



Exploring Ultralight Wave-like Dark Matter with Quantum Spin Sensors

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ArXiv:2306.08039 (ChangE collaboration)

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Outlines

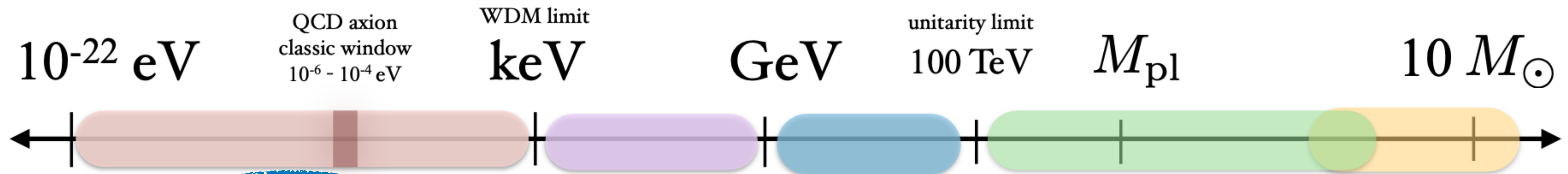
- Ultralight bosonic dark matter
 - General ALP studies
- ALP-nucleon searches
 - NMR method
 - ALP DM stochastic nature
 - Hybrid-Spin Resonance
 - Results
- Summary

What is the nature of dark matter?

Unknown matter and energy $\sim 95\%$

The dark matter candidate models

1904.07915, TASI lecture



“Ultralight” DM

non-thermal
bosonic fields

“Light” DM

dark sectors
sterile ν
can be thermal

WIMP

Composite DM
(Q-balls, nuggets, etc)

**Primordial
black holes**

Today's focus


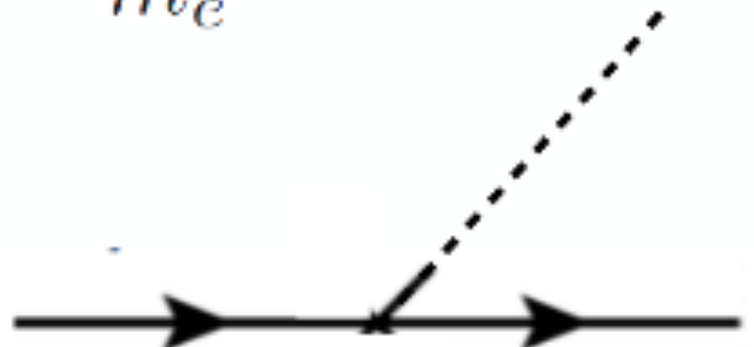
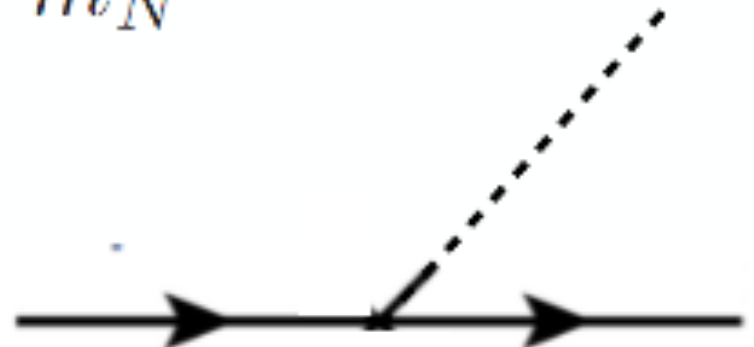
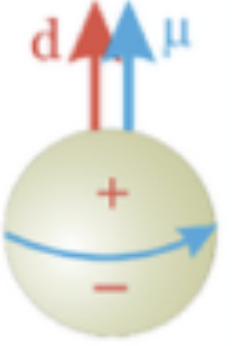


HEP at a cross-road: explore all directions!

Ultralight Bosonic Dark Matter

- Ultralight: $m \lesssim \text{keV}$, ultralight due to shift symmetry (pseudo-Nambu Goldstone, e.g. Axion)
- Bosonic: Pauli-exclusion for fermionic DM
- Behave as classical fields ($m \lesssim \mathcal{O}(1) \text{ eV}$)

Ultralight Bosonic Dark Matter

photon coupling	electron coupling	nucleon coupling	CP Neutron electric dipole
$-\frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a$ 	$\frac{g_{ae}}{m_e} [\bar{e} \gamma^\mu \gamma^5 e] \partial_\mu a$ 	$\frac{g_{aN}}{m_N} [\bar{N} \gamma^\mu \gamma^5 N] \partial_\mu a$ 	$\propto \frac{1}{m_n} [F_{\mu\nu} \bar{n} \sigma^{\mu\nu} \gamma_5 n] \frac{A}{f_A}$ 

Couples to gauge bosons, fermion spins

- Typical models:

- Pseudo-scalar: Axion, Axion-like Particle

- Dark Scalar: dilaton-like coupling

- Vector: kinetic mixing dark photon, $U(1)_{B-L}$ dark photon etc

$$\mathcal{L}_{\text{ALP}} = g_{ag} \frac{a}{f_a} G \tilde{G} + g_{a\gamma} \frac{a}{f_a} F \tilde{F} + g_{af} \frac{\partial_\mu a}{2f_a} \bar{f} \gamma^\mu \gamma_5 f$$

Ultralight Bosonic Dark Matter

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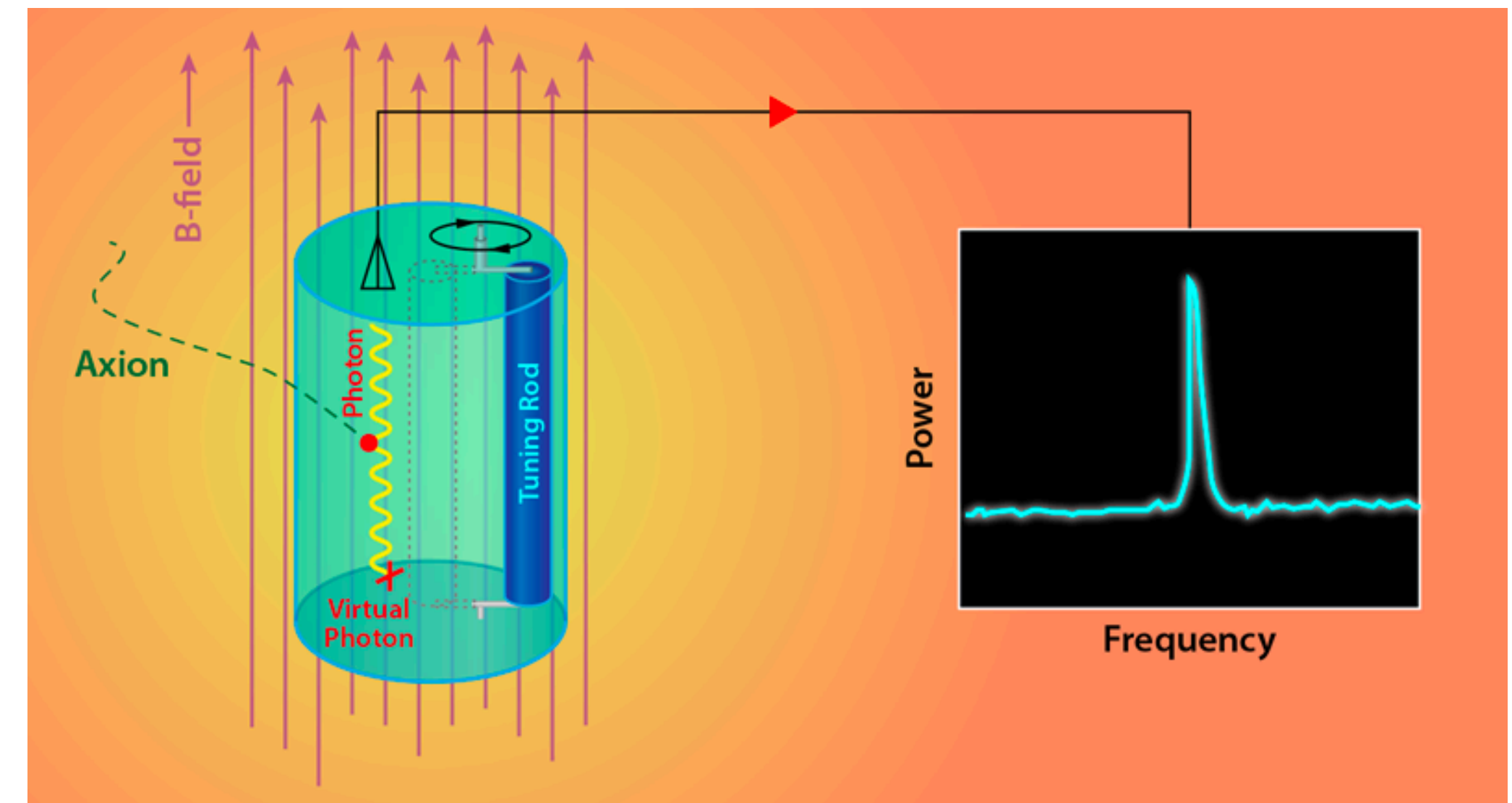
Low energy probe of high energy physics

$$m_a = \frac{\Lambda_{qcd}^2}{f_a}, \quad m_{\nu_L} = \frac{m_D^2}{m_R}$$

- Pseudo-scalar: Axion, Axion-like Particle
- Dark Scalar: dilaton-like coupling
- Vector: kinetic mixing dark photon, $U(1)_{B-L}$ dark photon etc

The detection of ultralight bosonic dark matter

- Mass ranges from $[10^{-22}, 10^3]$ eV, DM exist as **classical fields**
- **Interacting feebly** with SM sector, interdisciplinary collaboration with **Atomic Molecular Optics, Astrophysics, Astronomy and Cosmology**
- Various detection methods:
 - Star as Laboratory: exotic energy loss (A', ALP, S)
 - Early universe CMB, Gamma ray propagation, Black Hole picture and polarization (ALP, A')
 - **Lab resonant cavity searches: (ADMX, HAYSTAC ...)** (ALP, A')
 - **Lab broad-band searches: (WISPDMMX, Dark E-field)** (ALP, A')
 - 5th force, Equivalent Principle test (S, A')
 - DM direct detection experiments (XENONnT, PANDAX-4T, CDEX) (ALP, A')
 - **Radio astronomy (ALP, A')**



Experimental searches is related to model and couplings

$$g_{a\gamma\gamma} a F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \sim g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

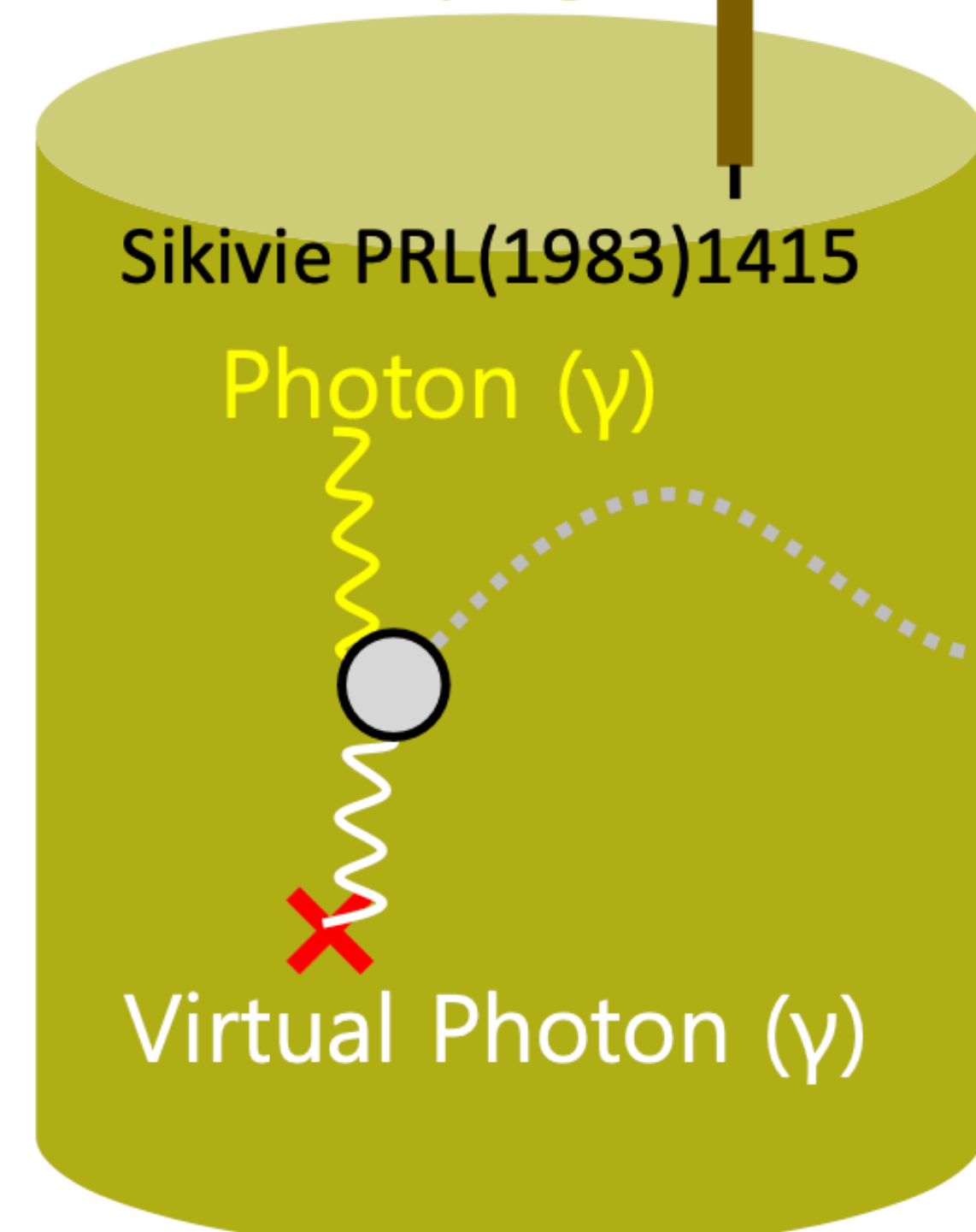
The resonant searches for ALP via photon coupling

- Tuning cavity resonant frequency to match axion mass

$$g_{a\gamma\gamma} a F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \sim g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

From Danho Ahn@Patras2023

Antenna Coupling (β)



Sikivie PRL(1983)1415

Photon (γ)

Virtual Photon (γ)



Magnetic Field (B)

Loaded Quality Factor (Q_l)

Volume (V)

Resonant Angular Frequency (ω_0)

Form Factor (C)

System Temperature (T_{sys})

$$P_{sig} = \frac{\beta}{1 + \beta} g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a^2} B^2 V \omega_0 C \frac{Q_a Q_l}{Q_a + Q_l}$$

Labels in the equation:
 - β : Antenna Coupling
 - $g_{a\gamma\gamma}^2$: Coupling Constant
 - ρ_a : Dark Matter Axion Density
 - m_a^2 : Axion Mass
 - B^2 : Magnetic Field squared
 - V : Volume
 - ω_0 : Resonant Angular Frequency
 - C : Form Factor
 - Q_a : Axion Quality Factor
 - Q_l : Loaded Quality Factor

Kim et al. JCAP03(2020)066

$$\frac{df}{dt} \propto \frac{B^4 V^2 C^2}{k_B^2 T_{sys}^2} Q_l Q_a$$

Labels in the equation:
 - k_B : Boltzmann constant
 - T_{sys} : System Noise Temperature ~ 200 mK

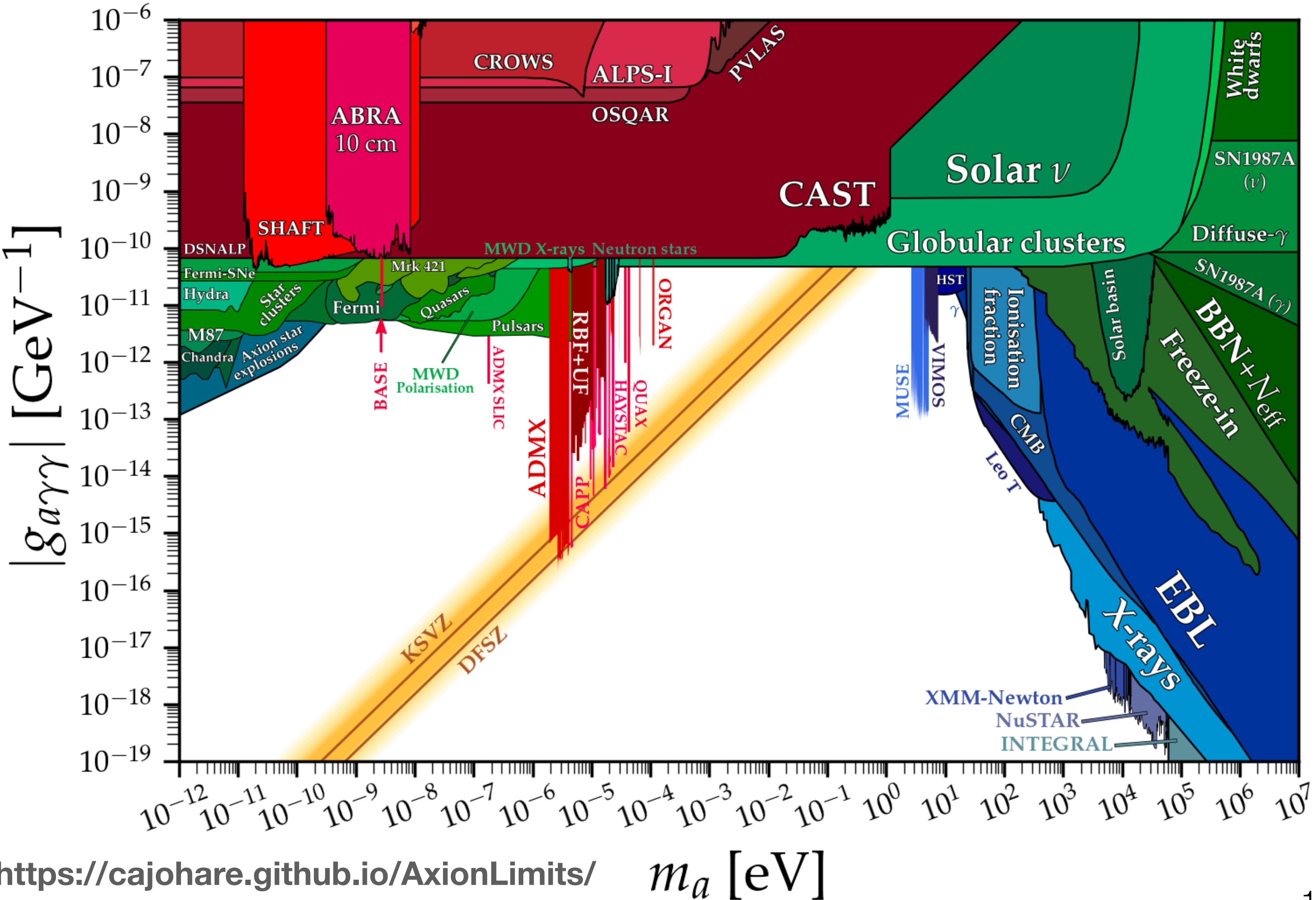
Scan Rate

$Q_l \gg Q_a \sim 10^6$

Refer to Session 02, Thu, Dr. Jinsu Kim

The resonant searches for ALP via photon coupling

- The overview of ALP-photon coupling searches
- Very competitive field



The searches for ultralight bosonic dark matter



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The resonant searches of nucleon couplings

- The ALP DM field

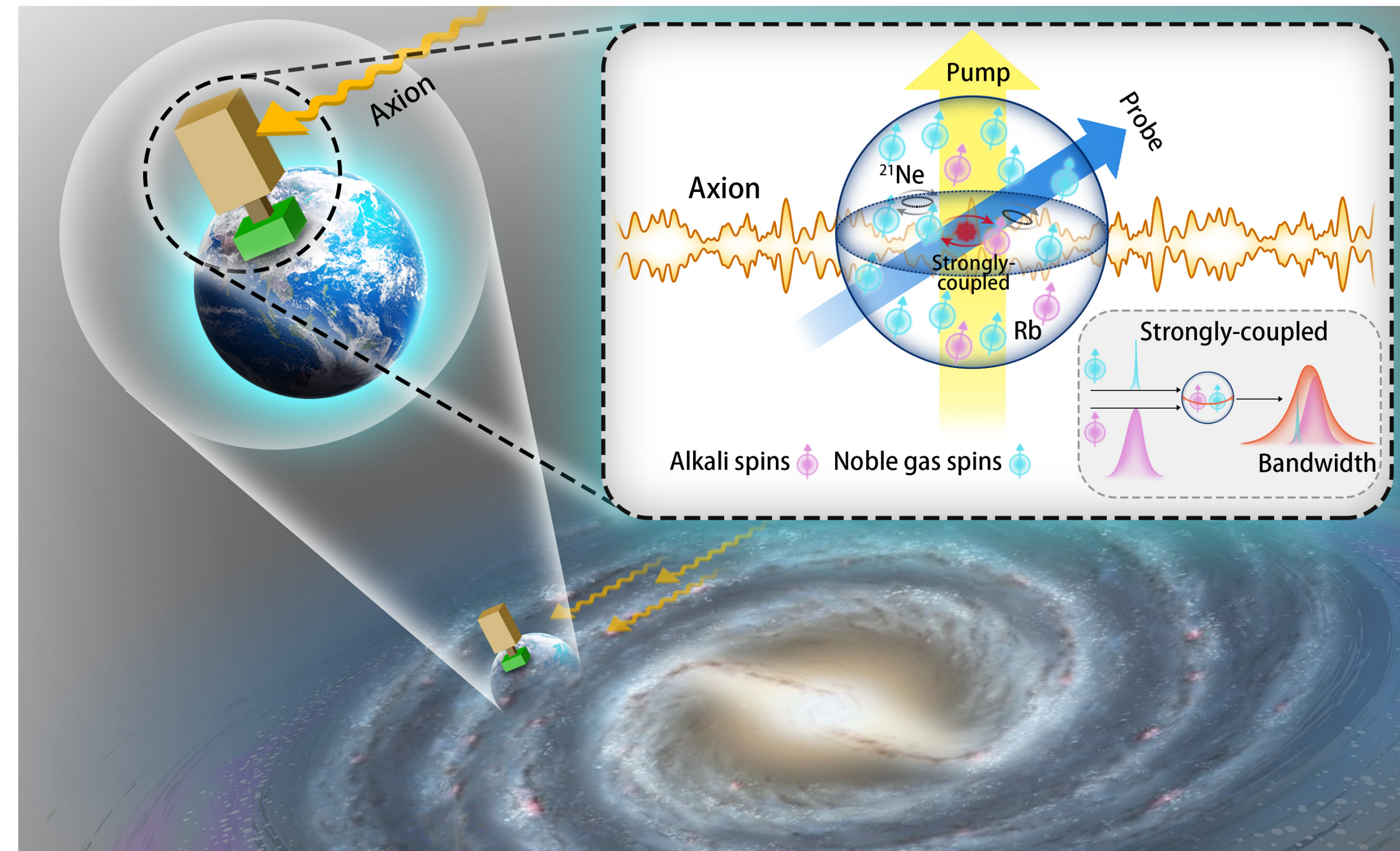
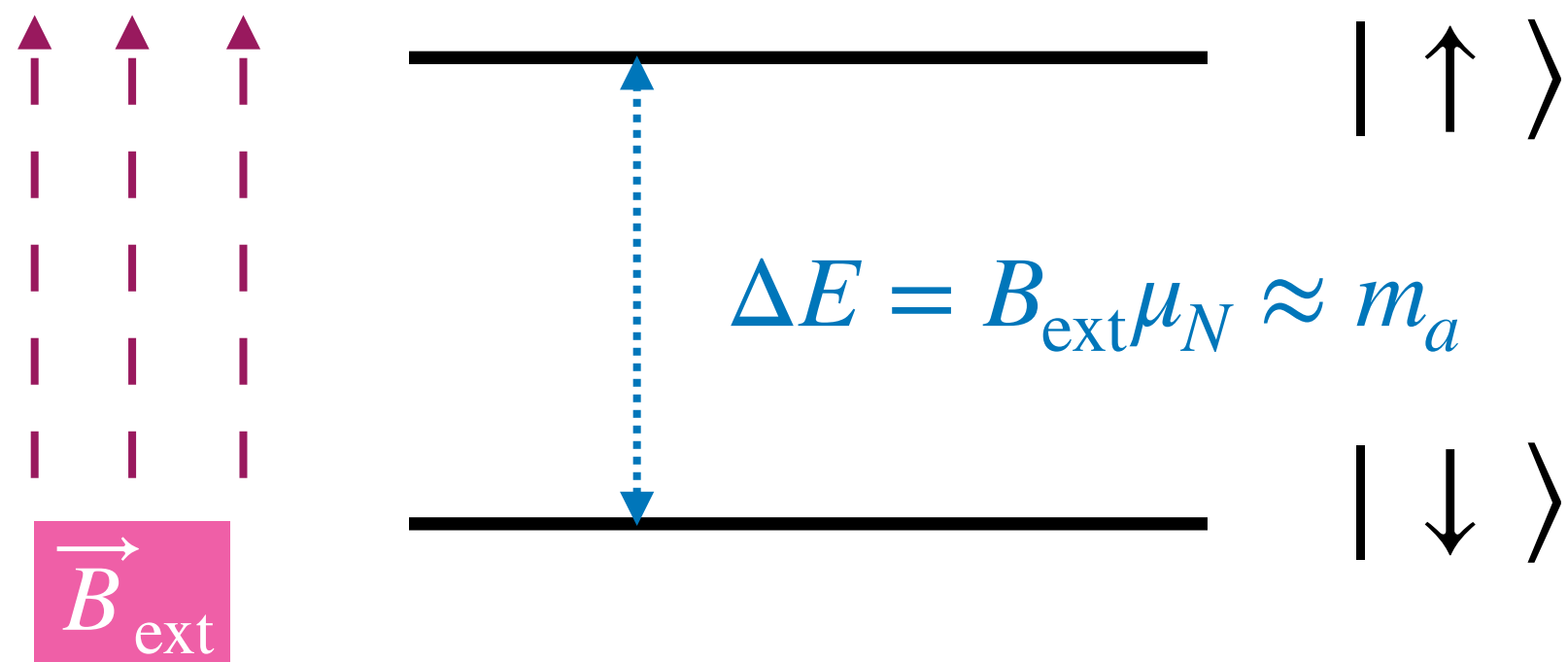
$$a(x, t) \approx a_0 \cos(\omega t - \vec{p} \cdot \vec{x} + \theta_0)$$

- The **axion-wind** Hamiltonian

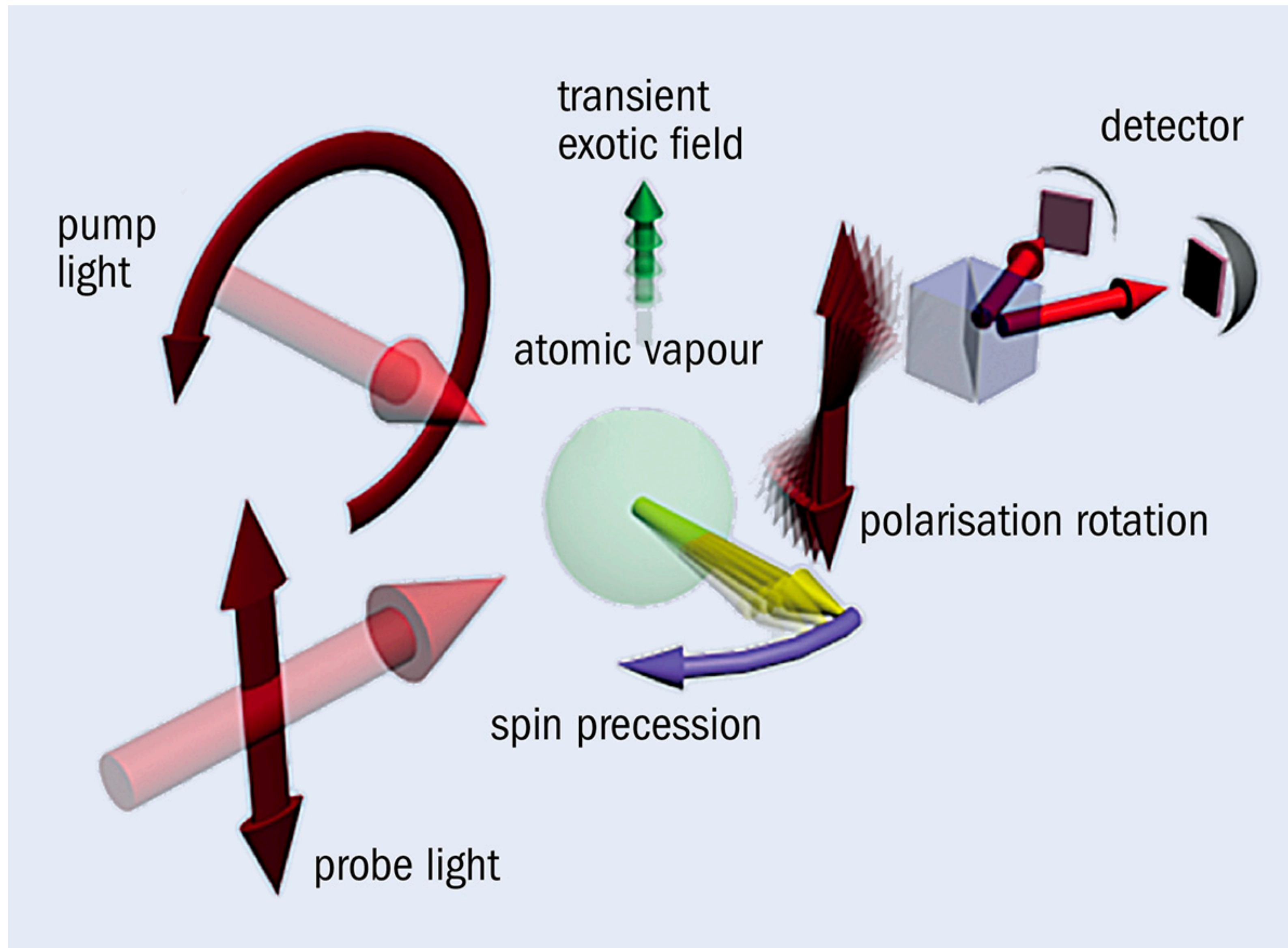
$$H = g_{aNN} \frac{\partial_\mu a}{2f_a} \bar{N} \gamma^\mu \gamma_5 N = g_{aNN} \vec{\nabla} a \cdot \vec{\sigma}_N$$

$$\approx g_{aNN} \vec{v}_a \cdot \vec{\sigma}_N \times \sqrt{2\rho_a} \sin(p \cdot x)$$

- A Zeeman split in B field

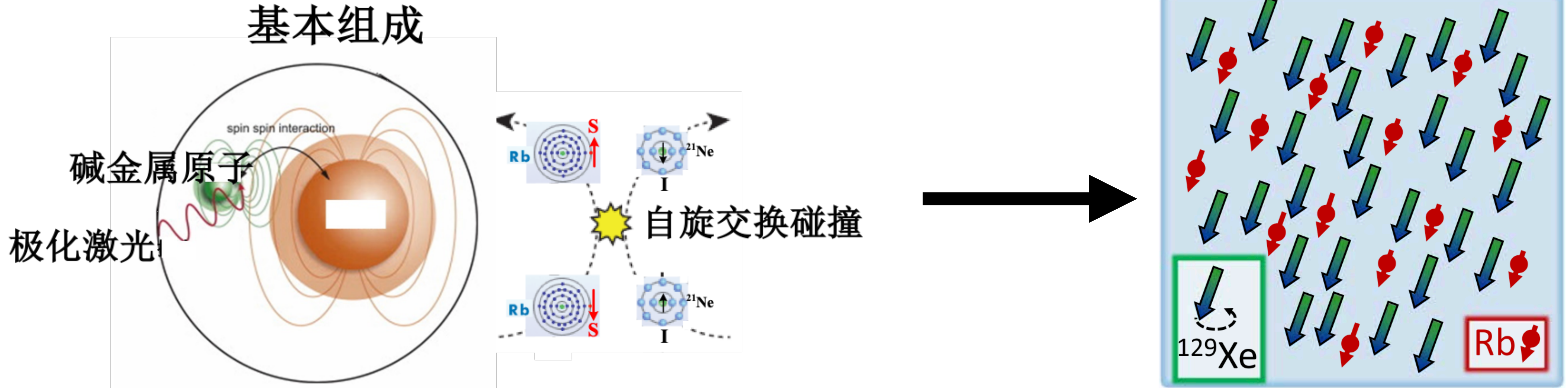


Spin precession detection mechanisms



Comagnetometer

- Alkali atoms and noble-gas atom



$$\frac{\delta \mathbf{P}^e}{\delta t} = \frac{\gamma_e}{Q} [\mathbf{B} + \mathbf{L} + \lambda M_0^n \mathbf{P}^n + \mathbf{b}^e] \times \mathbf{P}^e - \boldsymbol{\Omega} \times \mathbf{P}^e +$$

Fermi contact interaction and amplify

$$B_{\text{eff}} = \lambda M_0 P^n \quad \lambda = 540 \times \frac{8\pi}{3}$$

$$\eta \equiv B_{\text{eff}} / b^n \quad \text{Rb-Xe}$$

Jiang et al. Nature Physics 2021

Coupled Bloch equation

$$\frac{R_p \mathbf{S}_p + R_m \mathbf{S}_m + R_{se}^{\text{ne}} \mathbf{P}^n}{Q} - \frac{\{R_1^e, R_2^e, R_2^e\}}{Q} \mathbf{P}^e$$

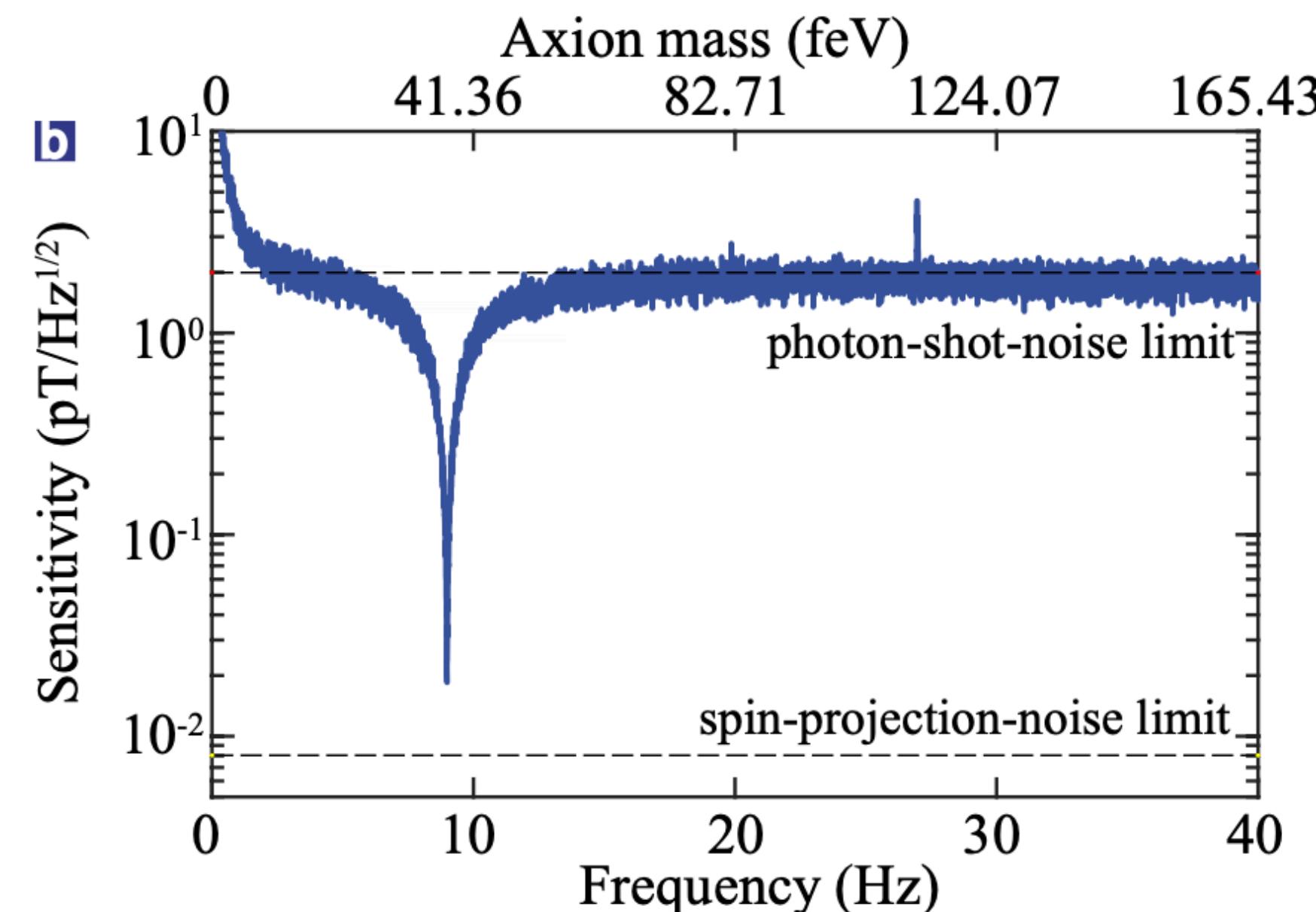
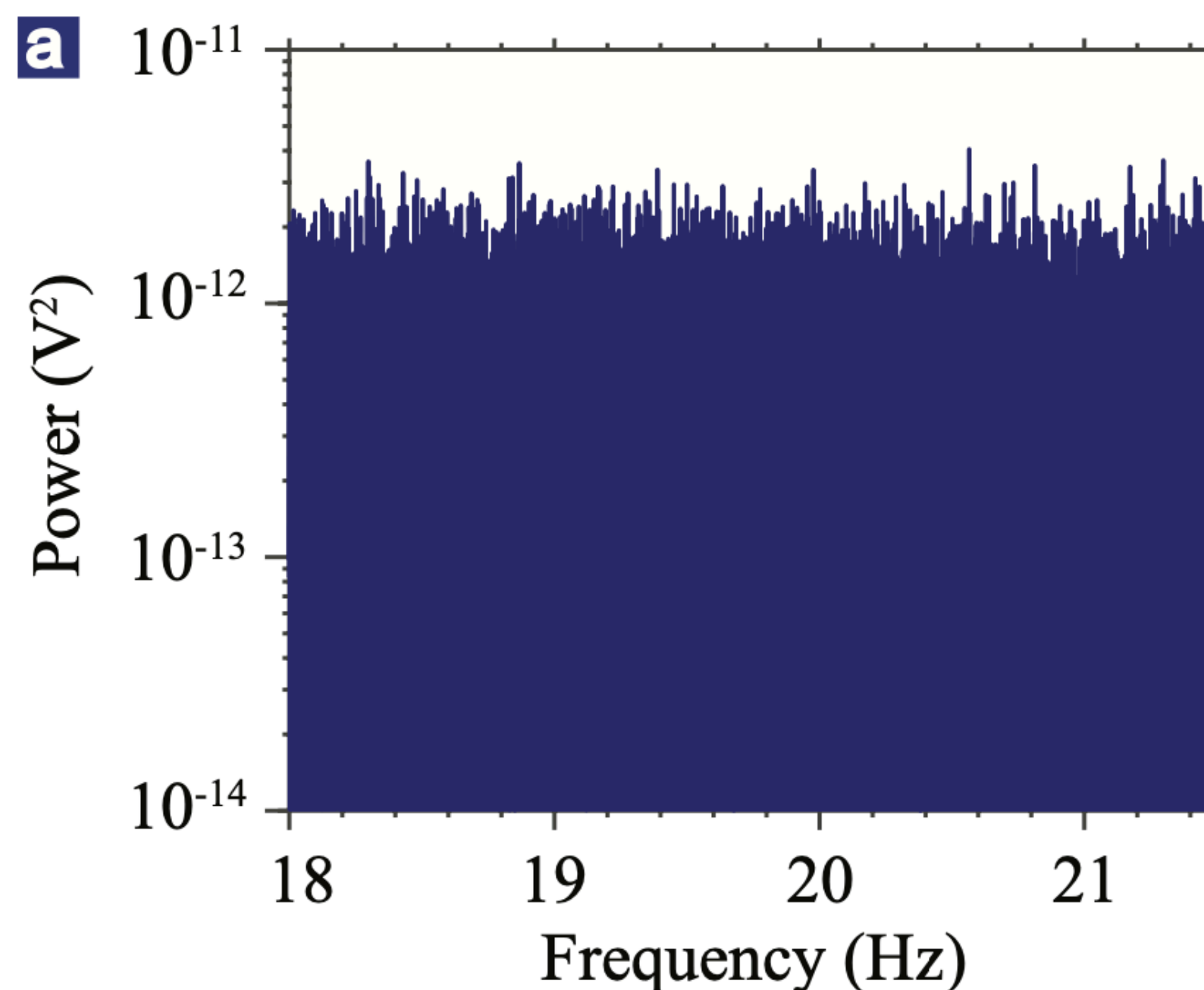
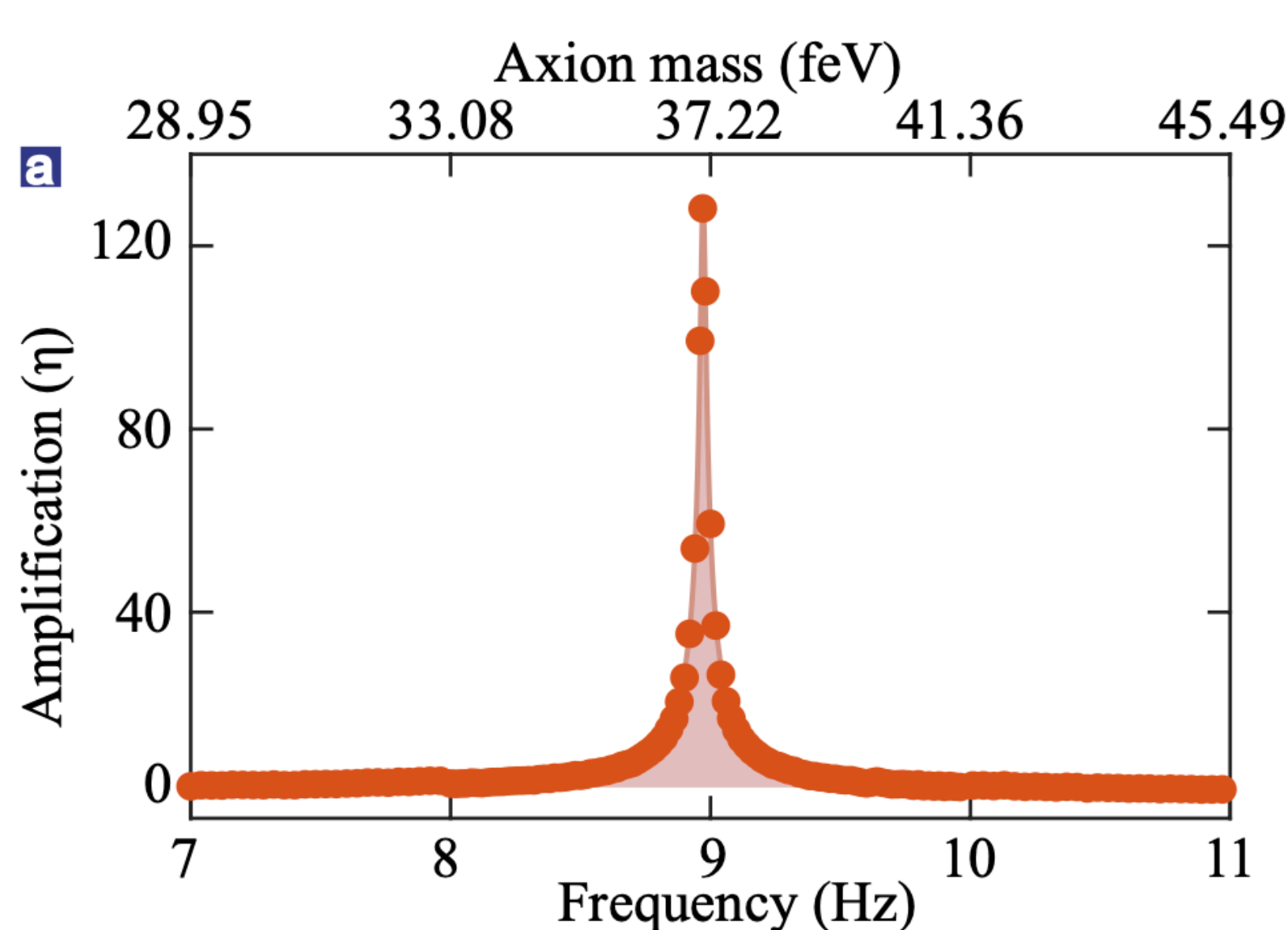
Exotic B field 自旋交换碰撞

$$\frac{\delta \mathbf{P}^n}{\delta t} = \gamma_n (\mathbf{B} + \lambda M_0^e \mathbf{P}^e + \mathbf{b}^n) \times \mathbf{P}^n - \boldsymbol{\Omega} \times \mathbf{P}^n + R_{se}^{\text{en}} \mathbf{P}^e - \{R_1^n, R_2^n, R_2^n\} \mathbf{P}^n$$

Comagnetometer NMR mode (Spin-base Amplifier)

- Enhanced sensitivity at resonance frequency

Jiang et al. Nature Physics 2021



Lorentzian amplification shape

$$\eta(f) = \eta(f_0) \frac{\Lambda/2}{\sqrt{(f-f_0)^2 + (\Lambda/2)^2}}$$

$$\sqrt{3}\Lambda = 0.052 \text{ Hz}$$

Experimental data

Tuning B_0 field

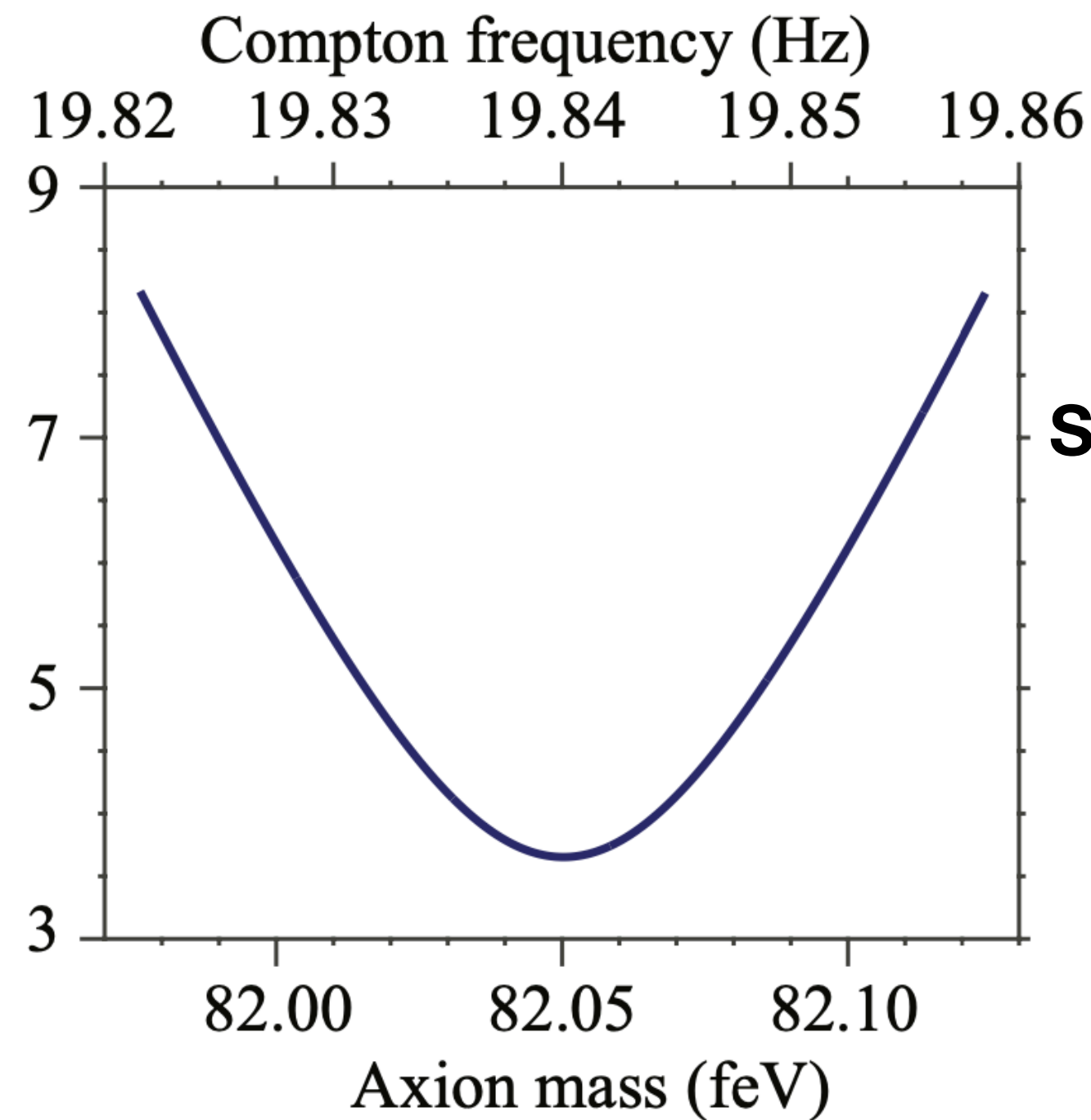
Resonant frequency $f_0 = 19.84$ Hz

**Good sensitivity on
Resonant frequency 19.84 Hz**

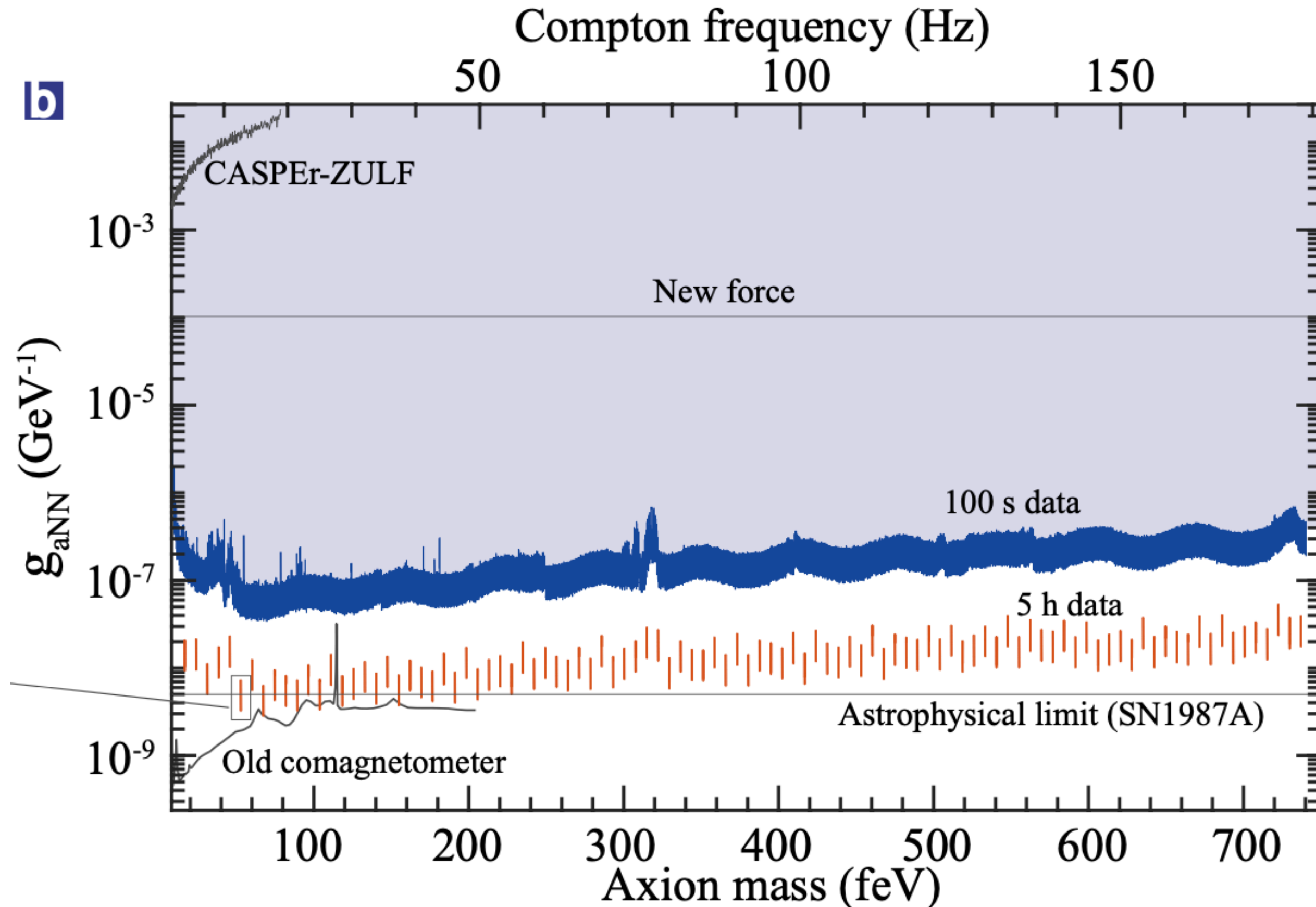
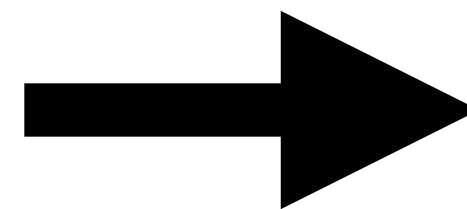
Comagnetometer NMR mode (Spin-based Amplifier)

- Resonant search + scanning of f_0

Jiang et al. Nature Physics 2021



Scanning



Constrain on certain frequency
19.84 Hz

Very hard!
Motivate HSR work.

100 sec dataset: scanning time ~ 138 hour
5 hr data estimation: ~ 25000 hr ~ 35 months



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Complication from stochastic nature of ULDM

- Random phase in different p mode

$$\nabla a(x) = \sum_p \sqrt{\frac{2N_p}{V\omega_p}} \cos(\omega_p t - \mathbf{p} \cdot \mathbf{x} + \phi_p) \mathbf{p}$$

ϕ_p : is uniform random variable in $[0, 2\pi]$

$N_p = \rho_{\text{DM}} V f(p) (\Delta p)^3 / \omega_p$: is mean occupation number of p mode

- Signal is stochastic instead of deterministic

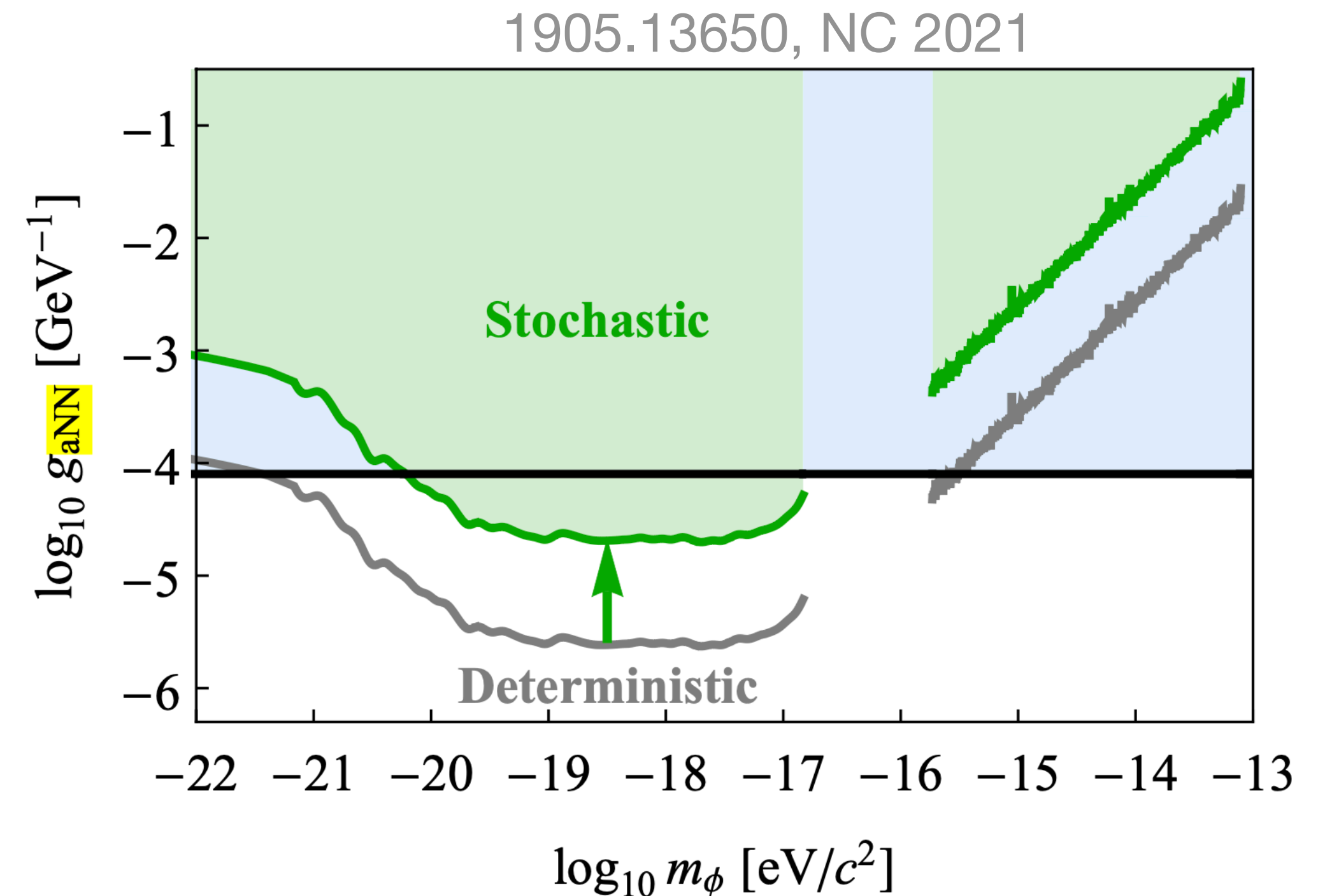
$$\beta_j = \frac{g_{aN}}{\gamma_N} \nabla a(j\Delta t) \cdot \hat{\mathbf{m}}(j\Delta t)$$

$$A_k = \frac{2}{N} \text{Re}[\tilde{\beta}_k], \quad B_k = -\frac{2}{N} \text{Im}[\tilde{\beta}_k].$$

$$L(\mathbf{d} | g_{aNN}, \sigma_b^2) = \frac{1}{\sqrt{(2\pi)^{2N} \det(\Sigma)}} \exp\left(-\frac{1}{2} \mathbf{d}^T \Sigma^{-1} \mathbf{d}\right)$$

$$\Sigma = \Sigma_a + \sigma_b^2 \cdot \mathbb{1} \quad \text{Junyi Lee et al, 2209.03289, PRX 2023}$$

- Signal and white background are multivariate Gaussian distribution
Signal contains non-diagonal term



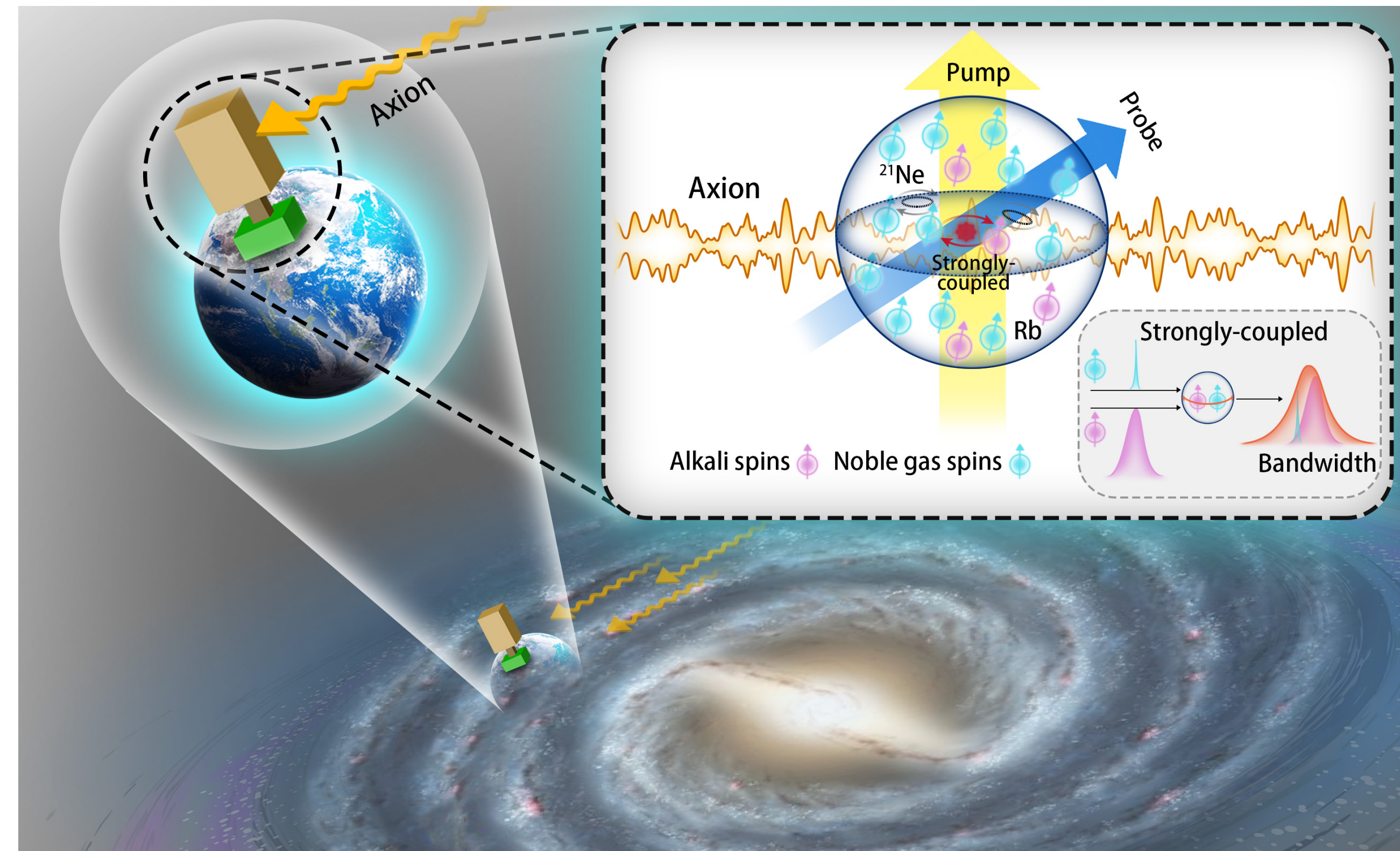
$$\gamma_{95\%}^{\text{stoch}} = 8.4 \gamma_{95\%}^{\text{det}}$$

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Comagnetometer in Hybrid Spin Resonance: Motivation

- Motivation: good control on photon-shot-noise and magnetic noise
- Sharp amplification is wasted
- Smaller amplification but with much wider resonance
- Do not need to scan (e.g. 35 months)
- Long-time measurement at single point to compensate amplification lost



ChangE experiment: Kai Wei, .. **JL** .. et al, 2306.08039

Comagnetometer in Hybrid Spin Resonance: Method

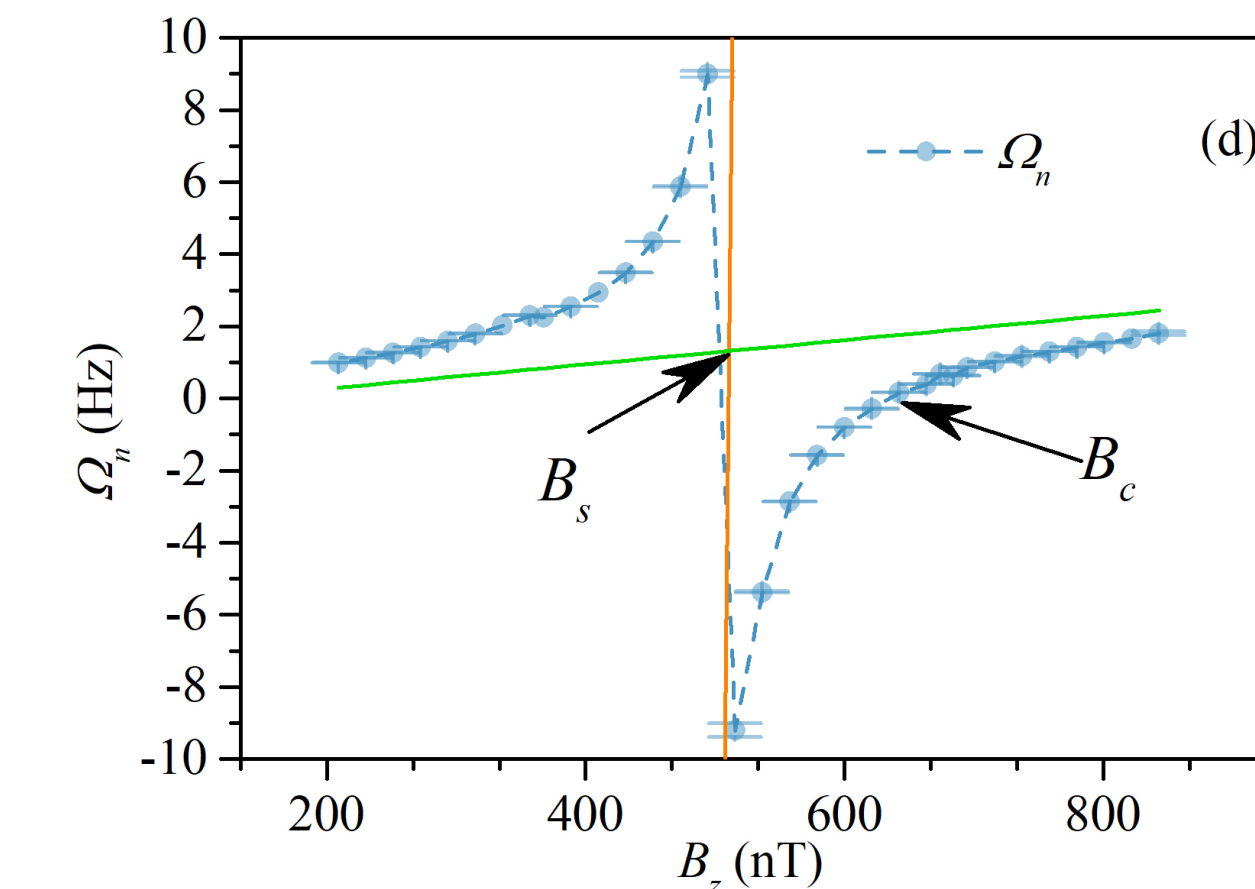
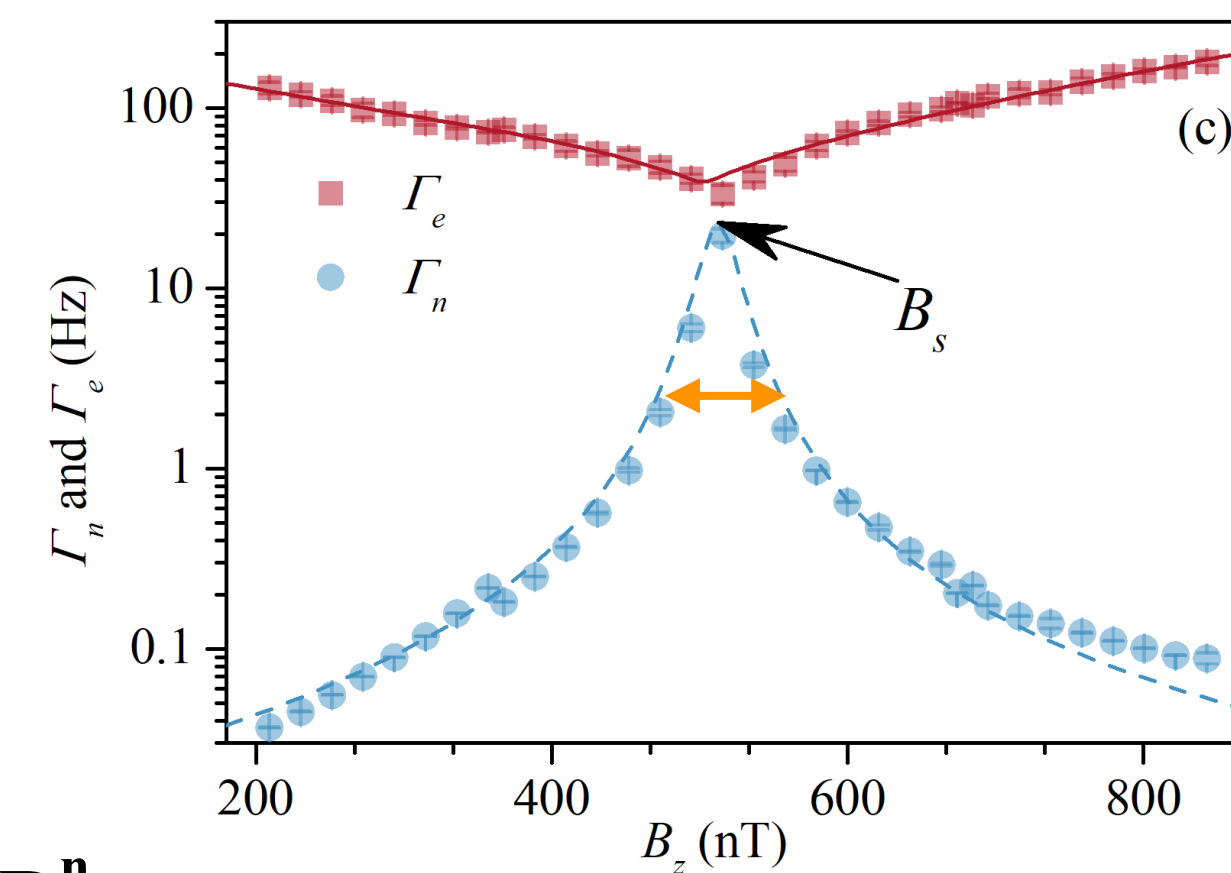
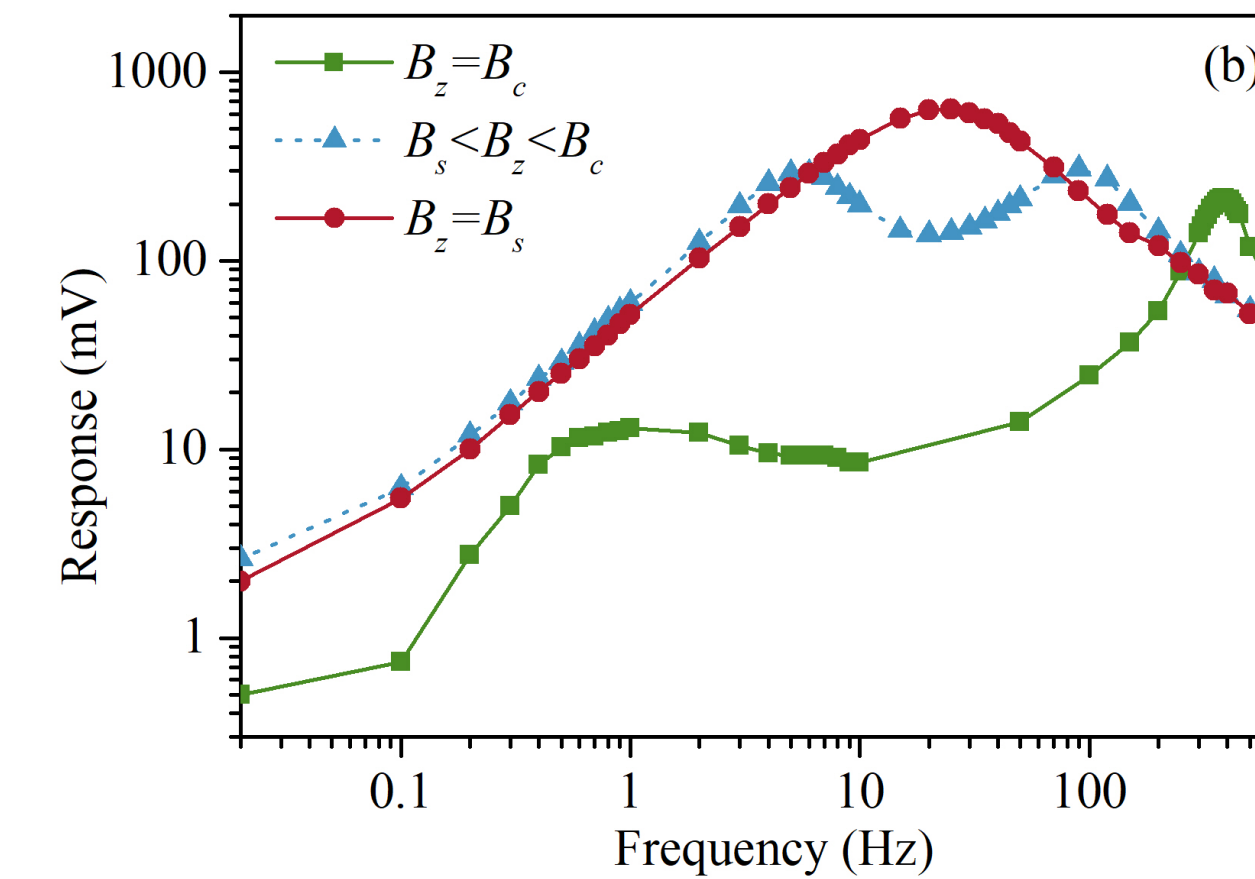
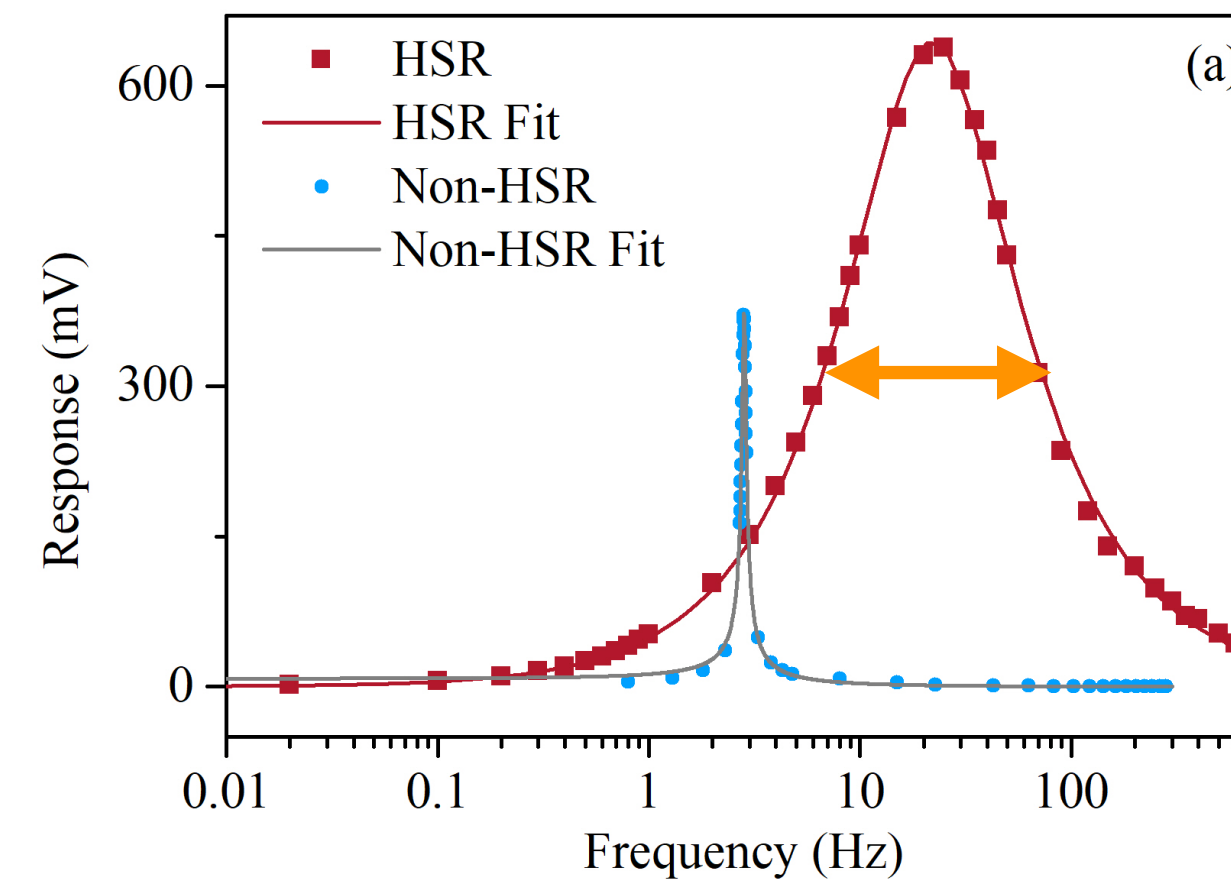
- Method: tune external B field to make Larmor frequency equal

- HSR: $\omega_K \approx \omega_{Ne}$

- Width Γ_n is about 100 Hz now

$$\frac{\delta \mathbf{P}^e}{\delta t} = \frac{\gamma_e}{Q} [\mathbf{B} + \mathbf{L} + \lambda M_0^n \mathbf{P}^n + \mathbf{b}^e] \times \mathbf{P}^e - \mathbf{\Omega} \times \mathbf{P}^e + \frac{R_p \mathbf{S}_p + R_m \mathbf{S}_m + R_{se}^n \mathbf{P}^n}{Q} - \frac{\{R_1^e, R_2^e, R_2^e\}}{Q} \mathbf{P}^e$$

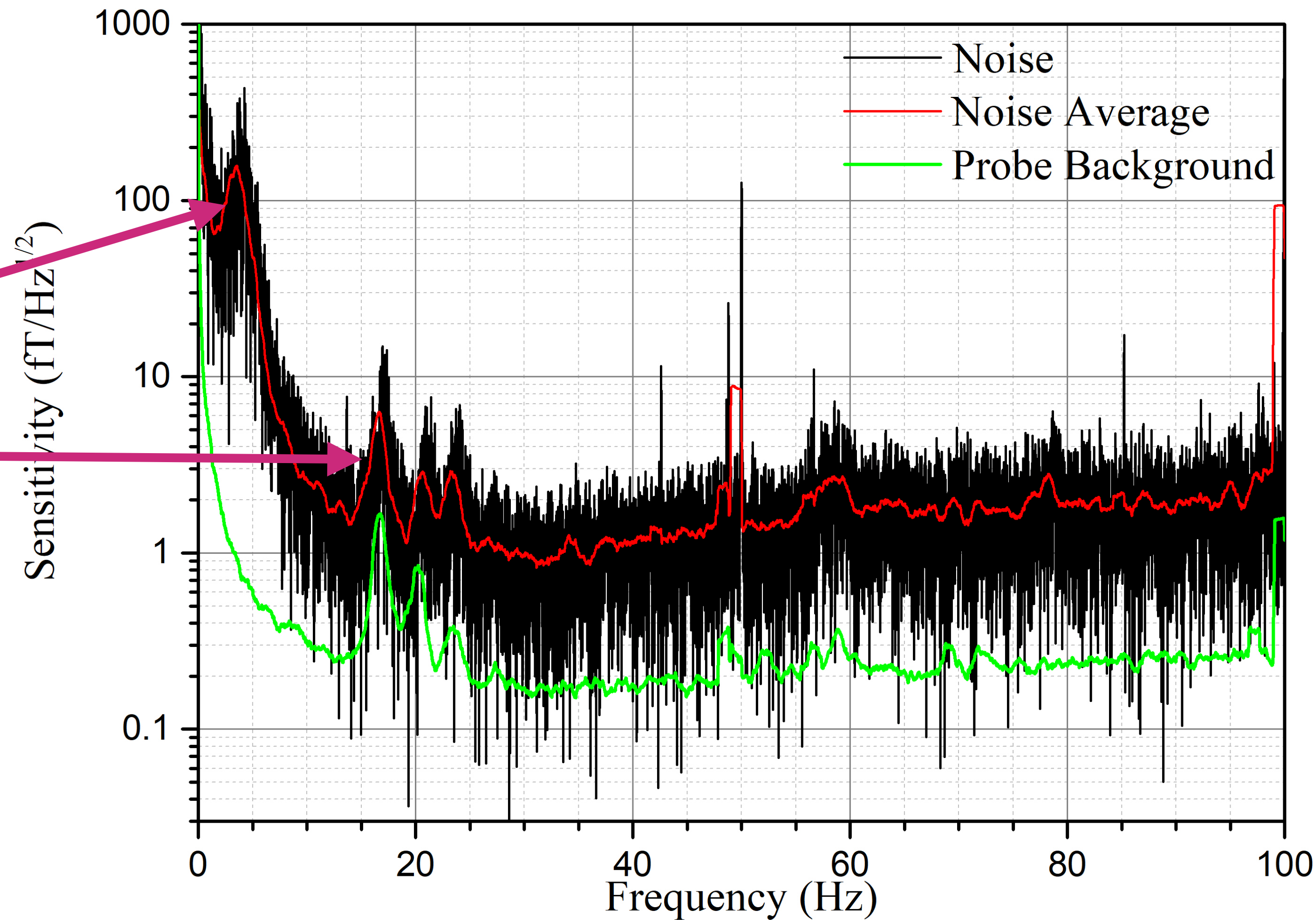
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ChangE experiment: Kai Wei, .. JL .. et al, 2306.08039

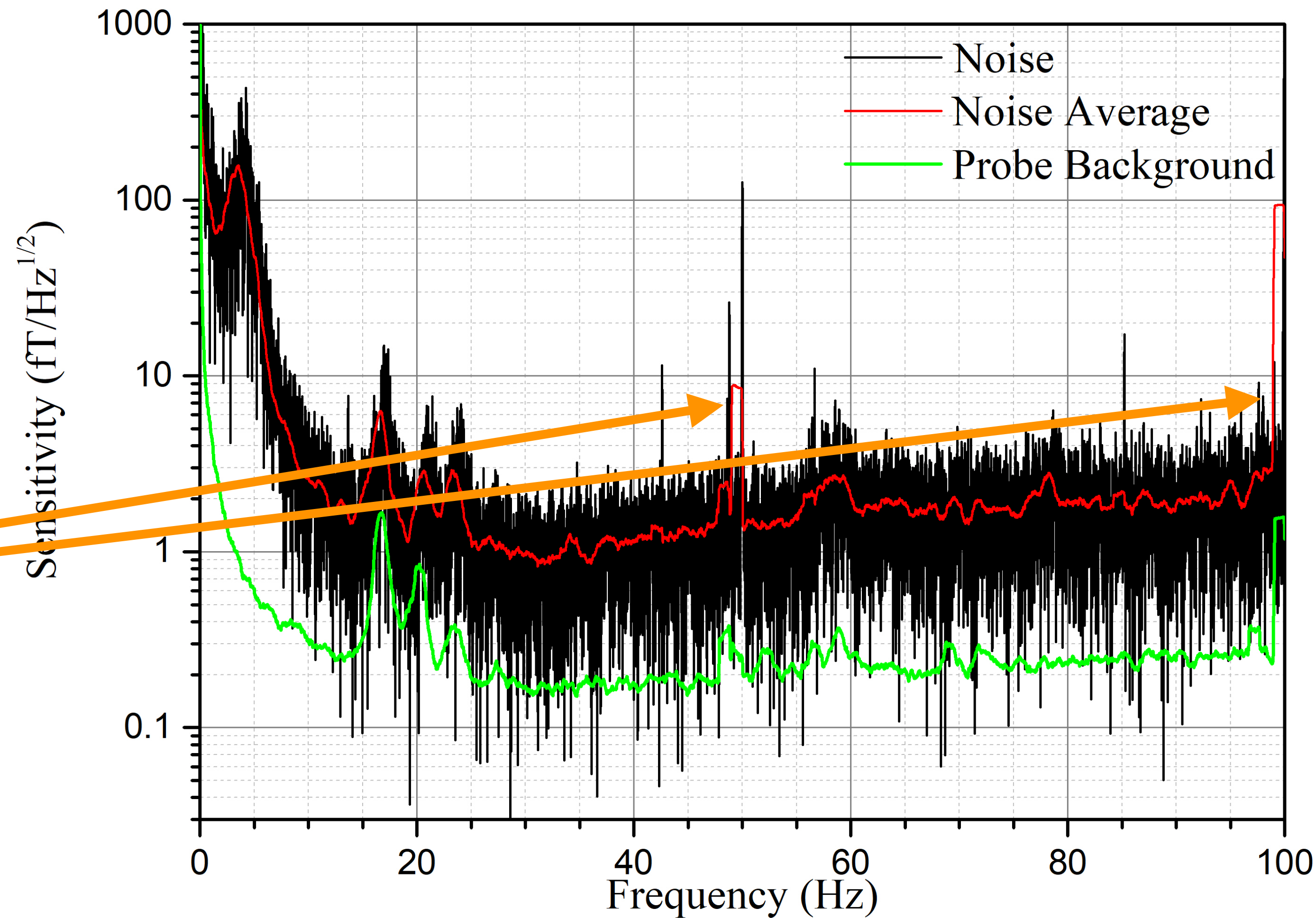
Comagnetometer sensitivity

- The sensitivity at the strongly coupled hybrid spin resonance to a y -directed magnetic field is $0.78 \text{ fT/Hz}^{1/2}$ from 28 to 32 Hz
- Vibration noise
- Power-line noise
- Probe light noise



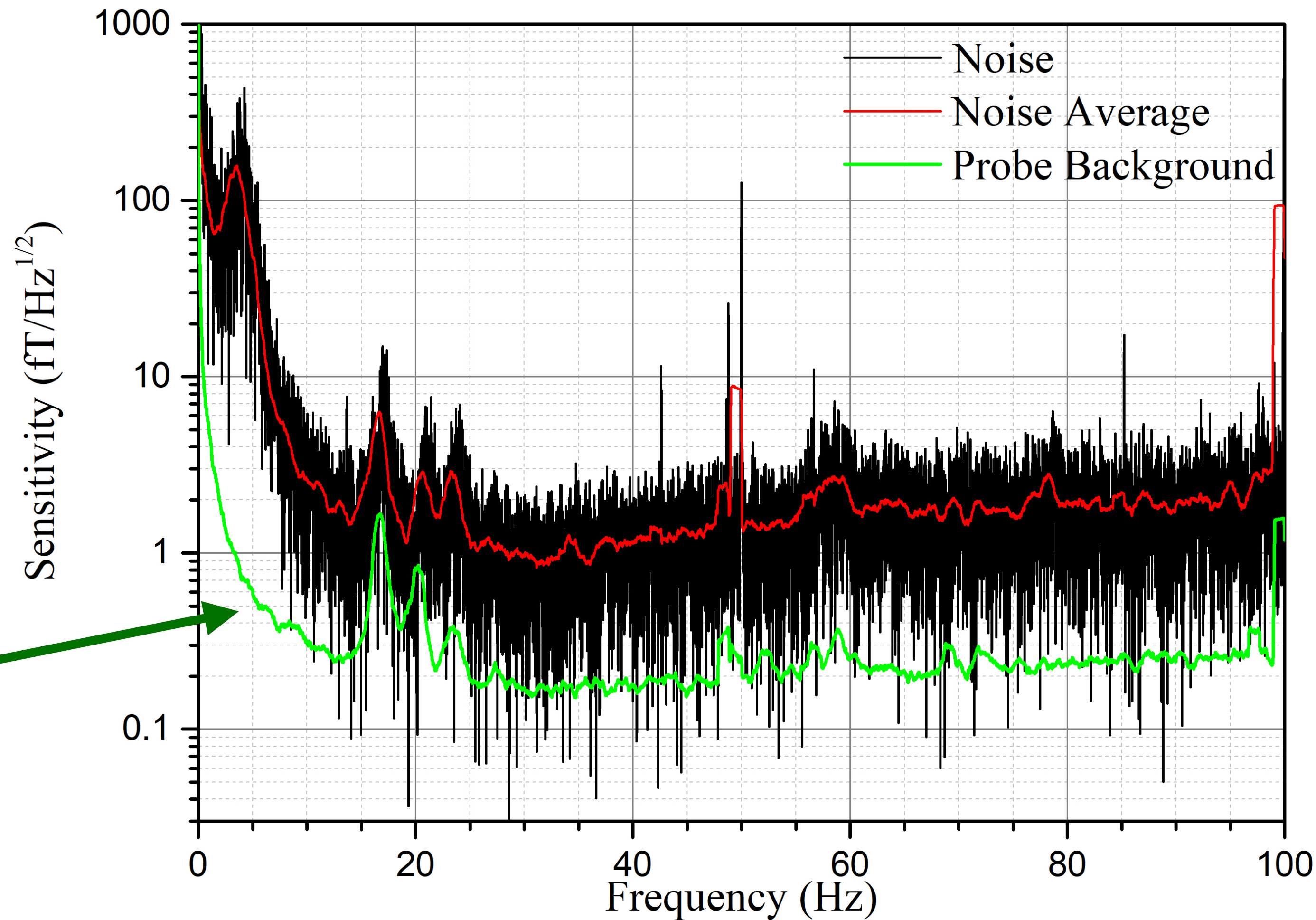
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Comagnetometer HSR search on ALP DM

- The response to ultra-light dark matter field b_x^n coupling with noble-gas nuclear spins

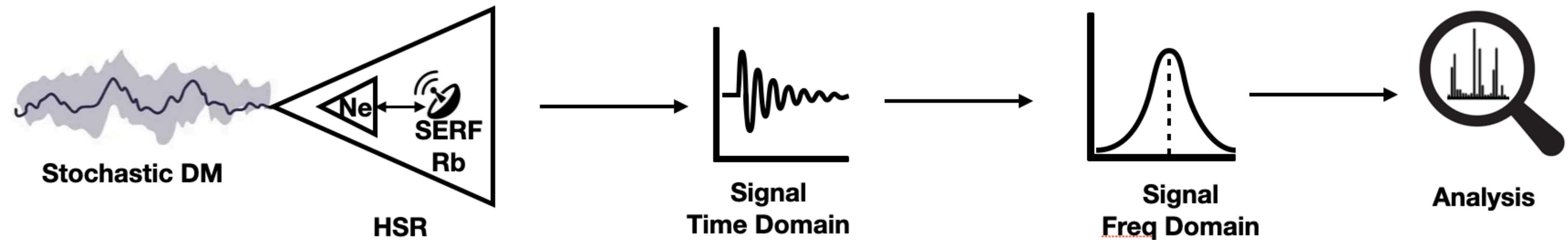
$$S_x^e = K_{b_x^n} b_x^n$$

- The response to magnetic field

$$S_x^e = K_{B_y} B_y$$

- The scale factor relation

$$K_{B_y} = K_{b_x^n} \omega / \hat{\omega}_z^n$$



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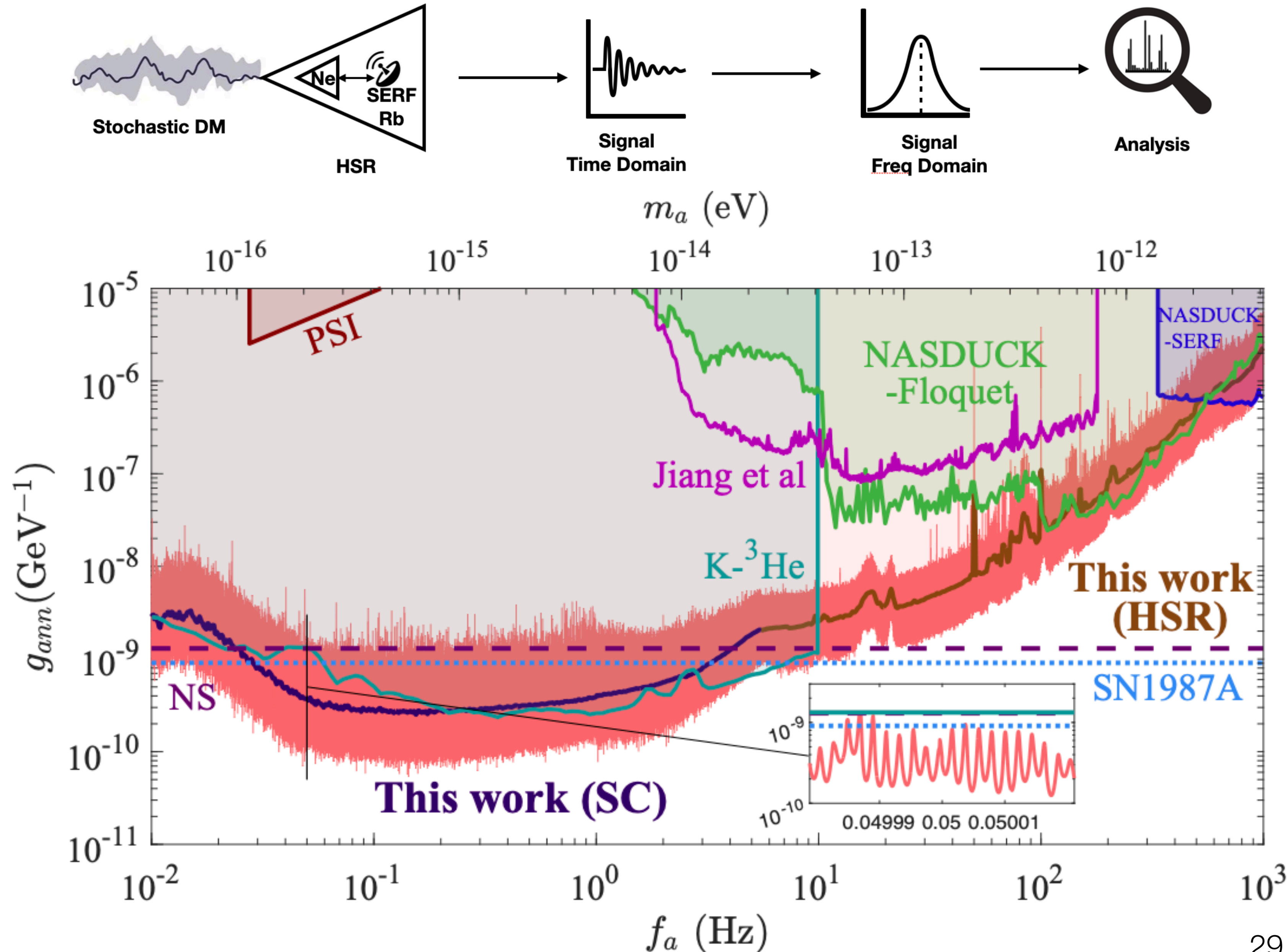
- Search on ALP-neutron coupling g_{ann}

- The relation between nucleus coupling and nucleon coupling

$$g_{aNN} = \xi_n g_{ann} + \xi_p g_{app}$$

- Spin polarization fraction to Ne

$$\xi_n^{\text{Ne}} = 0.58 \text{ and } \xi_p^{\text{Ne}} = 0.04$$



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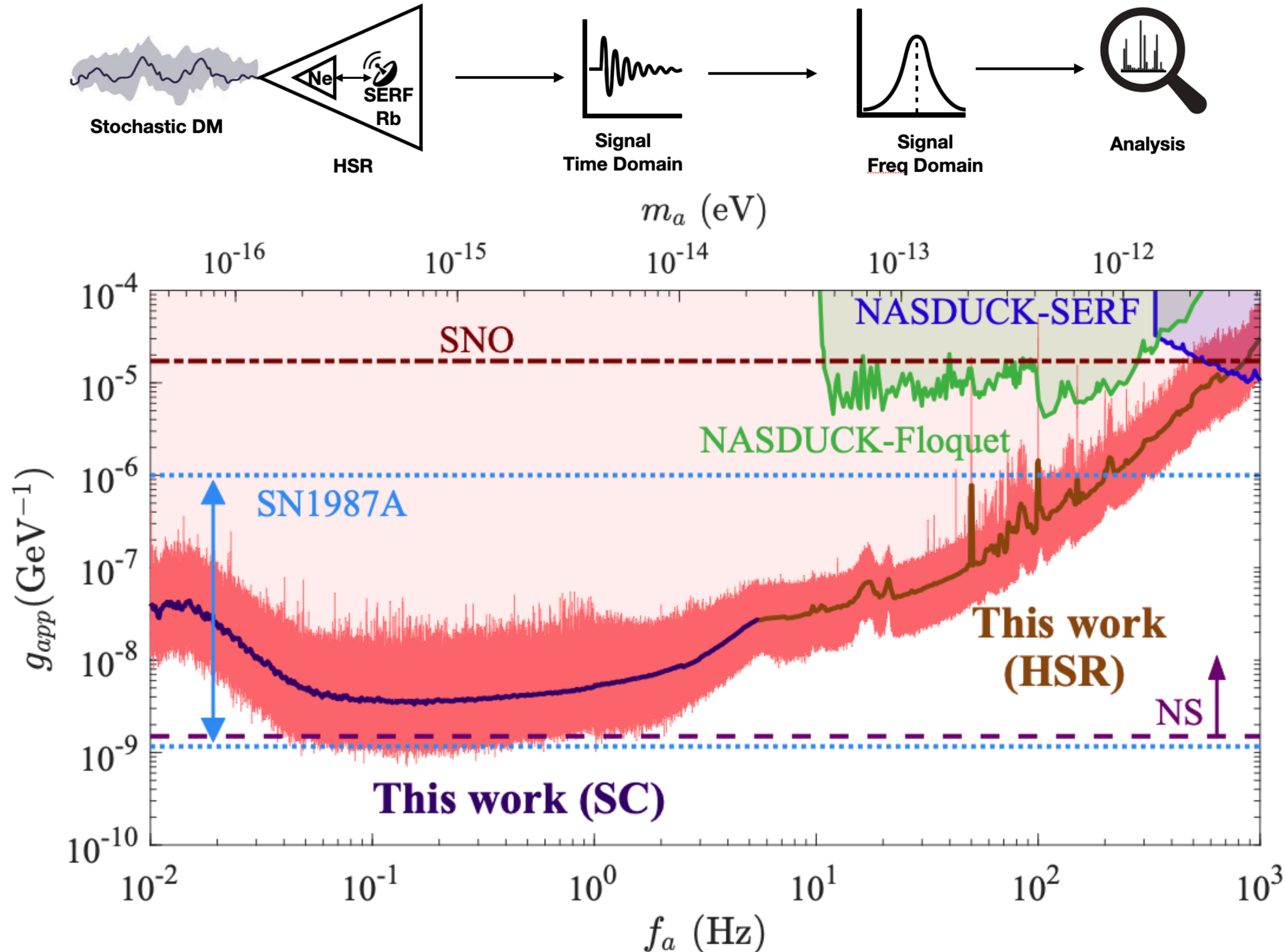
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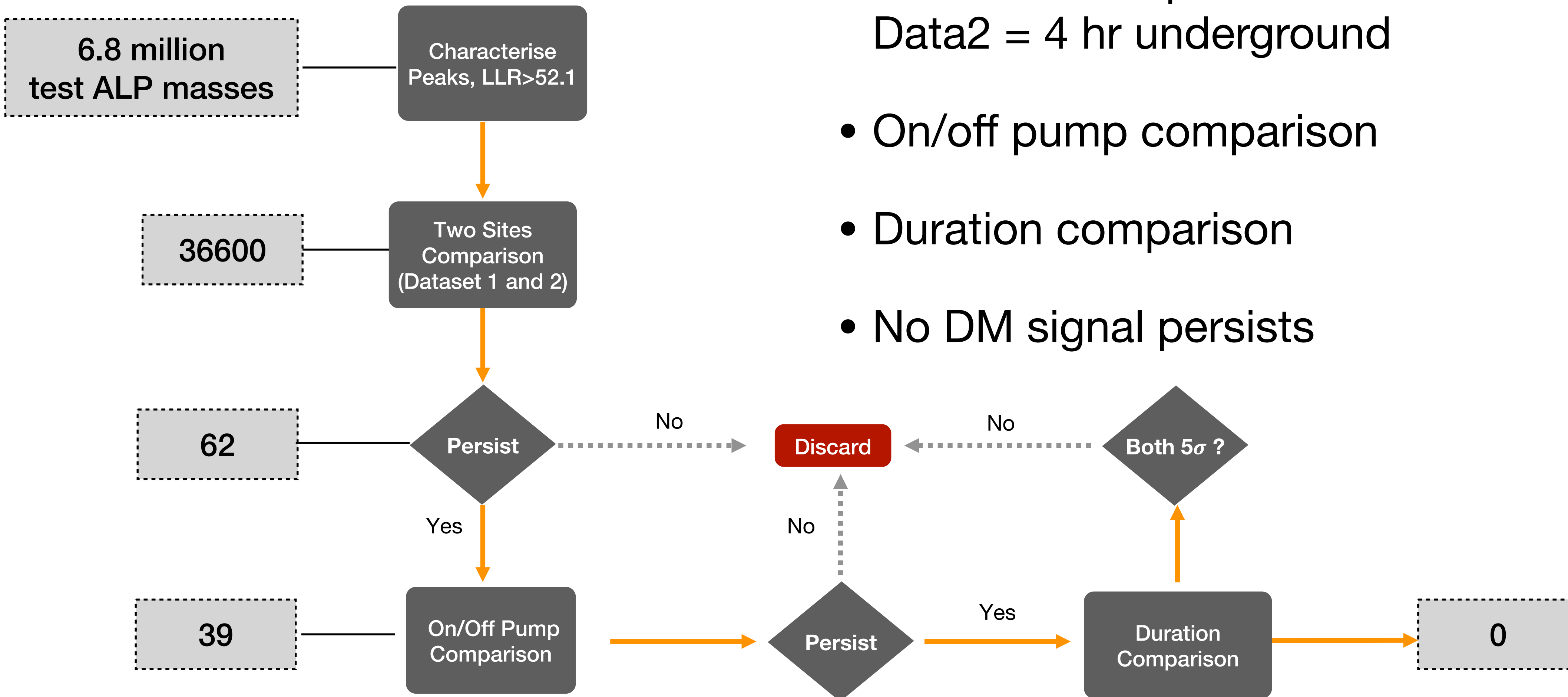
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$$\xi_n^{\text{Ne}} = 0.58 \text{ and } \xi_p^{\text{Ne}} = 0.04$$



Possible DM candidates analysis

- Two-sites comparison: Data1 = 209 hr, Data2 = 4 hr underground
- On/off pump comparison
- Duration comparison
- No DM signal persists



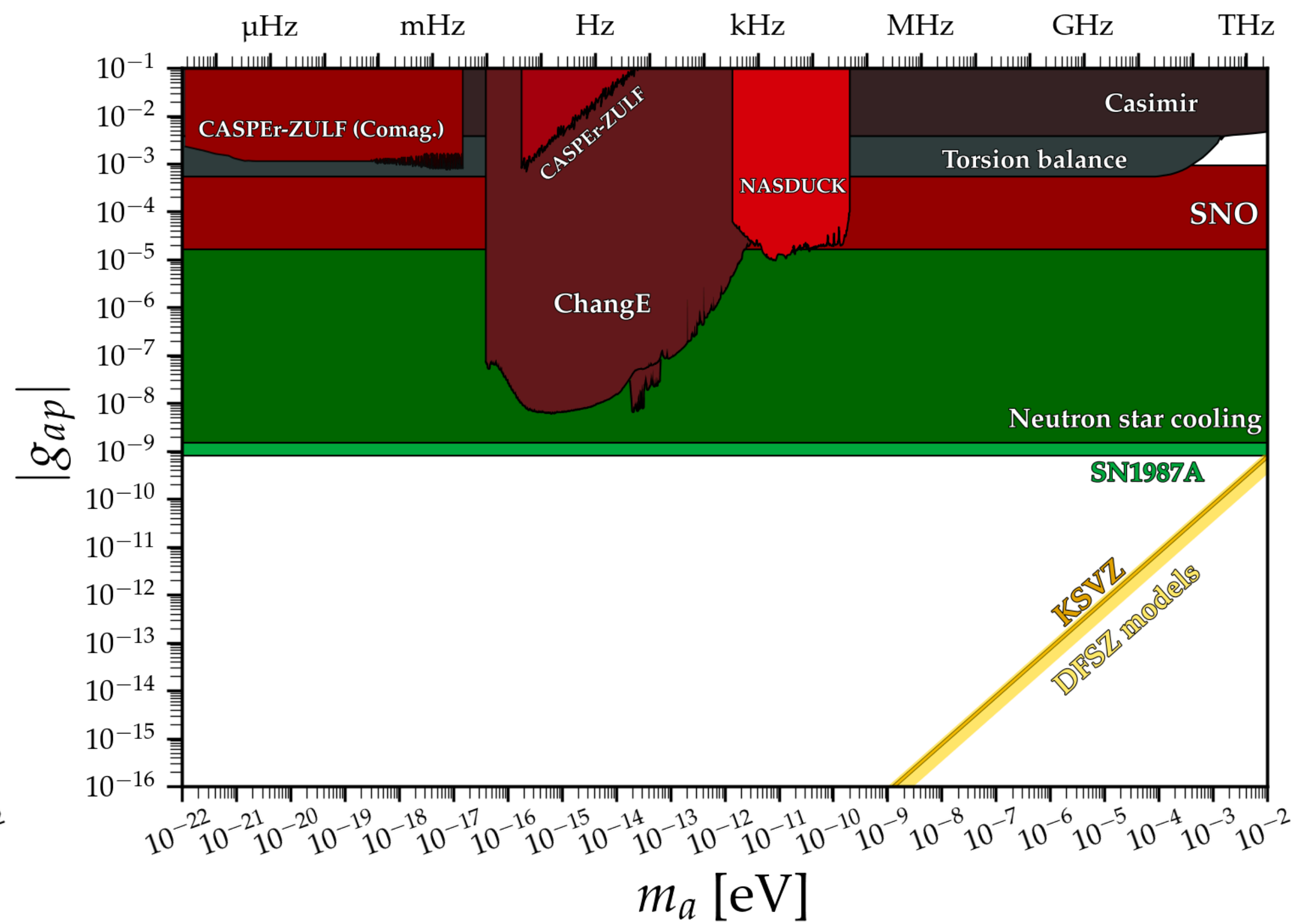
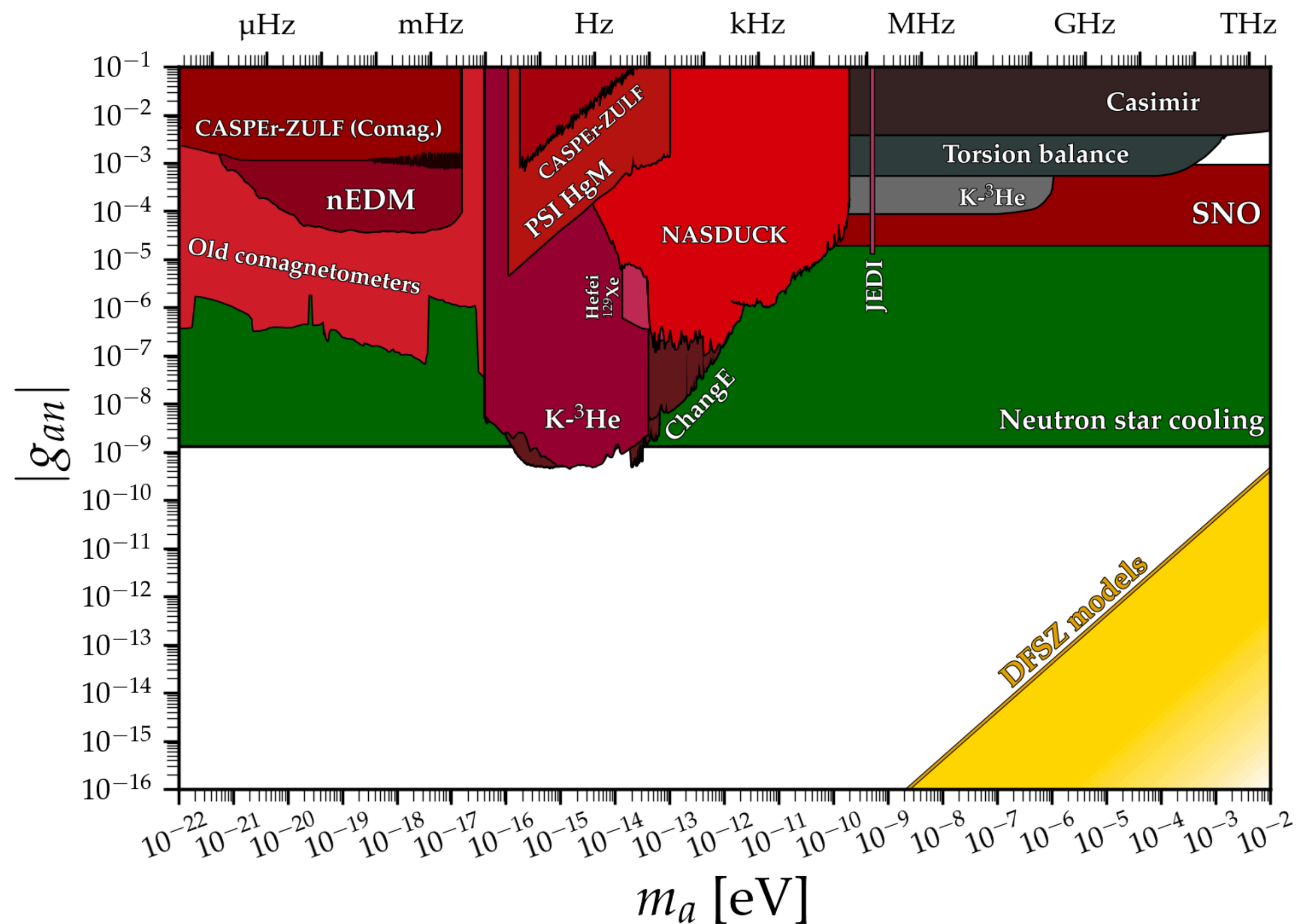
Possible DM candidates analysis

- Two-sites comparison
- On/off pump comparison
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- No DM signal persists!

frequency[Hz]	off-HSR bkg	1A	1B	Final result	frequency[Hz]	off-HSR bkg	1A	1B	Final result
46.704996	✓	3.3 (✗)	0.7 (✗)	✗	81.504437	✓	0.9 (✗)	0.0 (✗)	✗
48.391586	✗	0.1 (✗)	46.6 (✓)	✗	81.722087	✓	2.3 (✗)	3.7 (✗)	✗
67.129321	✗	0.0 (✗)	51.9 (✓)	✗	81.754539	✓	0.0 (✗)	0.0 (✗)	✗
67.143839	✗	0.0 (✗)	63.6 (✓)	✗	81.841119	✓	0.2 (✗)	0.0 (✗)	✗
67.162956	✓	1.7 (✗)	61.1 (✓)	✗	97.660449	✗	35.9 (✓)	2.5 (✗)	✗
67.164261	✗	0.3 (✗)	58.9 (✓)	✗	134.141310	✓	143.1 (✓)	0.5 (✗)	✗
67.239592	✓	0.0 (✗)	61.1 (✓)	✗	134.248210	✓	98.1 (✓)	0.0 (✗)	✗
67.256066	✗	1.9 (✗)	71.6 (✓)	✗	134.451360	✗	106.1 (✓)	0.0 (✗)	✗
67.299372	✓	3.2 (✗)	54.1 (✓)	✗	134.454310	✓	87.6 (✓)	0.0 (✗)	✗
67.305285	✗	0.0 (✗)	66.5 (✓)	✗	134.459880	✓	148.7 (✓)	0.0 (✗)	✗
67.372806	✓	11.5 (✗)	59.7 (✓)	✗	137.940290	✗	74.1 (✓)	0.0 (✗)	✗
67.378668	✗	0.2 (✗)	70.1 (✓)	✗	138.303850	✓	39.4 (✓)	0.0 (✗)	✗
67.384759	✓	0.0 (✗)	53.7 (✓)	✗	140.709640	✓	76.1 (✓)	4.5 (✗)	✗
67.399959	✗	2.5 (✗)	65.7 (✓)	✗	140.717360	✓	73.8 (✓)	0.0 (✗)	✗
67.401895	✓	0.6 (✗)	71.8 (✓)	✗	140.733530	✓	169.9 (✓)	0.0 (✗)	✗
67.424104	✓	0.9 (✗)	53.1 (✓)	✗	140.736620	✗	81.8 (✓)	0.0 (✗)	✗
67.439142	✓	0.0 (✗)	86.6 (✓)	✗	140.791670	✗	143.3 (✓)	1.8 (✗)	✗
67.447232	✗	0.0 (✗)	63.9 (✓)	✗	140.794650	✓	68.7 (✓)	0.0 (✗)	✗
67.457887	✗	4.4 (✗)	75.2 (✓)	✗	141.246730	✗	120.5 (✓)	0.3 (✗)	✗
72.782530	✓	8.2 (✗)	11.2 (✗)	✗	141.701700	✓	125.1 (✓)	6.7 (✗)	✗
72.785297	✓	0.0 (✗)	10.7 (✗)	✗	141.952930	✗	68.8 (✓)	0.0 (✗)	✗
72.788802	✓	0.0 (✗)	24.4 (✓)	✗	142.624590	✓	95.9 (✓)	3.4 (✗)	✗
72.797656	✓	0.8 (✗)	24.0 (✓)	✗	142.729810	✗	51.9 (✓)	4.5 (✗)	✗
72.803745	✗	0.0 (✗)	24.7 (✓)	✗	143.372440	✓	70.6 (✓)	4.3 (✗)	✗
72.823120	✓	0.0 (✗)	23.4 (✗)	✗	143.969920	✓	57.0 (✓)	0.2 (✗)	✗
72.825273	✓	10.2 (✗)	16.0 (✗)	✗	157.812310	✓	0.0 (✗)	40.1 (✓)	✗
72.839546	✓	0.7 (✗)	32.0 (✓)	✗	159.152270	✓	88.1 (✓)	0.1 (✗)	✗
72.869210	✓	0.0 (✗)	27.0 (✓)	✗	161.744220	✗	53.2 (✓)	11.2 (✗)	✗
72.871118	✓	1.5 (✗)	25.6 (✓)	✗	186.715230	✗	19.5 (✗)	0.0 (✗)	✗
72.874196	✗	0.0 (✗)	34.7 (✓)	✗	188.360580	✓	1.0 (✗)	0.0 (✗)	✗
72.921797	✓	1.1 (✗)	34.1 (✓)	✗	363.317150	✗	9.6 (✗)	119.5 (✓)	✗

ChangeE-HSR results

- **ChangeE** experiments set competitive limits on ALP-nucleon couplings
- Improving **ALP-proton coupling** limits by $10^5 - 10^6$
- Provideing best limits on **ALP-neutron couplings** at $\sim [0.02, 0.2]$ Hz and $[10, 200]$ Hz



Summary

- **Ultralight Bosonic or Wave-like Dark Matter** represents an exciting new frontier in the quest to unravel the mysteries of dark matter
- A multitude of experiments are underway, each tailored to investigate different possible interactions between dark matter and ordinary matter
- **ChangE** experiments set competitive limits on ALP-nucleon couplings
 - Improving **ALP-proton coupling** limits by $10^5 - 10^6$
 - Provideing best limits on **ALP-neutron couplings** at $\sim[0.02, 0.2]$ Hz and $[10, 200]$ Hz
 - No definitive dark matter candidates yet.
 - **Noise suppressions play the central role in future improvements**

Thank you!

Backup slides

The QCD axion and the Strong CP problem

$$\mathcal{L} \supset -\frac{\theta g_s^2}{32\pi^2} G\tilde{G} - (\bar{u}_L M_u u_R + \bar{d}_L M_d d_R + \text{h.c.})$$

- The CKM matrix from $M_{u,d}$
 - CP violating phase $\theta_{\text{CP}} \sim 1.2$ radian
- QCD induced CP violating phase, $\bar{\theta}$

$$\bar{\theta} = \theta + \arg [\det [M_u M_d]]$$

- $\bar{\theta}$ is invariant under quark chiral rotation
- According to neutron EDM experiment

$$d_{\text{EDM}}^n \sim \theta \times 10^{-16} \text{ e cm}$$

$$d_{\text{exp}}^n < 10^{-26} \text{ e cm}$$

$$\bar{\theta} \lesssim 1.3 \times 10^{-10} \text{ radian}$$