Title: Studying new physics with nuclear spins

Speakers: Will Terrano

Series: Particle Physics

Date: July 26, 2022 - 1:00 PM

URL: https://pirsa.org/22070029

Abstract: I will discuss the wide - range of new physics that can be probed with nuclear-spin comagnetometers, from EDM measurements to dark matter direct detection experiments.

I will outline the potential for improvement in these measurements, and how improved quantum control could have a significant impact in our sensitivity. I will present some new dark matter detection results using comagnetometers.

Searching for dark matter and new physics with nuclear spins

William Terrano, ASU

Perimeter

New Physics with Nuclear Spins

- Prepare highly-coherent state
  - 10^21 particles
  - Lifetimes of hours or days
- Readout with quantum sensors

- Study nuclear-spin symmetries and interactions:
  - Baryogenesis (CP-violation)
  - Dark matter couplings (low mass axions)
  - New high-energy symmetries
  - 5th forces (goldstone boson exchange)

Highly Coherent Nuclear Spins

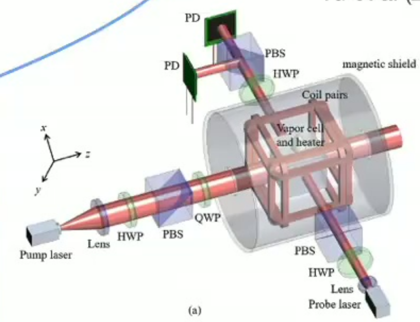
Simple but Powerful **Great for testing new physics!**

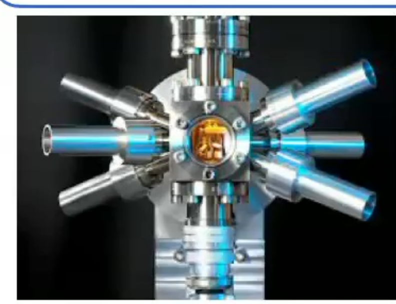
- Measure energy difference between spin-up and spin-down nuclei

$$\mathcal{H}_{\text{spin}} = \mathcal{H}_{\text{mag}} + \mathcal{H}_{\text{BSM}} + ... = \vec{\mu}_N \cdot \vec{B} + \vec{\sigma}_N \cdot \vec{\beta} + ...$$

- Best *absolute* sensitivity to date for measuring energy splitting of quantum states @ 10^-25eV or O(100 pHz)/10 Hz

Yu et al (2020)





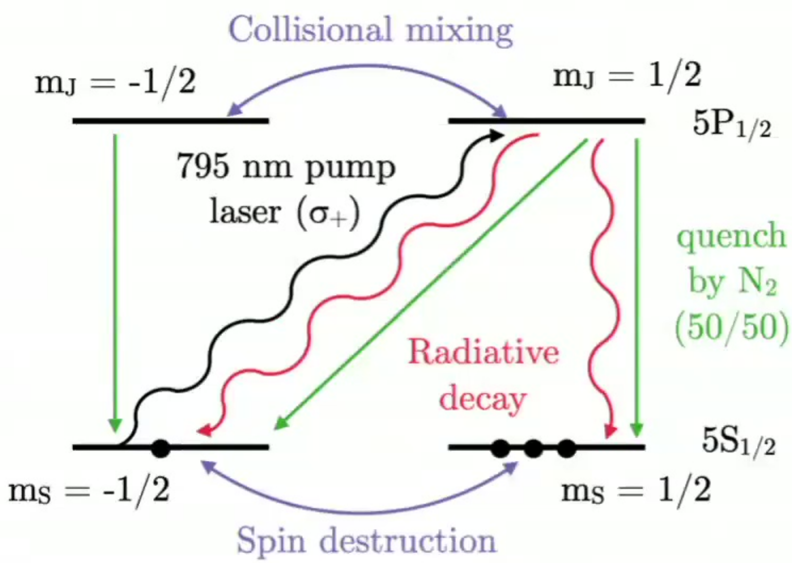
Npl & Andrew Brookes/Science Photo Library/Corbis

Atomic Clocks best *fractional* uncertainty O(mHz)/THz

- Typical magnetic field stability O(10^{-4}): must compare two spins

Spin Exchange Optical Pumping 2

Noble gas nuclei: intrinsically well isolated!
Need optical control



Circularly polarized laser carries spin 1: selectively pump alkali electron S_z (if decay non-radiative)

Spin Exchange Optical Pumping 1

Noble gas nuclei: intrinsically well isolated! Closed electron shell

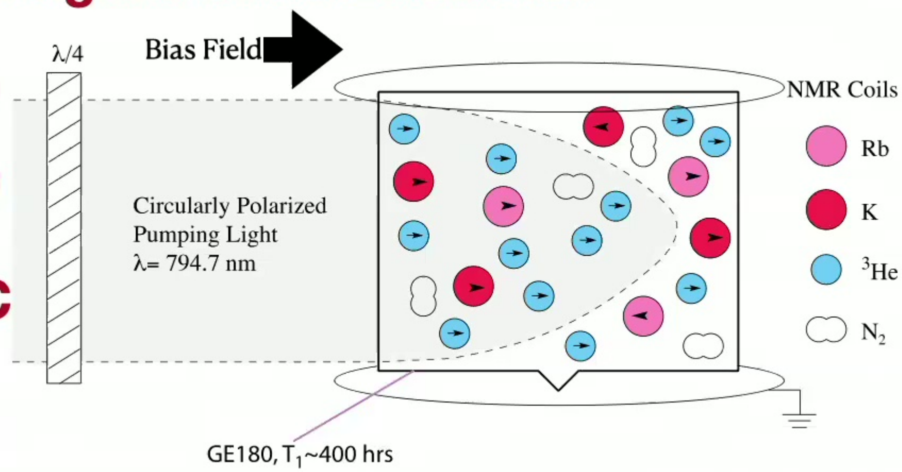
How to align the spins?

Alkali Vapors have single valence electron!

Can optically pump

Can turn on and off

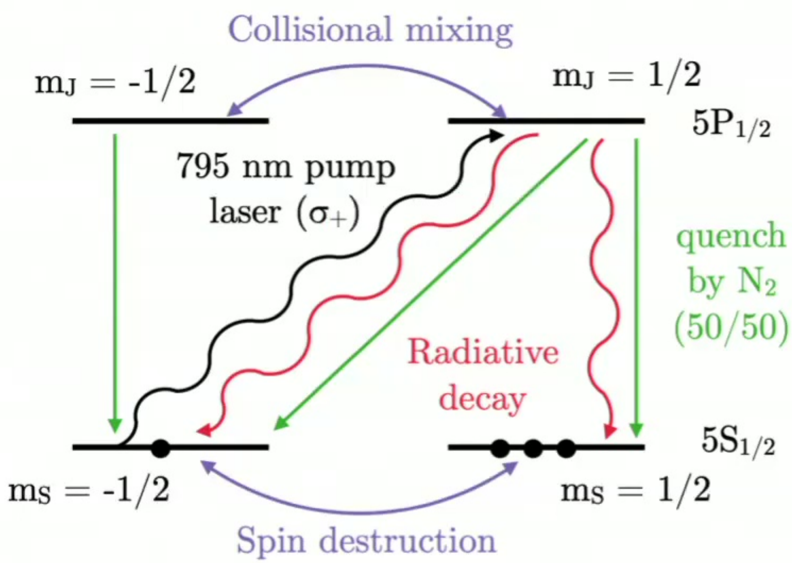
— Vapor temp 100C



From Walker Rev. Mod. Phys., Vol. 69, No. 2, April 1997

Spin Exchange Optical Pumping 2

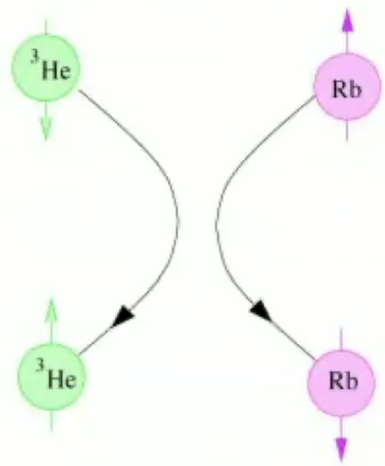
Noble gas nuclei: intrinsically well isolated!
Need optical control

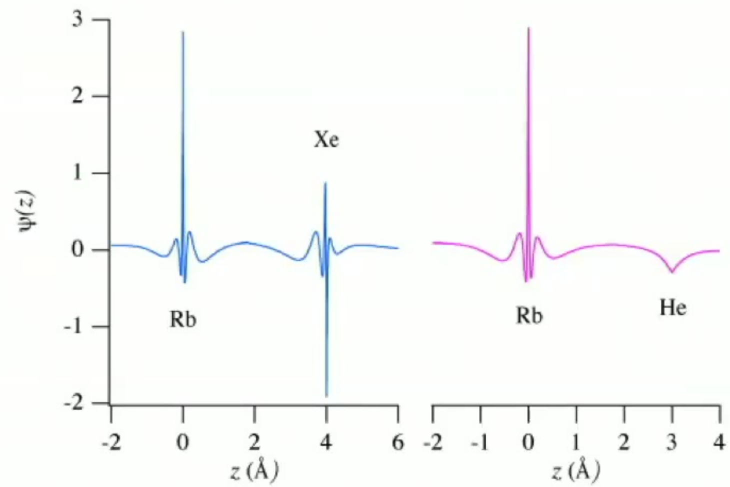


Circularly polarized laser carries spin 1: selectively pump alkali electron S_z (if decay non-radiative)

Spin Exchange Optical Pumping 3

Noble gas nuclei: intrinsically well isolated!
Need optical control



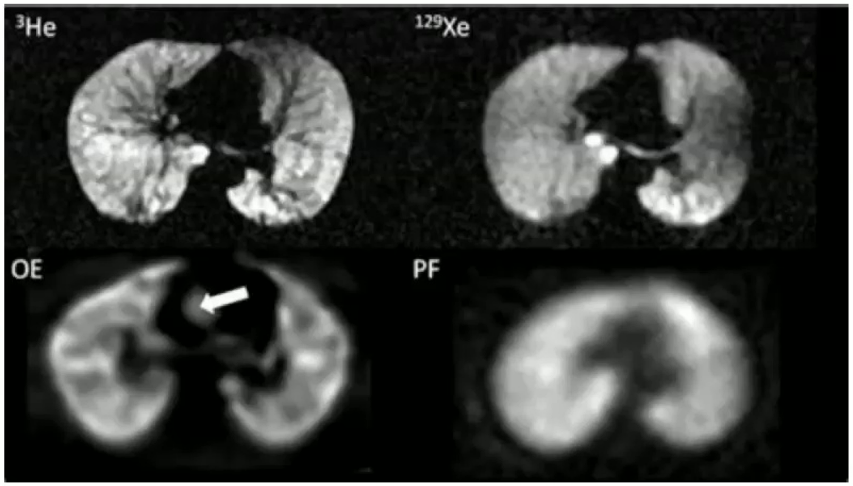


Spin Exchange Optical Pumping 3

Biomedical Advance #1

Medical Imaging applications

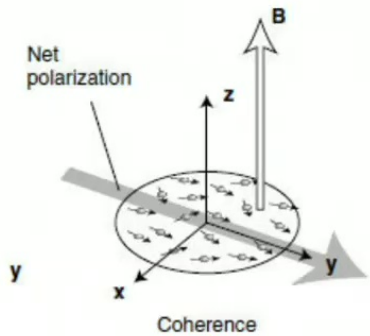
- **MRI image lungs**
- **Study blood flow**
- **Developed high-powered lasers for high pressure**

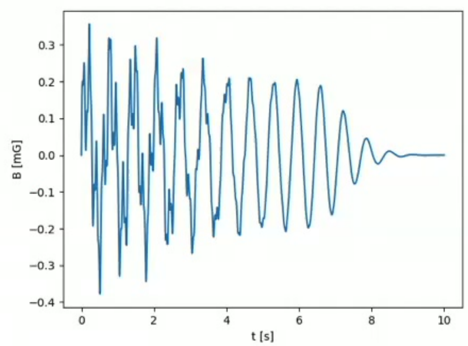


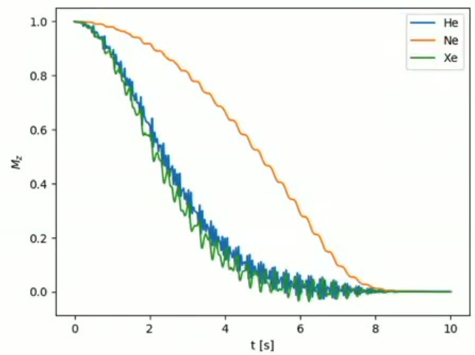
Measuring Energy Splitting 1

- Transfer both ensembles to spin-up/spin-down superposition (excite density matrix coherence)

$$\mathcal{H}_{\text{mag}} = \vec{\mu}_N \cdot \vec{B} \qquad \mathcal{H}_{\text{BSM}} = \vec{\sigma}_N \cdot \vec{\beta} \qquad \mathcal{T}(t) = \exp\left(iS_z \omega t\right)$$







Measuring Energy Splitting 2

Biomedical Advance #2

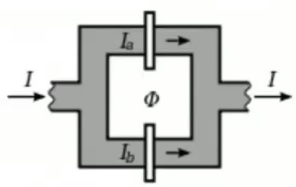
$$\mathcal{H}_{\text{mag}} = \vec{\mu}_N \cdot \vec{B} \qquad \mathcal{H}_{\text{BSM}} = \vec{\sigma}_N \cdot \vec{\beta} \qquad \mathcal{T}(t) = \exp\left(i S_z \omega t\right)$$

- **Measure oscillation frequency of S_x or S_y in 2 nuclei**
  - Need different mag and BSM terms

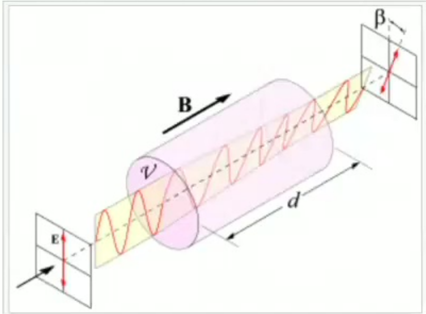
SQUID

QUANTUM INTERFERENCE EFFECTS IN JOSEPHSON TUNNELING

R. C. Jaklevic, John Lambe, A. H. Silver, and J. E. Mercereau
Ford Scientific Laboratories, Dearborn, Michigan
(Received 16 January 1964)



SERF/Optical rotation

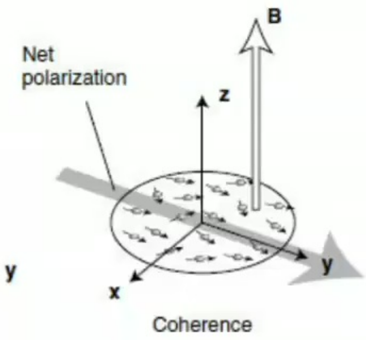


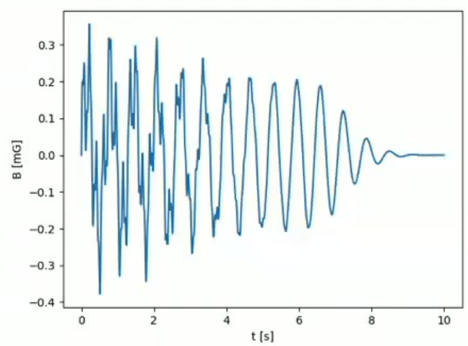
Pro: Cheaper & easier to use,
Con: lower bandwidth and in-situ

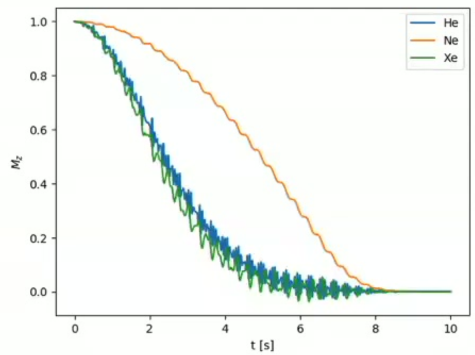
Measuring Energy Splitting 1

- Transfer both ensembles to spin-up/spin-down superposition (excite density matrix coherence)

$$\mathcal{H}_{\rm mag} = \vec{\mu}_N \cdot \vec{B} \qquad \mathcal{H}_{\rm BSM} = \vec{\sigma}_N \cdot \vec{\beta} \qquad \mathcal{T}(t) = \exp\left(iS_z\omega t\right)$$

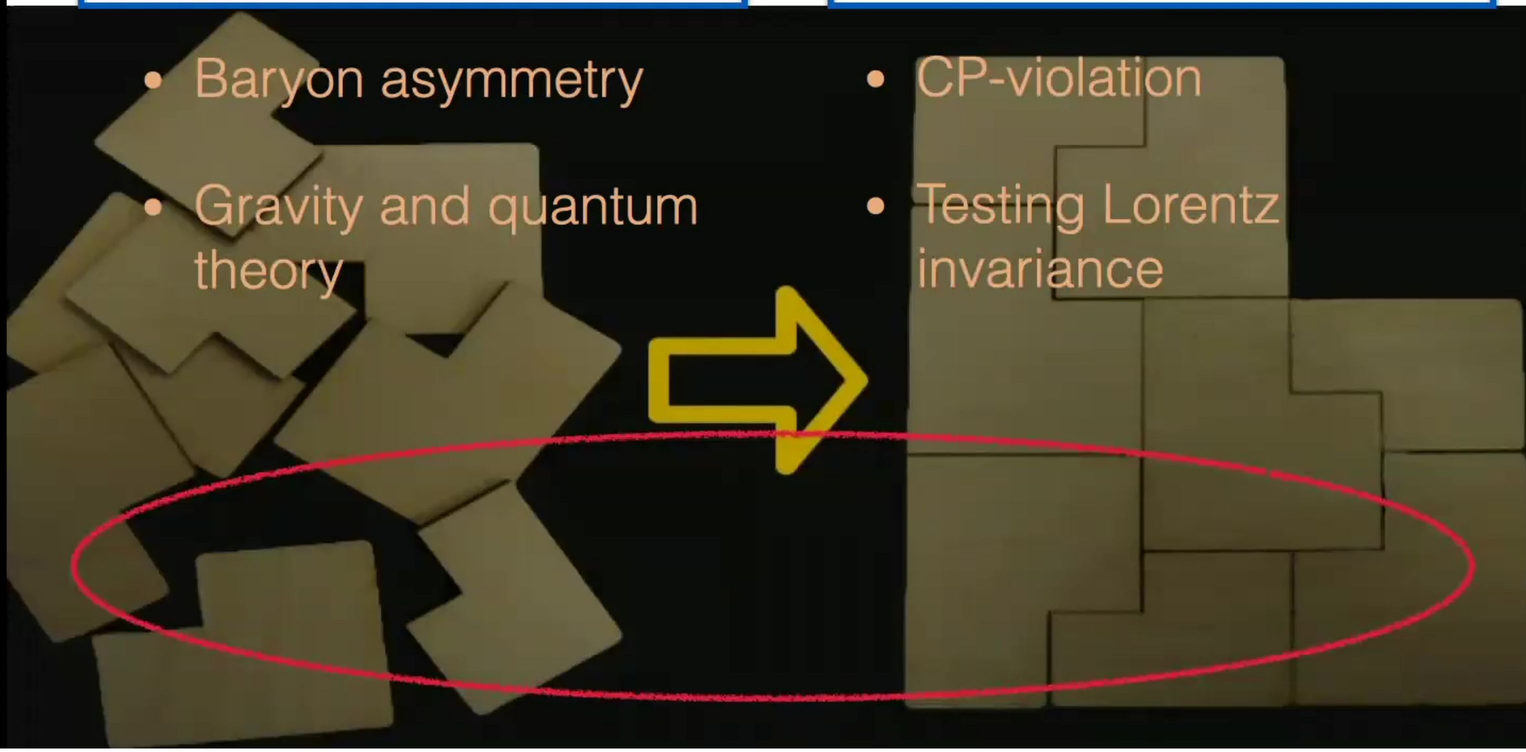






Wide range of new physics

Major Puzzles in SM	*Clues from Spins*
• Baryon asymmetry	• CP-violation
• Gravity and quantum theory	• Testing Lorentz invariance



Fuzzy Dark Matter:

- DM with $m_a = 10^{-22}$ eV explains minimum size of Dwarf galaxies

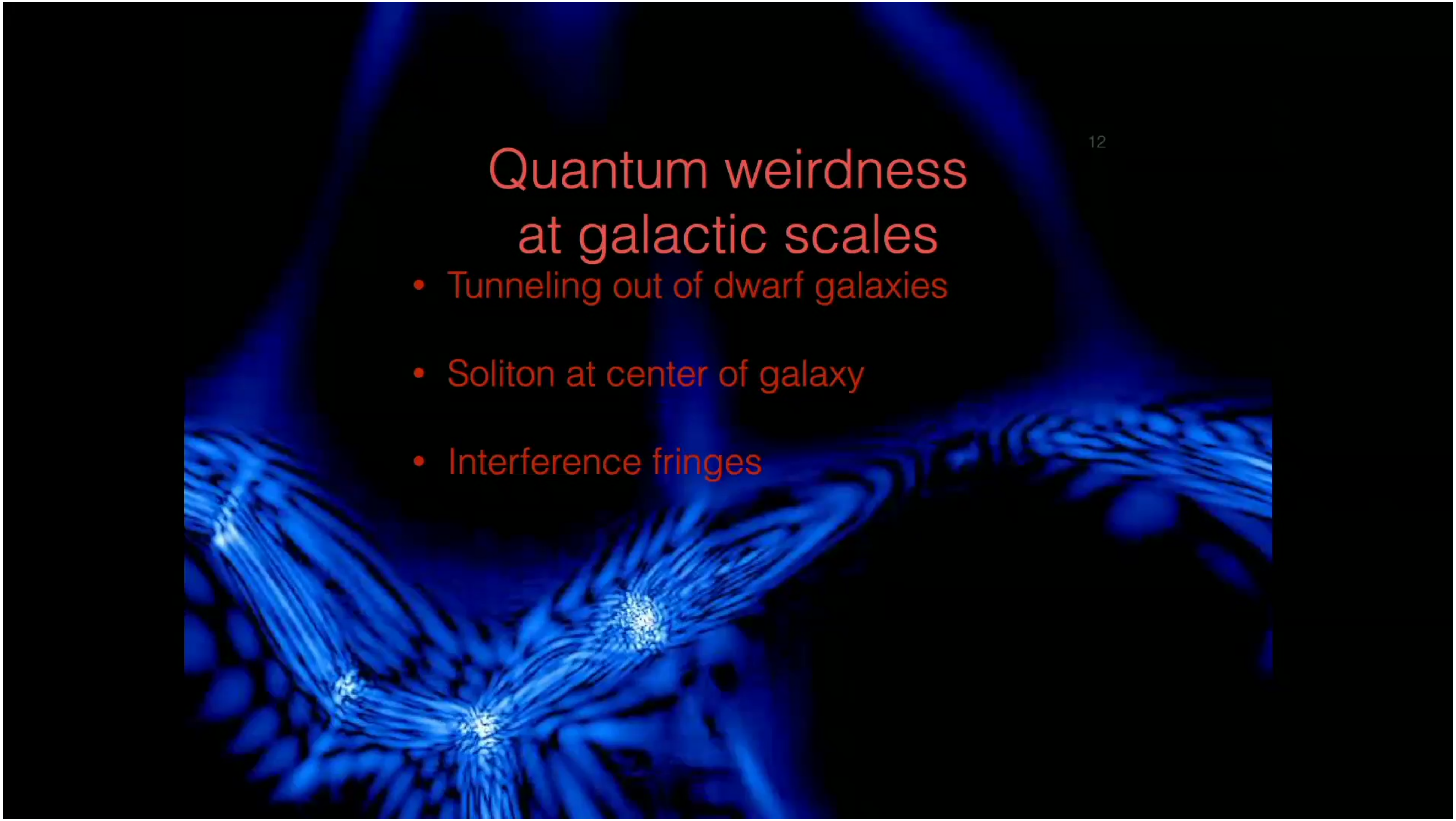
Hu, Barkana, Gruzinov Phys. Rev. Lett. **85**, 1158

- Natural scale for axion is GUT scale ~ 10^{16} GeV

- With $m_a = 10^{-22}$ eV and $F_a = 10^{16}$ GeV:

➔ Generic density = relic dark matter density

Hui, Ostriker, Tremaine and Witten; Phys. Rev. D **95**, 043541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Quantum weirdness
at galactic scales
• Tunneling out of dwarf galaxies
• Soliton at center of galaxy
• Interference fringes

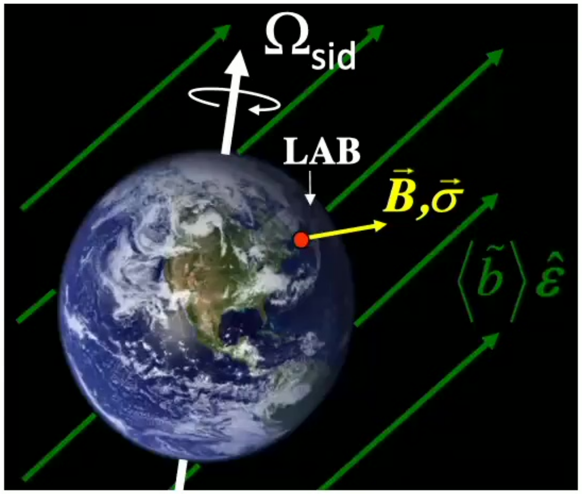
Searching for Dark Matter

DM signature for axionic dark matter

Energy-splitting of Spin along velocity of DM

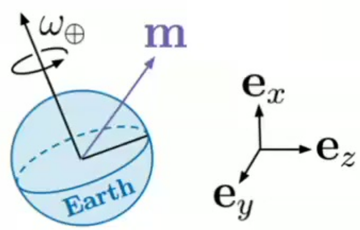
Doubly-modulated at Earths rotation rate and axion Debroglie frequency

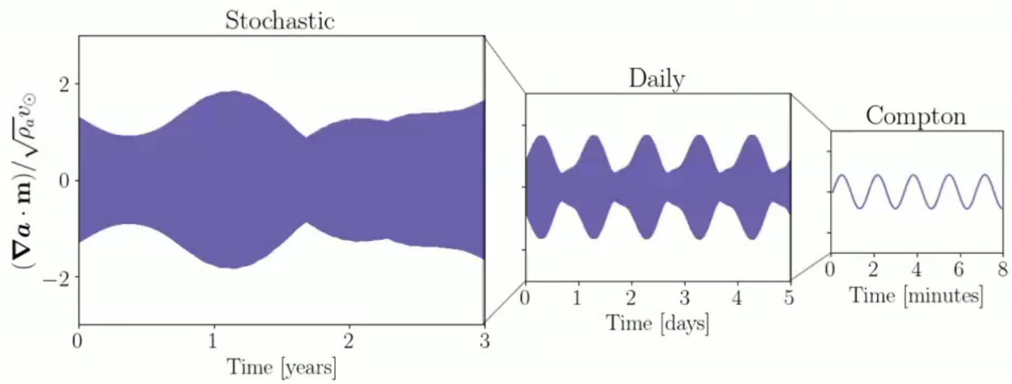
$\mathcal{L} = (\partial_\mu a)\bar{\psi}\gamma^\mu\gamma_5\psi \qquad a = a_0 \cos\omega_C t \qquad H_{ax} \sim \sqrt{2\rho_{DM}}\vec{v}\cdot\vec{\sigma}_\psi \cos m_a t.$



Magnitude ~ axion velocity in lab frame

DM signal:
huge number of modes —
velocity spread matters

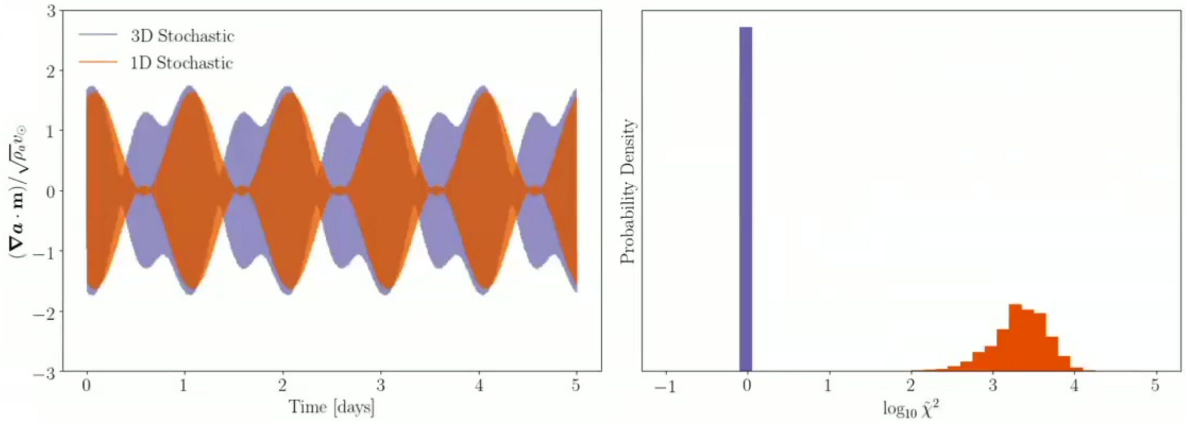




w Matt Moschella and Mariangela Lisanti

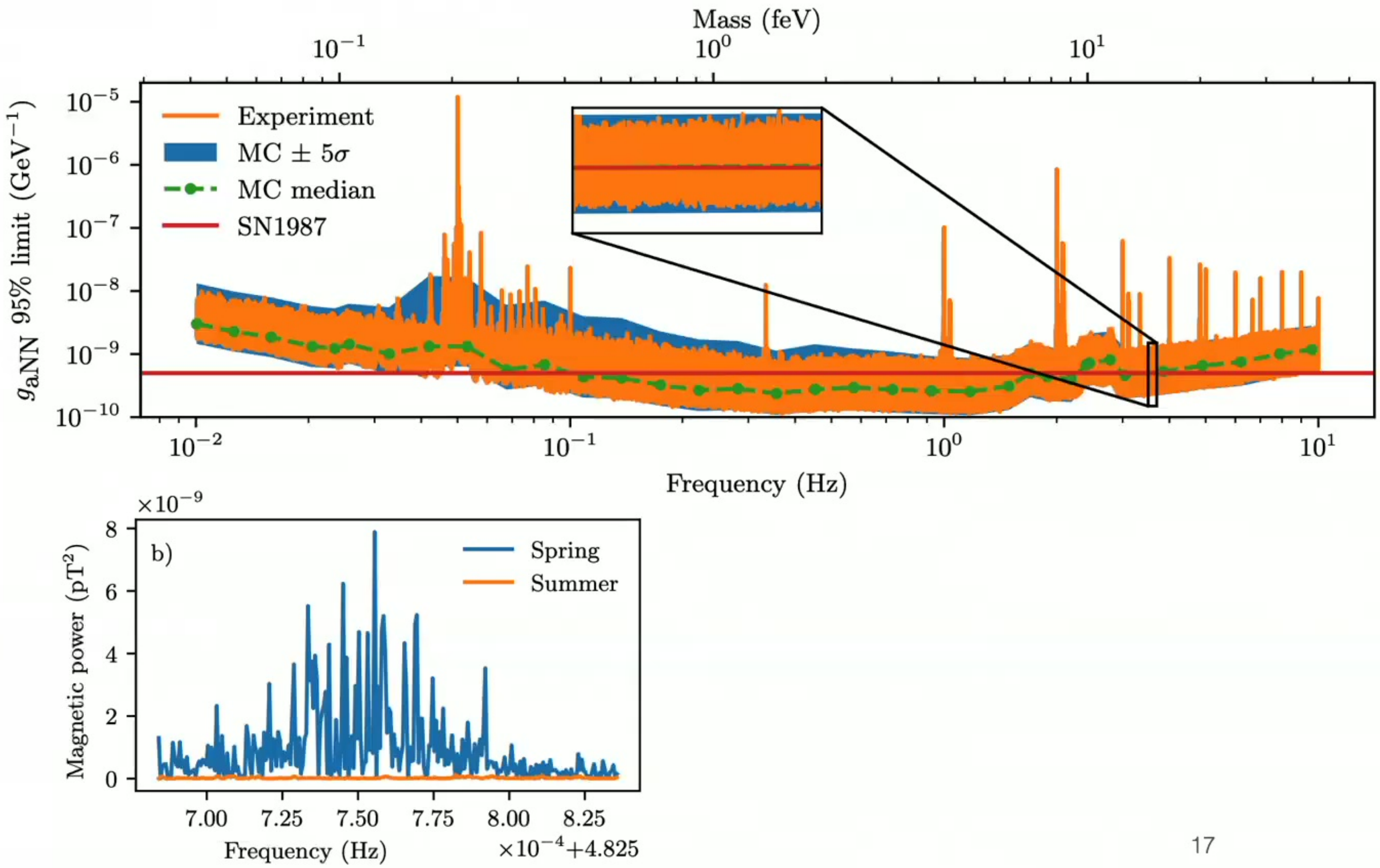
DM signal: velocity spread matters

Dark Matter Direction changes stochastically!



w Matt Moschella and Mariangela Lisanti

Limits on Axion Dark Matter



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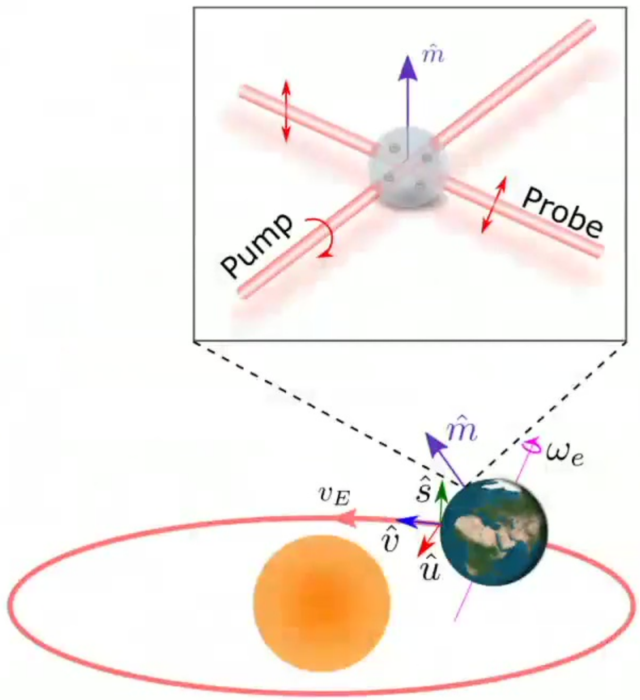
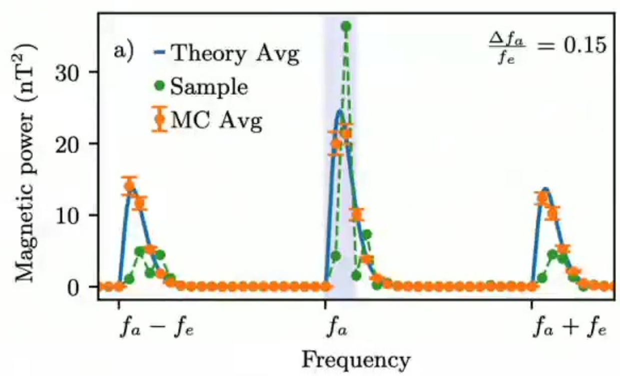
K-He comagnetometer





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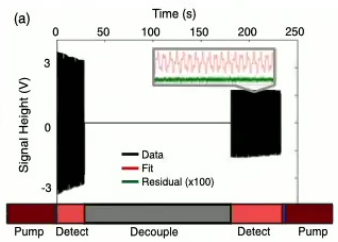
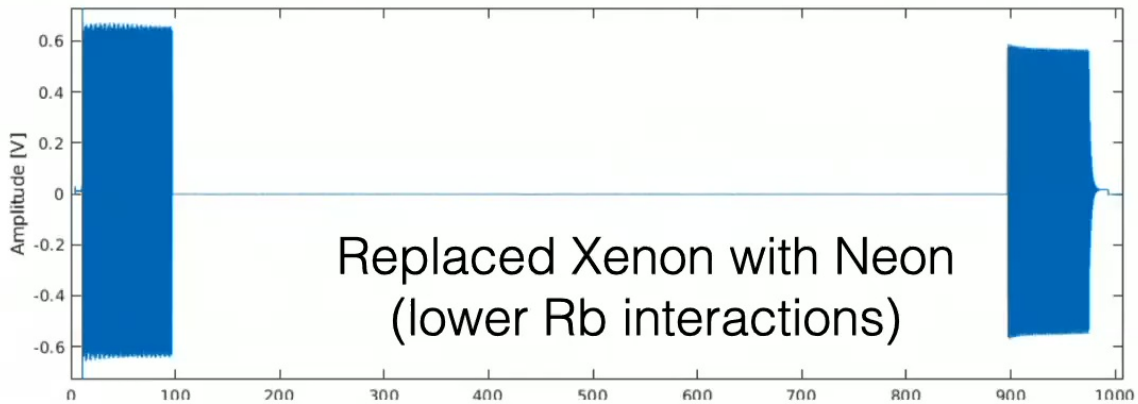
New Data:
Measurement in the dark

Limes et al
2019



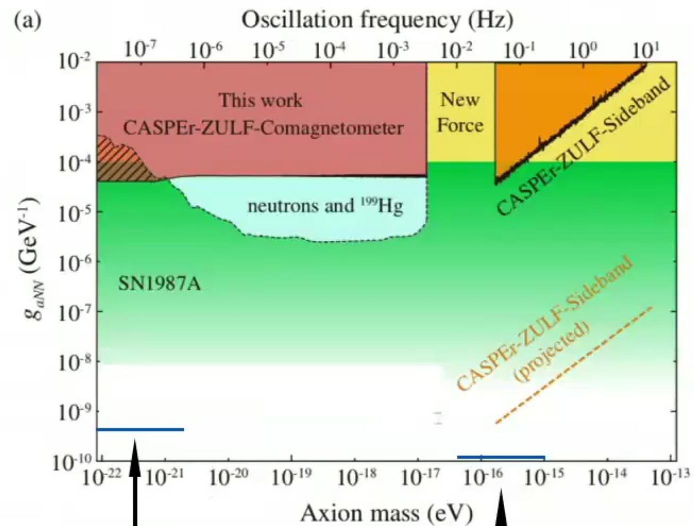
Pump — Probe cycles
Detection/Precession measurements

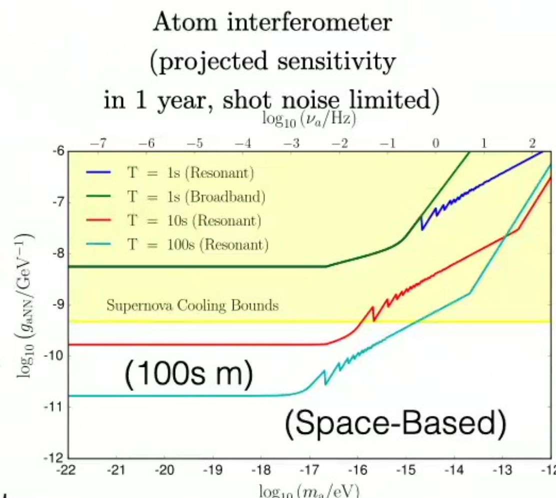


Replaced Xenon with Neon
(lower Rb interactions)

Rb depolarized with RF fields

Dark Matter Limits





Ne-He Data
30 days

K-He Data
40 days

(analysis by Junyi Li & Matt Moschella)

30 Days of Data

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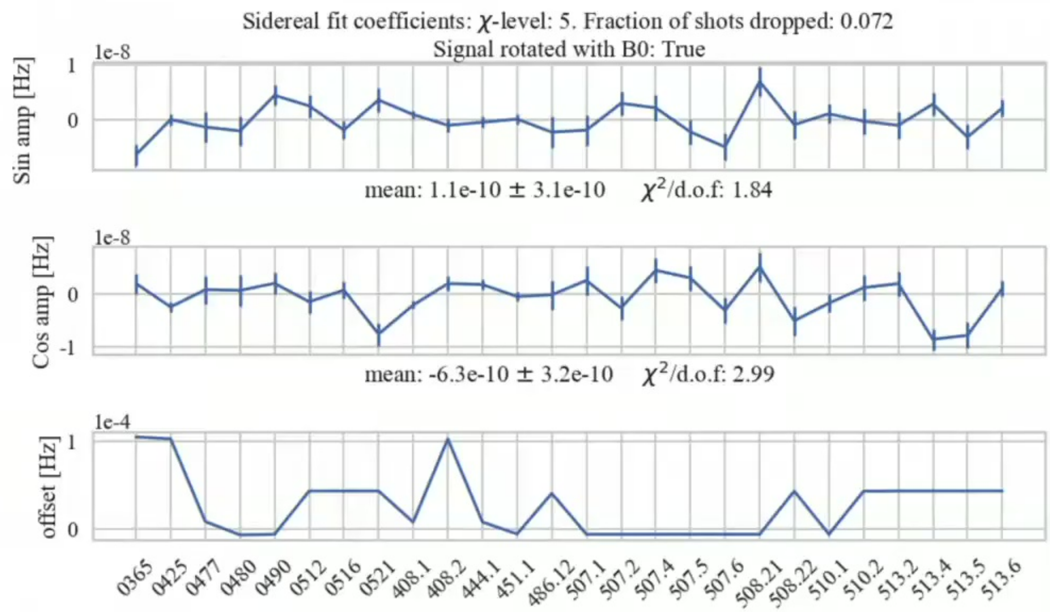
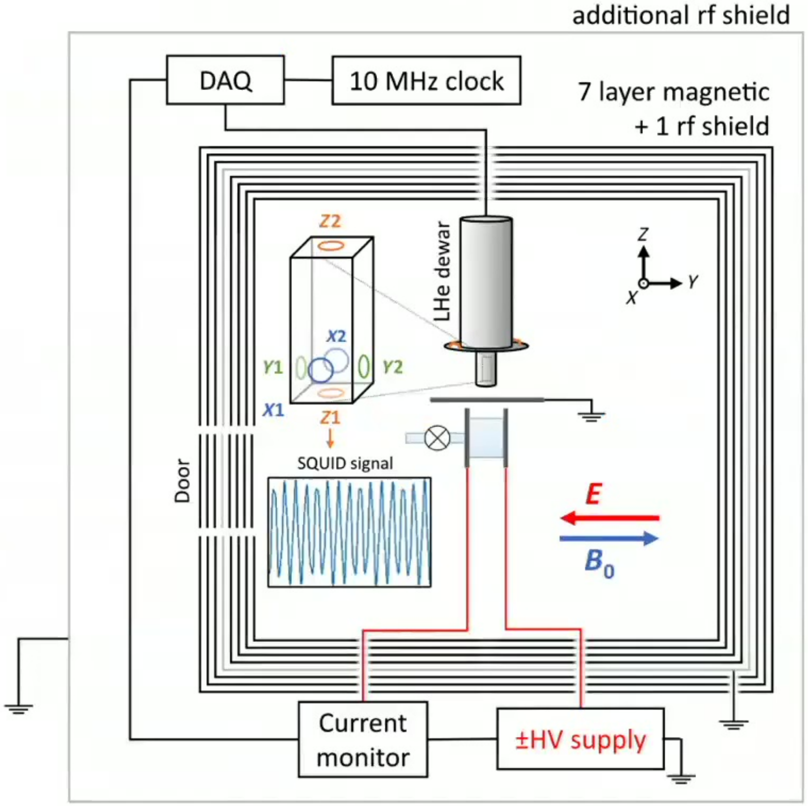


2019 Xe-EDM —— Setup



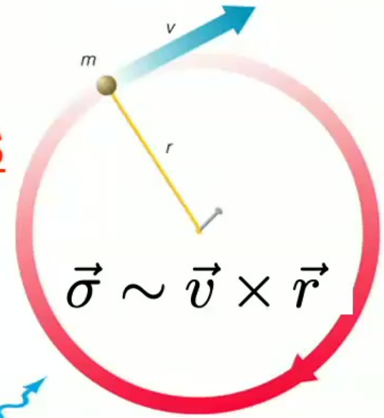
Separate Pumping station (~10% polarization)

Prepared cells placed in magnetically shielded room near SQUID (~6 fT/rt(Hz))

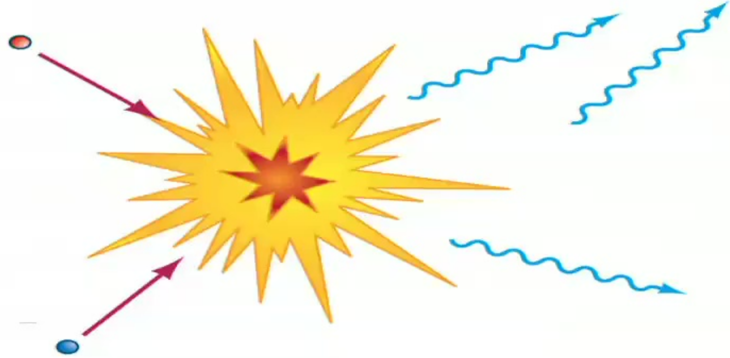
Spins tipped, Electric fields applied (6-9kV)

CP-violation and spins

Baryogenesis requires new CP-violation



$\vec{\sigma} \sim \vec{v} \times \vec{r}$



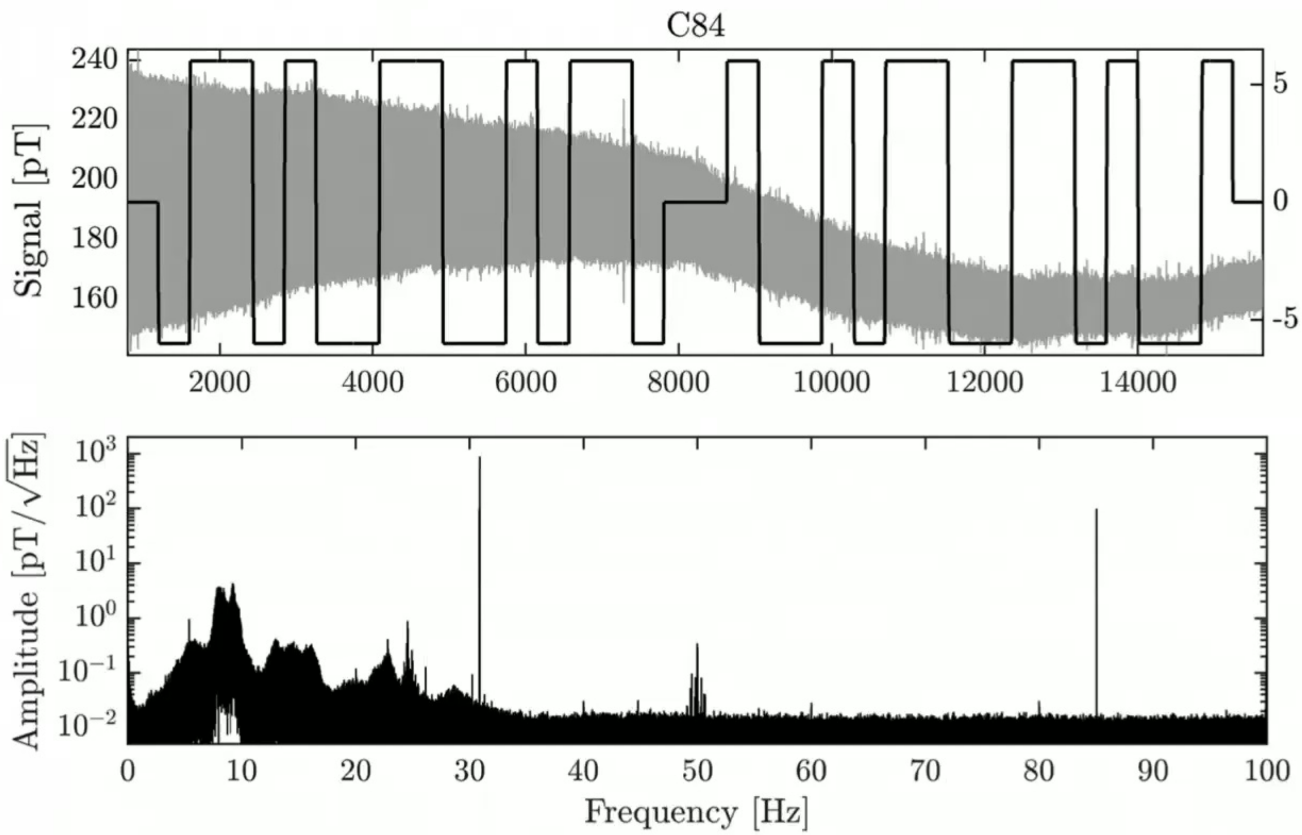
Intrinsic EDM

$$\vec{d} \sim \vec{\sigma}$$

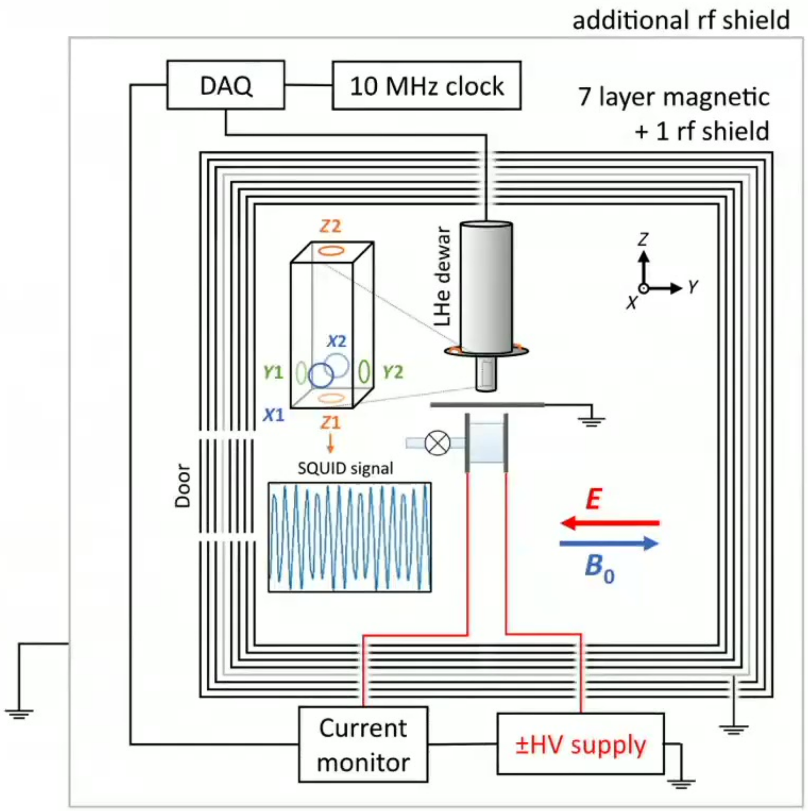
$$\mathcal{H} = \mu\,\hat{\sigma} \cdot \vec{B} + d\,\hat{\sigma} \cdot \vec{E}$$

- *Energy of spin perturbed by relative orientation of electric field*

2019 Xe-EDM measurement — Raw Data



2019 Xe-EDM —— Setup



Separate Pumping station (~10% polarization)

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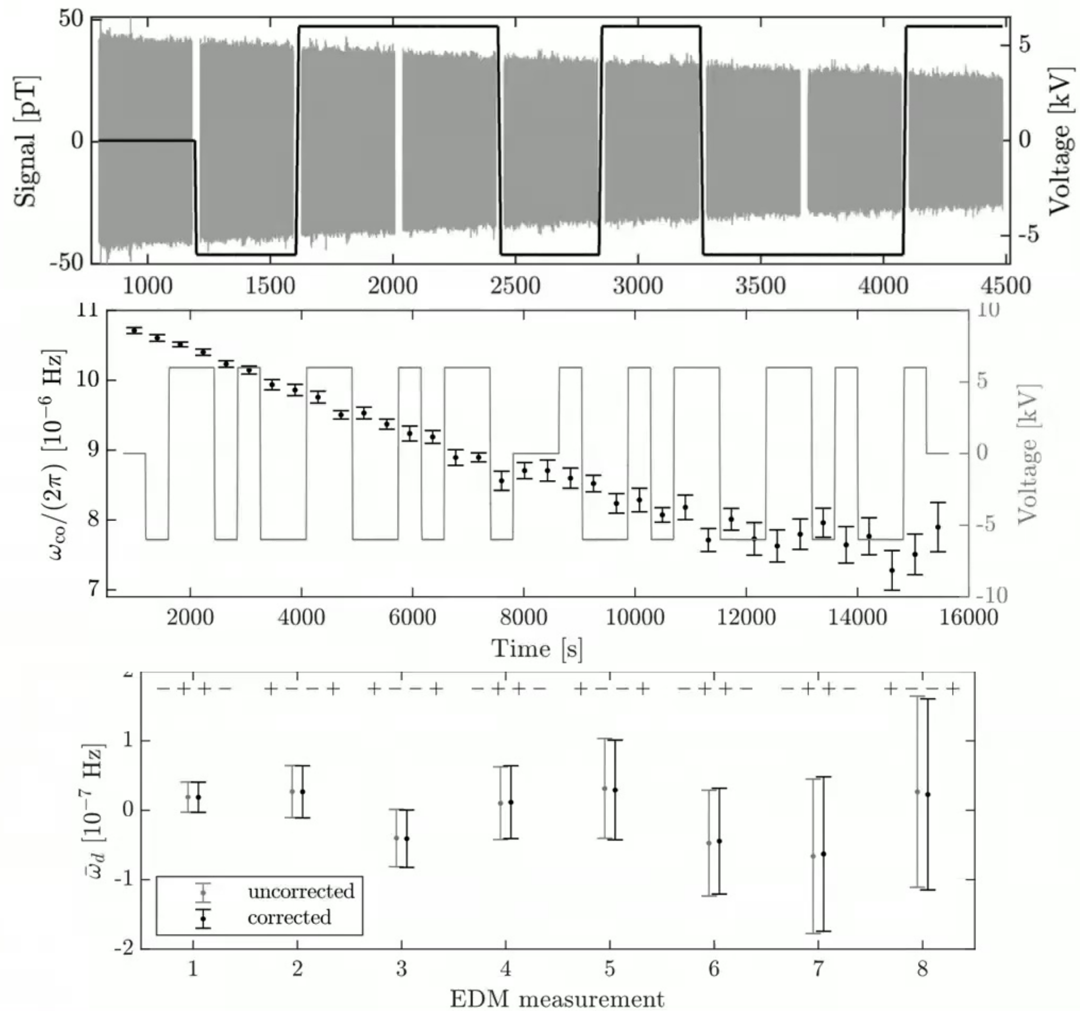
Spins tipped, Electric fields applied (6-9kV)

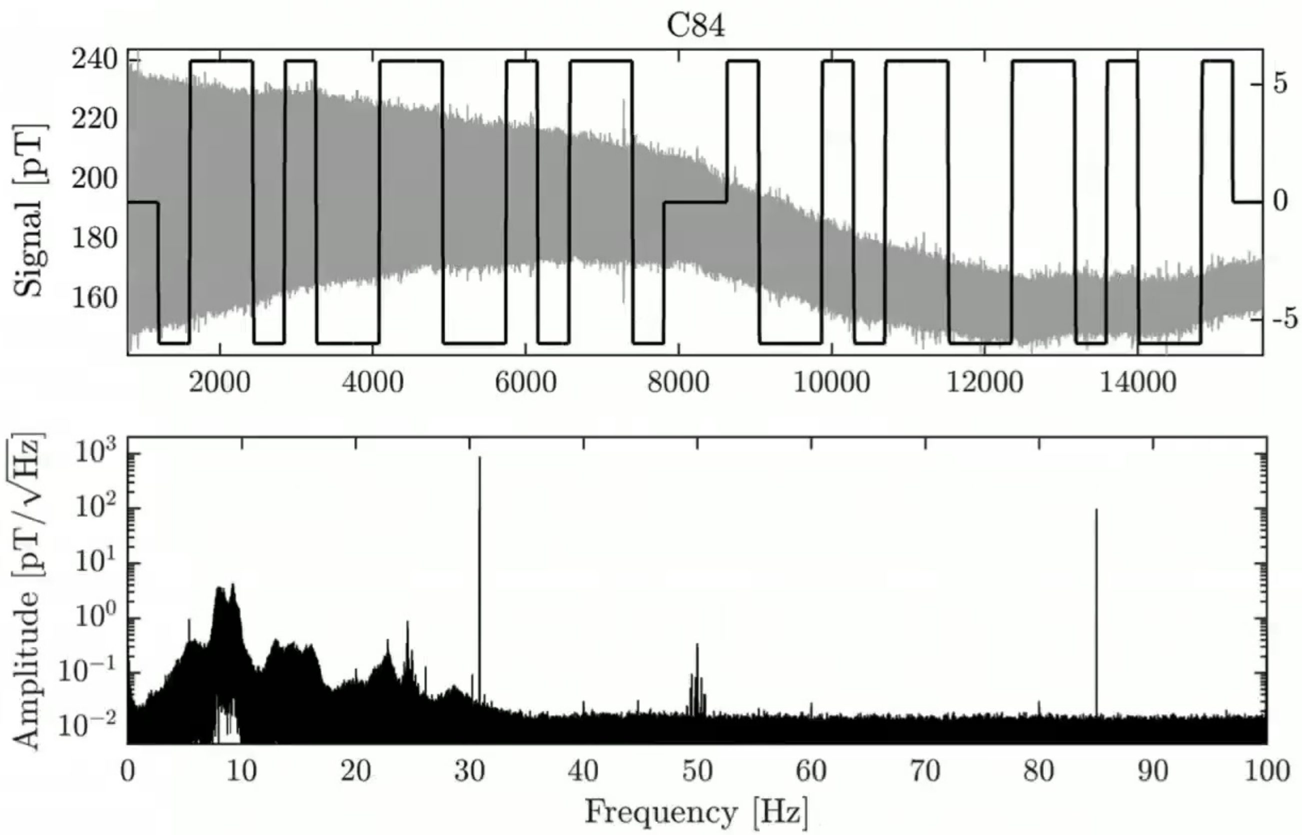
2019 Xe-EDM measurement — EDM extraction



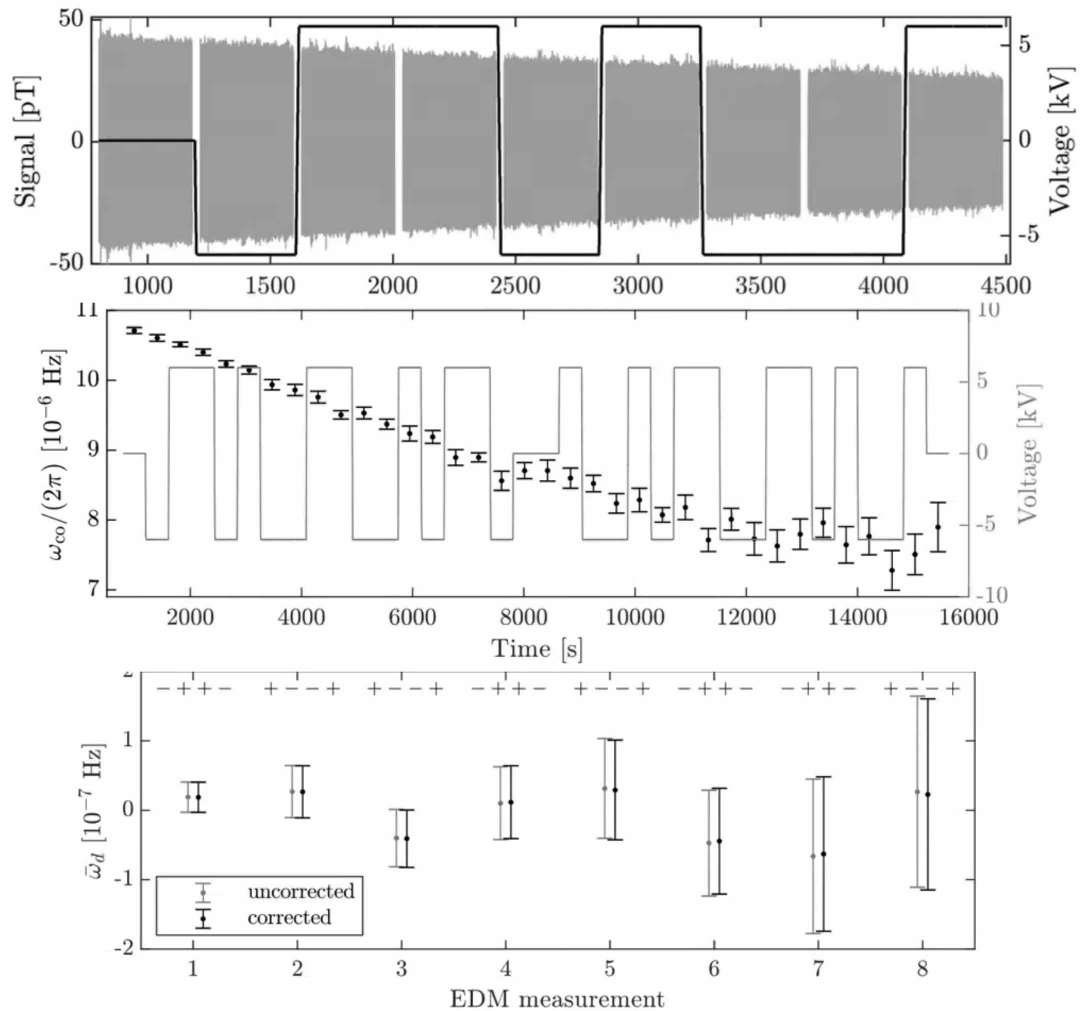
2019 Xe-EDM measurement — Error Table

	2017 (e cm)	2018 (e cm)
EDM	7.2×10^{-28}	0.9×10^{-28}
Statistical error	23.5×10^{-28}	6.8×10^{-28}
Systematic Source		
Leakage current	1.2×10^{-28}	4.5×10^{-31}
Charging currents	1.7×10^{-29}	1.2×10^{-29}
Cell motion (rotation)	4.2×10^{-29}	4.0×10^{-29}
Cell motion (translation)	2.6×10^{-28}	1.9×10^{-28}
Comagnetometer drift	2.6×10^{-28}	4.0×10^{-29}
$\lvert\vec{E}\rvert^2$ effects	1.2×10^{-29}	2.2×10^{-30}
$\lvert\vec{E}\rvert$ uncertainty	2.6×10^{-29}	9.4×10^{-30}
Geometric phase	$\leq 2 \times 10^{-31}$	$\leq 2 \times 10^{-31}$
Total Systematic Error	3.9×10^{-28}	2.0×10^{-28}

2019 Xe-EDM measurement — Raw Data



2019 Xe-EDM measurement — EDM extraction



Non-linear Interactions:

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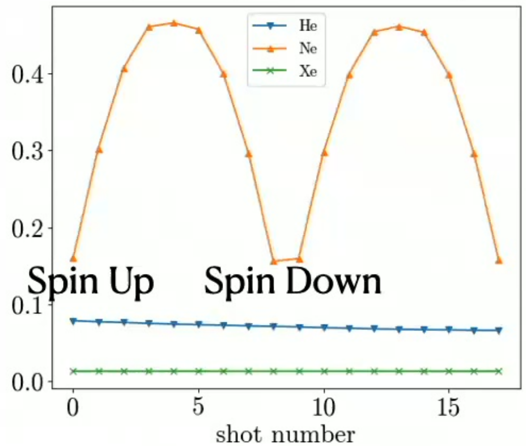
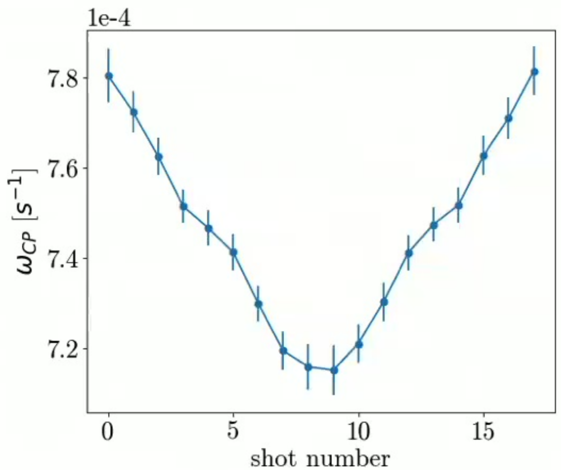
$$\mathcal{H}_{\text{Scalar}} = \kappa_0 \vec{\sigma}_N \cdot \vec{\sigma}_N$$

Neon amplitude (proxy for state)

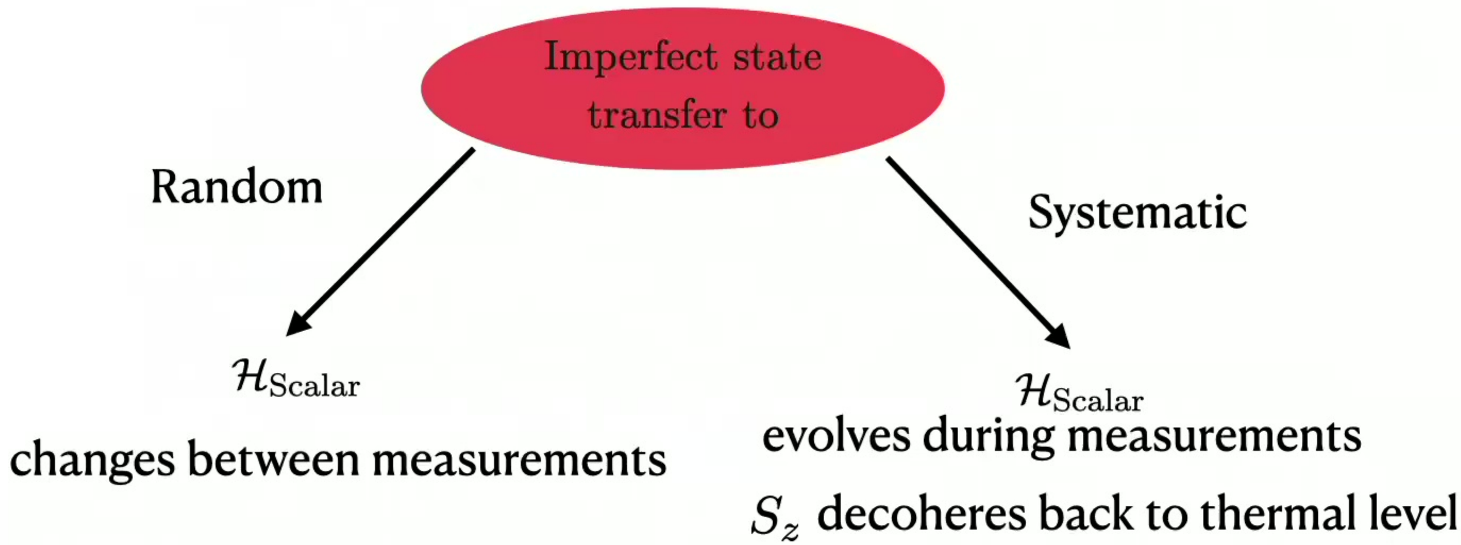


Energy Splitting



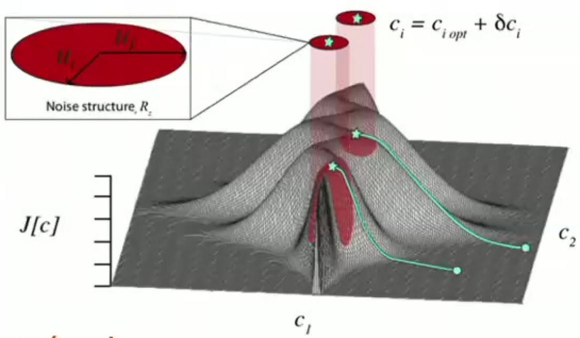
Non-linear Frequency Instabilities:

$$\mathcal{H}_{\text{Scalar}} = \kappa_0 \vec{\sigma}_N \cdot \vec{\sigma}_N$$



Quantum Control (w V. Batista and L. Santos)

- <u>Optimal and robust control:</u> protocol to minimize error in target state in the presence of experimental errors



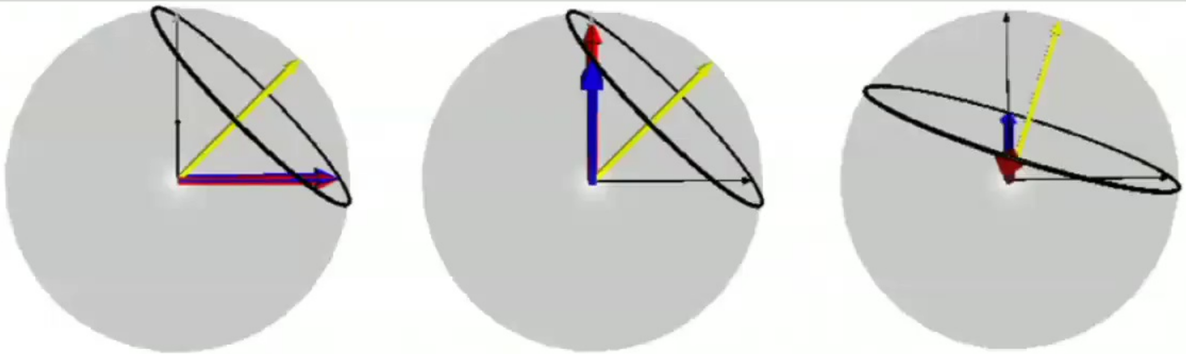
- <u>Dynamical decoupling:</u>
  invert unwanted terms in the Hamiltonian (spin-echo for magnetic gradients).

  Has been done for a scalar term; need to develop sequence for ~4 equal sized scalars

$$I(\tau/2) - \pi_X - I(\tau) - \pi_Y - I(\tau) - \pi_X - I(\tau) - \pi_Y - I(\tau/2)$$

$$I(\tau/2) - \pi_{\pi/6+\phi} - I(\tau) - \pi_\phi - I(\tau) - \pi_{\pi/2+\phi} - I(\tau) - \pi_\phi - I(\tau) - \pi_{\pi/6+\phi} - I(\tau/2)$$

Optimal Control



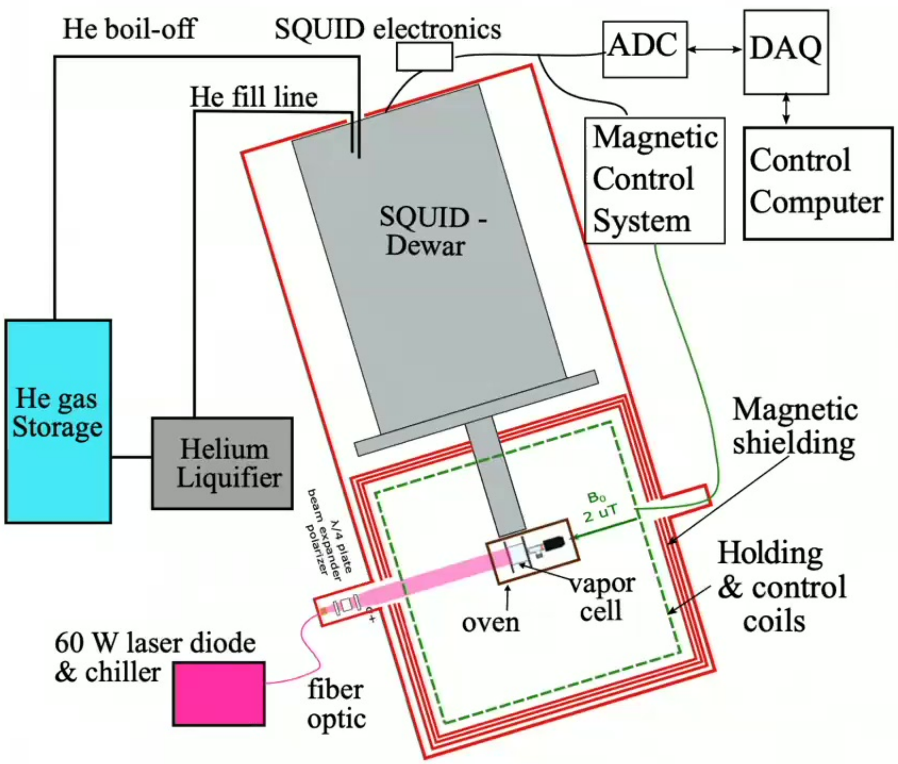
- Diffeomorphic modulation under observable response preserving homotopy (D-MORPH) gradient and the Broyden Fletcher Goldfarb Shannon (BFGS) iterative scheme for nonlinear optimization.

- Measure and minimize state-asymmetry

ASU system

Rb-free system

SQUID readout (more expensive, more complicated)

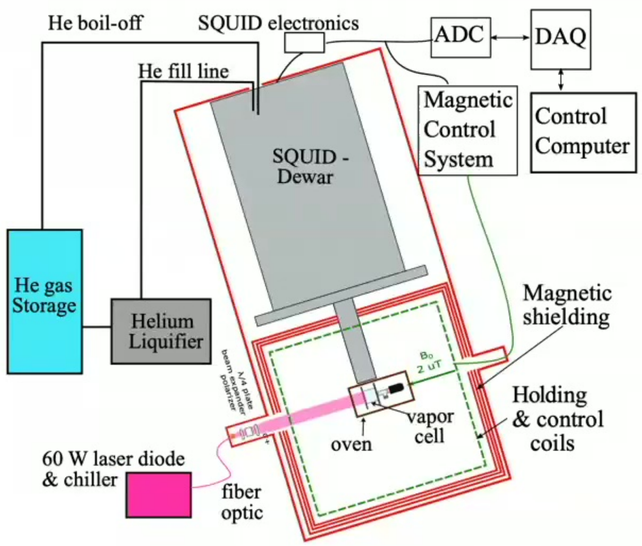


- Compact shielding
- In-situ SEOP
- closed cycle liquid Helium system
- Aligned with Earths rotation axis

ASU system

Rb-free system

SQUID readout (more expensive, more complicated)

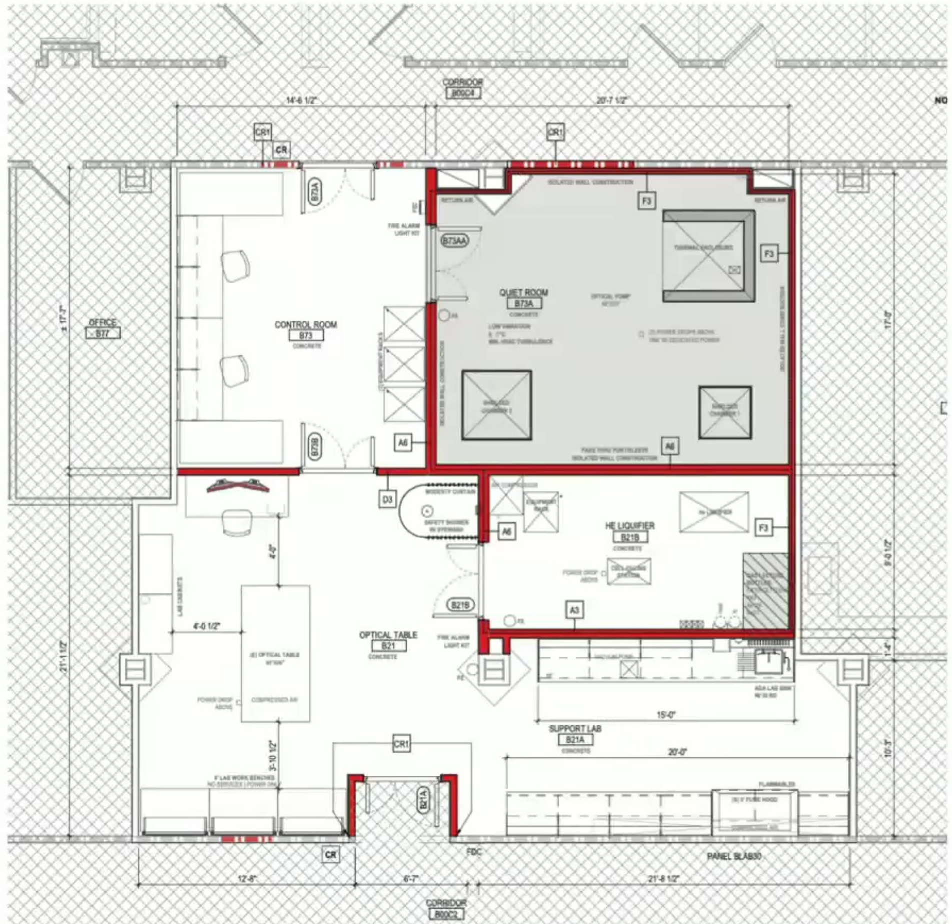


- Must control nuclear self-interactions (collisional and geometric couplings)
    - Controlled cell geometry
    - Precise quantum state initialization
    - Decouple self-interaction Hamiltonian
- Rotation rate of lab itself
- Maintain or monitor magnetic field direction (Earths rotation effect)
- Operate SQUID without disturbing Nuclei

ASU System

Great time to get involved :)

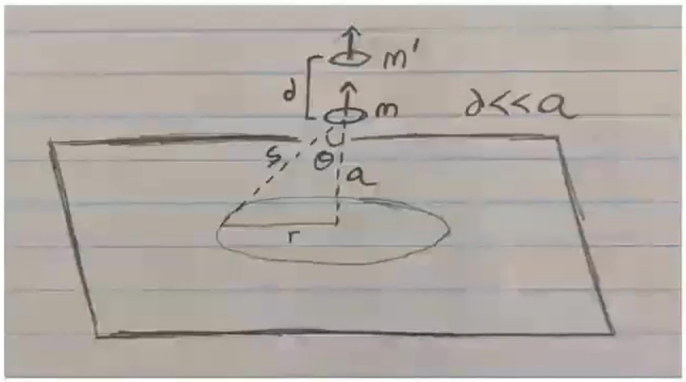
- Separate slab for helium reliquification and mechanicals
- Separate room for control system



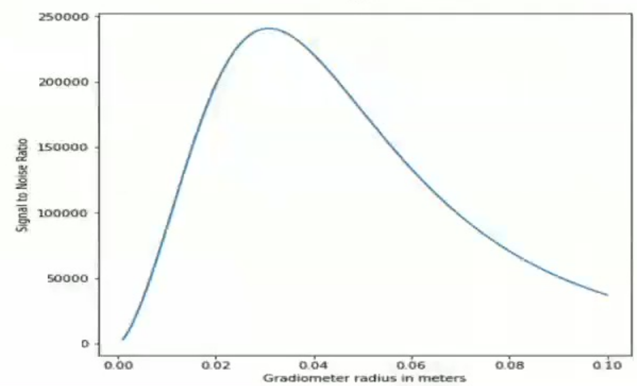
ASU System

Design Underway — SQUID gradiometer and magnetic shielding

- Limiting noise source in SQUID: magnetic shielding (Johnson Eddy Currents)
- Calculations (by Keaten Wood) of gradiometer options



- Extended to nth order, and varying radii
- Optimize Signal to Noise — don't cancel signal!

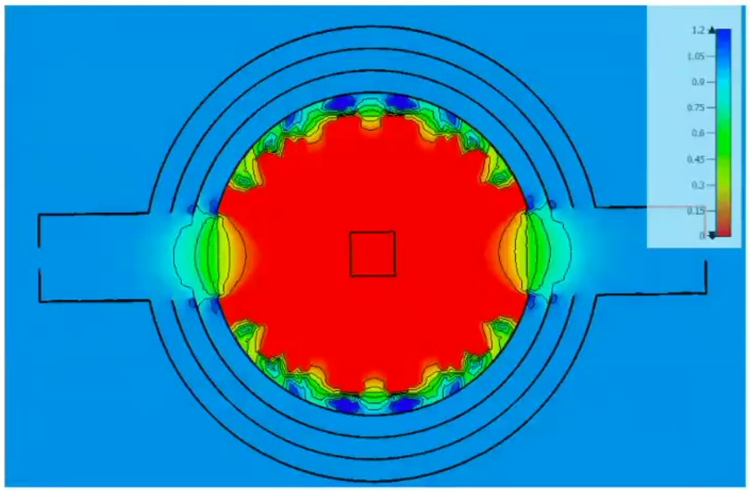


- **35x improvement in SNR**

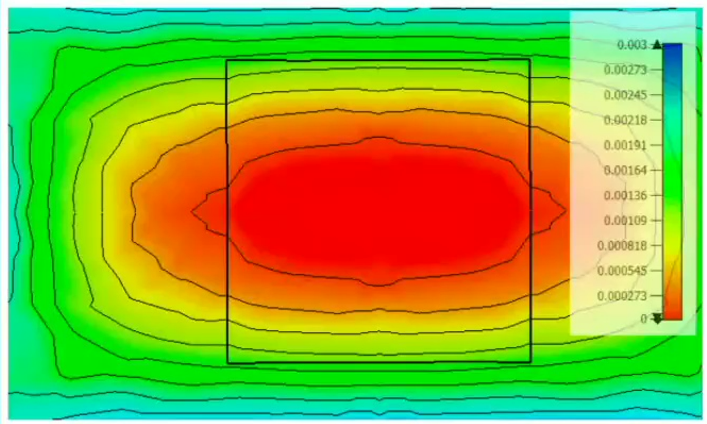
ASU System

Design Underway — Magnetic control fields

- Limitation on spin precession lifetime
- Extend formalism to 2nd order gradients



(A)



(B)

Potential for Ultra-light Axion search

Reach	F_{DM}	Xe EDM [e-cm]
Astro-	$\sim 3 \cdot 10^{8}$ GeV (?)	
Current	$2 \cdot 10^{9}$ GeV	10^{-27}
Next	$6 \cdot 10^{10}$ GeV	$3 \cdot 10^{-27}$
Near-Term	$1 \cdot 10^{12}$ GeV	2.9×10^{-30}
Optimistic	$3 \cdot 10^{13}$ GeV	1.1×10^{-31}
Speculative	$7 \cdot 10^{14}$ GeV	4×10^{-33}

Optimistic/Speculative

Density & Polarization: same / 1atm&50%

Cell size: 6 cm/same

SQUID-spin coupling: same

Spin life time: 2x longer/same

SQUID noise: 0.1 fT/same

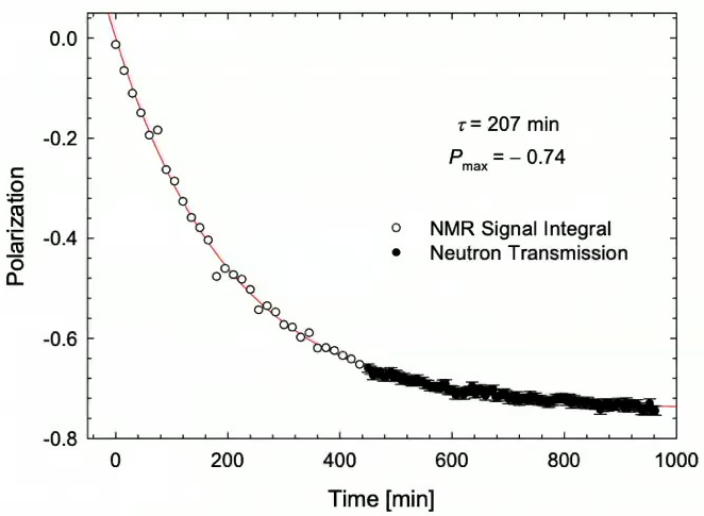
SQUID distance: 4.1 cm/same

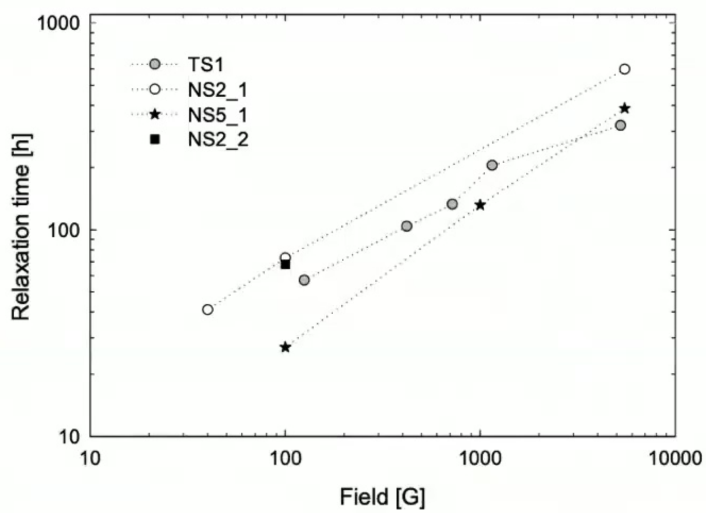
Within 20x of GUT and SM prediction respectively

Technical requirements already achieved;
systematics and self-interactions are the obstacle

High proton-spin sources

Napthalene doped with Pentacene
Electron polarized optically
Microwave transfer to protons





Thank You

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