Searching for ALP DM in Alkali-Noble-Gas Haloscopes

Xiao-Ping Wang（王小平）

Apr, 10 @IHEP

Base On: *arXiv: 2309.16600*
arXiv:2306.08039 (ChangE collaboration)

Outiline

- Strong CP problem and Dark Matter candidate of SM
- Axion solution to CP problem and as a DM candidate
- Axion DM search via different particle experiments
- ALP DM search via NMR method(CASPEr)
- ALP DM search via Comagnetometer method
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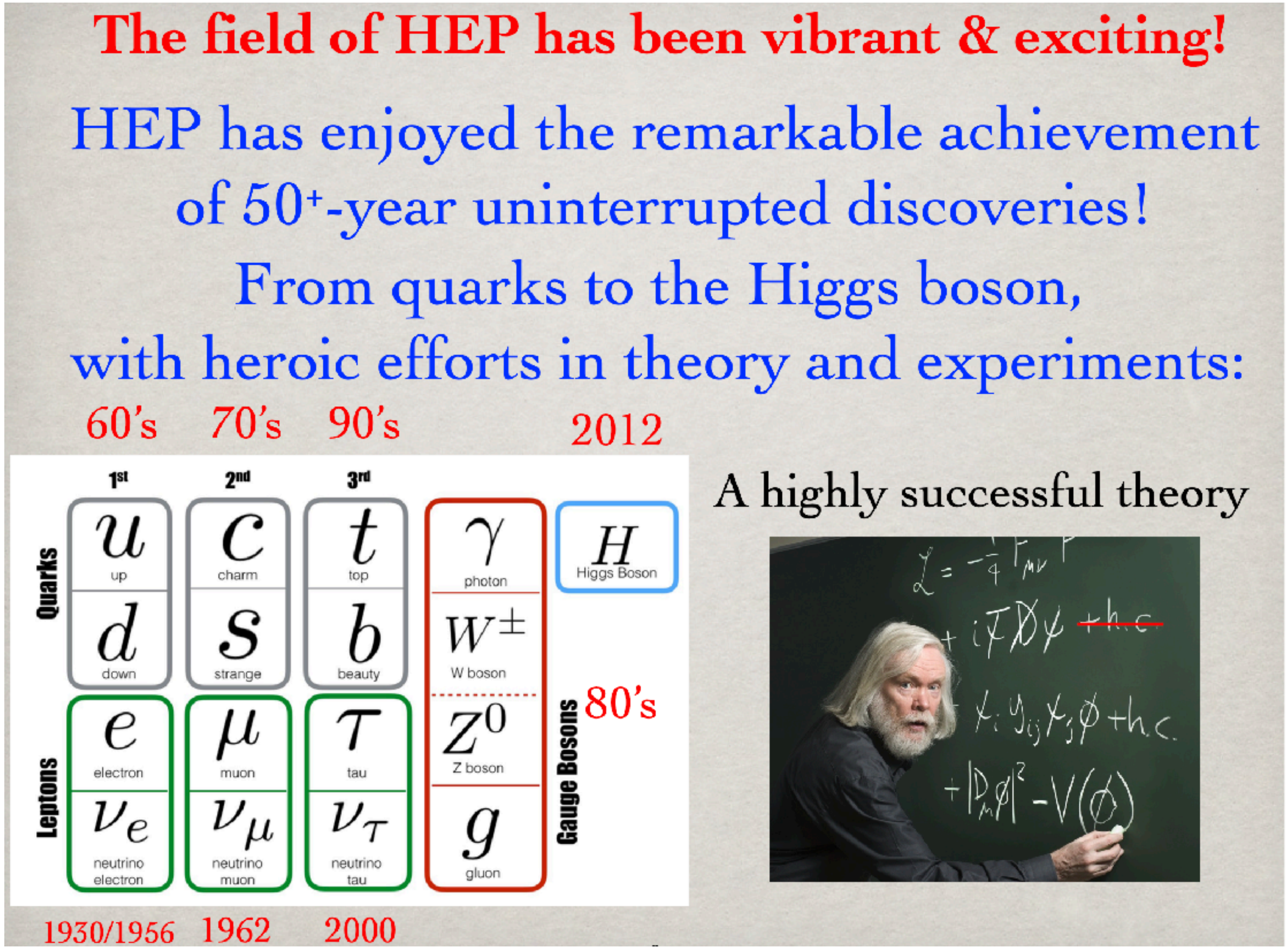
- Summary

Successful of SM



Credit: Tao Han

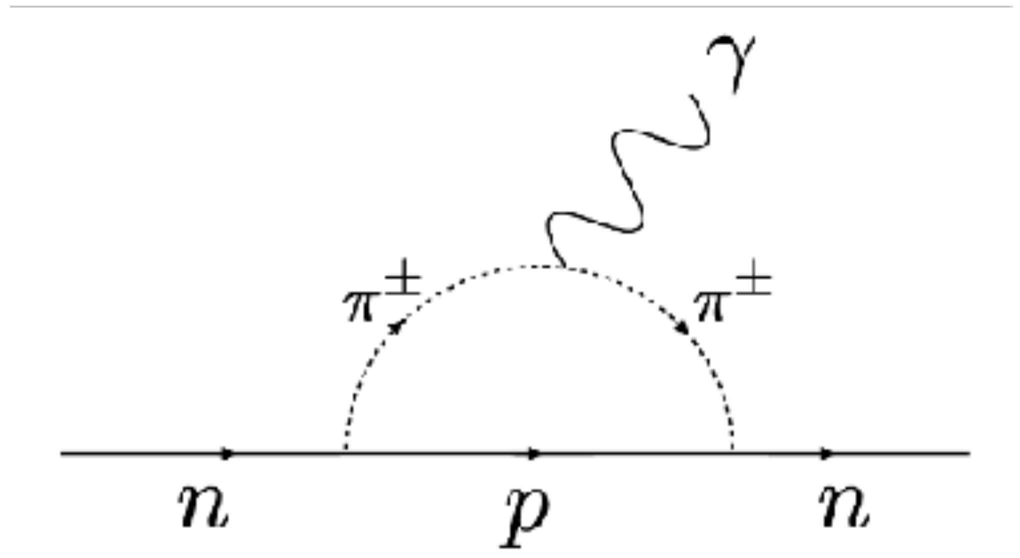
Problem of SM-Strong CP problem

- Low-energy QCD done predict

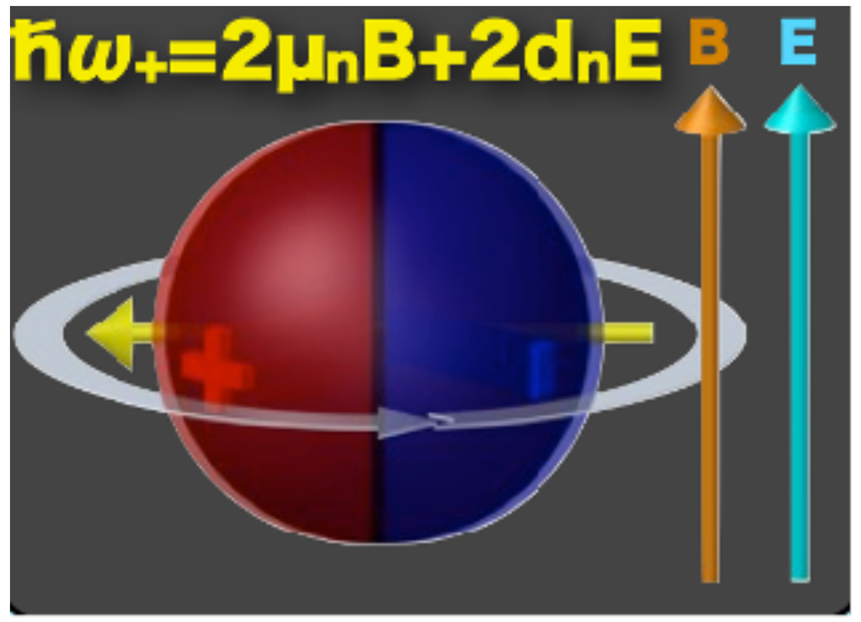
$$\mathscr{L} \supset \frac{\bar{\theta} g_s^2}{32\pi^2} G\tilde{G}$$

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

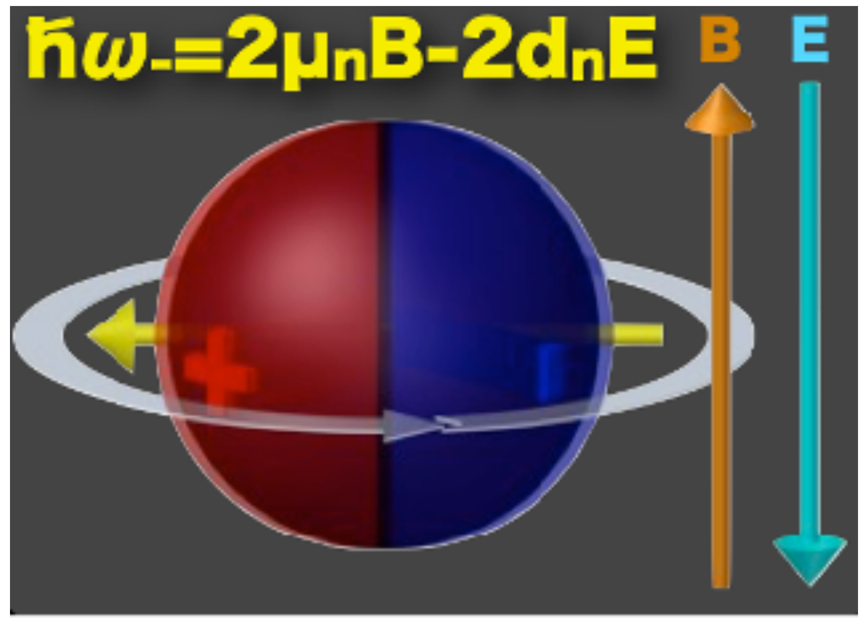
$$d_n = \frac{e\bar{\theta} g_A c_+ \mu}{8\pi^2 f_\pi^2} \log \frac{\Lambda^2}{m_\pi^2} \sim 3 \times 10^{-16} \bar{\theta} \text{ e cm}$$



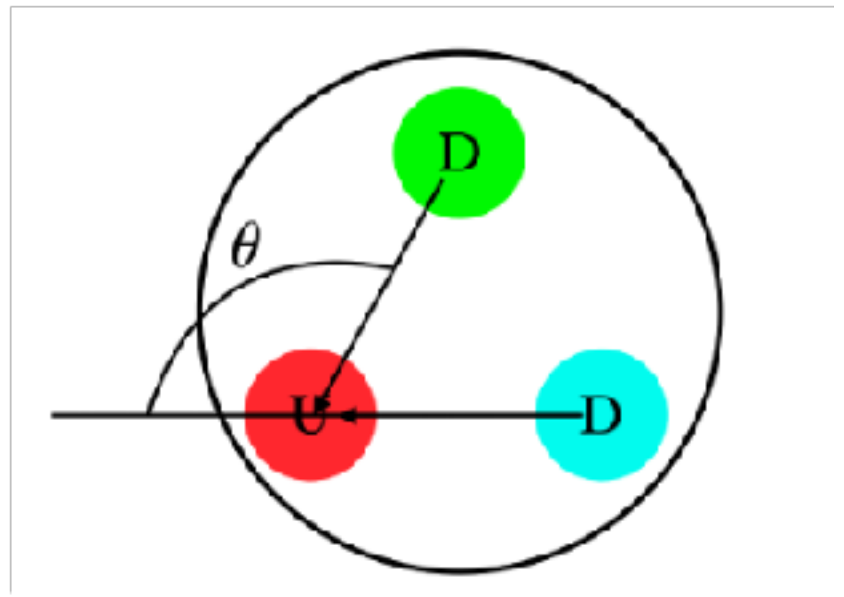
- Pression measurement



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



Classical solution to Strong CP problem



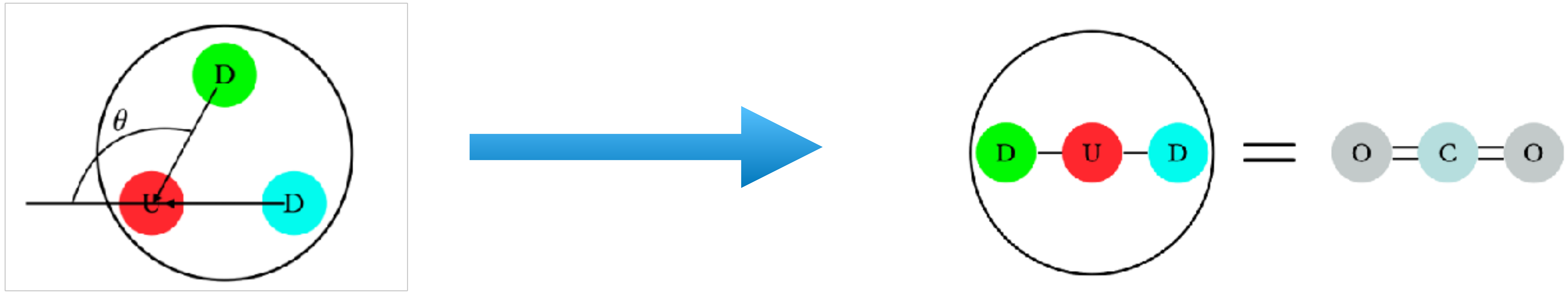
- The neutron eDM in classical formula

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

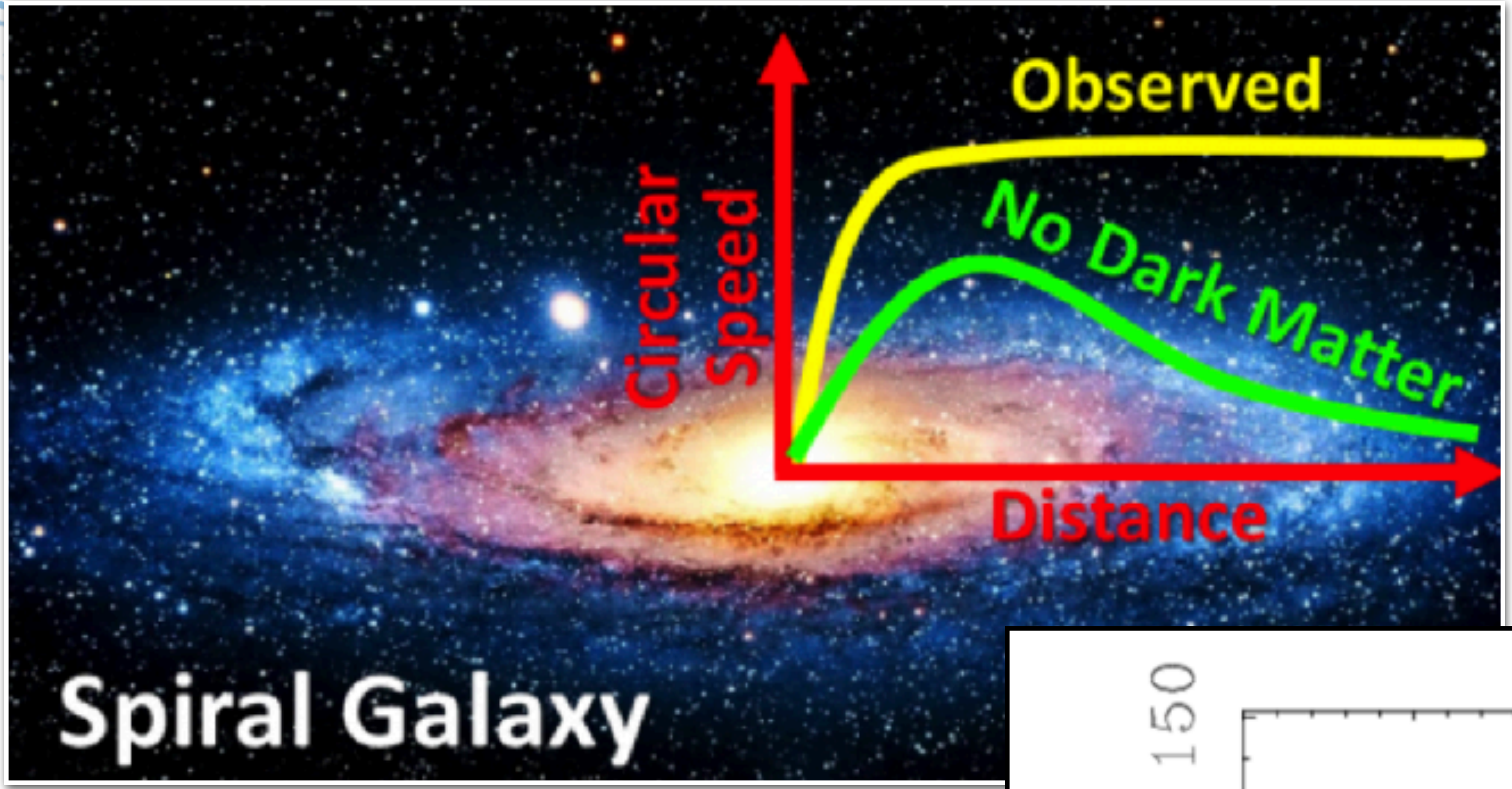
- Use the neutron has a size $r_n \sim 1/m_\pi$

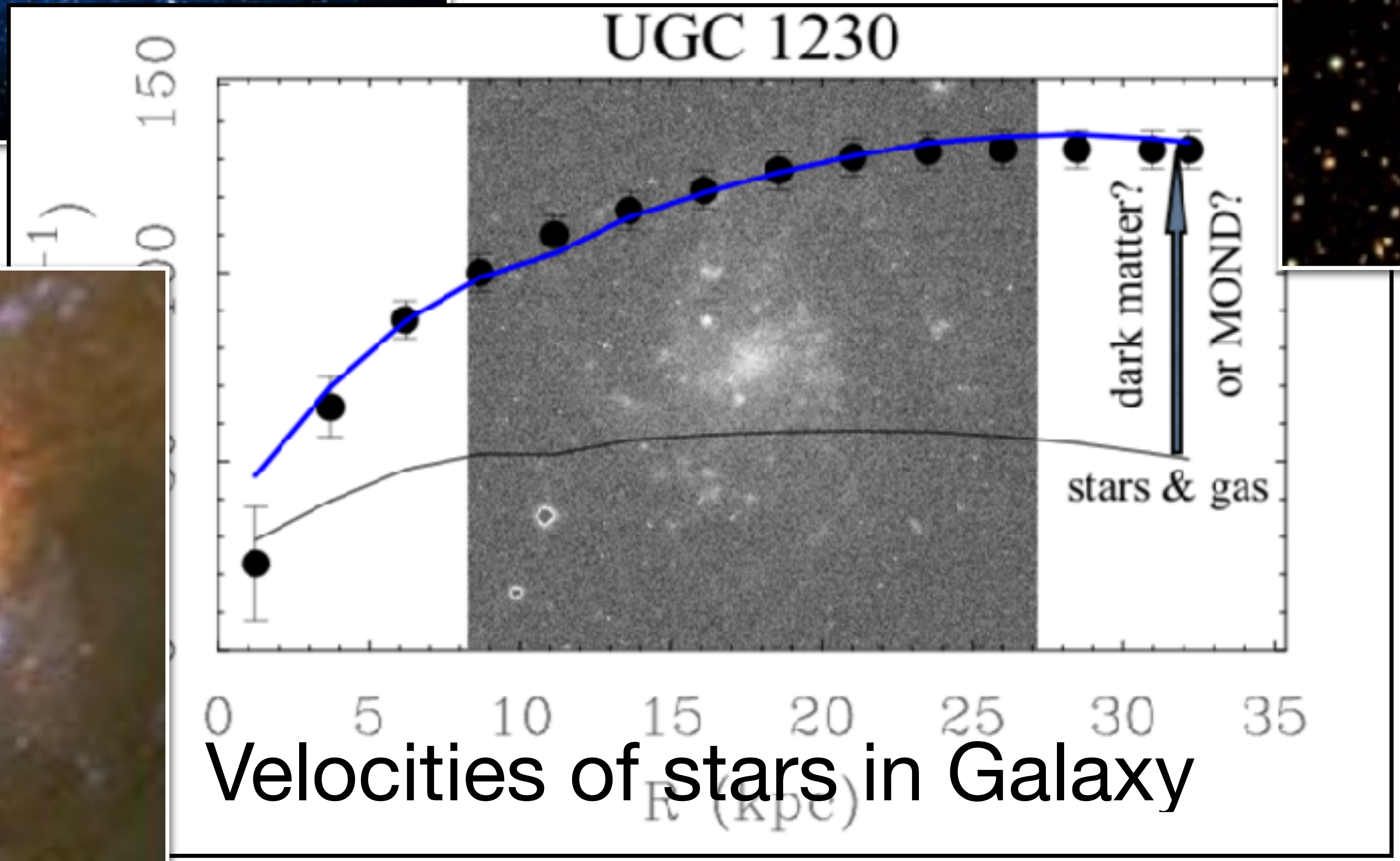
$$\left| d_n \right| \approx 10^{-13}\sqrt{1-\cos\theta}e \text{ cm}$$

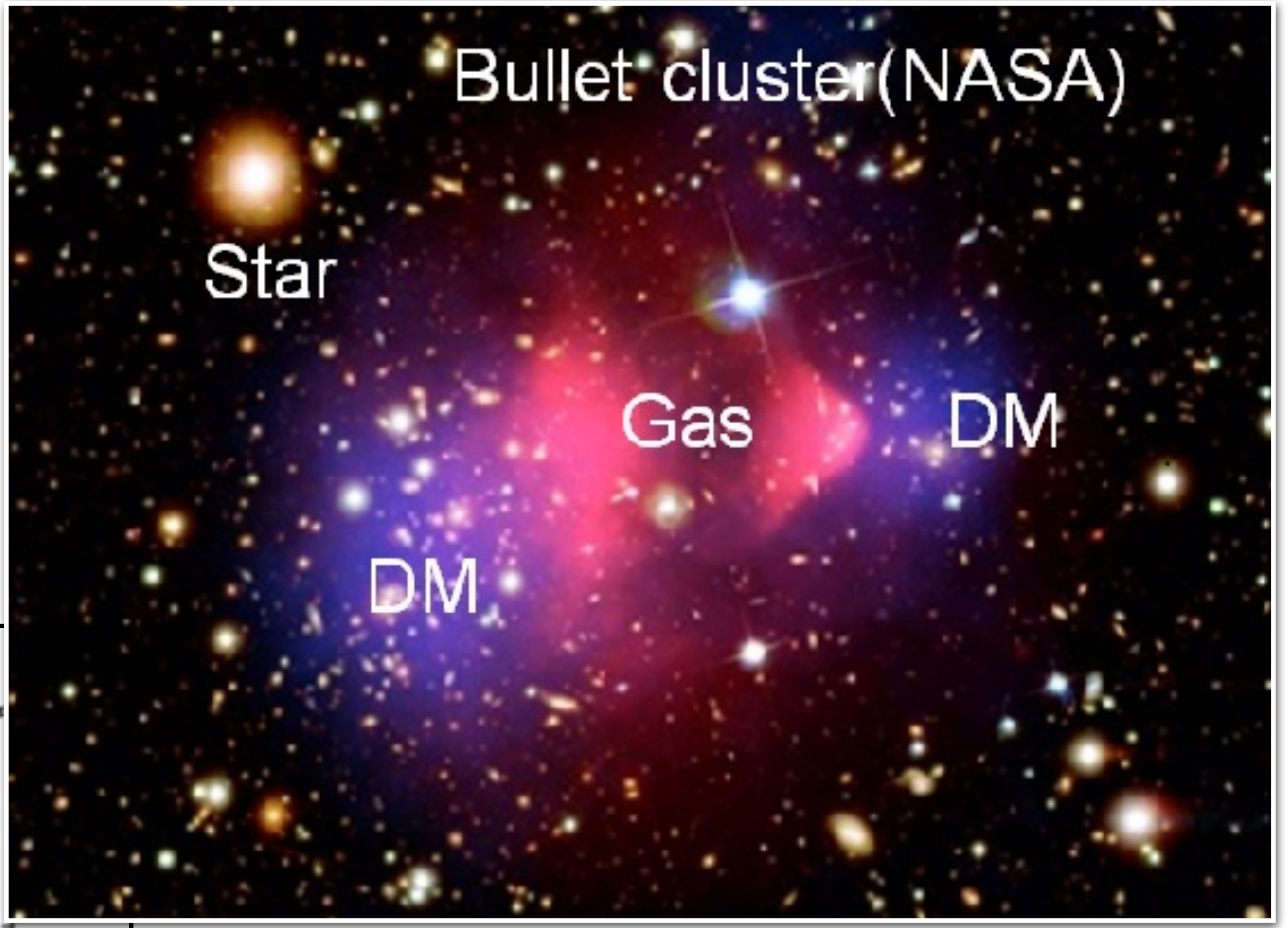
- Comparing to the experiment results, we need $\cos\theta = 1$



Problem of SM-DM candidate







Problem of SM-DM candidate

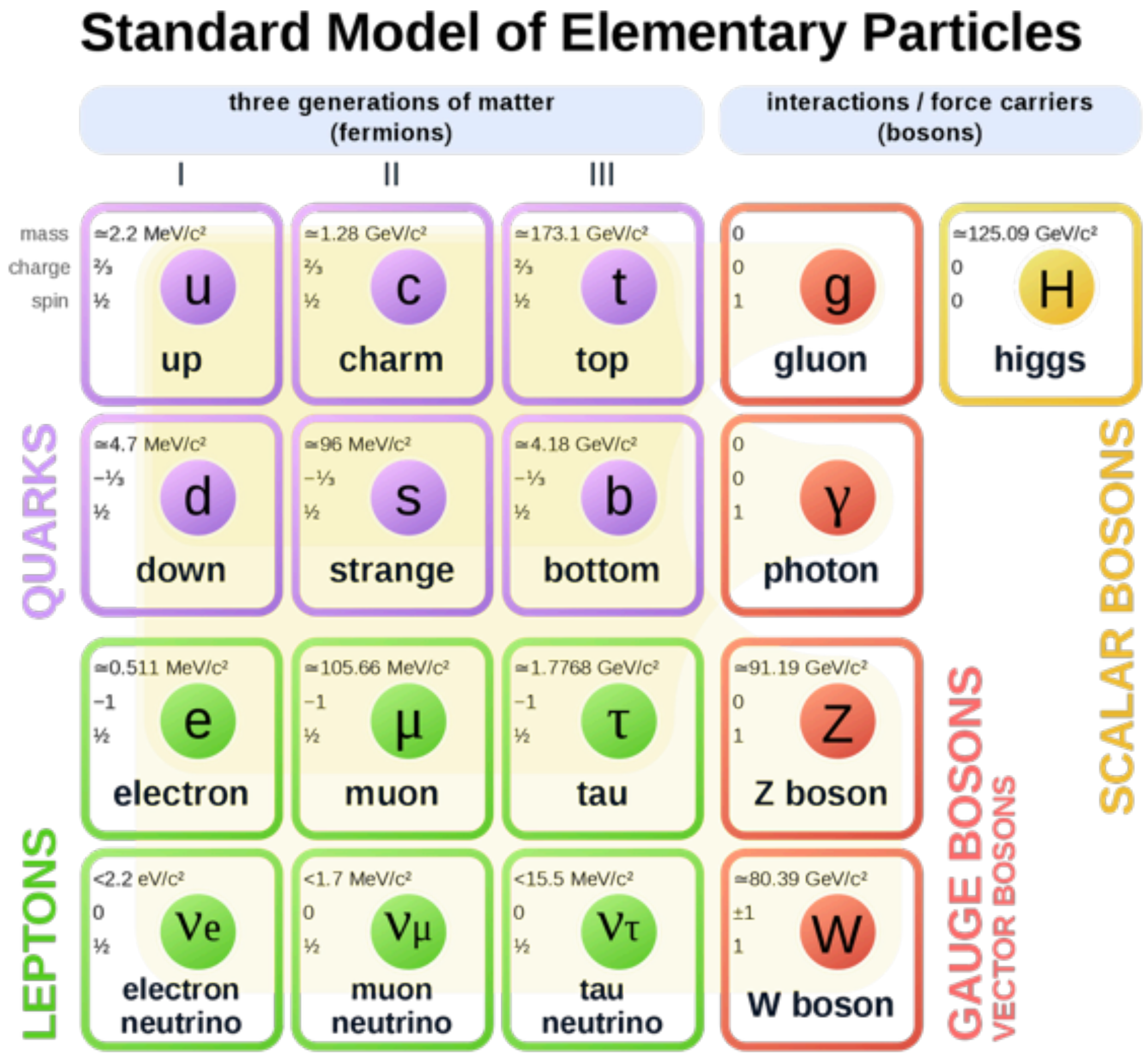
- Dark matter properties:
  1. No Charge (Not charged Quark, Leptons)
  2. Massive (Not gluon, photon)
  3. Long enough life-time (not Z, W, H)

- Only Possibility: Neutrino

$$\Omega_\nu h^2 = \frac{m_\nu}{94\mathrm{eV}}$$

$$\Omega_{\mathrm{DM}} h^2 \sim 0.12$$

No DM candidate in SM



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The QCD axion for Strong CP problem

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

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

- To solve strong CP problem

$$d_n \propto \frac{a}{f_a} + \bar{\theta} = 0$$

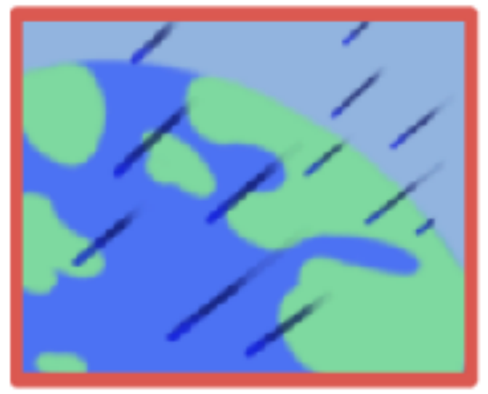
- QCD axion mass relationship

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

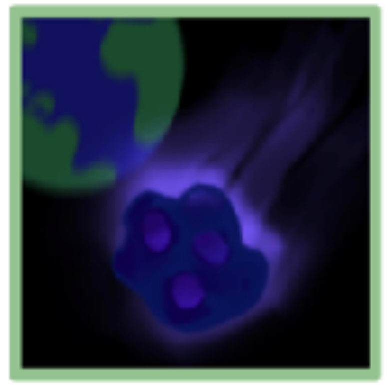
Dark Matter Candidates

Wave-like

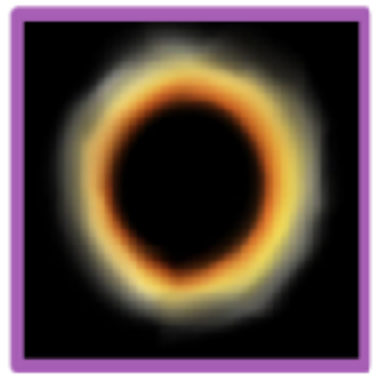
Particle-like



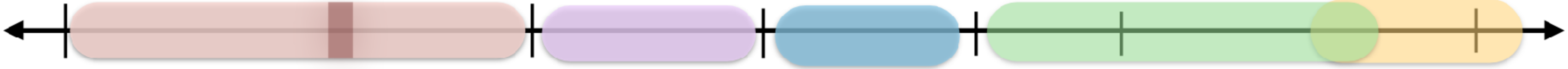
Object-like



Astro Candidates



10^{-22} eV | QCD axion classic window 10^{-6} - 10^{-4} eV | WDM limit keV | GeV | unitarity limit 100 TeV | $M_{\rm pl}$ | $10\ M_{\odot}$



``Ultralight" DM
non-thermal bosonic fields

``Light" DM
dark sectors
sterile ν
can be thermal

WIMP

Composite DM
(Q-balls, nuggets, etc)

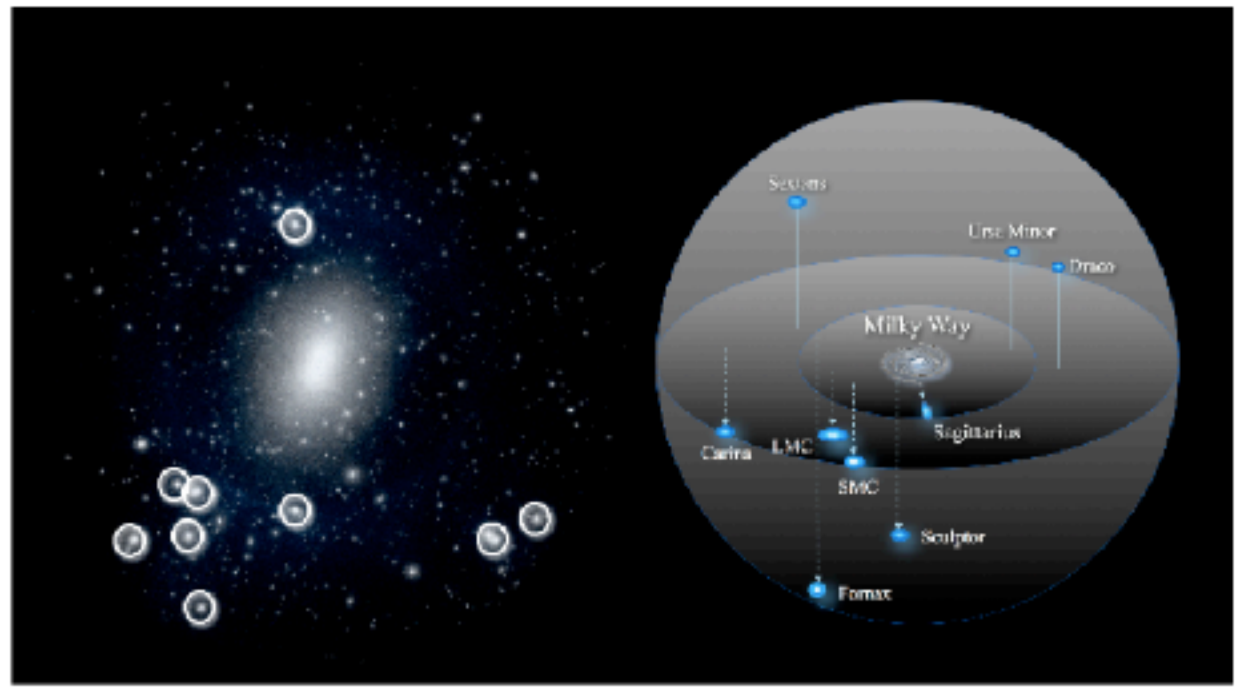
Primordial black holes

Today's focus

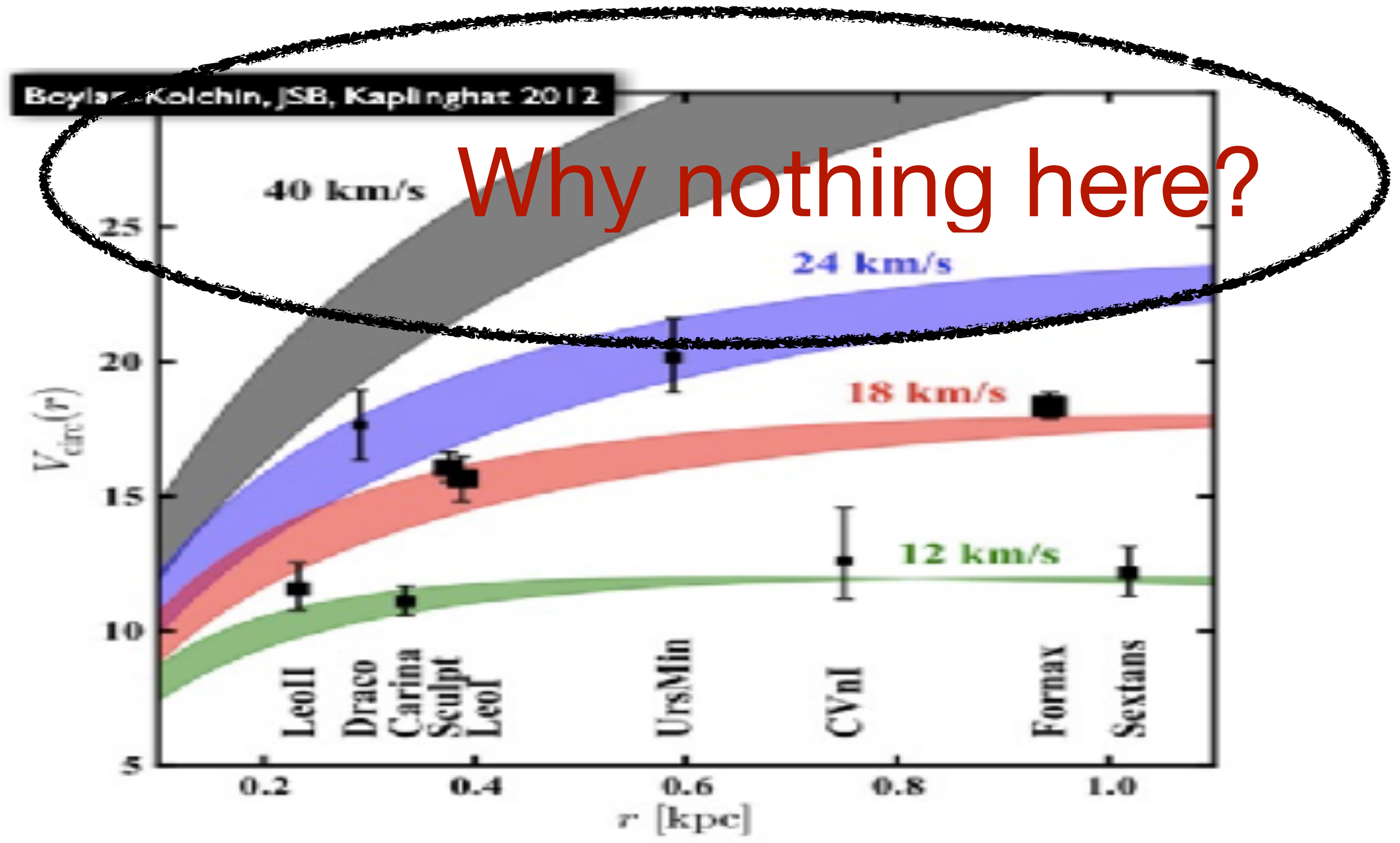
HEP at a cross-road: explore all directions!

The Small Scale problem

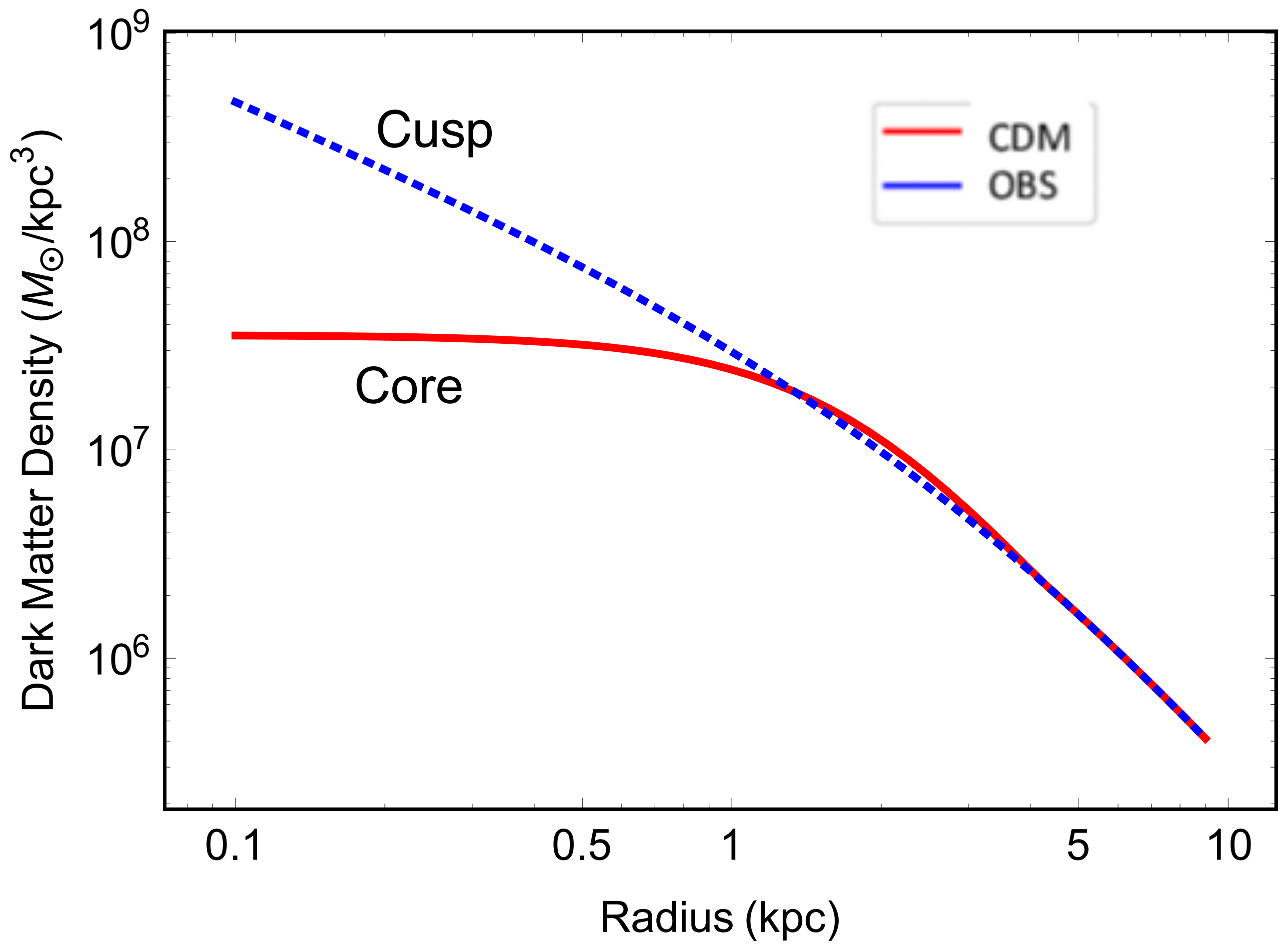
- Missing Satellites Problem



- Too-big-to-fail Problem:



- Core-Cusp Problem



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

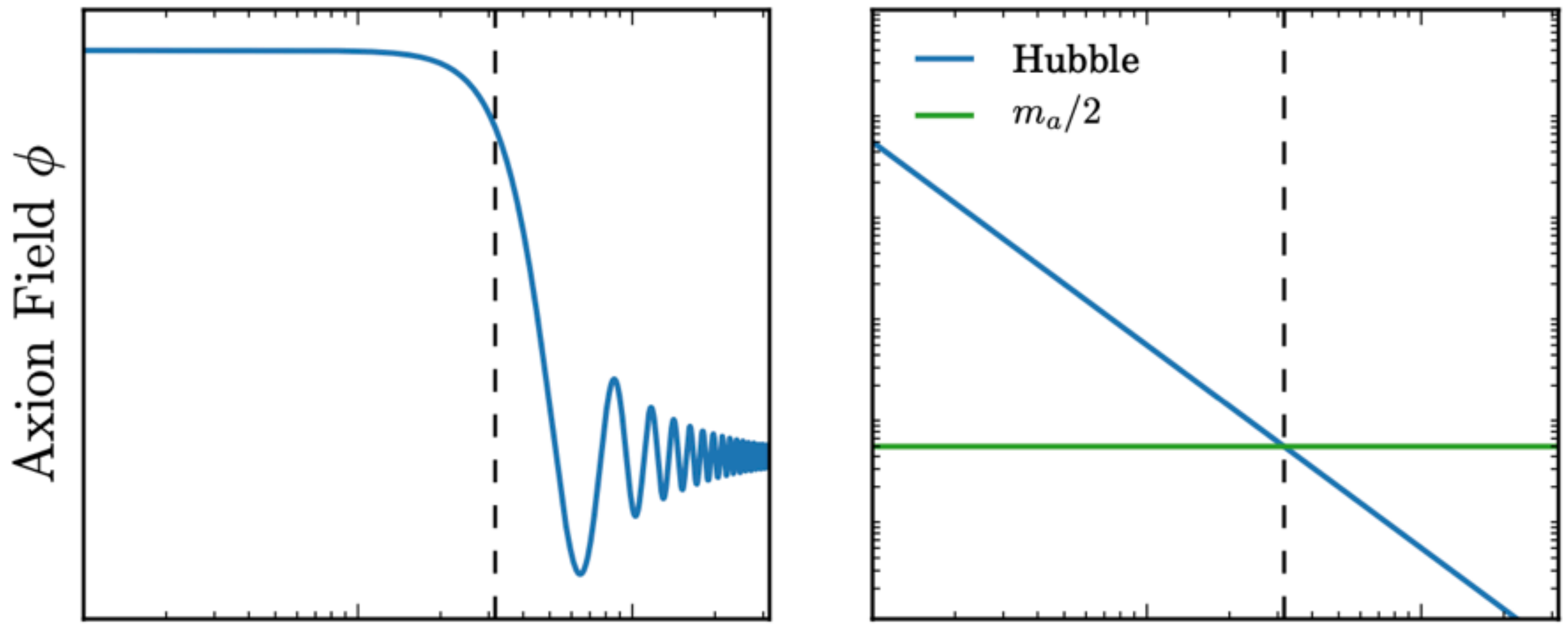
$$m_{\rm a} \simeq 6 \times 10^{-6}{\rm eV} \left(\frac{10^{12}{\rm GeV}}{f_{\rm a}}\right)$$

- The Axion energy density will be

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

- The critical time change from field to particle

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



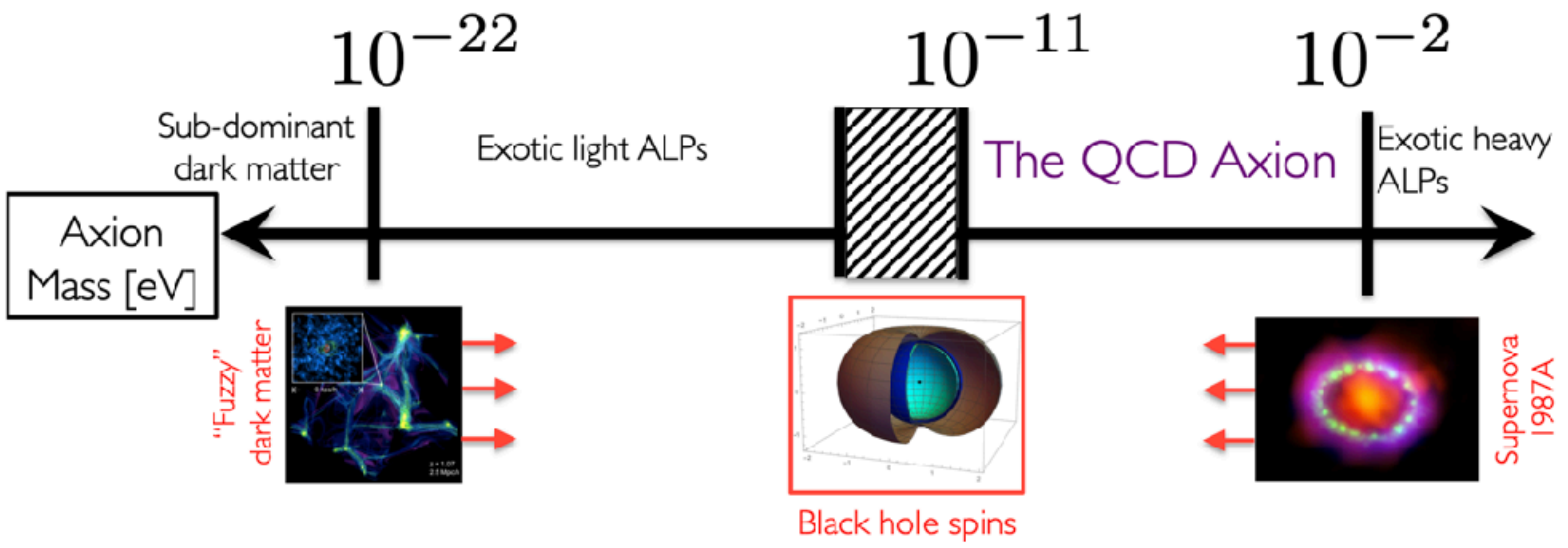
Ultralight Dark Matter-ALP

- The ALP Lagrangian

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

- 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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ALP Dark Matter Search

- The ALP Lagrangian

$$\mathcal{L}_a^{\text{int}} \supset \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a} aF\tilde{F} + C_{af}\frac{\partial_\mu a}{2f_a}\bar{f}\gamma^\mu\gamma_5 f + \frac{C_{a\pi}}{f_a f_\pi}\partial_\mu a[\partial\pi\pi\pi]^\mu + C_{ae}\frac{\partial_\mu a}{2f_a}\bar{e}\gamma^\mu\gamma_5 \mathrm{e}$$

Coupling to photon

Coupling to axion nuclear moment
Creates
Spin dependent energy shifts/spin precession in fermions

Coupling to mesons, induce Meson decay

Coupling to axial electron moment

Axioelectric effect, Analogous to ohotoelectric

$$C_{a\gamma} = \frac{E}{N} - 1.92(4)$$

$$C_{ap} = -0.47(3) + 0.88(3)c_u^0 - 0.39(2)c_d^0$$

$$C_{an} = -0.02(3) + 0.88(3)c_d^0 - 0.39(2)c_u^0$$

$$C_{a\pi} = 0.12(1) + \frac{1}{3}\left(c_d^0 - c_u^0\right)$$

$$C_{ae} = c_e^0 + \frac{3\alpha^2}{4\pi^2}\left[\frac{E}{N}\log\left(\frac{f_a}{m_e}\right) - 1.92(4)\log\left(\frac{\text{GeV}}{m_e}\right)\right]$$

ALP Dark Matter Search-Photon Coupling

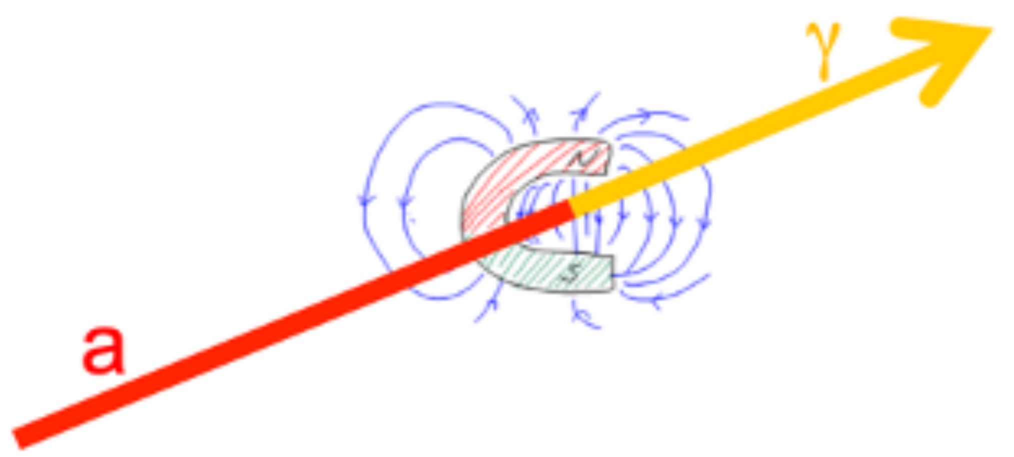
- Axion to photon Coupling

$$\mathscr{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} aF\tilde{F} = g_{a\gamma}\vec{E}\cdot\vec{B}a$$

- Modifies Maxwell equations: Additional source term

$$\vec{\nabla}\times\vec{B} - \dot{\vec{E}} = \vec{J} + g_{a\gamma}\vec{B}\dot{a}$$

Oscillating



- With local DM density: $\rho_a = \frac{m_a^2 a_0^2}{2} = f_a \frac{300\text{MeV}}{\text{cm}^3}$

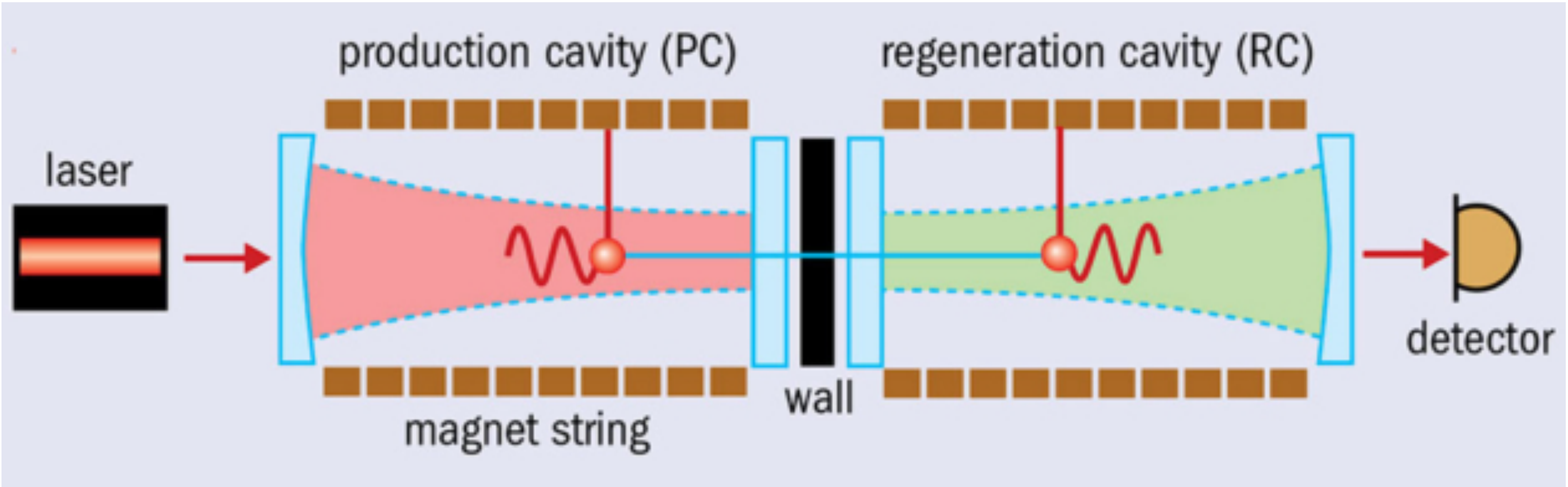
- The probability of $\gamma \rightarrow a$ is

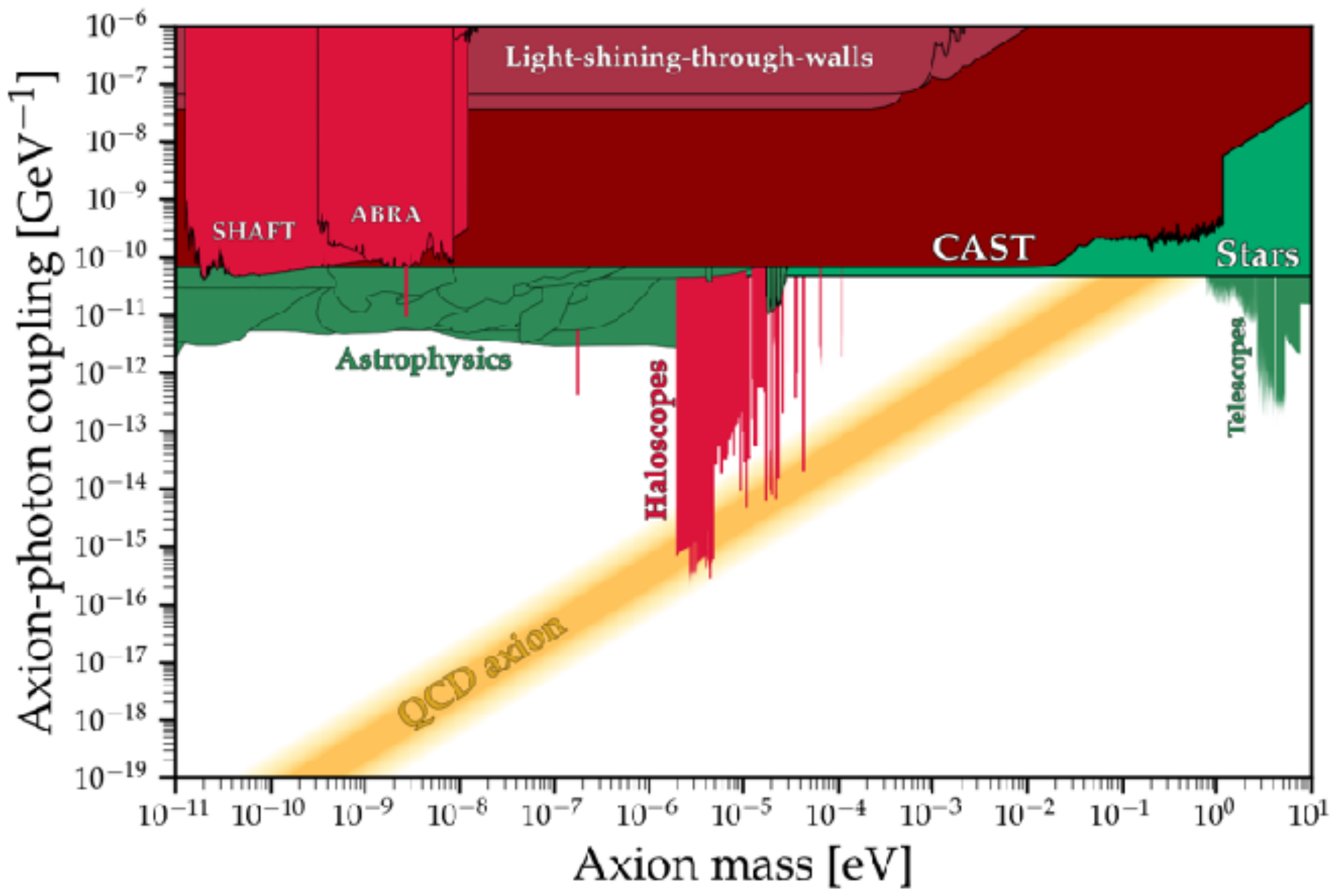
$$P_{\gamma\rightarrow a}(B,l,q) = \frac{1}{4}\left(g_{a\gamma}Bl\right)^2 \left[\frac{\sin\left(\frac{1}{2}ql\right)}{\frac{1}{2}ql}\right]^2$$

$$\mathrm{q} = \kappa_\gamma - \kappa_a \sim m_a^2/2\omega$$

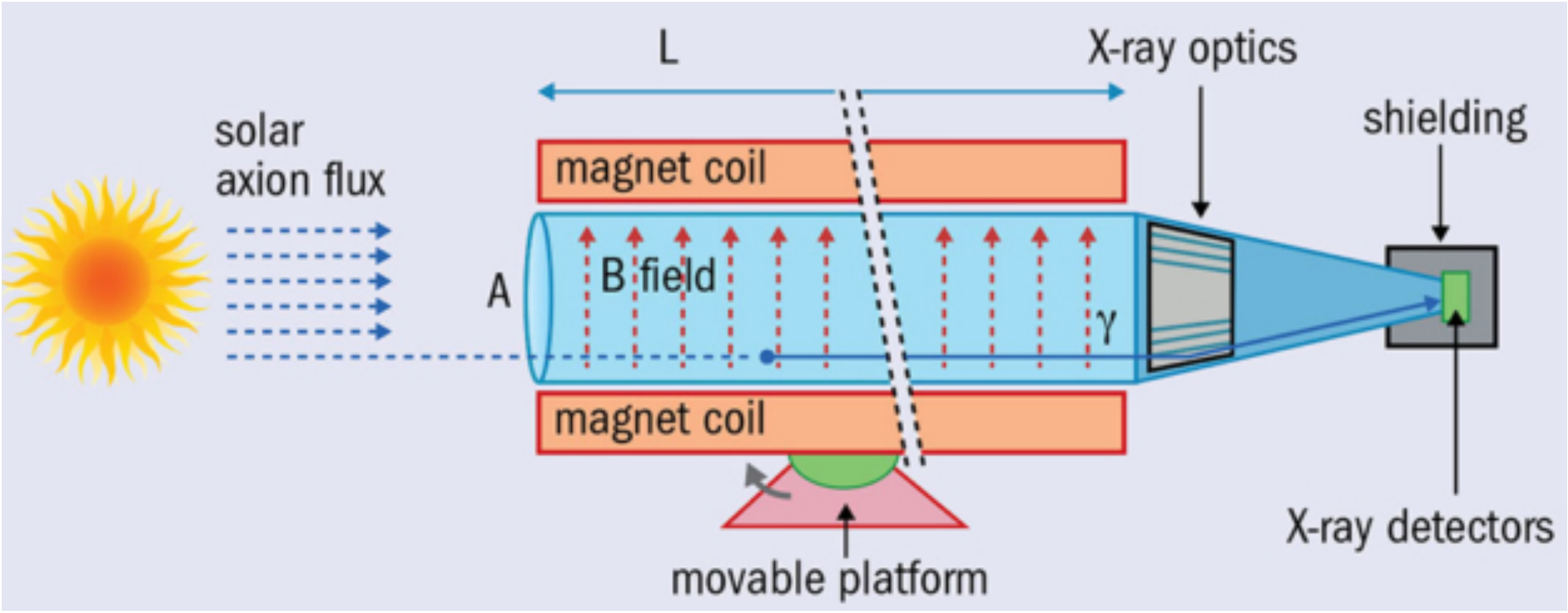
ALP Dark Matter Experiments

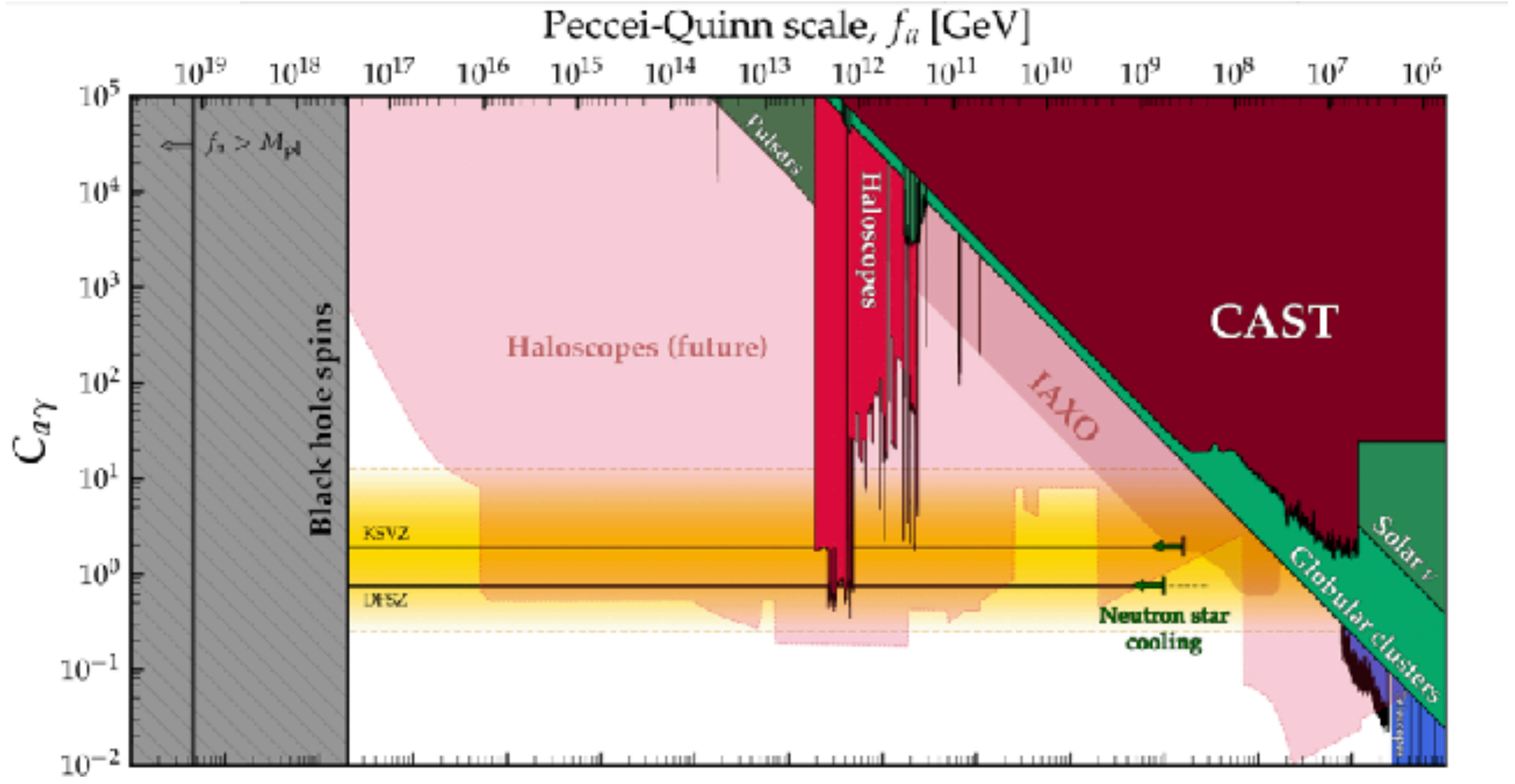
- Laboratory Experiments: Lasers (light shining through walls)





•Search for Solar Axions (Helioscopes)





Haloscopes for ALP DM!

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Nuclear magnetic resonance method

- Axion couples to SM particles

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

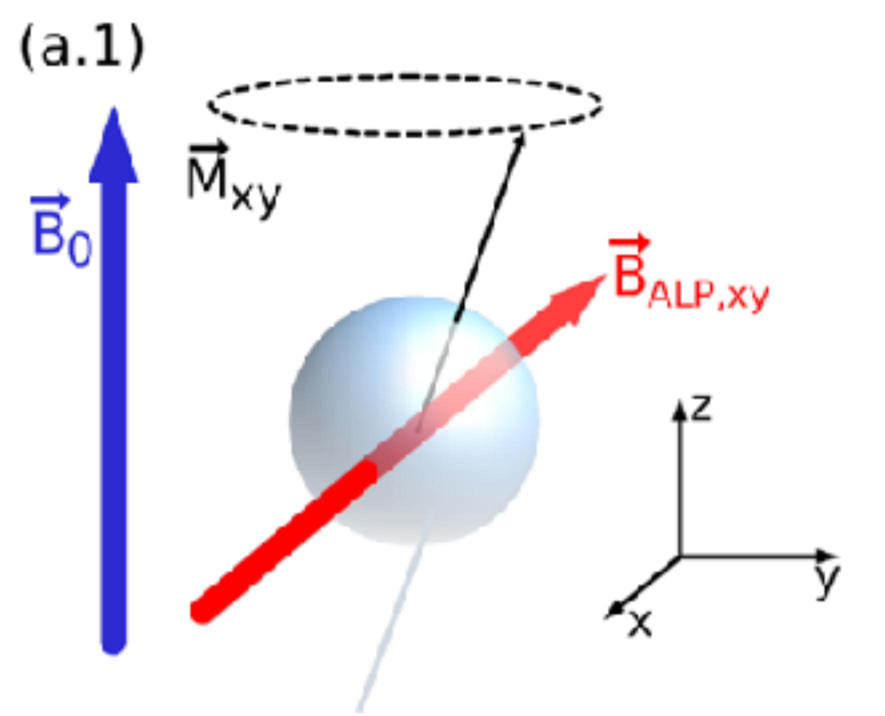
- Oscillate the mass at Larmor frequency

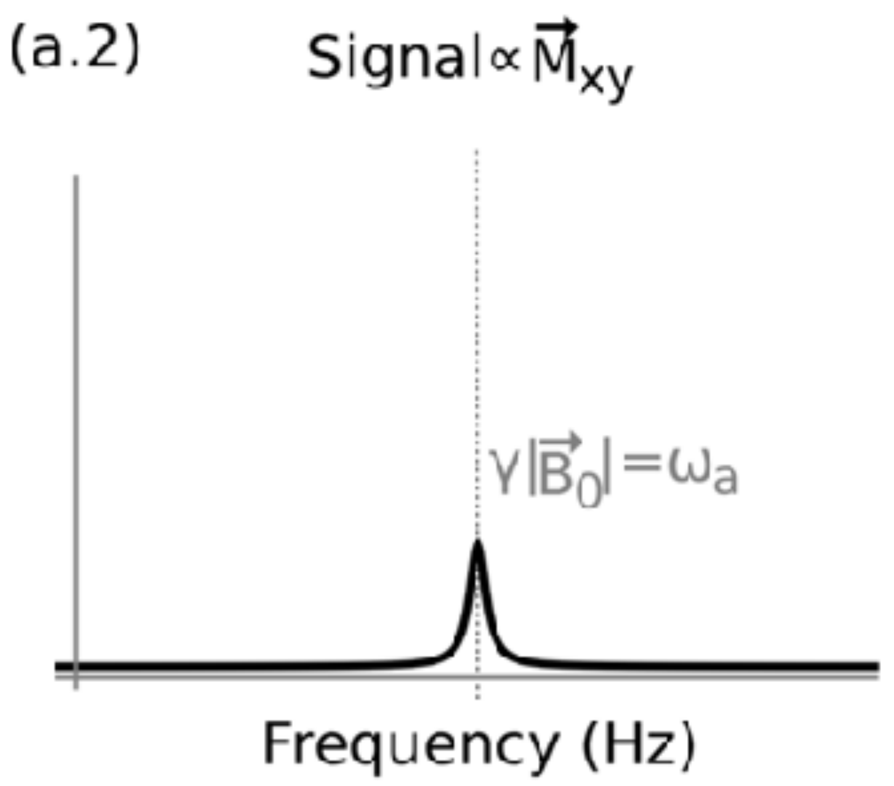
$$\vec{B}_{\mathrm{ALP}} = g_{aNN}\sqrt{2\rho_{\mathrm{DM}}}\cos(m_a t) = g_{aNN}\sqrt{2\rho_{\mathrm{DM}}}\cos(\omega_a t)$$

- Bloch Equations

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

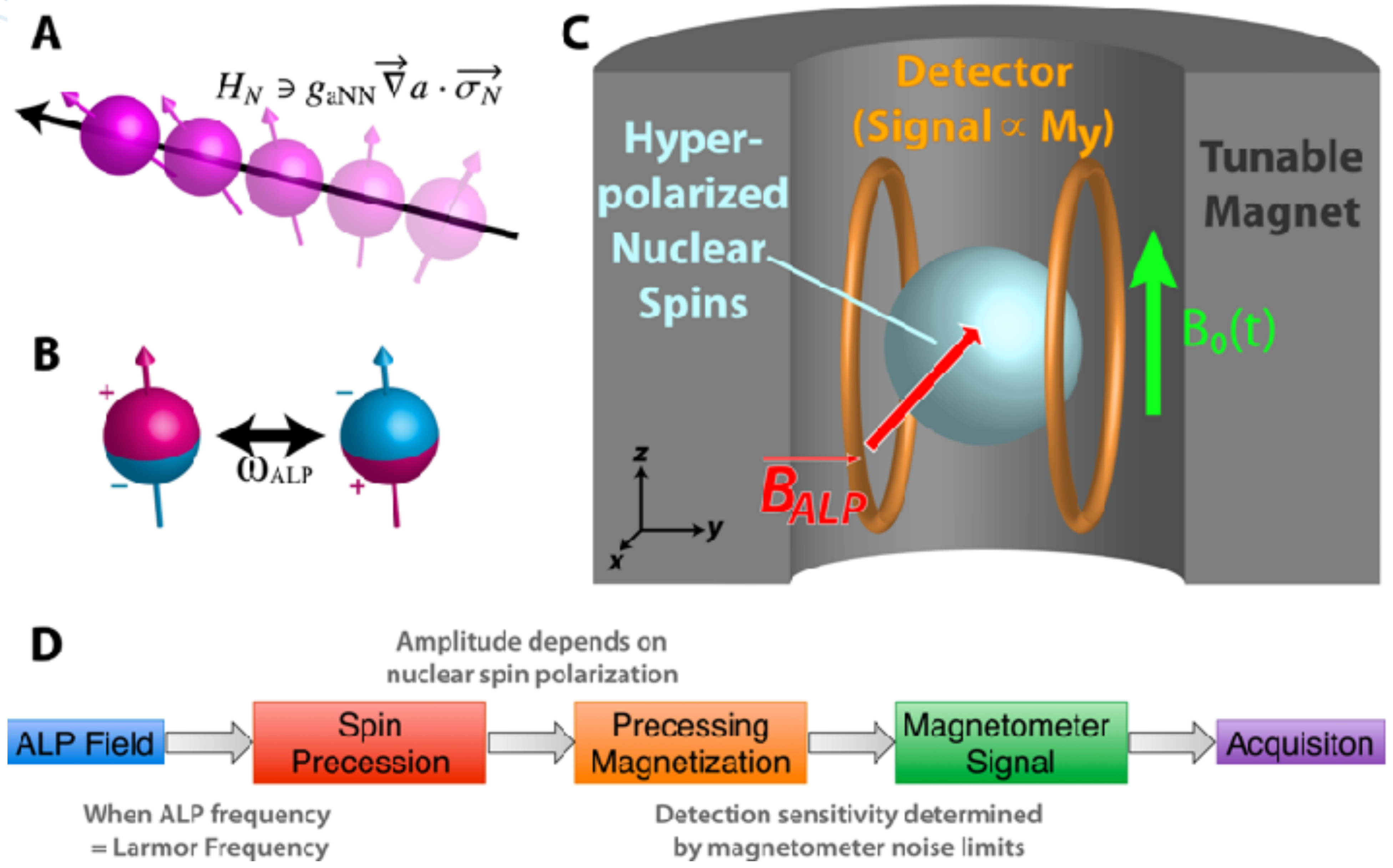
Generate transverse from longitudinal

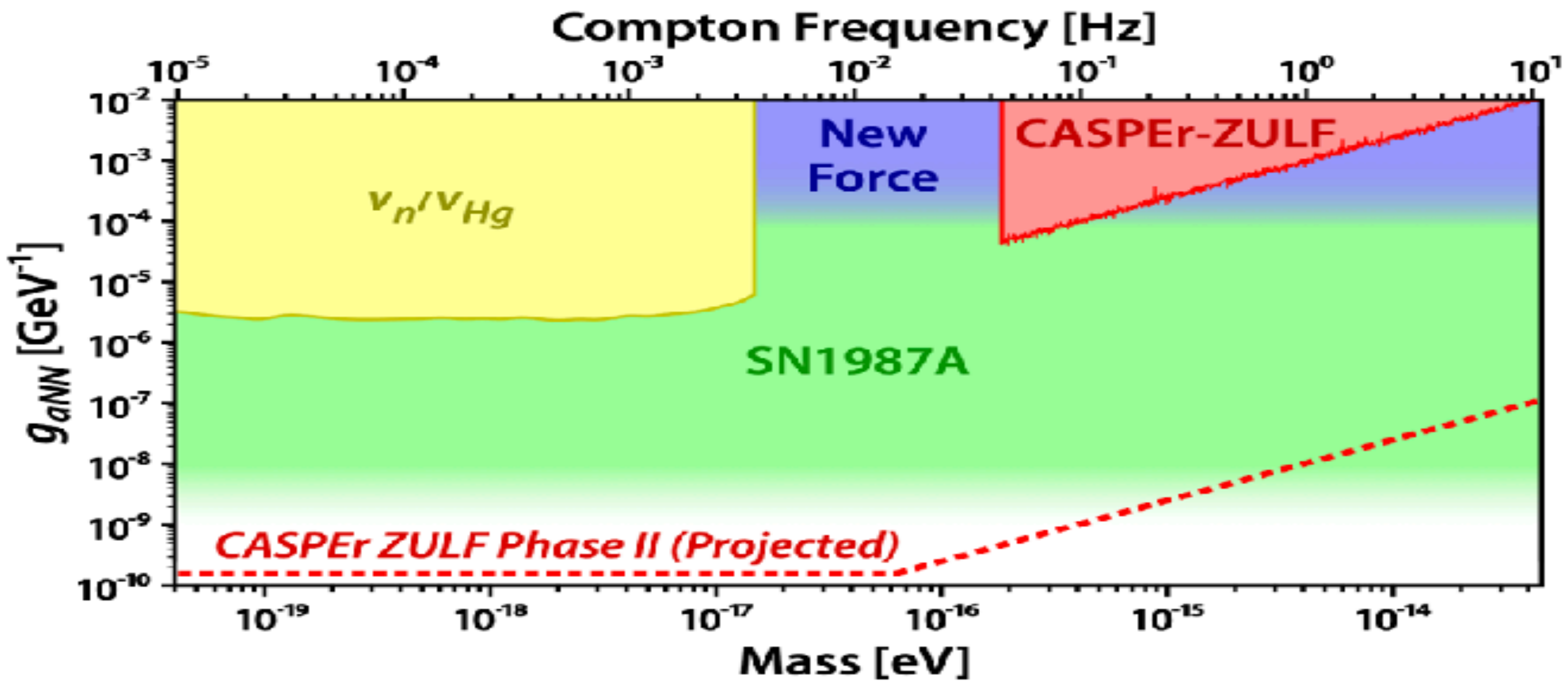


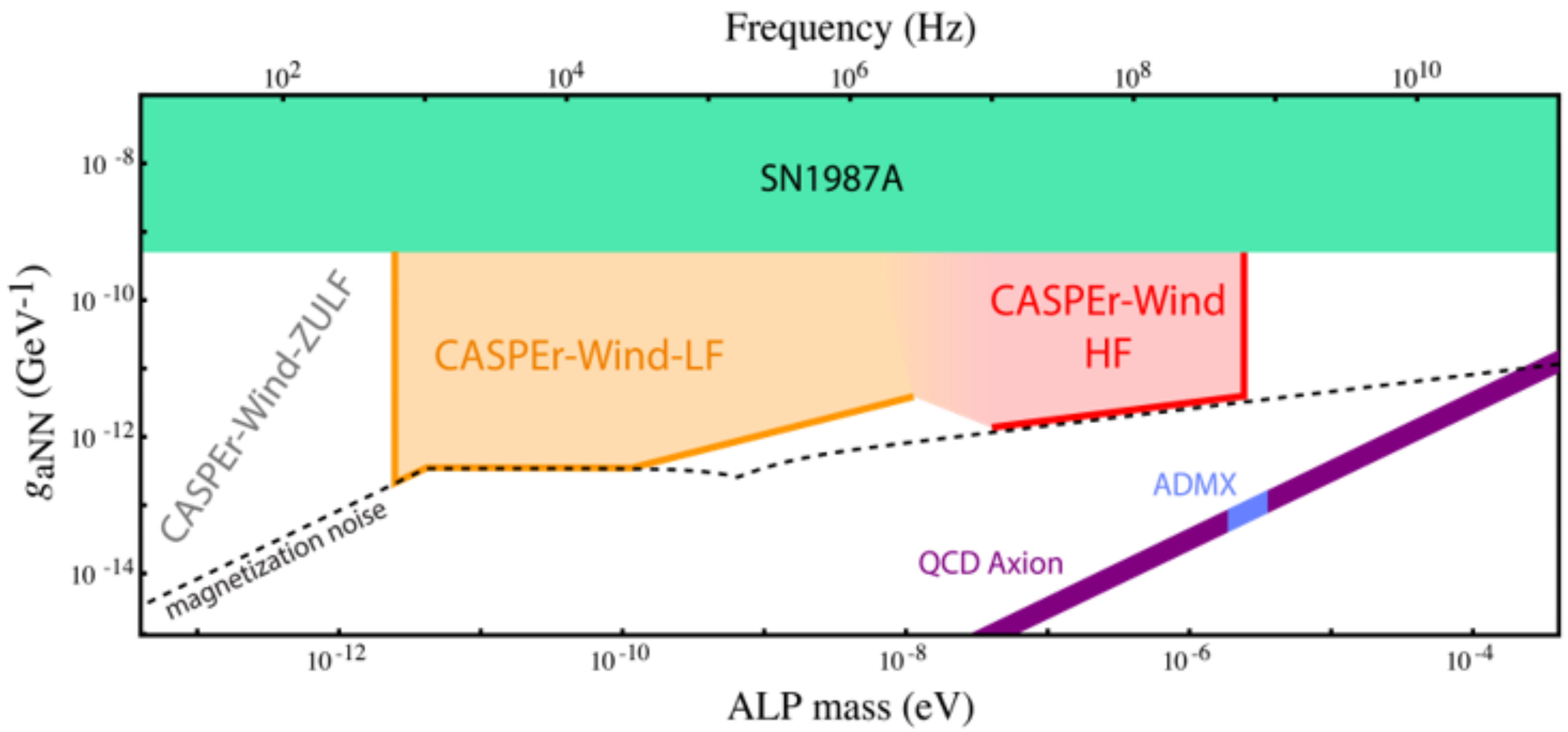


Time varying Axion B_{ALP} drives spin precession → produces transverse magnetization

Cosmic Axion Spin Precession Experiment







CASPEr Group; *Sci.Adv.* 5 (2019) 10, eaax4539

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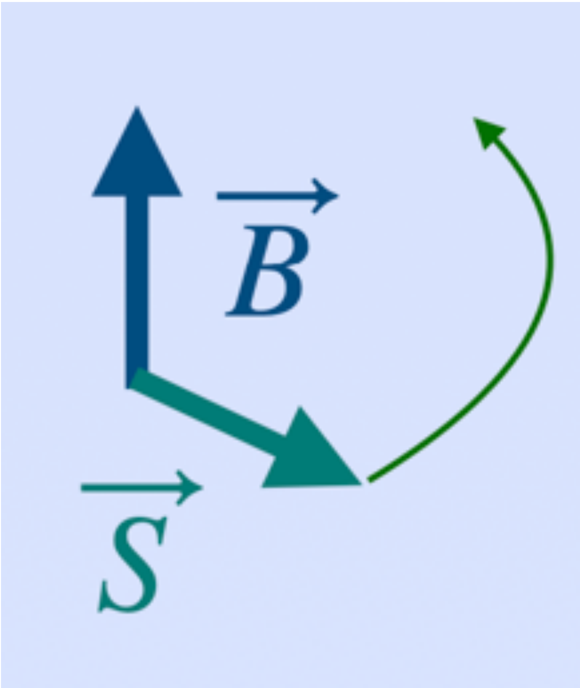
Comagnetic resonance method

- 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

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

Signal: Generated from ALP

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

Spin in Z direction

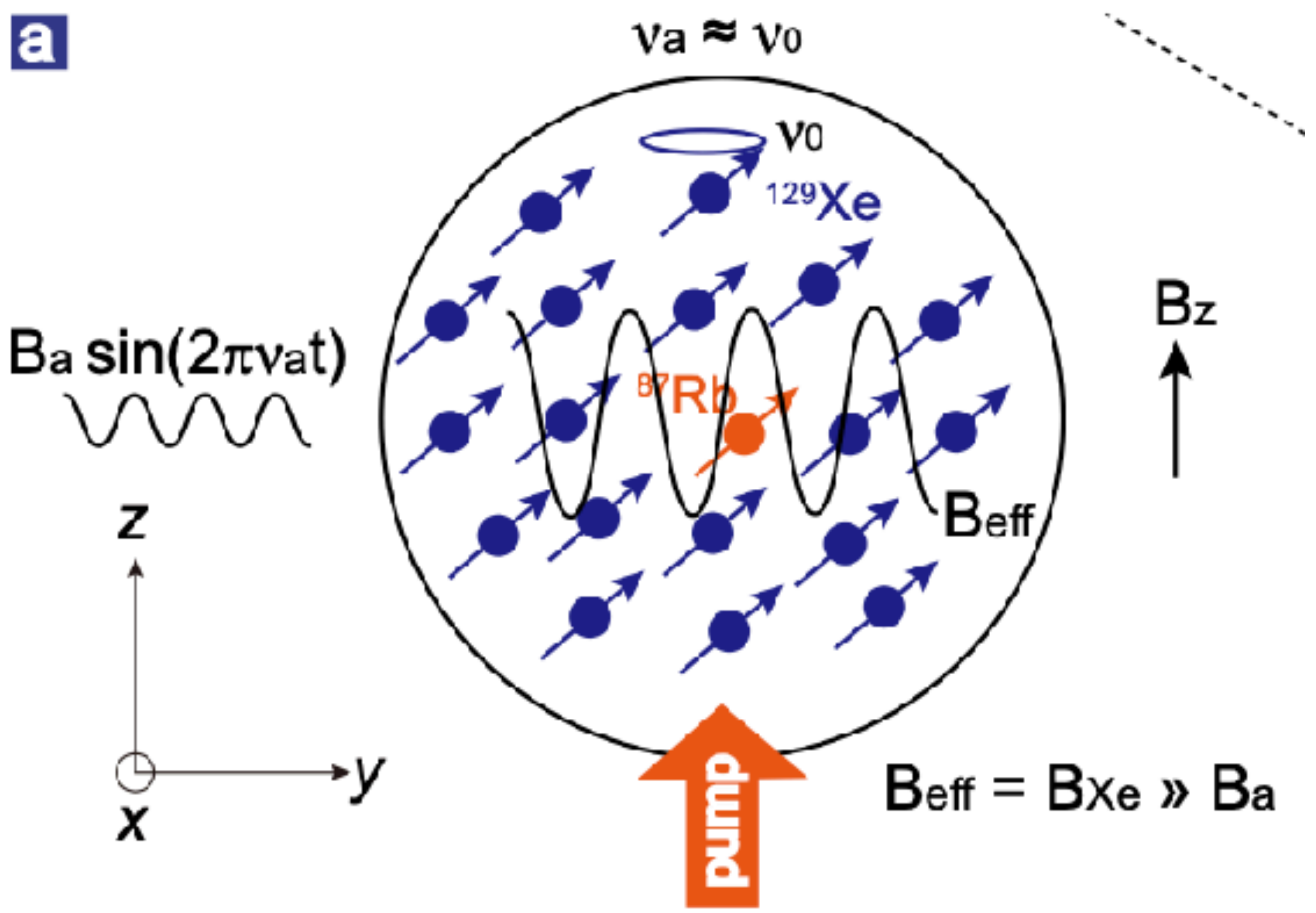
Controlled Resonance Frequency

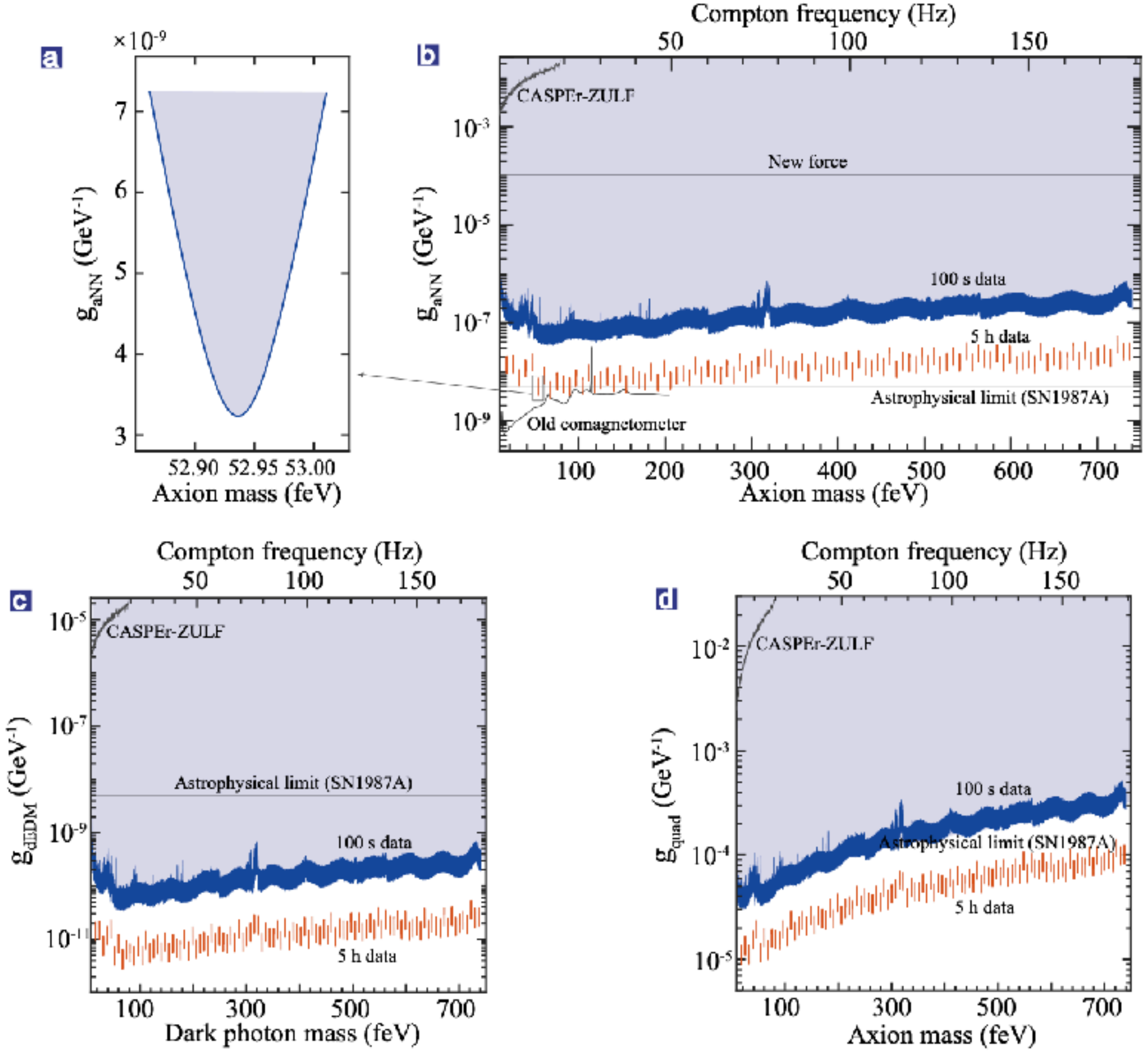
ALP mass

Decoherence Rate

Comagnetic - Fermi-contact enhancement

- nuclear spins can be directly hyperpolarized to achieve a polarization of by spin-exchange optical pumping
- nuclear spin signals can be enhanced due to large Fermi-contact enhancement factor (~100)

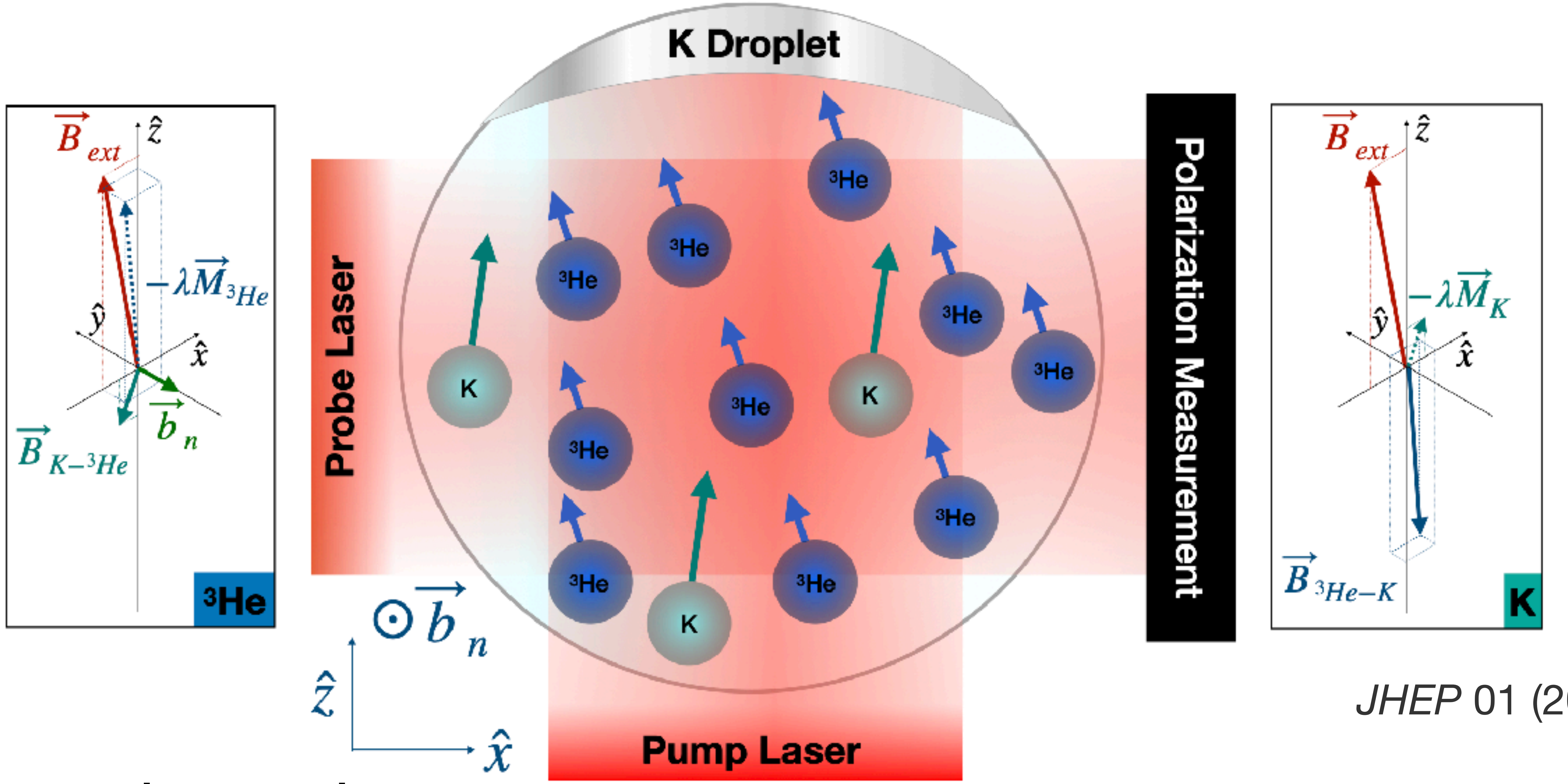




Jiang et al., Nature Physics 17, pages 1402–1407 (2021)

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.

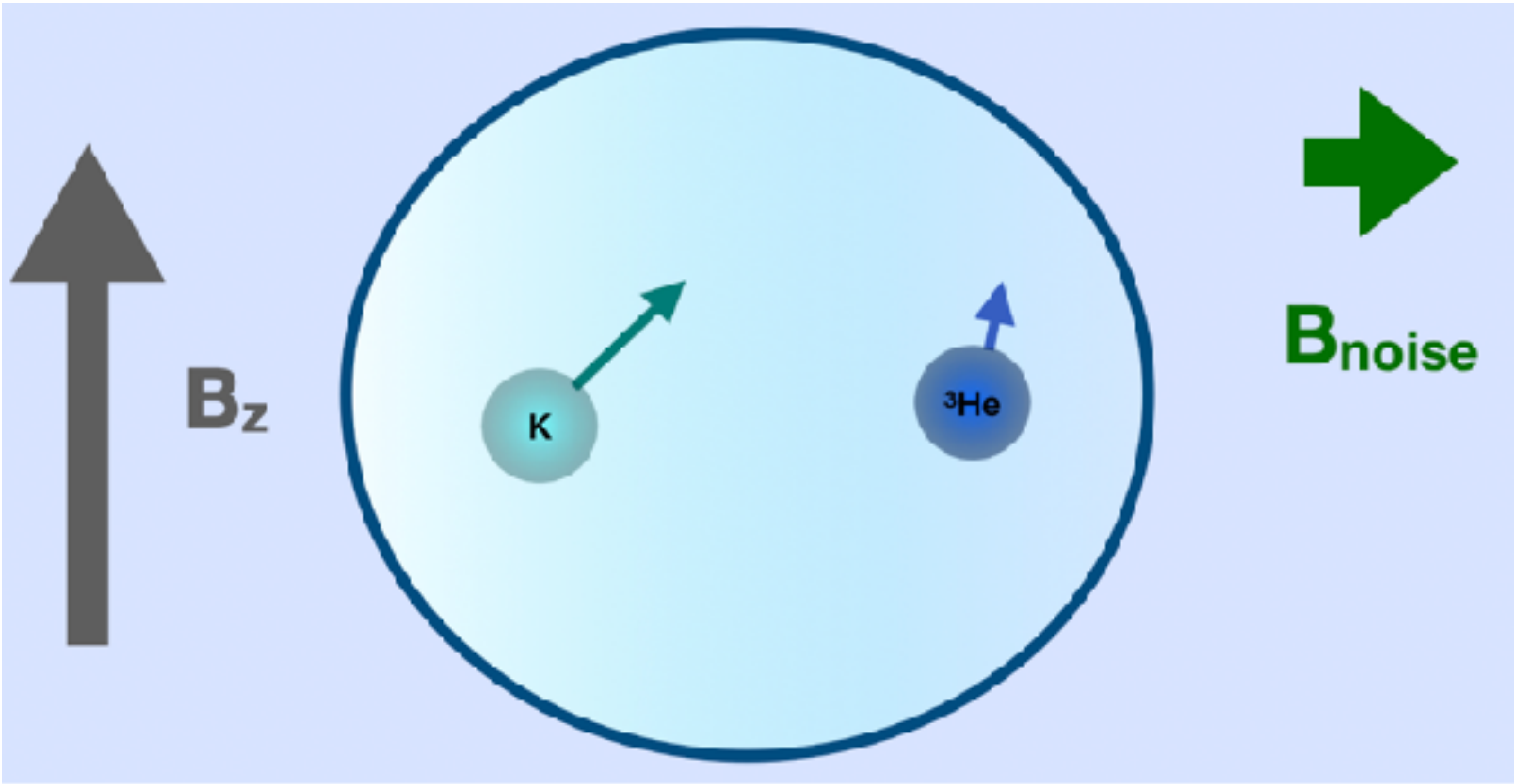
Comagnetic - The compensation point

$$S_{\text{Alk}}\left(\omega = m_a\right) = \frac{\text{signal} + \gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}}{\left(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a\right) + i\Gamma_{\text{Alk}}}$$

With $B_{\perp,\text{Alk}} = B_{\perp,\text{ noise}} + 2\lambda M_{\text{Nob}} S_{\perp,\text{Nob}} / S_{\text{Nob,z}}$

$$\frac{\partial S_{\text{Alk}}}{\partial B_{\perp,\text{ noise}}} = \frac{\gamma_{\text{Alk}} S_{\text{Z,Alk}}}{\left(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a\right) + i\Gamma_{\text{Alk}}} \left(1 + \frac{2\gamma_{\text{Nob}} \lambda M_{\text{Nob}}}{\left(\gamma_{\text{Nob}} B_{\text{z,Nob}} - m_a\right) + i\Gamma_{\text{Nob}}}\right)$$

$\Gamma_{\text{Nob}} \approx 0, m_a \approx 0,$ For $B_{\text{Z,Nob}}$ is tunable such that $\partial_{B_{\perp,\text{ noise}}} S_{\text{Alk}} = 0$



$$S_K^{\perp} \propto \gamma_K B_{\text{tot}}^{\perp} = \gamma_K B_{ind}^{\perp} + \gamma_K B_{\text{noise}}^{\perp} = 0!$$

No Signal!

Comagnetic - The compensation point

$$\frac{\partial S_{\text{Alk}}}{\partial B_{\perp,\ \text{noise}}} = \frac{\gamma_{\text{Alk}} S_{\text{Z,Alk}}}{(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a) + i\Gamma_{\text{Alk}}} \left(1 + \frac{2\gamma_{\text{Nob}} \lambda M_{\text{Nob}}}{(\gamma_{\text{Nob}} B_{\text{z,Nob}} - m_a) + i\Gamma_{\text{Nob}}} \right)$$

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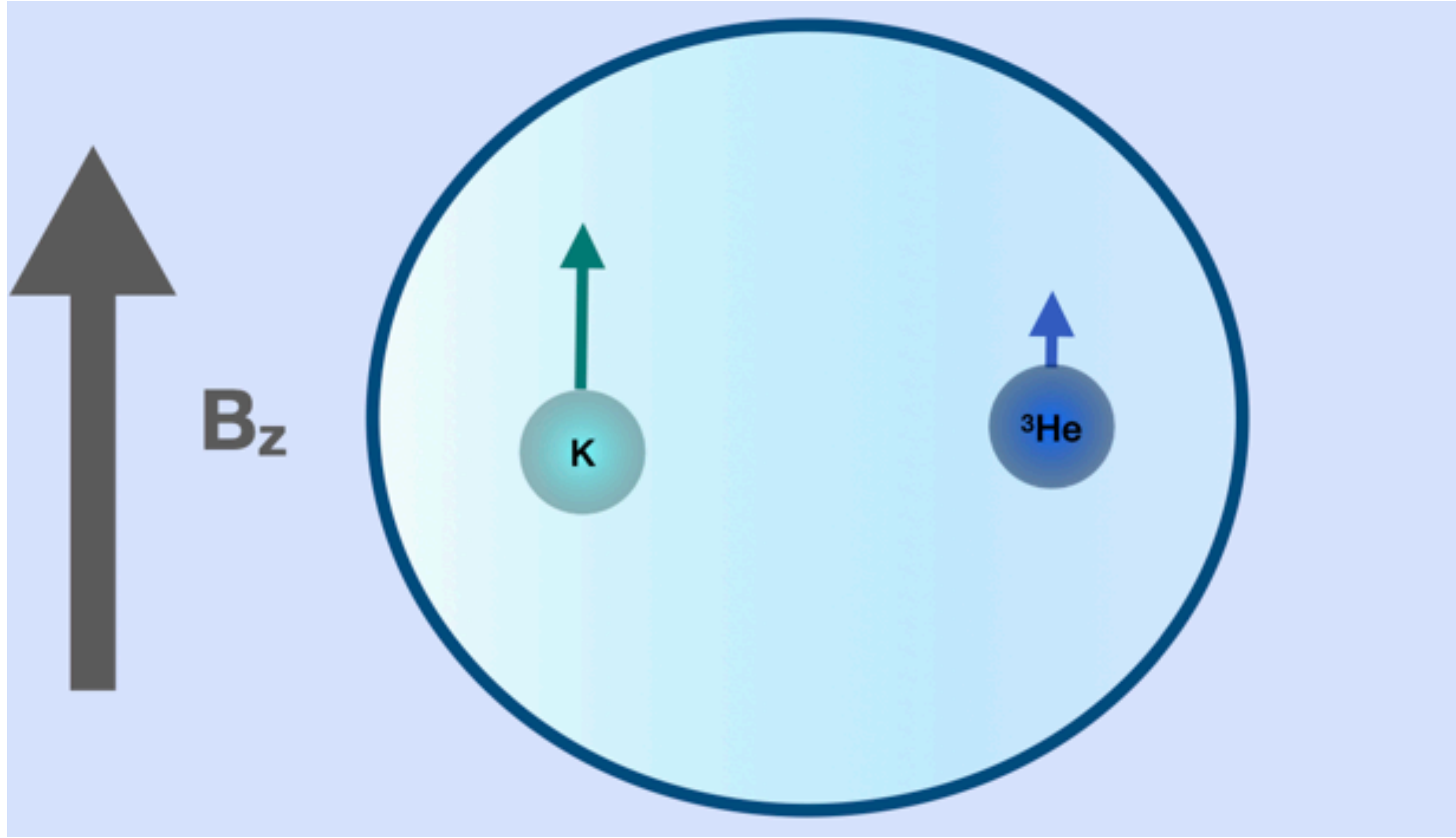
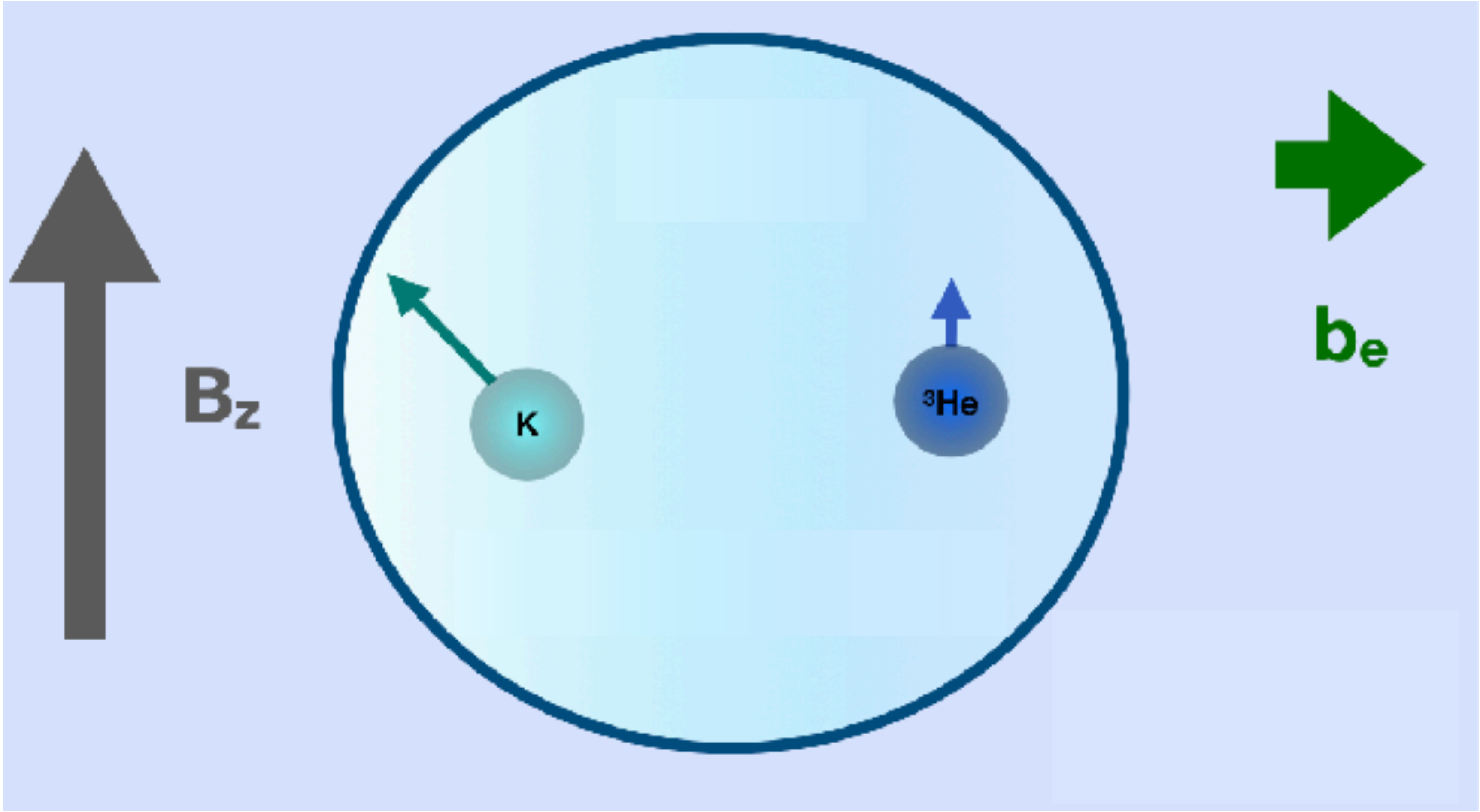




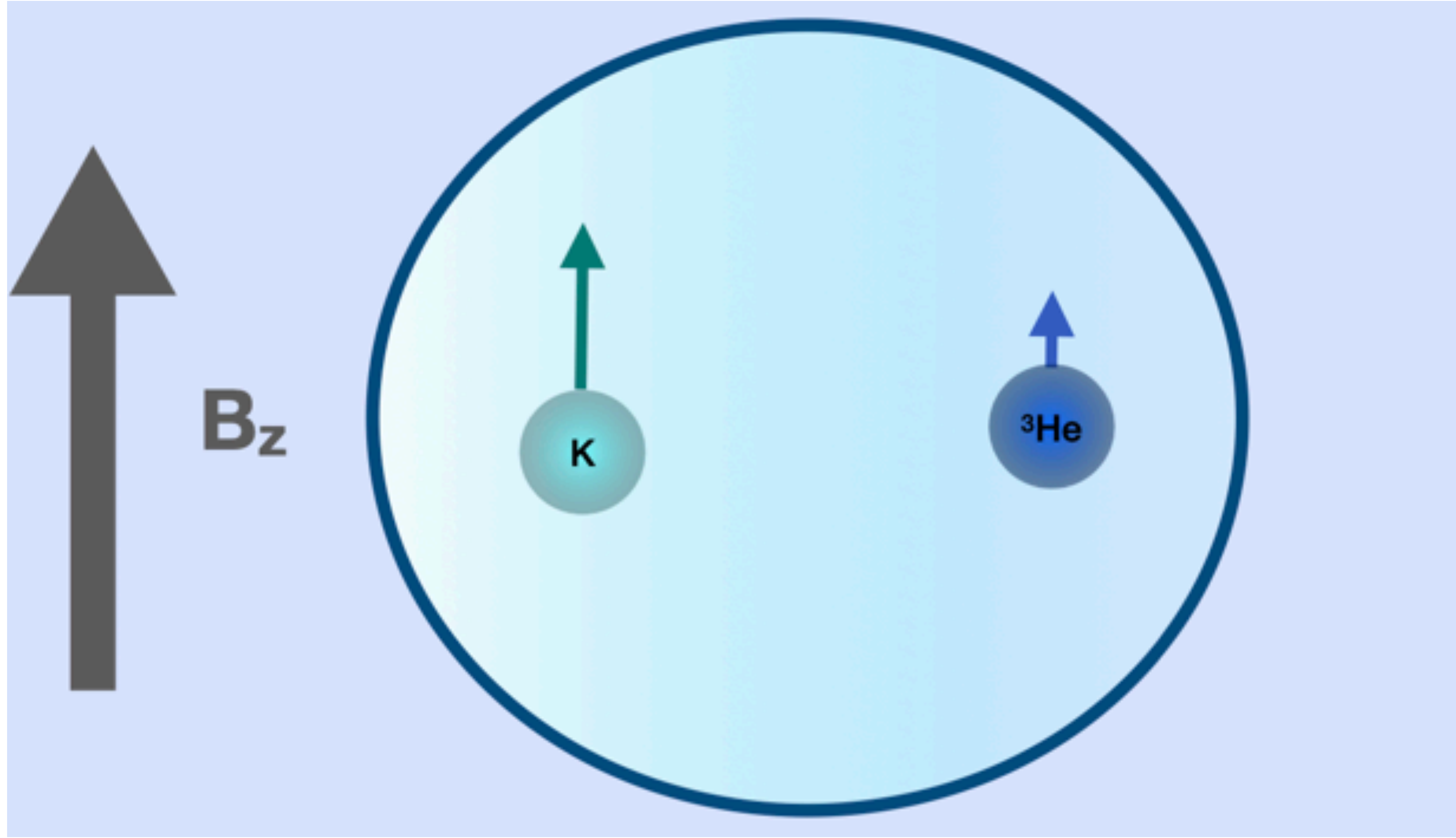
$$S_K^{\perp} \propto \gamma_K B_{tot}^{\perp} = b_e^{\perp}$$

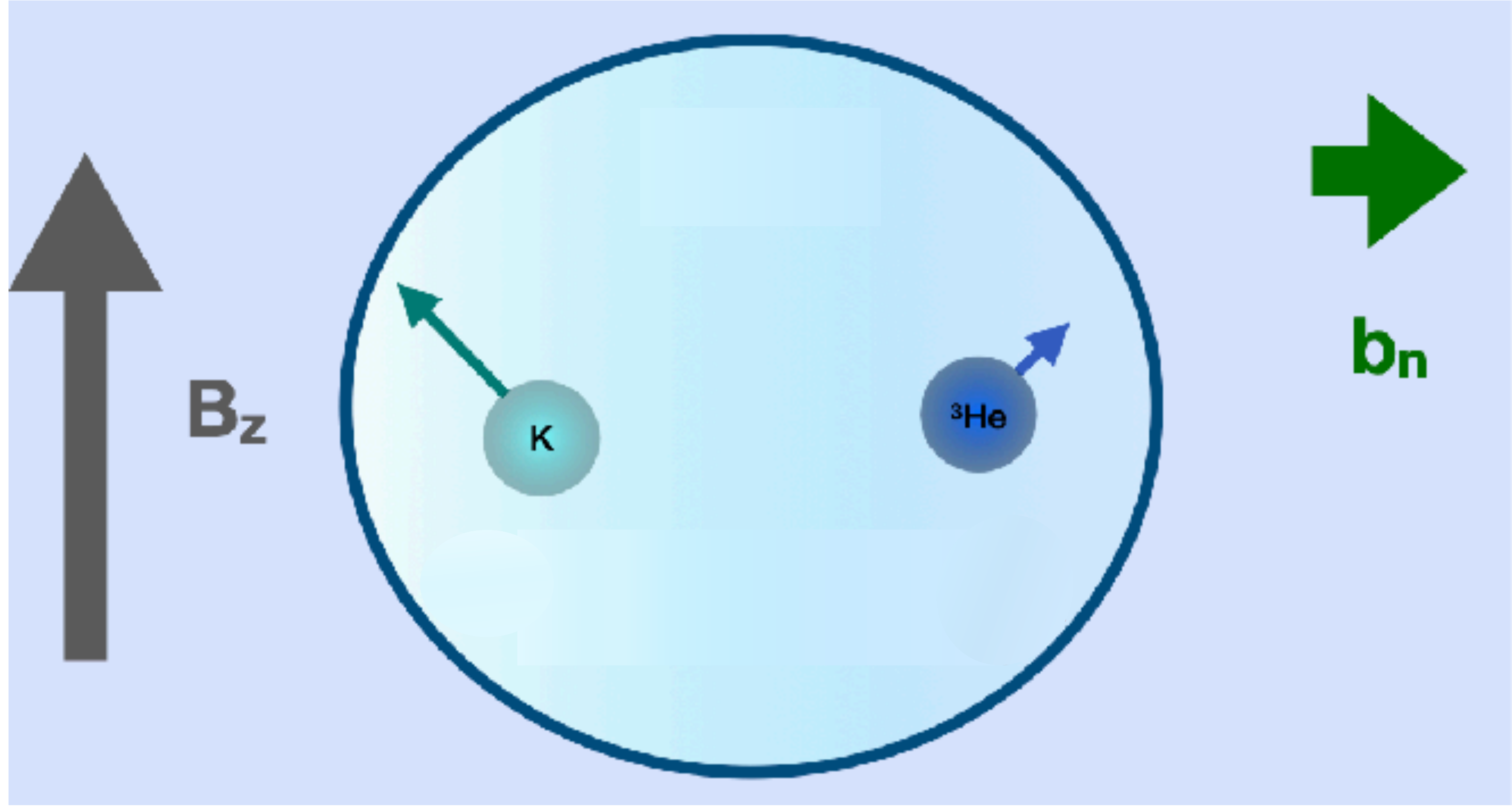
Measurable Signal!

Comagnetic - The compensation point

$$\frac{\partial S_{\text{Alk}}}{\partial B_{\perp,\ \text{noise}}} = \frac{\gamma_{\text{Alk}} S_{Z,\text{Alk}}}{\left(\gamma_{\text{Alk}} B_{z,\text{Alk}} - m_a\right) + i\Gamma_{\text{Alk}}} \left(1 + \frac{2\gamma_{\text{Nob}} \lambda M_{\text{Nob}}}{\left(\gamma_{\text{Nob}} B_{z,\text{Nob}} - m_a\right) + i\Gamma_{\text{Nob}}}\right)$$

$\Gamma_{\text{Nob}} \approx 0, m_a \approx 0,\quad B_{Z,\text{Nob}}$ For is tunable such that $\partial_{B_{\perp,\ \text{noise}}} S_{\text{Alk}} = 0$



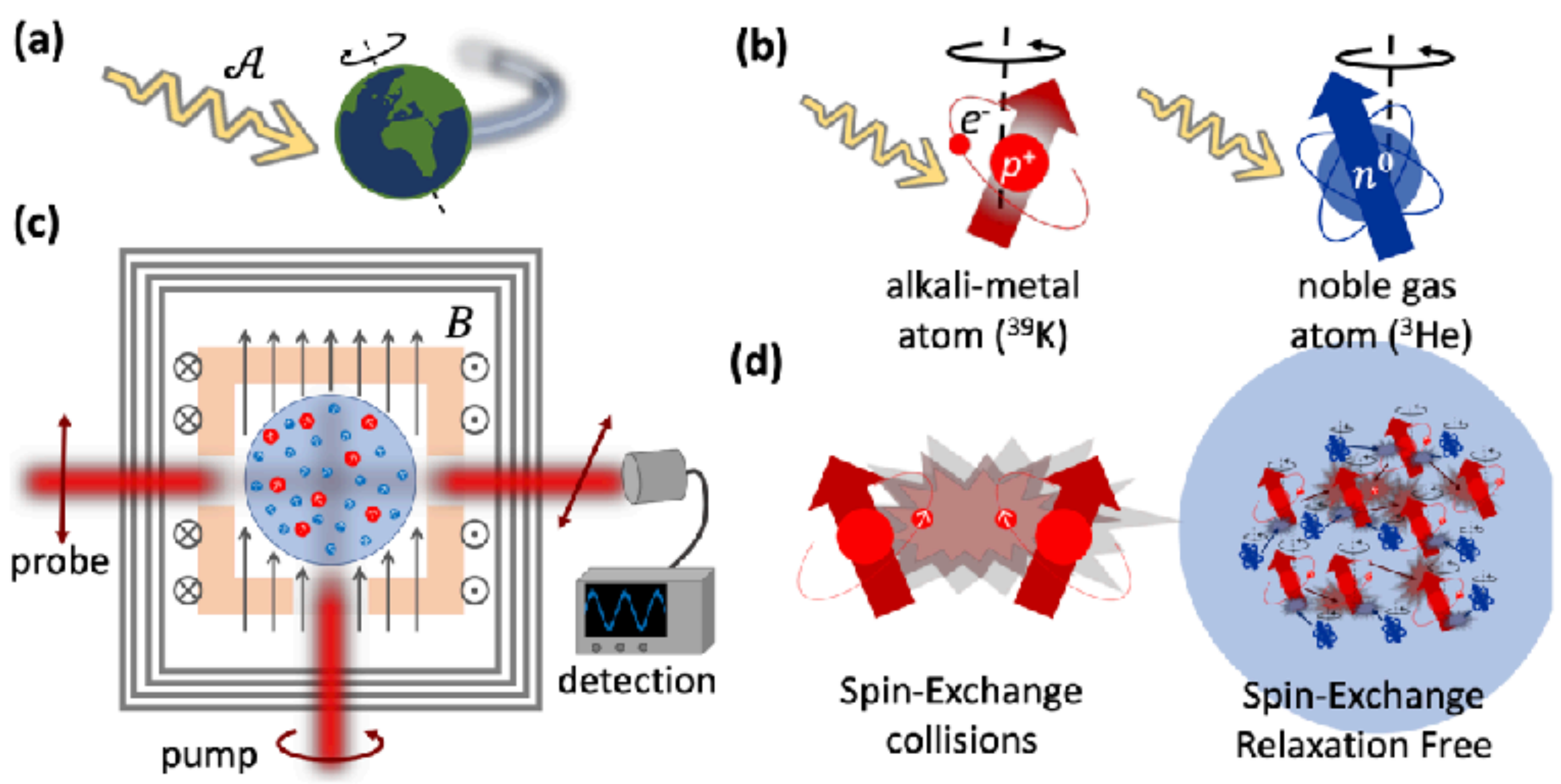


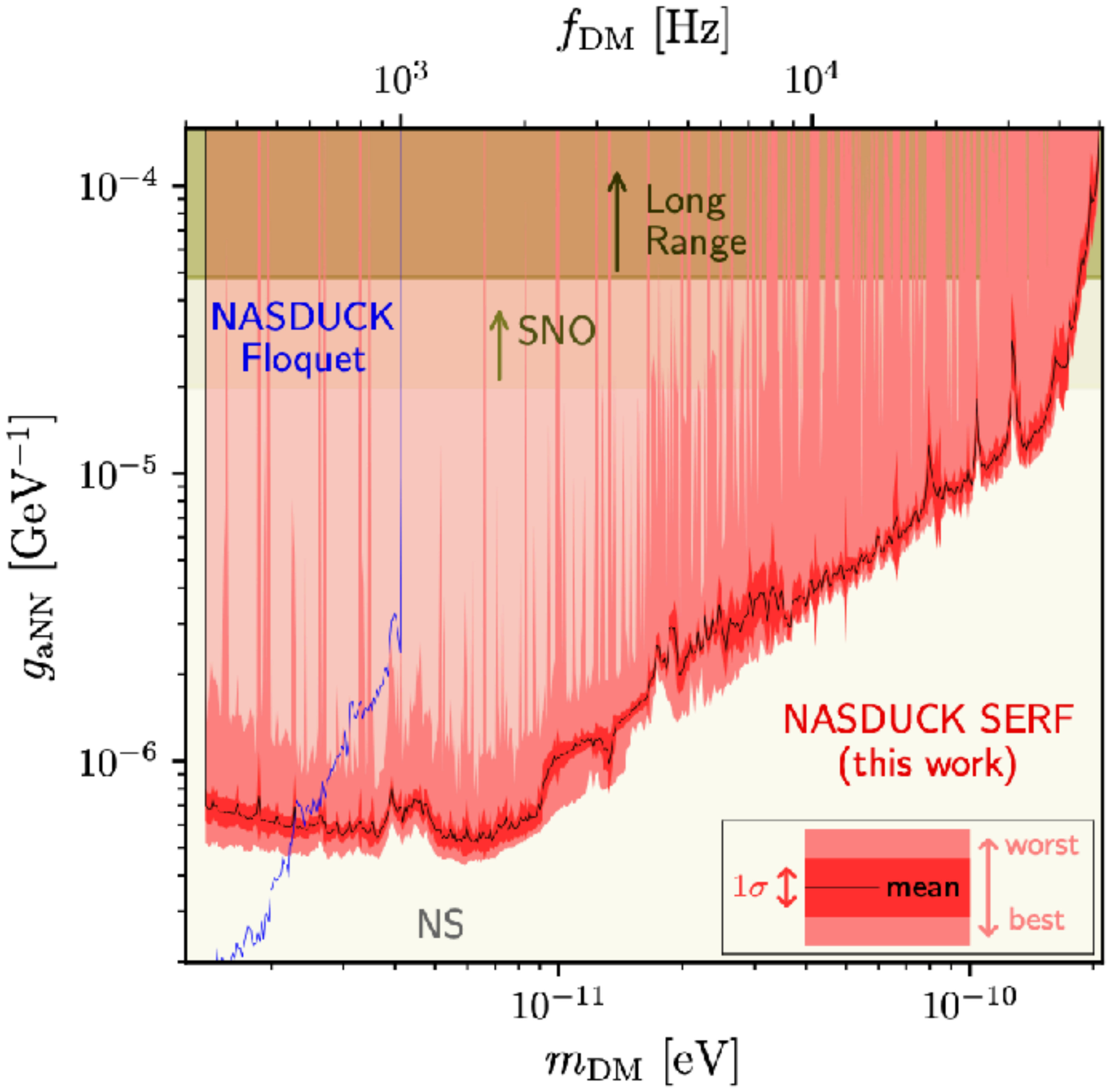
$$S_K^{\perp} \propto \gamma_K B_{\text{tot}}^{\perp} = \gamma_K B_{ind}^{\perp} \sim \frac{\gamma_e}{\gamma_n} b_n$$

Measurable, Enhanced Signal!

Noble and Alkali Spin Detectors for Ultralight Coherent darK matter

- NASDUCK SERF





NASDUCK Collaboratiion, Published in: *Nature Commun.* 14 (2023) 1, 5784

NUSDUCK-Floquet detector

- Response to Signal

$$S_{\text{Alk}}\left(\omega = m_a\right) = \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}}{\left(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a\right) + i\Gamma_{\text{Alk}}} = \frac{\gamma_{\text{Alk}} \lambda M_{\text{Nob}} S_{\text{z,Alk}}}{\left(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a\right) + i\Gamma_{\text{Alk}}} \frac{b_{\perp,\text{ALP-Nob}}}{\left(\gamma_{\text{Nob}} B_{\text{z,Nob}} - m_a\right) + i\Gamma_{\text{Nob}}}$$

Alkali response

Noble response

- Floquet fields: $B_z = B_{z,0} + B_F \cos\left(\omega_F t\right)$

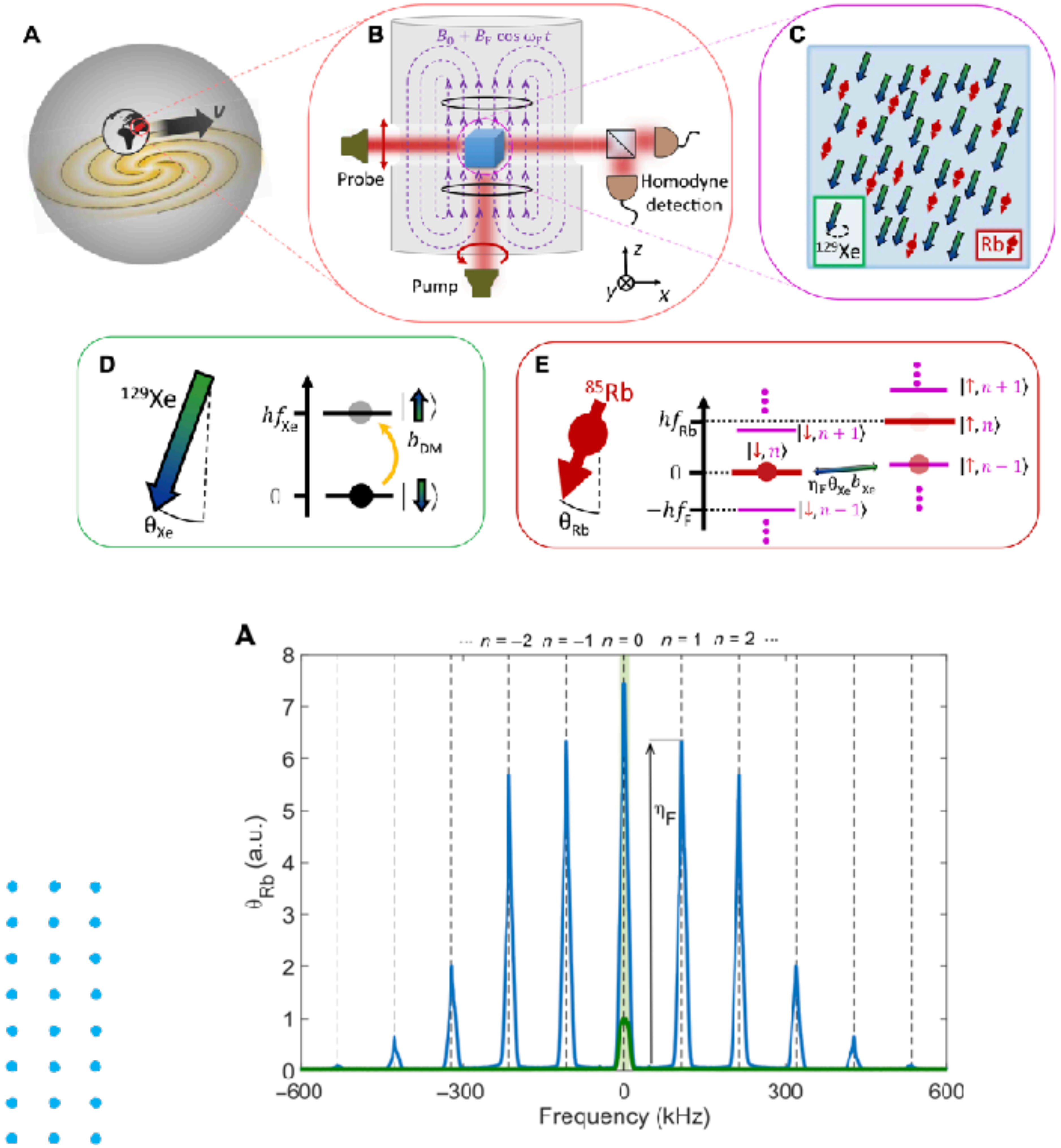
$$S_{\text{Alk}}(t) = \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}\left(\omega = m_a\right) \cdot e^{i m_a t}}{\left(\gamma_{\text{Alk}} B_{\text{z,Alk}} - m_a\right) + i\Gamma_{\text{Alk}}} \rightarrow \sum_n \eta_F^{(n)} \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}\left(\omega = m_a\right) \cdot e^{i m_a t + n\omega_F t}}{\left(\gamma_{\text{Alk}} B_{\text{z,Alk,0}} - m_a - n\omega_F\right) + i\Gamma_{\text{Alk}}}$$

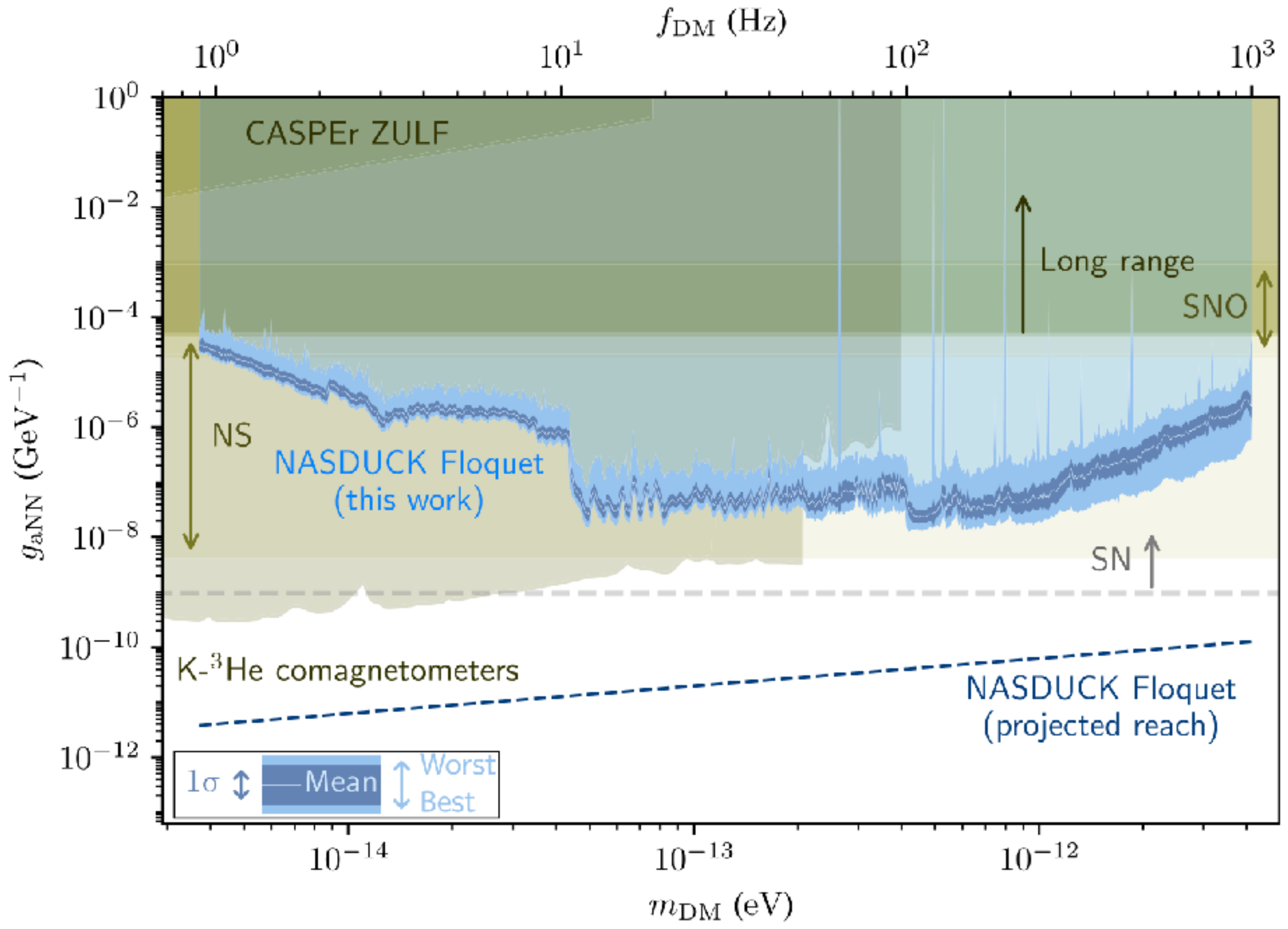
- For $\omega_F = \gamma_{\text{Alk}} B_{\text{z,Alk,0}} - \gamma_{\text{Nob}} B_{\text{z,Nob,0}}$, we get that around the floquet frequency

$$S_{\text{Alk}}\left(\omega = m_a + \omega_F\right) = \eta_F^{(1)} \frac{\gamma_{\text{Alk}} S_{\text{z,Alk}} B_{\perp,Alk}\left(\omega = m_a\right)}{\left(\gamma_{\text{Nob}} B_{\text{z,Nob,0}} - m_a\right) + i\Gamma_{\text{Alk}}}$$

So that for $m_a = \gamma_{\text{Nob}} B_{\text{z,Nob,0}}$, we can now have both the species in resonance!

NUSDUCK-Floquet detector





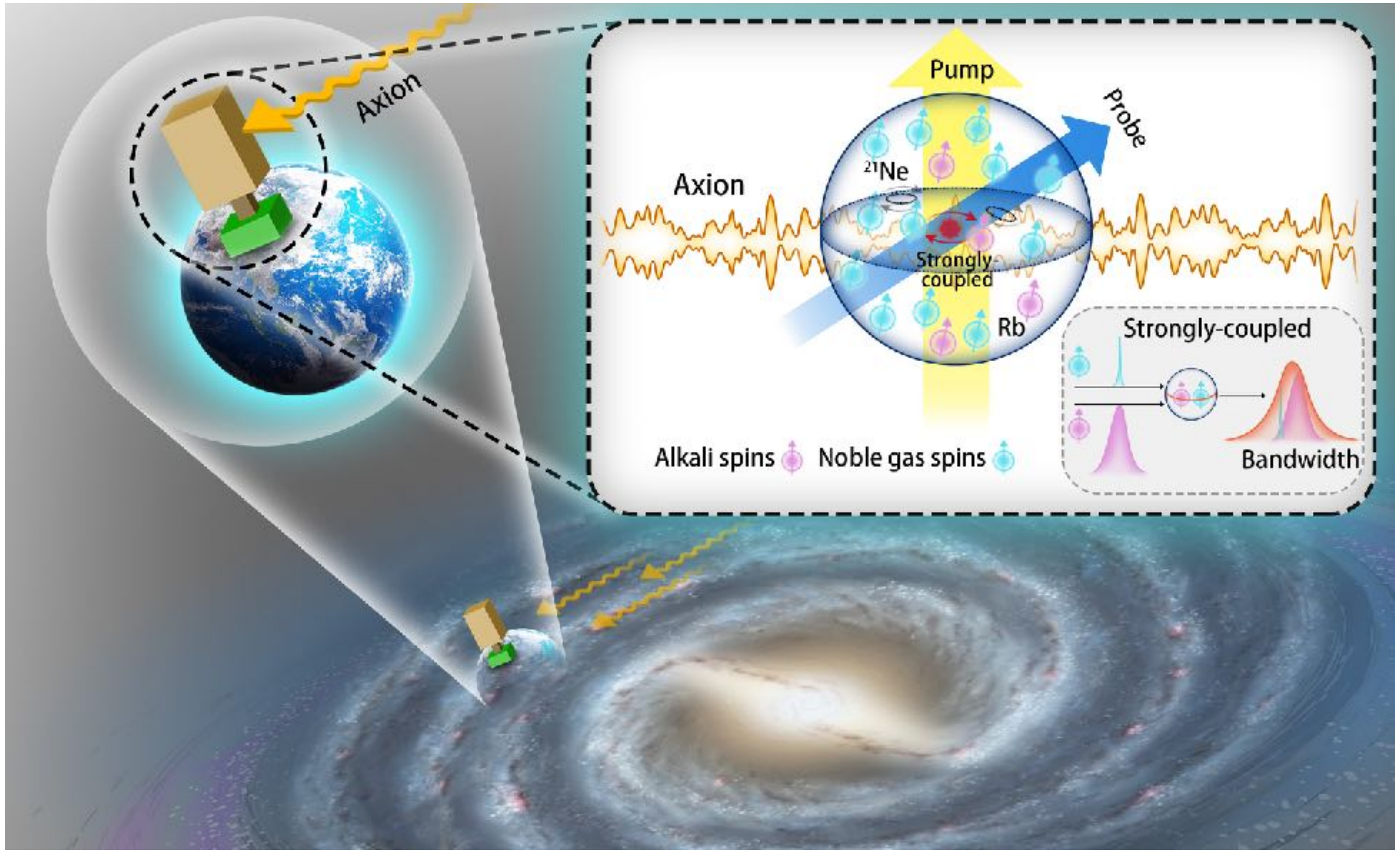
NASDUCK Collaboratiion, Published in: *Sci.Adv.* 8 (2022) 5, abl8919

Outiline

- Strong CP problem and Dark Matter candidate of SM
- Axion solution to CP problem and as a DM candidate
- Axion DM search via different particle experiments
- ALP DM search via NMR method(CASPEr)
- ALP DM search via Comagnetometer method
- ALP DM search via CHANGE experiment
- Summary

Comagnetometer in Hybrid Spin Resonance

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



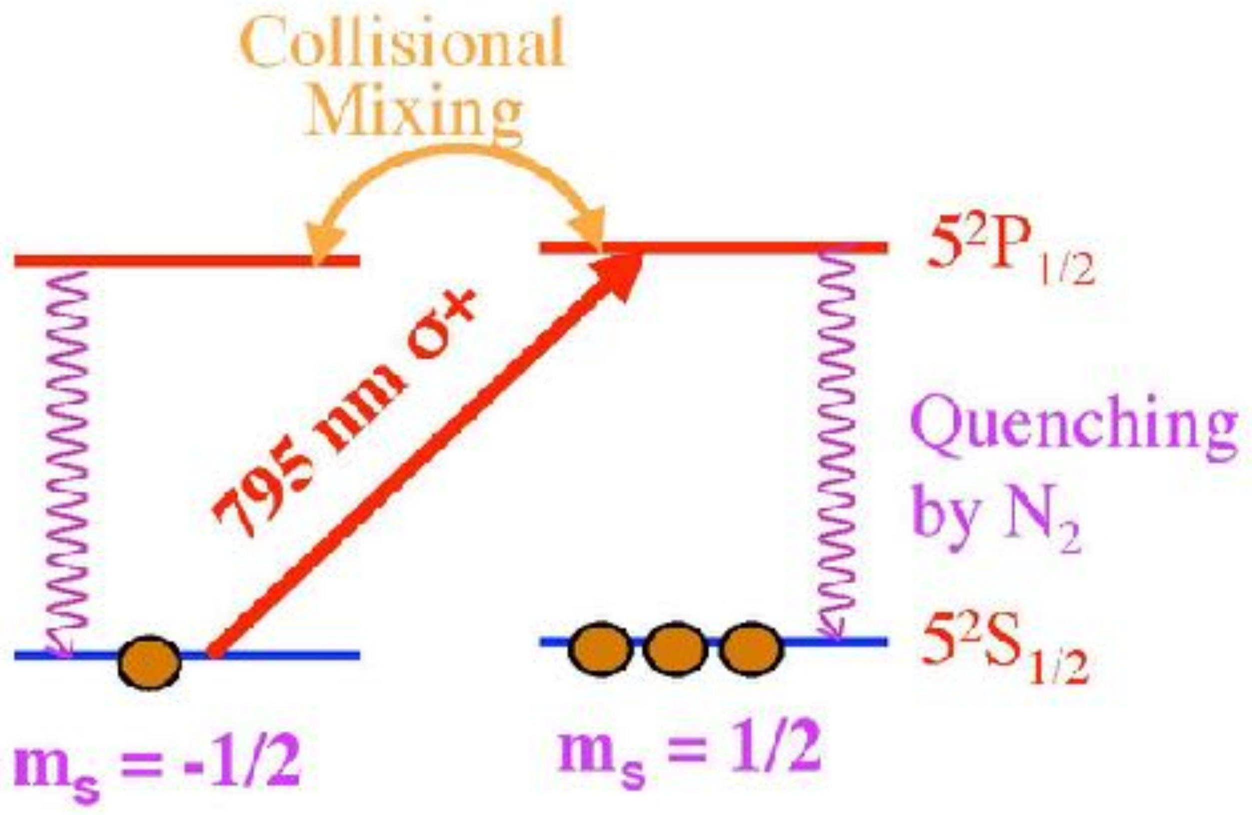
ChangE experiment: Kai Wei, .. **XPW**.. et al, 2306.08039

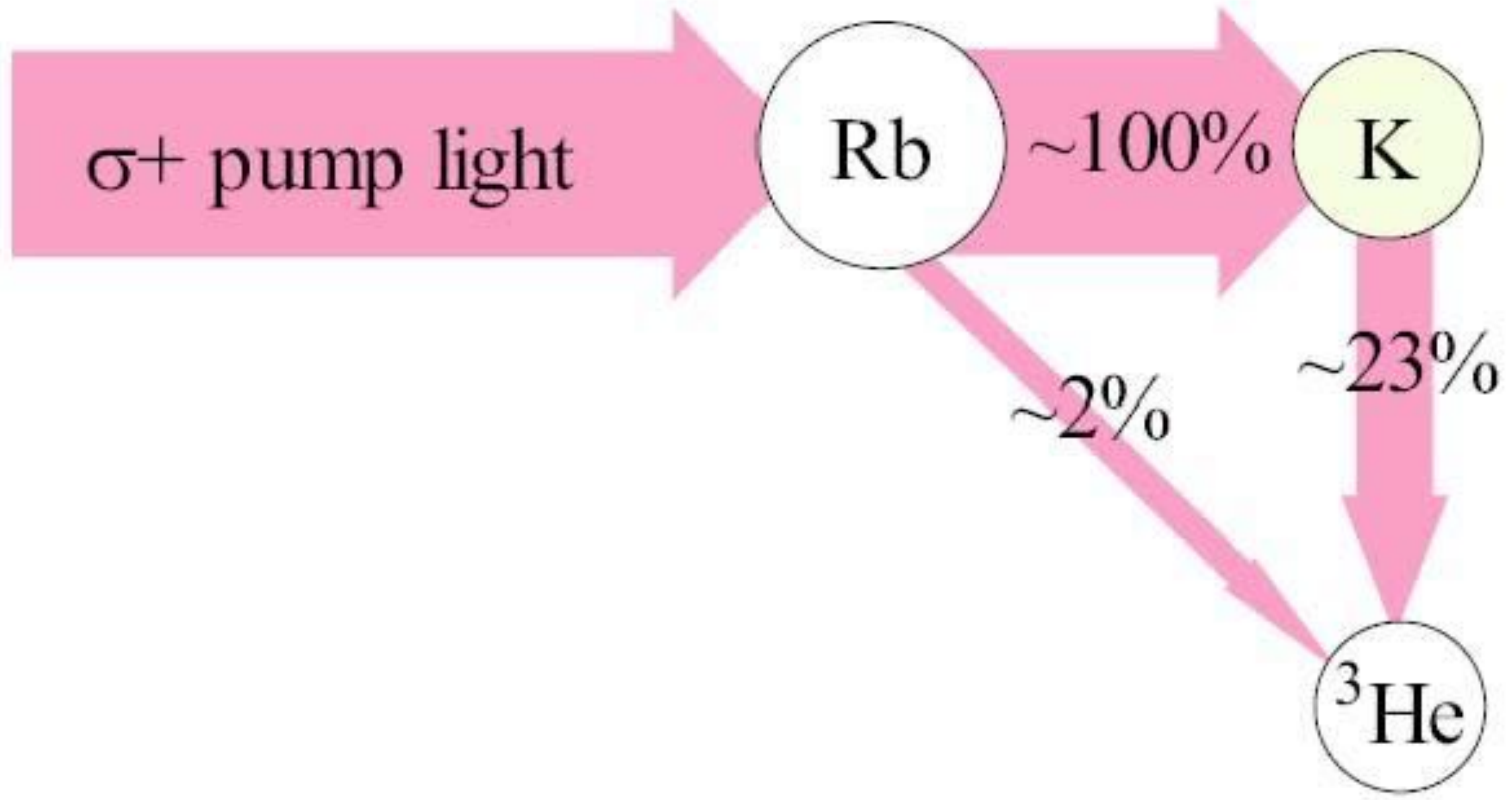
Comagnetometer—Optical pumping

- The ^{3}He polarization rate is

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

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





Spin-exchange Optical Pumping:

- 1960: Bouchiat/Carver/Varnum (Princeton), PRL 5, 373, P=0.01%
- Now:Rb-K optical pumping P>70%

Comagnetometer in Hybrid Spin Resonance

- Bloch Equation

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

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

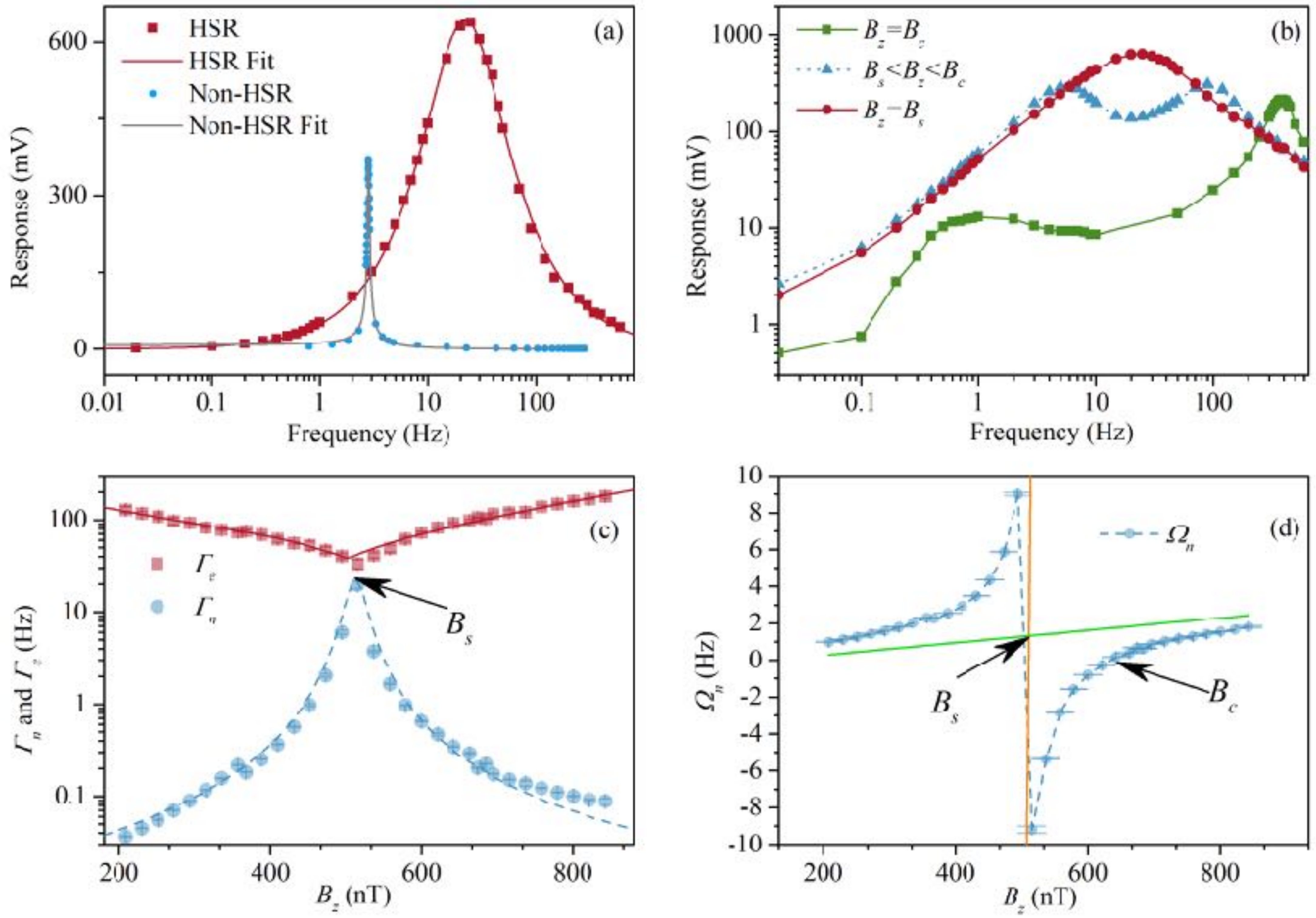
- Method: tune external B field to make Larmor frequency equal (HSR region)

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

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

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

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



Comagnetometer HSR search on ALP DM

- Random phase in different p mode

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

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

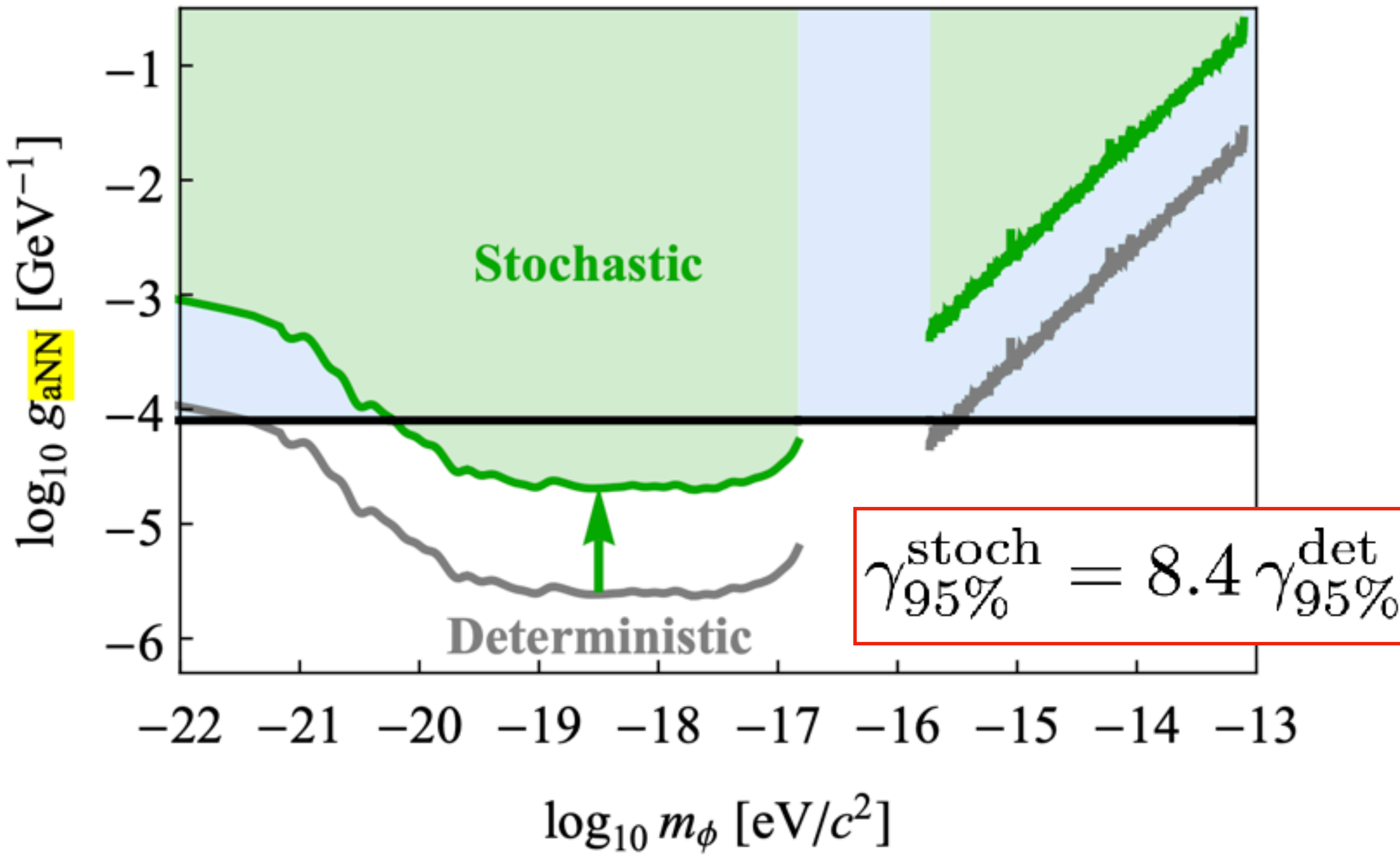
$$\beta_j = \frac{g_{aN}}{\gamma_N} \nabla a(j\Delta t) \cdot \hat{\mathbf{m}}(j\Delta t)$$

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

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

$$\mathbf{d} = \left\{A_k, B_k\right\} \qquad \Sigma = \Sigma_a + \sigma_b^2 \cdot 1$$

1905.13650, NC 2021

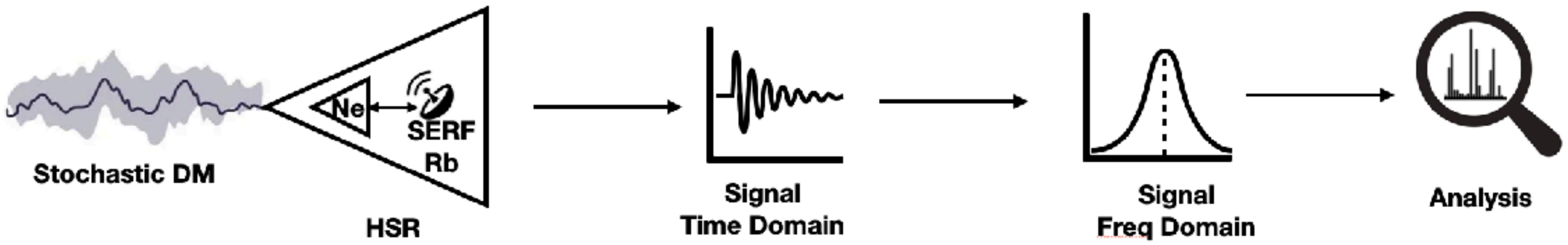


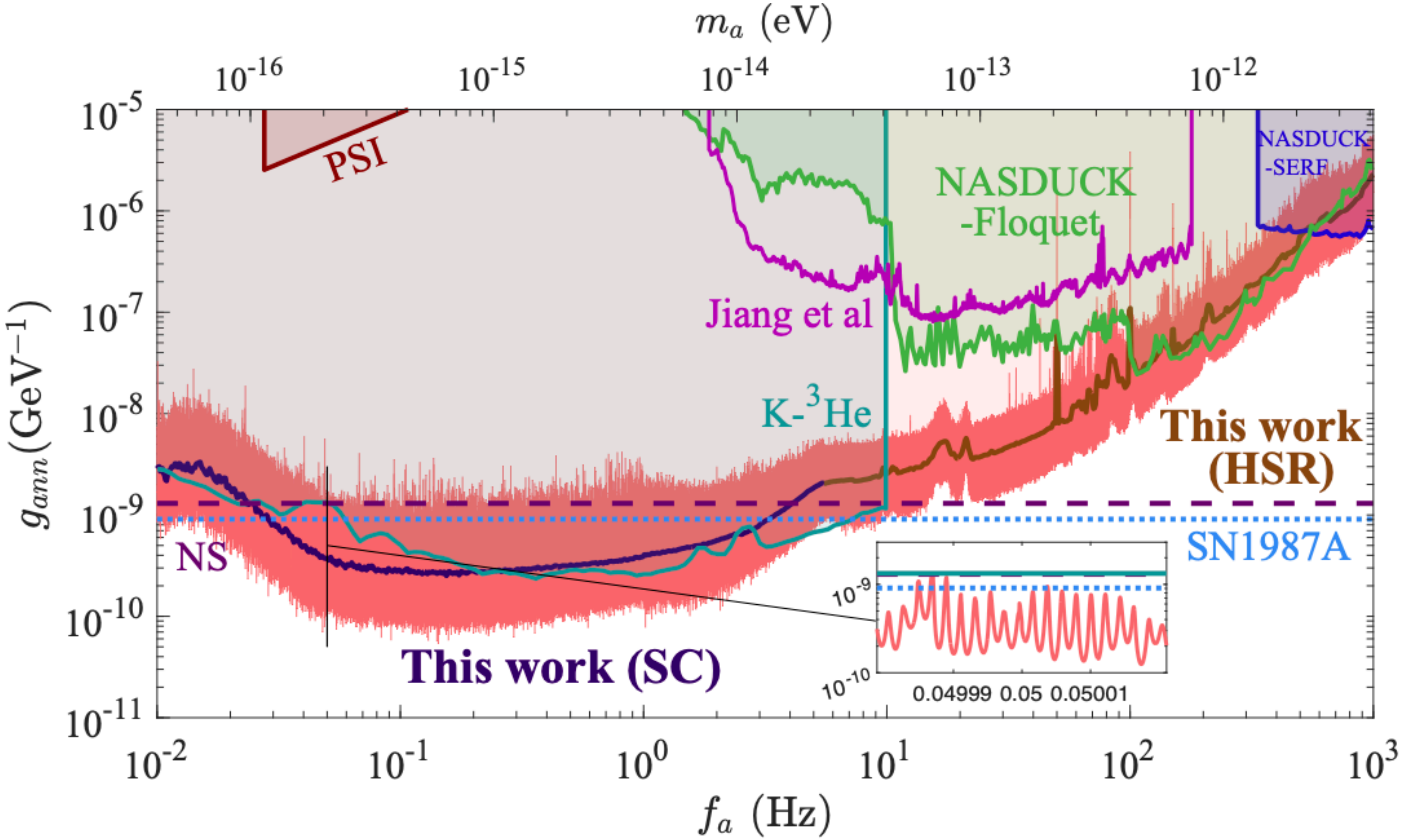
- Signal and white background are multivariate Gaussian distribution Signal contains non-diagonal term

Junyi Lee et al, 2209.03289, PRX 2023

Comagnetometer HSR search on ALP DM

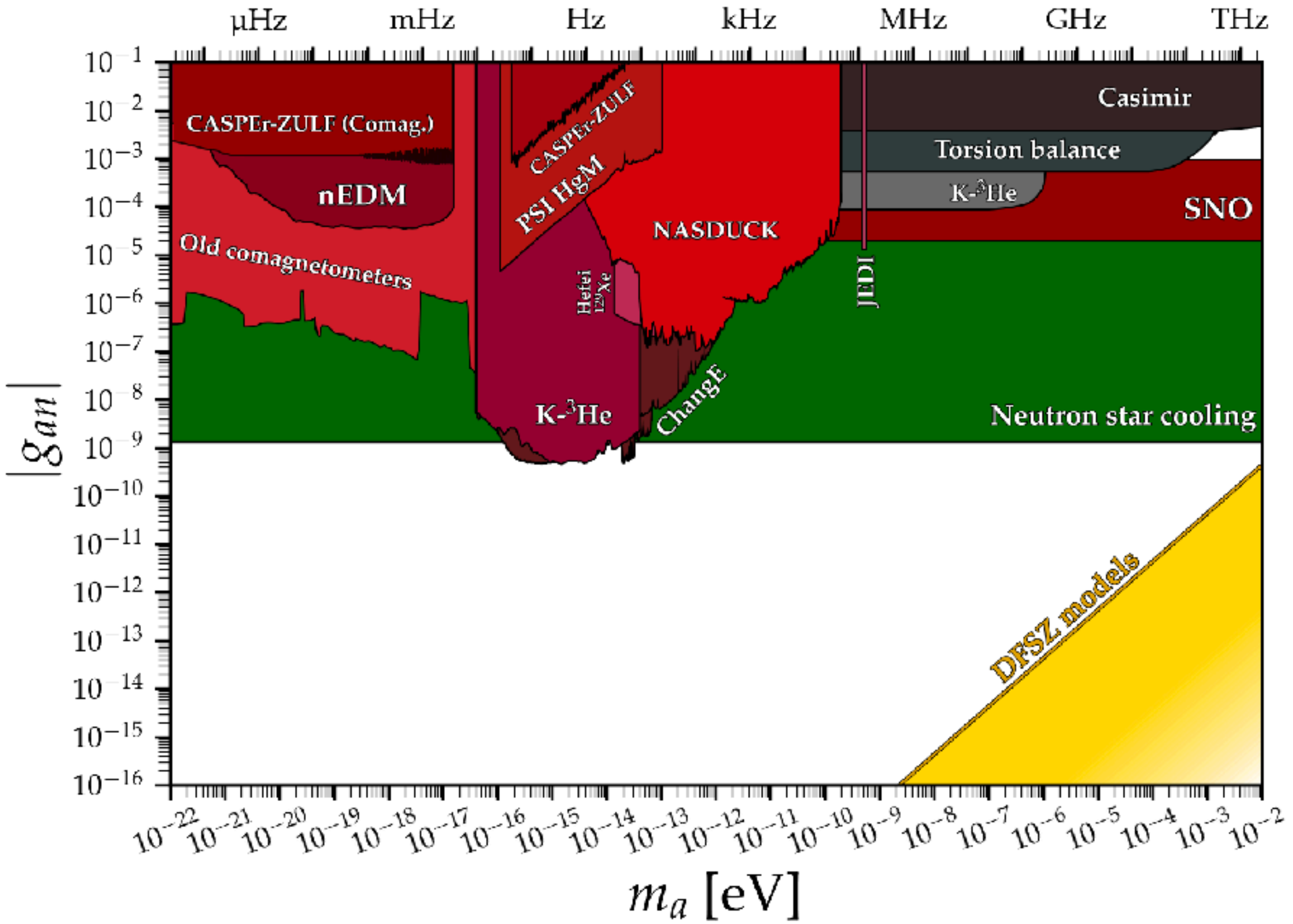
- The response to ultra-light dark matter field b_x^n coupling with noble-gas nuclear spins
  $S_x^e = K_{b_x^n} b_x^n$
- The response to magnetic field
  $S_x^e = K_{B_y} B_y$
  - The scale factor relation
    $K_{B_y} = K_{b_x^n} \omega / \hat{\omega}_z^n$
- Search on ALP-neutron coupling g_{ann}
  - 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 $\xi_p^{\mathrm{Ne}} = 0.04$

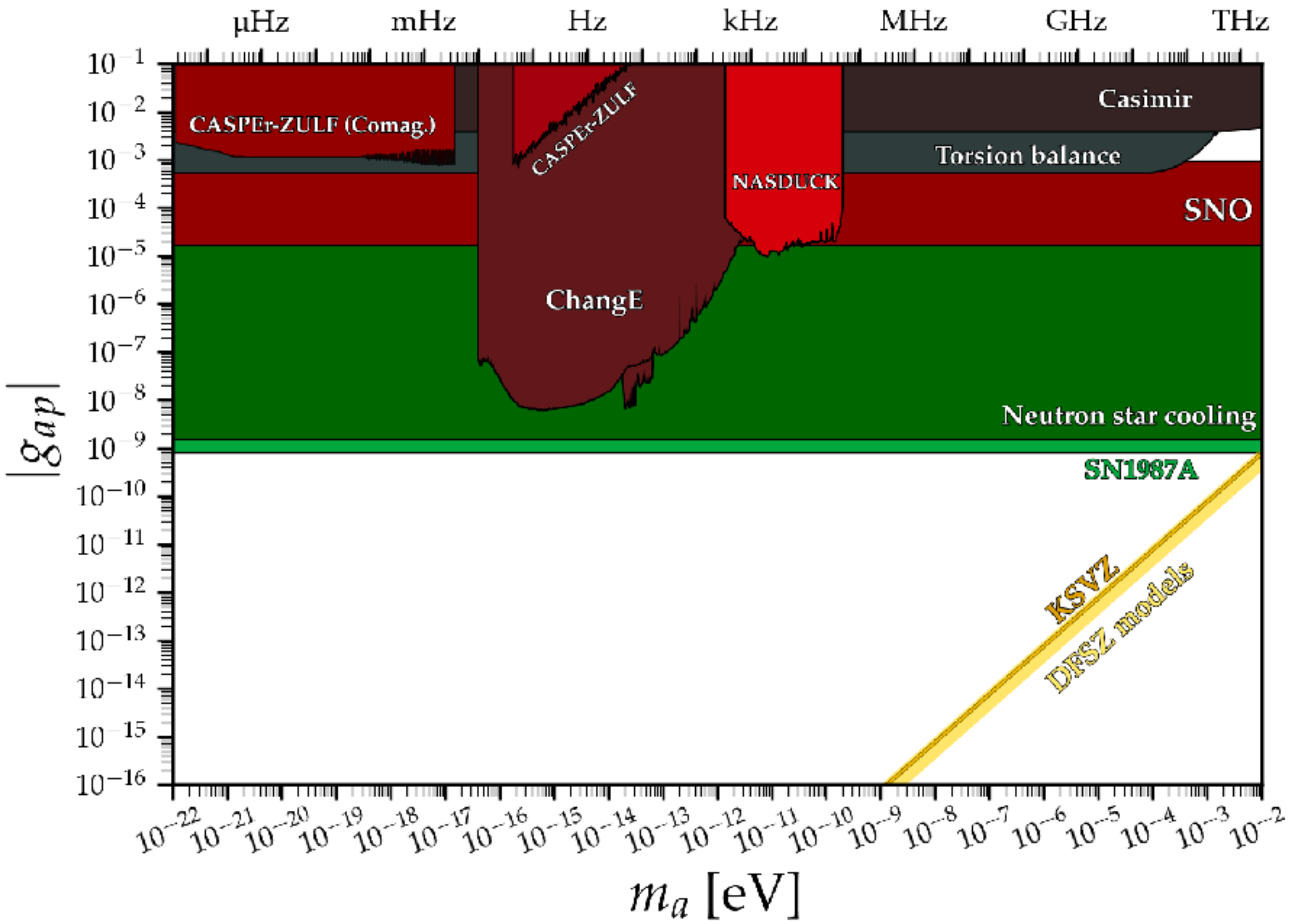




Comagnetometer HSR search on ALP DM

- 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





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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 ~[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!