The Cosmic Axion Spin Precession Experiment (CASPEr)

Progress and Results

Arne Wickenbrock, J.W. Blanchard

Axion workshop, Stockholm, 28.11.2018

HIM
Helmholtz-Institut Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

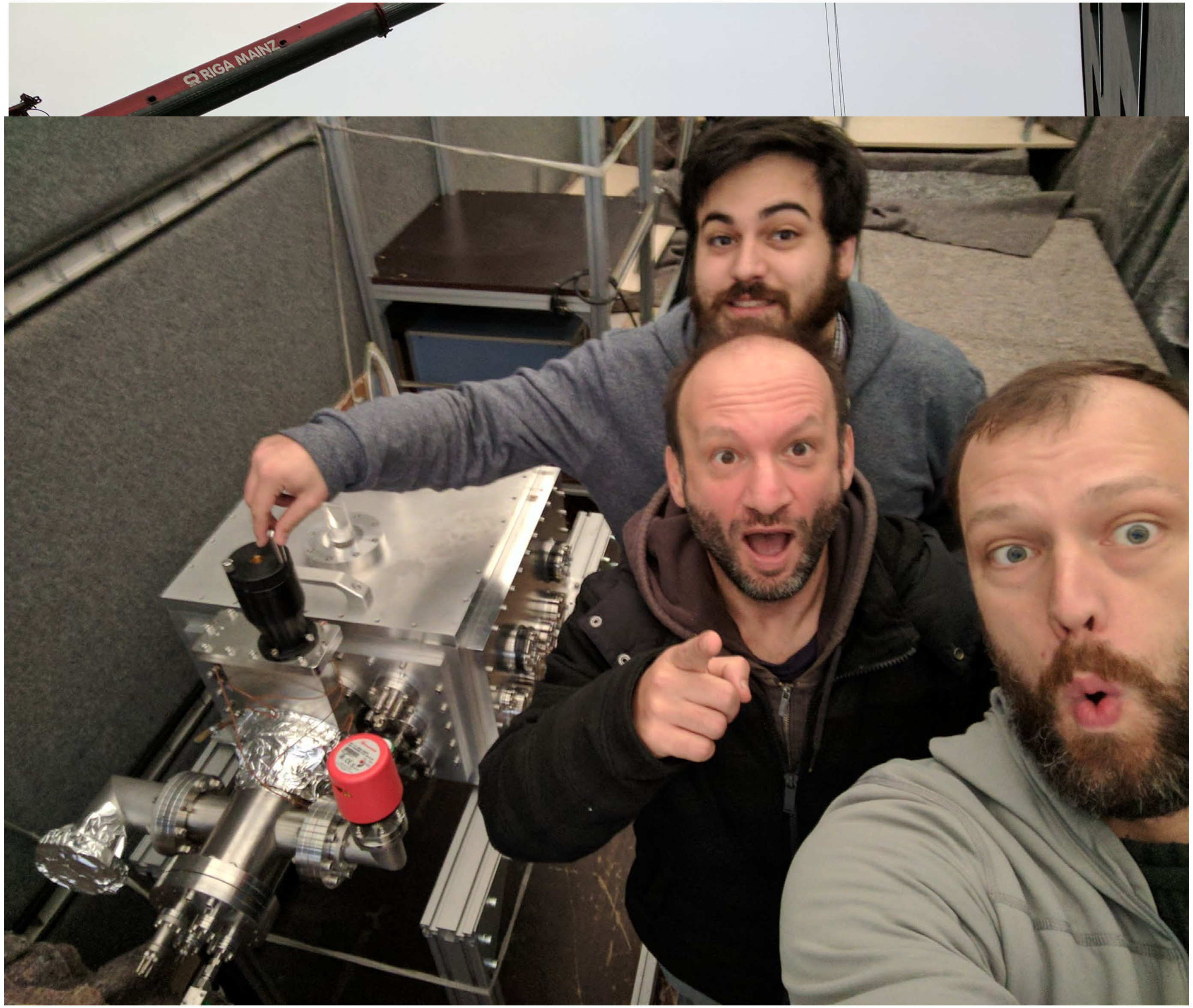
Helmholtz Institute Mainz

Cooperation between the JGU and GSI

6 Sections:
EMP Hadron structure
SPECF Hadron spectroscopy
MAM Matter Antimatter Asymmetry
SHE Super heavy elements
ACID Accelerator design
THFL Theory

MAM
atomic physics branch
=> QUANTUM

15.12.2016




Bitte zerkleinern!

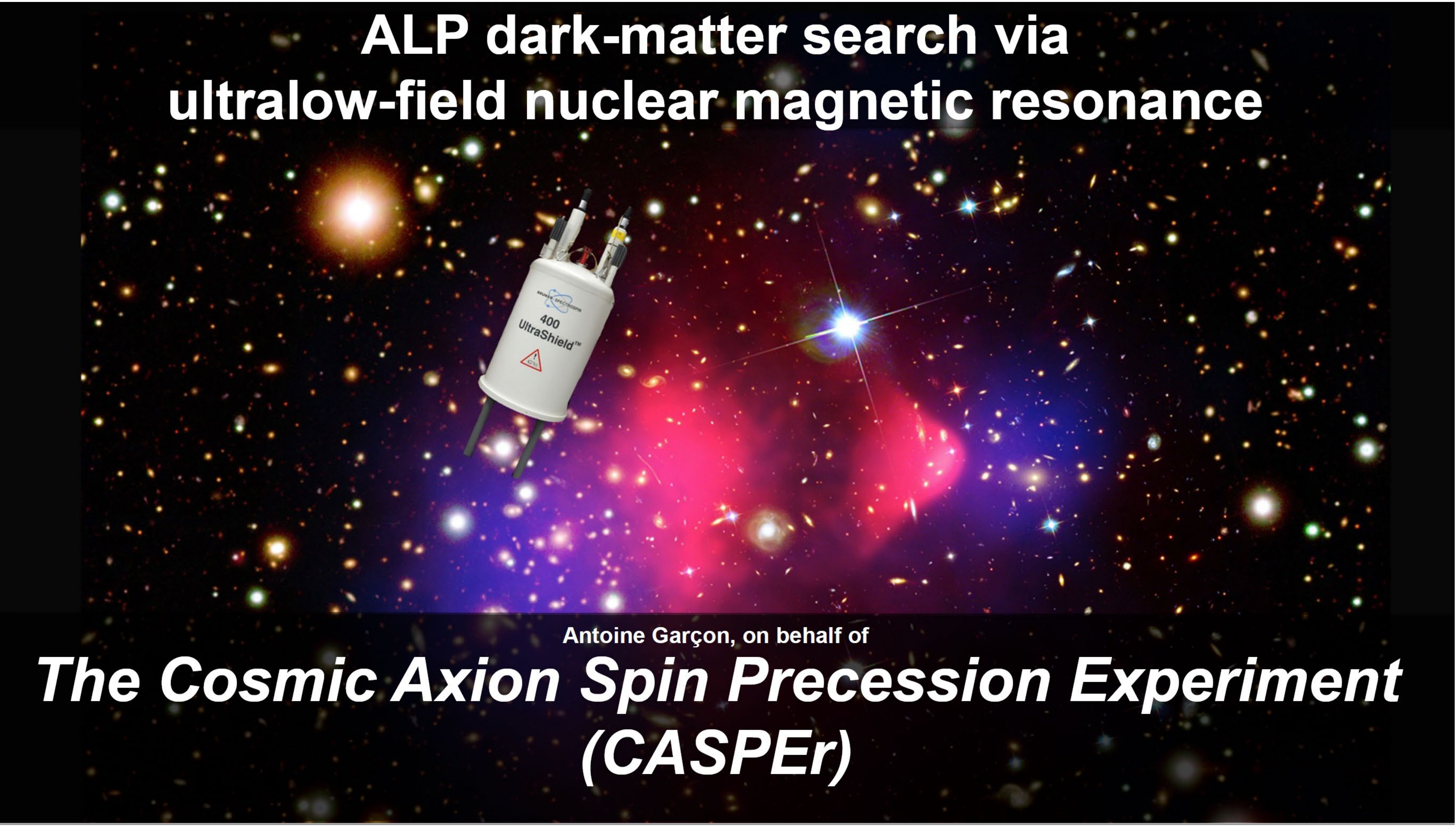
MAM Section September 2014

HIM Foyer 03.2015

MAM Section 2015

MAM Section January 2017

ALP dark-matter search via ultralow-field nuclear magnetic resonance



Antoine Garçon, on behalf of

The Cosmic Axion Spin Precession Experiment (CASPEr)

28.11.2018, Axion Workshop, Stockholm

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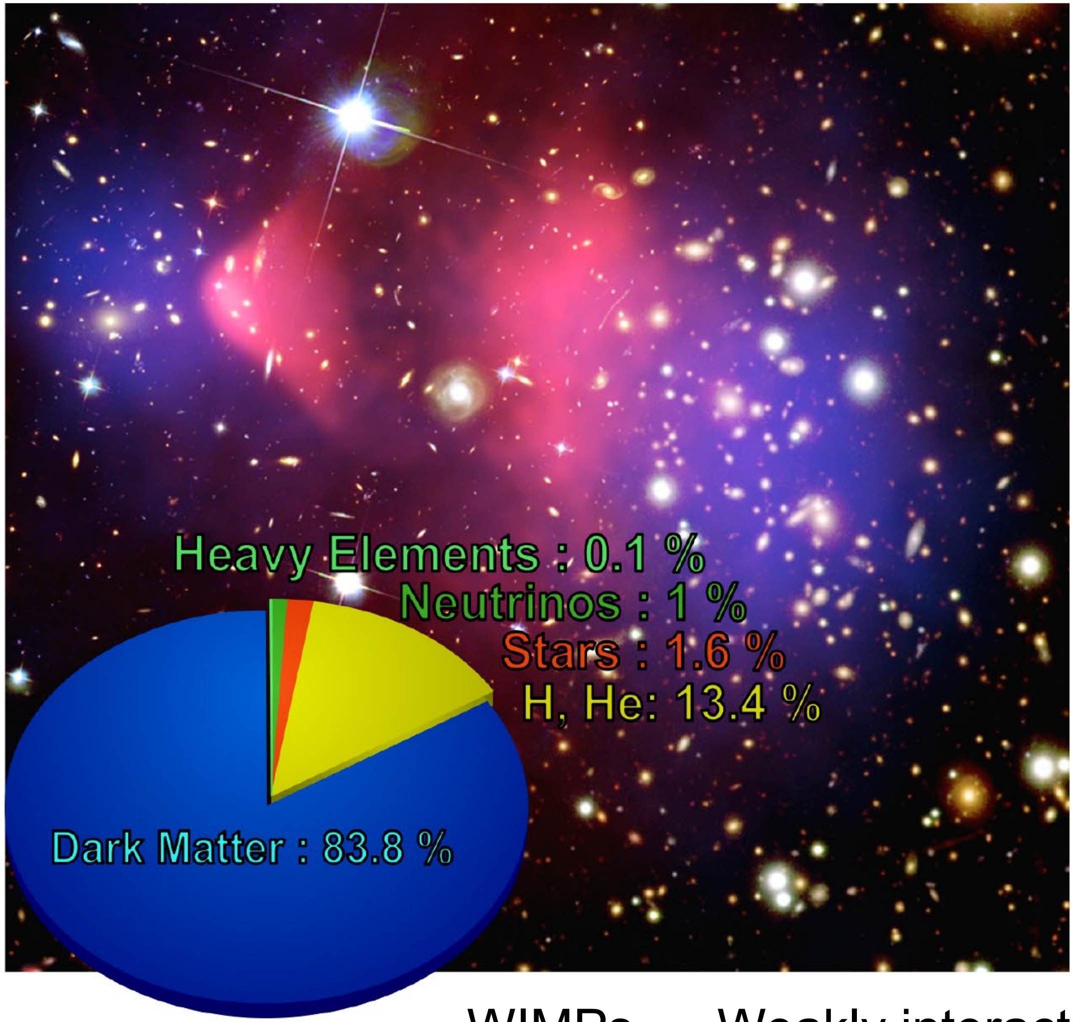
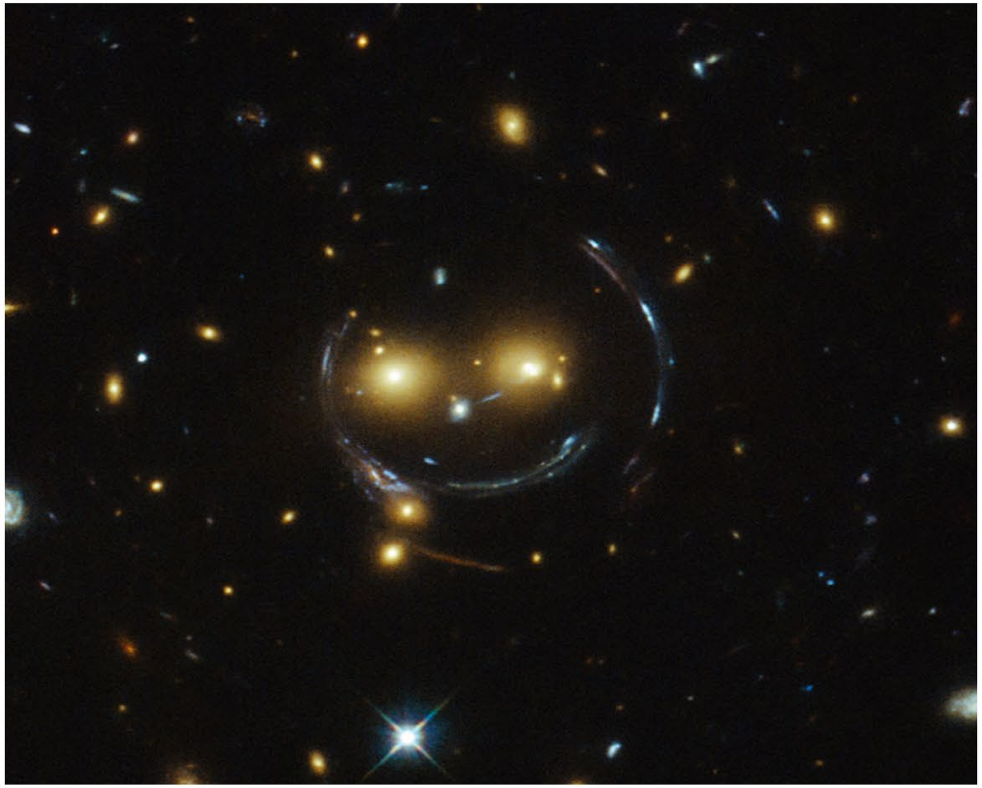
The dark matter problem



- **Axion-like particles (ALPs):**
  - very light bosons (unknown mass)
  - weakly interacting with “normal” matter
  - could be dark matter

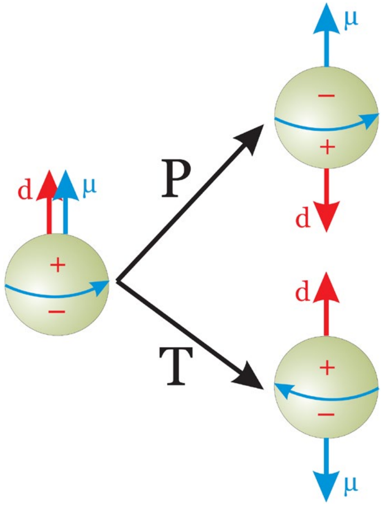


WIMPs	Weakly interacting massive particles
MACHOs	Massive compact halo object
RAMBOs	Robust associations of massive baryonic objects

Axions

R. D. Peccei and Helen R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)

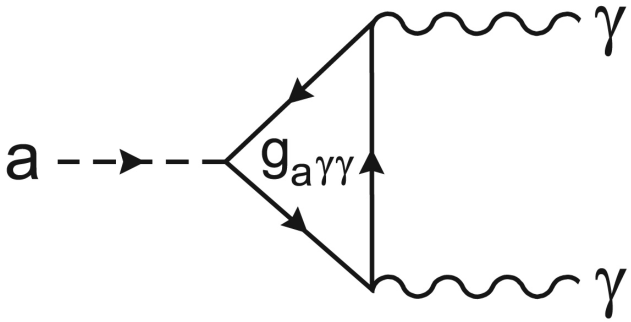
Particle suggested to solve the strong CP problem:
Strong interaction does not
violate CP symmetry even though it could.

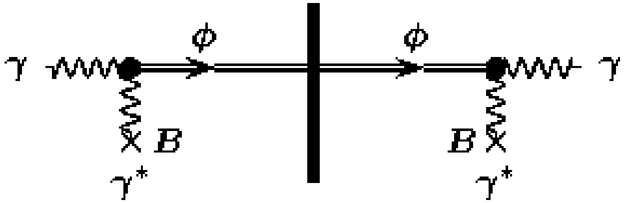


Limit set by nEDM
measurements:
(10 orders of mag.)

Axion:
Very light (mass 10^{-12}-1eV/c^2)
Spin 0
Minimal interaction

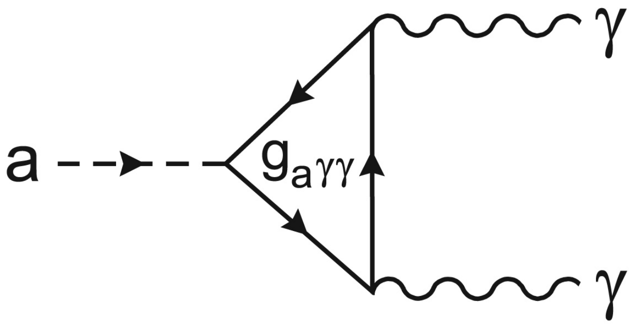
Axion experiments

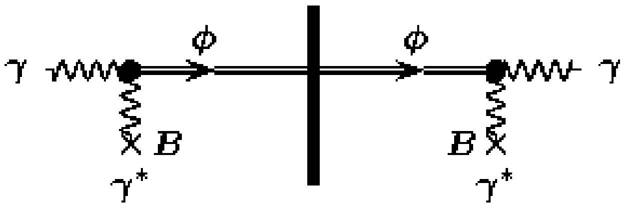




e.g. CAST (Cern Axion Solar Telescope)

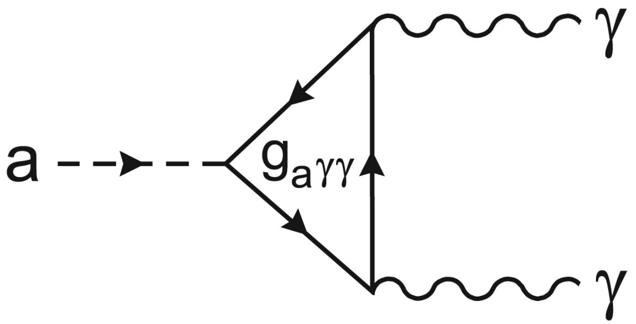
Axion experiments

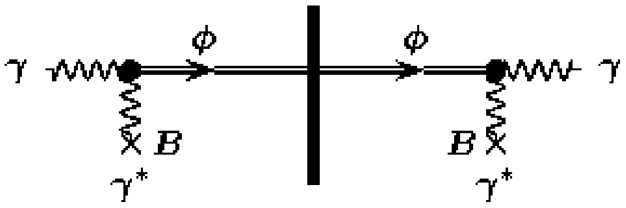




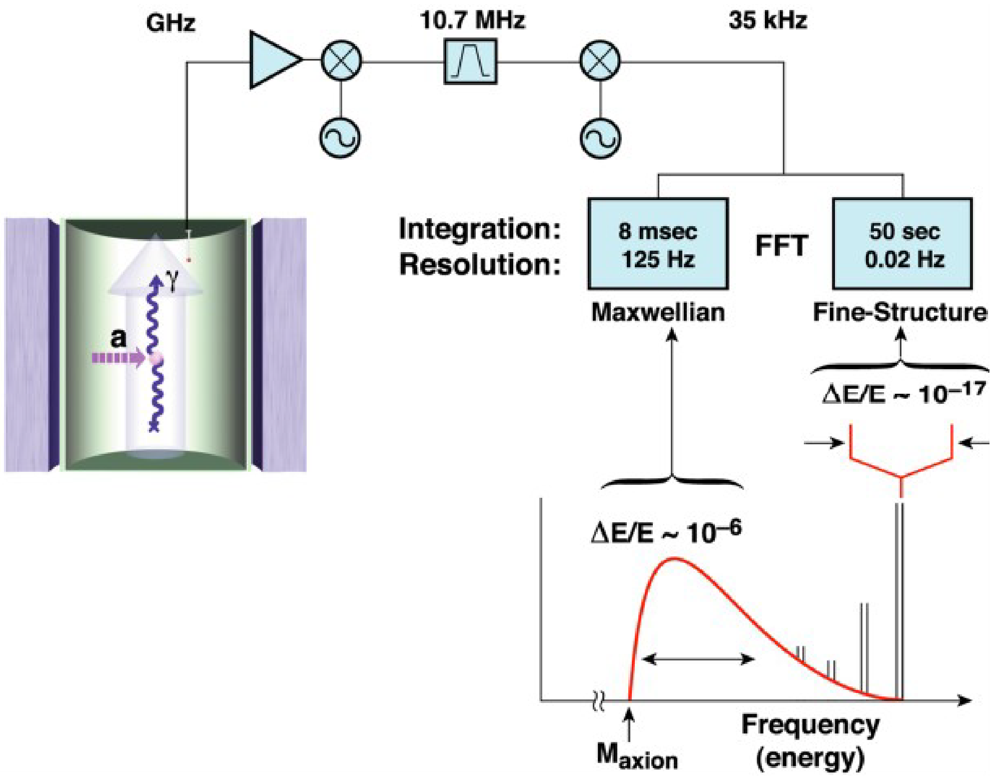
e.g. ALPS @ DESY (Light shining through a wall)

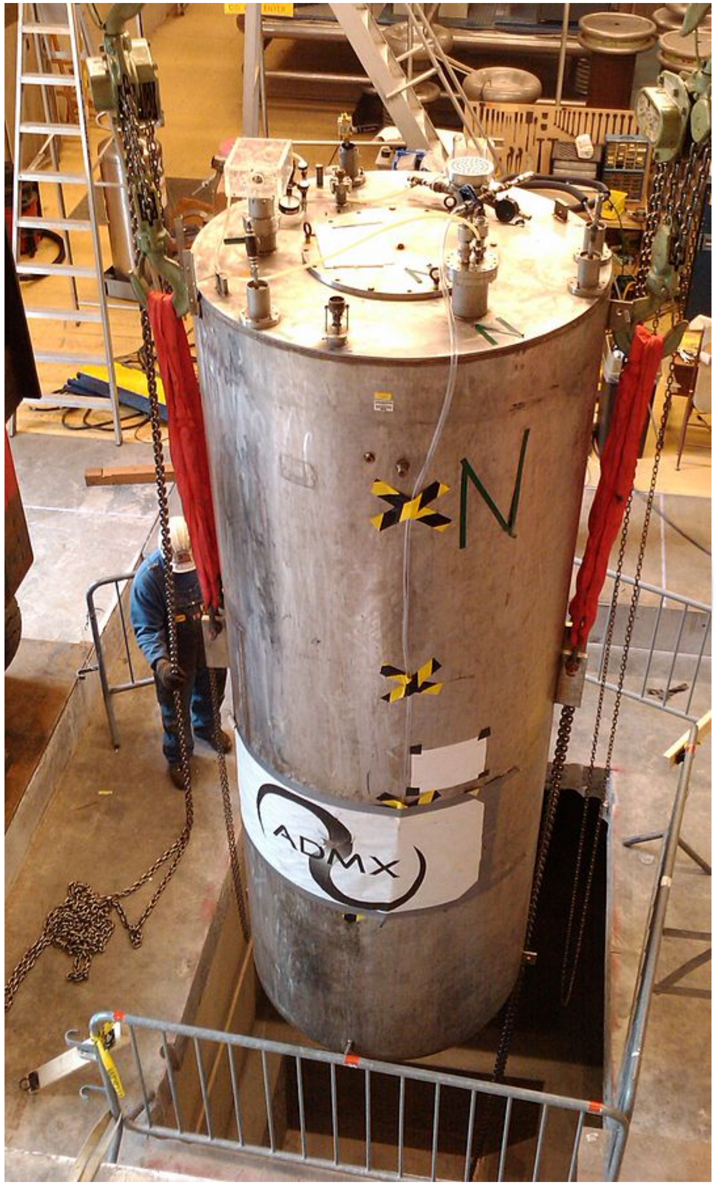
Axion experiments



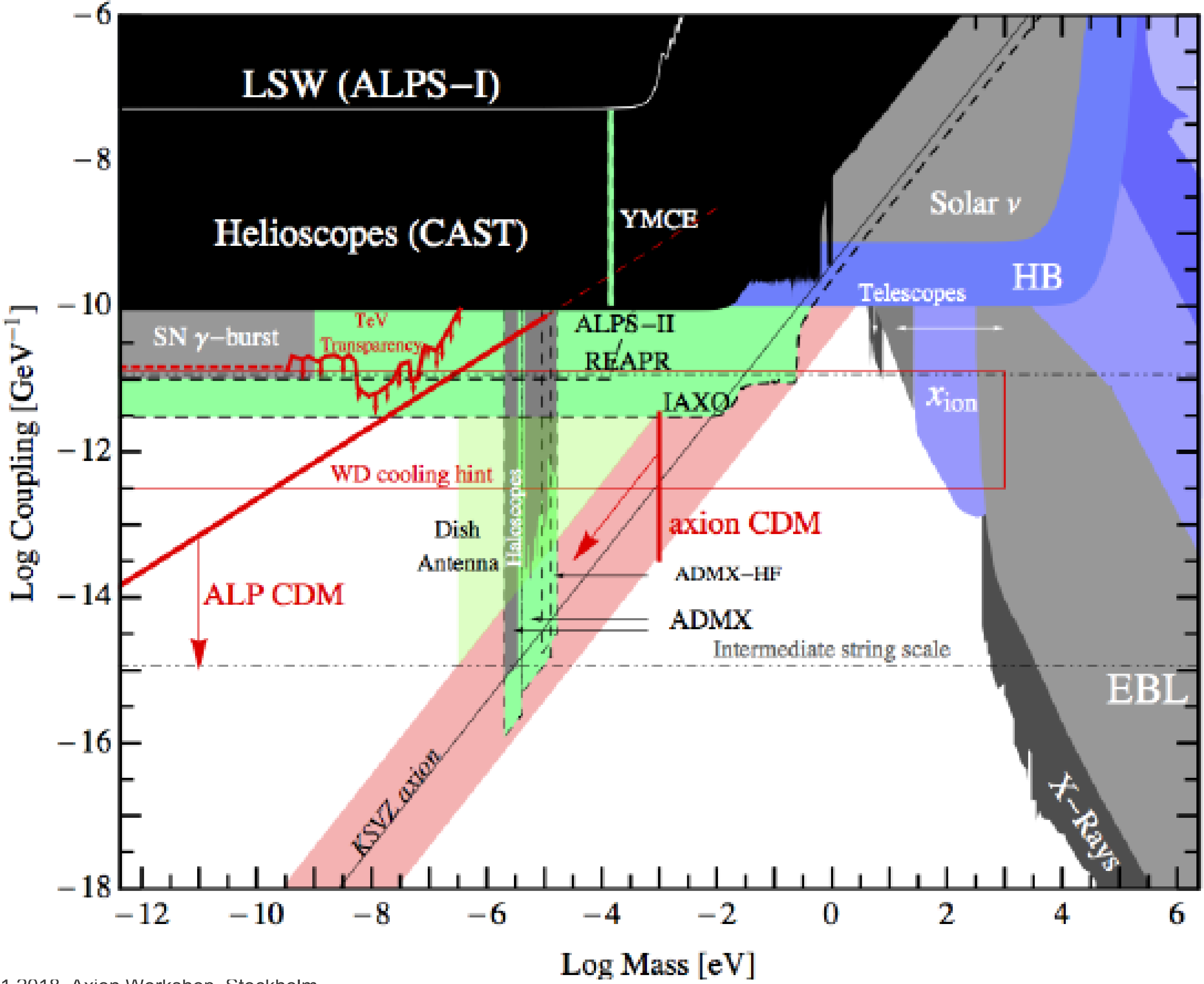


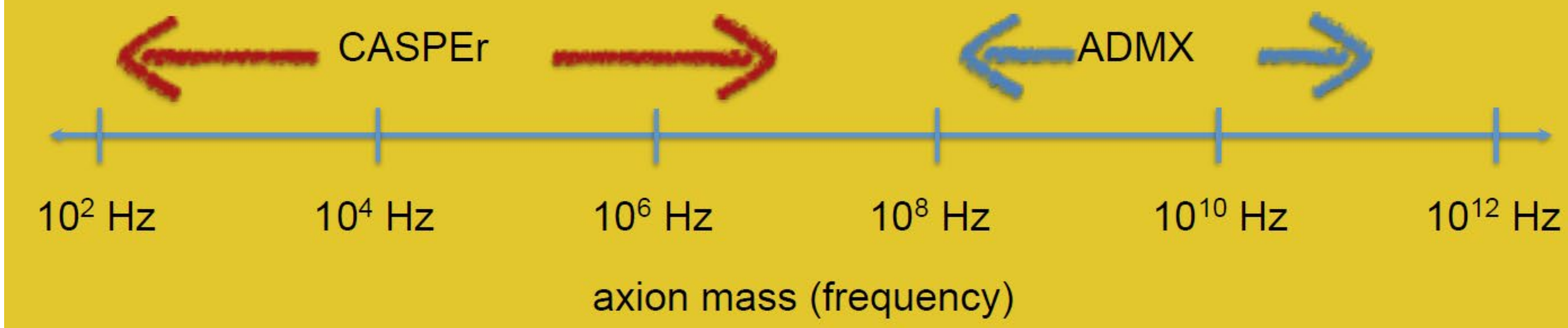
e.g. ADMX (*Axion Dark Matter eXperiment*)





"ADMX magnet installation" by Lamestlamer


LSW (ALPS−I)
Helioscopes (CAST)
YMCE
Solar ν
HB
Telescopes
SN γ−burst
TeV
Transparency
ALPS−II
REAPR
IAXO
x_{ion}
WD cooling hint
axion CDM
Dish
Antenna
Haloscopes
ADMX−HF
ADMX
ALP CDM
Intermediate string scale
EBL
KSVZ axion
X−Rays
Log Coupling [GeV^{-1}]
Log Mass [eV]
−6
−8
−10
−12
−14
−16
−18
−12
−10
−8
−6
−4
−2
0
2
4
6



Cosmic Axion Spin Precession Experiment (CASPEr)

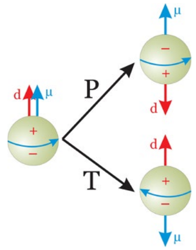
with

Peter Graham
Surjeet Rajendran
Alex Sushkov
Micah Ledbetter

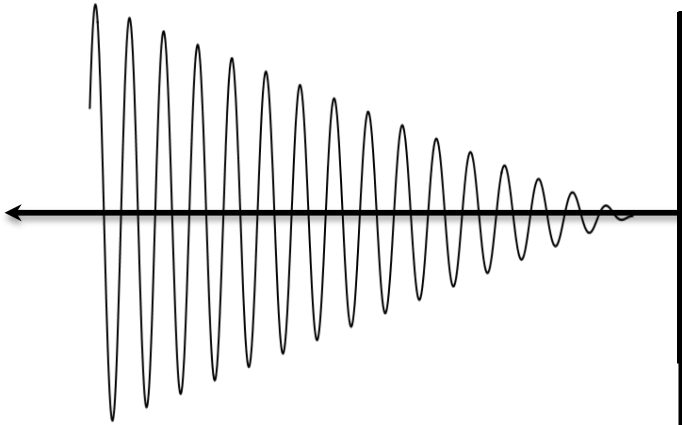
PRD **88** (2013) arXiv:1306.6088,
PRX (2014) arxXiv:1306.6089,
PRD **84** (2011) arXiv:1101.2691

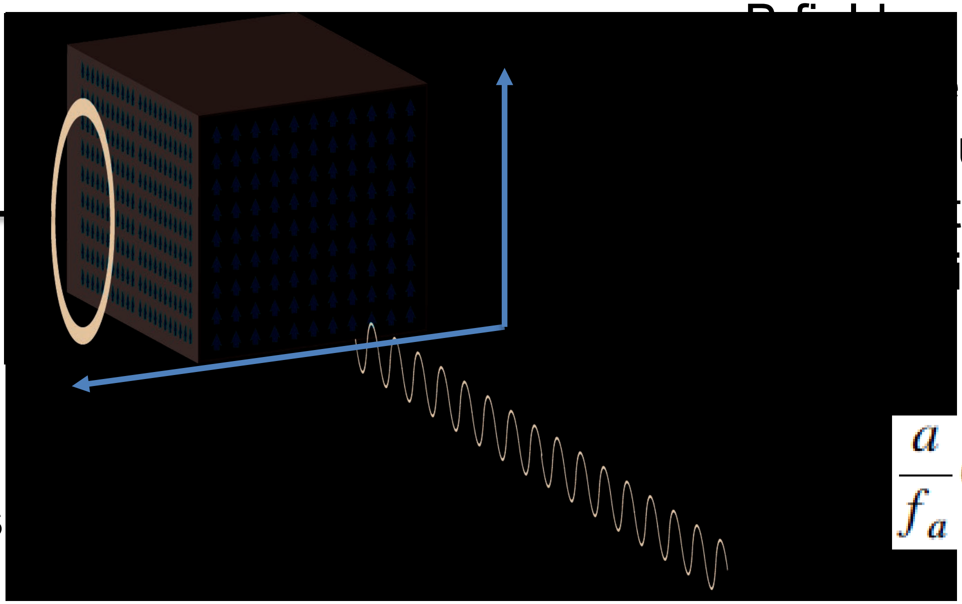
CASPEr – Electric idea

Detecting oscillating induced electric dipole moment with NMR



- Polarized nuclear spins
- rp to B
- uces EDM
- ing torque on spins
- ith SQUIDs





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

Larmor Frequency=Axion mass
=>Resonant enhancement

Cosmology: $Q=10^6$!

How to search for Axions (ALPs) ?

Axion (ALP) Interactions

Gravity

+

Gauge Fields

Fermions

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

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

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

Most Searches

(CASPEr-E)

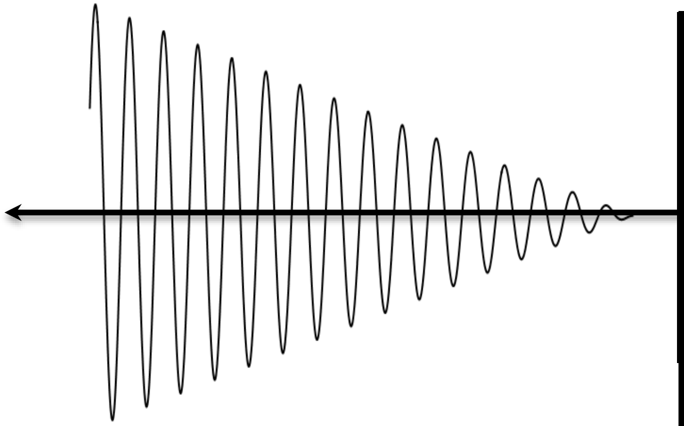
(CASPEr-Wind, GNOME, QUAX)

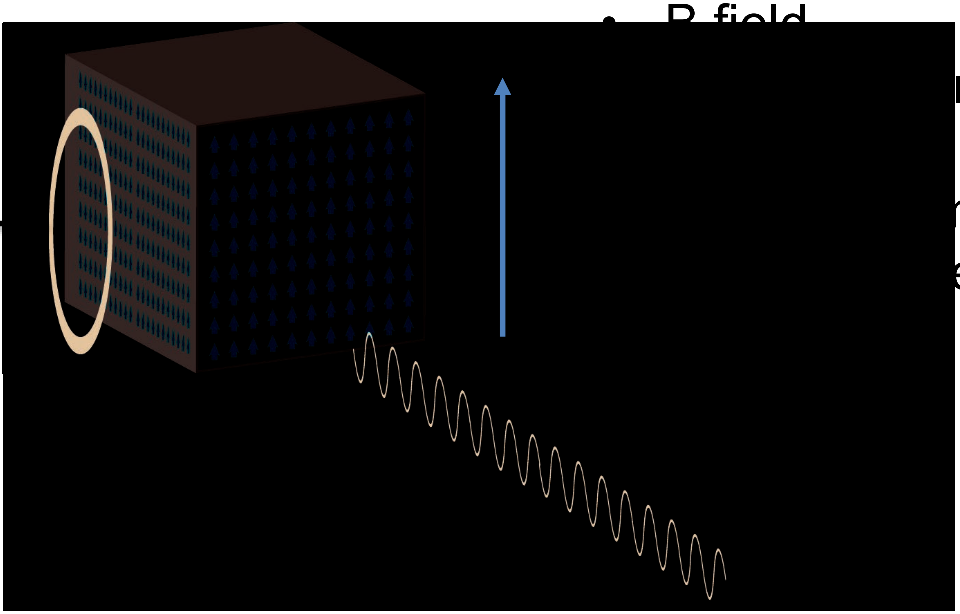
CASPEr – Wind idea

Detecting oscillating torque on nuclear spins

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

- Polarized nuclear spins
- B field
- nt couples to spins
- torque on spins
- magnetization
- ehow)





Larmor Frequency=Axion mass
=>Resonant enhancement

CASPEr stages

CASPEr now → Analysing existing data (low frequency)

CASPEr Wind → Measurement of axion field gradient (Wind) with nuclear spins in magnetic field

-ultra low field (optical magnetometer)

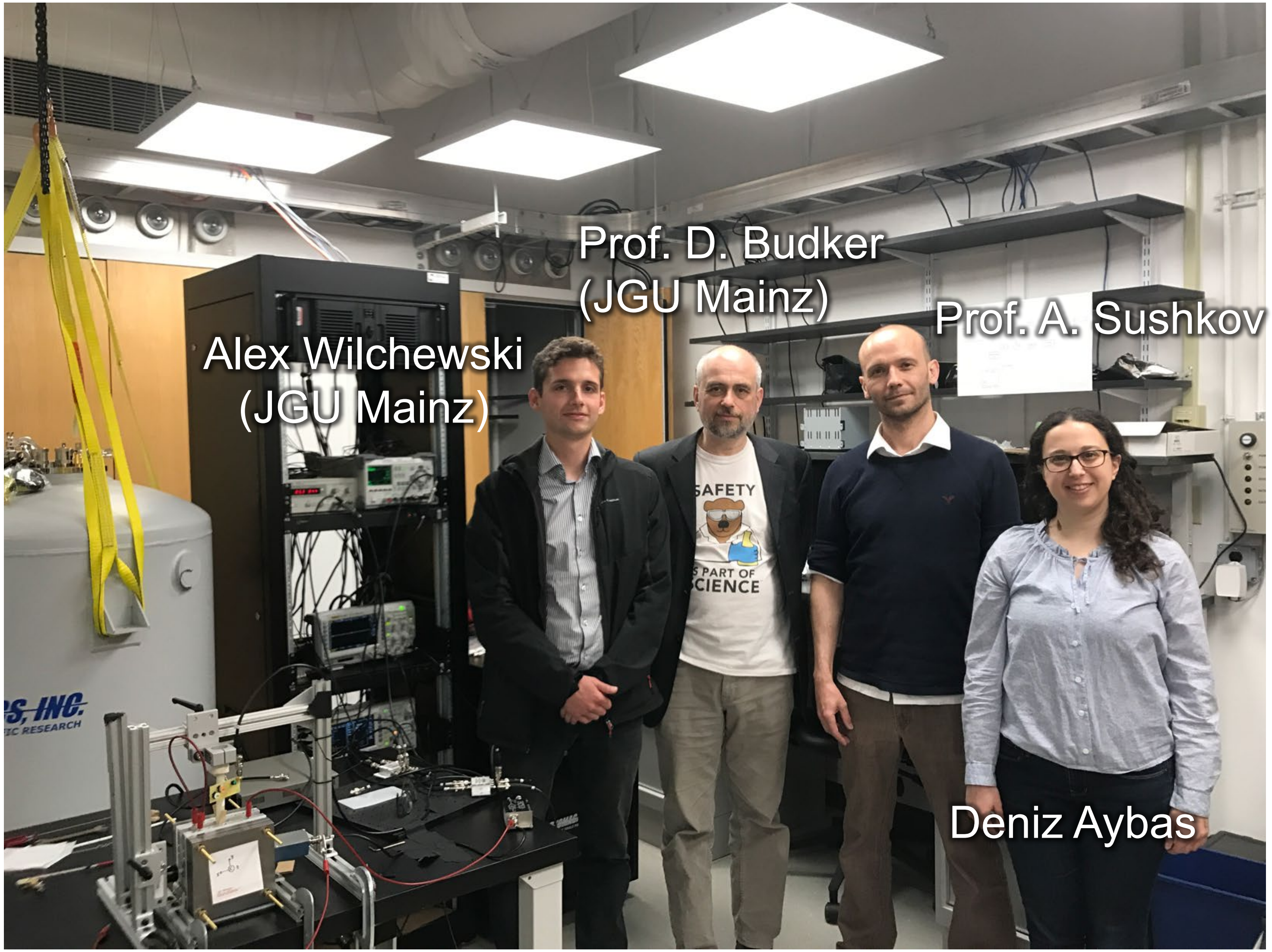
-low field (Super conducting quantum interference devices)

-high field (inductive pick-up)

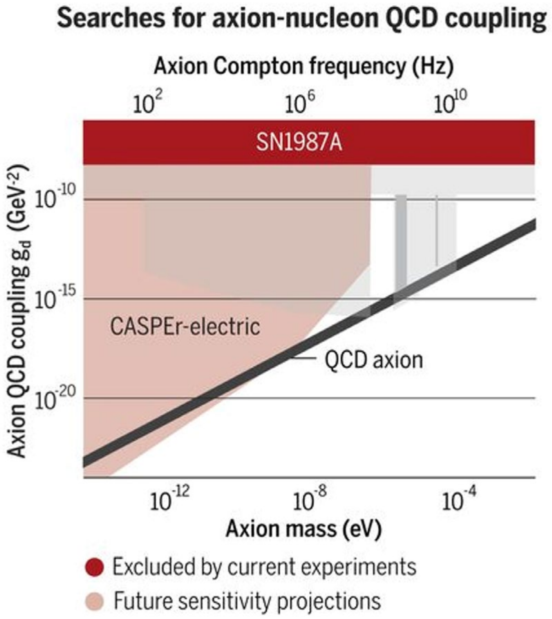
CASPEr Electric → Applying additional electric field

Alex Sushkov et al @ Boston university

CASPER Electric



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



QCD Axion < 100neV

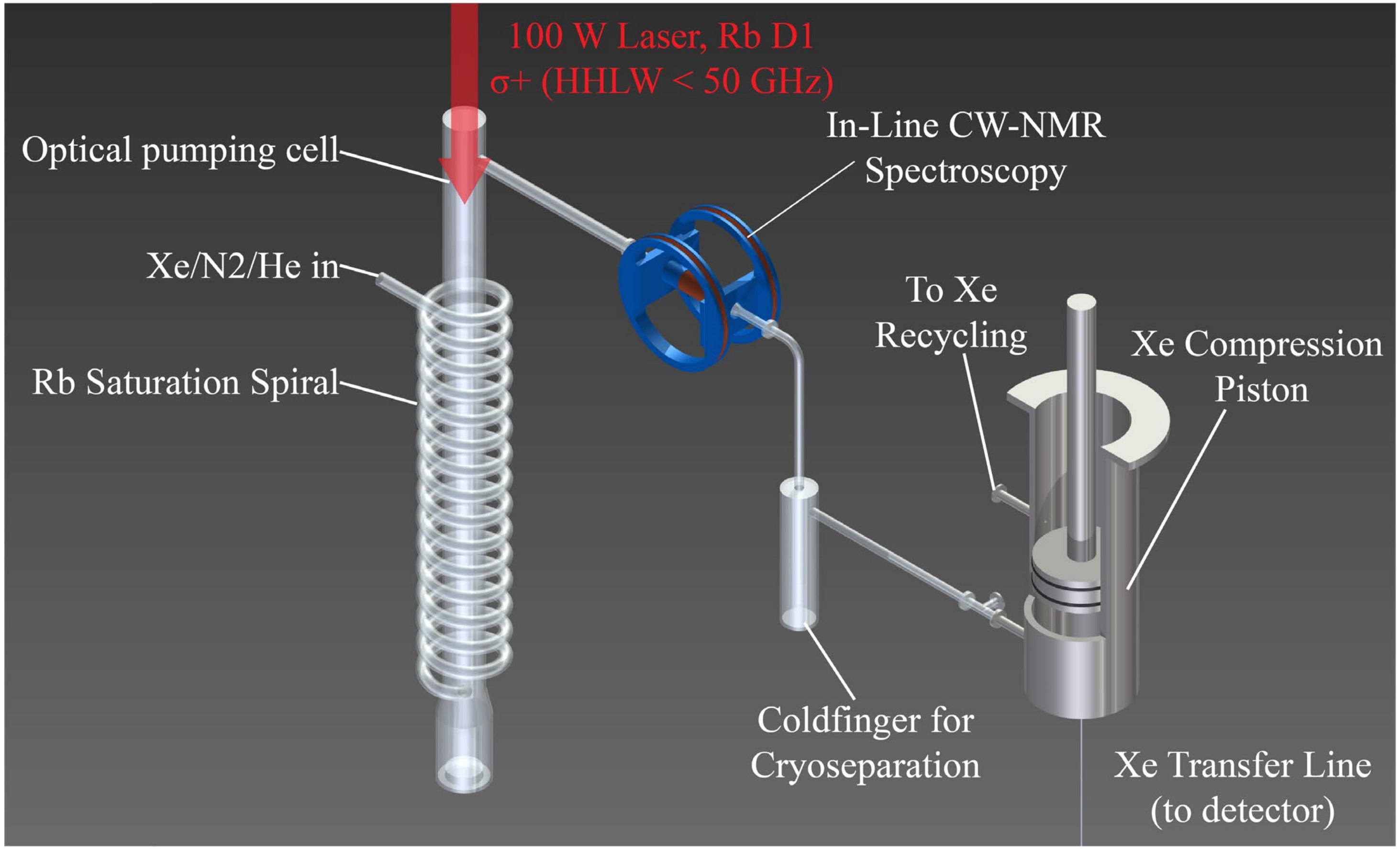
David DeMille, John. Doyle, and Alexander Sushkov. Science 2017;357:990-994

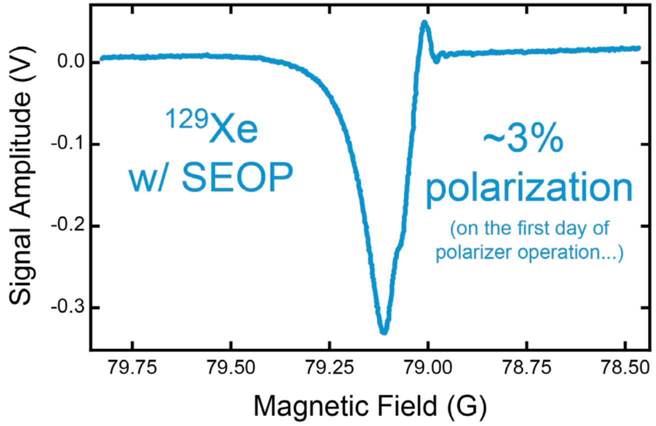
CASPEr Wind in Mainz

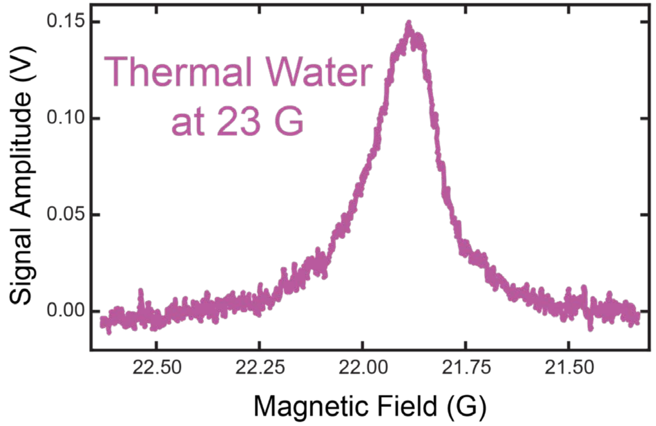
Cosmic Axion Spin Precession experiment (CASPEr)

Hyperpolarized Xenon NMR
driven by axion-like dark matter

CASPEr Wind – inline Xenon polarization







CASPEr Wind LF status

Actively stabilized magnet
-0-1500G (up to 2-3MHz)
-superconducting shims 1ppm
-magnetically shielded

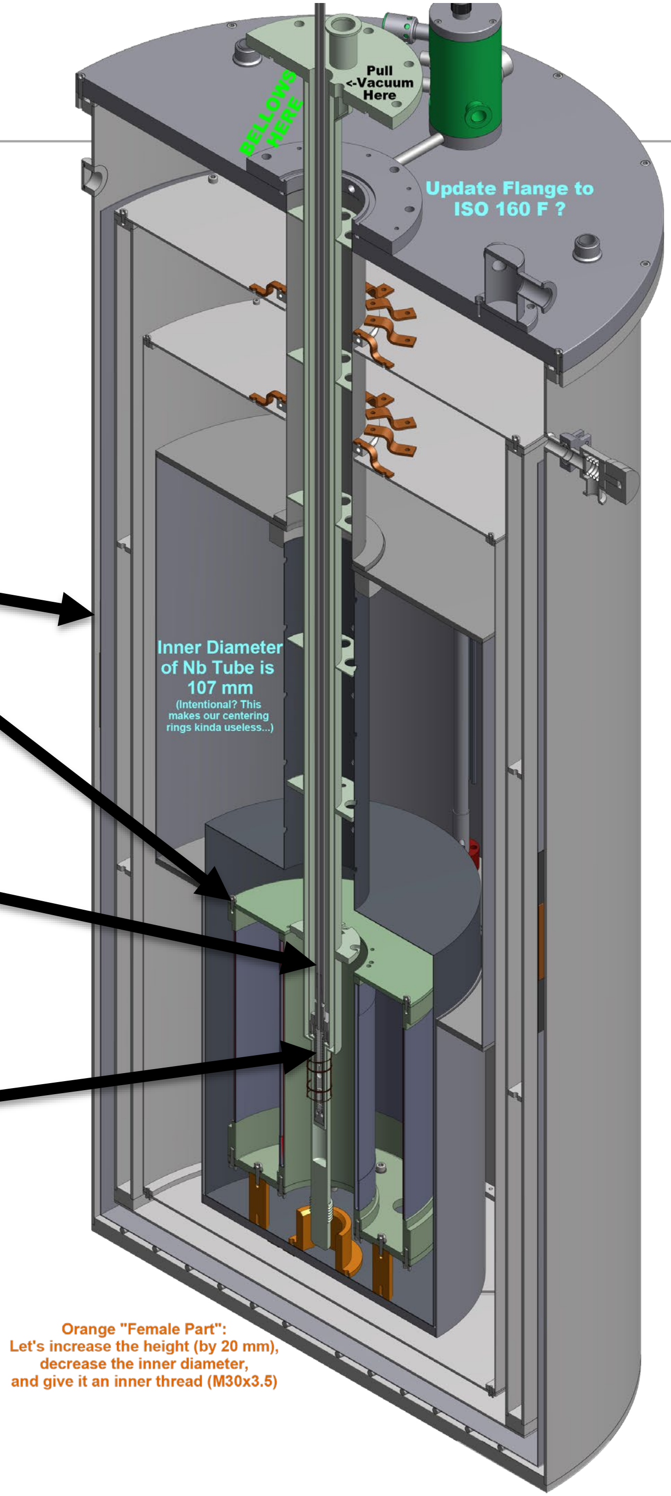
Ordered-> 11/18

Variable temperature insert
- 160-180K

Ordered-> 11/18

Super-conducting pick-up coils
Triple SQUID system

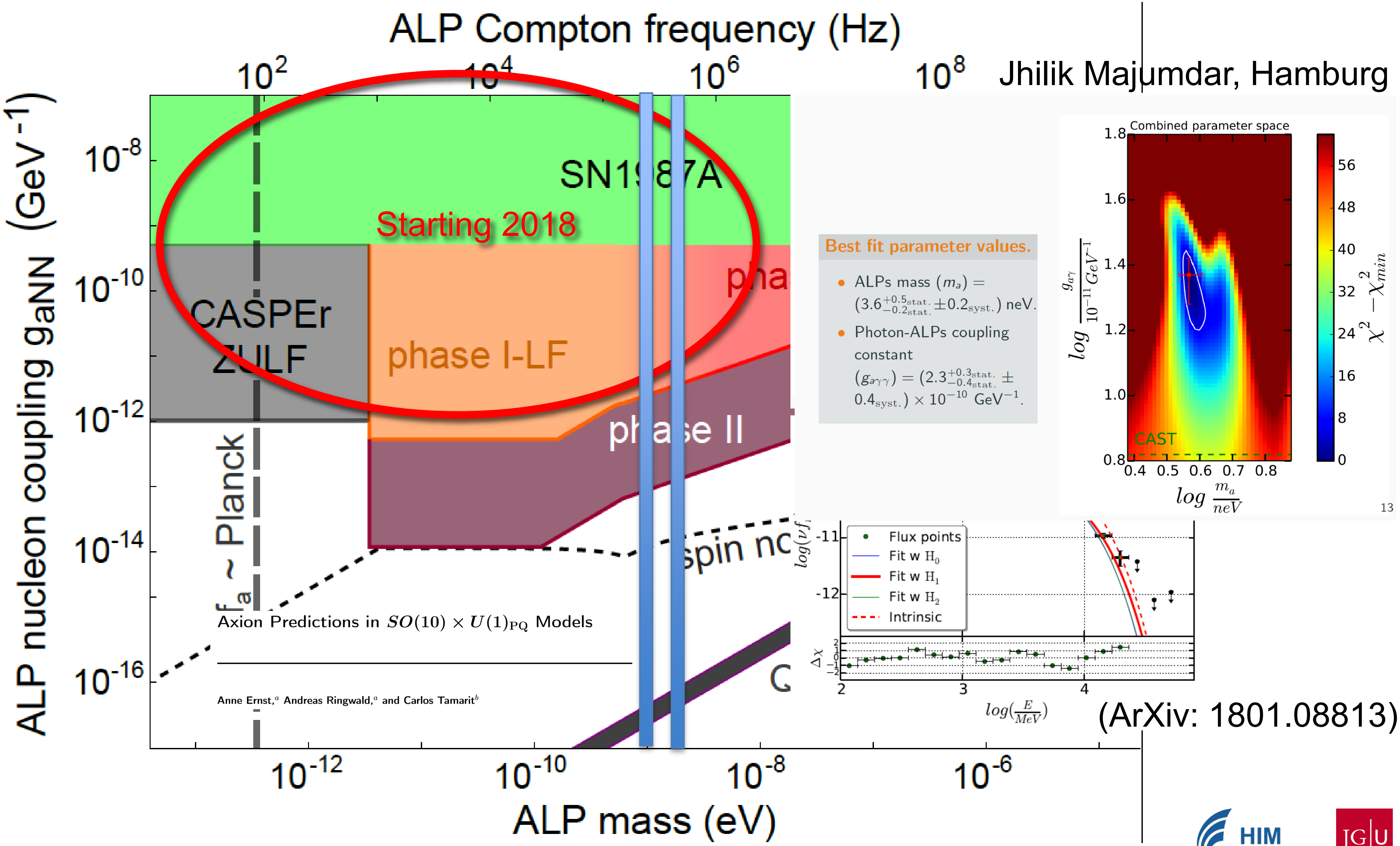
Ordered-> 11/18



Summary CASPEr Wind LF (+HF)

- Wind LF is technically designed (90%)
- Crucial components are ordered or already there
- Limited currently by delivery times of the SQUIDS
- **First measurement campaign to start in 2018**

- High field magnet is designed and waits to be ordered



Best fit parameter values.

- ALPs mass $(m_a) = (3.6^{+0.5_{\text{stat.}}}_{-0.2_{\text{stat.}}} \pm 0.2_{\text{syst.}})$ neV.
- Photon-ALPs coupling constant $(g_{a\gamma\gamma}) = (2.3^{+0.3_{\text{stat.}}}_{-0.4_{\text{stat.}}} \pm 0.4_{\text{syst.}}) \times 10^{-10}$ GeV^{-1}.

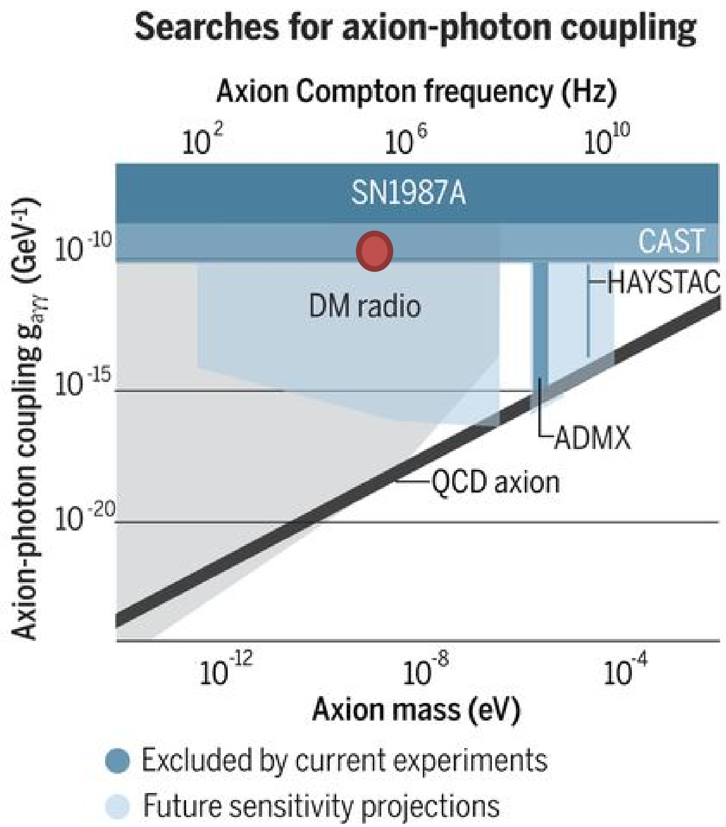
Axion Predictions in $SO(10) \times U(1)_{\text{PQ}}$ Models

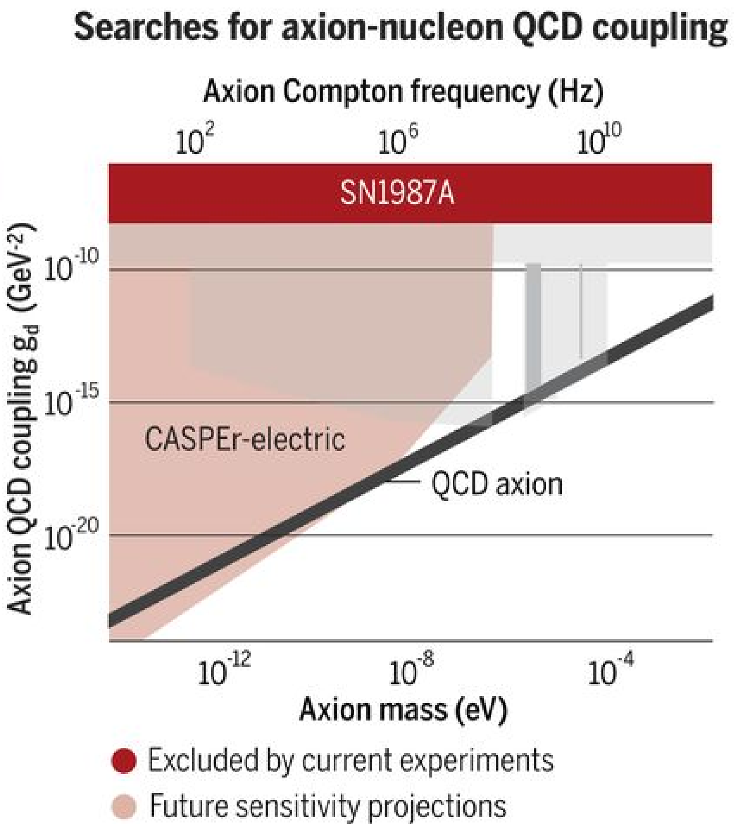
Anne Ernst,[a] Andreas Ringwald,[a] and Carlos Tamarit[b]

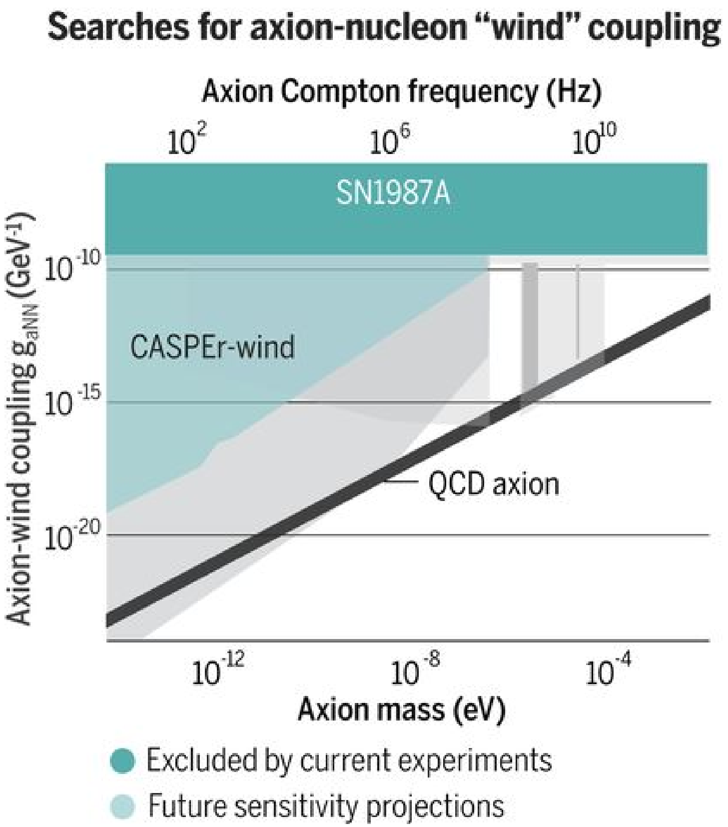
Jhilik Majumdar, Hamburg

(ArXiv: 1801.08813)

Experimental constraints and projected sensitivities of axion dark-matter searches


Searches for axion-photon coupling

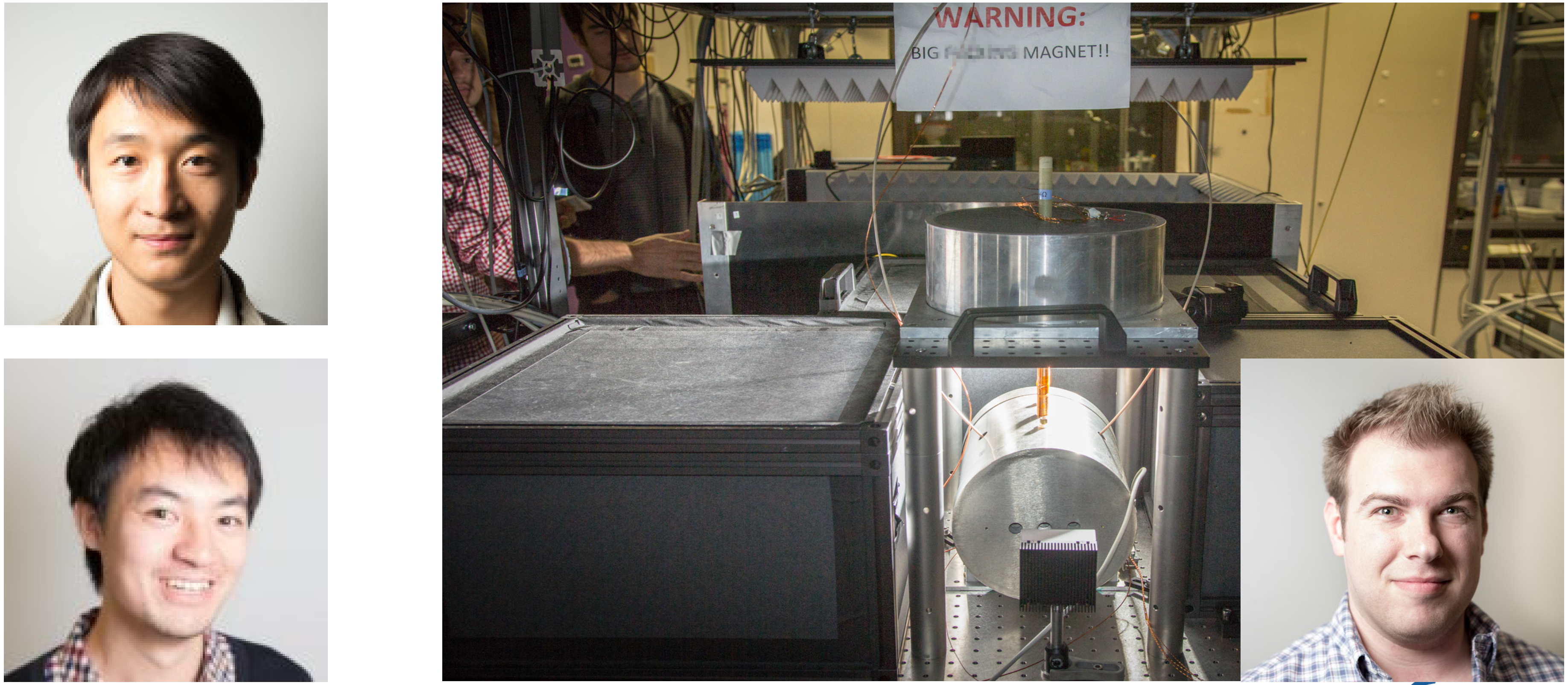

Searches for axion-nucleon QCD coupling

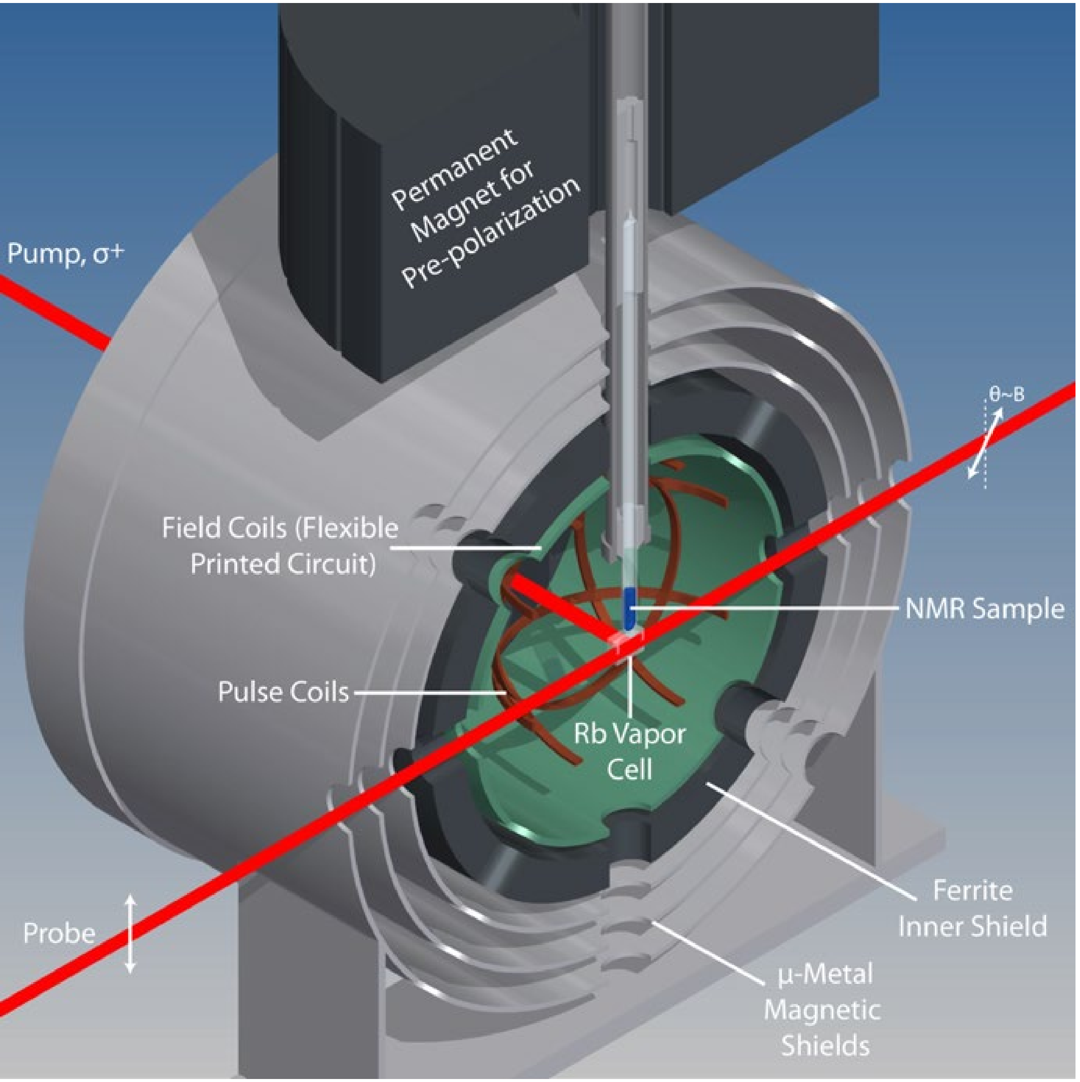

Searches for axion-nucleon "wind" coupling

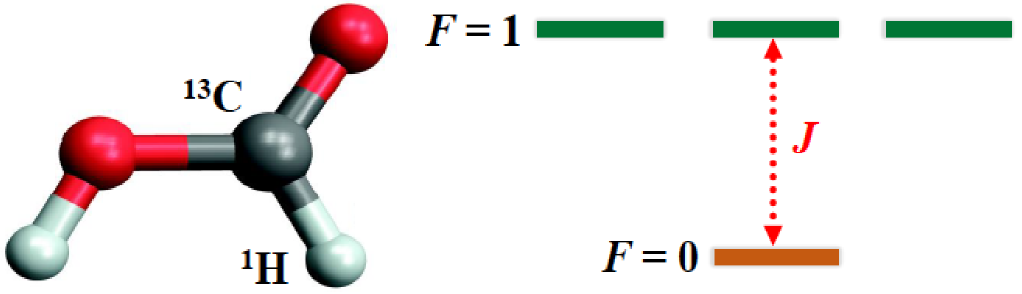
David DeMille, John. Doyle, and Alexander Sushkov. Science 2017;357:990-994

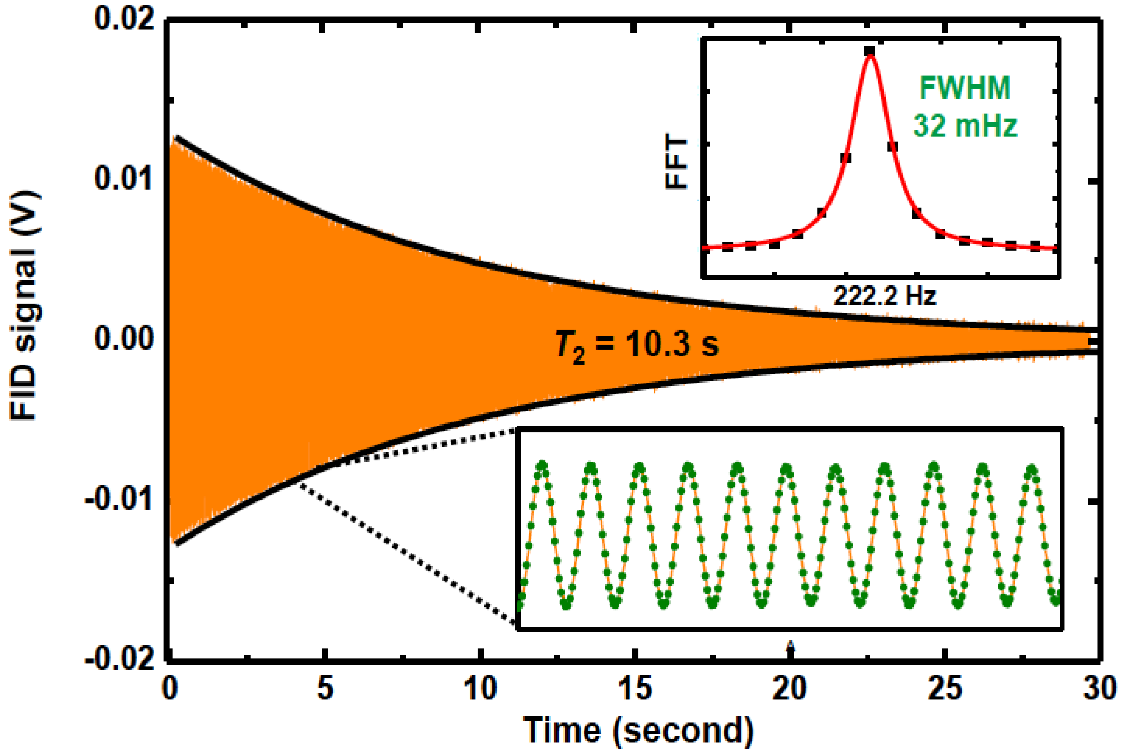
CASPEr ZULF

- Zero-ultra low field nuclear magnetic resonance with **atomic magnetometers** (SERF)

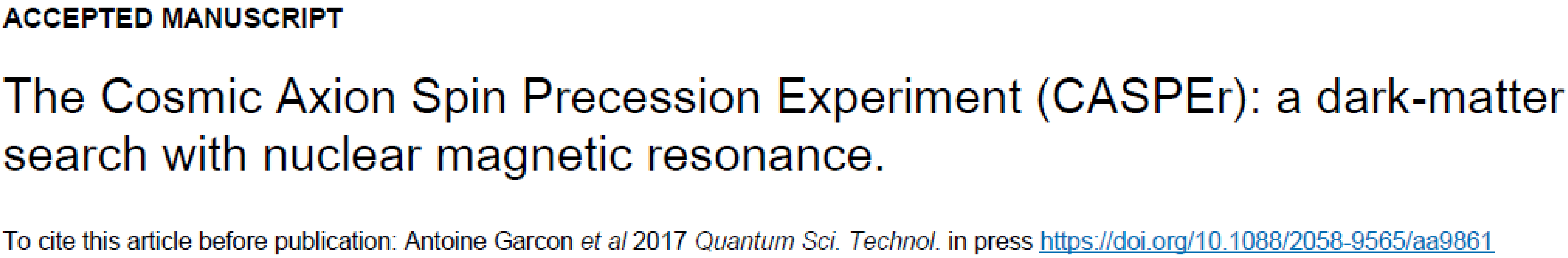



Permanent Magnet for Pre-polarization
Pump, σ+
θ~B
Field Coils (Flexible Printed Circuit)
NMR Sample
Pulse Coils
Rb Vapor Cell
Ferrite Inner Shield
Probe
μ-Metal Magnetic Shields


^{13}C
^{1}H
F = 1
J
F = 0


FID signal (V)
0.02
0.01
0.00
-0.01
-0.02
0
5
10
15
20
25
30
Time (second)
T_2 = 10.3 s
FFT
FWHM 32 mHz
222.2 Hz

CASPEr ZULF



ACCEPTED MANUSCRIPT

The Cosmic Axion Spin Precession Experiment (CASPEr): a dark-matter search with nuclear magnetic resonance.

To cite this article before publication: Antoine Garcon *et al* 2017 *Quantum Sci. Technol.* in press https://doi.org/10.1088/2058-9565/aa9861

https://arxiv.org/abs/1707.05312

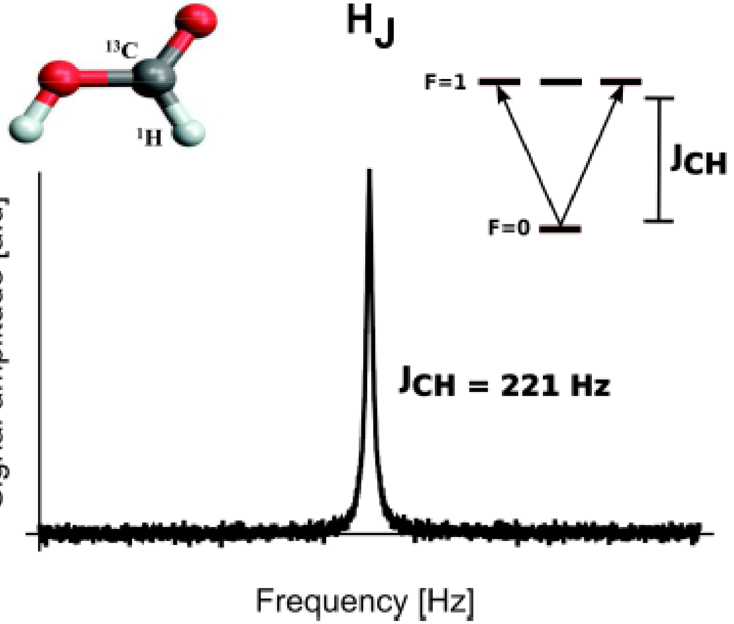
Suggestion:
Sideband detection using ZULF NMR
(zero-to-ultralow field)
Very light ALP dark matter

Formic acid

single J-coupling: ^{13}C-^{1}H

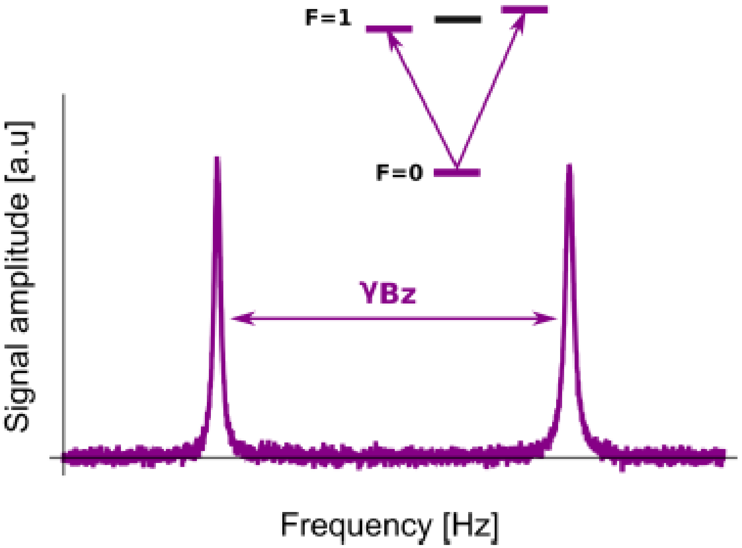
J-coupling only:

H_J



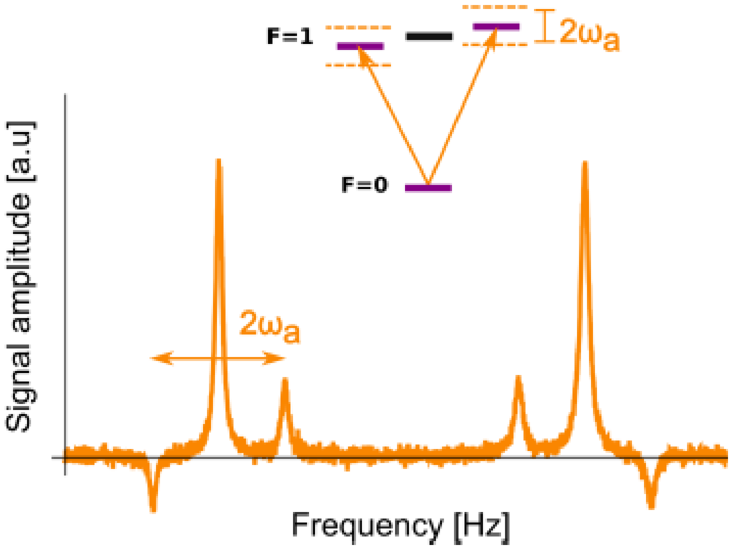
J-coupling + DC-field:

$H_J + B_z$



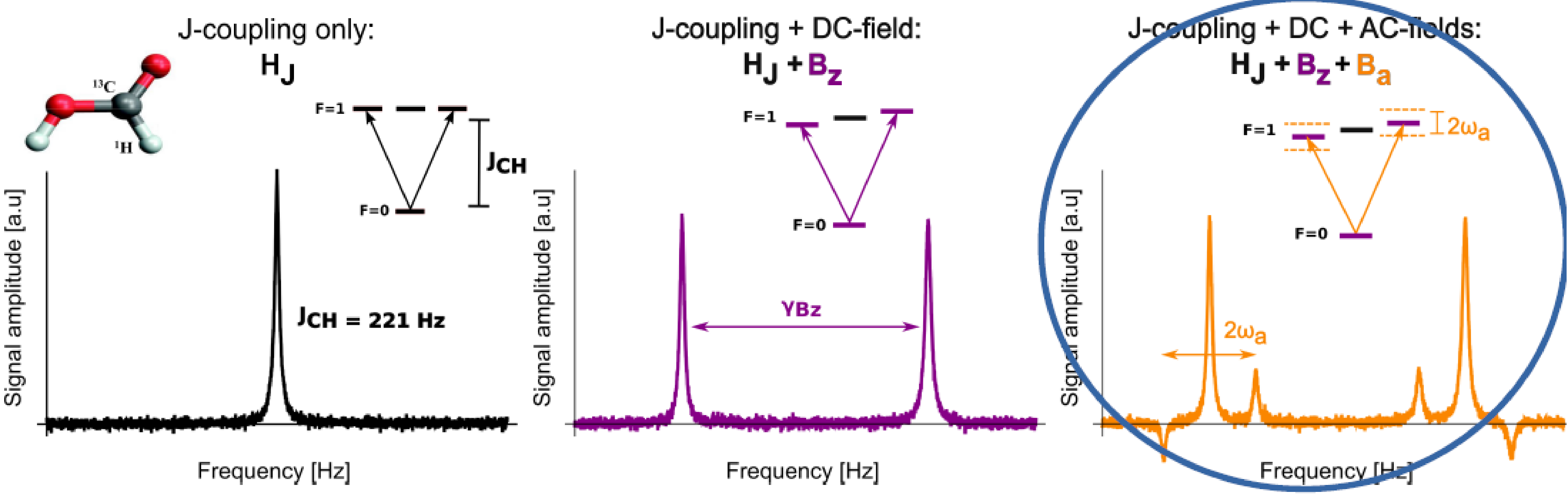
J-coupling + DC + AC-fields:

$H_J + B_z + B_a$



Dark-matter field induces sidebands !

sidebands amplitude ∝ B_{ALP}/ω_{ALP}


J-coupling only: H_J

J-coupling + DC-field: $H_J + B_z$

J-coupling + DC + AC-fields: $H_J + B_z + B_a$

n coherence time > T_2

RESEARCH

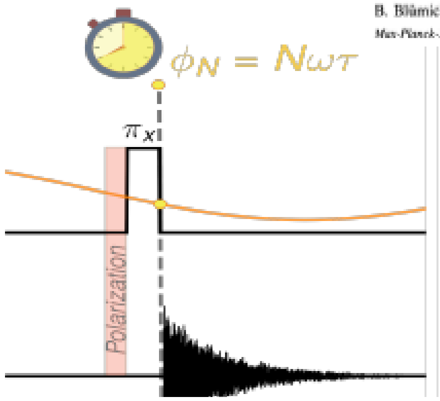
REPORT

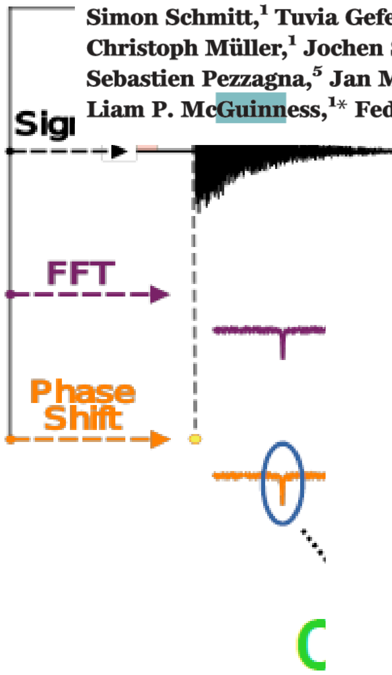
QUANTUM MEASUREMENT

Submillihertz magnetic spectroscopy performed with a nanoscale quantum sensor

Simon Schmitt,[1] Tuvia Gefen,[2] Felix M. Stürner,[1] Thomas Unden,[1] Gerhard Wolff,[1] Christoph Müller,[1] Jochen Scheuer,[1,3] Boris Naydenov,[1,3] Matthew Markham,[4] Sebastien Pezzagna,[5] Jan Meijer,[5] Ilai Schwarz,[3,6] Martin Plenio,[3,6] Alex Retzker,[2] Liam P. McGuinness,[1*] Fedor Jelezko[1,3]

Oscillati
ALP fie





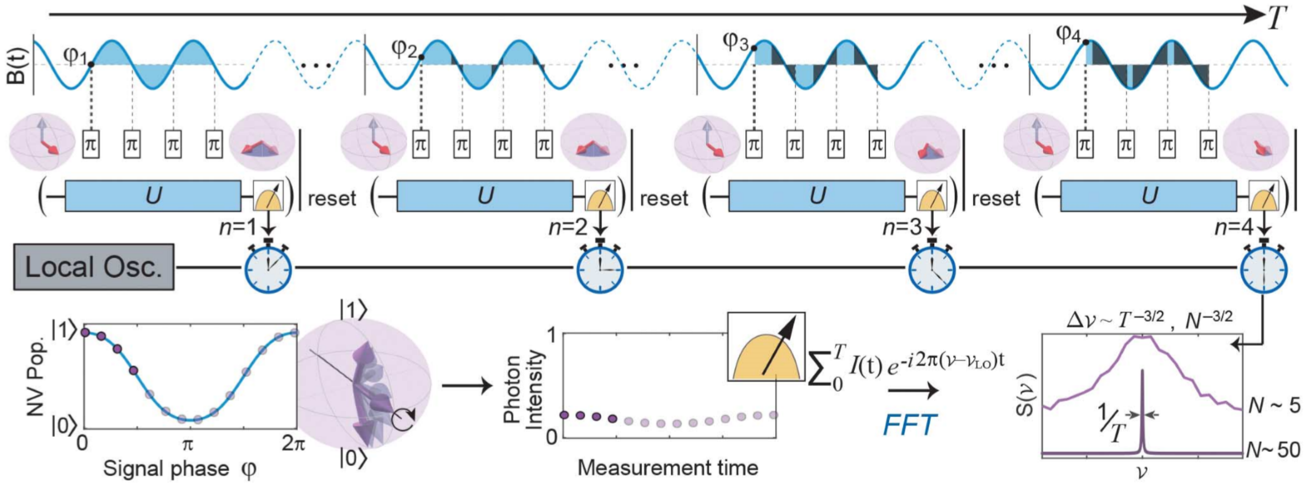
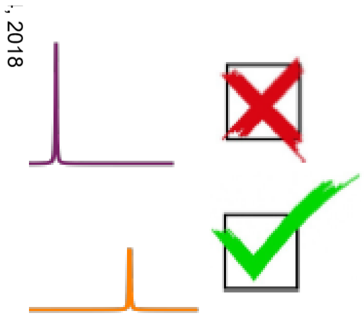


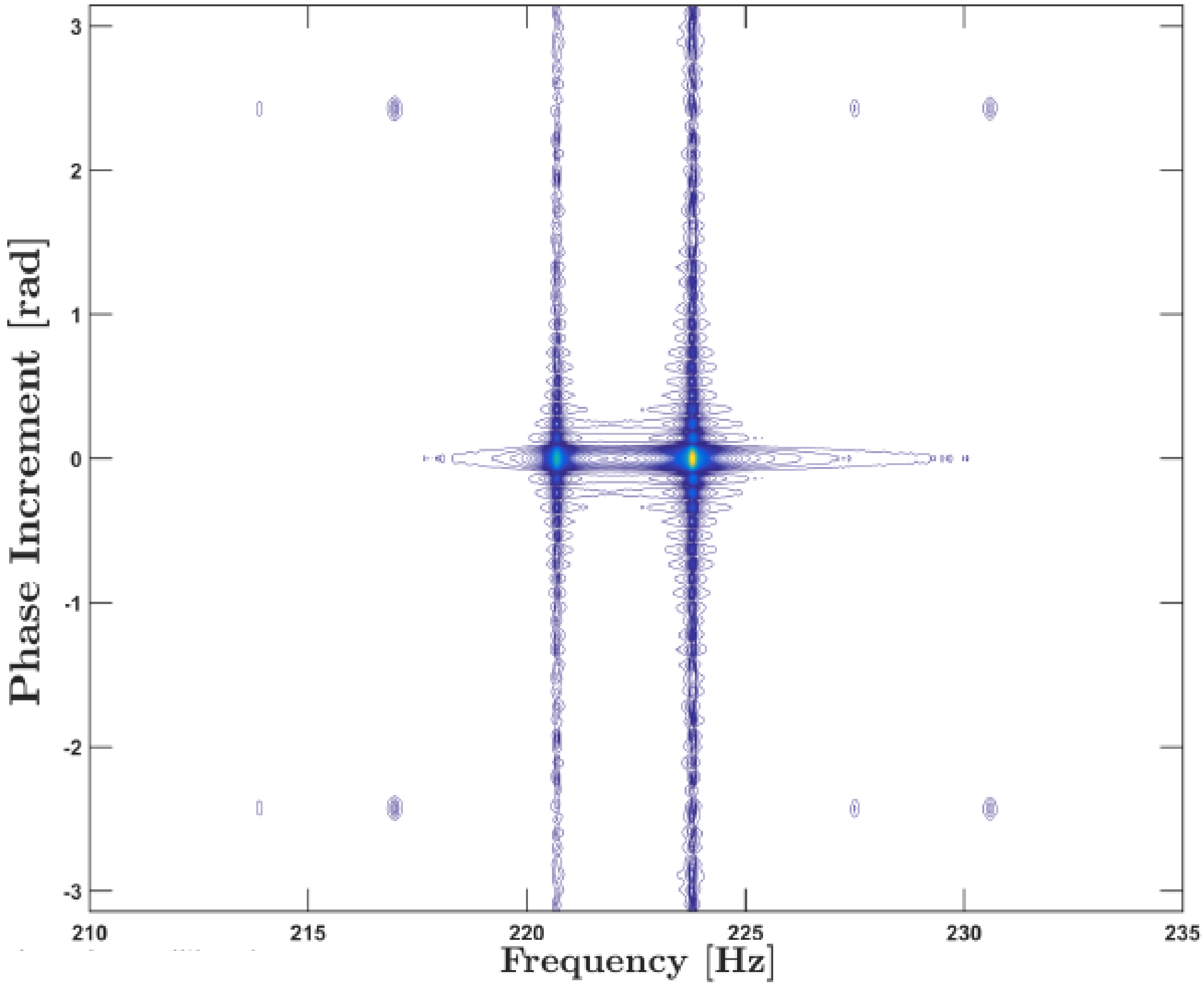
Fig. 2. Qdyne detection scheme. The output state of the sensor qubit depends on the initial phase φ_1 of the signal field. The measurement result is recorded and synchronized with an external clock before the next measurement is performed for a second signal phase φ_2. This procedure is repeated for the entire measurement time *T*. By heterodyning with an external clock, the NV population—and therefore the measured photon intensity—records the signal phase evolution in time. A FFT then allows the signal frequency, with respect to local oscillator (osc.) frequency, to be determined. For Qdyne detection, the precision of frequency estimation scales as $T^{-3/2}$.

Presentation of sideband envelopes by two-dimensional one-pulse (TOP) spectroscopy

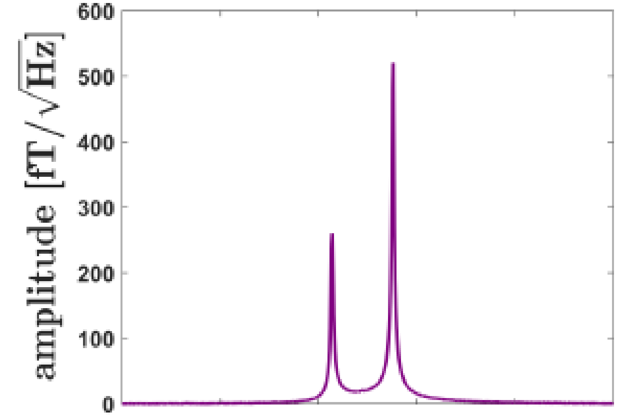
B. Blümich, P. Blümler and J. Jansen
Max-Planck-Institut für Polymerforschung, Postfach 3148, D-6500 Mainz, Germany



Simulated signal – coherent averaging

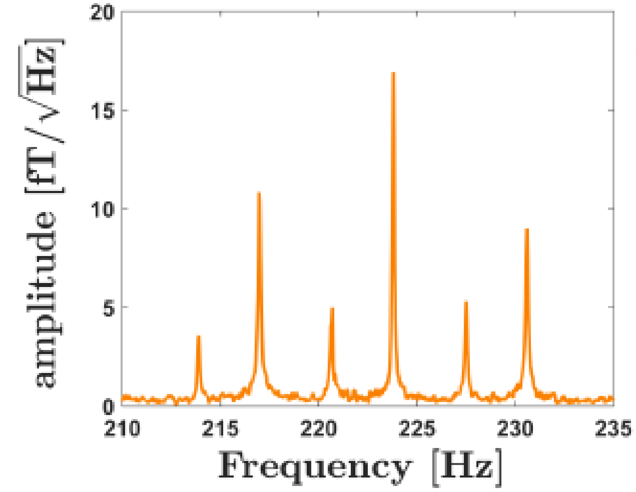


Zero-phase: coherent J-couplings



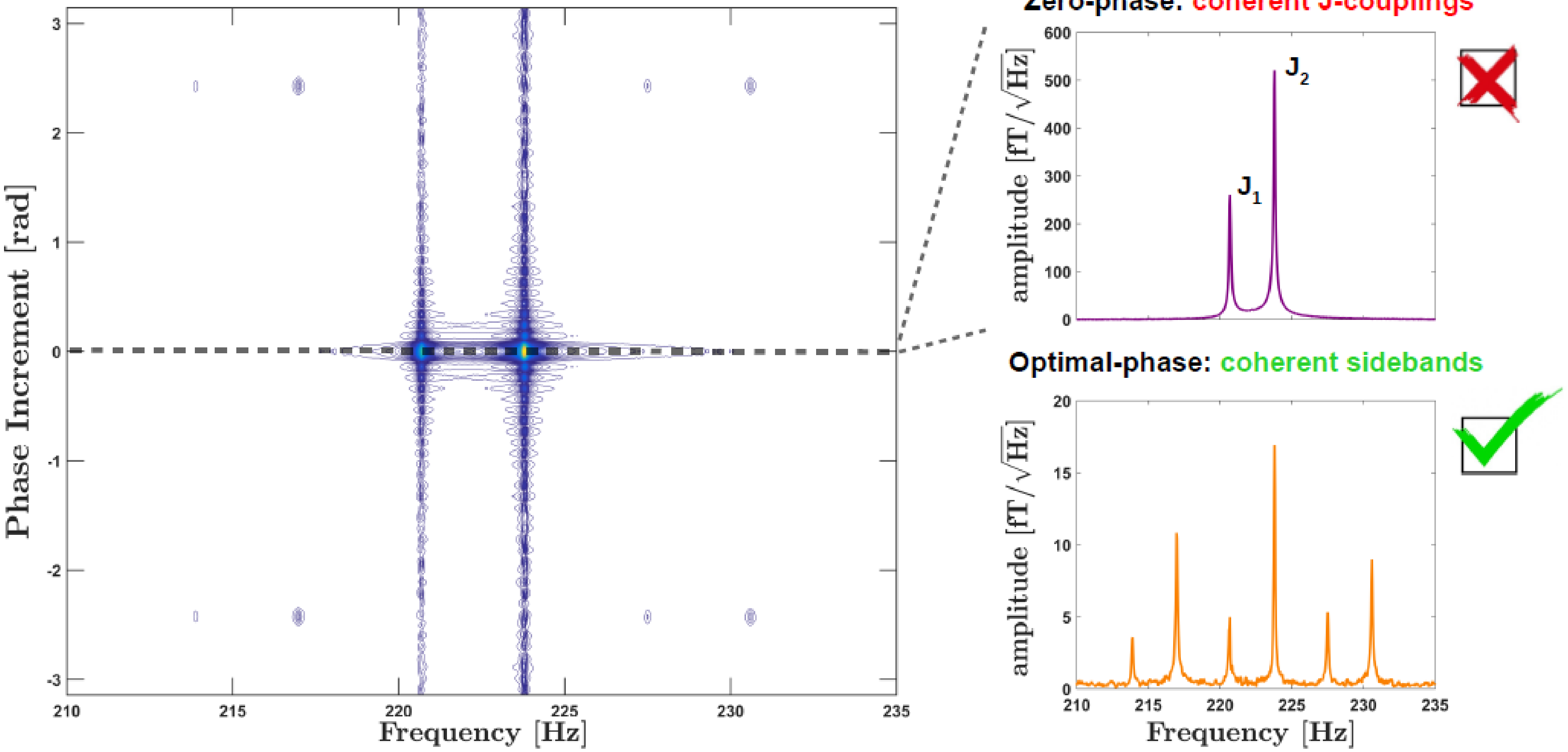
☒

Optimal-phase: coherent sidebands

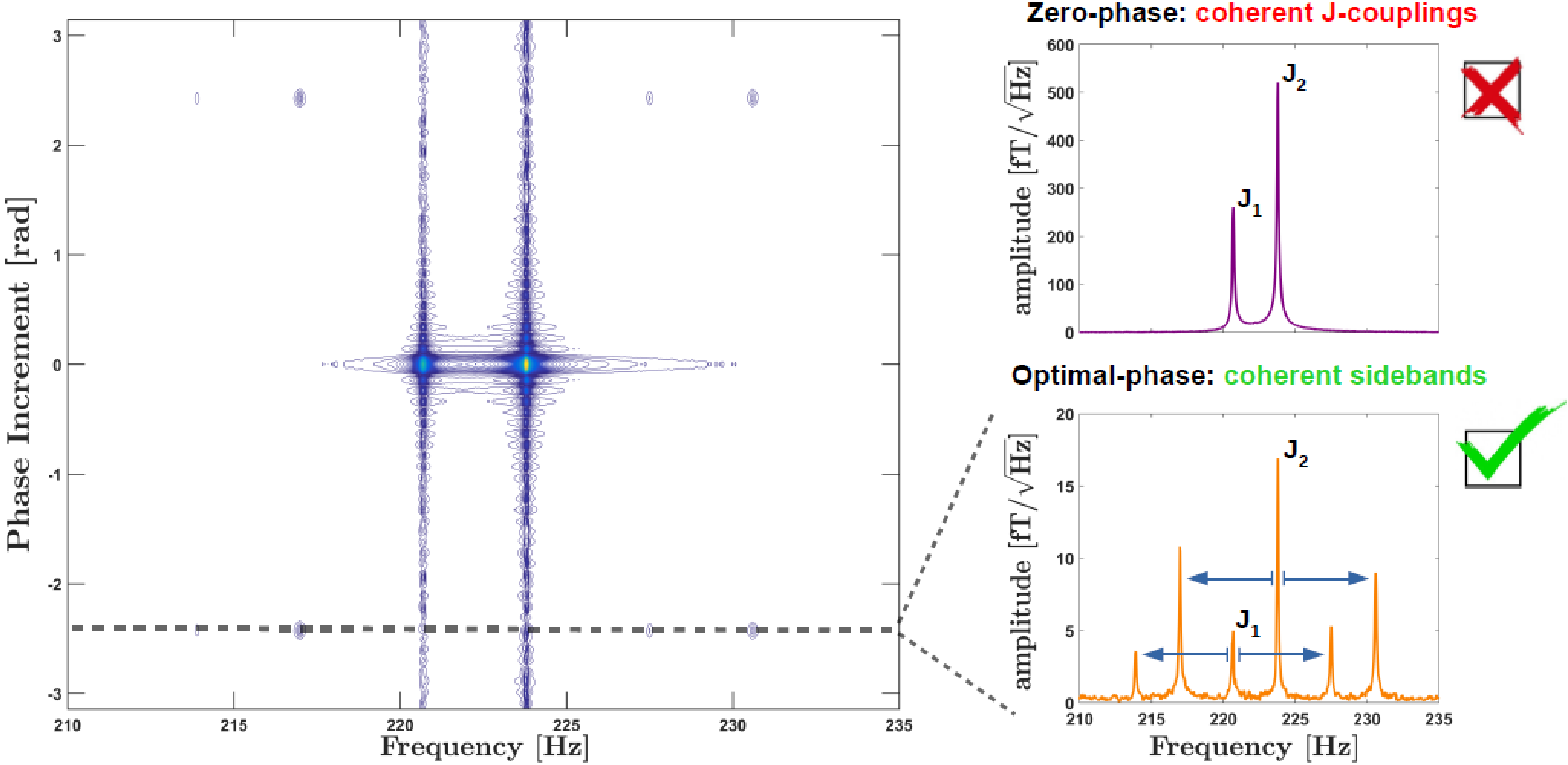


☑

Simulated signal – coherent averaging

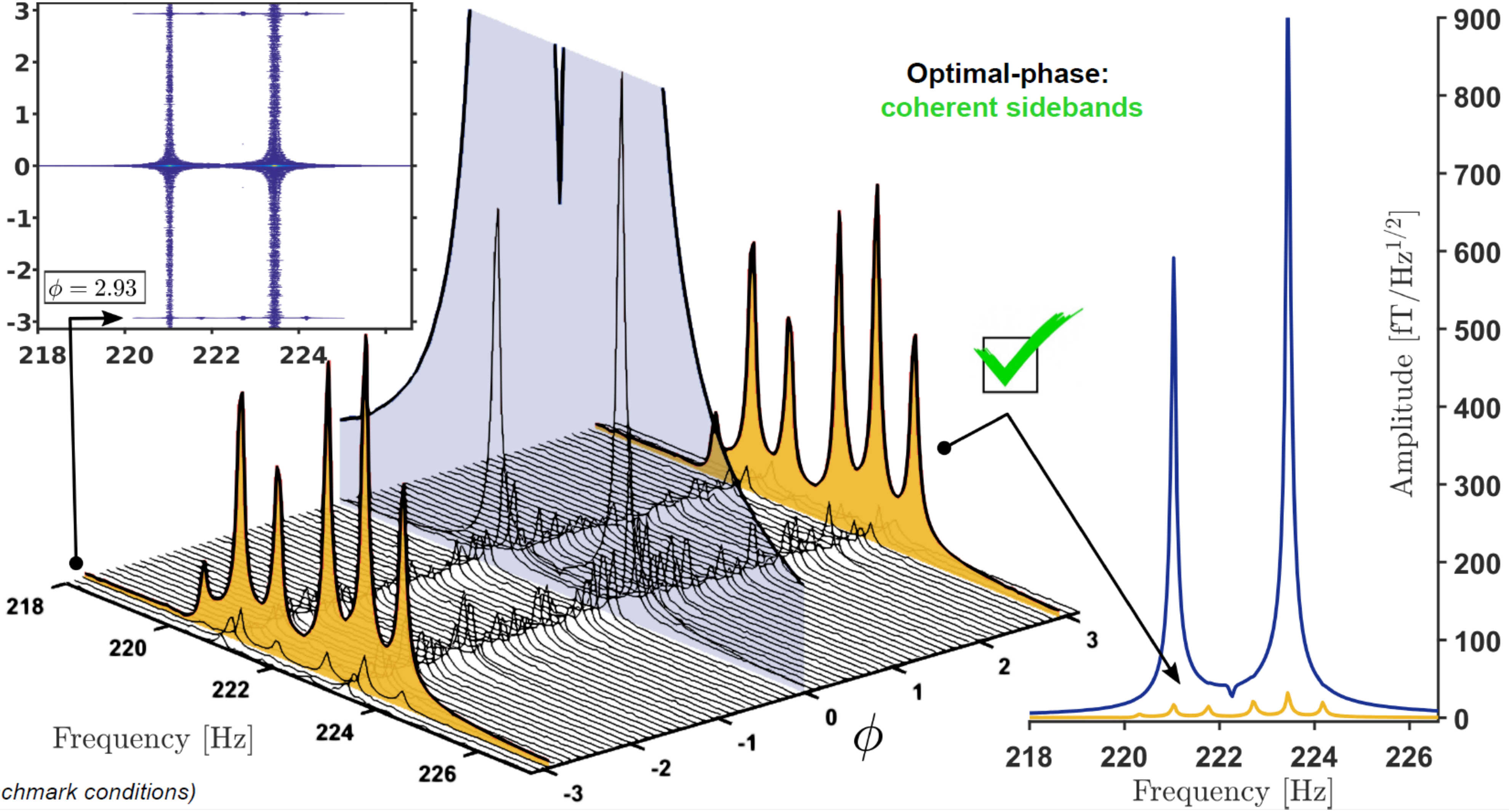


Simulated signal – coherent averaging



Zero-phase: coherent J-couplings

Optimal-phase: coherent sidebands

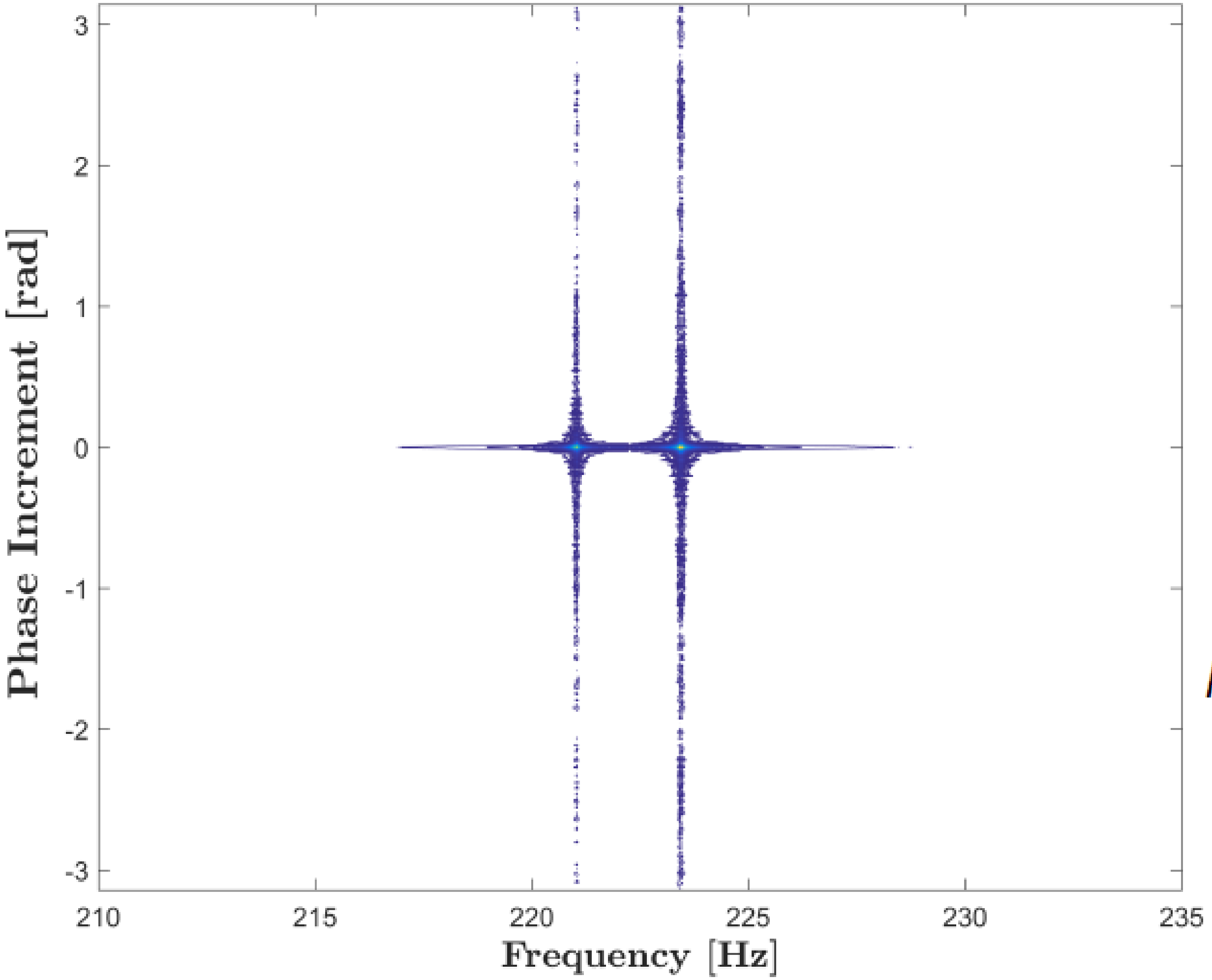


Optimal-phase:
coherent sidebands

☑

(*benchmark conditions)

Real Data – relating the noise floor to axion parameters



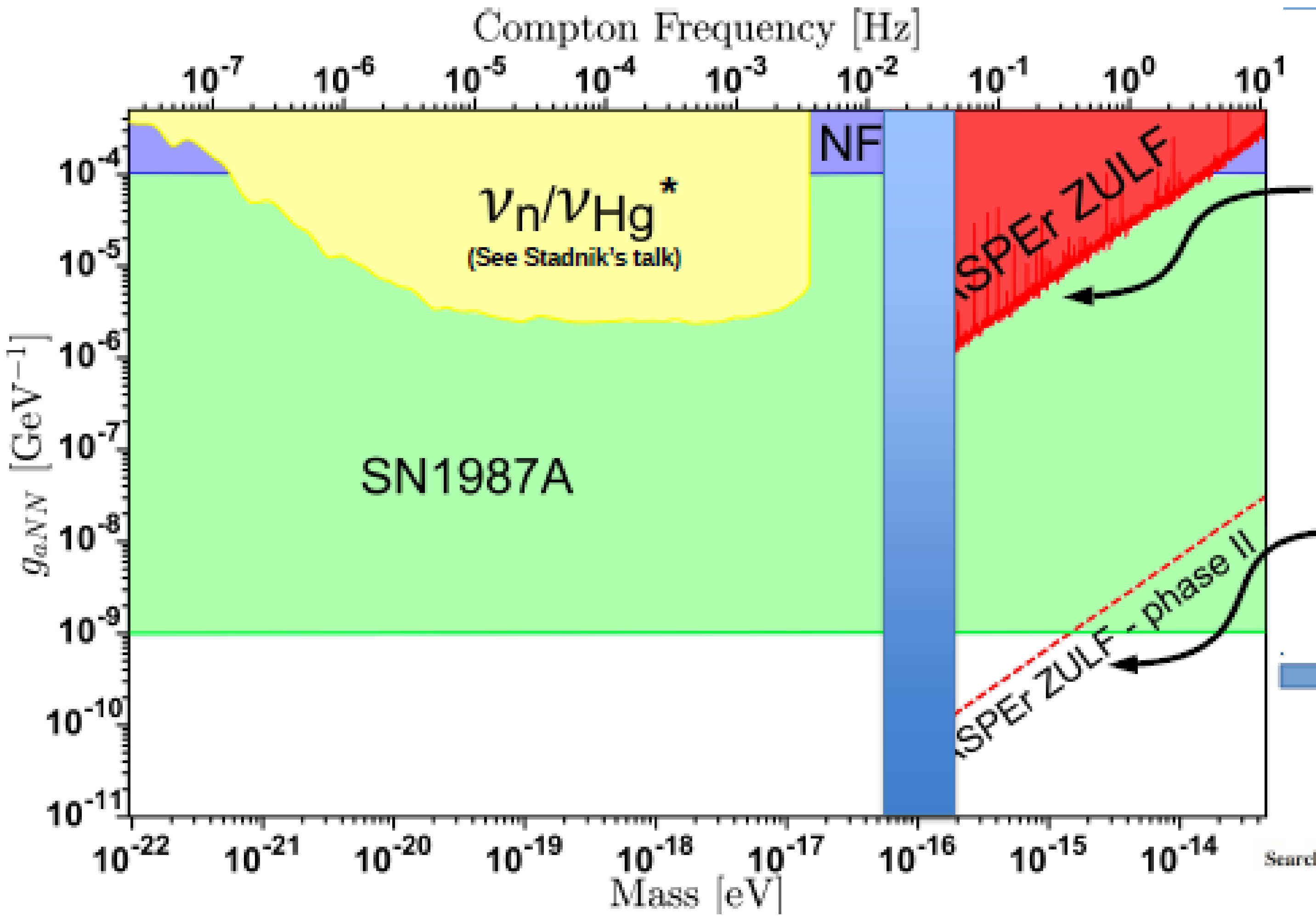
- No sidebands in *real* conditions

- New limits:
Amplitude & frequency

$$\vec{B}_{\mathrm{ALP}} \propto g_{\mathrm{aNN}} \cos(m_{\mathrm{ALP}} t)\vec{v}$$

New upper bounds at given frequencies

New limits



Current :
Thermal polarisation (ppm)
1440 x 30 s integration time

Next up:
parahydrogen-induced
hyperpolarization
(10'000x)

Higher masses:
- Resonant ZULF search
- CASPEr-Wind low/high field

*PHYSICAL REVIEW X 7, 041034 (2017)
Search for Axionlike Dark Matter through Nuclear Spin Precession in Electric and Magnetic Fields

+CASPEr Wind device ready 2018!

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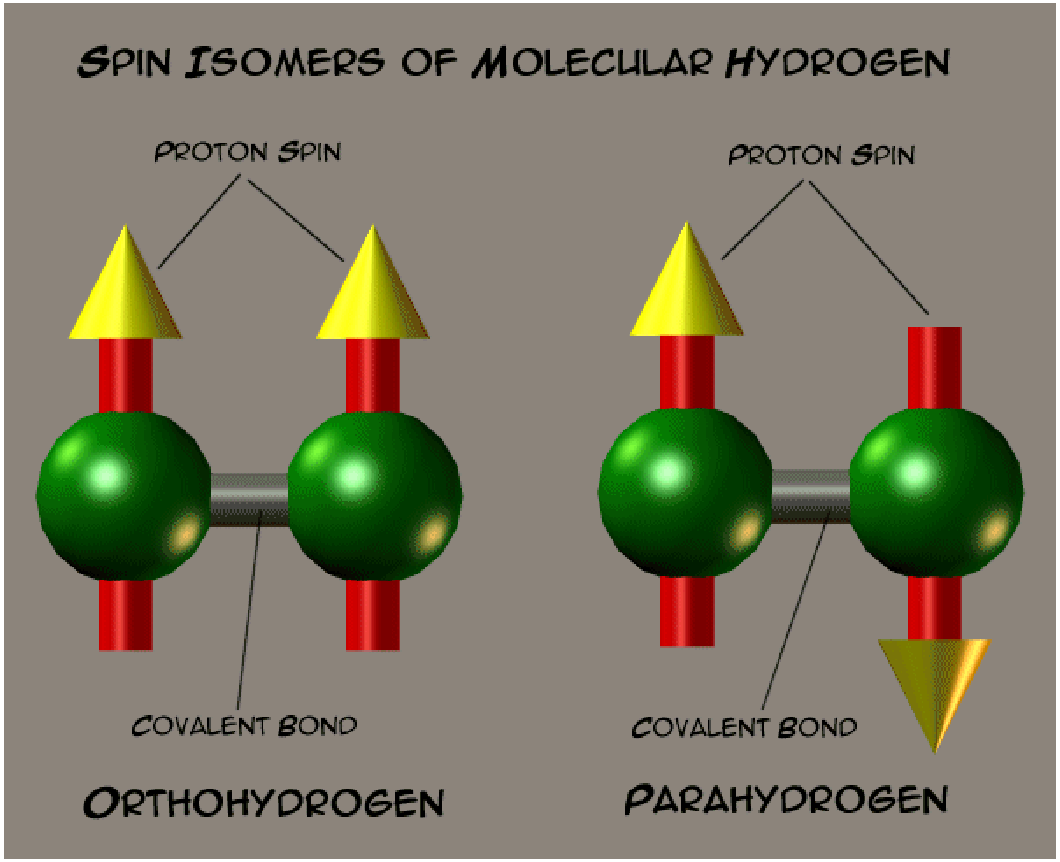
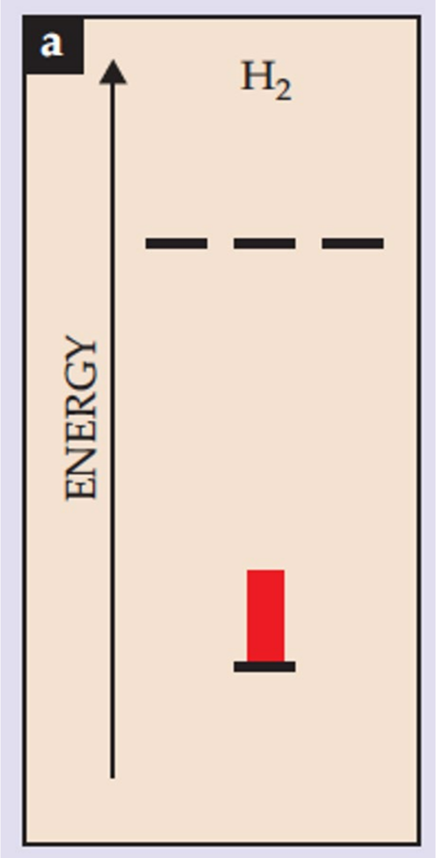
Parahydrogen induced polarization (PHIP)
Parahydrogen 101





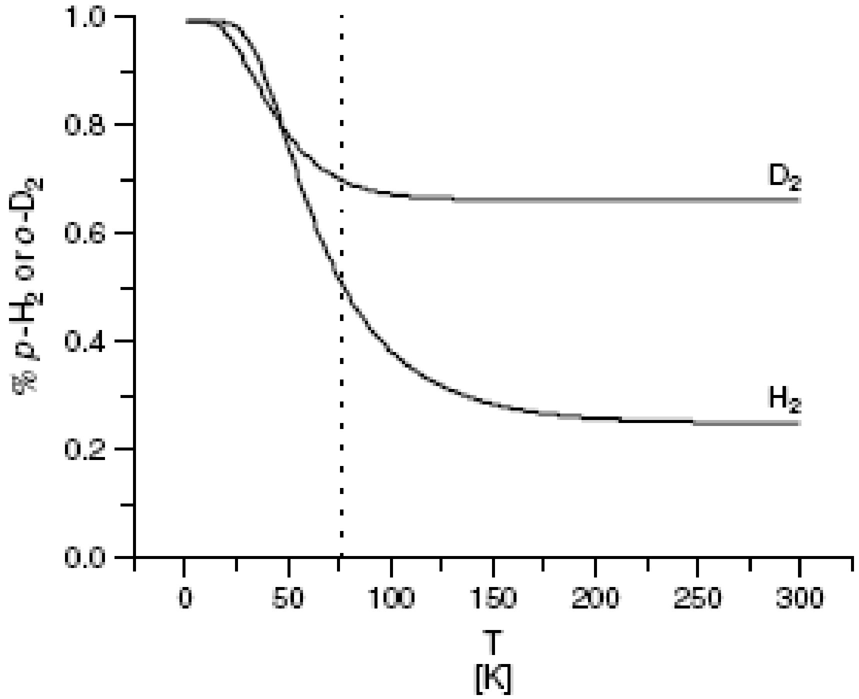
Odd J

Even J

http://en.wikipedia.org

Parahydrogen 102

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




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★]