Hadronic Axions and Axino Dark Matter

Jihn E. Kim
Seoul National University

GGI DM Conference 2010
Firenze, 21. 05. 2010

In this talk, we unify the ideas talked about in this conference:

Dark matter → observed in the Universe
Axion → natural sol. of strong CP
Supersymmetry → natural sol. of the Higgs mass problem

All three are touched upon here.

1. Introduction

2. The strong CP problem

3. Axions and hadronic axion

4. Axino CDM

Three new observations:

1. On the solution
2. White dwarf and F_a
3. Axino

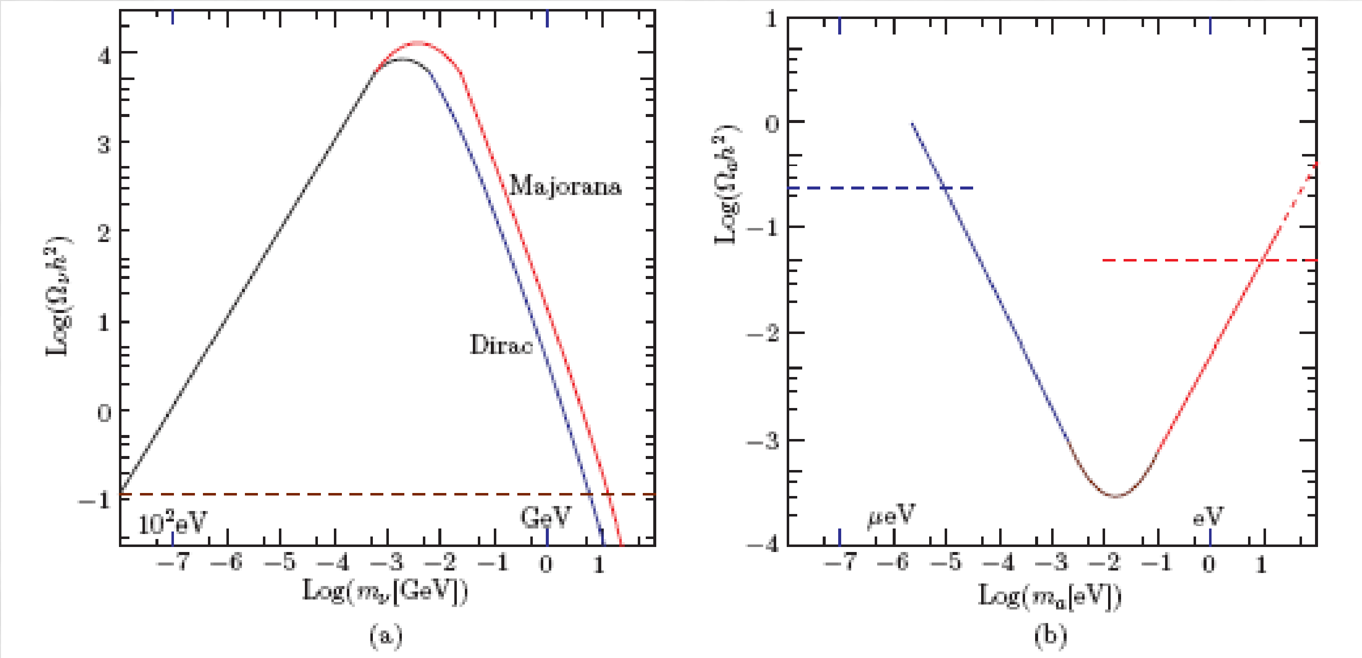
1. Introduction

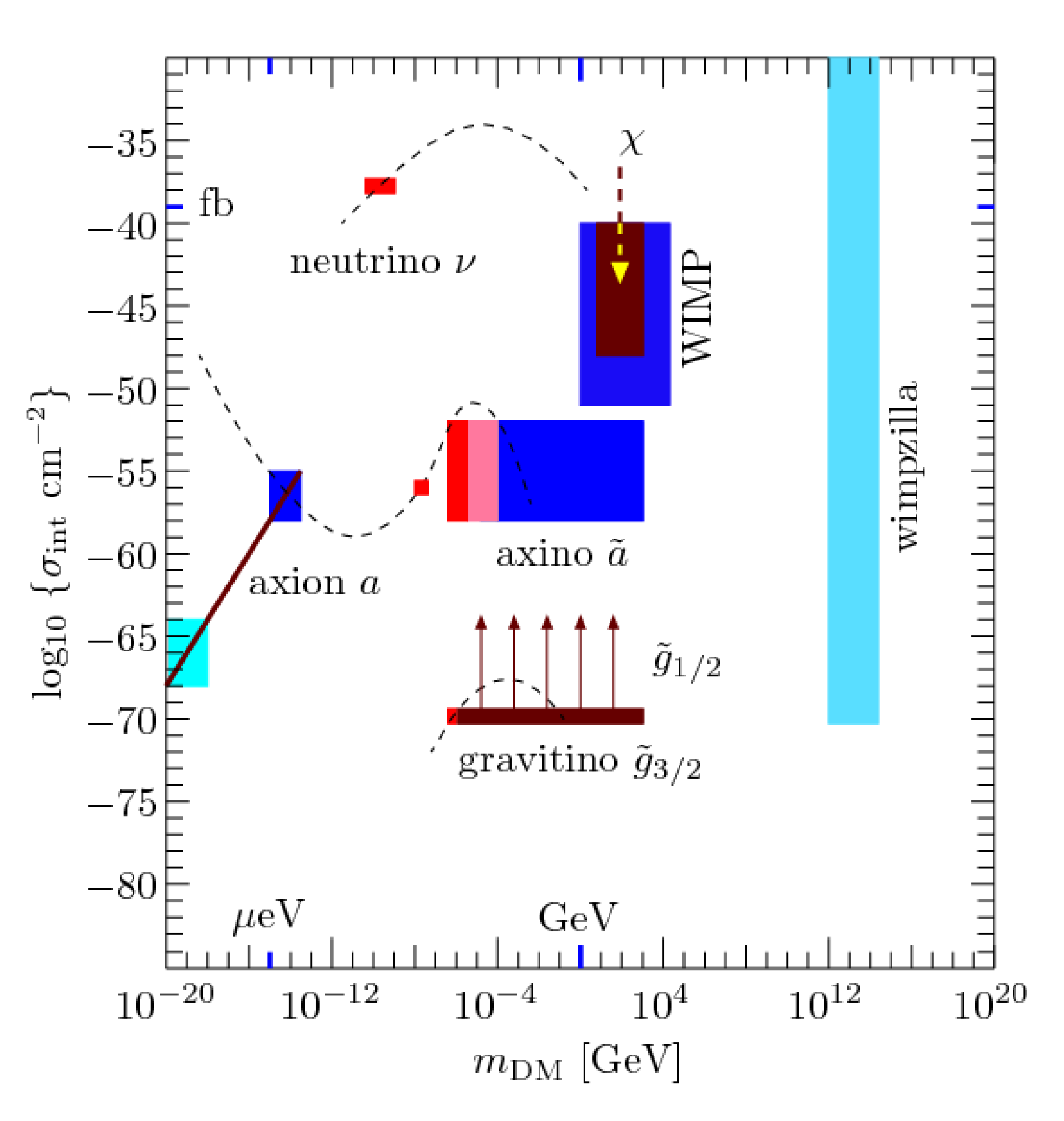
Axion is a Goldstone boson arising when the PQ global symmetry is spontaneously broken. The axion models have the spontaneous symmetry breaking scale F and the axion decay constant F_a which are related by $F=N_{DW} F_a$.

Here, I present the general idea on axions and then focus on the phenomenology of hadronic axion and axino.

The axion cosmic energy density has the opposite behavior from that of WIMP. It is because of the bosonic collective motion.

Kim-Carosi, "axions and the strong CP problem" RMP 82, 557 (2010) [arXiv:0807.3125]





A rough sketch of masses and cross sections. Bosonic DM with collective motion is always CDM.

[Kim-Carosi with Roszkowski modified]

A recent calculation of the cosmic axion density is,

$$10^9 \text{ GeV} < F_a < \{10^{12} \text{ GeV ?}\}$$

Turner (86), Grin et al (07),
Giudice-Kolb-Riotto (08),
Bae-Huh-K (JCAP 08, [arXiv:0806.0497]): recalculated including the anharmonic term carefully with the new data on light quark masses.

It is the basis of using the anthropic argument for a large F_a.

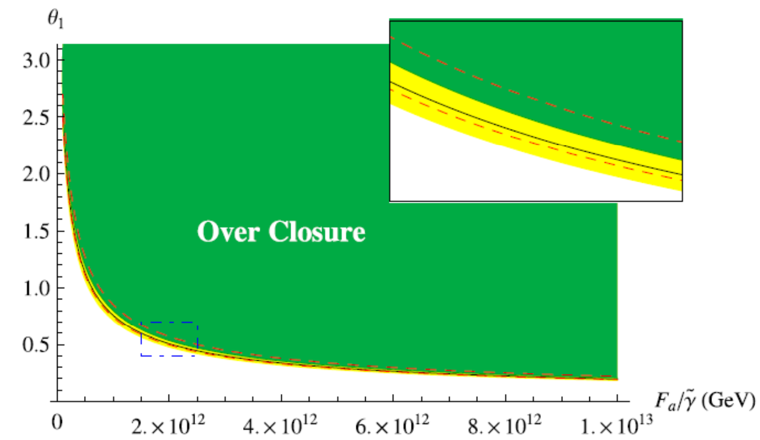
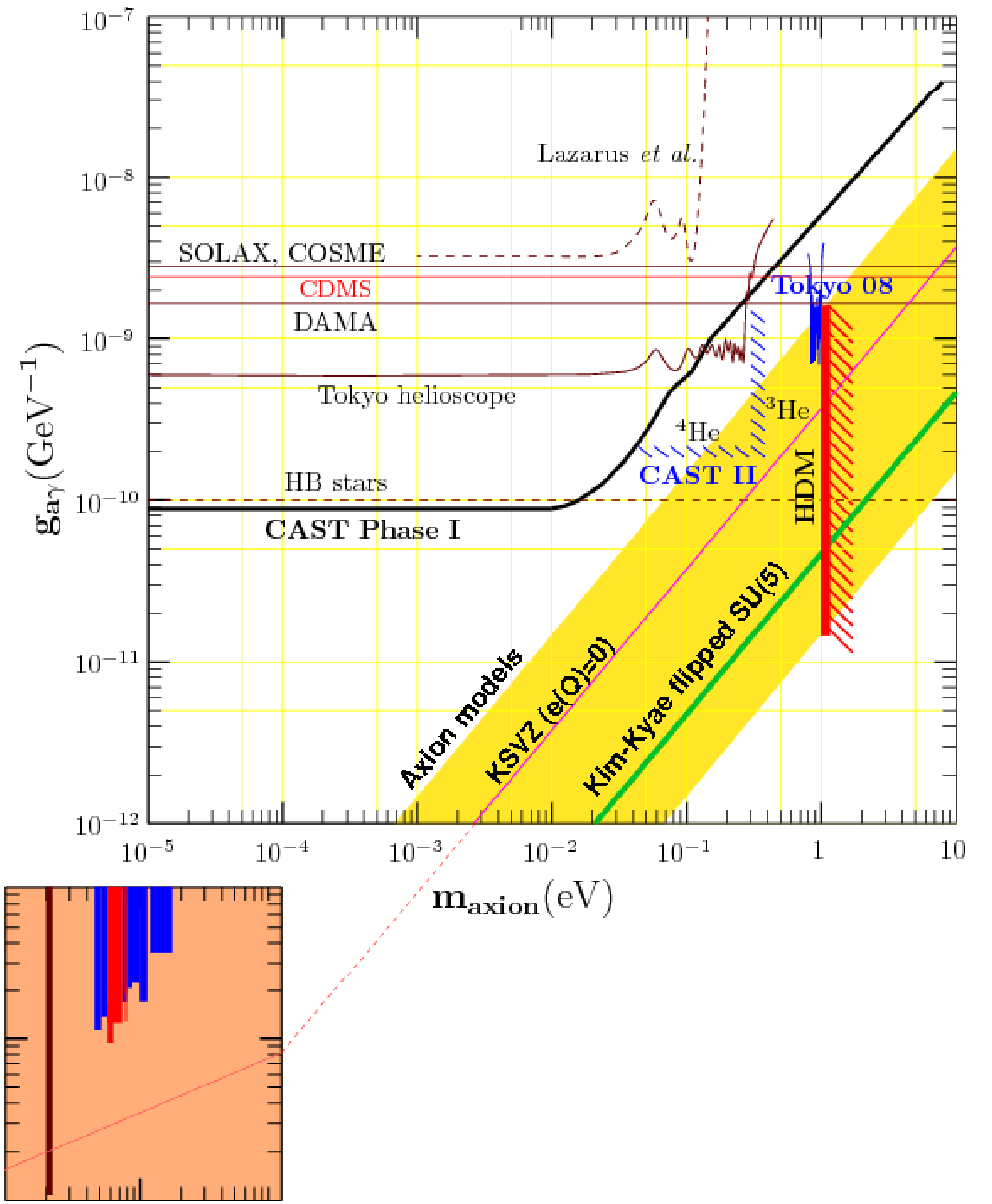


Figure 9. The bound from overclosure of the universe. The yellow band shows the error bars of Λ and two red dashed lines are the limits of the allowed current quark masses. The anharmonic effect is taken into account, including the initial correction factor of equation (15). Here, the entropy production ratio γ is absorbed into the bracket of F_a: $\tilde{\gamma} = \gamma^{(n+4)/(n+6)} \simeq \gamma^{0.84}$.

Many lab. searches were made, and we hope the axion be discovered .

The current status is



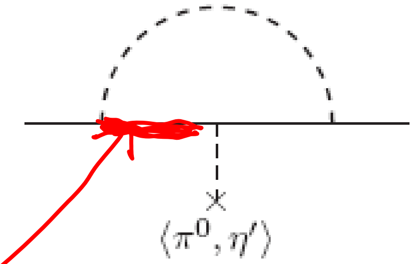
2. Strong CP problem

Axion's attractive strong CP solution is the bottom line in every past and future axion search experiments. So, let us start with the strong CP problem.

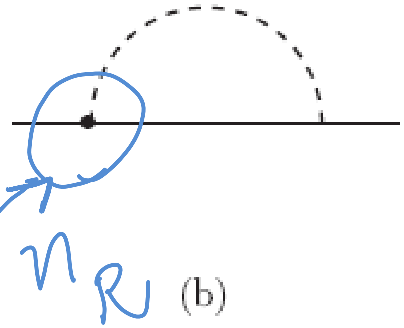
The instanton solution introduces the so-called θ term, and the resulting NEDM.

Look for the neutron mass term by CPV meson VEVs

$$g_{\pi NN}\frac{i}{-m_n}\left\langle m_n e^{-i\pi/f_\pi}\right\rangle$$

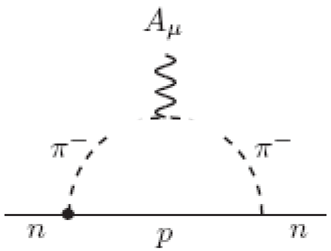


(a)

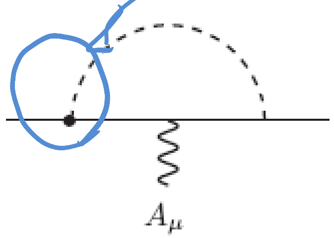


(b)

The NMDM and NEDM terms



(a)



(b)

The mass term and the NMDM term have the same chiral transformation property. So, (b)s are simultaneously removed.

(a) So, d(proton)= - d(neutron). is the NEDM contribution.

In our study, so the VEV of pi-zero determine the size of NEDM.

$$\overline{g_{\pi NN}} = -\bar{\theta}\frac{Z}{(1+Z)} \simeq -\frac{\bar{\theta}}{3} \qquad d_n = \frac{g_{\pi NN}\overline{g_{\pi NN}}}{4\pi^2 m_N} \ln\left(\frac{m_N}{m_\pi}\right) e\mathrm{cm}$$

We used C A Baker et al, PRL 97 (2006) 131801, to obtain

$$|\bar{\theta}| < 0.7 \times 10^{-11}$$

It is an order of magnitude stronger than Crewther et al bound.

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 model produces the KM type weak CP violation at low energy. Still, at one loop the appearance of θ must be forbidden, and a two-loop generation is acceptable.

The weak CP violation must be spontaneous so that θ_0 must be 0.

2. Massless up quark

Suppose that we chiral-transform a quark,

$$q \to e^{i\gamma_5\alpha} q: \quad \int d^4x \left(-m\bar{q}q + \frac{\theta}{32\pi^2} F\tilde{F} \right)$$

$$\to \quad \int d^4x \left(-m\bar{q}q e^{2i\gamma_5\alpha} + \frac{\theta - 2\alpha}{32\pi^2} F\tilde{F} \right)$$

If m=0, it is equivalent to changing $\theta \to \theta - 2\alpha$. Thus, there exists a shift symmetry $\theta \to \theta - 2\alpha$. Here, θ is not physical, and there is no strong CP problem. The problem is, "Is massless up quark phenomenologically viable?"

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

$$m_u = 2.5 \mp 1 MeV,$$

$$m_d = 5.1 \pm 1.5 MeV$$

(Manohar-Sachrajda)

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

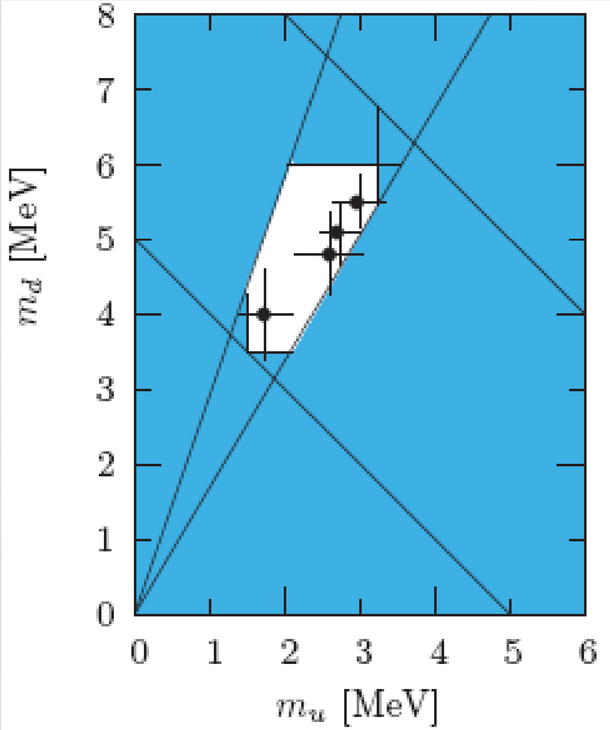


FIG. 6: The allowed $m_u - m_d$ region [265].

Particle Data (2008)

3. Axions

Kim-Carosi, RMP 82, 557 (2010) arXiv:0807.3125

Historically, Peccei-Quinn tried to mimick the symmetry $\theta \to \theta - 2\alpha$, 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,

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

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

$$\to \qquad \int d^4x \left(-H_u e^{i\beta} \bar{u} e^{i\gamma_5 \alpha} u - H_d e^{i\beta} \bar{d} e^{i\gamma_5 \alpha} d + \frac{\theta - 2\alpha}{32\pi^2} F\tilde{F} \right)$$

Eq. $\beta=\alpha$ 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. At the Lagrangian level, there seems to be no strong CP problem. But <H_u> and <H_d> breaks the PQ global symmetry and there results a Goldstone boson, axion *a* [Weinberg,Wilczek]. Since θ is made field, the original cosθ dependence becomes the potential of the axion *a*.

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

$$\theta = 0$$

History: The Peccei-Quinn-Weinberg-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] (this is for hadronic)

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

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.

In most studies, a specific example is discussed. Here, we consider an effective theory just above the QCD scale. All heavy fields are integrated out.

In axion physics, heavy fermions carrying color charges are special. So consider the following Lagrangian

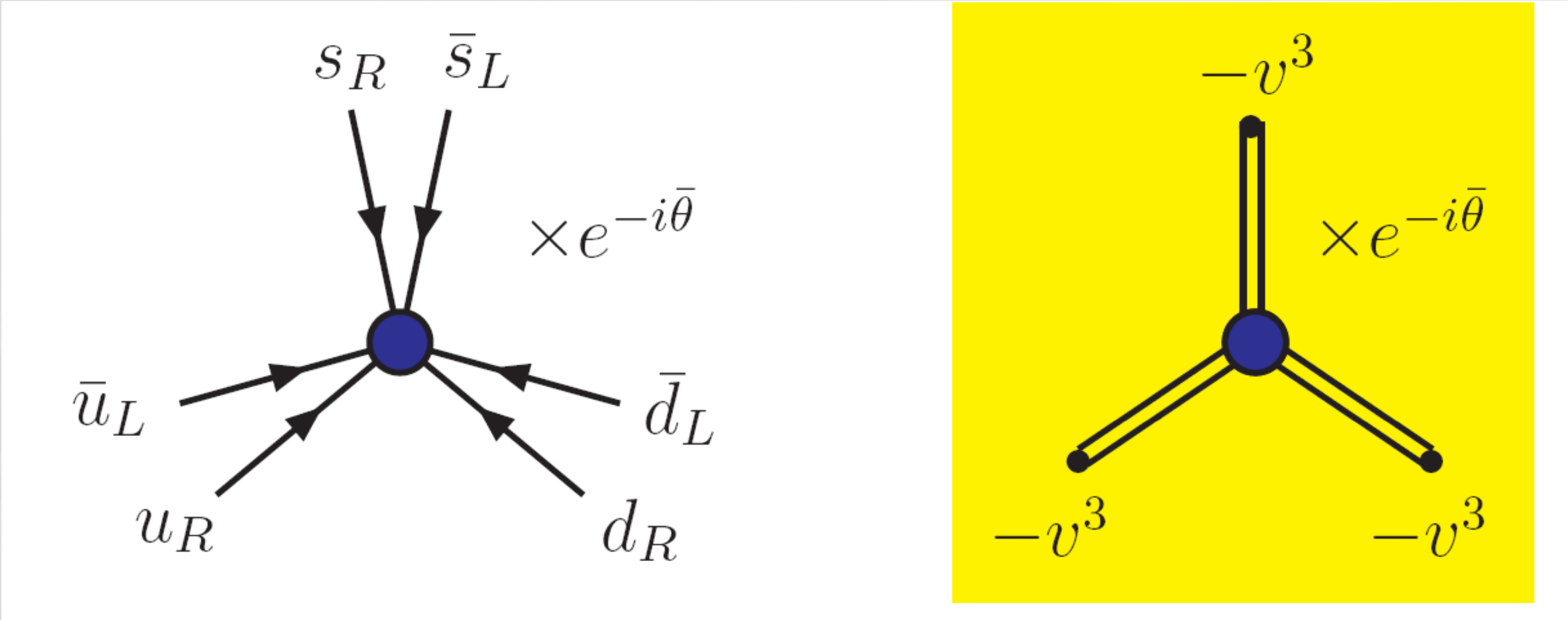
$$\mathcal{L}_\theta = \frac{1}{2} f_S^2 \partial^\mu \theta \partial_\mu \theta - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} + (\bar{q}_L i \not{D} q_L + \bar{q}_R i \not{D} q_R)$$
$$+ c_1 (\partial_\mu \theta) \bar{q} \gamma^\mu \gamma_5 q - (\bar{q}_L \; m \; q_R e^{i c_2 \theta} + \text{h.c.})$$
$$+ c_3 \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \;\; (\text{or } \mathcal{L}_{\text{det}})$$
$$+ c_{\theta\gamma\gamma} \frac{\theta}{32\pi^2} F^i_{\text{em},\mu\nu} \tilde{F}^{i\mu\nu}_{\text{em}} + \mathcal{L}_{\text{leptons},\theta}$$

heavy Qs are integrated out

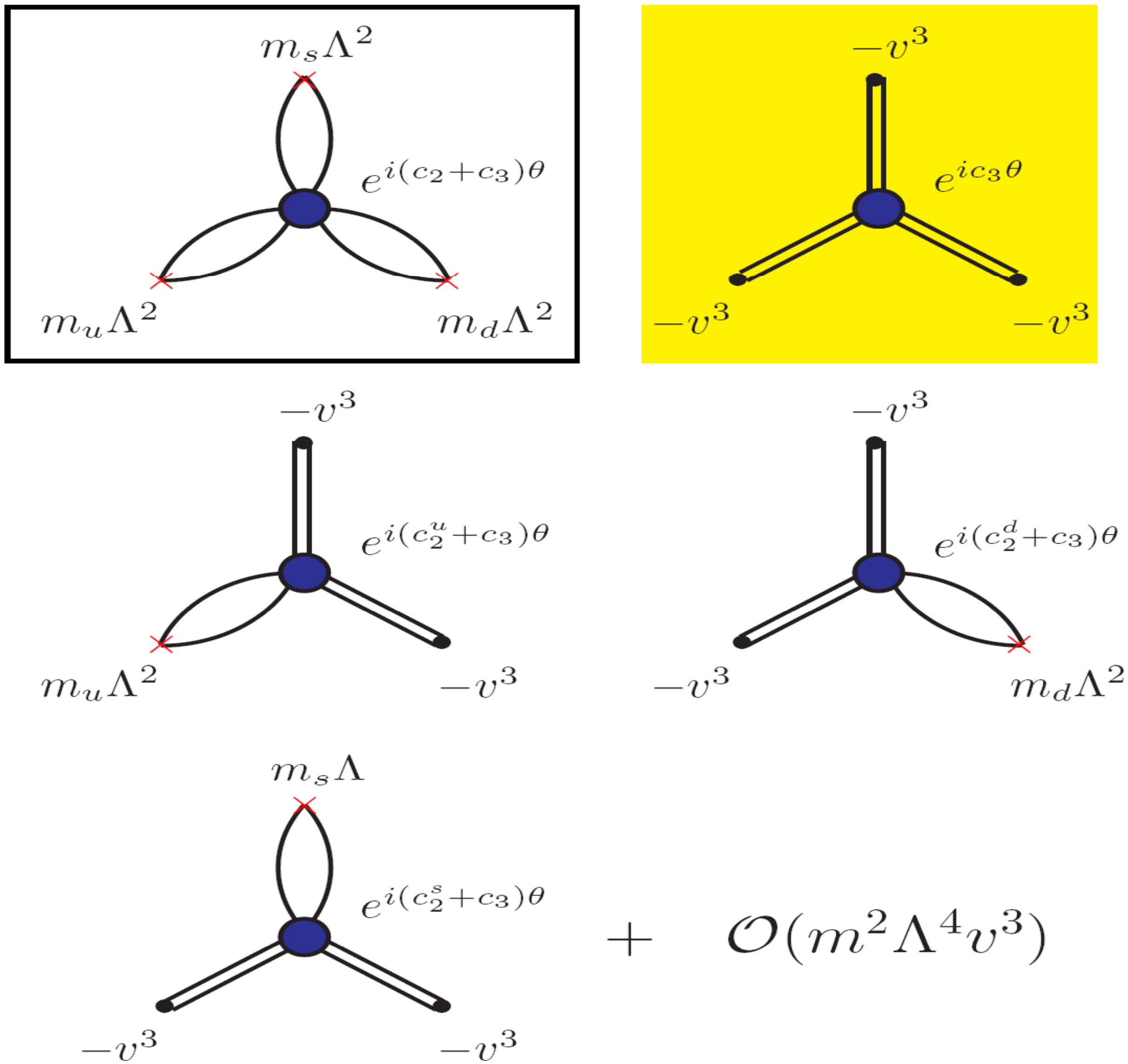
$$\mathcal{L}_{\text{det}} = -2^{-1} i c_3 \theta (-1)^{N_f} \frac{e^{-i c_3 \theta}}{K^{3N_f - 4}} \text{Det}(q_R \bar{q}_L) + \text{h.c.}$$

$$\Gamma_{1PI}[a(x), A^a_\mu(x); c_1, c_2, c_3, m, \Lambda_{\text{QCD}}] = \Gamma_{1PI}[a(x), A^a_\mu(x); c_1 - \alpha, c_2 - 2\alpha, c_3 + 2\alpha, m, \Lambda_{\text{QCD}}].$$

The axion mass depends only on the combination of (c_2+c_3). The 'hadronic axion' usually means c_1=0, c_2=0, $c_3 \neq 0$. It is almost MI and simple, which may be the reason O specified the title.



't Hooft determinental interaction and the solution of the U(1) problem. If the story ends here, the axion is exactly massless. But,….


$m_s\Lambda^2$
$e^{i(c_2+c_3)\theta}$
$m_u\Lambda^2$
$m_d\Lambda^2$
$-v^3$
$e^{ic_3\theta}$
$-v^3$
$-v^3$
$-v^3$
$e^{i(c_2^u+c_3)\theta}$
$m_u\Lambda^2$
$-v^3$
$-v^3$
$e^{i(c_2^d+c_3)\theta}$
$-v^3$
$m_d\Lambda^2$
$m_s\Lambda$
$e^{i(c_2^s+c_3)\theta}$
$-v^3$
$-v^3$
$+ \quad \mathcal{O}(m^2\Lambda^4v^3)$

$$\mathcal{L} = -m_u \langle \bar{u}_L u_R \rangle e^{i[(\theta_\pi + \theta_{\eta'}) + c_2^u \theta]} - m_d \langle \bar{d}_L d_R \rangle e^{i[(-\theta_\pi + \theta_{\eta'}) + c_2^d \theta]} + \text{h.c.} + \mathcal{L}_{\text{det}}$$

$$\begin{aligned} -V \; = \; & m_u v^3 \cos(\theta_\pi + \theta_{\eta'}) + m_d v^3 \cos(-\theta_\pi + \theta_{\eta'}) + \frac{v^9}{K^5} \cos\left(2\theta_{\eta'} - (c_2^u + c_2^d + c_3)\theta\right) \\ & + m_u \frac{\Lambda_u^2 v^6}{K^5} \cos\left(-\theta_\pi + \theta_{\eta'} - (c_2^u + c_2^d + c_3)\theta\right) + m_d \frac{\Lambda_d^2 v^6}{K^5} \cos\left(\theta_\pi + \theta_{\eta'} - (c_2^u + c_2^d + c_3)\theta\right) \end{aligned}$$

$$M^2_{a,\eta',\pi^0} = \begin{pmatrix} c^2[\Lambda_{\eta'}^4 + 2\mu\Lambda_{\text{inst}}^3]/F^2 & -2c[\Lambda_{\eta'}^4 + \mu\Lambda_{\text{inst}}^3]/f'F & 0 \\ -2c[\Lambda_{\eta'}^4 + \mu\Lambda_{\text{inst}}^3]/f'F & [4\Lambda_{\eta'}^4 + 2\mu\Lambda_{\text{inst}}^3 + m_+ v^3]/f'^2 & -m_- v^3/ff' \\ 0 & -m_- v^3/ff' & (m_+ v^3 + 2\mu\Lambda_{\text{inst}}^3)/f^2 \end{pmatrix}$$

$$\begin{aligned} m_{\pi^0}^2 & \simeq \frac{m_+ v^3 + 2\mu\Lambda_{\text{inst}}^3}{f_\pi^2} \\ m_{\eta'}^2 & \simeq \frac{4\Lambda_{\eta'}^4 + m_+ v^3 + 2\mu\Lambda_{\text{inst}}^3}{f_{\eta'}^2} \\ m_a^2 & \simeq \frac{c^2}{F^2} \frac{Z}{(1+Z)^2} f_\pi^2 m_{\pi^0}^2 (1 + \Delta) \end{aligned}$$

$$\Delta = \frac{m_-^2}{m_+} \frac{\Lambda_{\text{inst}}^3 (m_+ v^3 + \mu\Lambda_{\text{inst}}^3)}{m_{\pi^0}^4 f_\pi^4}$$

Leading to the cos form determines the axion mass

$$m_a = \frac{\sqrt{Z}}{1+Z} \frac{f_\pi m_{\pi^0}}{F_a} (1+\Delta)$$

The instanton contribution is included by Δ.

Numerically, we use

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

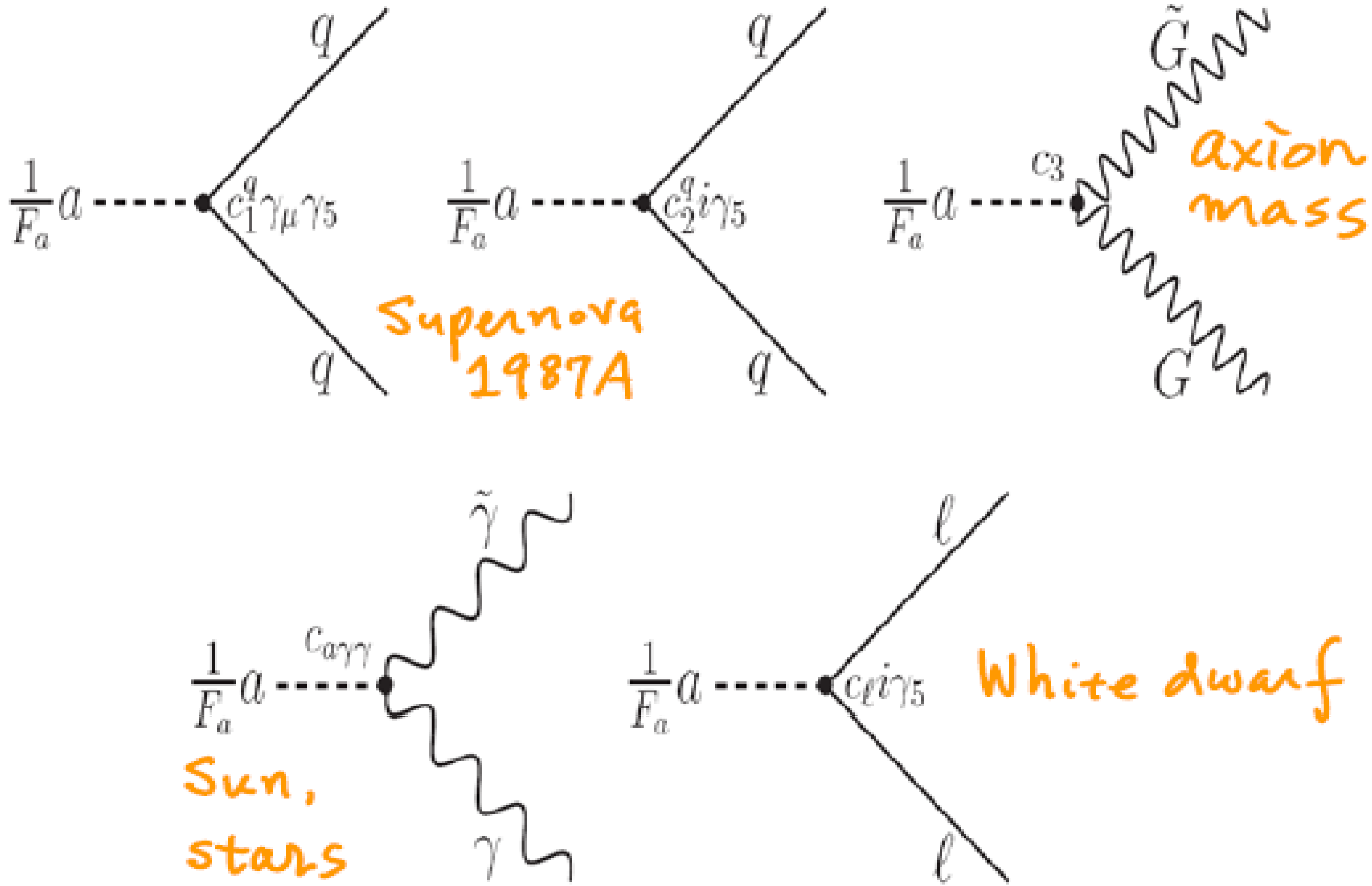
Axion couplings

Above the electroweak scale, we integrate out heavy fields. If colored quarks are integrated out, its effect is appearing as the coefficient of the gluon anomaly. If only bosons are integrated out, there is no anomaly term. Thus, we have

KSVZ: $c_1=0$, $c_2=0$, c_3=nonzero : hadronic

DFSZ: $c_1=0$, c_2=nonzero, $c_3=0$

PQWW: similar to DFSZ


$\frac{1}{F_a}a$
$c_1^q\gamma_\mu\gamma_5$
q
q
Supernova 1987A
$\frac{1}{F_a}a$
$c_2^q i\gamma_5$
q
q
$\frac{1}{F_a}a$
c_3
$\tilde{G}$
G
axion mass
$\frac{1}{F_a}a$
$c_{a\gamma\gamma}$
$\tilde{\gamma}$
γ
Sun, stars
$\frac{1}{F_a}a$
$c_\ell i\gamma_5$
ℓ
ℓ
White dwarf

Is the window of hadronic axion still open?

$0.06\ \text{eV} < m_a < 0.6\ \text{eV}$

[Raffelt; Raffelt-Deabon studied the giant star evolution arguing that the Primakoff process dominates, PRD 36 (1987) 2211]

$3\text{x}10^5\ \text{GeV} < F_a < 3\text{x}10^6\ \text{GeV}$, or

$0.02\ \text{eV} < m_a < 0.2\ \text{eV}$

[Chang-Choi, PLB 316 (1993) 51]

Raffelt's review, hep-ph/0611118; hep-ph/0611350

The hadronic axion in the 0.1 eV range has been allowed.

Hadronic coupling is important for the study of supernovae: The chiral symmetry breaking is properly taken into account, using the reparametrization invariance so that $c_3'=0$.

KSVZ:

$$\bar{c}_1^{u,d} = \frac{1}{2}\bar{c}_2^{u,d}$$
$$\bar{c}_2^u = \frac{1}{1+Z}, \quad \bar{c}_2^d = \frac{Z}{1+Z}$$

DFSZ:

$$\bar{c}_1^u = -\frac{|v_d|^2}{2v_{EW}^2} + \frac{1}{2}\bar{c}_2^u, \quad \bar{c}_1^d = -\frac{|v_u|^2}{2v_{EW}^2} + \frac{1}{2}\bar{c}_2^d,$$
$$\bar{c}_2^u = \frac{1}{1+Z}, \quad \bar{c}_2^d = \frac{Z}{1+Z},$$

The KSVZ axion has been extensively studied. Now the DFSZ axion can be studied, too.

General very light axion:

$$\bar{c}_2^u = \frac{1}{1+Z}$$

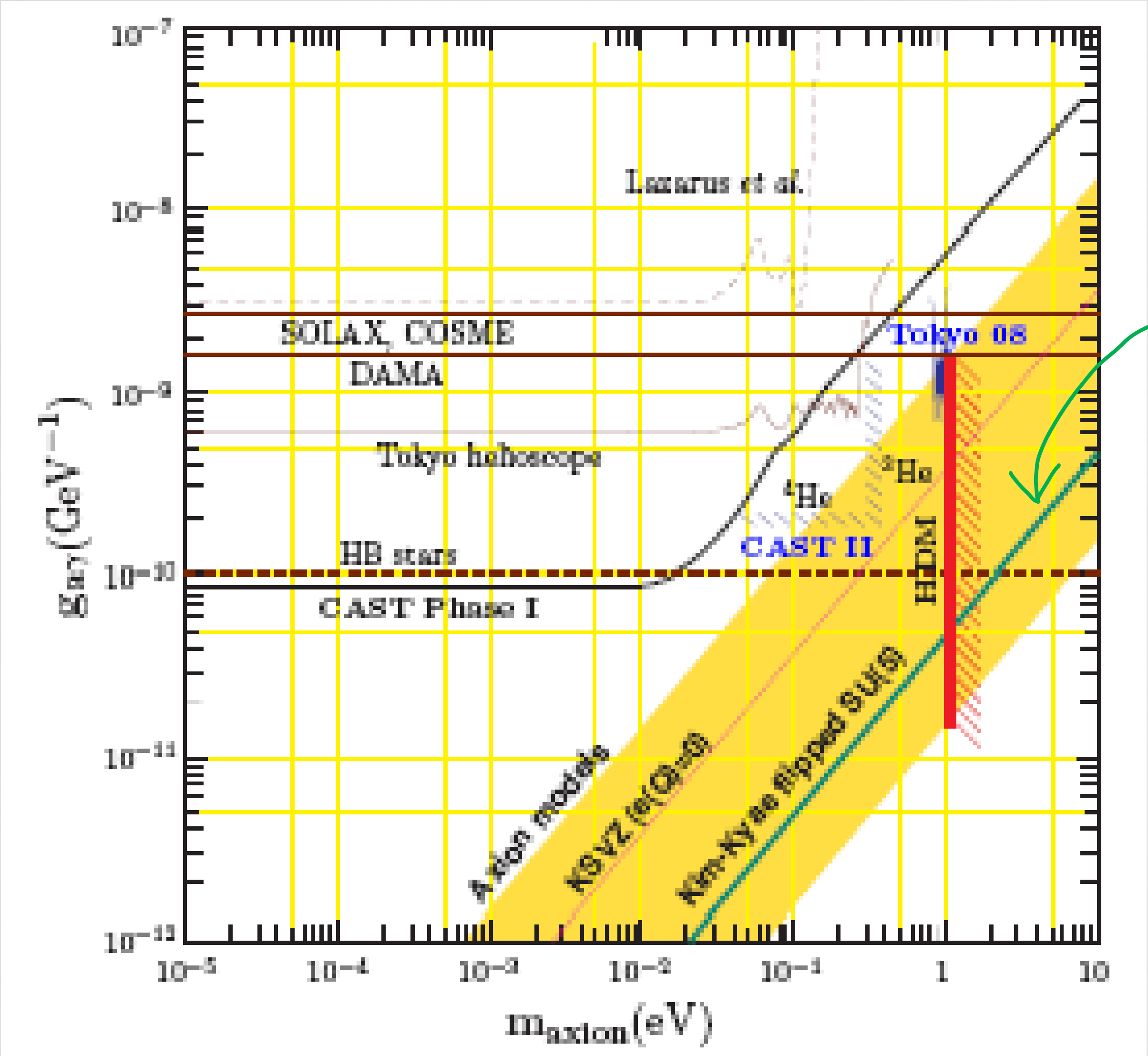
$$\bar{c}_2^d = \frac{Z}{1+Z}$$

$$\bar{c}_1^u = \frac{1}{2}\frac{1}{1+Z} \mp \frac{|v_d|^2}{2v_{EW}^2}\delta_{H_u}$$

$$\bar{c}_1^d = \frac{1}{2}\frac{Z}{1+Z} \mp \frac{|v_u|^2}{2v_{EW}^2}\delta_{H_d}$$

Axial vector couplings:

$$(\bar{c}_{1,2}^u - \bar{c}_{1,2}^d)F_3 + \frac{\bar{c}_{1,2}^u + \bar{c}_{1,2}^d}{\sqrt{3}}F_8 + \frac{\bar{c}_{1,2}^u + \bar{c}_{1,2}^d}{6}\mathbf{1}$$



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

There exist only one calculation in string compactification,

In a model explaining all MSSM phenomenology.

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($1/m_a$)

$$3H < m_a$$

This occurs when the temperature is about 0.92 GeV.

Bae-Huh-Kim, arXiv:0806.0497 [JCAP09 (2009) 005]

$$\rho_a(T_\gamma = 2.73\mathrm{K}) = m_a(T_\gamma)n_a(T_\gamma)f_1(\theta_2) = \frac{\sqrt{Z}}{1+Z}m_\pi f_\pi \frac{3\cdot 1.66 g_{*s}(T_\gamma)T_\gamma^3}{2\sqrt{g_*(T_1)}M_\mathrm{P}}\frac{F_a}{T_1}\frac{\theta_2^2 f_1(\theta_2)}{\gamma}\left(\frac{T_2}{T_1}\right)^{-3-n/2}$$

There is an overshoot factor of 1.8. So we use theta2, rather than theta1. If F_a is large(> 10^{12} GeV), then the axion energy density dominates. Since the energy density is proportional to the number density, it behaves like a CDM, but

$$10^9\ \mathrm{GeV} < F_a < 10^{12}\ \mathrm{GeV},$$

The axion field evolution eq. and time-varying Lagrangian

$$\ddot{\theta} + 3H\dot{\theta} + \frac{1}{F_a^2}V'(\theta) = 0$$

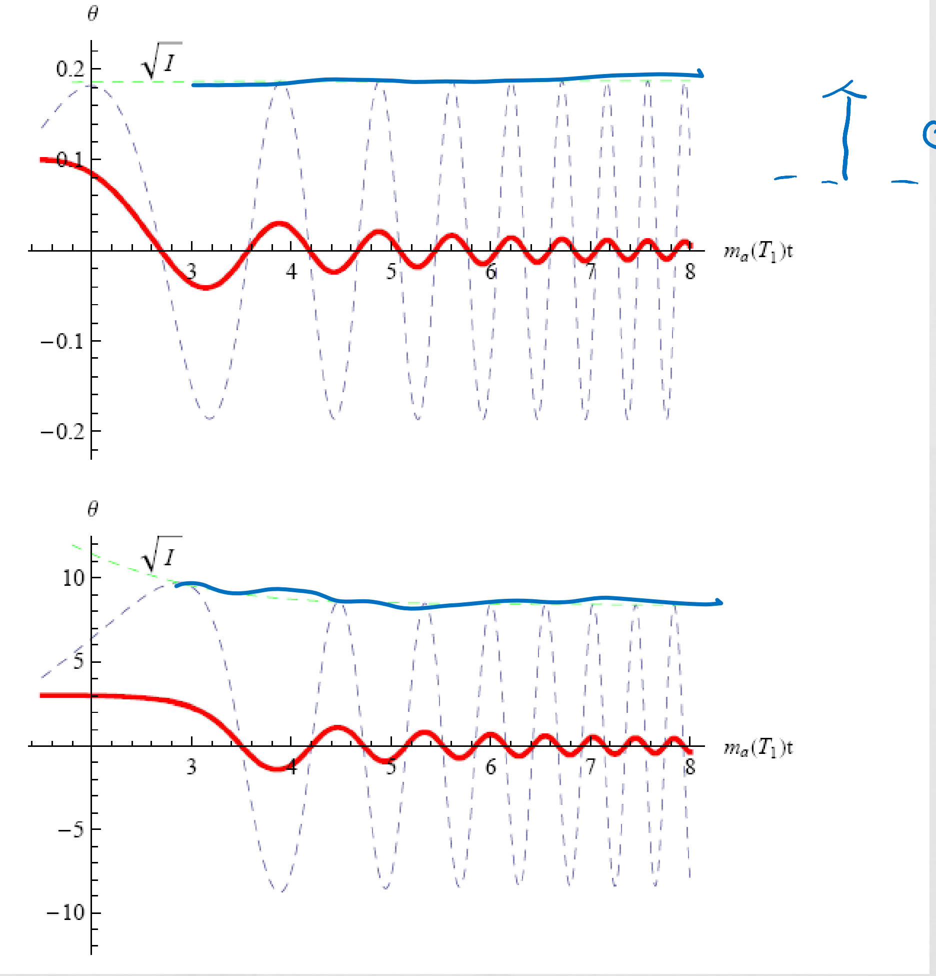
$$L = R^3(F_a^2\dot{\theta}^2 - V(\theta))$$

$$V = m_a^2 F_a^2(1-\cos\theta)$$

The adiabatic condition: $H, \dot{m}_a \langle\langle \quad m_a$

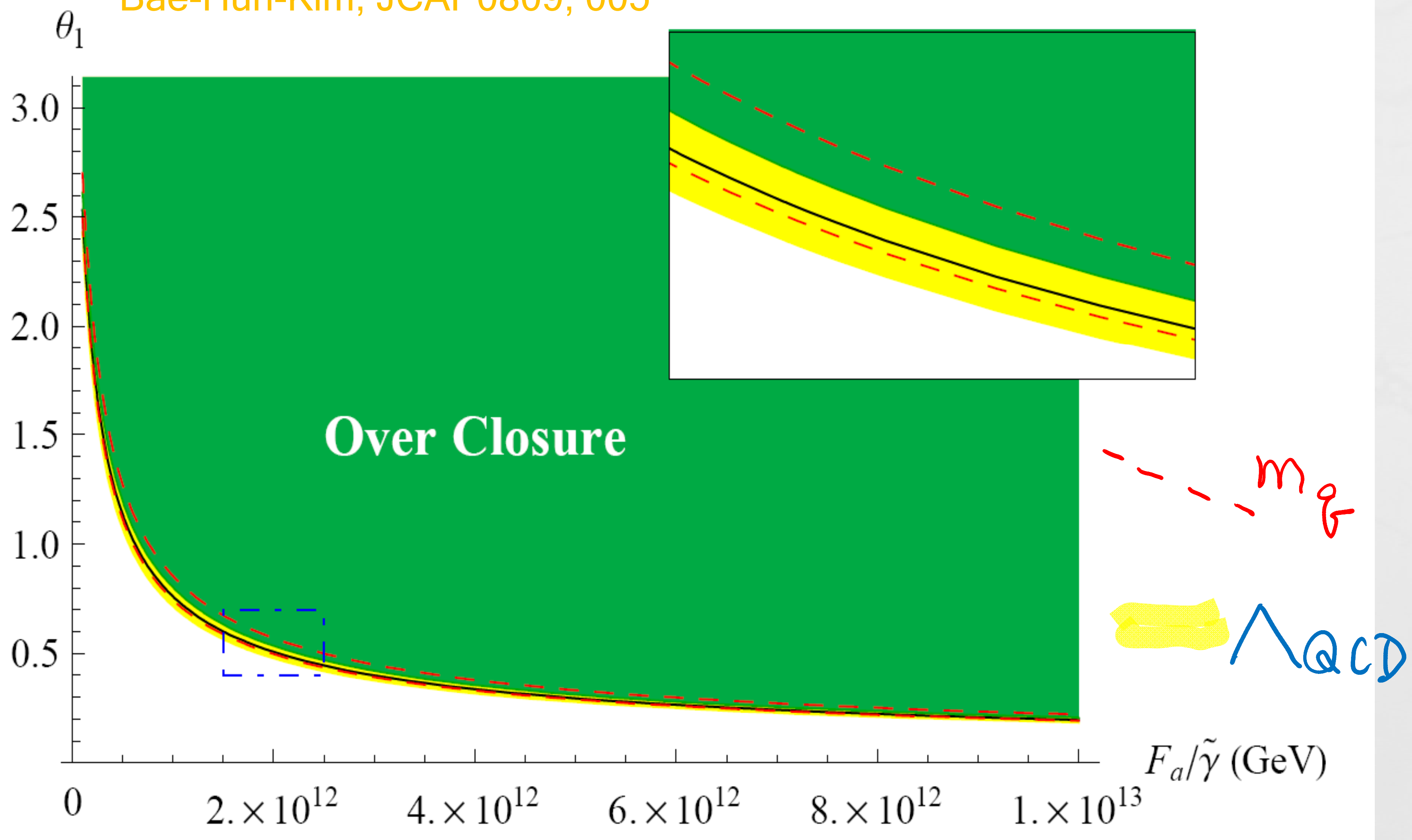
The adiabatic invariant quantity: $R^3 m_a \bar{\theta}^2 f_1(\bar{\theta})$

$$f_1(\bar{\theta}) = \frac{2\sqrt{2}}{\pi\bar{\theta}} \int_{-\bar{\theta}}^{\bar{\theta}} d\theta' \sqrt{\cos\theta' - \cos\bar{\theta}}$$



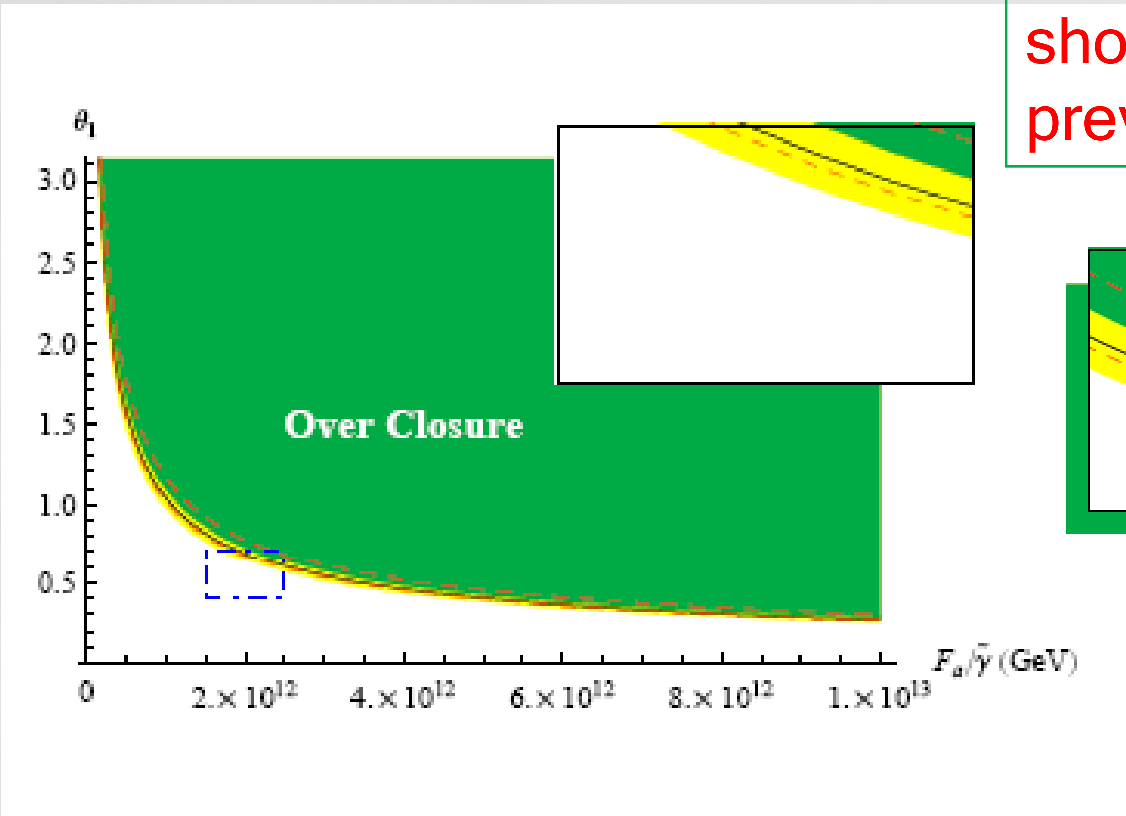
↑ overshoot

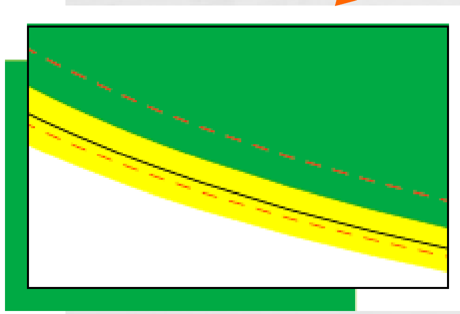
Bae-Huh-Kim, JCAP0809, 005



If we do not take into account the overshoot factor and the anharmonic correction,

Inclusion of these showed the region, prev. figure





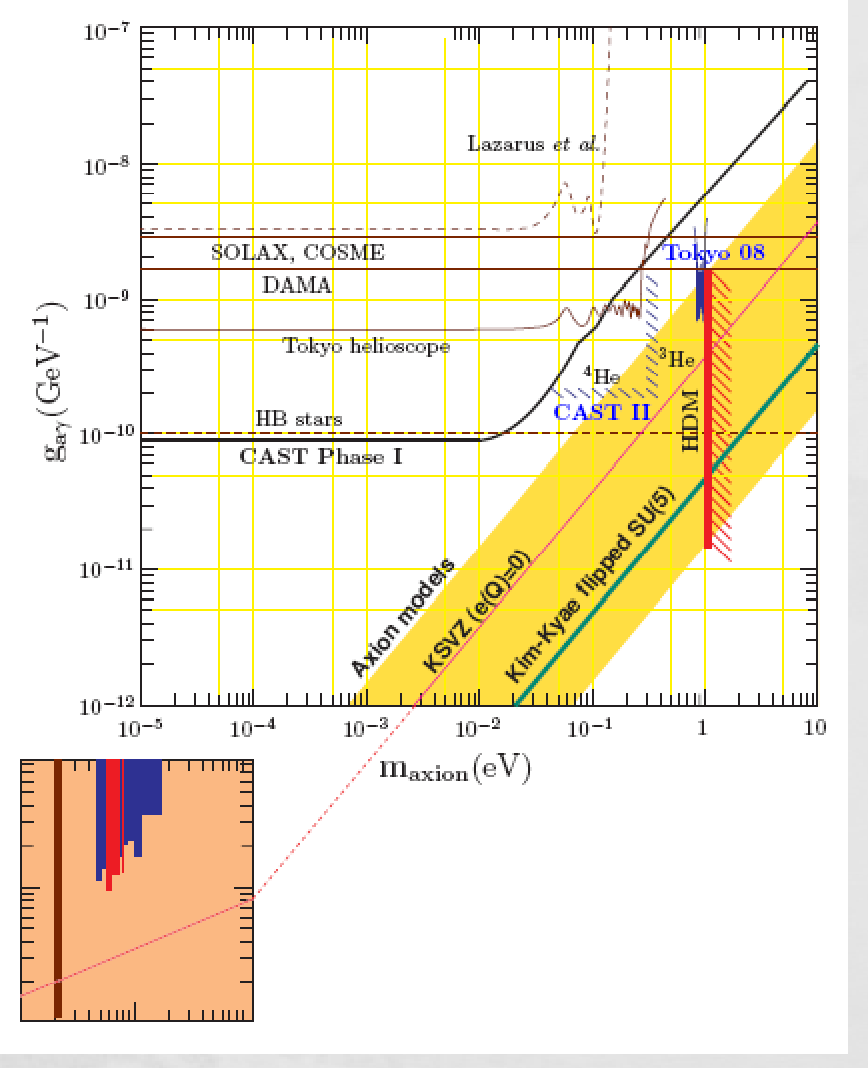
Then the axion energy fraction is given by

$$\Omega_a \simeq 0.379 \times \left(\frac{m_u m_d m_s}{3 \cdot 6 \cdot 103\ \mathrm{MeV}}\right)^{-0.092} \left(\frac{\theta_1^2 F(\theta_1)}{\gamma}\right)\left(\frac{0.701}{h}\right)^2 \times \left(\frac{\Lambda_{\mathrm{QCD}}}{380\mathrm{MeV}}\right)^{-0.733} \left(\frac{F_a}{10^{12}\mathrm{GeV}}\right)^{1.184-0.010x},$$

x=(L/380 MeV) -1

Cosmic axion search

If axion is the CDM component of the universe, then they can be detected [Sikivie].



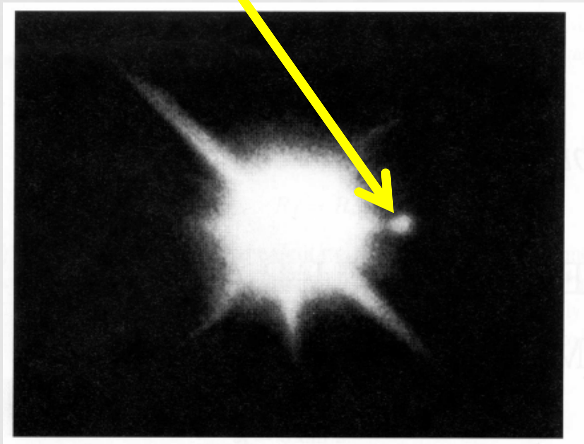
Lazarus et al.
SOLAX, COSME
DAMA
Tokyo 08
Tokyo helioscope
⁴He
³He
CAST II
HDM
HB stars
CAST Phase I
Axion models
KSVZ (e(Q)=0)
Kim-Kyae flipped SU(5)
$g_{a\gamma}$ (GeV^{-1})
m_{axion} (eV)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10

White dwarf evolution

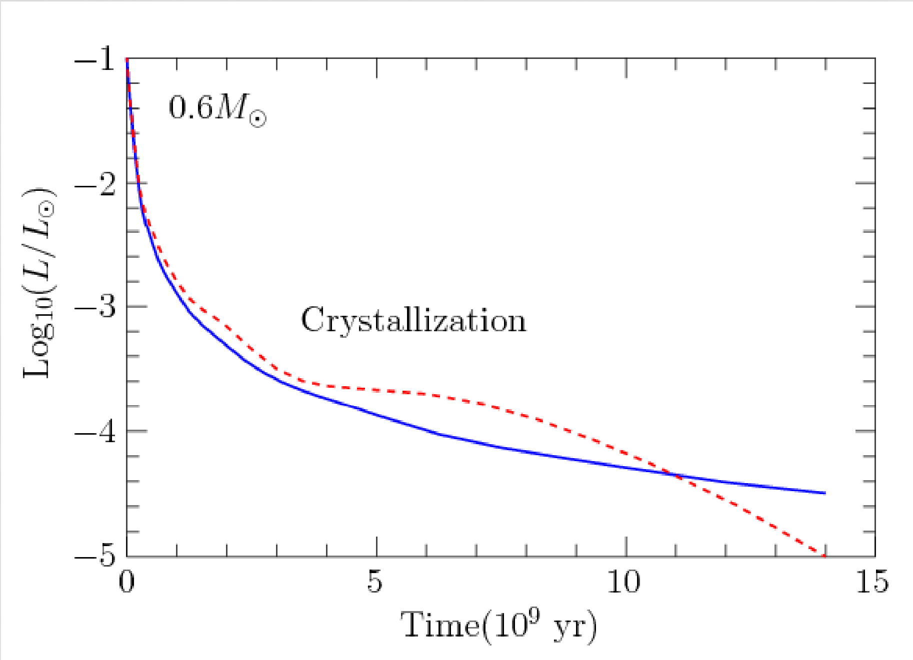
Isern et al., Ap. J. Lett. 682 (2008) 109

But they use $\tan\beta = v_d/v_u$. So, their number is ill presented. This unfortunate affair happened in many references because Srednicki used it and later citations of his did not correct for our conventional use of $\tan\beta = v_u/v_d$. We present a correct expression.

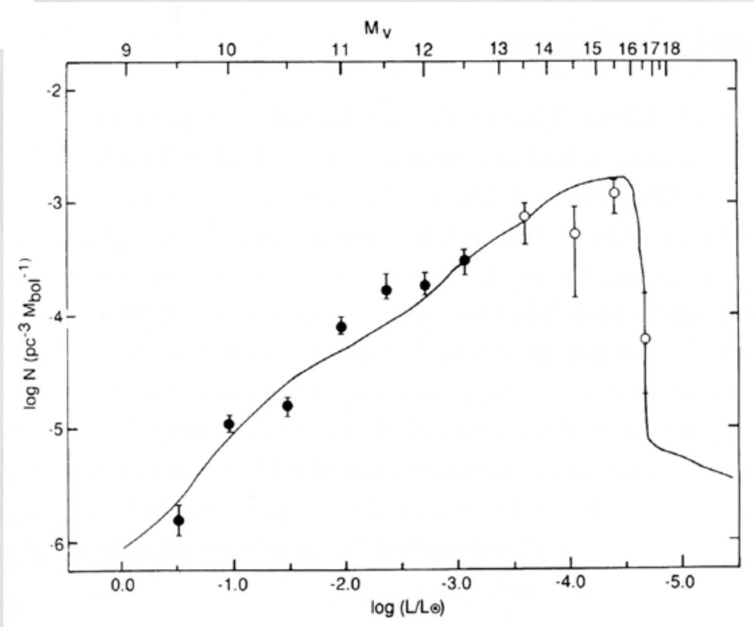
Sirius B, 1.05M_{Sun}
8.65 ly



White dwarfs can give us useful information about their last stage evolution. Main sequence stars will evolve after consuming all their nuclear fuel to WDs if their mass is less than 1.08 M_{Sun}. WDs of Sun's mass have the size of Earth, and DA WDs are studied most.



Winget et al., Ap. J. Lett. 315 (1987) L77.



The energy loss in the early stage is through the two photons conversion to neutrino pairs in the electron plasma.
This calculation of the photon conversion was initiated in 1960s, but the accurate number was available after 1972 when the NC interaction was taken into account.

D. A. Dicus, PRD6 (1972) 941;
E. Braaten, PRL66 (1991) 1655;
N. Itoh et al., Ap. J. 395 (1992) 622;
Braaten-Segel, PRD48 (1993)1478;
Y. Koyama et al., Ap. J. 431 (1994) 761

Isern et al., [Ap. J. Lett. 682 (2008) 109]
gives a very impressive figure on the most recent calculation of these pioneering works, including this early stage and the crystalization period.

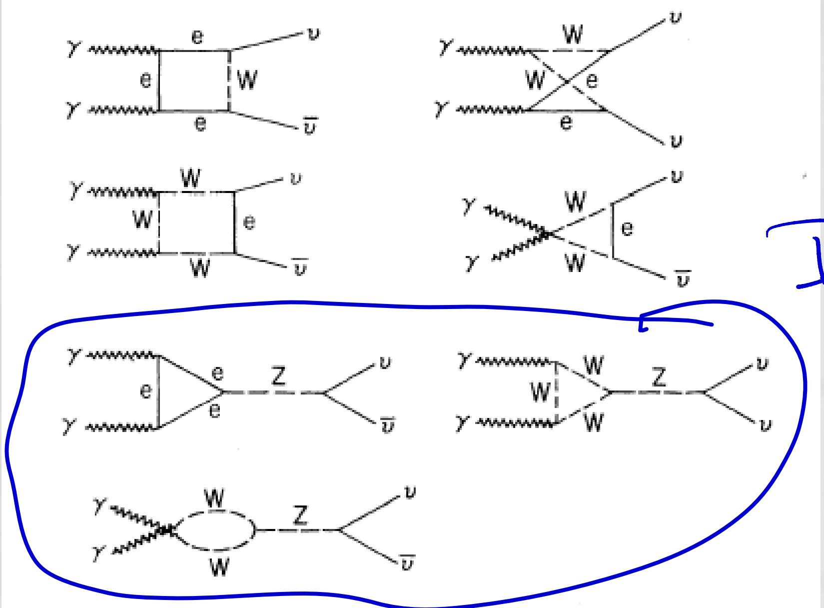


FIG. 4. The lowest-order diagrams for $\gamma + \gamma \to \nu + \bar{\nu}$.

Dicus

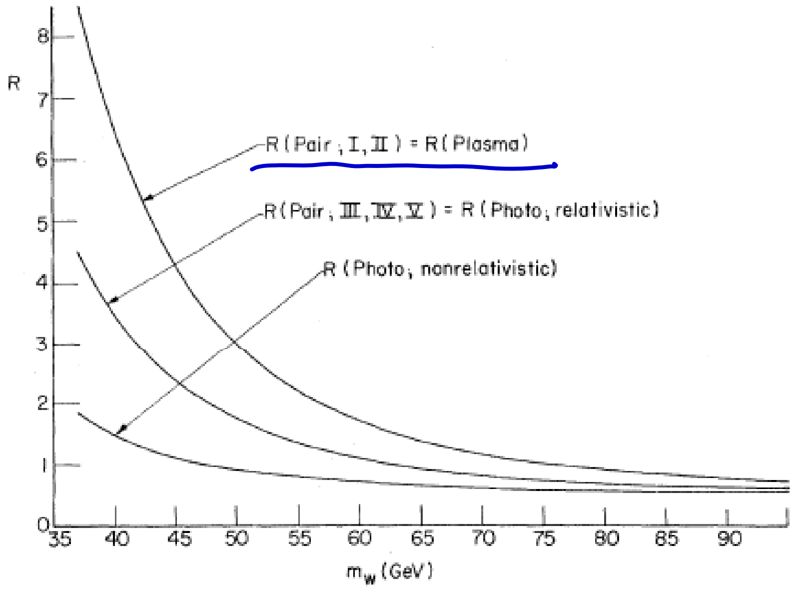


FIG. 5. The ratios of the energy-loss rates as calculated here to the energy-loss rates calculated in the ordinary theory vs the mass of the W meson. R (Pair;

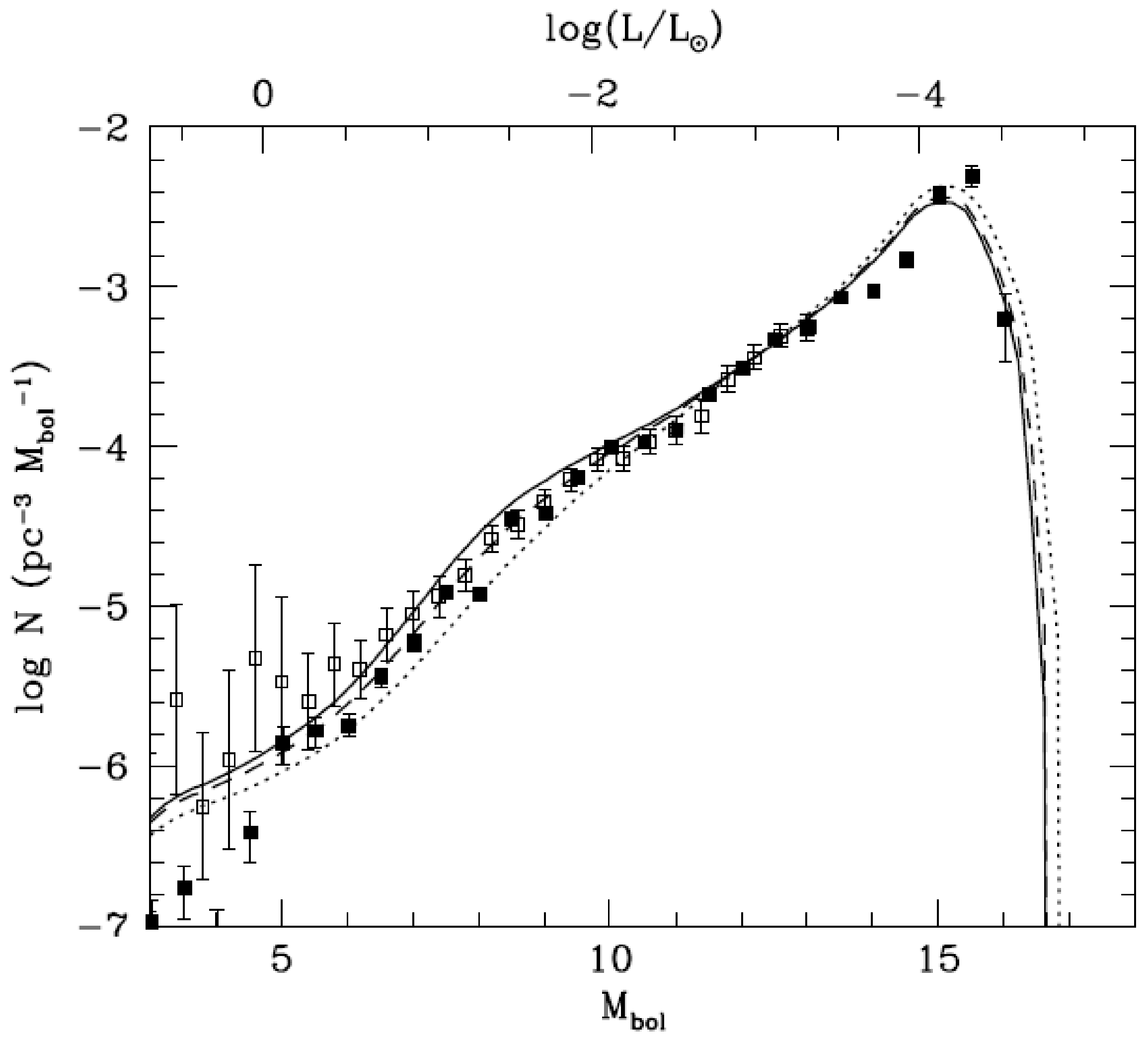


FIG. 3.— White dwarf luminosity functions for different values of the axion mass. The luminosity functions have been computed assuming $m_a \cos^2 \beta = 0$ (solid line), 5 (dashed line) and 10 (dotted line) meV.

Isern et al., Ap. J. Lett. 682 (2008) 109

Here, the luminocity is smaller than the above calculation.

One obvious possibility is the contribution from neutrino transition magnetic moments, and their plasmon decay leads to:

$$\frac{1}{2}\mu_{ij}\nu^{iT}C\gamma^{\mu\nu}\nu^{j}F_{\mu\nu} \rightarrow \quad \Gamma = \frac{|\mu|^2}{24\pi} Z_{T,L} \frac{\left(\omega_{T,L}^2 - \vec{p}_{plasmon}^{\,2}\right)^2}{\omega_{T,L}}$$

which can be compared to the SM decay to neutrinos in the plasma,

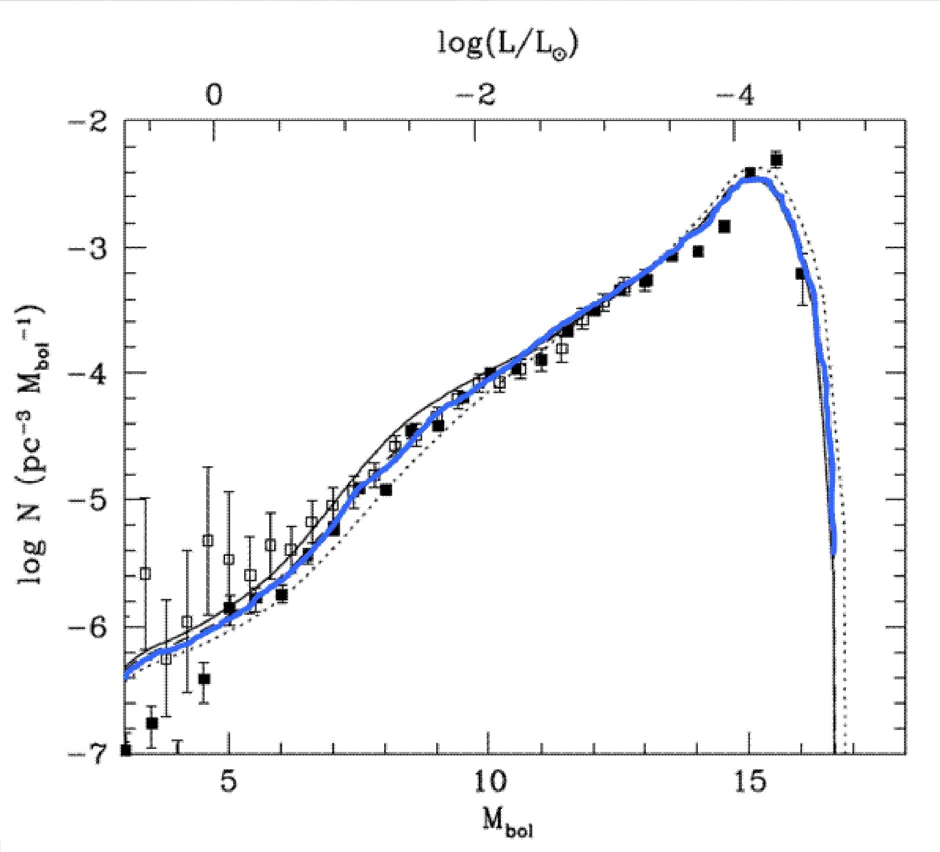
$$C_V = (e\,\nu)\ vector\ \ NC\ \ coupling \rightarrow \quad \Gamma = \frac{G_F^2\, C_V^2}{48\pi^2\alpha_{em}} Z_{T,L} \frac{\left(\omega_{T,L}^2 - \vec{p}_{plasmon}^{\,2}\right)^3}{\omega_{T,L}}$$

So, the radiation rate ratio is [Raffelt's book]

$$\frac{Q_{mag.\ mom.}}{Q_{SM}} = \quad 6.01\left(\frac{\mu}{10^{-11}\mu_{Bohr}}\right)^2\left(\frac{23\ keV}{\omega_P}\right)^2\frac{Q_3}{Q_2}, \quad \frac{Q_3}{Q_2} = O(1)$$

J. E. Kim

Isern et al. varied the star burst rates which is the only important uncertainty, and found that in the middle the predicted WD number stays almost the same. So, they used this almost burst rate independent region to estimate the WD luminocity.



The neutrino magnetic moment possibility is out in the SM.
So, they conclude that there must be another mechanism for the energy loss, and considered the axion possibility.

We translate their number to the axion-electron coupling

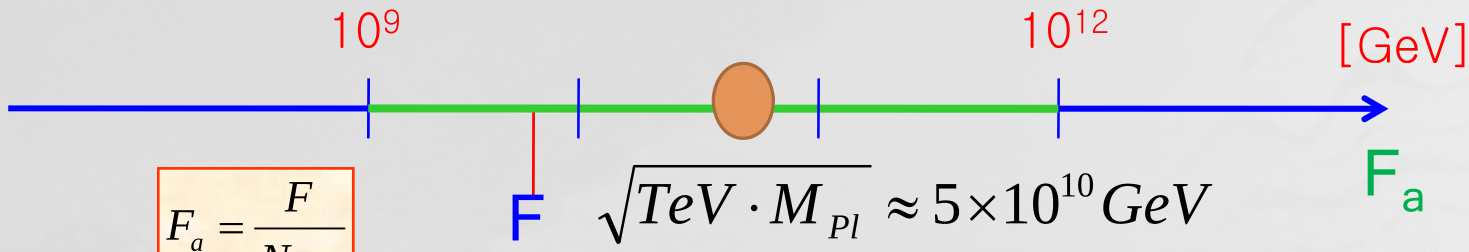
$$\left|\frac{m_e\Gamma(e)}{F}\right| = \frac{m_e}{0.72\times 10^{10}\,GeV} \cong 0.7\times 10^{-13} : any \quad axion \quad model$$

$$axion-electron \quad coupling: \quad \frac{m_e\Gamma(e)}{F}\bar{e}i\gamma_5 ea, \quad F = N_{DW}F_a$$

So, the axion-electron coupling has the form,

$$\frac{m_e\Gamma(e)/N_{DW}}{F_a}\bar{e}i\gamma_5 ea, \quad F = N_{DW}F_a, \quad \Gamma(e) = PQ \quad charge$$

To have a QCD axion at the intermediate scale, 10^9 - 10^{12} GeV, we need some PQ charge carrying scalar develop VEV(s) at that scale. But the domain wall number relates $F=N_{DW}F_a$ with $N_{DW}=1/2$.



$$F_a = \frac{F}{N_{DW}}$$

$$\sqrt{TeV \cdot M_{Pl}} \approx 5\times 10^{10}\,GeV$$

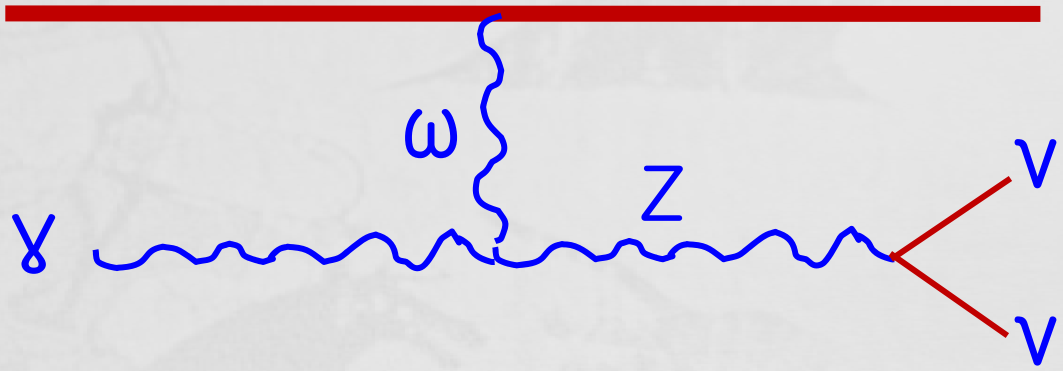
[K, PLB 136 (1984) 378]

If we anticipate the axion decay constant at the middle of the axion window, N_{DW} must be smaller than 1 since the needed axion-electron coupling is quite large.

If it is done by the phase of a singlet scalar S, presumably the PQ charges of the SM quark fields must be odd such that sum of the PQ charges of all the quarks(including heavy ones) be 1. But sum of the PQ charges of e_{2L} and e_R is 2. Then we obtain N_{DW} =1/2. Because our objective is the quark-lepton unification, this choice is the simplest.

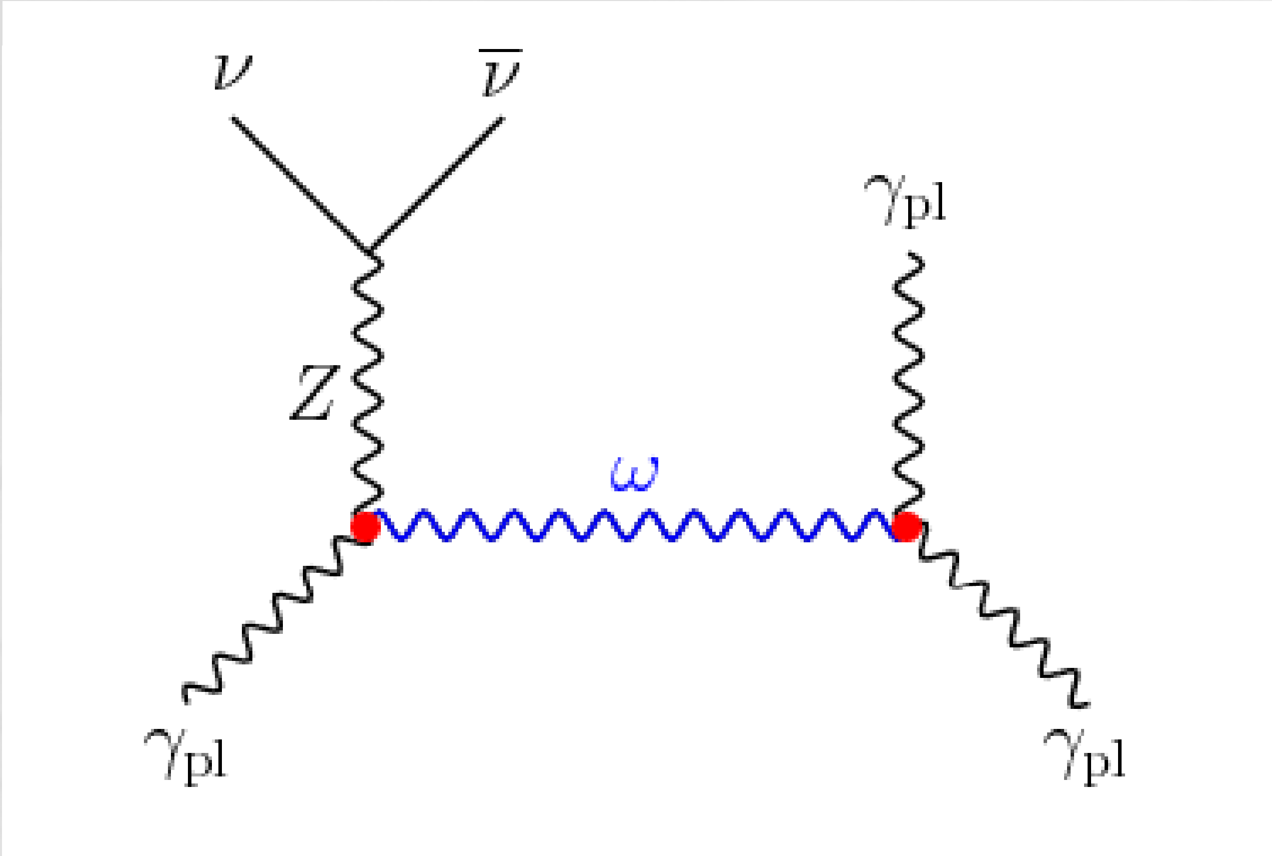
For a high density compact stars such as pulsars and WD, the anomaly interaction (Harvey-Hill) is important:

$$\varepsilon_{\mu\nu\rho\sigma}\omega^{\mu}Z^{\nu}F^{\rho\sigma}$$

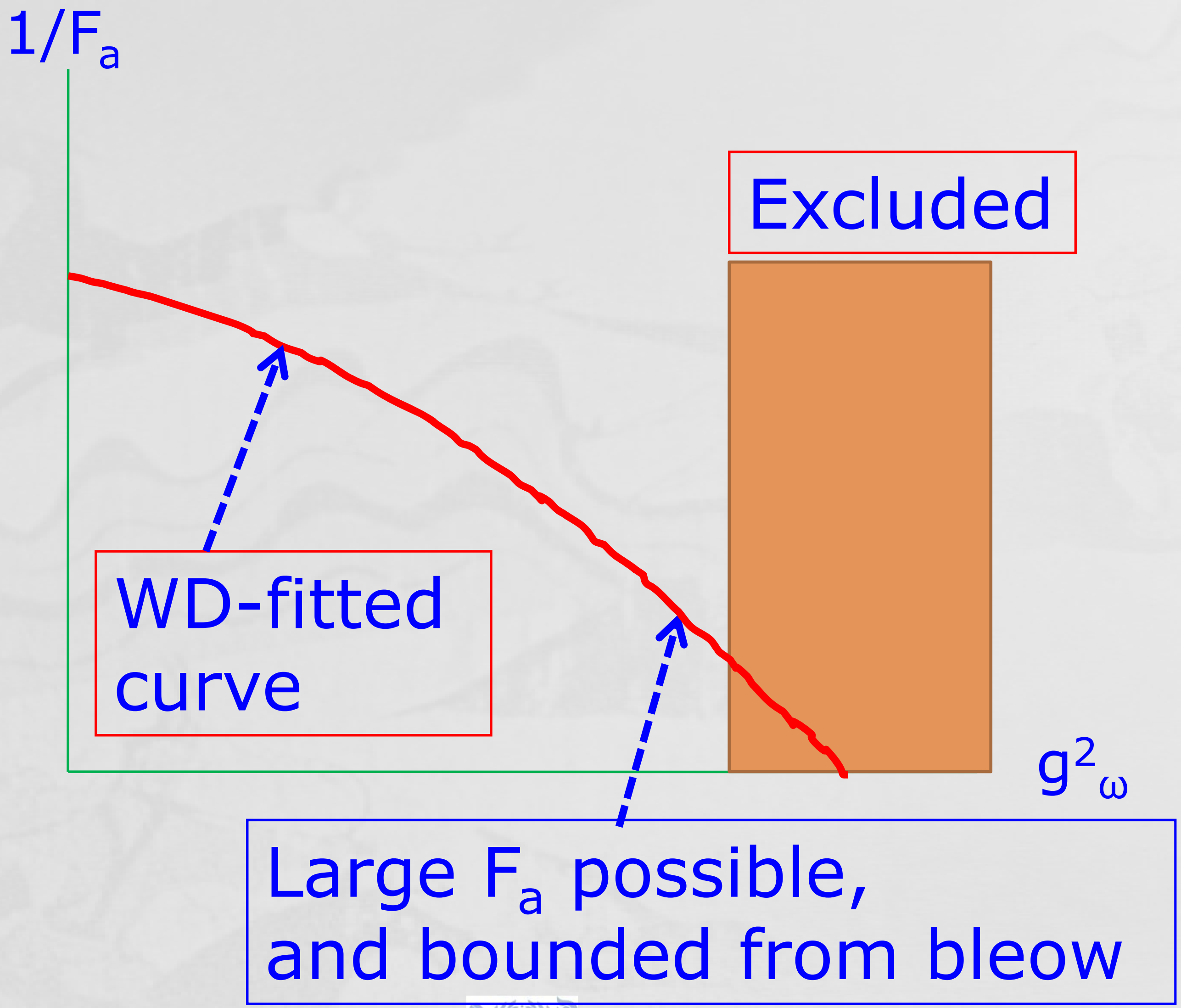


New term,
But small

J. E. Kim



It is negligible, but there may be others.


1/F_a
Excluded
WD-fitted curve
g^2_ω
Large F_a possible,
and bounded from bleow

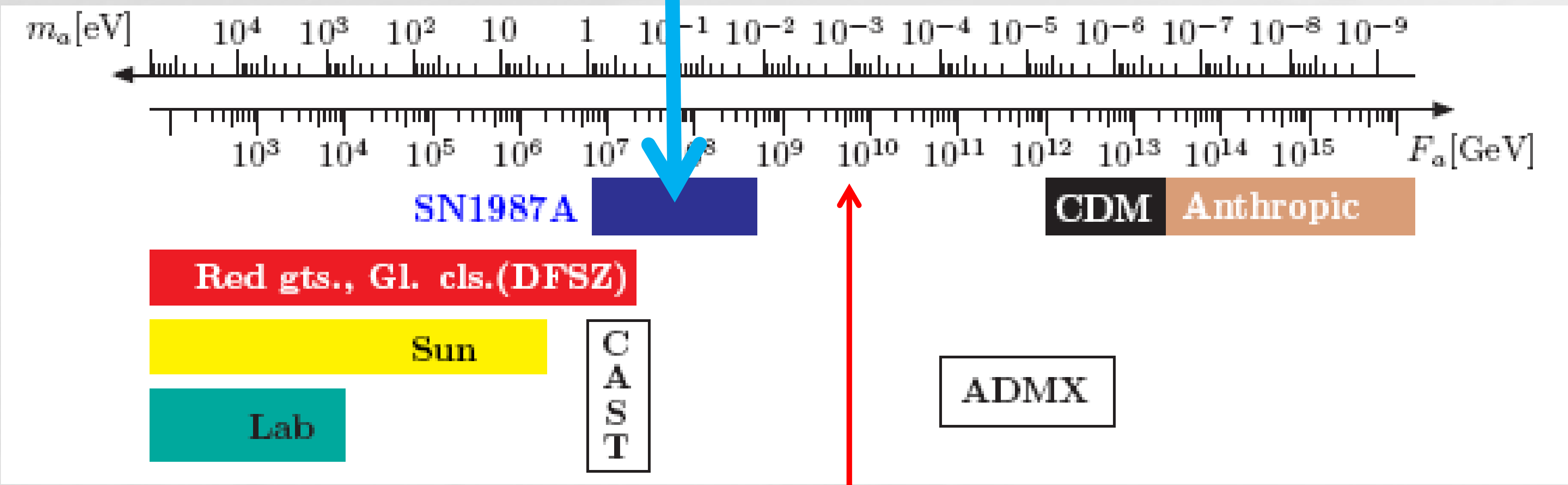
An enhanced electron coupling compared to the axion lower bound is possible by,

(i) Assign a large PQ charge to e.
The quark-lepton unification makes this idea not very promising, especially in GUTs.

(ii) Assign 1 PQ charge to e, but let the DW number be fractional.
In this case, only ½ is possible. For the quark sector, effectively only one chirality of one quark carries PQ charge, but both e_L and e_R carries PQ charges.

Bae-Huh-Kim-Kyae-Viollier, NPB817 (2009) 58 used only u_R for an effective PQ charged quark. It is possible in the flipped SU(5) since $(u^*, \nu, e)_L$ appear as 5 and e_R can be a singlet.

Hadronic axion window



White dwarf bound

(1^{st} hint at the center of the axion window)

Isern et al., ApJ 682 (2008) L109

Bae et al., NPB 817 (2009) 58 : $F_{1a}=1.4\times10^{10}$ GeV

$f_e=0.7\times10^{-13}$

4. SUSY extension and axino

Strong CP solution and SUSY:

axion : implies a superpartner axino

$T_R < 10^9$ GeV(old) from deuterium, He, ρ,

or 10^7 GeV(recent) from generating more heavier elements

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

Tamvakis+Wyler, 1982
Nilles+Raby, 1982
Frere+Gerard, 1982
K, 1983; Axino implemented with SUSY breaking

The LSP seems the most attractive candidate for DM, and needs an exact or effective R-parity for it to be sufficiently long lived. For the axino to be LSP, it must be lighter than the lightest neutralino. Here, 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

Cosmology:

eV axinos can be hot DM (80s) [K-Masiero-Nanopoulos]
KeV axinos can be warm DM (90s) [Rajagopal-Turner-Wilczek]
GeV axinos can be CDM (00s) [Covi-(H. B. Kim)-K-Roszkowski]
TeV axino (decaying) to DM(10s) [KY Choi et al., PRD77 (2008) 123501]

Helps in decaying DM: [Huh- Kim, PRD 80, 075012 (2009)]

CDM axino comes into two categories:

(1) GeV scale LSP: The LSP χ decays to axino. There can be thermal axino density [Covi-K-Roszkowski] and non- thermal axino density arising from

χ → axino + photon [Covi-Kim-K-Roszkowski]

(2) TeV scale decaying axino:

(a) Around several hundred GeV, producing nonthermal neutralinos. [Choi-K-Lee-Seto]

(b) Much above TeV [Huh-K] in view of PAMELA/Fermi data

$$\tilde{a} \rightarrow \quad N + \bullet\bullet\bullet \quad and \quad \tilde{G} + \bullet\bullet\bullet$$

$$\tilde{G} \downarrow \chi + \bullet\bullet\bullet$$

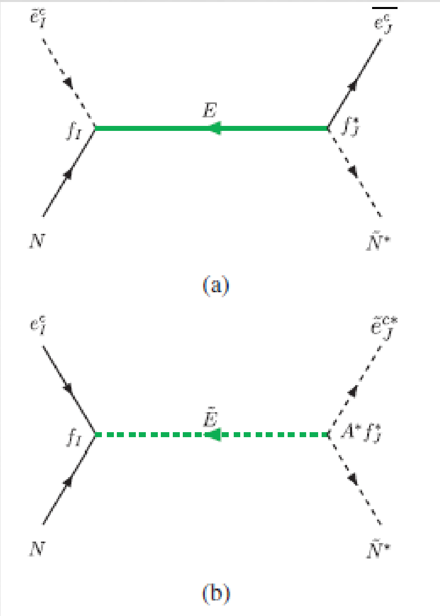
N is the decaying DM.

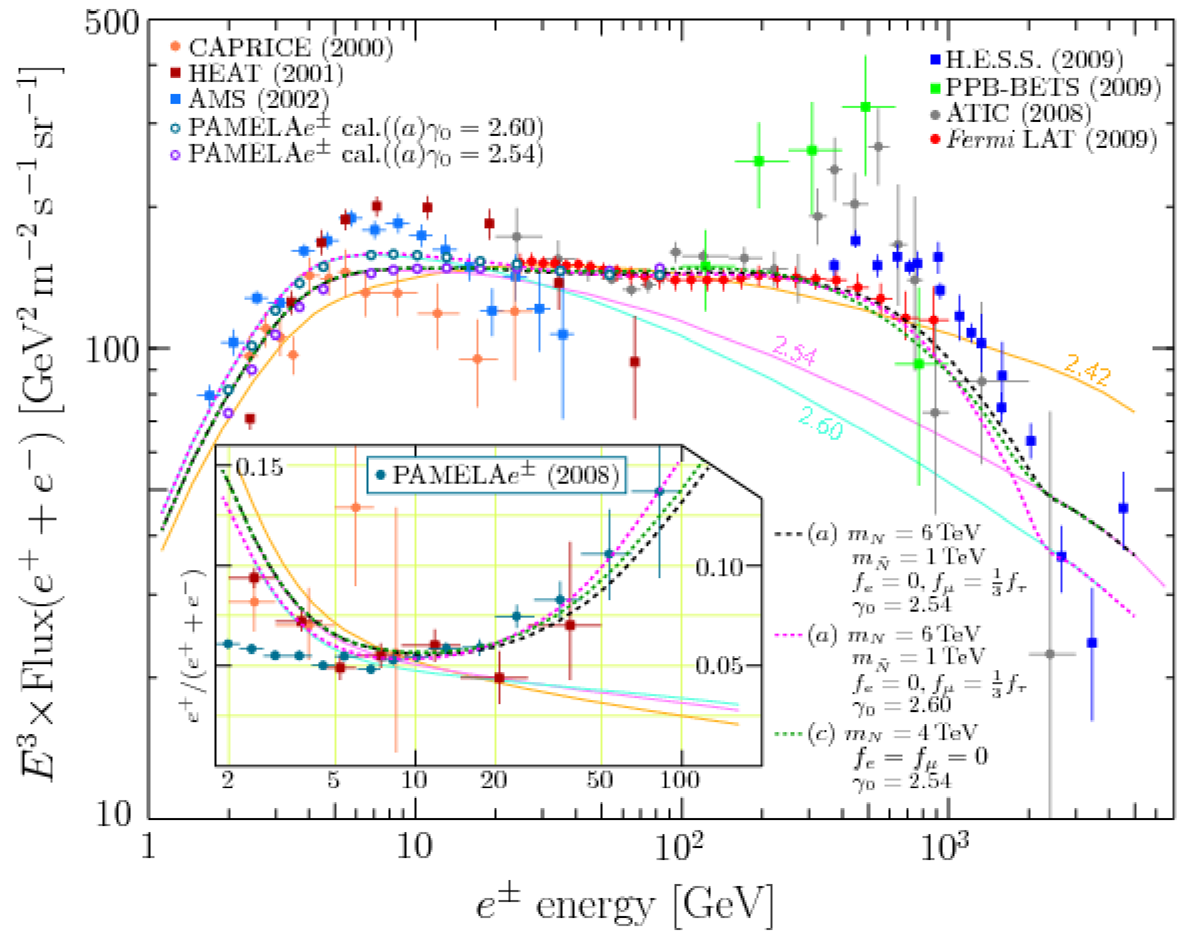
$$\int d^2\vartheta\left(\frac{1}{4M'}NNXX-\frac{c_g\alpha_g}{4\sqrt{2}\pi}\theta_g W_g W_g\right),$$

$$c_g\theta_g=\frac{A}{F_a}$$

$$\frac{\text{No. of } N}{\text{No. of } \chi}=2\left(\frac{32\pi^2}{\alpha_3^2}\right)\left(\frac{\langle X\rangle}{M'}\right)^2$$

We need $m_{N\chi}/m_N \sim 10^{-2}$ and $F_a \sim 4\text{x}10^{11}$ GeV $M' \sim 2\text{x}10^{15}$ GeV

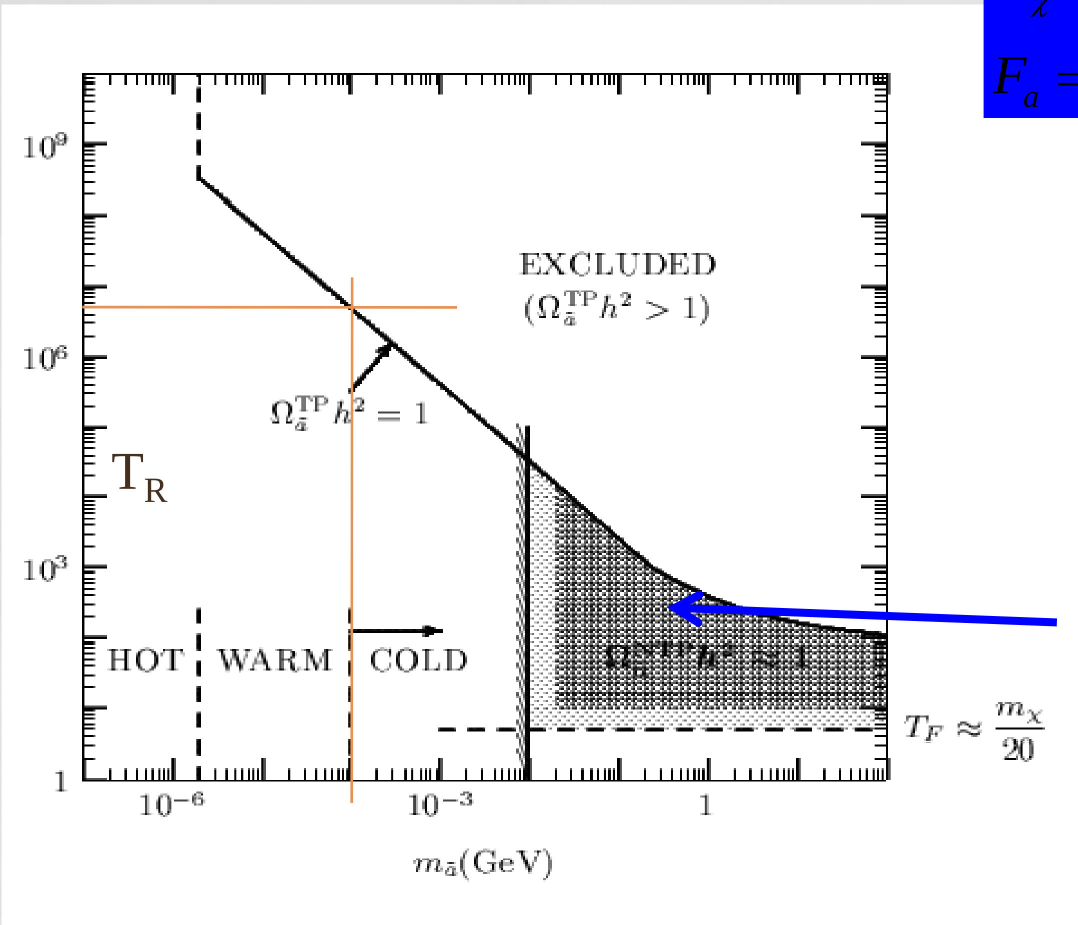




Huh-K, PRD 80 (2009) 075012 [arXiv:0908.0152]

$m_\chi = 100 GeV$

$F_a = 10^{11} GeV$



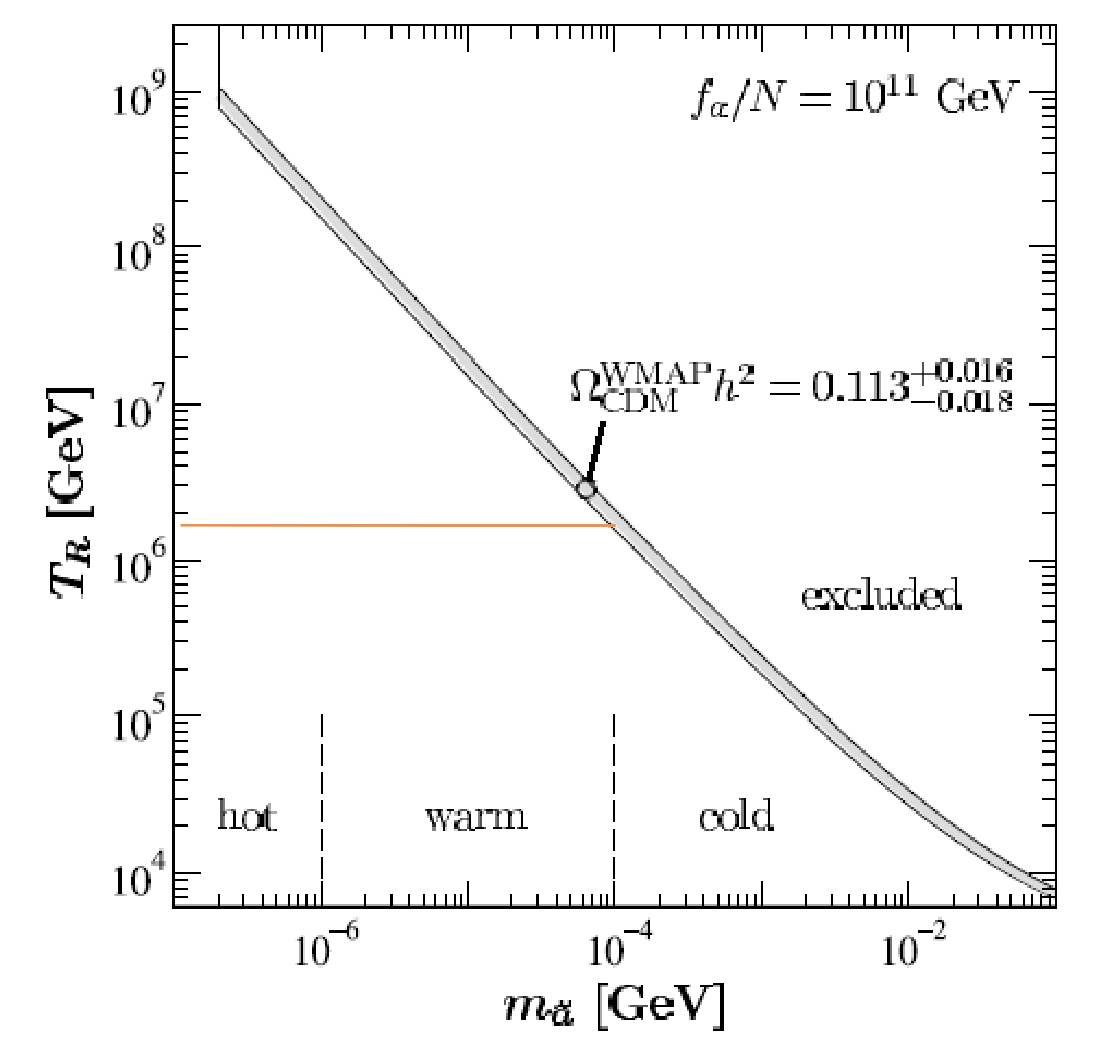
Covi-K-H B Kim-Roszkowski

Low re-heating T

Brandenburd+Steffen, JCAP 08 (2004) 008:

Stable thermal axinos, $m_{axino} < 100$ GeV

$$\Omega_{\tilde{a}}^{TP} h^2 \cong 5.5 g_c^6 \ln\left(\frac{1.108}{g_c}\right)\left(\frac{10^{11} GeV}{F_a}\right)^2\left(\frac{m_{\tilde{a}}}{0.1 GeV}\right)\left(\frac{T_{RH}}{10^4 GeV}\right)$$



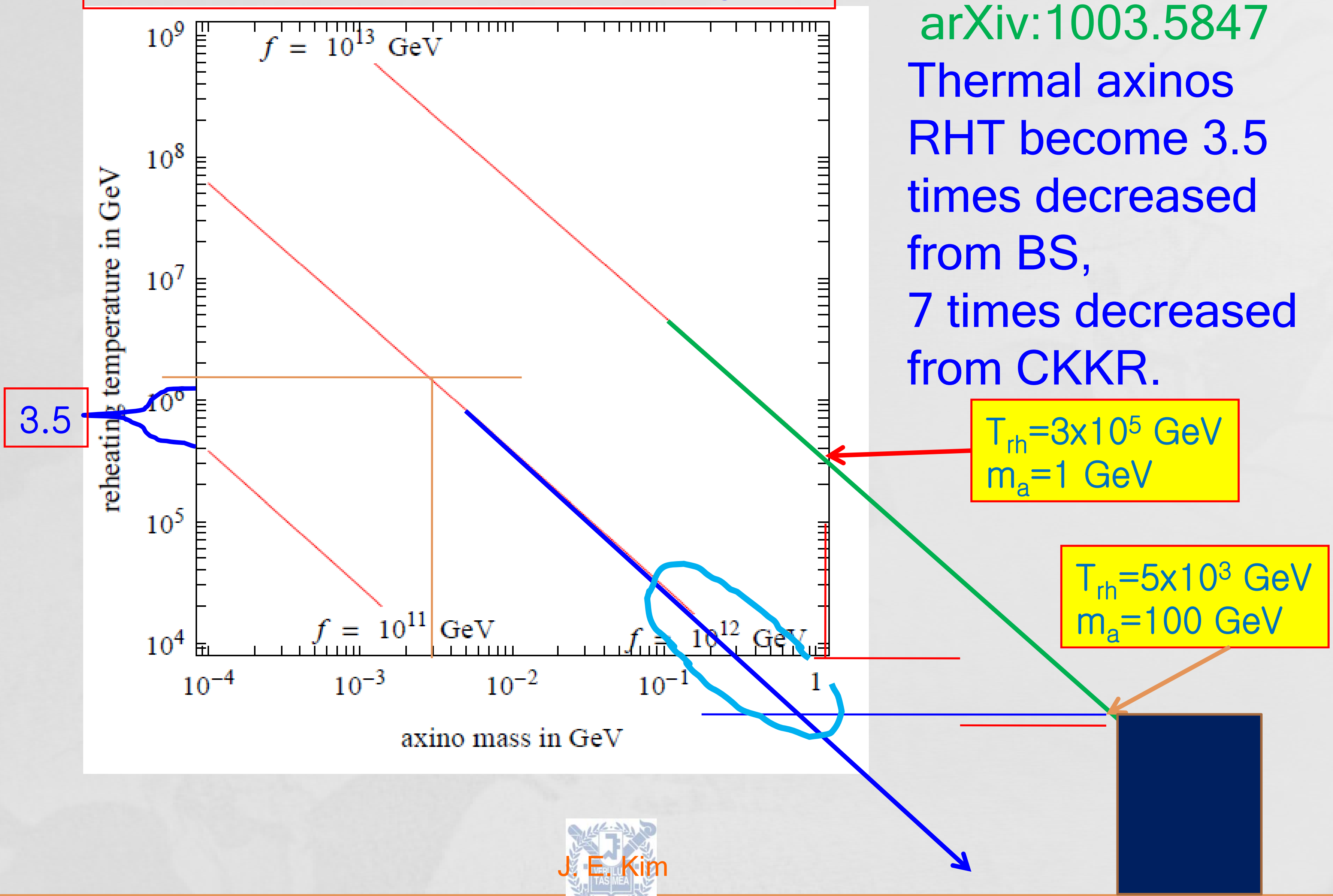
Brandenburd +Steffen,

JCAP 08 (2004) 008.

Thermal axinos become the whole CDM.

T_{RH} is lowered by a factor of 2 from CKKR.

What is the maximum reheat T, allowing ΔB?



Strumia,
arXiv:1003.5847
Thermal axinos
RHT become 3.5 times decreased from BS,
7 times decreased from CKKR.

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

Gravitino problem is resolved if gravitino is NLSP [Ellis et al, Moroi et al]

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

If χ is NLSP(=LOSP), the TP mechanism restricts the reheating temperature after inflation.

If the reheating temperature is below critical energy density line, there still exists the CDM possibility by the NTP axinos.
[Covi -Kim-K-Roszkowski(2000); Baer et al., 0812.2693]

NTP for

$$\Omega_{\tilde{a}} h^2 = \frac{m_{\tilde{a}}}{m_{\chi}} \Omega_{\chi} h^2$$

Thermal estimate

If the reheating temperature is greater than 5,000 GeV, the axino with mass greater than O(GeV) needs F_a larger than 10^{12} GeV to close the Universe by thermal axinos. Then, the axion density dominates that of axino.

High reheating temperature with SUSY with O(GeV) axino implies the axion domination of the Universe.

For a related comment, see [Baer-Box-Summy, JHEP 08 (2009) 080, arXiv:0906.2595]

Conclusion

1. Solutions of the strong CP problem : $|\bar{\theta}| \leq 10^{-11}$
   Nelson-Barr, *m_u=0 ruled out now*, axion.
2. Cosmology and astrophysics give bounds on the axion parameters. Hadronic axions in astrophysics and DFSZ axions from WD cooling process need attention.
3. With SUSY extension, axinos can be CDM or decaying axino to CDM [Choi-K-Lee-Seto(08)] can produce the needed number of non-thermal neutralinos. In any case, to understand the strong CP with axions in SUSY framework, the axino must be considered in the CDM discussion.