Quantum Magnetometry in Search of Dark Matter

March 2024

Itay M. Bloch
UC Berkeley & LBNL

Berkeley Week, IPMU

Dark Matter: The Broadest of Strokes

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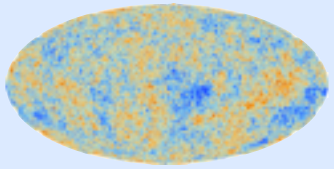
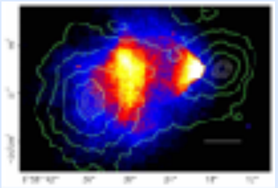

[Planck/ESA]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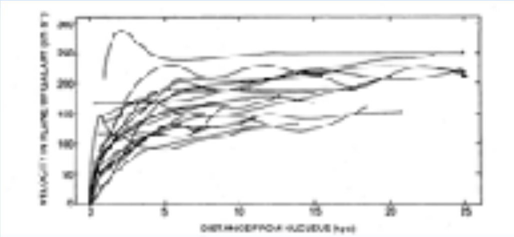
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Gravitational observations at many scales teach us that something is missing! That thing is Dark Matter!

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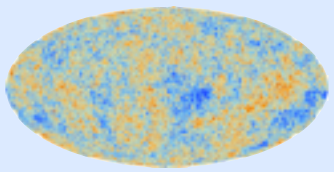

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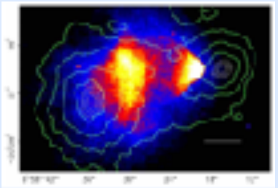

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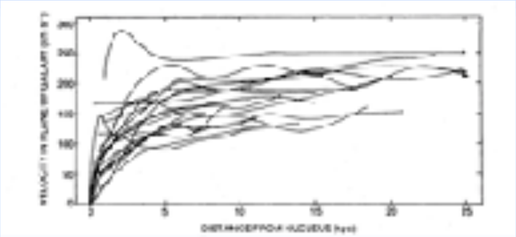

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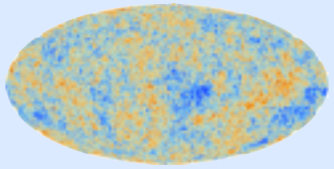

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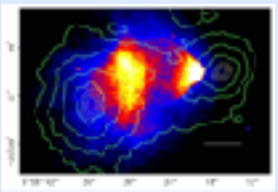

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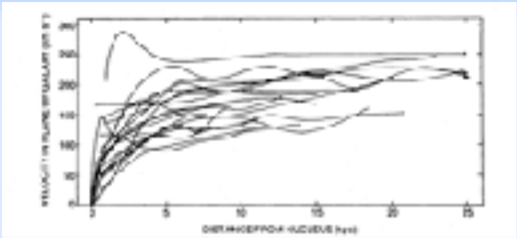

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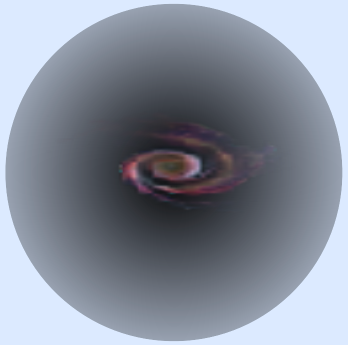

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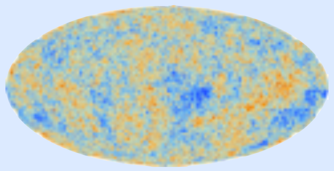

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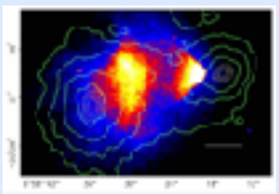

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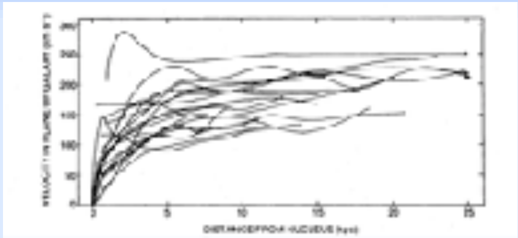

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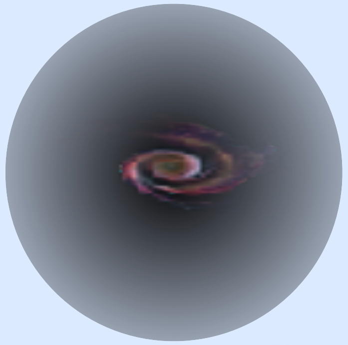

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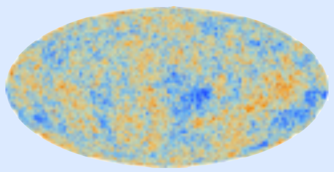

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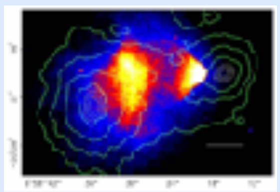

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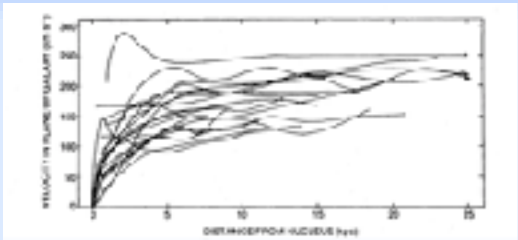

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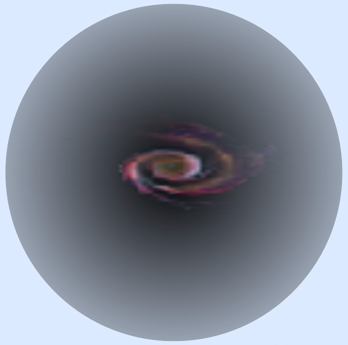

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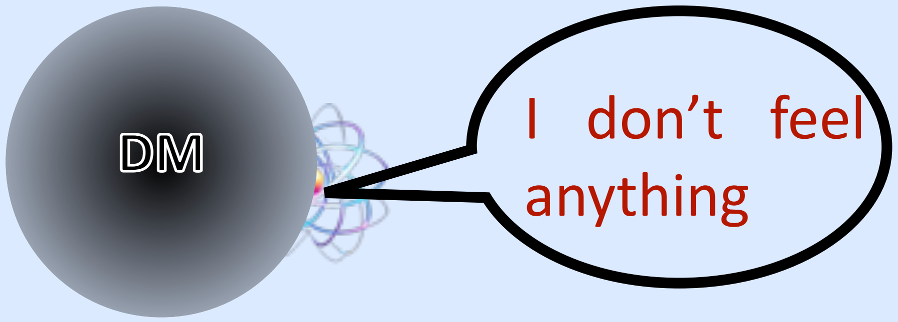

Small (if any) non-gravitational interactions. So if we want to measure DM in a lab, we have to be smart!

QCD Axion

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

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

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

QCD Axion

Axion Like Particles (ALPs)*

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*(I may accidentally say axions in this talk and I mean ALPs)

Looking For Ultralight DM: Wave/Particle Duality

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

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If DM is ultralight, ($m_a \lesssim 30\ \mathrm{eV}$), $n_a = \dfrac{0.4\ \mathrm{GeV}}{m_a \cdot \mathrm{cm}^3} > \dfrac{1}{\lambda^3_{\mathrm{de-broglie}}} = \left(\dfrac{m_a v_a}{2\pi}\right)^3$

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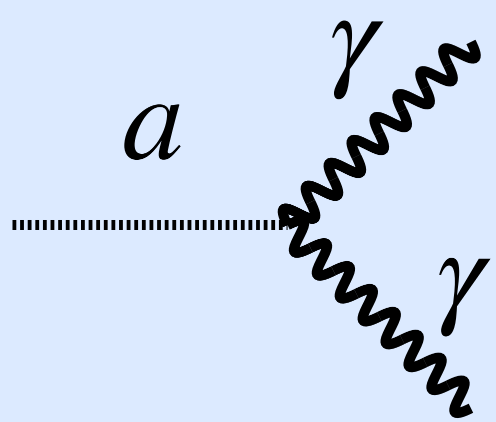
$$a = a_0 \cos(E_a t - \vec{k}_a \vec{x}) \approx a_0 \cos(m_a t)$$

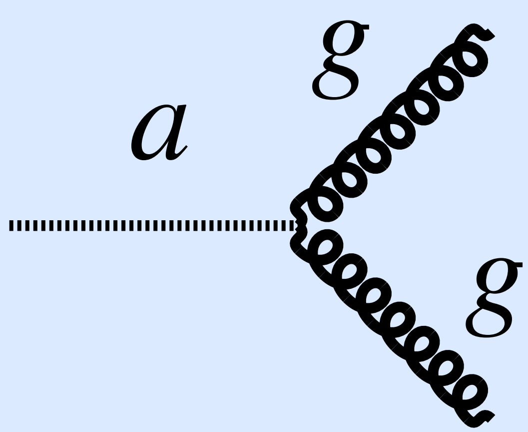
Ultralight ALPs behave like classical plane-waves!

(Mass$^{\pm}$ and frequency are used interchangeably)

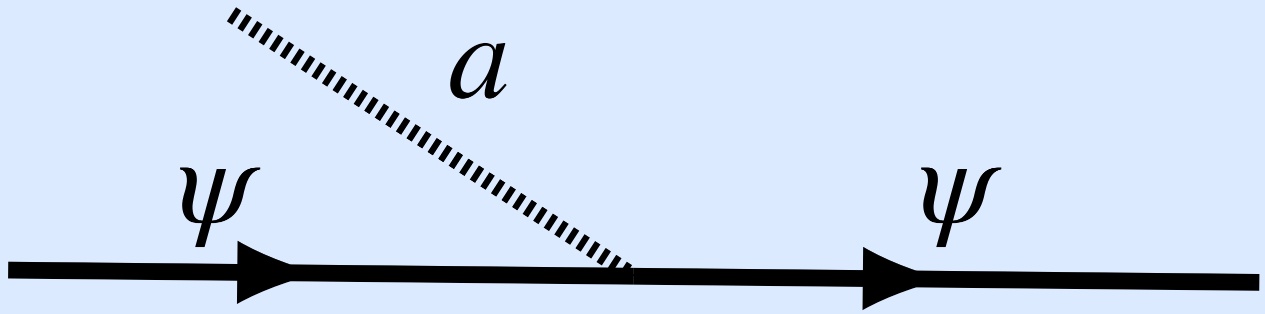
ALP-SM Interactions



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



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



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

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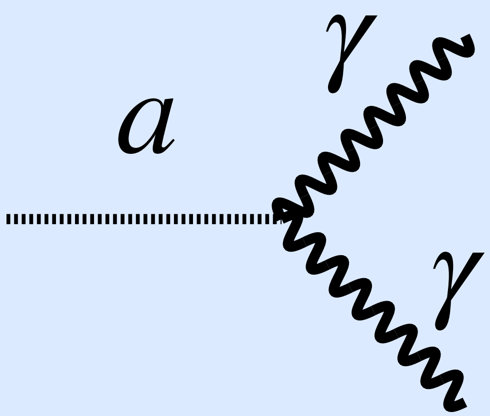

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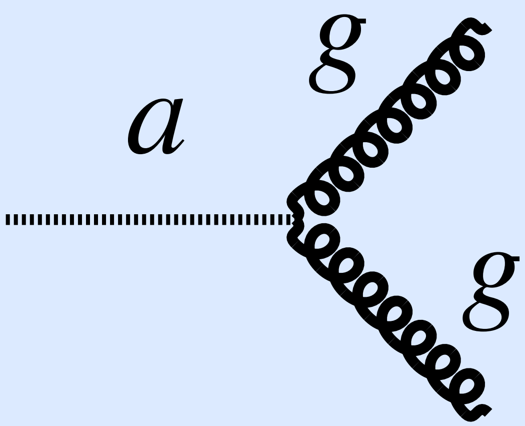

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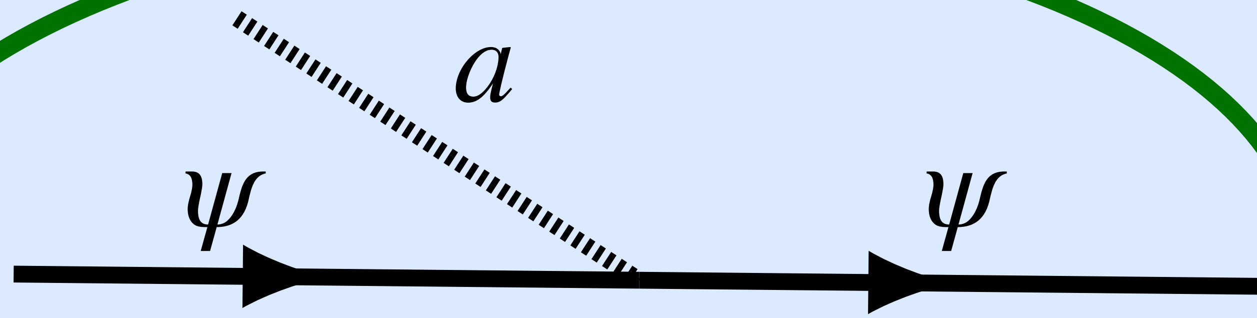

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$$\mathscr{L} = g_{a\psi\psi}\partial_\mu a \cdot \bar{\psi}\gamma^\mu\gamma_5\psi \rightarrow H = -\vec{b}_{a-\psi} \cdot \vec{S}_\psi$$

$$\vec{b}_{a-\psi} = g_{a\psi\psi}\sqrt{2\rho_a}\cos(m_a t) \cdot \vec{v}_{a-\psi}$$

[astro-ph/9501042]

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

Today's Papers

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

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

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= I did theory

= I did analysis

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Yonit Hochberg


Eric Kuflik


Tomer Volansky


Gil Ronen


Roy Shaham


Ori Katz


Or Katz


Dmitry Budker


Victor Flambaum


Igor Samsonov


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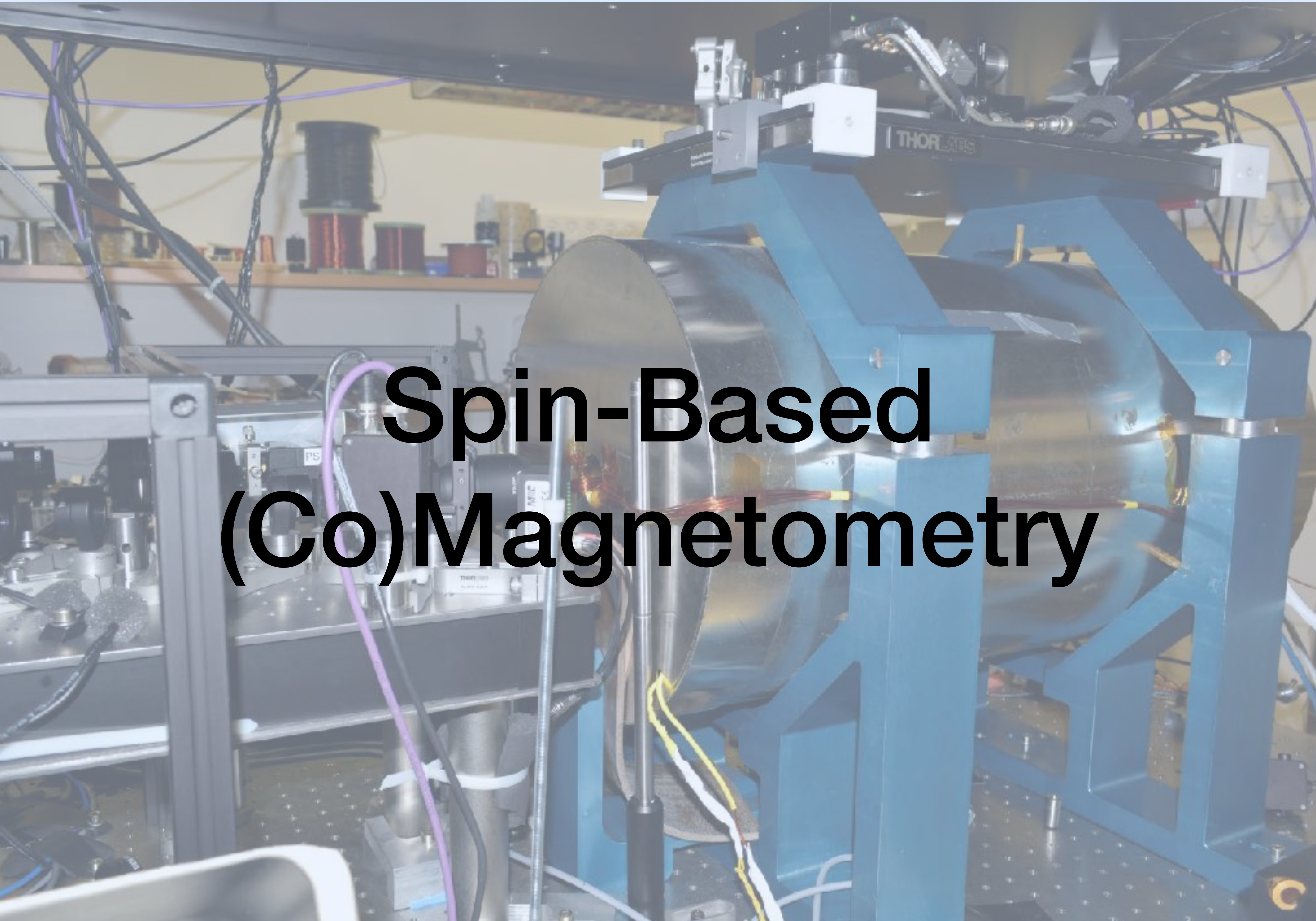
Spin-Based (Co)Magnetometry



Bloch Equations

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Describe the evolution of macroscopic spin systems

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

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

Torque

(generates transverse from longitudinal)

Bloch Equations

Describe the evolution of macroscopic spin systems

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

Torque

(generates transverse from longitudinal)

Decaying excitations

(causes stabilization)

Bloch Equations

Describe the evolution of macroscopic spin systems

Creating macroscopic polarization

(generates a non-trivial steady state solution)

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

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(Co)magnetometer
Ingredients List

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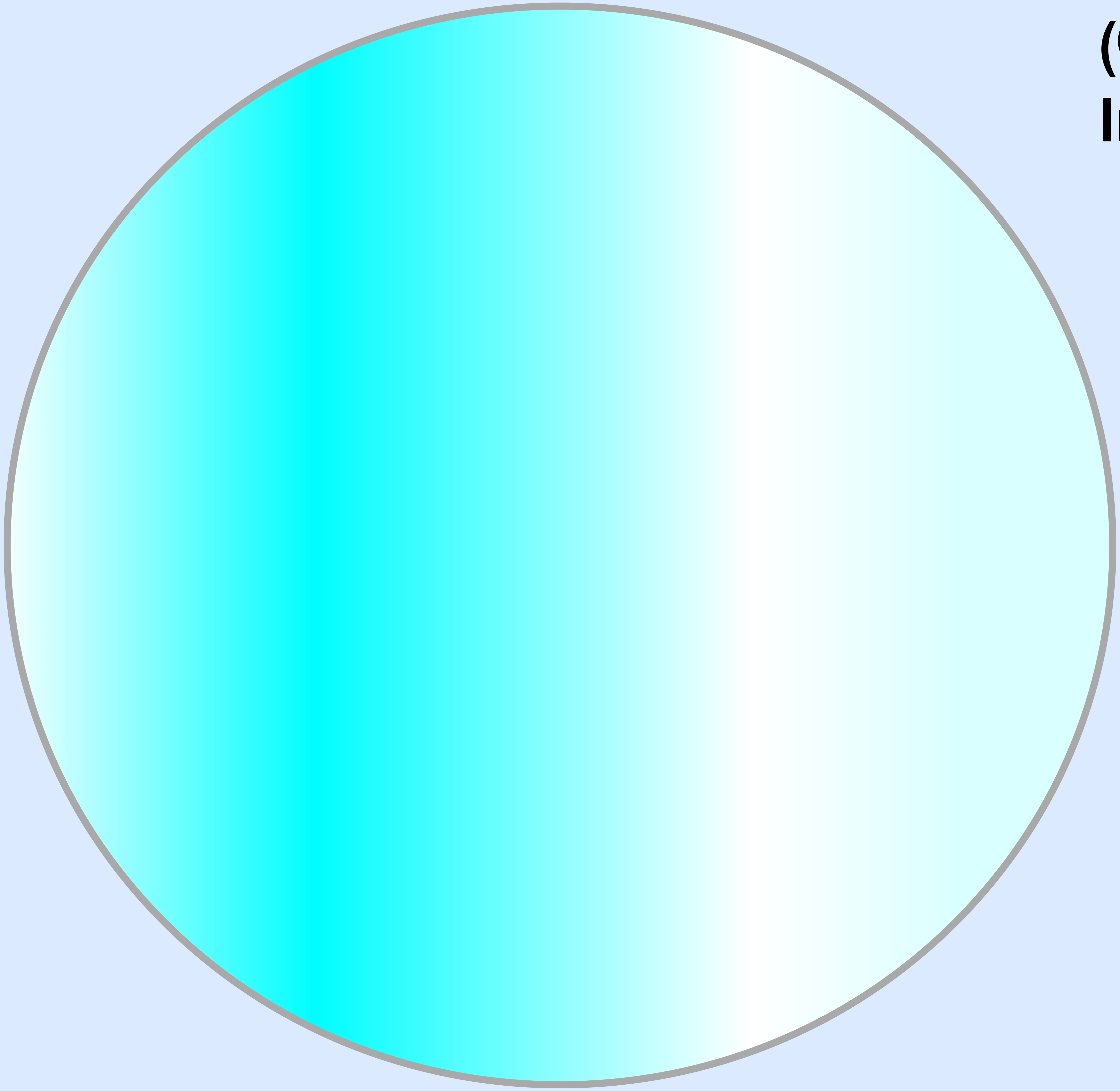
(Glass) Cell



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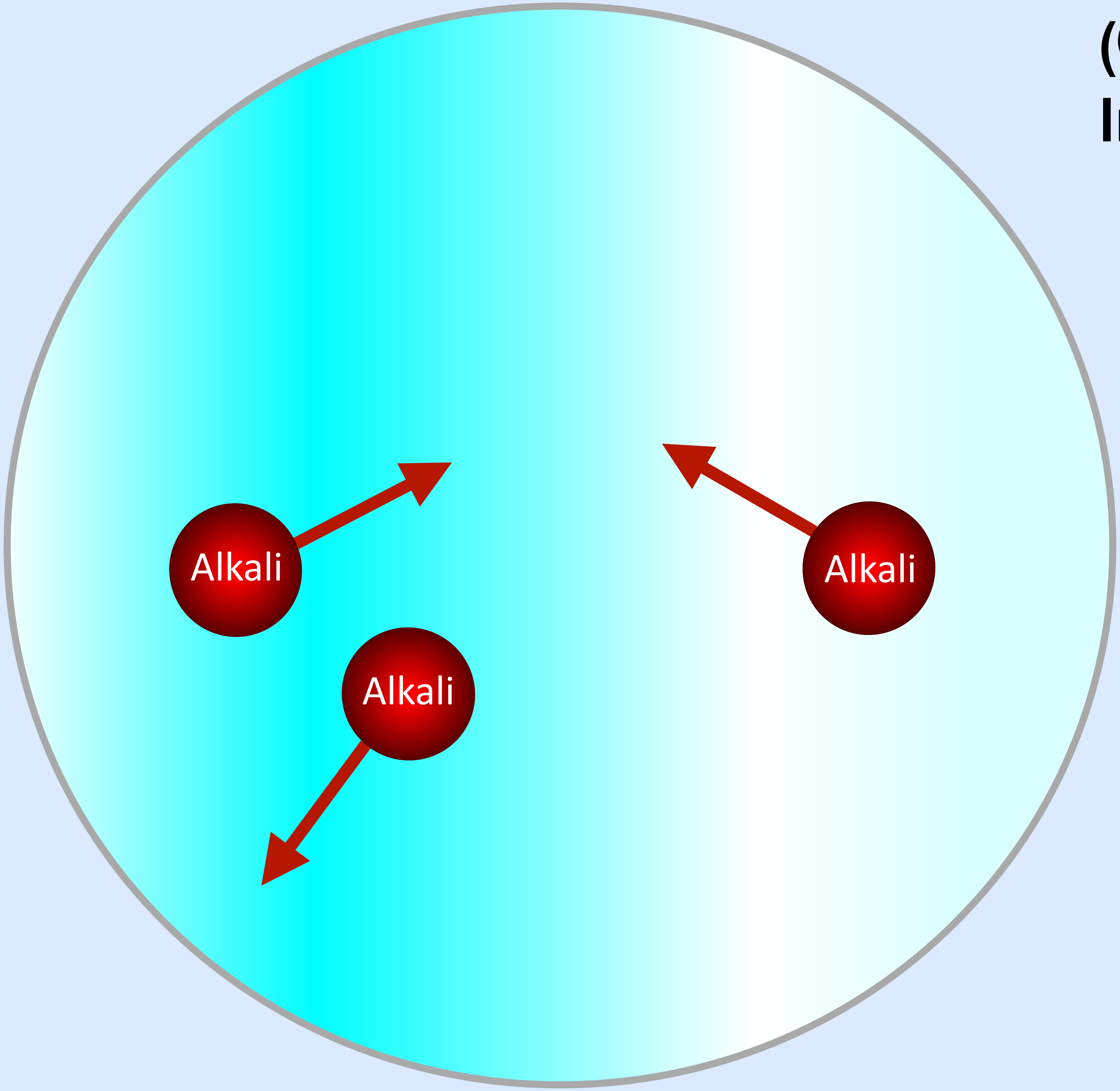

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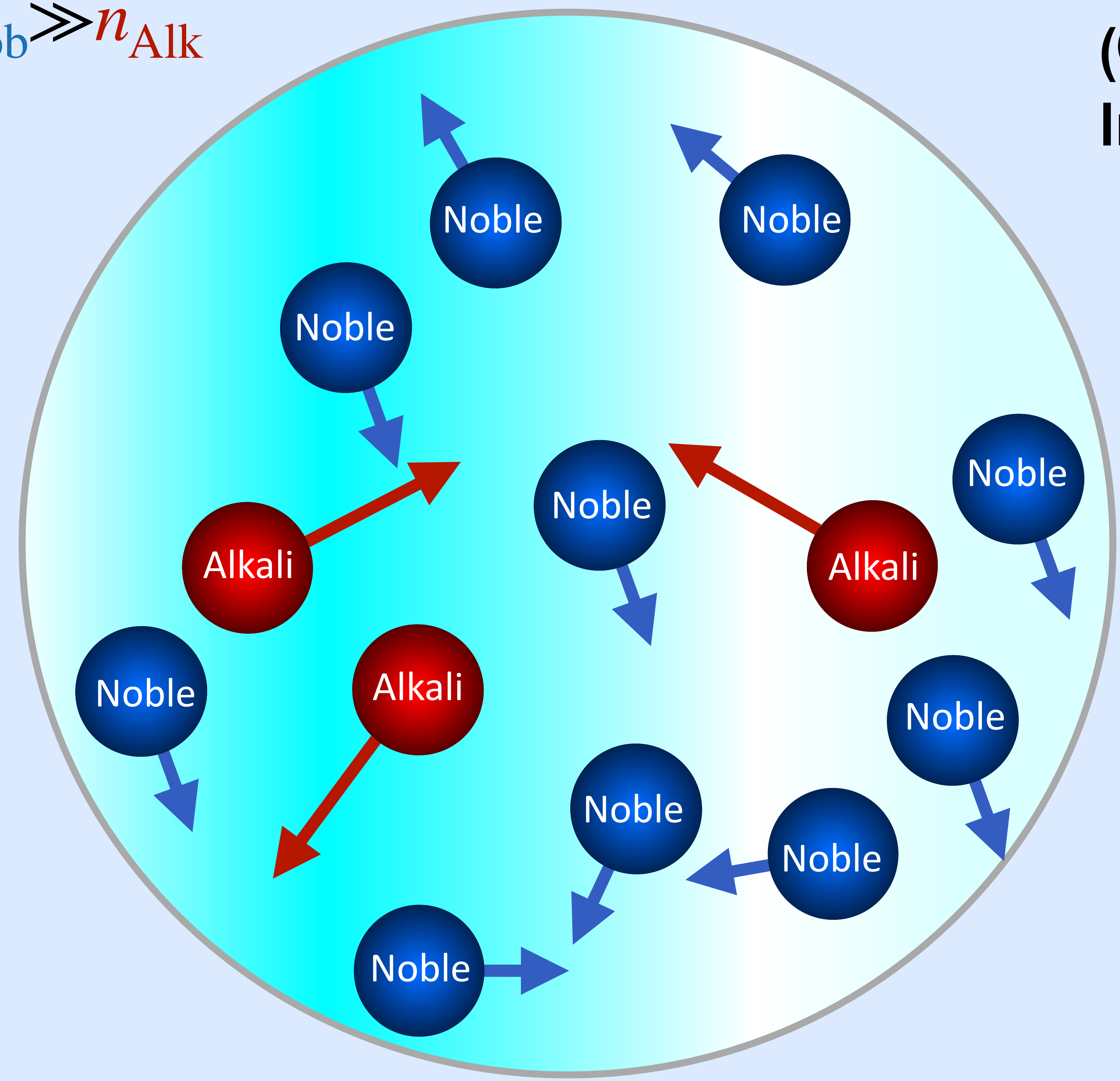

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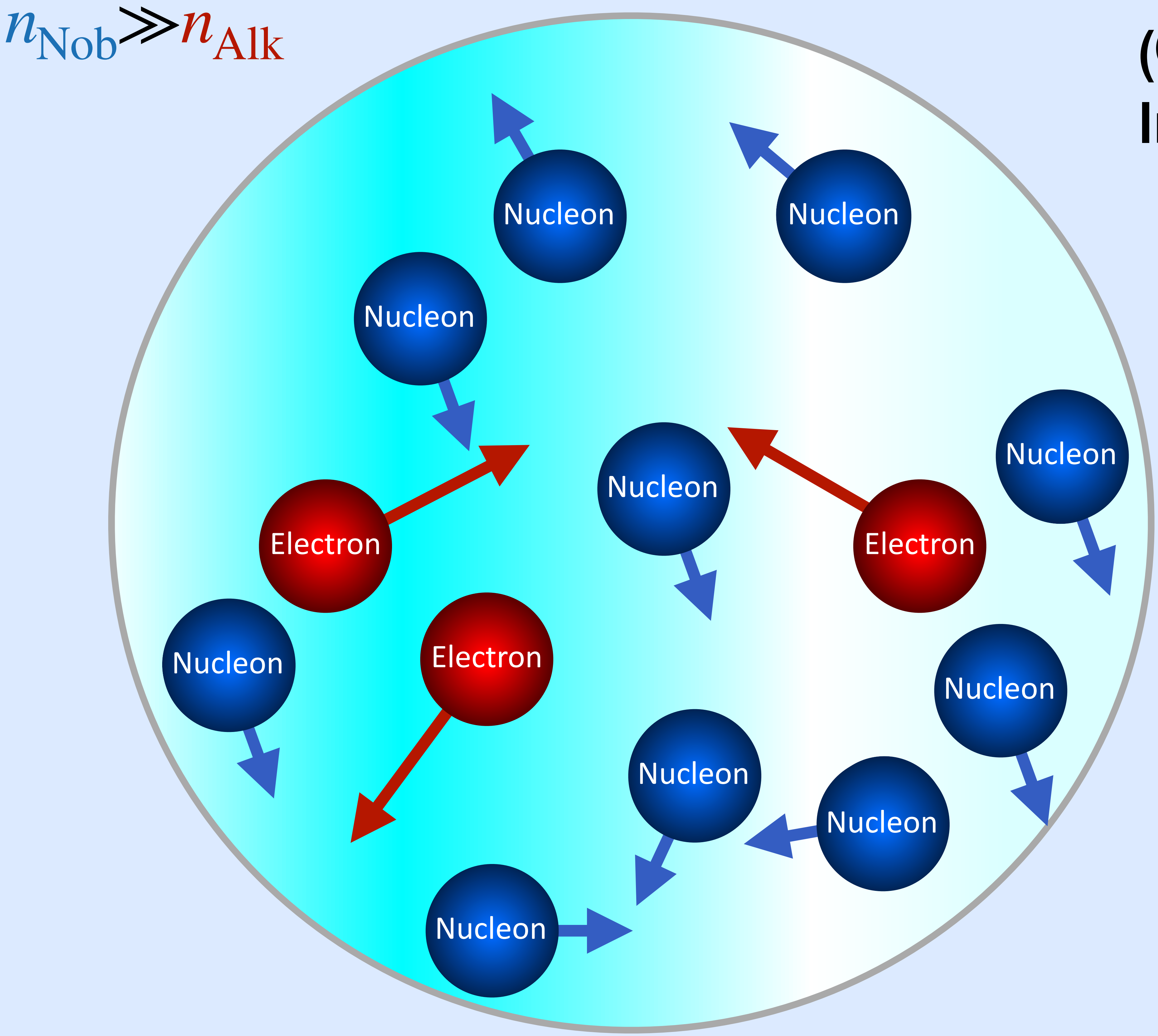

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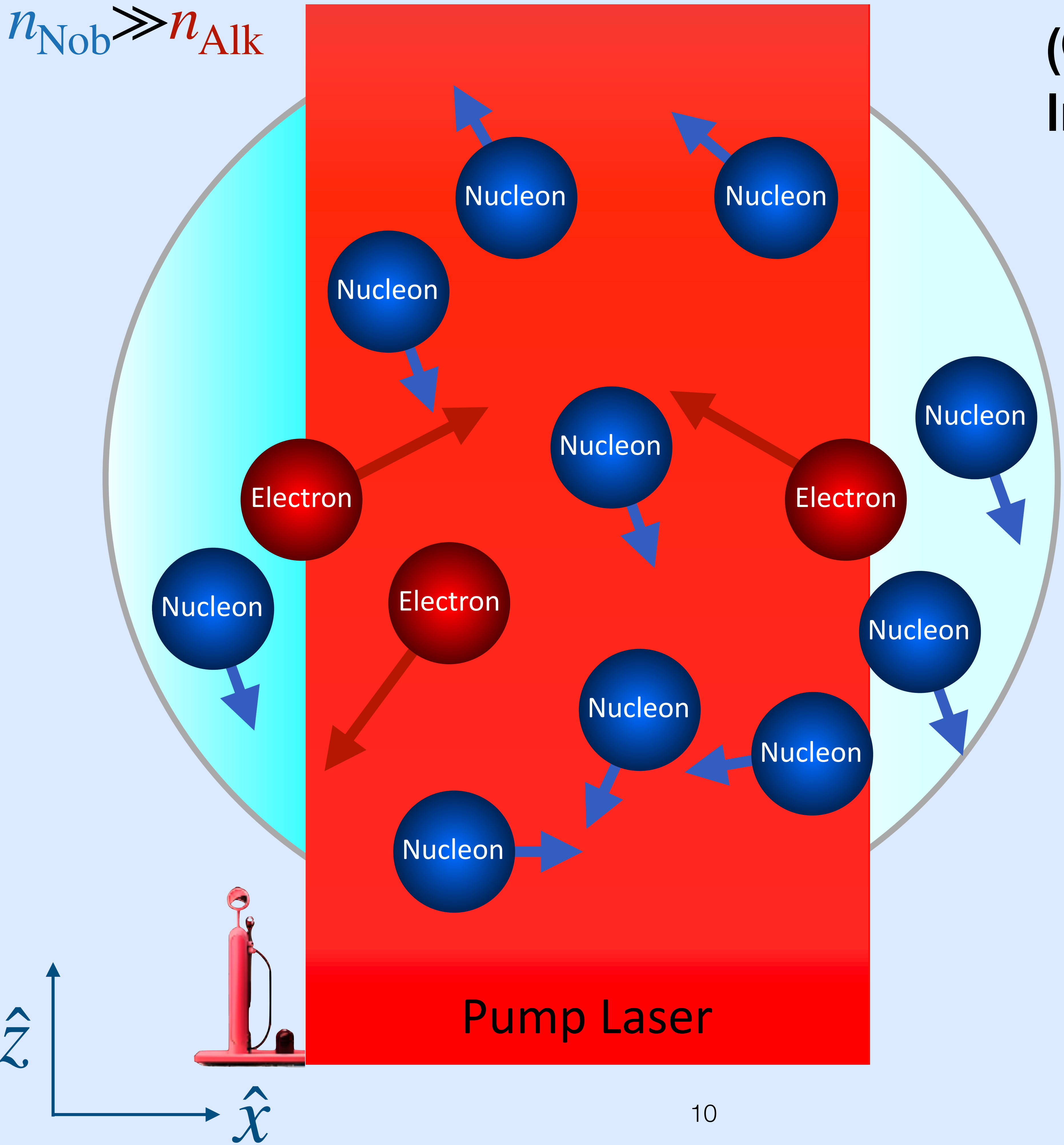

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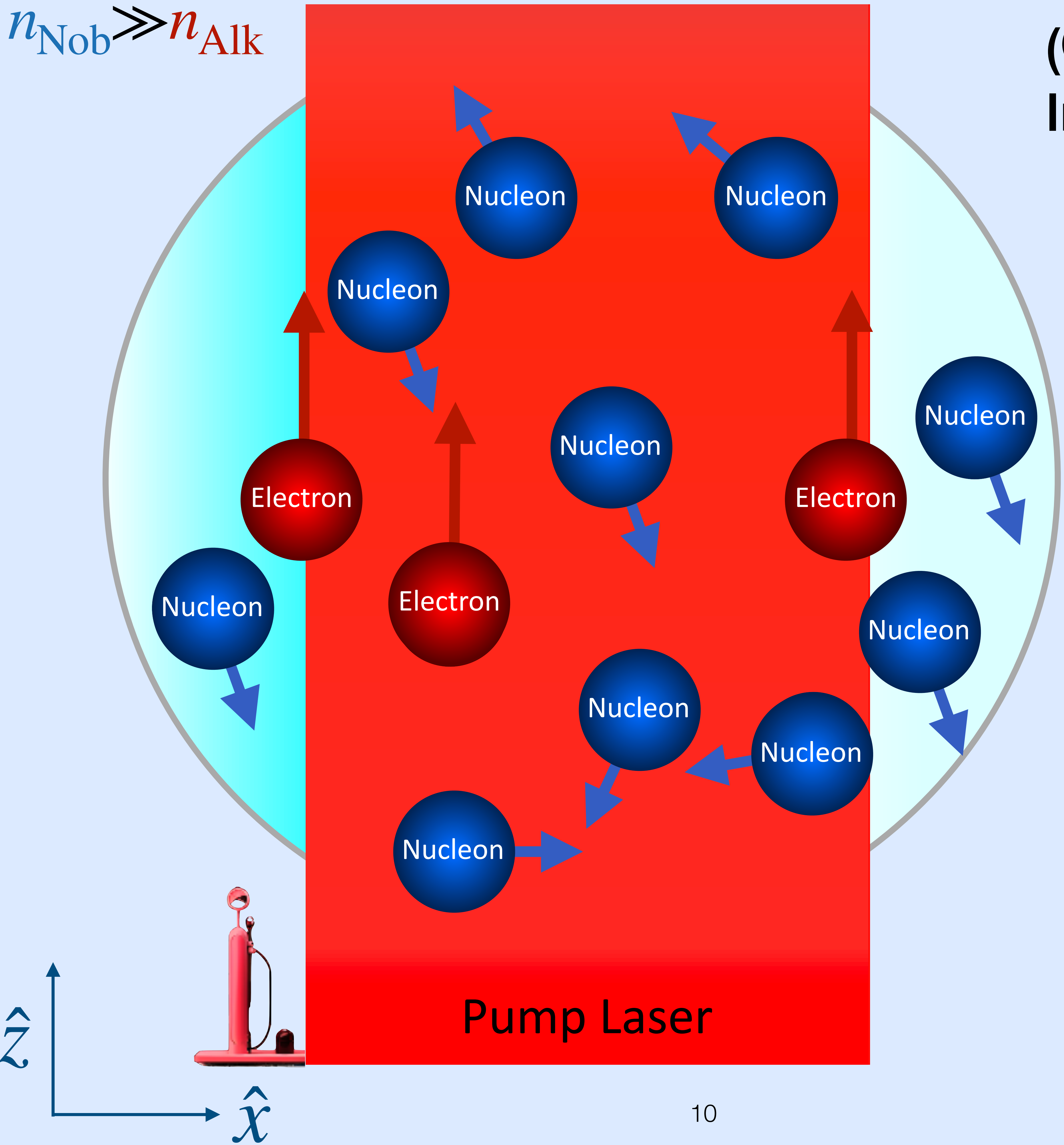

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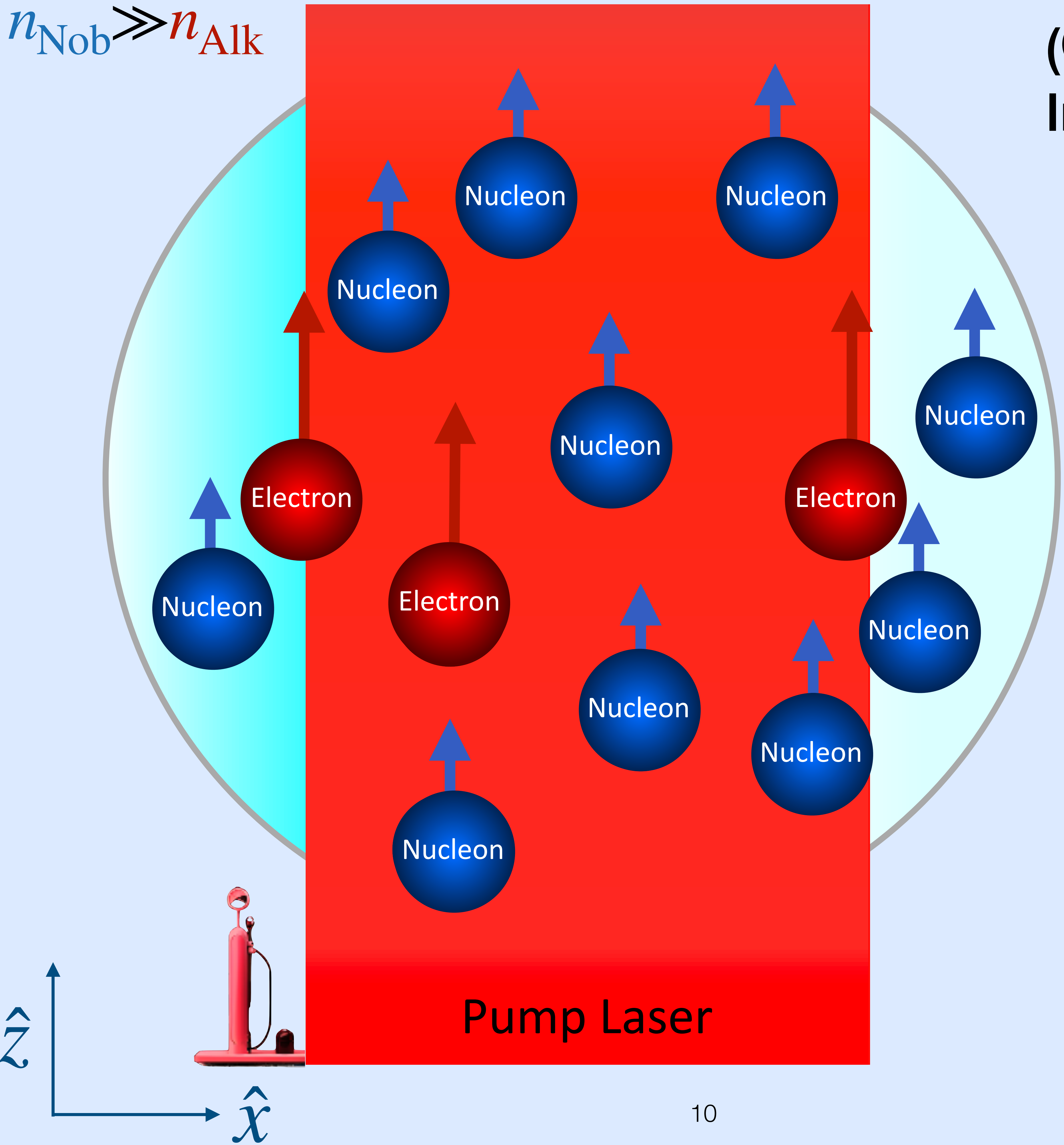

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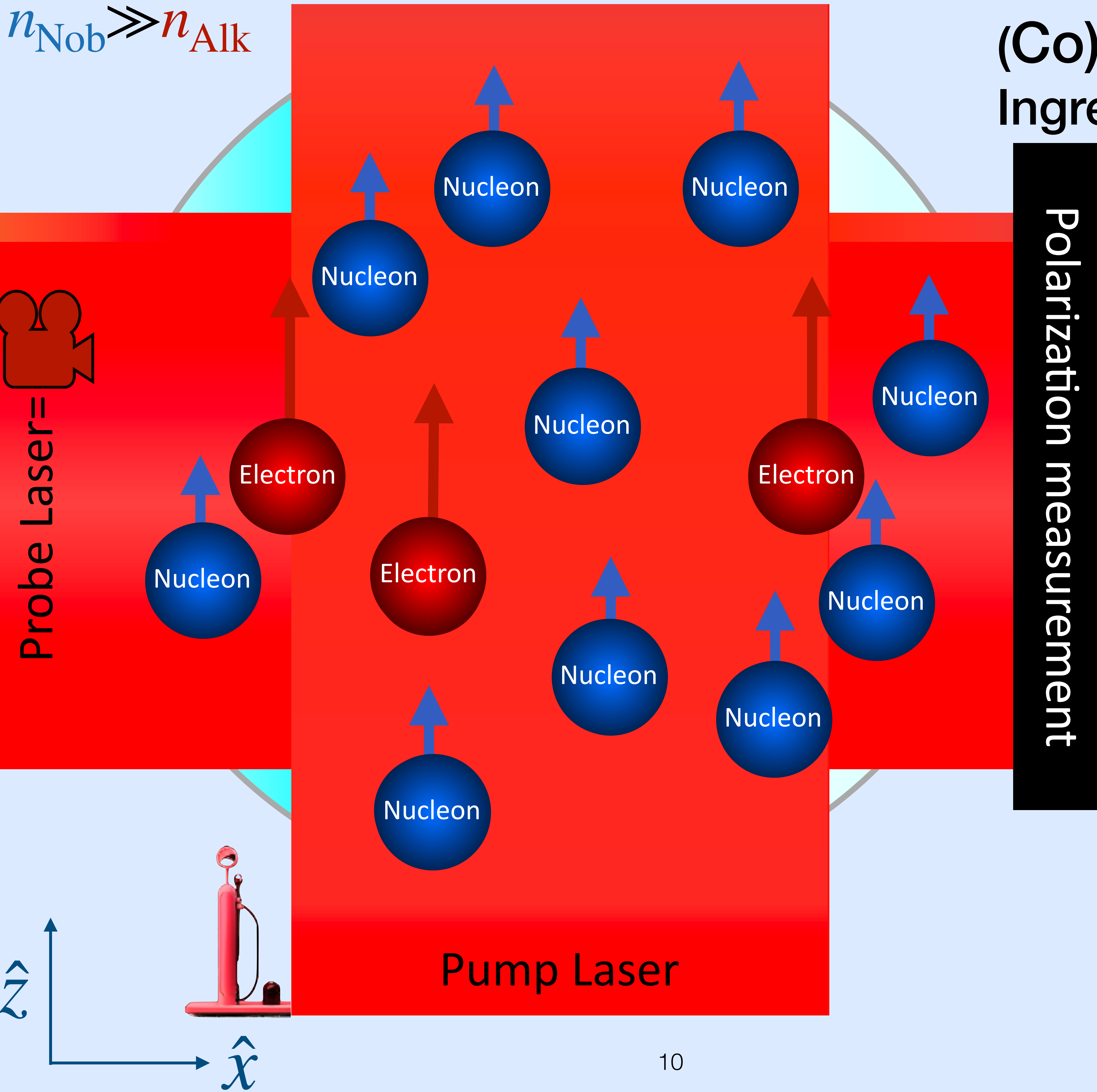

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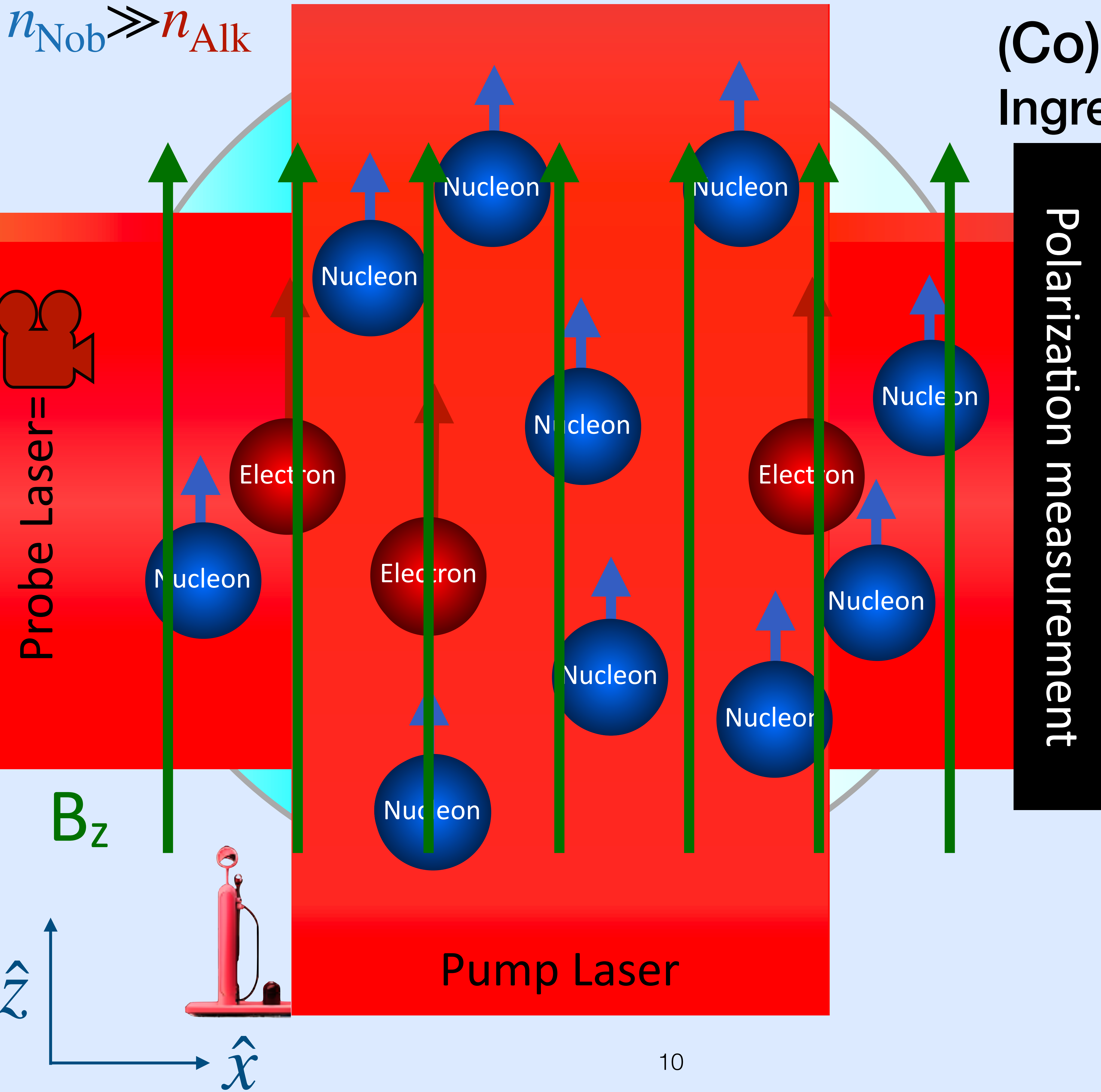

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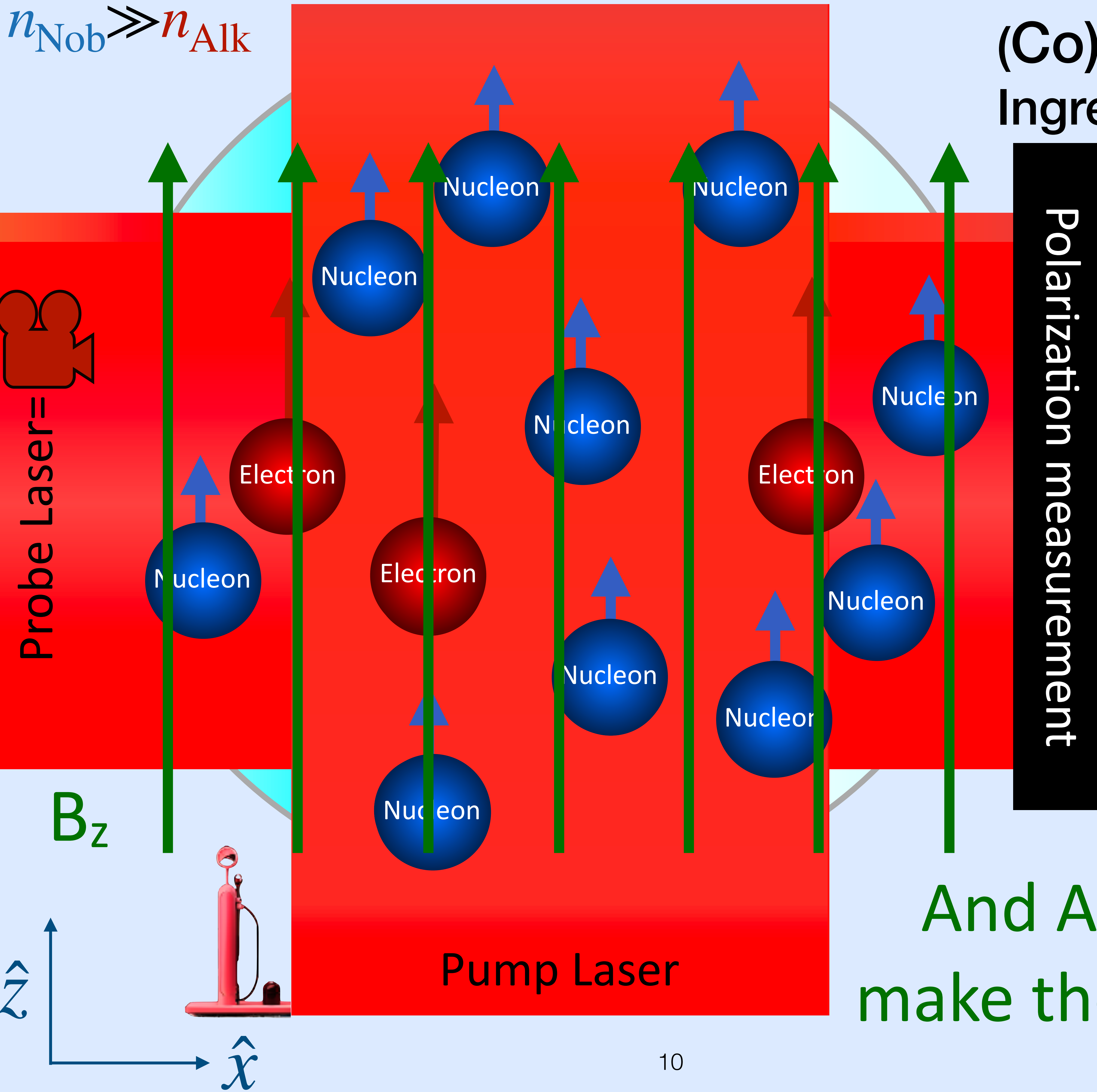
<u>Misc:</u>

- Magnetic Coils
- Magnetic Shields
- Oven
- Optical Components



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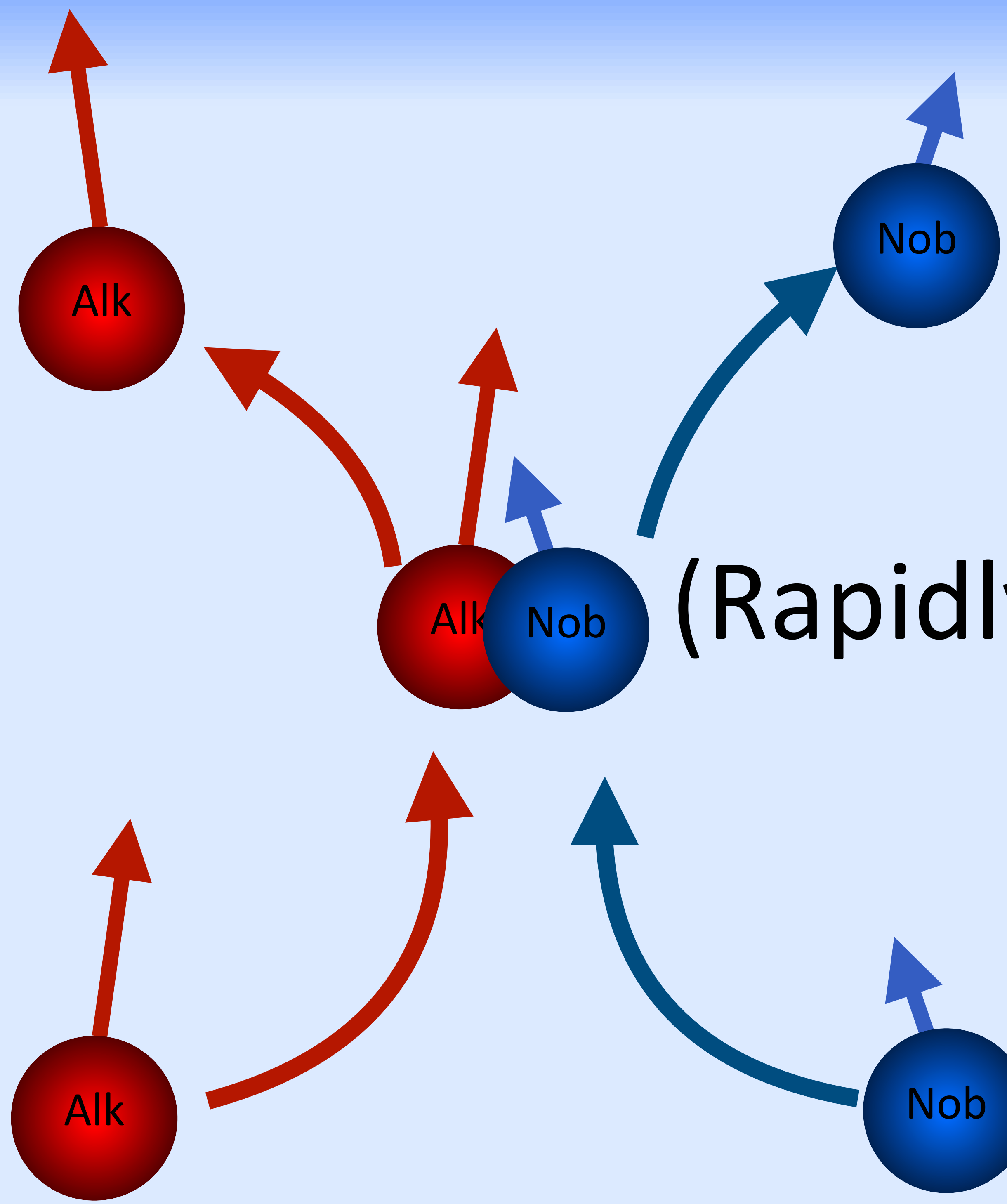
And ALPs would make the spins spin!

Magnetometer→ Comagnetometer: Inter-species collisions



(Rapidly)

Magnetic field from (quantum) point-like interactions

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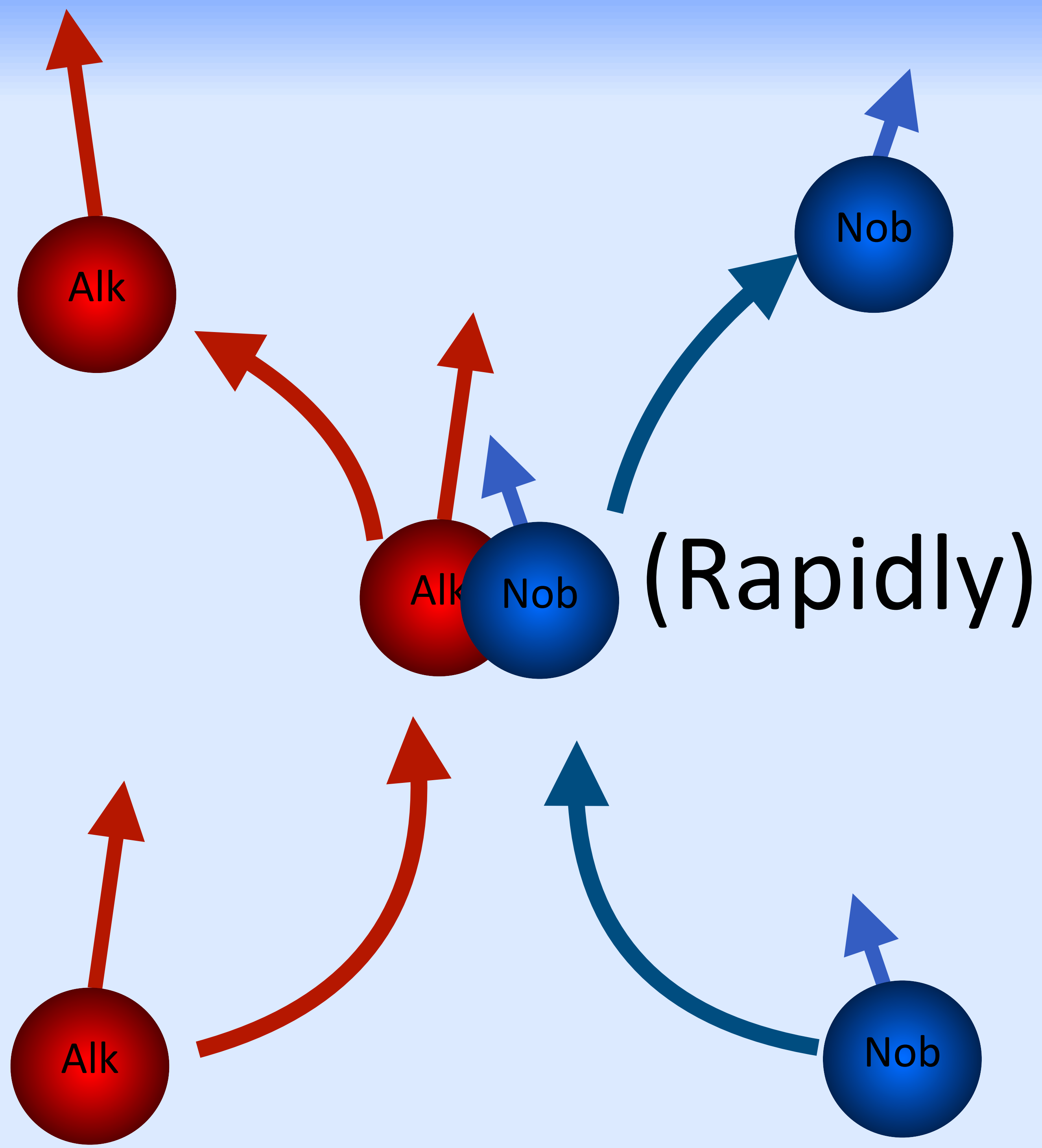

Magnetic field from (quantum) point-like interactions

$$B_{\text{induced on Alk}} = \mathscr{B}_{\text{Nob}} S_{\text{Nob}}$$

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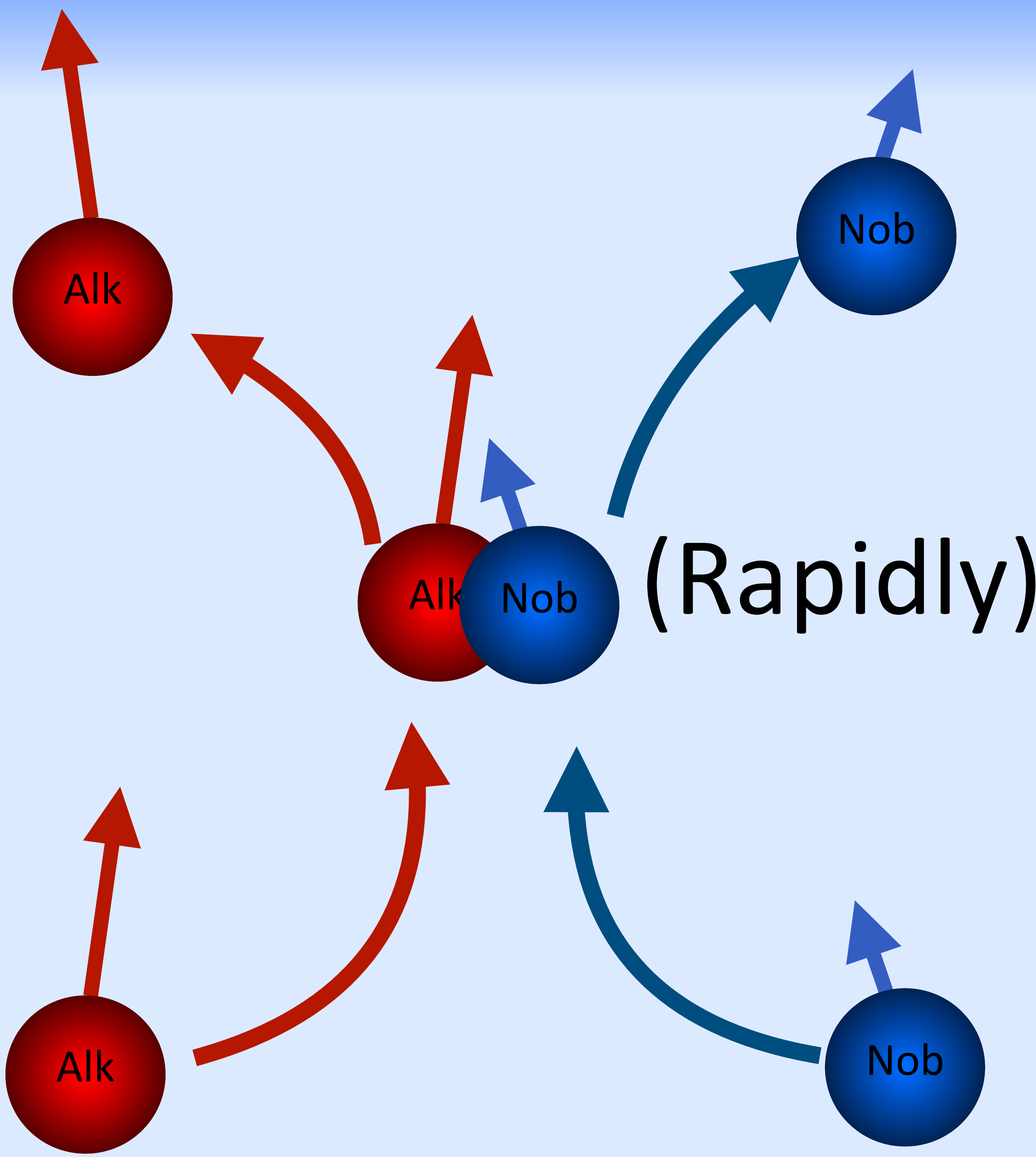

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(Sometimes important, but removed to simplify the talk)

Sketching the Comagnetometer Response (1)

$$\text{Spin Tilt} \sim \big(\text{magnetic response}(m_a)\big) \cdot (B_{x/y} + b_{x/y}/\gamma)$$

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This is true for both noble and alkali

(Though the actual response, γ, and fields are different)

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(Though the actual response, γ, and fields are different)

We only measure S_x, S_y of the alkali, and,

$$B_{x/y}(\text{Alkali}) = B_{\text{noise,x/y}} + \mathscr{B}_{\text{Noble}} \cdot S_{x/y}(\text{Noble})$$

$$B_{x/y}(\text{Noble}) = B_{\text{noise,x/y}}$$

Sketching the Comagnetometer Response (2)

$$\text{Alkali Spin} = \left(\text{Technical Noise}\right) +$$

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Sketching the Comagnetometer Response (2)

$$\text{Alkali Spin} = \left(\text{Technical Noise}\right) +$$

Direct noise measurement

$$+\left(\text{Alkali Response at } m_a\right) \times \left(\boxed{B_{\text{noise}}} + \frac{b_{\text{ALP}-\text{Alk}}}{\gamma_{\text{Alk}}} + B_{\text{ind}} \right)$$

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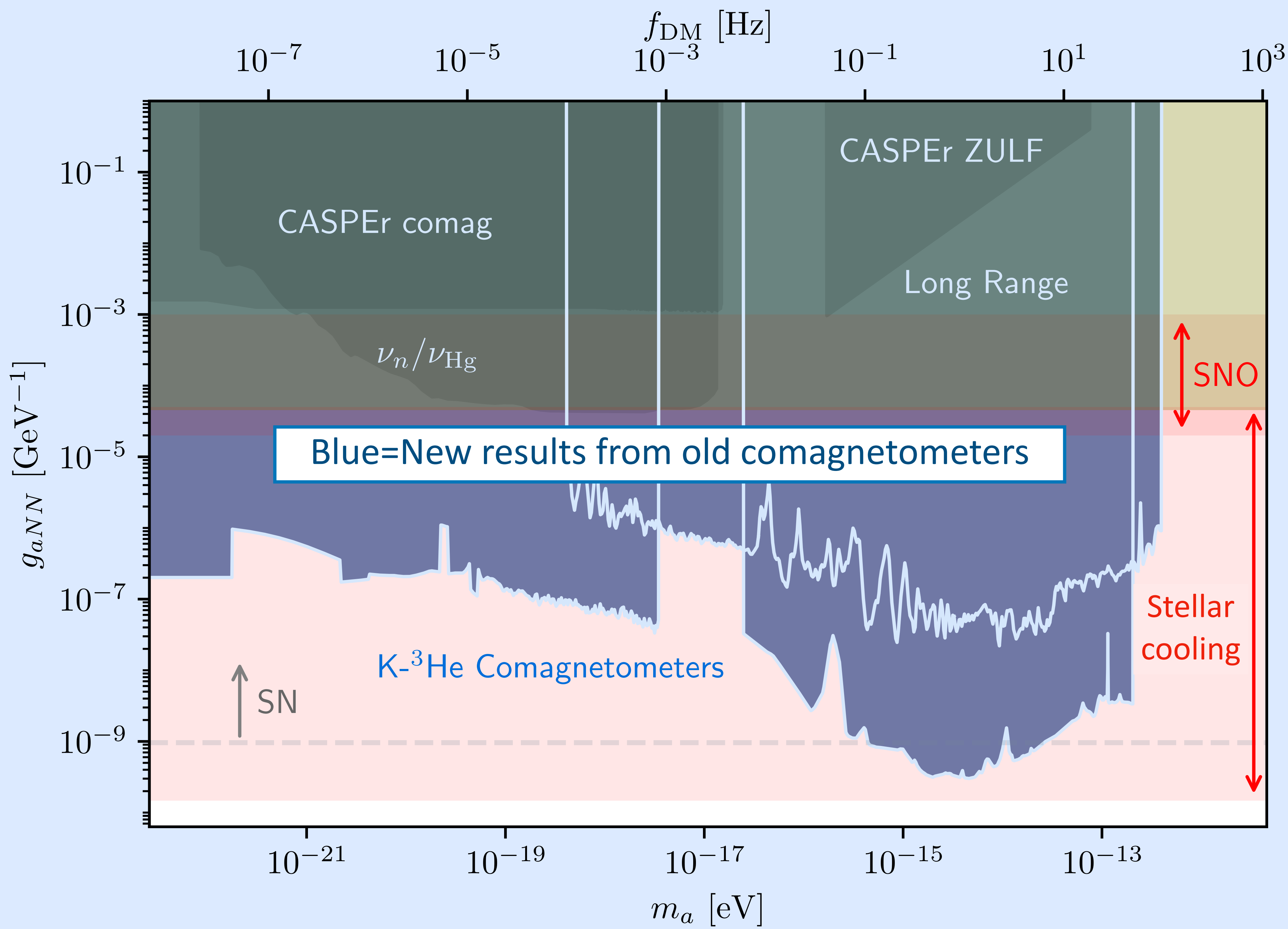
The magnetic subtraction stops working when $m_a \gtrsim 10\ \text{Hz} \cdot h$

Results

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



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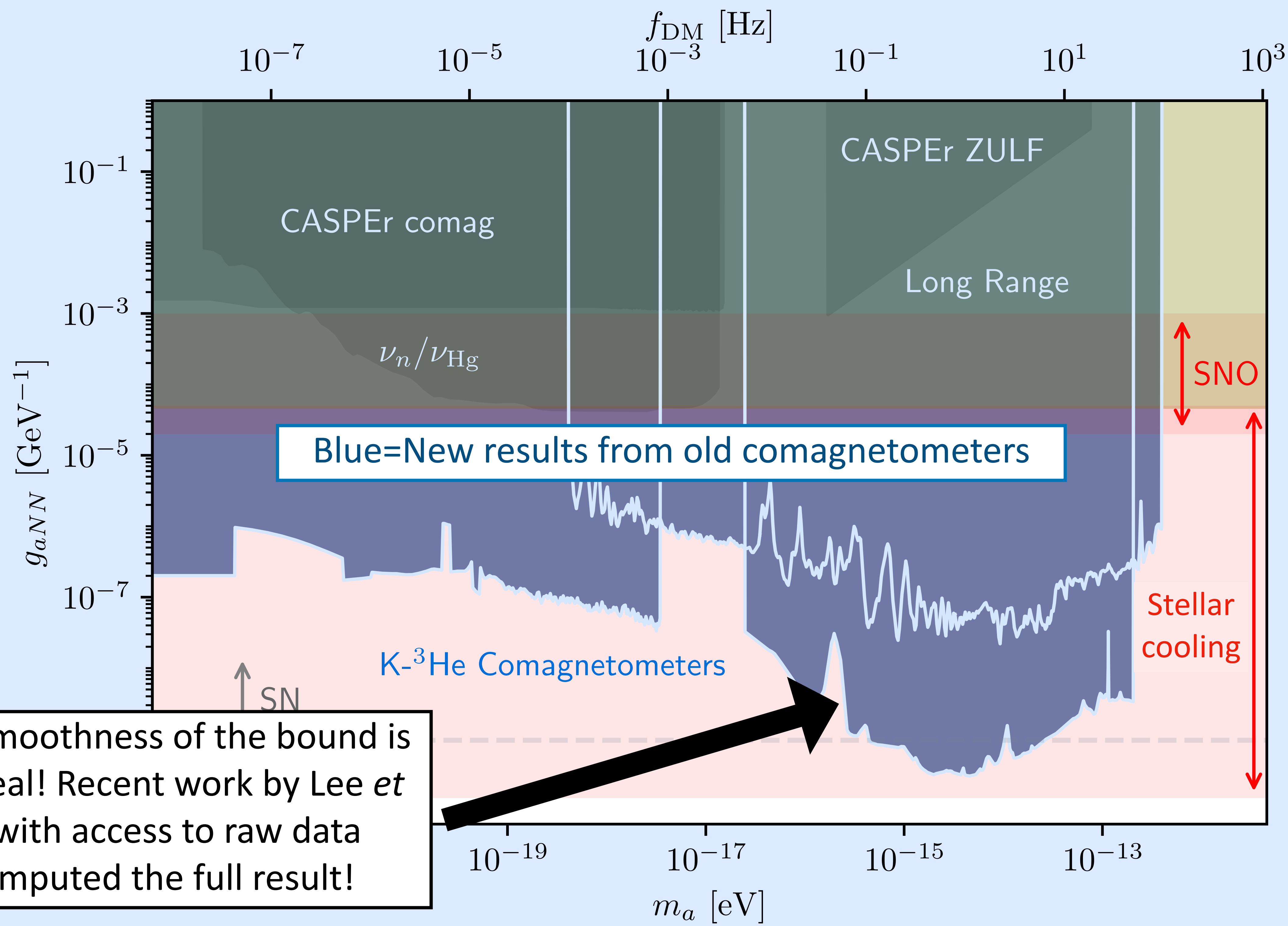

The smoothness of the bound is not real! Recent work by Lee *et al* with access to raw data computed the full result!

Lessons Learned

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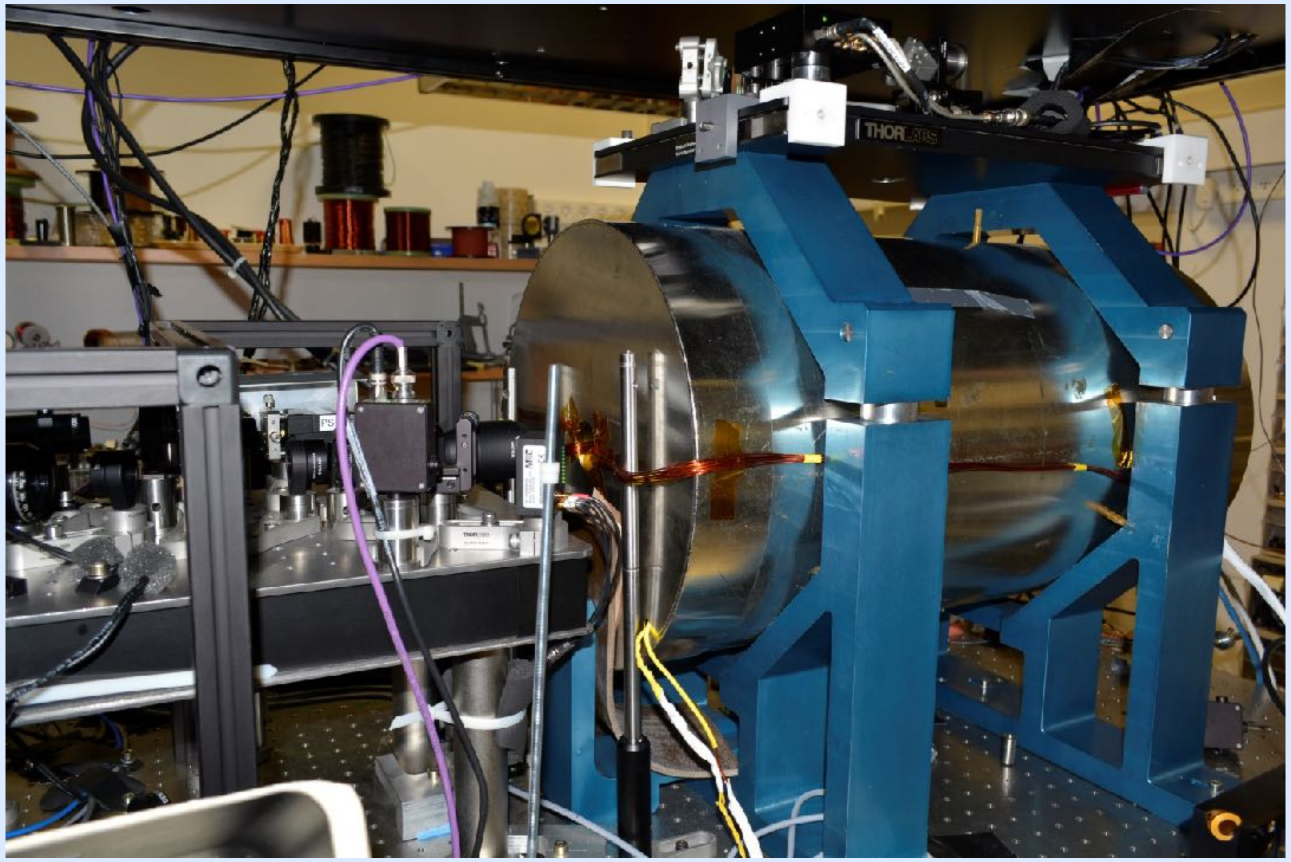
- We need our own experiment!

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

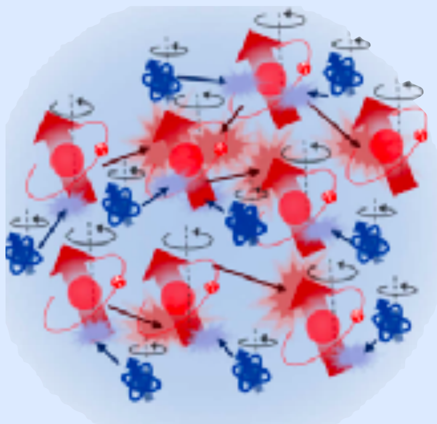
Noble and Alkali Spin Detectors for Ultralight Coherent darK matter

NASDUCK



Existing NASDUCK Experiments

NASDUCK SERF



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

NASDUCK Floquet

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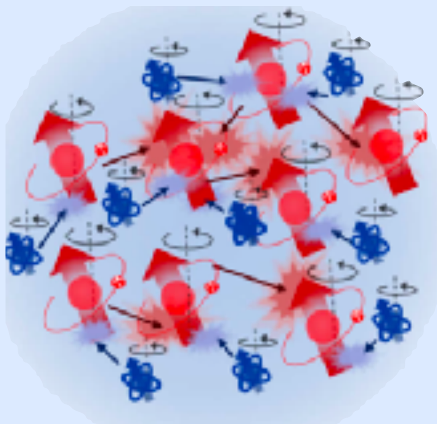

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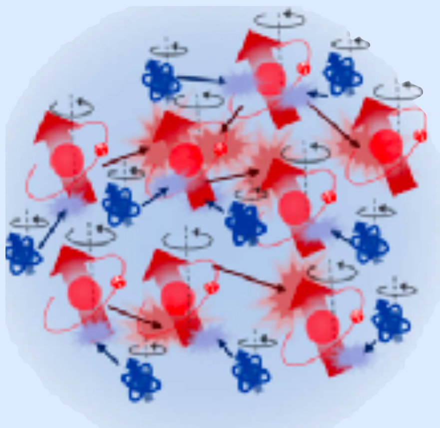

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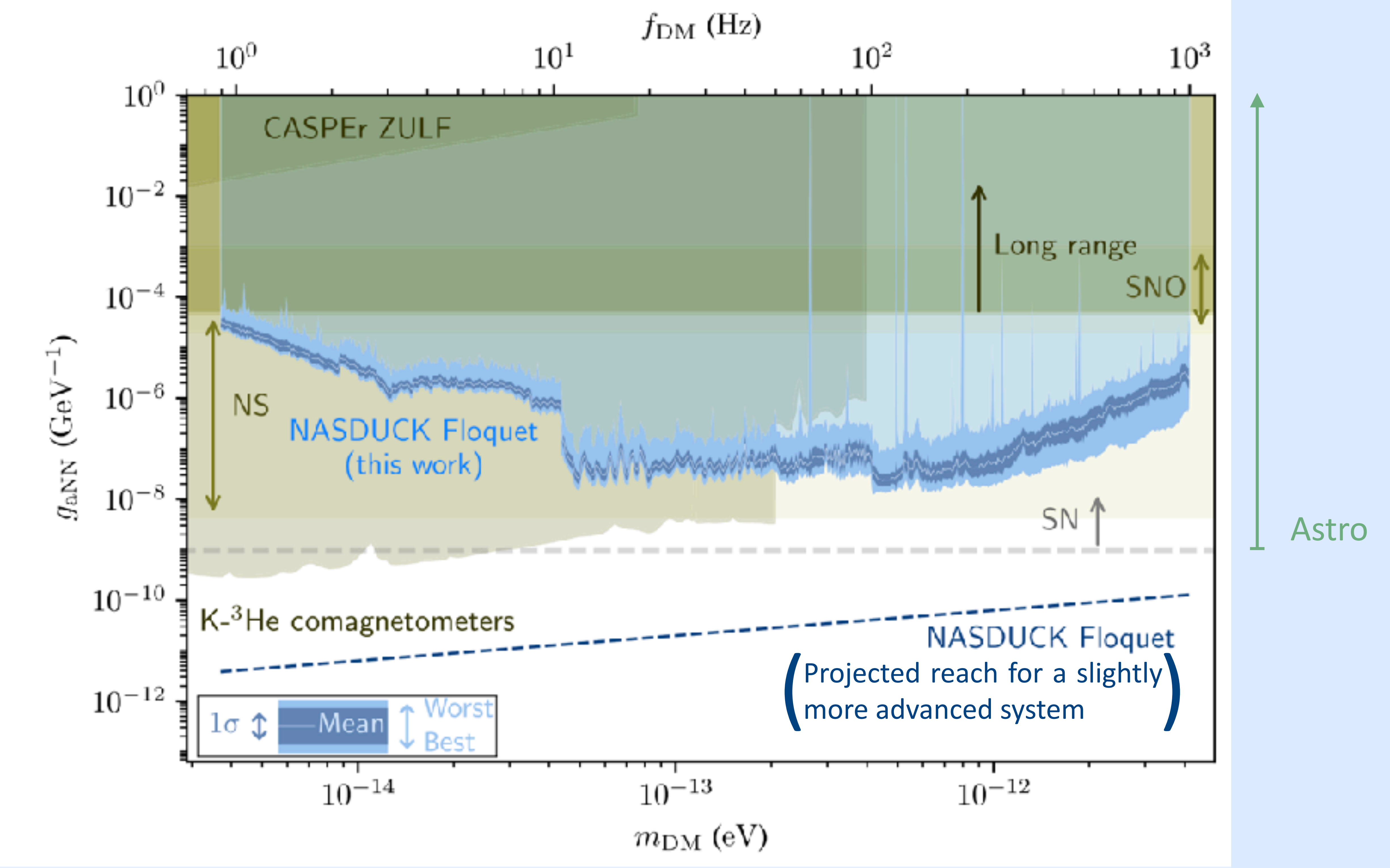
[2022 Science Adv., IMB, Ronen, Shaham, Katz, Volansky, Katz.]

A very fancy resonance search, where both the Alkali and the noble were on-resonance.

NASDUCK Floquet Results



Transverse vs. Longitudinal Magnetometry

Until now:

From now on:

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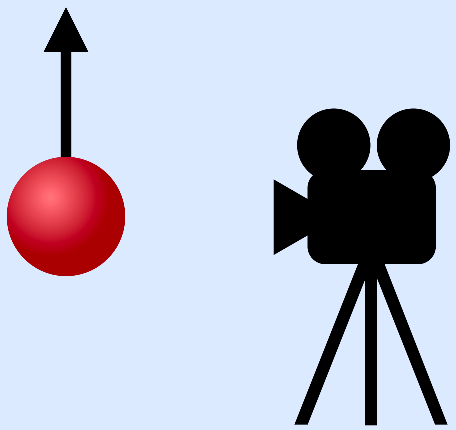

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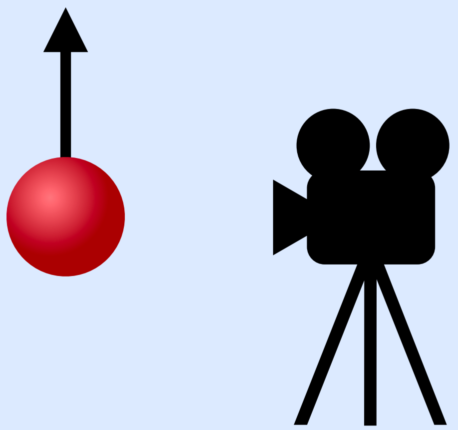

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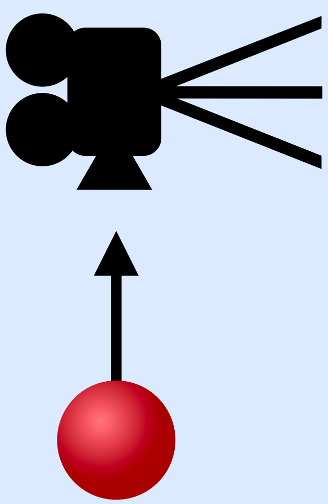

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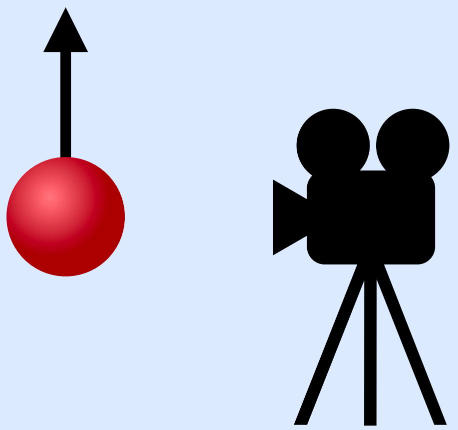

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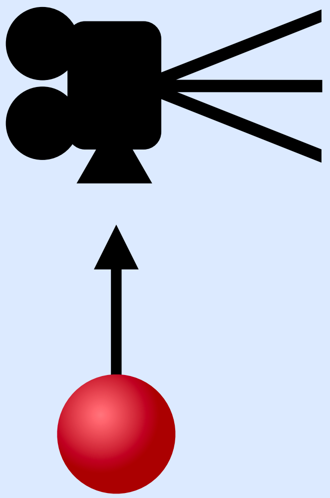

(P.S: We're also going to drop the noble gas, and start using non-alkali metals)

Scalar Longitudinal Magnetometry

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

Since coupling constants are scalars, scalar DM (not ALPs) can mimic variation in fundamental constants (for example: $\mathscr{L} = m_e \bar{e} e \rightarrow (m_e + g_{\phi ee}\phi)\bar{e}e$)

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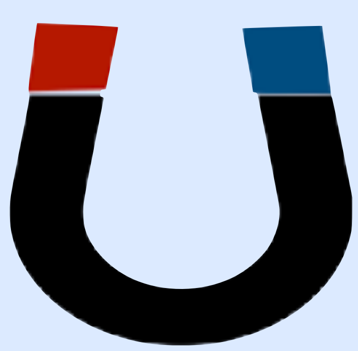

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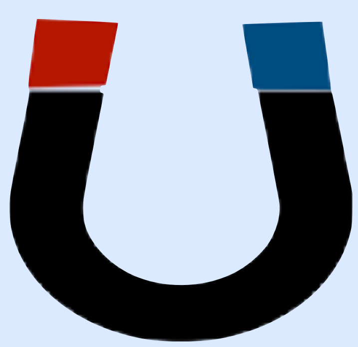

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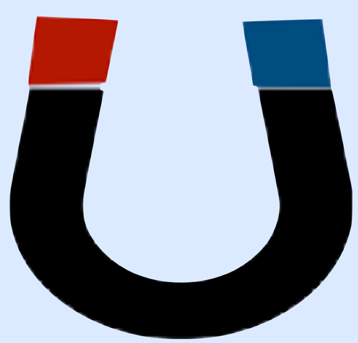

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First experiment is ongoing by Sushkov et al.

Can Longitudinal Magnetometry be used for ALPs?

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Naive answer:

NO!

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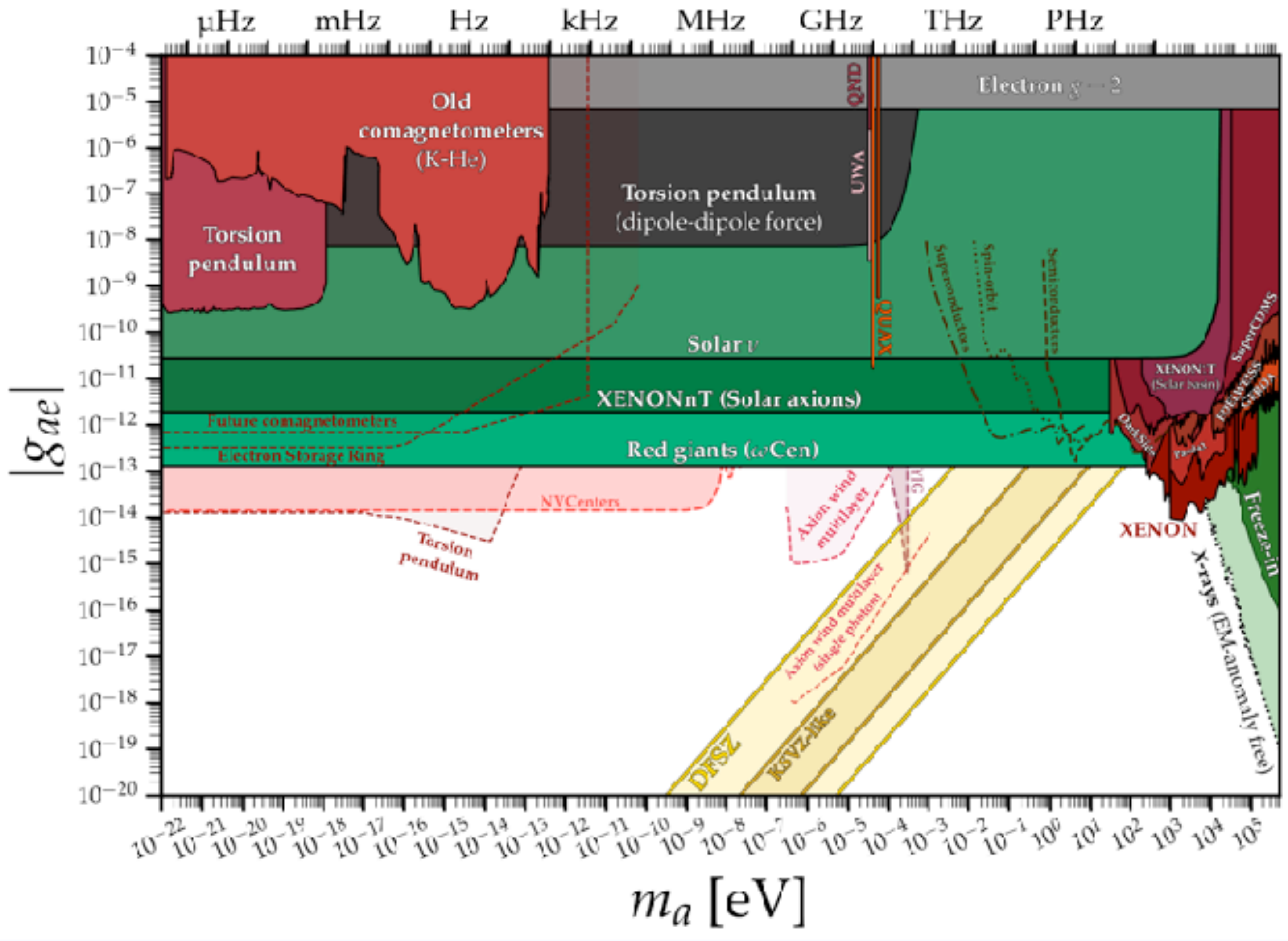
$$S_z(t \to \infty) \propto 1 - \frac{b^2_{\perp,\mathrm{ALP}}\Gamma}{((m_a - \omega_{\mathrm{res}})^2 + \Gamma^2)\Gamma_L}$$

δS_z is second order in the couplings!

Should we try to measure ALPs?



(Green are astro-bounds)

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

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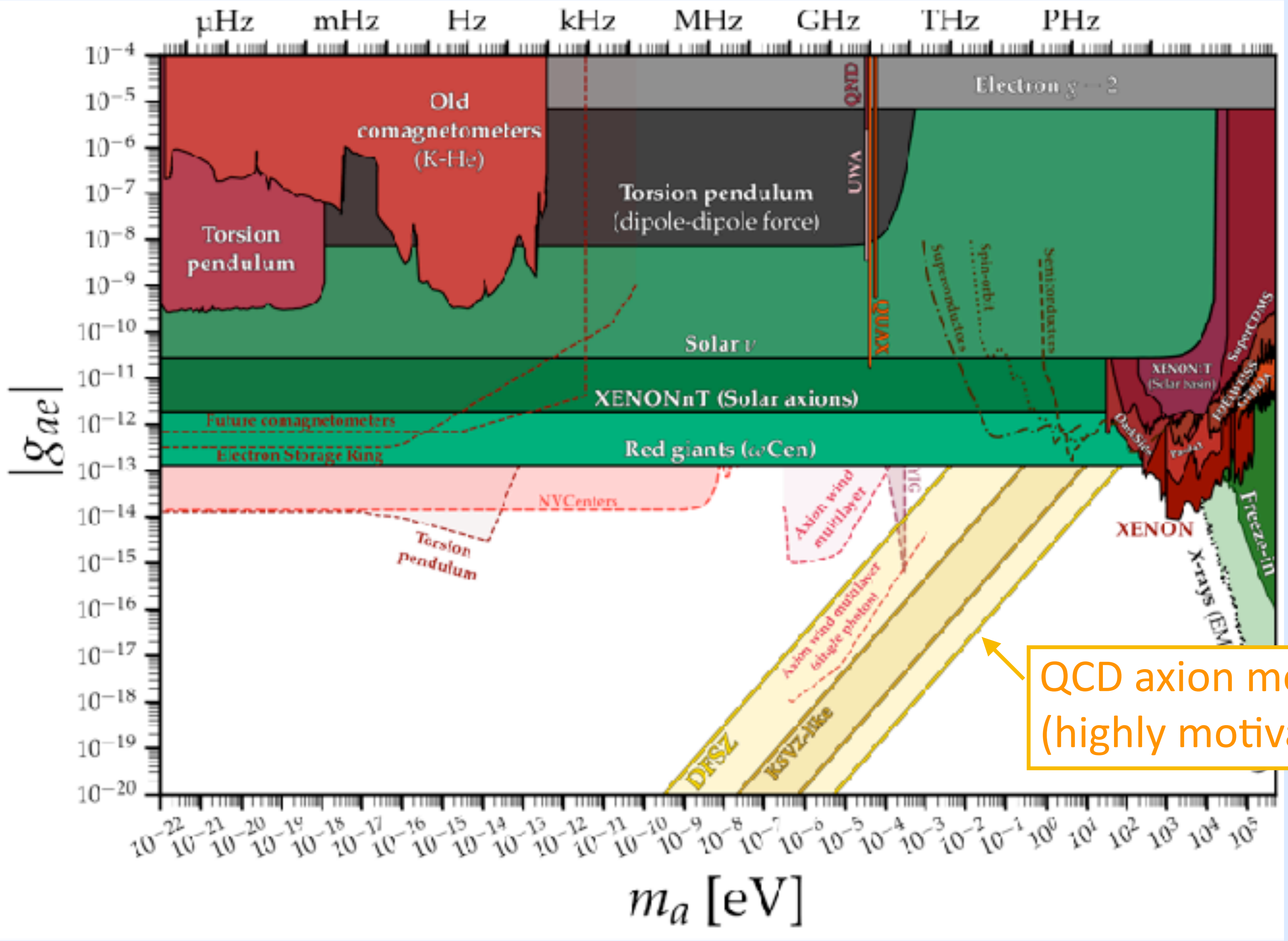

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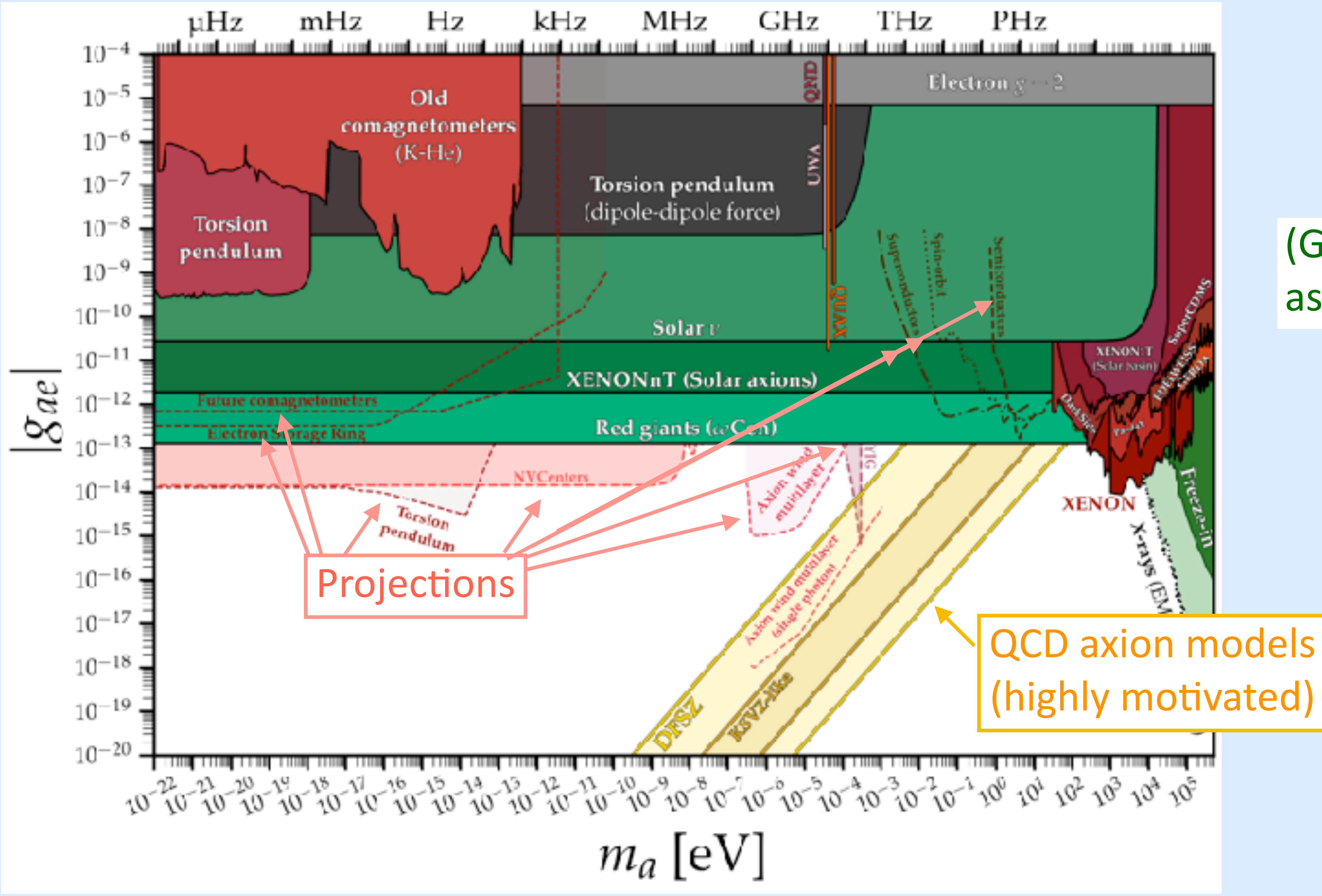

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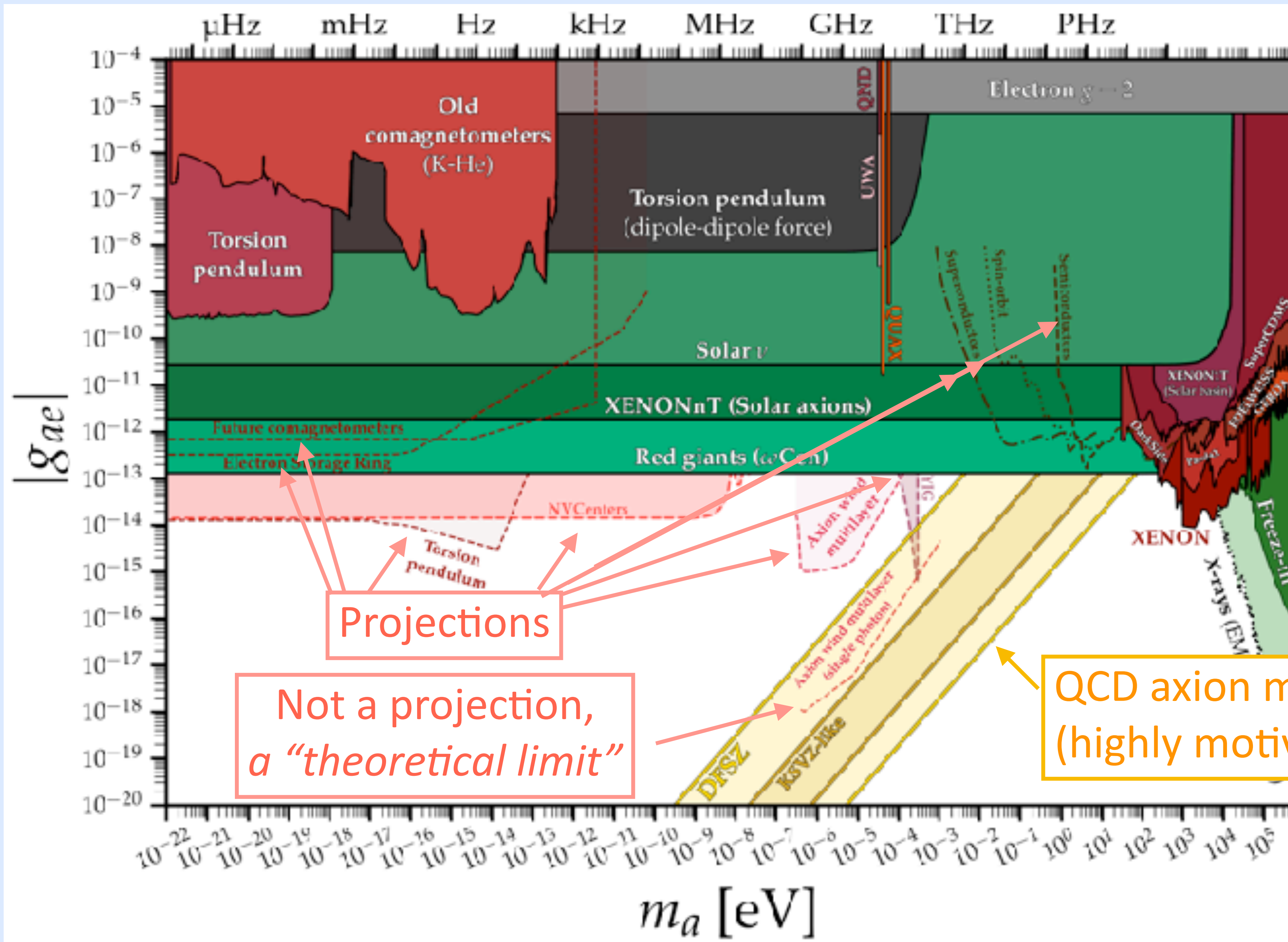

Projections

Not a projection, *a "theoretical limit"*

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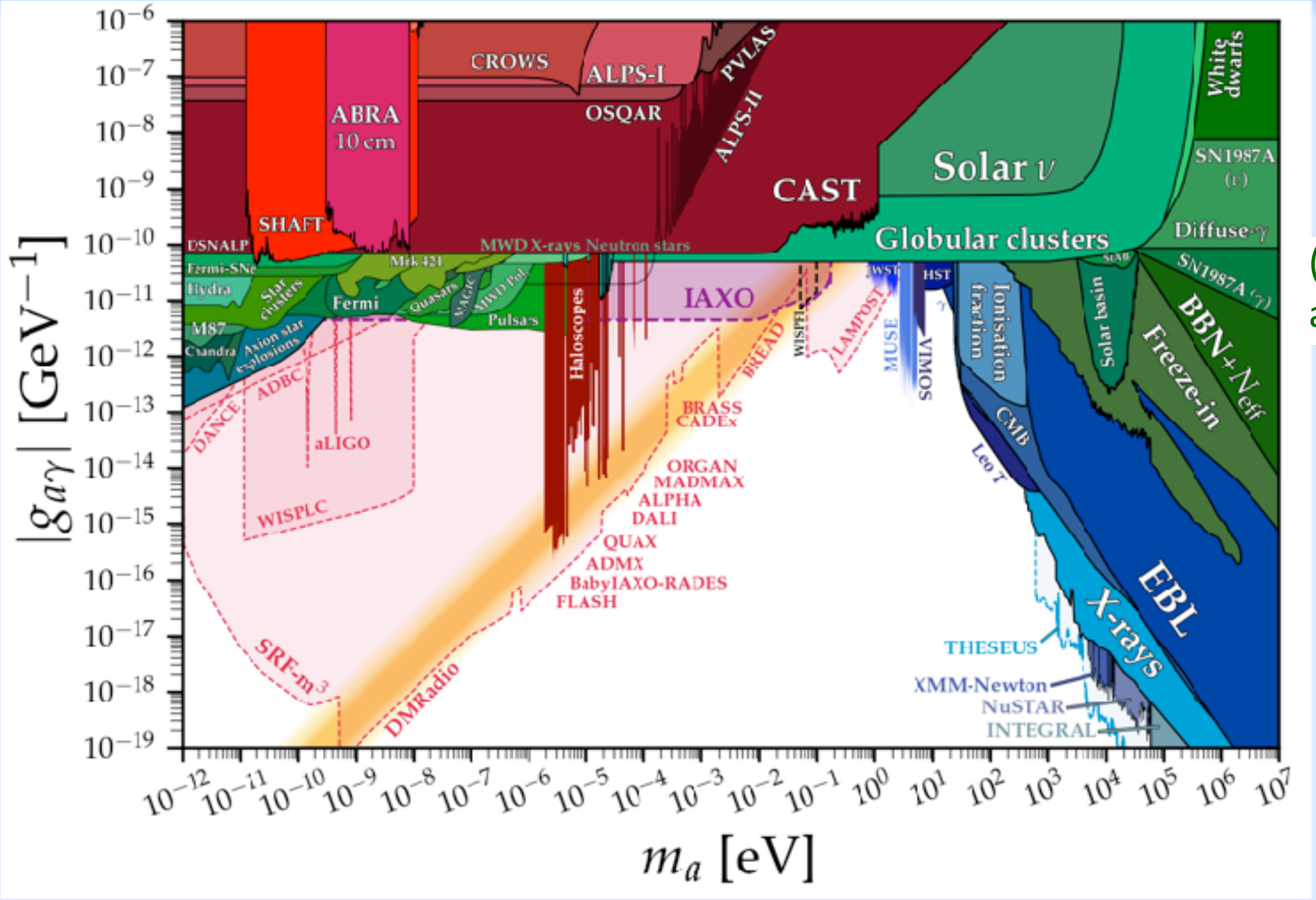

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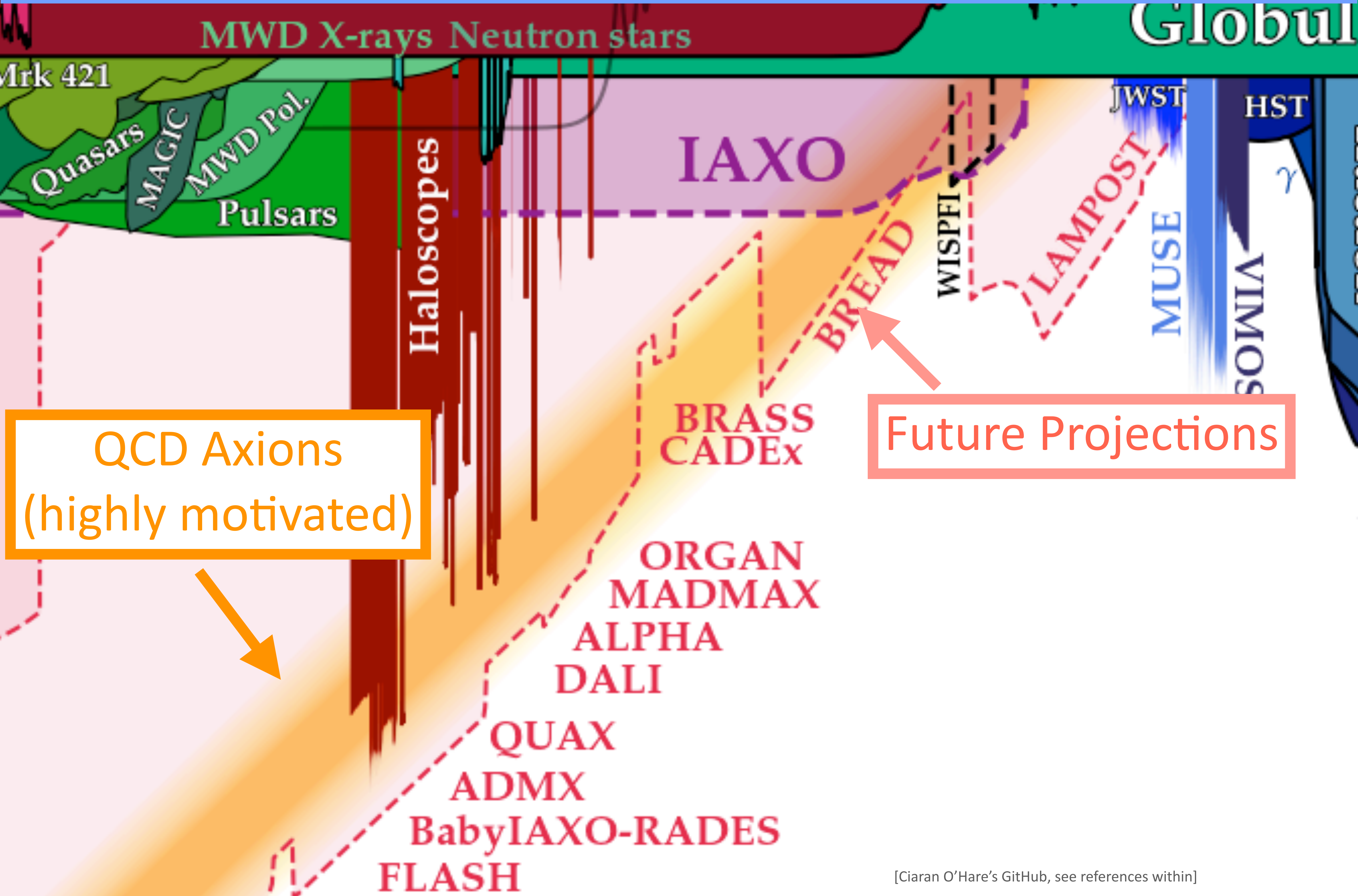

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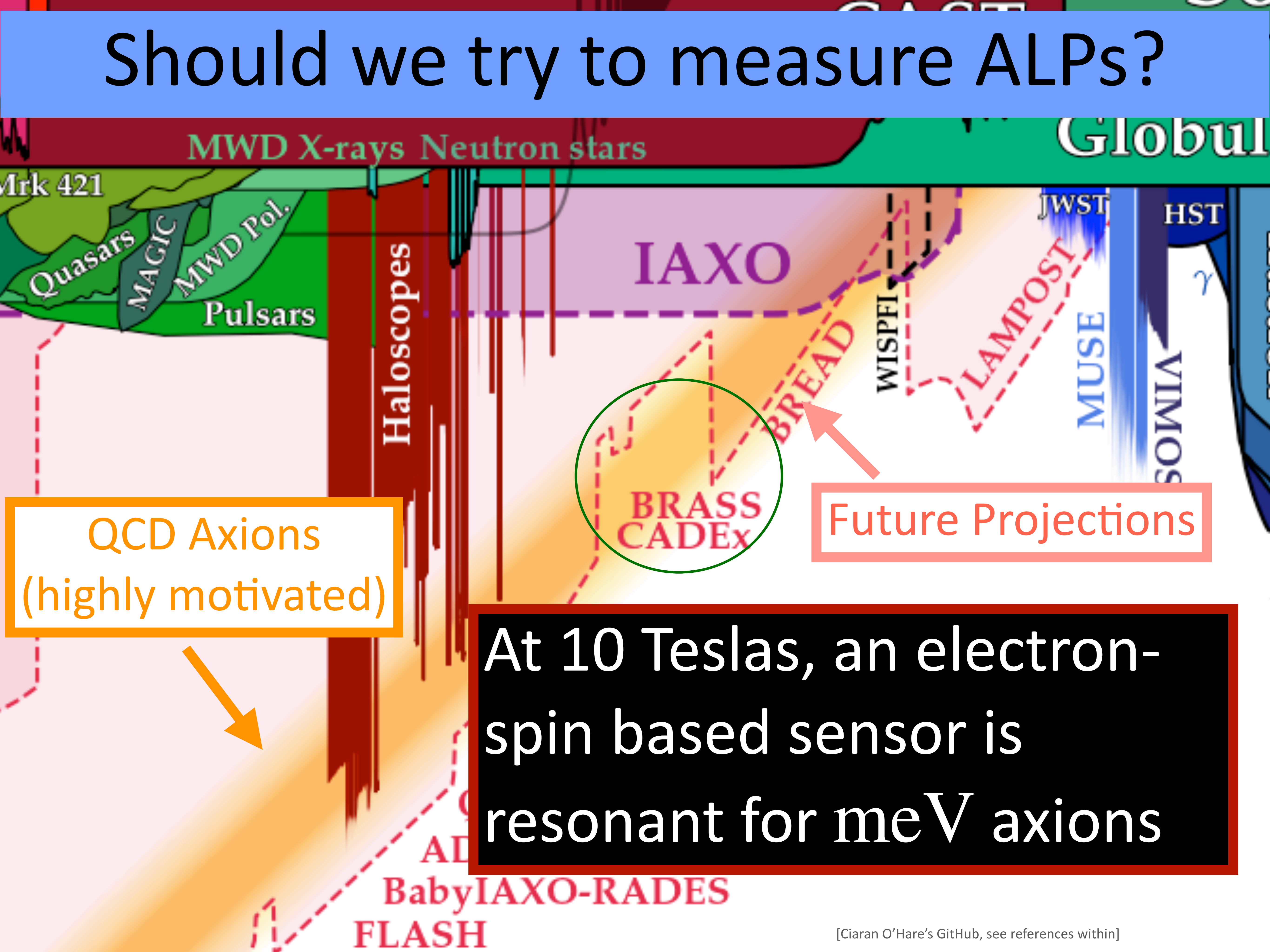

QCD Axions (highly motivated)

Future Projections

At 10 Teslas, an electron-spin based sensor is resonant for meV axions

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

Fundamental Noise of a Transverse Magnetometer

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This shot noise does not exist when measuring S_z!

Axion Longitudinal Signal

[In progress.]

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

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However

Due to the axions, $[S_z, H] \neq 0$, so measuring

$\langle S_z \rangle$ would induce a quantum noise $\sqrt{\langle S_z^2 \rangle}$

Spin Shot Noise as an Observable

[In progress.]

The relevant observable
(amplitude of shot noise
per square root bandwidth)

$$\sqrt{\text{signal spectral density}} \sim \frac{b_{\perp,\mathrm{ALP}}}{\sqrt{\max(10^{-6} m_a, \Gamma_2)(\Gamma_L)}\sqrt{N_{\mathrm{spins}}}}$$

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

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Many challenges for actual implementation but also many possibilities!

$2)(\Gamma_L)\sqrt{N_{\text{spins}}}$

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- With creativity, one can think of new ideas, with many promising directions!

Noble and Alkali Spin Detectors for Ultralight Coherent darK-matter

DUCK-matter

(Degree in beakness school)

NASDUCK-matter