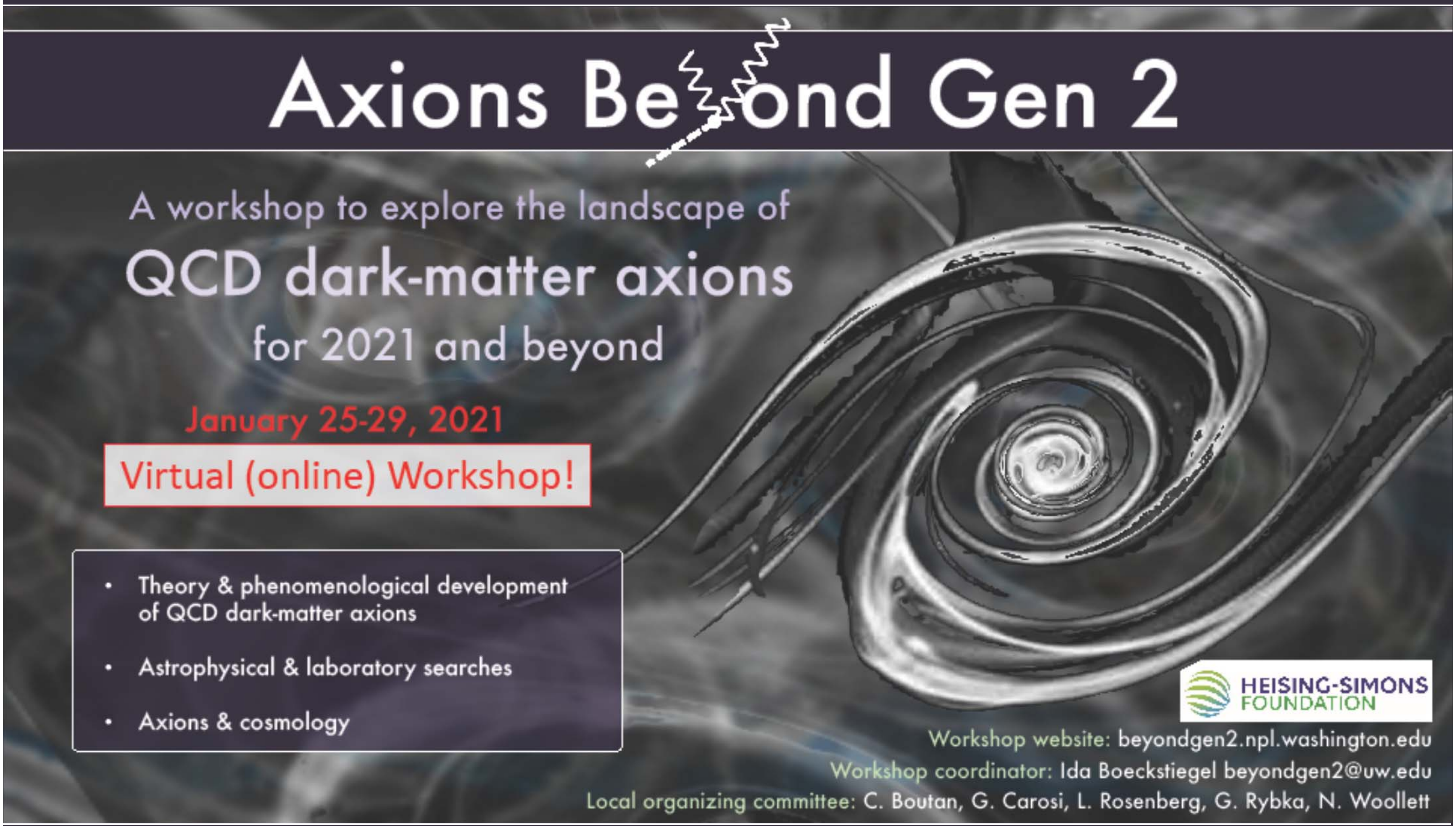
43 Years of Axions (Keynote Address)



Rocky Kolb, University of Chicago January 2021

Definition of *keynote address*

: an address designed to present the issues of primary interest to an assembly (such as a political convention) and often to arouse unity and enthusiasm

For this talk I leaned heavily on papers by

David J.E. Marsh, Physics Reports 643 (2016) 1–79

Anson Hook, 2018 TASI Lectures arXiv:1812.02669

A. Ringwald, L. Rosenberg, and G. Rybka, RPP

Conversations with my Chicago colleagues

My memory

Focus on evolution of theory. (Experiments will be exhaustively covered by others.)

What is an Axion?

QCD Axion: Nambu-Goldstone boson that is part of the solution to the strong CP-problem.

Axion-like particle: Like an axion, only it’s not since it does not solve the strong-QCD problem.

Any other light boson: Quite a large cast of characters

Axions Beyond Gen-2

Axions are one of the leading dark matter candidates and of great interest to the theoretical and experimental communities. This workshop aims to explore the current state of the axion field, including reviewing recent theoretical developments, astrophysical observations, laboratory-based experiments and novel ideas which could lead to the discovery of the QCD dark-matter axion.

If experiments are now Gen 2, theory is Gen-N ($N \gg 2$)

43 (Soon to be 44) Years Ago …

CP Conservation in the Presence of Pseudoparticles*

R. D. Peccei and Helen R. Quinn†
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 31 March 1977)

We give an explanation of the *CF* conservation of strong interactions which includes the effects of pseudoparticles. We find it is a natural result for any theory where at least one flavor of fermion acquires its mass through a Yukawa coupling to a scalar field which has nonvanishing vacuum expectation value.

It is experimentally obvious that we live in a world where *P* and *CP* are good symmetries at the level of strong interactions. In the context of quantum chromodynamics the strong interactions are believed to be due to non-Abelian vector gluons coupled to massive quarks. In such a theory, when the effects of gluon configurations of nonzero pseudoparticle number are included, *CP* invariance requires a very special choice of parameters. We will show, however, that *CP* invariance of the strong interactions is, in fact, a natural consequence, provided at least one flavor of quark acquires its mass from a Yukawa coupling to a scalar field which has a nonzero vacuum expectation value, and the Lagrangian originally possesses a U(1) invariance involving all Yukawa couplings.

The physical importance of gauge field configurations with nontrivial topology has been stressed by 't Hooft.[1] He has reminded us that the physics of such theories involves a parameter θ which does not appear in the original Lagrangian.[2] This parameter defines the choice of vacuum[3] among an infinity of possible distinct and generally inequivalent vacua. Each θ represents a possible true vacuum and there are in general an infinity of distinct theories arising from any given Lagrangian.

If all fermions which couple to the non-Abelian gauge fields are massless then the various θ choices give equivalent theories.[1,3] This is most clearly seen by remarking that a change in the effective value of θ can be induced by making an $\exp[i\gamma_5\eta]$ rotation of the fermion fields. We define the effective Euclidean action in the qth sector to be

$$S_{\rm eff}^{q} = \int d^4x\, \mathcal{L} + i\theta q, \qquad (1)$$

where

$$q = (g^2/32\pi^2)\int d^4x\, F_{\mu\nu}^{a}\tilde{F}^{a\mu\nu}. \qquad (2)$$

The rotation of a fermion field by $\exp[i\gamma_5\eta]$ induces a change in the effective action given by

$$\delta S_{\rm eff}^{q} = -i\int(\partial^{\mu} j_{\mu}^{5})\eta = -2iq\eta \qquad (3)$$

since

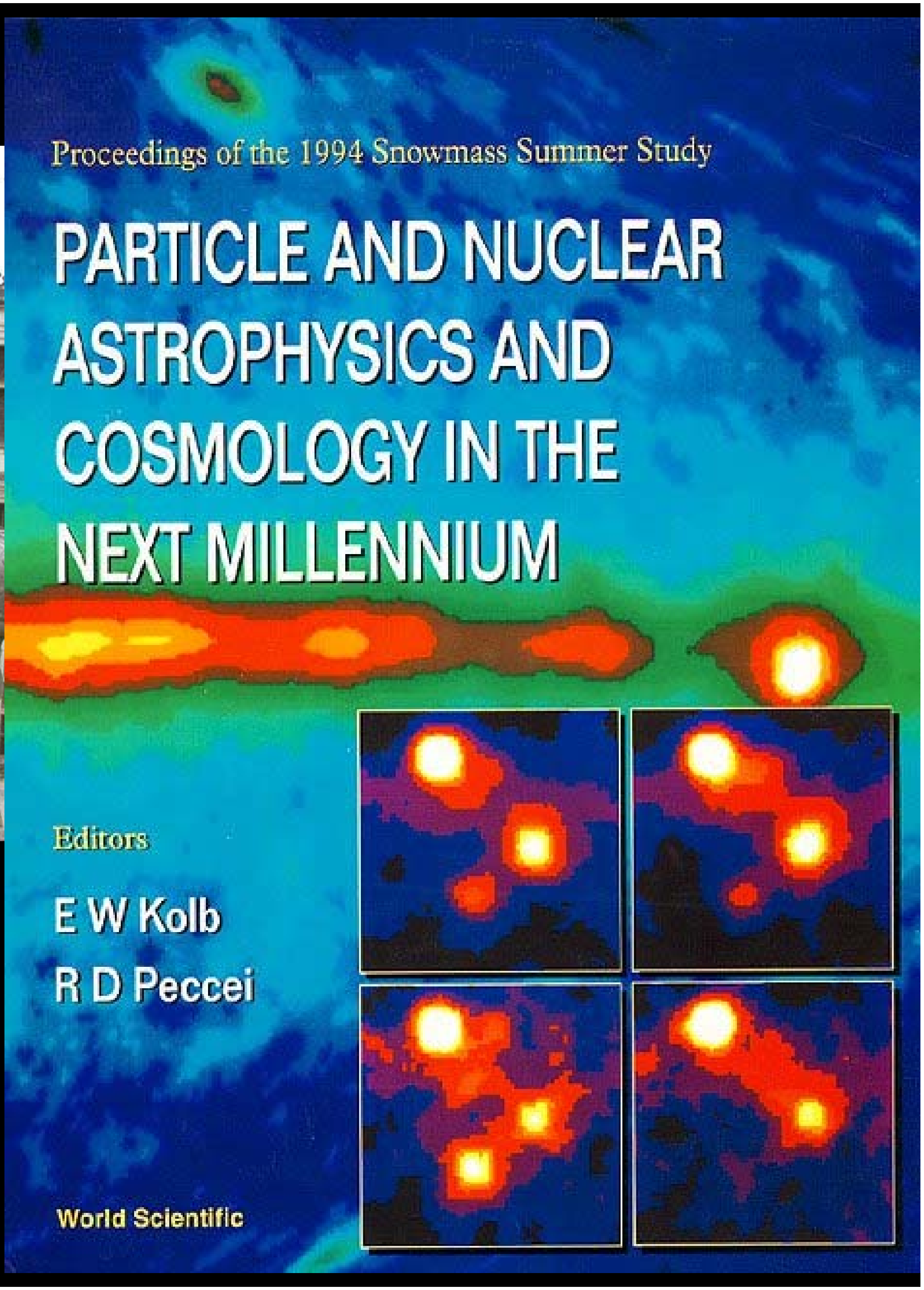
$$\partial^{\mu} j_{\mu}^{5} = (g^2/16\pi^2) F_{\mu\nu}^{a}\tilde{F}_{\mu}^{\mu\nu a}. \qquad (4)$$

Thus in such a theory the net effect of such a rotation is

$$\theta \to \theta' = \theta - 2\eta. \qquad (5)$$

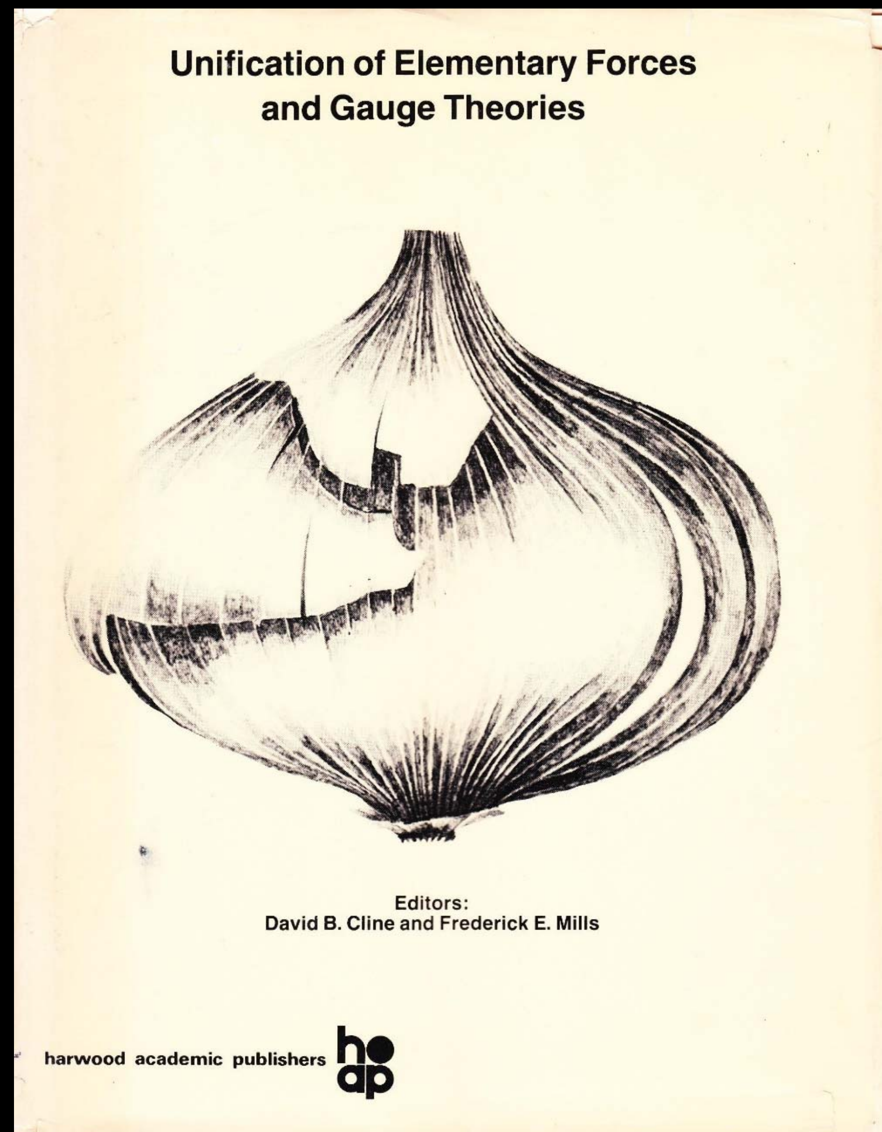
If, however, all fermions are massive such a rotation will also change the fermion mass term

Peccei: an inspirational & elegant
physicist
administrator
collaborator
friend
ski instructor
role model



First Ben Lee Memorial International Conference on Parity Nonconservation, Weak Neutral Currents and Gauge Theories

Fermilab
20-22 October 1977



First Ben Lee Memorial International Conference on Parity Nonconservation , Weak Neutral Currents and Gauge Theories

Wilczek

7. Peccei and Quinn[20] have proposed a different type of chiral symmetry, involving Higgs bosons as well as quarks, which also gives automatic strong P and T invariance. As pointed out by S. Weinberg and the author independently[26,19] this proposal requires the existence of a new particle, an axion, with remarkable properties. We cannot begin to give a full analysis here,[19,20,26] but the following should be noted:

i) The axion a has $J^{PC} = 0^{-+}$ and its mass is estimated as $100\ \text{keV} \times 10^{\pm 1}$.

ii) The coupling of a to leptons and quarks (in the simplest model) is given by

$$\mathcal{L}_{int.} = 2^{1/4} G_F^{1/2} a \Big(\tan\lambda \sum_{\substack{Q=2/3\\ \text{Quarks}}} m_i \bar{q}_i \gamma_5 q_i + \cot\lambda \sum_{\substack{Q=-1/3\\ \text{Quarks}}} m_j \bar{q}_j \gamma_5 q_j + \cot\lambda \sum_{\substack{Q=-1\\ \text{leptons}}} m_K \bar{\ell}_K \gamma_5 \ell_K \Big) \qquad (6)$$

Weinberg

At first sight it might appear that the U(1) symmetry of Peccei and Quinn could have no further physical consequences, because after all it *is* strongly broken by instantons. However, Wilczek and I have independently noticed that in fact it would have a dramatic consequence. The dynamics of the scalar fields is governed in tree approximation by the polynomial part $P(\phi)$ of the Lagrangian, which would have to satisfy the Peccei-Quinn symmetry, so the spontaneous breakdown of this symmetry leads to a Goldstone boson, whose mass vanishes in lowest order. Wilczek and I call this the "axion". The Peccei-Quinn symmetry *is* strongly broken by instantons, but the scalar field

...

m_a is between 10 keV and 1 MeV. Leaving aside the massless particles, the axion would be the lightest of all the elementary particles.

Gen-1 Axion:

axions solve strong CP

two mass scales, f_a and Λ

$f_a = 250$ GeV (EWK)

$\Lambda = \Lambda_{QCD}$

$m_a \approx \Lambda^2 / f_a$

$g_{a\gamma\gamma} \approx \alpha / f_a$

A New Light Boson?

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 6 December 1977)

It is pointed out that a global U(1) symmetry, that has been introduced in order to preserve the parity and time-reversal invariance of strong interactions despite the effects of instantons, would lead to a neutral pseudoscalar boson, the "axion," with mass roughly of order 100 keV to 1 MeV. Experimental implications are discussed.

One of the attractive features of quantum chromodynamics[1] (QCD) is that it offers an explanation of why C, P, T, and all quark flavors are conserved by strong interactions, and by order-α effects of weak interactions.[2] However, the discovery of quantum effects[3] associated with the "instanton" solution of QCD has raised a puzzle with regard to P and T conservation. Because of Adler-Bell-Jackiw anomalies, the chiral transformation which is needed in QCD to bring the quark-mass matrix to a real, diagonal, γ_5-free form will in general change the phase angle θ associated[3] with instanton effects, leaving $\bar{\theta} \equiv \theta + \arg\det m$ invariant. [Here m is the coefficient of $\frac{1}{2}(1+\gamma_5)$ in a decomposition of the quark-mass matrix into $\frac{1}{2}(1\pm\gamma_5)$.] The condition for P and T conservation is that $\theta = 0$ when the quark fields are defined so that m is real, or more generally, that $\bar{\theta} = 0$. But θ is a free parameter, and in QCD there is no reason why it should take the value $-\arg\det m$. Furthermore, even if we simply demanded that the strong interactions in isolation conserve P and T, so that $\bar{\theta} = 0$, there would still be a danger that the weak interactions would introduce P- and T-nonconserving phases of order $10^{-3}\alpha$ in m, leading to an unacceptable neutron electric dipole moment, of order 10^{-18} $e\cdot$cm.

An attractive resolution of this problem has been proposed by Peccei and Quinn.[5] They note that the quark-mass matrix is a function $m(\langle\varphi\rangle)$ of the vacuum expectation values of a set of weakly coupled scalar fields φ_i. Although θ is arbitrary, $\langle\varphi\rangle$ is not; it is determined by the minimization of a potential $V(\varphi)$ which depends on θ. Peccei and Quinn assume that the Lagrangian has a global U(1) chiral symmetry [which I will call $\mathrm{U(1)_{PQ}}$], under which $\det m(\varphi)$ changes by a phase. The phase of $\det m(\varphi)$ at the minimum of $V(\varphi)$ is then undetermined in any finite order of perturbation theory, and is fixed only by instanton effects which break the $\mathrm{U(1)_{PQ}}$ symmetry. However, the potential will then depend on $\bar{\theta}$, but not separately on θ and $\arg\det m$, so that it is not a miracle if the phase of $\det m(\varphi)$ at the minimum of $V(\varphi)$ happens to have the P- and T-conserving value $-\theta$. Peccei and Quinn[5] show in a number of examples that this is just what happens.

Now, the $\mathrm{U(1)_{PQ}}$ symmetry of the Lagrangian is intrinsically broken by instantons, and so at first sight one might not expect that it would have any further physical consequences. Certainly it does not lead to the strongly interacting isoscalar pseudoscalar meson below $\sqrt{3}m_\pi$,[6] that was the bugbear of the old U(1) problem. However, the scalar fields φ do not know about instantons, except through a semiweak ($\propto G_F^{1/2}$) coupling to quarks. Hence the spontaneous breakdown of the chiral $\mathrm{U(1)_{PQ}}$ symmetry associated with the appearance of nonzero vacuum expectation values $\langle\varphi\rangle$ leads[7] to a very light pseudoscalar pseudo-Goldstone boson,[8] the "axion," with m_a^2 proportional to the Fermi coupling G_F.

For insight in to the properties of the axion, it is useful to examine how they appear in the simplest realistic model that admits a $\mathrm{U(1)_{PQ}}$ symmetry. We assume an $\mathrm{SU(2)}\otimes\mathrm{U(1)}$ gauge group, with quarks in $N/2$ left-handed doublets and N right-handed singlets, and just two scalar doublets $\{\varphi_i^+, \varphi_i^0\}$, carrying $\mathrm{U(1)_{PQ}}$ quantum numbers such that φ_1 (φ_2) couples right-handed quarks of charge $-\frac{1}{3}$ ($+\frac{2}{3}$) to left-handed quarks. By writing the Yukawa interaction in terms of quark fields of definite mass, we easily see that the interaction of neutral scalar fields with quarks is[9]

$$\mathfrak{L}_N = -[m_d\bar{d}_R d_L + m_s\bar{s}_R s_L + m_b\bar{b}_R b_L + \cdots]\varphi_1^{0*}\langle\varphi_1^0\rangle^{*-1} - [m_u\bar{u}_R u_L + m_c\bar{c}_R c_L + m_t\bar{t}_R t_L + \cdots]\varphi_2^0\langle\varphi_2^0\rangle^{-1} + \mathrm{H.c.}, \qquad (1)$$

where L and R indicate multiplication with $\frac{1}{2}(1\pm\gamma_5)$. The part of $\mathfrak{L}_N$ involving the light quarks u, d, and s may be treated as a perturbation $\mathfrak{L}_{uds}$, while terms in $\mathfrak{L}_N$ involving c, t, b,... must be included in the

Problem of Strong P and T Invariance in the Presence of Instantons

F. Wilczek[a]
Columbia University, New York, New York 10027, and The Institute for Advanced Studies, Princeton, New Jersey 08540[b]
(Received 29 November 1977)

The requirement that P and T be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

One of the main advantages of the color gauge theory of strong interactions is that so many of the observed symmetries of strong interactions seem to follow automatically as a consequence of the gauge principle and renormalizability—P, T, C, flavor conservation, the $\underline{3}\oplus\underline{3}^*$ structure of chiral symmetry breaking, and asymptotic scale invariance. As a result of this, gauge theories of the weak and strong interactions mesh nicely, and effects such as parity-nonconserving and flavor-changing processes can be calculated to be small, potentially dangerous renormalization effects being under control.[1] This attractive picture, however, is based upon neglect of possible interactions of the form

$$\mathfrak{L}_{\rm int} = (\theta/32\pi^2)\,\mathrm{tr}\,G_{\mu\nu}\tilde{G}_{\mu\nu}, \qquad (1)$$

where $G_{\mu\nu}$ is the gauge field and $\tilde{G}_{\mu\nu}$ its dual, written in matrix form. Although this interaction is formally a total divergence,

$$\mathrm{tr}\,G_{\mu\nu}\tilde{G}_{\mu\nu} = \partial_\mu \mathrm{tr}\,\epsilon_{\mu\nu\lambda\sigma}A_\nu(\partial A_\sigma + \tfrac{2}{3}A_\lambda A_\sigma), \qquad (2)$$

recent work[2-6] has made it clear that it cannot be neglected. The interaction in Eq. (1) breaks P and T but conserves C, so it contributes directly to the neutron electric dipole moment d_n. The extremely good experimental limits on d_n require a very small θ

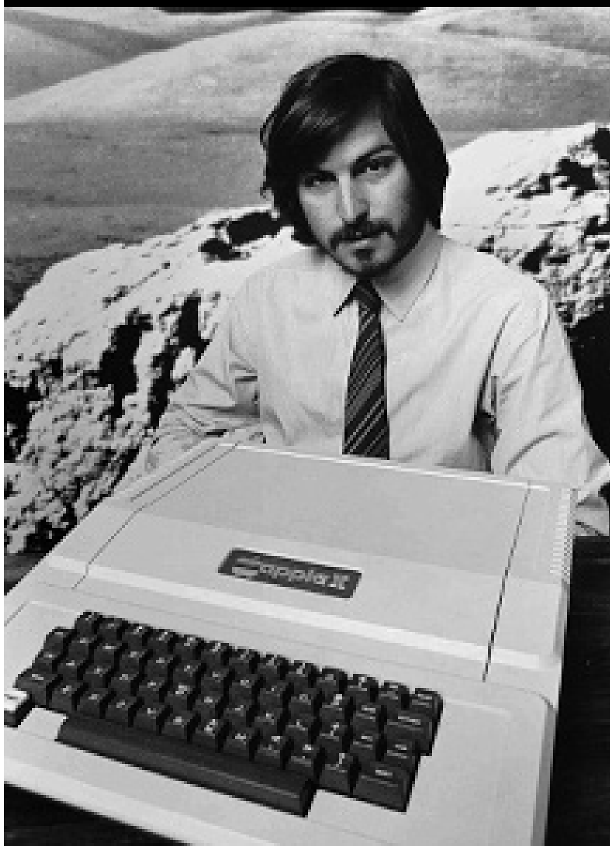
$$\theta/32\pi^2 \lesssim 10^{-7}. \qquad (3)$$

In this Letter I will analyze whether such a small quantity can emerge in a credible way from gauge theories, or if θ can be made zero in some sense. Three possibilities can be distinguished: (i) If the interactions which break P and T lead to infinite renormalization of θ, we shall say strong P and T invariance is *unnatural*. (ii) If the interactions which break P and T lead to a small finite renormalization of θ, we shall say strong P and T invariance is *natural*. In this case, if a bare value $\theta = 0$ is imposed as a symmetry requirement, a physically acceptable theory may result with no further adjustment. (iii) In a certain class of theories[4,5,7] the parameter θ is physically meaningless,[4,5] or dynamically determined.[7] In this case, if the strong interaction conserves P and T, we shall say the conservation is *automatic*.

I regard a theory of type (i) as very unattractive. Below I shall argue that a theory of type (ii) requires that either P or T be softly broken — that is, that the breaking occurs through a dimensional coupling in the bare Lagrangian or spontaneously. A theory of type (iii) requires that the mass of some quark be zero or that a remarkable new kind of particle ($\alpha\ 0^{-+}$ meson of mass ~ 100 keV, which we call an *axion*) exist. So if our arguments are correct, at least one of the following four conditions must hold: (i) P is softly broken—this condition leads to some awkwardness in understanding the two-component neutrino. (ii) T is softly broken. (iii) The mechanical mass[8] of some quark is zero—this does not agree with current-algebra estimates,[9] but it is not completely clear that it is excluded, given the uncertainties of these estimates. If this case is realized, it gives an interesting parallel between the quark and lepton sectors (massless quark and massless neutrino). (iv) An axion, with properties to be detailed below, exists.[10] This is in some ways the most attractive and certainly the most exciting possibility. Among these four alternatives, P and T conservation for strong interactions is natural in the first two and automatic in the second two.

Renormalization of θ.—Naively, one might expect that since $\mathrm{tr}\,G_{\mu\nu}\tilde{G}_{\mu\nu}$ is a dimension-four interaction it will get infinitely renormalized (logarithmic divergences) unless it does not conserve quantum numbers— here the only candidates are P and T invariance— which are only softly broken. I believe that this is correct, but it requires some special discussion since the vertex of $\mathrm{tr}\,G_{\mu\nu}G_{\mu\nu}$ vanishes (as do all instanton effects) in the usual Feynman perturbation theory. A convenient method for recognizing the divergences

In ‘77 “axions” entered our culture, along with



After 43 (Soon to be 44) Years, Axions Are "Stayin' Alive"

ADMX

Theory Gen-1 Axion Was Not Long-Lived

PHYSICAL REVIEW D VOLUME 18, NUMBER 5 1 SEPTEMBER 1978

Do axions exist?

T. W. Donnelly, S. J. Freedman, R. S. Lytel, R. D. Peccei, and M. Schwartz

Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

(Received 21 March 1978)

We critically examine various existing experiments which could provide evidence for the axion. Although our conclusions regarding the existence of this particle are somewhat pessimistic, we discuss other possible experiments which could throw additional light on this question.

$K^+ \to \pi^+ \, a$

Other flavor-changing decays

Beam Dumps

Reactors

Nuclear De-excitation

Theory Gen-1 Axion Was Not Long-Lived

PHYSICAL REVIEW D VOLUME 18, NUMBER 6 15 SEPTEMBER 1978

Astrophysical bounds on the masses of axions and Higgs particles

Duane A. Dicus and Edward W. Kolb*
Center for Particle Theory, The University of Texas, Austin, Texas 78712
Vigdor L. Teplitz†
Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
Robert V. Wagoner
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

(Received 27 April 1978)

Lower bounds on the mass of a light scalar (Higgs) or pseudoscalar (axion) particle are found in three ways: (1) by requiring that their effect on primordial nucleosynthesis not yield a deuterium abundance outside present experimental limits, (2) by requiring that the photons from their decay thermalize and not distort the microwave background, and (3) by requiring that their emission from helium-burning stars (red giants) not disrupt stellar evolution. The best bound is from (3); it requires the axion or Higgs-particle mass to be greater than about 0.2 MeV.

The first process considered is the Primakoff process,[16] $\gamma + Z \to \phi + Z$, shown in Fig. 2. The cross section for this process near threshold is

$$|v|\sigma = 64\pi\alpha Z^2 \frac{\omega\Gamma(\phi\to 2\gamma)}{m_\phi^2}\frac{(\omega^2 - m_\phi^2)^{1/2}(\omega - m_\phi)}{(m_\phi^2 - 2\omega m_\phi)^2}, \tag{7}$$

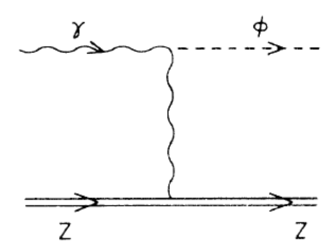


FIG. 2. $\gamma + Z \to \phi + Z$ via the Primakoff process.

Theory Gen-2 : “Invisible” Axion

Weak-Interaction Singlet and Strong *CP* Invariance

Jihn E. Kim
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104
(Received 16 February 1979)

Strong *CP* invariance is *automatically* preserved by a spontaneously broken chiral $U(1)_4$ symmetry. A weak-interaction singlet heavy quark Q, a new scalar meson σ^0, and *a very light axion* are predicted. Phenomenological implications are also included.

Gen-2 Axion:
- axions solve strong CP
- two mass scales, f_a and Λ

KSVZ, DFSZ, …

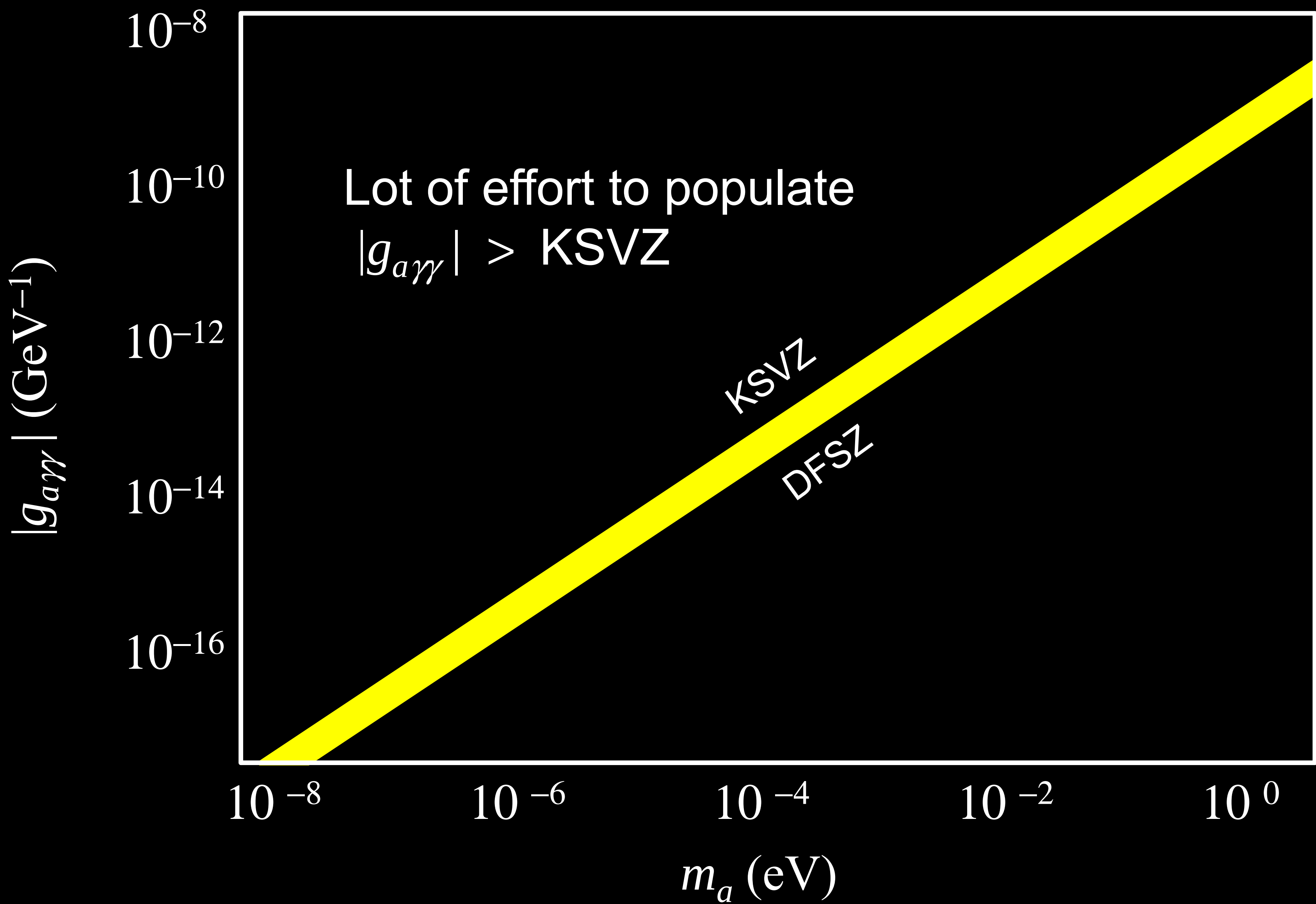
$f_a \gg$ EWK
(undetermined, but large)

$\Lambda = \Lambda_{\text{QCD}}$

$m_a \approx \Lambda^2 / f_a$

$g_{a\gamma\gamma} \approx \alpha / f_a$

Theory Gen-2 : “Invisible” Axion



Theory Gen-2 : “Invisible” Axion

PHYSICAL REVIEW D VOLUME 22, NUMBER 4 15 AUGUST 1980

Astrophysical bounds on very-low-mass axions

Duane A. Dicus
Center for Particle Theory, The University of Texas, Austin, Texas 78712

Edward W. Kolb
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

Vigdor L. Teplitz
*U.S. Arms Control and Disarmament Agency, Washington, D.C. 20451
and Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061*

Robert V. Wagoner
Institute of Theoretical Physics, Stanford University, Stanford, California 94305

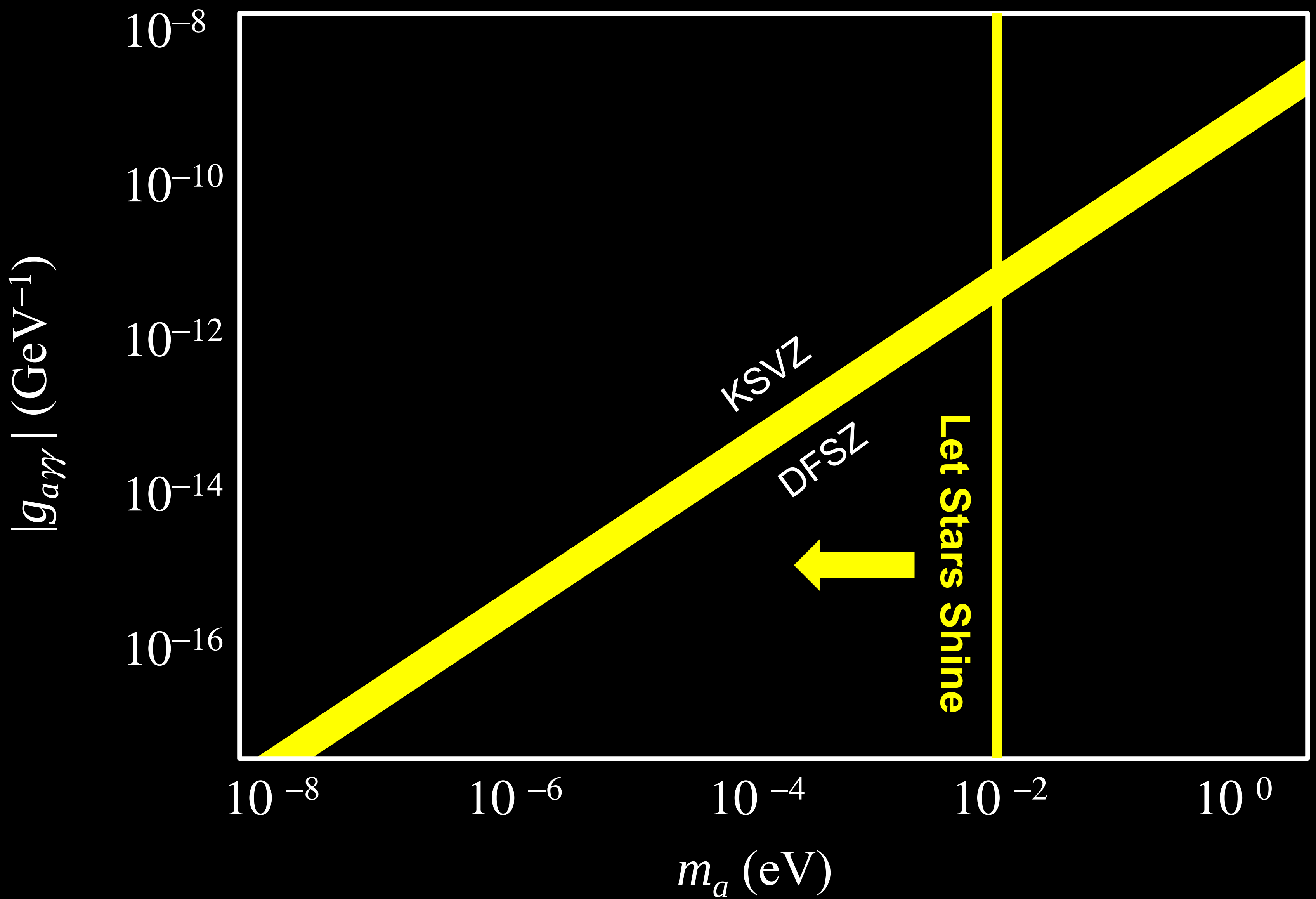
(Received 26 December 1979)

We consider the contribution to stellar energy loss that would result from the existence of a recently proposed very-low-mass ($\lesssim 1$ eV) axion. We calculate the energy loss rate of hydrogen-burning stars and of red giants from very-light-axion production through the Primakoff process. The result is an *upper* bound of about 10^{-2} eV on the mass of such a particle. We also consider briefly the cosmic background produced by the decay products of primordial axions, and the possibility of laboratory measurements of the long-range force a low-mass pseudoscalar boson would create.

Sun, Red Giants, SN 87A, White Dwarfs, Neutron Stars, ….

$$m_a \lesssim 10^{-2 \text{ to } -3} \text{ eV}$$

Theory Gen-2 : “Invisible” Axion



Axion Astrophysics Extremely Rich & Varied

Axions (& ALPs) and

- Stellar energy loss
- Supernovae
- The Sun
- Black hole superradiance
- Neutron stars
- White Dwarfs
- Quasar polarizations
- Photons from axion decay
- Gamma-ray observations
- Photon polarization

Theory Gen-2 : “Invisible” Axion

Phys Lett 120B January 1983

COSMOLOGY OF THE INVISIBLE AXION

John PRESKILL [1], Mark B. WISE [2]
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

and

Frank WILCZEK
Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA

Received 10 September 1982

A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

L.F. ABBOTT [1]
Physics Department, Brandeis University, Waltham, MA 02254, USA

and

P. SIKIVIE [2]
Particle Theory Group, University of Florida, Gainesville, FL 32611, USA

Received 14 September 1982

THE NOT-SO-HARMLESS AXION

Michael DINE
The Institute for Advanced Study, Princeton, NJ 08540, USA

and

Willy FISCHLER
Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA

Received 17 September 1982
Received manuscript received 14 October 1982

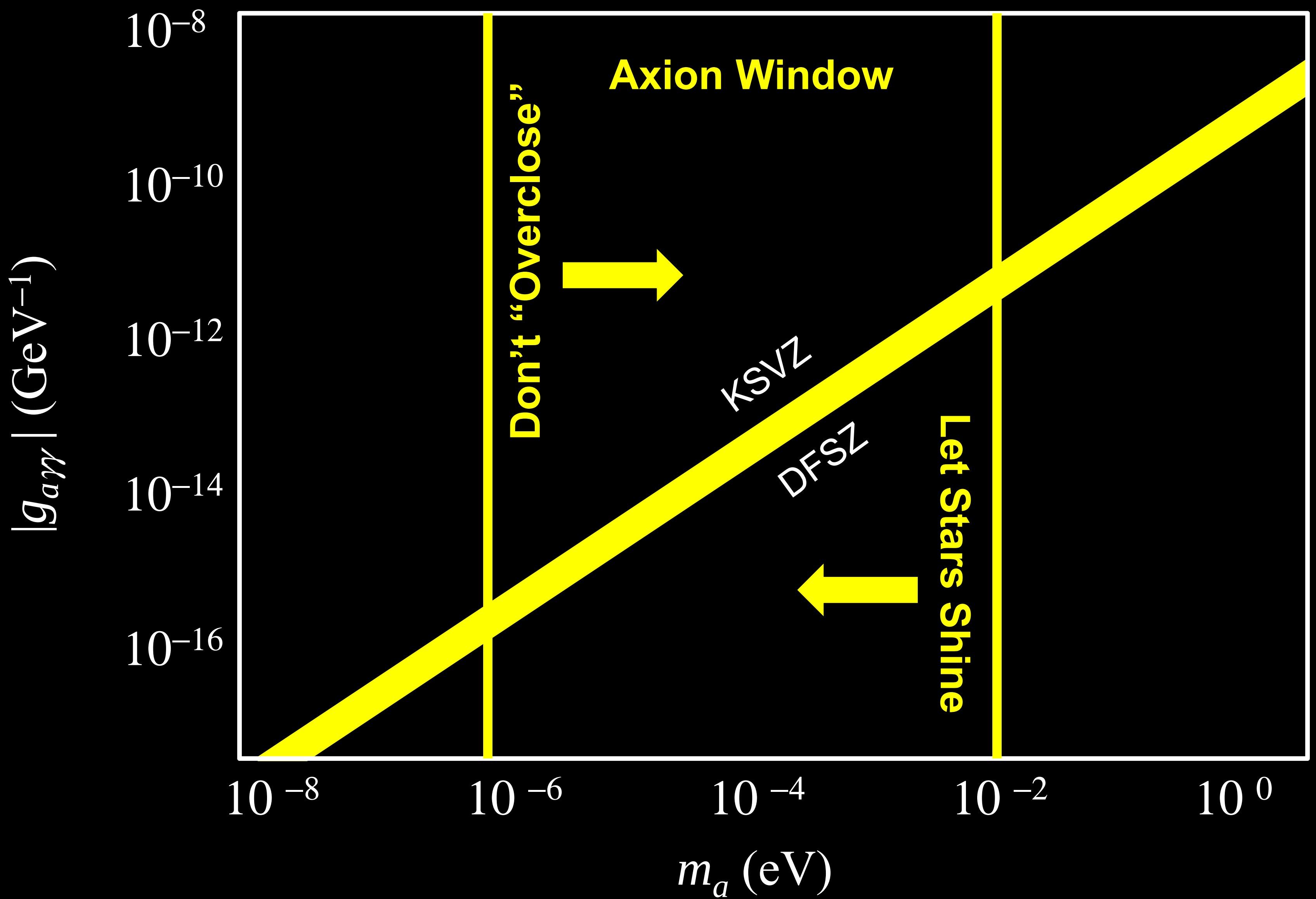
Cosmological Axion Production:
- Thermal
- Topological Defects
- Misalignment

Misalignment:
- Axion Dark Matter
- Isocurvature fluctuations
- Axion solitons

Misalignment:
- $f_a \lesssim 10^{12}$ GeV
- $m_a \approx \Lambda^2 / f_a \gtrsim \mu\mathrm{eV}$

Dark-Matter candidate for
- $m_a \approx \mu\mathrm{eV}$-ish !!!!!

Theory Gen-2 : “Invisible” Axion



Axion Windows ... $10^{-2}\,\mathrm{eV} \gtrsim m_a \gtrsim 10^{-6}\,\mathrm{eV}$

Should There Be a Defenestration?

Window 1

Window 2

.

.

.

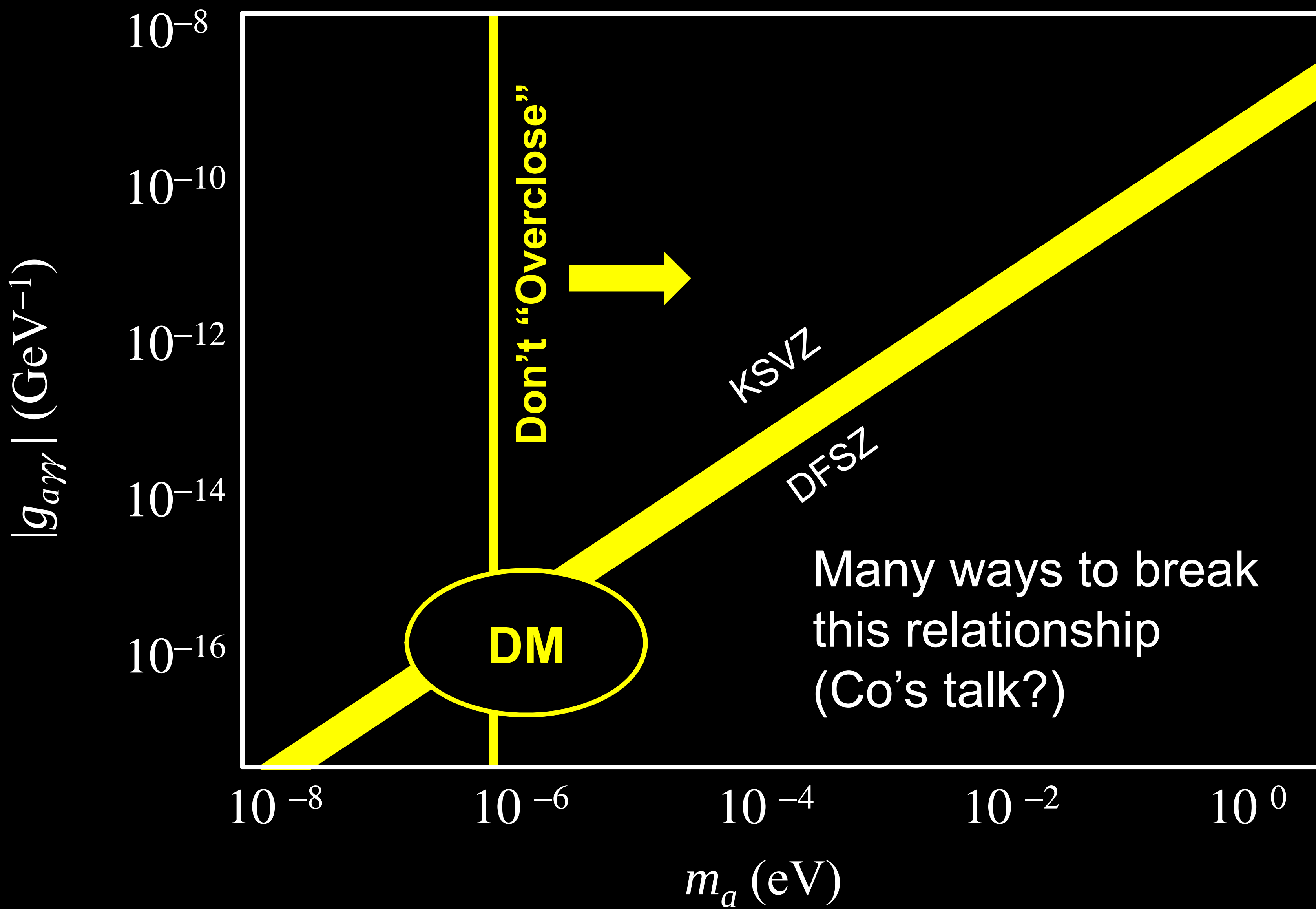
Window N

Theory Gen-2 : "Invisible" Axion

Theory sidebar:

- $\mathrm{U}(1)_{\mathrm{PQ}}$ is anomalous symmetry
- can't forbid other couplings which break $\mathrm{U}(1)_{\mathrm{PQ}}$ and spoil solution of strong-CP problem.
- "axion quality problem" (Holman,Hsu, Kephart, Kolb, Watkins; Kamionkowski & March-Russell; Barr & Seckel)
- E.g. Gravity: $V \sim \dfrac{\Phi^n}{M_{\mathrm{Pl}}^{n-4}} \qquad n \geq 14$
- Ways to evade problem: see Hook's review

Theory Gen-2 : “Invisible” Axion



Many ways to break this relationship (Co’s talk?)

95% of mass-energy in the universe is dark!
25% Dark Matter   70% Dark Energy

Dark matter seems to be (usually assumed to be)

- Non-baryonic (not quark nuggets, $30\ M_\odot$ Black Holes, planets, little stars, etc.)
- Cold (slowly moving)
- Dissipationless
- Not self-interacting
- Associated with all galaxies and other structures
- A particle
  - Stable
  - No strong or electromagnetic interactions

Two philosophies:

Simplicio	**Salviati**
I don't care about the nature of dark matter, as long as it is dark, cold, & dissipationless (CDM) I can calculate (simulate) its role in the evolution of structure and understand necessary astrophysics.	I care about the nature of dark matter because it must exist for a reason other than to be a part of Simplicio's code. Feynman: "Nature weaves its tapestry from the longest threads." What is the dark matter thread?

Oxford English Dictionary

Lost for Words?

simulation

Find Word

simulation

SECOND EDITION 1989

Pronunciation Spellings Etymology Quotations Date chart

1. a. The action or practice of simulating, with intent to deceive; false pretence, deceitful profession.

1340 *Ayenb*. 23 And þerof wexeþ uele zennes, ase ariȝthalf; þet is to wytene: lozengerie, simulacion. **c1400** *Rom. Rose* 7230 He nys no full good champioun That dredith such similacioun. **1412-20** LYDG. *Chron. Troy* IV. 4504 Amonge hem silfe to bringe in tresoun, Feyned trouþe and symulacioun. **1542** UDALL *Erasm. Apoph*. 170 He..did with mutual simulacion on his partie cover & kepe secrete the colorable dooyng of the saied feloe. **1577** tr. *Bullinger's Decades* (1592) 319 This precept doth commaunde vs..that..wee doe our neighbor harme..neither by simulation nor dissimulation. **1611** SPEED *Hist. Gt. Brit*. VI. (1632) 114 His nature relishing too much of the Punick craft and simulation. **1692** SOUTH *Serm*. (1697) I. 525 A Deceiving by Actions, Gestures, or Behaviour, is called Simulation, or Hypocrisie. **1711** STEELE *Tatler* No. 213 ¶1 Simulation is a Pretence of what is not, and Dissimulation a Concealment of what is. **1788** WESLEY *Wks*. (1872) VII. 43 Simulation is the seeming to be what we are not; dissimulation, the seeming not to be what we are. **1836** LANDOR *Pericles & Aspasia* Wks. 1846 II. 379, I wish he were as pious as you are: occasionally he appears so. I attacked him on his simulation. **1872** SHIPLEY *Gloss. Eccl. Terms* 71 Fraud.., whether it consists in simulation or dissimulation.

Particle dark-matter bestiary

- (sub-) eV mass neutrinos (WIMPs exist!) (hot)
- sterile neutrinos, gravitini (warm)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

} thermal relics, or decay of or oscillation from thermal relics

- Bose-Einstein condensates
- axions, axion miniclusters
- solitons (Q-balls, B-balls, …)

} from phase transitions

- supermassive WIMPZILLAs — from inflation
- Plancktons

} nonthermal relics

<u>Mass</u>

$10^{-22}\,\mathrm{eV}$ $(10^{-56}\,\mathrm{g})$ Bose-Einstein

$10^{-8}\,M_\odot$ $(10^{+25}\,\mathrm{g})$ axion miniclusters

<u>Interaction Strength</u>

only gravitational: WIMPZILLAs

strongly interacting: B balls

Dark Matter particle mass range

Mass Range for Particle Dark Matter

$m > 10^{-22}$ eV: de Broglie wavelength smaller than dark-matter dominated objects

$m < 10^{19}$ GeV: mass less than Planck mass

$m >$ few eV: if fermion (exclusion principle)

If thermal freeze-out

$m > m_e$: annihilation to SM particles

$m < 100$ TeV: annihilation cross section too small for larger masses

Is Dark Matter a Particle Or a Wave?

$m < 1$ eV: occupation number in de Broglie-wavelength volume $\gg 1 \rightarrow$ WAVE

$m > 1$ eV: occupation number in de Broglie-wavelength volume $< 1 \rightarrow$ PARTICLE

Dark Matter particle mass range

Plancktons: $m \sim m_{\text{Planck}} = 10^{19}$ GeV

WIMPzillas: $m \sim m_{\text{inflaton}} = 10^{10} - 10^{13}$ GeV

Supermassive: 100 TeV < m

WIMP range: $m_{\text{proton}} < m < 1$ TeV

Light dark matter: $m_{\text{electron}} < m < m_{\text{proton}}$

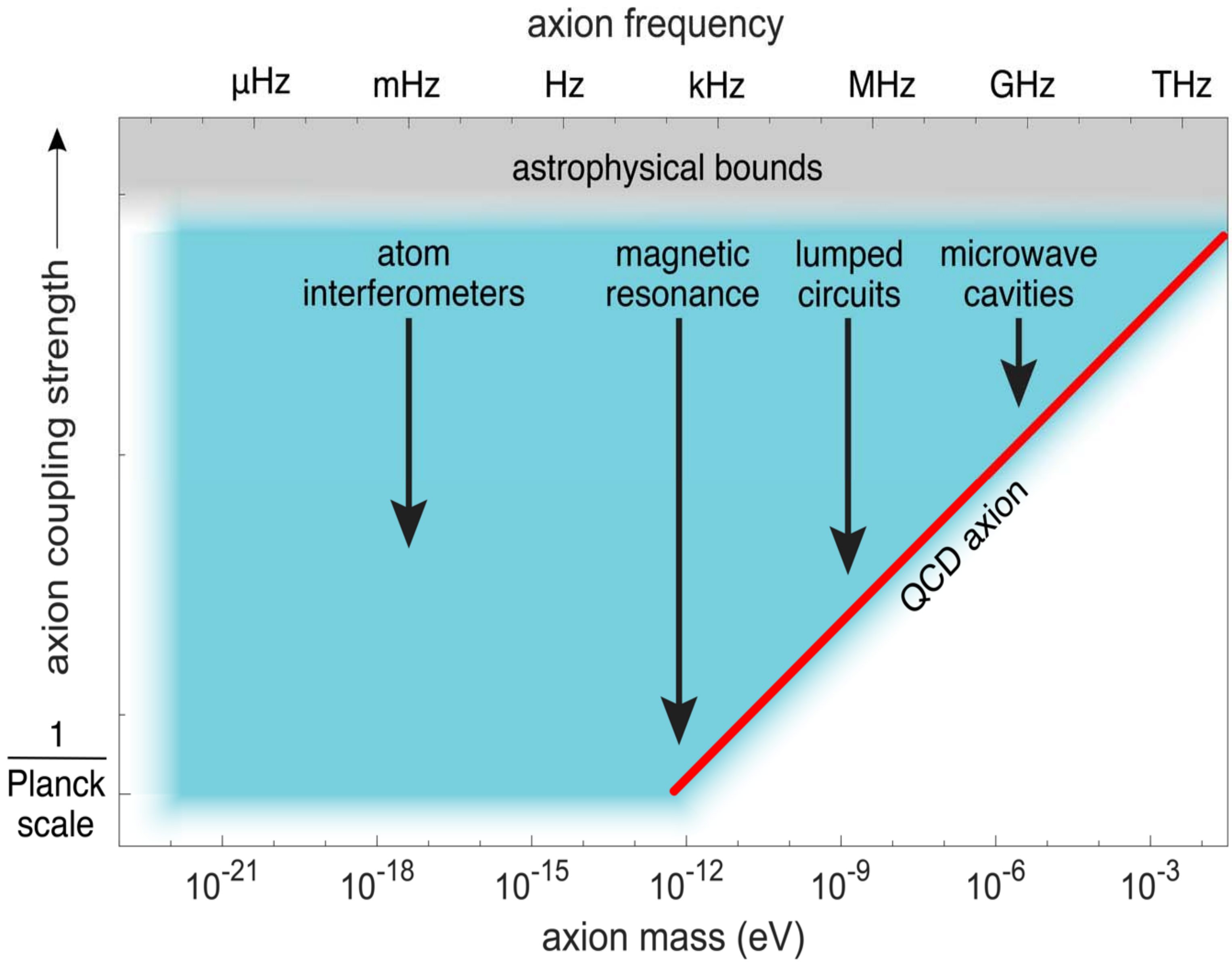
Ultralight dark matter: $m < 1$ eV

Theory Gen-3: ALPs, Dark Photons, …

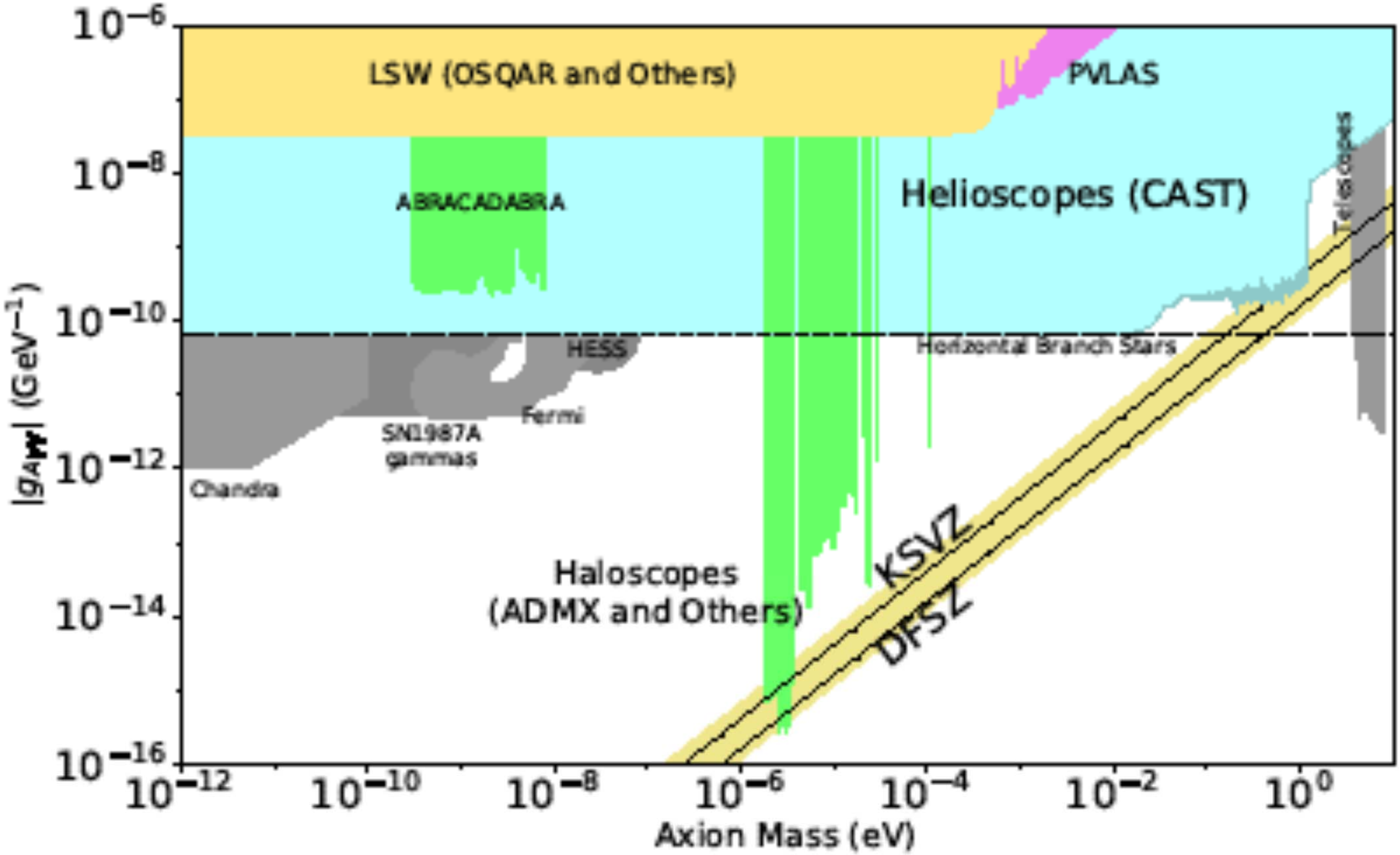
Axion theory and cosmology is extremely rich:

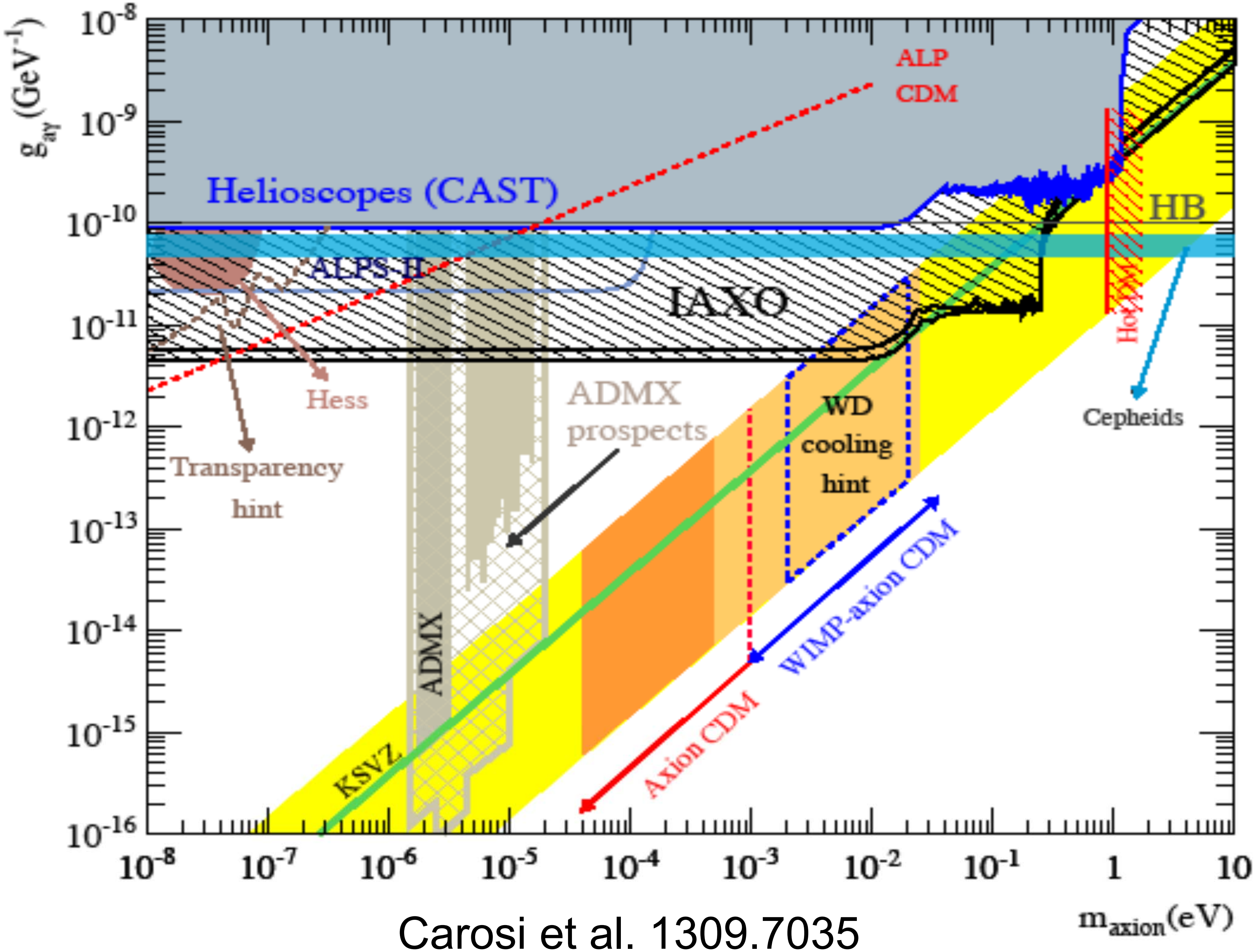
- Axions from string theory
- Axions and Baryogenesis
- Axion defects
- Dependence on initial misalignment angle
- Axion solitons
- Hidden sector
- Freeze-in
- Gravitational production

Detection Techniques



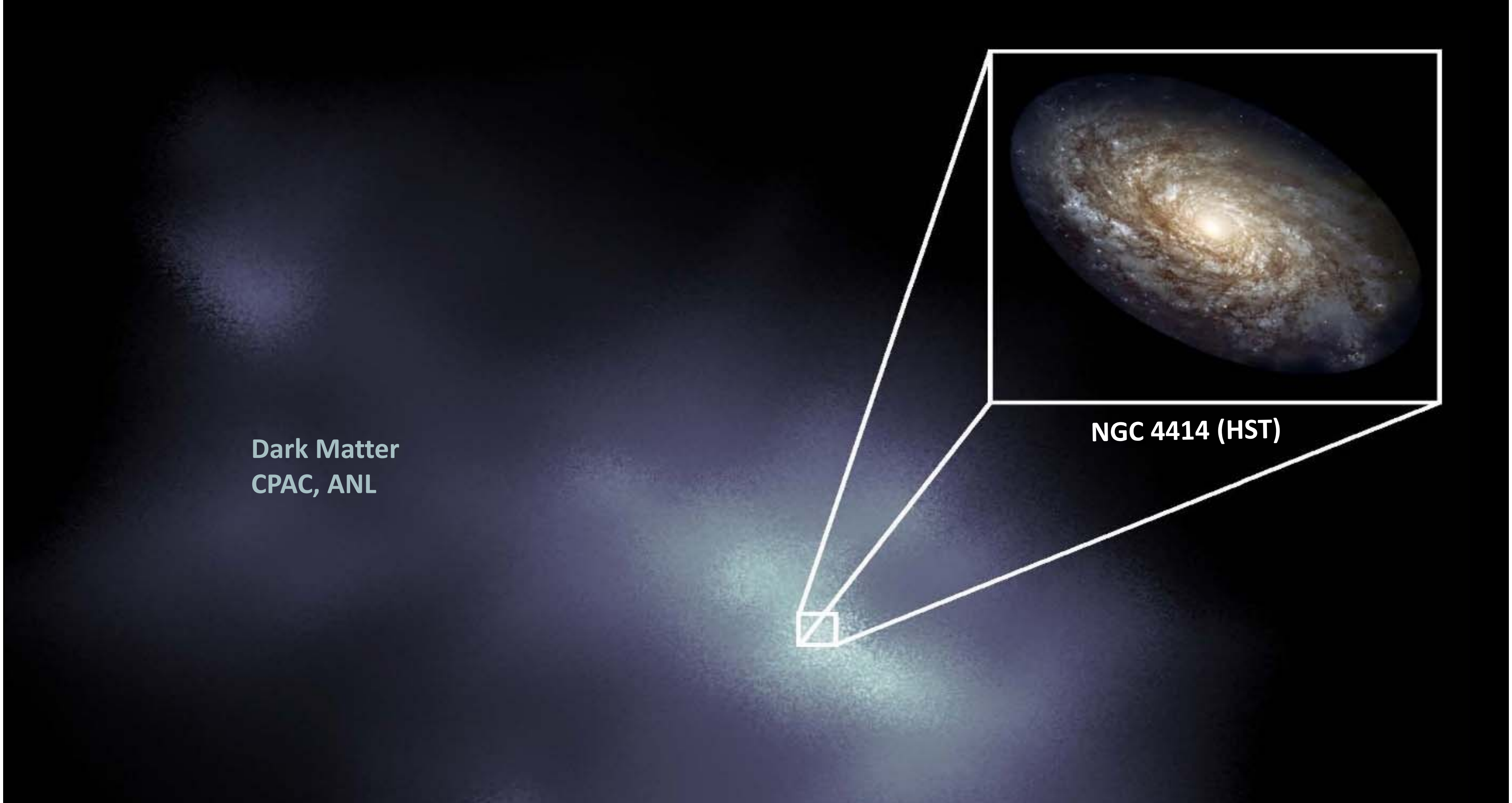
RPP Ringwald, Rosenberg, and Rybka





Carosi et al. 1309.7035

Basic Research Needs (BRN) Study for Dark-Matter Small Projects

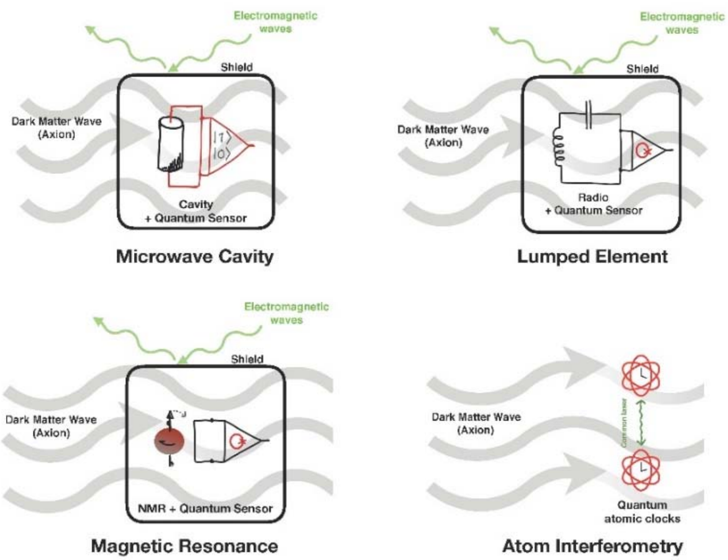


Summary of the High Energy Physics Workshop on

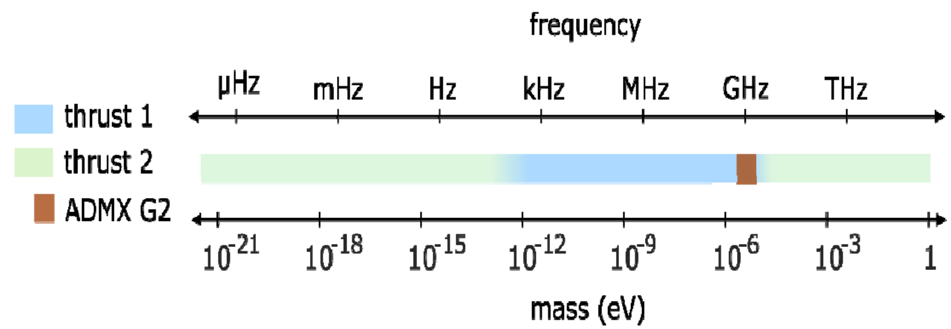
Basic Research Needs for Dark-Matter Small Projects New Initiatives

October 15 – 18, 2018

Observe wave dark matter using innovative technologies



Improvements in our understanding of cosmology show these very light particles to be excellent dark-matter candidates. Techniques required to search for very light particles differ from those for previous dark-matter searches and rely heavily on advances in quantum sensing.



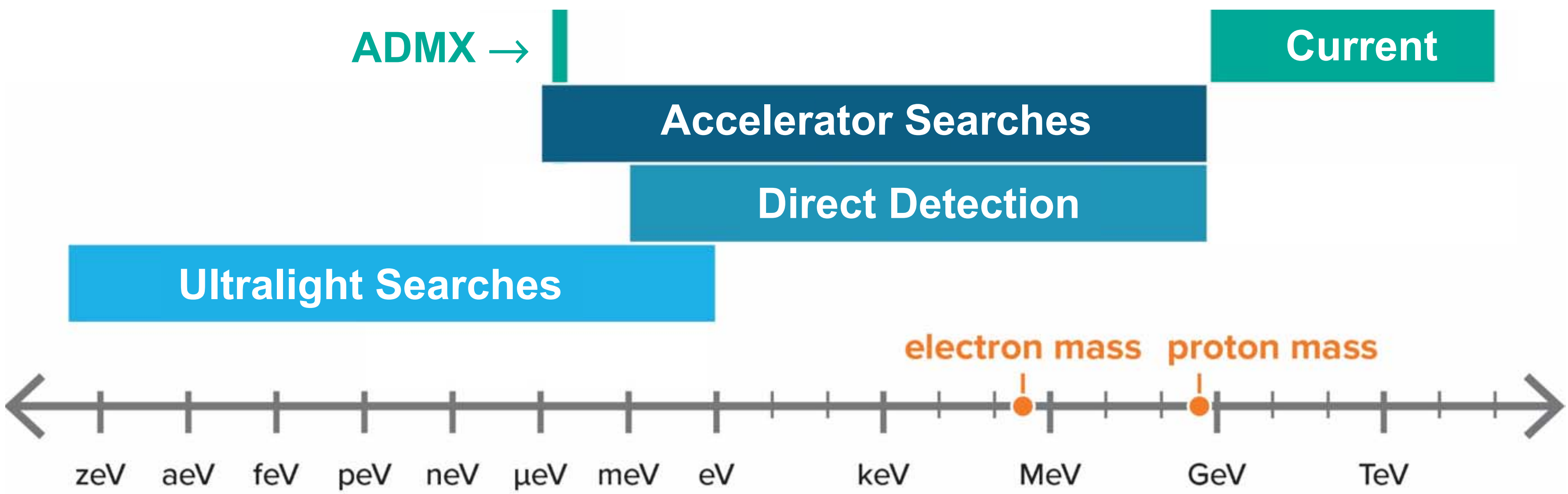
Thrust 1: Utilize new detector technologies to explore large parts of dark-matter parameter space covering a broad range of mass from 100 Hz to 10 GHz (roughly 10^{-12} eV - 10^{-4} eV), and targeting sensitivity to the QCD axion where possible.

Thrust 2: Develop or transfer new detector technologies to enable experiments to cover the remaining parameter space for well-motivated dark-matter models spanning the entire 20 orders of magnitude in mass and also targeting complete coverage of QCD axion models.

For discussion

- Dark Matter is not a cold thermal relic WIMP.
- 2020s is not the decade of the WIMP! Time to MOVE ON!

- Where to move?
  - Axions/dark photons
  - Lighter thermal DM
  - Ultraheavy DM
  - DM sector with interactions
  - Is DM a particle? Soliton?



43 Years….why not give up?

Sometimes patience is rewarded:

Higgs boson theorized 1964 } 49 years
Higgs boson discovered 2013

Discovery of axion in 2026 (Gen-3?)

GAMES | BROWSE THESAURUS | WORD OF THE DAY | WORDS AT PLAY

Merriam-Webster SINCE 1828

keynote address

Dictionary | Thesaurus

Definition of *keynote address*

: an address designed to present the issues of primary interest to an assembly (such as a political convention) and often to arouse unity and enthusiasm

Simple, Elegant, Compelling

Axions are the simplest, most elegant, most compelling explanation for the strong CP problem.

Axions are the best motivated dark-matter candidate.

Axions must be pursued.

Beyond Gen-2

“Don’t be afraid to take a big step when one is indicated. You can’t cross a chasm in two small jumps.”

– David Lloyd George

“Go big or go home”

– American Authors

Merriam-Webster SINCE 1828

GAMES | BROWSE THESAURUS | WORD OF THE DAY | WORDS AT PLAY

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Definition of *off-key*

1: varying in pitch from the proper tone of a melody

2: IRREGULAR, ANOMALOUS

Off-Key Question:

- Tommy Gold's comment
- When should we stop looking for axions, ALPs, etc.?
- Gen-X … what is X ?
- WIMP searches (Xenon, LZ, etc.) have a natural place to stop (the neutrino floor).
- Open-ended searches have an (undeserved) bad rep.

43 Years of Axions (Keynote Address)

Rocky Kolb, University of Chicago January 2021