# 轴子物理与轴子暗物质

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Based on ArXiv: 2306.08039, 2309.16600, 2312.09491 (ChangE collaboration), 2406.11948

第三届高能物理理论与实验融合发展研讨会日程
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# Outlines

- Axion and its couplings
- Axion couplings to vector mesons
- Axion and axion-like dark matter
- Summary

# 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 $\theta_{\mathrm{CP}}$ ~ 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

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

- According to neutron EDM experiment

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

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

# The Peccei-Quinn solution to Strong CP problem

- Experiment requires $\bar{\theta} = \theta + \arg\left[\det\left[M_u M_d\right]\right] \lesssim 10^{-1}\mathrm{rad}$
- PQ: promote the constant $\bar{\theta}$ to a dynamical field, a
- Vafa-Witten theorem: vector-like theory (QCD) has ground state $\langle\theta\rangle = 0$
- Introduce a *global* PQ-symmetry $U(1)_{\mathrm{PQ}}$, *anomalous* under the QCD
  - The massless Goldstone boson a is called *axion*
  - $a \to a + \kappa f_a \ \Rightarrow \mathcal{S} \to \mathcal{S} + \frac{\kappa}{32\pi^2}\int d^4x G\tilde{G}$ , cancels $\bar{\theta}$
  - Low energy: $\mathscr{L} = \sum_q \bar{q}\left(iD_\mu\gamma^\mu - m_q\right)q - \frac{1}{4}GG + \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G} + \frac{1}{2}\left(\partial_\mu a\right)^2 + \mathscr{L}_{\mathrm{int}}[\partial_\mu a]$

# The axion effective Lagrangian at quark-level

- A more detailed effective Lagrangian

$$\mathscr{L}_{\text{eff},0} = \bar{q}_0(iD_\mu\gamma^\mu - \mathbf{m}_{q,0})q_0 + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2$$
$$+ g_{ag,0}\frac{a}{f_a}G\tilde{G} + g_{a\gamma,0}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{f_a}\left(\bar{q}_L\mathbf{k}_{L,0}\gamma^\mu q_L + \bar{q}_R\mathbf{k}_{R,0}\gamma^\mu q_R + \ldots\right)$$

Bauer et al, PRL 127 (2021), 081803

- Quark mass $\mathbf{m}_{q,0}$ diagonal and real

- Coupling to both left/right fermions $\mathbf{k}_{L,0}$ and $\mathbf{k}_{R,0}$

# The axion-dependent chiral rotation

- Use an axion-dependent chiral rotation to eliminate $aG\tilde{G}$ term

Bauer et al, PRL 127 (2021), 081803

$$q_0(x) = \exp\left[-i(\boldsymbol{\delta}_{q,0} + \boldsymbol{\kappa}_{q,0}\gamma_5)c_{gg}\frac{a(x)}{f_a}\right] q(x) \qquad \mathrm{Tr}(\kappa_{q,0}) = 1$$

- New effective Lagrangian

$$\mathscr{L}_{\text{eff}} = \bar{q}(iD_\mu\gamma^\mu - \mathbf{m}_q(a))q + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2$$

$$+ g_{a\gamma}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{f_a}\left(\bar{q}_L\mathbf{k}_L(a)\gamma^\mu q_L + \bar{q}_R\mathbf{k}_R(a)\gamma^\mu q_R + \ldots\right)$$

# The axion-dependent chiral rotation

- Define the chiral rotations (2-flavor for simplicity)

$$\boldsymbol{\theta}_L \equiv \boldsymbol{\delta}_{q,0} - \boldsymbol{\kappa}_{q,0} \qquad U_L \equiv \exp\left[-i\boldsymbol{\theta}_L a/f_a\right]$$

$$\boldsymbol{\theta}_R \equiv \boldsymbol{\delta}_{q,0} + \boldsymbol{\kappa}_{q,0} \qquad U_R \equiv \exp\left[-i\boldsymbol{\theta}_R a/f_a\right]$$

- The relations between parameters

$$\mathbf{m}_q(a) = U_L^\dagger \mathbf{m}_0 U_R \to \begin{pmatrix} m_{u,0}e^{-2i\kappa_{u,0}c_{gg}} & 0 \\ 0 & m_{d,0}e^{-2i\kappa_{d,0}c_{gg}} \end{pmatrix}$$

$$\mathbf{k}_L(a) = U_L^\dagger[\mathbf{k}_{L,0} + c_{gg}\boldsymbol{\theta}_{L,0}]U_L \to \mathbf{k}_{L,0} + c_{gg}\boldsymbol{\theta}_{L,0}$$

$$\mathbf{k}_R(a) = U_R^\dagger[\mathbf{k}_{R,0} + c_{gg}\boldsymbol{\theta}_{R,0}]U_R \to \mathbf{k}_{R,0} + c_{gg}\boldsymbol{\theta}_{R,0}$$

**Anomalous axion contribution**

$$g_{a\gamma} = g_{a\gamma_0} - 2N_c c_{gg}\mathrm{Tr}\left[\mathbf{Q}^2\boldsymbol{\kappa}_{q,0}\right]$$

# The consistent ChPT axion Lagrangian

$$\mathcal{L}_{\rm eff} = \bar{q}(iD_\mu\gamma^\mu - \mathbf{m}_q(a))q + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2$$

$$+g_{a\gamma}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{f_a}\left(\bar{q}_L\mathbf{k}_L(a)\gamma^\mu q_L + \bar{q}_R\mathbf{k}_R(a)\gamma^\mu q_R + \ldots\right)$$

- ChPT Lagrangian matching for PS mesons $U = \exp[(\sqrt{2}i/f_\pi)\pi^a\boldsymbol{\tau}^a]$

$$\mathcal{L}_{\chi\rm PT} = \frac{f_\pi^2}{8}\left[(D^\mu U)(D_\mu U)^\dagger\right] + \frac{f_\pi^2}{4}B_0{\rm Tr}\left[\mathbf{m}_q(a)U^\dagger + h.c.\right] + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + g_{a\gamma}\frac{a}{f_a}F\tilde{F}$$

- The axion derivative coupling

Bauer et al, PRL 127 (2021), 081803

$$D^\mu U \to D^\mu U - i\frac{\partial^\mu a}{f_a}\left(\mathbf{k}_L U - U\mathbf{k}_R\right)$$

# The importance of consistency

- The physical results should be independent of auxiliary parameters

$$q_0(x) = \exp\left[-i(\boldsymbol{\delta}_{q,0} + \boldsymbol{\kappa}_{q,0}\gamma_5)c_{gg}\frac{a(x)}{f_a}\right] q(x)$$

- The most important channel BR($K \to \pi a$) is off by a factor of 37 for 35 years

H. Georgi, D. B. Kaplan and L. Randall, Phys. Lett. B 169, 73-78 (1986)

- Model-independent expression for $K \to \pi a$ and $\pi^- \to e^- \bar{\nu}_e a$ have been obtained for all axion couplings

Bauer et al, PRL 127 (2021), 081803

- The electroweak scale axion (PQWW) is excluded by e.g. meson experiments like K meson and $J/\Psi$ decay immediately

# The invisible axion models

- SM particles does not directly charge under $U(1)_{\rm PQ}$
  - KSVZ model:
    - Heavy vector-like quark: $Q_{L,R}$
    - $Q_L$ and $Q_R$ has different charge under $U(1)_{\rm PQ}$
    - A heavy complex scalar $\Phi = re^{ia}$ charge under $U(1)_{\rm PQ}$
    - Yukawa: $y\Phi\bar{Q}_L Q_R \supset \frac{yf_a}{\sqrt{2}} e^{ia/f_a}\bar{Q}_L Q_R$
    - $\mathscr{L} \supset \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G\tilde{G}$

# The invisible axion models

- DFSZ model:

  - Two Higgs doublet $H_{u,d}$ and a complex singlet $\Phi$ charged under $U(1)_{\text{PQ}}$, with phase factor $e^{i\phi_{u,d,0}}$

  - Similar to previous UV model, but $\langle\Phi\rangle \gg v_h$

  - Yukawa: $\left(\bar{Q}Y_u H_u u_R + \bar{Q}Y_d H_d d_R + \bar{L}Y_e H_d e_R\right) + h.c.$

  - Potential term: e.g. $H_u H_d \Phi^2$, Axion mode: $a = \frac{1}{f_a}\sum_{i=u,d,0} Q_i v_i \phi_i$

  - Axion have direct quark and lepton couplings

  - Low energy: $\mathscr{L} \supset \frac{\alpha_s}{8\pi^2}\frac{a}{f_a}G\tilde{G} + \frac{\alpha_{em}}{8\pi}\frac{E}{N}\frac{a}{f_a}F\tilde{F} - \bar{f}_L M_f f_R + \frac{\partial_\mu a}{2f_a}\bar{f}c_f\gamma^\mu\gamma_5 f$

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# Wess-Zumino-Witten Interactions in QCD

- Describing anomalies in QCD
- Ensuring gauge invariance and completing chiral L
- Low-energy dynamics of mesons
  e.g. multiple mesons and photons interactions, $\pi_0 \to \gamma\gamma$

$$\begin{aligned}\Gamma_{WZW}(U,\mathcal{A}_L,\mathcal{A}_R) = \Gamma_0(U) \; &+ \mathcal{C}\int \mathrm{Tr}\Big\{(\mathcal{A}_L\alpha^3 + \mathcal{A}_R\beta^3) - \frac{i}{2}[(\mathcal{A}_L\alpha)^2 - (\mathcal{A}_R\beta)^2] \\ &+ i(\mathcal{A}_L U\mathcal{A}_R U^\dagger\alpha^2 - \mathcal{A}_R U^\dagger\mathcal{A}_L U\beta^2) + i(d\mathcal{A}_R dU^\dagger\mathcal{A}_L U - d\mathcal{A}_L dU\mathcal{A}_R U^\dagger) \\ &+ i\big[(d\mathcal{A}_L\mathcal{A}_L + \mathcal{A}_L d\mathcal{A}_L)\alpha + (d\mathcal{A}_R\mathcal{A}_R + \mathcal{A}_R d\mathcal{A}_R)\beta\big] + (\mathcal{A}_L^3\alpha + \mathcal{A}_R^3\beta) \\ &- (d\mathcal{A}_L\mathcal{A}_L + \mathcal{A}_L d\mathcal{A}_L)U\mathcal{A}_R U^\dagger + (d\mathcal{A}_R\mathcal{A}_R + \mathcal{A}_R d\mathcal{A}_R)U^\dagger\mathcal{A}_L U \\ &+ (\mathcal{A}_L U\mathcal{A}_R U^\dagger\mathcal{A}_L\alpha + \mathcal{A}_R U^\dagger\mathcal{A}_L U\mathcal{A}_R\beta) + i\left[\mathcal{A}_L^3 U\mathcal{A}_R U^\dagger - \mathcal{A}_R^3 U^\dagger\mathcal{A}_L U - \frac{1}{2}(U\mathcal{A}_R U^\dagger\mathcal{A}_L)^2\right]\Big\}.\end{aligned}$$

$$\Gamma_0(U) = -\frac{i\mathcal{C}}{5}\int_{M^5}\mathrm{Tr}\left(\alpha^5\right) = \frac{iN_c}{240\pi^2}\int d^5x\,\epsilon^{ABCDE}\;\mathrm{Tr}\left(\alpha_A\alpha_B\alpha_C\alpha_D\alpha_E\right),$$

$$\alpha = dUU^\dagger$$
$$\beta = U^\dagger dU$$

# WZW counter terms for global symmetry

J. A. Harvey, C. T. Hill, and R. J. Hill,
PRL 99 (2007) 261601,
PRD 77(2008) 085017

- Generic WZW interactions with counter terms
  - Vector fields in 1-form: $\mathscr{A}_{L/R} \equiv \mathbb{A}_{L/R} + \mathbb{B}_{L/R}$
    Similar to Hidden Local Symmetry

$$\mathscr{L}^{\text{full}}_{\text{WZW}}(U, \mathscr{A}_{L/R}) = \mathscr{L}_{\text{WZW}}(U, \mathscr{A}_L, \mathscr{A}_R) + \mathscr{L}_c(\mathbb{A}_{L/R}, \mathbb{B}_{L/R})$$

- Counter terms ensures SM invariance

$$\Gamma_c = -2\mathscr{C}\int Tr\Big[(\mathbb{A}_L d\mathbb{A}_L + d\mathbb{A}_L \mathbb{A}_L)\mathbb{B}_L + \frac{1}{2}\mathbb{A}_L(\mathbb{B}_L d\mathbb{B}_L + d\mathbb{B}_L \mathbb{B}_L) - \frac{3}{2} i \mathbb{A}_L^3 \mathbb{B}_L - \frac{3}{4} i \mathbb{A}_L \mathbb{B}_L \mathbb{A}_L \mathbb{B}_L - \frac{i}{2}\mathbb{A}_L \mathbb{B}_L^3\Big] - (L \leftrightarrow R)$$

- Suitable for chiral gauge fields and background fields

# Axion treatment as a fictitious background field

$$\mathscr{L}_{\text{eff}} = \bar{q}(iD_\mu\gamma^\mu - \mathbf{m}_q(a))q + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2$$

$$+ g_{a\gamma}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{f_a}\left(\bar{q}_L \mathbf{k}_L(a)\gamma^\mu q_L + \bar{q}_R \mathbf{k}_R(a)\gamma^\mu q_R + \ldots\right)$$

Yang Bai, Ting-Kuo Chen, JL, Xiaolin Ma
2406.11948

- $D_\mu = \partial_\mu - ig(A_L P_L + A_R P_R)$
- Hints from quark-level L: $D_\mu \to D_\mu + i\frac{\partial_\mu a}{f_a}\left(\mathbf{k}_L P_L + \mathbf{k}_R P_R\right)$
- Hints from ChPT L: $D^\mu U \to D^\mu U - i\frac{\partial^\mu a}{f_a}\left(\mathbf{k}_L U - U\mathbf{k}_R\right)$

$$\mathscr{L}_{\chi\text{PT}} = \frac{f_\pi^2}{8}\left[(D^\mu U)(D_\mu U)^\dagger\right] + \frac{f_\pi^2}{4}B_0 \text{Tr}\left[\mathbf{m}_q(a)U^\dagger + h.c.\right] + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + g_{a\gamma}\frac{a}{f_a}F\tilde{F}$$

# Axion treatment as a fictitious background field

- Vector fields in 1-form: $\mathscr{A}_{L/R} \equiv \mathbb{A}_{L/R} + \mathbb{B}_{L/R}$
  Similar to Hidden Local Symmetry

- Axion 1-form field can be added into background fields:

$$\mathbb{B}_{L/R} \to \mathbb{B}_{L/R} + \mathbf{k}_{L/R,0}\frac{da}{f_a}$$

- 2-flavor ChPT with SM gauge bosons and background fields

$$\mathbb{A}_L = \frac{e}{s_W} W^a \frac{\boldsymbol{\tau}^a}{2} + \frac{e}{c_W} W^0 \mathbf{Y}_Q, \ \mathbb{A}_R = \frac{e}{c_W} W^0 \mathbf{Y}_q$$

$$\mathbb{B}_V \equiv \mathbb{B}_L + \mathbb{B}_R = g\begin{pmatrix} \rho_0 & \sqrt{2}\rho^+ \\ \sqrt{2}\rho^- & -\rho_0 \end{pmatrix} + g'\begin{pmatrix} \omega & \\ & \omega \end{pmatrix} + (\mathbf{k}_{L,0} + \mathbf{k}_{R,0})\frac{da}{f}$$

$$\mathbb{B}_A \equiv \mathbb{B}_L - \mathbb{B}_R = g\begin{pmatrix} a_1 & \sqrt{2}a^+ \\ \sqrt{2}a^- & -a_1 \end{pmatrix} + g'\begin{pmatrix} f_1 & \\ & f_1 \end{pmatrix} + (\mathbf{k}_{L,0} - \mathbf{k}_{R,0})\frac{da}{f}$$

# The consistent axion Lagrangian at low energy

- ChPT:

$$\mathscr{L}_{\chi\mathrm{PT}} = \frac{f_\pi^2}{8}\mathrm{Tr}\left[(D^\mu U)(D_\mu U)^\dagger\right] + \frac{f_\pi^2}{4}B_0\,\mathrm{Tr}\left[\mathbf{m}_q(a)U^\dagger + h.c.\right] + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}a^2 + \frac{a}{f}\sum_{\mathscr{A}_{1,2}} c_{\mathscr{A}_1\mathscr{A}_2} F_{\mathscr{A}_1\,\mu\nu}\widetilde{F}^{\mu\nu}_{\mathscr{A}_2}$$

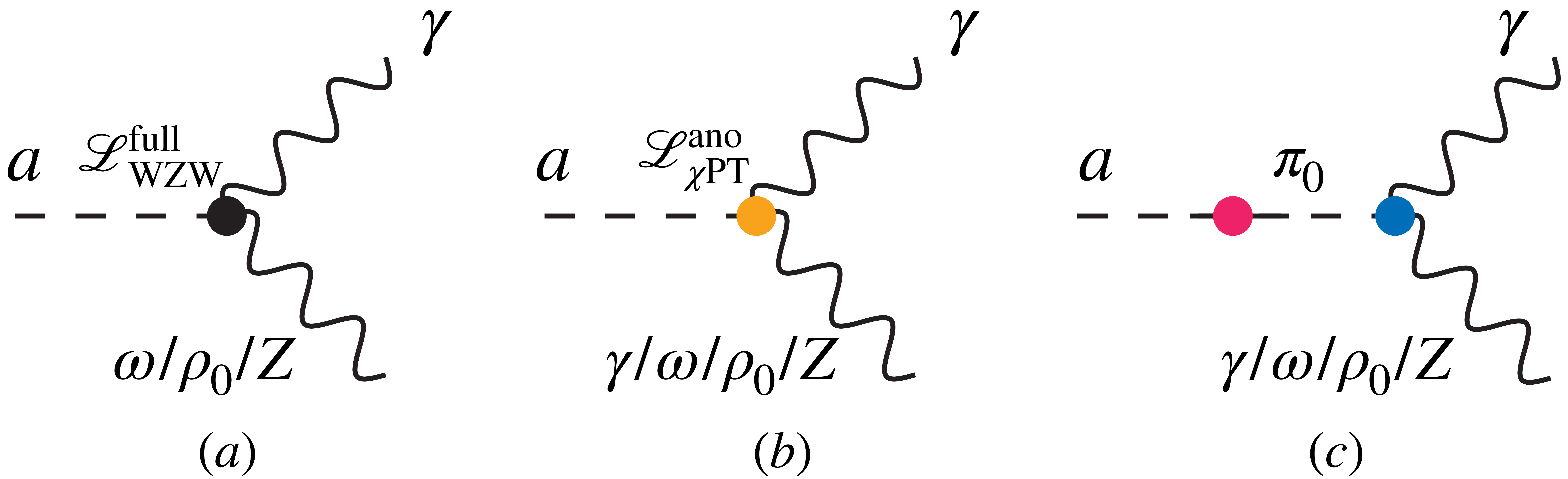
- Full WZW: $\mathscr{L}^{\mathrm{full}}_{\mathrm{WZW}}(U,\mathscr{A}_{L/R}) = \mathscr{L}_{\mathrm{WZW}}(U,\mathscr{A}_L,\mathscr{A}_R) + \mathscr{L}_c(\mathbb{A}_{L/R},\mathbb{B}_{L/R})$

- Full $\mathscr{L}$: $\mathscr{L}^{\mathrm{full}}_{\mathrm{axion}} \equiv \left[\mathscr{L}_{\chi\mathrm{PT}} + \mathscr{L}^{\mathrm{full}}_{\mathrm{WZW}}\right]\left(U, \mathbf{m}_q(a), \mathscr{A}_{L/R} + \mathbf{k}_{L/R}(a)da/f_a\right)$

# Consistent physical amplitudes

- A consistent Lagrangian will give physical amplitudes independent of auxiliary rotations

- Full WZW interactions are important for a-A-B amplitudes



# Consistent amplitudes for three point vertex

$$c_{\gamma\gamma}^{\text{eff}} = c_{\gamma\gamma}^{0} + \frac{e^2 c_{gg}}{16\pi^2 f}\left(-\frac{10}{3} - 2\frac{m_u - m_d}{m_u + m_d}\frac{m_\pi^2}{m_a^2 - m_\pi^2}\right) - \frac{e^2}{16\pi^2 f}\frac{m_a^2}{m_\pi^2 - m_a^2}(c_u - c_d)$$

$$c_{\omega\gamma}^{\text{eff}} = eg'\left\{\frac{-c_{gg}}{8\pi^2 f} - \frac{3}{8\pi^2 f}\left[\frac{m_a^2}{m_\pi^2 - m_a^2}\left(\frac{c_u - c_d}{2}\right) + c_{gg}\frac{m_u - m_d}{m_u + m_d}\frac{m_\pi^2}{m_a^2 - m_\pi^2}\right] + \frac{1}{16\pi^2 f}(c_d + c_Q - 2c_u)\right\}$$

$$c_{\rho\gamma}^{\text{eff}} = eg\left\{\frac{-3c_{gg}}{8\pi^2 f} - \frac{1}{8\pi^2 f}\left[\frac{m_a^2}{m_\pi^2 - m_a^2}\left(\frac{c_u - c_d}{2}\right) + c_{gg}\frac{m_u - m_d}{m_u + m_d}\frac{m_\pi^2}{m_a^2 - m_\pi^2}\right] + \frac{1}{16\pi^2 f}\left(3c_Q - 2c_u - c_d\right)\right\}$$

$$c_{\gamma Z}^{\text{eff}} = c_{\gamma Z}^{0} + \frac{N_c c_{gg}}{48\pi^2 f}\frac{e^2}{s_w c_w}(-9 + 20 s_w^2) - c_{\pi_0}\frac{f_\pi}{\sqrt{2}f}\left(\frac{m_a^2}{m_\pi^2 - m_a^2}\frac{c_d - c_u}{2} - c_{gg}\frac{m_u - m_d}{m_u + m_d}\frac{m_\pi^2}{m_a^2 - m_\pi^2}\right) - \frac{N_c}{48\pi^2 f}\frac{2e^2}{s_{2w}}(c_d + 2c_u + 3c_Q)$$

- Vertex $\omega \to \gamma a$ benefit from large $g' \approx 5.7 \gg e$

$\mathbf{k}_{L,0} = \{c_Q, c_Q\}$ $\mathbf{k}_{R,0} = \{c_u, c_d\}$

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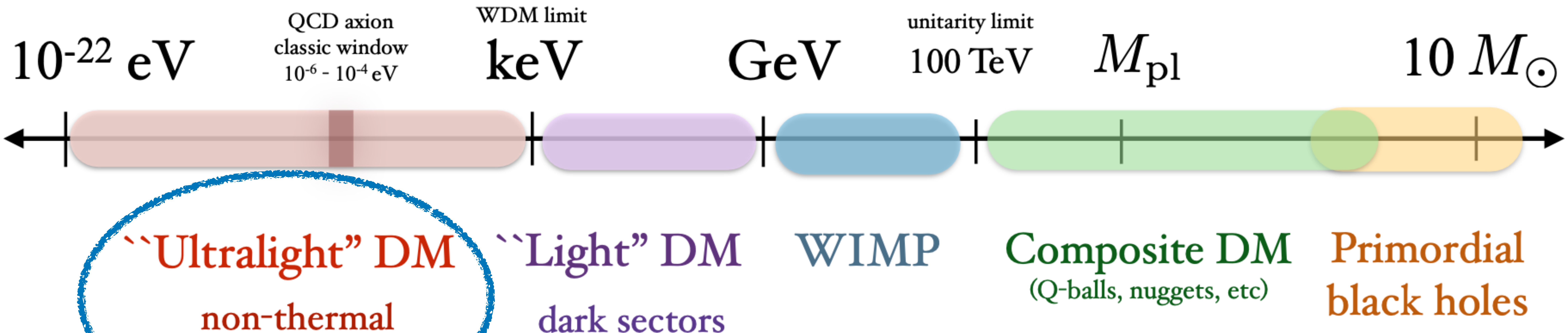
# The dark matter candidate models

1904.07915， TASI lecture



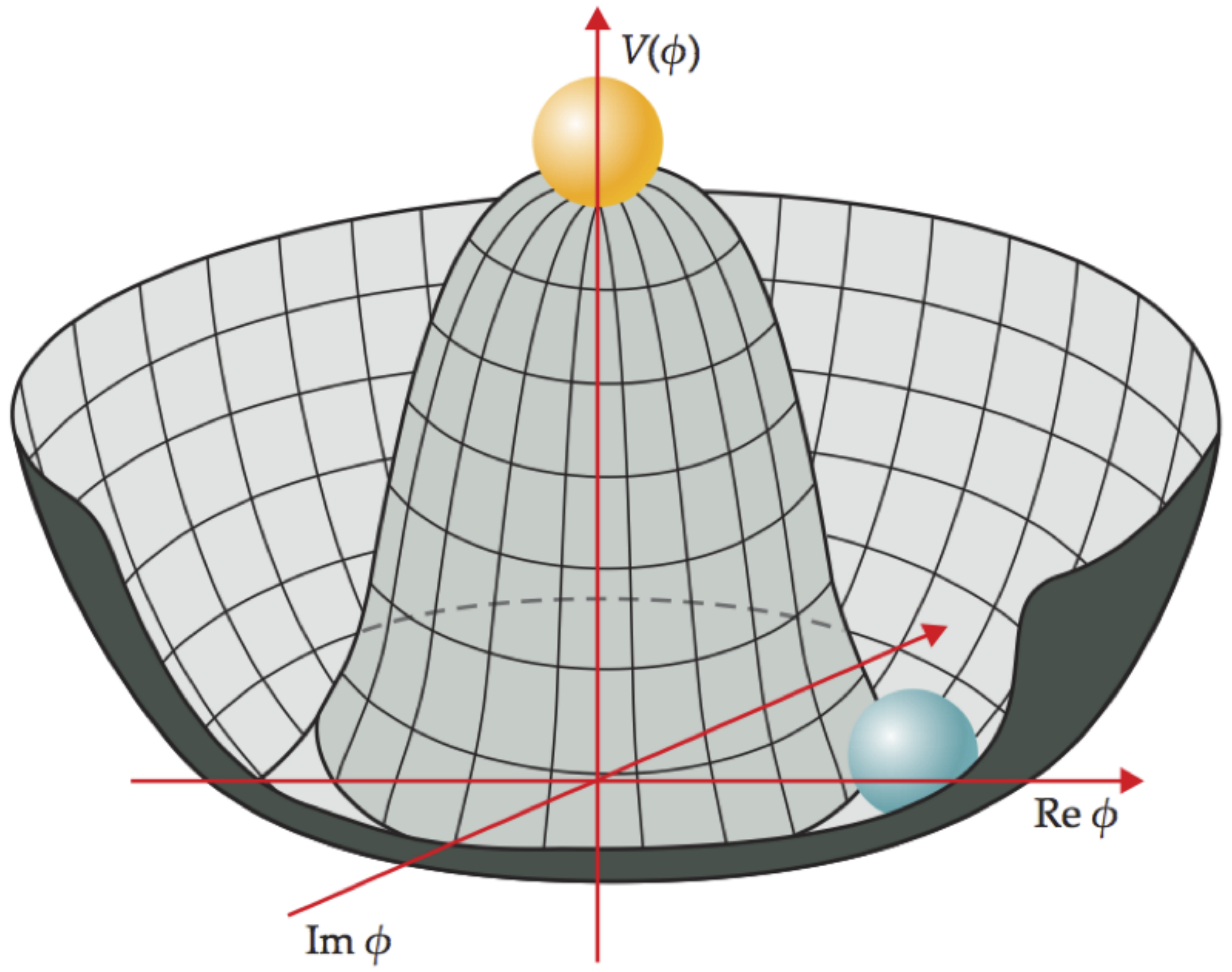

**Axion and ALP dark matter**


**HEP at a cross-road: explore all directions!**

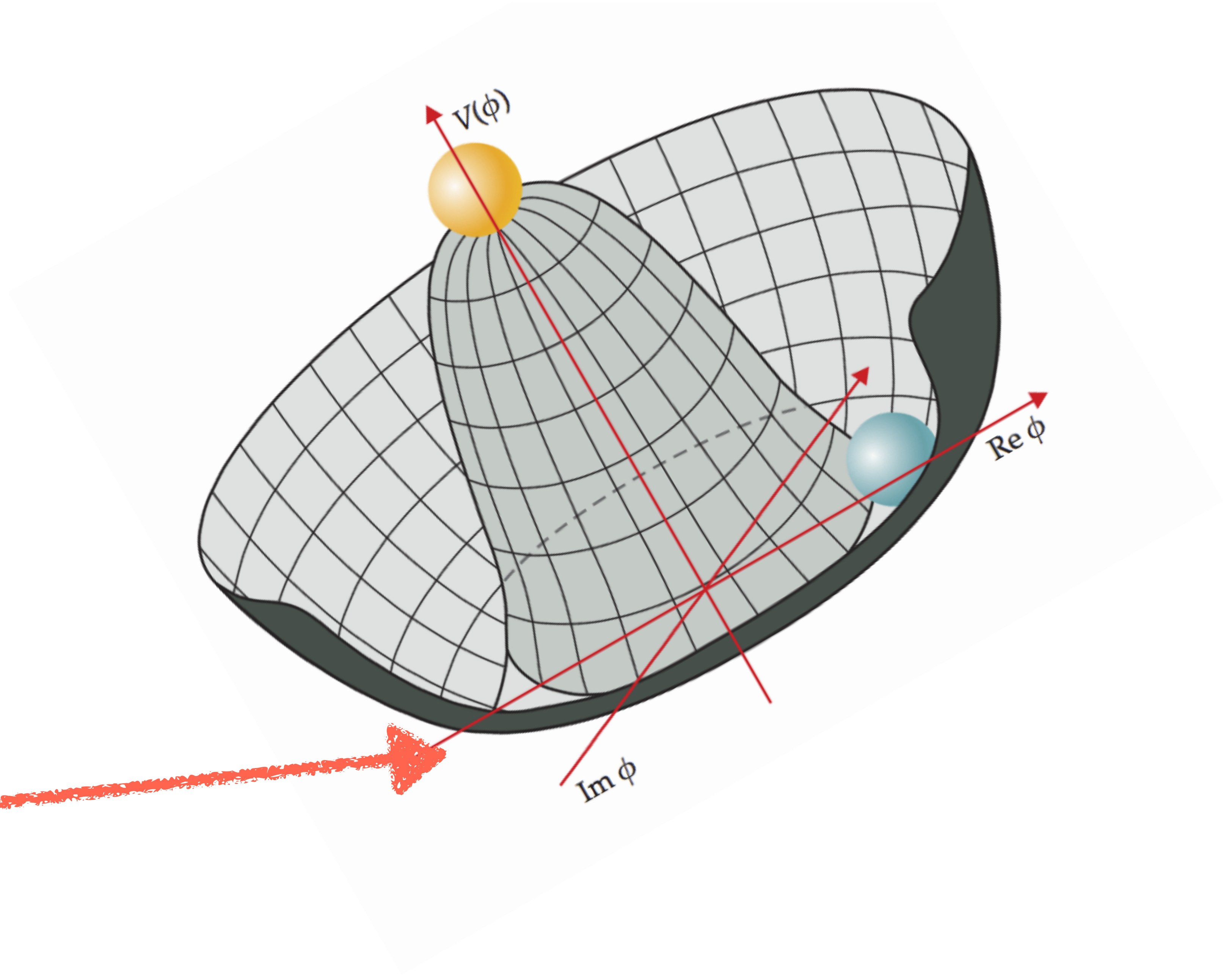
# Misalignment and Axion Dark Matter

- Global U(1)$_{PQ}$ symmetry
  - Spontaneous broken leads to massless goldstone (Axion)

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$




- At QCD scale ~ O(1) GeV,
  - Potential from Chiral Lagrangian explicitly breaks the symmetry leads to massive axion
  - Energy stored in coherent oscillation of axion field
  - When $m_\phi \sim \frac{\Lambda^2}{f_\phi} \sim H$, misalignment happens and the fields turns into particles: cold dark matter
  - QCD vacuum picks $\Theta = \theta_{\rm QCD} + \xi \langle a \rangle / f_a = 0$

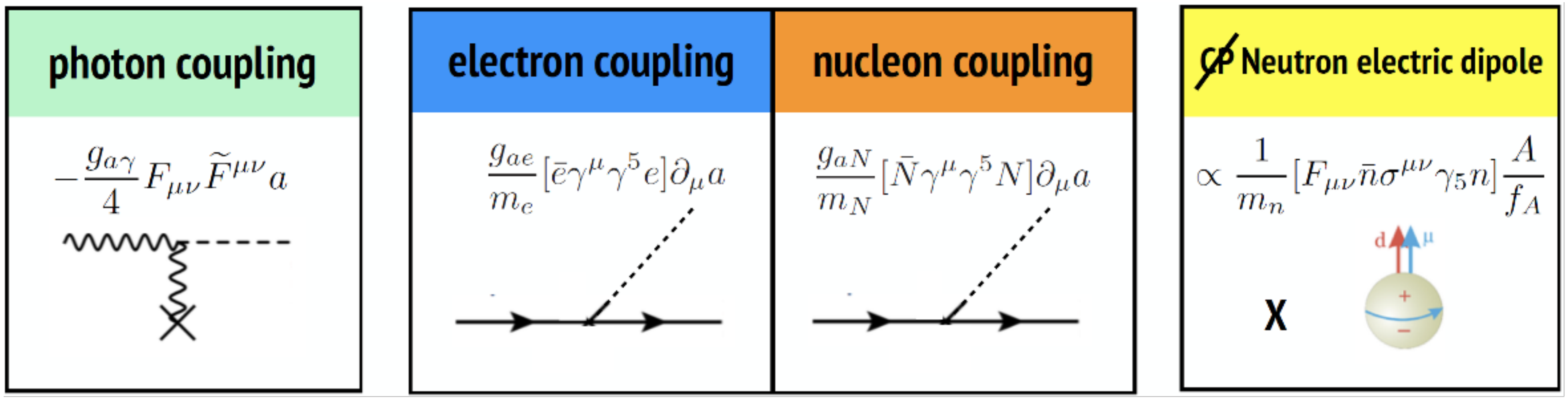


# The axion effective Lagrangian at quark-level

- Axion can couple to SM gauge bosons and fermions

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

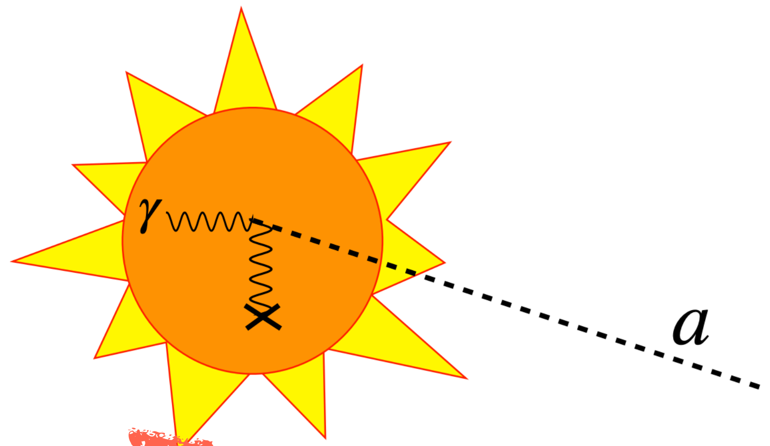
- Detection of axion through various couplings

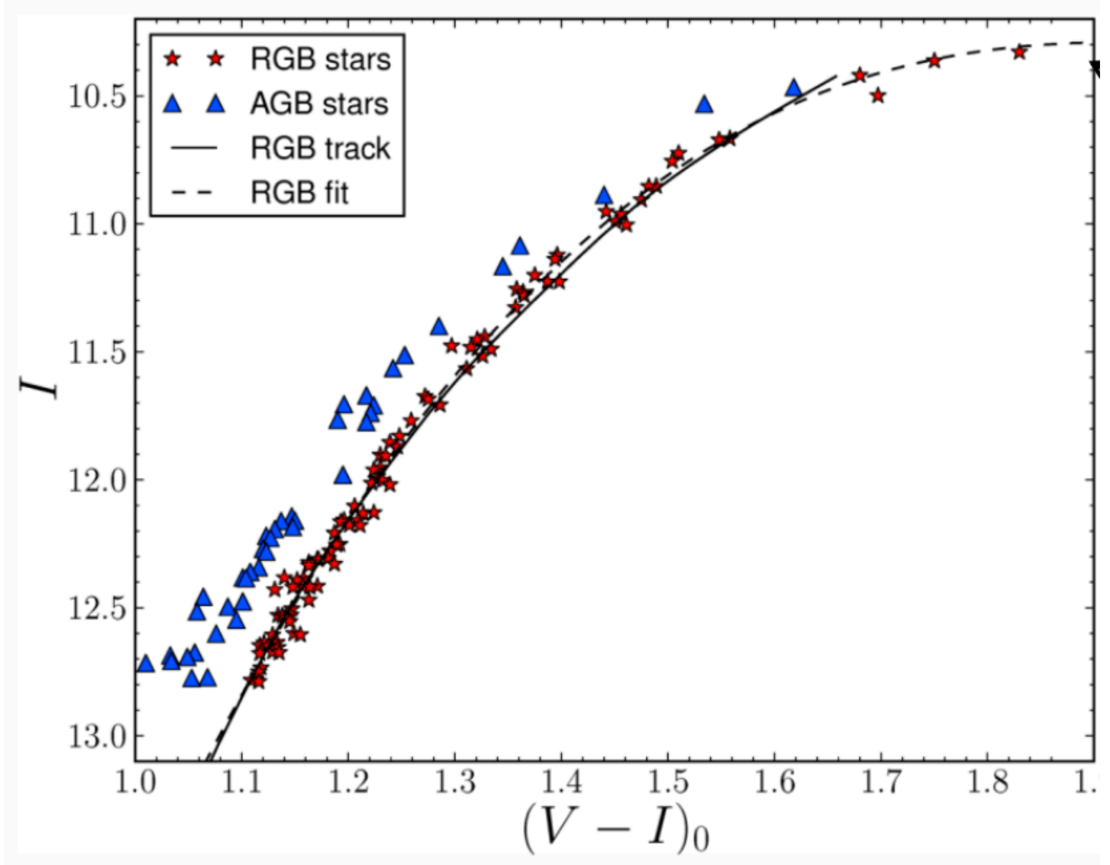


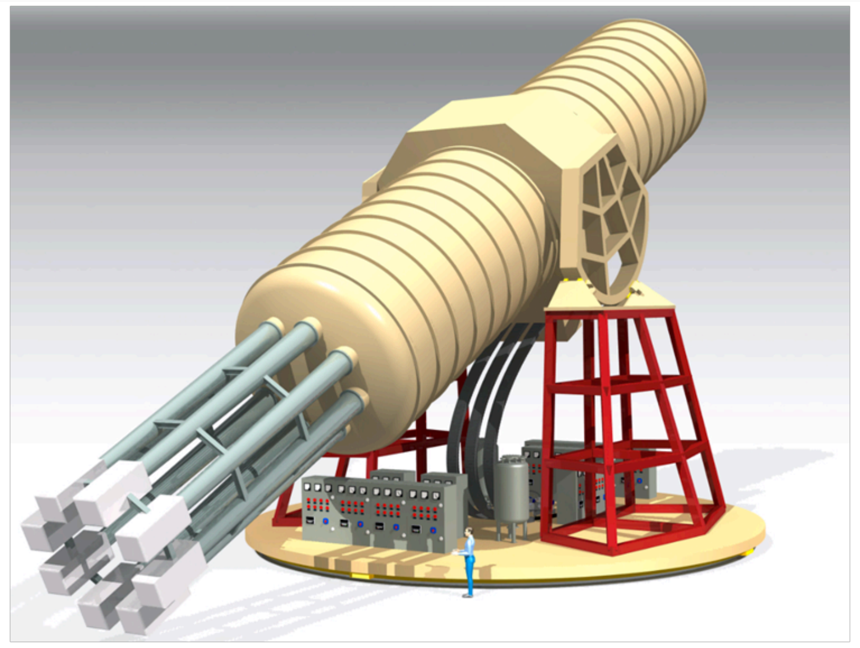
# Experimental searches for Axion-Like Particles axion

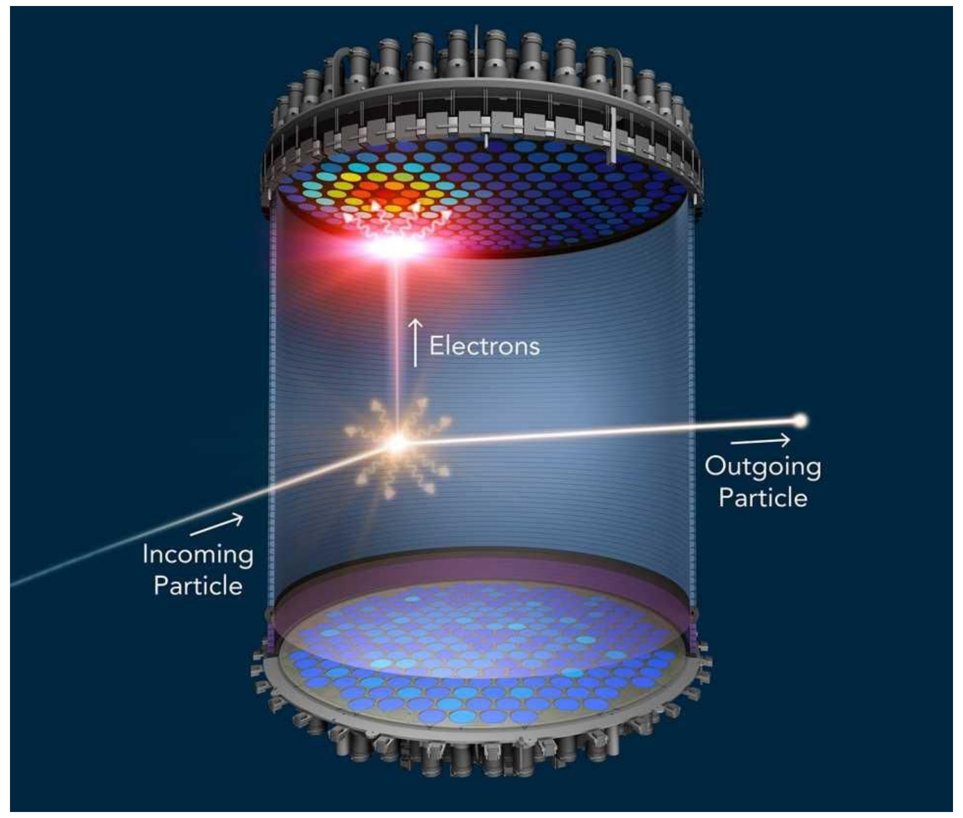
**Methodology:**

- Dark Matter Axion: haloscopes ..
- Axion independent searches:
  - Rare meson decays
  - Stellar cooling
  - Supernova
  - Helioscopes: solar axion (CAST, IAXO, or DM direct detection searches)
  - Light shining through walls
  - Polarization
  - Fifth force
  - Radio wave detection



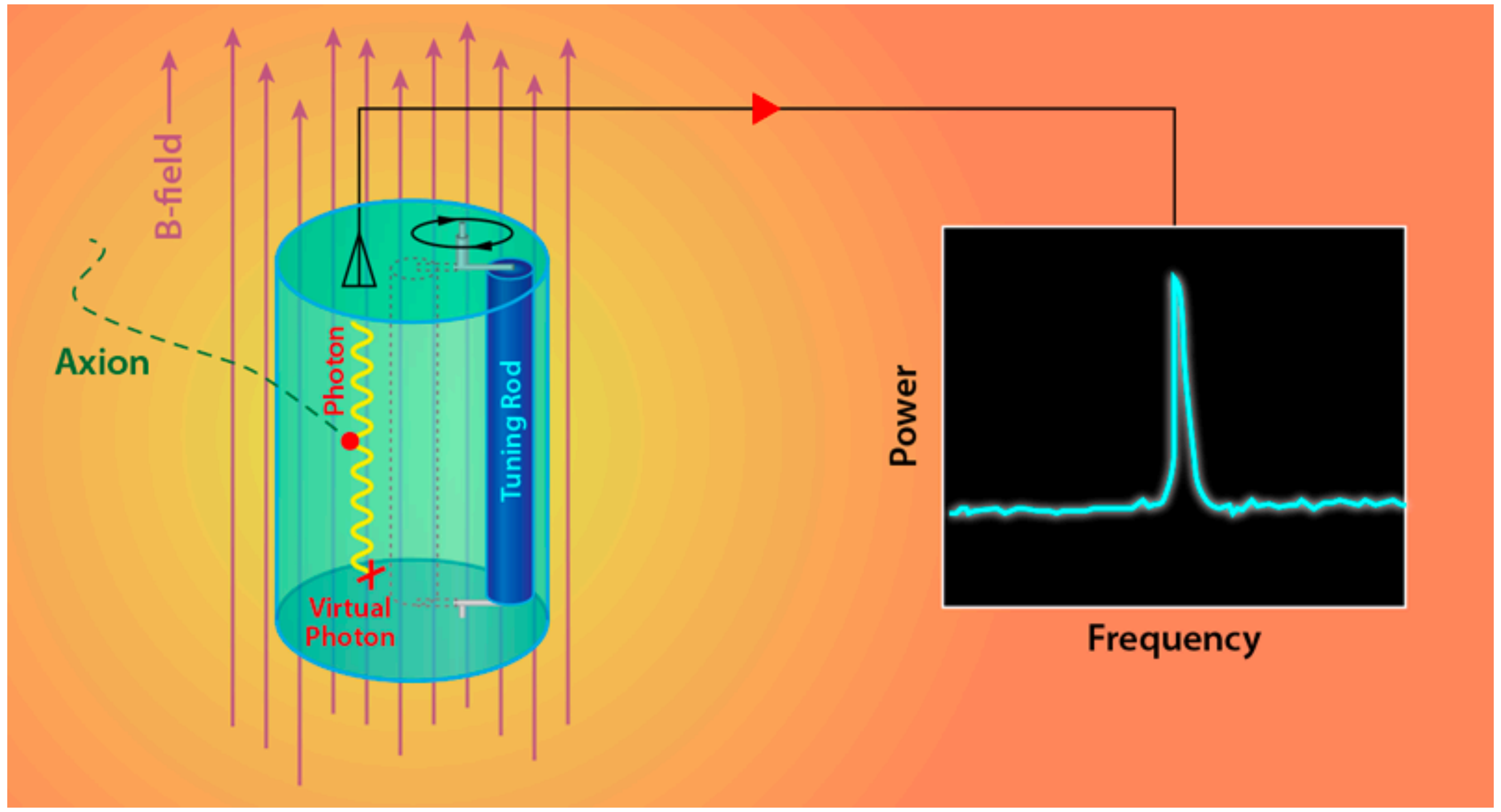





# The detection of ultralight bosonic dark matter

- 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: (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

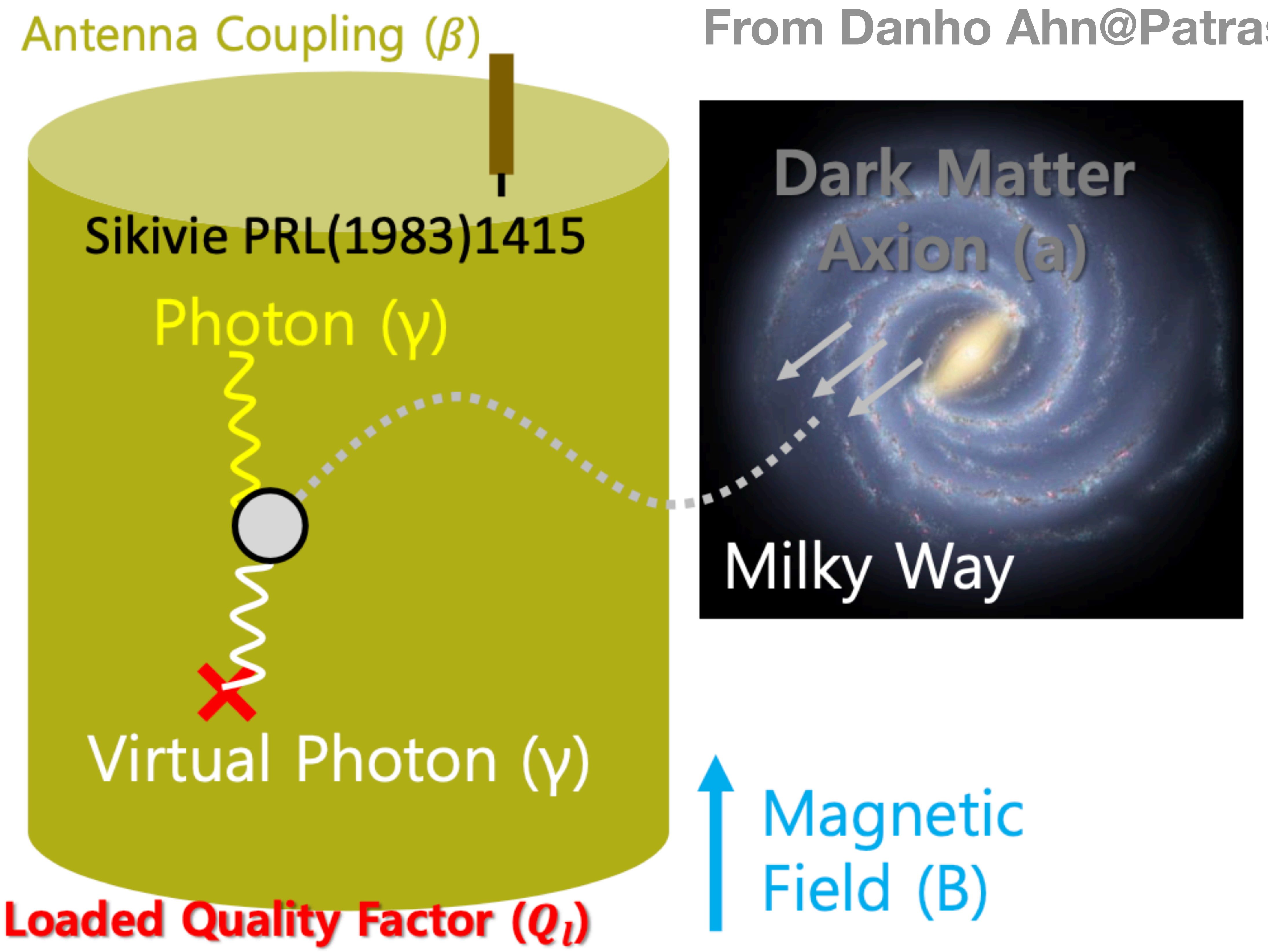
$$g_{a\gamma\gamma} a F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} F_{\alpha\beta} \sim g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

# 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




**Loaded Quality Factor ($Q_l$)**
Volume (V)
Resonant Angular Frequency ($\omega_0$)
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 ($\rho_a$); Axion Mass ($m_a^2$); Axion Quality Factor ($Q_a$)

Kim *et al.* JCAP03(2020)066

Scan Rate

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

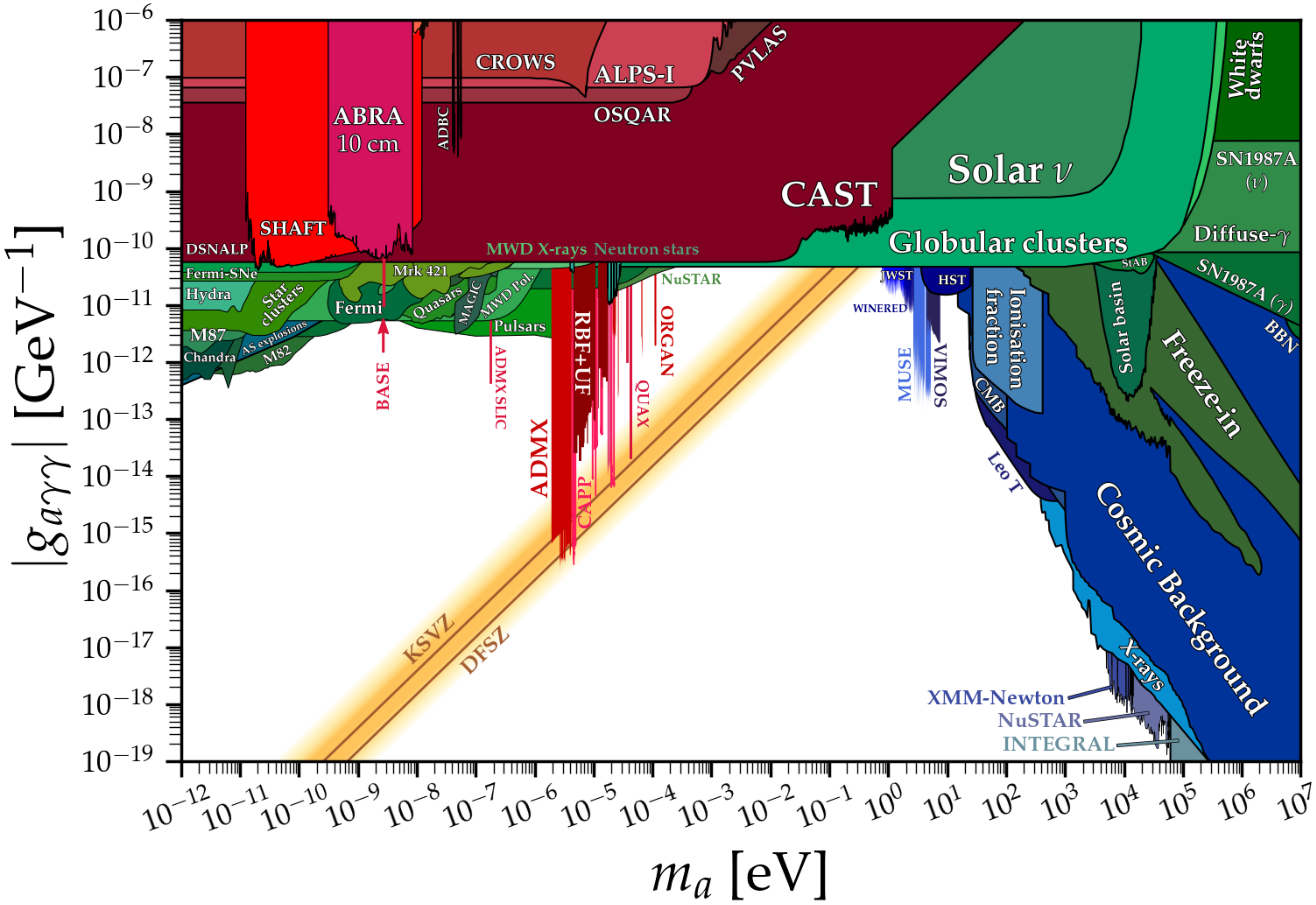
$Q_l \gg Q_a \sim 10^6$

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 research field




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

# The resonant searches for ALP via photon coupling


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

# The resonant searches of nucleon couplings

- The ALP DM field

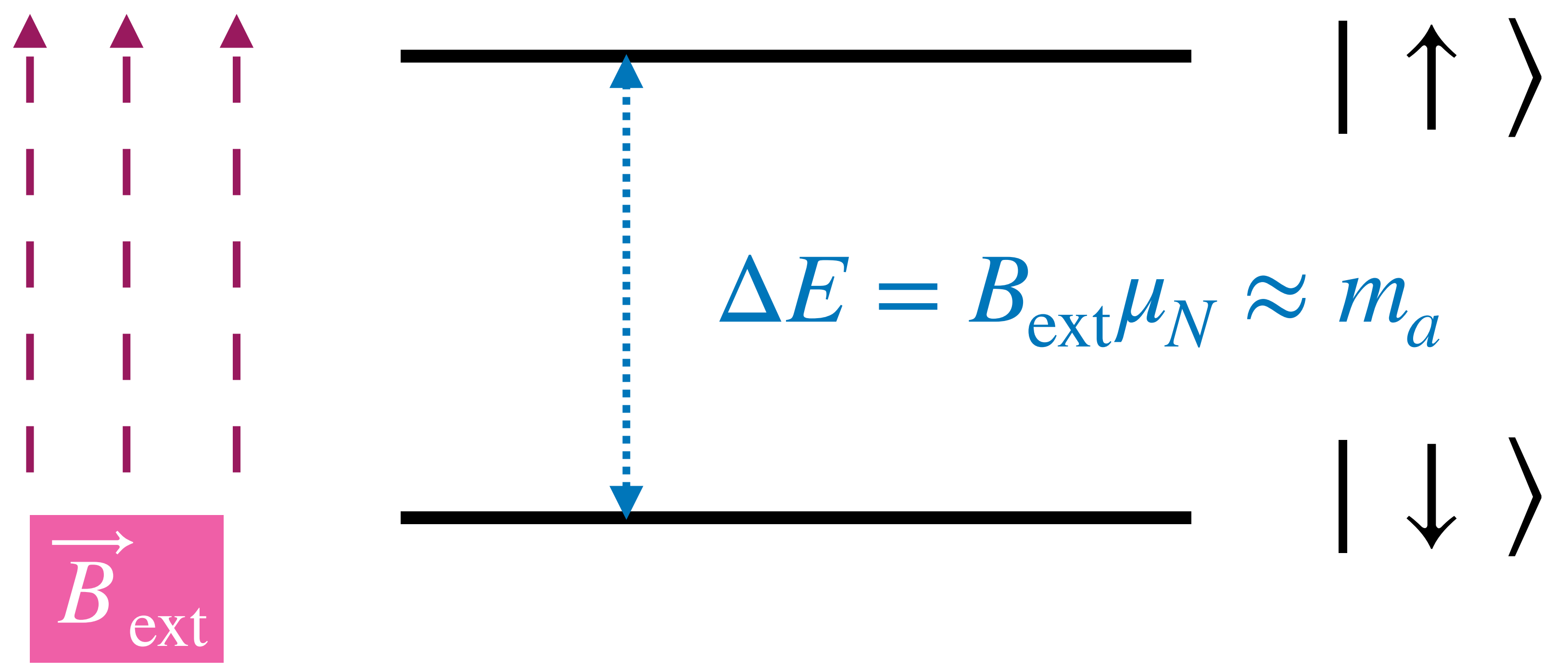
$$a(x,t) \approx a_0 \cos(\omega t - \vec{p}\cdot\vec{x} + \theta_0)$$

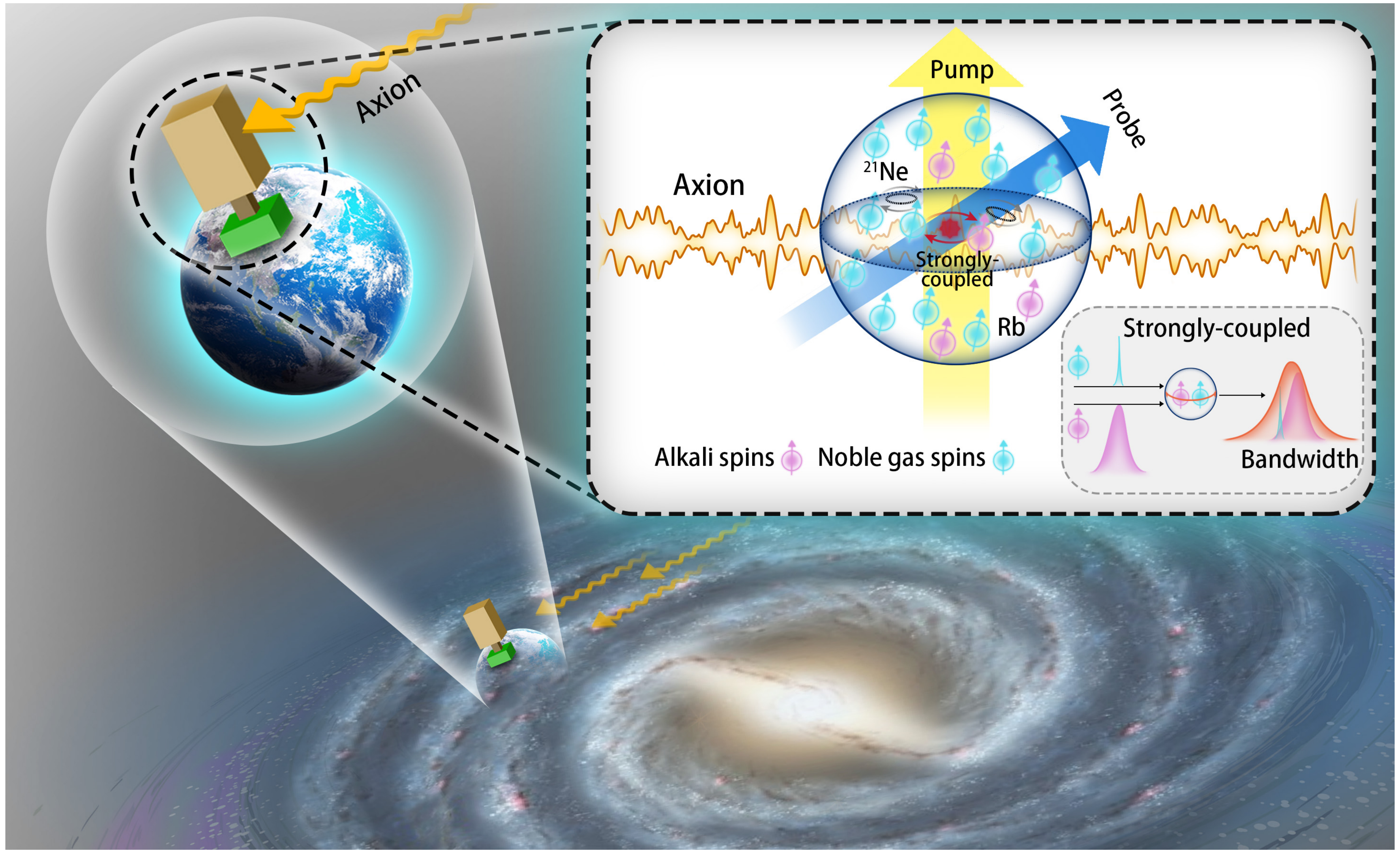
- The axion-wind Hamiltonian

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

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

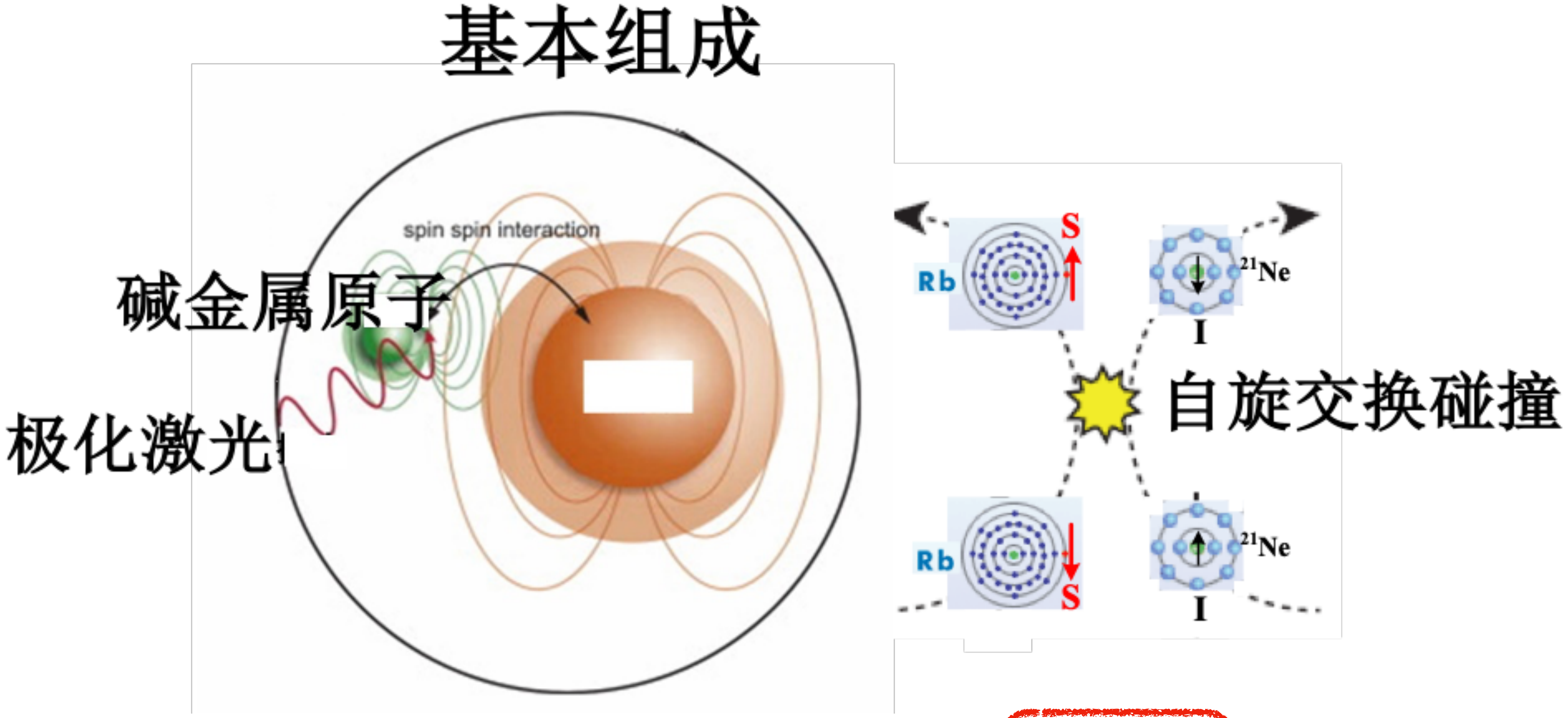
- A Zeeman split in B field

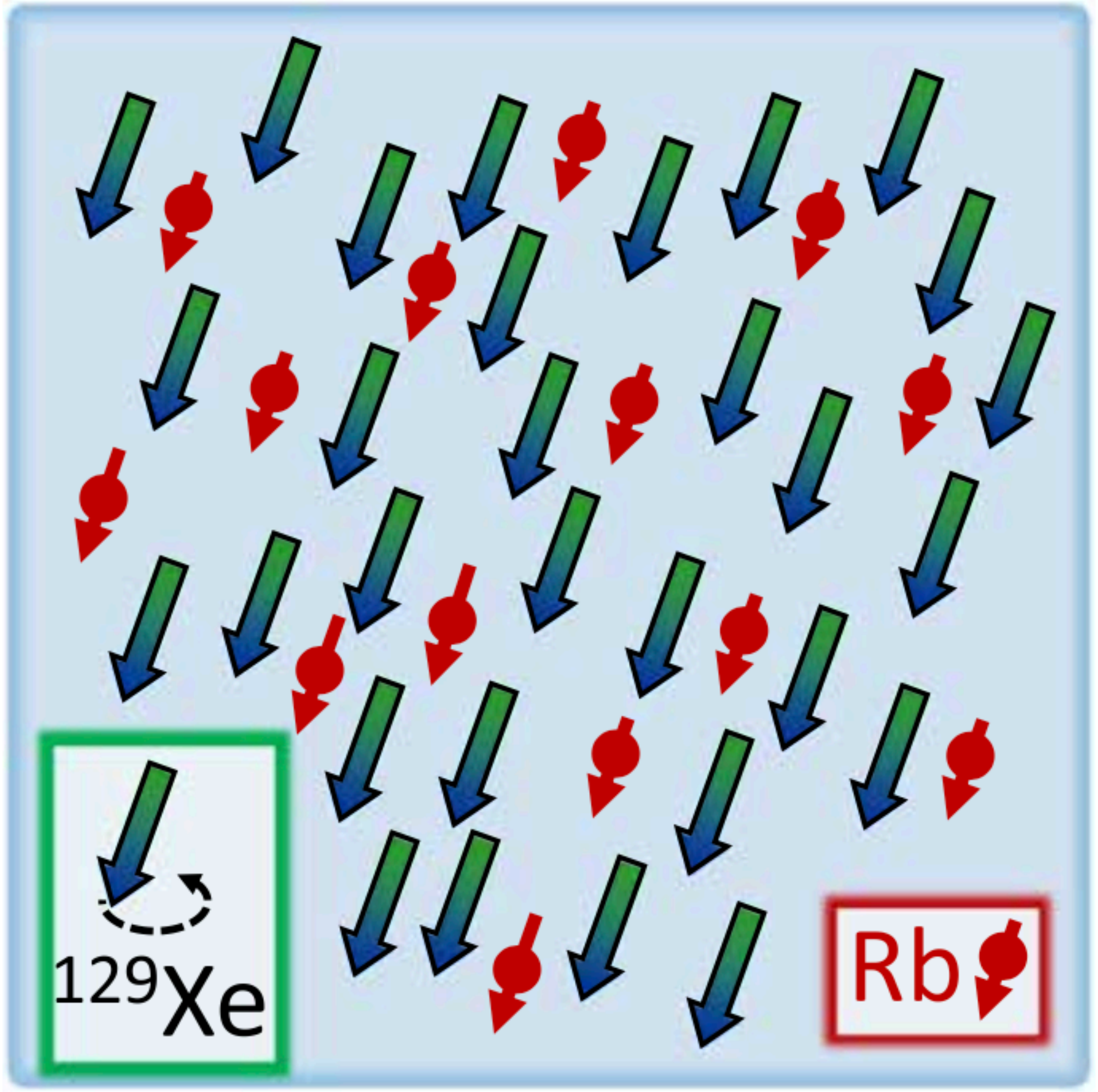


# Comagnetometer

- Alkali atoms and nobel-gas atom




Coupled Bloch equation

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

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

Fermi contact interaction and amplify

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

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

Exotic B field

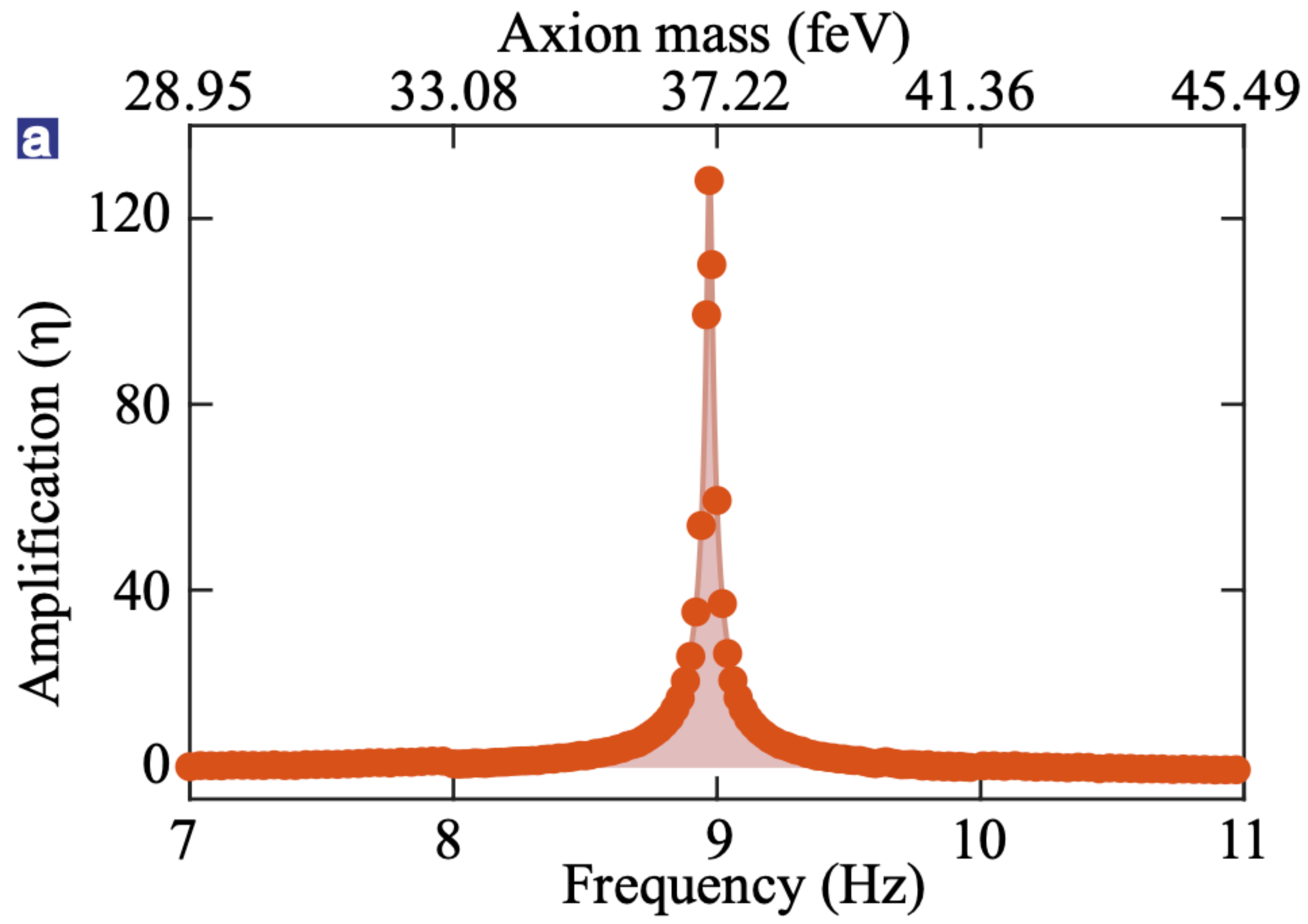
自旋交换碰撞

Jiang et al. Nature Physics 2021

# Comagnetometer NMR mode (Spin-base Amplifier)

- Enhanced sensitivity at resonance frequency

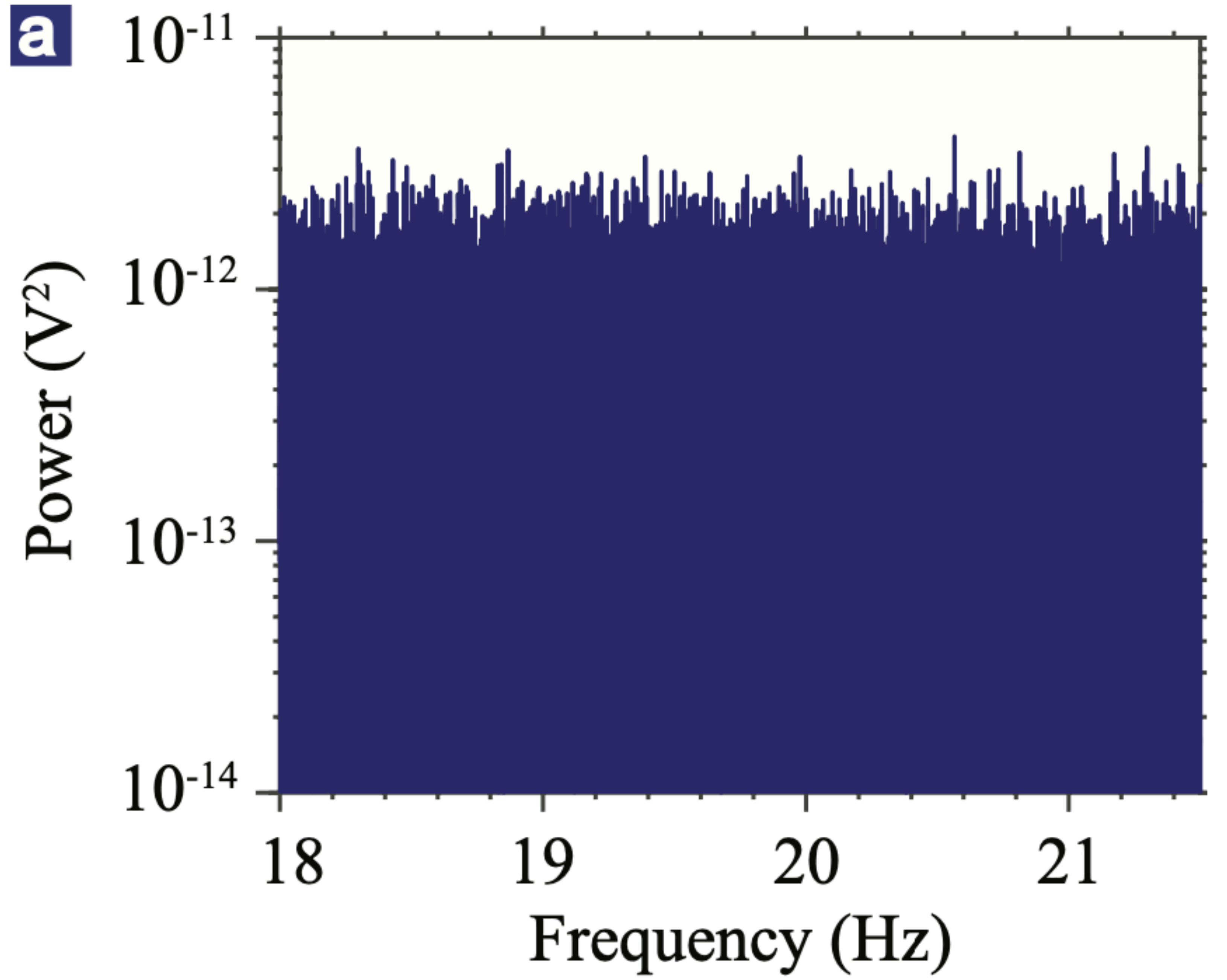
Jiang et al. Nature Physics 2021




**Lorenzian amplification shape**

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

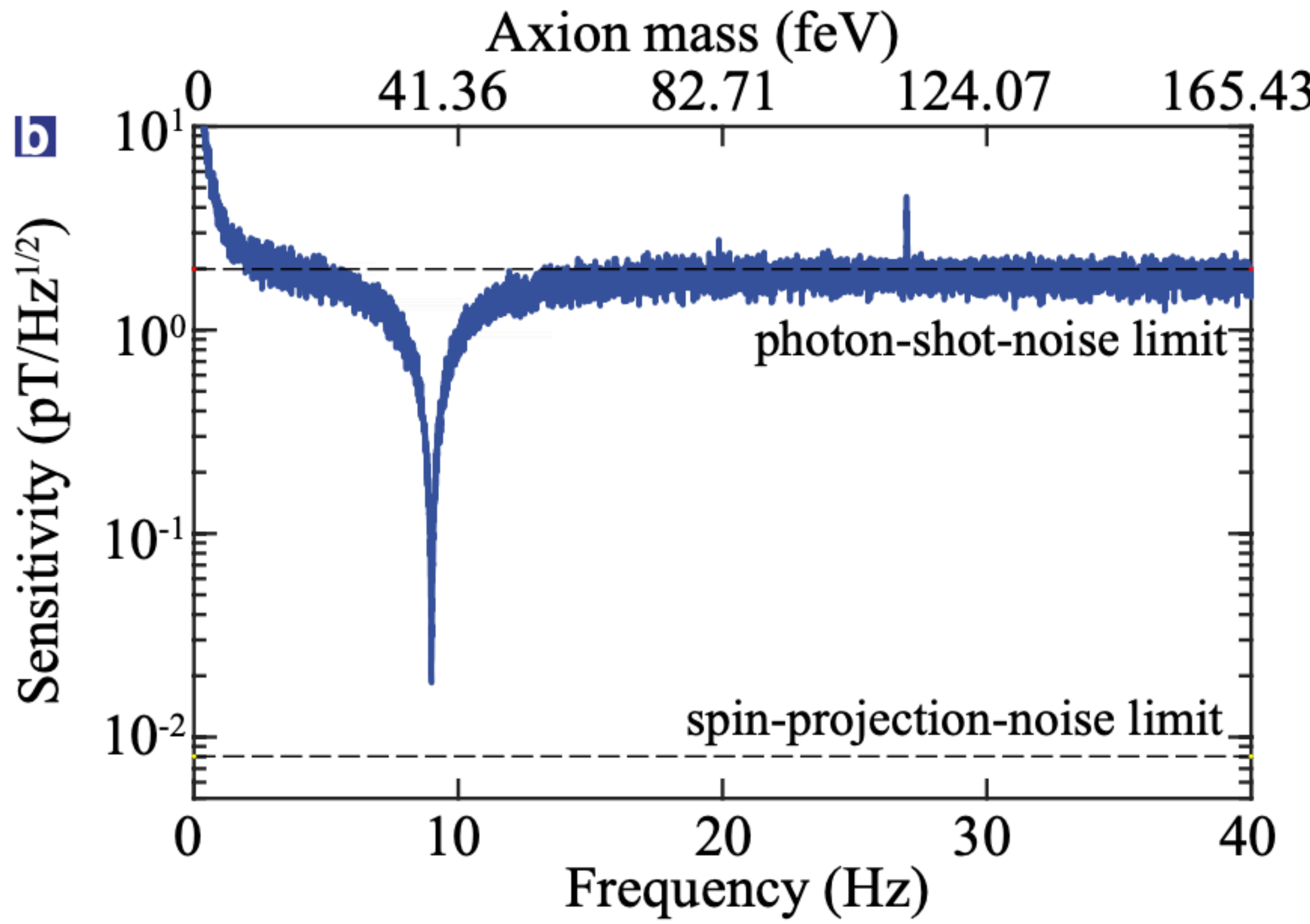
$$\sqrt{3}\Lambda = 0.052 \text{ Hz}$$




**Experimental data**

**Tuning $B_0$ field**

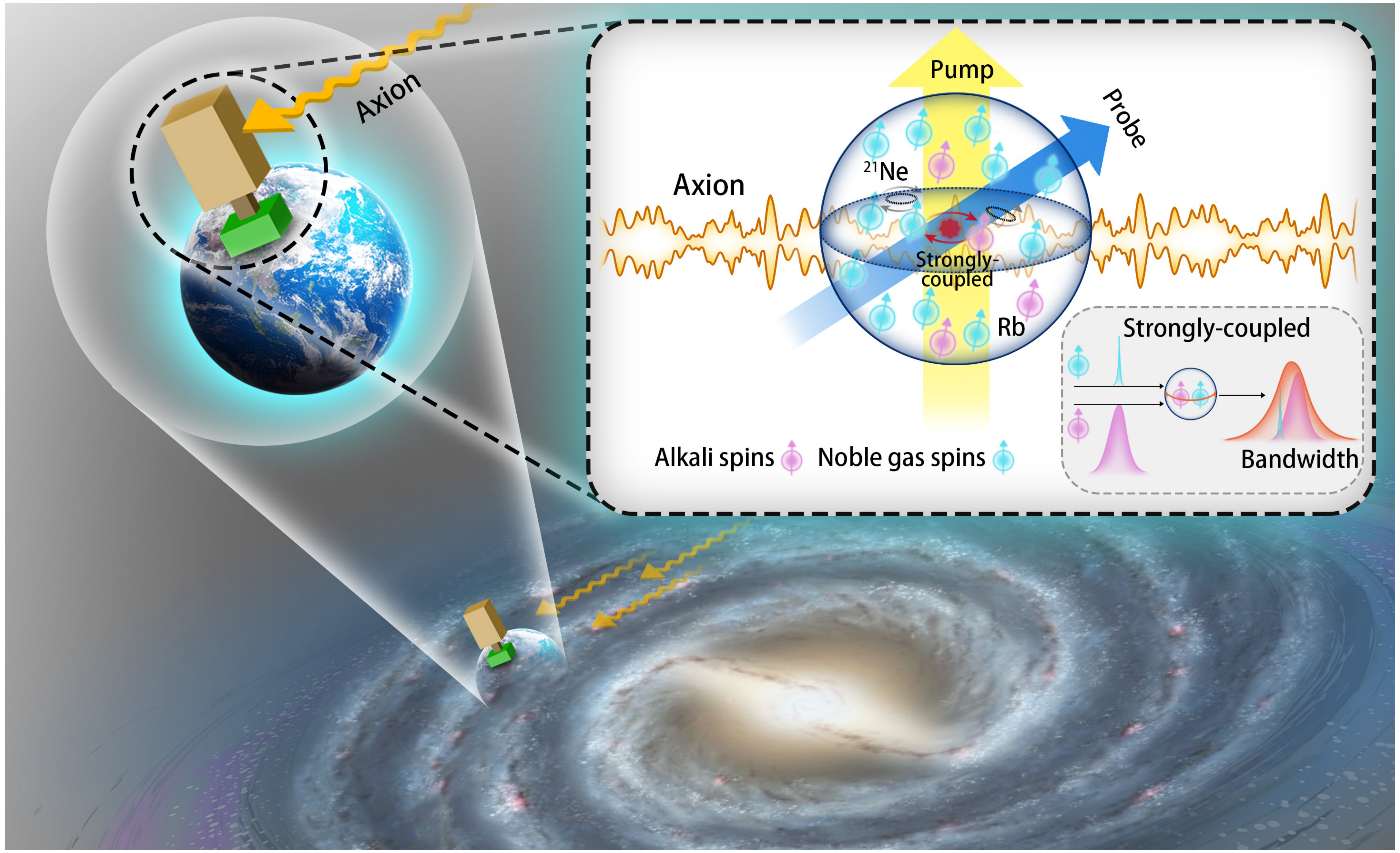
**Resonant frequency $f_0 = 19.84$ Hz**




**Good sensitivity on**
**Resonant frequency 19.84 Hz**

# Comagnetometer 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



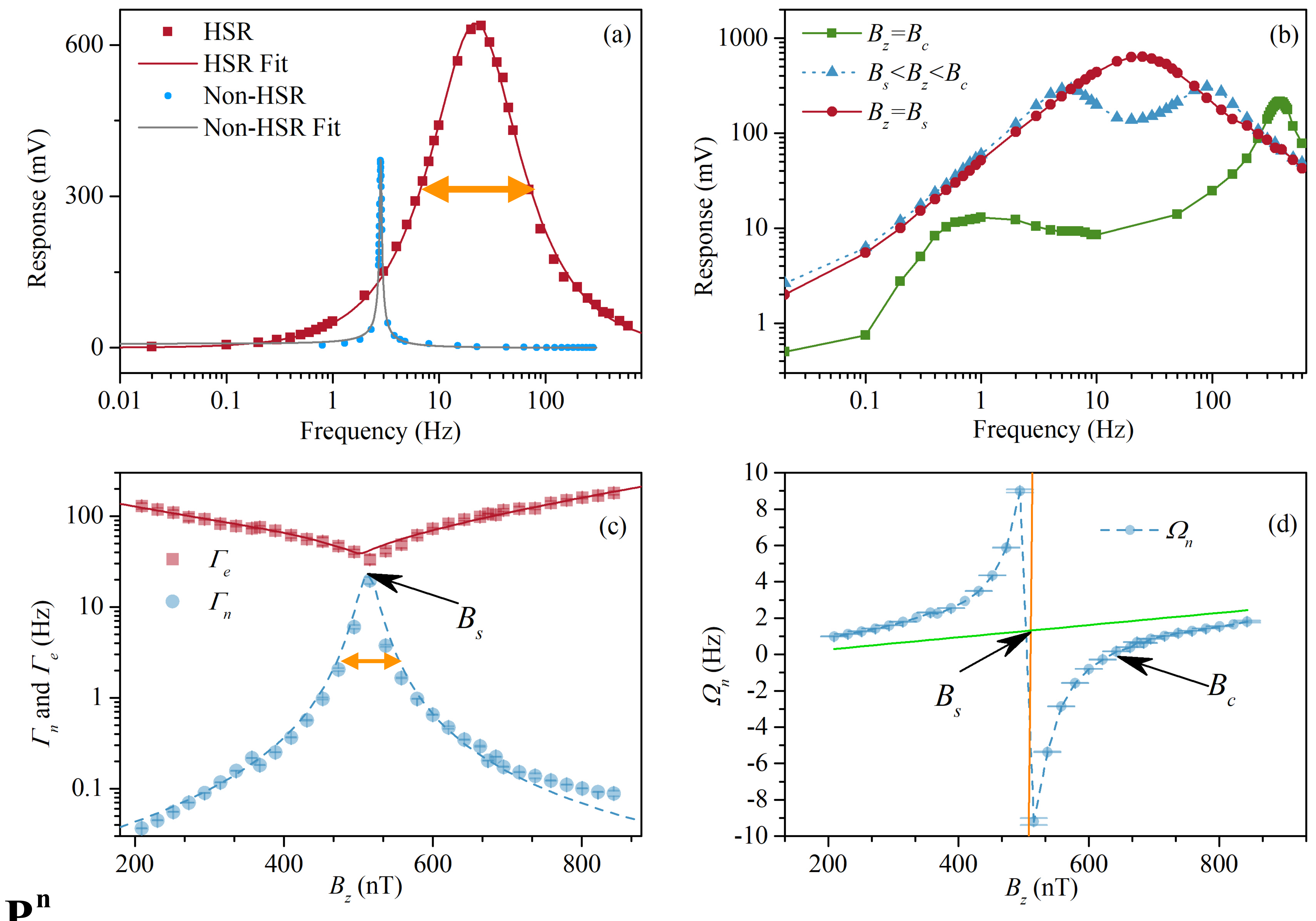

ChangE experiment: Kai Wei, .. **JL** .. et al, 2306.08039

# Comagnetometer in Hybrid Spin Resonance: Method

- Method: tune external B field to make Larmor frequency equal
  - HSR: $\omega_K \approx \omega_{Ne}$
  - Width $\Gamma_n$ is about 100 Hz now
  - NMR: $\omega_{Ne} \approx m_a c^2$

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

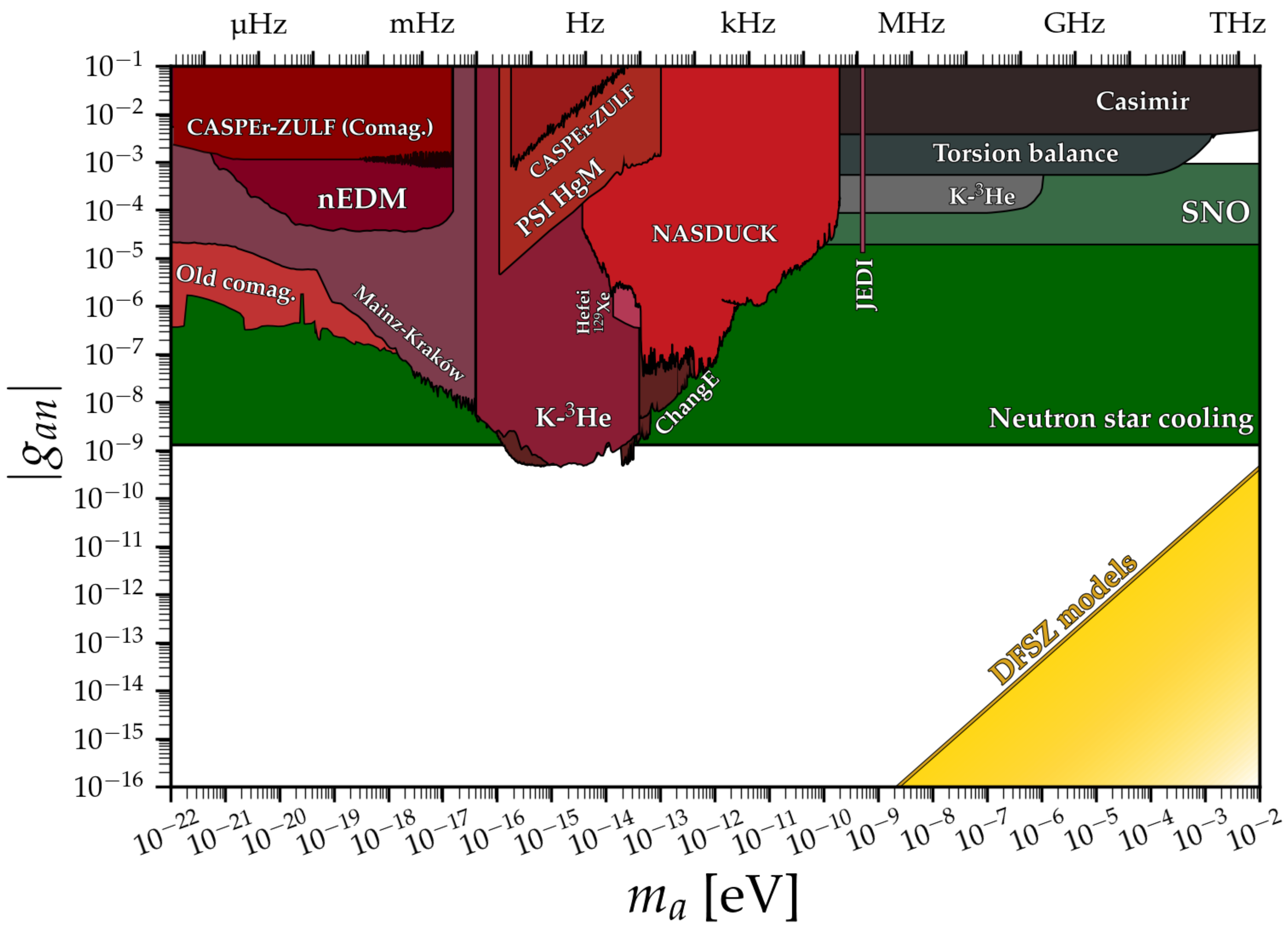
$$\frac{\delta \mathbf{P}^n}{\delta t} = \gamma_n (\mathbf{B} + \lambda M_0^e \mathbf{P}^e + \mathbf{b}^n) \times \mathbf{P}^n - \boldsymbol{\Omega} \times \mathbf{P}^n + R_{se}^{en} \mathbf{P}^e - \{R_1^n, R_2^n, R_2^n\} \mathbf{P}^n$$

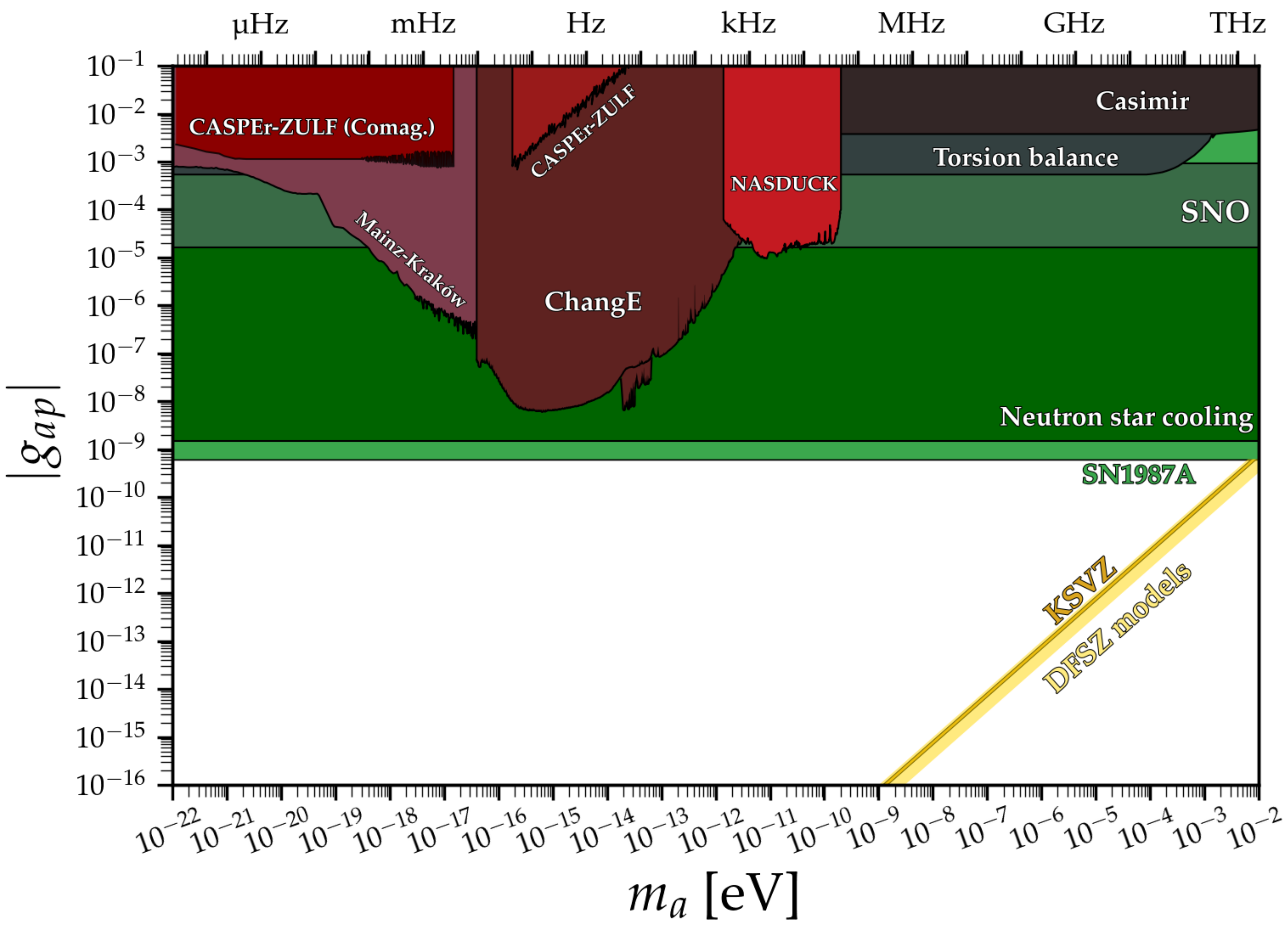



ChangE experiment: Kai Wei, .. **JL** .. et al, 2306.08039

# ChangE results

- ChangE experiments set competitive limits on ALP-nucleon couplings (AxionLimits version)
- 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

- Axion is an important BSM physics model, providing solutions to strong CP problem and dark matter problem
- Invisible QCD axion is the high priority model stimulating lots of experiment searches
- Axion vector meson couplings are introduced with Wess-Zumino-Witten interactions, providing consistent amplitudes under auxiliary chiral rotations
- ChangE experiments set competitive limits on ALP-nucleon couplings

*Thank you!*

# Backup slides