Dark matter search with a strongly-coupled hybrid spin system

Jia Liu
Peking University

ArXiv:2306.08039 (ChangE collaboration)

Beihang Univ: Kai Wei, Zitong Xu, Xing Heng,Xiaofei Huang,Wei Quan,Xiao-Ping Wang,Jiancheng Fang
Helmholtz-Institute Mainz & JGU Mainz Univ: Wei Ji, Dmitry Budker
Peking Univ: Yuxuan He,Xiaolin Ma, Jia Liu

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2023-07-28

Outlines

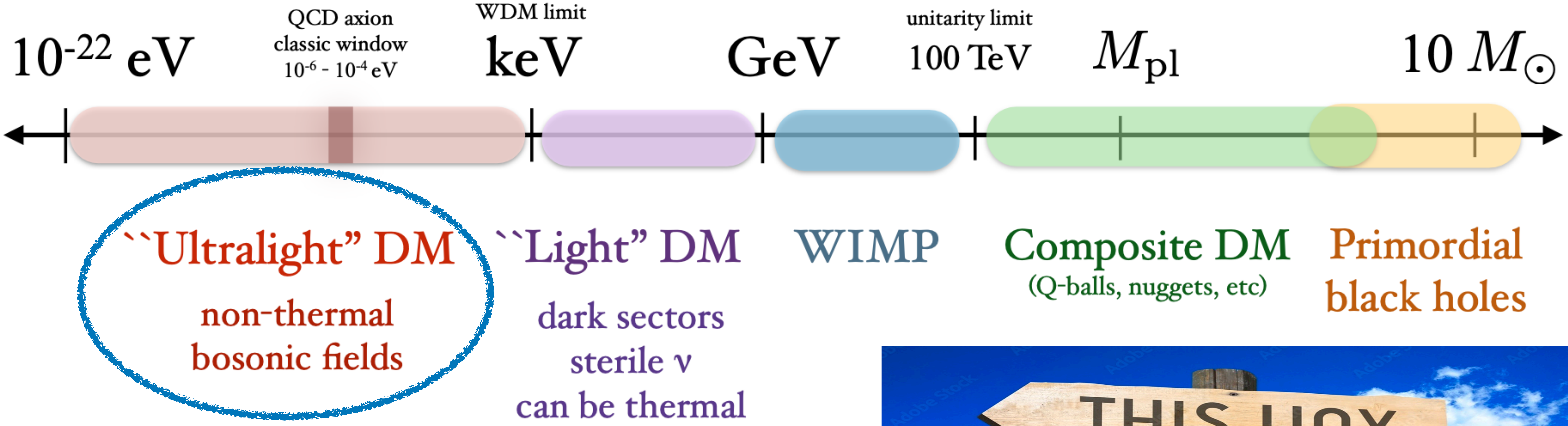
- Ultralight bosonic dark matter
  - General ALP studies
- ALP-nucleon searches
    - NMR method
    - ALP DM stochastic nature
    - Hybrid-Spin Resonance
    - Results
  - Summary

What is the nature of dark matter?

Unknown matter and energy ~ 95%

The dark matter candidate models

1904.07915，TASI lecture



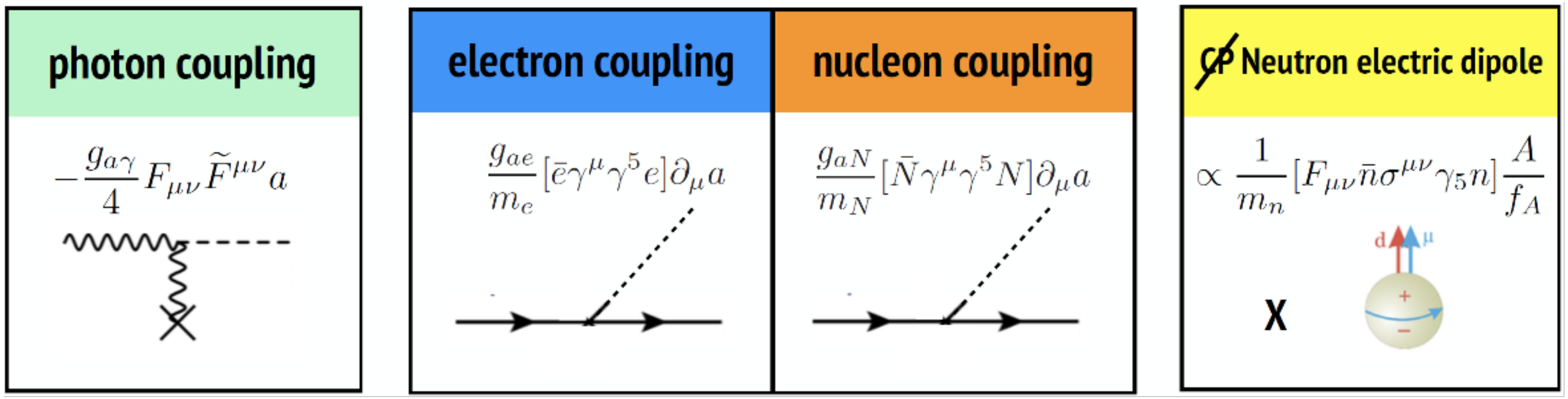
Today’s focus

HEP at a cross-road: explore all directions!

Ultralight Bosonic Dark Matter

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

Ultralight Bosonic Dark Matter



- Typical models:

Couples to gauge bosons, fermion spins

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

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

Ultralight Bosonic Dark Matter

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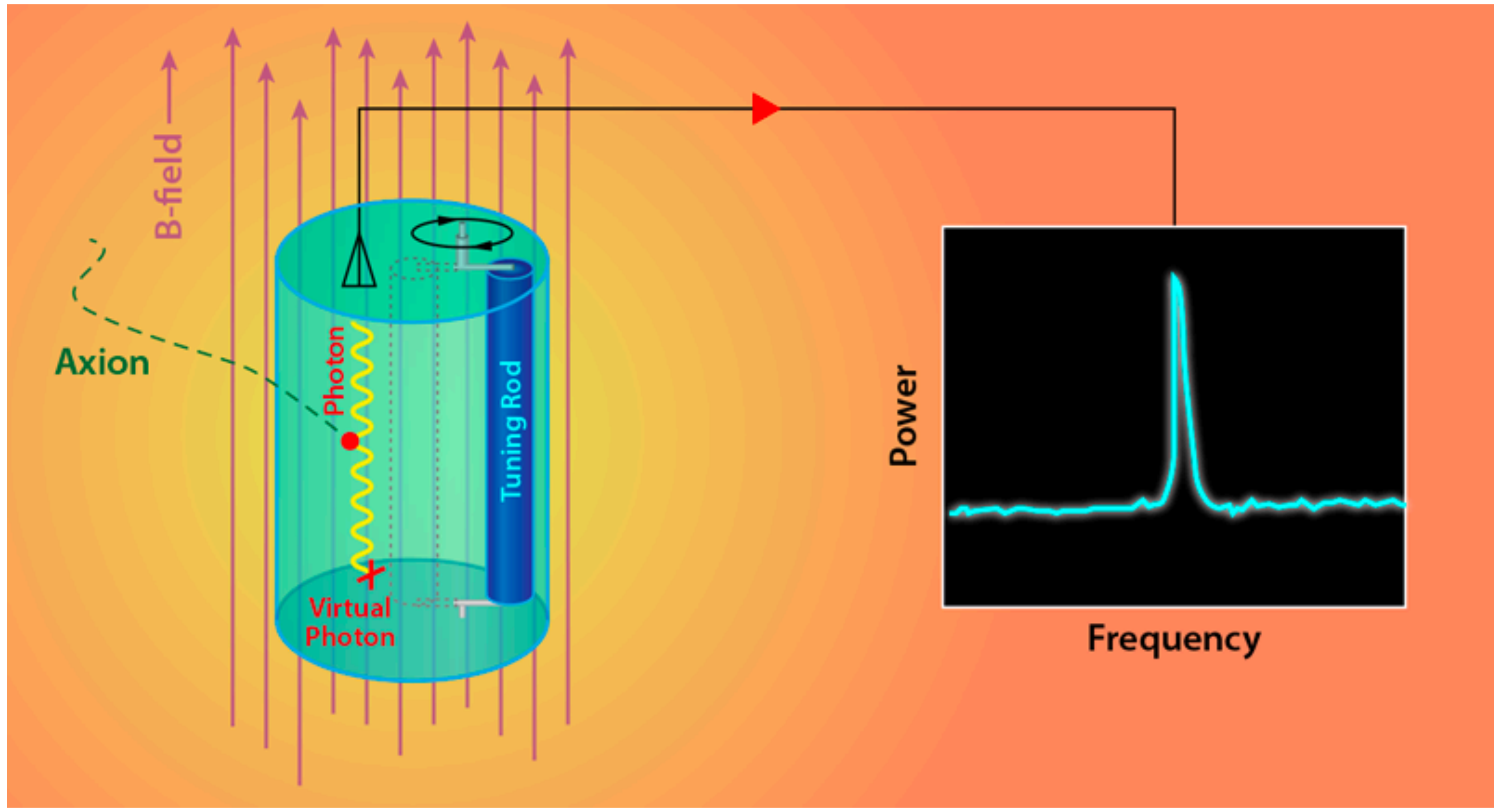
Low energy probe of high energy physics

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

The detection of ultralight bosonic dark matter

- Mass ranges from $[10^{-22},\ 10^{3}]\ \mathrm{eV}$, 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: (WISPDMX, 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

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

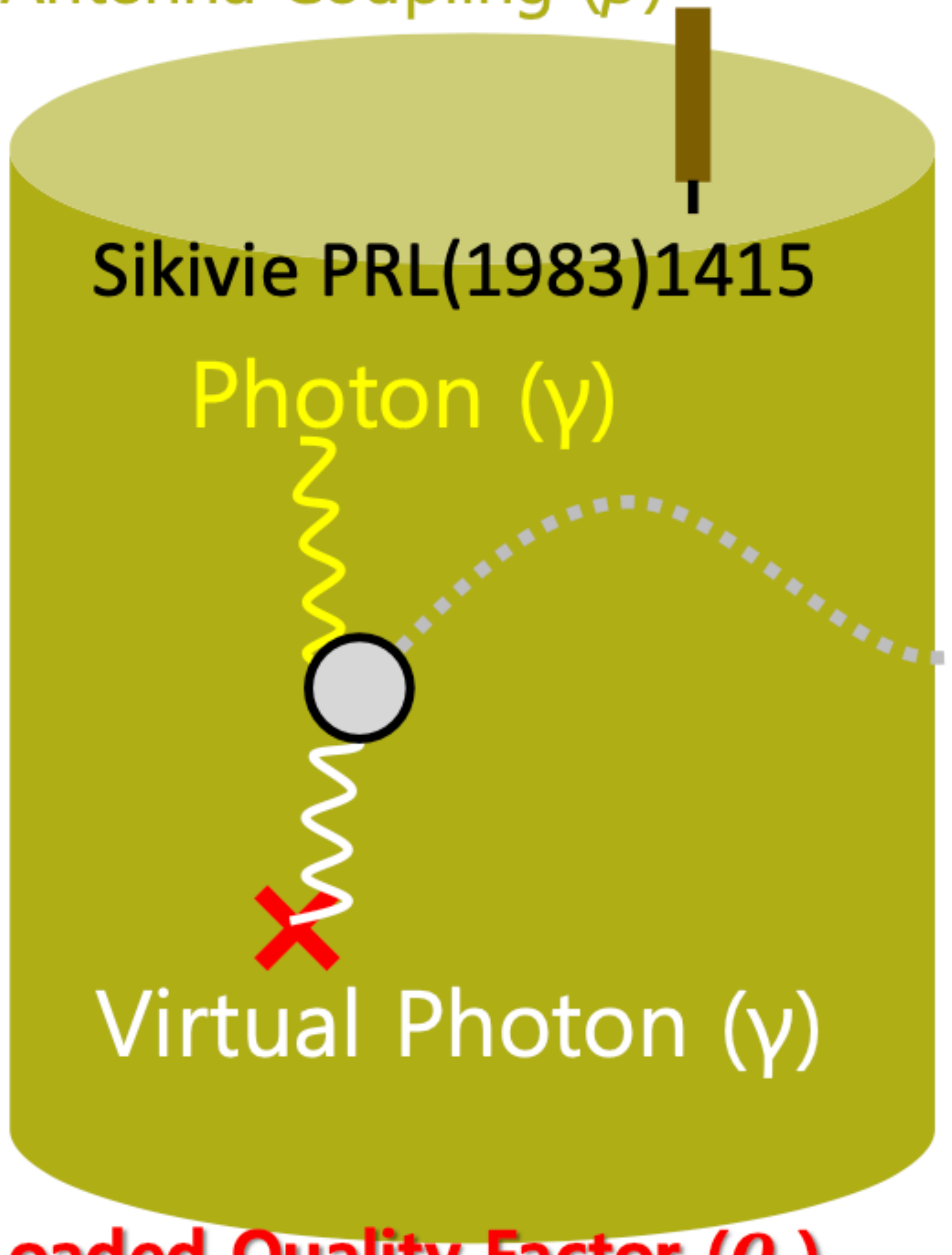
The resonant searches for ALP via photon coupling

- 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)



Magnetic Field (B)

Loaded Quality Factor (Q_l)
Volume (V)
Resonant Angular Frequency (ω_0)
Form Factor (C)
System Temperature (T_{sys})

Signal Power

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

Coupling Constant: $g_{a\gamma\gamma}^2$; Dark Matter Axion Density: ρ_a; Axion Mass: m_a; Axion Quality Factor: Q_a

Kim *et al.* JCAP03(2020)066

Scan Rate

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

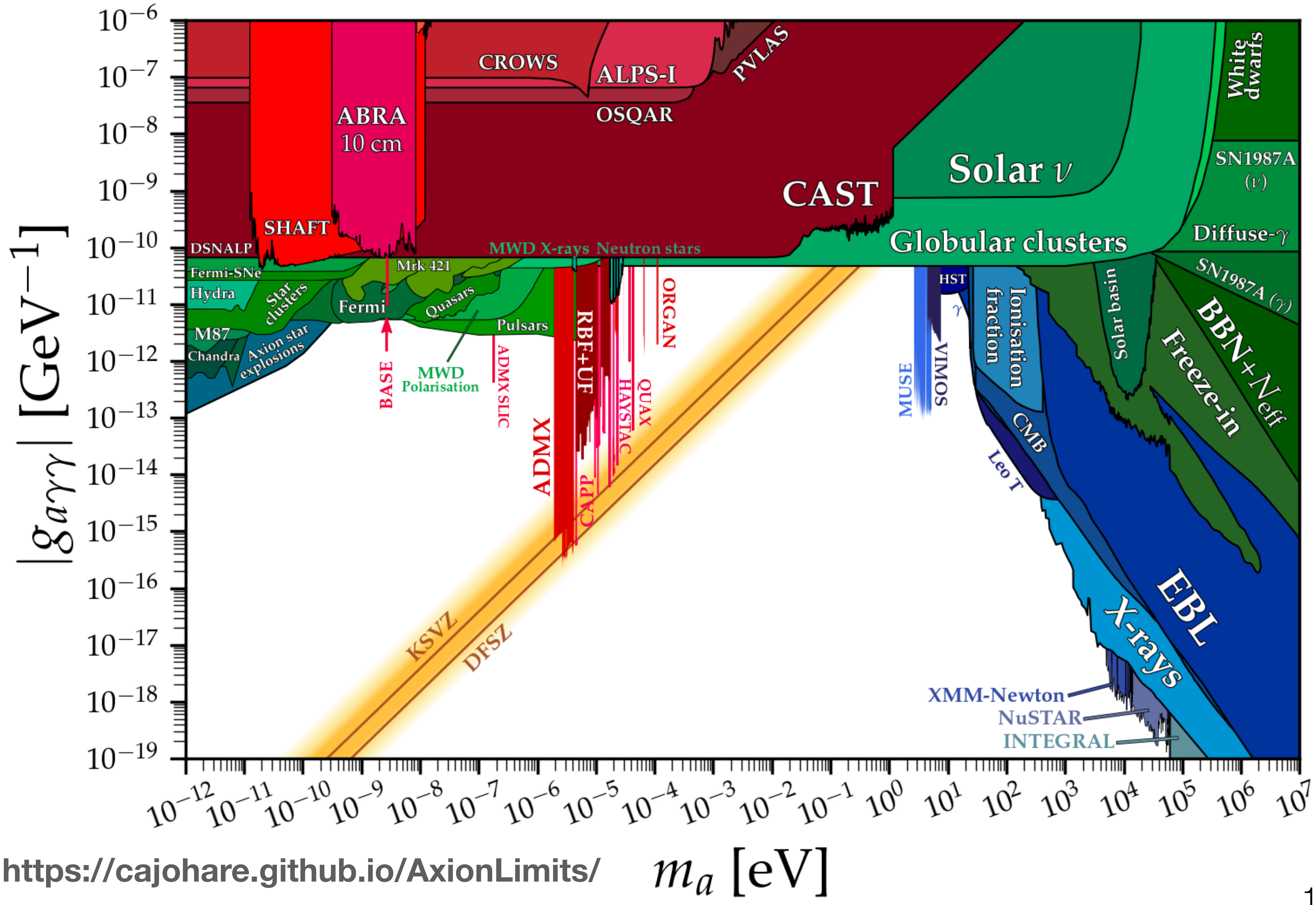
$Q_l \gg Q_a \sim 10^6$

System Noise Temperature ~ 200 mK

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



https://cajohare.github.io/AxionLimits/

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The resonant searches of nucleon couplings

- The ALP DM field

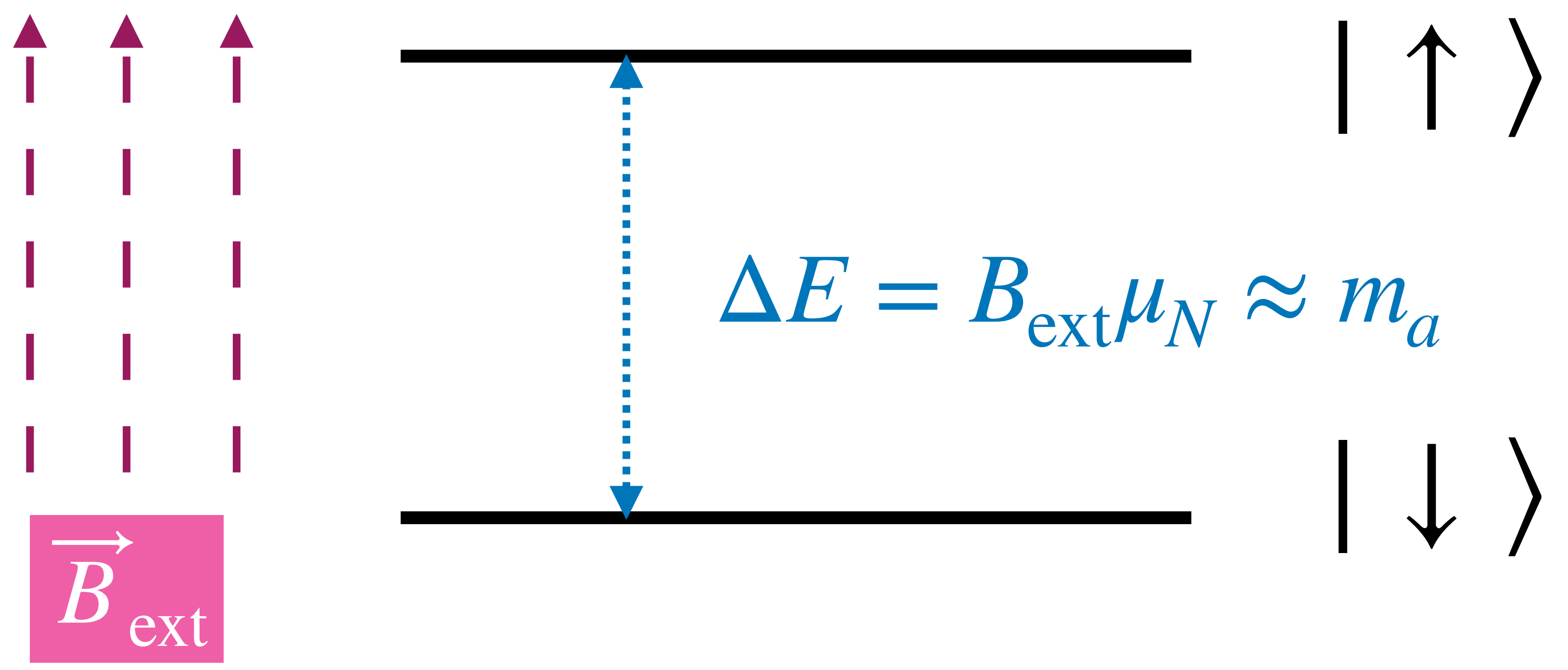
$$a(x,t) \approx a_0 \cos(\omega t - \vec{p}\cdot\vec{x} + \theta_0)$$

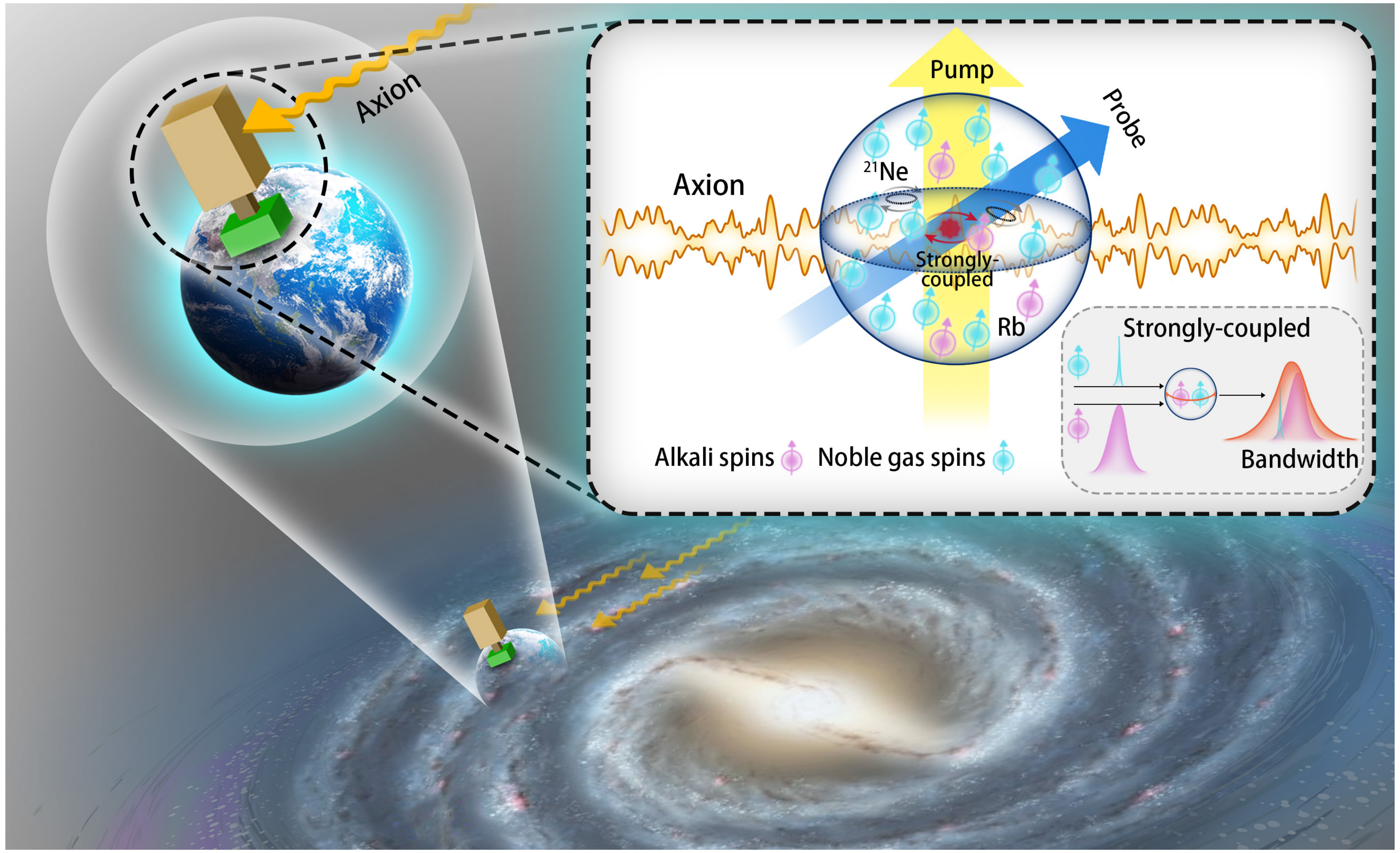
- The axion-wind Hamiltonian

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

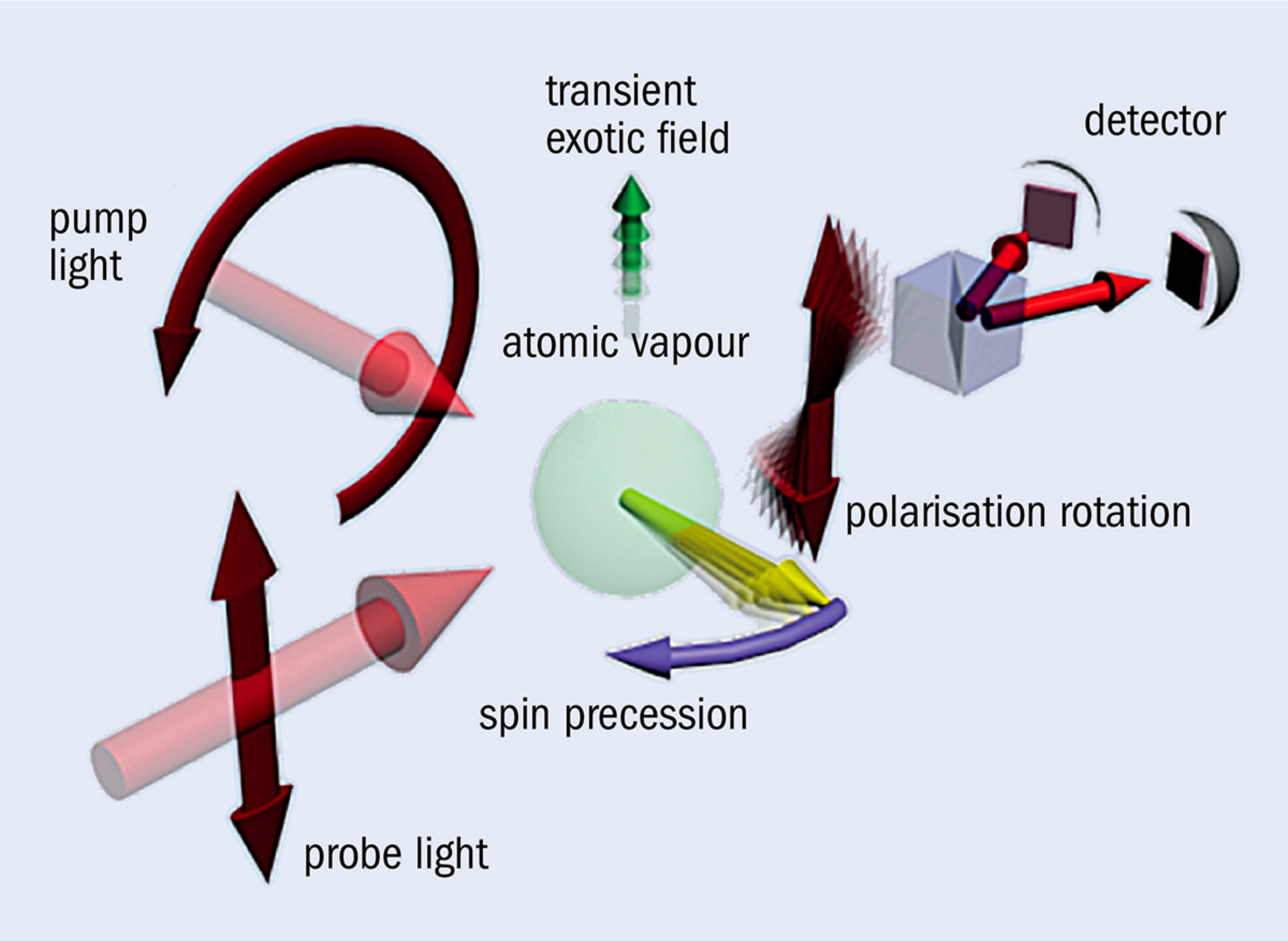
$$\approx g_{aNN}\vec{v}_a \cdot \vec{\sigma}_N \times \sqrt{2\rho_a}\sin(p\cdot x)$$

- A Zeeman split in B field





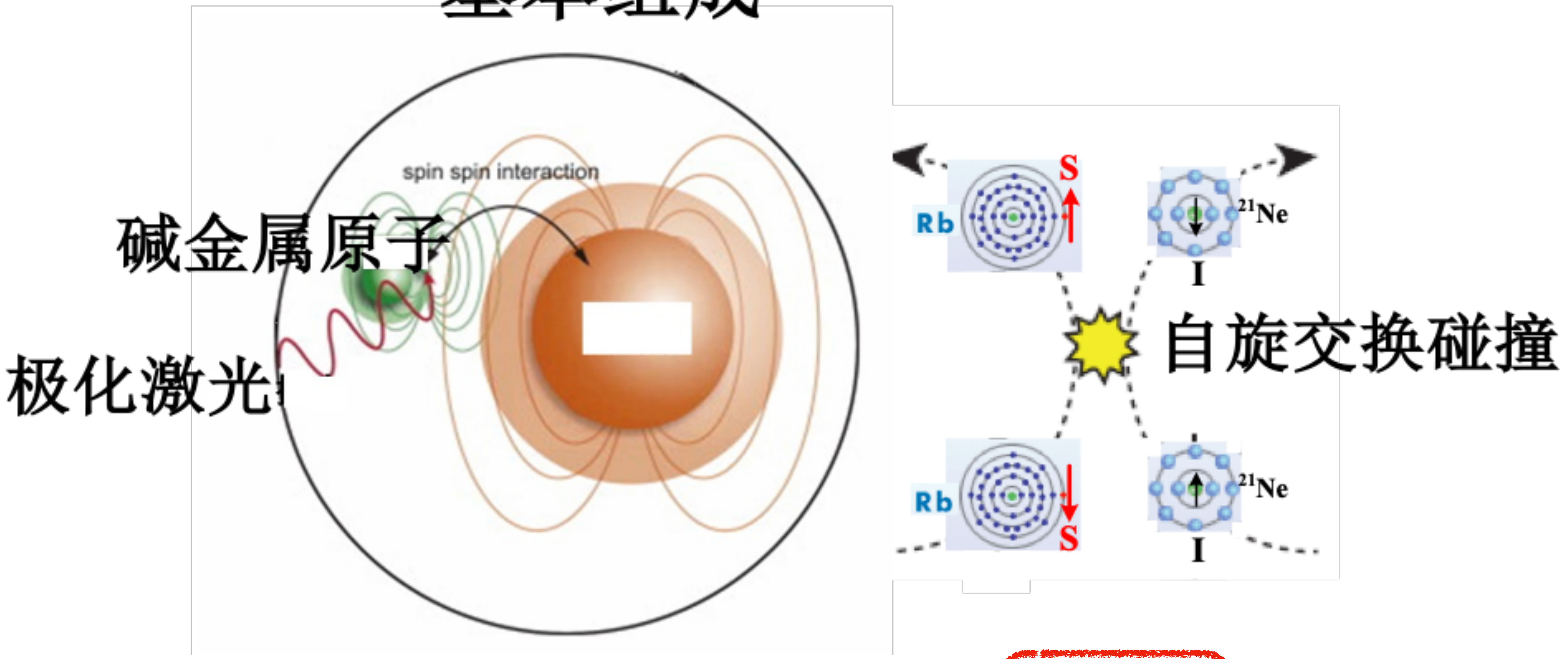
Spin precession detection mechanisms

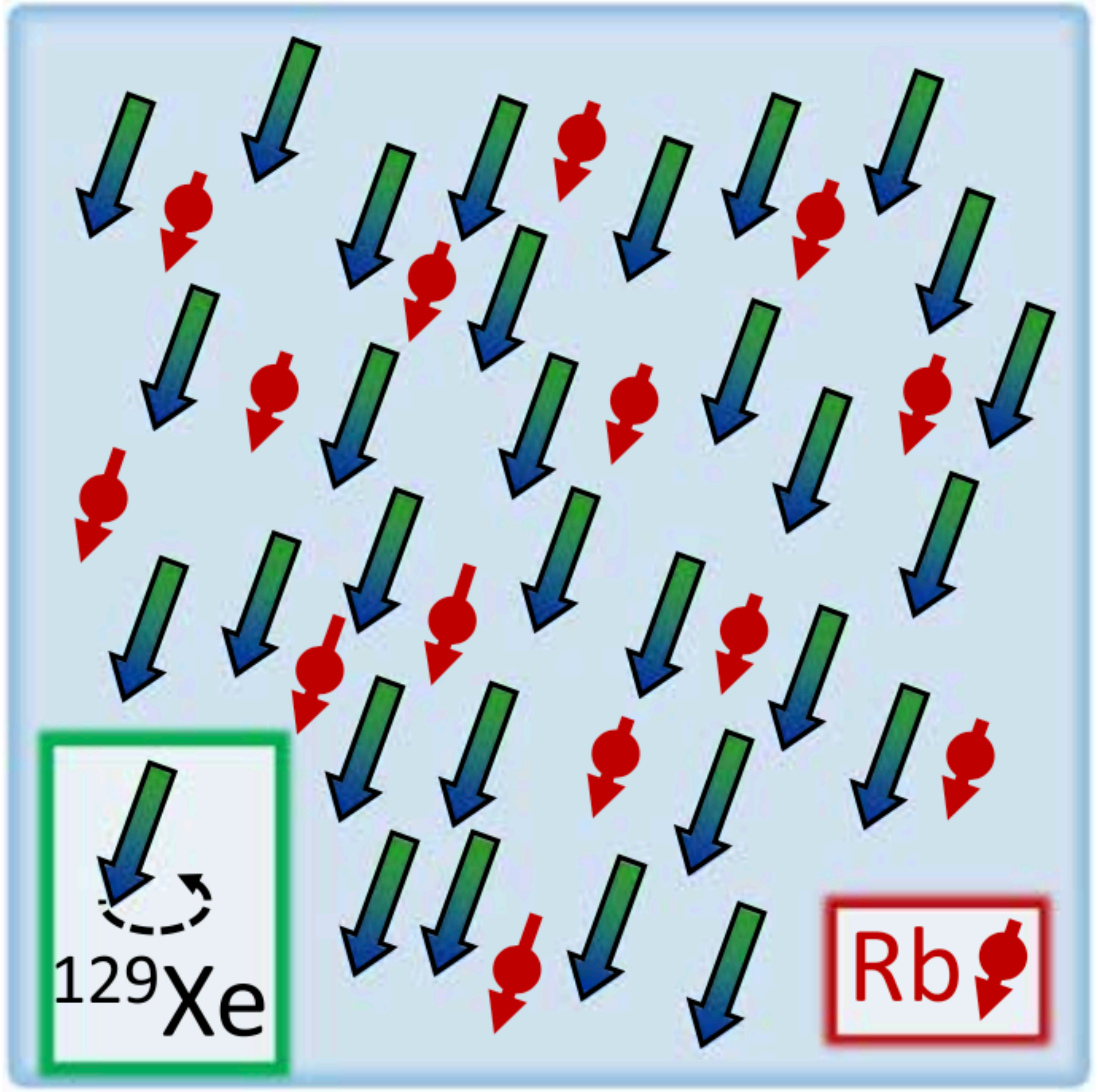


Comagnetometer

- Alkali atoms and nobel-gas atom

基本组成





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

Coupled Bloch equation

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

Exotic B field

自旋交换碰撞

Fermi contact interaction and amplify

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

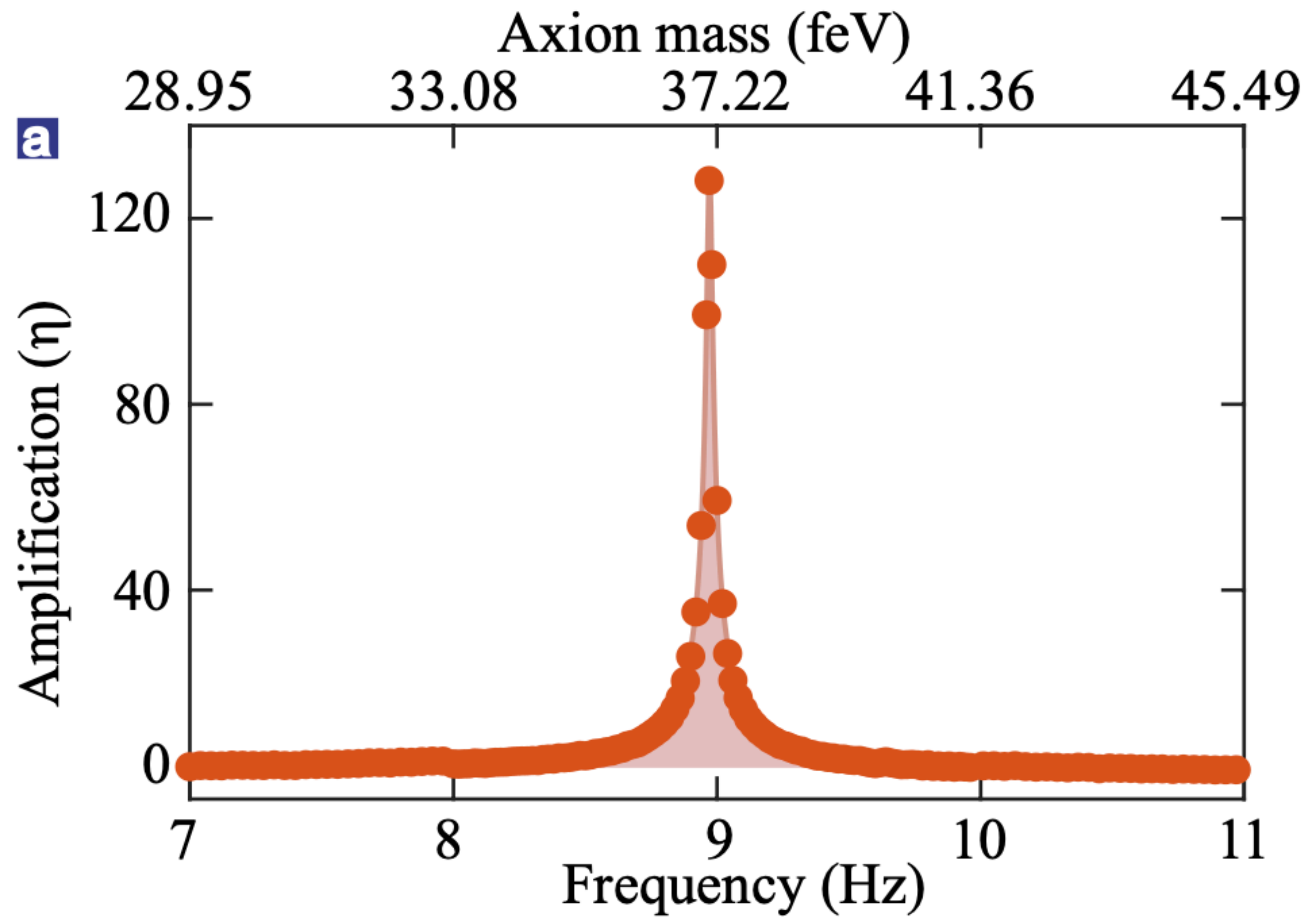
$\eta \equiv B_{eff}/b^n$ $\qquad$ **Rb-Xe**

Jiang et al. Nature Physics 2021

Comagnetometer NMR mode (Spin-base Amplifier)

- Enhanced sensitivity at resonance frequency

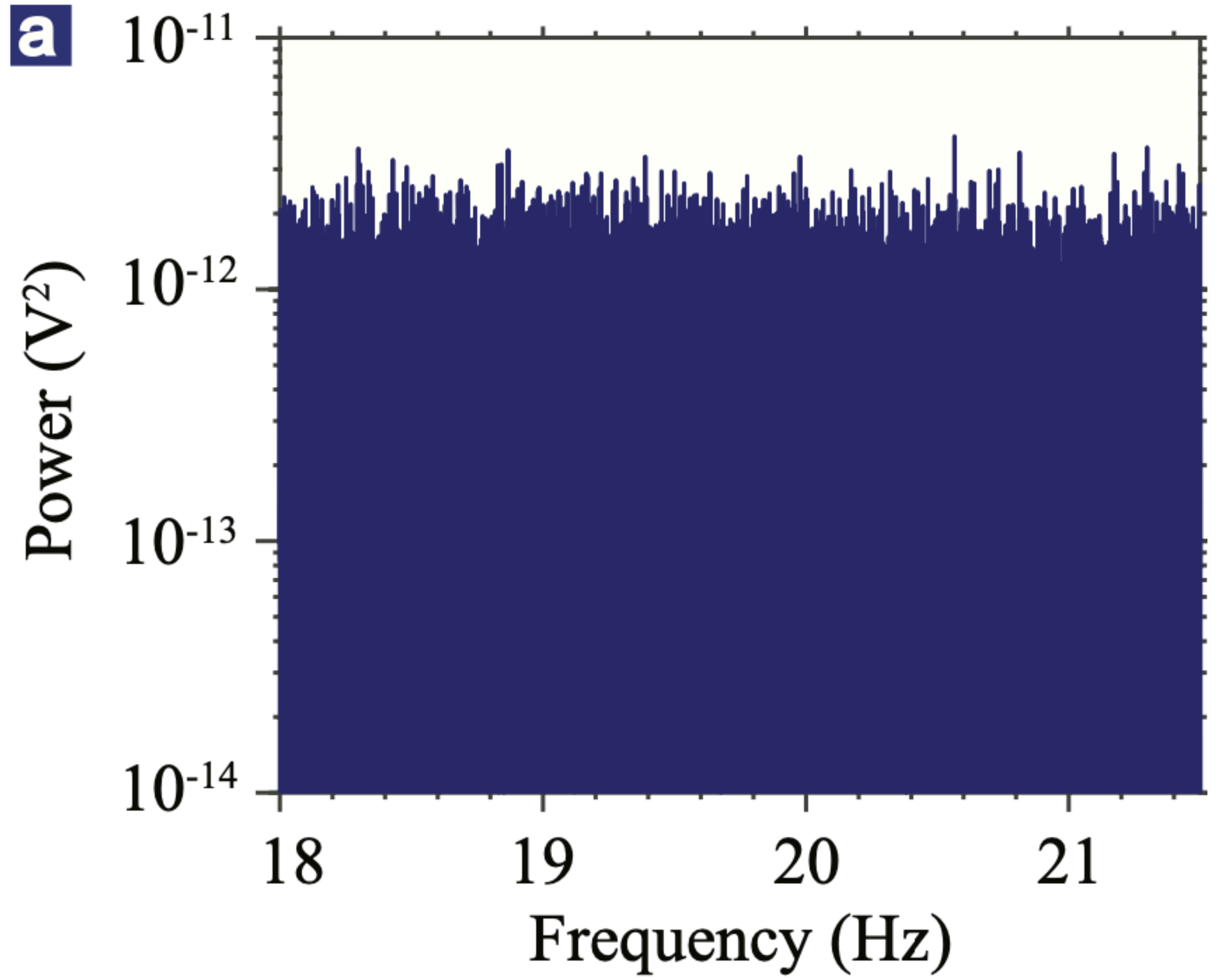
Jiang et al. Nature Physics 2021



Lorenzian amplification shape

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

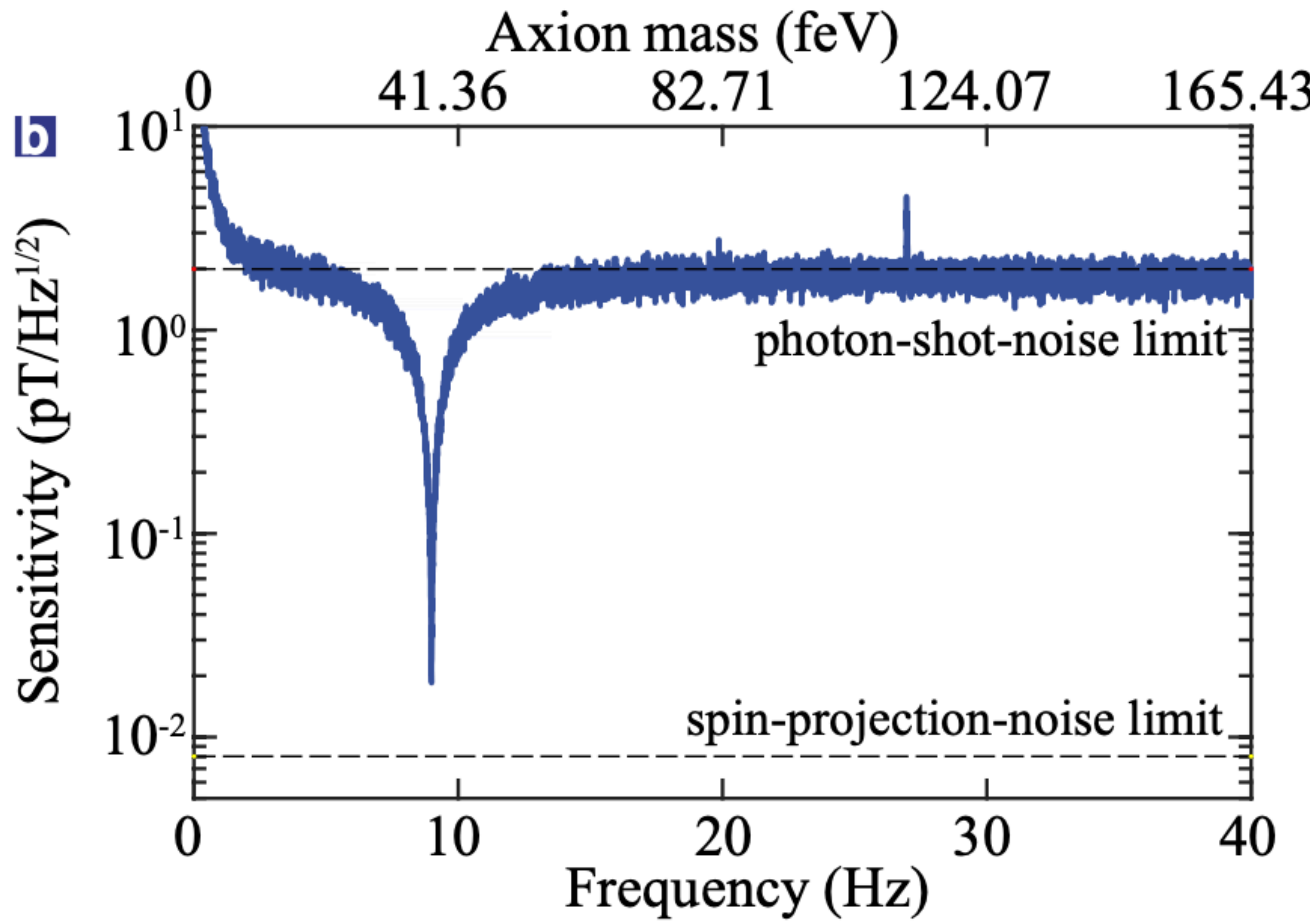
$$\sqrt{3}\Lambda = 0.052\ \text{Hz}$$



Experimental data

Tuning B_0 field

Resonant frequency $f_0 = 19.84$ Hz



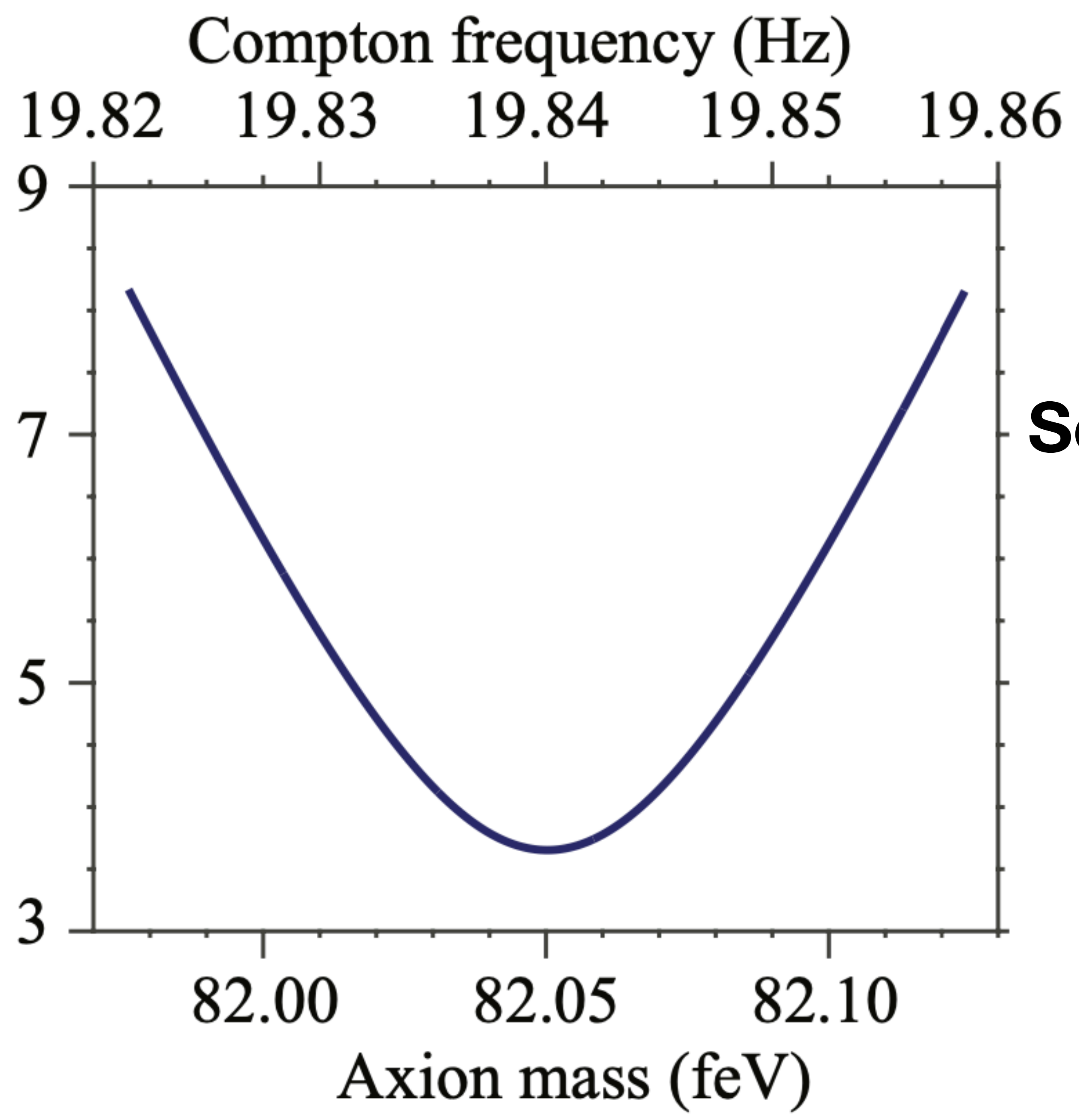
Good sensitivity on

Resonant frequency 19.84 Hz

Comagnetometer NMR mode (Spin-base Amplifier)

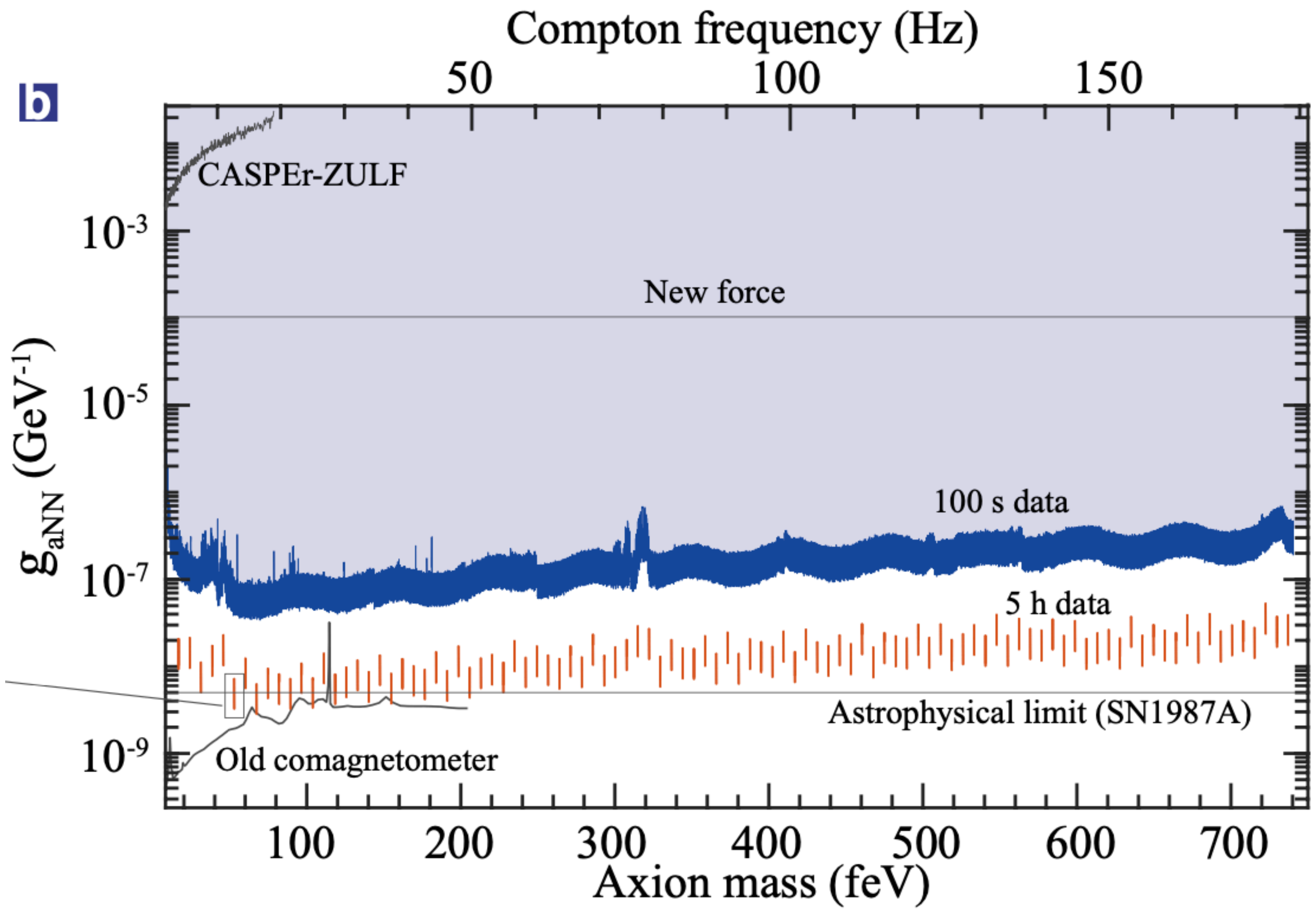
- Resonant search + scanning of f_0

Jiang et al. Nature Physics 2021



Constrain on certain frequency 19.84 Hz

Scanning



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

$$\nabla a(x) = \sum_{\boldsymbol{p}} \sqrt{\frac{2N_{\boldsymbol{p}}}{V\omega_{\boldsymbol{p}}}} \cos(\omega_{\boldsymbol{p}} t - \boldsymbol{p}\cdot\boldsymbol{x} + \phi_{\boldsymbol{p}})\boldsymbol{p}$$

ϕ_p: is uniform random variable in [0, 2Pi]

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

- Signal is stochastic instead of deterministic

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

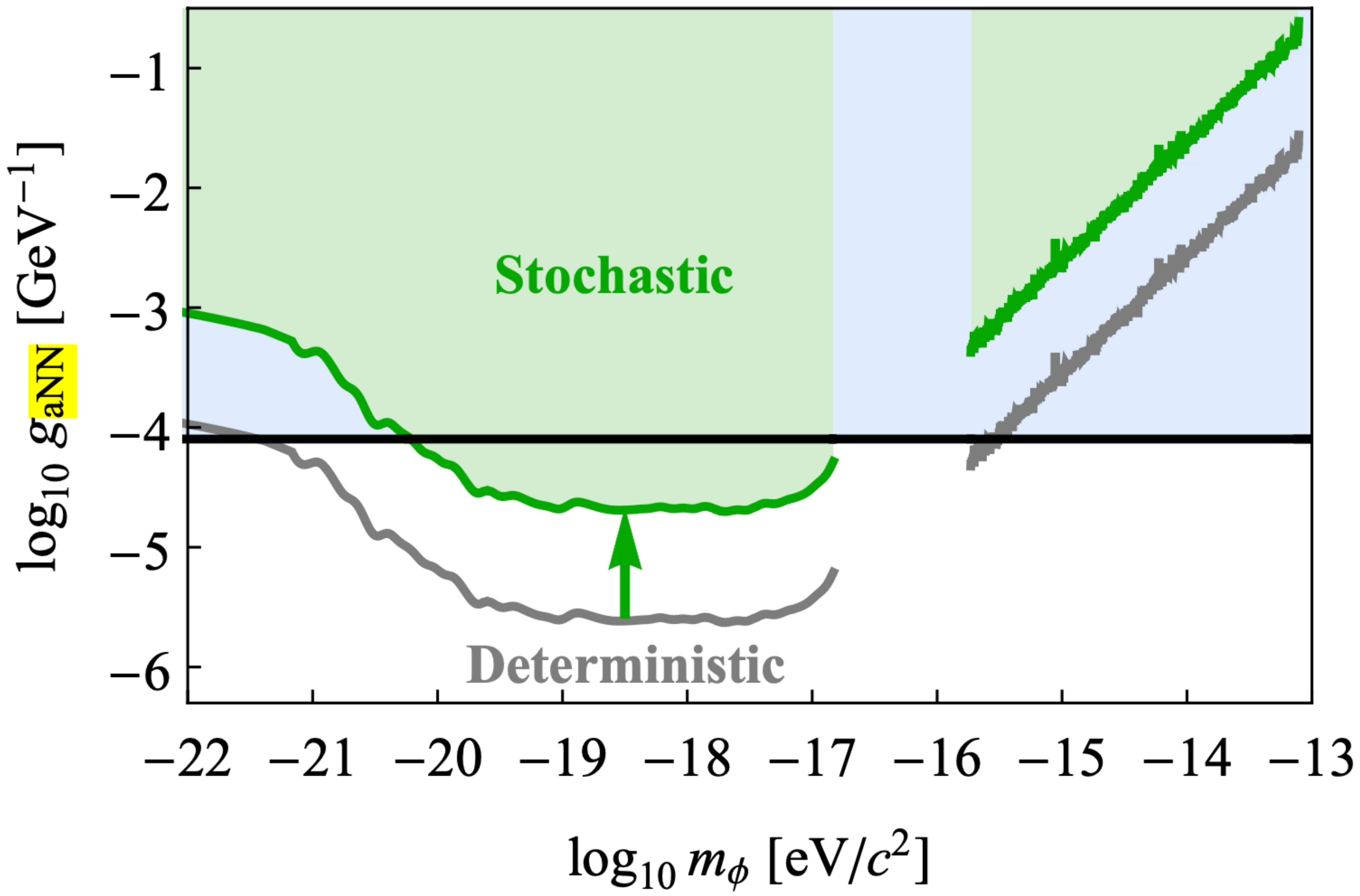
$$A_k = \frac{2}{N}\mathrm{Re}[\tilde{\beta}_k], \quad B_k = -\frac{2}{N}\mathrm{Im}[\tilde{\beta}_k].$$

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

$$\Sigma = \Sigma_a + \sigma_b^2 \cdot \mathbb{1}$$

Junyi Lee et al, 2209.03289, PRX 2023

1905.13650, NC 2021



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

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

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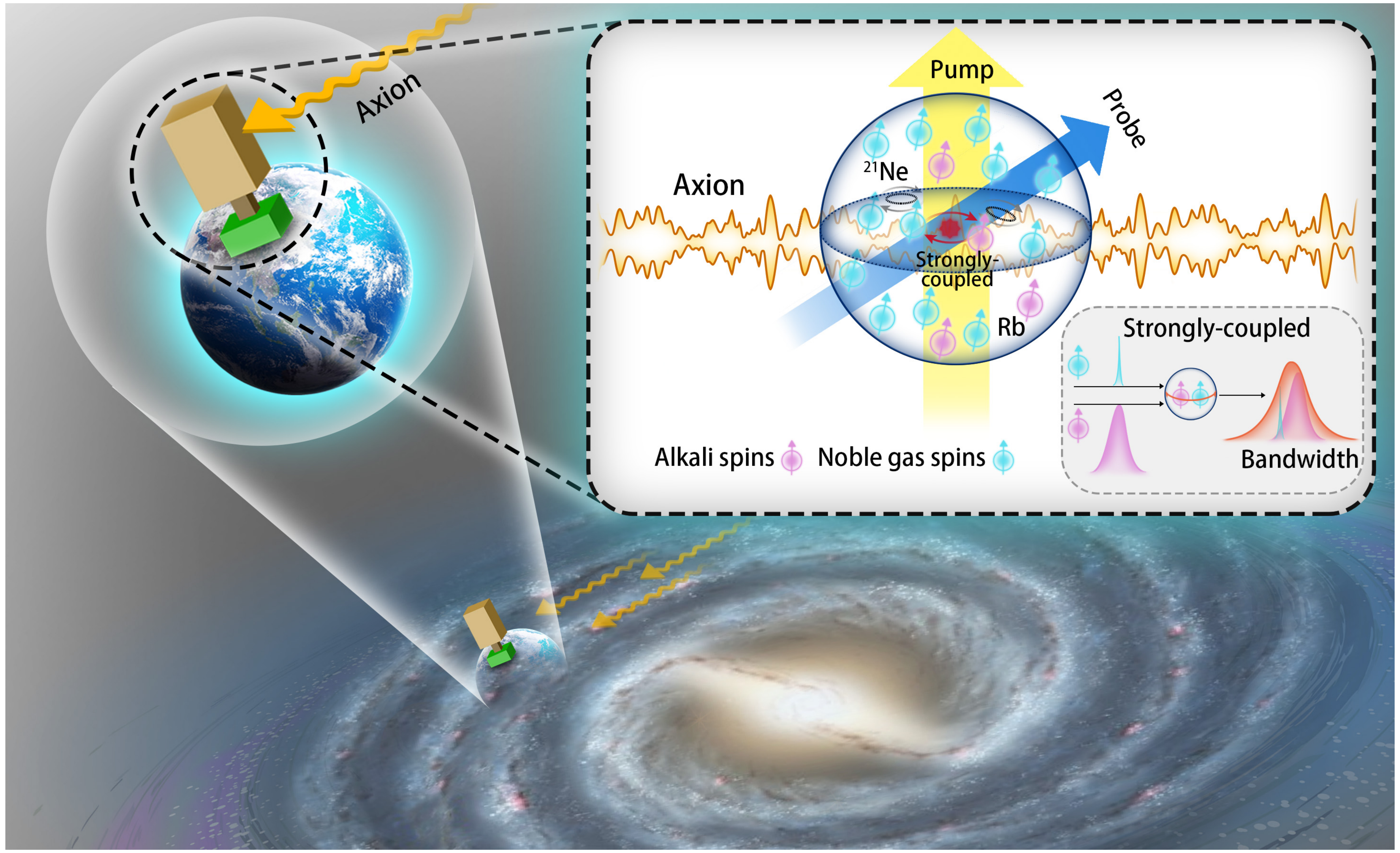
Comagnetometer in Hybrid Spin Resonance: Motivation

- 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



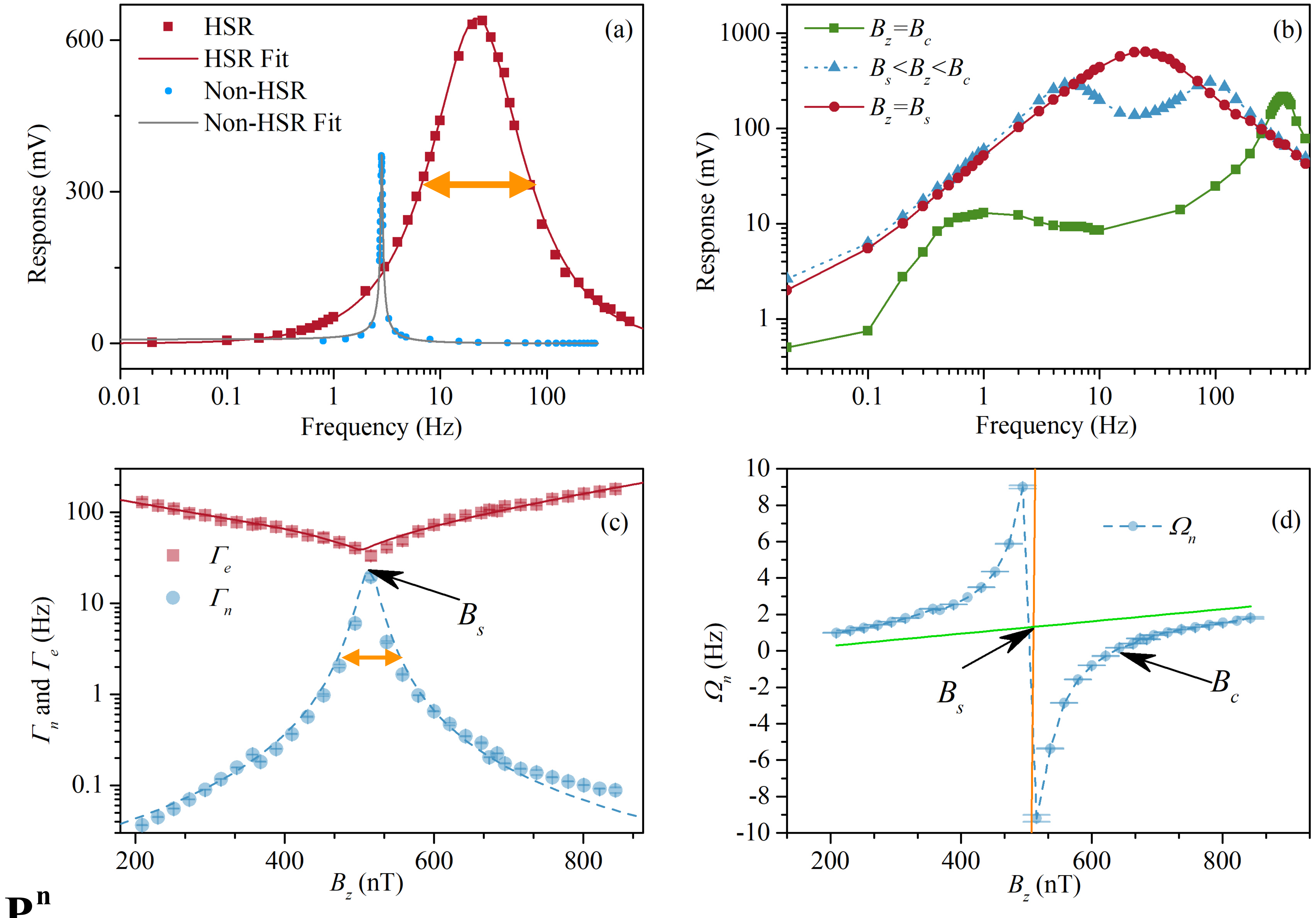
ChangE experiment: Kai Wei, .. **JL** .. et al, 2306.08039

Comagnetometer in Hybrid Spin Resonance: Method

- Method: tune external B field to make Larmor frequency equal
  - HSR: $\omega_K \approx \omega_{\mathrm{Ne}}$
  - Width Γ_n is about 100 Hz now

$$\frac{\delta \mathbf{P}^{\mathrm{e}}}{\delta t} = \frac{\gamma_e}{Q}\left[\mathbf{B} + \mathbf{L} + \lambda M_0^n \mathbf{P}^{\mathrm{n}} + \mathbf{b}^{\mathrm{e}}\right] \times \mathbf{P}^{\mathrm{e}} - \mathbf{\Omega} \times \mathbf{P}^{\mathrm{e}} + \frac{R_p \mathbf{S_p} + R_m \mathbf{S_m} + R_{\mathrm{se}}^{\mathrm{ne}} \mathbf{P}^{\mathrm{n}}}{Q} - \frac{\left\{R_1^e, R_2^e, R_2^e\right\}}{Q} \mathbf{P}^{\mathrm{e}}$$

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



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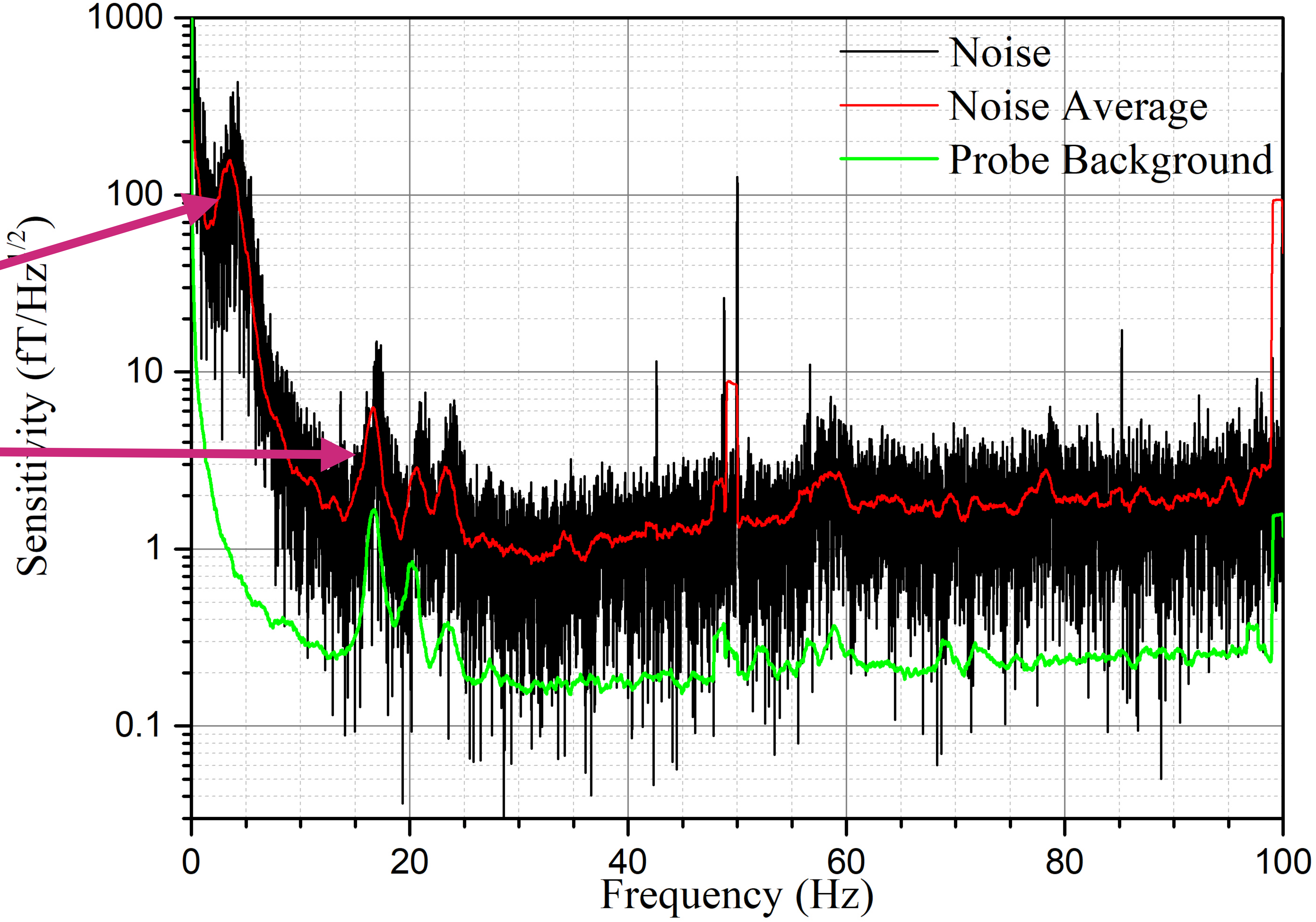
Comagnetometer sensitivity

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



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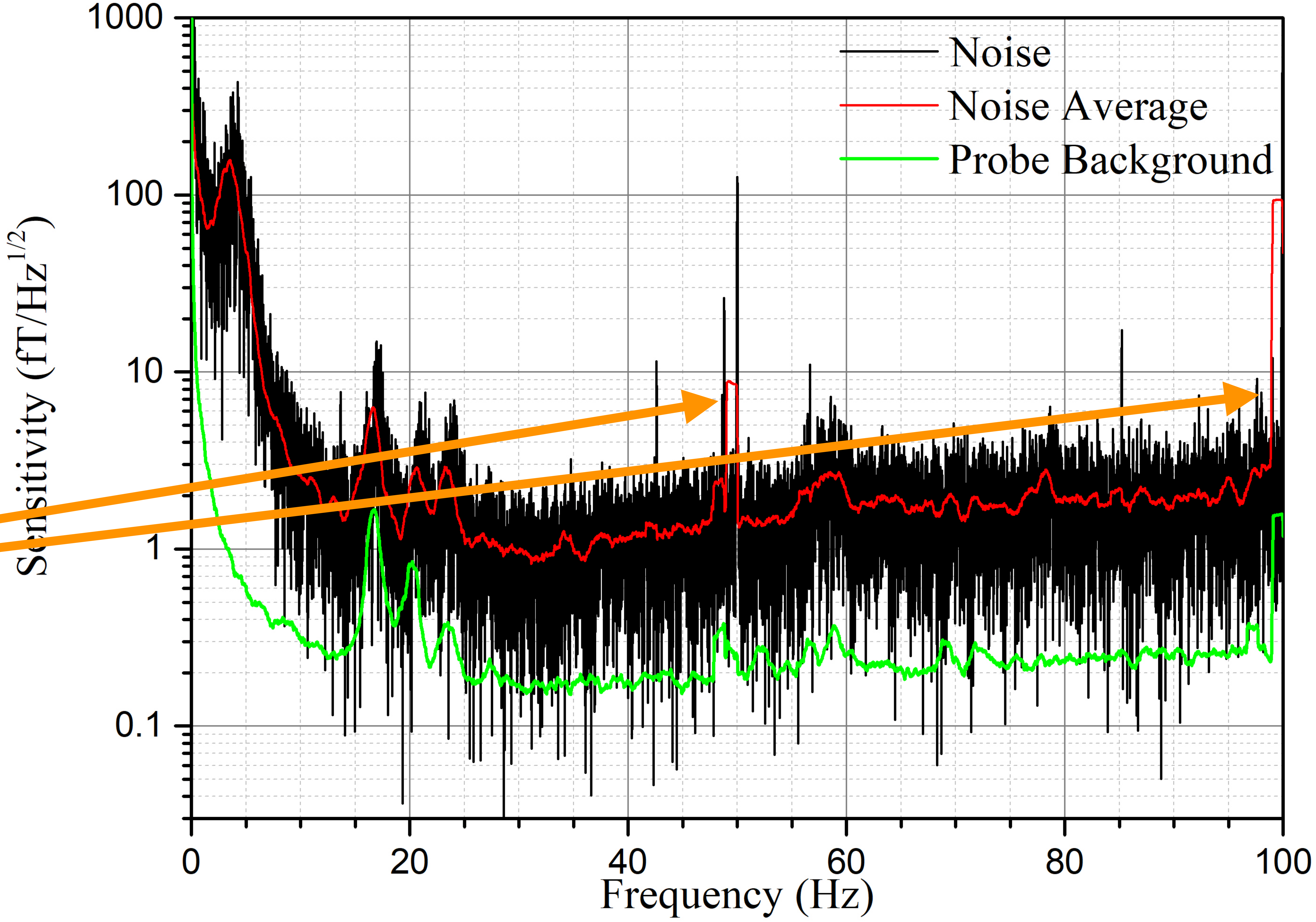

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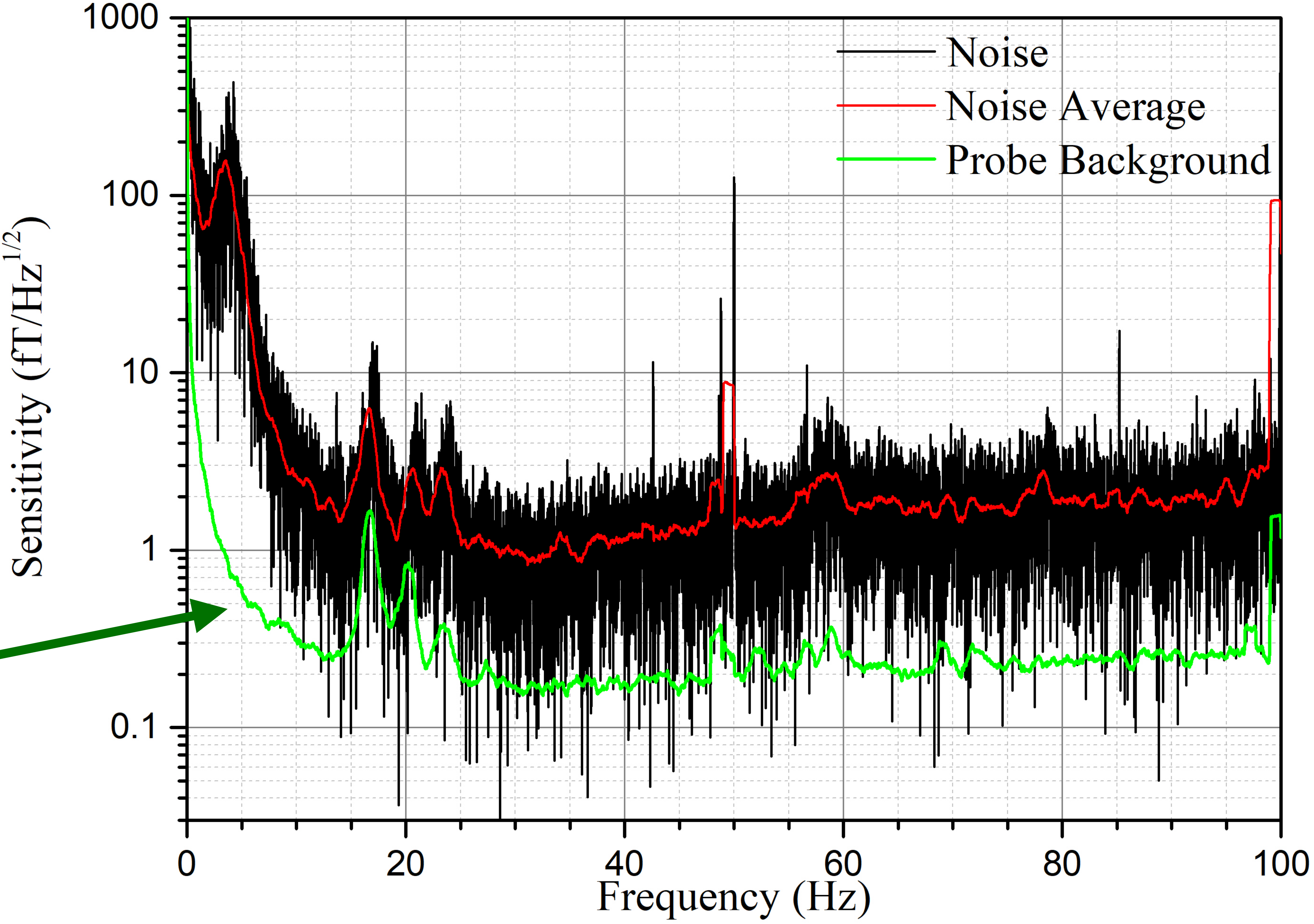
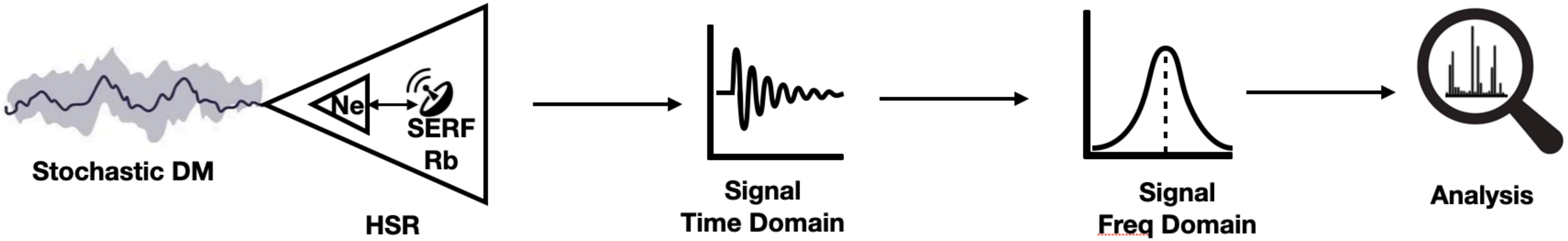


Comagnetometer HSR search on ALP DM

- 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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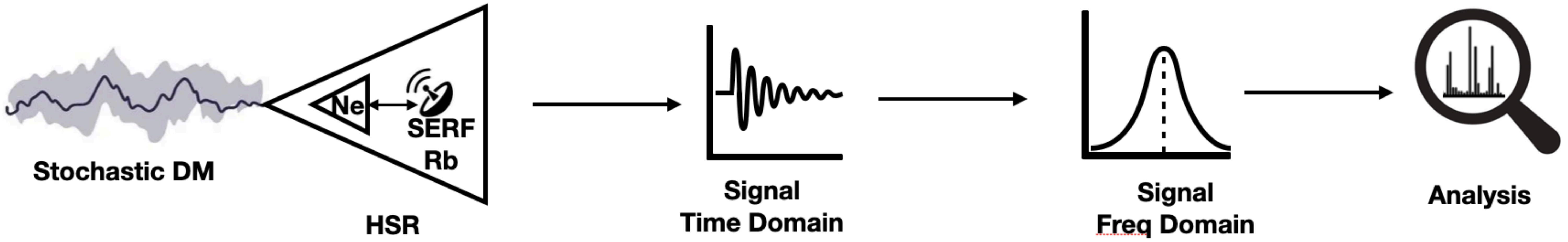
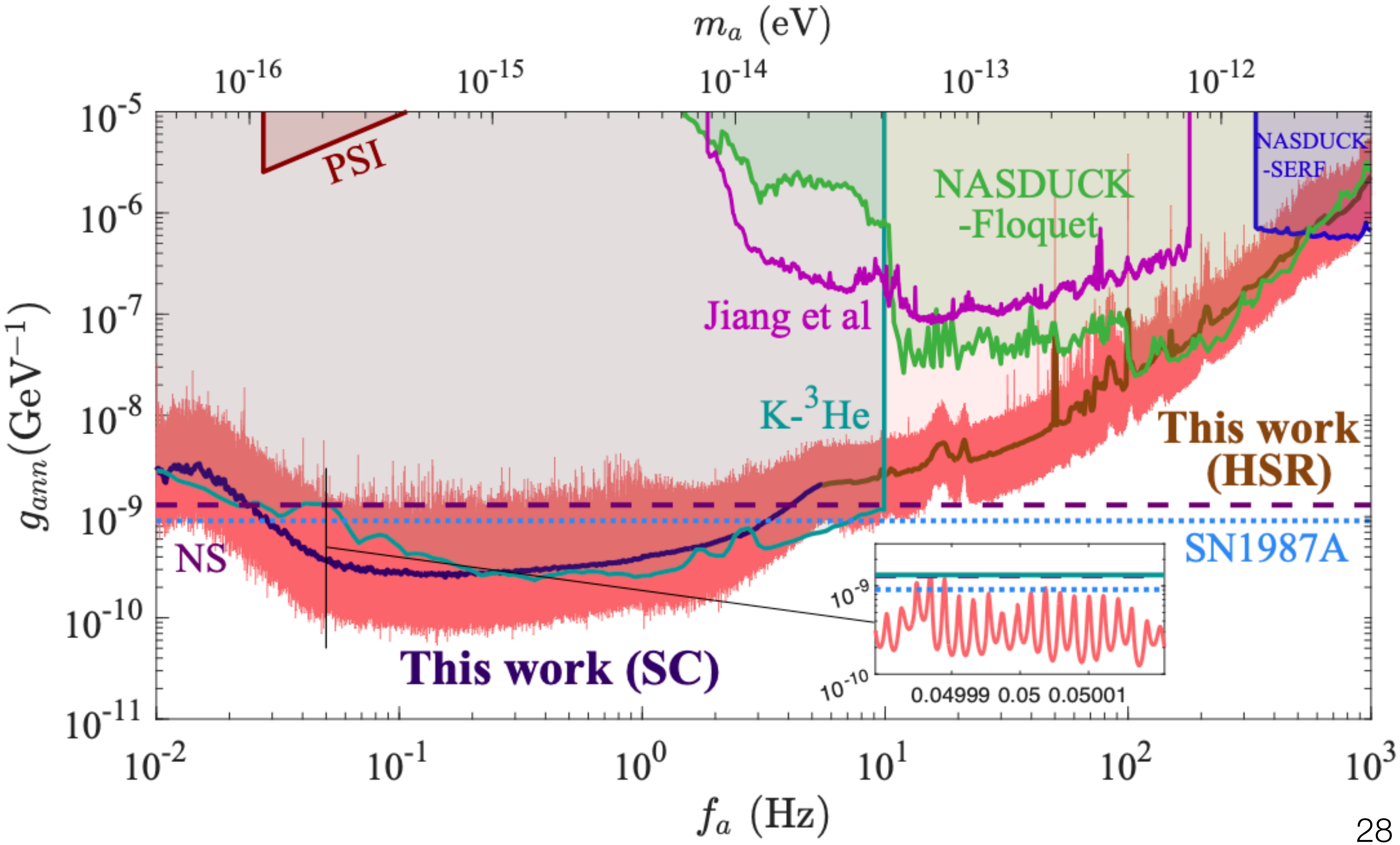
- Search on ALP-neutron coupling g_{ann}
  - The relation between nucleus coupling and nucleon coupling
    $g_{aNN} = \xi_n g_{ann} + \xi_p g_{app}$
  - Spin polarization fraction to Ne
    $\xi_n^{\mathrm{Ne}} = 0.58$ and $\xi_p^{\mathrm{Ne}} = 0.04$





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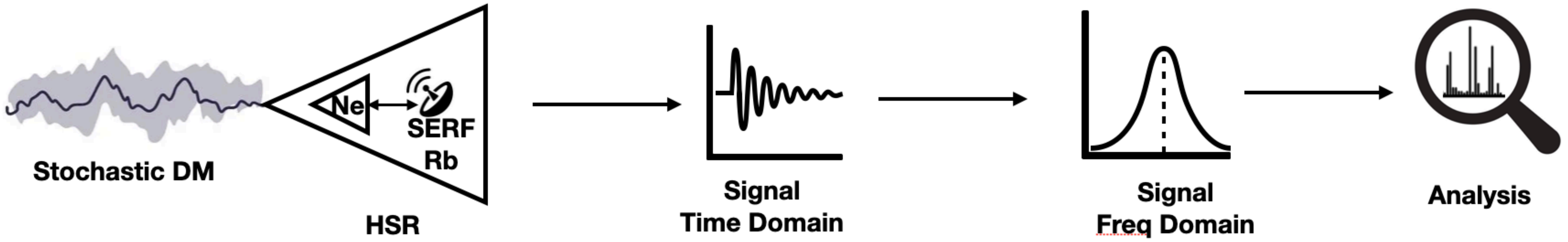
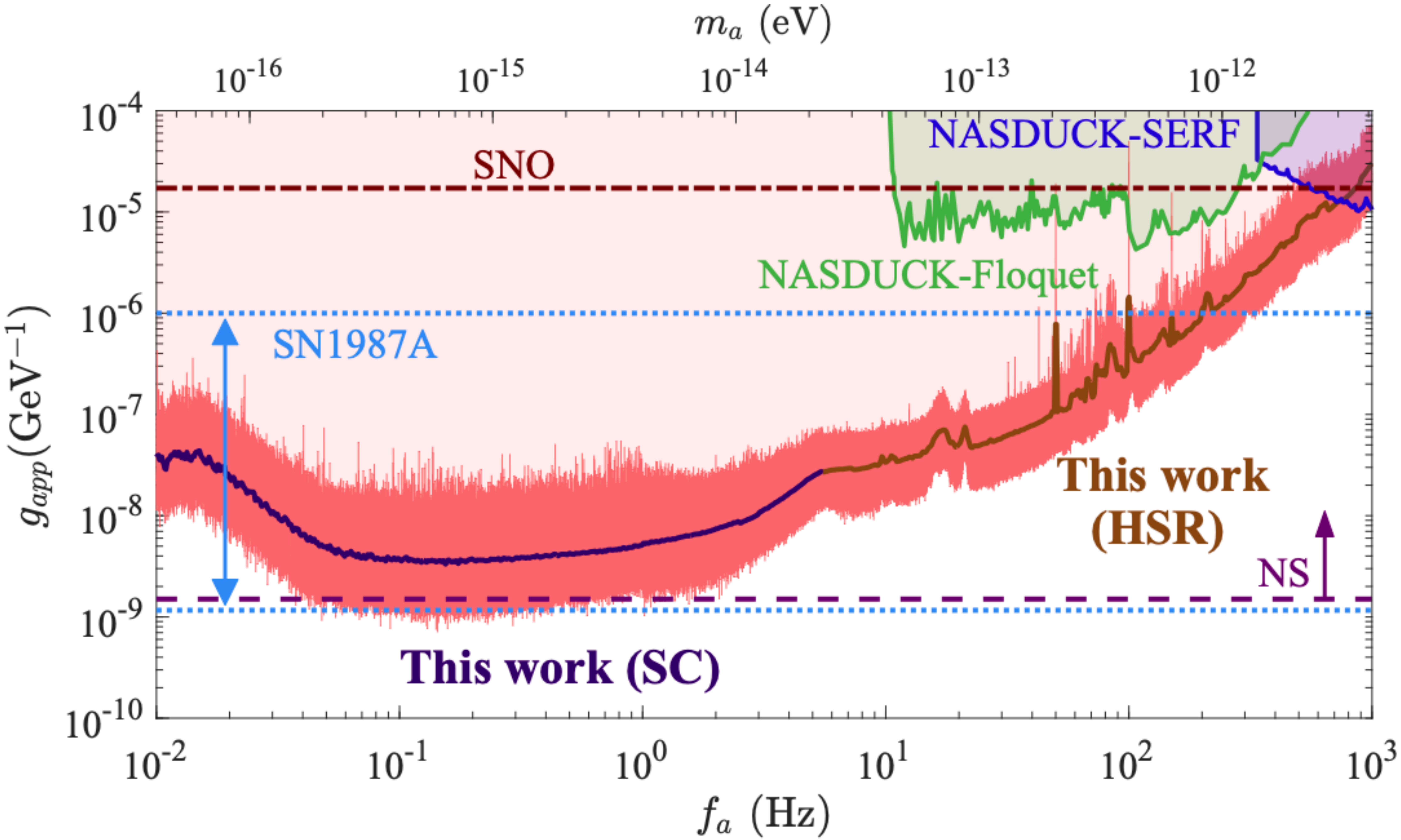
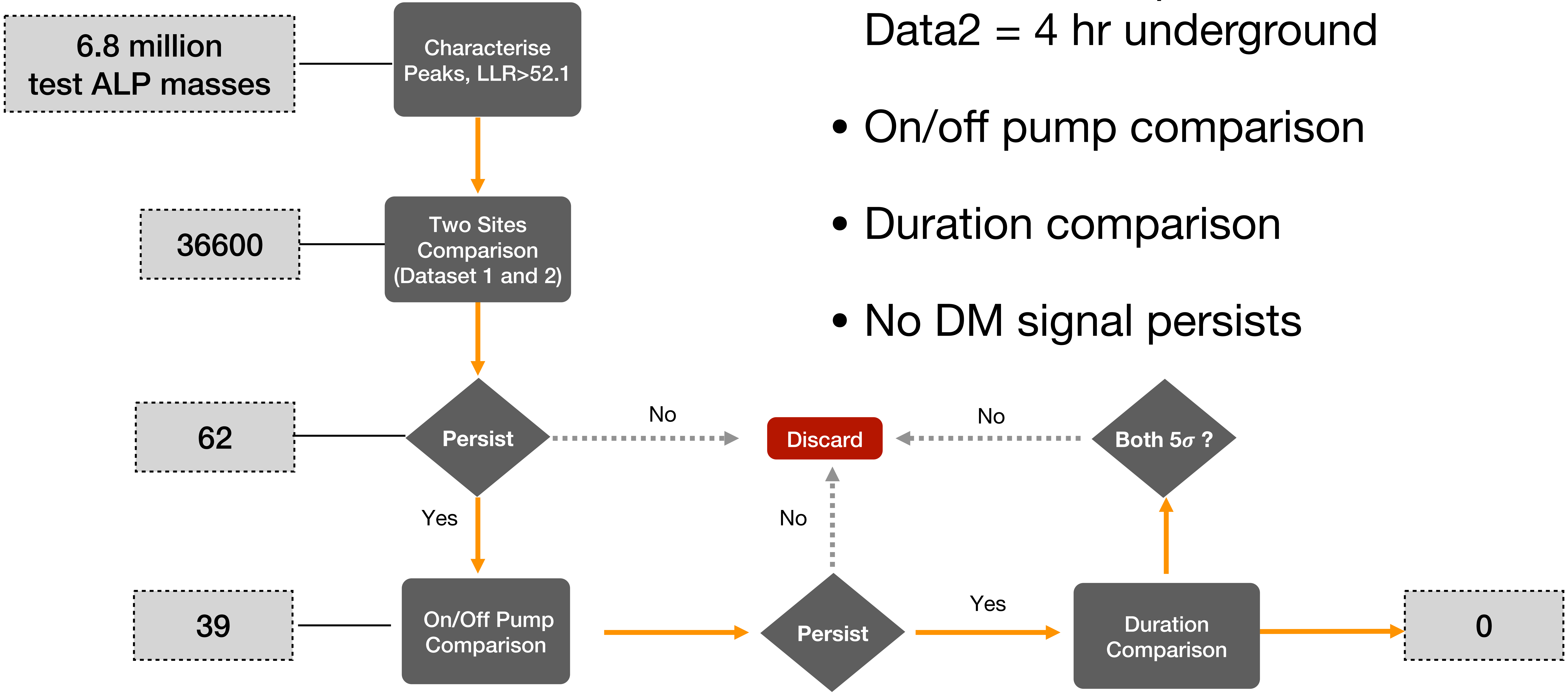




Possible DM candidates analysis



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

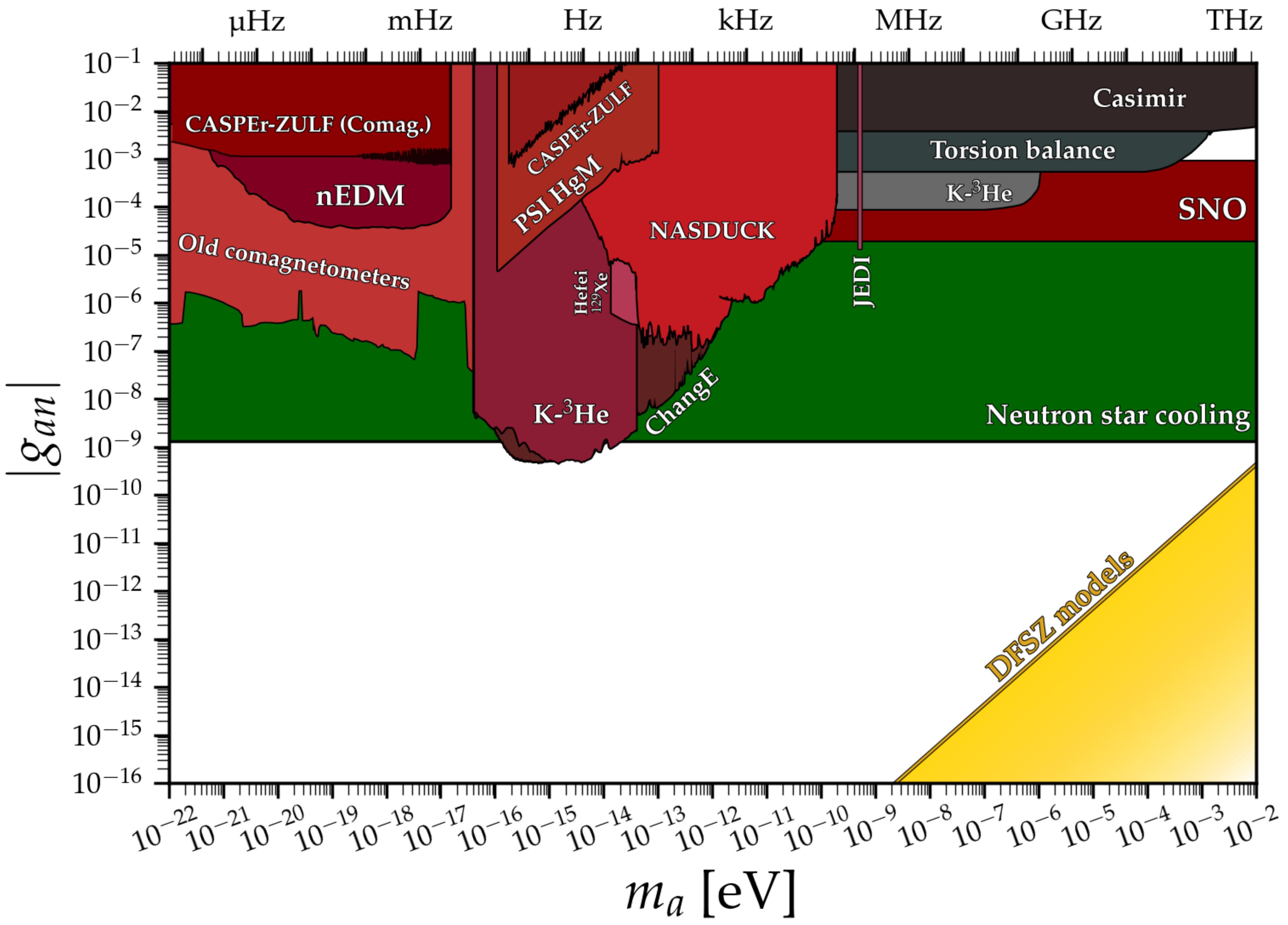
Possible DM candidates analysis

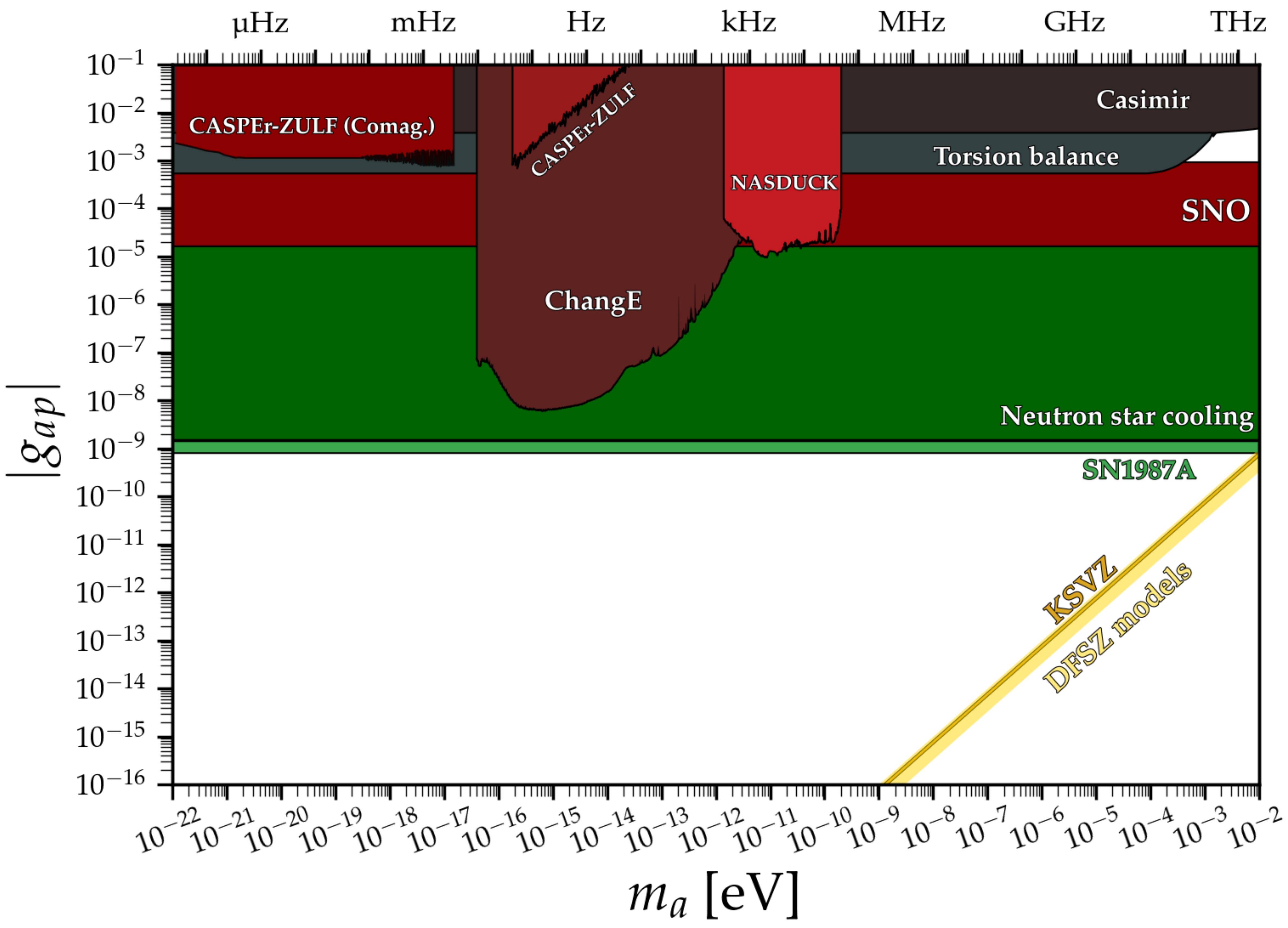
- Two-sites comparison
- On/off pump comparison
- Duration comparison
- No DM signal persists!

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 (✓)	✗

Summary

- 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 ~[0.02, 0.2] Hz and [10, 200] Hz





Summary

- 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 ~[0.02, 0.2] Hz and [10, 200] Hz
  - No DM candidates persists!
- The experiments has long duration at single working point
  Data-1 = 209 hr, Data-2 = 4 hr (underground)
  - The sensitivity goes as $T^{1/4}$
  - Long time data taking suffers noise shifts
- Self-compensating mode (146 hr) completes searches at [0.01, 10] Hz
- Noise suppressions play the central role in future improvements

Thank you!

Backup slides

The QCD axion and the Strong CP problem

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

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

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

- $\bar{\theta}$ is invariant under quark chiral rotation

$$d^n_{\mathrm{EDM}} \sim \theta \times 10^{-16} \text{ e cm}$$

- According to neutron EDM experiment

$$d^n_{\mathrm{exp}} < 10^{-26} \text{ e cm}$$

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