The **NASDUCK** Collaboration: Using Quantum Magnetometers to Look for Ultralight DM

Oct 2021

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Tel Aviv University
(Work done in the Rafael Quantum Optics Lab)

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Collaborators:
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E. Kuflik, G. Ronen, R. Shaham, T. Volansky.
Based on works presented in arXiv:1907.03767, and arXiv:2105.04603

Outline

- **Axion Like Particles (ALPs)**
    - ALPs Brief Overview
    - Coherent Interactions
- **Noble-Alkali Comagnetometers**
    - Spin-Based Magnetometry
    - Why Noble-Alkali?
    - Old Results
    - NASDUCK
- **Conclusions**

Axion Like Particles

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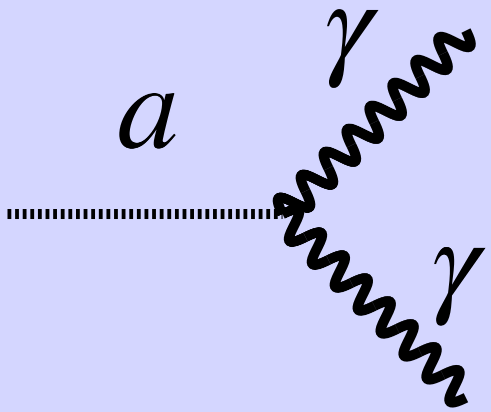
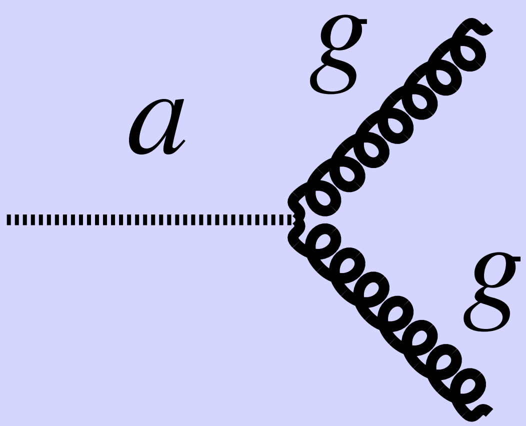
- Pseudo-scalars.
- Can be a CDM component (we assume all).
- Can be very light and remain CDM candidate:

$$m_a(\text{relevant to talk}) < 4 \times 10^{-12}\ \text{eV}$$

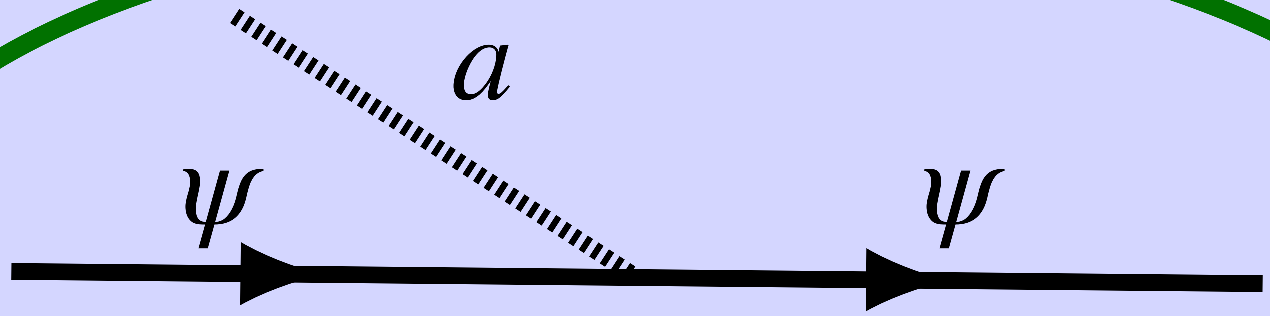
ALP-SM Interactions



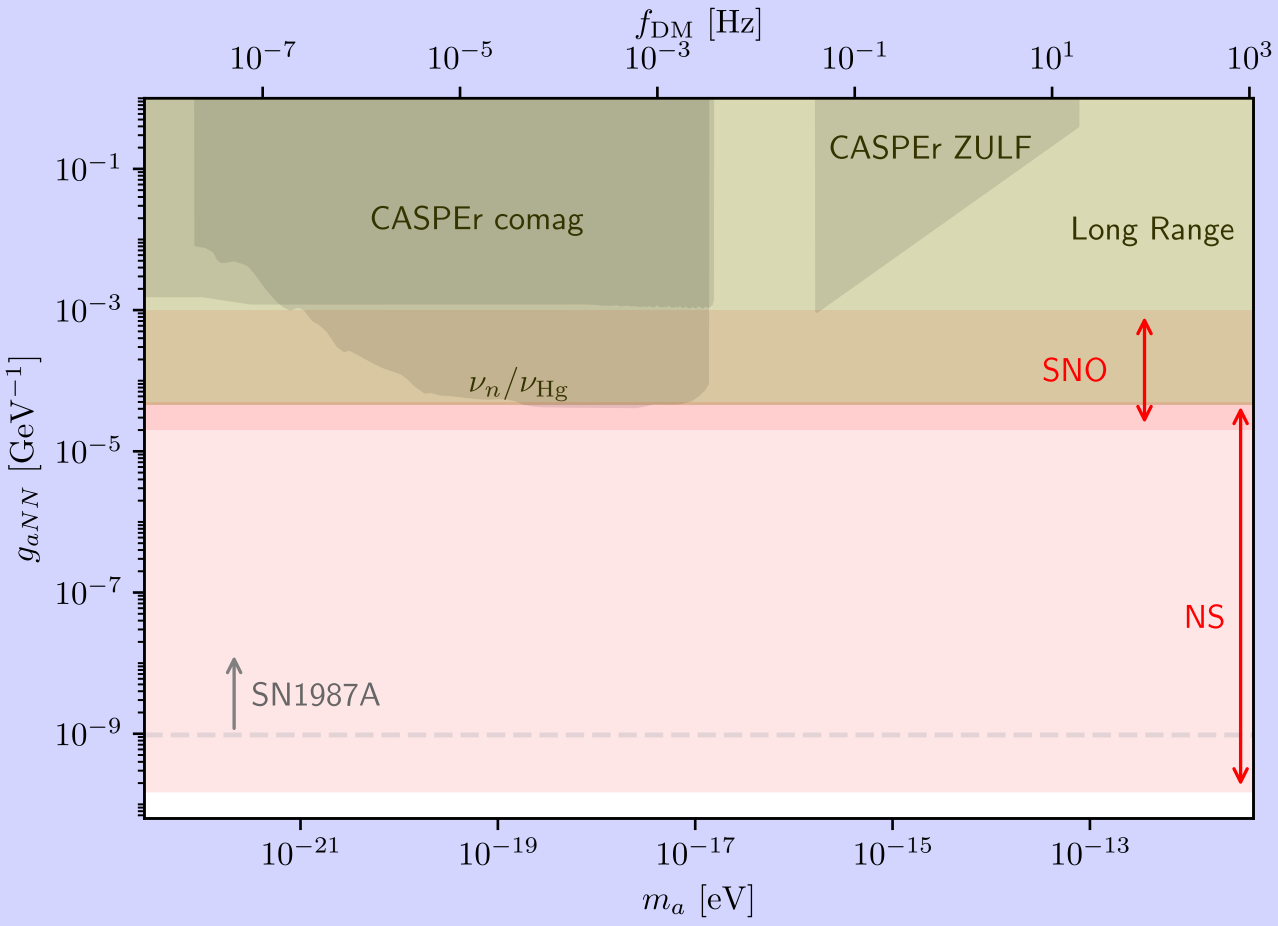
$$-\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F}$$

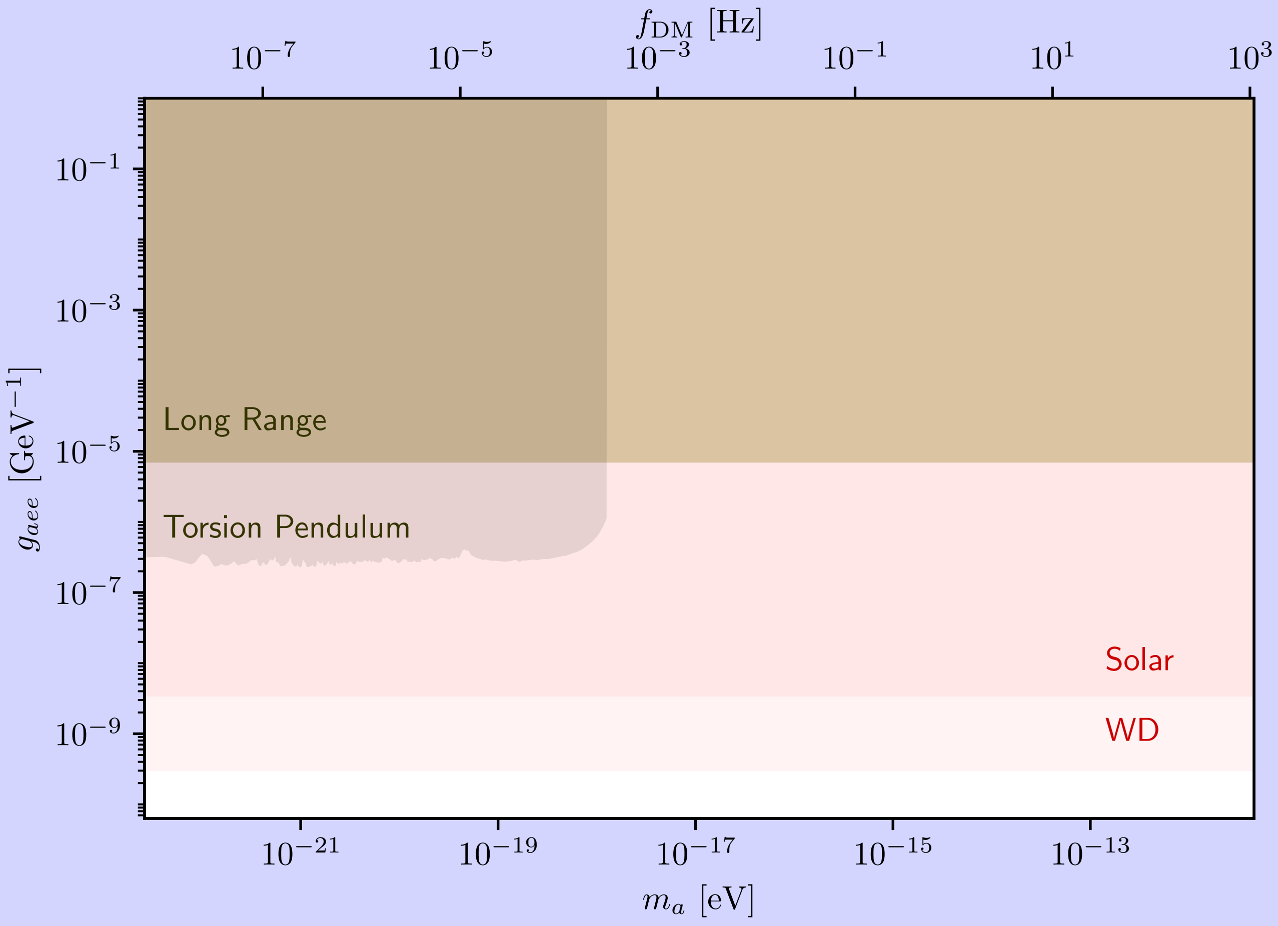


$$-\frac{a}{f_a}\frac{G\tilde{G}}{32\pi^2}$$



$$g_{a\psi\psi}\partial_\mu a \cdot \bar{\psi}\gamma^\mu\gamma_5\psi$$





ALP-neutron

ALP-electron

Coherent Interactions (1)

$$n_a = \frac{0.4\ \mathrm{GeV}}{m_a \cdot \mathrm{cm}^3}$$

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For light ALPs ($m_a \lesssim 30\ \mathrm{eV}$), $n_a = \dfrac{0.4\ \mathrm{GeV}}{m_a \cdot \mathrm{cm}^3} > 1/\lambda^3_{\mathrm{de-Broglie}}$

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In the non-relativistic limit…

Coherent Interactions (2)

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

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

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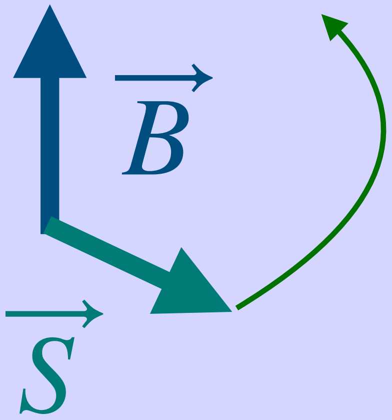
But how to measure it?

Larmor Precession and Zeeman Splitting

Interaction of a classical magnetic field $\overrightarrow{B}$ with a spin $\overrightarrow{S}$:



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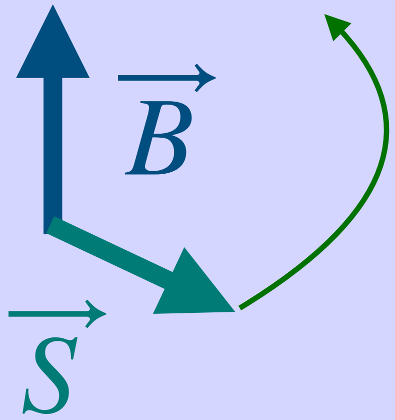

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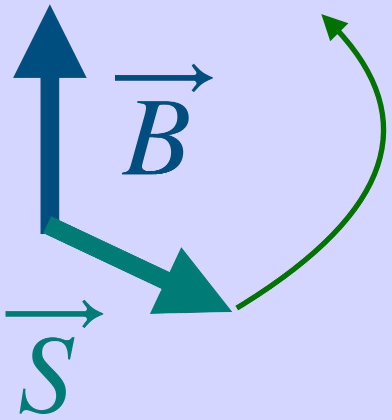

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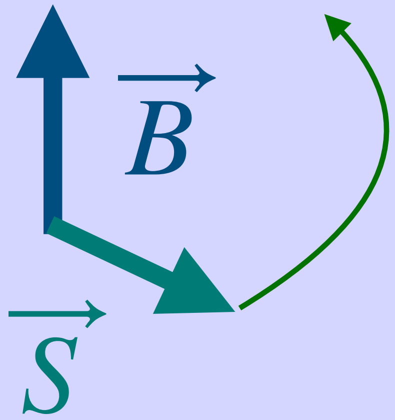

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Is there a known way to measure magnetic fields?

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Noble-Alkali Comagnetometers

Bloch Equations

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

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

Torque
(generates transverse from longitudinal)

Bloch Equations

- To leading order in important stuff

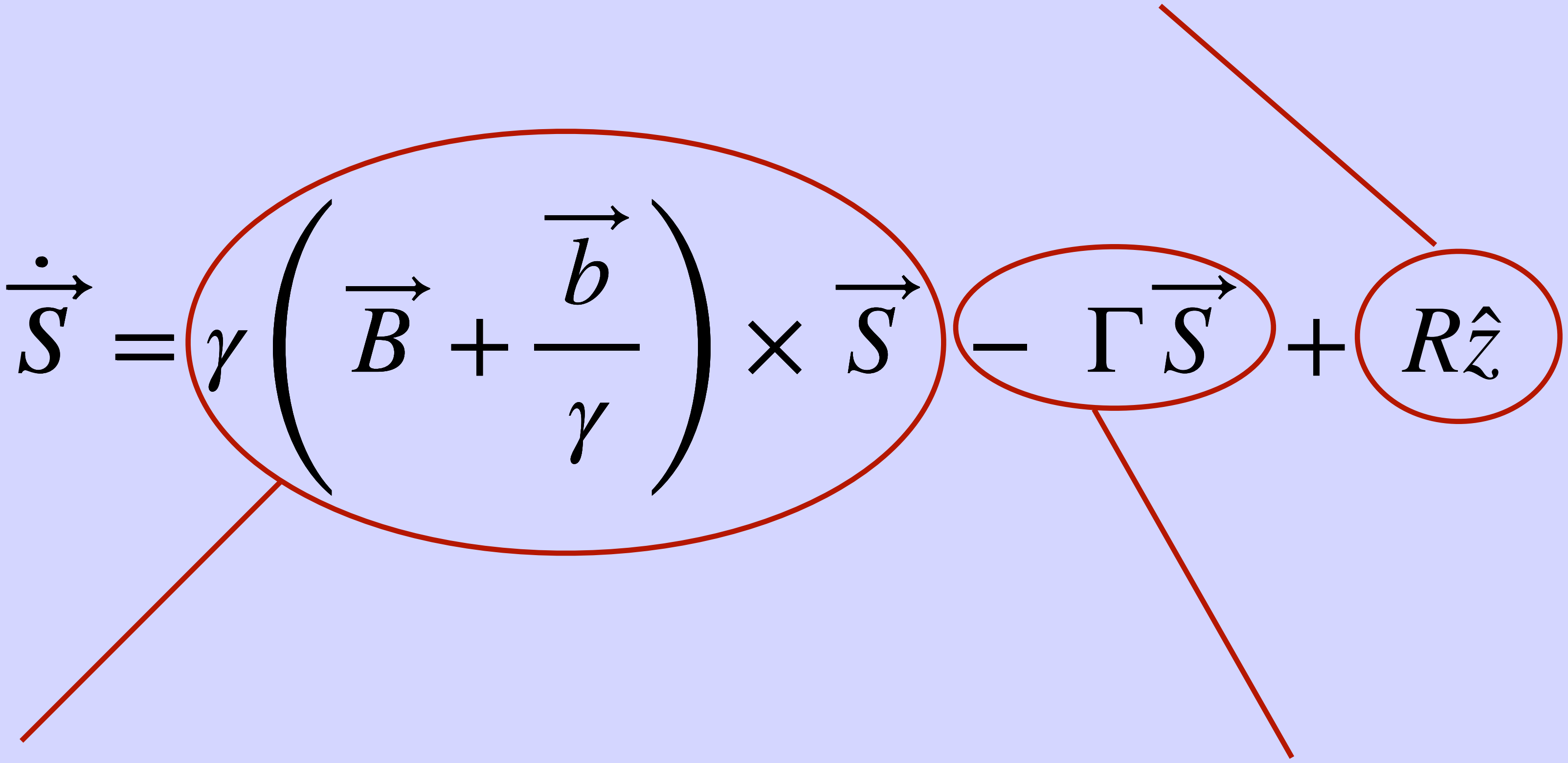
$$\dot{\vec{S}} = \gamma\left(\vec{B}+\frac{\vec{b}}{\gamma}\right)\times\vec{S} - \Gamma\vec{S}$$

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)

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

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(generates transverse from longitudinal)

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Transverse EOMs

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

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If B_z is constant ↓ (Fourier. From now on I'm going to ignore subtleties regarding $\cos(m_a t) \neq e^{i m_a t}$)

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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

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

The Result

The transverse spin

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

The transverse spin:
Everything is encoded in the spin projections in the directions perpendicular to the pump

The Result

Signal

The transverse spin

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

Signal:

The thing we want to measure that an ALP generates

The Result

Transverse Magnetic fields

Signal

The transverse spin

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

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

Transverse
Magnetic fields

Signal

The transverse
spin

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

Spin in the z
direction

Spin in the z direction

Main demand: Don’t be tiny

The Result

Transverse Magnetic fields

Signal

The transverse spin

Spin in the z direction

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

ALP mass

ALP Masses

Our experiments can only probe ultralight ALPs. To date we can probe up to ~5peV, can probably be extended to neV, theoretically $\mu\mathrm{eV}$, though that is unlikely.

The Result

Transverse
Magnetic fields

Signal

The transverse
spin

Spin in the z
direction

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

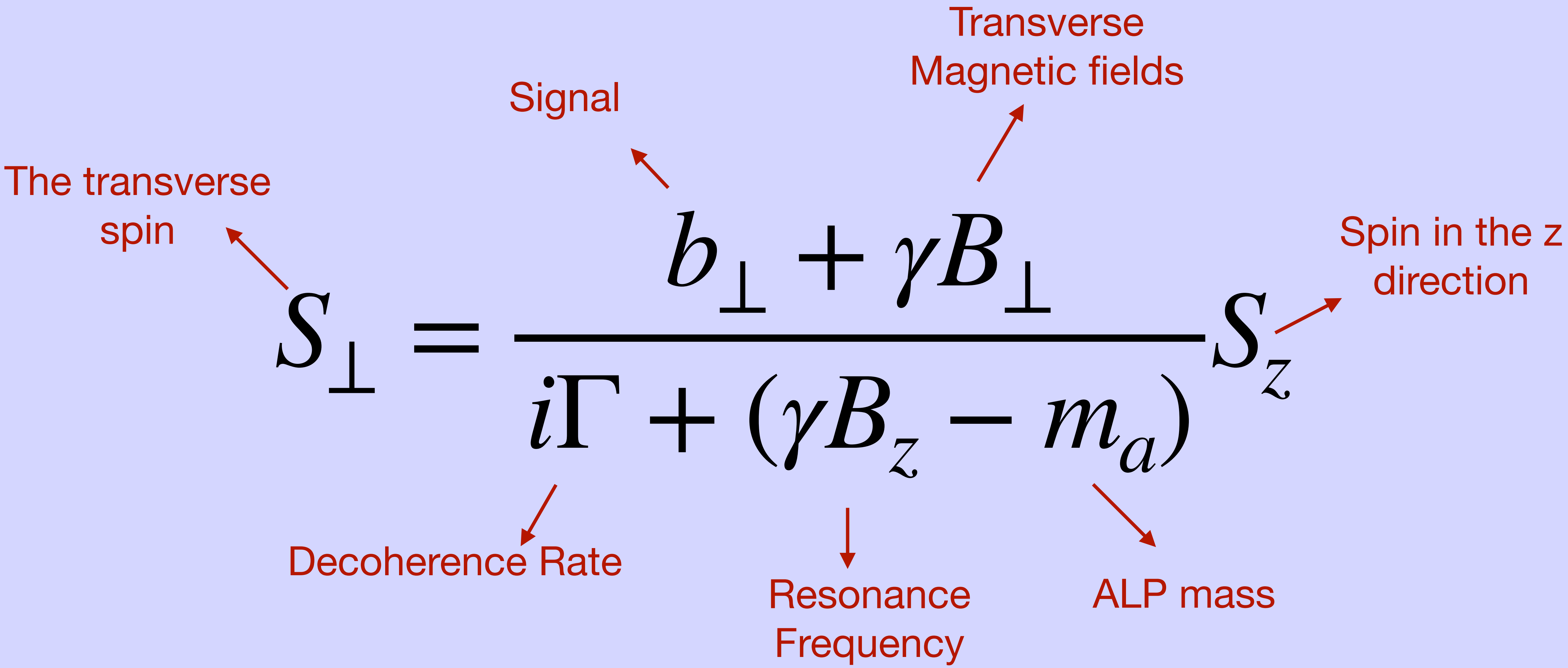
Resonance
Frequency

ALP mass

Resonance Frequency

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

The Result



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

The transverse spin

Signal

Transverse Magnetic fields

Spin in the z direction

Decoherence Rate

Resonance Frequency

ALP mass

Decoherence Rate:

The decoherence rate determines the width of the atomic response to ALPs. Can be mHz-kHz (though exceptions exist). A small decoherence rate can be problematic due to slow response time.

Outline

✓

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    - ALPs Brief Overview
    - Coherent Interactions

Ultra Light ALP DM generates magnetic-like fields.

- **Noble-Alkali Comagnetometers**
    - ✓ Spin-Based Magnetometry
    - Why Noble-Alkali?
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By measuring the spins of a “system”, we are also measuring the ALPs.

Why Alkali?

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"Pump" laser polarizes the spins,
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Problem:

$SNR \propto \gamma$, and the gyromagnetic ratio of alkali metals is large.

Why Noble?

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Noble gases have a gyromagnetic ratio which is smaller by 2-3 orders of magnitude!

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Noble gases have a gyromagnetic ratio which is smaller by 2-3 orders of magnitude!

Noble gases do not interact with the lasers

but

They can be both polarized, and measured by Alkali spins.

Spin Exchange: Polarizing $S_{\mathrm{Nob},z}$

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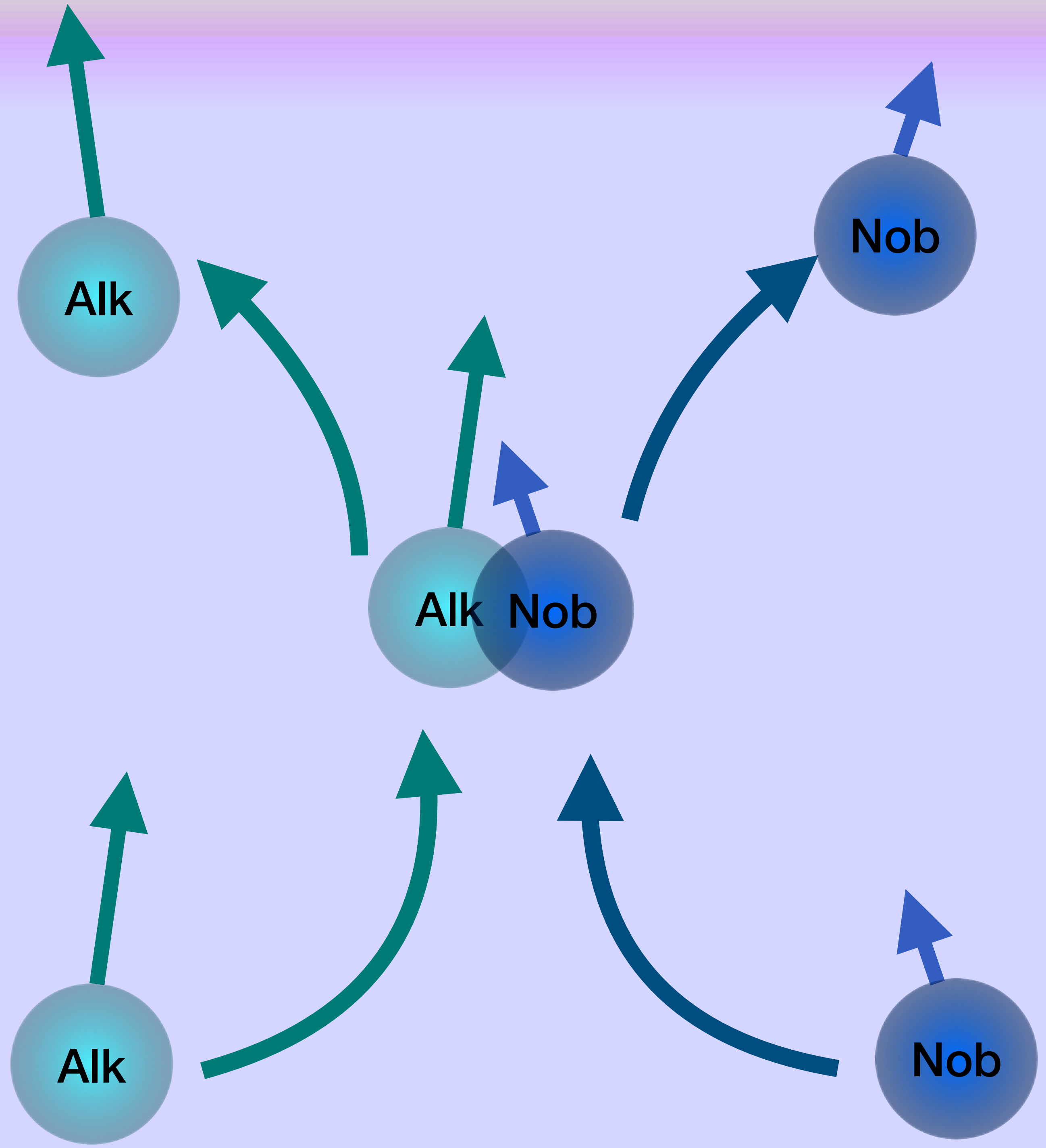

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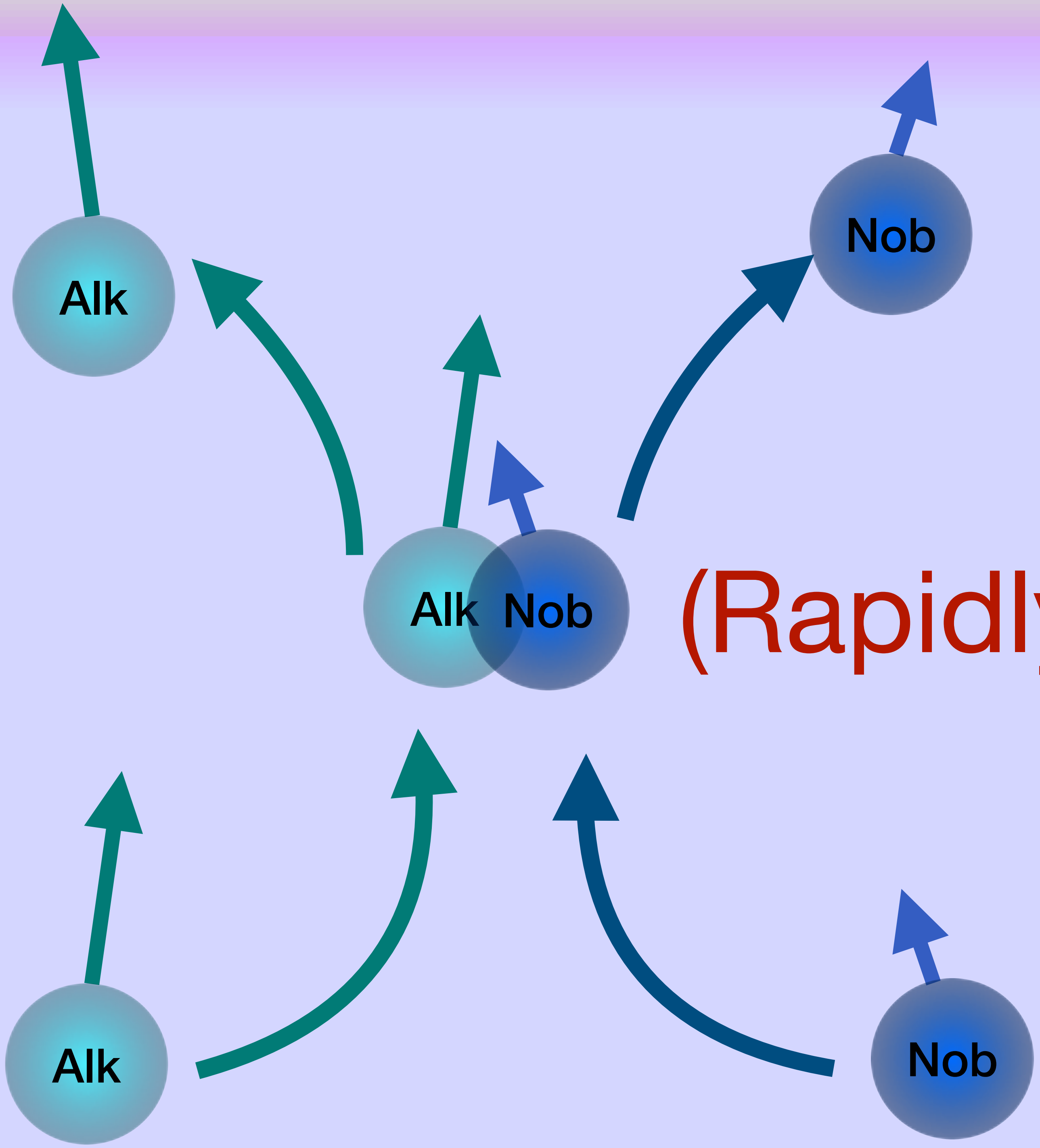

(Rapidly)

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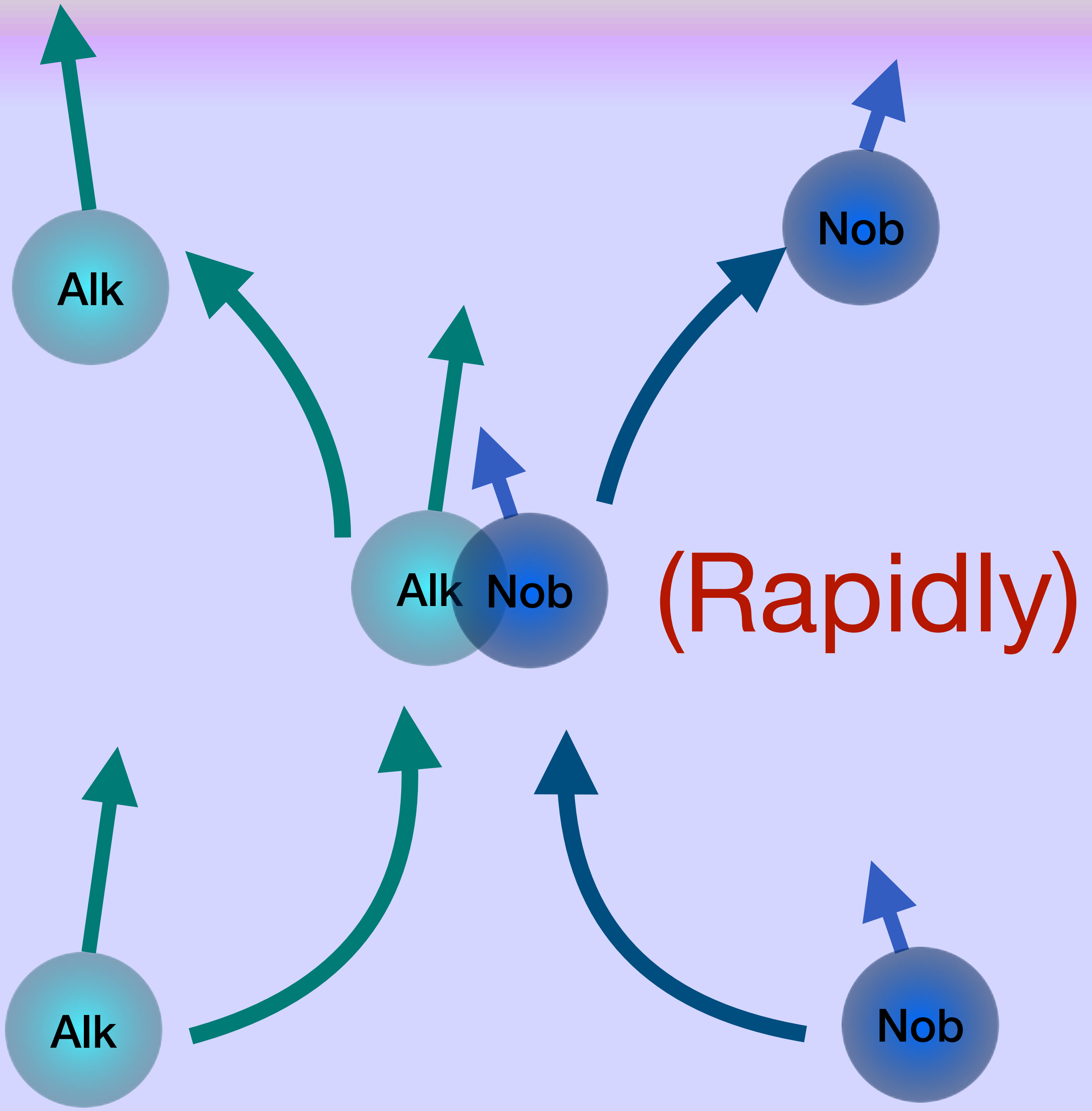
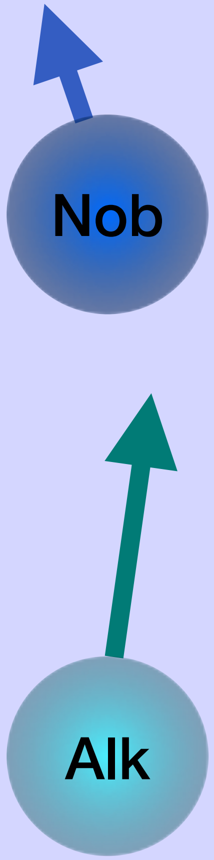


Spin passed from one atom to the other during collision:



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

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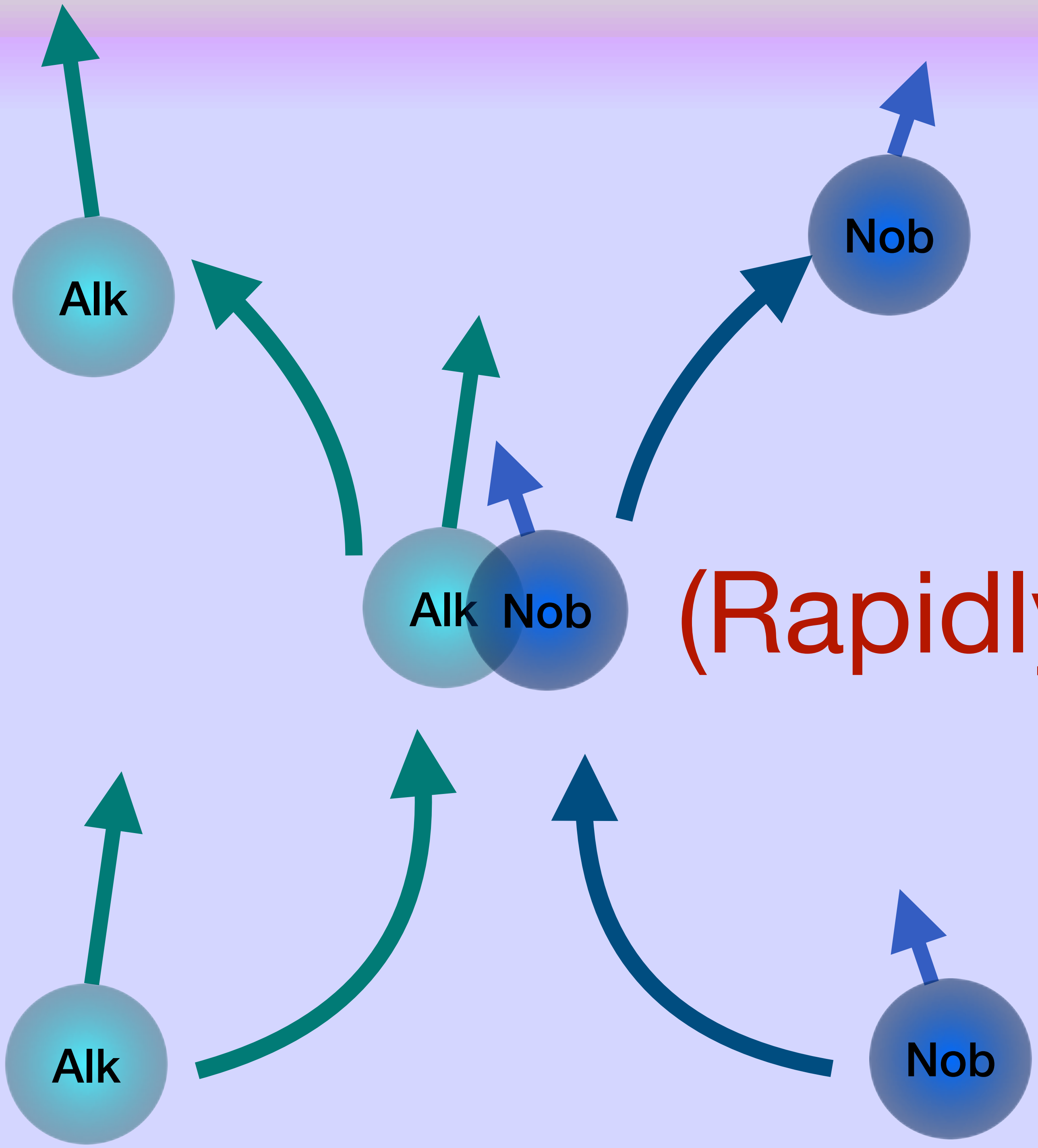

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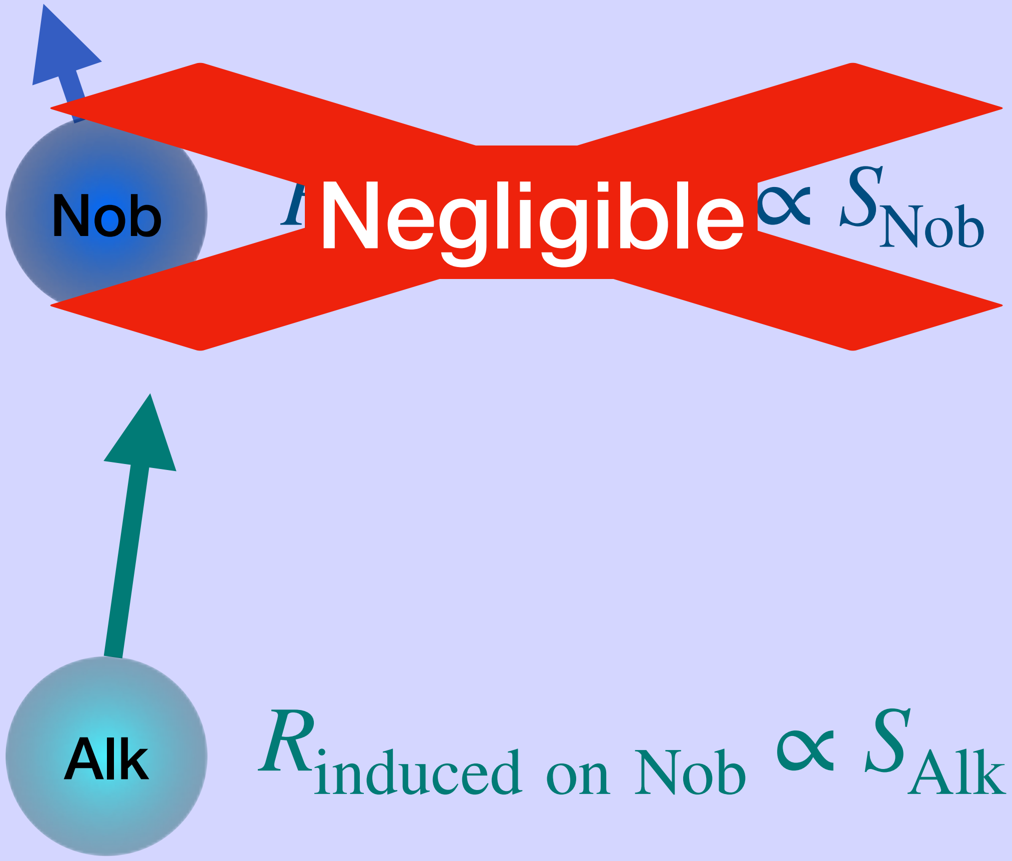
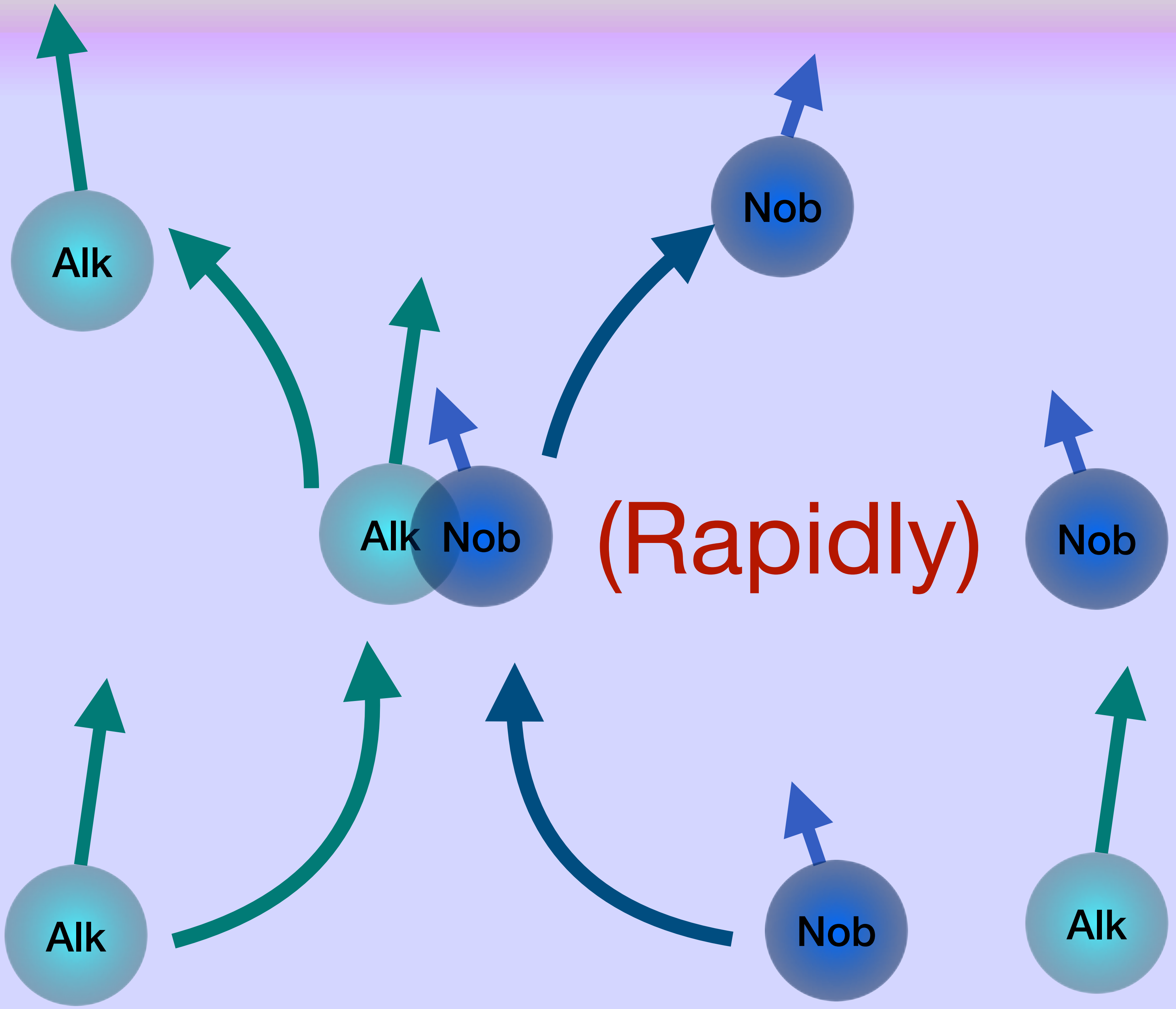


$\propto S_{\text{Nob}}$

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

Spin Exchange: “Measuring” $S_{\perp,\mathrm{Nob}}$



(Rapidly)

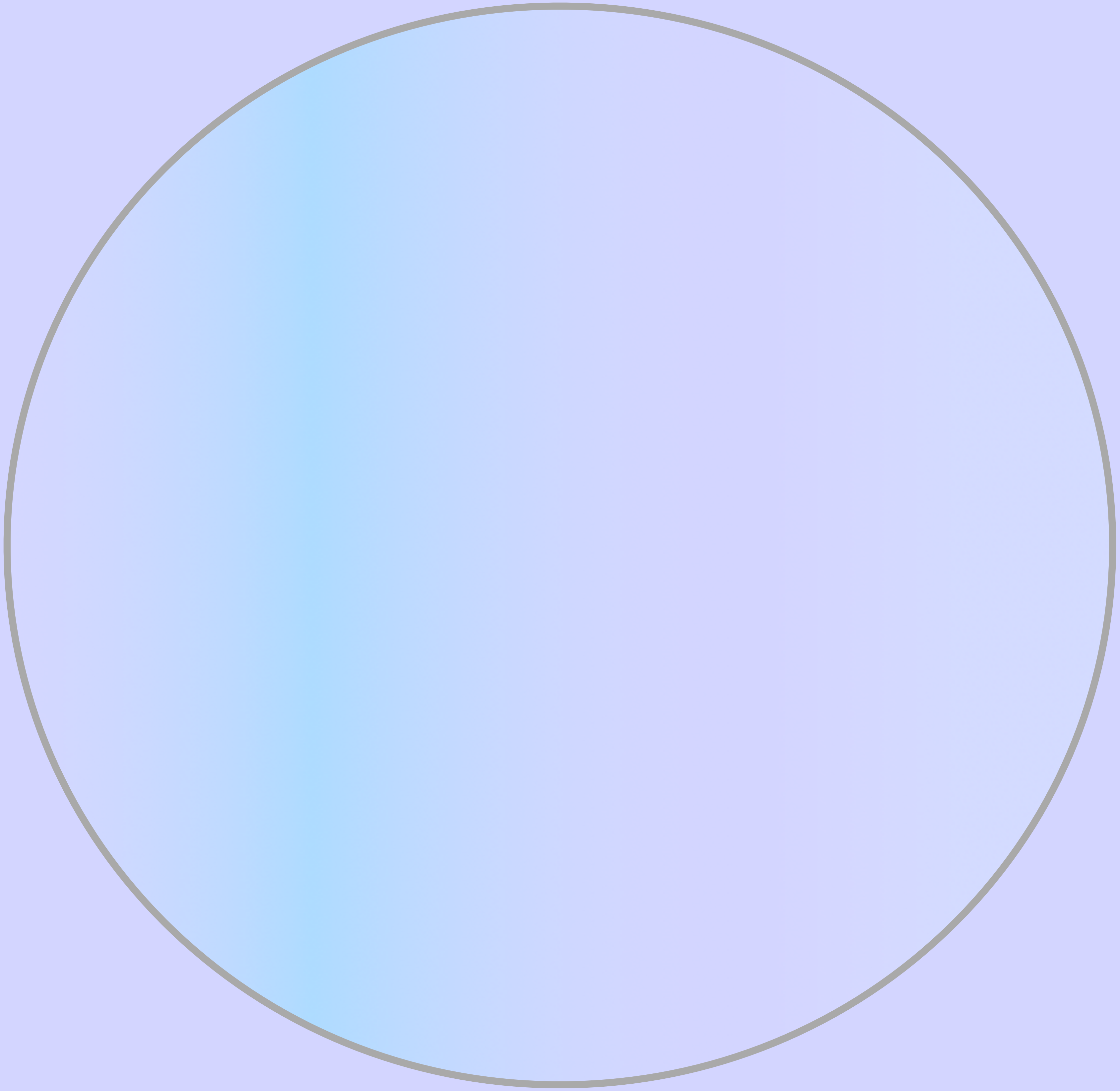
Magnetic field from (quantum) point-like interactions

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

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

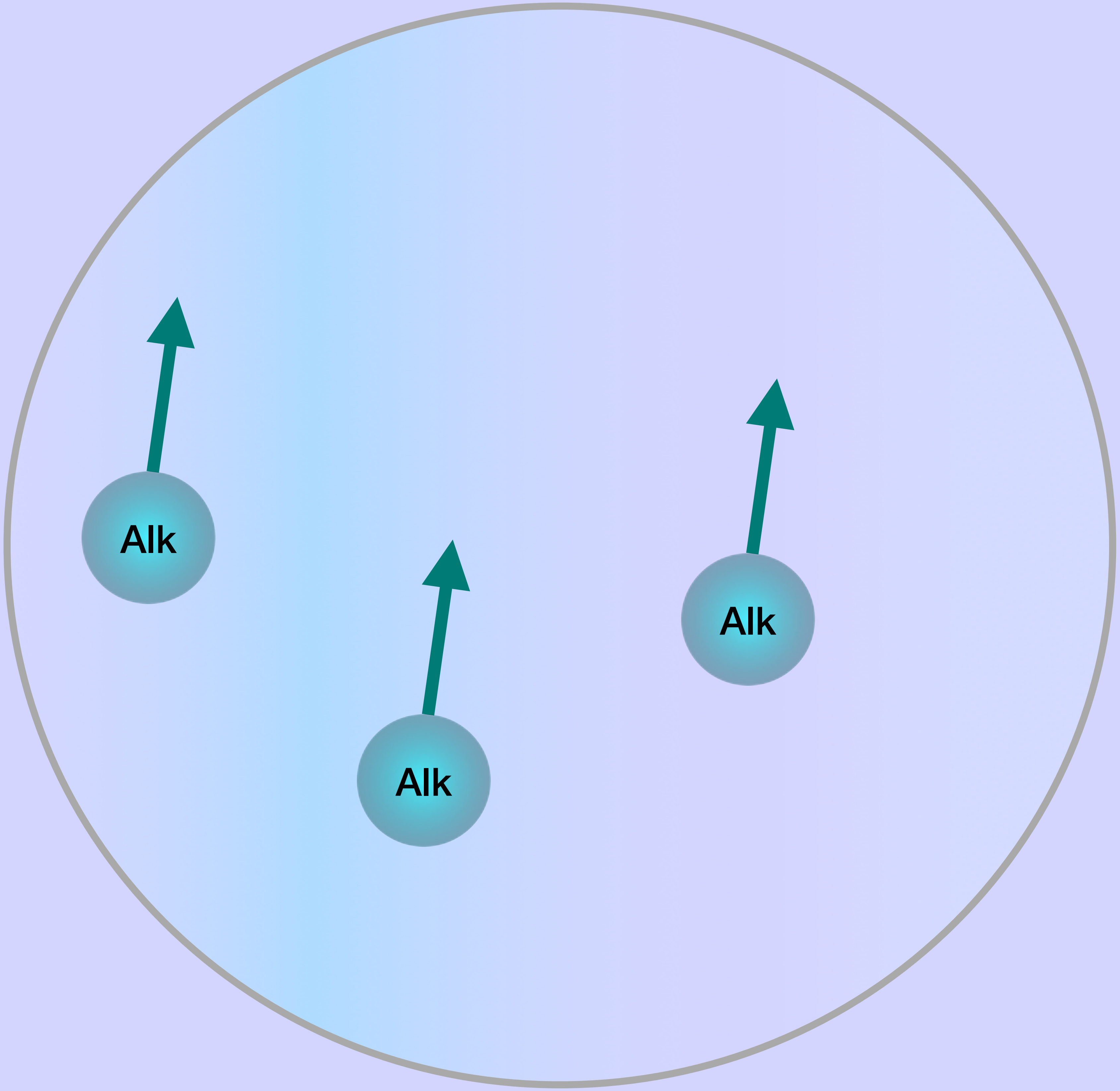
Comagnetometer

Ingredients List



Comagnetometer
Ingredients List

Glass Cell



Comagnetometer
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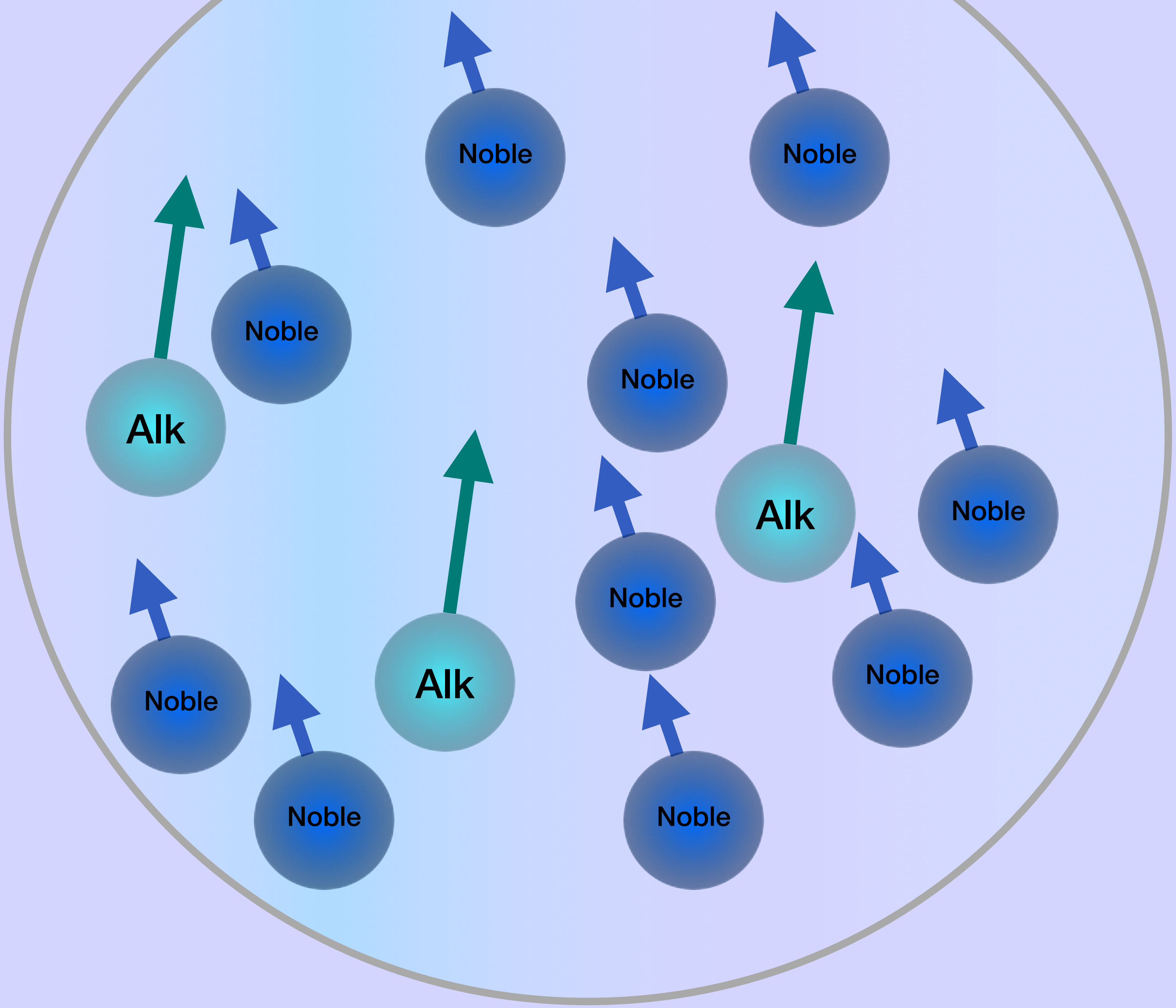
Glass Cell

Alkali Vapor

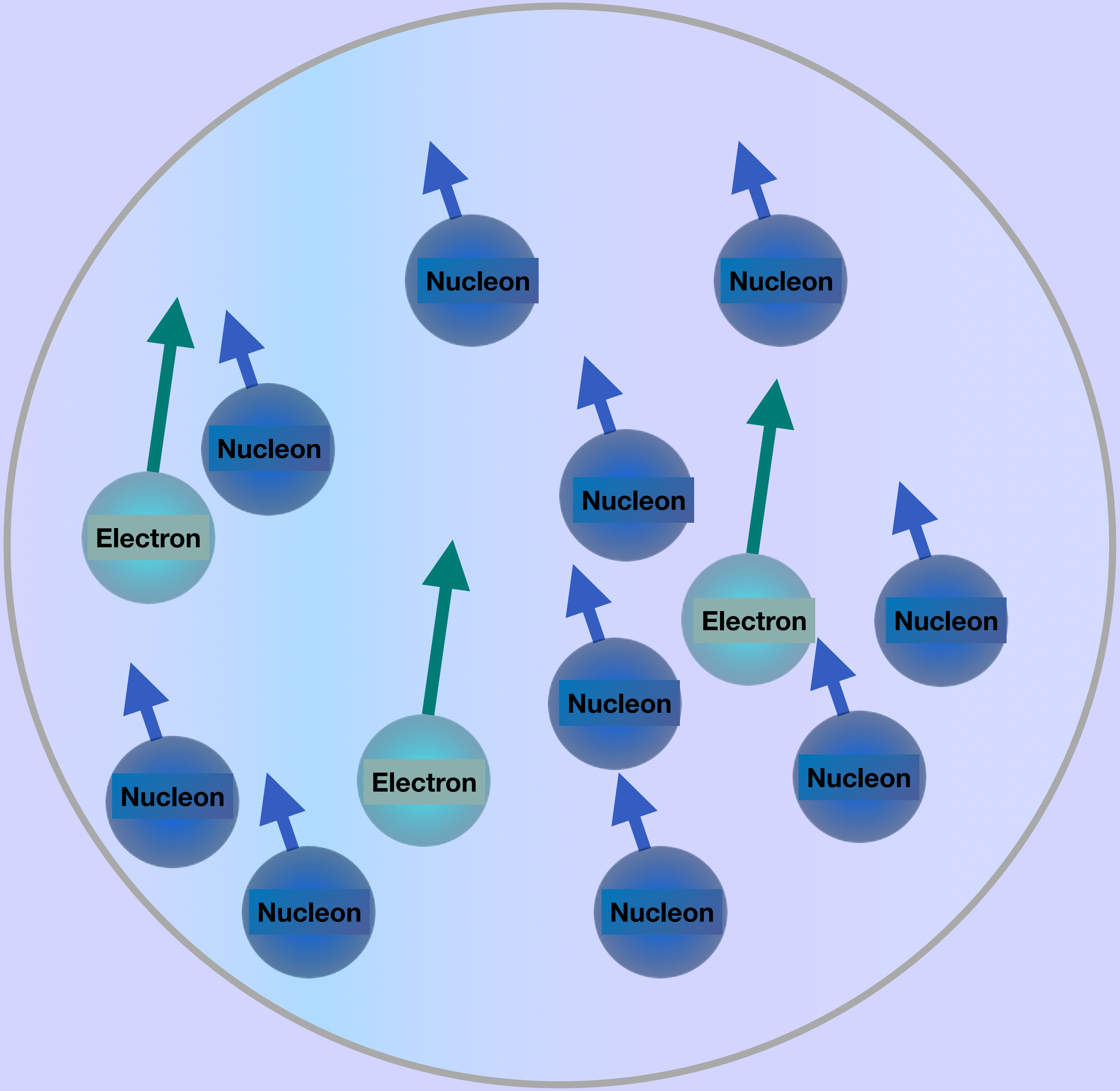
Comagnetometer
Ingredients List



Glass Cell

Alkali Vapor

Noble Gas



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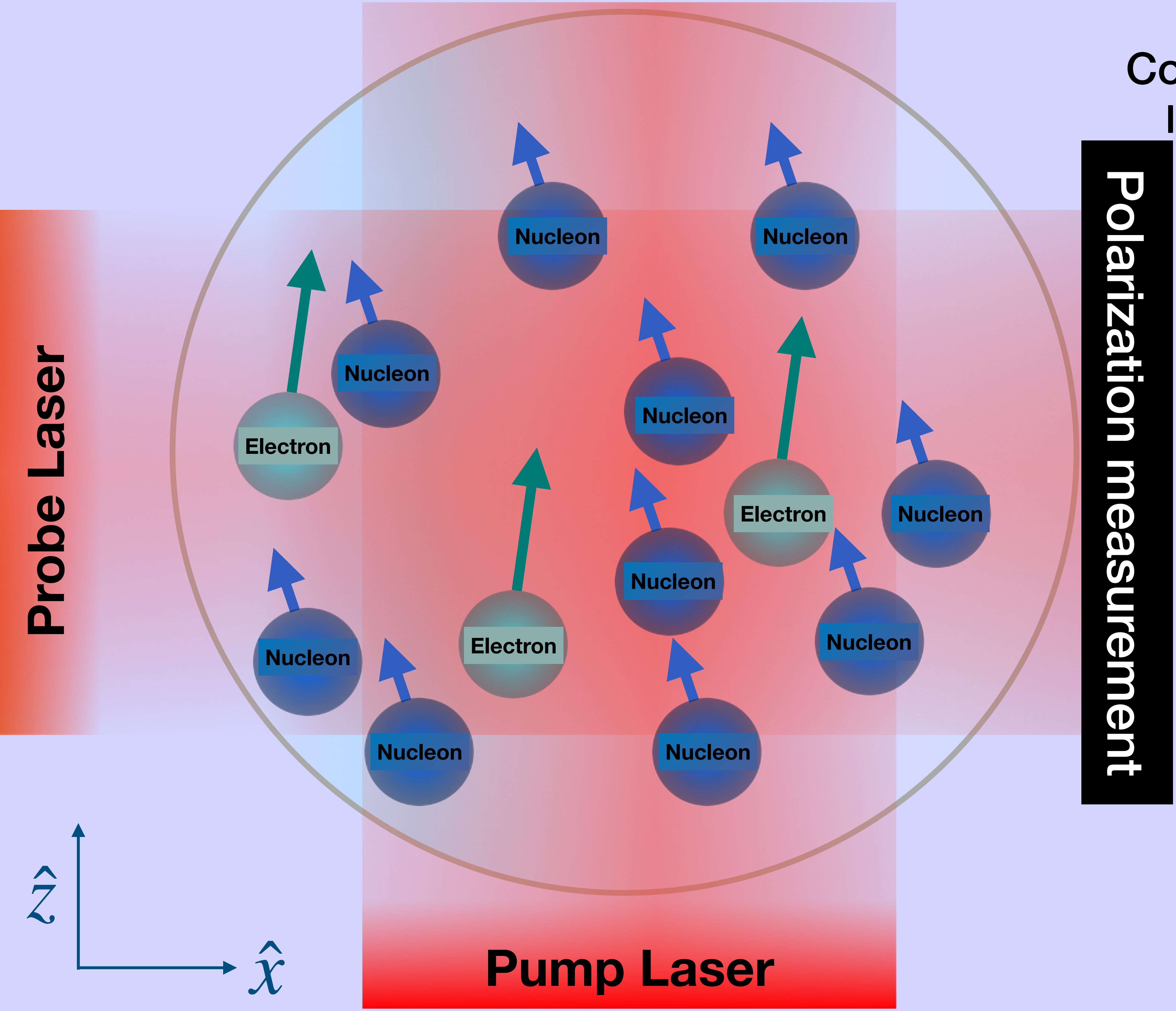

Comagnetometer
Ingredients List

Glass Cell

Alkali Vapor

Noble Gas

Lasers

Comagnetometer
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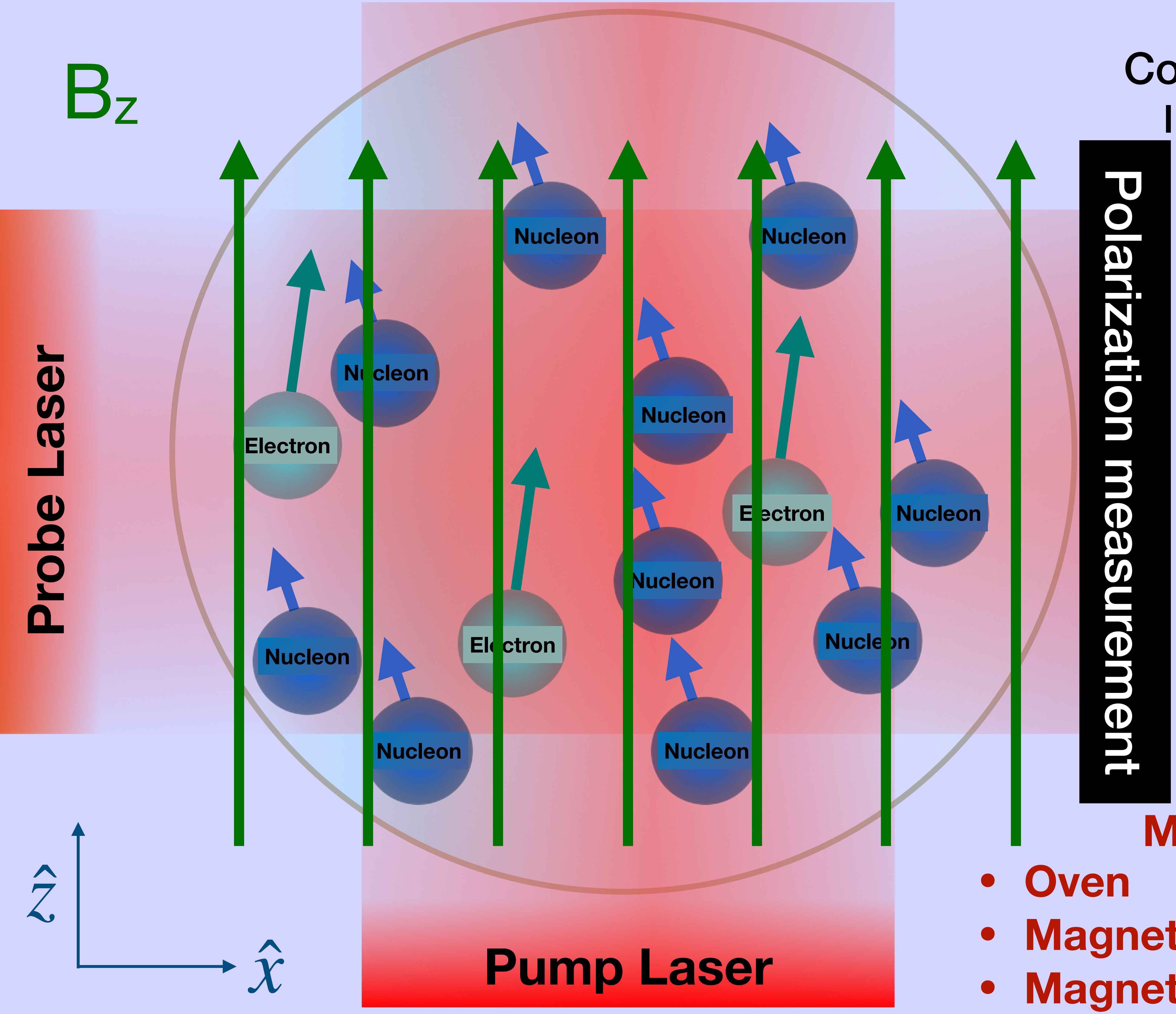

Glass Cell

Alkali Vapor

Noble Gas

Lasers

Misc:

- **Oven**
- **Magnetic Shields**
- **Magnetic Coils**
- **Optical Components**

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- ✓ **Noble-Alkali Comagnetometers**
  - Spin-Based Magnetometry
  - Why Noble-Alkali?
  - Old Results
  - NASDUCK
- **Conclusions**

Ultra Light ALP DM generates magnetic-like fields.

Magnetometers can measure ALPs. Alkali magnetometers are easy to work with, while Noble magnetometers are more sensitive.

“Compensation Point” Comagnetometer

[IMB, Y. Hochberg, E. Kuflik, T. Volansky. arxiv:1907.03767]

Response to Magnetic Noise

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

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

The Compensation Point

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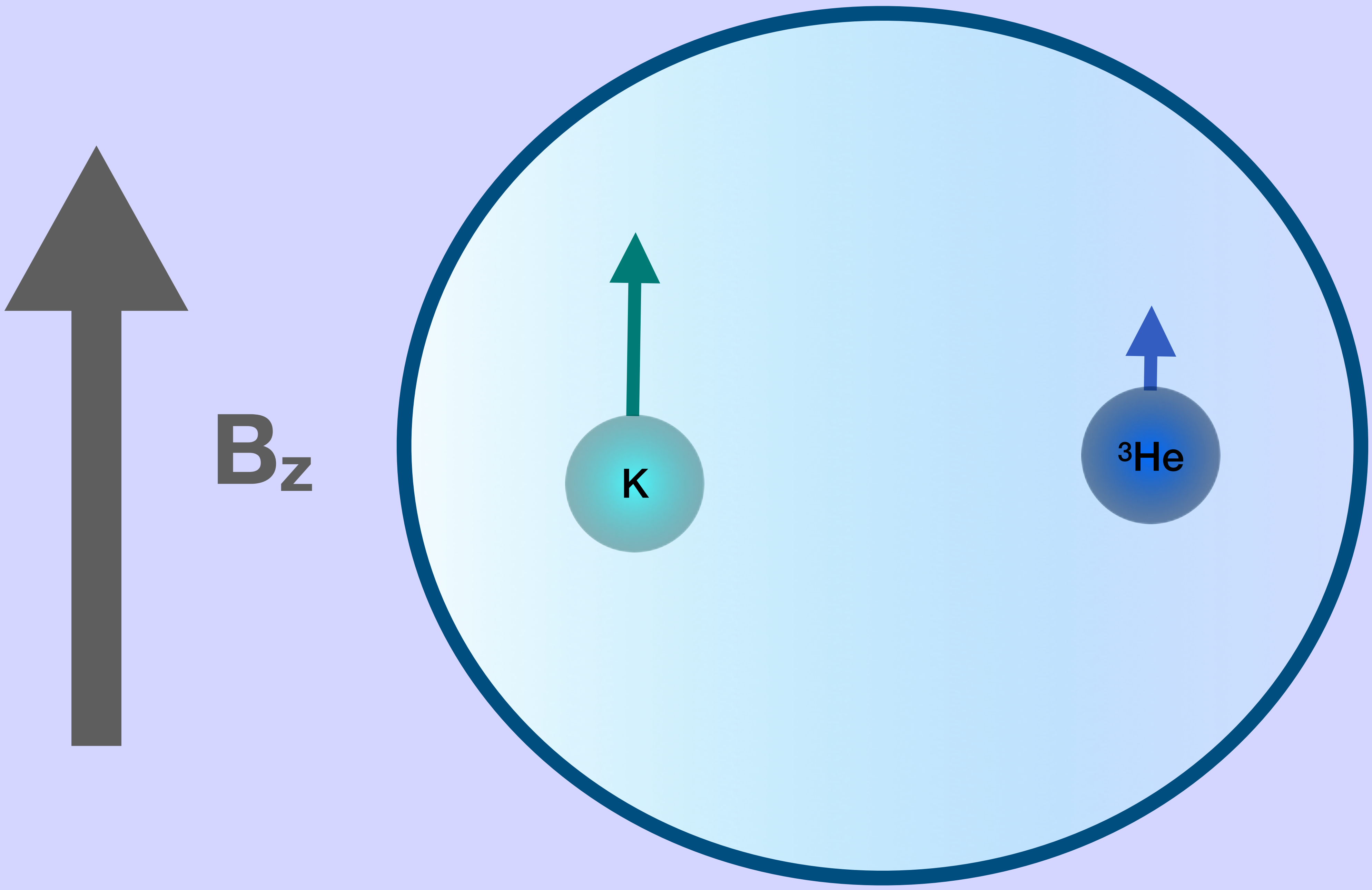
Let’s illustrate

Compensation Point Illustration (B)

- **A 2D heuristic illustration, so some artistic freedom was taken.**



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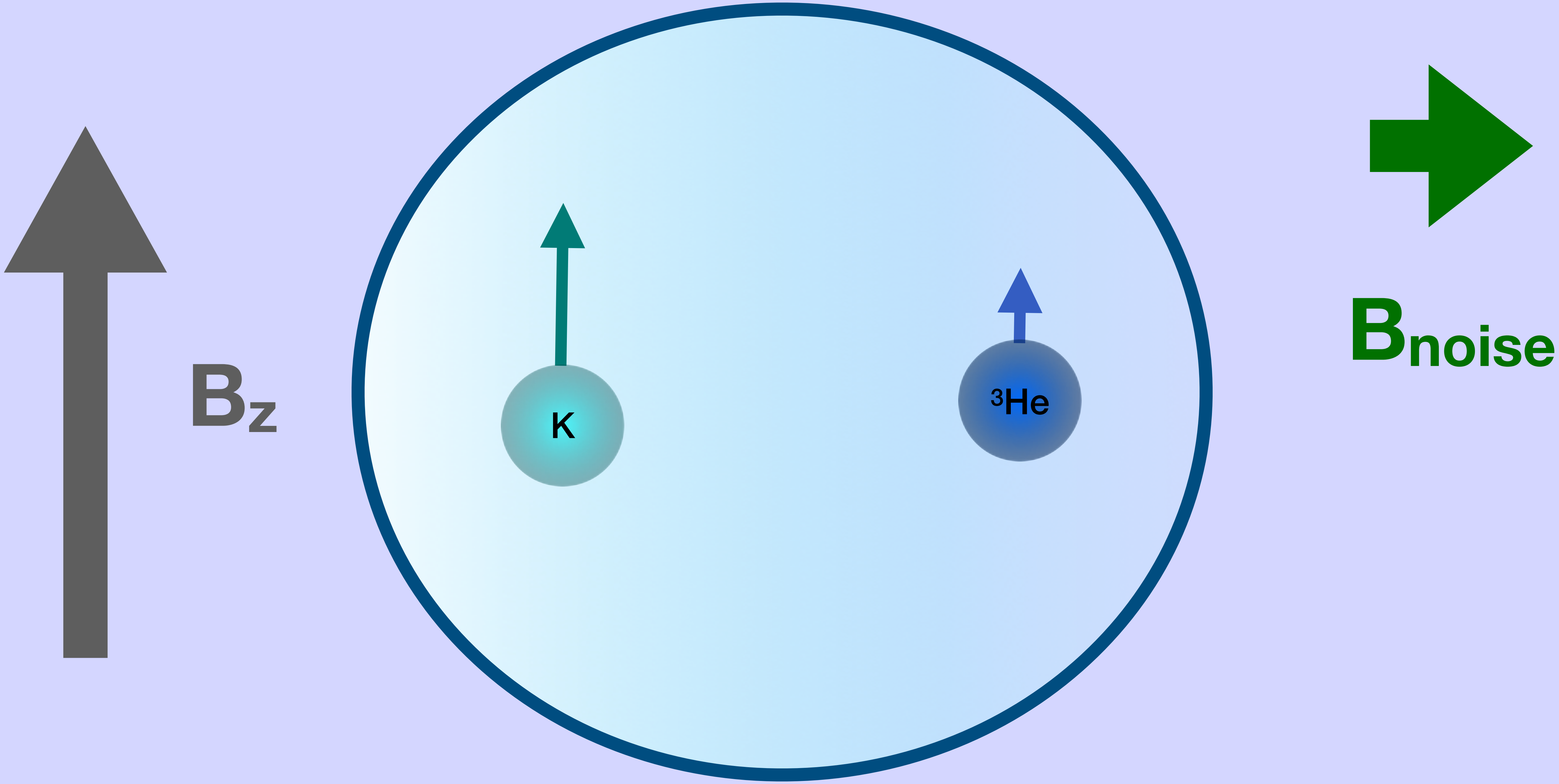

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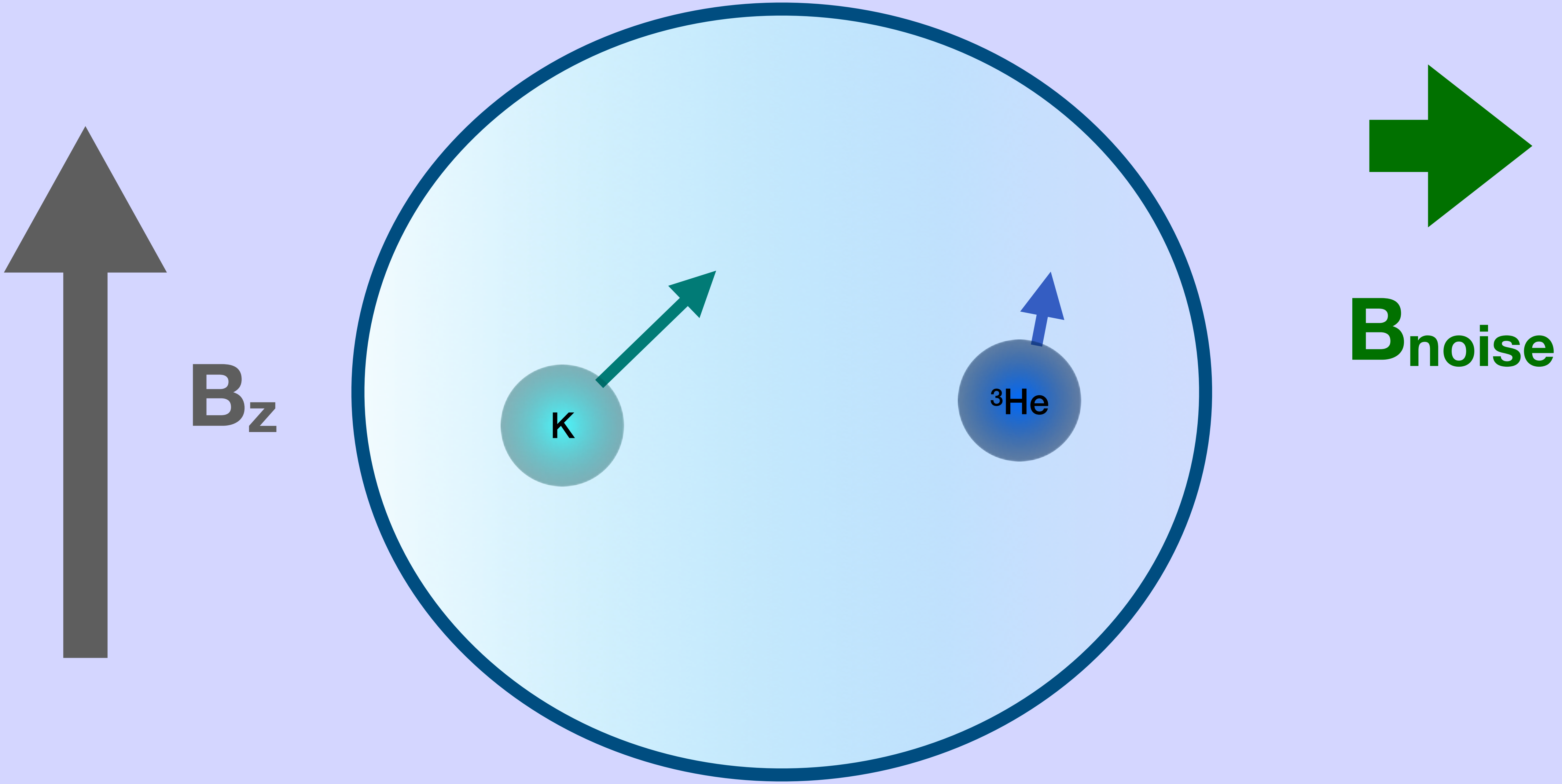

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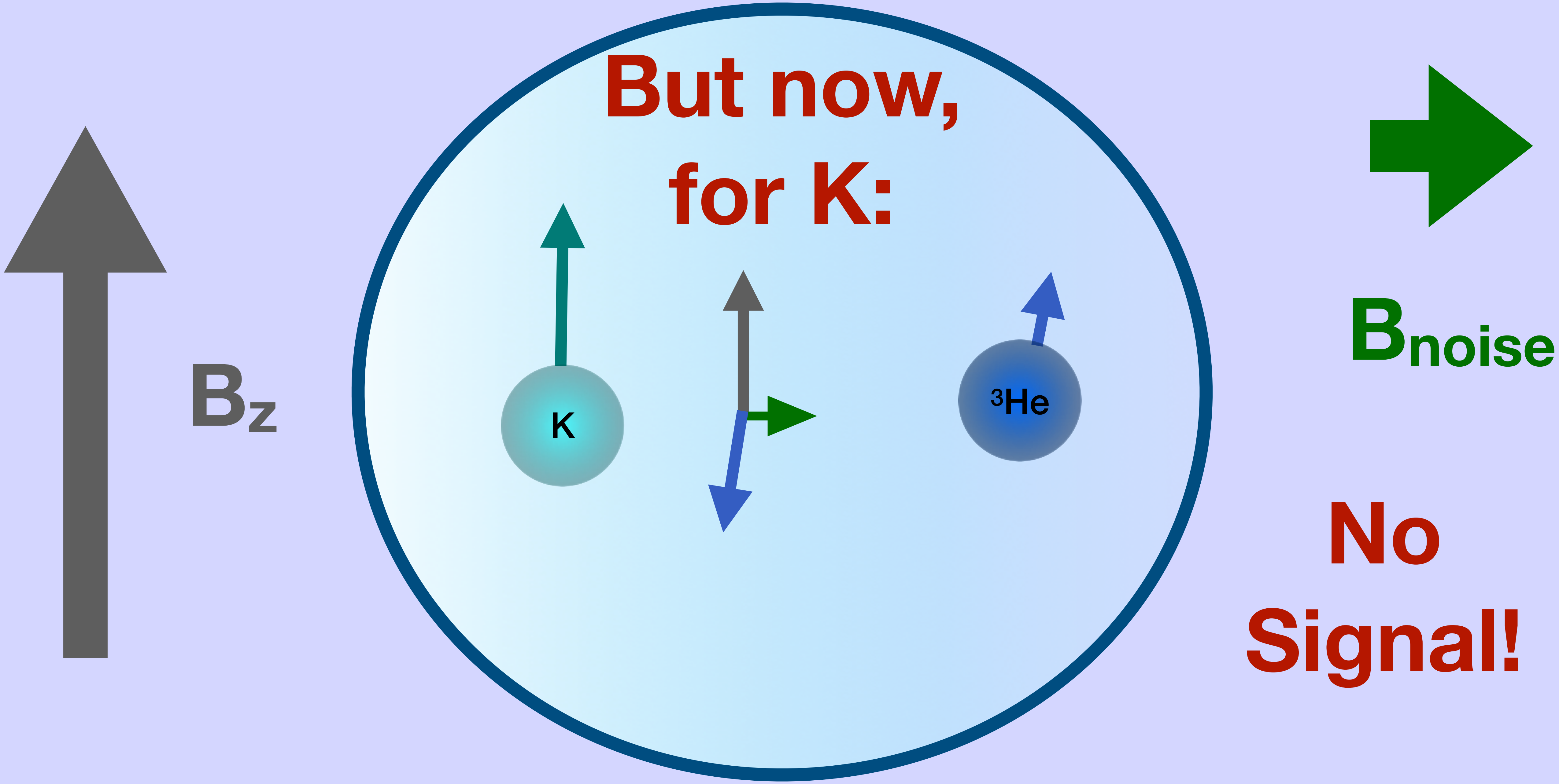

$$S_K^\perp \propto \gamma_K B_{tot}^\perp = \gamma_K B_{ind}^\perp + \gamma_K B_{noise}^\perp = 0!$$

Compensation Point Illustration (b_e)

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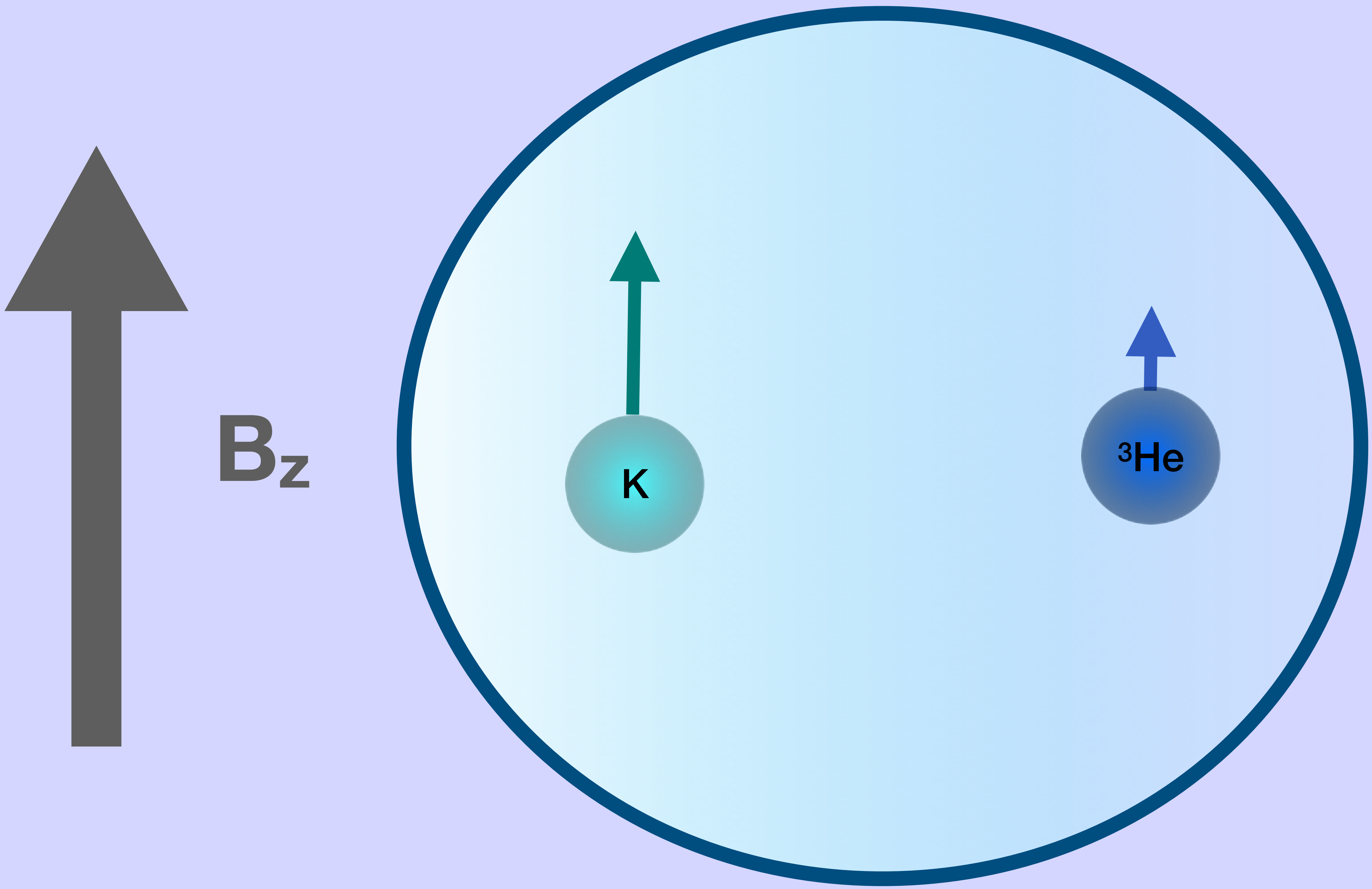

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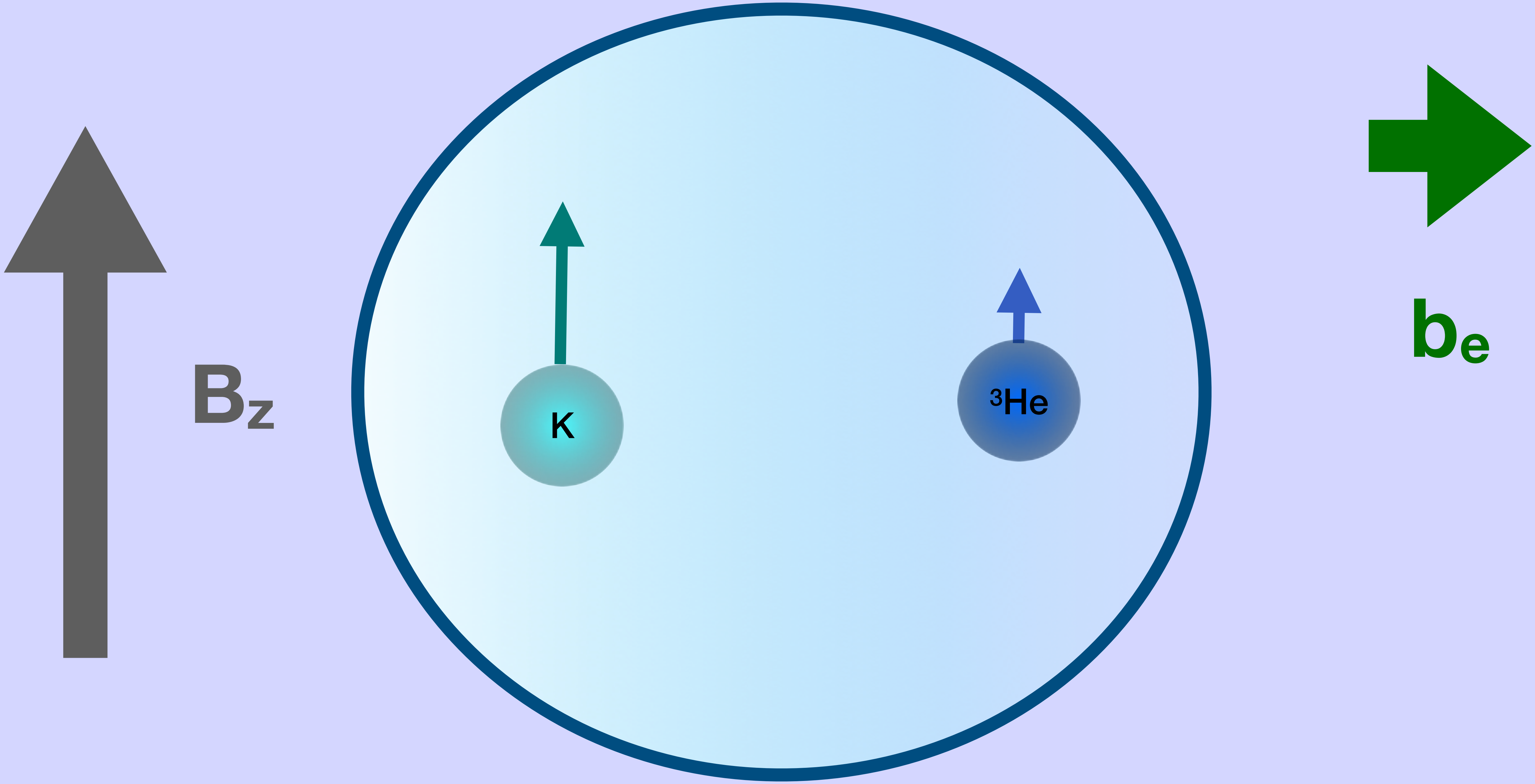

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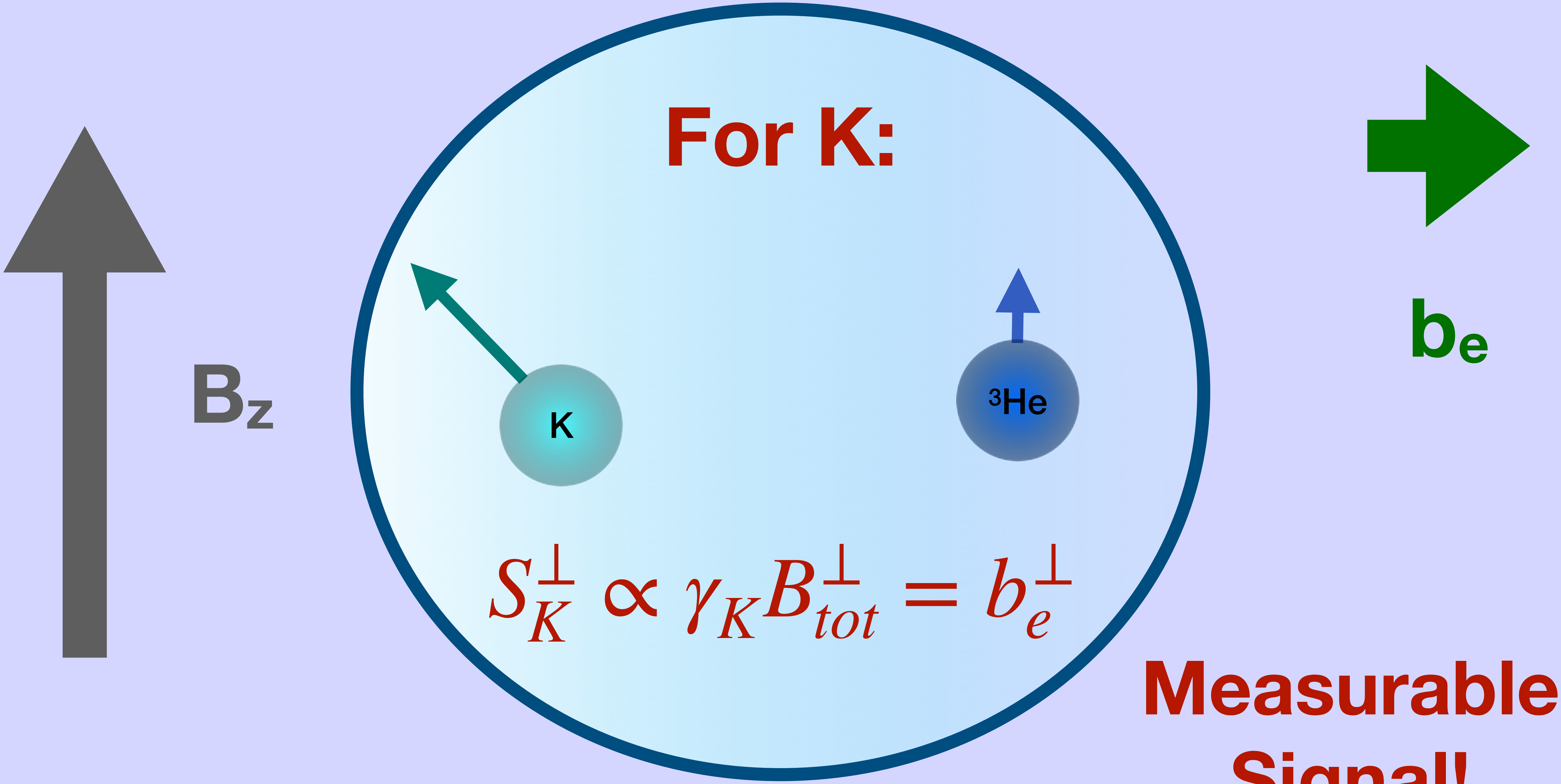

For K:

$$S_K^{\perp} \propto \gamma_K B_{tot}^{\perp} = b_e^{\perp}$$

Measurable Signal!

Compensation Point Illustration (b_n)

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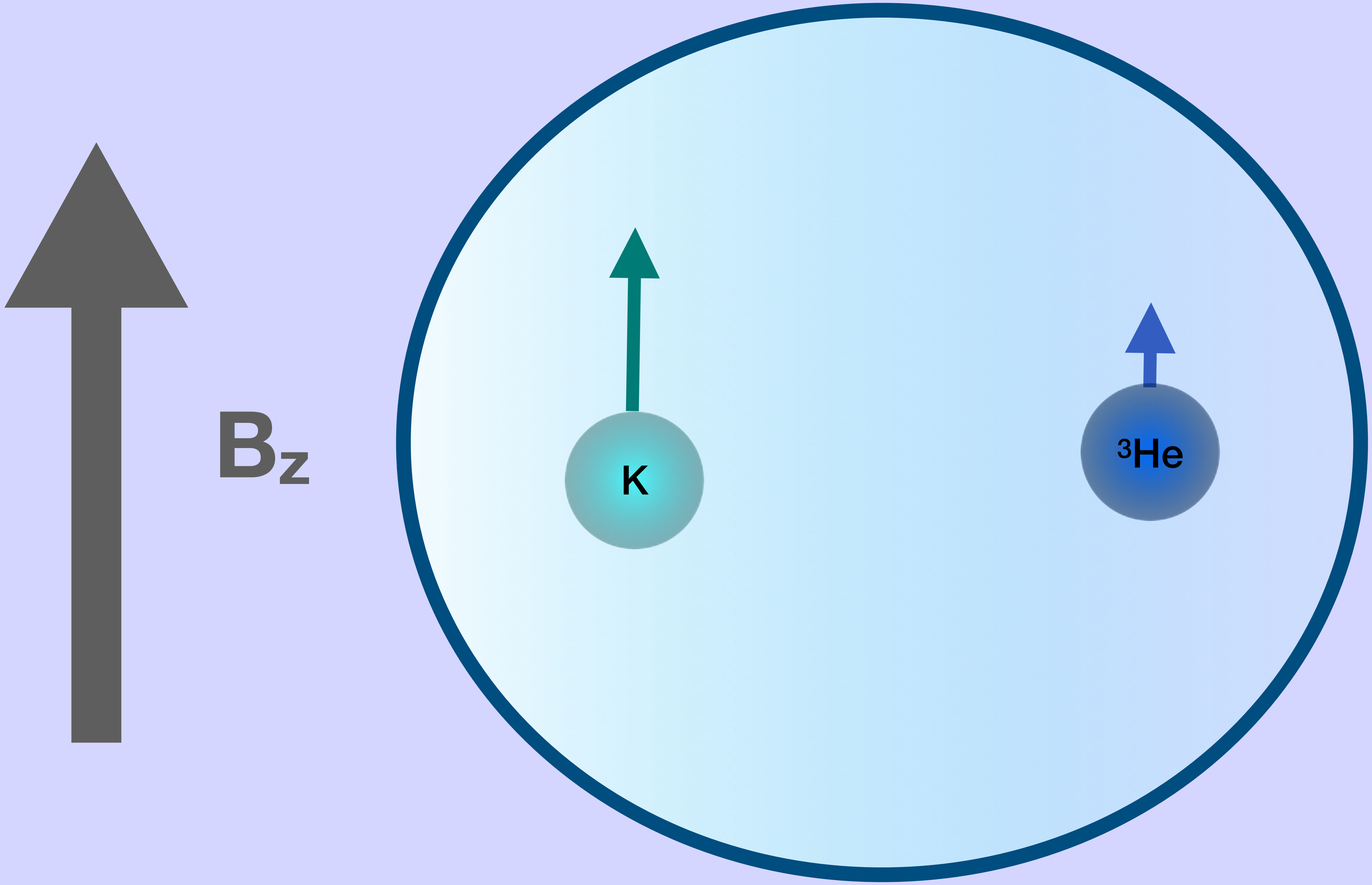

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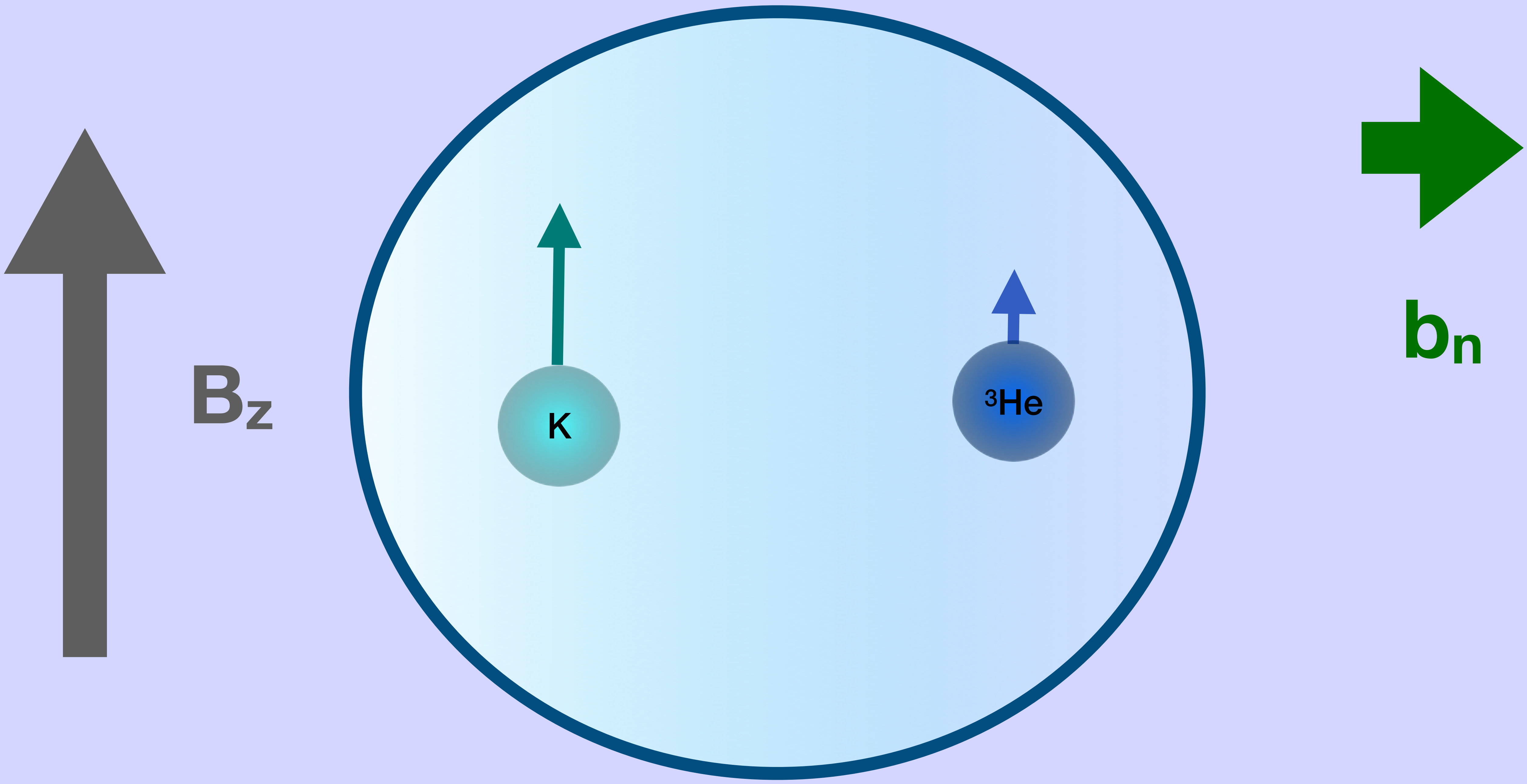

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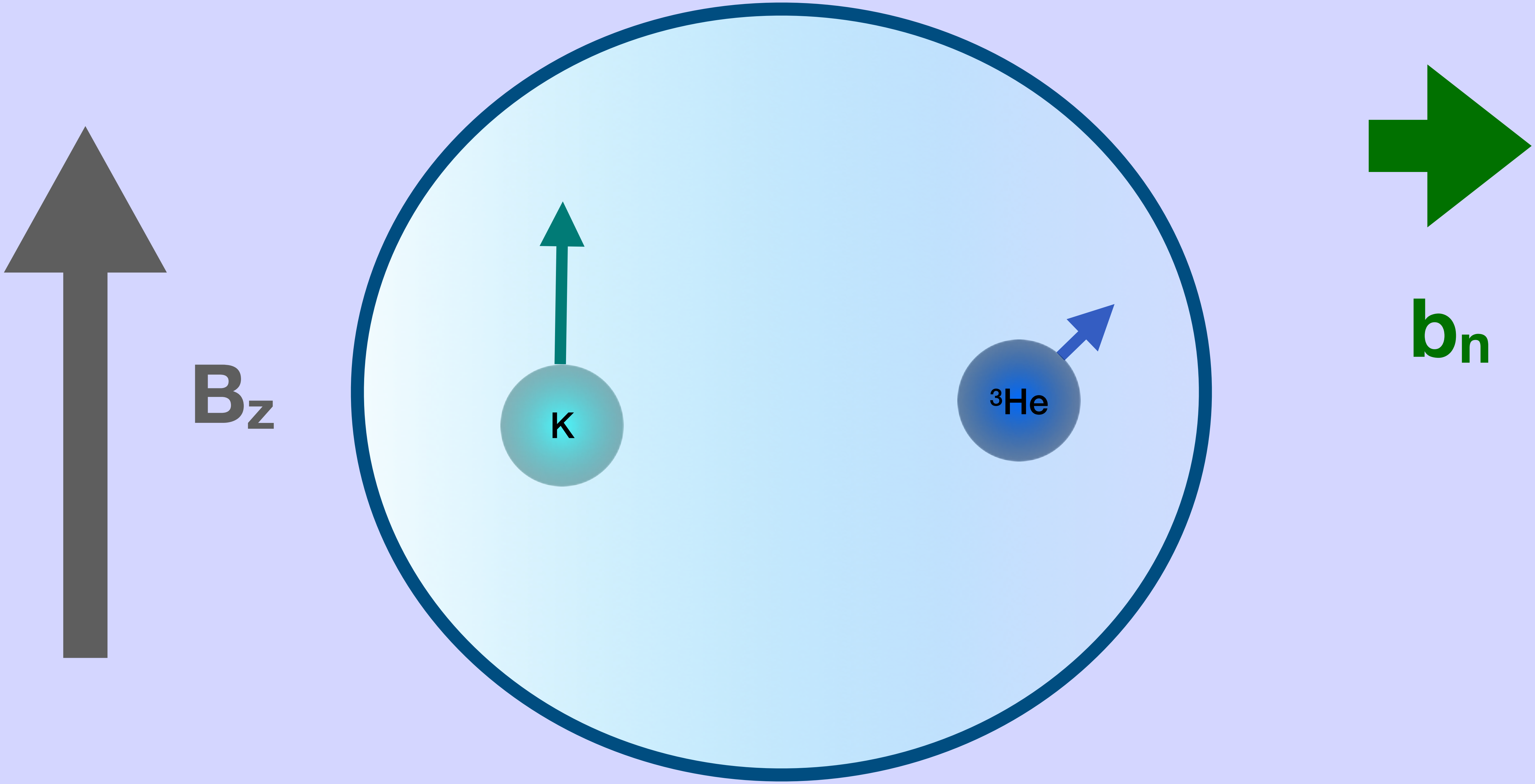

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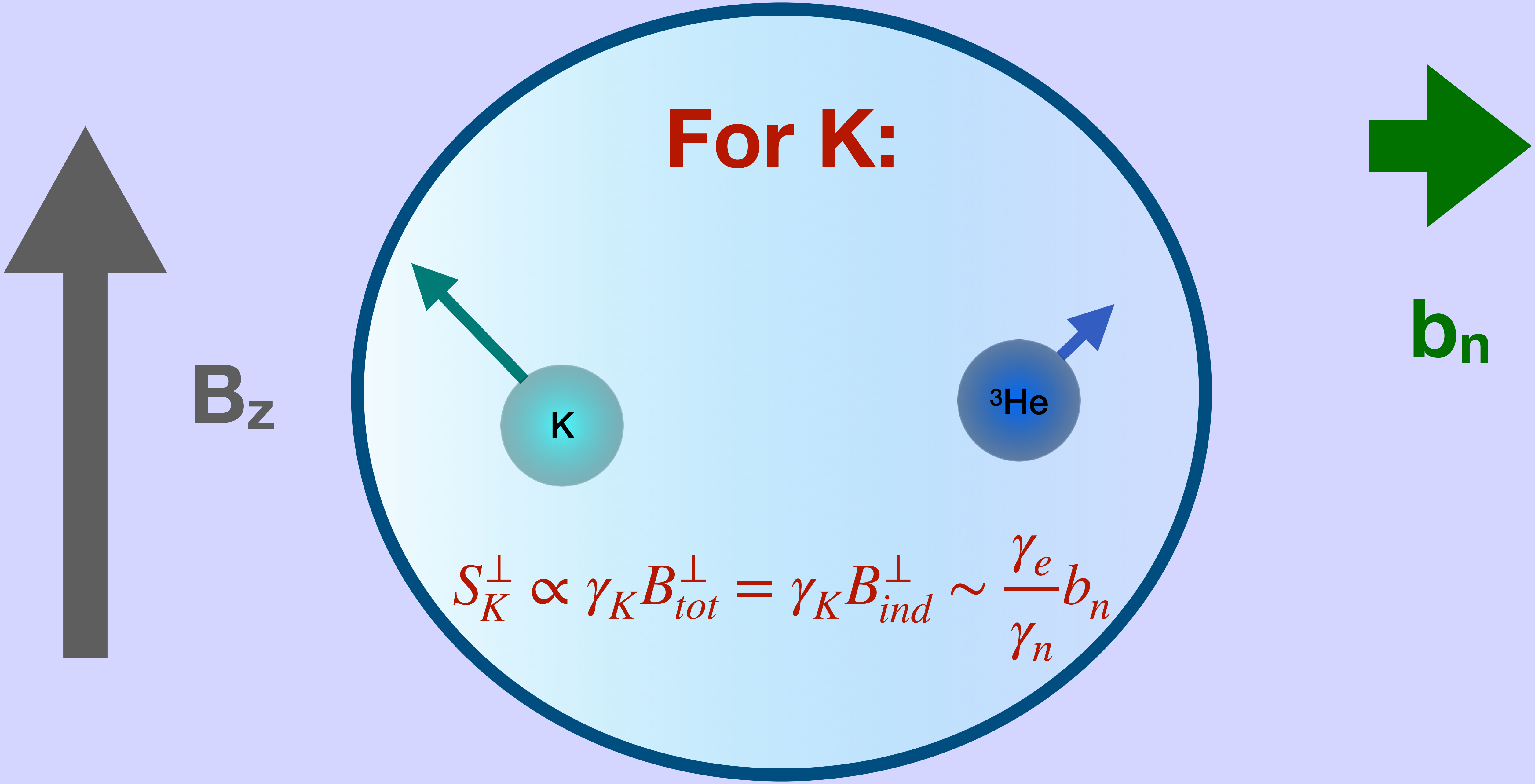
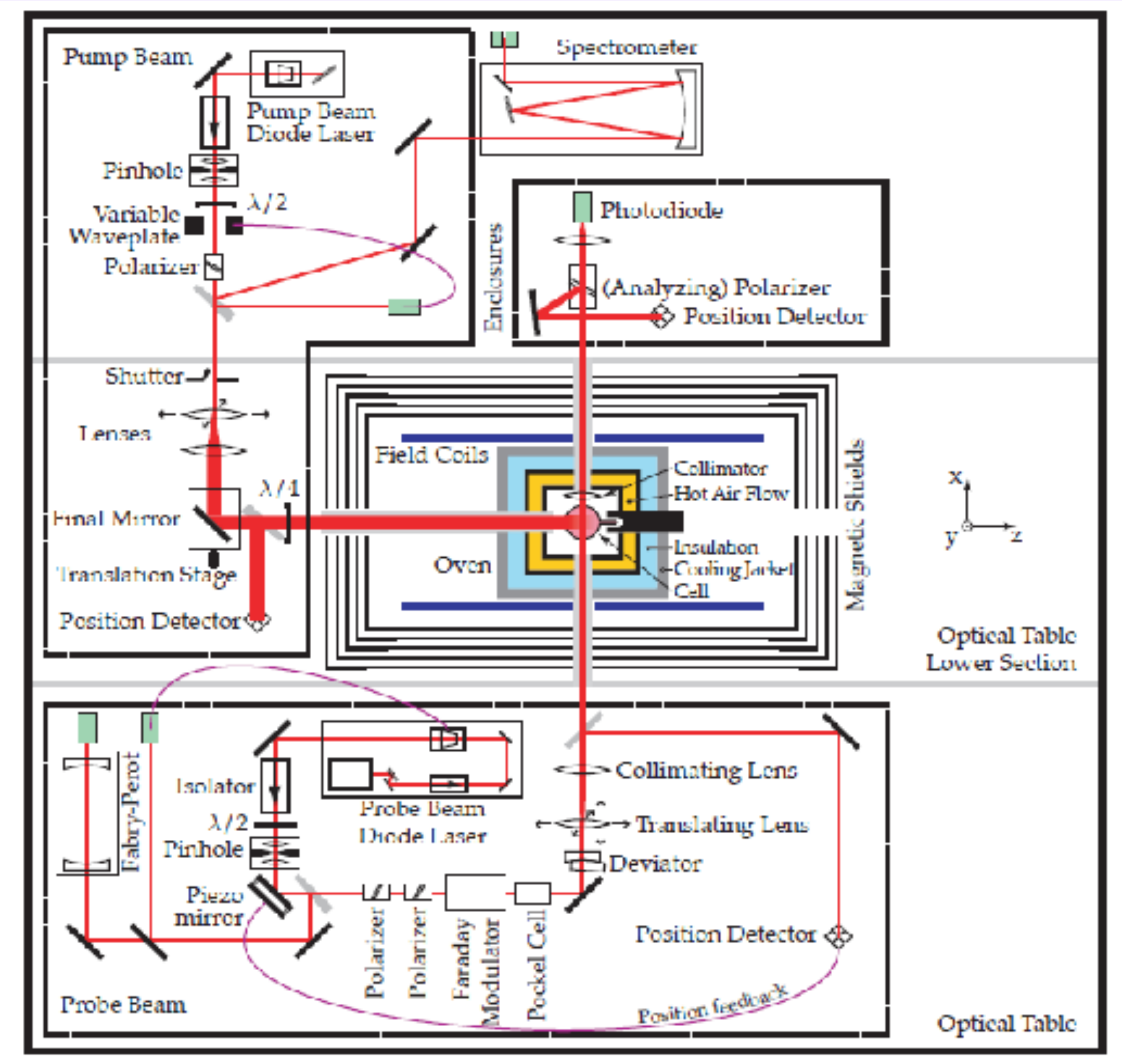
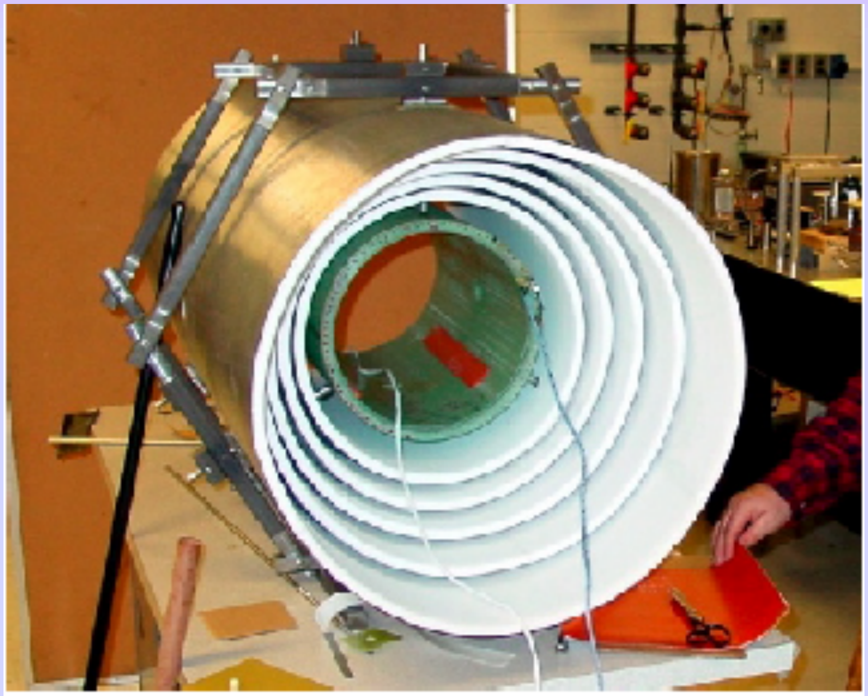


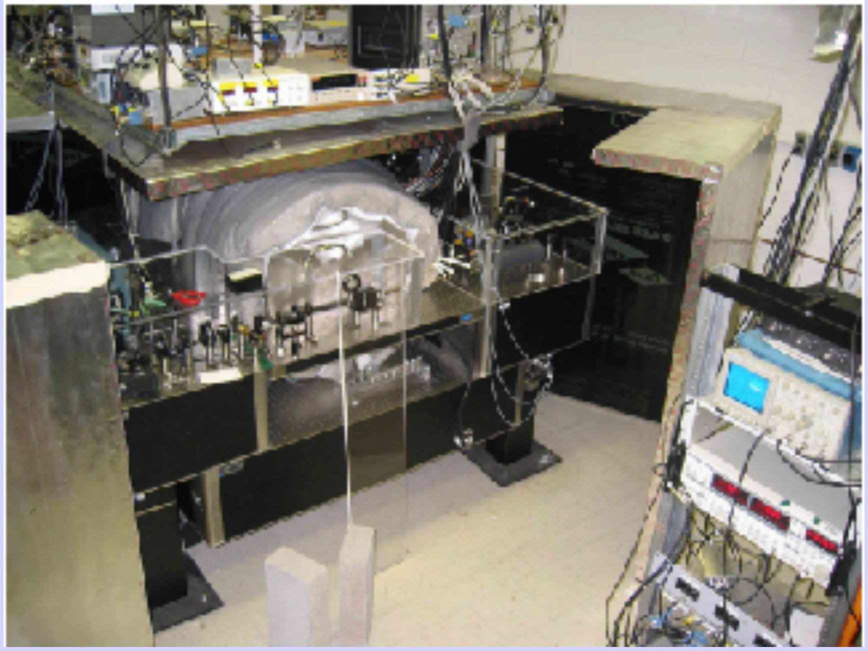
$$S_K^{\perp} \propto \gamma_K B_{tot}^{\perp} = \gamma_K B_{ind}^{\perp} \sim \frac{\gamma_e}{\gamma_n} b_n$$

Measurable, Enhanced Signal!

The Romalis Group Comags

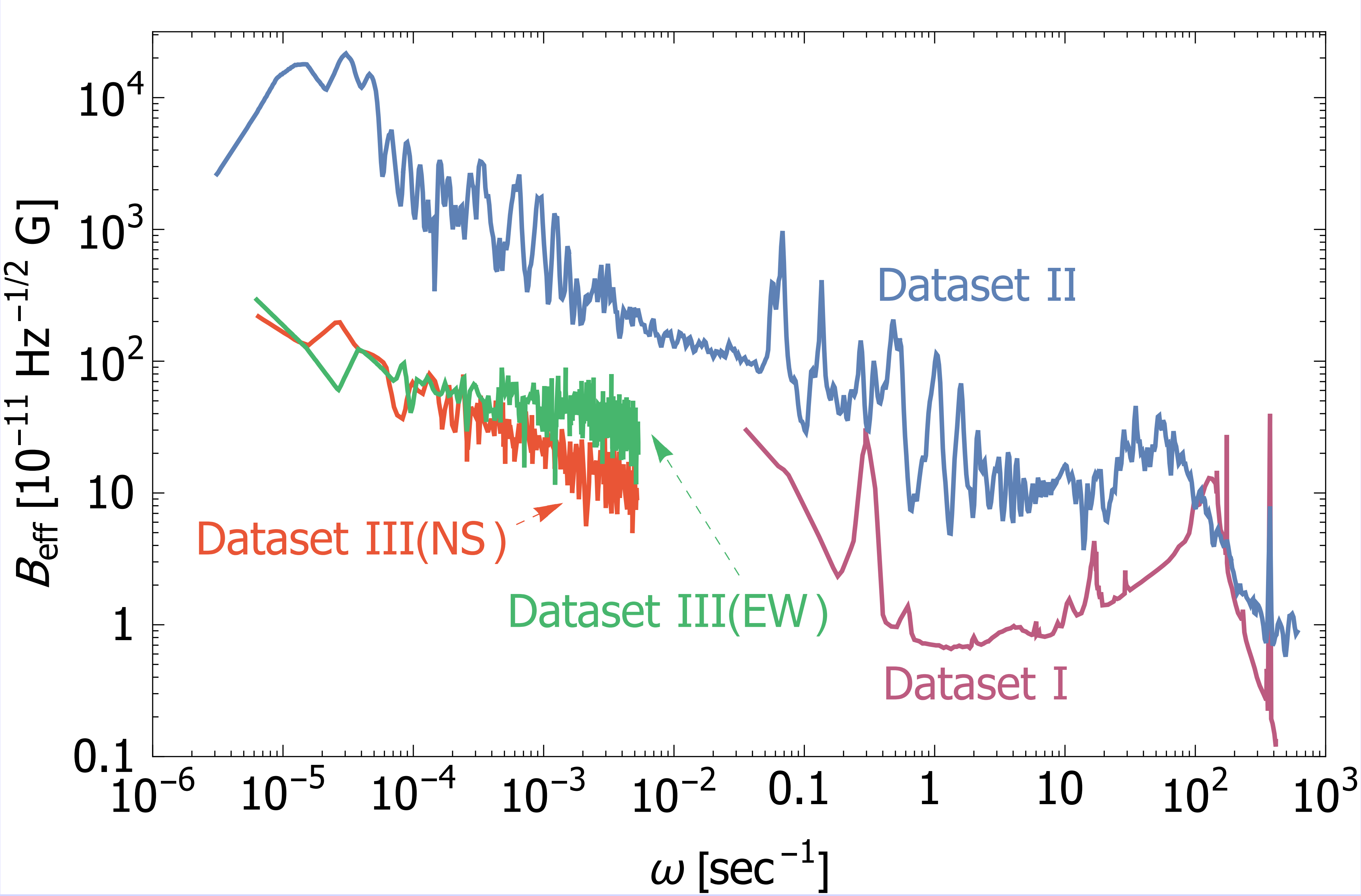




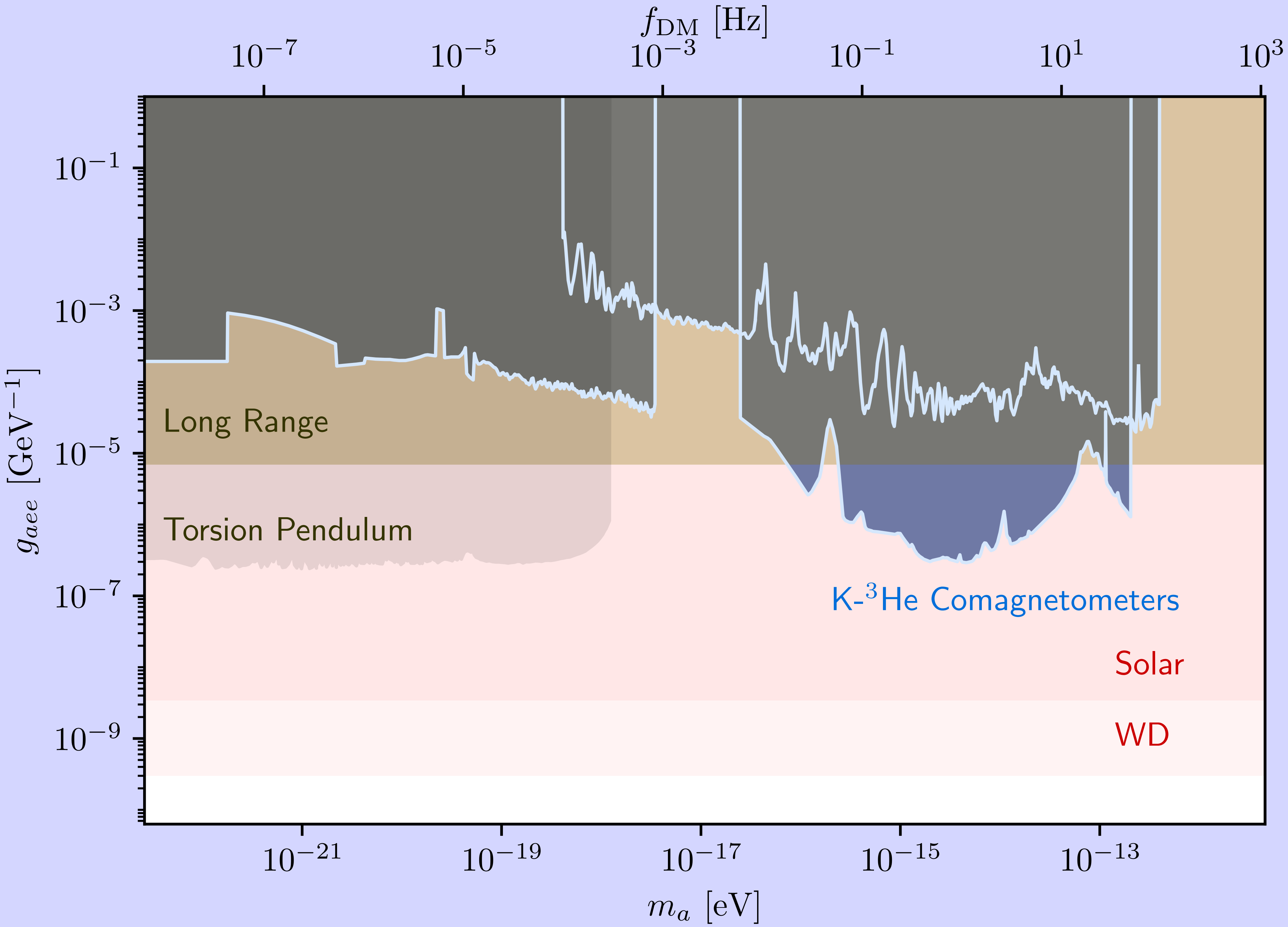


[Gergoios Vasilakis Dissertation 2011], [Justin M. Brown Dissertation 2011], [Thomas W. Kornack Dissertation 2005]

Old Data

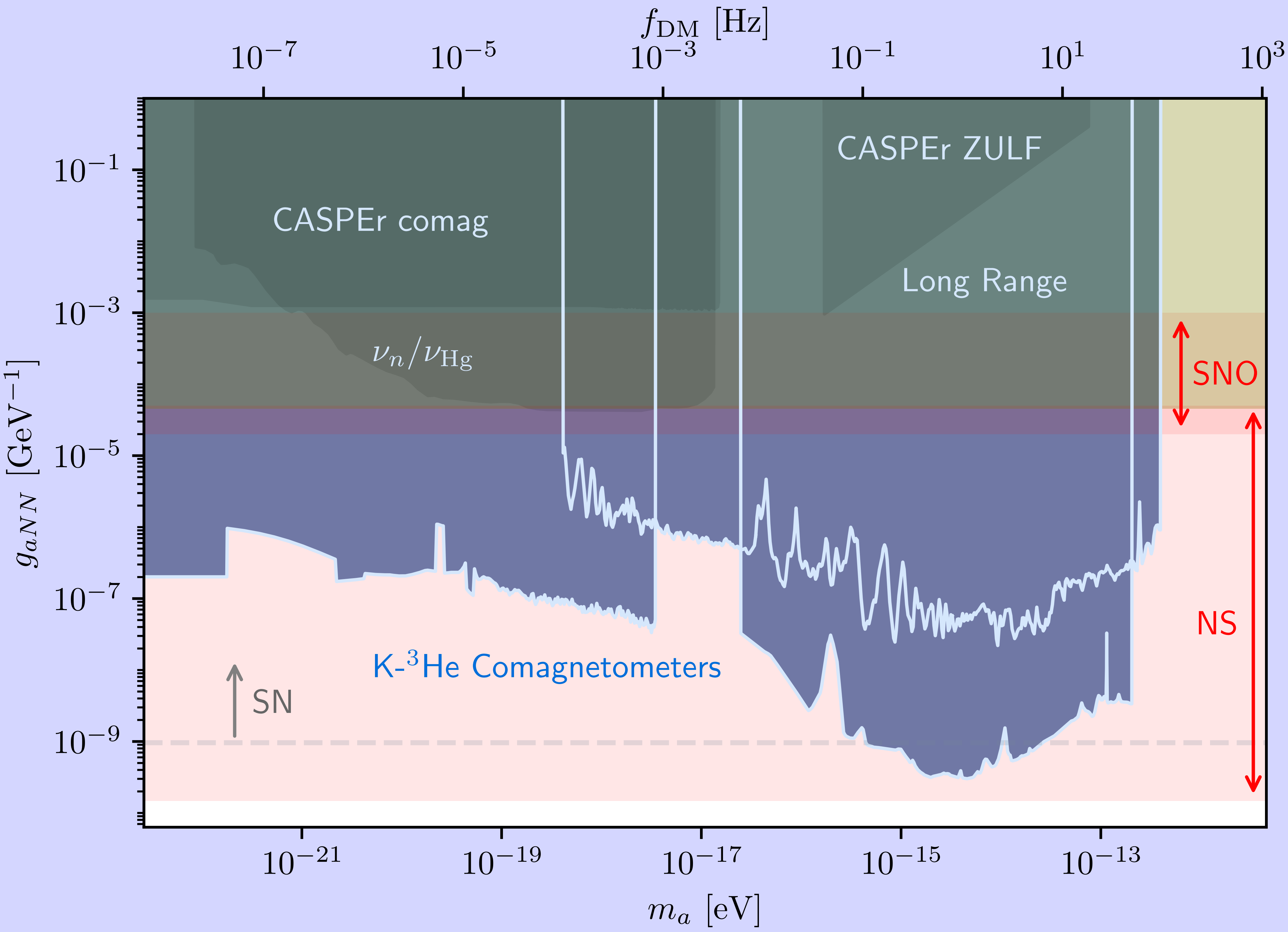

$B_{\rm eff}$ [10^{-11} Hz$^{-1/2}$ G]
10^4
10^3
10^2
10
1
0.1
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
ω [sec^{-1}]
Dataset II
Dataset III(NS)
Dataset III(EW)
Dataset I

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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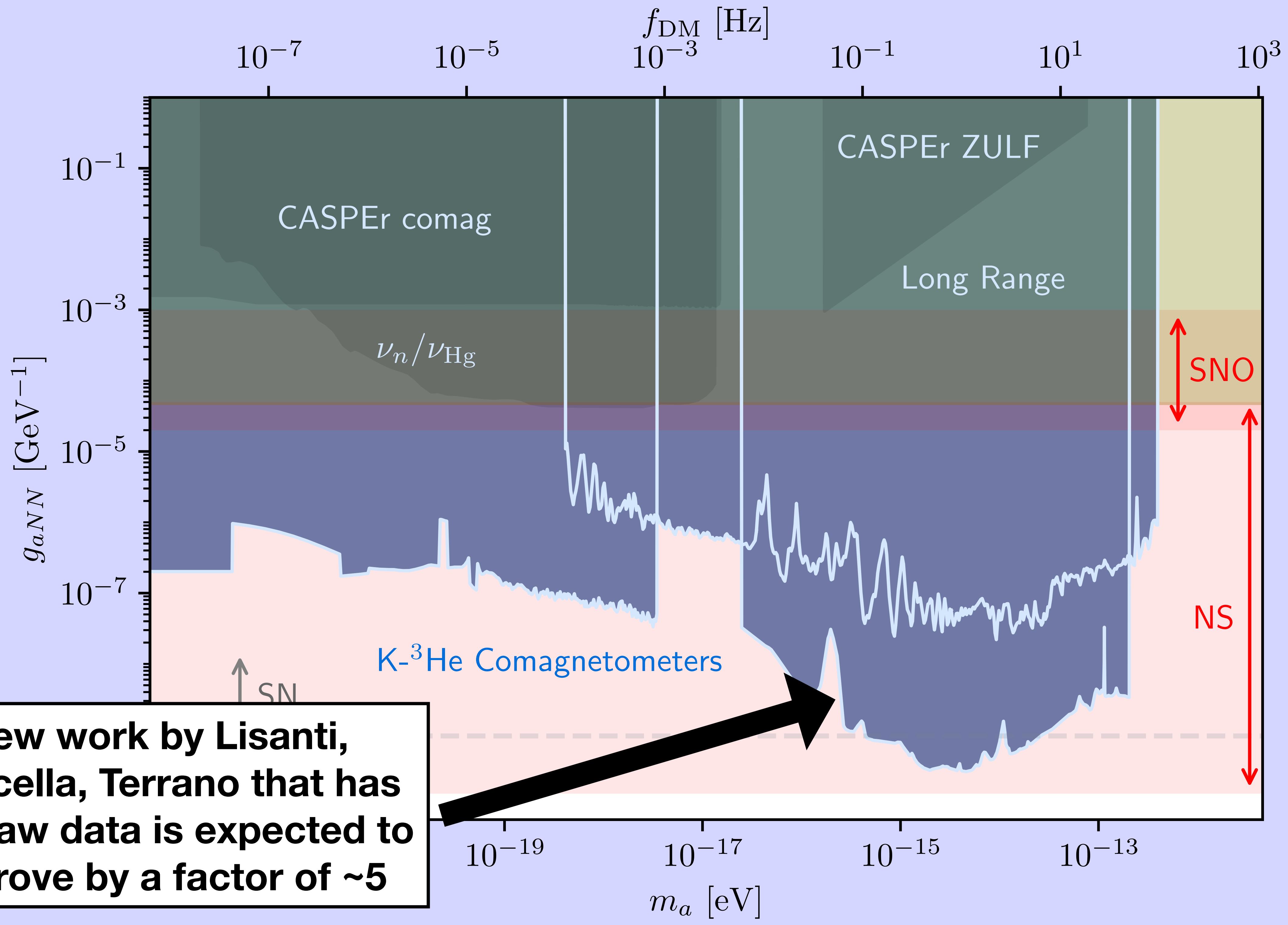

New work by Lisanti, Moscella, Terrano that has the Raw data is expected to improve by a factor of ~5

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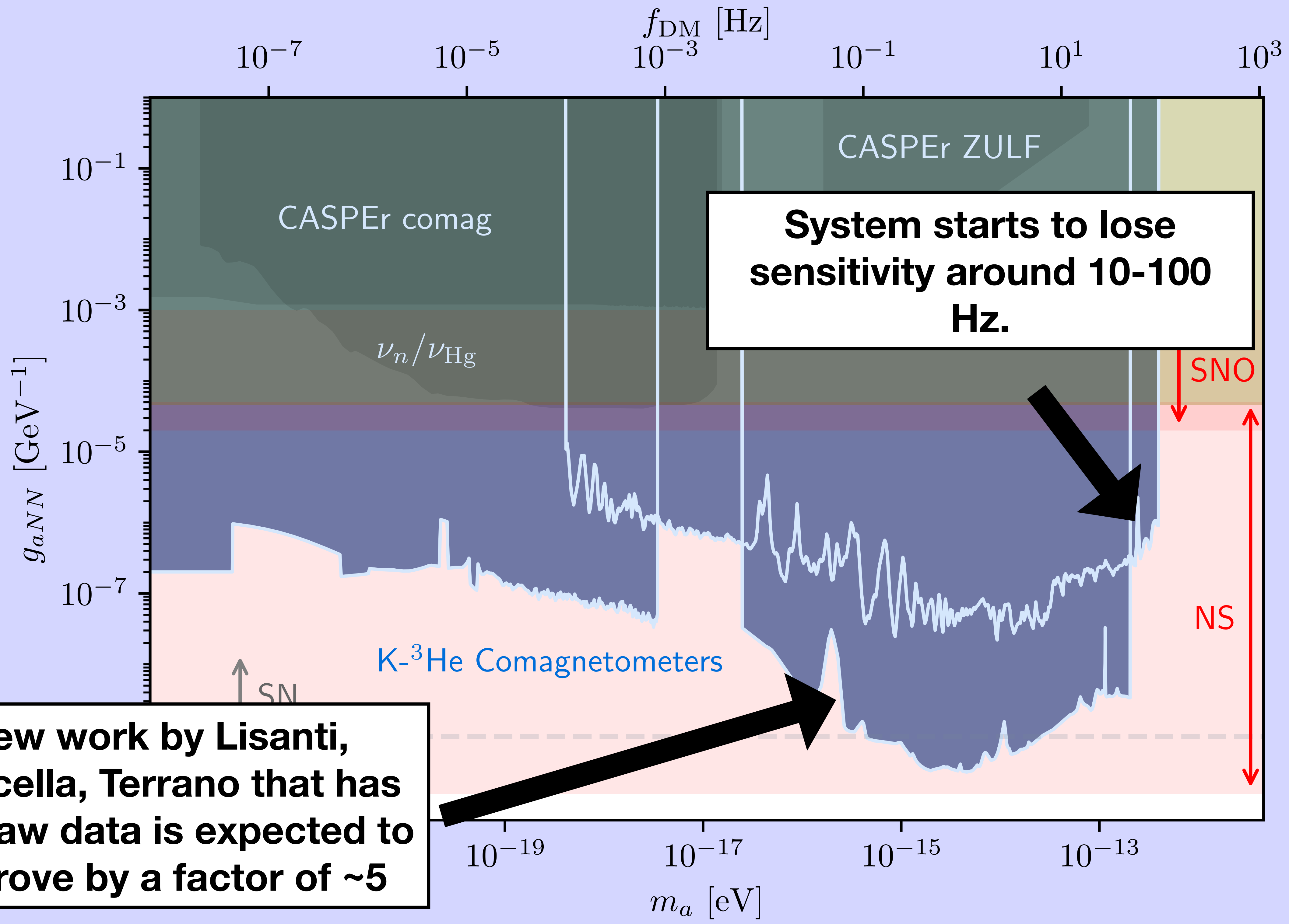

System starts to lose sensitivity around 10-100 Hz.

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

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Noble and Alkali Spin Detectors for Ultralight Coherent darK matter

NASDUCK

[**IMB**, Y. Hochberg, O. Katz, O. Katz
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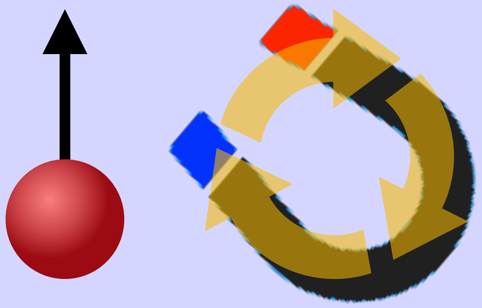
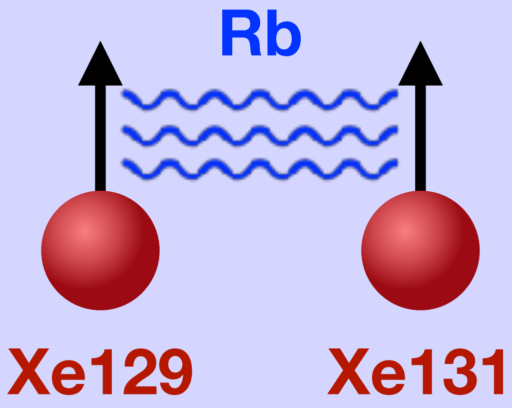
NASDUCK Experiments

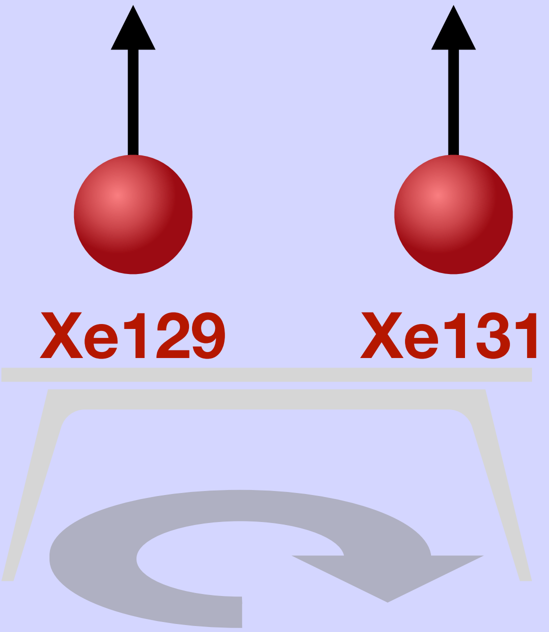


NASDUCK Floquet

[NASDUCK, 2105.04603]

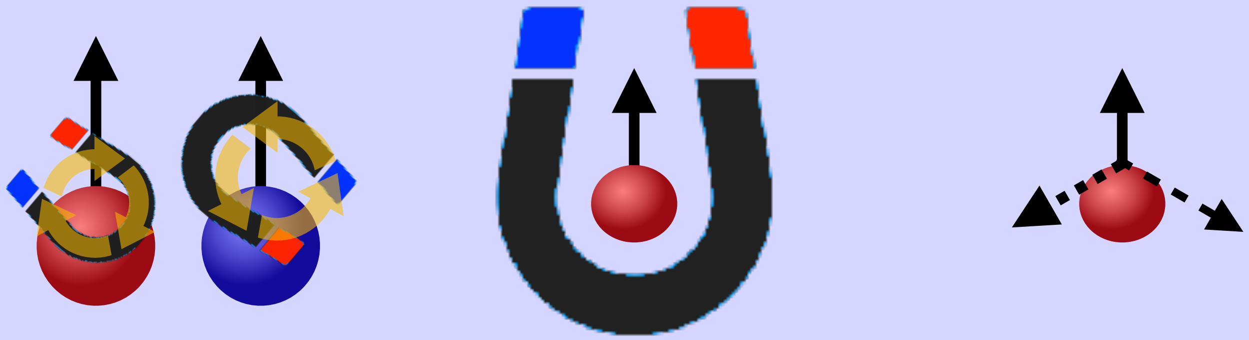


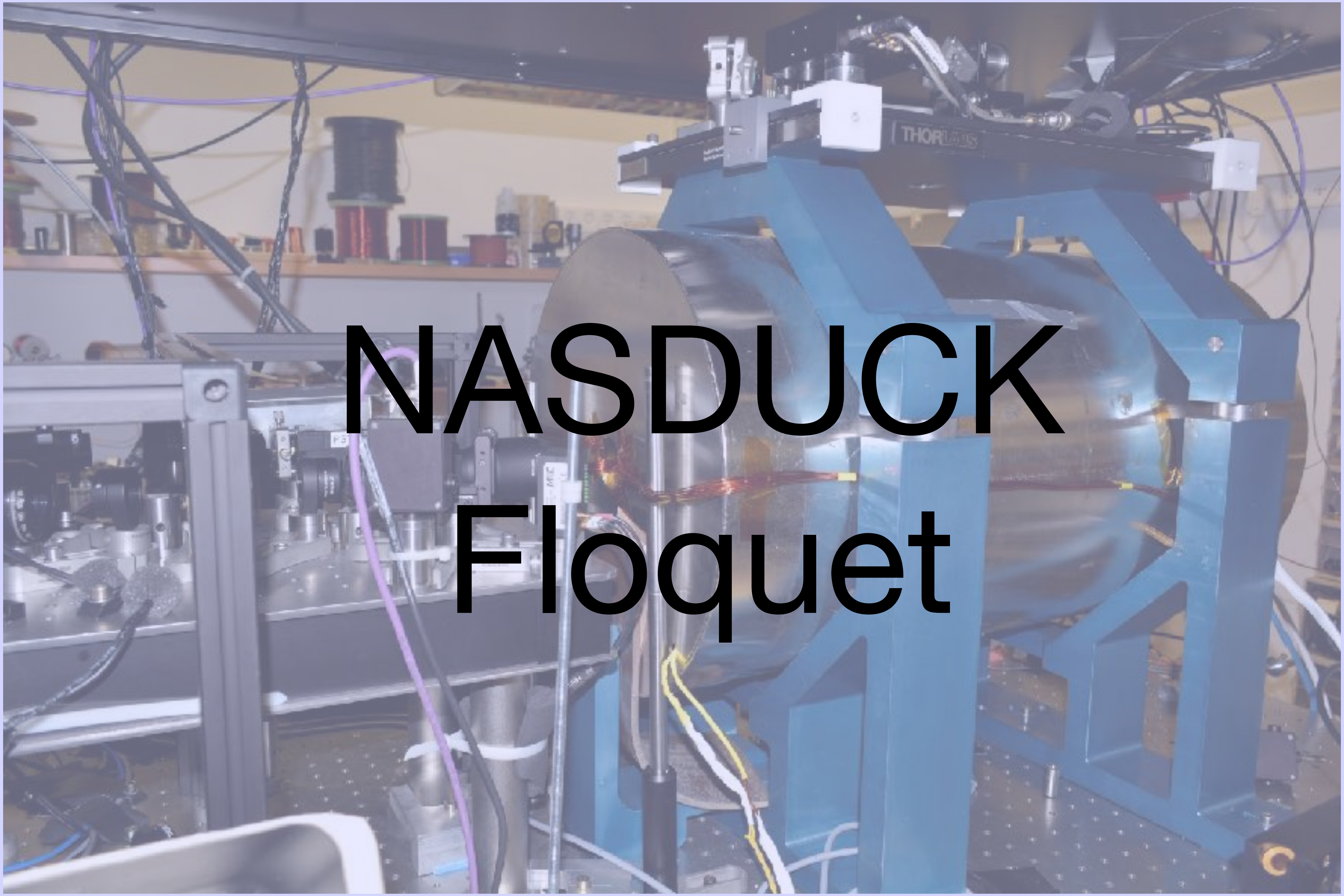
NASDUCK
“Cocomag”



NASDUCK
Modulated

And more!





NASDUCK
Floquet

Response to Signal

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

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$$\frac{\gamma_{\mathrm{Alk}} \lambda M_{\mathrm{Nob}} S_{\mathrm{z,Alk}}}{\left((\gamma_{\mathrm{Alk}} B_{\mathrm{z,Alk}} - m_a) + i\Gamma_{\mathrm{Alk}}\right)} \frac{b_{\perp,\mathrm{ALP-Nob}}}{\left((\gamma_{\mathrm{Nob}} B_{\mathrm{z,Nob}} - m_a) + i\Gamma_{\mathrm{Nob}}\right)}$$

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Alkali response

Noble response

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Alkali response **Noble response**

$$|\gamma_{\mathrm{Alk}}| \gg |\gamma_{\mathrm{Nob}}|, B_{\mathrm{z,Alk}} = B_{\mathrm{z,Nob}} + c$$

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Alkali response **Noble response**

$$|\gamma_{\mathrm{Alk}}| \gg |\gamma_{\mathrm{Nob}}|, B_{\mathrm{z,Alk}} = B_{\mathrm{z,Nob}} + c$$

For large magnetic fields (=high frequencies), we cannot be in resonance for both the alkali and the noble simultaneously!

$$\left| \frac{\gamma_{\mathrm{Alk}} B_{\mathrm{z,Alk}}}{\gamma_{\mathrm{Nob}} B_{\mathrm{z,Nob}}} \right| \gg 1$$

Floquet Fields

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$$S_{\text{Alk}}(\omega = m_a + \omega_F) = \eta_F^{(1)} \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}(\omega = m_a)}{(\gamma_{\text{Nob}} B_{\text{z,Nob,0}} - m_a) + i\Gamma_{\text{Alk}}}$$

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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!

NASDUCK Floquet

NASDUCK Floquet

For each measurement, we only get bounds on

$$|m_a - \gamma_{\mathrm{Nob}} B_{\mathrm{z,Nob,0}}| < \mathcal{O}(1)\Gamma_{\mathrm{Nob}}$$

Therefore, nearly 3000 measurements were taken during a 5-months period

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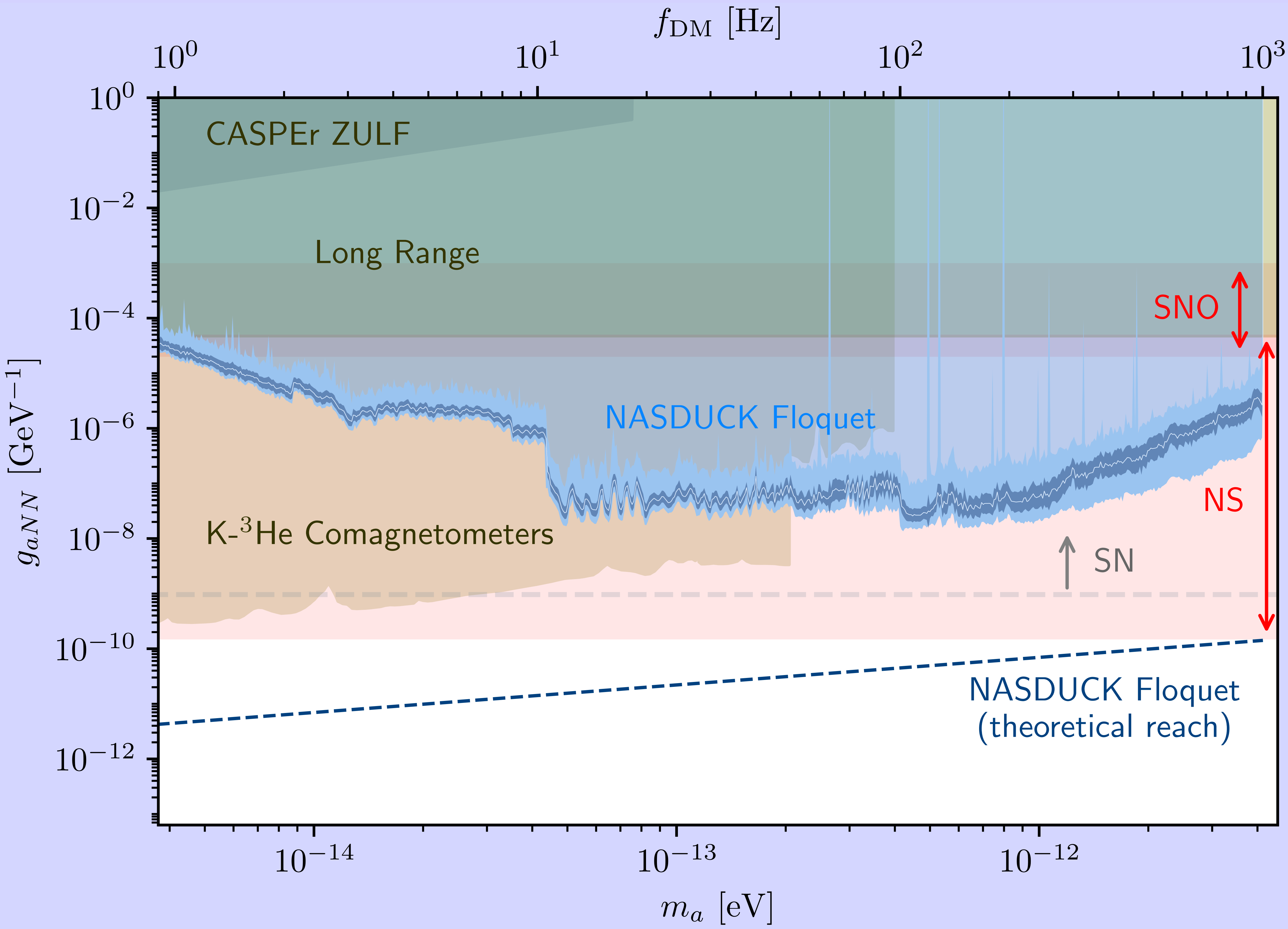
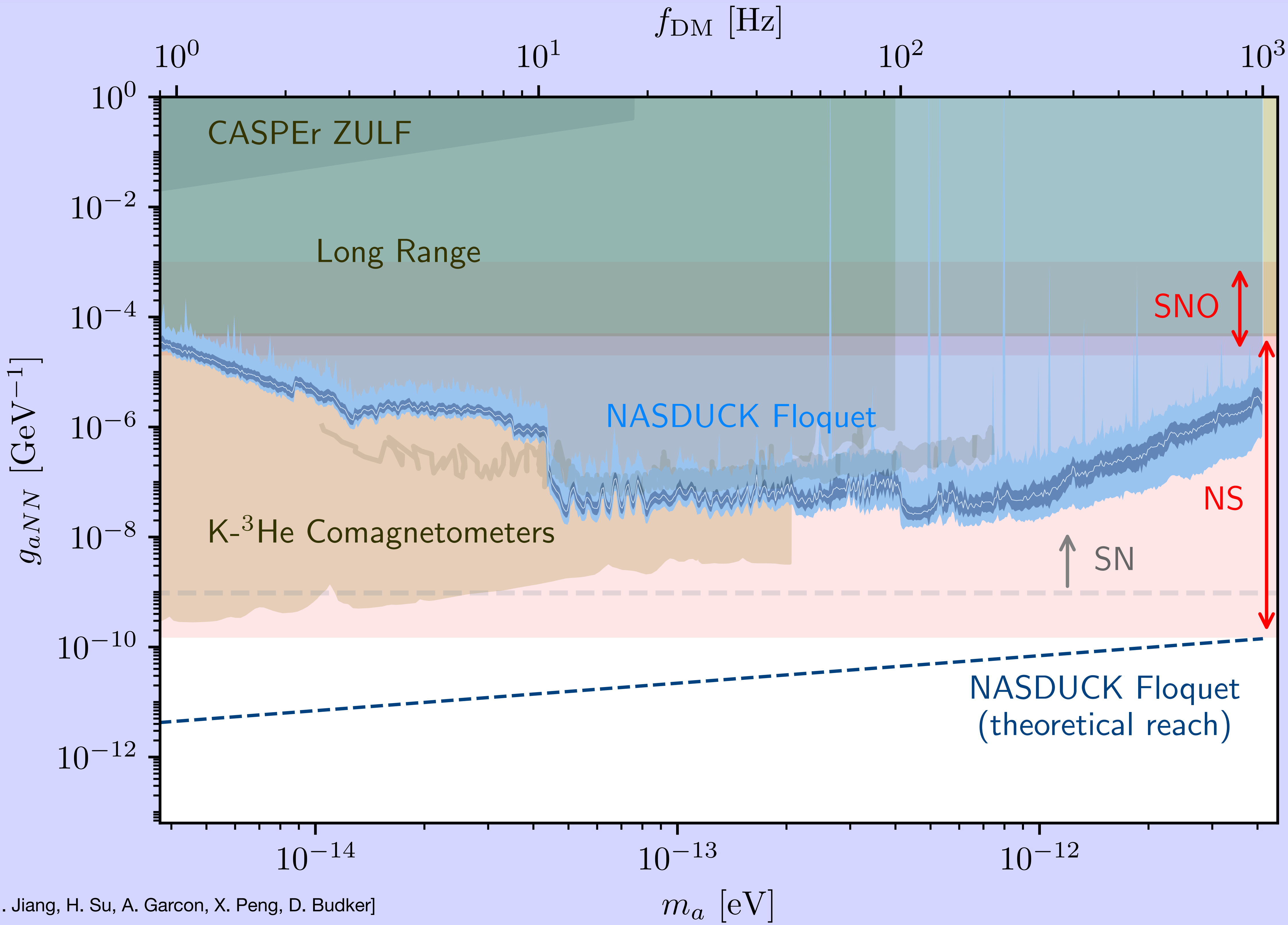
↓

An improvement by an order of magnitude should not be too difficult*

NASDUCK Floquet Results (n)

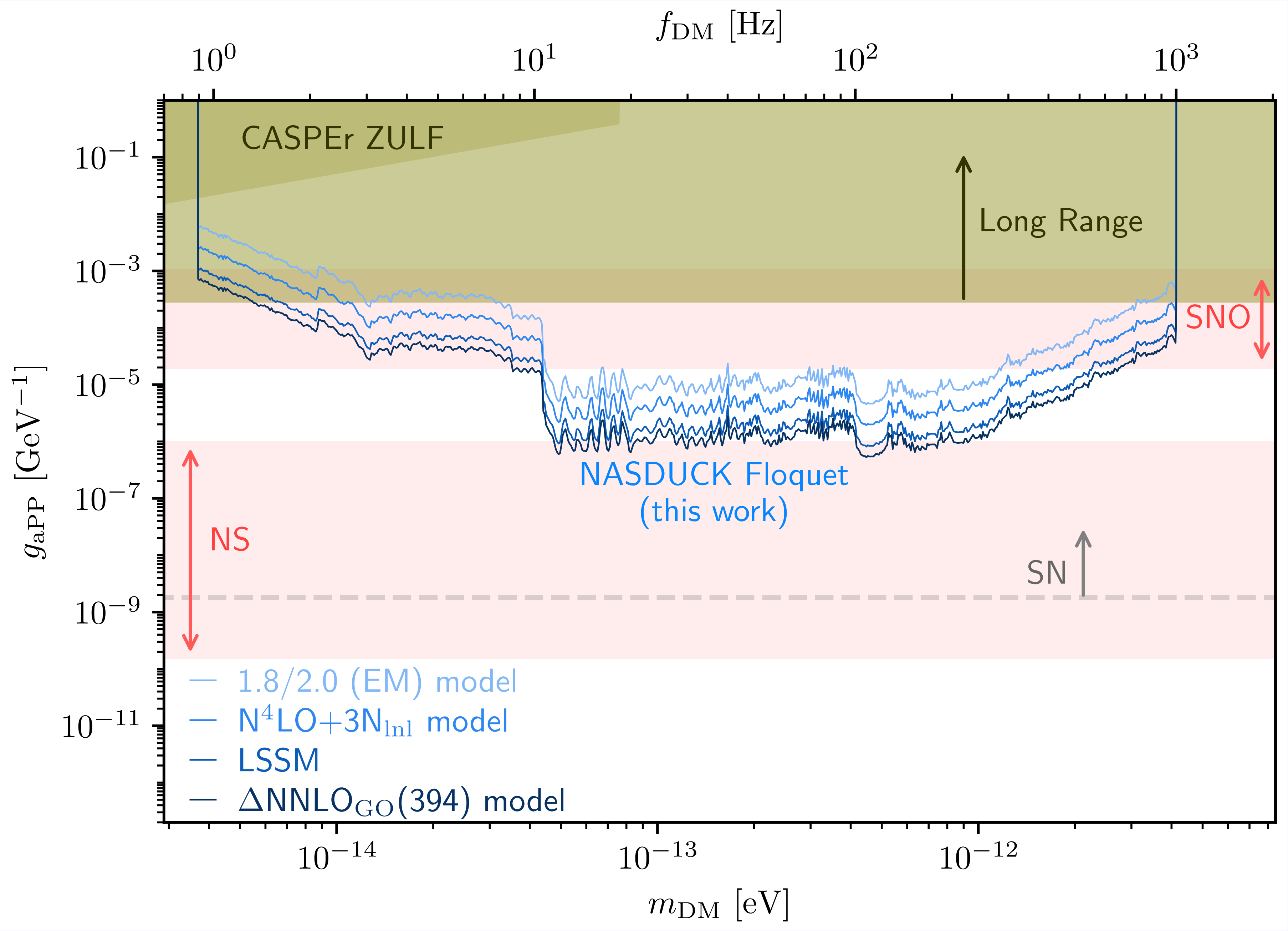


NASDUCK Floquet Results (n)



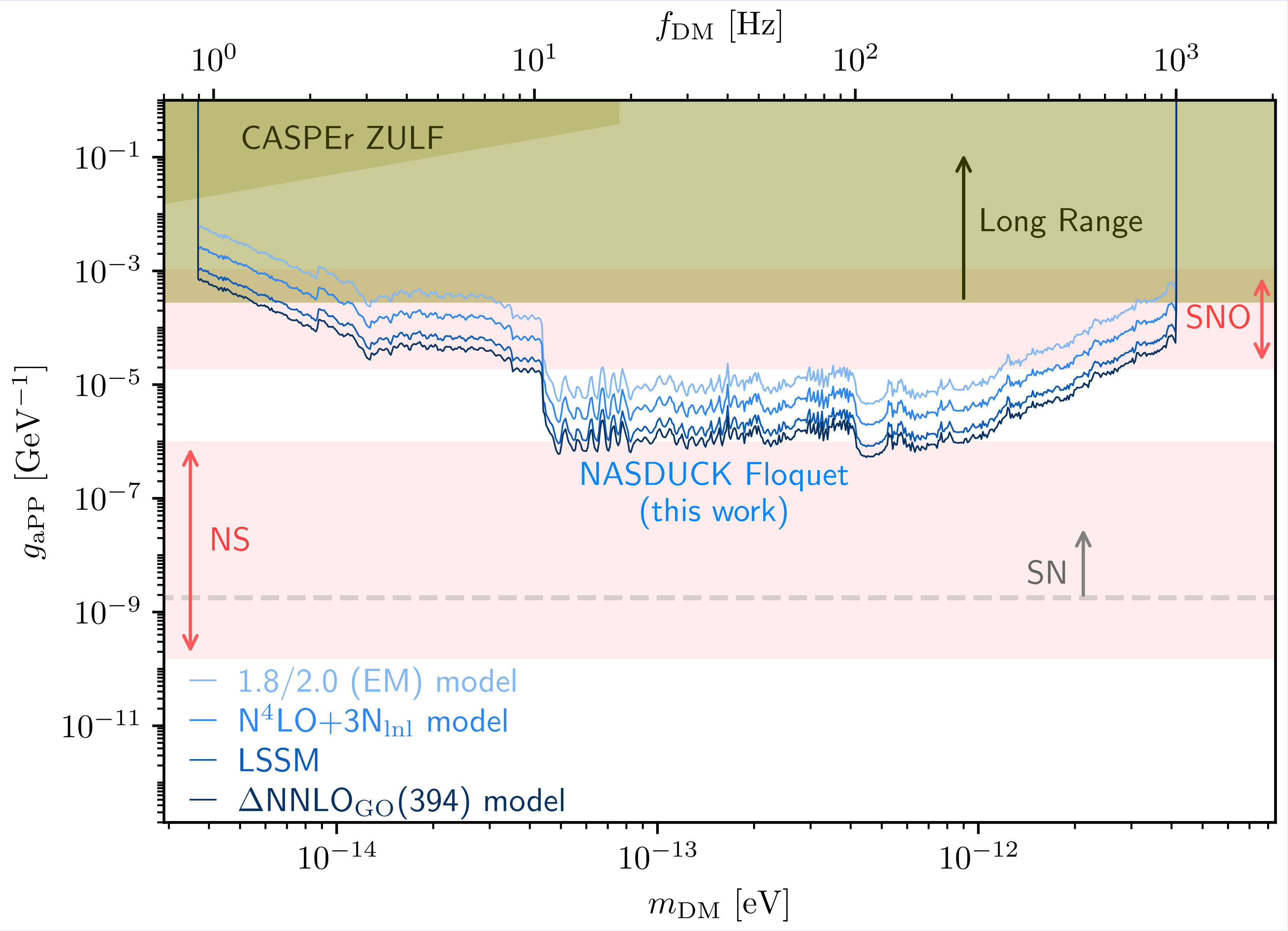
[2102.01448 M. Jiang, H. Su, A. Garcon, X. Peng, D. Budker]

NASDUCK Floquet Results (p?)



[T. Wu *et al*.:1901.10843, E. G. Adelberger *et al*. *2007*, C. Abel *et al*.:1708.06367, CASPEr Collaboration: 1902.04644, K. Hamaguchi *et al*. 1806.07151, J. Keller *et al*. 1205.6940, A Sedrakian 1512.07828]

NASDUCK Floquet Results (p?)



SN1987A have significant theoretical uncertainties [Bar *et al.* 1907.05020]. We need new experiments!

[T. Wu *et al*.:1901.10843, E. G. Adelberger *et al*. *2007*, C. Abel *et al*.:1708.06367, CASPEr Collaboration: 1902.04644, K. Hamaguchi *et al*. 1806.07151, J. Keller *et al*. 1205.6940, A Sedrakian 1512.07828]

Conclusions

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- Comagnetometers offer unprecedented sensitivity for Ultralight ALPs
- The NASDUCK collaboration has many experiments it can do/has already done.
- With creativity, one can think of new experiments to run! We already have several ideas for how to utilize existing experiments for other things.

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

DUCK-matter

(Degree in beakness school)

↓

NASDUCK-matter