Axion superconducting string
Cosmic axion Background

Hitoshi Murayama (Berkeley, Kavli IPMU)

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Hajime Fukuda, Aneesh Manohar, HM, Ofri Telem, 2010.02763

Jeff Dror, HM, Nick Rodd, 2101.09287

QCD axion

- An old puzzle: Why doesn't strong interaction violate CP?
- periodic in $\theta \to \theta$ +2π

$$\mathcal{L}_\theta = \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

- leads to $H_{\mathit{eff}} = d_e \ \vec{s}_n \cdot \vec{E}$
- $\theta < 10^{-10}$

$$d_e \approx \frac{e m_u \sin\theta}{m^2_{\rm constituent}} < 2.9 \times 10^{-26} e \text{ cm}$$

- blow up neutron to Earth size: allowed separation of electric charge <3μ

QCD axion

- Promote θ-parameter to a dynamical field

$$\mathcal{L}_{eff} = \frac{1}{64\pi^2}\left(\theta_0 + \frac{a}{f_a}\right)\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}$$

- effect on pion Lagrangian in low energy:

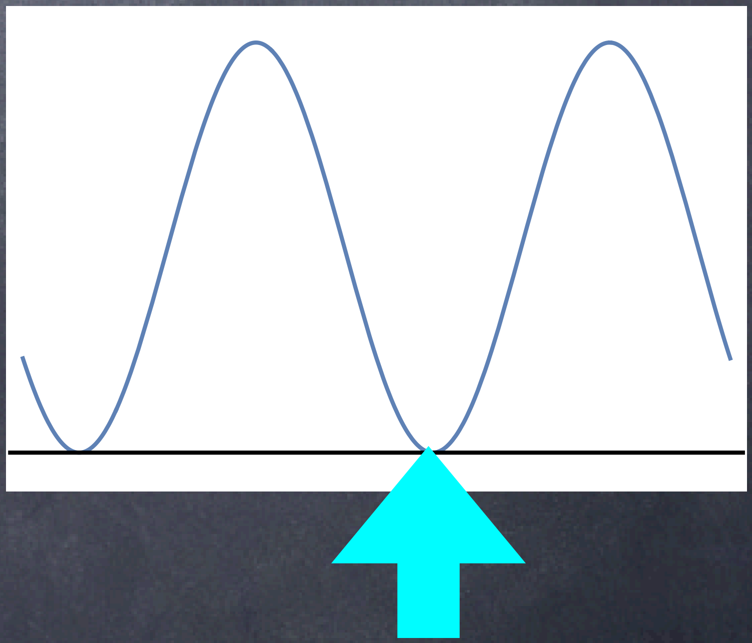
$$\mathcal{L}_\chi = f_\pi^2 \mathrm{tr}\partial U^\dagger \partial U + \mu^3 \mathrm{tr} M e^{i(\theta_0 + a/f_a)} U + \mathrm{c.c.}$$

- potential for axion (U=1)

$$V = -m_\pi^2 f_\pi^2 \cos\left(\theta_0 + \frac{a}{f_a}\right)$$

- it settles $a = -\theta_0 f_a$, canceling θ_0
- no CP violation at the minimum!

$$m_a = \frac{m_\pi f_\pi}{f_a}$$



$a = -\theta_0 f_a$

KAVLI


AXION
EL VERDADERO ARRANCAGRASA
Antibacterial
AXION
EL VERDADERO ARRANCAGRASA
Limòn
AXION
EL VERDADERO ARRANCAGRASA
BICARBONATO
AXION
EL VERDADERO ARRANCAGRASA
OXY
Plus
AXION
EL VERDADERO ARRANCAGRASA
Lima

axion

- motivated by strong CP problem
- moduli/dilaton in string theory
- could be dark matter
- consider generically axion-like particle
- couplings: $aF\tilde{F}$, $aG\tilde{G}$

Cosmic axion Background (CaB)

Jeff Dror, HM, Nick Rodd, 2101.09287

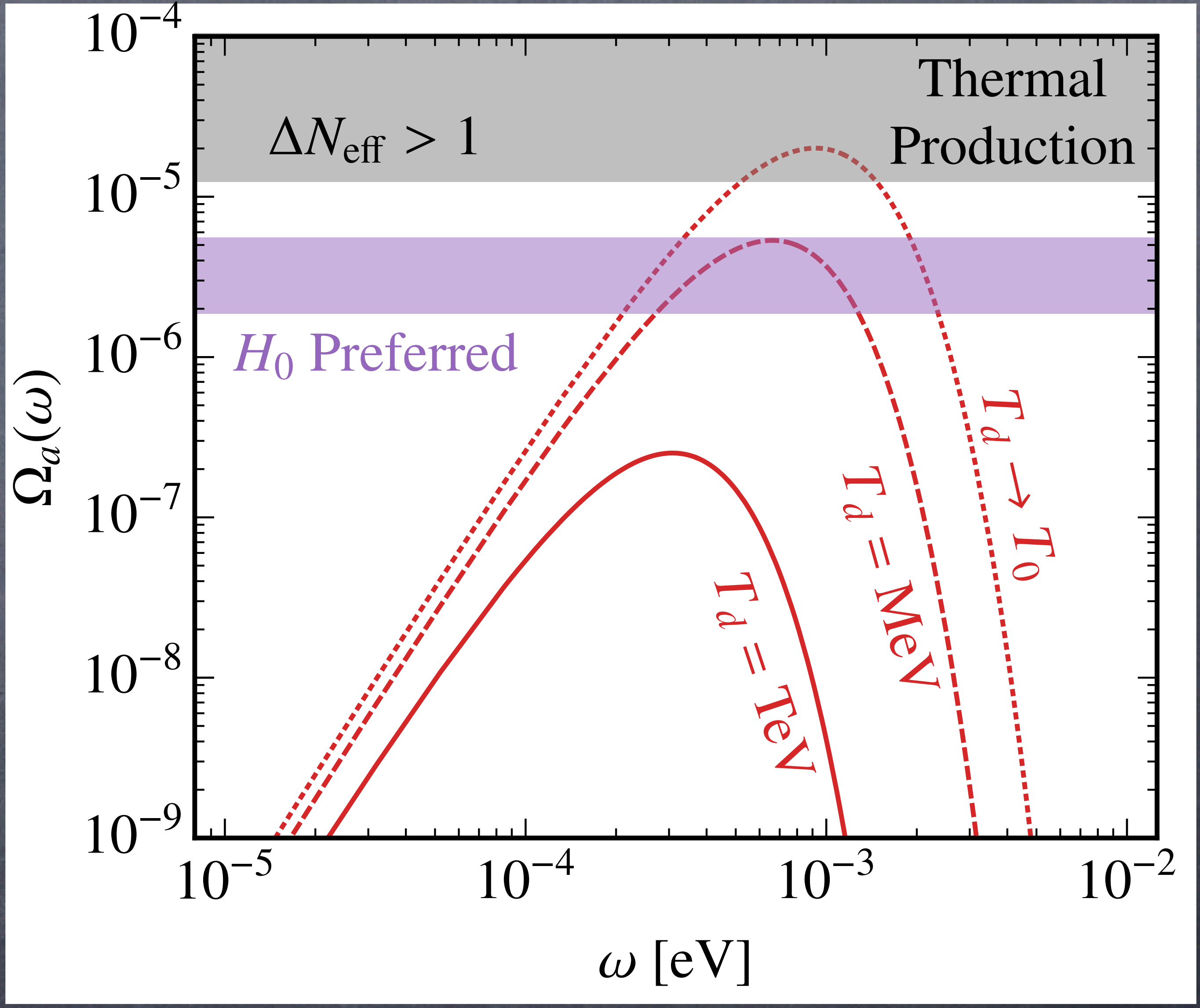
relativistic axion

- sources of relativistic axions
  - thermal axions
  - decay of dark matter into axions today
  - decay of topological defect e.g. string, wall

thermal axion

$$\Omega_a(\omega) = \frac{1}{\rho_c}\frac{d\rho_a}{d\ln\omega}$$

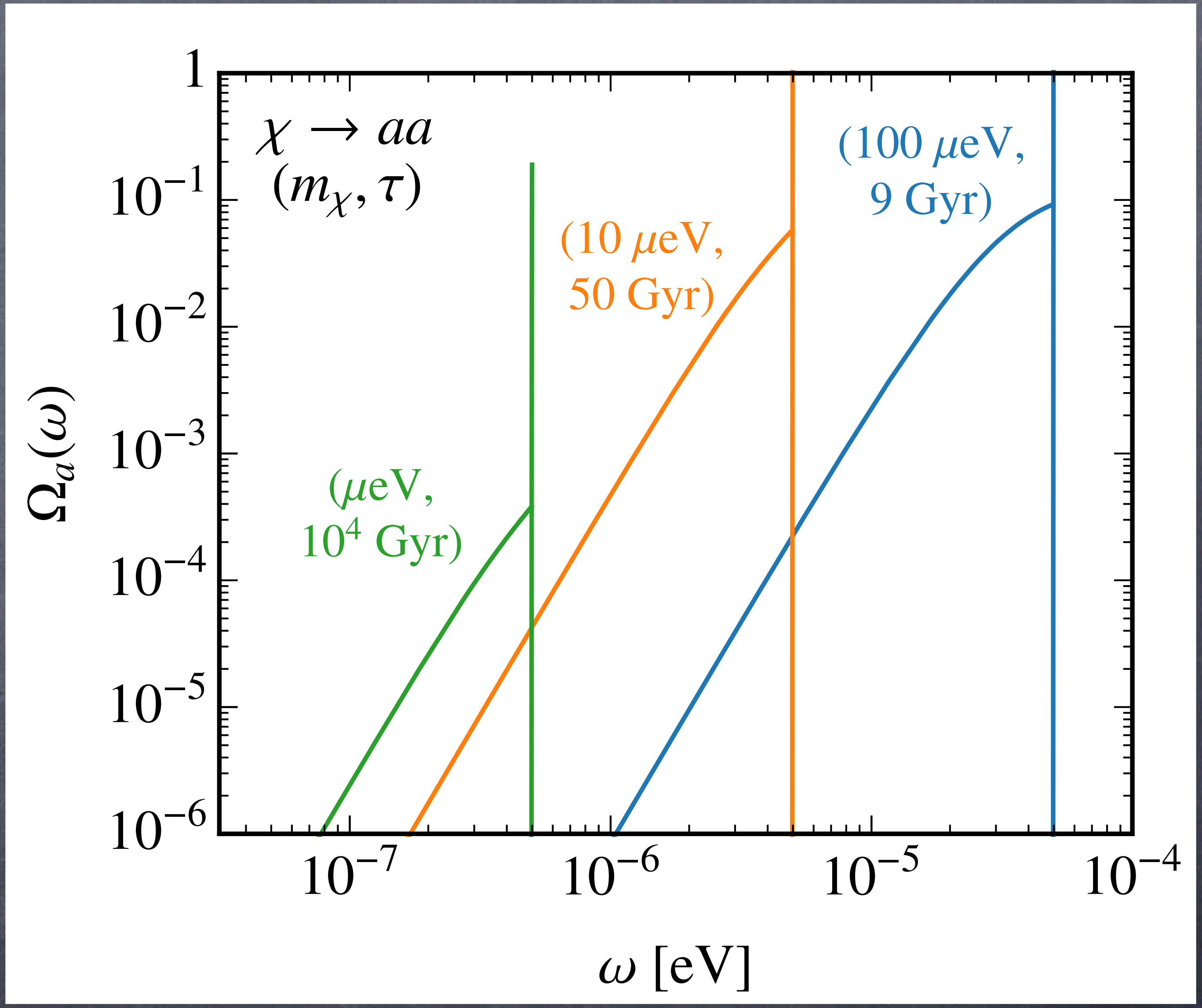
- for QCD axion, decoupling temperature is typically T_d>10TeV due to SN1987A constraint
- regard free parameter
- potentially addresses H_0 tension



axion energy E=$\hbar\omega$

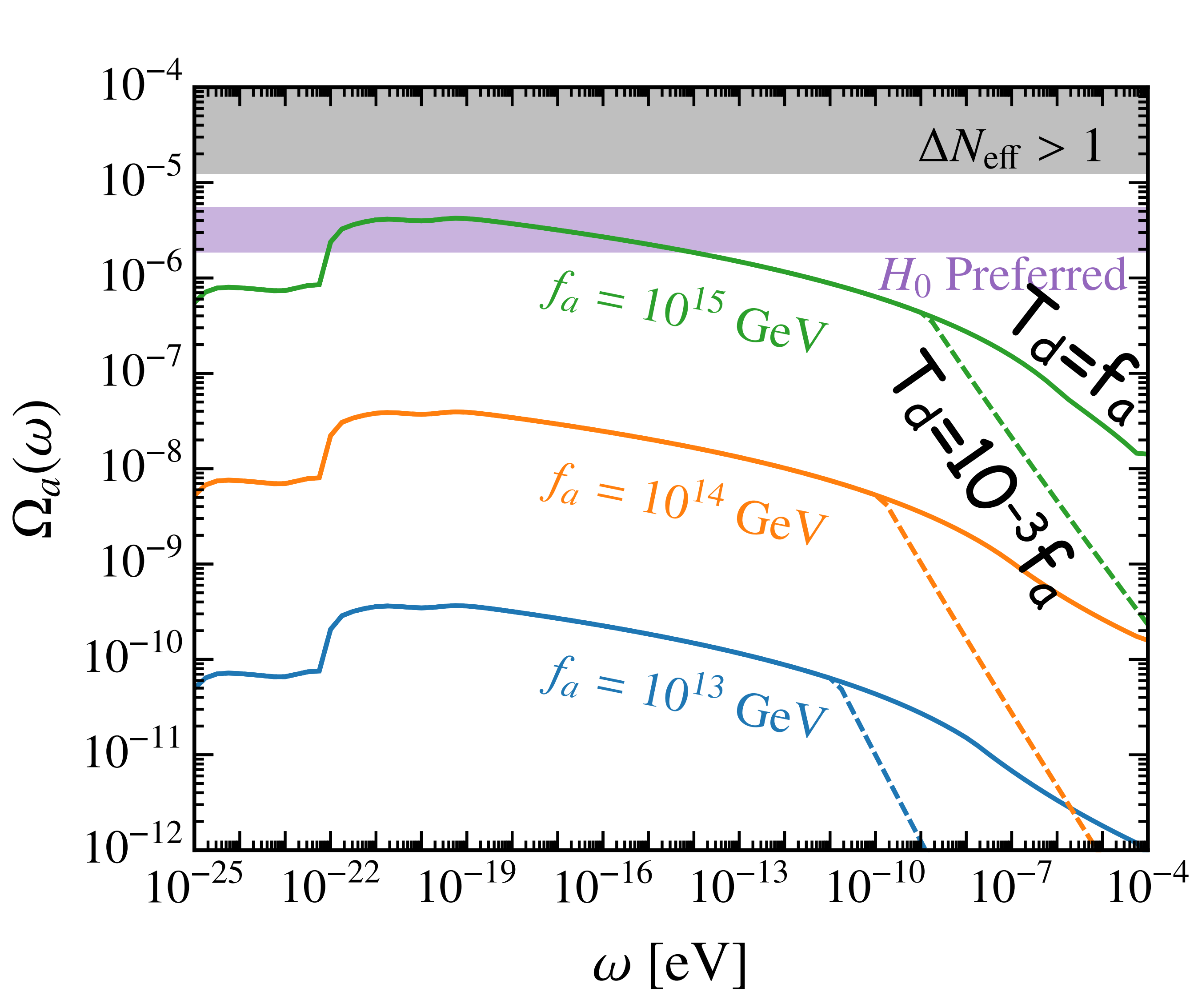
dark matter decay

- consider scalar dark matter $\chi \to a\ a$
- decay in galactic halo gives monochromatic peak
- decays in other galaxies add up to continuum due to redshifts



string

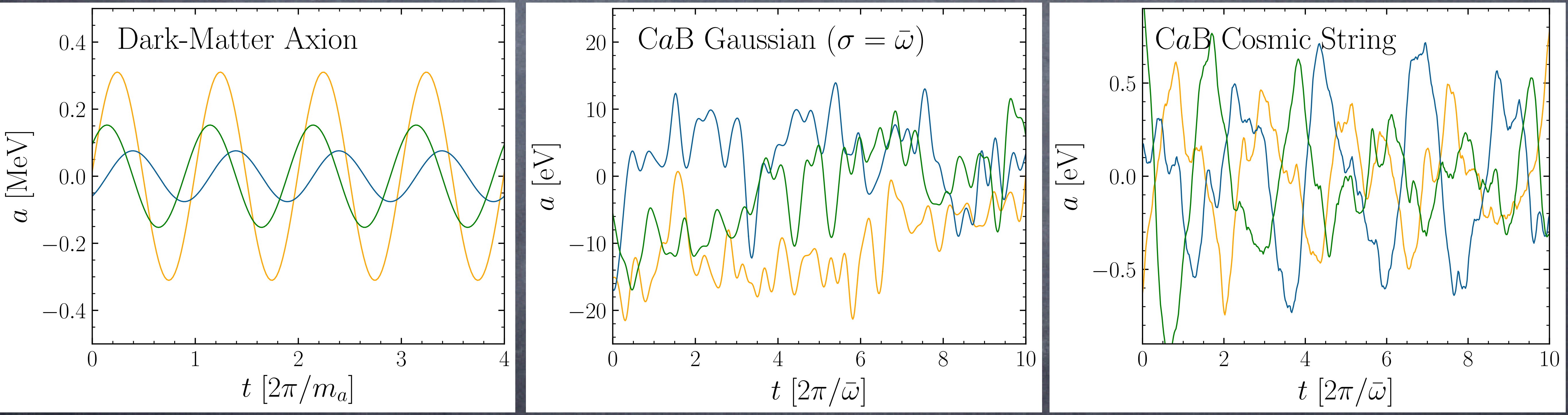
- relied on simulation for QCD strings by M. Gorghetto, E. Hardy, G. Villadoro, 1806.04677, 2007.04990
- depends on decoupling temperature
- assumed PMF=0



Can we detect CaB?

- assume $aF\tilde{F}$
- dark matter $v \sim 10^{-3}$ with narrow frequency distribution $E=\hbar\omega=m_a c^2+m_a v^2/2$
- axion experiments focus on very narrow frequency range and scan
- relativistic axion spread out in frequencies
- interactions need to be worked out without assuming non-relativistic

frequency spectrum



Maxwell equations

$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\partial_t \mathbf{B}$$

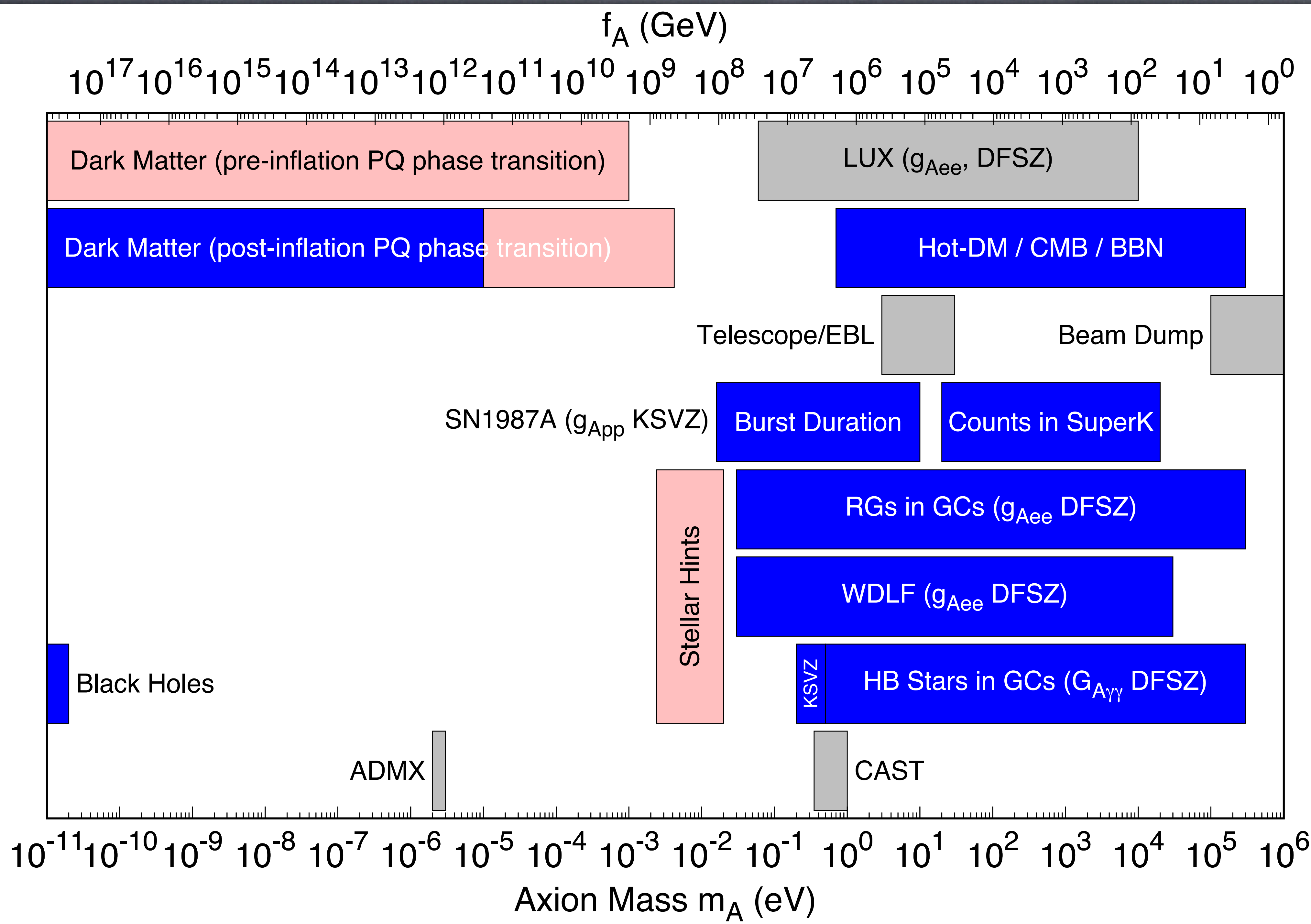
$$\nabla \times \mathbf{B} = \partial_t \mathbf{E} + \mathbf{J} + g_{a\gamma\gamma} \left(\mathbf{B}\, \partial_t a - \mathbf{E} \times \nabla a\right)$$

$$(\Box + m_a^2) a = g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B}$$

$$\rho = -g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\mathbf{J} = g_{a\gamma\gamma} (\mathbf{B}\, \partial_t a - \mathbf{E} \times \nabla a)$$

QCD axion

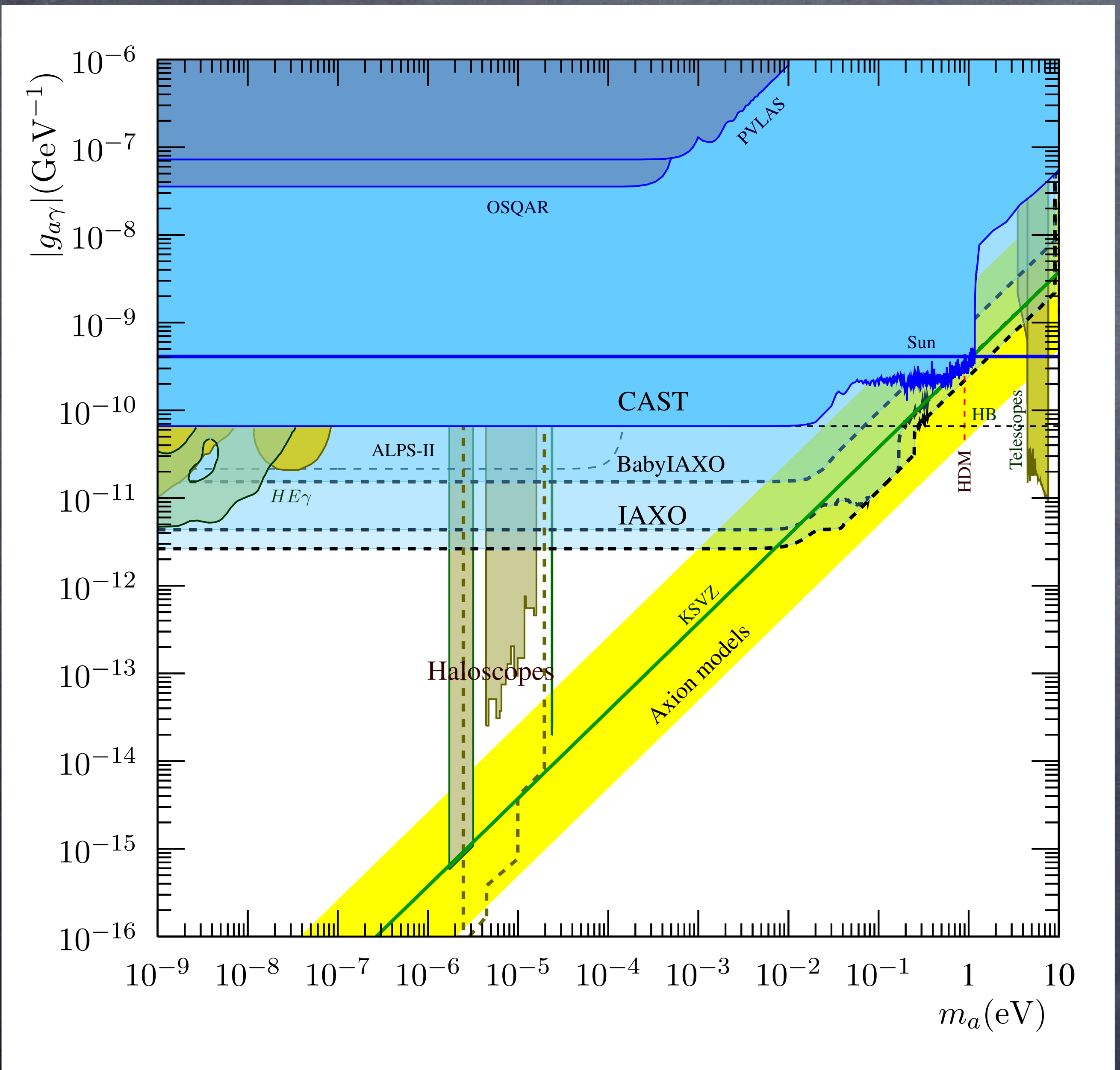


$m_a = m_\pi f_\pi / f_a$ [eV]

a × B → γ

Use the effective coupling

$$\mathcal{L}_{eff} \sim \frac{e^2}{4\pi^2}\frac{a}{f_a}\vec{E}\cdot\vec{B}$$



Results from phase 1 of the HAYSTAC microwave cavity axion experiment

L. Zhong,[1] S. Al Kenany,[2] K. M. Backes,[1,*] B. M. Brubaker,[1] S. B. Cahn,[1] G. Carosi,[3] Y. V. Gurevich,[1] W. F. Kindel,[4] S. K. Lamoreaux,[1] K. W. Lehnert,[4] S. M. Lewis,[2] M. Malnou,[4] R. H. Maruyama,[1] D. A. Palken,[4] N. M. Rapidis,[2] J. R. Root,[2] M. Simanovskaia,[2] T. M. Shokair,[2] D. H. Speller,[1] I. Urdinaran,[2] and K. A. van Bibber[2]

[1]*Department of Physics, Yale University, New Haven, Connecticut 06511, USA*

[2]*Department of Nuclear Engineering, University of California Berkeley, Berkeley, California 94720, USA*

[3]*Physical and Life Sciences Directorate, Lawrence Livermore National Laboratory, Livermore, California 94551, USA*

[4]*JILA and the Department of Physics, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309, USA*

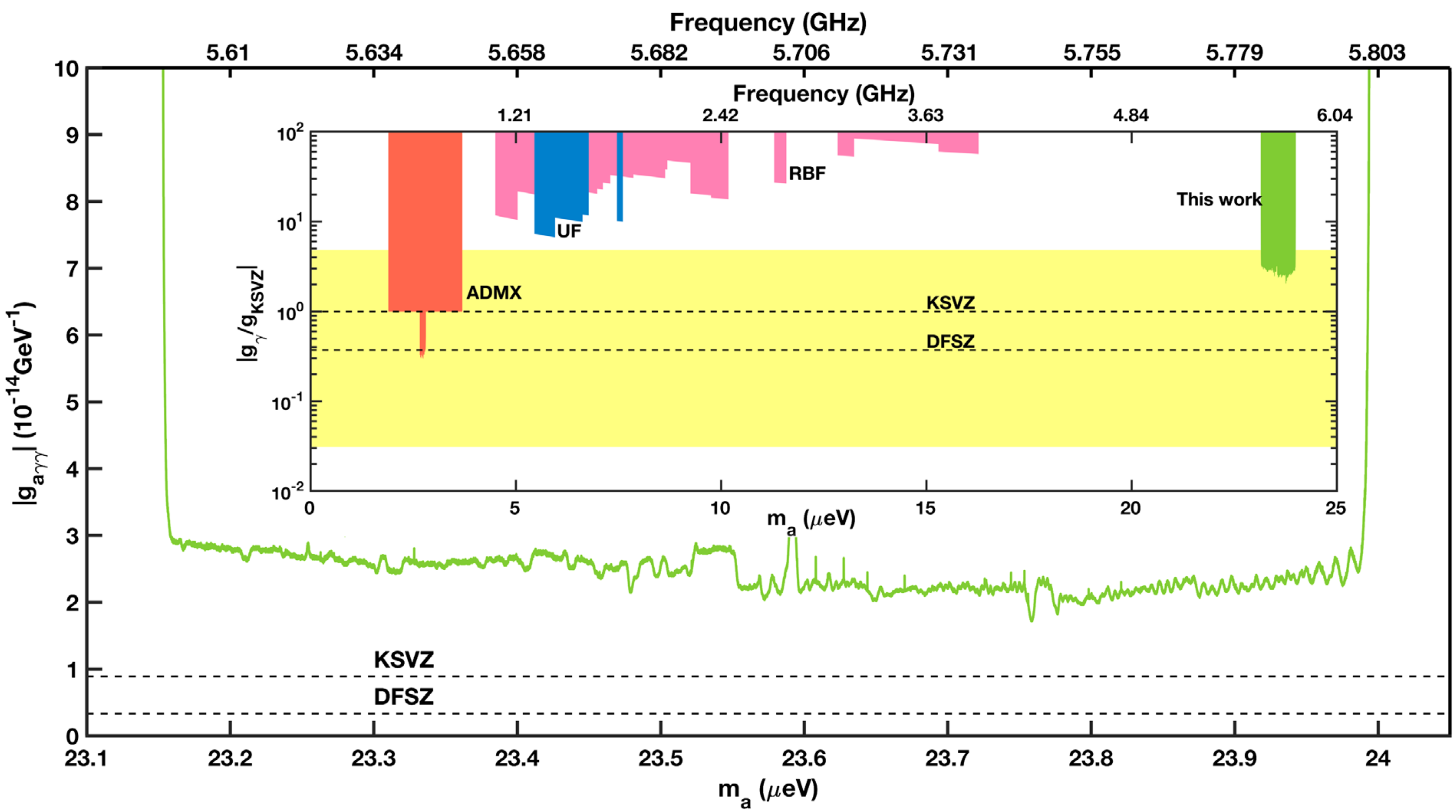
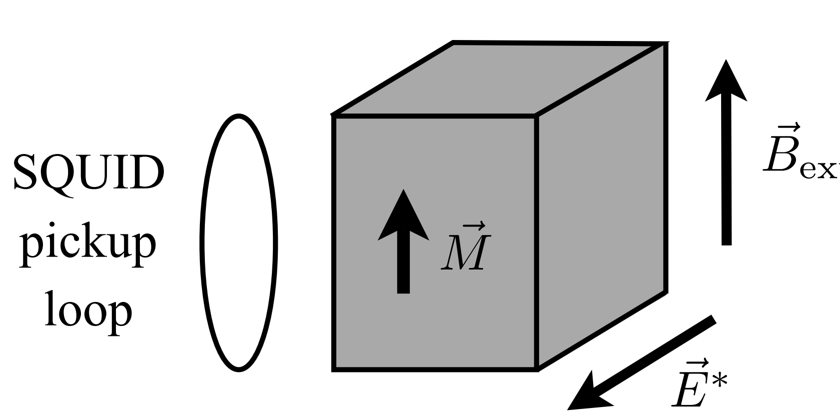


FIG. 4. Our exclusion limit at 90% confidence. Green represents this work combined with our previous results presented in Ref. [15]. Red represents previous cavity limits from ADMX [21–24], pink represents results from Brookhaven [25], and blue represents results from the University of Florida [26]. The axion model band is shown in yellow [27]. The KSVZ [11,12] and DSVZ [28,29] couplings are plotted as dashed lines.

Cosmic Axion Spin Precession

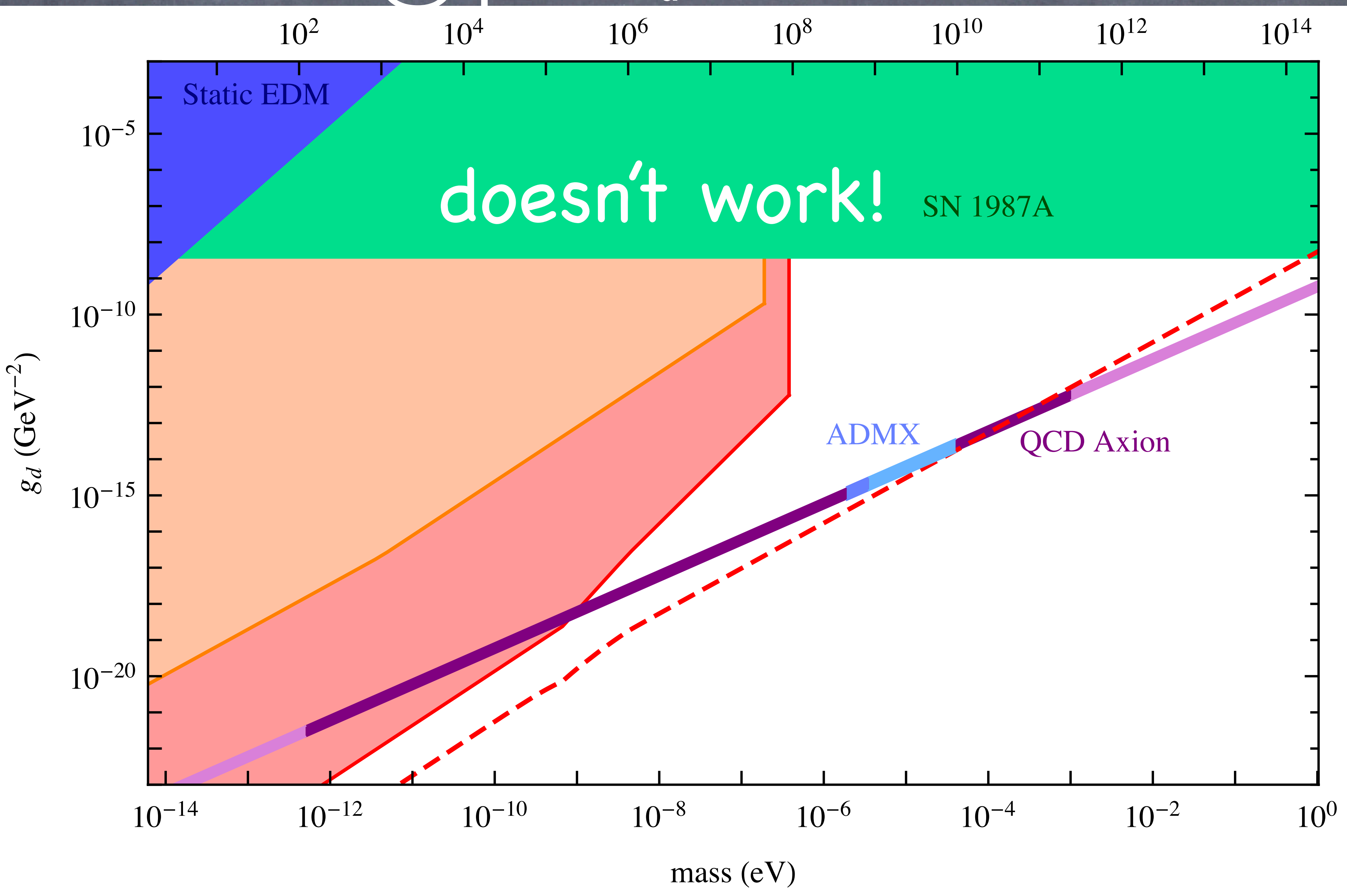
$$H_{eff}(t) = -\vec{\mu}\cdot\vec{B} - \frac{m_u}{m_{\rm const}^2}\sin(m_a t)\times\vec{s}_n\cdot\vec{E}$$



coherent $a(t)=a_0 \sin m_a t$

resonance @ $\mu B=m_a$

Budker et al
arXiv:1306.6089



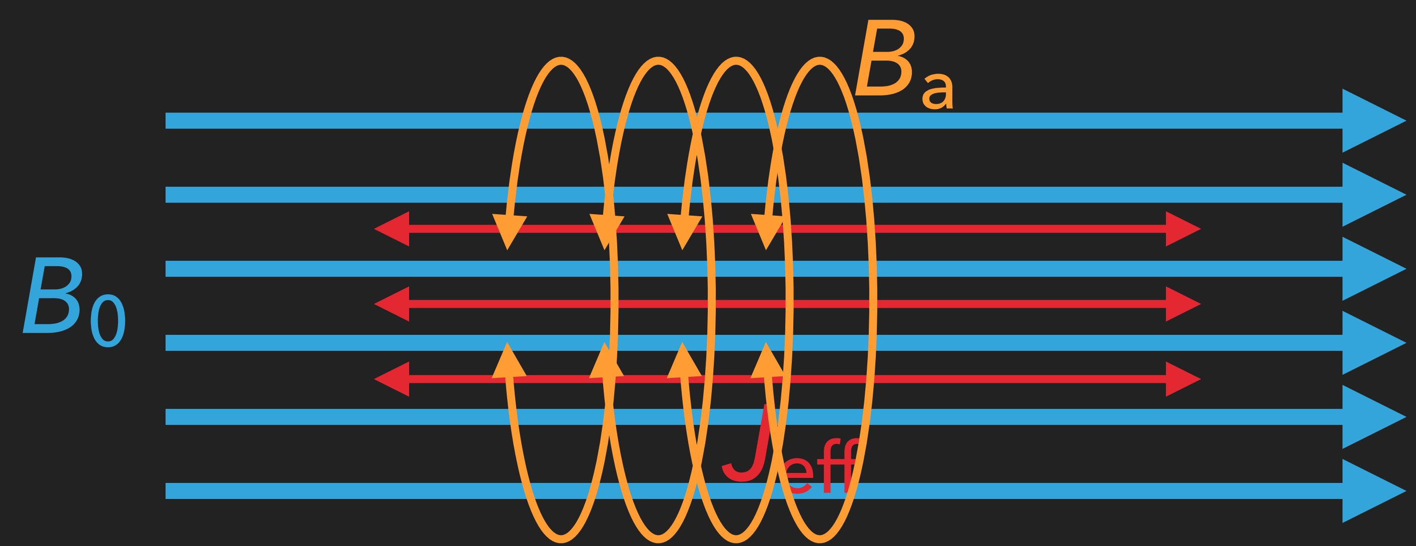
An Axion In a Magnetic Field

- Modification to Ampere's law (MQS approximation)

$$\nabla \times \mathbf{B} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$

- An oscillating axion field creates an "effective current" in the presence of a magnetic field

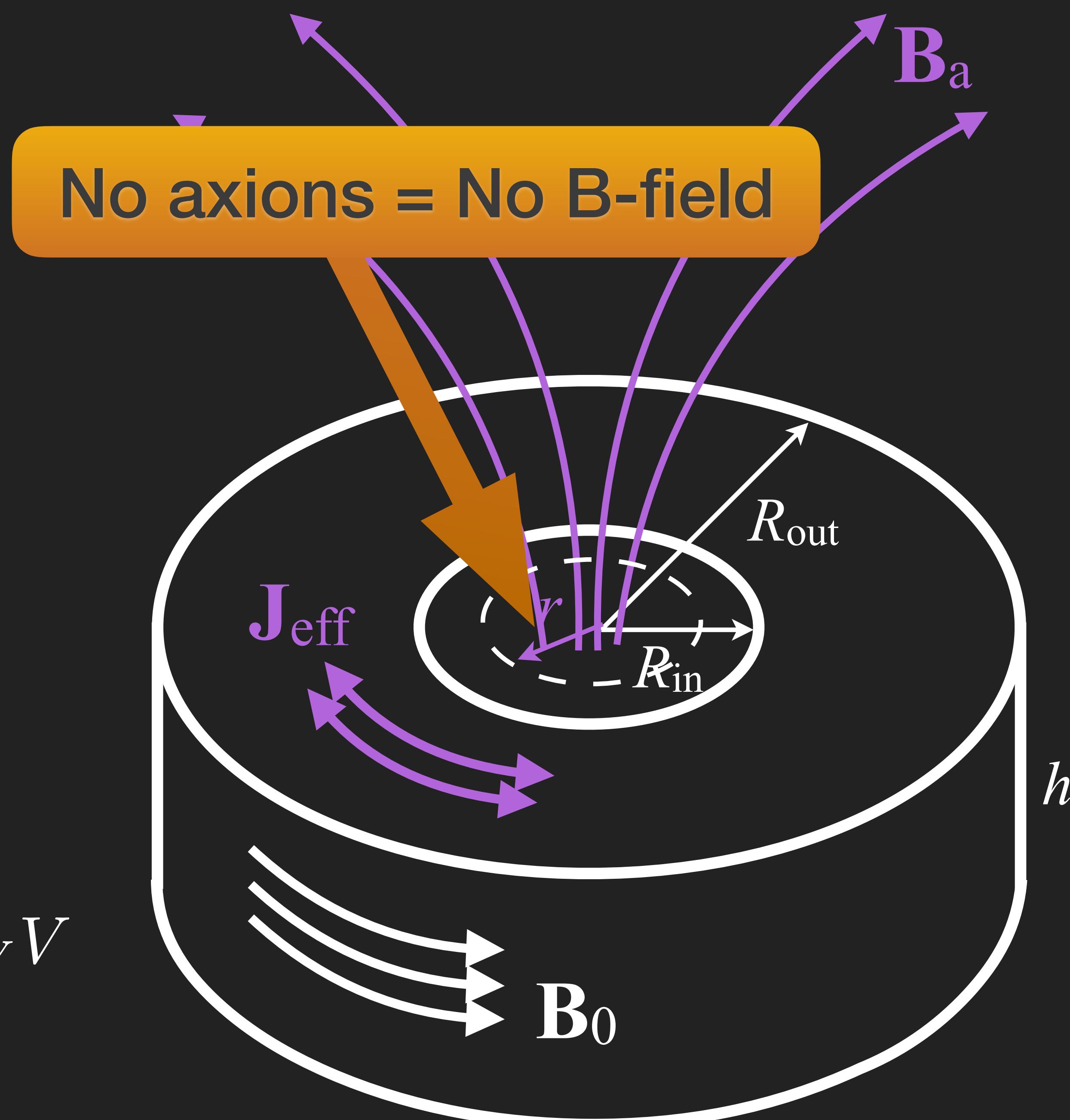
$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\partial a}{\partial t} \mathbf{B}$$



A Broadband/Resonant Approach to Cosmic Axion Detection with an Amplifying B-Field Ring Apparatus

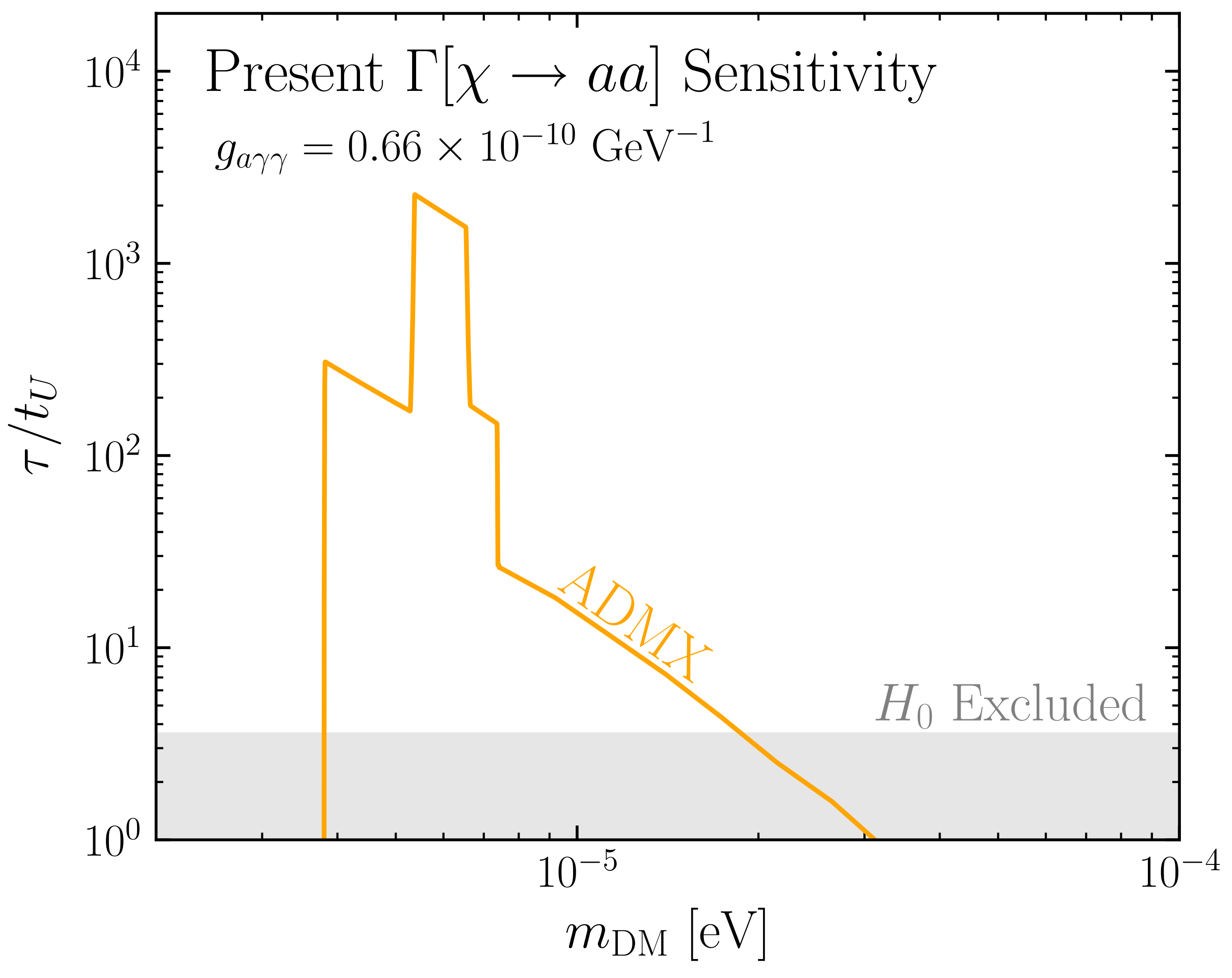
- Start with a toroidal magnet with a fixed magnetic field B_0
- ADM generates an oscillating effective current around the ring (MQS approx: $\lambda \gg R$)
- … this generates an oscillating magnetic field through the center of the toroid
- Insert a pickup loop in the center and measure the induced current in the loop read out by a SQUID based readout

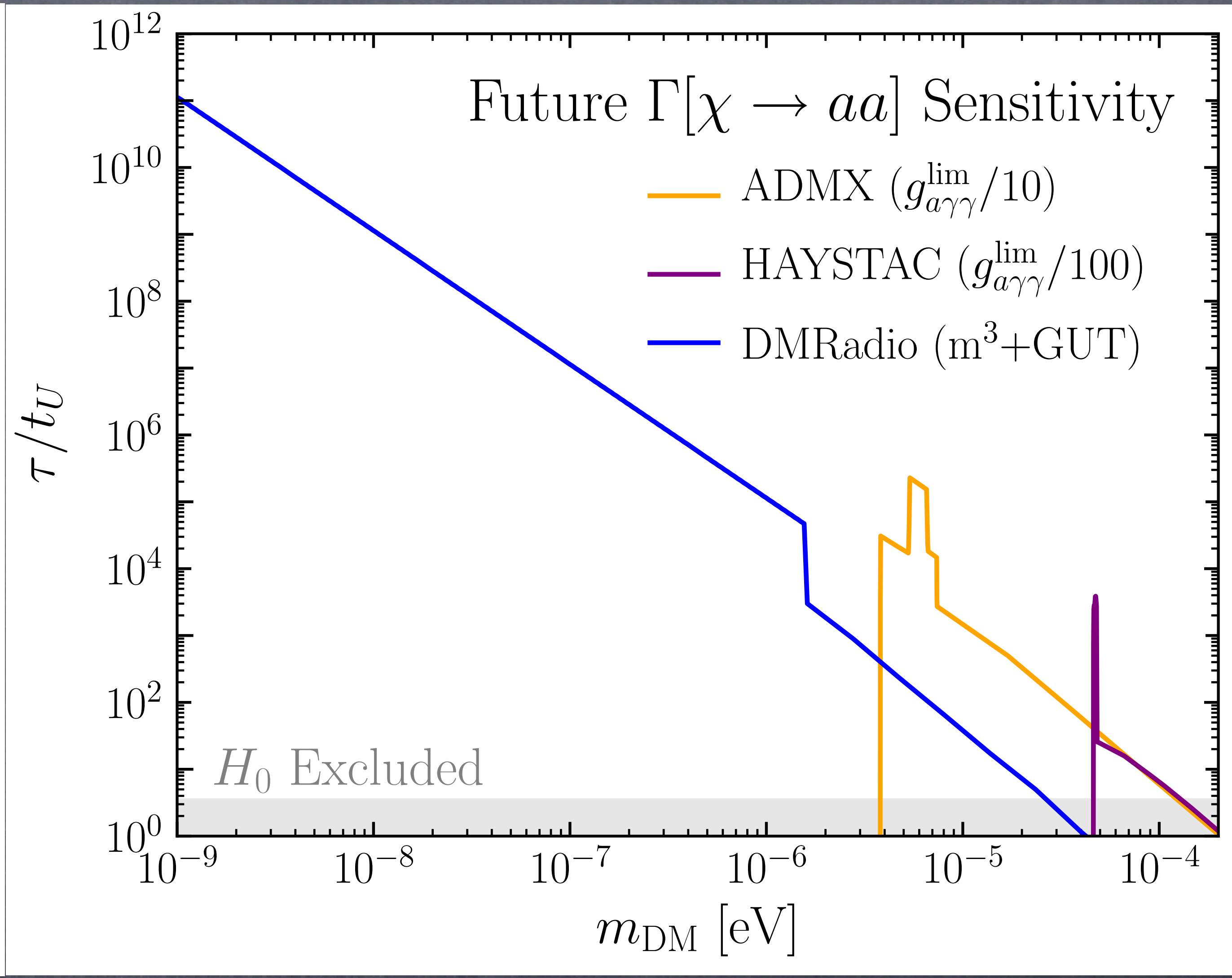
$$\Phi(t) = g_{a\gamma\gamma} B_{\max} \sqrt{2\rho_{\mathrm{DM}}} \cos(m_a t) \mathcal{G}_V V$$



Phys. Rev. Lett. 117, 141801 (2016)

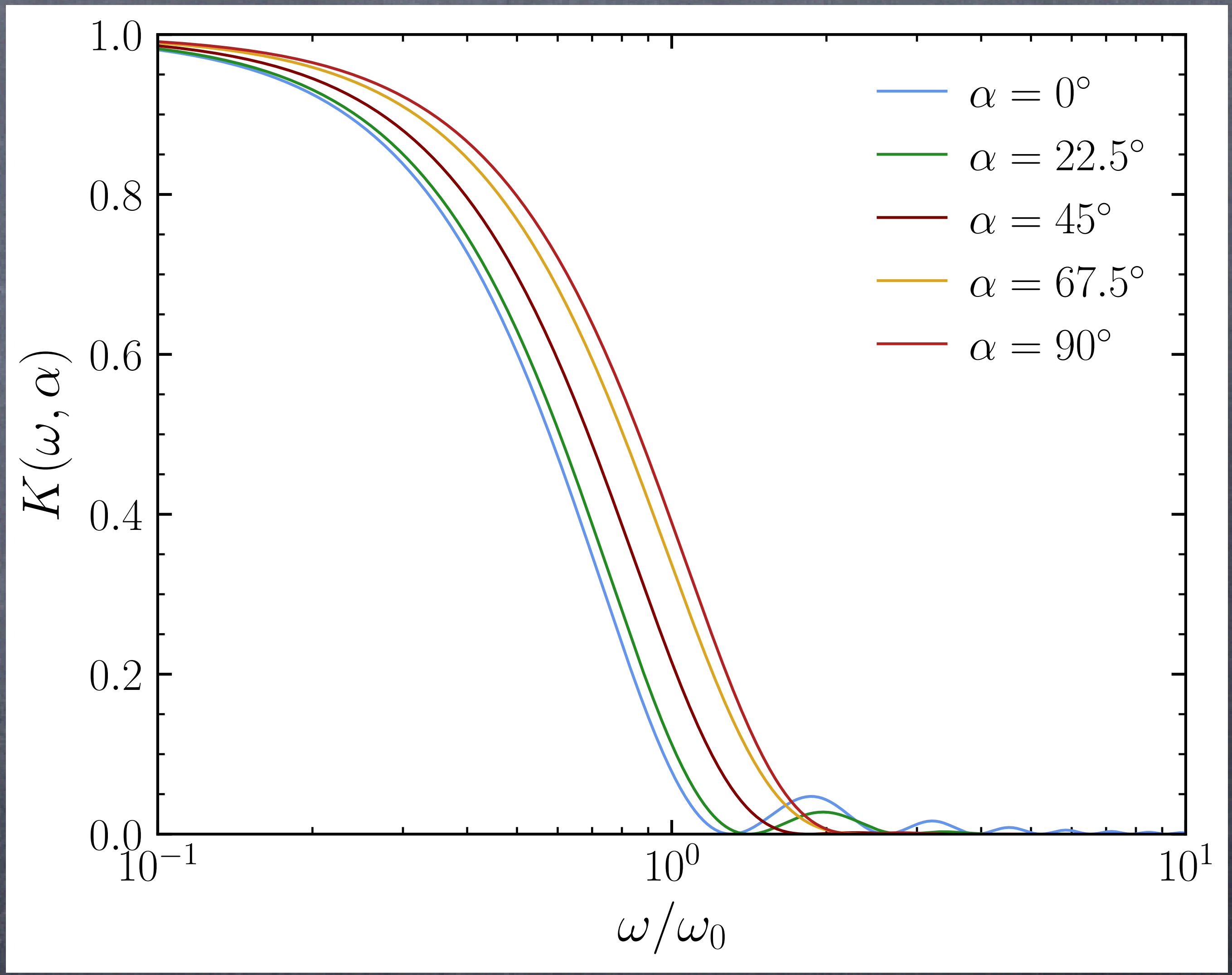
dark matter decay



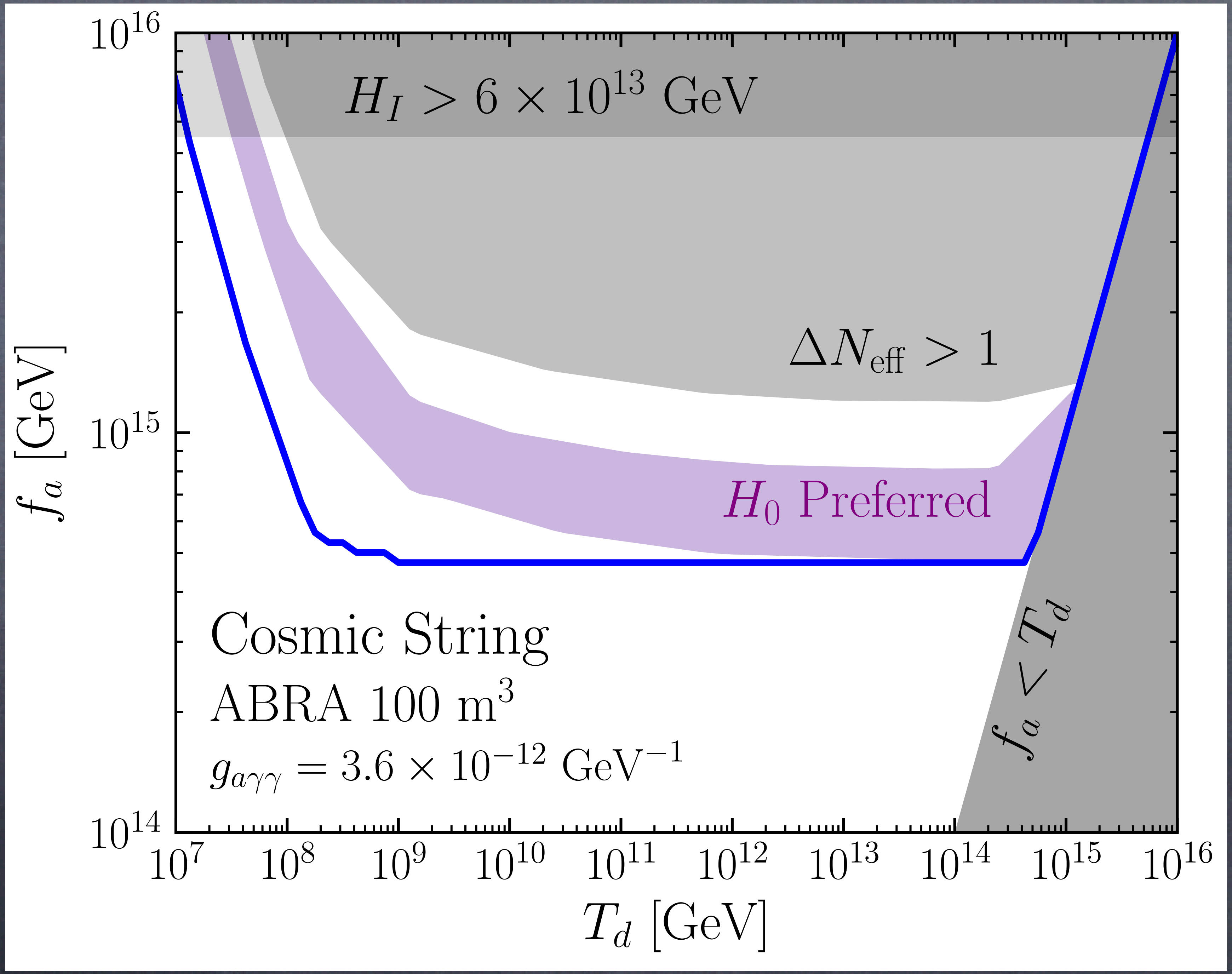


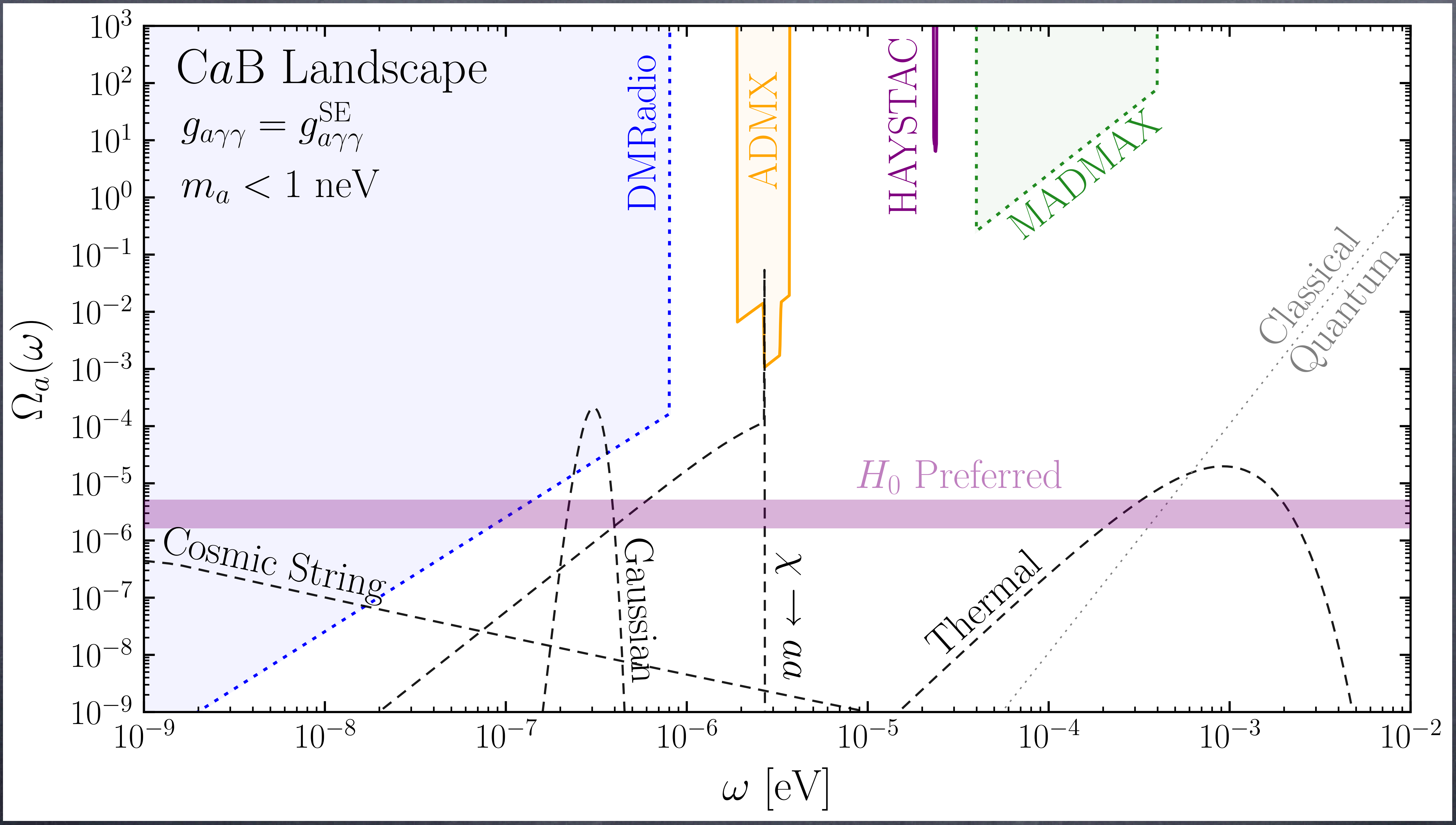
daily modulation

- detection rate depends on the incident angle
- e.g. ADMX
- dark matter concentrated in galactic center
- expect daily modulation



string


$H_I > 6 \times 10^{13}$ GeV
$\Delta N_{\rm eff} > 1$
H_0 Preferred
Cosmic String
ABRA 100 m^3
$g_{a\gamma\gamma} = 3.6 \times 10^{-12}$ GeV^{-1}
$f_a < T_d$
f_a [GeV]
T_d [GeV]
10^{14}
10^{15}
10^{16}
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}


CaB Landscape
$g_{a\gamma\gamma} = g_{a\gamma\gamma}^{\rm SE}$
$m_a < 1$ neV
DMRadio
ADMX
HAYSTAC
MADMAX
Classical
Quantum
H_0 Preferred
Cosmic String
Gaussian
$\chi \to aa$
Thermal
$\Omega_a(\omega)$
ω [eV]
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}

Conclusions

- CaB detection is not easy
  - we've not detected C ν B either!
- possible for
  - dark matter decay
  - string
- requires different analysis strategy
- potential daily modulation

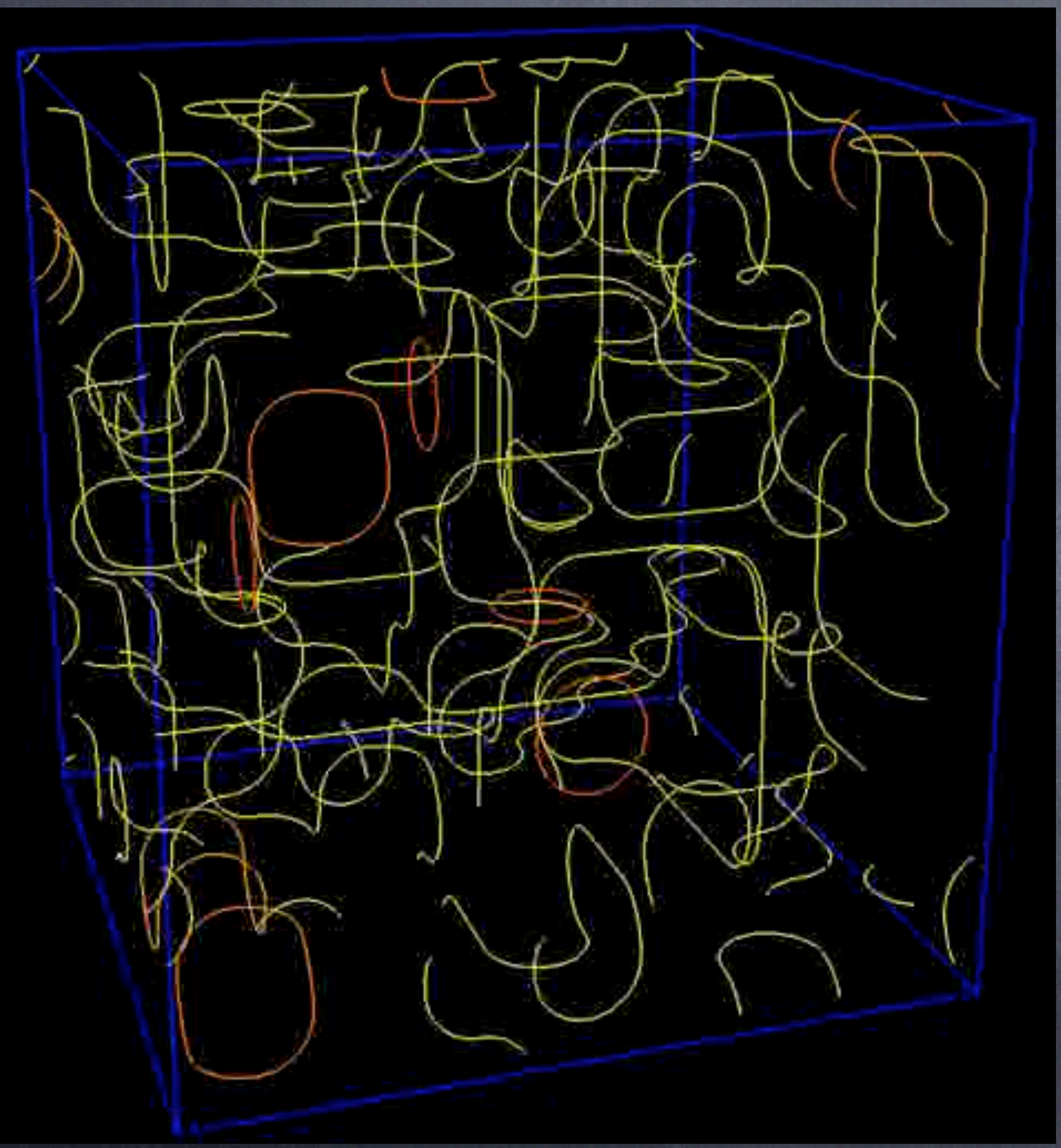
axion string is superconducting

Hajime Fukuda, Aneesh Manohar, HM, Ofri Telem, 2010.02763

QCD axion string

- axion is Nambu-Goldstone boson of spontaneously broken $U(1)_{PQ}$ symmetry
- if broken after inflation, creates cosmic string by Kibble-Zurek mechanism
- $U(1)_{PQ}$ anomalous, strings ultimately unstable
- if there is an exact (non-anomalous) Z_N subgroup of $U(1)_{PQ}$ also domain walls
  - dominates the universe, disaster
- not possible for DFSZ. Assume KSVZ
- consider minimal PQ fermions: one triplet

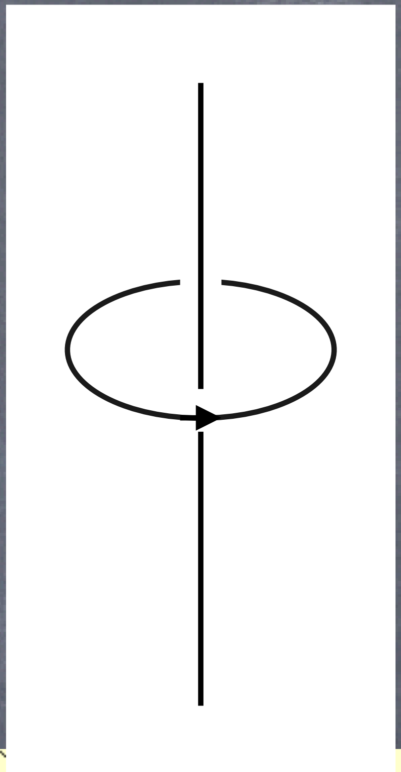
scaling behavior

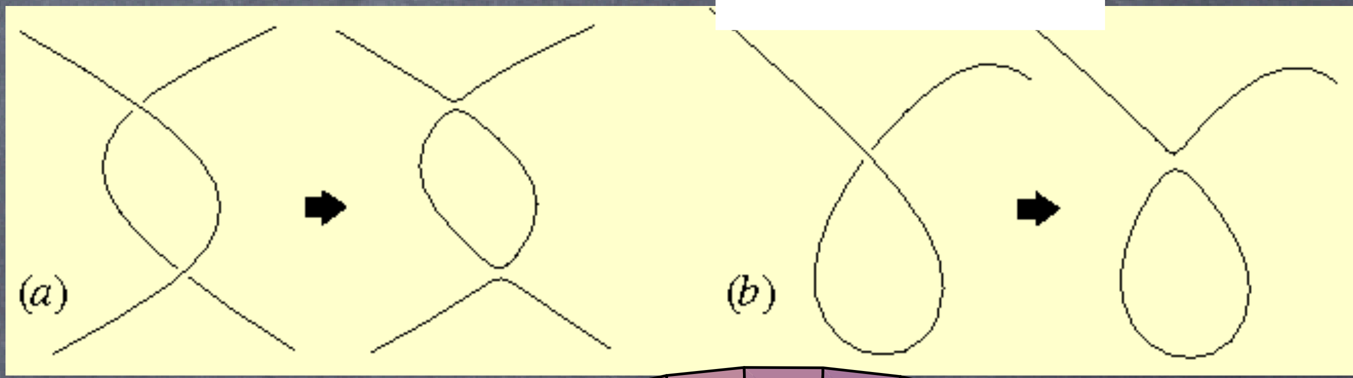


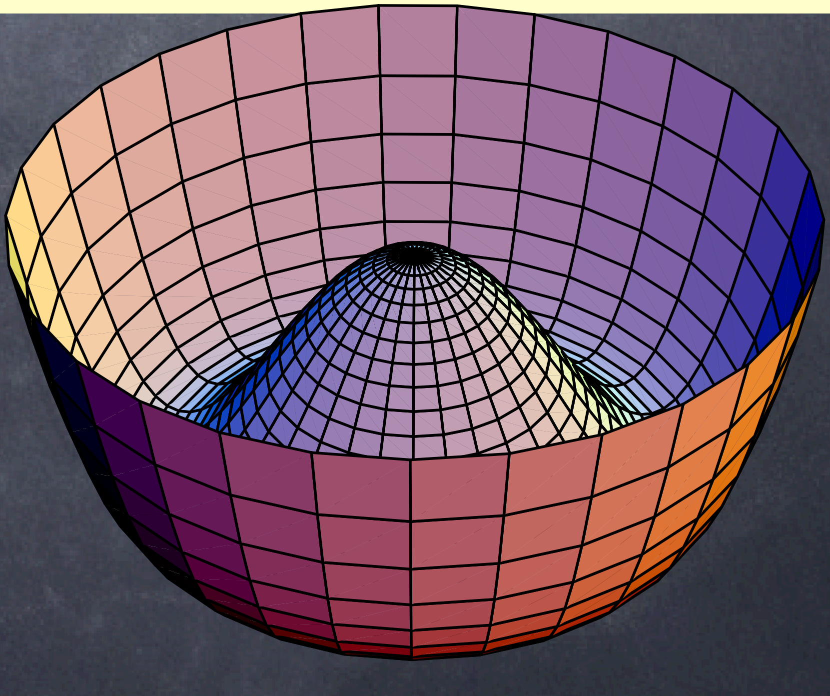
$$\phi(\theta) = f_a e^{i\theta}$$

$$\phi = f_a e^{ia/f_a}$$

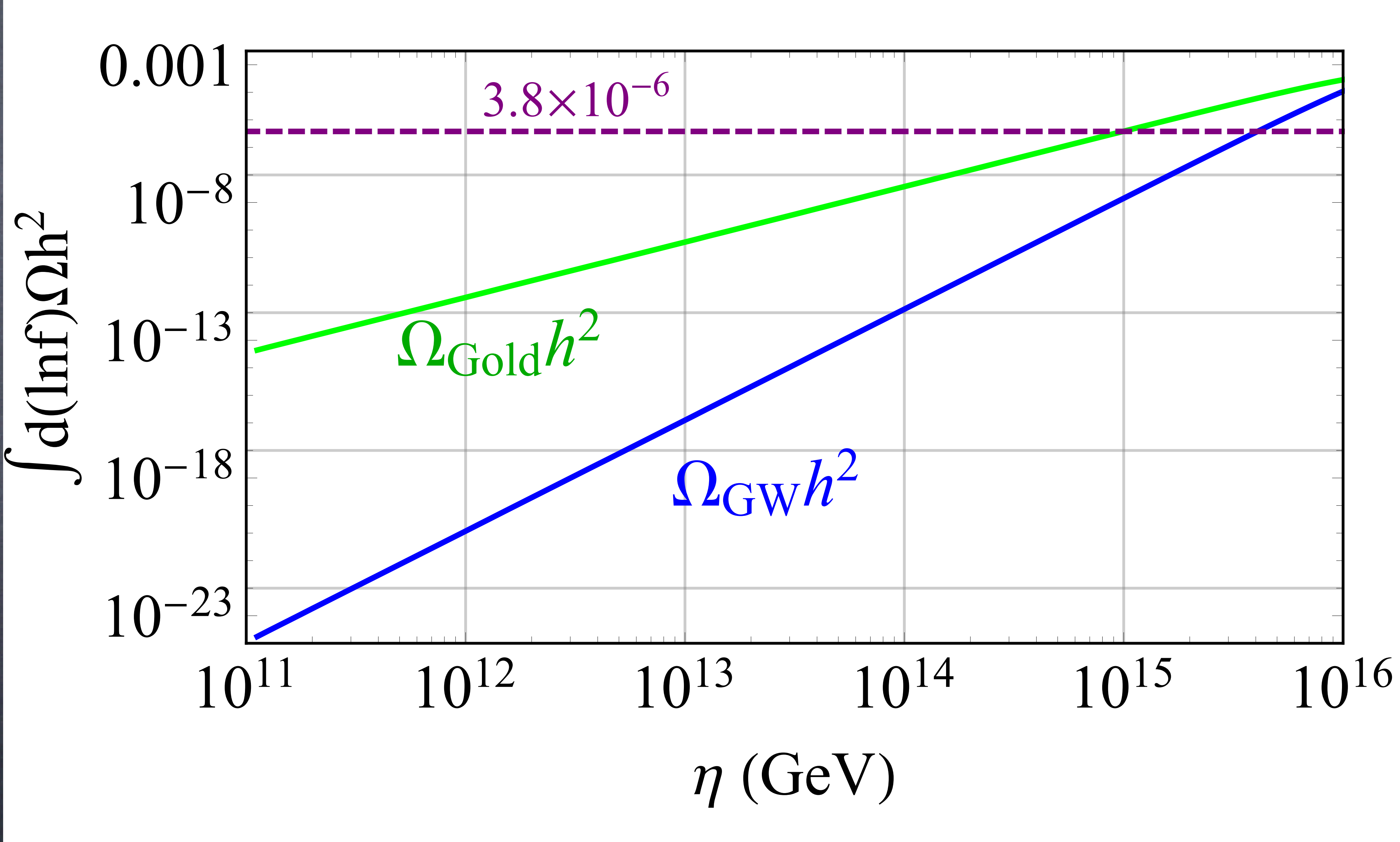
$$a = f_a \theta$$





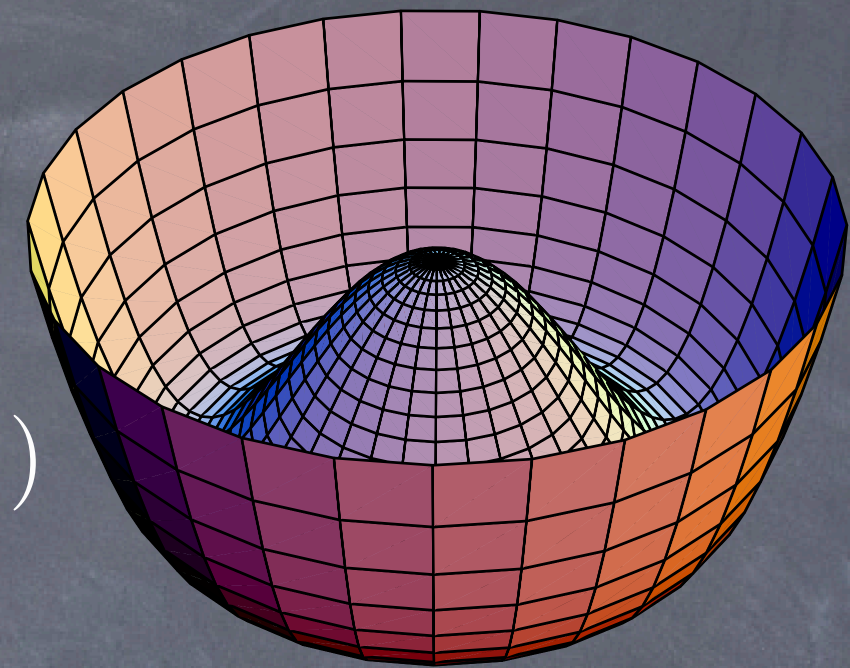


axion vs GW



Chang, Cui, 1910.04781

KSVZ axion



$$\mathcal{L}_{UV} = \lambda(\phi^*\phi - f_a^2)^2 - y_Q(\phi\bar{Q}_L Q_R + c.c.)$$

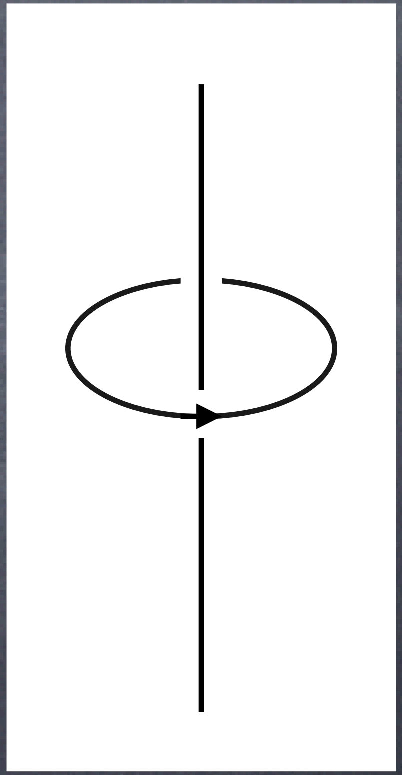
- integrate out massive Q

$$\mathcal{L}_{eff} = \frac{g_s^2}{16\pi^2 f_a} a \mathrm{Tr} G\tilde{G} + \frac{N_C q_Q^2 e^2}{16\pi^2 f_a} a F\tilde{F}$$

$$a = f_a \theta$$

- new contribution to the EM current

$$j^\mu = -\frac{\mathcal{L}_{eff}}{\delta A_\mu} = -\frac{N_C q_Q^2 e^2}{4\pi^2 f_a}\tilde{F}^{\mu\nu}\partial_\nu a$$

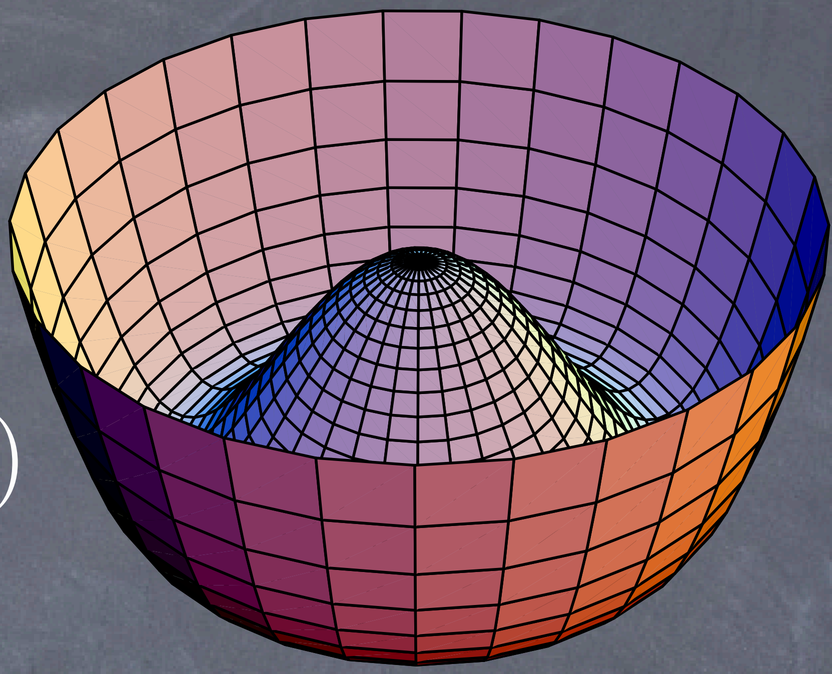


- EM current not conserved??

$$\partial_\mu j^\mu = -\frac{\mathcal{L}_{eff}}{\delta A_\mu} = -\frac{N_C q_Q^2 e^2}{4\pi^2 f_a}\tilde{F}^{\mu\nu}\partial_\mu\partial_\nu a$$

$$= -\frac{N_C q_Q^2 e^2}{4\pi^2 f_a}\tilde{F}^{12}\partial_\mu 2\pi f_a \delta^2(x) = -\frac{N_C q_Q^2 e^2}{2\pi} F^{03}\delta^2(x) \neq 0$$

KSVZ axion



$$\mathcal{L}_{UV} = \lambda(\phi^*\phi - f_a^2)^2 - y_Q(\phi\bar{Q}_L Q_R + c.c.)$$

$$\partial_\mu j^\mu = -\frac{\mathcal{L}_{\mathit{eff}}}{\delta A_\mu} = -\frac{N_C q_Q^2 e^2}{4\pi^2 f_a}\tilde{F}^{\mu\nu}\partial_\mu\partial_\nu a \qquad a = f_a\theta$$

$$= -\frac{N_C q_Q^2 e^2}{4\pi^2 f_a}\tilde{F}^{12}\partial_\mu 2\pi f_a \delta^2(x) = -\frac{N_C q_Q^2 e^2}{2\pi}F^{03}\delta^2(x) \neq 0$$

- then not gauge-invariant??
- implies massless chiral fermion on the string that cancels the anomaly
- similar to edge state in FQHE
- in the UV description, it is the zero mode of PQ fermion Q on the string

Witten, Callan, Goldstone-Wilczek, ...

superconducting string

- chiral massless fermion on the string

$$\partial_\mu j^\mu = \frac{N_C q_Q^2 e^2}{2\pi} E_z \neq 0$$

- translational invariance along the z direction

$$\partial_t \rho = \partial_t j_z = \frac{N_C q_Q^2 e^2}{2\pi} E_z \neq 0$$

$$\rho = j = \frac{N_C q_Q^2 e^2}{2\pi} E_z t$$

- build-up of charge and current: London eq
- superconducting!

current dissipation

$$\mathcal{L}_{UV} = \lambda(\phi^*\phi - f_a^2)^2 - y_Q(\phi\bar{Q}_L Q_R + c.c.) - y_q\bar{Q}_R q_L H$$

+1 -1 0

- heavy Q would overclose the Universe
- Q needs to decay to SM
- H or q_R hitting the string and knocking out the zero mode of Q from the string
- dissipation stops below the temperature

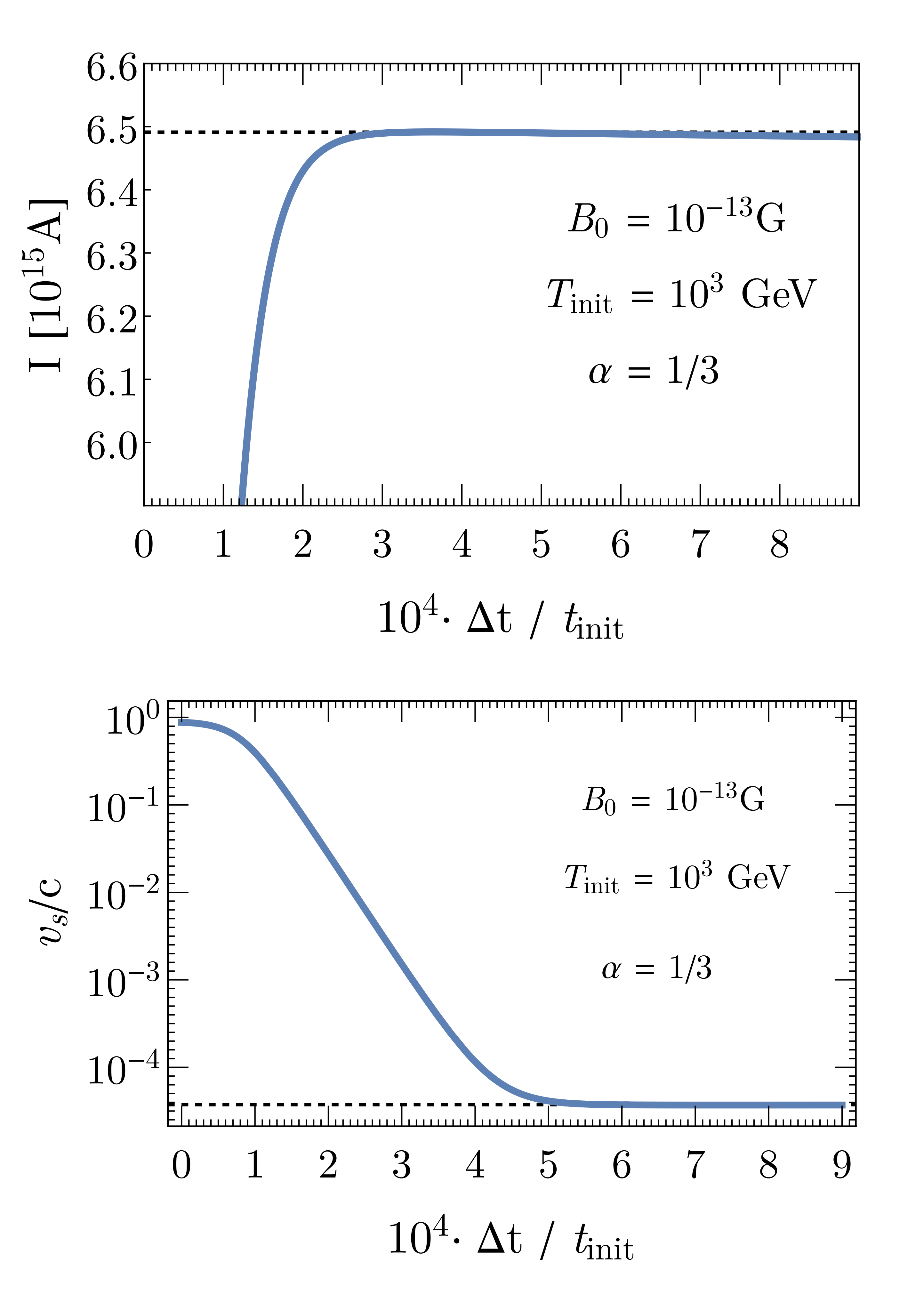
$$T_X = \left(3.8\times 10^2\,\mathrm{GeV}\right)\frac{1}{y}\left(\frac{f_a}{10^{10}\,\mathrm{GeV}}\right)^4\left(\frac{10^{10}\,\mathrm{GeV}}{I/(N_c e_\psi)}\right)^2\left(\frac{y_\Phi^2 g_\star^{1/2}}{h_\star}\right)$$

primordial magnetic field

- the origin of intergalactic magnetic field $B \approx 10 \mu G$ is not understood
- possible primordial magnetic field from phase transition
- string moves in the magnetic field
- string sees the electric field
- leads to build up of charge

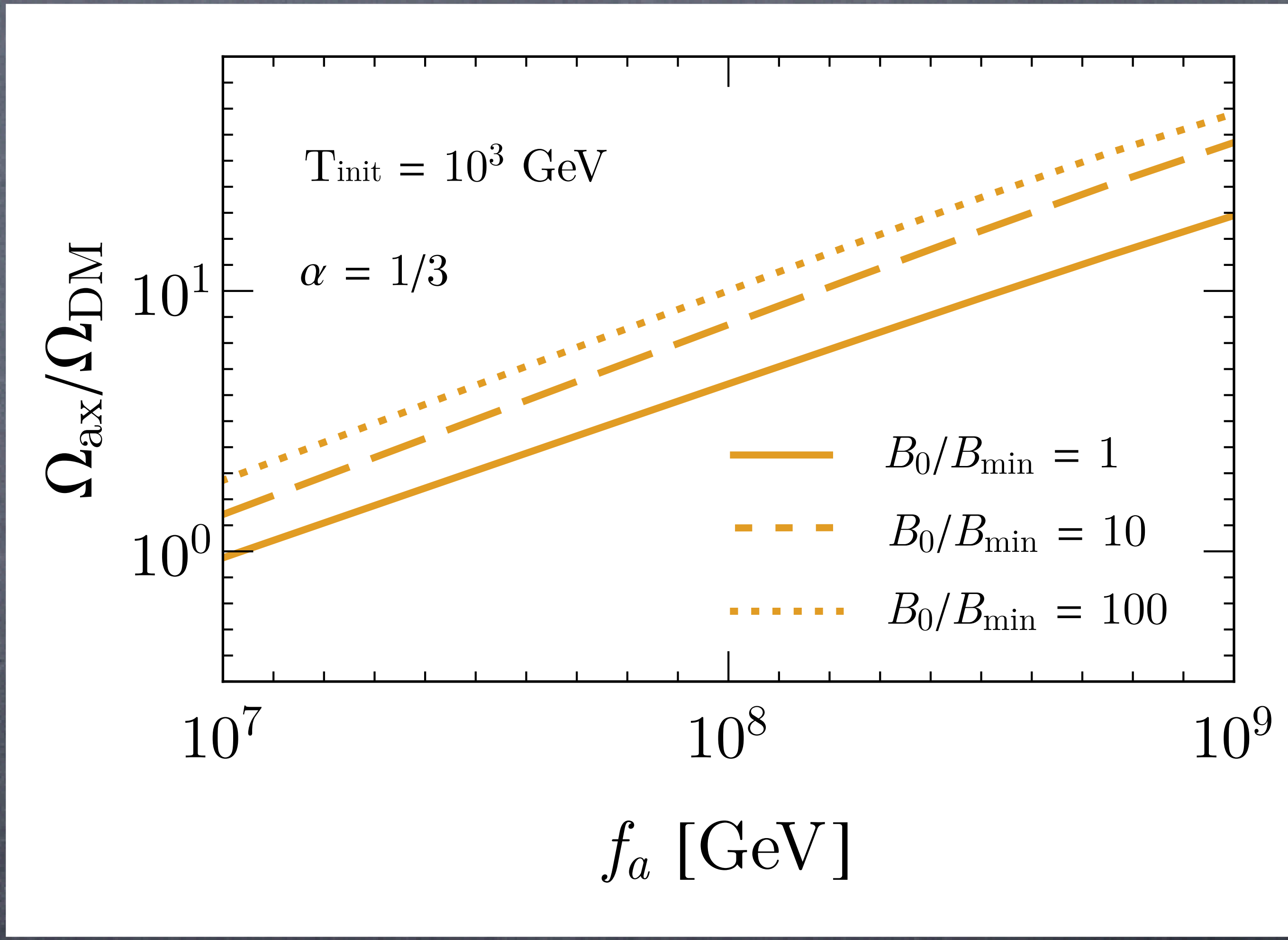
friction

- once string charged, friction in plasma
- string does not move freely to simplify its network
- does not reach scaling, disappears much more slowly
- leads to denser network
- leads to much more axions



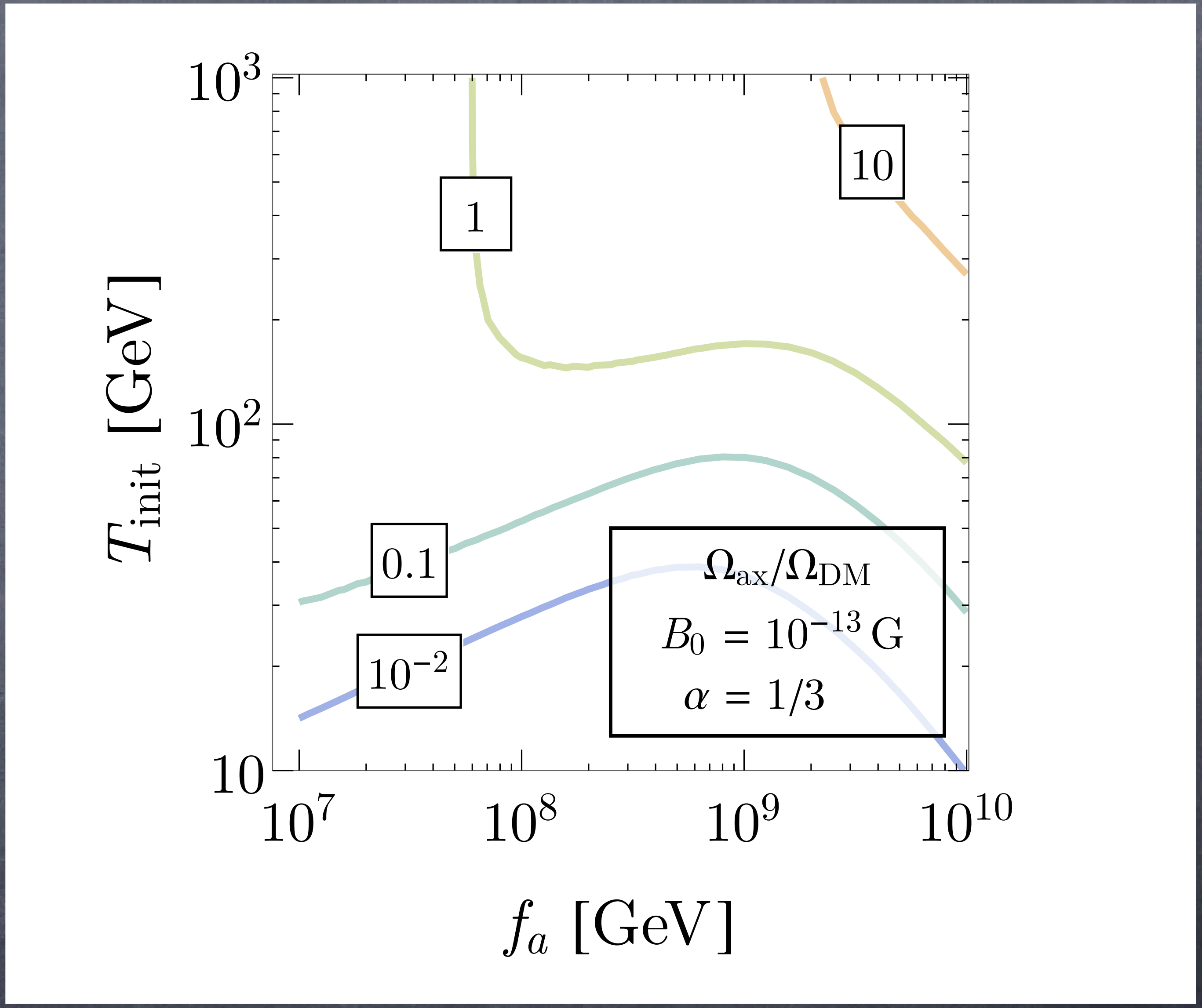
axion abundance

- normally dark matter axion from misalignment $f_a > 10^{12}$ GeV
- Here, $f_a \approx 10^7$ GeV
- tension with astrophysical bounds $f_a \gtrsim 10^9$ GeV
- needs simulation for more detailed study



axion abundance

- If T_{init} < 100 GeV or so, higher f_a allowed
- challenge to models of PMF generation



Conclusion

- axion string is superconducting (generic for all axion-like particles with $aF\tilde{F}$ coupling)
- QCD axion string needs minimal KSVZ model
- with PMF, charge builds up, creates friction in string motion, enhances axion abundance
- other consequences?