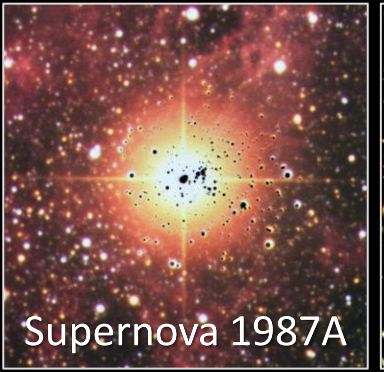
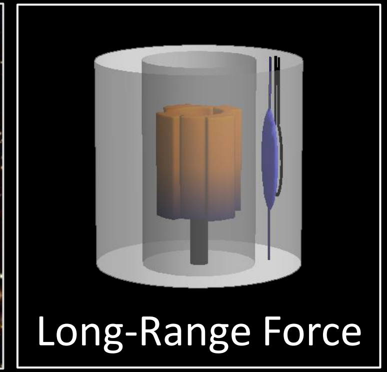
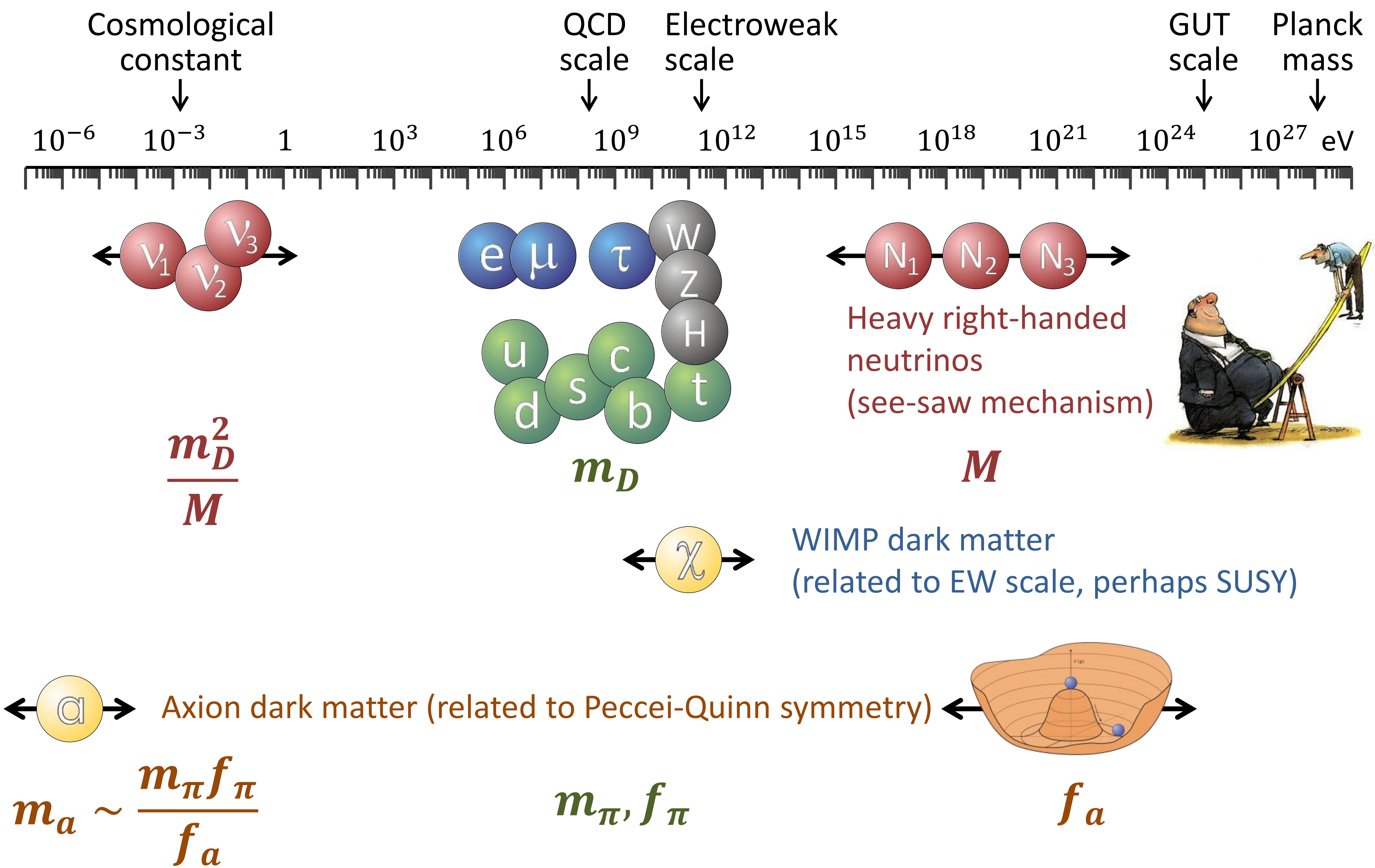




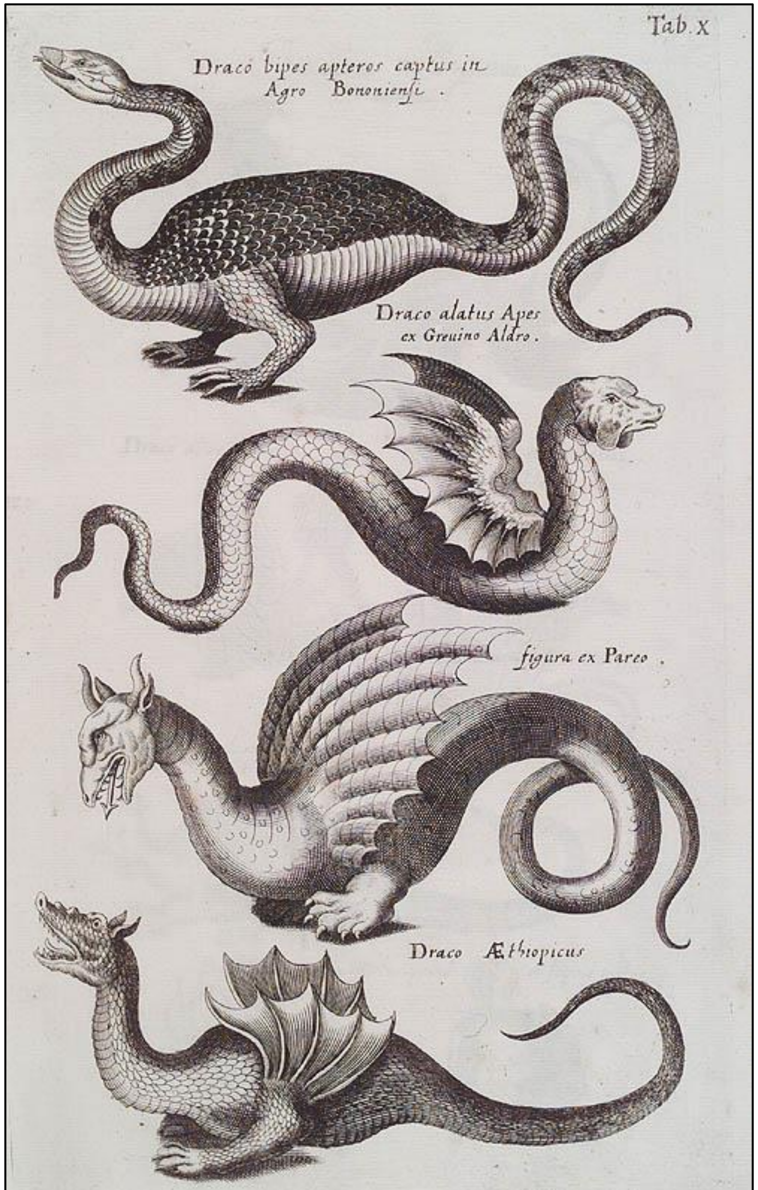
Axion Landscape

Georg G. Raffelt, Max-Planck-Institut für Physik, München

High- and Low-Energy Frontiers in Particle Physics



Bestiarium of Low-Mass Bosons



Weakly Interacting Sub-eV Particles (WISPs)

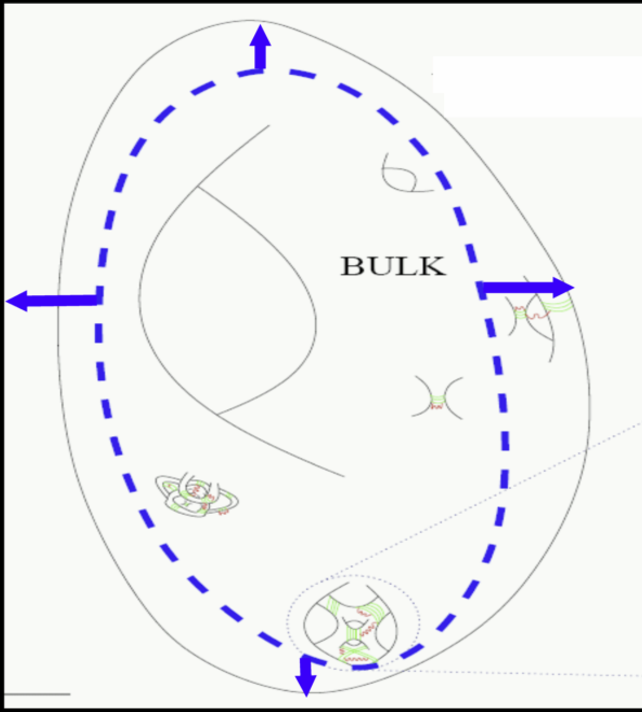
- **Axions** (1 parameter family $m_a f_a \sim m_\pi f_\pi$)
  Solves strong CP problem
  Could be dark matter
- **String axions**
  (almost massless pseudoscalars in string theory)
  One of them may solve CP problem
- **Axion-like particles (ALPs)**
  Generic two-photon vertex, could be dark matter
  (2 parameters m_a and $g_{a\gamma}$)
- **Hidden photons**
  Low-mass gauge bosons from $U'(1)$
  (kinetic mixing parameter χ and mass $m_{\gamma'}$)
- **Chameleons**
  Scalars in certain models of scalar-tensor gravity
  Motivated by dark energy
  Environment-dependent properties

String theory: Moduli and Axions

- String theory needs Extra Dimensions

Must compactify

- Shape and size deformations correspond to fields: Moduli (WISPs) and Axions Connected to the fundamental scale, here string scale



WISP candidates

[Joerg Jaekel]

CP Violation in Particle Physics

Discrete symmetries in particle physics

C – Charge conjugation, transforms particles to antiparticles
violated by weak interactions

P – Parity, changes left-handedness to right-handedness
violated by weak interactions

T – Time reversal, changes direction of motion (forward to backward)

CPT – exactly conserved in quantum field theory

CP – conserved by all gauge interactions
violated by three-flavor quark mixing matrix

Physics Nobel Prize 2008

- All measured CP-violating effects derive from a single phase in the quark mass matrix (Kobayashi-Maskawa phase), i.e. from complex Yukawa couplings
- Cosmic matter-antimatter asymmetry requires new ingredients

The CP Problem of Strong Interactions

Real quark mass → m_q; Phase from Yukawa coupling → θ_q; Angle variable → Θ; CP-odd quantity $\sim \mathbf{E}\cdot\mathbf{B}$ → $G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$

$$\mathcal{L}_{\rm QCD} = \sum_q \bar{\psi}_q\left(\mathrm{i}D - m_q e^{\mathrm{i}\theta_q}\right)\psi_q - \tfrac{1}{4}G_{\mu\nu a}G_a^{\mu\nu} - \Theta\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$$

Remove phase of mass term by chiral transformation of quark fields

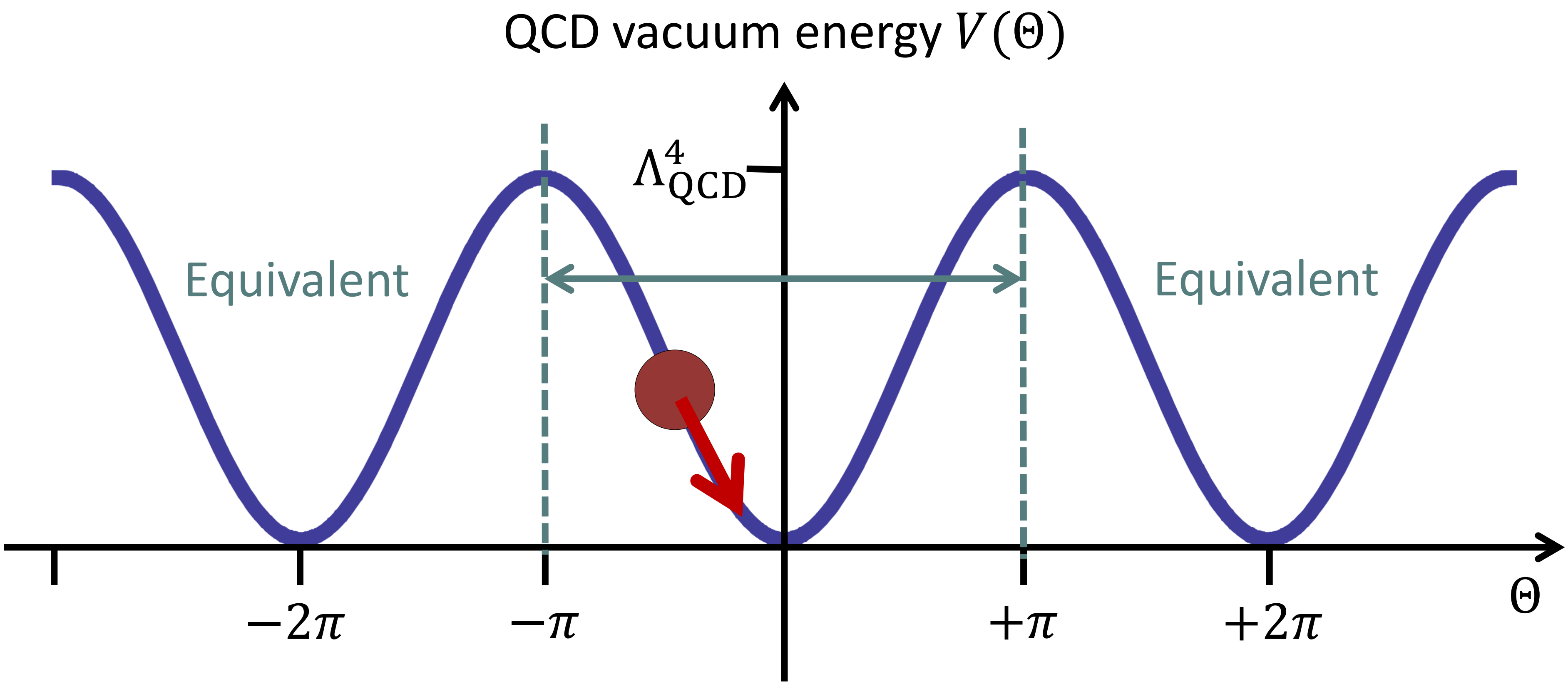
$$\psi_q \to e^{-i\gamma_5\theta_q/2}\psi_q$$

$$\mathcal{L}_{\rm QCD} = \sum_q \bar{\psi}_q\left(\mathrm{i}D - m_q\right)\psi_q - \tfrac{1}{4}GG - \underbrace{\left(\Theta - \arg\det M_q\right)}_{-\pi\le\bar{\Theta}\le+\pi}\frac{\alpha_s}{8\pi}G\tilde{G}$$

- $\bar{\Theta}$ can be traded between quark phases and $G\tilde{G}$ term
- No physical impact if at least one $m_q = 0$
- Induces a large neutron electric dipole moment (a T-violating quantity)

Experimental limits: $|\bar{\Theta}| < 10^{-11}$ Why so small?

Strong CP Problem



- CP conserving vacuum has $\Theta = 0$ (Vafa and Witten 1984)
- QCD could have any $-\pi \leq \Theta \leq +\pi$, is "constant of nature"
- Energy can not be minimized: Θ not dynamical

Peccei-Quinn solution:

Make Θ dynamical, let system relax to lowest energy

37 Years of Axions

VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

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.

VOLUME 40, NUMBER 5 PHYSICAL REVIEW LETTERS 30 JANUARY 1978

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)

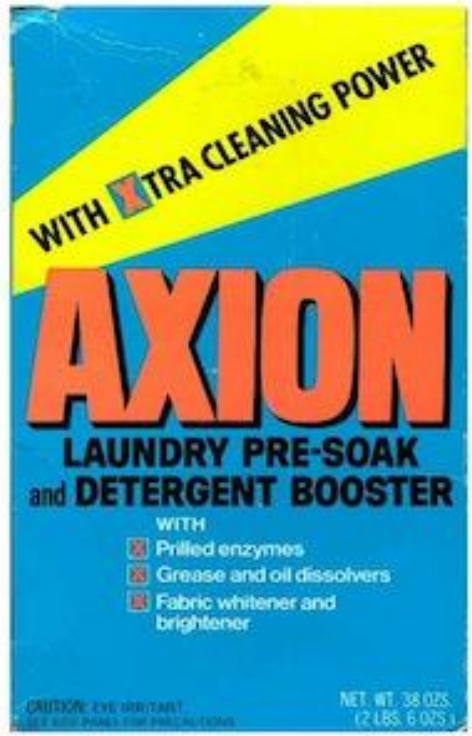
The requirement that *P* and *T* be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

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 $3\oplus 3^*$ structure of chi-

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 unattrac-

The Cleansing Axion

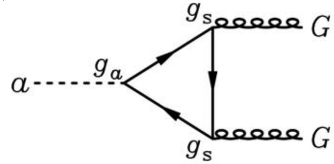


Frank Wilczek

"I named them after a laundry detergent, since they clean up a problem with an axial current."
(Nobel lecture 2004)

Gluon coupling (generic), defines normalization of axion scale f_a

$$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi} \frac{a}{f_a} G\tilde{G}$$



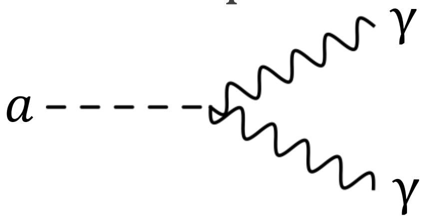
Mass (generic) depends on up/down quark masses

$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$$

Axion-photon coupling (model dependent)

Generic from a-π-η mixing

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\,\mathbf{E}\cdot\mathbf{B}\,a = \frac{\alpha}{2\pi}\left(\frac{E}{N} - 1.92\right)\frac{a}{f_a}\mathbf{E}\cdot\mathbf{B}$$

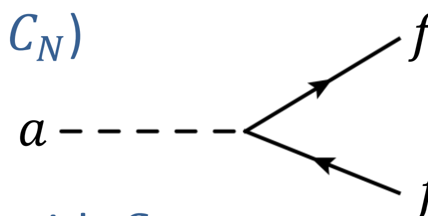


Model-dependent,
E/N = 0 (KSVZ), 8/3 (DFSZ), many others

Axion-nucleon coupling (model-dependent numerical factors C_N)

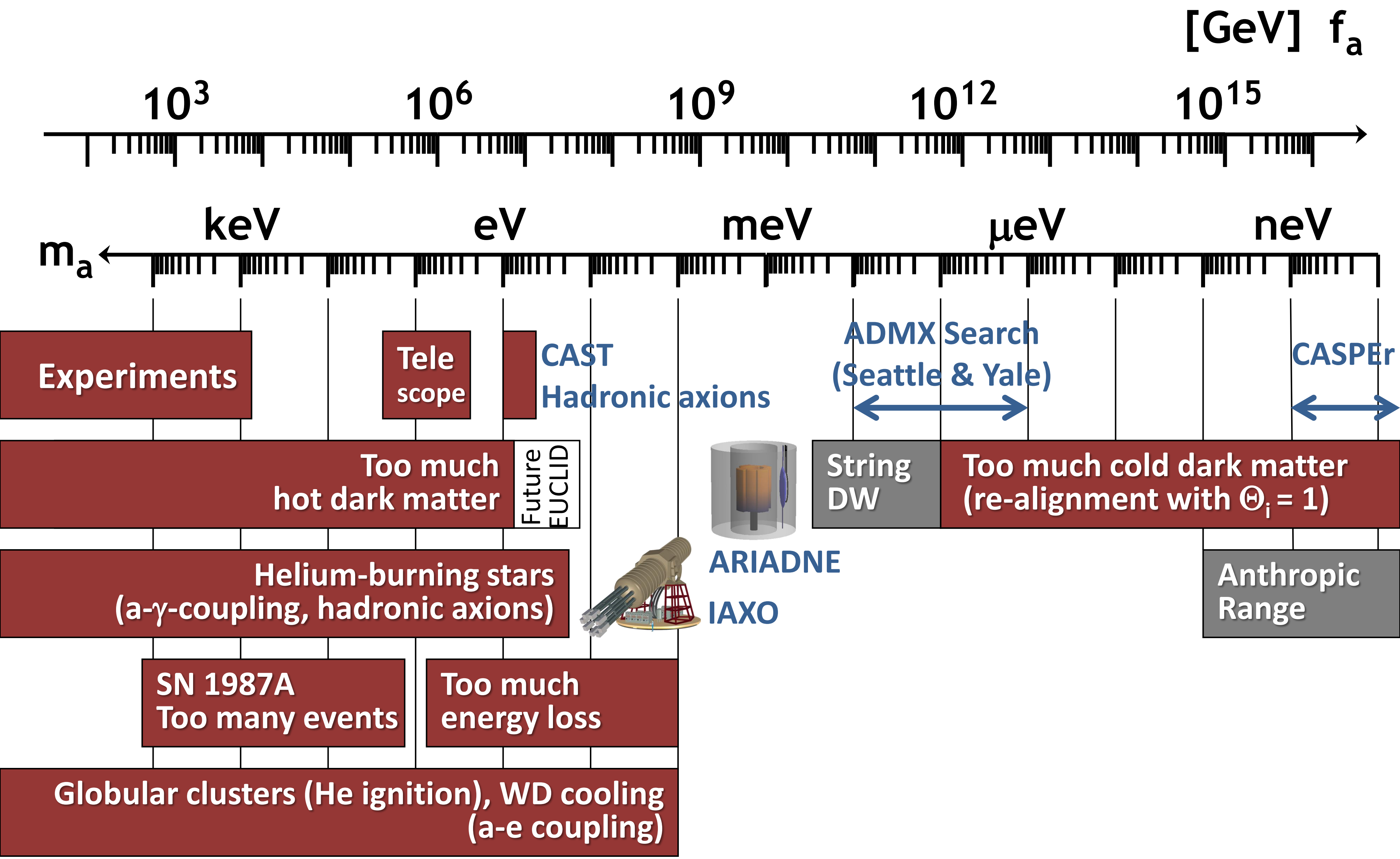
$$\mathcal{L}_{aN} = C_N\,\overline{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \frac{\partial_\mu a}{2 f_a}$$

- Axial-vector current
- Spin-dependent int'n

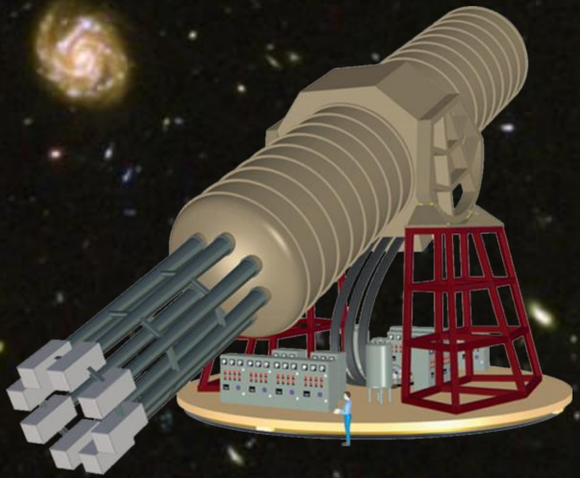


Axion-electron coupling in non-hadronic models is analogous with C_e

Axion Bounds and Searches



Let there be light



VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

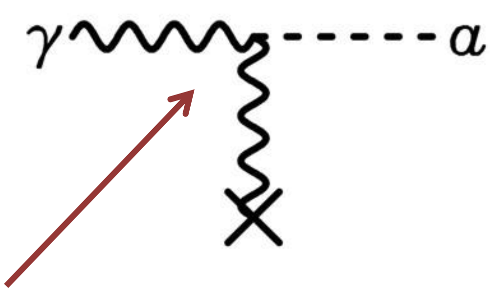
Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.

Primakoff effect:

Axion-photon transition in external static E or B field
(Originally discussed for π^0
by Henri Primakoff 1951)



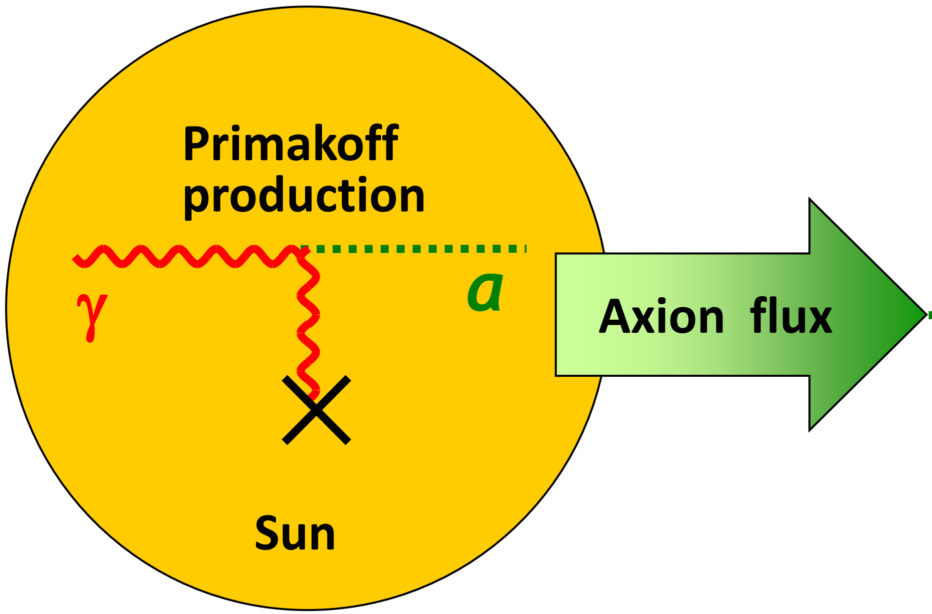
Two-photon vertex generic for
π^0, η, axion-like particles (ALPs), gravitons

Pierre Sikivie:

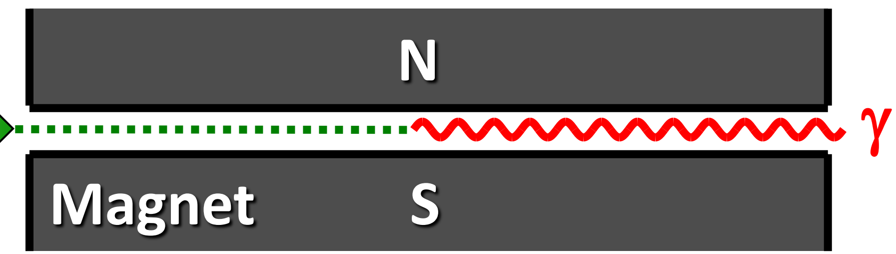
Macroscopic B-field can provide a large coherent transition rate over a big volume (low-mass axions)

- Axion helioscope:
  Look at the Sun through a dipole magnet
- Axion haloscope:
  Look for dark-matter axions with a microwave resonant cavity

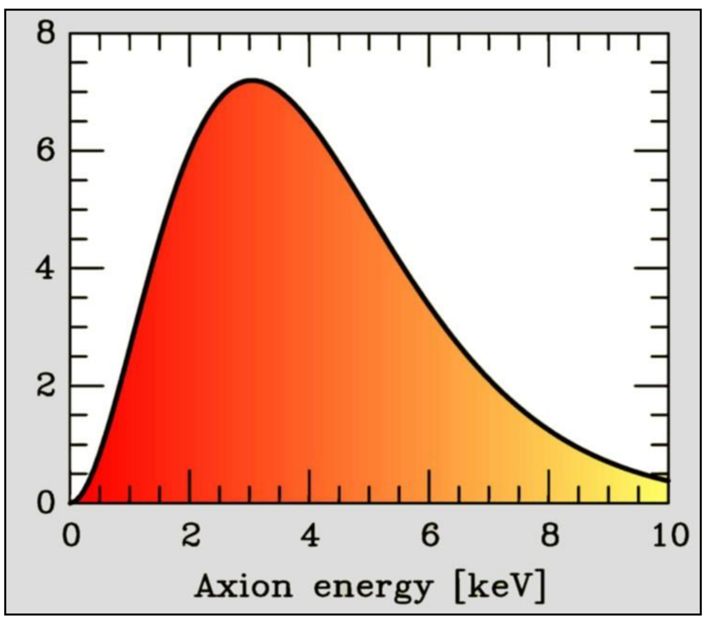
Search for Solar Axions



Axion Helioscope (Sikivie 1983)



Axion-Photon-Oscillation



- Tokyo Axion Helioscope ("Sumico") (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST) (Data since 2003)

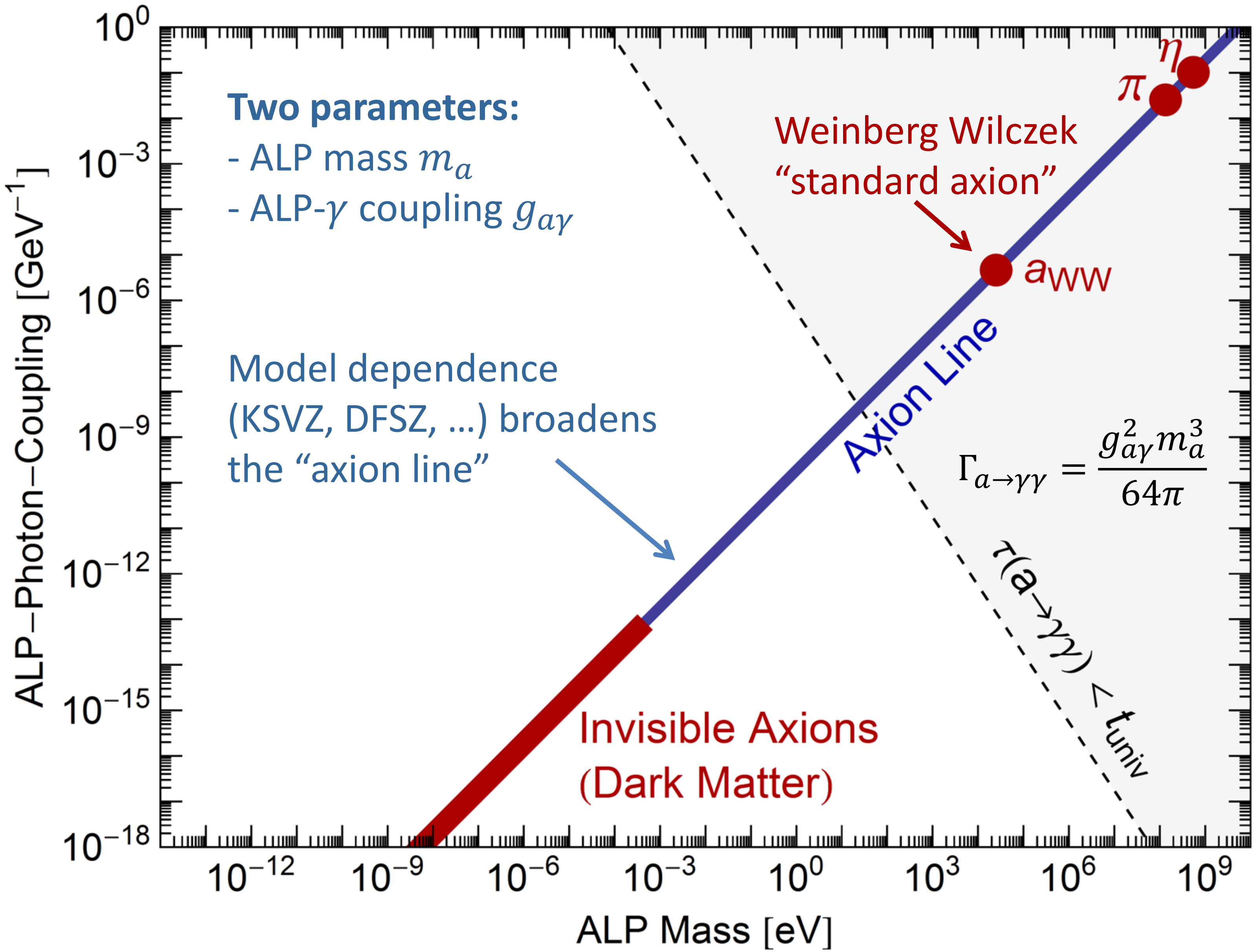
Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux from dark-matter experiments (SOLAX, COSME, DAMA, CDMS ...)

Let's point a magnet at the sun…

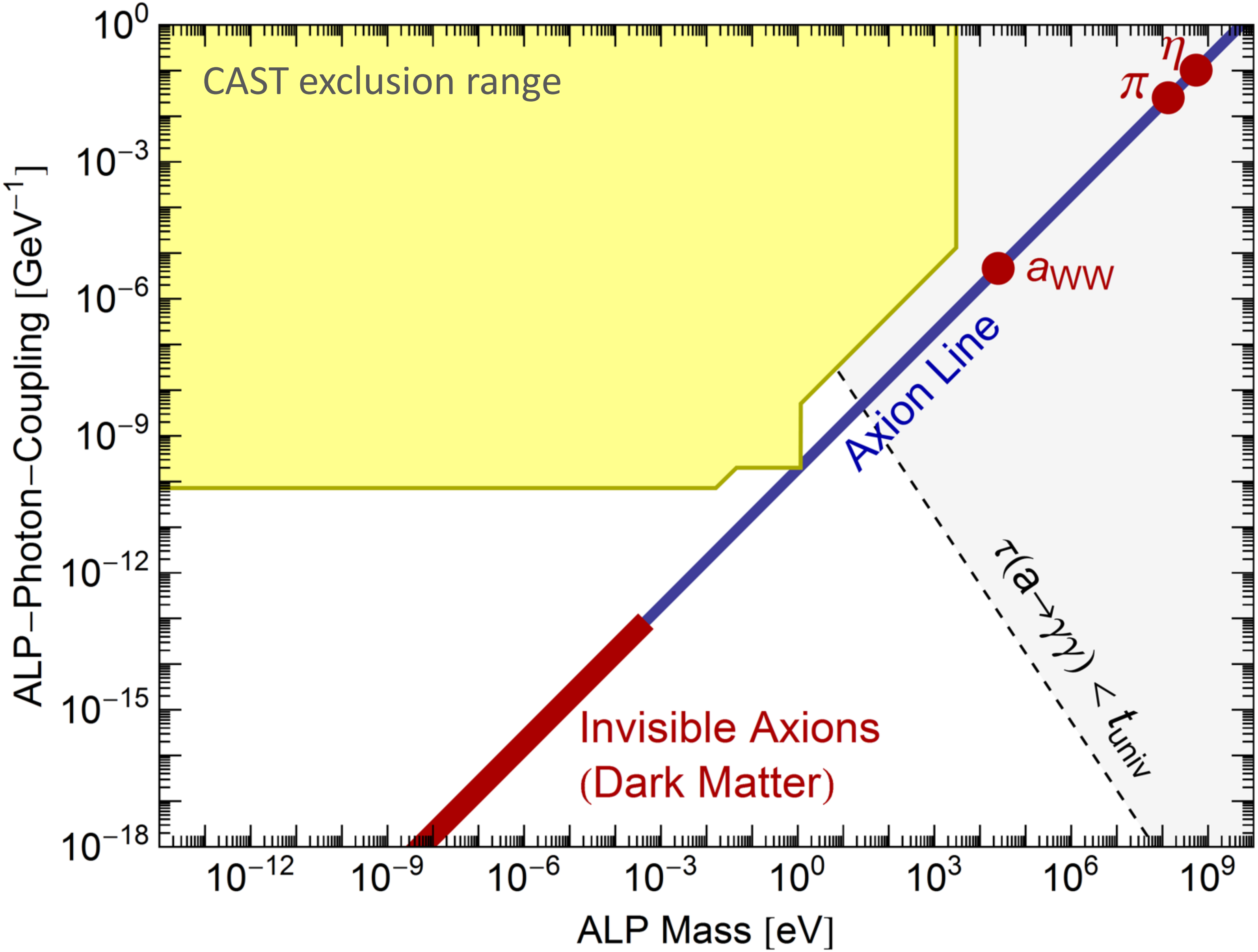
…and look for X-Rays!

By CAST student Sebastian Baum

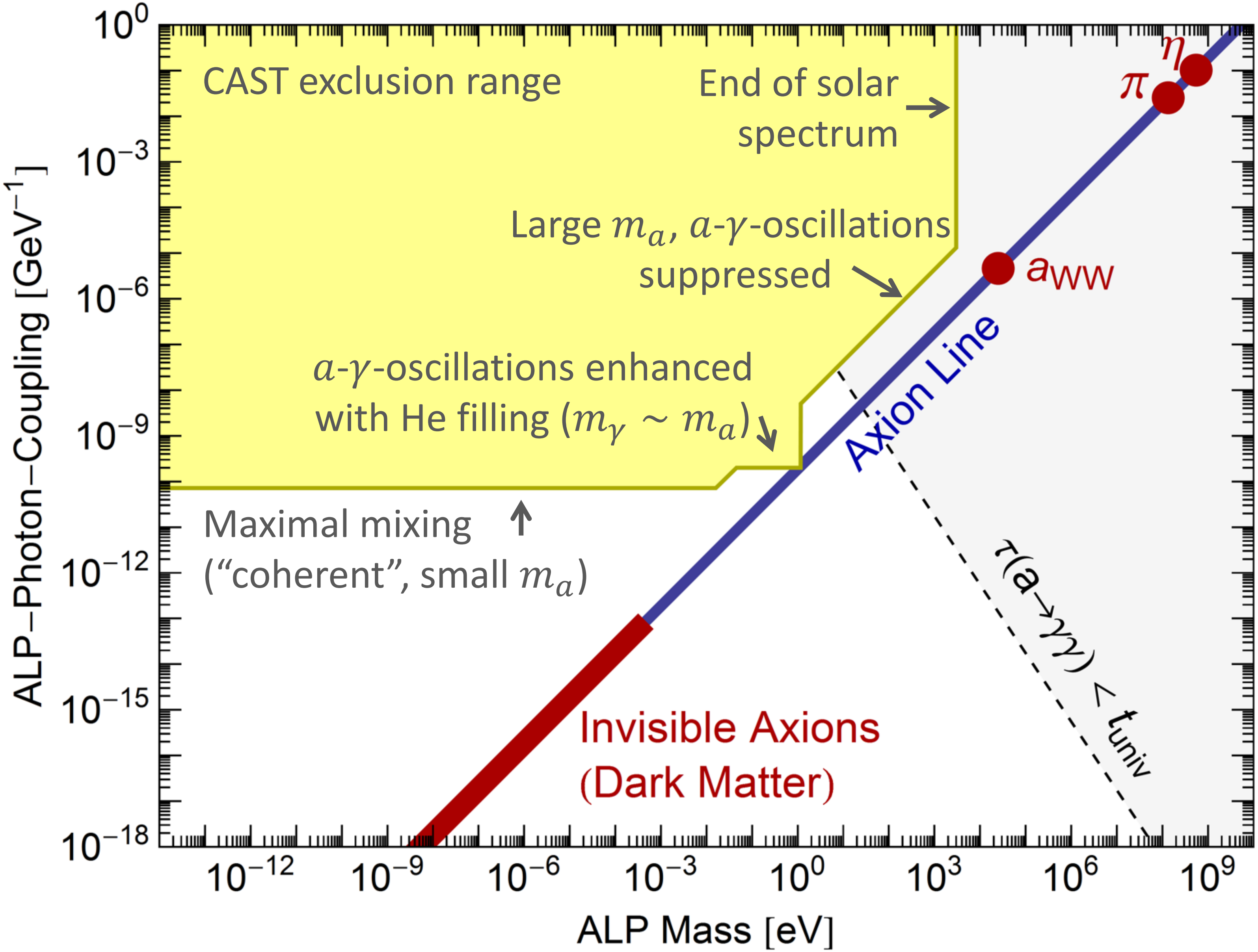
Parameter Space for Axion-Like Particles (ALPs)



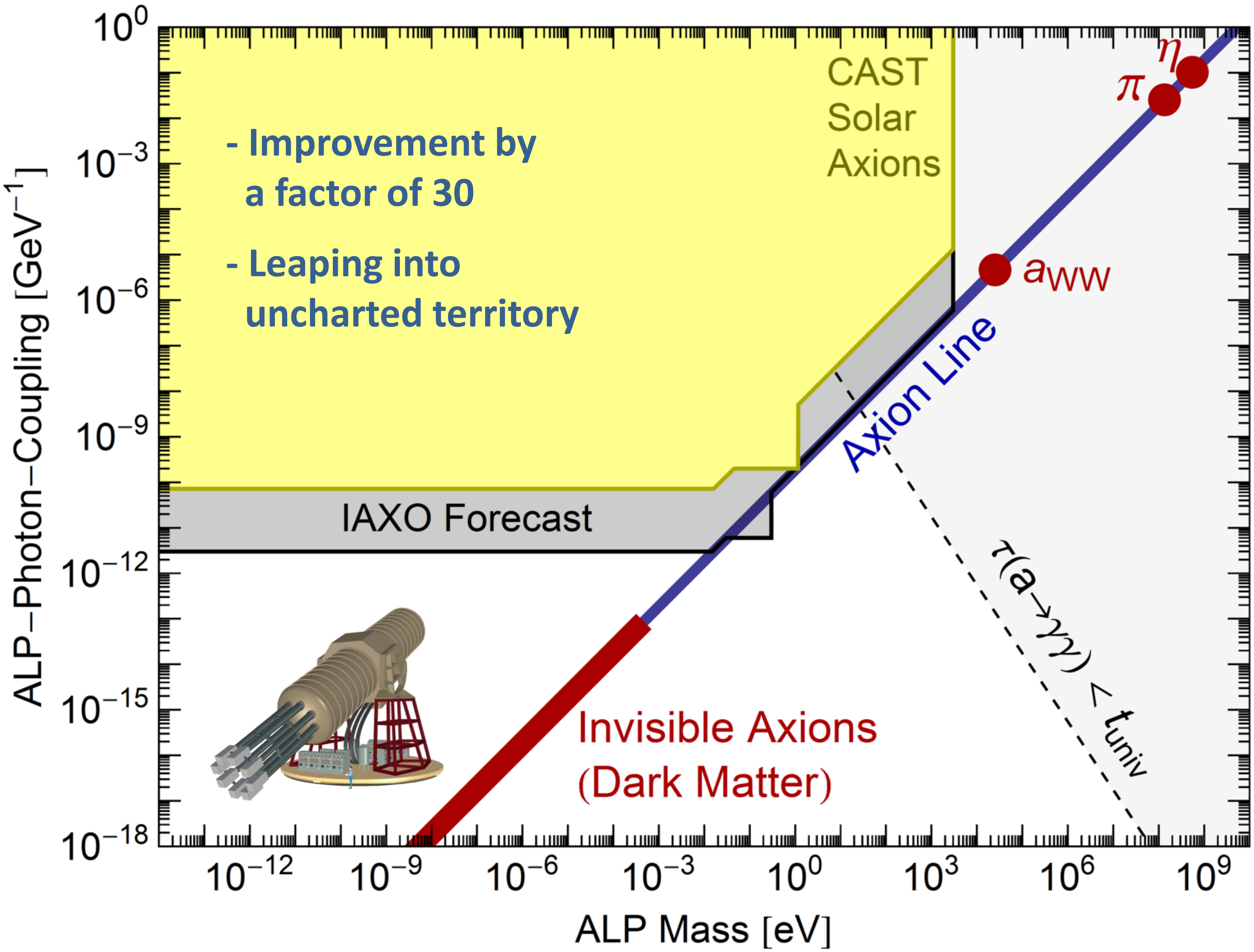
Parameter Space for Axion-Like Particles (ALPs)



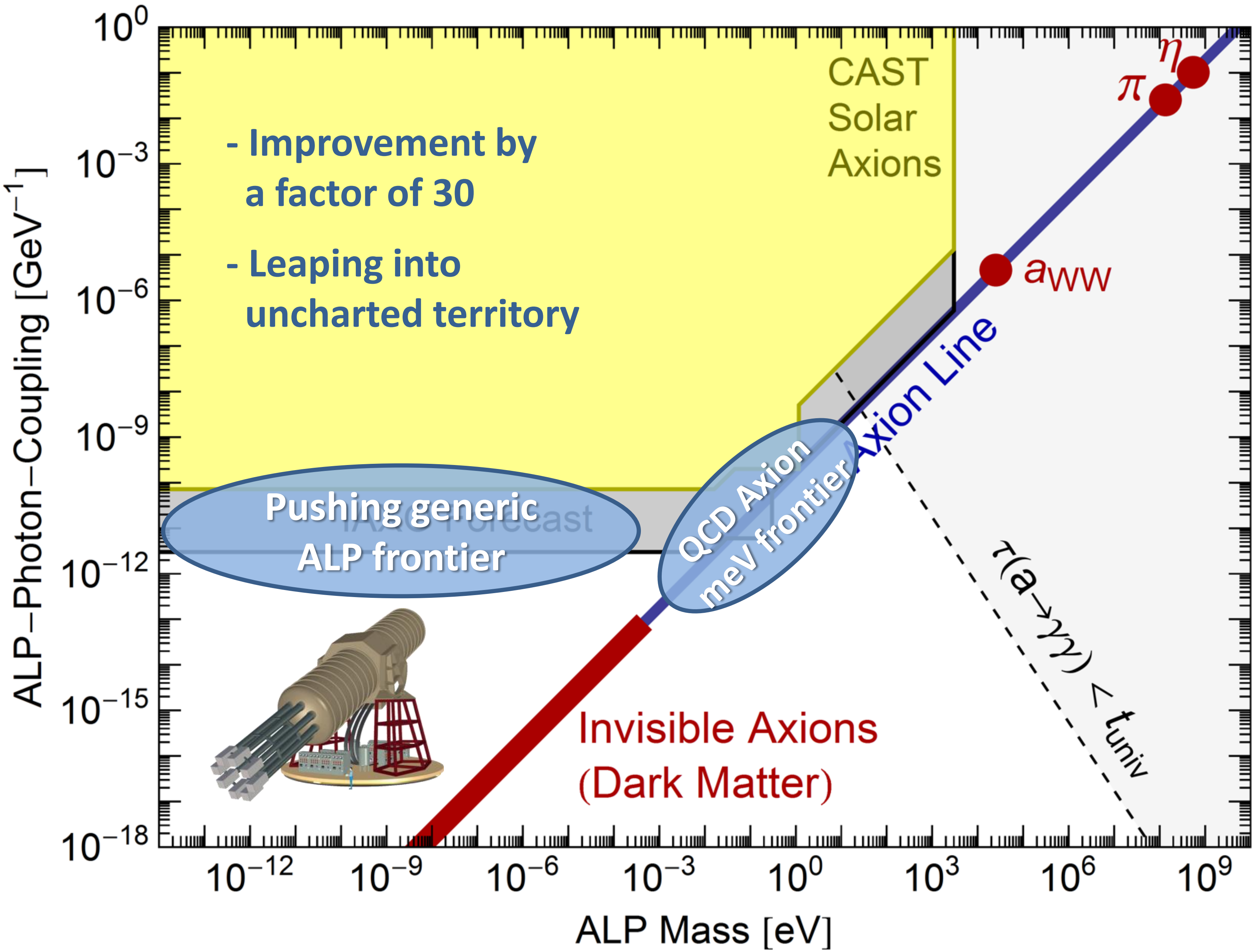
Parameter Space for Axion-Like Particles (ALPs)



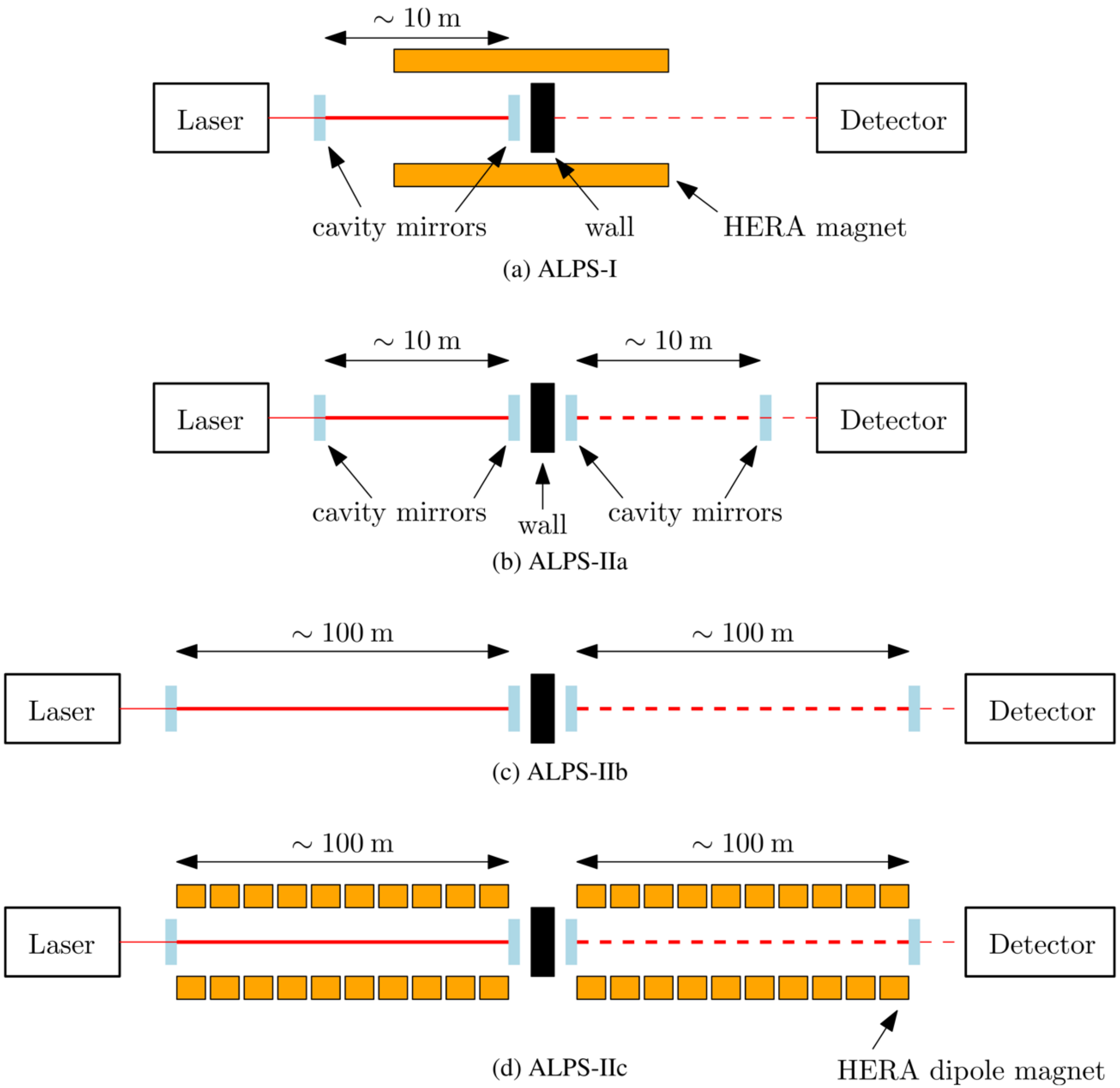
Parameter Space for Axion-Like Particles (ALPs)



Parameter Space for Axion-Like Particles (ALPs)



Any Light Particle Search II (ALPS-II) at DESY



ALPS-I (finished)

ALPS-IIa (2014)

ALPS-IIb (2015)

ALPS-IIc (2017)

ALPS-II Technical Design Report, arXiv:1302.5647

Shining TeV Gamma Rays through the Universe

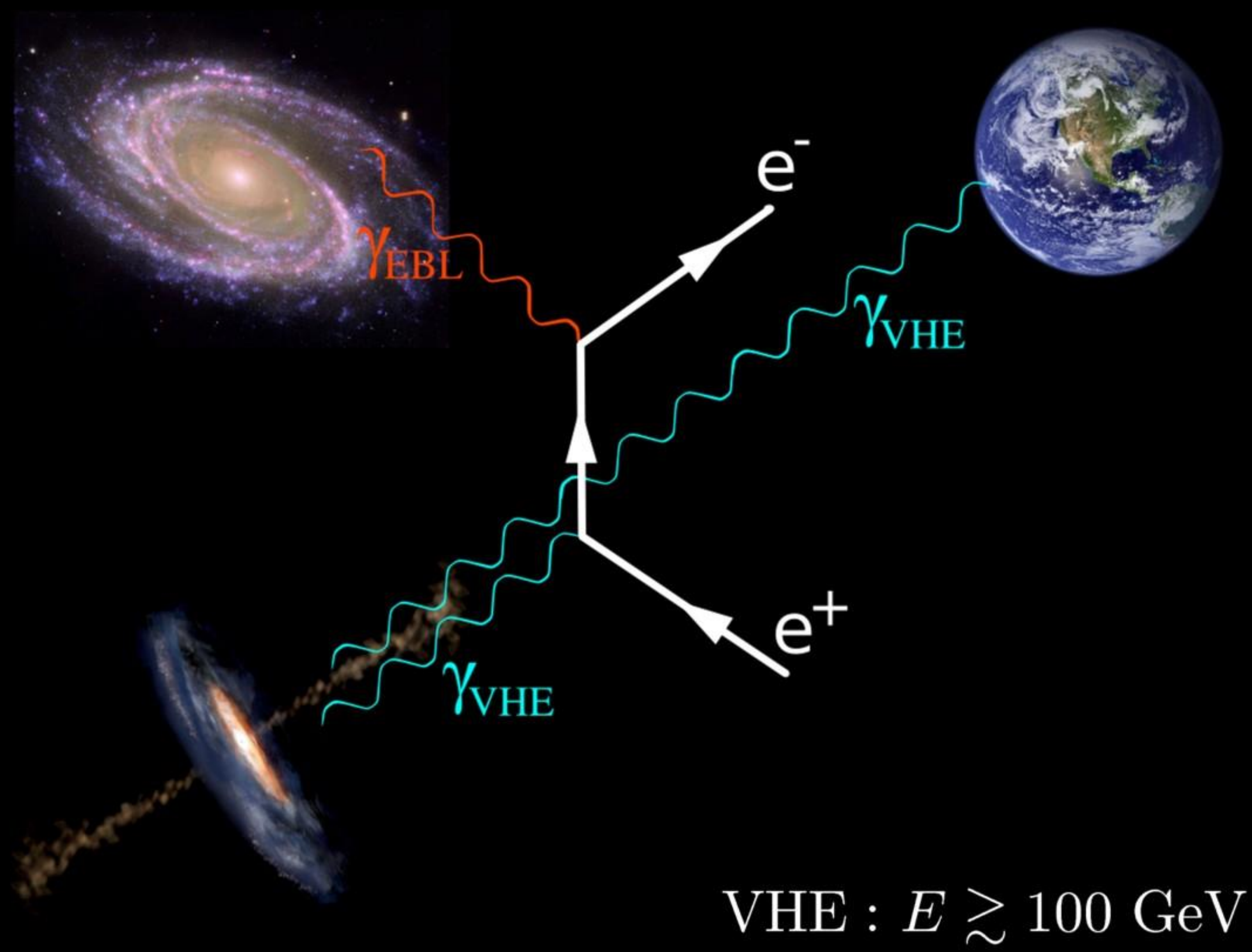


Figure from a talk by Manuel Meyer (Univ. Hamburg)

Shining TeV Gamma Rays through the Universe

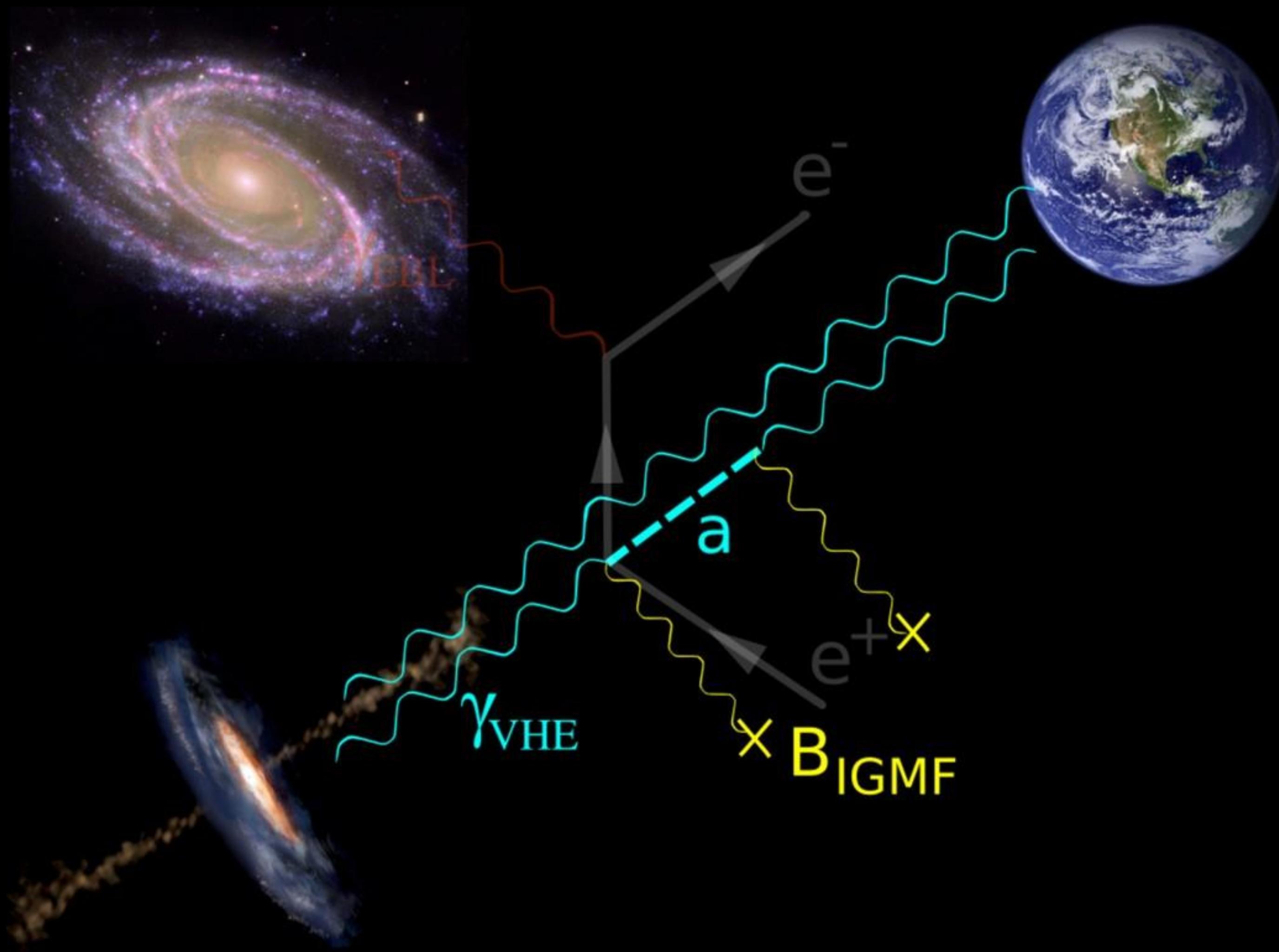
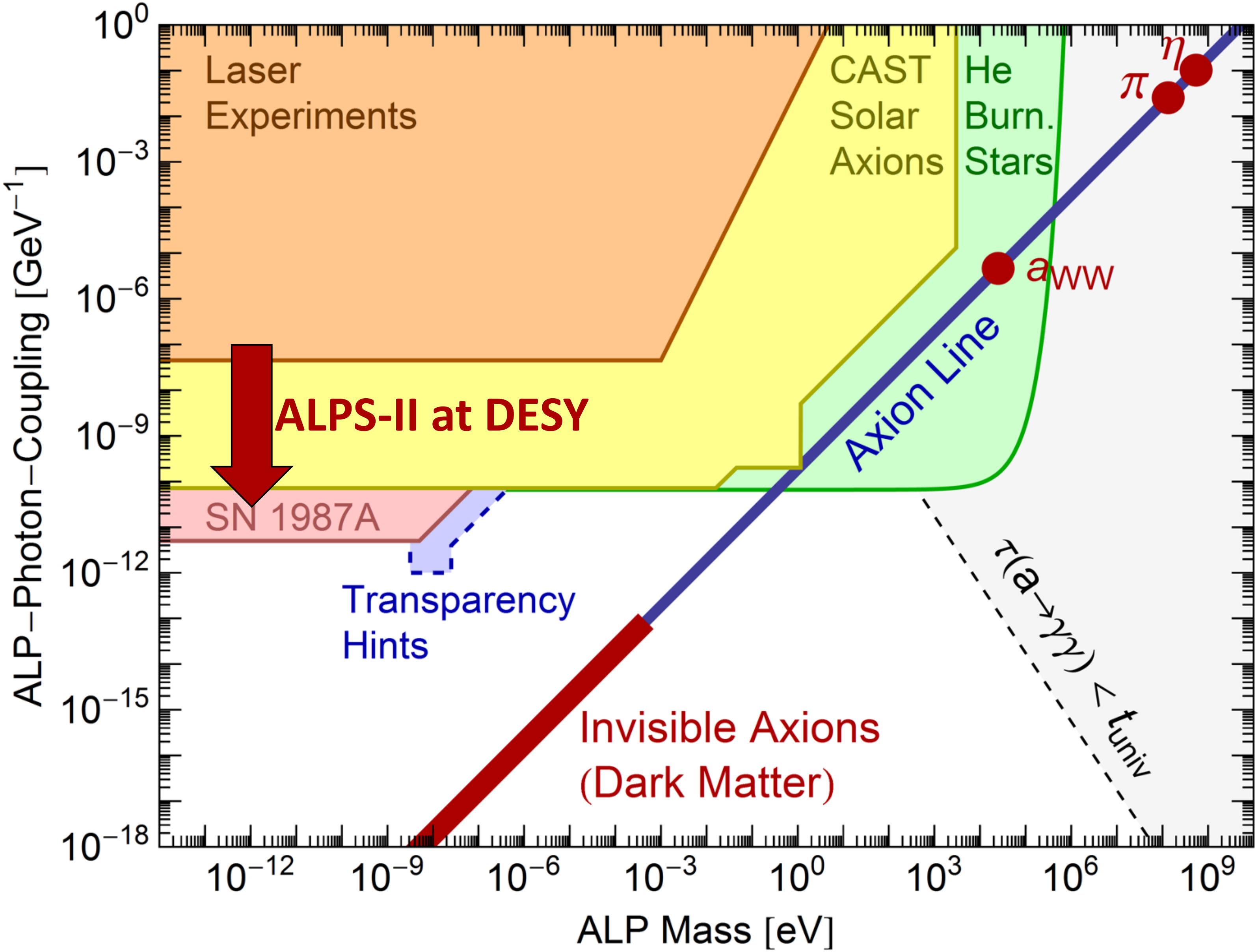
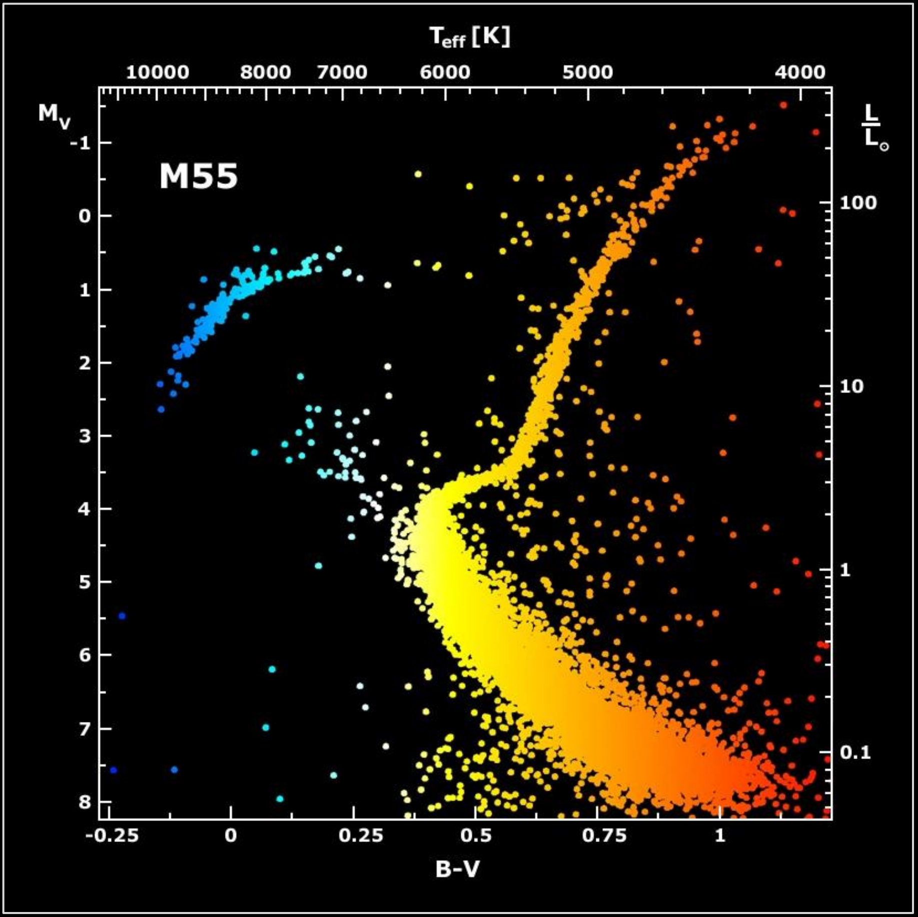


Figure from a talk by Manuel Meyer (Univ. Hamburg)

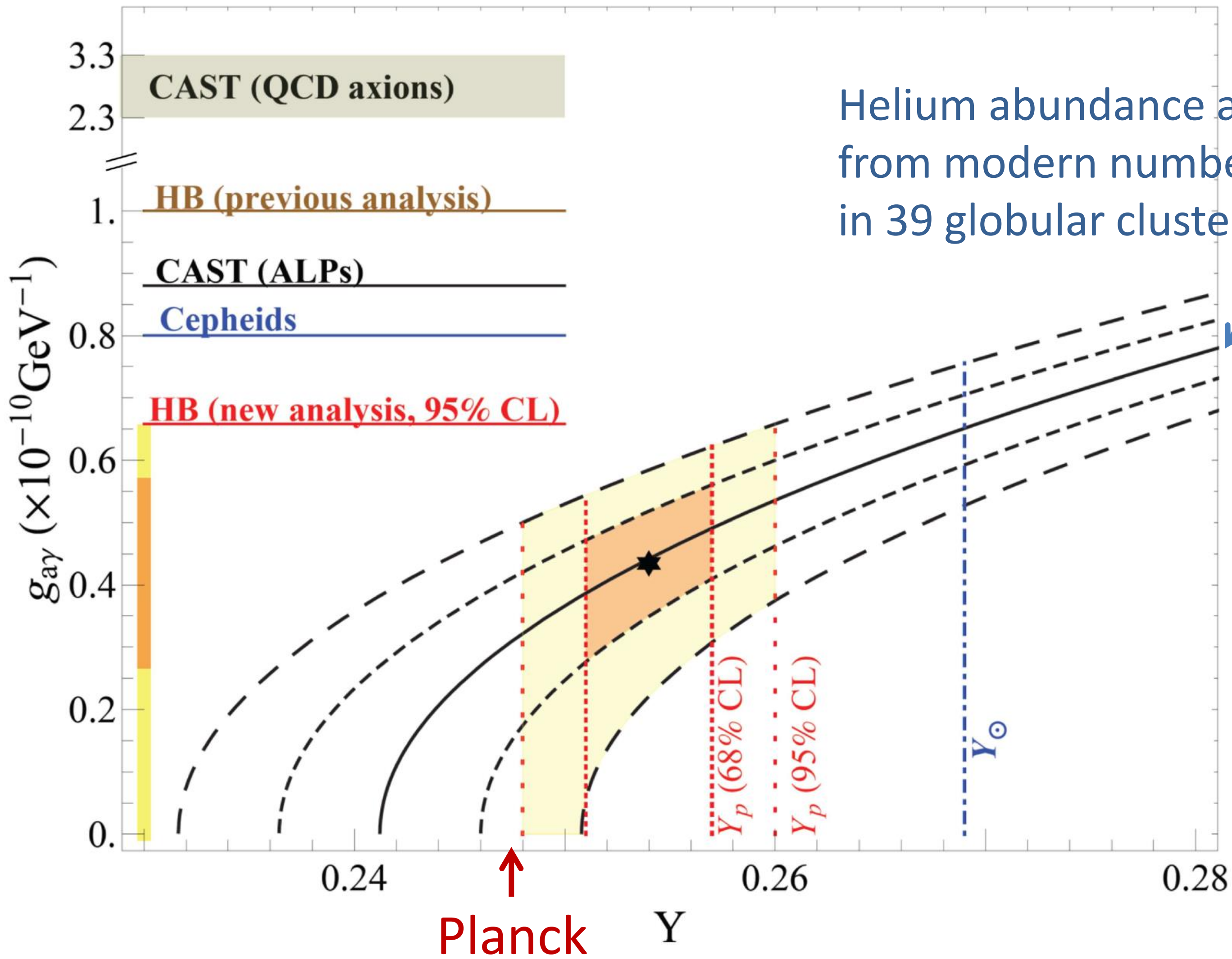
Parameter Space for Axion-Like Particles (ALPs)



Galactic Globular Clusters



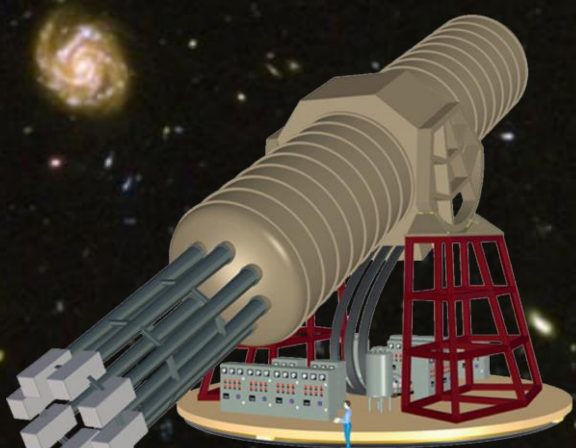
New ALP Limit from Globular Clusters



Helium abundance and energy loss rate from modern number counts HB/RGB in 39 globular clusters

Ayala, Dominguez, Giannotti, Mirizzi & Straniero, arXiv:1406.6053

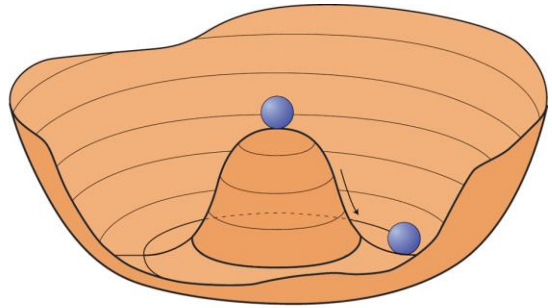
Axion and ALP Dark Matter

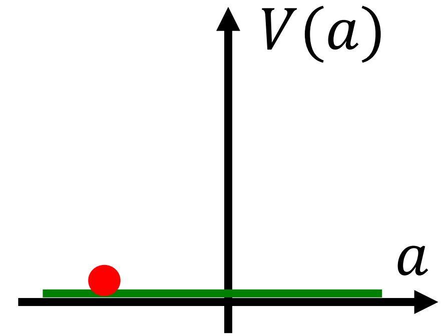


Creation of Cosmological Axions by Re-alignment

$T \sim f_a$ (very early universe)

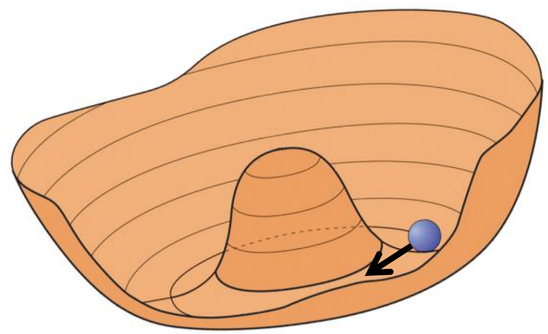
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_i = \Theta_i f_a$

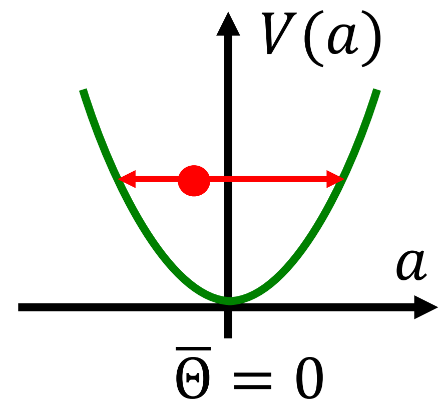




$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_a \gtrsim 3H$
- Classical field oscillations (axions at rest)





Axions are born as nonrelativistic, classical field oscillations
Very small mass, yet cold dark matter

Axion Cosmology in PLB 120 (1983)

THE NOT-SO-HARMLESS AXION

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

and

Willy FISCHLER
Department of Physi

Received 17 Septem
Received manuscript

Cosmological asp
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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

Received 14 Se

The produc
GeV are found

COSMOLOGY OF THE INVISIBLE AXION

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

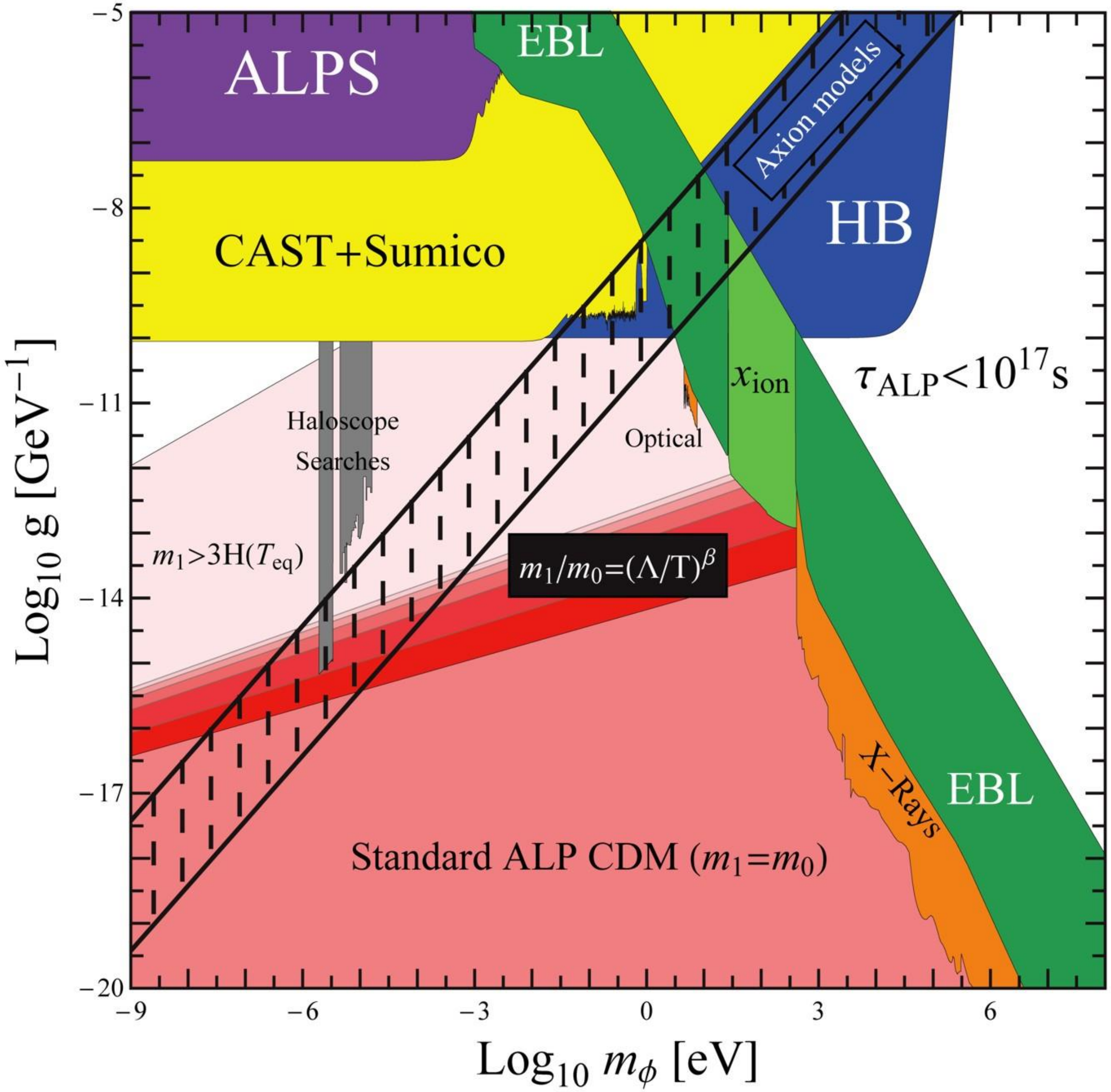
and

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

Received 10 September 1982

We identify a new cosmological problem for models which solve the strong *CP* puzzle with an invisible axion, unrelated to the domain wall problem. Because the axion is very weakly coupled, the energy density stored in the oscillations of the classical axion field does not dissipate rapidly; it exceeds the critical density needed to close the universe unless $f_a \leqslant 10^{12}$ GeV, where f_a is the axion decay constant. If this bound is saturated, axions may comprise the dark matter of the universe.

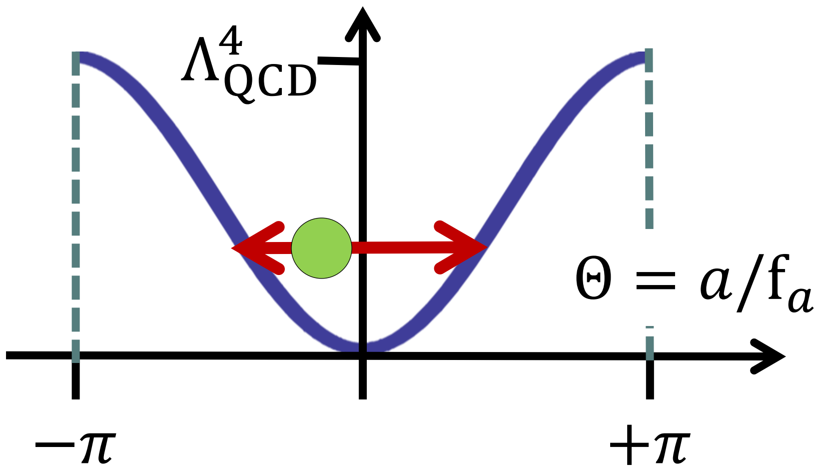
WISPy Cold Dark Matter



General ALPs produced
by re-alignment
as cold dark matter

Arias, Cadamuro, Goodsell,
Jaeckel, Redondo, Ringwald,
arXiv:1201.5902

Axion Dark Matter Driving Oscillators



Oscillating axion field (DM)
→ Oscillating Θ term
- **Drives oscillating neutron EDM**
- **Drives oscillating E-field in microwave cavity w/ B-field**

Assume axions are the galactic dark matter: $\rho_a \sim 300\ \mathrm{MeV/cm^3}$

$$\rho_a = m_a^2 \Phi_a^2 = m_a^2 (\Theta f_a)^2 \sim \Theta^2 (m_\pi f_\pi)^2 \sim \Theta^2 \Lambda_{\rm QCD}^4$$

Independently of f_a expect

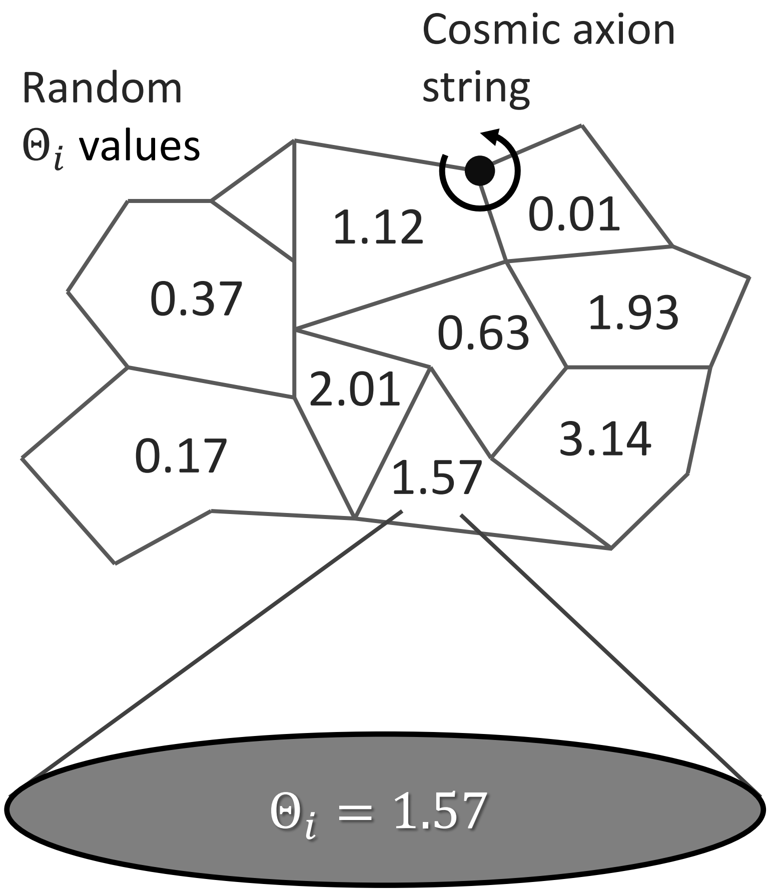
$$\Theta(t) = a(t)/f_a \sim 3 \times 10^{-19} \cos(m_a t)$$

Expect time-varying neutron EDM, MHz frequency for $f_a \sim 10^{16}$ GeV

$$d_n \sim \frac{e}{2m_n} \frac{m_q}{m_N} \Theta \sim 3 \times 10^{-34}\ e\text{–cm}\ \cos(m_a t)$$

8 orders of magnitude below limit on static EDM, but oscillates! → CASPEr Project

Cold Axion Populations



Scenario 1

- Cosmic inflation first
- PQ symmetry breaking at $T \sim f_a$
- Every causal patch has different random Θ_i
- Topological defects at interfaces
- Axion dark matter from
  - average re-alignment
  - cosmic-string (CS) & domain-wall (DW) decay

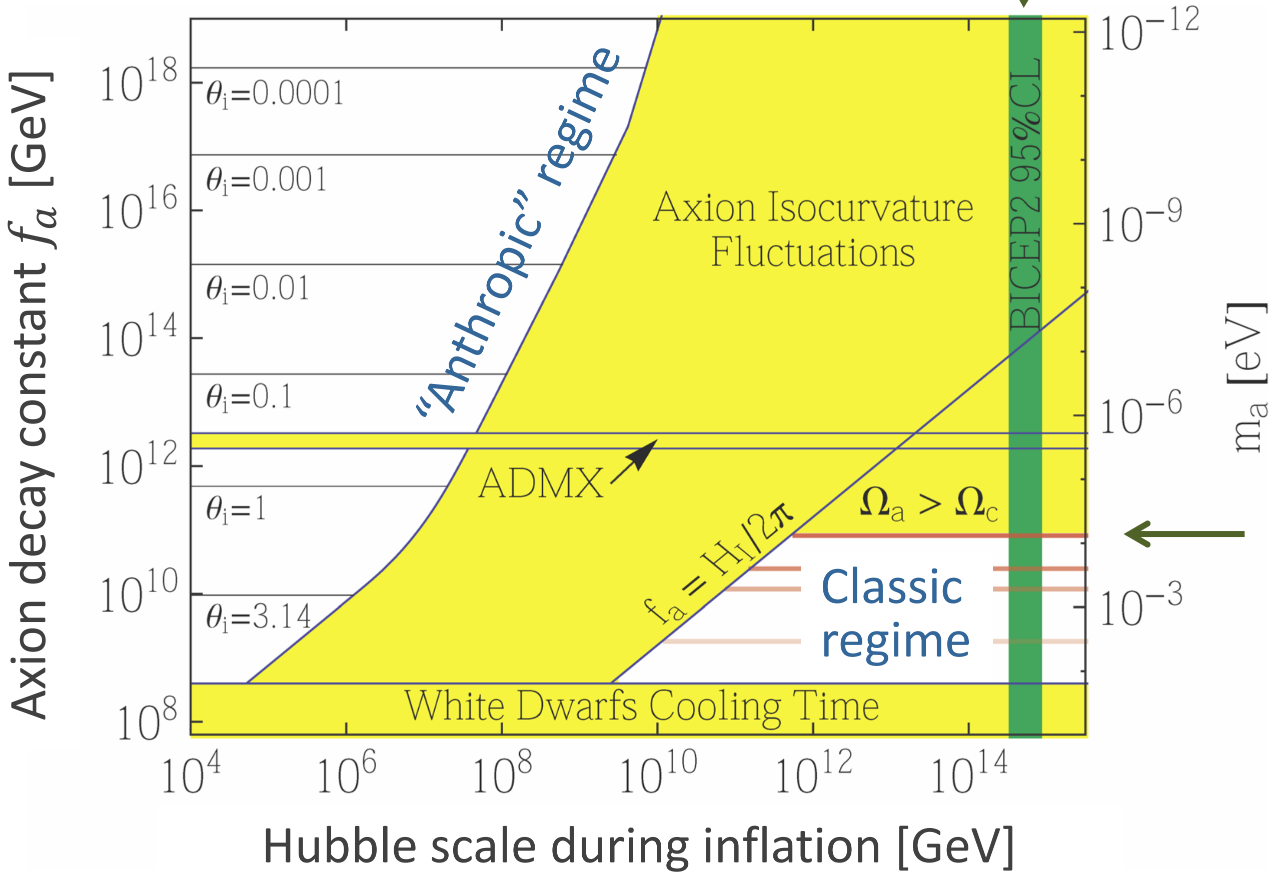
Scenario 2

- Cosmic inflation after PQ symmetry breaking
- All axions from re-alignment of one random Θ_i in our patch of the universe
- Allows large f_a if $\Theta_i \ll 1$ (“anthropic” case)

$$\Omega_a h^2 = 0.20\, \Theta_i^2 \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.184} = 0.11\, \Theta_i^2 \left(\frac{10\ \mu\mathrm{eV}}{m_a}\right)^{1.184}$$

Isocurvature Constraints

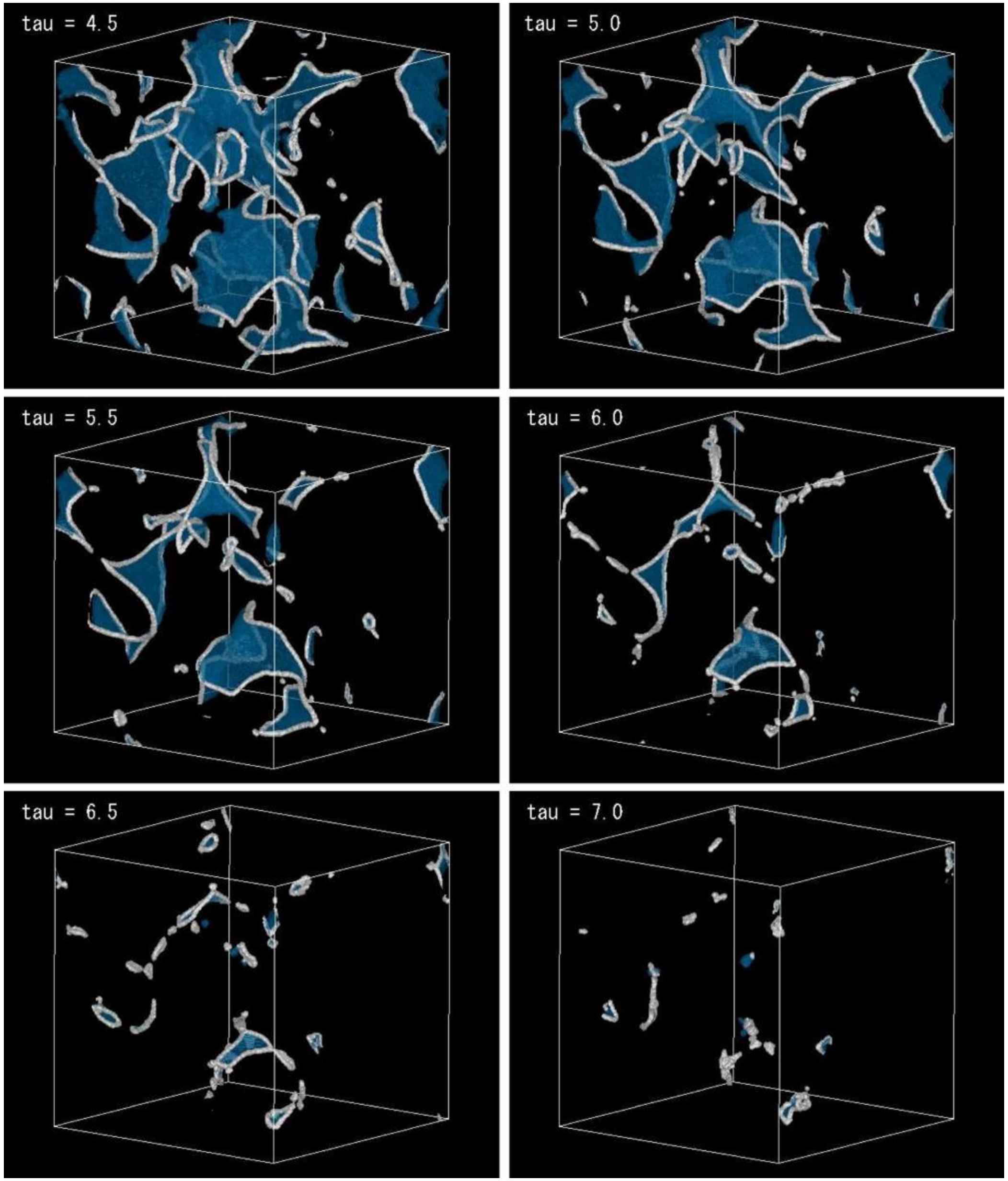
B-modes in CMB would exclude "anthropic" regime of large f_a



B-modes in CMB would suggest "large" m_a for dark matter axions

Visinelli & Gondolo, arXiv:1403.4594

Axion Production by Domain Wall and String Decay



Recent numerical studies of collapse of string-domain wall system

$$\Omega_a h^2 = (8.4 \pm 3.0) \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.19} \times \left(\frac{g_{*,1}}{70}\right)^{-0.41} \left(\frac{\Lambda}{400\ \mathrm{MeV}}\right)$$

Implies a CDM axion mass of

$$m_a \sim 300\ \mu\mathrm{eV}$$

Hiramatsu, Kawasaki, Saikawa & Sekiguchi, arXiv:1202.5851 (2012)

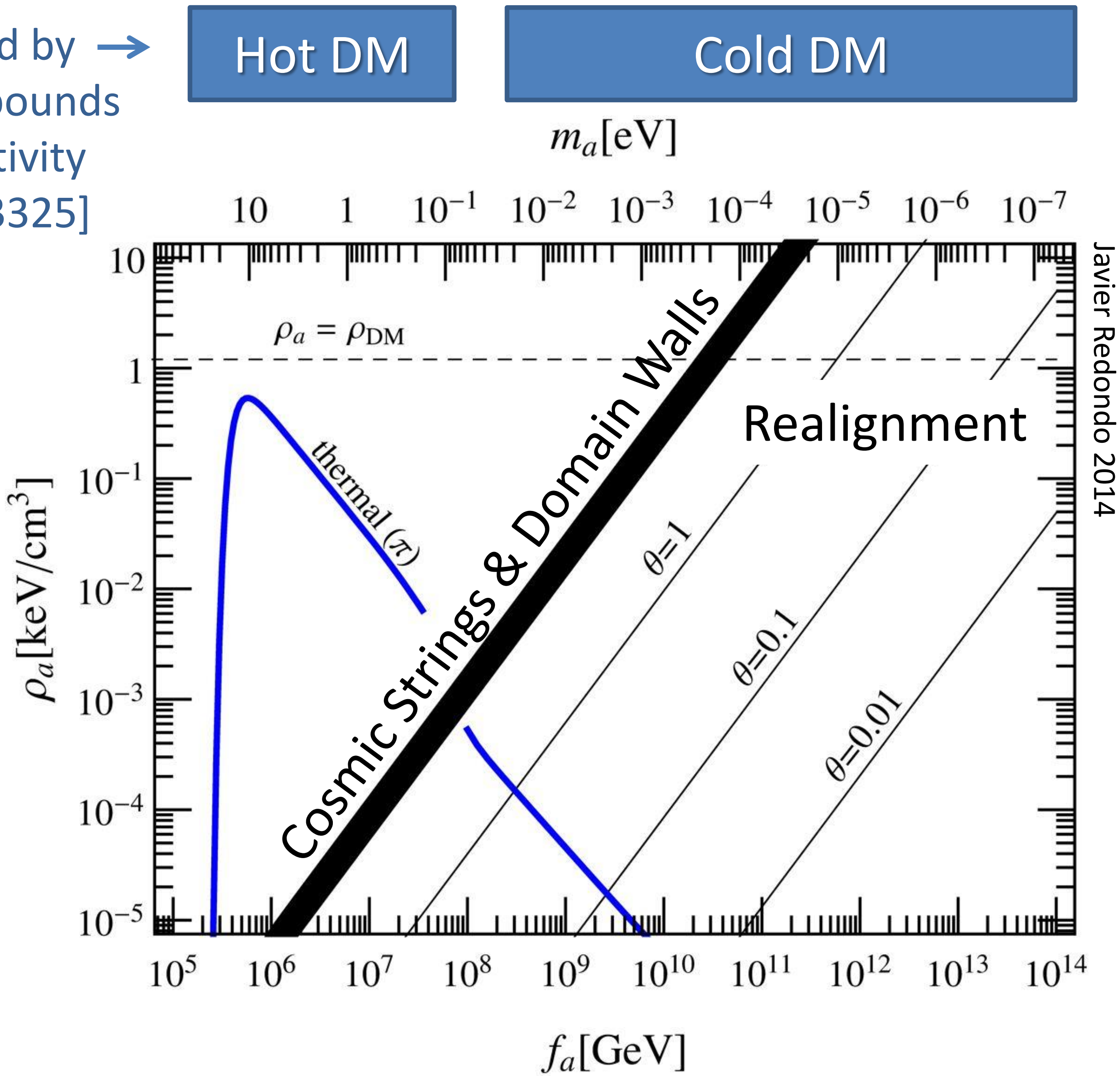
More recently by the same group

$$m_a \sim 90 - 140\ \mu\mathrm{eV}$$

Kawasaki, Saikawa & Sekiguchi, arXiv:1412.0789 (PRD 2015)

Axion Dark Matter Density

Partly excluded by cosmic HDM bounds & Euclid sensitivity [arXiv:1502.03325] →

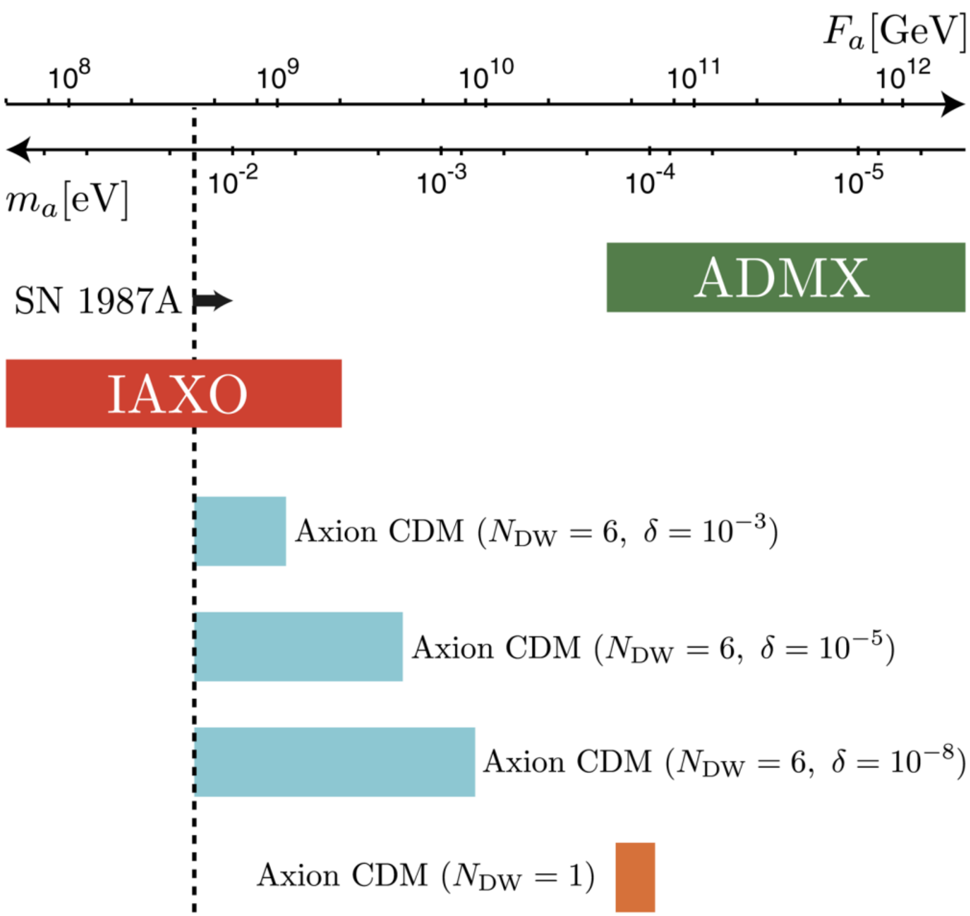


PHYSICAL REVIEW D **91**, 065014 (2015)

Editor's suggestion

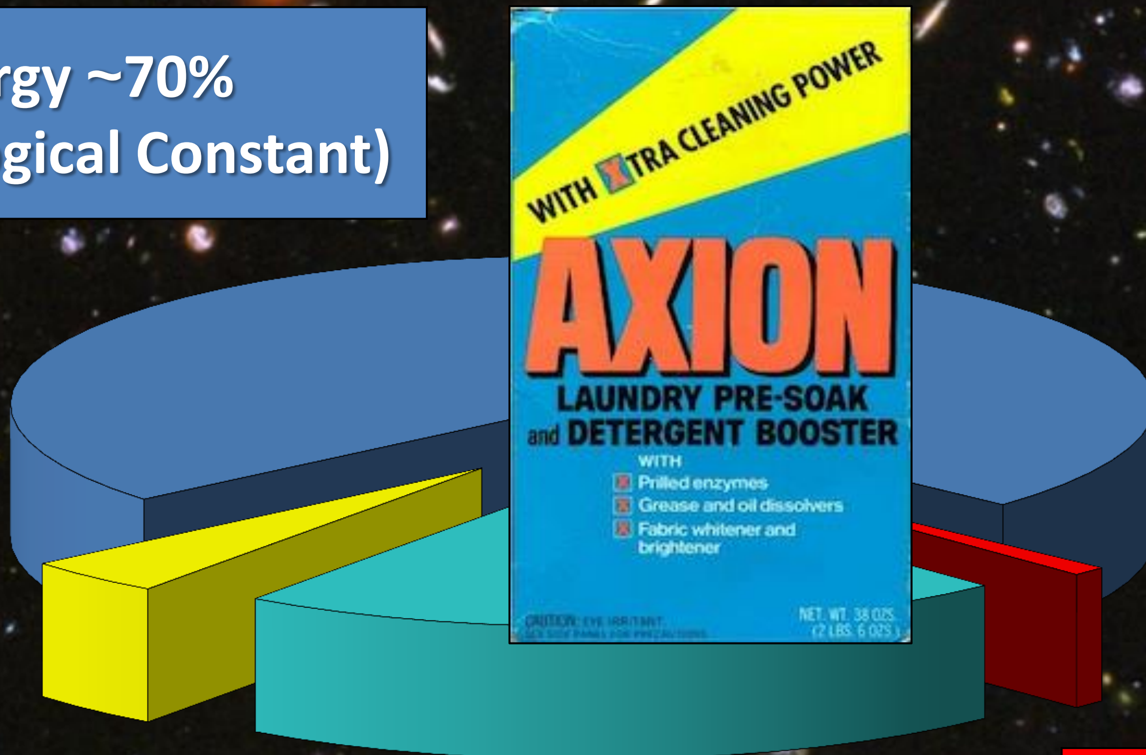
Axion dark matter from topological defects

Masahiro Kawasaki,[1,2,*] Ken'ichi Saikawa,[3,†] and Toyokazu Sekiguchi[4,‡]



Diversity of scenarios for cosmic axion production depending on domain-wall index N_{DW} and phase parameter δ of the bias term

Dark Energy ~70%
(Cosmological Constant)



Ordinary Matter ~5%
(of this only about
10% luminous)

Dark Matter
~25%

Neutrinos
0.1–2%

Historical Neutrino Dark Matter Lessons

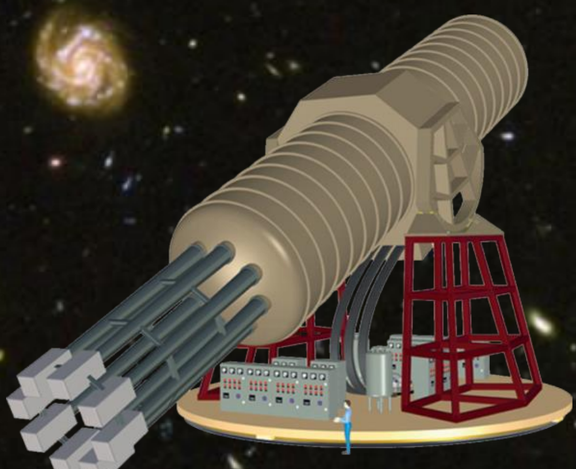
Early 1980s
- If neutrinos have mass, probably they are dark matter ($m_\nu \sim 10$ eV)
  ("Neutrinos are known to exist", only SM candidate)
- Detection of $m_{\nu_e} \sim 30$ eV at ITEP, Moscow (PRL 58:2019, 1987)
- Dedicated oscillation experiments
  (NOMAD 1995–1998 and CHORUS 1994–1997)

Status 2015
- 70% of gravitating "mass" is dark energy
- Dark matter must be mostly "cold" (structure formation)
- Neutrinos have sub-eV masses (oscillations, cosmo limits)
- Sub-dominant dark matter component

History does not always repeat itself, but …
- If axions (or similar) exist, MUST be ALL of dark matter?

DENNIS the MENACE
"LOTS OF THINGS ARE INVISIBLE, BUT WE DON'T KNOW HOW MANY BECAUSE WE CAN'T SEE THEM."

Landscape of Axion Searches



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New macroscopic forces?

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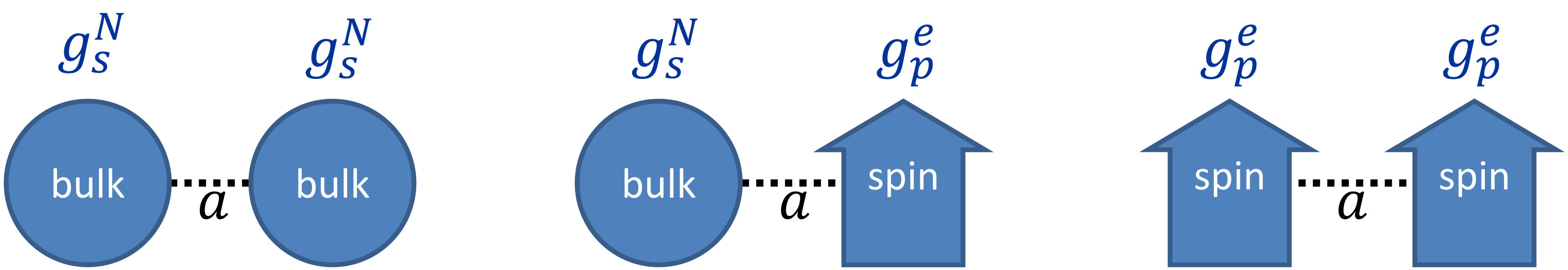
(Received 17 January 1984)

The forces mediated by spin-0 bosons are described, along with the existing experimental limits. The mass and couplings of the invisible axion are derived, followed by suggestions for experiments to detect axions via the macroscopic forces they mediate. In particular, novel tests of the *T*-violating axion monopole-dipole forces are proposed.



Tests of Newton's law
& equivalence principle:
Scalar axion coupling $(g_s^N)^2$

Torsion balance using
polarized electron spins
Axion couplings $g_s^N g_p^e$
T-violating force

Spin-spin forces
hard to measure
Axion couplings $(g_s^e)^2$

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

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(Received 5 March 2014; revised manuscript received 27 August 2014; published 14 October 2014)

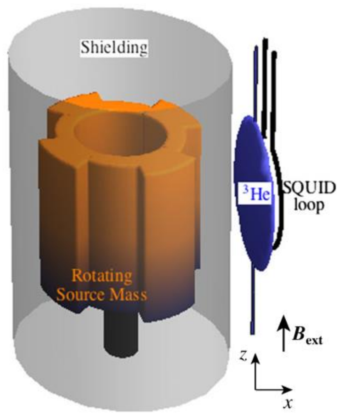


FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N \cdot \vec{B}_{ext}/\hbar$ of the NMR sample. Superconducting cylinders screen the NMR sample from the source mass and (not shown) the setup from the environment.

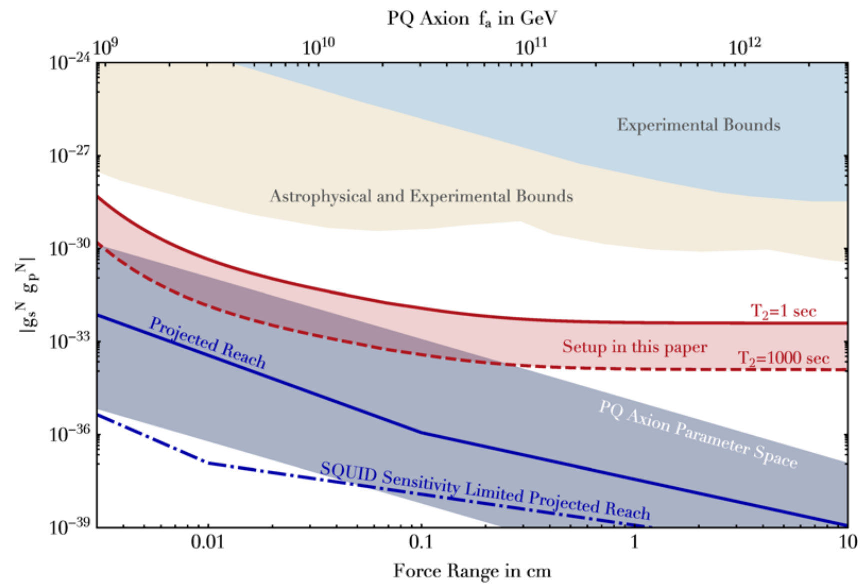


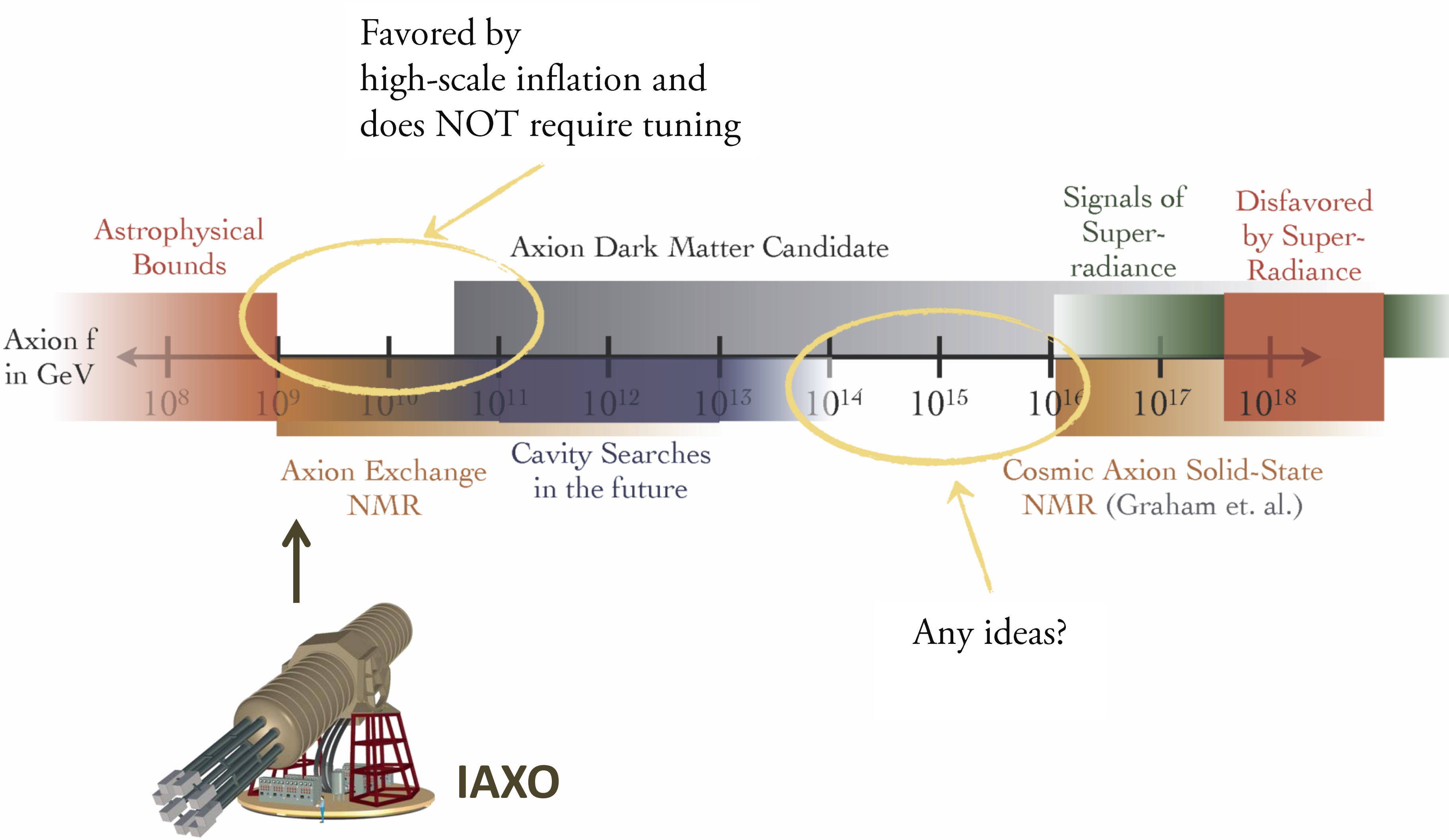
FIG. 2 (color online). Projected reach for monopole-dipole axion mediated interactions.

ARIADNE: Axion Resonant InterAction DetectioN Experiment

A.Geraci, A.Arvanitaki, A.Kapitulnik, Chen-Yu Liu, J.Long, Y.Semertzidis, M.Snow

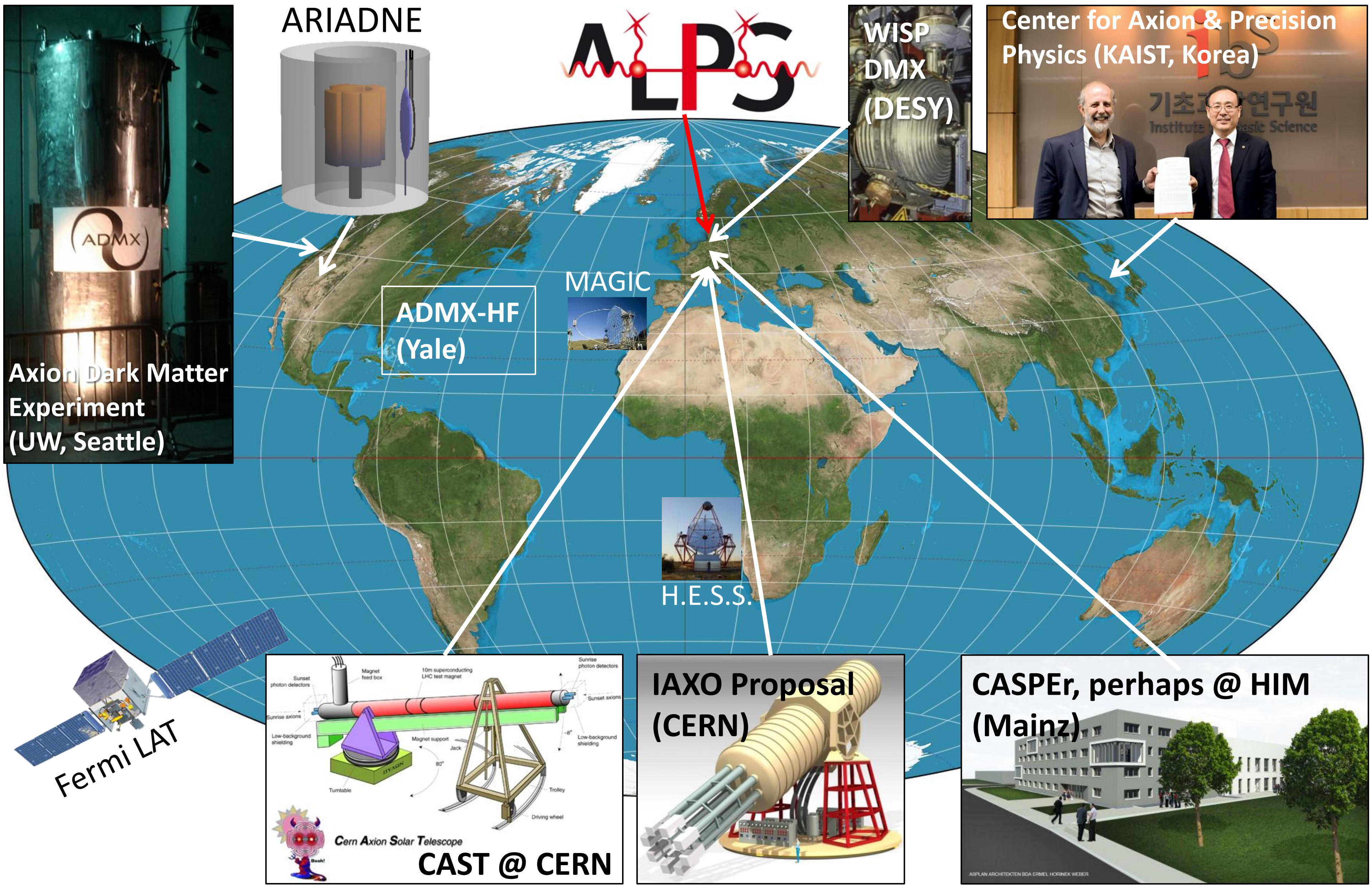
(to be supported by NSF and/or DoE?)

New Ideas for Axion Detection



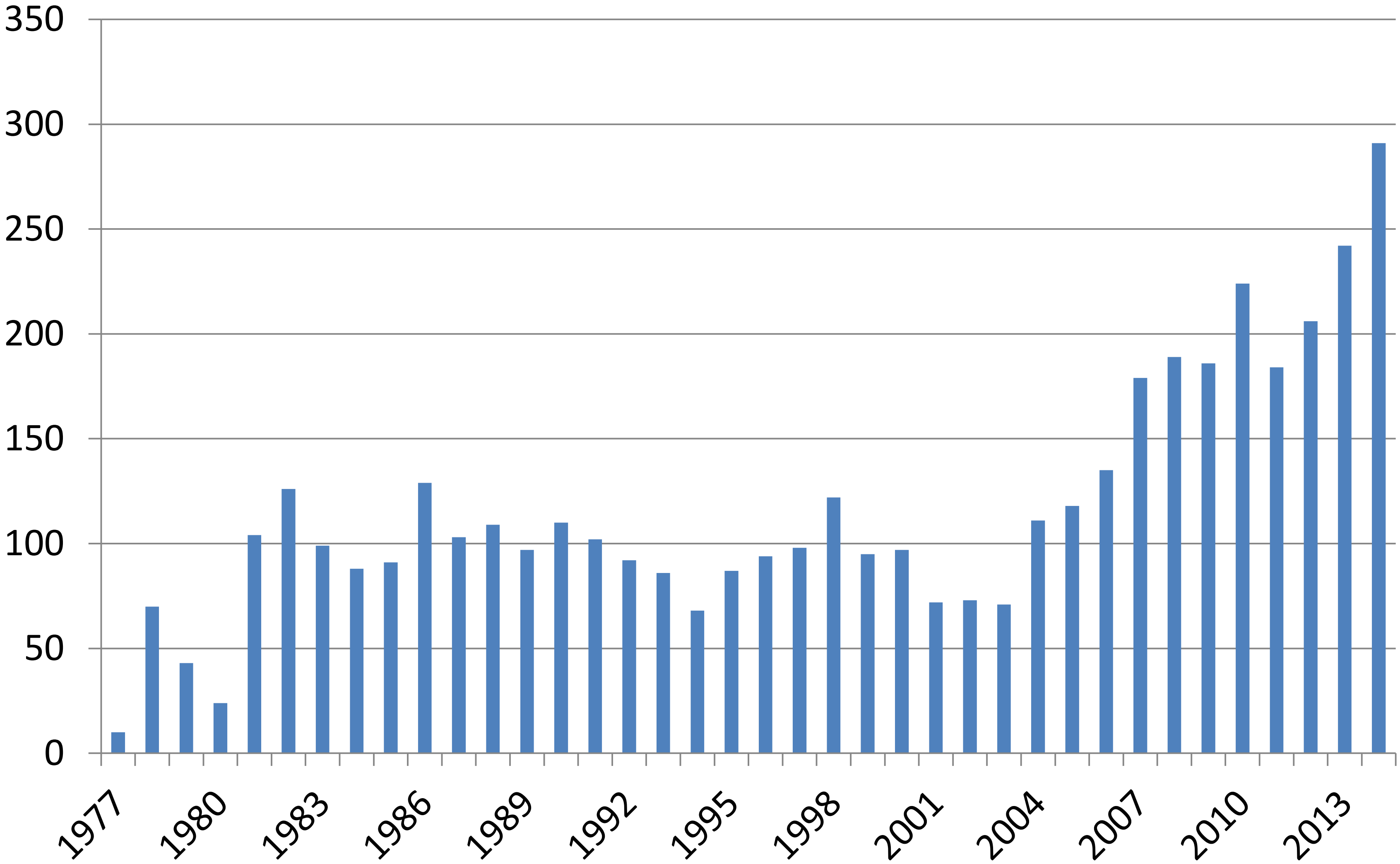
[Arvanitaki 2015]

Axion and Axion-Like Particle Searches



Dow Jones Index of Axion Physics

inSPIRE: Citation of Peccei-Quinn papers or title axion (and similar)



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