Title: Axion-like Relics: New Constraints from Old Comagnetometer Data

Speakers: Itay Bloch

Series: Particle Physics

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Abstract: Abstract: TBD

Comagnetometers as a Probe to New Physics

Oct 2020

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(Work done in the Rafael Quantum Optics Lab)

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Based on work presented in arxiv:1907.03767
(New information based on active works with Gil Ronen and Or Katz)

Outline

- **Axion Like Particles (ALPs)**
  - Axions and Axion Like Particles
  - Coherent Interactions
- **The Comagnetometer**
  - What is a Comagnetometer?
  - Comagnetometer Dynamics
  - Comagnetometer Experiments
  - Future Prospects (and recent developments)
- **Conclusions**

QCD Axion

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

  [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]

QCD Axion

- A solution to the strong CP problem, $\theta_{QCD} \to a/f_a$.
  [Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]
- Pseudo-scalars. Has derivative couplings, e.g.: $\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma_5\gamma^\mu\psi$
- $m_a \propto \frac{\Lambda^2_{\rm QCD}}{f_a}$
- Can be a CDM component
- Can be very light and remain CDM candidate:

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

4

QCD Axion

Axion Like Particles (ALPs)

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

  ~~[Peccei, Quinn 1977; Weinberg 1978; Wilczek 1978]~~

- Pseudo-scalars. Has derivative couplings, e.g.: $\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma_5\gamma^\mu\psi$

- ~~$m_a \propto \frac{\Lambda^2_{QCD}}{f_a}$~~

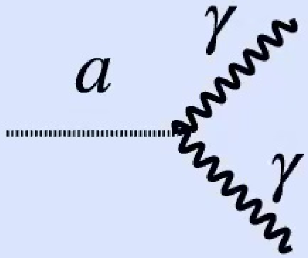
- Can be a CDM component (we assume all)

- Can be very light and remain CDM candidate:

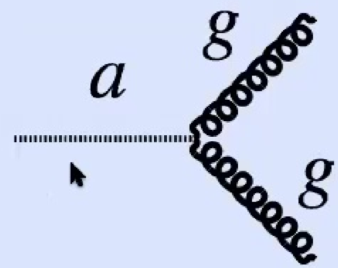
$$m_a(\text{relevant to talk}) < 10^{-12}\ \text{eV}$$

4

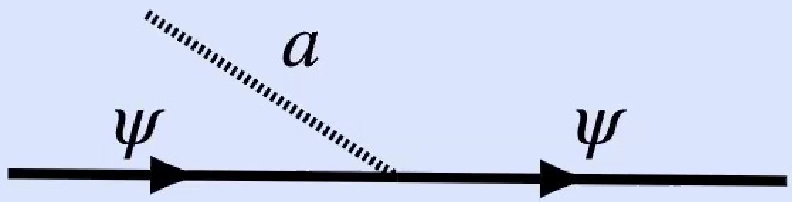
ALP-SM Interactions



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



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

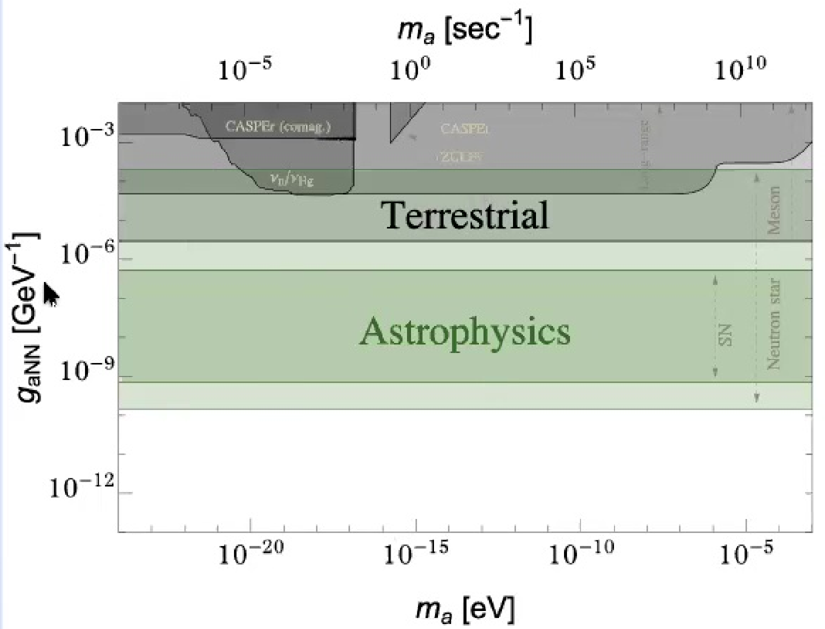


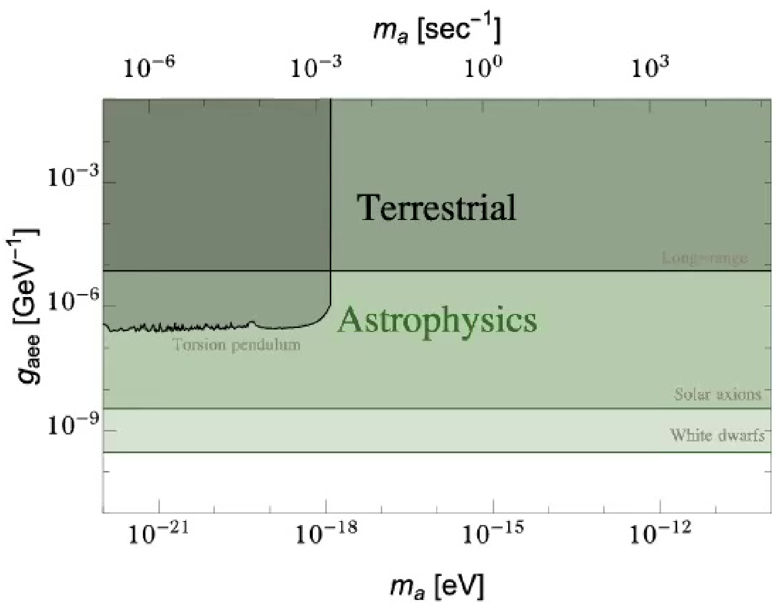
$$g_{a\psi\psi}\partial_\mu a \cdot \bar{\psi}\gamma^\mu\gamma_5\psi$$

ALP Interactions with Neutrons and Electrons

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

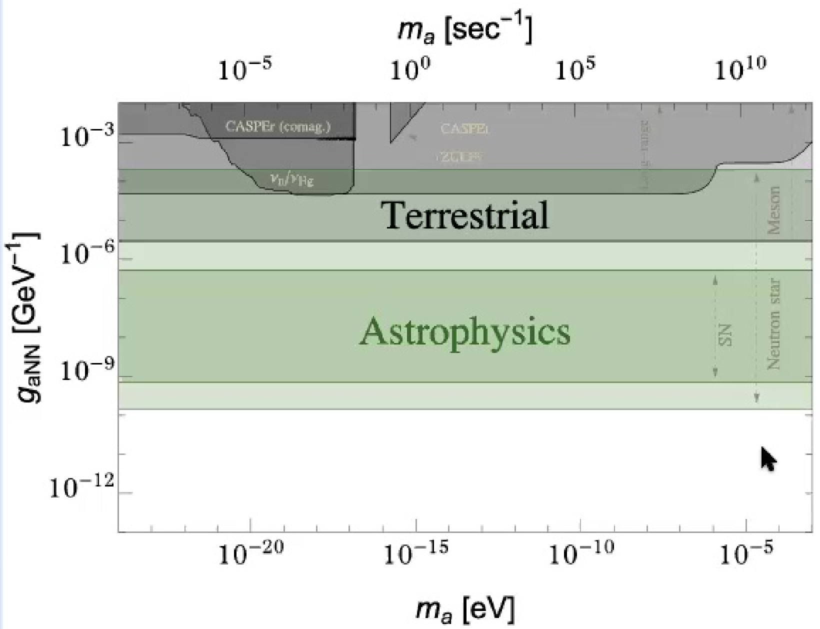
$$g_{aee}\partial_\mu a \cdot \bar{e}\gamma^\mu\gamma_5 e$$

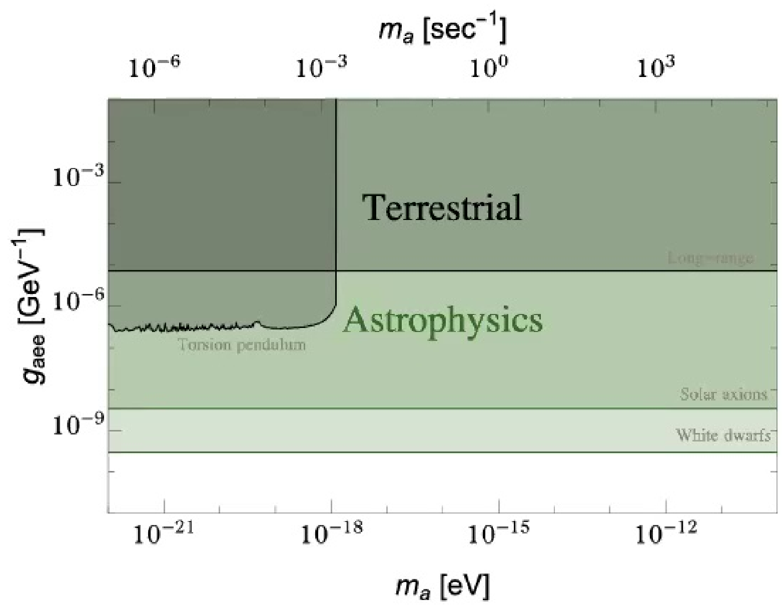




ALP Interactions with Neutrons and Electrons

$$g_{ann}\partial_\mu a \cdot \bar{n}\gamma^\mu\gamma_5 n \qquad g_{aee}\partial_\mu a \cdot \bar{e}\gamma^\mu\gamma_5 e$$





Is there a way to improve on the astrophysical bounds?

Coherent Interactions (1)

For light ALPs $(m_a \lesssim 30\ \text{eV})$, $n_a = \dfrac{0.3\ \text{GeV}}{m_a \cdot \text{cm}^3} > 1/\lambda^3_{\text{de-Broglie}}$

Coherent Interactions (1)

For light ALPs $(m_a \lesssim 30\ \mathrm{eV})$, $n_a = \dfrac{0.3\ \mathrm{GeV}}{m_a \cdot \mathrm{cm}^3} > 1/\lambda^3_{\mathrm{de-Broglie}}$

↓

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

In the non-relativistic limit, for $\mathscr{L}_{a\psi\psi} \sim \partial_\mu a \cdot \bar{\psi}\gamma^\mu\gamma_5\psi$,

$$H_{a\psi\psi} \sim \partial_i a \cdot \bar{\psi}\gamma^i\gamma_5\psi \sim a_0 \cdot \vec{p}_a \cdot \vec{S}_\psi$$

Coherent Interactions (2)

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

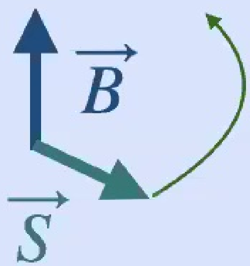
$$\overrightarrow{b}_{a-\psi} = g_{a\psi\psi} \sqrt{2\rho_a} \cos(m_a t) \cdot \overrightarrow{v}_{a-\psi}$$ [astro-ph/9501042]

This is an effect linear in $g_{a\psi\psi}$!

But how to measure it?

Larmor Precession and Zeeman Splitting

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



$$\dot{\vec{S}} = \gamma \vec{S} \times \vec{B} \quad \Rightarrow \quad H = -\gamma \vec{B} \cdot \vec{S}$$

Reminder: $H_{a\psi\psi} = -\vec{b}_{a-\psi} \cdot \vec{S}_{\psi}$

Is there a known way to measure magnetic fields?

Using Alkali Magnetometers to Hunt ALPs

Magnetometers can measure the magnetic-like effect of the ALPs!

But they also measure the actual magnetic fields of the SM…

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Differentiating: EM vs. ALPs

Magnetic Fields:

$$H = -\gamma_e \vec{S}_e \cdot \vec{B} - \gamma_n \vec{S}_n \cdot \vec{B}$$

Anomalous Fields:

$$H = -g_{aee} \vec{S}_e \cdot \vec{b}_a - g_{ann} \vec{S}_n \cdot \vec{b}_a$$

$$\equiv - \vec{S}_e \cdot \vec{b}_e - \vec{S}_n \cdot \vec{b}_n$$

What if we measure with two particles?

But That is Not Enough

(subtracting two numbers is harder than it sounds)

Can we **build a device** that subtracts the two splittings from each other?

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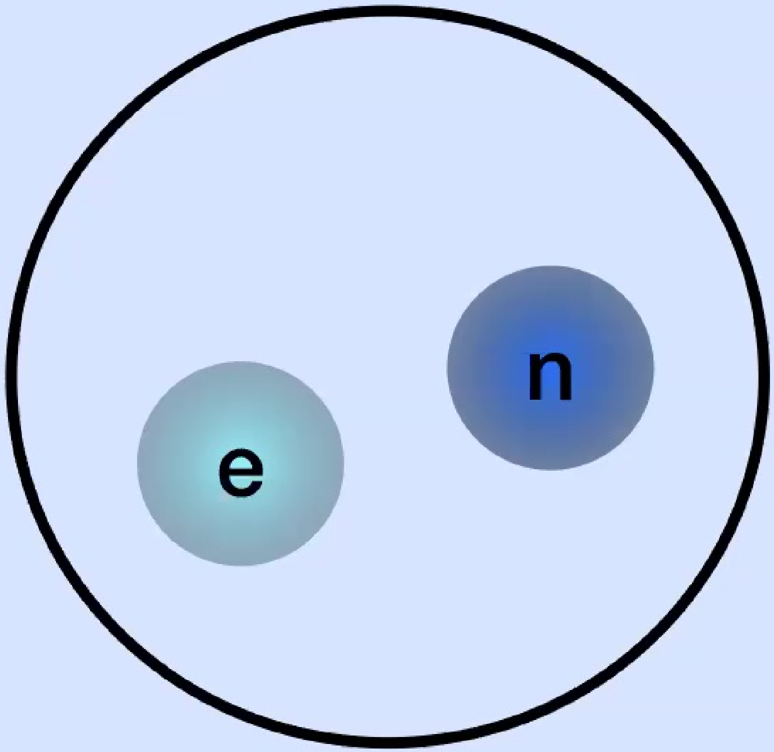
ALP DM generate a magnetic-like field, but it couples differently to different particles compared to the SM.

Comagnetometer
Concept

Comagnetometer
Concept

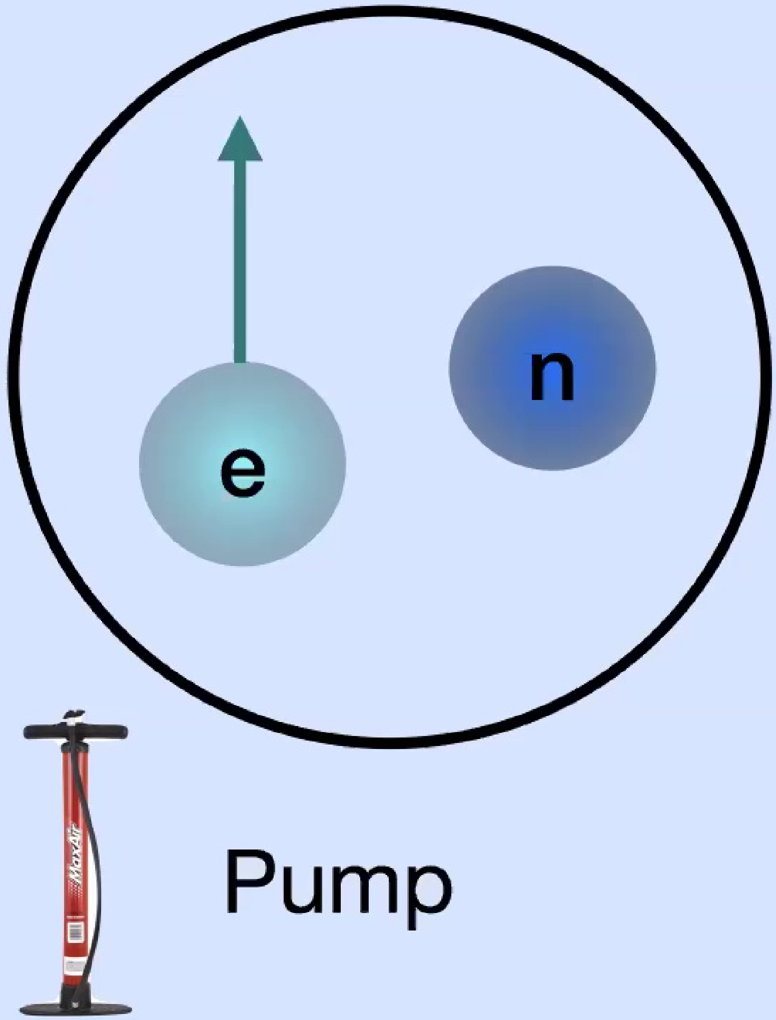
Electrons and neutrons are in a cell



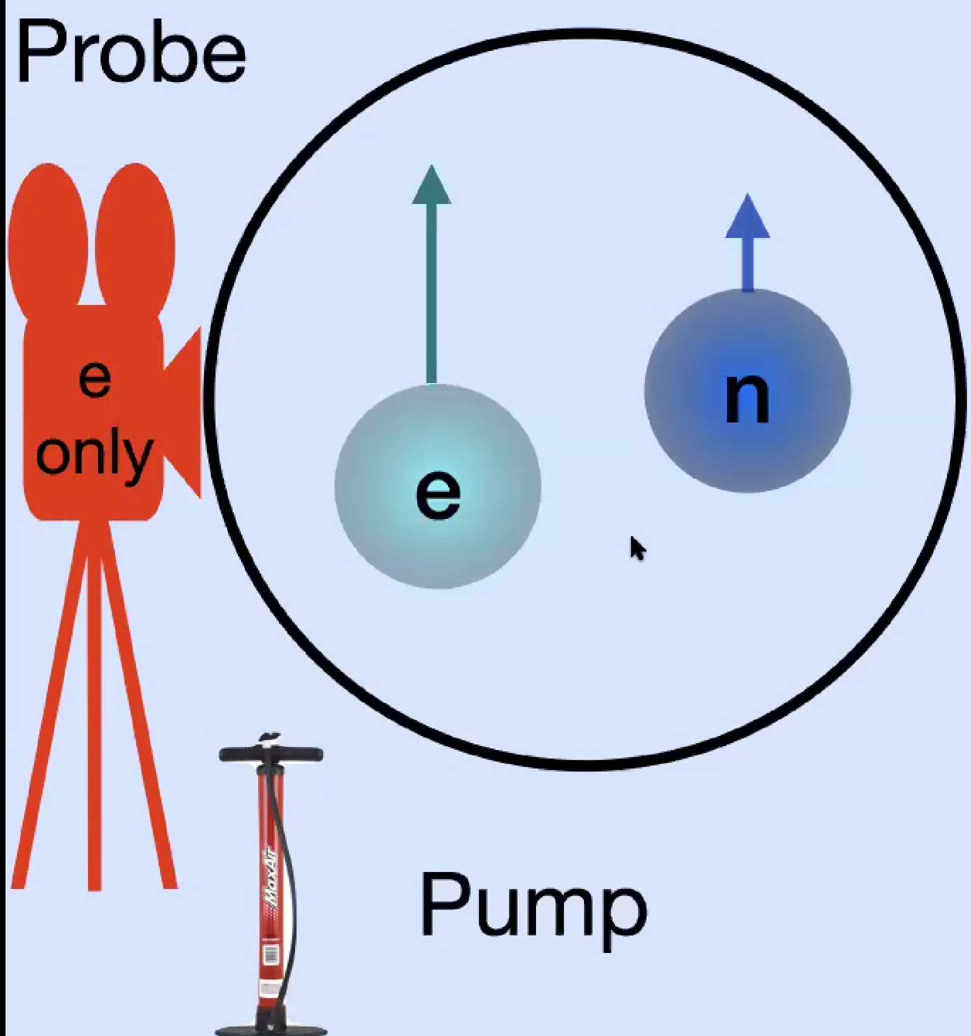
Comagnetometer
Concept

Electrons and neutrons are in a cell

Pump pumps electrons



Comagnetometer
Concept



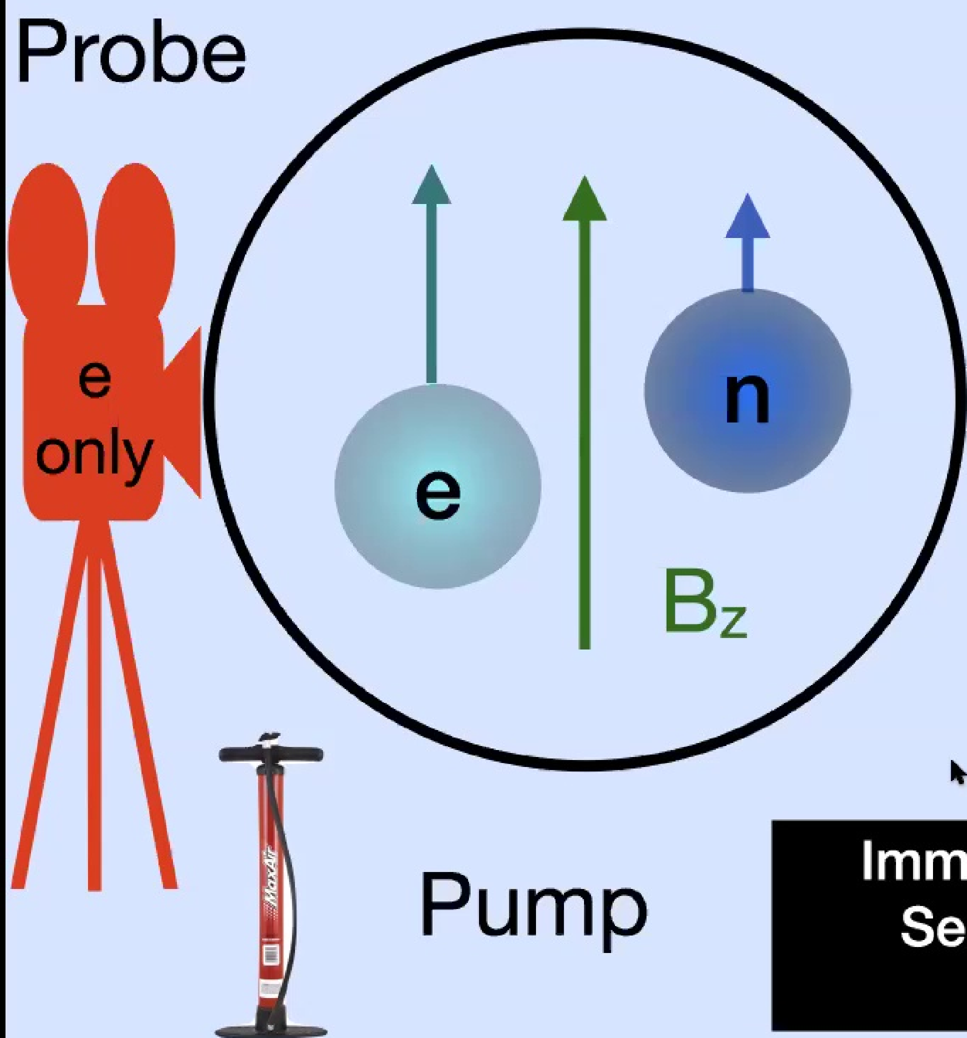
Electrons and neutrons are in a cell

Pump pumps electrons

Electrons pump neutrons

Probe measures electrons

Comagnetometer
Concept



Electrons and neutrons are in a cell

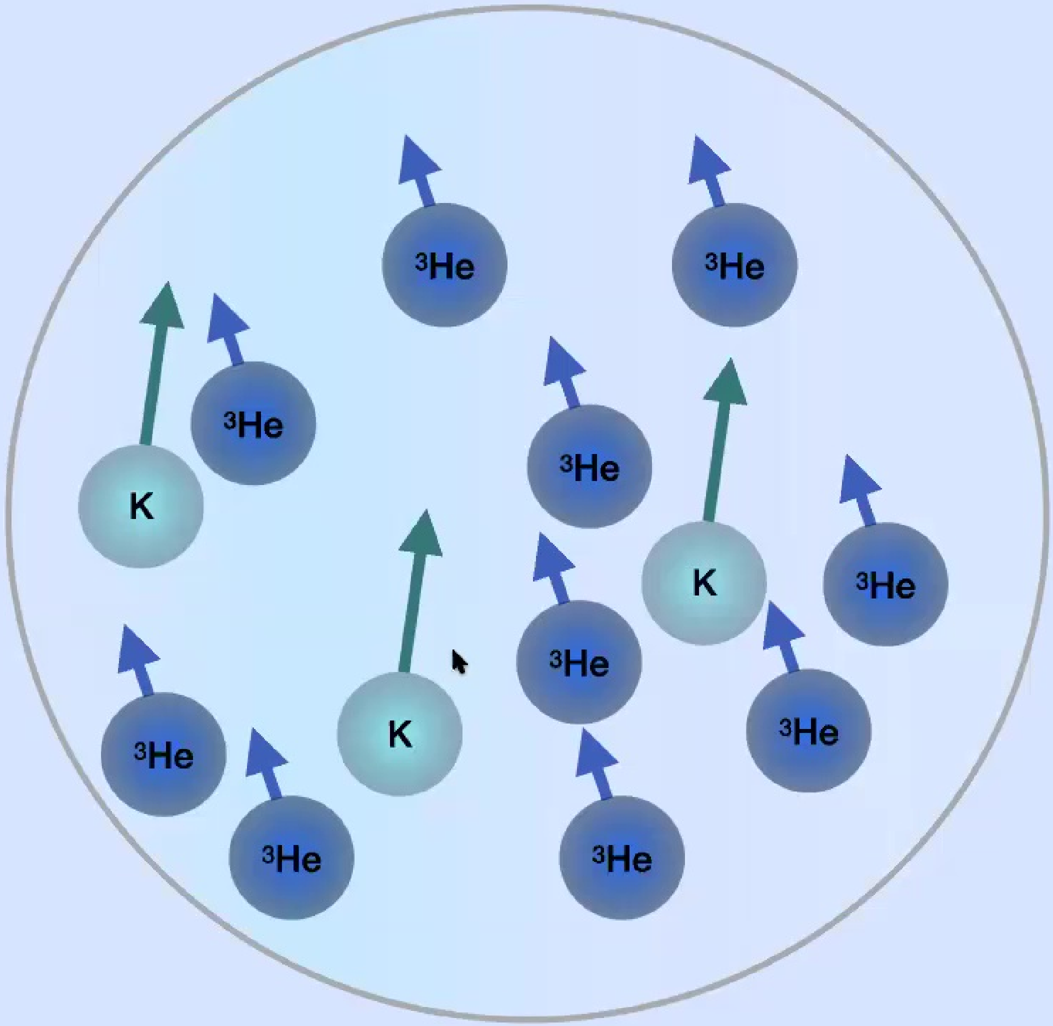
Pump pumps electrons

Electrons pump neutrons

Probe measures electrons

Magnetic fields induce a resonance regime

Immunity to magnetic fields!
Sensitivity to (transverse) anomalous fields!

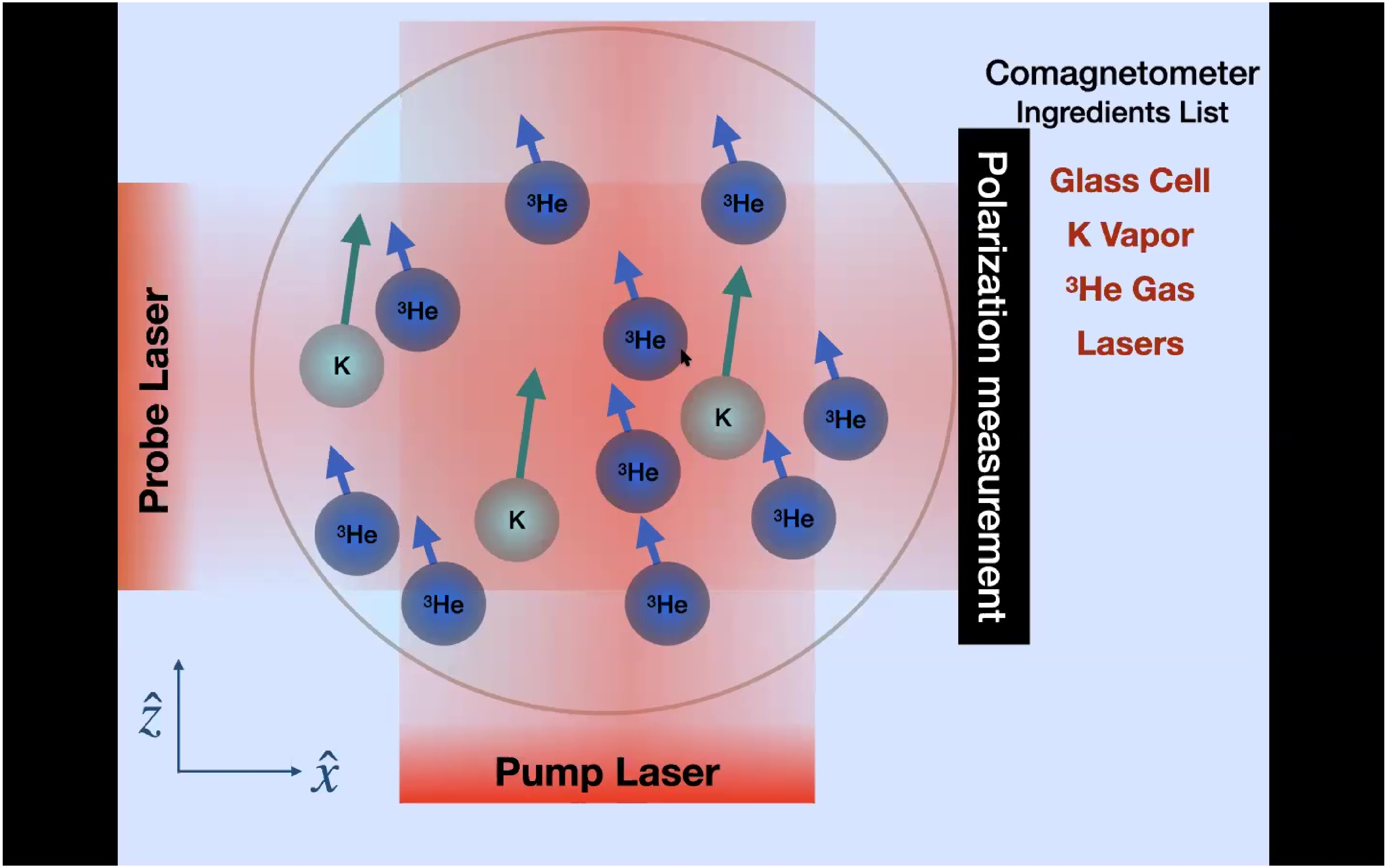


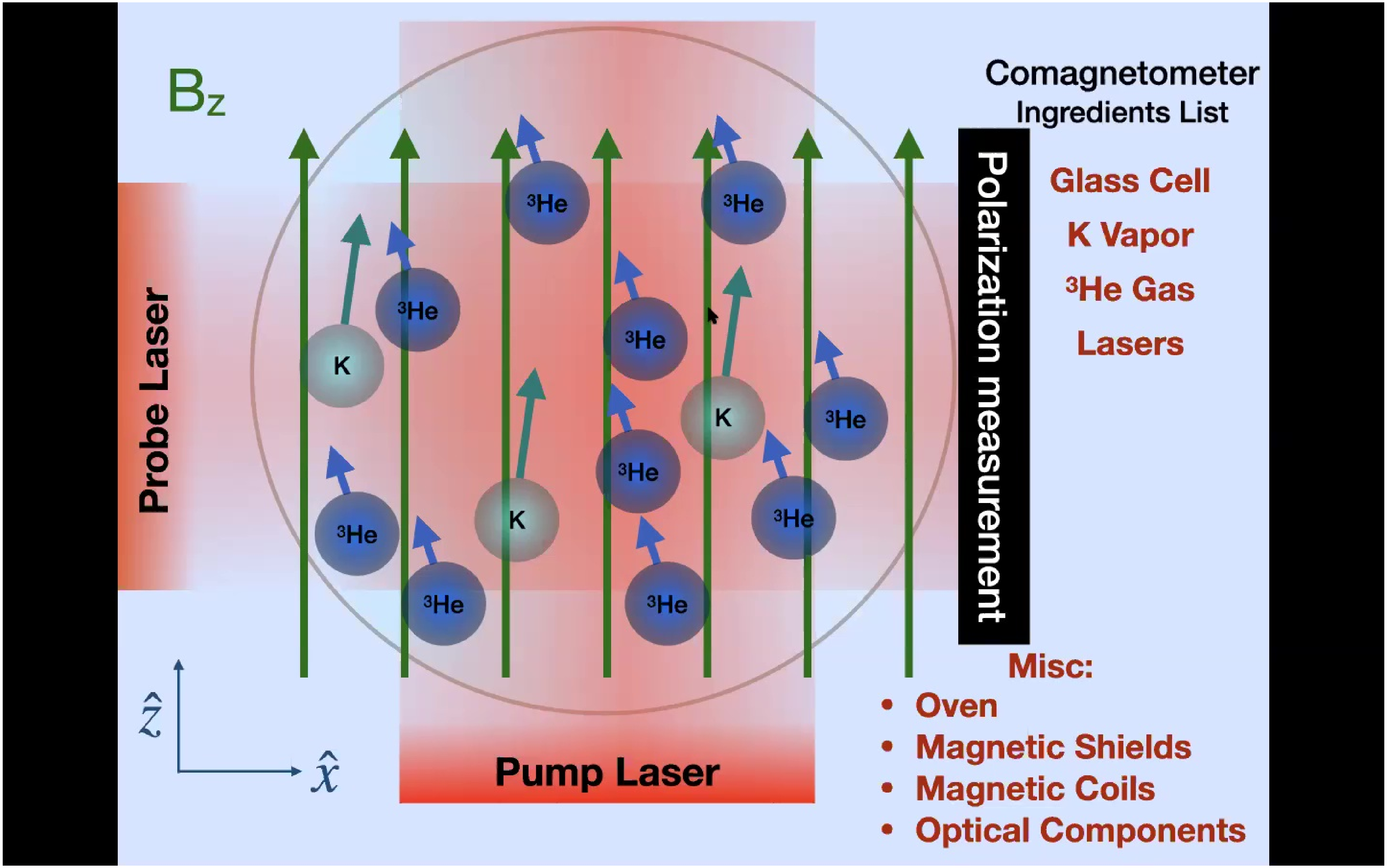
Comagnetometer
Ingredients List

Glass Cell

K Vapor

^{3}He Gas


Comagnetometer
Ingredients List
Glass Cell
K Vapor
³He Gas
Lasers
Polarization measurement
Probe Laser
Pump Laser
K
³He
ẑ
x̂



Bz
Probe Laser
Pump Laser
Polarization measurement
K
³He
ẑ
x̂
Comagnetometer
Ingredients List
Glass Cell
K Vapor
³He Gas
Lasers
Misc:
• Oven
• Magnetic Shields
• Magnetic Coils
• Optical Components

First Magnetometer:

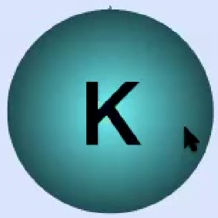
Alkali

Alkali Magnetometer Dynamics

$t = 0$

$t \approx 0.02$ [sec]

Laser Pumps,
Relaxation "steadies"



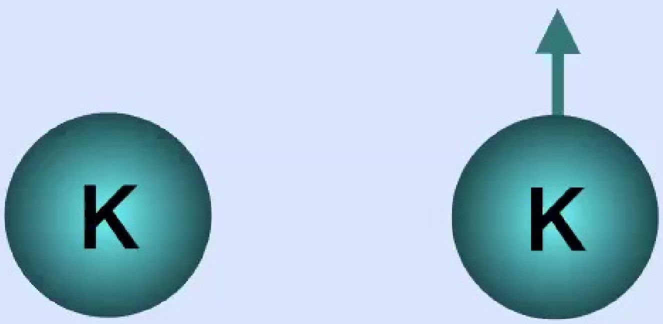
$$\dot{\vec{S}}_K = \frac{1}{2} R_{\text{pu}} \vec{s}_{\text{pu}} - R_K \vec{S}_K$$

Alkali Magnetometer Dynamics

$t = 0$

$t \approx 0.02$ [sec]

Laser Pumps,
Relaxation "steadies"



$$\dot{\vec{S}}_K = \frac{1}{2} R_{\mathrm{pu}} \vec{s}_{\mathrm{pu}} - R_K \vec{S}_K$$

$$\overrightarrow{S_K} \sim S_z \hat{z} + e^{-R_k t} \cdot \overrightarrow{\delta S}$$

Alkali Magnetometer Dynamics

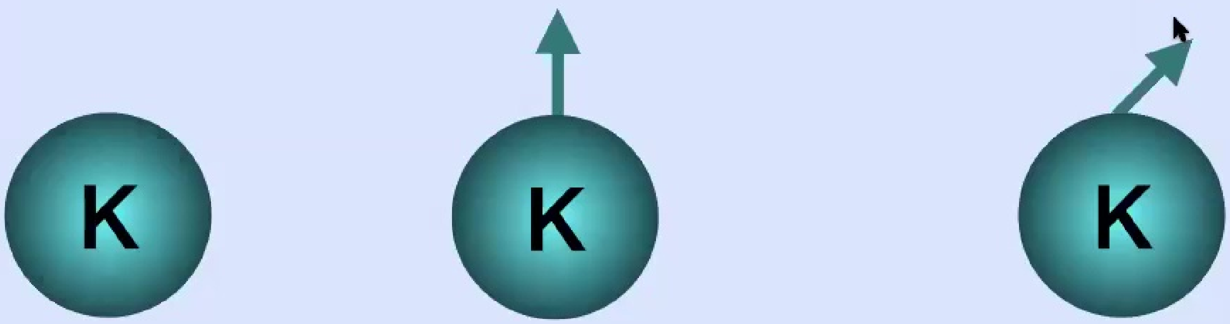
$t = 0$

$t \approx 0.02$ [sec]

Laser Pumps,
Relaxation "steadies"

$t \gtrsim 0.02$ [sec]

Anomalous and Regular
Magnetic fields tilt
the steady state solution



(Keeps wiggling
with the fields)

$$\dot{\vec{S}}_K = \frac{1}{2}R_{\mathrm{pu}}\vec{s}_{\mathrm{pu}} - R_K\vec{S}_K \quad + \gamma_K\left(\vec{B} + \frac{\vec{b}_K}{\gamma_K}\right)\times\vec{S}_K$$

$$\overrightarrow{S_K} \sim S_z\hat{z} + e^{-R_k t}\cdot\overrightarrow{\delta S}$$

Alkali Steady State

* To leading order in important stuff.

$$\dot{\vec{S}}_K = \gamma_K \left(\vec{B} + \frac{\vec{b}_K}{\gamma_K} \right) \times \vec{S}_K - R_K \vec{S}_K + \frac{1}{2} R_{\text{pu}} \vec{s}_{\text{pu}} = 0$$

$$S^z = \frac{R_{pu}}{2R_K}$$

z spin determined by the pump. No sensitivity to b.

$$S^x = S^z \frac{(\gamma_K B + b_K)_y}{R_K}$$

$$S^y = -S^z \frac{(\gamma_K B + b_K)_x}{R_K}$$

Reducing Magnetic Noise

One problem was that γ_K is very large

can we find another atom with smaller γ?

Noble Gases*!

* Mostly ^{3}He,Xe,^{21}Ne.

(BONUS):

Almost no chemical interactions

↓

Can have higher density (quieter measurements)

(Naive) Noble Magnetometer Dynamics

$t = 0$

$t \approx \mathcal{O}(1)$ [hr]

Alkali Pumps,
Relaxation "steadies"

$t \gtrsim$ few hours

Anomalous and Regular
Magnetic fields tilt
the steady state solution

(Keeps wiggling with the fields — if they vary slowly)

$$\dot{\vec{S}}_{He} = -R_{He}\vec{S}_{He} + R_{\text{pu,eff}}\vec{S}_K + \gamma_{He}\left(\vec{B} + \frac{\vec{b}_{He}}{\gamma_{He}}\right) \times \vec{S}_{He}$$

$\Downarrow$

$$\overrightarrow{S_{\text{He}}} \sim S_z\hat{z} + e^{-R_{\text{He}}t} \cdot \overrightarrow{\delta S}$$

Noble Steady State

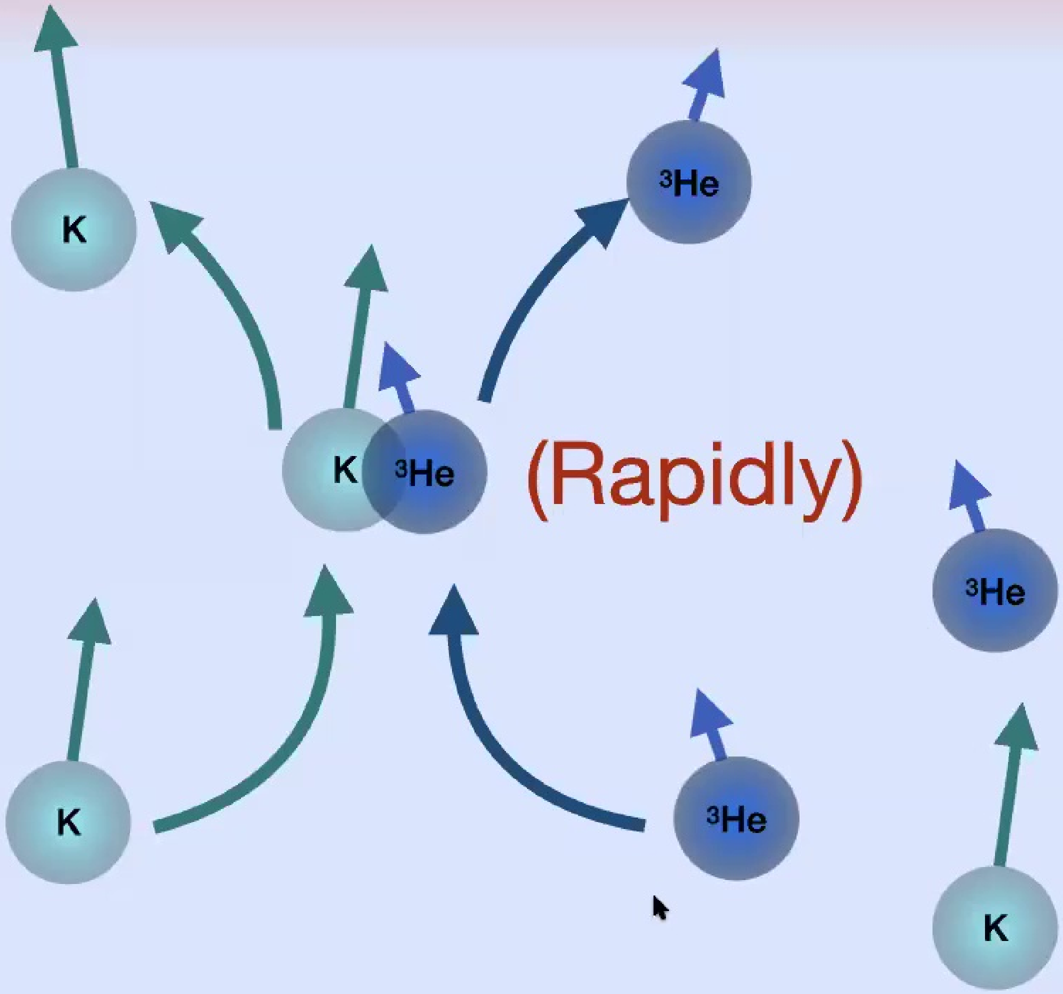
*To leading order in important stuff.

$$S^z = \frac{R_{pu,eff}}{R_{He}} S_K^z, S^x = S^z \frac{(\gamma_{He} B + b_{He})_x}{\gamma_{He} B_z}, S^y = S^z \frac{(\gamma_{He} B + b_{He})_y}{\gamma_{He} B_z}$$

Magnetic noise is still too big!

And since $b_{\mathrm{He}} \sim e^{i m_a t}$, we can only look at masses which are $m_a \lesssim 1/[\mathrm{hr}]$

Mutually Induced Magnetic Fields



Magnetic field from (quantum) point-like interactions

$B_{\text{induced on K}} \propto -S_{He}$

$B_{\text{induced on He}} \propto -S_K$

(Warning: a math-filled slide is coming)

The Mixed Alkali-Noble Equations (1)

* To leading order in important, relevant stuff.
* From now on we will only discuss the transverse state, with $v^{\perp} = v^{x} + i \cdot v^{y}$.

$$\dot{\vec{S}}_K = \gamma_K \left(\vec{B} + \frac{\vec{b}_K}{\gamma_K} \right) \times \vec{S}_K - R_K \vec{S}_K$$

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

$$\begin{pmatrix} \dot{S}_K^{\perp} \\ \dot{S}_{He}^{\perp} \end{pmatrix} = \begin{pmatrix} i\omega_K - R_K & \\ & i\omega_{He} \end{pmatrix} \begin{pmatrix} S_K^{\perp} \\ S_{He}^{\perp} \end{pmatrix}$$

$$\omega_K = \gamma_K B_z \qquad \omega_{He} = \gamma_{He} B_z$$

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The Mixed Alkali-Noble Equations (1)

- To leading order in important, relevant stuff.
- From now on we will only discuss the transverse state, with $v^{\perp} = v^x + i \cdot v^y$.

$$\dot{\vec{S}}_K = \gamma_K \left(\vec{B} + \frac{\vec{b}_K}{\gamma_K} \right) \times \vec{S}_K - R_K \vec{S}_K + 2\gamma_K \lambda M_{\mathrm{He}} \vec{S}_{He} \times \vec{S}_K$$

$$\dot{\vec{S}}_{He} = \gamma_{He} \left(\vec{B} + \frac{\vec{b}_{He}}{\gamma_{He}} \right) \times \vec{S}_{He} + 2\gamma_{\mathrm{He}} \lambda M_{\mathrm{K}} \vec{S}_K \times \vec{S}_{\mathrm{He}}$$

$$\begin{pmatrix} \dot{S}_K^{\perp} \\ \dot{S}_{He}^{\perp} \end{pmatrix} = \begin{pmatrix} i\omega_K - R_K & -i\omega_{He-K} \\ -i\omega_{K-He} & i\omega_{He} \end{pmatrix} \begin{pmatrix} S_K^{\perp} \\ S_{He}^{\perp} \end{pmatrix}$$

$$\omega_K = \gamma_K B_z + \omega_{K0} \qquad \omega_{He} = \gamma_{He} B_z + \omega_{He0}$$

The Mixed Alkali-Noble Equations (2)

* To leading order in important stuff.

$$\begin{pmatrix} \dot{S}_K^{\perp} \\ \dot{S}_{He}^{\perp} \end{pmatrix} = \begin{pmatrix} i\omega_K - R_K & -i\omega_{He-K} \\ -i\omega_{K-He} & i\omega_{He} \end{pmatrix} \begin{pmatrix} S_K^{\perp} \\ S_{He}^{\perp} \end{pmatrix}$$

ODE with two modes and two eigenvalues.

$$\omega_K = \gamma_K B_z + \omega_{K0} \qquad \omega_{He} = \gamma_{He} B_z + \omega_{He0}$$

Can we resonantly couple the two modes?
What would that do?

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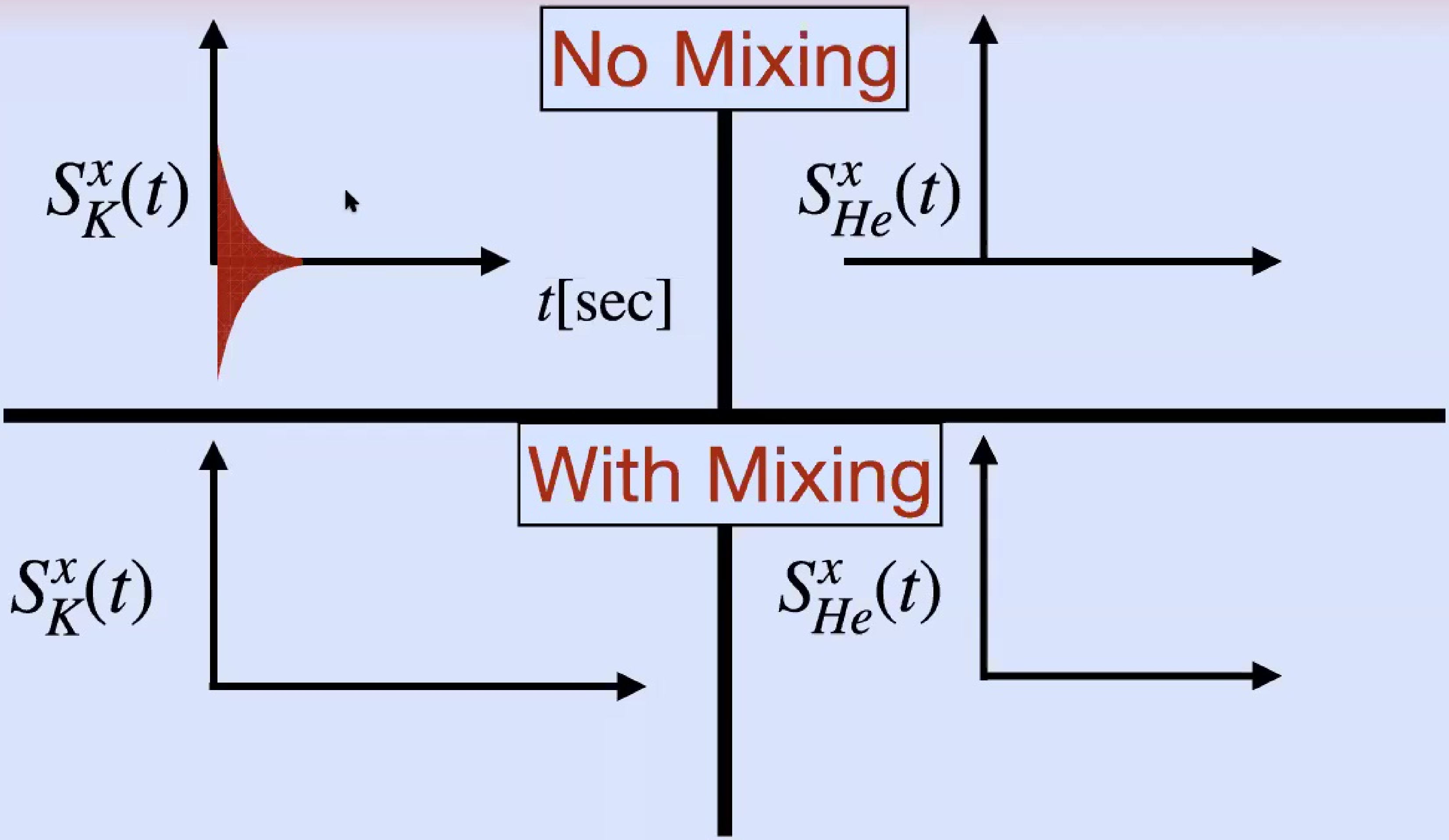
Reaction Time of the System

Far From Resonance



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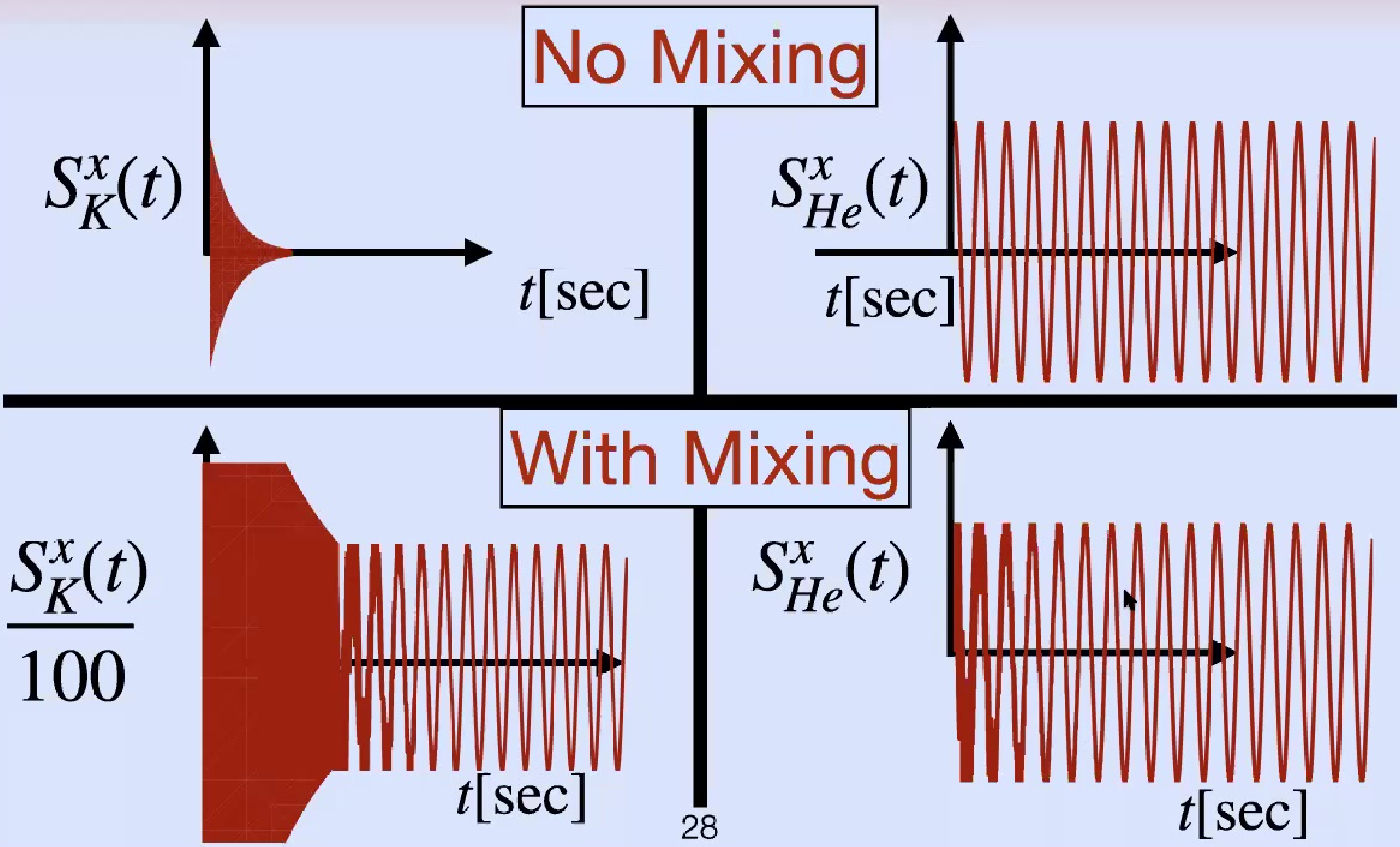
Reaction Time of the System

Far From Resonance



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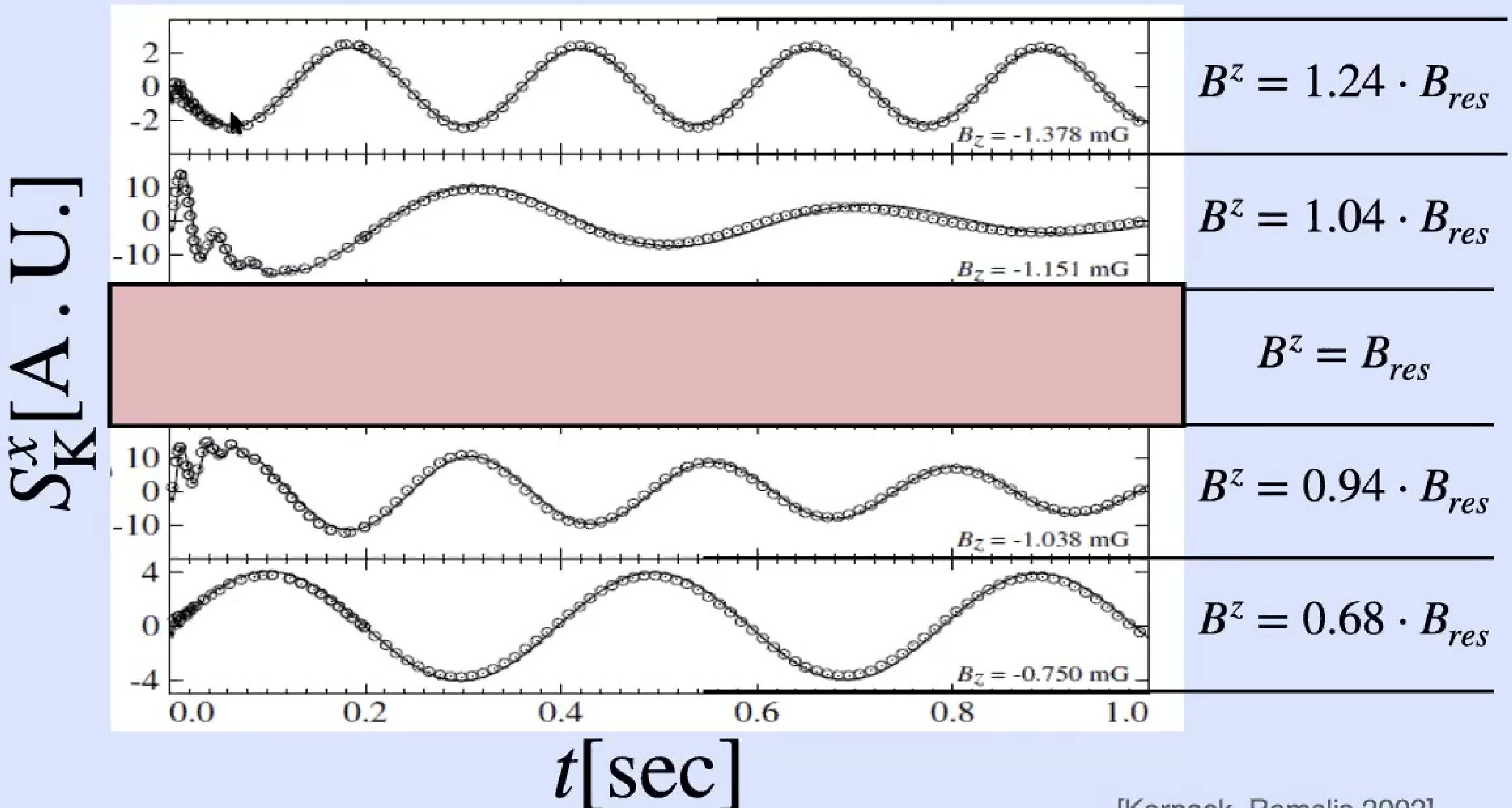
The Resonance Regime (1)



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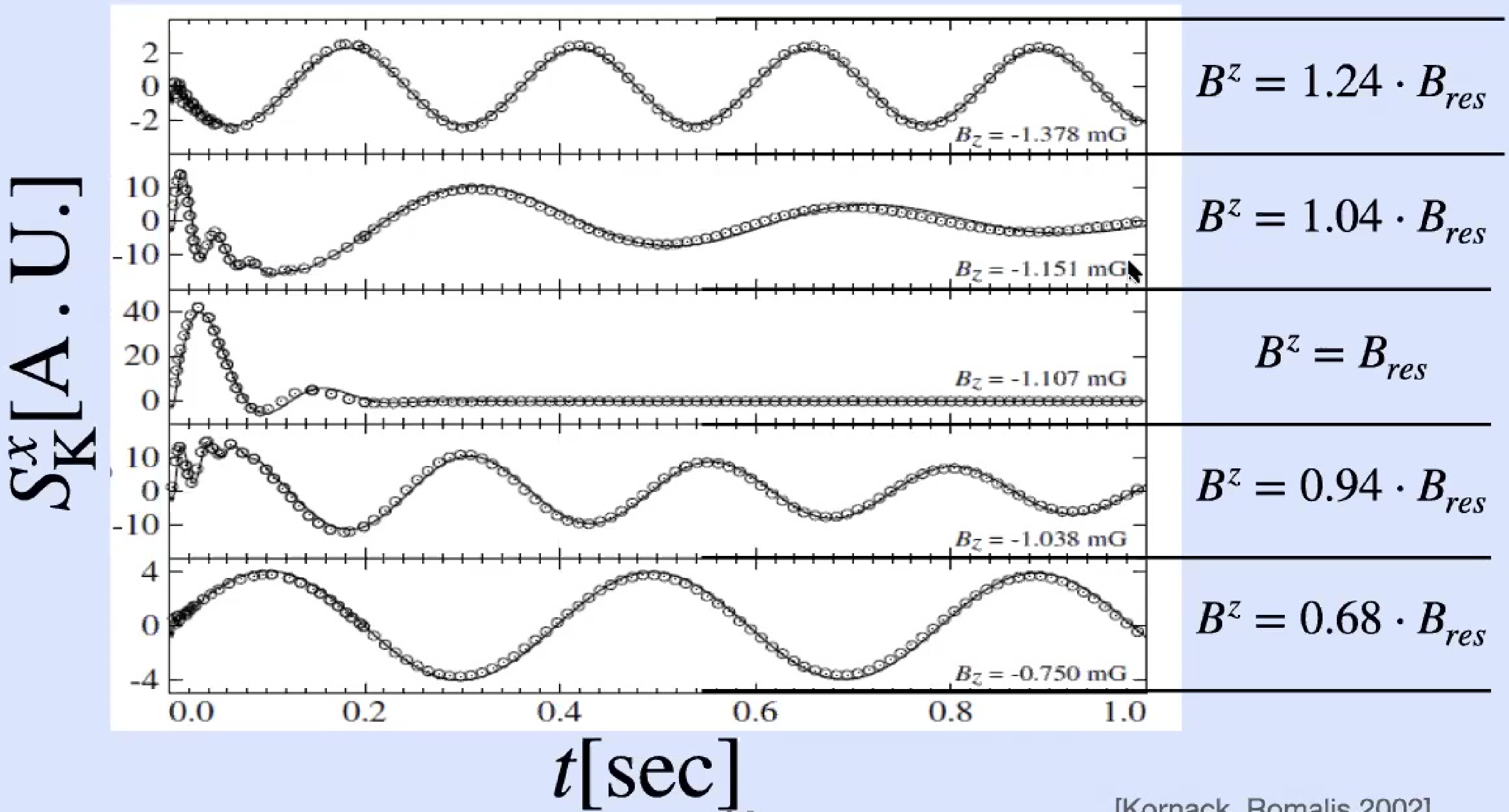
[Kornack, Romalis 2002]

The Resonance Regime (1)



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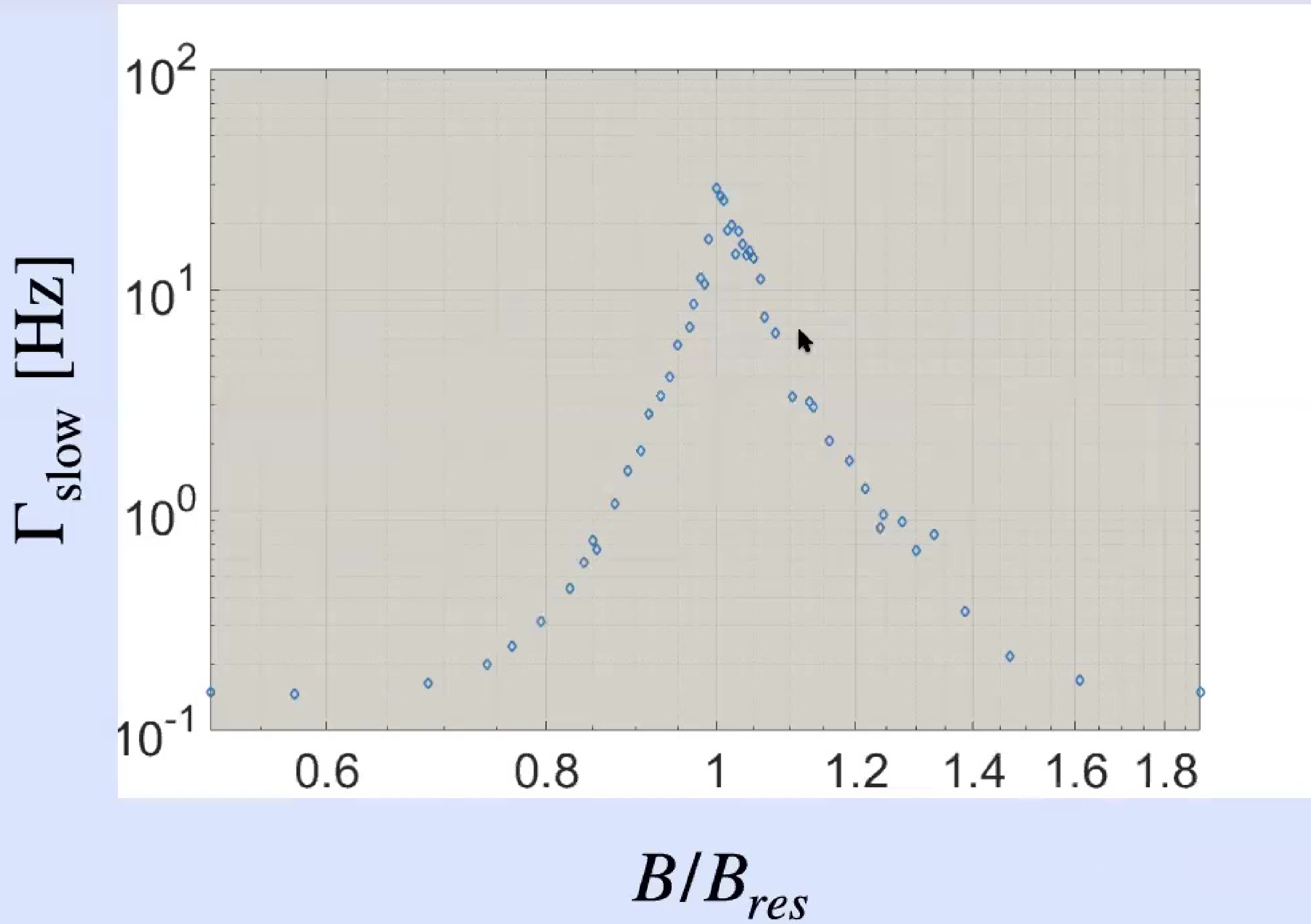
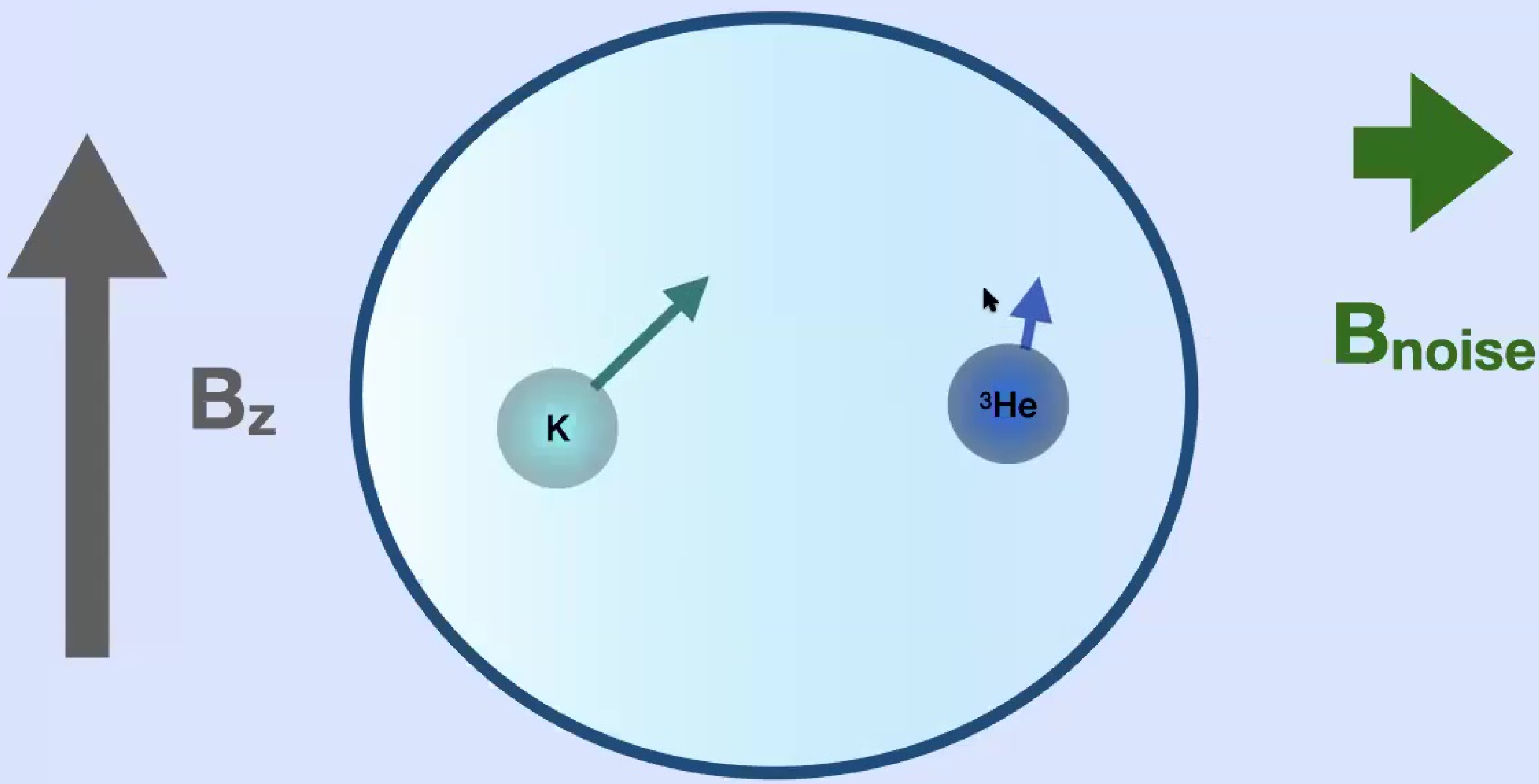
[Kornack, Romalis 2002]

The Resonance Regime (2)



Compensation Point Illustration (B)

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



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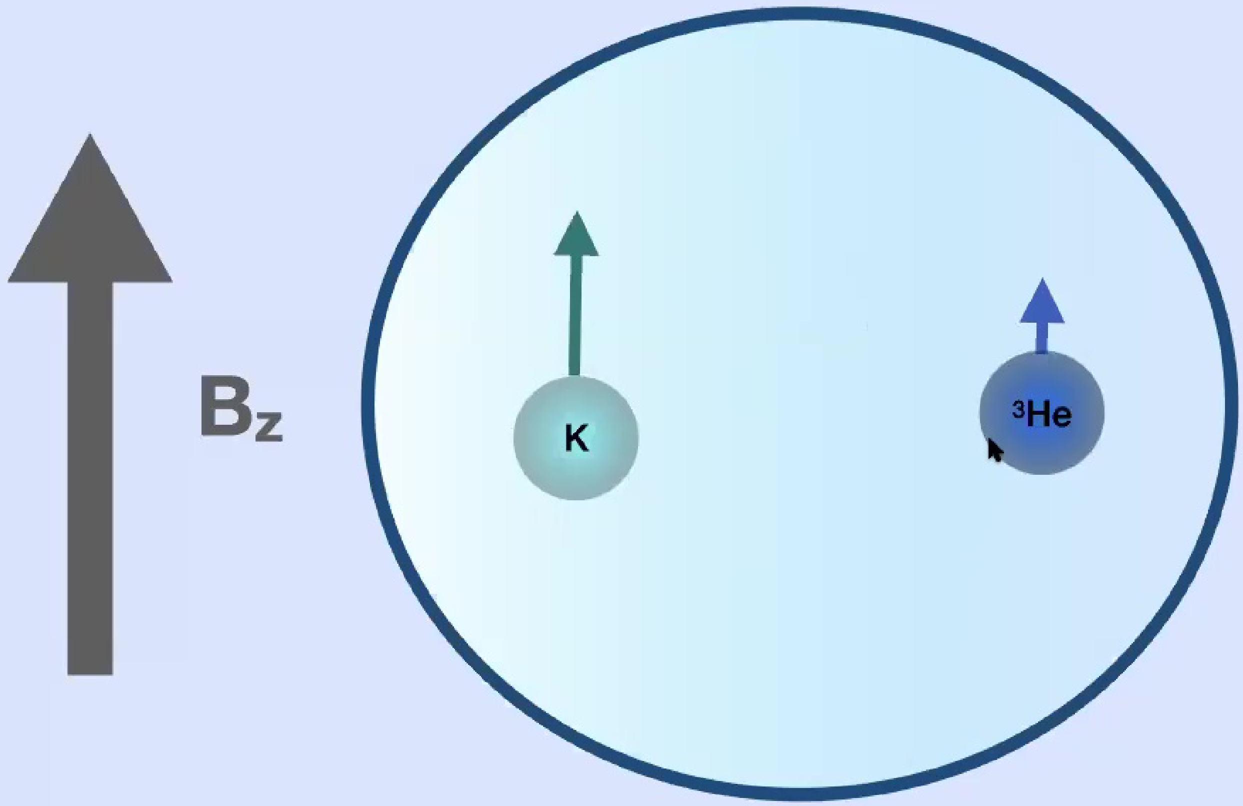
Compensation Point Illustration (b_e)

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



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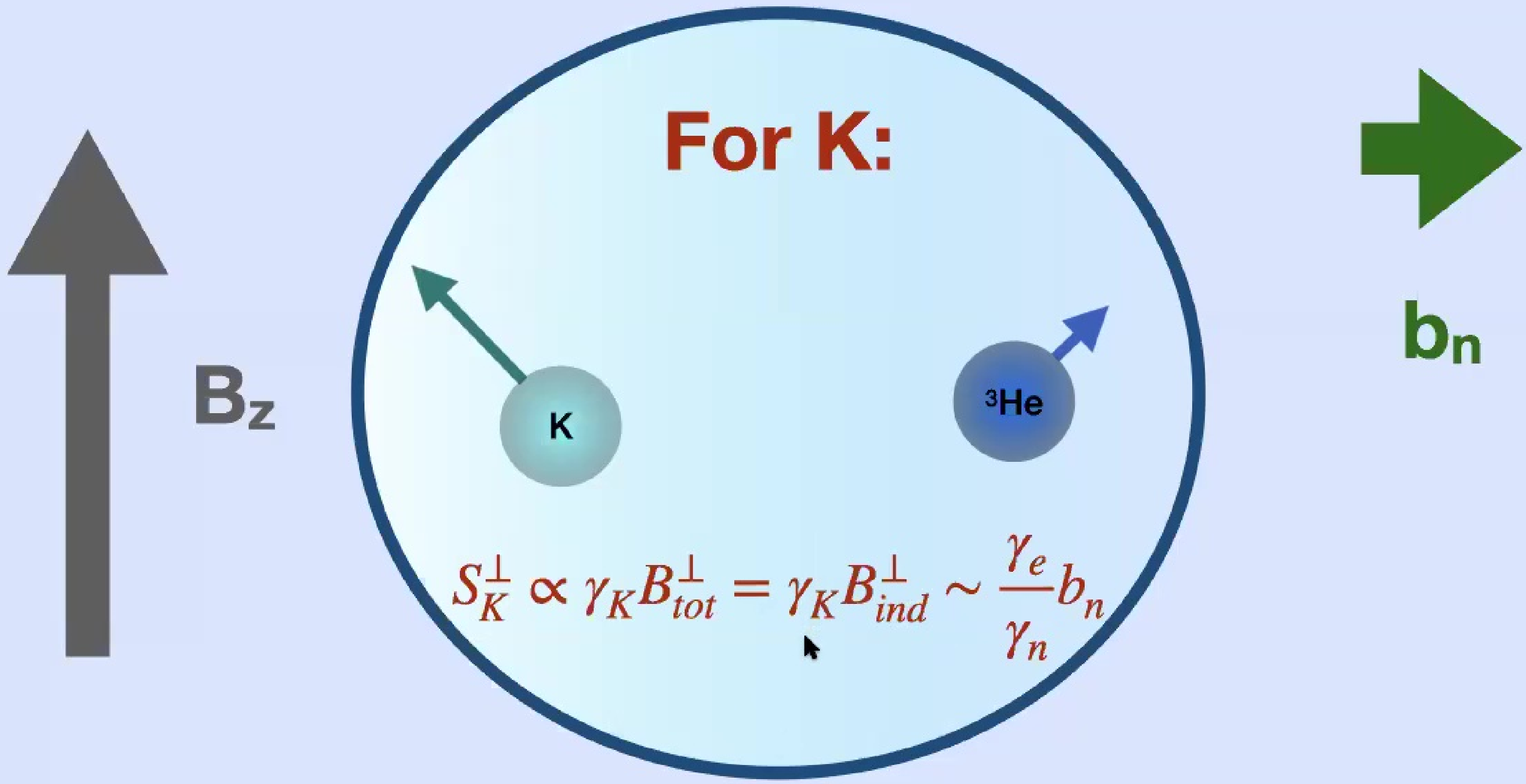
Compensation Point Illustration (b_n)

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



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

Measurable, Enhanced Signal!

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  - ✓ What is a Comagnetometer?
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  - Comagnetometer Experiments
  - Future Prospects (and recent progress)
- **Conclusions**

ALP DM generate a magnetic-like field, but it couples differently to different particles compared to the SM.

Through a special tuning of the controlled magnetic fields, comagnetometers are sensitive to anomalous fields, while immune to magnetic noise.

Compensation Point Illustration (B)

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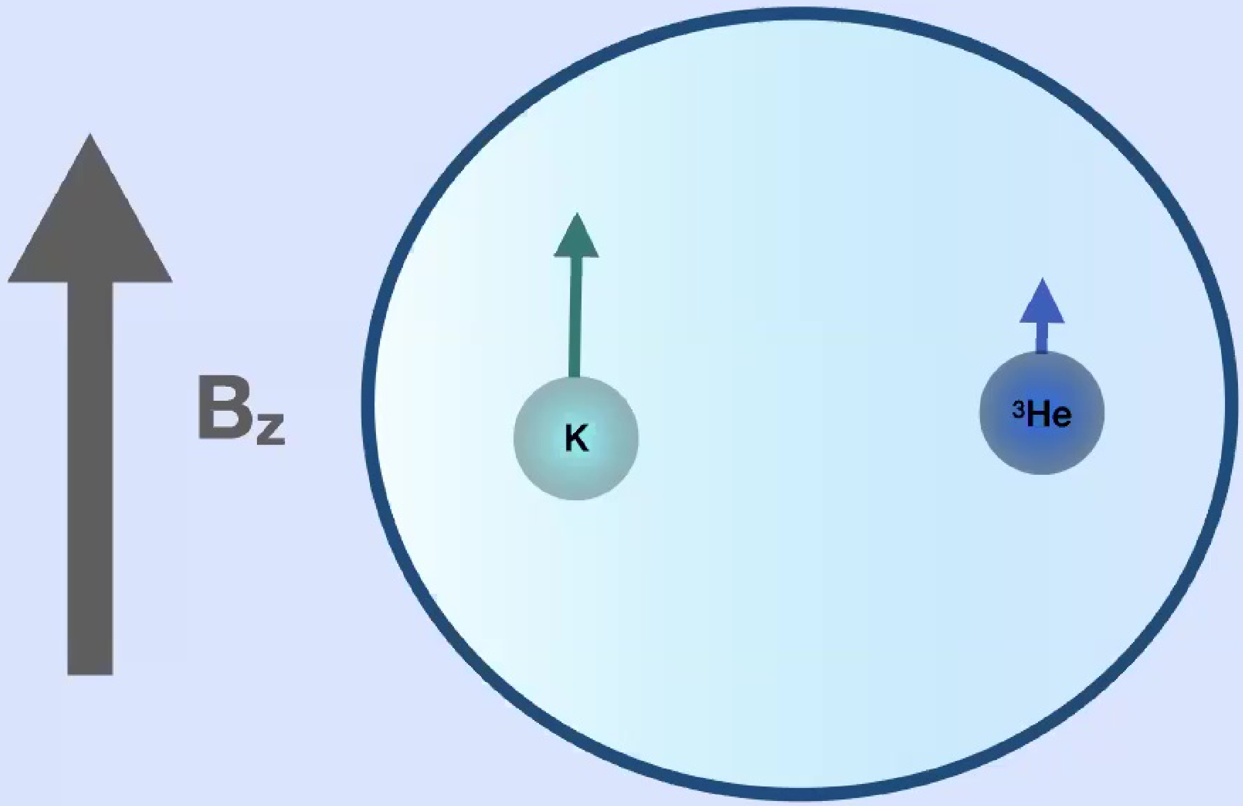

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Compensation Point Illustration (B)

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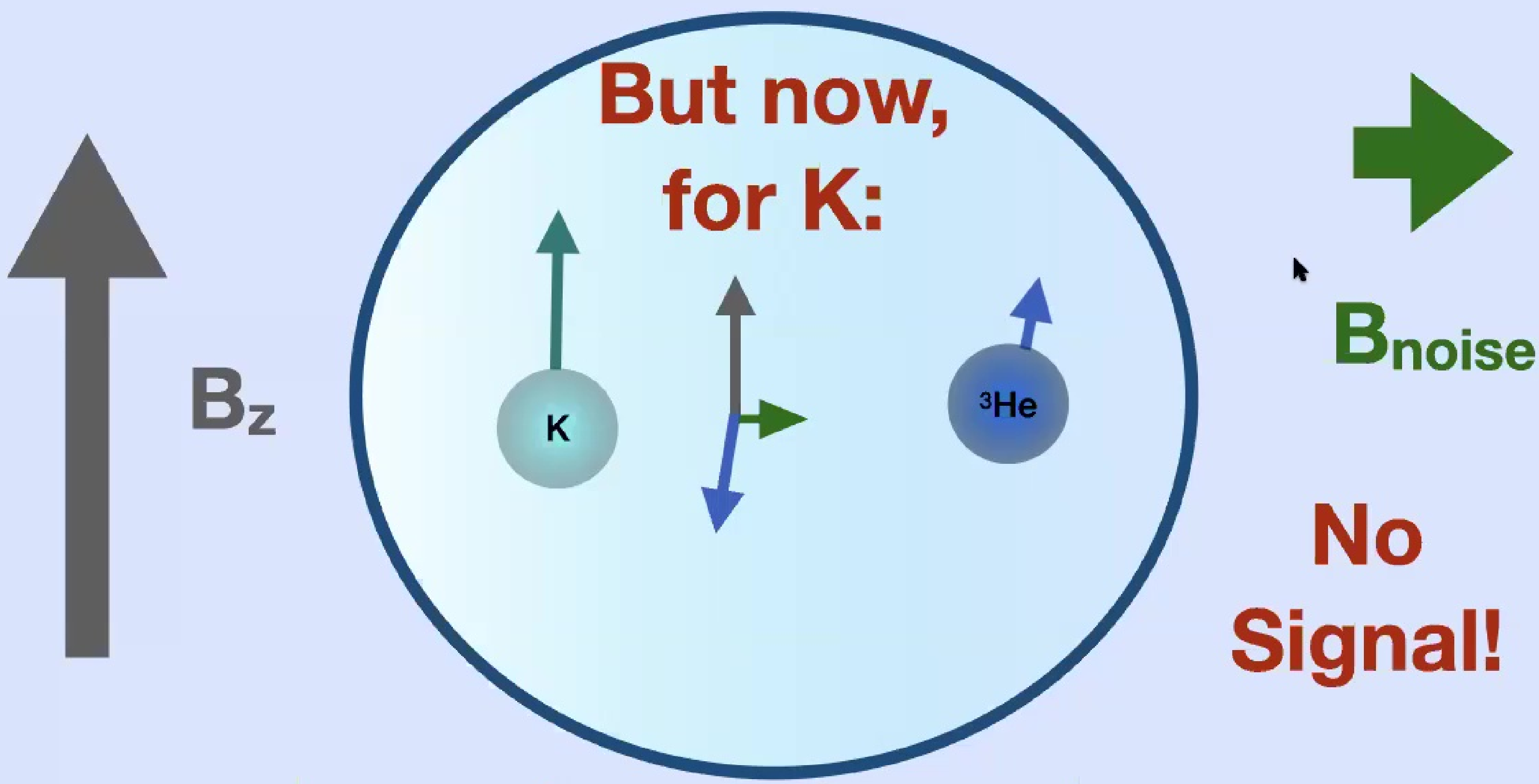

$$S_K^{\perp} \propto \gamma_K B_{tot}^{\perp} = \gamma_K B_{ind}^{\perp} + \gamma_K B_{noise}^{\perp} = 0!$$

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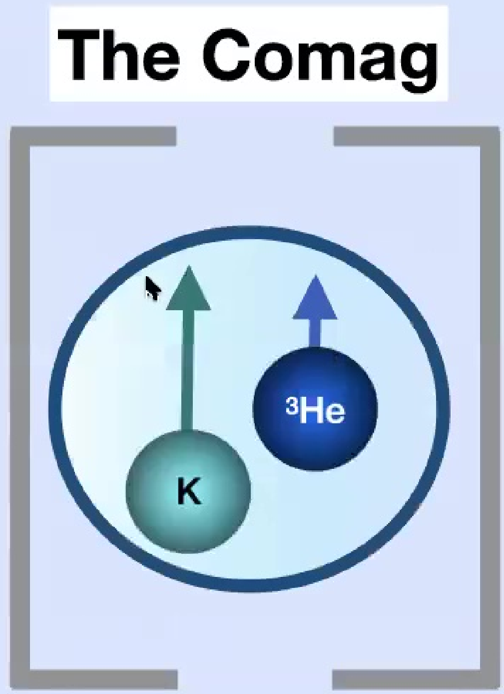
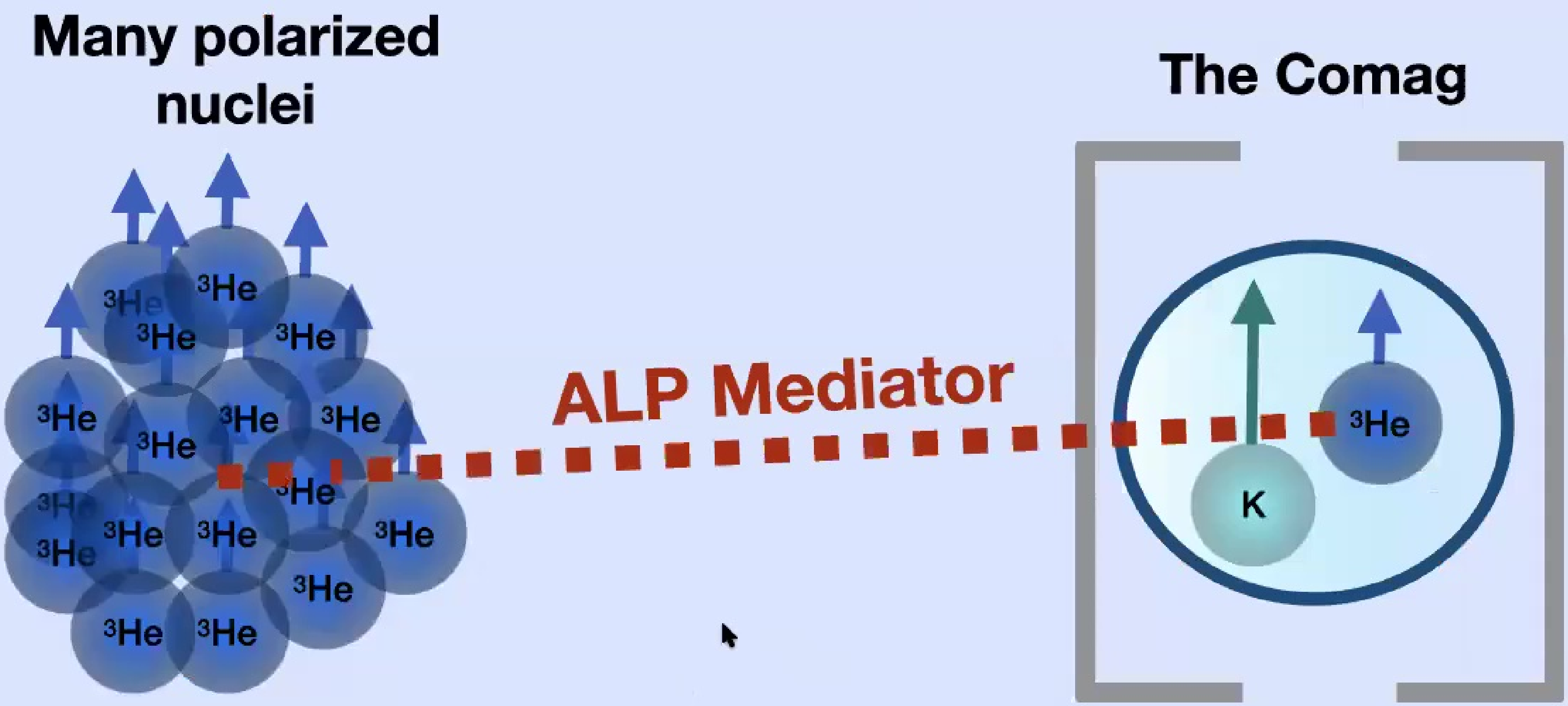
Direct Detection with the Comag



Fifth Force Search



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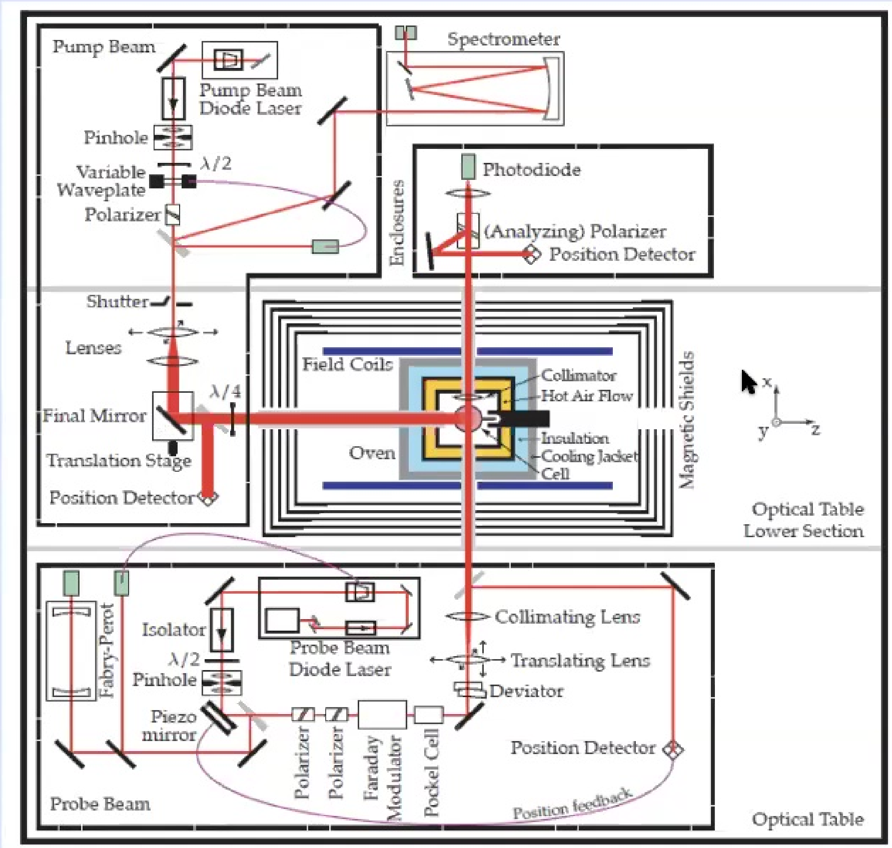
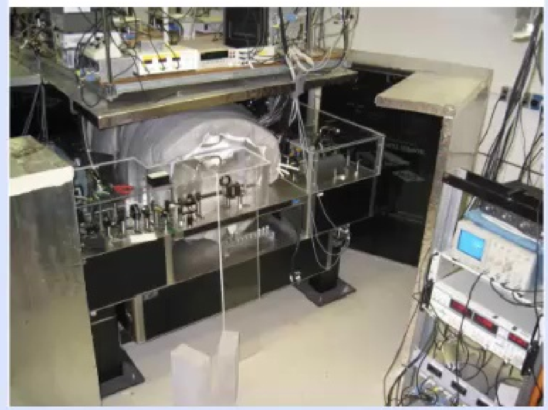
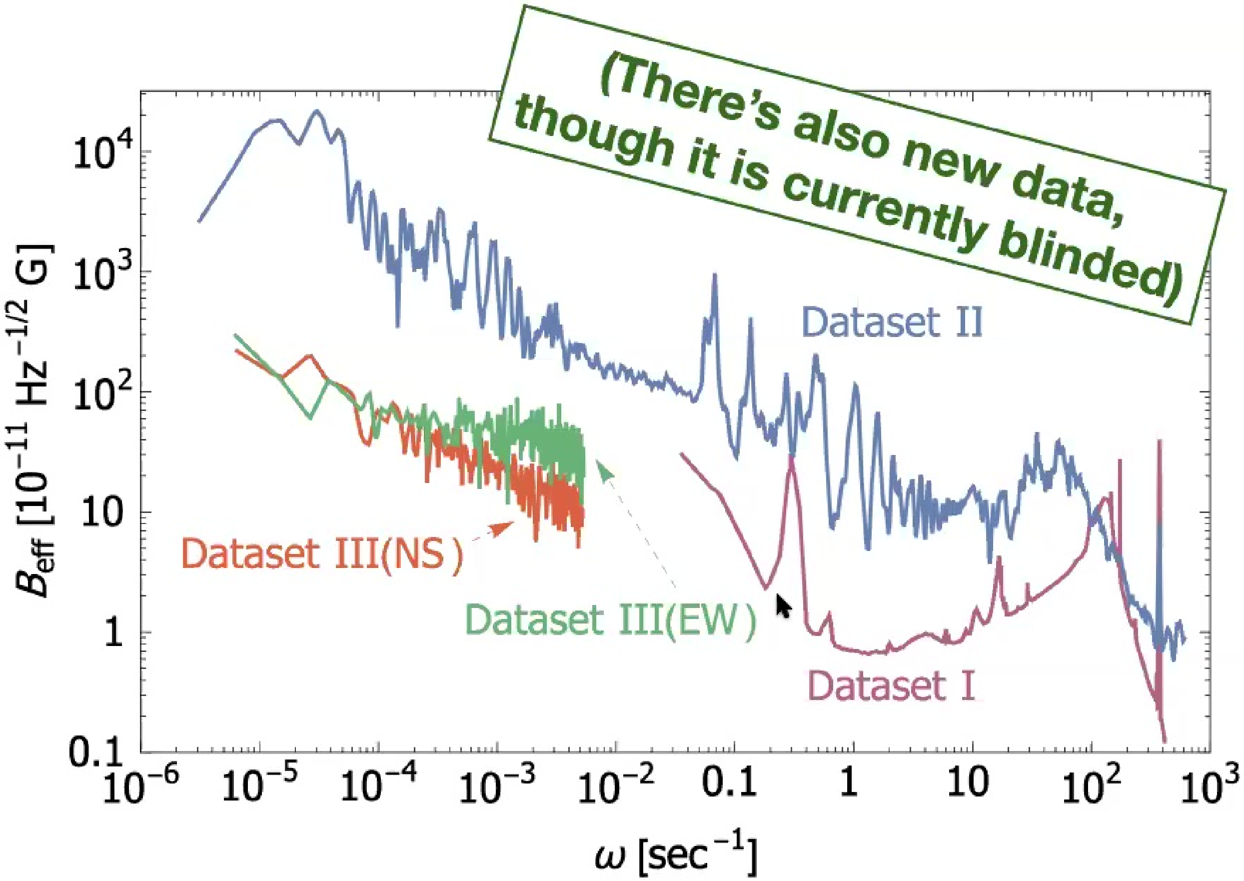
Old Systems



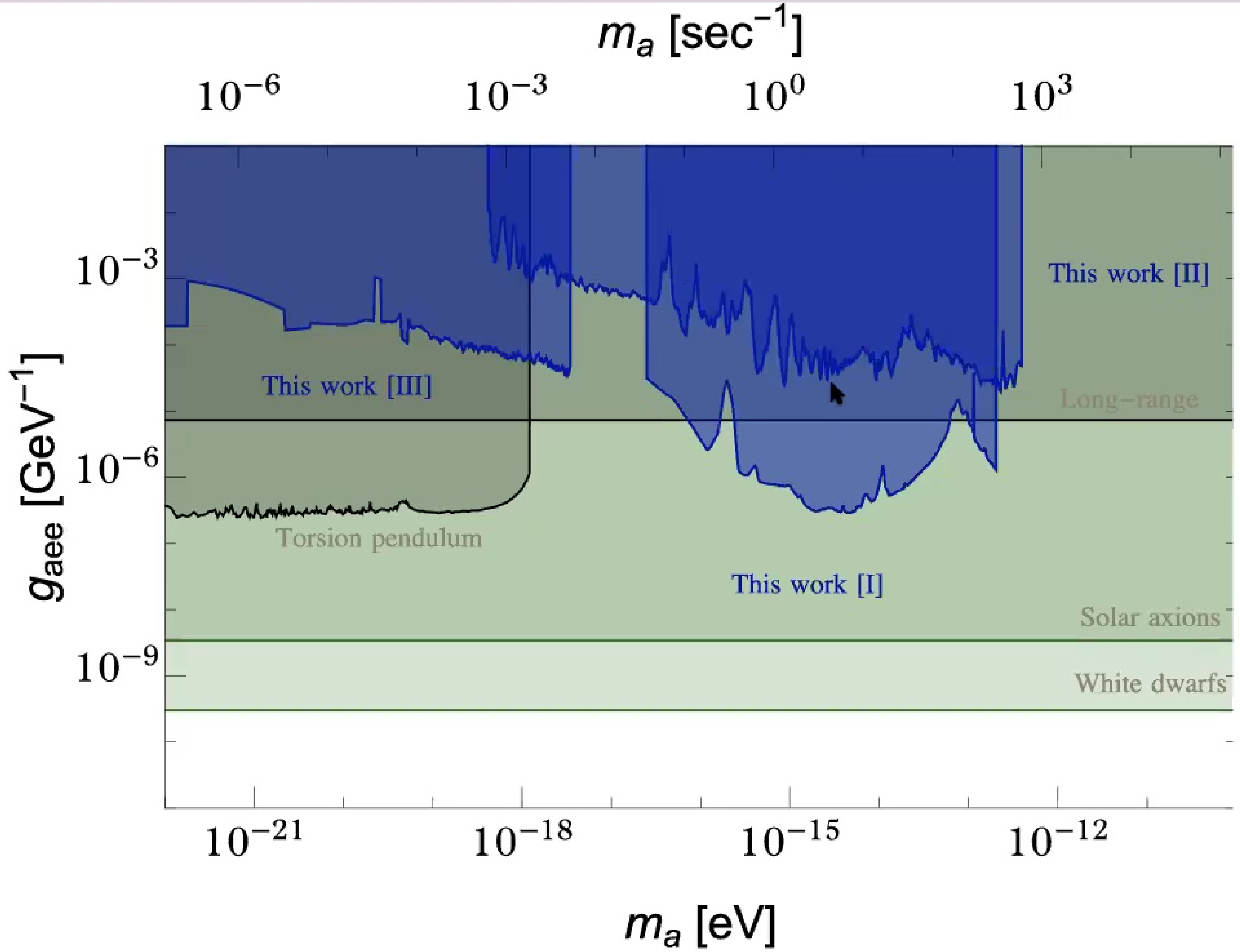


[Gergoios Vasilakis Dissertation 2011], [Justin M. Brown Dissertation 2011], [Thomas W. Kornack Dissertation 2005]

The Existing Data



Results (e)



(See paper for a list of citations)

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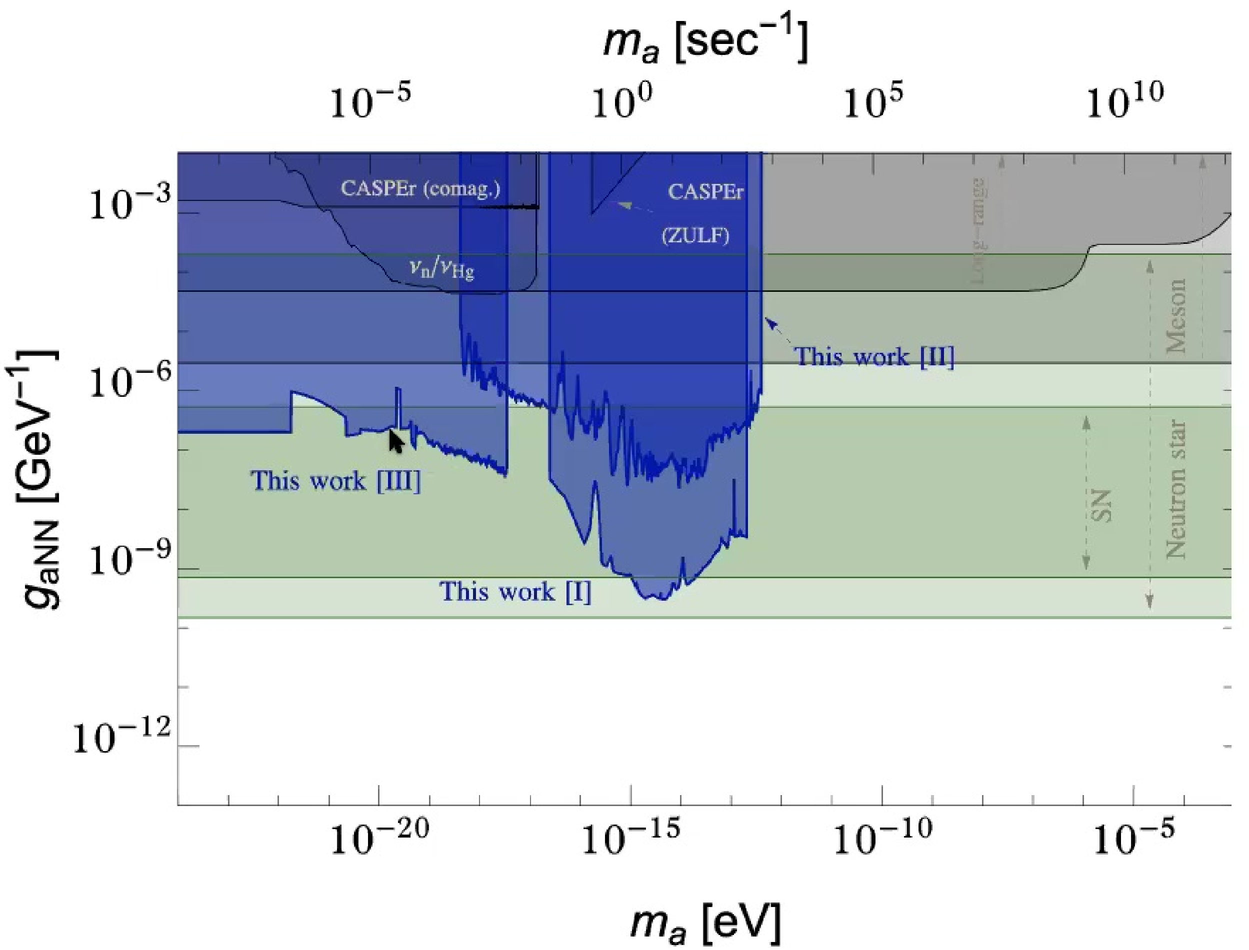
Results and Projections (n)



(See paper for a list of citations)

Future Prospects:

Unlikely to be done by us

Cold Xenon
Long Range Search

A Dedicated
Comagnetometer Search

Dedicated "Comagnetometer
-Adjacent" searches

Experiment will be performed/
already has been

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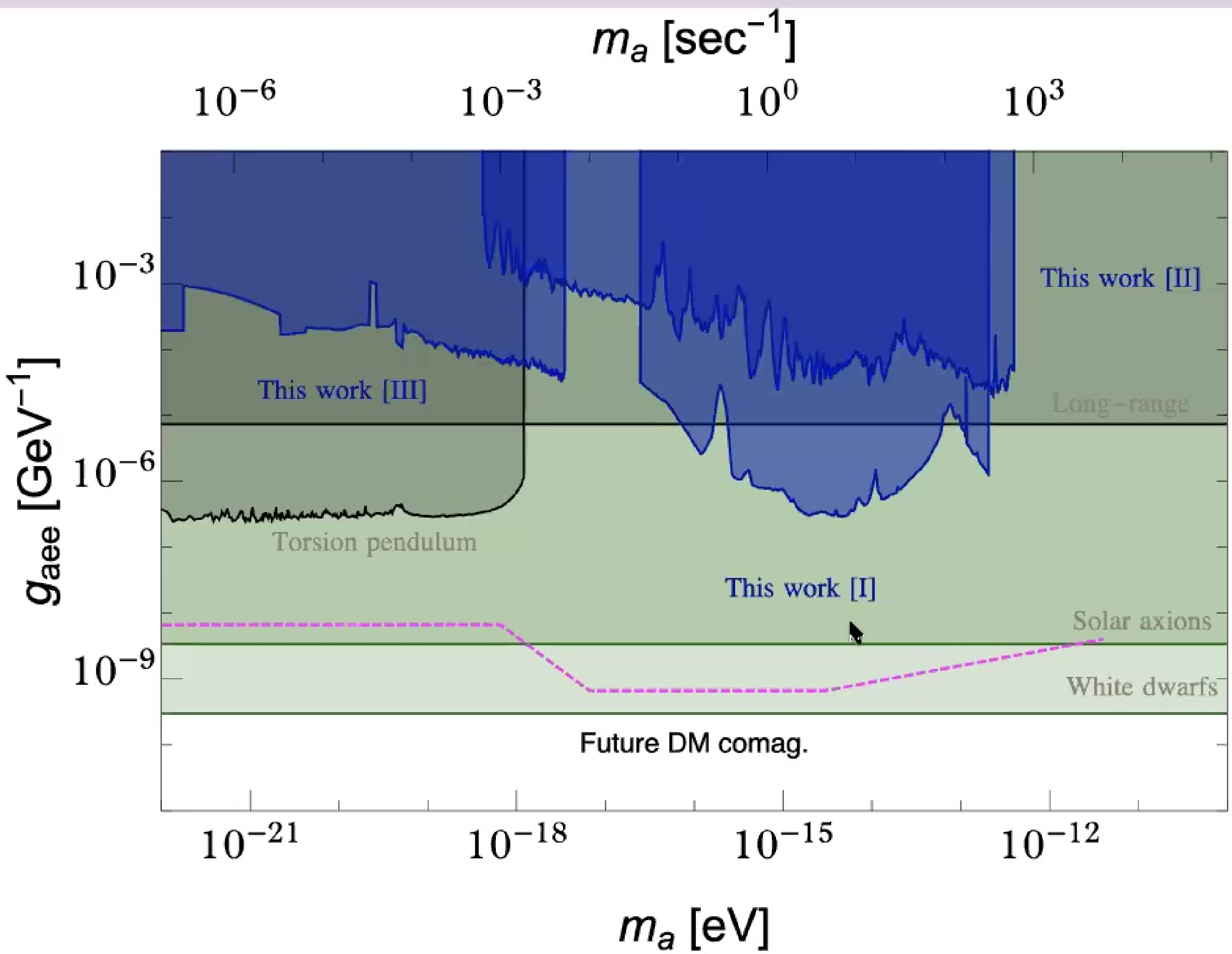
Four experiments should occur in the near future

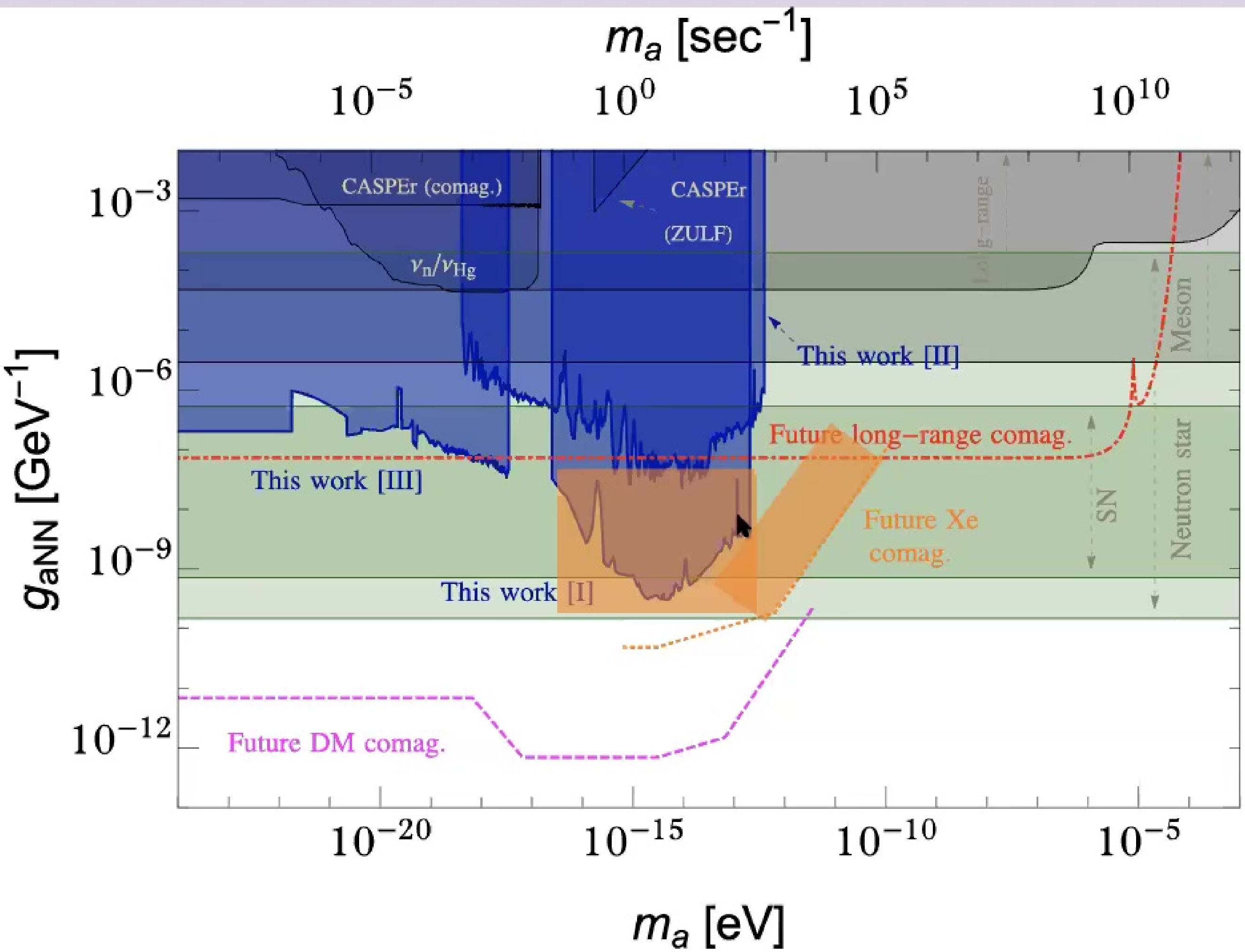
1. High frequency "comagnetometer" — (Data is waiting to be analyzed)
2. Rb Xe-Xe "Co-Comagnetometer" — (Proof of concept stage, no clear schedule for full experiment)
3. Rb-Xe mid-frequency "Comangetometry" — (Initial measurements taken, full data in a few months)
4. Rb-Xe low-frequency "Comangetometry" — (Proof of Concept stage, true experiment in a few months)

Results and Projections (e)



(See paper for a list of citations)

Results and Projections (n)



(See paper for a list of citations)

Conclusions

- Comagnetometers offer a strong probe to the ALPs parameter space.
- Future experiments with comagnetometers could supersede the best existing bounds.
- If unexpected improvements occur in the experimental direction, comagnetometers might be sensitive to (asymmetric) cosmic neutrinos.

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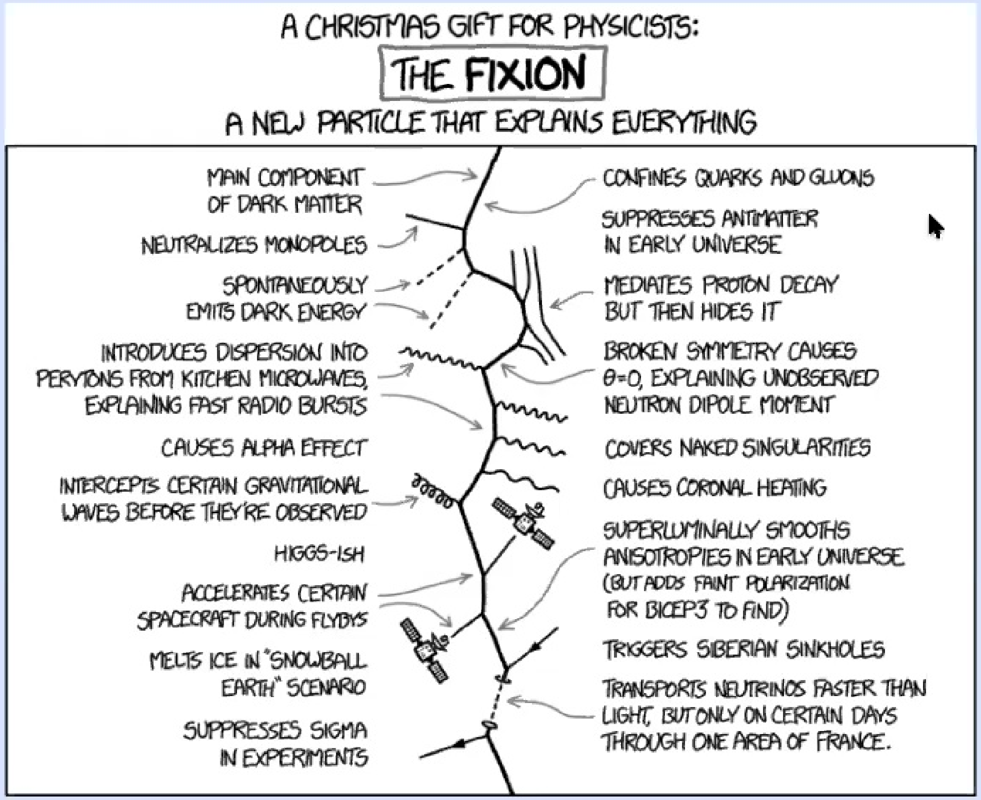
- Future experiments with comagnetometers could supersede the best existing bounds.
- If unexpected improvements occur in the experimental direction, comagnetometers might be sensitive to (asymmetric) cosmic neutrinos.
- ALPs in these masses could not only be so-called fuzzy DM, but might in fact be **the** QCD axion.

[L. Hui *et al.*:1610.08297;Marques-Tavares *et al.*:1803.07575]



[xkcd]

Thanks For Listening!