Axion dark matter in high scale inflation scenario

KC, K.S. Jeong and M.S. Seo, arXiv:1404.3880

KC, E.J. Chun, S.H. Im, K.S. Jeong and S.H. Lim, in preparation

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Outline

* Introduction

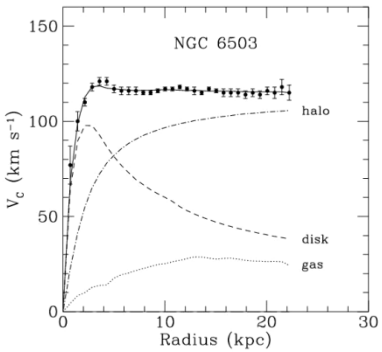
* Cosmological constraints on axion

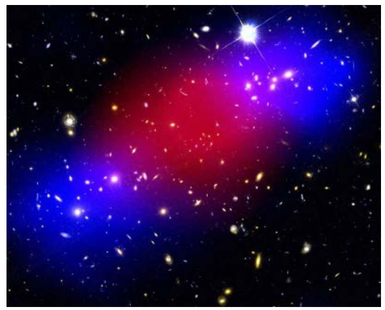
* Axion dark matter with high scale inflation:

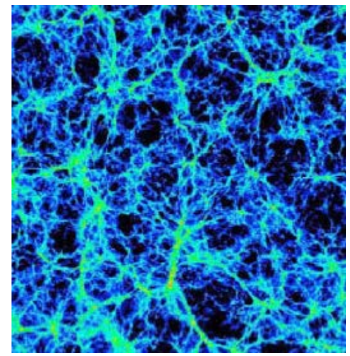
  A model for diluting away the axion isocurvature perturbation produced during the primordial high scale inflation, while providing a right amount of axion dark matter: $\Omega_{axion} = 0.24$

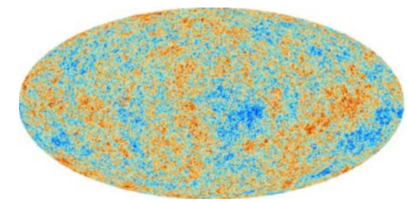
* Conclusion

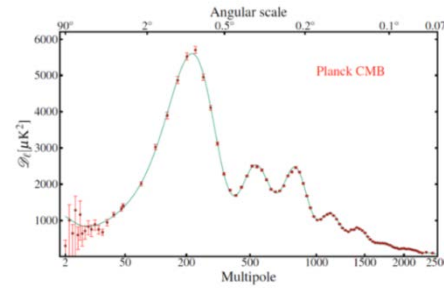
Plenty of evidence for dark matter (DM)



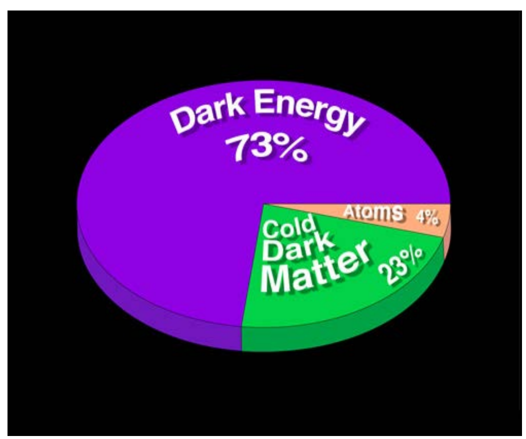




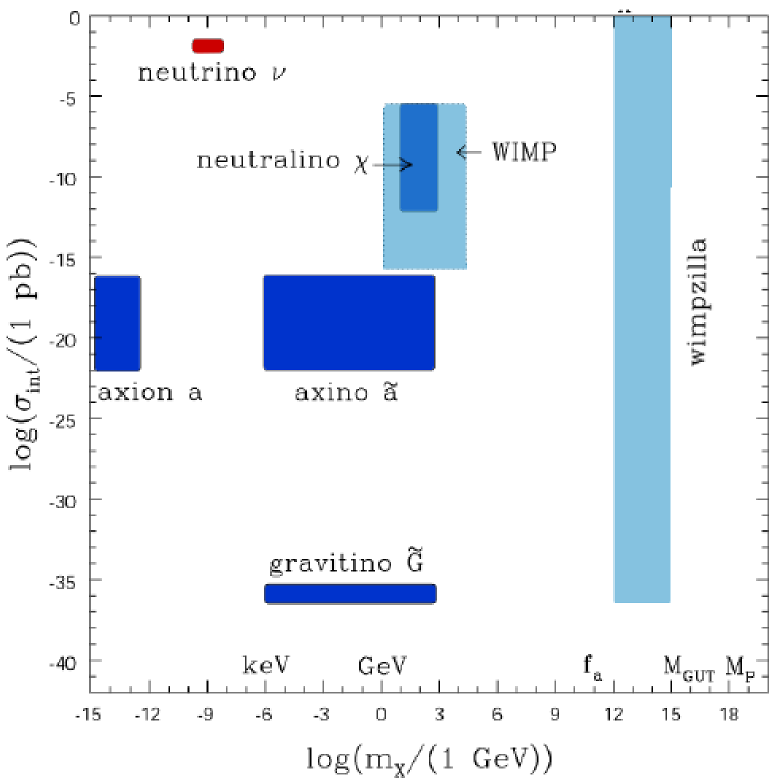




➔



More plenty of candidates for dark matter



Roszkowski (2004)

There are in fact a lot more candidates
(fuzzy DM, hidden photons, ultra-light axions ...)
discussed in the literatures, and

in principle m_{DM} can be anywhere

between 10^{-31} GeV and 10^{18} GeV.

Which one is the better motivated candidate?

Axion is one of the few best motivated DM candidates.

Axion has been introduced to solve the strong CP problem:

CP violation in the SM: $\frac{\theta_{QCD}}{32\pi^2} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} + (y_q H \bar{q}_L q_R + h.c)$

➔ $\bar{\theta} = \theta_{QCD} + Arg \cdot Det(y_q)$ (CP violation in the strong interactions)

$\delta_{KM} \sim Arg(y_q)$ (CP violation in the weak interactions)

Nearly maximal CP violation in the weak interactions ➔ $\delta_{KM} \sim 1$

CP conserving strong interactions ➔ $|\bar{\theta}| = |\theta_{QCD} + Arg \cdot Det(y_q)| < 10^{-10}$

(Neutron EDM: $d_n \sim 10^{-16}\,\bar{\theta}\ e\cdot cm < 10^{-26}\ e\cdot cm$)

Why $|\theta_{QCD}$+ Arg Det$(y_q)| < 10^{-10}$, while $\delta_{KM} \sim$ Arg$(y_q) \sim 1$?

Anthrophic argument can not explain this puzzle, it is thus likely that there should exist some physical reason for the small value of $\bar{\theta}$.

Axion solution of the strong CP problem

Introduce a spontaneously broken anomalous global U(1) symmetry

(Peccei-Quinn symmetry)

➔ θ_{QCD} becomes a dynamical field "axion"

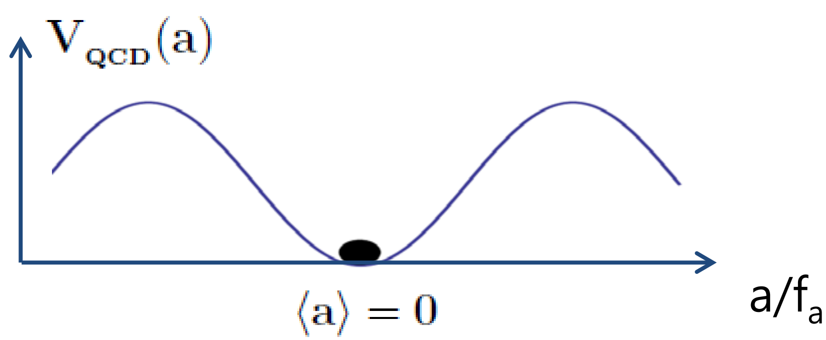
= Nambu-Goldstone boson of the spontaneously broken $U(1)_{PQ}$

$$\frac{1}{32\pi^2}\left(\theta_{QCD} + \mathrm{Arg}\cdot\mathrm{Det}(y_q)\right) G^{a\mu\nu}\tilde{G}^a_{\mu\nu} \;=\; \frac{1}{32\pi^2}\frac{\langle a\rangle}{f_a} G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

$\mathbf{f_a}$ = Axion scale = Mass scale of the spontaneous breakdown of $U(1)_{PQ}$

(Axion decay constant)

Low energy QCD dynamics develops an axion potential minimized at $\langle a \rangle = 0$:



➔ QCD becomes CP conserving after the axion is settled down at its VEV.

Most of axion physics is determined by the axion scale f_a:

* axion mass (at present) : $m_a \sim 5 \times 10^{-6} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mathrm{eV}$

* axion-photon couplings

$$\frac{g_{a\gamma\gamma}}{2} a \vec{E} \cdot \vec{B} \;\; : \quad g_{a\gamma\gamma} \sim 10^{-15} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mathrm{GeV}^{-1}$$

* axion-nucleon couplings

$$g_{aNN} a \bar{N} \gamma_5 N \; : \quad g_{aNN} \sim 10^{-12} \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right)$$

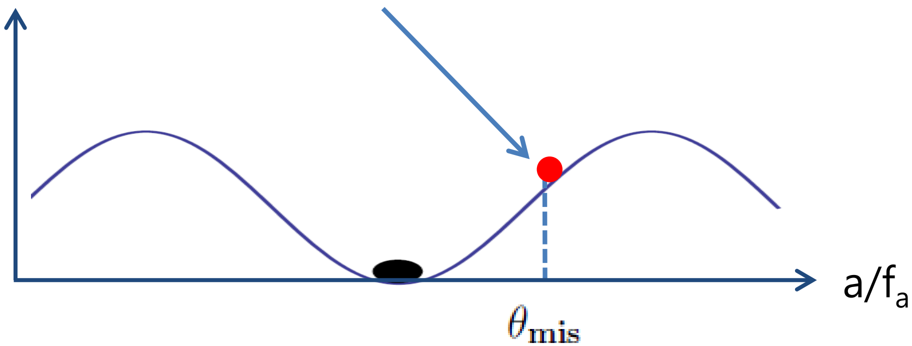
Star cooling by axion emission: $\mathbf{f_a} > 4 \times 10^8$ GeV

➔ $\tau_a \gg 10^{17}$ sec, so once axions were produced in the early universe, they constitute (part of) the DM in the present universe.

Cosmological production of axion dark matter:

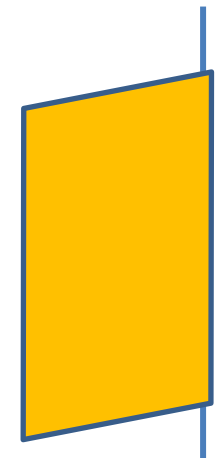
Misalignment + Topological defects (PQ-strings and domain walls)

Initial axion field misaligned
from the minimum of the axion potential



PQ-string attached
by axion domain wall

(if the PQ phase transition
took place after inflation
is over)

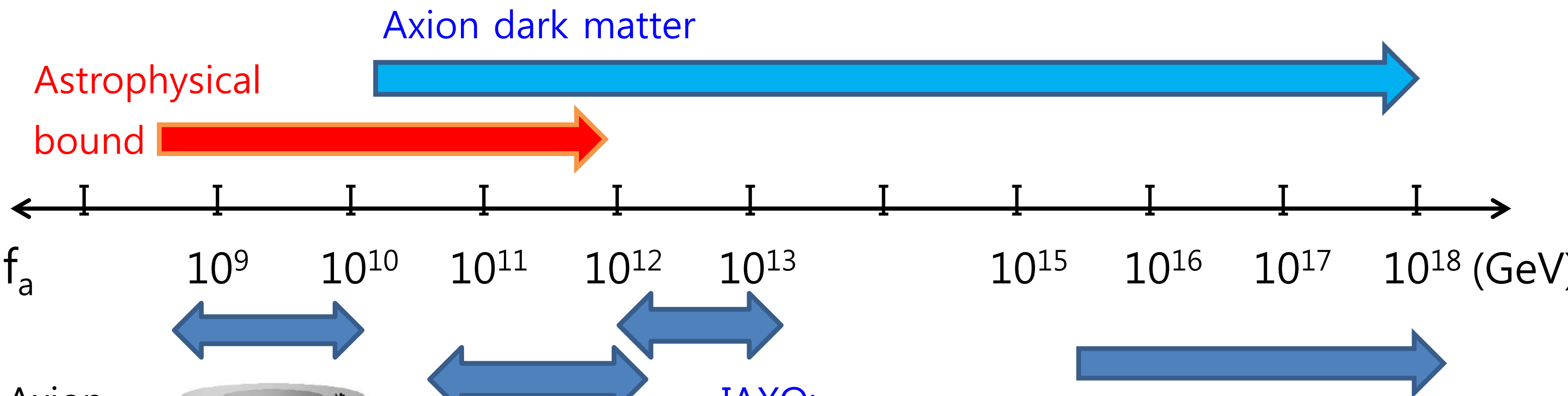


➔ Cold axions with $\Omega_a \sim 0.2\,(\theta_{\rm mis}^2 + {\rm R}_{\rm defect})\left(\frac{f_a}{10^{12}\,{\rm GeV}}\right)^{7/6} \quad \left(f_a < \mathcal{O}(10^{17}\,{\rm GeV})\right)$

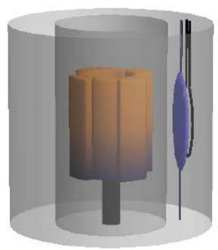
$\sim$ 30 = Efficiency factor for the axion production
by collapsing string-wall system

Cold axion DM is a generic consequence of solving the strong CP problem with a PQ symmetry, but the question is whether the axion abundance can have a right value, i.e. $\Omega_{\rm axion} = 0.24$

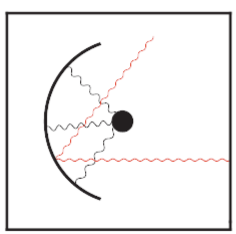
QCD axion has a good potential to be experimentally tested!



Axion mediated force



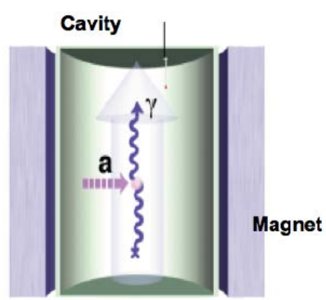
(Arvanitaki & Geraci '04)



Dish antenna

(Horns et al '12)

Resonant cavity:



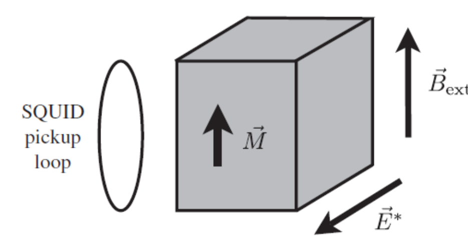
(Sikivie '83)

IAXO:

Next generation of axion helioscope

Oscillating EDM induced by oscillating DM axions

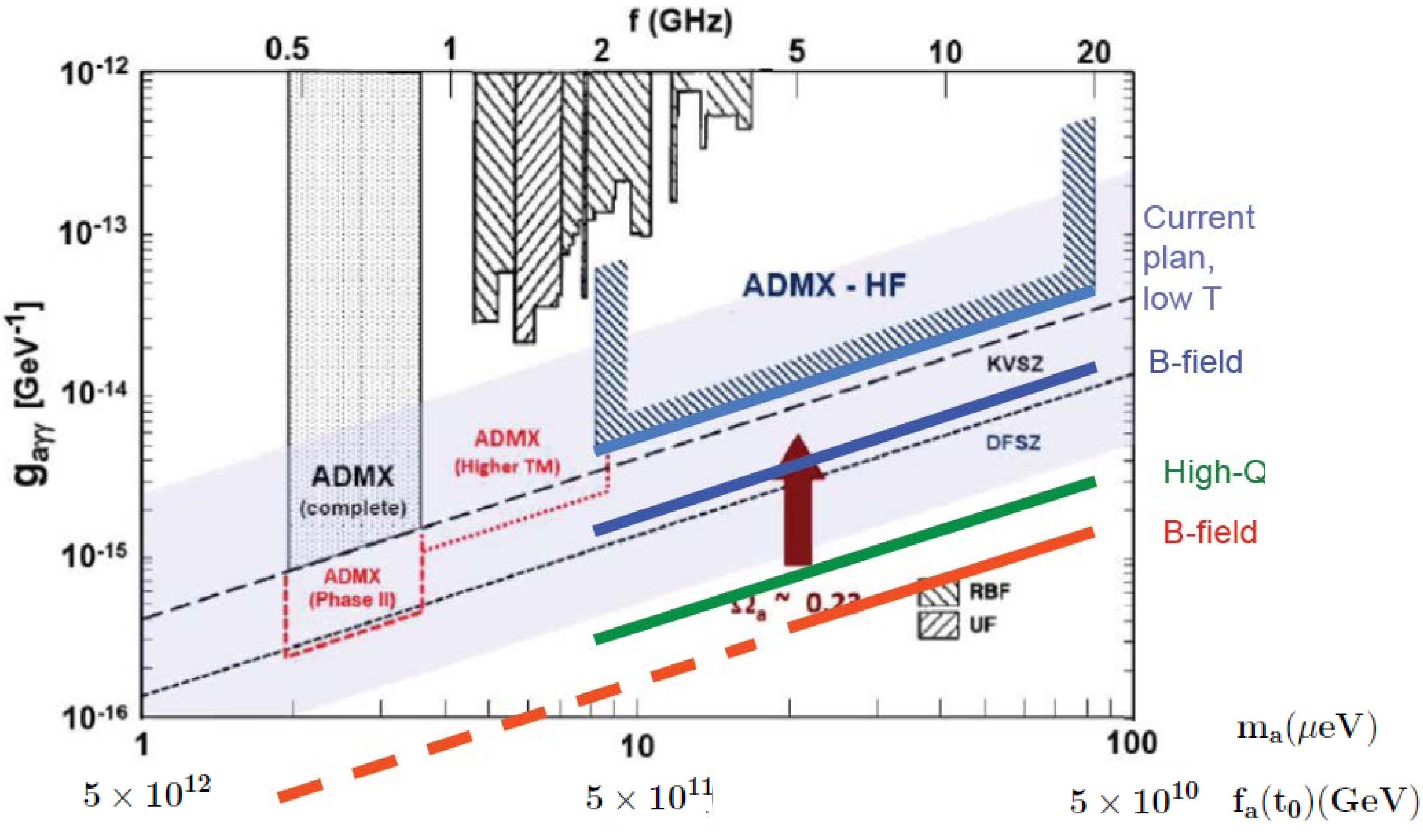
(Graham & Rajendran '13)



Axion dark matter search with microwave cavity

ADMX (Axion Dark Matter eXperiment) (Seattle, USA)

vs **CAPP** (Center for Axion and Precision Physics) (IBS/KAIST, Korea)



Cosmological constraints on axions

Generically $\mathbf{f_a}$ and $\mathbf{m_a}$ can depend on some field variables (e.g. the Higgs fields, saxion, moduli, …), and therefore can have nontrivial cosmological evolution from the inflation epoch to the present time:

t_I = Primordial inflation epoch

t_{QCD} = QCD phase transition epoch with $T(t_{QCD}) \sim 1\ \mathrm{GeV}$

when the axion DM are produced ($m_a(t_{QCD}) \sim H(t_{QCD})$)

t_0 = Present

Depending on how $\mathbf{f_a}$ and $\mathbf{m_a}$ evolve from t_I to t_{QCD}, cosmological constraints on axions take a different form.

(We will always assume the standard cosmology from t_{QCD} to t_0 .)

A particularly relevant question:

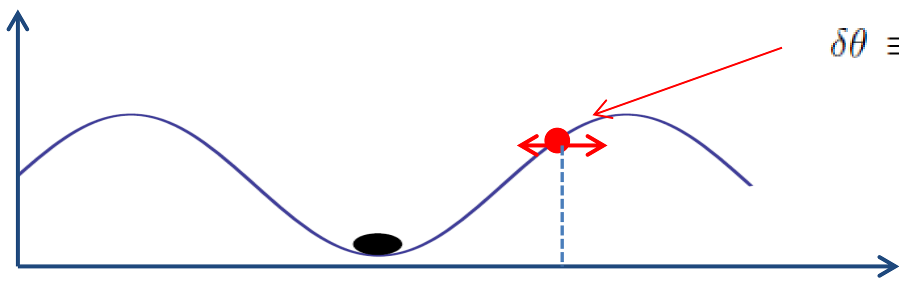
Was the PQ symmetry restored during the inflation epoch or not?

Scenario A:

PQ symmetry is non-linearly realized (spontaneously broken) during inflation, and never restored thereafter

There is no PQ-strings or domain walls within our horizon, but the axion field could have a nonzero misalignment together with a fluctuation produced during the inflation epoch:

$$\delta\theta \equiv \frac{\delta a(t_I)}{f_a(t_I)} = \frac{H(t_I)}{2\pi f_a(t_I)}$$



$\langle a \rangle = 0$

$a/f_a(t_0) = \theta$

$$\theta_0 = \langle \theta_{mis} \rangle = \text{Averaged axion misalignment angle}$$

$$\delta a(t_I) = \frac{H(t_I)}{2\pi} = \text{axion fluctuation generated during inflation}$$

* Relic axion dark matter: Preskill, Wise, Wilczek '83; Abbott , Sikivie '83; Dine, Fischler '83; ...

$$\Omega_a \sim 0.2 \langle \theta_{mis}^2 \rangle \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \leq 0.24$$

* Axion isocurvature perturbation: Axenides et al '83; Turner et al '85; Fox et al '04; ...

Axion field fluctuation produced during the primordial inflation:

$$\delta\theta = \frac{\delta a(t_I)}{f_a(t_I)} \sim \frac{H(t_I)}{2\pi f_a(t_I)}$$

If this fluctuation survives until t_{QCD} , which is the case as long as $m_a(t) \ll H(t)$ over $t < t_{QCD}$, it gives rise to an isocurvature perturbation of the axion dark matter:

$$\left(\frac{\delta T}{T} \right)_{iso} \sim \frac{\delta\rho_a}{\rho_{DM}} \sim \frac{\Omega_a}{\Omega_{DM}} \frac{\delta\rho_a}{\rho_a} \sim \frac{\Omega_a}{\Omega_{DM}} \frac{2\delta\theta}{\theta_0}$$

(PLANCK)

$$\sim \left(\frac{\Omega_a}{\Omega_{DM}} \right)^{1/2} \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}} \right)^{7/12} \left(\frac{H(t_I)}{\pi f_a(t_I)} \right) < 10^{-5}$$

Axion abundance in Scenario A is determined by two independent parameters, $f_a(t_0)$ and θ_{mis}, and severely constrained by the isocurvature bound depending on $H(t_I)/f_a(t_I)$.

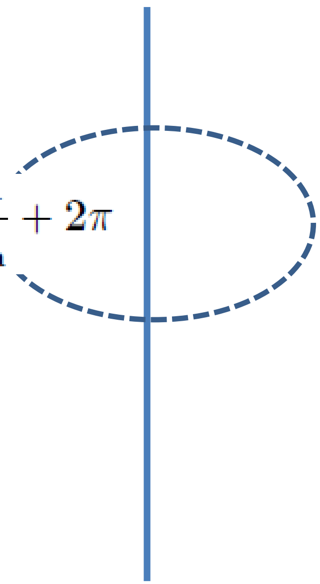
Scenario B:

The last spontaneous PQ breaking occurred after inflation

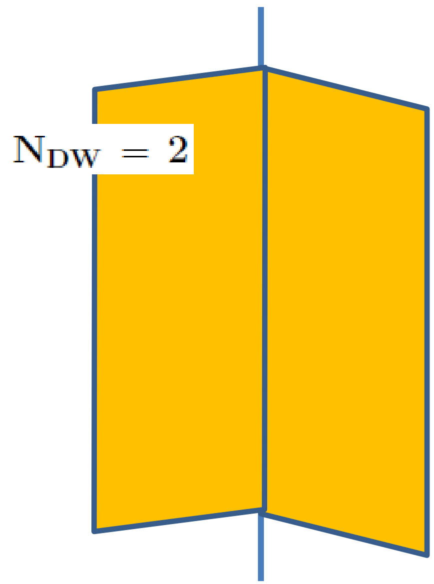
There are PQ -strings attached by N_{DW} domain walls, which cause cosmological domain wall problem unless N_{DW} = 1:

Cosmic string produced during the PQ phase transition

$$\frac{a}{f_a} \to \frac{a}{f_a} + 2\pi$$



PQ-string attached by domain walls formed during the QCD phase transition



$$N_{DW} = \sum_i q_i \mathrm{Tr}(T_c^2(\psi_i))$$
$$= \text{nonzero integer}$$

➔ Axion domain-wall number = $N_{DW} = \sum_i q_i \mathrm{Tr}(T_c^2(\psi_i)) = 1$

There is no axion isocurvature perturbation, but axion dark matters can be produced by the collapsing string-wall networks with $N_{DW} = 1$,

Davis '86; Davis, Harari, Sikivie '87; Davis, Shellard '89, …

as well as by the coherent oscillation of misaligned axion field:

$$\Omega_a \sim 0.2 \left(\langle \theta^2_{mis} \rangle + R_{defect}\right) \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}}\right)^{7/6}$$

Extensive numerical simulation ➔ $R_{defect} \sim 30$

Kawasaki et al, '14, Hiramatsu et al, '12, …

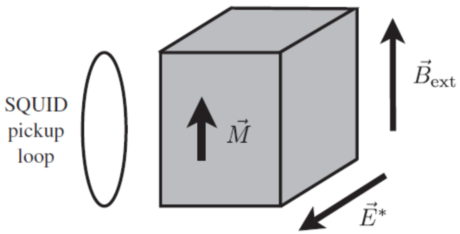
➔ Axions are produced mostly by the collapsing string-wall network!

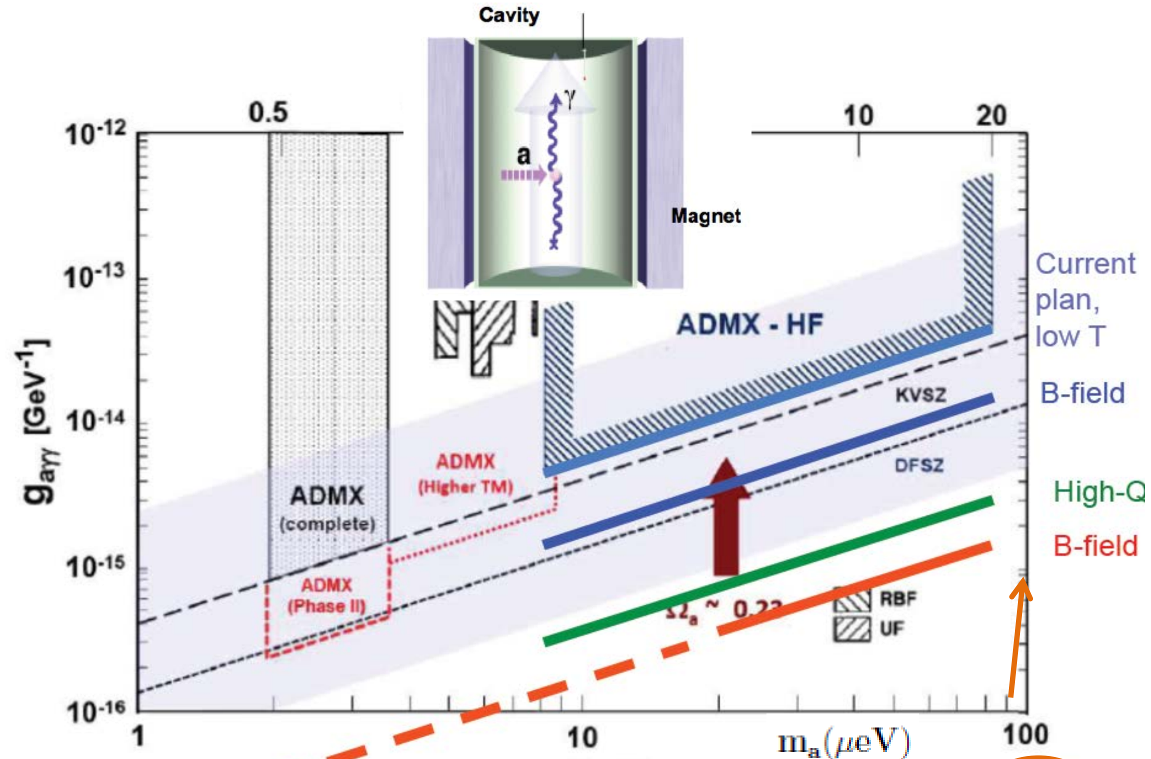
$$\Omega_a \sim 6 \times \left(\frac{f_a(t_0)}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \lesssim 0.24$$

➔ $4 \times 10^8\ \mathrm{GeV} \lesssim f_a(t_0) \lesssim 5 \times 10^{10}\ \mathrm{GeV}$

Axion abundance in Scenario B is determined by the single parameter $f_a(t_0)$, and the model is required to have $N_{DW} = 1$, which is an unlikely feature of the PQ symmetry obtained in top-down approach.

Scenario A and Scenario B are experimentally distinguishable!





Axion DM
from misalignment
(Scenario A)

$$f_a \geq 3 \times 10^{11} \text{ GeV}$$

$$\Omega_a \sim 0.2 \langle \theta_{mis}^2 \rangle \left(\frac{f_a(t_0)}{10^{12} \text{ GeV}} \right)^{7/6}$$

Axion DM
from string-walls
(Scenario B)

$$f_a \sim 5 \times 10^{10} \text{ GeV}$$

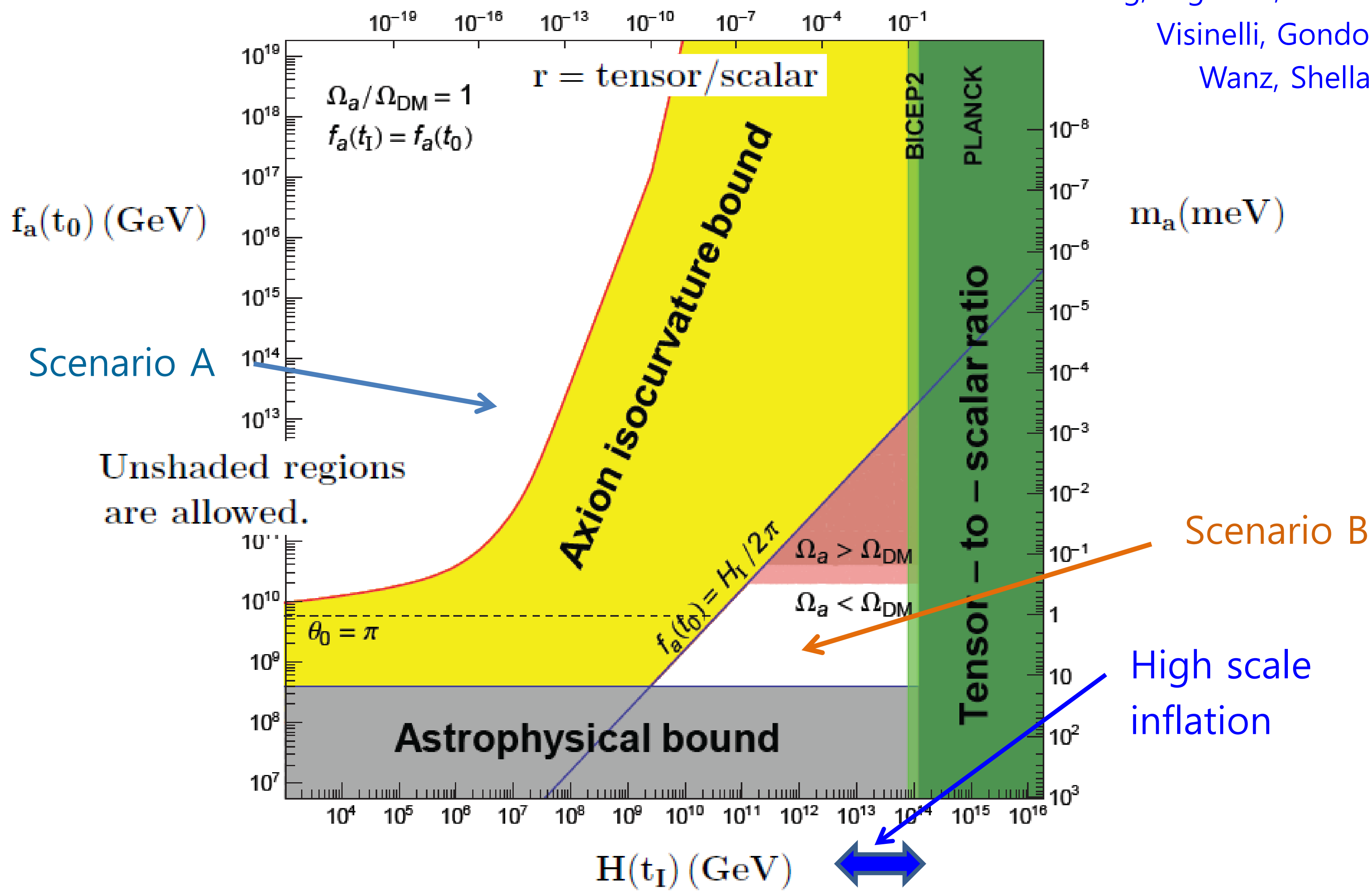
$$\Omega_a \sim 6 \times \left(\frac{f_a(t_0)}{10^{12} \text{ GeV}} \right)^{7/6}$$

Different velocity dispersion?

A frequently used summary of the constraints, which applies only when

$f_a(t_I) \sim f_a(t_0),\ m_a(t) \ll H(t)$ for $t < t_{QCD},\ \&\ \Omega_a = \Omega_{DM}$ for Scenario A:

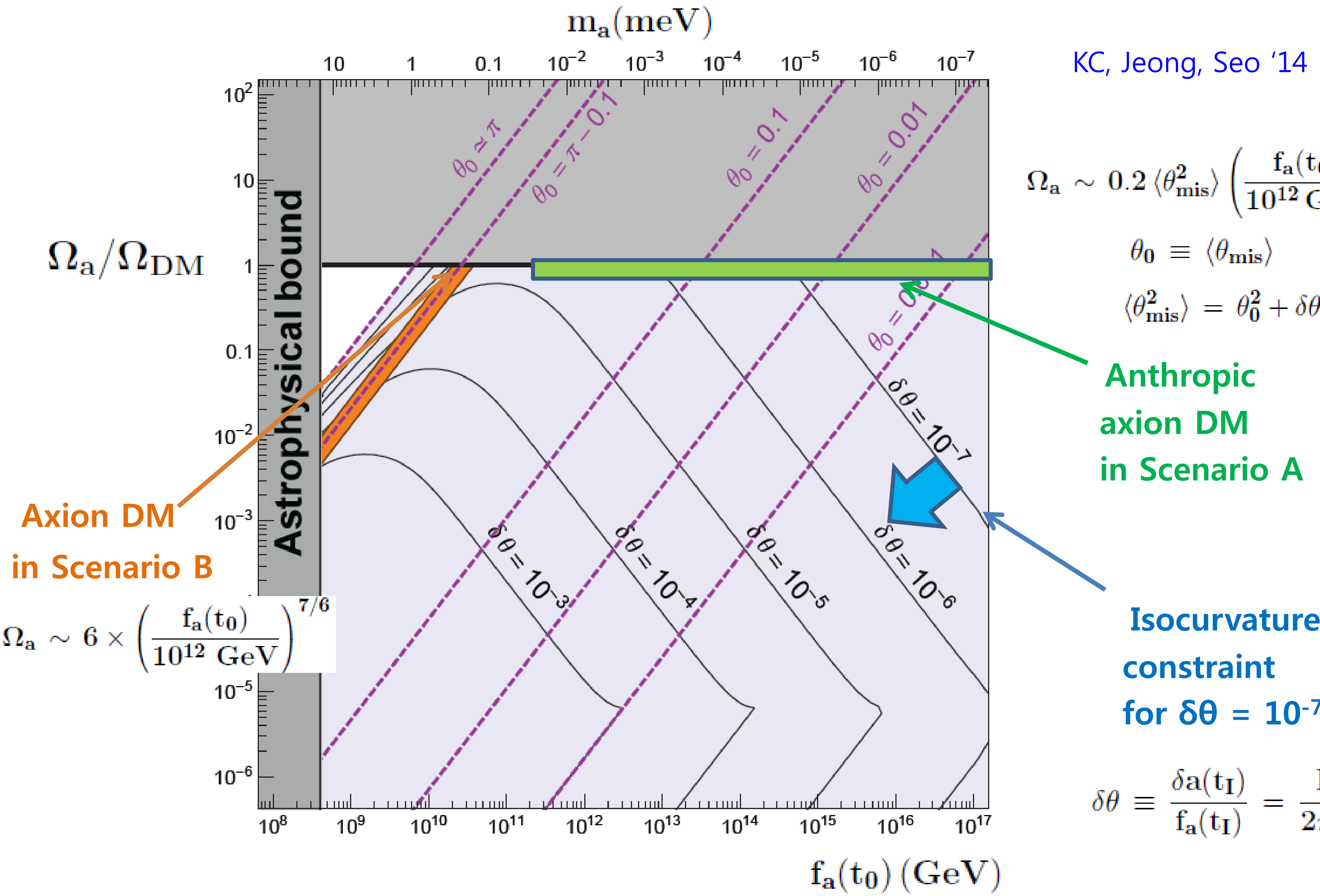
Hertzberg, Tegmark, Wilczek '08;
Visinelli, Gondolo '09;
Wanz, Shellard '10;



Constraints for more generic situation with

$$\mathrm{f_a(t_I) \neq f_a(t_0),\ \ m_a(t) \ll H(t)\ \ for\ \ t < t_{QCD},\ \ \&\ \ \Omega_a \leq \Omega_{DM}}$$

KC, Jeong, Seo '14



$$\Omega_a \sim 6 \times \left(\frac{f_a(t_0)}{10^{12}\ \mathrm{GeV}}\right)^{7/6}$$

$$\Omega_a \sim 0.2\,\langle\theta^2_{\rm mis}\rangle \left(\frac{f_a(t_0)}{10^{12}\ \mathrm{GeV}}\right)^{7/6}$$

$$\theta_0 \equiv \langle\theta_{\rm mis}\rangle$$

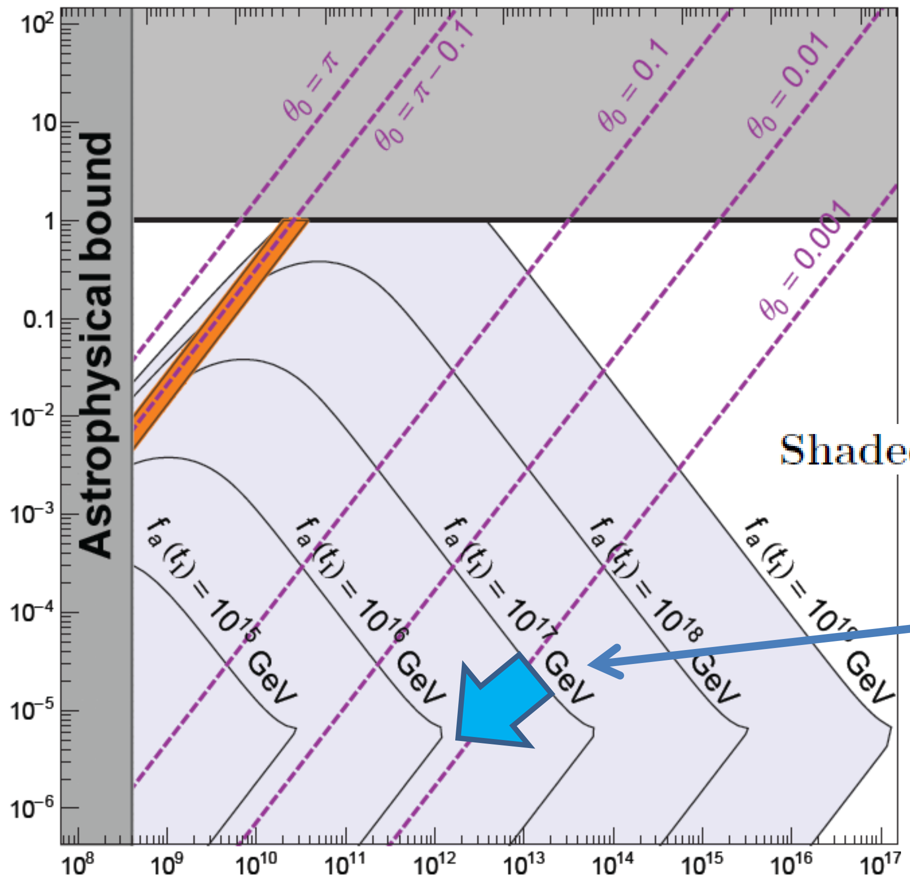
$$\langle\theta^2_{\rm mis}\rangle = \theta_0^2 + \delta\theta^2$$

$$\delta\theta \equiv \frac{\delta a(t_I)}{f_a(t_I)} = \frac{H(t_I)}{2\pi f_a(t_I)}$$

For high scale inflation: $H(t_I) \sim 10^{14}$

KC, Jeong, Seo '14

Ω_a/Ω_{DM}



$f_a(t_0)\,(\mathrm{GeV})$

$$\left(\delta\theta = \frac{10^{14}\,\mathrm{GeV}}{2\pi f_a(t_I)}\right)$$

Shaded regions are allowed.

isocurvature constraint for **$f_a(t_I)$** = 10^{17} GeV

The PQ symmetry should be either restored (Scenario B), or spontaneously broken at much higher scale during inflation (Scenario A), regardless of the value of Ω_a/Ω_{DM} : $f_a(t_I) = 0$ or $f_a(t_I) \gg f_a(t_0)$

What would be the most probable parameter region for the QCD axion compatible with high scale inflation?

* For Scenario B (PQ symmetry restored during inflation), if one tries to get such a PQ symmetry from top-down approach, e.g. within the framework of string theory, usually one finds $N_{DW} > 1$ which is not acceptable.

* For Scenario A (PQ symmetry spontaneously broken during inflation), the axion scale during inflation can not be arbitrarily high as the perturbative axion coupling can not be significantly weaker than the gravitational interaction:

(Weak gravity conjecture)

Arkani-Hamed, Motl, Nicolis, Vafa '07

$$\frac{g^2}{32\pi^2 f_a} a G\tilde{G} \;\rightarrow\; f_a(t_I) \leq \mathcal{O}\left(\frac{g^2}{8\pi^2} M_{Pl}\right) \;\rightarrow\; f_a(t_I) \leq 10^{17}\,\mathrm{GeV}$$

* Accept the tuning of θ_0 if there is an anthropic reasoning, but no more tuning than the one required by anthropic argument.

Axion DM in high scale inflation scenario compatible with the weak gravity conjecture (also with $m_a(t) \ll H(t)$ for $t < t_{QCD}$)

Most probable region

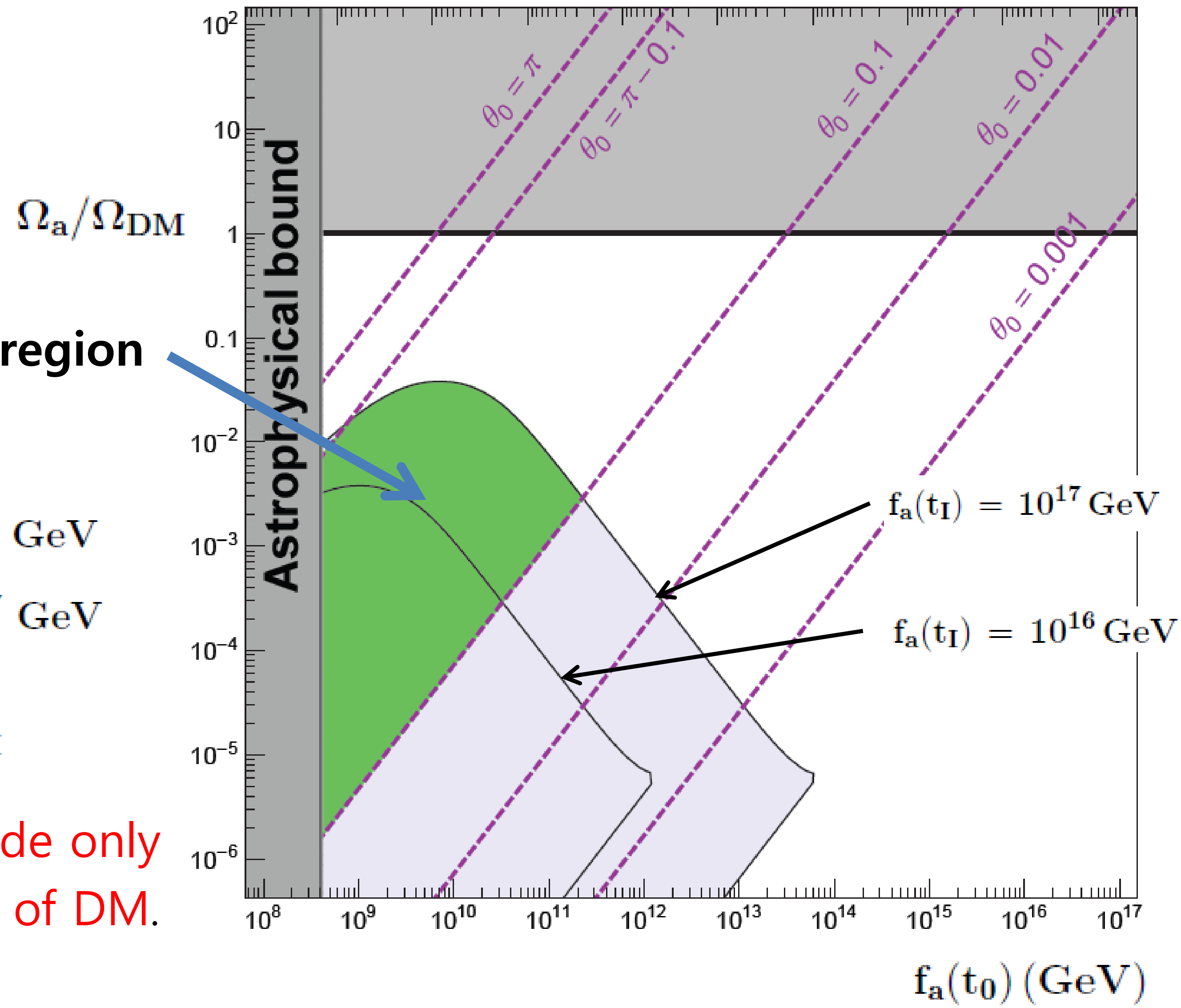
$\theta_0 \sim 0.1 - \mathcal{O}(1)$

$f_a(t_0) \sim 10^9 - 10^{11}$ GeV

$f_a(t_I) \sim 10^{15} - 10^{17}$ GeV

→ $\Omega_a \ll \Omega_{DM}$

Axion can provide only a small fraction of DM.



A model for axion DM in high scale inflation scenario

KC, Chun, Jeong, Im, in preparation

To avoid the isocurvature perturbation constraint on axion DM in high scale inflation scenario, we need an epoch with $m_a(t) \geq H(t)$ between the primordial inflation and the conventional QCD phase transition.

A key theoretical question about the axion model:

* What is the mechanism to determine the axion scale?

For $f_a \ll M_{Pl}$, PQ breaking triggered by SUSY breaking:

$$V(\phi) = -m_{SUSY}^2|\phi|^2 + \frac{|\phi|^6}{M_{Pl}^2} + \ldots \quad \rightarrow \quad f_a \sim \langle\phi\rangle \sim \sqrt{m_{SUSY}M_{Pl}}$$

Such models can be easily embedded in string theory:

Shift symmetry which originates from higher-dim gauge symmetry

+ Anomalous U(1) gauge symmetry broken by the Stuckelberg mechanism

➔ $U(1)_{PQ}$ which is unbroken in supersymmetric limit, and is well protected from quantum gravity effects.

Models of PQ breaking triggered by SUSY breaking ($f_a \sim \sqrt{m_{SUSY} M_{Pl}}$) provides

* an attractive solution of the μ-problem Kim, Nilles '84

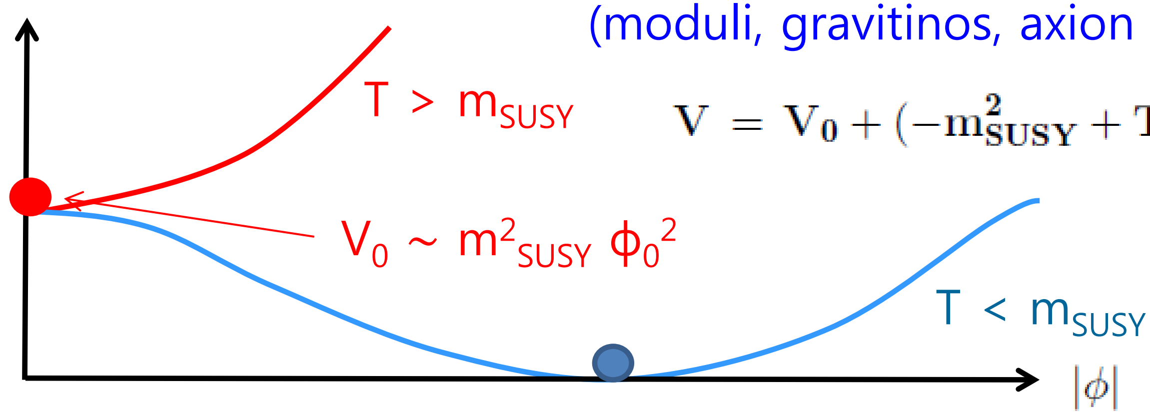
The bare Higgsino mass term (μ-term) is forbidden by the PQ symmetry, and a right size of $\mu \sim m_{SUSY}$ is generated by the spontaneous PQ breaking:

$$W = \frac{\phi^2 H_u H_d}{M_{Pl}} + \ldots \equiv \mu H_u H_d + \ldots \quad \rightarrow \quad \mu \sim \frac{f_a^2}{M_{Pl}} \sim m_{SUSY}$$

* late thermal inflation (TI) diluting the undesirable primordial relics Lyth, Stewart '95

(moduli, gravitinos, axion fluatuations, ...)

$$V = V_0 + (-m_{SUSY}^2 + T^2)|\phi|^2 + \frac{|\phi|^6}{M_{Pl}^2}$$



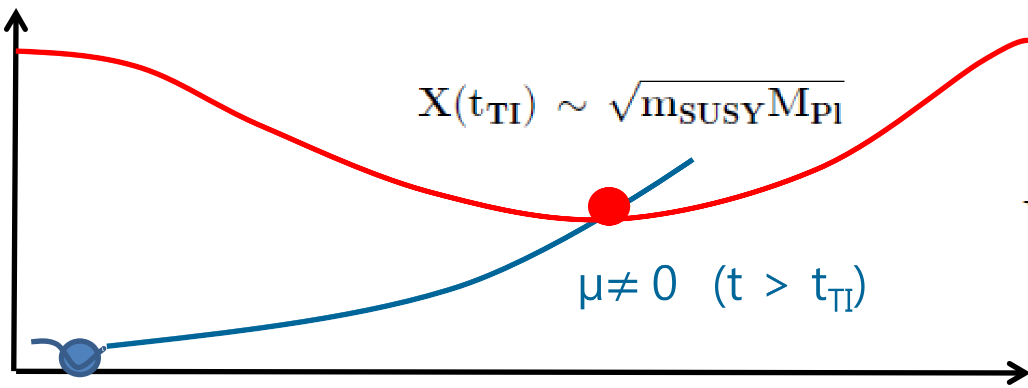
$\phi_0 \sim \sqrt{m_{SUSY} M_{Pl}}$

→ Vacuum domination over $V_0^{1/4} > T > m_{SUSY}$

(# of e-foldings: $N_e \sim \frac{1}{4} \ln(M_{Pl}/m_{SUSY})$)

With this way to generate the μ-term, the MSSM Higgs and/or sleptons can have an unusual cosmological evolution.

Cosmological evolution of the MSSM flat directions H_uH_d & LH_u can severely depend on how the μ-term is generated:



$$V(X) = m_X^2|X|^2 + \frac{|X|^6}{M_{Pl}^2}$$

$$X = \{\sqrt{H_uH_d}, \sqrt{LH_u}\}$$

$$m^2_{H_uH_d}(t \sim t_{TI}) = m^2_{H_u} + m^2_{H_d} < 0, \qquad m^2_{H_uH_d}(t > t_{TI}) = m^2_{H_u} + m^2_{H_d} + 2|\mu|^2 > 0$$

$$m^2_{LH_u}(t \sim t_{TI}) = m^2_{\tilde{\ell}} + m^2_{H_u} < 0, \qquad m^2_{LH_u}(t > t_{TI}) = m^2_{\tilde{\ell}} + m^2_{H_u} + |\mu|^2 > 0$$

➔ * Higher EW scale, which gives rise to a higher QCD scale, and therefore a heavier axion mass during thermal inflation

* Affleck-Dine type leptogenesis with LH_u

A SUSY model for axion DM in high scale inflation scenario:

$$W = y_u H_u Q U^c + y_d H_d Q D^c + y_\ell H_d L E^c \quad \text{(MSSM)}$$

$$+ \frac{\tilde{\phi}\phi^3}{M_{Pl}} + \frac{\tilde{\phi}^2 H_u H_d}{M_{Pl}} + \frac{L H_u H_u H_d}{M_{Pl}} + \phi\Psi\Psi^c \ \text{(PQ - sector)} \ + \text{Inflaton - sector}$$

$U(1)_{PQ}:$	ϕ	$\tilde{\phi}$	H_u	H_d	L, D^c	Q, U^c, E^c
	1	-3	0	6	-6	0

Mass scales of the model:

* Fundamental scale near the Planck scale M_{Pl}
* Primordial inflation energy scale $M_I: \ H(t_I) \sim \frac{M_I^2}{M_{Pl}}$
* SUSY breaking scale (at present) m_{SUSY}

Induced scales:

* EW scale: $\mathcal{V}_{EW} \sim \max(\sqrt{H_u H_d}, \sqrt{L H_u})$
* Axion scale: $f_a \sim \max(\phi, \tilde{\phi}, \sqrt{H_u H_d}, \sqrt{L H_u})$
* QCD scales: $\Lambda_{QCD} \sim 5 \text{ TeV} \left(\frac{m_{SUSY}}{\text{TeV}}\right)^{2/11} \left(\frac{\mathcal{V}_{EW}}{10^{11}\text{ GeV}}\right)^{6/11} \quad \text{for } \mathcal{V}_{EW} > 10^5 m_{SUSY}$

Cosmological history of the model:

Effective potential of the PQ-charged flat directions $X_i = \{\phi, \tilde{\phi}, \sqrt{H_u H_d}, \sqrt{L H_u}\}$

$$V_{eff} = \sum_i \left|\frac{\partial W}{\partial X_i}\right|^2 + \left(m_i^2 + \xi_i \langle \mathcal{R} \rangle\right) |X_i|^2 + \left(A_i X_i \frac{\partial W}{\partial X_i} + h.c\right)$$

$$\left(m_i \sim A_i \sim m_{SUSY}, \quad \langle \mathcal{R} \rangle \sim H^2 \right)$$

Primordial inflation epoch:

$$\xi_{H_u H_d,\, LH_u} < 0, \quad \xi_{\phi,\, \tilde{\phi}} > 0$$

➔ $$\mathcal{V}_{EW}(t_I) \sim \sqrt{H_u H_d} \sim \sqrt{L H_u} \sim \sqrt{H(t_I) M_{Pl}} \sim 10^{16}\ \mathrm{GeV}$$

$$f_a(t_I) \sim \sqrt{H_u H_d} \sim \sqrt{L H_u} \sim \sqrt{H(t_I) M_{Pl}} \sim 10^{16}\ \mathrm{GeV}$$

$$\phi(t_I) = \tilde{\phi}(t_I) = 0$$

$$\mu(t_I) = \frac{\tilde{\phi}^2(t_I)}{M_{Pl}} = 0$$

Thermal inflation epoch:

$$m^2_{H_uH_d,\,LH_u} \sim -m^2_{SUSY} < 0$$

$$m^2_{\phi} \sim -m^2_{SUSY} + T^2 > 0, \quad m^2_{\tilde{\phi}} \sim m^2_{SUSY} > 0$$

➔ $$\mathcal{V}_{EW}(t_{TI}) \sim \sqrt{H_uH_d} \sim \sqrt{LH_u} \sim \sqrt{m_{SUSY}M_{Pl}} \sim 10^{11}\ \mathrm{GeV}$$

$$f_a(t_{TI}) \sim \sqrt{H_uH_d} \sim \sqrt{LH_u} \sim \sqrt{m_{SUSY}M_{Pl}} \sim 10^{11}\ \mathrm{GeV}$$

$$\phi(t_{TI}) = \tilde{\phi}(t_{TI}) = 0 \quad \rightarrow \quad \mu(t_{TI}) = \frac{\tilde{\phi}^2(t_{TI})}{M_{Pl}} = 0$$

$$\Lambda_{QCD}(t_{TI}) \sim 5\ \mathrm{TeV}\left(\frac{m_{SUSY}}{\mathrm{TeV}}\right)^{2/11}\left(\frac{\mathcal{V}_{EW}}{10^{11}\,\mathrm{GeV}}\right)^{6/11}$$

$$\frac{m_a(t_{TI})}{H(t_{TI})} \sim 10\left(\frac{\mathrm{TeV}}{m_{SUSY}}\right)^{9/11}\left(\frac{10^{11}\ \mathrm{GeV}}{f_a(t_{TI})}\right)^{16/11} > 1 \quad \left(m_a(t_{TI}) \sim \frac{\Lambda^2_{QCD}(t_{TI})}{f_a(t_{TI})}\right)$$

➔ During the thermal inflation epoch, axion field is settled down at the minimum of its potential, effectively eliminating the primordial axion field fluctuations.

Present (or the QCD phase transition epoch):

$$\mathrm{m}^2_{\mathrm{H_uH_d}} \sim -\mathrm{m}^2_{\mathrm{SUSY}} + 2|\mu|^2 > 0\ , \quad \mathrm{m}^2_{\mathrm{LH_u}} \sim -\mathrm{m}^2_{\mathrm{SUSY}} + |\mu|^2 > 0$$

$$\mathrm{m}^2_{\phi} \sim -\mathrm{m}^2_{\mathrm{SUSY}} < 0, \quad \mathrm{m}^2_{\tilde{\phi}} \sim \mathrm{m}^2_{\mathrm{SUSY}} > 0$$

,

➔ $$\mathrm{f_a(t_0)} \sim \phi(\mathrm{t_0}) \sim \tilde{\phi}(\mathrm{t_0}) \sim \sqrt{\mathrm{m_{SUSY}M_{Pl}}} \sim 10^{11}\ \mathrm{GeV}$$

$$\left(\Delta \mathrm{V} = \mathrm{A}_{\phi}\frac{\tilde{\phi}\phi^3}{\mathrm{M_{Pl}}}\ \ \text{with}\ \ \mathrm{A}_{\phi} \sim \mathrm{m_{SUSY}}\right)$$

$$\mu(\mathrm{t_0}) = \frac{\tilde{\phi}^2(\mathrm{t_0})}{\mathrm{M_{Pl}}} \sim \mathrm{m_{SUSY}}$$

$$\mathcal{V}_{\mathrm{EW}}(\mathrm{t_0}) \sim \mathrm{m_{SUSY}}$$

The minimum of the axion potential at present (making $|\bar{\theta}| = 0$) differs from the minimum of the axion potential during the thermal inflation epoch!

The minimum of $V_a(t_{TI})$ depends on the interaction $\Delta V = A_{LH_u} \frac{LH_uH_uH_d}{M_{Pl}}$,

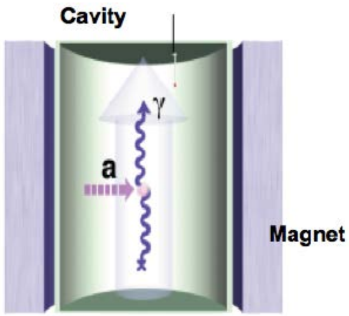
while the minimum of $V_a(t_0)$ depends on $\Delta V = A_{\tilde{\phi}} \frac{\tilde{\phi}^2 H_u H_d}{M_{Pl}} \equiv B\mu H_u H_d$.

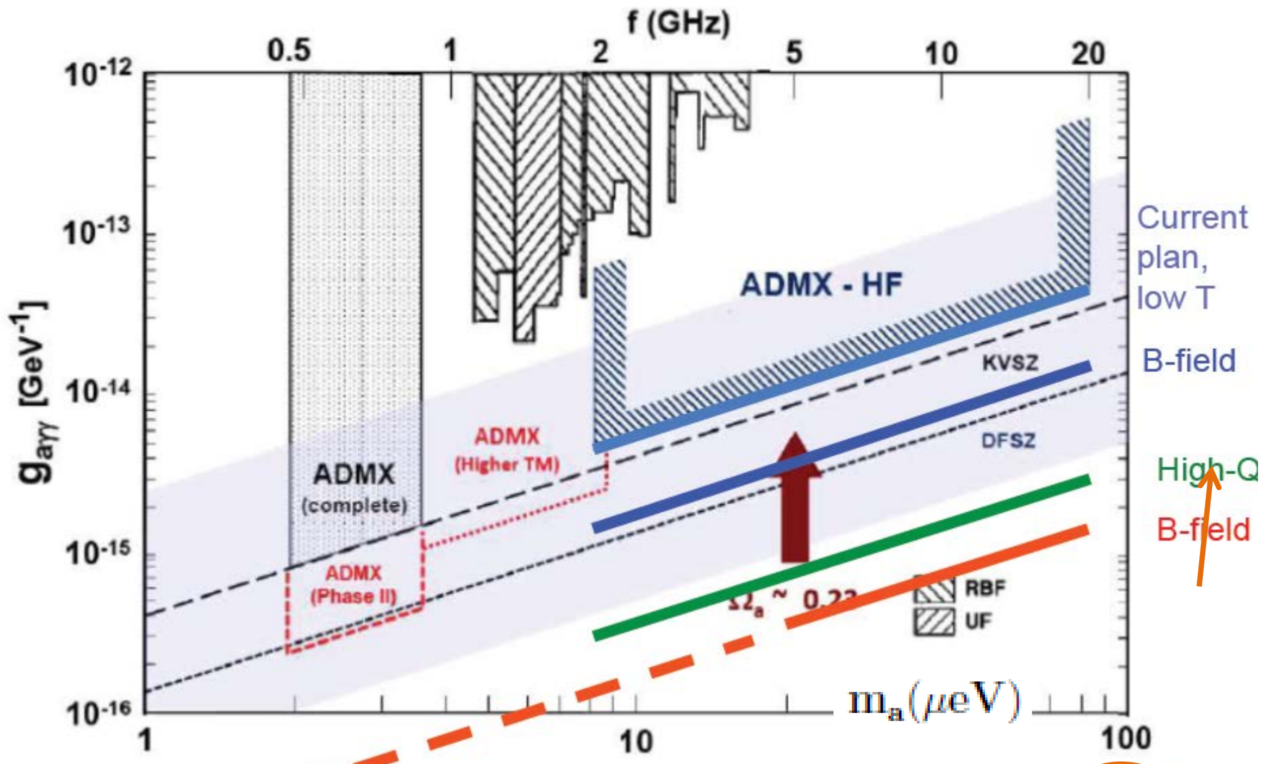
➔ O(1) misalignment of the axion field for $\Omega_a \sim 0.2\,\theta_{mis}^2 \left(\frac{f_a}{10^{12}\,GeV}\right)^{7/6} \simeq 0.24$ is produced during the thermal inflation epoch, while the primordial axion fluctuations are diluted away.

(The cosmological evolution of LH_u in this model successfully implements the AD leptogenesis after the thermal inflation is over.)

Conclusion

* Axion is one of the best motivated DM candidates:





Axion DM
from misalignment

$$\Omega_a \sim 0.2\,\langle\theta^2_{mis}\rangle \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}}\right)^{7/6}$$

$$f_a \geq 3\times 10^{11}\,\mathrm{GeV}$$

Axion DM
from string-walls

$$\Omega_a \sim 6\times \left(\frac{f_a(t_0)}{10^{12}\,\mathrm{GeV}}\right)^{7/6}$$

$$f_a \sim 5\times 10^{10}\,\mathrm{GeV}$$

* Within a conventional cosmological scenario with $m_a(t) \ll H(t)$ over $t < t_{QCD}$, axion DM from misalignment is in conflict with high scale inflation:

Bound on axion isocurvature perturbation + Weak gravity conjecture

➔ The most probable parameter region:

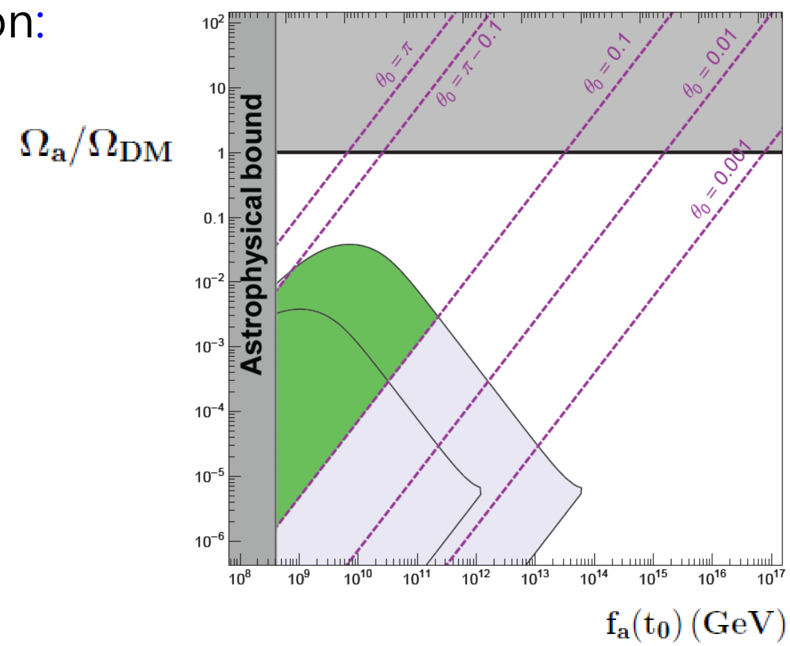
for $\mathrm{H}(\mathrm{t_I}) \sim 10^{13} - 10^{14}\ \mathrm{GeV}$:

$(\,\mathrm{tensor/scalar}\,=\,0.002 - 0.2\,)$

$$\mathrm{f_a}(\mathrm{t_I}) \sim 10^{15} - 10^{17}\ \mathrm{GeV}$$

$$\mathrm{f_a}(\mathrm{t_0}) \sim 10^{9} - 10^{11}\ \mathrm{GeV}$$

$$\Omega_\mathrm{a} \ll \Omega_\mathrm{DM}$$



* Axion DM from string-wall networks usually suffers from the domain wall problem.

* Within a theoretically well motivated framework which explains

  - Origin of the PQ symmetry which is unusually well protected from quantum gravity effects:

    Shift symmetry from higher-dim gauge symmetry

    + Anomalous U(1) gauge symmetry

  - Origin of the axion scale:

    Spontaneous PQ breaking triggered by SUSY breaking

    ➔ $f_a \sim \sqrt{m_{SUSY} M_{Pl}} \sim 10^{11}$ GeV

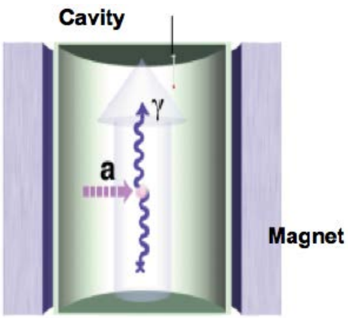
  - Origin of $\mu \sim m_{SUSY}$:

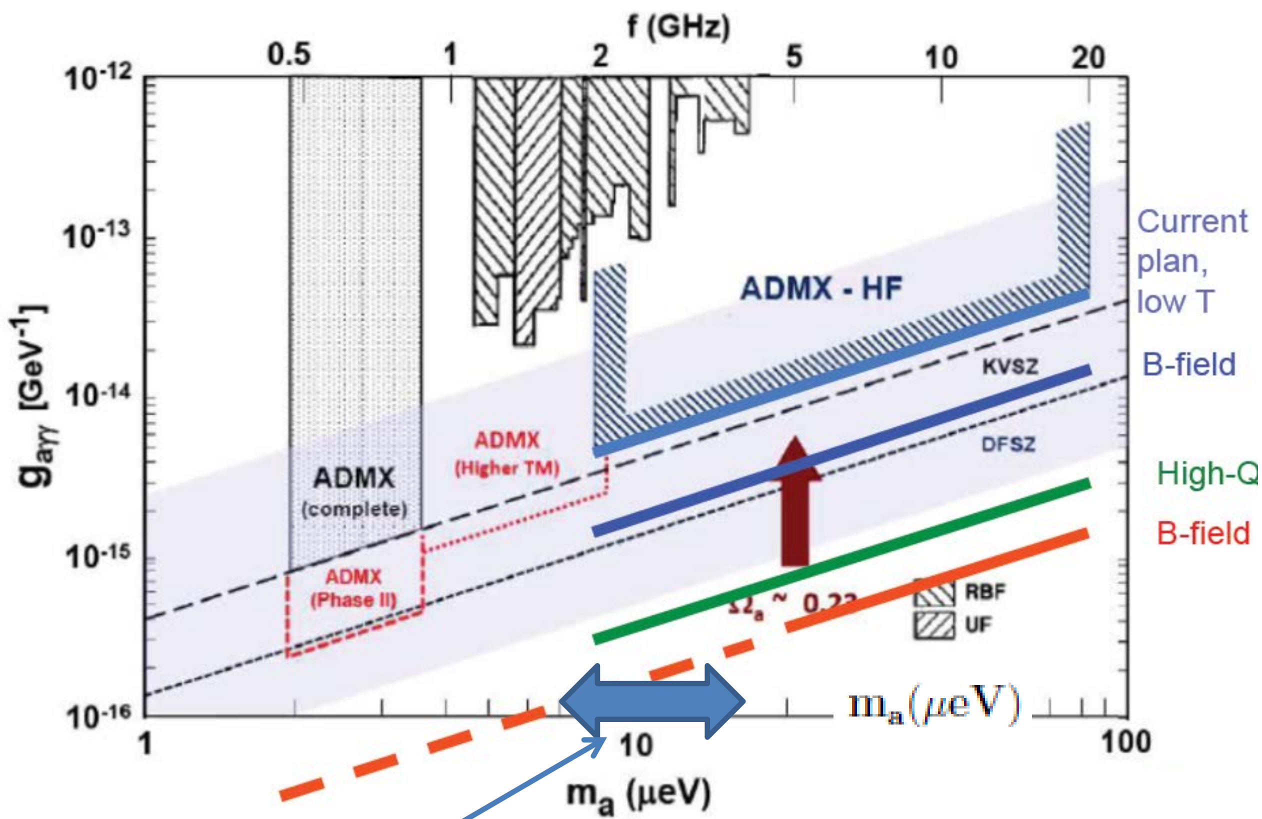
    The Higgs μ-term generated as a consequence of PQ breaking

    ➔ $\mu \sim \frac{f_a^2}{M_{Pl}} \sim m_{SUSY}$

a late thermal inflation with $m_a(t_{TI}) > H(t_{TI})$ can be naturally realized, which dilutes away the primordial axion fluctuations, while producing an axion misalignment of O(1) necessary for $\Omega_a \sim 0.2\,\theta_{mis}^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \simeq 0.24$

* This type of SUSY axion models predict





Axion DM is around here.