Comagnetometers as Probes for Ultralight Dark Matter

May 2021

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(Work done in the Rafael Quantum Optics Lab)

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E. Kuflik, G. Ronen, R. Shaham, T. Volansky.

Based on work presented in arxiv:1907.03767, and arXiv:2105.XXXX

Outline

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

Axion Like Particles

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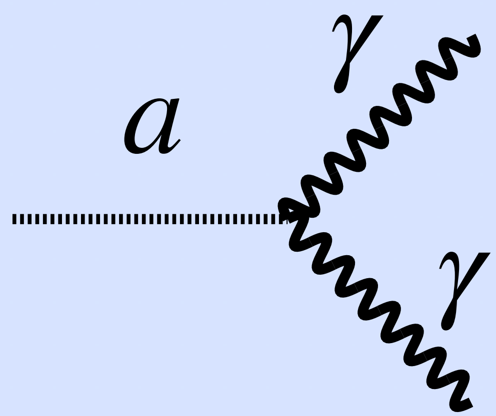
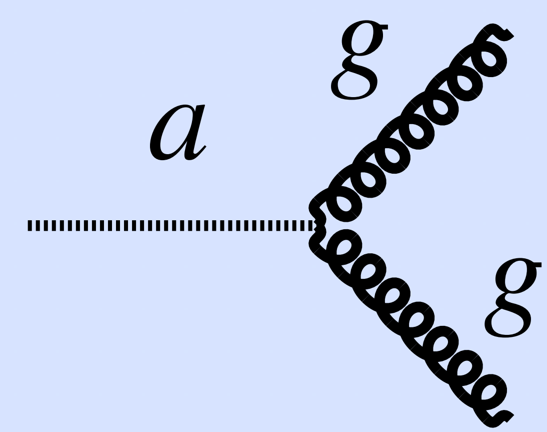
- Pseudo-scalars.
- Can be a CDM component (we assume all).
- Can be very light and remain CDM candidate:

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

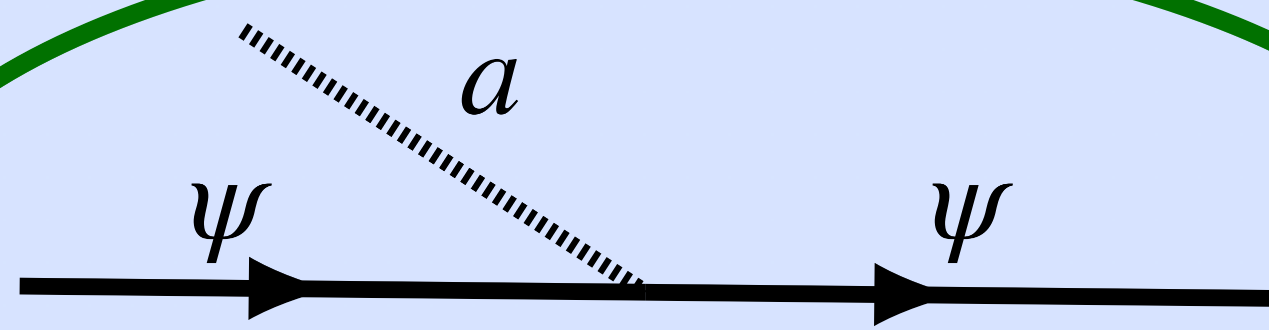
ALP-SM Interactions



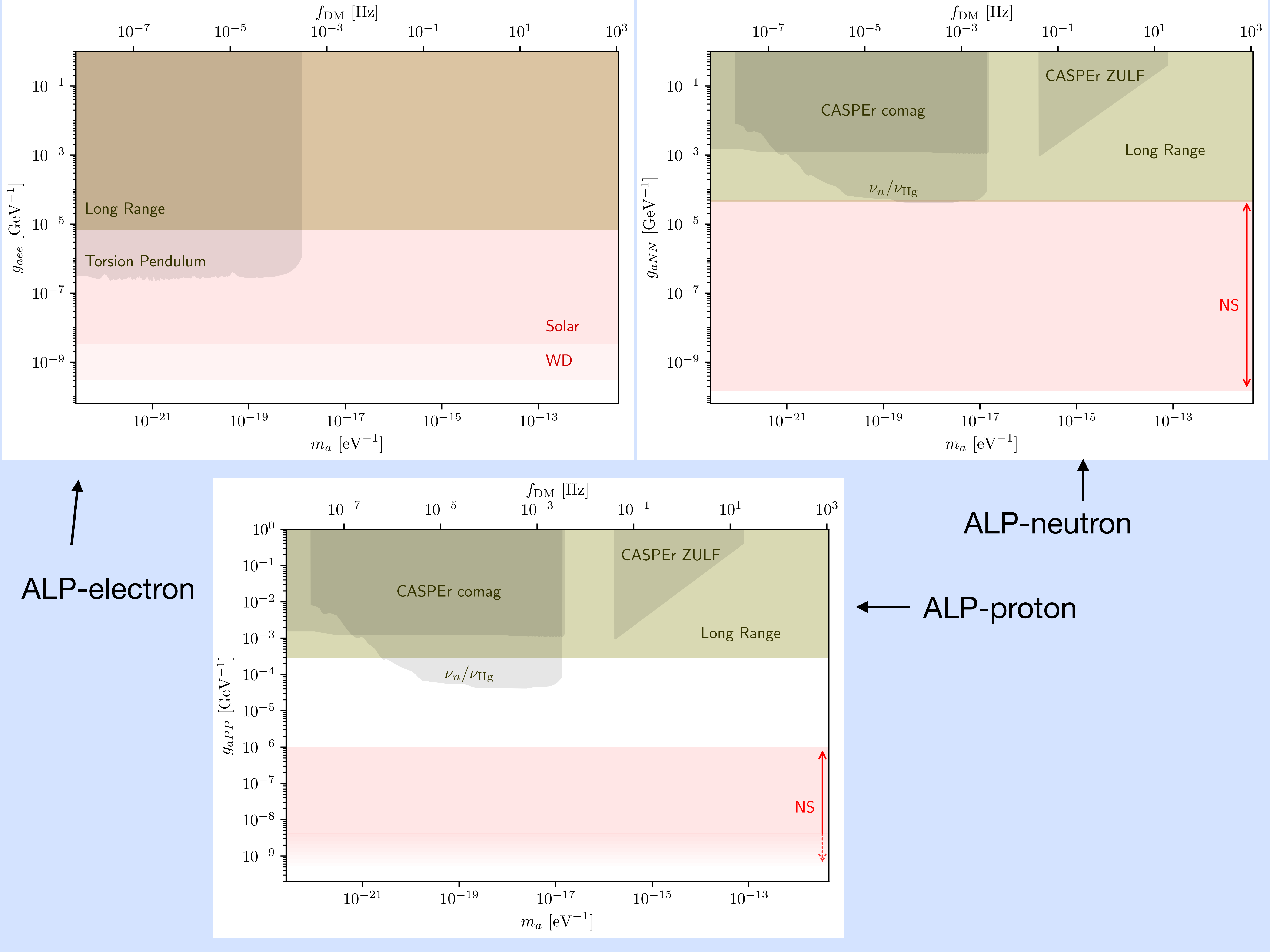
$$-\frac{1}{4} g_{a\gamma\gamma} a F\tilde{F}$$



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



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



$f_{\rm DM}$ [Hz]
g_{aee} [GeV^{-1}]
m_a [eV^{-1}]
Long Range
Torsion Pendulum
Solar
WD
g_{aNN} [GeV^{-1}]
CASPEr ZULF
CASPEr comag
Long Range
$\nu_n/\nu_{\rm Hg}$
NS
g_{aPP} [GeV^{-1}]
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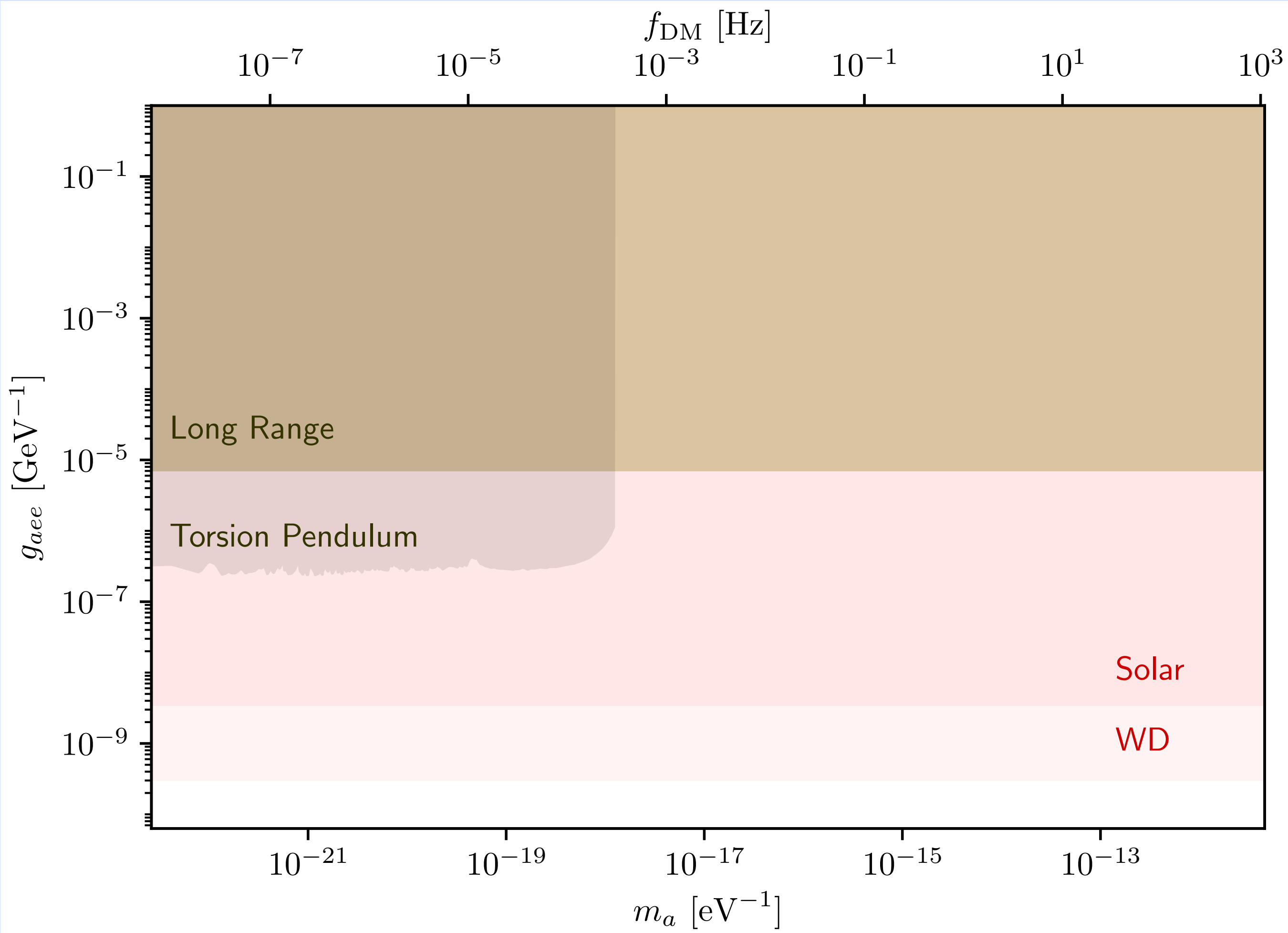
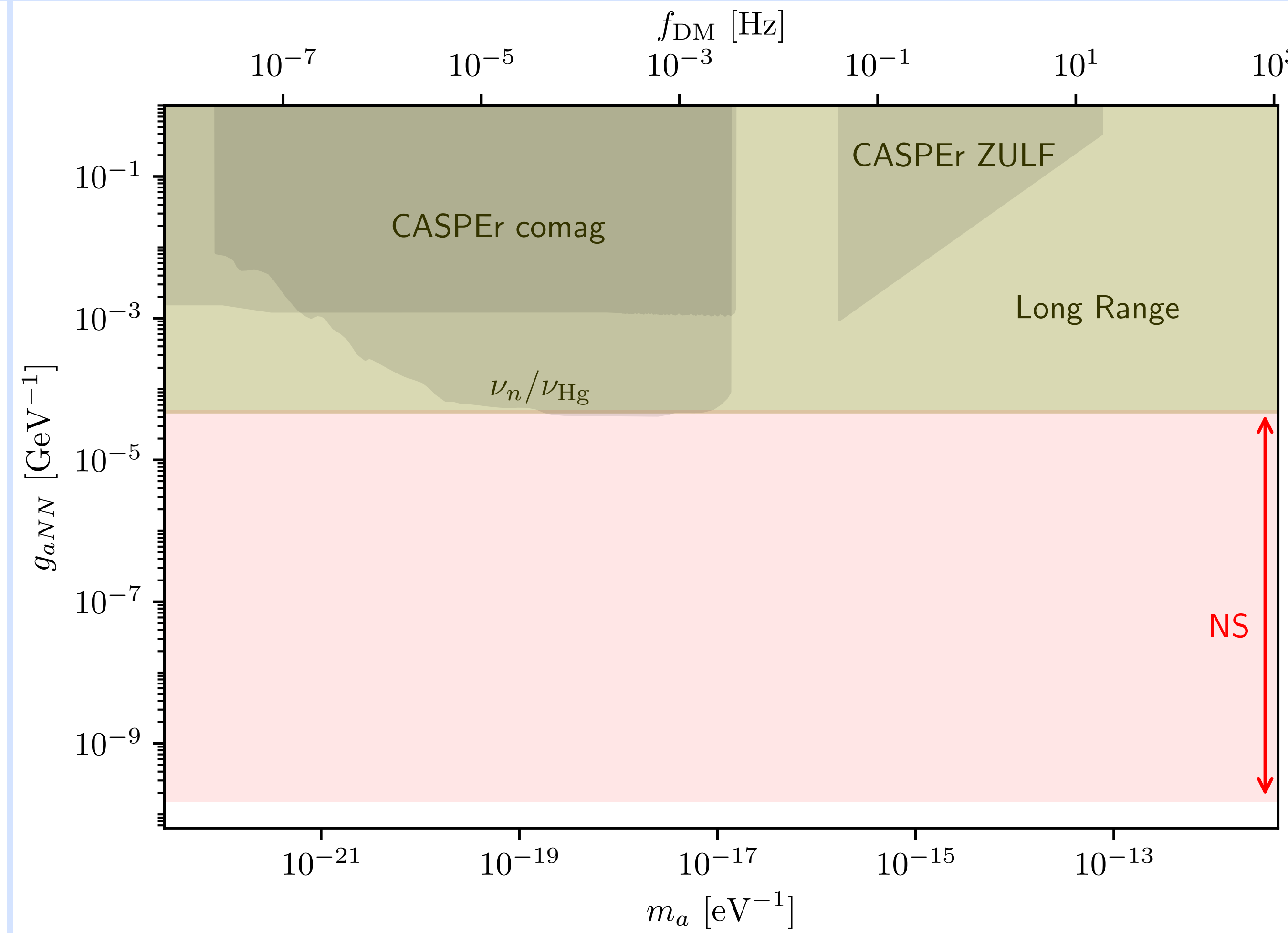
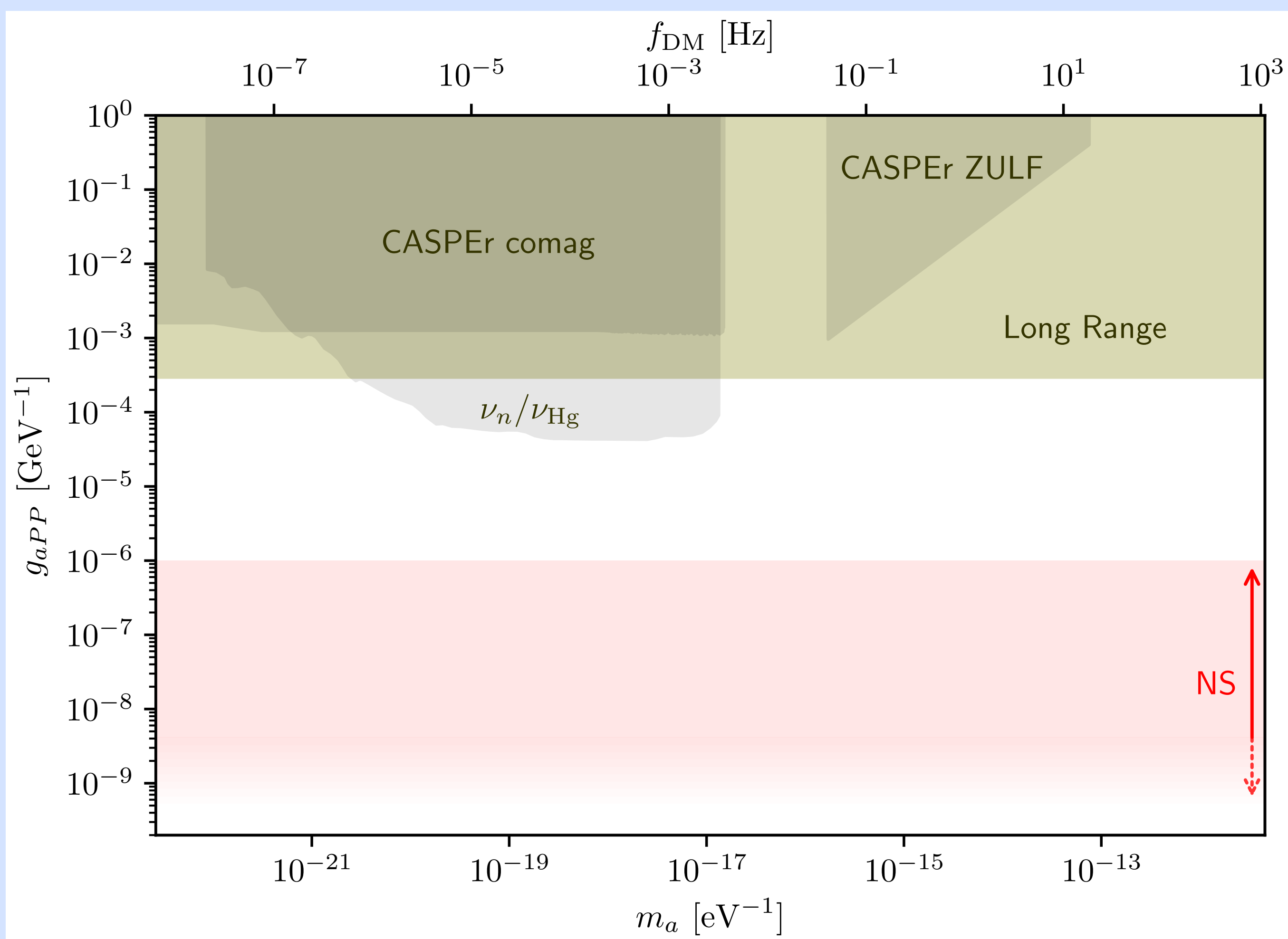
CASPEr comag
Long Range
$\nu_n/\nu_{\rm Hg}$
NS
ALP-electron
ALP-neutron
ALP-proton





ALP-electron

ALP-neutron



ALP-proton

SN1987A not shown due to significant theoretical uncertainties [Bar *et al.* 1907.05020]

Coherent Interactions (1)

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

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

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$$a = a_0 e^{i x^\mu p_\mu}$$

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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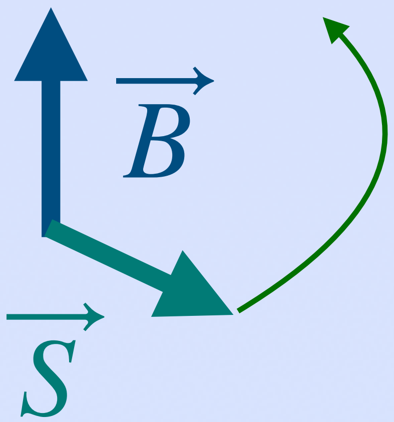
But how to measure it?

Larmor Precession and Zeeman Splitting

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



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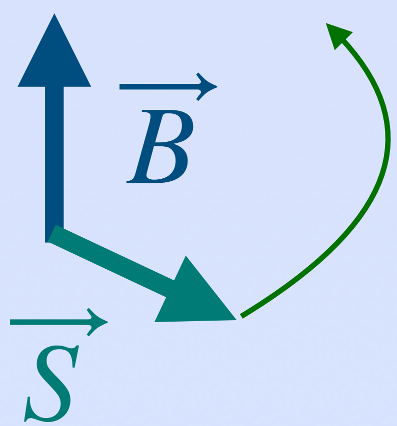

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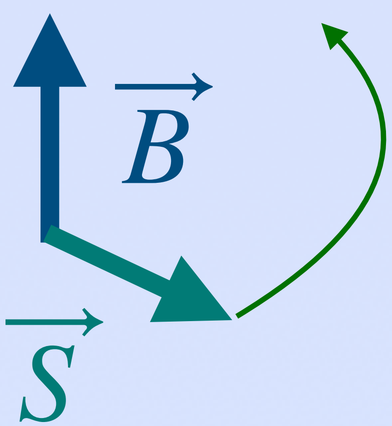

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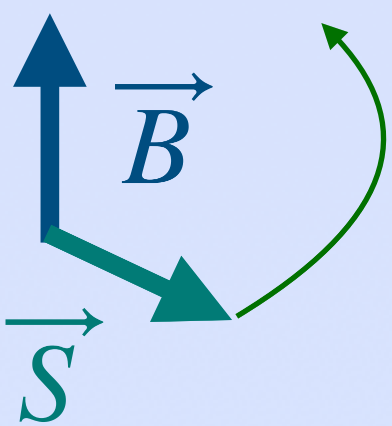

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Is there a known way to measure magnetic fields?

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Ultra Light ALP DM generates magnetic-like fields.

Noble-Alkali Comagnetometers

Bloch Equations

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

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* To leading order in important stuff

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

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)

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

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(generates transverse from longitudinal)

Decaying excitations
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Transverse EOMs

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

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

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$$\Big\downarrow$$

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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

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

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

The transverse spin

Signal

Transverse Magnetic fields

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

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

The transverse spin

Signal

Transverse Magnetic fields

Spin in the z direction

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

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

Signal

Transverse
Magnetic fields

The transverse
spin

Spin in the z
direction

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

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.

Why Alkali?

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Problem:

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

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

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

Noble gasses 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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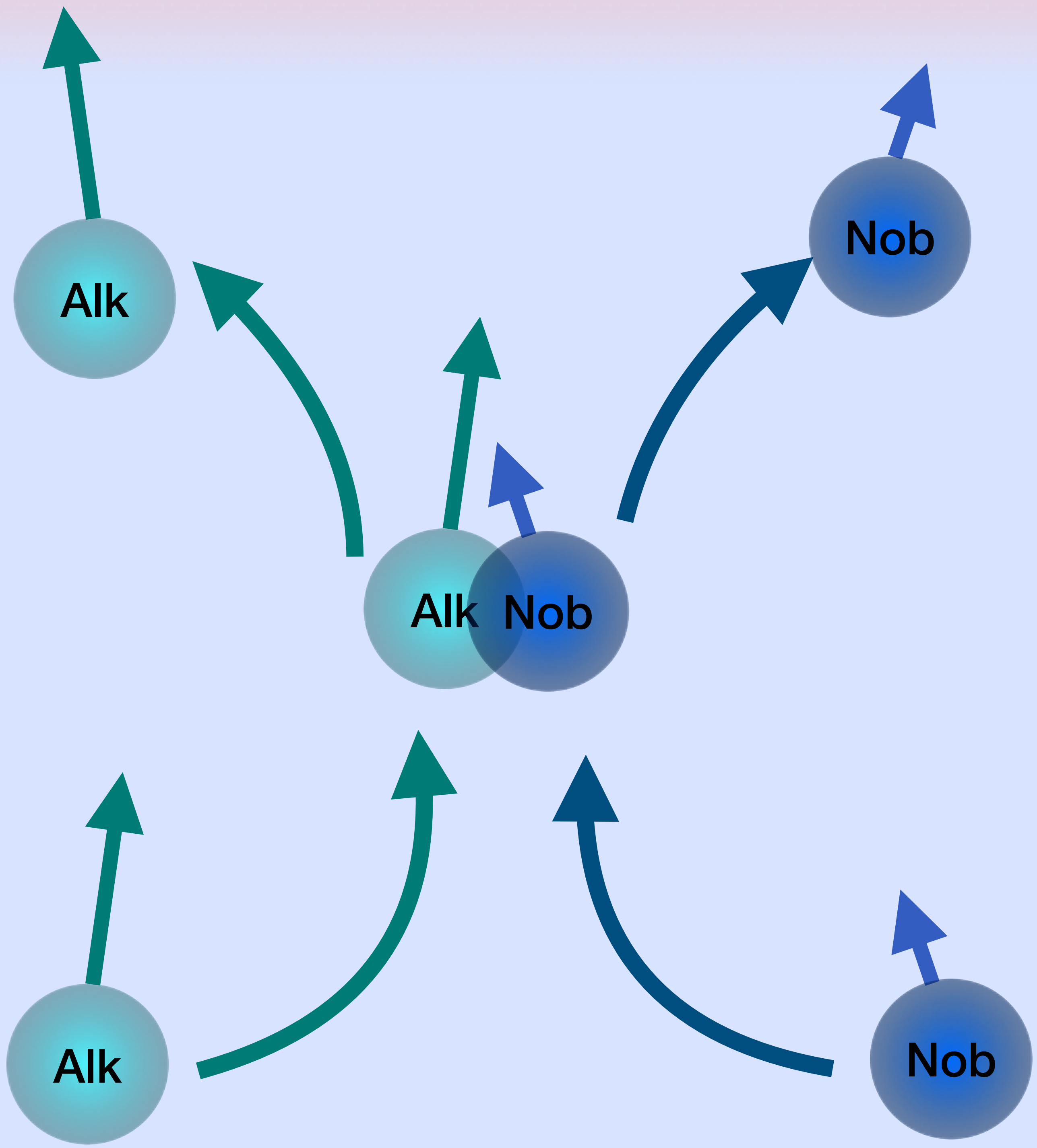
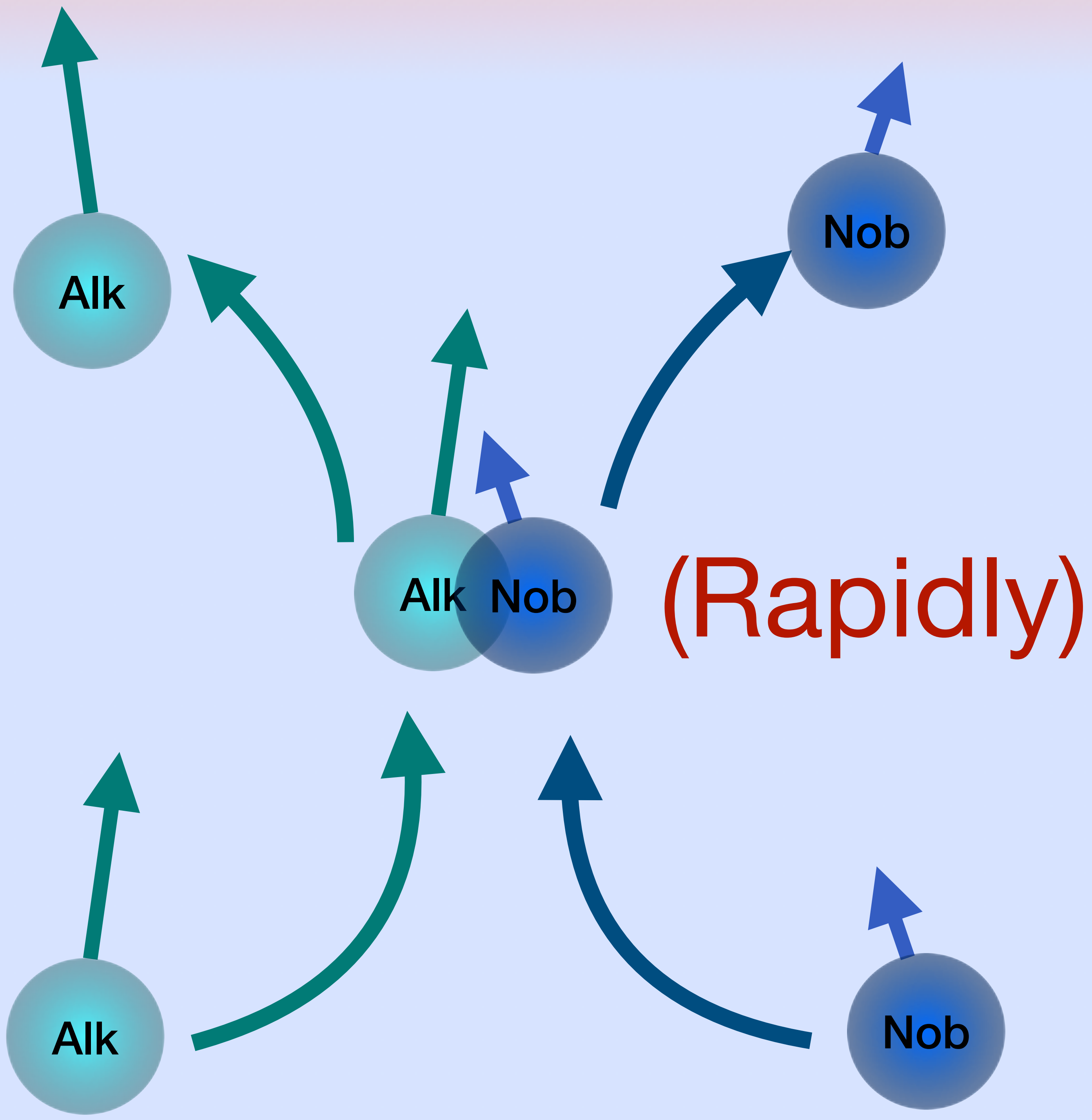


Spin Exchange: Polarizing $S_{\mathrm{Nob},z}$



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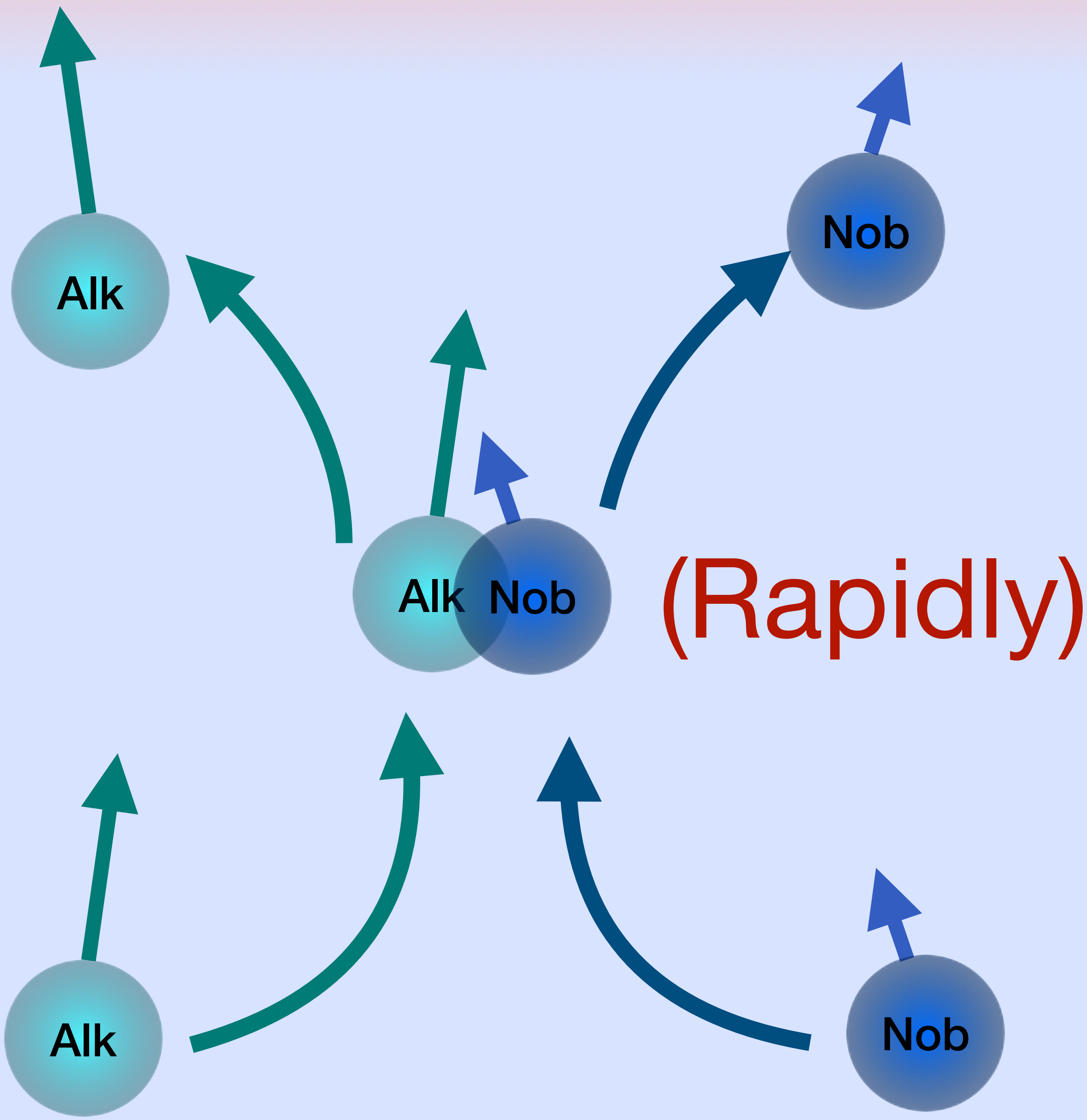
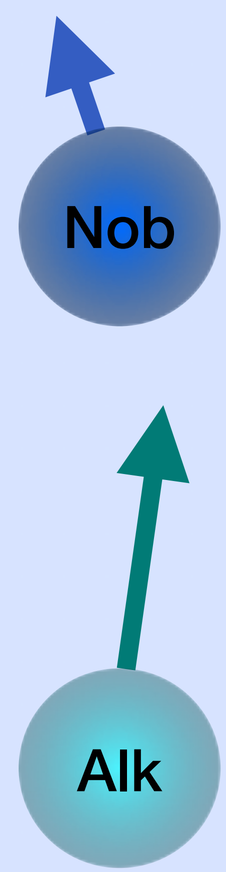


Spin passed from one atom to the other during collision:



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

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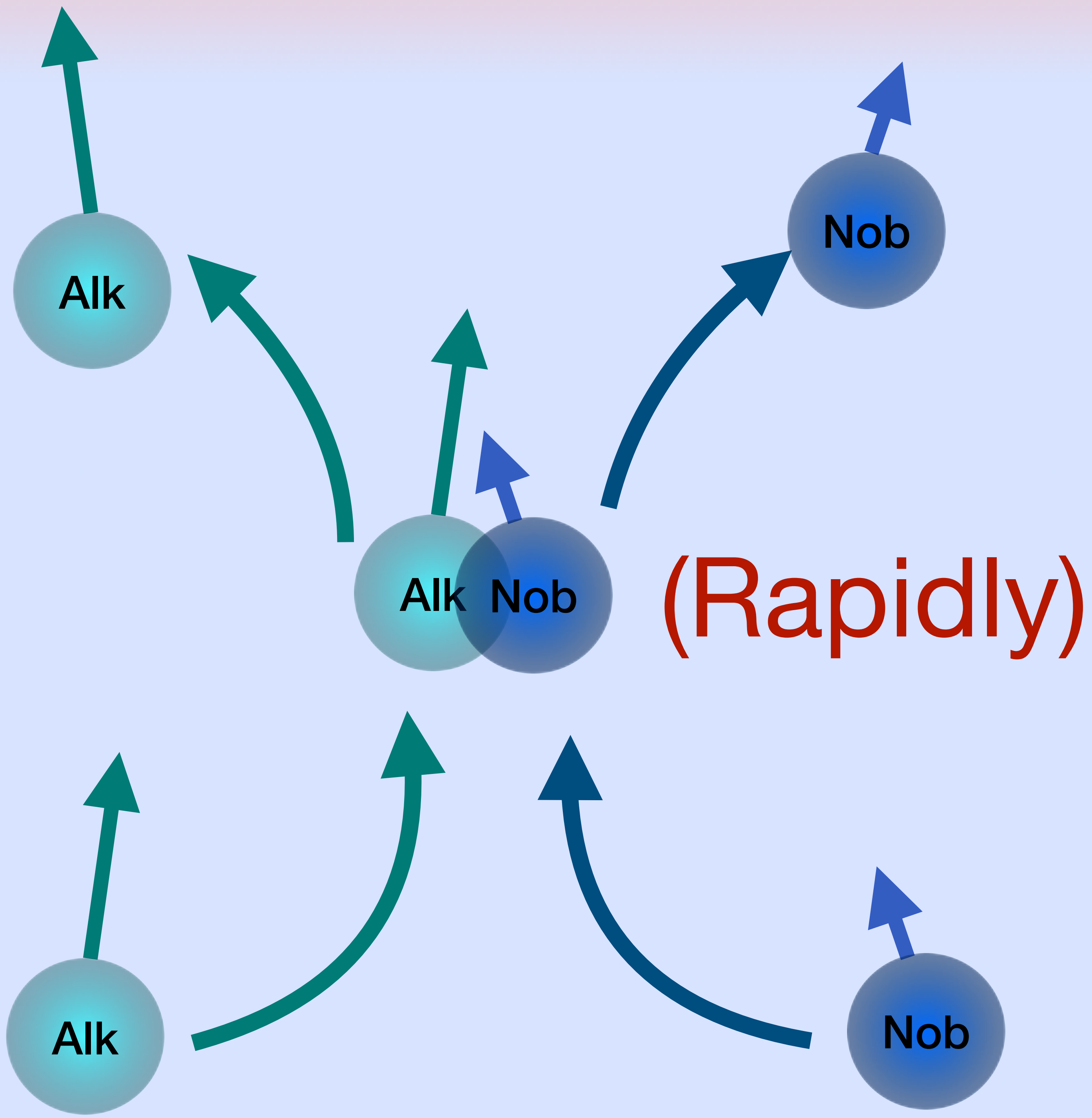

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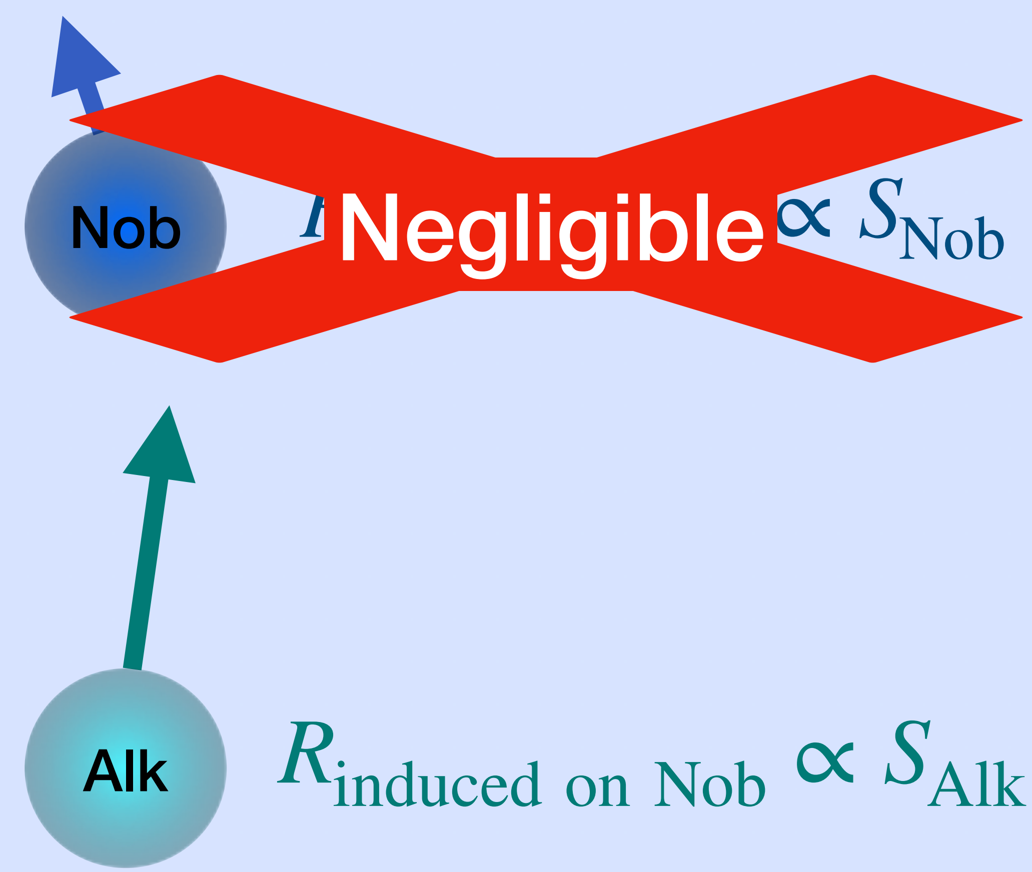
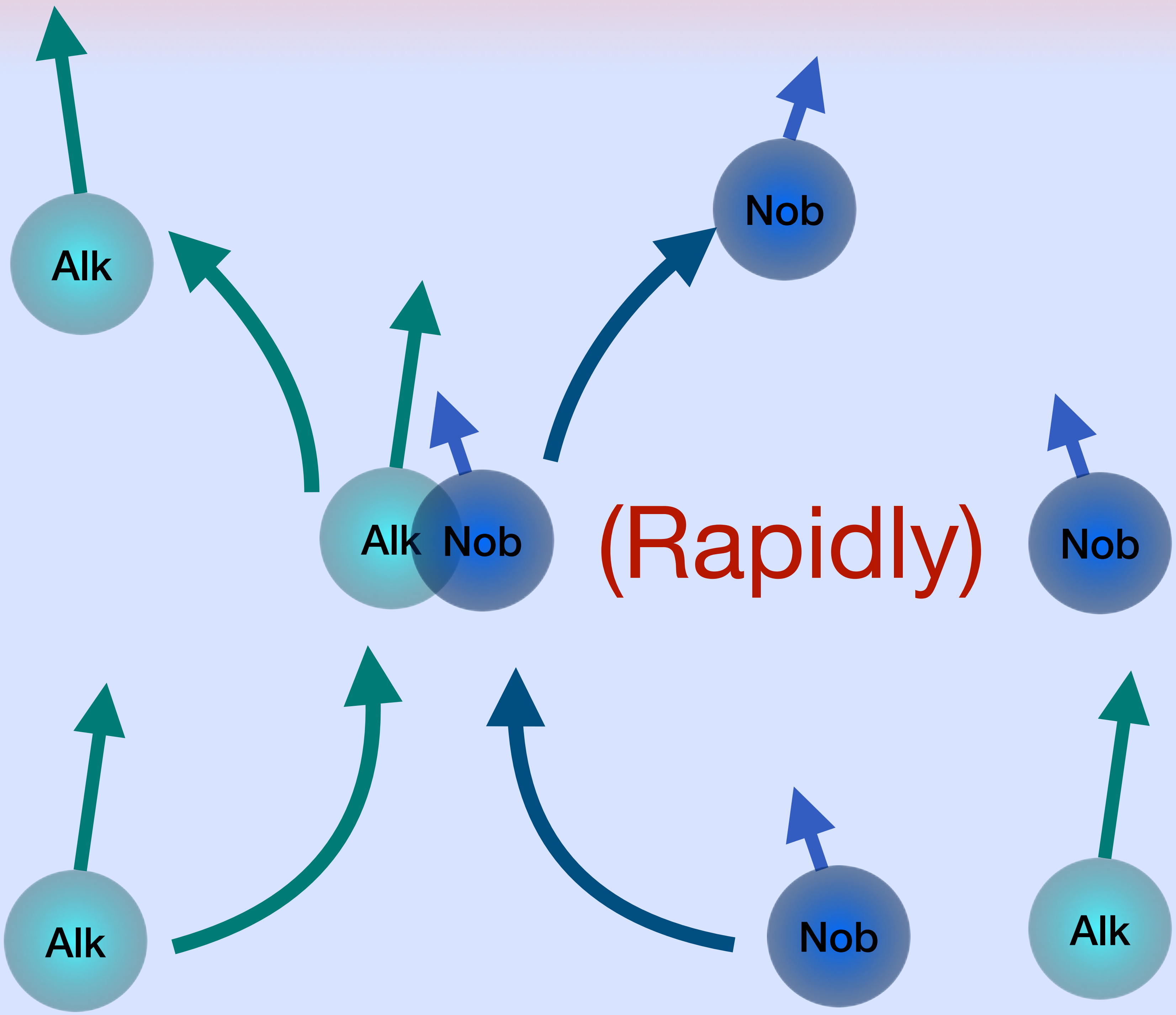


Spin Exchange: “Measuring” $S_{\perp,\mathrm{Nob}}$



Magnetic field from (quantum) point-like interactions

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

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

Comagnetometer
Ingredients List

Comagnetometer
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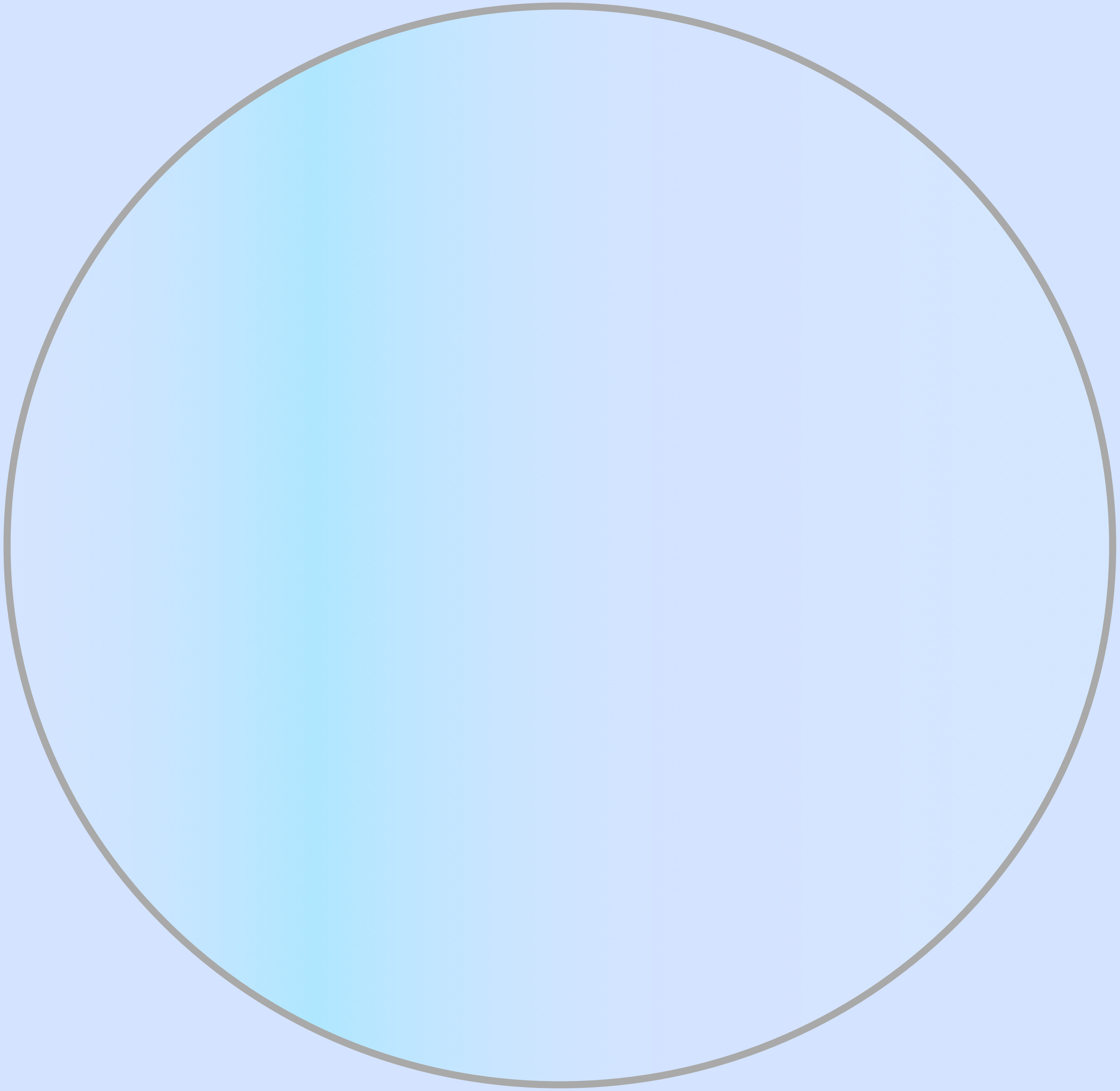
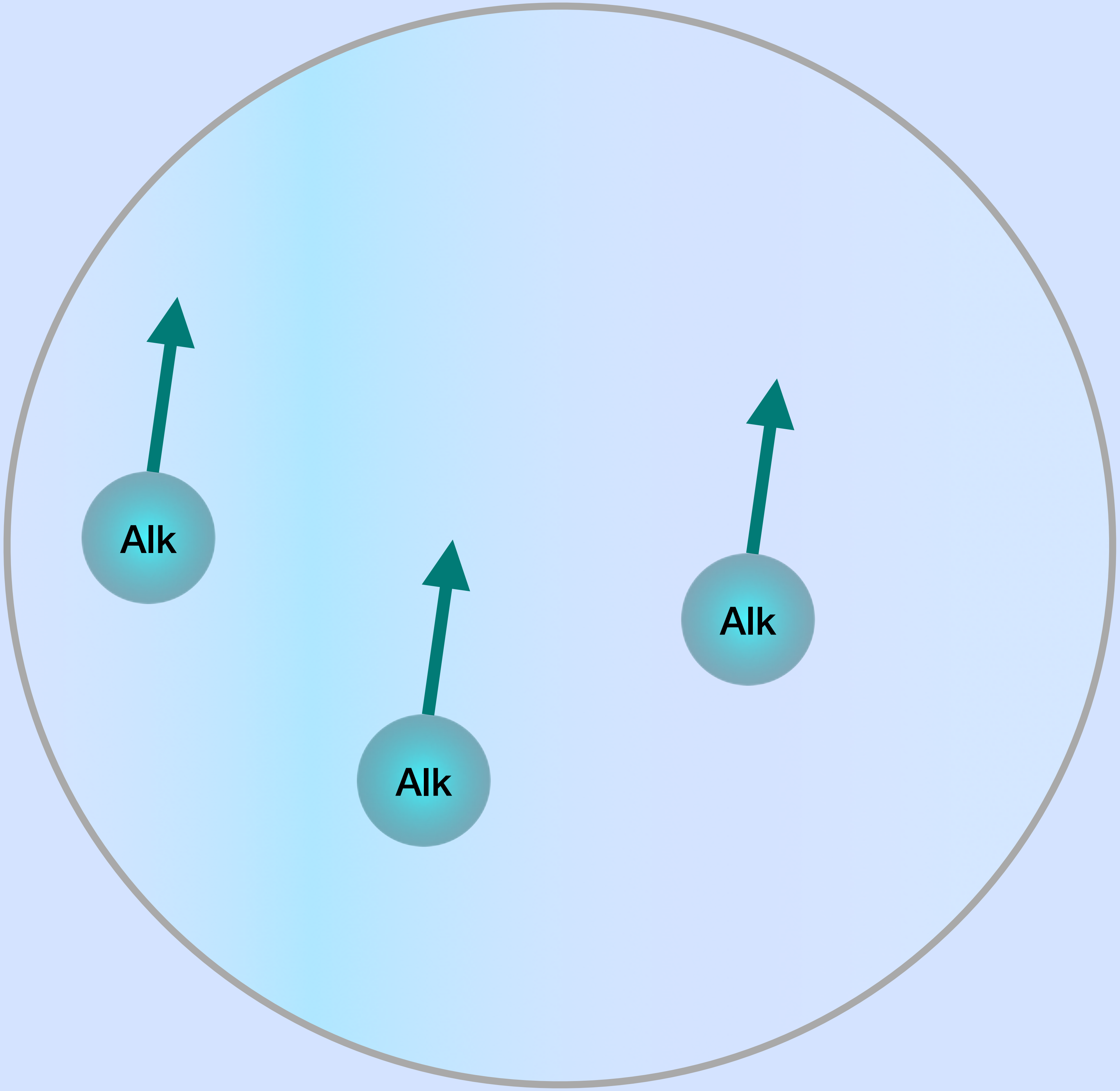
Glass Cell

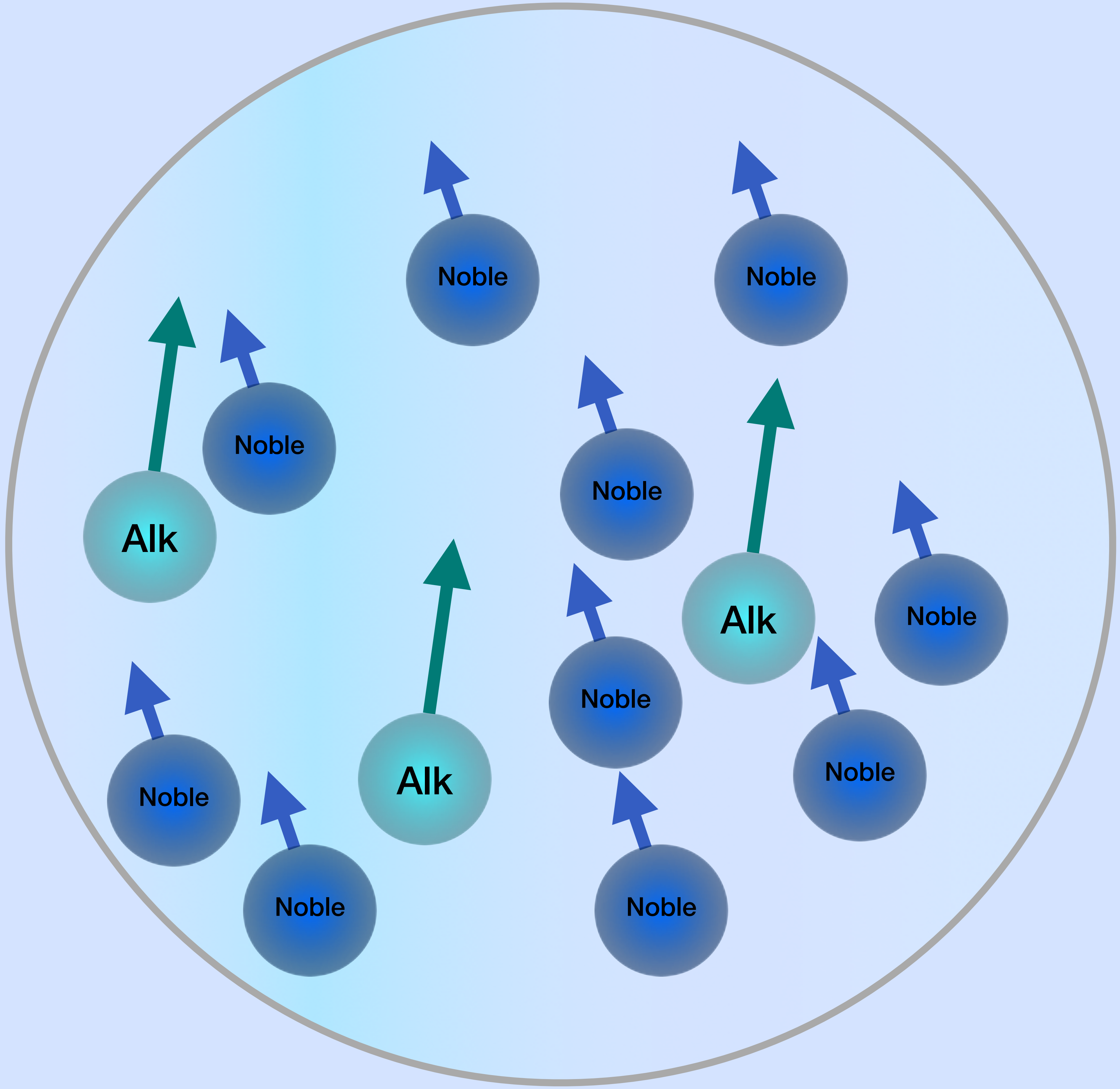




Comagnetometer
Ingredients List

Glass Cell

Alkali Vapor



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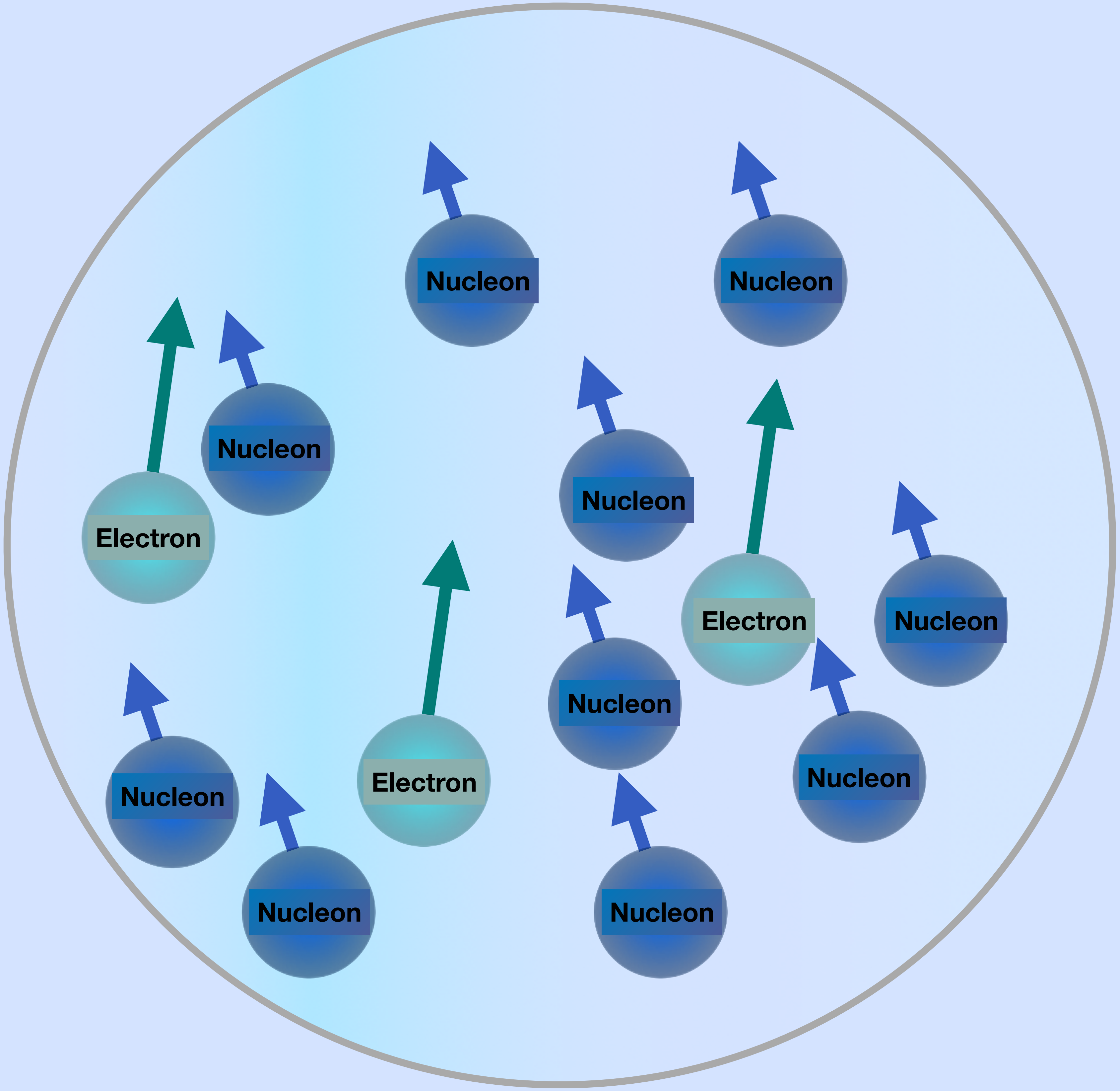
Noble Gas



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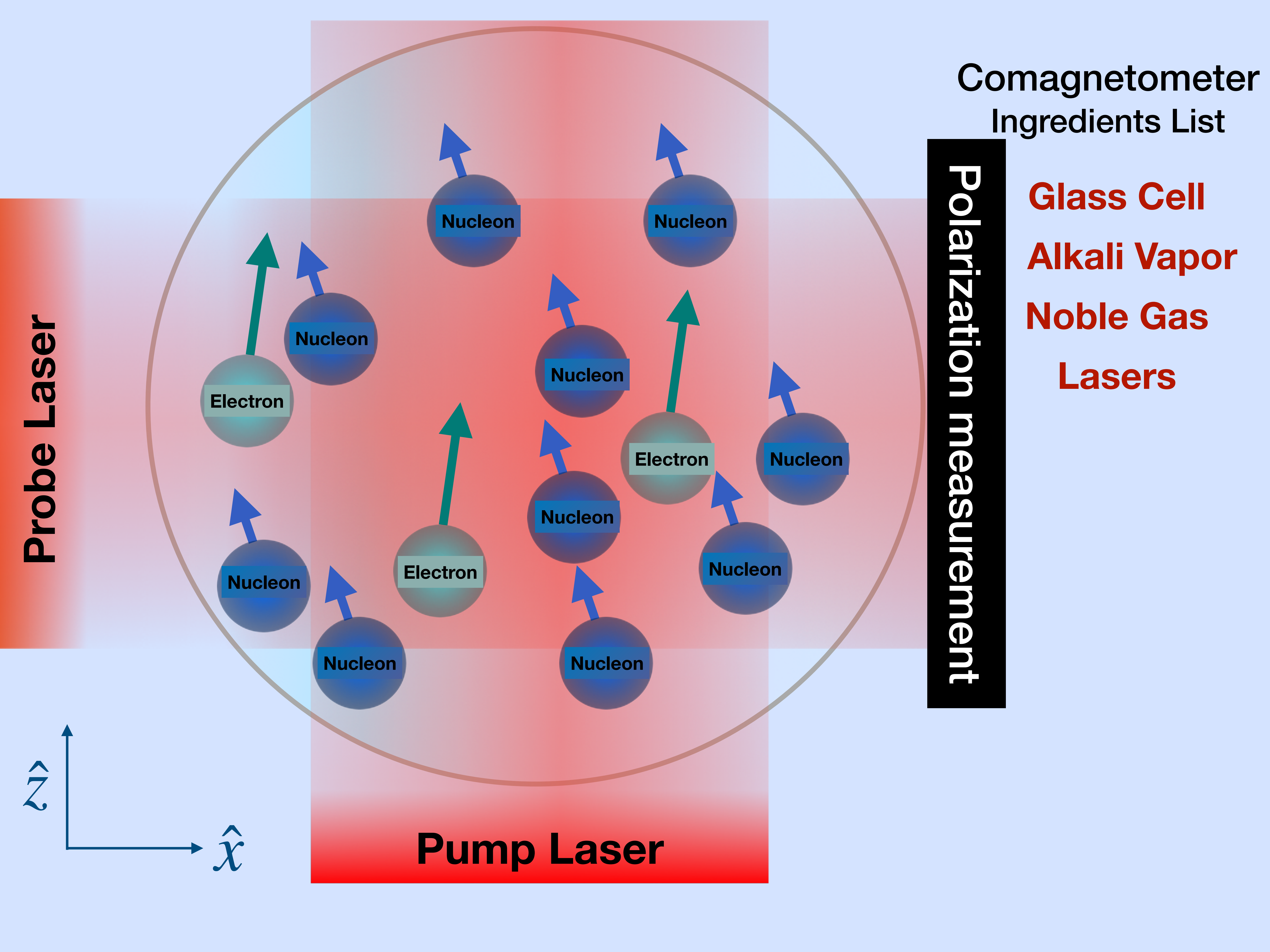
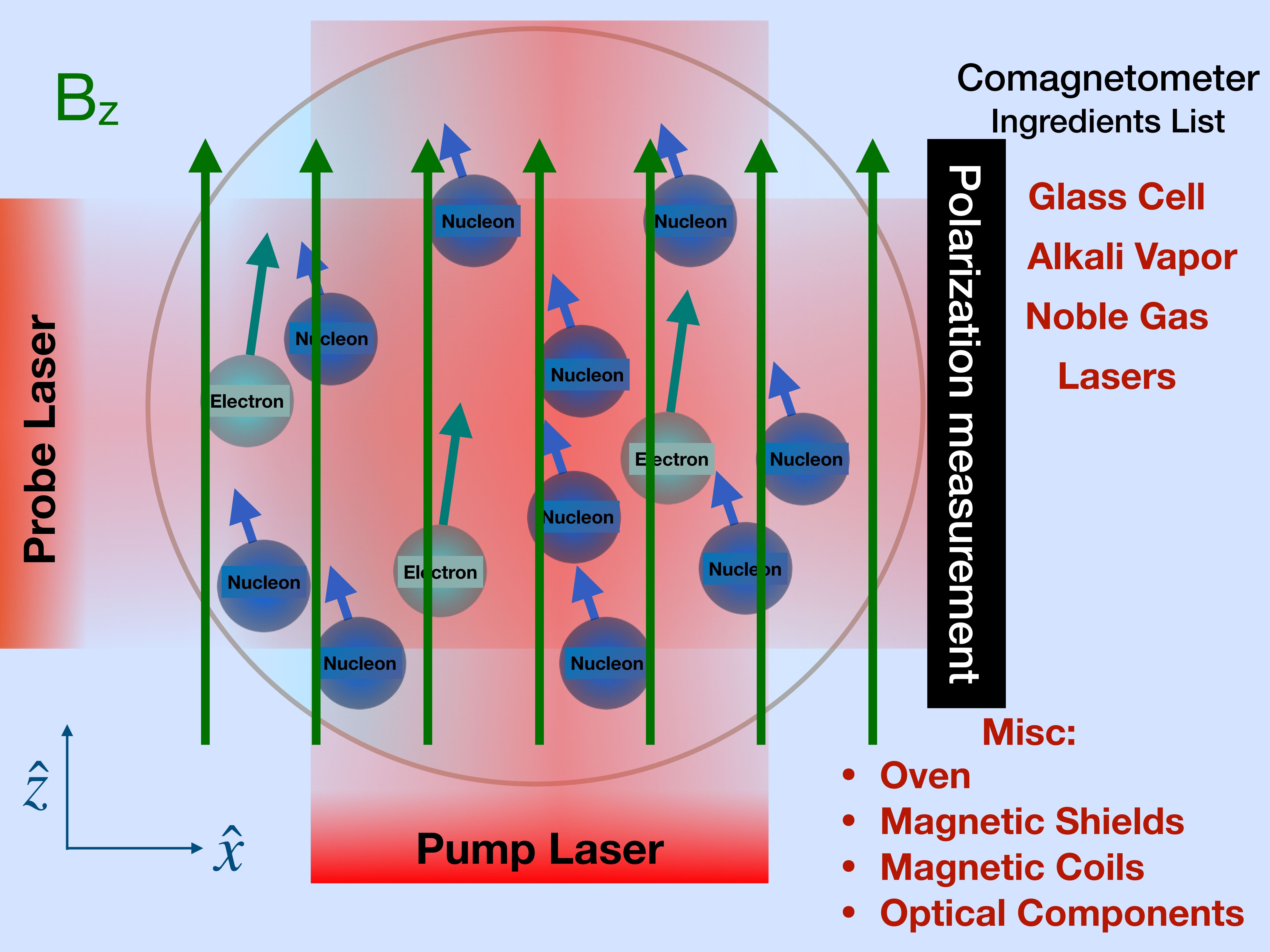

Comagnetometer
Ingredients List
Glass Cell
Alkali Vapor
Noble Gas
Lasers
Polarization measurement
Probe Laser
Pump Laser
Nucleon
Electron
$\hat{z}$
$\hat{x}$



Comagnetometer
Ingredients List
Glass Cell
Alkali Vapor
Noble Gas
Lasers
Misc:
• Oven
• Magnetic Shields
• Magnetic Coils
• Optical Components
Bz
Probe Laser
Pump Laser
Polarization measurement
Nucleon
Electron
$\hat{z}$
$\hat{x}$

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

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$$B_{\perp,\rm Alk} = B_{\perp,\rm noise} + 2\lambda M_{\rm Nob} S_{\perp,\rm Nob}/S_{\rm Nob,z}$$

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(Ignoring backreaction of Alkali on Noble)

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

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For $\Gamma_{\text{Nob}} \approx 0, m_a \approx 0,$ $B_{\text{z,Nob}}$ is tunable 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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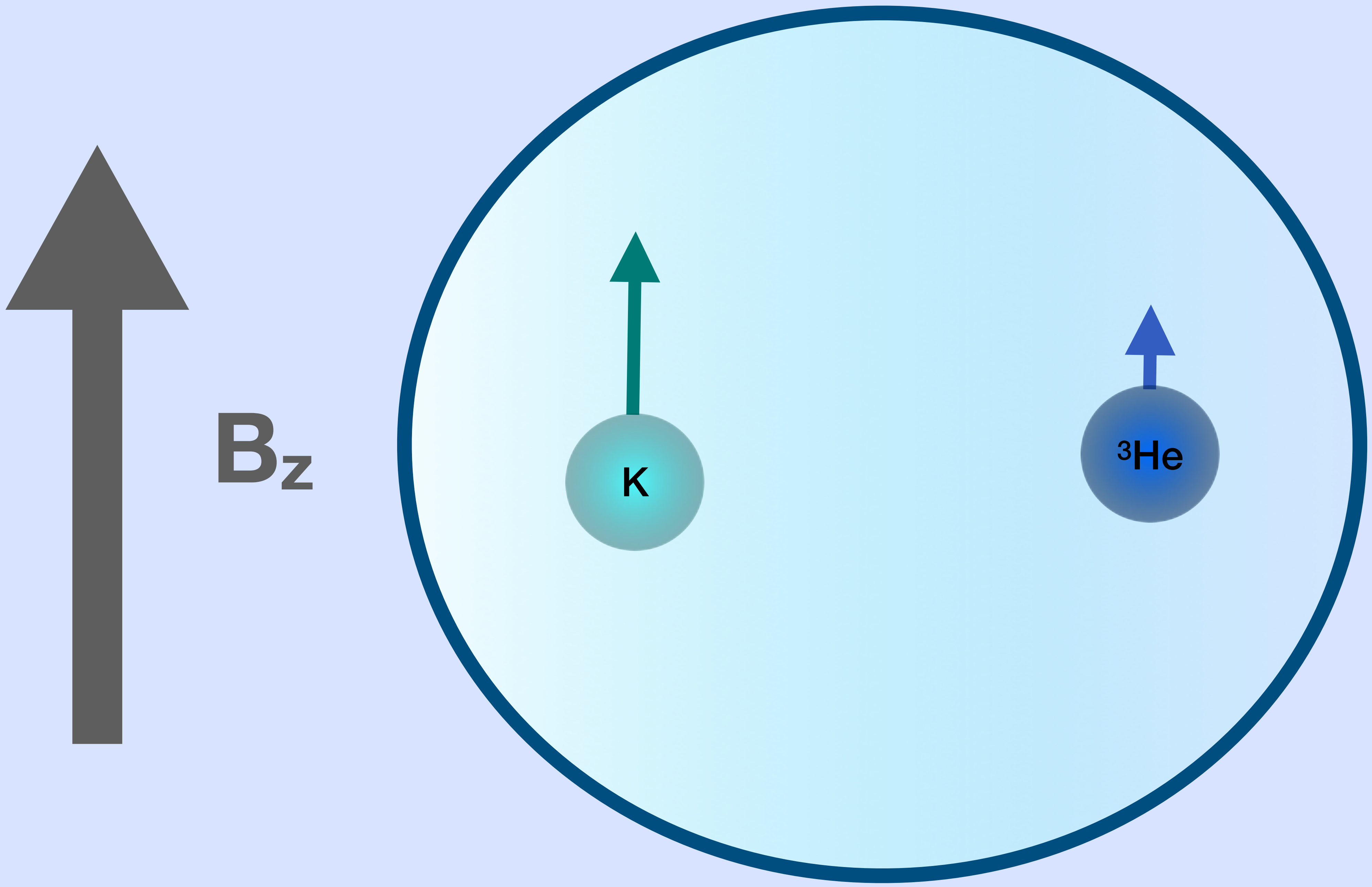
Let’s illustrate

Compensation Point Illustration (B)

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



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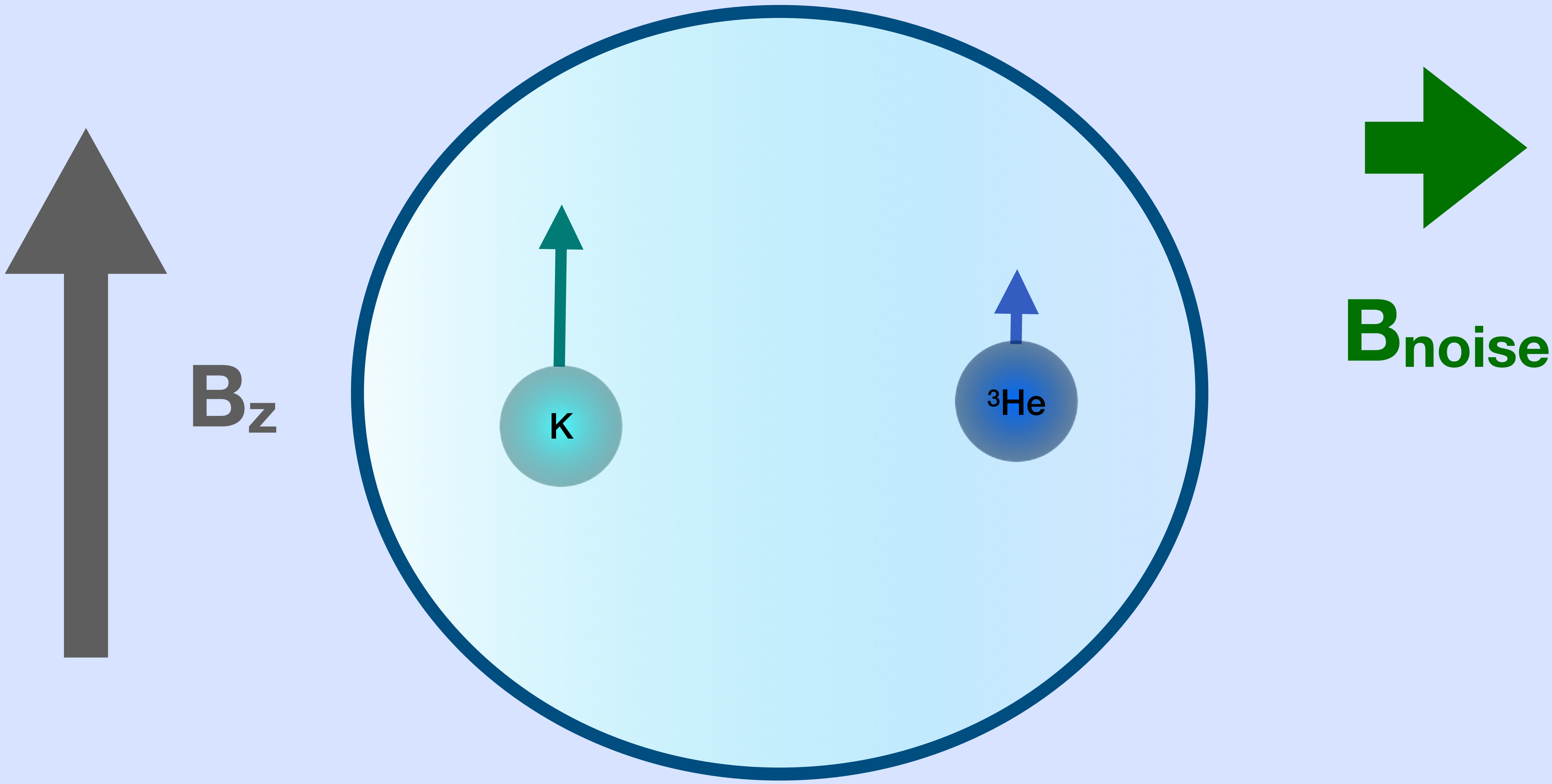

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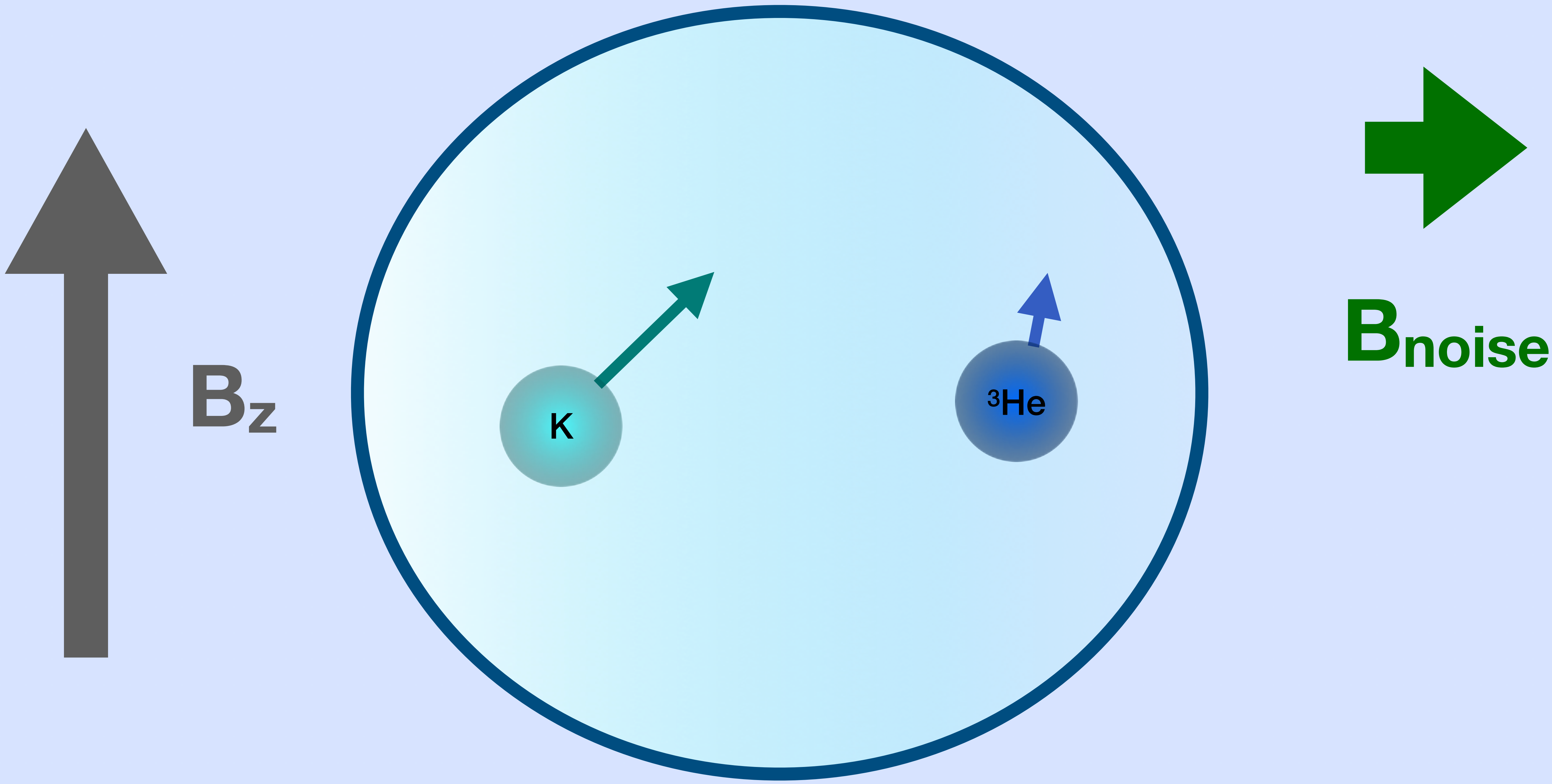

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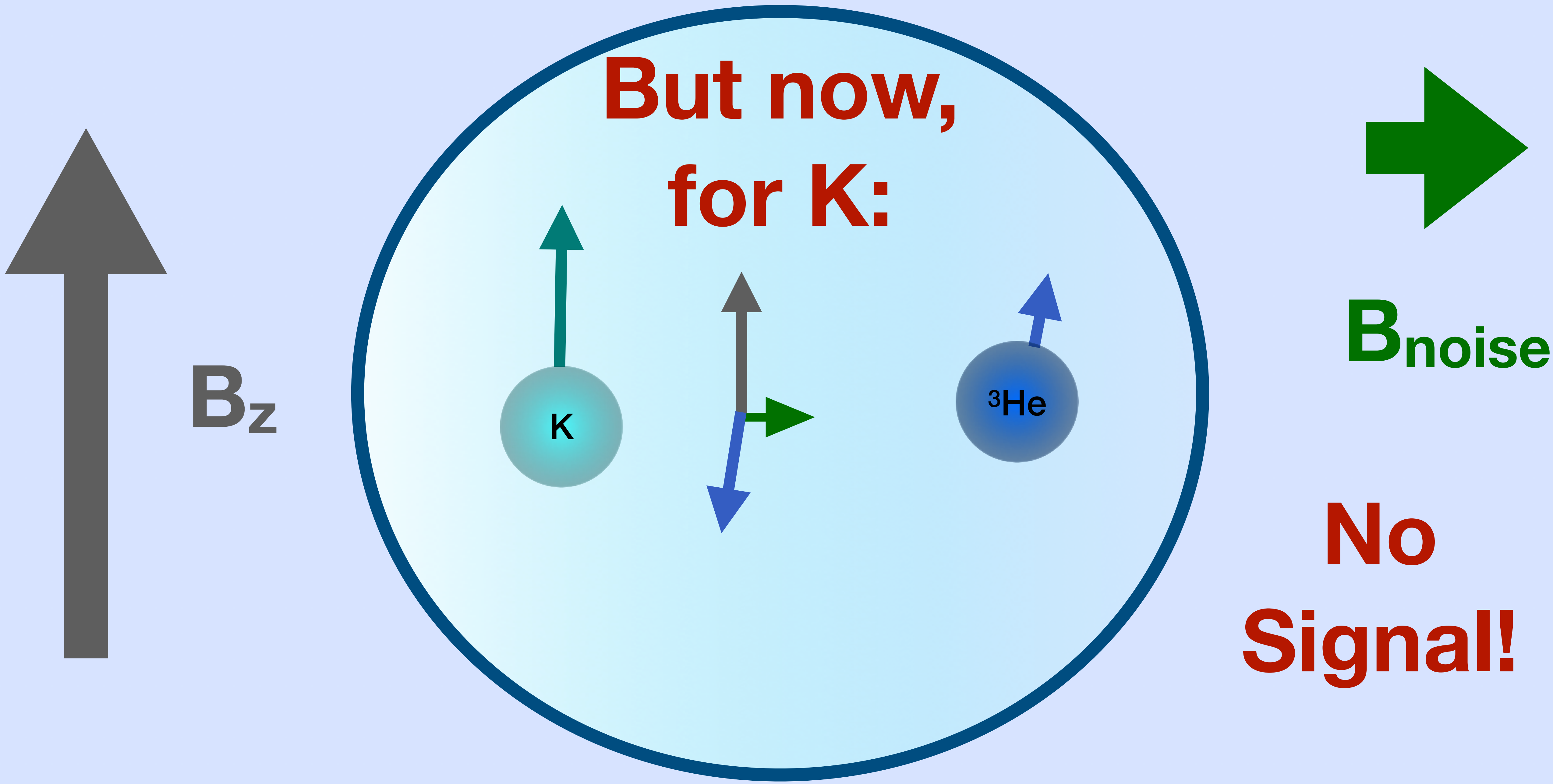

$$S_K^{\perp} \propto \gamma_K B_{tot}^{\perp} = \gamma_K B_{ind}^{\perp} + \gamma_K B_{noise}^{\perp} = 0!$$

Compensation Point Illustration (b_e)

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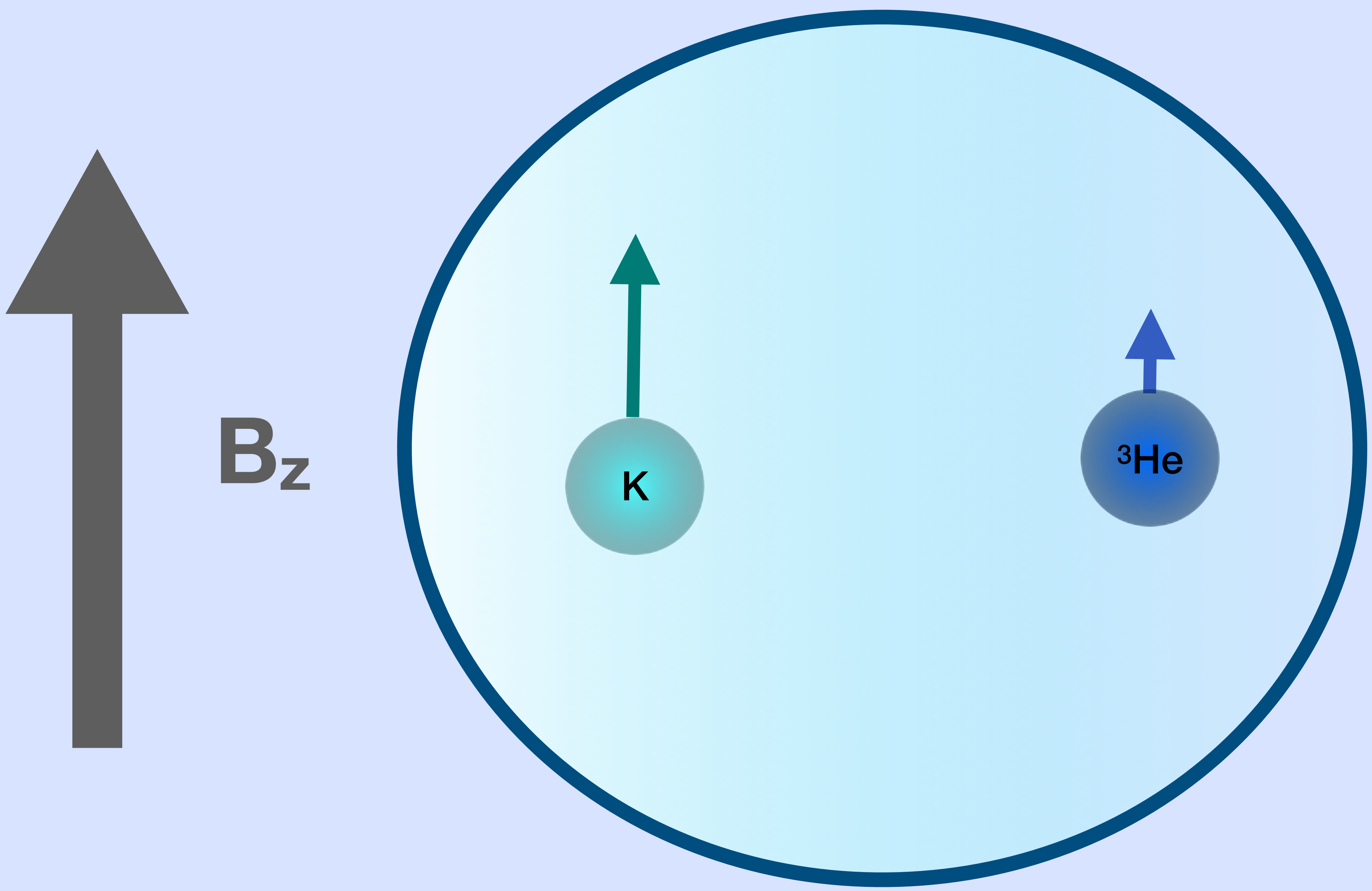

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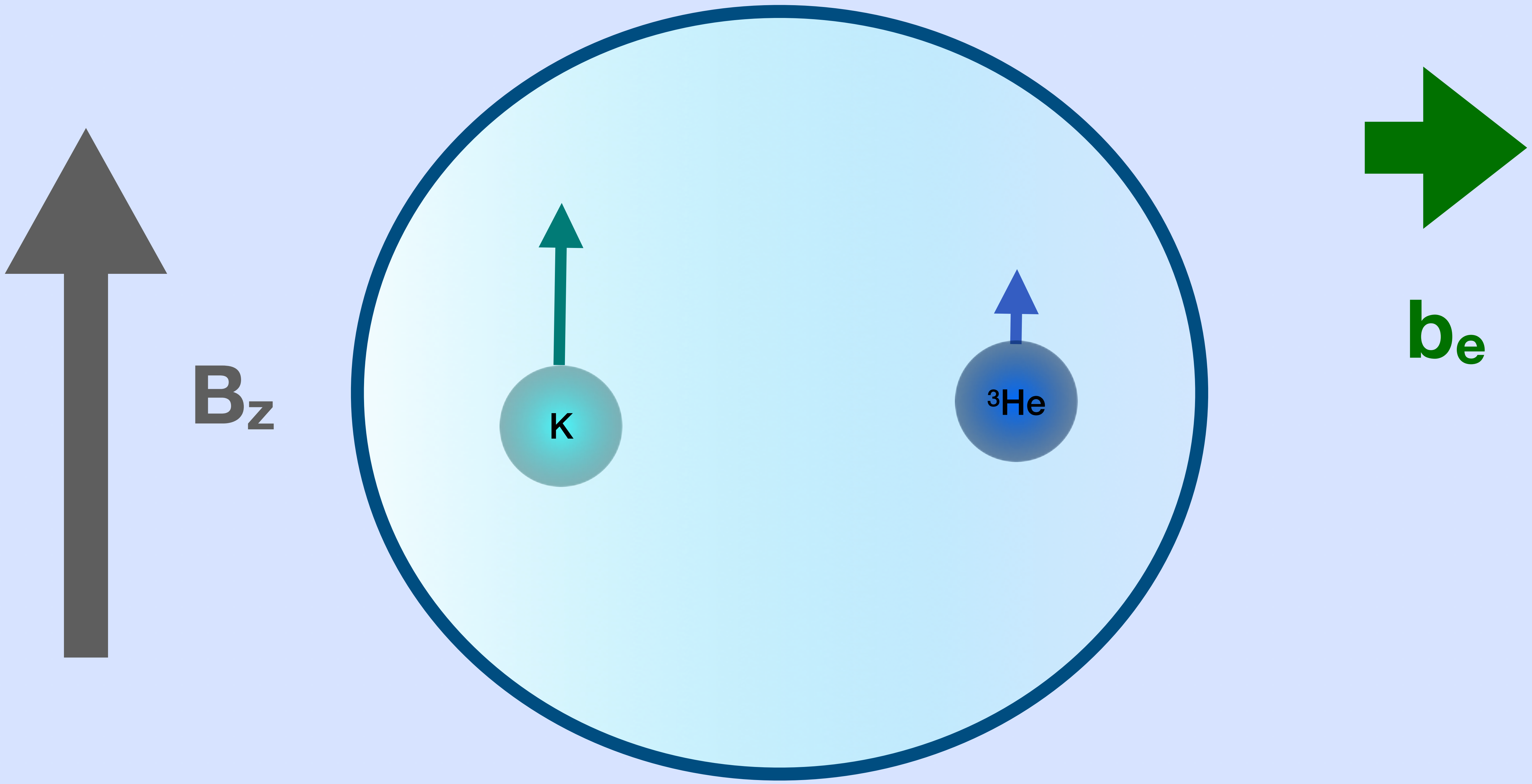

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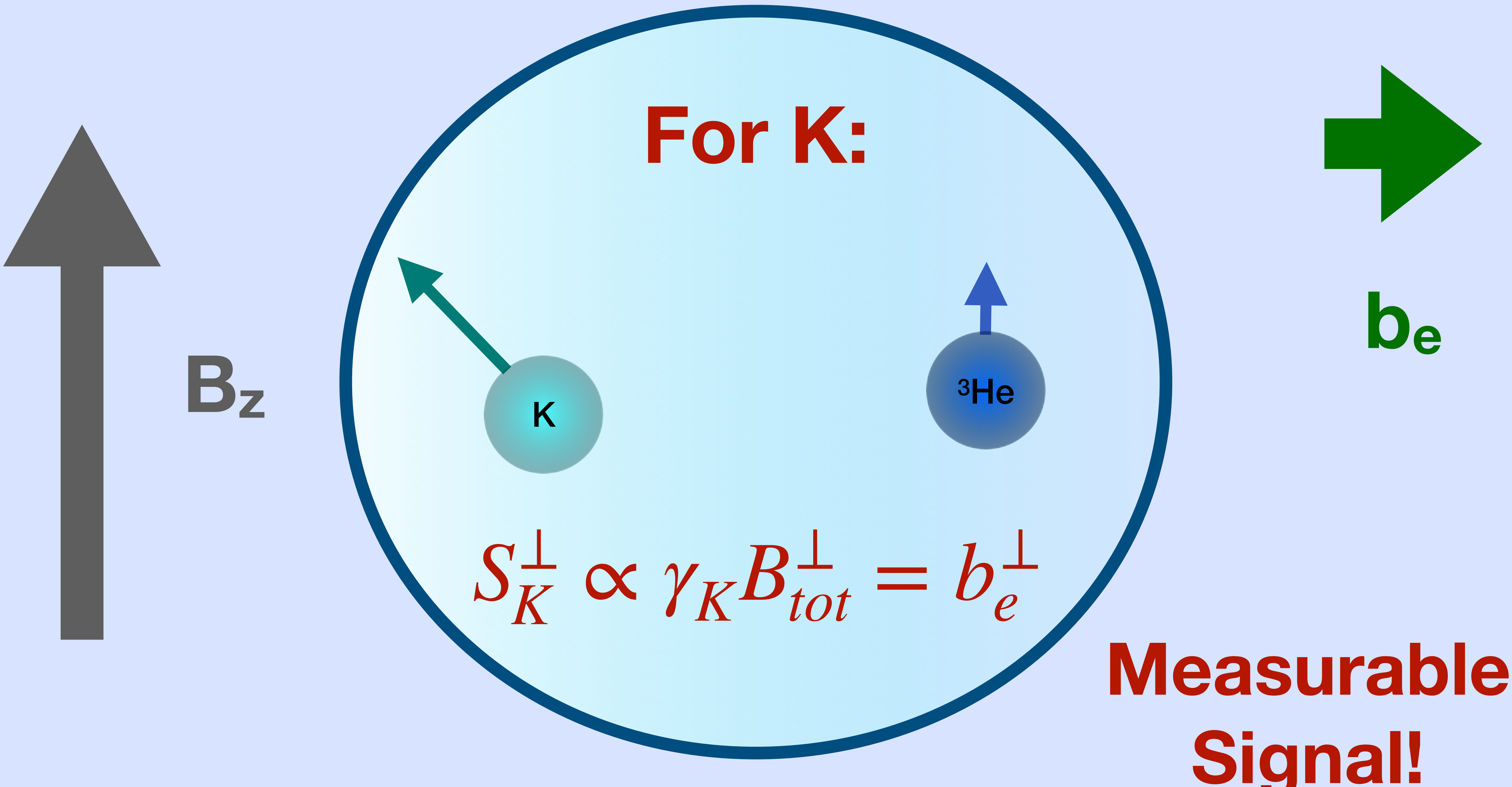

$$S_K^\perp \propto \gamma_K B_{tot}^\perp = b_e^\perp$$

Compensation Point Illustration (b_n)

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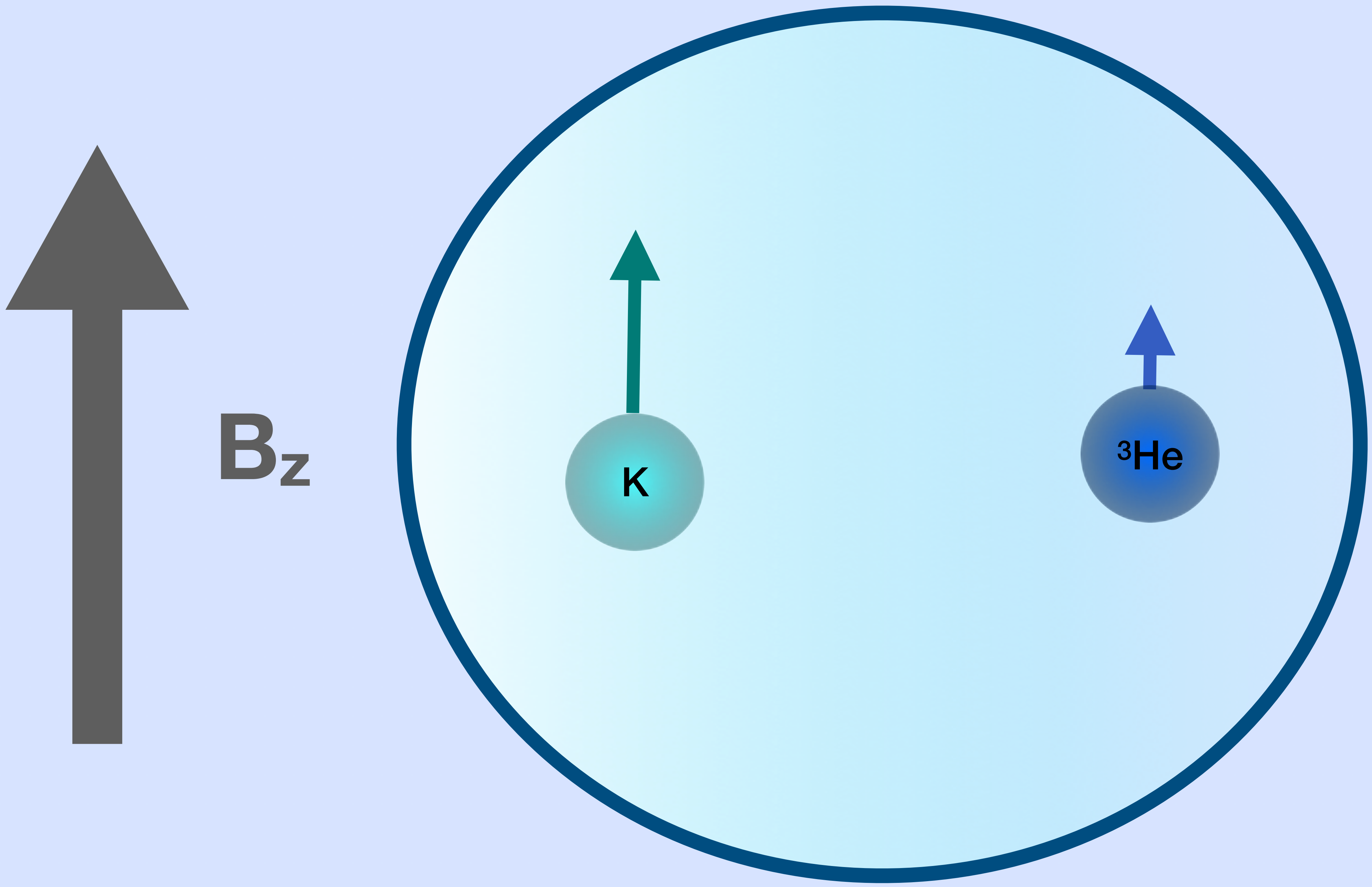

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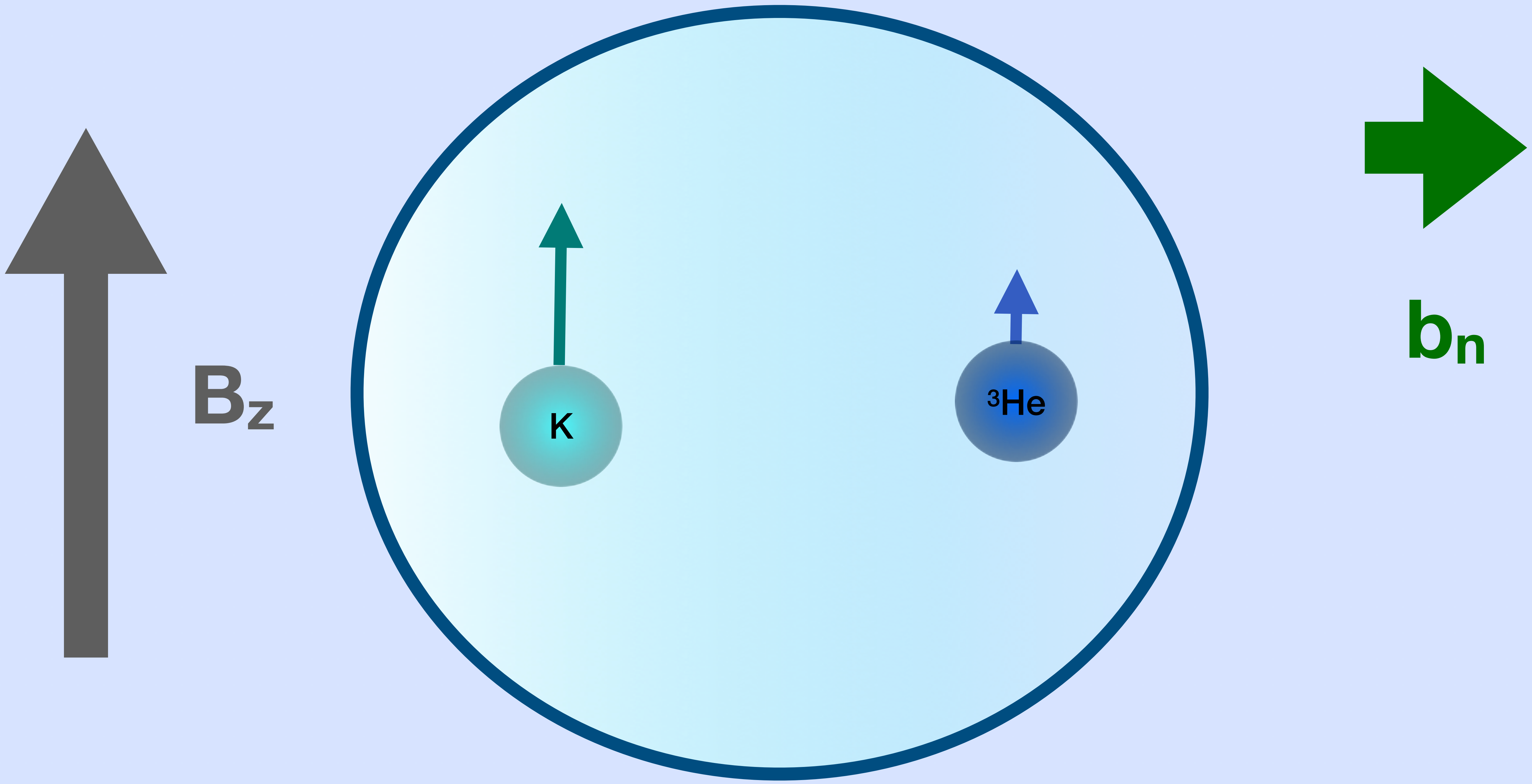

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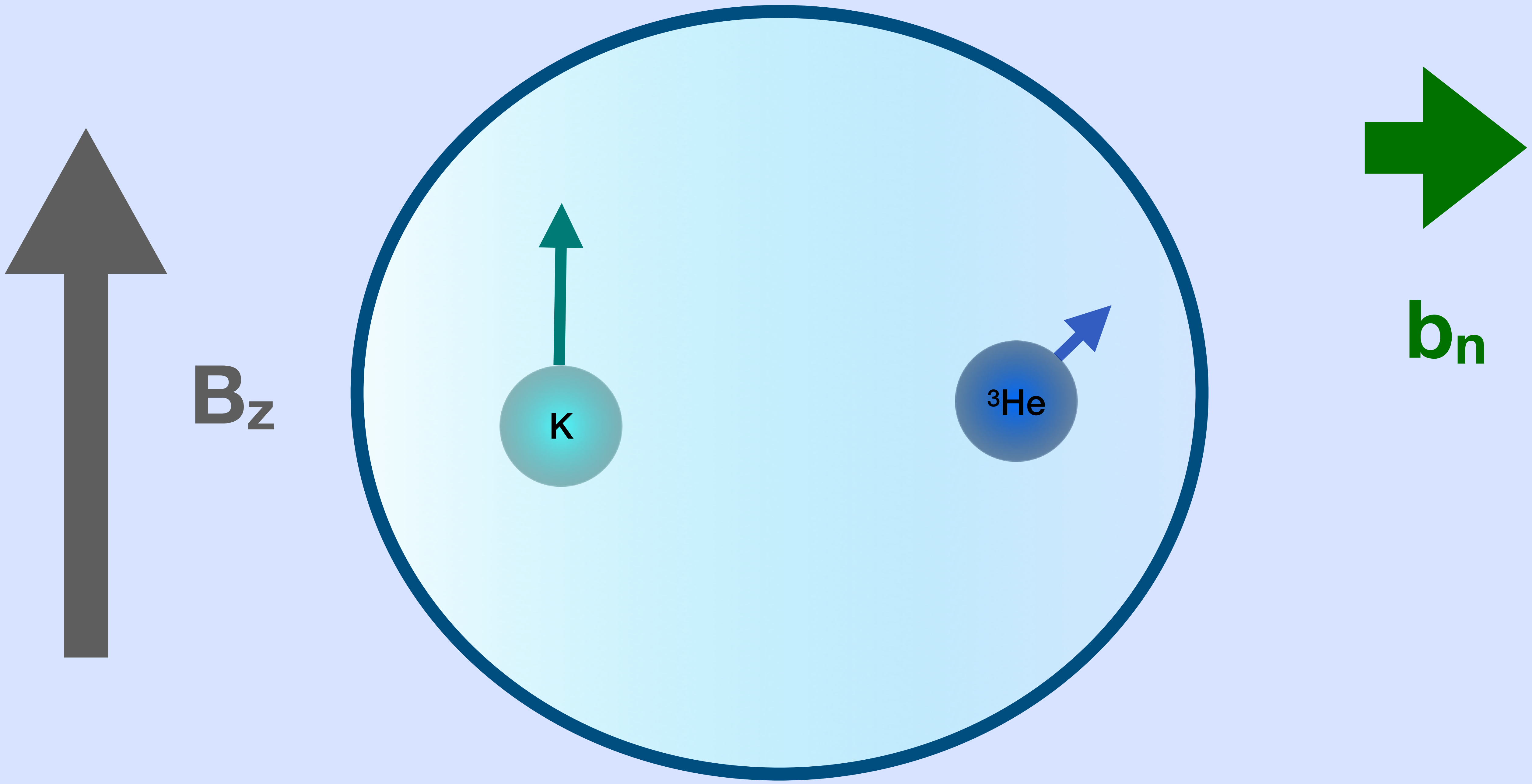

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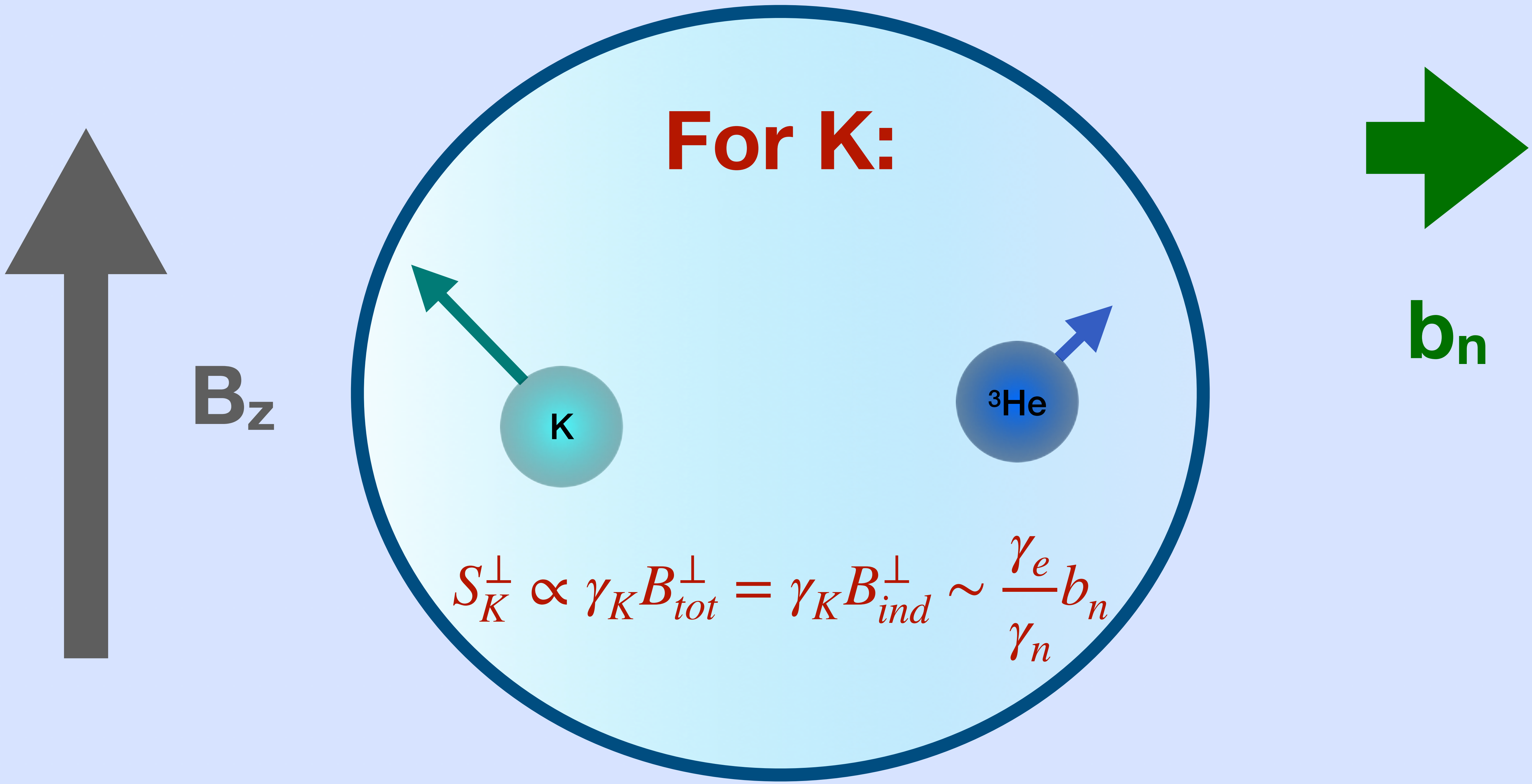
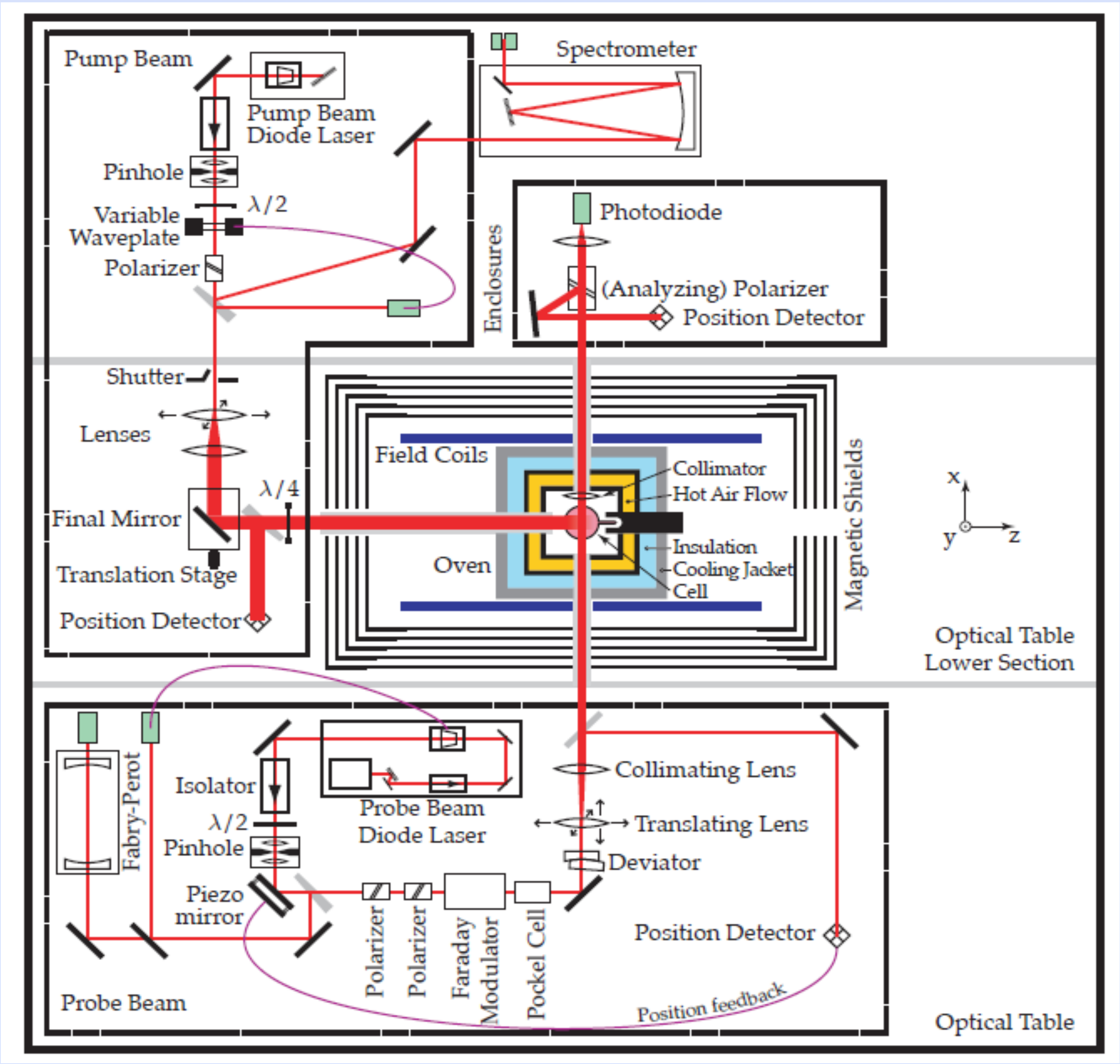
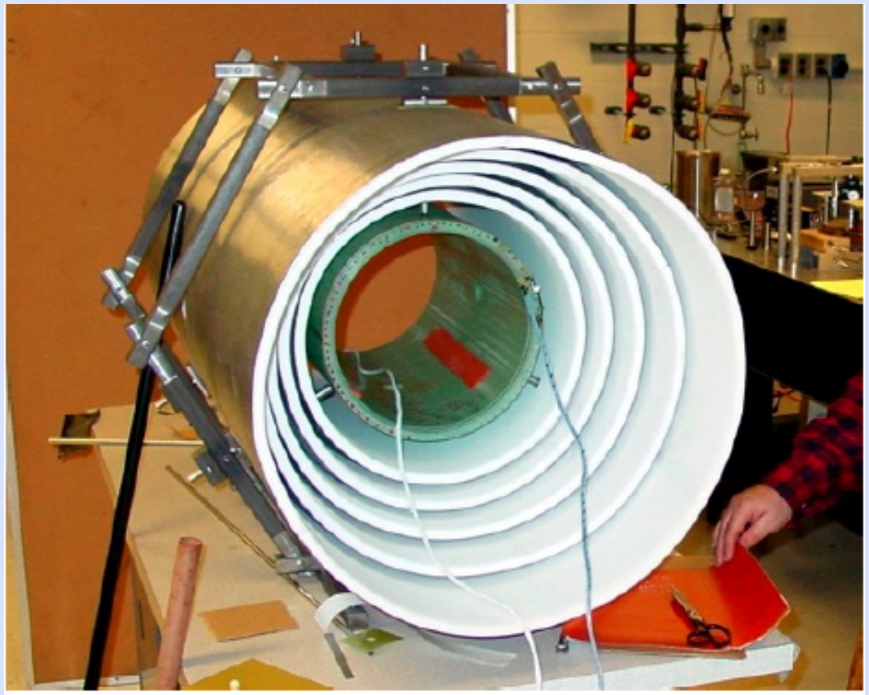
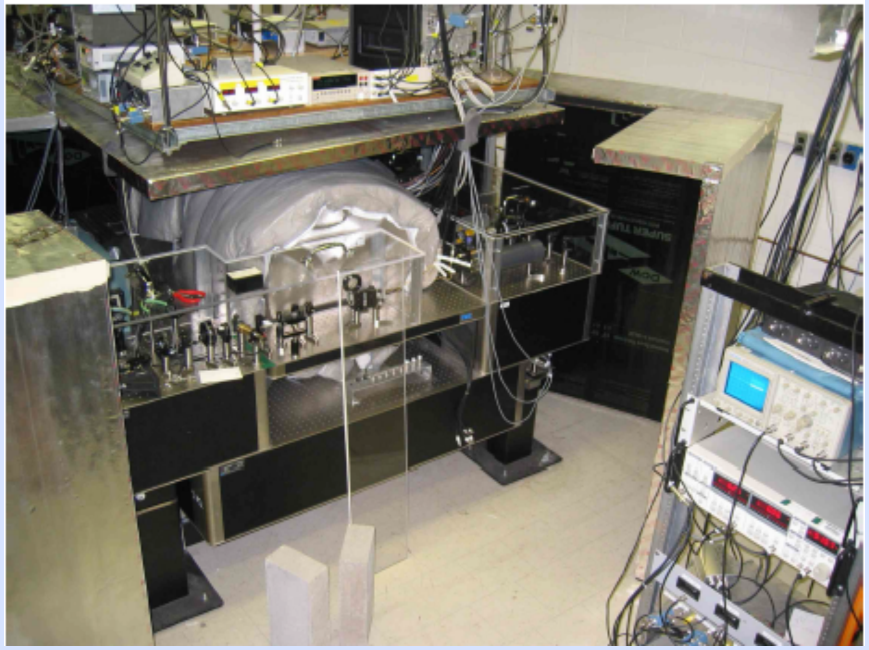


Measurable, Enhanced Signal!

The Romalis Group Comags

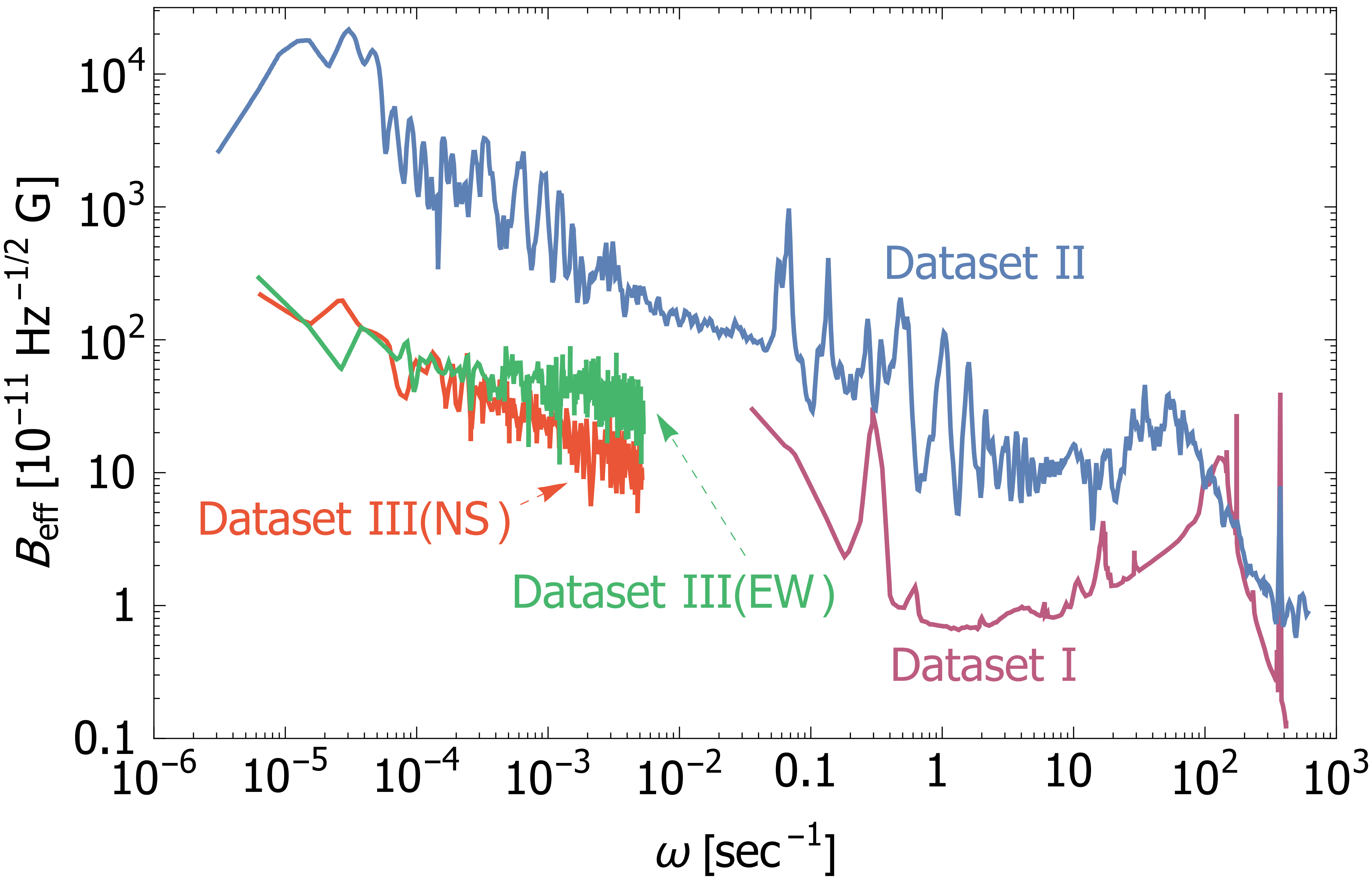






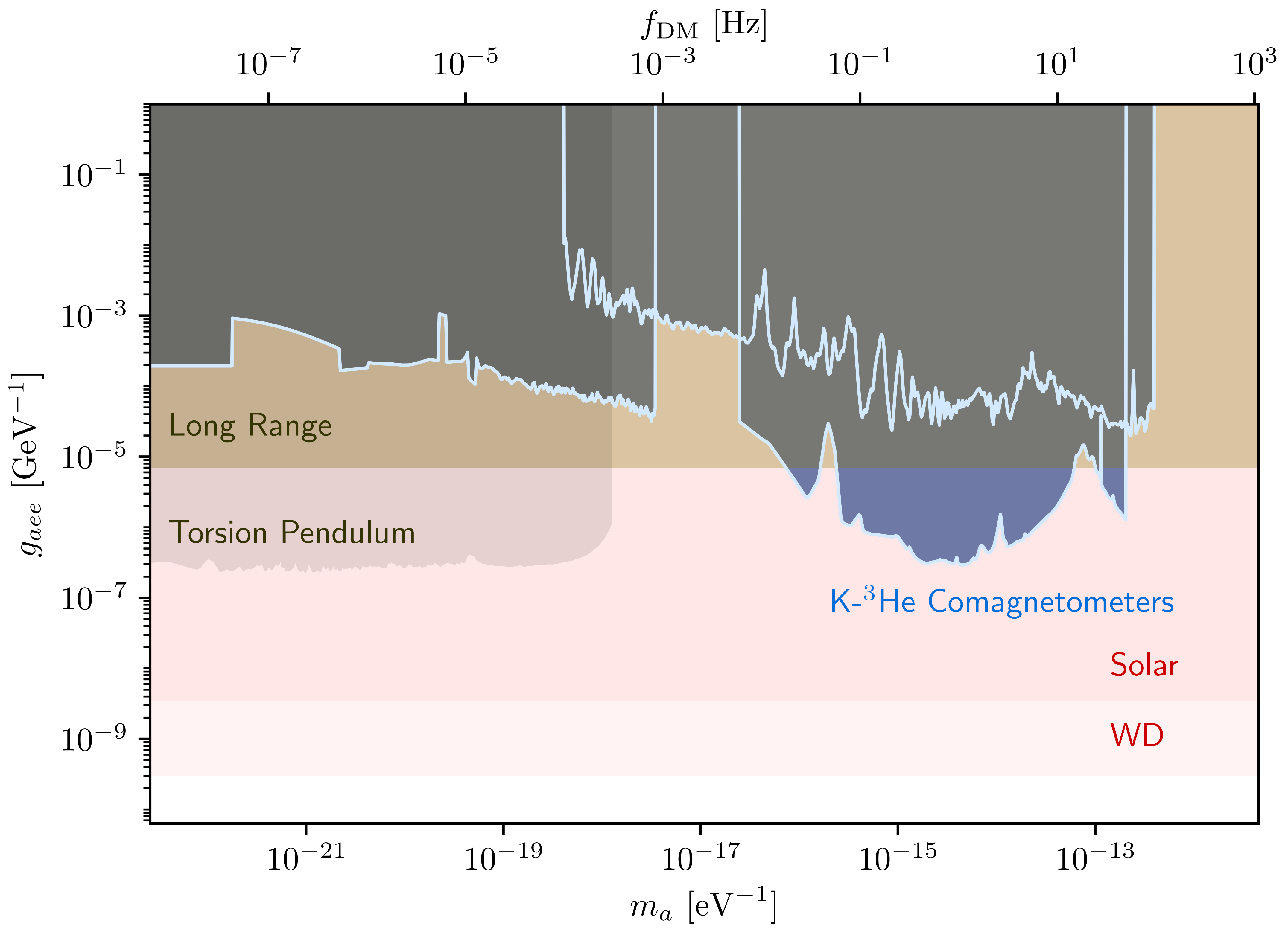
[Gergoios Vasilakis Dissertation 2011], [Justin M. Brown Dissertation 2011], [Thomas W. Kornack Dissertation 2005]

Old Data



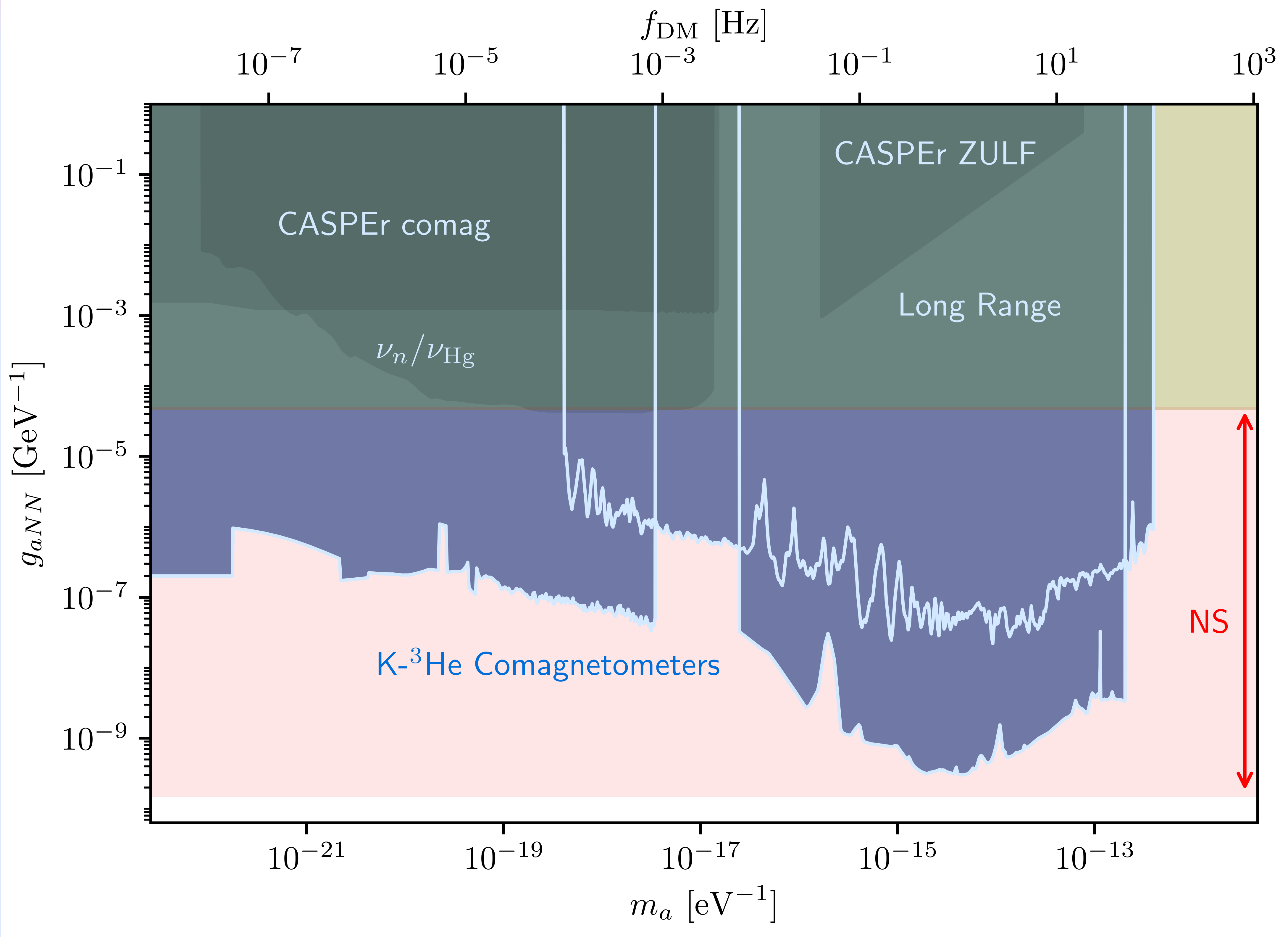
10^4
10^3
10^2
10
1
0.1
B_{eff} [10^{-11} Hz$^{-1/2}$ G]
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
0.1
1
10
10^2
10^3
ω [sec^{-1}]
Dataset II
Dataset III(NS)
Dataset III(EW)
Dataset I

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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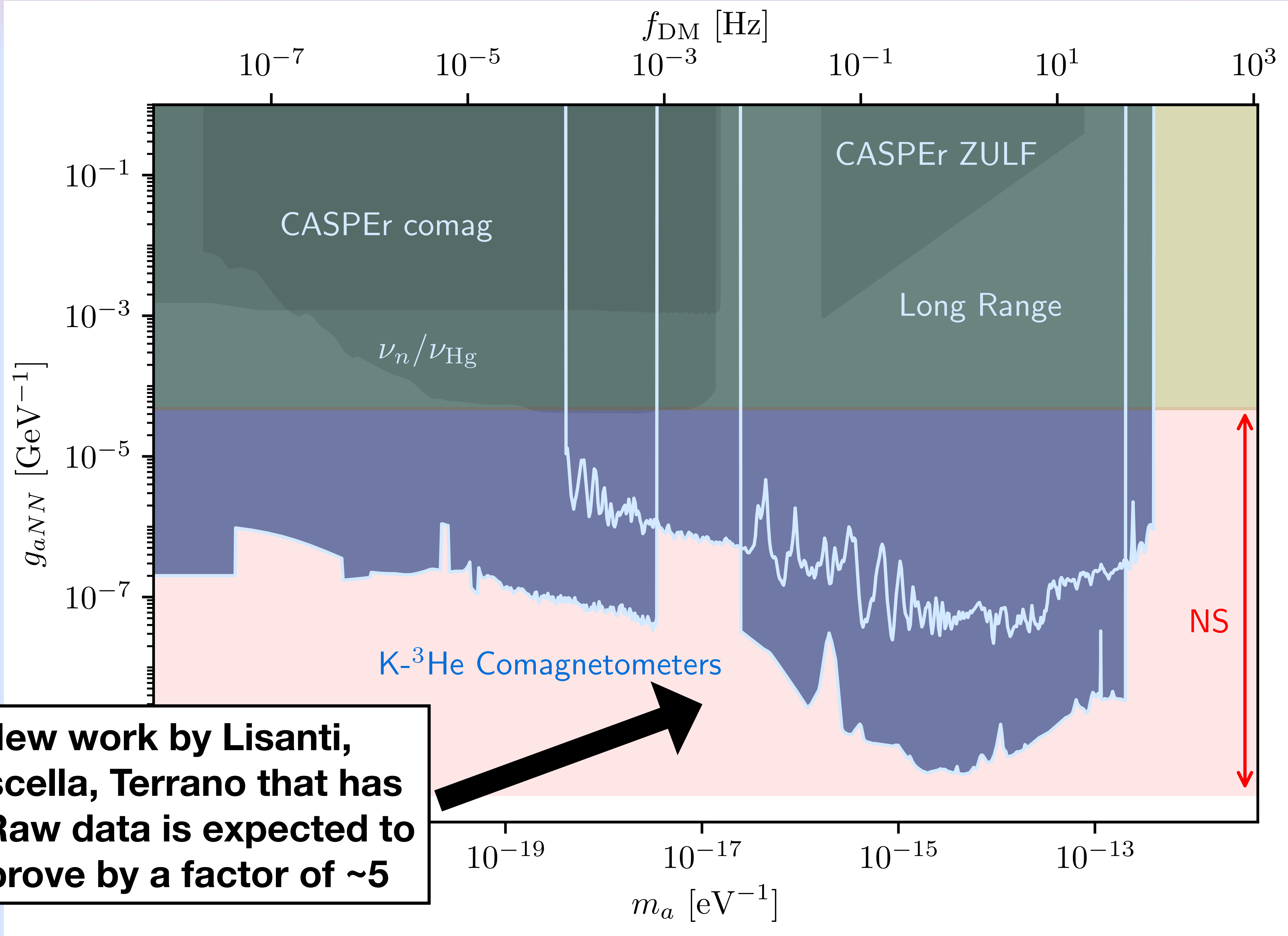

New work by Lisanti, Moscella, Terrano that has the Raw data is expected to improve by a factor of ~5

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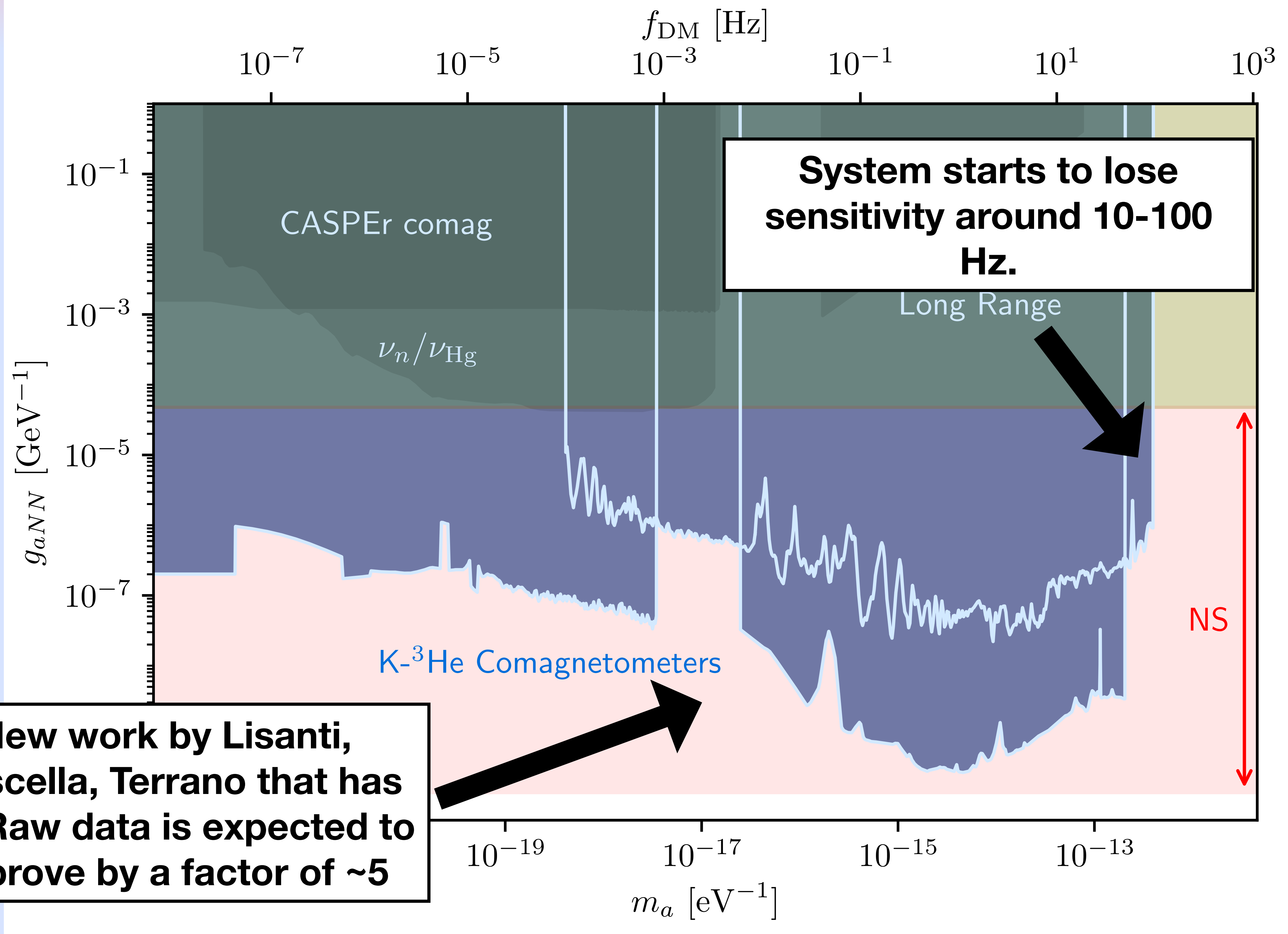

System starts to lose sensitivity around 10-100 Hz.

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

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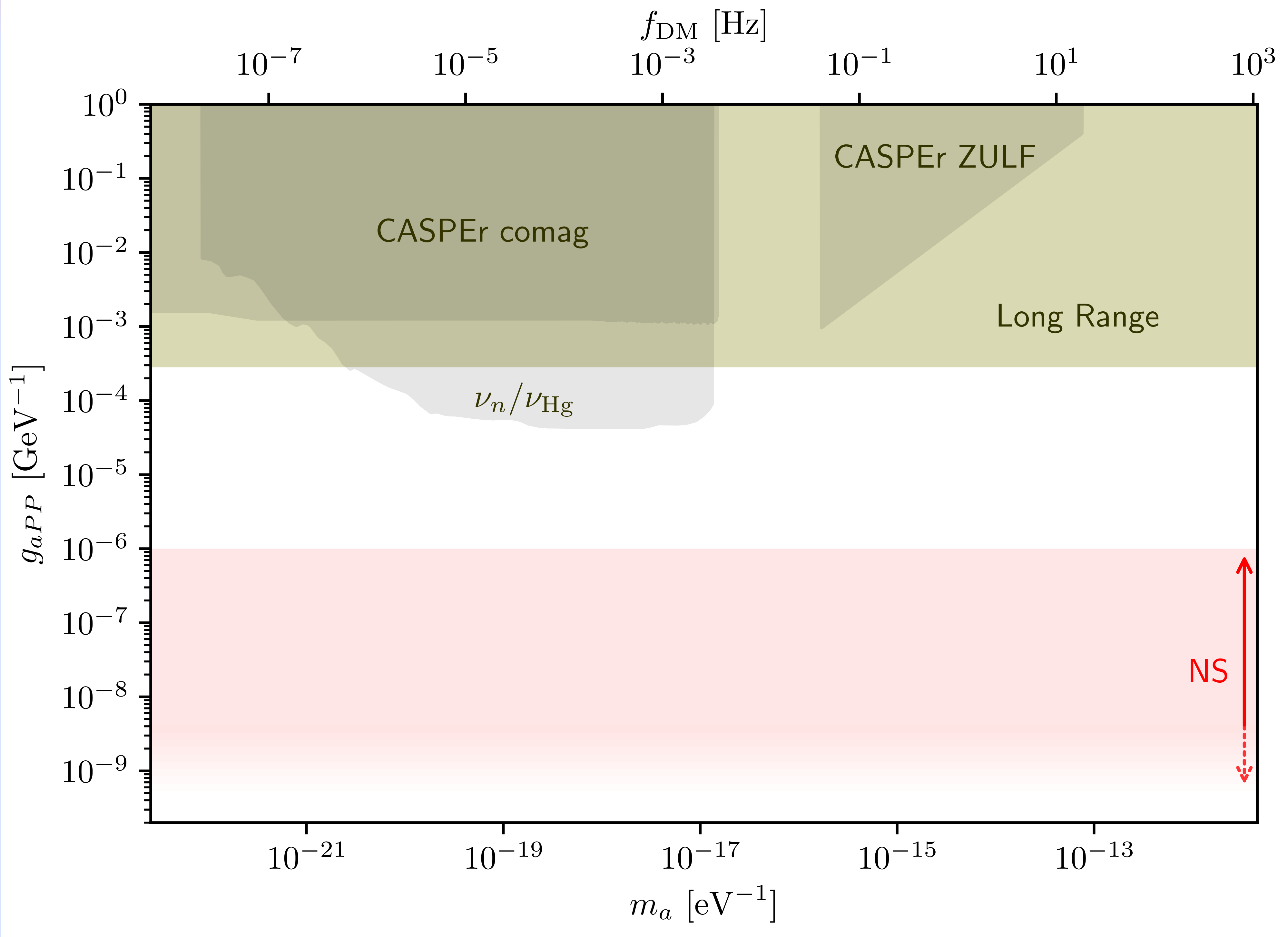
Results (p)



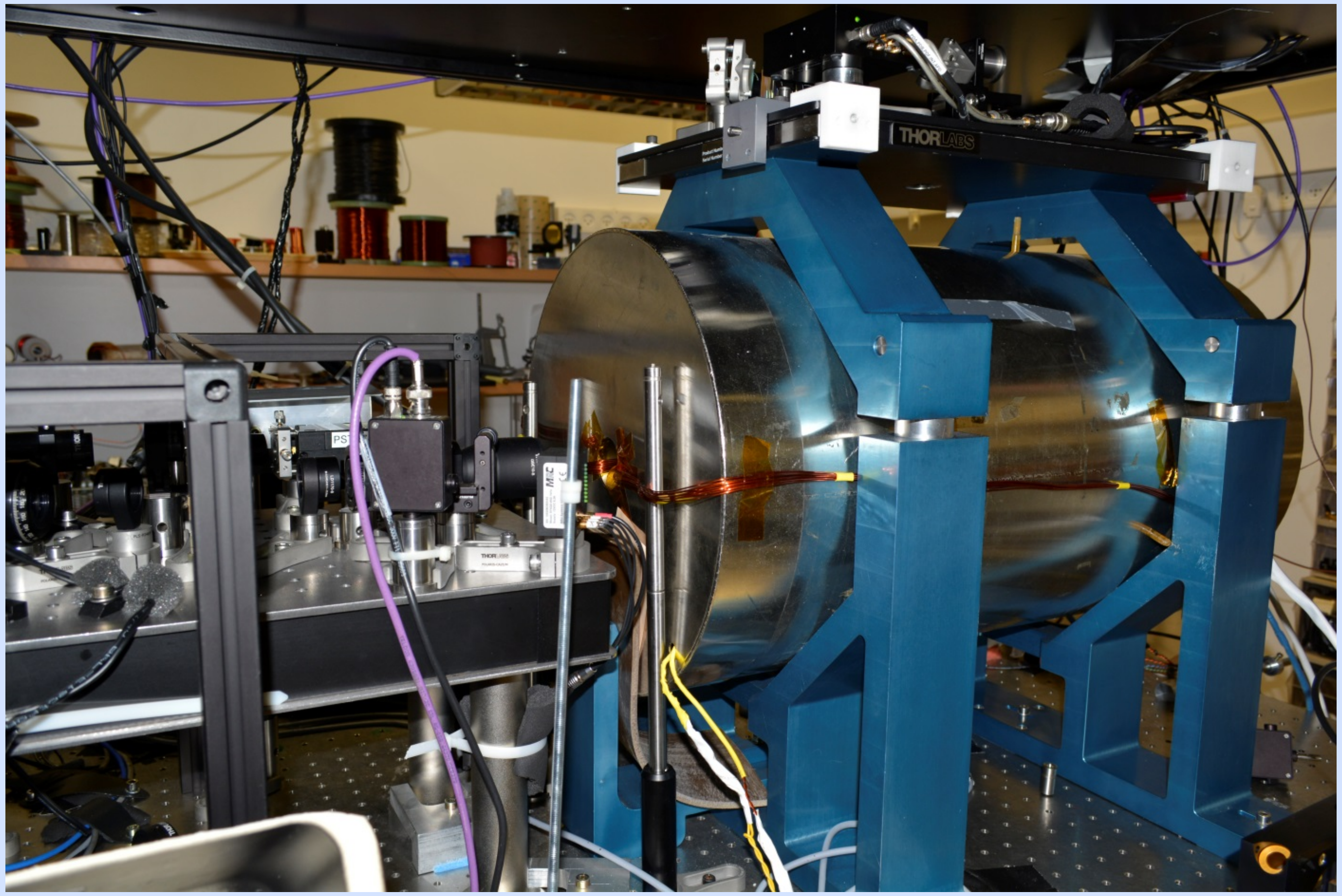
[T. Wu *et al.*:1901.10843, E. G. Adelberger *et al. 2007*, C. Abel *et al.*:1708.06367, CASPEr Collaboration: 1902.04644, K. Hamaguchi *et al*. 1806.07151, J. Keller *et al*. 1205.6940, A Sedrakian 1512.07828]

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

NASDUCK collaboration

[**IMB**, Y. Hochberg, O. Katz, O. Katz
E. Kuflik, G. Ronen, R. Shaham, T. Volansky. 2105.XXXX, and a bit of 21YY.XXXX]

Five experiments should occur in the “near” future



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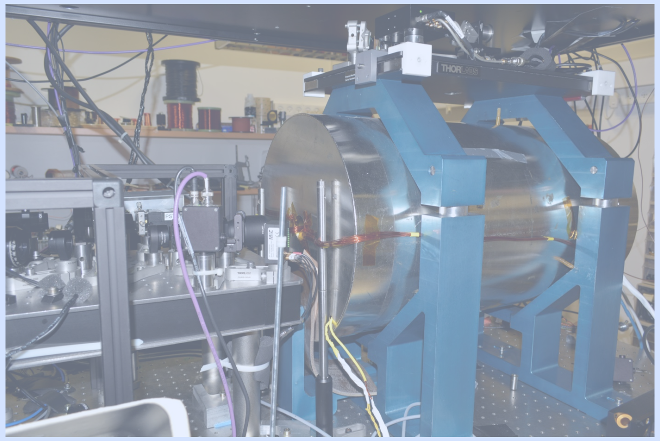

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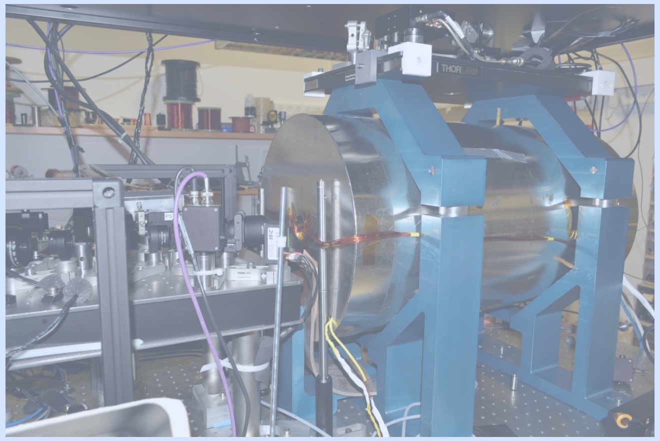
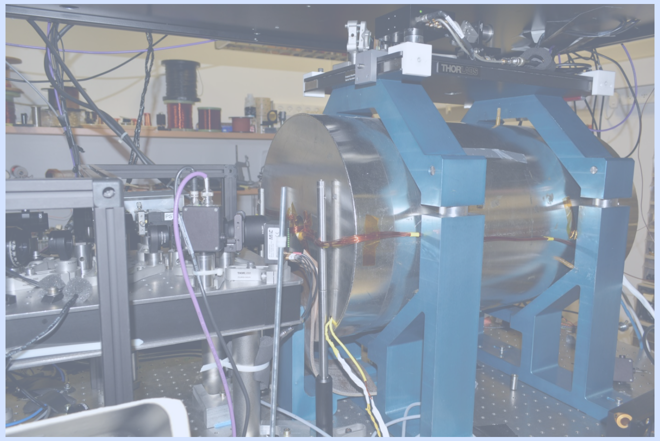


1. **NASDUCK Floquet**

Wait a few slides

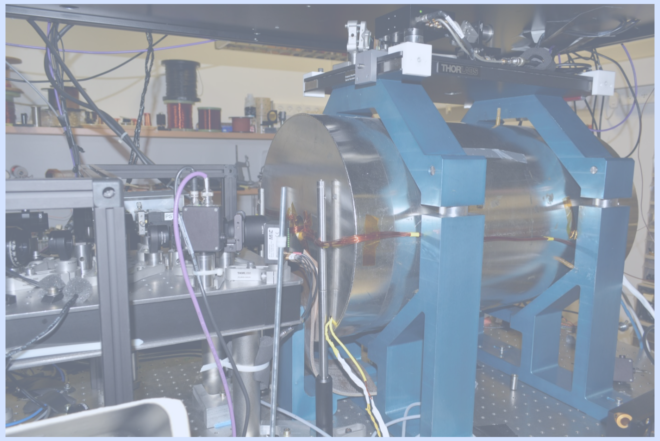
Five experiments should occur in the “near” future



1. NASDUCK Floquet — Wait a few slides

2. NASDUCK High Frequencies — Data is waiting to be analyzed.

Five experiments should occur in the “near” future



1. **NASDUCK Floquet** — **Wait a few slides**

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3. **NASDUCK Floquet Low** — **Experiment will start running in the next few months**

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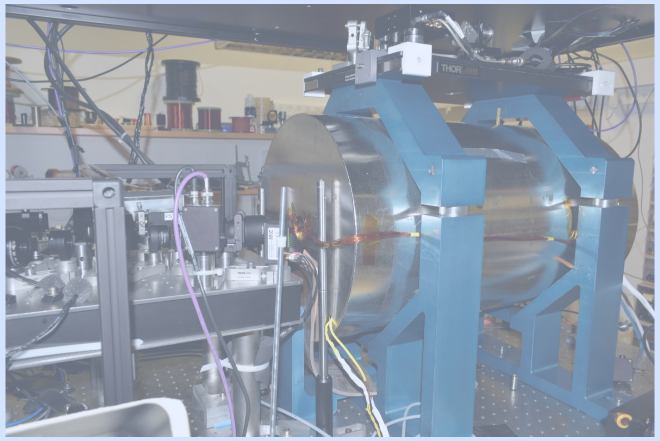

1. NASDUCK Floquet — Wait a few slides
2. NASDUCK High Frequencies — Data is waiting to be analyzed.
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4. NASDUCK Modulated — Some data already taken, more data will be taken soon.

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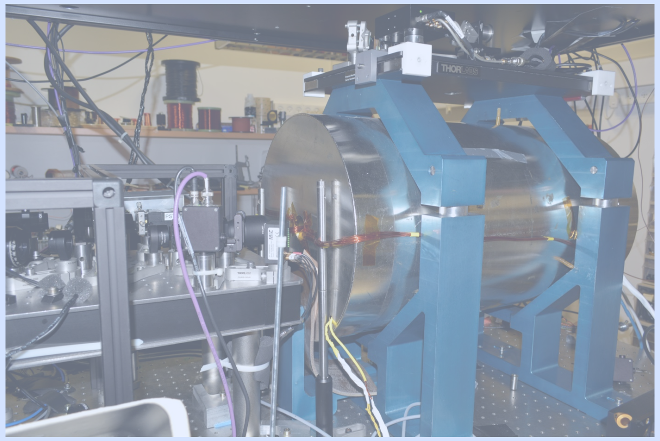

1. NASDUCK Floquet	Wait a few slides
2. NASDUCK High Frequencies	Data is waiting to be analyzed.
3. NASDUCK Floquet Low	Experiment will start running in the next few months
4. NASDUCK Modulated	Some data already taken, more data will be taken soon.
5. NASDUCK CoComag	Data exists for Proof of concept. Needs to be analyzed. No clear schedule for a full experiment.

NASDUCK
Floquet

Response to Signal

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

Response to Signal

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

Response to Signal

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

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

Alkali response **Noble response**

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Alkali response **Noble response**

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

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Alkali response **Noble response**

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

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

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

Floquet Fields

Floquet Fields

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

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$$S_{\mathrm{Alk}}(t) = \frac{\gamma_{\mathrm{Alk}} S_{\mathrm{z,Alk}} B_{\perp,Alk}(\omega = m_a) \cdot e^{i m_a t}}{(\gamma_{\mathrm{Alk}} B_{\mathrm{z,Alk}} - m_a) + i\Gamma_{\mathrm{Alk}}}$$

Floquet Fields

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

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Floquet Fields

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For $\omega_F = \gamma_{\text{Alk}} B_{\text{z,Alk,0}} - \gamma_{\text{Nob}} B_{\text{z,Nob,0}}$, we get that around the floquet frequency

Floquet Fields

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For $\omega_F = \gamma_{\text{Alk}} B_{\text{z,Alk,0}} - \gamma_{\text{Nob}} B_{\text{z,Nob,0}}$, we get that around the floquet frequency

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

Floquet Fields

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

$$S_{\text{Alk}}(t) = \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}(\omega = m_a) \cdot e^{im_a t}}{(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a) + i\Gamma_{\text{Alk}}} \rightarrow \sum_n \eta_F^{(n)} \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}(\omega = m_a) \cdot e^{im_a t + n\omega_F t}}{(\gamma_{\text{Alk}} B_{\text{z,Alk,0}} - m_a - n\omega_F) + i\Gamma_{\text{Alk}}}$$

For $\omega_F = \gamma_{\text{Alk}} B_{\text{z,Alk,0}} - \gamma_{\text{Nob}} B_{\text{z,Nob,0}}$, we get that around the floquet frequency

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

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

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

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$$\Downarrow$$

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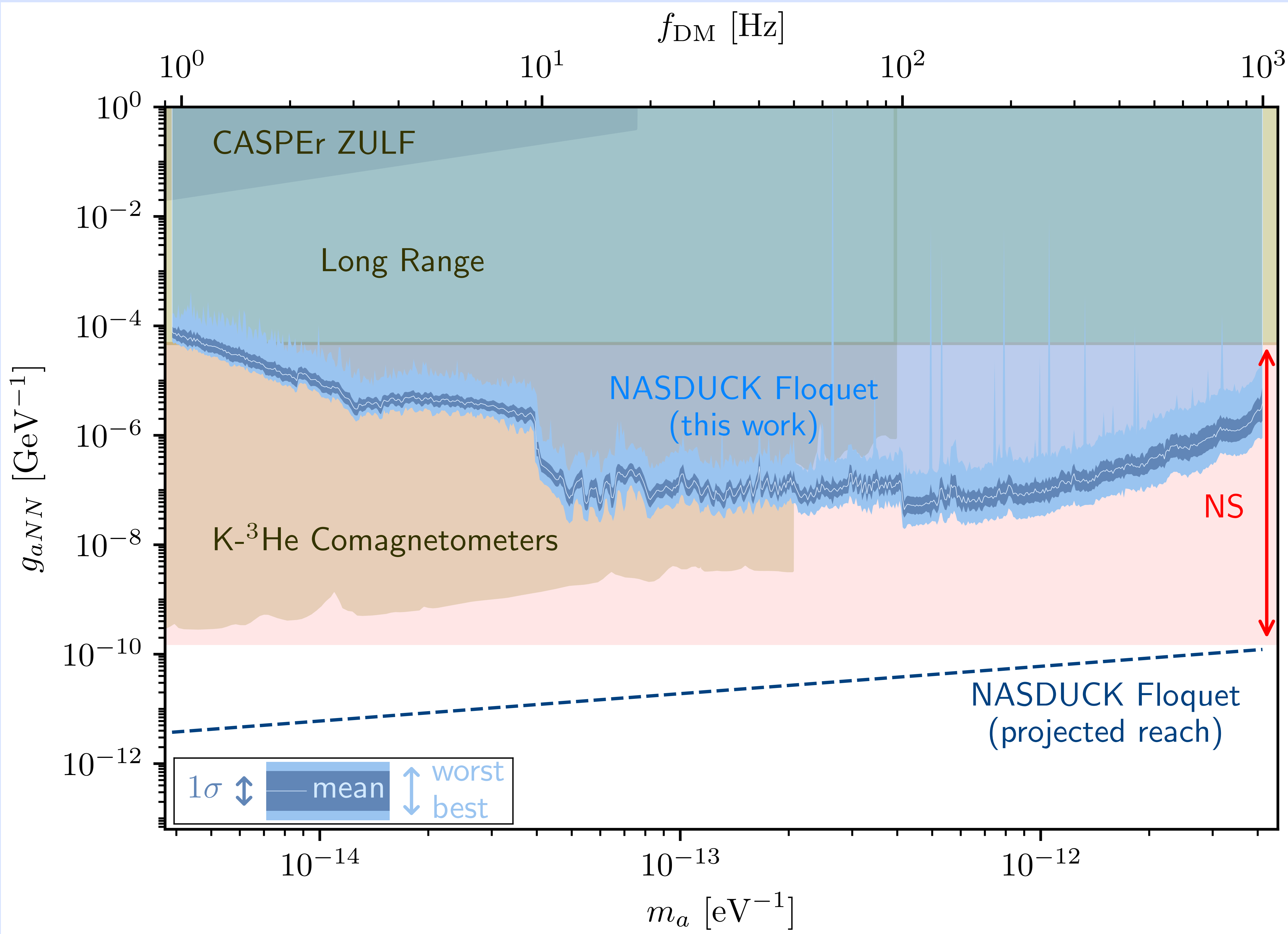
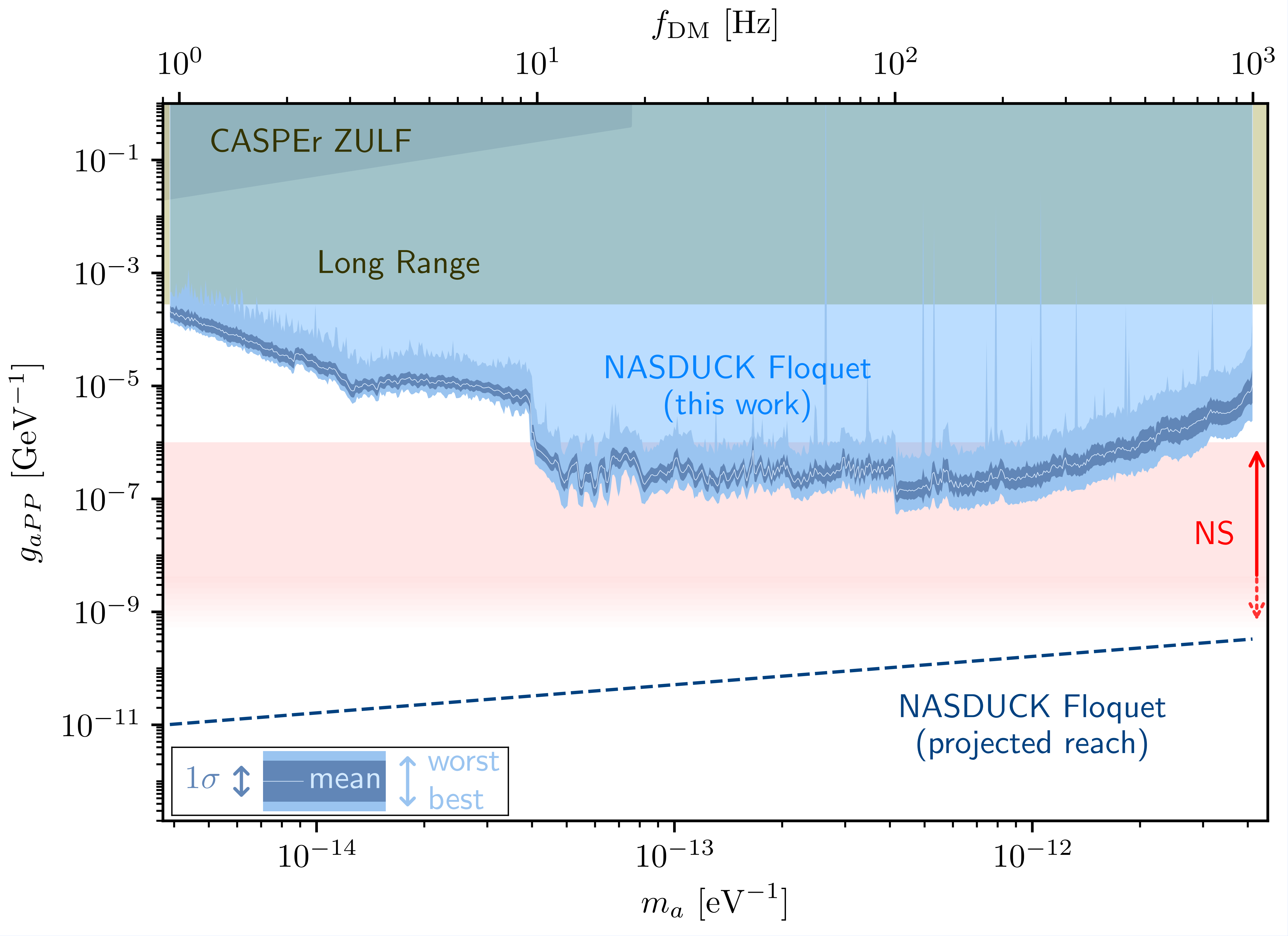
Analysis procedure was determined pre-unblinding, final stages of the processing.

NASDUCK Floquet Results (n)



NASDUCK Floquet Results (p)



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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

NASDUCK-matter

Thanks For Listening!