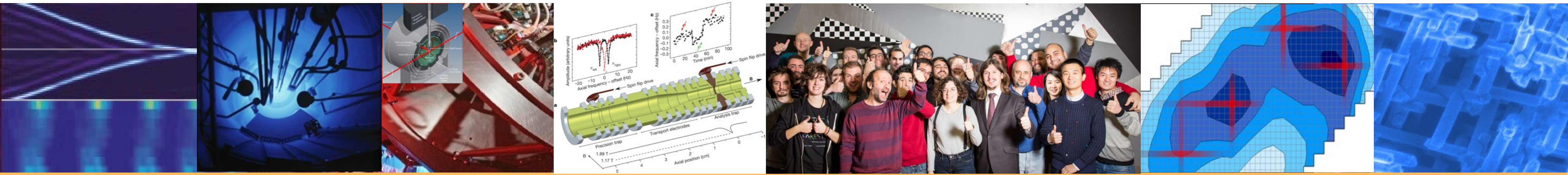
GSI HELMHOLTZ Helmholtz Institute Mainz JG|U

# Magnetometry and applications

*Arne Wickenbrock*
*Helmholtz Institute and JGU Mainz*
*14.05.2025*



- Magnetometry and applications

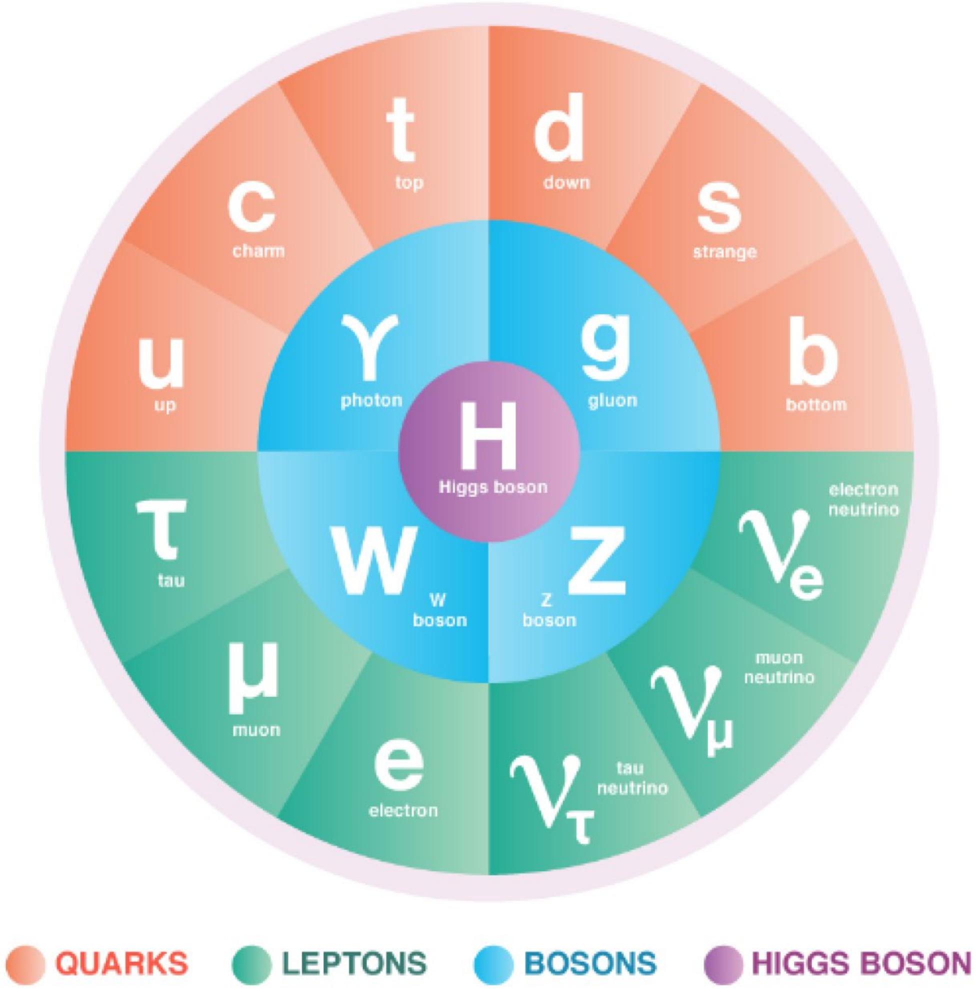
  - Introduction
  - Sensors: Vapor cell and diamond magnetometry
  - Interlude: Current measurements

  - Dark matter experiments in Mainz
  - Lineshape of gradient coupled galactic dark matter
  - Beyond magnetometry
  - Techniques

Ask questions!

# Standard model

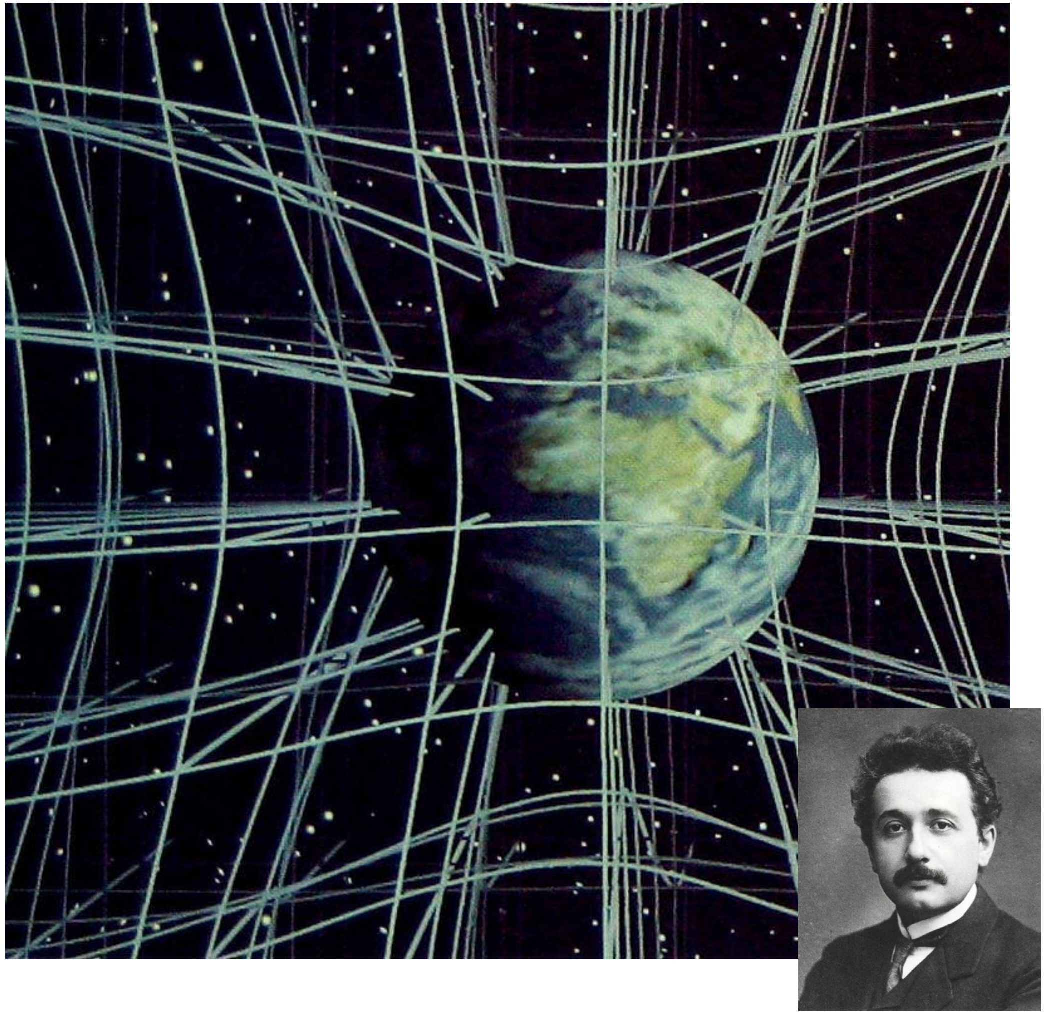
Quantum field theory




small: molecules, atoms, nuclei etc.

# General Relativity

No quantum theory



Large: planets, stars, galaxies

# Fundamental questions of physics

Quantum description of gravity?

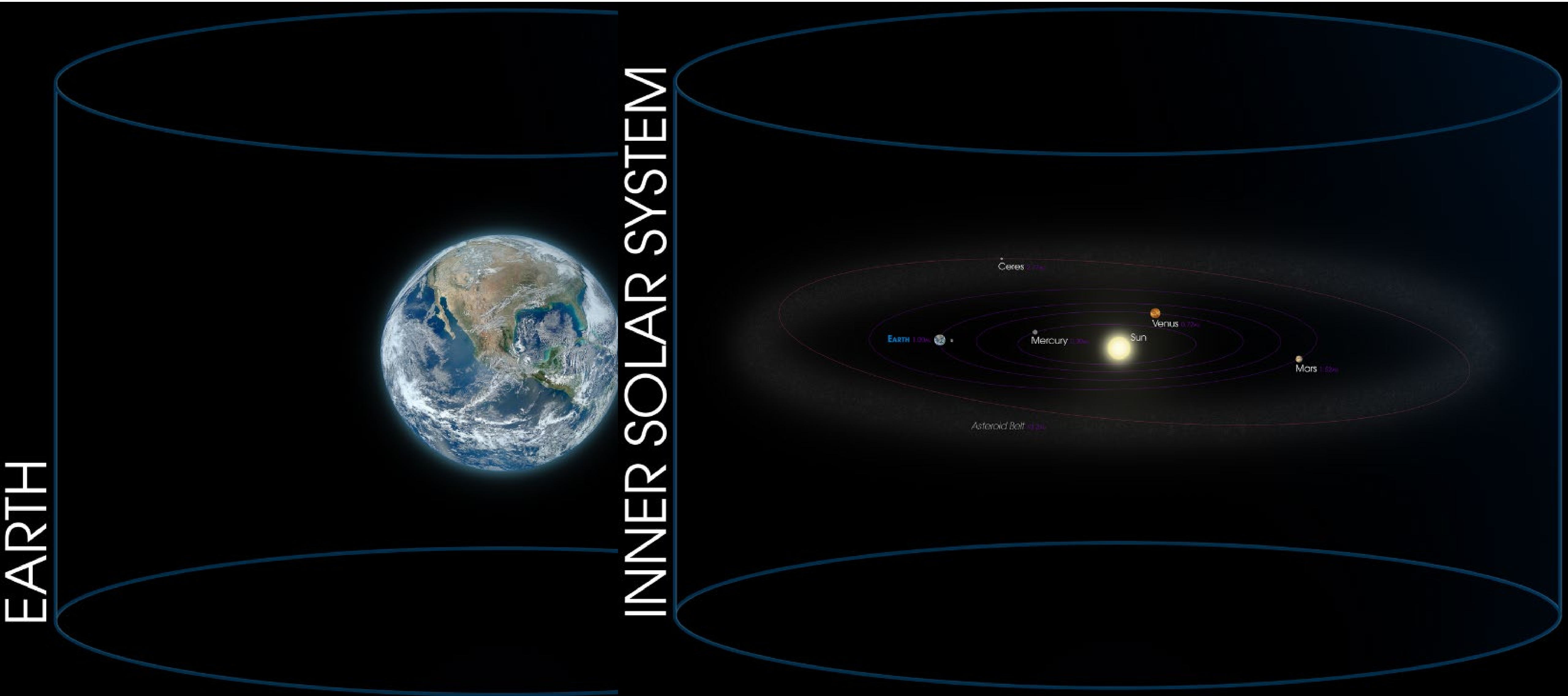
Where is antimatter?

What is dark energy?

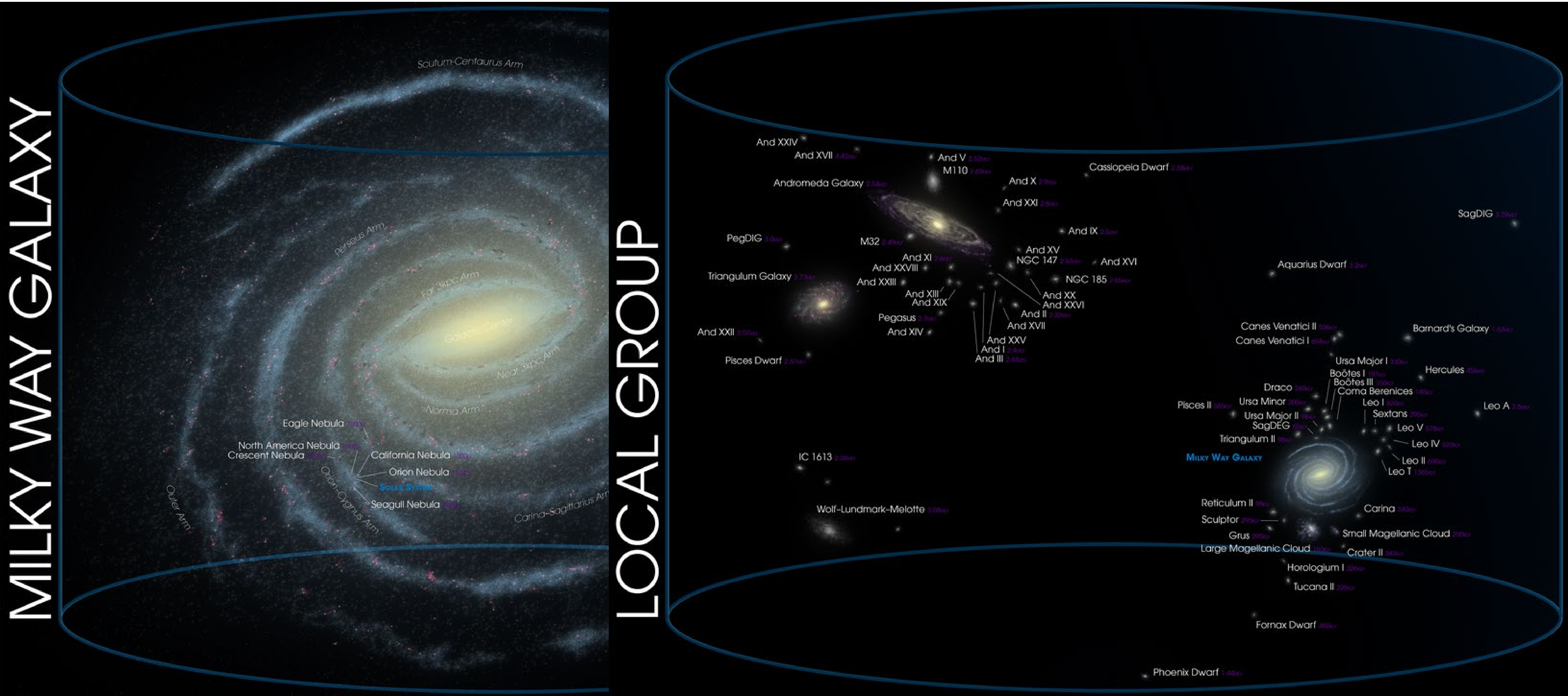
What is dark matter?

...

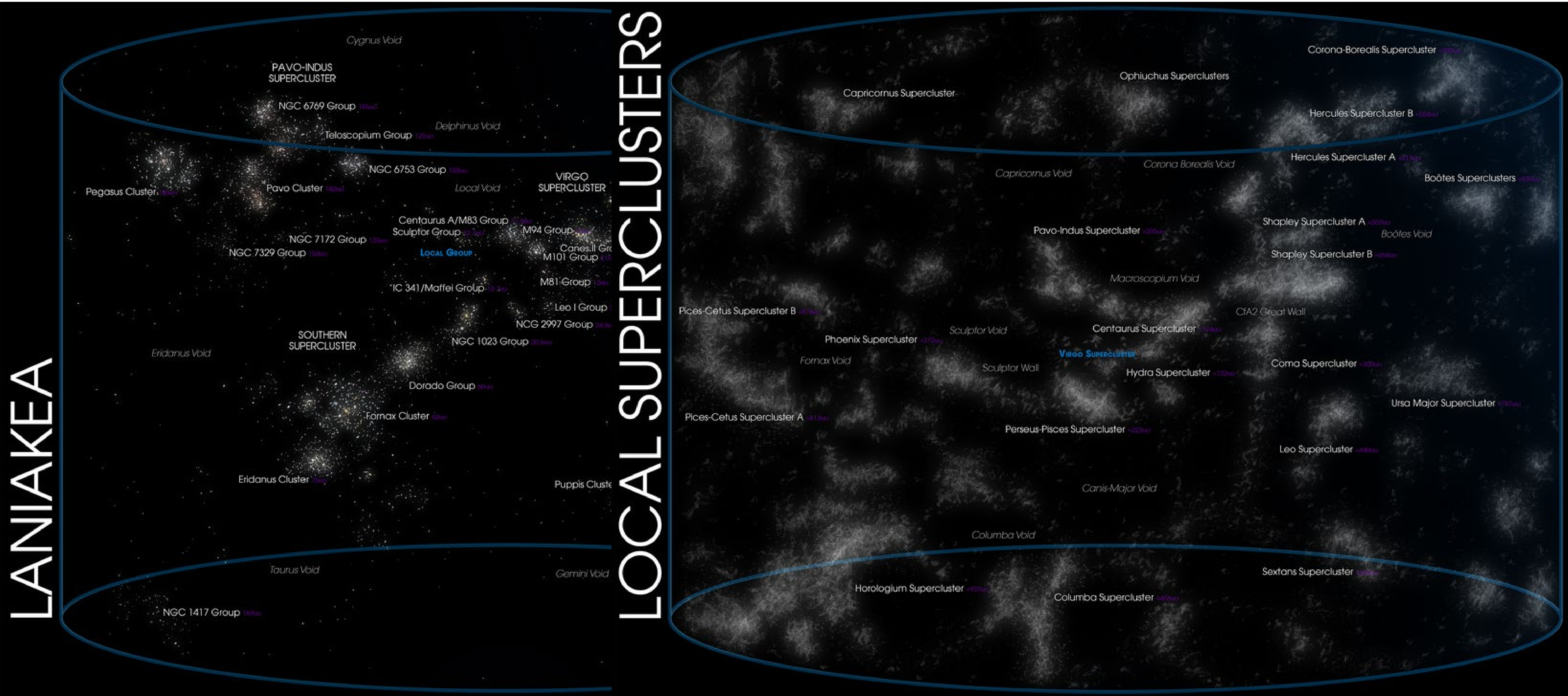
# Our universe (Wikipedia)



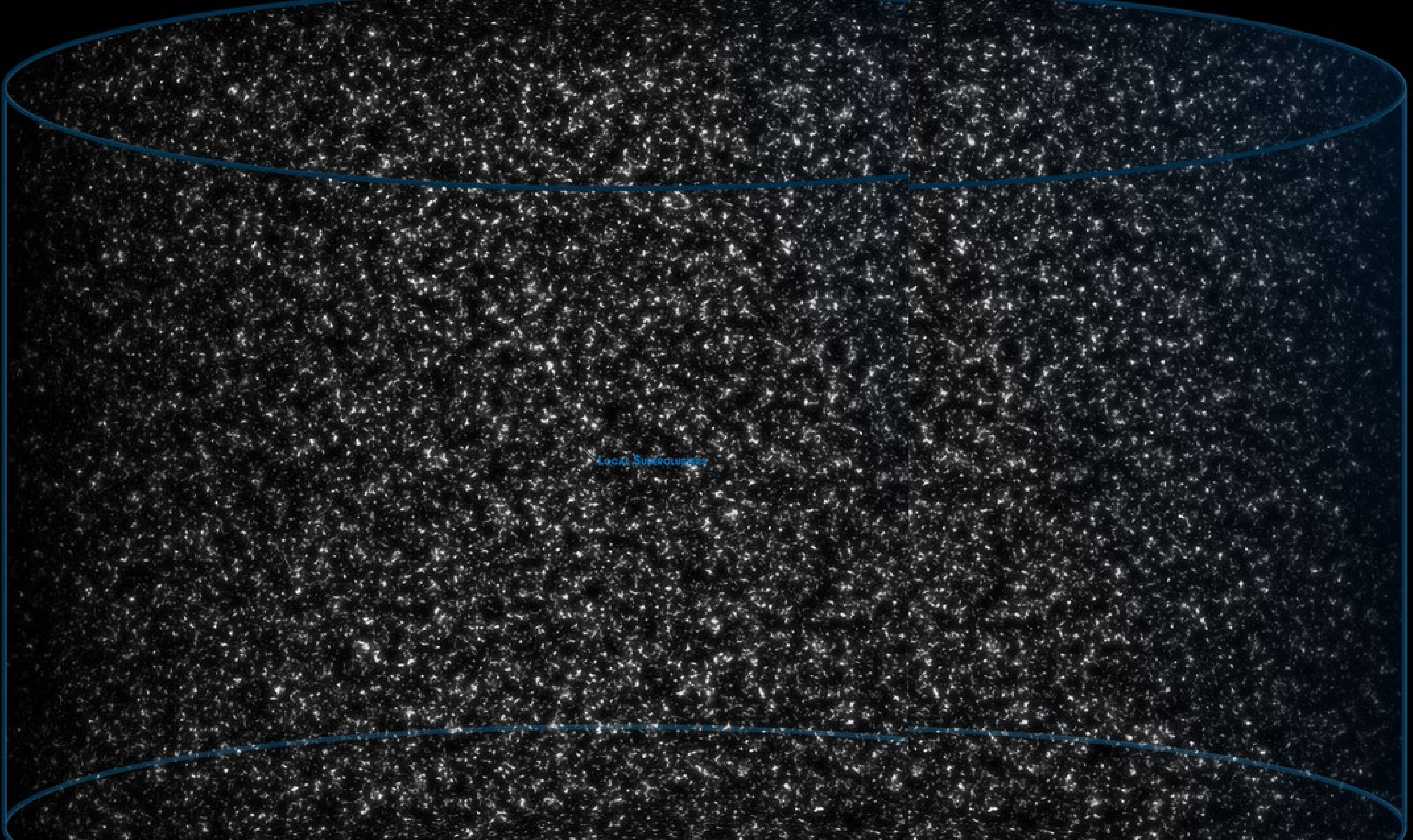
# Our universe



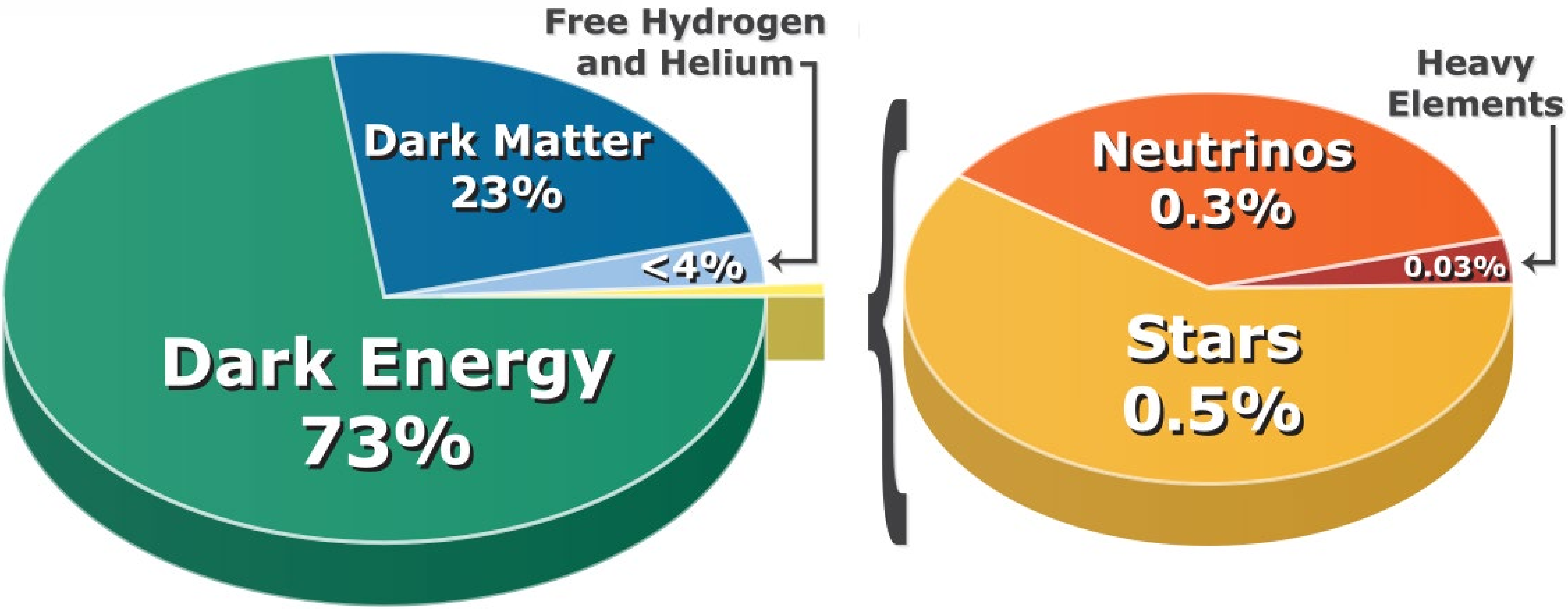
# Our universe



# OBSERVABLE UNIVERSE

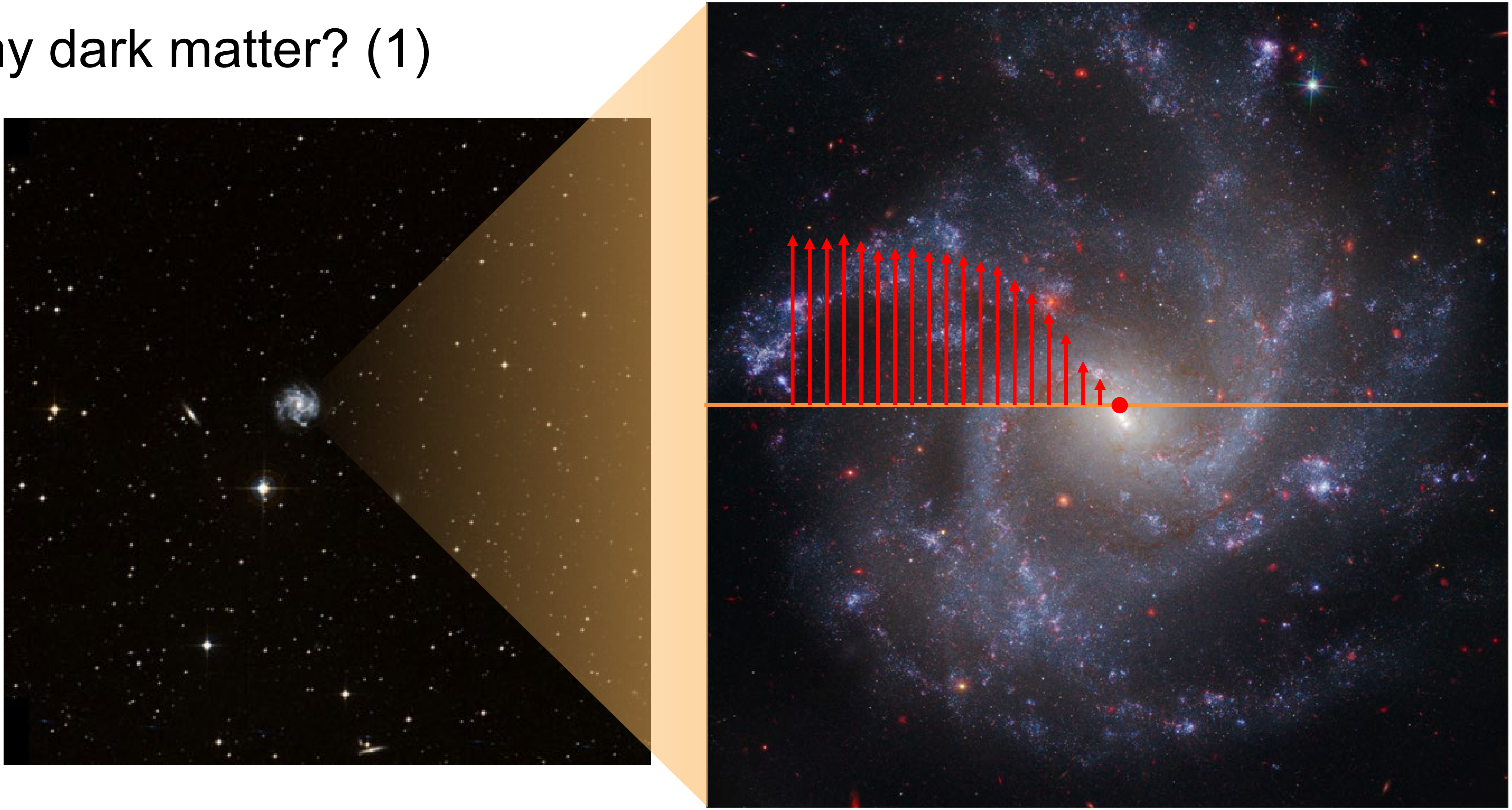


# The universe:

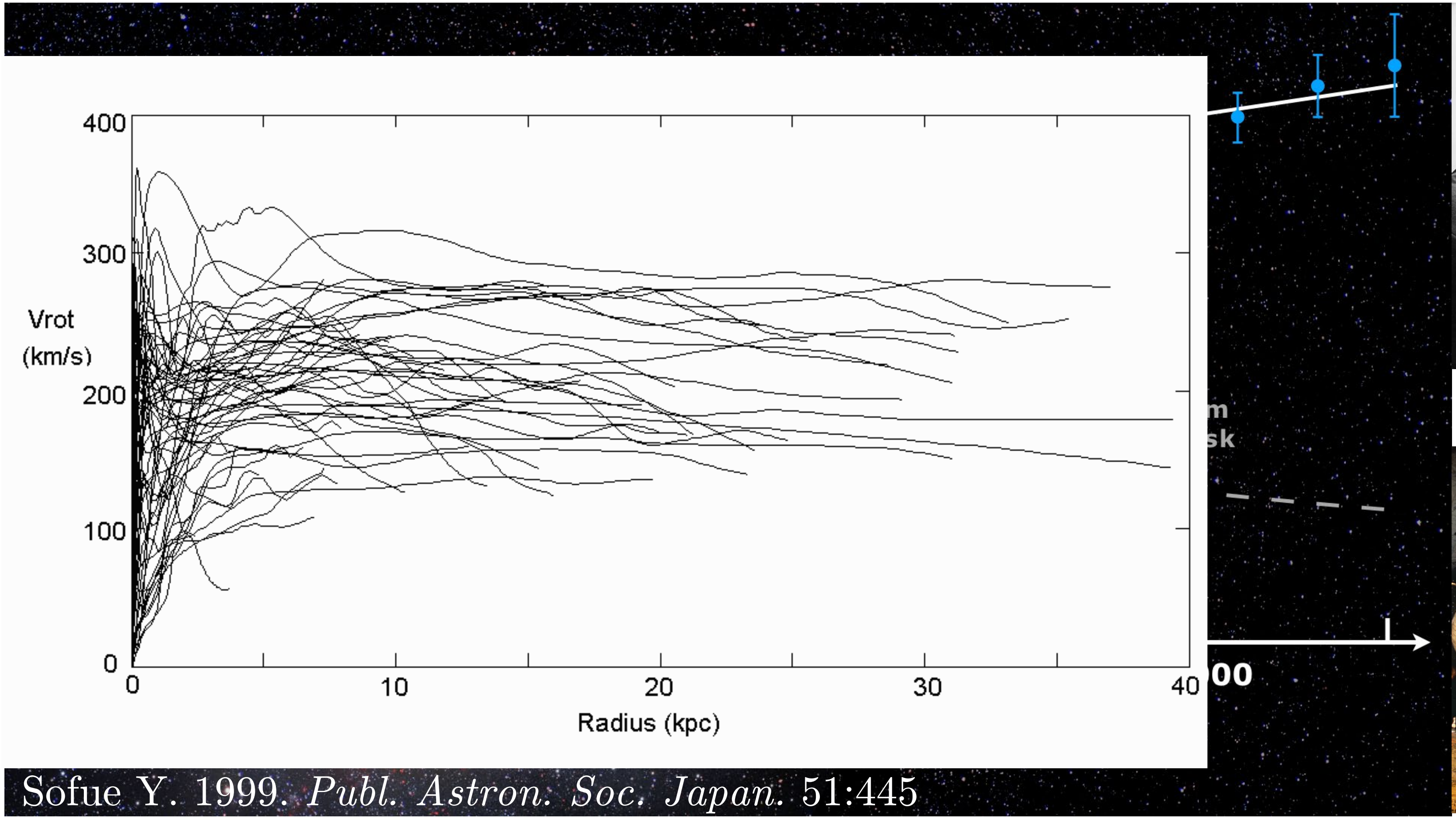



<4% described by the standard model!

## Why dark matter? (1)



# Galaxies rotate too fast!




By Mario De Leo - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=74398525

Peter Zwicky, 1933
Coma Cluster

“Dark matter”

Vera Rubin, 1980
Rotation curves

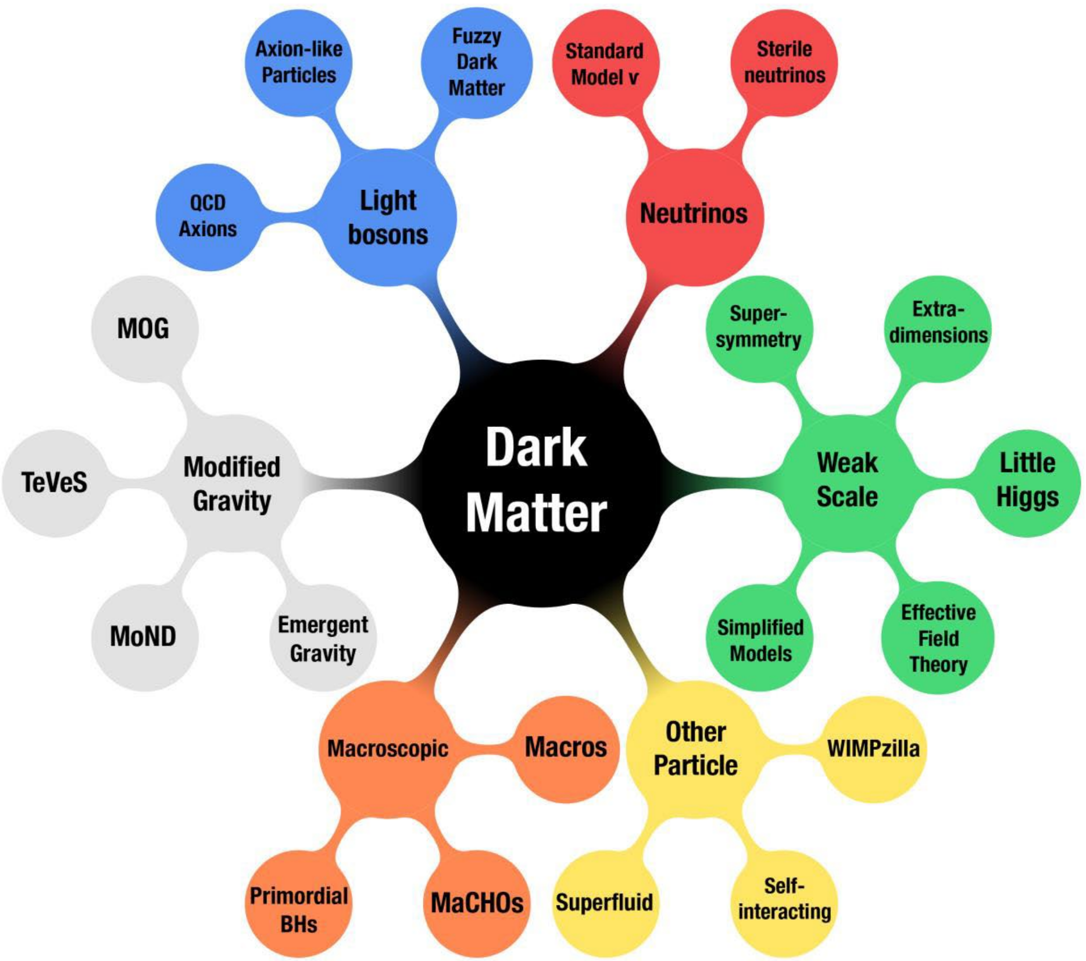
# Assumption: galaxies are embedded in dark matter

Dark matter acts via gravity

# Or?

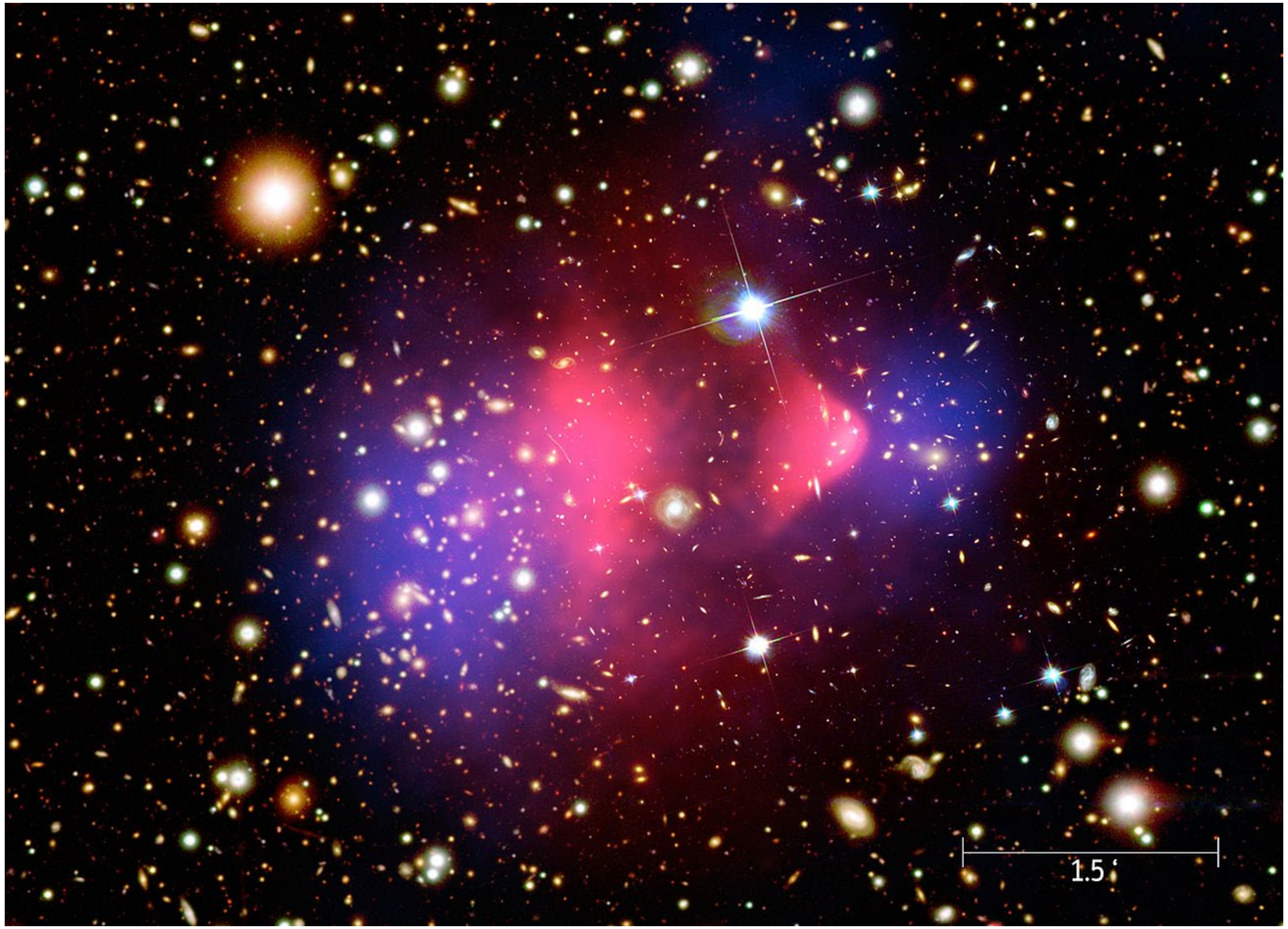
General relativity could be wrong?

→ **Modifizierte Newtonian Dynamics (MOND)**




G. Bertone and T. M. P. Tait

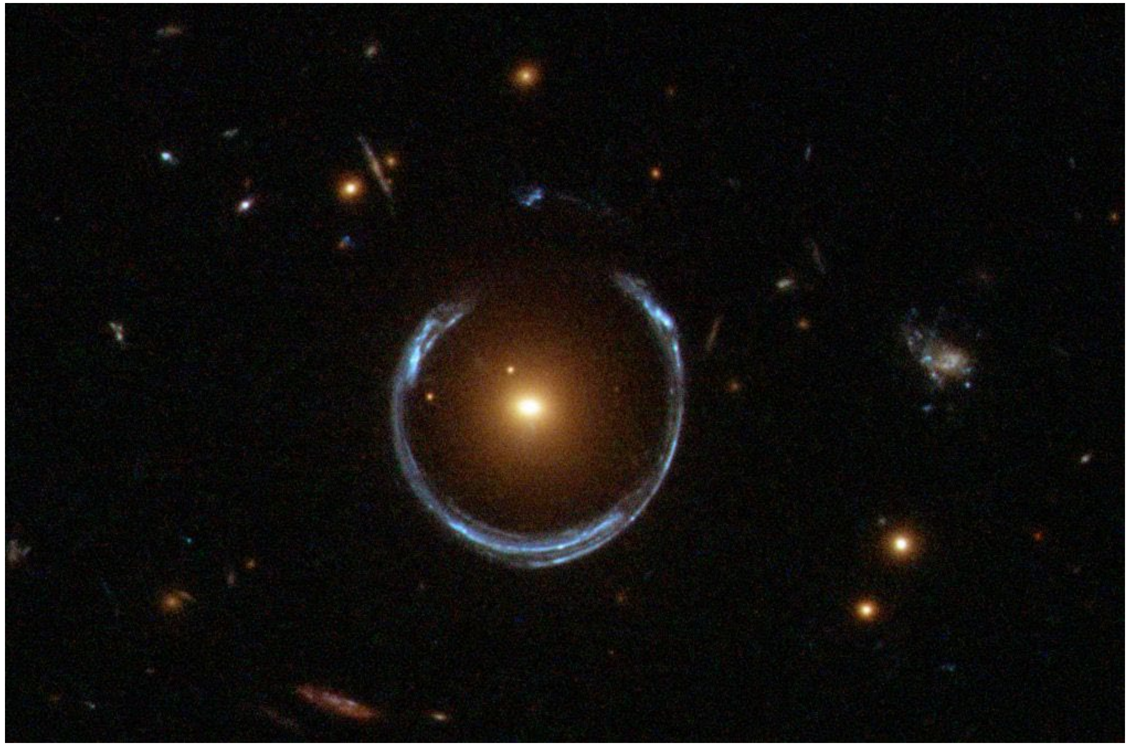
# Collisions of galaxy clusters? (2) (Bullet Cluster)




X-Ray emission

Reconstructed mass

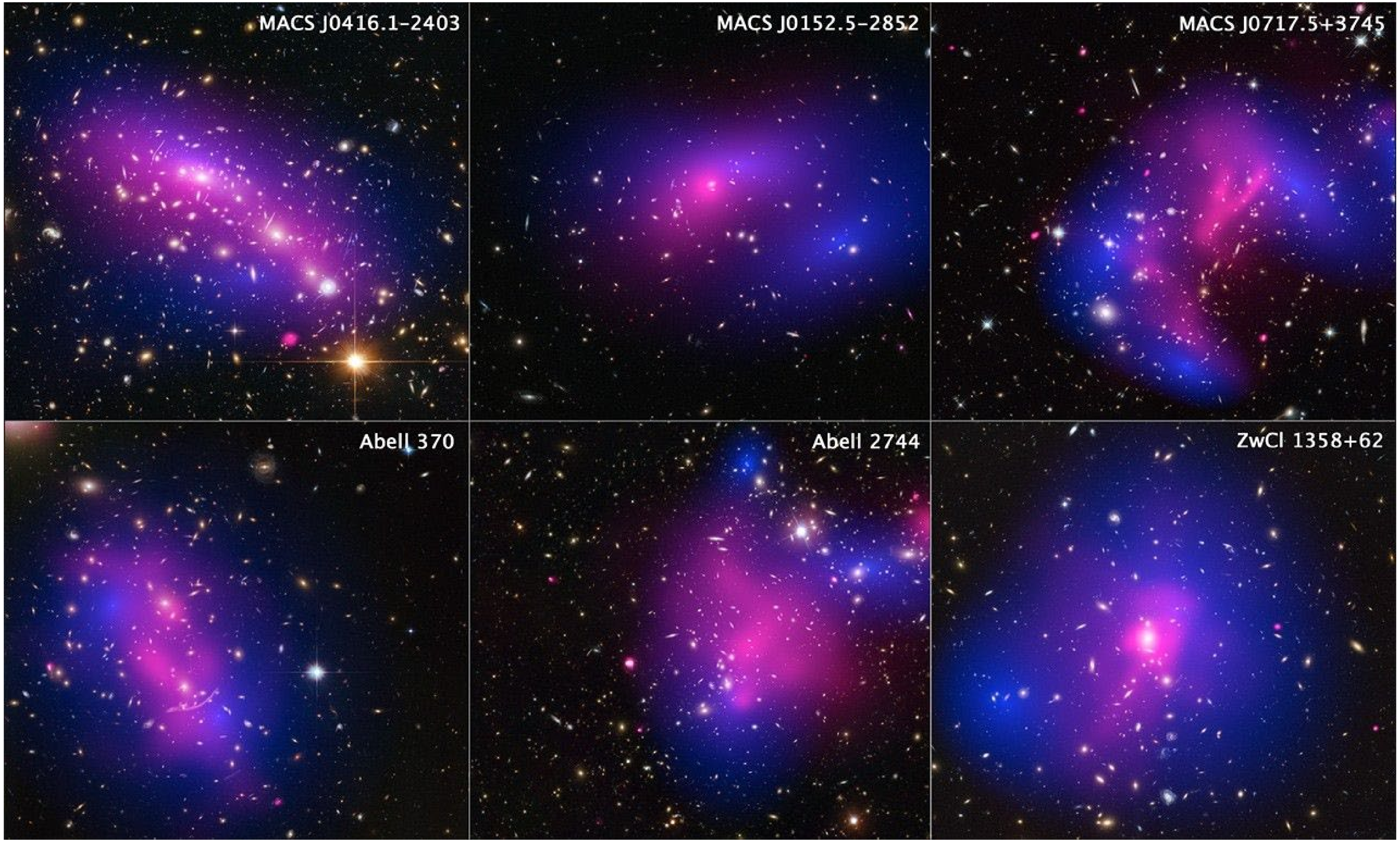
Gravitational lensing effects



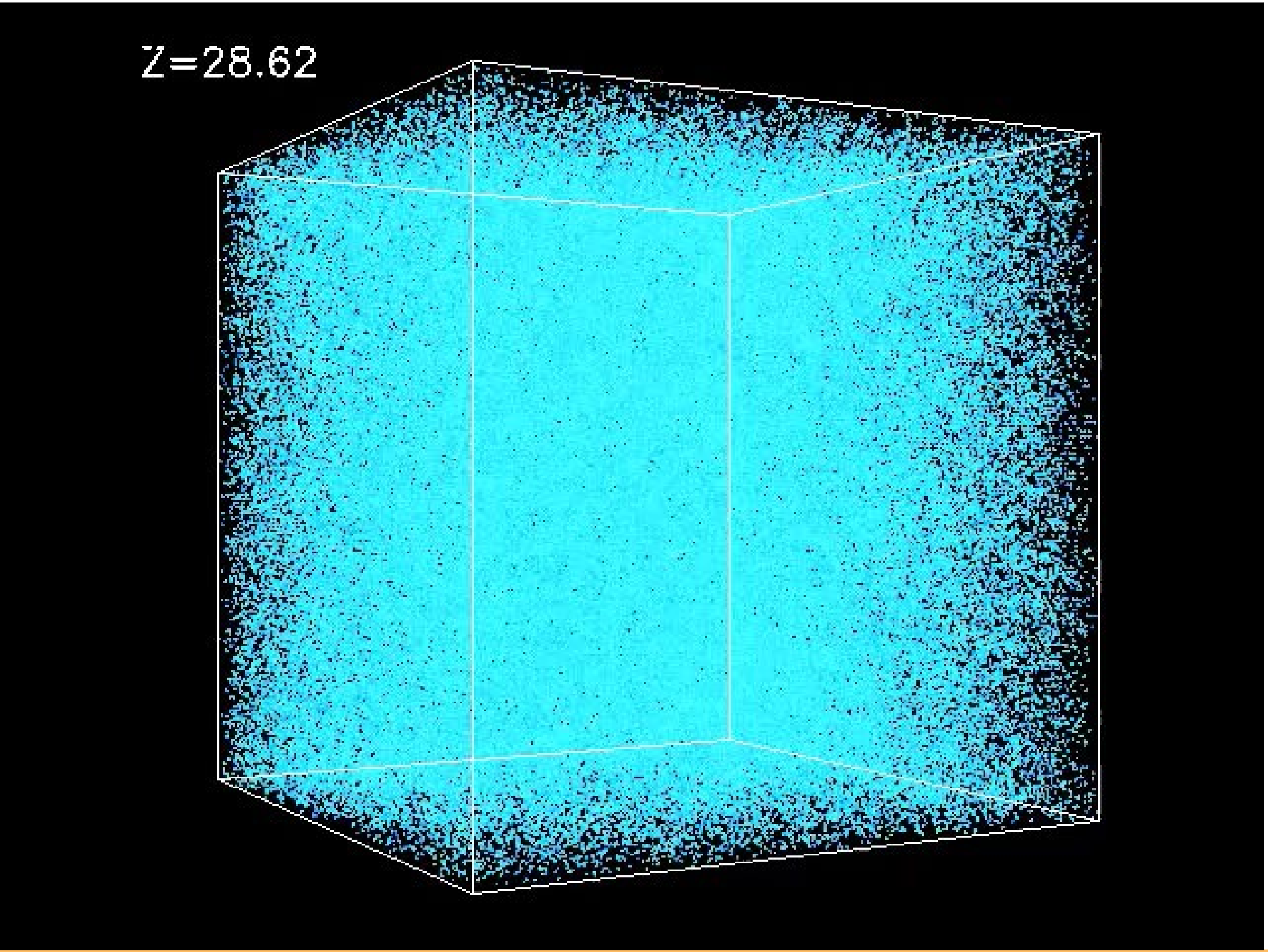
Center of mass and gas separated

By NASA/CXC/M. Weiss - Chandra X-Ray Observatory: 1E 0657-56, Public Domain, https://commons.wikimedia.org/w/index.php?curid=10749247

# Collision of galaxy clusters? (2)



# Structure formation of the universe



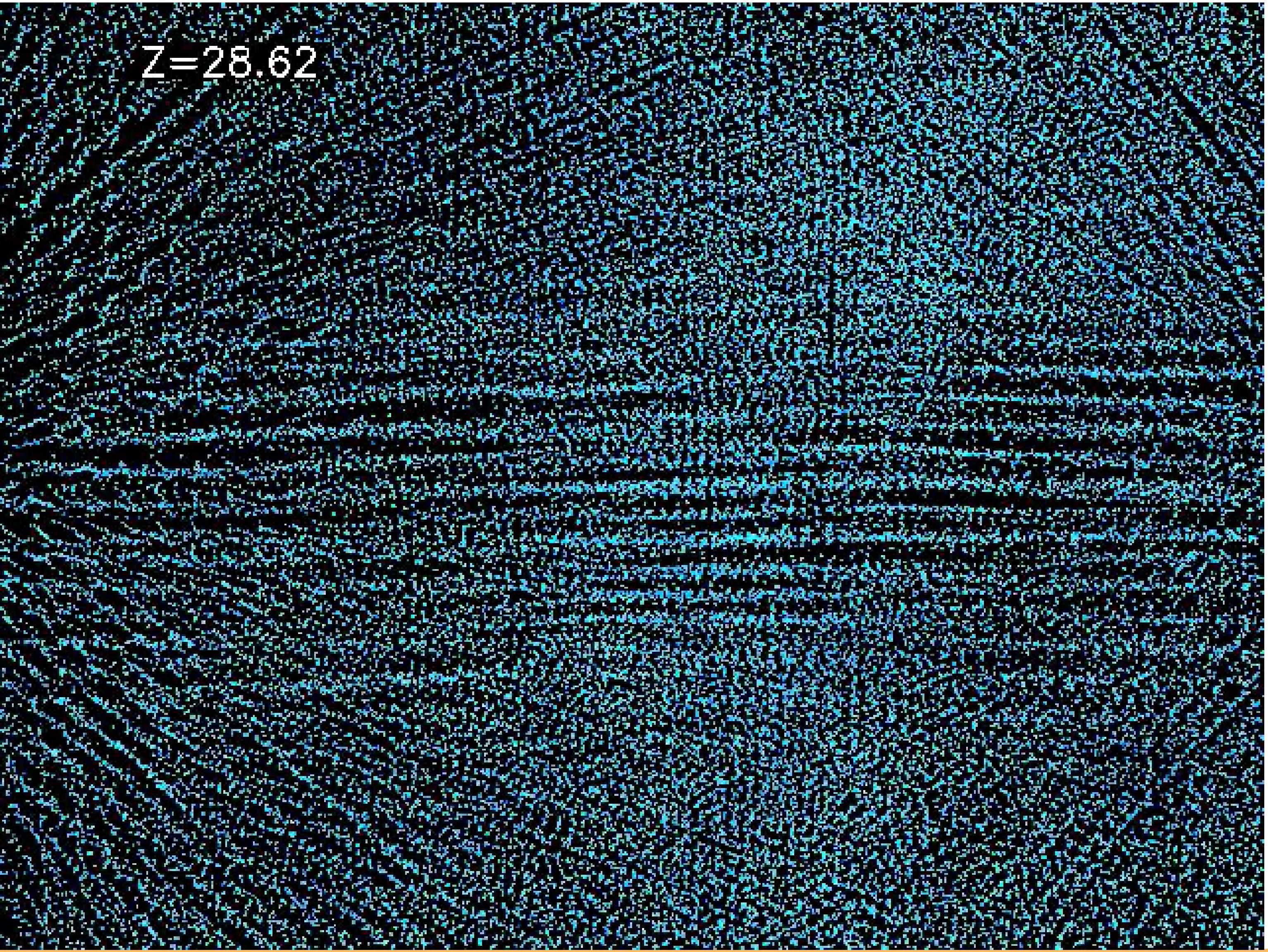

140 million light years

Computer simulation of the universe:

No dark matter
No structure

https://cosmicweb.uchicago.edu/filaments.html

# Because it is so nice!




14 Millionen Lichtjahre

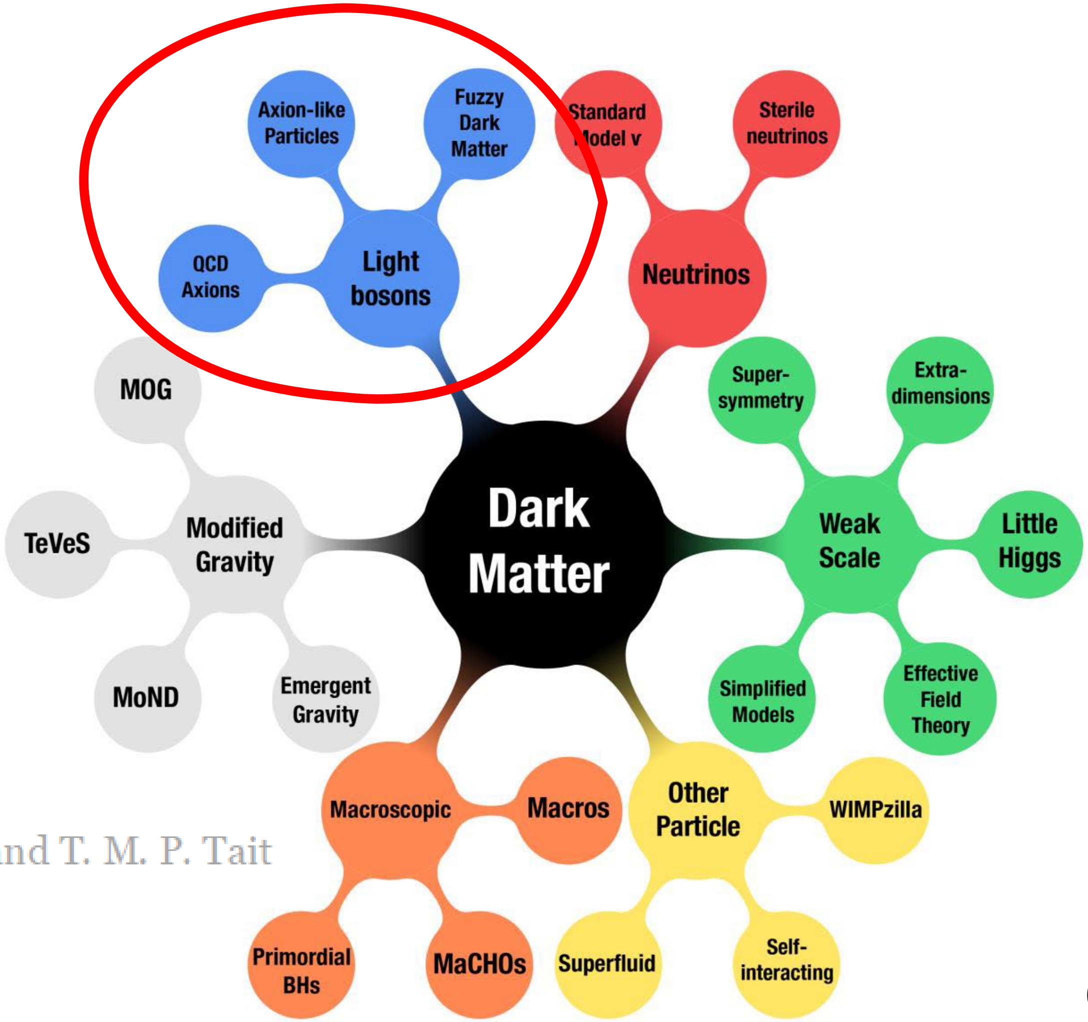
Computer simulation

Formation of galaxy groups

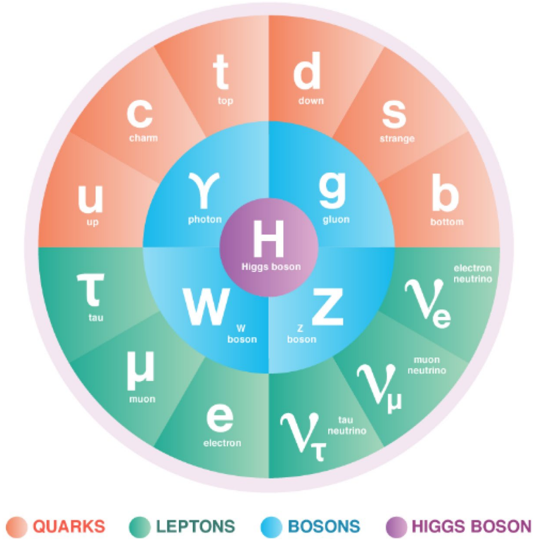
Even better:
https://www.tng-project.org/media/

https://cosmicweb.uchicago.edu/filaments.html

# What can dark matter be?




G. Bertone and T. M. P. Tait




+ new particle


Minimal assumptions:

Detectable!

(unknown mass, unknown frequency)

Axion-like dark matter = oscillating background field!

# Axion (ALP) Interactions



Gravity

+

Gauge Fields

Fermions

Most Searches

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

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

CASPEr-E

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

CASPEr-Gradient, GNOME, QUAX ....

$HfF^+$, T. Roussy et al., Phys. Rev. Lett. **126**, 171301 (2021)

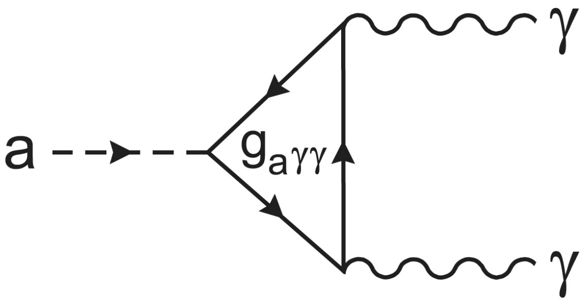
nEDM, C. Abel *et al.*, Phys. Rev. X **7**, 041034 (2017).

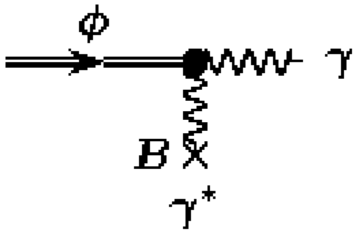
Axion-like dark matter = free photons!

Axion-like dark matter = oscillating electric dipole moments!

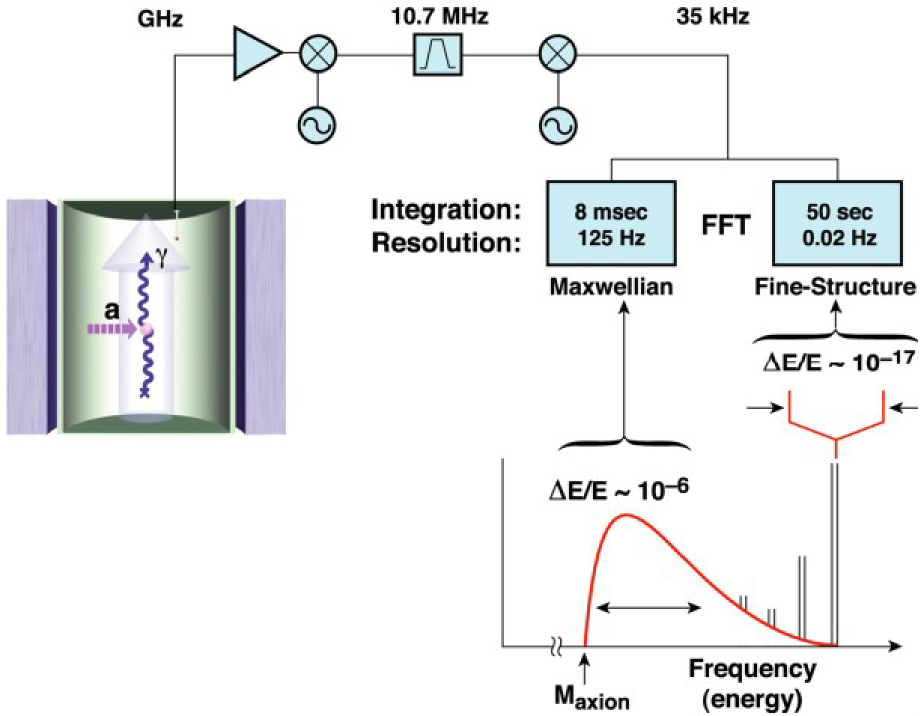
Axion-like dark matter = oscillating magnetic fields on spins!

# 1. Galactic axion searches - Haloscopes

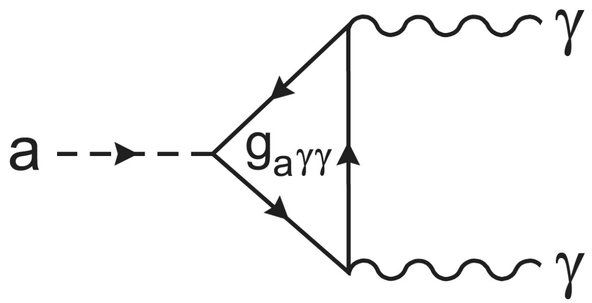


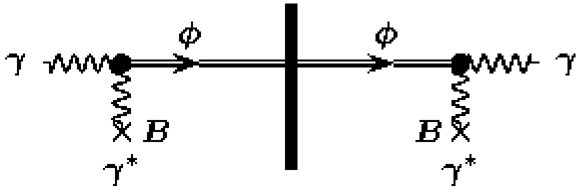



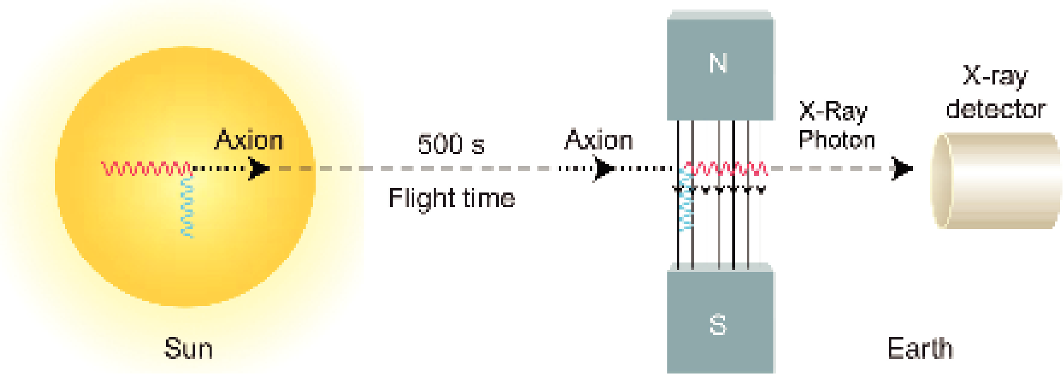

e.g. ADMX (*Axion Dark Matter eXperiment*)

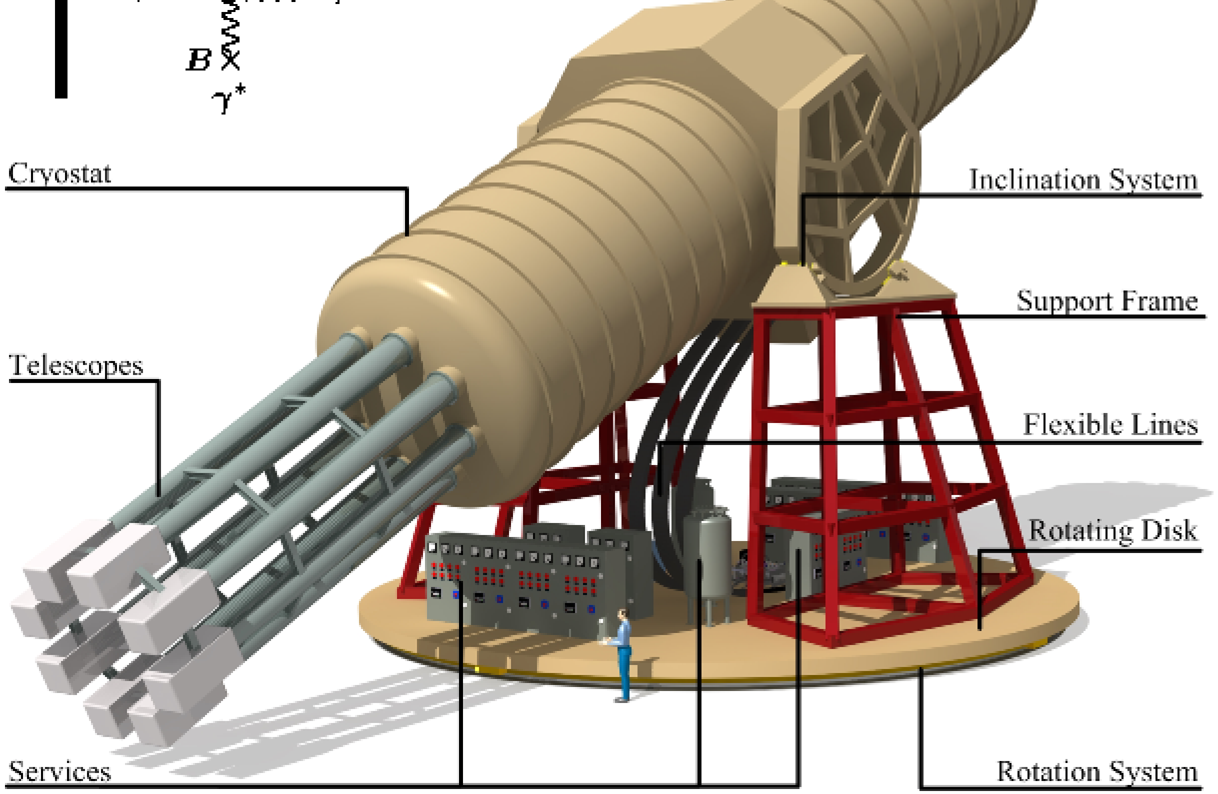



# 2. Axions from stars: International Axion Observatory (IAXO)



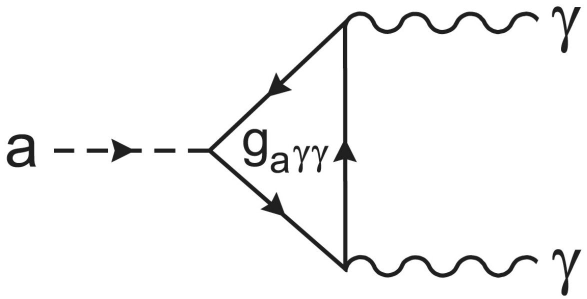



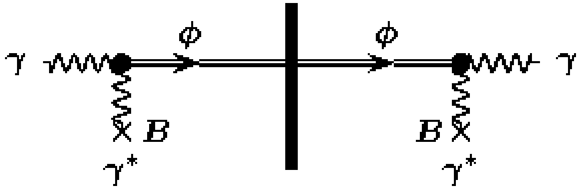



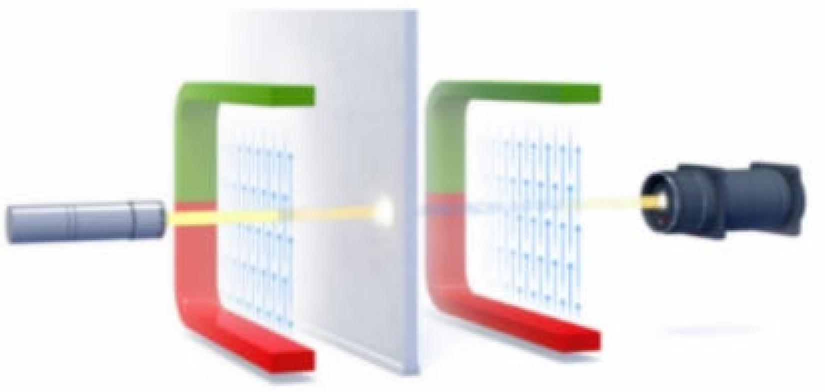

Pathfinder is on the way!

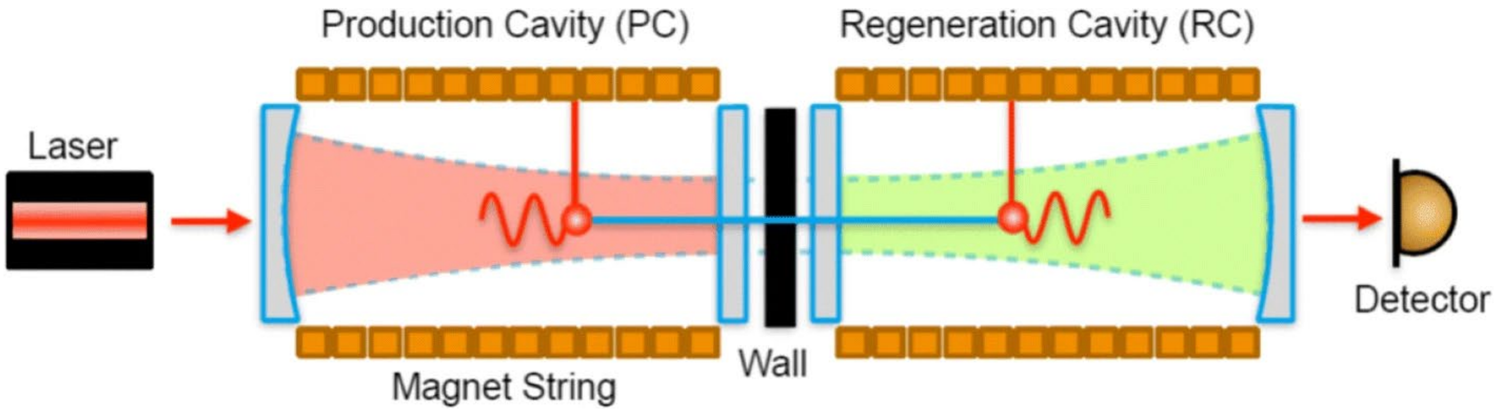
# 3. Light Shining through the wall experiment – Fifth forces

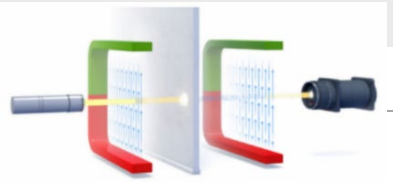


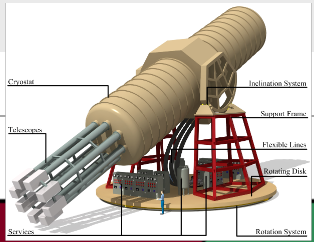



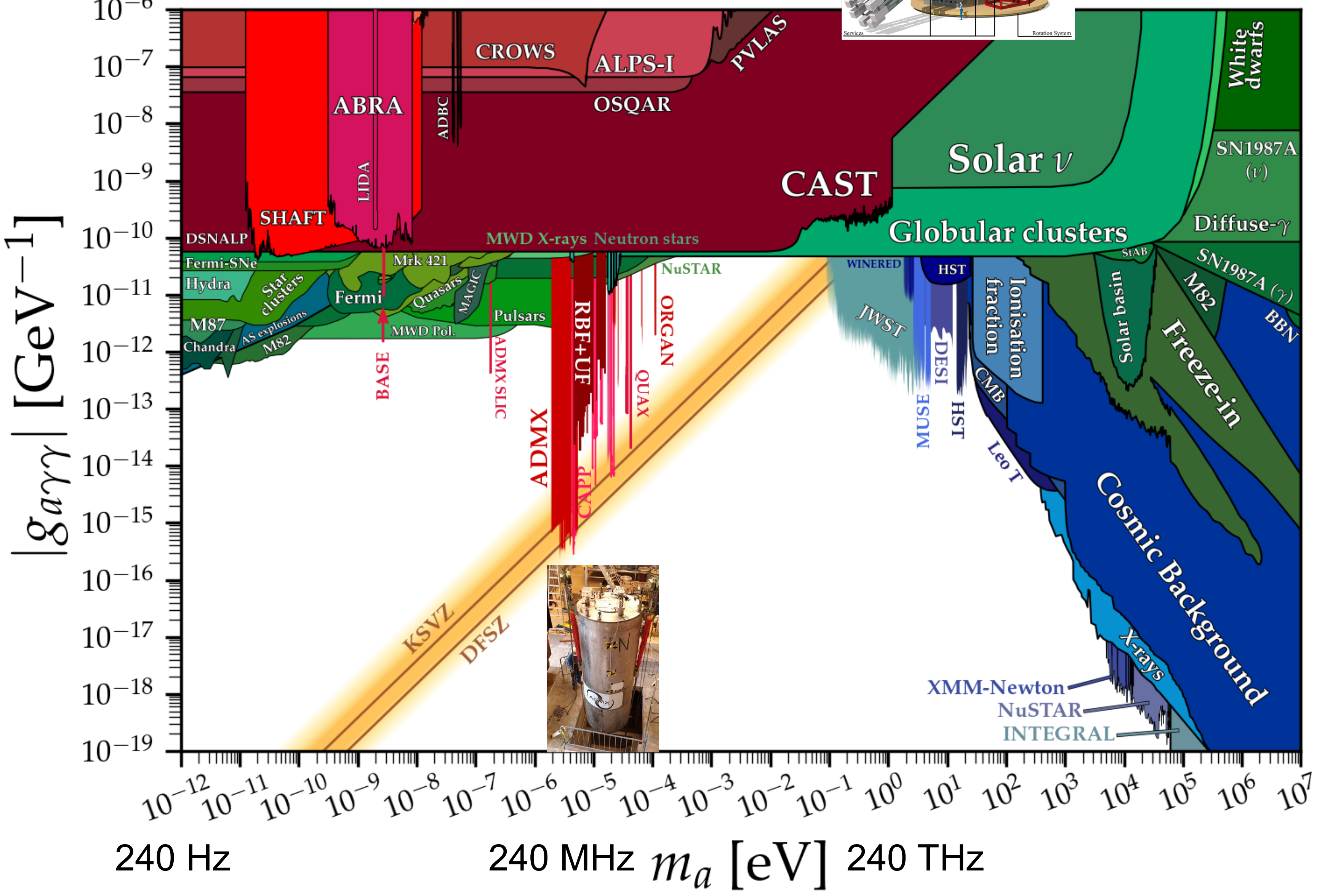

e.g. ALPS II @ DESY (Light shining through a wall)











Ciaran O'Hare

10.5281/zenodo.3932429

# How to search for Axions (ALPs) ?

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## Axion (ALP) Interactions

Gravity

+

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)

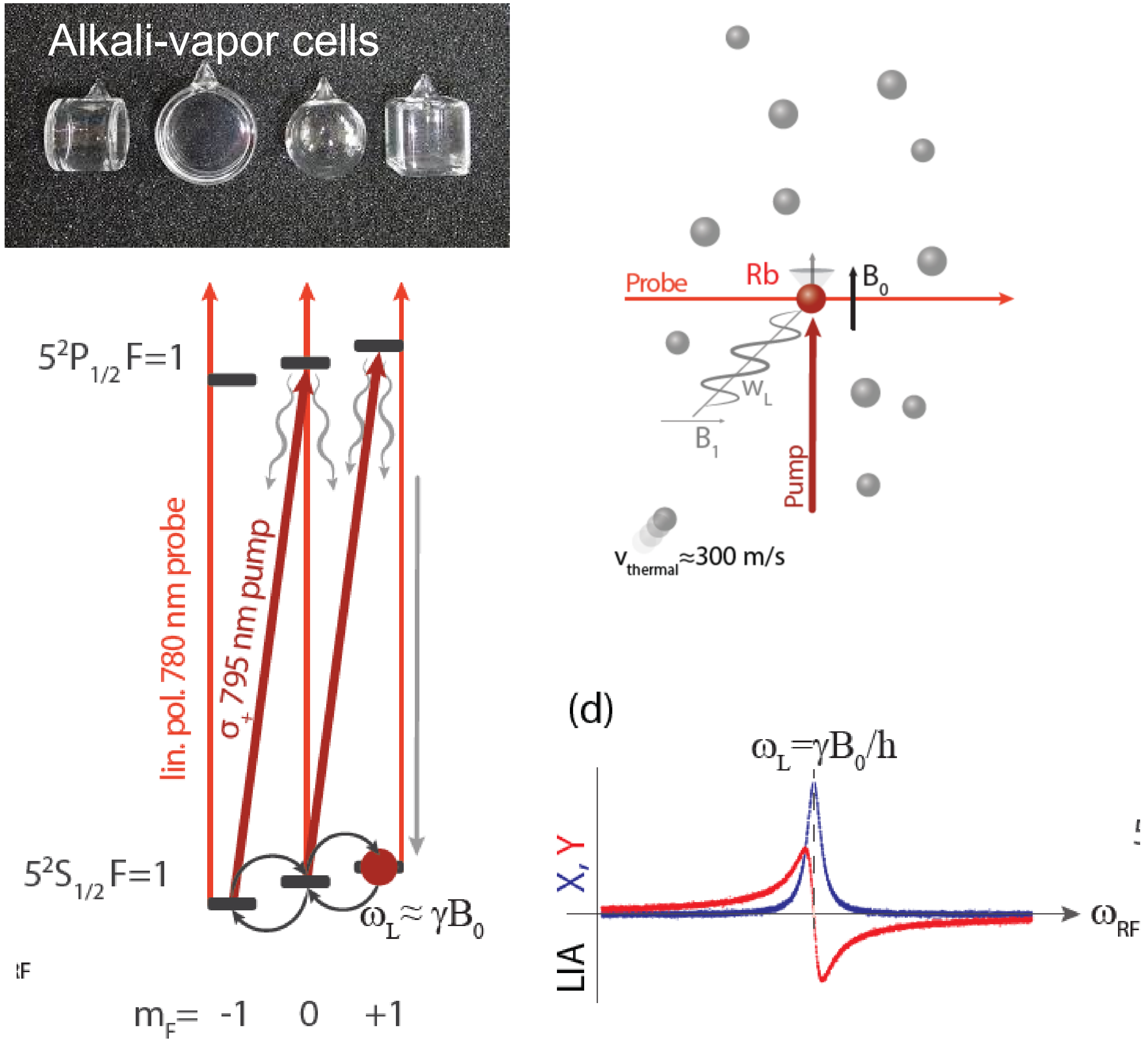
Fermions

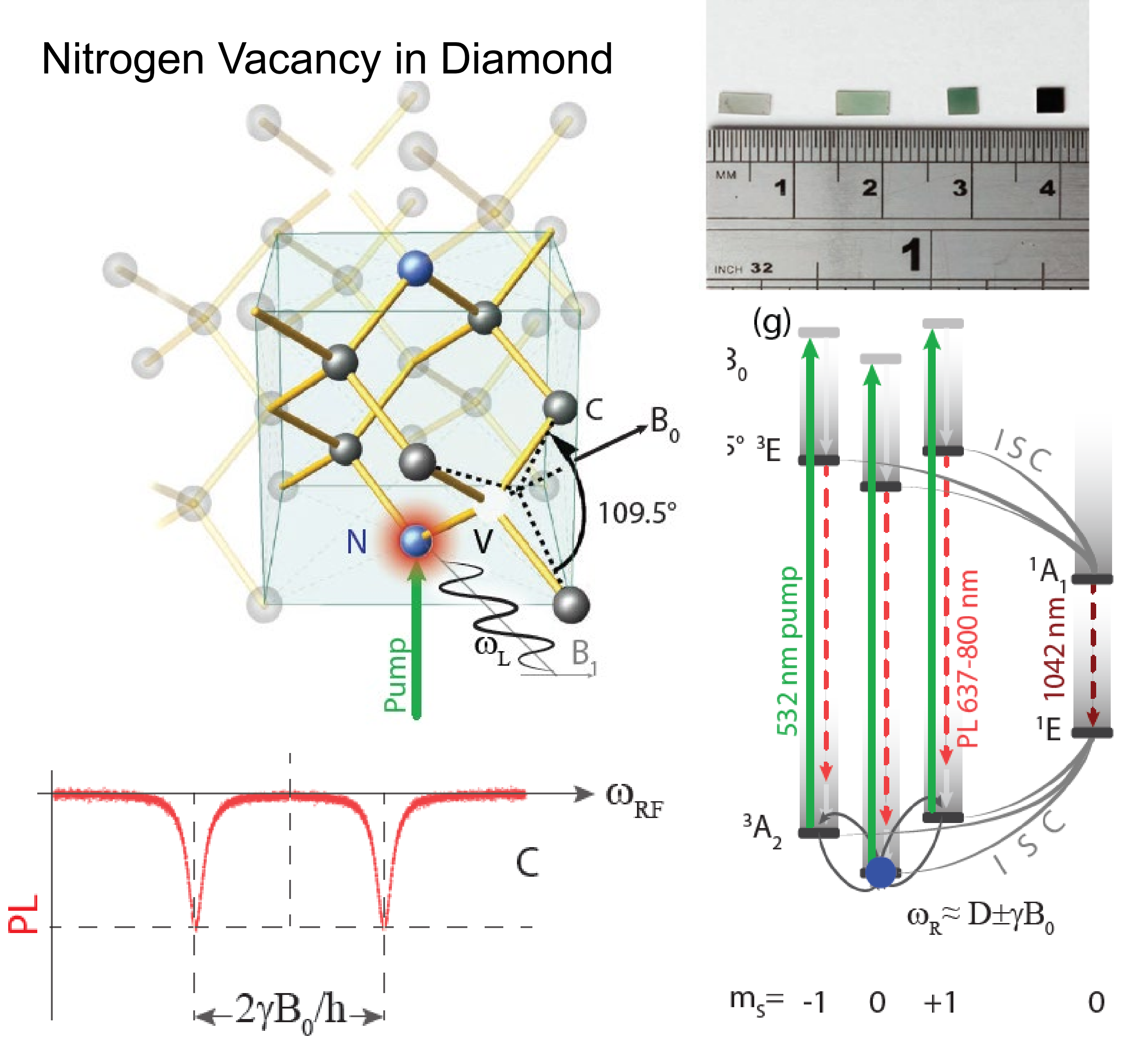
$$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$$

(CASPEr-Gradient, GNOME, QUAX)

Axion-like dark matter = oscillating magnetic fields on spins!

# Optically pumped magnetometry



# Workshop on optically pumped magnetometry WOPM 2019 in the HIM

- Advertisement 2:


Aug 6 – 8, 2025
PSI
Europe/Zurich timezone

# Workshop on optically-pumped magnetometers - WOPM2025

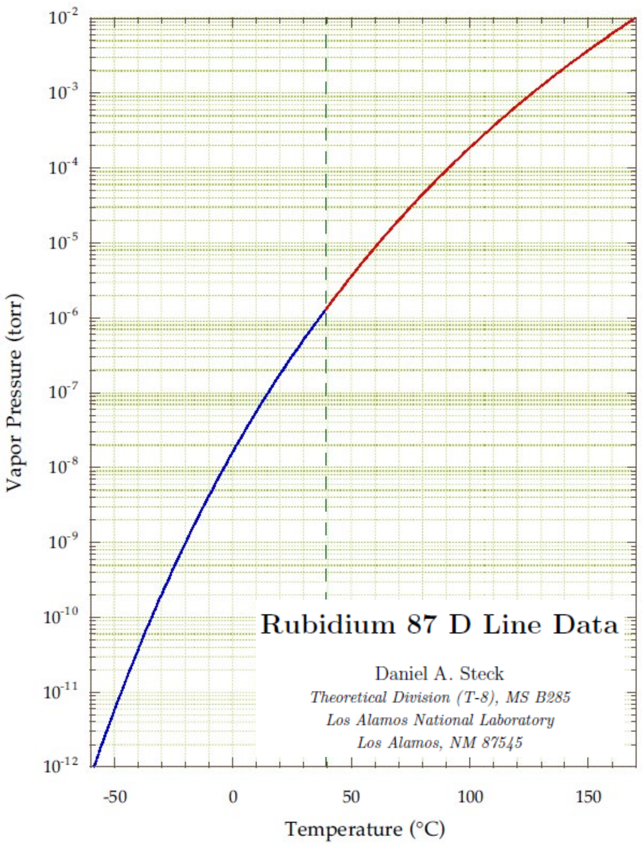
**Starts** Aug 6, 2025, 9:00 AM
**Ends** Aug 8, 2025, 7:05 PM
Europe/Zurich

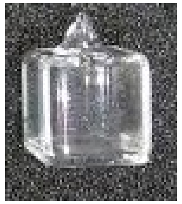
Anita Govaerts Van Loon
Bernhard Lauss
Georg Bison

Submission deadline

**May 19, 2025, 11:59 PM**

- Question:
- What is the spin density? Which one is higher?



Vapor cell or diamond?

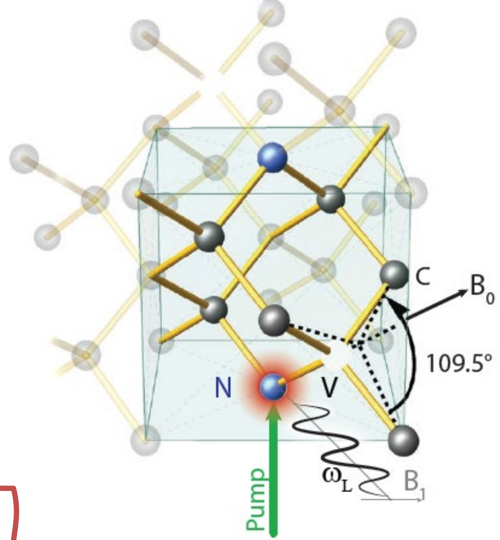
**Vapor** pressure: $10^{-2}$ torr (mbar)

$\Rightarrow 5 \times 10^{13}$ atoms/cm$^3$

**Diamond** density
$1.8 \times 10^{23}$ atoms/cm$^3$

NV density 2-3 ppm

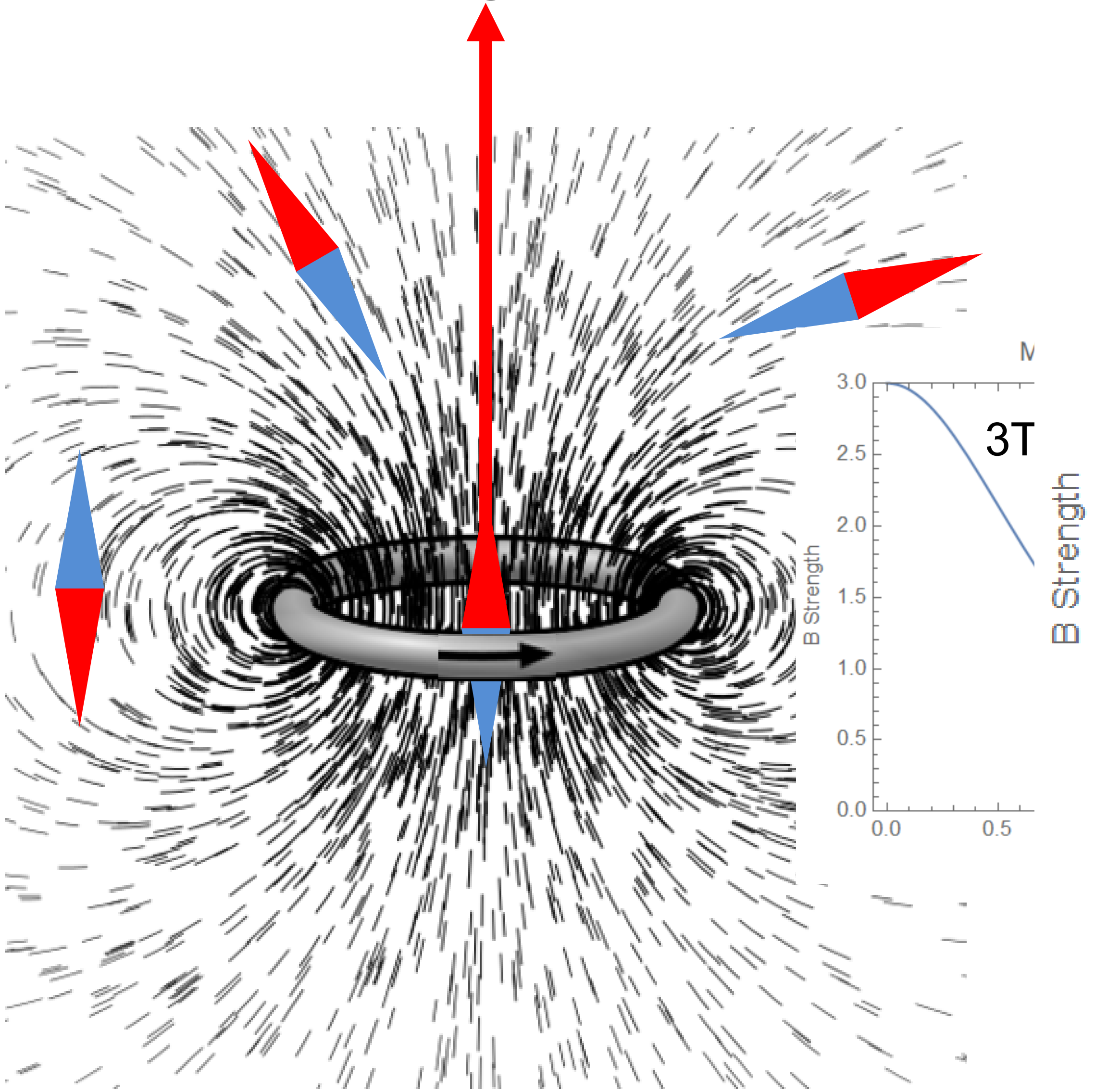
$\Rightarrow 5 \times 10^{17}$ atoms/cm$^3$

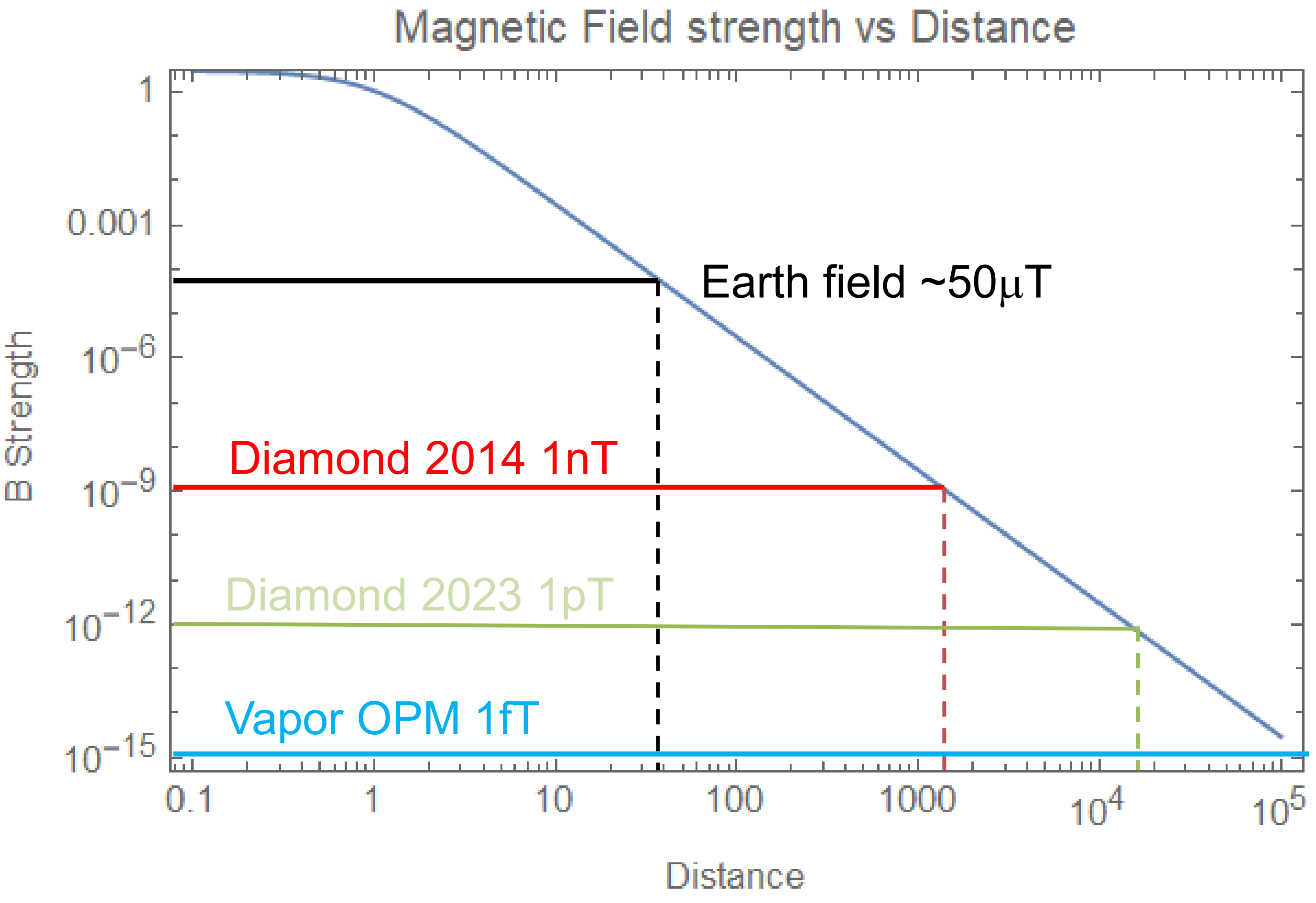



**Vapor** cell (5 mm)$^3 \Rightarrow 6 \times 10^{12}$ spins

**Diamond (0.2 mm)$^3$** $\Rightarrow 4 \times 10^{12}$ spins

- Dipole scaling with distance

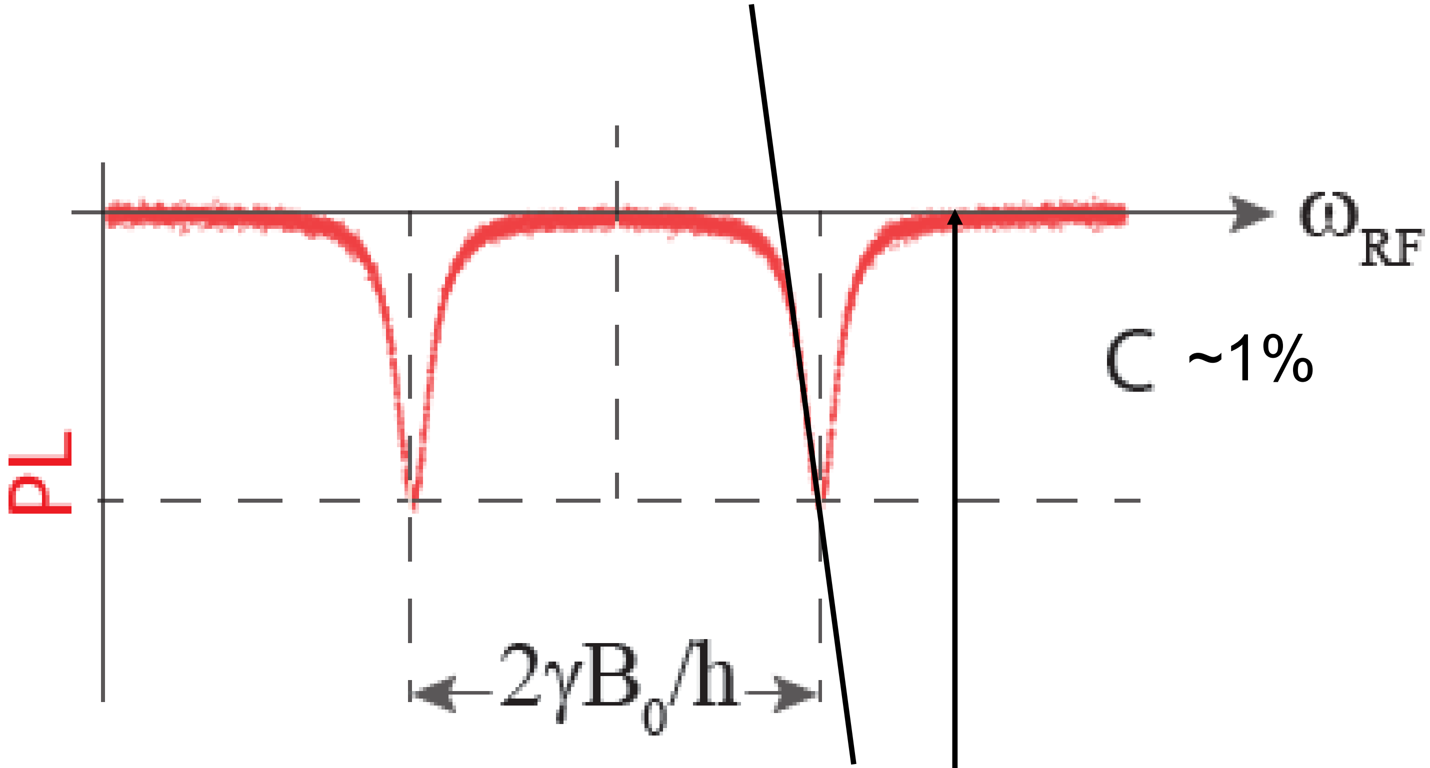


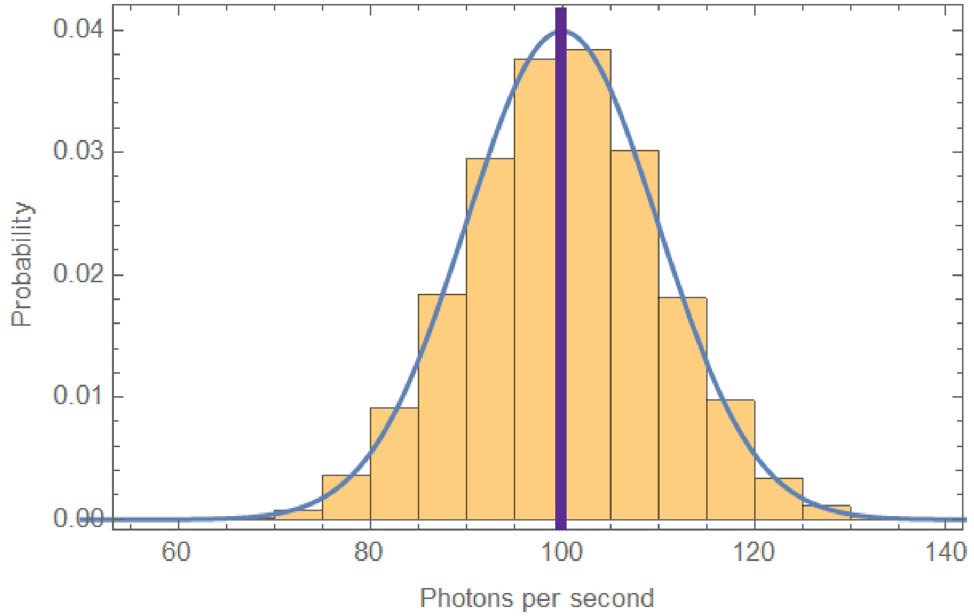




2 x further ⇒ Signal reduces by factor 8

0.5 x closer ⇒ Signal increases by factor 8

# How good can we measure B?




Photon shot noise

280 000 Hz

1 pT ⇔ 0.028 Hz

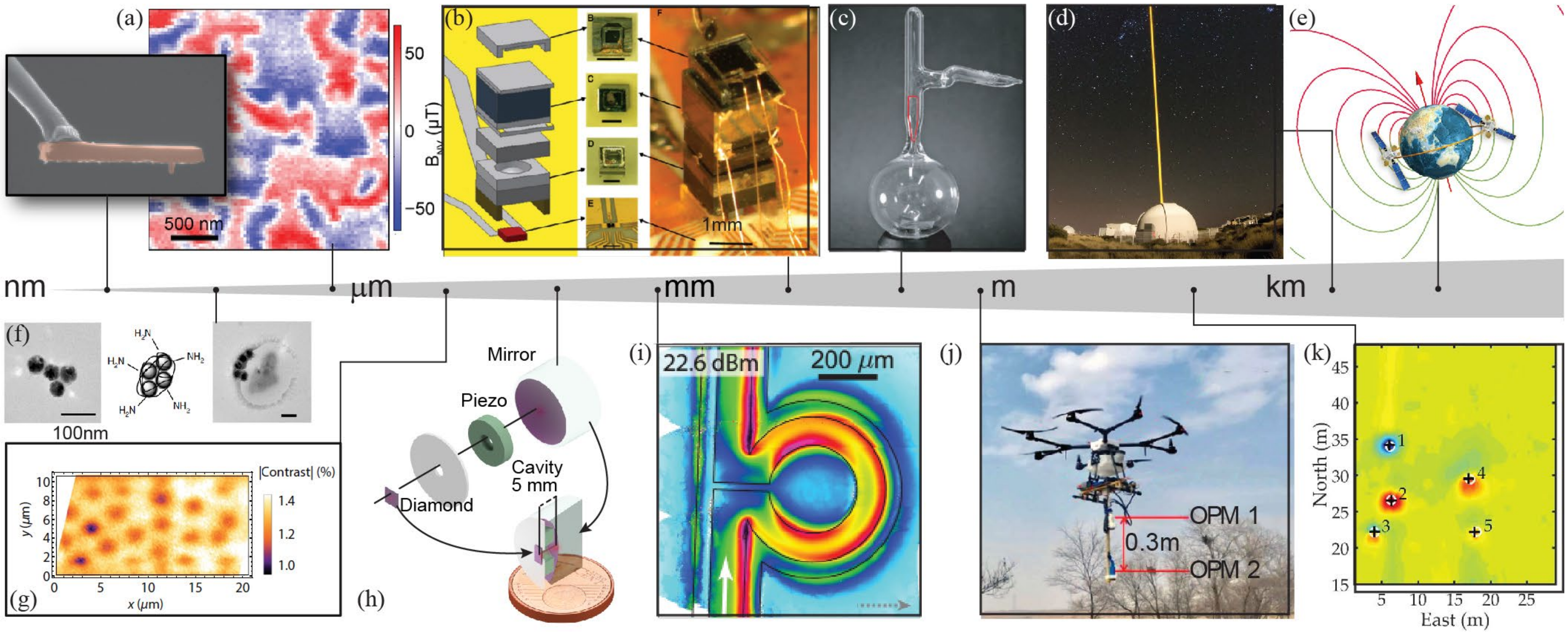
0.1 in 1 Million ($10^{-7}$)

Intensity = photons per second

noise = intensity

>$10^{14}$ Photons/s (mW!)

- Which sensor? – Length scales




- Fifth force searches: length scale ~ 1/mass

AVS Quantum Sci. 2, 044702 (2020); https://doi.org/10.1116/5.0025186

arXiv > hep-ph > arXiv:2408.15691

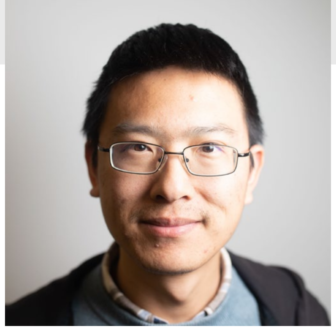
Search...
Help

**High Energy Physics - Phenomenology**

*[Submitted on 28 Aug 2024 (v1), last revised 14 Oct 2024 (this version, v3)]*

# Spin-dependent exotic interactions

Lei Cong, Wei Ji, Pavel Fadeev, Filip Ficek, Min Jiang, Victor V. Flambaum, Haosen Guan, Derek F. Jackson Kimball, Mikhail G. Kozlov, Yevgeny V. Stadnik, Dmitry Budker



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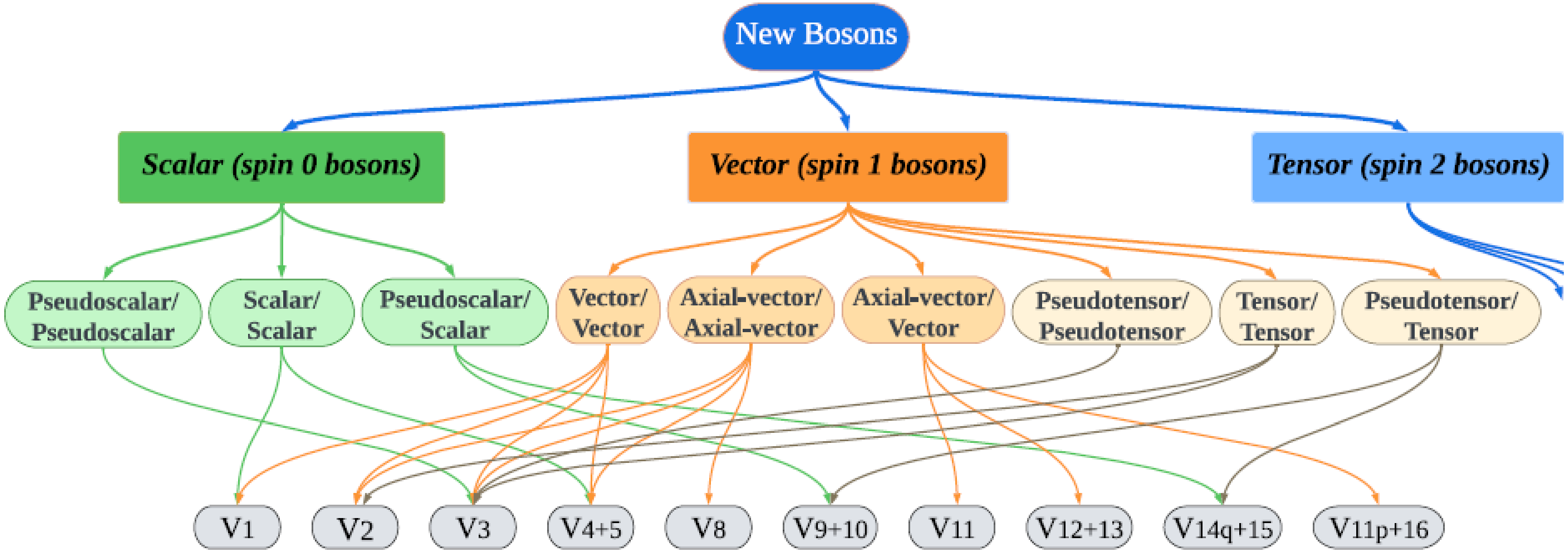
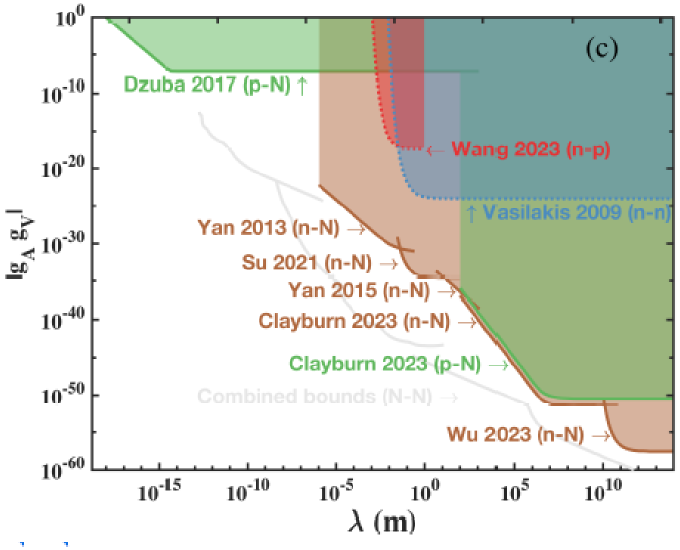




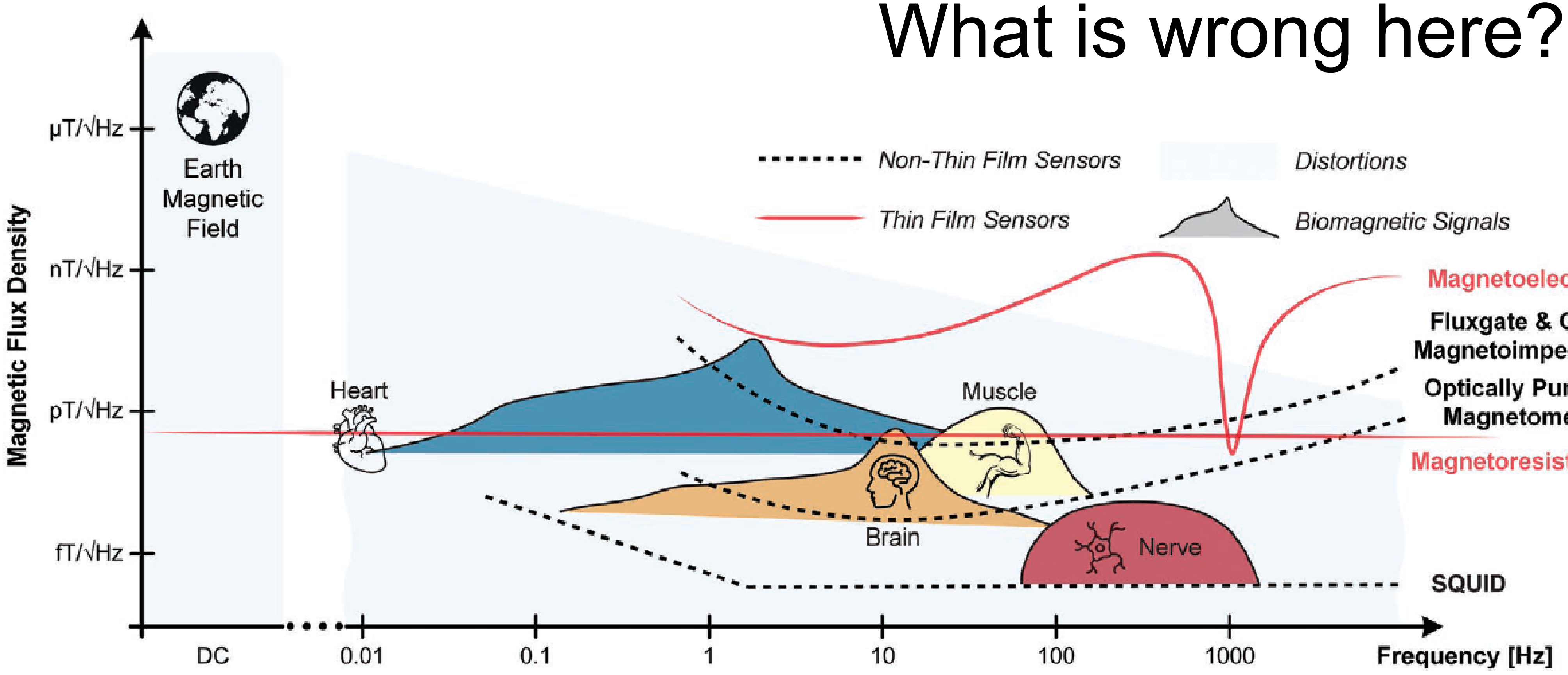

arXiv:2408.15691 Rev. Mod. Phys. under review

# (Interlude)

Biomagnetic measurements: like dark matter but actually something to sense

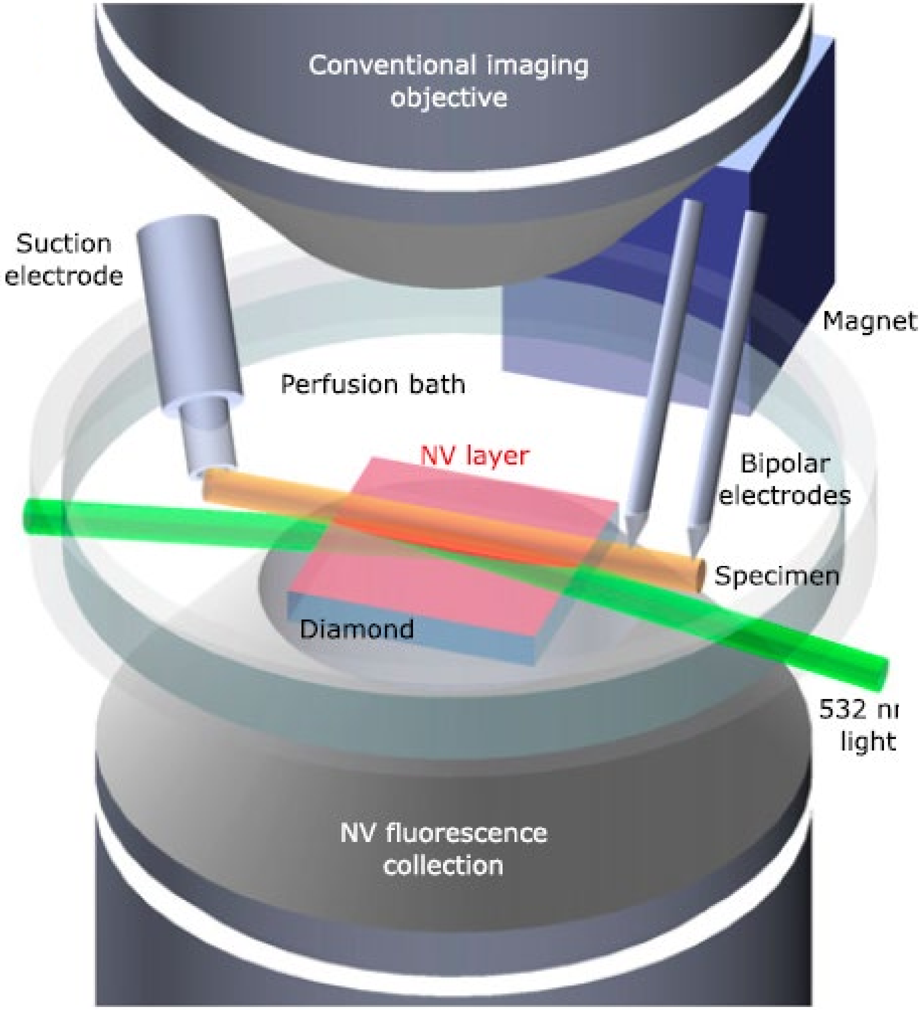
- Biomagnetic signatures - Magnitudes

What is wrong here?

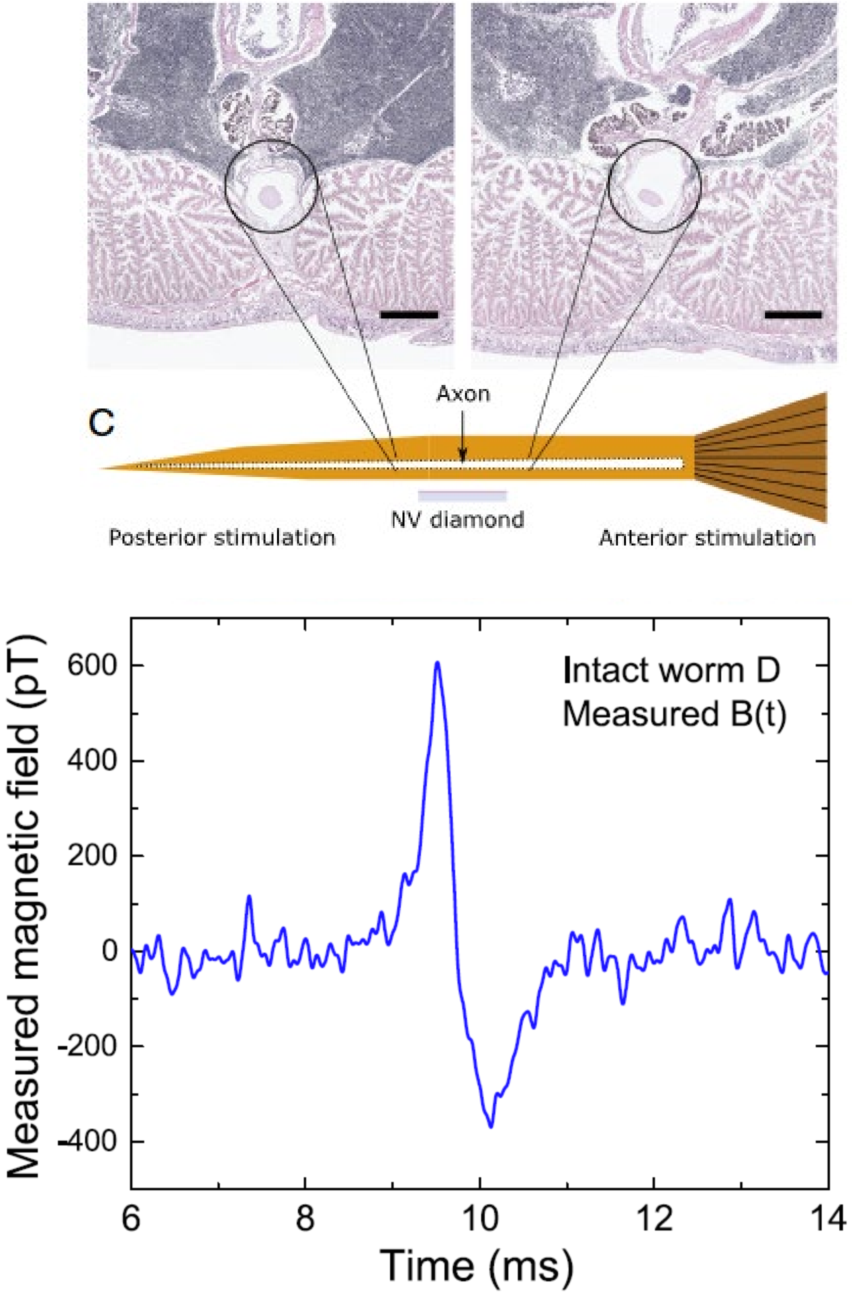



*Adv. Mater. Technol.* **2020**, 5, 2000185 **2000185 (5 of 15)** 

- Sensing individual nerves




Barry et al, PNAS, 113, 49 (2016)




Getting closer:
Signal Size: 1nT!

~ 10 pT/Hz$^{1/2}$

**Leuchtturmprojekte der quantenbasierten Messtechnik zur Bewältigung gesellschaftlicher Herausforderungen**

# DiaQNOS

DIAmond based Quantum sensing for NeurOSurgery

## Advertisement 3:

## PhD Position open!

01.10.2022 - 30.09.2027

**Verbundname: DIAmond based Quantum sensing for NeurOSurgery**

JGU GSI HELMHOLTZ Helmholtz Institute Mainz

Industry partners

Sacher Lasertechnik

SQUTEC TECHNOLOGIE TRANSFER INITIATIVE

inomed

Associated Partner

NVISION

SCHOTT glass made of ideas

Academic partners

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University of Stuttgart

universität ulm

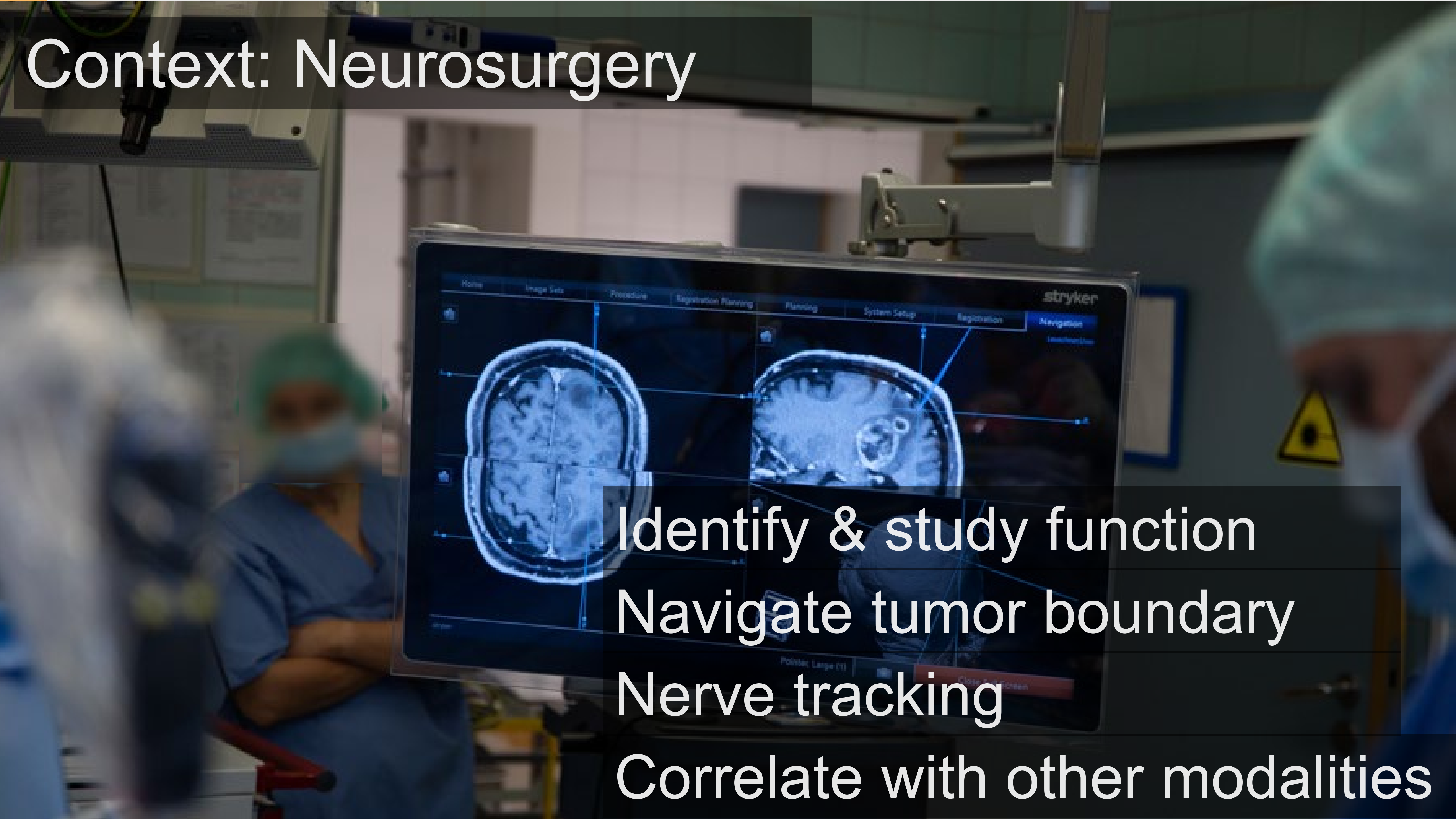
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

UNIVERSITÄTS KLINIKUM FREIBURG

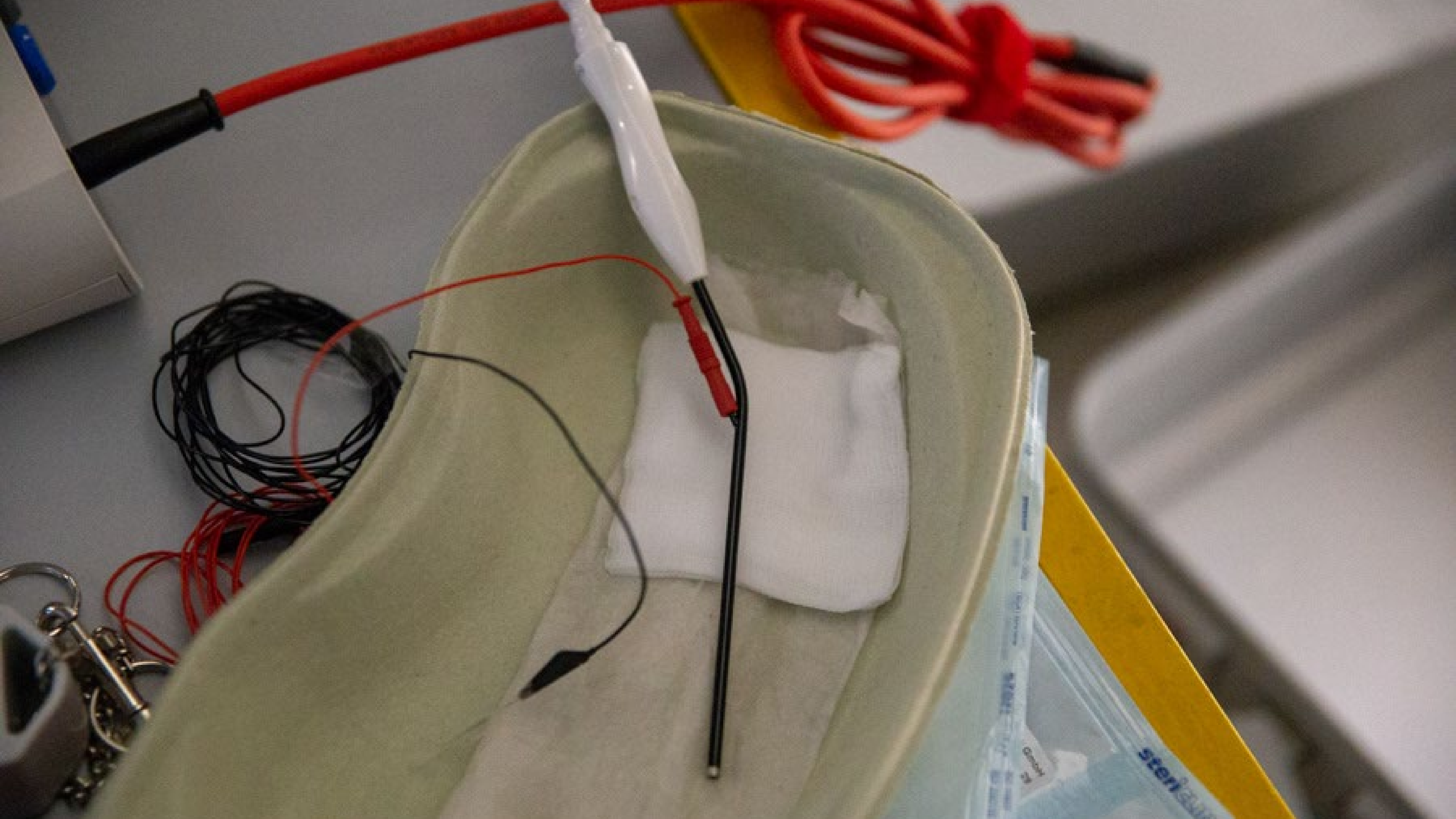
# Sensitive magnetometry in …

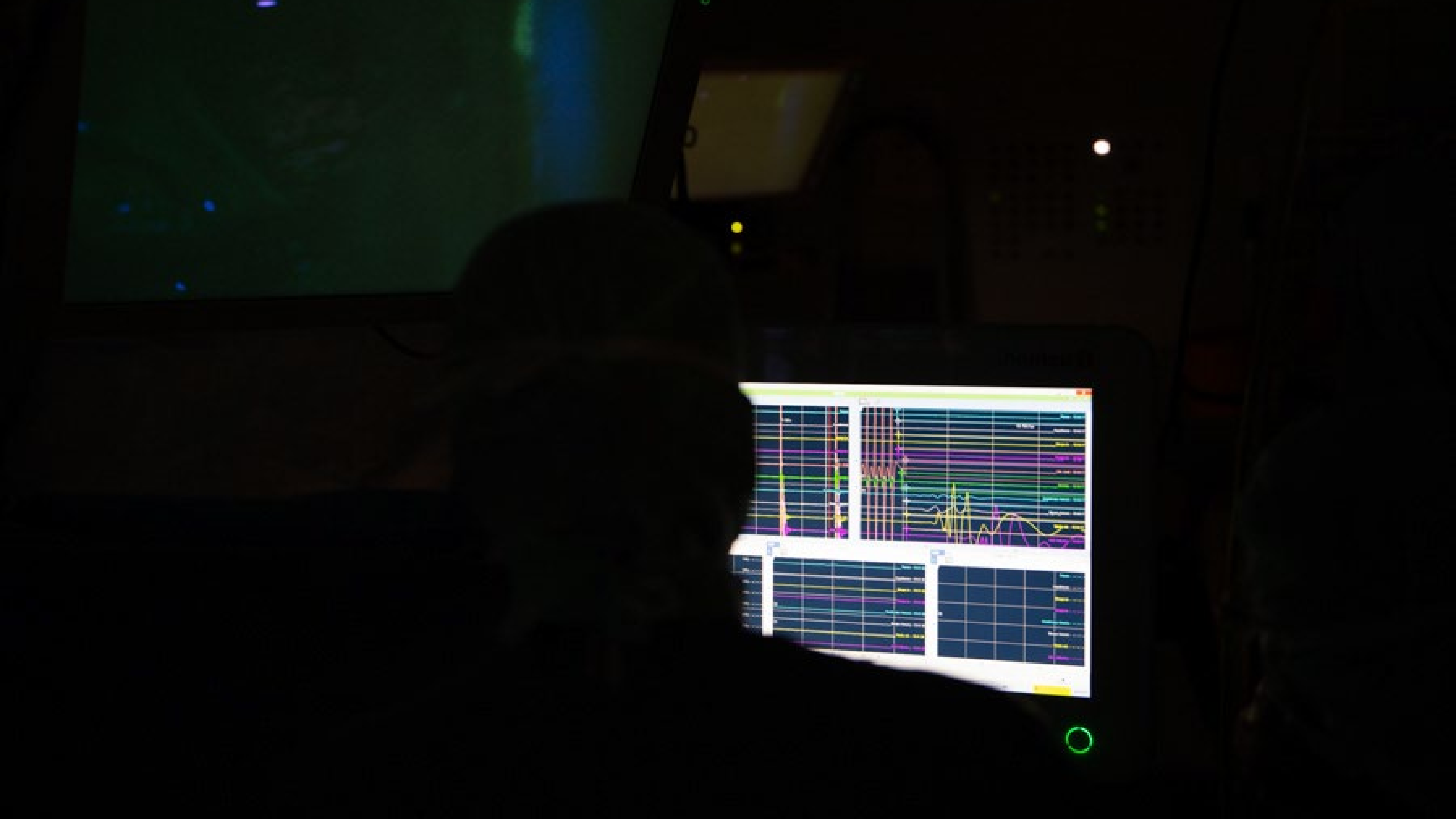
...Neurosurgery theater environment

# Context: Neurosurgery




- Identify & study function
- Navigate tumor boundary
- Nerve tracking
- Correlate with other modalities

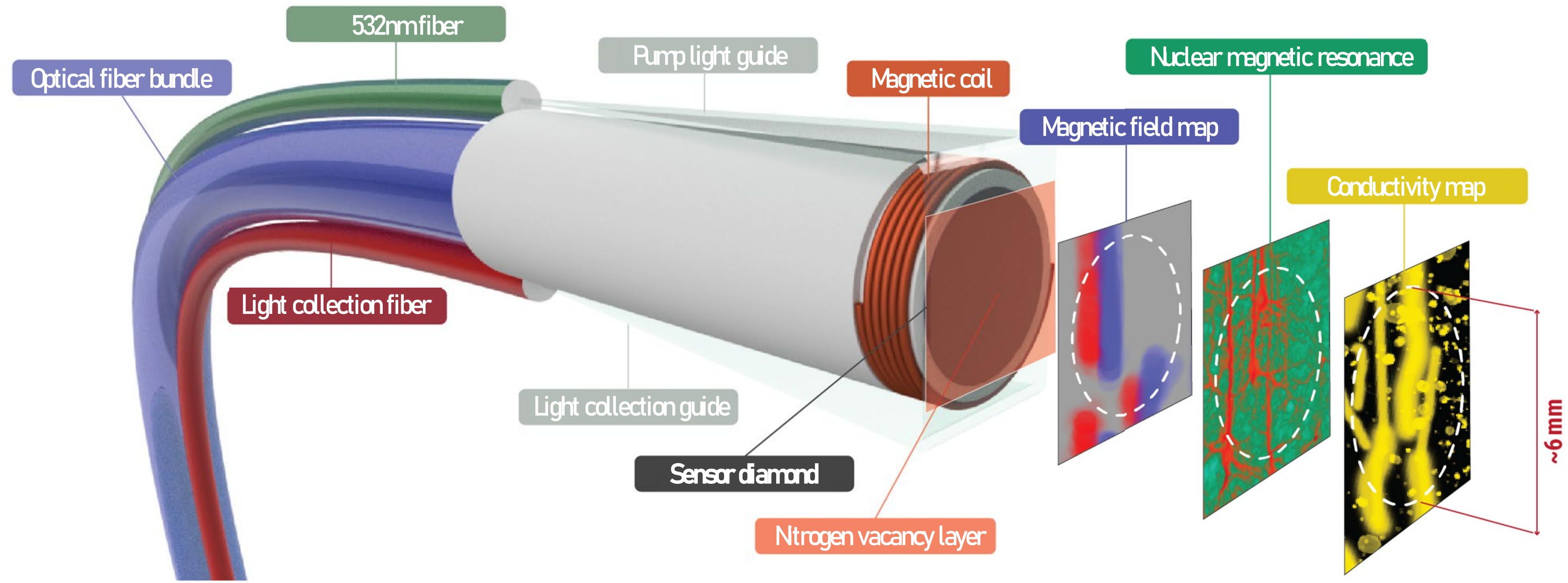




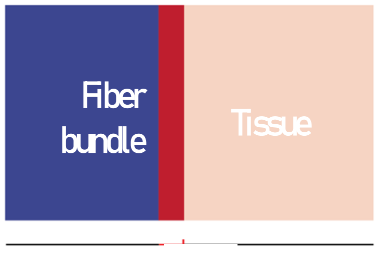
# Endoscopic magnetic field imaging sensor

a) Schematic

**Quantum-Neuro-Analyzer**




b) Cross Section




Magnetically sensitive nitrogen vacancy layer

Spatial Resolution 20µm

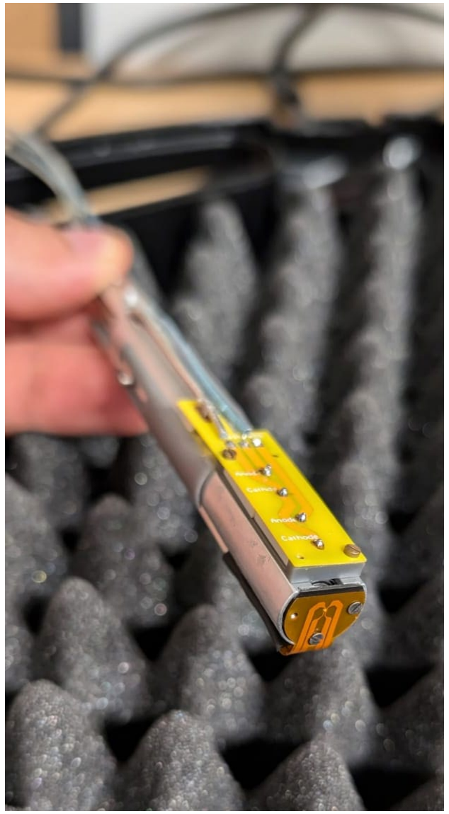
Study human (brain) tissue

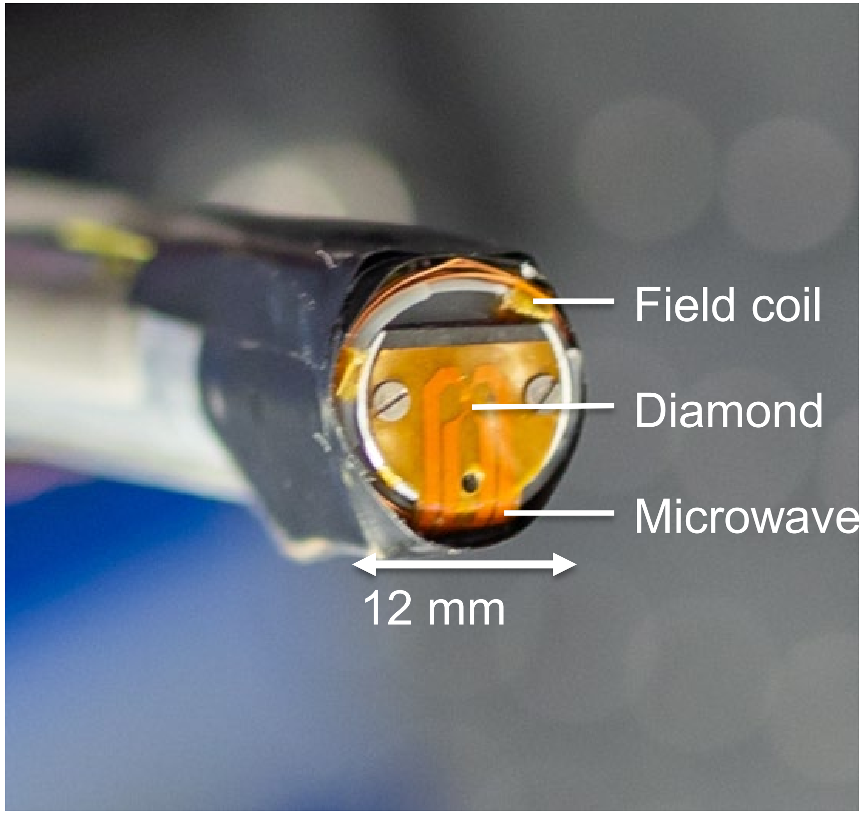
3y device development
2y studies

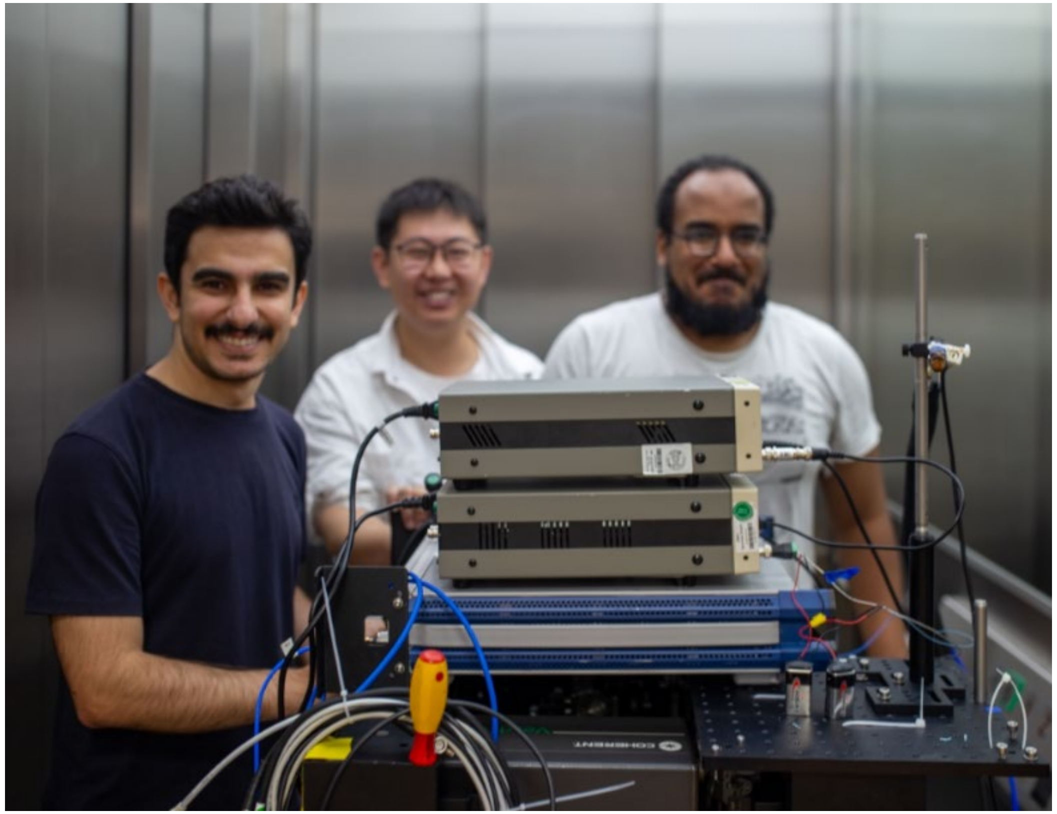
**Three different modalities:**

- Magnetophysiology (DC-kHz)
- Nuclear magnetic resonance imaging
- Conductivity imaging

- Since 10.2024: Single pixel magnetic sensor endoscopes

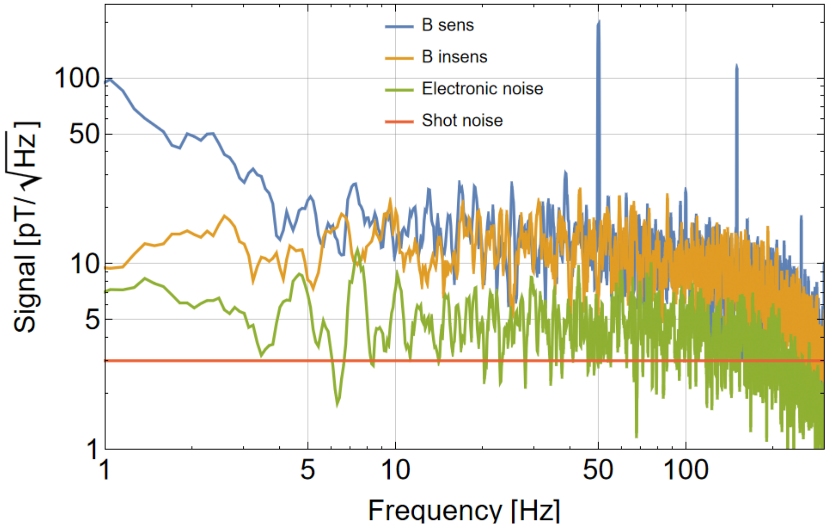


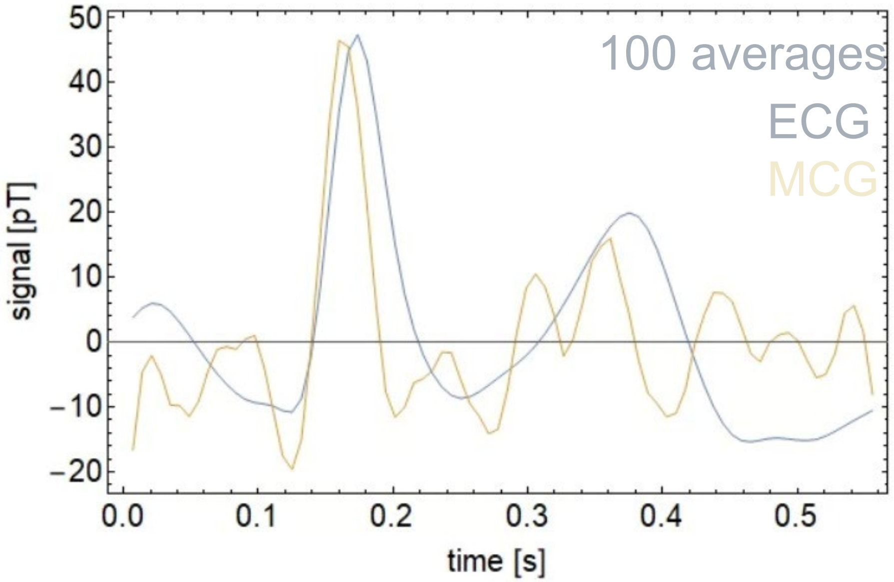


Sensor on 5m umbilical cord
Transportable!

- First measurement: biomagnetic signatures

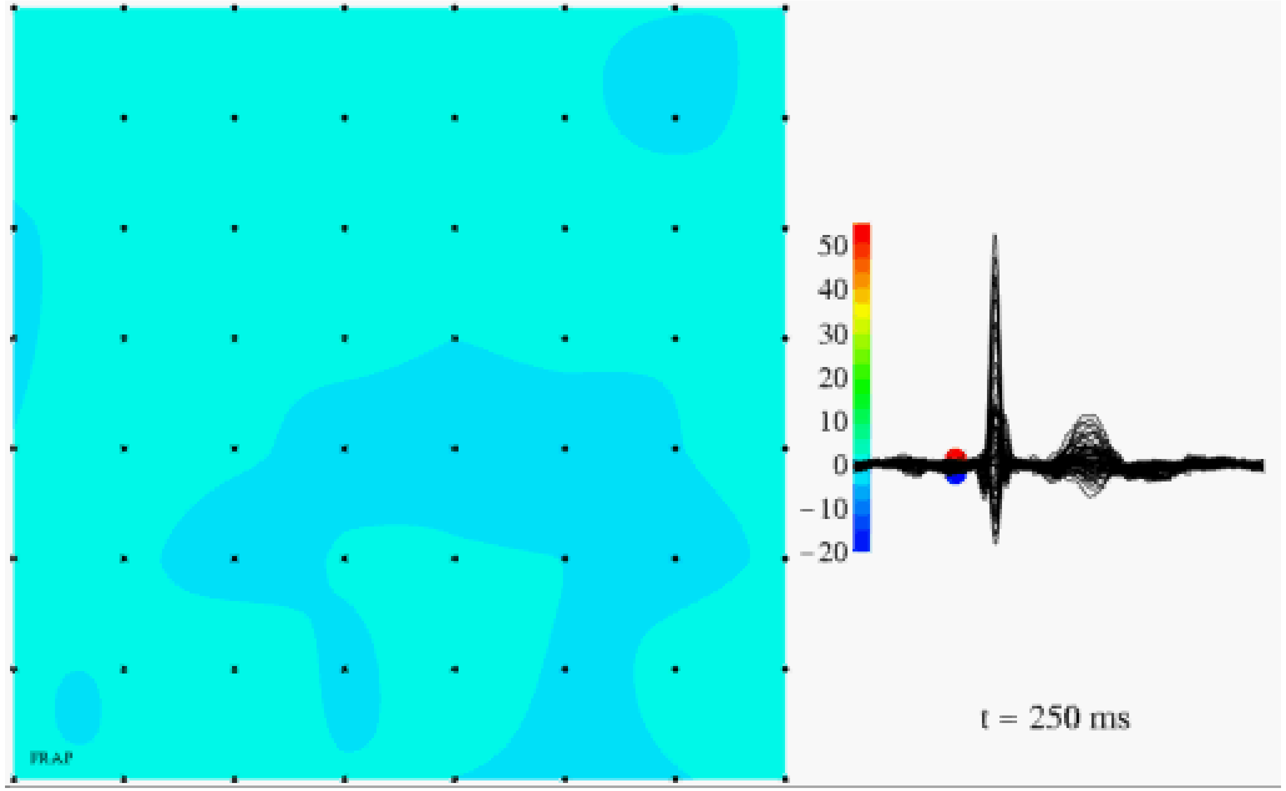



- 10 pT noise floor
- Sensor Volume: (60 μm)³
- Stand-off distance: < 0.2 mm

Human magnetocardiography!

■ Magnetocardiography?

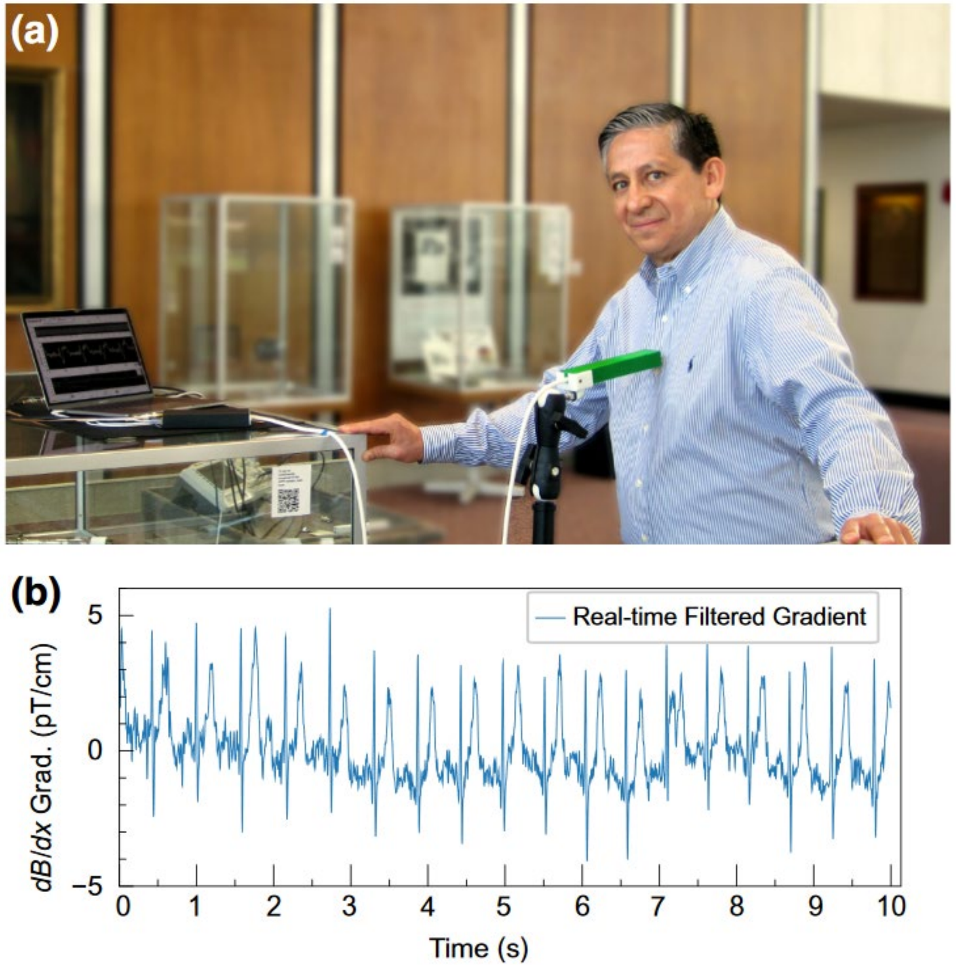



APPLIED PHYSICS LETTERS **95**, 173701 (2009)

**A room temperature 19-channel magnetic field mapping device for cardiac signals**

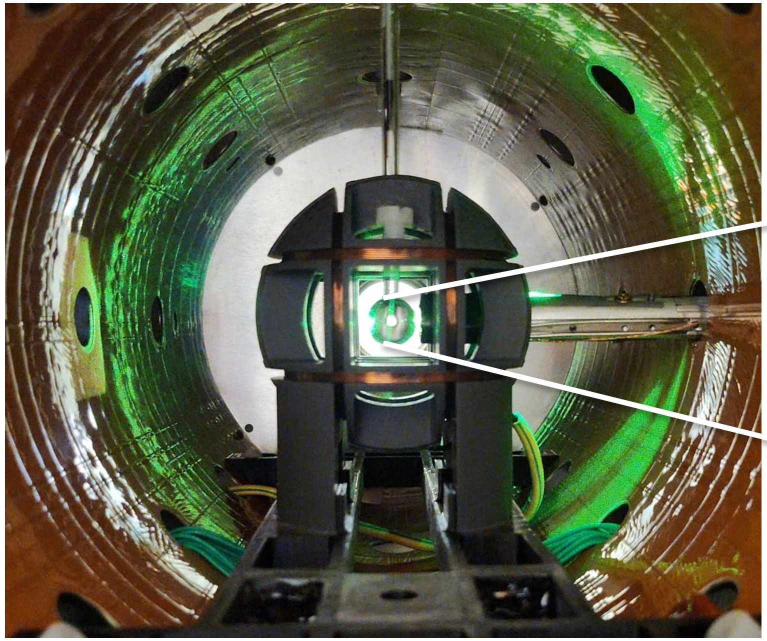
G. Bison,[1] N. Castagna,[2] A. Hofer,[2] P. Knowles,[2] J.-L. Schenker,[2] M. Kasprzak,[2] H. Saudan,[2] and A. Weis[2,a)]
[1]*Department of Neurology, Friedrich–Schiller–University, D–07740 Jena, Germany*
[2]*Department of Physics, University of Fribourg, CH–1700 Fribourg, Switzerland*

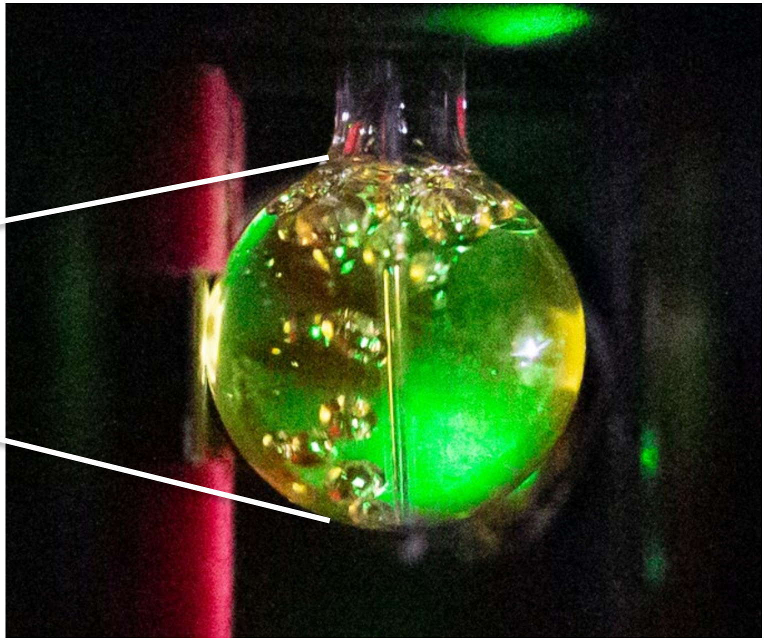
By 2029
With diamond!
Unshielded environment!

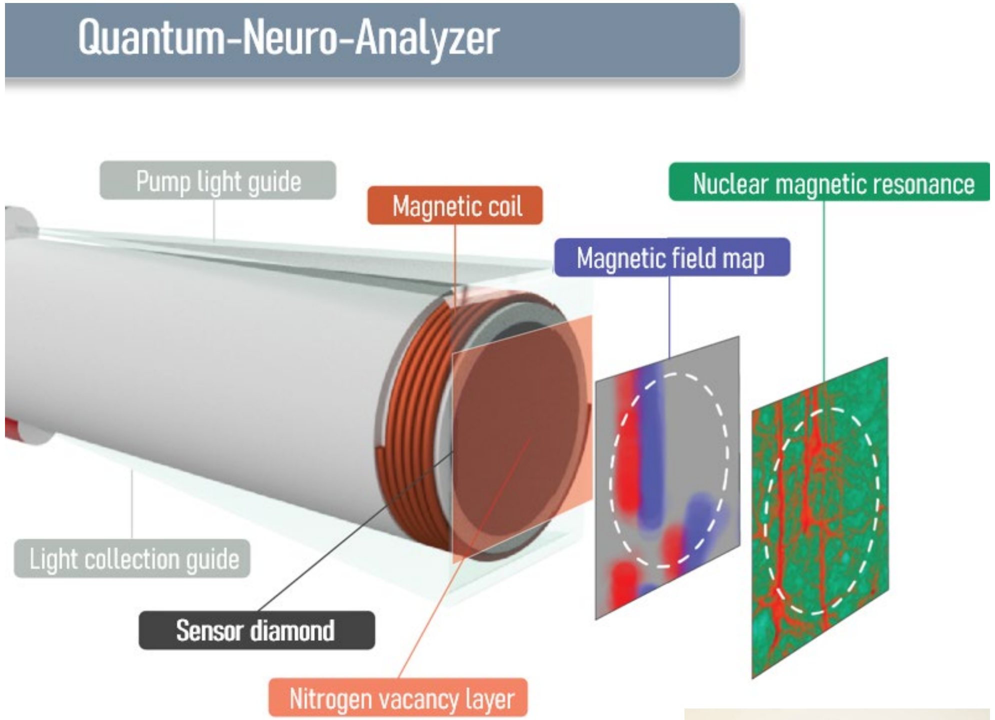



Phys. Rev. Applied **14**, 011002 – Published 20 July 2020

- $2^{nd}$ measurement: Zero-field J-coupling spectroscopy of hyperpolarized acetonitrile





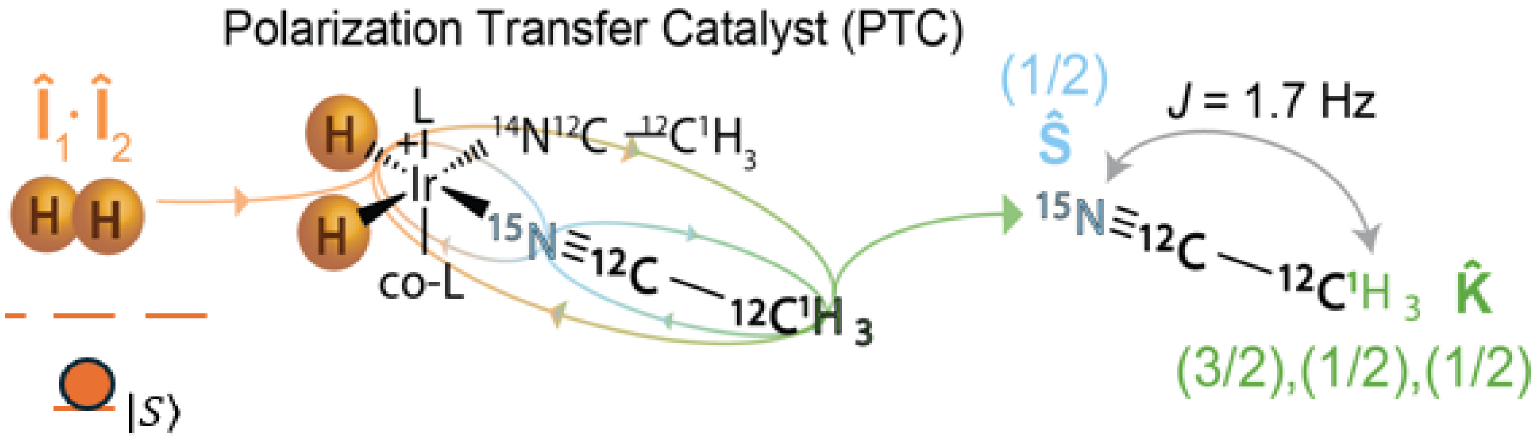



- Parahydrogen (spin-order) transferred to chemicals
- Chemical specificity without magnets
- Hyperpolarization mechanisms
- Enables NMR maps

Muhib Omar

# NMR at zero field with diamond magnetometer

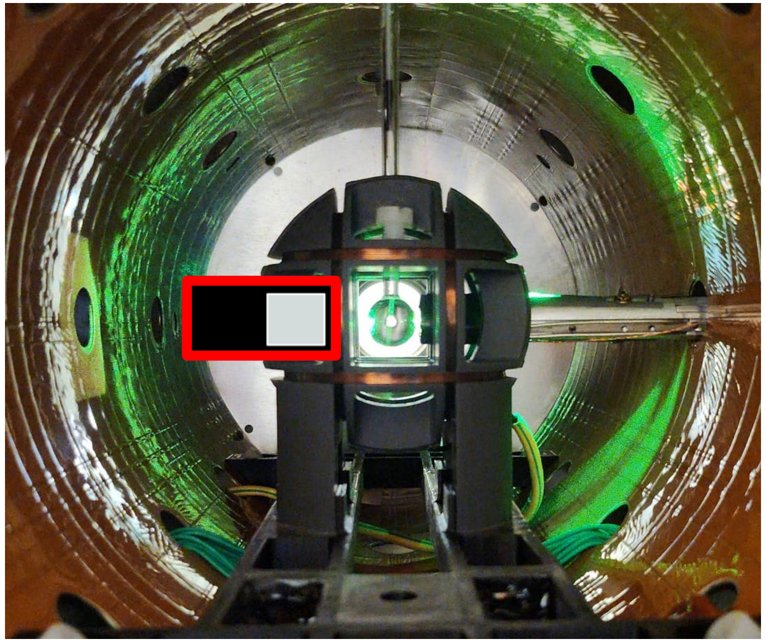
- Creating observable magnetization with parahydrogen

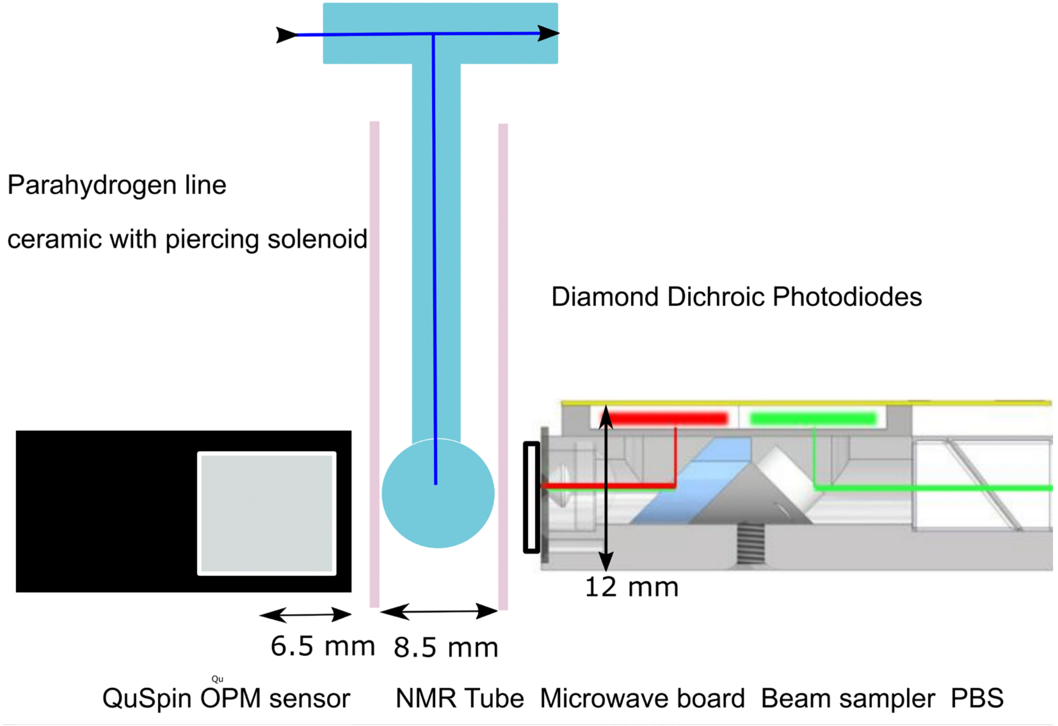



- Parahydrogen spin order at cryogenic temperature
- Transient compound: parahydrogen+catalyst+acetontrile
- Spin order transfers via J couplings
- Transient compound breaks up
- Acetonitrile nuclei remain polarised

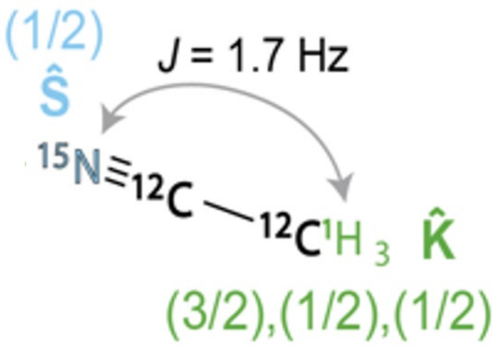
# NMR at zero field with diamond magnetometer

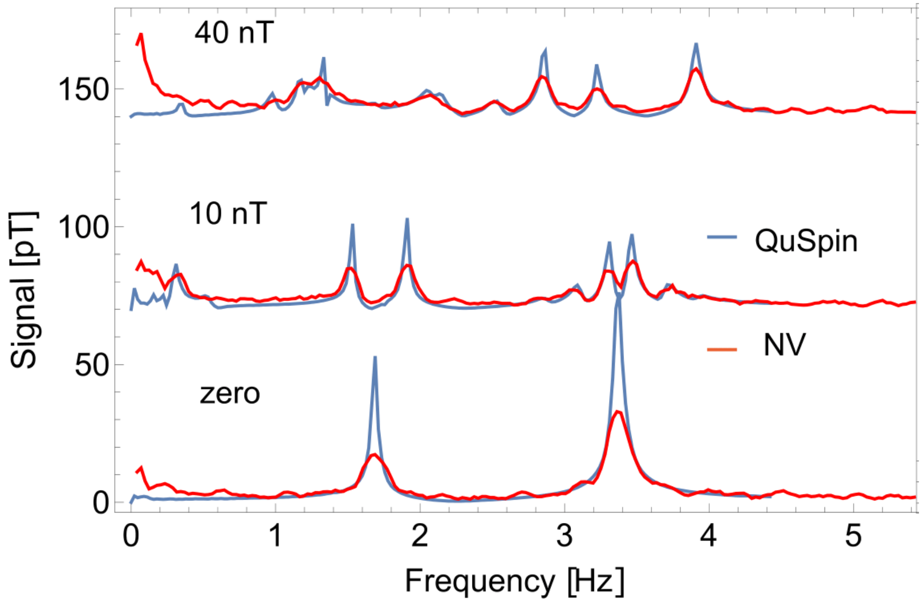
- 1 μT pulse 10-30 ms
- Magnetization evolution
- Measurement with NV sensor and QuSpin

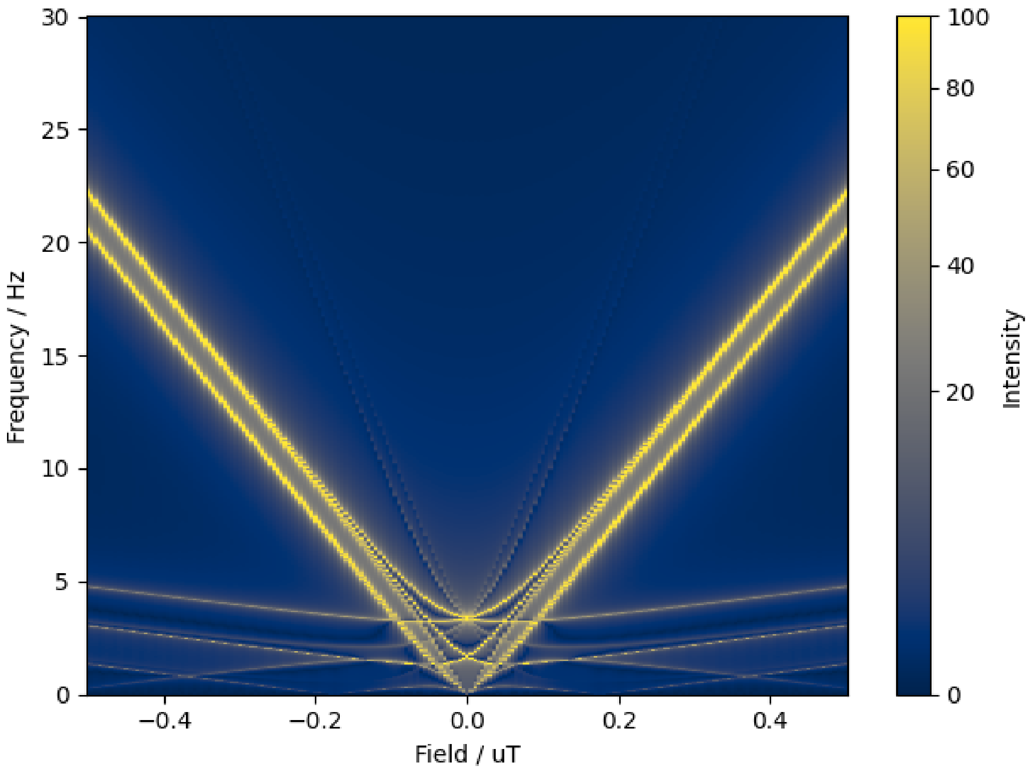


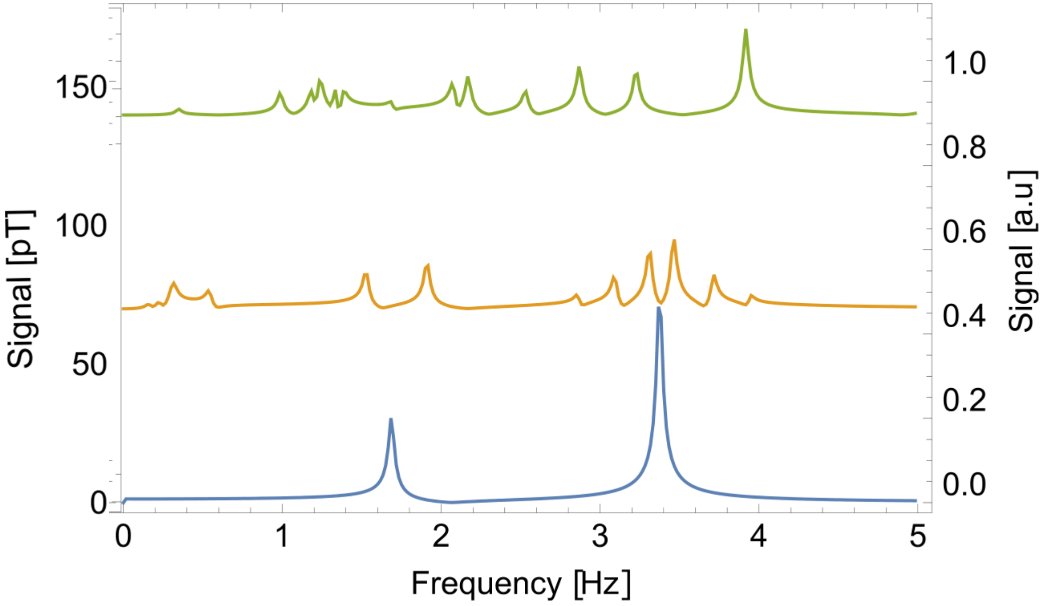


# Diamond NMR at nT fields

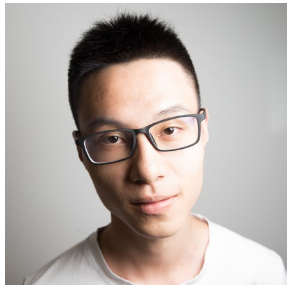


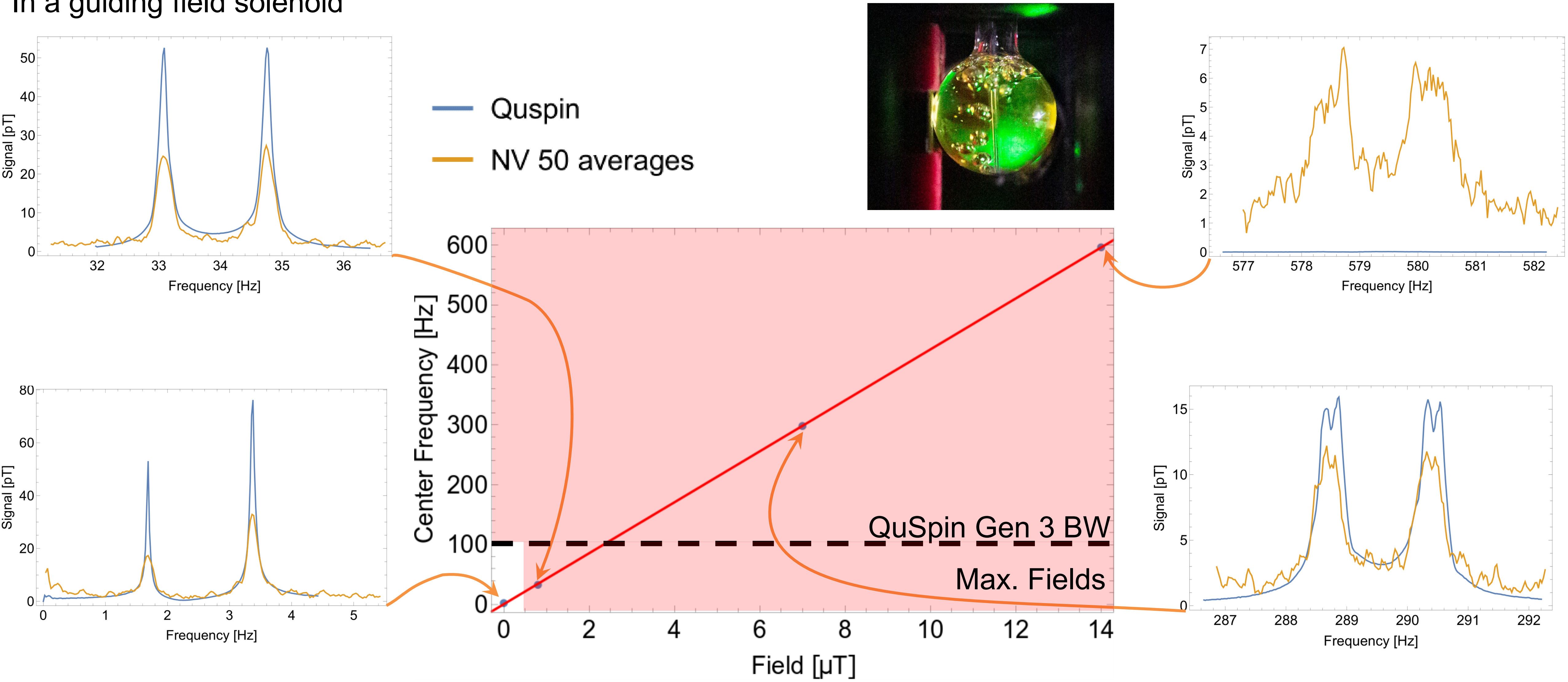

Simulations



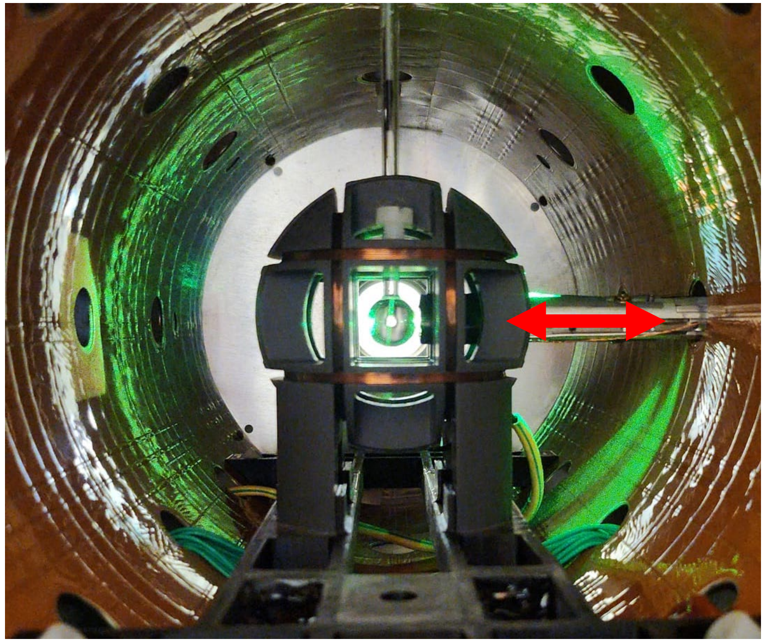
Jingyan Xu

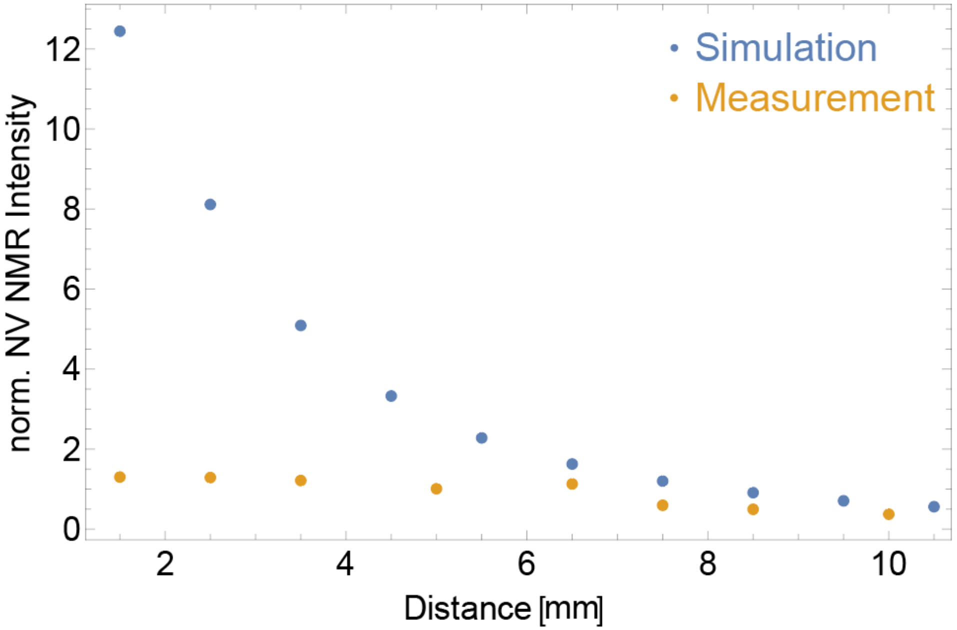
# Diamond NMR at µT fields

In a guiding field solenoid

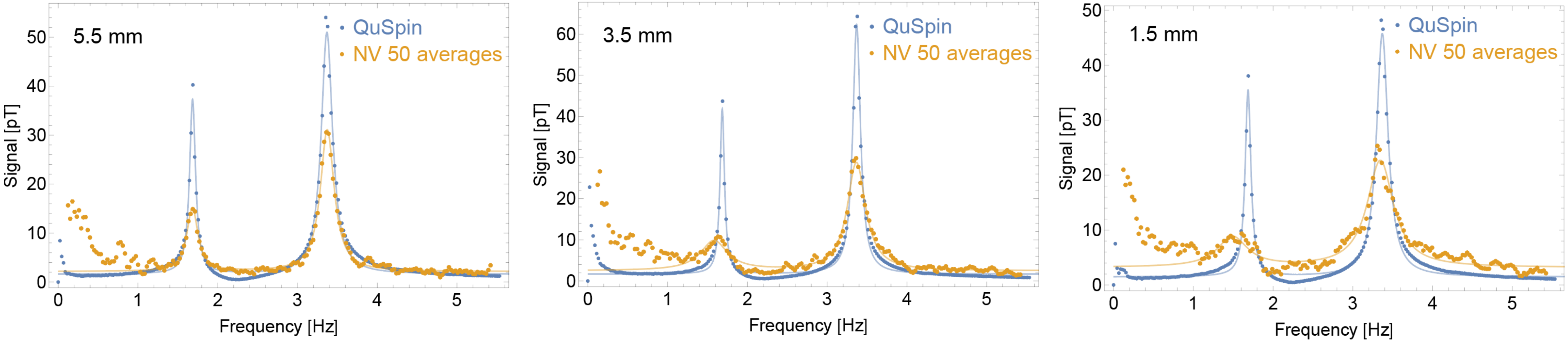


# Diamond NMR: distance variation



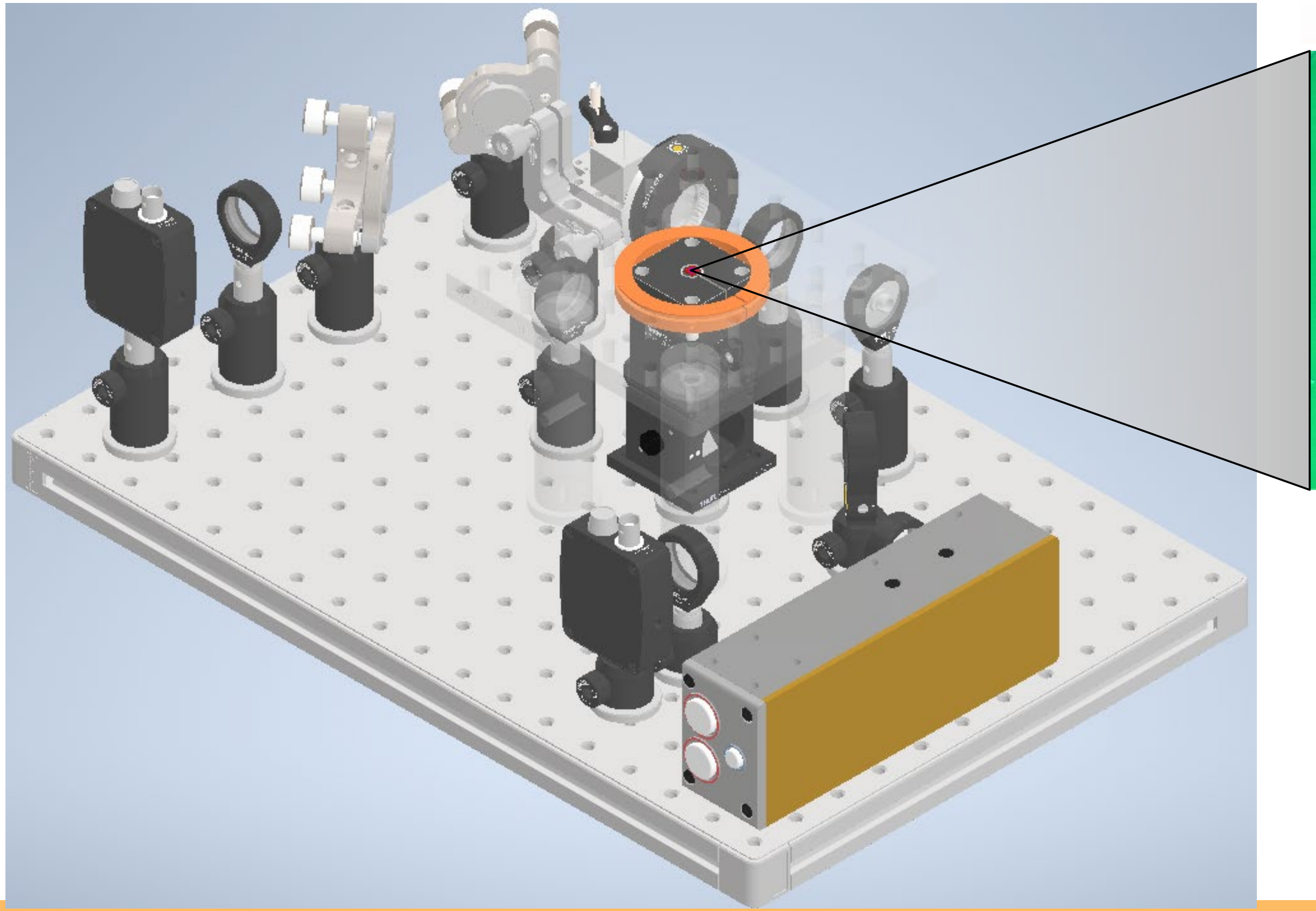



- Reducing the distance
- Width increases
- No improvement
- Different ensemble?
- Sensor backaction?

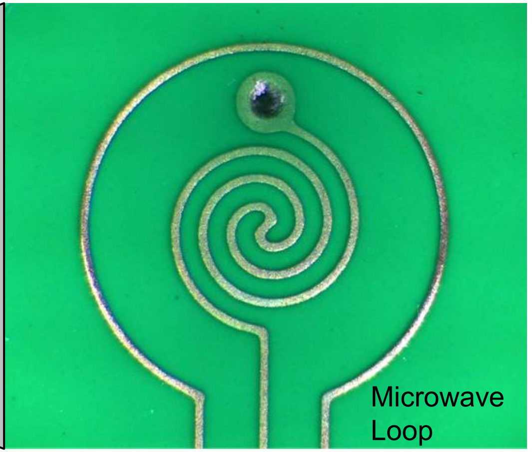


# Parallel sensing - Imaging

- 5 x 5 $mm^2$ NV diamond sensor
- Image detected by a C4 lock-in camera
- Bio-magnetic imaging at zero-field



Test coil



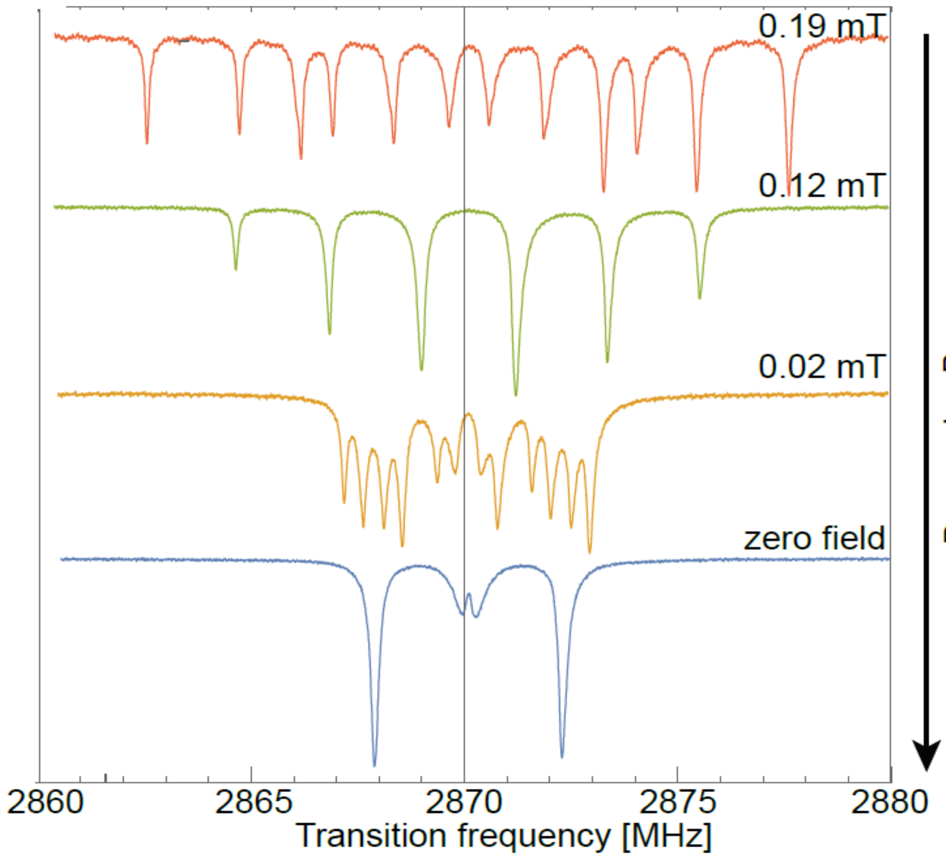

PCB Signal layer, Line width 0.1 mm

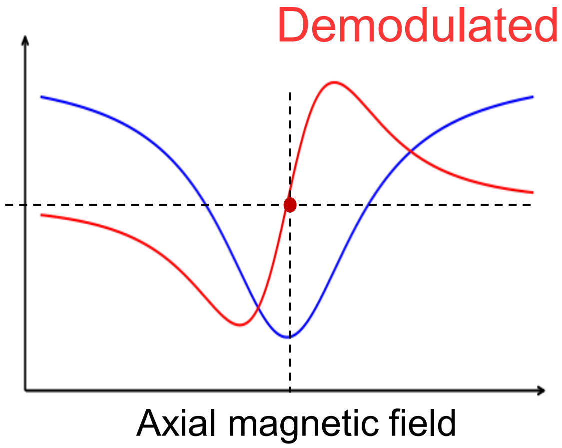
Ara Rahimpour

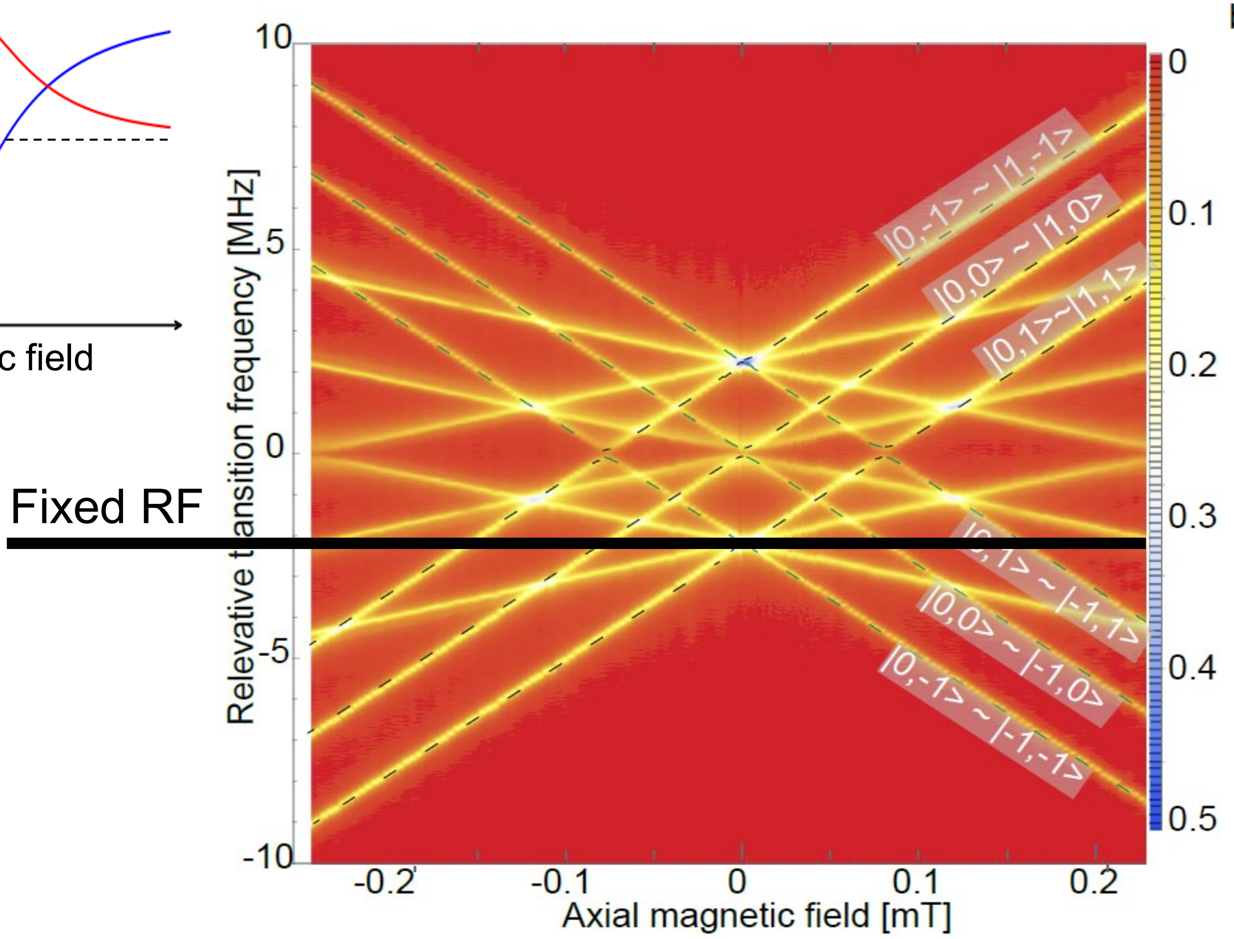
Shaowen Zhang

Jonas Raabe

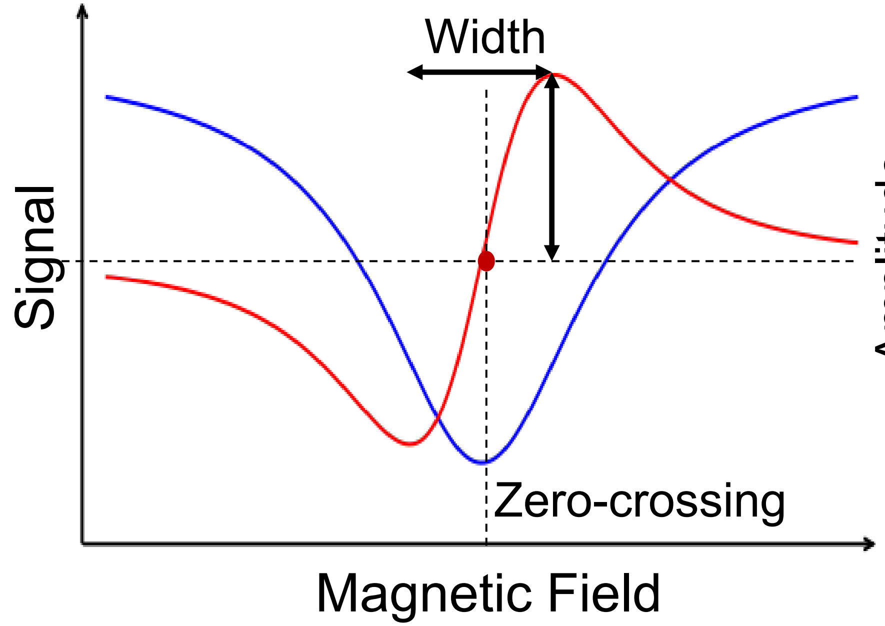
# Zero-field magnetometry



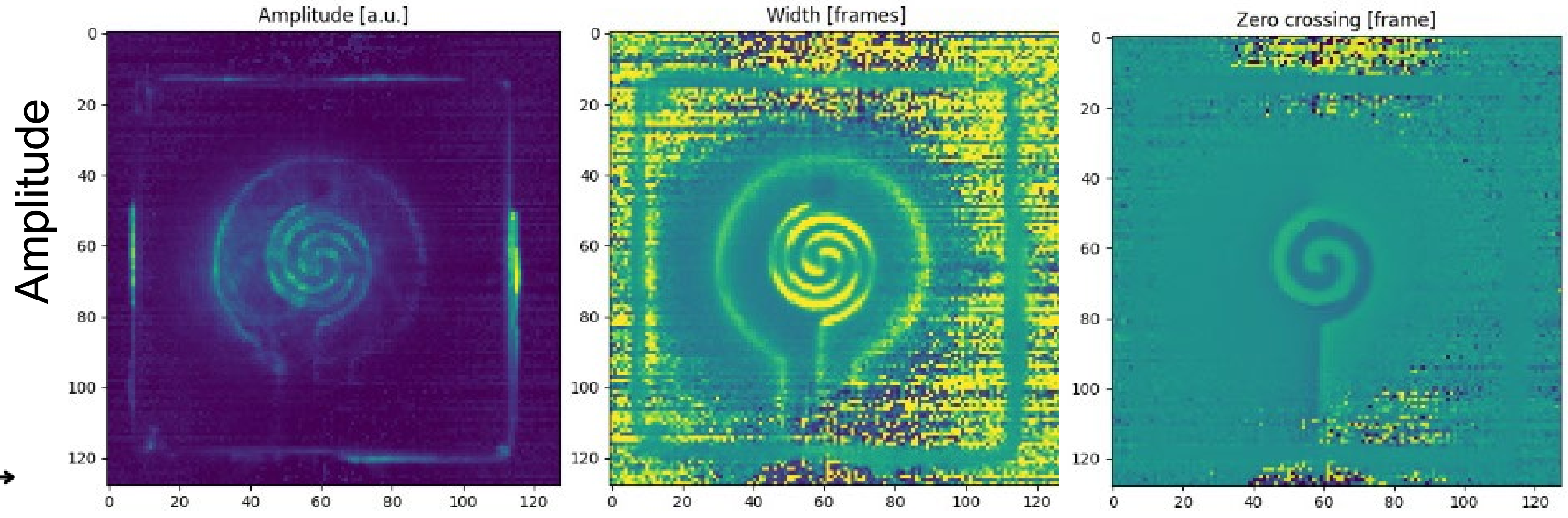



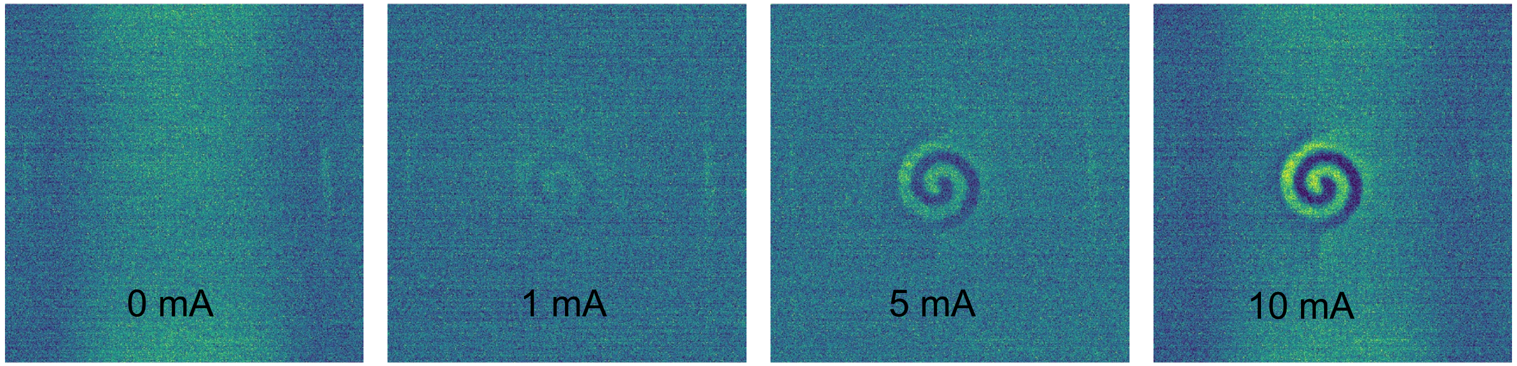
- 2D magnetic imaging diamond 5x5mm²




Background field sweep

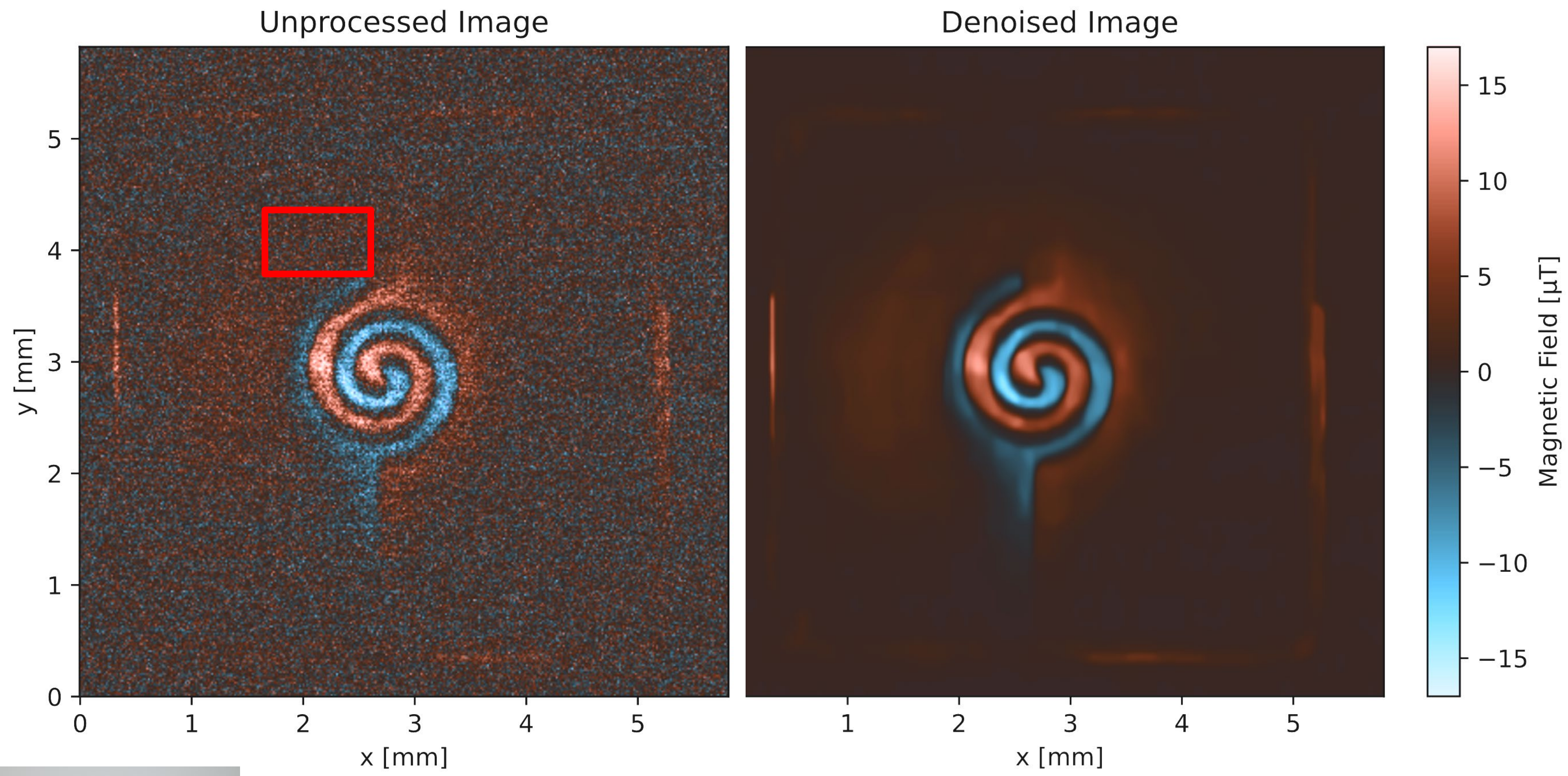


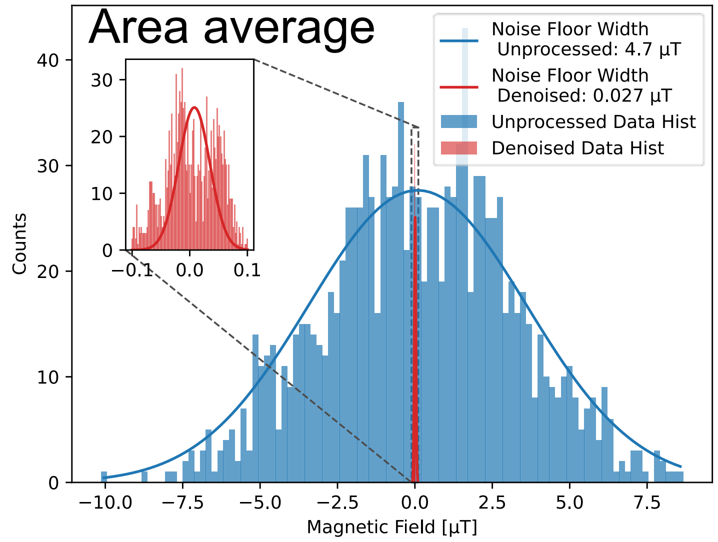

Test coil current

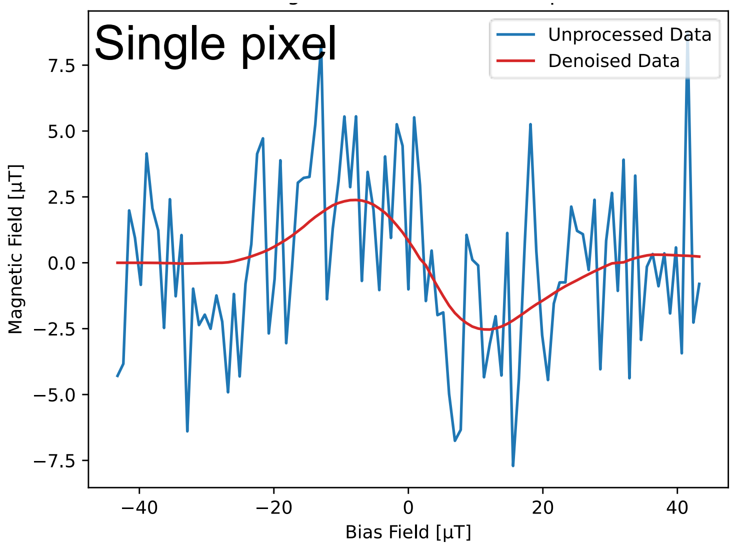



- Modulation frequency 1 kHz,
- Modulation amplitude 8.7 μT
- **Spatial resolution ~7 μm,**
- **magnetic resolution <100 μm**

# Noise Suppression: Image Denoising




BM4D image processing

Jonas Raabe

M. Maggioni et al., *IEEE Transactions on Image Processing*,22,1,119-133: 10.1109/TIP.2012.2210725

# Noise Suppression: Result

Laser noise suppression lock-in

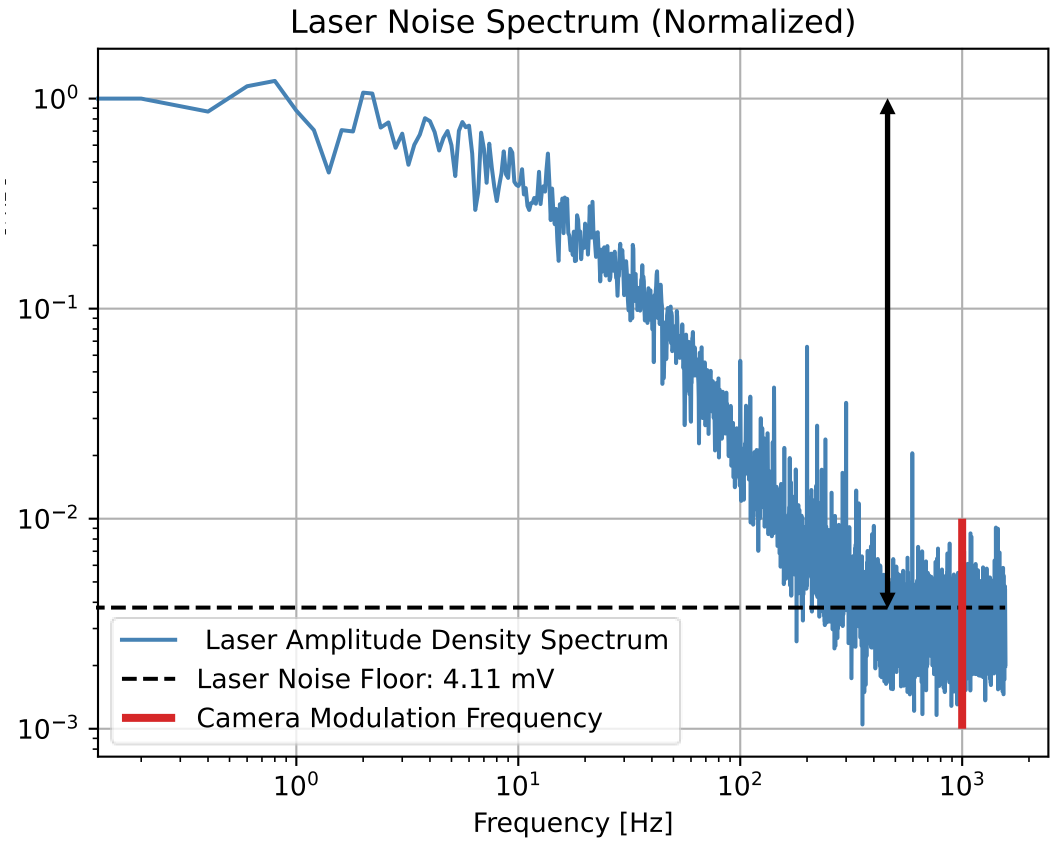
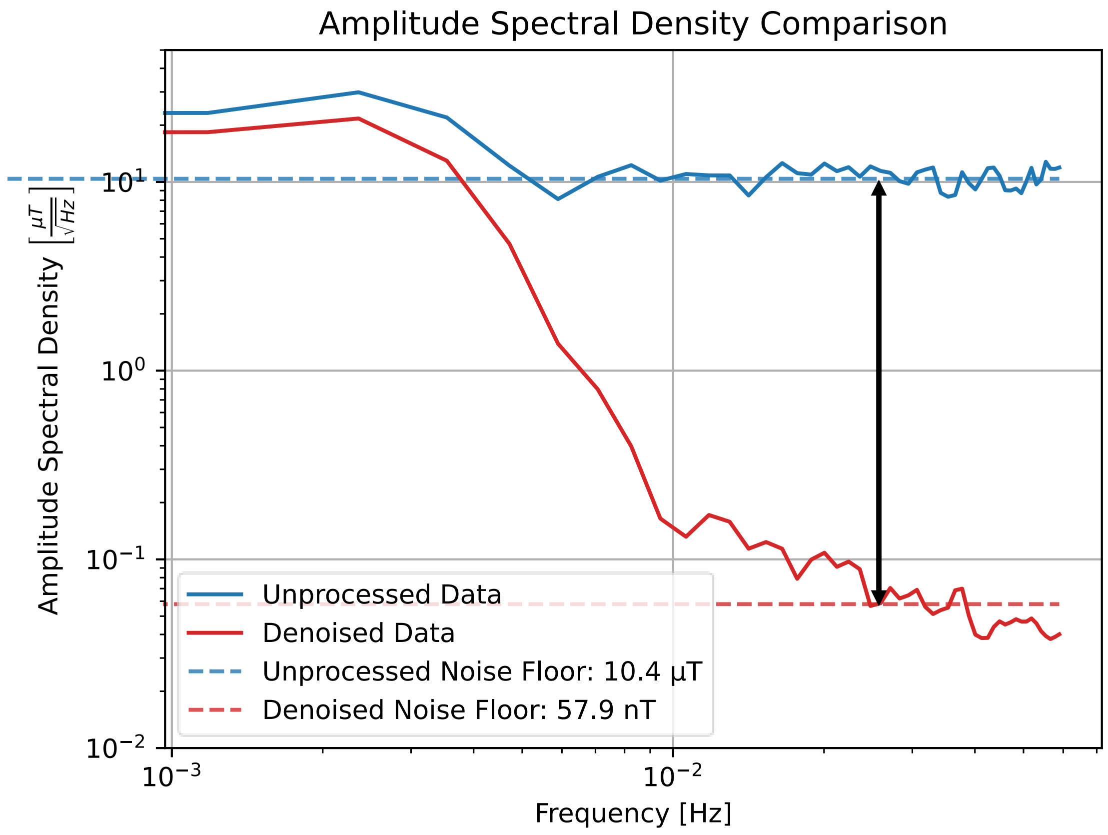



Image denoising




Lock-in camera laser noise suppression: 250

BM4D image denoising: 170

Total noise suppression: > 4 x $10^4$

- Summary
- Searching for biomedical signals
  - Signal: hyperpolarization
  - Signal: reduce distance
  - Noise: upconverting the signal and perform lock-in detection
  - Noise: parallel sensing $\Rightarrow$ denoising algorithms
- Searching for new bosons (acting magnetically on nuclear spins)
  - Signal: (hyper)polarization (the only way)
  - Signal: reduce distance $\Rightarrow$ higher mass
  - Noise: upconverting the signal and perform lock-in detection
  - Noise: parallel sensing $\Rightarrow$ denoising algorithms, sensor networks

Leuchtturmprojekte der quantenbasierten Messtechnik zur Bewältigung gesellschaftlicher Herausforderungen

DiaQNOS

DIAmond based Quantum sensing for NeurOSurgery

Verbundname: DIAmond based Quantum sensing for NeurOSurgery

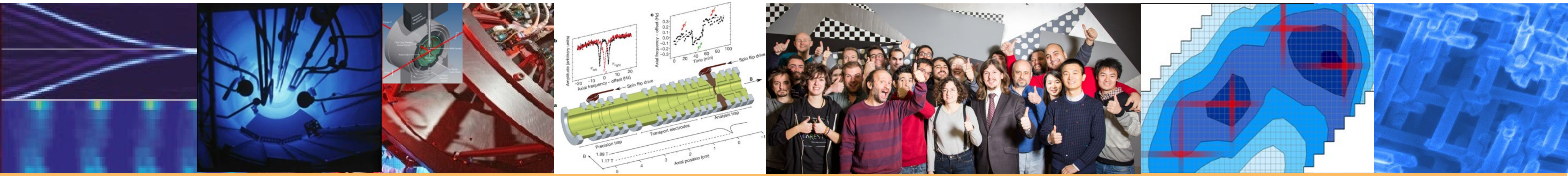
GSI HELMHOLTZ Helmholtz Institute Mainz JG|U

# Searching new physics with quantum sensors


*Arne Wickenbrock*

*Helmholtz Institute and JGU Mainz*


*15.05.2025*



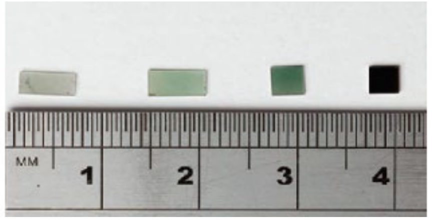
- Magnetometry and applications

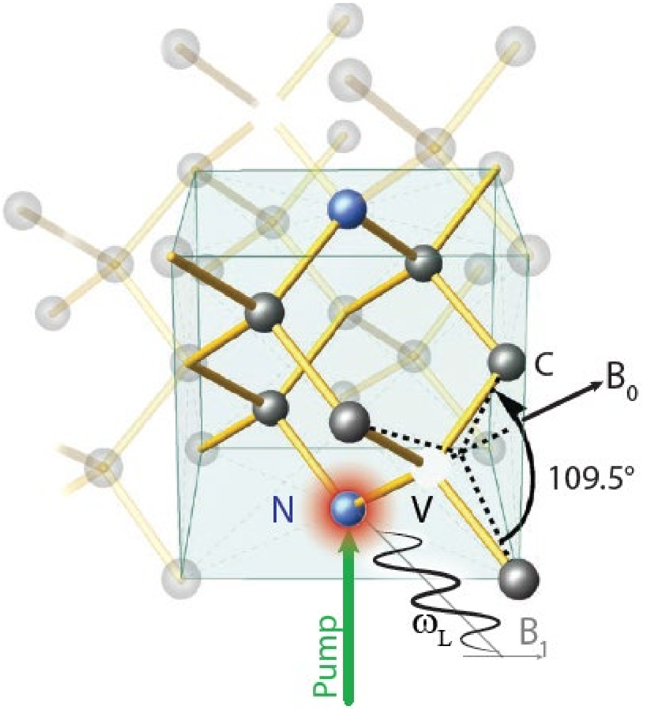
  - Introduction
  - Sensors: Vapor cell and diamond magnetometry
  - Interlude: Current measurements

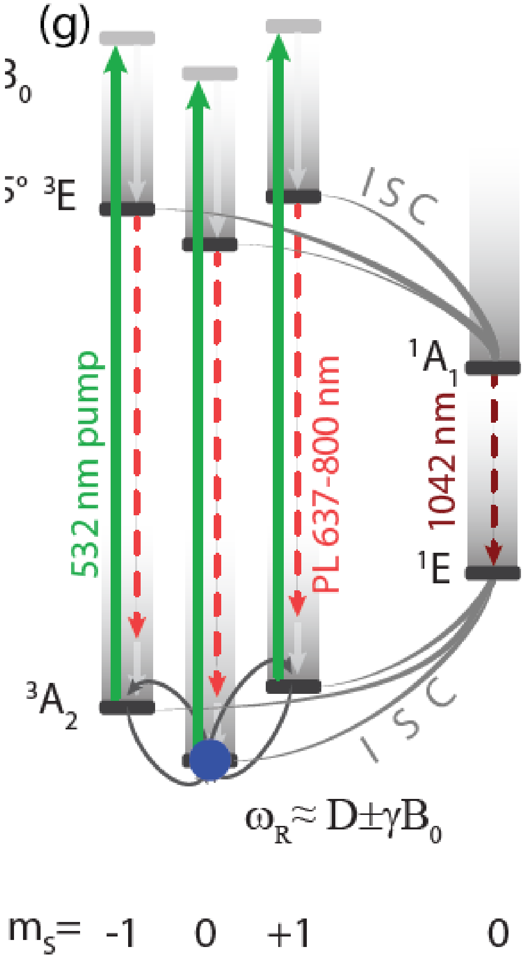
  - Dark matter experiments in Mainz
  - Lineshape of gradient coupled galactic dark matter
  - Beyond magnetometry
  - Techniques

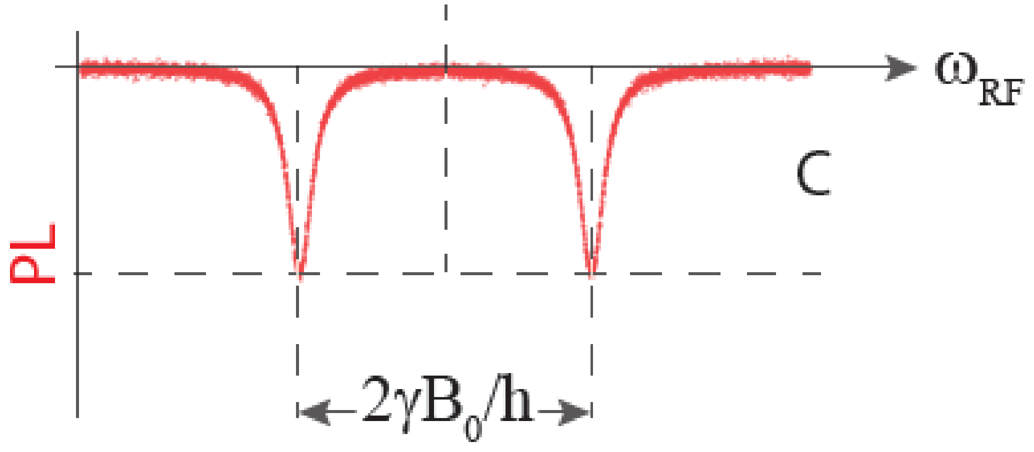
Ask questions!

- Nitrogen Vacancy in Diamond

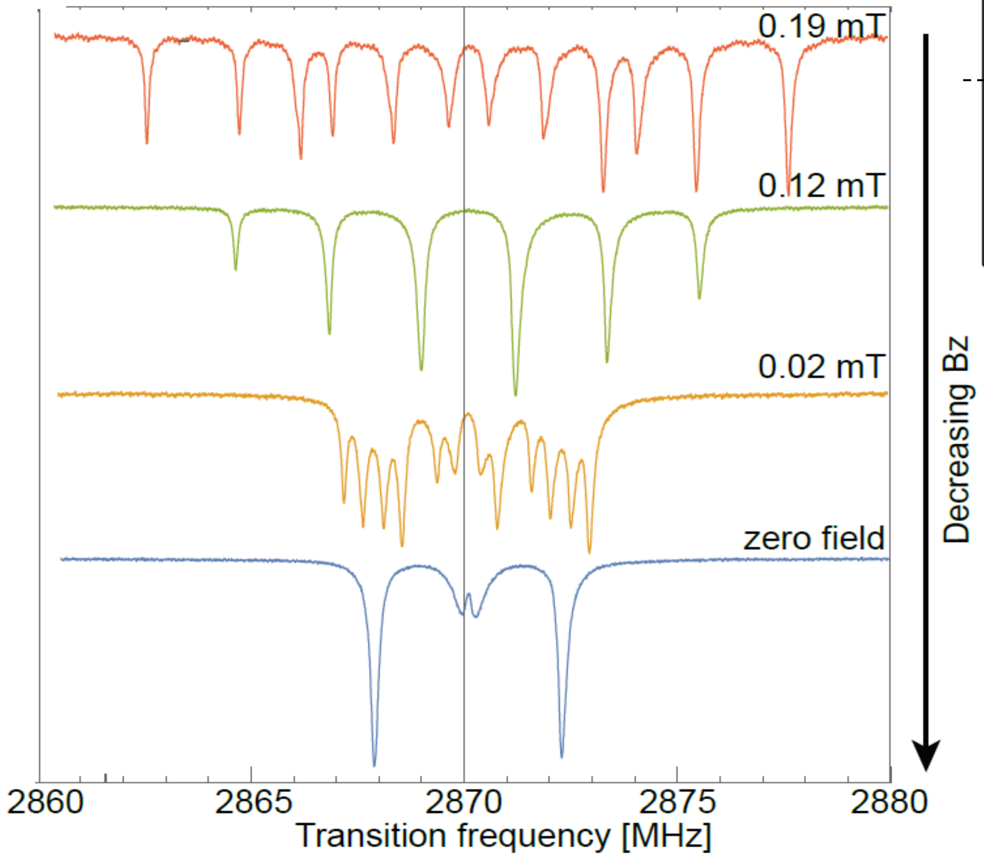


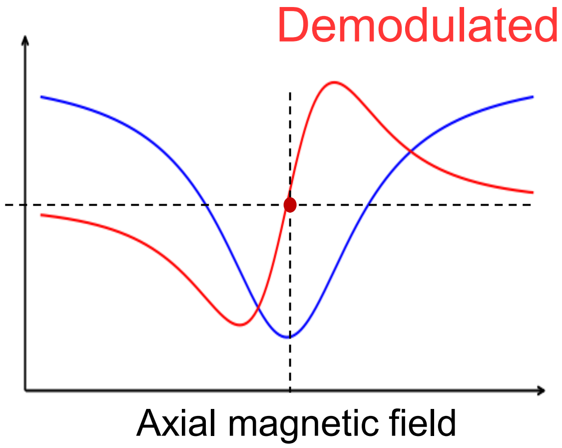



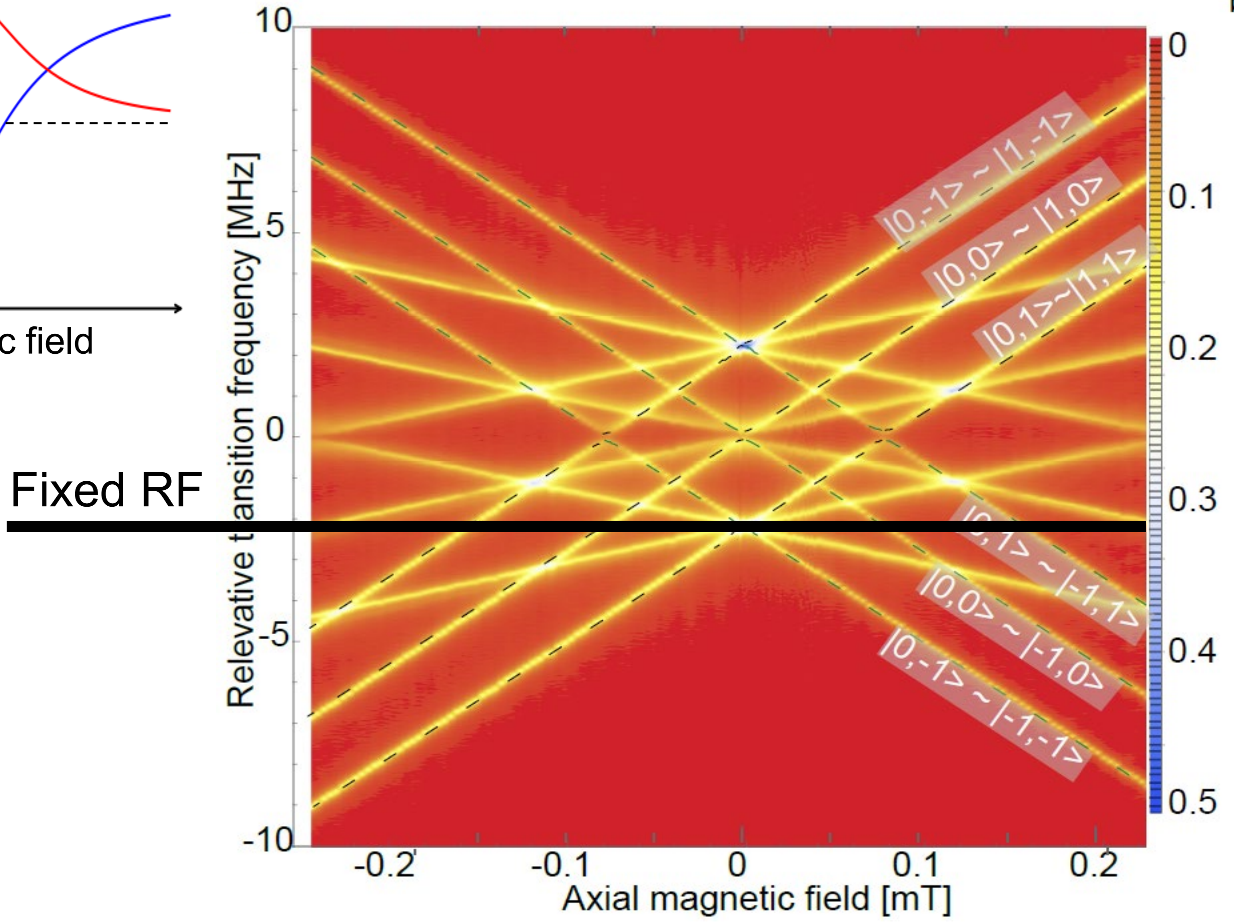



# Zero-field magnetometry with NVs



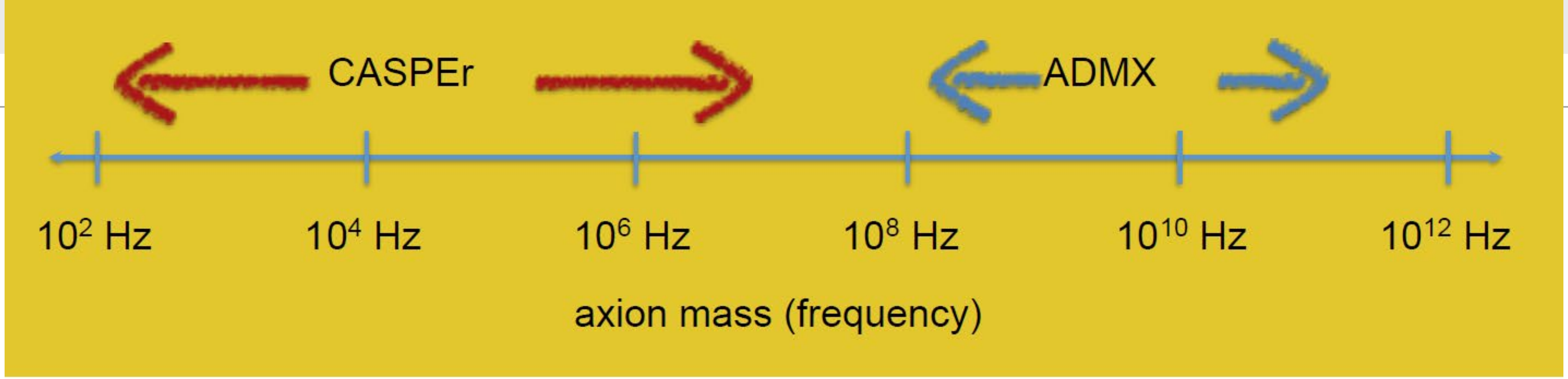



## Nuclear Magnetic Resonance Meets Dark Matter


# *The Cosmic Axion Spin Precession Experiment (CASPEr)*

HIM
Helmholtz-Institut Mainz




# Cosmic Axion Spin Precession Experiment (CASPEr)

with
Peter Graham
Surjeet Rajendran
Alex Sushkov
Micah Ledbetter

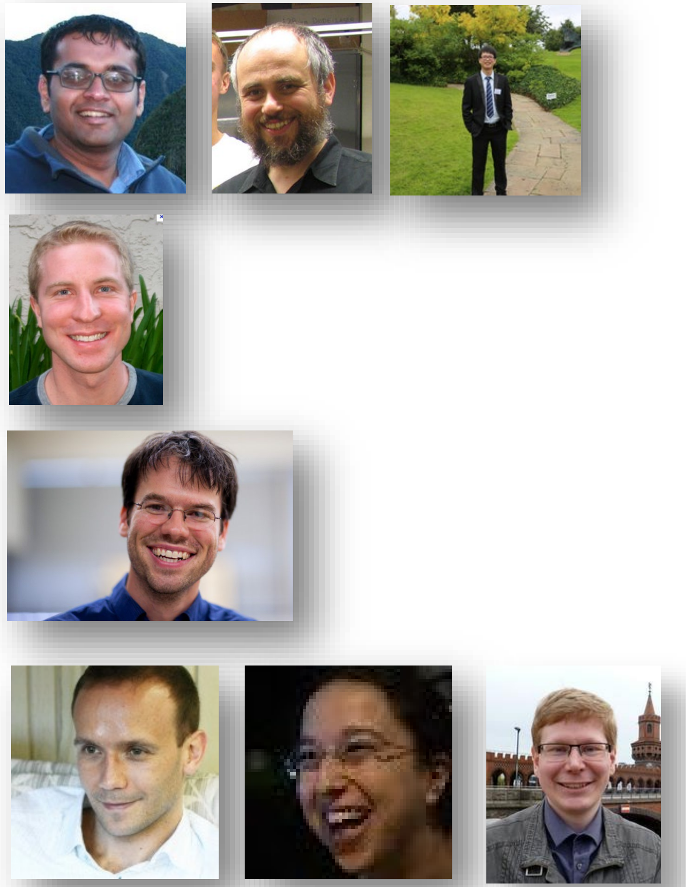
PRD **88** (2013) arXiv:1306.6088,
PRX (2014) arxXiv:1306.6089,
PRD **84** (2011) arXiv:1101.2691

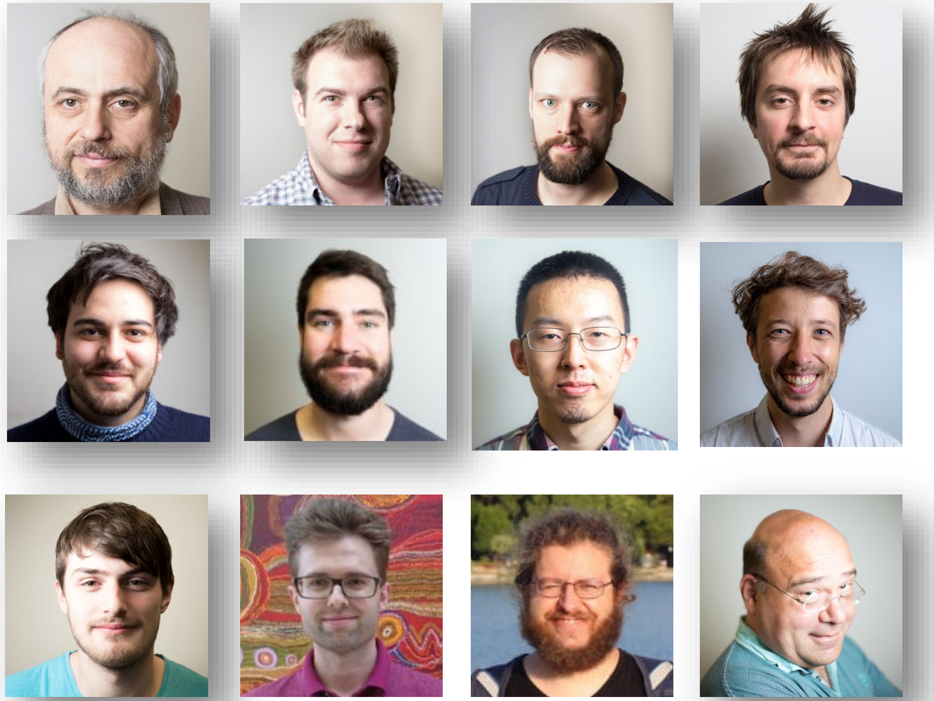
# Acknowledgements

HELMHOLTZ
Helmholtz Institute Mainz

HELMHOLTZ GEMEINSCHAFT
Helmholtz-Institut Mainz

JOHANNES GUTENBERG UNIVERSITÄT MAINZ





Arian Dogan

SIMONS FOUNDATION

DFG

erc

HEISING - SIMONS FOUNDATION



HELMHOLTZ

# How to search for Axions (ALPs) ?

## Axion (ALP) Interactions

Gravity

+

Gauge Fields

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

Most Searches

(CASPEr-E)

Fermions

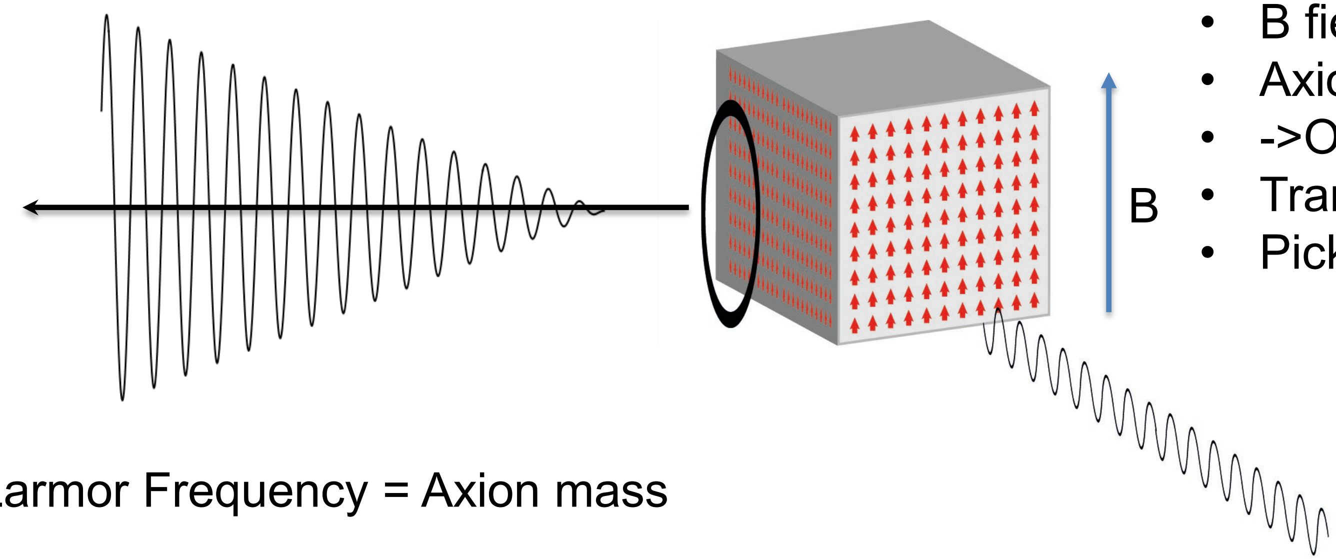
$\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$

(CASPEr-Gradient, GNOME, QUAX)

# CASPEr – Gradient – idea

Detecting oscillating torque on nuclear xenon-129 spins from (0.01-4) MHz

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

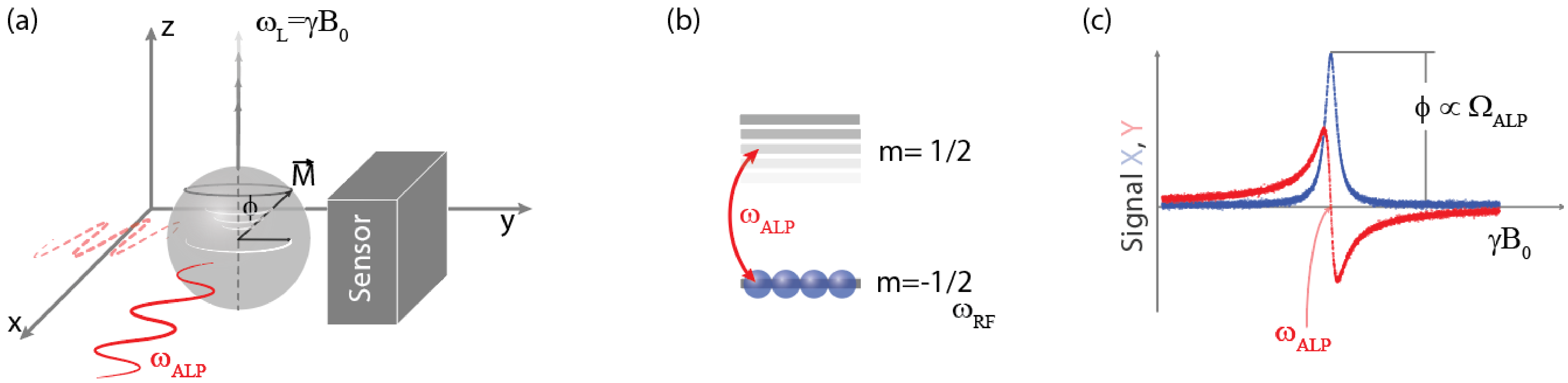



- **Polarized nuclear spins**
- B field (set Larmor frequency)
- Axion gradient couples to spins
- ->Oscillating torque on spins
- Transversal magnetization
- Pickup (somehow)

Larmor Frequency = Axion mass

=>Resonant enhancement

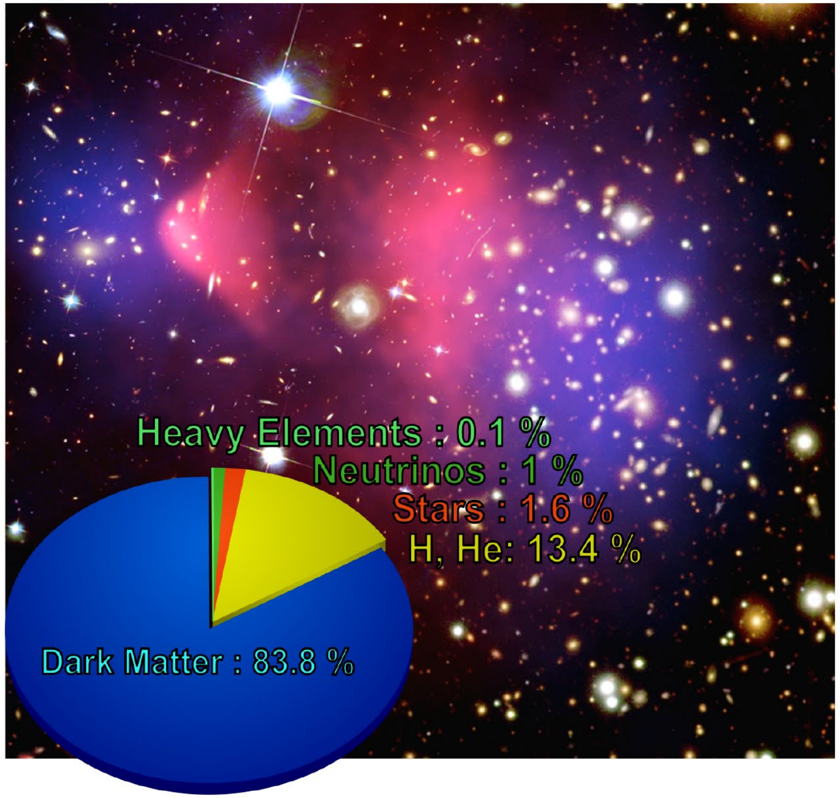
Two ways to search




Perp. To B
Sensitivity plane

Parallel to B
Sensitivity axis

# New Physics - Dark matter




## Stochastic fluctuations of bosonic dark matter

Gary P. Centers, John W. Blanchard, Jan Conrad, Nataniel L. Figueroa, Antoine Garcon, Alexander V. Gramolin, Derek F. Jackson Kimball, Matthew Lawson, Bart Pelssers, Joseph A. Smiga, Alexander O. Sushkov, Arne Wickenbrock, Dmitry Budker & Andrei Derevianko

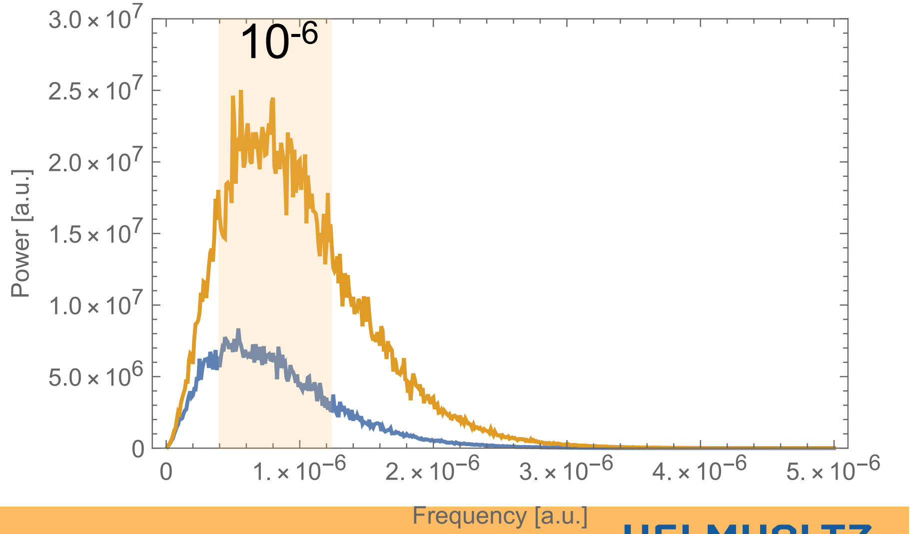
*Nature Communications* **12**, Article number: 7321 (2021) | Cite this article

## Spectral signatures of axionlike dark matter

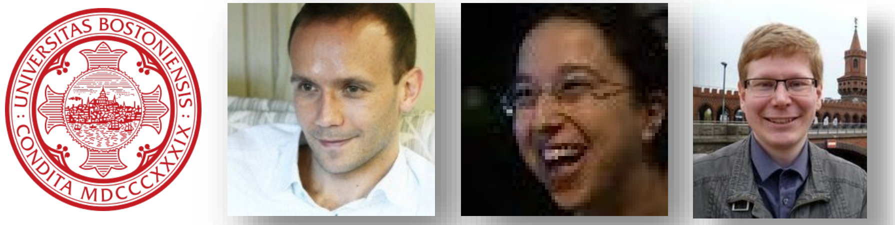
Alexander V. Gramolin, Arne Wickenbrock, Deniz Aybas, Hendrik Bekker, Dmitry Budker, Gary P. Centers, Nataniel L. Figueroa, Derek F. Jackson Kimball, and Alexander O. Sushkov

Phys. Rev. D **105**, 035029 – Published 24 February 2022

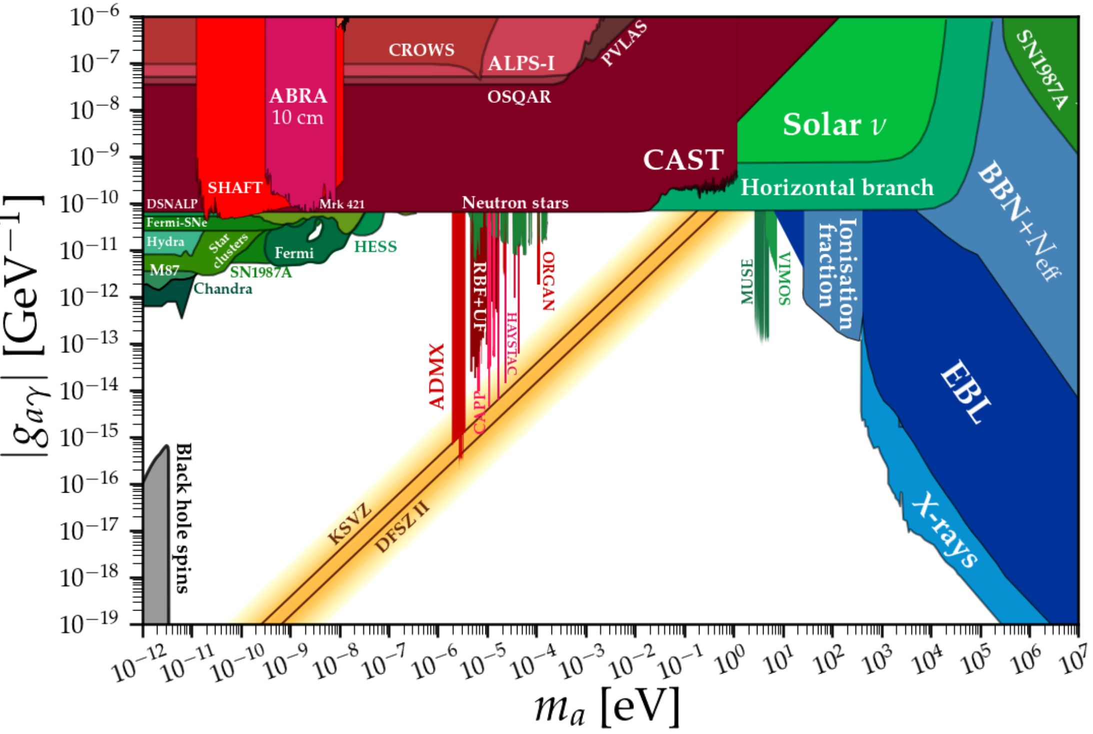
- ALP dark matter: oscillating magnetic field on spins
- Unknown frequency: nHz→THz
- Virialized → Q~$10^6$
- Strong daily modulation! (directional) → Sidebands

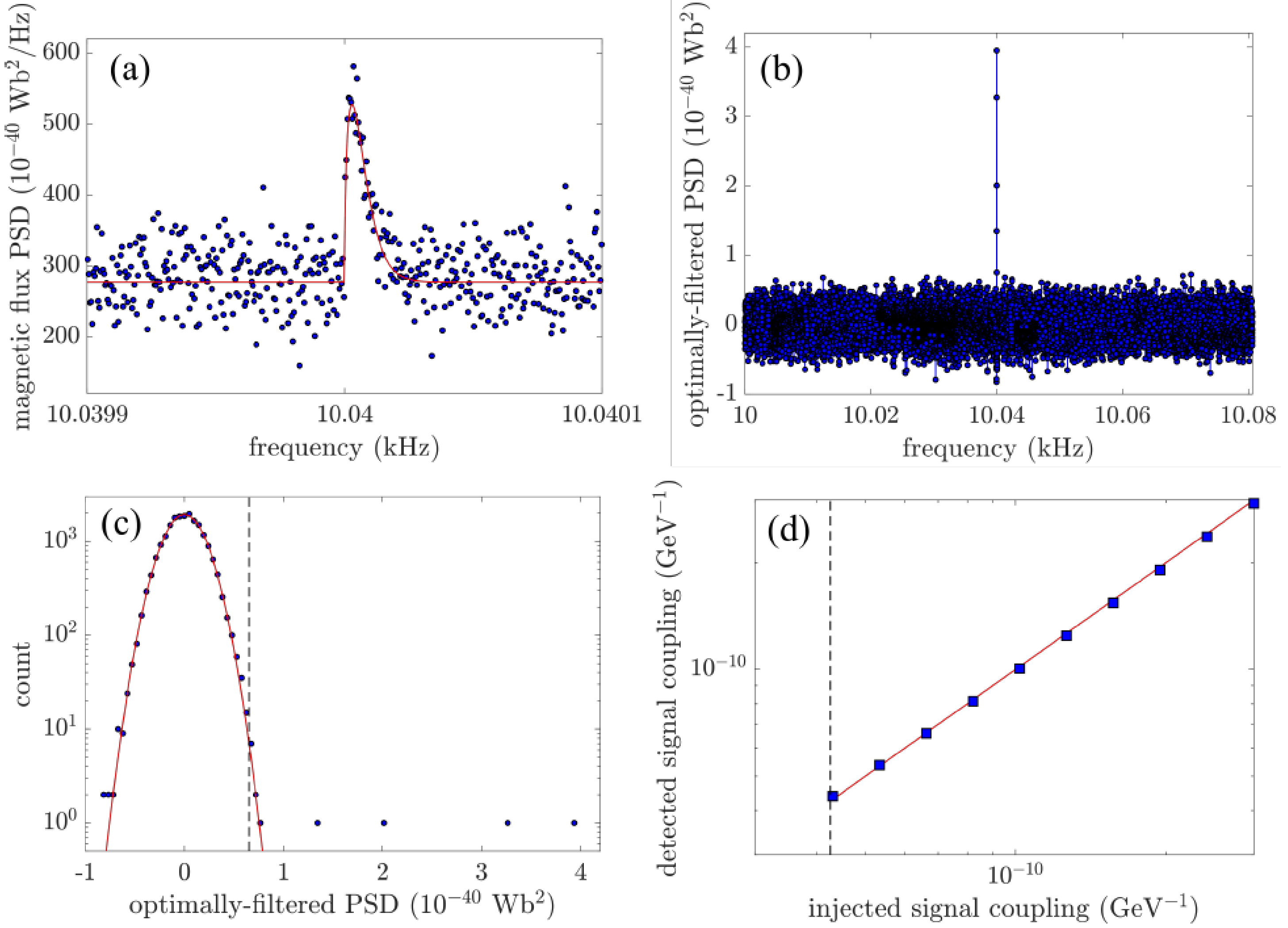


# Why is the lineshape relevant?



Improving limits by optimally filtering the power spectrum data in SHAFT



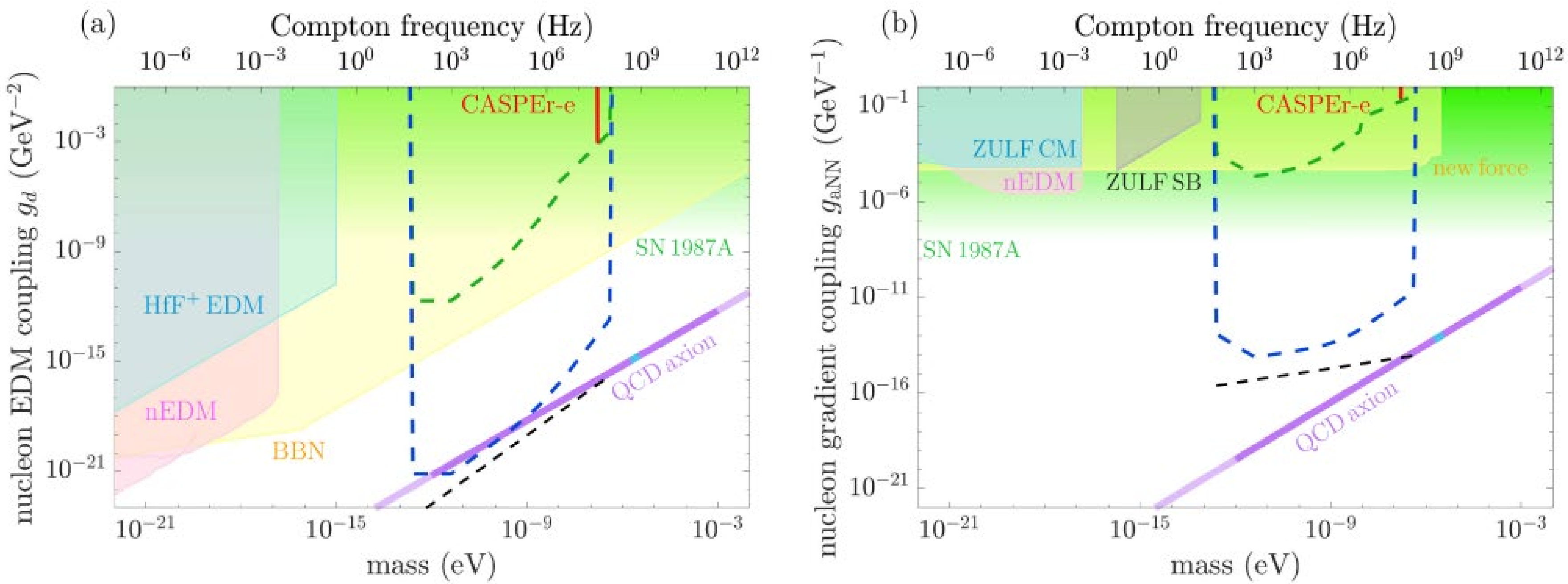



# CASPEr Boston result

## Search for Axionlike Dark Matter Using Solid-State Nuclear Magnetic Resonance

Deniz Aybas, Janos Adam, Emmy Blumenthal, Alexander V. Gramolin, Dorian Johnson, Annalies Kleyheeg, Samer Afach, John W. Blanchard, Gary P. Centers, Antoine Garcon, Martin Engler, Nataniel L. Figueroa, Marina Gil Sendra, Arne Wickenbrock, Matthew Lawson, Tao Wang, Teng Wu, Haosu Luo, Hamdi Mani, Philip Mauskopf, Peter W. Graham, Surjeet Rajendran, Derek F. Jackson Kimball, Dmitry Budker, and Alexander O. Sushkov

Phys. Rev. Lett. **126**, 141802 – Published 9 April 2021




Optimal filtering in CASPEr-E Boston required the gradient coupling lineshape

# Take home messages

1. **Gradient signal** = 3D pseudo magnetic field vector rotating in space with two independent phases
2. **Gradient line shape** fundamentally different (from the scalar lineshape)
3. Most power in the direction of movement (~ linear polarized signal )
4. Larger effect of annual and daily modulation
    1. On signal amplitude
    2. On signal frequency
5. Not new, but still: Virialized dark matter power spectra = modulated white noise

Spectral signatures of axionlike dark matter

Alexander V. Gramolin, Arne Wickenbrock, Deniz Aybas, Hendrik Bekker, Dmitry Budker, Gary P. Centers, Nataniel L. Figueroa, Derek F. Jackson Kimball, and Alexander O. Sushkov
Phys. Rev. D **105**, 035029 – Published 24 February 2022

PHYSICAL REVIEW D 97, 123006 (2018)

# Derivation of the **scalar** lineshape

**Revealing the dark matter halo with axion direct detection**

Joshua W. Foster,[1] Nicholas L. Rodd,[2] and Benjamin R. Safdi[1]
[1]Leinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA
[2]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 19 January 2018; published 14 June 2018)

## Axion field

$$\nu_n = \left(1 + \frac{v_n^2}{2c^2}\right)\nu_a$$

Random speed! Random!

$$a(\mathbf{r}, t) = \frac{a_0}{\sqrt{N}} \sum_{n=1}^{N} \cos\left(2\pi \nu_n t - \mathbf{k}_n \cdot \mathbf{r} + \phi_n\right)$$

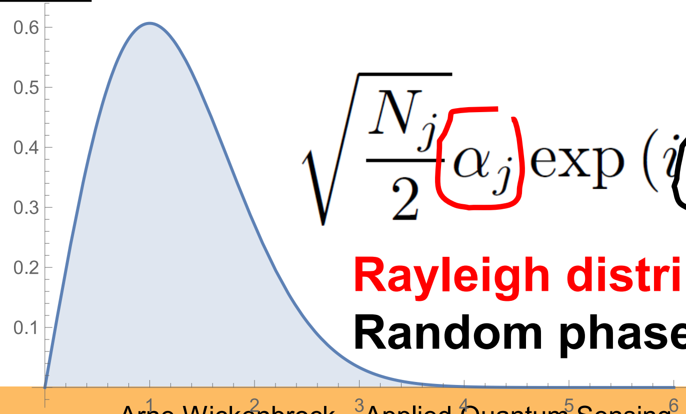
## Axion field frequency class j

Oscillation Amplitude + Phase

$$a_j(t) = \frac{a_0}{\sqrt{N_j}} \sum_{i\in\Omega_j} \cos\left(\omega_j t + \phi_i\right) \propto \Re\left[\exp\left(i\omega_j t\right) \sum_{i\in\Omega_j} \exp\left(i\phi_i\right)\right]$$

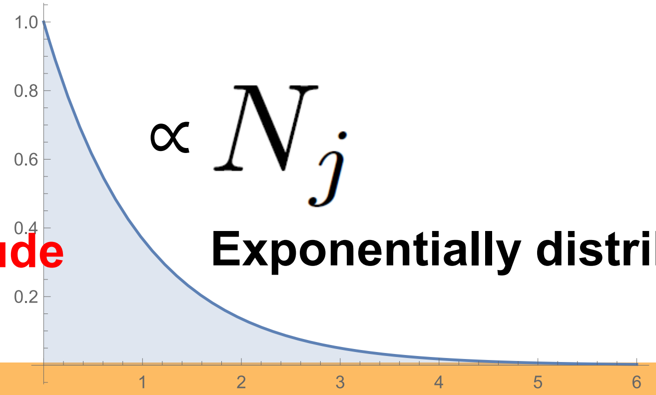
## Central limit theorem:

$$\sum_{i\in\Omega_j} \exp\left(i\phi_i\right) = \sqrt{\frac{N_j}{2}}\,\alpha_j \exp\left(i\phi_j\right)$$




**Rayleigh distributed amplitude**
**Random phase**

$$\propto N_j$$




**Exponentially distributed power!**

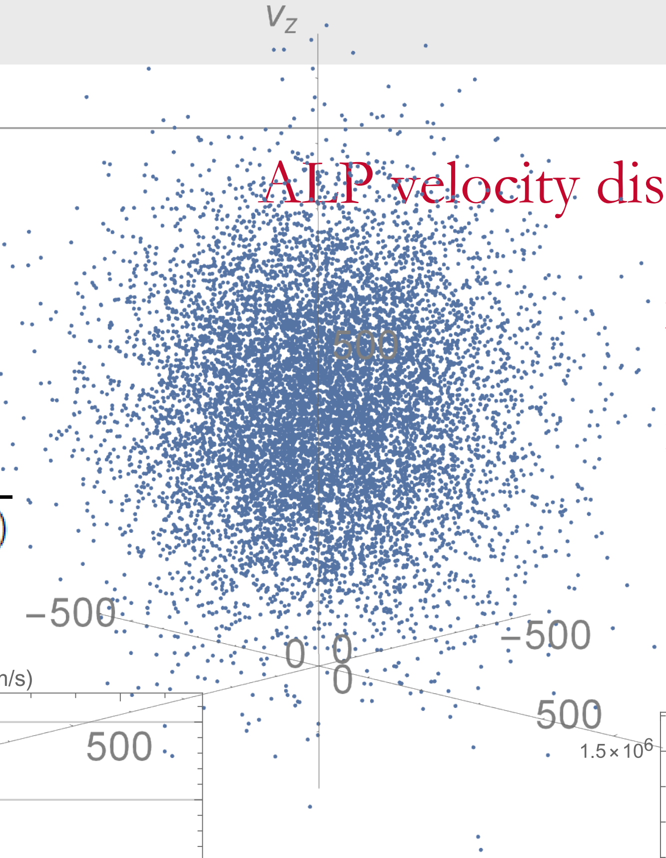


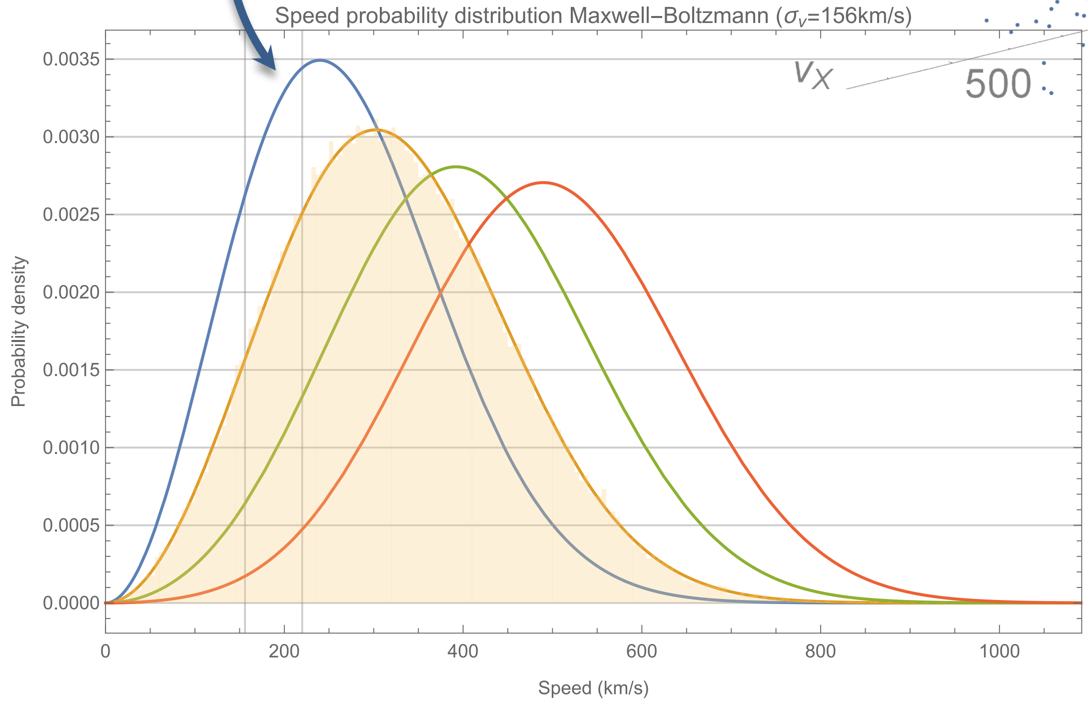
JG|U HELMHOLTZ

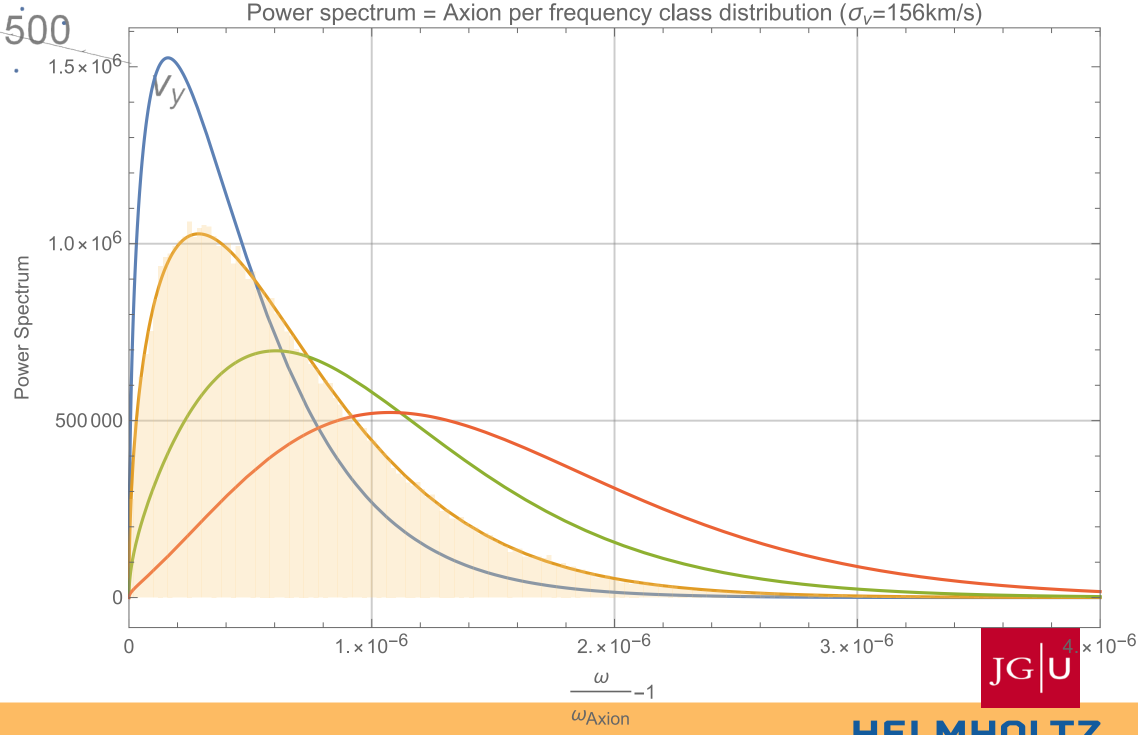
# Scalar lineshape – ALP velocity distribution

- Standard Halo Model:
- DM Velocity distribution 3D Gaussian [0,156km/s]
- Cut-off at galactic escape velocity [550km/s ignored]
- Earth velocity: ~230km/s towards Cygnus


$$\lambda(\nu) = f(v)\,\frac{dv}{d\nu}\bigg|_{v=c\sqrt{2(\nu/\nu_a-1)}}$$

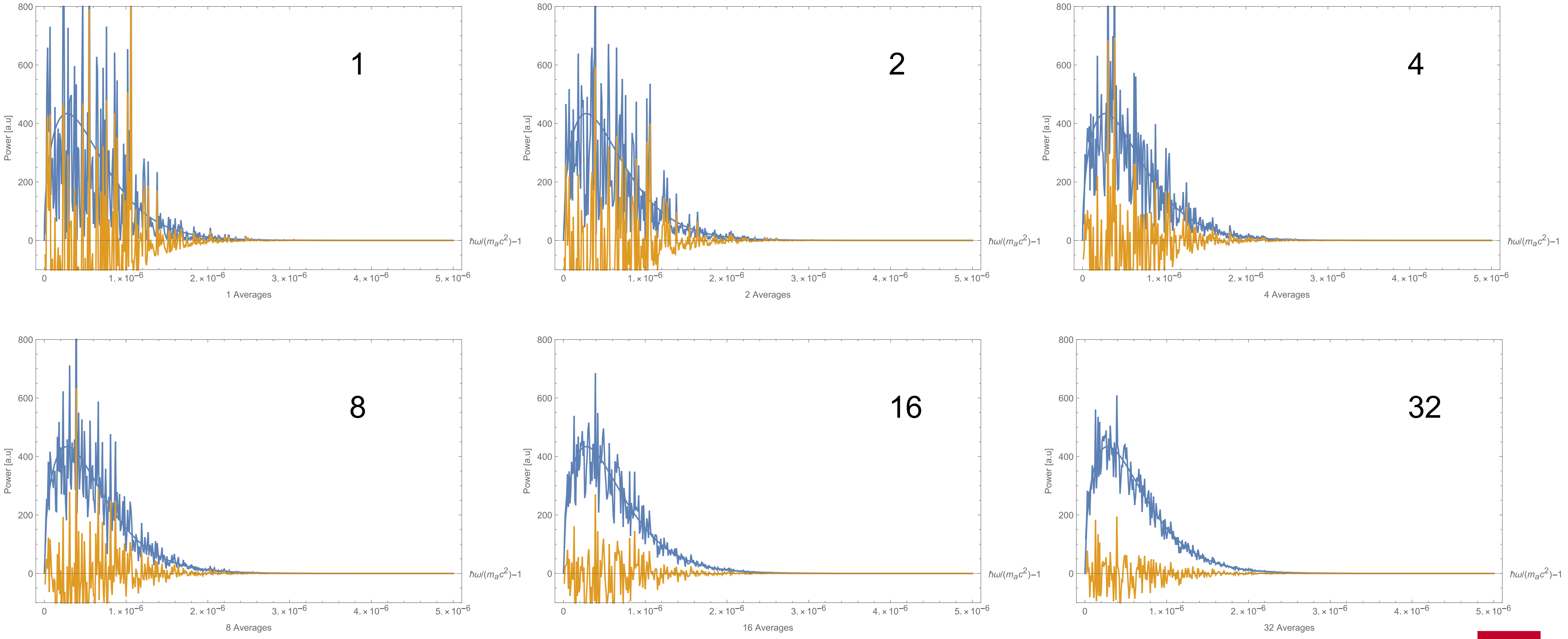



Ciaran O'Hare PHYSICAL REVIEW D 95, 063017 (2017)

# Scalar lineshape – Power spectra , exponentially distributed in each bin.



# Derivation of the **gradient** lineshape

Gradient Axion field

Random 3D velocity — Random acc. speed! — Random!

$$\nabla a(\mathbf{r},t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{c\sqrt{N}} \sum_{n=1}^{N} \mathbf{v}_n \sin\left(2\pi\nu_n t - \mathbf{k}_n\cdot\mathbf{r} + \phi_n\right)$$

Gradient field frequency class j, x-

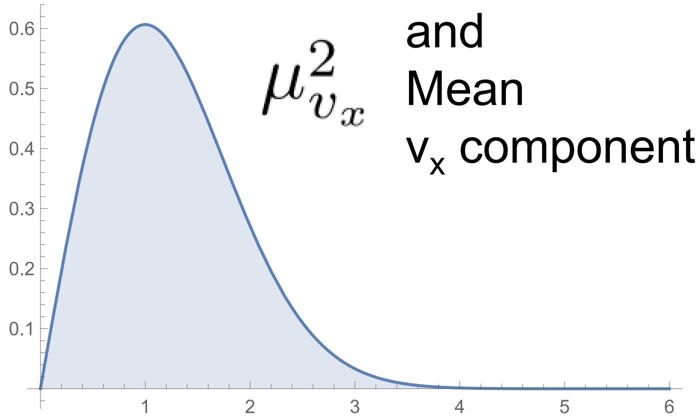
Oscillation — Amplitude + Phase — New!

$$\nabla a_{j,x}(t) \propto \Im\left[\exp\left(i\omega_j t\right)\sum_{i\in\Omega_j} v_{x,i}\exp\left(i\phi_i\right)\right]$$

$\sigma^2_{v_x}$ Variance and

$\mu^2_{v_x}$ Mean

$v_x$ component for a given frequency

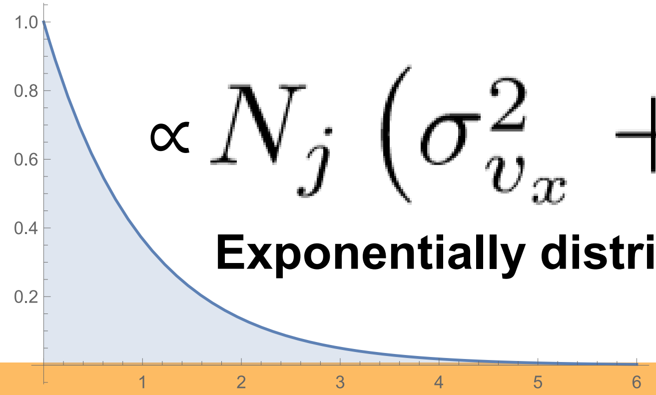



Central limit theorem:

$$\sum_{i\in\Omega_j} v_{x,i}\exp\left(i\phi_i\right) \propto \sqrt{N_j\left(\sigma^2_{v_x}+\mu^2_{v_x}\right)}\,\alpha_j \exp\left(i\phi_j\right)$$

**Rayleigh distributed amplitude**

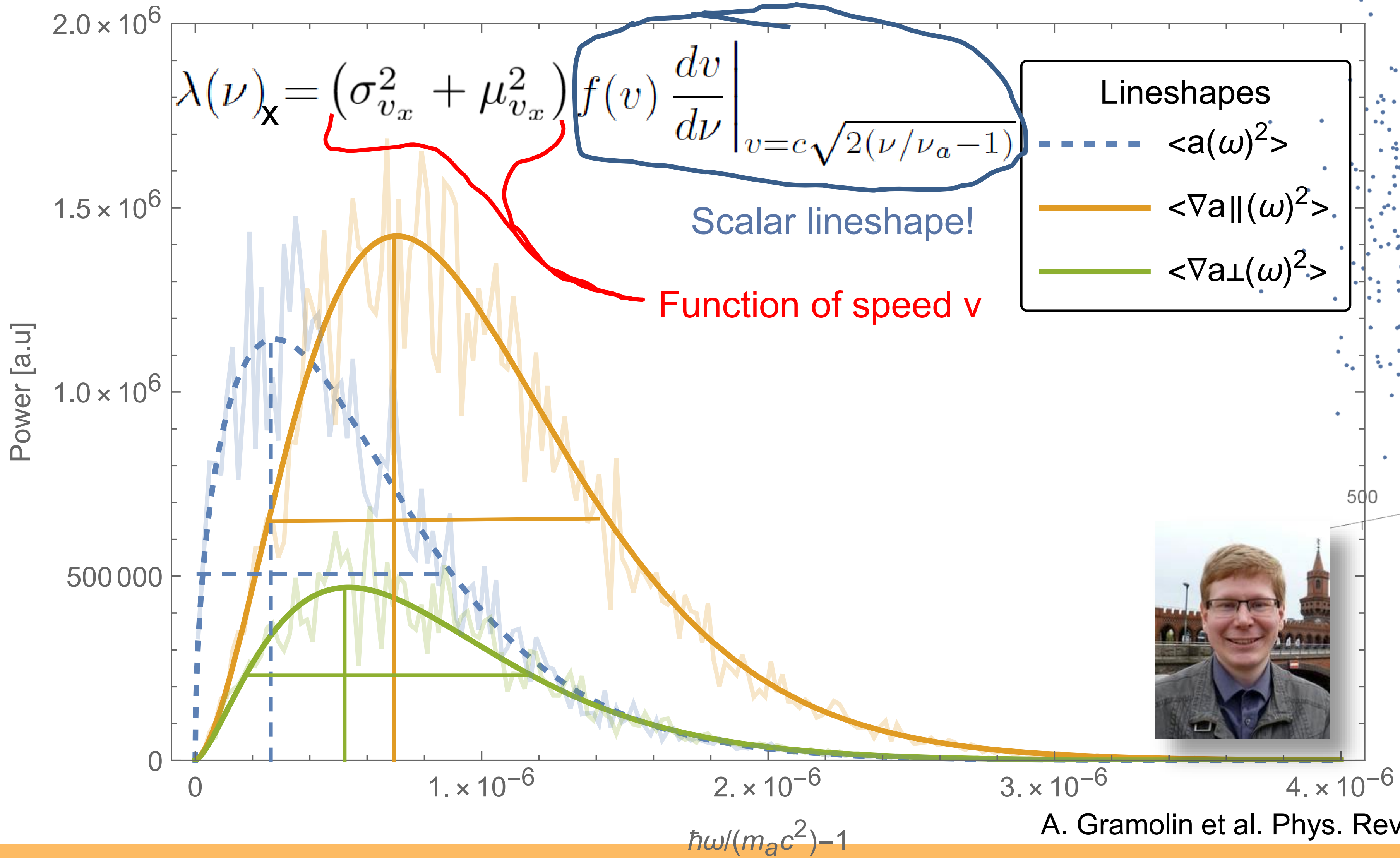
**Random phase, different for different directions!**

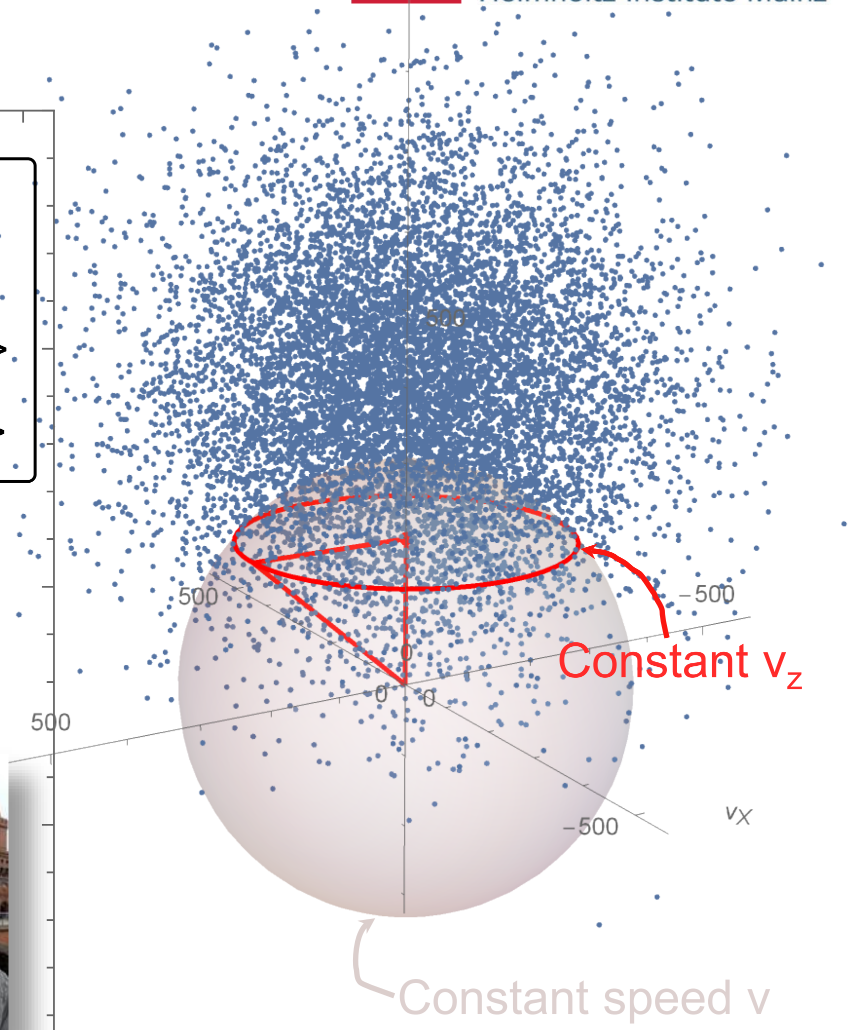



$$\propto N_j\left(\sigma^2_{v_x}+\mu^2_{v_x}\right)$$

**Exponentially distributed power!**

# Gradient lineshape – ALP velocity distribution

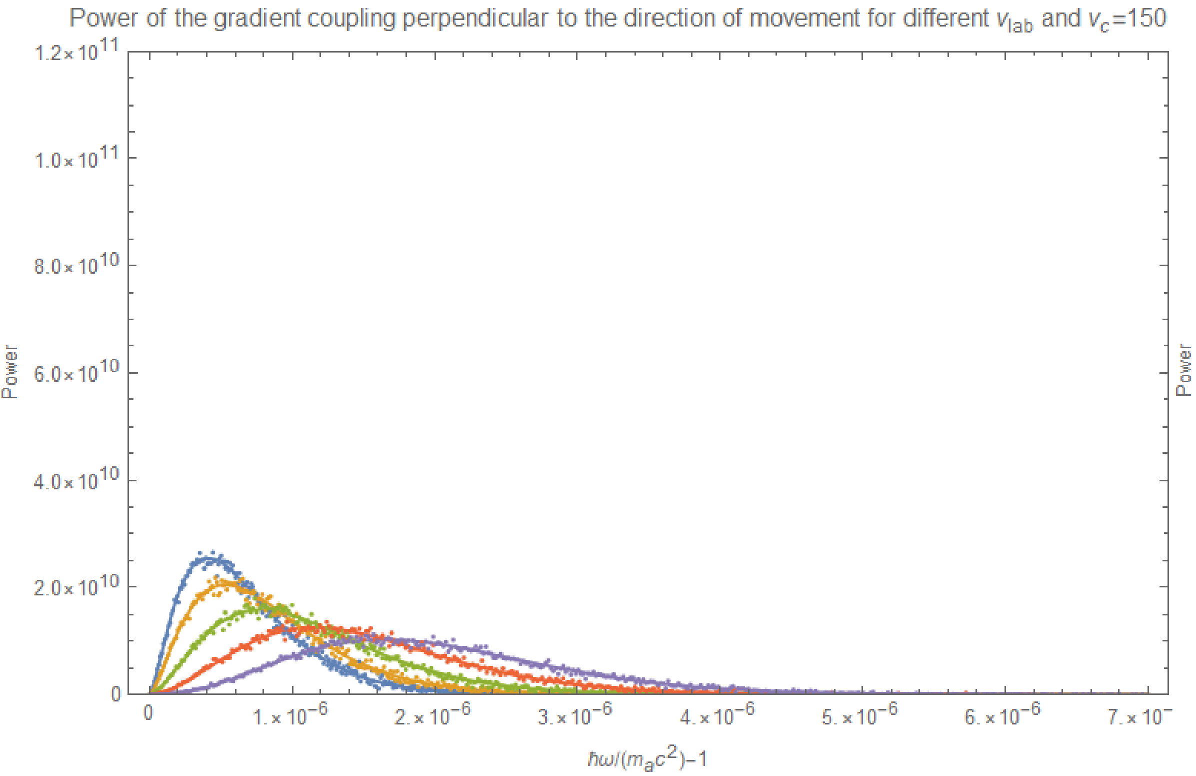


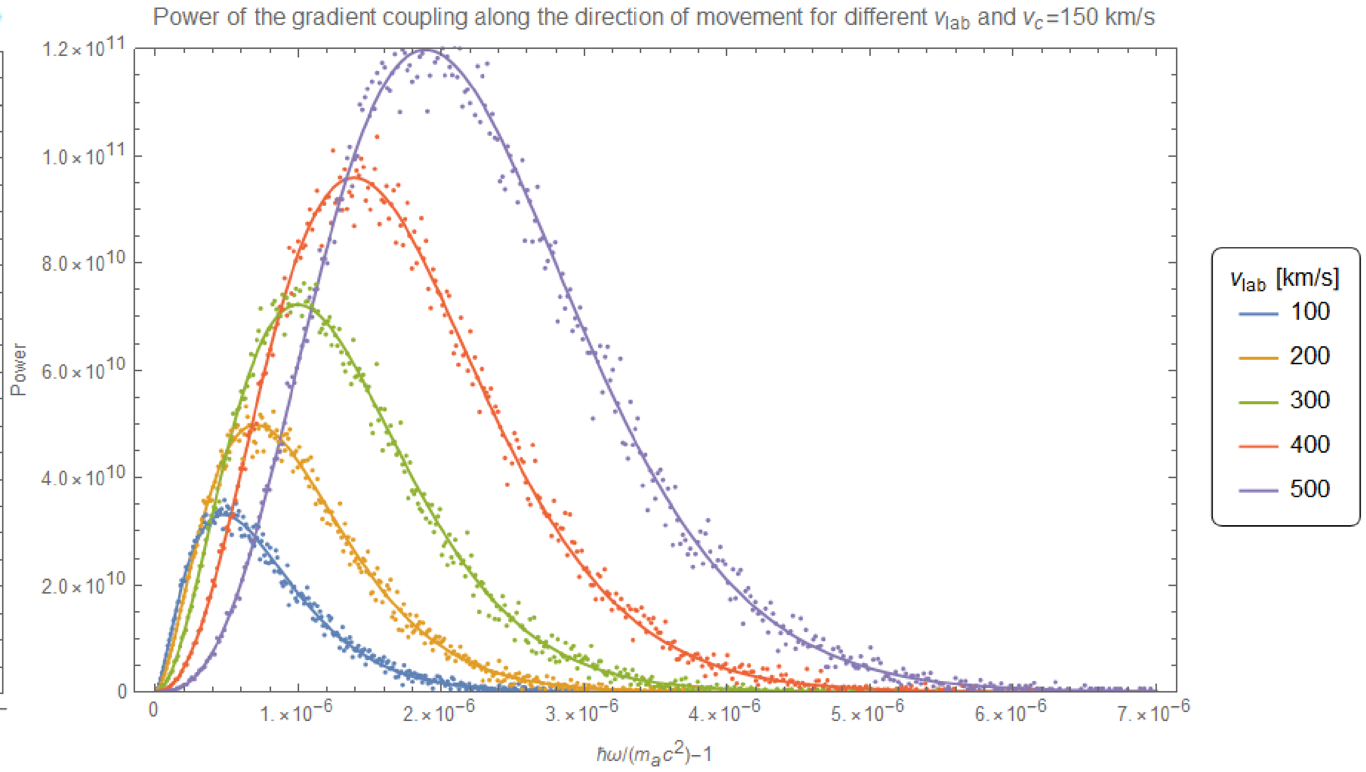

A. Gramolin et al. Phys. Rev. D **105**, 035029

# Scaling with lab velocity

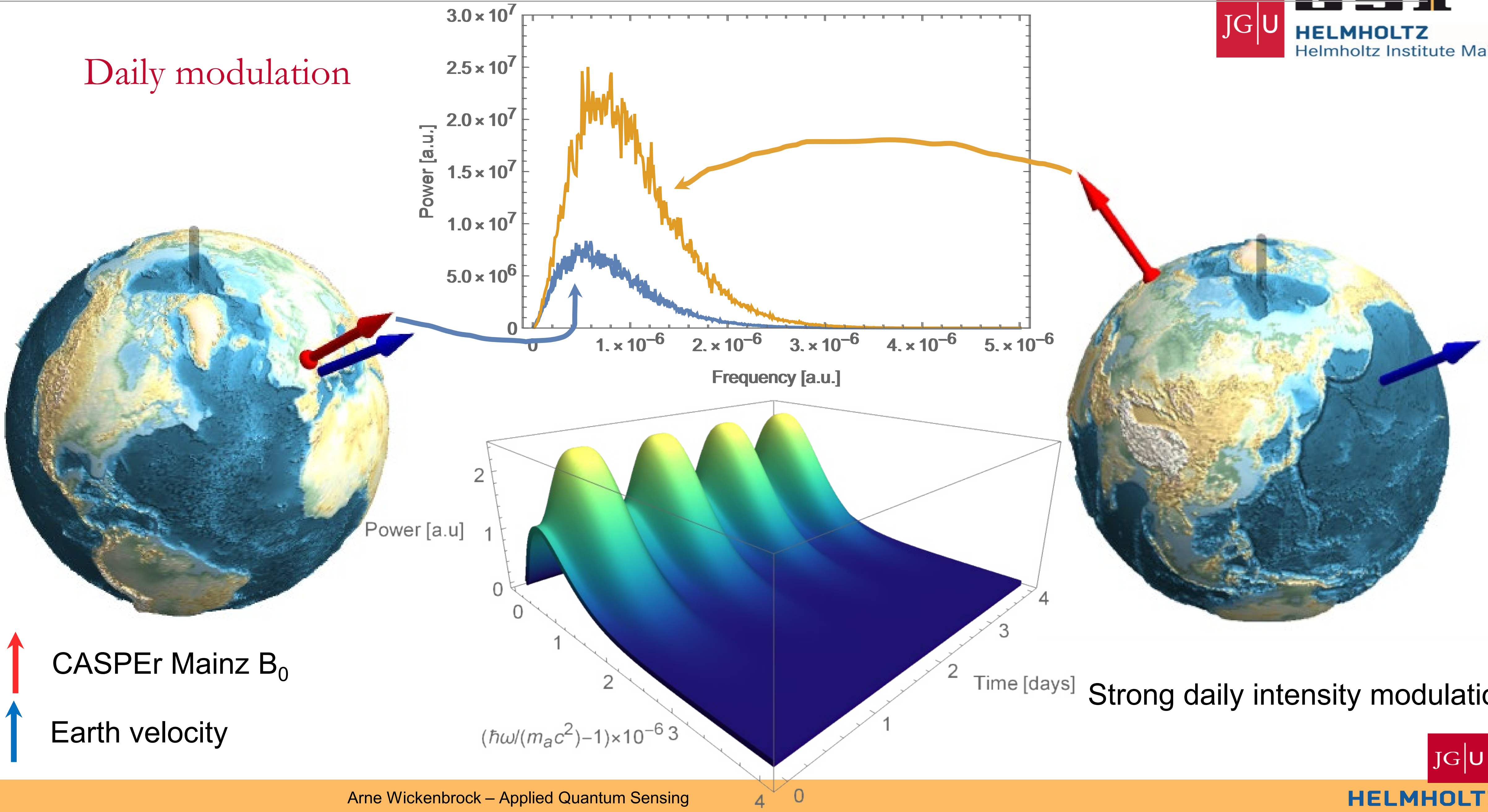
## Perpendicular to the direction of movement




## In the direction of movement



# Daily modulation

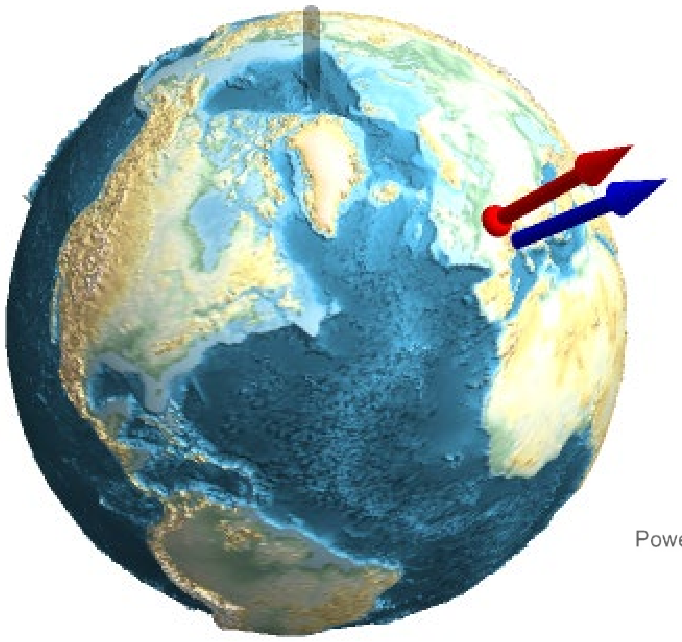


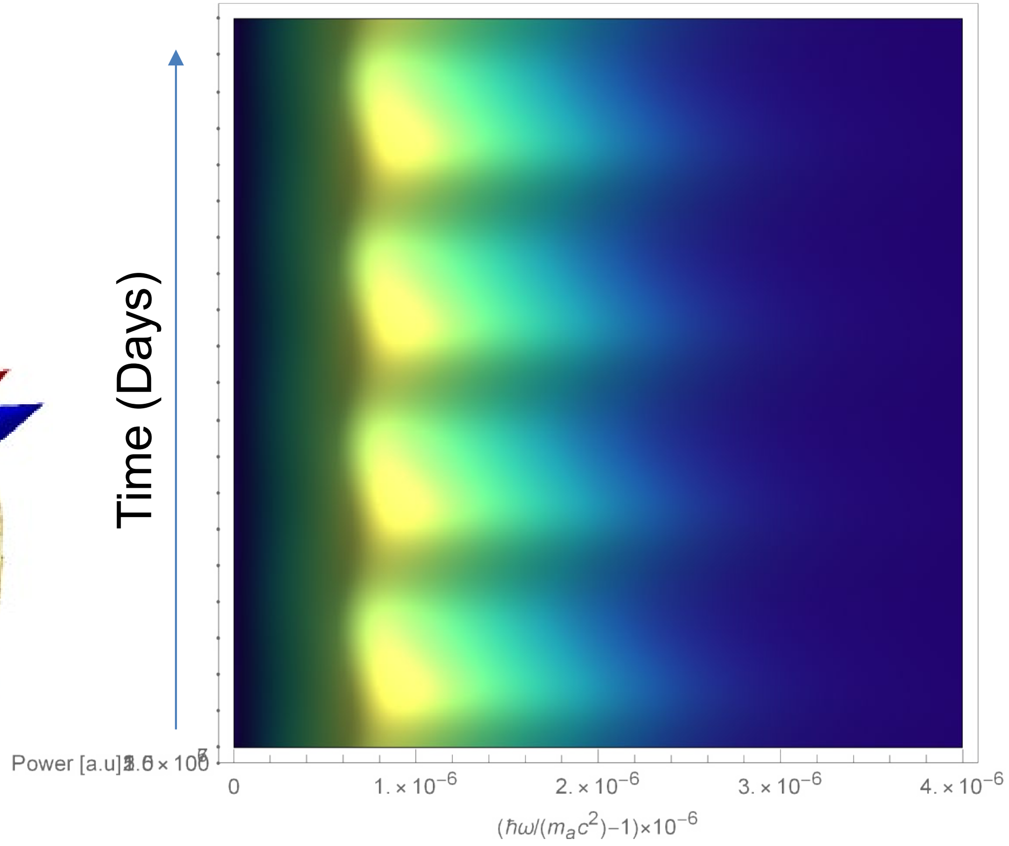

CASPEr Mainz $B_0$

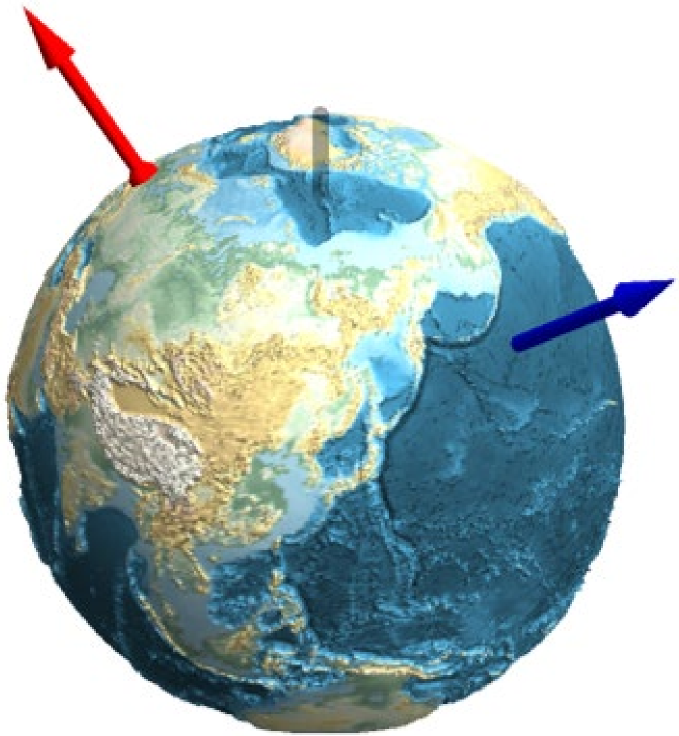
Earth velocity

Strong daily intensity modulation

# Daily modulation





CASPEr Mainz $B_0$

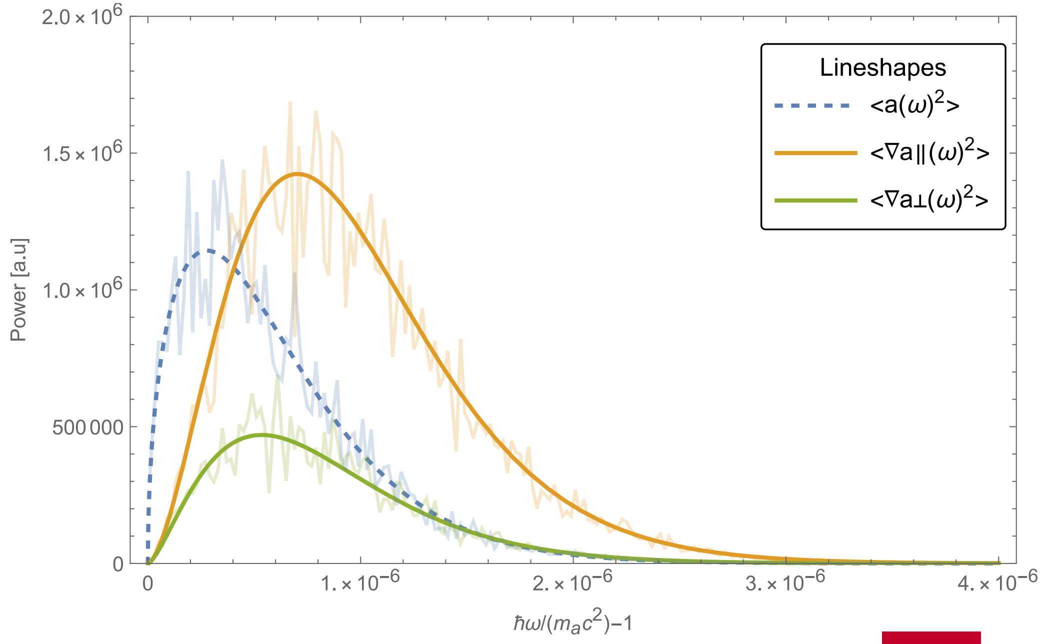
Earth velocity

Strong daily intensity modulation
And
Daily frequency modulation! (10%-15% FWHM)

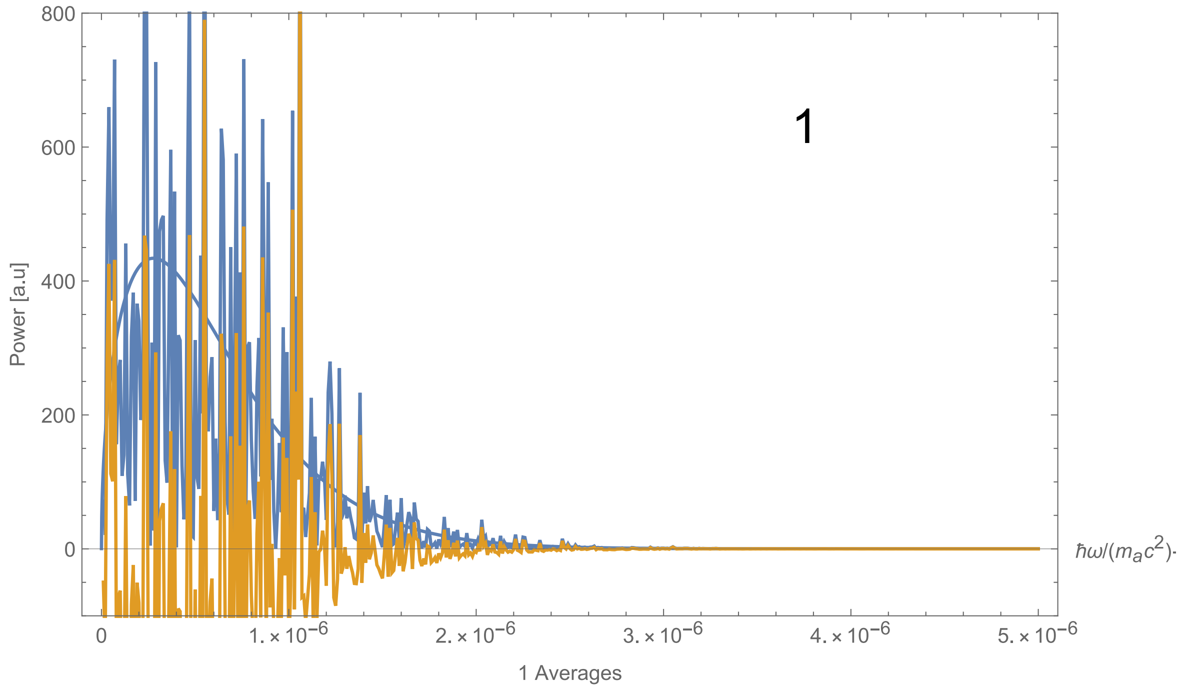
# Take home messages

1. **Gradient signal** = 3D pseudo magnetic field vector rotating in space with two independent phases
2. **Gradient line shape** fundamentally different (from the scalar lineshape)
3. Most power in the direction of movement (~ linear polarized signal )
4. Larger effect of annual and daily modulation
   1. On signal amplitude
   2. On signal frequency
5. Not new, but still:

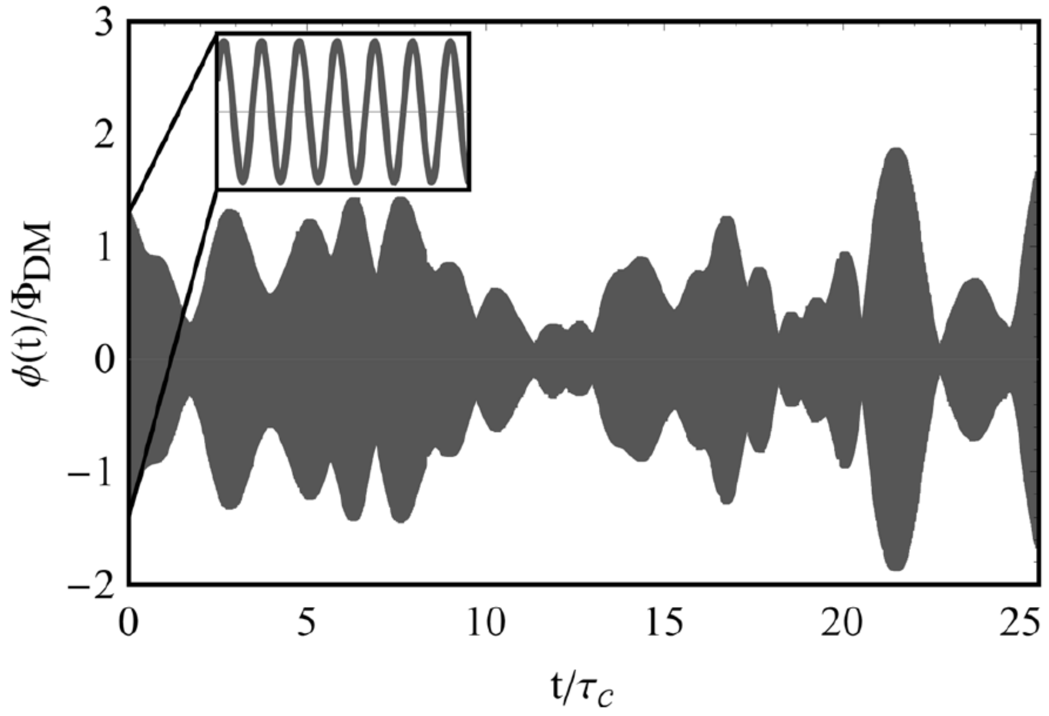
Virialized dark matter power spectra = modulated white noise



## Fourier spectra




## Time series




Implications on search results: maybe the signal was just small!

Igor Pikovski

PHYSICAL REVIEW D **106**, 043517 (2022)

## Nonclassicality of axionlike dark matter through gravitational self-interactions

Michael Kopp,[1,*] Vasileios Fragkos,[2,†] and Igor Pikovski[2,3,‡]

[1]*Nordita, KTH Royal Institute of Technology and Stockholm University, Hannes Alfvéns väg 12, SE-106 91 Stockholm, Sweden*

[2]*Department of Physics, Stockholm University, SE-106 91 Stockholm, Sweden*

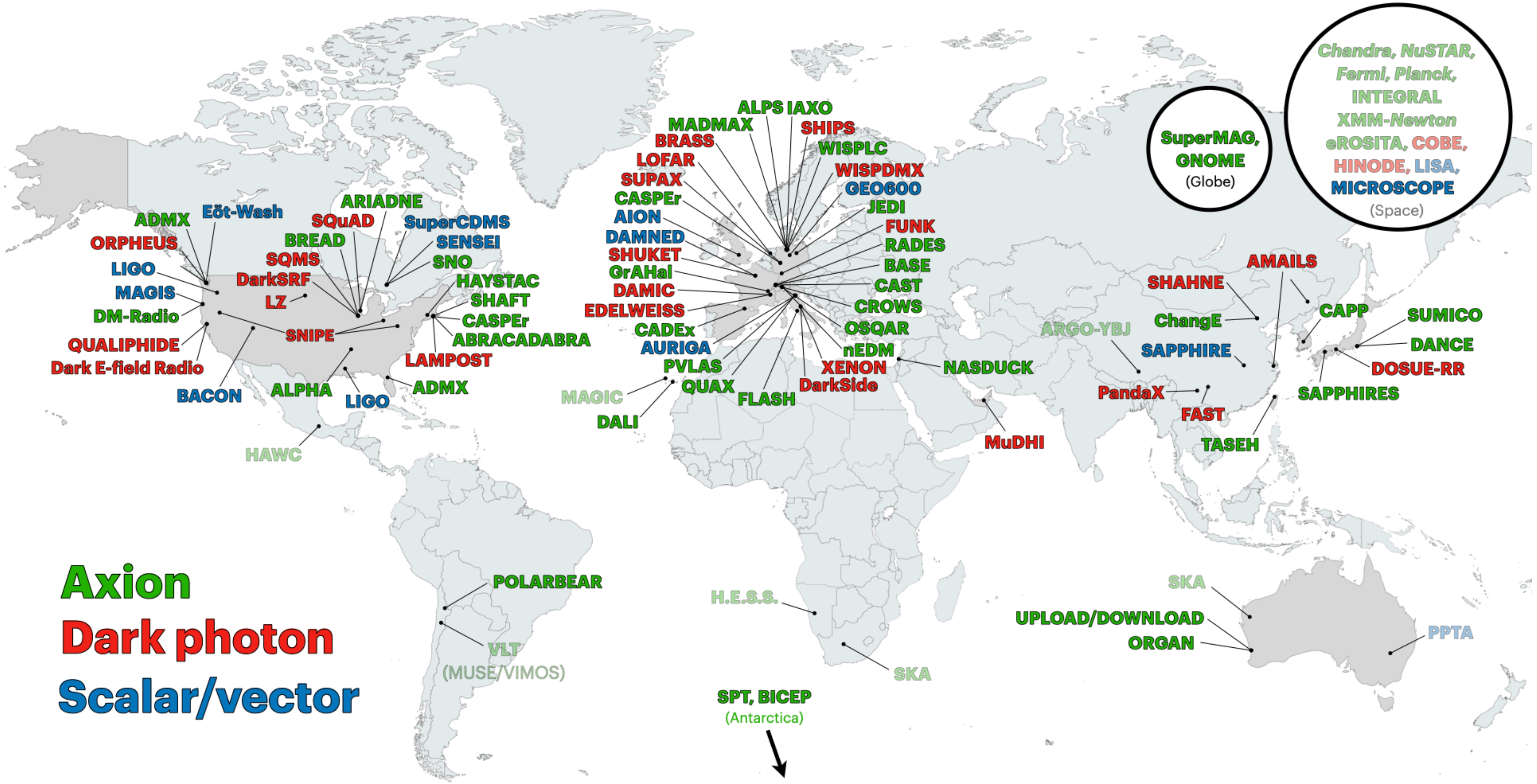
[3]*Department of Physics, Stevens Institute of Technology, Hoboken, New Jersey 07030, USA*

(Received 5 June 2021; accepted 20 July 2022; published 10 August 2022)

ALP state highly nonclassical.
Extremely squeezed.

Potential implications on the lineshape

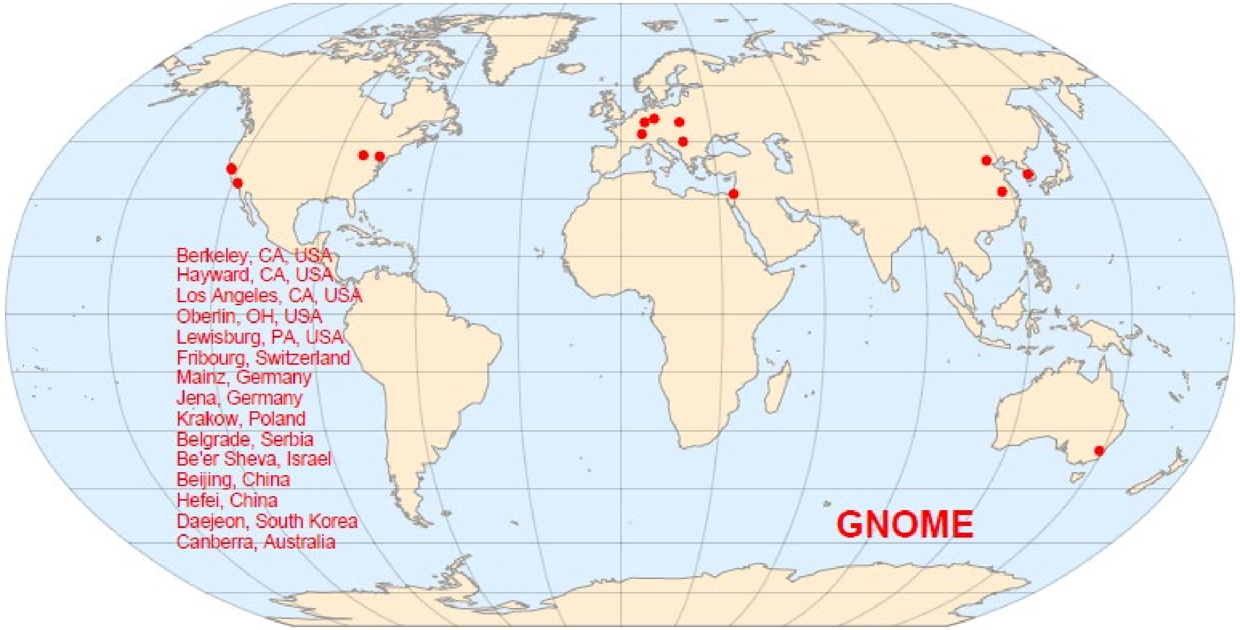
- Global search effort!




https://cajohare.github.io/AxionLimits/

# GNOME: Global network of optically pumped magnetometers

- Topological manifestations of dark matter





GNOME network: Alkali Vapor Magnetometers

Adv. GNOME network: Comagnetometers

→ 3-5 OOM more sensitivity!

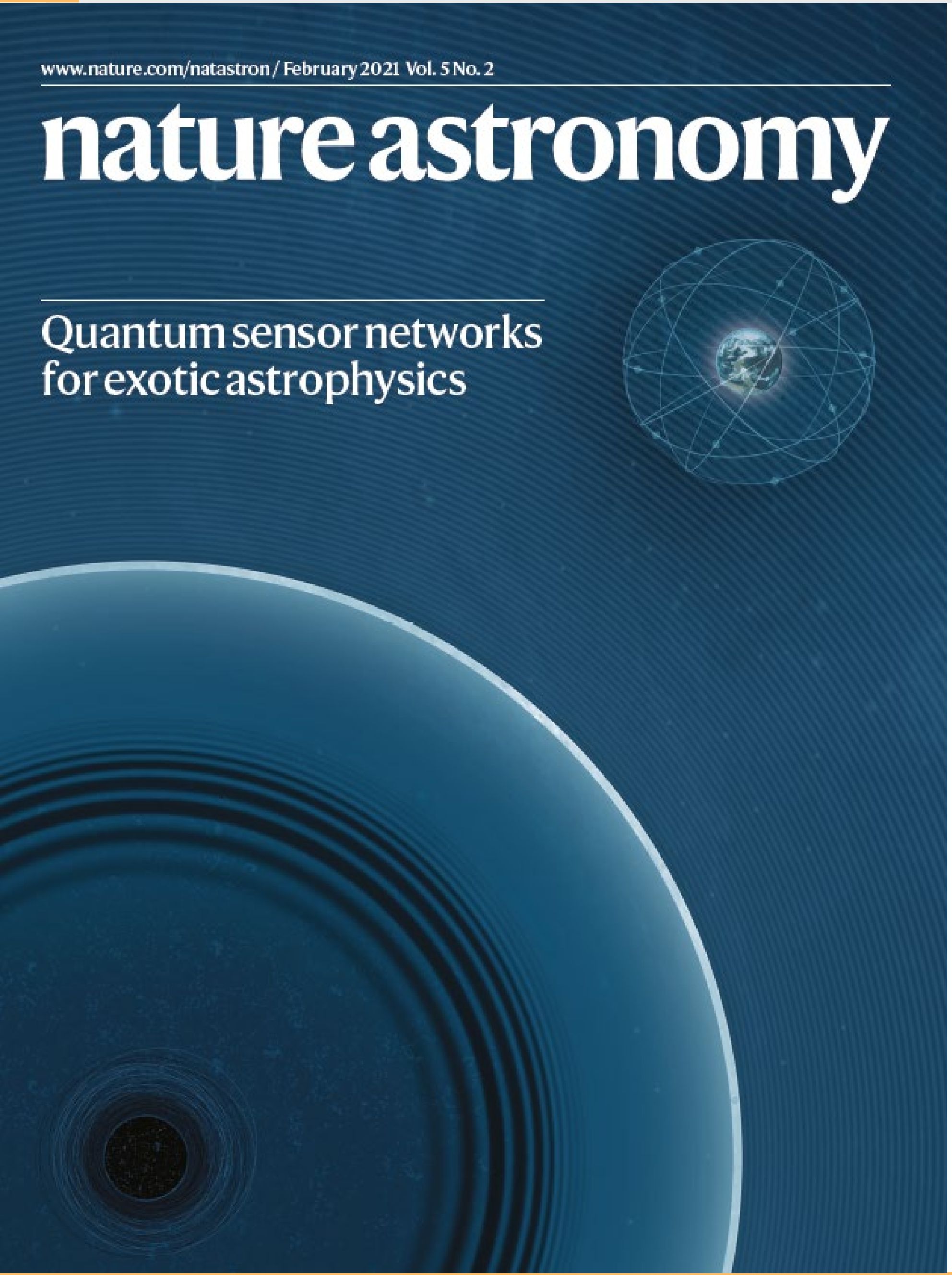
What can a GNOME do?

Search targets for the Global Network of Optical Magnetometers for Exotic physics searches

arXiv:2305.01785v2

ANNALEN DER PHYSIK 2023, 536, 2300083

# Multi-messenger astronomy



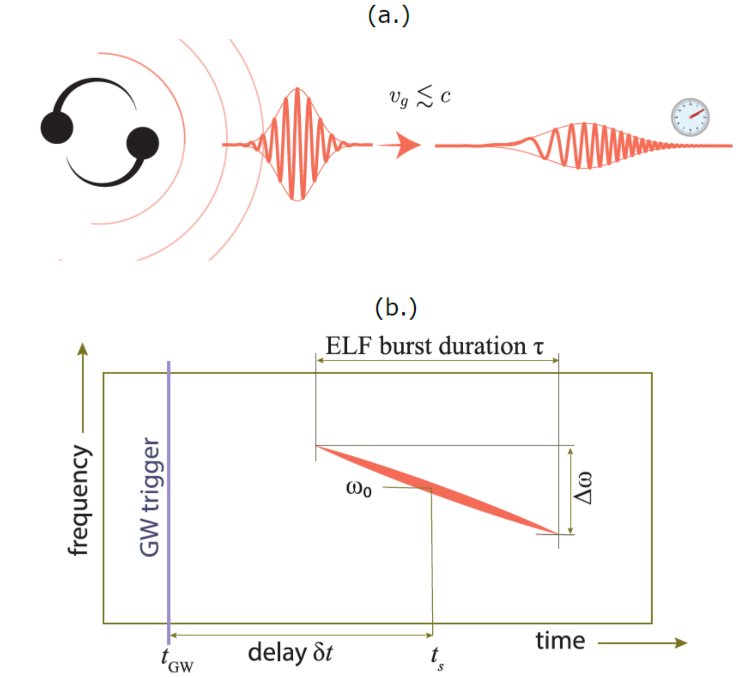

JG|U GSI HELMHOLTZ Helmholtz Institute Mainz

Letter | Published: 02 November 2020

## Quantum sensor networks as exotic field telescopes for multi-messenger astronomy

Conner Dailey, Colin Bradley, Derek F. Jackson Kimball, Ibrahim A. Sulai, Szymon Pustelny, Arne Wickenbrock & Andrei Derevianko

*Nature Astronomy* (2020) | Cite this article

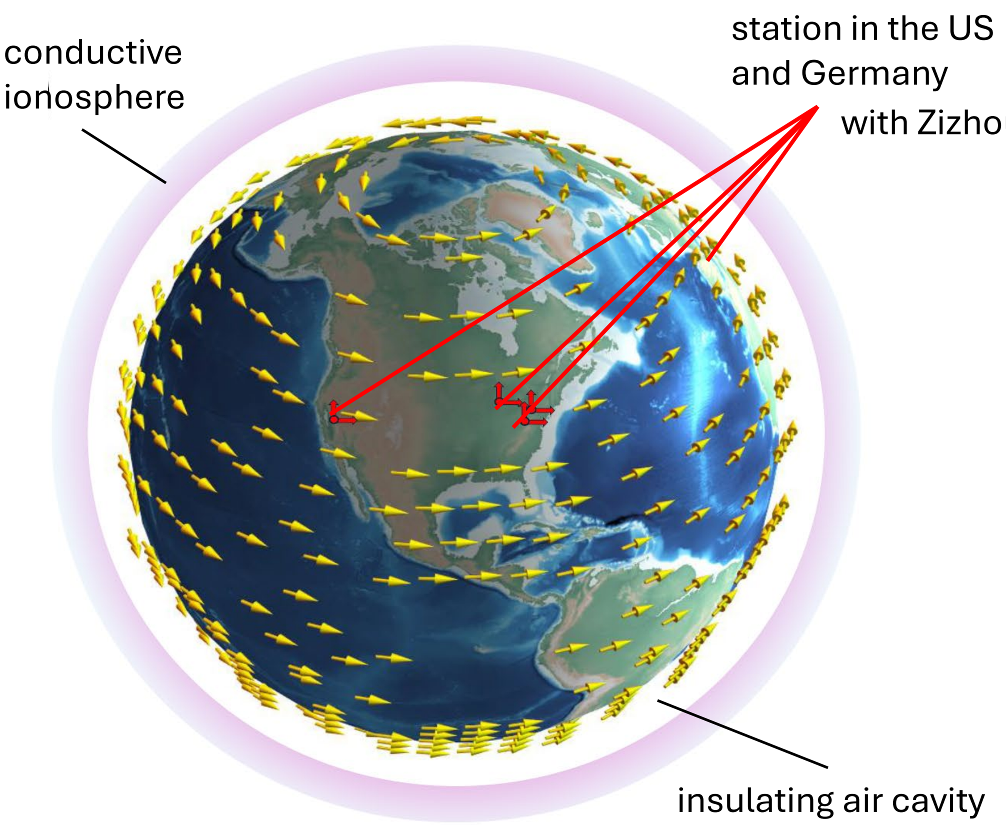



- Burst release
- 1 solar mass
- Coherent
- Ultrarelativistic
- Reach 1-10 Mly
- 1 event per year (linear)
- $10^5$ events (quadratic)

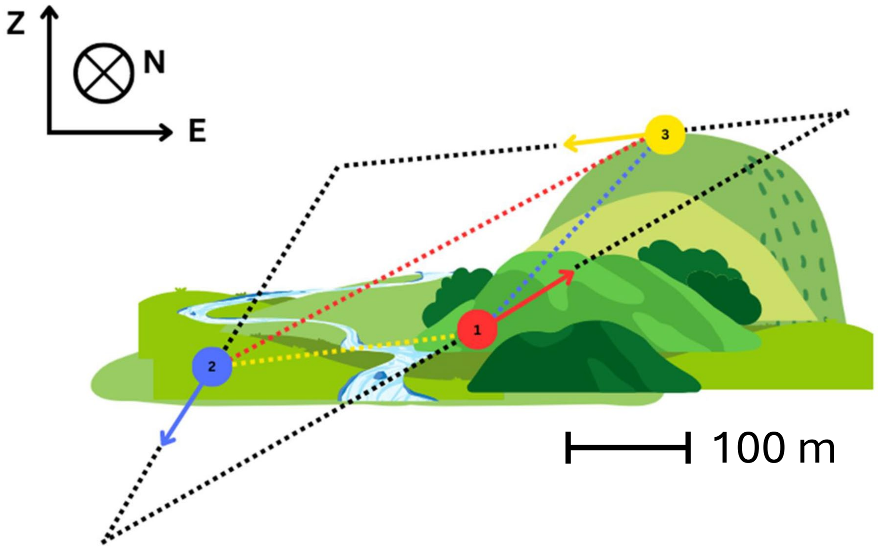
11.03.2020
Binary black hole merger S200311bg

Sami Khamis et al.
arXiv:2407.13919 (2024)

# Search for Noninteracting Particles Experimental Hunt (SNIPE-hunt)

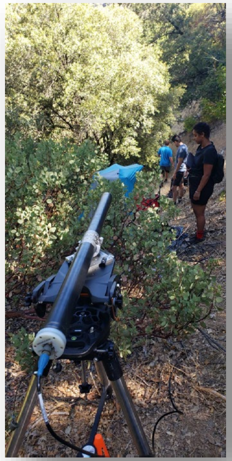


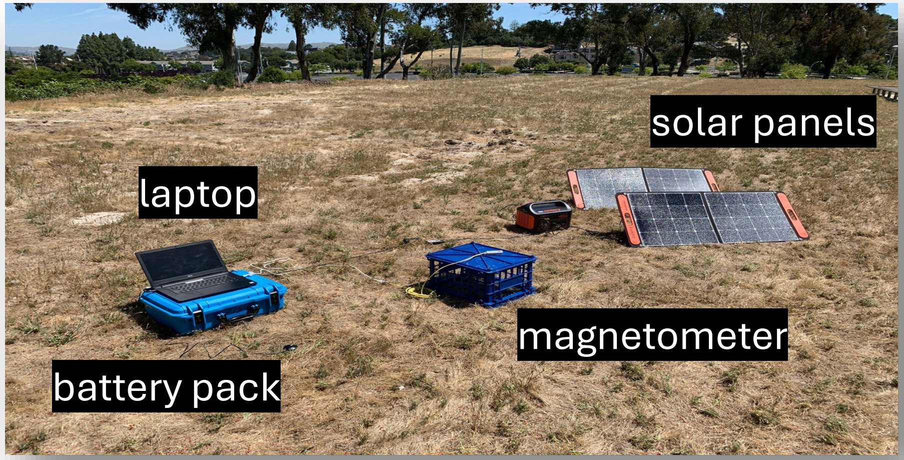

3 magnetometers per station to measure $(\nabla \times B)_{north}$




Conversion of hidden photon and axion dark matter into a global magnetic field

Practical implementation of noise suppression:
**Go into the wilderness**



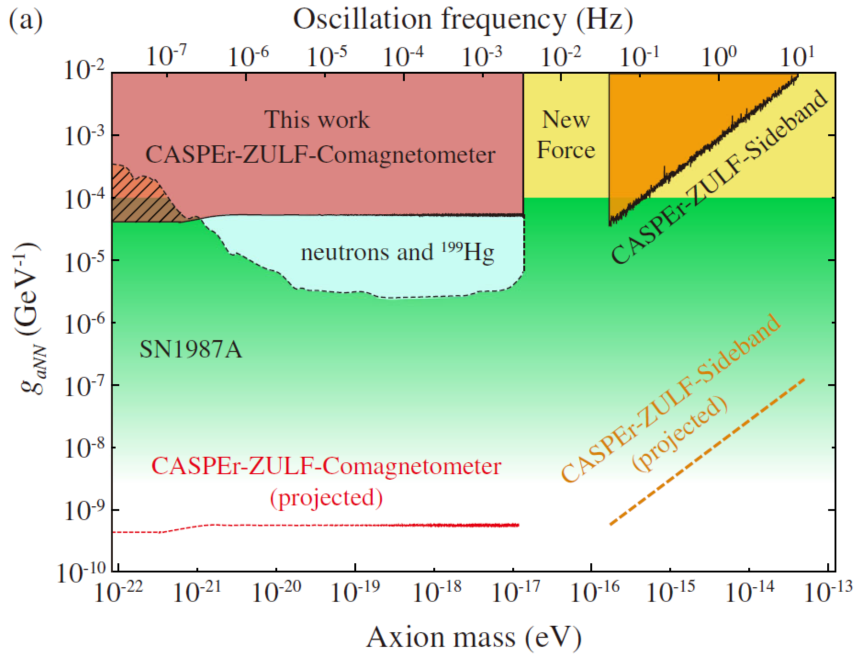


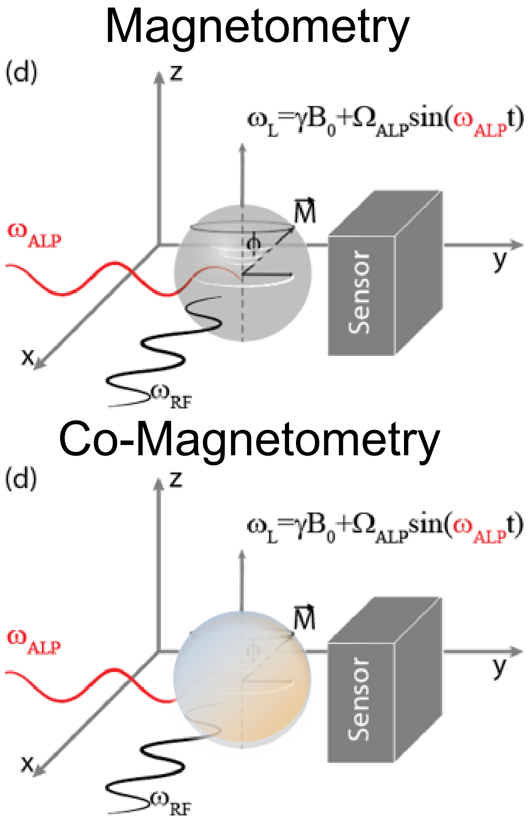

Slide by H. Bekker

Fedderke et al., PRD 104, 075023 (2021)
Fedderke et al., PRD 104, 095032 (2021)
Arza et al., PRD 105, 095007 (2022)
Bloch and Kalia, JHEP 2024, 178 (2024).

Sulai, et al. "Hunt for Magnetic Signatures of Hidden-Photon and Axion Dark Matter in the Wilderness." *Physical Review D* 108, no. 9 (November 27, 2023): 096026

- Constraining dark matter parameter space since 2018




CASPEr-G LF 0.01-4 MHz
CASPEr-G HF 4-600 MHz

# CASPEr Low field result

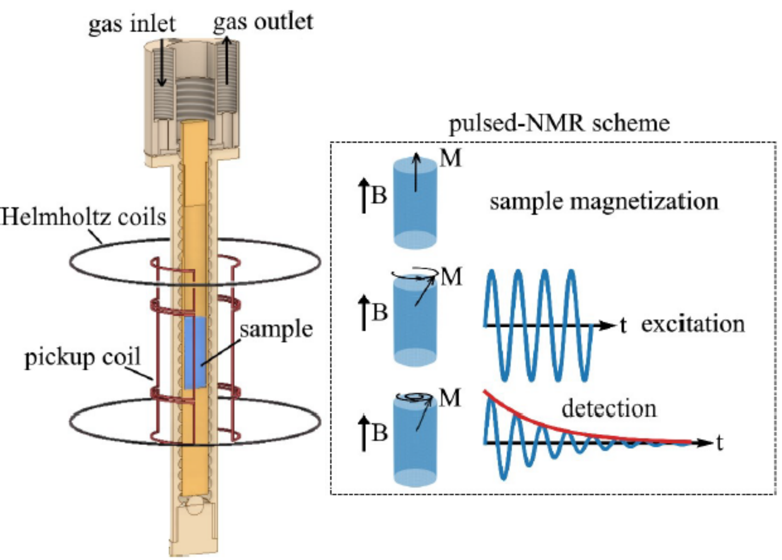
[Submitted on 22 Apr 2025]

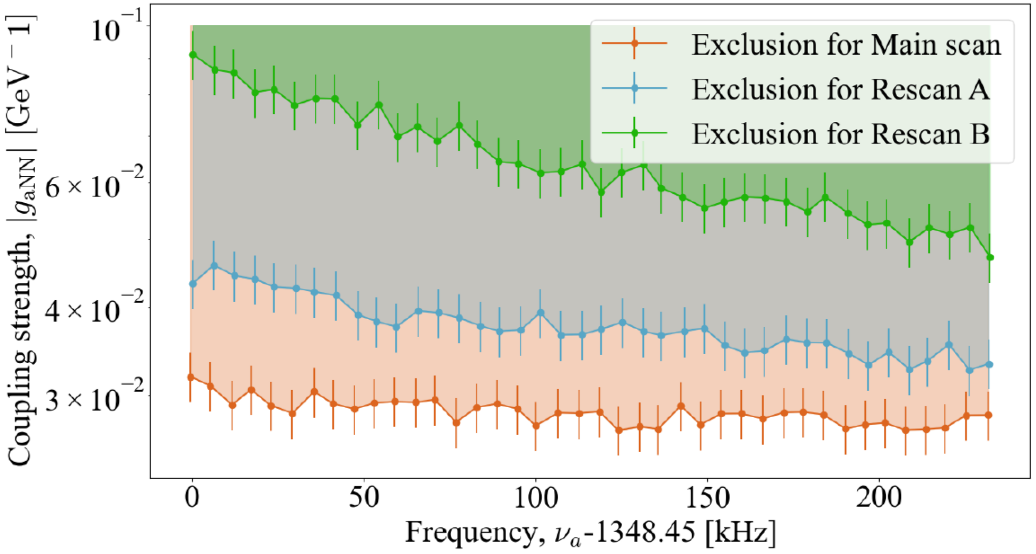
**Search for Axionlike Dark Matter Using Liquid-State Nuclear Magnetic Resonance**

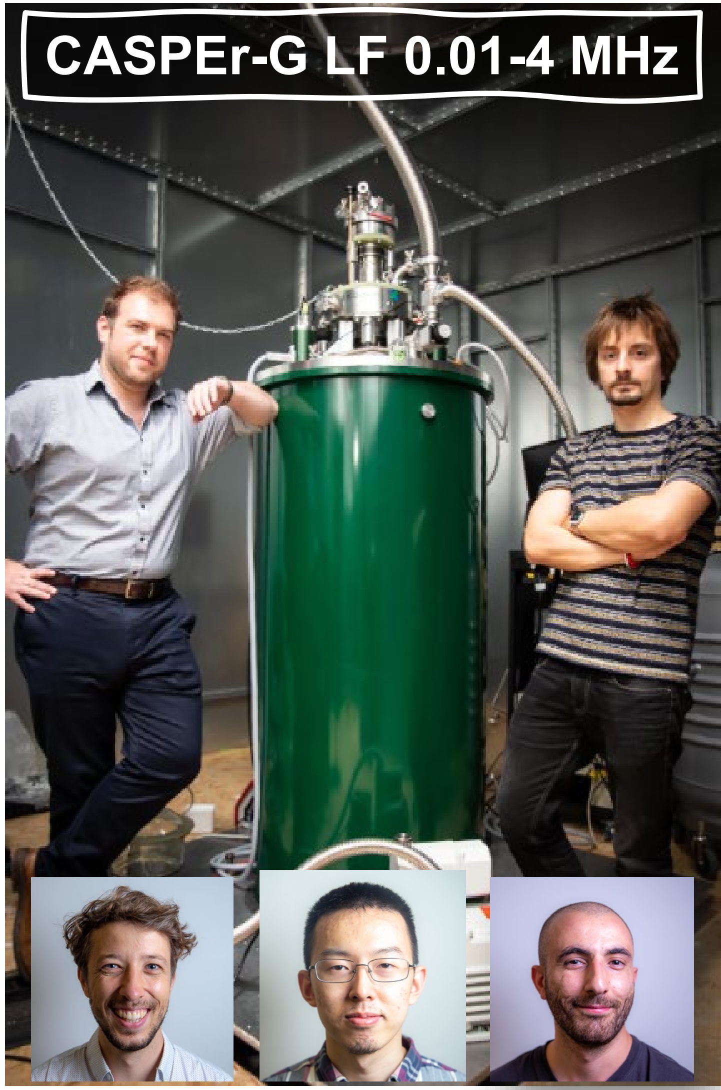
Julian Walter, Olympia Maliaka, Yuzhe Zhang, John Blanchard, Gary Centers, Arian Dogan, Martin Engler, Nataniel L. Figueroa, Younggeun Kim, Derek F. Jackson Kimball, Matthew Lawson, Declan W. Smith, Alexander O. Sushkov, Dmitry Budker, Hendrik Bekker, Arne Wickenbrock

We search for dark matter in the form of axionlike particles (ALPs) in the mass range $5.576741\,\mathrm{neV}/c^2$ - $5.577733\,\mathrm{neV}/c^2$ by probing their possible coupling to fermion spins through the ALP field gradient. This is achieved by performing proton nuclear magnetic resonance spectroscopy on a sample of methanol as a technical demonstration of the Cosmic Axion Spin Precession Experiment Gradient (CASPEr-Gradient) Low-Field apparatus. Searching for spin-coupled ALP dark matter in this mass range with associated Compton frequencies in a 240 Hz window centered at 1.348570 MHz resulted in a sensitivity to the ALP-proton coupling constant of $g_{ap} \approx 3 \times 10^{-2}\,\mathrm{GeV}^{-1}$. This narrow-bandwidth search serves as a proof-of-principle and a commissioning measurement, validating our methodology and demonstrating the experiment's capabilities. It opens the door to probing large swaths of hitherto unexplored mass-coupling parameter space in the future by using hyperpolarized samples.

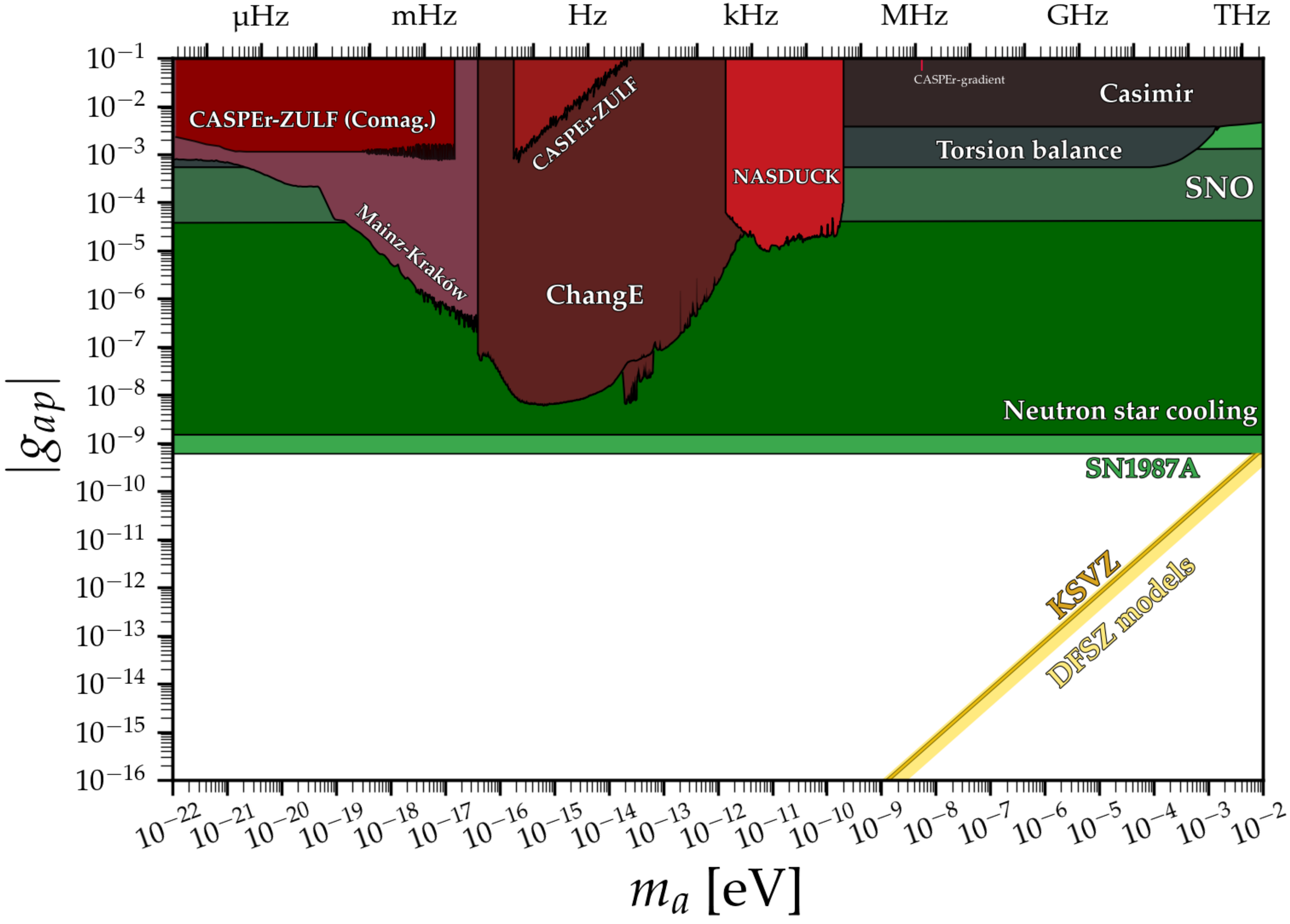
Subjects: **High Energy Physics - Experiment (hep-ex)**; Atomic Physics (physics.atom-ph)
Cite as: arXiv:2504.16044 **[hep-ex]**
(or arXiv:2504.16044v1 **[hep-ex]** for this version)
https://doi.org/10.48550/arXiv.2504.16044



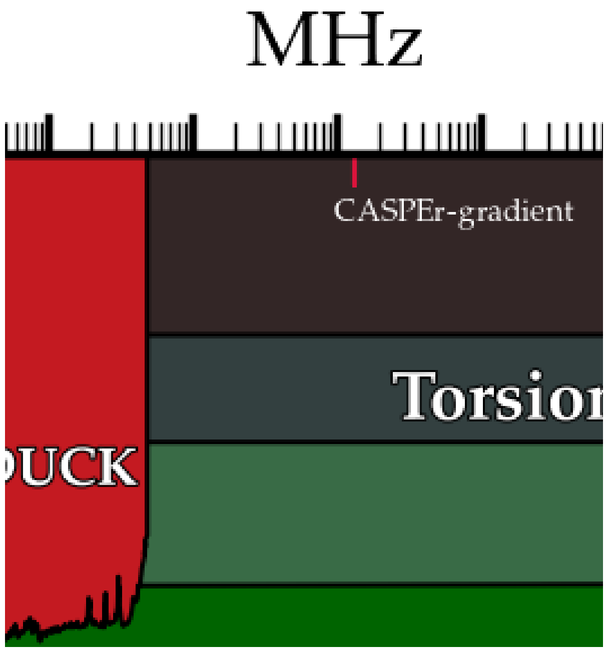




https://doi.org/10.48550/arXiv.2504.16044 (2025)

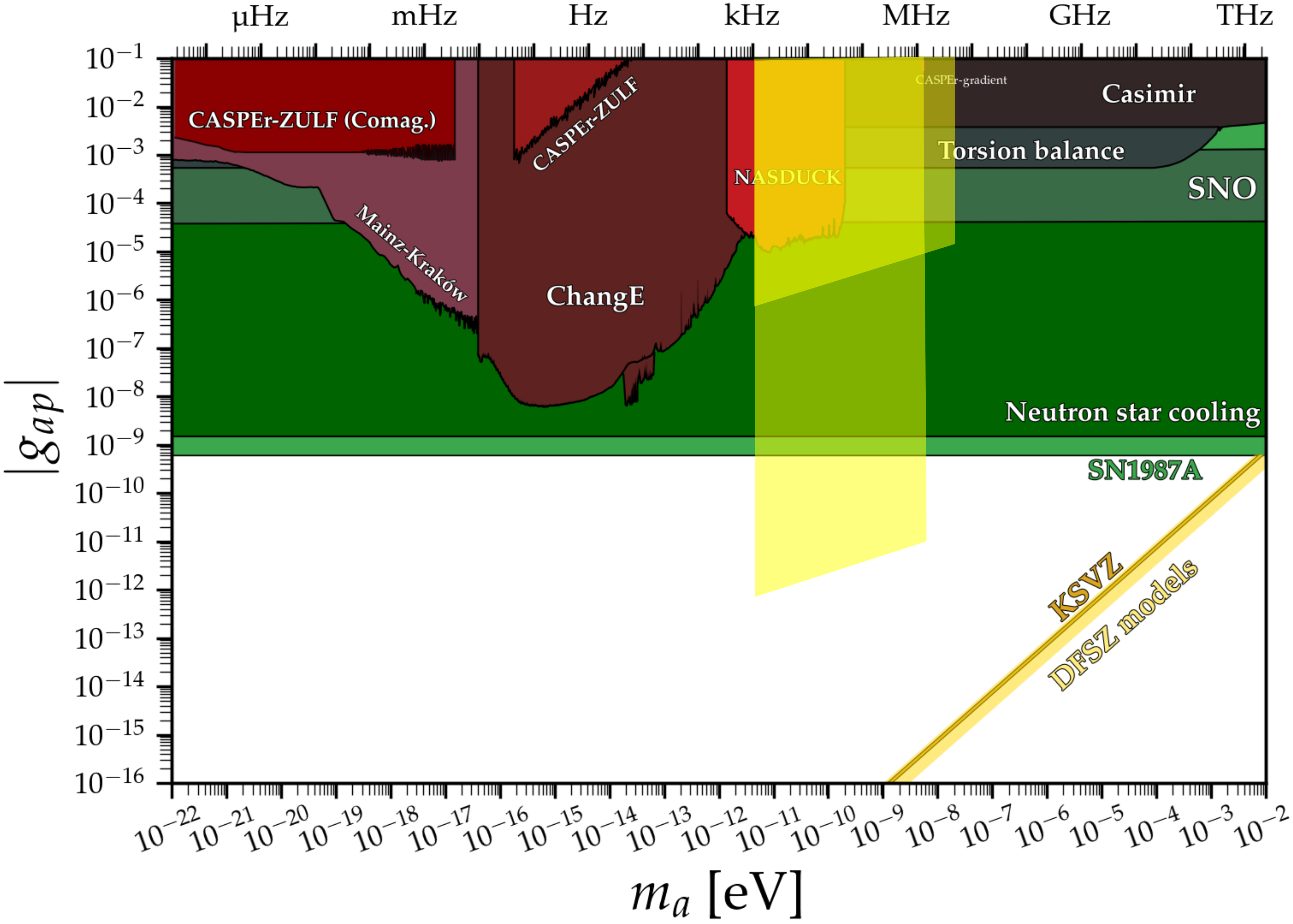


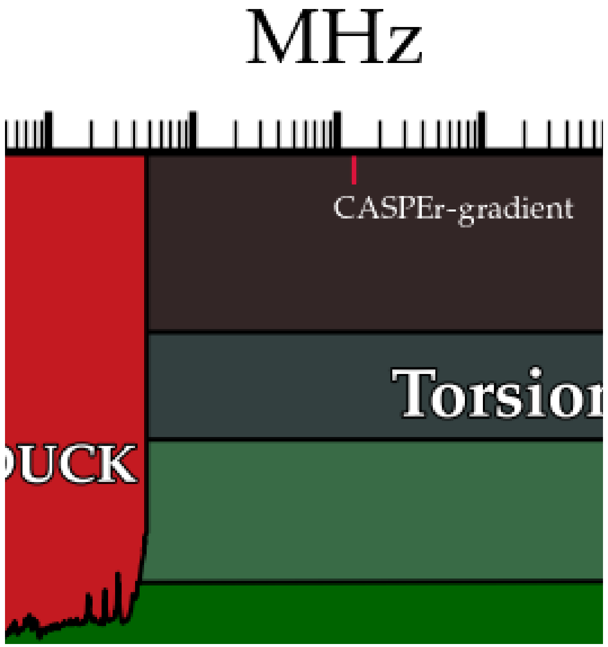
μHz
mHz
Hz
kHz
MHz
GHz
THz
CASPEr-ZULF (Comag.)
CASPEr-ZULF
NASDUCK
CASPEr-gradient
Casimir
Torsion balance
SNO
Mainz-Kraków
ChangE
Neutron star cooling
SN1987A
KSVZ
DFSZ models
$|g_{ap}|$
$m_a$ [eV]

MHz
CASPEr-gradient
Torsion
UCK

| | This work | Examples of future CASPEr-Gradient-LF | |
|---|---|---|---|
| Sample | Methanol | Methanol | Liquid $^{129}$Xe |
| Spin density ($cm^{-3}$) | $6.0 \times 10^{22}$ | $6.0 \times 10^{22}$ | $\sim 10^{22}$ |
| Sample volume ($cm^3$) | 1.2 | 1.2 | $\sim 1$ |
| Polarization technique | Thermal polarization | Brute Force / PHIP / DNP | SEOP |
| Polarization | $1.8 \times 10^{-7}$ | $> 1.1 \times 10^{-5}$ | $\sim 1$ |
| $T_2$ (s) | 0.71 | 1 | 1000 |
| $B_0$ inhomogeneity (ppm) | 10 | $\leq 2$ | |
| Maximum scan range | 1.348 450 MHz – 1.348 690 MHz<br>5.576 741 neV/c$^2$ – 5.577 733 neV/c$^2$ | ~1 kHz – 4.3 MHz<br>~4.1 peV/c$^2$ – 17 neV/c$^2$ | ~1 kHz – 1.2 MHz<br>~4.1 peV/c$^2$ – 4.9 neV/c$^2$ |
| Spectrum noise ($\mu\Phi_0/Hz^{1/2}$) | 7.1 | 1 | |
| Spin projection noise in scan range ($\mu\Phi_0/Hz^{1/2}$) | 0.11 | 8.7 at 1 kHz<br>0.13 at 4.3 MHz | 3.5 at 1 kHz<br>0.11 at 1.2 MHz |
| $\lvert g_{aNN} \rvert$ sensitivities in scan range ($GeV^{-1}$) | $3 \times 10^{-2}$ | $1.0 \times 10^{-6}$ at 1 kHz<br>$1.2 \times 10^{-5}$ at 4.3 MHz | $10^{-12}$ at 1 kHz<br>$10^{-11}$ at 1.2 MHz |

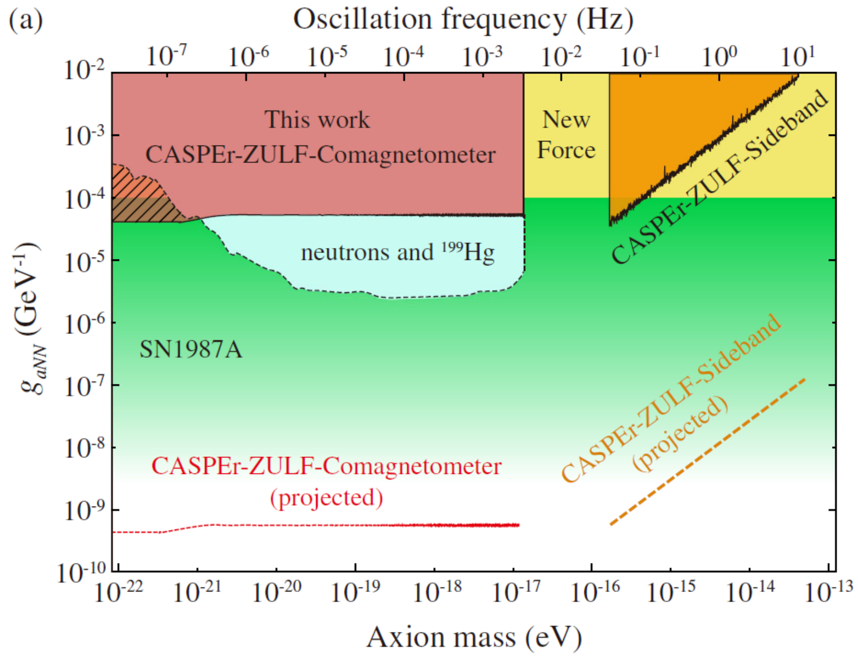


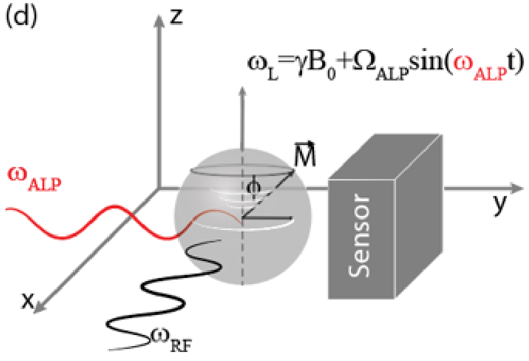

Strongest experimental search

Strongest search

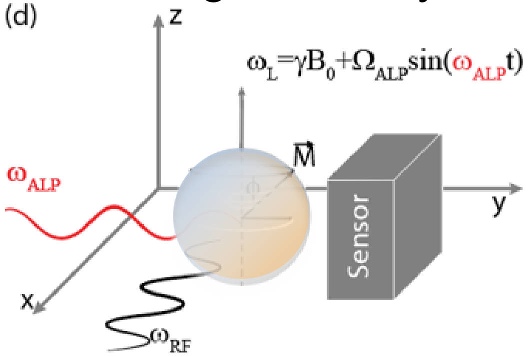
# Constraining dark matter parameter space since 2018




## Magnetometry




## Co-Magnetometry

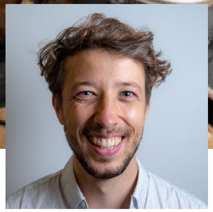
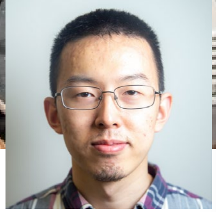
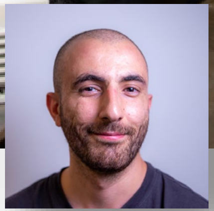



Federal Ministry of Education and Research



MiLiQuant Mainz:
Spin-based gyroscopes!

JG|U GSI HELMHOLTZ Helmholtz Institute Mainz

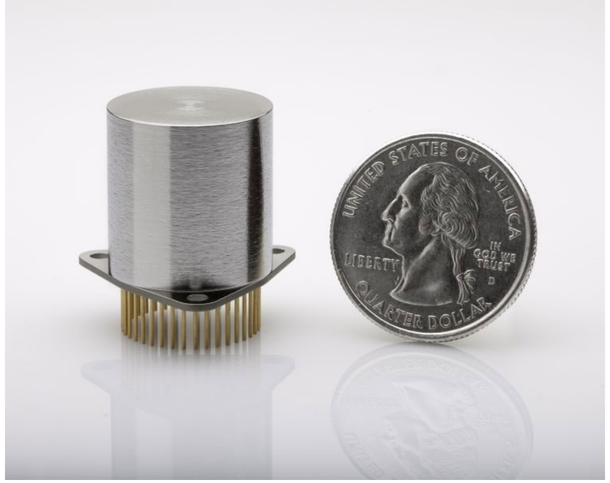
# Off-topic: Comagnetometers as gyroscopes

BEAUFTRAGT VOM

Bundesministerium
für Bildung
und Forschung

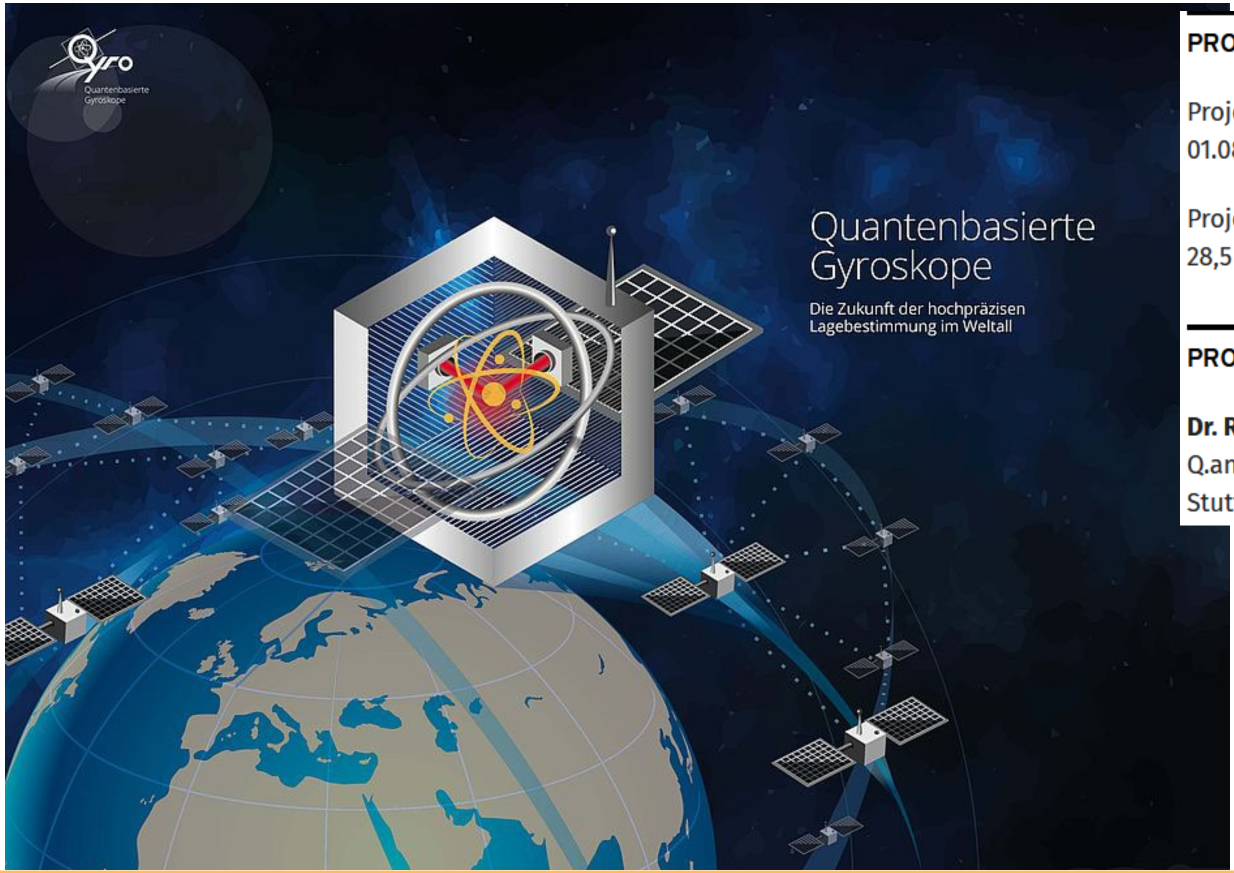
## German quantum initiatives like spin-based gyroscopes

MiLiQuant proposal with Bosch: 01.2019 – 12.2022     FKZ 13N15064




2013 Northrup Grumman

Miniaturized
Spin-Gyroscope
For Navigation




**PROJEKTDETAILS**

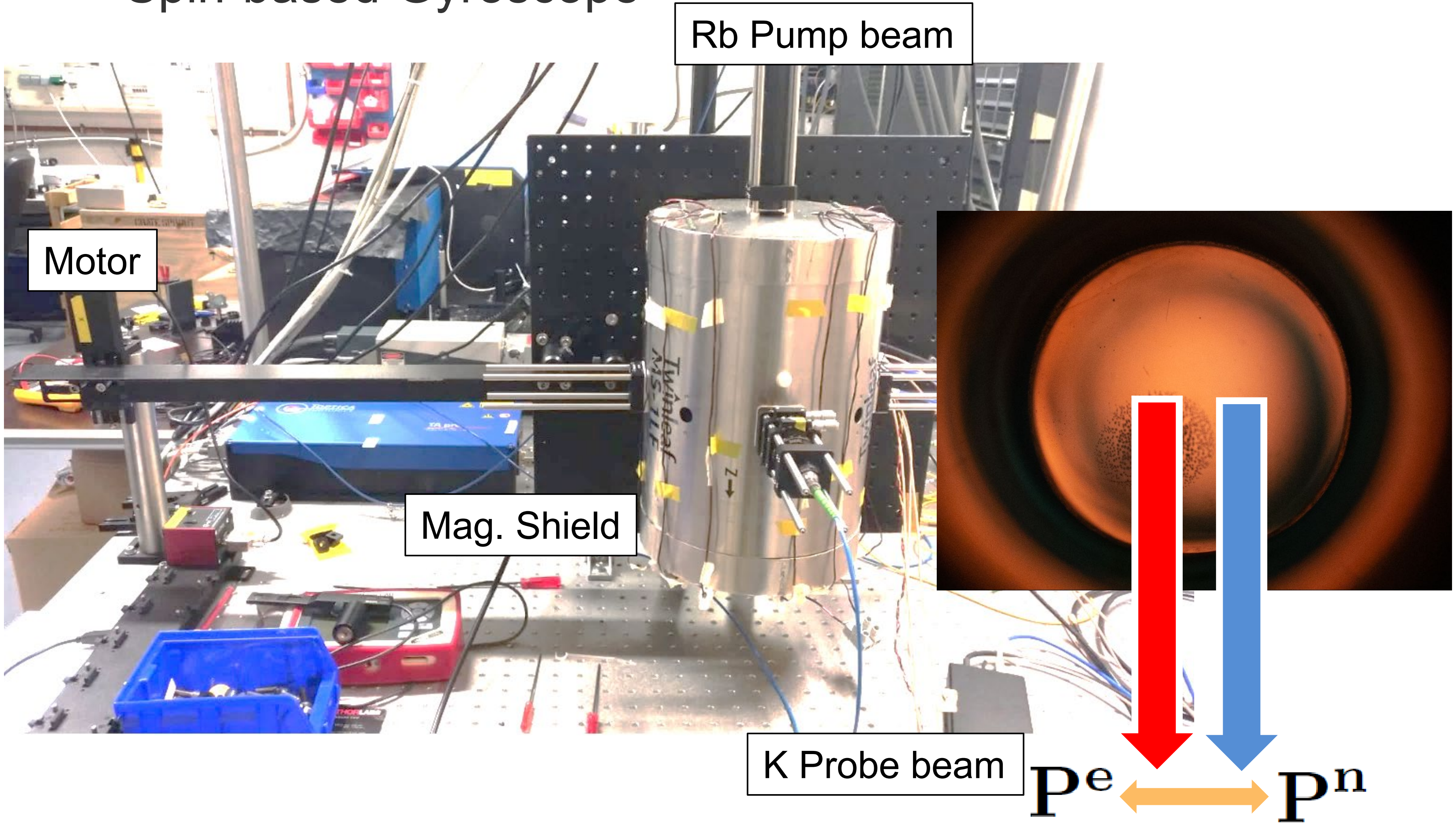
Projektlaufzeit:
01.08.2022 - 31.07.2027

Projektvolumen:
28,5 Mio. Euro (zu 66,5 % durch das BMBF gefördert)

**PROJEKTKOORDINATION**

**Dr. Robert Rölver**
Q.ant GmbH
Stuttgart

# Spin-based Gyroscope




- 20mm gas cell
- 3 bar $^3$He ($\gamma$= 32 mHz/nT)
- $N_2$
- Rb
- K
- 200°C

~1 fT/Hz$^{1/2}$ $P^e$ $P^n$ Magnetization looks like a magnetic field

Sensitive SERF magnetometer

Macroscopic nuclear polarization

Coupled Bloch equations

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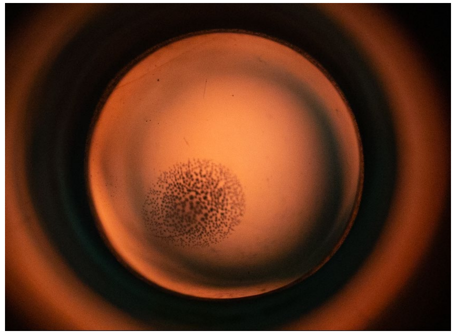


- Coupled Bloch equations

Other/exotic spin interaction

Fermi contact interaction

Electron spin

$$\frac{d\mathbf{P^e}}{dt} = \gamma_e(\mathbf{B} \qquad\qquad ) \times \mathbf{P^e} \qquad + \text{Damping}^e$$

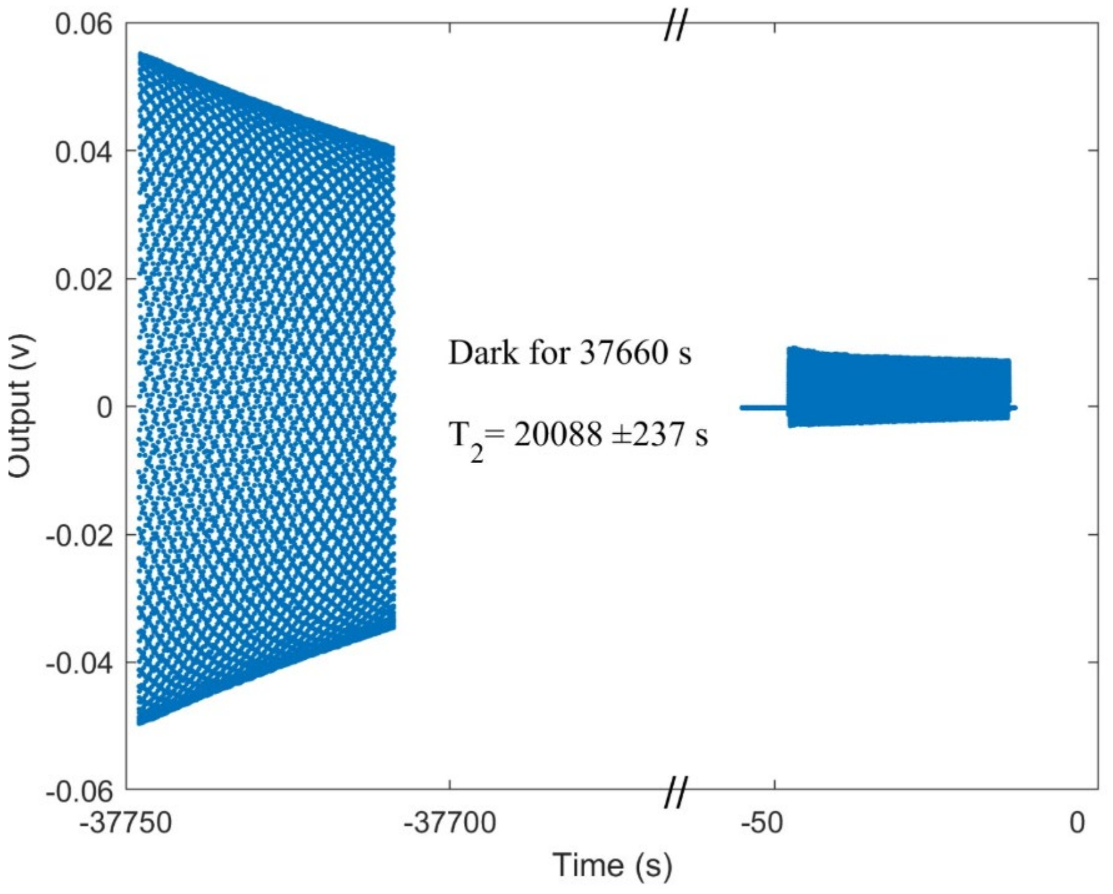
Nuclear spin

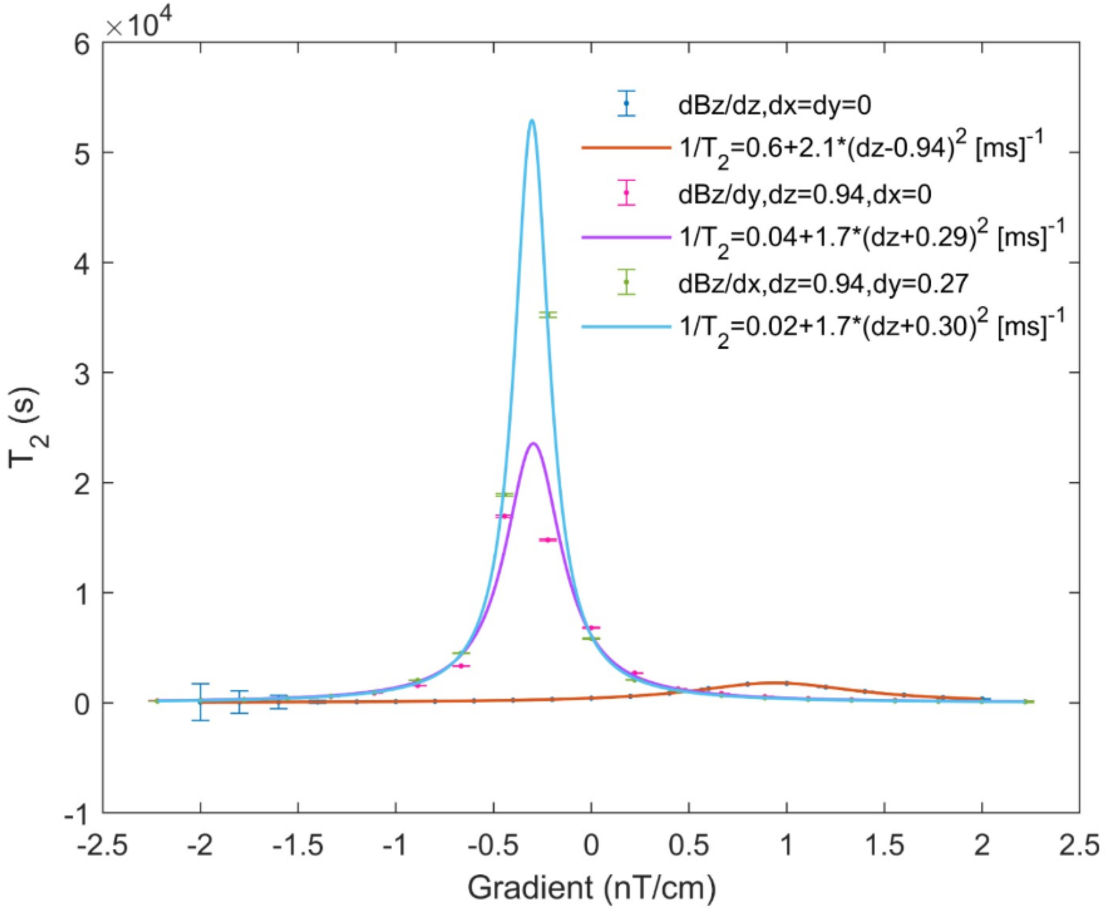
$$\frac{d\mathbf{P^n}}{dt} = \gamma_n(\mathbf{B} \qquad\qquad ) \times \mathbf{P^n} \qquad + \text{Damping}^n$$

B.C. Grover, Phys. Rev. Lett. **40**, 391 (**1978**)

M. Padniuk, et al., Sci. Rep. 12 (2022)

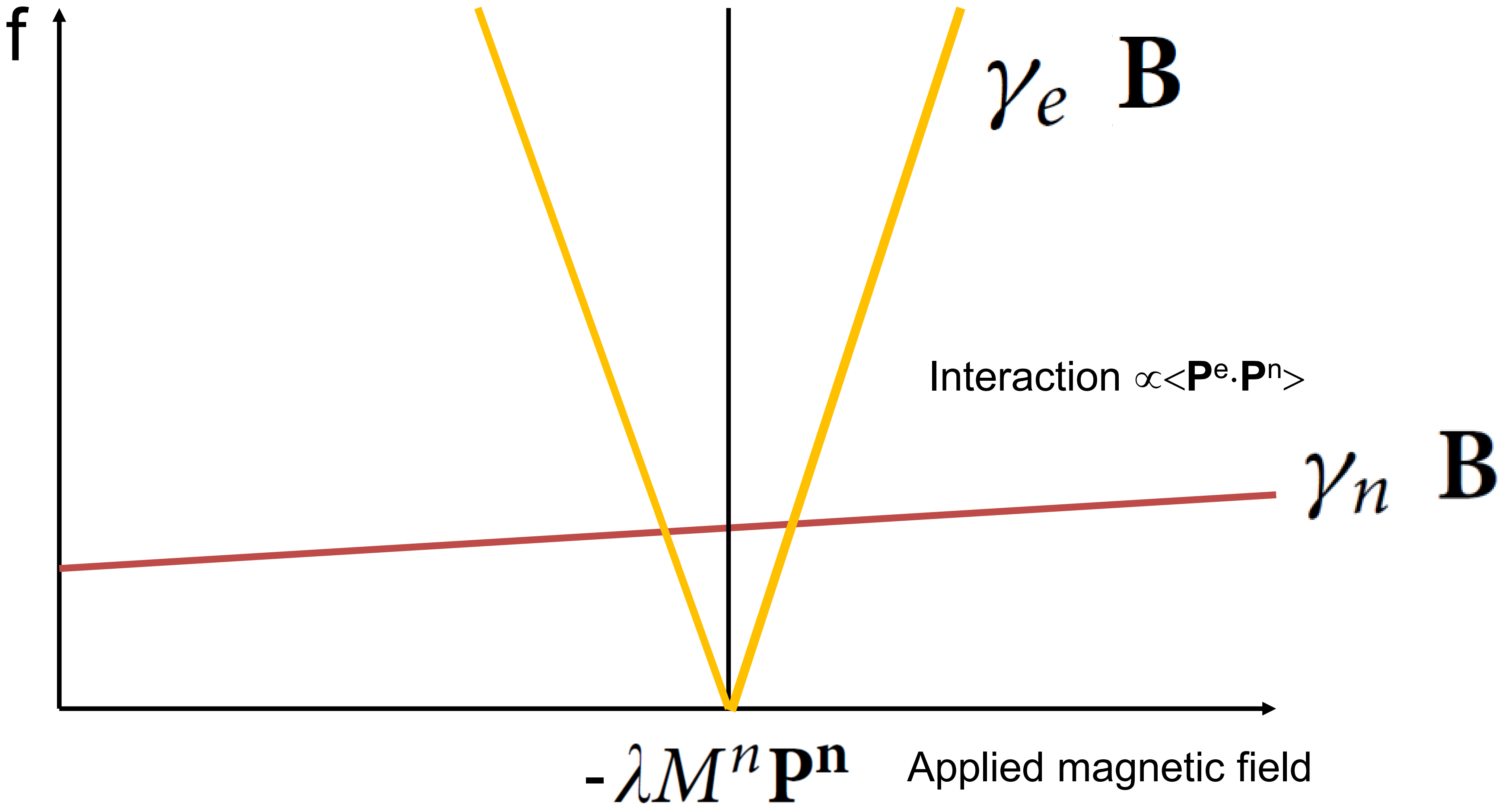
## 1. Observing nuclear precession with alkali magnetometer



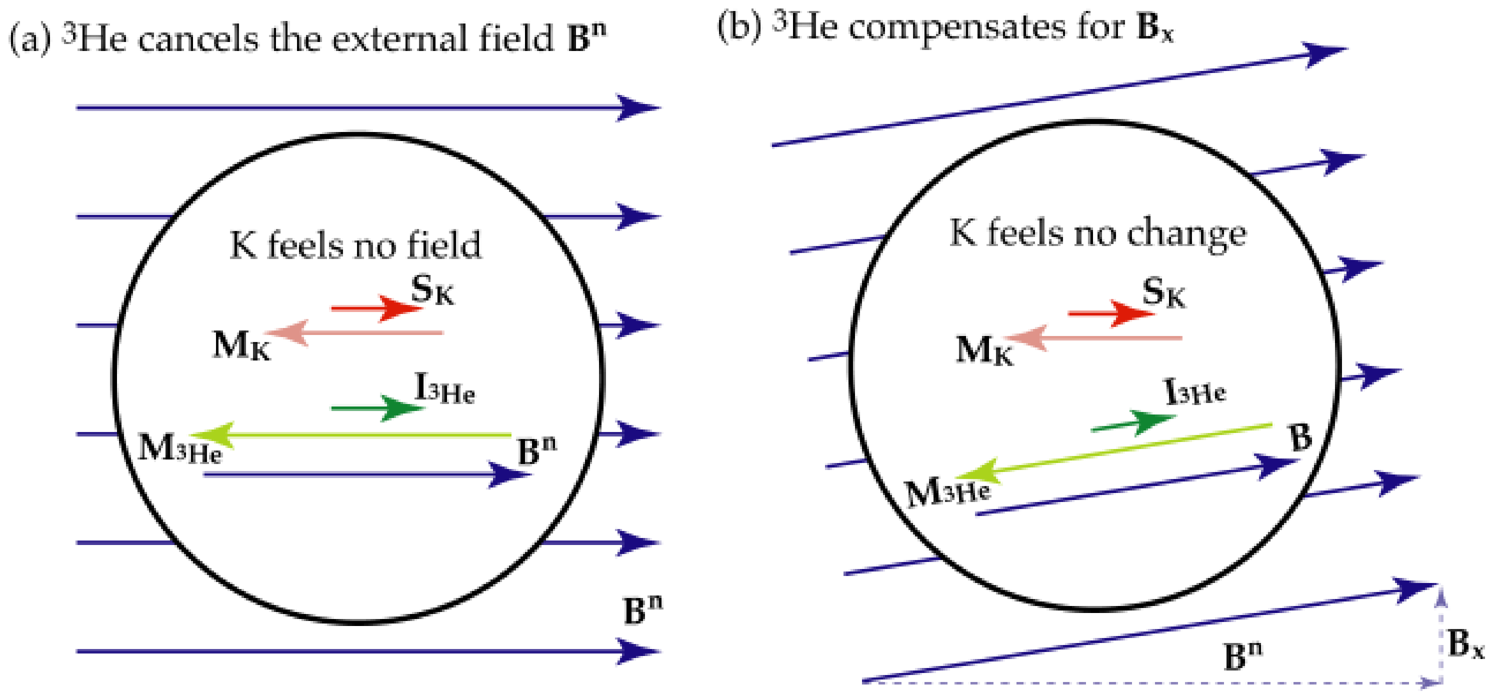

→ T2*>50000s ~ 14h!

- Coupled Bloch equations




Self-compensated comagnetometer

- 2. Compensation point – magnetically insensitive to transverse fields




Self-compensated:

$\sim B_n = M_{^3He}$ ~130nT

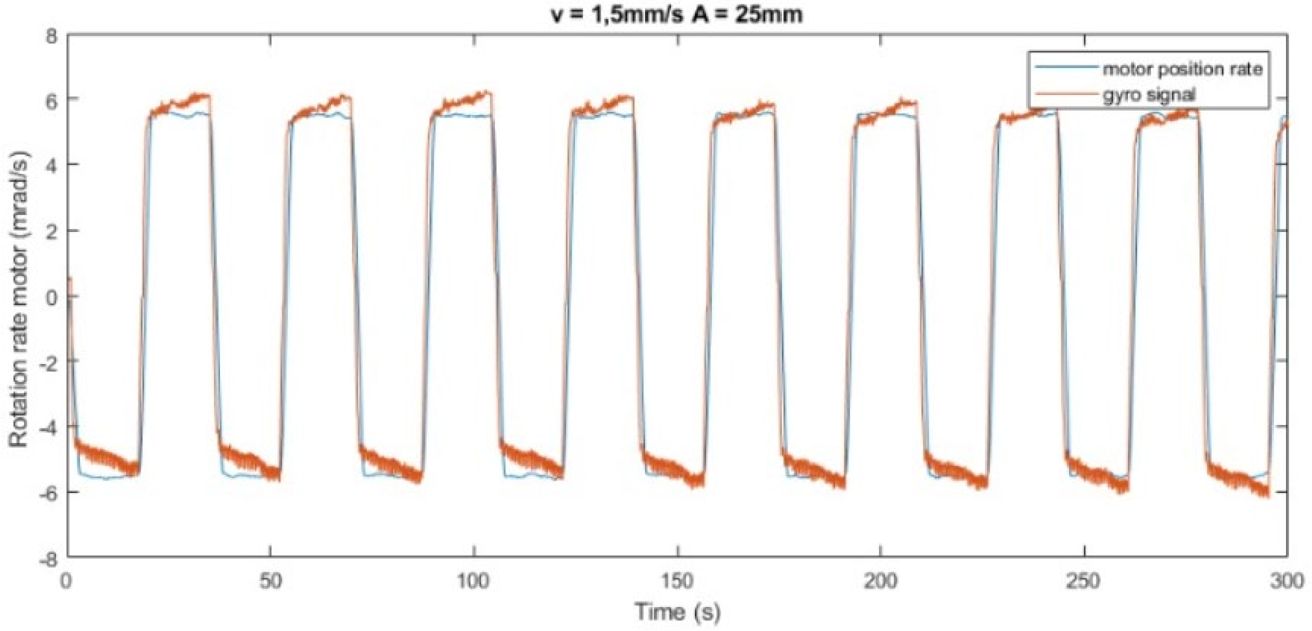
External field=Helium field

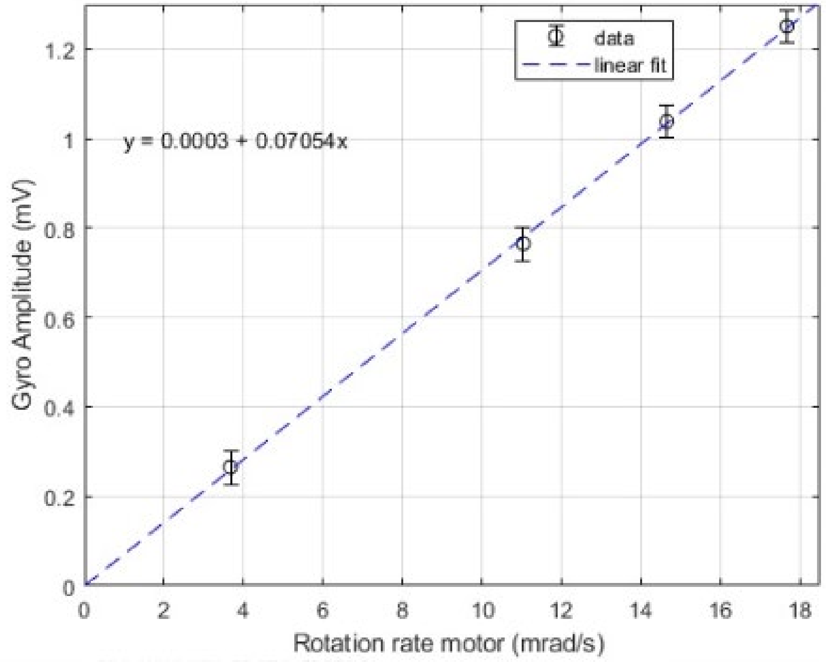
Insensitive to transverse fields!

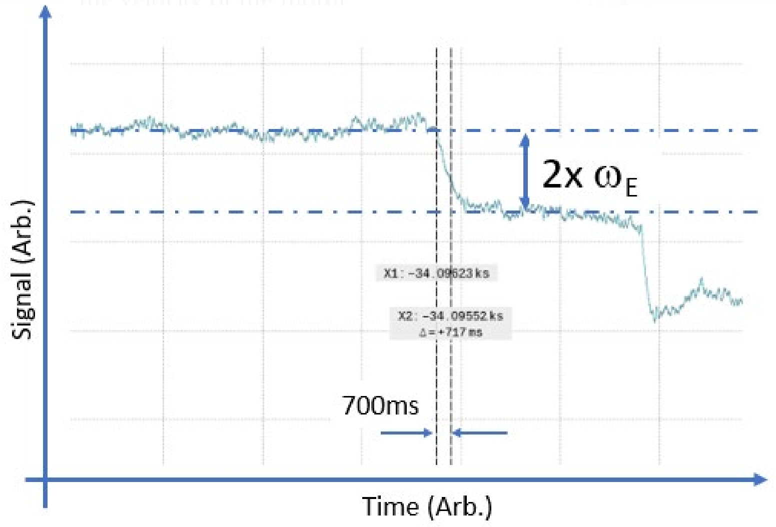
T. Kornack, *A test of CPT and Lorentz Symmetry Using a K-$^3$He Co-magnetometer*, Ph.D. thesis, Princeton University (2005).

- Self-compensated comagnetometer = gyroscope!

Apply rotations!




Sensitive nuclear spin gyroscope!

Use rotations to calibrate dark matter sensitivity

Sensitive dark matter detector!

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OPEN ACCESS

# Universal determination of comagnetometer response to spin couplings

Mikhail Padniuk[1,*], Emmanuel Klinger[2,3,4], Grzegorz Łukasiewicz[1], Daniel Gavilan-Martin[2,3], Tianhao Liu[2,3,5,†], Szymon Pustelny[1], Derek F. Jackson Kimball[6], Dmitry Budker[2,3,7], and Arne Wickenbrock[2,3]

**Spin perturbation to study:**

- Magnetic fields
- Rotations
- Exotic fields (for electrons and nucleons)

**To do what?**

- Measure magnetic frequency response
- Infer all other responses

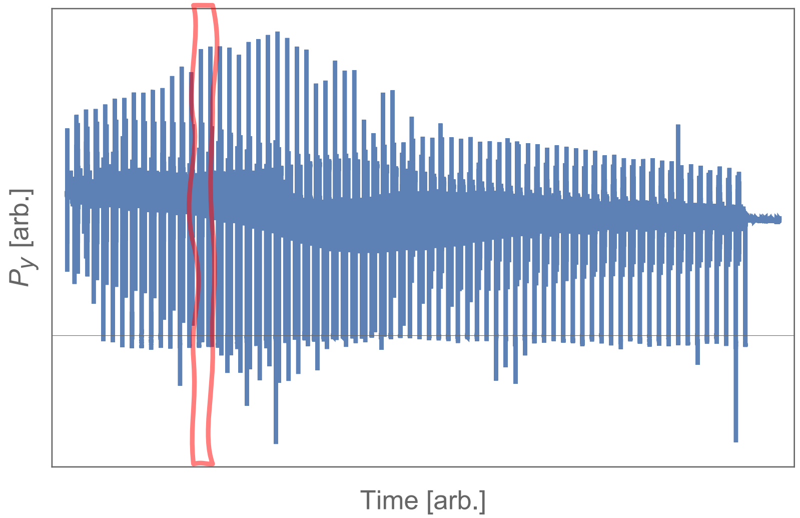
**Recipe**:

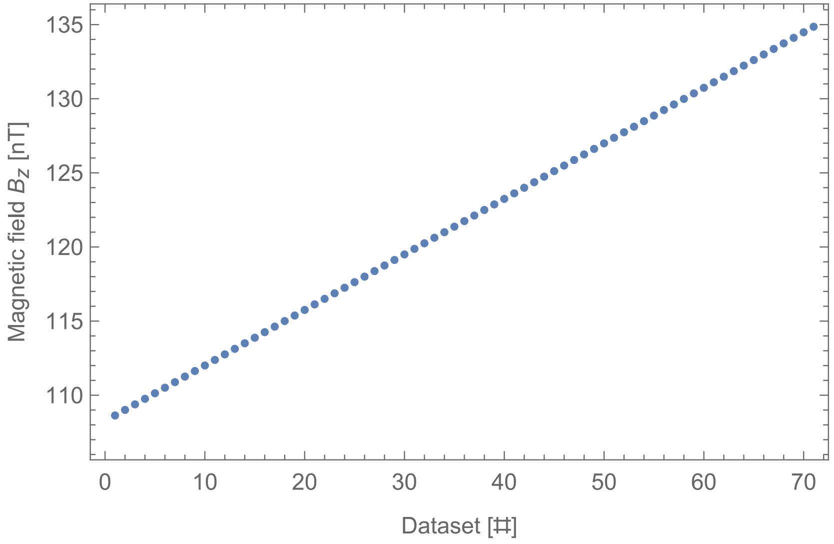
- Step response data
- Temporal derivative
- Fourier transform

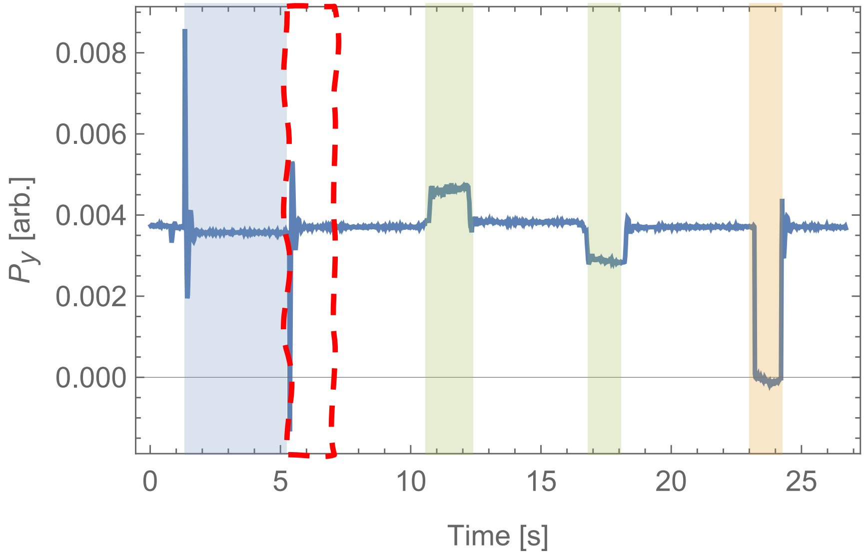
<u>Frequency response</u>

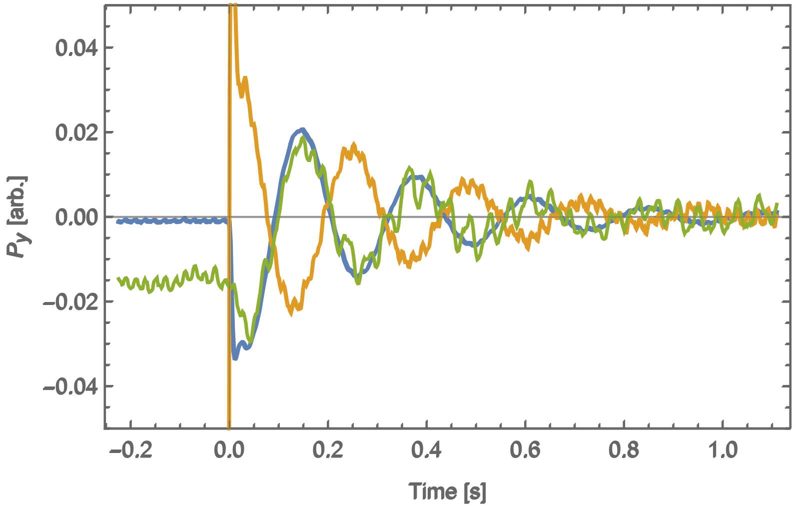
Phys. Rev. Research 6, 013339 (2024)

# Frequency response data



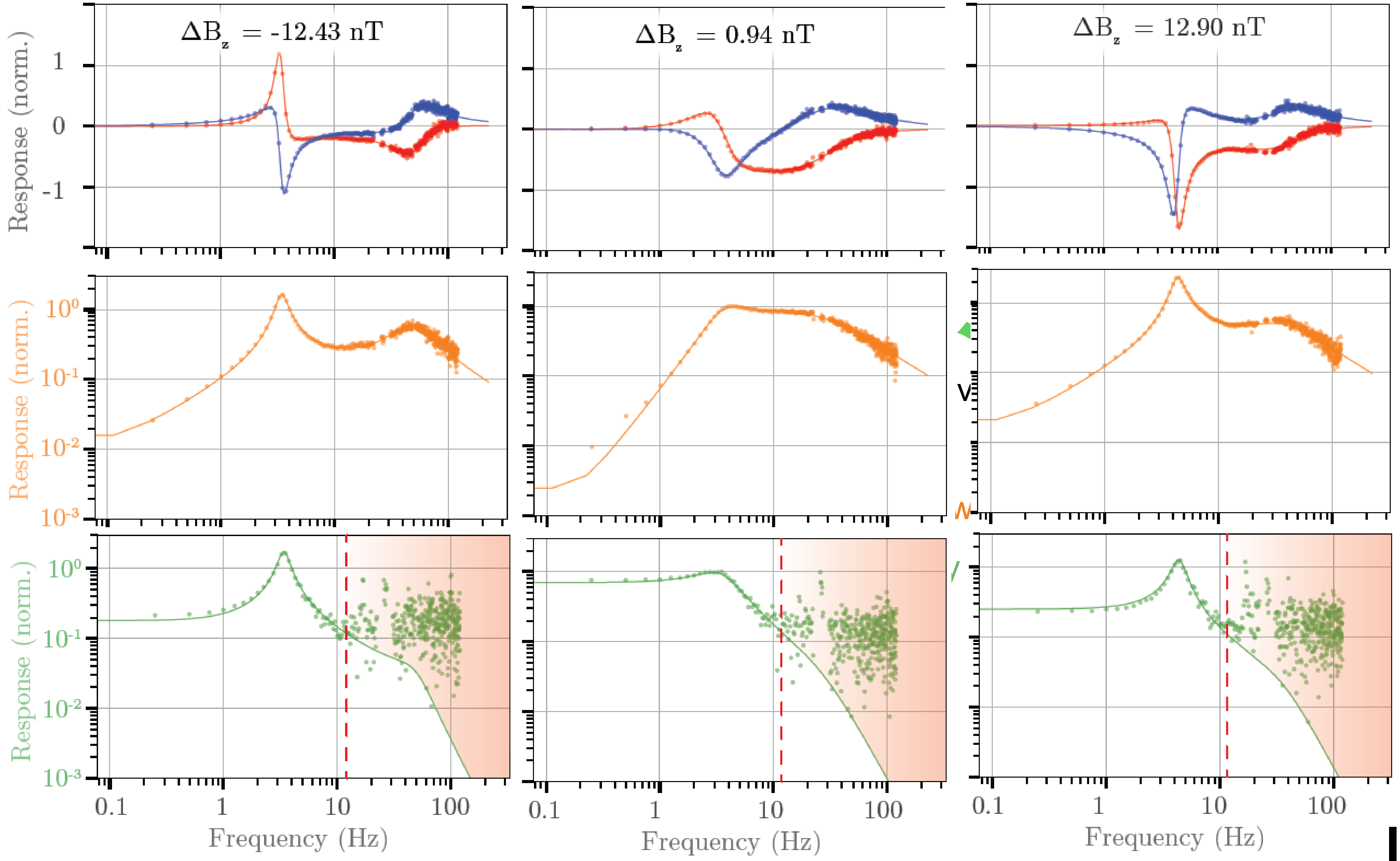




Magnetic $B_y$ field (~100 pT)

Rotation ~ 1 mrad/s

Light shift field (electron spin)

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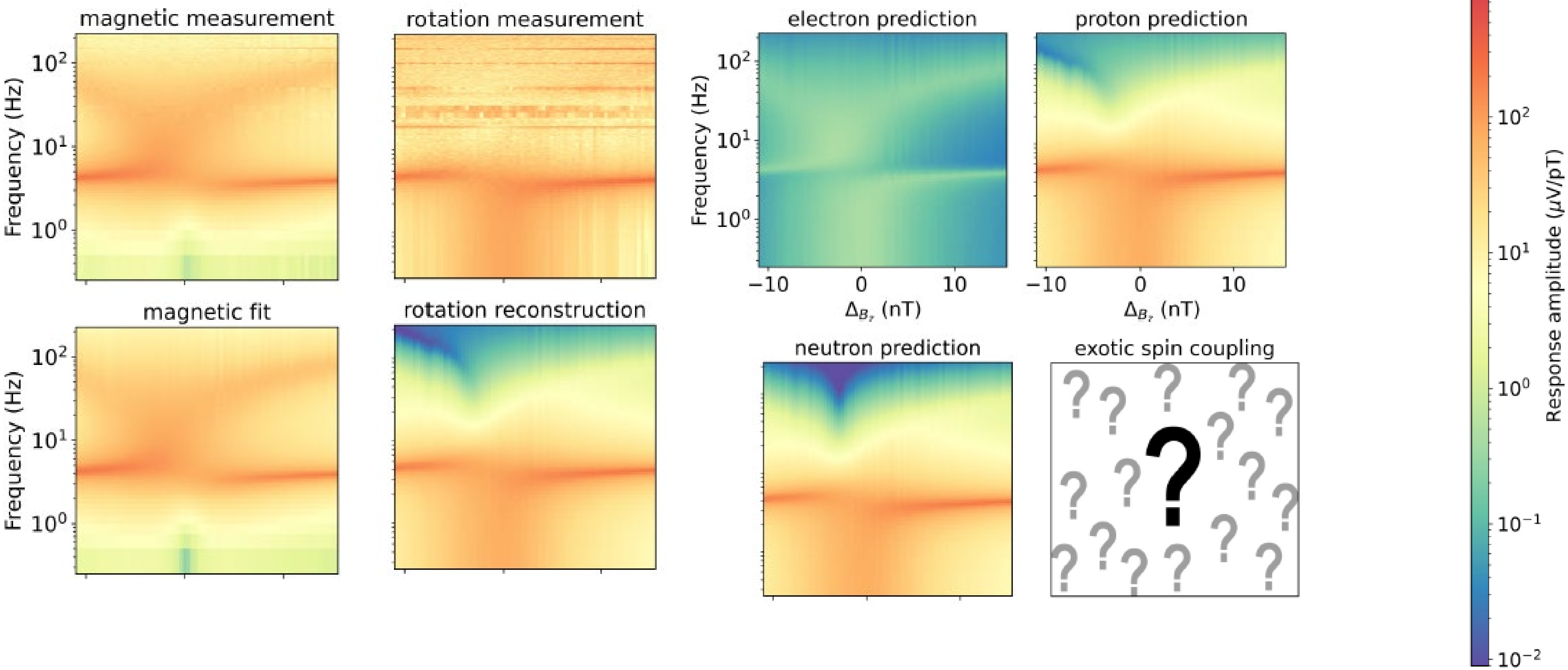
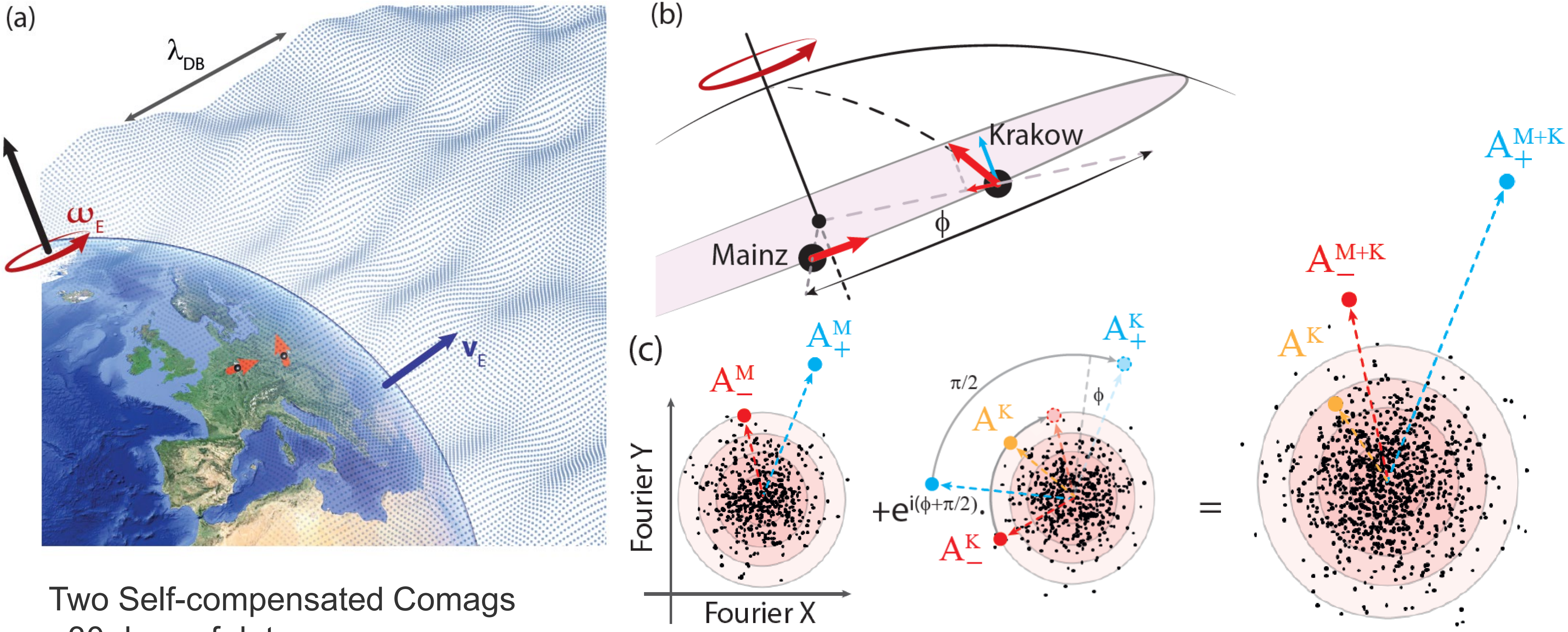
**It matters!**

**Good agreement! We can infer dark matter frequency response!**

## Universal determination of the frequency response



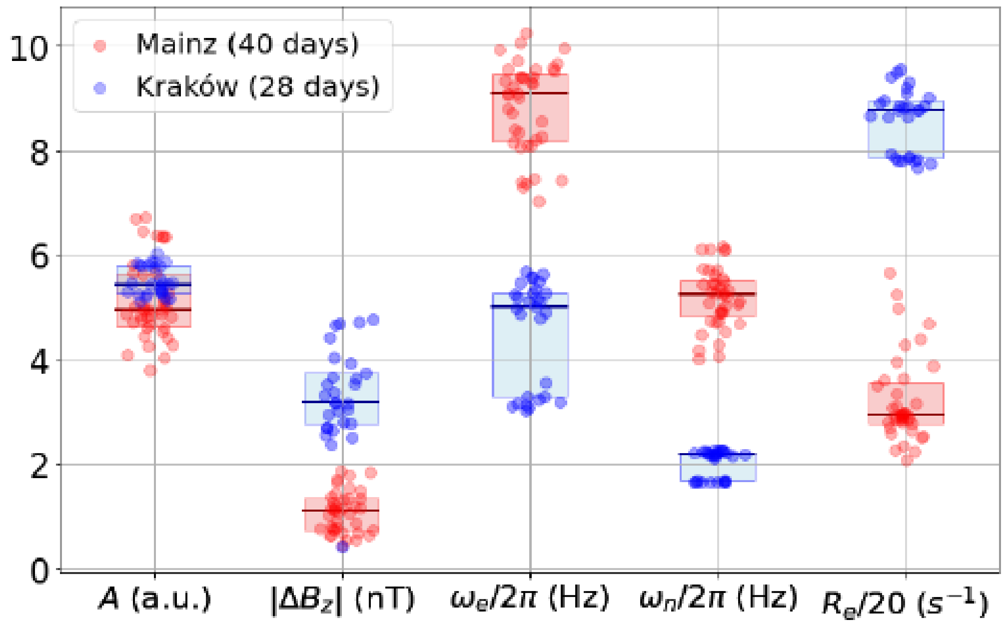
- Dark matter interferometer – Krakow/Mainz – arXiv:2408.02668



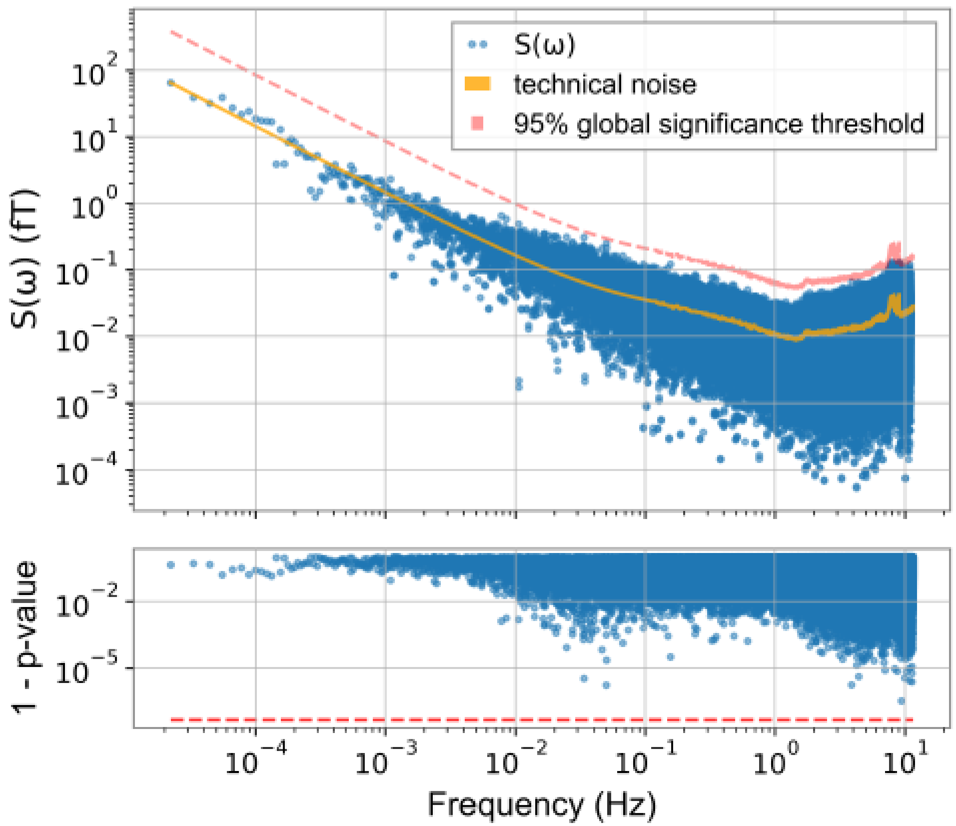

Two Self-compensated Comags
~30 days of data

# Collected data

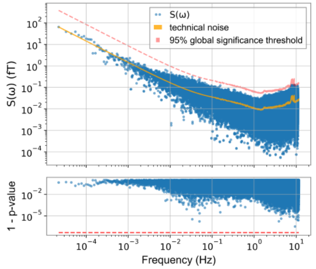
## Daily frequency calibration



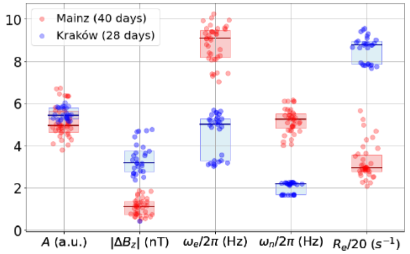

## Combined interferometer data



- No dark matter signal found -> experimental exclusions!

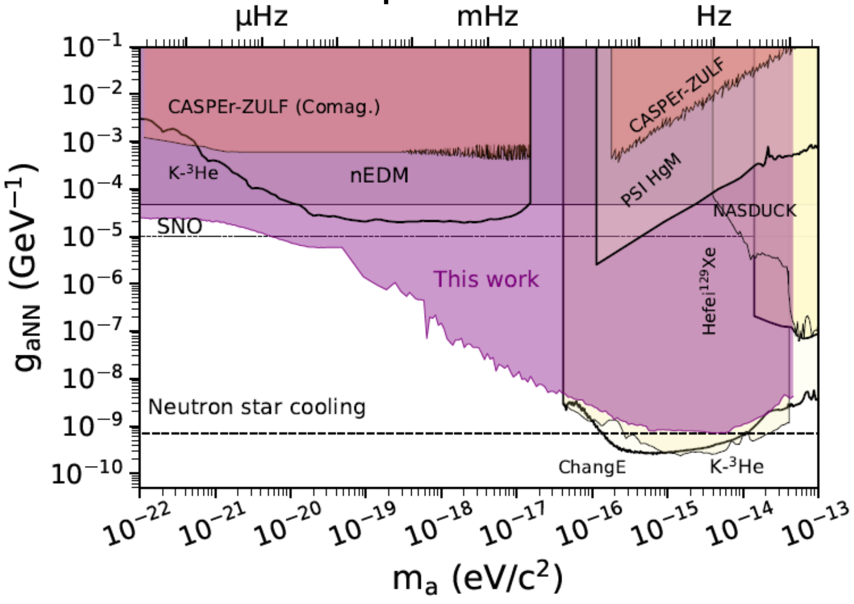



+

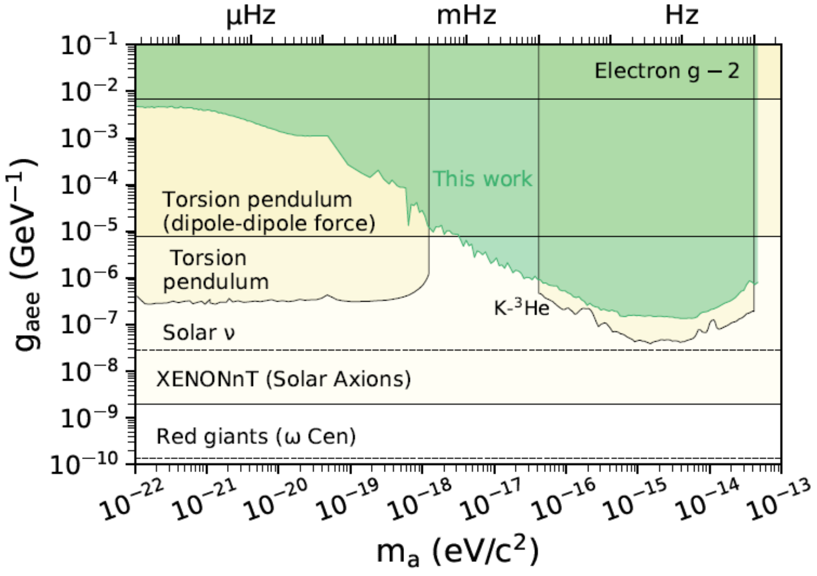



=

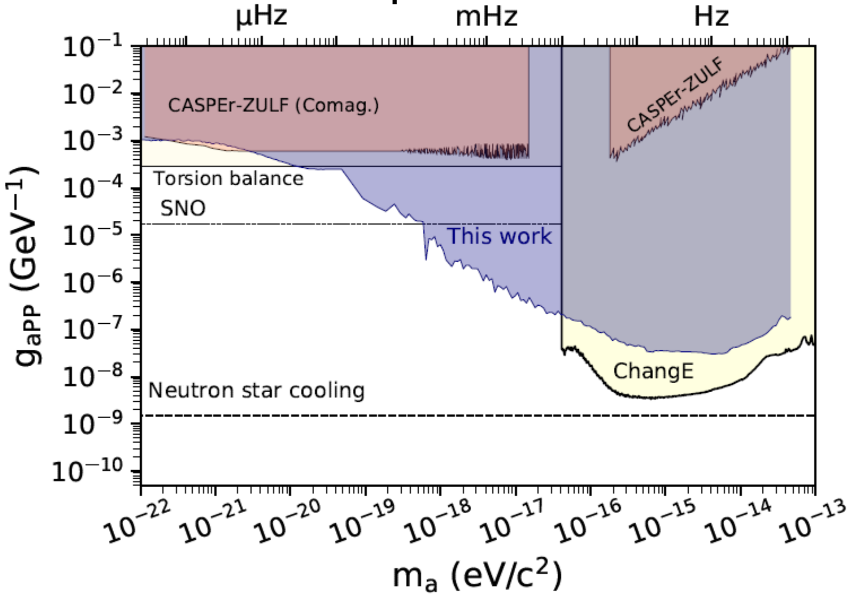
ALPs coupled to neutrons




ALPs coupled to protons




ALPs coupled to electrons

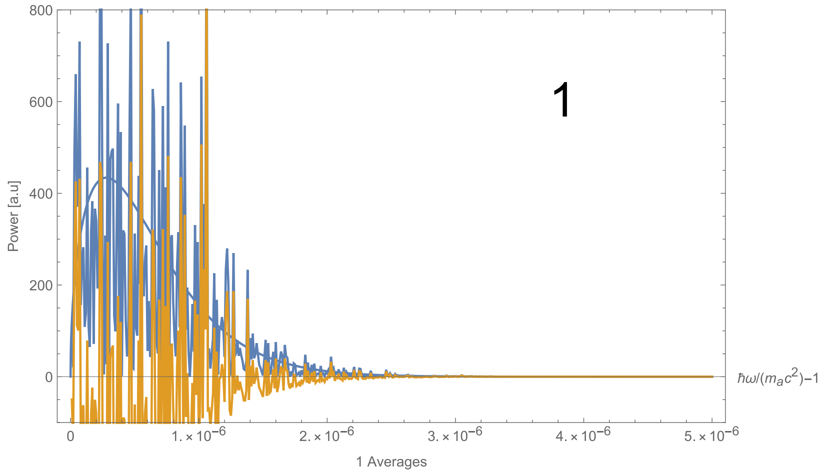


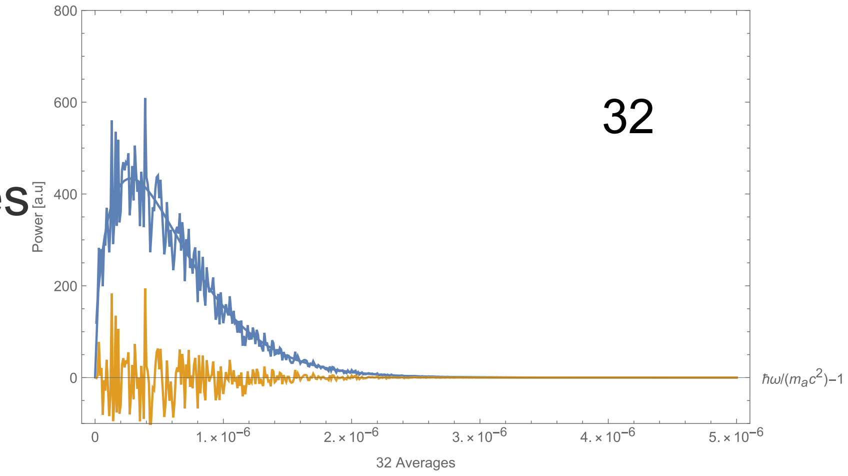
# Summary

- Spin sensors can search for new physics
- Frequency response matters
- Broadband approaches!
  - Three couplings, 6 OOM mass range

**ALP Gradient signal** = 3D pseudo magnetic field vector rotating in space with two independent phases

Virialized dark matter power spectra = modulated white noise




Thank you!
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GSI
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