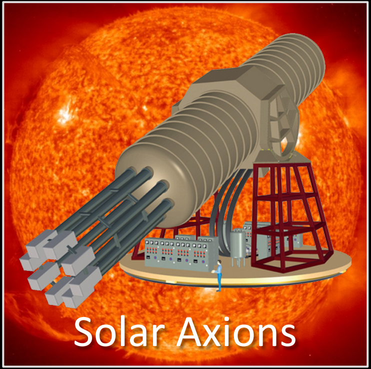
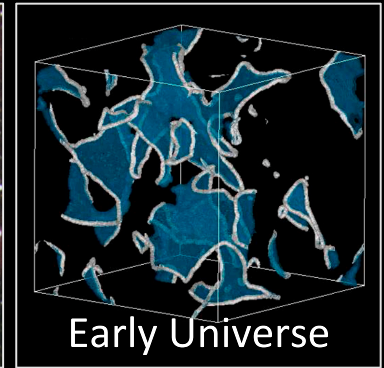
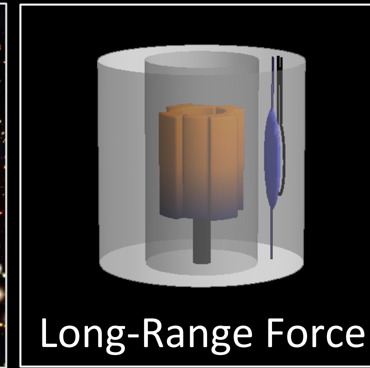

Solar Axions


Supernova 1987A


Early Universe


Dark Matter


Long-Range Force

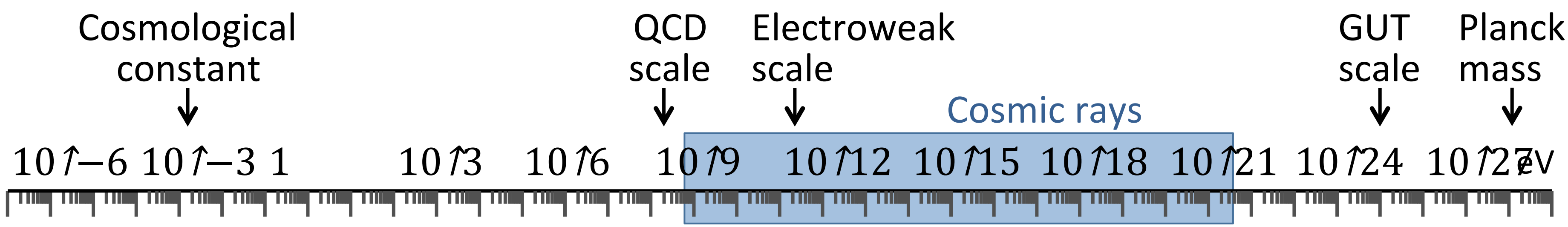
Axion Landscape

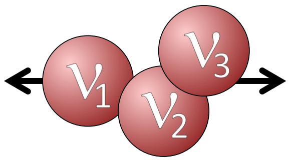
Georg Raffelt
Max Planck Institute for Physics, Munich

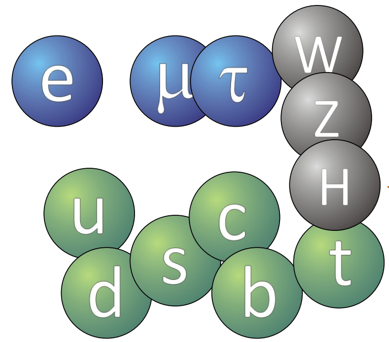
MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

High- and Low-Energy Frontiers in Particle Physics

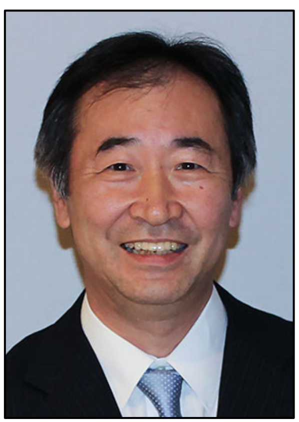




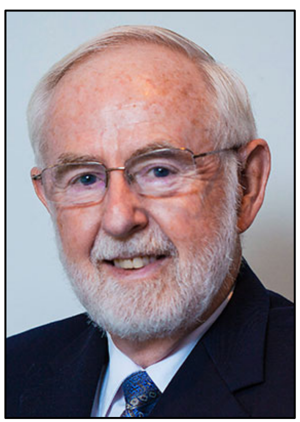


"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"



T. Kajita



A. McDonald

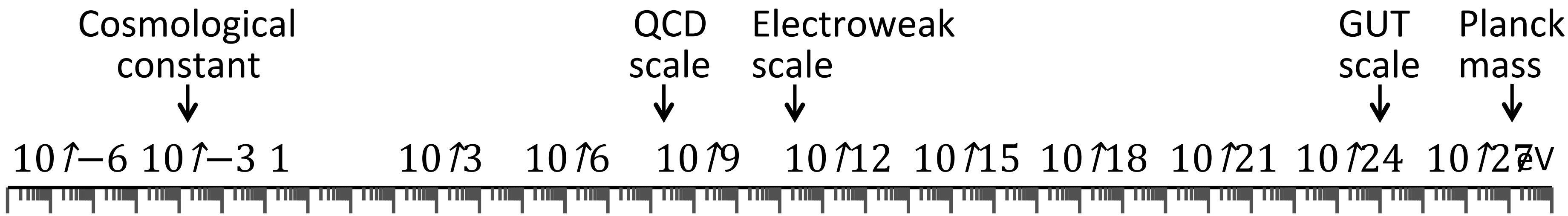
2015

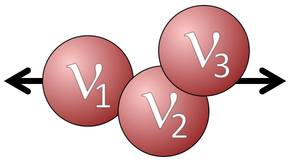
2013

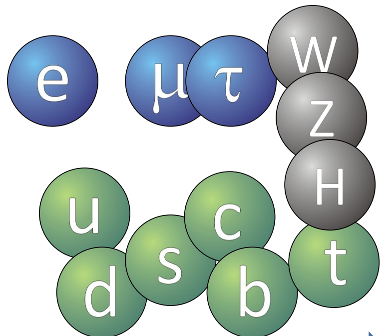
F. Englert

P. Higgs

High- and Low-Energy Frontiers in Particle Physics



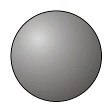




“Intensity Frontier”
(feeble interactions)

Low-E Frontier

High-Energy Frontier



New 750 GeV boson?
few-sigma hint @ CMS & ATLAS
many theory papers since Dec 2015

High- and Low-Energy Frontiers in Particle Physics

Cosmological constant | QCD scale | Electroweak scale | GUT scale | Planck mass

10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21} 10^{24} 10^{27} eV

ν_1 ν_2 ν_3

m_D^2/M

e μ τ W Z H u d s c b t

m_D

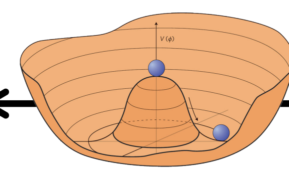
N_1 N_2 N_3

Heavy right-handed neutrinos (see-saw mechanism)

M

χ WIMP dark matter (related to EW scale, perhaps SUSY)

a Axion dark matter (related to Peccei-Quinn symmetry)

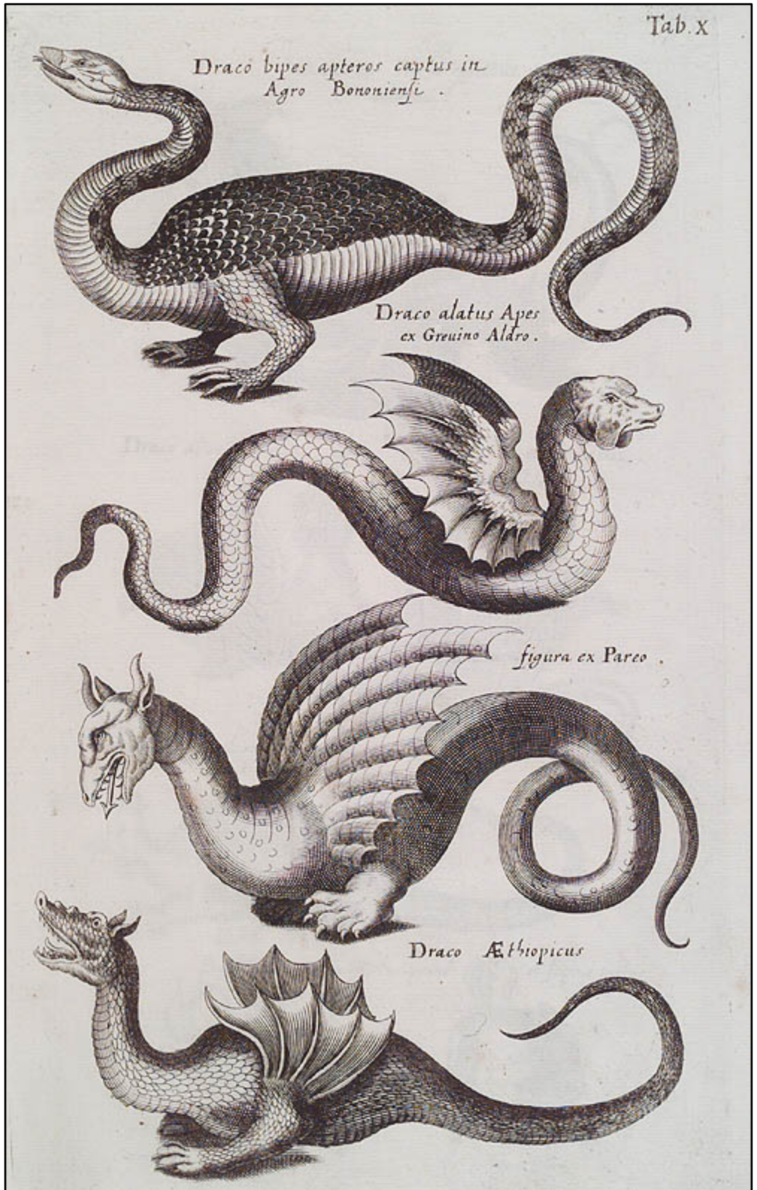


$m_a \sim m_\pi f_\pi / f_a$

m_π, f_π

f_a

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
- **Axion-like particles (ALPs)**
  Generic two-photon vertex, could be dark matter
  (2 parameters m_a and $g_{a\gamma}$)
- **String axions**
  (almost massless pseudoscalars in string theory)
  One of them may solve CP problem
- **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

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

Phase from Yukawa coupling

Angle variable

CP-odd quantity $\sim \mathbf{E}\cdot\mathbf{B}$

$$\mathcal{L}_{\rm QCD} = \sum_q \bar{\psi}_q \left(\mathrm{i}\not{D} - m_q e^{\mathrm{i}\theta_q}\right)\psi_q - \frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} - \Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu}$$

Remove phase of mass term by chiral transformation of quark fields

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

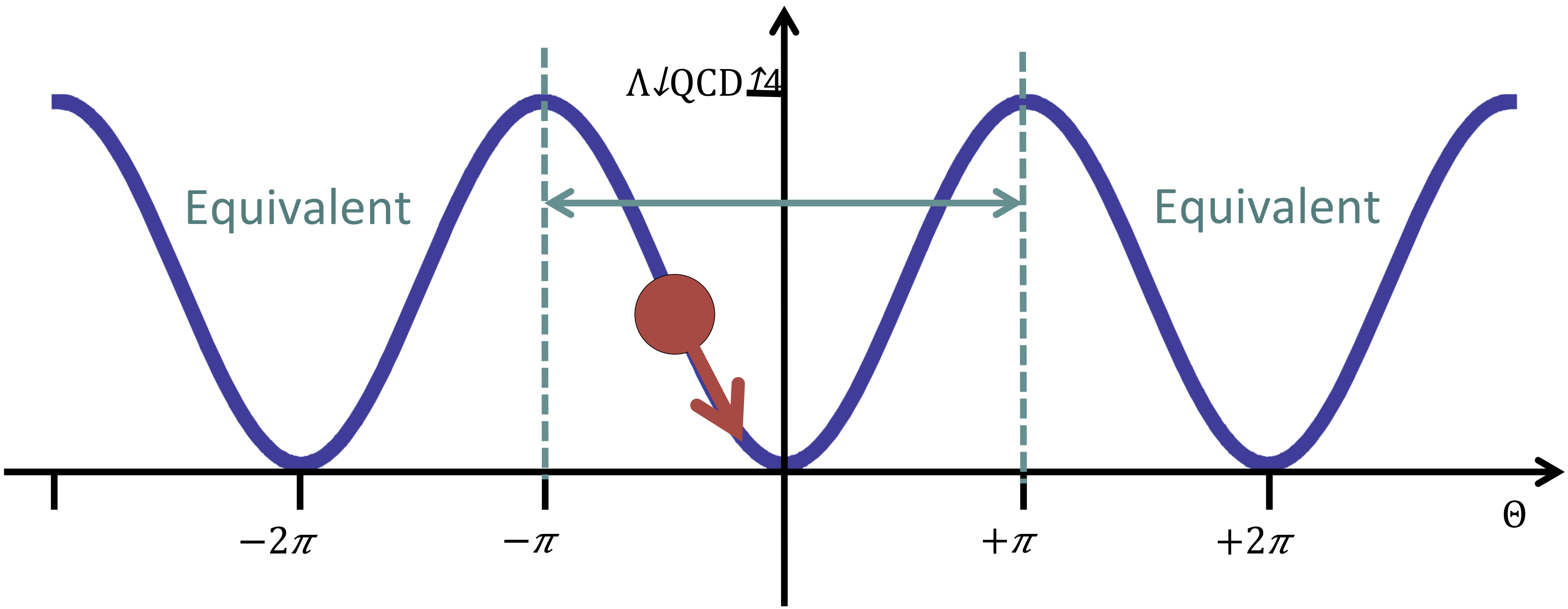
$$\mathcal{L}_{\rm QCD} = \sum_q \bar{\psi}_q \left(\mathrm{i}\not{D} - m_q\right)\psi_q - \frac{1}{4} G G - \underbrace{\left(\Theta - \arg\det M_q\right)}_{-\pi \le \bar{\Theta} \le +\pi} \frac{\alpha_s}{8\pi} G\tilde{G}$$

- Θ 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

QCD vacuum energy $V(\Theta)$



- 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

38 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)

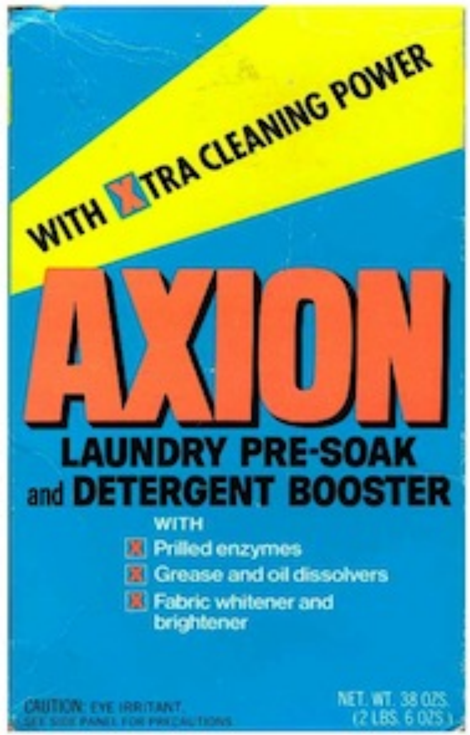
The requirement that P and T be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

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

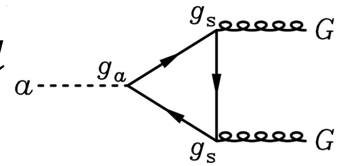


"I named them after a laundry detergent, since they clean up a problem with an axial current."
(Nobel lecture 2004)

Phenomenological Axion Properties

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

$$\mathcal{L}_{aG}=\frac{\alpha_s}{8\pi}\,\frac{a}{f}$$



Mass (generic) depends ark masses

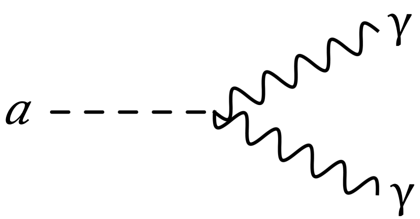
$$m_a=\frac{\sqrt{m_u m_d}}{m_u+m_d}\,\frac{m_\pi f_\pi}{f_a}\approx 6\,\mu\mathrm{eV}\,\frac{10^{12}\ \mathrm{GeV}}{f_a}$$

Axion-photon coupling (model dependent)

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

Generic from a-π-η mixing

↓



↑

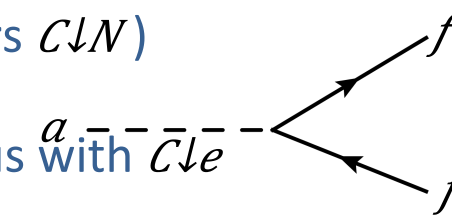
Model-dependent,
E/N = 0 (KSVZ), 8/3 (DFSZ), many others

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

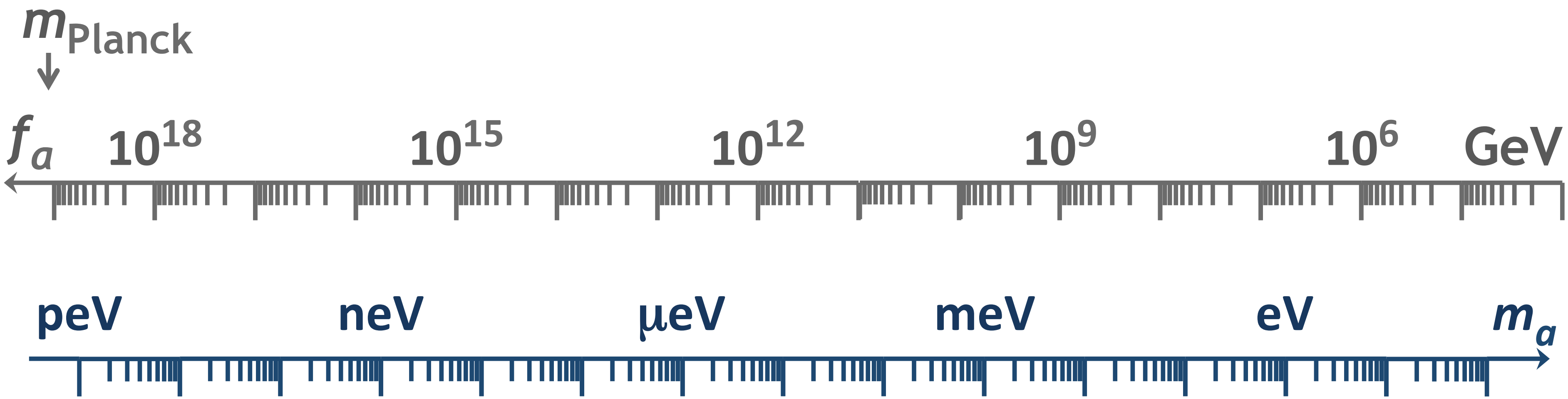
$$\mathcal{L}_{aN}=C_N\,\bar{\Psi}_N\gamma^\mu\gamma_5\Psi_N\,\frac{\partial_\mu a}{2f_a}$$

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

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



Axion Bounds

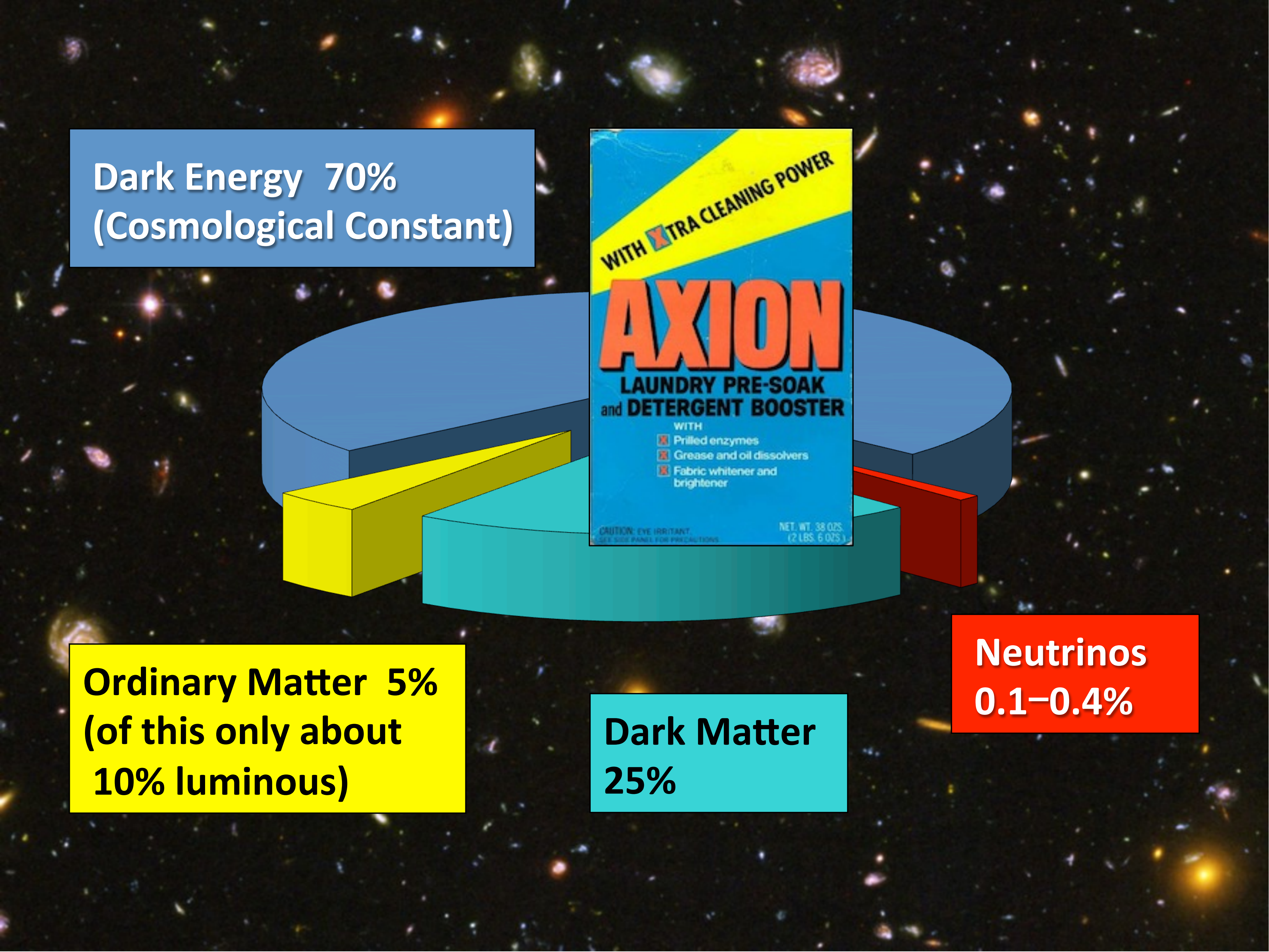


Astrophysical Bounds (Energy loss of stars)

Opportunities for detection


Supernova 1987A

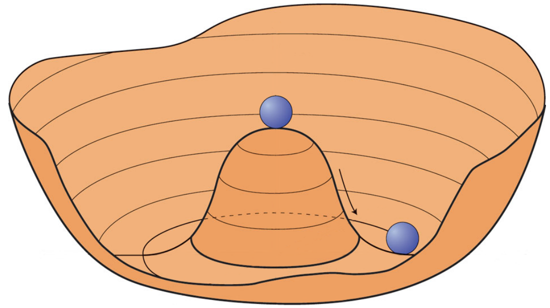

Globular Cluster

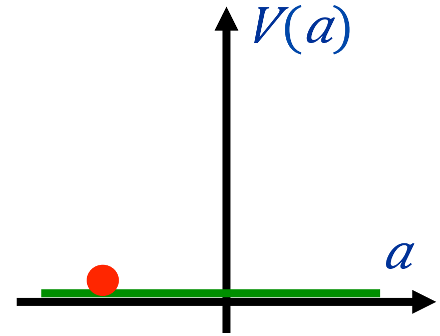

Dark Energy 70%
(Cosmological Constant)
WITH XTRA CLEANING POWER
AXION
LAUNDRY PRE-SOAK
and DETERGENT BOOSTER
WITH
Prilled enzymes
Grease and oil dissolvers
Fabric whitener and brightener
CAUTION: EYE IRRITANT.
NET. WT. 38 OZS.
(2 LBS. 6 OZS.)
Ordinary Matter 5%
(of this only about
10% luminous)
Dark Matter
25%
Neutrinos
0.1–0.4%

Creation of Cosmological Axions by Re-alignment

$T \sim f_a$ (very early universe)

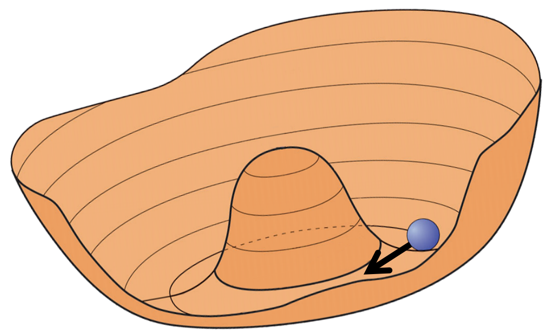
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_i = \Theta_i f_a$

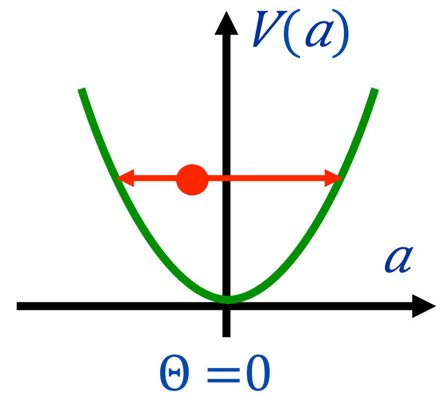




$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

- 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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to give an upper bou

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 product
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.

VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

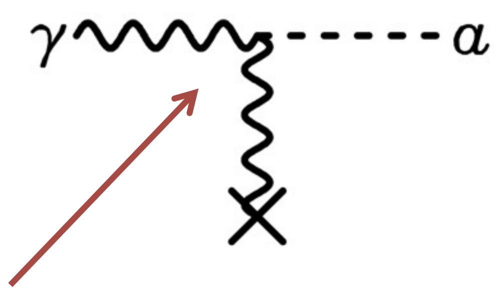
Experimental Tests of the "Invisible" Axion

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)

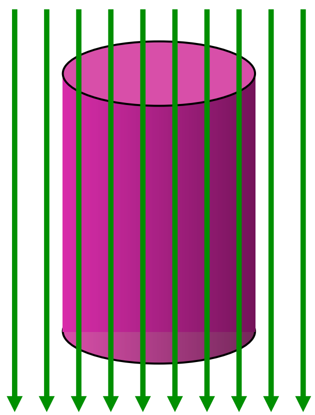
- Axion helioscope:
  Look at the Sun through a dipole magnet
- Axion haloscope:
  Look for dark-matter axions with a microwave resonant cavity

Search for Galactic Axions (Cold Dark Matter)

Dark matter axions $m_a = 1\text{–}100\ \mu\text{eV}$
Velocities in galaxy $v_a \approx 10^{-3}\ c$
Energies therefore $E_a \approx (1 \pm 10^{-6})\ m_a$

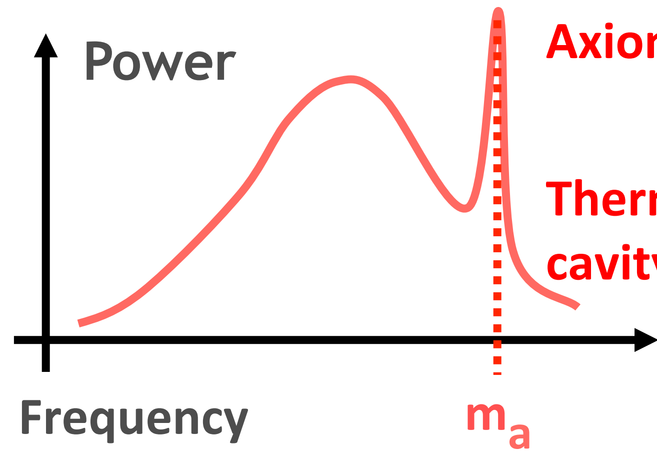
Microwave Energies (1 GHz ≈ 4 μeV)

Axion Haloscope (Sikivie 1983)



$B_{ext} \approx 8$ Tesla

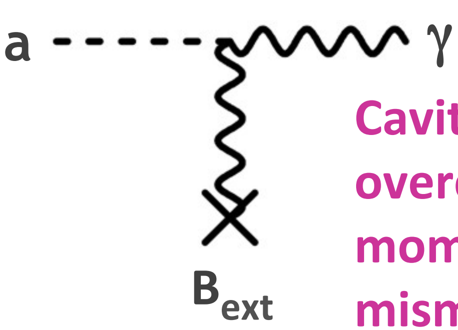
Microwave Resonator $Q \approx 10^5$



Axion Signal

Thermal noise of cavity & detector

Primakoff Conversion

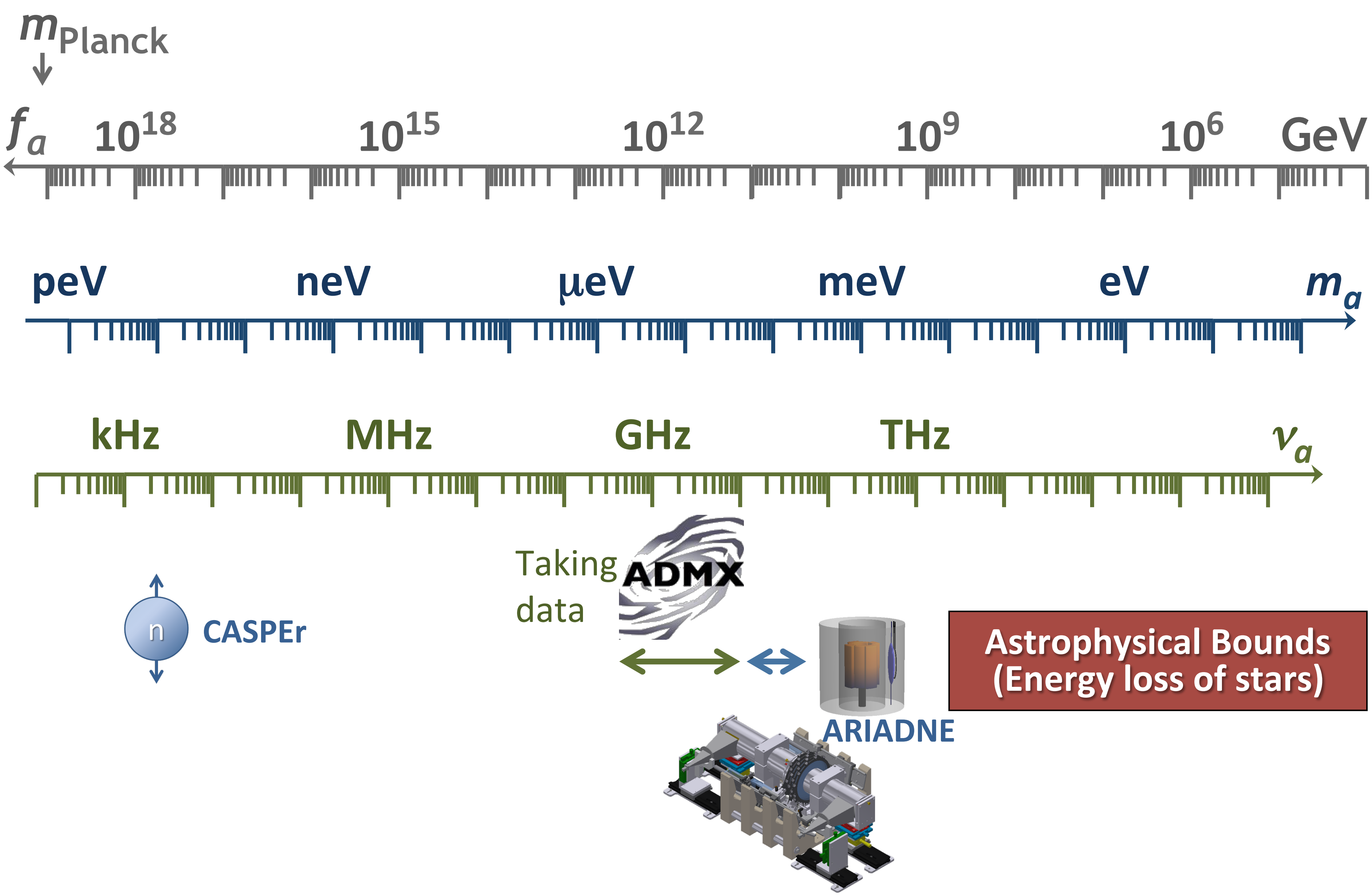


Cavity overcomes momentum mismatch

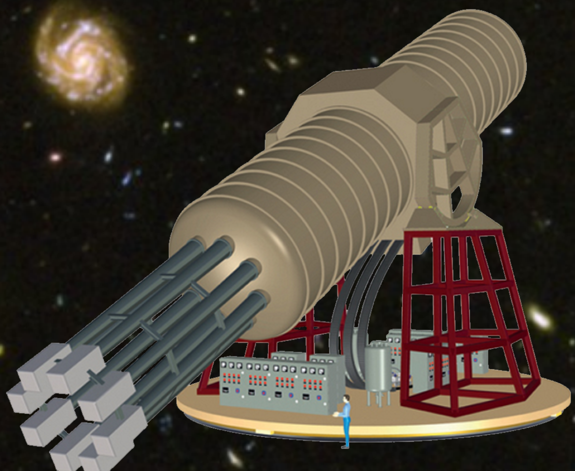
Power of galactic axion signal

$$4\times10^{-21}\,W\,\frac{V}{0.22\,m^3}\left(\frac{B}{8.5\,T}\right)^2\frac{Q}{10^5}\times\left(\frac{m_a}{2\pi\,GHz}\right)\left(\frac{\rho_a}{5\times10^{-25}\,g/cm^3}\right)$$

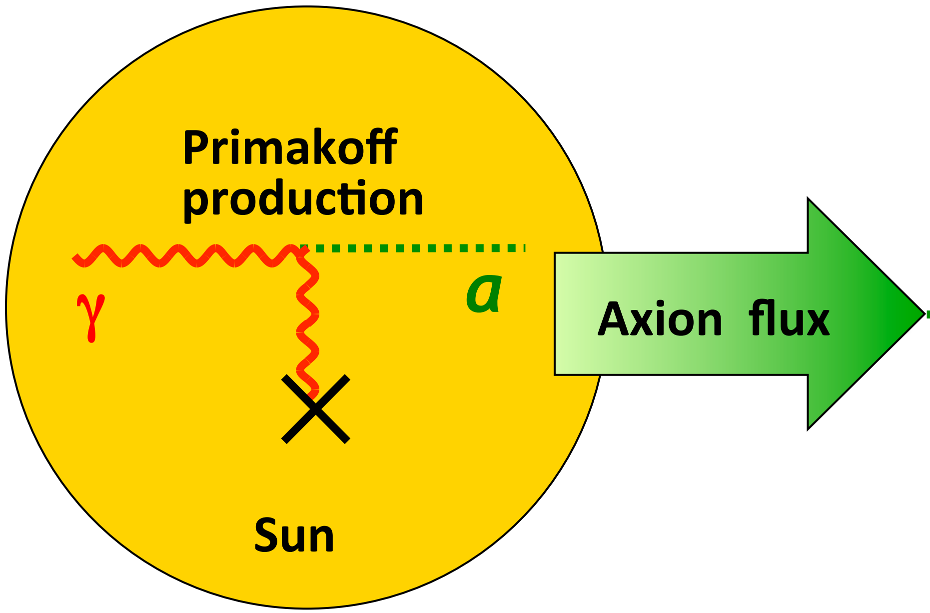
Axion Searches



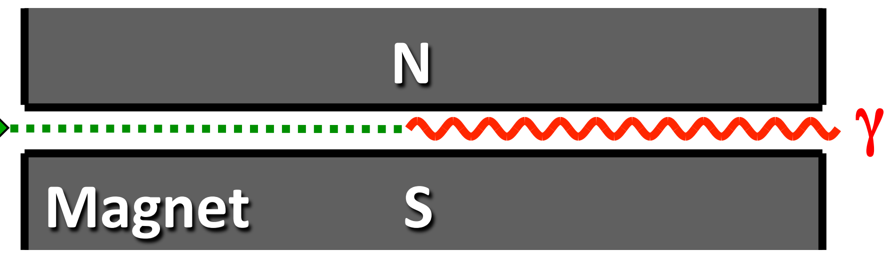
Looking for axion-like particles (ALPs)



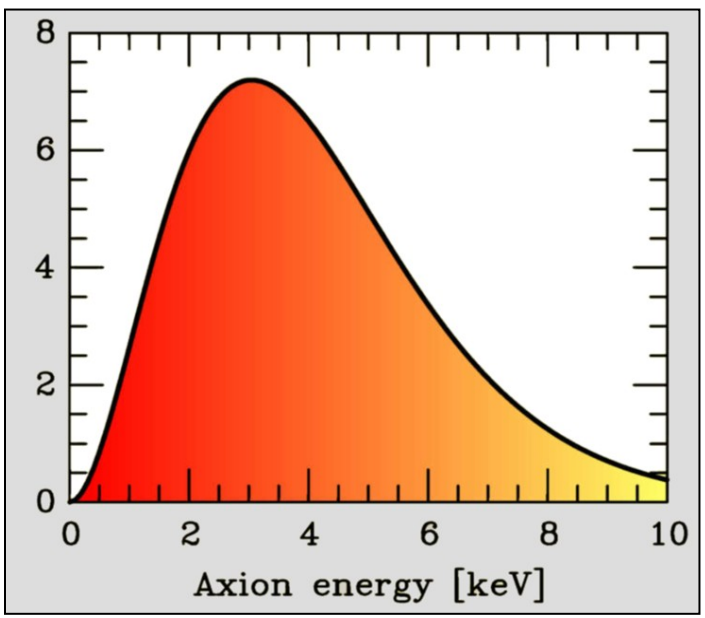
Search for Solar Axions



Axion Helioscope
(Sikivie 1983)



Axion-Photon-Oscillation

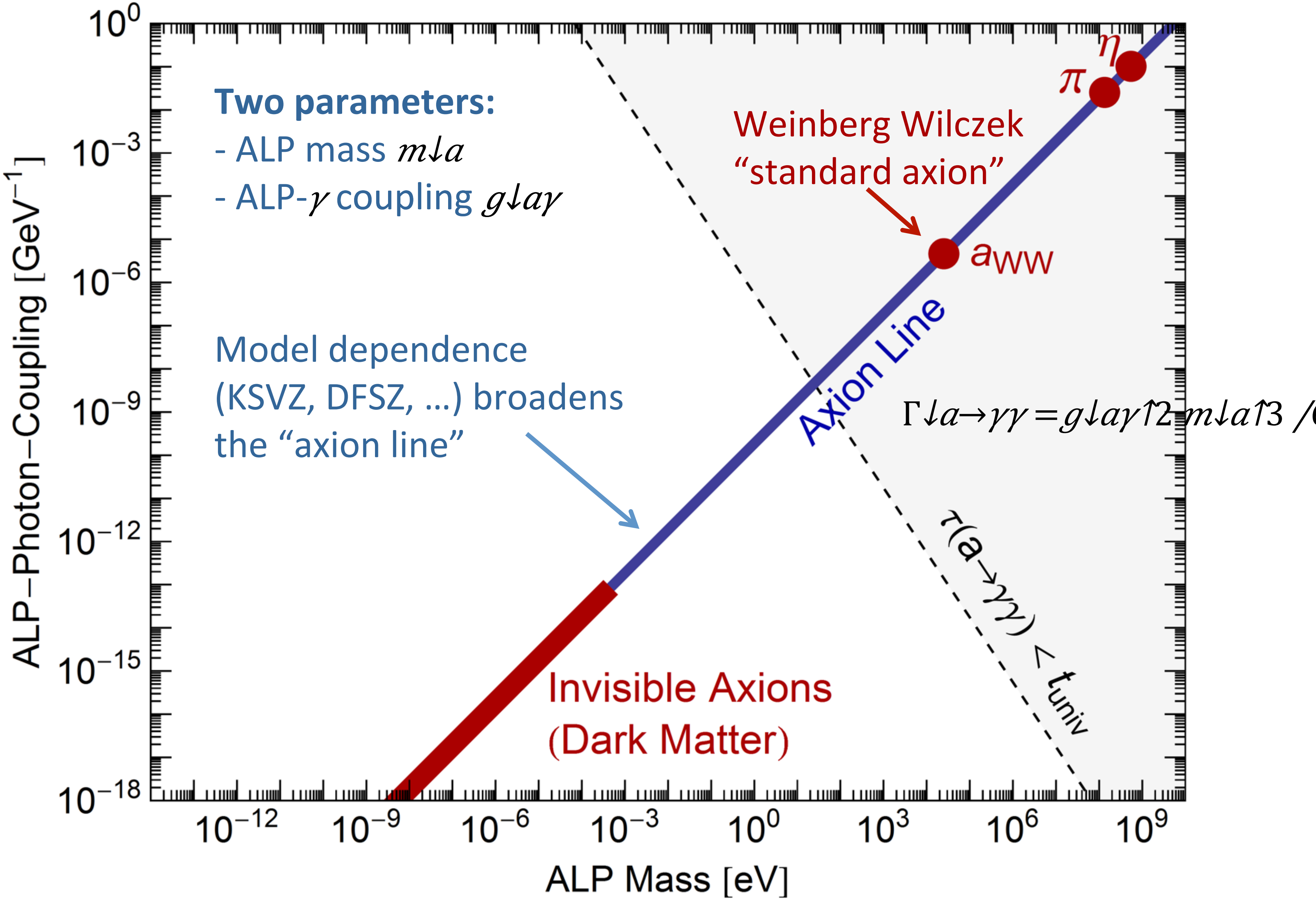


- Tokyo Axion Helioscope (“Sumico”)
  (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST)
  (Data taking 2003–2015)

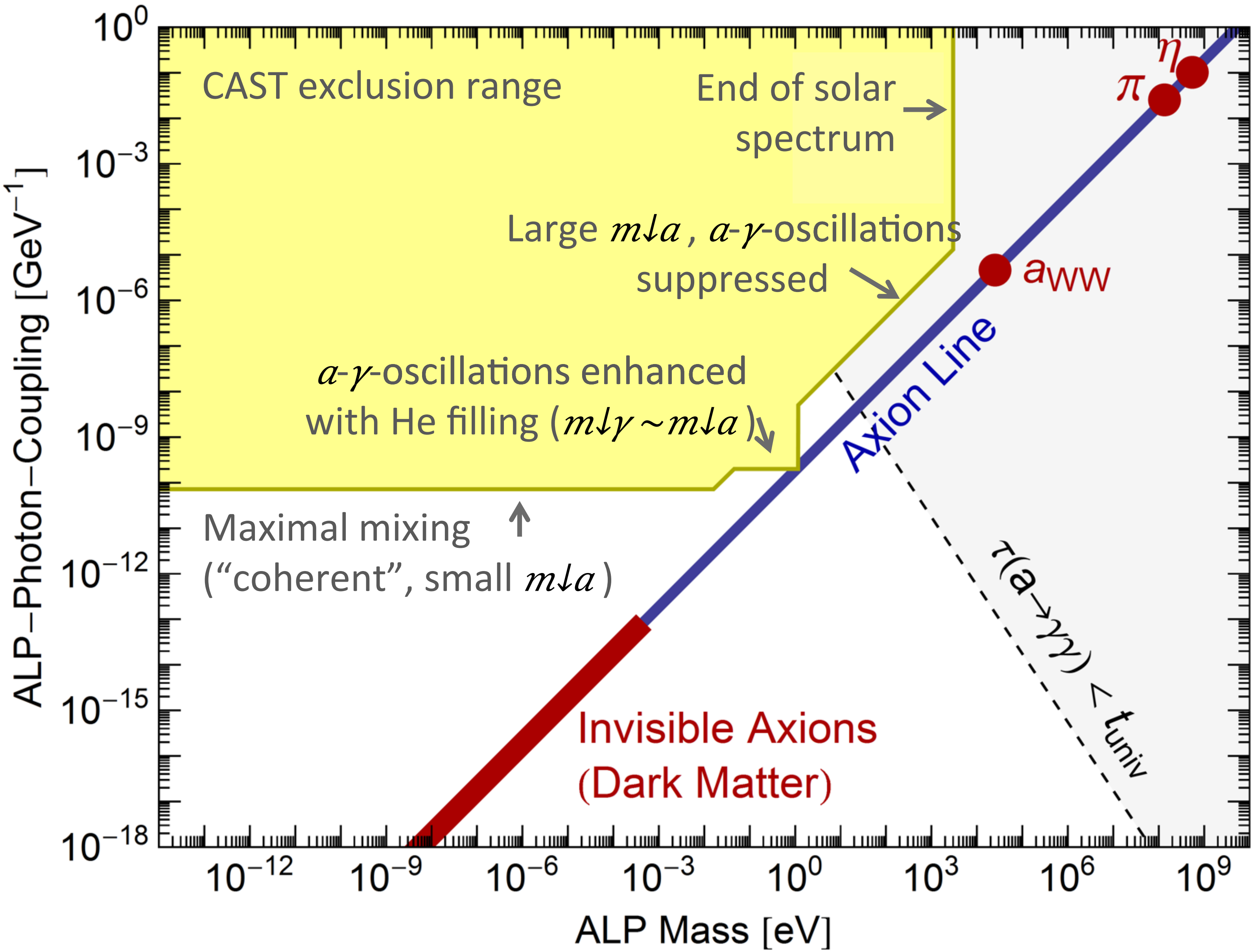
Alternative technique:
Bragg conversion in crystal
Experimental limits on solar axion flux
from dark-matter experiments
(SOLAX, COSME, DAMA, CDMS ...)

CERN Axion Solar Telescope (CAST)

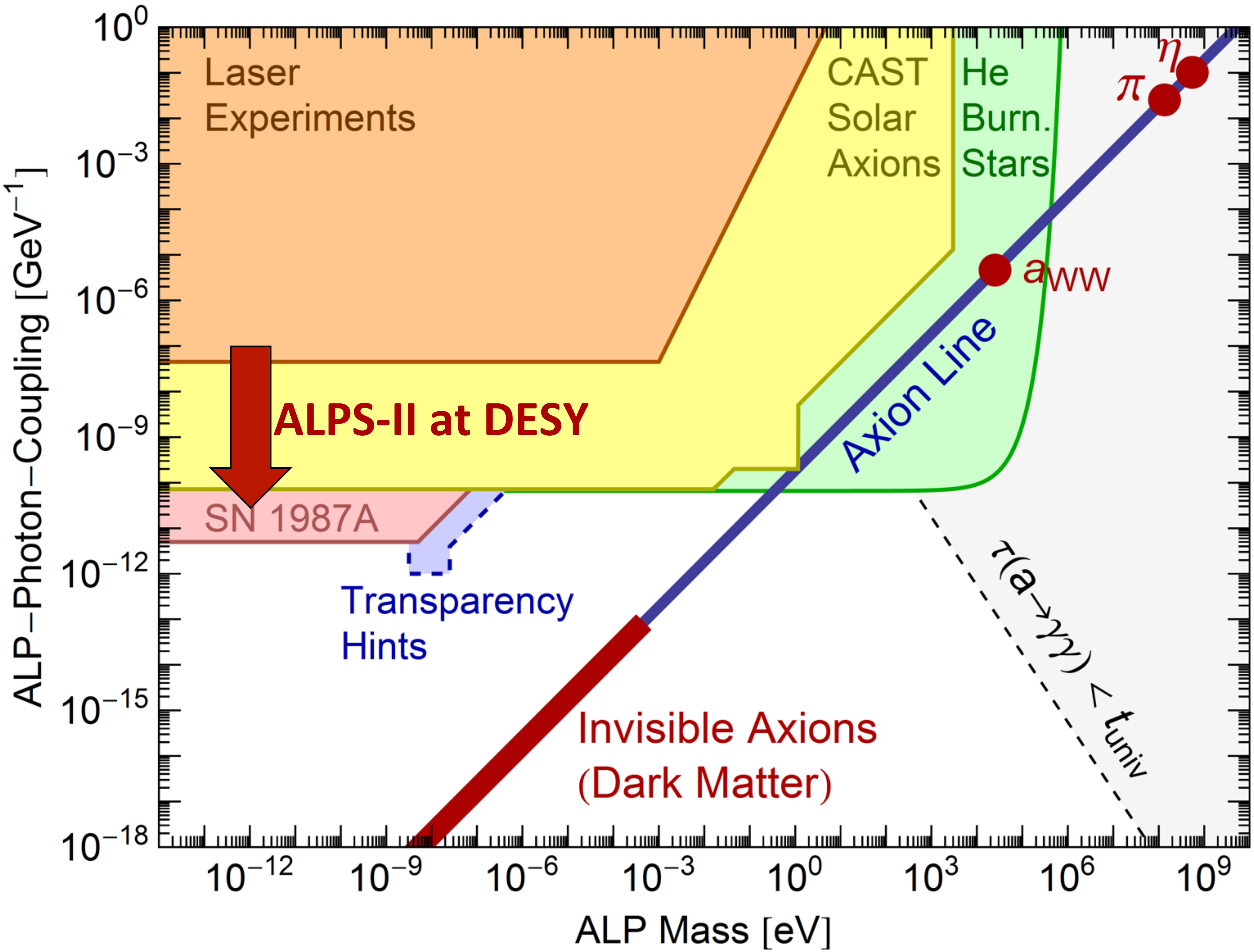
Parameter Space for Axion-Like Particles (ALPs)



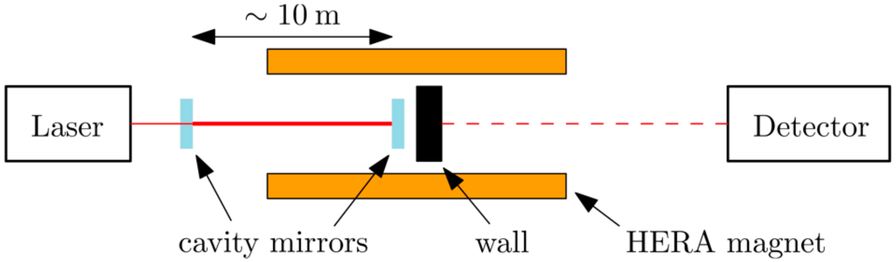
Parameter Space for Axion-Like Particles (ALPs)



Parameter Space for Axion-Like Particles (ALPs)

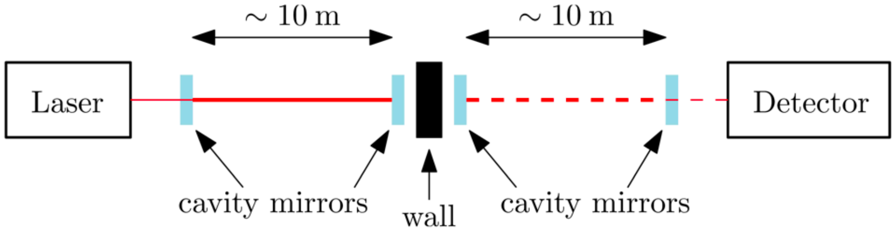


Any Light Particle Search II (ALPS-II) at DESY



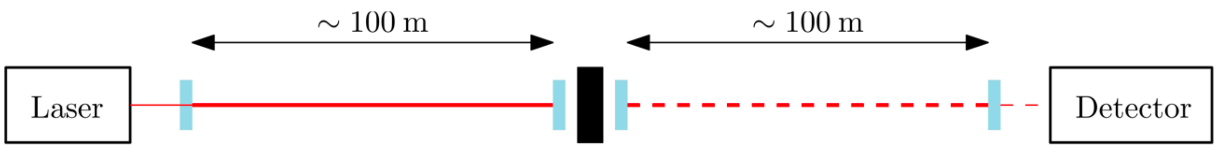
(a) ALPS-I

ALPS-I (finished)



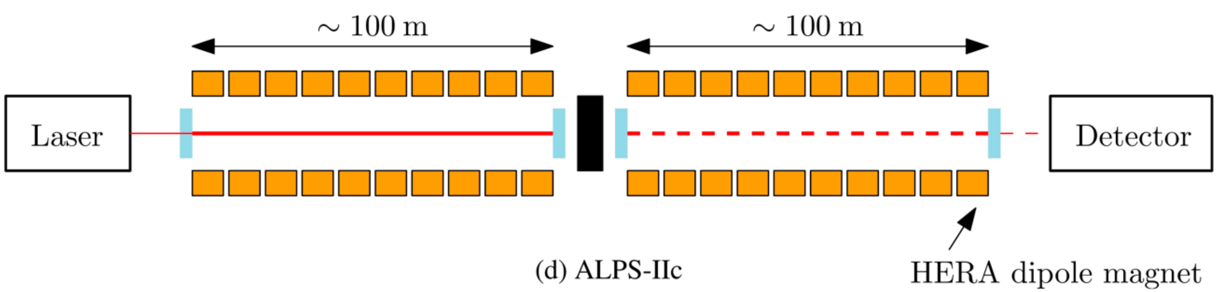
(b) ALPS-IIa

ALPS-IIa (2014)



(c) ALPS-IIb

ALPS-IIb (2015)



(d) ALPS-IIc

ALPS-IIc (2017)

ALPS-II Technical Design Report, arXiv:1302.5647

Shining TeV Gamma Rays through the Universe

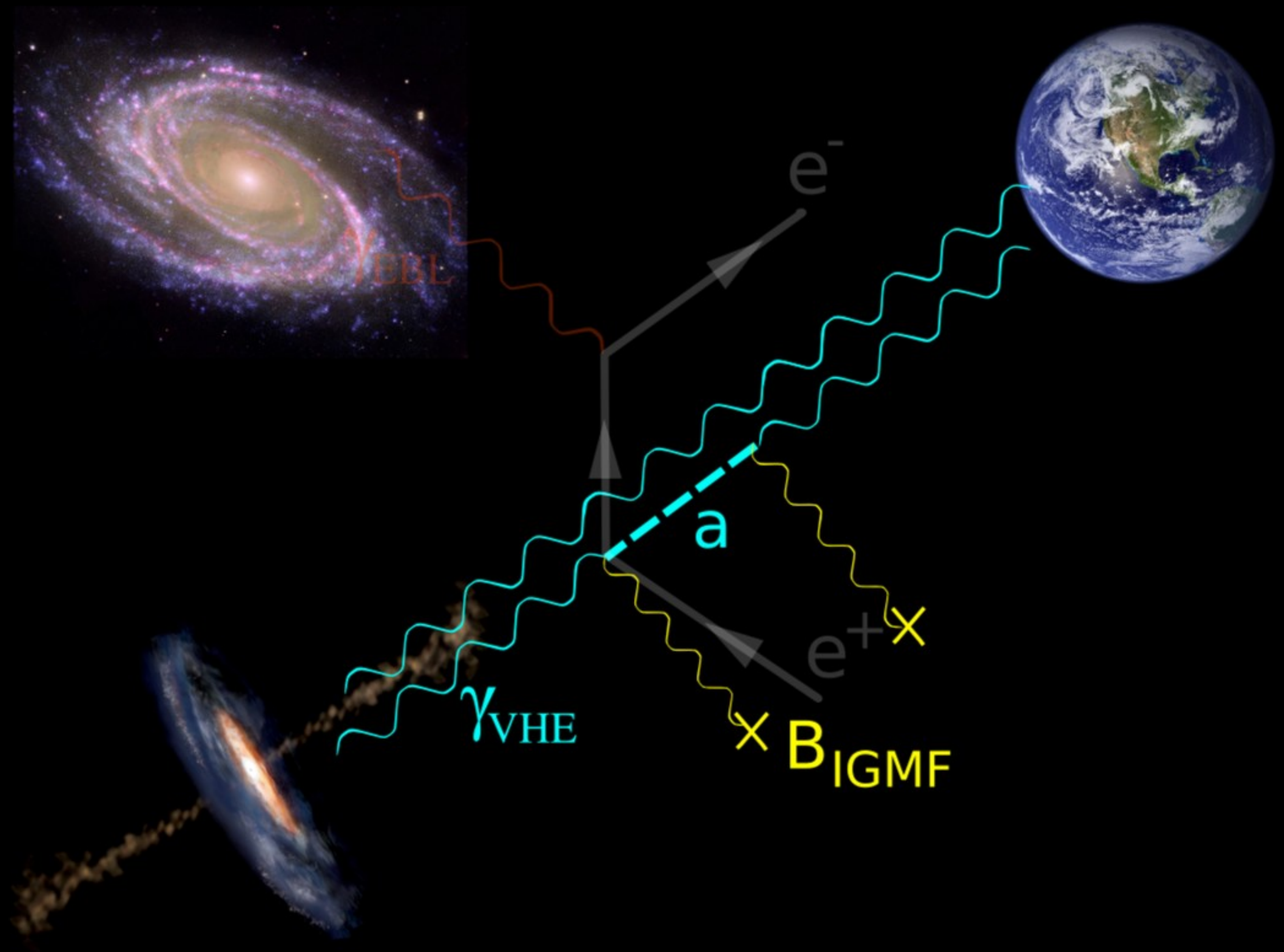
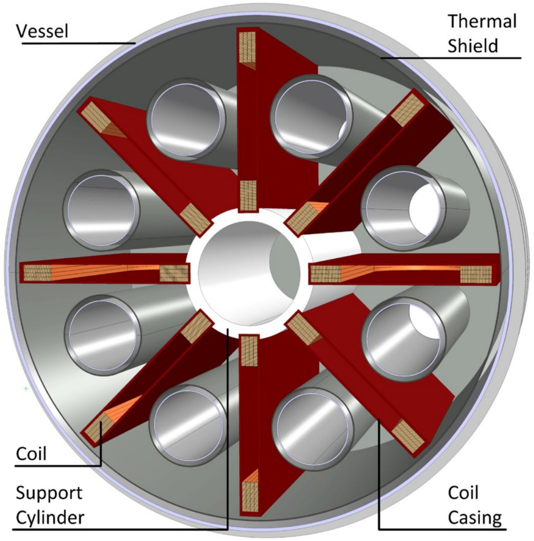
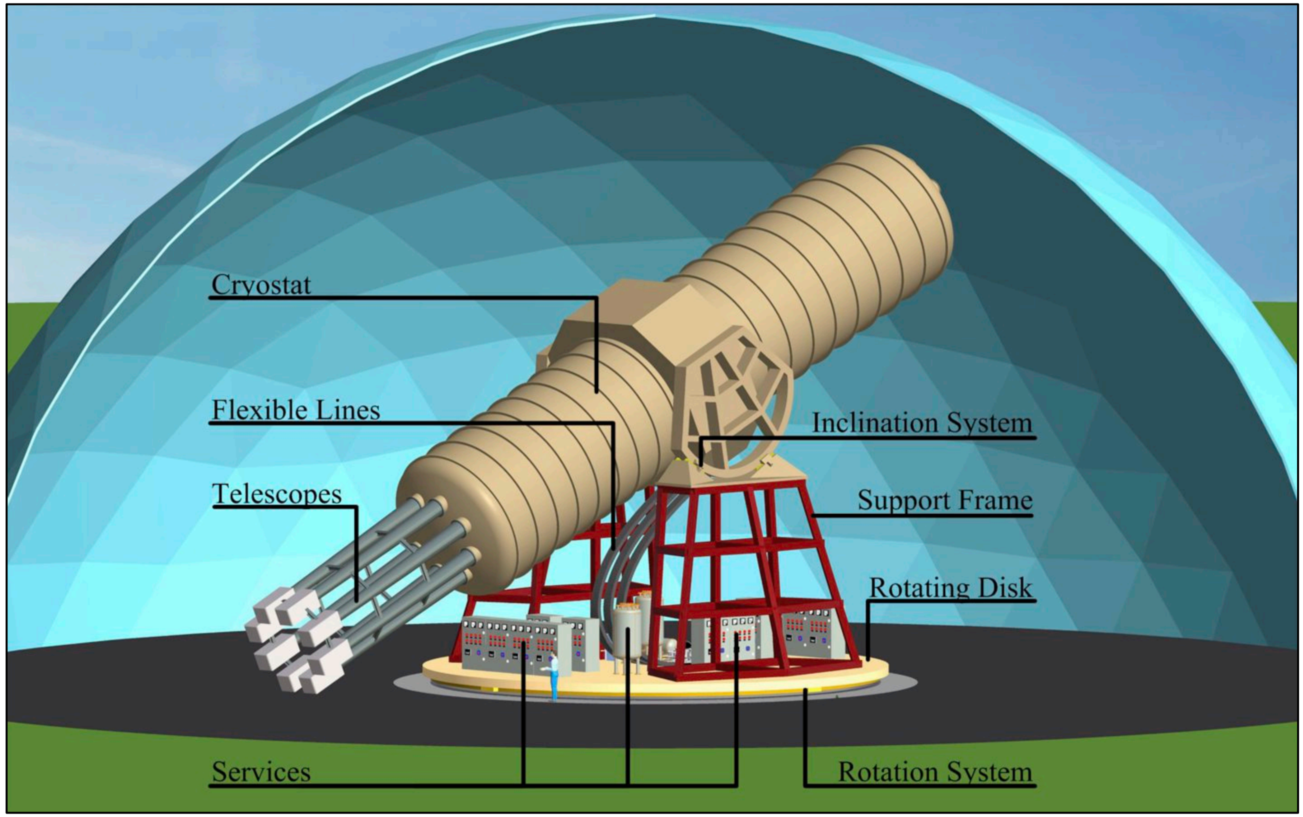


Figure from a talk by Manuel Meyer (Univ. Hamburg)

Next Generation Axion Helioscope (IAXO) at CERN

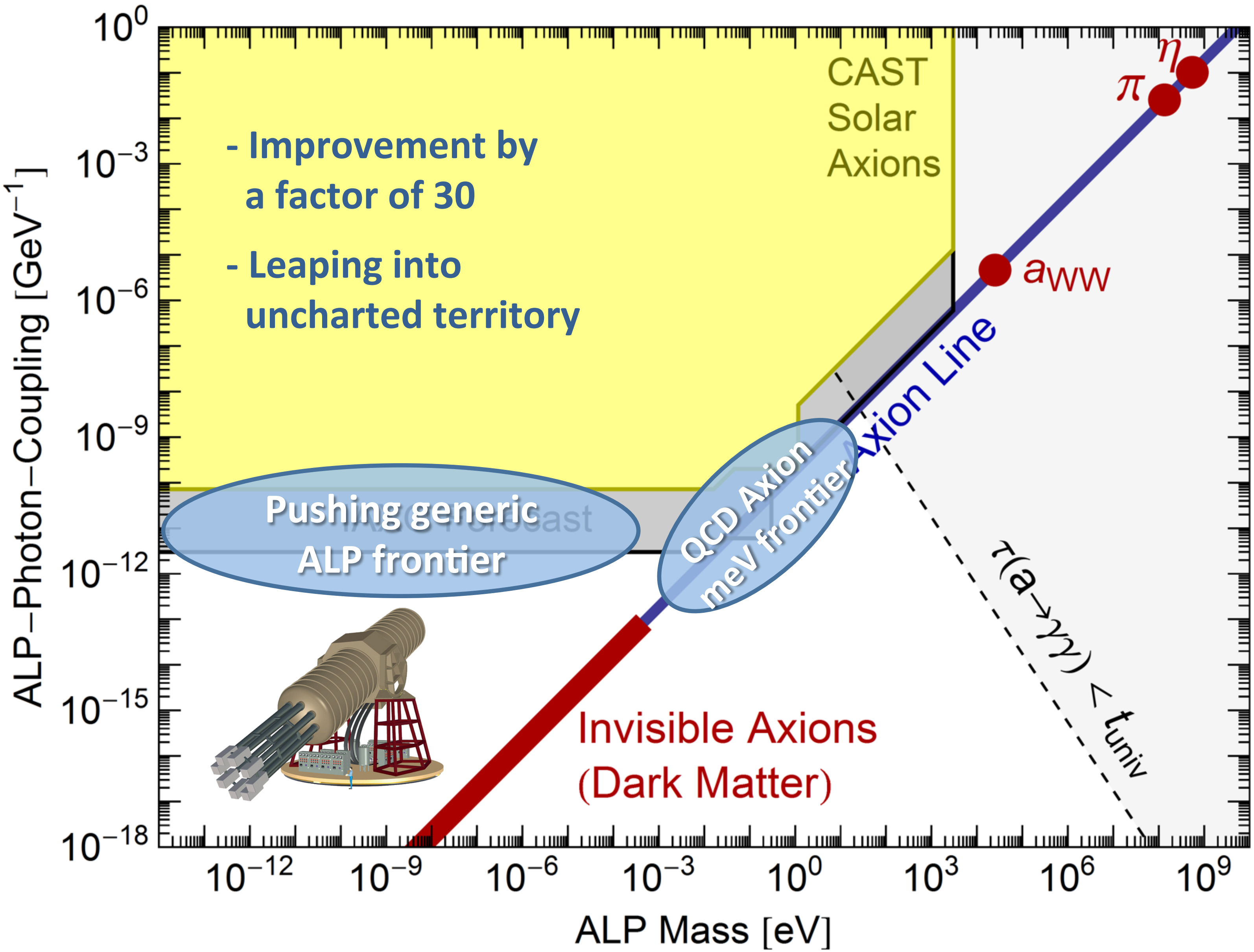




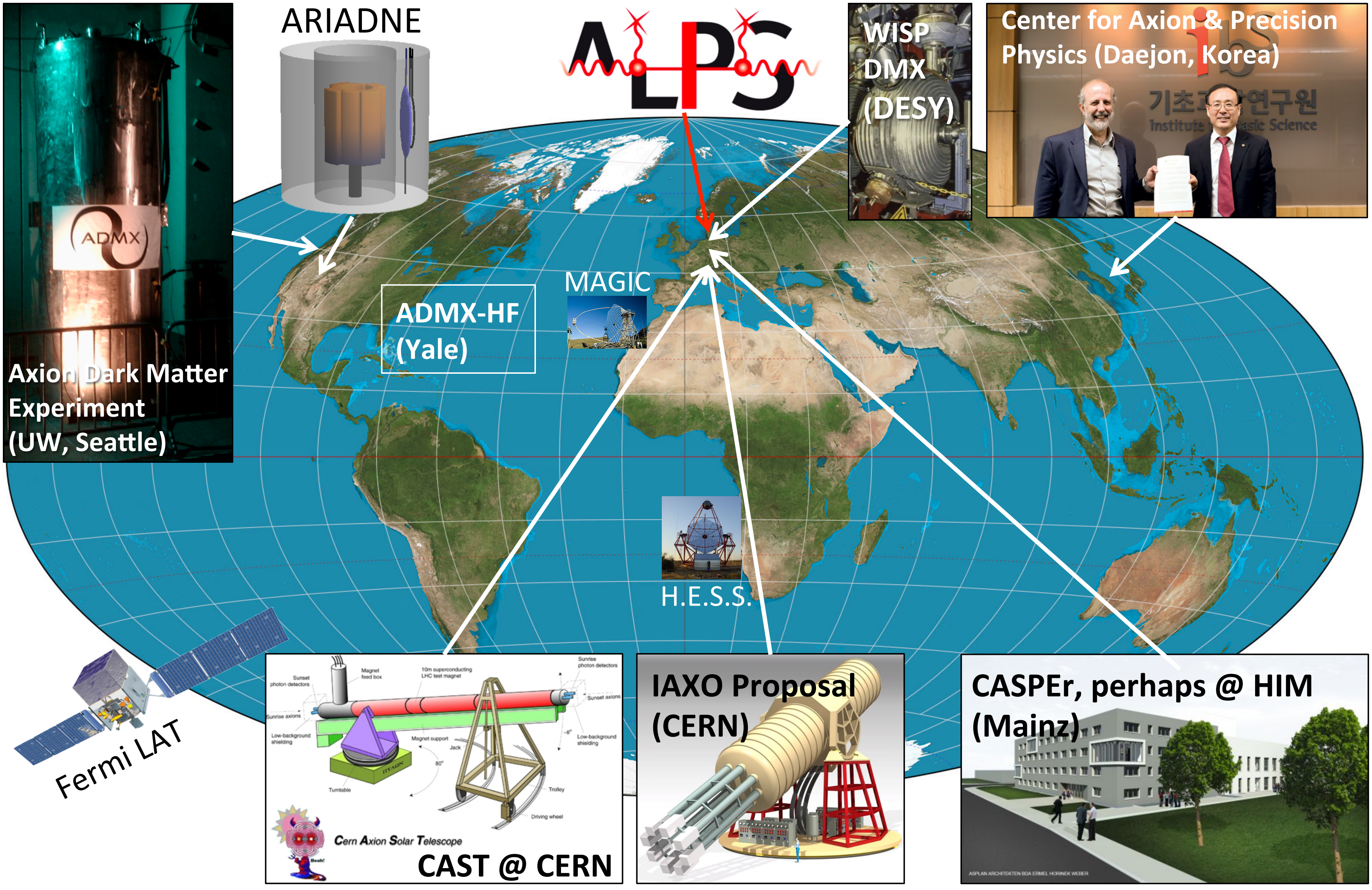
Need new magnet w/
– Much bigger aperture: $\sim 1\ m2$ per bore
– Lighter (no iron yoke)
– Bores at T_{room}

- Irastorza et al.: Towards a new generation axion helioscope, arXiv:1103.5334
- Armengaud et al.: Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233

Parameter Space for Axion-Like Particles (ALPs)



Axion and Axion-Like Particle Searches



Dow Jones Index of Axio

inSPIRE: Citation of Peccei-Quinn pa