Axion as a Dark Matter Component

J. E. Kim
Seoul National University
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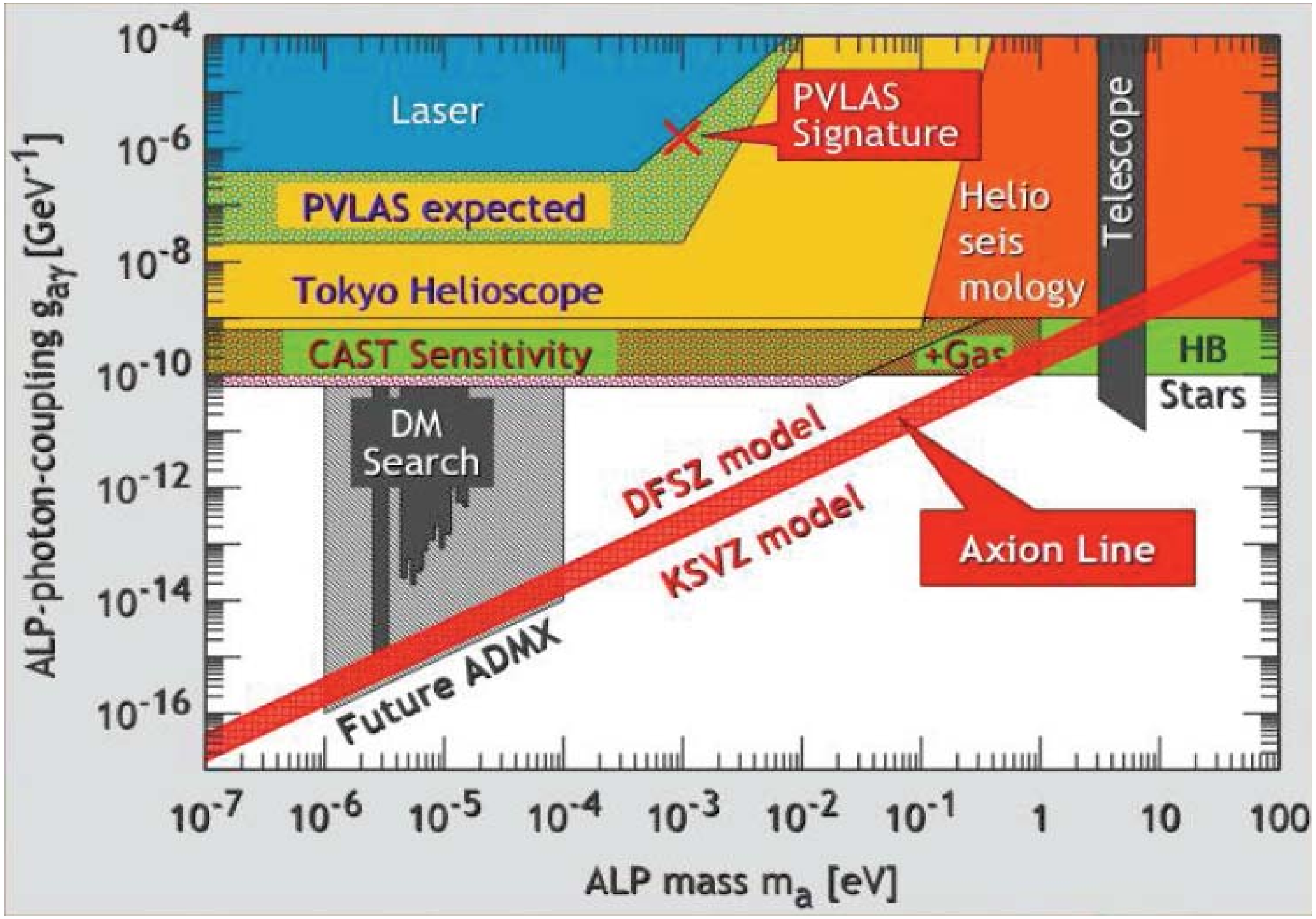
1. Introduction

The new cosmology advocated since 1998 needs CDM and DE in the universe: $\Omega_{CDM} \cong 0.23$, $\Omega_{\Lambda} \cong 0.73$.

There are several particle physics candidates for CDM: LSP, axion, axino, gravitino, LKP and other hypothetical heavy particles appearing with Z_2.

In this talk, we will review on axion and its CDM-related possibility.

There has been numerous efforts to test axions in last 20 ys.



Compilation by G. Raffelt, 05.2007

Let us start with the axion role in the solution of the strong CP problem. Its attractiveness in the strong CP solution is the bottom line in every past and future axion search experiments.

Also, I will discuss superstring axions briefly, since most SM ideas are checked with superstring compactification these days.

The existence of instanton solution in nonabelian gauge theories needs Θ vacuum [CDG, JR]. In the Θ vacuum, we have

$$\frac{1}{32\pi^2}\bar{\theta}\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} = \bar{\theta}\{F\tilde{F}\}$$

$$\bar{\theta} = \theta_{QCD} + \theta_{weak}, \quad \theta_{weak} = \arg.Det.M_q$$

Here theta-bar is the final value taking into account the electroweak CP violation. Weak interactions can contribute O(10-17) [George-Randall]. For QCD to become a correct theory, this CP violation must be sufficiently suppressed.

A nonvanishing θ contributes to the NEDM.

$|d_n| < 3\times10^{-26}$ e cm [C A Baker et al, PRL 97, 131801 (06)] $\rightarrow |\theta| < 10^{-9}$

Why is this so small? : Strong CP problem.

1. Calculable θ, 2. Massless up quark (X)
3. Axion [as a new section]

1. Calculable θ

The Nelson-Barr CP violation is done by introducing vectorlike heavy quarks at high energy. This means that at low energy, the Yukawa couplings are real, which is needed anyway from the beginning. Specific form for coupling assumed, (F=SM, R=heavy)

- SU(2)xU(1) breaking VEV appear only F-F Yukawa
- CP viol. phases in the VEV appear only in F-R Yukawa.

2. Massless up quark

Suppose that we chiral-transform a quark,

$$q \rightarrow e^{i\gamma_5 \alpha} q \quad : \quad \int (-m\bar{q}q + \frac{\theta}{32\pi^2} F\tilde{F})$$

$$\rightarrow \int (-m\bar{q}e^{2i\gamma_5\alpha} q + \frac{\theta - 2\alpha}{32\pi^2} F\tilde{F})$$

If m=0, it is equivalent to changing Θ → Θ -2α. Thus, there exists a shift symmetry Θ → Θ -2α. Here, Θ is not physical, and there is no strong CP problem. The problem is, “Is massless up quark phenomenologically viable?”

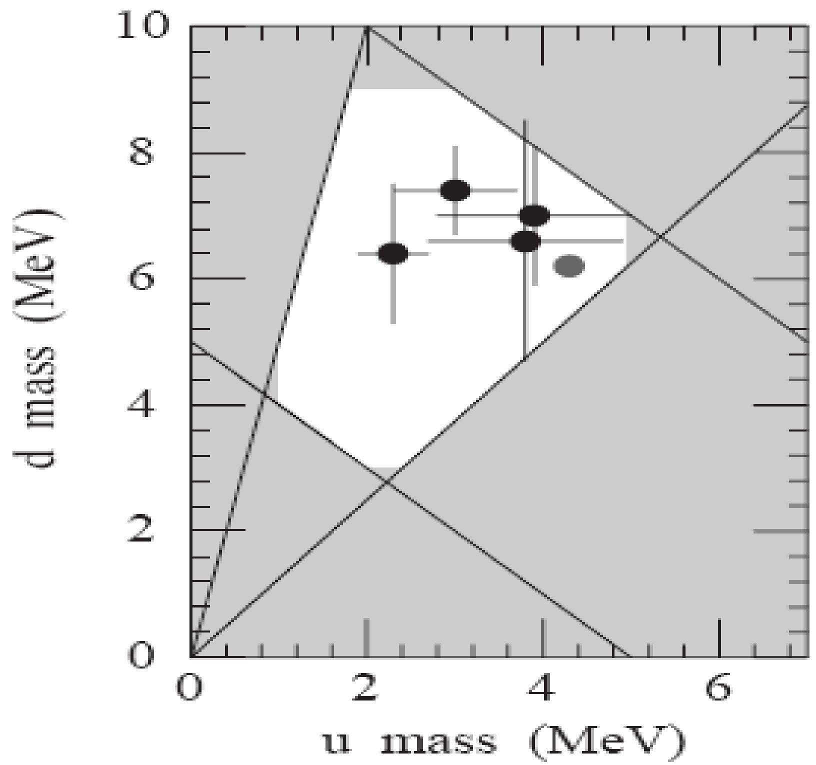
The famous up/down quark mass ratio from chiral pert. calculation is originally given as 5/9 [Weinberg, Leutwyler] which is very similar to the recent compilation,

$$\frac{m_u}{m_d} = 0.5,$$

$$m_u = 3 \mu 1 MeV,$$

$$m_d = 6.0 \pm 1.5 MeV$$

(Manohar-Sachrajda)



Particle Data (2006), p.510

Excluding the lattice cal., this is convincing that m_u=0 is not a solution now.

2. Axions

Peccei-Quinn tried to mimick the symmetry $\Theta \to \Theta$ -2α, by the full electroweak theory. They found such a symmetry if H_u is coupled to up-type quarks and H_d couples to down-type quarks,

$$L = \bar{q}_L u_R H_u + \bar{q}_L d_R H_d - V(H_u, H_d) + \cdots$$

Certainly, if we assign the same global charge under the γ_5 transformation to H_u and H_d, the flavor independent part contributes to

$$q \to e^{i\gamma_5 \alpha} q, \qquad \{H_u, H_d\} \to e^{i\gamma\beta}\{H_u, H_d\}:$$

$$\int (-H_u e^{i\beta} \bar{u} e^{i\gamma_5 \alpha} u - H_d e^{i\beta} \bar{d} e^{i\gamma_5 \alpha} d + \frac{\theta - 2\alpha}{32\pi^2} F\tilde{F})$$

Eq. β=α achieves the same thing as the m=0 case.

The Lagrangian is invariant under changing $\Theta \to \Theta - 2\alpha$. Thus, it seems that Θ is not physical, since it is a phase of the PQ transformation. But, Θ is physical, which can be seen from the free energy dependence on $\cos\Theta$. At the Lagrangian level, there seems to be no strong CP problem. But $\langle H_u \rangle$ and $\langle H_d \rangle$ breaks the PQ global symmetry and there results a Goldstone boson, axion *a* [Weinberg,Wilczek]. Since Θ is made field, the original $\cos\Theta$ dependence becomes the potential of the axion *a.*

If its potential is of the $\cos\Theta$ form, always $\Theta = a/F_a$ can be chosen at 0 [Instanton physics,PQ,Vafa-Witten]. So the PQ solution of the strong CP problem is that the vacuum chooses

$$\theta = 0$$

The Peccei-Quinn-Weinber-Wilczek axion is ruled out early in one year [Peccei, 1978]. The PQ symmetry can be incorporated by heavy quarks, using a singlet Higgs field [KSVZ axion]

$$L = \overline{Q}_L Q_R S - V(S, H_u, H_d) + \cdots$$

Here, Higgs doublets are neutral under PQ. If they are not neutral, then it is not necessary to introduce heavy quarks [DFSZ]. In any case, the axion is the phase of the SM singlet *S*, if the VEV of *S* is much above the electroweak scale.

Now the couplings of *S* determines the axion interaction. Because it is a Goldstone boson, the couplings are of the derivative form except the anomaly term.

The complex SU(2) singlet scalar field *S* may contain very tiny SU(2) doublet components ($<10^{-7}$), and practically we can consider the axion as the phase of *S*,

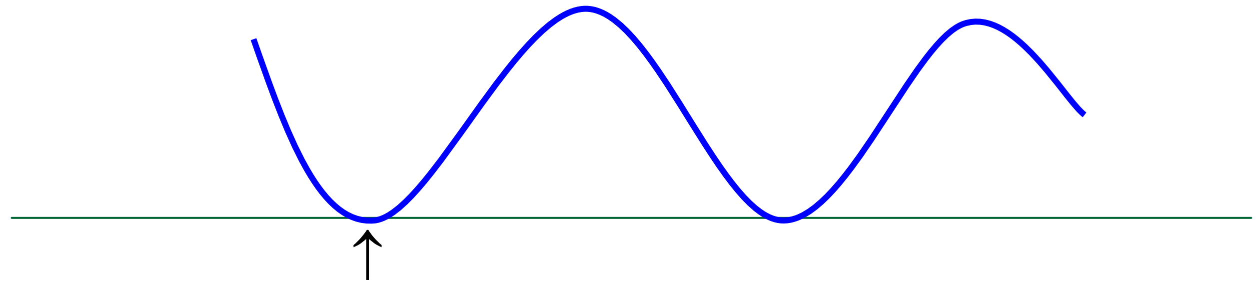
$$s = \frac{1}{\sqrt{2}}(V+\rho)e^{ia/F_a}\ ; \quad a = a + 2\pi N_{DW} F_a \quad ; \quad V = N_{DW} F$$

Since the DW number appears in the phase of *S*, F_a can be in general equal to or smaller than $\langle 2^{1/2} S \rangle$.

Axion is directly related to Θ. Its birth was from the PQ symmetry whose spontaneous breaking introduced a boson. However, we can define axion as a pseudoscalar *a* without potential except that arising from, $\frac{1}{32\pi^2}\frac{a}{F_a}\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma} = \frac{a}{F_a}\{F\tilde{F}\}$

Then this nonrenor. term can arise in several ways	F_a
From string theory or M-theory :	Planck scale
Large extra dimensions, cf. $M_{Pl}=M_D(R/M_D)n/2$	Depends on R
From composite models :	Comp. scale

From renormalizable theories:
Goldstone boson(global symm.) coupl. to the one-loop gluon anomaly. Glob. sym. break. scale



$$\bar{\theta} = 0 \qquad\qquad m_u m_d \Lambda^2 \leftarrow \Lambda^4$$

$$V[a] = \frac{Z}{(1+Z)^2} f_\pi^2 m_\pi^2 \left(1 - \cos\frac{a}{F_a}\right)$$

The essence of the axion solution is that <a> seeks

θ=0

whatever happened before. In this sense it is a cosmological solution. The height of the potential is the scale Λ of the nonabelian gauge interaction.

The potential arising from the anomaly term after integrating out the gluon field is the axion potential. with two important properties:

(i) periodic potential with $2\pi F_a$ period (Pontryagin)

(ii) minimum is at a=0, $2\pi F_a$, , 4 πF_a, , ... [PQ, VW]

The interaction

$$\frac{1}{32\pi^2}\frac{a}{F_a}\frac{1}{2}\varepsilon_{\mu\nu\rho\sigma}F^{\mu\nu}F^{\rho\sigma}=\frac{a}{F_a}\{F\tilde{F}\}$$

leading to the cos form determines the axion mass

$$-m_u\Lambda^3\cos\frac{a}{F_a}\Rightarrow m_a=\frac{\sqrt{Z}}{1+Z}\frac{f_\pi m_\pi}{F_a}=0.6[eV]\frac{10^7 GeV}{F_a}$$

A similar axion-photon-photon *aE·B* term is present

in any axion model with a coefficient

$$c_{a\gamma\gamma}$$

Old lab bounds:

Meson decays

$J/\Psi \to a+\gamma$, $\Upsilon \to \gamma a$, $K^+ \to \pi + a$,

Beam dump experiments

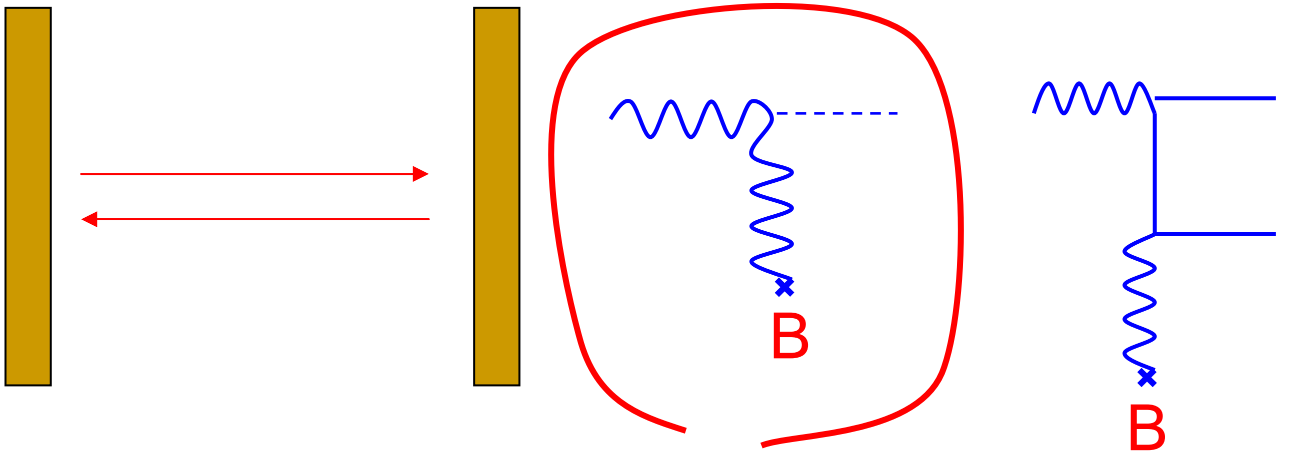
$p(e^-)N \to aX$, $a \to \gamma\gamma$, e^+e^-

Nuclear deexcitation

$N^* \to Na$, $a \to \gamma\gamma$, e^+e^-

$$F_a > 10^4 \quad GeV$$

Laser induced axion search lab experiments:



BFRT, PVLAS experiments

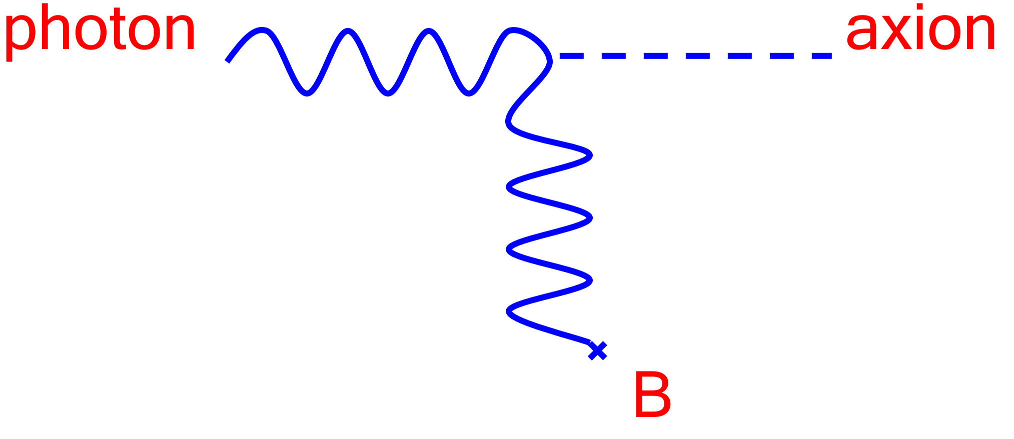
The polarized laser will change the polarization if some photons decay.

PVLAS-I: e.g. alp such as millicharged particles
with m=0.1eV and Q=10^{-6} [Ringwalt,…]

PVLAS-II: signal went away

3. Axions from stars

Use axion couplings: to e, p, n, and photon.



In the hot plasma in stars, axions once produced most probably escape the core of the star and take out energy. This contributes to the energy loss mechanism of star and should not dominate the luminocity.

The Primakoff process: $\gamma \to a$ (present in any model)

$g_{a\gamma\gamma} < 0.6\text{x } 10^{-10}$ GeV^{-1} or $F_a > 10^7$ GeV

0.4eV < m_a < 200 keV ruled out

beyond this, too heavy to produce

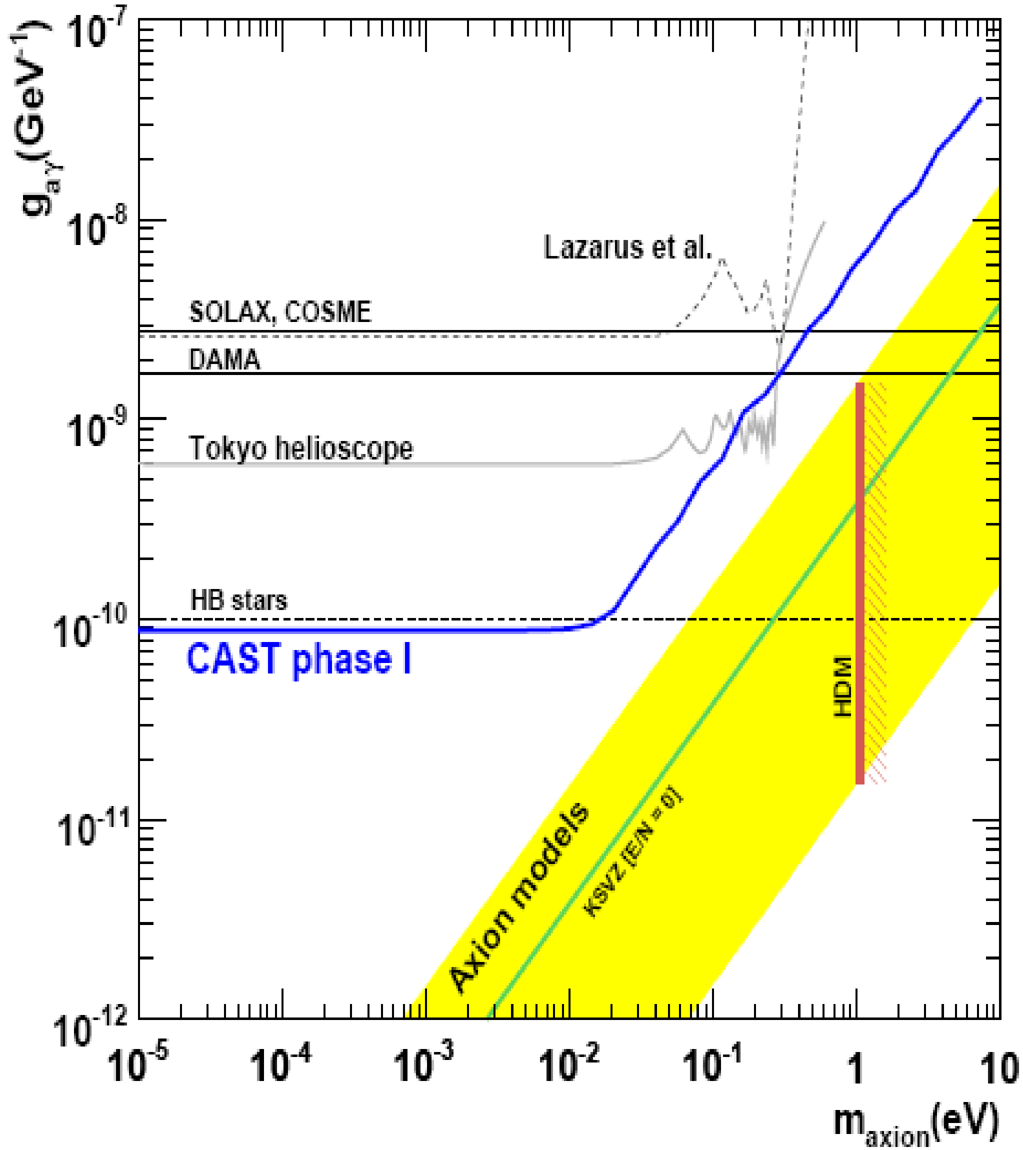
Compton-like scattering: $\gamma\, e \to a e$ (DFSZ axion has *aee* coupling)

$g_{aee} < 2.5\text{x}10^{-13}$ 0.01eV < m_a < 200 keV

SN1987A: $NN \to NNa$

$3\text{x}10^{-10} < g_{aNN} < 3\text{x } 10^{-7}$ $\Rightarrow$ $Fa > 0.6\text{x } 10^9$ GeV

The improved supernova(gl. cl.) limit is 10^{10} GeV.



CAST Coll. (Andriamonje *et al.*). JCAP 0704:010,2007

The coupling depends on axion models.
The numbers are given usually in field theoretic assumptions.

4. Axions in the universe

The axion potential is of the form

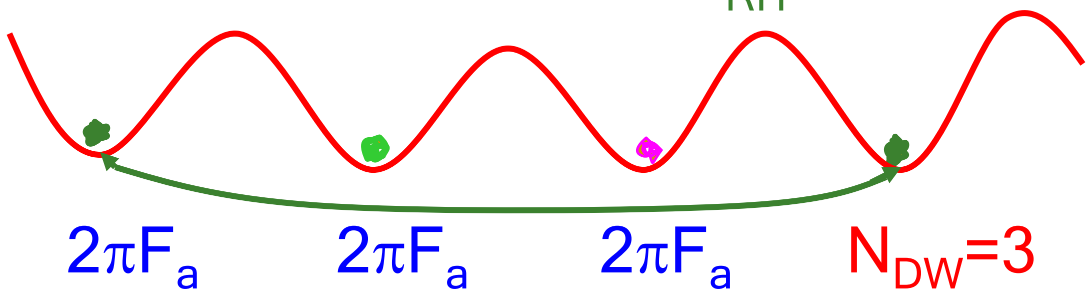
The vacuum stays there for a long time, and oscillates when the Hubble time(1/H) is larger than the oscillation period($1/m_a$)

$$H < m_a$$

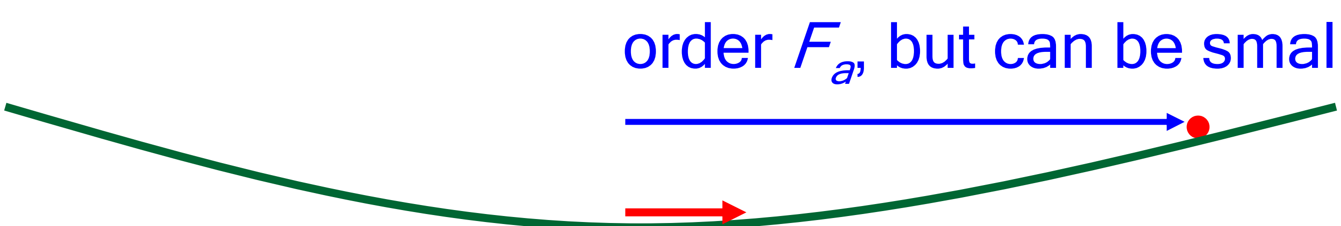
This occurs when the temperature is about 1 GeV.

In cosmology, we consider

- Axion decay constant F_a.
- Domain wall number N_{DW} . Standard BB allows only N_{DW}=1. [Sikivie] Inflation is the one most interesting due to COBE and WMAP observation. Then, NDW problem is not an issue with $T_{RH} < 10^9$ GeV.



Recently, we do not worry about N_{DW} thanks to RT below Fa after inflation.



From $T=F_a$, the classical field <a> starts to oscillate. Similar to the harmonic oscillator energy, axion energy density = m_a x *number density* = like CDM.

See a review, Asztalos-Rosenberg-Bibber-Sikivie-Zioutas, Ann. Rev. Nuc. Part. Sci. 56, 293 (06)

$$\Omega_a \cong \frac{1}{2}\left(\frac{0.6\times 10^{-5} eV}{m_{axion}}\right)^{7/6}\left(\frac{0.7}{h}\right)^2, \quad H = h \cdot 100 km/s/Mpc$$

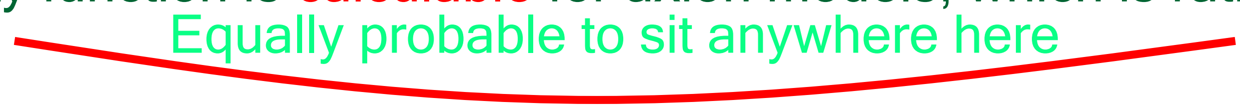
From astro and cosmo physics,

10^{10} GeV < F_a < 10^{12} GeV, but

Anthropic argument [Pi(84), Tegmark-Aguirre-Rees-Wilczek(05)]

Axion field values right after inflation can take any value between [0,π]. So Ω_a may be at the required value by an appropriate misalignment angle for any F_a in the new inflation scenario. [Pi(84)]

Tegmark et al studied the landscape scenario for 31 dimensionless parameters and some dimensionful parameters with which habitable planets are constrained. They argue that for axion the prior probability function is calculable for axion models, which is rather obvious.



They considered astrophysical conditions and nuclear physics conditions. For axion, one relevant figure is Q(scalar fluctuation) vs ξ(matter density per CMB photon). If axion is the sole candidate for CDM, the decay constant is predicted near 10^{12} GeV. But there may be more favored heavy WIMP candidates in which case axions supply the extra needed CDM amount.

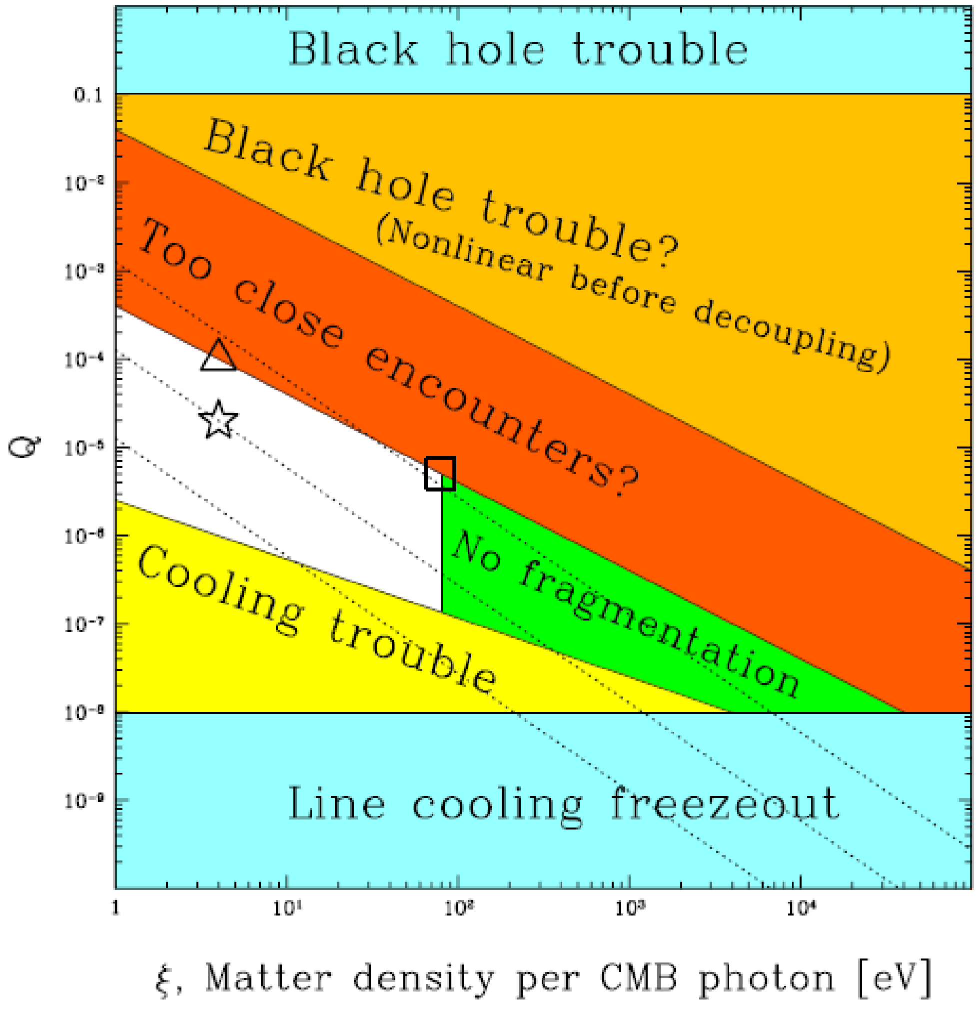


FIG. 12: Crude summary of constraints (ξ, Q)-plane constraints from Table 4. The star shows our observation $(\xi, Q) \approx (4\text{eV}, 2 \times 10^{-5})$. The parallel dotted lines are lines of constant characteristic

Tegmark, Aguirre, Rees, Wilczek, PRD (2005)

Q=scalar fluctuation amplitude δH on horizon, $(2\pm0.2)\text{x}10^{-5}$

WIMP may be dominantly CDM, and the rest is provided by axion.

Cosmic axion search

If axion is the CDM component of the universe, then they can be detected. The feeble coupling can be compensated by a huge number of axions. The number density ~ F_a^2, and the cross section ~ $1/F_a^2$, and there is a hope to detect. Sikivie's cavity detector of m dim is effective. [10^{-5} eV range]

$$L = -\frac{a}{F_a} c_{a\gamma\gamma} \frac{e^2}{16\pi^2} F_{em}\tilde{F}_{em} \quad \Rightarrow \quad E\cdot B$$

Positive for 1 HQ

$$c_{a\gamma\gamma} = \bar{c}_{a\gamma\gamma} + 6 \sum_{i=light\ quarks} \tilde{\alpha}_i (Q_i^{em})^2 = \bar{c}_{a\gamma\gamma} - 1.95$$

$$\bar{c}_{a\gamma\gamma} = Tr(Q_{em}^2)|_{E>>M_Z} = 0, \ \frac{8}{3}$$

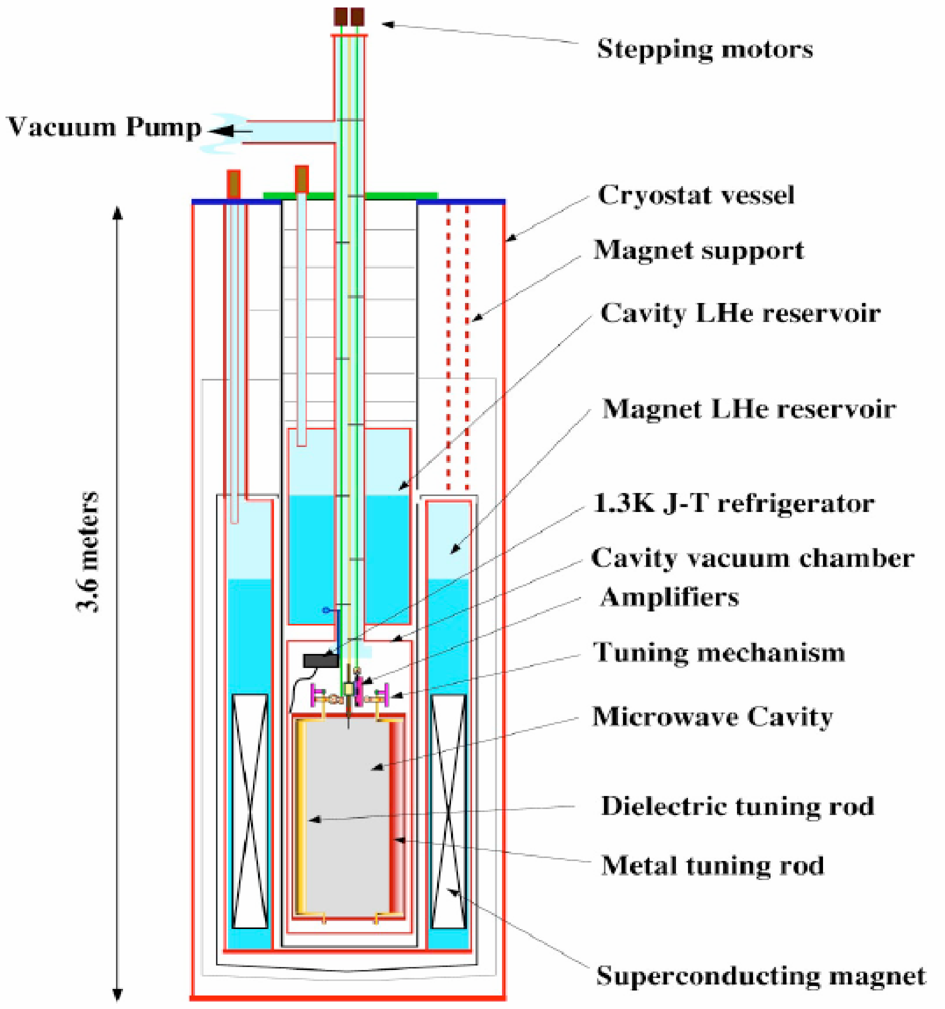
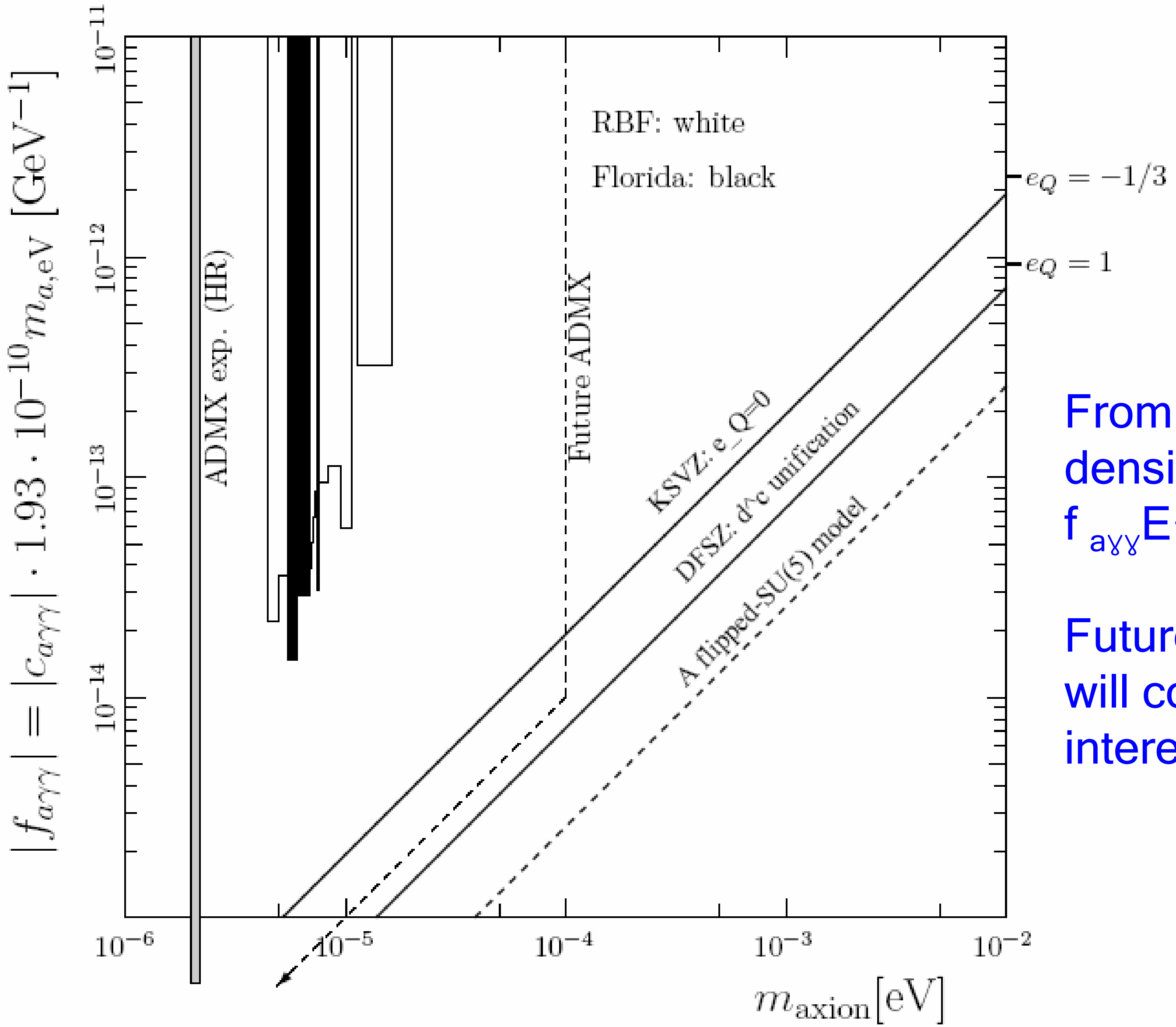
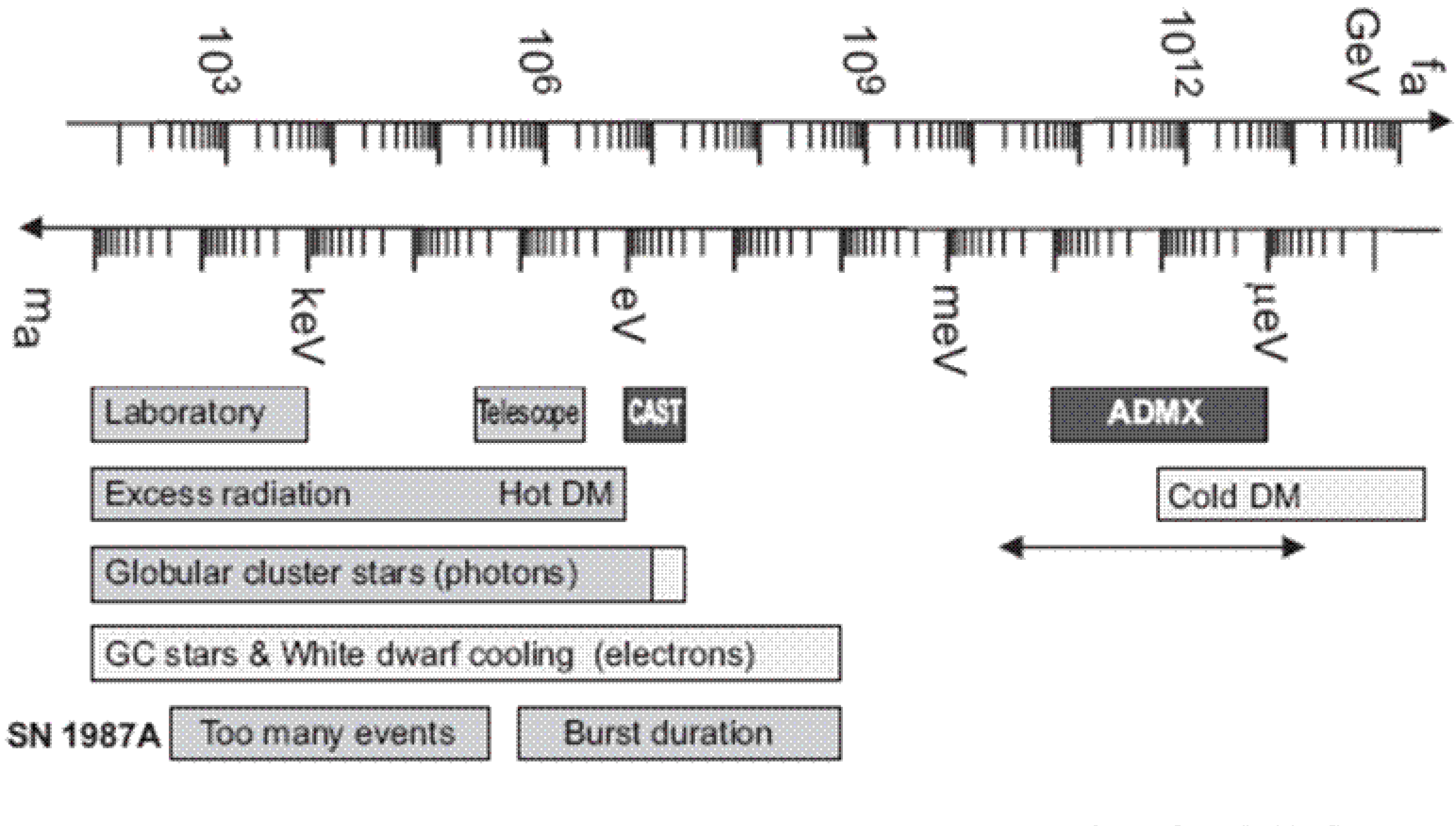


FIG. 1. Sketch of the rf cavity axion detector.



From local density with $f_{a\gamma\gamma} E \cdot B$

Future ADMX will cover the interesting region.



Raffelt hep-ph/0611350

5. SUSY extension and axino

Strong CP solution and SUSY:

axion : implies a superpartner axino

The gravitino constraint: gravitinos produced thermally after inflation decays very late in cosmic time scale (>10^3 sec) and can dissociate the light nuclei by its decay products. Not to have too many gravitinos, the reheating temperature must be bounded,

$$T_R < 10^9 \text{ GeV(old), or } 10^7 \text{ GeV(recent)}$$

Thus, in SUSY theories we must consider the relatively small reheating temperature.

The LSP seems the most attractive candidate for DM simply because the TeV order SUSY breaking scale introduces the LSP as a WIMP. This scenario needs an exact or effective R-parity for it to be sufficiently long lived.

For axino to be LSP, it must be lighter than the lightest neutralino. The axino mass is of prime importance. The conclusion is that there is no theoretical upper bound on the axino mass. For axino to be CDM, it must be stable or practically stable. Thus, we require the practical

R-parity or effective R-parity

KeV axinos can be warm DM (90s) [Rajagopal-Turner-Wilczek]
GeV axinos can be CDM (00s) [Covi-H. B. Kim-K-Roszkowski]

Gravitino problem is resolved if gravitino is NLSP, since the TP gravitinos would decay to axino and axion which do not affect BBN produced light elements. [Ellis et al, Moroi et al]

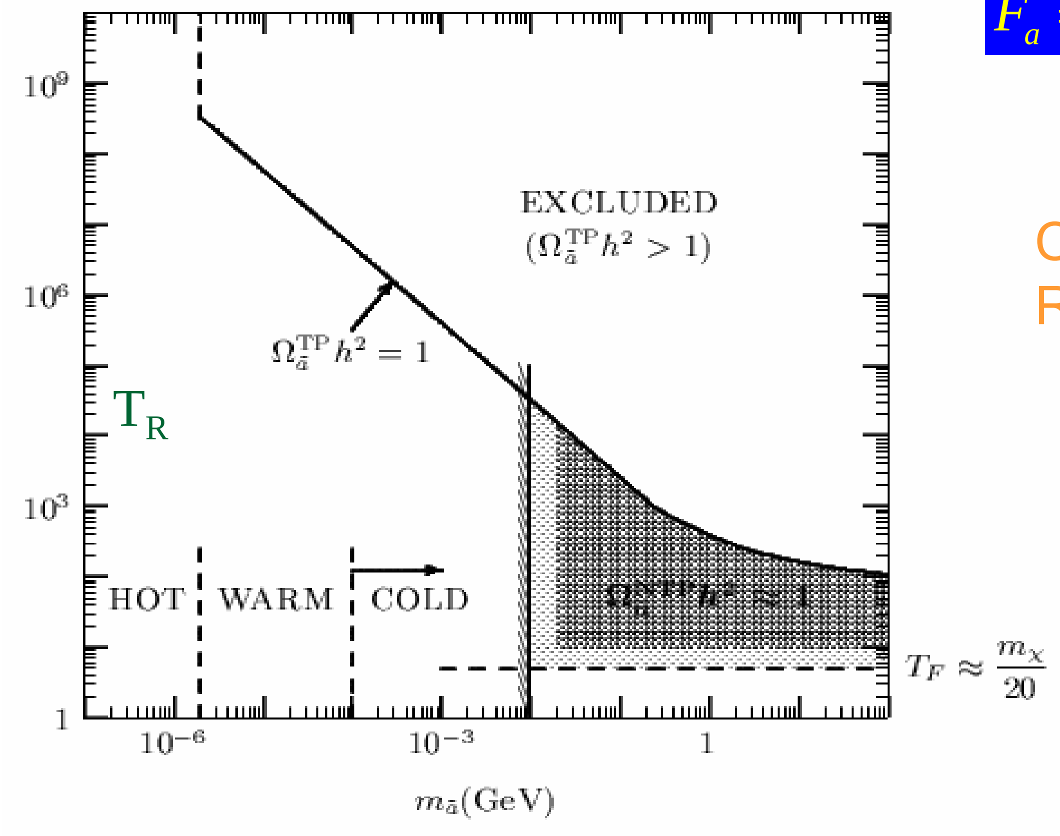
$$m_{\tilde{a}} < M_{3/2} < m_{\chi}$$

On the other hand, if χ is NLSP(=LOSP), the TP mechanism restricts the reheating temperature after inflation. We do not consider GMSB, here. At high reheating temperature, TP contributes dominantly in the axino production.If the reheating temperature is below c. energy density line, there still exists the CDM possibility by the NTP axinos. [Covi et al]

NTP $$\Omega_{\tilde{a}} h^2 = \frac{m_{\tilde{a}}}{m_{\chi}} \Omega_{\chi} h^2$$ for $m_{\tilde{a}} < m_{\chi} < M_{3/2}$

$$m_\chi = 100 GeV$$

$$F_a = 10^{11} GeV$$



Covi-K-H B Kim-Roszkowski

In this figure, NTP axinos can be CDM for relatively low reheating temperature < 10 TeV, in the region

$$10\,MeV < m_{\tilde{a}} < m_{\chi}$$

NTP axino as CDM possibility

The shaded region corresponds to the MSSM models with $\Omega_\chi h^2 < 10^4$, but a small axino mass renders the possibility of axino closing the universe or just 30 % of the energy density. If all SUSY mass parameters are below 1 TeV, then $\Omega\chi\ h^2 < 100$ and sufficient axino energy density requires

$$m_{\tilde{a}} > 1GeV$$

If LHC does not detect the neutralino needed for closing the universe, the axino closing Is a possibility. Contributed paper ABS-S11-006 [K.-Y. Choi, et al]

6. Axions from superstring

$$Boson \quad fields: \quad g_{MN}, \phi, B_{MN}$$

- Superstring tells us definite things about global symmetries. If axion is present, it is better to be realized in superstring. Bosonic degrees in B_{MN} (MI-axion $B_{\mu\nu}$ and MD-axion B_{ij} [Witten])and bosons from compactification are candidates.
- Superstring does not allow global symmetries. But there is an important exception to this claim: the shift symmetry of $H_{\mu\nu\rho}$, the MI-axion. It is the only allowed global symmetry. B_{ij} are generally heavy; but it is a model-depen't statem't..

The superstring axion decay constants are expected near the string scale which is too large [Choi-K].

$F_a > 10^{16}$ GeV.

The key question in superstring models is

"How can one obtain a low value of F_a?"

An idea is the following:

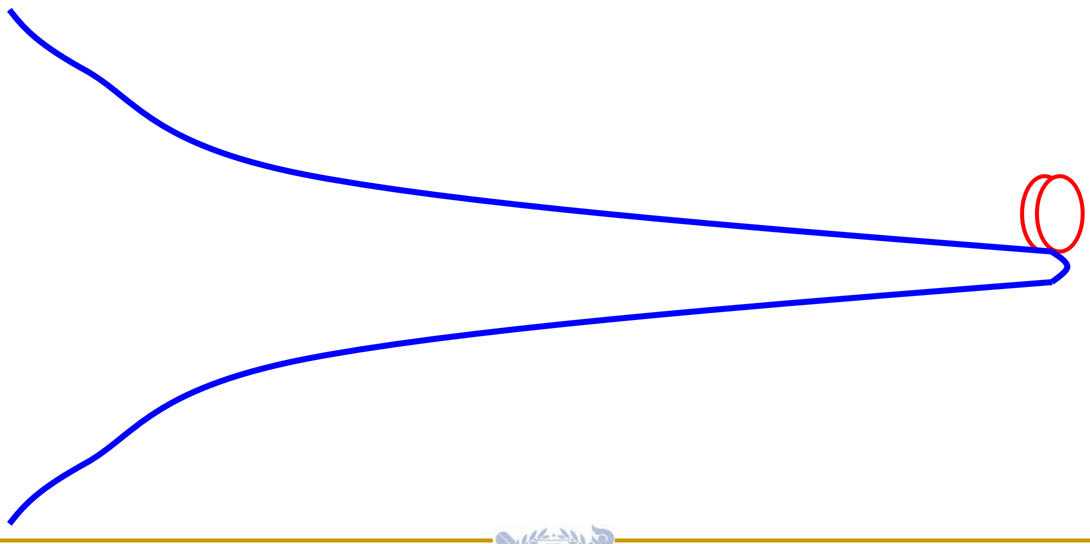
In some compactifications, anomalous U(1) results [Dine-Seiberg-Witten, Attick-Dixon-Sen, Dine-Ichinose,Seiberg], where U(1) gauge boson eats the MI-axion to become heavy [K] .

Earlier, this direction, even before discovering anomalous U(1) gauge boson, was pointed out by Barr [Barr(85)]. It became a consistent theory after discovering the anomalous U(1). Then, a global symmetry survives down the string scale. F_a may be put in the axion window. It was stressed early by [K(88)], and recently by [Svrcek-Witten(06)] .

However, this does not work necessarily.

Somehow MD axion(s) may not develop a large superpotential terms. But the problem here is the magnitude of the decay constant.

MD-axion decay constants were tried to be lowered by localizing them at fixed points [Conlon, I.W.Kim-K]. It uses the flux compactification idea and it is possible to have a small F_a compared to the string scale as in the RS model. One needs a so-called throat:



Axion mixing

Even if we lowered some F_a, we must consider hidden sector also. In this case, axion mixing must be considered. There is an important theorem.

Cross theorem on decay constant and condensation scales [K99]:

Suppose two axions a_1 with F_1 and a_2 with F_2 ($F_1 << F_2$) couples to two nonabelian groups whose scales have a hierarchy, $\Lambda_1 << \Lambda_2$.

Then, diagonalization process gives the

larger condensation scale Λ_2 chooses smaller decay constant F_1,

smaller condensation scale Λ_1 chooses larger decay constant F_2.

So, just obtaining a small decay constant is not enough. Hidden sector may steal the smaller decay constant. It is likely that the QCD axion chooses the larger decay constant. [See also, I.-W. Kim-K, PLB, 2006]

In this regard, we point out that the MI-axion with Anomalous U(1) always has a large decay constant since all fields are charged under this anomalous U(1). Phenomenologically successful axion must need the approximate PQ.

An approximate PQ global symmetry with discrete symmetry in SUGRA was pointed out long time ago: for Z_9 given by [L-P-Shafi]. Z_9 is not possible in orbifold compactification. May need $Z_3 x Z_3$ orbifold.

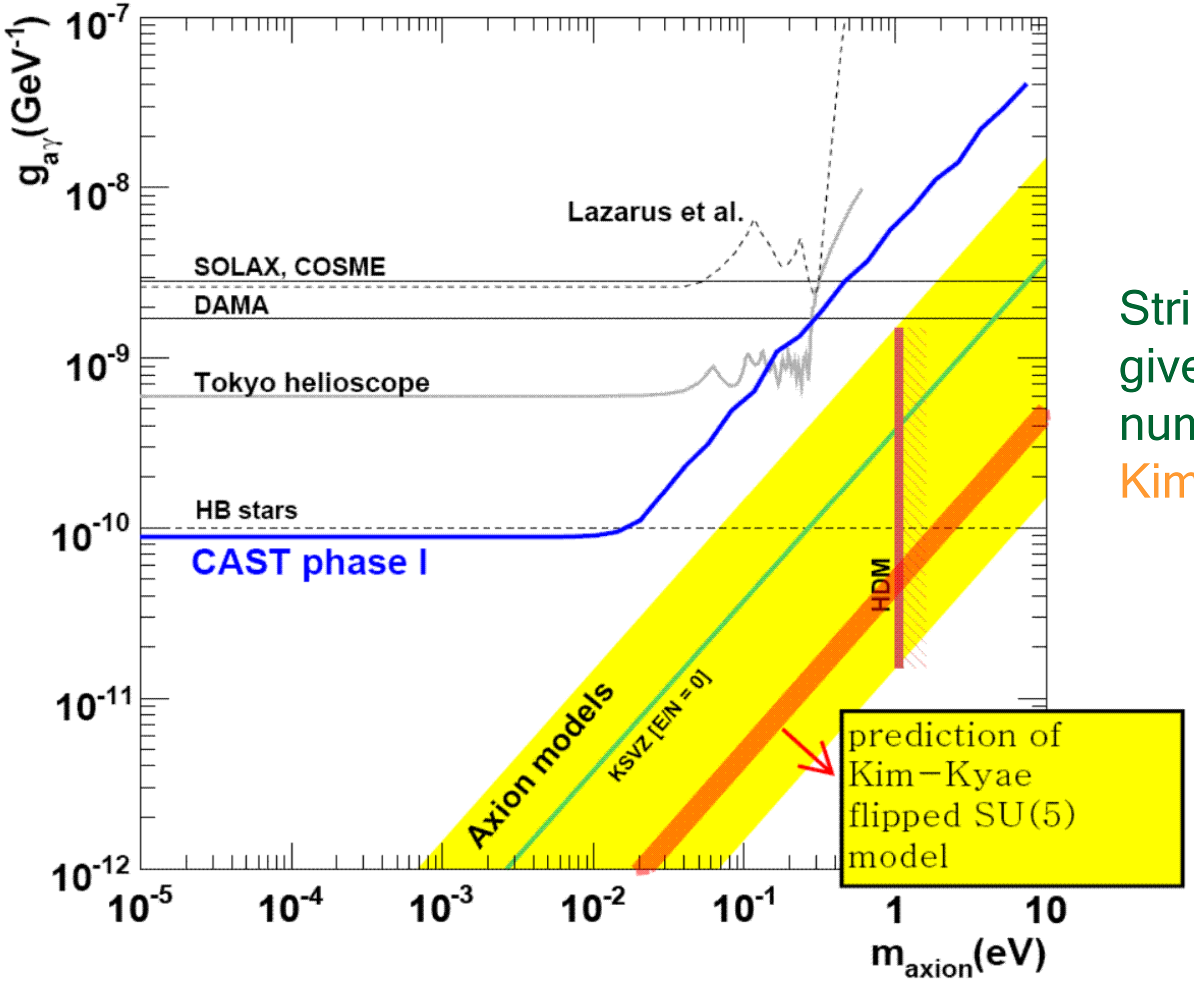
But most probably, our axion will come from the μ term:

$$H_u H_d\, f(S_1, S_2, \bullet\bullet\bullet)$$

After all, the topologically attractive B_{MN} may not be the axion we want which caused anyway many problems, and we go back to earlier field theoretic invisible axion.

In string models, its effect was not calculated before. Now we have an explicit model for MSSM [K-Kyae], and we can see whether this idea of approximate global symmetry is realized. It is better that at sufficiently higher orders the PQ symmetry is broken.

Here we could calculate the axion-photon-photon coupling from superstring, for the first time [Choi-I. W. Kim-K]. There are so many Yukawa couplings to consider. For example, we encountered $O(10^4)$ terms for d=7 superpotential and it is not a trivial task to find a PQ symmetry direction.



String models give definite numbers. [I-W Kim-K]

9. Conclusion

I reviewed axion and related issues.

1. Solutions of the strong CP problem: Nelson-Barr, $m_u=0$ *ruled out now*, axion.
2. Axions can contribute to CDM. Maybe solar axions are easier to detect. Then, axion is not the dominant component of CDM. Most exciting is, its discovery confirms instanton physics by exp.
3. With SUSY extension, O(GeV) axino can be CDM. It is difficult to detect this axino from the DM search, but possible to detect at LHC as missing energy.
4. Detectable QCD axions from superstring is looked for, but not successful so far.

Axion as dark matter candidate

J. E. Kim
Seoul National University

APPC10, Pohang
20.08.2007

Axion and axino contribution to dark matter

Jihn E. Kim
Seoul National University

Dark 2007
Sydney, 27.09.2007