Physics of Axion Like Particle (ALP)

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at 1st C^3 collaboration meeting
Aug 13, 2018

Outline

ALP intro

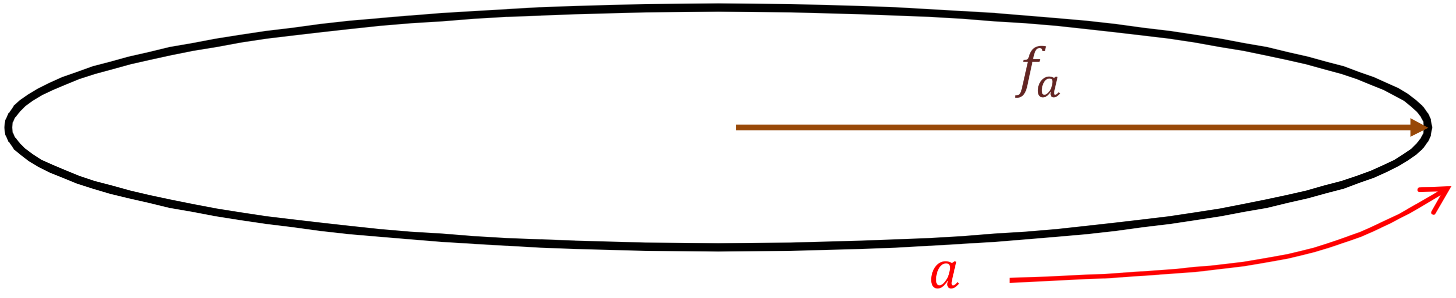
Various roles of ALP in physics problems (works at CTPU)

Conclusions

ALP intro

ALP, $a(x)$*, is the scalar field in effective theories well below the scale* f_a *:*

1) *SM singlet, and compact with a period:* $2\pi f_a$



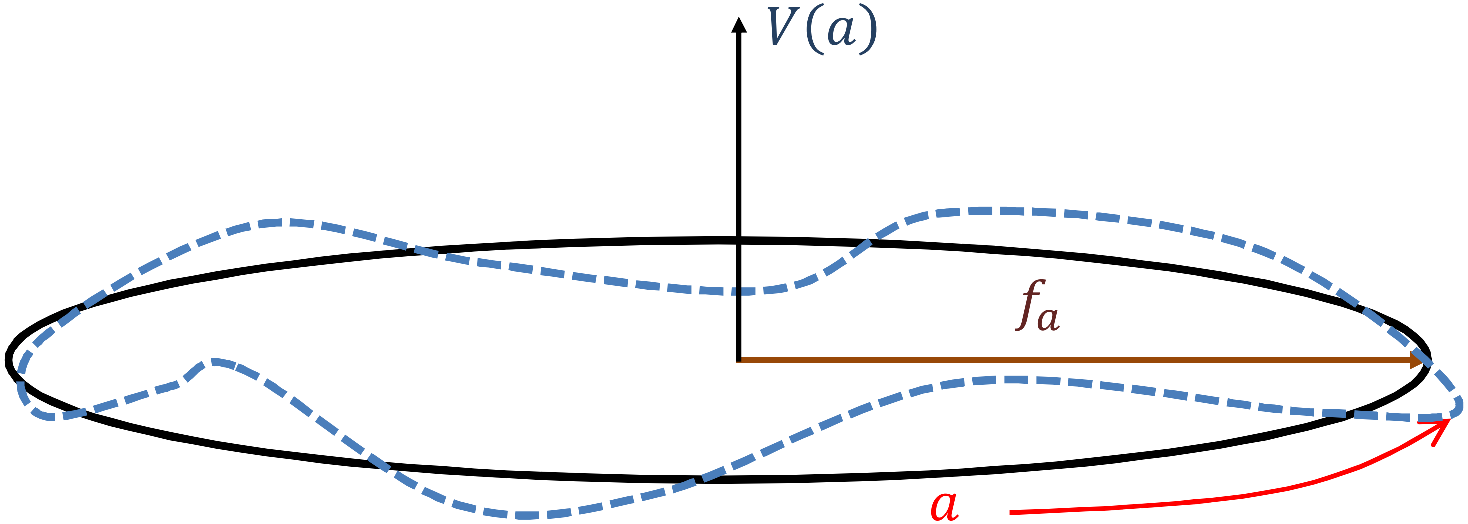
The action should be invariant under the change of $a \to a + 2\pi f_a$

ALP intro

ALP, $a(x)$, is the scalar field in effective theories well below the scale f_a :

2) Approximate continuous shifty symmetry $U(1)_{PQ}$

($a \to a + 2\pi f_a \beta$, where β is a real number)



The potentials and interactions to explicitly break shift symmetry are generated at a scale (μ) much lower than f_a ($\mu \ll f_a$)

ALP intro

All interactions between ALP and matters can be given by the combination of

$$\frac{a}{f_a}$$

A natural way to introduce higher dim. operators, weak couplings, and small mass of the ALP.

E.g. for the scalar potential of the axion with $\Lambda \ll f_a$

$$V(a) = -\Lambda^4 \cos\frac{a}{f_a} = \Lambda^4 + \frac{\Lambda^4}{2f_a^2}a^2 - \frac{\Lambda^4}{24f_a^4}a^4 + \frac{\Lambda^4}{720f_a^6}a^6 + \cdots$$

the axion mass,

$$m_a = \frac{\Lambda^2}{f_a} \ll f_a,\ \Lambda$$

the self coupling,

$$\lambda_{\text{quartic}} = \frac{\Lambda^4}{6f_a^4} \ll O(1)$$

Axion couplings to matter

$$\mathcal{L} \ni \frac{a}{16\pi^2 f_a}\left(c_G G\tilde{G} + c_W W\widetilde{W} + c_B B\tilde{B}\right) + x_q e^{ia/f_a} H Q_L q_R + h.c. + \cdots$$

The energy scale that we concern: $E \ll f_a \rightarrow \Gamma_{\text{int}} \propto (E/f_a)^2$

QCD axion

For the QCD axion, $U(1)_{PQ}$ is broken PQ anomaly

$$V(a) = -m_\pi^2 f_\pi^2 \sqrt{\frac{m_u^2 + m_d^2 + 2m_u m_d \cos(N_{DM} a/f_a)}{(m_u+m_d)^2}} \sim -m_u \Lambda_{QCD}^3 \cos\frac{N_{DM} a}{f_a}$$

The axion-photon coupling contains O(1) model dependence ($\mathcal{E}, N_{DM}$)

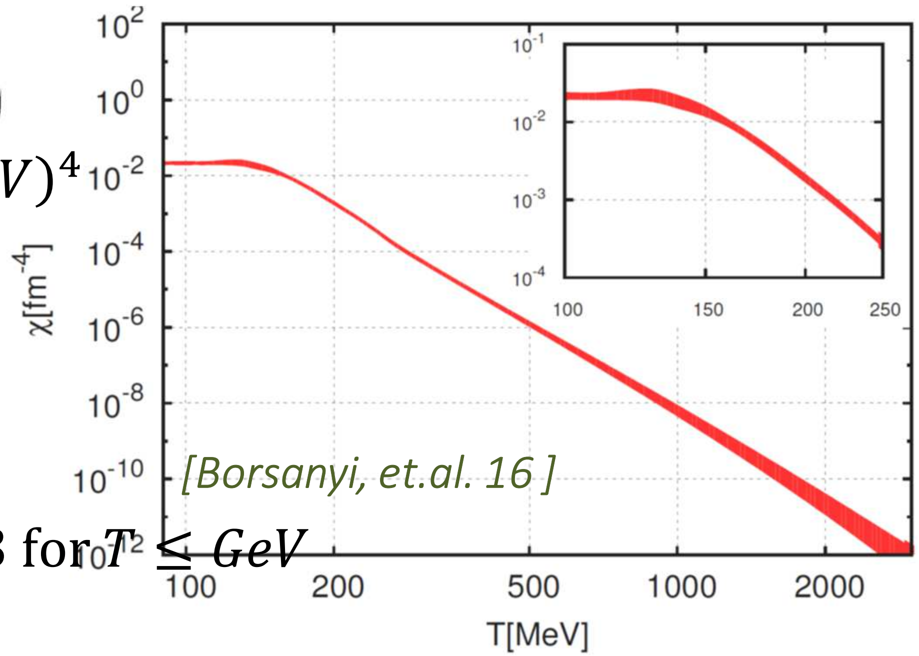
$$\mathcal{L} \ni -\frac{1}{4}\frac{e^2}{8\pi^2 f_a}\left(\mathcal{E} - N_{DM}\frac{2}{3}\frac{4+m_u/m_d}{1+m_u/m_d}\right) a\, F_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{g_{a\gamma}}{4} a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

The (finite temperature) axion mass is calculated

$$\chi(T=0) = m_a^2 (f_a/N_{DM})^2 \simeq (75.6\, MeV)^4$$

$$\rightarrow\ m_a \simeq 5.7\times 10^{-6}\text{eV}\frac{10^{12}GeV}{f_a/N_{DM}}$$

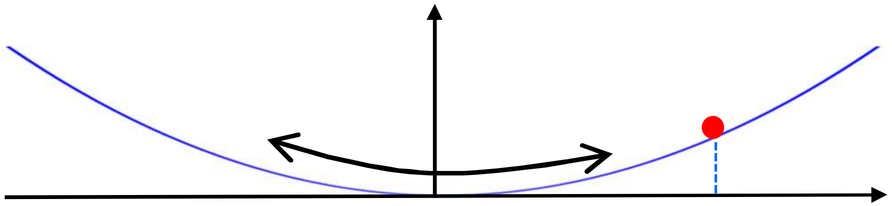
$$m_a(T) \simeq m_a \left(\frac{T}{\Lambda_{QCD}}\right)^{-b},\ b = 3.55 \pm 0.3 \text{ for } T \lesssim GeV$$



QCD axion dark matter

QCD axion could be dark matter from different cosmological history (mainly by two ways)

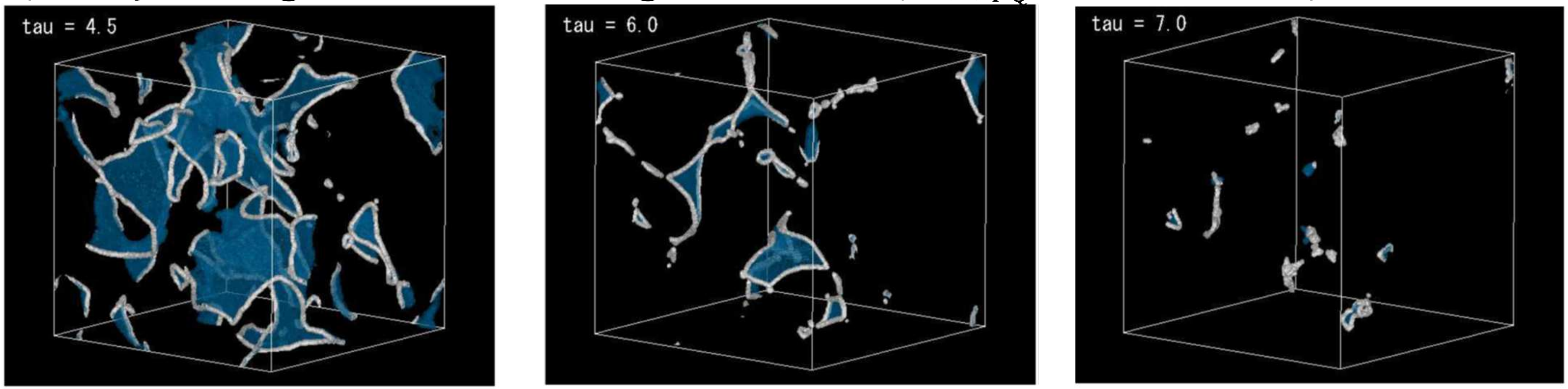
1) *Coherent oscillation with an initial misalignment ($U(1)_{PQ}$ broken before/during inflation)*



$$\Omega_a h^2 \simeq 0.1 \left(\frac{f_a/N_{DM}}{3\times 10^{11} GeV}\right)^{\frac{7}{6}} \theta_i^2 f(\theta_i)$$

$\rightarrow m_a = O(10)\mu\text{eV}$ for $\theta_i = O(1)$

2) *Decay of string-wall network & realignment axions ($U(1)_{PQ}$ broken after inf.)*



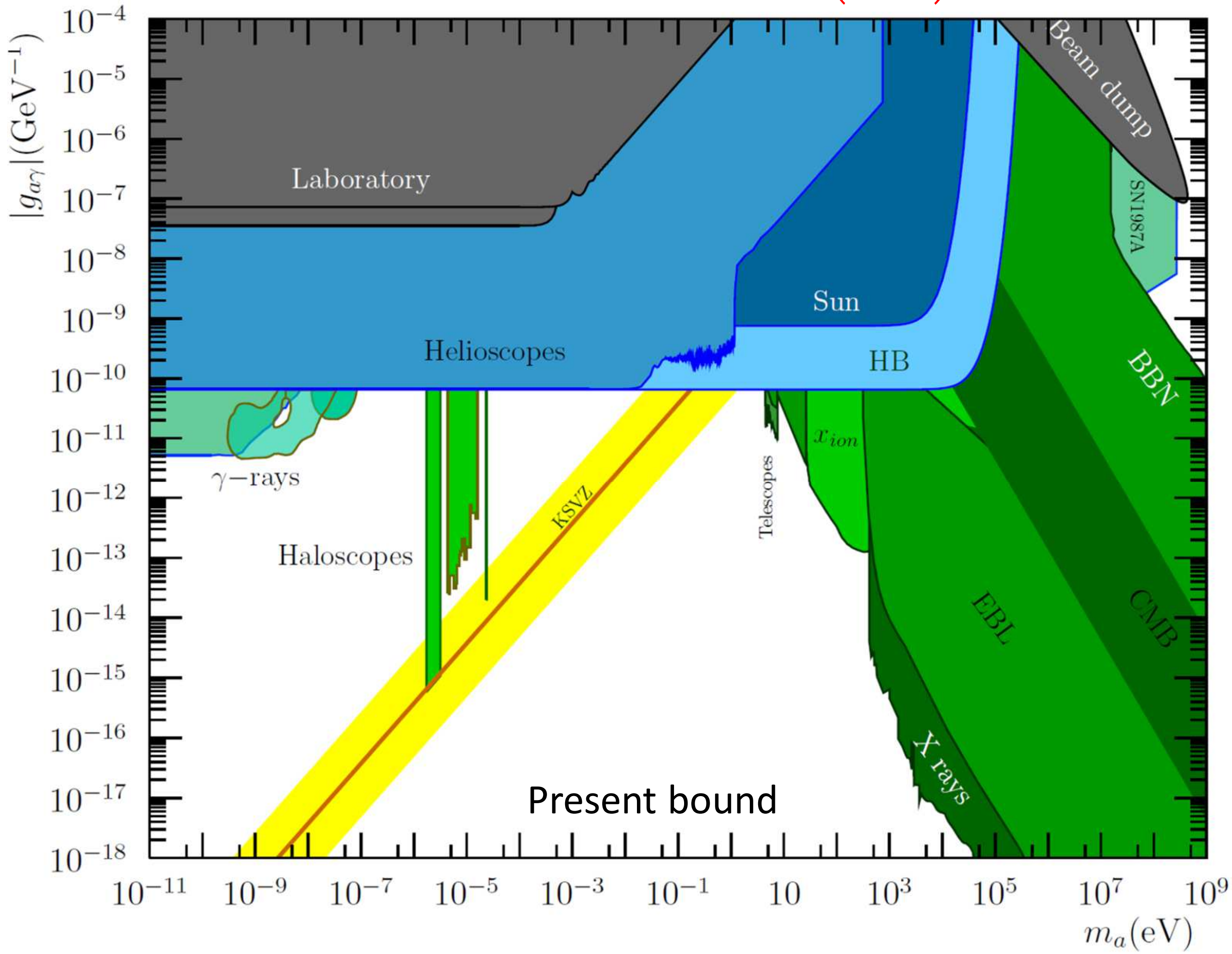
$$\Omega_a h^2 \simeq 0.1 \left(\frac{f_a}{3\times 10^{10} GeV}\right)^{1.19} \rightarrow m_a = 190\mu\text{eV}$$ *[Hiramatsu et.al. 12]*

However other [Klaer, Moore 17] claims $m_a = 26\ \mu\text{eV}$ *for full DM: still need more study*

QCD axion dark matter

The axion mass $m_a \sim 10\mu eV$ *corresponds to Compton wavelength* $10\mathrm{cm}$ *(and frequency GHz)*

$$g_{a\gamma}^{KSVZ(DFSZ)} \sim (0.1 - 0.4)\left(\frac{m_a}{10^{-5}eV}\right)\left(\frac{10^{-14}}{GeV}\right)$$



QCD axio

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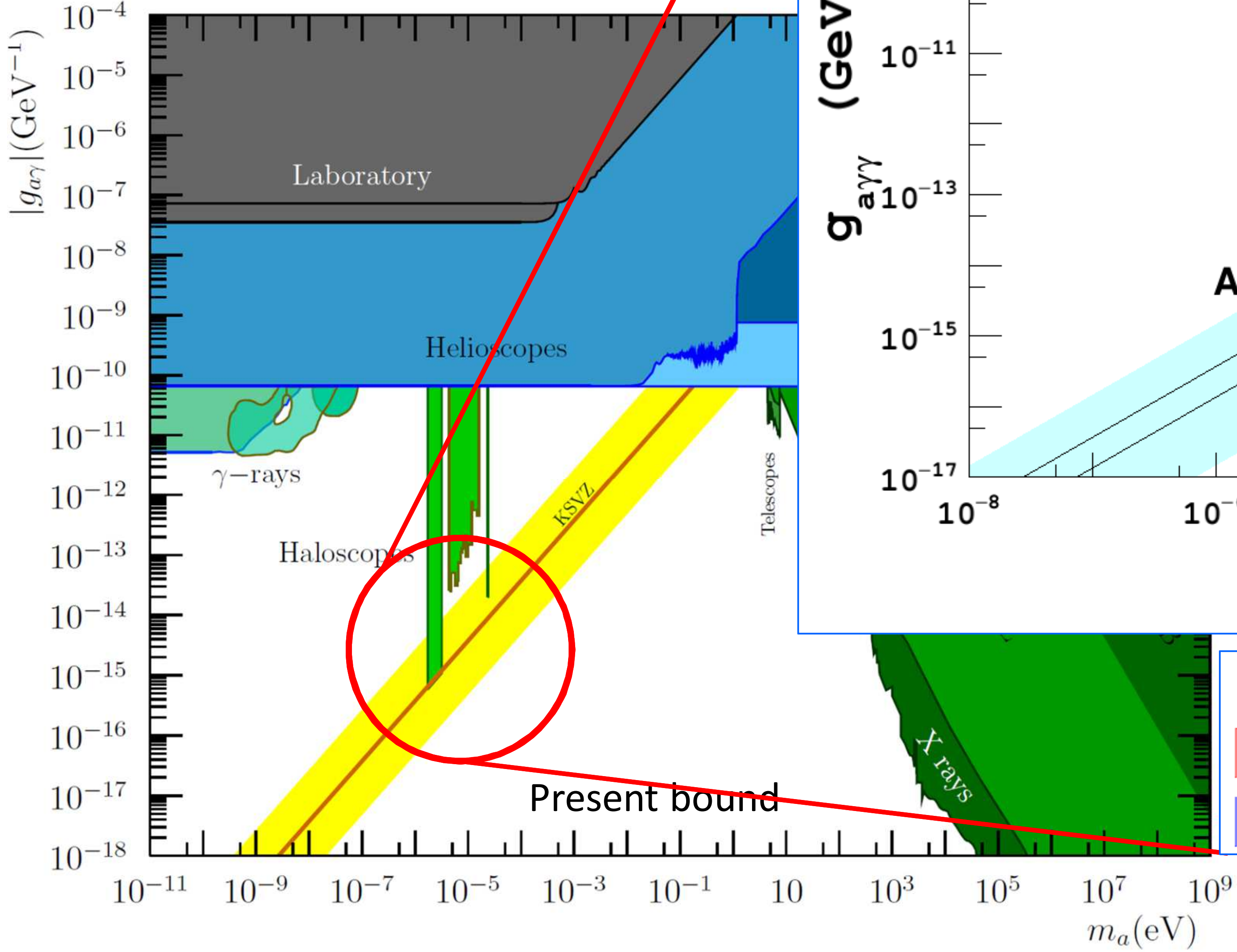
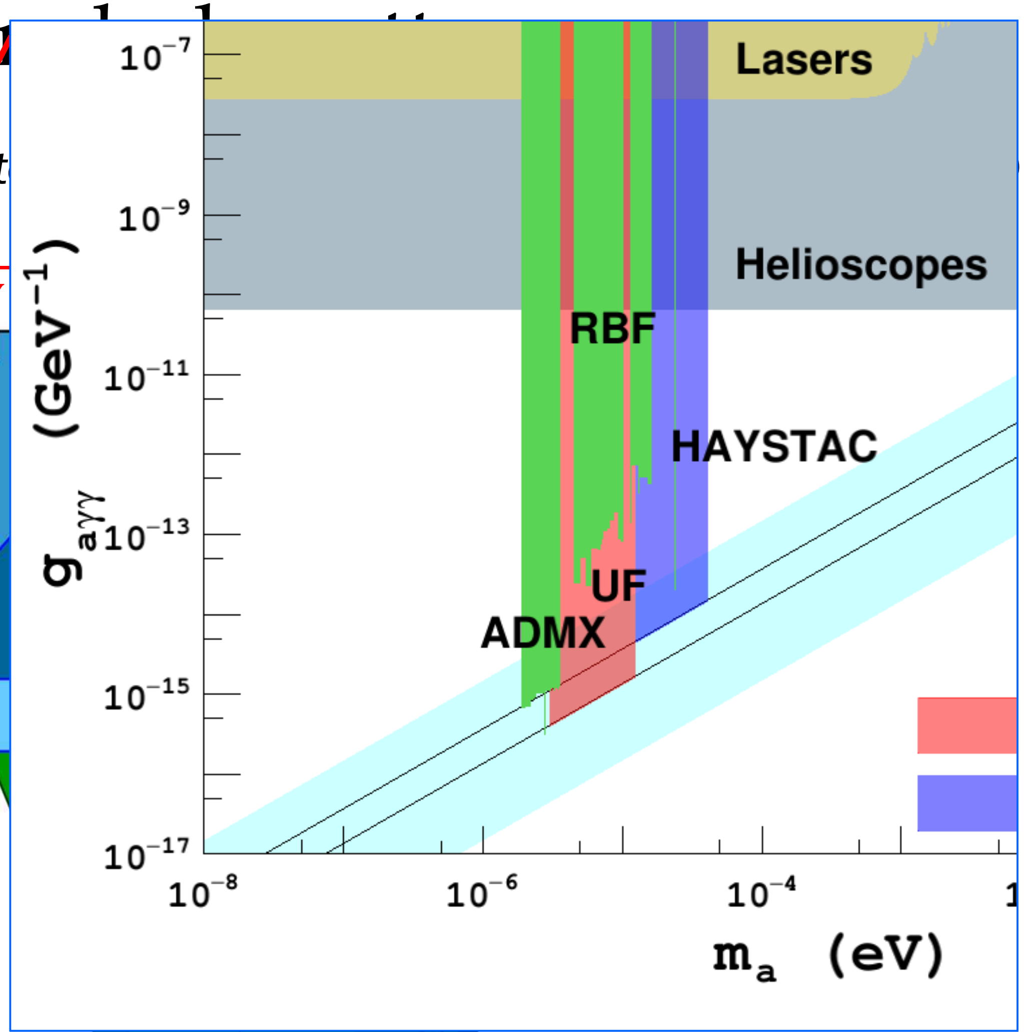
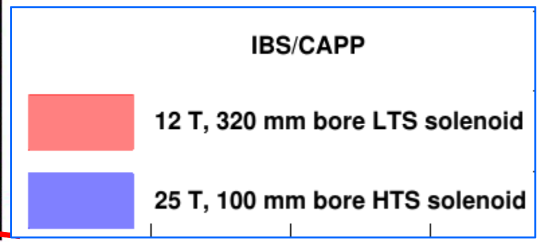






Proposals with Cosmic Axion Like Fields

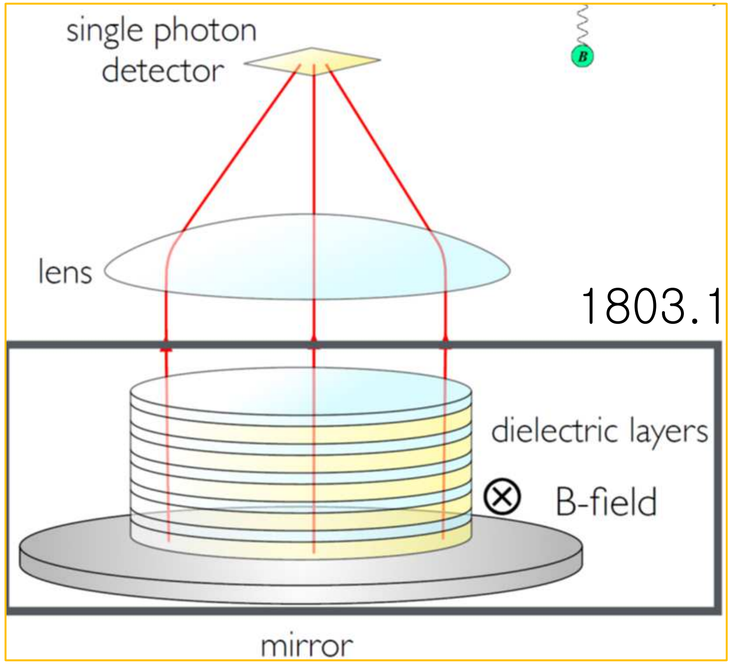
Lots of new experimental set-ups are suggested to search for different mass and coupling ranges for ALP dark matter. Among them some examples to use coherent nature of axion dark matter background within its de Broglie wavelength ($\lambda_a = 1/m_a v \sim 10^3/m_a$)

$$a(t,x) \simeq a_0 \cos(\omega_a t - k\,x) \rightarrow \dot{a}(t) \neq 0, \vec{\nabla} a \neq 0$$

Maxwell EQ in ALF background from $\frac{g_{a\gamma}}{4} a\, F\tilde{F}$ *with periodic index of refraction:*

$$\epsilon \vec{\nabla} \cdot \vec{E} = \rho - g_{a\gamma}\, \vec{B}_{ex} \cdot \vec{\nabla} a$$

$$\vec{\nabla} \times \vec{B}/\mu - \epsilon \dot{\vec{E}} = J + g_{a\gamma}\, \vec{B}_{ex} \dot{a}$$



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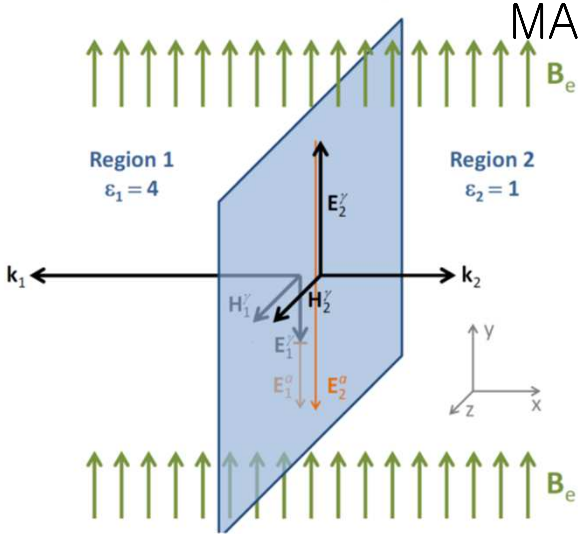
$$\mathbf{E}_a(t) = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a(t)$$

MADMAX



$$m_a \sim 10^{-4} - 1\ \text{eV}\,, g_{a\gamma} \sim 10^{-12} - 10^{-10}/\text{GeV}$$

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Maxwell EQ in ALF background from $\frac{g_{a\gamma}}{4} a\, F\tilde{F}$ *with propagating lights with* ($\omega \gg m_a$)

$$\epsilon \vec{\nabla} \cdot \vec{E} = \rho - g_{a\gamma} \vec{B}_{ex} \cdot \vec{\nabla} a$$

$$\vec{\nabla} \times \vec{B}/\mu - \epsilon \dot{\vec{E}} = J + g_{a\gamma} \vec{B}_{ex} \dot{a}$$

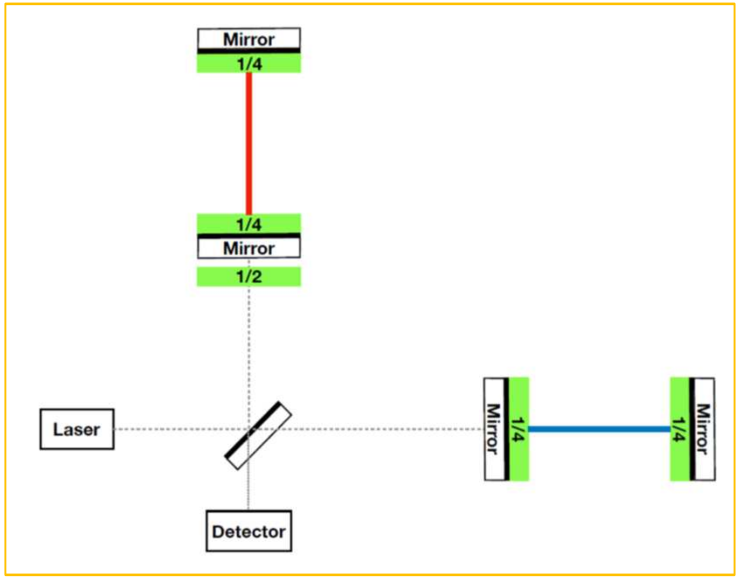
$$\vec{\nabla} \times \vec{E} = -\dot{\vec{B}}, \ \vec{\nabla} \cdot \vec{B} = 0$$

$$\ddot{\vec{E}} - \nabla^2 \vec{E} = g_{a\gamma}\, \dot{a} (\vec{\nabla} \times \vec{E})$$

$$\rightarrow \ \omega^2 - k^2 \pm g_{a\gamma} \dot{a}\, k = 0$$

$$v_{phase}^{L/R} \approx 1 \pm g_{a\gamma} \frac{\dot{a}}{2k}$$

(different phase velocity of left & right polzarized light)



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$m_a \sim 10^{-13} - 10^{-9}$ eV , $g_{a\gamma} \sim 10^{-12} - 10^{-10}$/GeV

Proposals with Cosmic Axion Like Fields

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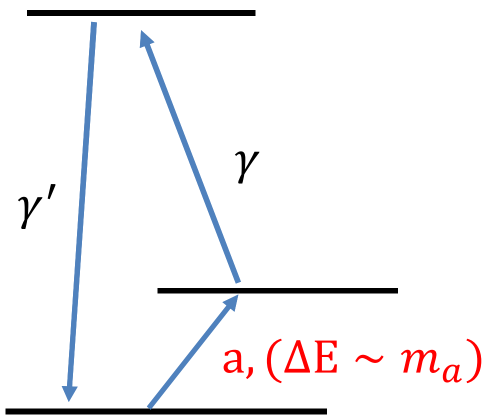
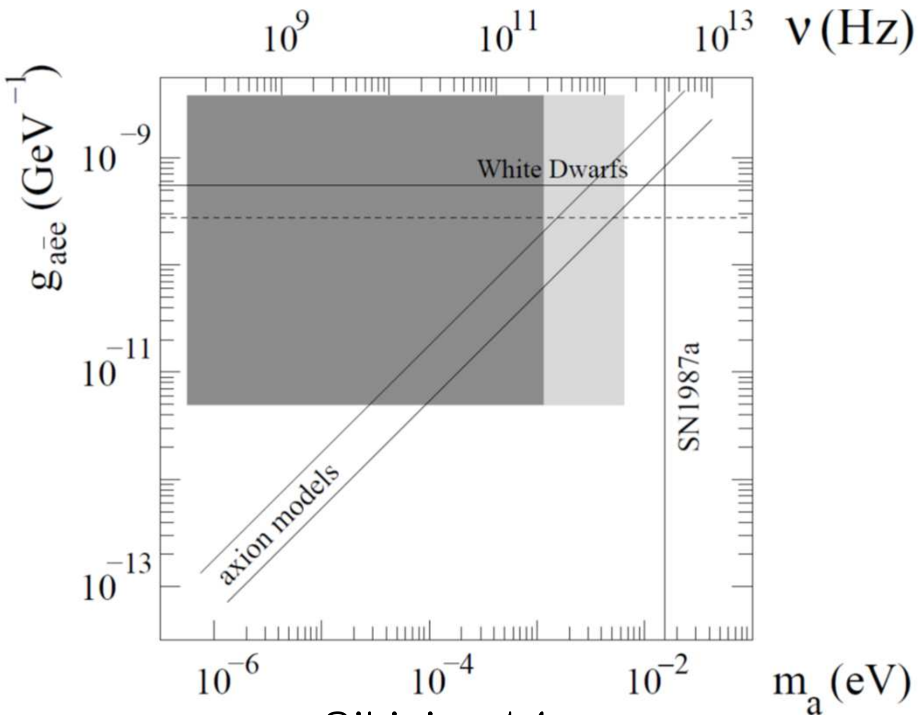
$$a(t,x) \simeq a_0 \cos(\omega_a t - k\,x) \rightarrow \dot{a}(t) \neq 0, \vec{\nabla} a \neq 0$$

Atomic energy levels in ALF background from $\frac{g_f}{2f_a}(\partial_\mu a)(\bar{f}\,\gamma^\mu \gamma_5 f)$

$$H_{aff} = \frac{g_f}{2f_a} \vec{\sigma}_f \cdot \vec{\nabla} a$$



(transition tuned by Zeeman effect)



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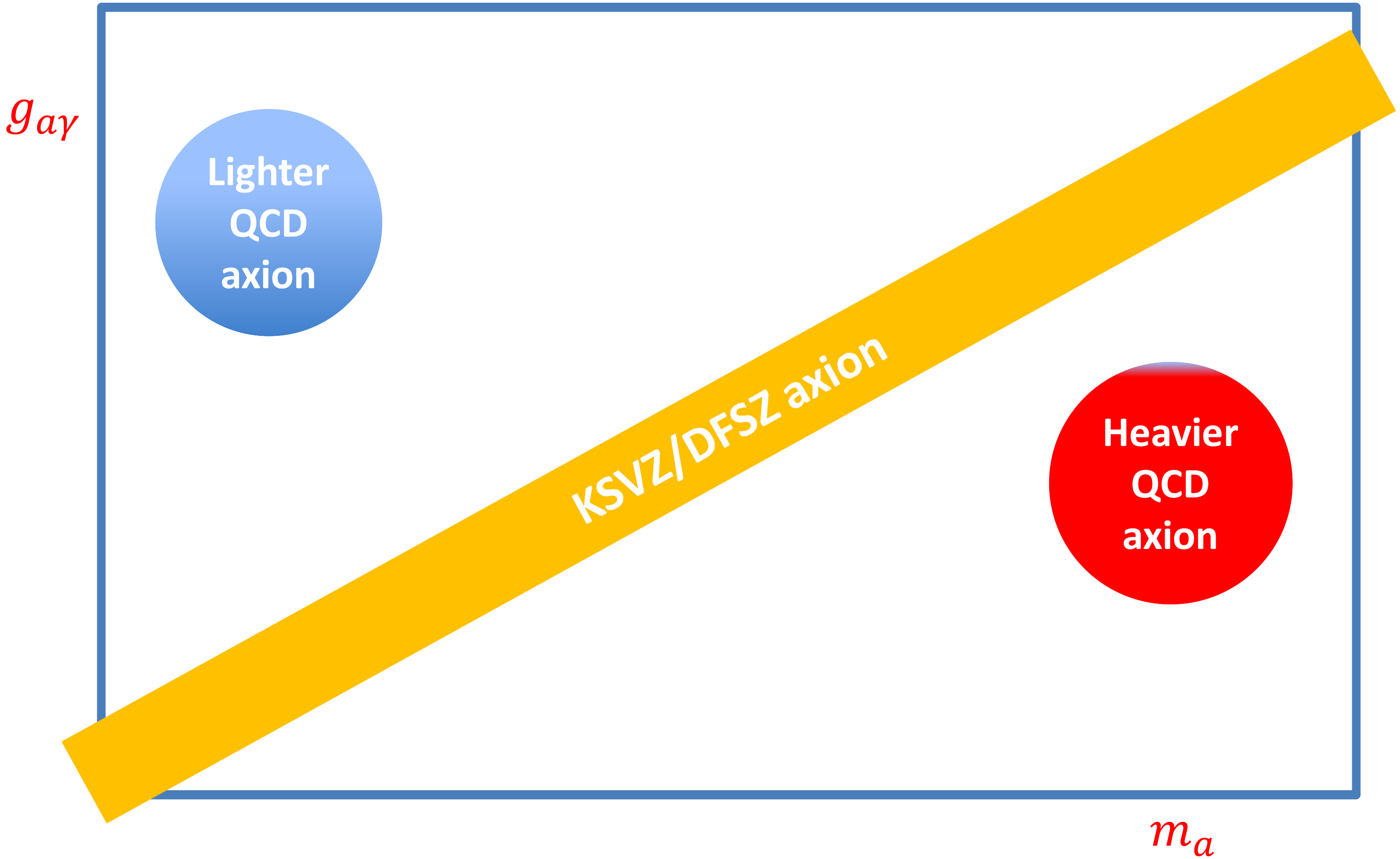
QCD axion variations

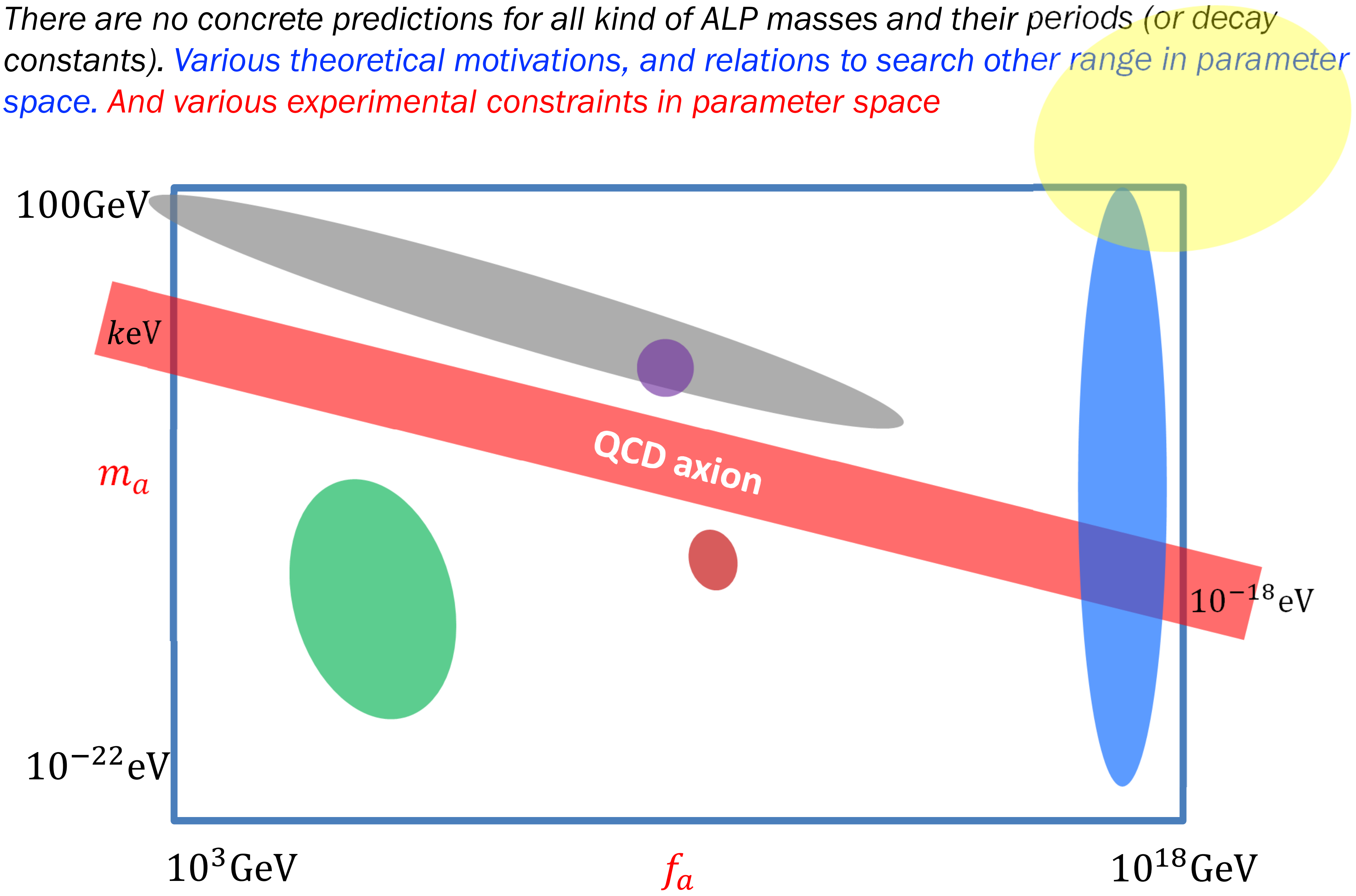
Even for the QCD axion case, the axion mass can be quite different if the contributions from other sectors come in (with discrete symmetries to evade strong CP problem, hidden confining groups etc.)

$$V(a) = V_{QCD}(a) + \sum V_{\text{others}}(a)$$

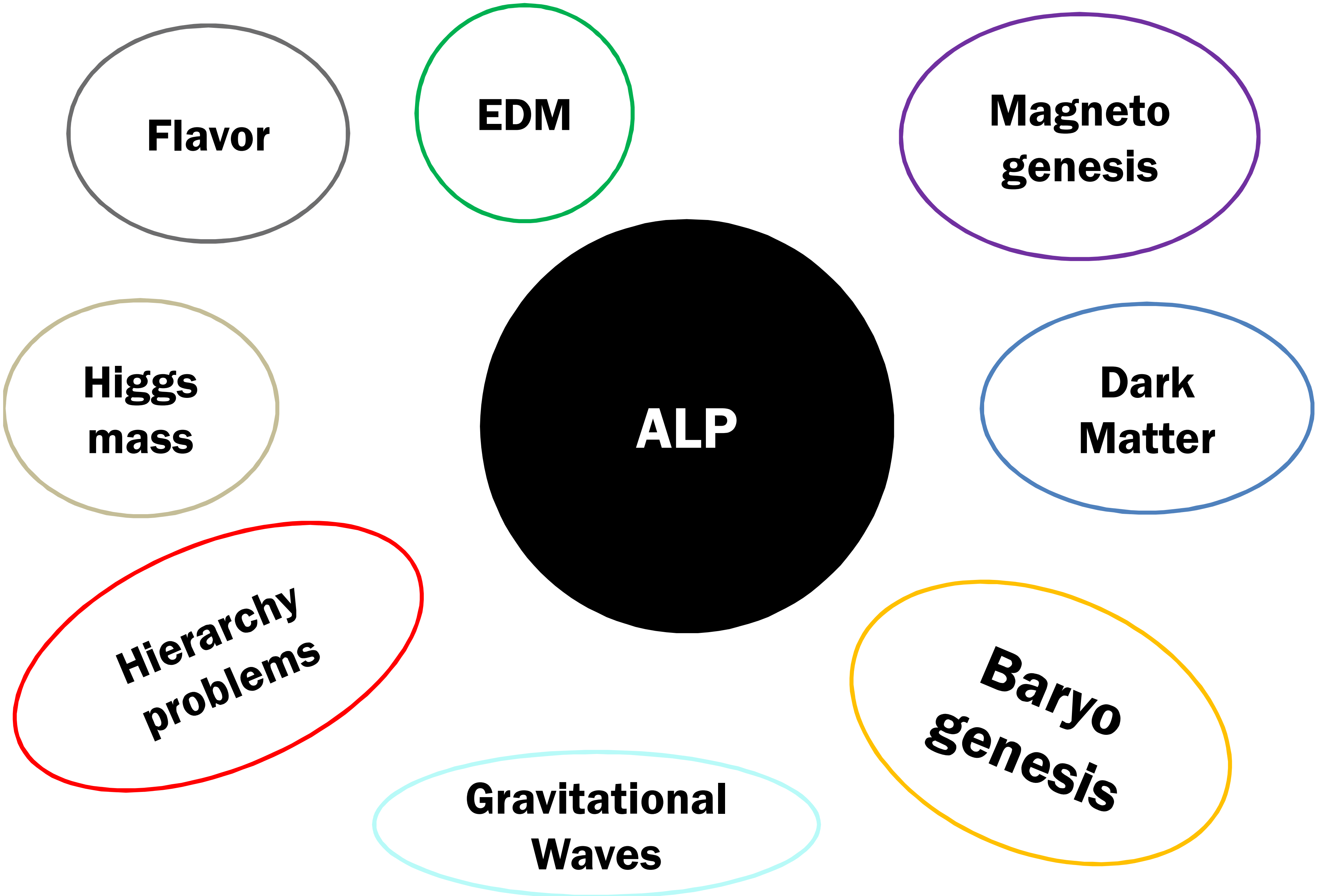


ALP beyond the QCD axion

There are no concrete predictions for all kind of ALP masses and their periods (or decay constants). Various theoretical motivations, and relations to search other range in parameter space. And various experimental constraints in parameter space



ALP Landscape



Axion Landscape studied at CTPU

ALP as the source of dark matter (dark photon) production

[Kaneta, Lee, Yun 16]

ALP as the source of solution to the hierarchy problem and its constraints

[Flacke, Frugiuele, Fuchs, Gupta, Perez 16] [Choi, Im 16]

ALP as the source of large scale magnetic fields in the Universe

[Choi, Kim, Sekiguchi, 18]

ALP can be the source of radio signals by resonance conversion of ALP CDM around neutron stars with strong magnetic fields

[Huang, Kadota, Sekiguchi, Tashiro 18]

ALP as the source of electroweak baryogenesis

[Jeong, Jung, Shin 18]

ALP as the source of excess or dips of gamma-ray spectrum from (extra) galaxies

[Choi, Lee, Seong, Yun 18], [Bae, Kamada, Kim 18]

And so on..

Late-time magnetogenesis through ALP DM

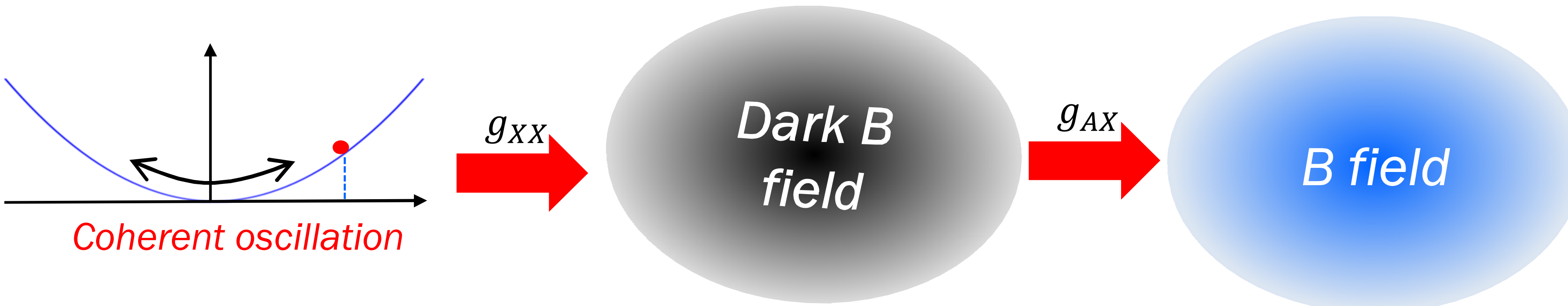
[Choi, Kim, Sekiguchi, 18]

There are several hints on the seed of magnetic field in cosmological scales from observation of radio and gamma-rays. For the seed of galactic magnetic fields,

$$B_{seed} \geq O\left(10^{-30}\right)\text{Guass} \;\; \text{with } \lambda \geq 0.1\text{kpc}$$

There is the attractive way to generate magnetic fields at late time ($200\text{eV} \leq T \leq 20\text{keV}$*) via ultralight axion-like particle (DM) and dark* $U(1)_X$ *gauge field,* X_μ *:*

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu}$$
$$-\frac{a}{4f}\left(g_{AA}\, F_{\mu\nu}\tilde{F}^{\mu\nu} + g_{XX}\, X_{\mu\nu}\tilde{X}^{\mu\nu} + g_{AX}F_{\mu\nu}\tilde{X}^{\mu\nu}\right) + J^\mu A_\mu$$



$$E_X \sim B_X$$
$$\sim 10^{-8}G\left(\frac{m_a}{10^{-17}\text{eV}}\right)^{-1/2}$$

$$B \sim 10^{-24}G\left(\frac{m_a}{10^{-17}\text{eV}}\right)^{\frac{5}{4}} \text{ for } \lambda \sim \left(\frac{m_a}{10^{-17}\text{eV}}\right)^{-\frac{1}{2}}\text{kpc}$$

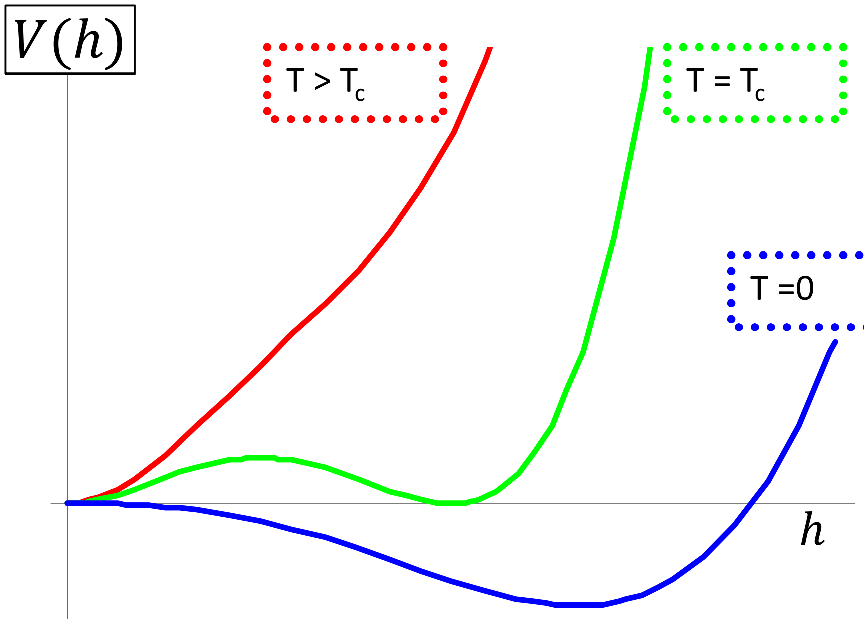
Electroweak baryogenesis through ALP

[Jeong, Jung, Shin 18]

Present baryon abundance is the result of baryogenesis at the early Universe

$$\frac{n_B - n_{\bar{B}}}{s} = 10^{-10} \quad \rightarrow \quad \Omega_B \simeq 0.05$$

Electrobaryogenesis (EWBG) is a very attractive idea to use first order electroweak phase transition (EWPT) for baryogenesis. It is related with various low scale observables.



Usually in order to get a strong 1st order EWPT, we need (dangerous) strong couplings between new pts and the Higgs.

However in ALP extension, the strong 1st order EWPT can be naturally achieved within weakly coupled models

$$V(h,a) = V(a) + \frac{1}{2}m^2(a)h^2 + \frac{\lambda}{4}h^4$$

where (for $\mu = O(m_W), 0 < \epsilon < 1$)

$$m^2(a) = \mu^2(\epsilon - \cos a/f_a)$$

In order to explain the present baryon symmetry, we need

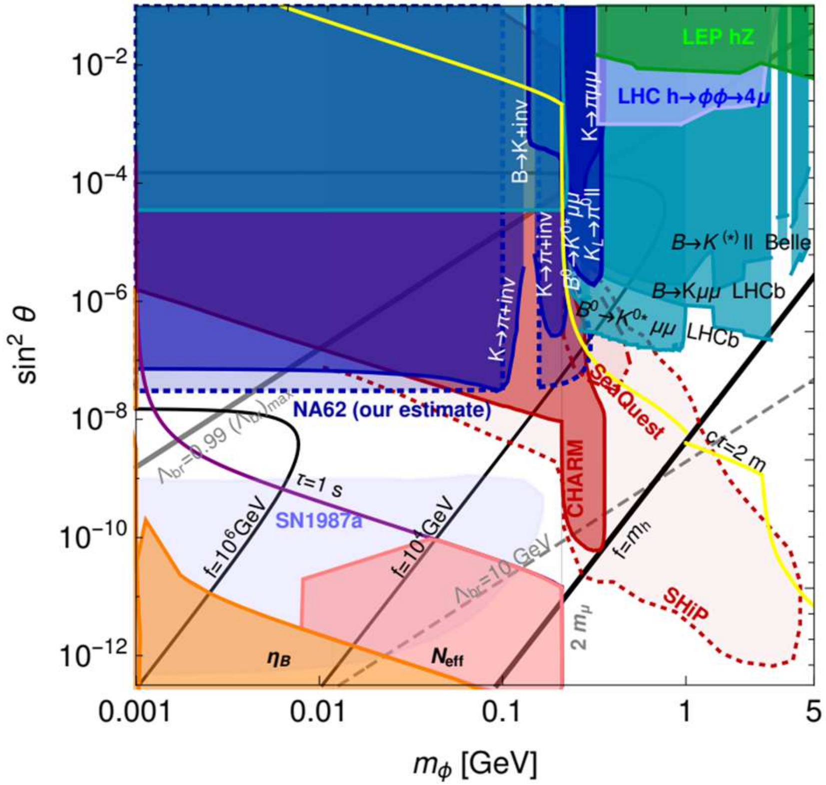
$$m_a \sim \left(\frac{m_W^2}{f_a}\right) \sim 5 - 20 \text{ GeV}: \ f_a \sim 1 - 3 \text{ TeV} \ \left(g_{a\gamma} = 10^{-5} - 10^{-6}/\text{GeV}\right)$$

ALP searches in Axionic EWBG

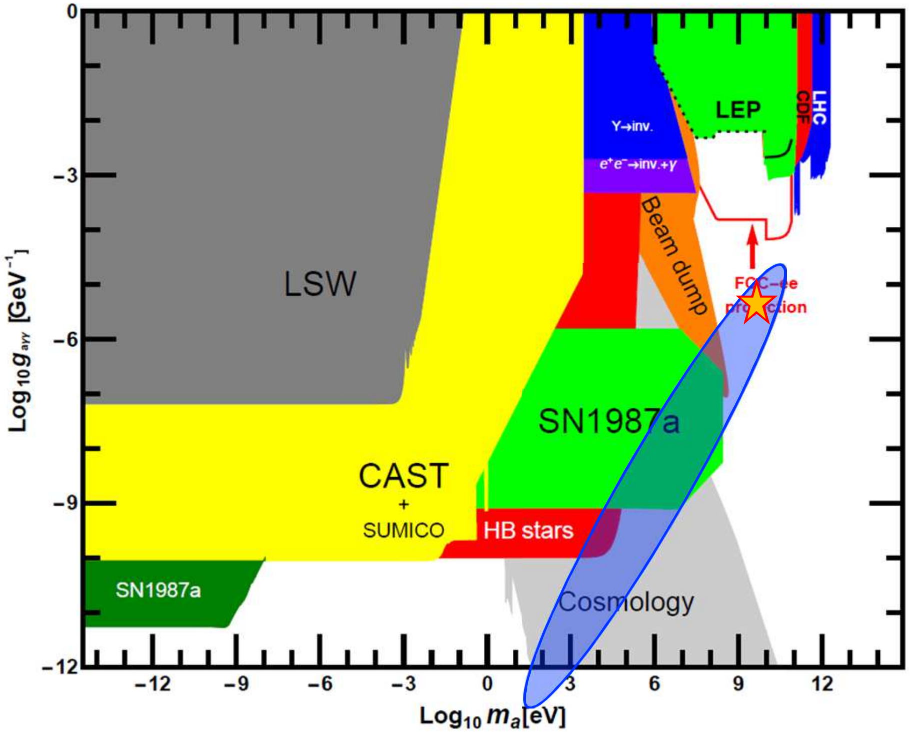
After integrating out top and Higgs, ALP couplings to <gluon, photon, light quark and lepton> are generated. Model dependent (axion decay channels) constraints are applied

$$\mathcal{L}_{eff} = \frac{1}{16\pi^2}\frac{(\delta a)}{f}\left(c_1 G_{\mu\nu}\tilde{G}^{\mu\nu} + c_2 F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots\right) + \frac{\delta a}{f}\delta_{\rm mix} m_q \bar{q} q + \frac{\delta a}{f}\delta_{\rm mix} m_\ell \bar{\ell}\ell$$

Axion with mass around $(5-20)\mathrm{GeV}$ *is model independently safe.*



[Flacke, Frugiuele, Fuchs, Gupta, Perez 16]
[Choi, Im 16]



[Jaeckel, Spannowsky 15]

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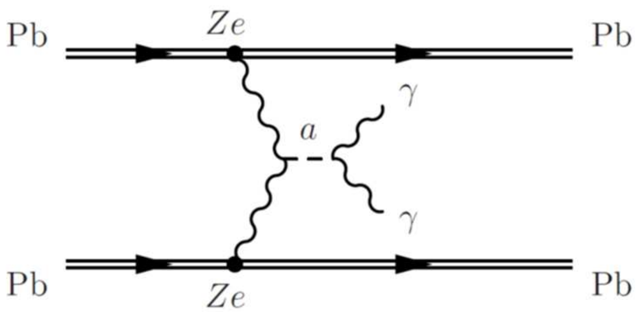
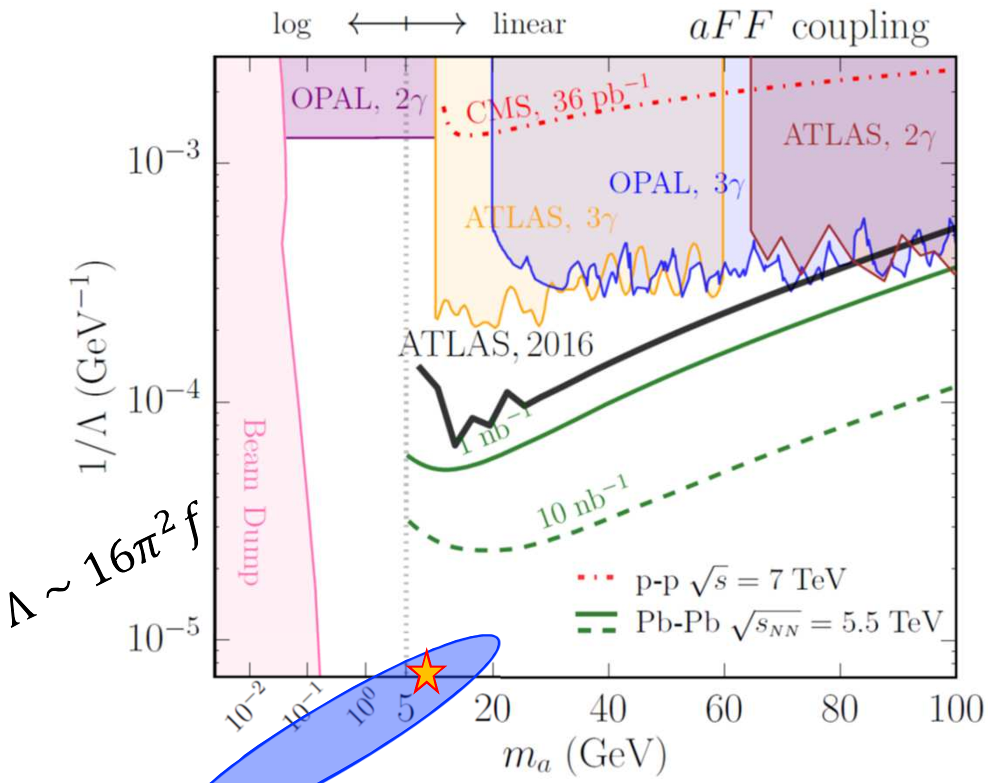




[Knapen, Lin, Lou, Melia 17]

Small scale problems and ALP signal

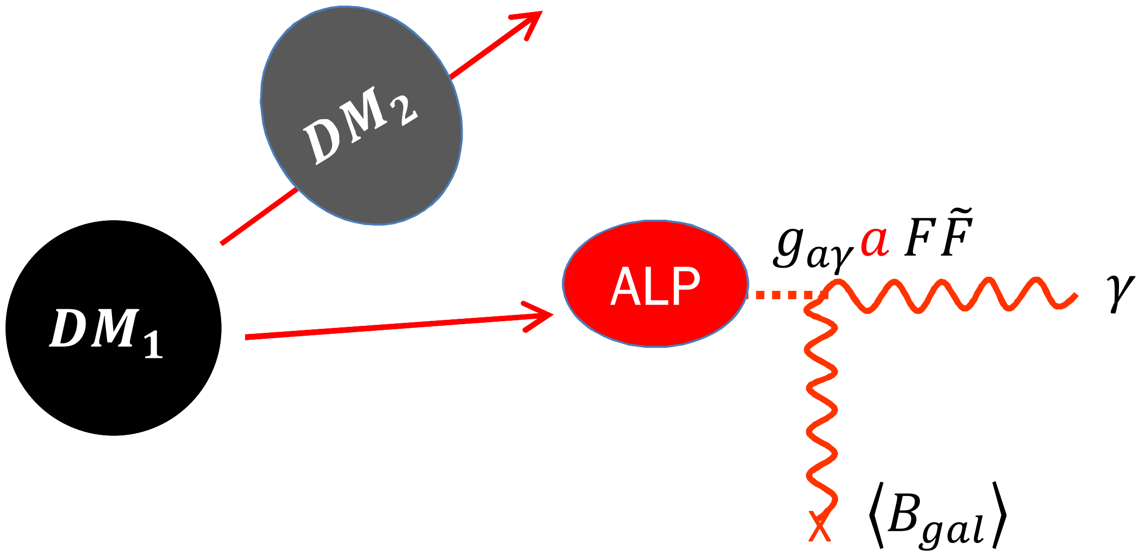
[Bae, Kamada, Kim 18]

Cold Dark Matter framework is very successful to explain large scale structures. For a galactic scales, it is not perfectly clear yet because of small scale problems such as missing satellite, too big to fail, and core-cusp problems.

Interesting idea to resolve the problem by nearly present time decay of dark matter to a little boosted dark matter : $DM_1 \rightarrow DM_2$ (with small boost as $v_{kick} \sim$ 30 km/sec)

$$\tau_{DM} \sim \text{Age of the Universe} \sim 10 \text{ Gyr}$$

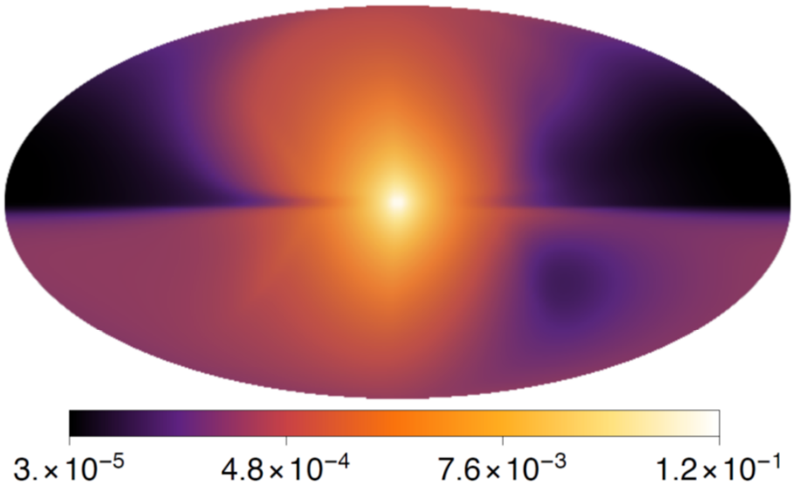
Concrete model can be realized by introducing ALP as $DM_1 \rightarrow DM_2 + a$ (DM_1 : axino, DM_2: gravitino, $\Delta m_{DM}/m_{DM} = 10^{-4}$). *The axions are produced by decays of DMs around the galaxy center which are converted to photons via galactic magnetic field,* B_{gal}



Small scale problems and ALP signal

[Bae, Kamada, Kim 18]

Signal morphology is very different from that of ordinary decaying (annihilating) dark matter scenario



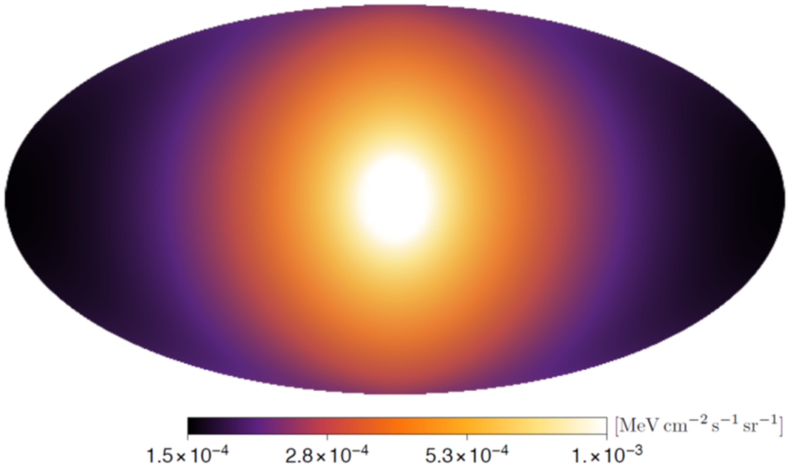
Our scenario

$E_\gamma = 47\,\mathrm{GeV}$ $g_{a\gamma} = 10^{-13}\,\mathrm{GeV}^{-1}$

$\tau_{\tilde{a}} \simeq 3 \times 10^{17} s$ $m_a = 10^{-8}\,\mathrm{eV}$

Magnetic field profile from Jansson & Farrar, Astrophys. J., vol. 757, p. 14, 2012

$$B_{\text{galactic}} \simeq 5\,\mu\mathrm{G}$$



Simple Decaying DM to diphoton

$E_\gamma = 47\,\mathrm{GeV}$ $m_{\mathrm{DM}} = 94\,\mathrm{GeV}$

$\tau_{\mathrm{DM}} \simeq 10^{28}\,\mathrm{s}$

Conclusions

- *QCD axion is a well motivated particle, whose main feature can be generalized to Axion Like Particle (ALP)*
- *QCD axion mass in simple models can be calculated rather precisely which encourage experimental test for certain mass scales.*
- *Other parameter ranges of the axion mass and axion decay constant also play interest roles in HEP physics problems*
- *All those consideration encourage new experiments and model buildings*