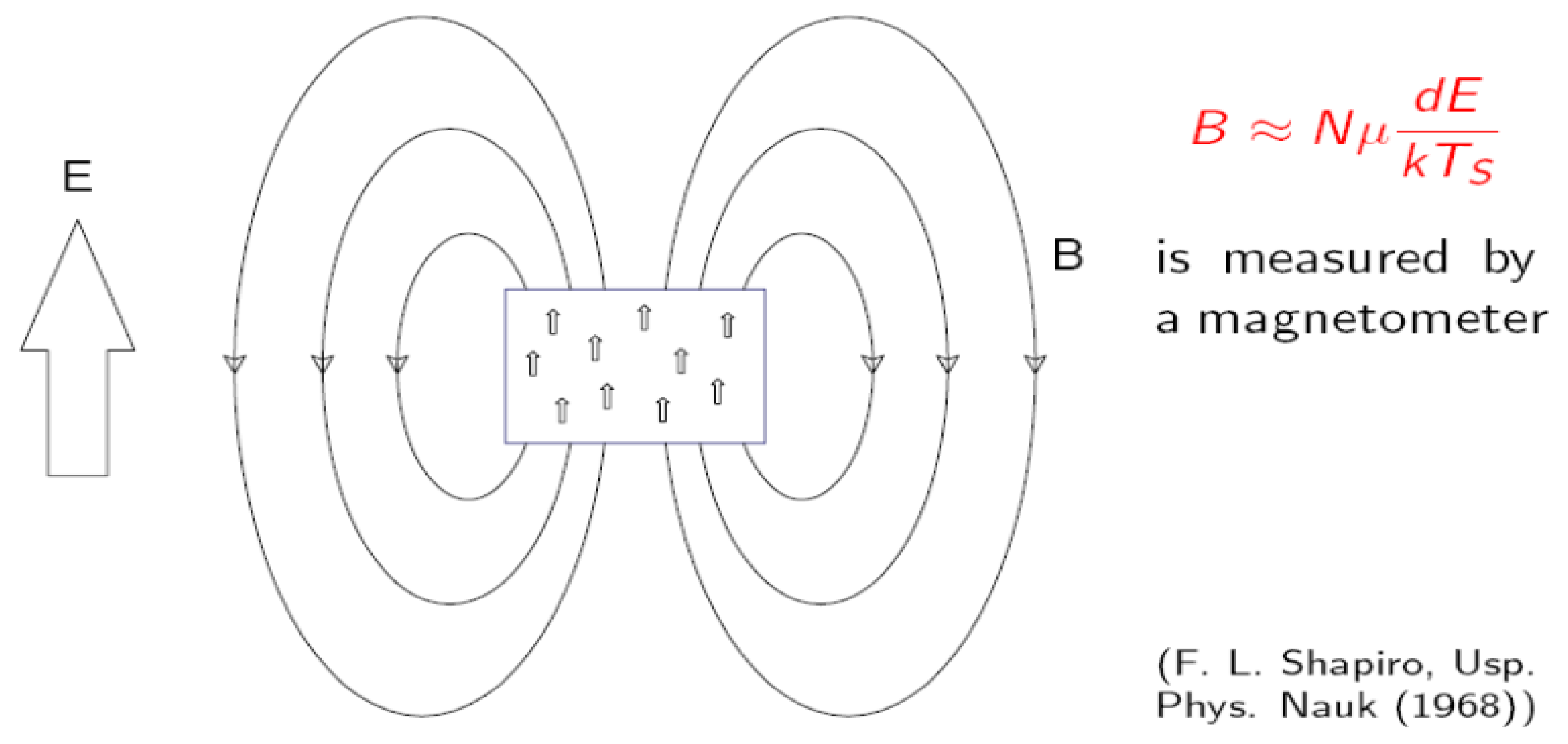
OSCILLATING-EDM NMR

$$d_n \approx 4 \times 10^{-35} \cos(m_a t)\ \mathrm{e \cdot cm}$$

- The oscillating EDM is tiny
- But lots of potential advantages over static EDM expts
- For example, can increase T_2 via dynamic decoupling
- Easier to fight technical noise at high frequency
- Solid-state NMR seems promising
- Take advantage of large intrinsic fields in **polar crystals**
- Relates to recent theoretical and experimental work on solid-state non-oscillating EDM searches

D. Budker, P. Graham, M. Ledbetter, S. Rajendran, and A. Sushkov: in preparation

Solid-state “magnetization” experiment:



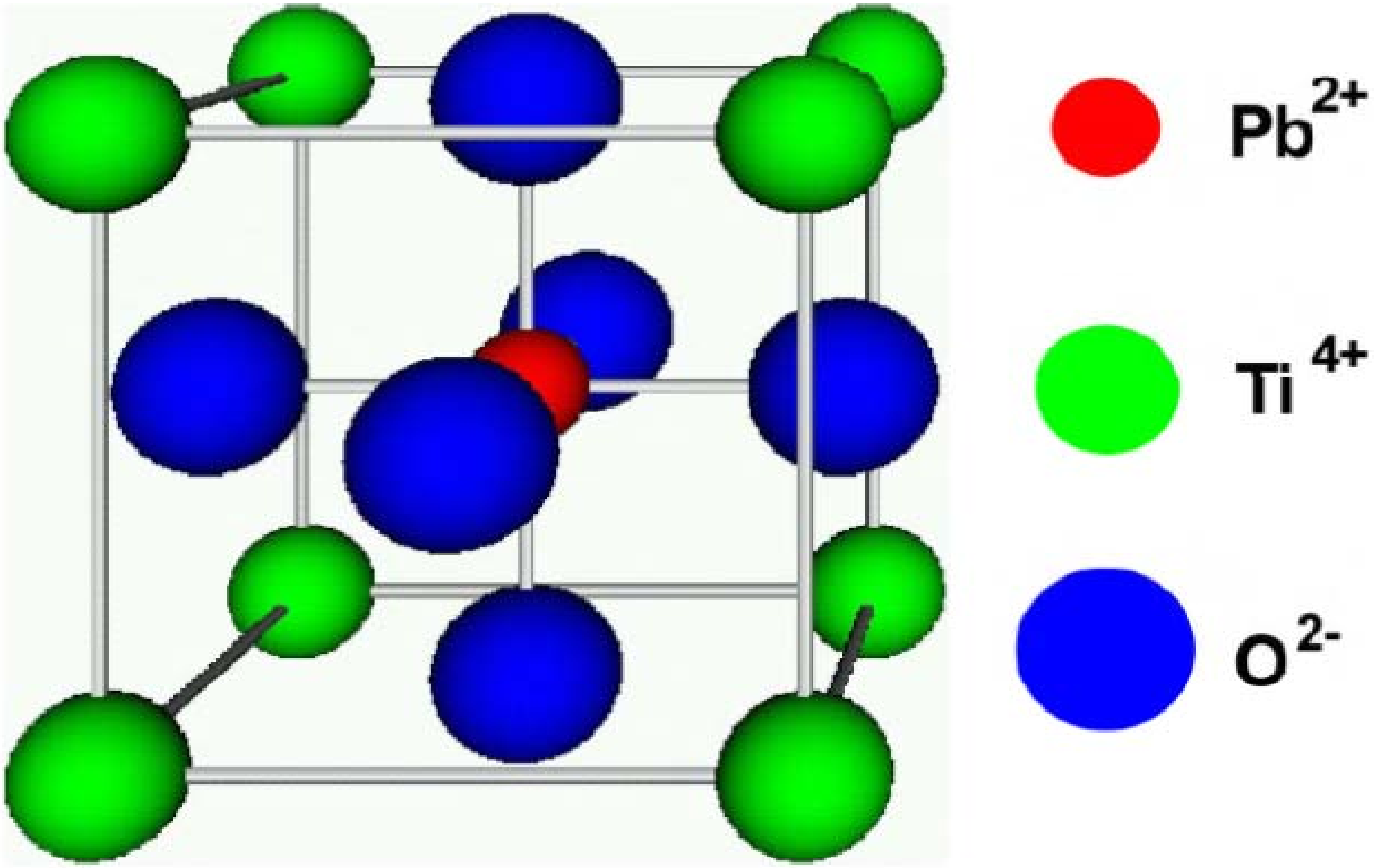
$$B \approx N\mu \frac{dE}{kT_S}$$

B is measured by a magnetometer

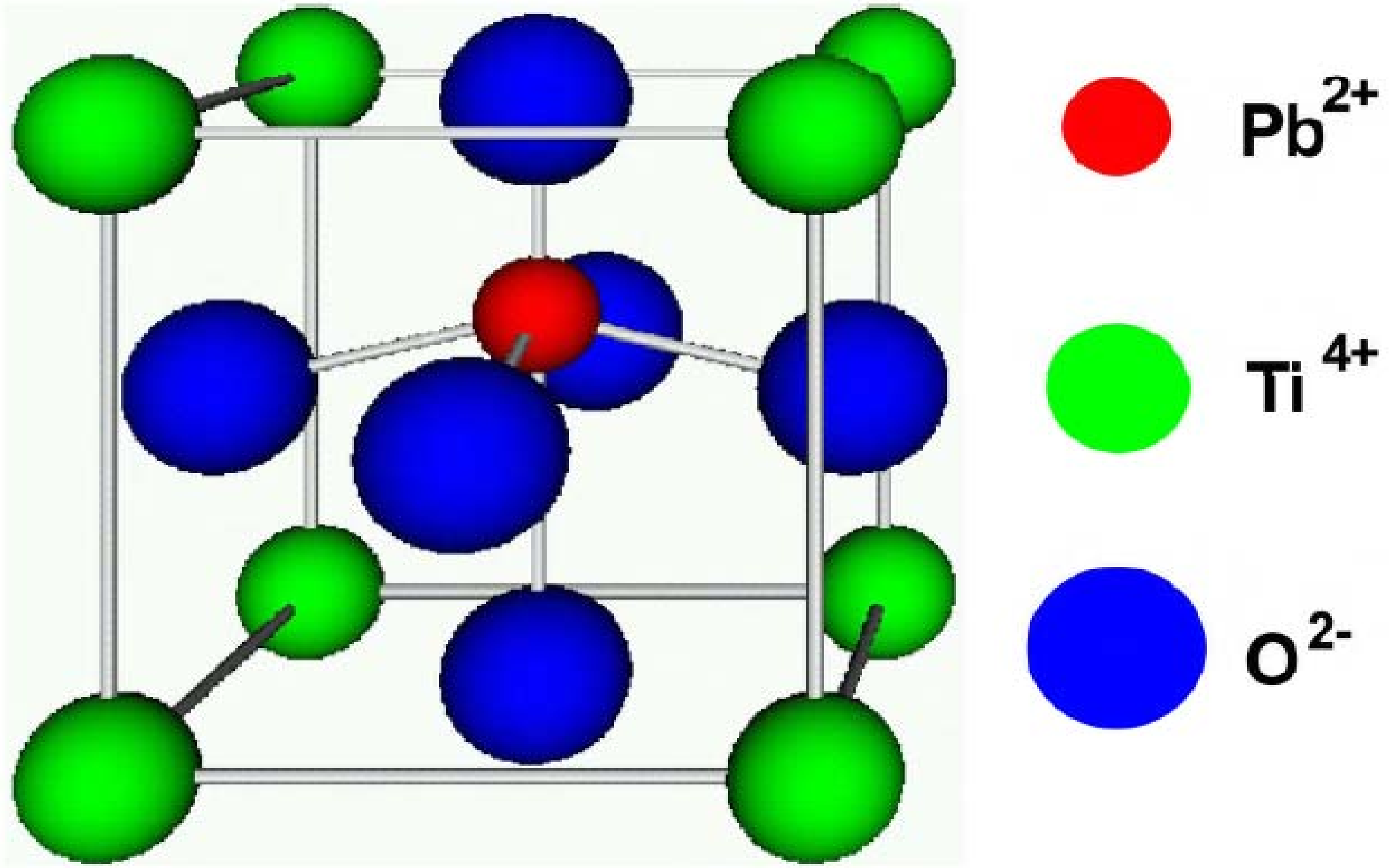
(F. L. Shapiro, Usp. Phys. Nauk (1968))

- Obvious benefit: very large *N*
- But there could be more…

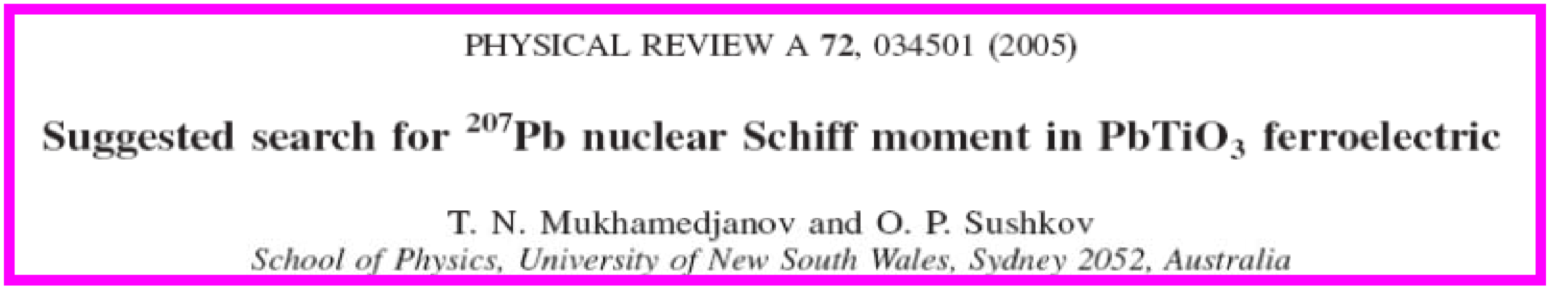
The perovskite crystal structure of $PbTiO_3$



The perovskite crystal structure of $PbTiO_3$



Where does the improvement come from?



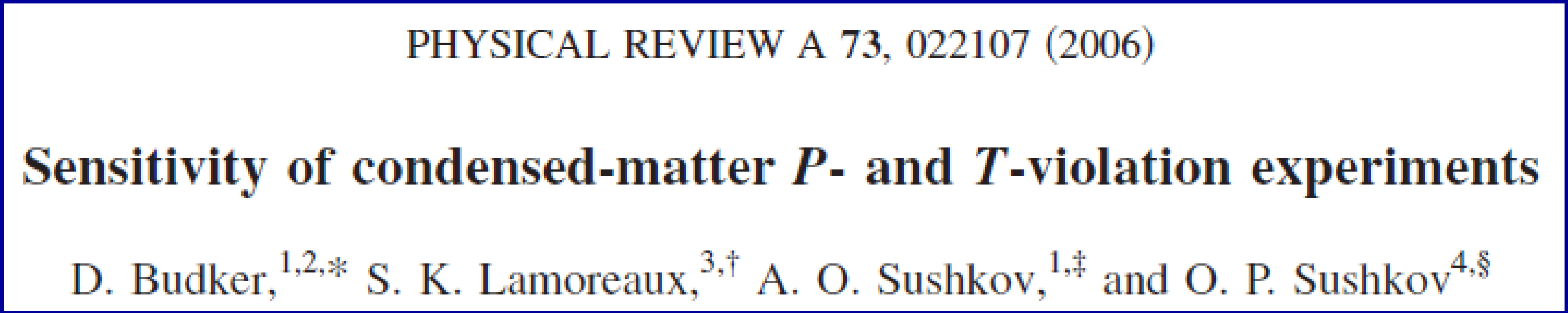
PHYSICAL REVIEW A **72**, 034501 (2005)

Suggested search for ^{207}Pb nuclear Schiff moment in PbTiO$_3$ ferroelectric

T. N. Mukhamedjanov and O. P. Sushkov

School of Physics, University of New South Wales, Sydney 2052, Australia

- $PbTiO_3$ is a ferroelectric crystal → large effective electric field: $E_{\text{int}} \approx 10^8$ V/cm as in diatomic molecules !
- A solid-state experiment → large number of atoms: $N \approx 10^{22}\ \text{cm}^{-3}$
- Nuclear de-magnetization cooling to reach nuclear spin temperature: $T_s \approx 10^{-4}$ K
- Other schemes (optical pumping?) may give even lower nuclear spin temperature: $T_s \approx 10^{-8}$ K


PHYSICAL REVIEW A **73**, 022107 (2006)

Sensitivity of condensed-matter *P*- and *T*-violation experiments

D. Budker,[1,2,*] S. K. Lamoreaux,[3,†] A. O. Sushkov,[1,‡] and O. P. Sushkov[4,§]

PRECESSION EDM EXPERIMENTS

- Single-shot Ramsey-type measurement over coherence time (τ):

Signal: $S_1 \approx N\frac{dE}{\hbar}\tau.$ Noise: $N_1 \approx \sqrt{N}.$

Things get better for longer measurement (*t*): $S/N \approx \frac{S_1}{N_1}\sqrt{\frac{t}{\tau}} = \sqrt{N}\frac{dE}{\hbar}\sqrt{\tau t}.$

CM MAGNETIZATION EXPERIMENTS

Signal: $S_1 \propto N\frac{dE}{T}\mu,$ Noise: $N_1 \propto \sqrt{N}\mu.$

Things still get better for longer measurement (*t*): $S/N \approx \frac{S_1}{N_1}\sqrt{\frac{t}{\tau}} = \sqrt{N}\frac{dE}{T}\sqrt{t/\tau}.$

but…

it is better to have a **short** relaxation time **τ**

What happens at low temperature?

- Relaxation is determined by dipole-dipole interactions between spins
- Relaxation time scale and energy of the d-d interaction are related:

$$\mathfrak{J} \approx \frac{\hbar}{\tau}.$$

- Induced magnetization scales as T^{-1} down to: $T_{opt} \approx \mathfrak{J}.$

  below that ⇒ (anti)ferromagnetic transition

- Substituting into

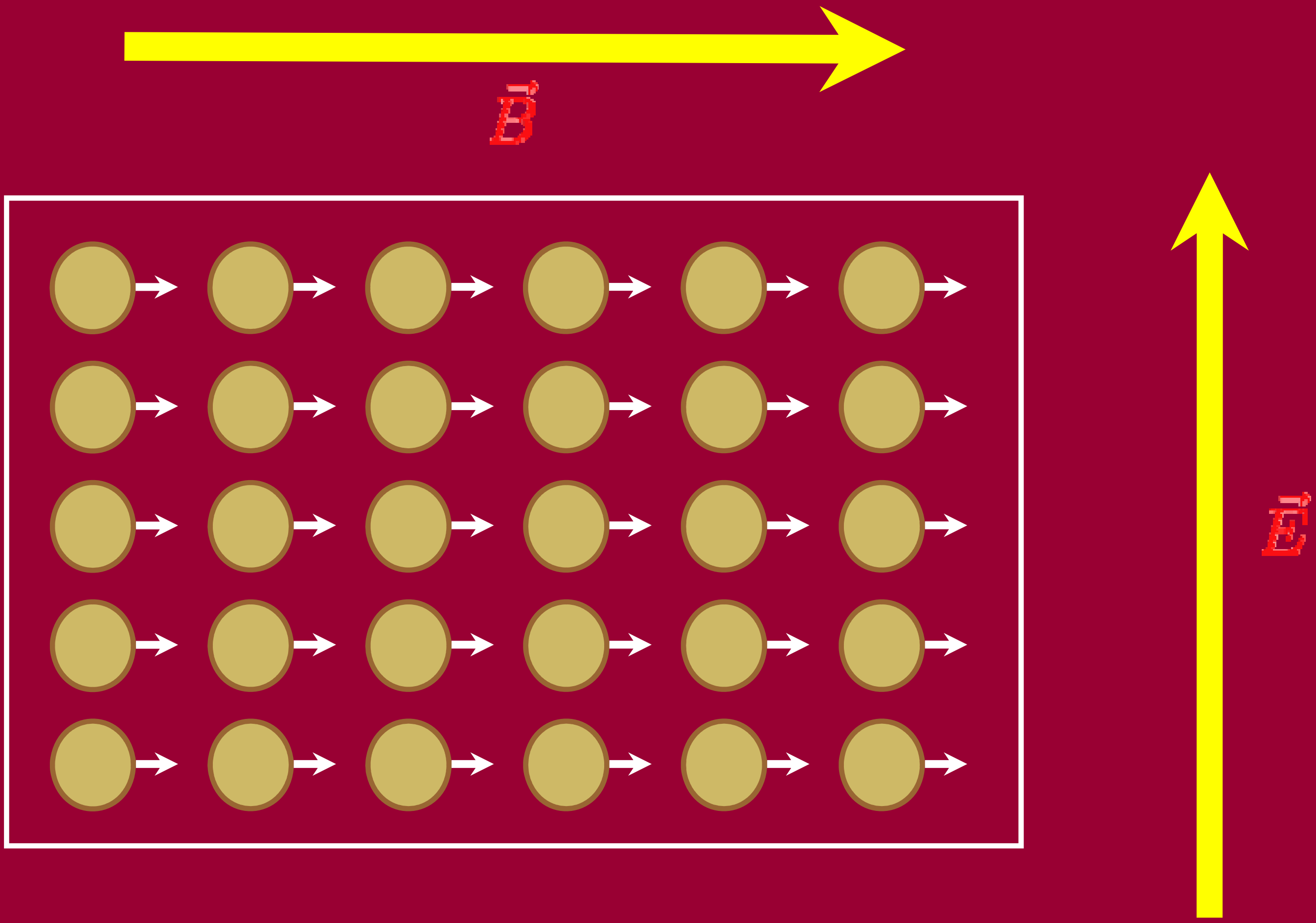
$$S/N \approx \frac{S_1}{N_1}\sqrt{\frac{t}{\tau}} = \sqrt{N}\frac{dE}{T}\sqrt{t/\tau}.$$

recovers the usual scaling:

$$\boxed{S/N \approx \frac{S_1}{N_1}\sqrt{\frac{t}{\tau}} = \sqrt{N}\frac{dE}{\hbar}\sqrt{\tau t}.}$$

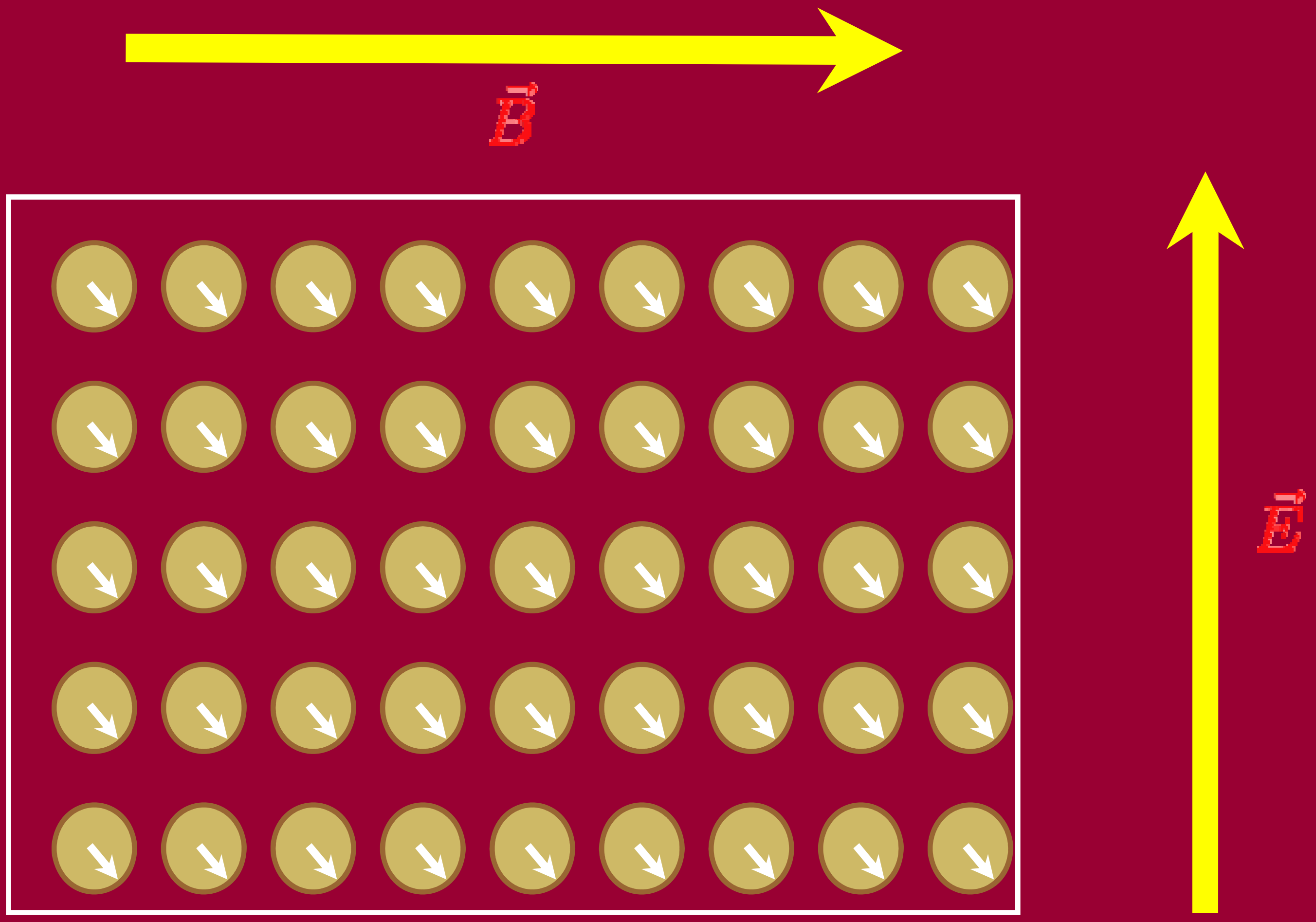
Back to the oscillating EDM story…

Conceptual Setup



Surjeet Rajendran

Conceptual Setup



$$\delta\theta \sim \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right) t\right) \sin\left(2\mu_N B t\right)$$

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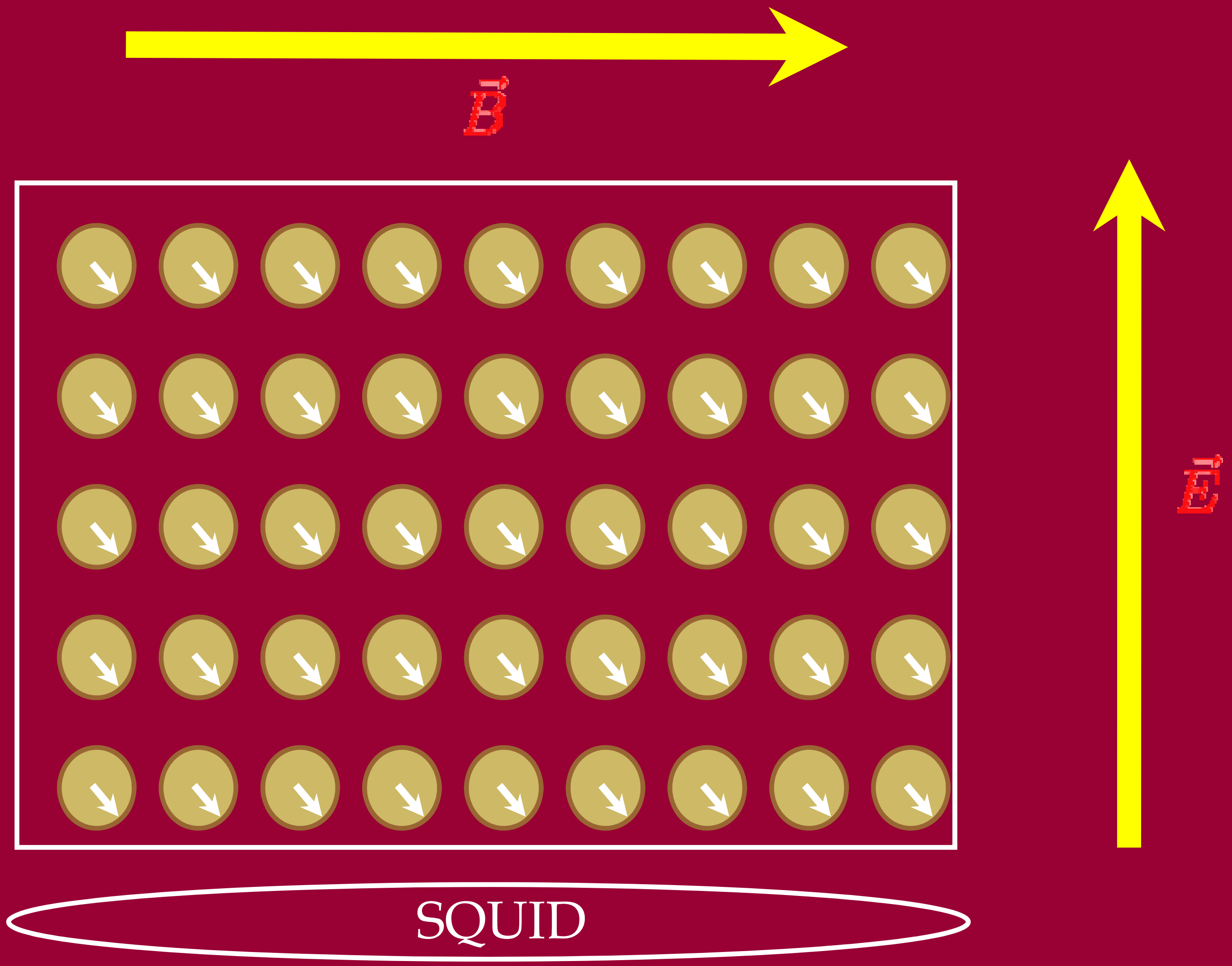
Conceptual Setup



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Rough Estimate

$$\delta B \sim np\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right) t\right) \sin\left(2\mu_N B t\right)$$

$$n \sim \frac{10^{22}}{\mathrm{cm}^3}$$

$$\mu_N \sim \frac{\mathrm{e}}{\mathrm{GeV}}$$

$$d_N \sim 10^{-34}\ \mathrm{e\text{-}cm}$$

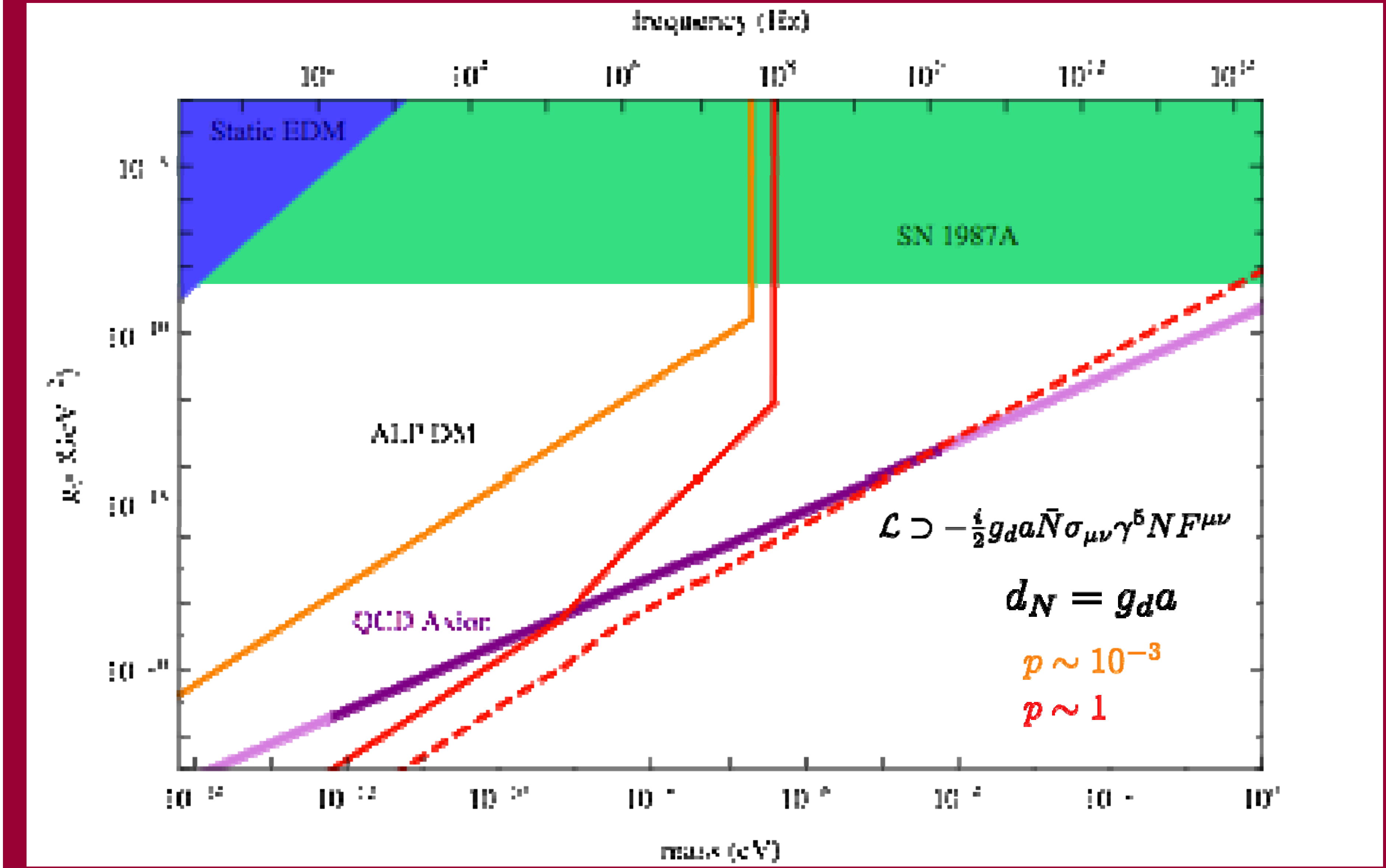
$$p \sim \mathcal{O}(1)$$

$$E_{\mathrm{eff}} \sim 10^6\,\frac{\mathrm{V}}{\mathrm{cm}}$$

$$\left(\mu_N B - m_a\right)^{-1} \sim \left(10^{-6} m_a\right)^{-1} \sim t \sim 1\ \mathrm{s}\left(\frac{f_a}{10^{16}\mathrm{GeV}}\right)$$

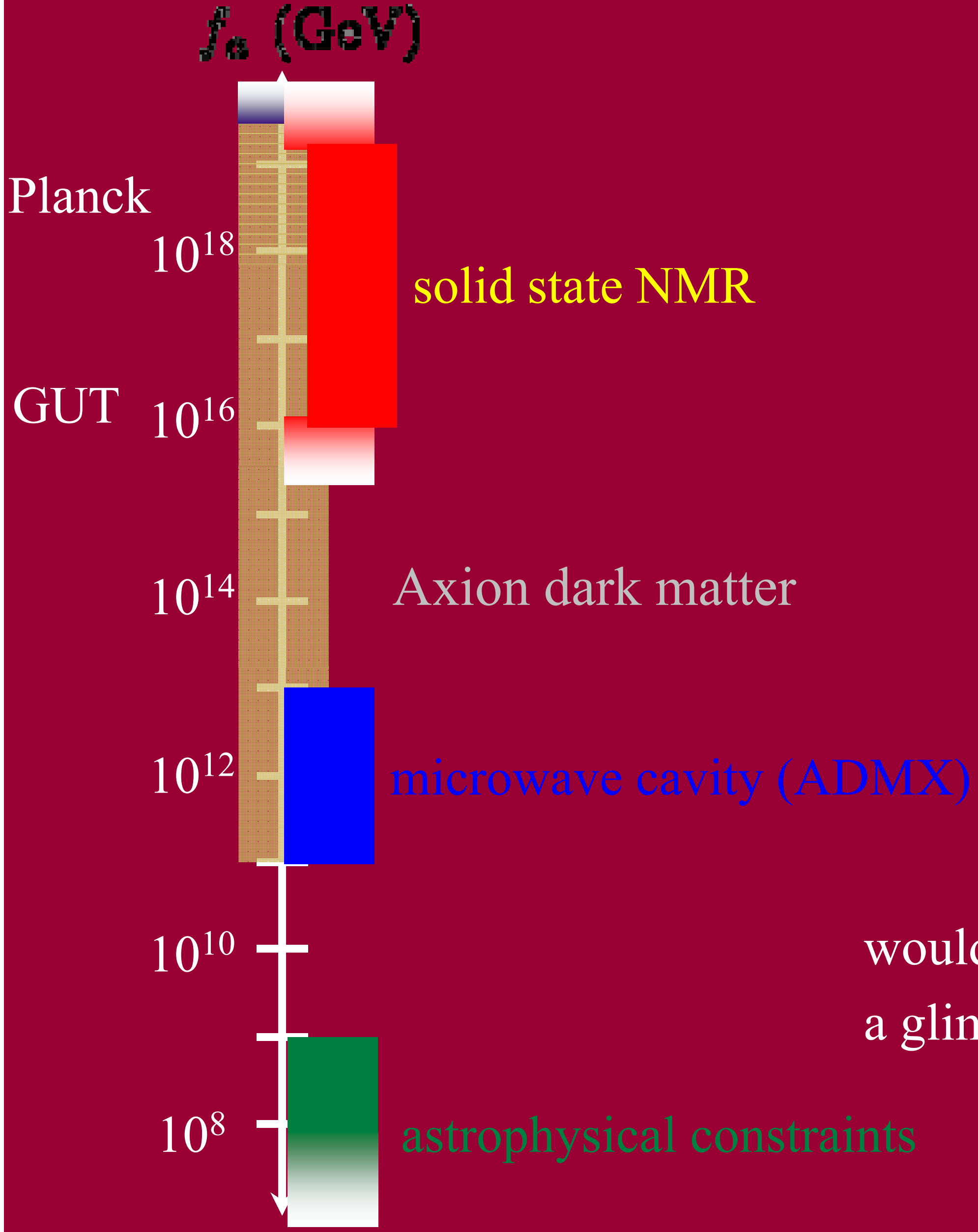
$$\delta B \sim 10^{-2}\ \mathrm{fT}$$

Projected Sensitivity in Lead Titanate



$$\delta B = 0.1 \frac{\text{fT}}{\sqrt{\text{Hz}}},\ n = \frac{10^{22}}{\text{cm}^3},\ V = 1000\ \text{cm}^3,\ T_2 = 1\ \text{s}$$

Solid State Axion Searches



can most easily search in kHz - MHz frequencies → high f_a

technological challenges, similar to early stages of WIMP detection

axion dark matter is very well-motivated, no other way to search for at high f_a

would be both the discovery of dark matter and a glimpse into physics at very high energies

Surjeet Rajendran

Another story:
How would you know you went through a wall?

All-optical magnetometers

- Pump
- "Precession"
- Probe

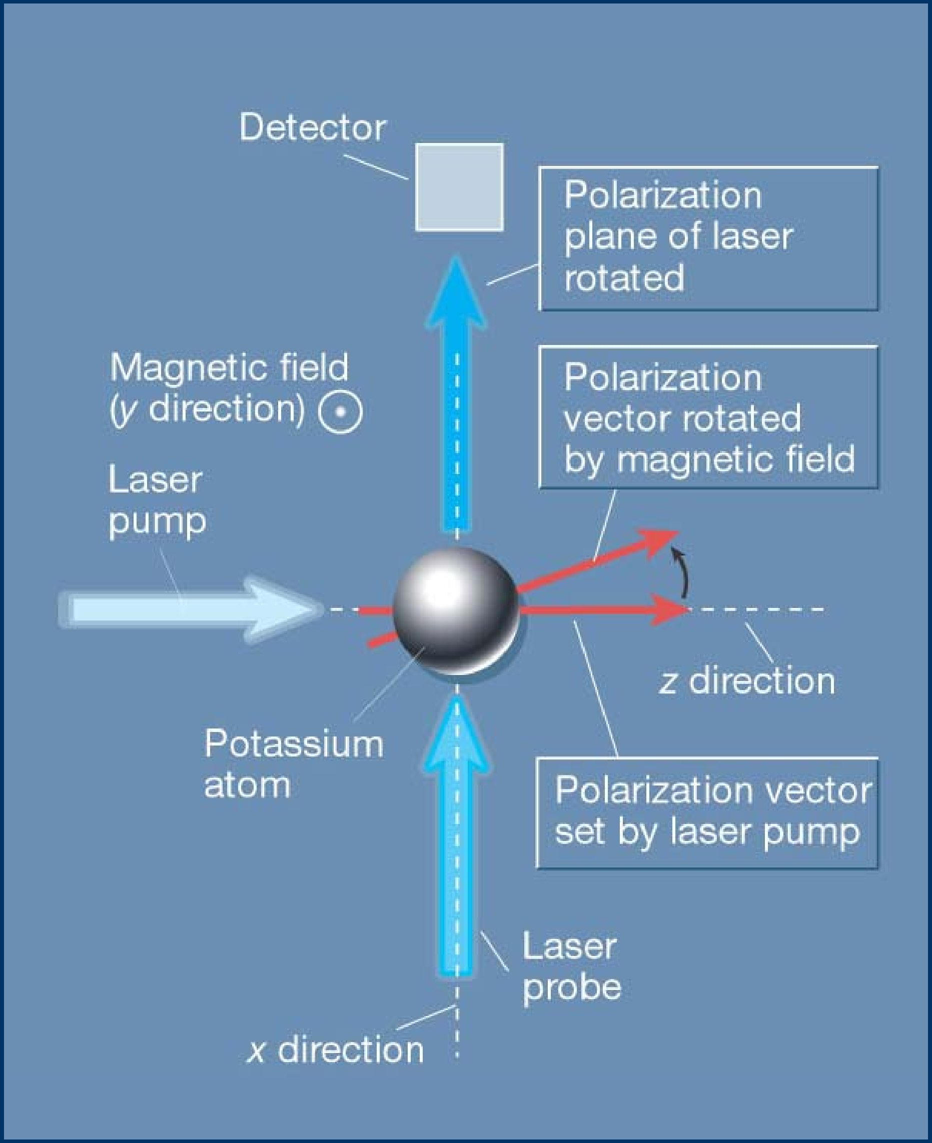


Figure from: D.B. ***: A new spin on magnetometry***
Nature (News&Views) **422**, 574 - 575 (2003)

Fundamental sensitivity limit

$$\delta B \simeq \frac{1}{g\mu}\frac{\hbar}{\sqrt{N\tau T}}$$

Ground-state gyromagnetic ratio

Number of atoms

Spin-relaxation time

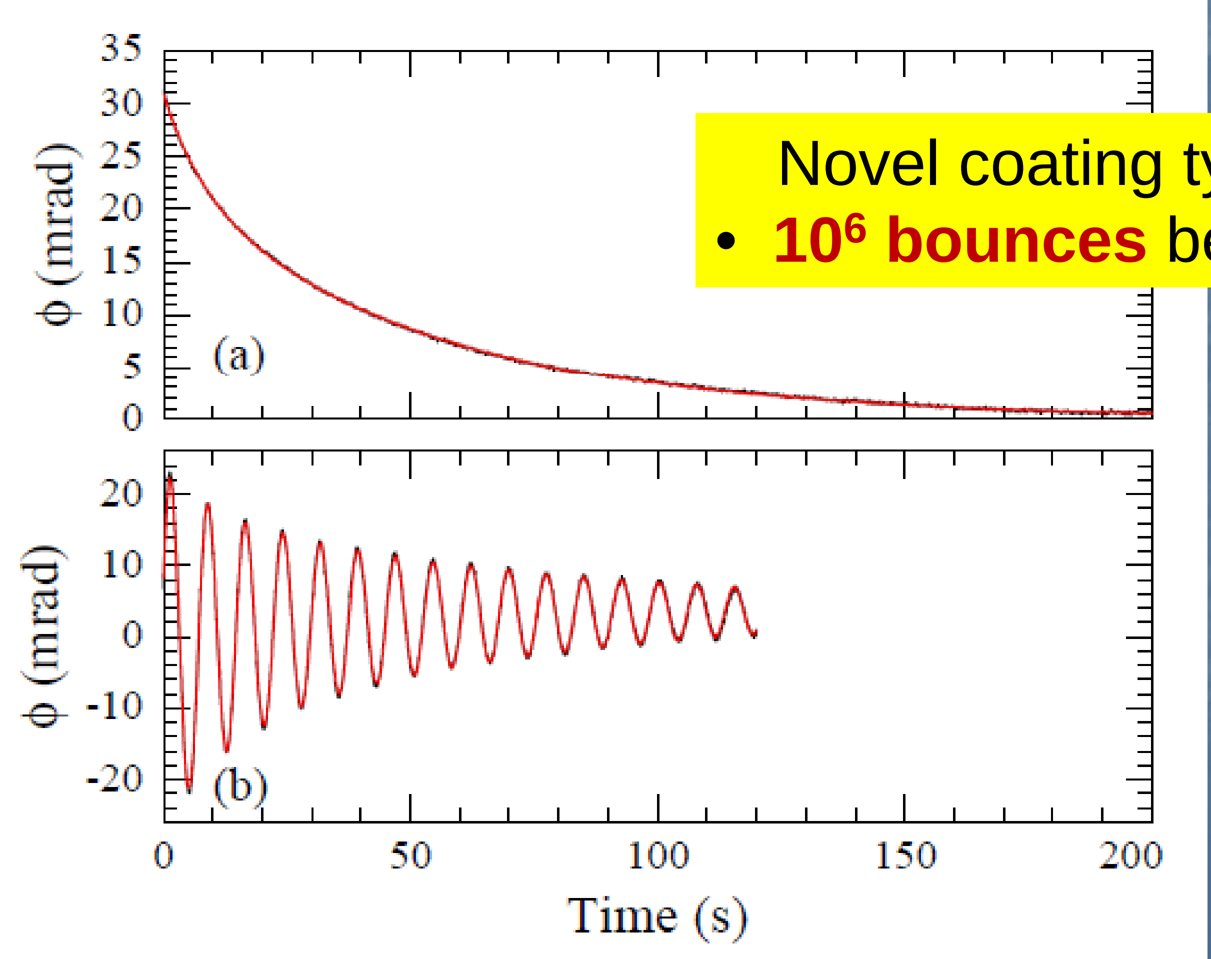
Measurement time

Interlude: breakthrough in coating

PRL **105,** 070801 (2010) PHYSICAL REVIEW LETTERS week ending 13 AUGUST 2010

Polarized Alkali-Metal Vapor with Minute-Long Transverse Spin-Relaxation Time

M. V. Balabas,[1] T. Karaulanov,[2] M. P. Ledbetter,[2,*] and D. Budker[2,3]



Novel coating type

- **10^6 bounces** before depolarization !

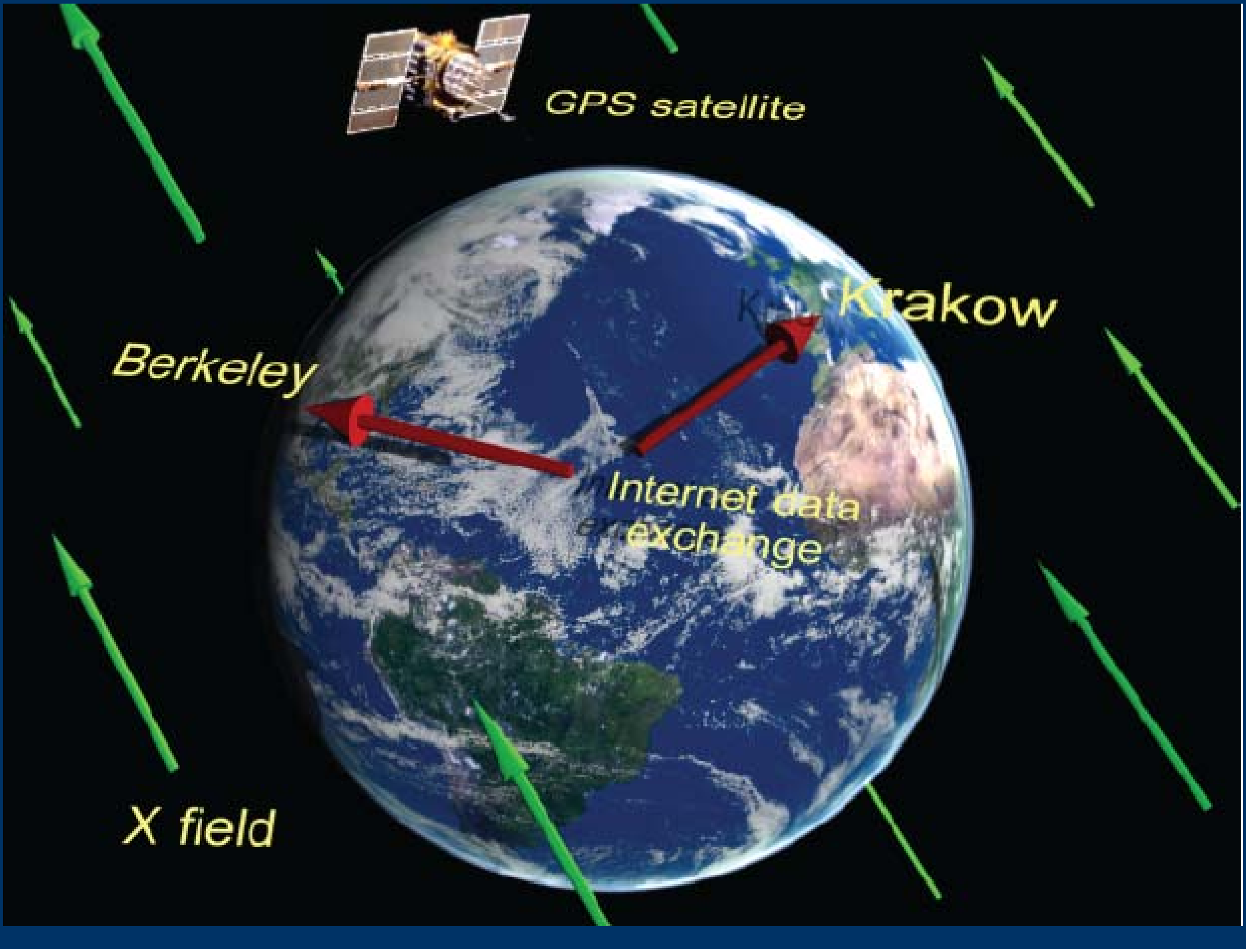
The Cell

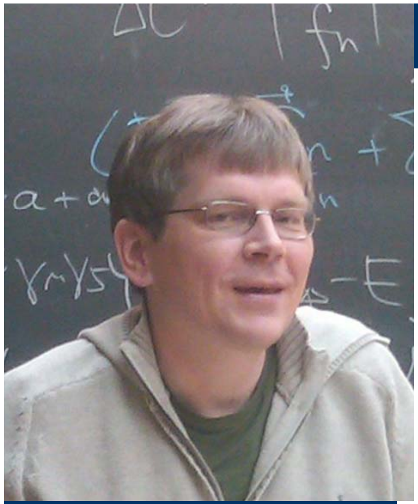
Correlated magnetometers...

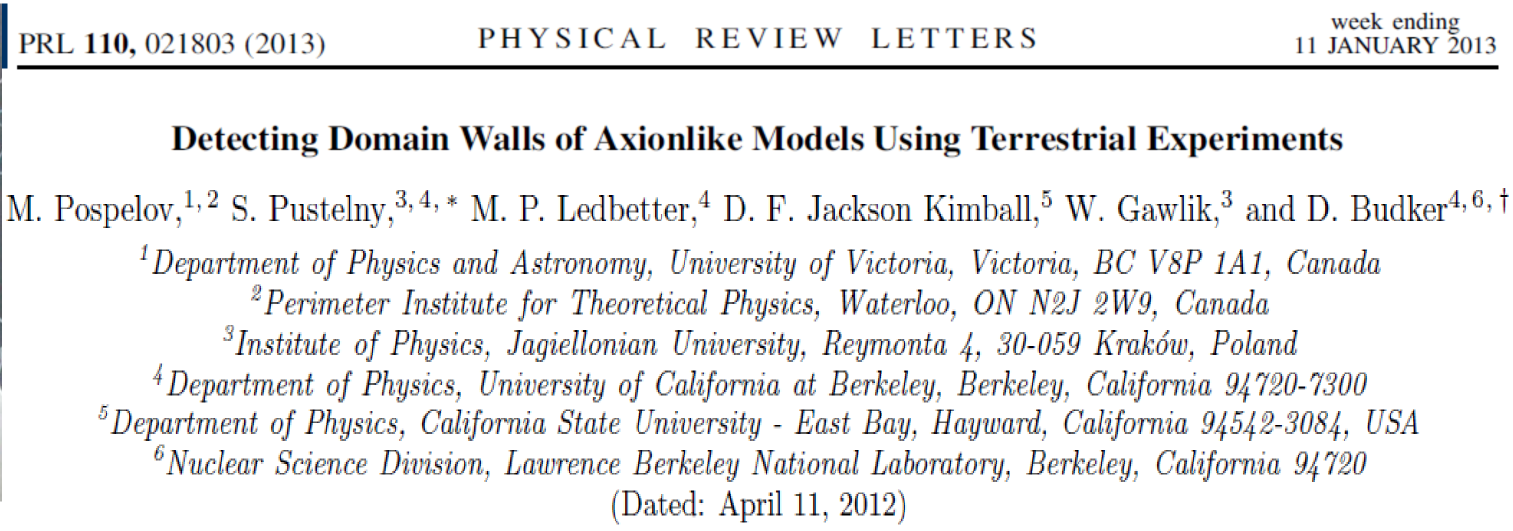
- Modern atomic magnetometers are sensitive at the level of <1 fT/Hz$^{1/2}$
- Electron and nuclear spin based mags
- What can we learn comparing synchronized separated shielded mags?

Search for exotic fields: GNOME

Globabal **N**etwork **O**f **M**agnetometers for **E**xotic physics







PRL **110,** 021803 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

Detecting Domain Walls of Axionlike Models Using Terrestrial Experiments

M. Pospelov,[1,2] S. Pustelny,[3,4,*] M. P. Ledbetter,[4] D. F. Jackson Kimball,[5] W. Gawlik,[3] and D. Budker[4,6,†]

[1] *Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, ON N2J 2W9, Canada*
[3] *Institute of Physics, Jagiellonian University, Reymonta 4, 30-059 Kraków, Poland*
[4] *Department of Physics, University of California at Berkeley, Berkeley, California 94720-7300*
[5] *Department of Physics, California State University - East Bay, Hayward, California 94542-3084, USA*
[6] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720*
(Dated: April 11, 2012)

- Ultralight (m_a~neV) axion-like fields forming domain networks
- Wall thickness $d \sim 2/m_a$
- Domain size $L = 10^{-2}$ ly consistent with Dark Energy density constraints
- We may be going through a wall every 10 y or so!
- Bottom line: **GNOME** is quite sensitive to such events!

Outline:

- General introduction to EDMs
- Proposed search for **oscillating** EDM
- Proposed search for cosmic domains of **A**xion **L**ike **P**articles

Conclusions:

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