ALP dark matter search via Alkali-Noble-Gas Haloscopes

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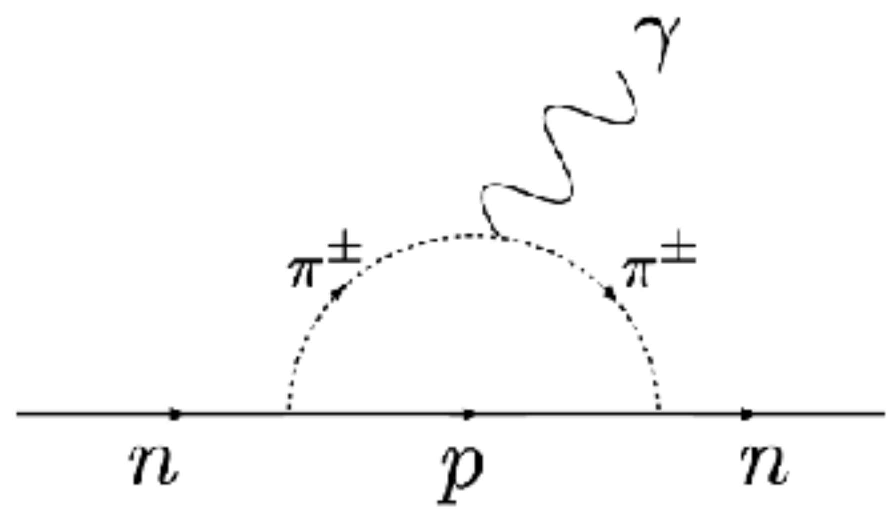
Outiline

- Strong CP problem and QCD Axion
- ALP Dark Matter
- ALP DM search via NMR method
- Summary

SM and New Physics

Strong CP problem



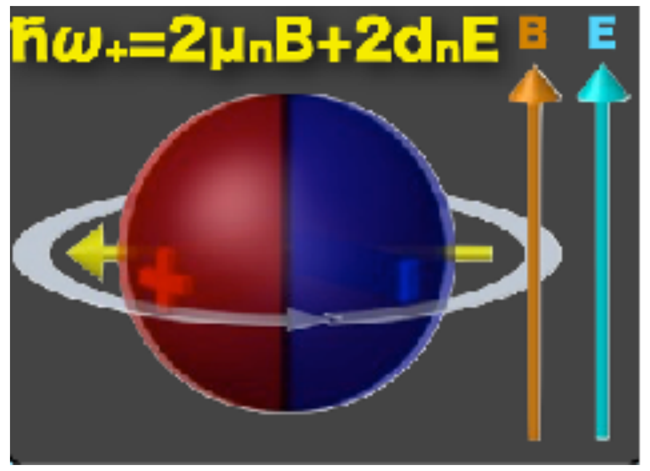
- Low-energy QCD done predict

$$\mathscr{L} \supset \frac{\bar{\theta} g_s^2}{32\pi^2} G\tilde{G}$$

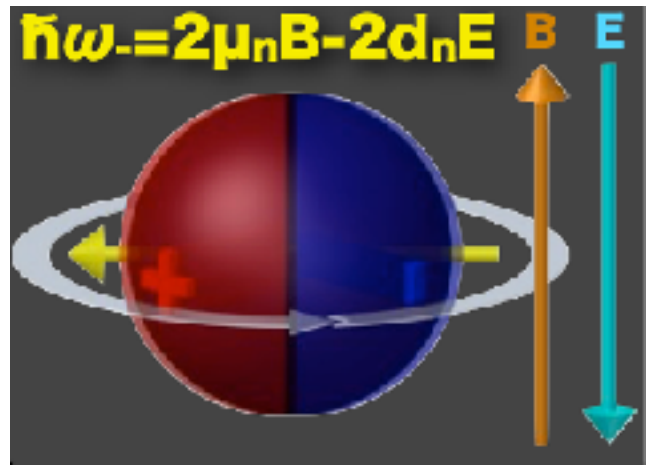
- Based on above QCD, we can build a theory for meson, then induce the neutron eDM at nucleon level

$$d_n = \frac{e\bar{\theta} g_A c_+ \mu}{8\pi^2 f_\pi^2} \log \frac{\Lambda^2}{m_\pi^2} \sim 3 \times 10^{-16} \bar{\theta} \text{ e cm}$$

- Pression measurement

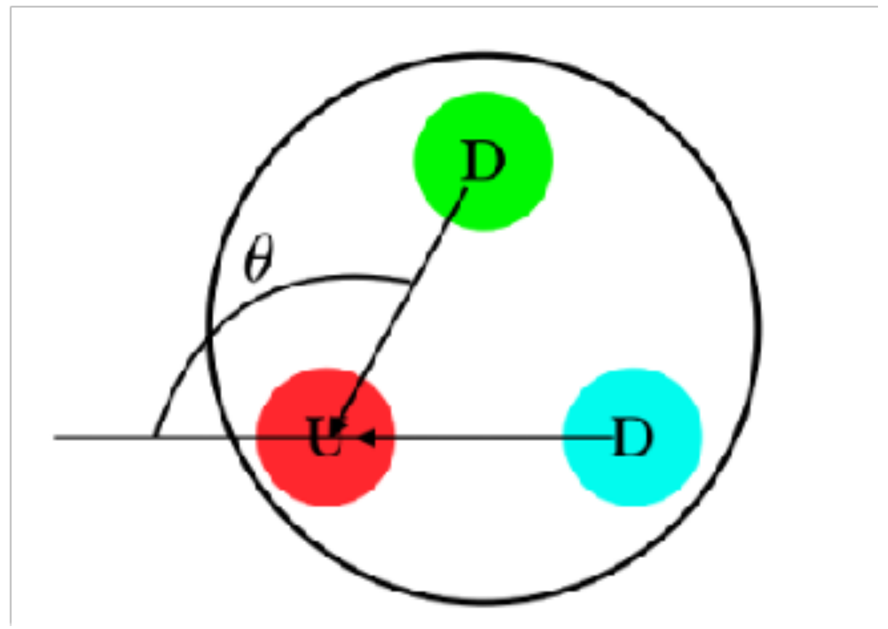


$$d_n = \frac{\hbar \Delta\omega}{4E} \le 10^{-26} \text{ e cm}$$



Solution to Strong CP problem

- The neutron eDM in classical formula

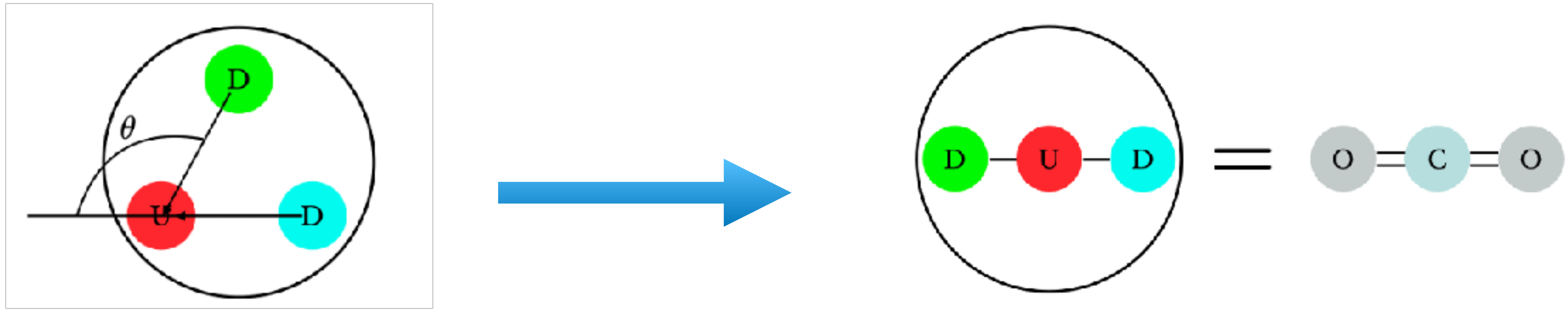


$$\vec{d} = \sum q\vec{r}$$

- Use the neutron has a size $r_n \sim 1/m_\pi$

$$\left|d_n\right| \approx 10^{-13}\sqrt{1-\cos\theta}e \text{ cm}$$

- Comparing to the experiment results, we need $\cos\theta = 1$



Solution to Strong CP problem

- The EFT consists of a single new particle, the axion (a), and a single new coupling (f_a)

$$\mathscr{L} \supset \left(\frac{a}{f_a} + \bar{\theta}\right) \frac{1}{32\pi^2} G\tilde{G}$$

- The axion obeys an anomalous symmetry

$$a \to a + \alpha f_a, \theta \to \theta - \alpha$$

- UV completions of the QCD axion will occasionally generate other couplings, (To quark coupling can be generated by RG evolution)

$$\mathscr{L} \supset \frac{a}{f_B}\frac{1}{32\pi^2}B\tilde{B} + \frac{a}{f_W}\frac{1}{32\pi^2}W\tilde{W} + \frac{\partial_\mu a}{f_Q}Q^\dagger \sigma^\mu Q$$

Solution to Strong CP problem

- The axion potential is

$$V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2 \frac{\bar{\theta}}{2}} \rightarrow V = -m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4m_u m_d}{(m_u + m_d)^2} \sin^2 \left(\frac{a}{2f_a} + \frac{\bar{\theta}}{2}\right)}$$

- To solve strong CP problem

$$d_n = \frac{e\bar{\theta} g_A c_+ \mu}{8\pi^2 f_\pi^2} \log \frac{\Lambda^2}{m_\pi^2} \sim 3 \times 10^{-16} \bar{\theta} \text{ecm} \rightarrow d_n \propto \frac{a}{f_a} + \bar{\theta} = 0$$

- QCD axion mass relationship, expand V at the minimal potential, with small a/fa

$$V = -m_\pi^2 f_\pi^2 + \frac{1}{2} \frac{m_u m_d}{(m_u + m_d)^2} \frac{m_\pi^2 f_\pi^2}{f_a^2} a^2 \rightarrow m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 5.7 \left(\frac{10^{12}\text{GeV}}{f_a}\right) \mu\text{eV}$$

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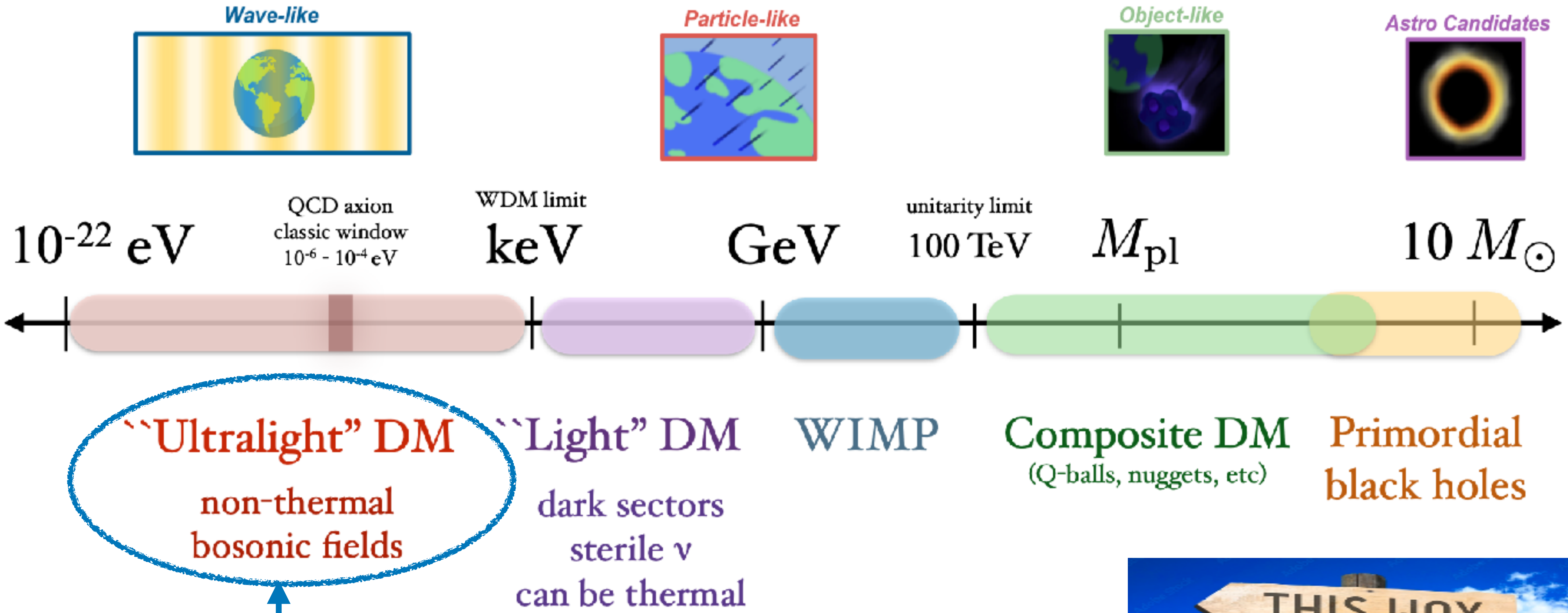
Dark Matter Candidates



Today's focus

HEP at a cross-road: explore all directions!

Ultralight Dark Matter-Axion

- Production: Misalignment

$$\ddot{a} + 3H(t)a + m_a^2 a = 0$$

$$a(t) = a_0 \left(H \gg m_a\right)$$

$$a(t) = a_0 \sin\left(m_a t\right) \left(H \ll m_a\right)$$

- QCD Axion having a very small mass

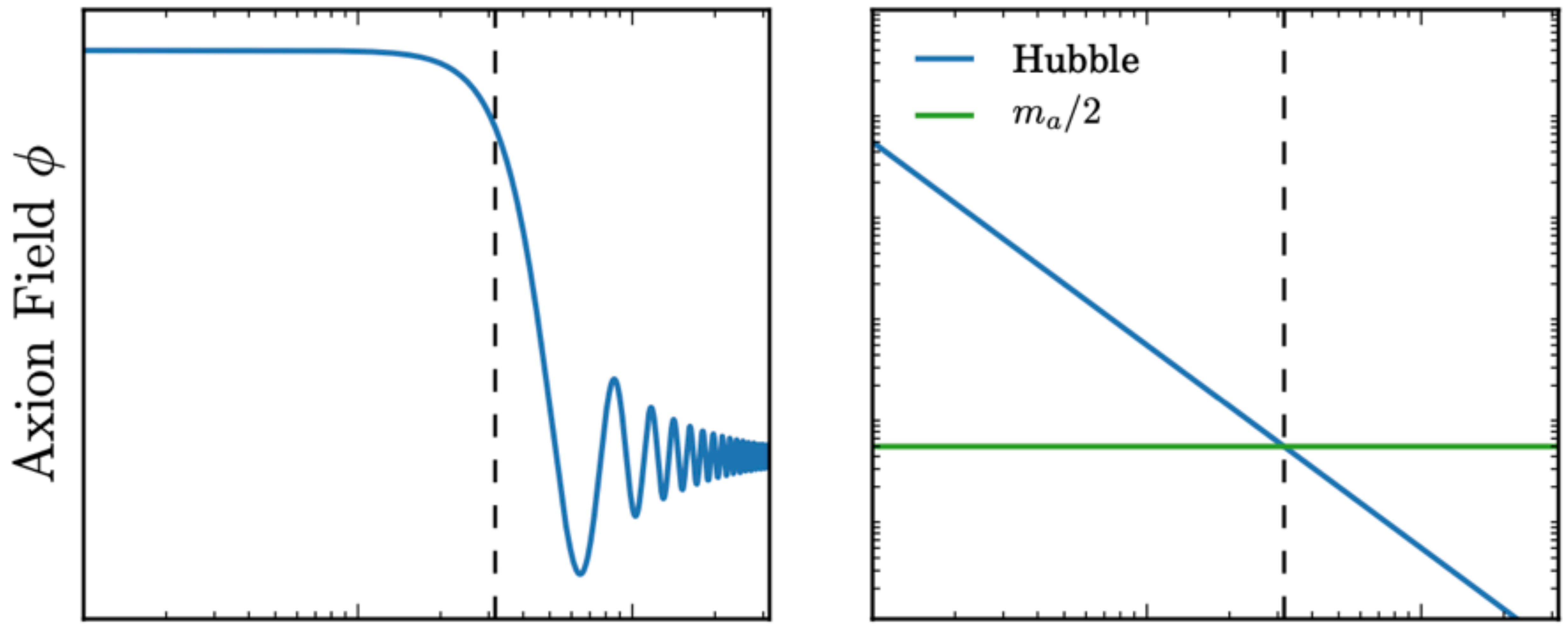
$$m_{\mathrm{a}} \simeq 6 \times 10^{-6}\mathrm{eV} \left(\frac{10^{12}\mathrm{GeV}}{f_{\mathrm{a}}}\right)$$

- The Axion energy density will be

$$\Omega_{\mathrm{a}} \sim 0.15 \left(\frac{f_{\mathrm{a}}}{10^{12}\mathrm{GeV}}\right)^{7/6}$$

- The critical time change from field to particle

$$H(t_{\mathrm{osc}}) \approx m_a/2$$



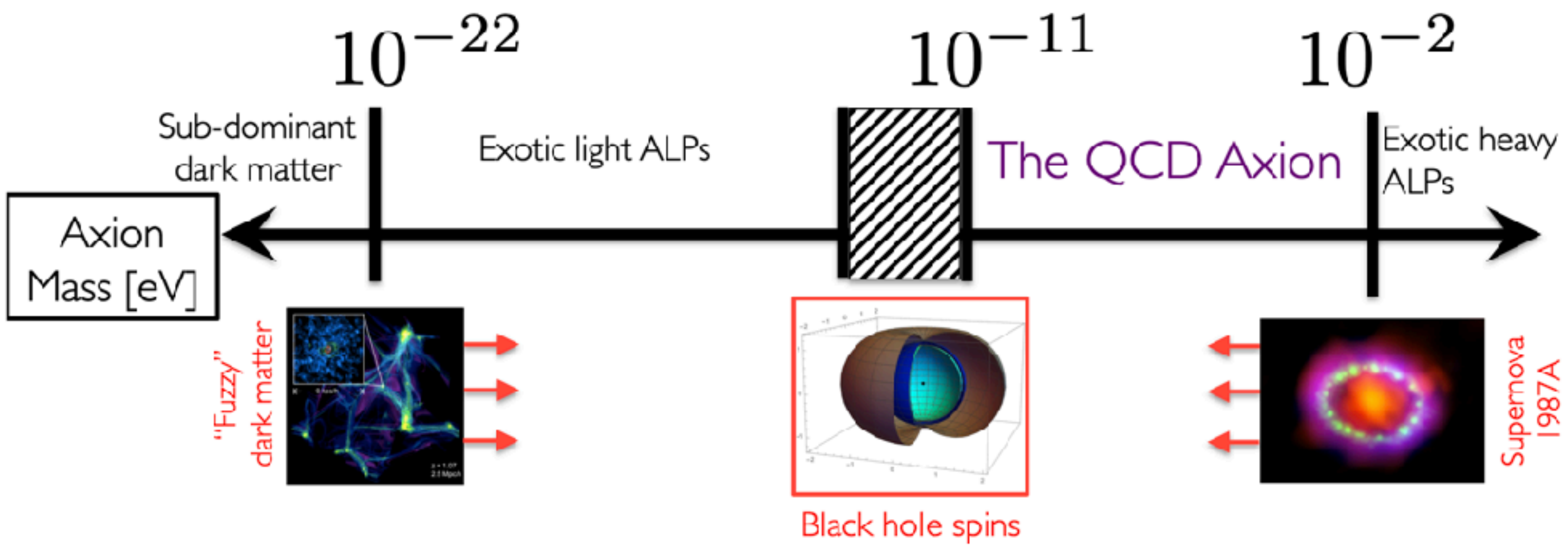
Ultralight Dark Matter-ALP

- The ALP Lagrangian

$$\mathcal{L}_a^{\rm int} \supset \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a} aF\tilde{F} + C_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f + \frac{C_{a\pi}}{f_a f_\pi}\partial_\mu a[\partial\pi\pi\pi]^\mu - \frac{i}{2}\frac{C_{an\gamma}}{m_n}\frac{a}{f_a}\bar{n}\sigma_{\mu\nu}\gamma_5 n F^{\mu\nu}$$

- The ALP energy density will be

$$\Omega_{\rm ALP}^{\rm MIS}h^2 = 0.12\left(\frac{m_a}{4.7\times10^{-19}{\rm eV}}\right)^{1/2}\left(\frac{f_a}{10^{16}{\rm GeV}}\right)^2\left(\frac{\Omega_m h^2}{0.15}\right)^{3/4}\left(\frac{1+z_{\rm eq}}{3.4\times10^3}\right)^{-3/4}\Theta_{\rm i}^2$$



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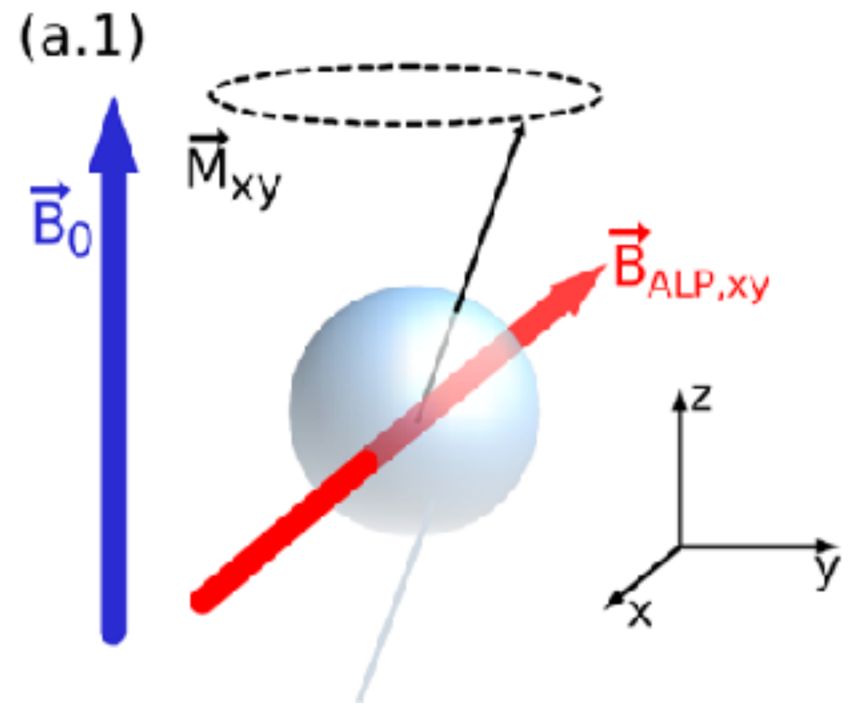
Nuclear magnetic resonance method

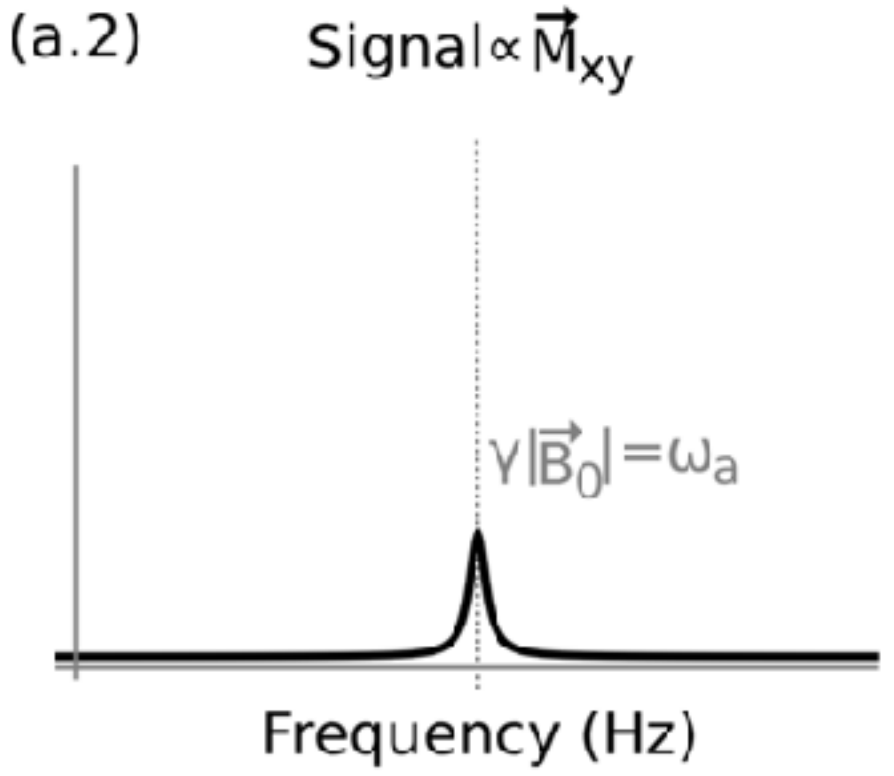
- Axion couples to SM particles

$$\mathscr{H}_{\sigma} = g_{\mathrm{aNN}}\sqrt{2\rho_{\mathrm{DM}}}\cos\left(m_a t\right)\vec{v}\cdot\vec{\sigma}_{\mathrm{N}} = \gamma\vec{B}_{\mathrm{ALP}}\cdot\vec{\sigma}$$



- Oscillate the mass at Larmor frequency

$$\vec{B}_{\mathrm{ALP}} = g_{aNN}\sqrt{2\rho_{\mathrm{DM}}}\cos(m_a t) = g_{aNN}\sqrt{2\rho_{\mathrm{DM}}}\cos(\omega_a t)$$



- Bloch Equations

$$\frac{d\vec{M}}{dt} = \gamma\vec{M}\times\vec{B}$$

Generate transverse from longitudinal

Time varying Axion B_{ALP} drives spin precession → produces transverse magnetization

Comagnetic resonance method

- Bloch Equation: Describe the evolution of macroscopic spin systems

$$\dot{S}_\perp = i\gamma B_z S_\perp - i\gamma\left(B_\perp + \frac{b_\perp}{\gamma}\right) S_z - \Gamma S_\perp$$

Torque: generates transverse from longitudinal

Decaying excitations: causes stabilization

Creating macroscopic polarization :generates a non-trivial steady state solution

- If B_z is constant & $\dot{S}_\perp = 0$

$$S_\perp(\omega = m_a) = \frac{b_\perp + \gamma B_\perp(\omega = m_a)}{(\gamma B_z - m_a) + i\Gamma} S_z$$

Signal: Generated from ALP ($b_\perp$)

Spin in Z direction (S_z)

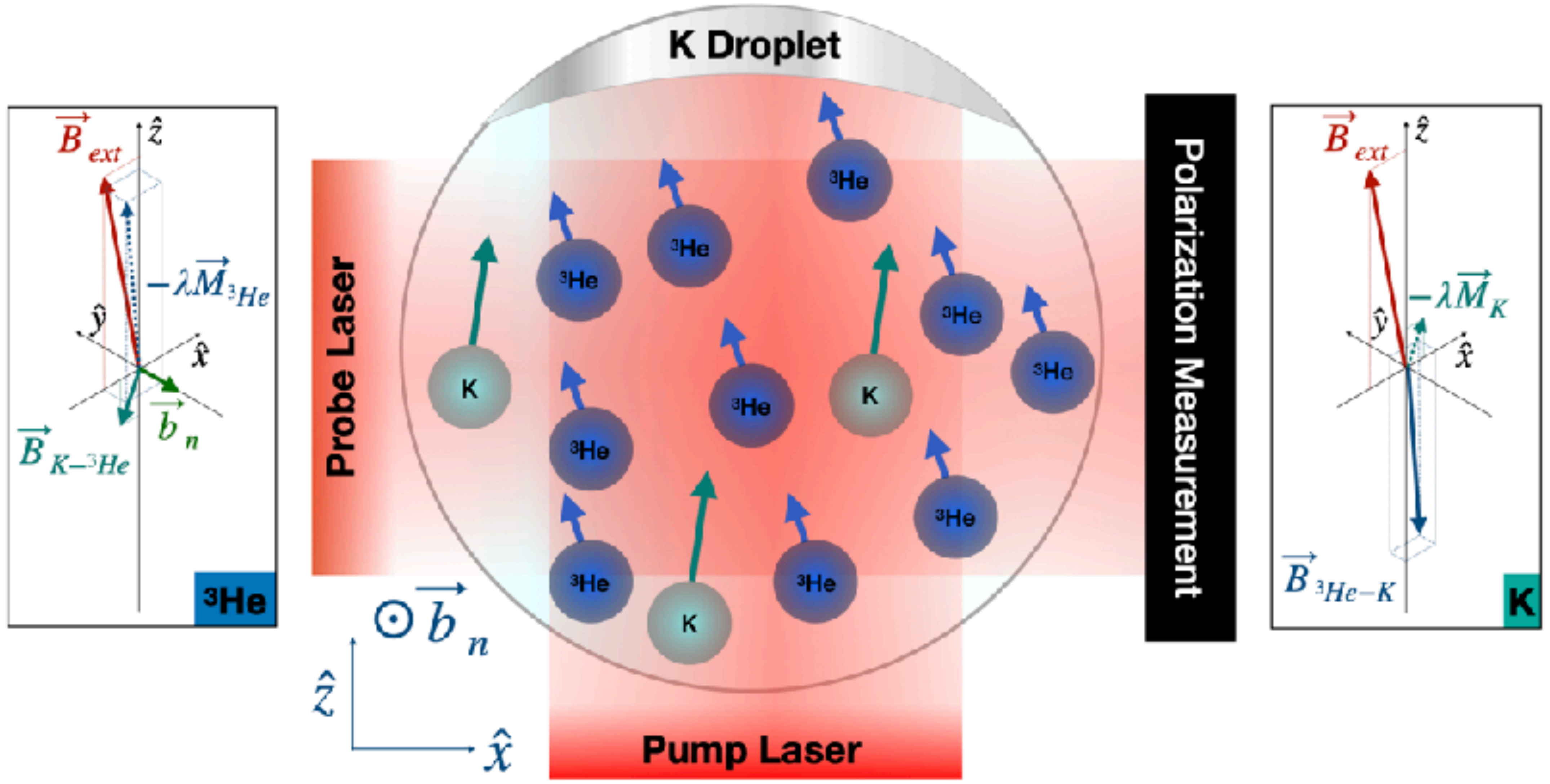
Controlled Resonance Frequency (γB_z)

ALP mass (m_a)

Decoherence Rate ($i\Gamma$)

Comagnetic resonance method

Magnetometers can measure ALPs. Alkali magnetometers are easy to work with, while Noble magnetometers are more sensitive.



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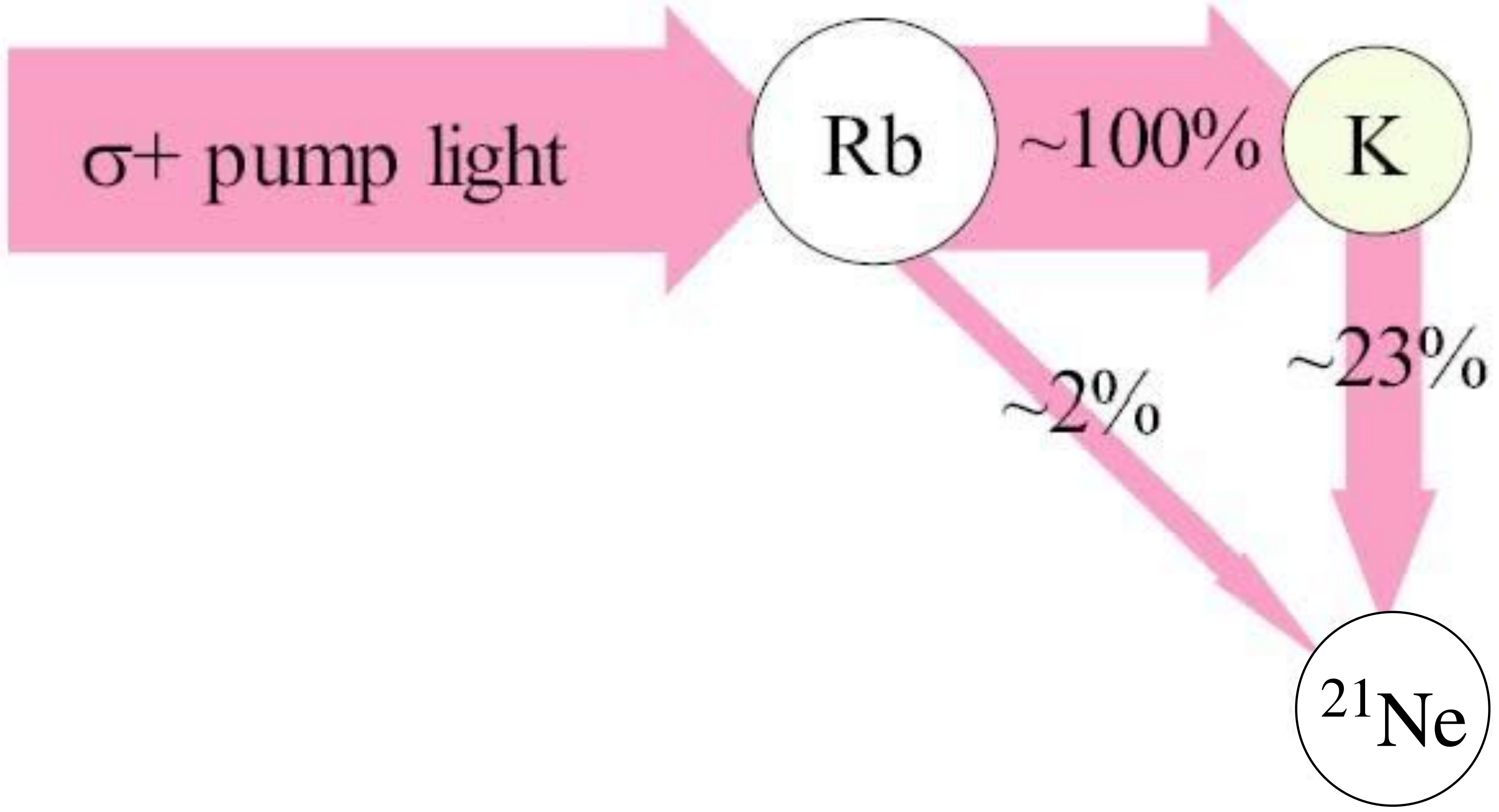
- At the compensation point:
  1. any magnetic noise (at low frequencies) has no effect on the alkali spins!
  2. the two species are "in resonance", allowing for a fast response to sudden changes.

Comagnetometer—Optical pumping

- The ^{21}Ne polarization rate is

$$\frac{dP_{\mathrm{Ne}}}{dt} = \Gamma_{\mathrm{SE}}\left(P_A - P_{\mathrm{Ne}}\right) - \Gamma_{\mathrm{Ne}} P_{\mathrm{Ne}}$$

- Spin-exchange Rate： $\Gamma_{\mathrm{SE}} = k_{\mathrm{K}}[\mathrm{K}] + k_{\mathrm{Rb}}[\mathrm{Rb}]$



Comagnetometer in Hybrid Spin Resonance

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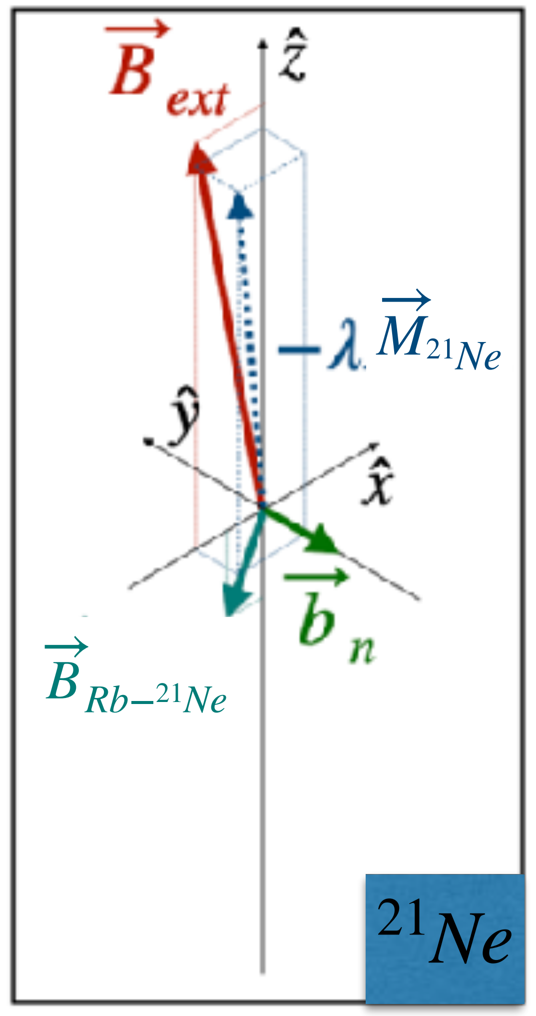
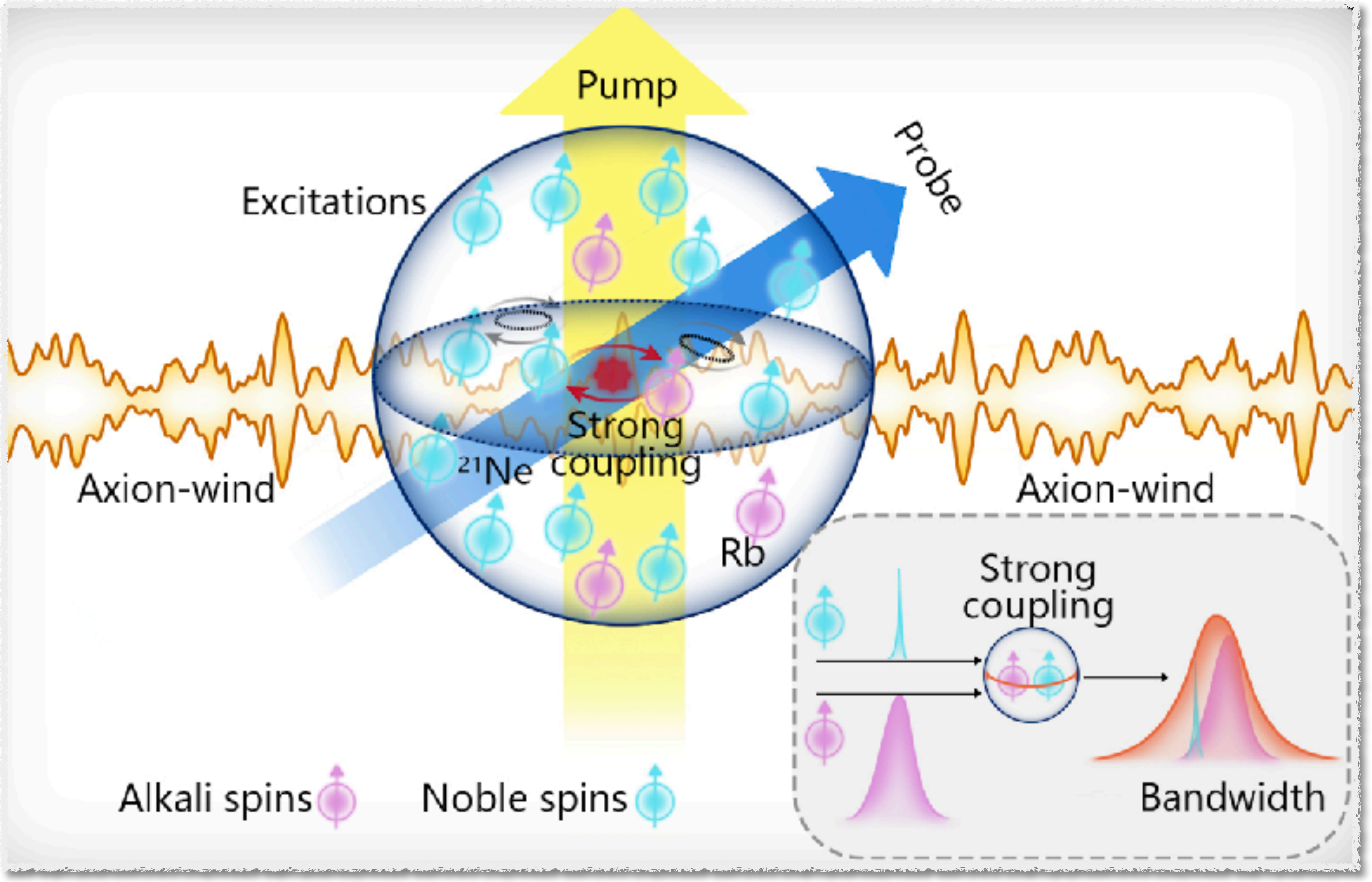
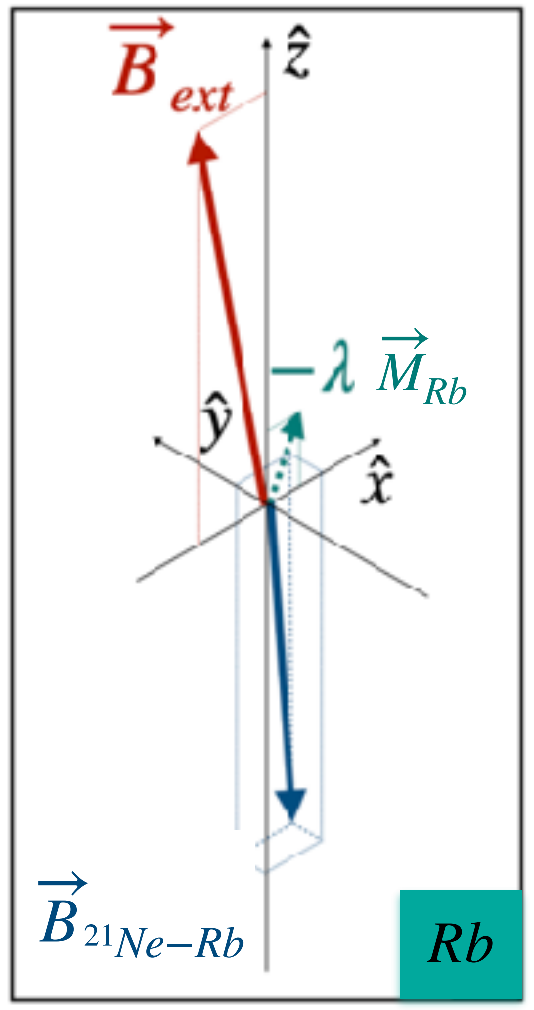






Comagnetometer in Hybrid Spin Resonance

- Bloch Equation

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

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

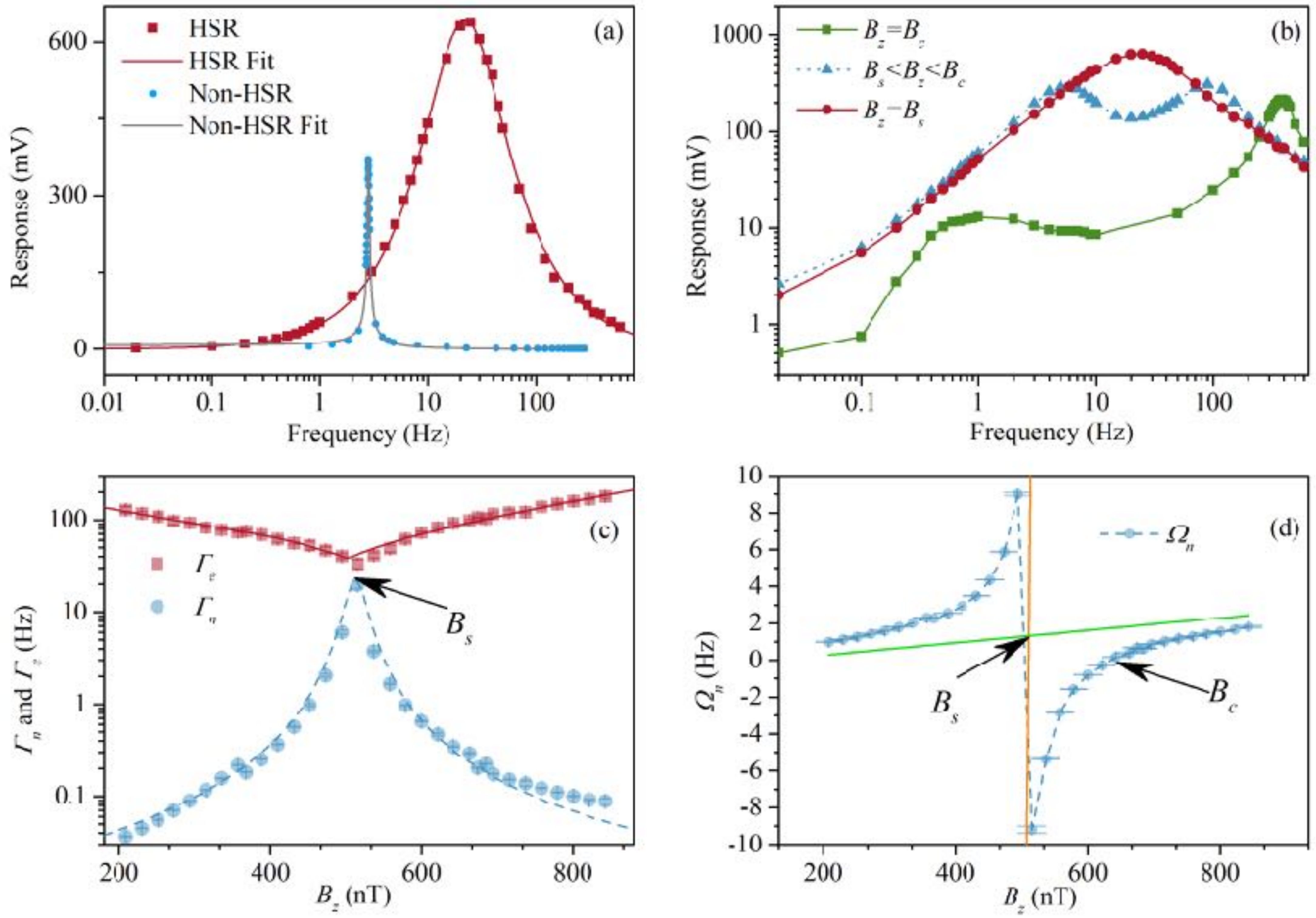
- Method: tune external B field to make Larmor frequency equal (HSR region)

$$\omega_\mathrm{alkali} = \gamma_\mathrm{alkali}\left(\hat{B}_\mathrm{ext} + \hat{B}_\mathrm{noble}\right)$$

$$\omega_\mathrm{noble} = \gamma_\mathrm{noble}\left(\hat{B}_\mathrm{ext} + \hat{B}_\mathrm{alkali}\right)$$

- Require $\omega_\mathrm{alkali} = \omega_\mathrm{noble}$

$$B_\mathrm{HSR} \sim -B_\mathrm{noble}$$



Comagnetometer HSR search on ALP DM

- Random phase in different p mode

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

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

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

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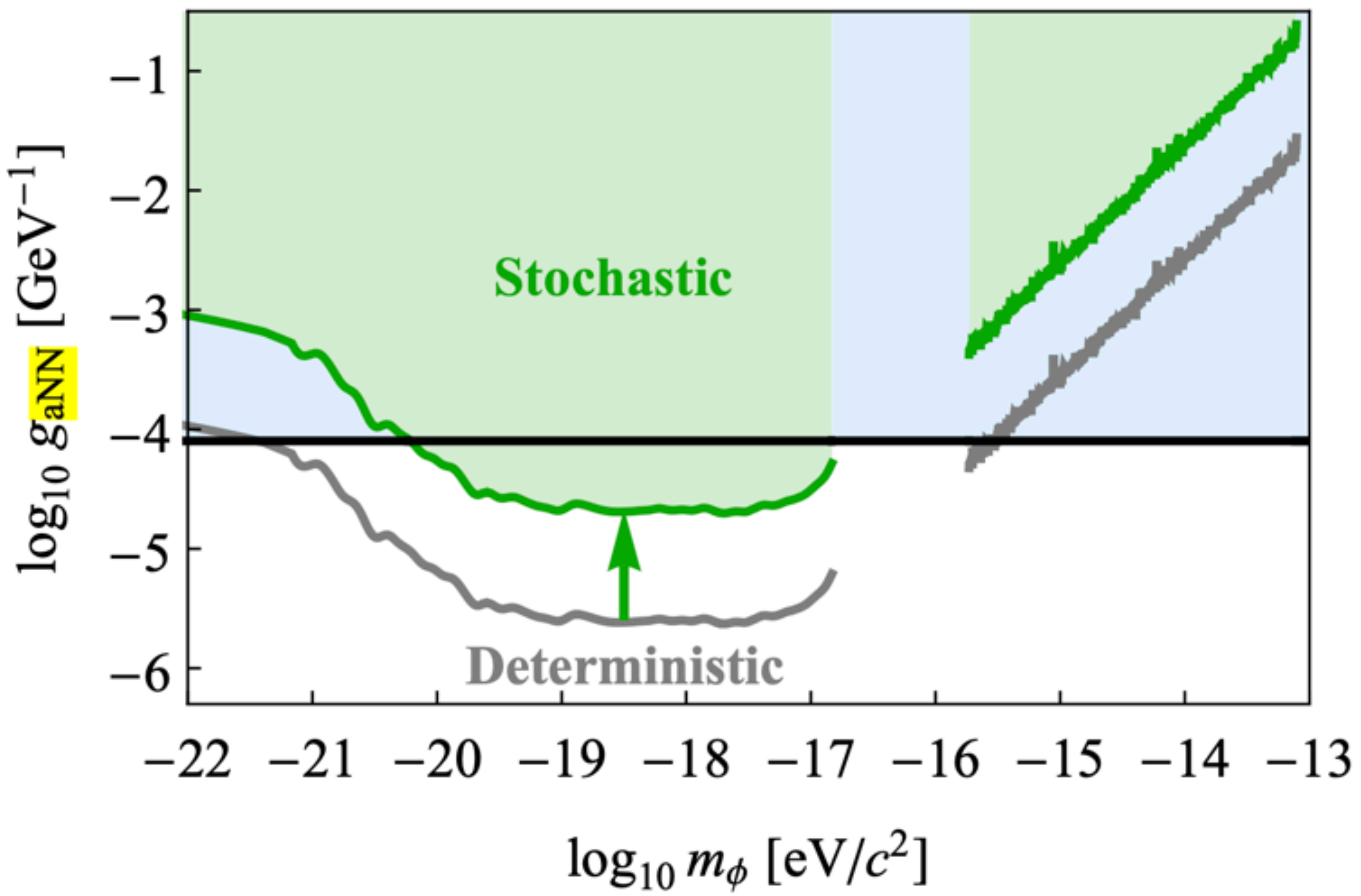
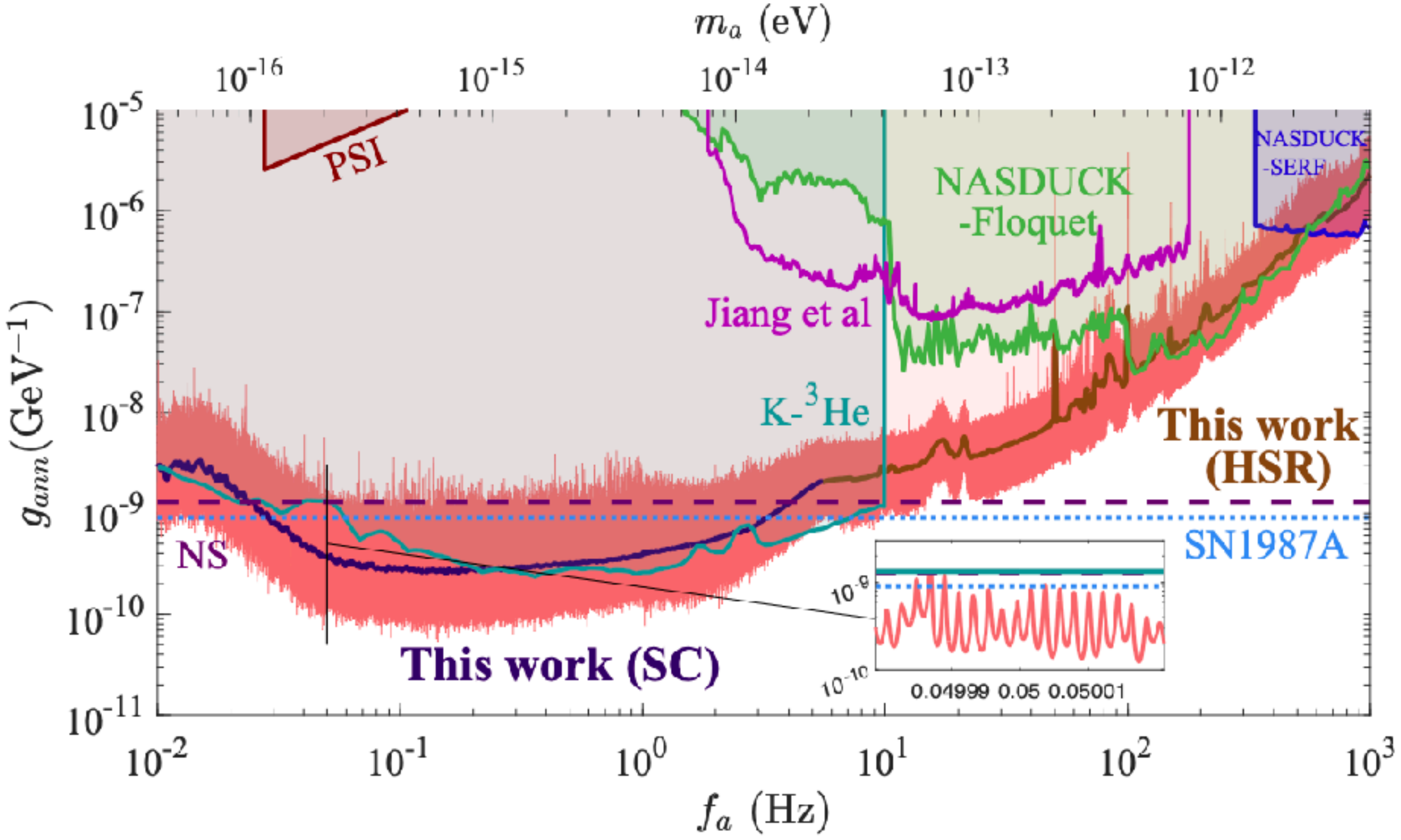


$$\gamma_{95\%}^{\mathrm{stoch}} = 8.4\,\gamma_{95\%}^{\mathrm{det}}$$



Summary

- ALP have potential to solve strong CP problem
- Ultra-light ALP can be dark matter
- ALP dark matter can be detected with spin precession experiments.

Thank you!