Quantum Magnetometry in Search of Dark Matter

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Outline

- Introduction:
  - Axions and ALPs
  - Spin-Based (Co)magnetometers
- Established Magnetometry Techniques for DM Research
- Novel Magnetometry Techniques
- Summary

QCD Axion

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- A solution to the strong CP problem, $\theta_{QCD} \to a/f_a$.

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- Can be a CDM component (I assume all)

QCD Axion

Axion Like Particles (ALPs)

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- $m_a \sim \Lambda^2_{QCD}/f_a$

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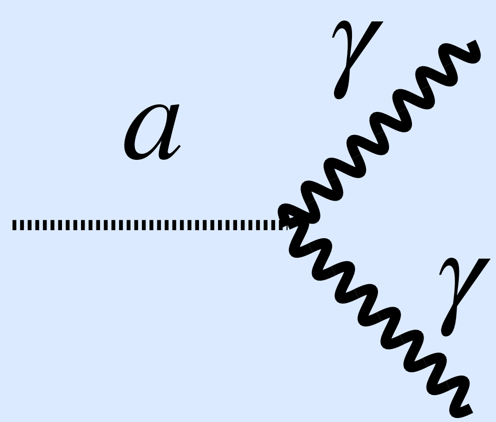
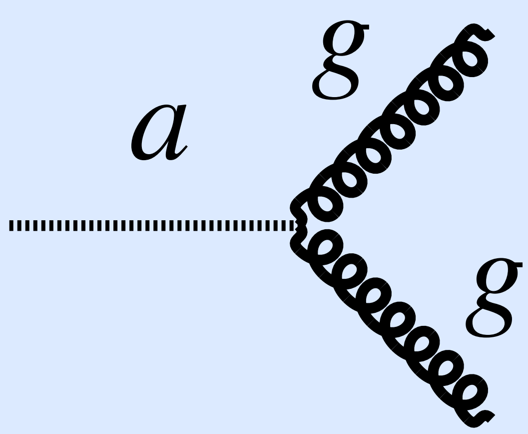
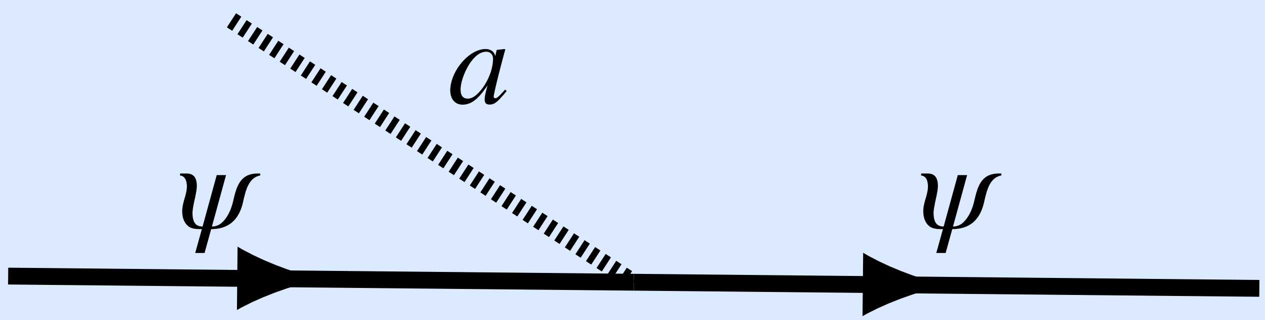
ALP-SM Interactions



$$-\frac{1}{4}g_{a\gamma\gamma}aF\tilde{F}$$



$$-\frac{a}{f_a}\frac{G\tilde{G}}{32\pi^2}$$



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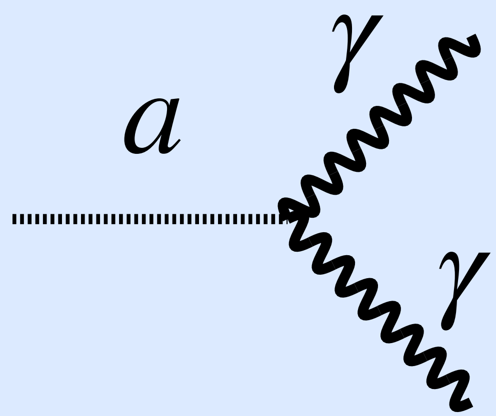
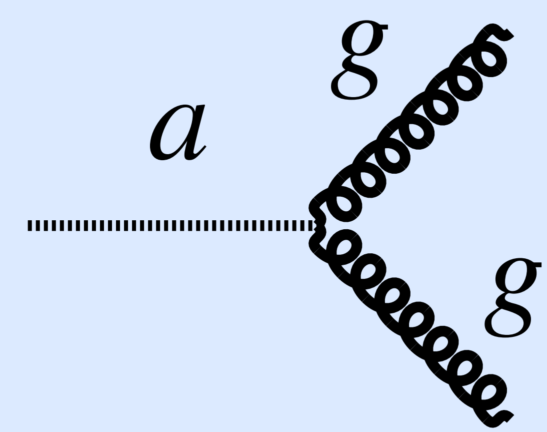


[2024, JHEP: IMB, Kalia],[2023 PRD, SNIPE Hunt (incl. IMB)], [several more in progress]



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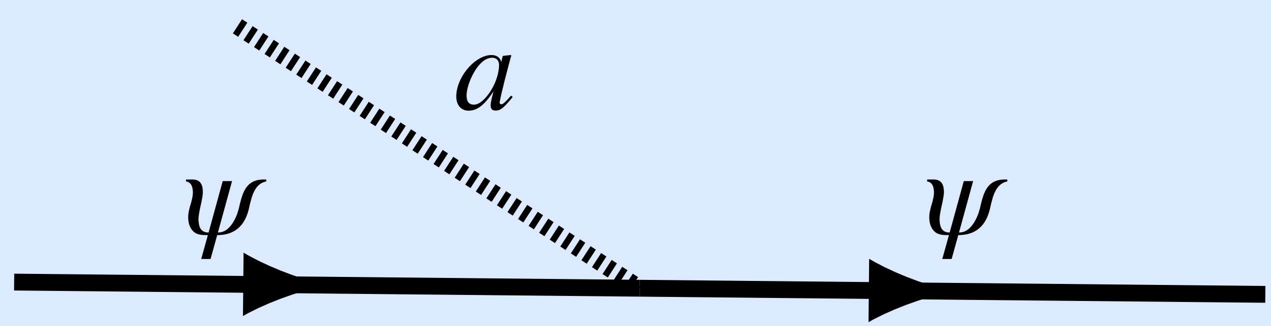

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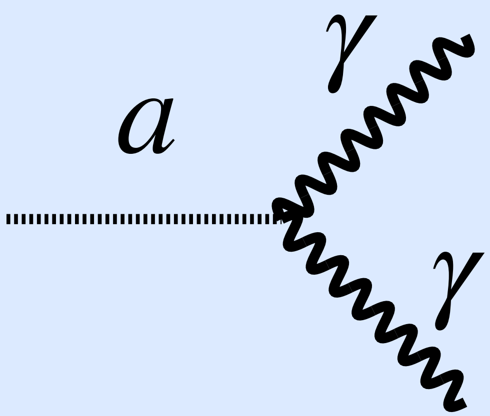

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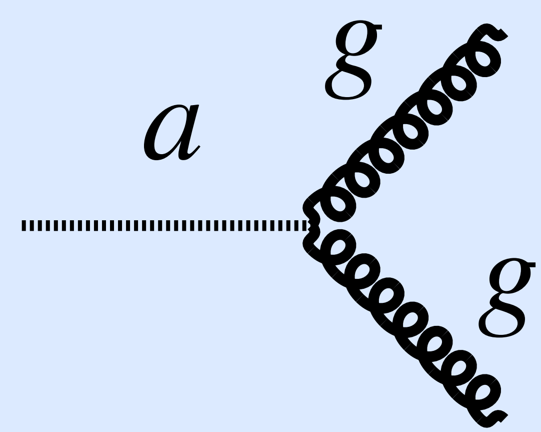

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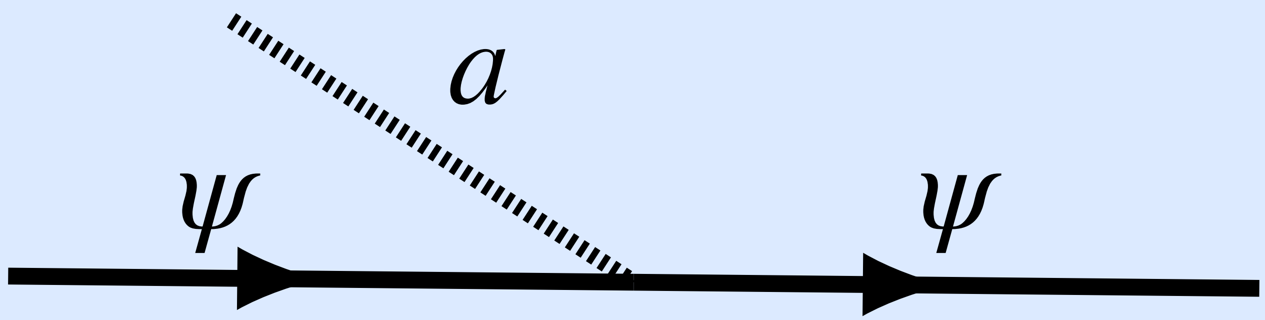

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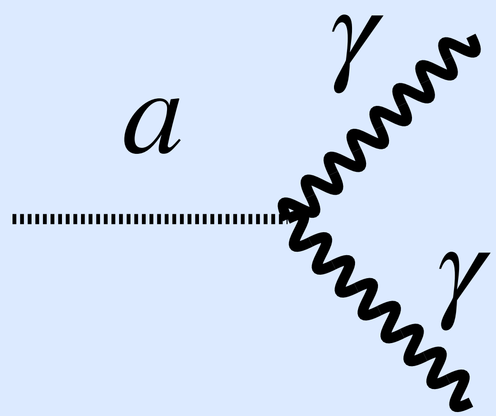

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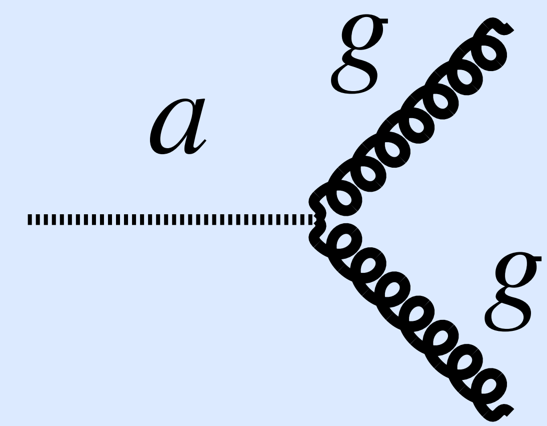

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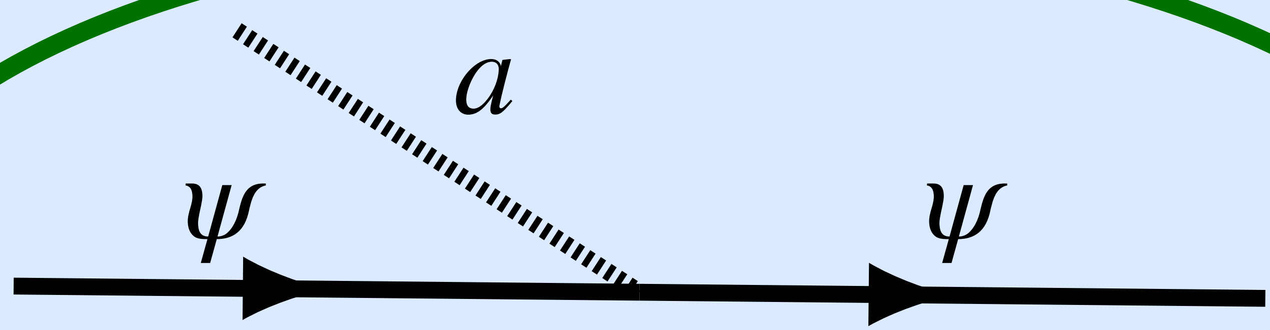

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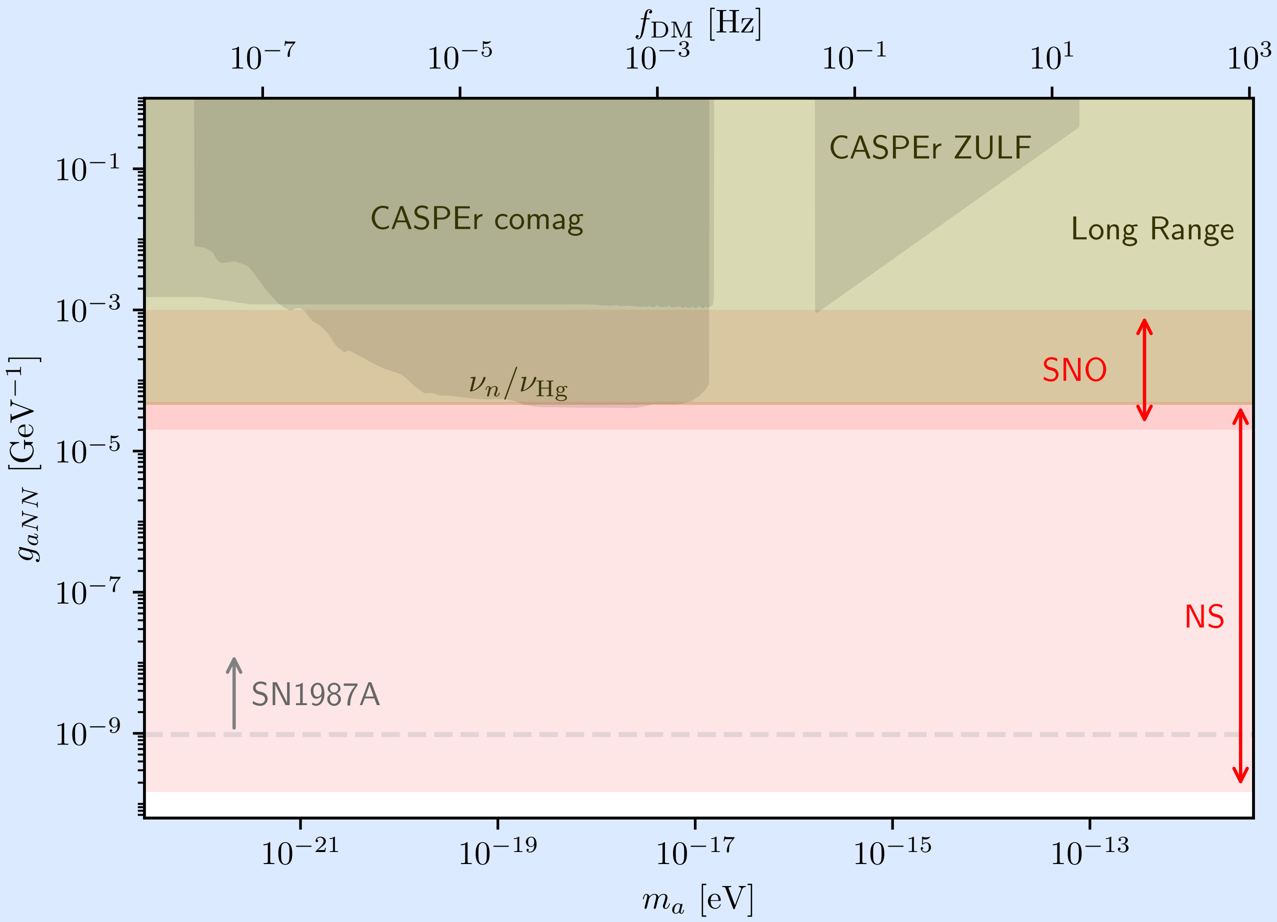
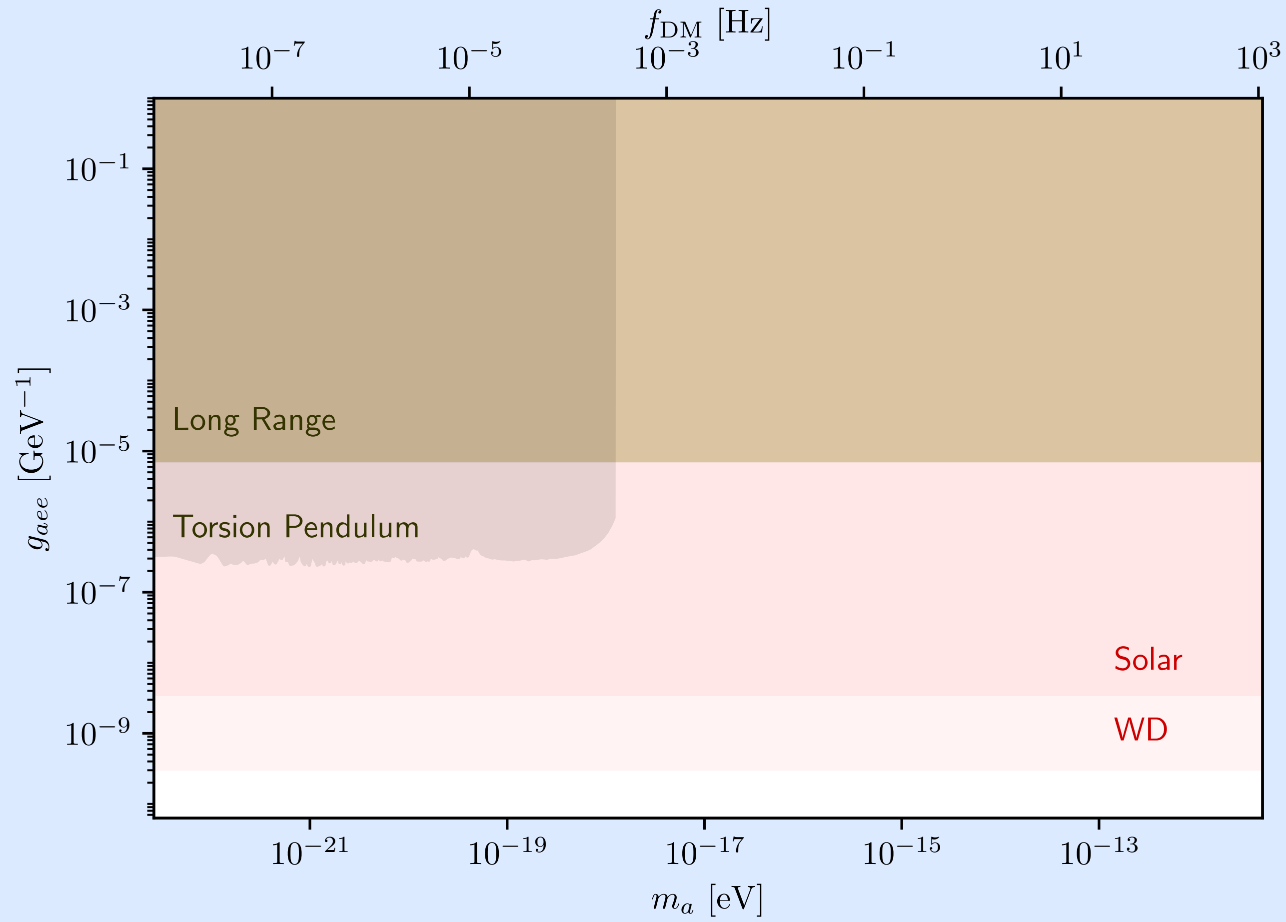
ALP-Fermion parameter spaces (circa late 2019)





ALP-neutron

ALP-electron

ALP-Spin interaction

$$H_{a\psi\psi} = -\,g_{a\psi\psi}\vec{b}_a \cdot \vec{S}_\psi = -\,\vec{b}_{a-\psi} \cdot \vec{S}_\psi$$

$$\vec{b}_{a-\psi} = g_{a\psi\psi}\sqrt{2\rho_a}\cos(m_a t) \cdot \vec{v}_{a-\psi}$$ [astro-ph/9501042]

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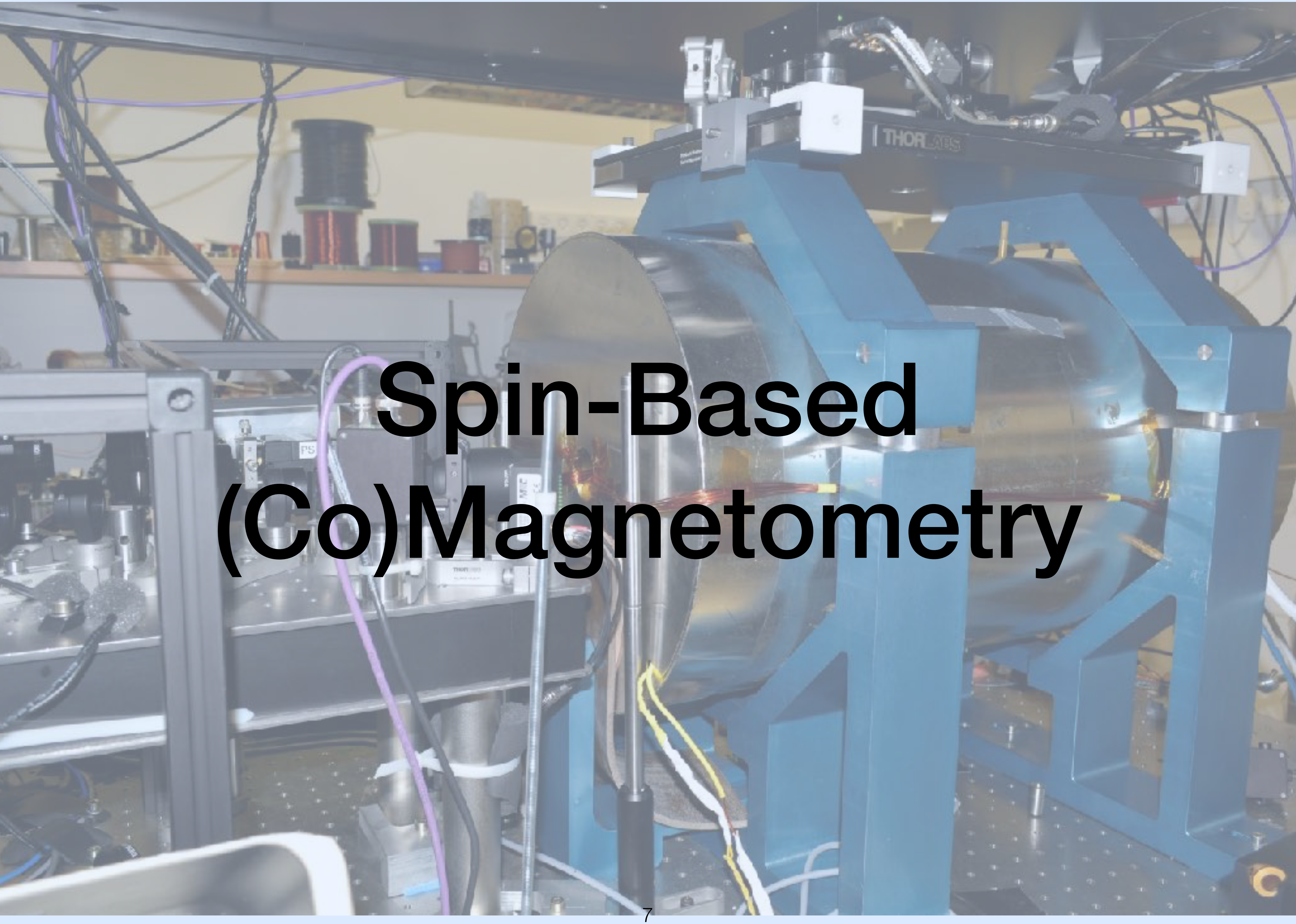
(Hint : $H_{zeeman} = -\gamma \overrightarrow{B}\vec{S}$)



Spin-Based (Co)Magnetometry

Bloch Equations

$$\dot{\vec{S}} =$$

Bloch Equations

* To leading order in important stuff

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Bloch Equations

- To leading order in important stuff

$$\dot{\vec{S}} = \gamma\left(\vec{B} + \frac{\vec{b}}{\gamma}\right) \times \vec{S}$$

Torque
(generates transverse from longitudinal)

Bloch Equations

* To leading order in important stuff

$$\dot{\vec{S}} = \gamma\left(\vec{B} + \frac{\vec{b}}{\gamma}\right) \times \vec{S} - \Gamma\vec{S}$$

Torque
(generates transverse from longitudinal)

Decaying excitations
(causes stabilization)

Bloch Equations

* To leading order in important stuff

Creating macroscopic polarization

(generates a non-trivial steady state solution)

$$\dot{\vec{S}} = \gamma\left(\vec{B} + \frac{\vec{b}}{\gamma}\right)\times\vec{S} - \Gamma\vec{S} + R\hat{z}$$

Torque

(generates transverse from longitudinal)

Decaying excitations

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Transverse EOMs

We usually assume $\dot{S}_z = 0$ (also that $|\vec{S}| \approx |S_z|$),

and care only about $S_\perp = S_x + iS_y$

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The transverse EOMs become

$$\dot{\vec{S}} = \gamma\left(\overrightarrow{B} + \frac{\vec{b}}{\gamma}\right) \times \vec{S} \; - \; \Gamma\vec{S} \; + \; R\hat{z}$$

$$\Downarrow$$

$$\dot{S}_\perp = i\gamma\left(B_z + \frac{b_z}{\gamma}\right) S_\perp - i\gamma\left(B_\perp + \frac{b_\perp}{\gamma}\right) S_z \; - \; \Gamma S_\perp$$

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Solving the EOMs

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$$S_\perp(\omega = m_a) = \frac{b_\perp + \gamma B_\perp(\omega = m_a)}{(\gamma B_z - m_a) + i\Gamma} S_z$$

The Result

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\mathrm{eff}}$$

The Result

The transverse spin

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\text{eff}}$$

The transverse spin:
Everything is encoded in the spin projections in the directions perpendicular to the pumping term.

The Result

The transverse spin

Signal

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\text{eff}}$$

Signal:
The thing we want to measure that an ALP generates

The Result

The transverse spin

Signal

Transverse magnetic fields

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\text{eff}}$$

Transverse magnetic fields:

Can either be noise, or (as we will see) the effect of one atom species on the other. Note that it is proportional to γ.

The Result

The transverse spin

Signal

Transverse magnetic fields

Spin in the z direction

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\text{eff}}$$

Spin in the z direction

Main demand: Don't be tiny

The Result

The transverse spin

Signal

Transverse magnetic fields

Spin in the z direction

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\text{eff}}$$

Technical Noise

Technical Noise:

In addition to the magnetic field noise, whatever system is used for readout introduces noise that does not "care" whether the spins are on or off resonant.

The Result

The transverse spin

Signal

Transverse magnetic fields

Spin in the z direction

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\text{eff}}$$

ALP mass

Technical Noise

ALP Masses

Our experiments can only probe ultralight ALPs. Until now we focused mostly on things that are <neV, but in principle, can go as high as meVs.

The Result

The transverse spin

Signal

Transverse magnetic fields

Spin in the z direction

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\text{eff}}$$

Resonance Frequency

ALP mass

Technical Noise

Resonance Frequency

Determined mostly by external magnetic fields (which we can control with coils). Note that it is proportional to γ.

The Result

$$S_\perp = \frac{b_\perp + \gamma B_\perp}{i\Gamma + (\gamma B_z - m_a)} S_z + \delta S_{\text{eff}}$$

- $S_\perp$: The transverse spin
- $b_\perp$: Signal
- $\gamma B_\perp$: Transverse magnetic fields
- S_z: Spin in the z direction
- $i\Gamma$: Decoherence Rate
- γB_z: Resonance Frequency
- m_a: ALP mass
- δS_{eff}: Technical Noise

Decoherence Rate:

The decoherence rate determines the width of the atomic response to ALPs. Varies by 10 orders of magnitude depending on the system at hand (in most systems here it is Hz-kHzs). A small decoherence rate can be problematic due to slow response time.

(Co)magnetometer
Ingredients List

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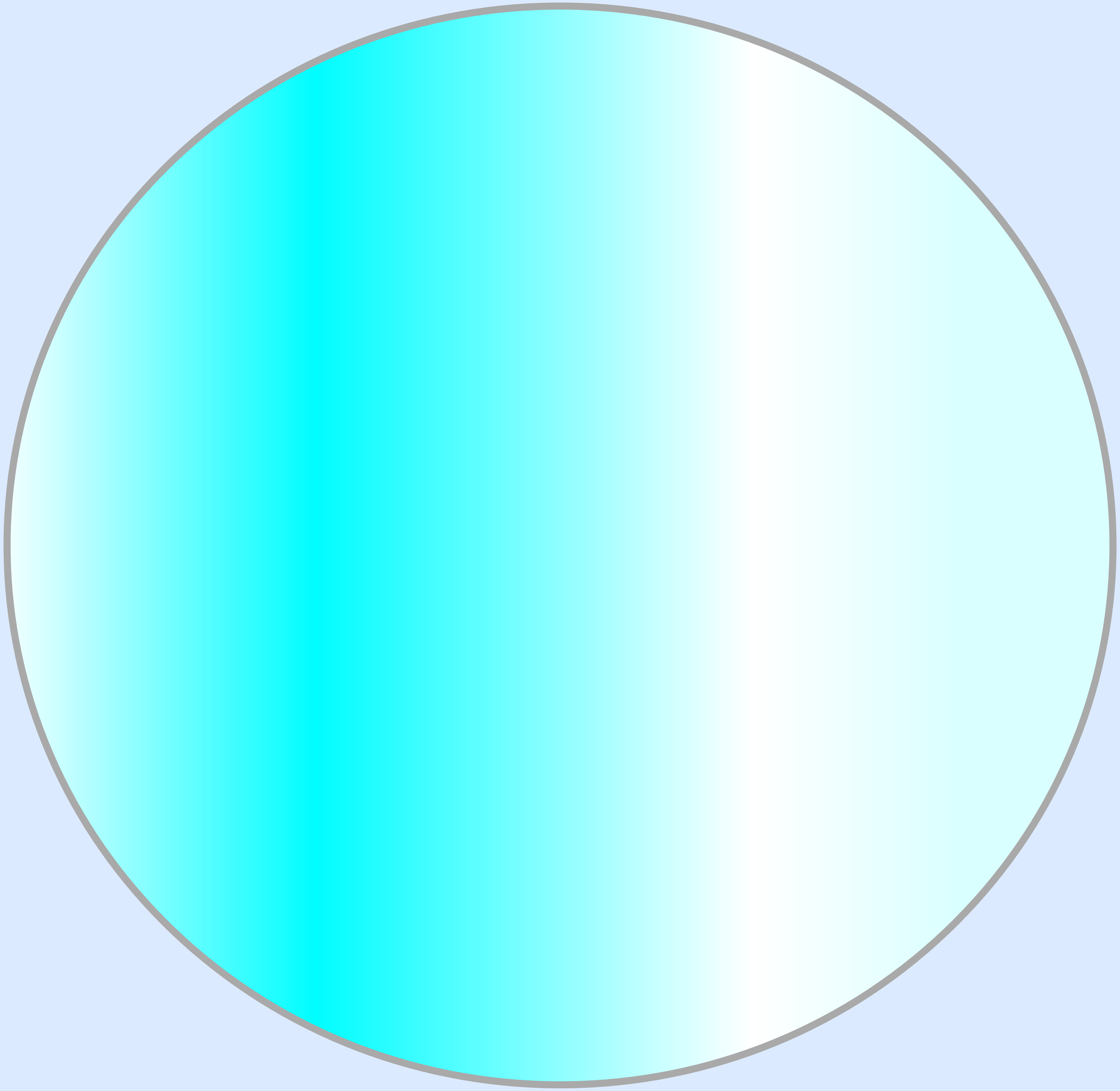
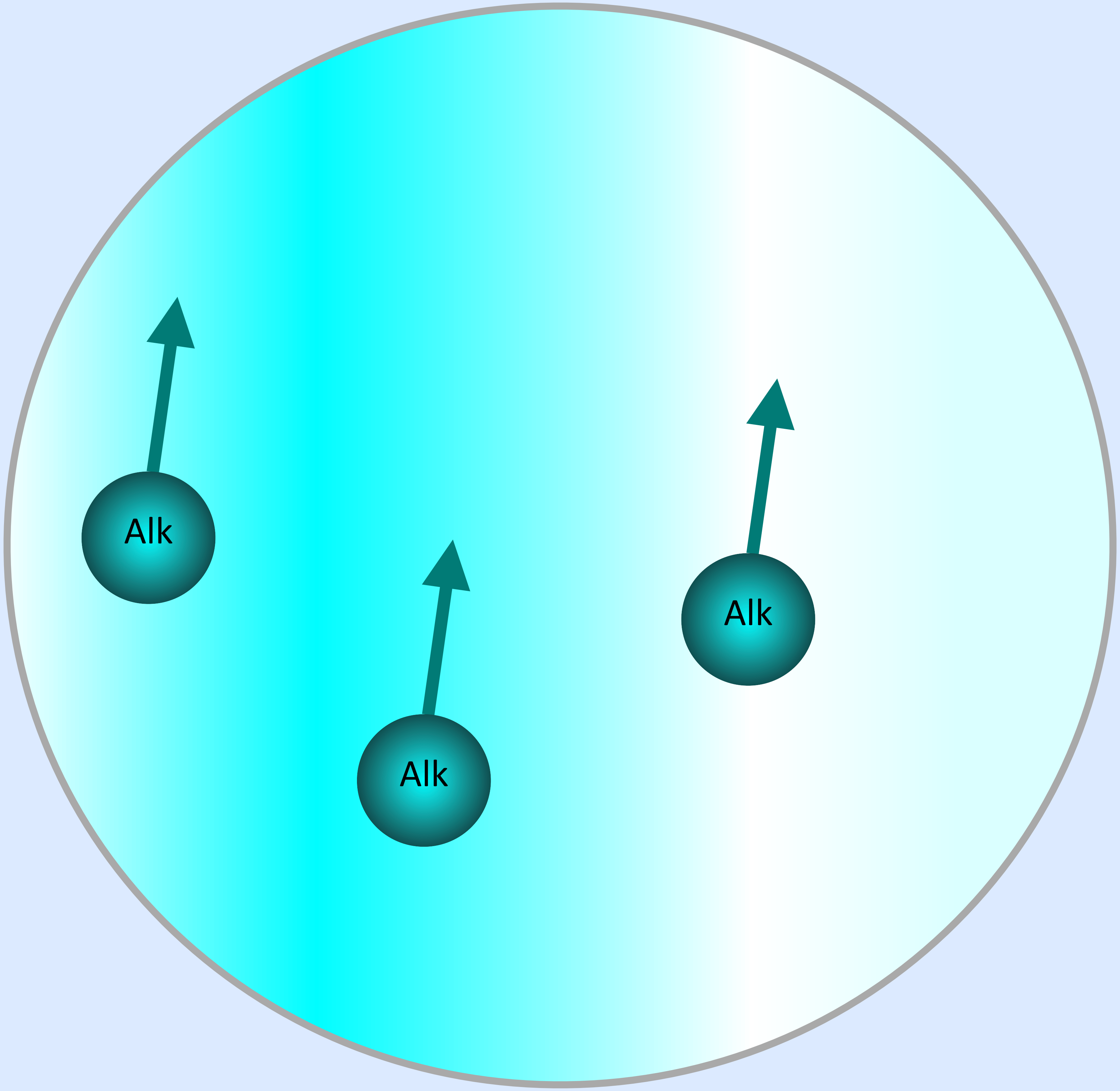


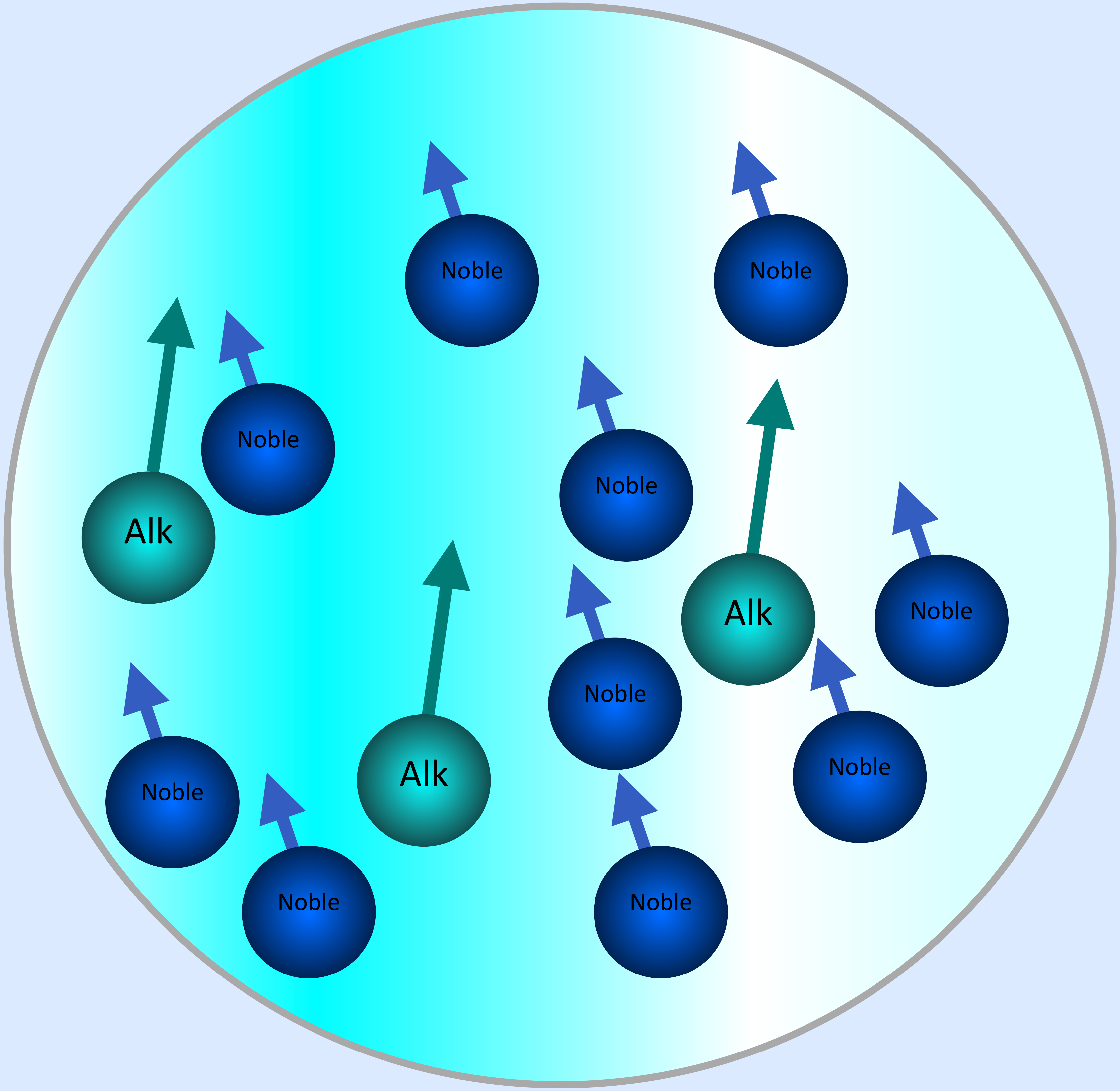
Glass Cell



(Co)magnetometer
Ingredients List

Glass Cell

Alkali Vapor

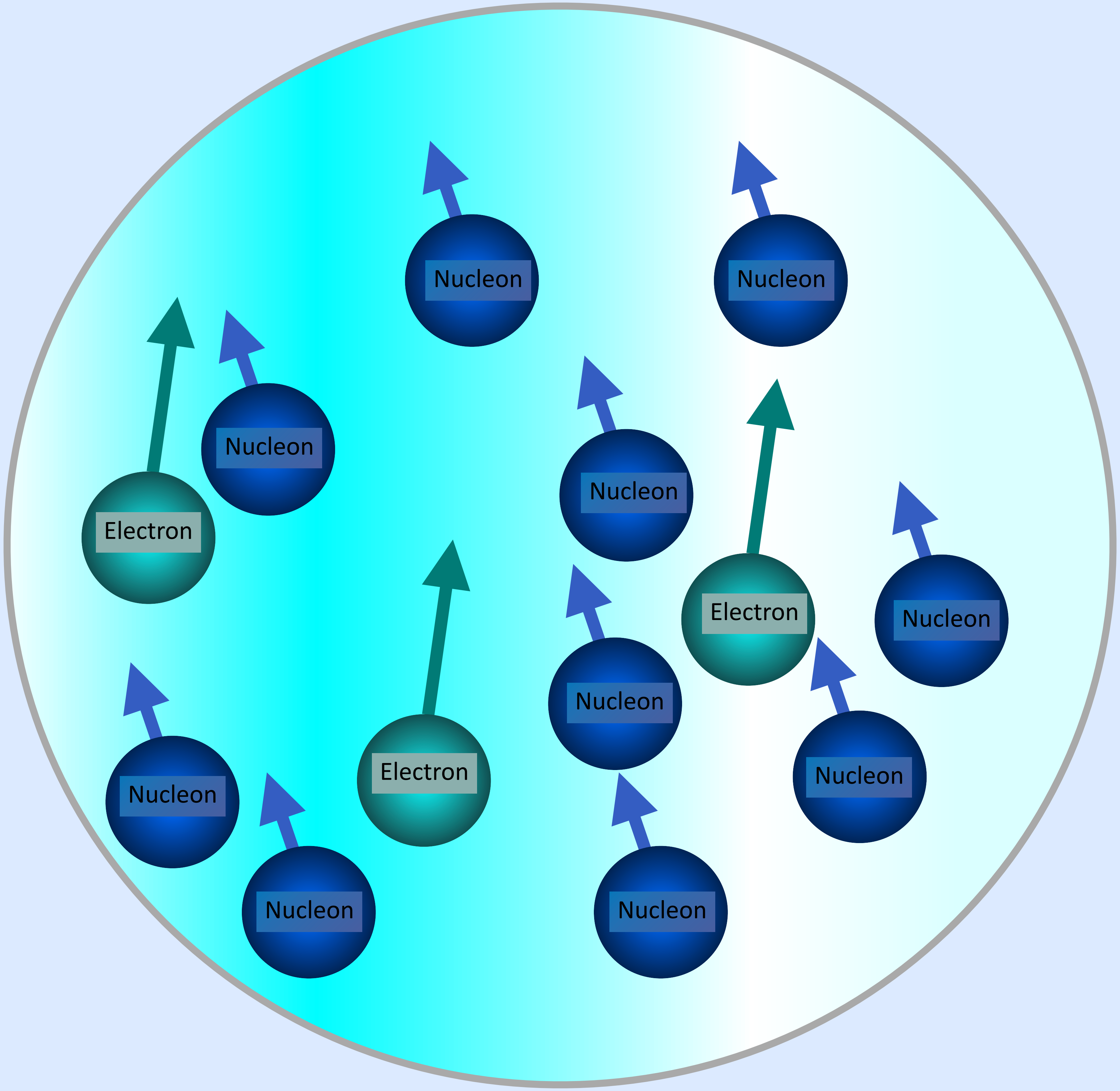


(Co)magnetometer
Ingredients List

Glass Cell

Alkali Vapor

Noble Gas



(Co)magnetometer
Ingredients List

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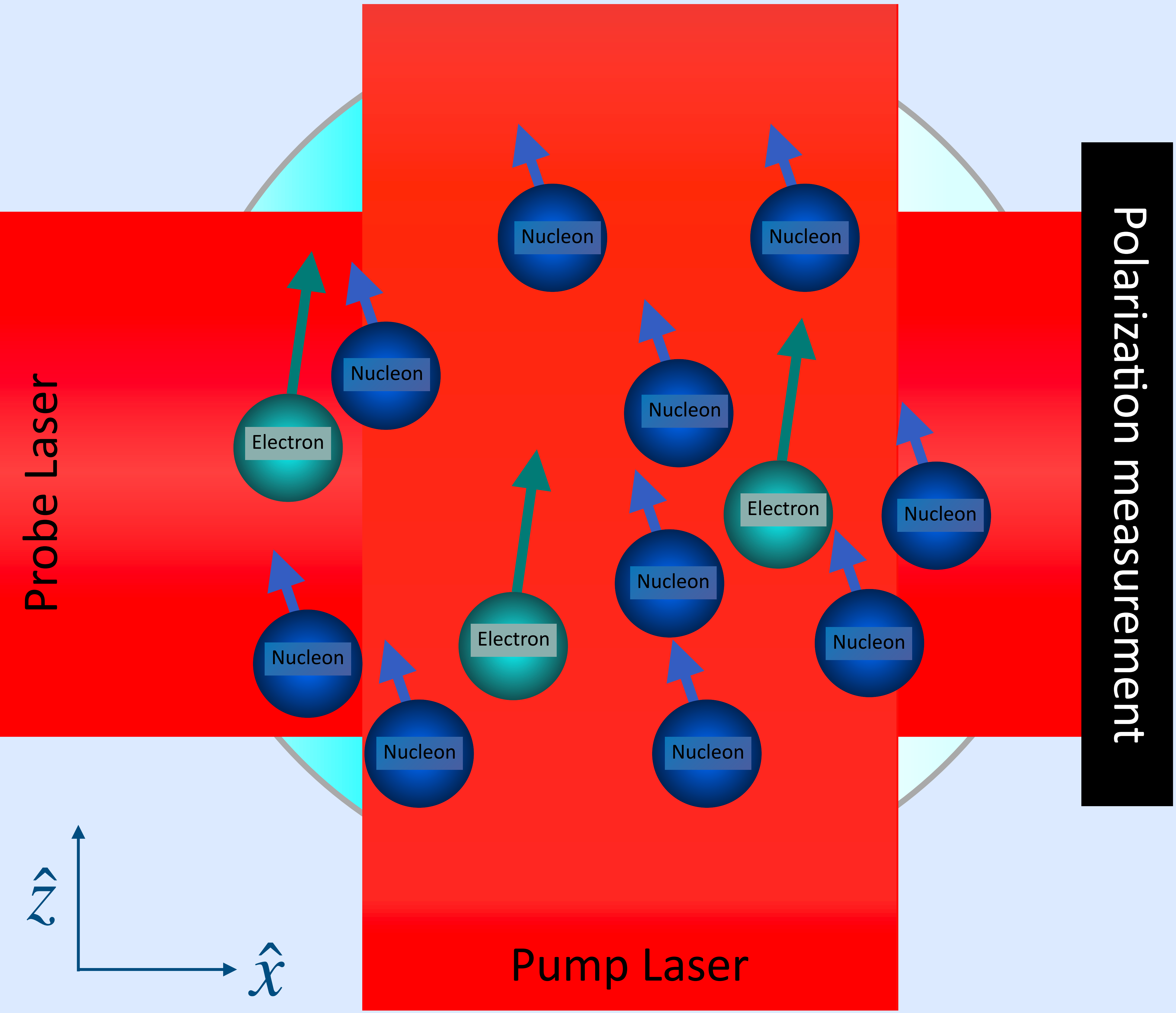
Noble Gas



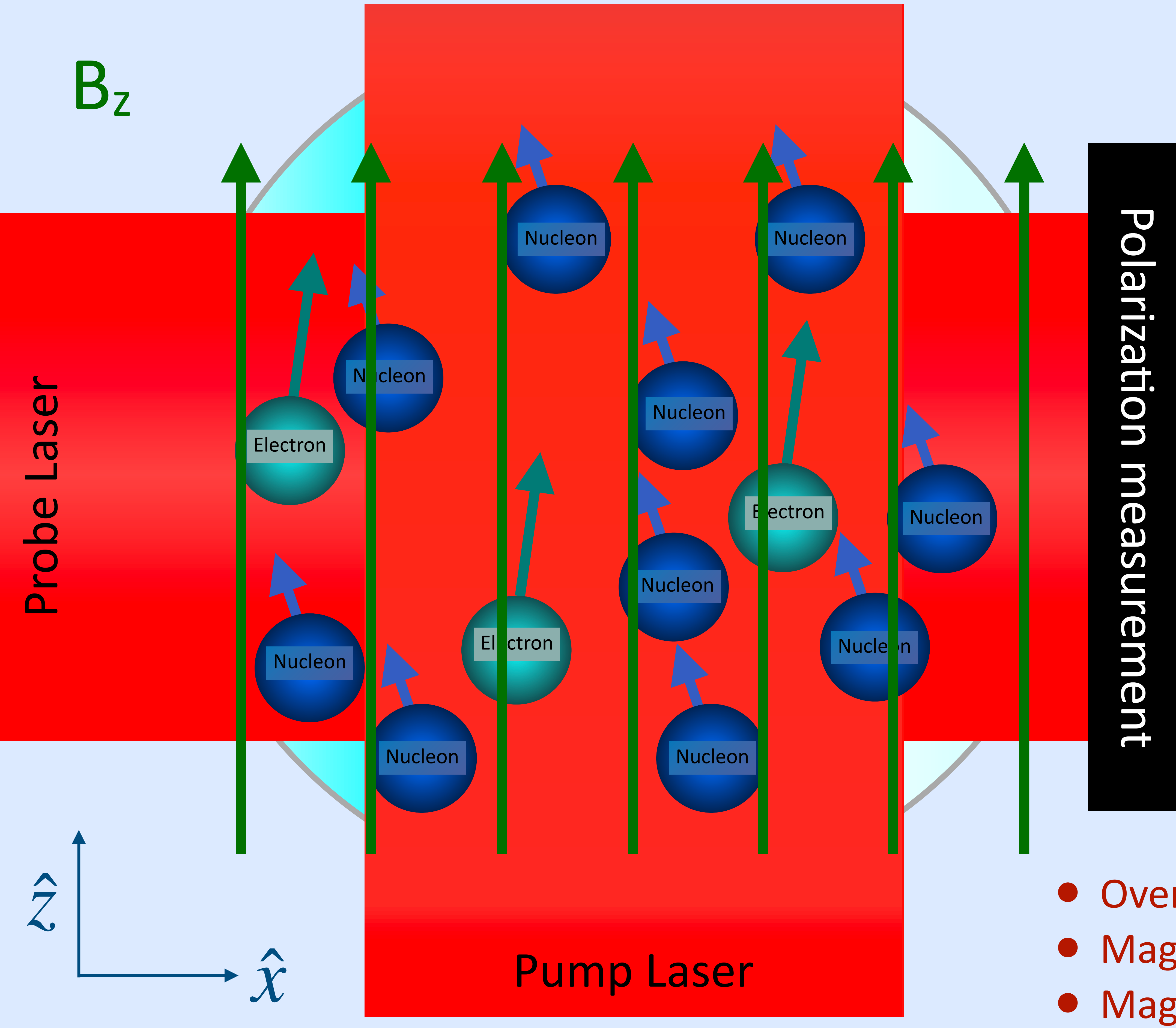
(Co)magnetometer
Ingredients List

Glass Cell

Alkali Vapor

Noble Gas

Lasers



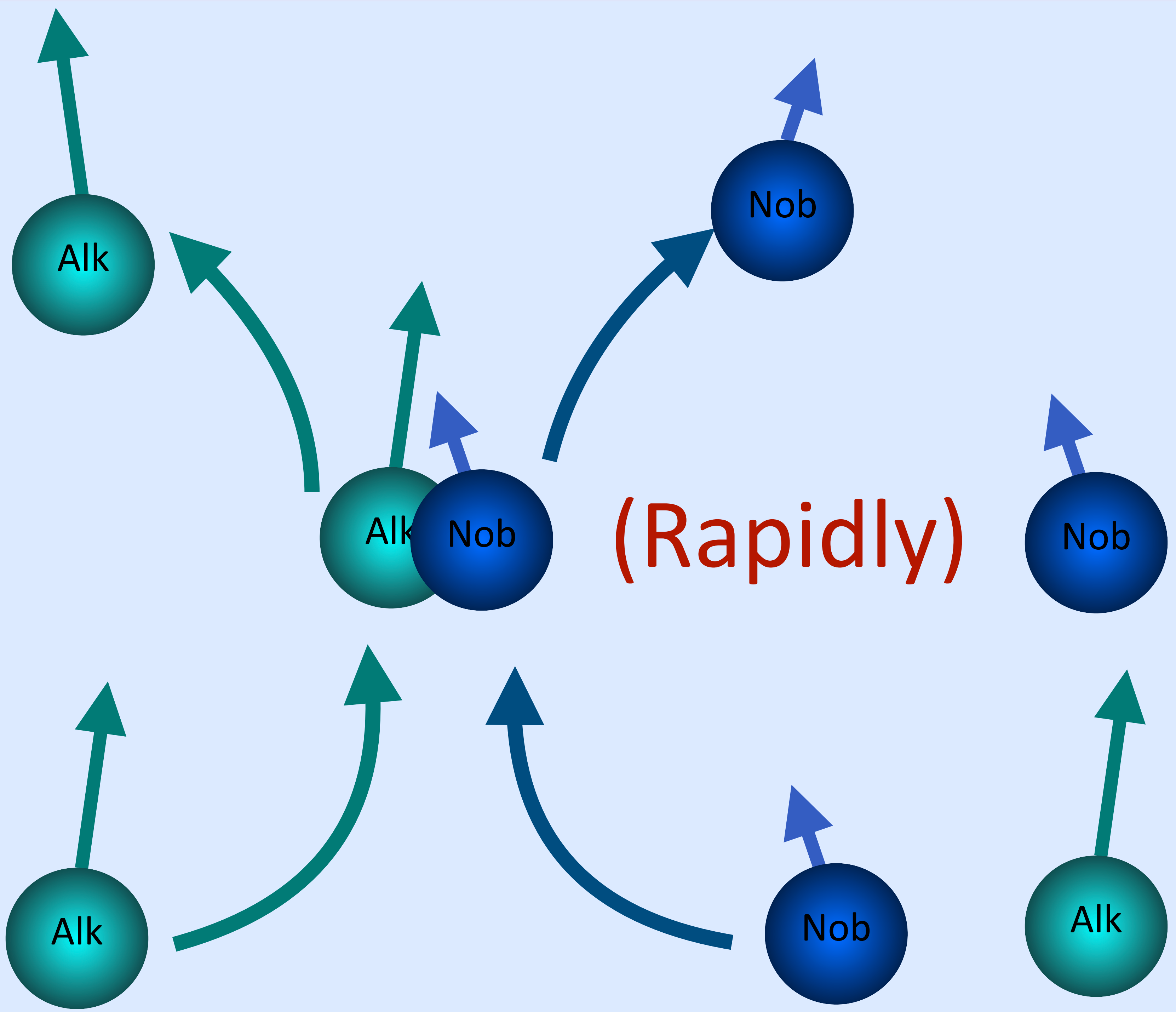
(Co)magnetometer Ingredients List

- Glass Cell
- Alkali Vapor
- Noble Gas
- Lasers

<u>Misc:</u>

- Oven
- Magnetic Shields
- Magnetic Coils
- Optical Components

Alk-Nob Spin Exchange



Magnetic field from (quantum) point-like interactions

$B_{\text{induced on Alk}} \propto S_{\text{Nob}}$

$B_{\text{induced on Nob}} \propto S_{\text{Alk}}$

Current Summary

- Introduction:
  - Axions and ALPs
  - Spin-Based (Co)magnetometers
- Established Magnetometry Techniques for DM Research
- …

ALPs create a magnetic-like field that can be measured by spin-based magnetometers.

“Compensation Point” Comagnetometer

[2020 JHEP: IMB, Hochberg, Kuflik, Volansky]

Response to Magnetic Noise

Response to Magnetic Noise

$$S_{\text{Alk}}(\omega = m_a) = \frac{\text{signal} + \gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}}{(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a) + i\Gamma_{\text{Alk}}}$$

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(ignoring backreaction of Alkali on Noble)

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$$\frac{\partial S_{\text{Alk}}}{\partial B_{\perp,\text{noise}}} = \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}}}{(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a) + i\Gamma_{\text{Alk}}} \left(1 + \frac{2\gamma_{\text{Nob}} \lambda M_{\text{Nob}}}{(\gamma_{\text{Nob}} B_{\text{z,Nob}} - m_a) + i\Gamma_{\text{Nob}}} \right)$$

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For $\Gamma_{\text{Nob}} \approx 0, m_a \approx 0,$ $B_{\text{z,Nob}}$ is adjustable such that $\partial_{B_{\perp,\text{noise}}} S_{\text{Alk}} = 0$

The Compensation Point

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At the compensation point, any magnetic noise (at low frequencies) has no effect on the alkali spins!

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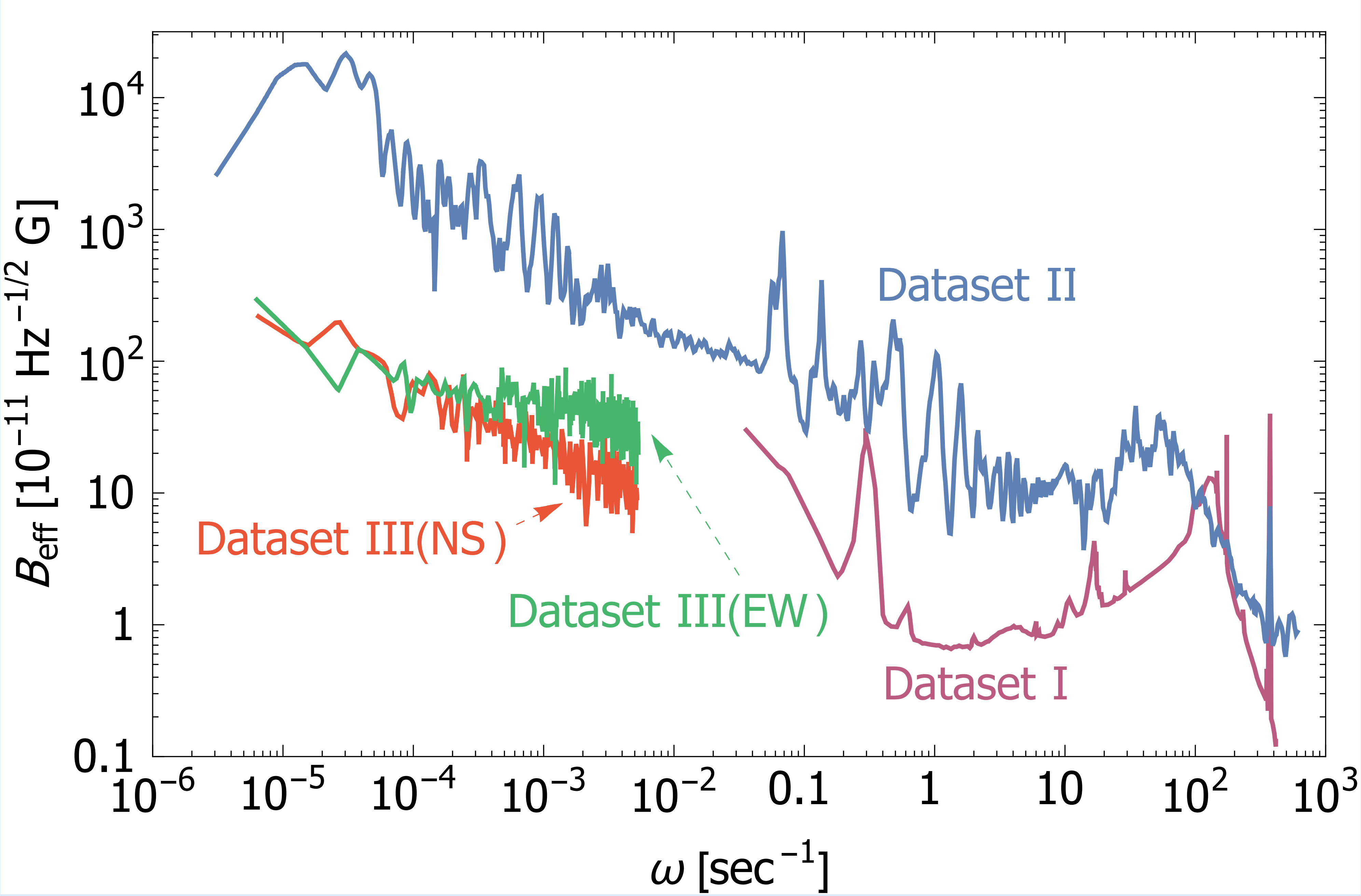
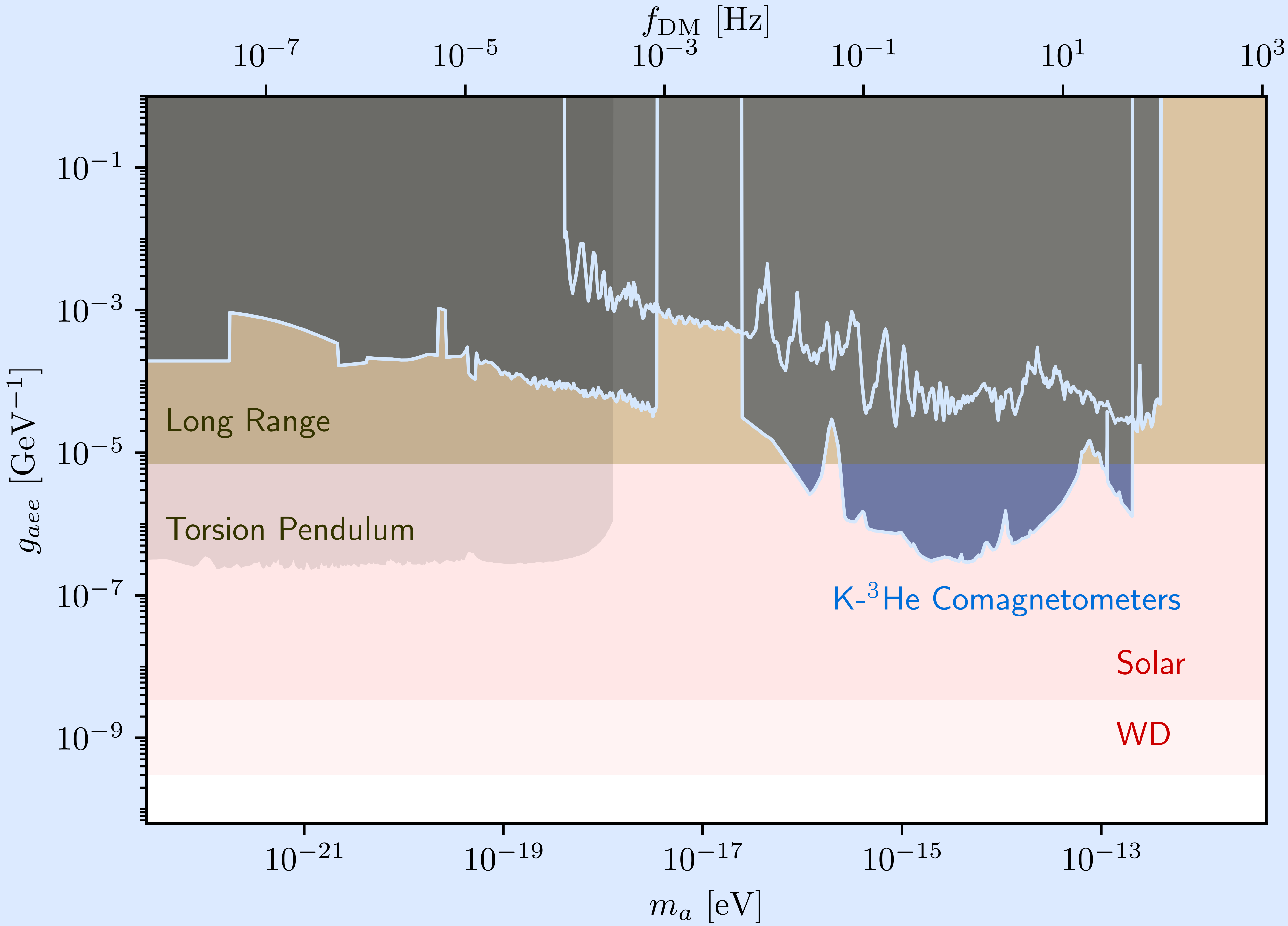
Additionally, the two species are “(near) in resonance”, allowing for a fast response of the system to sudden changes.

Existing Data



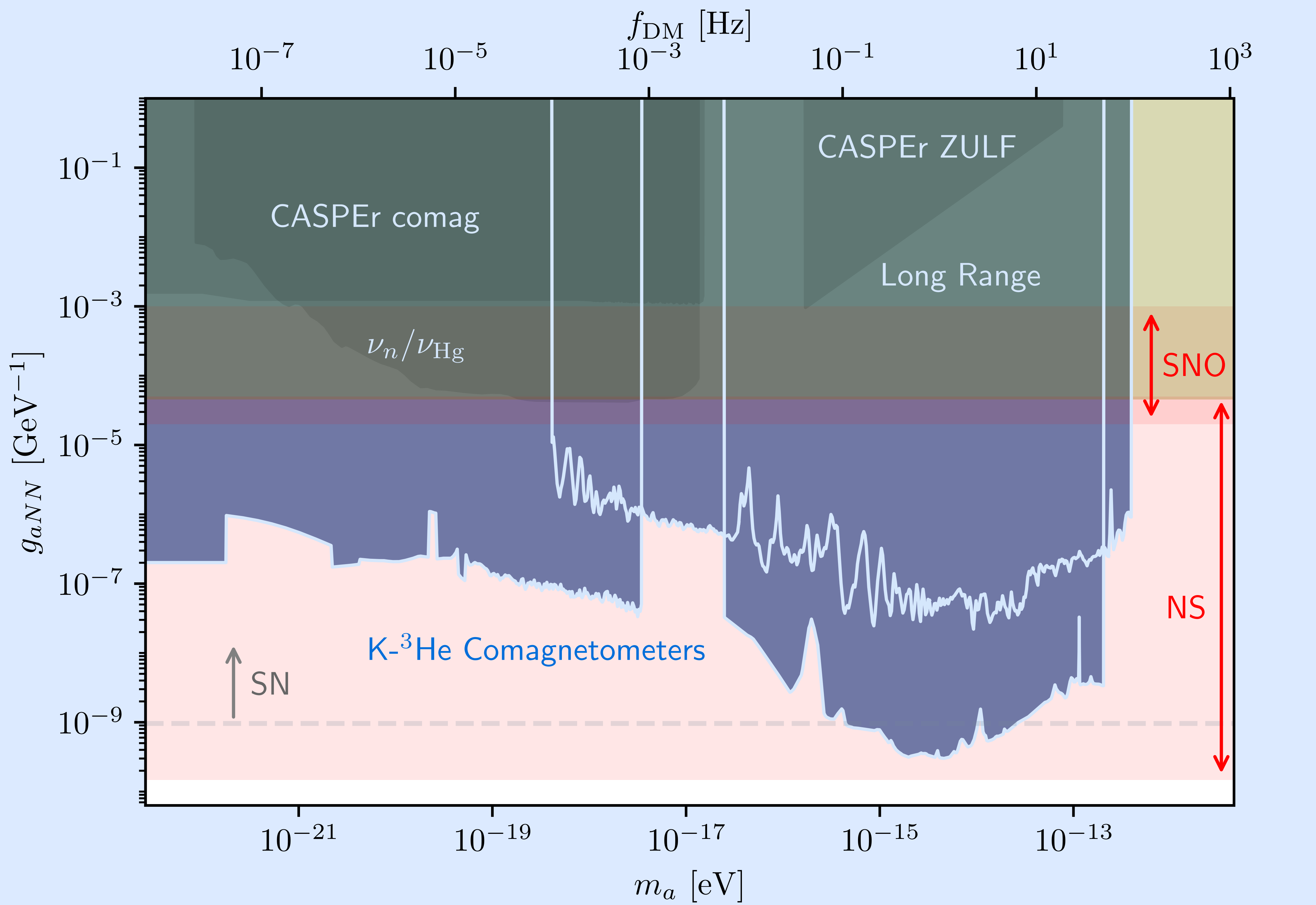
[Gergoios Vasilakis Dissertation 2011], [Justin M. Brown Dissertation 2011], [Thomas W. Kornack Dissertation 2005]

Results (e)



[**Y. Hochberg, E. Kuflik, T. Volansky, IMB 1907.03767.** W. A. Terrano, *et al*.:1508.02463, LUX Collaboration:1704.02297, M. M. M Bertolami, *et al*. :1406.7712, W. A. Terrano, *et al*.: 1902.04246, G. Vasilakis, Dissertation: 2011, J. M. Brown, Dissertation: 2011, T. W. Kornack Dissertation: 2005].

Results (n)



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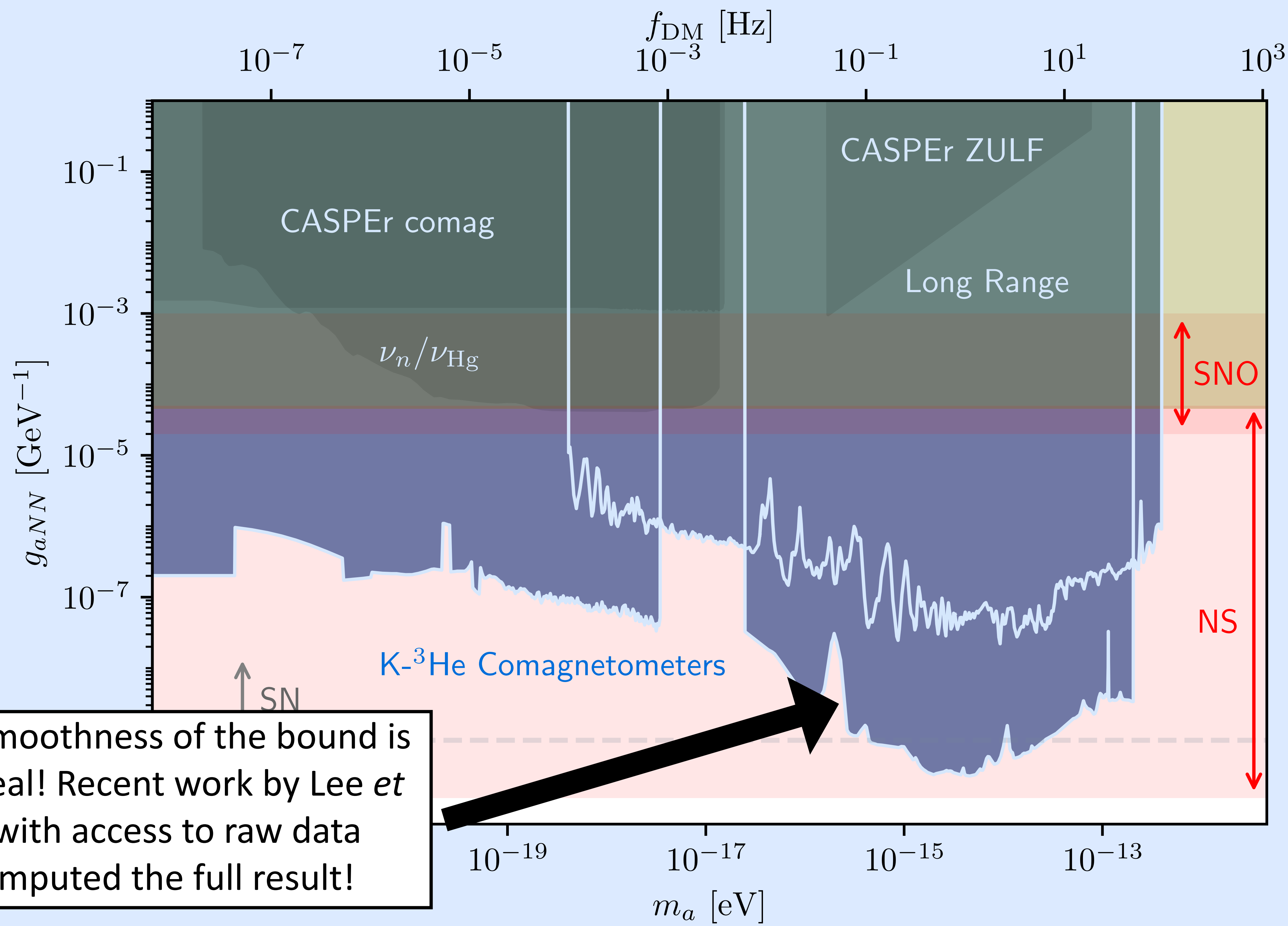

The smoothness of the bound is not real! Recent work by Lee *et al* with access to raw data computed the full result!

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- Electrons are very hard to work with due to their (i) wide bandwidth and (ii) large response to background magnetic fields.
- We need our own experiment!

Noble and **A**lkali **S**pin **D**etectors for **U**ltralight **C**oherent dar**K** matter

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NASDUCK

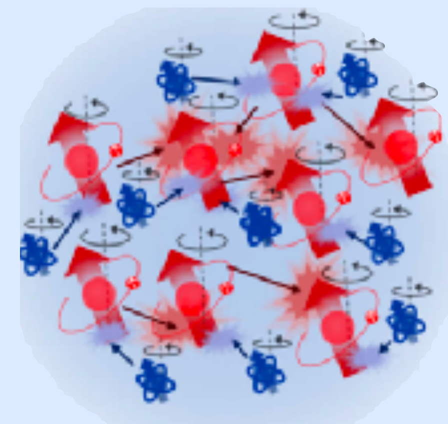
[2022, Science Adv. IMB, Ronen, Shaham, Katz, Volansky, Katz (NASDUCK)],[2023, Nature Comm. IMB, Shaham, Hochberg, Kuflik, Volansky, Katz (NASDUCK)] and [in progress: NASDUCK (incl. IBM)]

Existing and Upcoming Experiments

NASDUCK Floquet

[2022, Science Adv. IMB, Ronen, Shaham, Katz, Volansky, Katz]

NASDUCK SERF



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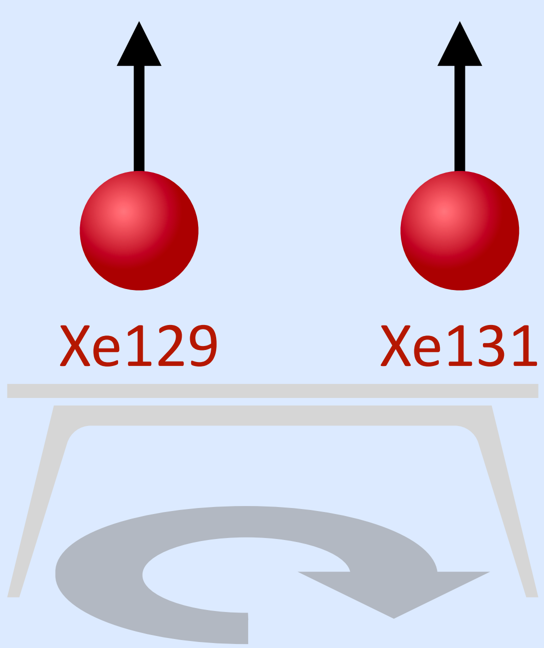
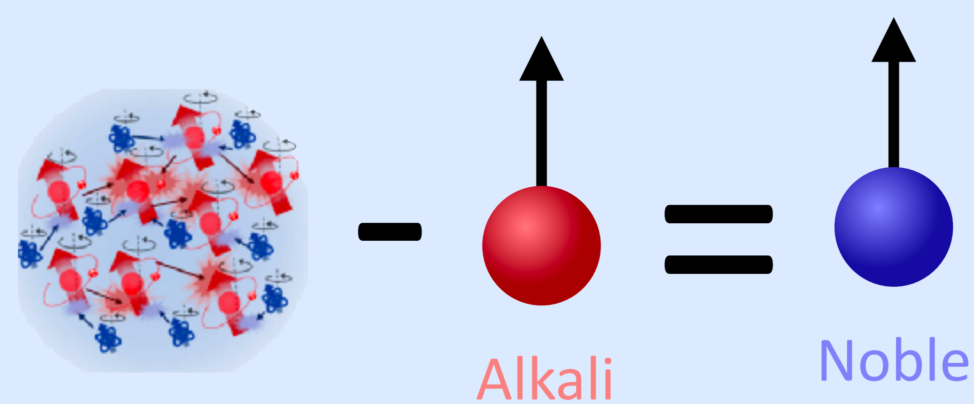


NASDUCK Modulated

(Prototype data exists, redone pre-publication)

NASDUCK Subtracted(?)

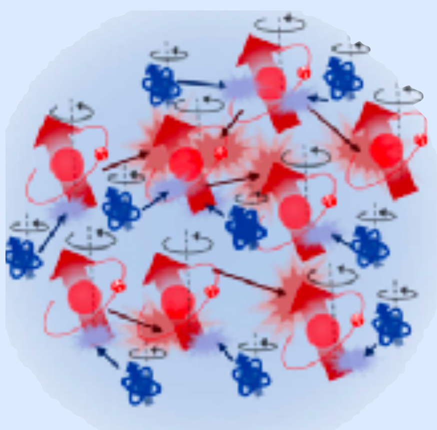


[In progress: NASDUCK (incl. IMB)]

(+in theory stage: NASDUCK HF Compensation)

Existing and Upcoming Experiments

NASDUCK SERF



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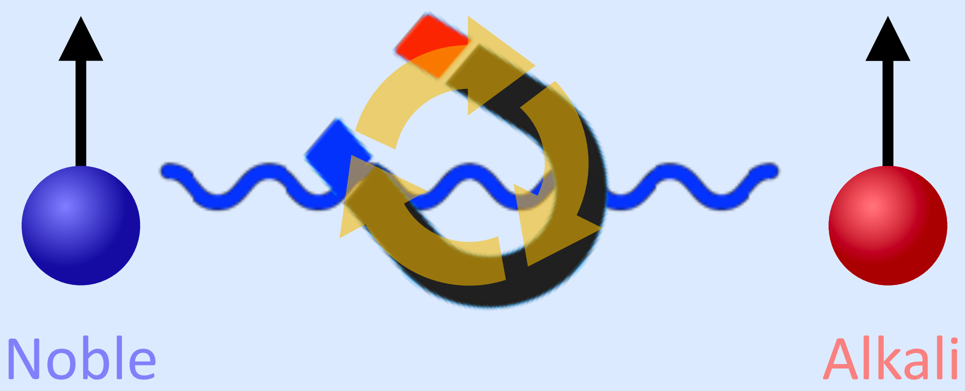

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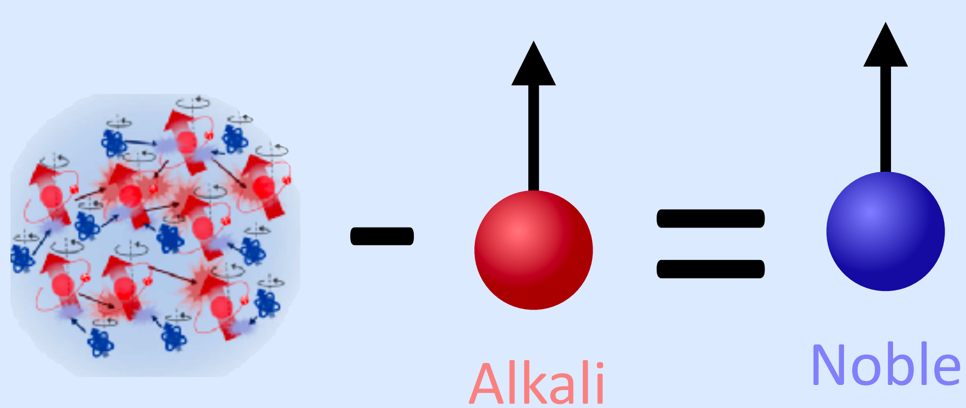

[In progress: NASDUCK (incl. IMB)]

Signal Response of Self-Compensating Comag

- **To leading order in relevancy**

$$S_{\text{Alk}}(\omega = m_a) = \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}}{(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a) + i\Gamma_{\text{Alk}}} =$$

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Tuning $\gamma_{\text{Alk}} B_{z,Alk} \approx m_a \pm \Gamma_{\text{Alk}}$ gives an enhancement of $\frac{m_a}{\Gamma_{\text{Alk}}}$!

NASDUCK SERF

[2023, Nature Comm. IMB, Shaham, Hochberg, Kuflik, Volansky, Katz]

The Briefest of Explanations on “SERF”

plots from: [PRA, 1977, Happer and Tam], though [PRL 2002 Alfred, Lyman, Kornack, Romalis] developed the SERF magnetometer

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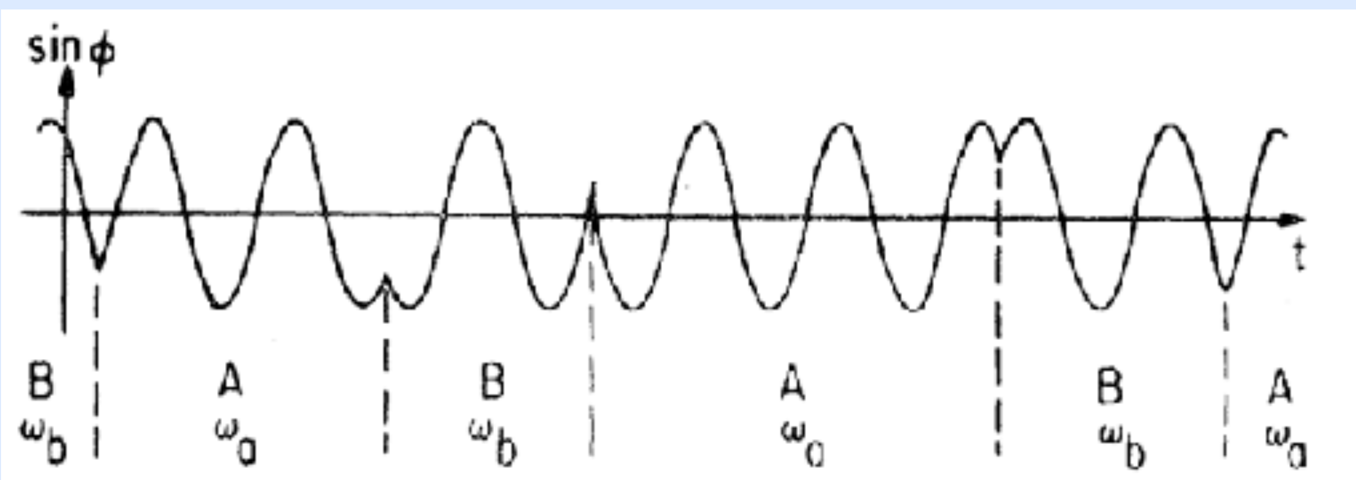

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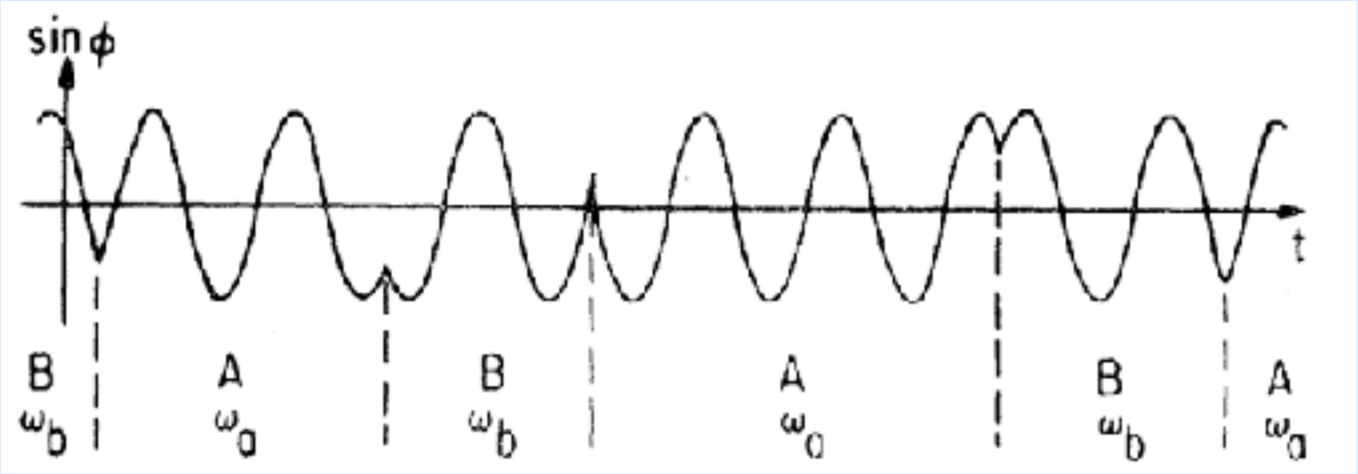

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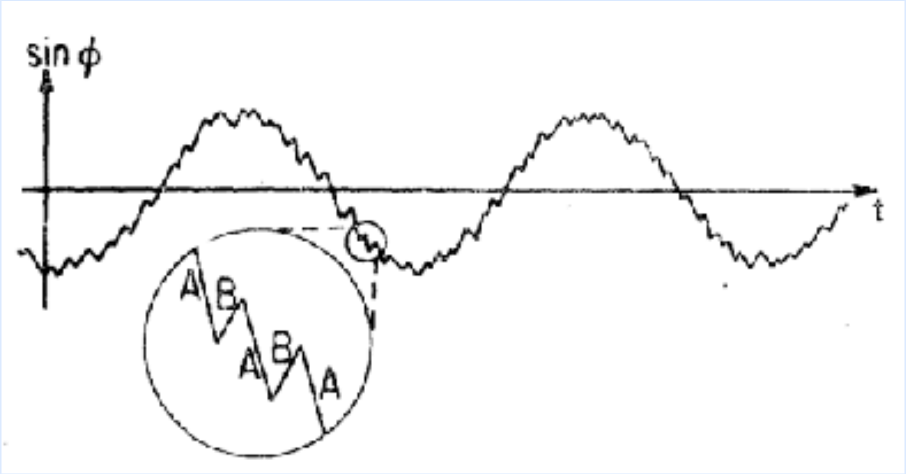

Rapid spin exchange (from low B fields and high densities) causes no relaxation, **Spin Exchange Relaxation Free (SERF)**

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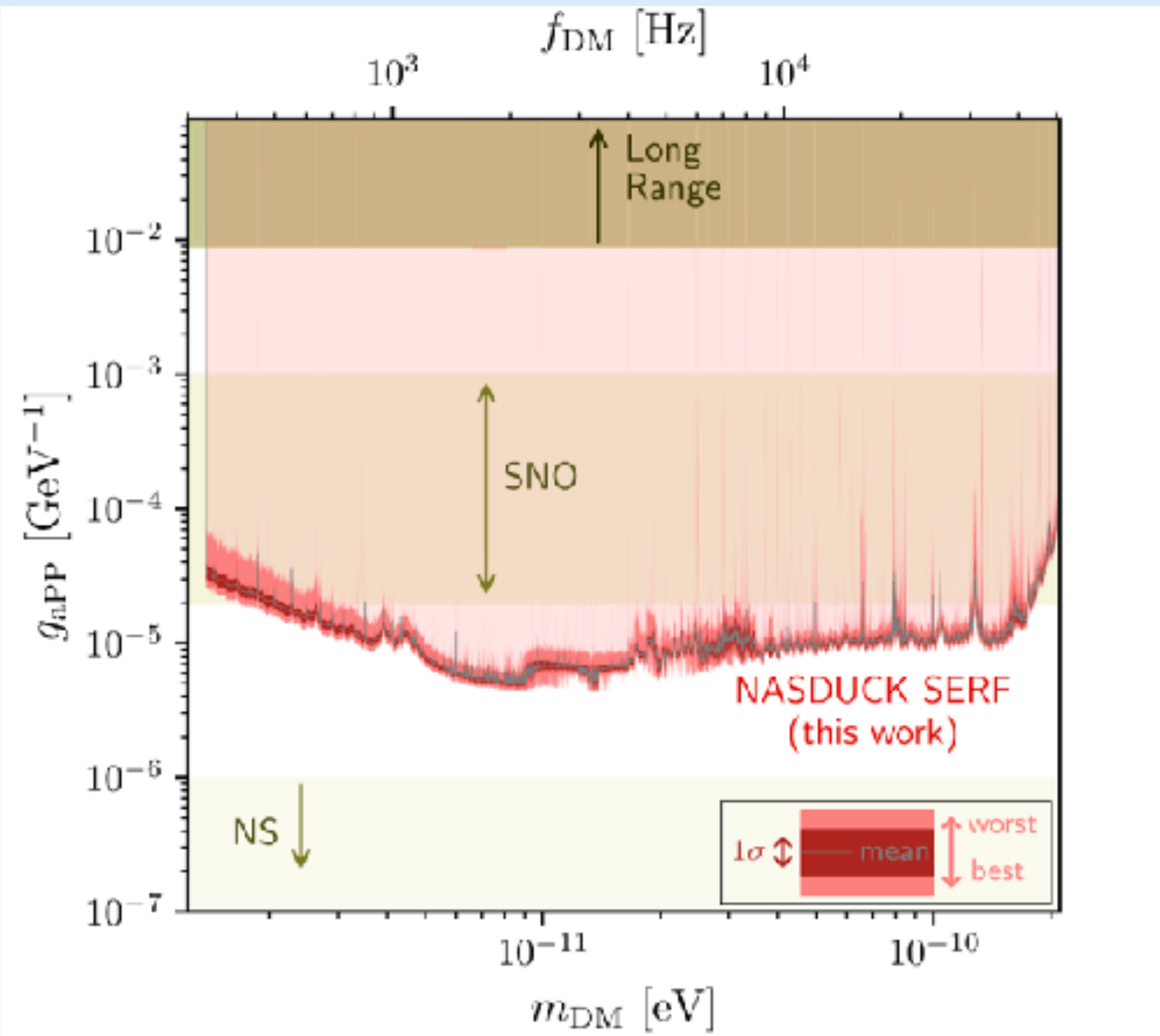
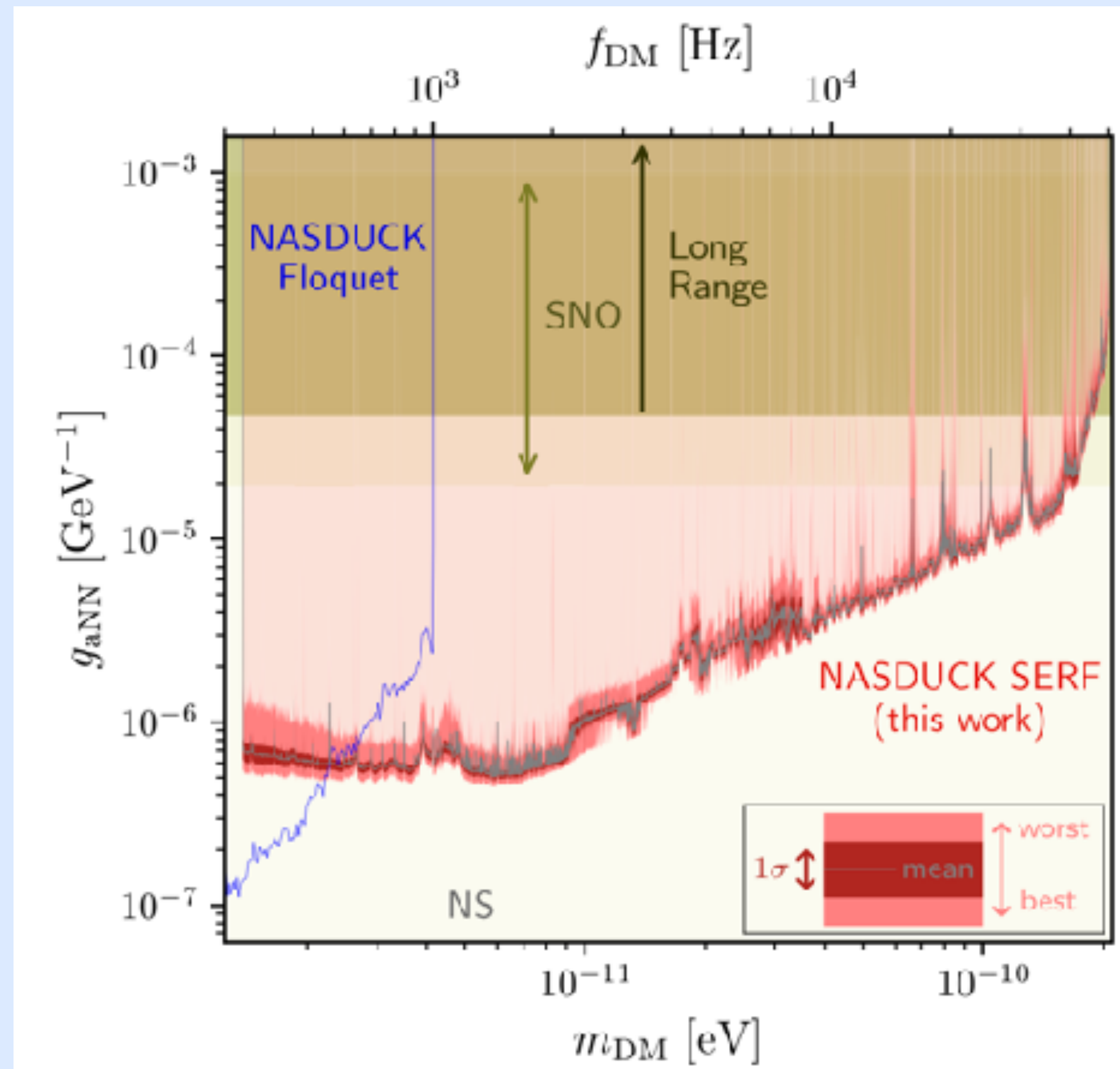
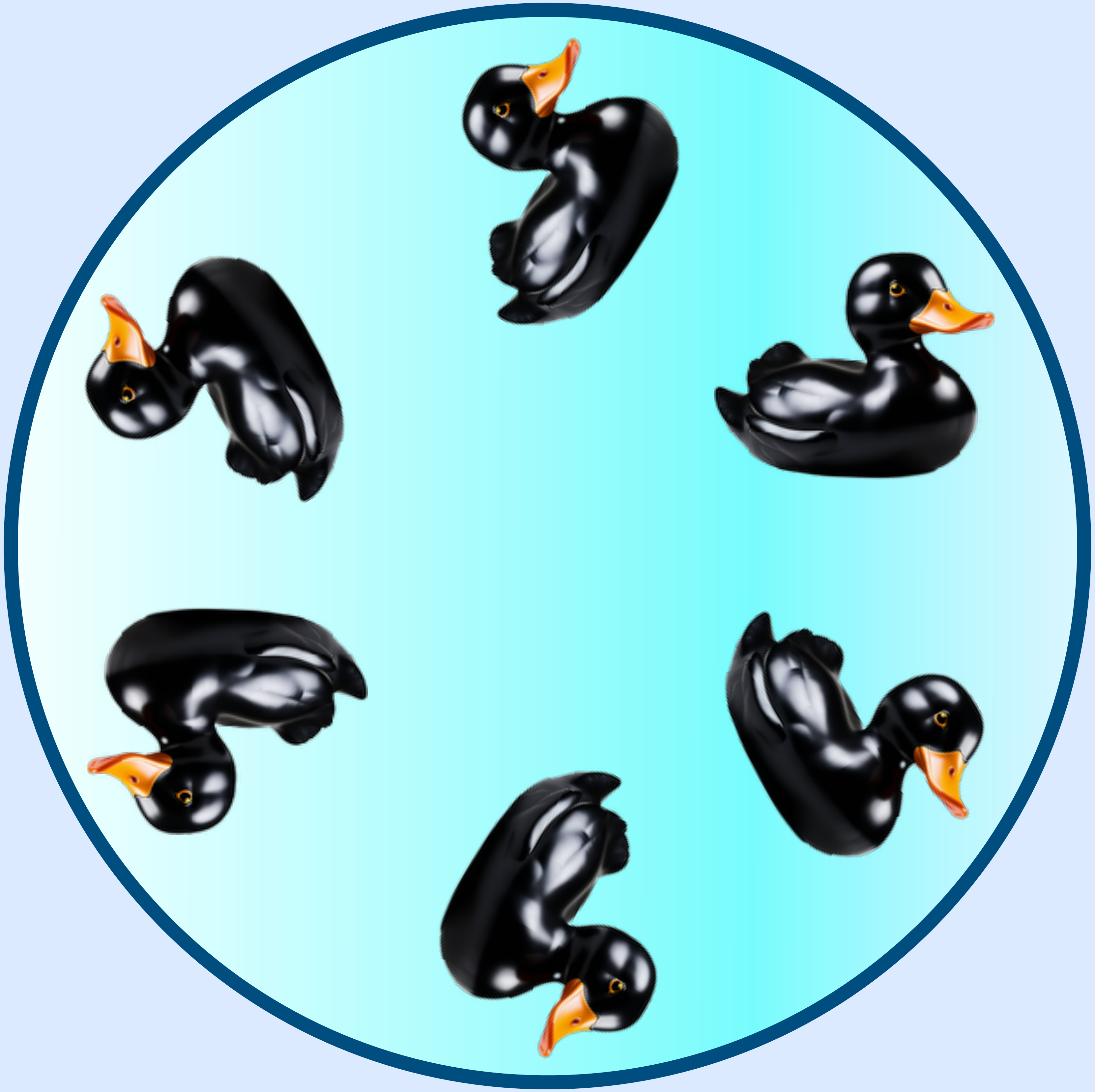
NASDUCK SERF Results







NASDUCK Floquet

[2022, Science Adv. IMB, Ronen, Shaham, Katz, Volansky, Katz]

The Problem at High Frequencies

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$$\text{signal} = \frac{\text{const} \cdot b_{\perp,\text{ALP}-\text{Nob}}}{\left((\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a) + i\Gamma_{\text{Alk}}\right)\left((\gamma_{\text{Nob}} B_{\text{z,Nob}} - m_a) + i\Gamma_{\text{Nob}}\right)}$$

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Alkali response

Noble response

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The noble gas for large B fields (large frequencies) is off resonant!

Floquet Fields (Math Slide)

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$$B_z = B_{z,0} + B_F \cos(\omega_F t)$$

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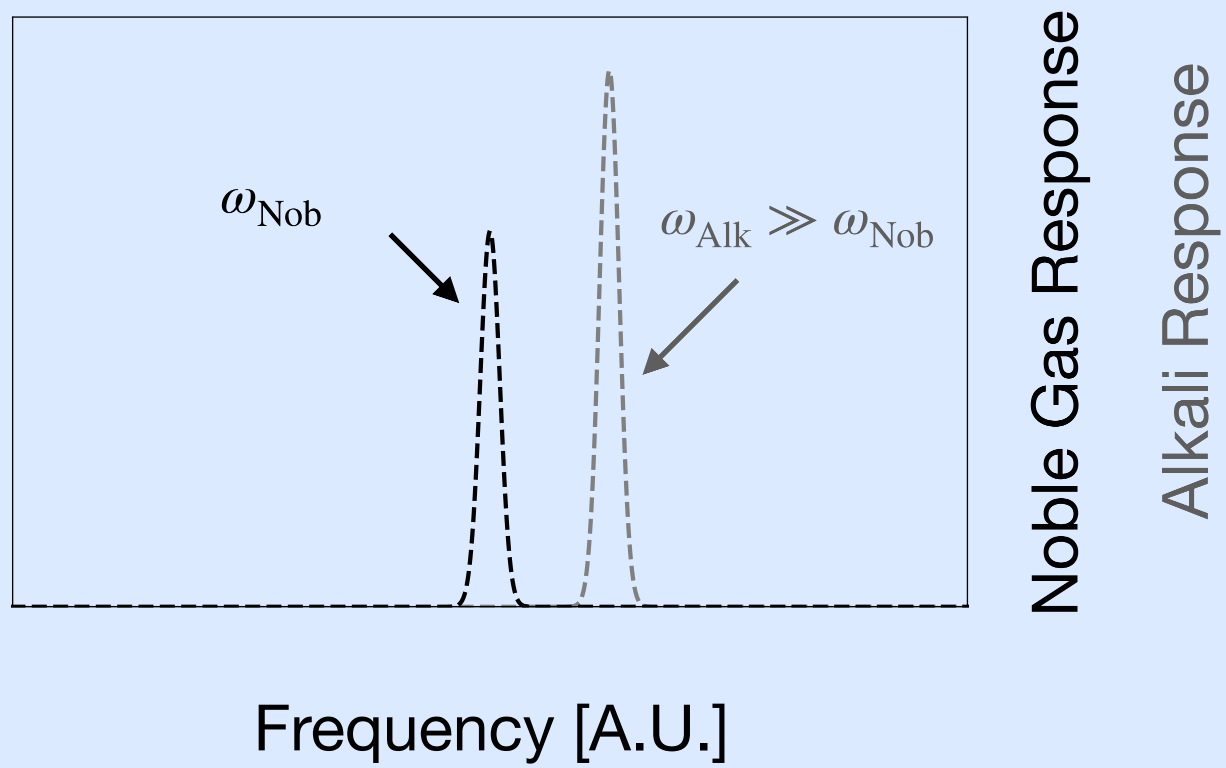
So that for $m_a = \gamma_{\text{Nob}} B_{\text{z,Nob,0}}$, we can now have both the species in resonance!

Floquet Fields (Illustration Slide)

* Plots are **not** to scale



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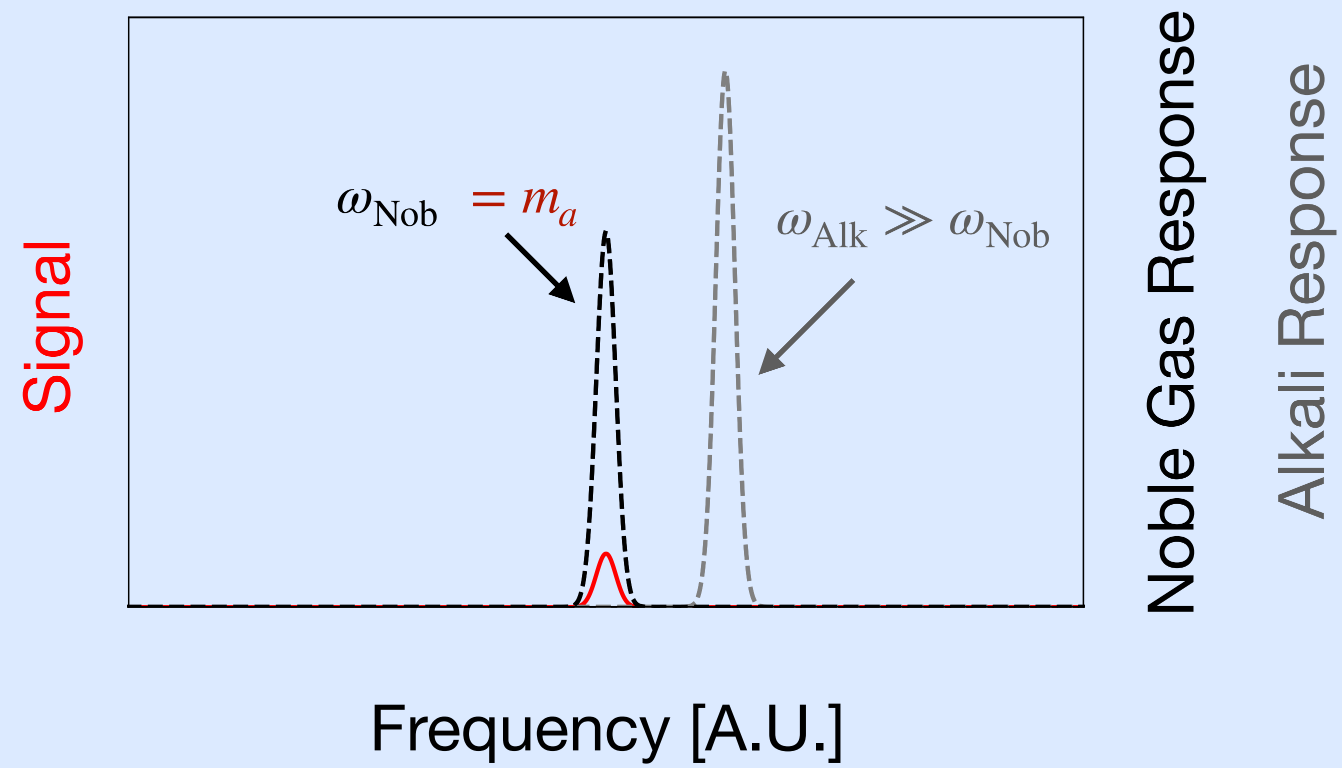

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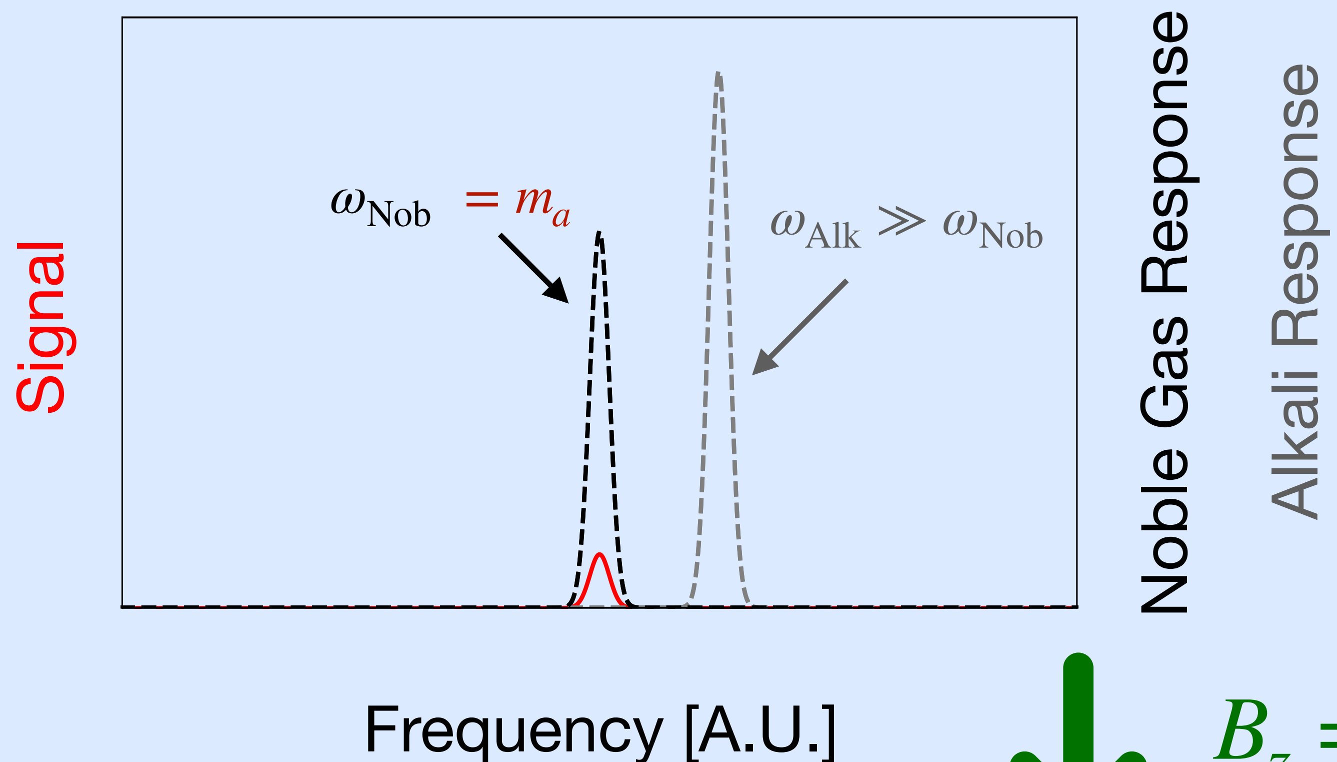

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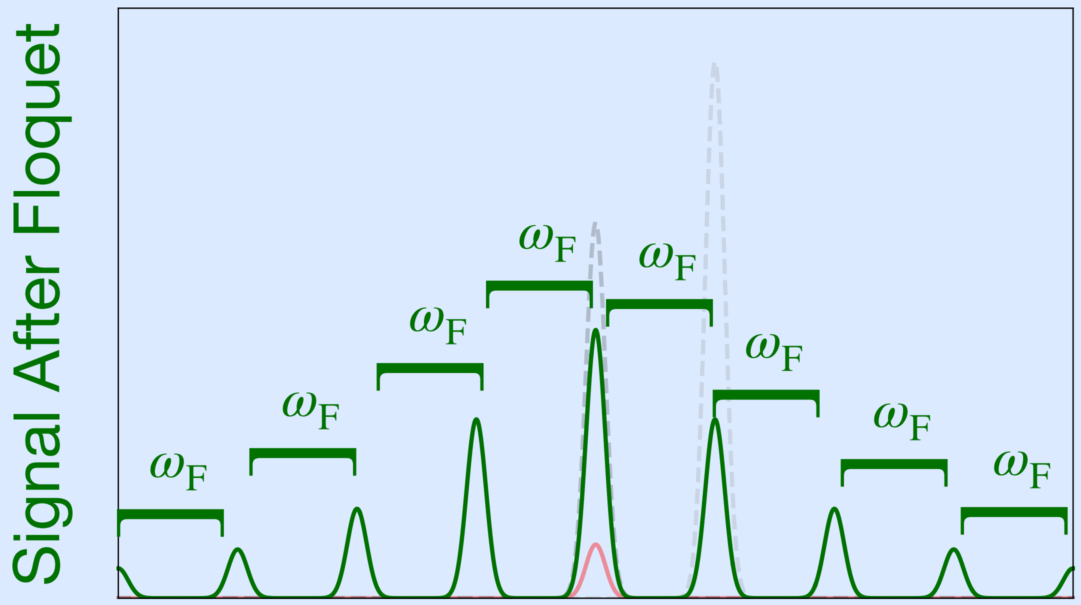
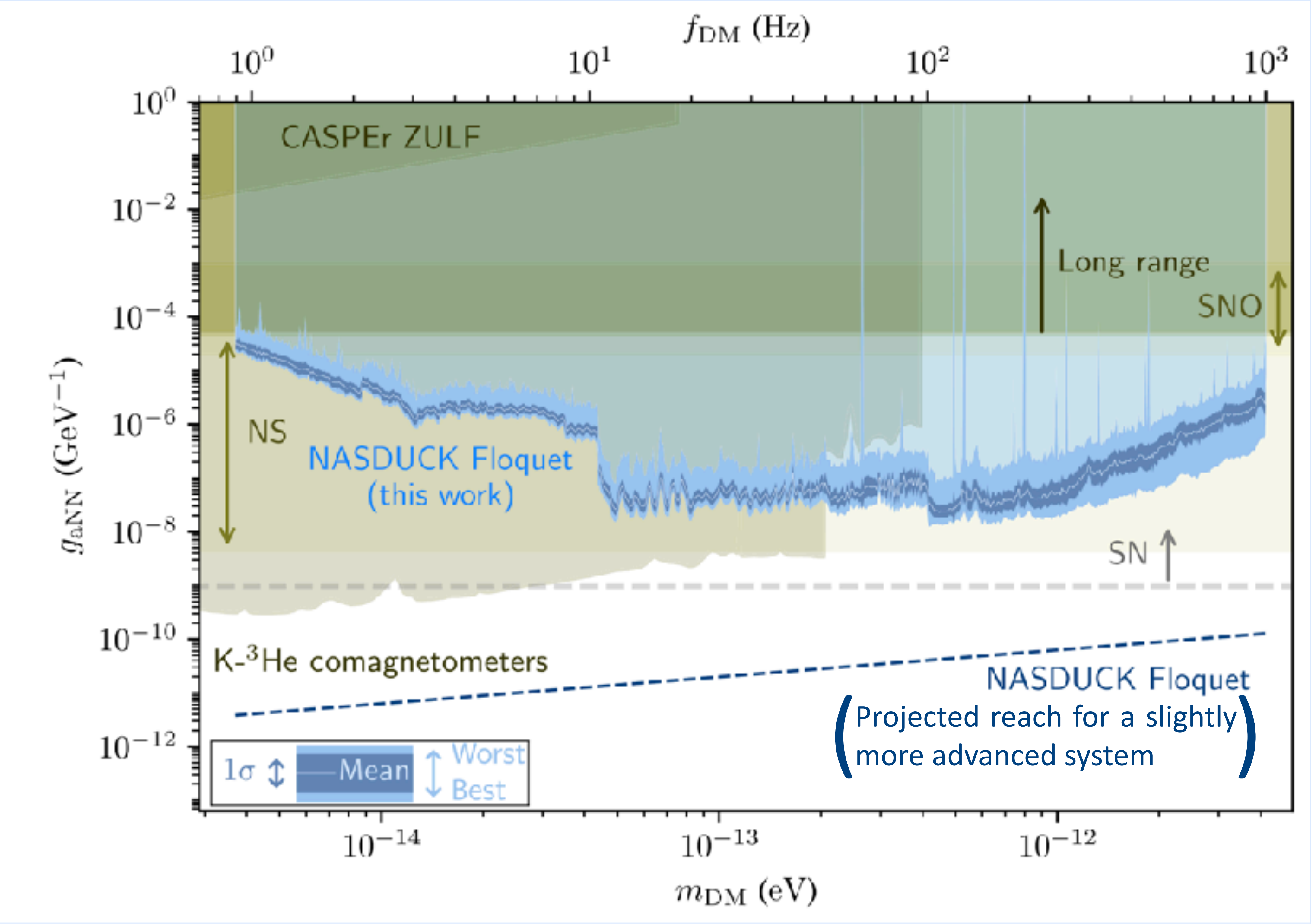


$$\omega_F = \omega_{\rm Alk} - \omega_{\rm Nob}$$

NASDUCK Floquet Results



NASDUCK Floquet Results Commentary

Sensitivity was limited by noise of probe beam (i.e. OOM larger than magnetic noise)

↓

An improvement by an order of magnitude is fairly easy*

Current Summary

Part 1: ALPs create a magnetic-like field that can be measured by spin-based magnetometers.

- Established Magnetometry Techniques for DM Research
- Novel Magnetometry Techniques

Part 2: NASDUCK opened up new possibilities using existing magnetometry techniques!

Sidenote: what else can be done with these detectors

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- Look for other “Anomalous Fields”:
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  - High Frequency Gravity Waves [IMB et al. in progress]
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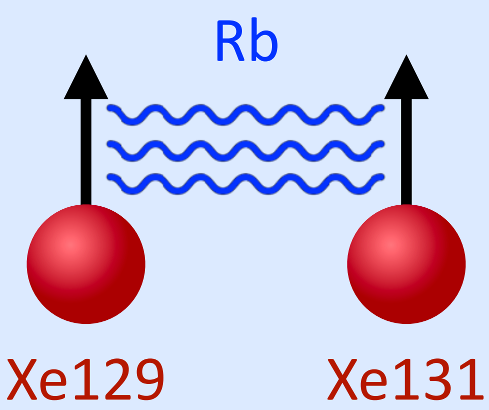
Ongoing Experiments with new techniques*

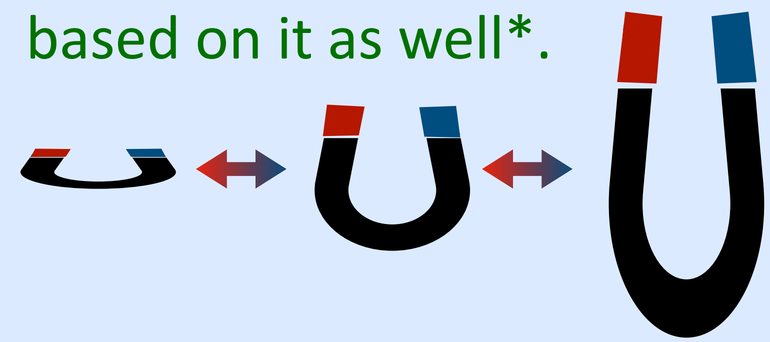


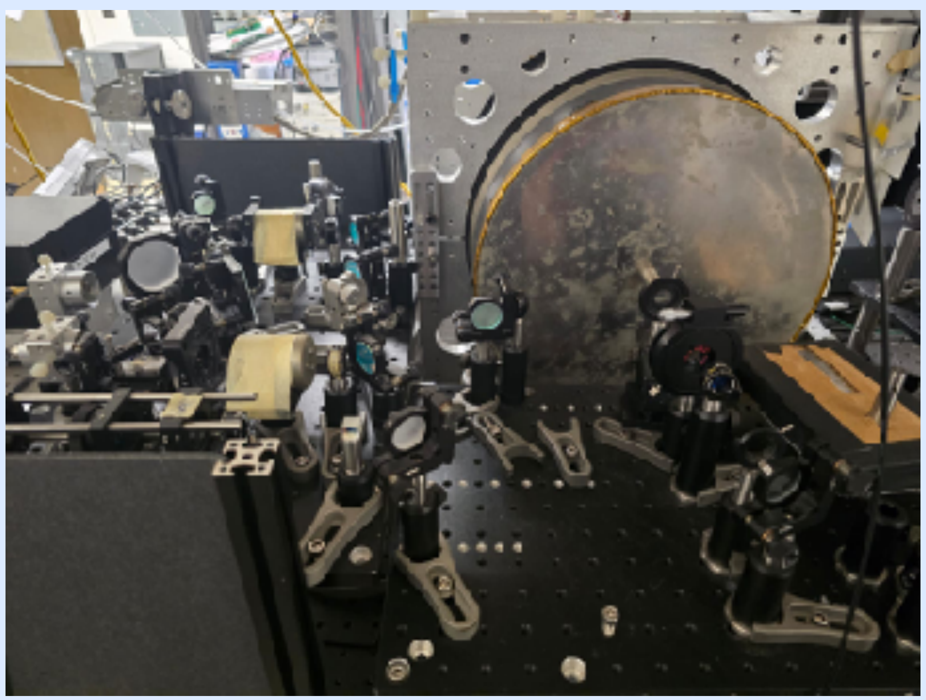
<u>“Cocomag”</u>

Data exists, waiting to be analyzed, this possibly has relevance to QI*.

<u>Longitudinal Measurements</u>

The theory paper is out, and an experiment has already been performed based on it as well*.

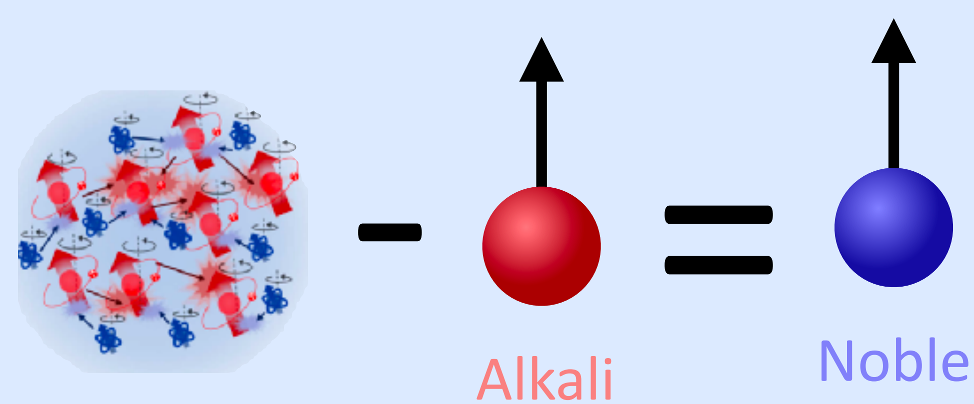




<u>Dual Alkali Subtraction</u>

Ongoing calibrations in preparation to data-taking

<u>NASDUCK “Subtracted”</u>



At the design stages, optimizing methodologies.

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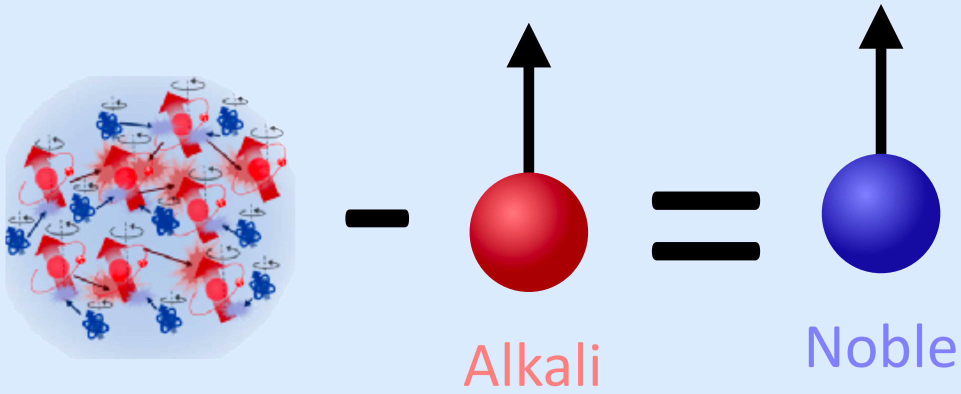
NASDUCK "Subtracted"



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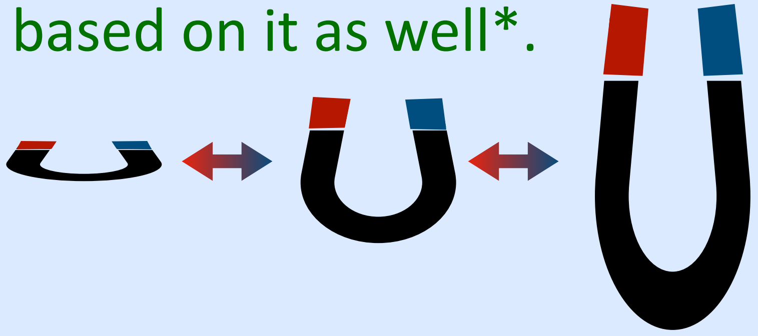
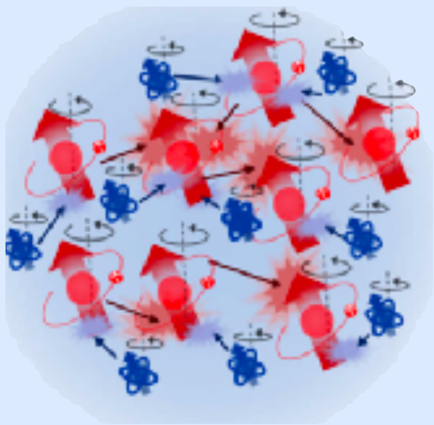
Longitudinal Measurements

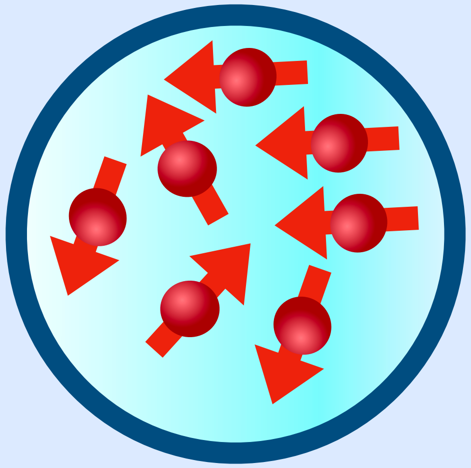
The theory paper is out, and an experiment has already been performed based on it as well*.



NASDUCK Subtraction

* To leading order in details





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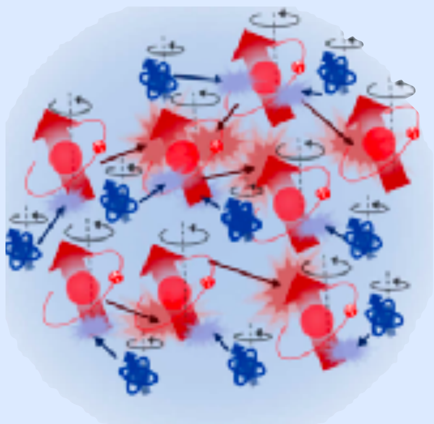
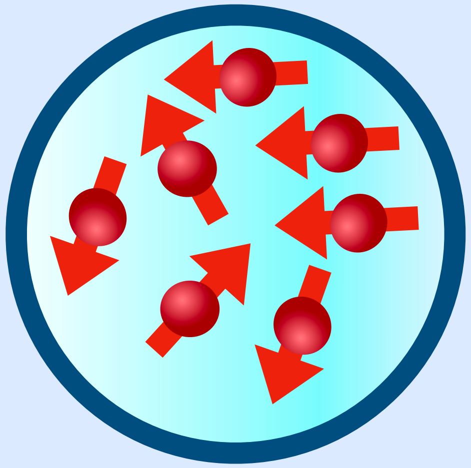


$$S_{\perp,1} = c_1 B_\perp + c_2 b_{\perp,\mathrm{ALP-Nob}} + \delta S_\perp$$



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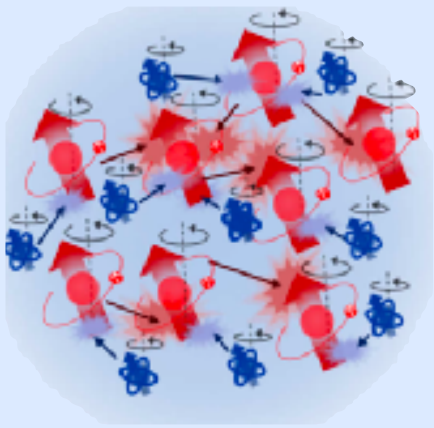

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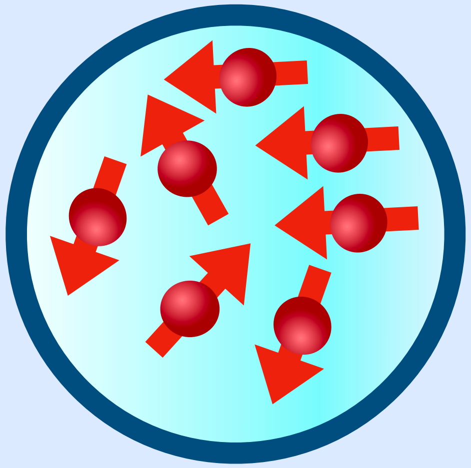

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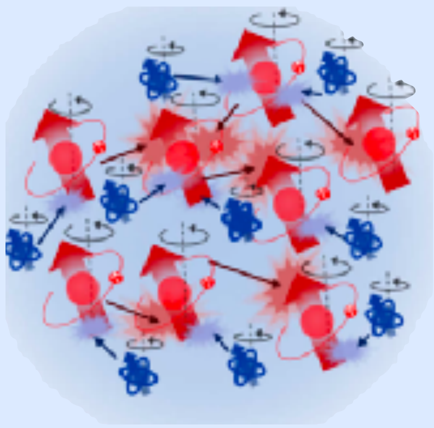

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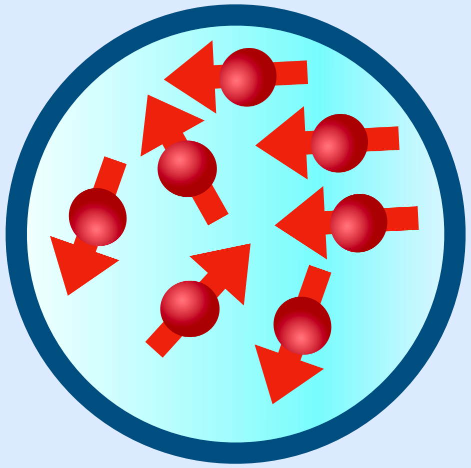

$$S_{\perp,2} = c_3 B_\perp + \delta S_\perp$$

$$\Delta S \equiv S_{\perp,1} - \frac{c_1}{c_3} S_{\perp,2}$$

$$\mathrm{SNR}(\Delta S) = \frac{c_2}{\sqrt{1+(c_1/c_3)^2}} \cdot \frac{b_{\perp,\mathrm{ALP-Nob}}}{\delta S_\perp}$$

Scalar Longitudinal Magnetometry

[2023, PRD. IMB, Budker, Flambaum, Samsonov, Sushkov, Tretiak]

Since coupling constants are scalars, scalar DM (not axions) can mimic variation in fundamental constants.

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First experiment is ongoing by Sushkov et al.

Can Longitudinal Magnetometry be used for ALPs?

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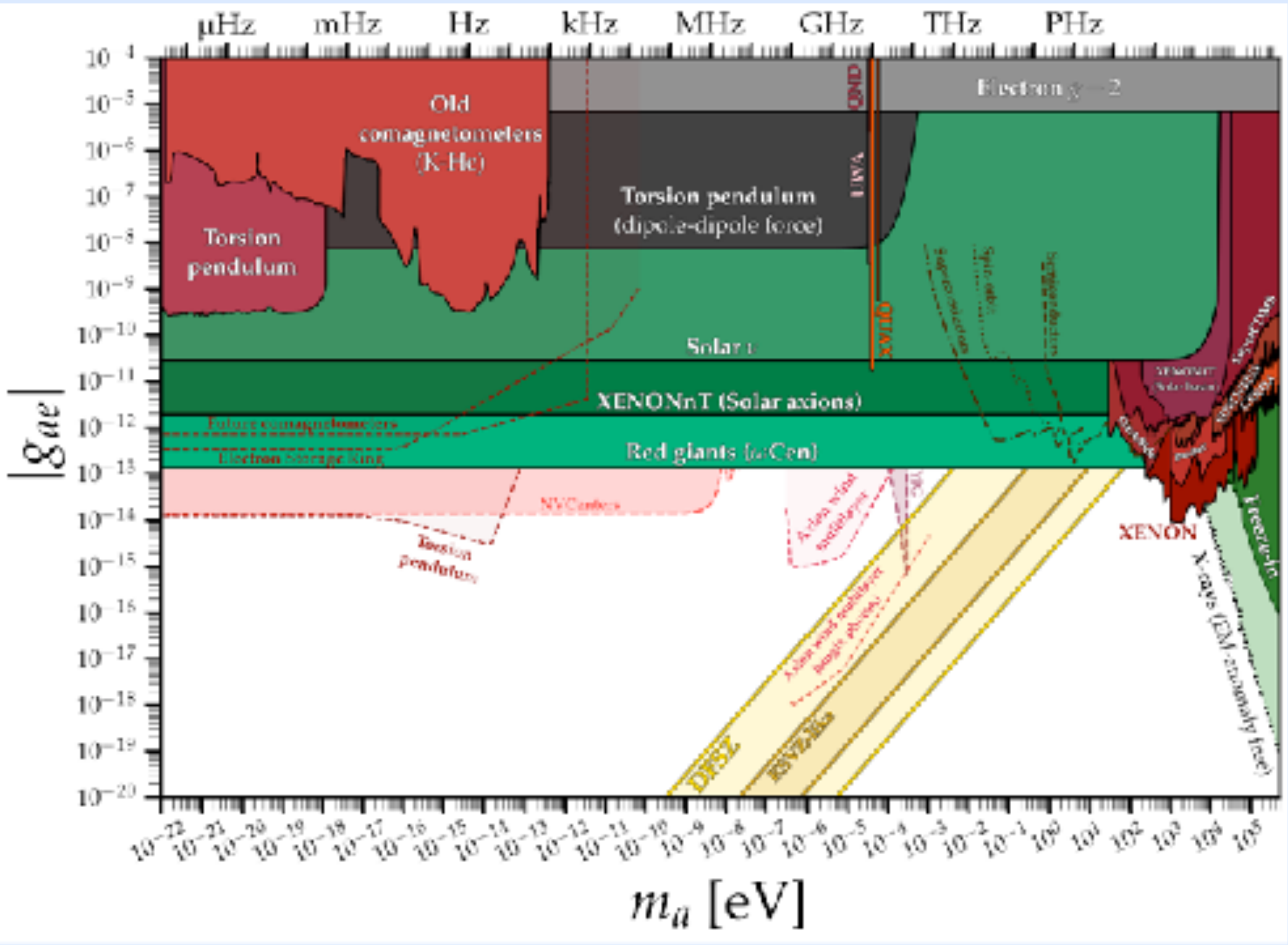
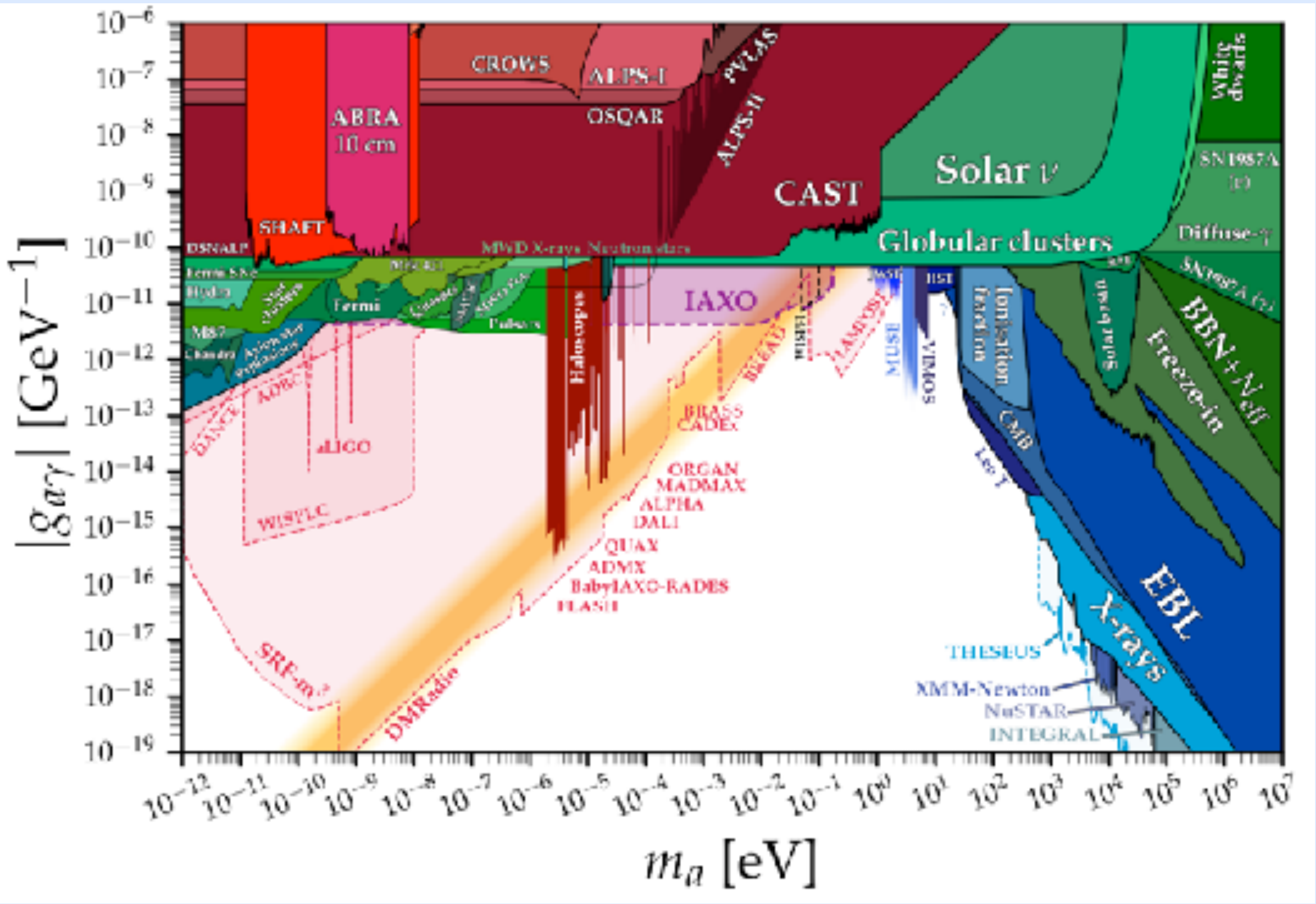
$$S_z(t \to \infty) \propto 1 - \frac{b^2_{\perp,\mathrm{ALP}}\Gamma}{((m_a - \omega_{\mathrm{res}})^2 + \Gamma^2)\Gamma_L}$$

Second order in the couplings!

Should we try to measure ALPs?





[Ciaran O'Hare's GitHub, see references within]

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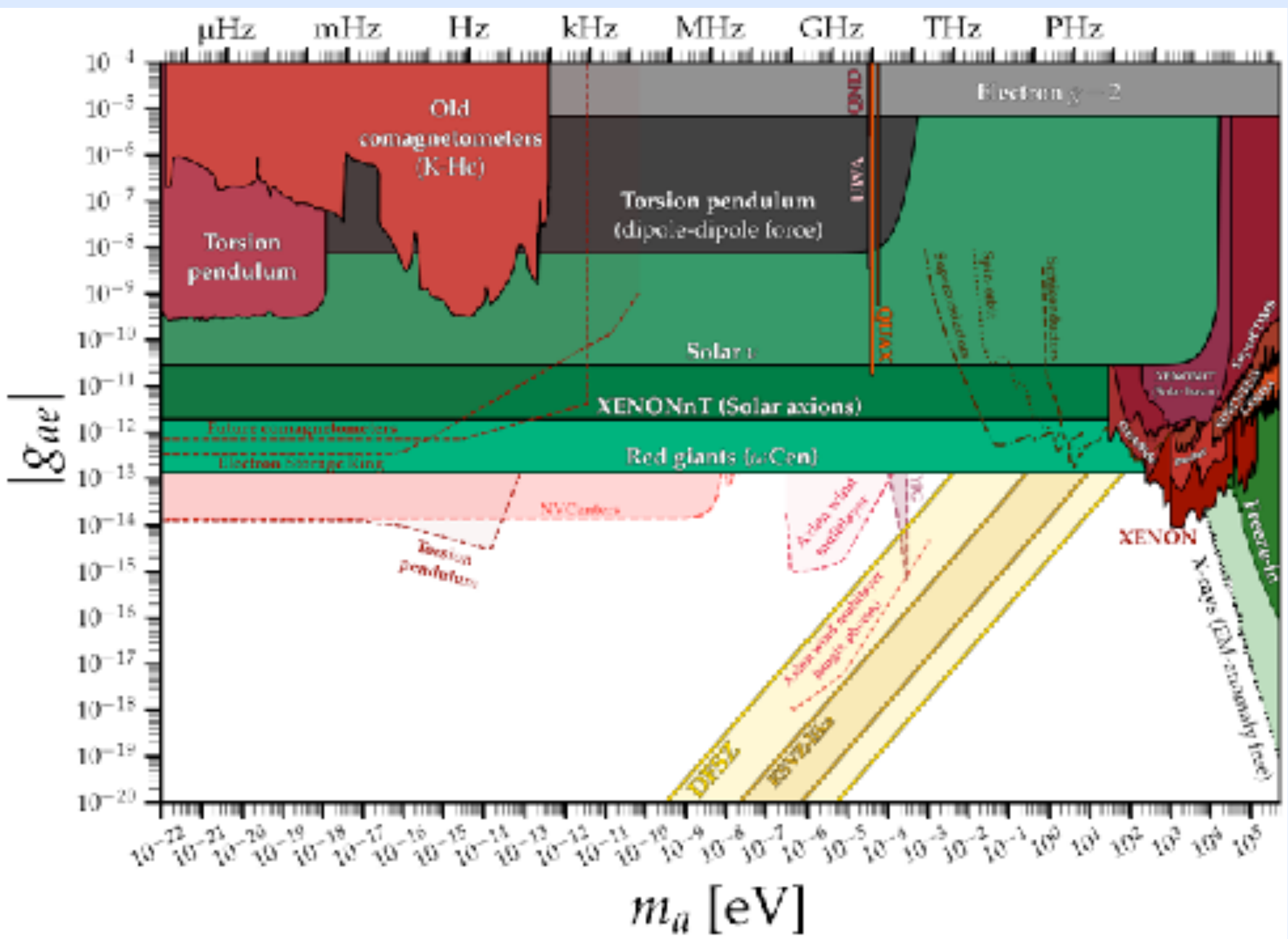

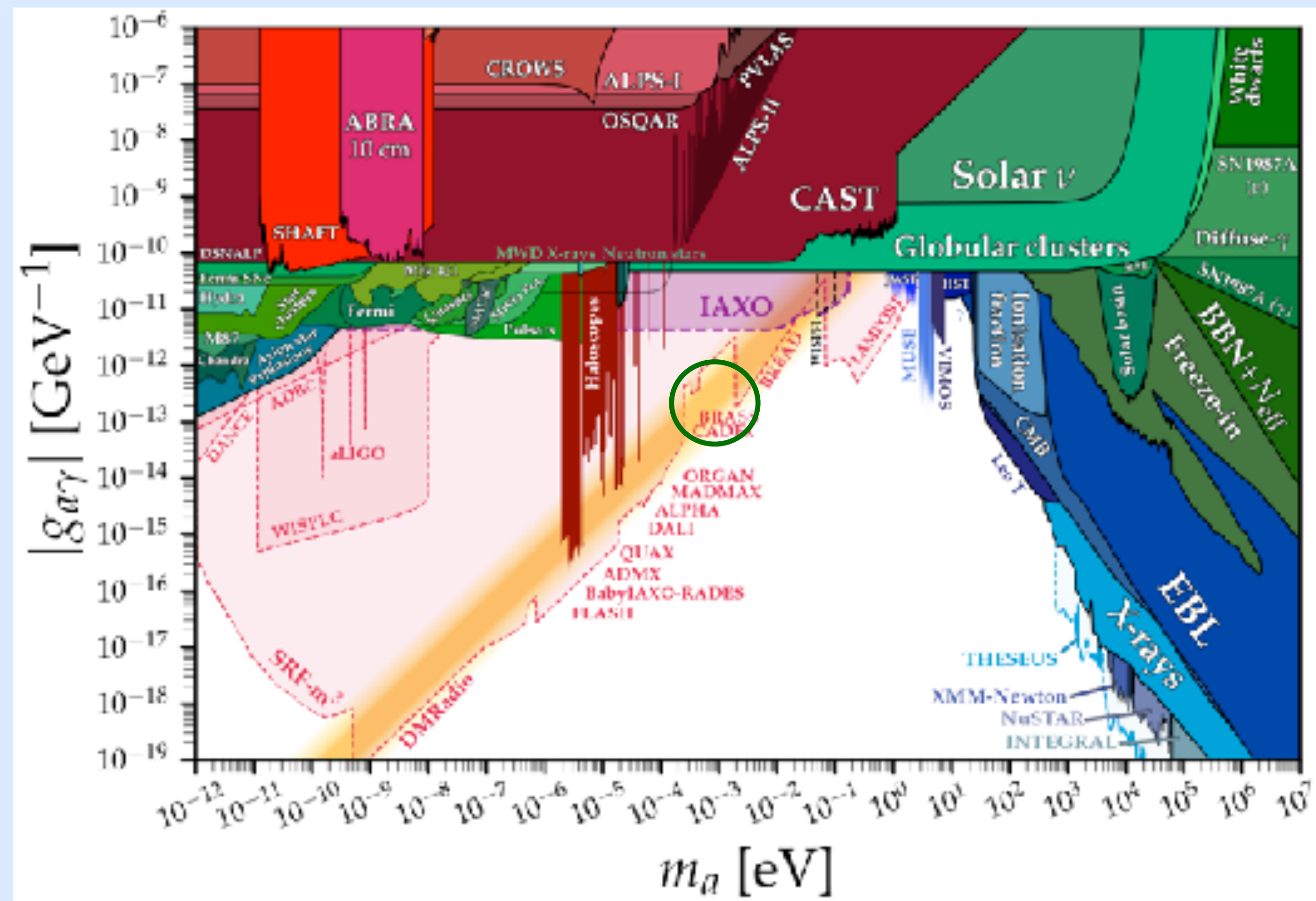

At 10 Teslas, an electron-spin based sensor would be sensitive to meV axions

[Ciaran O'Hare's GitHub, see references within]

Spin Shot Noise

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At zero temperature, under $\overrightarrow{B} = B_z\hat{z}$ (and no axions):

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This does not exist when measuring S_z! No Spin Shot Noise*

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Spin Shot Noise as an Observable

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Number of spins, usually one wants this to be big, but here it's not clear

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(Some) Additional Points of Note

- Due to the lack of resonance at the measured signal frequency, one can add a secondary spin/EM amplifier.
- Due to the quantum nature, measuring EMF ($\propto d\mathbf{B}/dt \sim \Gamma_1 \mathbf{B}$) can greatly enhance signal (and noise).
- Due to finite B_z stability, a gradiometer is necessary*.
- The "naive observable" isn't as bad as it seems (given a floquet)
- Many challenges for actual implementation but also many possibilities!

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- Existing technologies can already enhance the current capabilities, but…
- With creativity, one can think of new ideas, with many promising directions!

Noble and **A**lkali **S**pin **D**etectors for **U**ltralight **C**oherent dar**K**-matter

DUCK-matter

(Degree in beakness school)

↓

NASDUCK-matter