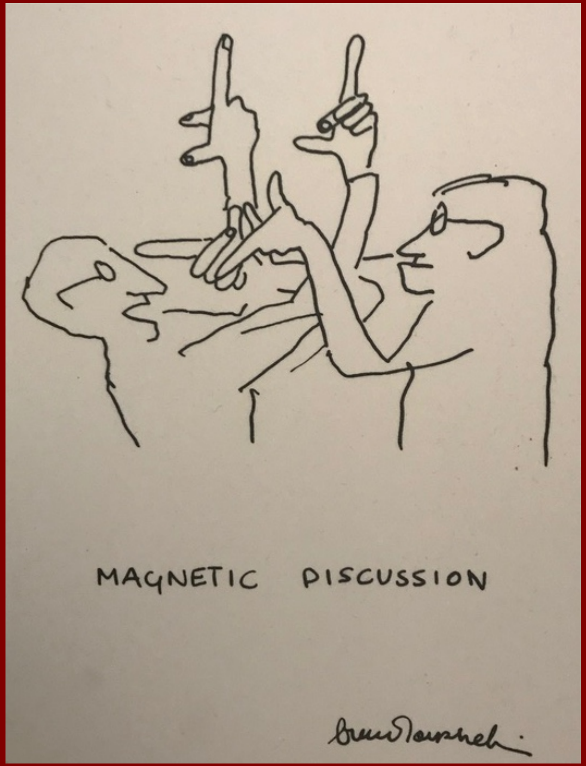
Ultralight dark matter search with nuclear magnetic resonance



Dmitry Budker

Helmholtz Institute JGU Mainz

UC Berkeley Physics NSD LBNL

Axion2017 Osaka, Japan

So what is DM or what mimics it ?

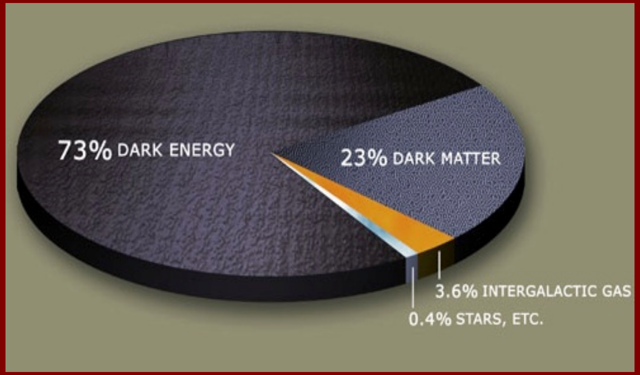
- A gross misunderstanding of gravity (MOND, …) ☹?
- Proca MHD (finite photon mass) ?
- Black holes, dark planets, interstellar gas, … ☹
- WIMPS ☺
- Ultralight bosonic particles
  - Axions (pseudoscalar) ☺ ⇐
  - ALPs (pseudoscalar) ☺ ⇐
  - Dilatons (scalar) ☺
  - Vector particles ☺ ⇐
  - Tensor particles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

"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

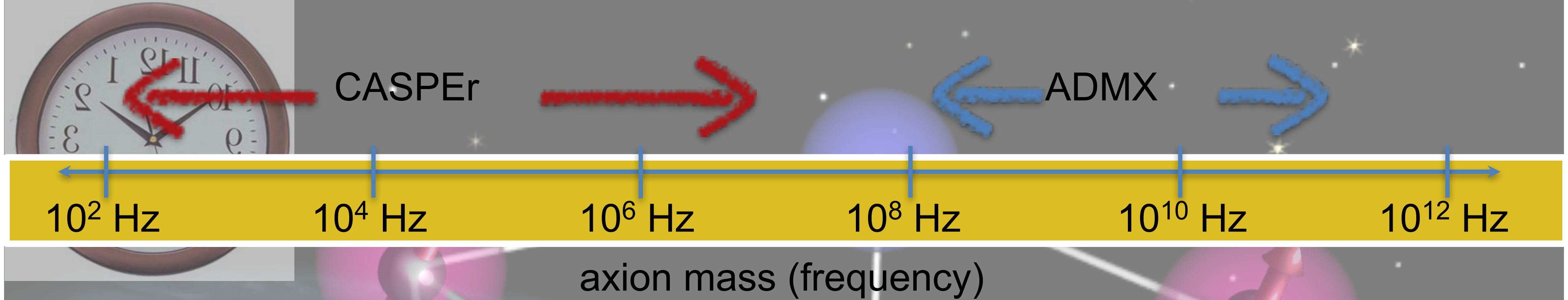
$$\frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

(CASPEr-E)

Fermions

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

(CASPEr-Wind, GNOME, QUAX)



Cosmic Axion Spin Precession Experiment (CASPEr)

Proposal:

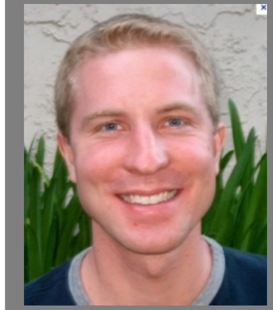
Peter Graham

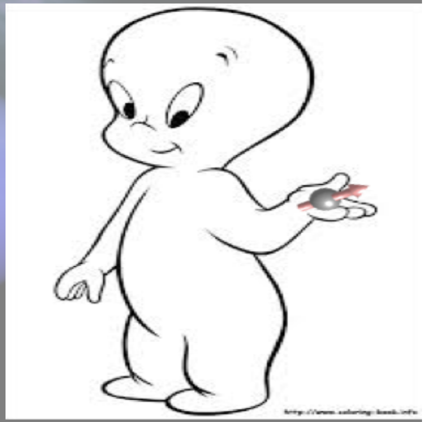
Surjeet Rajendran

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, …

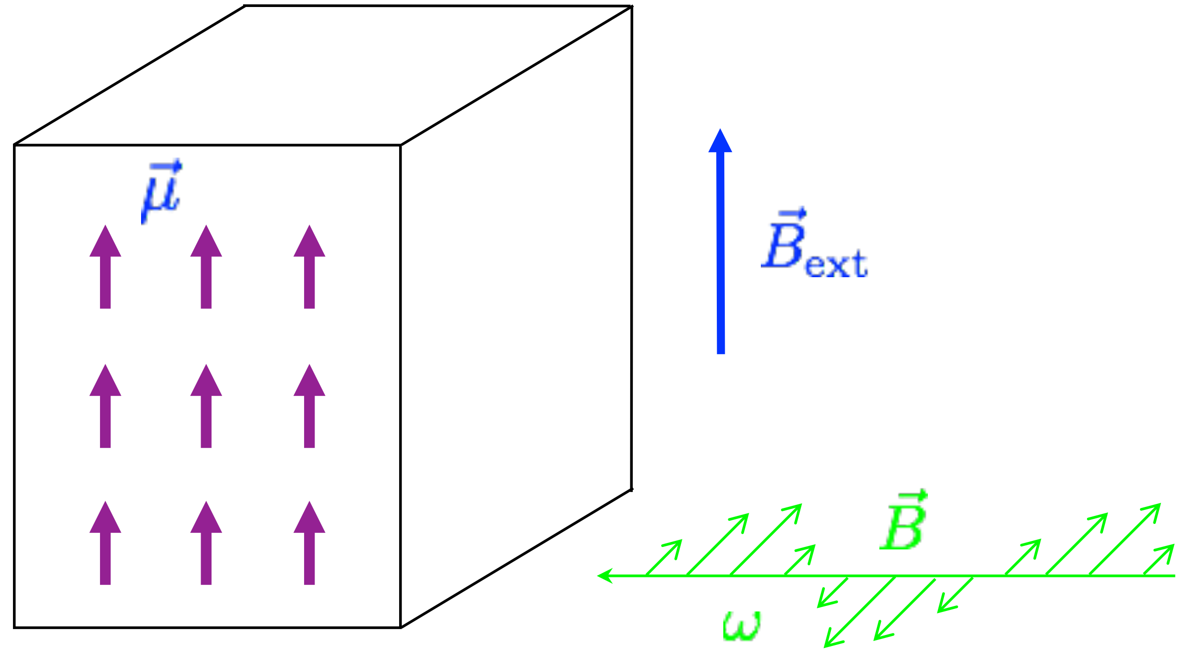
CASPEr-Electric

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

CASPEr-Wind

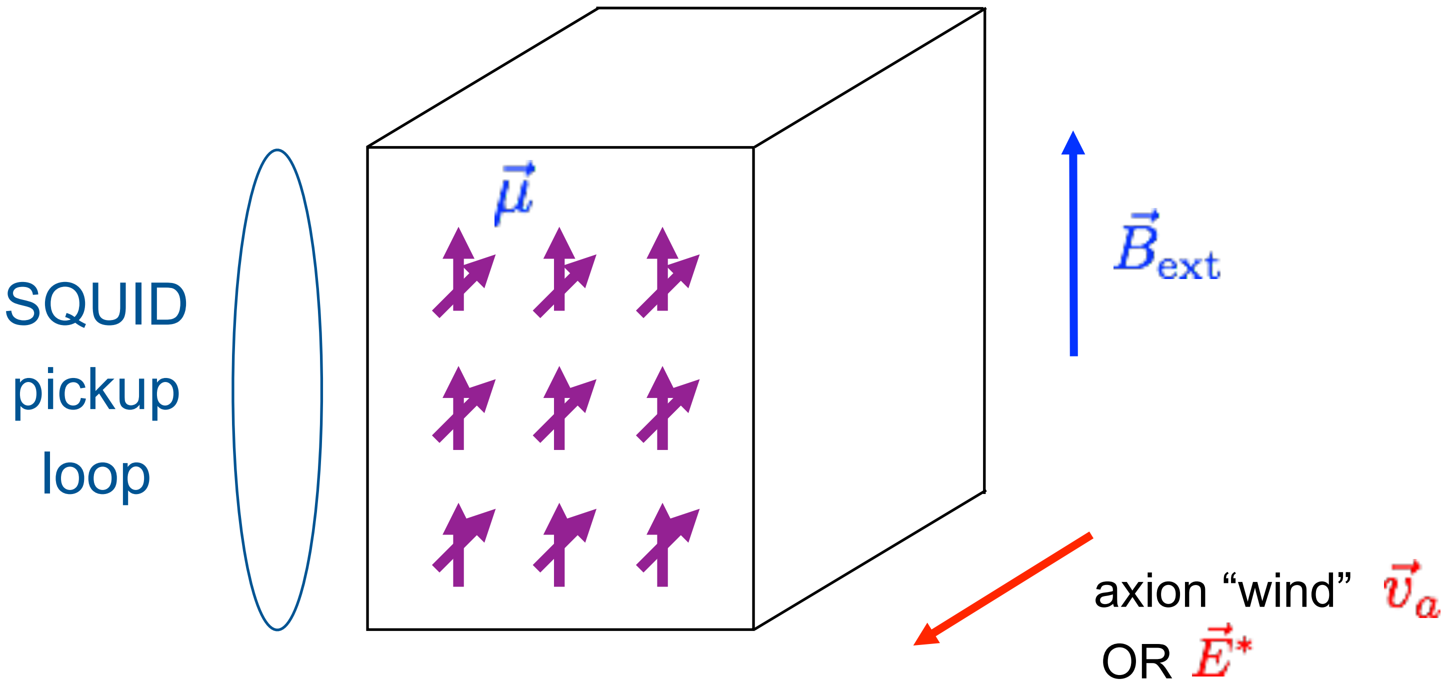
- Coherence time: $[m_a(v/c)^2]^{-1}$ → $Q \sim 10^6$

Nuclear Magnetic Resonance (NMR)



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

CASPEr

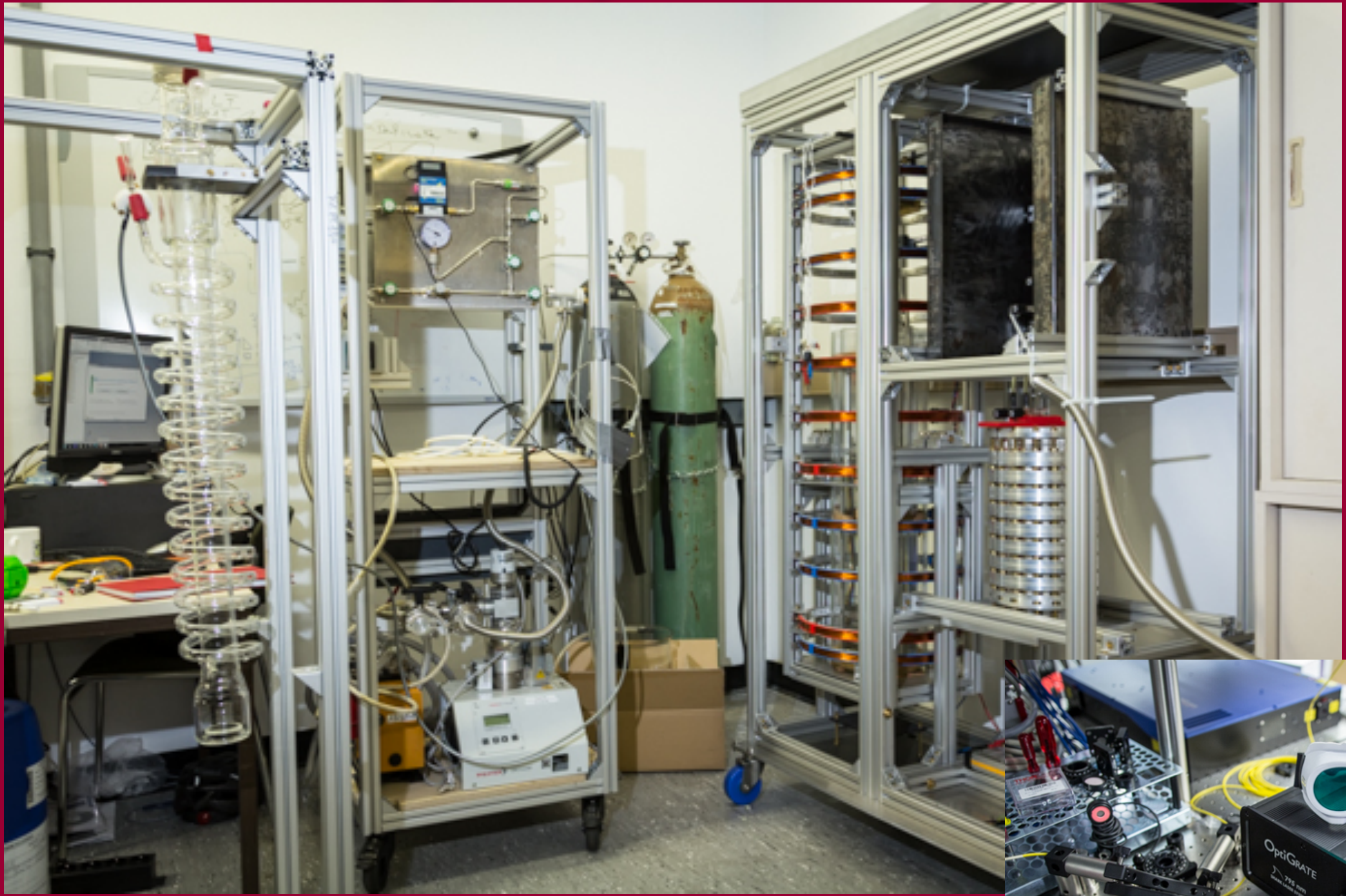


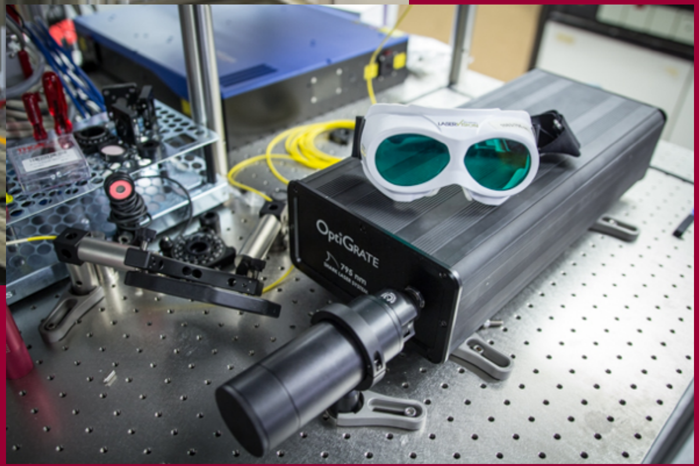
Larmor frequency = axion mass ➔ resonant enhancement

SQUID measures resulting transverse magnetization

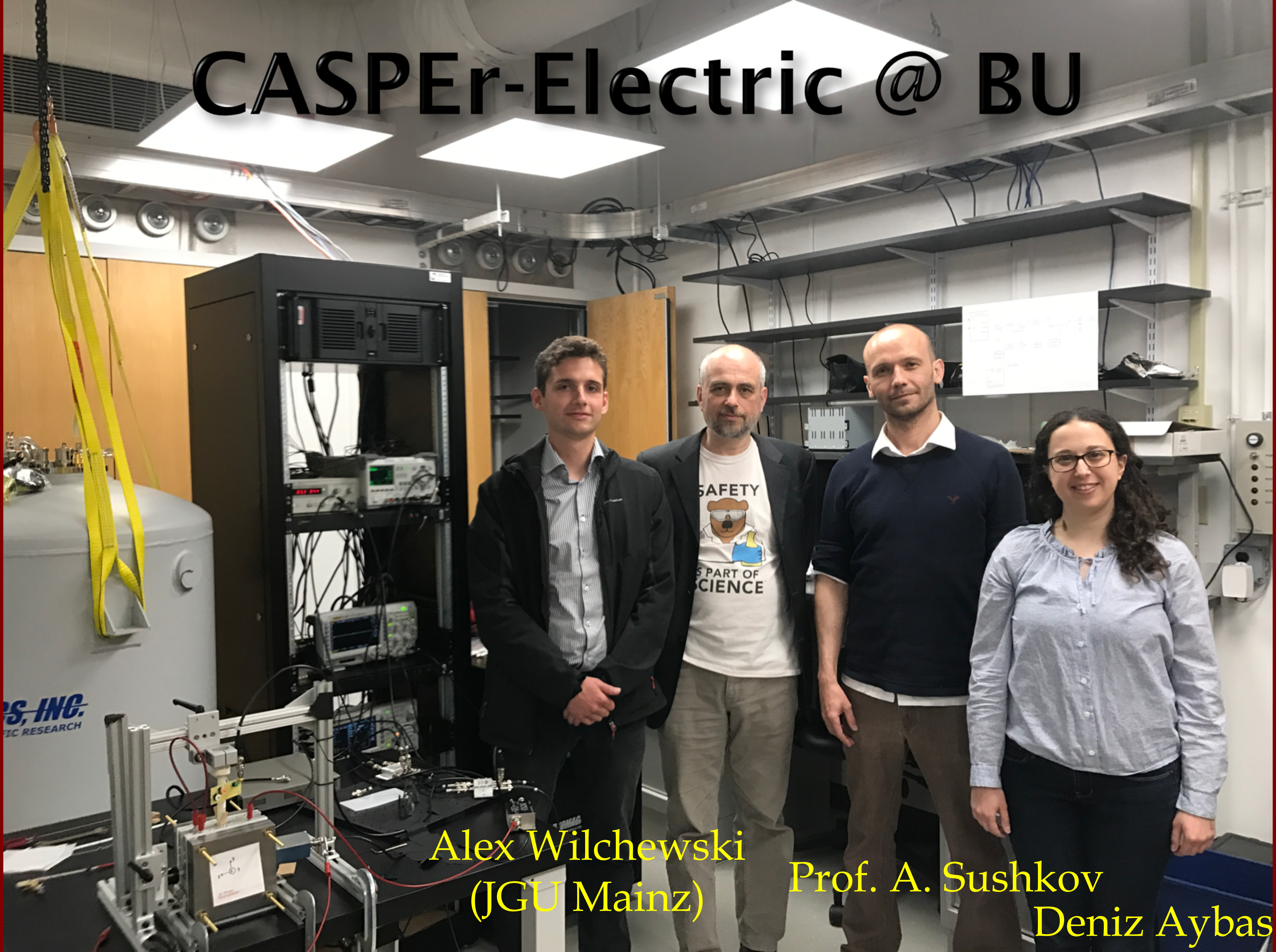
Example materials: liquid ^{129}Xe, ferroelectric $PbTiO_3$

Xe hyperpolarizer @ Mainz

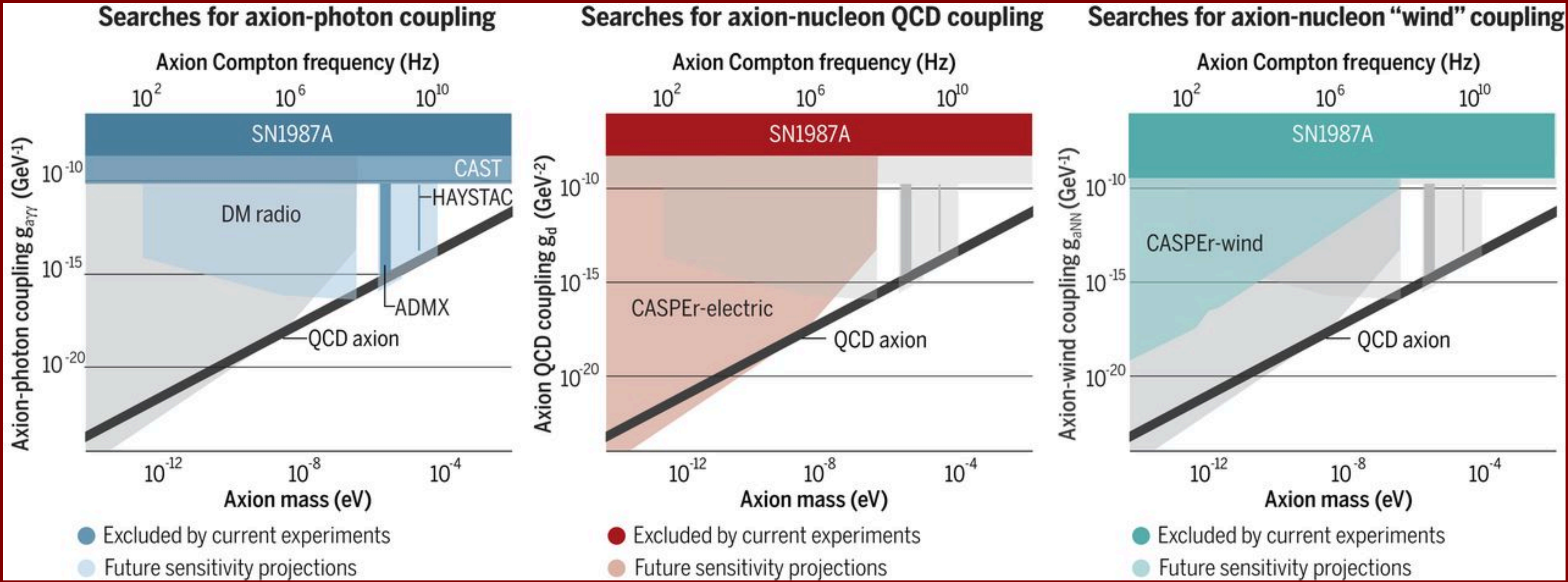




CASPEr-Electric @ BU



Experimental constraints and projected sensitivities of axion dark-matter searches



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

ZERO-FIELD nuclear magnetic resonance

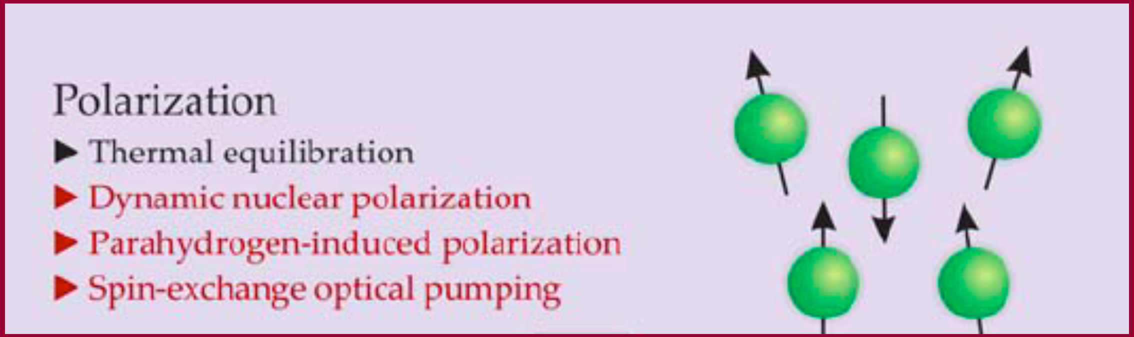
Micah P. Ledbetter and Dmitry Budker

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

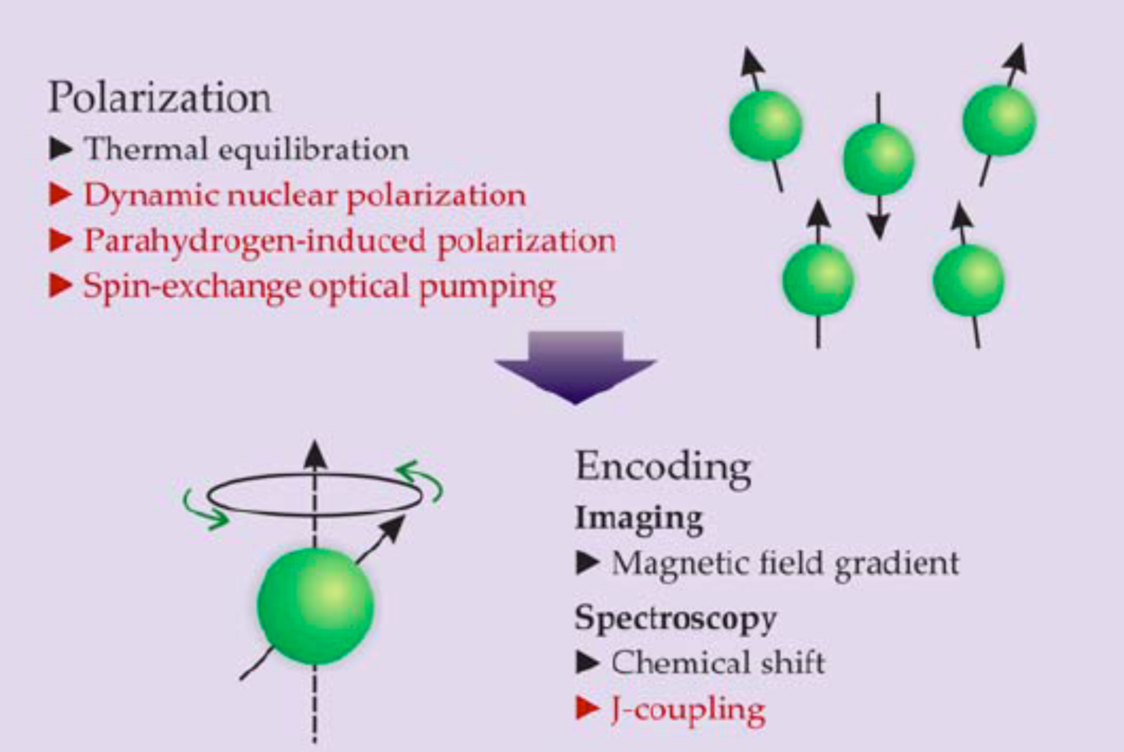
Three Stages of NMR



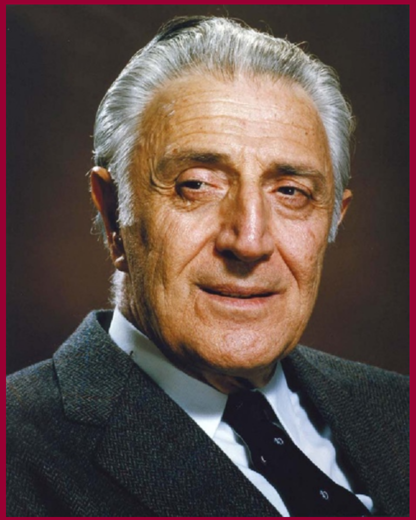
No need to polarize in <u>spin-noise spectroscopy</u>

→ small N

Three Stages of NMR

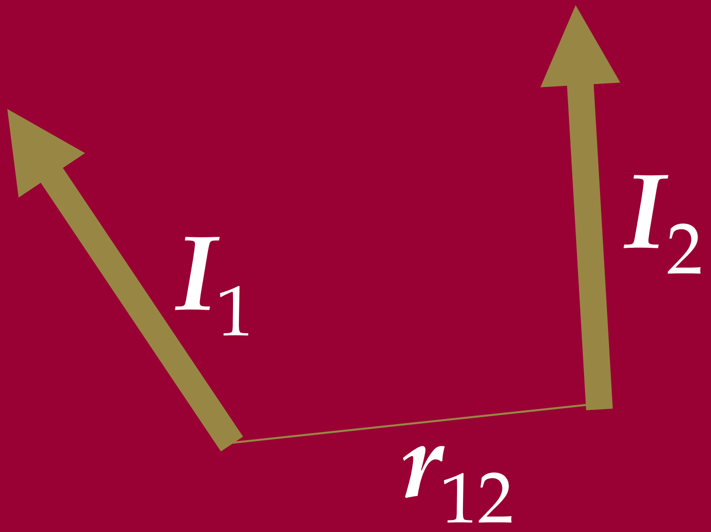


J-coupling



Erwin L. Hahn

C. P. Slichter



Dipole-dipole interaction

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

averages by tumbling

J-coupling

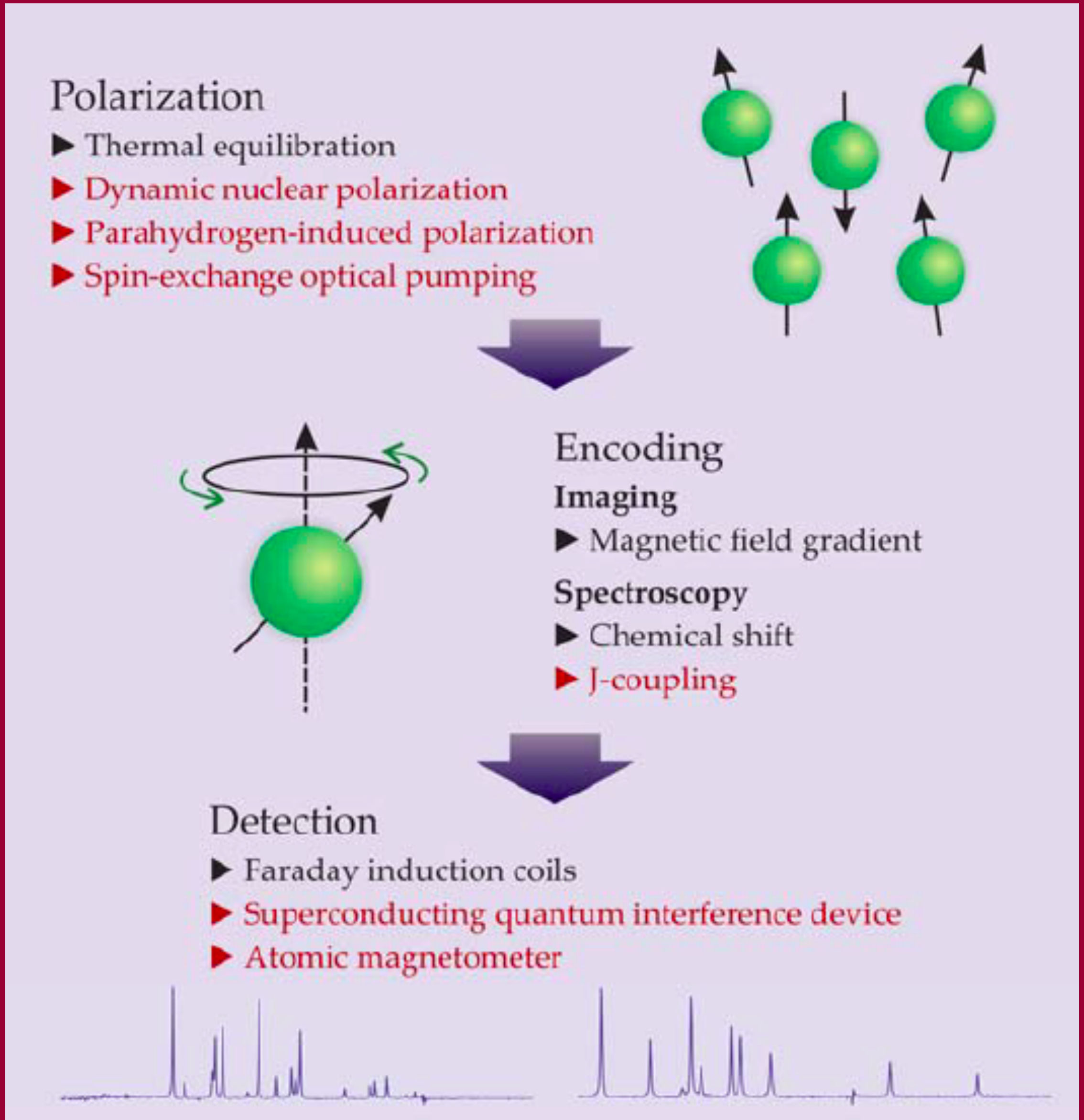
$$H = J\boldsymbol{I}_1 \cdot \boldsymbol{I}_2$$

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



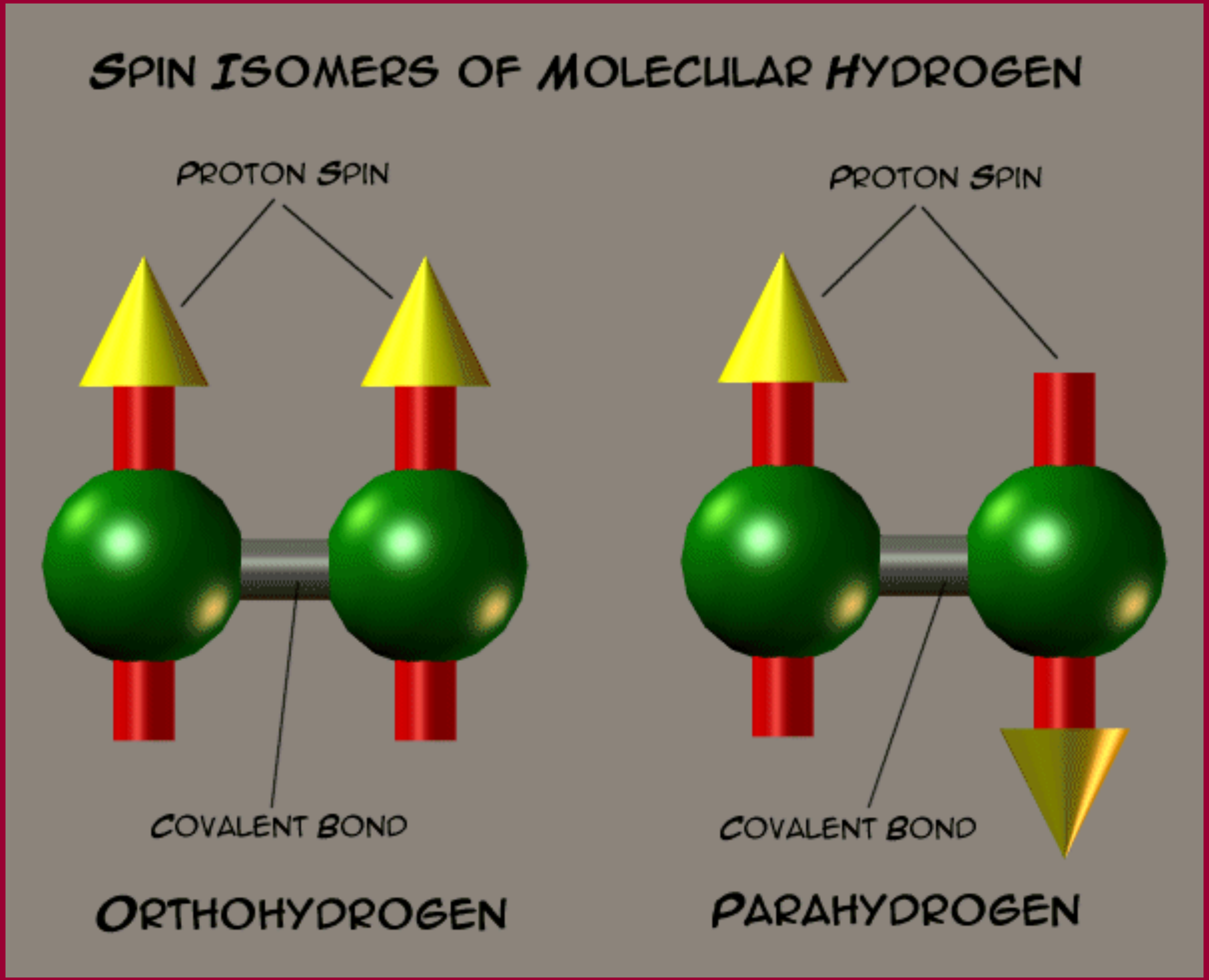
April 2013 Physics Today www.physicstoday.org

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

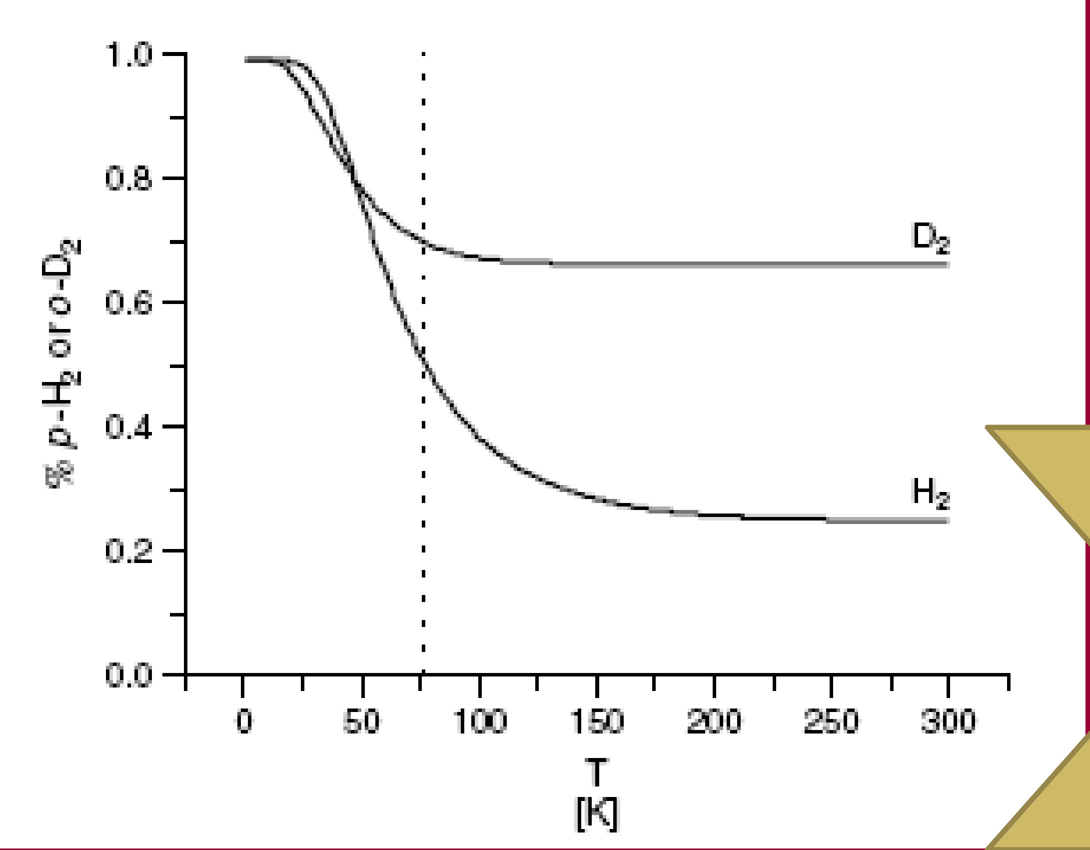


Odd J | Even J

http://en.wikipedia.org

Parahydrogen 102

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



51% para @ 77K

99.9% para @ 4K

Spin-Statistics in action!

Parahydrogen Induced Polarization

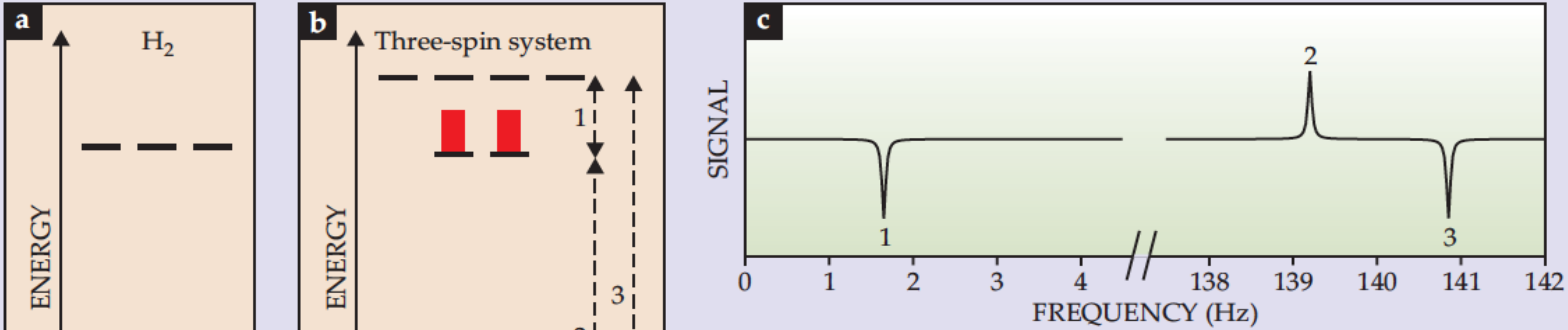
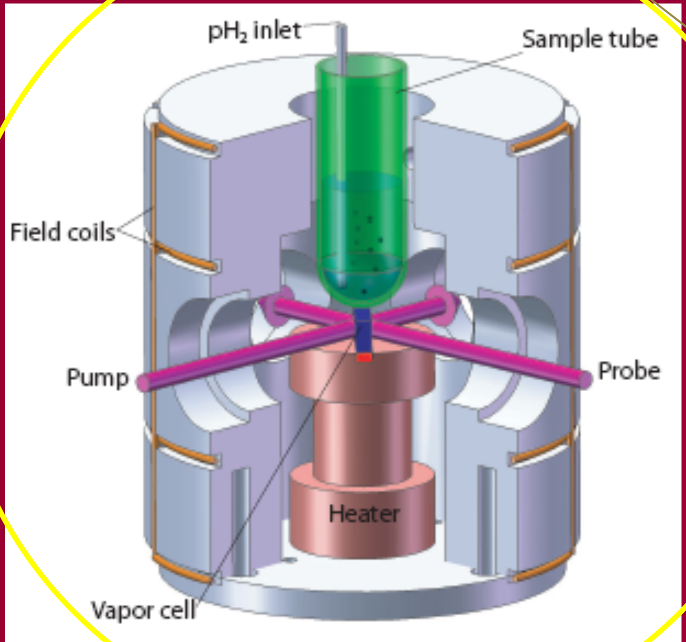
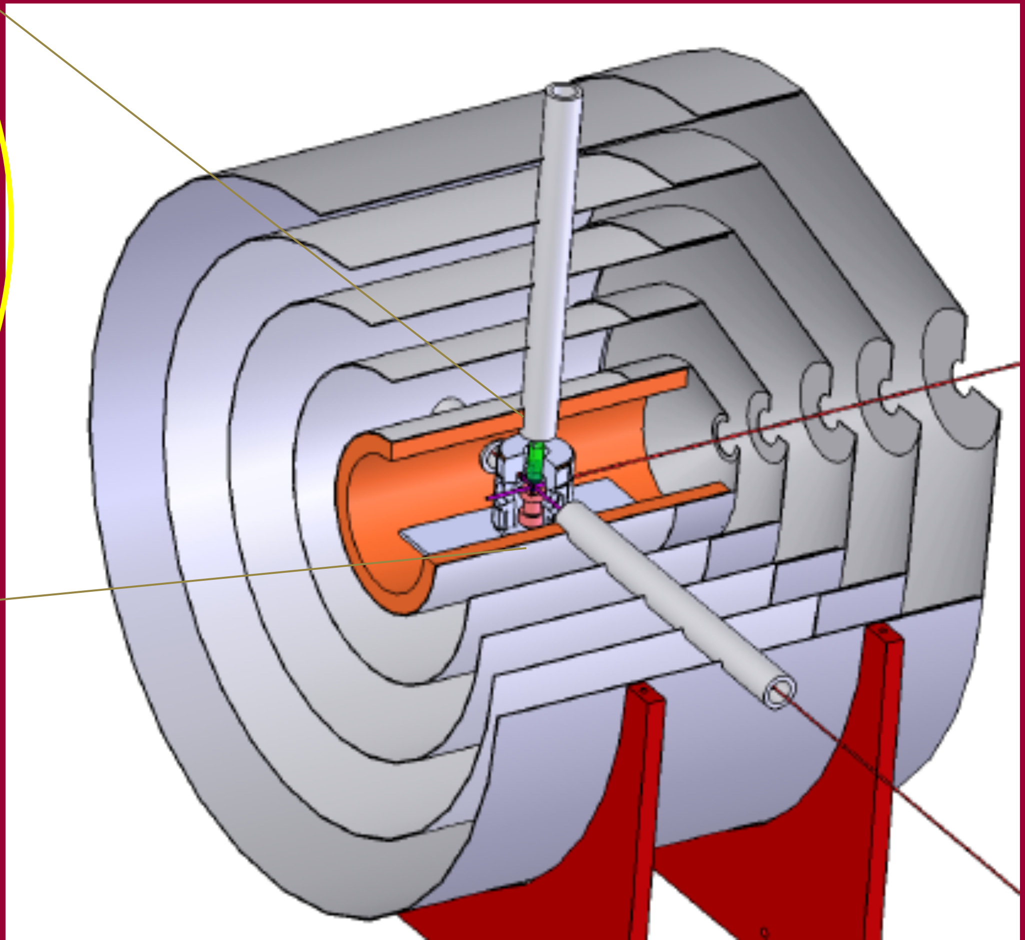


Figure 5. Parahydrogen-induced polarization can be used to obtain nuclear magnetic resonance signals in the absence of a magnetic field, as depicted here for a hypothetical three-spin system consisting of a carbon-13 nucleus and the nuclei of a parahydrogen molecule. **(a)** In isolation, the antiparallel 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

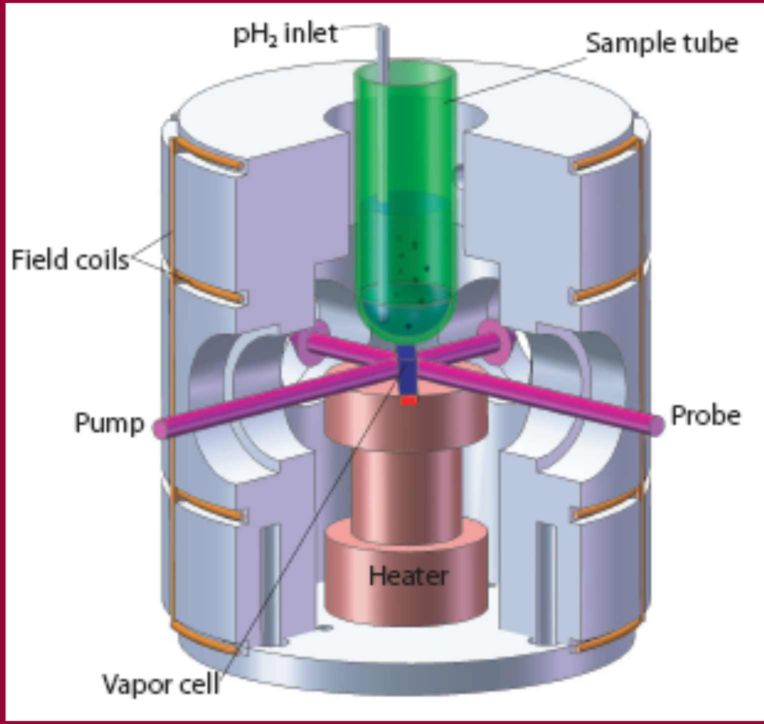


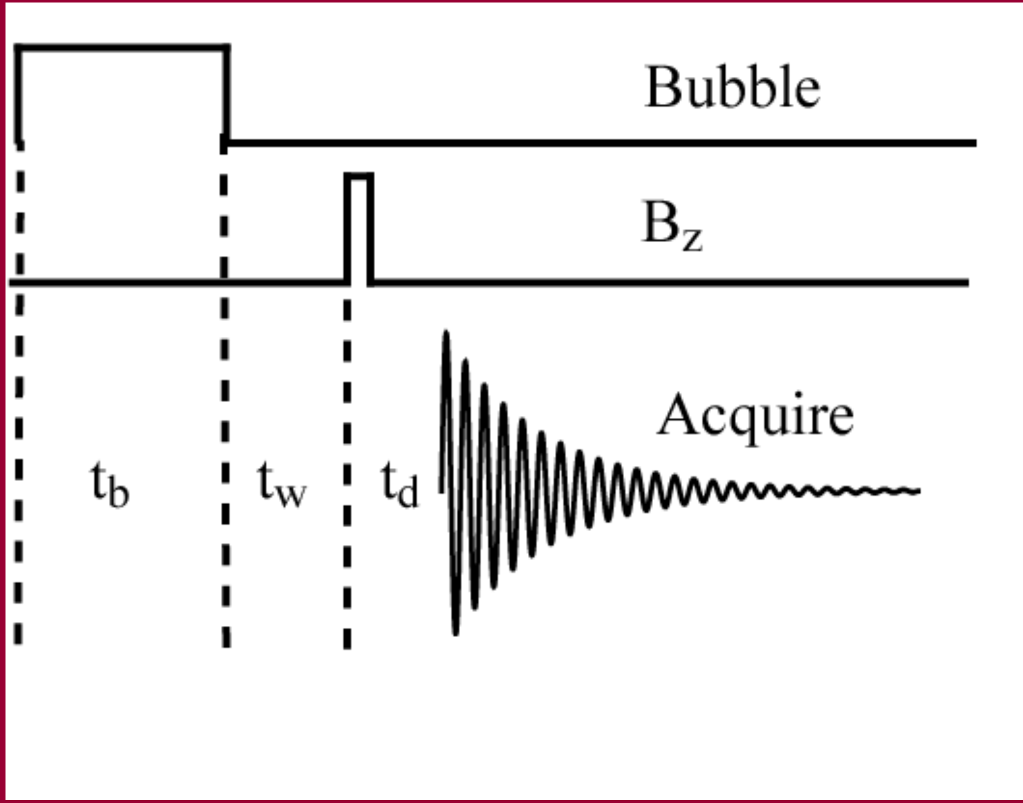
Magnetic
shields



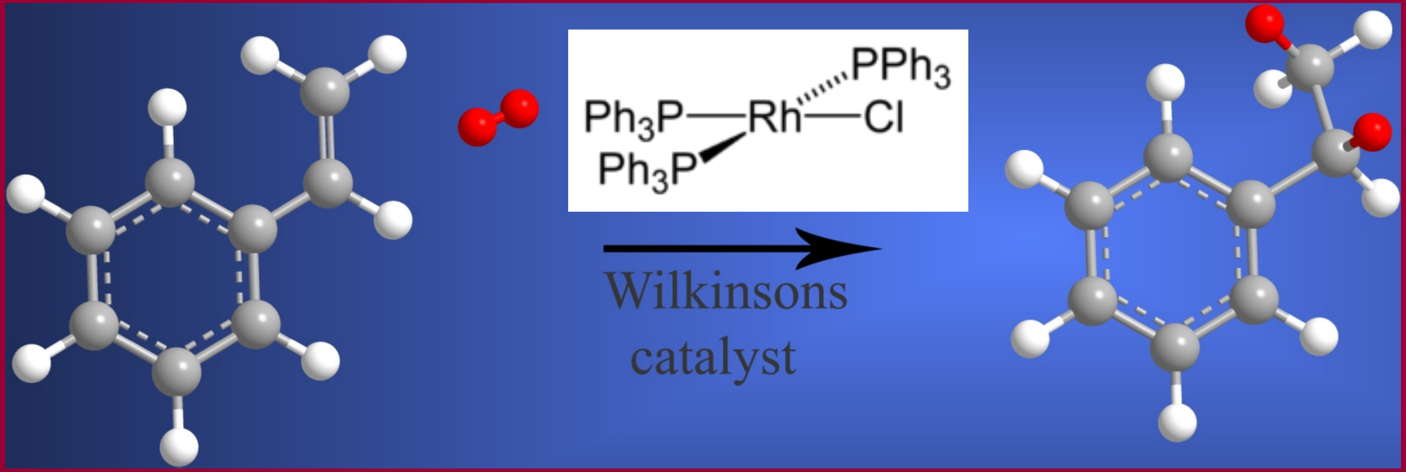
T. Theis
P. Ganssle
G. Kervern
M. P. Ledbetter
D. B.
A. Pines

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





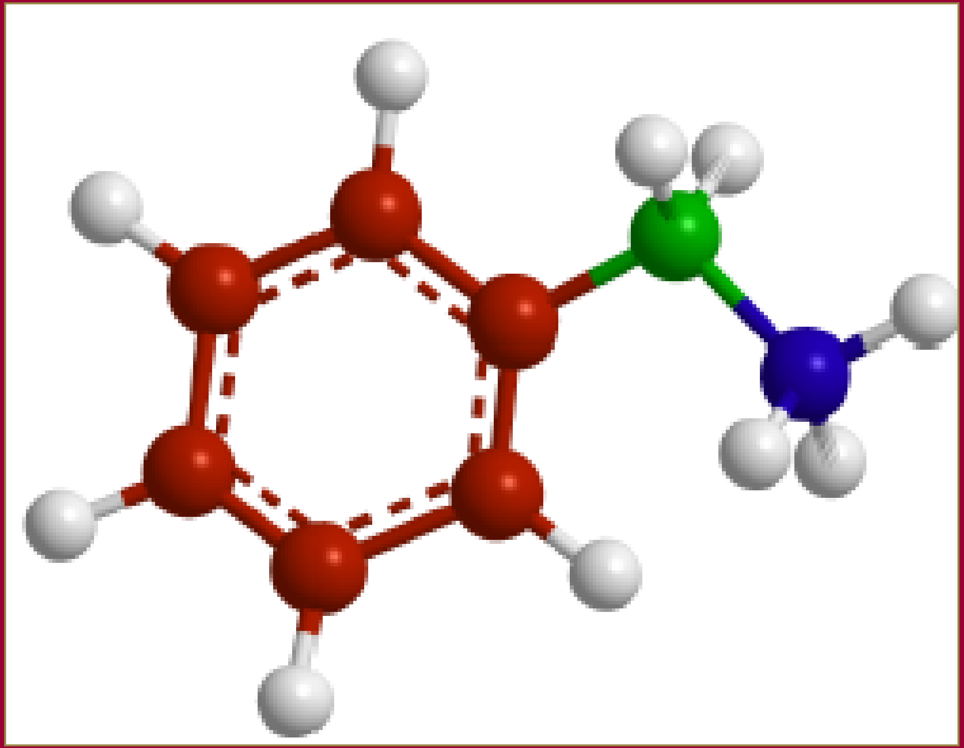
Hydrogenation with pH_2

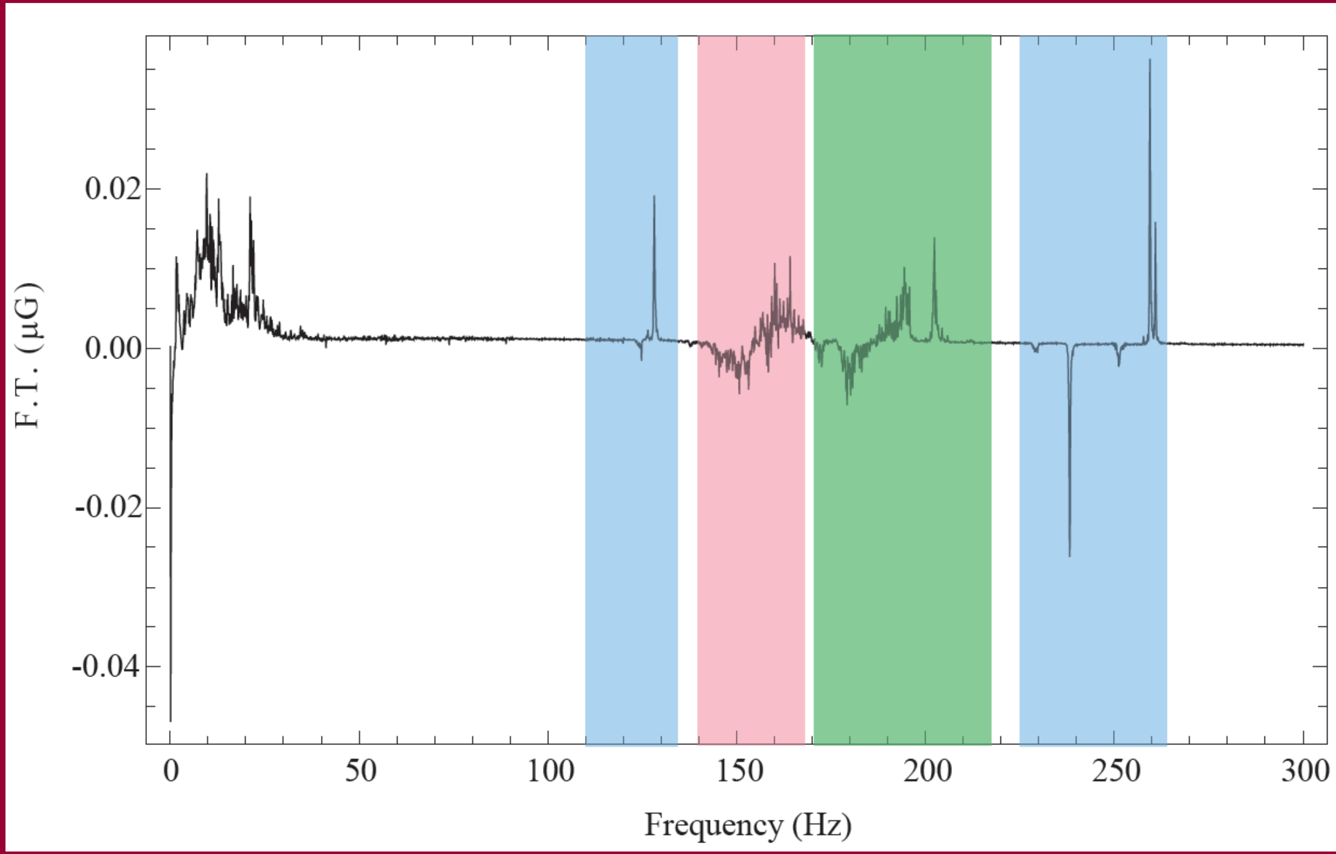


Styrene **Ethylbenzene**

Hydrogenation with pH_2

Natural Abundance
1.1% of ^{13}C





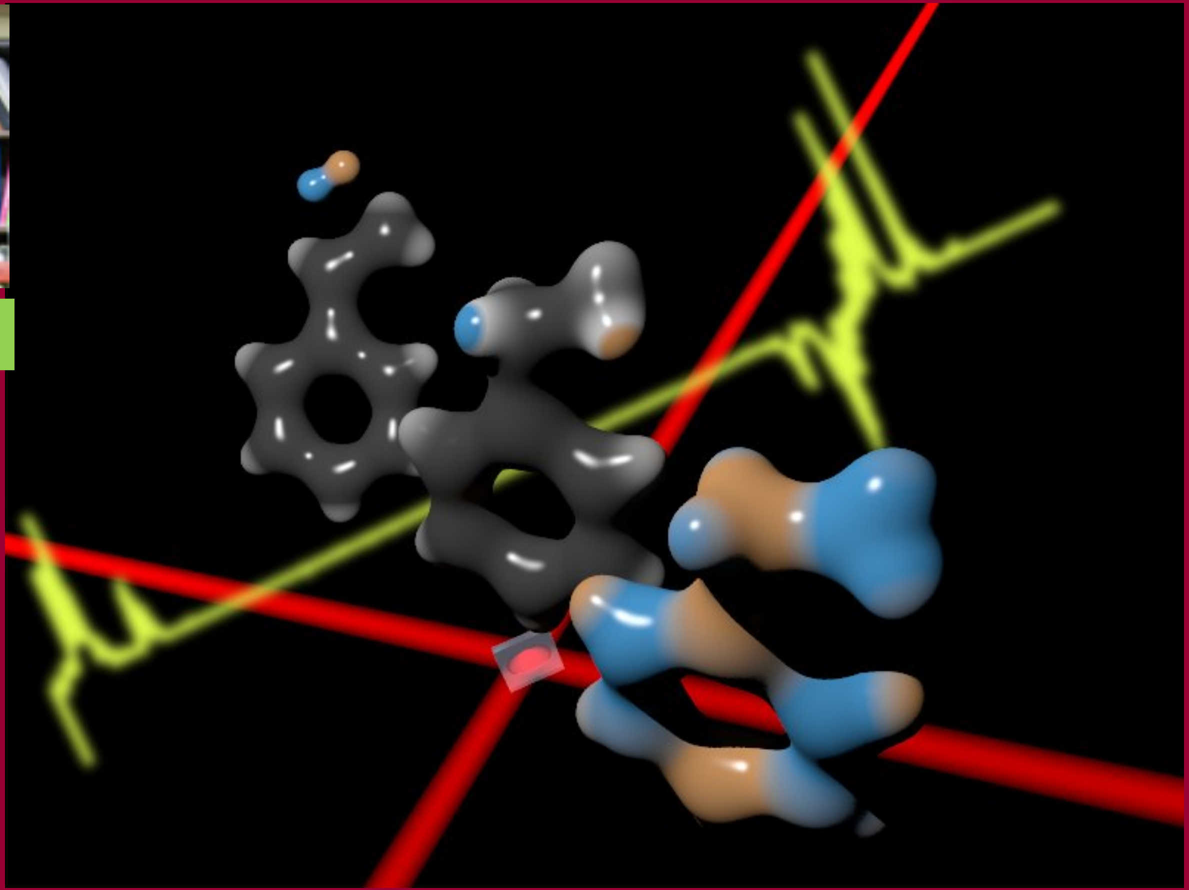
nature physics
ARTICLES
PUBLISHED ONLINE: 1 MAY 2011 | DOI: 10.1038/NPHYS1986

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]★

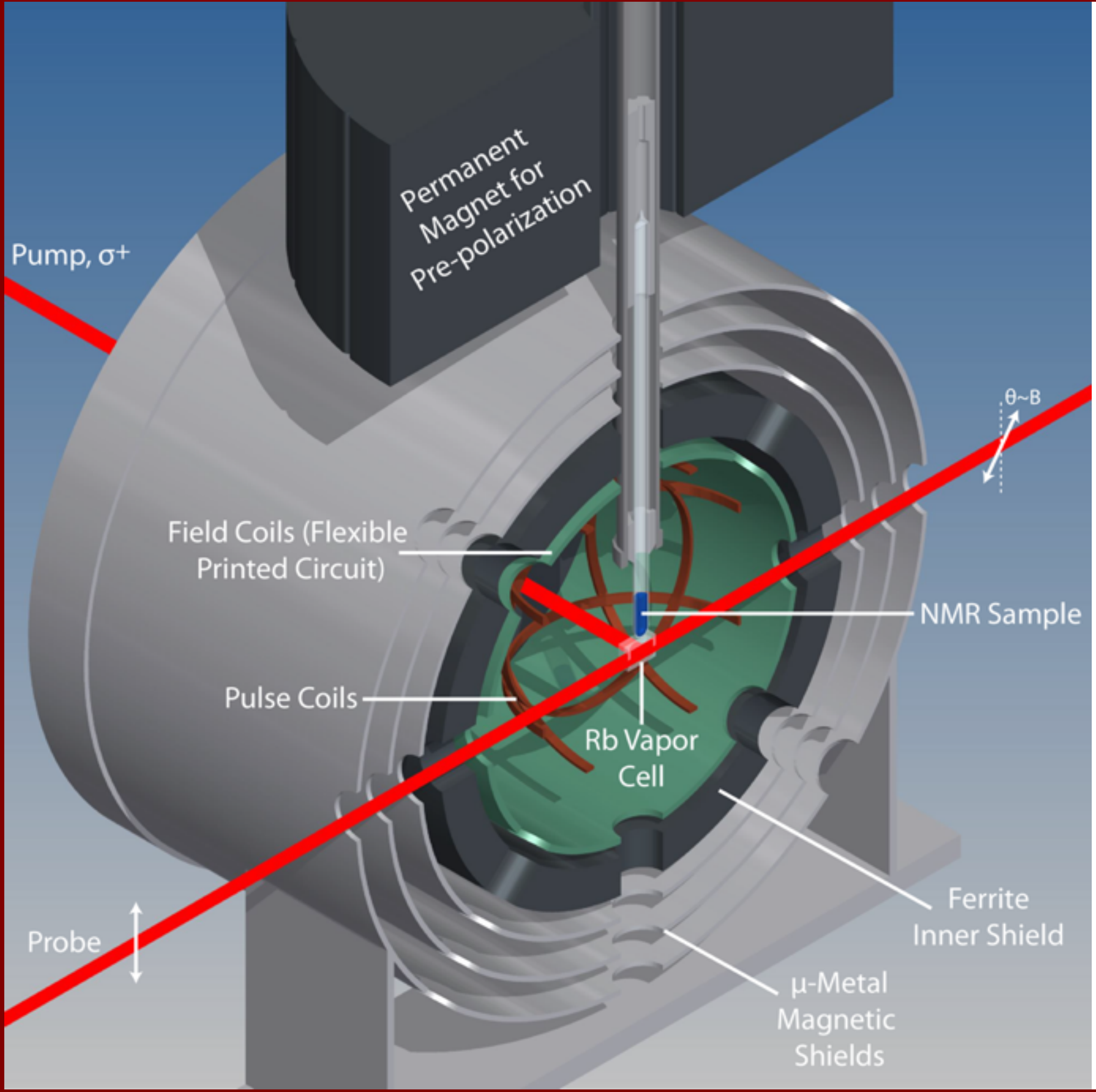
Thomas Theis

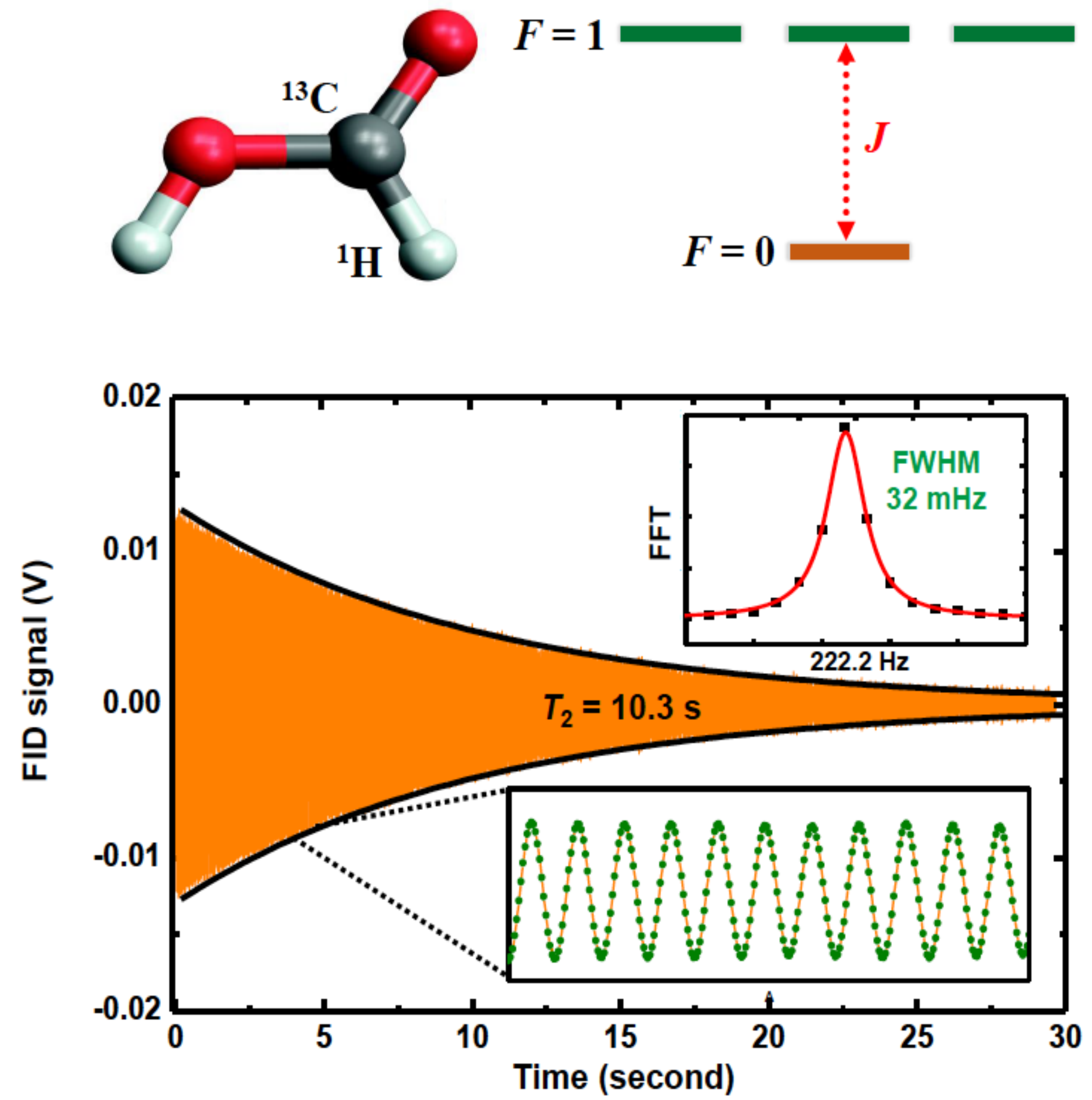
Alex Pines



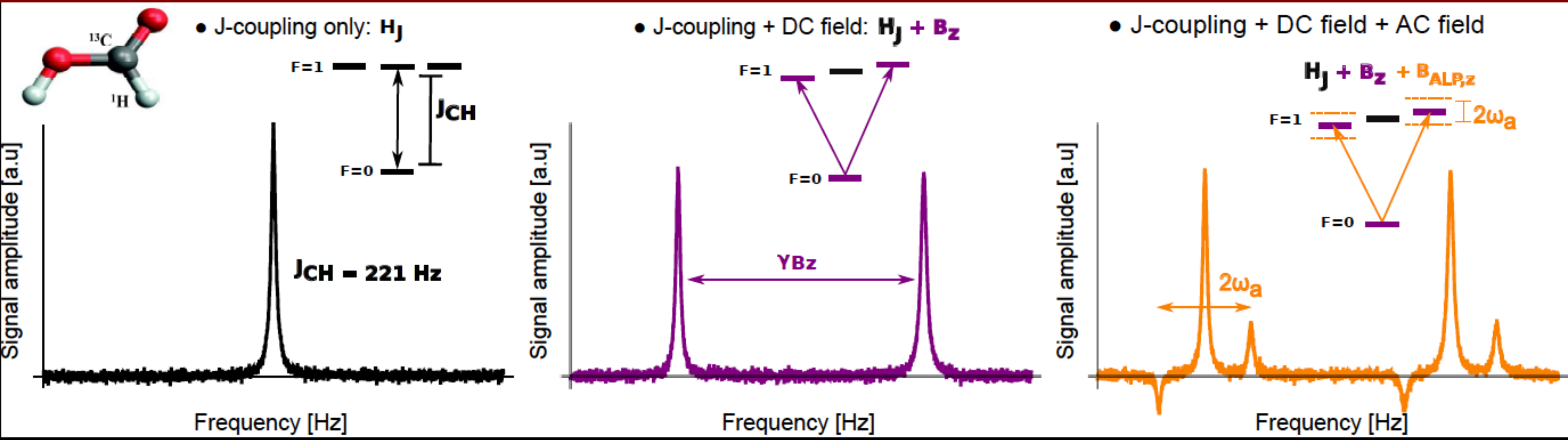
NMR without any magnets!

CASPEr-NOW with ZULF NMR



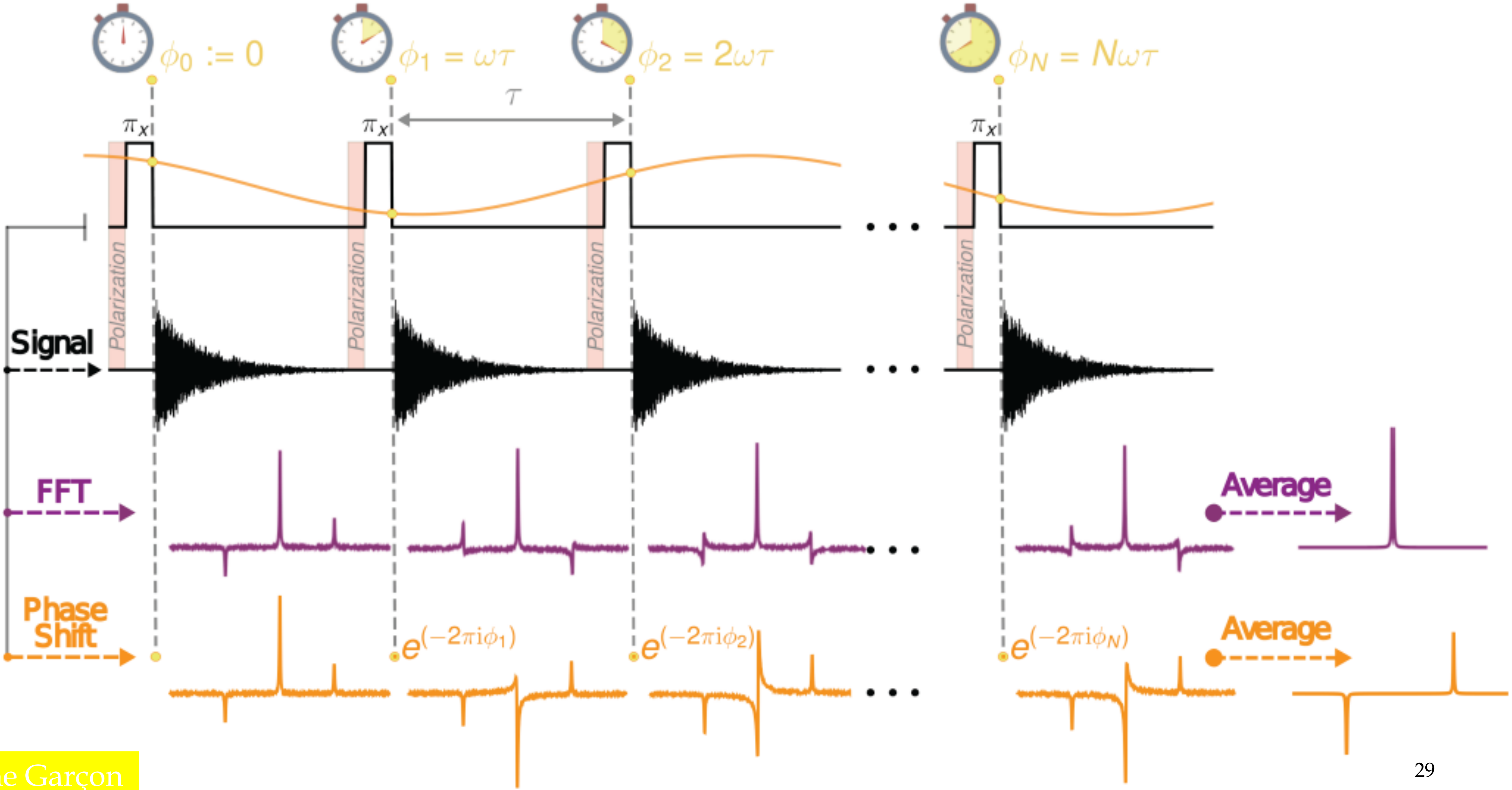


Sidebands…

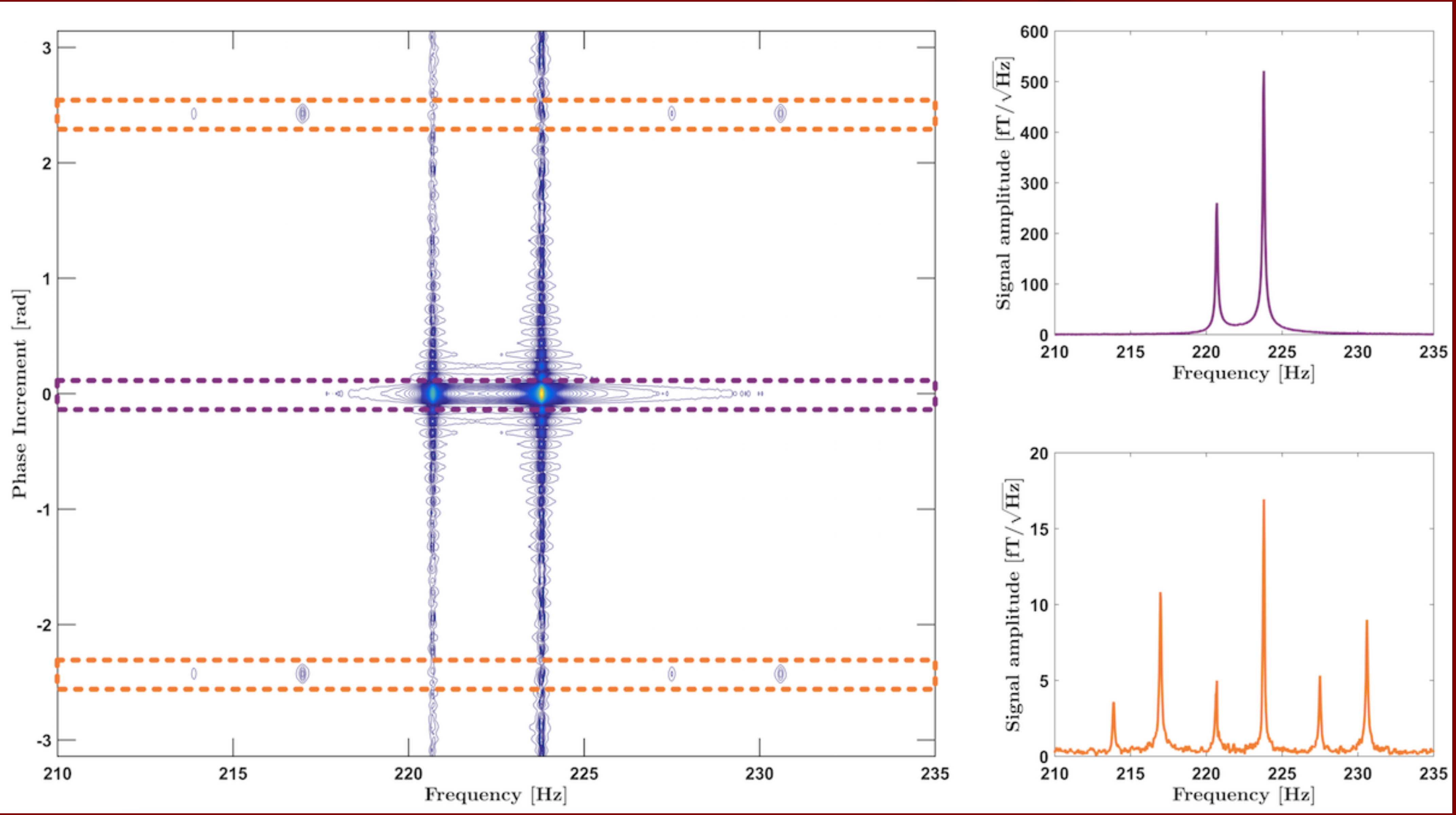


• J-coupling only: H_J
¹³C
¹H
F=1
F=0
J_CH
J_CH = 221 Hz
Signal amplitude [a.u]
Frequency [Hz]
• J-coupling + DC field: H_J + B_z
F=1
F=0
γB_z
Signal amplitude [a.u]
Frequency [Hz]
• J-coupling + DC field + AC field
H_J + B_z + B_ALP,z
F=1
2ω_a
F=0
2ω_a
Signal amplitude [a.u]
Frequency [Hz]

Coherent Averaging

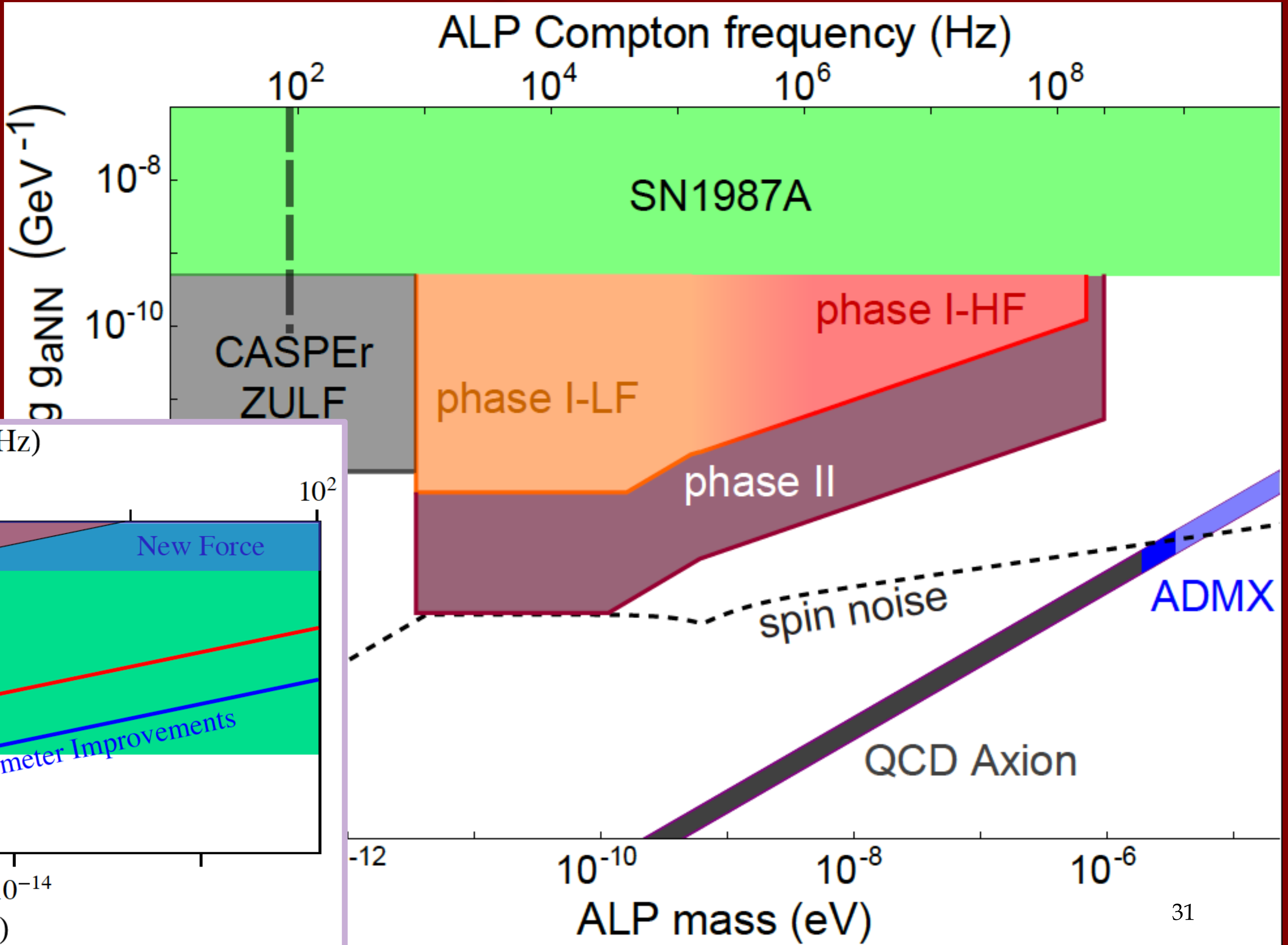


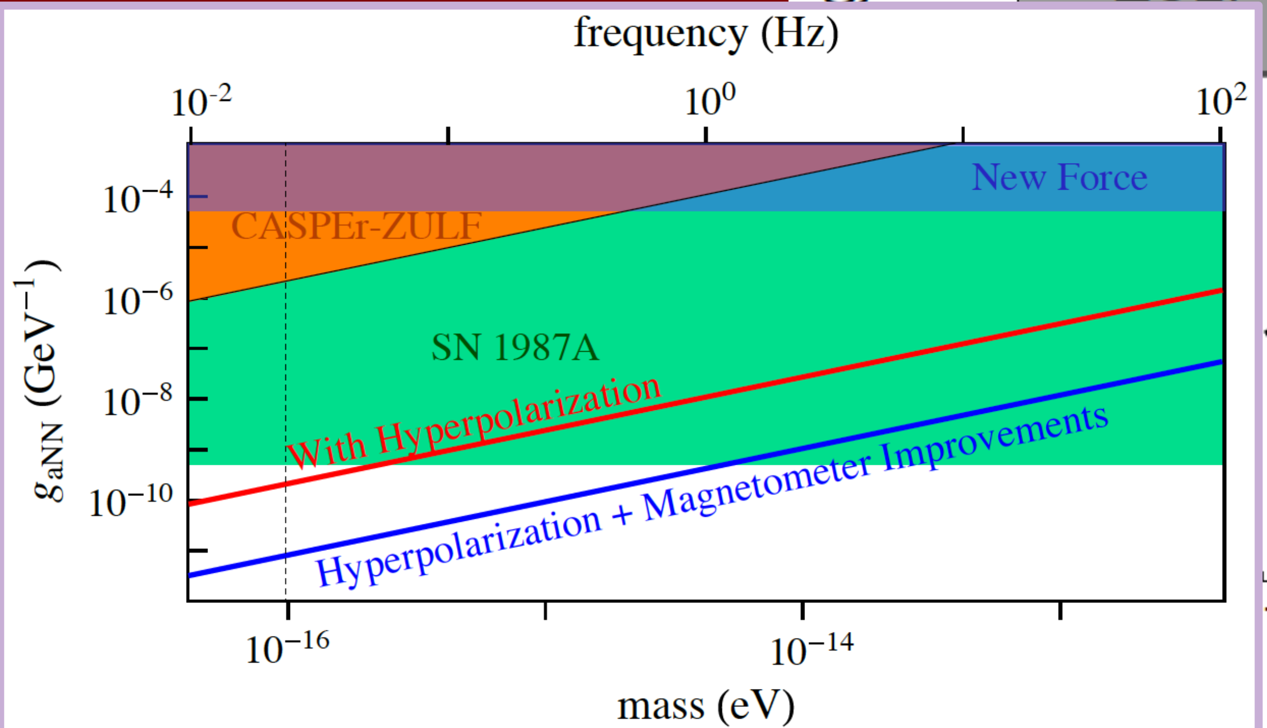
Coherent Averaging



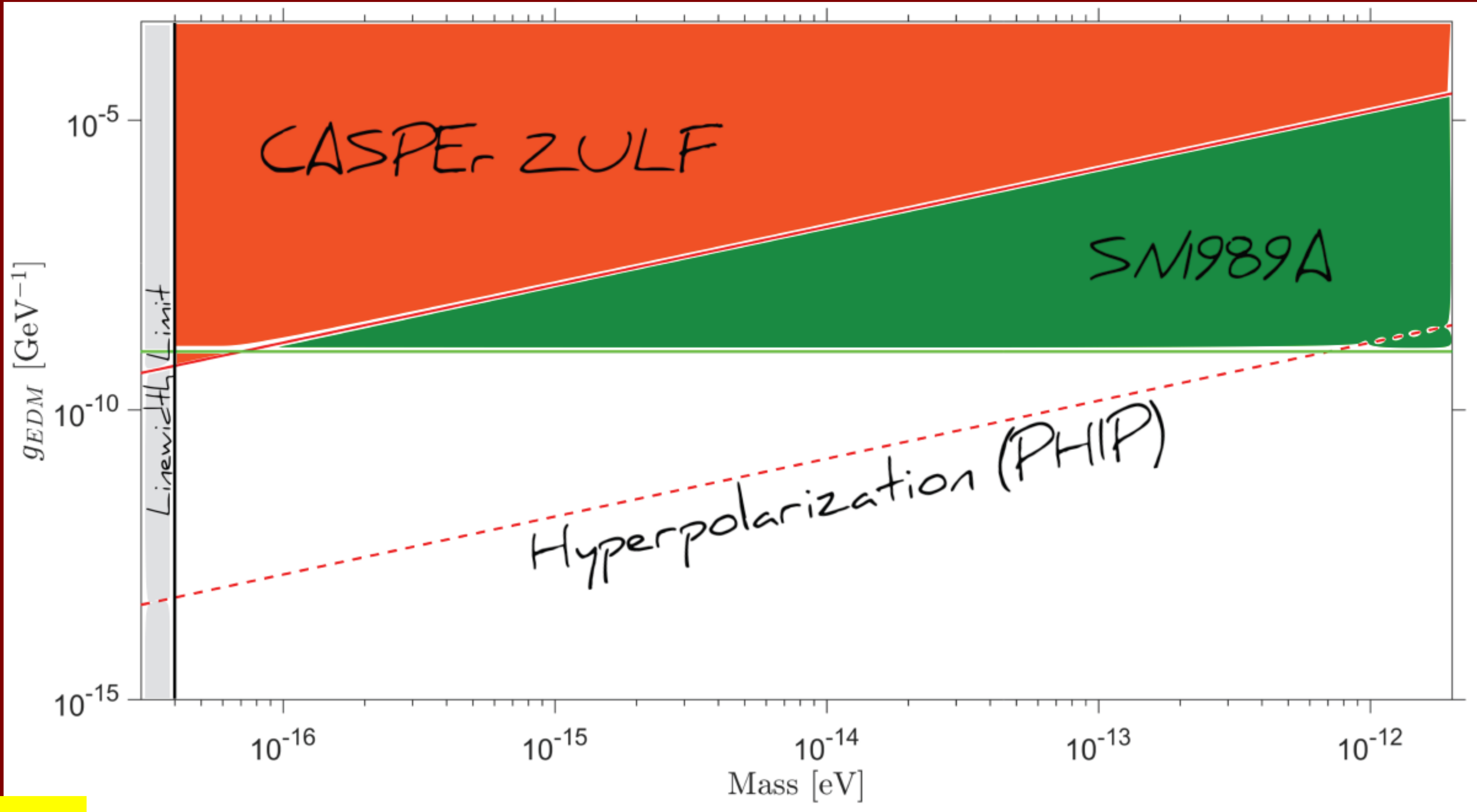
Antoine Garçon

CASPEr-Wind/NOW





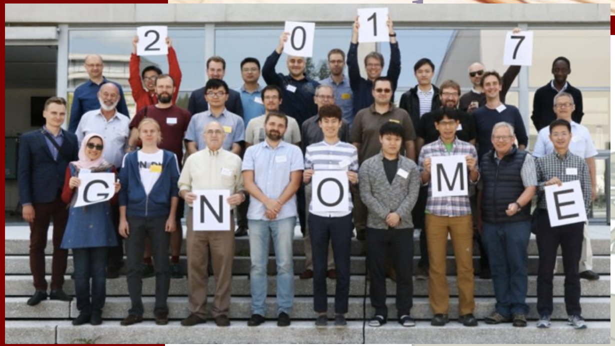
CASPEr-Wind/NOW: Dark Photon

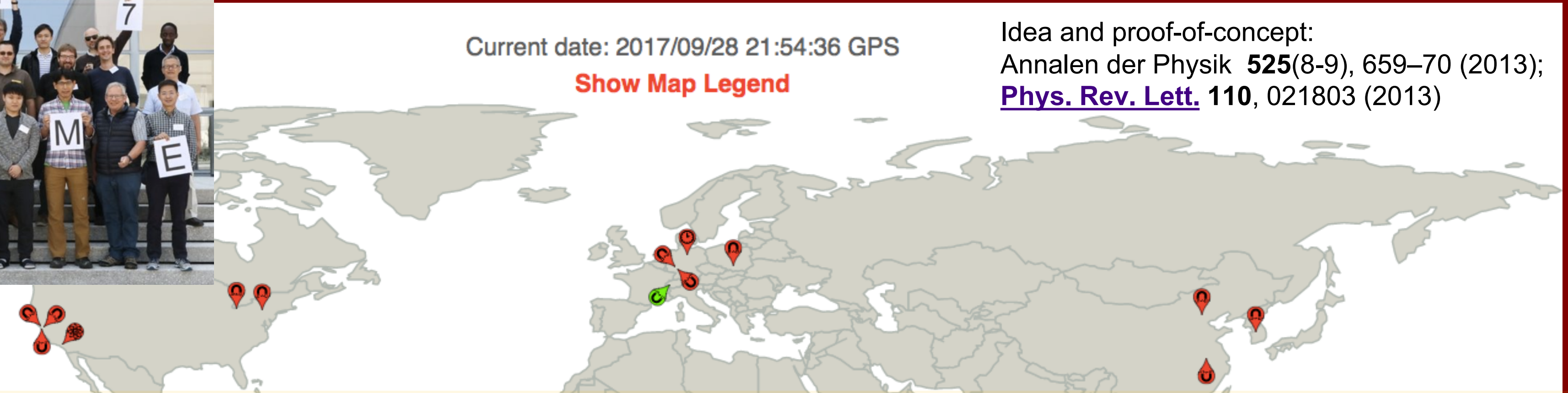


The GNOME Experiment

Collaboration website

Global **N**etwork of **O**ptical **M**agnetometers for **E**xotic





Idea and proof-of-concept:
Annalen der Physik **525**(8-9), 659–70 (2013);
Phys. Rev. Lett. **110**, 021803 (2013)

- Network of shielded, GPS-synchronized magnetometers + clocks, interferometers,...
- Sensitive to **topological Dark Matter**: domain walls, axion (ALP) stars, arXiv:1710.04323
- Multi-messenger astronomy (e.g., look for ALPs from sources of gravitational waves)
- Sensor-correlation techniques resembling those of LIGO/Virgo
- Status: Science Run 1 complete, results to be announced; Run 2: Nov/Dec 2017

Summary:

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

- ✧ Zero- and Ultralow-Field NMR
  - ☛ ParaHydrogen Induced Polarization
  - ☛ J-coupling spectroscopy @ ZULF

- ✧ CASPEr-ZULF
  - ☛ First physics results!

Thanks!

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HEISING - SIMONS FOUNDATION

HIM
Helmholtz-Institut Mainz

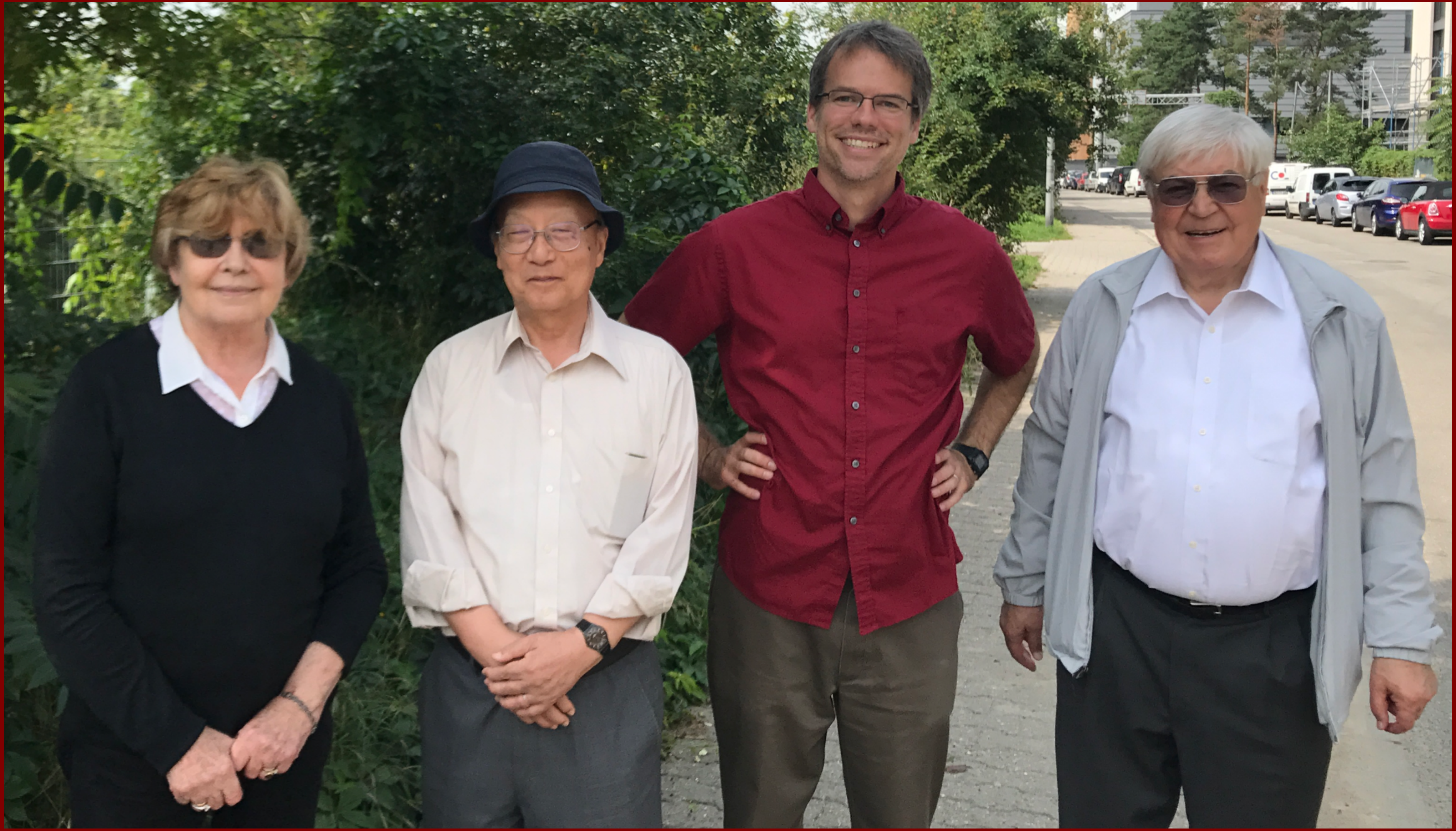
SIMONS FOUNDATION

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



The full picture…

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 eV $= 1.783 \times 10^{-33}$ g $= 1.957 \times 10^{-6}\ m_e$; $\lambda\!\!\!^{-}_C = (1.973 \times 10^{-7}\ \text{m}) \times (1\ \text{eV}/m_\gamma)$.

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

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

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

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

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