Shedding Light on Dark Matter

New Approaches in Light Dark Matter Detection

Christina Gao

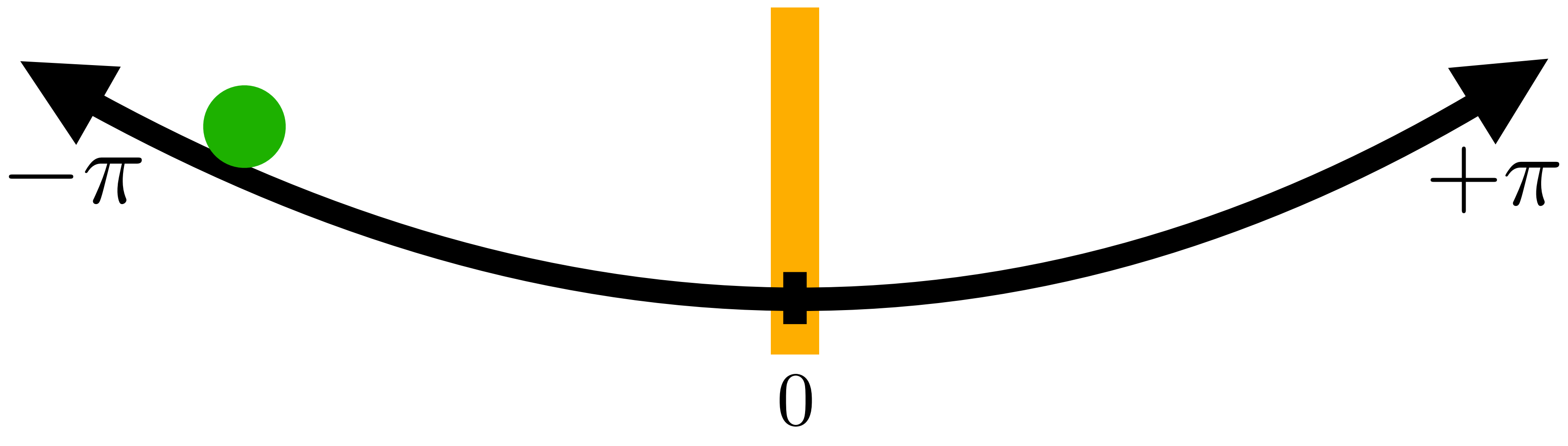
Southern University of Science and Technology, Shenzhen

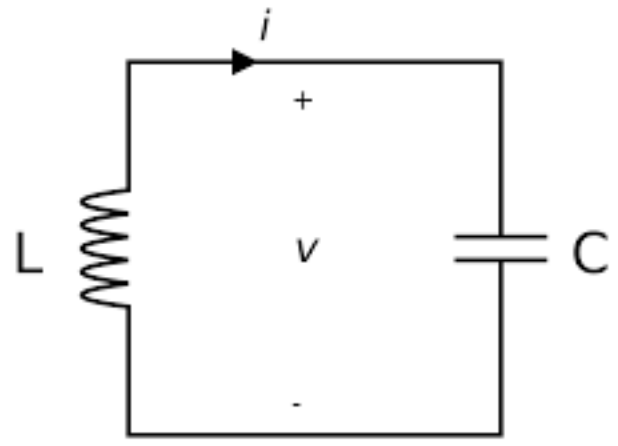
Light Dark World 25 IFT UAM/CSIC Madrid 9/18/2025

Resonant Detection of Wavelike Dark Matter

$$a_{\rm DM}(t) \sim A\cos(m_a t)$$

ω





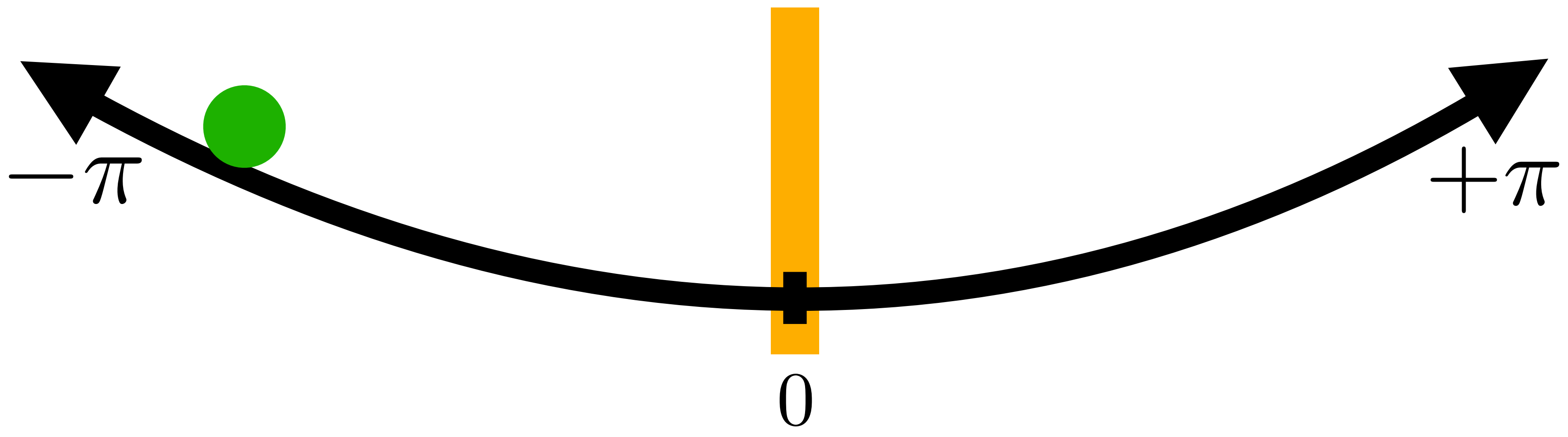
Resonance occurs when:

- Axion couples to a local oscillator
- and $m_a = \omega$

Resonant Detection of Axion Dark Matter

ω

$$a_{\rm DM}(t) \sim A\cos(m_a t)$$



Axion-photon coupling

Haloscopes

Axion-fermion coupling

Spin precession experiments

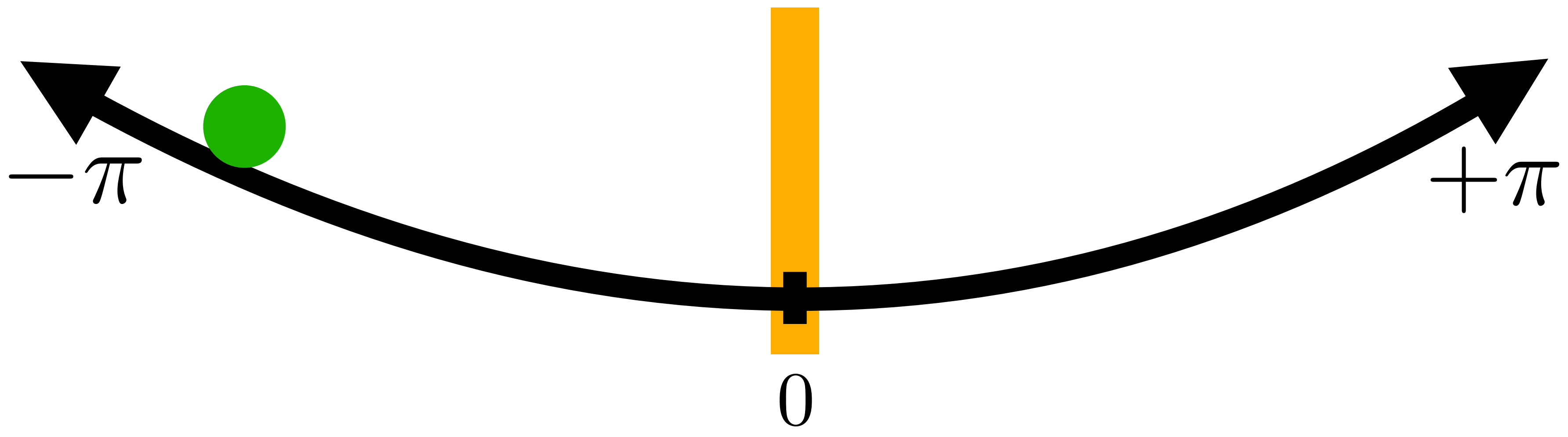
Resonance occurs when:

- Axion couples to a local oscillator
- and $m_a = \omega$

Resonant Detection of Axion Dark Matter

ω

$$a_{\rm DM}(t) \sim A\cos(m_a t)$$



Axion-photon coupling

Haloscopes

Axion-fermion coupling

Spin precession experiments

Resonant detection

- Pro: large amplitude
- Con: axion mass unknown, need to scan

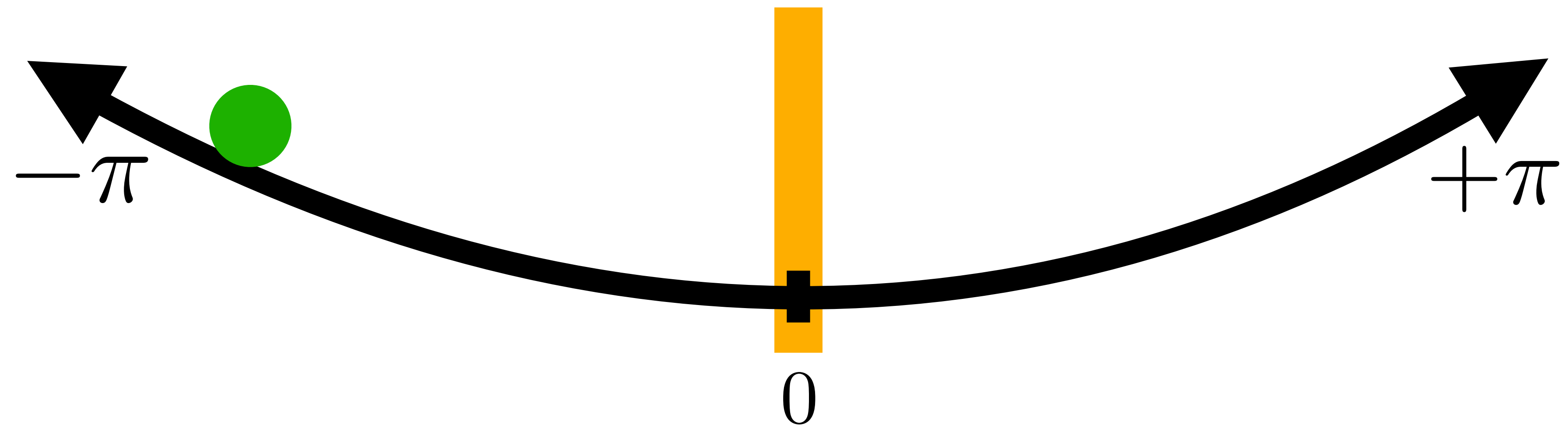
Resonant Detection of Axion Dark Matter

$$a_{\rm DM}(t) \sim A\cos(m_a t)$$

ω

Axion-photon coupling

Haloscopes



Axion-fermion coupling

Spin precession experiments

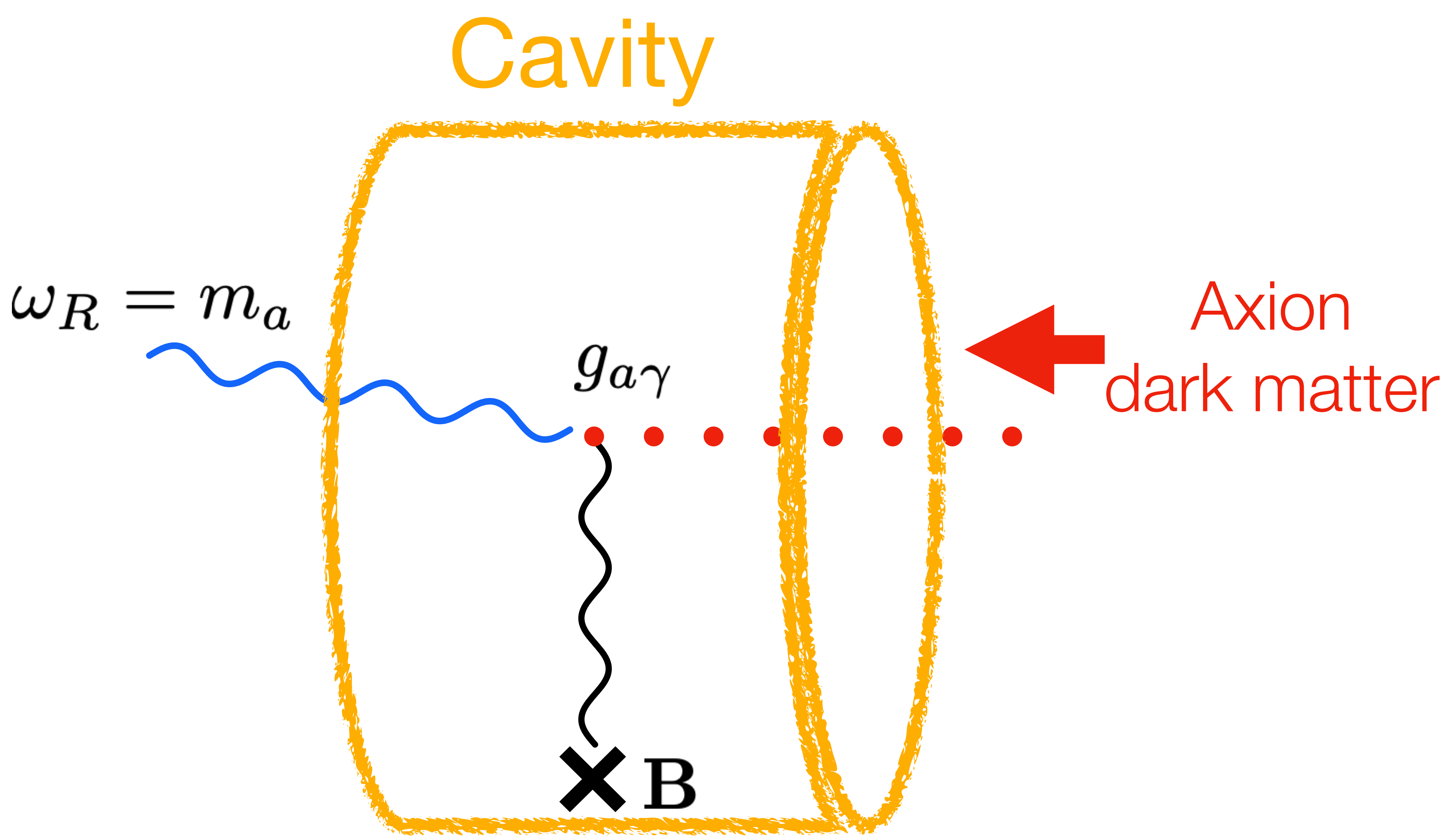
Resonant detection

- Pro: large amplitude
- ~~Con~~: axion mass unknown, **Much tabletop opportunity!**

Plan of the talk

- Introduction
- eV axion searches using integrated photonics
- neV axion searches using superfluid ^3He
- feV axion searches using levitated ferromagnet

Cavity based axion DM Searches



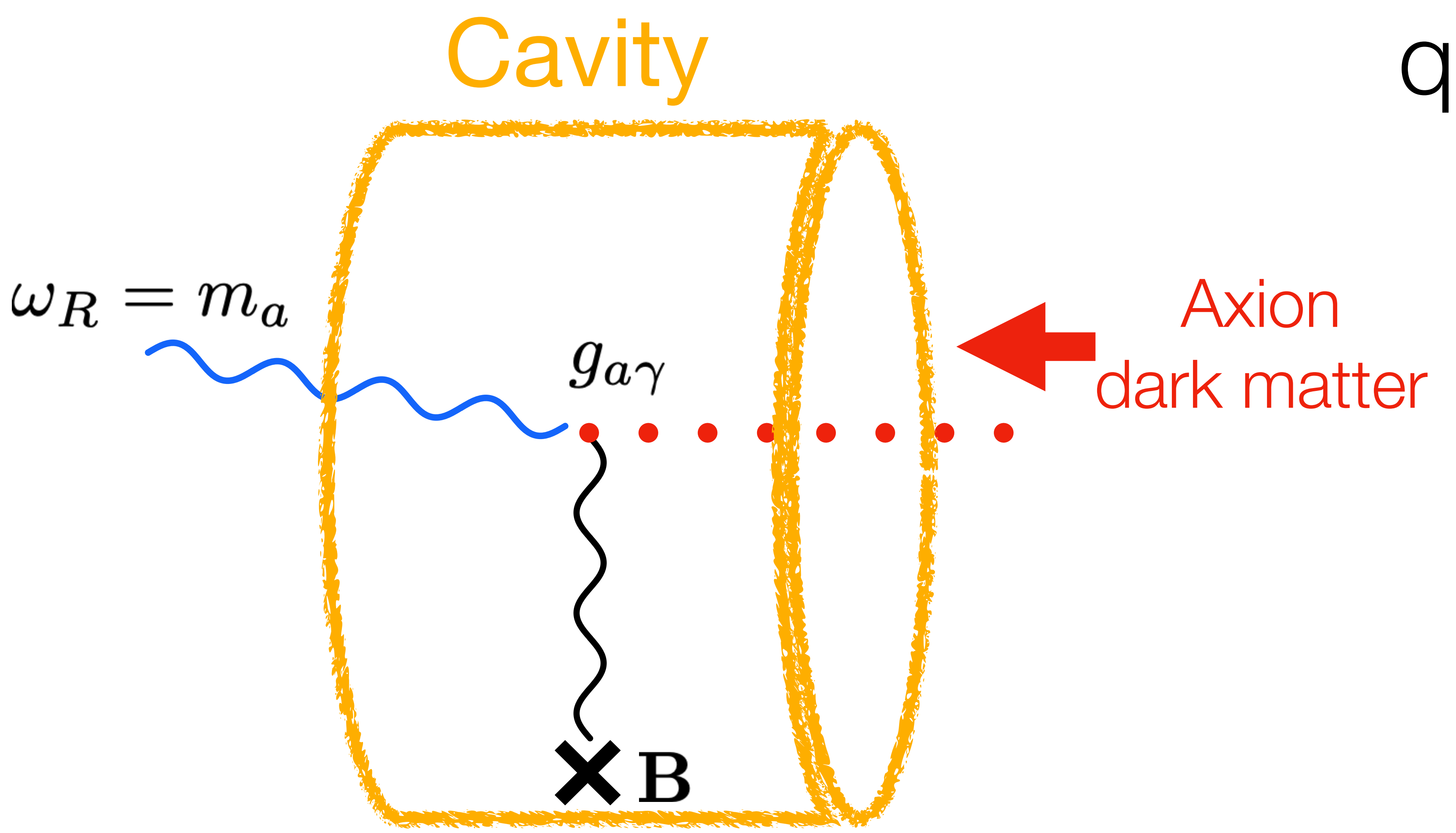
$$P_{\rm sig} \simeq \frac{Q}{m_{\rm D}} J_{\rm D}^2 |\eta|^2 V$$

Axion $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$

Dark photon $\frac{1}{2} \chi F'_{\mu\nu} F_{\mu\nu}$

SUSTech

Cavity based DM Searches

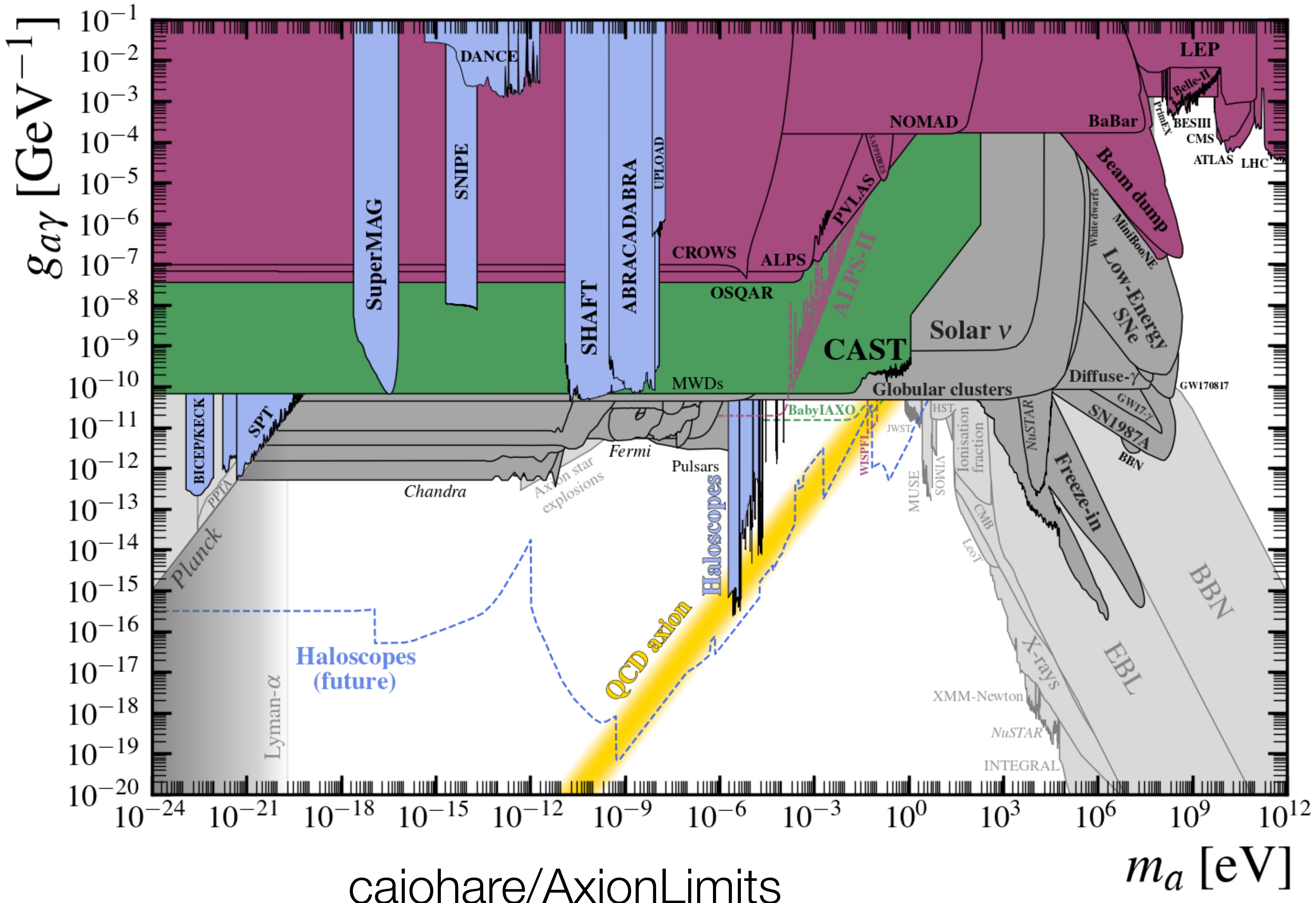


$$P_{\rm sig} \simeq \frac{Q}{m_{\rm D}} J_{\rm D}^2 |\eta|^2 V$$

quality factor → Q; effective DM current → $J_{\rm D}^2$; momentum conservation → $|\eta|^2$

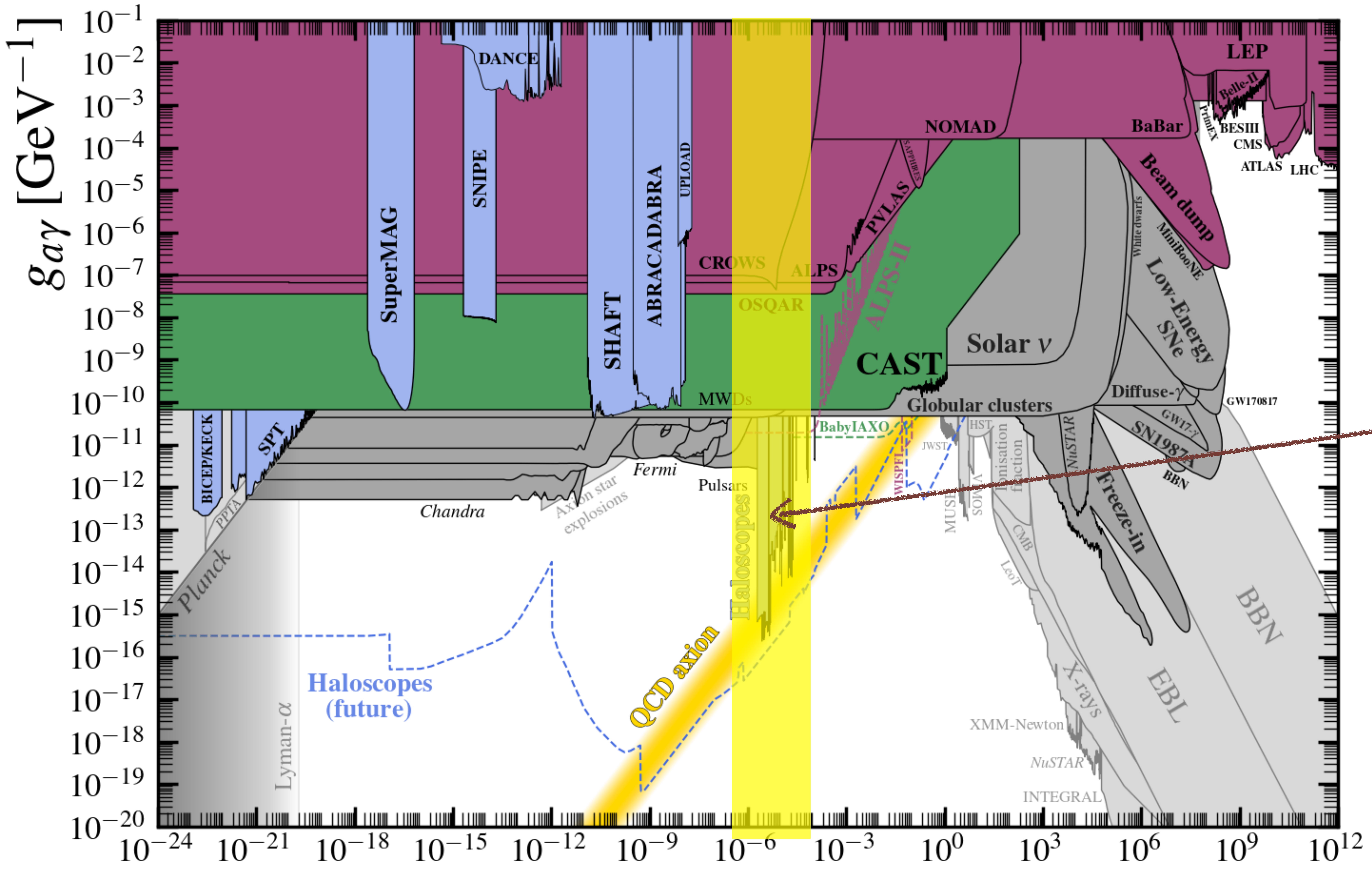
Axion $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$

Dark photon $\frac{1}{2}\chi F'_{\mu\nu} F_{\mu\nu}$

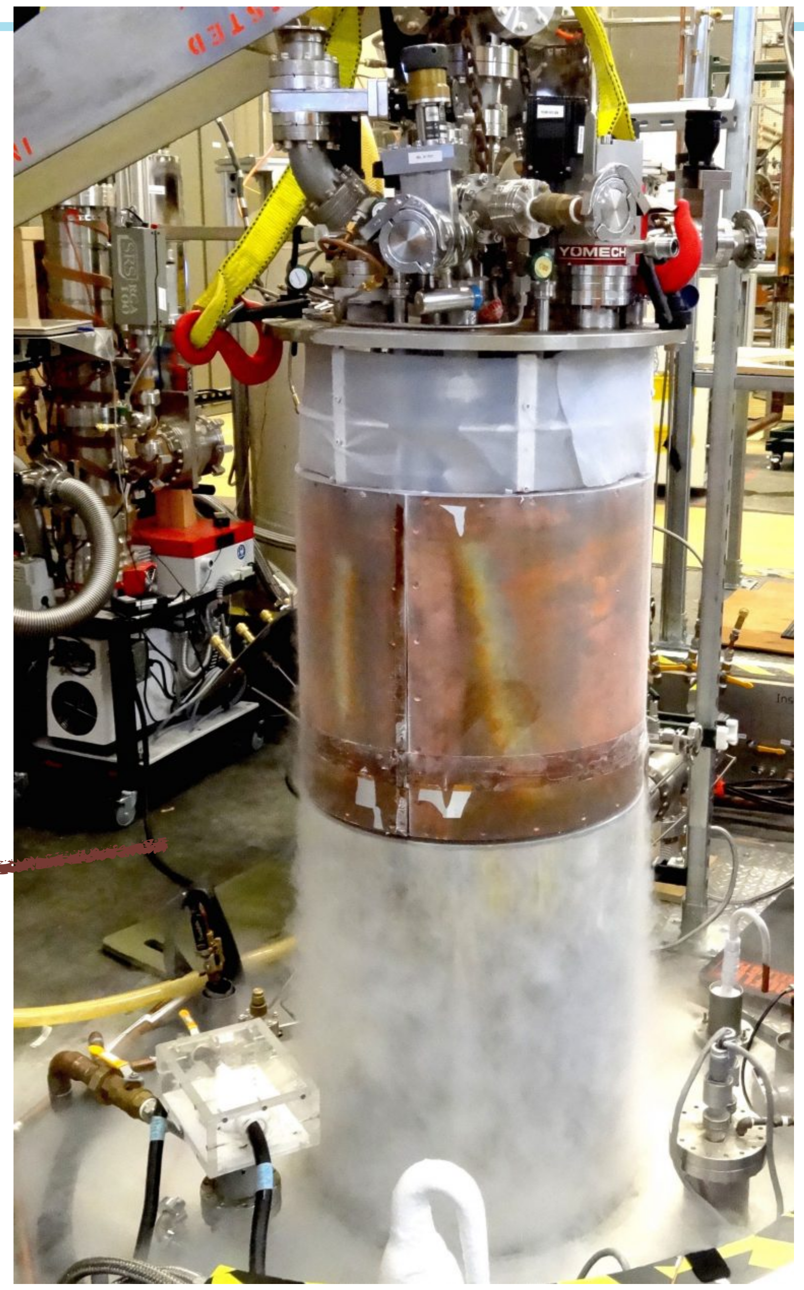


cajohare/AxionLimits

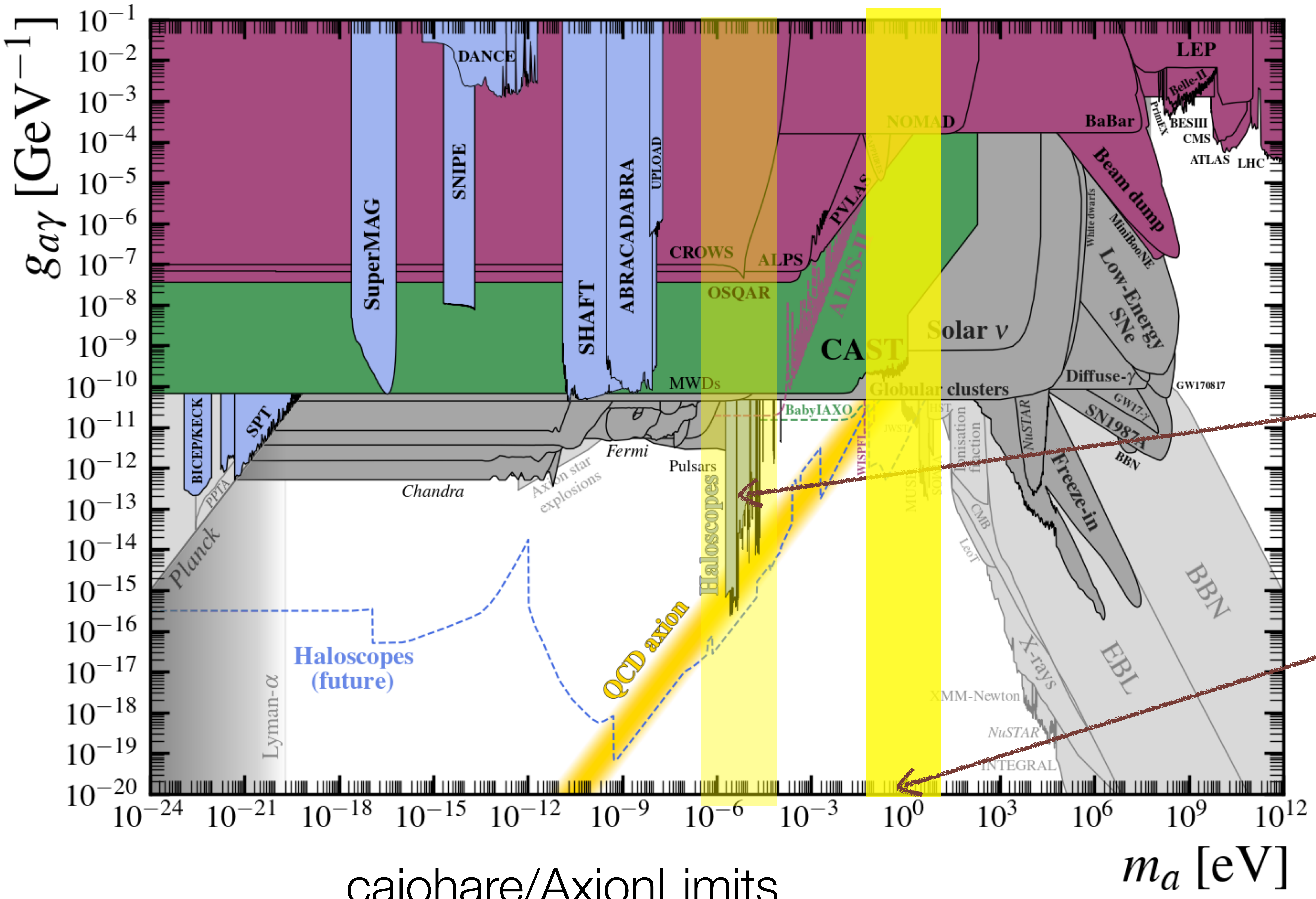
SUSTech



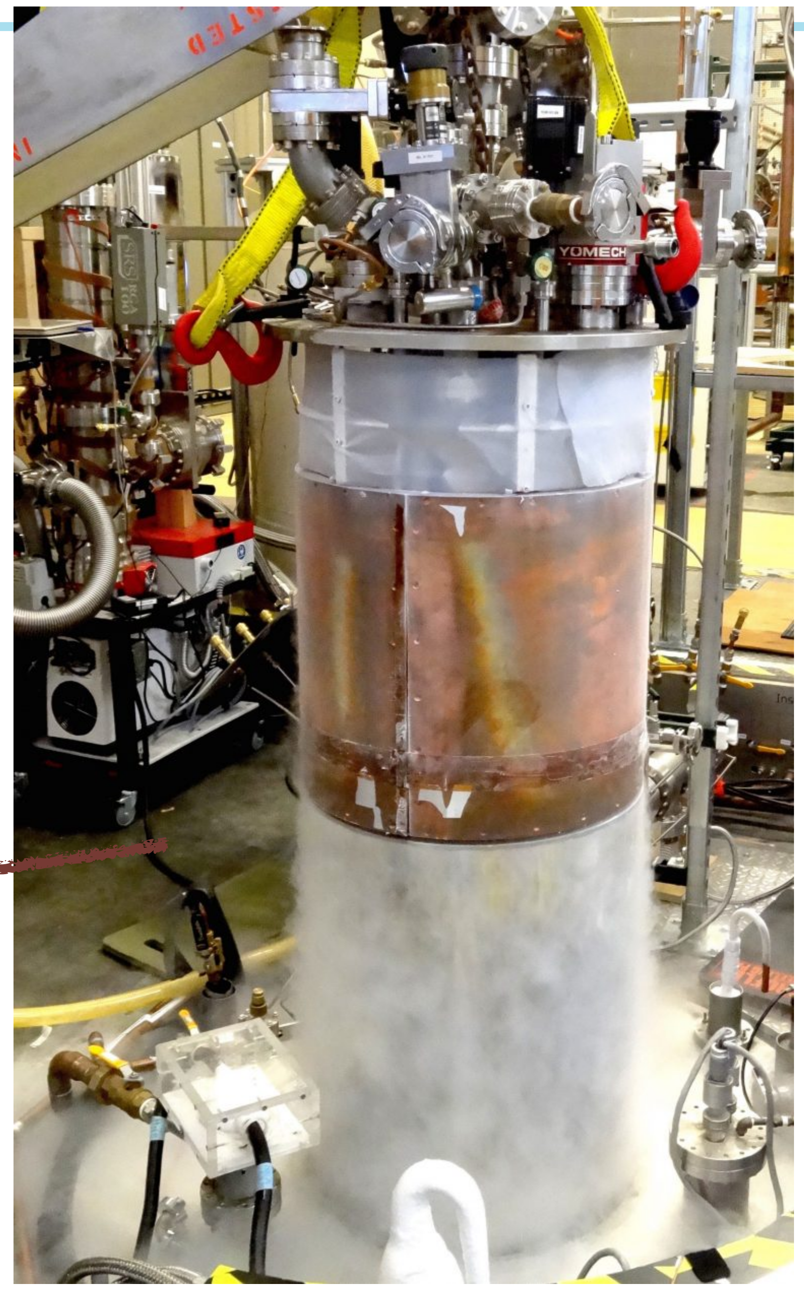
cajohare/AxionLimits



SUSTech



cajohare/AxionLimits

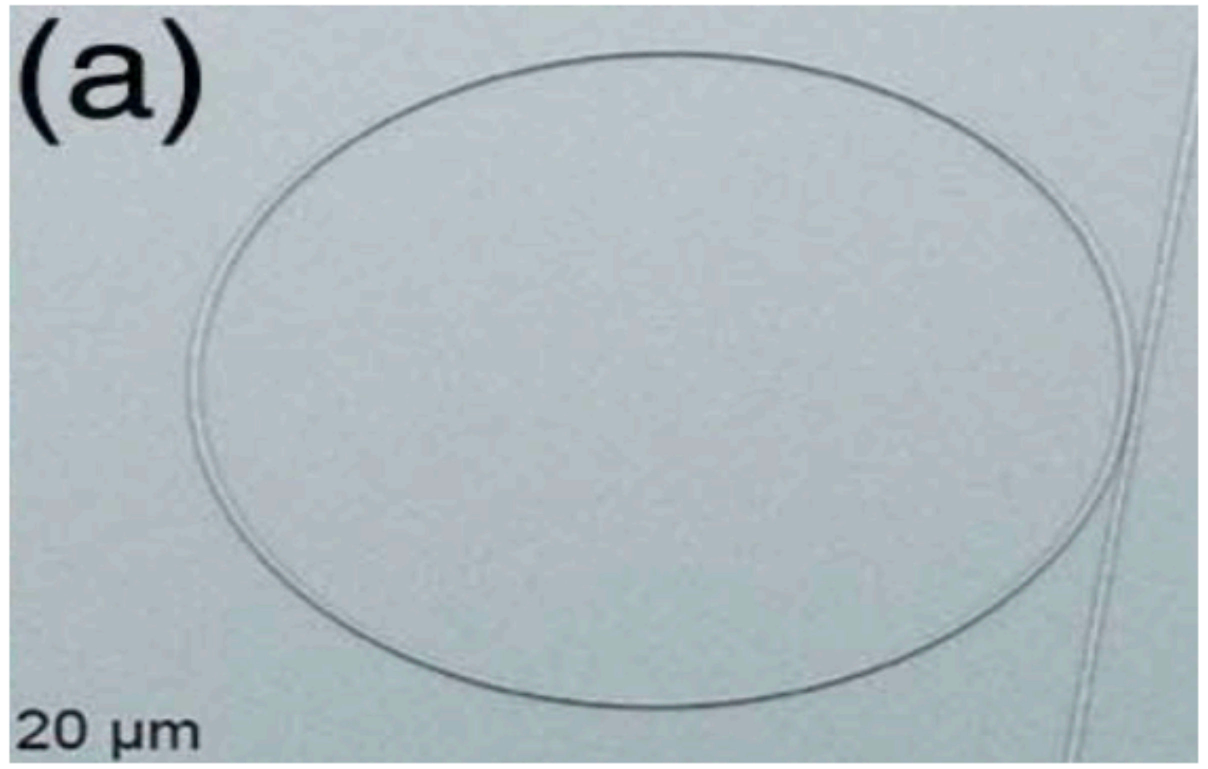


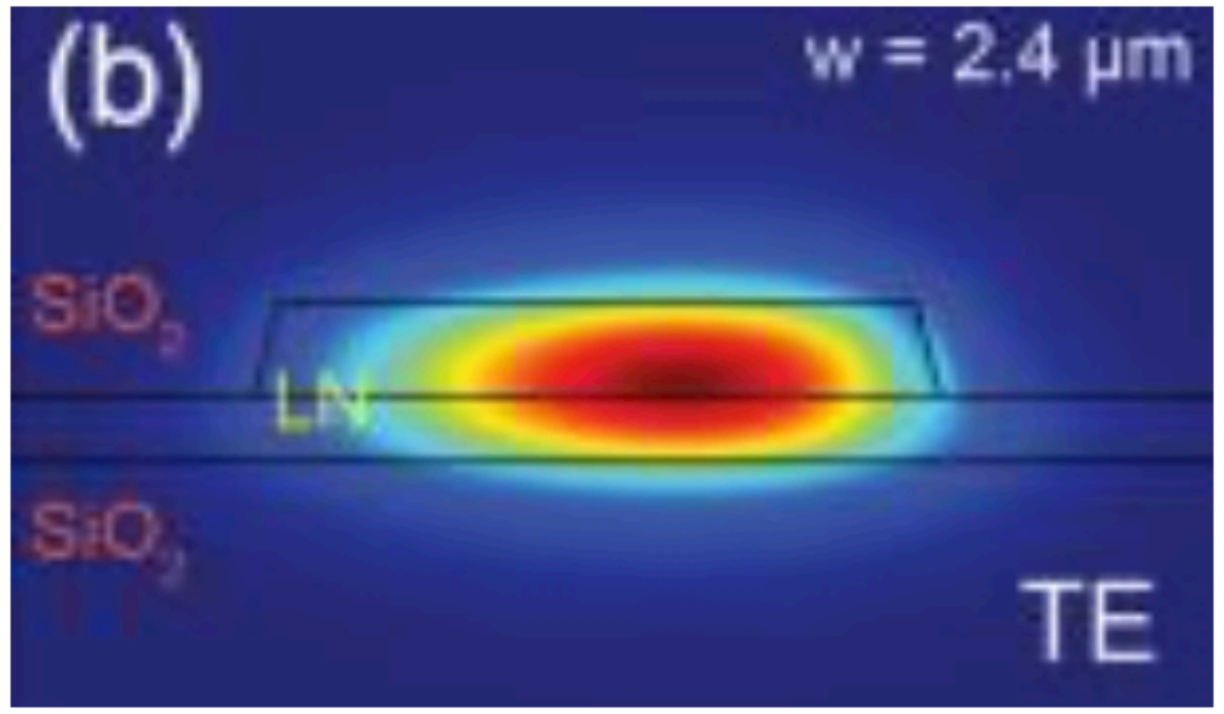
LAMPOST

BREAD

Photonic chips?

Ring Resonator: eV axion/dark photon

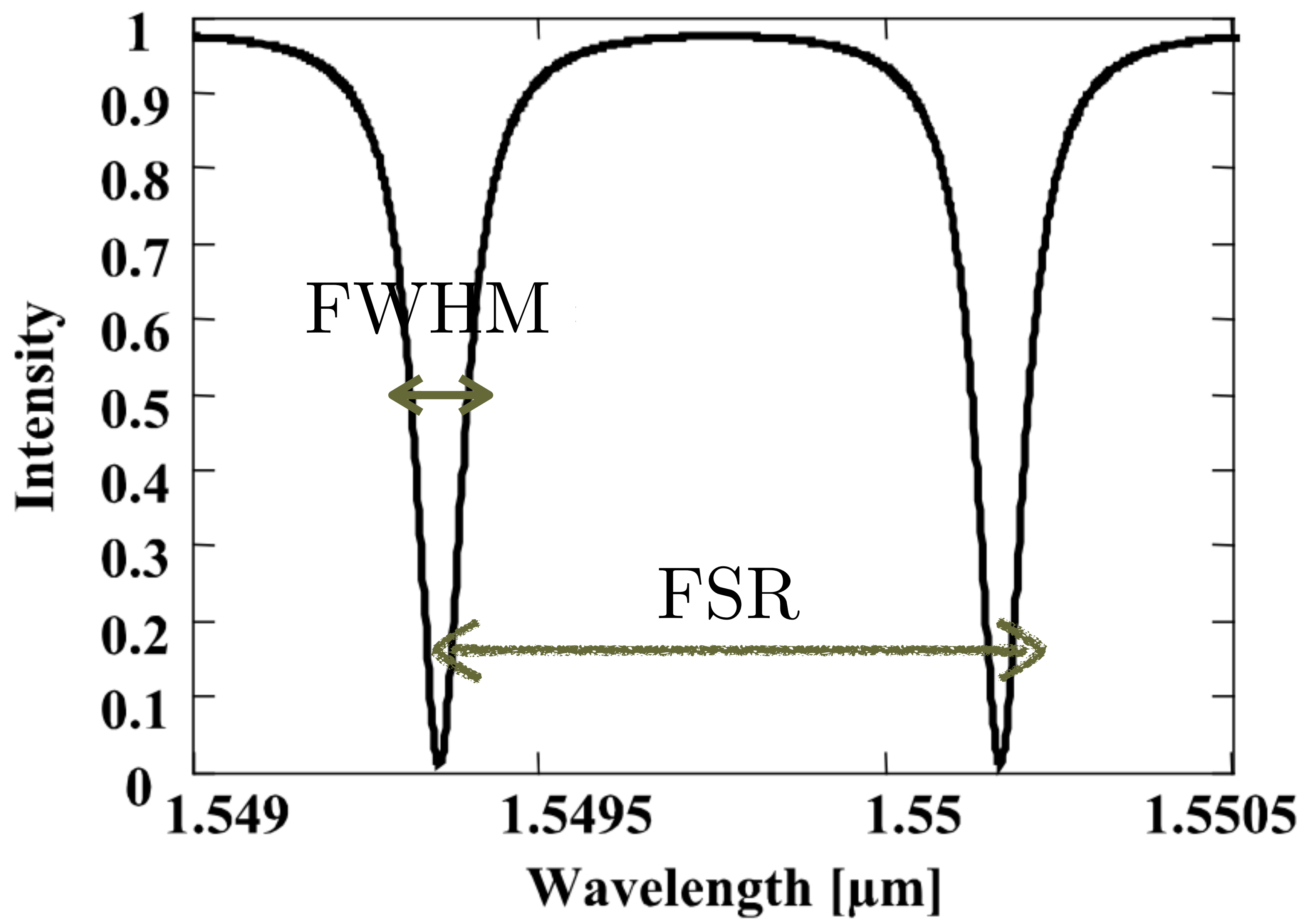




[Zhang et al 1712.04479]

$$\lambda \sim \mu\text{m} \sim {m_a}^{-1}$$

$$L \sim 100\mu\text{m}$$



$$Finesse = \frac{\text{FSR}}{\text{FWHM}}$$

$$Q = \frac{\lambda}{\text{FWHM}} = \frac{n_{\text{eff}} L}{\lambda} finesse$$

Ring Resonator: eV axion/dark photon

Axion $g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$

Dark photon $\frac{1}{2} \chi F'_{\mu\nu} F_{\mu\nu}$

New Challenges:

- Phase matching
- Large Q
- Large V

quality factor

effective DM current

$$P_{\rm sig} \simeq \frac{Q}{m_{\rm D}} J_{\rm D}^2 |\eta|^2 V$$

momentum conservation

SUSTech

Our Proposal

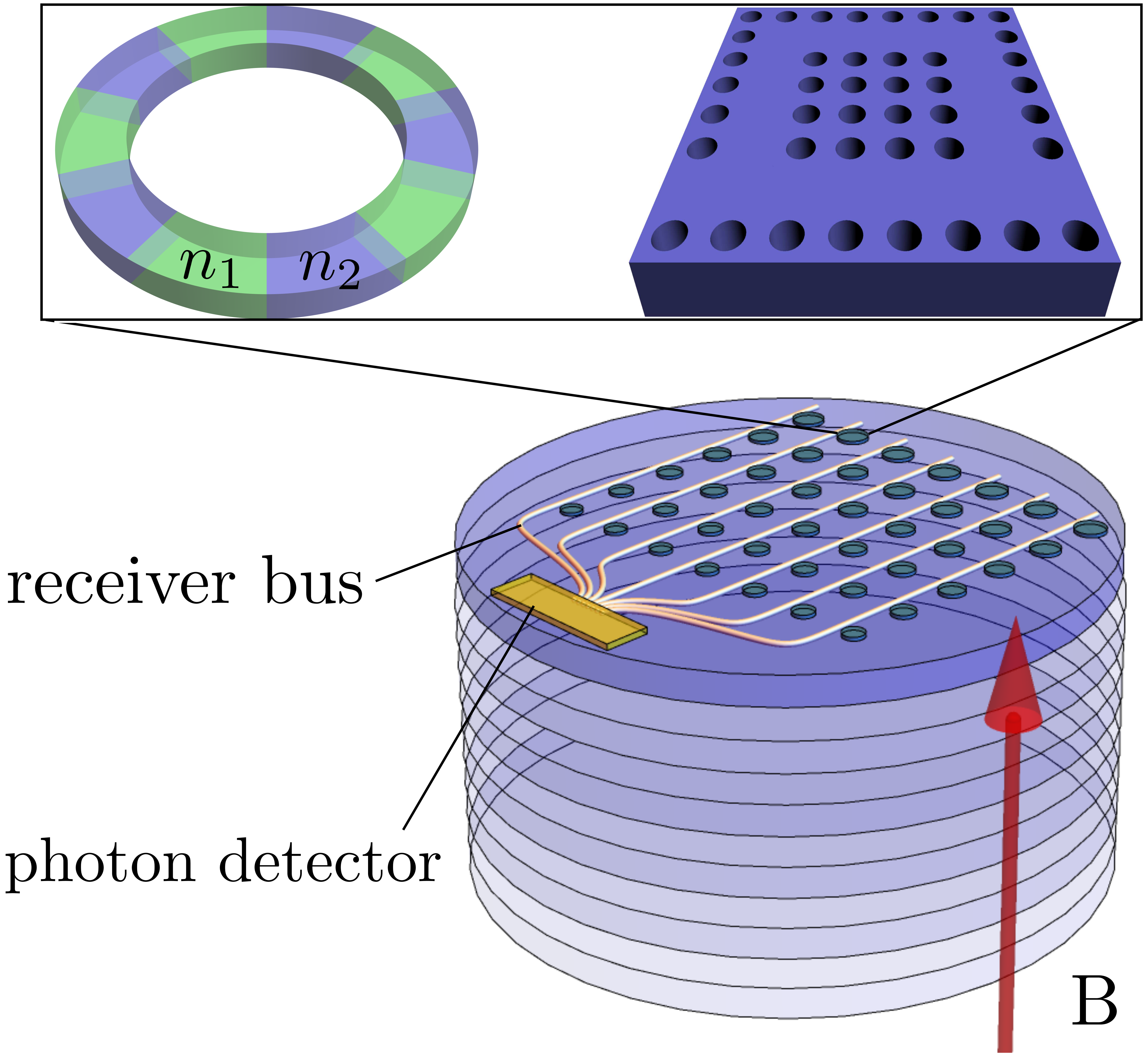
arXiv:2401.17260

with R. Harnik, R. Janish (Fermilab); N.Blinov (York U); N. Sinclair (Harvard)

New Challenges:

- Phase matching
- Large Q
- Large V

examples of periodically varying resonators



Our Proposal

arXiv:2401.17260

with R. Harnik, R. Janish (Fermilab); N.Blinov (York U); N. Sinclair (Harvard)

New Challenges:

- Phase matching

Photonic Crystal

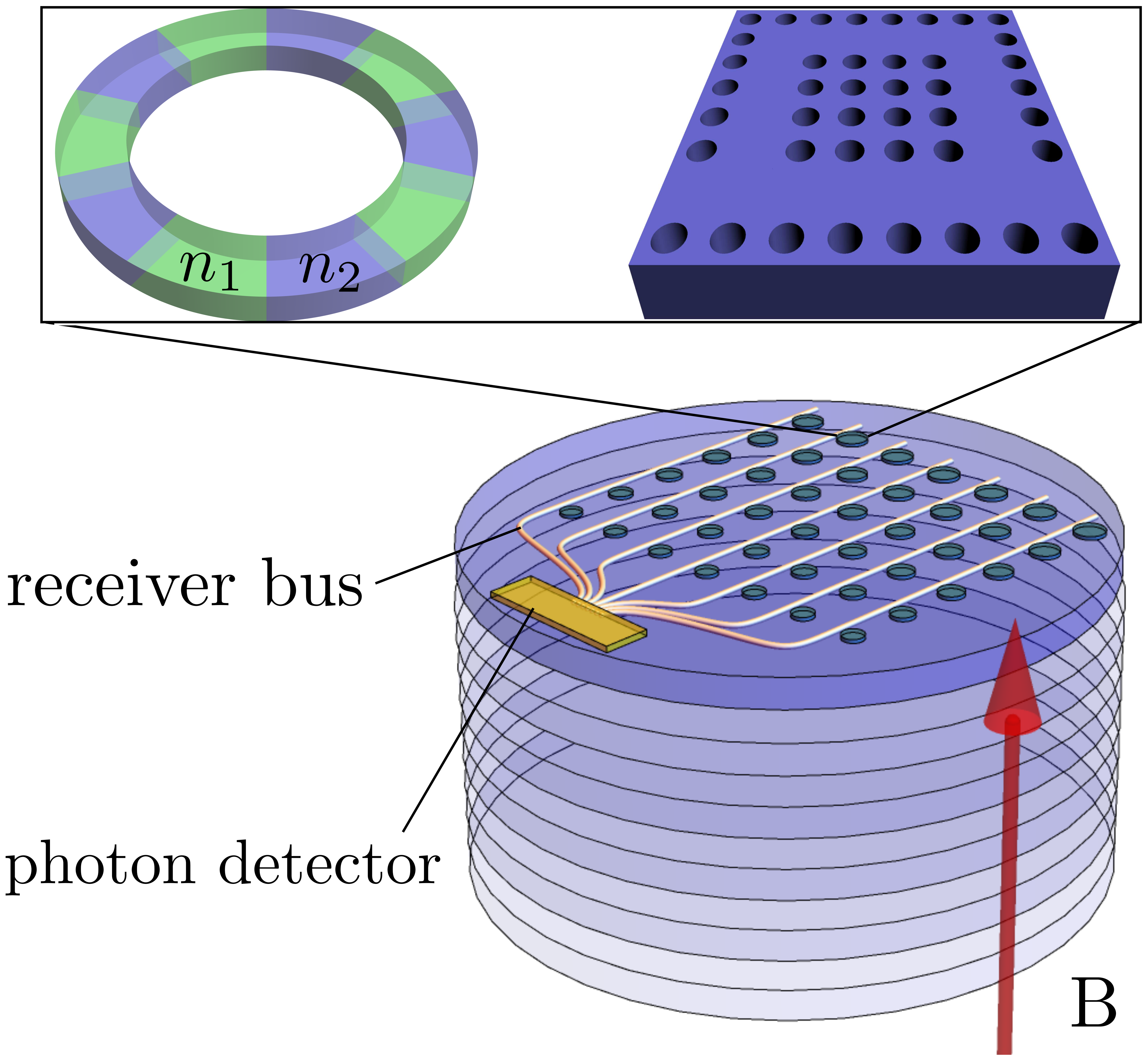
- Large Q

Bound States in Continuum

- Large V

Sensor Network

examples of periodically varying resonators



Phase Matching (Momentum Conservation)

Periodic Photonic Structure: Bloch Modes

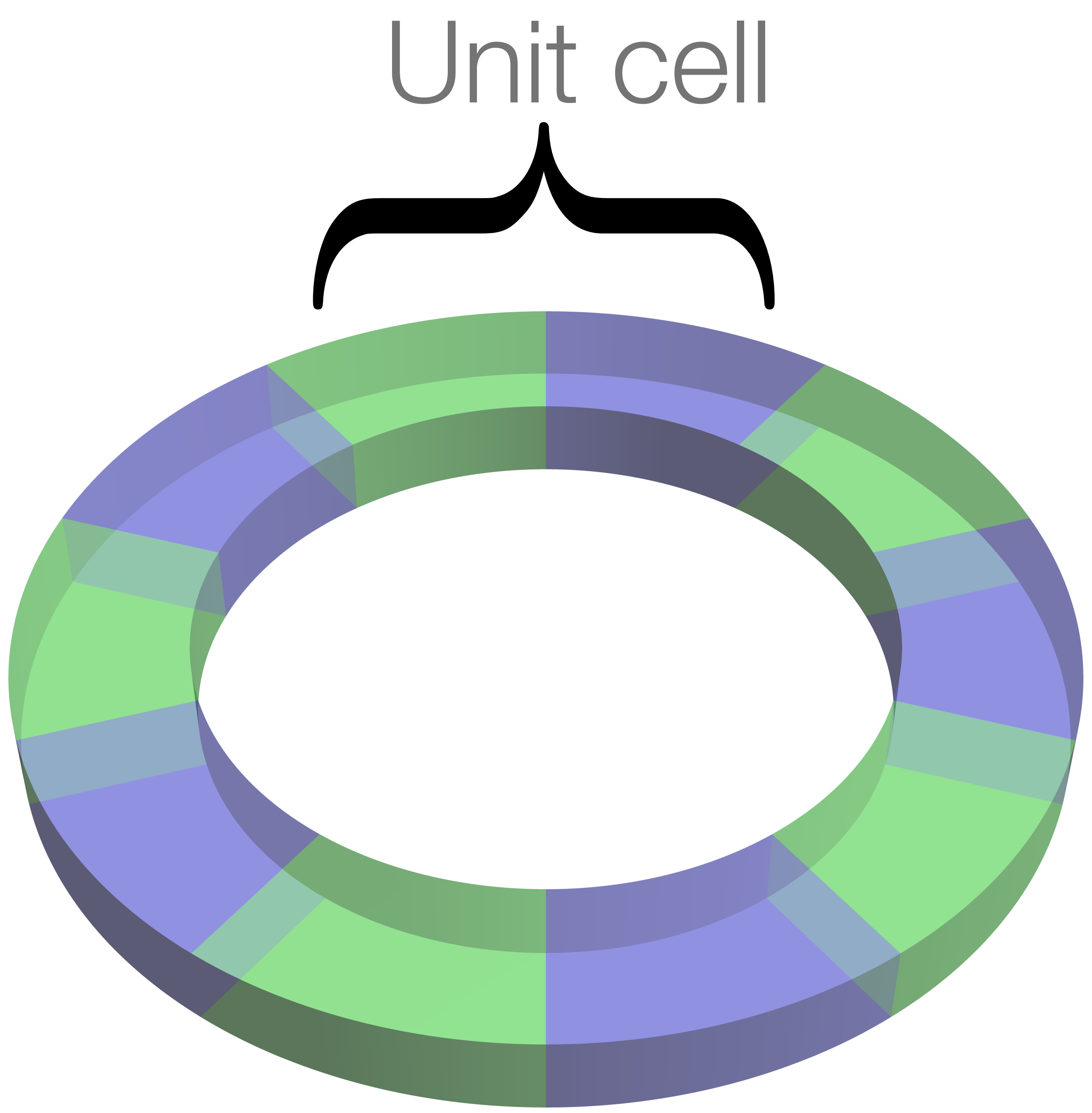
$$\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r} + \mathbf{R})$$

$$\mathbf{E_K} = \mathbf{u_K}(\mathbf{r})e^{\pm i\mathbf{K}\cdot\mathbf{r}} \ , \quad \mathbf{u_K}(\mathbf{r}) = \mathbf{u_K}(\mathbf{r} + \mathbf{R})$$

Lattice vector

Bloch wavevector

Resonator size << λ_{dB}



e.x. $N_u = 5$

Periodic Photonic Structure: Bloch Modes

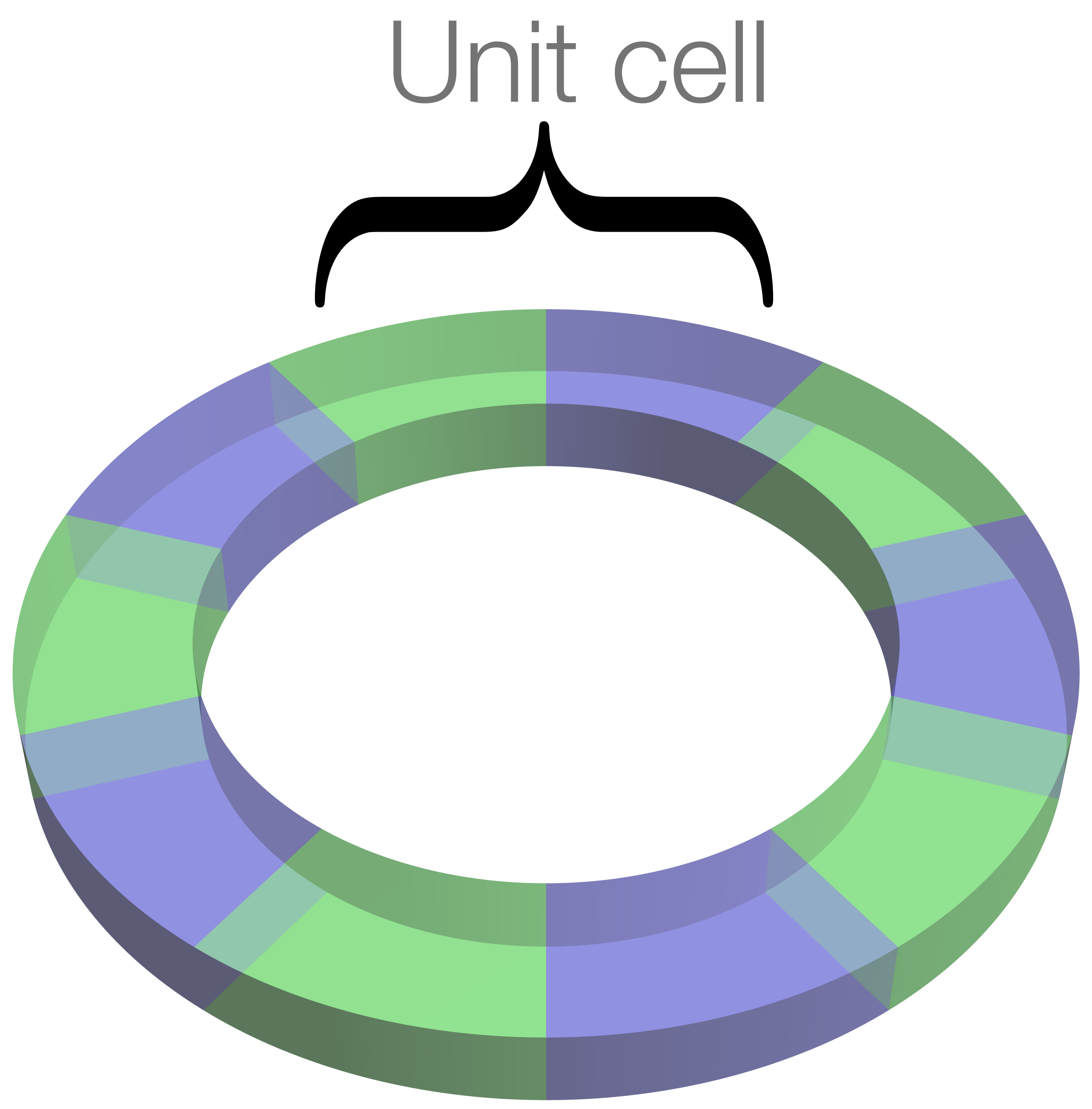
$$\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r} + \mathbf{R})$$

Lattice vector

$$\mathbf{E}_{\mathbf{K}} = \mathbf{u}_{\mathbf{K}}(\mathbf{r}) e^{\pm i \mathbf{K} \cdot \mathbf{r}} \quad , \quad \mathbf{u}_{\mathbf{K}}(\mathbf{r}) = \mathbf{u}_{\mathbf{K}}(\mathbf{r} + \mathbf{R})$$

Bloch wavevector

Resonator size << λ_{dB}



e.x. $N_u = 5$

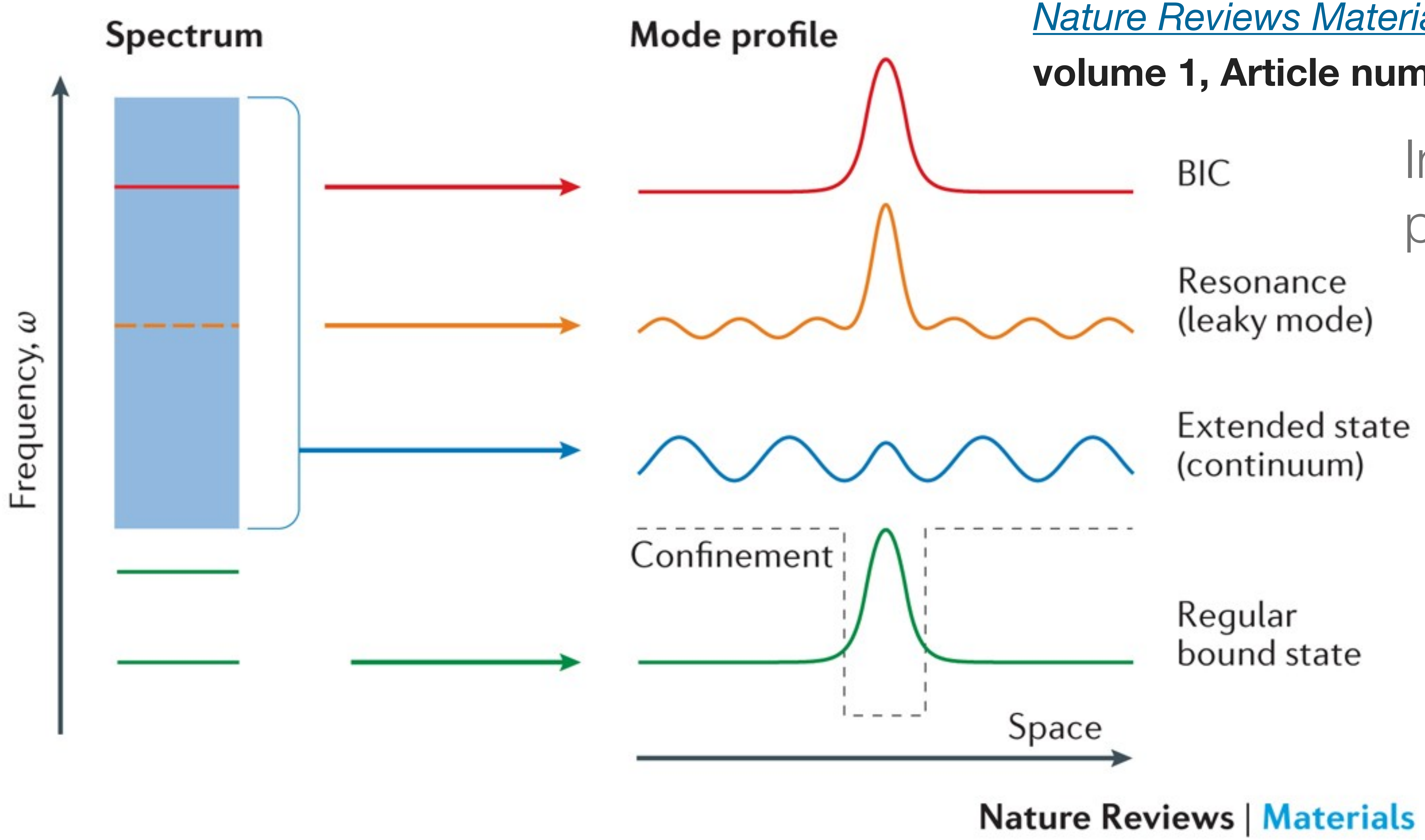
DM couples to $K \approx 0$ modes

$$|\eta|^2 = |\eta_u|^2 \frac{1}{N_u^2} \sum_{i,j} e^{-i\mathbf{K} \cdot (\mathbf{R}_i - \mathbf{R}_j)}$$

SUSTech

What about Q?

Bound States in the Continuum



Nature Reviews Materials

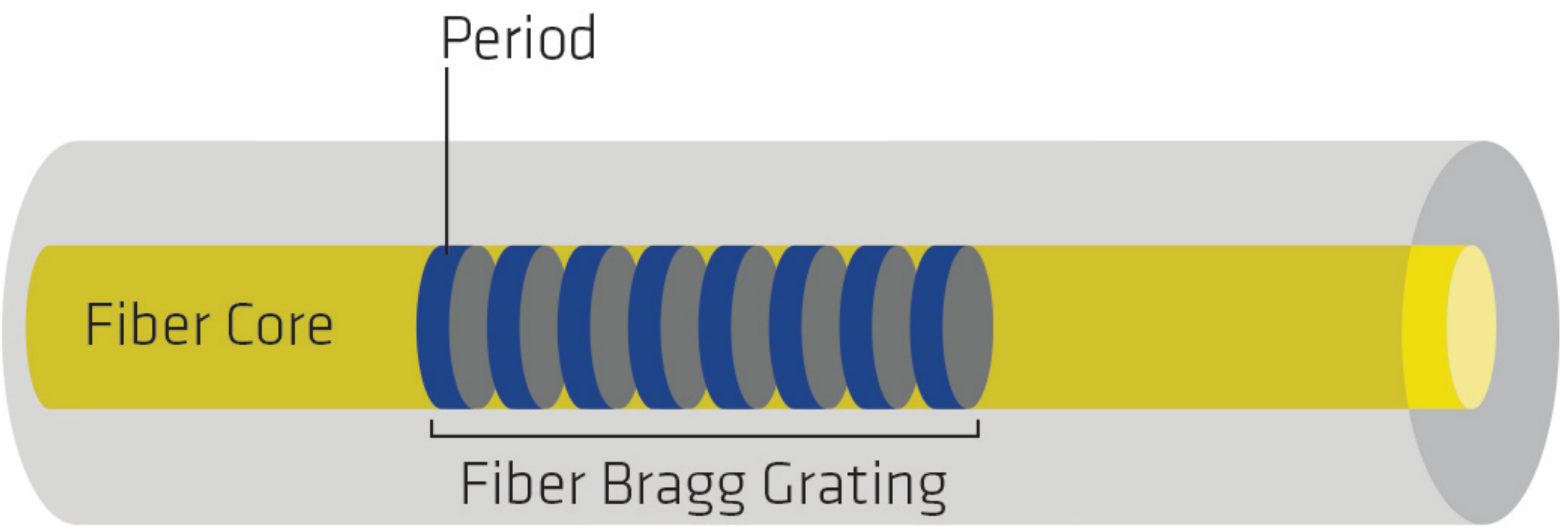
volume 1, Article number: 16048 (2016)

Infinite Q for perfect BIC

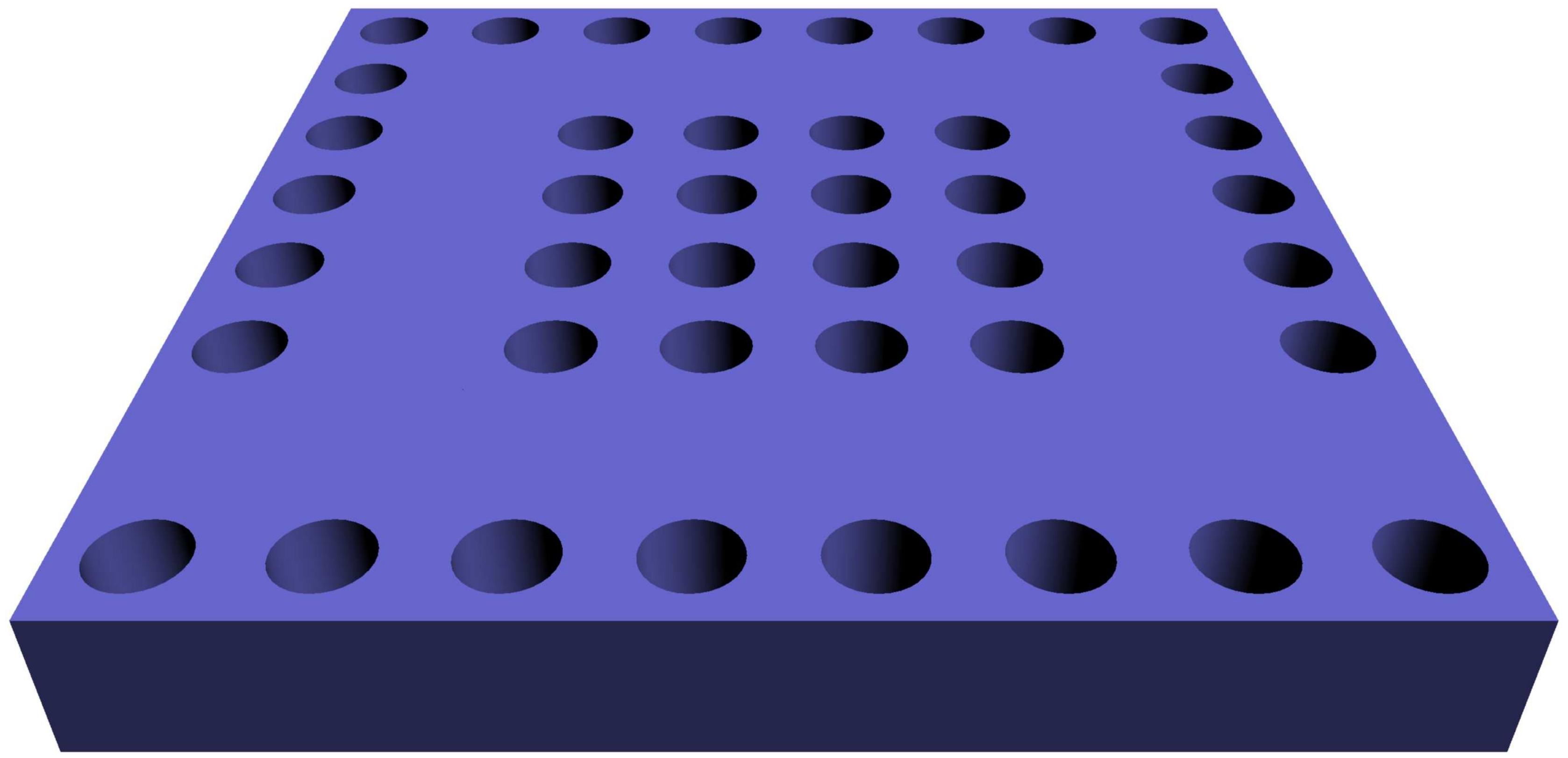
1D and 2D Examples that support BIC modes

$$|\eta|^2 = |\eta_u|^2 \frac{1}{N_u^2} \sum_{i,j} e^{-i\mathbf{K}\cdot(\mathbf{R}_i - \mathbf{R}_j)}$$

https://www.teraxion.com/en/company/fiberbragggrating/



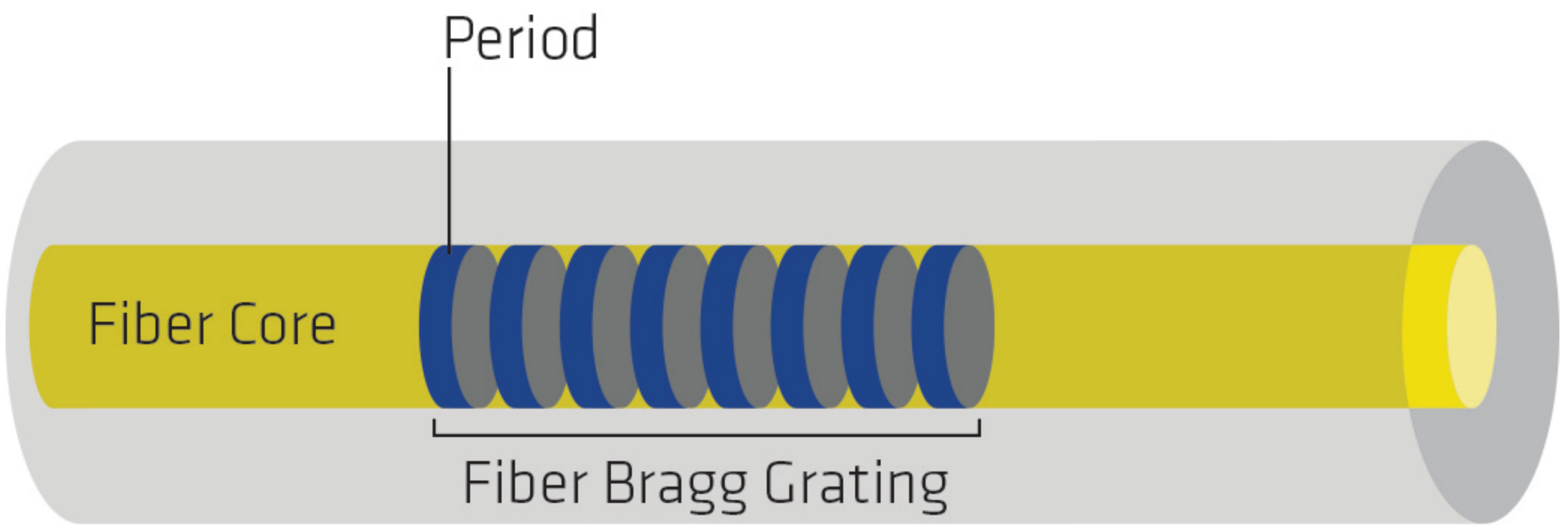
Patterned slab



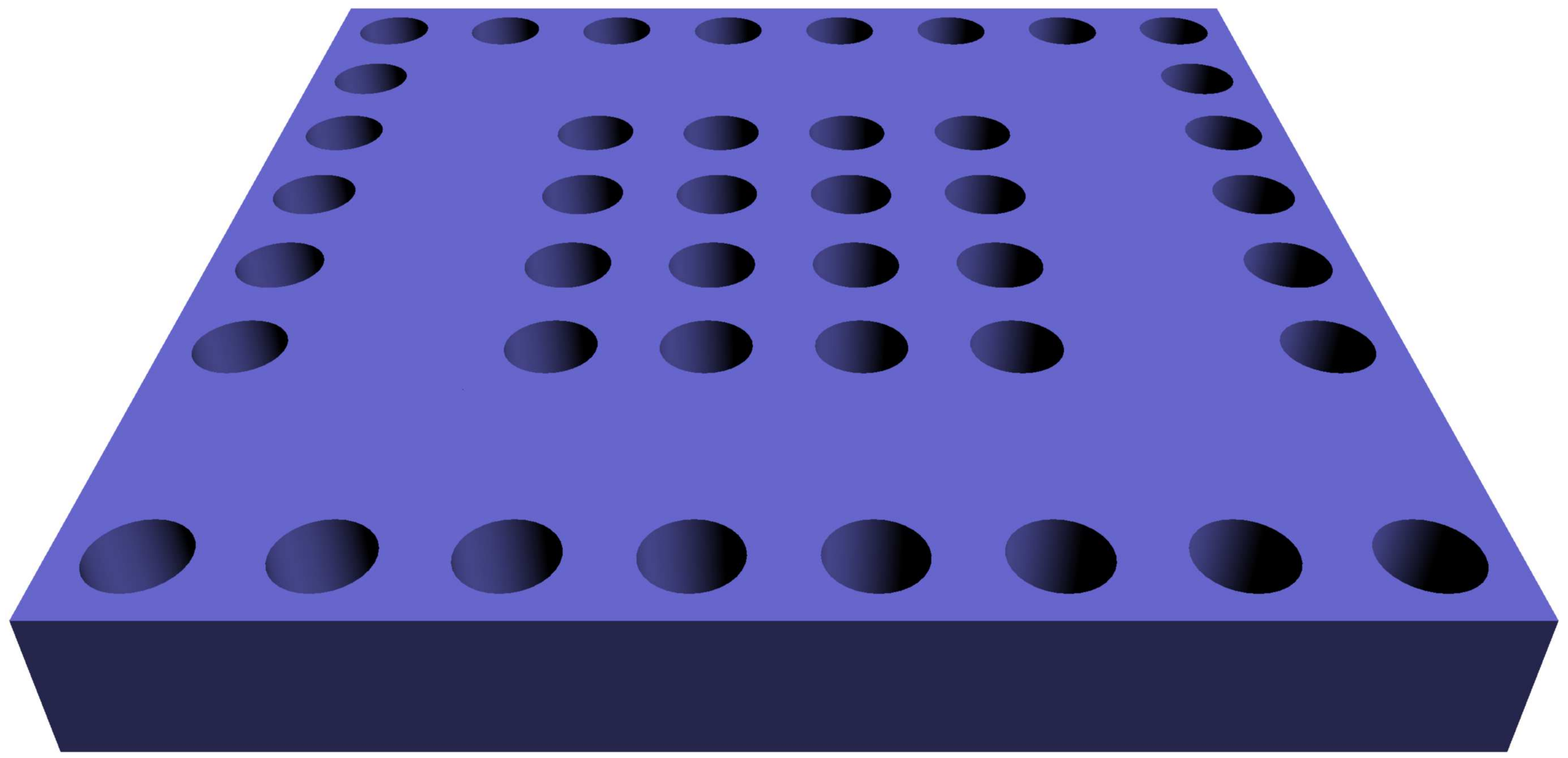
1D and 2D Examples that support BIC modes

$$|\eta|^2 = |\eta_u|^2 \frac{1}{N_u^2} \sum_{i,j} e^{-i\mathbf{K}\cdot(\mathbf{R}_i - \mathbf{R}_j)}$$

https://www.teraxion.com/en/company/fiberbragggrating/



Patterned slab



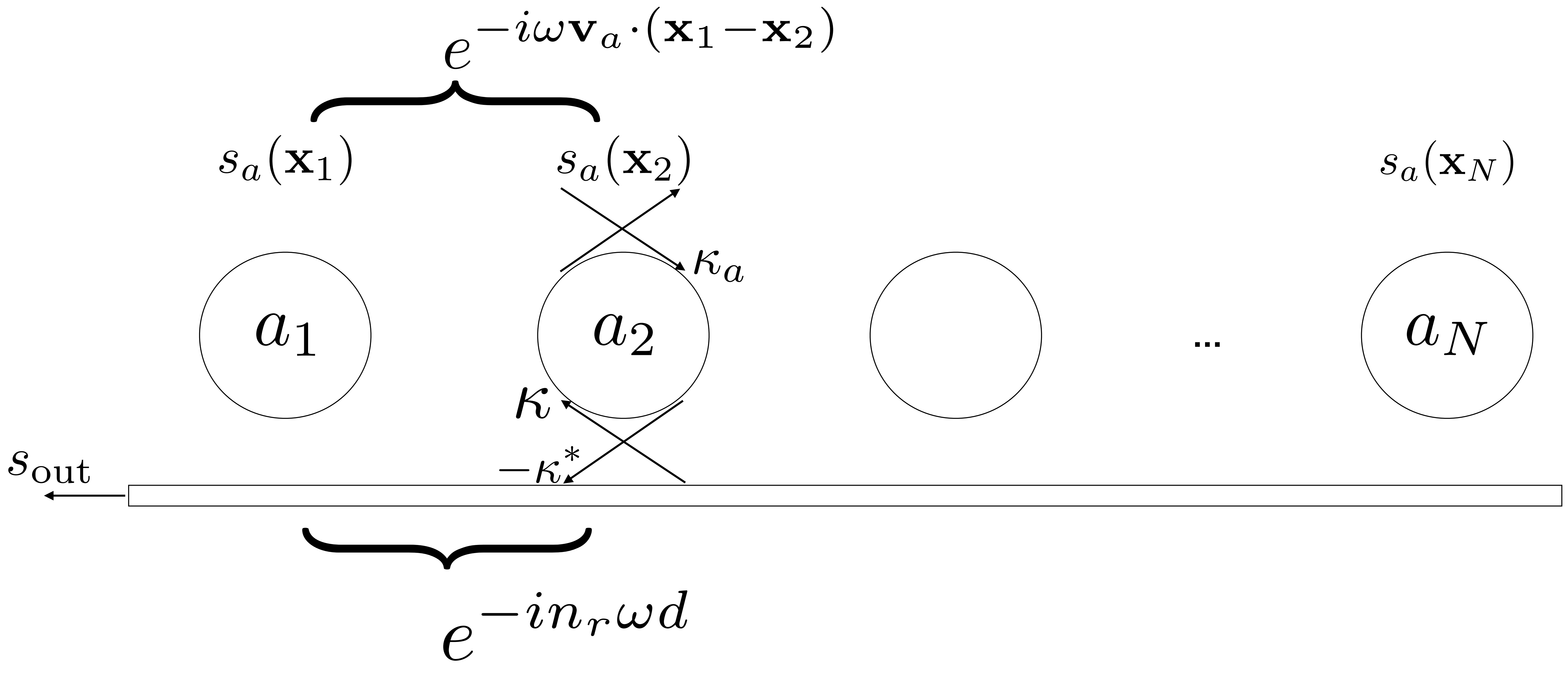
$|\eta_u| : 0.01 \sim 0.1$ Not optimized

Coupling *N* Resonators in Series

N Resonators in Series

N DM sources:

N resonators:

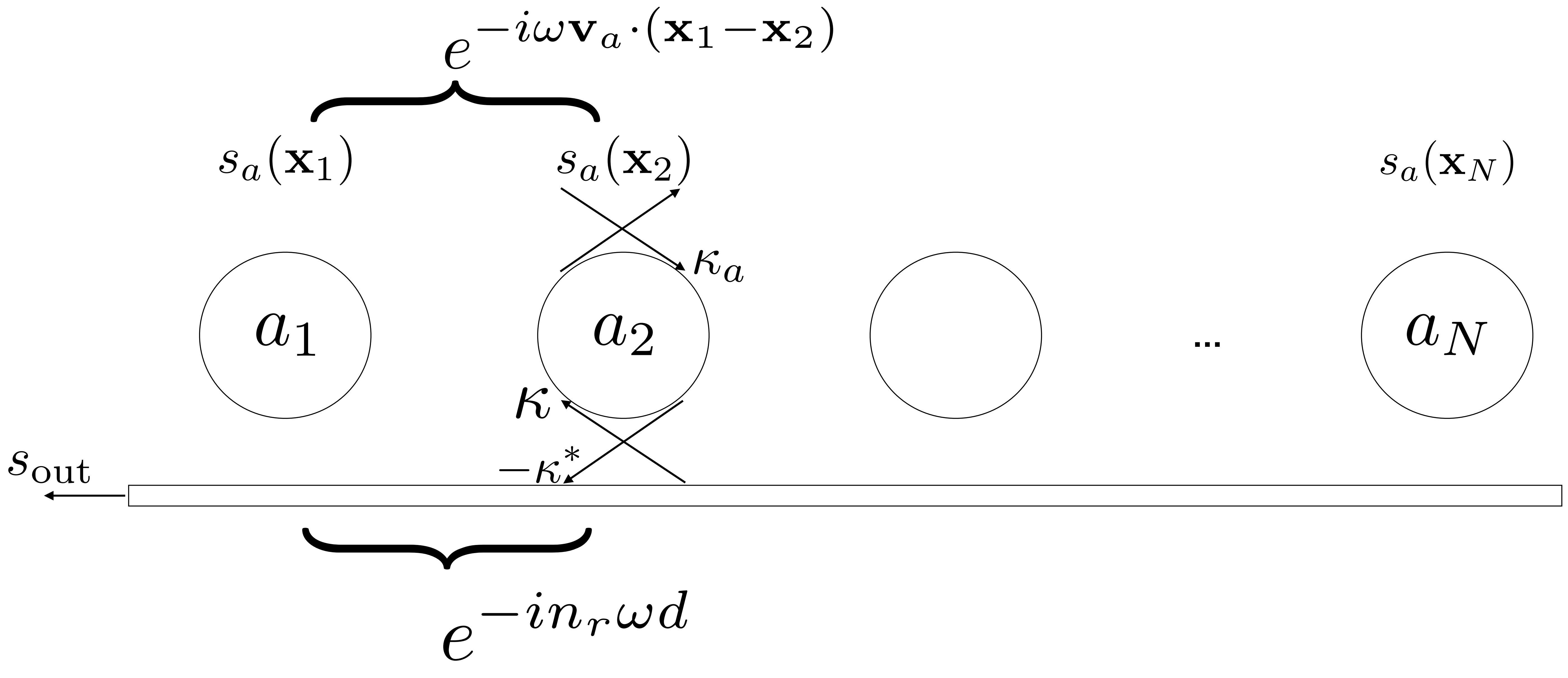


- DM sources a standing wave that can couple to either left or right-traveling wave in the bus.
- DM field is coherent over each resonator, but could be incoherent across neighboring resonators.

N Resonators in Series

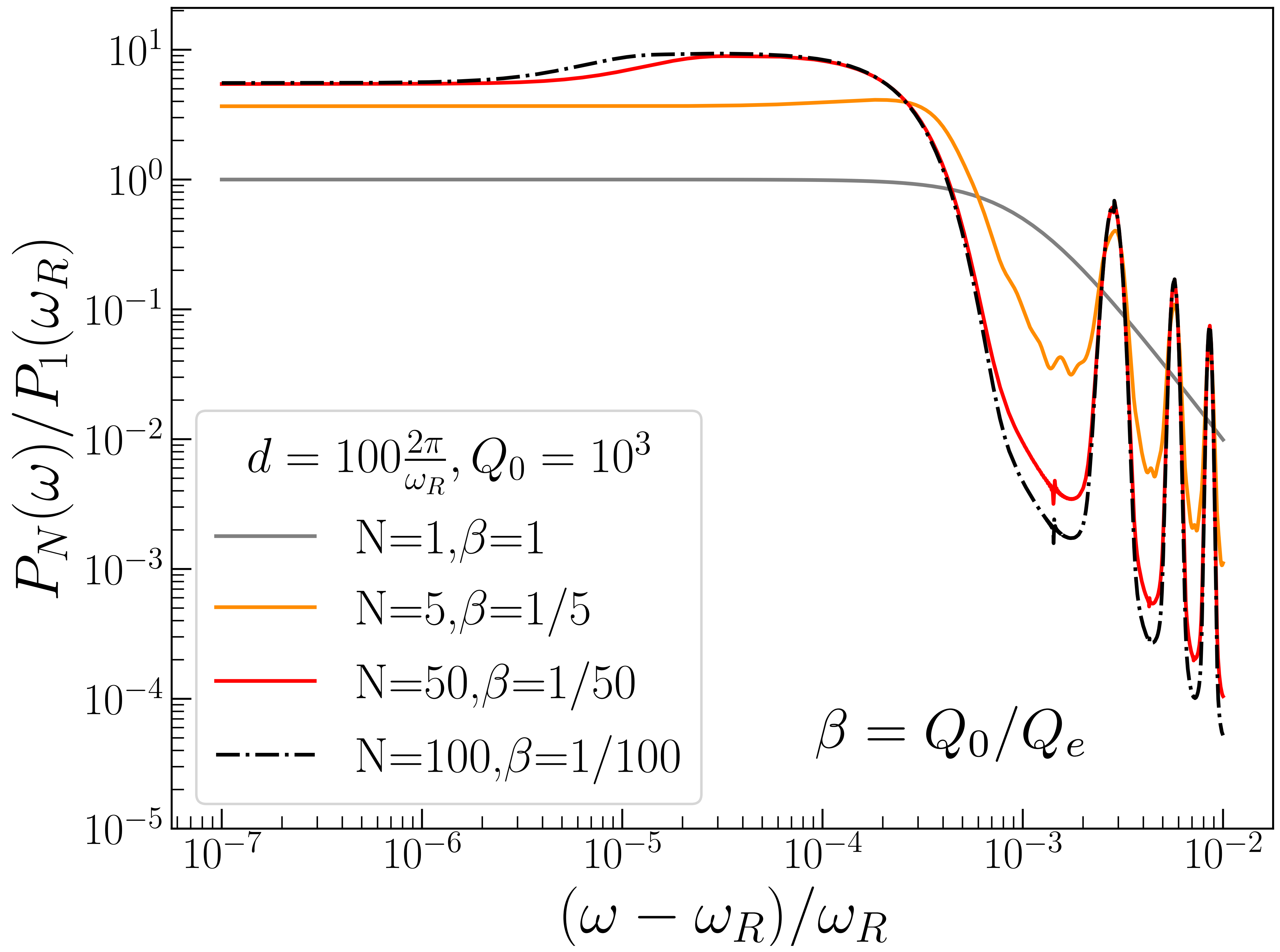
N DM sources:

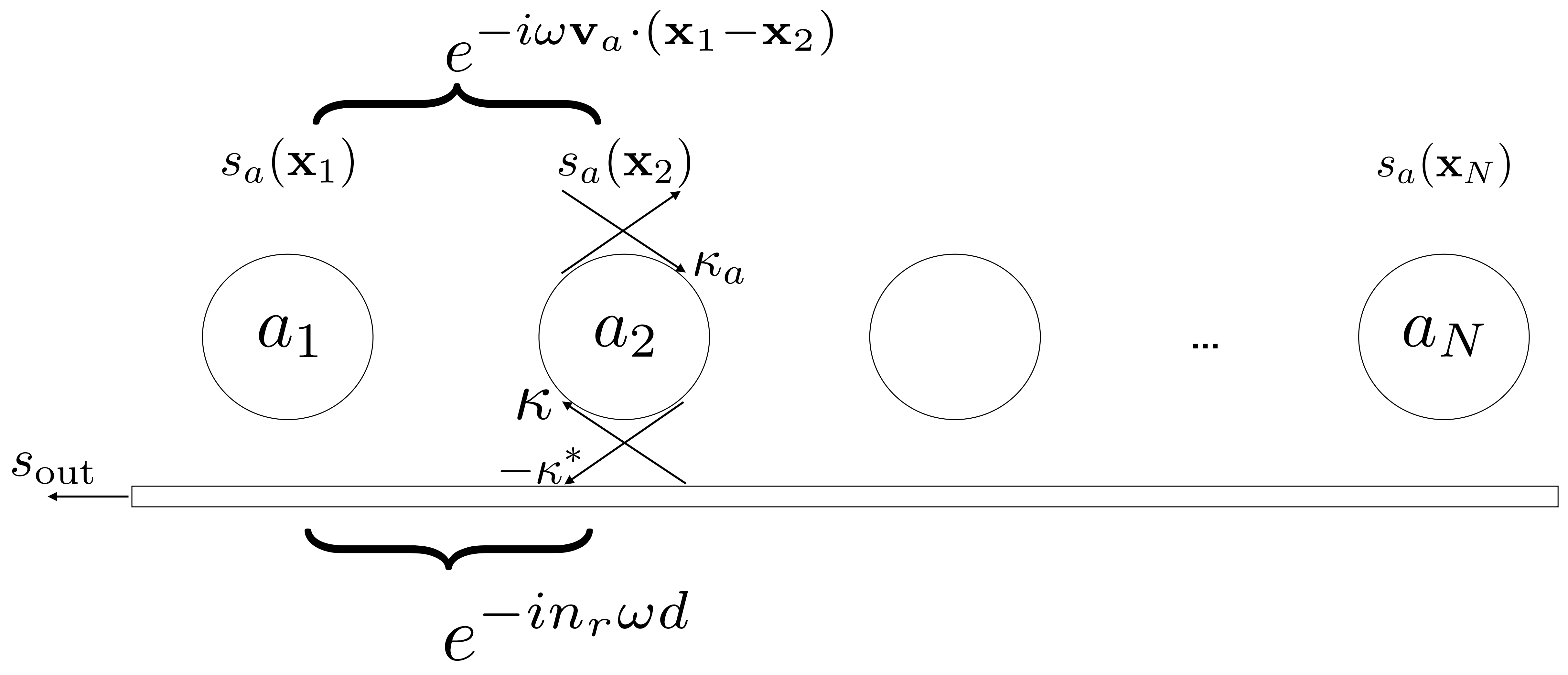
N resonators:



- Solve the output using Heisenberg Langevin equations
- Gaussian distribution of $\mathbf{v}_a$ is assumed.

Same Frequency





No gain after going beyond the DM coherence length.

First degree of coherence of axion field

$$g^{(1)}(\mathbf{x},\mathbf{x}',t,t') \sim \langle \hat{a}(\mathbf{x},t)\hat{a}(\mathbf{x}',t')\rangle \sim \int d^3v f(\mathbf{v}) e^{-im\mathbf{v}\cdot(\mathbf{x}-\mathbf{x}')+\frac{i}{2}mv^2(t-t')}$$

D. Y. Cheong, N. L. Rodd, L.-T. Wang, Phys. Rev. D 111, 015028 (2025)

Gaussian dist. $\mathbf{v} \sim f(\mathbf{v}) = \frac{1}{\pi^{3/2}v_0^3} e^{-(\mathbf{v}+\mathbf{v}_\odot)^2/v_0^2}$

$$|g^{(1)}(\mathbf{x},\mathbf{x}')| \approx e^{-\frac{1}{4}m_a^2 v_0^2 |\mathbf{x}-\mathbf{x}'|^2} \begin{cases} = 1 & \text{Perfectly coherent} \\ < 1 & \text{Partially coherent} \end{cases}$$

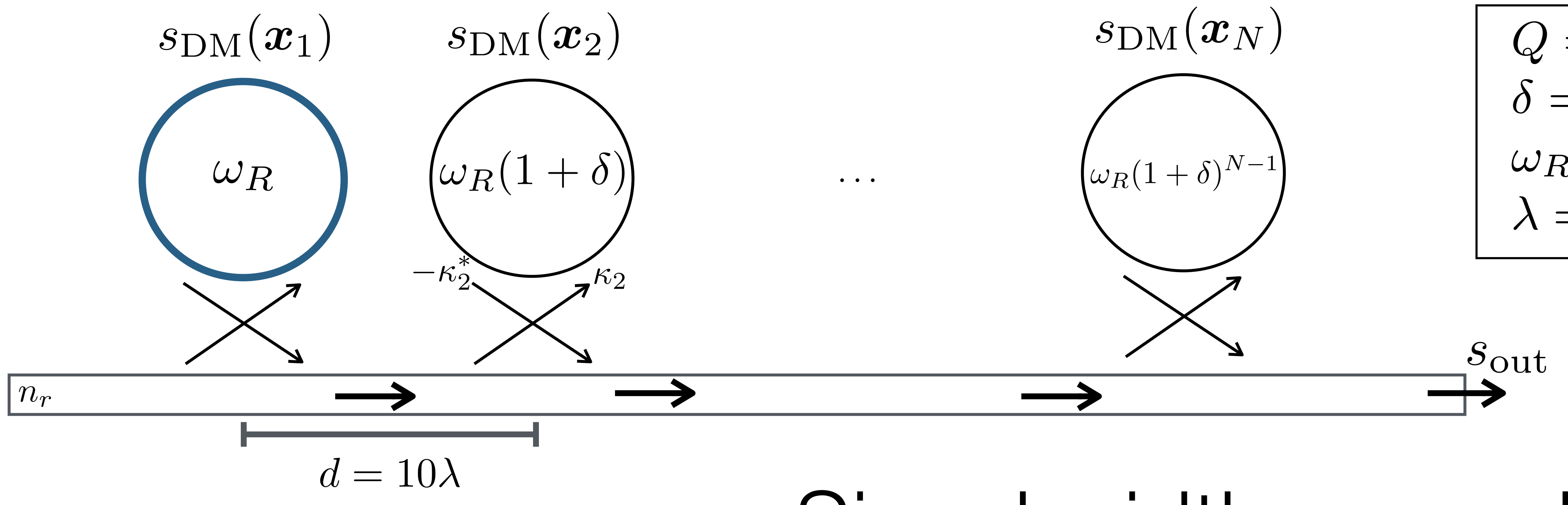
$$\therefore \lambda_{coh} \sim \frac{2}{m_a v_0}$$

How does coherence length affect signal power?

$$P_{\text{sig}} \simeq \frac{Q}{m_{\text{D}}} J_{\text{D}}^2 |\eta|^2 V$$

$$|\eta|^2 \equiv \frac{\int d^3x d^3x' \boldsymbol{E}^*(\boldsymbol{x}) \cdot \hat{\boldsymbol{n}} \boldsymbol{E}(\boldsymbol{x}') \cdot \hat{\boldsymbol{n}} e^{-(\boldsymbol{x}-\boldsymbol{x}')^2/\lambda_{\text{coh}}^2}}{V \int d^3x \, \varepsilon(\boldsymbol{x}) \, |\boldsymbol{E}|^2}$$

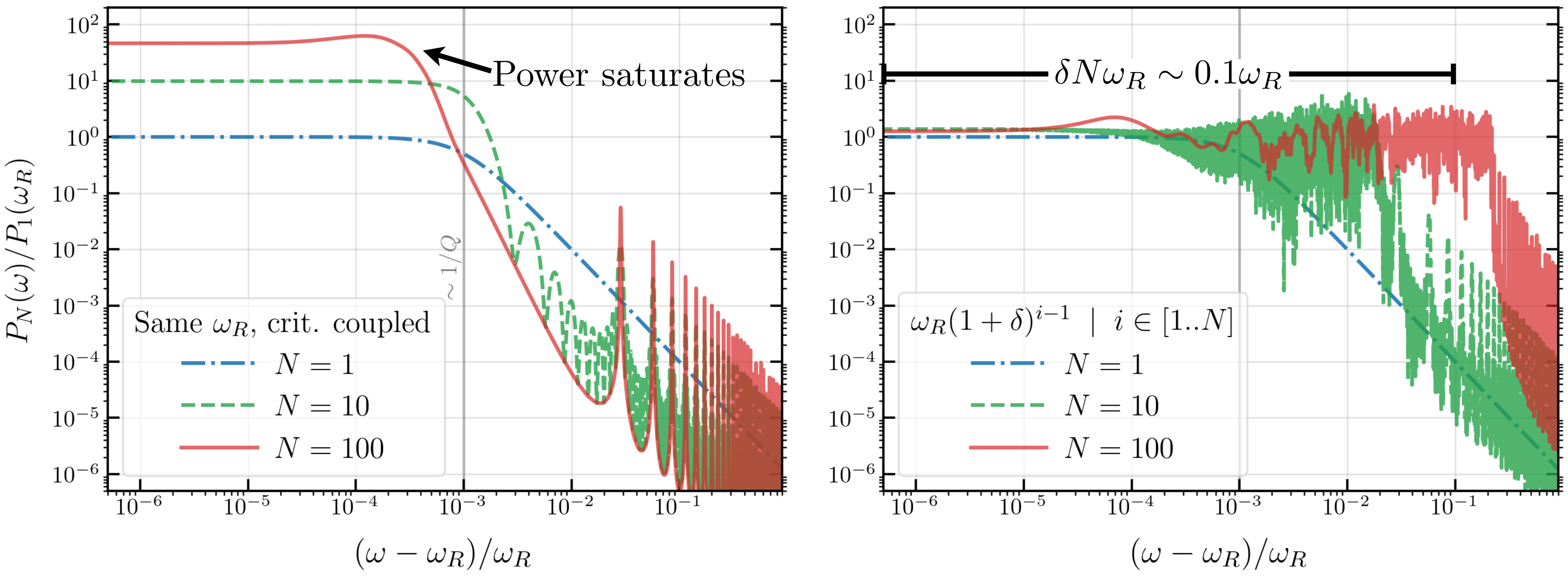
Different Frequencies



$Q = 500$
$\delta = Q^{-1}$
$\omega_R = 1$ eV
$\lambda = 2\pi/(n_r\omega_R)$

Signal width grows like $N \times \delta$.

(b)Scaling comparison



SUSTech

Projected Sensitivity

Axion DM Search Needs a Background Magnetic Field

B (T)	Bore (mm)	$V_{\rm act}$ (cm^3)	$B^2 V_{\rm act}$ (kJ)	References
40	34	9×10^{-2}	0.11	[70]
21	123	1.18	0.40	[71]
9.4	800	1000	67.3	[72]
11.7	900	1270	133	[73]
20[a]	680	726	221	[74]

Above ~1.1 eV, Skipper CCD

Below ~1.1 eV, Superconducting Nanowire Single Photon Detector

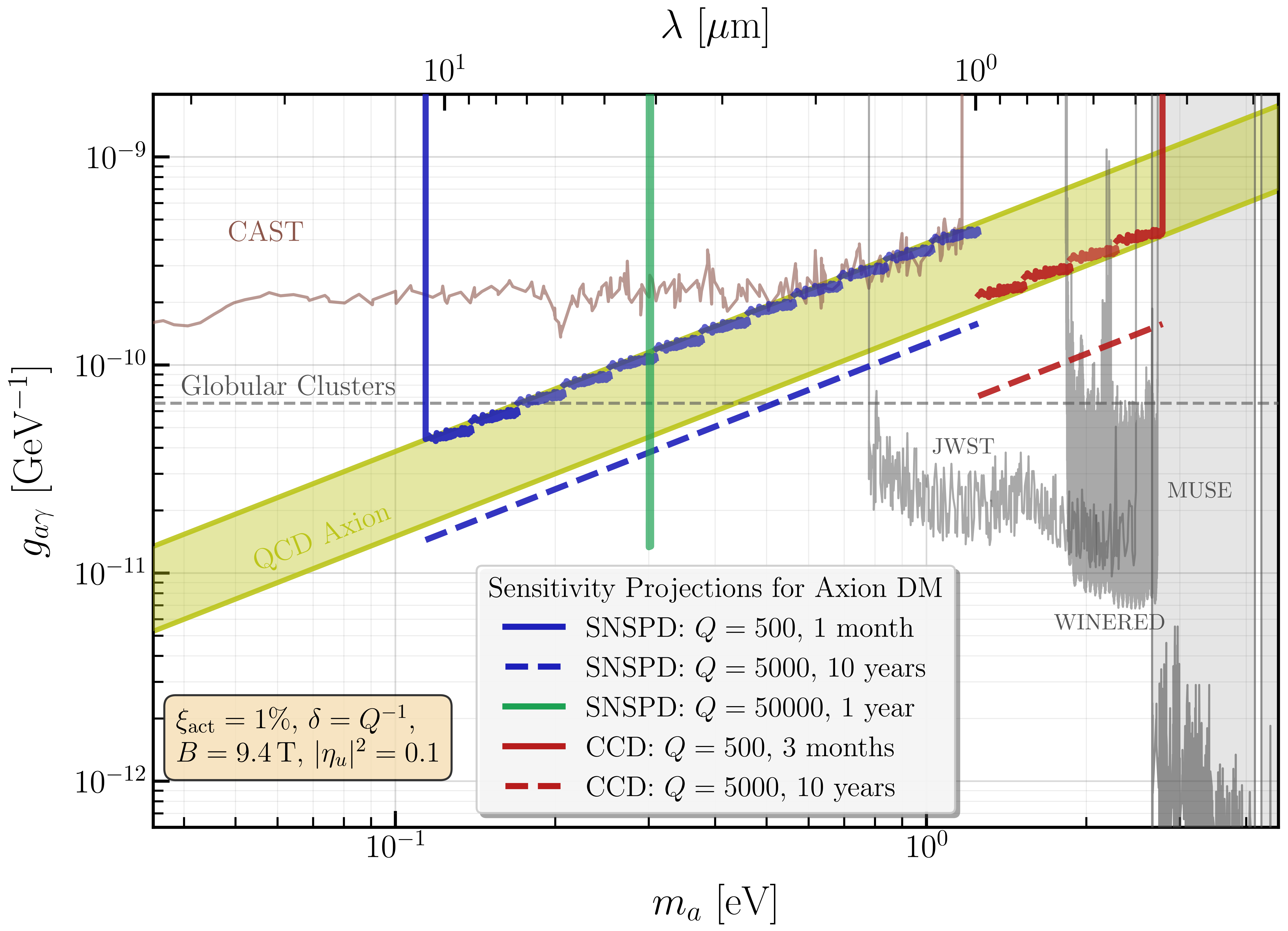
$$\mathrm{SNR} = \frac{\Gamma_{\rm sig} t_{\rm int}}{\mathrm{Max}\left[1, \Gamma_{\rm bkg} t_{\rm int}\right]^{1/2}}$$

Axion DM Search Needs a Background Magnetic Field

$$g_{a\gamma} a \mathbf{E} \cdot \mathbf{B}$$

$$\xi_{\rm act} \equiv \frac{V_{\rm int}}{\pi D^2 t_s/4} \sim 1\% \left(\frac{100}{N_u}\right) \left(\frac{t_w/t_s}{0.1}\right)$$

B (T)	Bore (mm)	$V_{\rm act}$ (cm^3)	$B^2 V_{\rm act}$ (kJ)	Refe
40	34	9×10^{-2}	0.11	[
21	123	1.18	0.40	[
9.4	800	1000	67.3	[
11.7	900	1270	133	[
20[a]	680	726	221	[

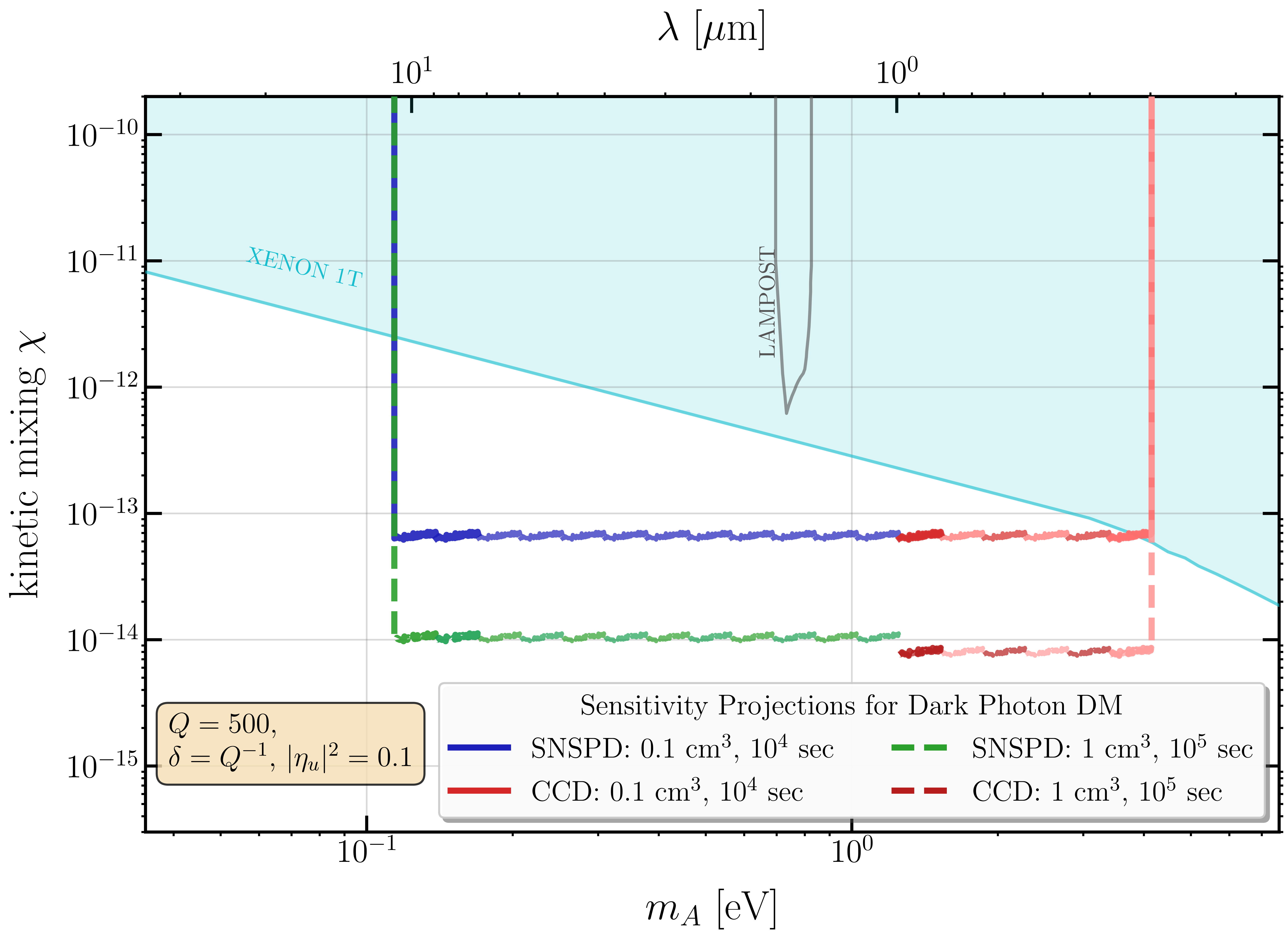


SUSTech

Dark Photon Dark Matter Searches

$$\frac{1}{2}\chi F'_{\mu\nu}F_{\mu\nu}$$

Dark photon searches do not need external magnetic field.



Plan of the talk

- Introduction
- eV axion searches using integrated photonics
- neV axion searches using superfluid ^{3}He
- feV axion searches using levitated ferromagnet

Nuclear magnetic resonance with a homogeneous precession domain of ^{3}He-B

Phys.Rev.Lett. 129 (2022) 21, 211801
Phys. Rev. D 110, 115020 (2024).

with W.P. Halperin, M. Nguyen, J.W. Scott (Northwestern);
Y. Kahn (Toronto U); J. Schütte-Engel (Berkeley); J. Foster (Fermilab)

Nuclear magnetic resonance

Resonance condition:

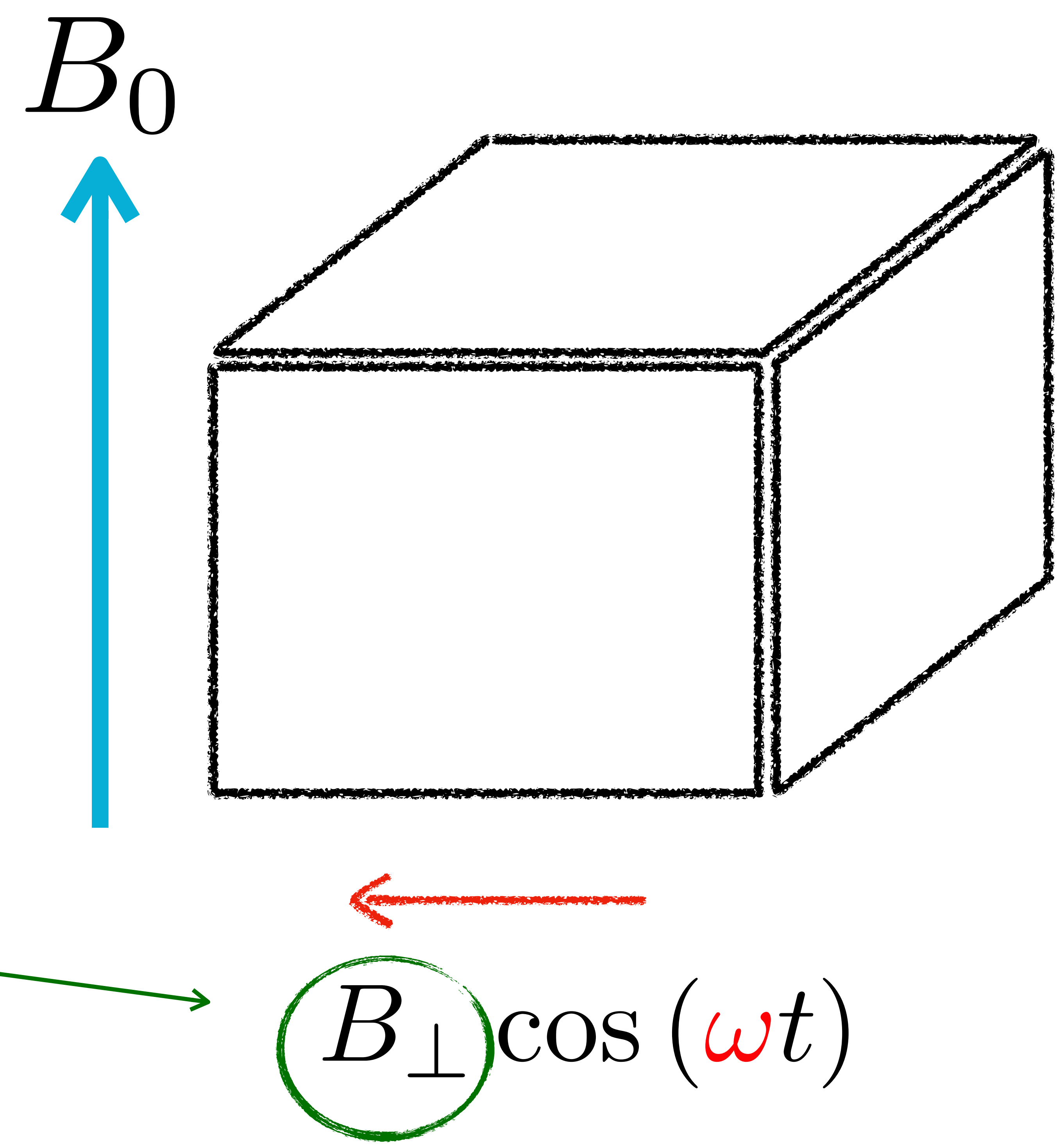
Larmor frequency = oscillation frequency

$\omega_L = \gamma B_0$ $\qquad\qquad \omega$

Graham and Rajendran (2013)

Gyromagnetic ratio of the material

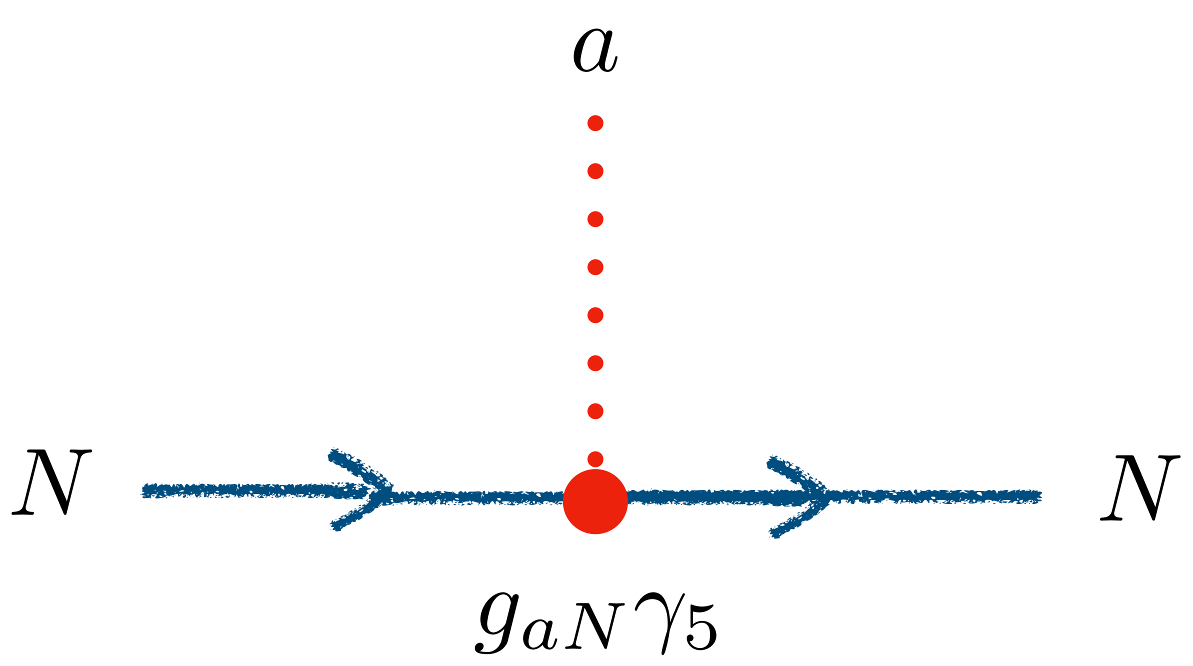
This can come from axion dark matter!



SUSTech

Axion's coupling to nucleons

Axion nucleon coupling



Effective Hamiltonian for nuclear spins

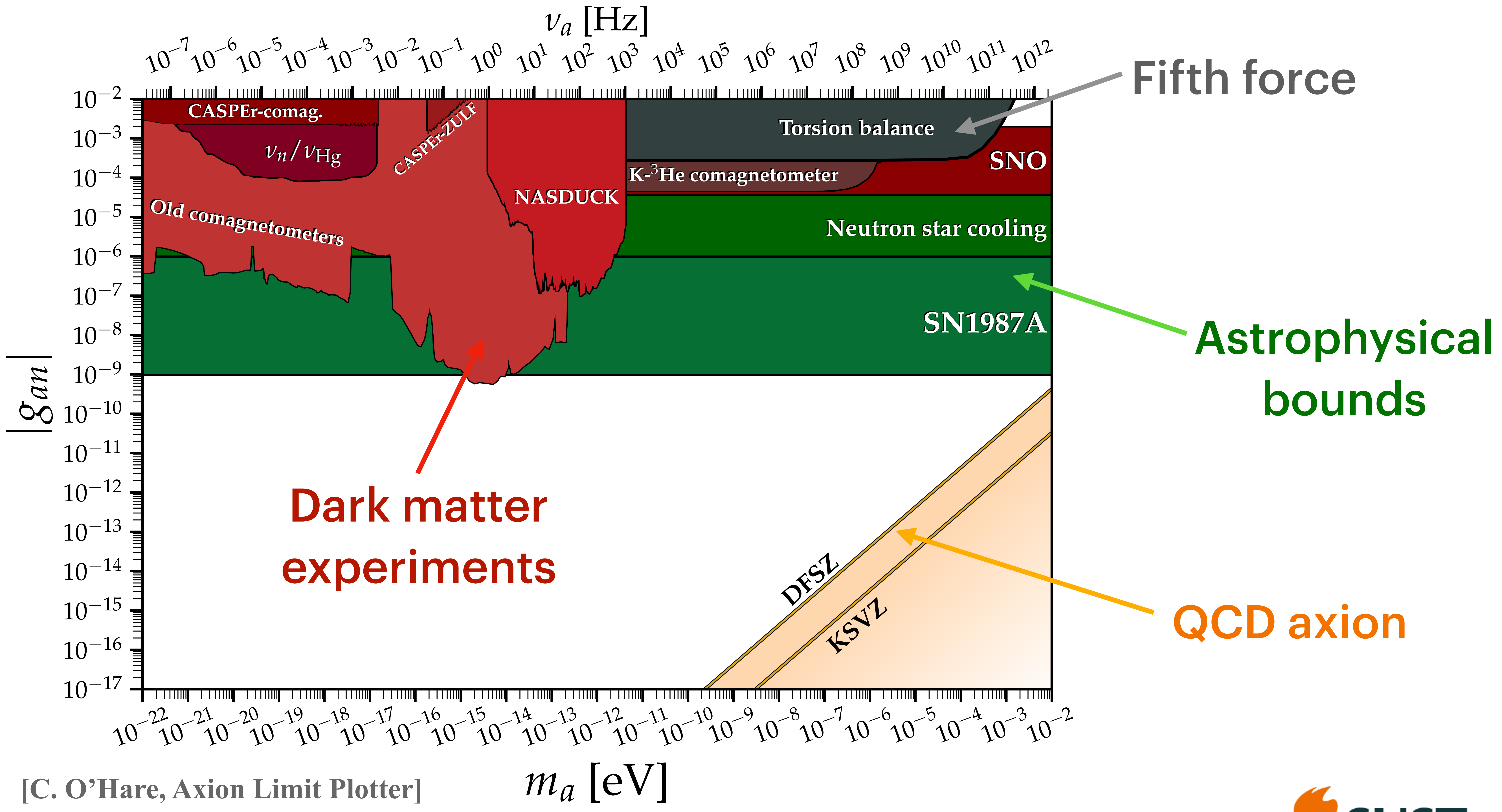
$$H_{\text{eff}} \supset \vec{S} \cdot \vec{B}_a$$

Effective magnetic field due to axion DM

$$B_a \sim \frac{1}{\gamma} g_{aN} \sqrt{\rho_{\text{DM}}} v_{\text{DM}}$$

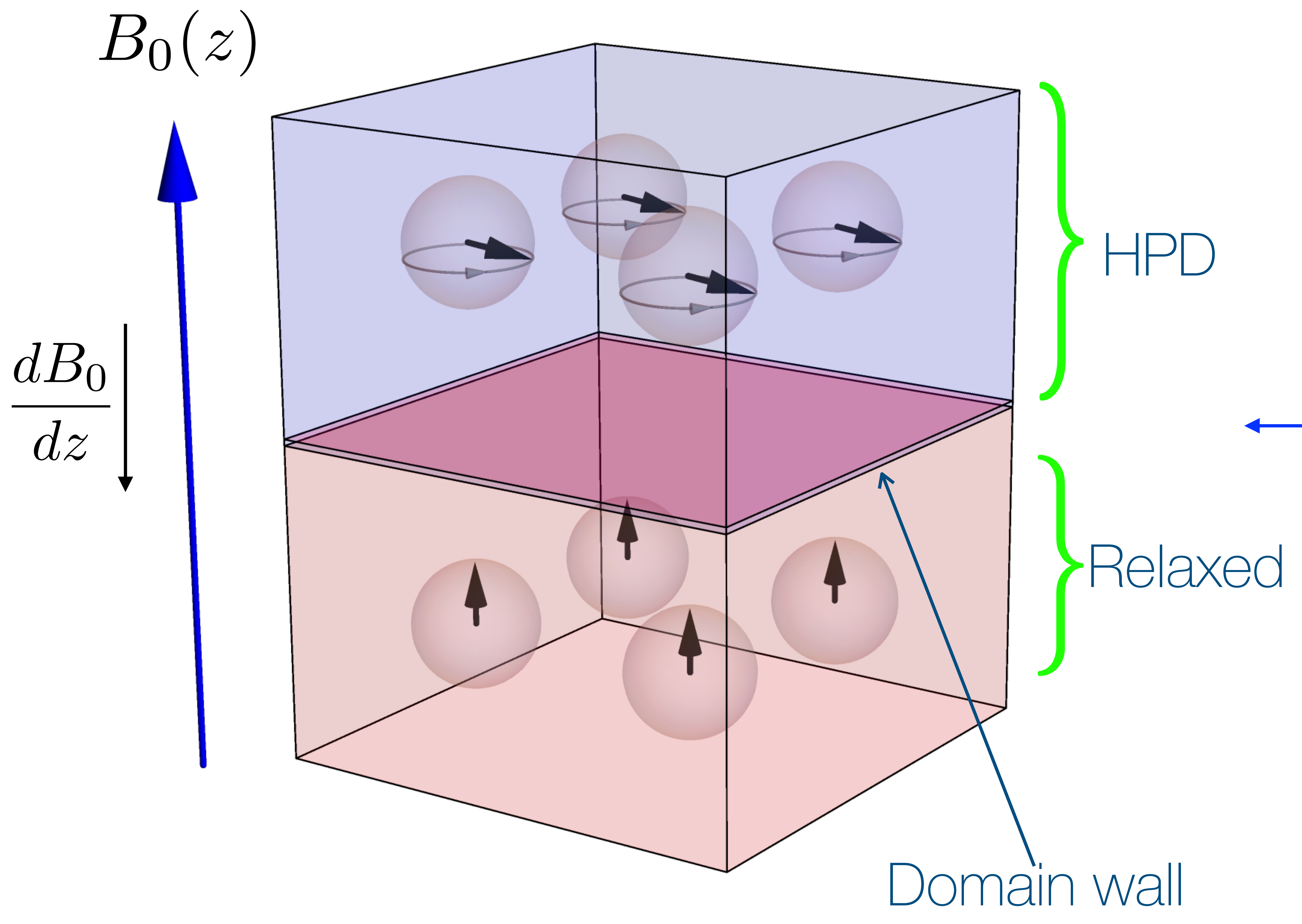
SUSTech

Constraints on axion nucleon coupling



[C. O'Hare, Axion Limit Plotter]

NMR in the homogeneous precession domain of ^{3}He-B



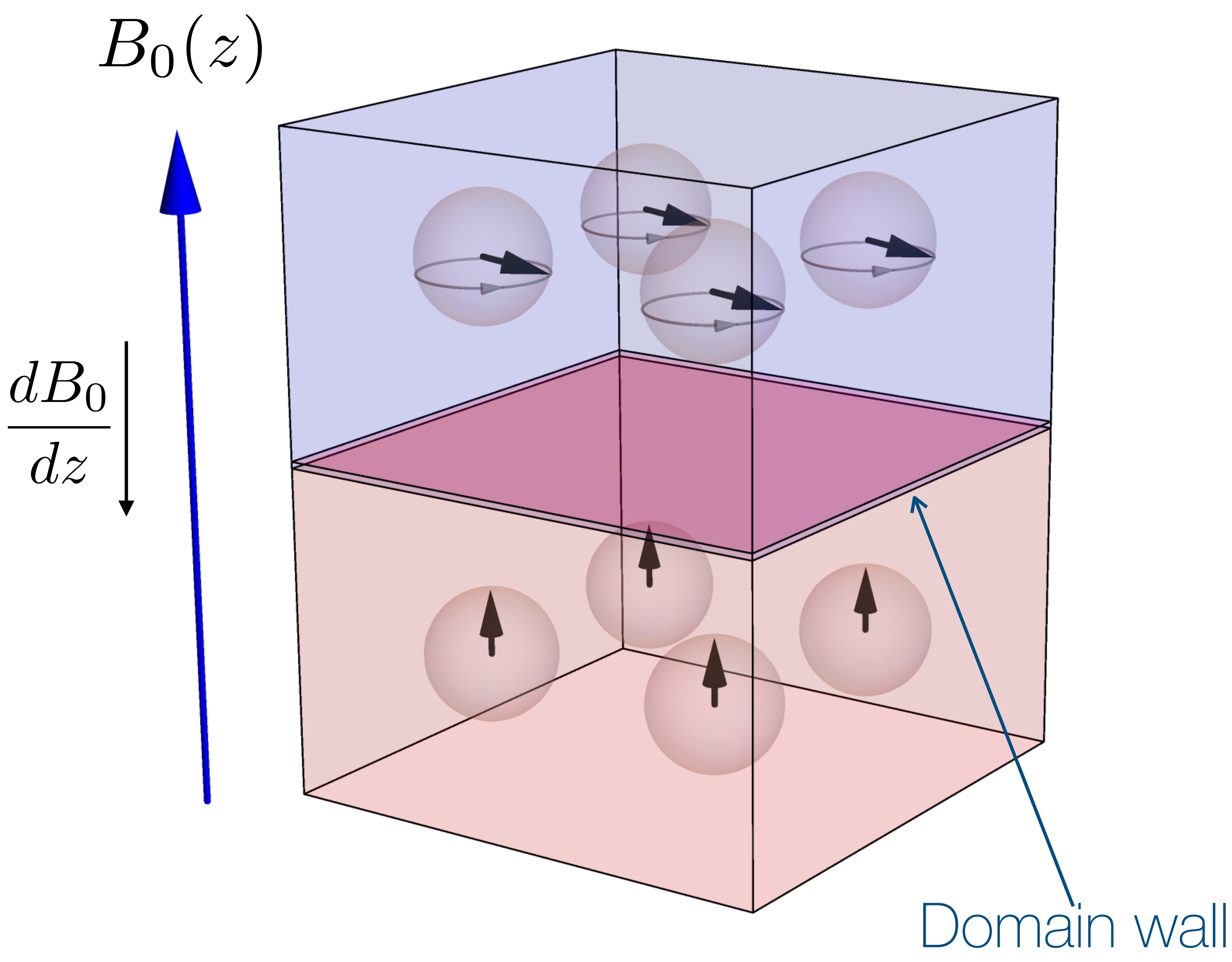
coherent precession
at fixed angle $\beta_0 = \cos^{-1}(-1/4)$
and same frequency

$$\omega_L(z_0) = \gamma B_0(z_0)$$

BEC of N Magnons

Axion wind pumps magnons into HPD

$$\vec{B}_{a_{\rm DM}} \sim B_a \cos(m_a t + \phi)$$

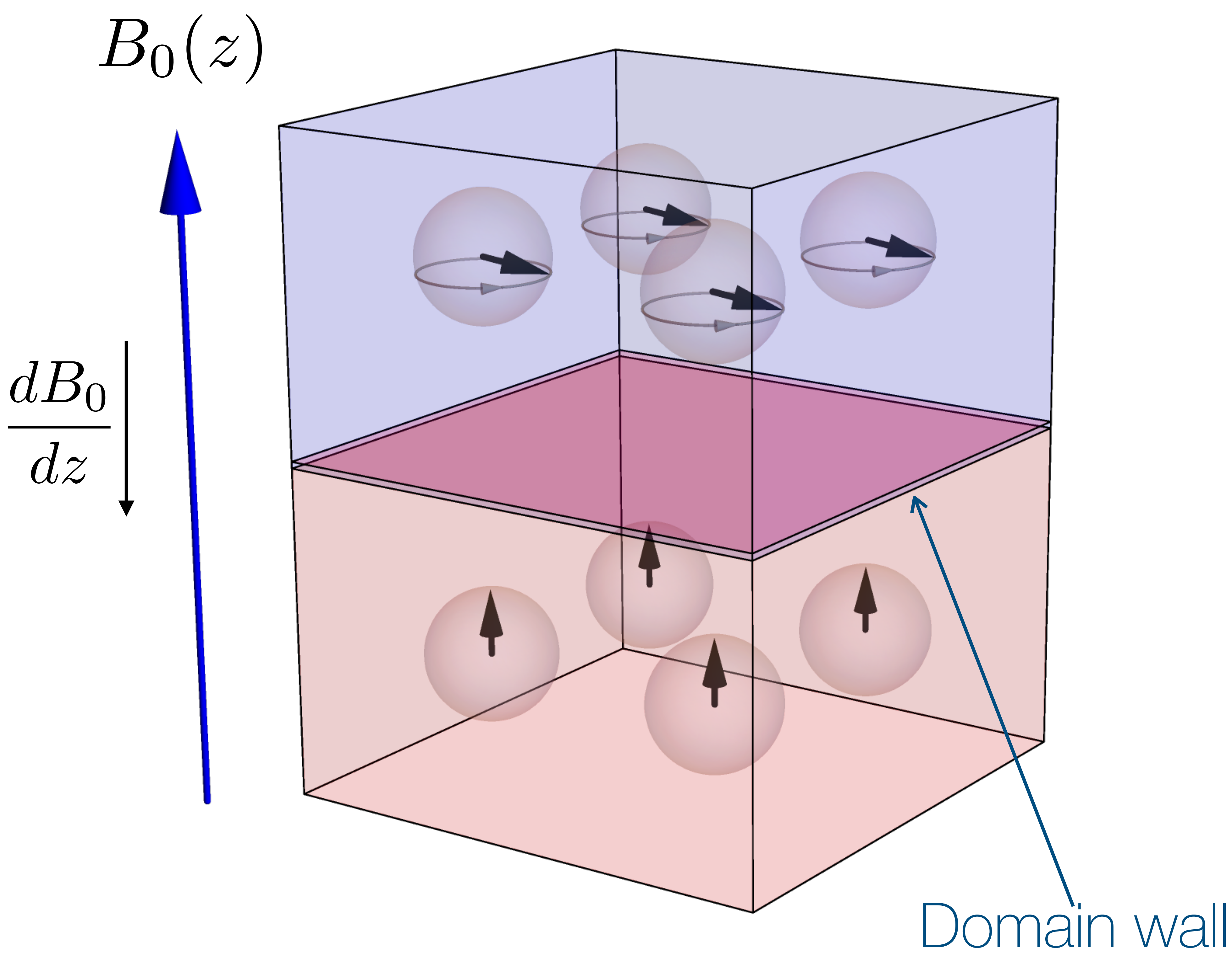


$$\frac{1}{V_{HPD}}\frac{dV_{HPD}}{dt} \sim -\frac{1}{T_1} - B_a \cos(m_a t + \phi_a) \sin(\omega_L(t) t)$$

Assuming transverse axion wind

Axion wind pumps magnons into HPD

$$\vec{B}_{a_{\rm DM}} \sim B_a \cos(m_a t + \phi)$$



Assuming transverse axion wind

$$\frac{1}{V_{HPD}}\frac{dV_{HPD}}{dt} \sim -\frac{1}{T_1} - B_a \cos(m_a t + \phi_a) \sin\left(\omega_L(t) t\right)$$

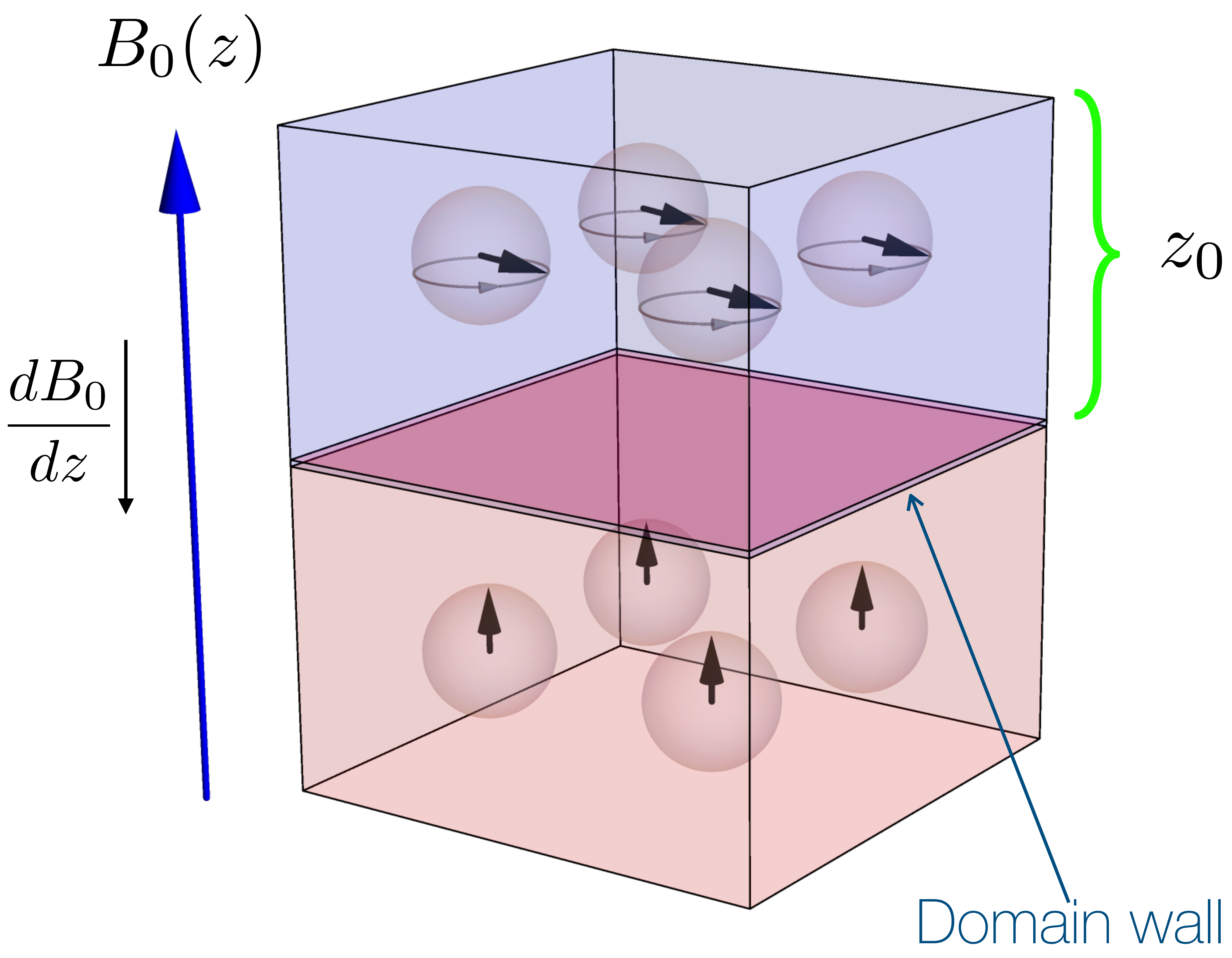
$$\omega_L(t) = m_a \pm \Delta m_a$$

$$\Delta V_{\rm HPD}\Big|_{\rm resonance} \sim B_a \tau_a$$

axion coherence time

Signal is a frequency shift

$$\vec{B}_{a_{\rm DM}} \sim B_a \cos(m_a t + \phi)$$

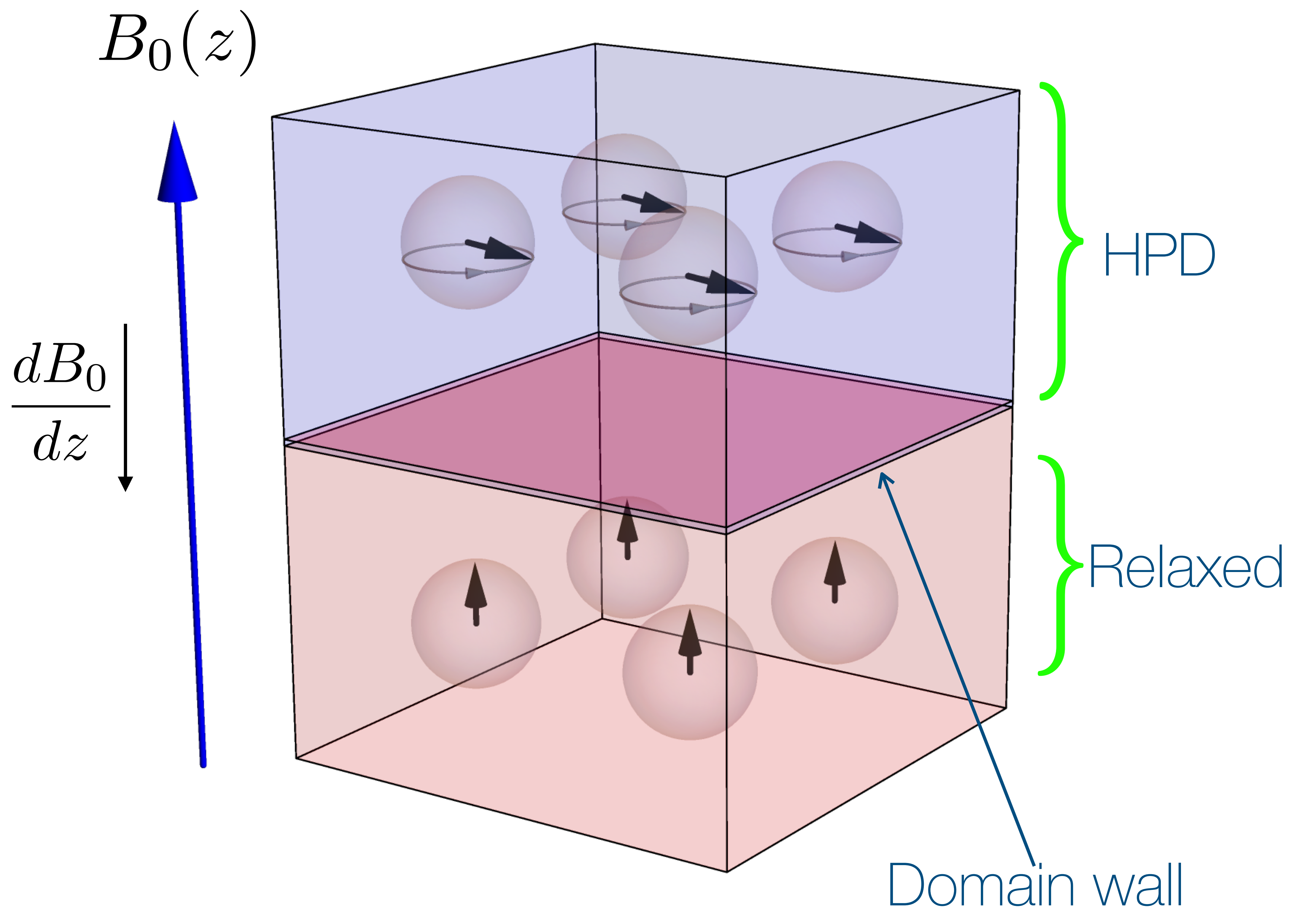


$$\frac{1}{V_{HPD}}\frac{dV_{HPD}}{dt} \sim -\frac{1}{T_1} - B_a \cos(m_a t + \phi_a) \sin\left(\omega_L(t) t\right)$$

$$\Delta V_{\rm HPD}\Big|_{\rm resonance} \sim B_a \tau_a$$

$$\Delta V_{\rm HPD} \to \Delta\omega_L \sim \omega_L \frac{z_0 \nabla_z B}{B_0} \frac{\Delta V_{\rm HPD}}{V_0}$$

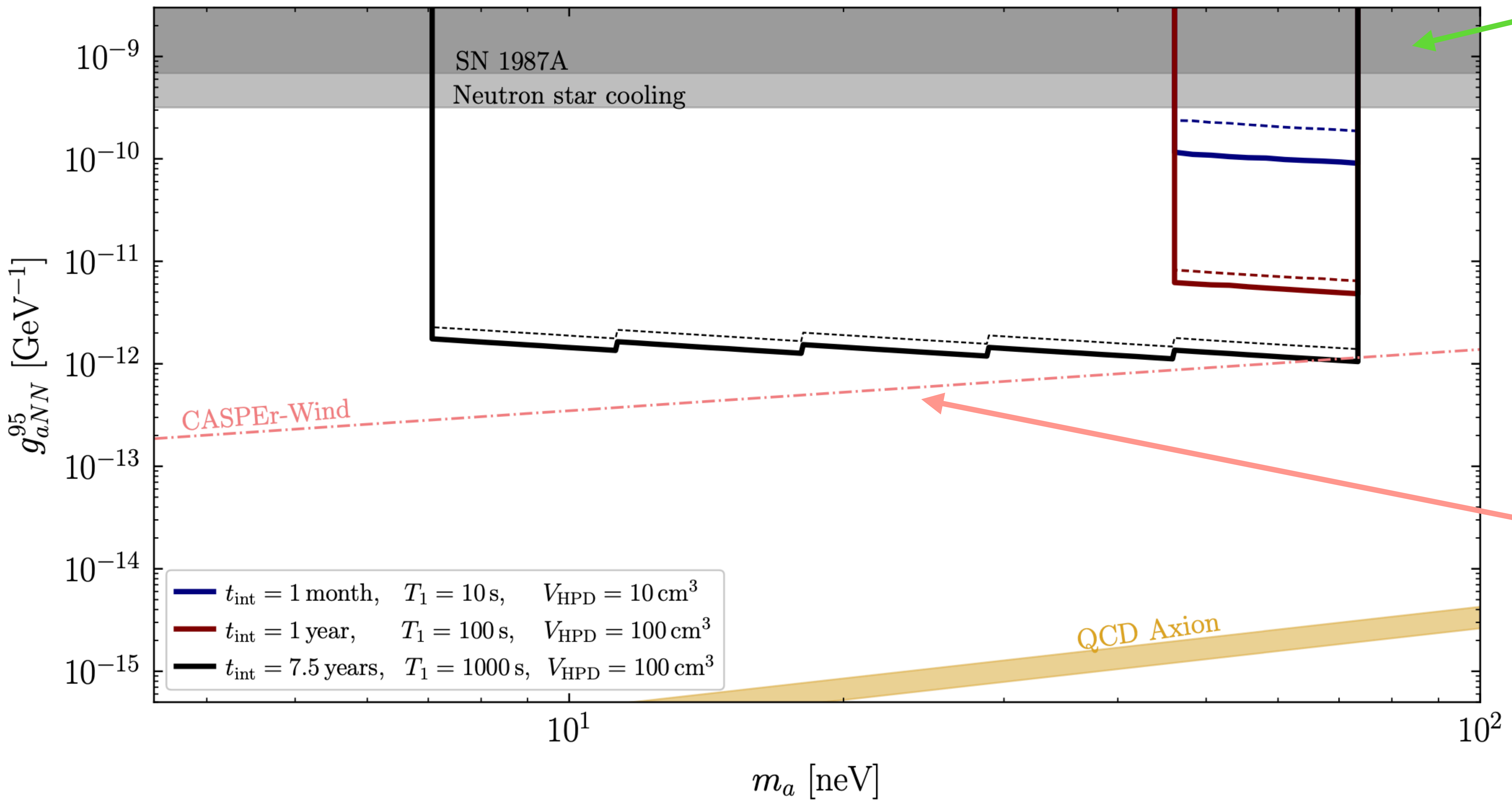
NMR in the homogeneous precession domain of ^{3}He-B



- Superfluid phase of helium 3, much more longer lived NMR signal
- Allows a small inhomogeneity in B_0, can scan in a single setup of the experiment.

Projected sensitivity of NMR using the HPD of ^{3}He-B

$$\mathrm{SNR} \approx \gamma B_a \sqrt{V_{\mathrm{HPD}} n_M} (T_1 t_{\mathrm{int}})^{1/4} \times \min[\sqrt{t_r}, \sqrt{\tau_a}].$$



Astrophysical bounds

$\mathrm{SNR} \propto g_{aN} \sqrt{V_{\mathrm{HPD}}}\, t_{\mathrm{int}}^{1/4}$

Assuming magnon shot noise, measurement noise, clock noise

Xe NMR proposal

Plan of the talk

- Introduction
- eV axion searches using integrated photonics
- neV axion searches using superfluid ^{3}He
- feV axion searches using levitated ferromagnet

feV axion searches using levitated ferromagnet

Axion electron coupling $$B_a \sim \frac{g_{ae}}{e}\sqrt{\rho_{\rm DM}}v_{\rm DM} \sim 10^{-18}{\rm T}\left(\frac{g_{ae}}{10^{-10}}\right)$$

SUSTech

feV axion searches using levitated ferromagnet

In progress

with P. Yin (Nanjing U);
Y. He (CUHK); Y. Mo (Sustech)

Axion electron coupling $$B_a \sim \frac{g_{ae}}{e}\sqrt{\rho_{\mathrm{DM}}}v_{\mathrm{DM}} \sim 10^{-18}\mathrm{T}\left(\frac{g_{ae}}{10^{-10}}\right)$$

Phys. Rev. D 94, 082005 (2016)

Budker et al.

Phys. Rev. D 110, 115029 (2024)

Wei Ji et al.

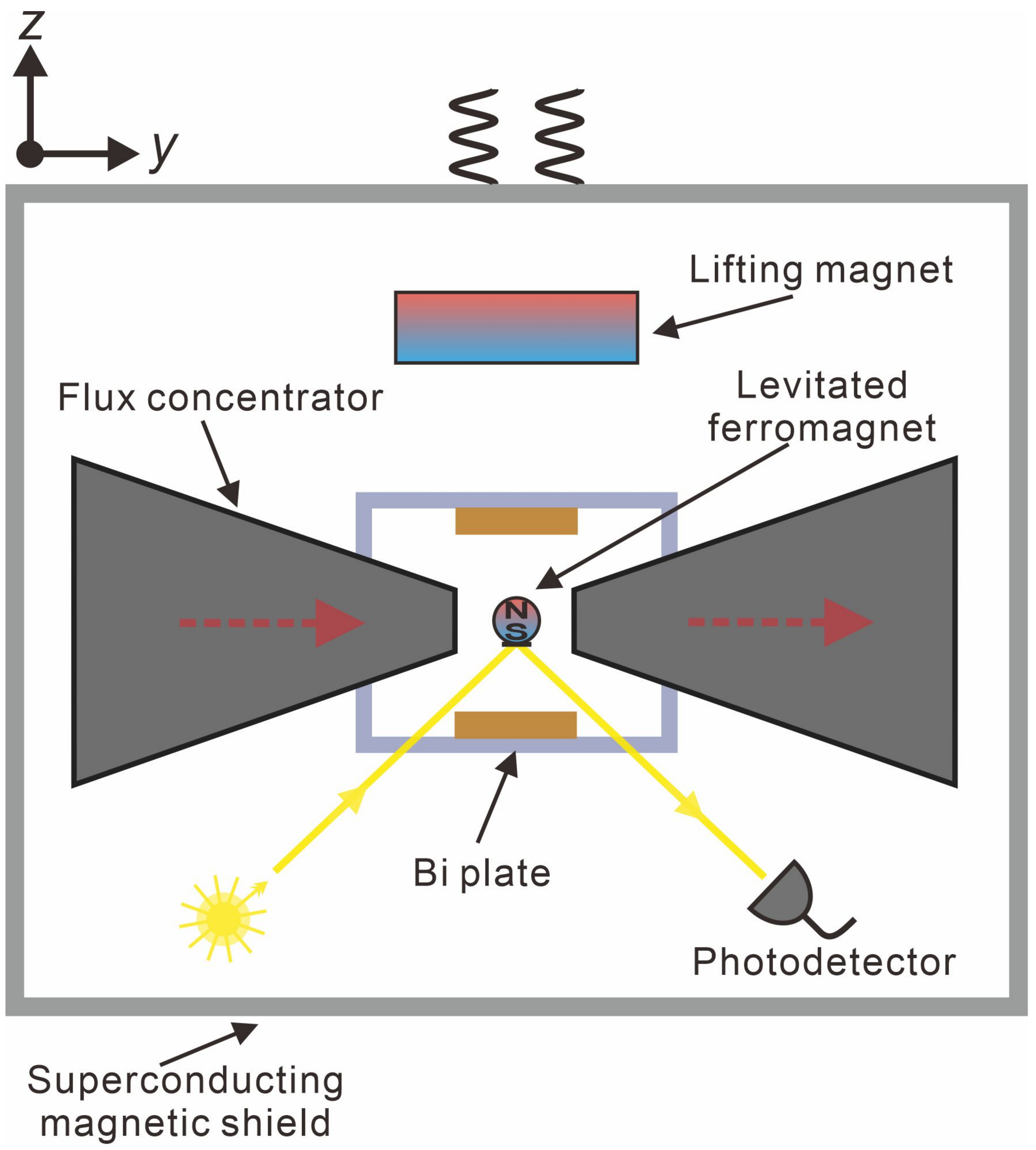
Axion wind could provide a remanent magnetization

In progress

with P. Yin (Nanjing U);
Y. He (CUHK); Y. Mo (Sustech)

$$\mathbf{B} = \mathbf{M}(\mathbf{H}) + \mathbf{H} + \mathbf{M}_r$$

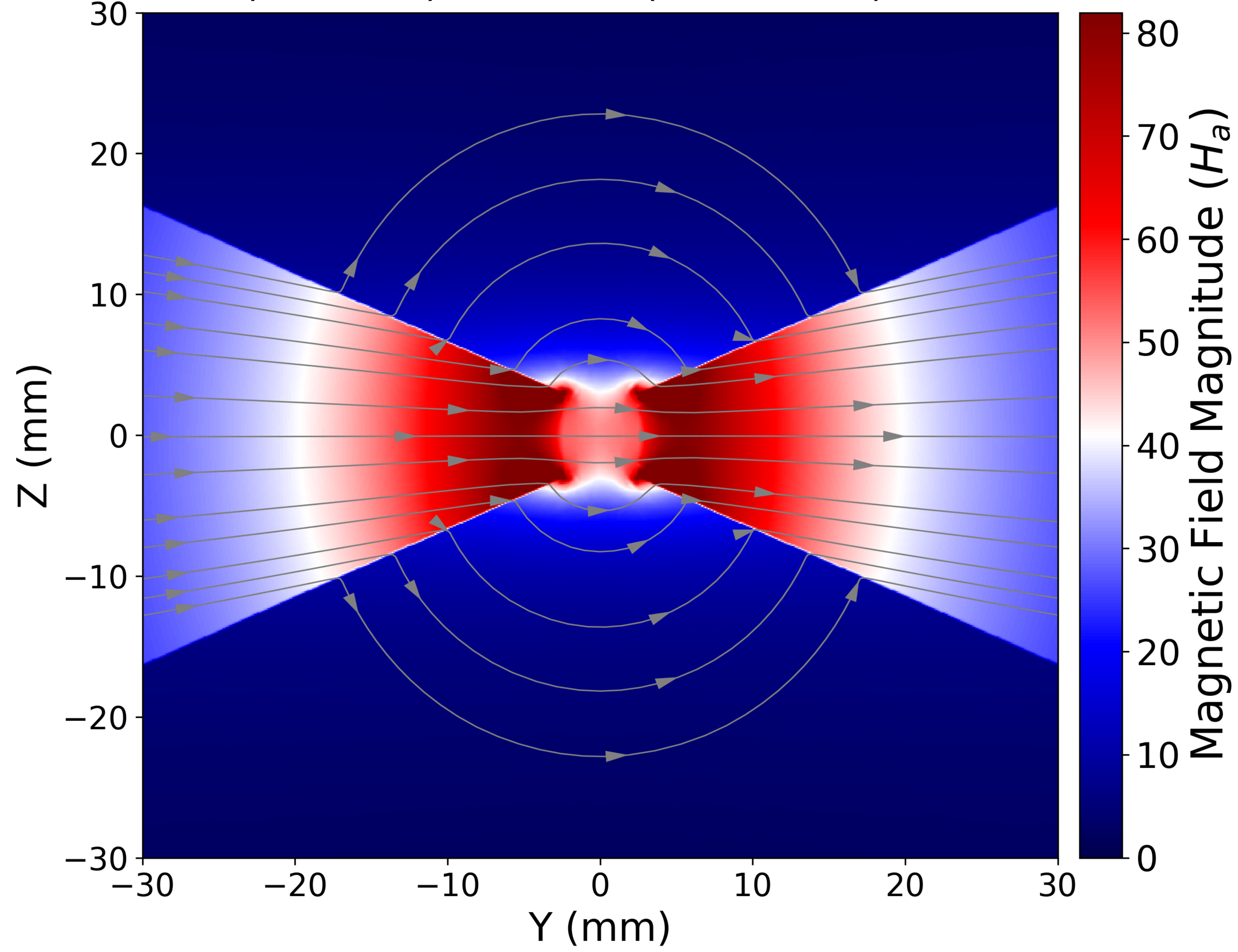
This can come from axion dark matter!

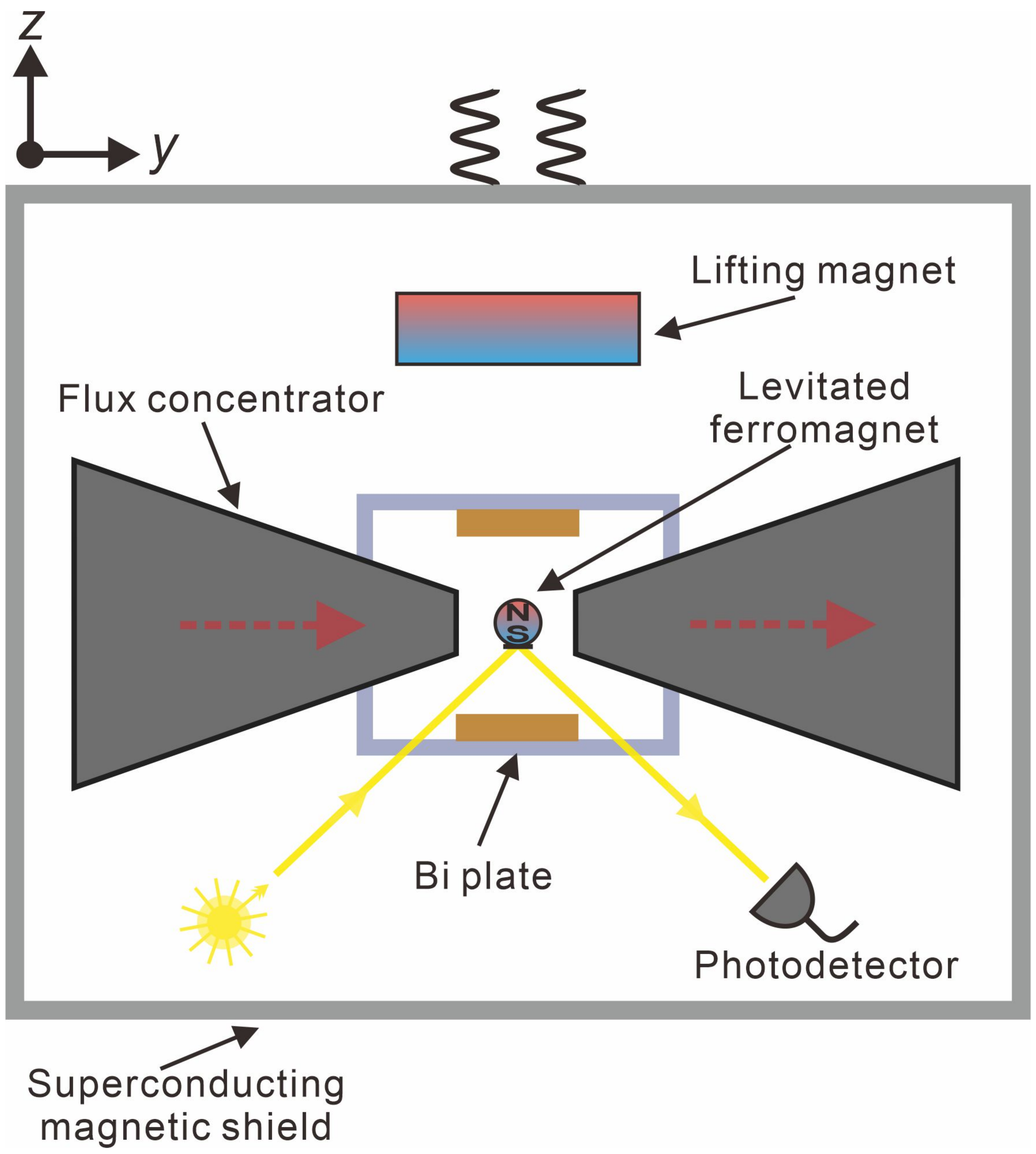


Axion wind could provide a remanent magnetization

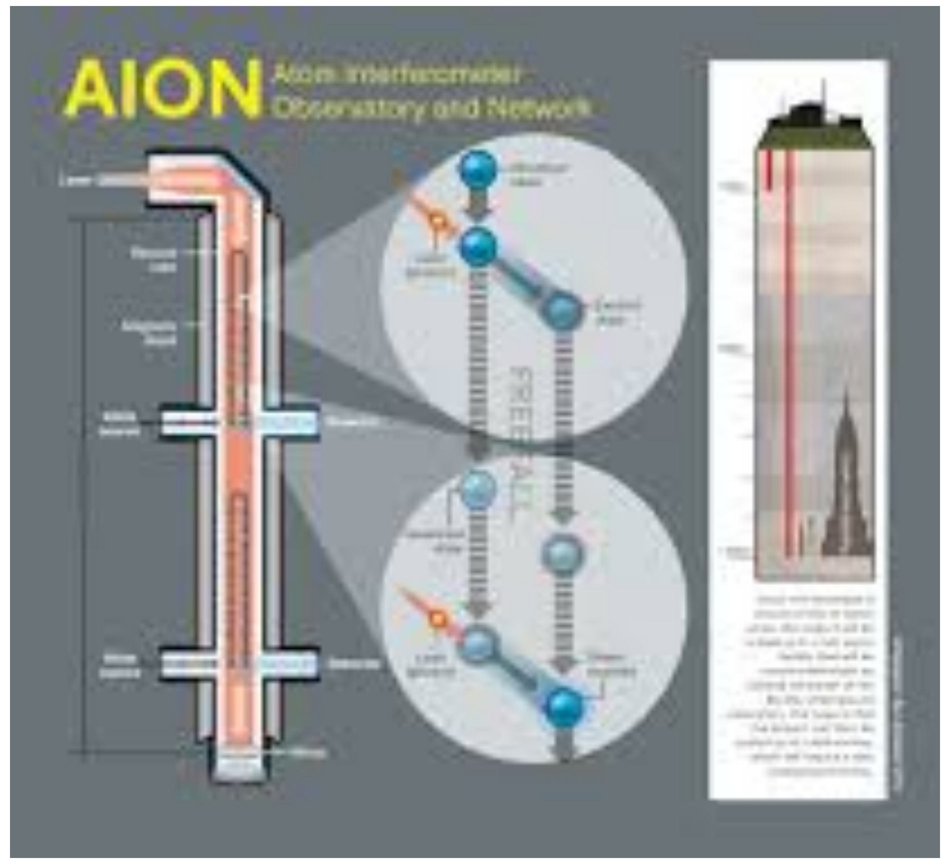
In progress

with P. Yin (Nanjing U); Y. He (CUHK); Y. Mo (Sustech)

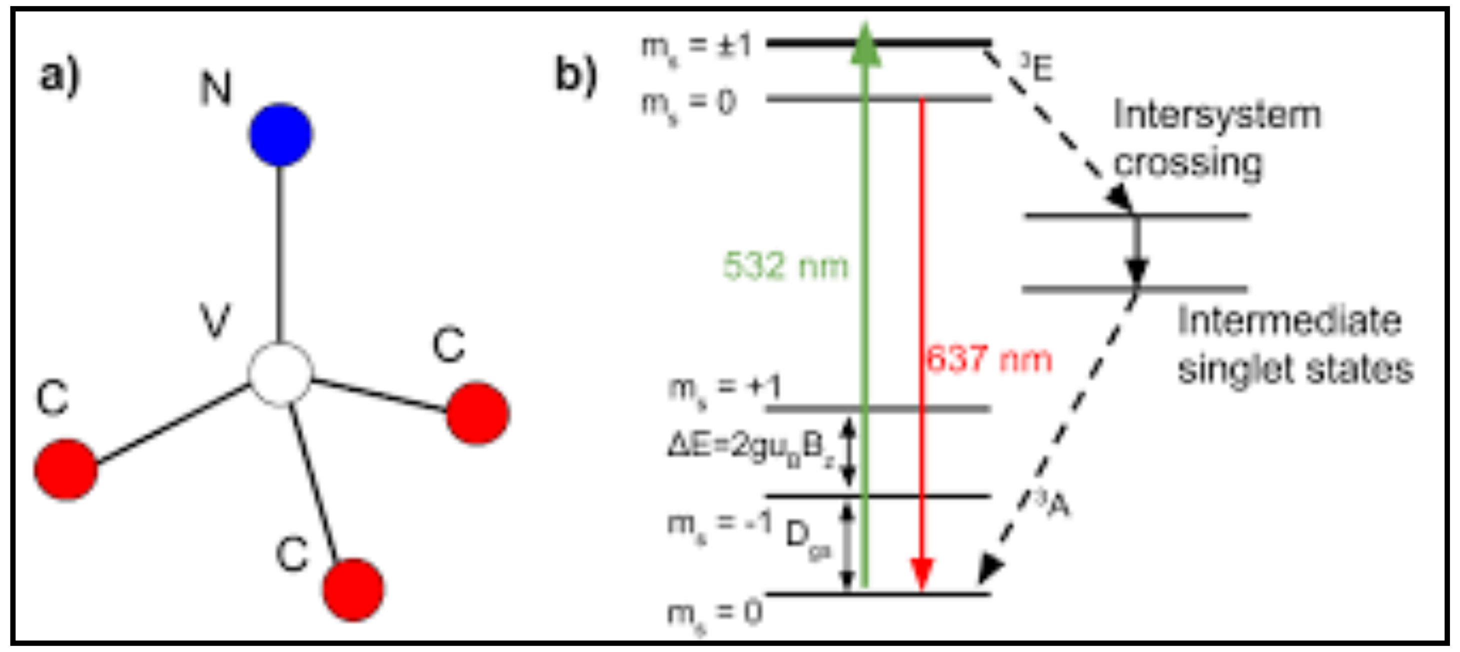




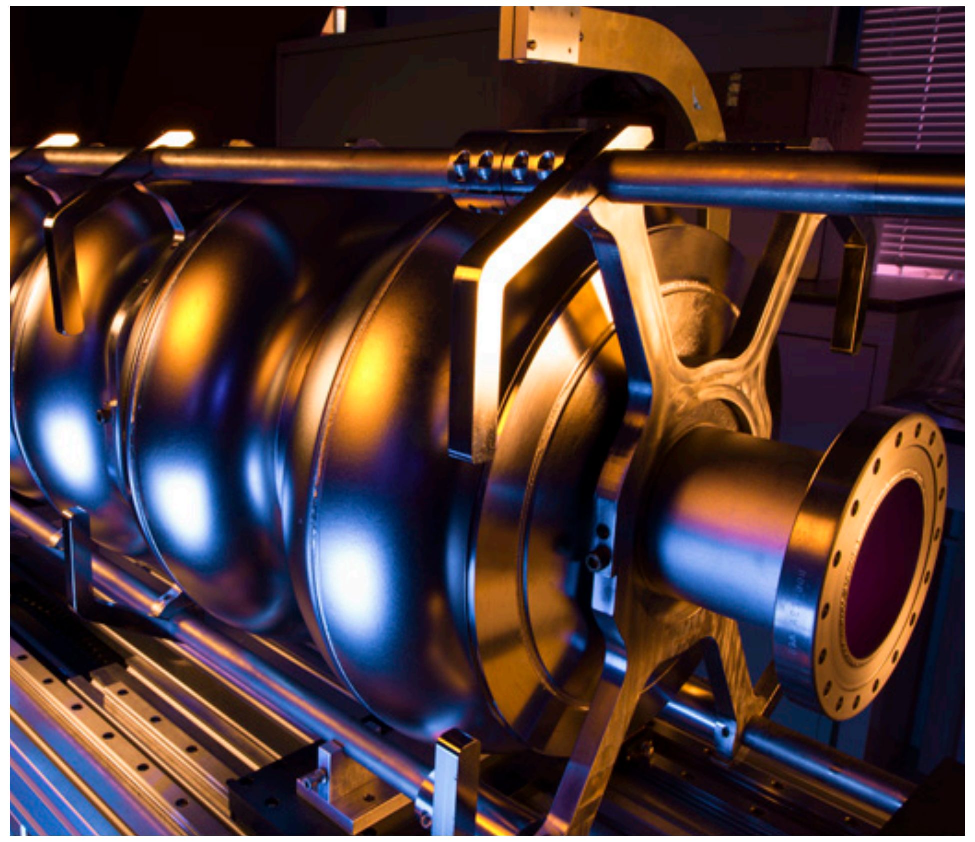
Future of quantum sensing in axion search



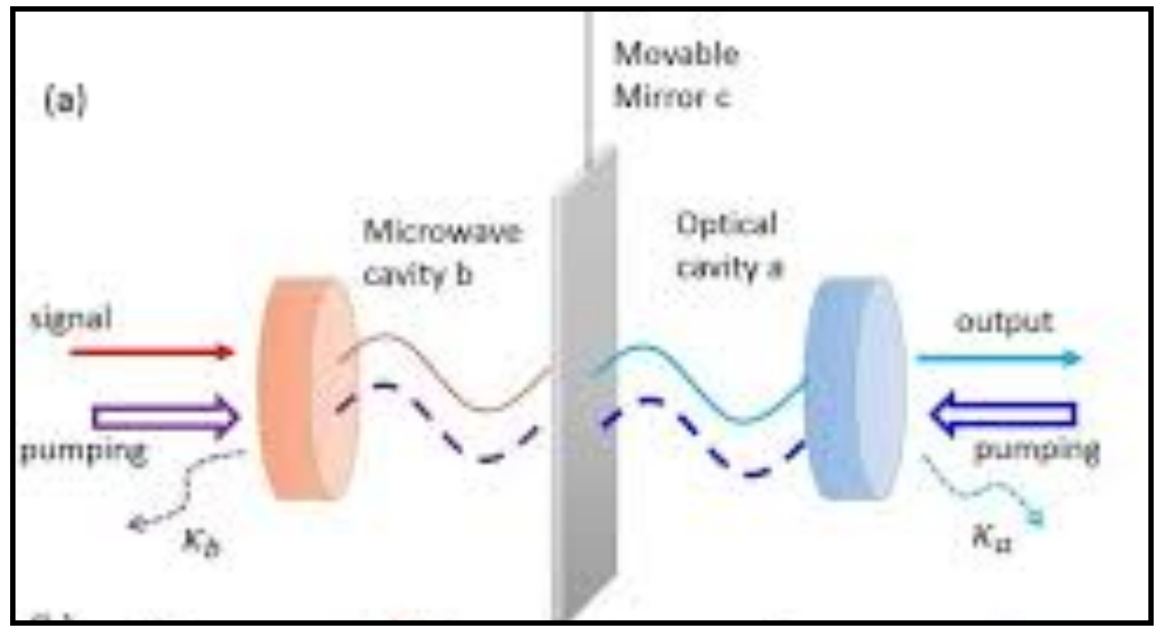
Atom interferometer



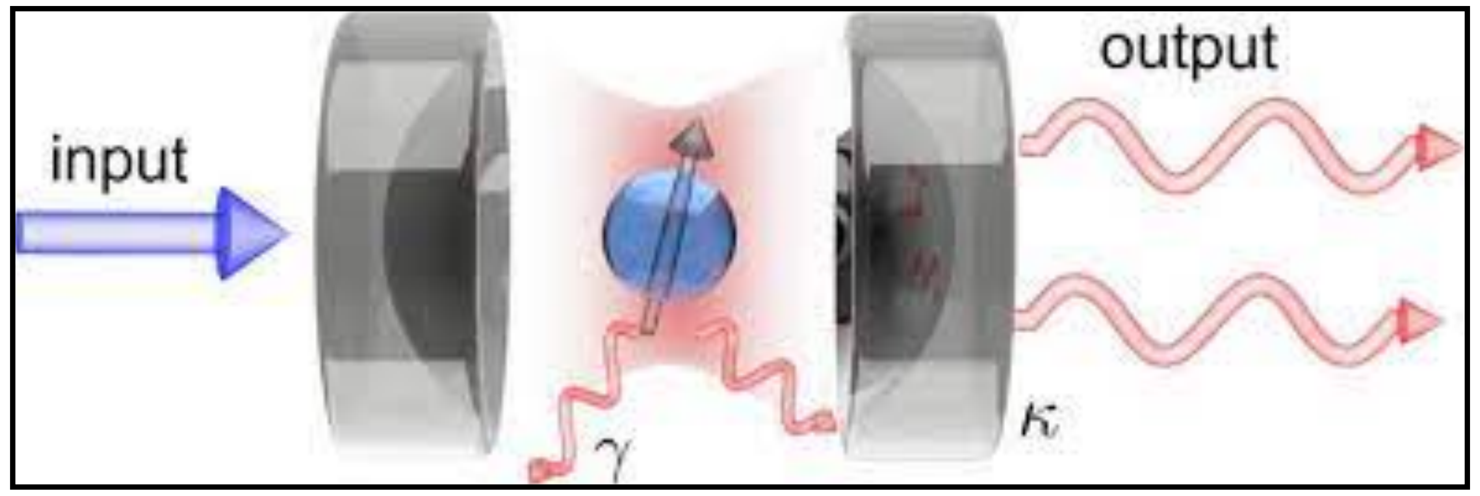
NV Center



Superconducting RF cavity



$$a_{\rm DM} \sim A\cos(m_{\rm DM}t)$$



Optomechanical sensor

Cavity QED

SUSTech

Conclusion

- Axion DM masses may span 20 orders of magnitude, thus different masses have to be probed using different experimental methods.
- Different axion couplings enable us to deploy different sensing techniques.
- Exciting time to apply quantum sensing to axion DM searches!

SUSTech

Backups

Axion Dark Matter

Basic Properties:

- Bosonic, high occupation number, behave like a classical field
- Velocity ~100 km/sec

$$a_{\mathrm{DM}}(t) \sim A\cos\left(\omega t - \mathbf{k}\cdot\mathbf{x}\right) \sim A\cos(m_a t)$$

$$A \leftarrow \frac{\sqrt{\rho_{\mathrm{DM}}}}{m_a} \qquad \omega \leftarrow m_a + \frac{1}{2}m_a v^2 \qquad \mathbf{k} \leftarrow m_a v$$

Example: Si-on-Insulator Photonic Crystal Ring Resonator

https://doi.org/10.1364/OL.39.001282

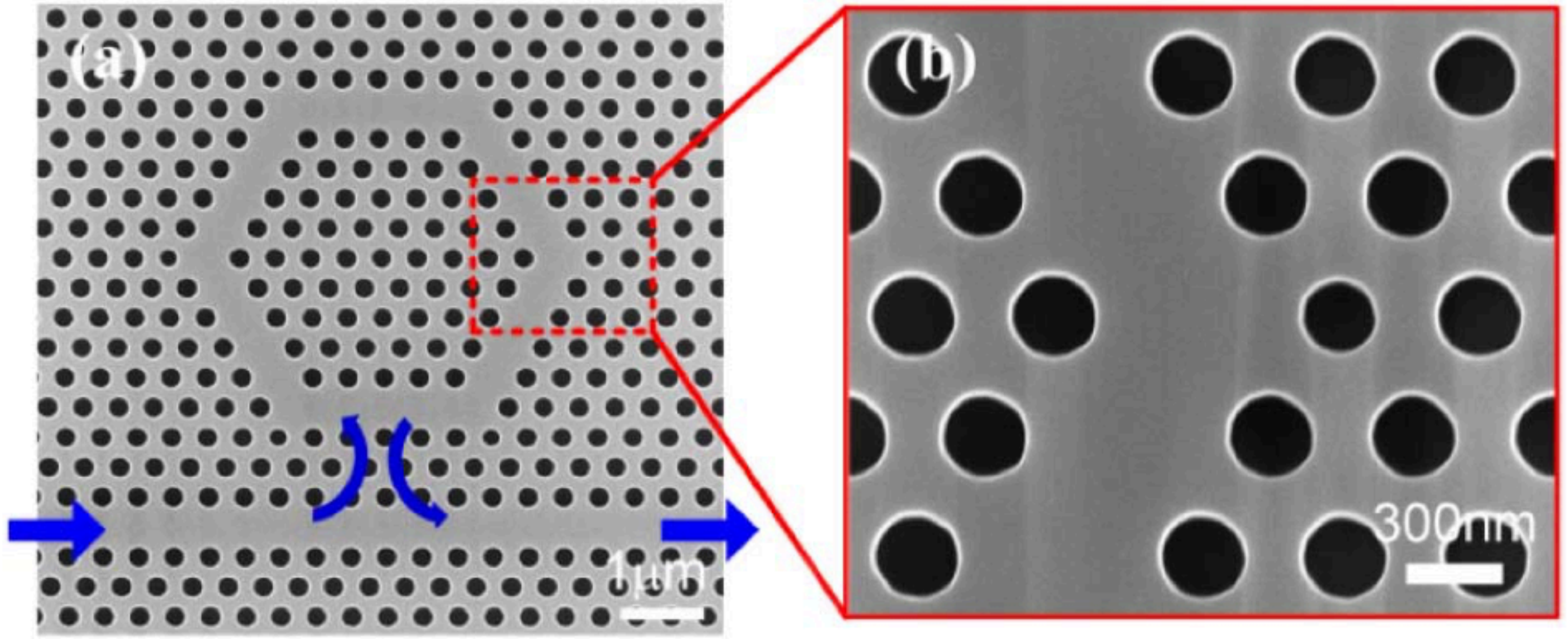
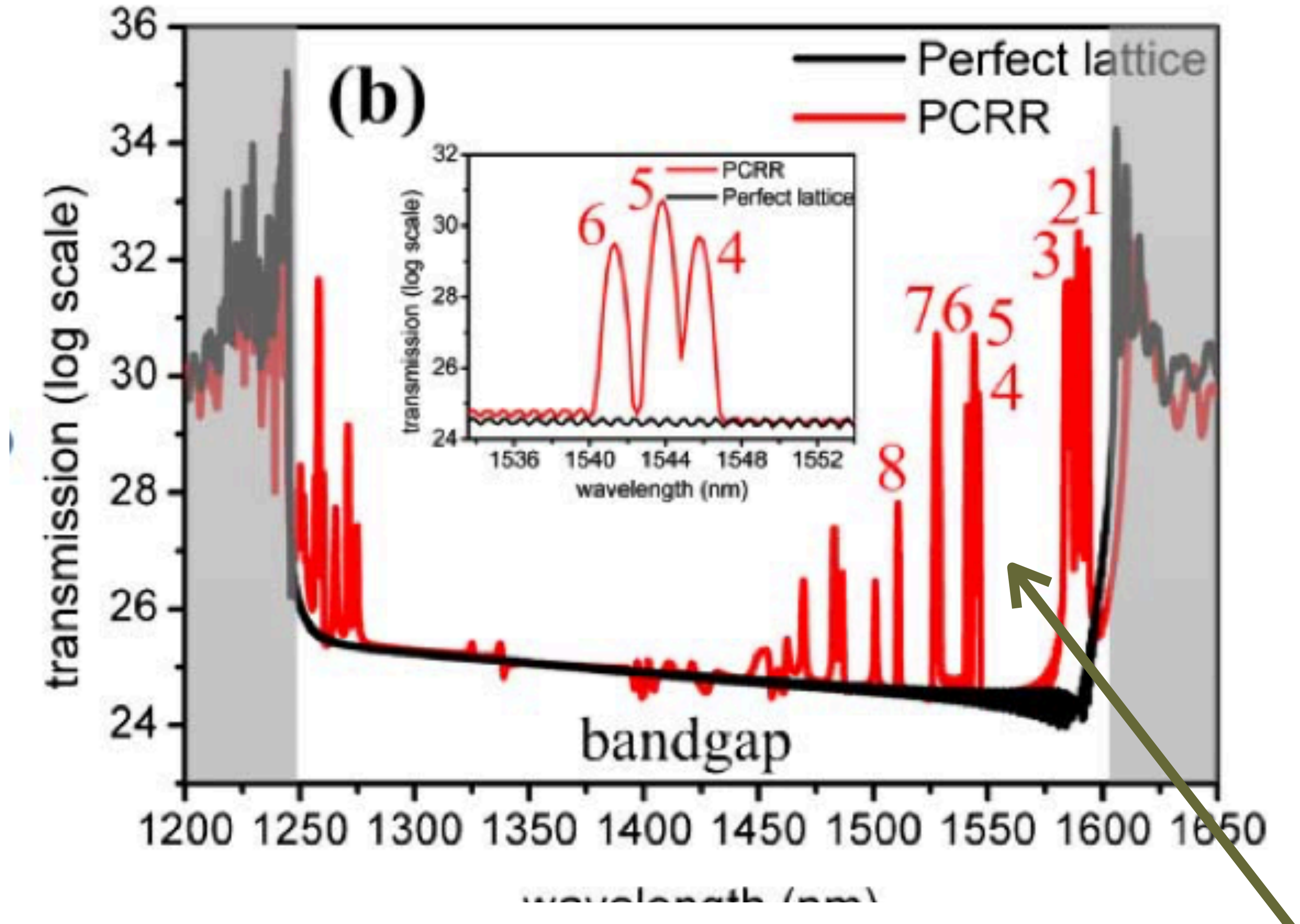
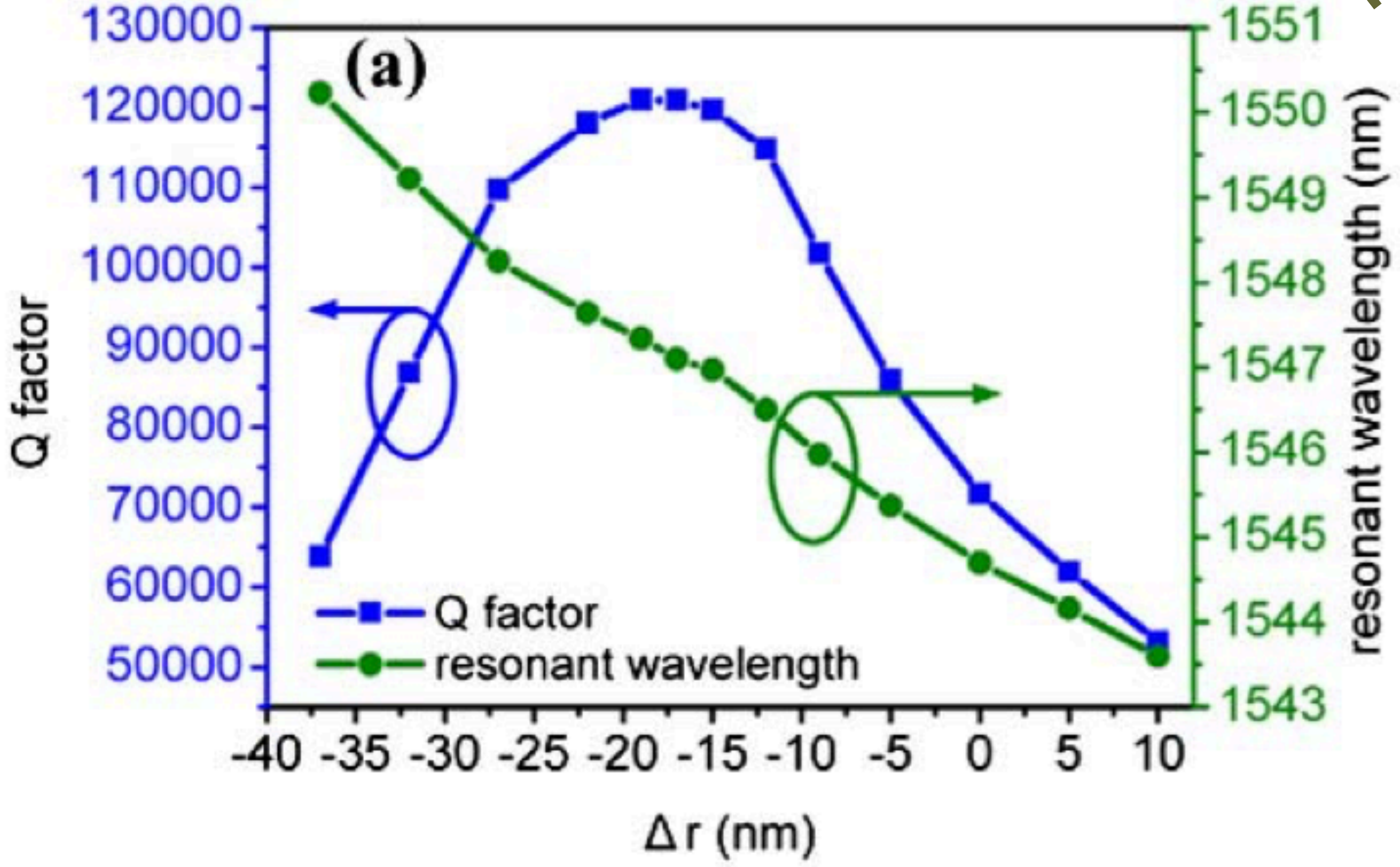


Fig. 4. (a) SEM image of the fabricated modified PCRR. (b) Magnified micrograph of the corner of the modified PCRR.

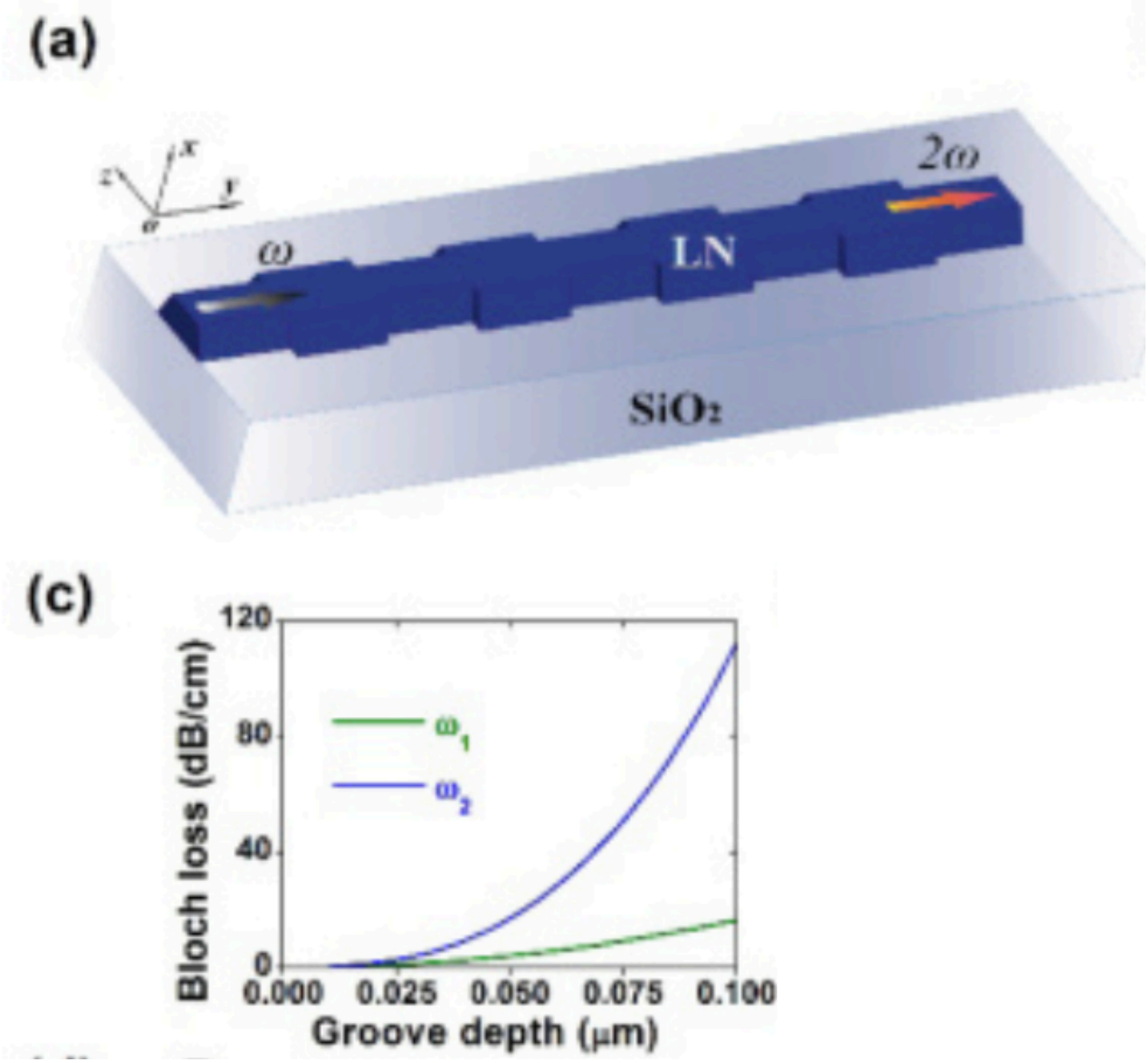


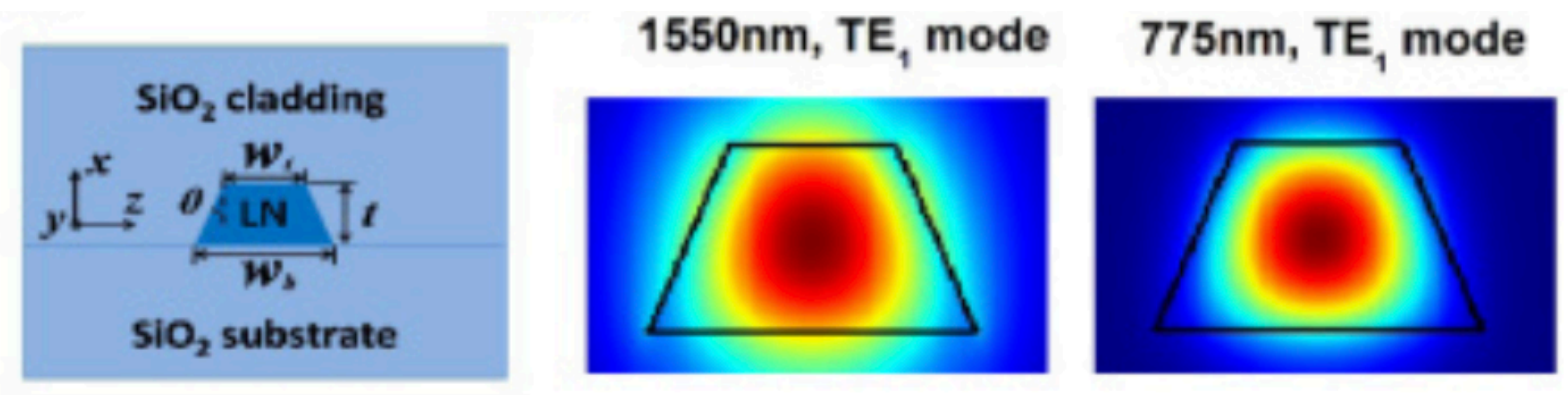


SUSTech

Example: Periodically Grooved LN-on-Insulator Waveguide

https://doi.org/10.1364/OE.25.006963





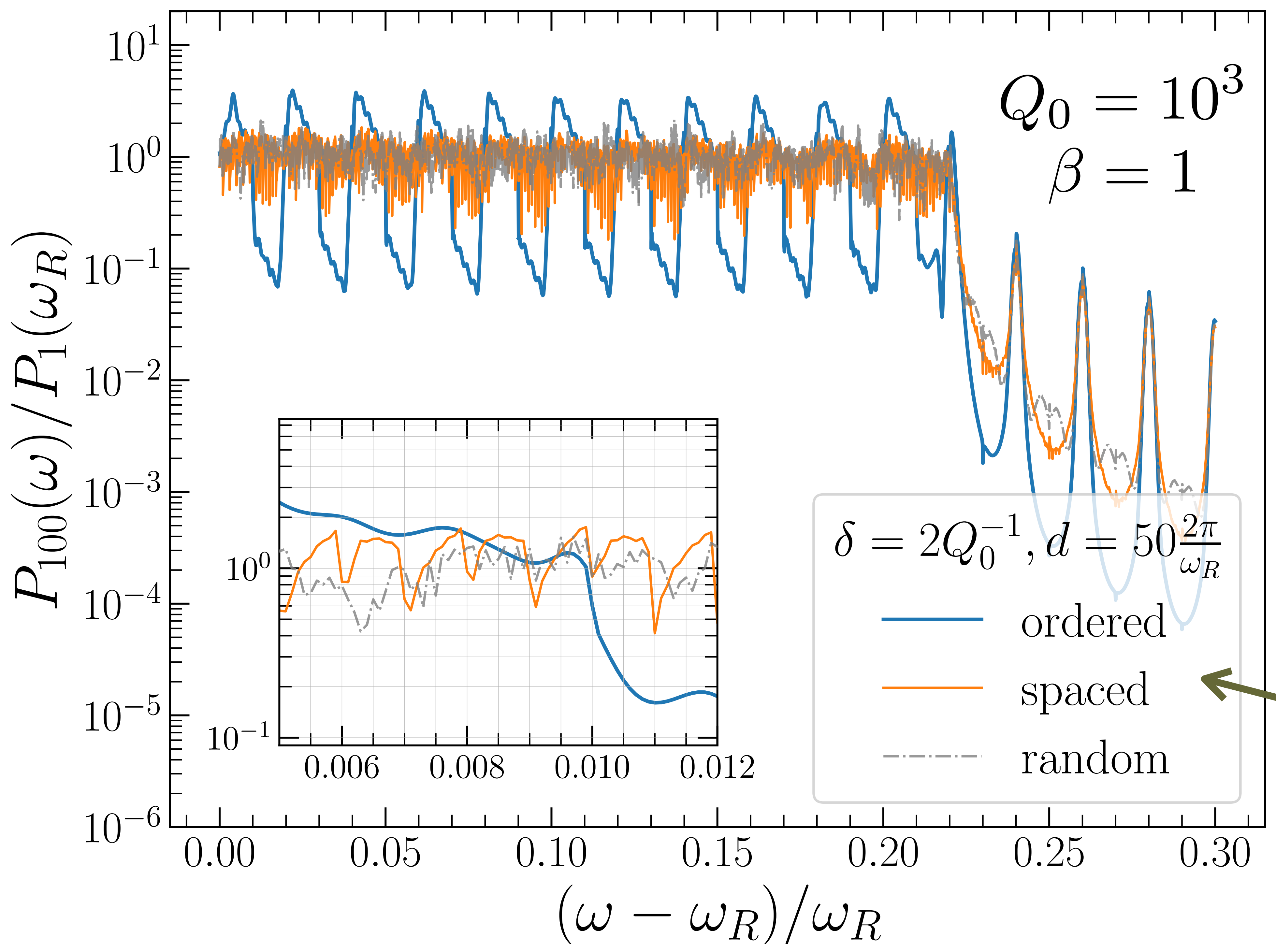
Q can be affected by:

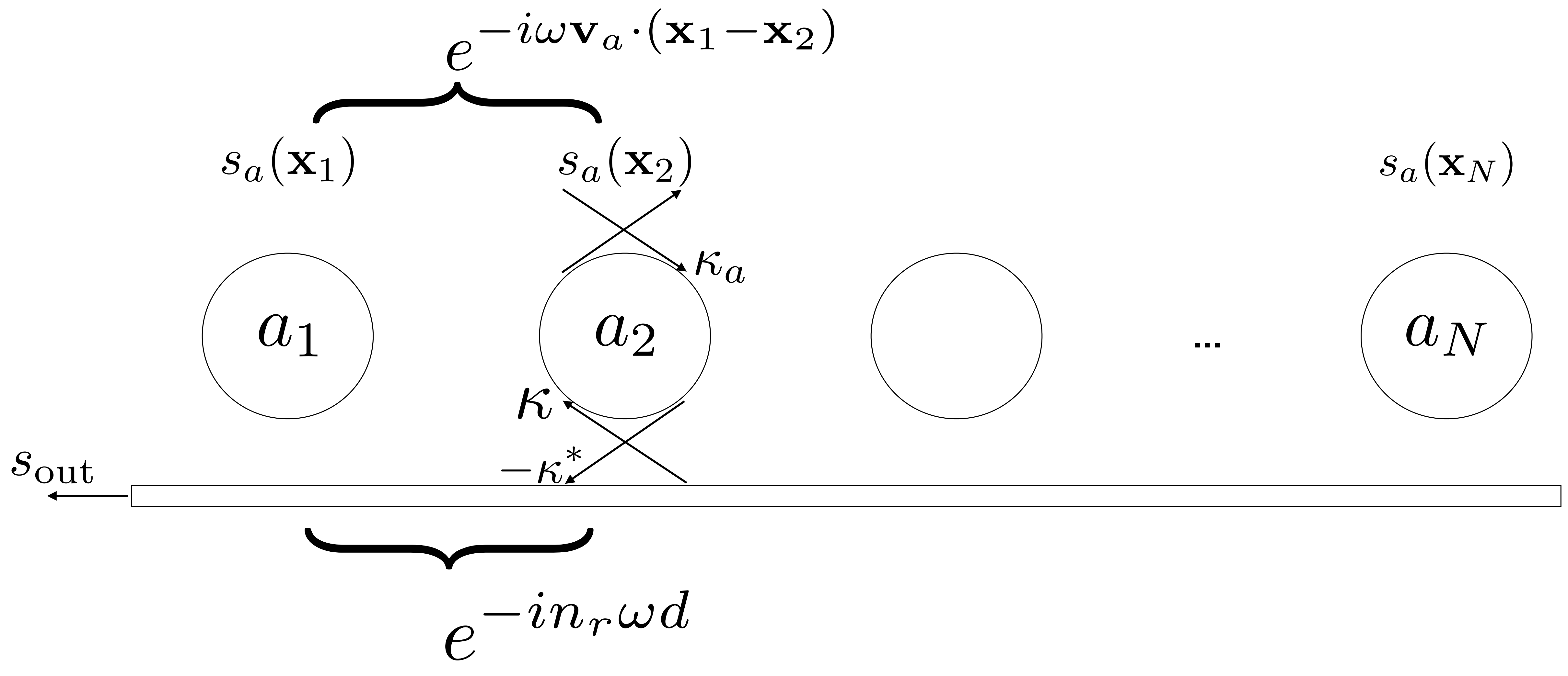
- Surface/volume scattering loss
- Bending/radiation loss
- Absorption by the material

$$Q \approx \frac{\pi n_{\rm eff}}{\alpha \lambda_0} \sim 10^3 \left(\frac{180\,\frac{\rm dB}{\rm cm}}{\mathcal{L}}\right)\left(\frac{1.5\mu{\rm m}}{\lambda_0}\right)\left(\frac{n_{\rm eff}}{2}\right)$$

Different Frequencies

$$\omega_R(1+\delta)^{i-1}, i = 1, 2, \cdots, N$$

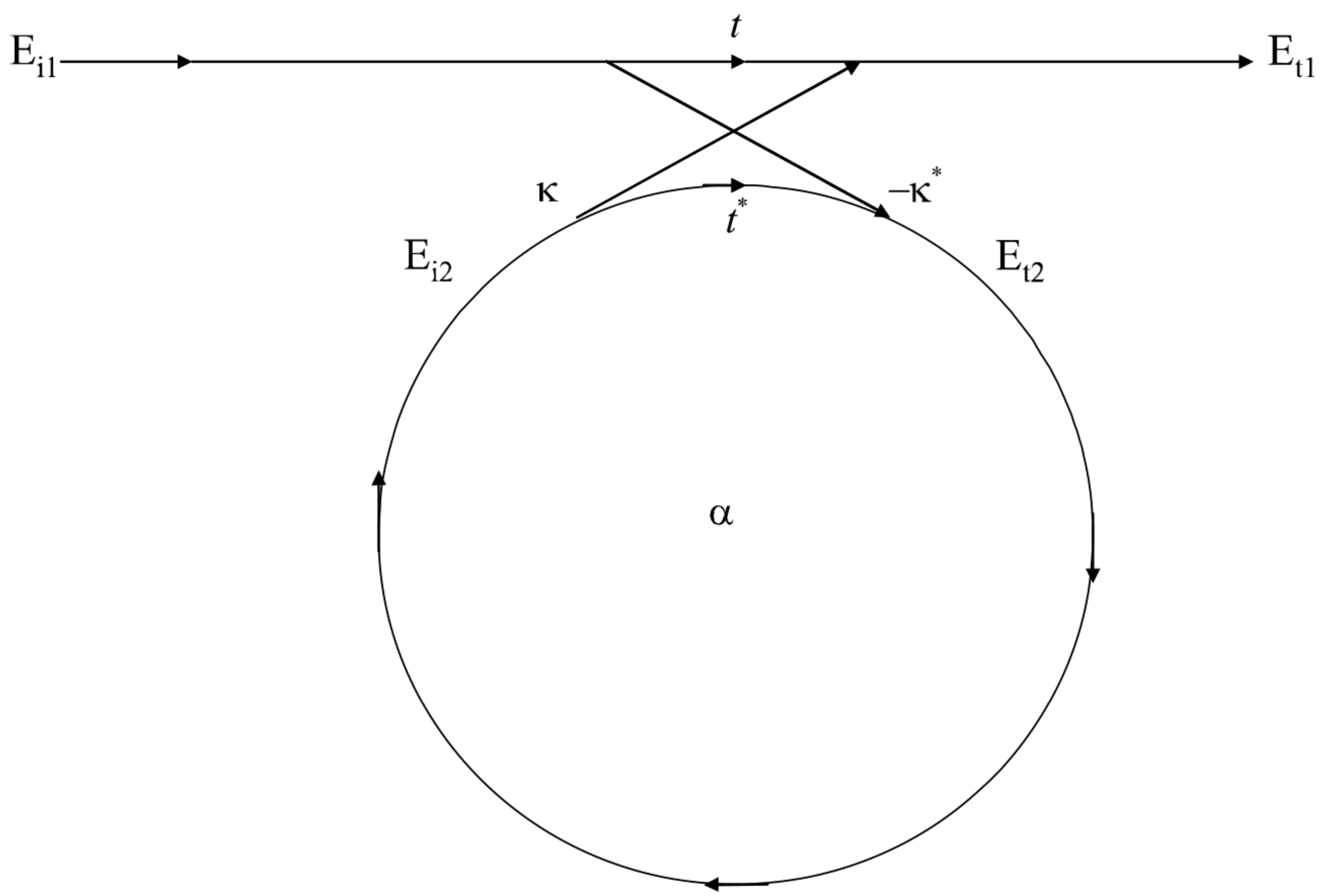




For lth resonator $\omega_R(1+\delta)^{g(l)}$

$$g(l) = \begin{cases} \lfloor \frac{l}{10} \rfloor + \frac{N}{10}((l \bmod 10) - 1) + 1 & l \bmod 10 \neq 0 \\ (l + 9N)/10 & l \bmod 10 = 0 \end{cases}$$

Ring Resonator

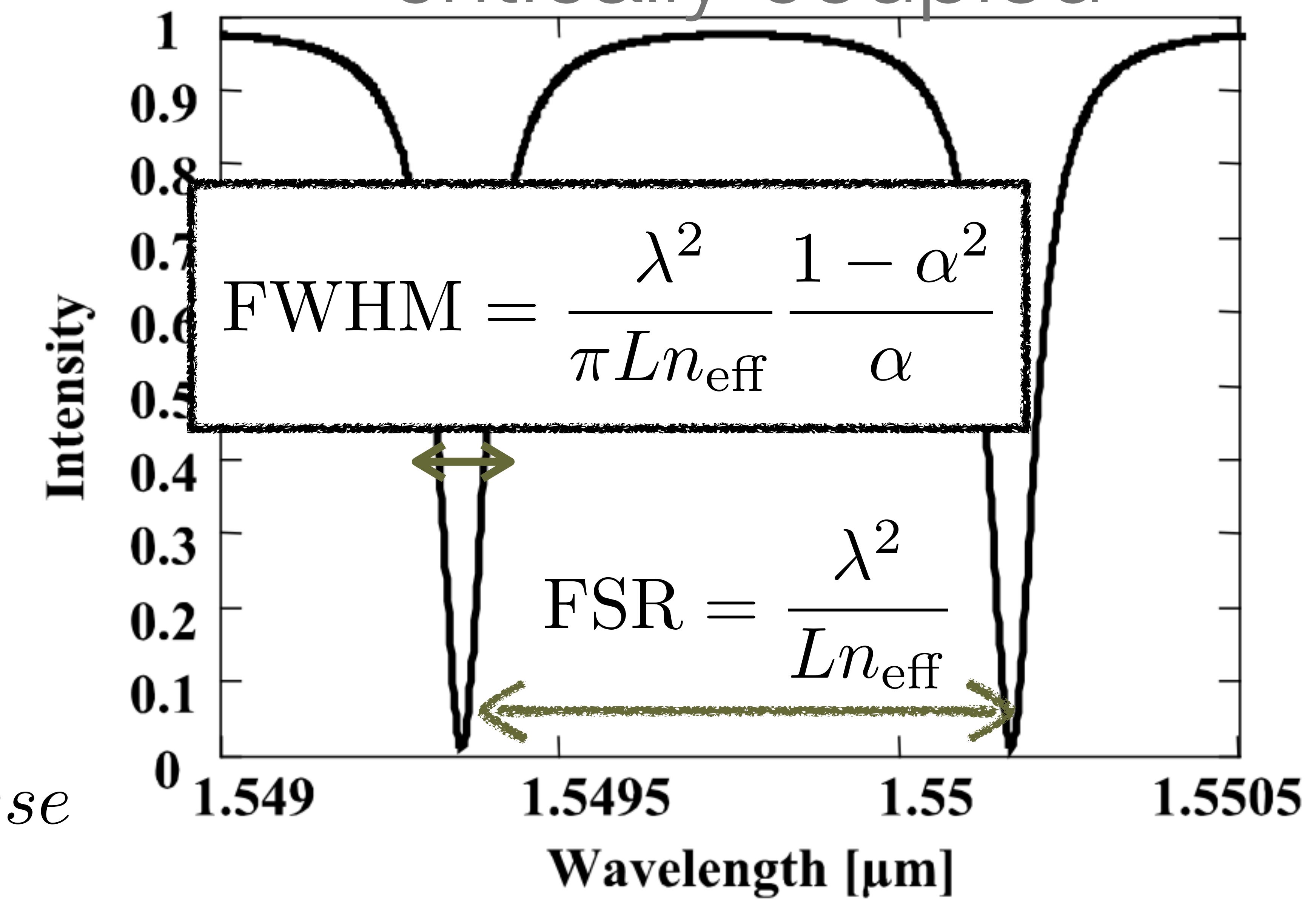


$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \qquad |\kappa^2| + |t^2| = 1$$

$$E_{i2} = \alpha \cdot e^{j\theta} E_{t2} \qquad \theta \approx n_{\text{eff}} \omega L$$

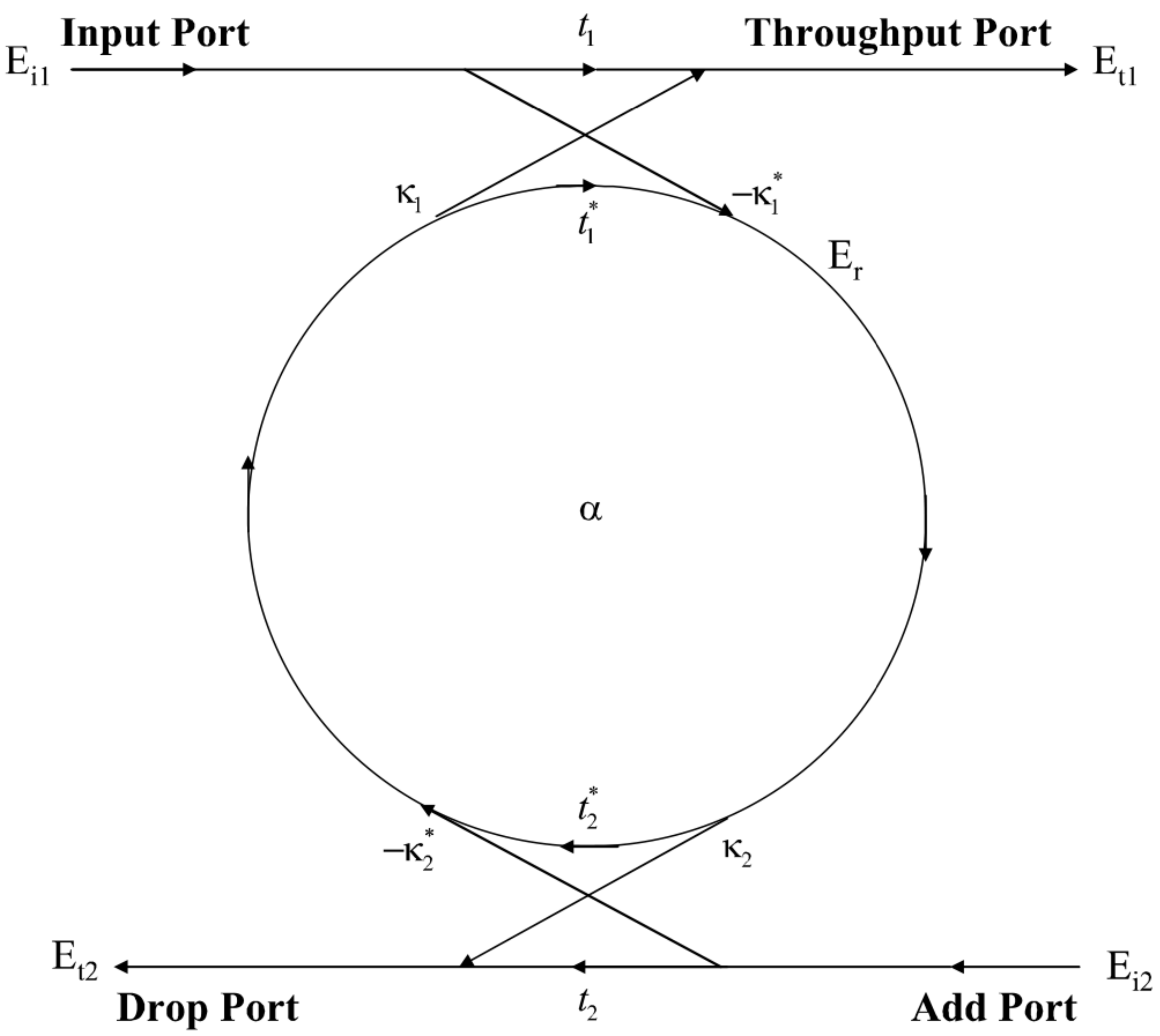
Loss

critically coupled



$$Finesse = \frac{\text{FSR}}{\text{FWHM}} = \frac{1-\alpha^2}{\alpha\pi} \qquad Q = \frac{\lambda}{\text{FWHM}} = \frac{n_{\text{eff}} L}{\lambda} finesse$$

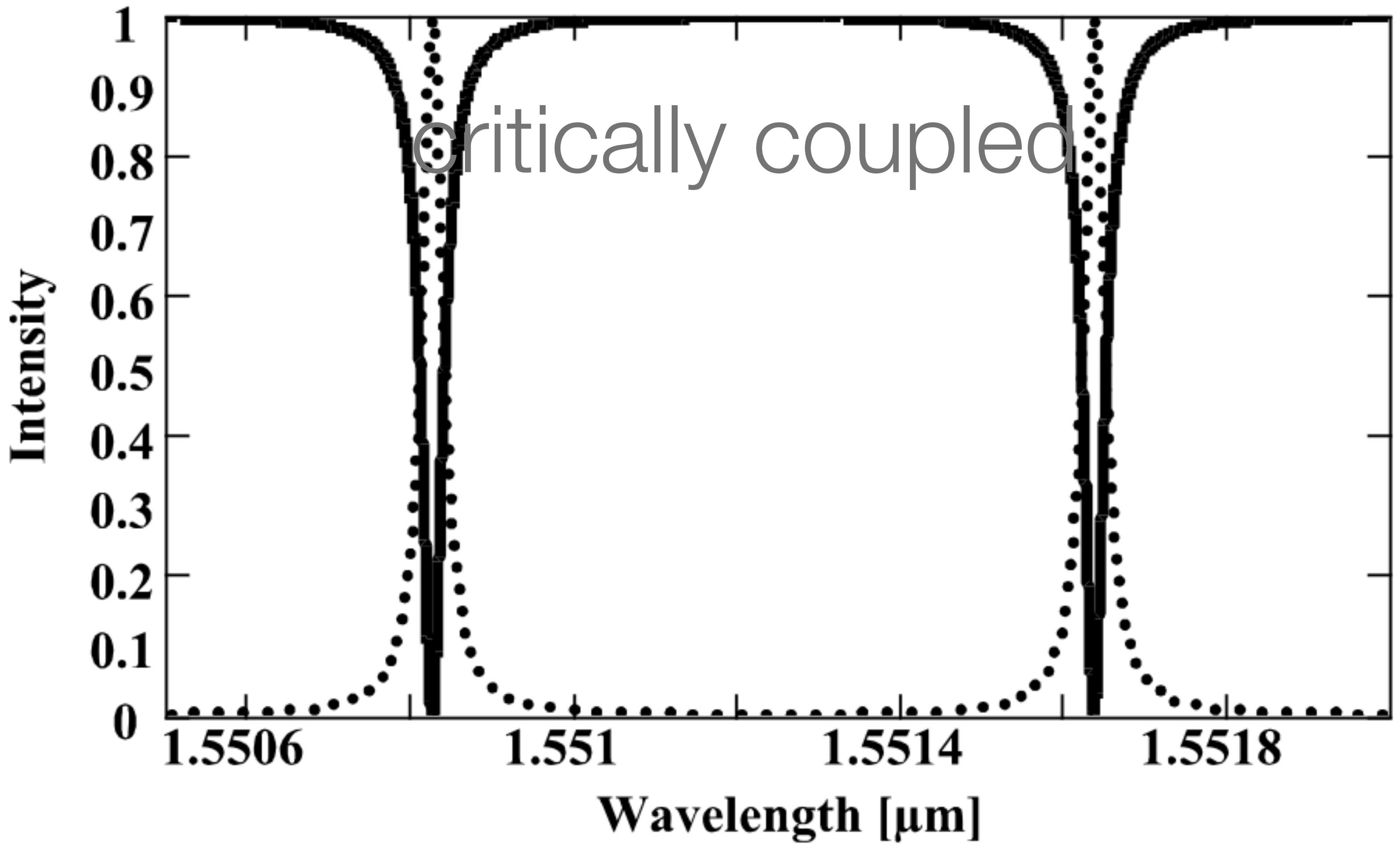
Ring Resonator



$$\begin{pmatrix} E_{t1} \\ E_{t2} \end{pmatrix} = \begin{pmatrix} t & \kappa \\ -\kappa^* & t^* \end{pmatrix} \begin{pmatrix} E_{i1} \\ E_{i2} \end{pmatrix} \qquad |\kappa^2| + |t^2| = 1$$

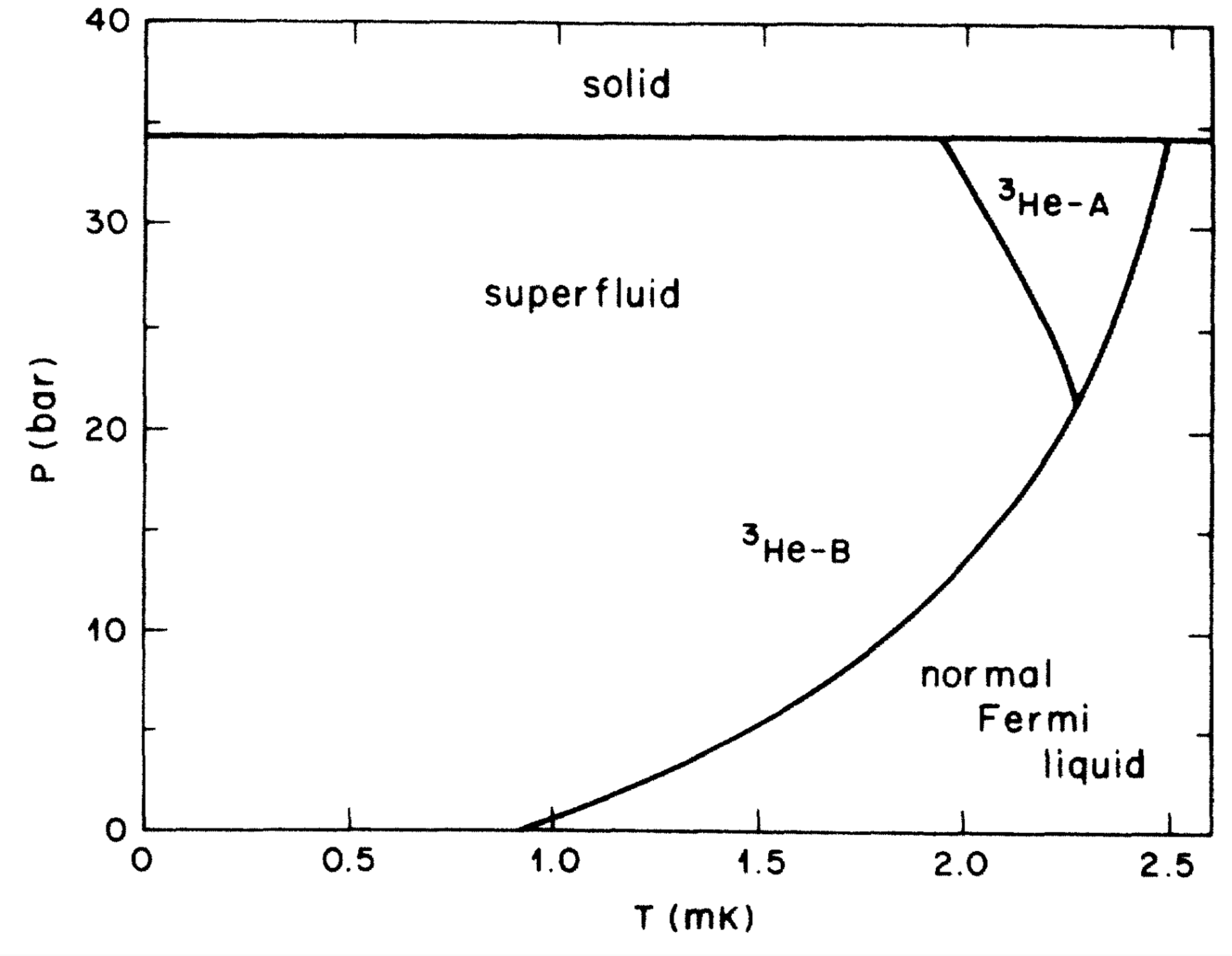
$$E_{i2} = \alpha \cdot e^{j\theta} E_{t2} \qquad \theta \approx n_{\text{eff}} \omega L$$

Loss



Helium 3 B, homogeneous precession domain

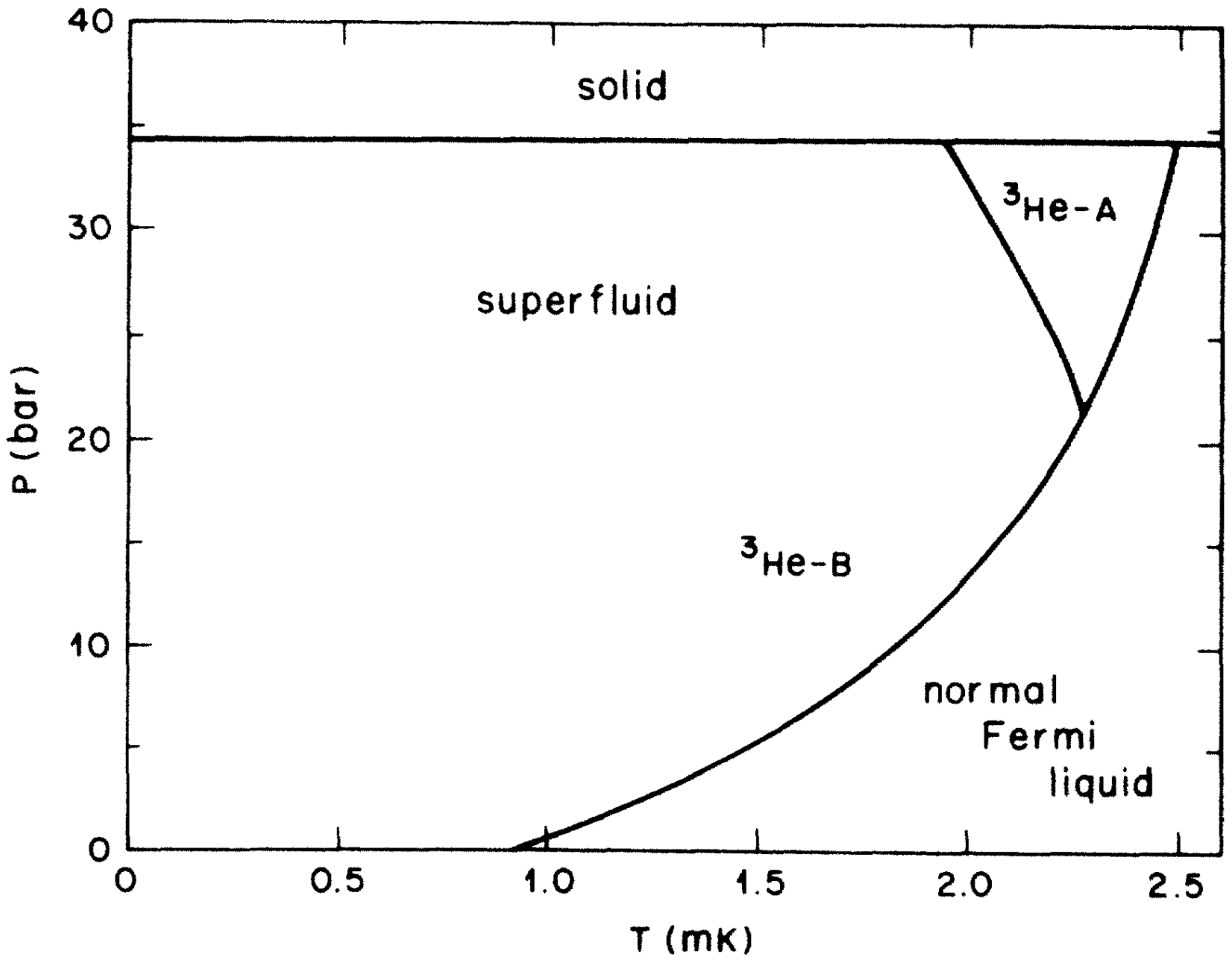
Properties of ^3He



Phys. Rev. B **33**, 7520 (1986)

- T<~1K, Fermi liquid, He-3 quasiparticles

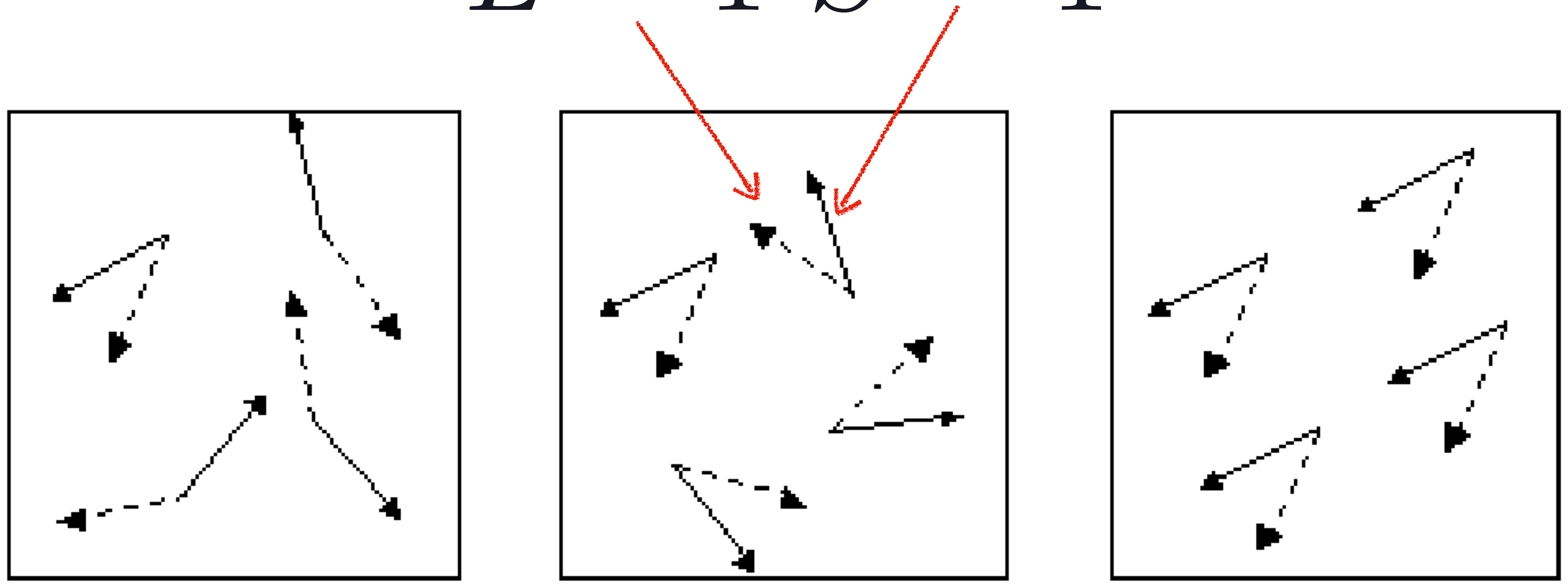
Properties of $^3\mathrm{He}$



Phys. Rev. B **33**, 7520 (1986)

- T<~mK, superfluid phase (~ BEC of Cooper pairs of He-3 quasiparticles)

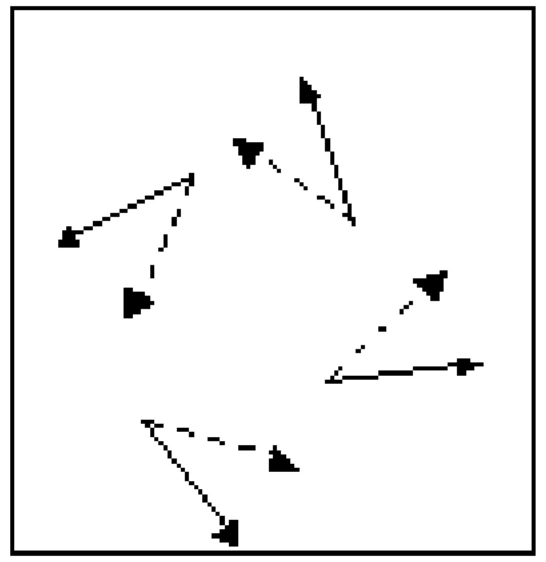
$L = 1 \; S = 1$



Unbroken phase B-phase A-phase

$^3\mathrm{He} - \mathrm{B}$

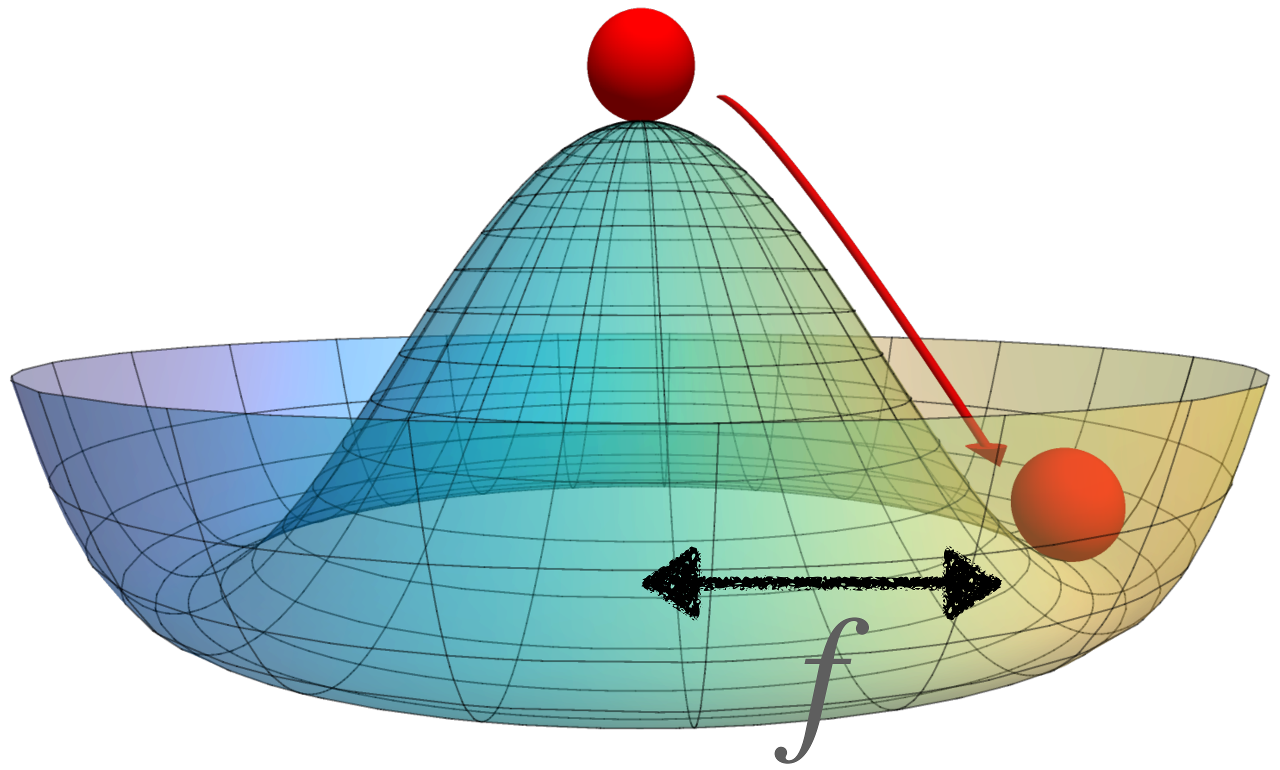
B-phase



spontaneously broken spin orbit symmetry

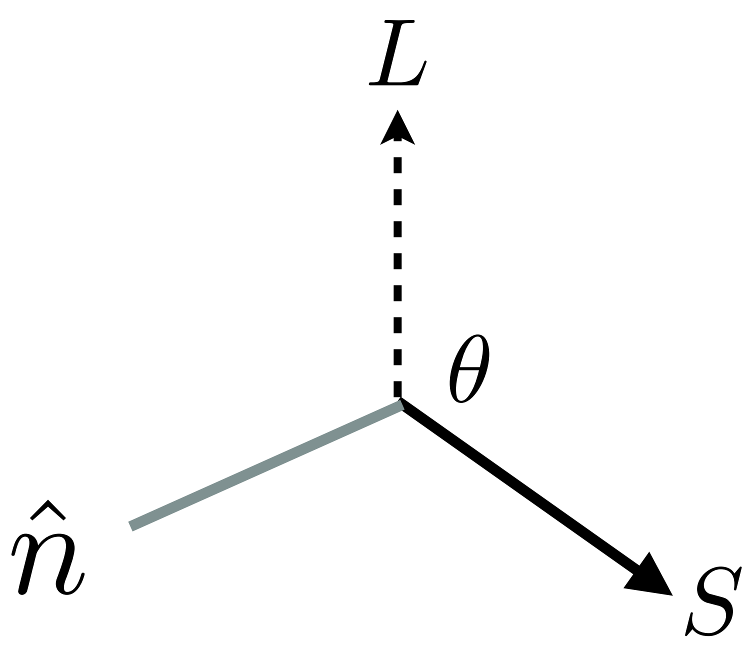
Leggett Rev. Mod. Phys. 47, 331 (1975)

$$SO(3)_S \times SO(3)_L \times U(1)_\phi \to SO(3)_{L+S}$$



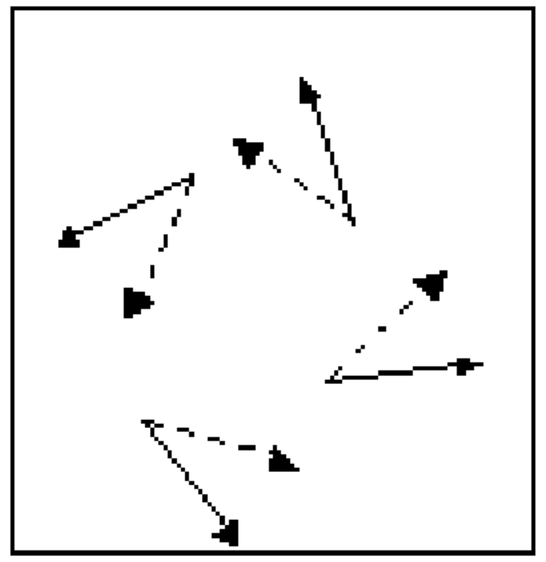
$$e^{i\phi} R_{\mu j}(\hat{n}, \theta)$$

But, a lot of degenerate ground states



$^{3}\mathrm{He} - \mathrm{B}$

B-phase

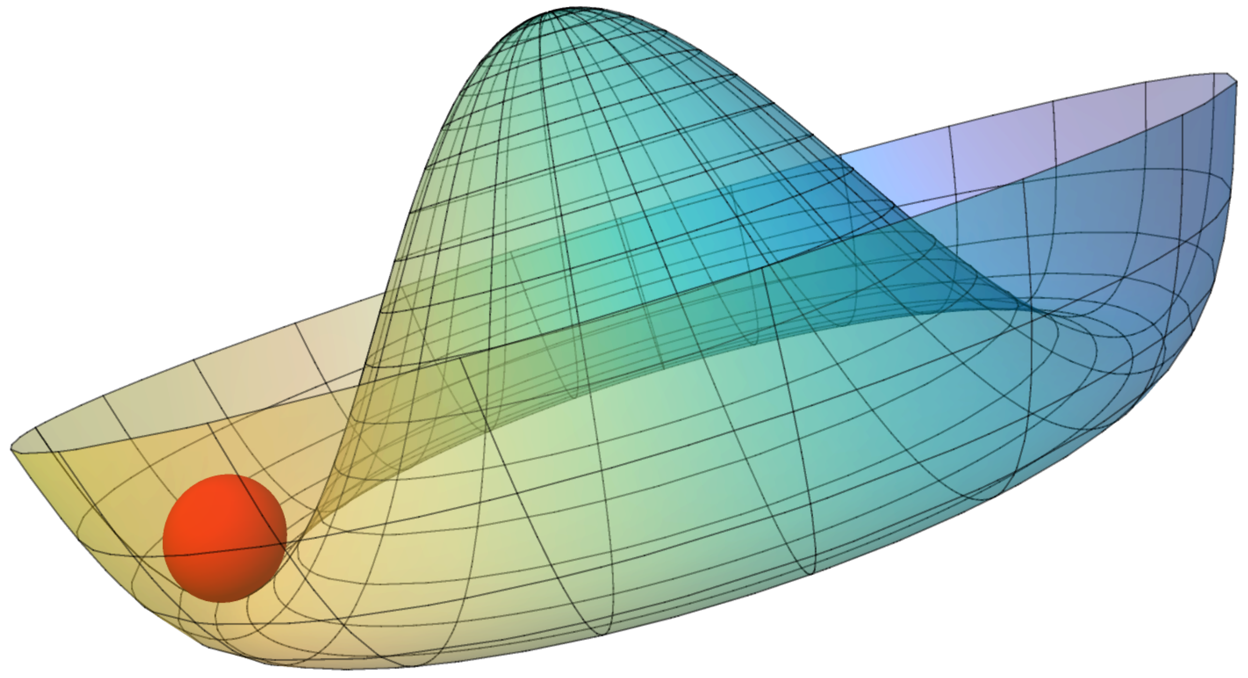


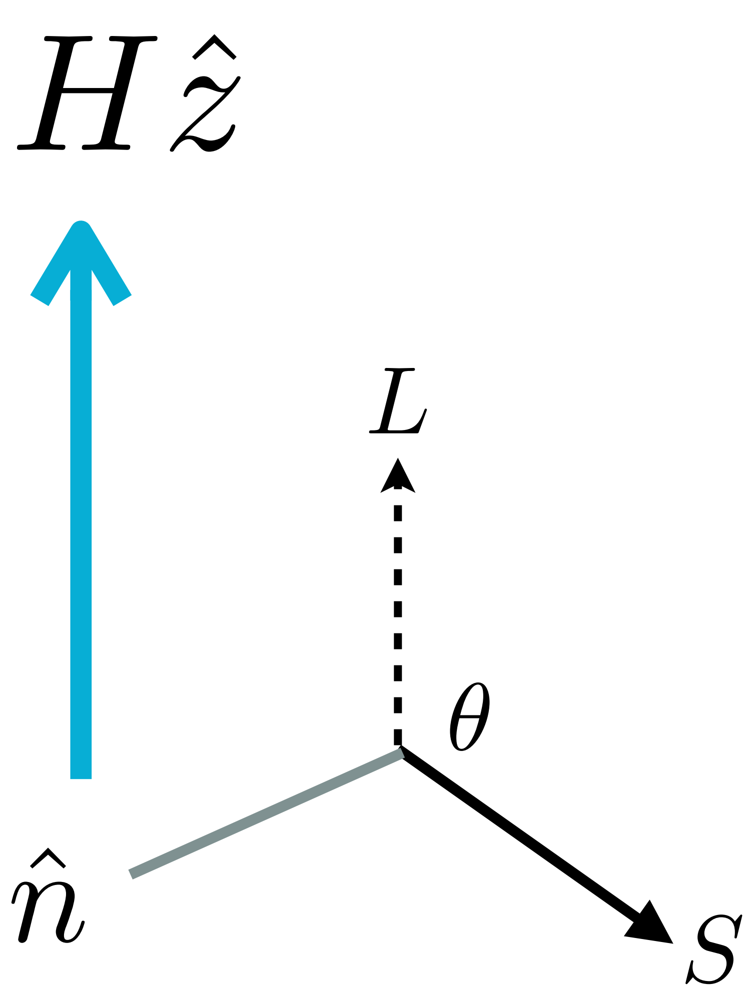
spontaneously broken spin orbit symmetry

$$SO(3)_S \times SO(3)_L \times U(1)_\phi \to SO(3)_{L+S}$$

$$e^{i\phi} R_{\mu j}(\hat{n}, \theta)$$

Leggett Rev. Mod. Phys. 47, 331 (1975)



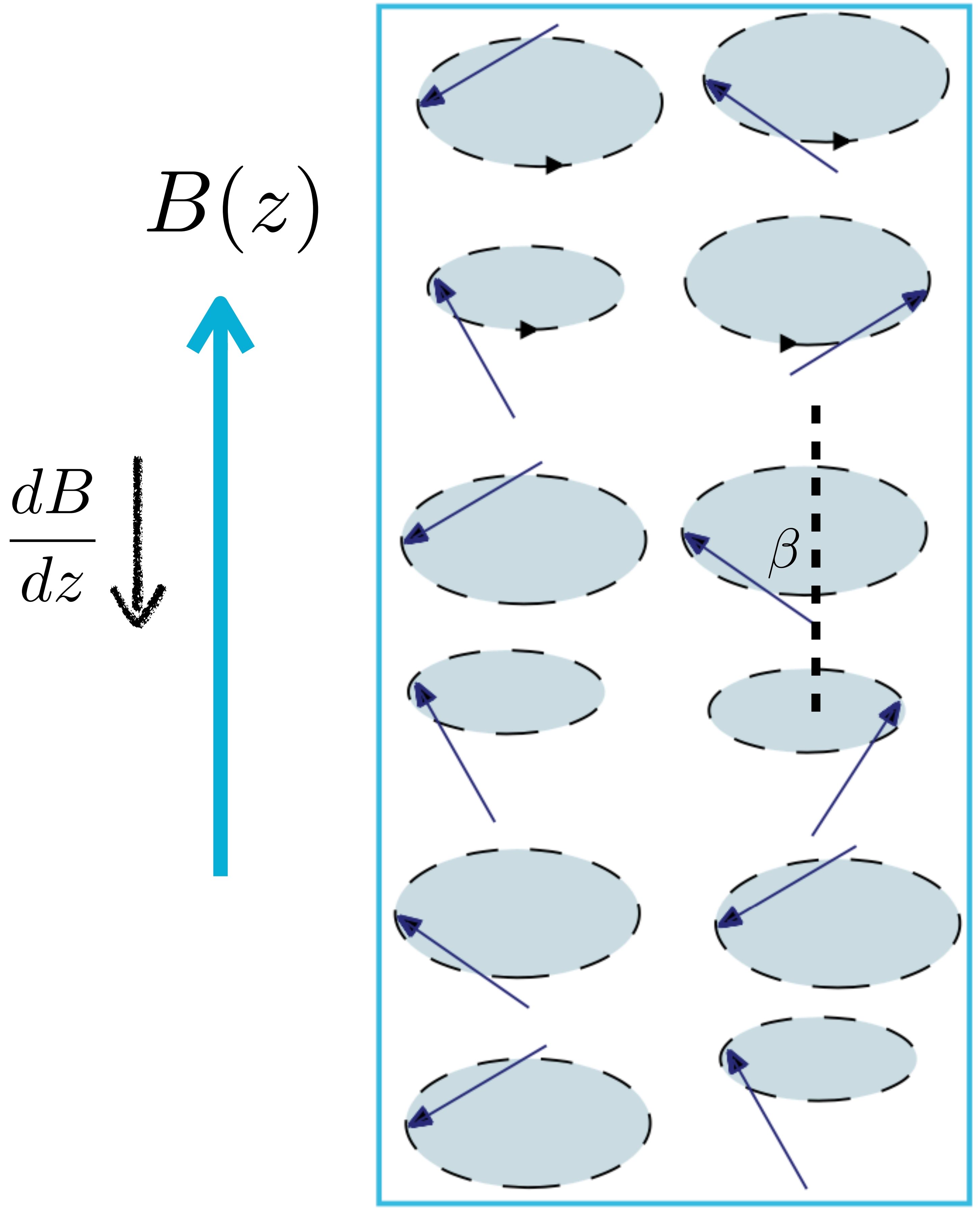


External magnetic field: $H\,\hat{z}$

Dipole interaction: $\cos\theta = -\dfrac{1}{4}$

Pulsed NMR with $^3\mathrm{He-B}$

[Bunkov and Volovik, 0904.3889 and 1003.4889]
Fomin Sov. Phys. JETP 61, 1207 (1985)



spins disoriented

Spins tipped by a tip angle β immediately after the pulse

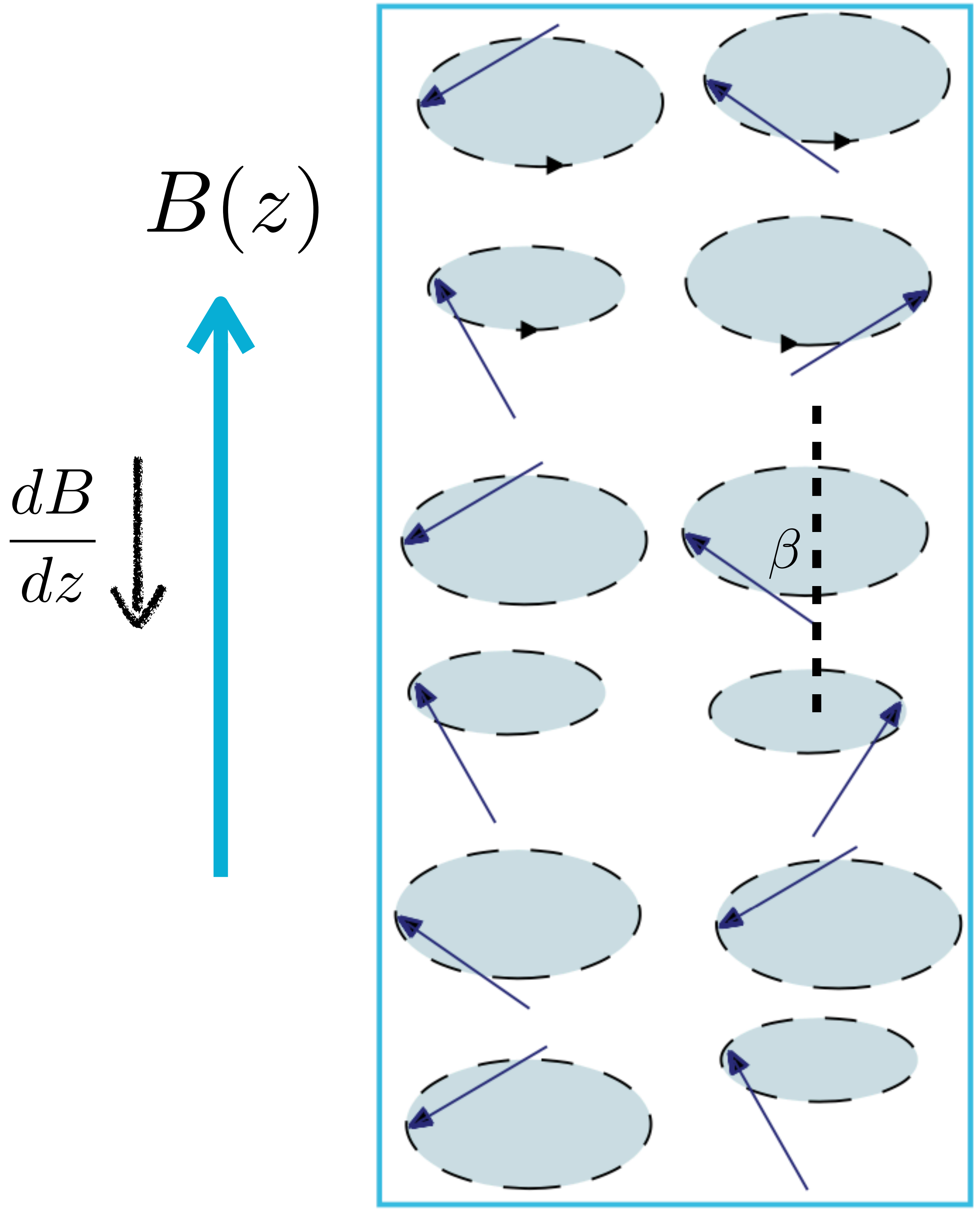
Characteristic time scale with superfluid $\hbar/\Delta(T)$

$$\Delta(T) \sim 10^2(1-T/T_c)^{1/2}\mathrm{MHz}$$

Pulsed NMR with $^3\mathrm{He}-\mathrm{B}$

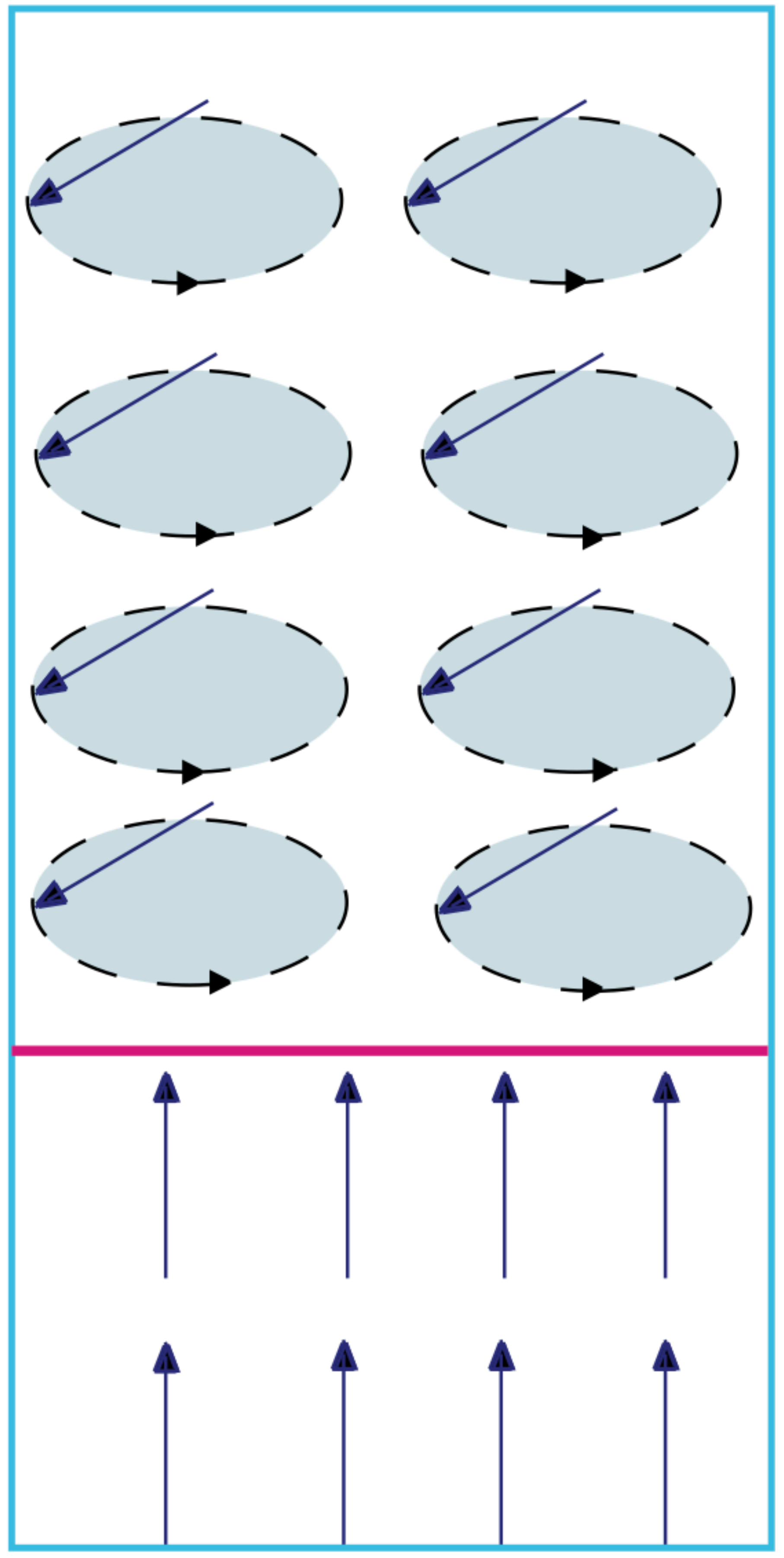
[Bunkov and Volovik, 0904.3889 and 1003.4889]
Fomin Sov. Phys. JETP 61, 1207 (1985)

BEC of N Magnons



spins disoriented

wait
20 ms



two domains

coherent precession
at fixed angle

$\beta_0 = \cos^{-1}(-1/4)$

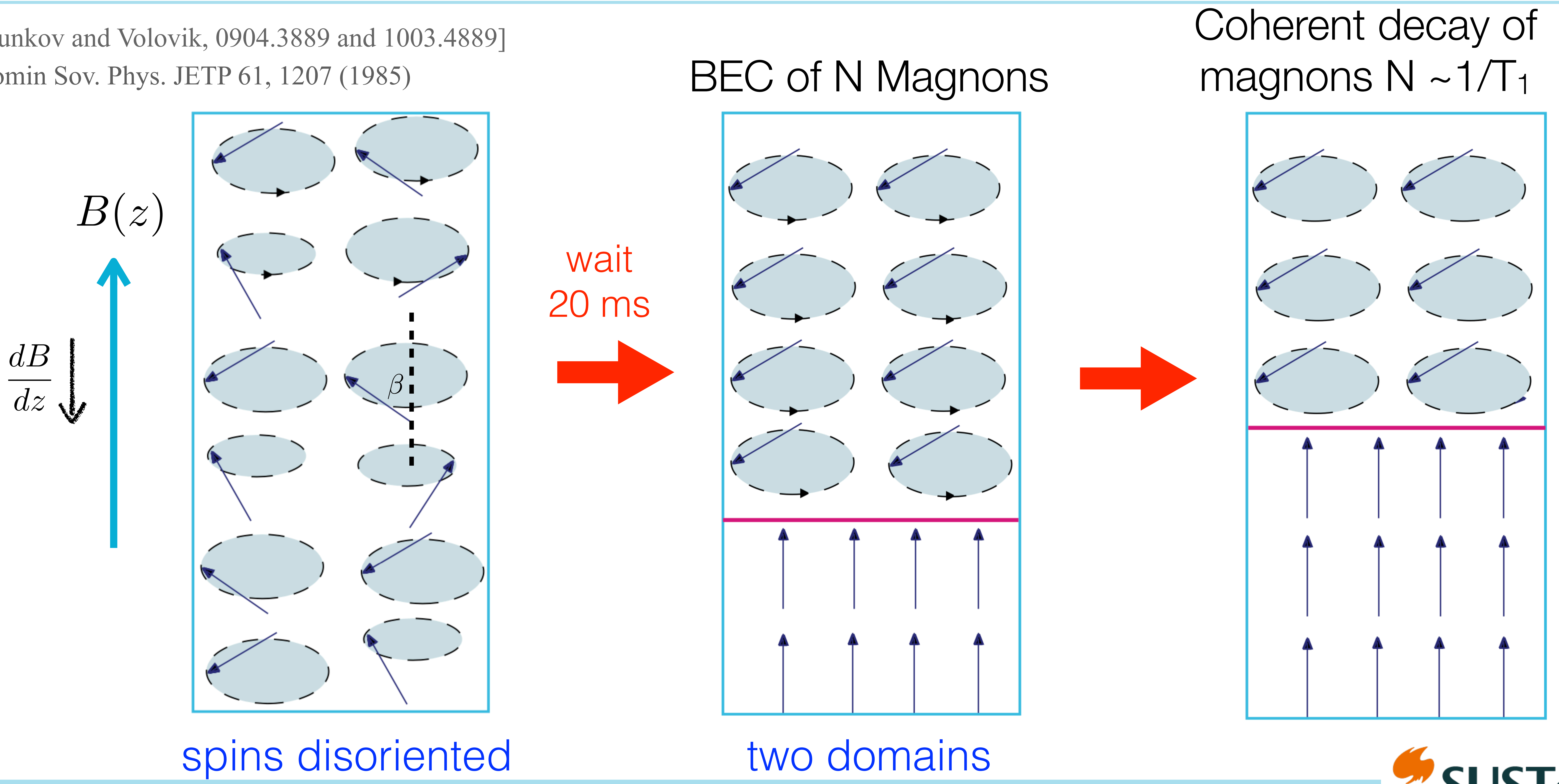
and same frequency

$\omega_L(z_0) = \gamma B_0(z_0)$

homogeneous
precession domain
(HPD)

Pulsed NMR with $^3\mathrm{He-B}$

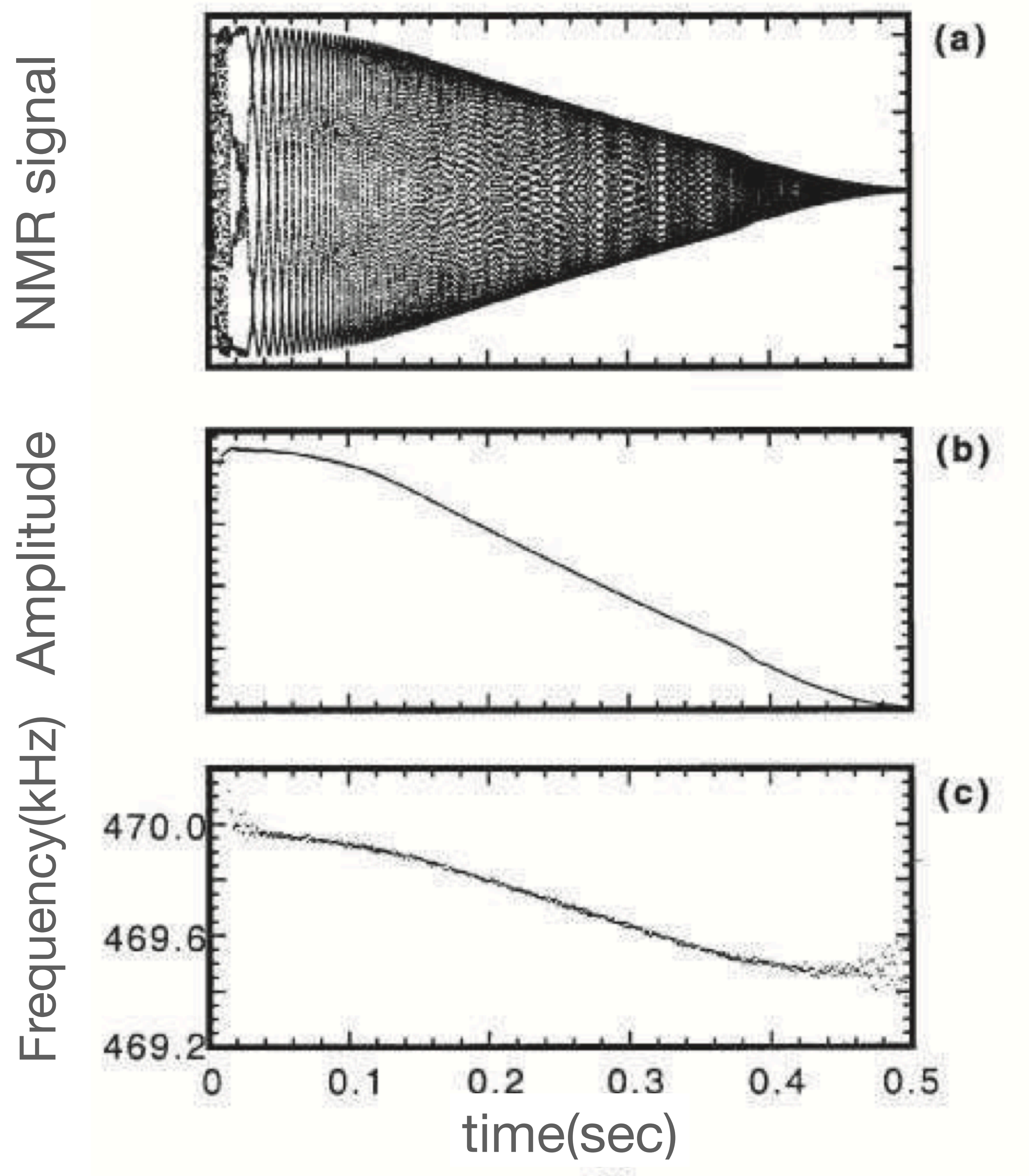
[Bunkov and Volovik, 0904.3889 and 1003.4889]
Fomin Sov. Phys. JETP 61, 1207 (1985)



Pulsed NMR with $^3\mathrm{He} - \mathrm{B}$

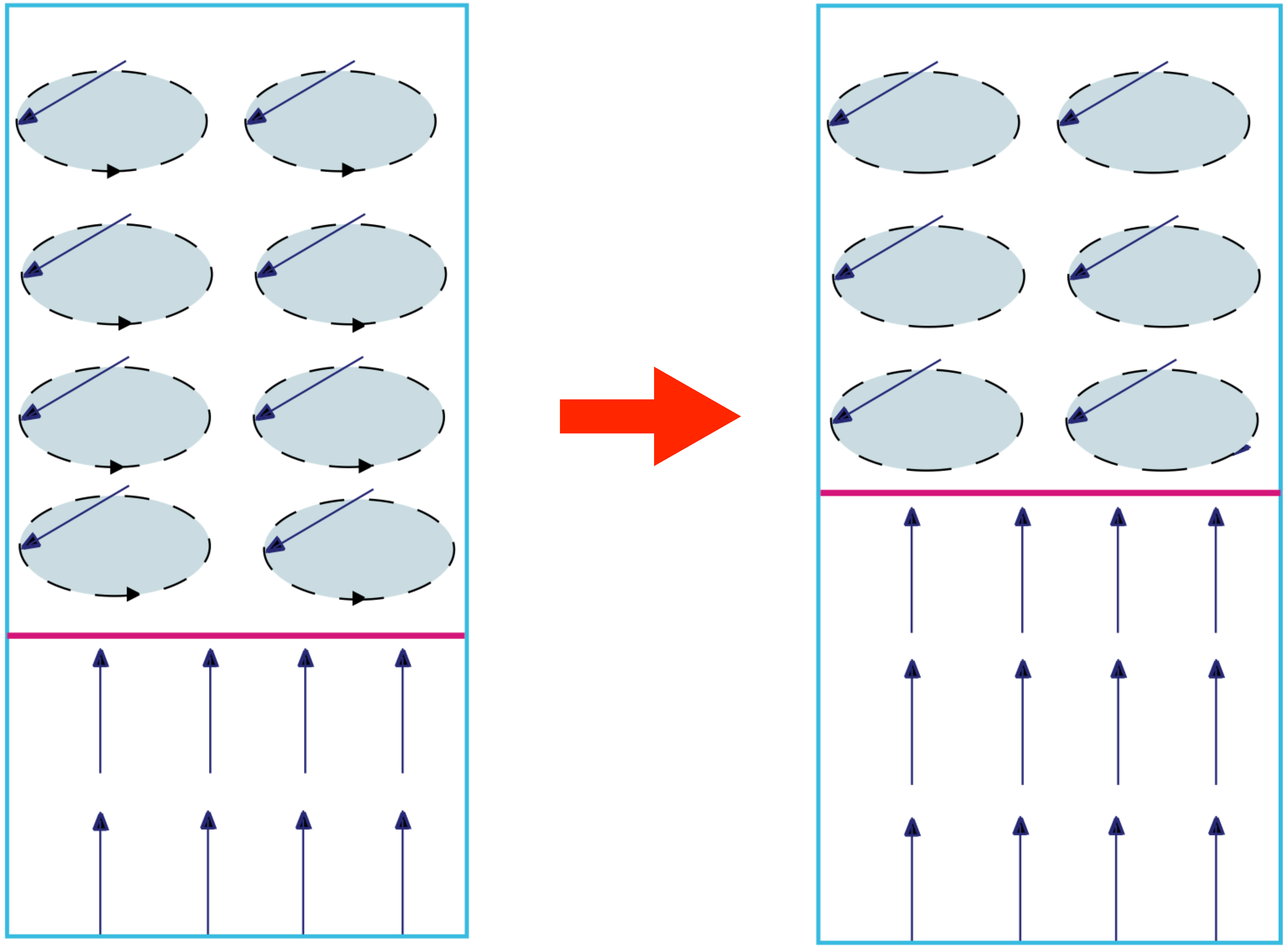
Naghiloo, Jordan, and Murch (2017)

NMR SQUID magnetometer



BEC of N Magnons

Coherent decay of magnons N ~1/T_1



[Bunkov and Volovik, arXiv:0904.3889]   Geller and Lee, Phys. Rev. Lett. 85, 1032 (2000)

SUSTech

Signal-to-noise

Measurement frequency

Stochastic magnon loss: $\frac{1}{\sqrt{T_1 N_0 f_{\rm m}}}$

Magnon number~ 10^{20}

Measurement noise: $\propto \frac{1}{T_q N_q} f_{\rm m}^{\frac{5}{2}}$

(Adaptive Coherent Control) Naghiloo, Jordan, and Murch (2017)

Clock noise: $\sqrt{10^{-31} f_{\rm m} {\rm sec}}$

$$\Delta\omega_a^2 \sim \rho_a v_0^2 g_{aN}^2 \omega_L T_1 \frac{z_0 \partial_z B}{B_0}$$

$$\mathrm{SNR} \sim \sqrt{\frac{\Delta\omega_a^2}{\Delta\omega_{\rm bkg}^2}} \times \begin{cases} \sqrt{t_{\rm int}} & \text{within } \tau_a \\ t_{\rm int}^{1/4} & \text{beyond } \tau_a \end{cases}$$

Noise

Stochastic magnon loss: $\frac{1}{\sqrt{T_1 N_0 f_{\rm m}}}$

Measurement frequency

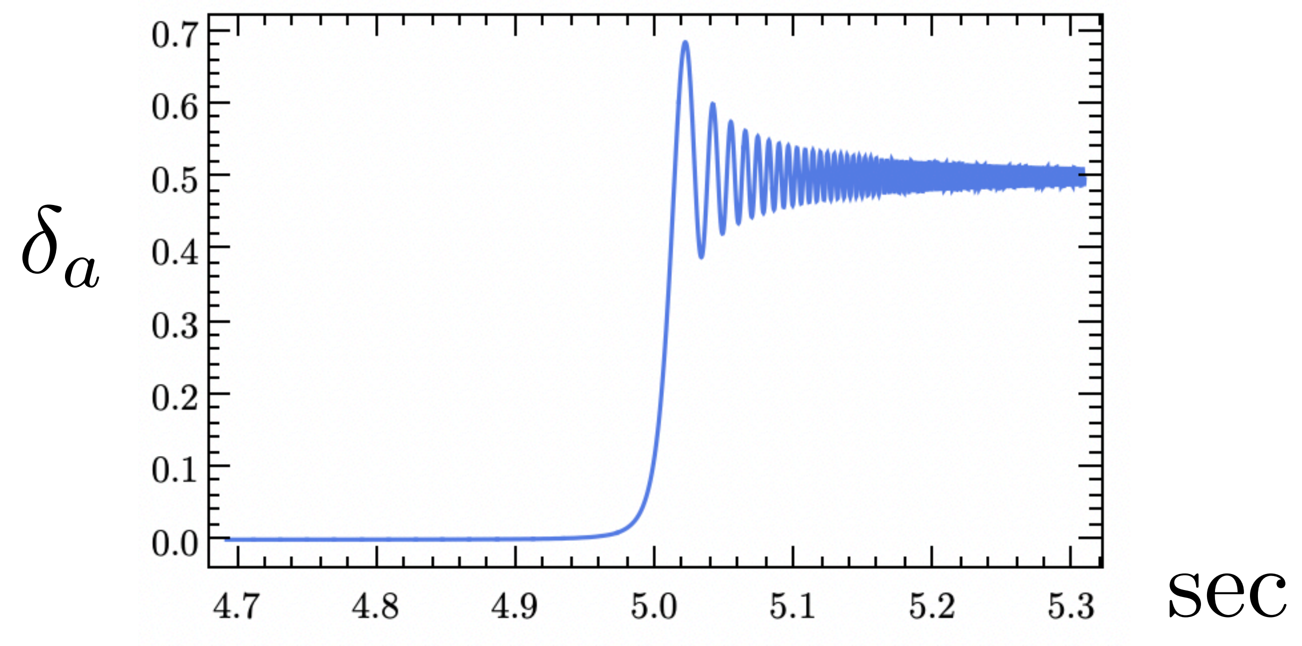
Magnon number

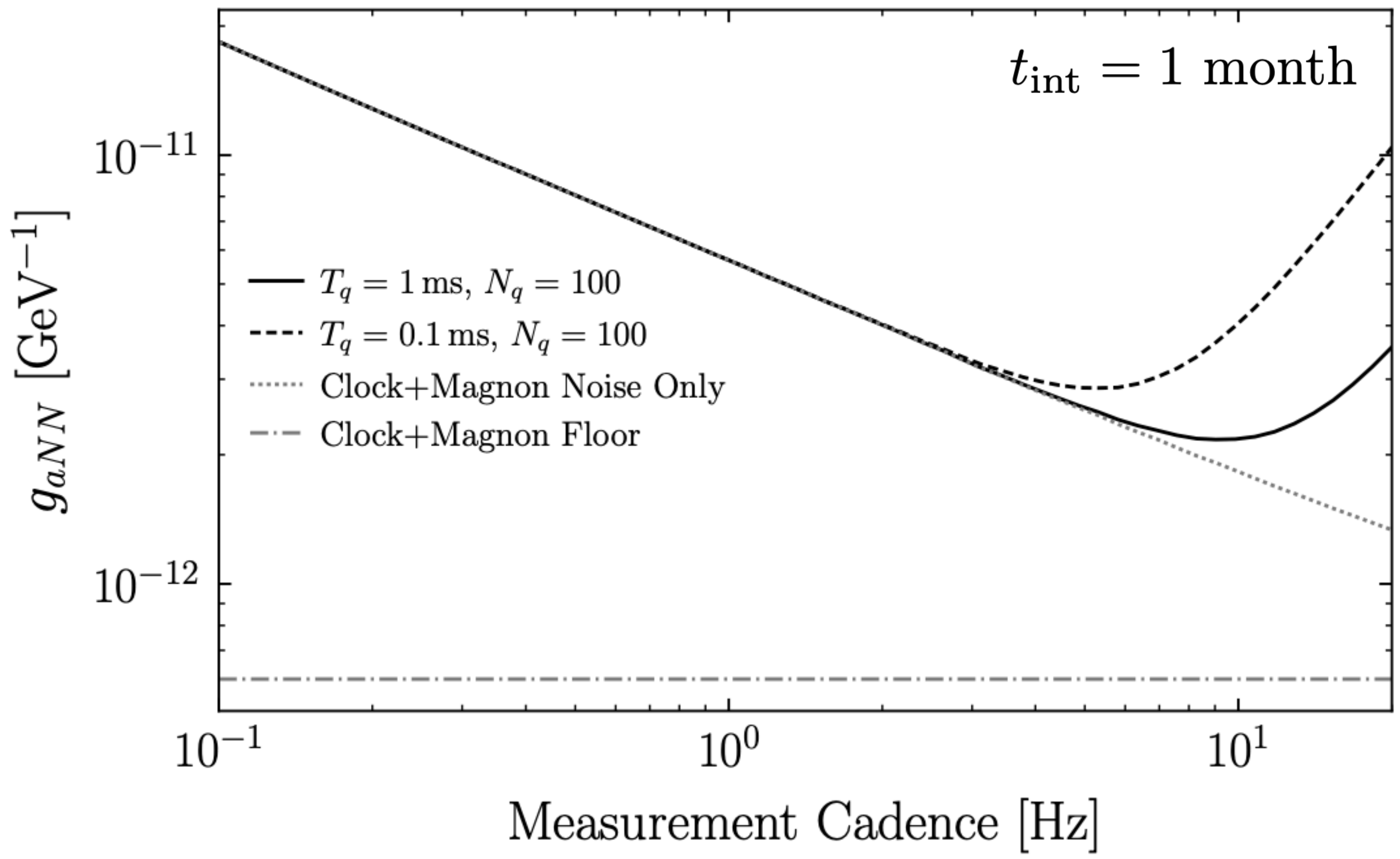
Measurement noise: $\propto \frac{1}{T_q N_q} f_{\rm m}^{\frac{5}{2}}$

Clock noise: $\sqrt{10^{-31} f_{\rm m} \mathrm{sec}}$

$$\Delta\omega_a^2 \sim \rho_a v_0^2 g_{aN}^2 \omega_L T_1 \alpha \qquad \alpha \equiv \frac{z_0 \partial_z B}{B_0}$$

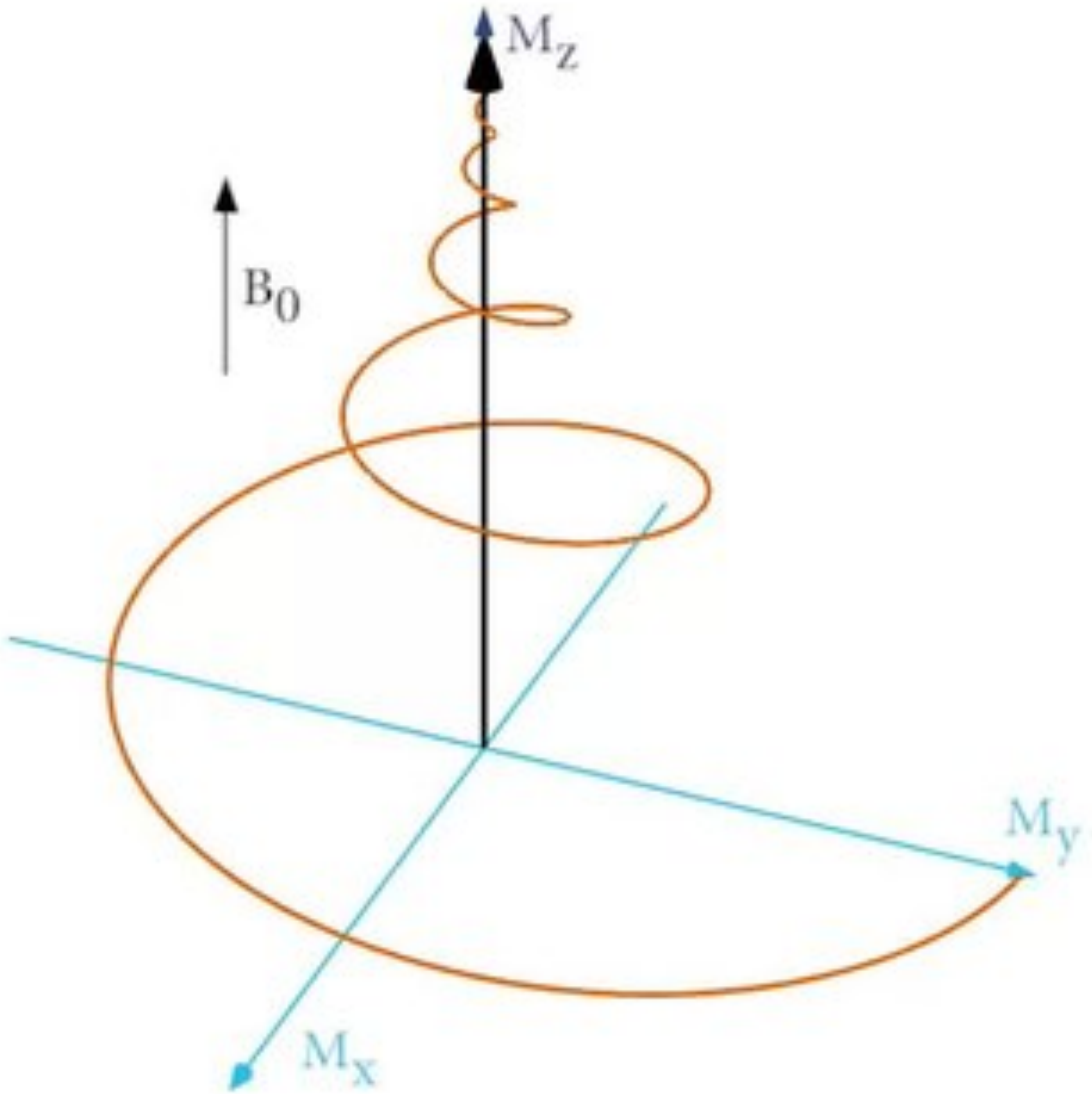
$$\mathrm{SNR} \sim \sqrt{\frac{\Delta\omega_a^2}{\Delta\omega_{\rm bkg}^2}} \times \begin{cases} \sqrt{t_{\rm int}} & \text{within } \tau_a \\ t_{\rm int}^{1/4} & \text{beyond } \tau_a \end{cases}$$

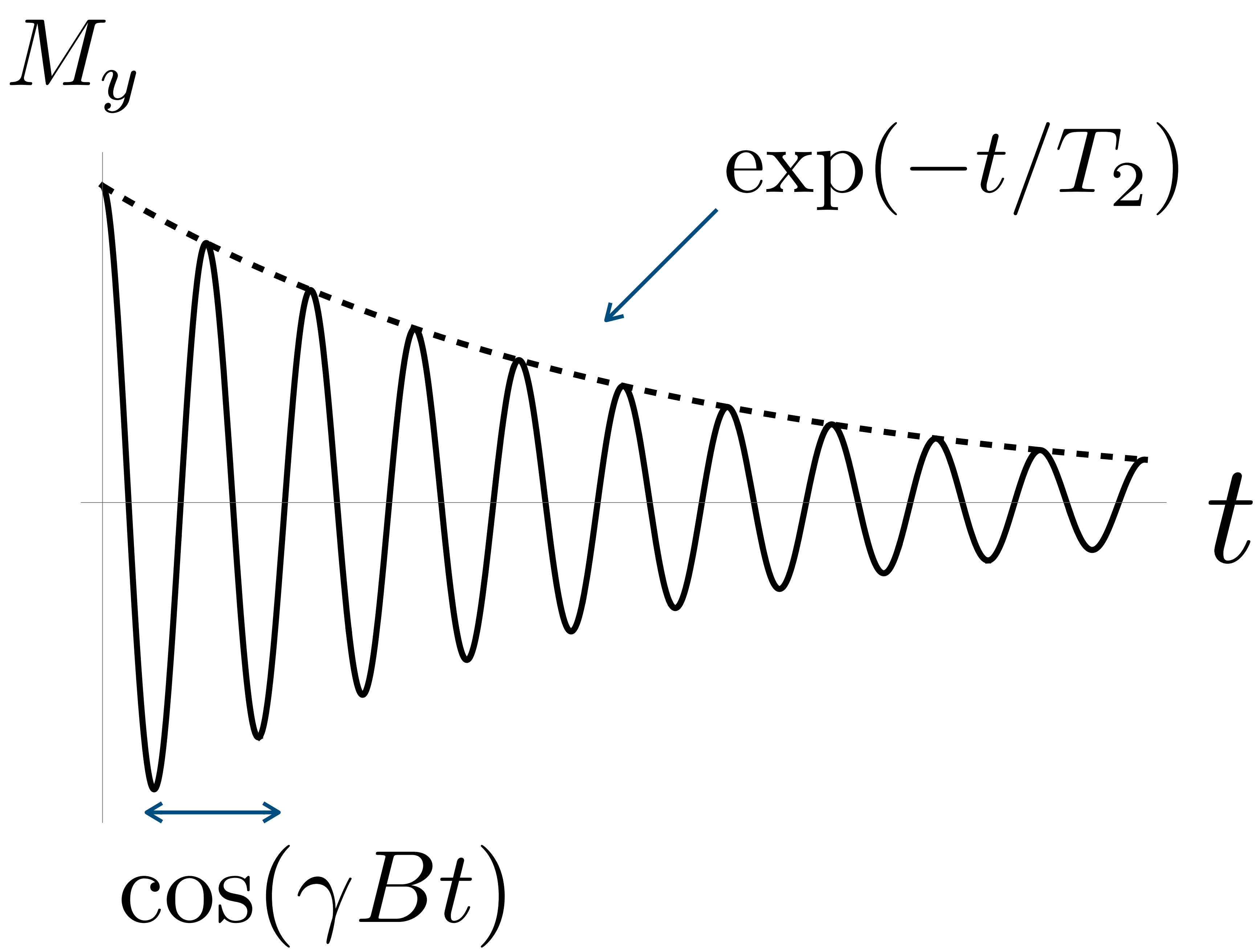




Pulsed NMR

$$\frac{d\mathbf{M}}{dt} = \mathbf{M} \times \gamma \mathbf{B} - \frac{M_x \hat{\mathbf{x}} + M_y \hat{\mathbf{y}}}{T_2} - \frac{(M_z - M_0)\hat{\mathbf{z}}}{T_1}$$





Note that for a HPD signal, $T_2 \sim T_1$

Axion's coupling to NR fermions

$$\mathcal{L}_{\rm int} \supset g_{af}\partial_\mu a \bar{f}\gamma^\mu\gamma^5 f$$

g_{af} **?**

NR fermions $g_{af}\nabla a \cdot \mathbf{S}_f$ ← spin density

Mean field $H_{\rm eff} \supset \mathbf{B}_a \cdot \langle \mathbf{m} \rangle$

$$g_{af}\frac{\nabla a}{\gamma_f} \qquad \int_V \mathbf{M}$$

gyromagnetic ratio

$$\gamma_n = \frac{e\hbar}{2m_p} g_n$$

magnetic susceptibility

$\mathbf{M} = \chi \mathbf{H}$

$^3\mathrm{He} : \chi \sim 10^{-7}$

J. C. Wheatley, Rev. Mod. Phys 47, 415 (1975)

Pulsed NMR with $^3\mathrm{He}-\mathrm{B}$

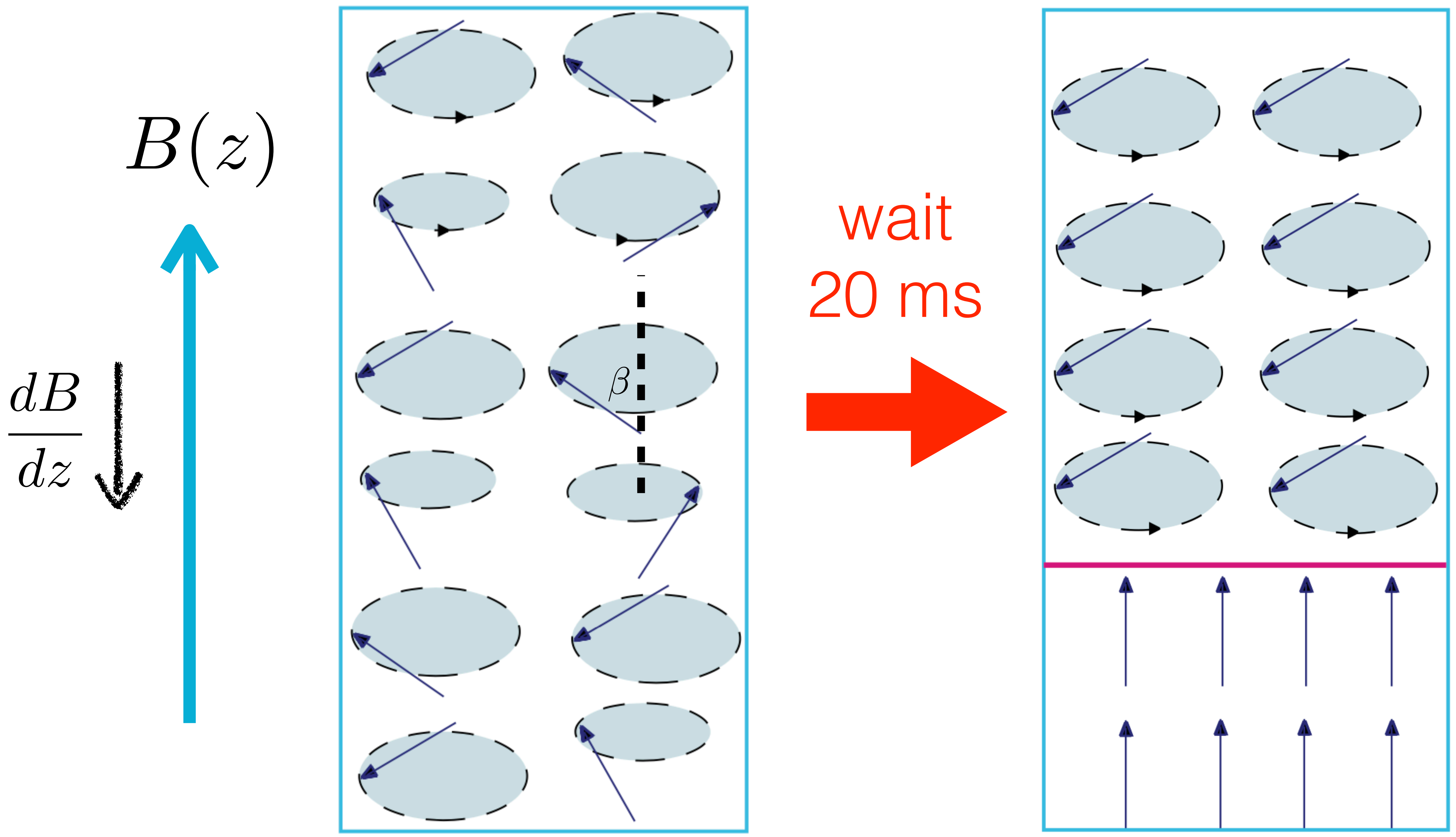
[Bunkov and Volovik, arXiv:0904.3889 and arXiv:1003.4889]

Fomin Sov. Phys. JETP **61**, 1207 (1985)

BEC of N Magnons

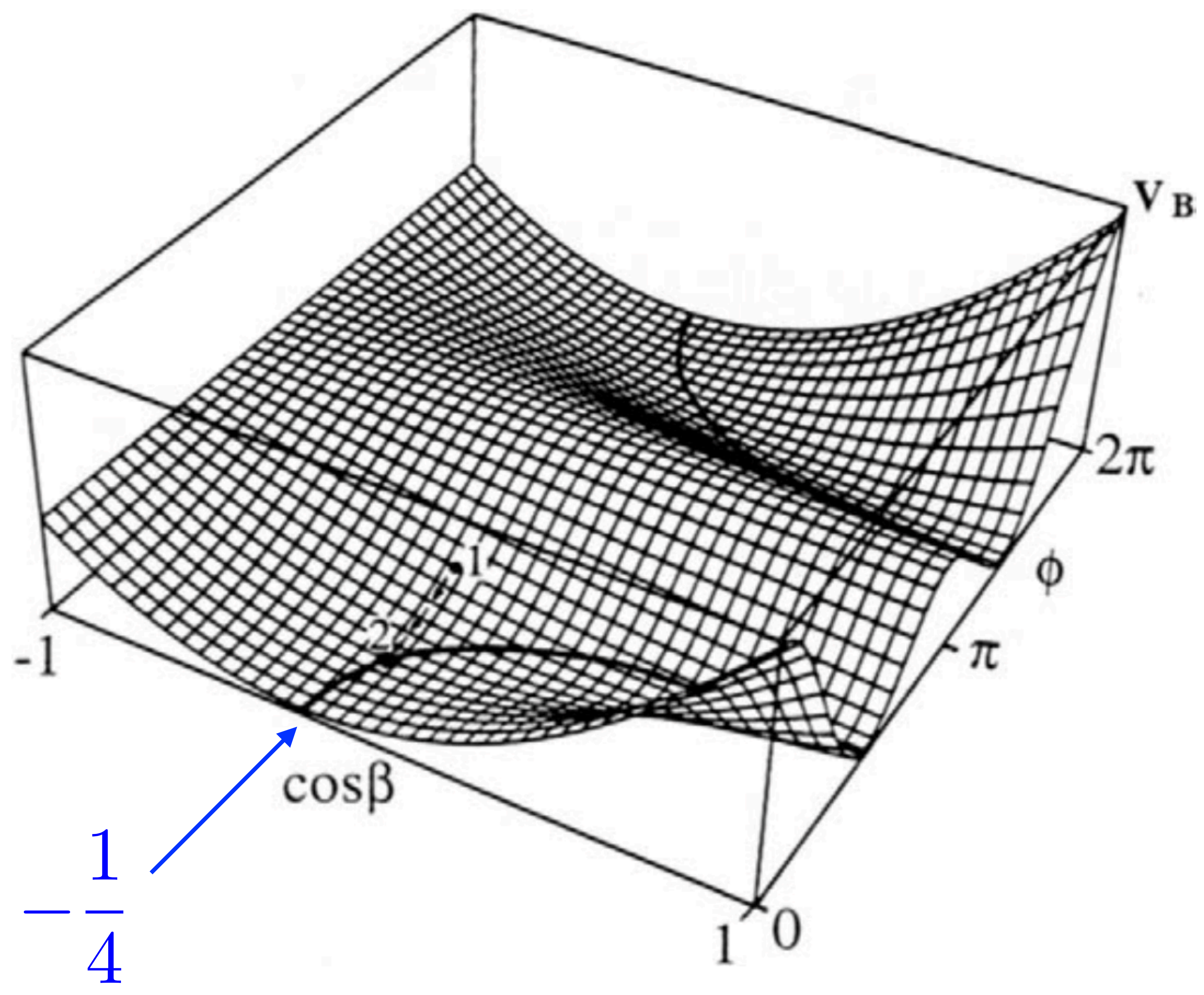
DOF: Euler angles

$$\omega(z) \sim \gamma B(z) + E_D(\cos\beta(z) + \frac{1}{4})$$



spins disoriented

two domains!



This is known as the homogeneous precession domain (HPD)

A more realistic model of axion wind

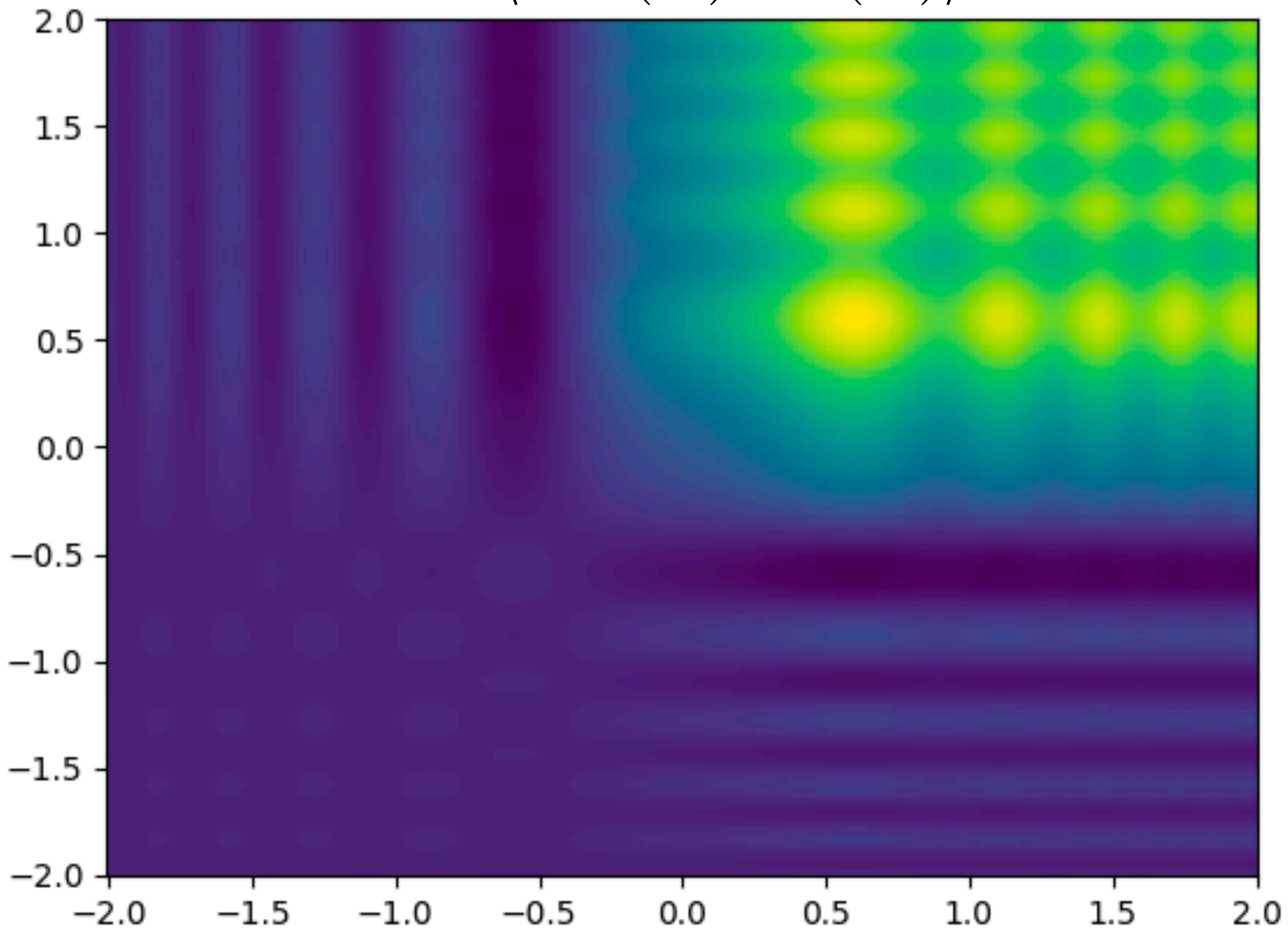
Fractional volume change due to axion wind

$$\frac{dx^{(1)}}{dt} \sim -B_{a_x}(t)\sin\left(\omega_L(t)t\right) - B_{a_y}(t)\cos\left(\omega_L(t)t\right)$$

$$x^{(1)}(t) \sim g_{aN}\int_0^t dt'\partial_x a(t')\sin(\omega_L(t')t') + \cdots$$

Gaussian random field $\langle x^{(1)}(t)\rangle = 0$

$\langle x^{(1)}(t_1)x^{(1)}(t_2)\rangle$



Resonance occurs