Strong CP needs Axions

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중이온가속기 및 핵심연구장비 구축 [KISTEP 박구선 11.02.08]

대형 연구시설로서 중이온가속기의 필요성

- 우리나라 **기초과학 선진화** 를 위한 핵심 시설
- 국제적 연구 네트워킹 및 우수 인력 유치의 **구심점**
- 노벨 물리학상 20%가 **가속기 기반 연구**
- 미국, EU 등의 대형연구시설 로드맵에서 **가속기가 가장 큰 비중**
  - 미국의 경우 50%가 가속기

예산 규모

- 가속기 1기 건설 **소요예산은 약 4,600억원 내외(6년간)**
  - 건설기간 정부 전체R&D 총액(추정치) 94조원의 0.49%, 기초R&D 총액(추정치) 22.8조원의 2.01%에 해당
  - 건설 이후 가속기 1기의 매년 운영비는 500억원으로 예상

제 원	가속입자	활용분야
에너지 200MeV/n, 빔전류 2pμA (세계최고수준)	H(수소)~U(우라늄)까지 대부분 중이온, 방사선 동위원소	핵물리·생명과학 등 기초과학 분야, 원자력·에너지 분야 등 첨단 연구

※ 현재 중이온가속기의 개념설계를 추진 중 (~11.2월)

중이온가속기 및 **핵심연구장비 구축** [KISTEP 박구선 11.02.08]

- 과학지식에서 대부분 **중요한 발전은 실험기법 향상** 으로 이루어짐
- **노벨상 수상 연구의 81%, 진보적 연구결과의 63%**가 연구시설·장비를 통해 도출 (NSF, 1997)

➡ 세계 최고수준의 대형기초과학연구시설 및 핵심연구장비의 **전략적 확충 및 공동활용 극대화** 필요

기초과학연구원에 구축할 **25대 기초연구 기반형 핵심연구장비** 목록

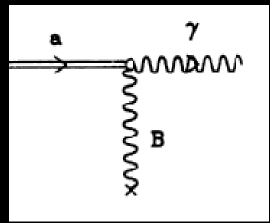
※ 전문가 설문조사 등을 통해 도출

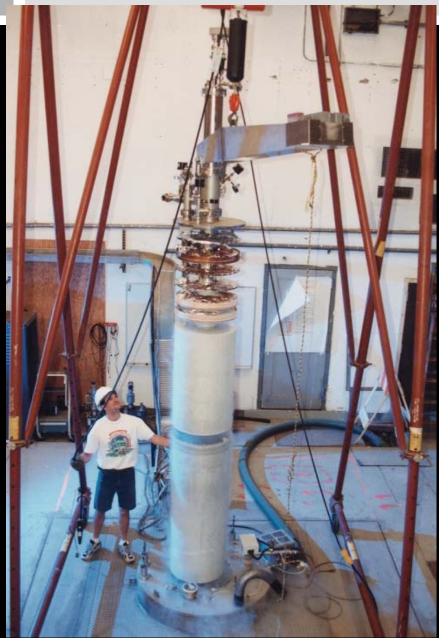
질량분석기(MS)	주사전자현미경(SEM)	아미노산분석기(AAA)
투과전자현미경(TEM)	X선 회절분석기(XRD)	공초점 주사현미경(LCSM)
유도결합 플라즈마분광기	염기서열분석기(DNA-S)	퓨리에변환 적외선분광기
X선 광전자분광기(XPS)	주사탐침현미경(SPM)	액체 크로마토그래피(LC)
가스 크로마토그래피(GC)	이미지분석기(IA)	원자흡수광도계(AAS)
이온 크로마토그래피(IC)	원심분리기(CS)	원자현미경(AFM)
X선 형광분광기(XRF)	자외-가시분광 광도계	열분석기(TA)
DNA증폭장치(PCR)	입도분석기(PSA)	원소분석기(EA)

핵자기공명분광기(NMR

Axion-photon mixing provides [P. Sikivie, PRL 51, 1415 (1983)]: Primakoff effect

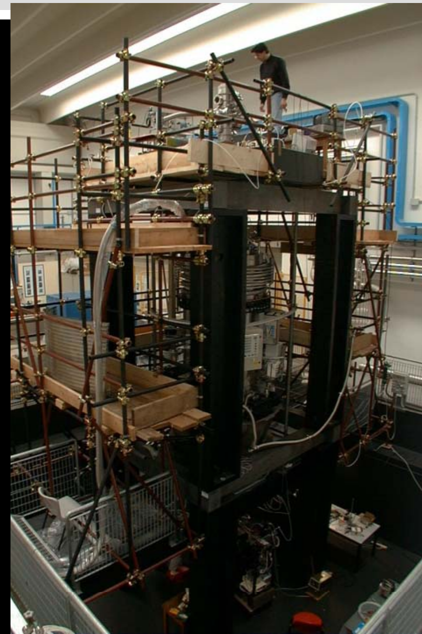
$$L_{\text{int}} = a g_{a\gamma\gamma} E \cdot B$$





Dark matter

Solar

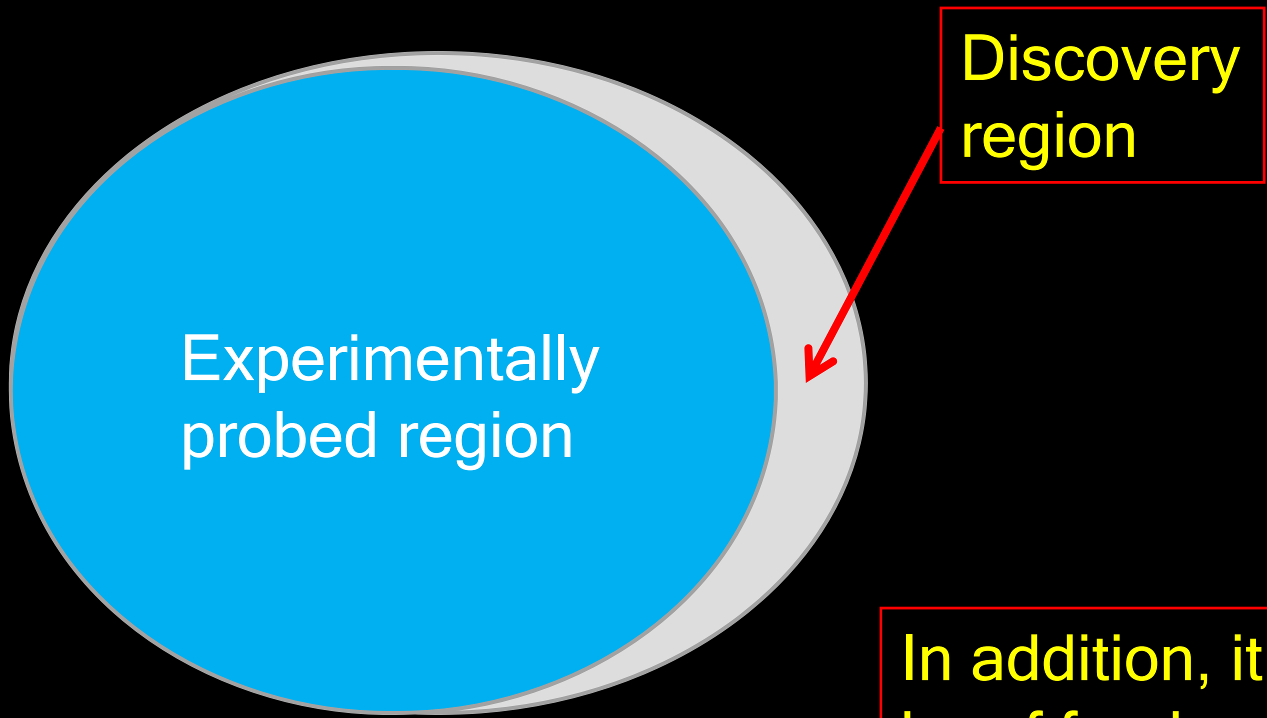


Laboratory

Coherent mixing of axions and photons over large spatial regions of strong magnetic fields (a sea of virtual photons) compensates for the extraordinarily small value of $g_{a\gamma\gamma}$

See Raffelt & Stodolsky for general treatment of axion-photon mixing – PRD 37, 1237 (1988)

In my general physics course, I mention



In addition, it must be of fundamental importance to be weighed very highly

In fundamental physics, the important subject is symmetry:

Theory: general covariance (Einstein)
QED (Feynman-Schwinger-Tomonaga)
QCD (Han-Nambu, Politzer-Gross-Wilczek)
SU(2)xU(1) (Glasow-Weinberg-Salam)
Parity (Lee-Yang)
CP (Kobayashi-Maskawa)

Particles: neutrinos spin 1/2
W/Z bosons spin 1
Higgs spin 0

What will be the next important symmetry and particle?

Peccei-Quinn symmetry
very light axion ----- is instanton related and is of fundamental importance

1. CP Symmetry
   (weak CP, strong CP)

2. The strong CP problem

3. Axion physics (detectable)

1. Symmetries

The charge conjugation C and parity P have been known as exact symmetries in atomic physics, i.e. in electromagnetic interactions.

1924: Atomic wave functions are either symmetric or antisymmetric:
Laporte rule

1927: Nature is parity symmetric, Wigner:
Laporte rule = parity symmetric

Quantum mechanics was developed after the atomic rule of Laporte was known. It is based on the

SYMMETRY PRINCIPLE !!!!

In QM, these symmetry operations are represented by unitary operators. For continuous symmetries, we represent them by generators

$$U = e^{i\theta\cdot F}$$

where F is a set of generators.

Lorentz symmetry:

$$(\eta^{\mu\nu}\partial_\mu\partial_\nu + m^2)\Phi(t,x,y,z) = 0,$$
$$(i\eta^{\mu\nu}\partial_\mu\gamma_\nu - m)\Psi(t,x,y,z) = 0$$

We claim that all physical laws are derived from symmetry principles. So is the case, any physical idea directly touching upon a symmetry principle is considered to be of the supreme importance.

Of course, discrete symmetries are simpler to discuss than continuous symmetries. And for the discrete symmetries, we use U directly rather than considering F. If a discrete symmetry is a subgroup of a continuous symmetry, one can use F of the continuous symmetry also.

What are the symmetries we know now?

A general covariance in 4D

$SU(3)\times SU(2)_L\times U(1)_Y$ SM gauge symmetry with 3 families at least.

So, we focus on the SM symmetry

$SU(3)xSU(2)_L xU(1)_Y$

It has

8 gluons, introduced by Han-Nambu
3 W/Z : 1 mass (other from coupl.)
1 photon
6 quarks : 6 masses+ 4 angles
3 charged leptons : 3 masses
3 neutrinos : (3+4+2)
1 neutral Higgs boson (Goldstones are absorbed to Z and W) : 1 mass

These particles have 20 couplings (neglecting neutrino masses)

3 gauge couplings, two θ's, totaling 20. Or 19.

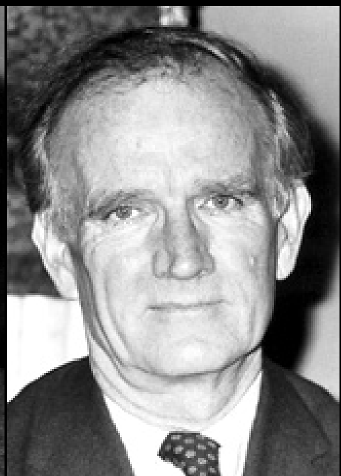
Parity has been known to be broken, as shown in the tau-theta puzzle. This led to

"P violation in weak interactions"

For the chiral SM, we must mention one most important breakthrough on the road : the "V-A" theory of Marshak-Sudarshan(1957); Feynman-Gell-Mann(1958).

In the SM, the P violation in weak interactions is ultimately given at low energy perspective by the Glashow-Salam-Weinberg chiral model of weak interactions.

The charge conjugation C is also broken in the GSW model, but the product CP or T is usually unbroken. So, in 1962 Feynman in his Feynman lecture Chapt. 52 commented on exact CP symmetry. T is an anti-unitary operator needing complex conjugation in QFT. So, CP violation observed in the neutral K-meson system needed to introduce a CP violation model with a phase in weak interactions. It is given by the Kobayashi-Maskawa model.

CP violation in weak interactions in the SM, four quark model is not enough but six quarks are needed.

In 1972, u, d, s quarks were known. With four quarks of u,d,s, c, CP violation was attempted by Mohapatra. Received at PRD on April 21, 1972. As far as I know, it was the first try

PHYSICAL REVIEW D VOLUME 6, NUMBER 7 1 OCTOBER 1972

Renormalizable Model of Weak and Electromagnetic Interactions with *CP* Violation*

Rabindra N. Mohapatra
Center for Theoretical Physics, Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 21 April 1972)

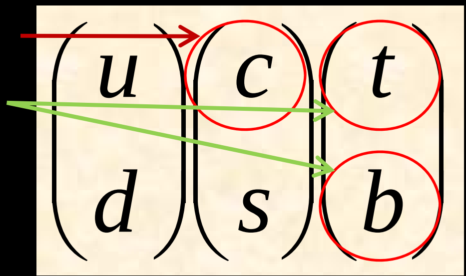
A renormalizable gauge-field model of weak and electromagnetic interaction of leptons and hadrons is constructed. The model can explain *CP* violation in hadronic weak processes and the suppression of hadronic neutral currents.

Compare KM's submission to Prog.Theor. Phys. on 01.09.1972.

$$Q_{em} = \frac{2}{3} \qquad Q_{em} = \frac{-1}{3} \qquad \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

Not known in 1972

Because of spin, we can think of LH and RH quarks independently. Only LH quarks participate in the weak CP violation. This was known in 1977.



$$\begin{pmatrix} u \\ d' \end{pmatrix} \begin{pmatrix} c \\ s' \end{pmatrix} \begin{pmatrix} t \\ b' \end{pmatrix}$$

In addition, the quark mixing involves only the LH quarks. It was footnoted by Gell-Mann and Levy in 1961 and suggested as a mixing model by Cabibbo in 1963.

3x3 matrix Has a phase.

Weak CP Violation

SM: SU(2) x U(1) x SU(3)
chiral model vector model

Seems to have CP violation in weak interactions, but not in strong interactions:

Weak CP violation: good and needed in the K phenomenology and baryogenesis or leptogenesis

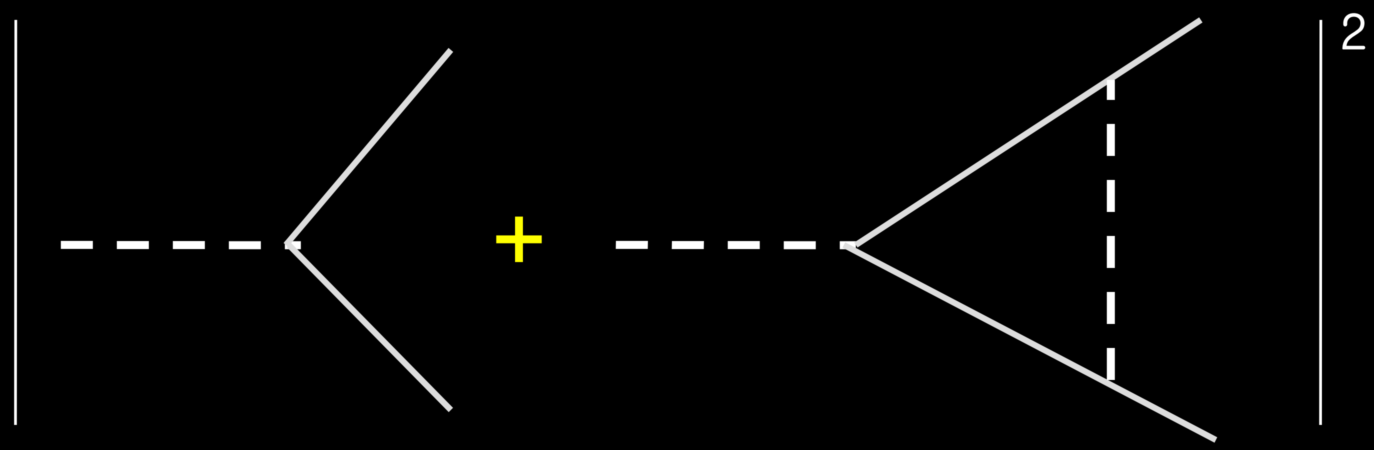
Strong CP violation: not allowed phenomenologically

The observable CP symmetry with a complex field involved is an interference phenomenon, due to the freedom in the definition of the CP phase. Always, we have to look at this freedom of redefinition of phases of complex fields.

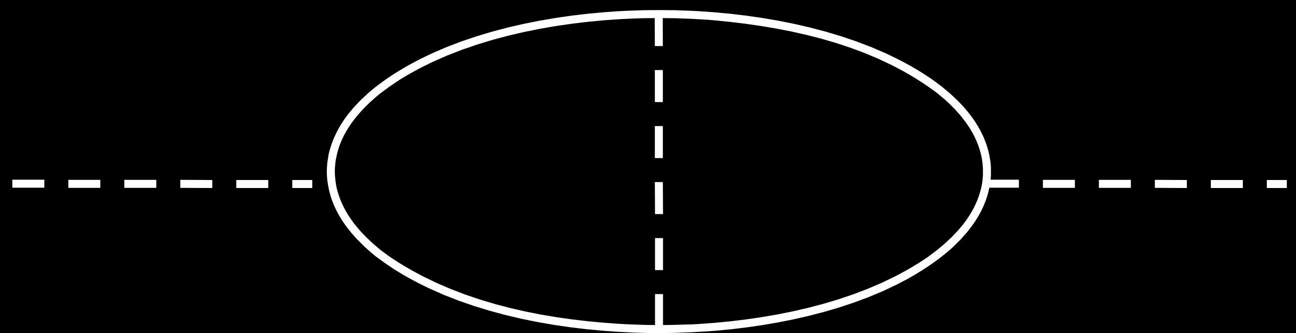
If there are appropriate CP phases for this to hold, then CP is conserved.

$$(CP)\quad L\quad (CP)^{-1} \rightarrow\quad L$$

For example, in a heavy particle decay, it is like



The interference of these two introduces an impossibility of redefining the phases such that the whole thing becomes real.



Strong CP

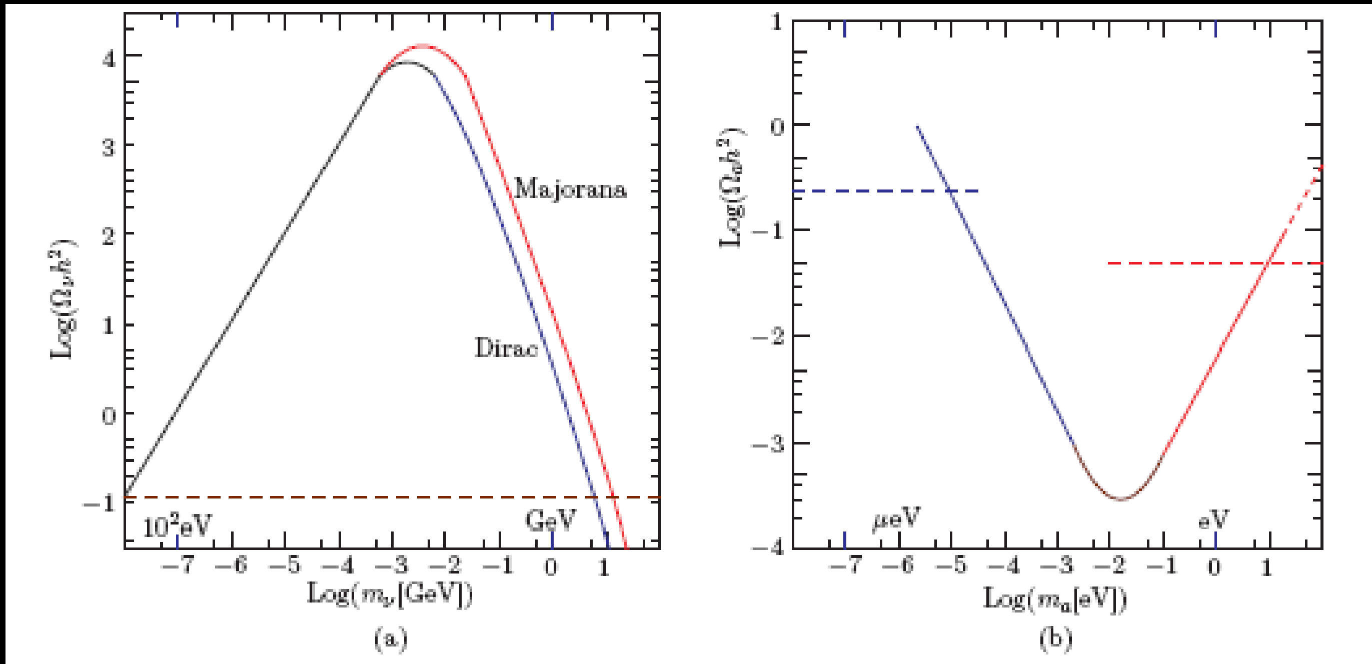
Axion is a Goldstone boson arising
when the PQ global symmetry is spontaneously broken.
The simple form dictates that its interaction is only through the anomaly term(hadronic axion), etc. The axion models have the spontaneous symmetry breaking scale F and the axion decay constant F_a which are related by $F=N_{DW} F_a$.

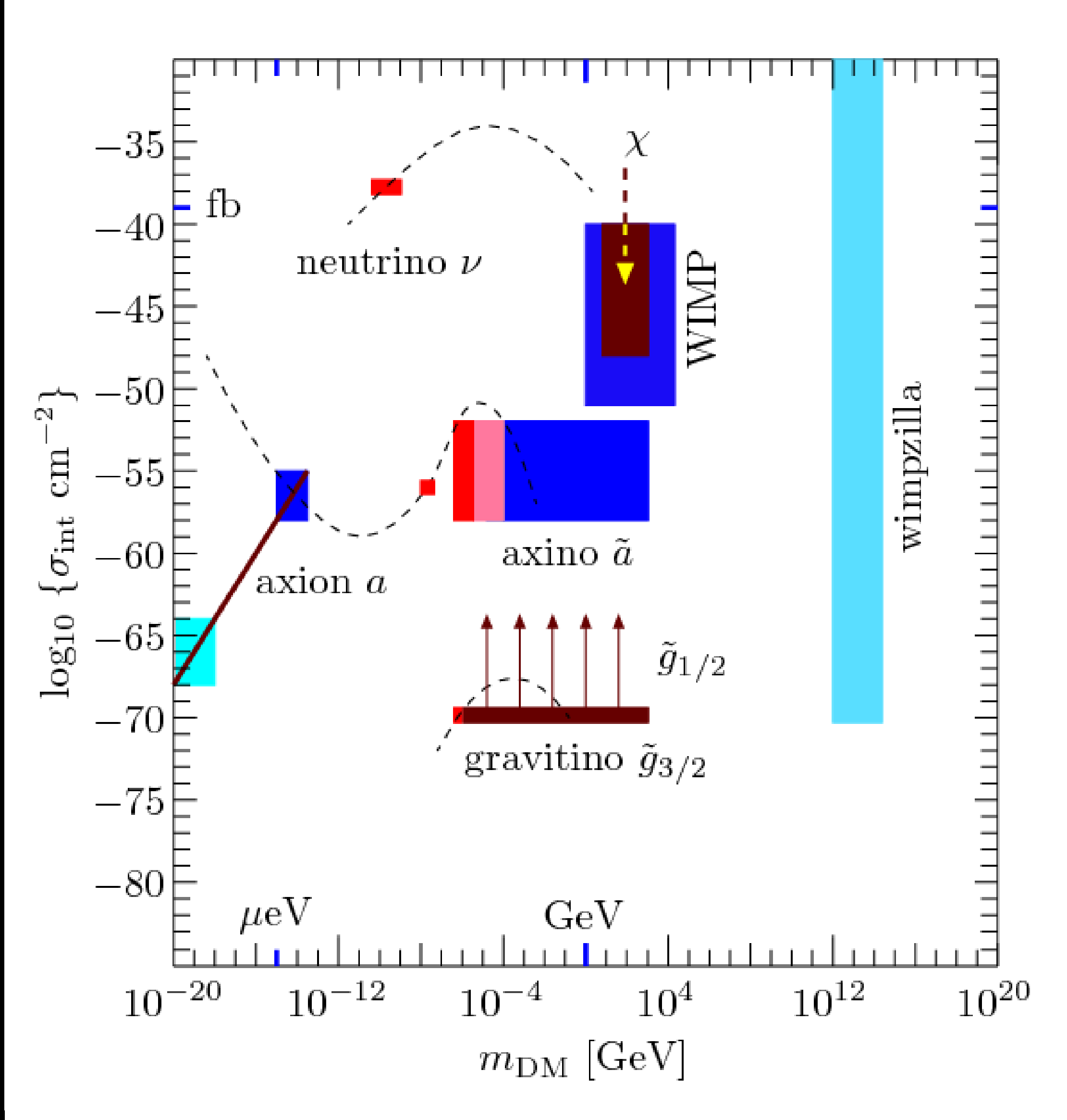
Here, I present the the general idea on axions and then focus on the phenomenology of axion and Karl will talk on the possibility of its detection.

The axion cosmic energy density has the opposite behavior from that of WIMP. It is because it is 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]

A recent calculation of the cosmic axion density is,

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

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.

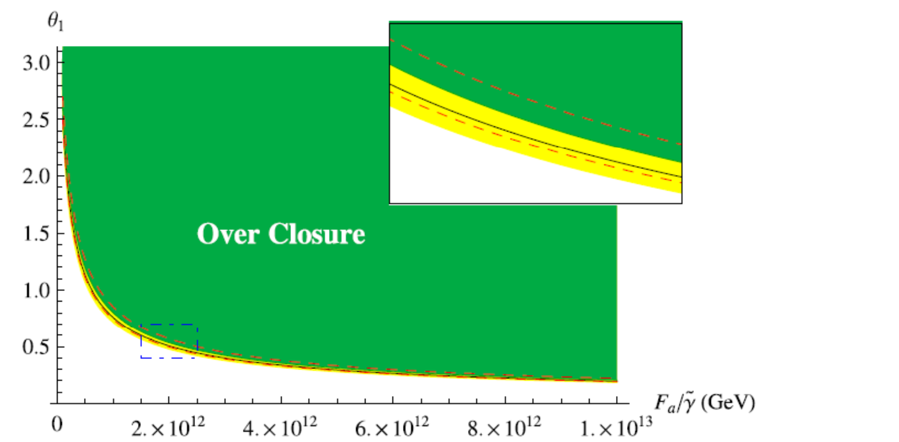
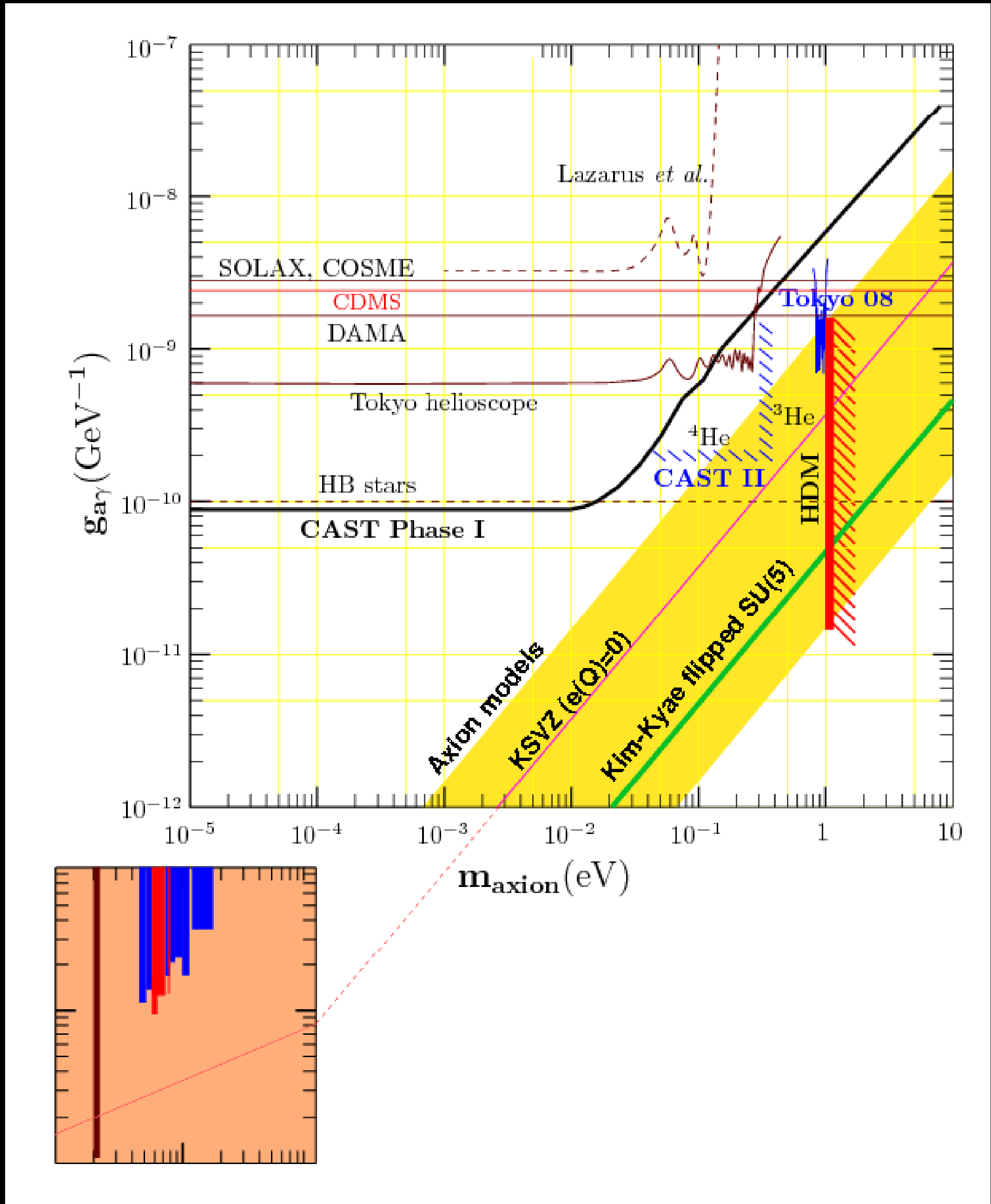


Figure 9. The bound from overclosure of the universe. The yellow band shows the error bars of Λ and two red dashed lines are the limits of the allowed current quark masses. The anharmonic effect is taken into account, including the initial correction factor of equation (15). Here, the entropy production 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



A SUSY Example

Recently, we encountered the NMSSM many times.

$$W = H_u U^c Q + H_d D^c Q + H_u H_d S + S^3$$

But this model seems to have an R symmetry. Look! However, it is broken by the gravitational effects, and there appear the A-terms, violating U(1)-R, and no problem!

$$V \supset m_{3/2}(H_u U^c Q + H_d D^c Q + H_u H_d S + S^3)$$

Then, we ask "how $m_{3/2}$ arises?" Maybe by the process of SUSY breaking? However, if it arises from spontaneous breaking when $m_{3/2}$ is generated, then there must be a Goldstone boson: R-axion.

So, the NMSSM introduced to solve the mu-problem without any dangerous light pseudoscalar has another light pseudoscalar. How do we resolve this dilemma? Most probably, in a complete theory like in a string model. String models do not have global symmetries, except MI axion.

So, approximate global symmetries are the only methods.

(1) This was explicitly studied in Z12-I orbifold model [K-Kyae, NPB 770, 47 (hep-ph/0608086)] first for the QCD axion [K.-S. Choi- I W Kim- JEK, (hep−ph/0612107)]

(2) For U(1)-R, this statement also applies. [Nilles et al., PRL 102, 121602 (2009) (arXiv:0812.2120)]
Even, a power law gauge hierarchy suggested.

In string compactification, the Yukawa couplings or superpotntial terms, including higher dimensional ones, are allowed if string superselection rules allow them. So, at the string compactification scale, there must appear U(1)-R breaking superpotential terms. These must give the R-axion a mass.

In this way, we may achieve the NMSSM objective. However, this must be stated in a specific model. Then, there are many sources contributing to the generation of mu. Introduction of S^3 as propaganded does not have a deep root at that level.

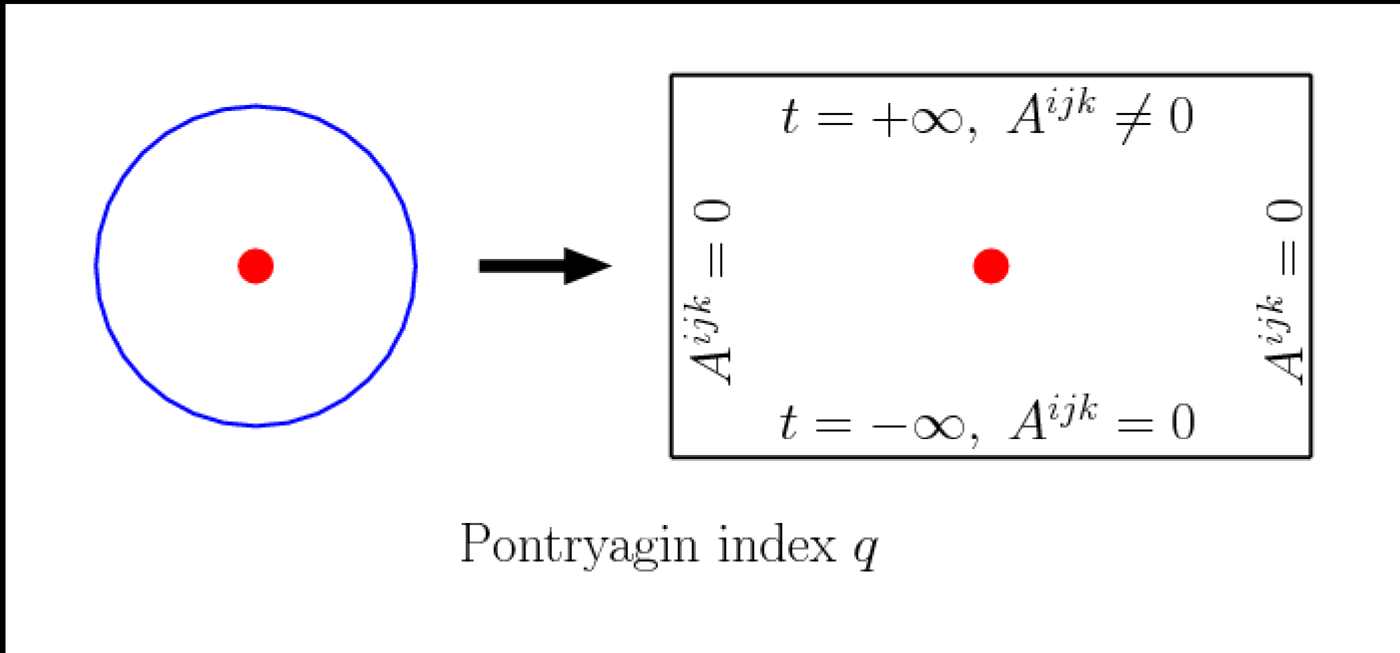
This closes an example of considering symmetries, and we move on to the discussion of axions.

2. Strong CP problem

Many considers the axion 'attractive' because it is a DM candidate.

But, axion's 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.



The arbitrary field configurations can be distinguished by the topological property, depending on its Pontryagin index. Thus, the classical vacuum can be a superposition of vacua of different Pontryagin indices. The criterion of superposition is that the vacuum is invariant under the gauge transformation. That vacuum is the so-called theta vacuum,

$$|\theta\rangle \propto \sum_{n=-\infty}^{+\infty} e^{in\theta}|n\rangle$$

The existence of instanton solution in nonabelian gauge theories needs θ vacuum [CDG, JR]. It introduces the θ term,

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

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

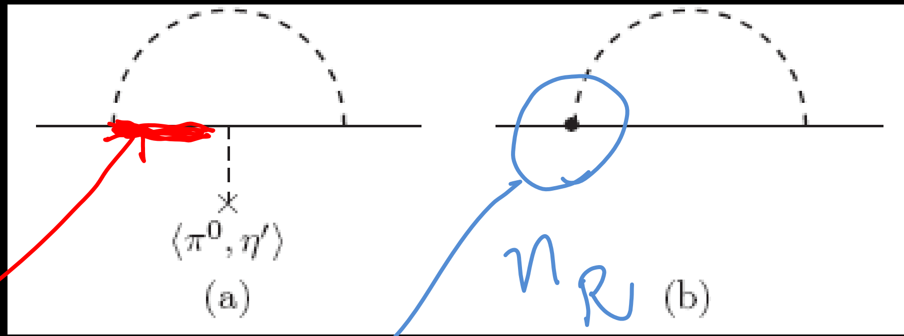
$$P: \quad G\tilde{G}\rightarrow -G\tilde{G}$$

$$T: \quad G\tilde{G}\rightarrow -G\tilde{G}$$

Here theta-bar is the final value taking into account the electroweak CP violation. For QCD to become a correct theory, this CP violation must be sufficiently suppressed.

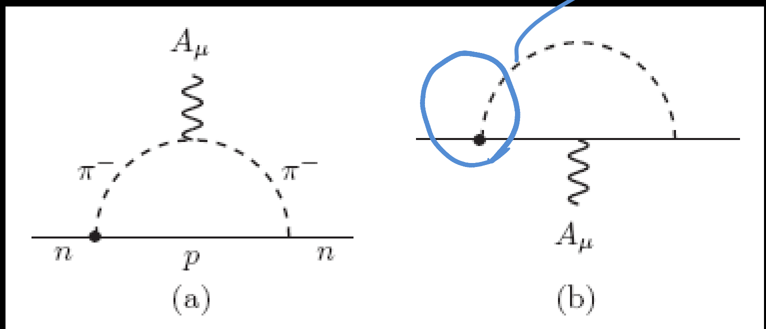
Look for the neutron mass term by CPV meson VEVs

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



CP|π[0]> = - |π[0]>

The NMDM and NEDM terms



Neutrom mass is real.

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.

If the real field pi0 have a VEV, AN OBSERVABLE CP viol. phenomenon occurs. No phase kind of thing.

$$\overline{g_{\pi NN}} = -\bar{\theta}\frac{Z}{(1+Z)} \simeq -\frac{\bar{\theta}}{3}$$

$$d_n = \frac{g_{\pi NN}\overline{g_{\pi NN}}}{4\pi^2 m_N}\ln\left(\frac{m_N}{m_\pi}\right) e\mathrm{cm}$$

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

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 (???).

Earlier attempts: Beg-Tsao, Mohapatra-Senjanovic, Georgi, Segre-Weldon, Barr-Langacker

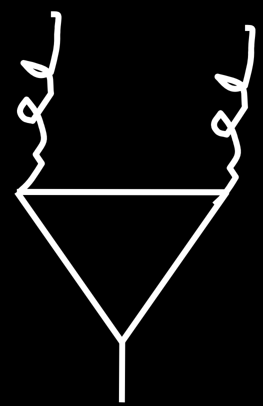
The weak CP violation must be spontaneous so that θ_0 must be 0.

2. Massless up quark

Suppose that we chiral-transform a quark,

$$q \to e^{i\gamma_5 \alpha} q: \qquad \int \left(-m\bar{q}q + \frac{\theta}{32\pi^2} G\tilde{G}\right)$$

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



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,

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

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

$$m_d = 5.1 \pm 1.5 MeV$$

(Manohar-Sachrajda)

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

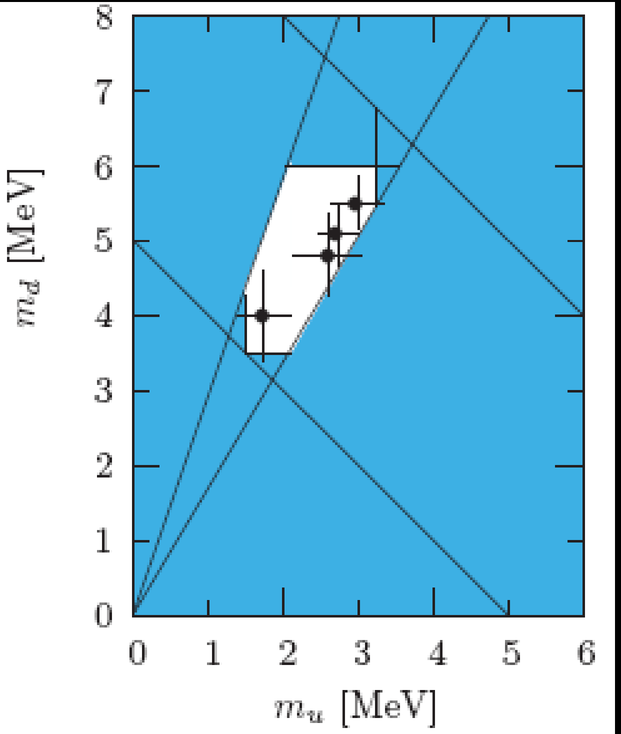


FIG. 6: The allowed $m_u - m_d$ region [265].

Particle Data (2008)

3. Axions

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

Historically, Peccei-Quinn tried to mimick the symmetry θ → θ -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,

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

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

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

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

The Lagrangian is invariant under changing $\theta \rightarrow \theta - 2\boldsymbol{\alpha}$. 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 $\langle H_u \rangle$ 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 cosθ dependence becomes the potential of the axion *a.*

If its potential is of the cosθ 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

$$\theta = 0$$

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]

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

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

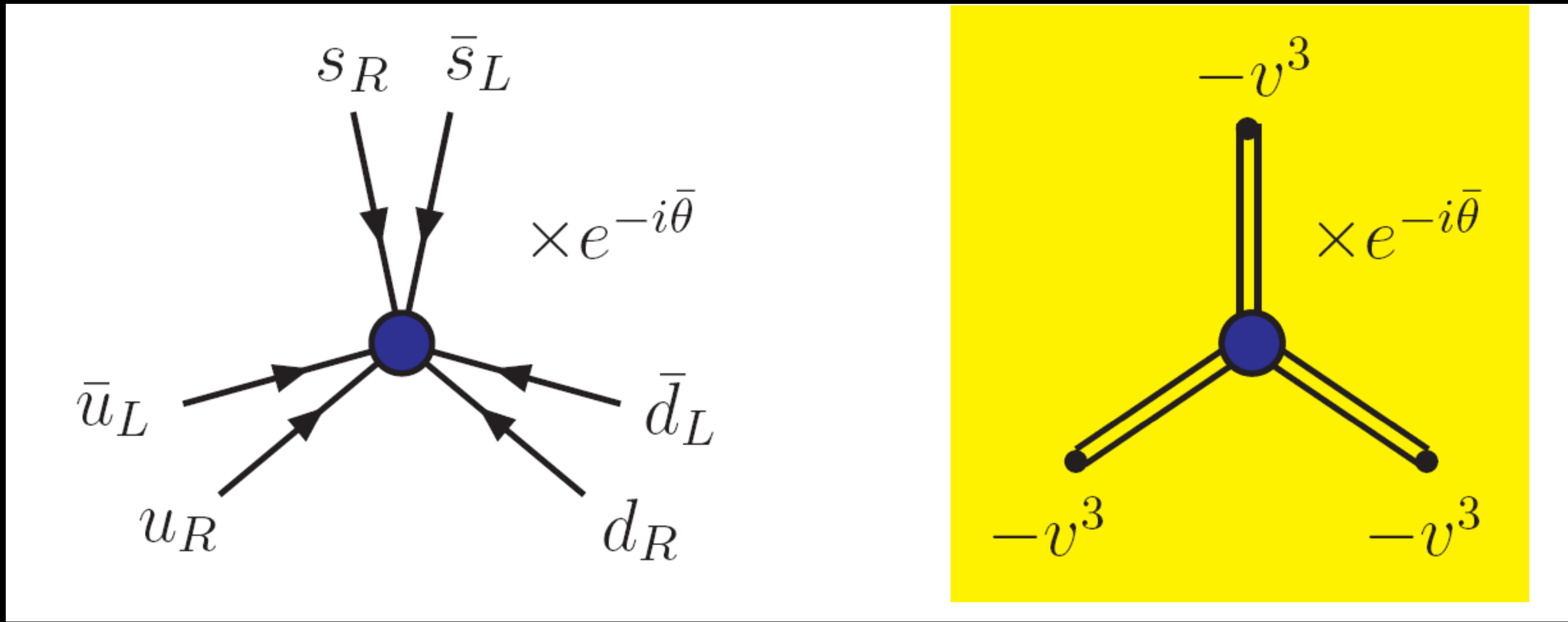
$$\mathcal{L}_\theta = \frac{1}{2} f_S^2 \partial^\mu \theta \partial_\mu \theta - \frac{1}{4g_c^2} G^a_{\mu\nu} G^{a\mu\nu} + (\bar{q}_L i \not{D}_{q_L} + \bar{q}_R i \not{D}_{q_R})$$
$$+ c_1 (\partial_\mu \theta) \bar{q} \gamma^\mu \gamma_5 q - (\bar{q}_L m q_R e^{ic_2\theta} + \text{H.c.})$$
$$+ c_3 \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} (\text{or } \mathcal{L}_{\det}) + c_{\theta\gamma\gamma} \frac{\theta}{32\pi^2} F^i_{\text{em}\,\mu\nu} \tilde{F}^{i\mu\nu}_{\text{em}}$$
$$+ \mathcal{L}_{\text{leptons},\theta}, \qquad (19)$$

$$\mathcal{L}_{\det} = -2^{-1} i c_3 \theta (-1)^{N_f} \frac{e^{-ic_3\theta}}{K^{3N_f-4}} \text{Det}(q_R \bar{q}_L) + \text{H.c.},$$

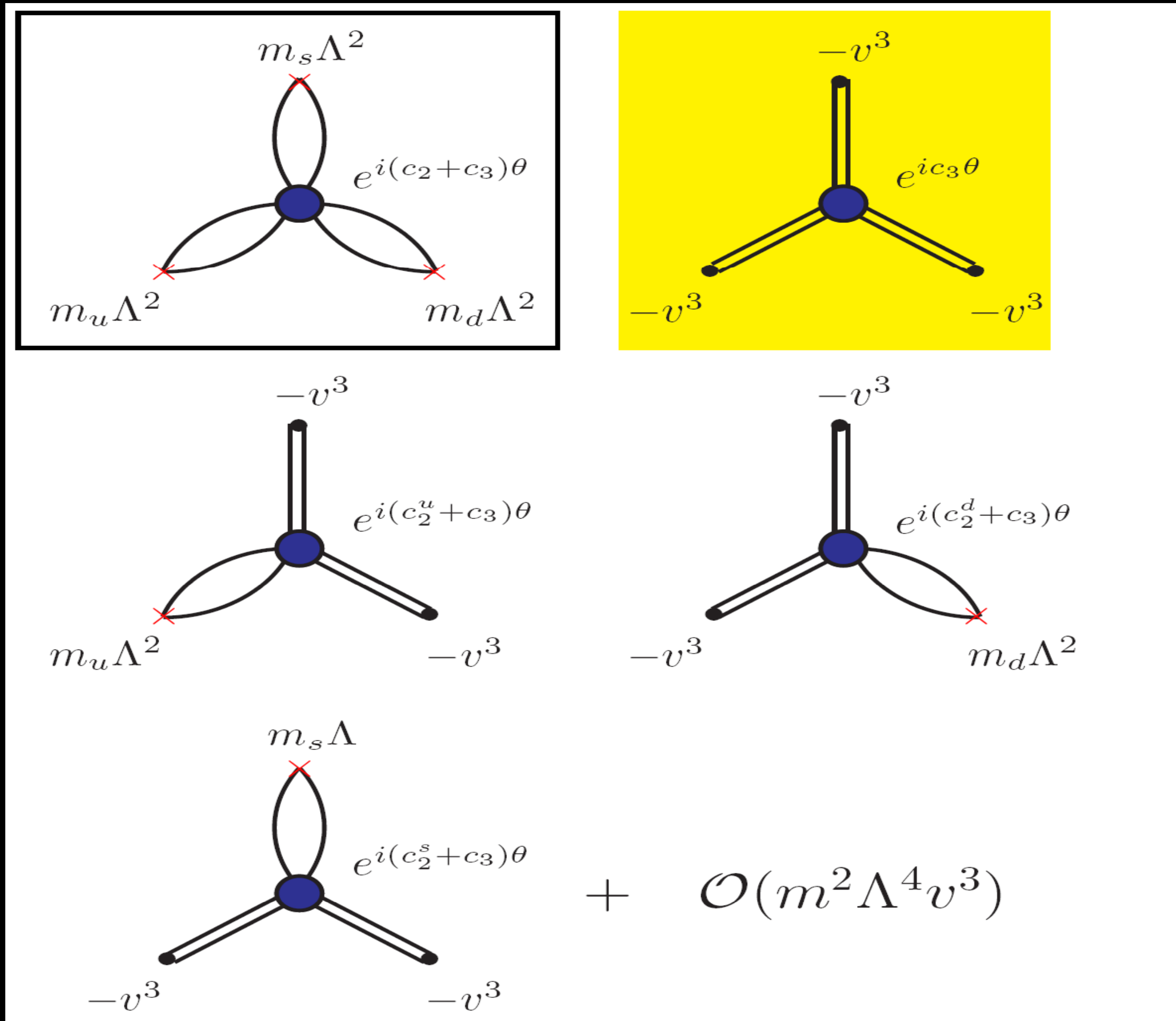
Heavy Q's are Integrated out

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

The axion mass depends only on the combination of (c_2+c_3). The 'hadronic axion' usually means $c_1=0$, $c_2=0$, $c_3 \neq 0$.



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



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

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

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

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

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

$$\Delta = \frac{m_-^2}{m_+}\,\frac{\Lambda^3_{\rm inst}(m_+v^3+\mu\Lambda^3_{\rm inst})}{m^4_{\pi^0}f_\pi^4}$$

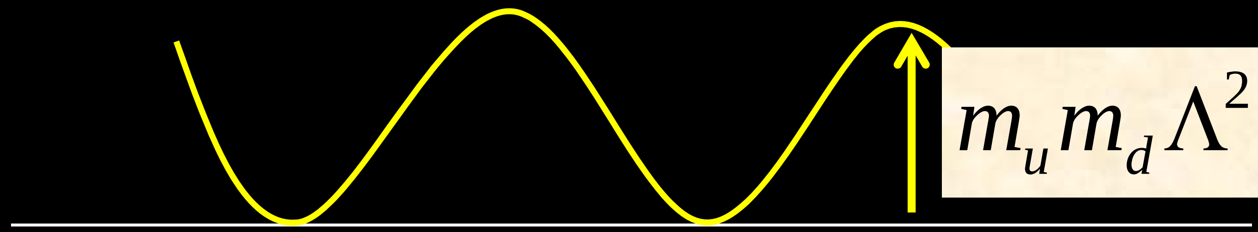
Leading to the cos form determines the axion mass

$$m_a = \frac{\sqrt{Z}}{1+Z}\frac{f_\pi m_{\pi^0}}{F_a}(1+\Delta), \qquad \cos(n\theta), \quad n \quad \text{fixed} \quad \text{by} \quad N_{DW}$$

The instanton contribution is included by Δ.

Numerically, we use

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



$$m_u m_d \Lambda^2 \leftarrow \Lambda^4$$

$$\uparrow$$

$$\bar{\theta} = 0$$

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

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.

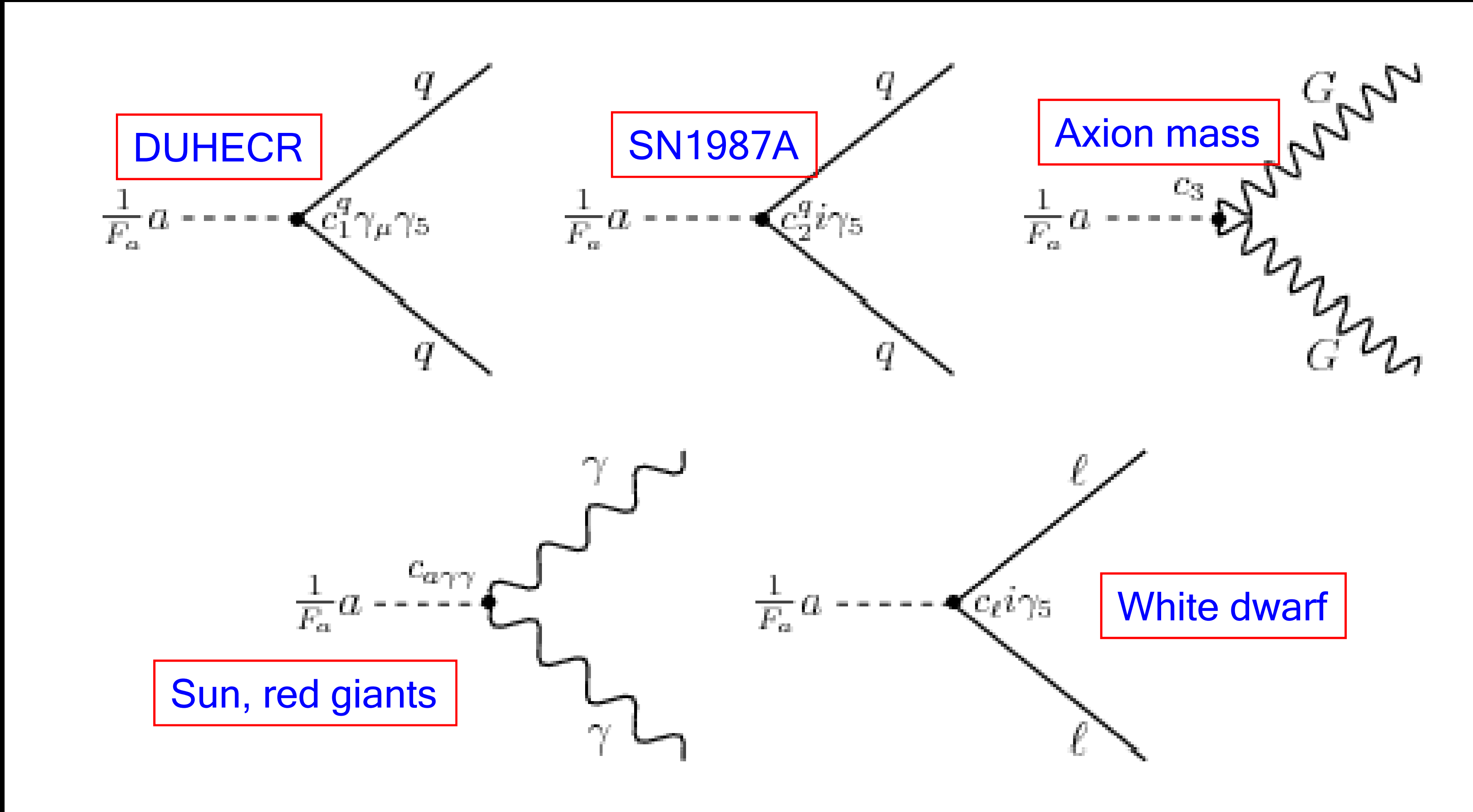
Axion couplings

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

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

PQWW: similar to DFSZ


DUHECR
SN1987A
Axion mass
Sun, red giants
White dwarf

Hadronic axion 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:

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

Axion mixing in view of hidden sector

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

[Kim, hep-ph/9811509, hep-ph/9907528]:

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 chooses the

larger condensation scale Λ_2 chooses smaller decay constant F_1,

smaller condensation scale Λ_1 chooses larger decay constant F_2.

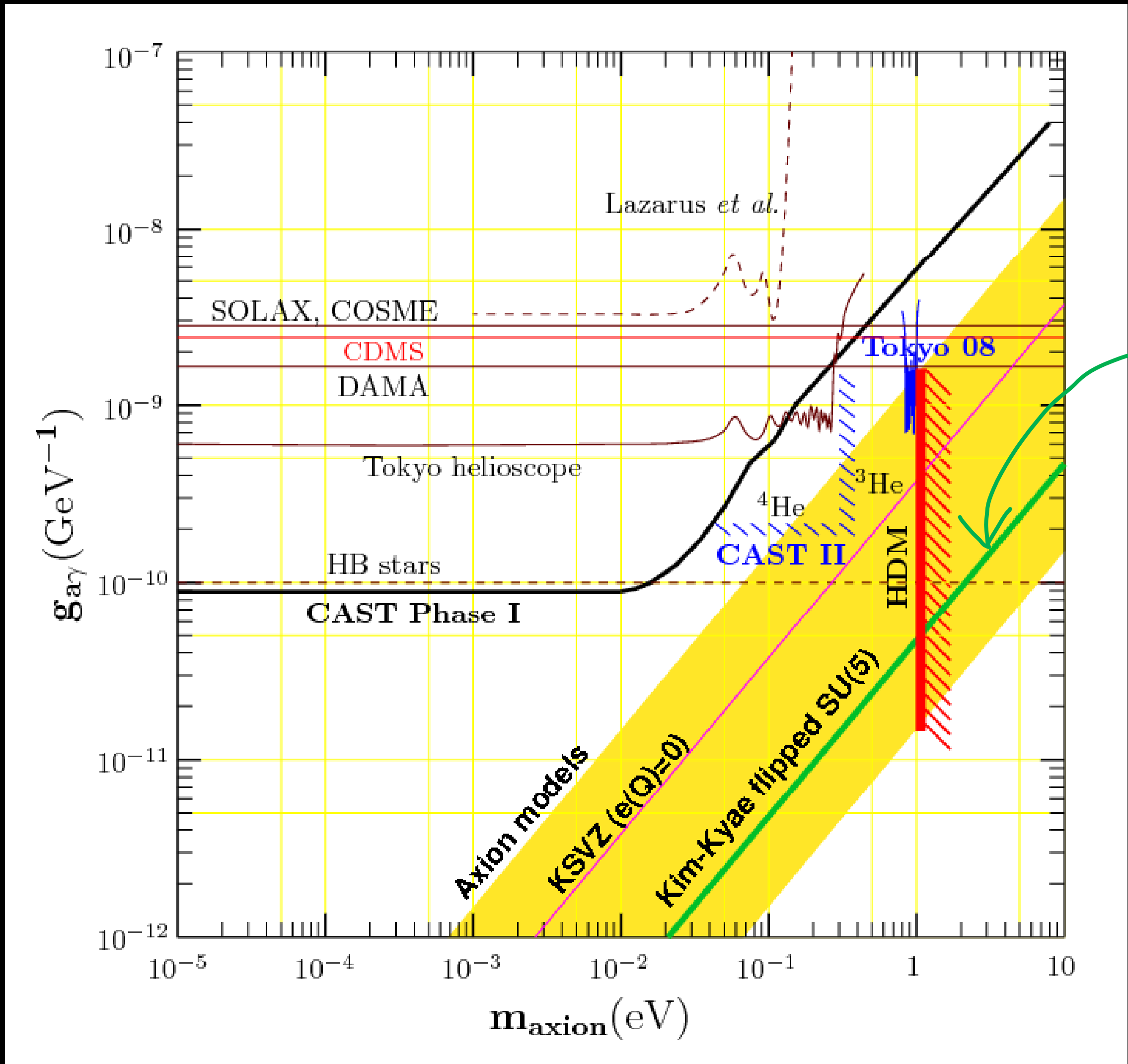
So, just obtaining a small decay constant is not enough. Hidden sector may steal the smaller decay constant. It is likely that the QCD axion chooses the larger decay constant. [See also, I.-W. Kim-K, PLB639 (2006) 342]

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 from heterotic string:

Choi-Kim-Kim, JHEP 03 (2007) 116 [hep-ph/0612107]

Choi-Nilles-RamosSanches-Vaudrevange, arXiv:0902.3070.

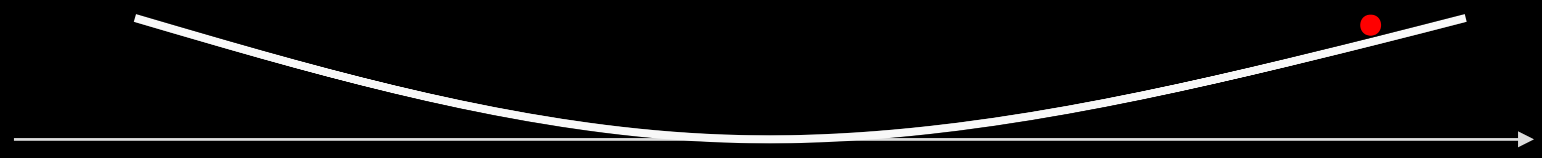


String models give definite numbers. [I-W Kim-K]

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.

The axion is created at $T=F_a$, but the universe • (<*a*>)does not roll until $3H=m_a$ ($T=0.92$ GeV [Bae-Huh-Kim]). From then, the classical field <*a*> starts to oscillate. Harmonic oscillator $m_a^2 F_a^2$ = energy density = m_a x *number density* = like CDM. See, Bae-Huh-Kim, arXiv:0806.0497 [JCAP09 (2009) 005]

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

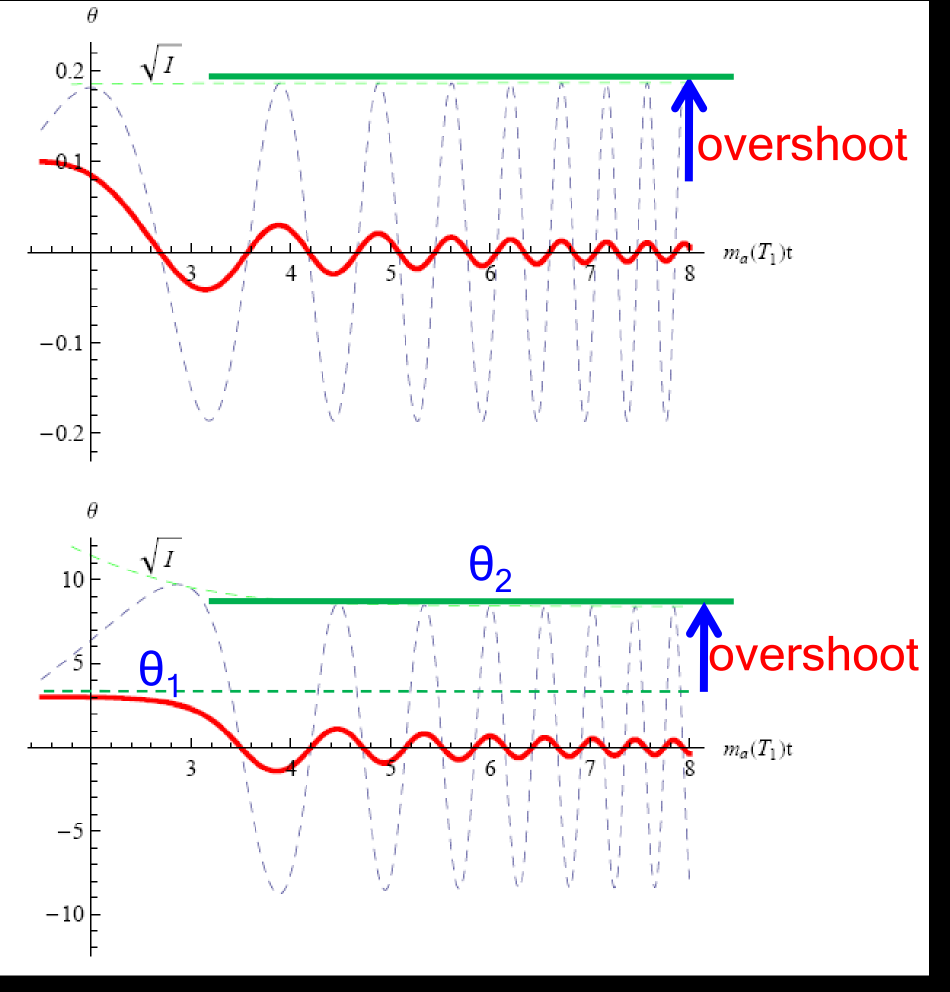
There is an overshoot factor of 1.8. So we use theta2, rather than theta1. If F_a is large(> 10^{12} GeV), then the axion energy density dominates. Since the ener gy density is proportional to the number density, it behaves like a CDM, but

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

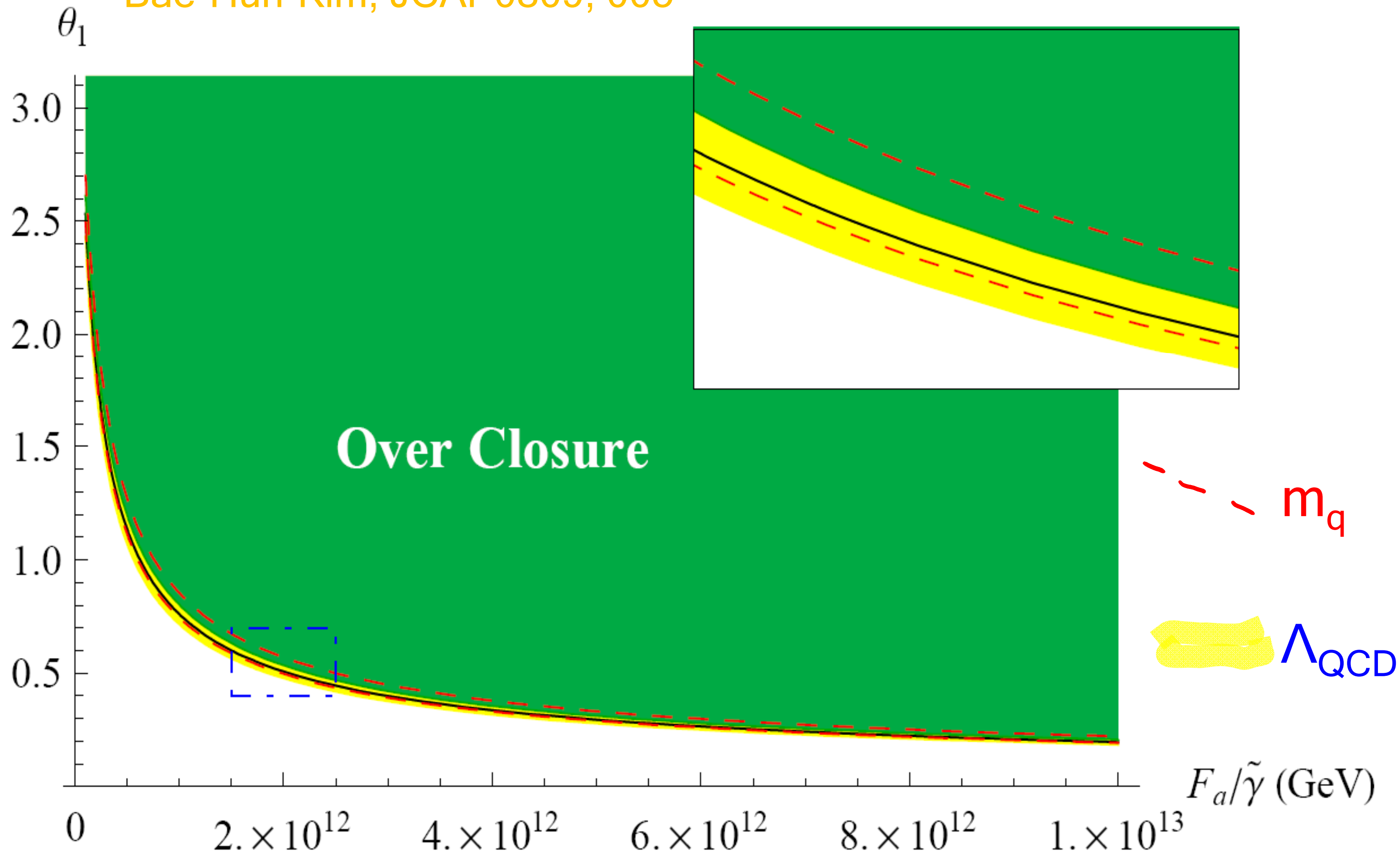
The axion field evolution eq. and time-varying Lagrangian

The adiabatic condition:

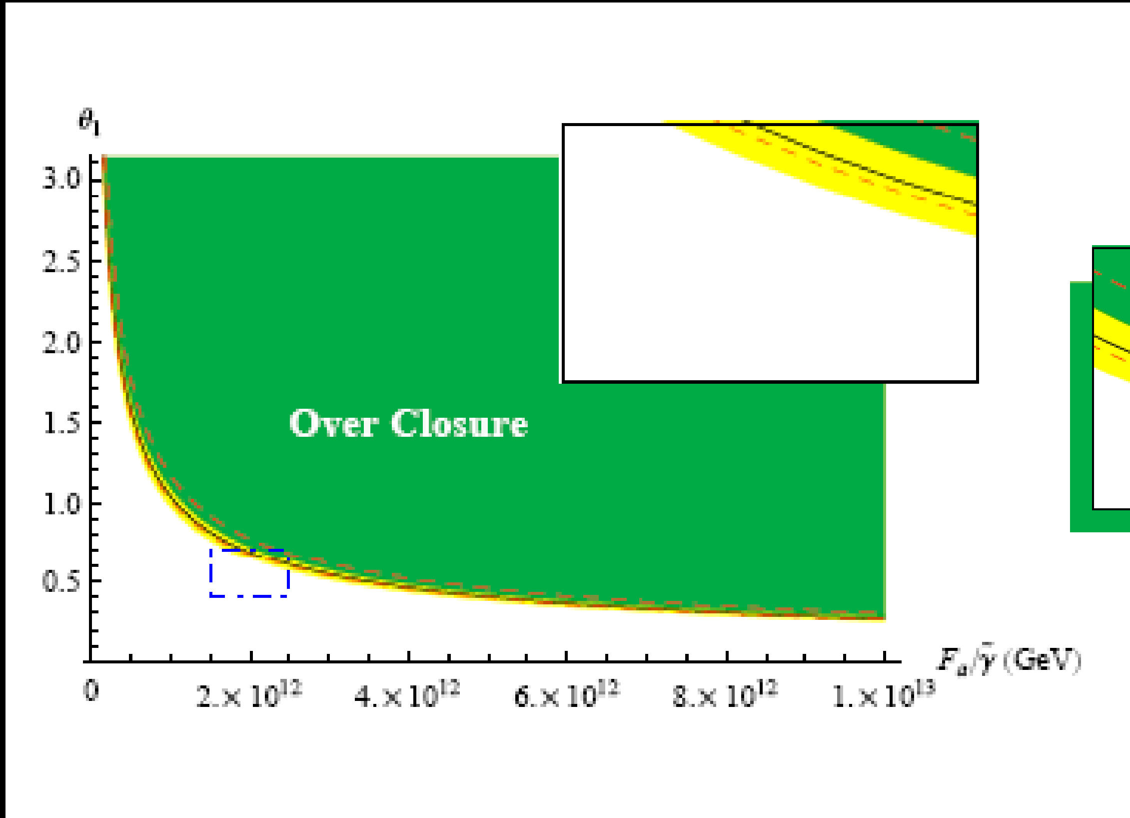
The adiabatic invariant quantity:


θ
√I
0.2
0.1
−0.1
−0.2
overshoot
3
4
5
6
7
8
$m_a(T_1)$t
θ
√I
10
5
−5
−10
θ1
θ2
overshoot
3
4
5
6
7
8
$m_a(T_1)$t

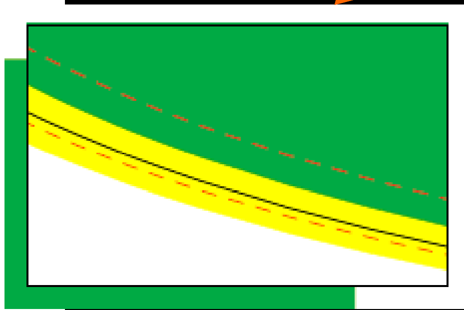
Bae-Huh-Kim, JCAP0809, 005



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



Inclusion of these showed the region, prev. figure



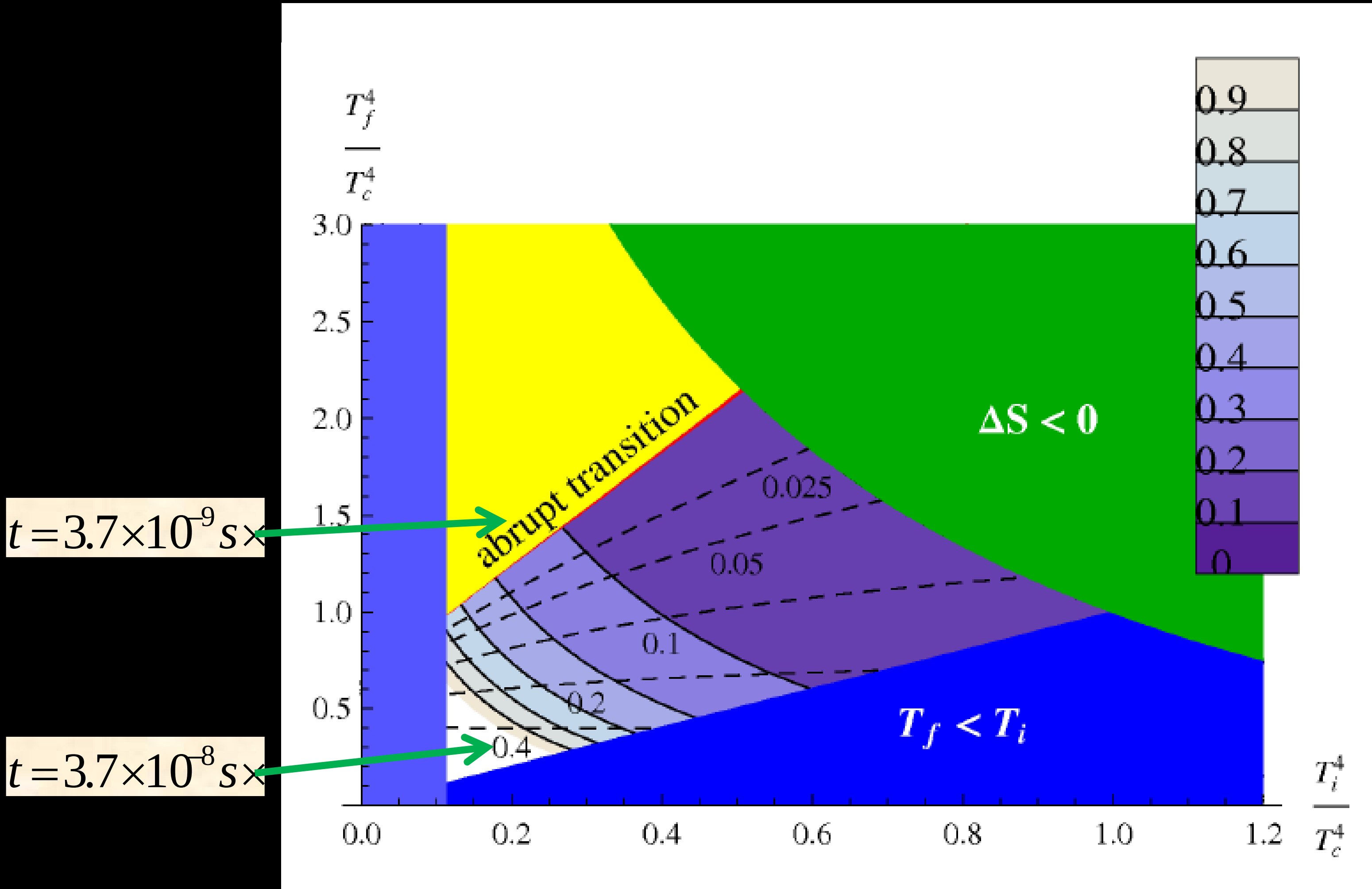
The anharmonic effect and the overshoot of roughly a factor of 1.8 (realized after a half cycle) are taken into account. Then, the axion energy fraction is given by

$$\Omega_a \cong 0.379 \times \left(\frac{m_u m_d m_s}{3 \cdot 6 \cdot 103 MeV^3} \right)^{-0.092} \left(\frac{\Lambda_{QCD}}{380 MeV} \right)^{-0.733} \left(\frac{0.701}{h} \right)^2$$

$$\times \left(\frac{\theta_1^2 F(\theta_1)}{\gamma} \right) \times \left(\frac{F_a}{10^{12} GeV} \right)^{1.184 - 0.010x}$$

$$x = \frac{\Lambda_{QCD}}{380 MeV} - 1$$

QCD phase transition effect does not change
The current axion density calculated above.



Cosmic axion search

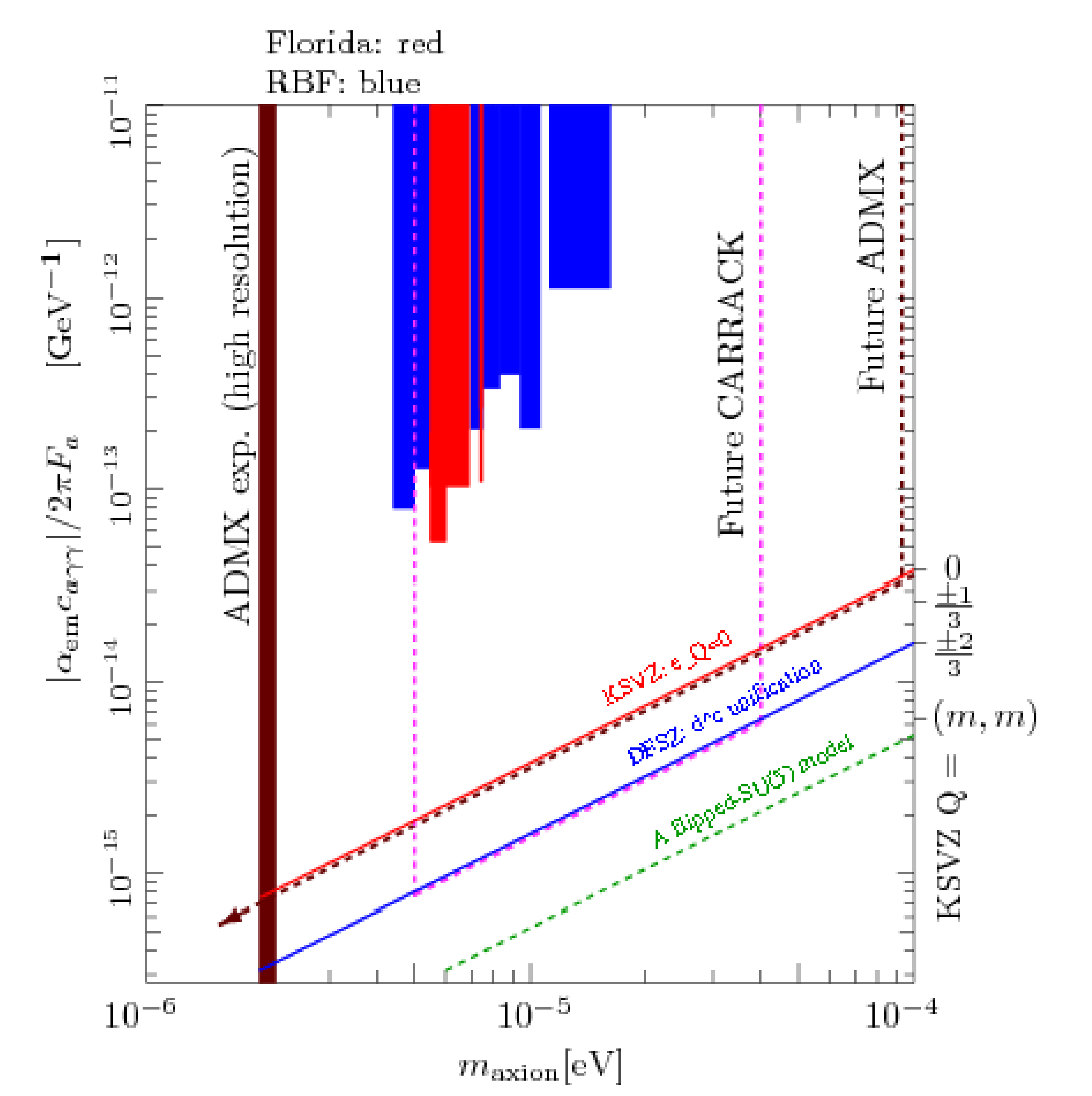
If axion is the CDM component of the universe, then they can be detected [Sikivie]. K. van Bibber's efforts. The feeble coupling can be compensated by a huge number of axions. The number density ~ F_a^2, and the cross section ~ $1/F_a^2$, and there is a hope to detect [10^{-5} eV range].

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

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

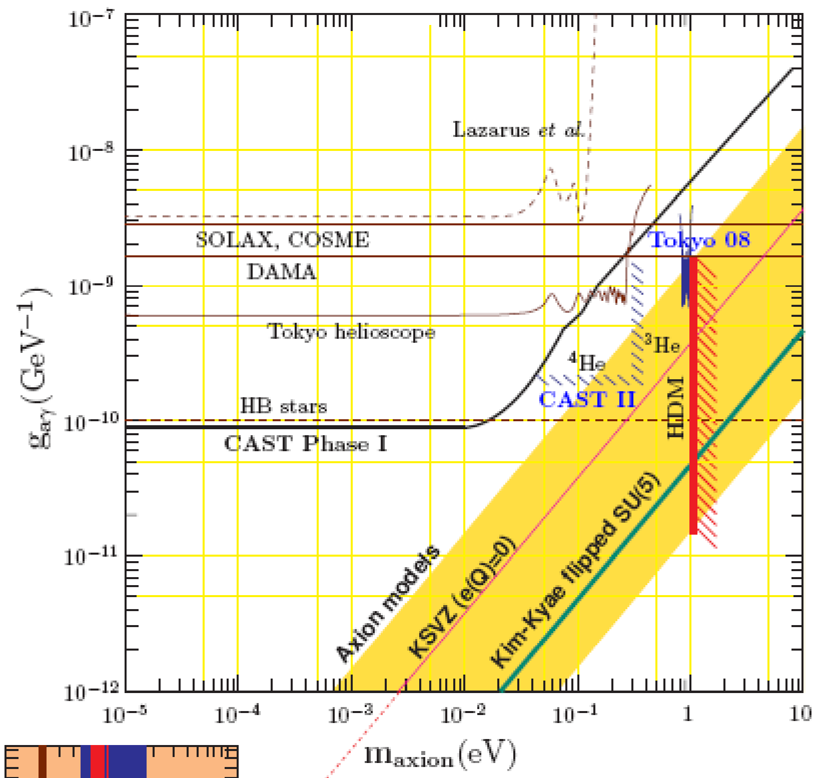
$$\bar{c}_{a\gamma\gamma} = Tr(Q_{em}^2)|_{E>>M_Z} = 0,\ \frac{8}{3}$$

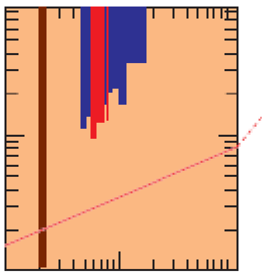
Positive for 1 HQ



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

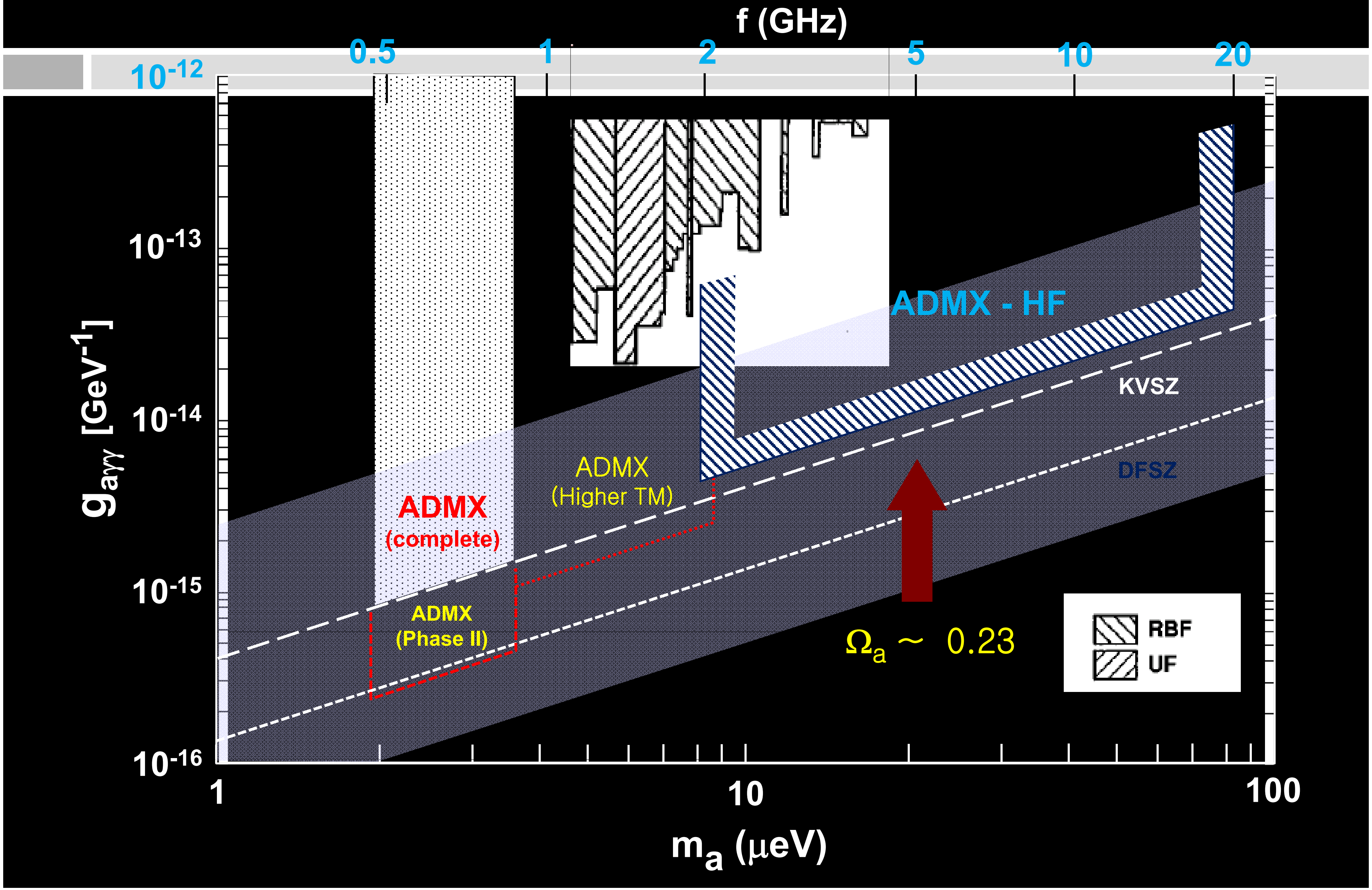
Future ADMX and CARRACK will cover the interesting region.





KSVZ		DFSZ		
$Q_{\rm em}$	$c_{a\gamma\gamma}$	$x = \tan\beta = v_u/v_d$,	same Higgs for (q^c, e) masses,	$c_{a\gamma\gamma}$
0	-1.95	any x,	(d^c, e)	0.72
$\pm\frac{1}{3}$	-1.28	any x,	(u^c, e)	-1.28
$\pm\frac{2}{3}$	0.72			
± 1	4.05			
(m, m)	-0.28			

ADMX Phase II & ADMX-HF Coverage

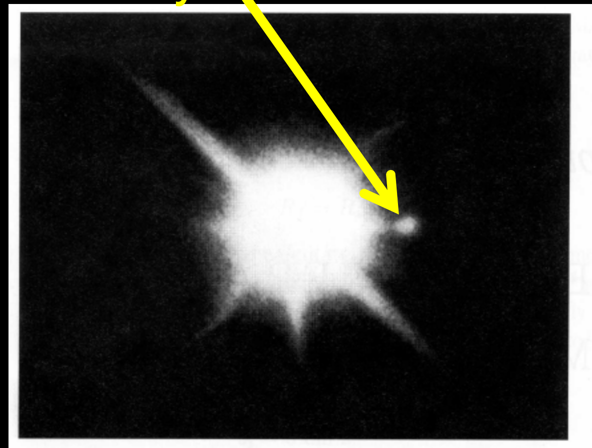


Two outer space examples

Low energy example: White dwarf energy loss

Very high energy example: Ultra High Energy
Cosmic Rays exceeding GZK bound

White dwarf axion possibility



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_{Sol}. WDs of Sun's mass have the size of Earth, and DA WDs are studied most.

The exceptionally strong pull of WD's gravity is the reason for the thin hydrogen surface of DA white dwarfs. In fact, the core of WDs follows simple physics, the degenerate fermion gas.

The Fermi energy at T=0 K is

$$\varepsilon_F = \frac{\hbar^2}{2m}(3\pi^2 n)^{2/3}$$
$$= \frac{\hbar^2}{2m}\left(3\pi^2 \frac{Z}{A}\frac{\rho}{m_H}\right)^{2/3}$$

The condition for a degenerate electron gas is

$$\frac{T}{\rho^{2/3}} < 1.3\times 10^5\, K cm^2 gr^{-2/3}$$

Sirius B: $3.6\text{x}10^3$

The pressure of the degenerate electron gas is

$$P = \frac{(3\pi^2)^{2/3}}{5}\frac{\hbar^2}{m_e}\left[\left(\frac{Z}{A}\right)\frac{\rho}{m_H}\right]^{5/3}$$

The Chandrasekhar limit

$$M_{Ch} = 1.44 M_{Sun}$$

The astronomers are able to recover the history of star formation in our Galaxy by studying the statistics of WD temperatures.

For this, the energy transport mechanism from the core is essential. Unlike in Sun, it is transported by neutrinos at high T since most electron are filling the degenerate energy levels. So, the transport mechanism is very simple. And the resulting luminosity at the surface is calculable and reliable.

$$L_{wd} = CT^{7/2}$$

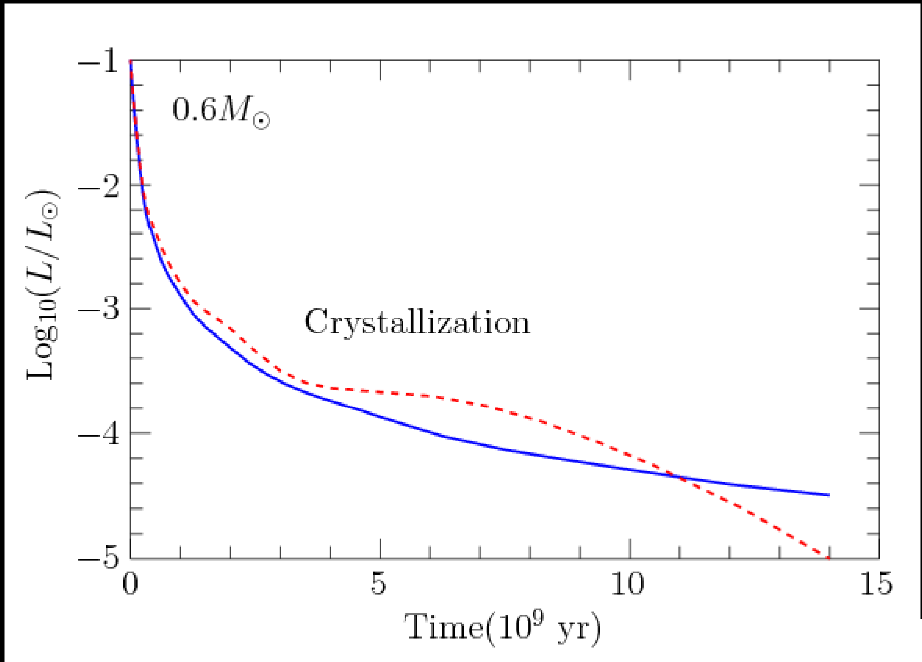
$$C = 7.3\times10^{5}\left(\frac{M_{wd}}{M_{Sun}}\right)\frac{\mu}{Z(1+X)}, \mu = av. \quad molar \quad wt.$$

The later stage of evolution is cristalization from the core. As time goes on, the luminosity drops. In terms of t,

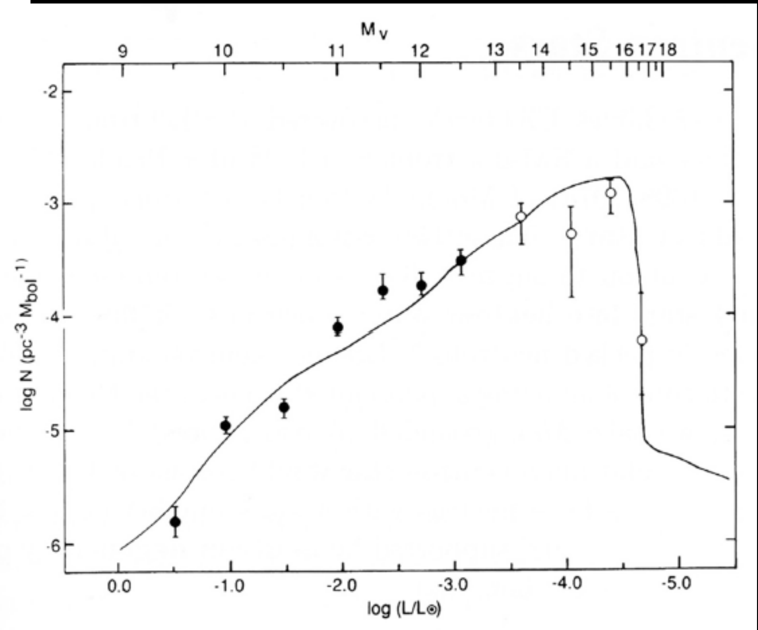
$$L_{wd} = L_0\left(1+\frac{5}{2}\frac{t}{\tau_0}\right)^{-7/5}, \qquad \tau_0 \cong 2.16\times10^{7}\, yrs$$

characteristic time of WD

A more complete treatment changes this simple behavior little bit (red dash line). With more data, Isern et al. gives a very impressive figure.



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



The energy loss in the early stage is through the photon conversion to neutrino pairs in the electron plasma.
This calculation of the photon decay 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. Kohyama et al., Ap. J. 431 (1994) 761

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

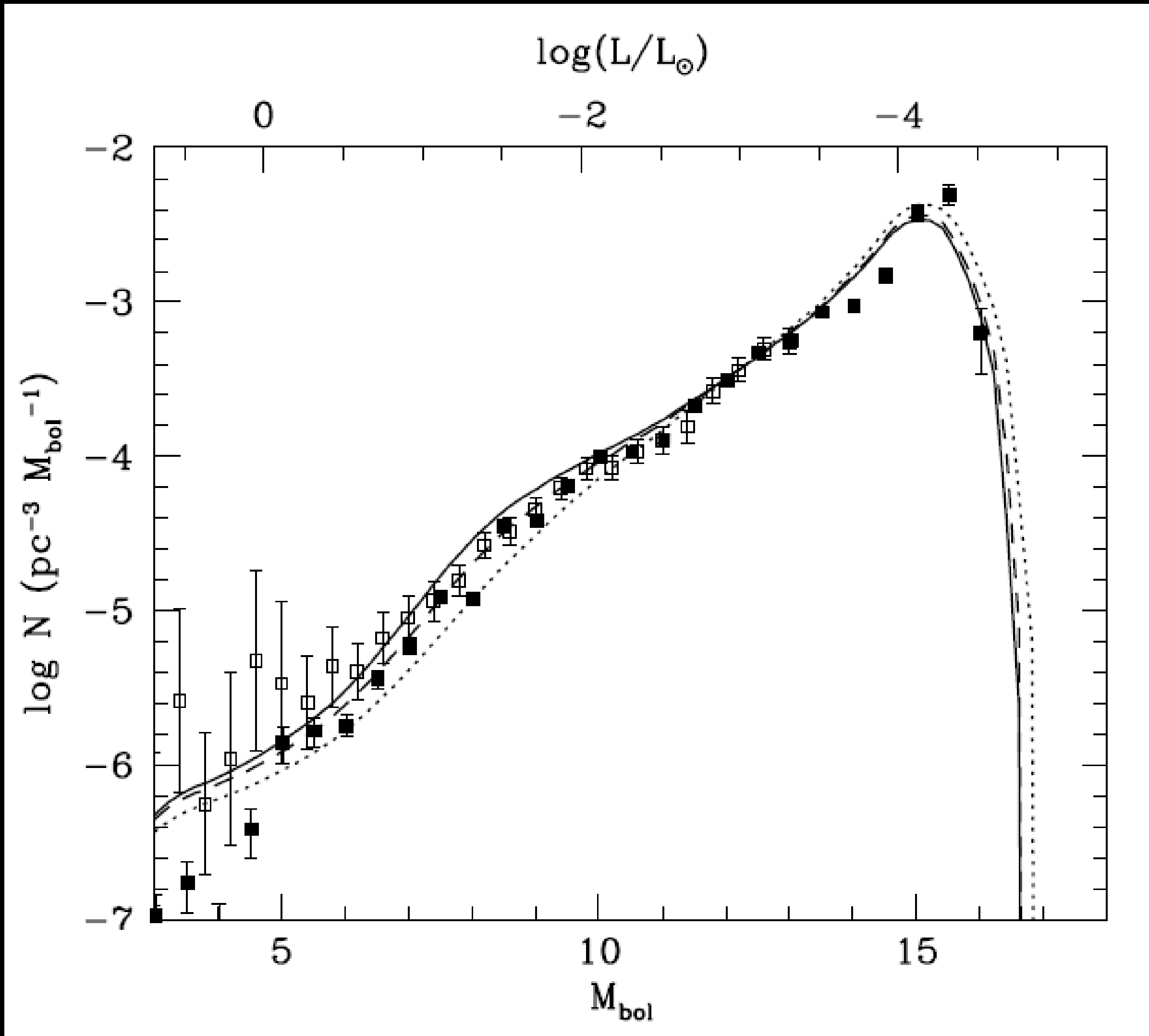


FIG. 3.— White dwarf luminosity functions for different values of the axion mass. The luminosity functions have been computed assuming $m_a \cos^2\beta = 0$ (solid line), 5 (dashed line) and 10 (dotted line) meV.

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,

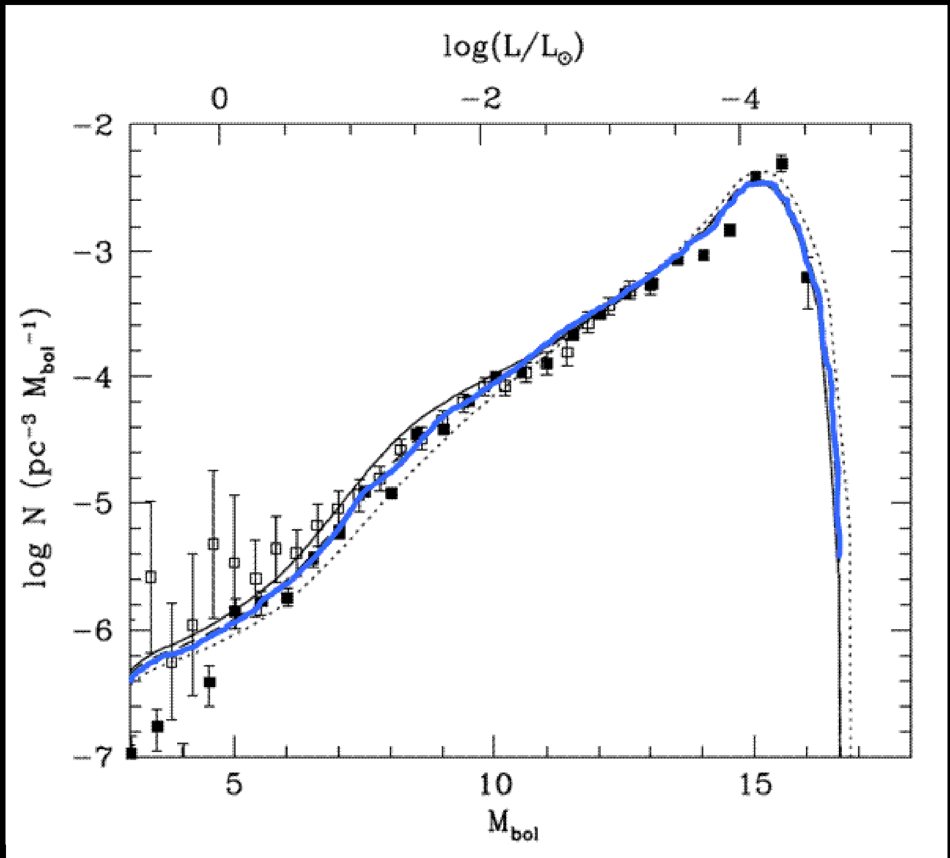
$$C_V = (e\,\nu)\ vector\ \ NC\ \ coupling \rightarrow \quad \Gamma = \frac{G_F^2\ C_V^2}{48\pi^2\alpha_{em}}Z_{T,L}\frac{\left(\omega_{T,L}^2 - \vec{p}_{plasmon}^{\,2}\right)^3}{\omega_{T,L}}$$

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

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

The neutrino magnetic moment possibility is out in the SM.

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.



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

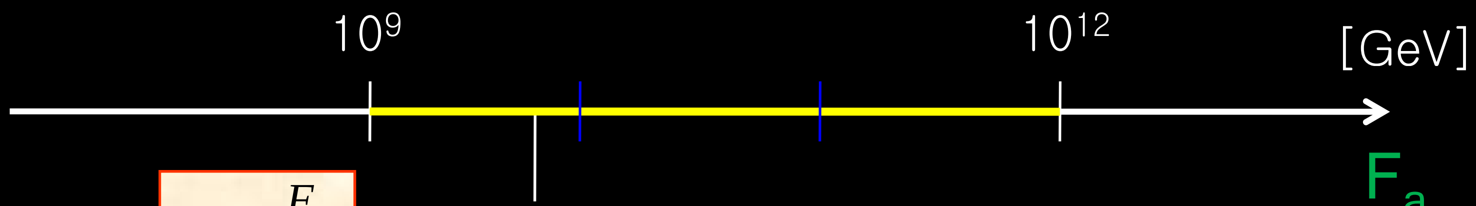
$$\left|\frac{m_e\Gamma(e)}{F}\right| = \frac{m_e}{0.72\times 10^{10}\,GeV} \cong 0.7\times 10^{-13} : any \quad axion \quad model$$

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

So, the axion-electron coupling has the form,

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

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 $N_{DW}=1/2$.



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

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.

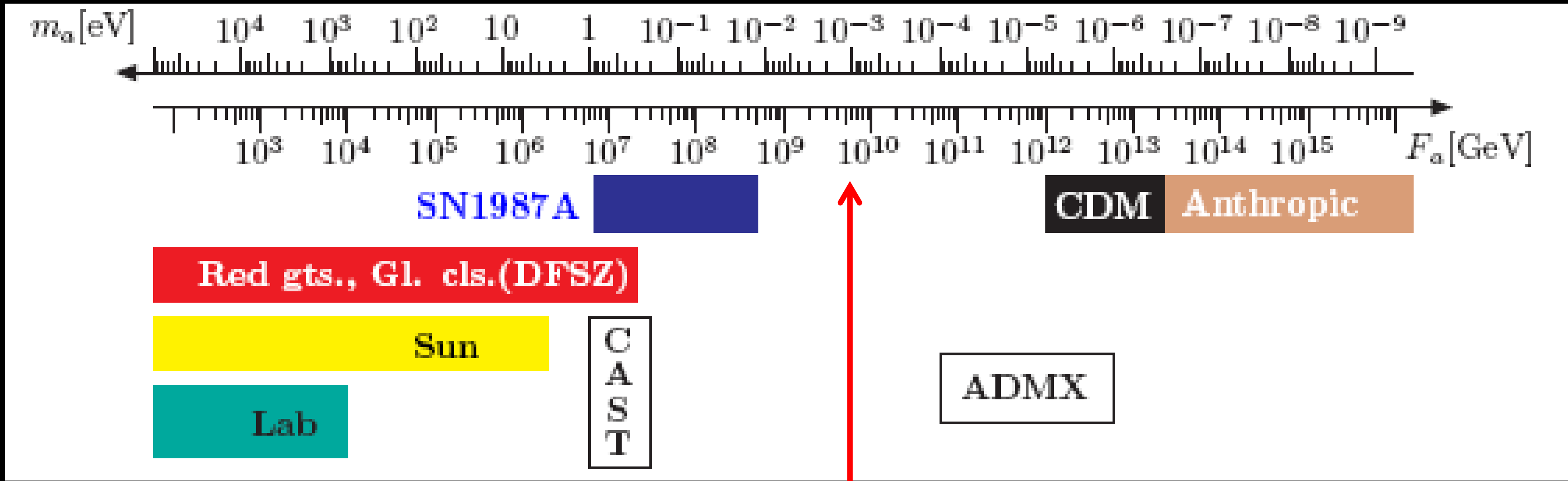
If it is done by the phase of a singlet scalar S, presumably the PQ charges of the SM quark fields must be odd such that sum of the PQ charges of all the quarks(including heavy ones) be 1. But sum of the PQ charges of e_{2L} and e_R is 2. Then we obtain N_{DW} =1/2. Because our objective is the quark-lepton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

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 and e_R can be a singlet.



White dwarf bound
(1st hint at the center of the axion window)

Is the window of hadronic axion still open?

$0.06 \text{ eV} < m_a < 0.6 \text{ eV}$
[Raffelt-Deabon, 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]

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

Conclusion

I discussed CP, weak and strong, and axion with related issues.

1. Solutions of the strong CP problem :

   Nelson-Barr, *m_u=0 ruled out now*, axion.

2. Axions can be detected by cavity experiments. Most exciting is, its discovery confirms instanton physics of QCD by experiments.

3. Cosmology and astrophysics give bounds on the axion parameters. Maybe, axions are coming out from WD cooling process and DUHECRs. It is the first hint, in the middle of

   the axion window. A specific variant very light axion

   model has been constructed for N_{DW}=1/2 for WD E loss mech.

4. With SUSY extension, O(GeV) axino can be CDM or decaying axino to CDM.