The Strong CP Problem and Axions

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- The $U(1)_A$ Problem of QCD
- The ‘t Hooft Solution
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The $U(1)_A$ Problem of QCD

- In the 1970's the strong interactions had a puzzling problem, which became particularly clear with the development of QCD.
- The QCD Lagrangian for N flavors

$$L_{QCD} = -1/4 F_a^{\mu\nu} F_{a\mu\nu} - \Sigma_f\ \bar{q}_f (-i\gamma^\mu D_\mu + m_f)\, q_f$$

in the limit $m_f \to 0$ has a large global symmetry: $U(N)_V \times U(N)_A$

$$q_f \to [e^{i\alpha_a T_a/2}]_{ff'}\, q_{f'}\ ;\ q_f \to [e^{i\alpha_a T_a \gamma_5/2}]_{ff'}\, q_{f'}$$

Vector Axial

- Since $m_u, m_d << \Lambda_{QCD}$, for these quarks the $m_f \to 0$ limit is sensible. Thus one expect strong interactions to be approximately $U(2)_V x\ U(2)_A$ invariant.

- Indeed, one knows experimentally that

$$U(2)_V = SU(2)_V \times U(1)_V \equiv \text{Isospin x Baryon \#}$$

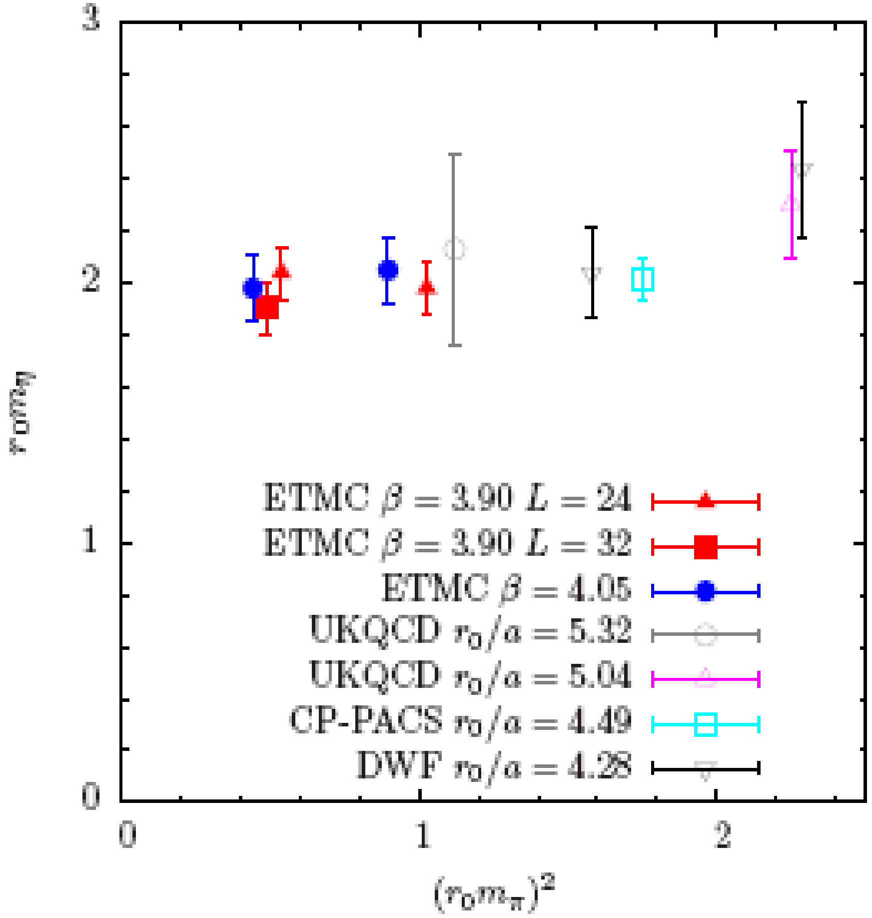
is a good approximate symmetry of nature

$\Rightarrow$ (p, n) and $(\pi^{\pm}, \pi^{\circ})$ multiplets in spectrum

- For axial symmetries, however, things are different. Dynamically, quark condensates $<\bar{u}u>=<\bar{d}d>\neq 0$ form and break $U(2)_A$ down spontaneously and, as a result, there are no mixed parity multiplets

- However, because $U(2)_A$ is a spontaneously broken symmetry, one expects now the appearance in the spectrum of approximate Nambu-Goldstone bosons, with $m \approx 0$ [$m \to 0$ as $m_u, m_d \to 0$]
- For $U(2)_A$ one expects 4 such bosons (π, η). Although pions are light, $m_\pi \approx 0$, there is no sign of another light state in the hadronic spectrum, since $m^2_\eta >> m^2_\pi$.
- Weinberg dubbed this the $U(1)_A$ problem and suggested that, somehow, there was no $U(1)_A$ symmetry in the strong interactions

That there is no $U(1)_A$ symmetry emerges explicitly in lattice QCD calculations, which show that indeed, as $m_\pi \to 0$, $m_\eta \to$ constant



(b) The η_2 mass (the analogue of the η' mass for two flavours of quarks) as a function of the pseudo scalar mass. The flatness in the mass dependence allows an estimate at the physical point of $\eta_2 \approx 865$MeV.

- It is useful to describe the $U(1)_A$ problem in the language of Chiral Perturbation Theory, which describes the QCD dynamics for the (π, η)- sector
- The effective Chiral Lagrangian needs to be augmented by an additional term which breaks explicitly $U(1)_A$, beyond the breaking term induced by the quark mass terms.
- Defining $\Sigma = \exp i/F_\pi [\tau_a \pi_a + \eta]$ and including a symmetry breaking pion mass $m^2_\pi \sim (m_u + m_d)$ one has:

$$L_{eff} = \tfrac{1}{4} F^2_\pi \, \mathrm{Tr}\, \partial_\mu \Sigma\, \partial^\mu \Sigma^\dagger + \tfrac{1}{4} F^2_\pi \, m^2_\pi \, \mathrm{Tr}\, (\Sigma + \Sigma^\dagger) - \tfrac{1}{2} M^2_o \, \eta^2$$

- Provided $M^2_o >> m^2_\pi$ this allows $m^2_\eta >> m^2_\pi$, but what is the origin of this last term?

The ‘t Hooft Solution

- The resolution of the $U(1)_A$ problem is due to ‘t Hooft who realized the crucial dynamical role played by the gluon pseudoscalar density

$$Q = \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

- Even though in the massless quark limit $U(1)_A$ is an apparent symmetry of the QCD Lagrangian , the current J^μ_5 associated with the $U(1)_A$ symmetry is anomalous [Adler Bell Jackiw]

$$\partial_\mu J_5^\mu = \frac{g^2 N}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu} = N\,Q$$

where N is the number of massless quarks

- Since Q enters in the anomaly equation, if it is dynamically important the $U(1)_A$ problem should be resolved, because then there is really no conserved $U(1)_A$ current
- This can be checked by explicitly including Q in the Chiral Lagrangian describing the low energy behavior of QCD [Di Vecchia Veneziano]
- Taking into account the anomaly in the $U_A(1)$ current and keeping terms up to $O(Q^2)$ one has:

$$L_{eff} = \tfrac{1}{4}F^2_\pi \, \mathrm{Tr}\, \partial_\mu\Sigma \, \partial^\mu\Sigma^\dagger + \tfrac{1}{4}F^2_\pi \, m^2_\pi \, \mathrm{Tr}\, (\Sigma + \Sigma^\dagger) \\ + \tfrac{1}{2}\, i \, Q \, \mathrm{Tr}\, [\ln \Sigma - \ln \Sigma^\dagger] + [1/ F^2_\pi M^2_o] \, Q^2 + \ldots$$

- In this Lagrangian, Q is essentially a background field and can be eliminated through its equation of motion:

$$Q = -i/4 \, [F^2_\pi M^2_o] \, \mathrm{Tr}\, [\ln \Sigma - \ln \Sigma^\dagger] = \tfrac{1}{2} \, [F_\pi M^2_o] \, \eta + \ldots$$

- Using this result for Q, the last two terms in L_{eff} reduce to:

  $$\tfrac{1}{2}\, i\, Q\, \mathrm{Tr}\, [\ln \Sigma - \ln \Sigma^{\dagger}] + [1/ F^2_{\pi} M^2_o]\, Q^2 \rightarrow -\tfrac{1}{2} M^2_o\, \eta^2$$

  providing an effective gluonic mass term for the η meson, and thus resolving the $U_A(1)$ problem
- Although one can see directly from the Chiral Lagrangian how the dynamical role of Q removes an apparent Nambu Goldstone boson (the η) from the spectrum, this follows also directly from QCD
- It can be traced to the non trivial properties of the QCD vacuum which involve a new dimensionless parameter – the vacuum angle θ [‘t Hooft]
- I’ll sketch below the principal points

- Because the integral of Q is a topological invariant:

$$\nu = \int d^4x\, Q = \int \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu} \quad \text{with } \nu = 0, \pm 1, \pm 2, \ldots,$$

all transition amplitudes in QCD contain sums over distinct sectors characterized by the winding number ν.

- The contributions of the $\nu \neq 0$ sectors break the $U(1)_A$ symmetry
- Furthermore, one can show that gauge invariance introduces a parameter θ associated with the sum over the distinct ν sectors in the QCD transition amplitudes [$e^{i\nu\theta}$ is Bloch phase]

$$A = \Sigma_\nu\, e^{i\nu\theta} A_\nu$$

- The parameter θ can be connected with the structure of the QCD vacuum and its presence gives an additional contribution to the QCD Lagrangian

- This can be seen as follows. In the case of QCD, by having to sum over the distinct ν sectors, the usual path-integral representation for the vacuum-vacuum transition amplitude is modified to read:

$$_{+}\langle vac|vac\rangle_{-} = \Sigma_{\nu}\, e^{i\nu\theta} \int \delta A\, e^{i S[A]}\, \delta\Big(\nu - \int \frac{g^{2}}{32\pi^{2}} F_{a}^{\mu\nu}\tilde{F}_{a\mu\nu} \Big)$$

- Denoting the QCD vacuum as $|\,\theta>$, one can re-interpret the θ term in the sum over ν as an addition to the usual QCD action
- That is:

$$_{+}<\theta\,|\,\theta>_{-} = \sum_{\nu}\int \delta A e^{iS_{eff}[A]}\delta(\nu - \frac{g^{2}}{32\pi^{2}}\int d^{4}x F_{a}^{\mu\nu}\tilde{F}_{a\mu\nu})$$

where

$$S_{eff} = S_{QCD} + \theta\frac{g^{2}}{32\pi^{2}}\int d^{4}x F_{a}^{\mu\nu}\tilde{F}_{a\mu\nu}$$

The Strong CP Problem and its Resolution

- The resolution of the $U(1)_A$ problem, however, engenders another problem: the strong CP problem
- As we have seen, effectively the QCD vacuum structure adds and extra term to L_{QCD}

$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \widetilde{F}_{a\mu\nu}$$

This term conserves C but violates P and T, and thus it also violates CP

- This is problematic, as there is no evidence of CP violation in the strong interactions!

- In fact, the θ term produces an electric dipole moment for the neutron of order:

$$d_n \approx e\, m_q/M_n^2\, \theta \approx 10^{-16}\, \theta \text{ ecm}$$

- The strong experimental bound $d_n < 2.9 \times 10^{-26}$ ecm requires the angle θ to be very small $\theta < 10^{-9} - 10^{-10}$ [Baluni; Crewther Di Vecchia Veneziano Witten].
- Why θ should be this small is the strong CP problem
- Problem is actually worse if one considers the effect of chiral transformations on the θ-vacuum
- Because of the chiral anomaly, these transformations change the θ-vacuum [Jackiw Rebbi]:

$$e^{i\alpha Q_5} \,|\, \theta > = |\, \theta + \alpha >$$

- If besides QCD one includes the weak interactions, in general the quark mass matrix is non-diagonal and complex

$$L_{Mass} = - \bar{q}_{iR} M_{ij} q_{jL} + h.\,c.$$

- To diagonalize M one must, among other things, perform a chiral transformation by an angle of Arg det M which, because of the Jackiw Rebbi result, changes θ into

$$\theta_{total} = \theta + \text{Arg det M}$$

- Thus, in full generality, the strong CP problem can be stated as follows: why is the angle θ_{total} , coming from the strong and weak interactions, so small?

- There are only three known classes of solutions to the strong CP problem:

i. Anthropically θ_{total} is small

ii. CP is broken spontaneously and the induced θ_{total} is small

iii. A chiral symmetry drives $\theta_{total} \to 0$

- I will make no comments on i
- Although ii. is interesting, the models which lead to $\theta_{total} \approx 10^{-10}$ are rather complex and often are at odds with the CKM paradigm and/or cosmology
- In my opinion, only iii. is a viable solution, although it necessitates introducing a new global, spontaneously broken, chiral symmetry

- Helen Quinn and I proposed the first prototype chiral solution [38 years ago!] suggesting that the SM had an additional U(1) chiral symmetry (now called $U(1)_{PQ}$) which drives $\theta_{total} \to 0$
- Very recently 4 other variant chiral solutions have been proposed:
  - Hook and independently Fukuda Harigaya Ibe Yanagida use a Z_2 symmetry which takes SM <-> SM’ and an anomalous U(1) symmetry to drive $\theta_{total} \to 0$
  - Ahn uses a flavored version of $U(1)_{PQ}$ [A_4 x $U(1)_{PQ}$] to accomplish the same
  - Kawasaki Yamada Yanagida use instead [SU(3)x $U(1)_{PQ}$] as a flavor group
- These are all very natural solutions to the strong CP problem, since chirality effectively rotates the θ -vacua away:

$$e^{-i\,\theta Q_5}\,|\,\theta > = |\,0 >$$

- Of course, in principle, this additional chiral symmetry could be intrinsic to QCD, if the u-quark had no mass, $m_u = 0$ [Kaplan Manohar]. However, calculations on the lattice exclude the $m_u = 0$ solution

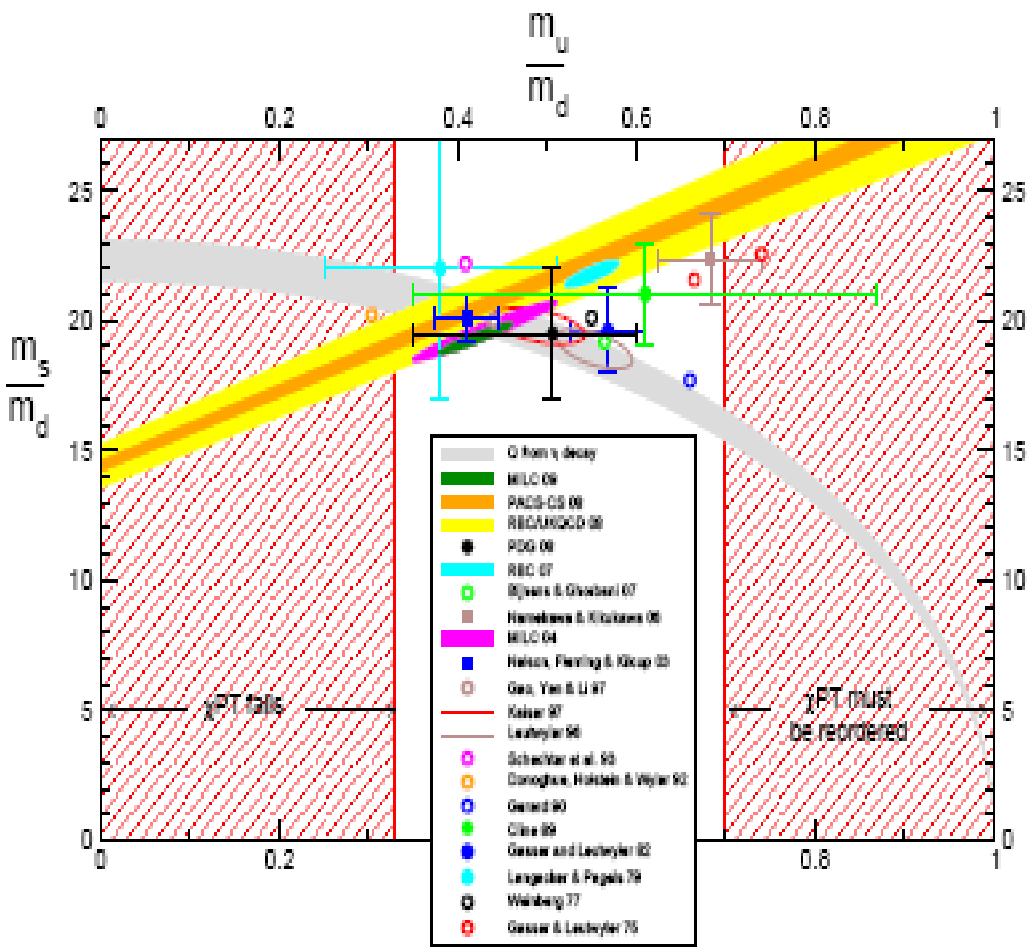


Figure 3: Ratios of the light quark masses

Leutwyler

MILC Collaboration

rules out m_u=0

at 10σ

Axions and their Role in Cosmology

- Introducing a global $U(1)_{PQ}$ symmetry, which is necessarily spontaneously broken, replaces:

θ ⇒ $a(x) / f_a$

Static CP Viol. Angle Dynamical CP conserving Axion field

and, effectively, eliminates CP violation in the strong sector

$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu} \quad \Rightarrow \quad L_a = \frac{a}{f_a} \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

- Here f_a is the scale of the breaking of the $U(1)_{PQ}$ symmetry , while $a(x)$ is the Nambu Goldstone axion field associated with the broken symmetry [Weinberg Wilczek]

- The property and interactions of axions depend on f_a the scale of the breaking of the $U(1)_{PQ}$ symmetry
- In particular, the axion mass, its coupling to two photons and its isoscalar and isovector couplings are inversely proportional to f_a

$$m_a = \lambda_m\, m_a^{st}\, [v_F / f_a]\ ; \quad L_{a\gamma\gamma} = \frac{\alpha}{4\pi} K_{a\gamma\gamma} \frac{a_{\rm phys}}{f_a} F^{\mu\nu} \widetilde{F}_{\mu\nu}$$

$$\xi_{a\eta} = \lambda_0\, [f_\pi / f_a] \quad ; \quad \xi_{a\pi} = \lambda_3\, [f_\pi / f_a]$$

where $m_a^{st} \approx 25$ KeV; $f_\pi = 92$ MeV ; and λ_m ; $K_{a\gamma\gamma}$; λ_0 ; λ_3 are of O(1)

- Initially, one assumed that $f_a = v_F = (\sqrt{2}\, G_F)^{-1/2} \approx 250$ GeV but weak scale axions are ruled out by experiment. For example, one predicts

$$BR(K^+ \to \pi^+ + a) > 1.2 \times 10^{-4}$$ [Bardeen Peccei Yanagida]

well above the bound obtained at KEK

$$BR(K^+ \to \pi^+ + \text{nothing}) < 3.8 \times 10^{-8}$$

- The choice $f_a = v_F$ is not necessary to solve the strong CP problem
- If $f_a >> v_F$ then the axion is very light, very weakly coupled and very long lived and such invisible axion models remain viable
- These models introduce fields which carry PQ charge but are SU(2)XU(1) singlets . Two different generic models exist:

i) DFSZ Models [Dine Fischler Srednicki; Zhitnisky]

These models add to the PQ model a scalar field σ which carries PQ charge and $f_a = \langle\sigma\rangle >> v_F$

ii) KSVZ Models [Kim; Shifman Vainshtein Zakharov]

Only a superheavy quark Q and a scalar field σ carry PQ charge.

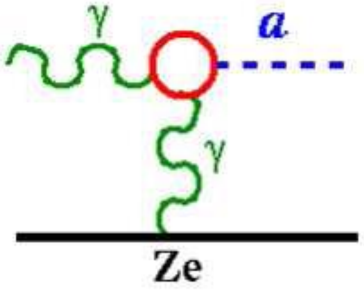
The dynamics is such that $f_a = \langle\sigma\rangle >> v_F$ and $M_Q \approx f_a$

- For both the KSVZ and the DFSZ models $\lambda_m=1$, hence:

$$m_a = m_a^{st}\,[v_F / f_a] \approx [10^6\ \mathrm{GeV} / f_a]\ 6.3\ \mathrm{eV}$$

- The KSVZ and DFSZ axions are very light, very weakly coupled and very long-lived, but are not totally invisible
- Upper bounds on m_a can be inferred from astrophysics since axion emission, through Primakoff and other processes, causes energy loss $\sim 1/f_a$ affecting stellar evolution.
- Typically these astrophysical bounds, which I will not discuss in detail here, allow axions lighter than

$$m_a \leq 1\text{-}10^{-3}\ \mathrm{eV}$$



- Rather remarkably, cosmology gives a lower bound for the axion mass (upper bound on f_a) [Preskill Wise Wilczek; Abbott Sikivie; Dine Fischler] and axions can have a significant cosmological role
- Physics is simple to understand. When Universe goes through the $U(1)_{PQ}$ phase transition at $T\sim f_a \gg \Lambda_{QCD}$ the QCD anomaly is ineffective and θ is arbitrary. Eventually, when Universe cools to $T\sim\Lambda_{QCD}$ the axion gets a mass and $\theta \rightarrow 0$.
- The coherent $\mathbf{p}_a=0$ axion oscillations towards this minimum contribute to the Universe's energy density and act as cold dark matter
- The detailed results depend on whether the PQ phase transition occurs before or after inflation and I'll sketch the main issues in both cases

Case i: the PQ phase transition happens before (or during) inflation

During inflation the axion field is homogenized over enormous distances. Thus only the evolution of the $\mathbf{p_a}=0$ mode is relevant

- A typical calculation of the axion contribution to Universe's energy density [Hannestad et al] then gives

$$\Omega_a h^2 = 0.195\ [f_a/10^{12}\ \mathrm{GeV}]^{1.184}\ [\theta_i^2]$$

where θ_i is the initial misalignment angle

- This quantity is bounded by the density of Cold Dark Matter in the Universe:

$$\Omega_{CDM} h^2 = 0.120 \pm 0.003 \qquad \text{WMAP Planck}$$

- If one assumes that axions are the dark matter in the Universe, this then gives a relation between θ_i and f_a :

$$\theta_i = 0.748\ [10^{12}\ \mathrm{GeV}/\ f_a]^{0.592}$$

- The table below gives some typical values for θ_i and f_a

f_a (GeV)	10^{12}	10^{15}	10^{18}
θ_i	0.75	1.3×10^{-2}	2.1×10^{-4}
$f_a\,\theta_i$ (GeV)	7.5×10^{11}	1.3×10^{13}	2.1×10^{14}

- One often assumes that θ_i is an average angle $\theta_i^2 = \langle\theta^2\rangle = \pi^2/3$ Then assuming that axions are the dark matter in the Universe

$$\Omega_a h^2 = \Omega_{CDM} h^2 = 0.120 \pm 0.003$$

gives the following value for the PQ scale and the axion mass:

$f_a = 0.24 \times 10^{12}$ GeV and $m_a = 26 \times 10^{-6}$ eV

- These results for $f_a\ \theta_i$ give an interesting bound, suggested long ago by Lyth, which originates because inflation induces measurable quantum fluctuations in the axion field

- These isocurvature axion perturbations correspond to fluctuations in the initial misalignment angle θ_i and have a power spectrum given by:

$$\Delta^2_a(k) = [2\ |\delta\theta_i|\ /\ \theta_i\ ]^2 = [H_I\ /\pi\ \theta_i\ f_a\ ]^2$$

where H_I is the expansion rate during inflation

- Both WMAP and Planck have put bounds on the ratio:

$$\beta_{iso} = \Delta^2_a(k)\ /(\Delta^2_R(k)\ + \Delta^2_a(k)\ )$$

where $\Delta^2_R(k)$ measures the curvature perturbation spectrum.

- At $k = 0.002\ \mathrm{Mpc}^{-1}$ these collaborations find:

$\beta_{iso} < 0.036$ (95% CL) Planck $\beta_{iso} < 0.047$ (95% CL) WMAP

- Using the best fit result of Planck for $\Delta^2_R(k)$:

$$\Delta^2_R(k) = 2.2 \times 10^{-9} (k / 0.05 \text{ Mpc}^{-1})^{-0.04}$$

the bound on β_{iso} implies a bound on the isocurvature axion perturbations at $k = 0.002 \text{ Mpc}^{-1}$:

$$\Delta^2_a(k) < 9.25 \times 10^{-11}$$

- Hence the fluctuation in the initial misalignment angle is very small:

$$|\delta\theta_i| / \theta_i < 4.8 \times 10^{-6}$$

and there is a strong bound on the expansion rate during inflation:

$$H_I < 3 \times 10^{-5} \theta_i f_a$$

- For a sensible range of PQ scales [10^{12} GeV $< f_a < 10^{18}$ GeV] this Lyth bound on H_I ranges from 2.25×10^{7} GeV to 6.3×10^{9} GeV .

- The Lyth bound makes only low energy scale inflation models tenable, predicting a very small contribution of the tensor perturbation spectrum $\Delta^2_h(k)$ to the CMB anisotropy.
- This tensor spectrum is given by the ratio of H_I to the Planck mass

$$\Delta^2_h(k) = 2\,(H_I/\,\pi M_P)^2$$

and, for example, for $f_a = 10^{18}$ GeV, $\Delta^2_h(k) < 5.4 \times 10^{-18}$

- This implies a negligibly small tensor to scalar ratio:

$$r(k) = \Delta^2_h(k)\,/\Delta^2_R(k) < 2.5 \times 10^{-9}$$

orders of magnitude below the recent joint bound of Planck and BICEP 2 [$r < 0.11$ at $k = 0.002\ \mathrm{Mpc}^{-1}$]

- The Lyth bound can be avoided, if f_a is not fixed during inflation [Linde]
- Imagine that $f_a = f_a(t)$, starting out very large before inflation $f_a > M_P$ and very slowly rolling down to its present value. In this case, the isocurvature perturbations have a power spectrum given by:

$$\Delta^2_a(k) = [H_I / \pi\, \theta_i\, f_a(t)\,]^2 \approx [H_I / \pi\, \theta_i\, M_P]^2$$

and the Lyth bound on H_I is much weakened:

$$H_I < 10^{-4}\, \theta_i\, M_P$$

- This bound is weakest when θ_i is large. For example, if $\theta_i = < \theta > = \pi / \sqrt{3}$, then

$$H_I < 2 \times 10^{15}\ \mathrm{GeV}\ [\theta_i / (\pi / \sqrt{3})]$$

similar to the bound from the tensor to scalar ratio r(k) :

$$H_I < 0.4 \times 10^{15}\ \mathrm{GeV}\ [r(k) / 0.11]^{1/2}$$

- However, the dynamics after inflation, may render irrelevant the solution proposed by Linde to allow for high scale inflation.
- In fact, if in the "preheating" stage after inflation large fluctuations in the axion field occur, they can lead to a non-thermal restoration of $U(1)_{PQ}$ [Kofman Linde Starobinsky Tkachev]
- To avoid this problem one needs to have, in effect, that:

$$f_a > \delta a$$

- This problem was studied by Kawasaki Yanagida Yoshino who found that, in general inflation models, $U(1)_{PQ}$ restoration could be avoided if:

$$f_a = (10^{12} - 10^{16})\ \mathrm{GeV}$$

Case ii: the PQ phase transition happens after inflation

- Because the PQ phase transition occurred after inflation, no isocurvature fluctuations ensue in this case
- However, as emphasized originally by Sikivie, in this case other dynamical issues arise due to the formation of axionic strings and domain walls, which are not erased by inflation
- At $T \approx f_a$ $U(1)_{PQ}$ gets spontaneously broken, and one-dimensional defects: axionic strings, around which $\theta = a/f_a$ winds by 2π, are formed
- These axionic strings have an energy per unit length $\mu \approx f_a^2 \ln L f_a$, where L is the inter-string separation. These strings decay very efficiently into axions up to temperatures $T \approx \Lambda_{QCD}$

- When $T \approx \Lambda_{QCD}$ $U(1)_{PQ}$ is explicitly broken by the gluon anomaly. However, since under a PQ transformation $\theta \rightarrow \theta + 2\alpha N_{fl}$ (where N_{fl} is the number of quarks carrying $U(1)_{PQ}$) a $Z(N_{fl})$ discrete symmetry is preserved
- Because of this $Z(N_{fl})$ symmetry there are N_{fl} degenerate vacuum states for the axion field. As a result, neighboring regions in the Universe which are in different axion vacua are separated by domain walls.
- At $T \approx \Lambda_{QCD}$, since θ winds by 2π as one goes around an axionic string, the axion field passes through each minimum. As a result each axionic string becomes the edge to N_{fl} domain walls, and the process of axion radiation stops

- If $N_{fl.} > 1$ (like in the DFSZ model) this string-wall network is stable and has a sizable surface energy density

$$\sigma \approx m_a\, f_a^{\,2} \approx 6.3 \times 10^9\ \mathrm{GeV}^3\ [f_a/10^{12}\ \mathrm{GeV}]$$

- This is a real problem, since the energy density in these walls dissipates slowly as the Universe expands [Zeldovich Kobzarev Okun]

$$\rho_{wall} = \sigma\, T$$

and ρ_{wall} now would vastly exceed the closure density of the Universe

- This disaster is avoided if $N_{fl} = 1$. Even though there is a unique vacuum, domain walls still form and attach to an axionic string –one wall per string.
- However, as Everett and Vilenkin showed, these walls very rapidly get chopped up into pieces, each enclosed by strings. These structures are unstable and disappear by radiating axions

- There has been an ongoing controversy on how much the axions radiated by these $N_{fl}=1$ walls, as well as by axionic strings, contribute to the Universe's energy density
- A recent compilation of Gondolo and Visinelli gives the following range for the ratio α of the contributions to the energy density of string/wall decay compared to that for **p_a**$=0$ oscillations :

$$0.16 \text{ [Sikivie et al]} < \alpha = \Omega_{str/wall} / \Omega_{p=0} < 186 \text{ [Battye Shellard]}$$

- In what follows, I will use the recent estimate of Hiramatsu et al:

$$\alpha = 19 \pm 10$$

and note that it alters the prediction for the axion mass (if $\theta_i^2=\pi^2/3$) for CDM axions to:

$$m_a = 26 \times 10^{-6}\,\text{eV}\,(1 + \alpha)^{.884} = 26 \times 10^{-6}\,\text{eV}\,(20 \pm 10)^{.884}$$

pushing it quite close to the astrophysical upper bound

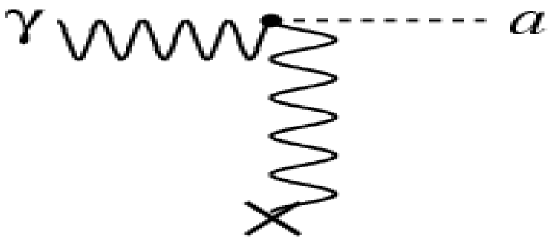
- So there may be trouble also in the $N_{fl}=1$ case!

Looking for Invisible Axions

- In the last decade there have been active searches for invisible axions using the idea of Sikivie of converting axions into γ by using a B-field in a resonant cavity

This possibility arises from the coupling:

$$L_{a\gamma\gamma} = \frac{\alpha}{4\pi} K_{a\gamma\gamma} \frac{a_{\rm phys}}{\rm f_a} F^{\mu\nu}\widetilde{F}_{\mu\nu} = g_{a\gamma\gamma}\, a\, \mathbf{E} \,.\, \mathbf{B}$$

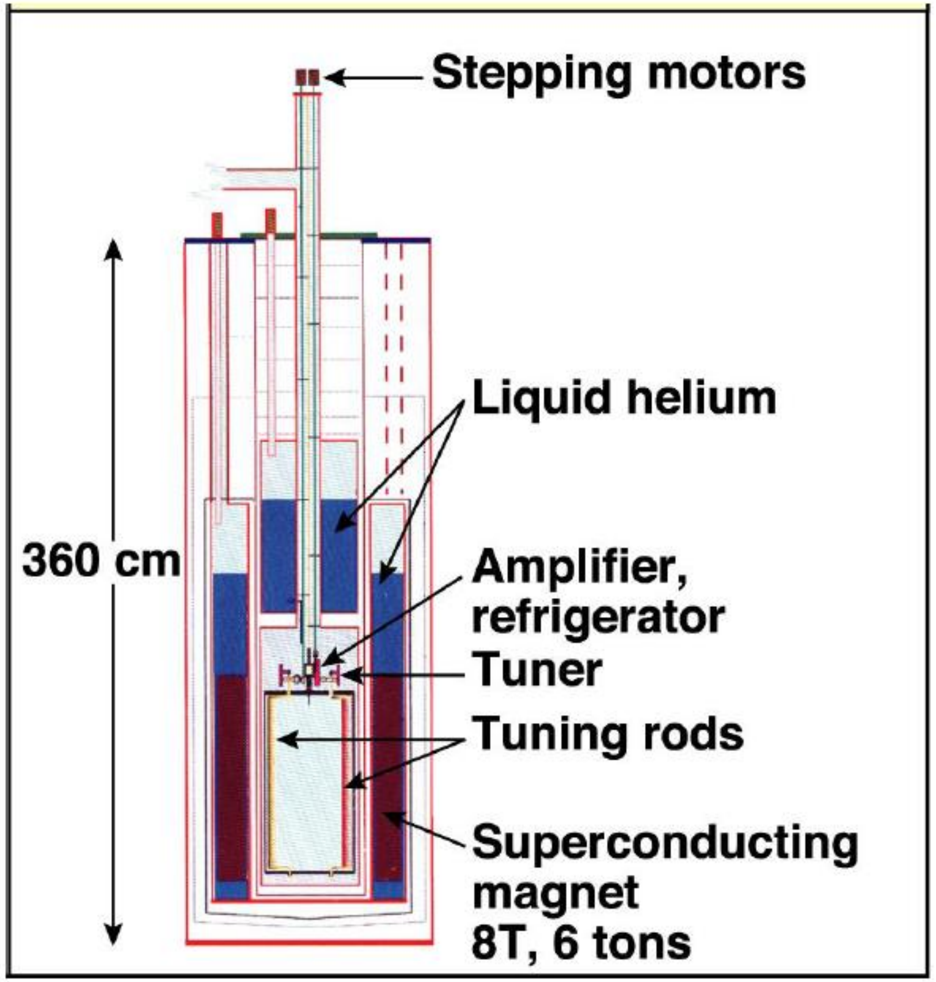


- In particular, the ADMX experiment is probing the parameter space that would allow invisible axions to be the dark matter in the Universe

- The ADMX experiment started at LLNL but now has moved to the Univ. Washington and is presently undergoing an upgrade to be able to cover more of the parameter space expected for dark matter axions
- Schematically

ADMX looks

like the Figure



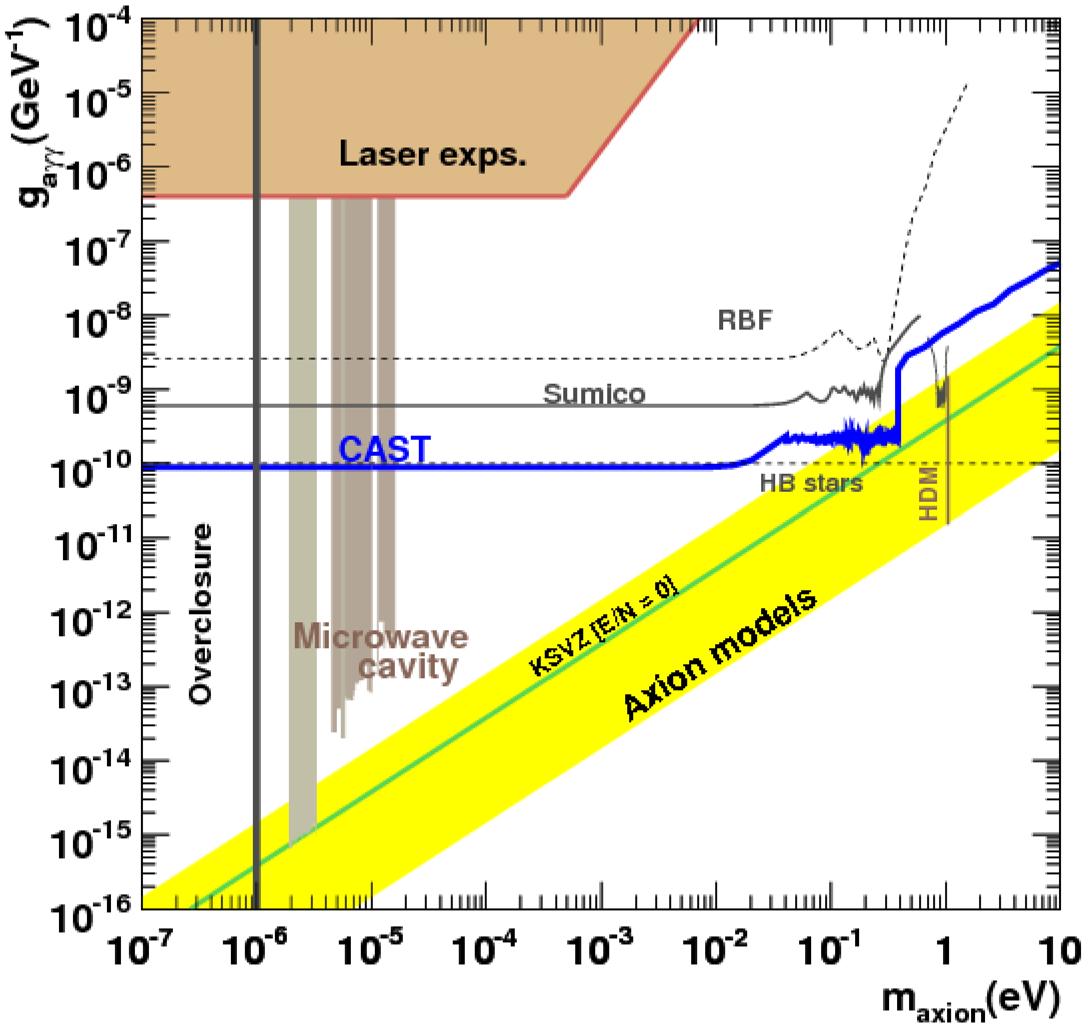
For $m_a \approx 10\ \mu eV$ the photon frequency which ADMX must detect is in the GHz range

Results of first 10 –years of operations

The ADMX experiment so far has explored the axion mass range

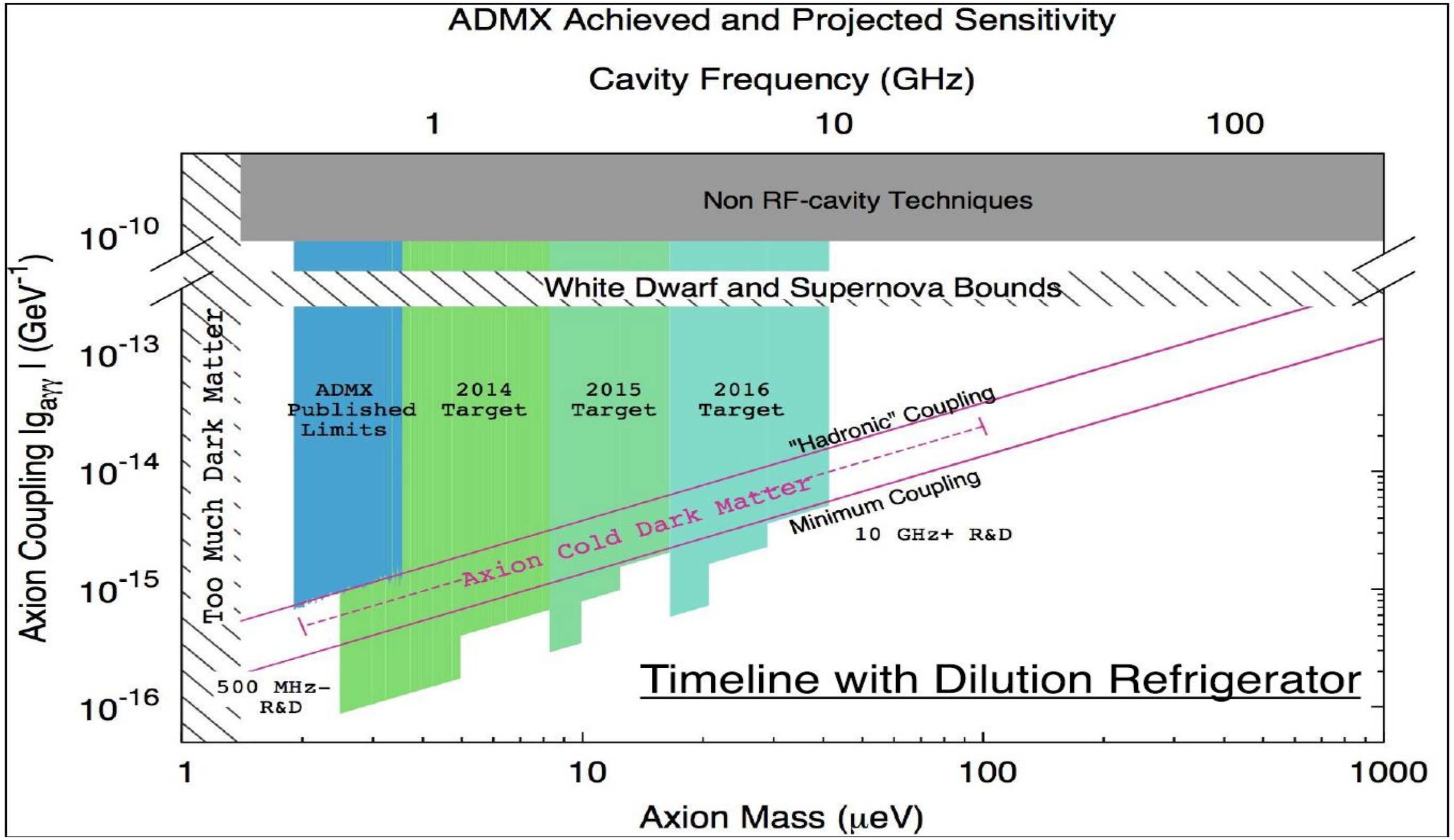
$1.9\ \mu eV < m_a < 3.3\ \mu eV$

at an appropriate strength $g_{a\gamma\gamma}$ for axions to be the dark matter



- Future reach of ADMX is in interesting region if PQ phase transition is before inflation

ADMX “Gen 2”: Science Prospects



i) Expected axion mass if $\theta_i^2 = \pi^2/3$

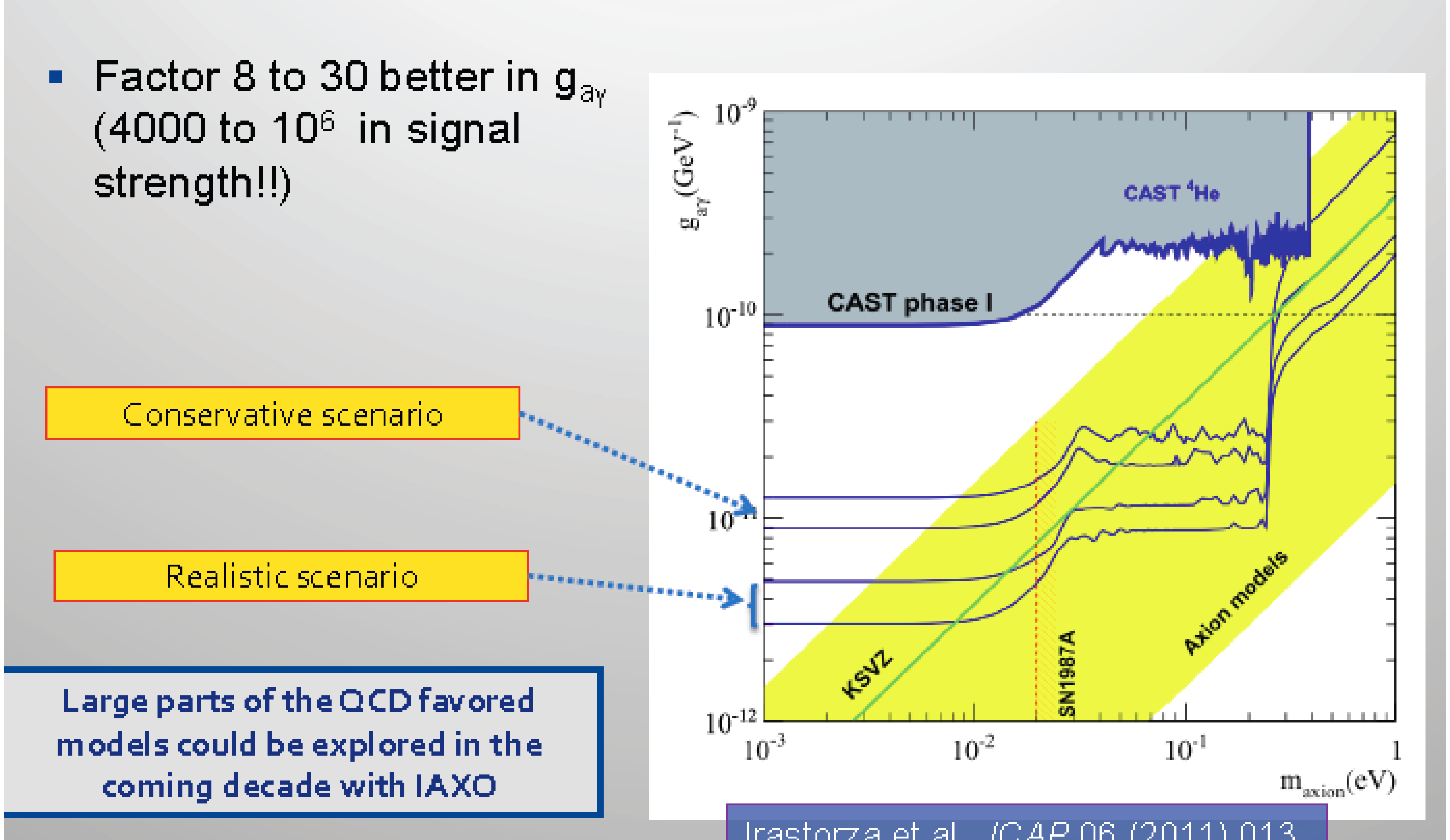
$m_a = 26\ \mu eV$

ii) If PQ after inflation and $N_{fl} = 1$ case expect

$200\ \mu eV < m_a < 526\ \mu eV$

axion mass is near astrophysical bounds and maybe unreachable?

- A next generation experiment after CAST (IAXO) is being planned which is more than an order of magnitude more sensitive to $g_{a\gamma\gamma}$
- Still not quite there [need to reach $m_a \approx 10^{-3}$ eV $g_{a\gamma\gamma} \approx 10^{-13}$ GeV^{-1}]



- Factor 8 to 30 better in $g_{a\gamma}$ (4000 to 10^6 in signal strength!!)

Conservative scenario

Realistic scenario

Large parts of the QCD favored models could be explored in the coming decade with IAXO

Irastorza et al., JCAP 06 (2011) 013

- It is possible that the misalignment angle θ_I is not of O(1) but much smaller $\theta_i << 1$. In this case, dark matter axions are associated with larger scales of $U(1)_{PQ}$ breaking [e.g. if θ_i = 1.3 x 10^{-2} then $f_a = 10^{15}$ GeV] and the axions are superlight [m_a = 6.3 x 10^{-9} eV for this example]
- In many ways PQ breaking scales $f_a \approx (10^{15} - 10^{18})$ GeV are very natural, since axions are ubiquitous in string theories [Svrcek Witten]
- Remarkably, one might be able to detect such high PQ breaking scales and superlight dark matter axions [Graham and Rajendran]

- Idea of Graham and Rajendran is very nice. Recall that the QCD angle gave a neutron electric dipole moment $d_n \approx e\, m_q/M_n^2\, \theta$
- If there is $U(1)_{PQ}$ symmetry, θ is replaced by the axion field: $\theta \rightarrow a(x)/f_a$
- So in invisible axion models there is a dynamical oscillatory neutron edm:

$$d_n \approx e\, m_q/M_n^2\, a(t)/f_a = e\, m_q/M_n^2\, [a/f_a] \cos m_a t$$

- However, if axions are the dark matter in the Universe, the ratio $[a/f_a]$ is fixed since:

$$\rho_{DM} \approx 0.3\, \frac{GeV}{cm^3} = \frac{1}{2} m^2{}_a a^2 = [4.4 \times 10^{-3}\, \mathrm{GeV}\, ^2]\, ^2\, [a/f_a]^2$$

which gives

$$[a/f_a] \approx 5.4 \times 10^{-20}$$

- Upshot is that, if axions are the dark matter, the amplitude of d_n is fixed and one predicts:

$$d_n = (4 \times 10^{-35} \cos m_a t\ )\ e\ \mathrm{cm}$$

- Only unknown is the oscillation frequency which depends on the axion mass m_a (or f_a):

$$m_a \approx 1\ \mathrm{kHz} \left(\frac{M_P}{f_a}\right) \approx 1\ \mathrm{MHz} \left(\frac{M_G}{f_a}\right)$$

- However, this tiny edm might be measurable because it is oscillatory

  - Graham Rajendran suggest using energy shifts in cold molecules to detect this effect

  - Budker Graham Ledbetter Rajendran Sushkov suggest looking for precession of nuclear spins in a material in the presence of a background electric field

Estimated reach of the proposed Budker et al experiment

$m_a < 10^{-9}$ eV

$f_a > 6 \times 10^{15}$ GeV

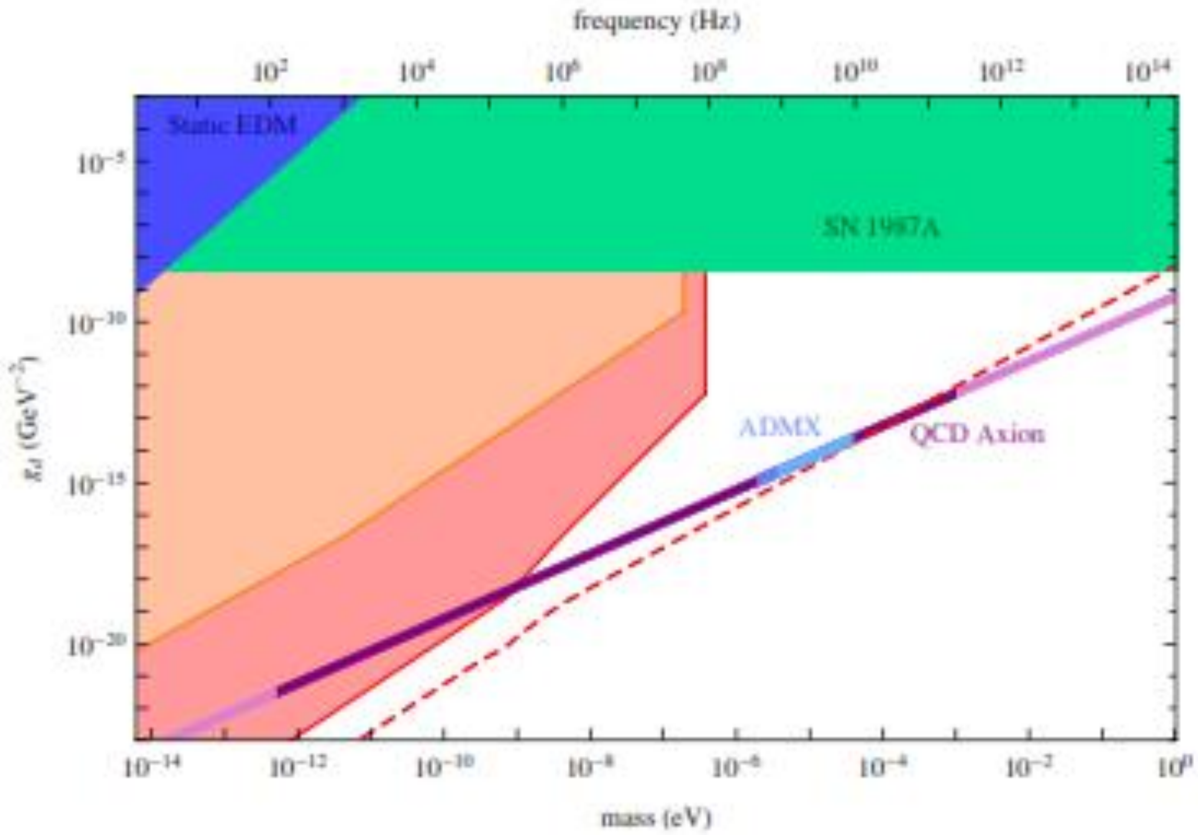


FIG. 2: Estimated constraints in the ALP parameter space in the EDM coupling g_d (where the nucleon EDM is $d_n = g_d a$ and a is the local value of the ALP field) vs. the ALP mass [56]. The green region is excluded by excess cooling of supernova 1987A [56]. The blue region is excluded by existing static nuclear EDM searches [56]. The QCD axion is in the purple region, whose width shows the theoretical uncertainty [56]. The solid red and orange regions show sensitivity estimates for our phase 1 and 2 proposals, set by magnetometer noise. Realistically, it would take several experiments to cover either curve. The red dashed line shows the limit from magnetization noise of the sample for phase 2. The ADMX region shows what region of the QCD axion has been covered (darker blue) [30] or will be covered (lighter blue) [57, 58]. We assume the ALP is all of the dark matter. Current EDM techniques that are optimized to search for a time-varying EDM can already search for ALP dark matter in the allowed region of parameter space [56].

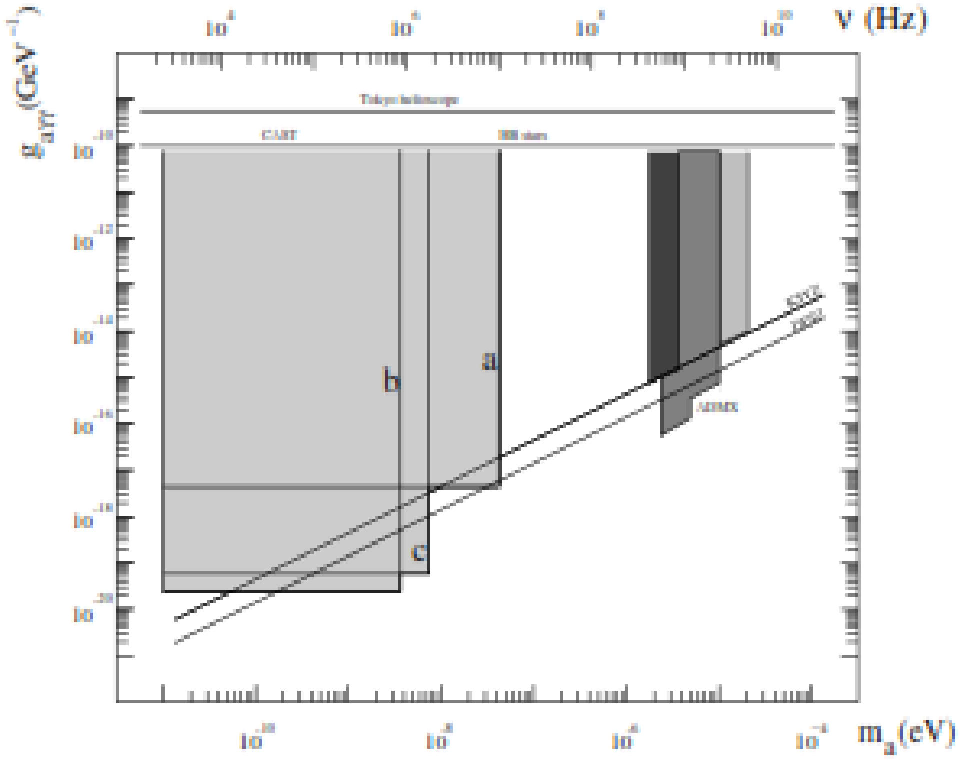
- A different, but similar, idea for detecting DM axions has been suggested by Sikivie Sullivan Tanner
- In the presence of a strong external B-field, B_{ext}, DM axions can induce a small B field, B_a, which can be detected after amplification by an LC circuit

$$\vec{\nabla} \times \vec{B}_a = \frac{\alpha K_{a\gamma\gamma}}{\pi f_a} \vec{B}_{ext} \partial_t a$$

- Strength of B_a is measure of f_a,

since $\frac{1}{2}(\partial_t a)^2 = \rho_{DM}$

Axion induced B field



Sensitivity of proposed experiment

(a, b, c –different magnets)

Concluding Remarks

- The existence of an additional chiral symmetry- like $U(1)_{PQ}$ - remains the most compelling solution to the strong CP problem
- The concomitant axions play an interesting cosmological role and arise naturally in theories beyond the Standard Model
- There are both ongoing and proposed experiments which in the next decade or so should tell us if axions exist