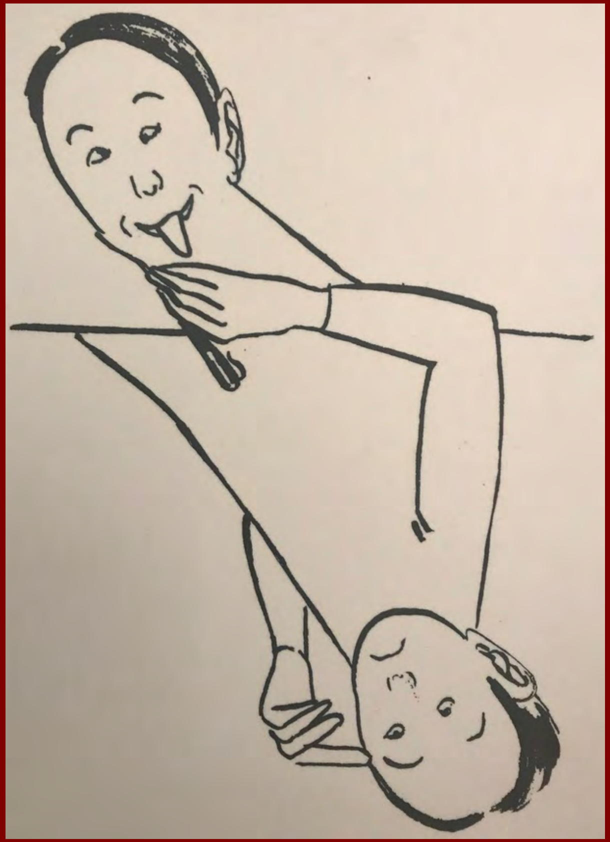
Fundamental Physics with (Weird) Magnetic Resonance



Dmitry Budker

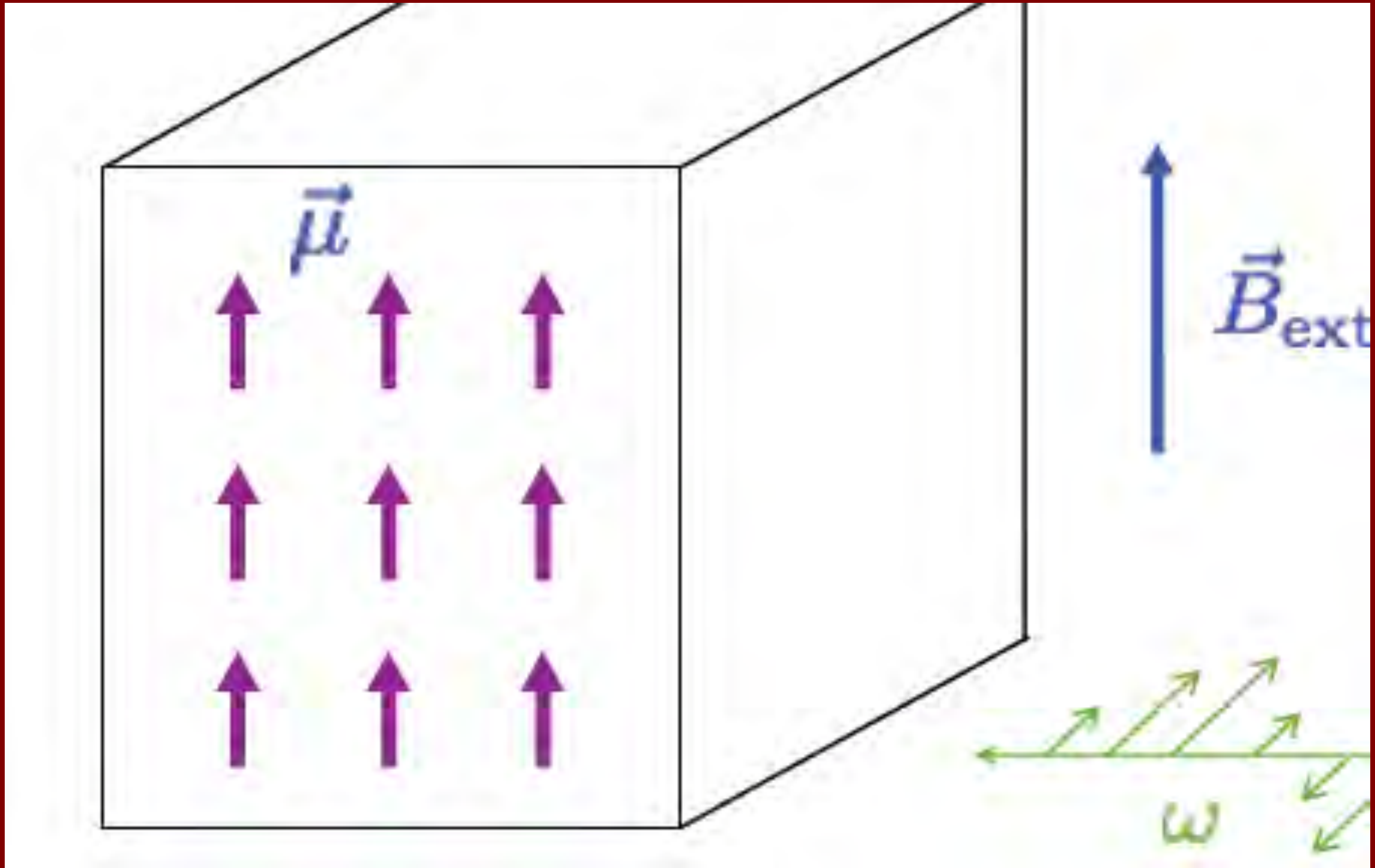
Helmholtz Institute
JGU Mainz

UC Berkeley Physics
NSD LBNL

Frascati, November 29, 2017

SEARCHING FOR ULTRALIGHT DARK MATTER WITH

nuclear magnetic resonance



So what is DM or what mimics it ?

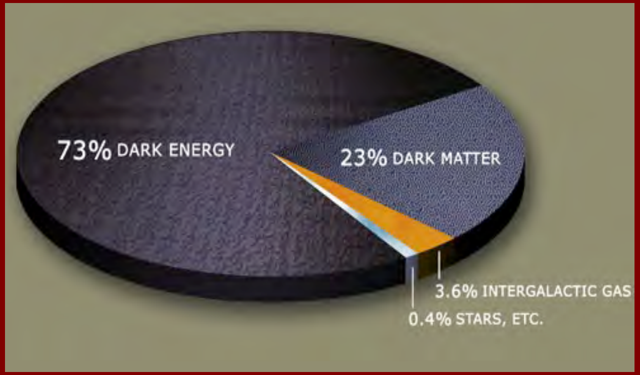
- A gross misunderstanding of gravity (MOND, …) ☹?
- Proca MHD (finite photon mass) ?
- Black holes, dark planets, interstellar gas, … ☹
- WIMPS ☺
- Ultralight bosonic particles
  - Axions (pseudoscalar) ☺ ⬅
  - ALPs (pseudoscalar) ☺ ⬅
  - Dilatons (scalar) ☺
  - Vector particles ☺ ⬅
  - Tensor particles ???

"Most Wanted" file on DM
What do we know?

- Galactic DM density: ~0.4 GeV/cm^3 (10 GeV/cm^3 d.g.)
- Has to be nonrelativistic: $v/c \sim 10^{-3}$ (cold DM)
- Has to be bosonic if $m < \sim 20$ eV (1 keV dwarf galaxies)
- "Bosonic Oscillator" with Q $\sim (v/c)^{-2} \sim 10^6$
- Cannot be lighter than $\sim 10^{-22}$ eV
- … (e.g., BEC ?)

Why Axions (ALPs) ?

- Big clean-up ?
  - Strong CP problem
  - Dark Matter
  - Dark Energy
  - Baryon asymmetry of the Universe
  - Hierarchy?
  - …



http://earthsky.org/space/

How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

P. Graham
S. Rajendran

2017
New Horizons
In Physics Prize

+

Gauge Fields

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Most
Searches

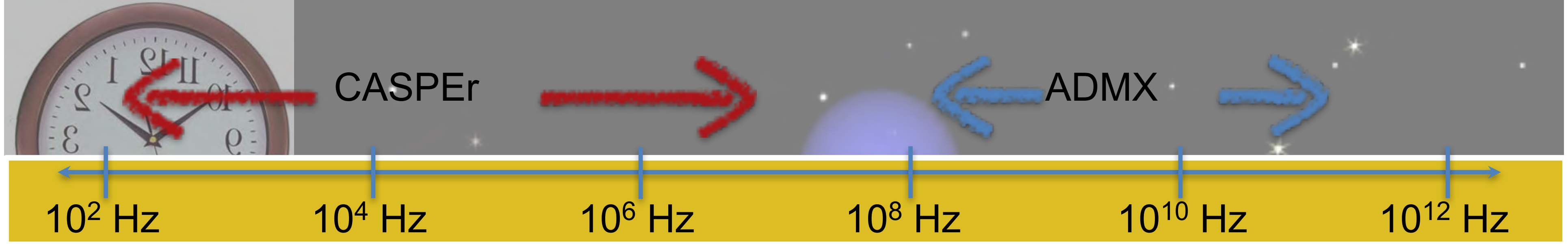
$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

(CASPEr-E)

Fermions

$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

(CASPEr-Wind, GNOME, QUAX)



axion mass (frequency)

Cosmic Axion Spin Precession Experiment (CASPEr)

Proposal:

Peter Graham

Surjeet Rajendran

Alex Sushkov

Micah Ledbetter

Dmitry Budker

P. Graham & S. Rajendran PRD **88** (2013) arXiv:1306.6088,
D. Budker *et al* PRX (2014) arxXiv:1306.6089

CASPEr Overview

Key ideas:

- Axion (ALP) field oscillates
- at a frequency equal to its mass (mHz to GHz)
- ➔ time varying CP-odd nuclear moments:
- nEDM, Schiff, …

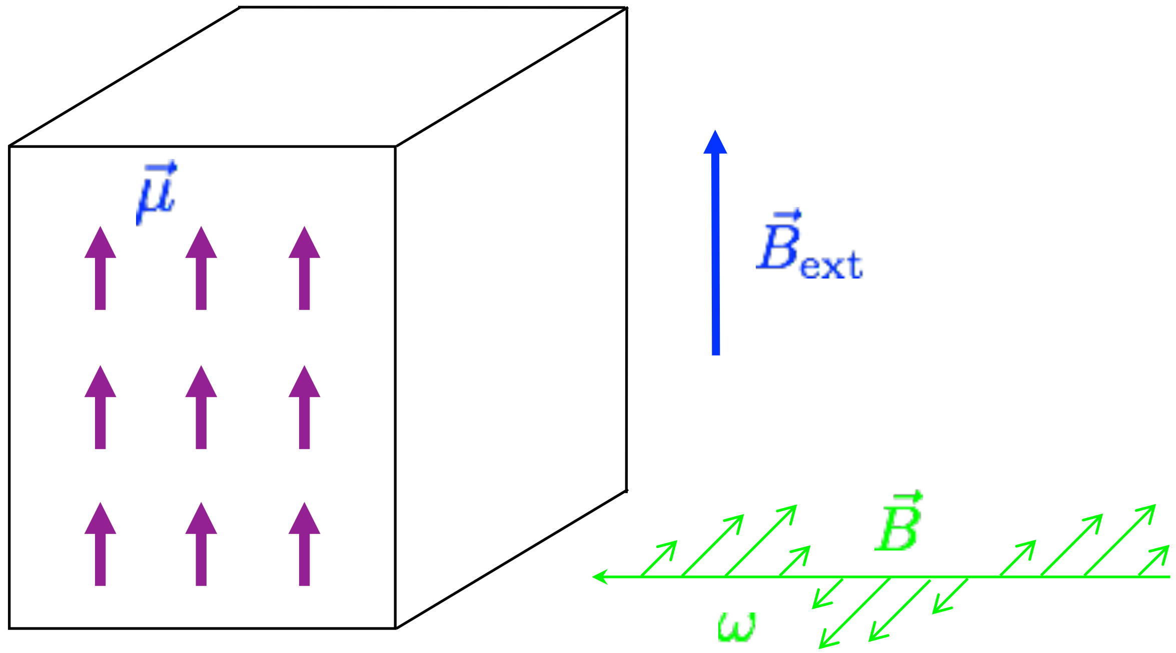
CASPEr-Electric

- Also: axion wind (like a magnetic field)
- $v \sim 10^{-3}\, c$ (virial velocity)

CASPEr-Wind

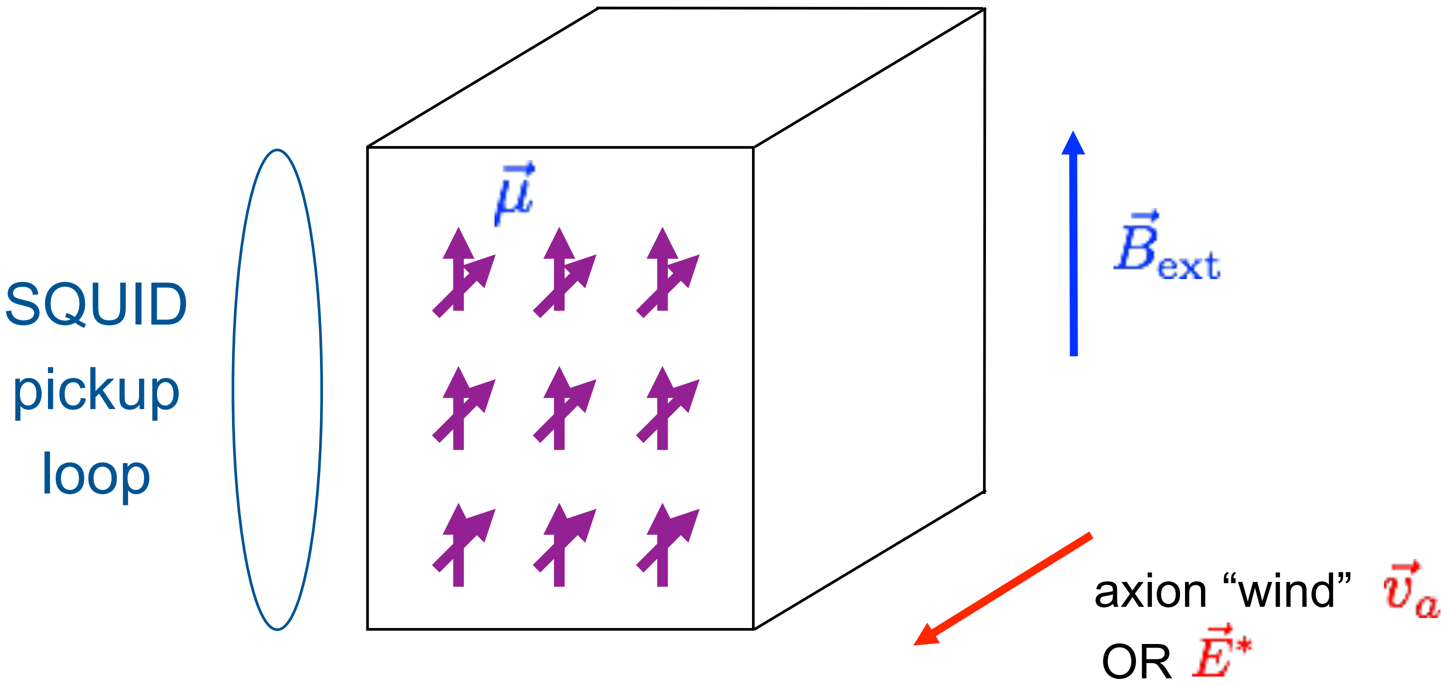
- Coherence time: $[m_a(v/c)^2]^{-1}$ ➔ $Q{\sim}10^6$

Nuclear Magnetic Resonance (NMR)



Resonance: $2\mu B_{\mathrm{ext}} = \omega$

CASPEr



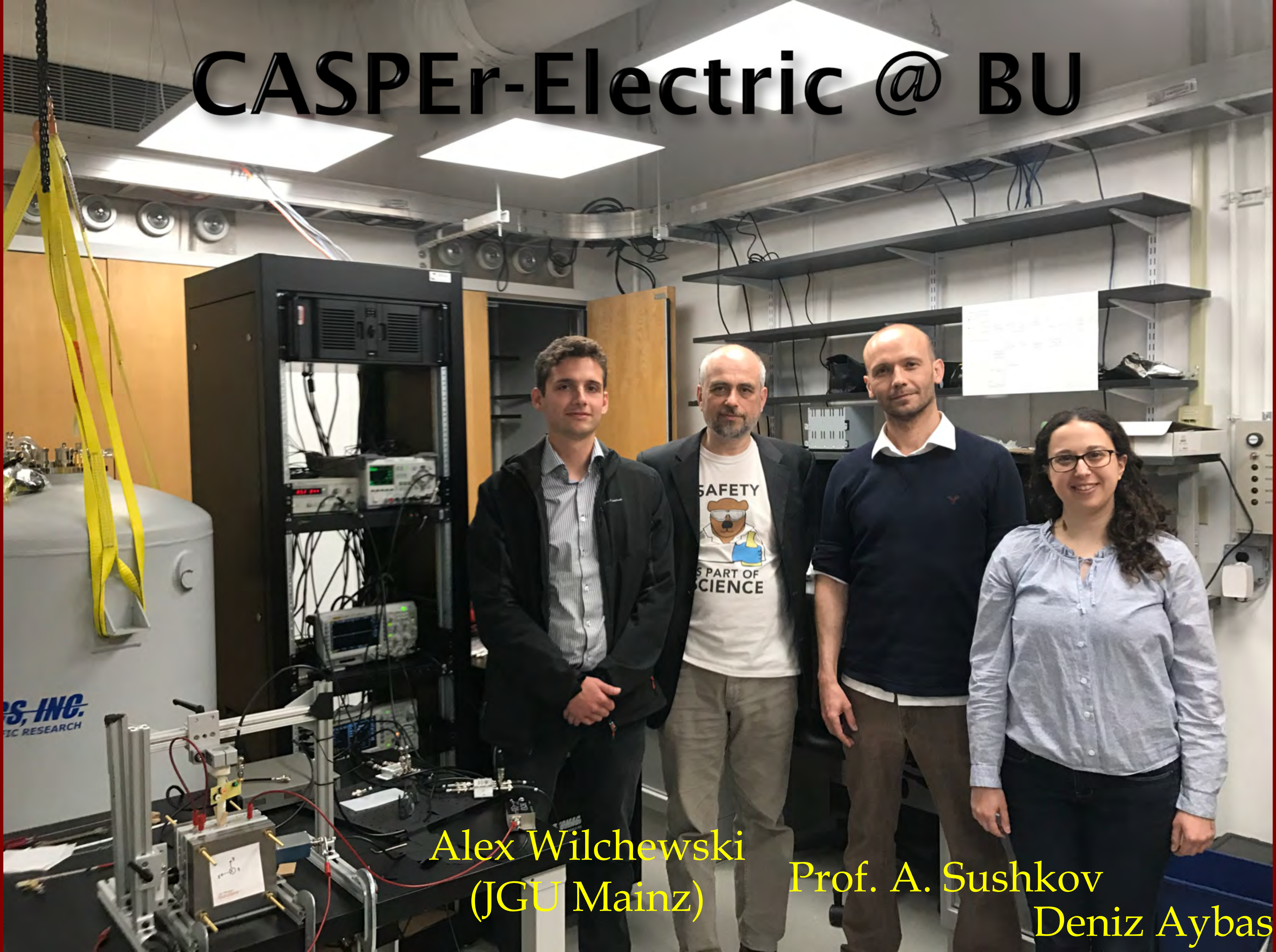
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

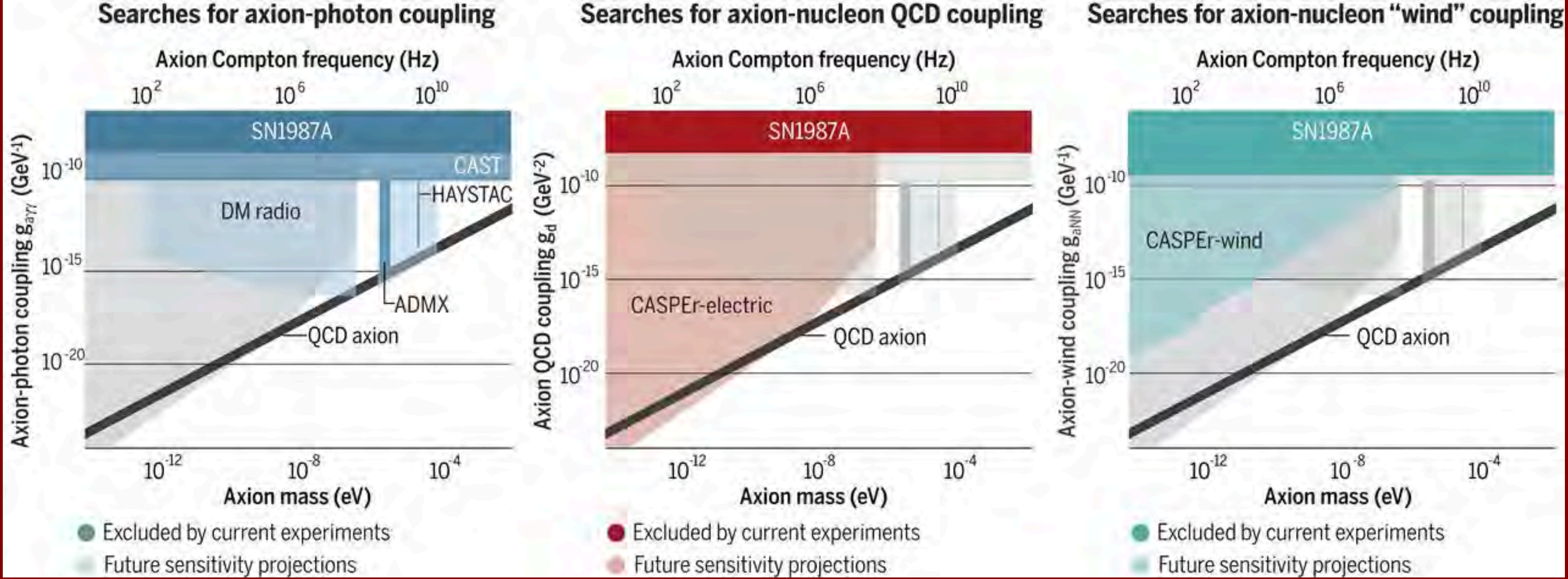
Example materials: liquid ^{129}Xe, ferroelectric $PbTiO_3$

Xe hyperpolarizer @ Mainz

CASPEr-Electric @ BU

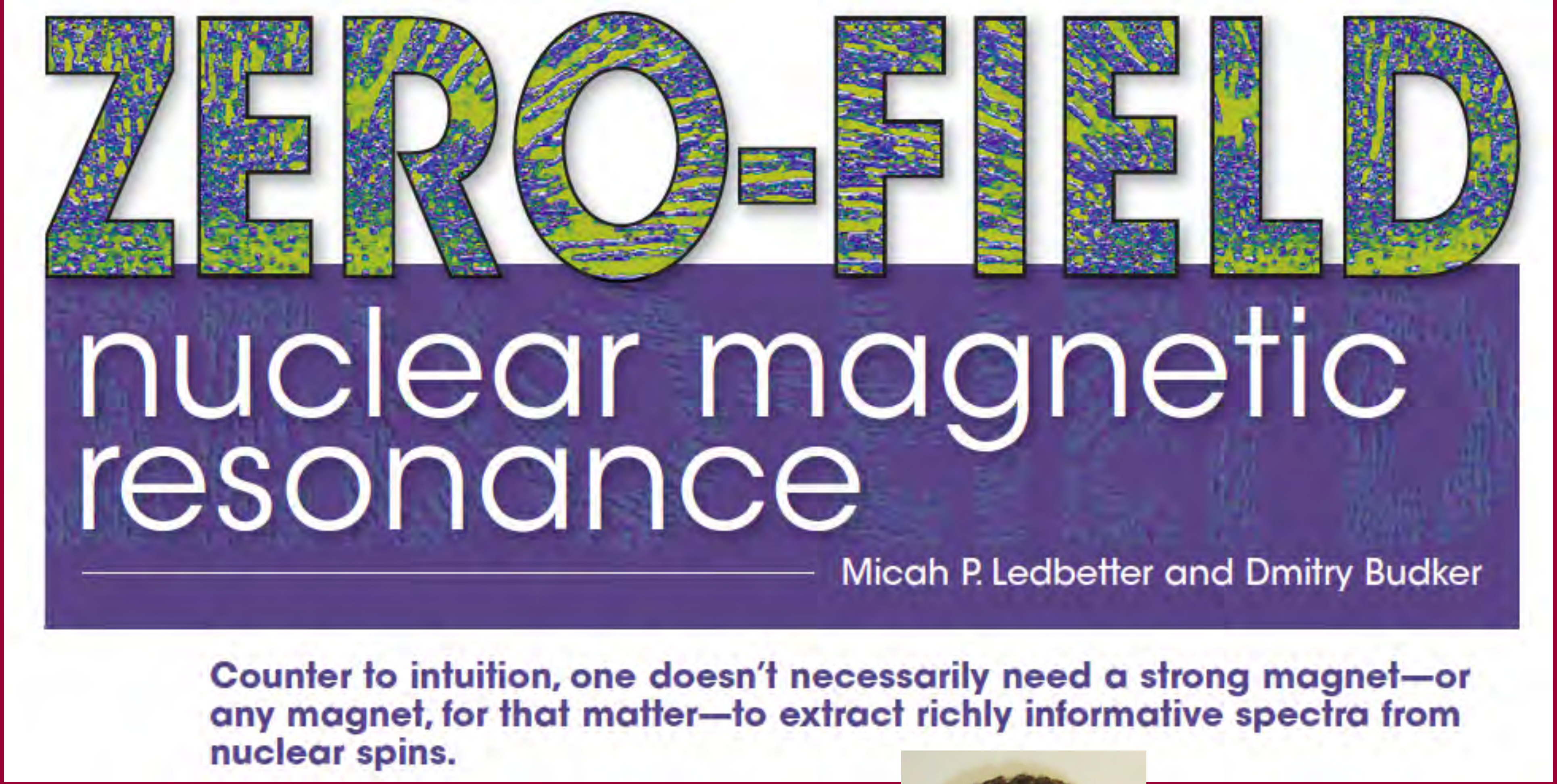


Experimental constraints and projected sensitivities of axion dark-matter searches



David DeMille, John. Doyle, and Alexander Sushkov. Science 2017;357:990-994

Science
AAAS



ZERO-FIELD nuclear magnetic resonance

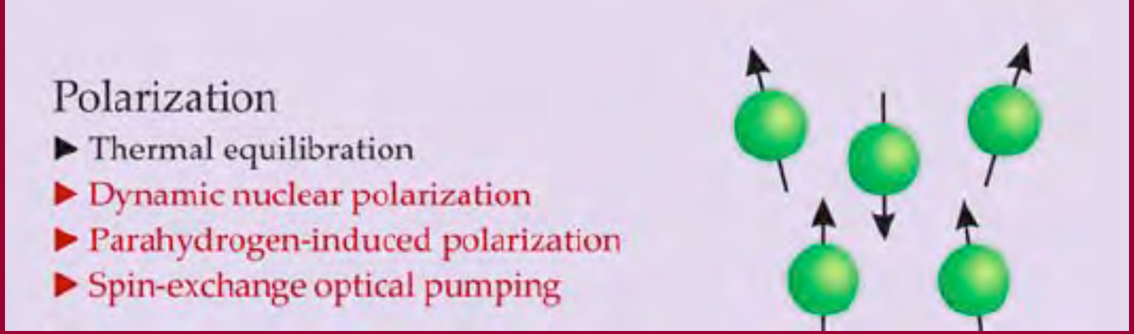
Micah P. Ledbetter and Dmitry Budker

Counter to intuition, one doesn't necessarily need a strong magnet—or any magnet, for that matter—to extract richly informative spectra from nuclear spins.

April 2013 Physics Today www.physicstoday.org

Micah Ledbetter

Three Stages of NMR



Polarization

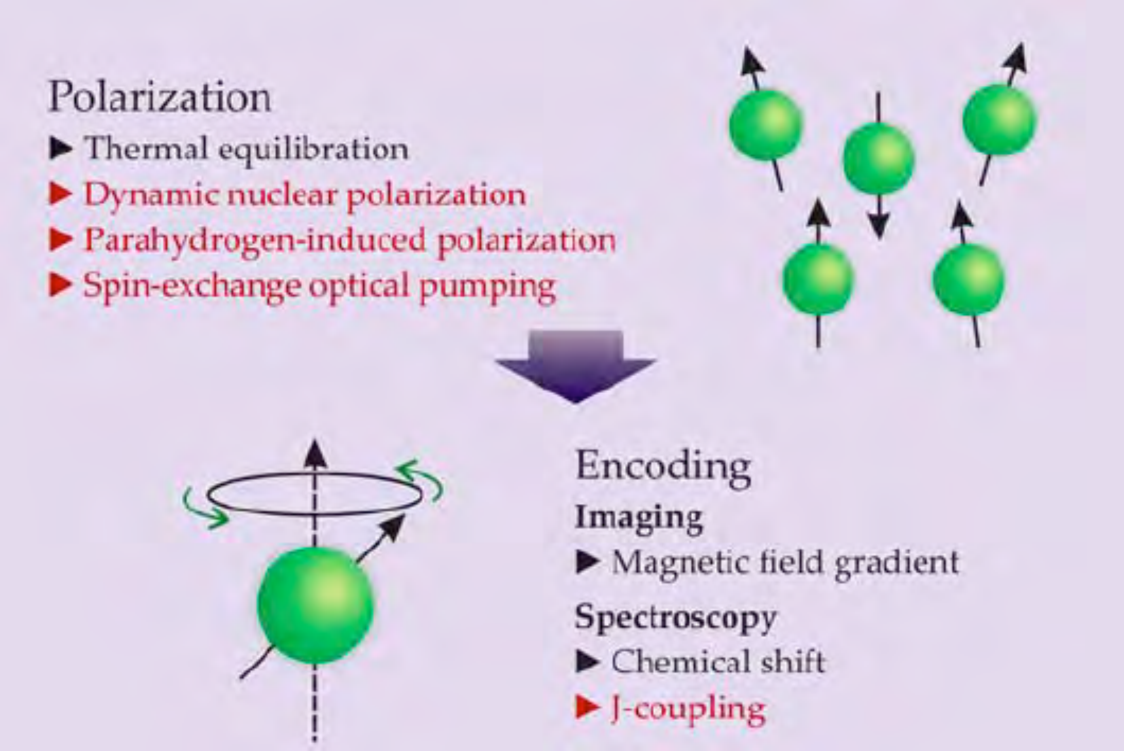
- Thermal equilibration
- Dynamic nuclear polarization
- Parahydrogen-induced polarization
- Spin-exchange optical pumping

No need to polarize in <u>spin-noise spectroscopy</u>

➔ small N

April 2013 Physics Today www.physicstoday.org

Three Stages of NMR



Polarization

- ▶ Thermal equilibration
- ▶ Dynamic nuclear polarization
- ▶ Parahydrogen-induced polarization
- ▶ Spin-exchange optical pumping

Encoding

Imaging

- ▶ Magnetic field gradient

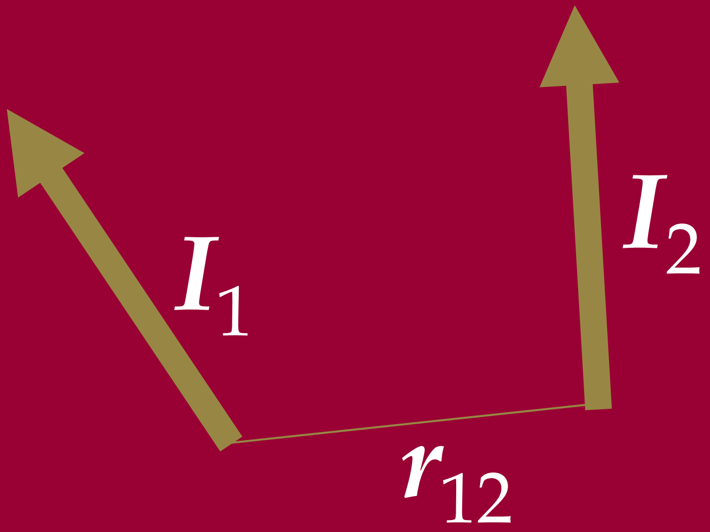
Spectroscopy

- ▶ Chemical shift
- ▶ J-coupling

J-coupling

Erwin L. Hahn

C. P. Slichter



<u>Dipole-dipole interaction</u>

$$H \propto \frac{\boldsymbol{I}_1 \cdot \boldsymbol{I}_2}{r_{12}^3}(1 - 3cos^2\theta)$$

averages by tumbling

<u>J-coupling</u>

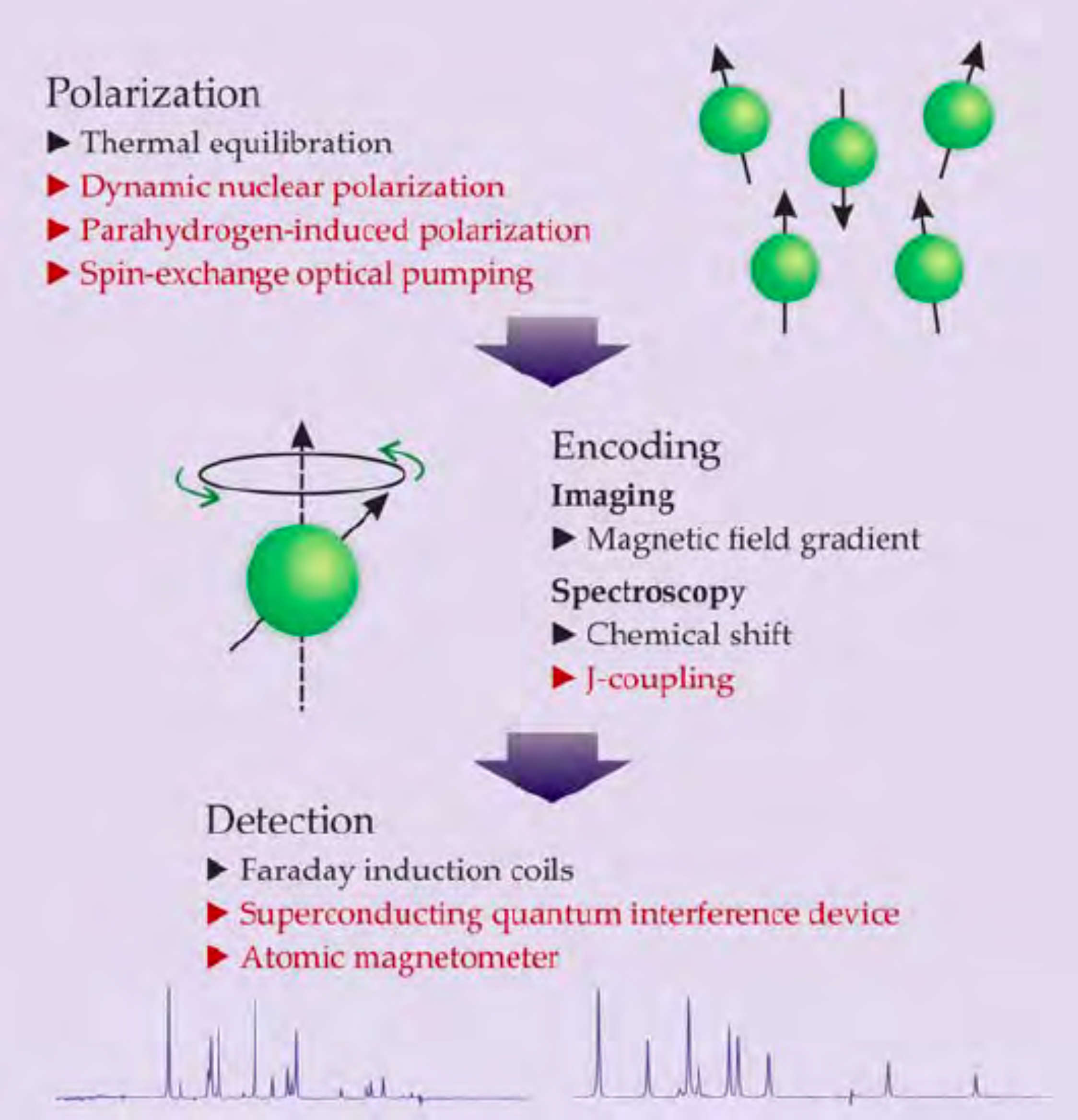
$$H = J\boldsymbol{I}_1 \cdot \boldsymbol{I}_2$$

survives tumbling!

☞ second-order hyperfine

Hahn, E.L. & Maxwell, D.E. *Phys. Rev.* **84** 1246-1247 (1952)
Gutowsky, H.S., McCall, D.W., & **Slichter, C.P. J.** *Chem. Phys.* **21**, 279-292 (1953)

Three Stages of NMR



Polarization

- Thermal equilibration
- Dynamic nuclear polarization
- Parahydrogen-induced polarization
- Spin-exchange optical pumping

Encoding

Imaging

- Magnetic field gradient

Spectroscopy

- Chemical shift
- J-coupling

Detection

- Faraday induction coils
- Superconducting quantum interference device
- Atomic magnetometer

April 2013 Physics Today www.physicstoday.org

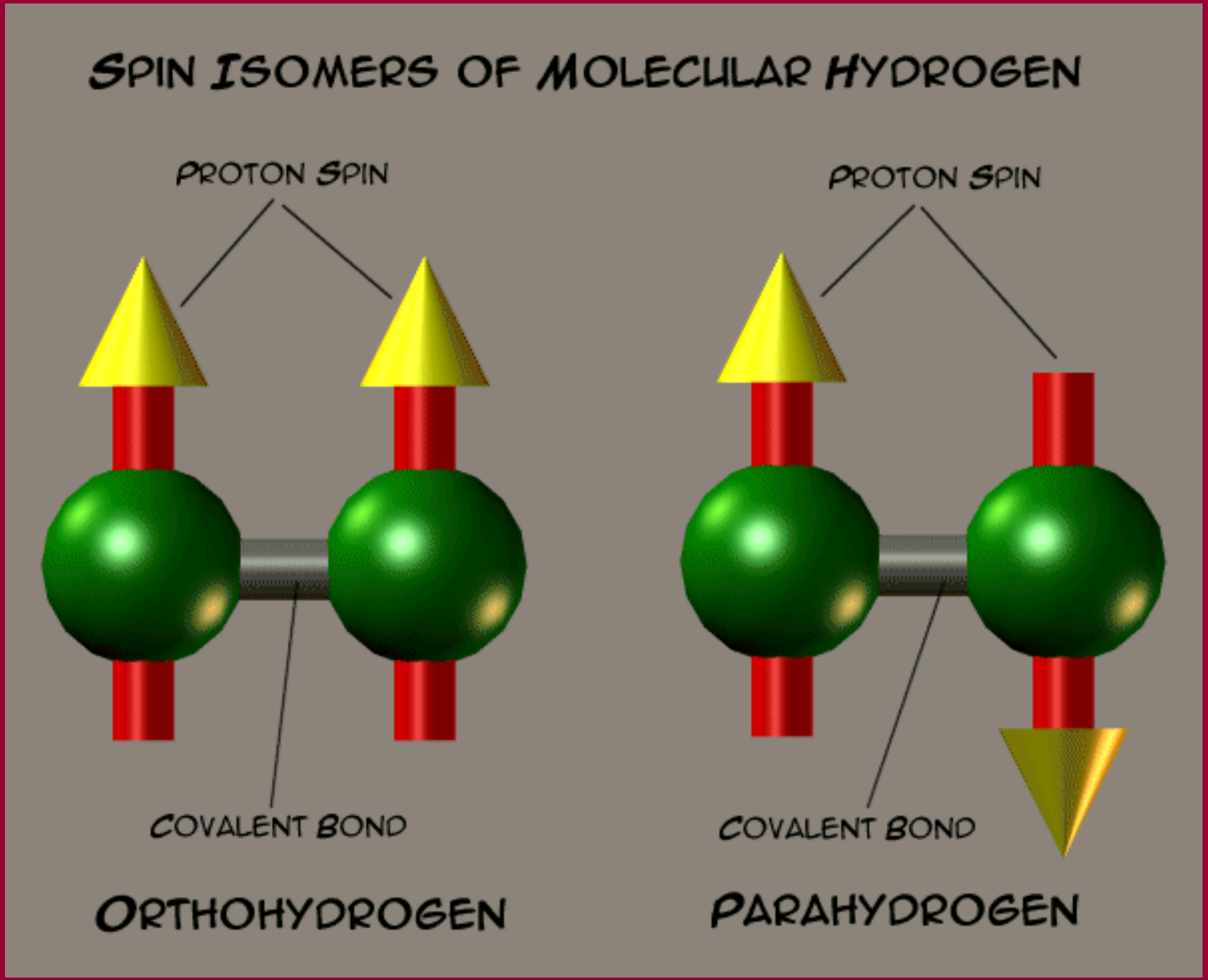
Parahydrogen induced polarization (PHIP)

C. R. Bowers

Daniel P. Weitekamp

Transformation of symmetrization order to nuclear-spin magnetization by chemical reaction and nuclear magnetic resonance
PRL **57** (21): 2645–2648 (1986)

Parahydrogen 101



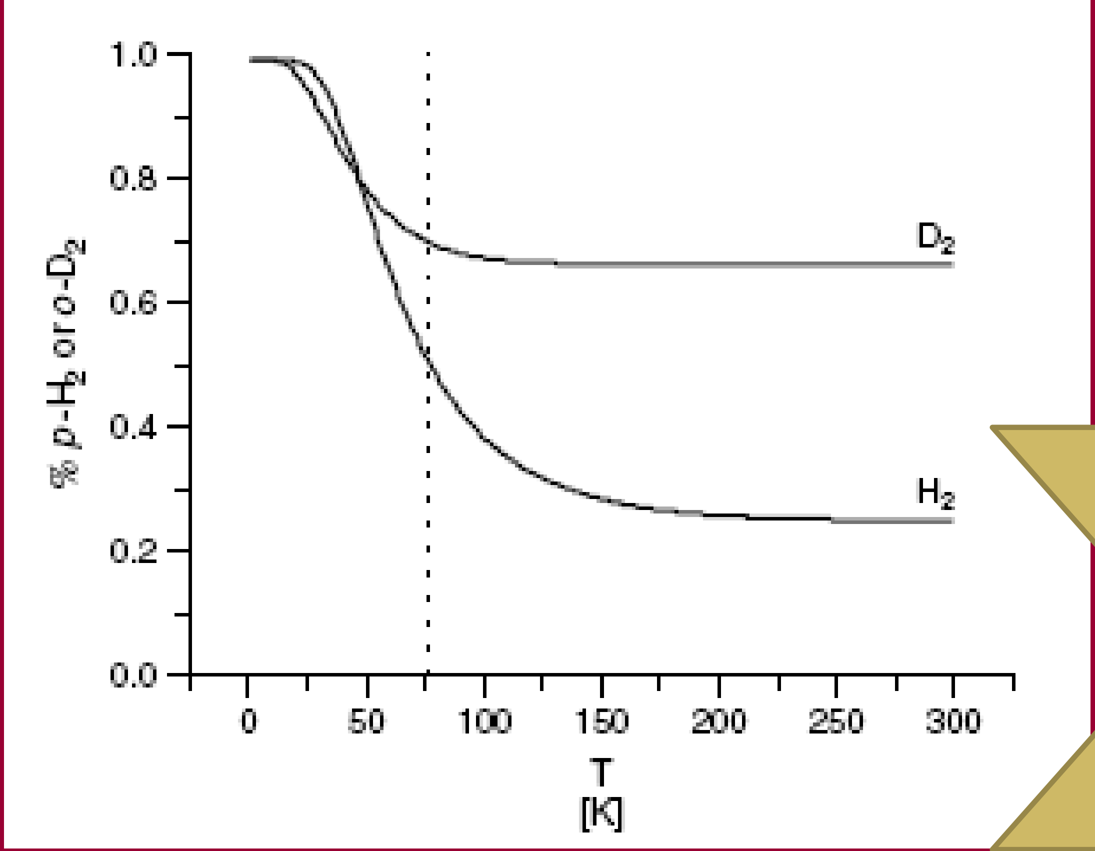
Odd J

Even J

http://en.wikipedia.org

Parahydrogen 102

$$\frac{E_{J=1} - E_{J=0}}{k_B} = 2\theta_{rot} = \frac{\hbar^2}{k_B I} = 174.98\ \text{K}$$



51% para @ 77K

99.9% para @ 4K

Spin-Statistics in action!

Parahydrogen Induced Polarization

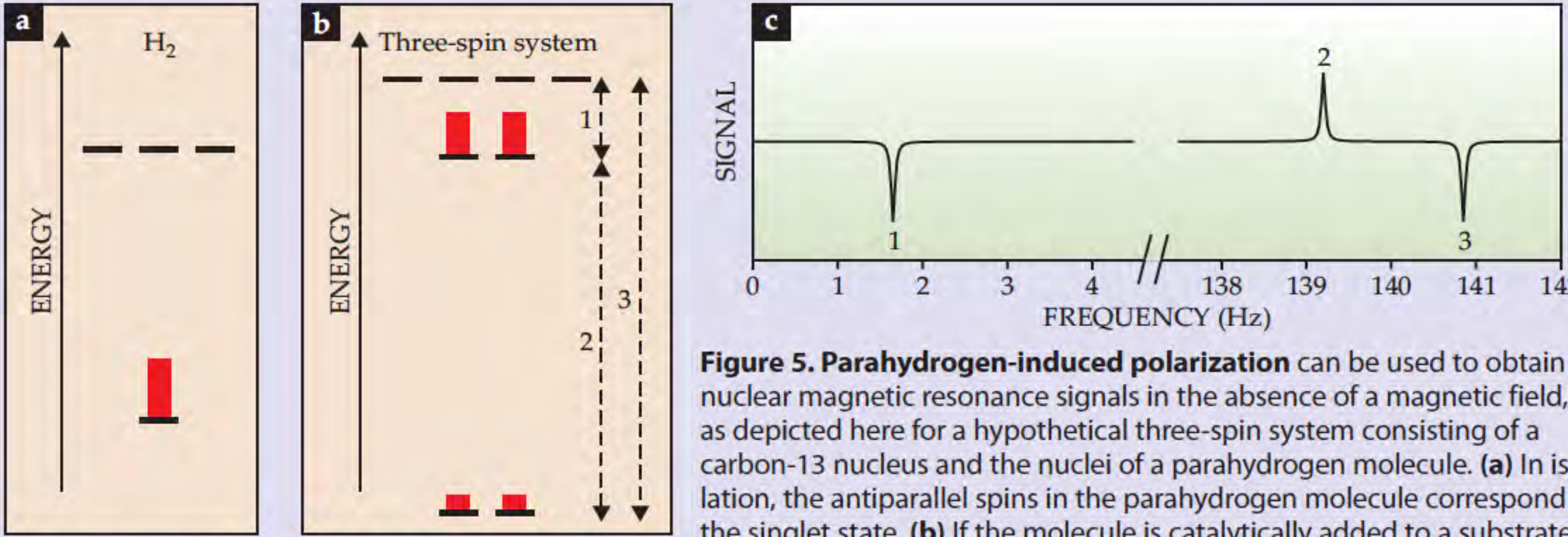
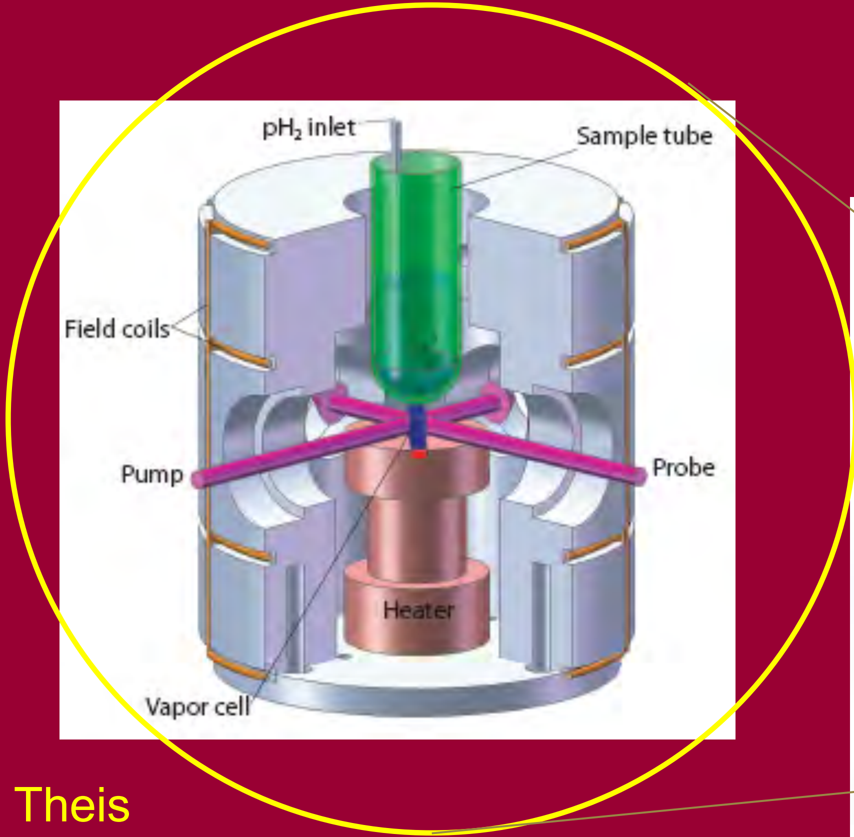
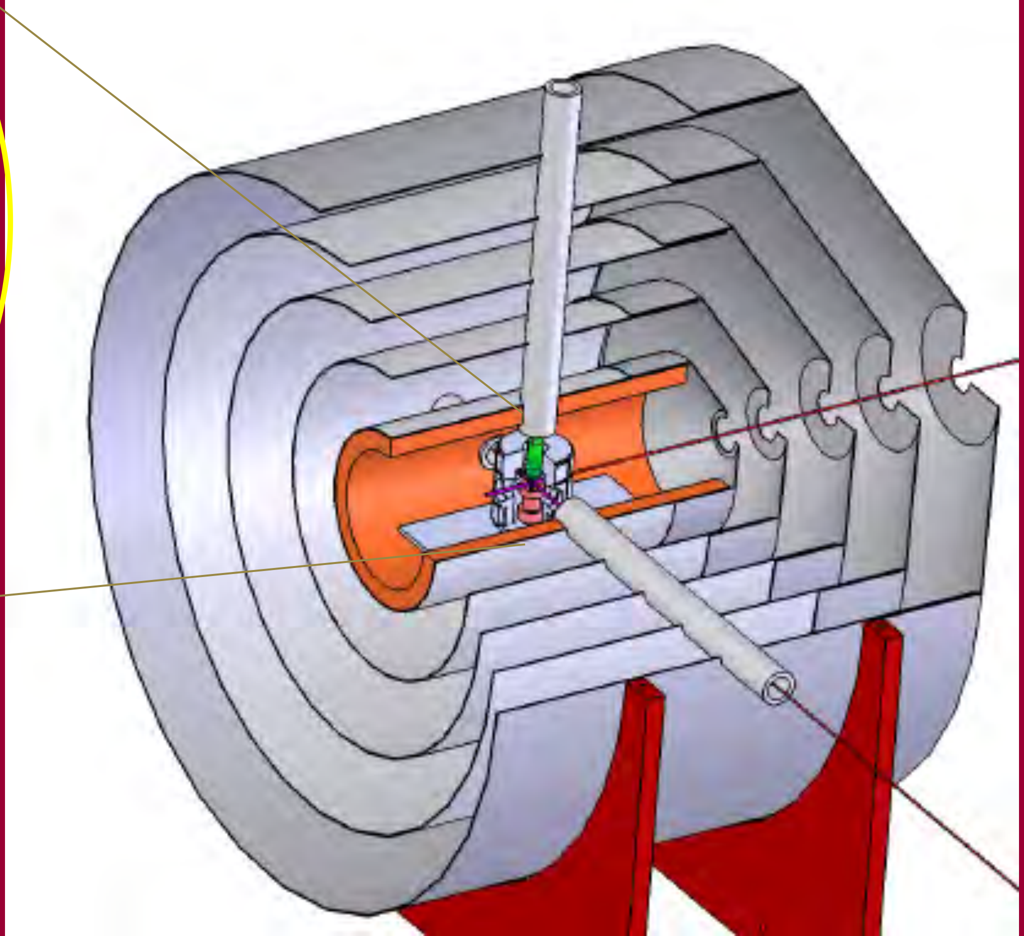


Figure 5. Parahydrogen-induced polarization can be used to obtain nuclear magnetic resonance signals in the absence of a magnetic field, as depicted here for a hypothetical three-spin system consisting of a carbon-13 nucleus and the nuclei of a parahydrogen molecule. **(a)** In isolation, the antiparallel spins in the parahydrogen molecule correspond to the singlet state. **(b)** If the molecule is catalytically added to a substrate molecule containing ^{13}C, and if one of the C–H couplings is much stronger than the other couplings in the system, the symmetry of the parahydrogen spins is broken and in the newly formed three-spin system, the population of the upper doublet is about three times that of the lower one. (Here, we ignore the rotational energies that may be correlated with the nuclear state.) The horizontal lines represent magnetic sublevels and the red rectangles represent the expected populations in each sublevel. **(c)** The simulated spectrum of a system with strong C–H coupling $J_{CH} = 140$ Hz, weak C–H coupling $J_{CH} = -5.2$ Hz, and H–H coupling $J_{HH} = 7.7$ Hz yields the three peaks shown here, which correspond to the three allowed transitions indicated by the dashed arrows in panel b.

NMR inside-out:
pH_2 polarization; laser-mag detection

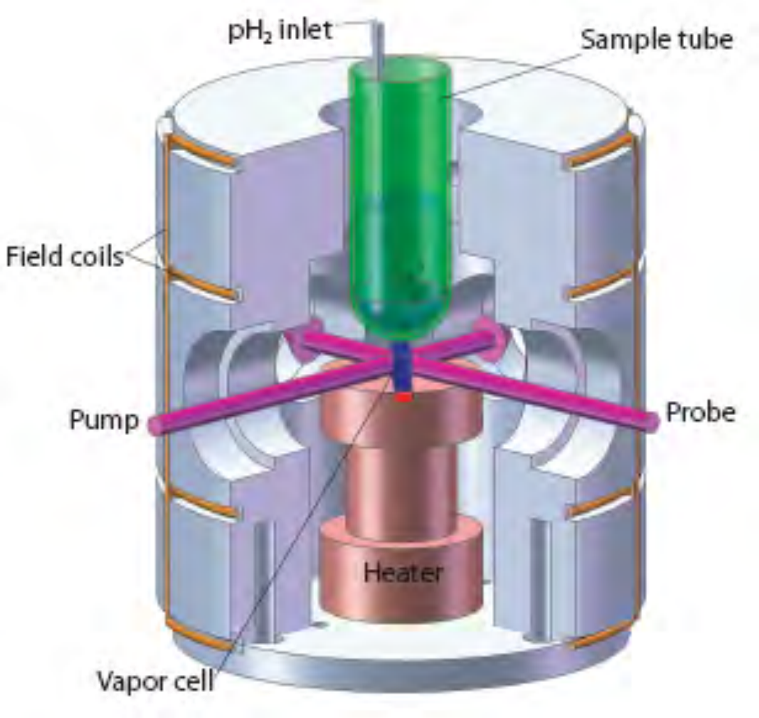


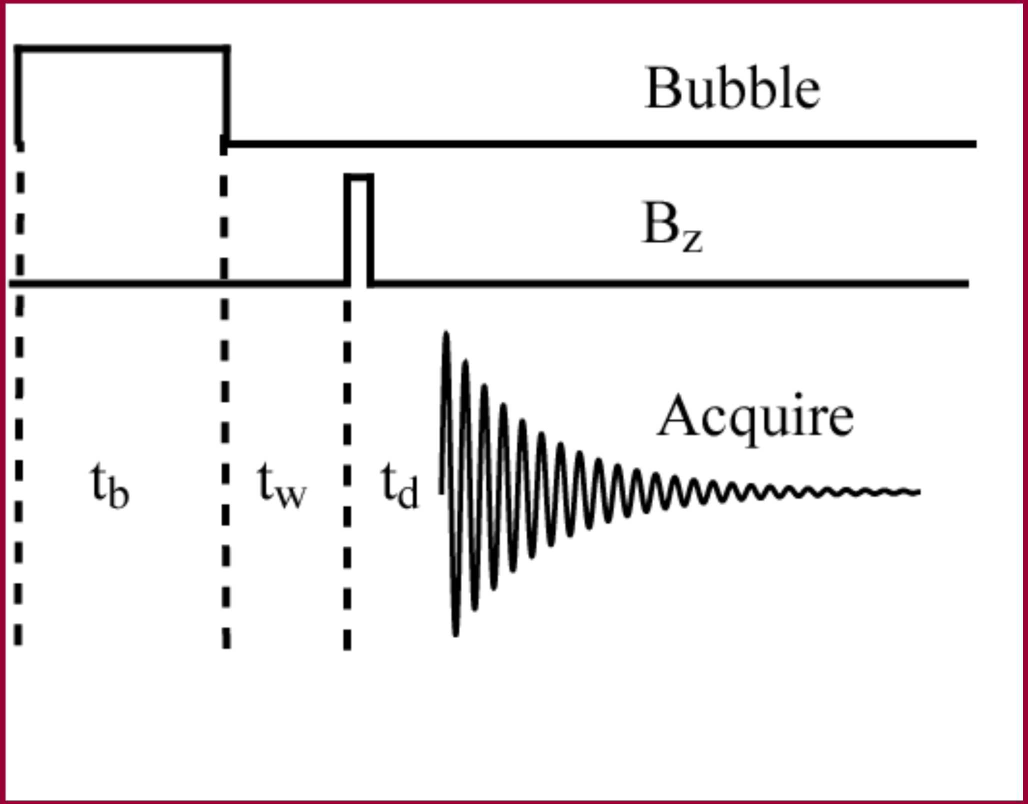
Magnetic
shields



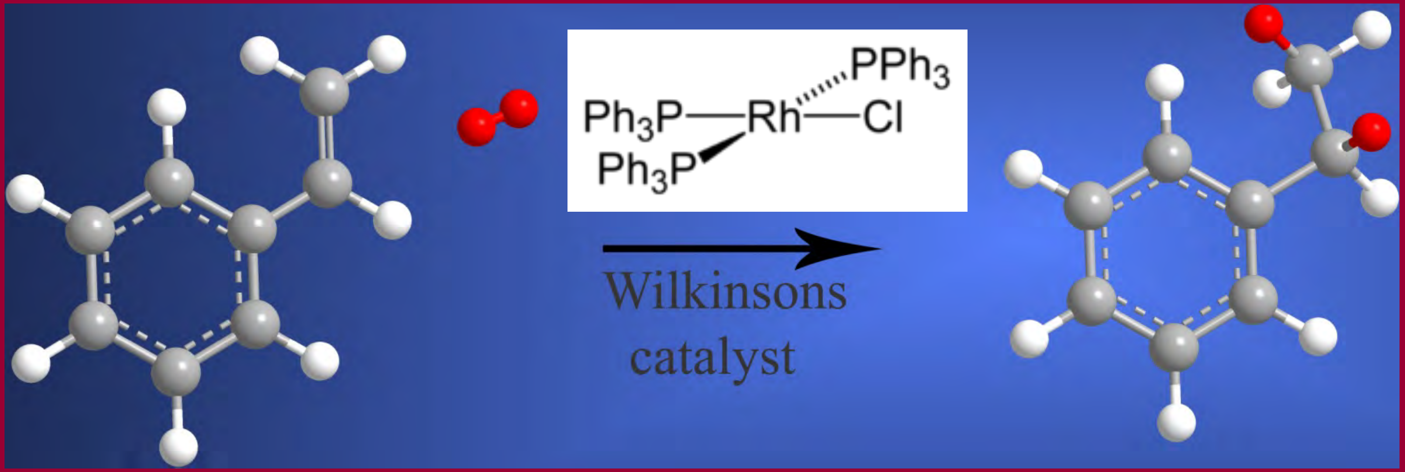
T. Theis
P. Ganssle
G. Kervern
M. P. Ledbetter
D. B.
A. Pines

NMR inside-out:
pH_2 polarization; laser-mag detection





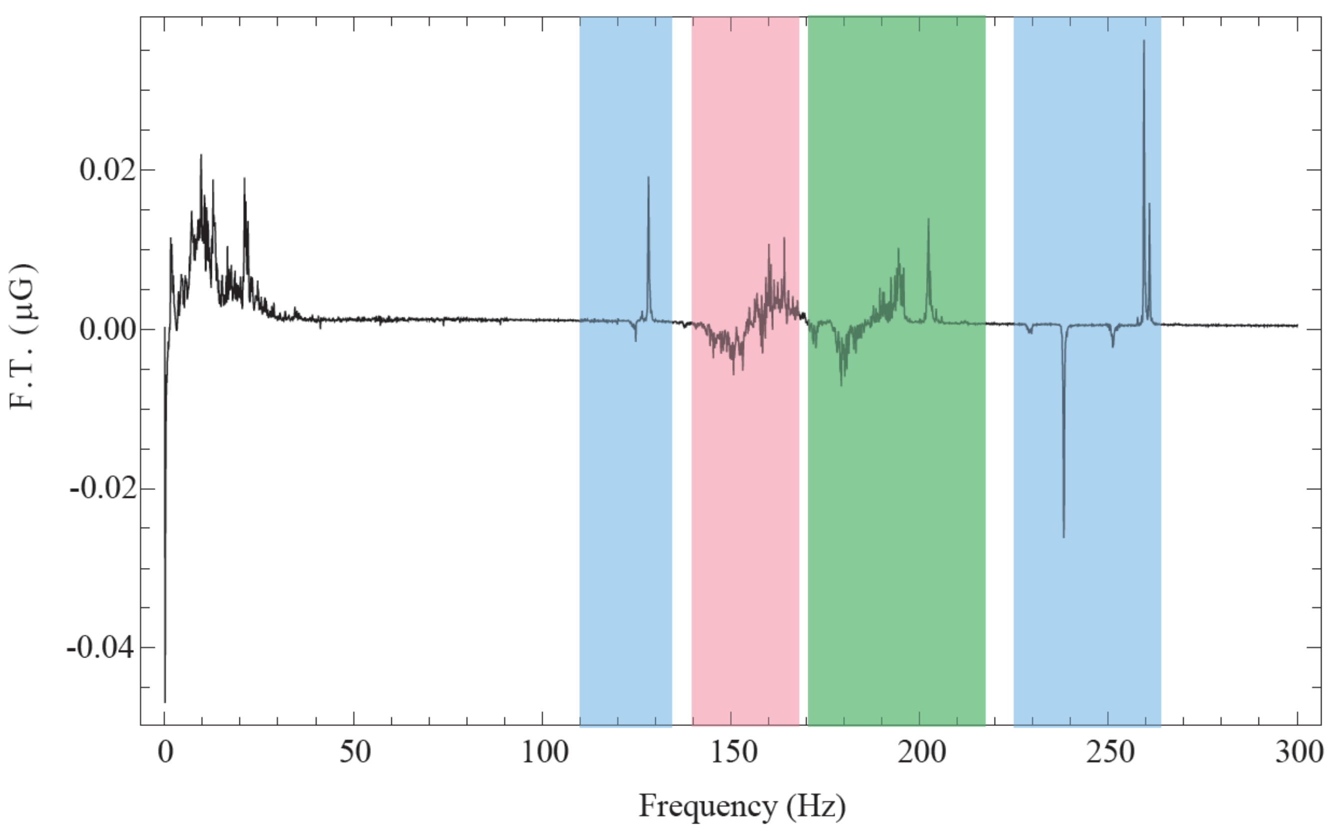
Hydrogenation with pH_2

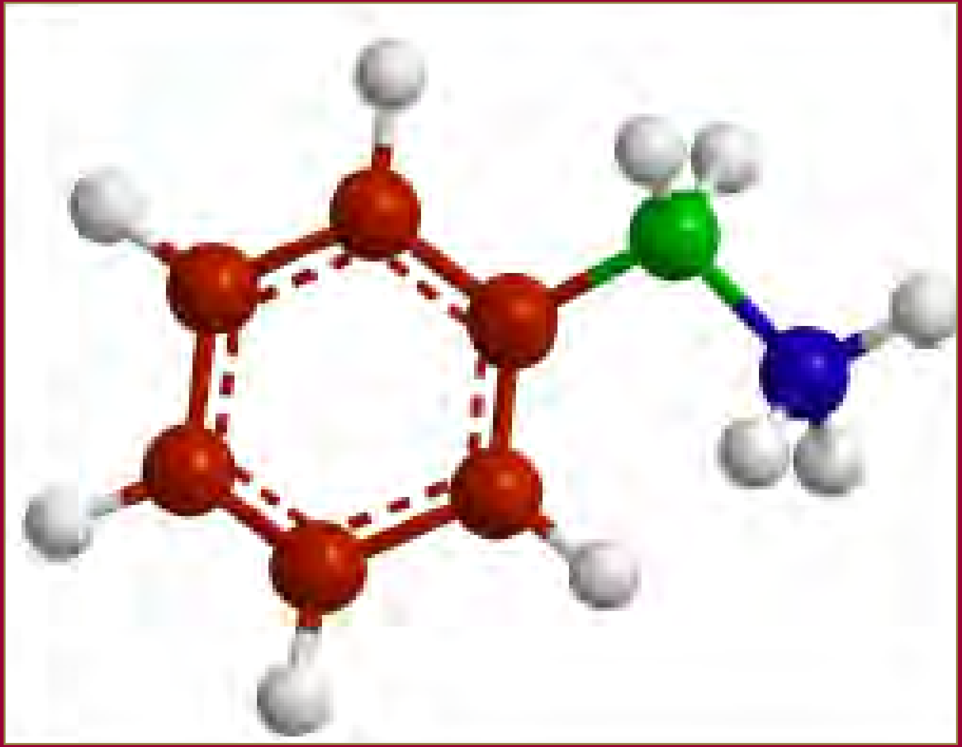


Styrene **Ethylbenzene**

Hydrogenation with pH_2

Natural Abundance
1.1% of ^{13}C





nature physics

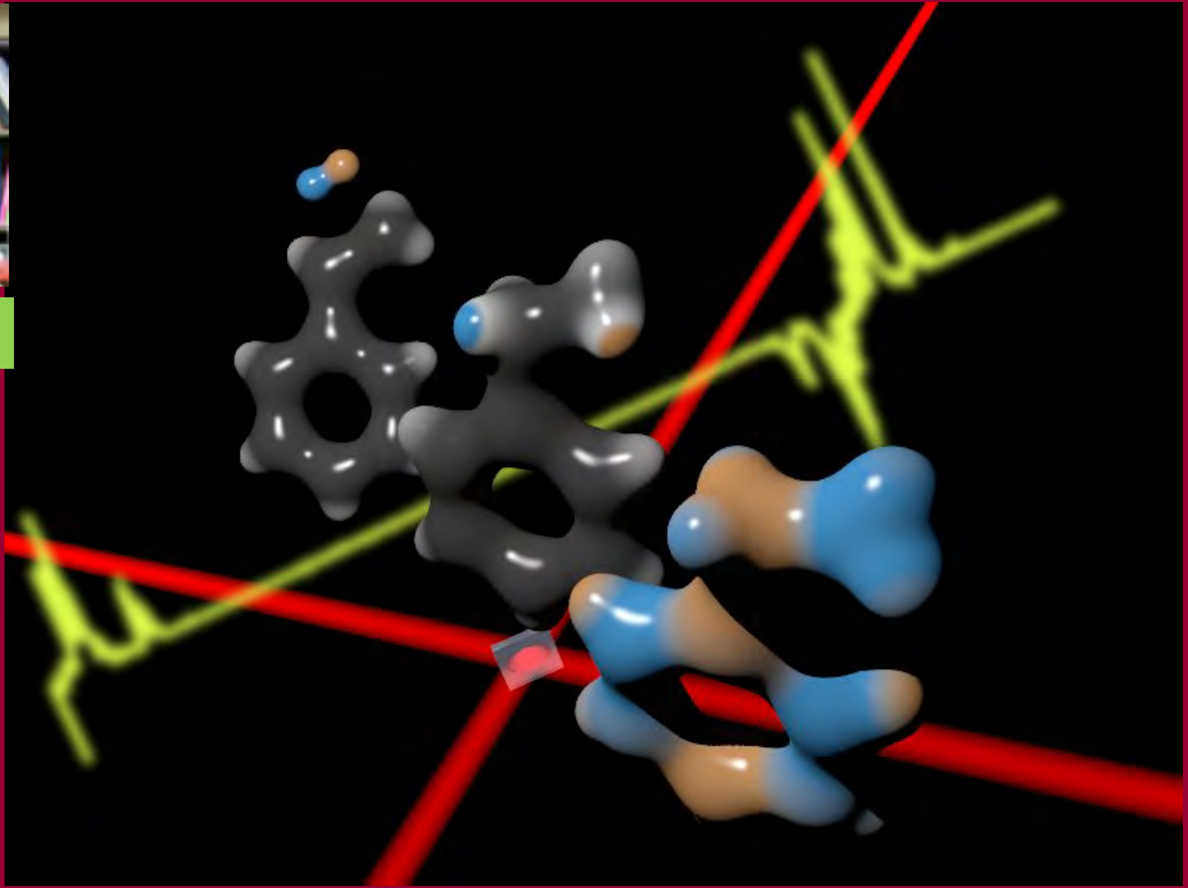
ARTICLES

Parahydrogen-enhanced zero-field nuclear magnetic resonance

T. Theis[1,2], P. Ganssle[1,2], G. Kervern[1,2], S. Knappe[3], J. Kitching[3], M. P. Ledbetter[4], D. Budker[4,5] and A. Pines[1,2]★

Thomas Theis

Alex Pines



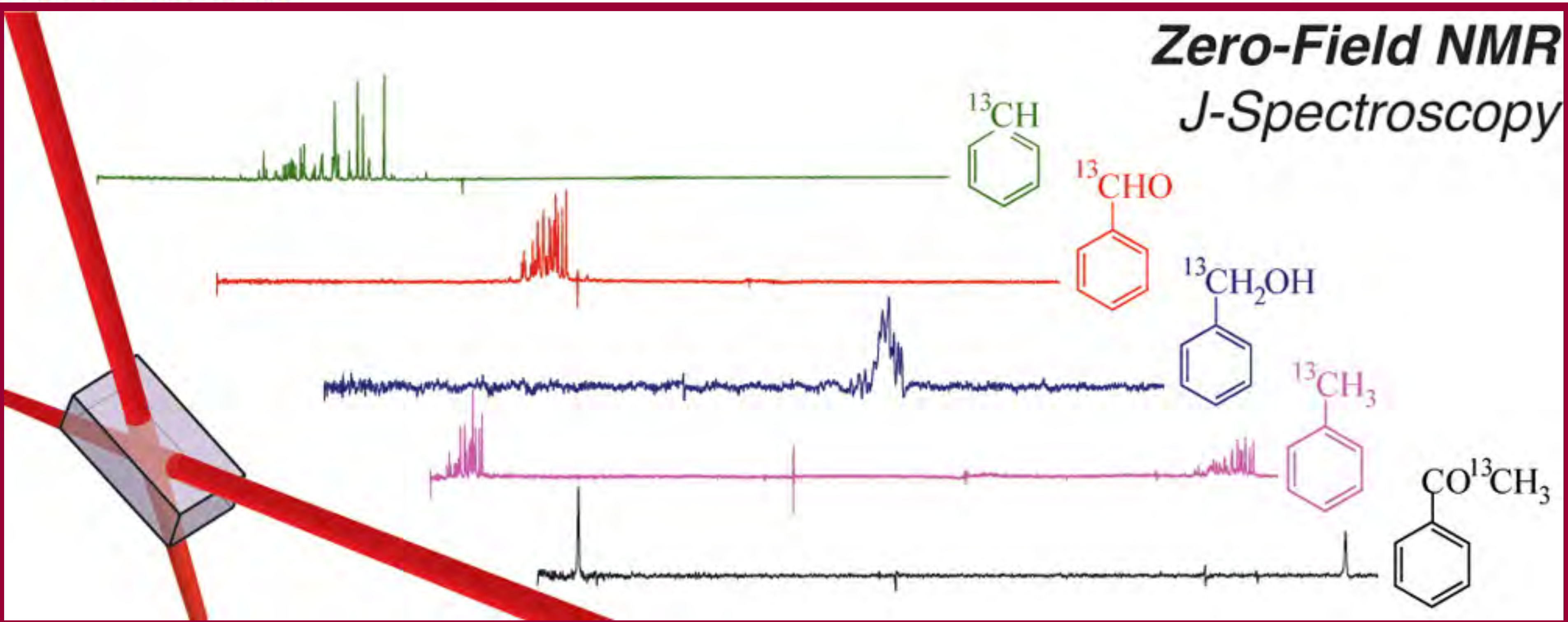
NMR
without any
magnets!

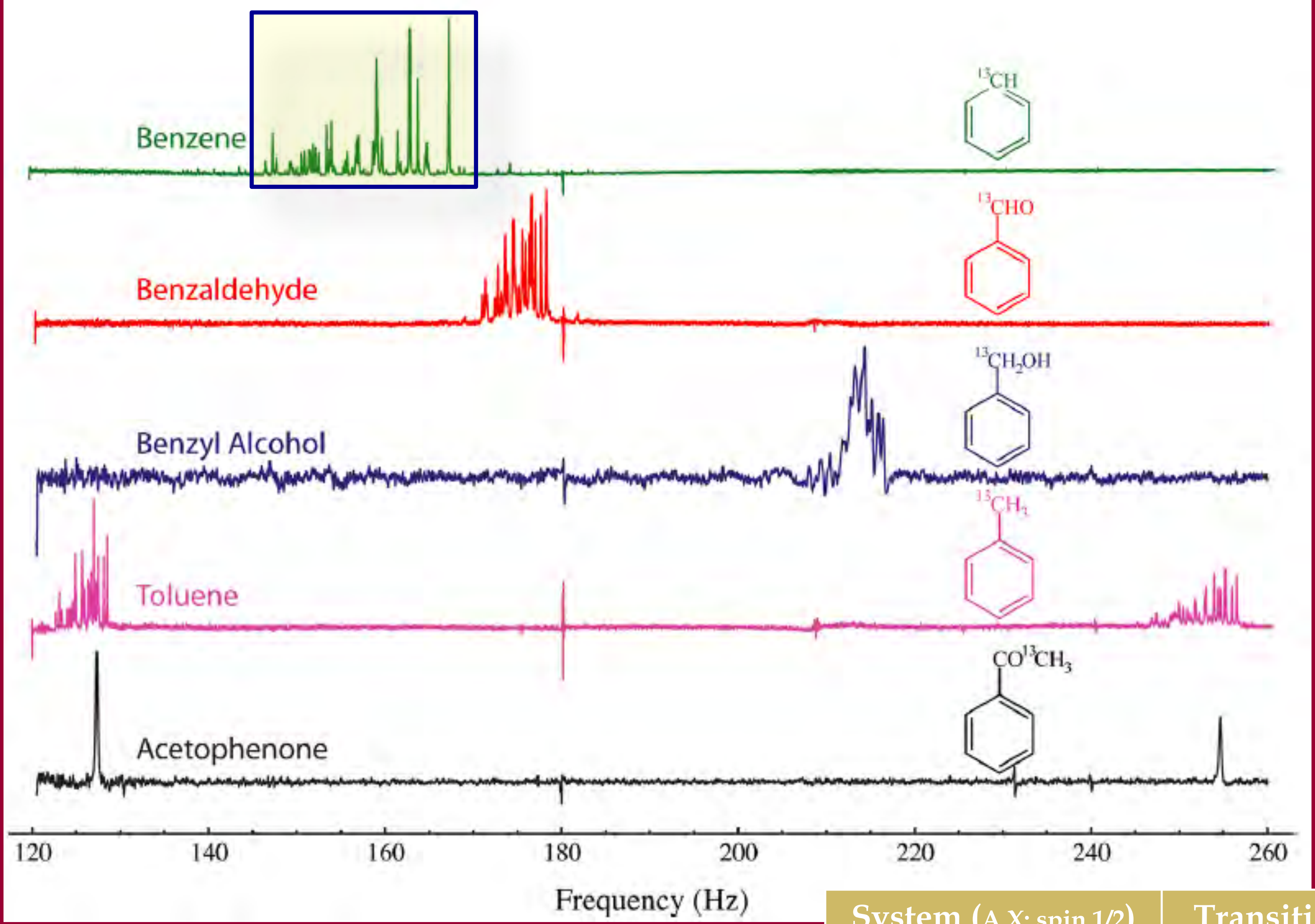
John Blanchard
In 203 Birge Hall

JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
135 (9) (2013)
Article
pubs.acs.org/JACS

High-Resolution Zero-Field NMR *J*-Spectroscopy of Aromatic Compounds

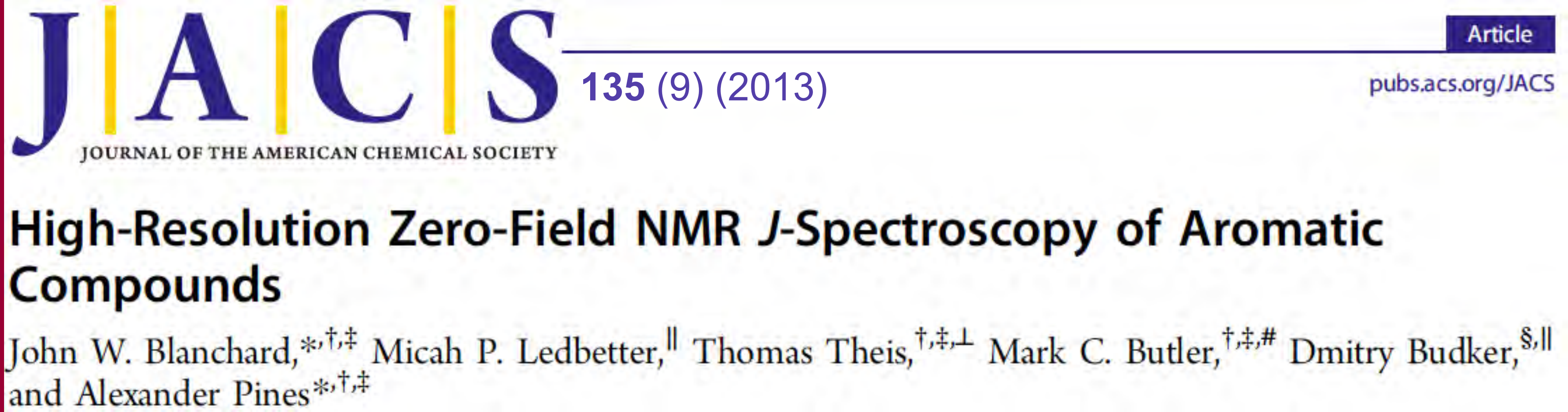
John W. Blanchard,*,†,‡ Micah P. Ledbetter,‖ Thomas Theis,†,‡,⊥ Mark C. Butler,†,‡,# Dmitry Budker,§,‖ and Alexander Pines*,†,‡





- ~ 100 μl samples
- First-order line positions are well resolved
- Line structure reports higher-order couplings
- 11 mHz linewidth (HWHM): high resolution

System (A,X: spin 1/2)	Transitions @
AX	J
AX_2	3J/2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John W. Blanchard,*[†,‡] Micah P. Ledbetter,[‖] Thomas Theis,[†,‡,⊥] Mark C. Butler,[†,‡,#] Dmitry Budker,[§,‖] and Alexander Pines*[†,‡]

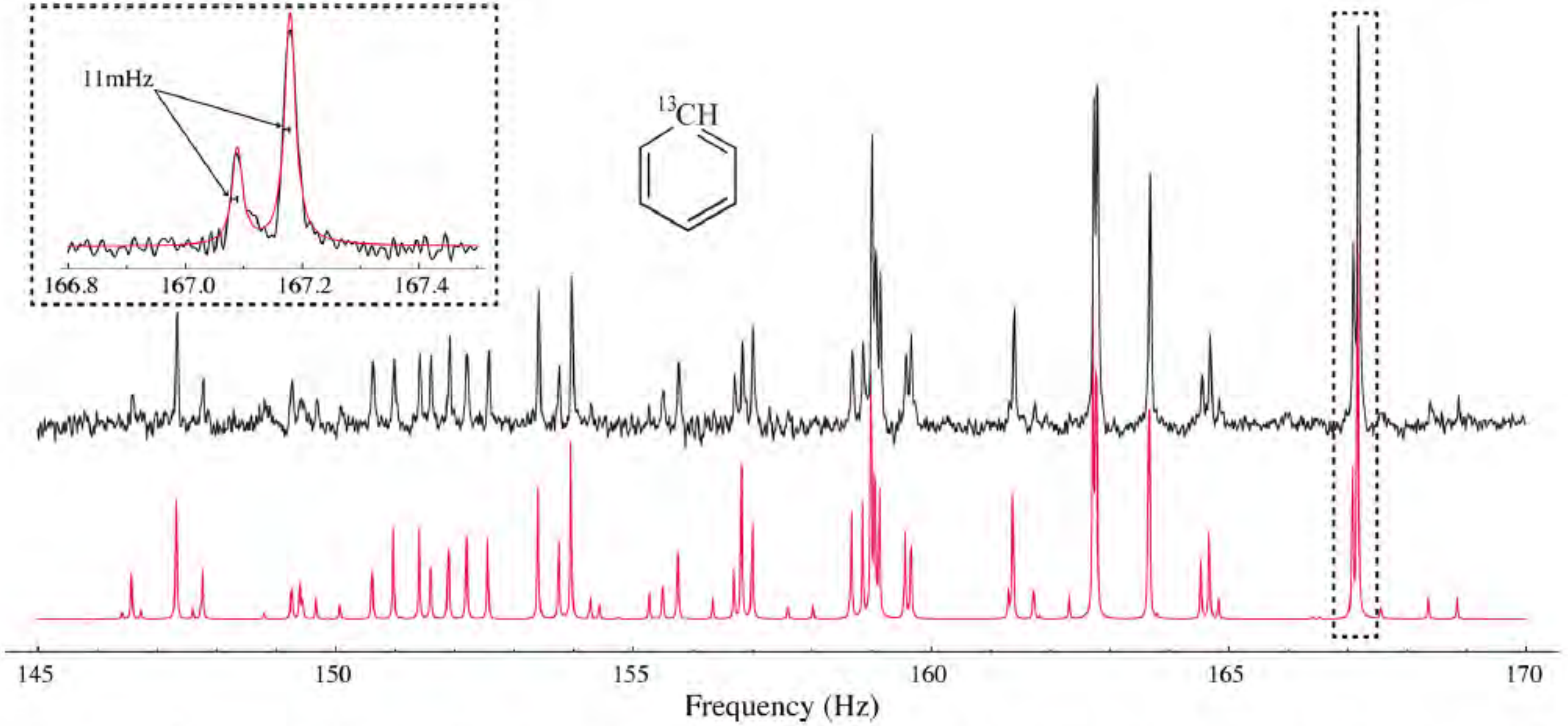
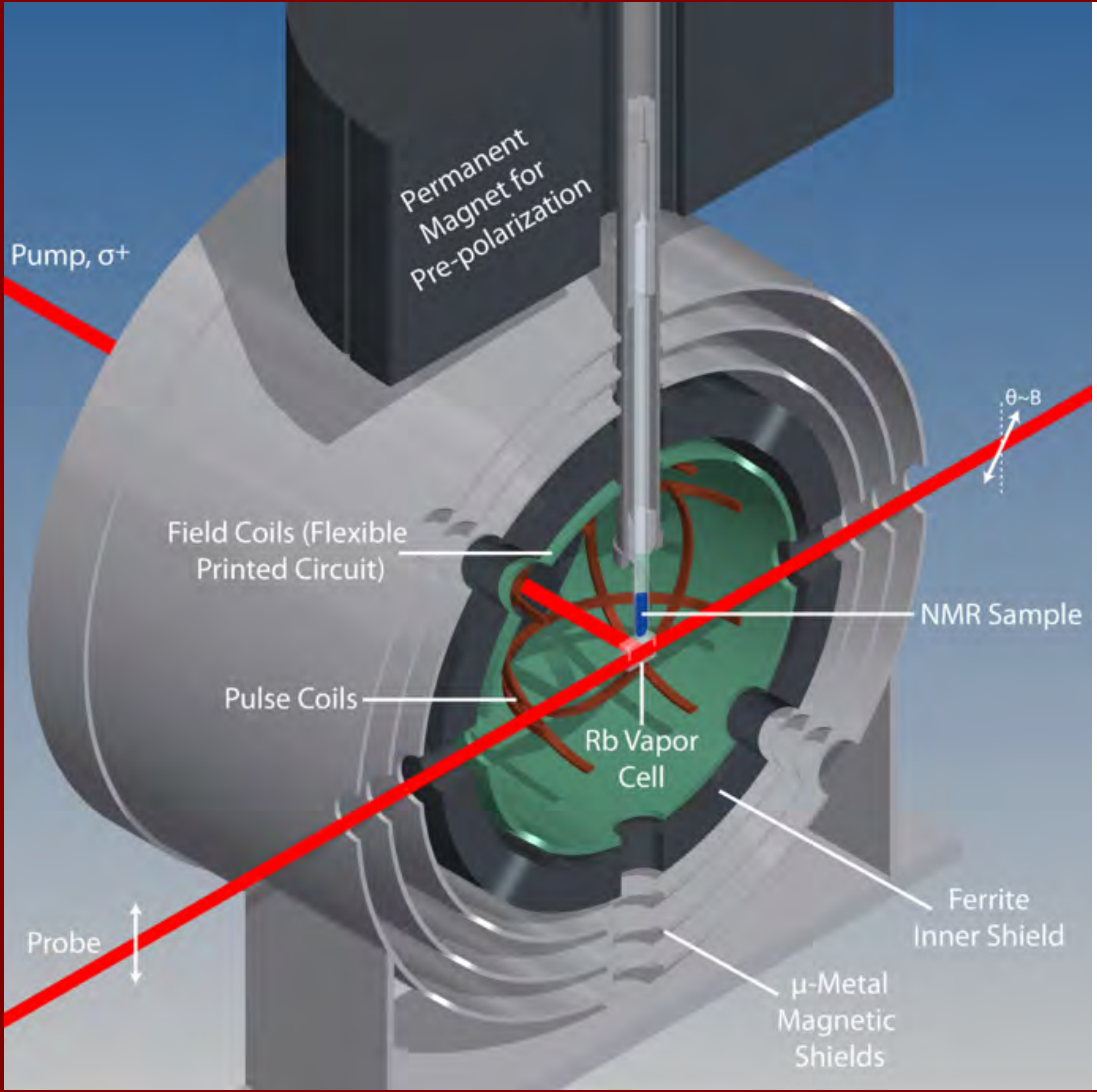
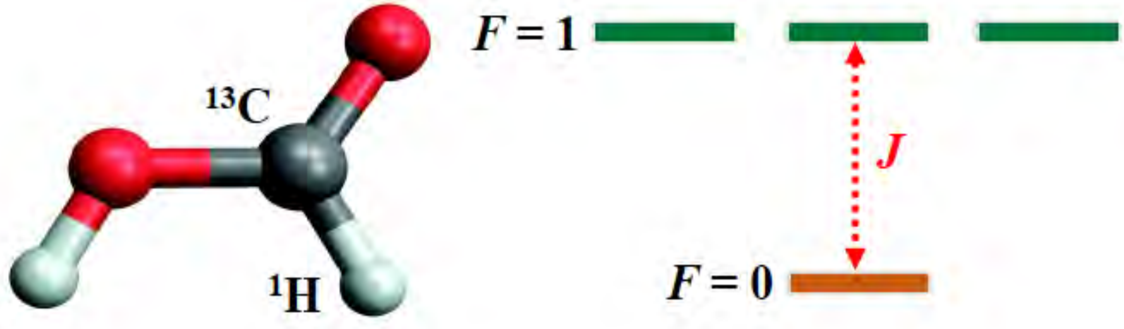
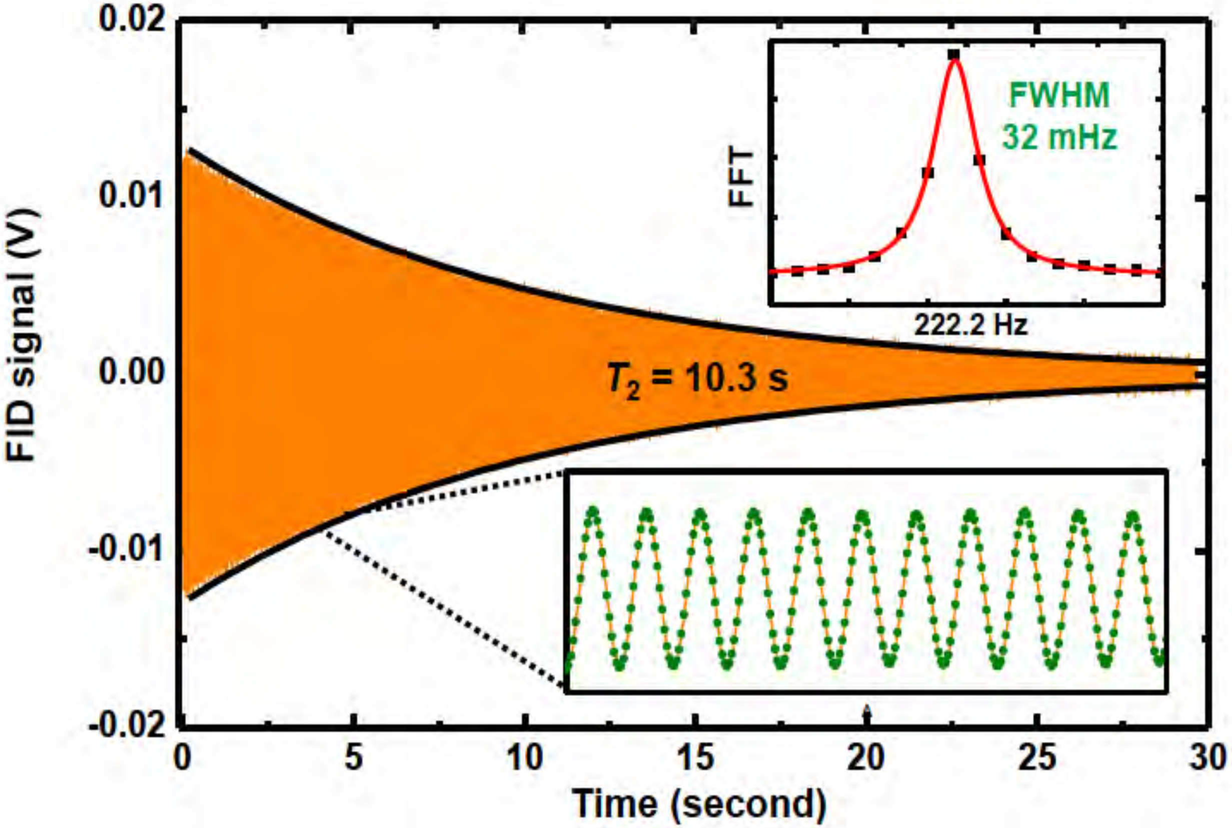


Figure 2. Experimental (upper trace) and simulated (lower trace) spectrum of benzene-$^{13}C_1$ in the neighborhood of $^1J_{CH}$. Inset shows fitting of two high-frequency peaks with 11 mHz half-width at half-maximum, consistent with Fourier resolution limited by 80s acquisition time.

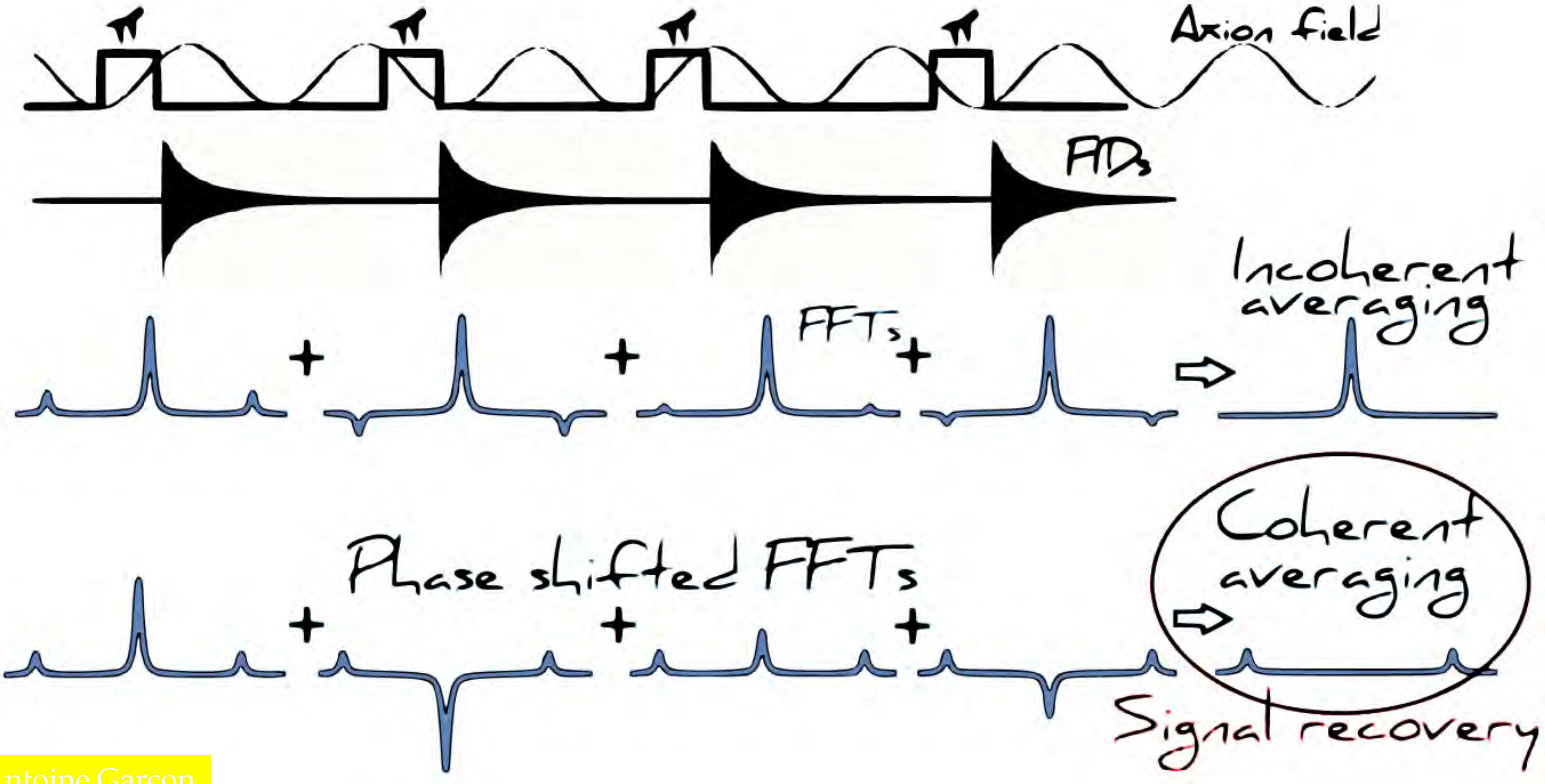
CASPEr-NOW with ZULF NMR





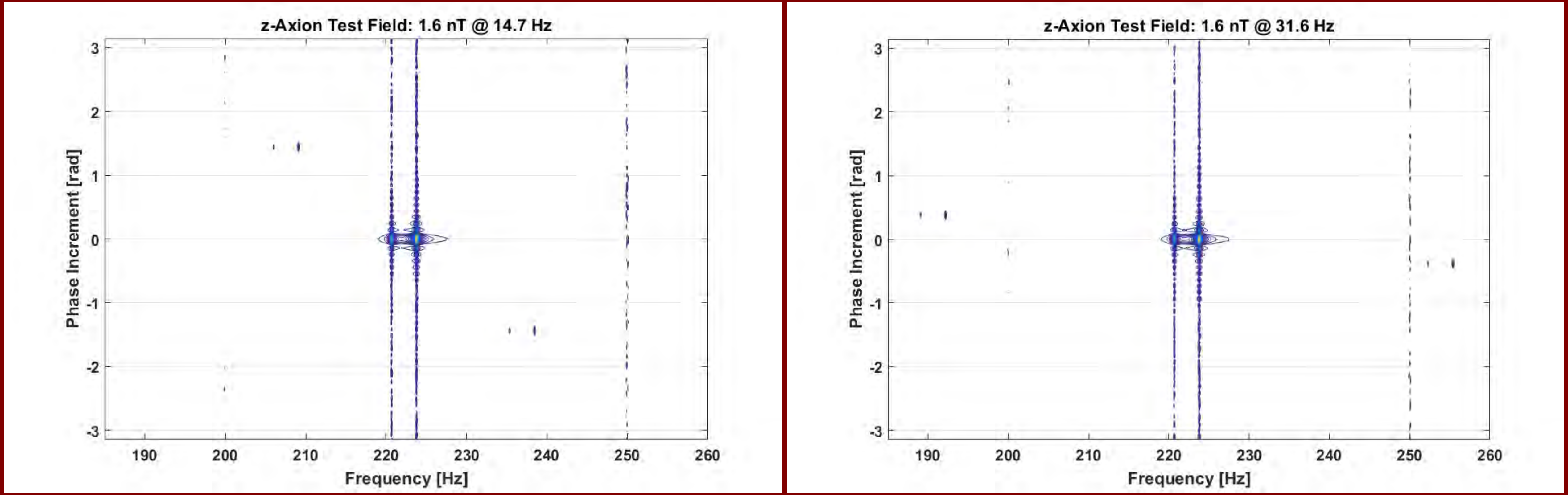


Coherent Averaging



Antoine Garçon

Coherent Averaging



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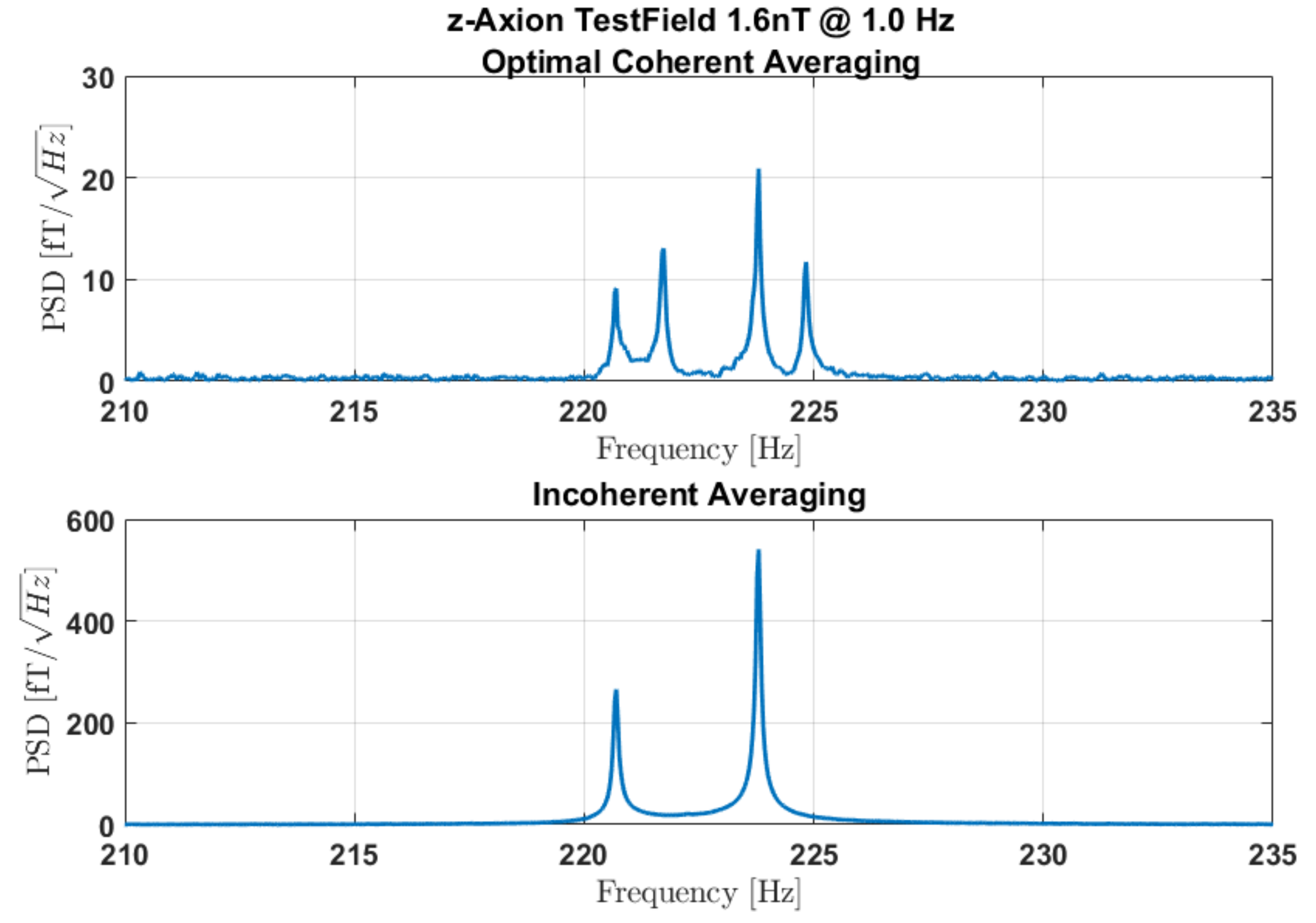
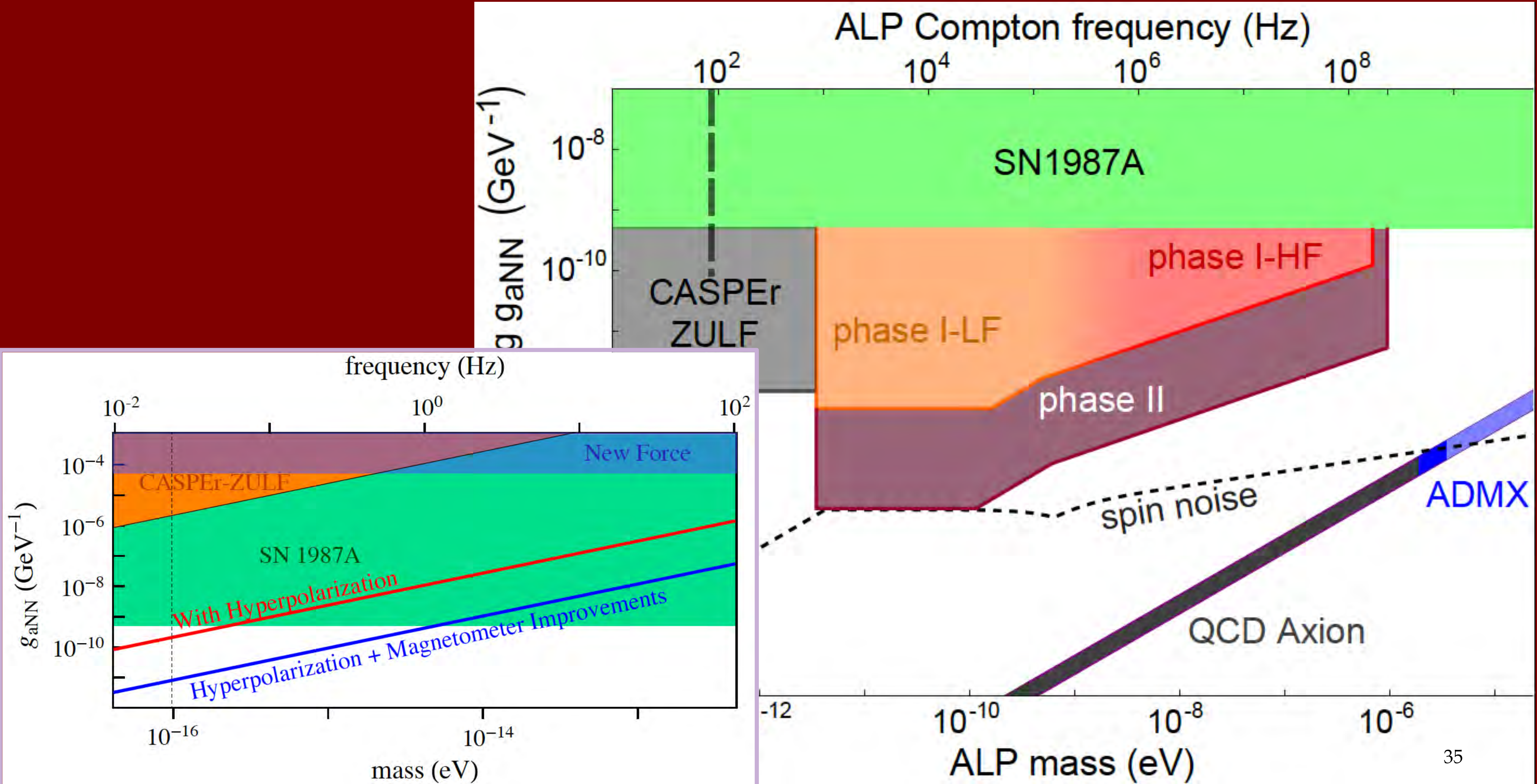


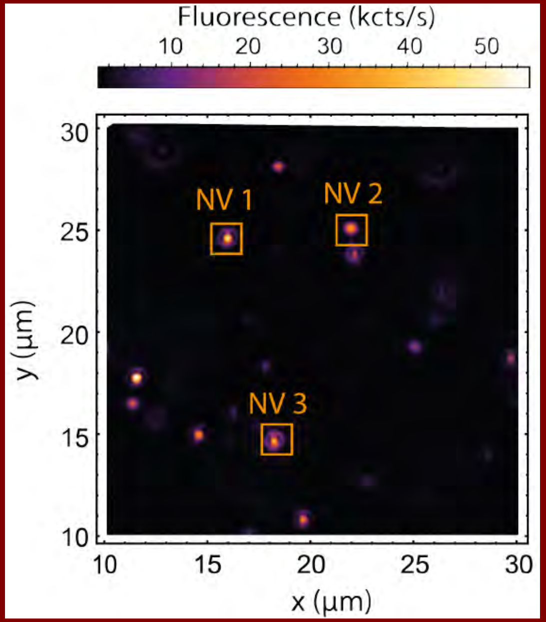
Antoine Garçon

CASPEr-Wind/NOW

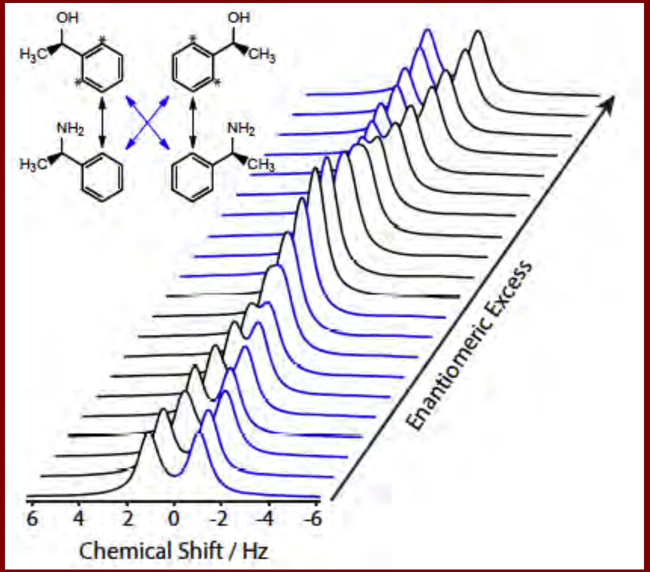


Summary: fundamental physics with weird NMR

- ✧ Cosmic Axion Spin Precession Experiment
  - ☛ CASPEr-E
  - ☛ CASPEr-Wind/ZULF/Now **New**



- ✧ Zero- and Ultralow-Field NMR
  - ☛ ParaHydrogen Induced Polarization
  - ☛ J-coupling spectroscopy @ ZULF
  - ☛ NV-ZULF NMR **New**
- ✧ Chiral parity violation in NMR **New**



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At Berkeley

Sean Lourette

Dr. Tao Wang D.B. Dr. Andrey Jarmola

Dr. Metin Kayci

Dr. Vincent Dumont

Michael Solarz

Prof. Pines

Prof. Hahn

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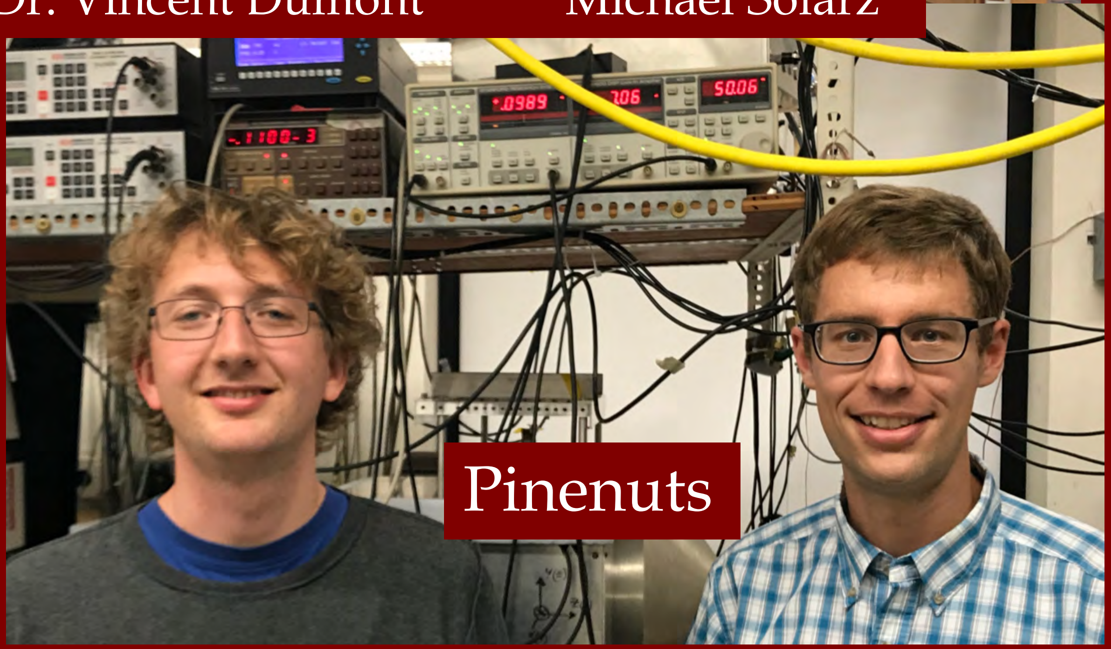

Pinenuts

Tobias Sjolander

Dr. Jonathan King

Suggested Questions

- So what about parity violation in chiral molecules?
- What was that Maxwell-Proca galactic business?
- What are some other ways to search for DM axions? (GNOME video)
- Tell us more about single-spin NMR
- What is the latest in atomic and diamond magnetometers?
- Can you do magnetic resonance 100 km up in the sky?
- What is Physics on Your Feet?

Suggested Questions

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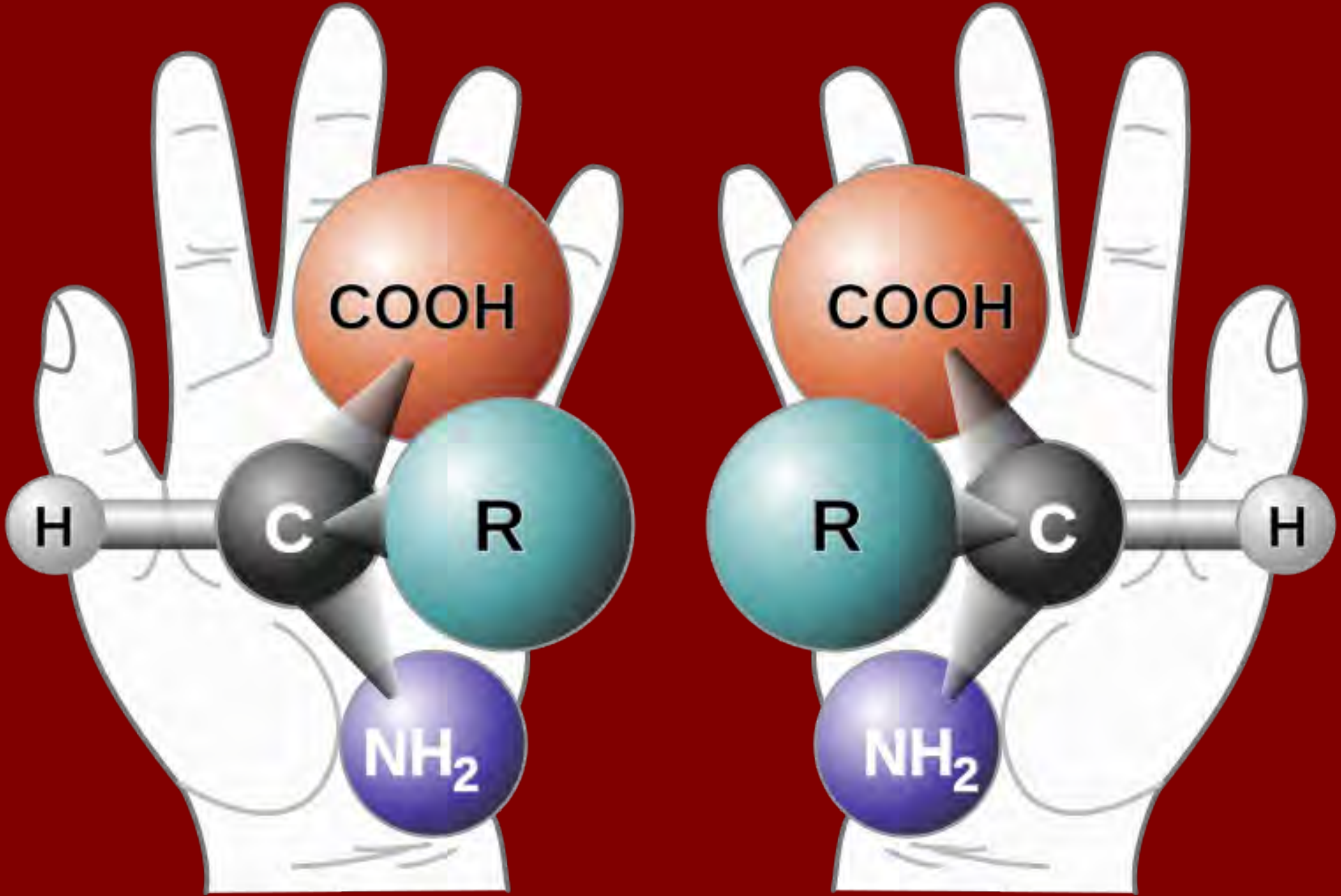
6. Can you do magnetic resonance 100 km up in the sky?
7. What is Physics on Your Feet?


V. Demas

Measuring molecular parity non-conservation using NMR Spectroscopy

J. Eills,[1,2] J. W. Blanchard,[3,4,5] L. Bougas,[2,6] M. G. Kozlov,[7] A. Pines,[5,4] and D.Budker[2,3,6,8]

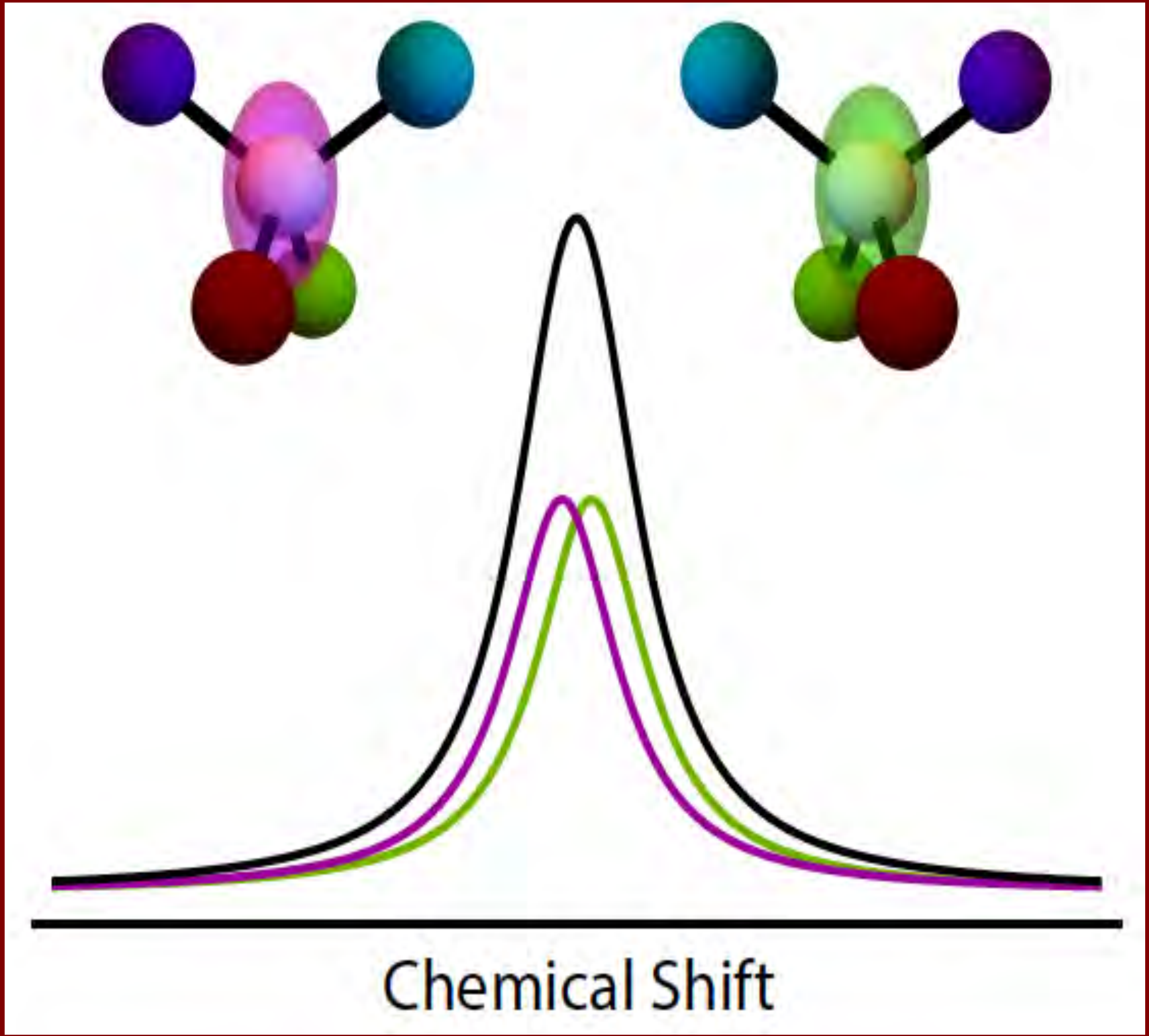
Phys. Rev. A **96,** 042119 – Published 30 October 2017



A PROVOCATIVE QUESTION:

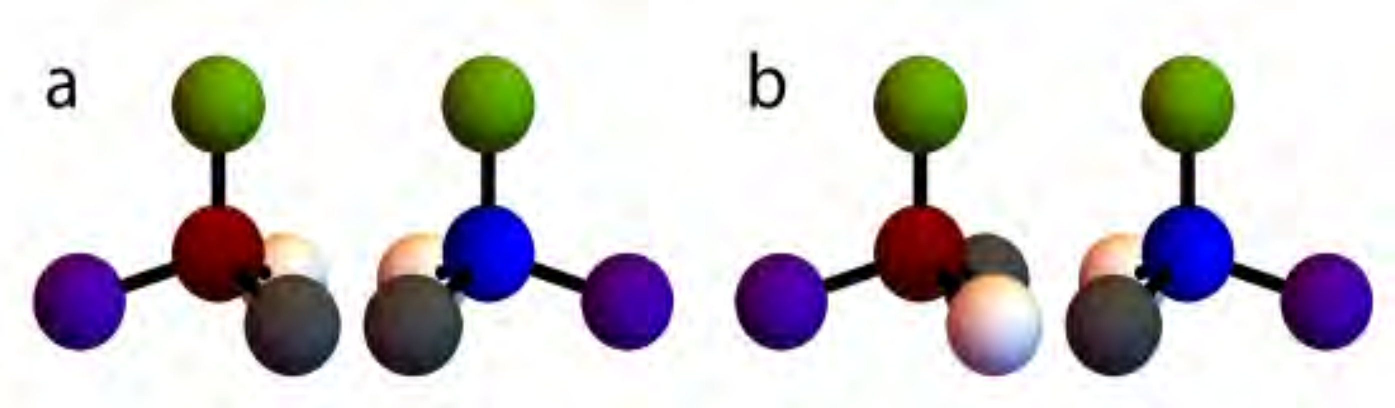
Why do chiral molecules have
first-order PNC energy shifts ?
(While this is normally forbidden)

PNC in racemic mixtures: impossible?

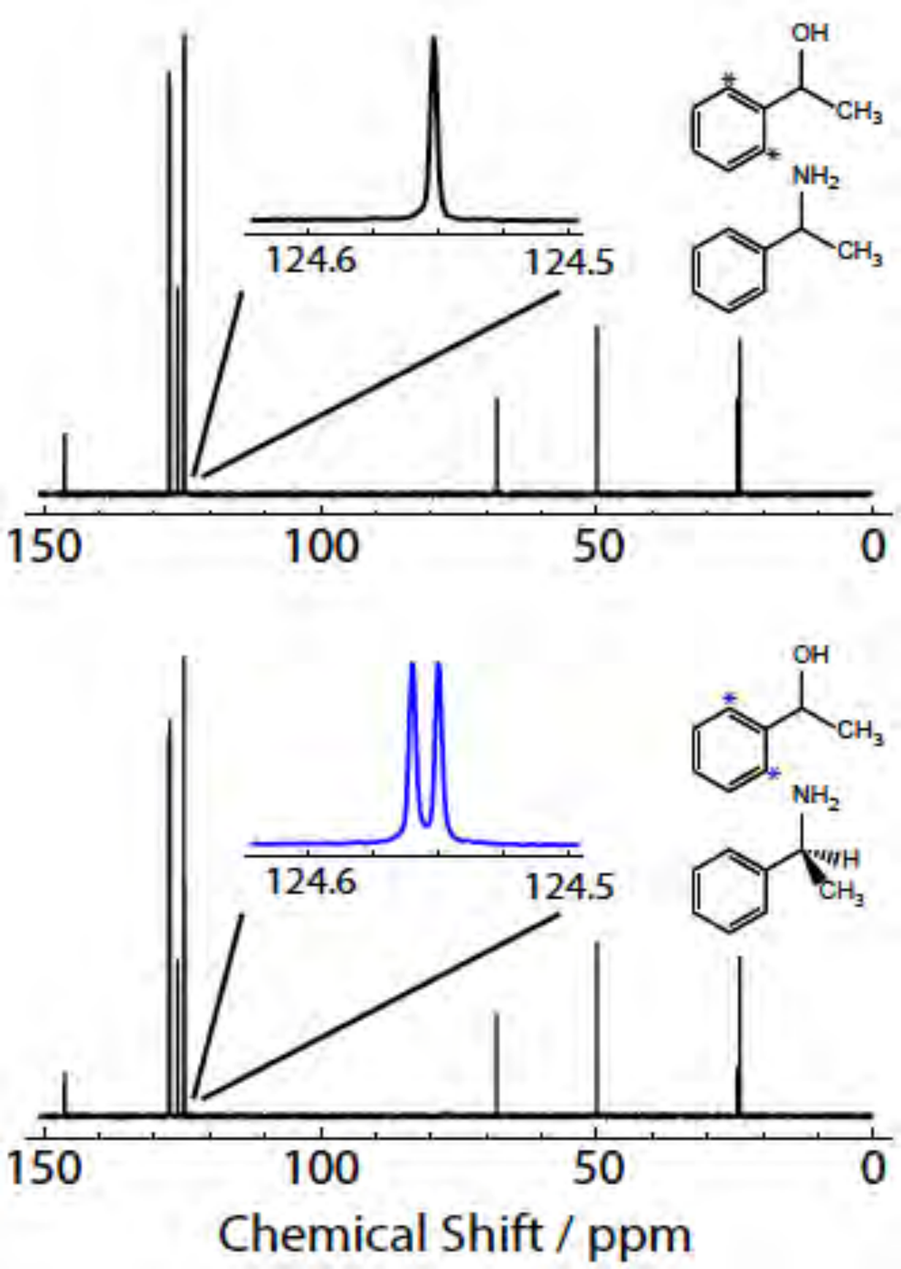


- PNC in chiral mol.➜ energy shift
- PNC in NMR ➜ Nucl.Spin.Dep PNC
- B=20 T ➜ ~ 1 mHz line shifts
- No way in a mixture…

Diastereomeric NMR shift



James Eills (SOTON)
John Blanchard
Lykourgos Bougas
Mikhail Kozlov
Alexander Pines
D.B.



Diastereomeric NMR shift

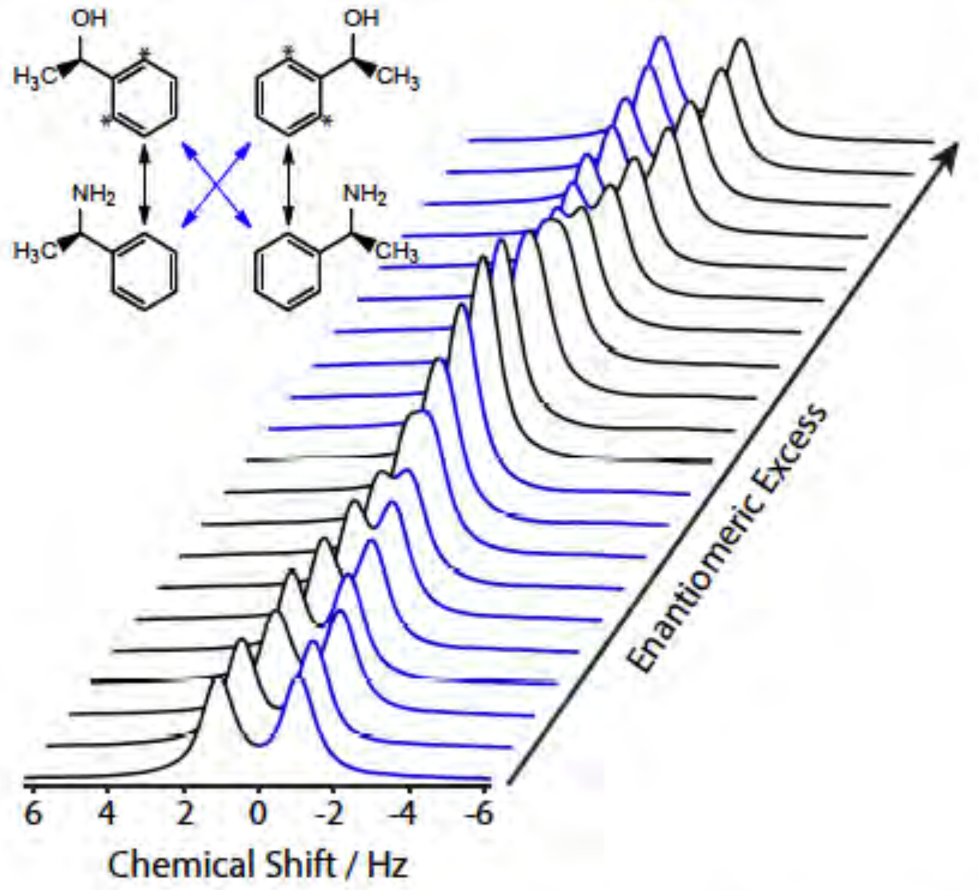


FIG. 4. Stacked ^{13}C spectra showing diastereomeric splitting of 1-phenylethanol as the enantiomeric excess of the 1-phenylethylamine environment is varied. The scale is in hertz, and centered on the peak of interest. All spectra were acquired at 298 K by averaging 32 transients, with proton decoupling, and have line broadening [35] of 0.5 Hz applied. The inset shows the four possible diastereomeric interactions between the sensor (1-phenylethanol) and chiral solvating reagent (1-phenylethylamine).

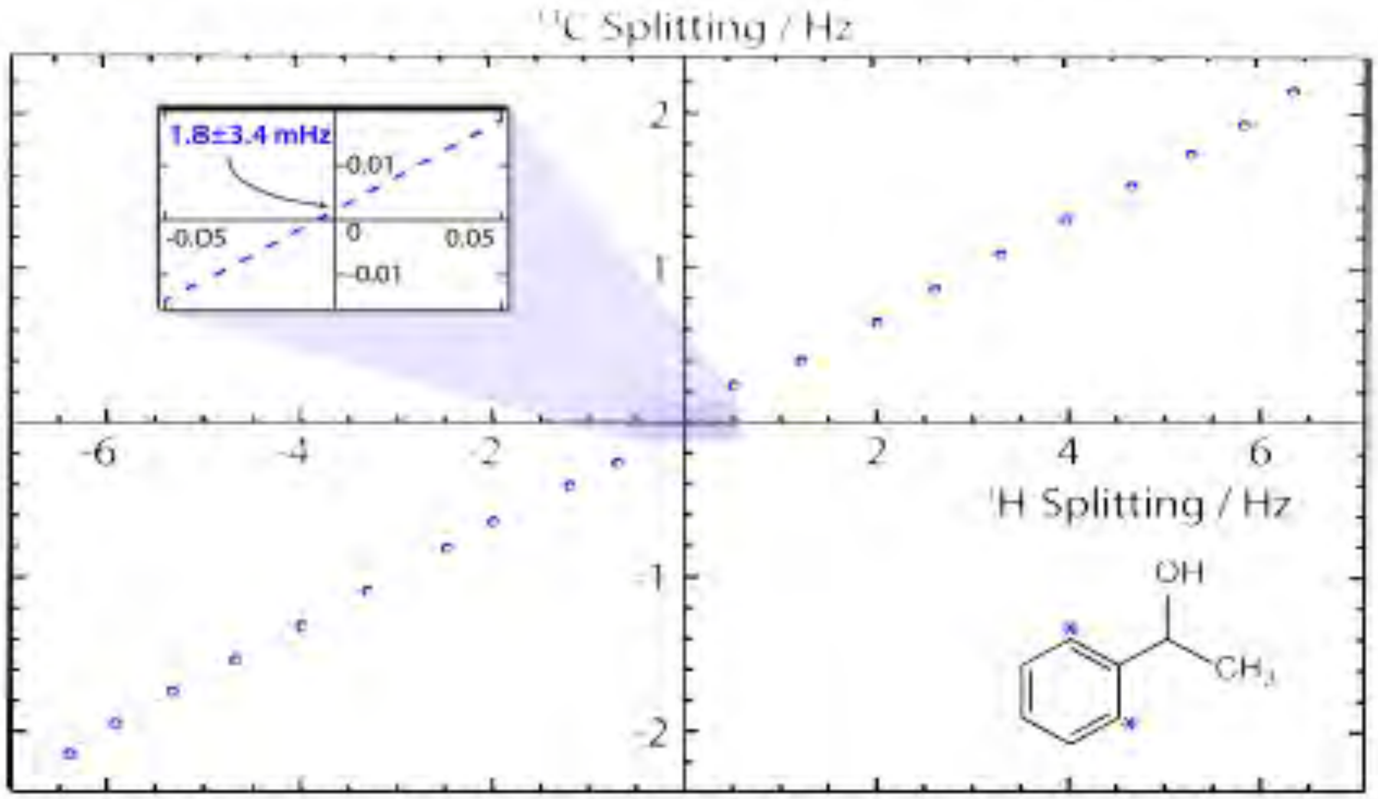


FIG. 5. Experimental data showing the diastereomeric splitting of the ^{13}C peaks as a function of the 1-phenylethylamine enantiomeric excess. Data points were acquired at 20 T and 298 K, by averaging 32 transients. The enantiomeric excess of each solution was determined by measuring the ^{1}H splitting, as discussed in more detail in the text.

"Built-in comagnetometer" !!!

Bottom line(s):

- Measure chiral PNC w/ racemic mixtures
- Built-in ^{1}H "comagnetometer"
- Systematics seem tractable
- It may, indeed, be possible to detect chiral PNC in NMR

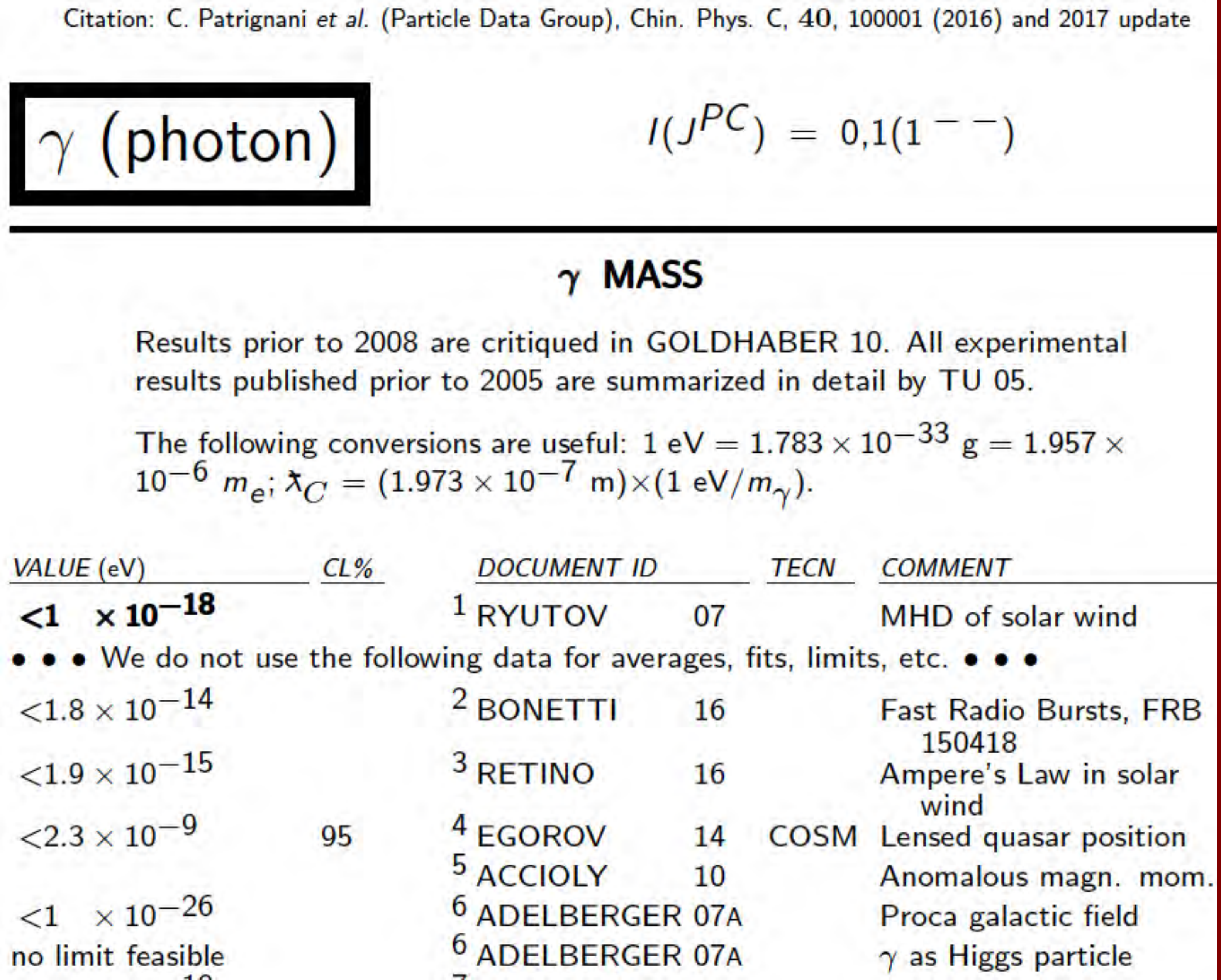
A hypothetical effect
of
Maxwell-Proca electromagnetic stresses
on
galaxy rotation curves

D.D. Ryutov, Dmitry Budker, and V.V. Flambaum

arXiv:1708.09514

Dmitri Ryutov Wins 2017
Maxwell Prize for Plasma Physics

Finite Photon Mass?



Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

γ (photon)

$I(J^{PC}) = 0,1(1^{--})$

γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: $1\ \text{eV} = 1.783 \times 10^{-33}\ \text{g} = 1.957 \times 10^{-6}\ m_e$; $\lambdabar_C = (1.973 \times 10^{-7}\ \text{m}) \times (1\ \text{eV}/m_\gamma)$.

VALUE (eV)	*CL%*	*DOCUMENT ID*	*TECN*	*COMMENT*
$<1 \times 10^{-18}$		[1] RYUTOV 07		MHD of solar wind
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<1.8 \times 10^{-14}$		[2] BONETTI 16		Fast Radio Bursts, FRB 150418
$<1.9 \times 10^{-15}$		[3] RETINO 16		Ampere's Law in solar wind
$<2.3 \times 10^{-9}$	95	[4] EGOROV 14	COSM	Lensed quasar position
		[5] ACCIOLY 10		Anomalous magn. mom.
$<1 \times 10^{-26}$		[6] ADELBERGER 07A		Proca galactic field
no limit feasible		[6] ADELBERGER 07A		γ as Higgs particle

Effect of Photon Mass on Galaxies?

NGC 4414, a typical spiral galaxy, is about 55,000 light-years in diameter and approximately 60 million light-years away from Earth

Key points:

- Sufficiently strong forces to explain galactic rotation curves without dark matter
- The effect of mass is indirect, through MHD

Maxwell-Proca Quasi-Static Electrodynamics

NGC 4414, a typical spiral galaxy, is about 55,000 light-years in diameter and approximately 60 million light-years away from Earth

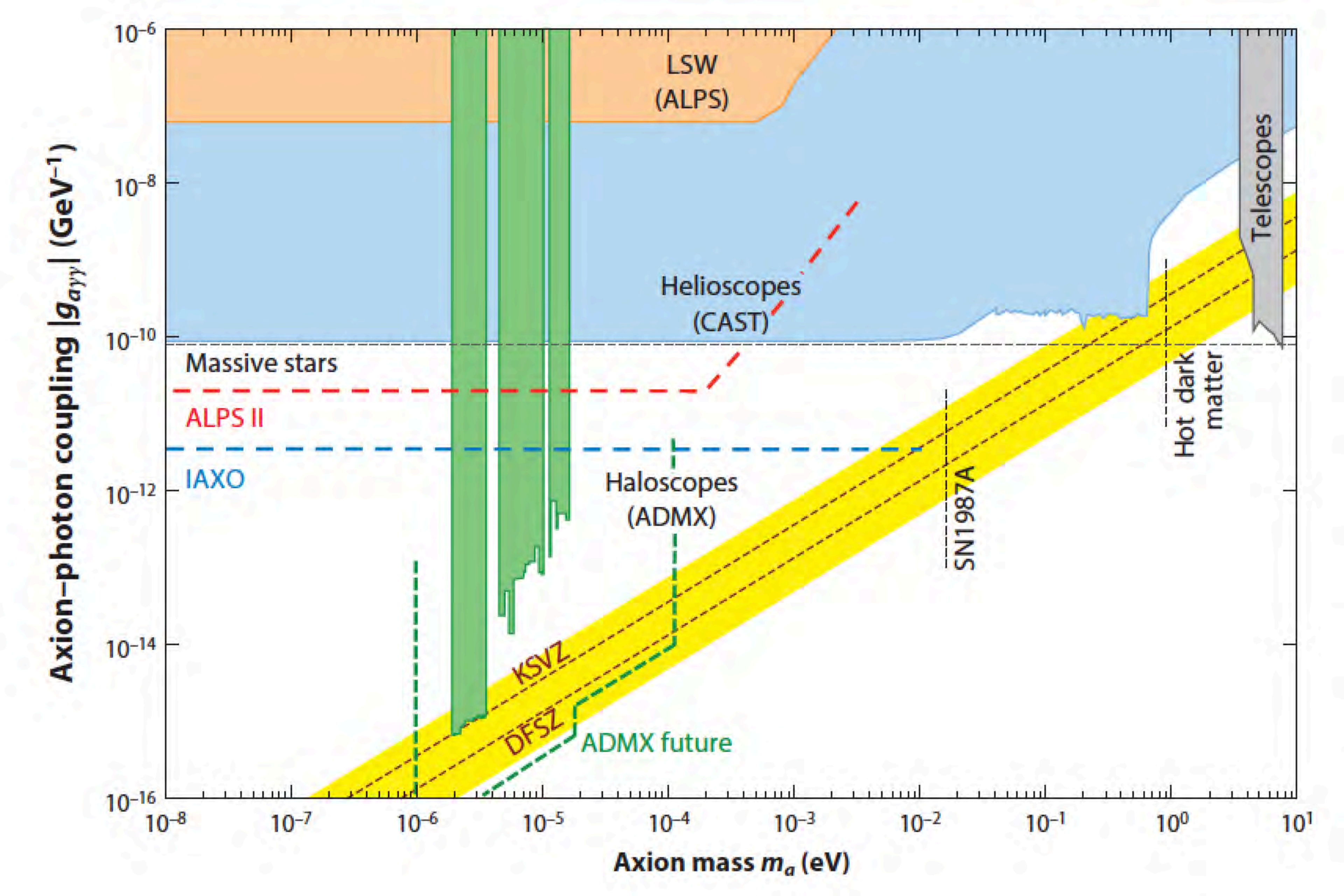
$$\boxed{\nabla \cdot \boldsymbol{A} = 0}$$

$$\boxed{\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}}$$

$$\boxed{\nabla \times \boldsymbol{A} = \boldsymbol{B}}$$

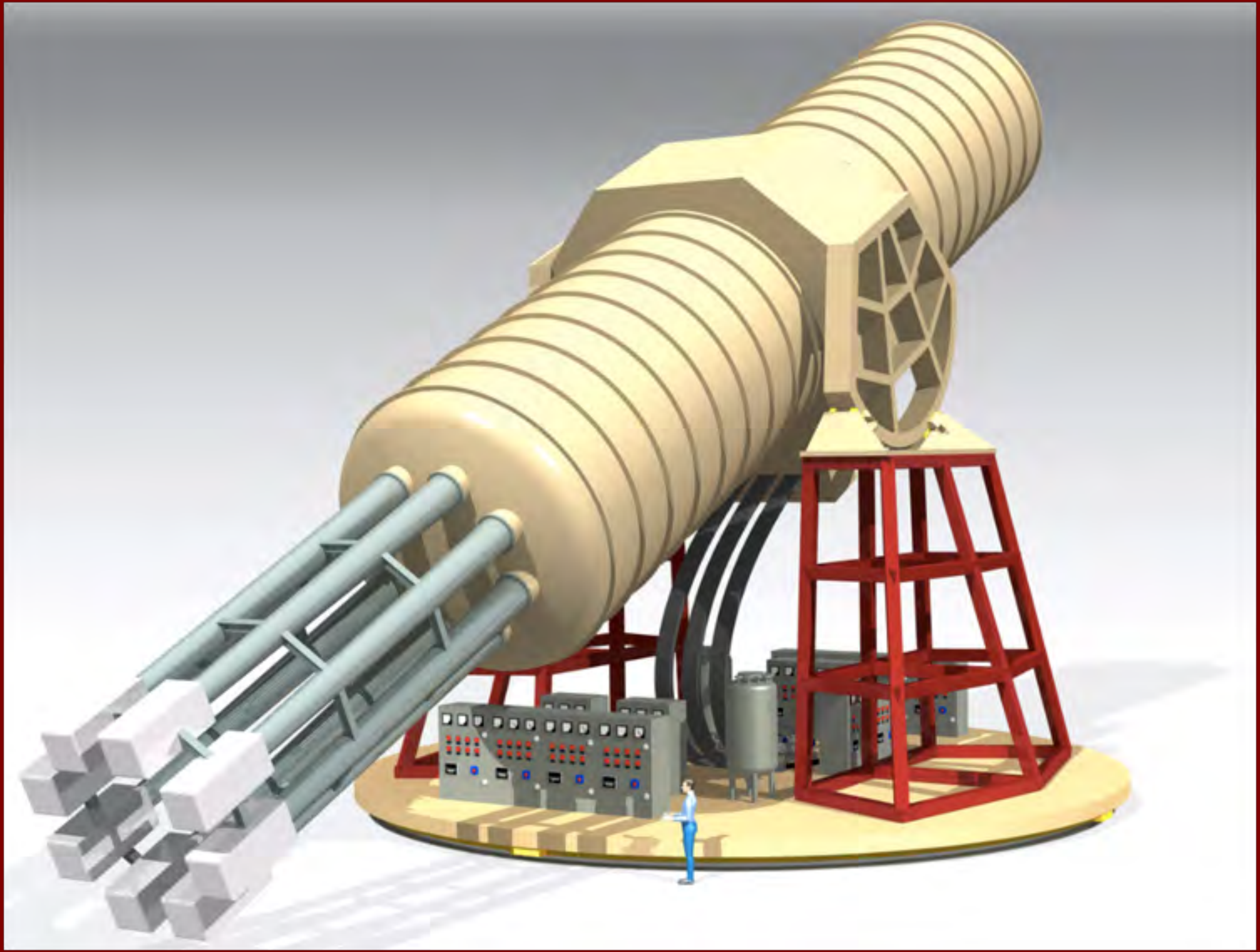
$$\boxed{\nabla \times \boldsymbol{B} + \frac{\boldsymbol{A}}{\lambda^2} = \frac{4\pi}{c}\boldsymbol{j}}$$

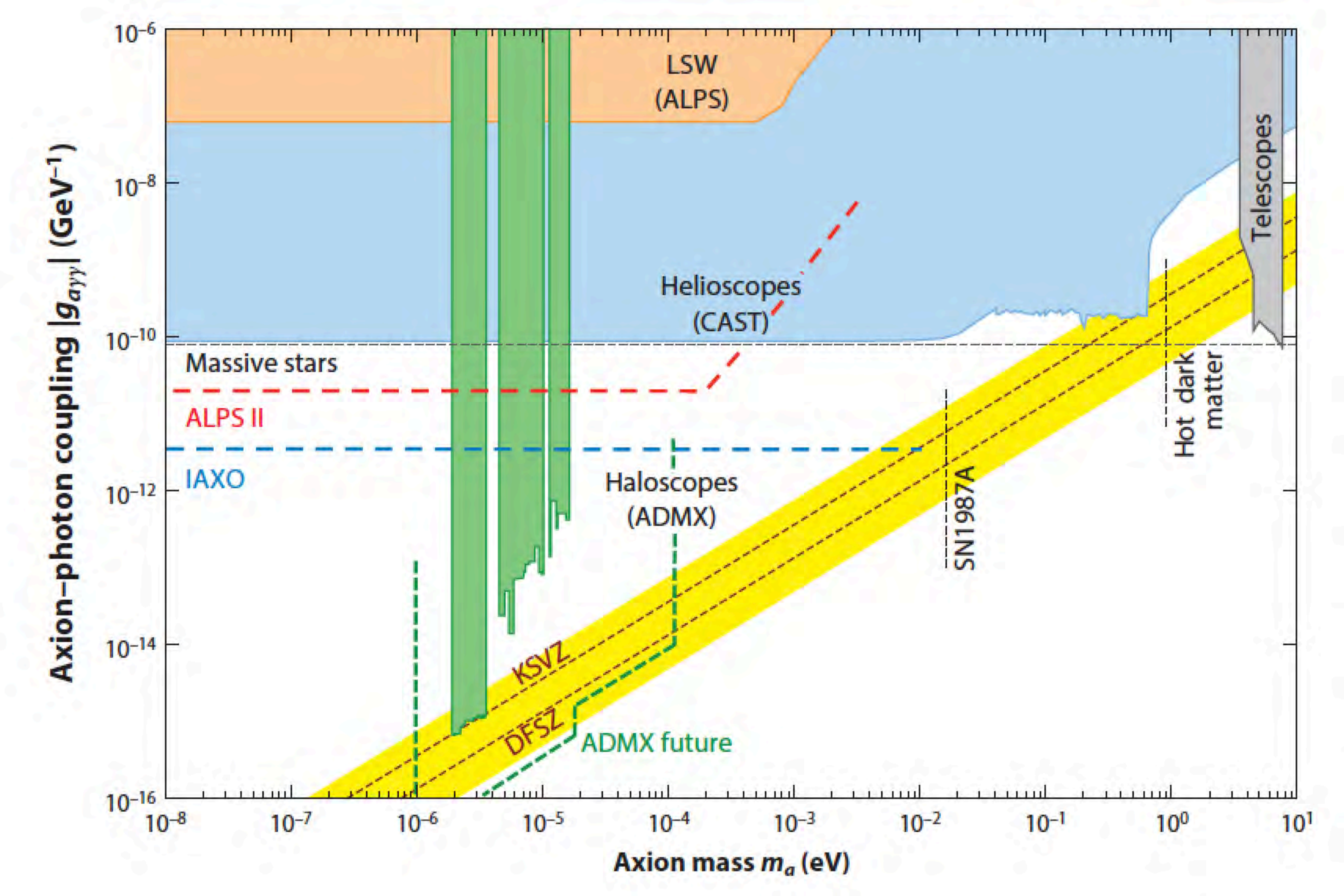
A few Axion/ALP experiments



Karl van Bibber

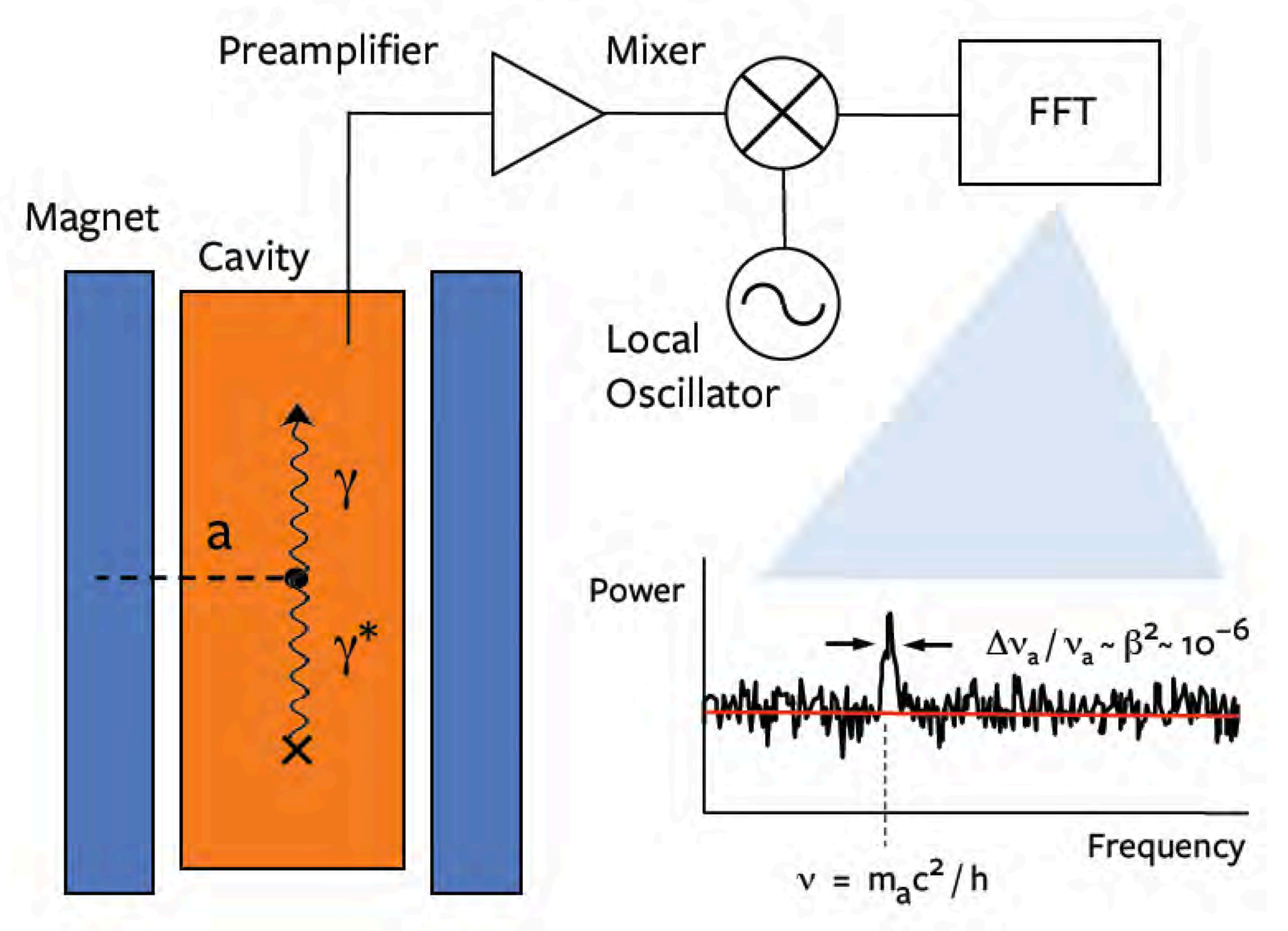
Helioscope of the future: IAXO





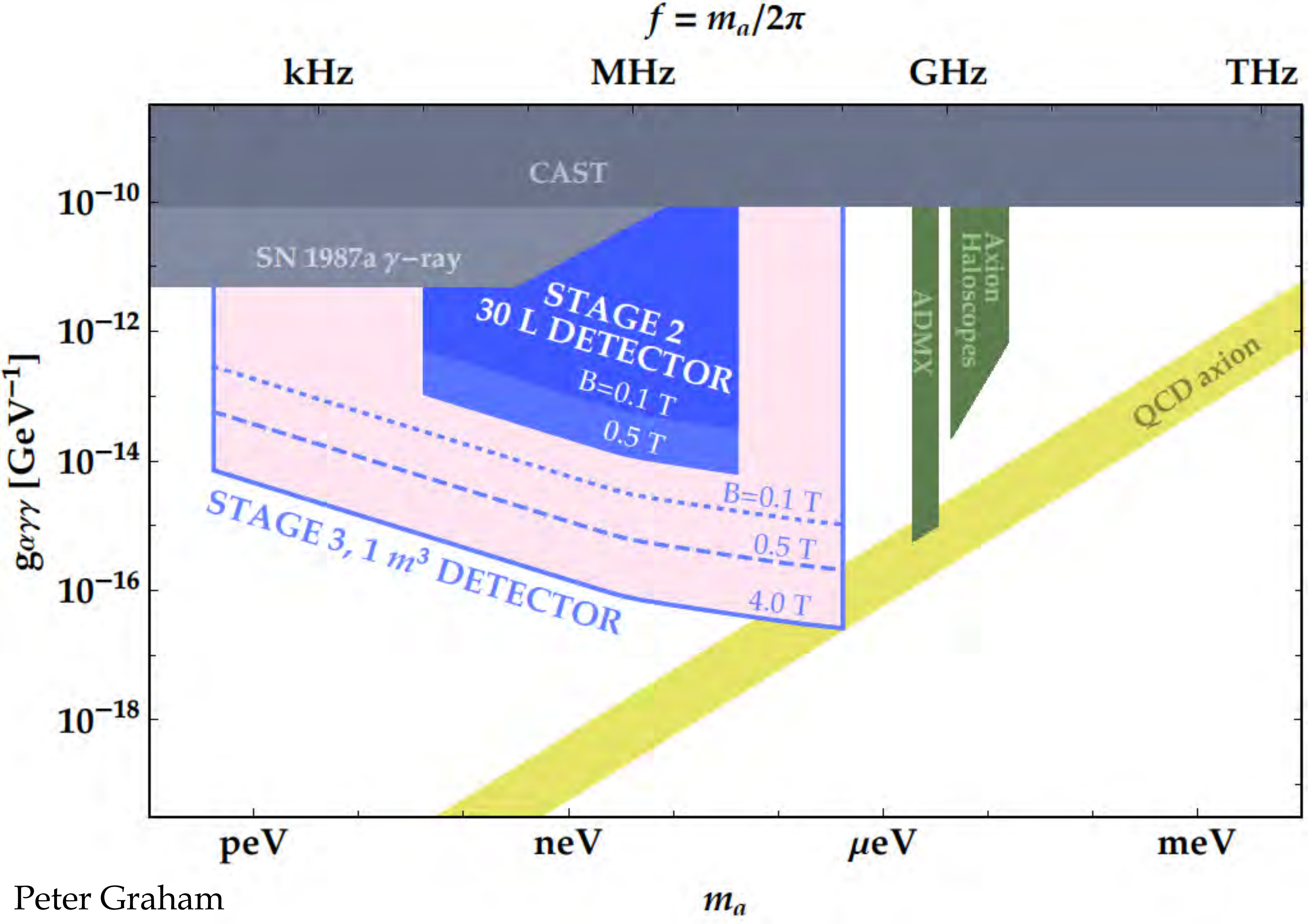
Karl van Bibber

The principle of the microwave-cavity haloscopes: ADMX, HAYSTACK, CAPP, ORGAN



Karl van Bibber

New Haloscope Proposals: ABRACADABRA (MIT) and DM Radio



Peter Graham

CASPEr-Wind: projected sensitivity

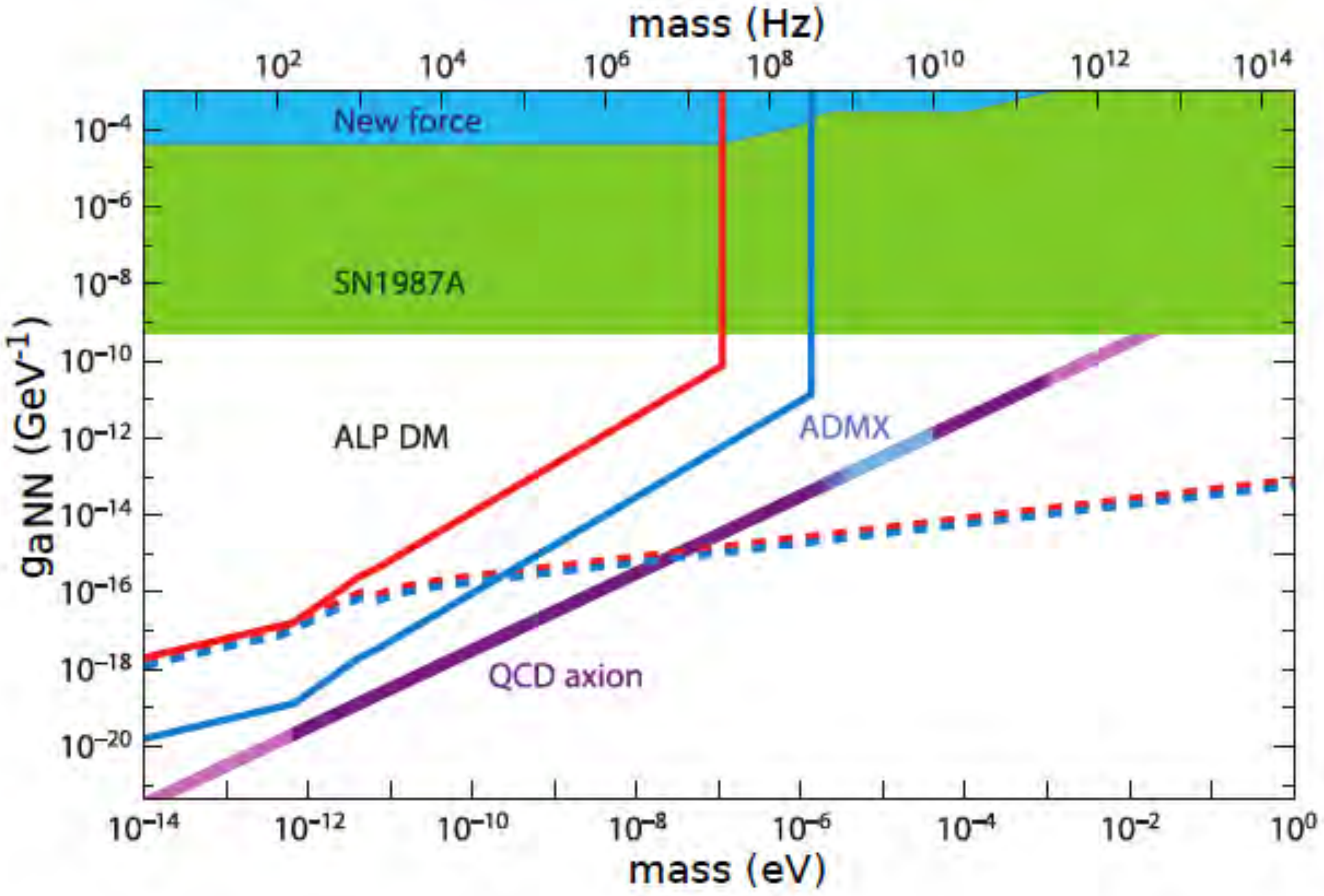


Figure 1: ALP-nucleon coupling parameter space: coupling strength g_{aNN} versus ALP mass m_a. The purple line represents the mass-coupling parameter space corresponding to the QCD axion proposed to solve the strong CP problem [25]. The darker purple region of the line shows where the QCD axion could be all of the dark matter. The red line is the projected sensitivity of CASPEr-Wind using hyperpolarized ^{129}Xe. The blue line is the sensitivity using hyperpolarized ^{3}He during a future upgrade of the experiment. The dashed lines are the limits from magnetization noise for ^{129}Xe (red) and ^{3}He (blue). The ADMX region shows the mass range already excluded (dark blue) or that will be covered (light blue) by ADMX (probing the axion-photon coupling). The green region is excluded by observations on Supernovae SN1987A [27, 28]. The blue region is excluded by searches for new spin-dependent forces. Figure adapted with permission from Ref. [29].

The GNOME Experiment

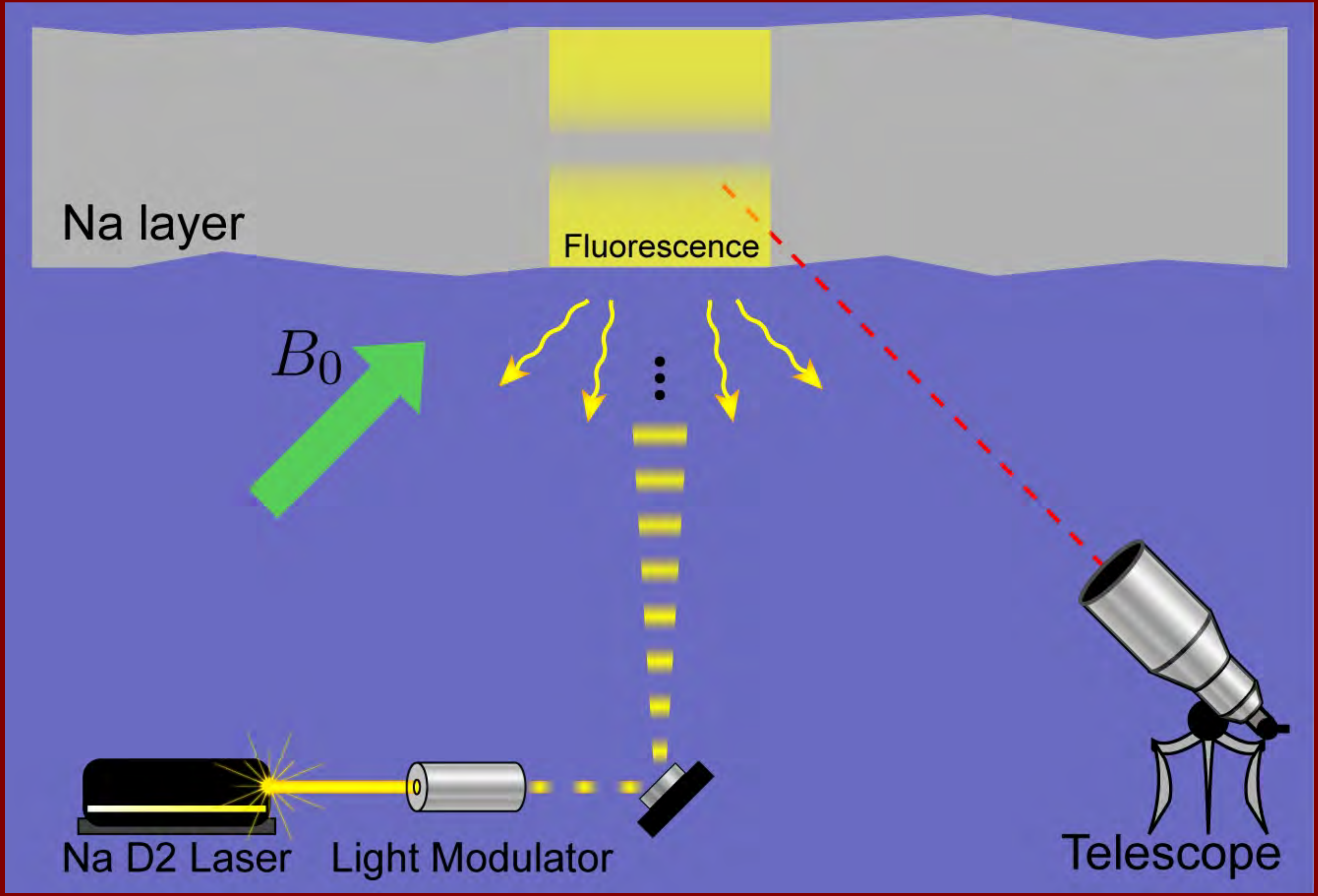
Collaboration website

Current date: 2017/09/28 21:54:36 GPS

budker.uni-mainz.de/gnome/

Video by Dr. Arne Wickenbrock

Laser Guide-Star magnetometry



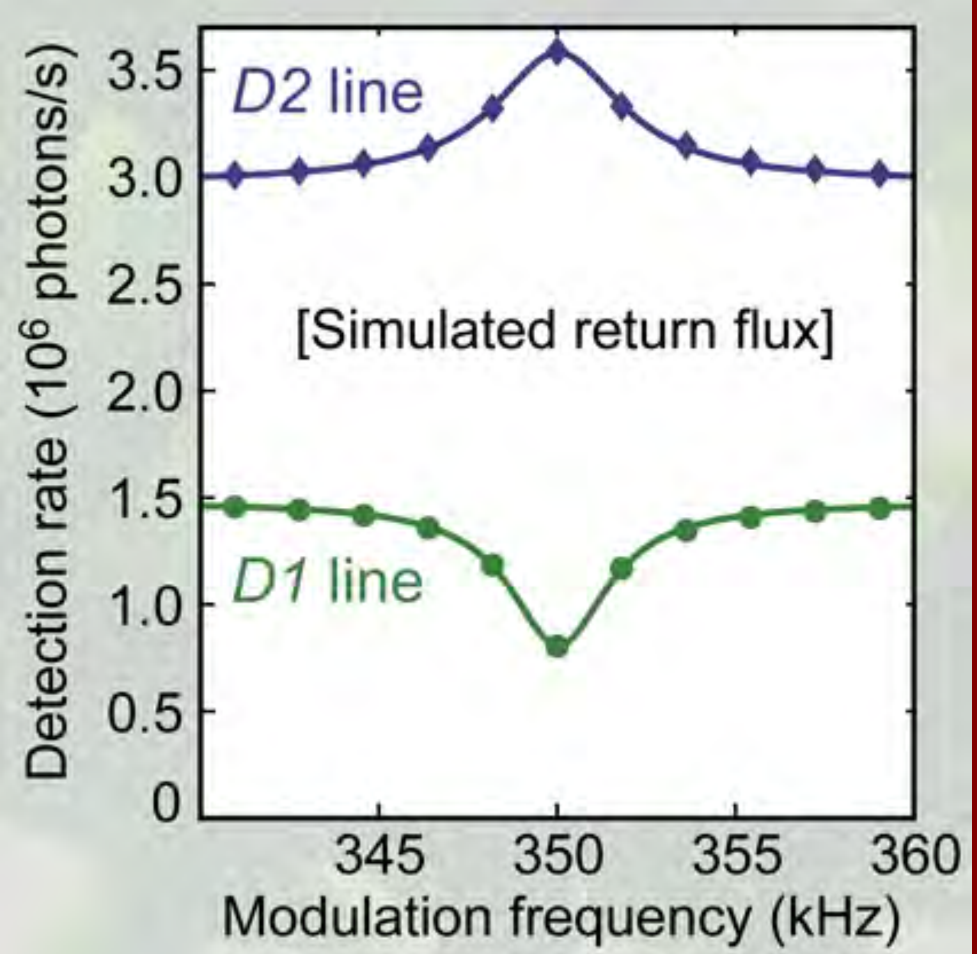
Magnetometry with mesospheric sodium

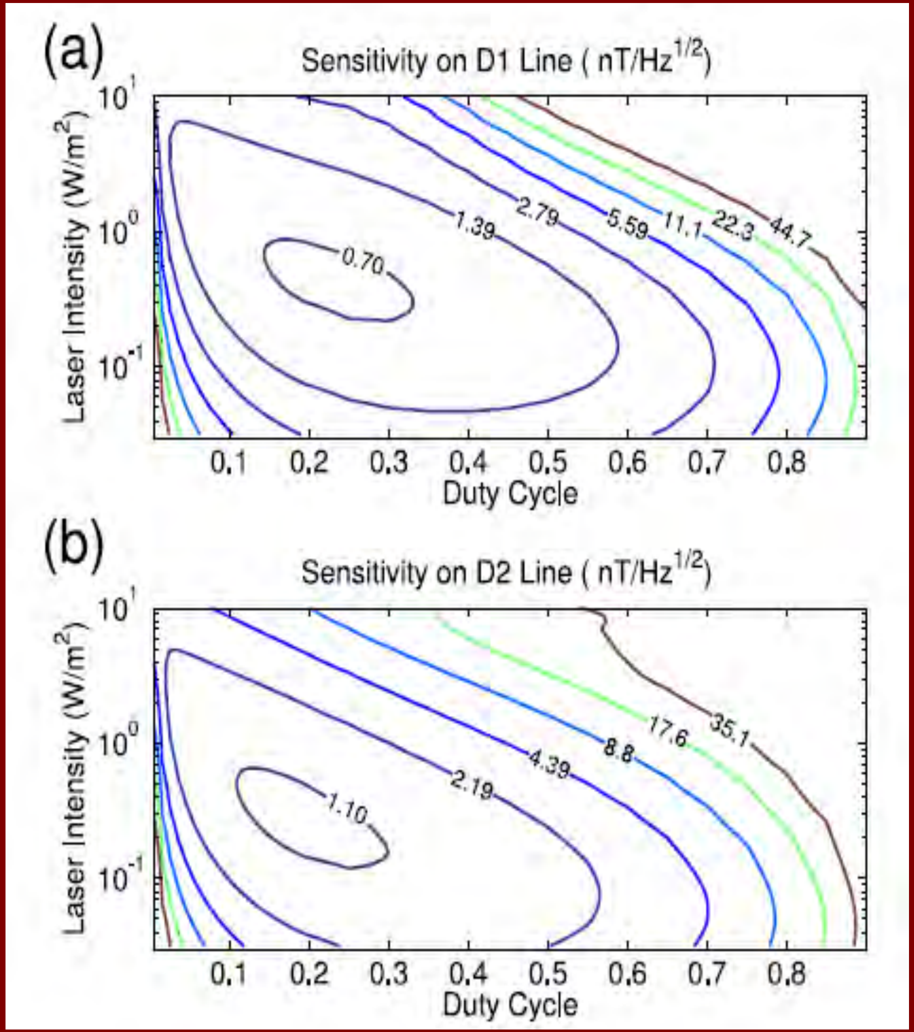
James M. Higbie[a,1], Simon M. Rochester[b], Brian Patton[b], Ronald Holzlöhner[c], Domenico Bonaccini Calia[c], and Dmitry Budker[b,d]

PNAS **108**, 3522 (2011).

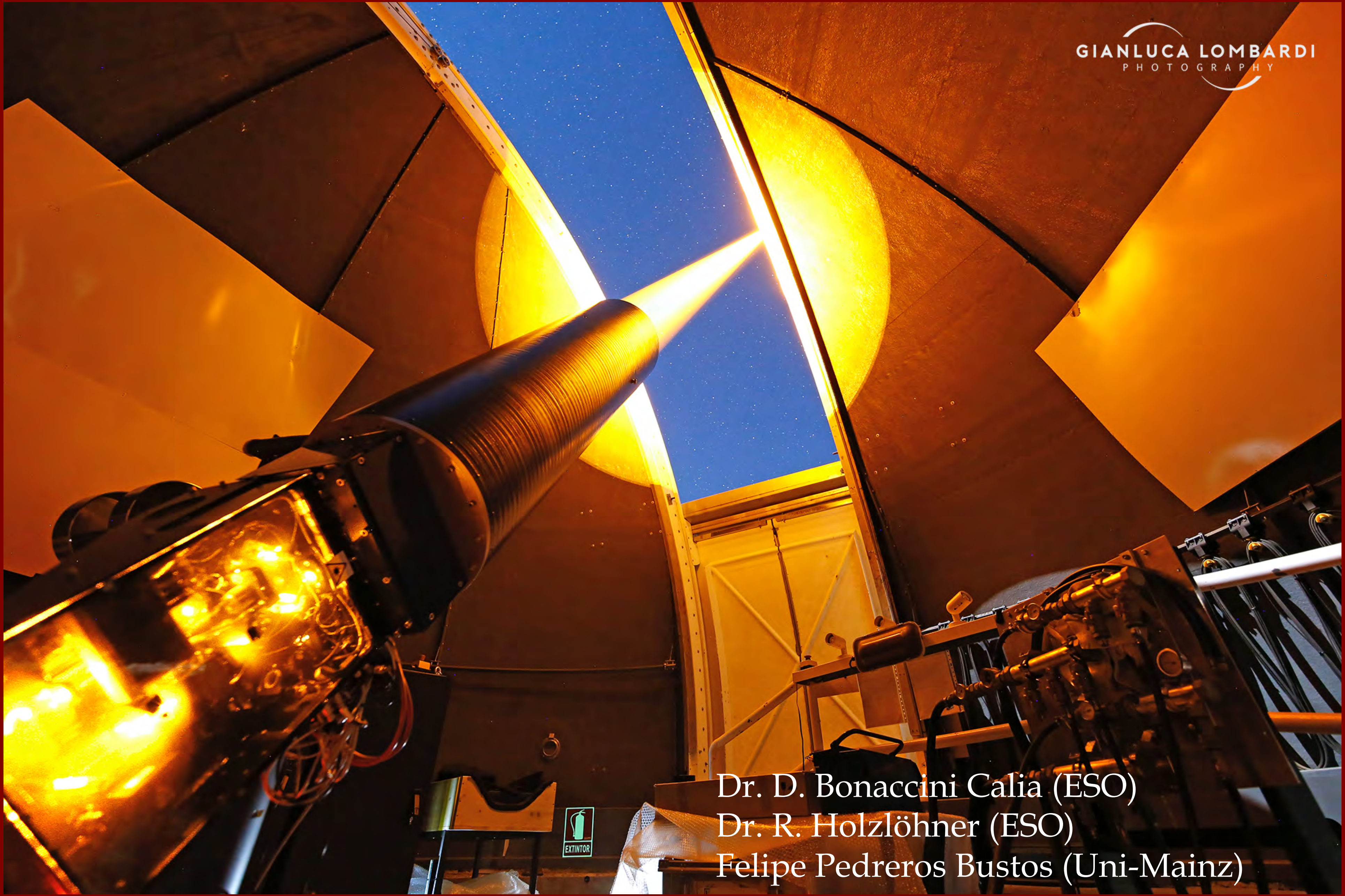
Brian Patton

Magneto-optical resonance of mesospheric sodium



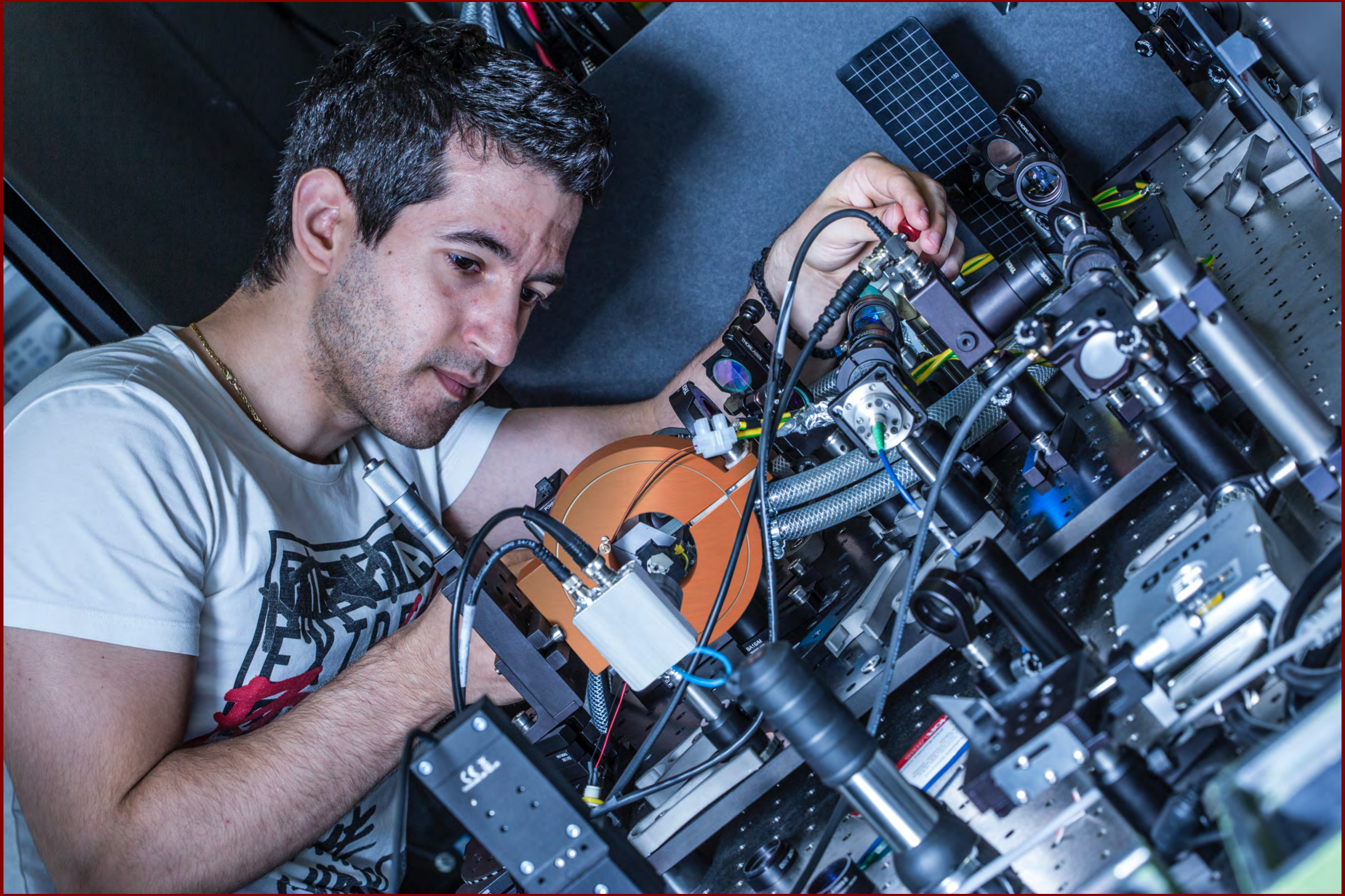


Magnetometer…in the sky!

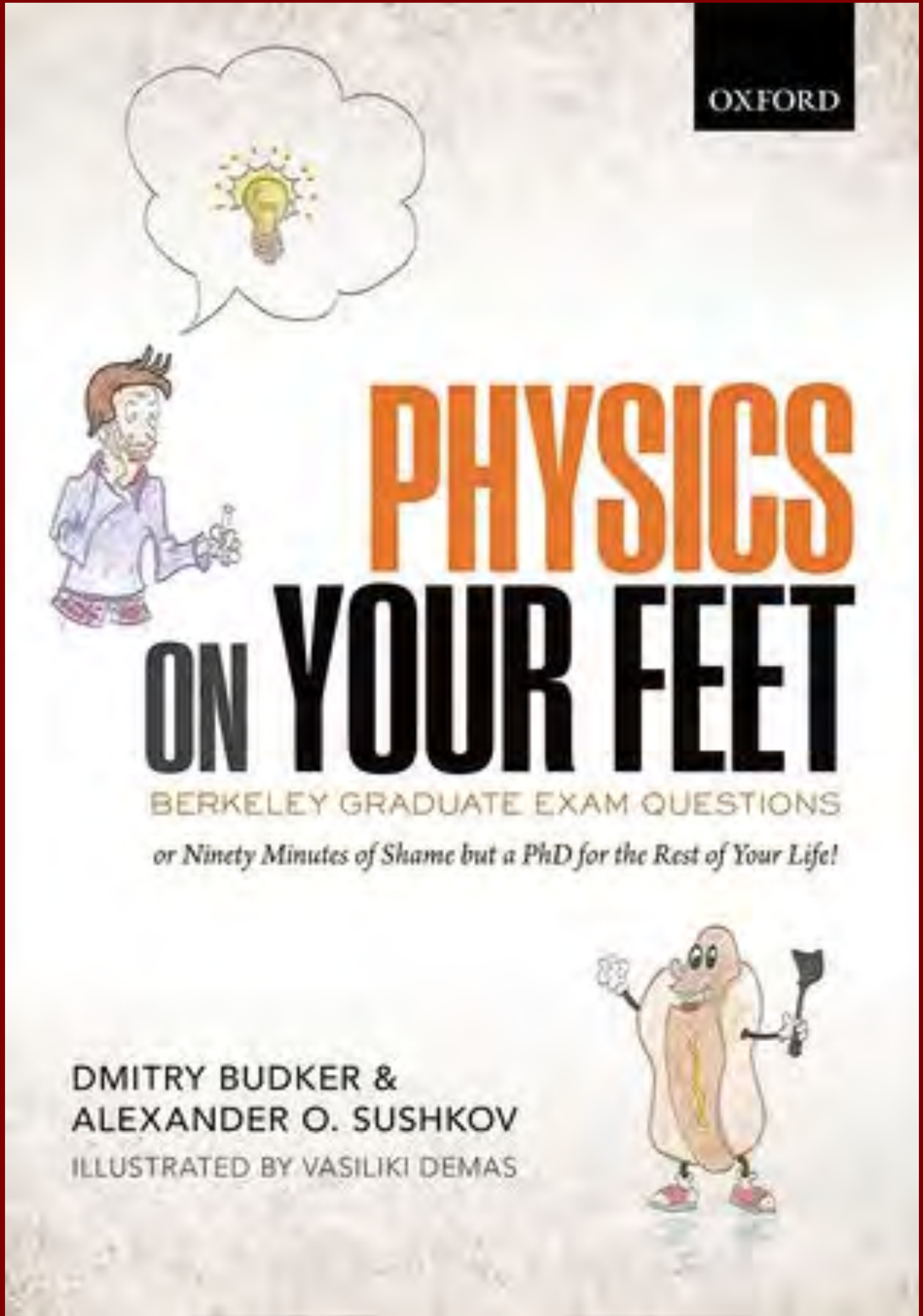


Dr. D. Bonaccini Calia (ESO)
Dr. R. Holzlöhner (ESO)
Felipe Pedreros Bustos (Uni-Mainz)

Magnetometer…in the sky!



Graduate student Georgios Chatzidrosos adjusting an NV-diamond magnetometer



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DMITRY BUDKER &
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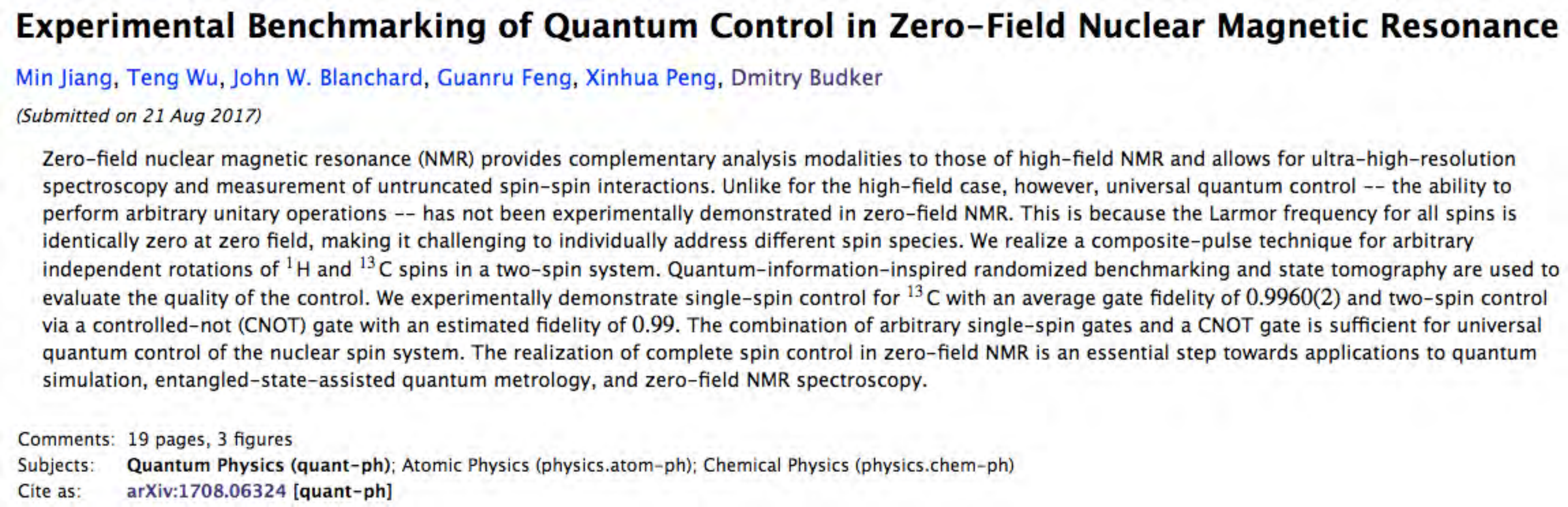
ILLUSTRATED BY VASILIKI DEMAS

There is more to do with ZULF NMR!



Experimental Benchmarking of Quantum Control in Zero-Field Nuclear Magnetic Resonance

Min Jiang, Teng Wu, John W. Blanchard, Guanru Feng, Xinhua Peng, Dmitry Budker

(Submitted on 21 Aug 2017)

Zero-field nuclear magnetic resonance (NMR) provides complementary analysis modalities to those of high-field NMR and allows for ultra-high-resolution spectroscopy and measurement of untruncated spin-spin interactions. Unlike for the high-field case, however, universal quantum control -- the ability to perform arbitrary unitary operations -- has not been experimentally demonstrated in zero-field NMR. This is because the Larmor frequency for all spins is identically zero at zero field, making it challenging to individually address different spin species. We realize a composite-pulse technique for arbitrary independent rotations of ^{1}H and ^{13}C spins in a two-spin system. Quantum-information-inspired randomized benchmarking and state tomography are used to evaluate the quality of the control. We experimentally demonstrate single-spin control for ^{13}C with an average gate fidelity of $0.9960(2)$ and two-spin control via a controlled-not (CNOT) gate with an estimated fidelity of 0.99. The combination of arbitrary single-spin gates and a CNOT gate is sufficient for universal quantum control of the nuclear spin system. The realization of complete spin control in zero-field NMR is an essential step towards applications to quantum simulation, entangled-state-assisted quantum metrology, and zero-field NMR spectroscopy.

Comments: 19 pages, 3 figures
Subjects: **Quantum Physics (quant-ph)**; Atomic Physics (physics.atom-ph); Chemical Physics (physics.chem-ph)
Cite as: arXiv:1708.06324 **[quant-ph]**