Late-time magnetogenesis with ALP dark matter and dark photon

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KC, Hyungjin Kim, Toyokazu Sekiguchi, [arXiv:1802.0xxxx]

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Outline

- Introduction
- Latetime magnetogenesis driven by axion-like particle constituting dark matter, and hidden U(1) gauge boson
- Conclusion

Magnetic fields are ubiquitous in the Universe.

B fields at large scales:

* Galactic B fields $B \sim 1 - 10\,\mu\mathrm{G}$ which may originate from a tiny seed field amplified by dynamo, compression, … *[For a review, Durrer, Neronov '13]*

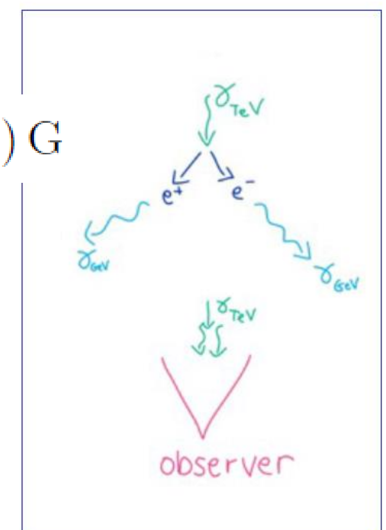
$$B_{\rm seed} \gtrsim \mathcal{O}(10^{-30})\,\mathrm{G} \quad (\lambda \gtrsim \mathcal{O}(0.1)\,\mathrm{kpc})$$

[Davis, Lilley, Tornkvist '99]

* Intergalactic B fields which may explain the lack of secondary GeV gamma rays in TeV blazar observations:

$$B_{\rm void} \times \min[1, \sqrt{\lambda/0.1\mathrm{Mpc}}] \gtrsim \mathcal{O}(10^{-19} - 10^{-16})\,\mathrm{G}$$

[Finke et al '15; Wood et al '17]



[Horan]

It is an interesting possibility that those large scale B fields have a cosmological origin related to BSM physics.

* Inflationary magnetogenesis *[Turner, Widrow '88; Ratra '92, ...]*

Inflaton couplings: $\sigma F^{\mu\nu} F_{\mu\nu},\ \sigma F^{\mu\nu} \tilde{F}_{\mu\nu}, \ldots$

Implications, constraints, ... are still under active investigation.

[Barnaby et al '12; Ferreira et al '14; Fujita et al '15; Adshead et al '16; Caprini et al '17; ...]

* Phase transition *[Vachaspati '91; Enqvist, Olesen '93, ...]*

Bubble dynamics in 1st order phase transition, topological defects, ...

However, lack of concrete model

Less explored possibility:

Cosmological magnetogenesis by BSM physics might occur much later, e.g. well after the BBN, as suggested by large coherent length scale.

Late-time magnetogenesis after the electron/positron annihilations driven by ALP dark matter ϕ & hidden U(1) gauge boson X_μ

[KC, H. Kim, T. Sekiguchi]

$$\mathcal{L}_{\rm eff} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$
$$- \frac{g_{\rm AA}}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{\rm XX}}{4f}\phi X_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{g_{\rm AX}}{2f}\phi F_{\mu\nu}\tilde{X}^{\mu\nu} + J^\mu_{\rm em}A_\mu$$
$$(\phi_{\rm initial} \equiv f)$$

1) Coherent oscillation of ALP

2) Exponential amplification of X by oscillating ALP

3) Conversion of X to A

Equations of motion:

$$ds^2 = a^2(\tau)(d\tau^2 - d\boldsymbol{x}^2) \qquad \left(\mathcal{H} = \frac{\dot{a}}{a} = \frac{da/d\tau}{a}\right)$$

$$\ddot{\phi} + 2\mathcal{H}\dot{\phi} - \nabla^2\phi + a^2 m_\phi^2 \phi = -\frac{1}{a^2}\left(\frac{g_{AA}}{f}\dot{\boldsymbol{A}}\cdot\nabla\times\boldsymbol{A} + \frac{g_{XX}}{f}\dot{\boldsymbol{X}}\cdot\nabla\times\boldsymbol{X} + \frac{g_{AX}}{f}(\dot{\boldsymbol{A}}\cdot\nabla\times\boldsymbol{X} + \dot{\boldsymbol{X}}\cdot\nabla\times\boldsymbol{A})\right)$$

$$\ddot{\boldsymbol{A}} + \sigma\left(\dot{\boldsymbol{A}} + \boldsymbol{v}\times(\nabla\times\boldsymbol{A})\right) + \nabla\times(\nabla\times\boldsymbol{A}) = \frac{g_{AA}}{f}\left(\dot{\phi}\nabla\times\boldsymbol{A} - \nabla\phi\times\dot{\boldsymbol{A}}\right) + \frac{g_{AX}}{f}\left(\dot{\phi}\nabla\times\boldsymbol{X} - \nabla\phi\times\dot{\boldsymbol{X}}\right)$$

$$(A_\mu = (0, \mathbf{A}), \quad X_\mu = (0, \mathbf{X}), \quad \mathbf{J} = \sigma(\mathbf{E} + \mathbf{v}\times\mathbf{B}))$$

Conductivity of the cosmic plasma

$$\ddot{\boldsymbol{X}} + \nabla\times(\nabla\times\boldsymbol{X}) = \frac{g_{XX}}{f}\left(\dot{\phi}\nabla\times\boldsymbol{X} - \nabla\phi\times\dot{\boldsymbol{X}}\right) + \frac{g_{AX}}{f}\left(\dot{\phi}\nabla\times\boldsymbol{A} - \nabla\phi\times\dot{\boldsymbol{A}}\right),$$

Brief sketch of the mechanism

* Beginning of ALP oscillation when $3\mathcal{H}(\tau_{\rm osc})/a(\tau_{\rm osc}) \approx m_\phi$

$$\theta(\tau) \equiv \frac{\phi(\tau)}{f} \approx \left(\frac{a(\tau)}{a(\tau_{\rm osc})}\right)^{-3/2} \cos\left(m_\phi(t - t_{\rm osc})\right) \quad \left(t = \frac{a(\tau)\tau}{2}\right)$$

* Exponential amplification of X_μ by oscillating ALP:

$$\ddot{\boldsymbol{X}}_{k\pm} + k(k \mp g_{XX}\dot{\theta})\boldsymbol{X}_{k\pm} \simeq 0$$

$$\rightarrow \quad k \sim g_{XX}\dot{\theta} \sim g_{XX} m_\phi a(\tau_{\rm osc})$$

* Soon after $\tau_{\rm osc}$, ρ_X catches up ρ_ϕ and some fraction of the produced X_μ is converted to A_μ :

$$\sigma \dot{\boldsymbol{A}} \simeq g_{AX}\left(\dot{\theta}\nabla \times \boldsymbol{X} - \nabla\theta \times \dot{\boldsymbol{X}}\right)$$

$$\rightarrow \quad B \propto g_{AX}\frac{\dot{\theta}}{\sigma} \sim g_{AX}\frac{m_\phi}{\sigma_{\rm phys}} \quad \text{at} \quad \tau \sim \tau_{\rm osc} \qquad \left(\sigma_{\rm phy} = \frac{\sigma}{a(\tau)}\right)$$

The mechanism is most efficient when the conversion factor $\frac{m_\phi}{\sigma_{\rm phys}}$ at $\tau \sim \tau_{\rm osc}$ is maximal, but under the constraint $\lambda \gtrsim 0.1$ kpc.

$$\sigma_{\rm phy} \begin{cases} T & (T \gg m_e) \\ 10^{-9}\frac{m_e^2}{T} & (T \ll m_e) \end{cases} \qquad k \sim g_{XX} m_\phi a(\tau_{\rm osc}) \ \text{at} \ \tau \sim \tau_{\rm osc}$$

baryon/photon ratio

➔ $$\frac{m_\phi}{\sigma_{\rm phys}} \ \text{at} \ \tau \sim \tau_{\rm osc} \begin{cases} 10^{-22}\left(\frac{m_\phi}{10^{-16}{\rm eV}}\right)^{1/2} & (T_{\rm osc} \gg m_e \ \leftrightarrow \ m_\phi \gg 10^{-16}{\rm eV}) \\ 10^{-12}\left(\frac{m_\phi}{10^{-16}{\rm eV}}\right)^{3/2} & (T_{\rm osc} \ll m_e \ \leftrightarrow \ m_\phi \ll 10^{-16}{\rm eV}) \end{cases}$$

$$\frac{\lambda}{1\,{\rm kpc}} \sim \frac{1}{g_{XX}}\left(\frac{m_\phi}{10^{-16}{\rm eV}}\right)^{-1/2}$$

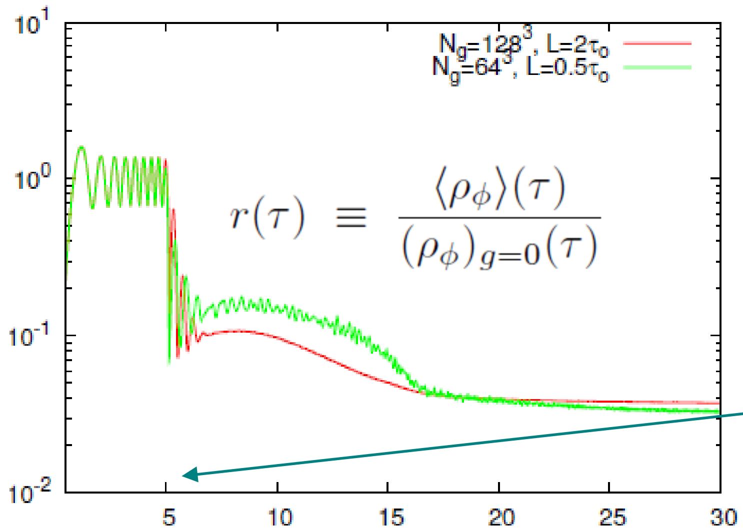
➔ $m_\phi \sim 10^{-17}\,{\rm eV}$ is the sweet spot point, and yet we can extend the ALP mass range to $10^{-21}\,{\rm eV} \lesssim m_\phi \lesssim 10^{-17}\,{\rm eV}$.

The existence of X_μ which is exponentially amplified by oscillating ALP is the key ingredient of our mechanism.

Instead, one may attempt to amplify A_μ through $g_{AA}\phi F\tilde{F}$, without introducing X_μ. However then the high conductivity $\sigma_{\rm phy} \gg m_\phi$ places a strong obstacle to the amplification of A_μ, and we can never get $B > 10^{-30}\,{\rm G}$.

On the other hand, if X_μ is amplified enough, the back reaction from the amplified X_μ becomes strong, and one needs a lattice calculation for quantitative analysis of the combined dynamics of ALP and X_μ.

Lattice results for $g_{XX} = 100$

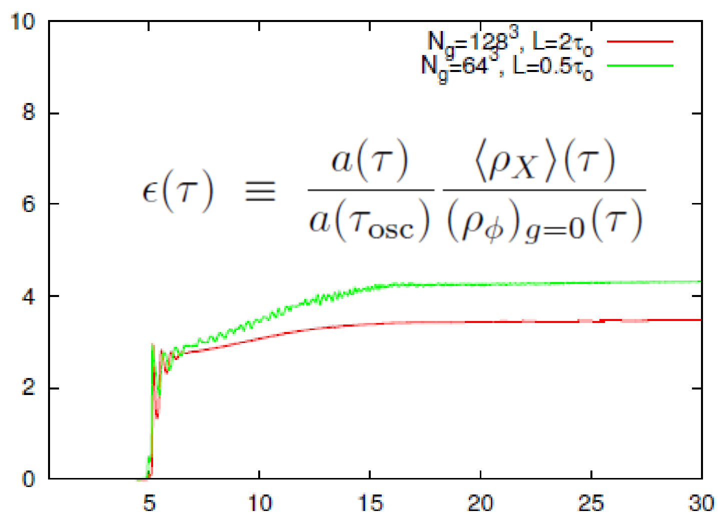


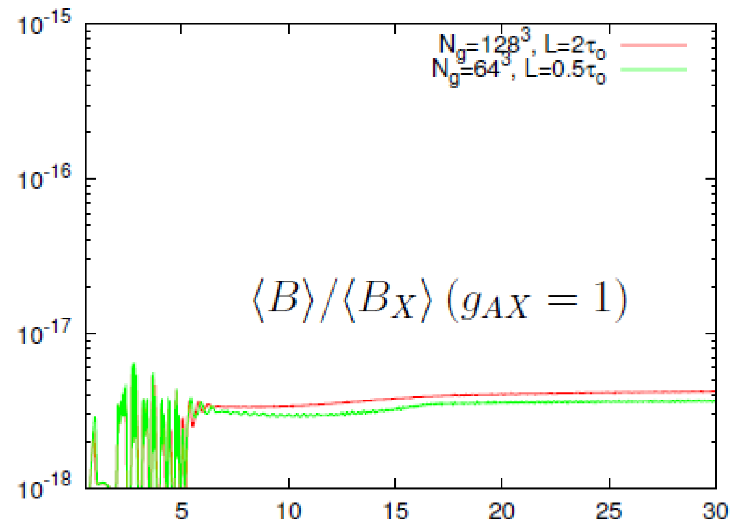
$$\frac{\tau}{\tau_{\rm osc}} = \frac{a(\tau)}{a(\tau_{\rm osc})}$$

$$ds^2 = a^2(\tau)(d\tau^2 - d\boldsymbol{x}^2)$$

$(\rho_\phi)_{g=0}$ = ρ_ϕ in the absence of gauge field production, i.e. when $g_{AA} = g_{XX} = g_{AX} = 0$

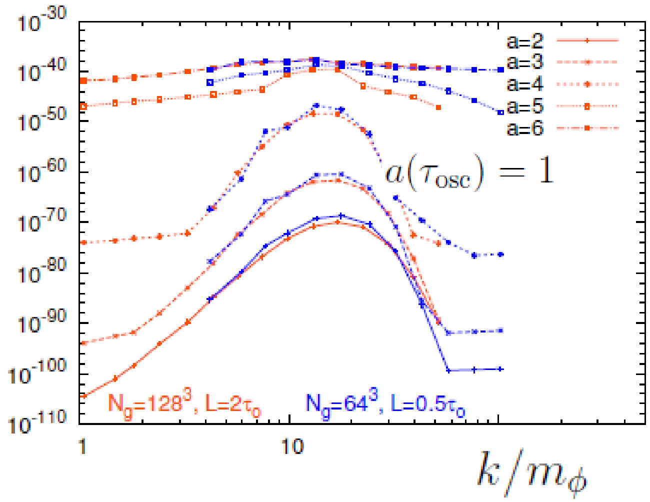
$\tau_X/\tau_{\rm osc}$ = moment when X_μ is amplified enough

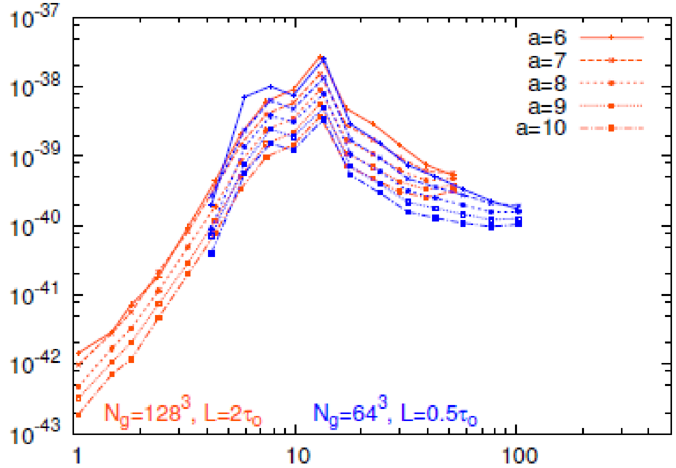


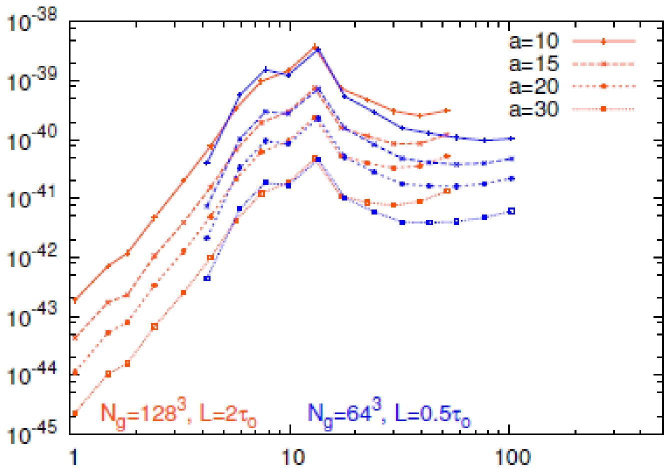


Evolution of the spectral shape of the produced magnetic fields

(from $\tau_{\rm osc}$ to $30\tau_{\rm osc}$)



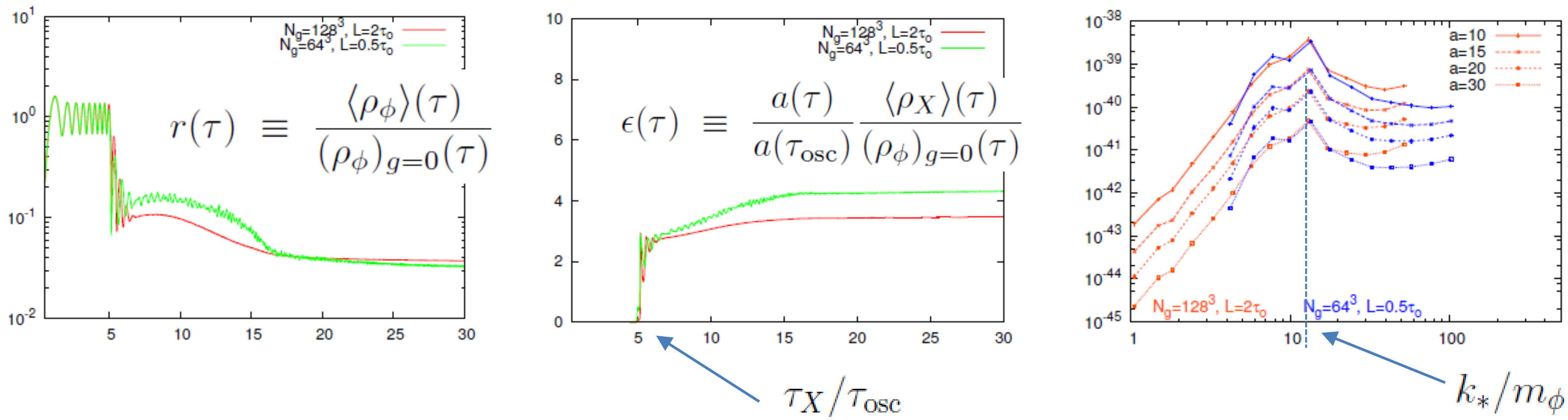




$$\lambda = \frac{a(\tau_0)}{a(\tau_{\rm osc})}\frac{2\pi}{k} \sim \frac{a(\tau_0)}{a(\tau_{\rm osc})}\frac{2\pi}{0.1 g_{XX} m_\phi}$$

$$\sim \frac{1}{g_{XX}}\left(\frac{10^{-16}{\rm eV}}{m_\phi}\right)^{1/2} {\rm kpc}$$

Due to the exponential sensitivity and strong back reactions, parametric dependence of the results on g_{XX} can be determined only by lattice simulations.



On the other hand, other parameter dependences can be read off by simple dimensional analysis.

$$a(\tau_X) \propto \tau_X \propto 1/T_X \propto a(\tau_{\rm osc}) \propto m_\phi^{-1/2},$$

$$B_X^2 \propto a^4\langle\rho_X\rangle(\tau_X) \propto a^4\langle\rho_\phi\rangle(\tau_X) \propto a^4(\tau_X) m_\phi^2 f^2 \propto f^2,$$

$$\sigma(\tau_X) = a(\tau_X)\sigma_{\rm phy}(\tau_X) \propto a(\tau_X)/T(\tau_X) \propto m_\phi^{-1}$$

$$k_* \sim g_{XX}\dot{\theta}(\tau_X) \propto a(\tau_X) m_\phi \propto m_\phi^{1/2},$$

Our scheme predicts (for $g_{XX} = 100$)

(The coefficients change for different g_{XX} , but not dramatically.)

* ALP dark matter with $\Omega_\phi h^2 \simeq 1.5 \times 10^{-2} \left(\frac{m_\phi}{10^{-17}\mathrm{eV}}\right)^{1/2} \left(\frac{f}{10^{16}\mathrm{GeV}}\right)^2$

* Seed B field: $B_{\mathrm{seed}} \simeq 3 \times 10^{-24} \left(\frac{g_{AX}/f}{10^{-15}\,\mathrm{GeV}^{-1}}\right) \left(\frac{m_\phi}{10^{-17}\mathrm{eV}}\right) \left(\frac{\Omega_\phi h^2}{0.12}\right) \mathrm{G}$

* Dark radiation existing in the form of long range classical field:

$$B_X \simeq 20 \left(\frac{m_\phi}{10^{-17}\mathrm{eV}}\right)^{-1/4} \left(\frac{\Omega_\phi h^2}{0.12}\right)^{1/2} \mathrm{nG}$$

$$N_{\mathrm{eff}} \simeq 6 \times 10^{-3} \left(\frac{m_\phi}{10^{-17}\mathrm{eV}}\right)^{-1/2} \left(\frac{\Omega_\phi h^2}{0.12}\right)$$

* Common coherent length of ALP dark matter, dark U(1) gauge field, and seed B-field:

$$\lambda \simeq \left(\frac{m_\phi}{10^{-17}\mathrm{eV}}\right)^{-1/2} \mathrm{kpc}$$

Observational constraints on the ALP couplings

$$-\frac{g_{\rm AA}}{4f}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} - \frac{g_{\rm XX}}{4f}\phi X_{\mu\nu}\widetilde{X}^{\mu\nu} - \frac{g_{\rm AX}}{2f}\phi F_{\mu\nu}\widetilde{X}^{\mu\nu}$$

* Star cooling by ALP emission

$$\frac{g_{AA}}{f} \lesssim 10^{-10}\,{\rm GeV}^{-1}, \quad \frac{g_{AX}}{f} \lesssim 10^{-9}\,{\rm GeV}^{-1} \ \ ({\rm from}\ \ \gamma_* \to \phi + X)$$

* ALP-photon conversion induced by background B or B_X

Cosmic opacity, spectral modulation, polarization rotations of X rays from AGN; CMB spectral distortion, …

[Mirizzi et al '05; Ostman et al '05; Avgoustidis et al '10; Tashiro et al '13; Wouters et al '13; Tiwari '16; Conlon et al '17 Mukherjee et al '18, …]

➔ $$\frac{g_{AX}}{f}\left(\frac{\langle B_X\rangle}{10\,{\rm nG}}\right) \lesssim 10^{-15}\,{\rm GeV}^{-1}$$

[Most stringent bound obtained by combining Tashiro et al '13 & Tiwari '16]

For the ALP mass range relevant for us,

$$10^{-21}\,\mathrm{eV} \lesssim m_\phi \lesssim 10^{-17}\,\mathrm{eV}$$

our scheme can generate

$$B \sim 2\times 10^{-24}\left(\frac{m_\phi}{10^{-17}\mathrm{eV}}\right)^{5/4}\,\mathrm{G}$$

$$\lambda \sim \left(\frac{m_\phi}{10^{-17}\mathrm{eV}}\right)^{-1/2}\,\mathrm{kpc}$$

which is large enough to be identified as the seed of galactic B fields:

$$B_{\rm seed} \gtrsim \mathcal{O}(10^{-30})\,\mathrm{G} \quad (\lambda \gtrsim \mathcal{O}(0.1)\,\mathrm{kpc})$$

but not enough to provide

$$B_{\rm void}\times \min[1, \sqrt{\lambda/0.1\mathrm{Mpc}}] \gtrsim \mathcal{O}(10^{-19} - 10^{-16})\,\mathrm{G}$$

(any astrophysical amplification of B at intergalactic voids?)

UV completion:

$$\mathcal{L}_{\rm eff} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi + \frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$
$$- \frac{g_{\rm AA}}{4f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{\rm XX}}{4f}\phi X_{\mu\nu}\tilde{X}^{\mu\nu} - \frac{g_{\rm AX}}{2f}\phi F_{\mu\nu}\tilde{X}^{\mu\nu} + J^\mu_{\rm em}A_\mu$$
$$(f \equiv \phi_{\rm initial} \sim \Delta\phi)$$

Naive field theoretical consideration suggests

$$g_{IJ} \sim \frac{\alpha}{2\pi} \sim 10^{-2}$$

while our scheme requires

$$g_{XX} \sim \mathcal{O}(1-100), \quad g_{AX} \sim \mathcal{O}(1-10) \quad (f = 10^{16} - 10^{17}\,{\rm GeV})$$

Clockwork mechanism: *[KC, Kim, Yun '14; KC, Im '15, Kaplan, Rattazzi '15]*

Exponential localization in theory space of an unbroken symmetry and also of the symmetry-protected light particle:

[Giudice, McCullgh' 16]

$$\mathcal{L}_{\rm CW} = \frac{1}{2}\left(\sum_{i=0}^{N}(\partial_\mu\phi_i)^2 - 2\sum_{i=0}^{N-1}\Lambda_i^4\cos\left(\frac{\phi_{i+1}}{f_*} - q\frac{\phi_i}{f_*}\right)\right)$$

$$(\phi_i \equiv \phi_i + 2\pi f_*)$$

➔ Localized lightest axion ϕ with an exponentially enlarged field range

$$\phi_i \propto q^i\phi, \qquad \Delta\phi \equiv f \sim q^N f_*$$

$$\Delta\mathcal{L} = -\mu^4\cos\left(\frac{\phi_0}{f_*}\right) - \frac{1}{16\pi^2}\frac{\phi_N}{f_*}\left(c_{AA}F\tilde{F} + c_{AX}F\tilde{X} + c_{XX}X\tilde{X}\right) \quad (c_{IJ} = \mathcal{O}(1))$$

[Hikaki et al '15; Farina et al '16]

➔ $$\mathcal{L}_{\rm eff} = \frac{1}{2}(\partial_\mu\phi)^2 + \frac{1}{2}m_\phi^2\phi^2 - \frac{\phi}{4f}\left(g_{AA}F\tilde{F} + 2g_{AX}F\tilde{X} + g_{XX}X\tilde{X}\right)$$

$$g_{IJ} \sim 10^{-2}q^N c_{IJ} = \mathcal{O}(1-100)$$