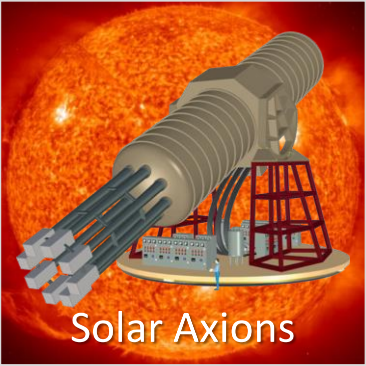
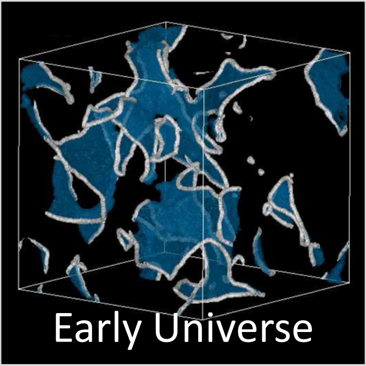
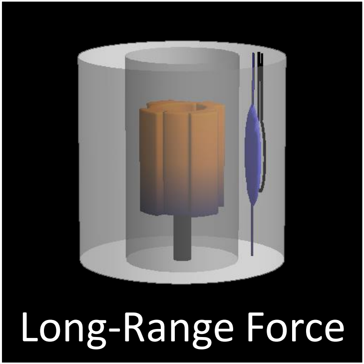

Solar Axions


Supernova 1987A


Early Universe


Dark Matter


Long-Range Force

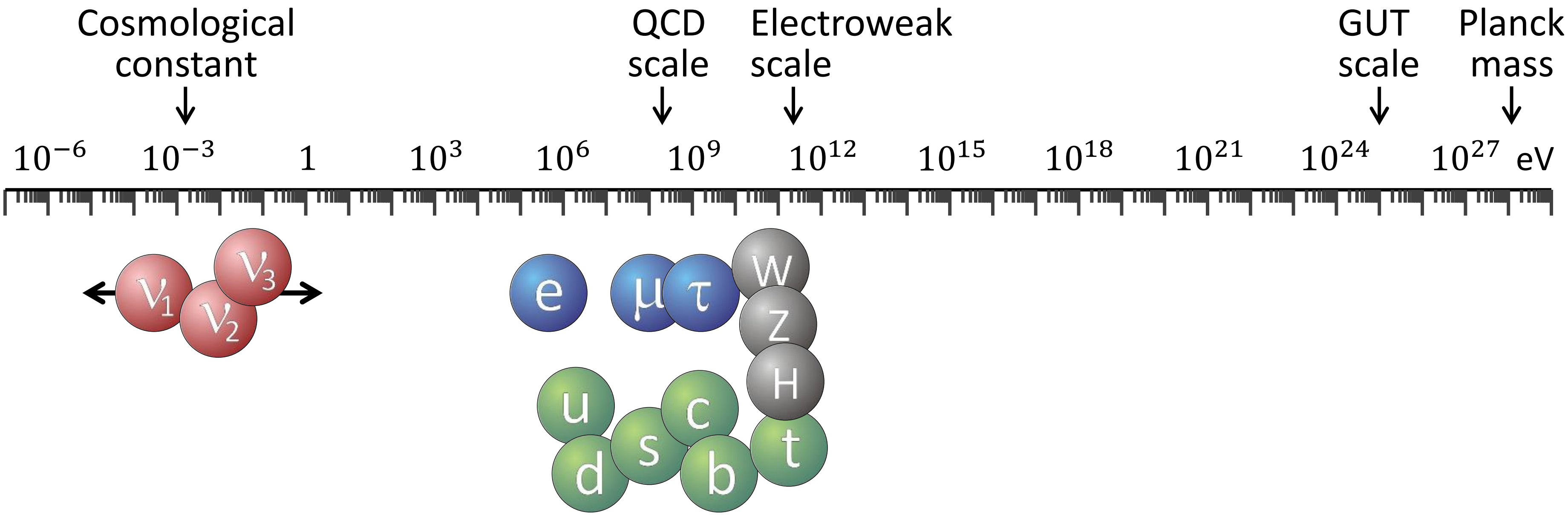
Axion Landscape

Georg Raffelt
Max Planck Institute for Physics, Munich

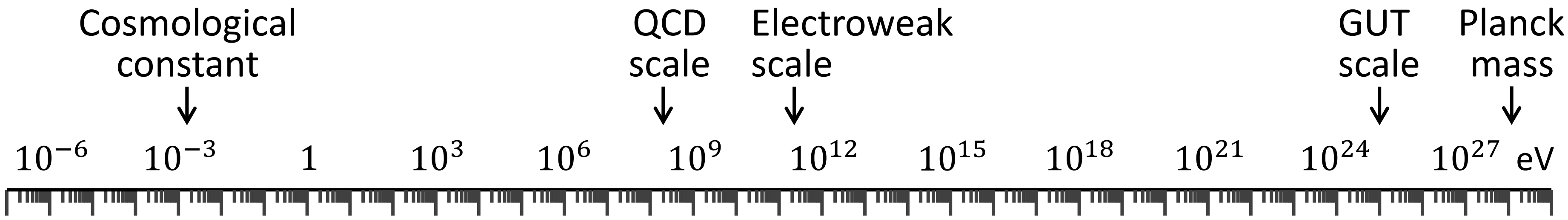
MAX-PLANCK-GESELLSCHAFT

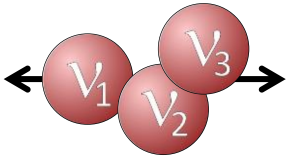
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

High- and Low-Energy Frontiers in Particle Physics

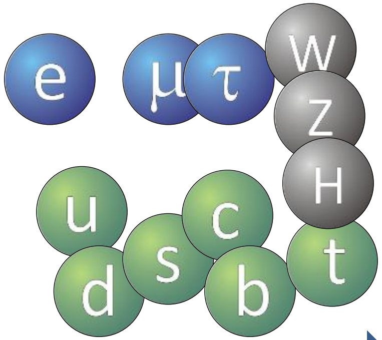


High- and Low-Energy Frontiers in Particle Physics





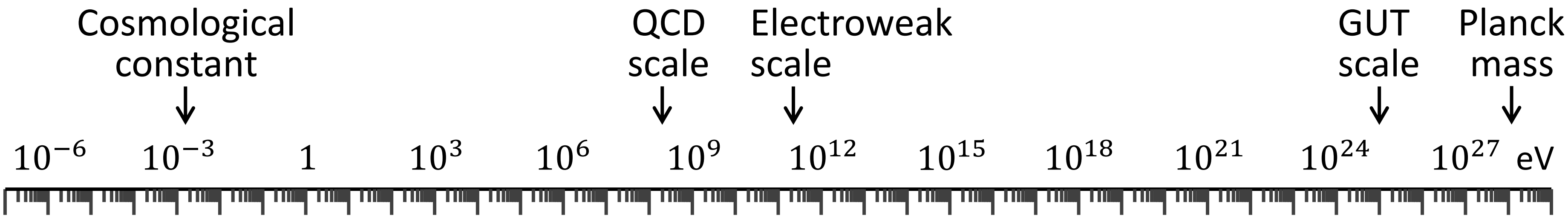
"Intensity Frontier"
(feeble interactions)

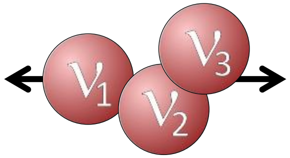


Low-E Frontier

High-Energy Frontier

High- and Low-Energy Frontiers in Particle Physics





“Intensity Frontier”
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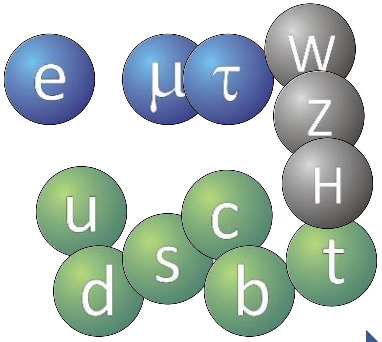
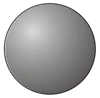


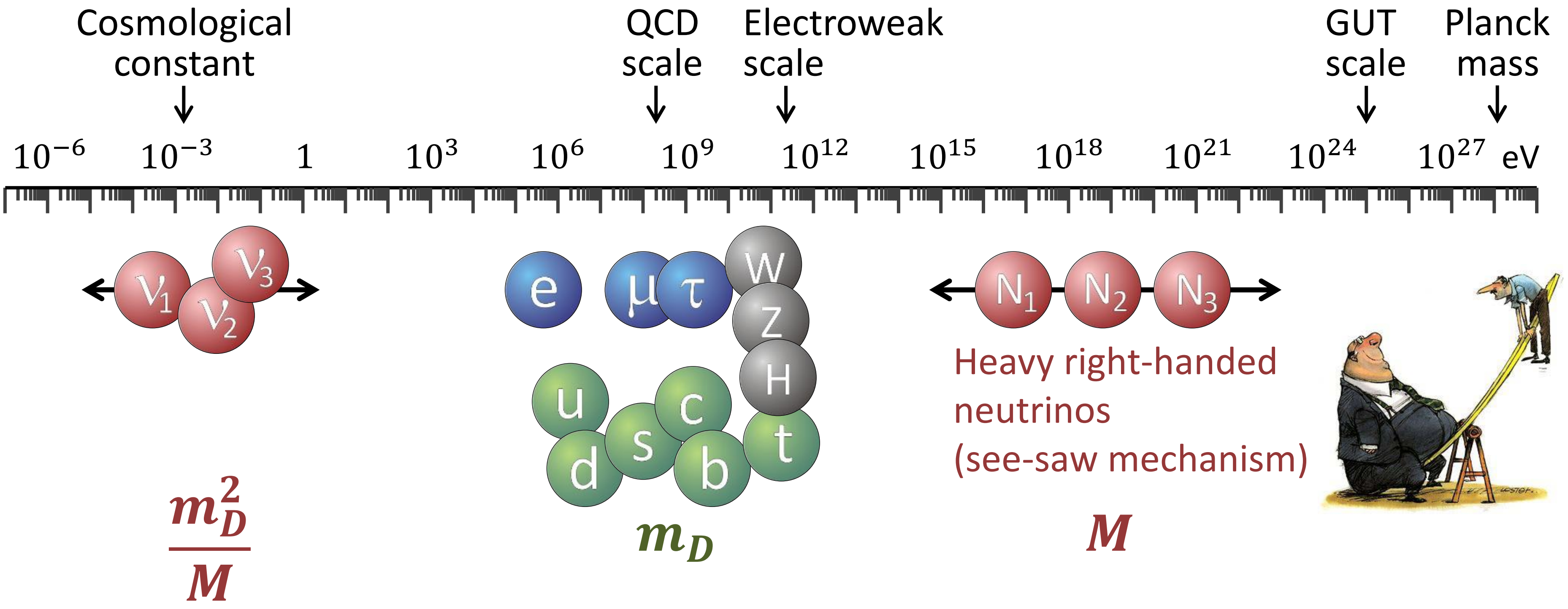
Low-E Frontier

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

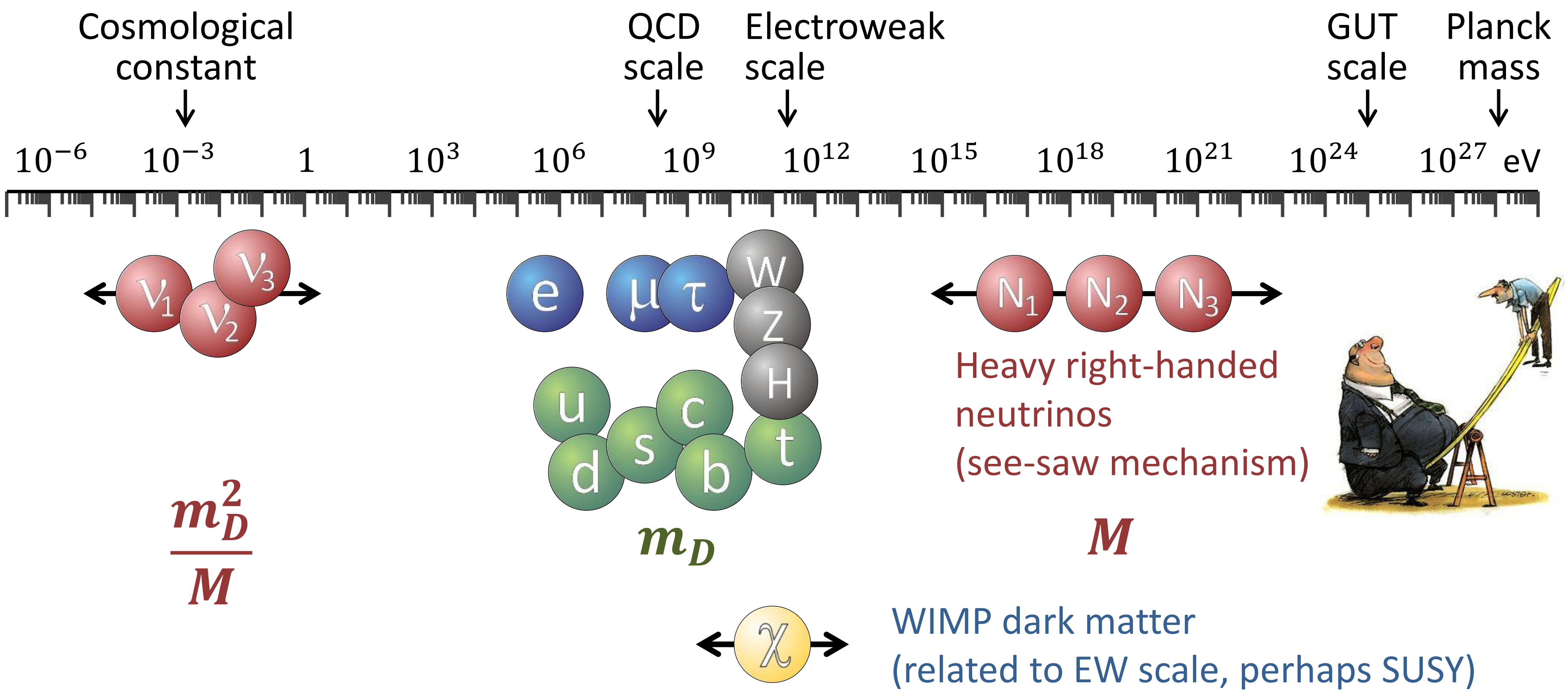
Heavy right-handed neutrinos (see-saw mechanism)

$$\frac{m_D^2}{M}$$

$$m_D$$

$$M$$

High- and Low-Energy Frontiers in Particle Physics



Heavy right-handed neutrinos (see-saw mechanism)

$$\frac{m_D^2}{M}$$

$$m_D$$

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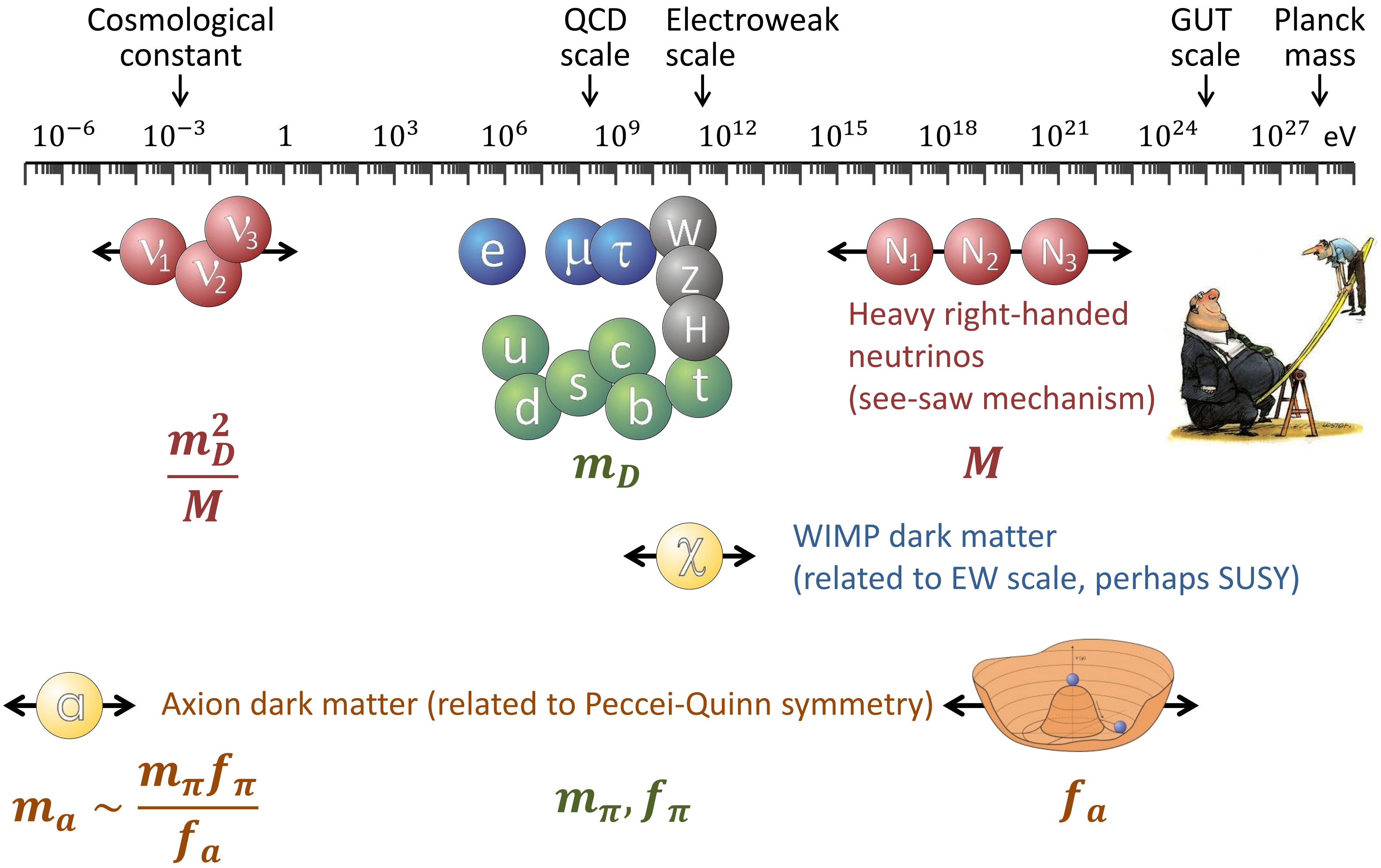
WIMP dark matter
(related to EW scale, perhaps SUSY)

High- and Low-Energy Frontiers in Particle Physics



Heavy right-handed neutrinos (see-saw mechanism)

$$\frac{m_D^2}{M}$$

$$m_D$$

$$M$$

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

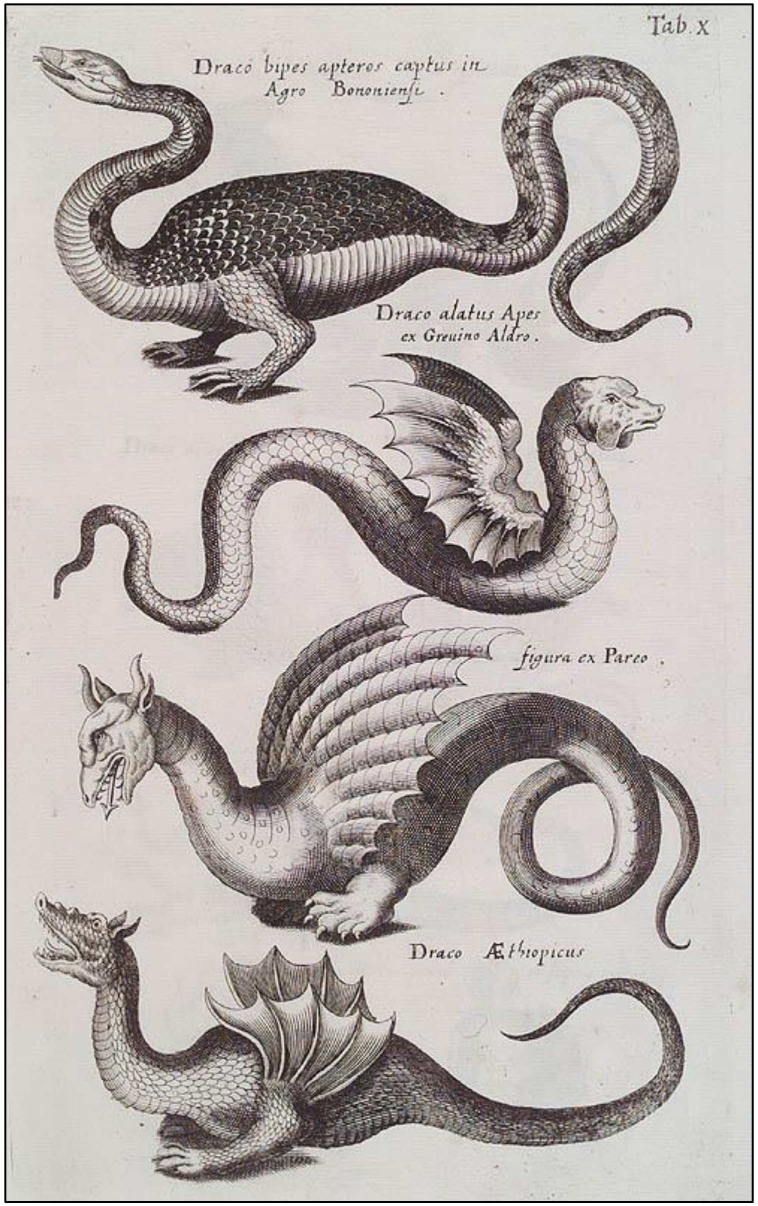
Axion dark matter (related to Peccei-Quinn symmetry)

$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$

$$m_\pi, f_\pi$$

$$f_a$$

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

The CP Problem of Strong Interactions

Real quark mass

Phase from Yukawa coupling

Angle variable

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

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

Remove phase of mass term by chiral transformation of quark fields

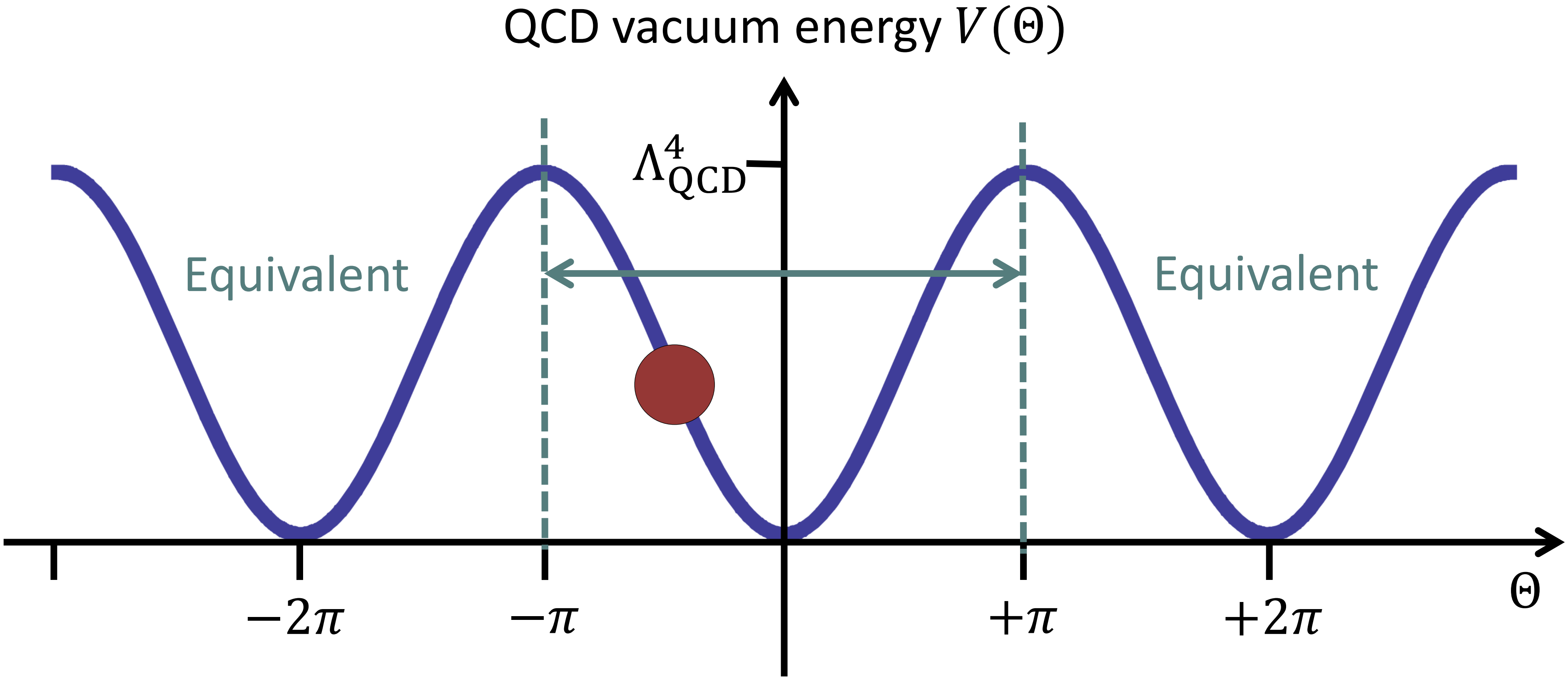
$$\psi_q \to e^{-i\gamma_5\theta_q/2}\psi_q$$

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

- $\bar\Theta$ 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)

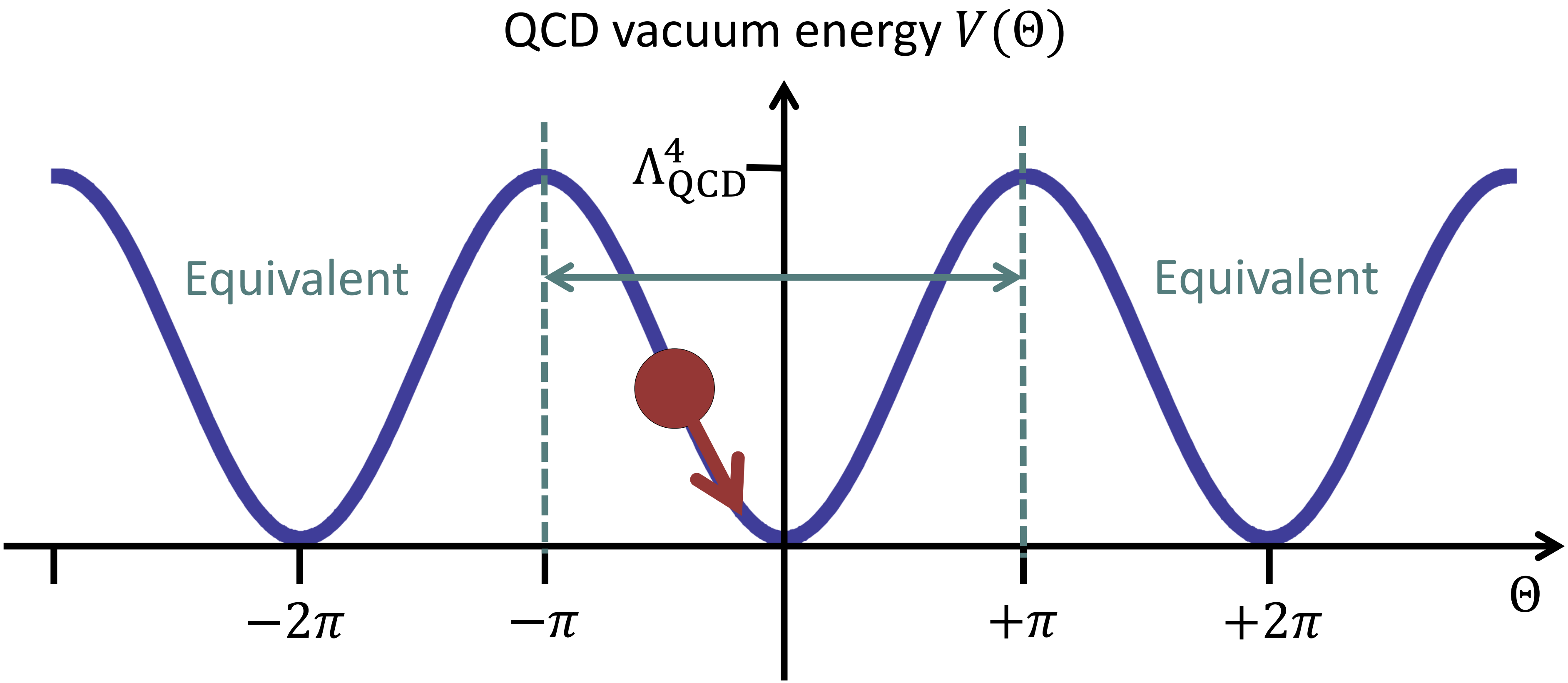
Experimental limits: $|\bar\Theta| < 10^{-11}$ **Why so small?**

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

Strong CP Problem

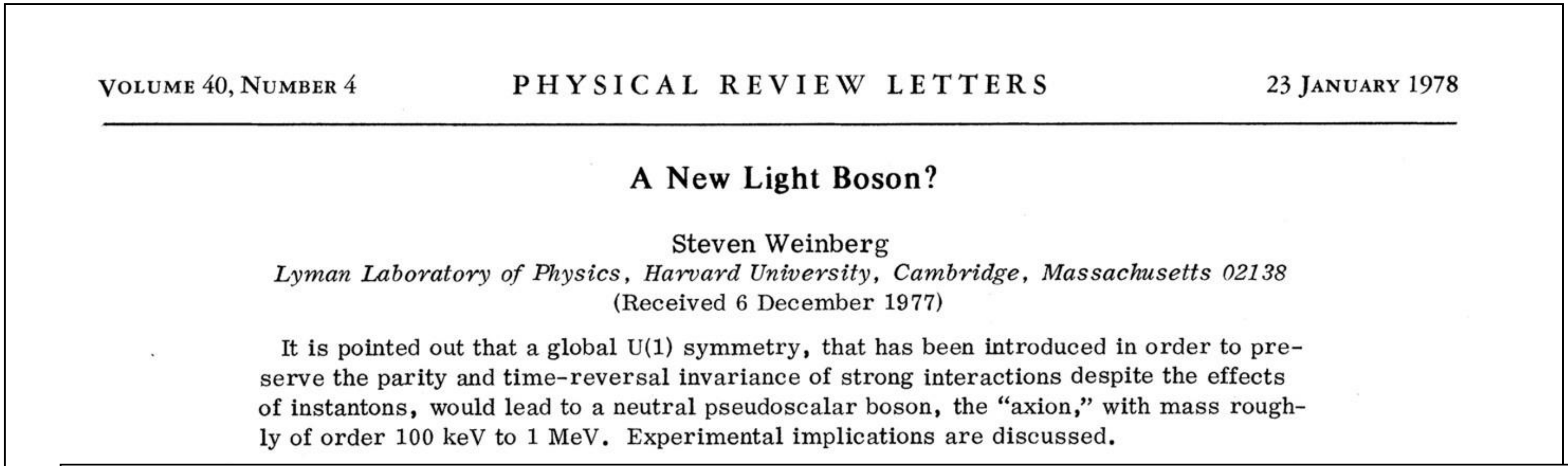


- CP conserving vacuum has $\Theta = 0$ (Vafa and Witten 1984)
- QCD could have any $-\pi \leq \Theta \leq +\pi$, is "constant of nature"
- Energy can not be minimized: Θ not dynamical

Peccei-Quinn solution:

Make Θ dynamical, let system relax to lowest energy

38 Years of Axions



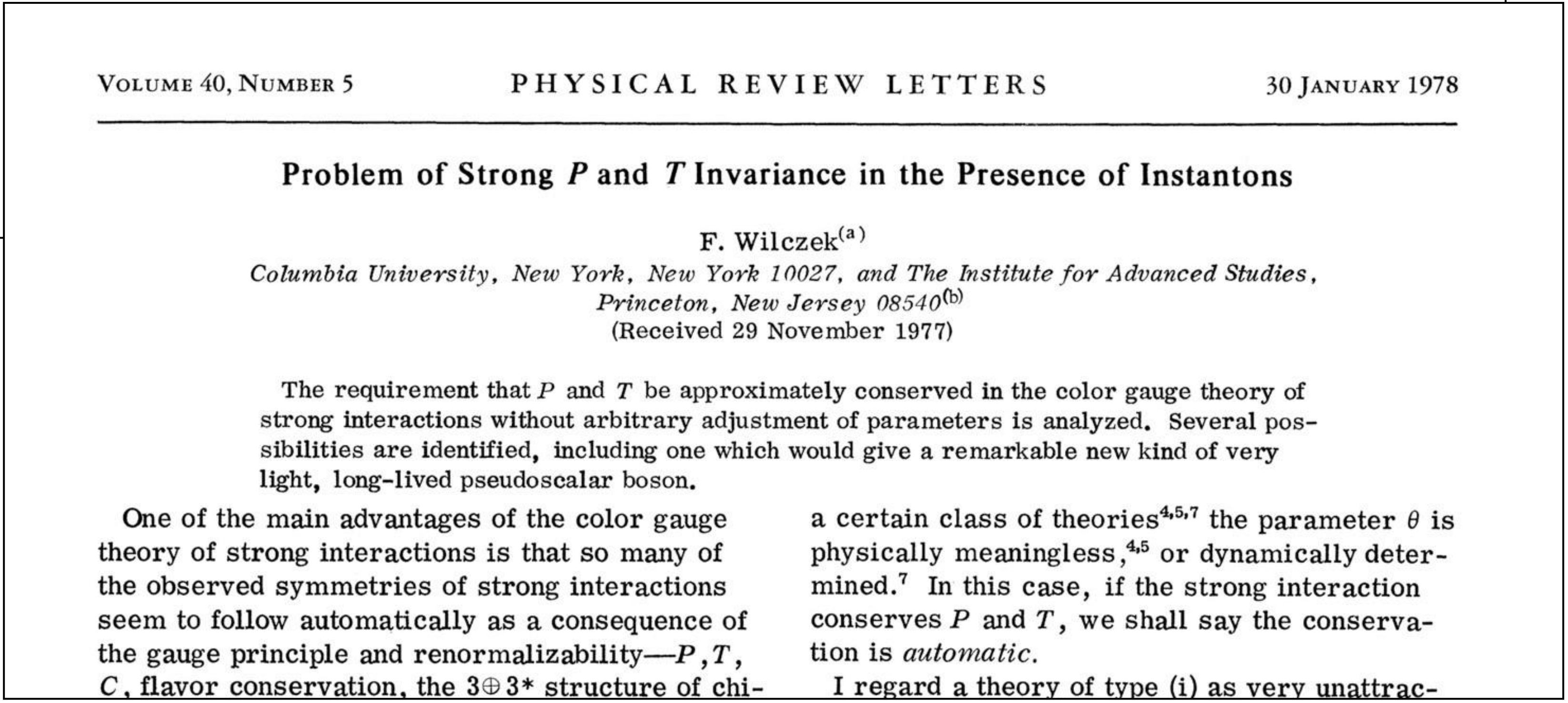
VOLUME 40, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JANUARY 1978

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)

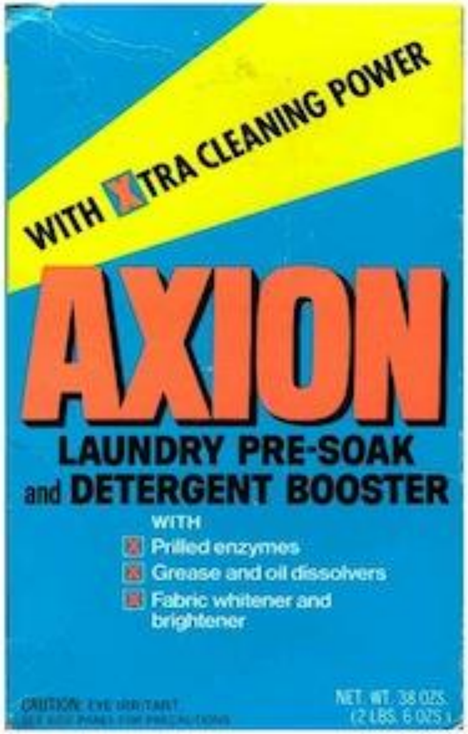
The requirement that *P* and *T* be approximately conserved in the color gauge theory of strong interactions without arbitrary adjustment of parameters is analyzed. Several possibilities are identified, including one which would give a remarkable new kind of very light, long-lived pseudoscalar boson.

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



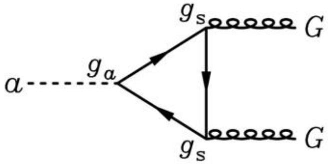

Frank Wilczek

“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

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



Mass (generic) depends on up/down quark masses

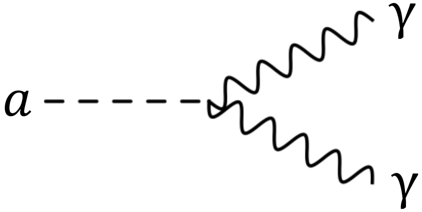
$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$$

Axion-photon coupling (model dependent)

Generic from a-π-η mixing

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

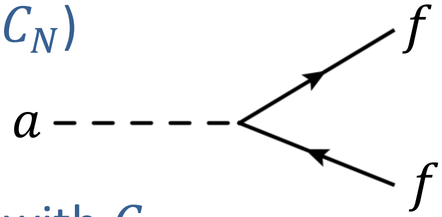
Model-dependent,
E/N = 0 (KSVZ), 8/3 (DFSZ), many others



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

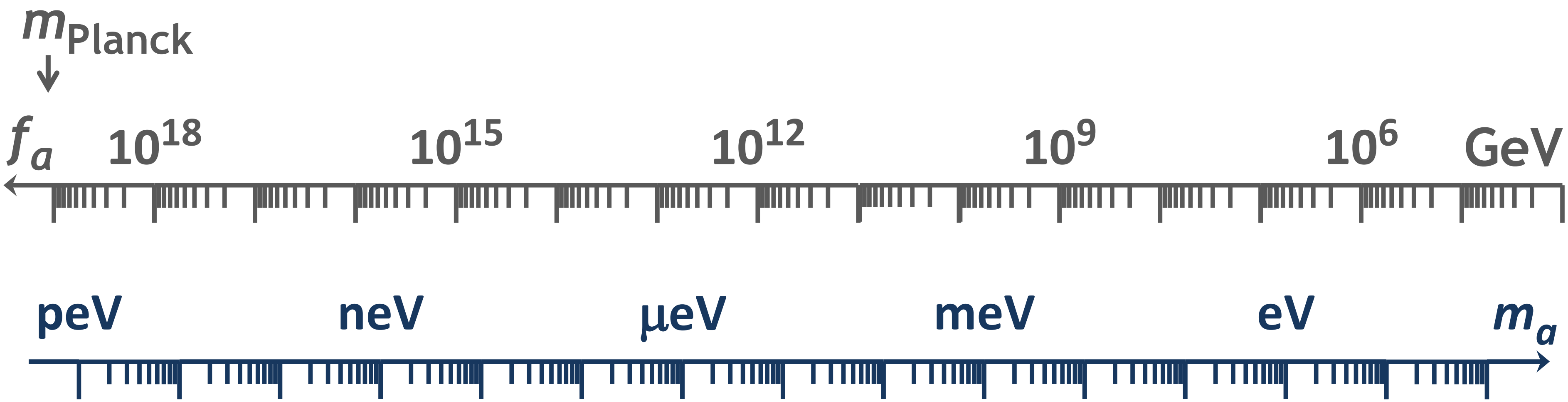
$$\mathcal{L}_{aN} = C_N\,\overline{\Psi}_N\gamma^\mu\gamma_5\Psi_N\frac{\partial_\mu a}{2f_a}$$

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



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

Axion Bounds



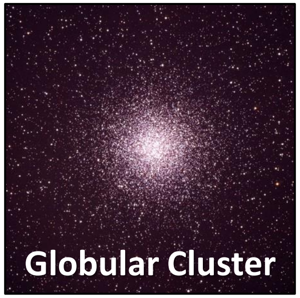
m_{Planck}

f_a 10^{18} 10^{15} 10^{12} 10^{9} 10^{6} GeV

peV neV μeV meV eV m_a

Astrophysical Bounds (Energy loss of stars)

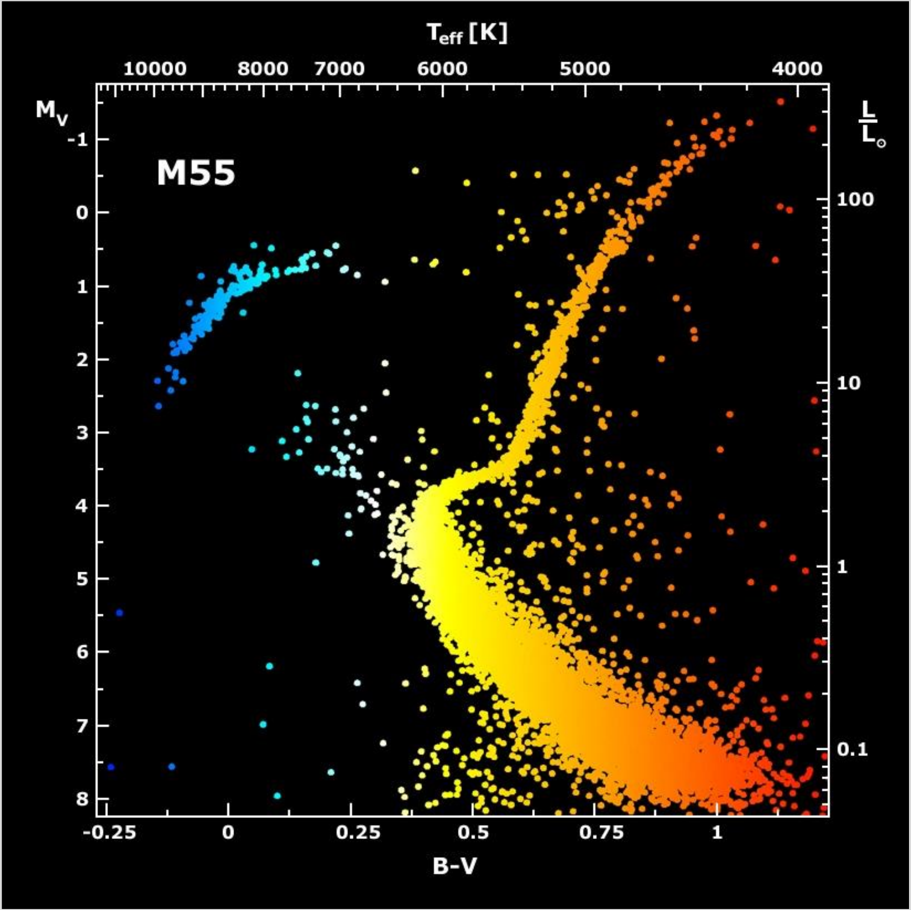
Supernova 1987A



Globular Cluster

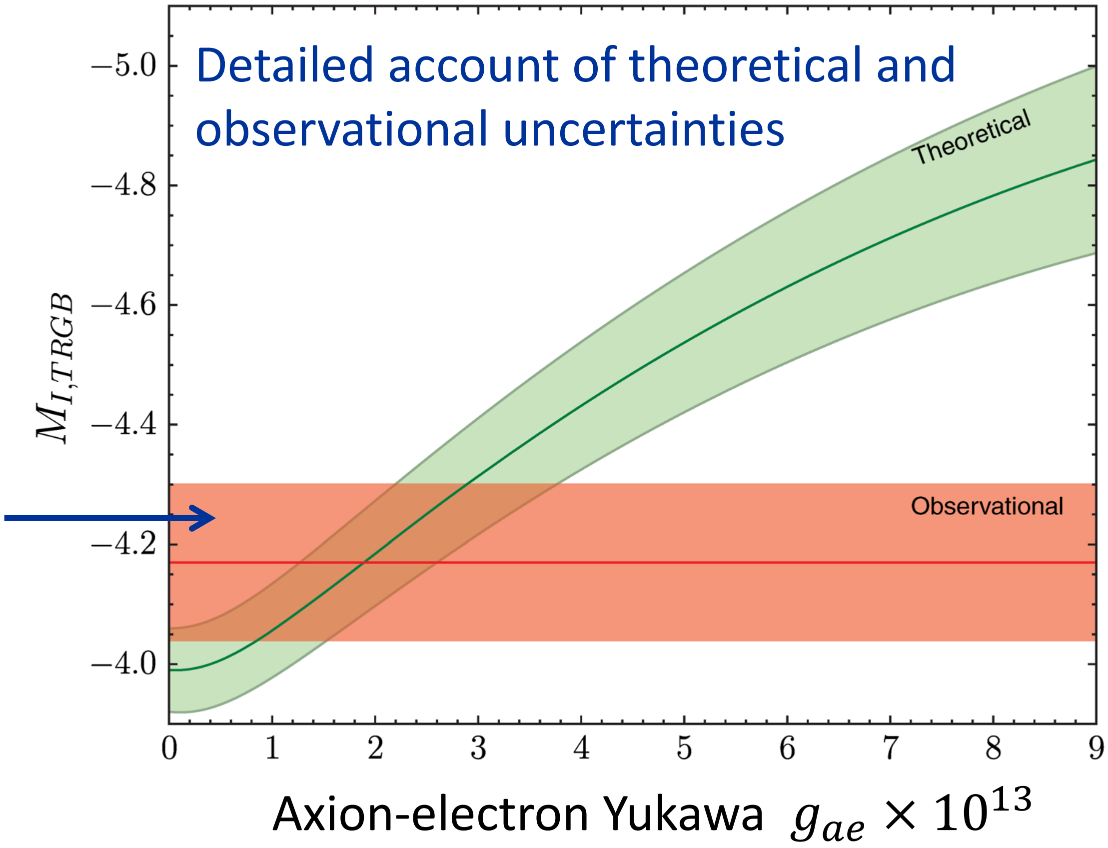
Opportunities for detection

Galactic Globular Clusters



Limits on Axion-Electron Coupling from GC M5

I-band brightness
of tip of red-giant brach
[magnitudes]



Detailed account of theoretical and observational uncertainties

- Uncertainty dominated by distance
- Can be improved in future (GAIA mission)

Limit on axion-electron Yukawa

$$g_{ae} < \begin{cases} 2.6 \times 10^{-13} & (68\%\ \mathrm{CL}) \\ 4.3 \times 10^{-13} & (95\%\ \mathrm{CL}) \end{cases}$$

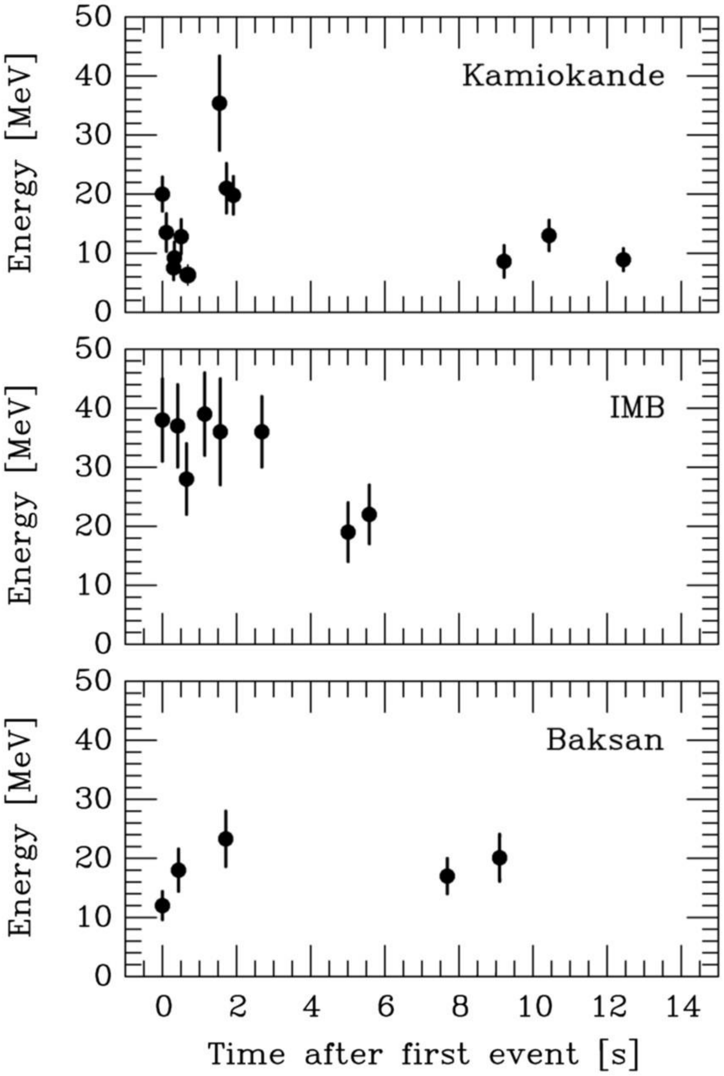
Mass limit in DFSZ model

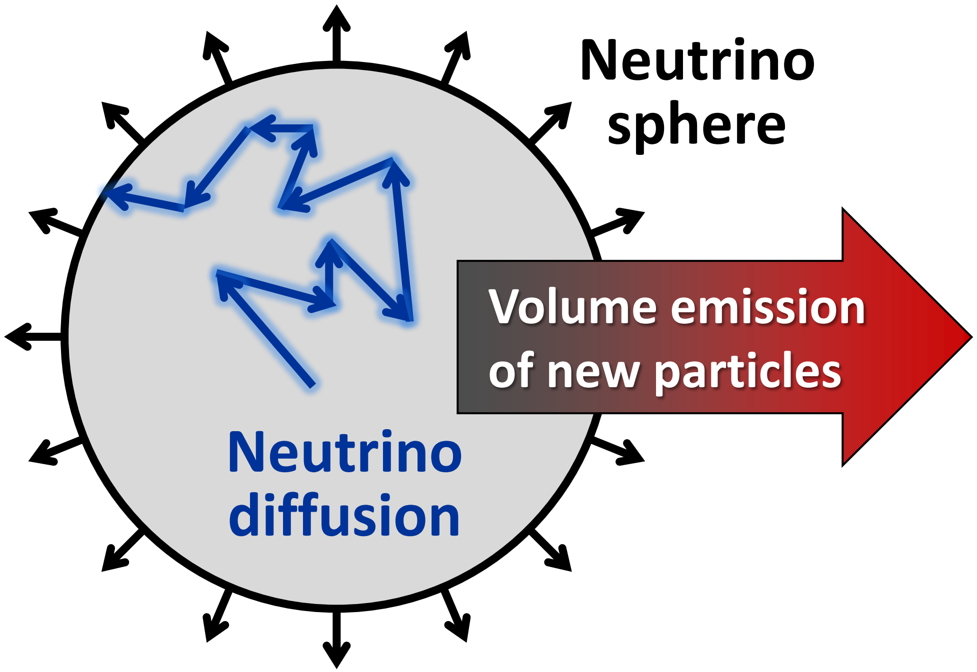
$$m_a \cos^2\beta < \begin{cases} 9.3\ \mathrm{meV} & (68\%\ \mathrm{CL}) \\ 15.4\ \mathrm{meV} & (95\%\ \mathrm{CL}) \end{cases}$$

Viaux, Catelan, Stetson, Raffelt, Redondo, Valcarce & Weiss, arXiv:1311.1669

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

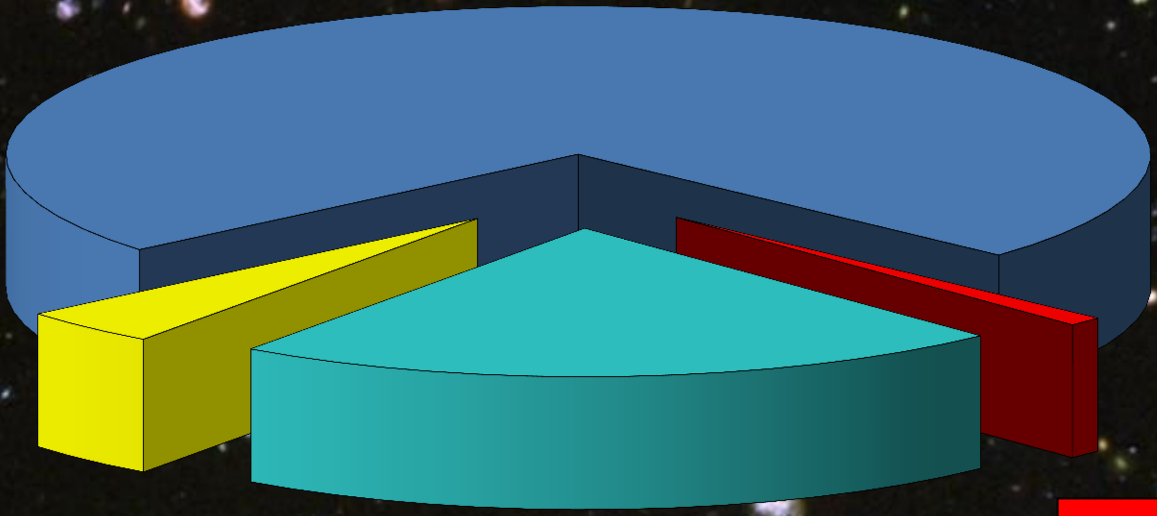




Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Dark Energy 70%
(Cosmological Constant)

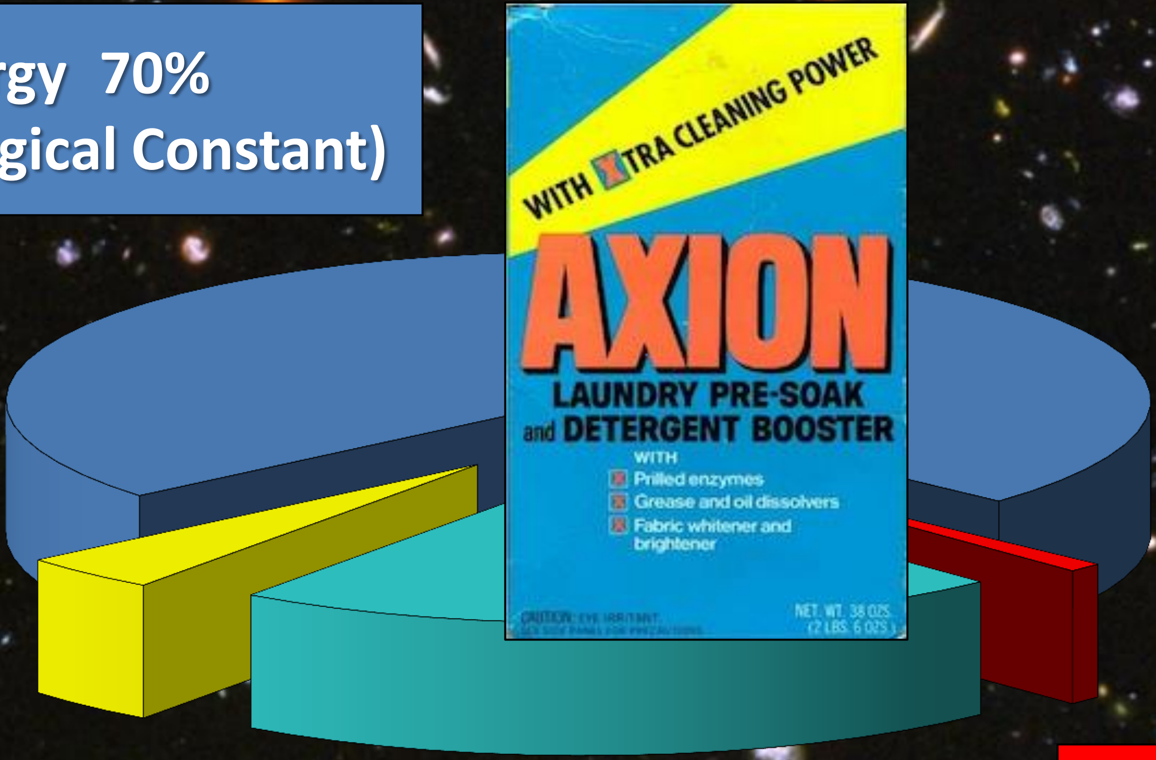


Ordinary Matter 5%
(of this only about
10% luminous)

Dark Matter
25%

Neutrinos
0.1–0.4%

Dark Energy 70%
(Cosmological Constant)



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

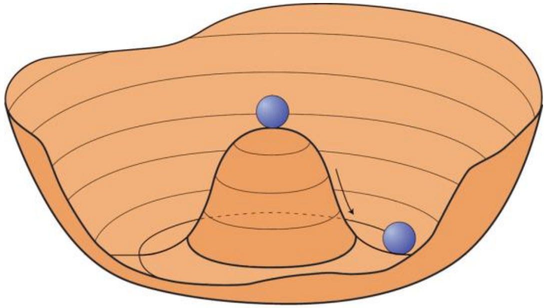
Dark Matter
25%

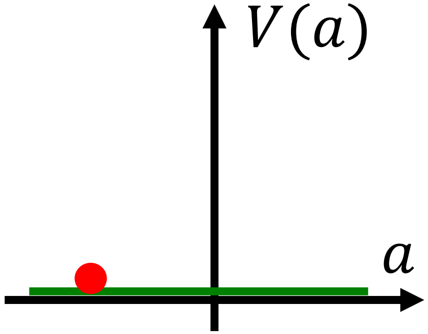
Neutrinos
0.1–0.4%

Creation of Cosmological Axions by Re-alignment

$T \sim f_a$ (very early universe)

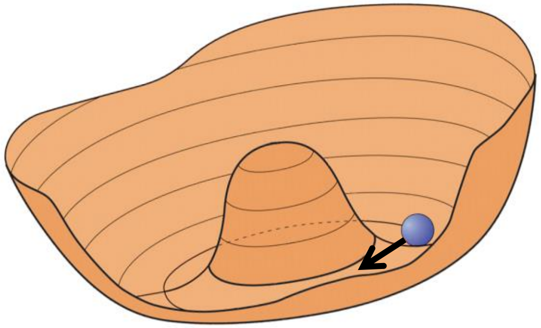
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_i = \Theta_i f_a$

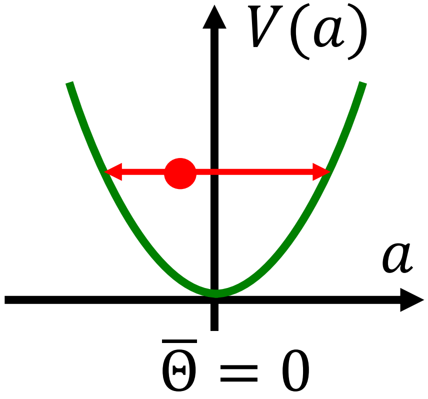




$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

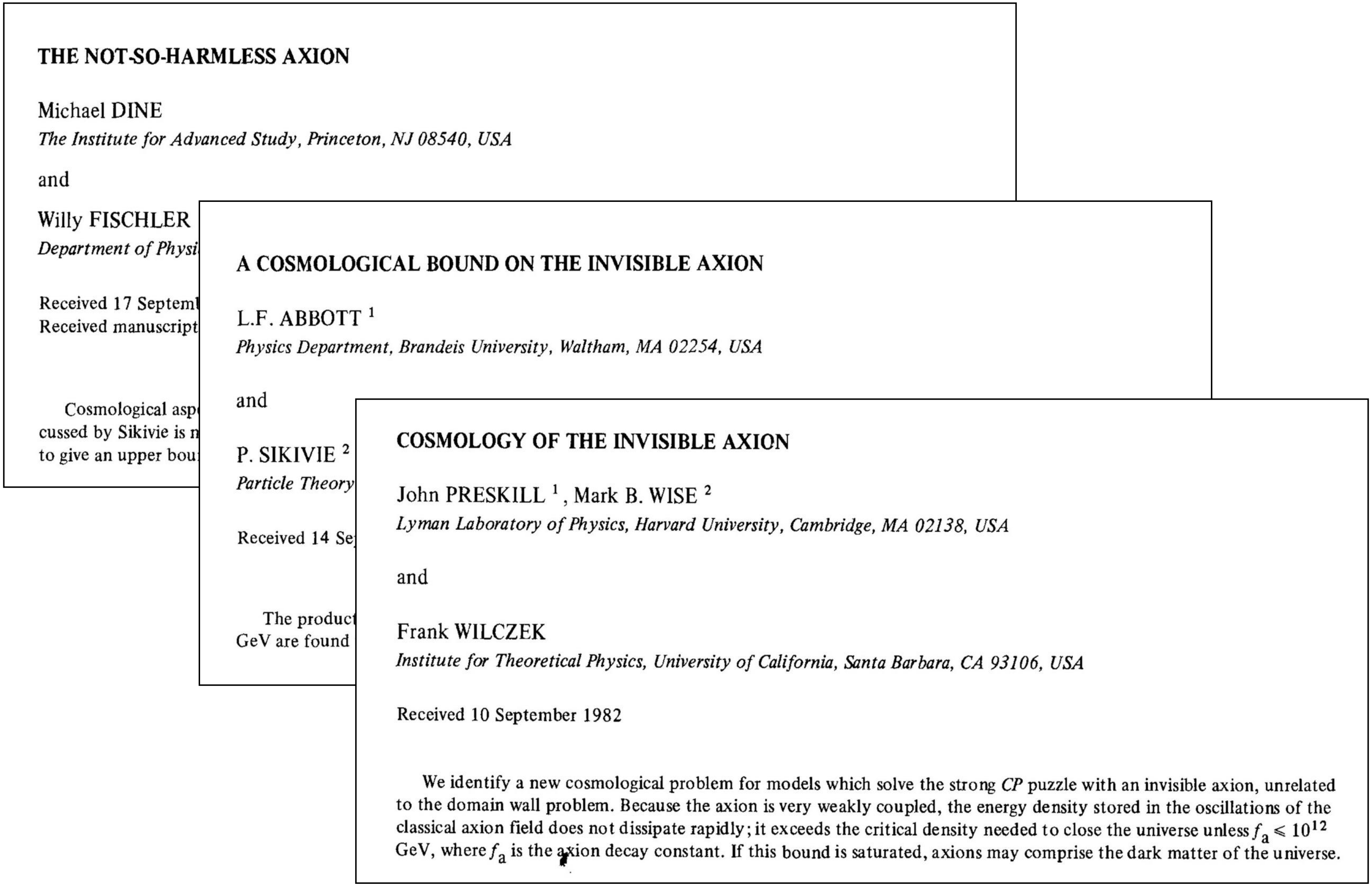
- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_a \gtrsim 3H$
- Classical field oscillations (axions at rest)





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.

Galactic WIMP vs Axion Dark Matter

Local dark matter density around 0.3 GeV/cm^3

WIMPs: Typical mass 100 GeV

- Local number density:

$$3000\ \mathrm{m}^{-3}\ \frac{100\ \mathrm{GeV}}{m_{\mathrm{WIMP}}}$$

Dilute gas of particles

Axions: Typical mass 10 μeV

- Local number density:

$$3\times 10^{19}\ \mathrm{m}^{-3}\ \frac{10\ \mu\mathrm{eV}}{m_a}$$

- Typical galactic virial velocity:

$$v_{\mathrm{gal}} \sim 10^{-3}\ c$$

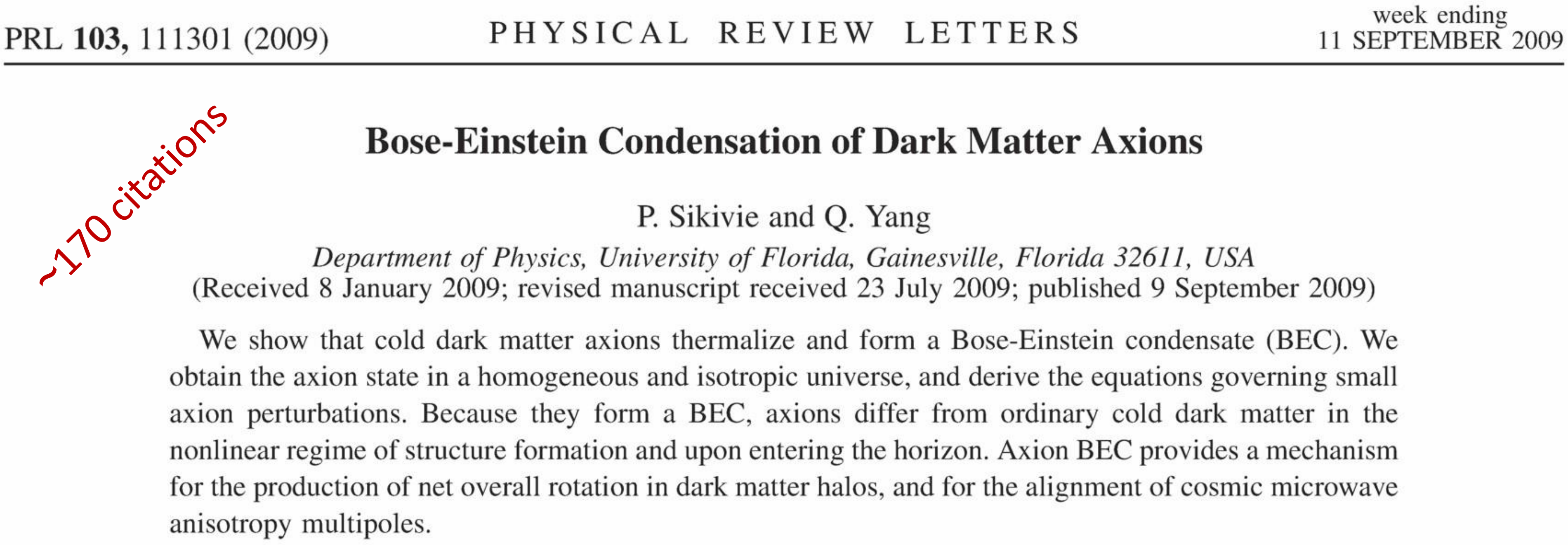
- Typical de Broglie wavelength (“localisation”)

$$\lambda \sim \frac{2\pi}{m_a v_{\mathrm{gal}}} \sim 100\ \mathrm{m}\ \frac{10\ \mu\mathrm{eV}}{m_a}$$

- Minimal occupation number

$$f \sim 10^{25}\ \left(\frac{10\ \mu\mathrm{eV}}{m_a}\right)^4$$

Highly degenerate Bose gas!



PRL **103,** 111301 (2009) PHYSICAL REVIEW LETTERS week ending 11 SEPTEMBER 2009

Bose-Einstein Condensation of Dark Matter Axions

P. Sikivie and Q. Yang

Department of Physics, University of Florida, Gainesville, Florida 32611, USA

(Received 8 January 2009; revised manuscript received 23 July 2009; published 9 September 2009)

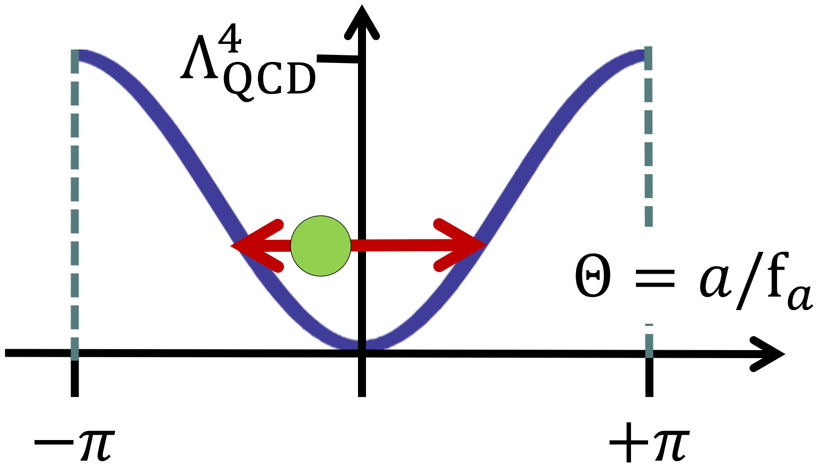
We show that cold dark matter axions thermalize and form a Bose-Einstein condensate (BEC). We obtain the axion state in a homogeneous and isotropic universe, and derive the equations governing small axion perturbations. Because they form a BEC, axions differ from ordinary cold dark matter in the nonlinear regime of structure formation and upon entering the horizon. Axion BEC provides a mechanism for the production of net overall rotation in dark matter halos, and for the alignment of cosmic microwave anisotropy multipoles.

~170 citations

- Axions ~ WIMP dark matter on scales ≫ axion de Broglie wavelength?
- Larger-range correlation established by BEC dynamics? (Observable?)
- BEC formation caused by gravitational interactions possible?

See also
- Erken, Sikivie, Tam & Yang, arXiv:1111.1157
- Saikawa & Yamaguchi, arXiv:1210.7080
- Noumi, Saikawa, Sato & Yamaguchi, arXiv:1310.0167
- Davidson & Elmer, arXiv:1307.8024, Davidson, arXiv:1405.1139
- Berges & Jaeckel, arXiv:1402.4776
- Guth, Hertzberg & Prescod-Weinstein, arXiv:1412.5930

Axion Dark Matter Driving Oscillators



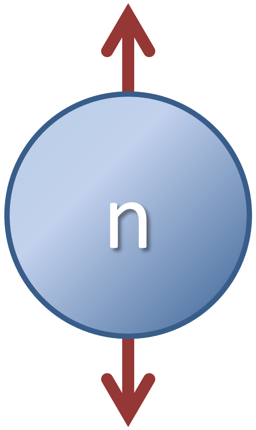
Oscillating axion field (DM)
→ Oscillating Θ term

- **Drives oscillating neutron EDM**
- **Drives oscillating E-field in microwave cavity w/ B-field**

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

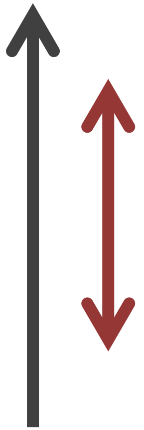
$$\rho_a = \frac{1}{2} m_a^2 \Phi_a^2 = \frac{1}{2} m_a^2 (\Theta f_a)^2 \sim \Theta^2 (m_\pi f_\pi)^2 \sim \Theta^2 \Lambda_{\rm QCD}^4$$

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



Neutron EDM oscillating with $\omega = m_a$

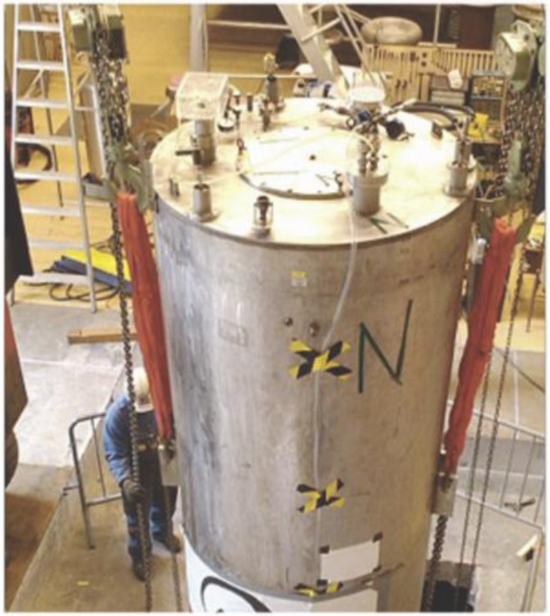
External static B-field



Axion-induced electric field oscillating with $\omega = m_a$

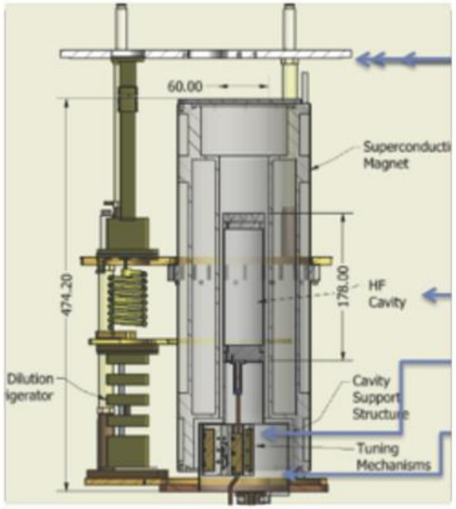
Landscape of Cavity Experiments

ADMX



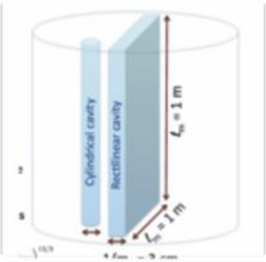
CARRACK (discontinued)

CULTASK - CAPP -Korea

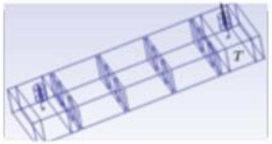


ADMX-HF

ADMX-Fermilab

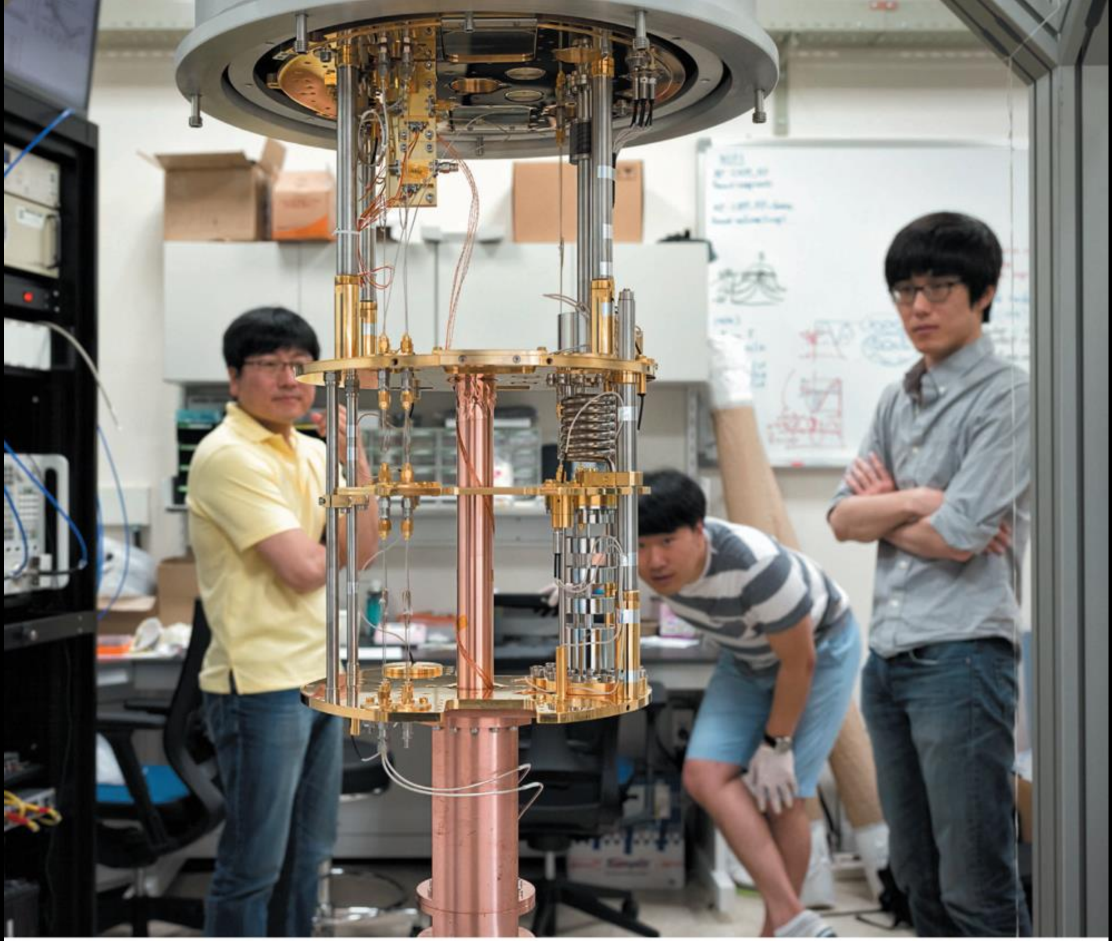


RADES



CAST-CAPP

Adapted from Javier Redondo



SHIN WOONG-JAE

South Korea's Nobel dream

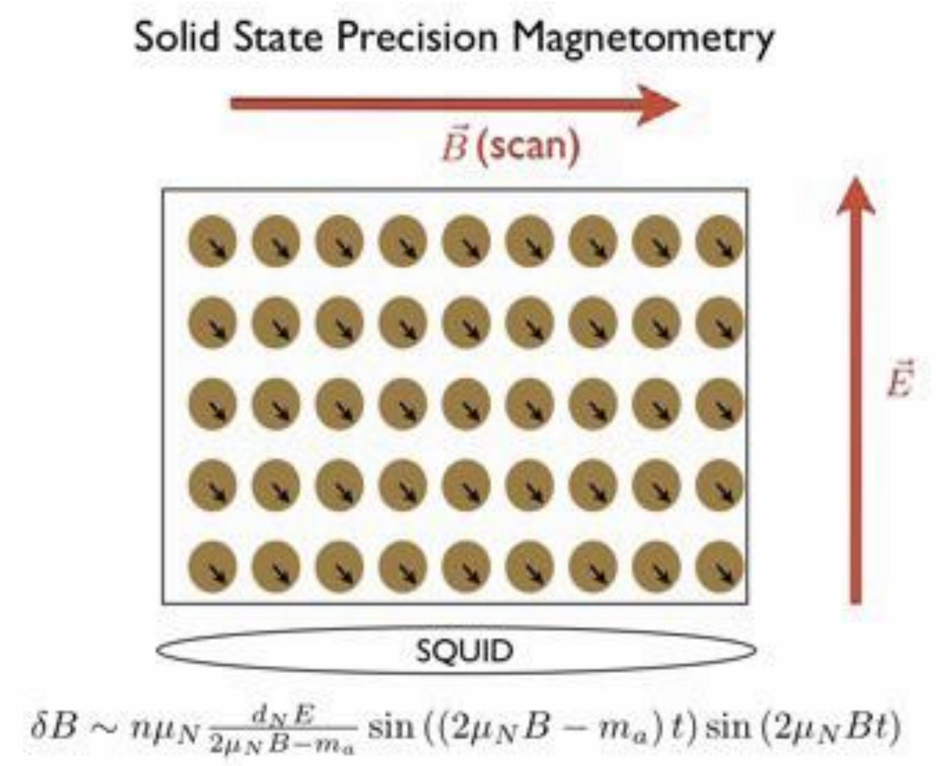
The Asian nation spends more of its economic output on research than anywhere else in the world. But it will need more than cash to realize its ambitions.

BY MARK ZASTROW

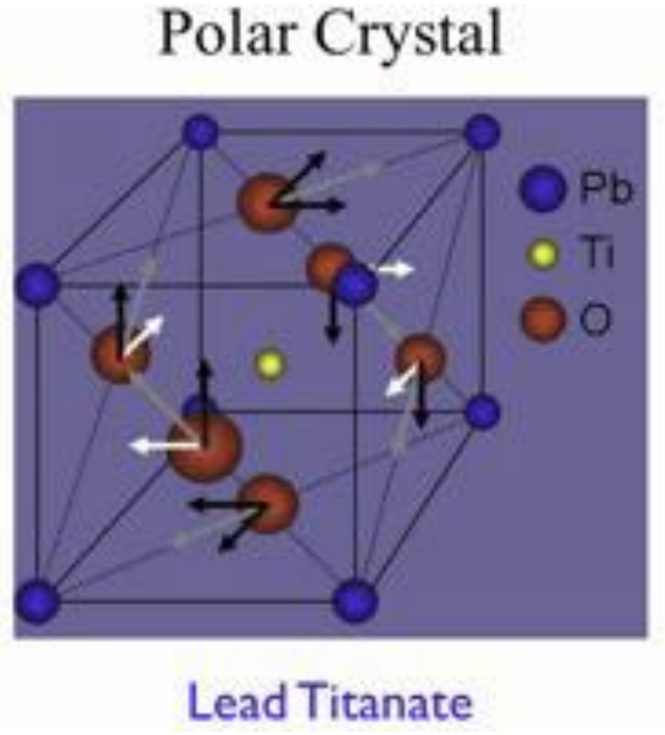
Behind the doors of a drab brick building in Daejeon, South Korea, a major experiment is slowly taking shape. Much of the first-floor lab space is under construction, and one glass door, taped shut, leads directly to a pit in the ground. But at the end of the hall, in a pristine lab, sits a gleaming cylindrical apparatus of copper and gold. It's a prototype of a device that might one day answer a major mystery about the Universe by detecting a particle called the axion — a possible component of dark matter.

If it succeeds, this apparatus has the potential to rewrite physics and win its designers a Nobel prize. "It will transform Korea, there's no question about it," says physicist Yannis Semertzidis, who leads the US$7.6-million-per-year centre at South Korea's premier technical university, KAIST. But there's a catch: no one knows whether axions even exist. It's the kind of high-risk, high-reward project

Searching for Axions in the Anthropic Range



$$\delta B \sim n\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left((2\mu_N B - m_a)\,t\right) \sin\left(2\mu_N B t\right)$$



CASPEr experiment
Precise magnetometry to measure
tiny deviations from Larmor frequency

Graham & Rajendran, arXiv:1101.2691
Budker, Graham, Ledbetter, Rajendran & Sushkov, arXiv:1306.6089

PRL **113,** 161801 (2014) PHYSICAL REVIEW LETTERS week ending 17 OCTOBER 2014

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

Asimina Arvanitaki[1] and Andrew A. Geraci[2,*]
[1]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L 2Y5, Canada*
[2]*Department of Physics, University of Nevada, Reno, Nevada 89557, USA*
(Received 5 March 2014; revised manuscript received 27 August 2014; published 14 October 2014)

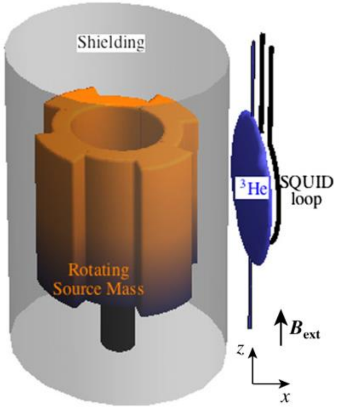


FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N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

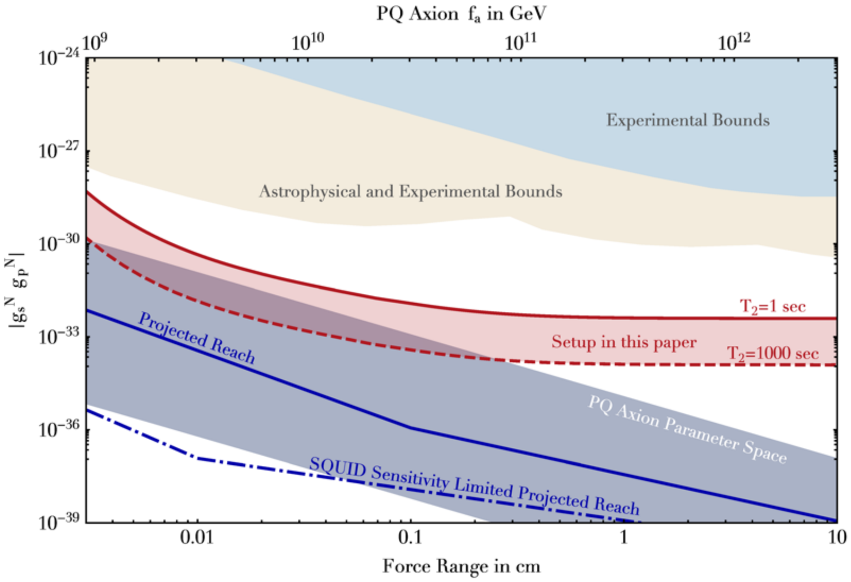
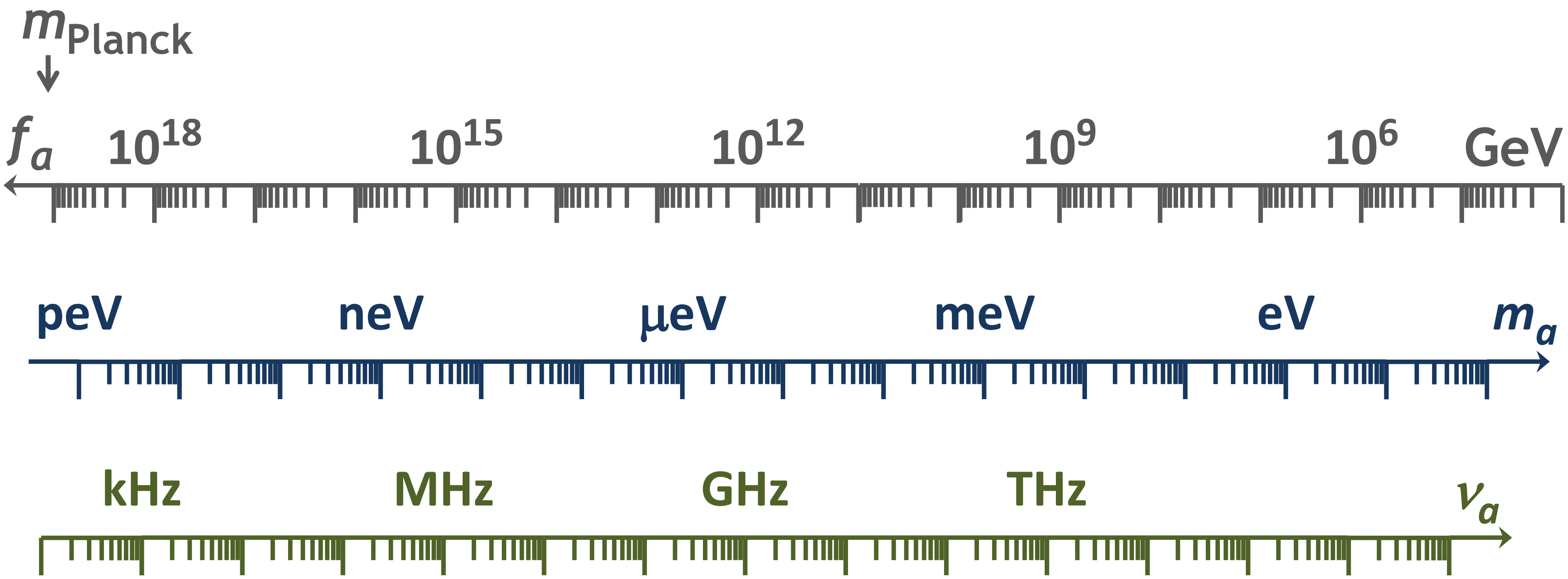


FIG. 2 (color online). Projected reach for monopole-dipole axion mediated interactions.

ARIADNE: Axion Resonant InterAction DetectioN Experiment

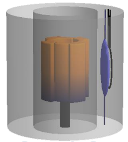
A.Geraci, A.Arvanitaki, A.Kapitulnik, Chen-Yu Liu, J.Long, Y.Semertzidis, M.Snow
(to be supported by NSF and/or DoE?)

Axion Searches

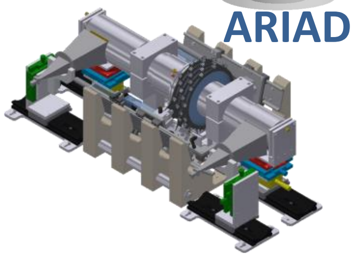


CASPEr

Taking data **ADMX**

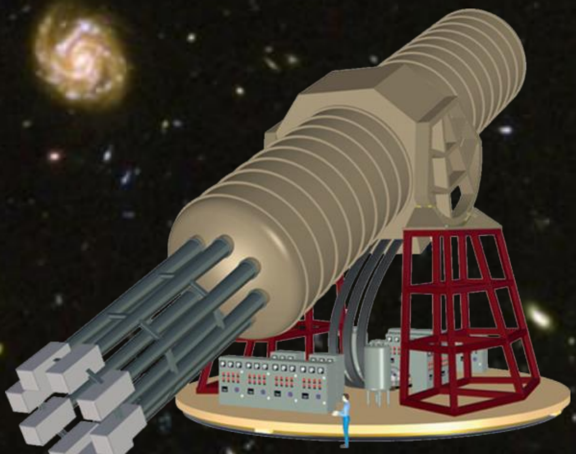


ARIADNE

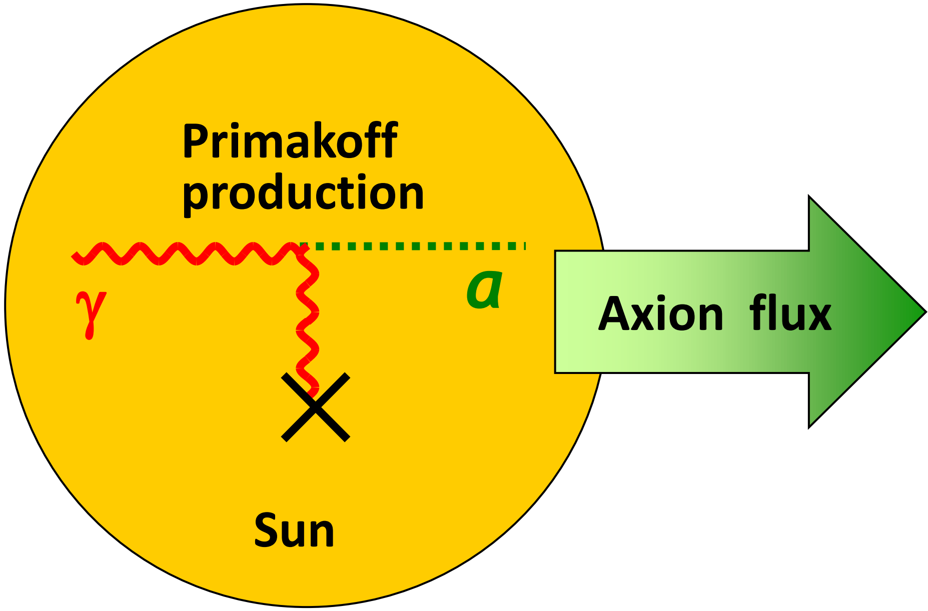


Astrophysical Bounds (Energy loss of stars)

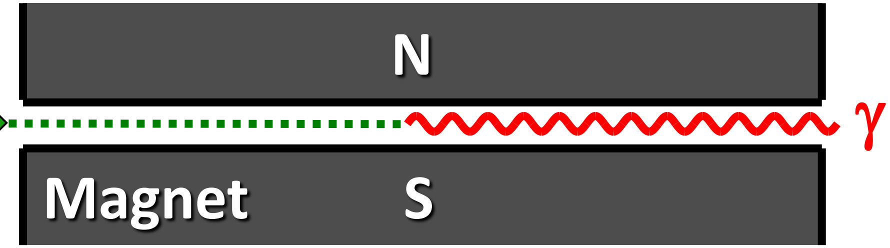
Looking for axion-like particles (ALPs)



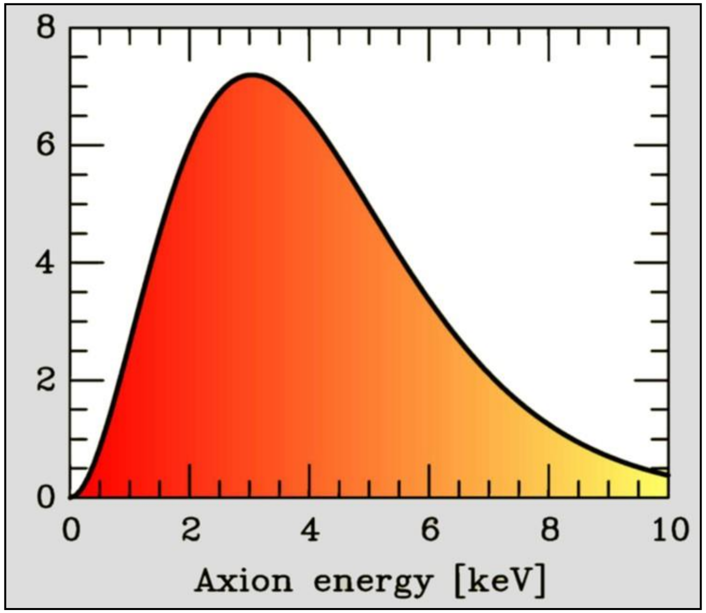
Search for Solar Axions



Axion Helioscope (Sikivie 1983)



Axion-Photon-Oscillation

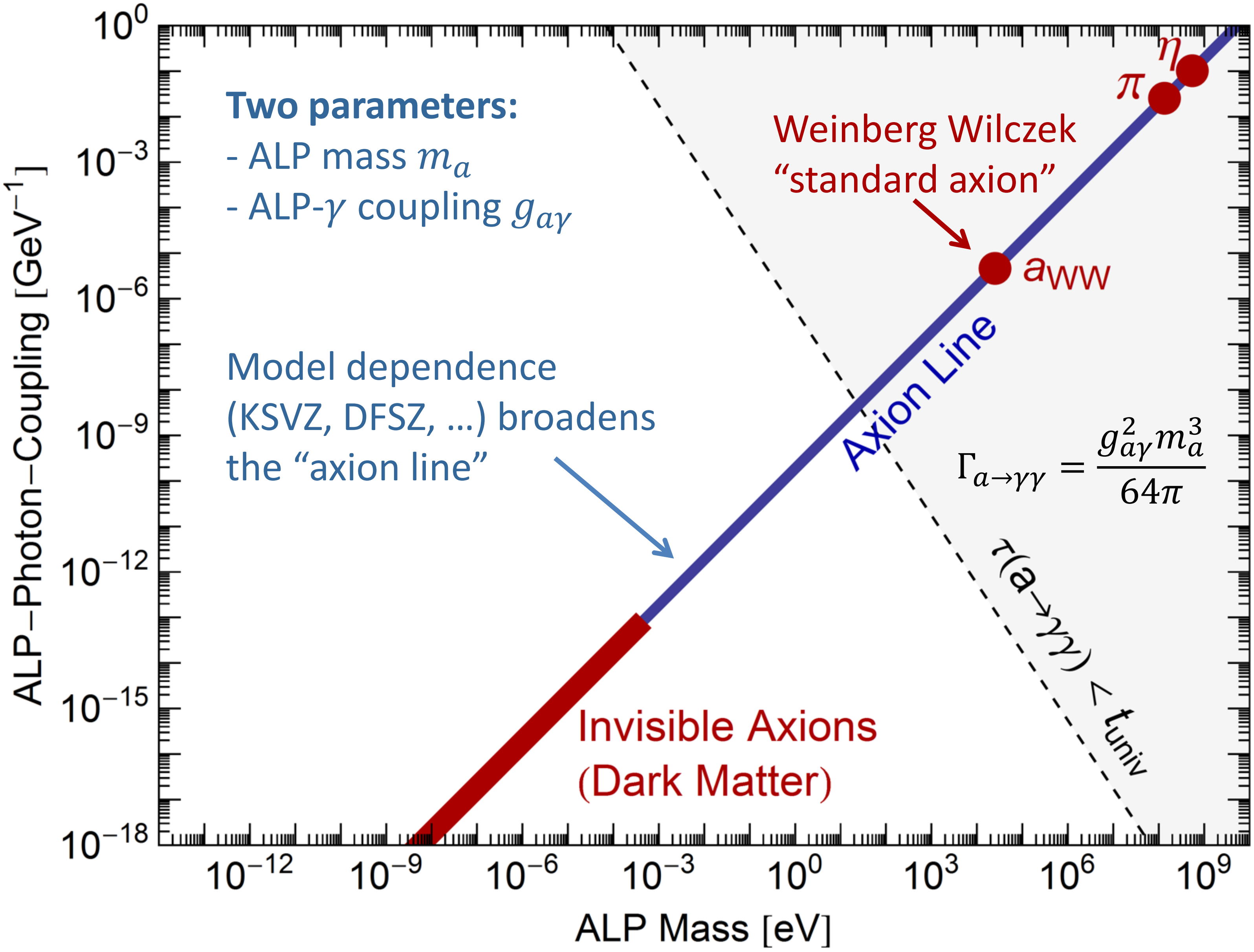


- Tokyo Axion Helioscope (“Sumico”) (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST) (Data taking 2003–2015)

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)



Two parameters:

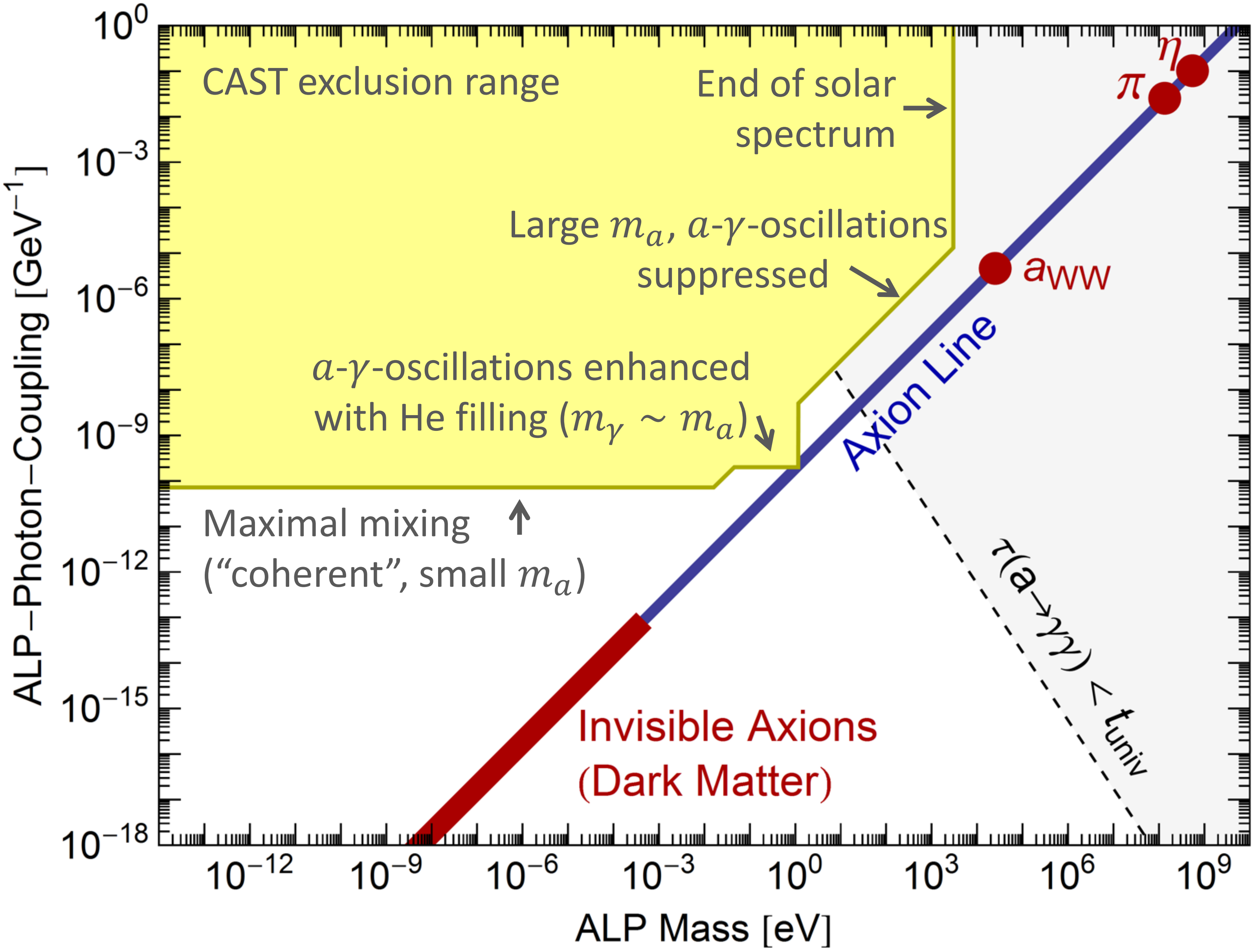
- ALP mass m_a
- ALP-γ coupling $g_{a\gamma}$

Weinberg Wilczek
“standard axion”

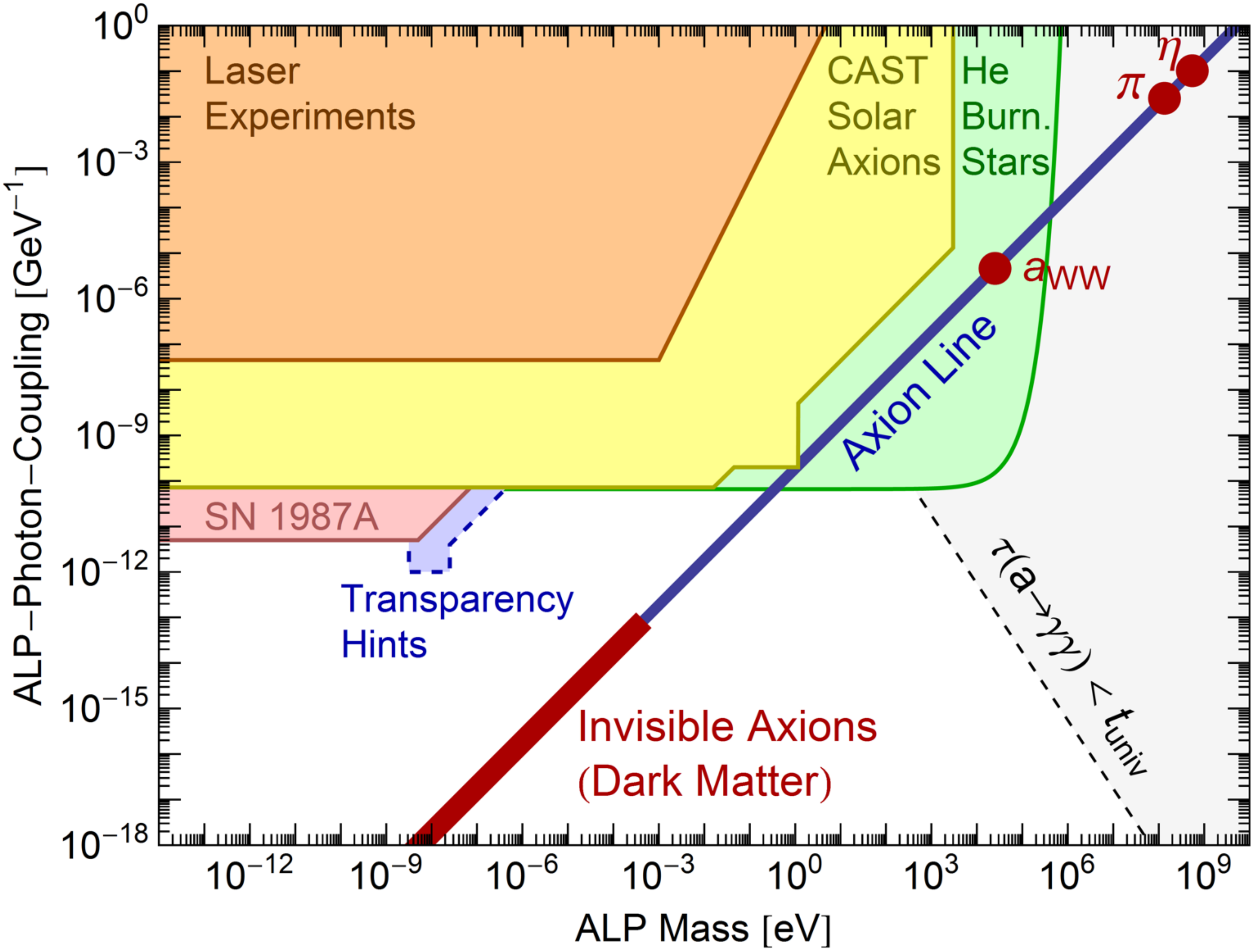
Model dependence
(KSVZ, DFSZ, …) broadens
the “axion line”

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\pi}$$

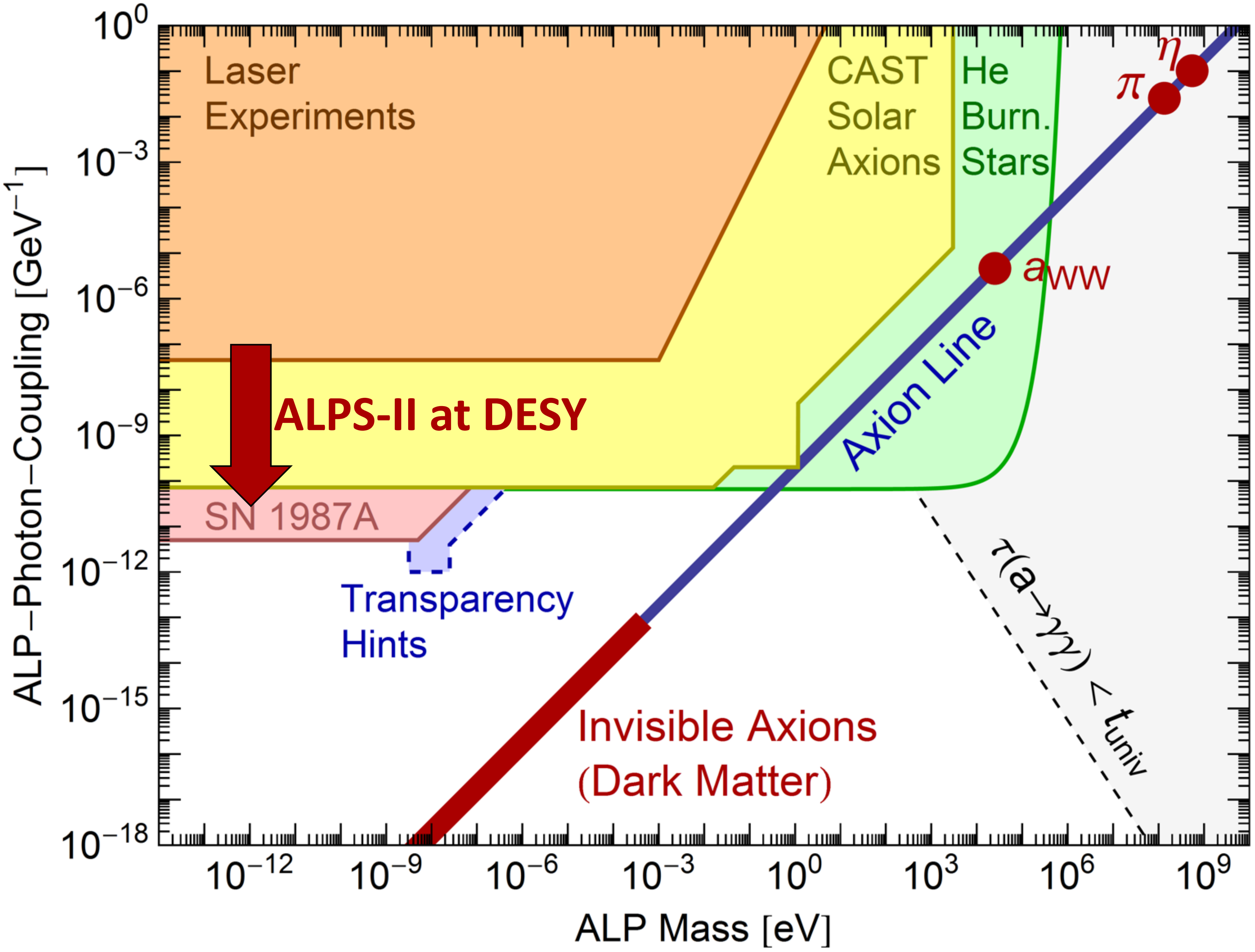
Parameter Space for Axion-Like Particles (ALPs)



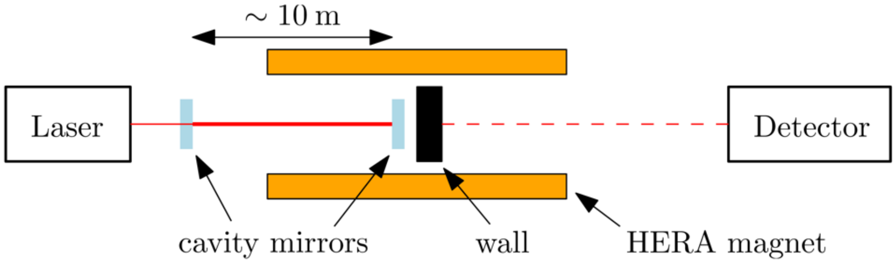
Parameter Space for Axion-Like Particles (ALPs)



Parameter Space for Axion-Like Particles (ALPs)

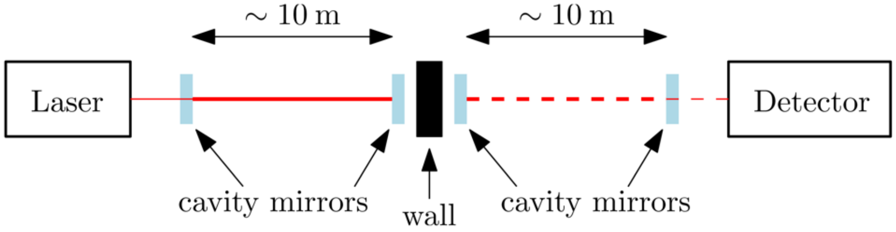


Any Light Particle Search II (ALPS-II) at DESY



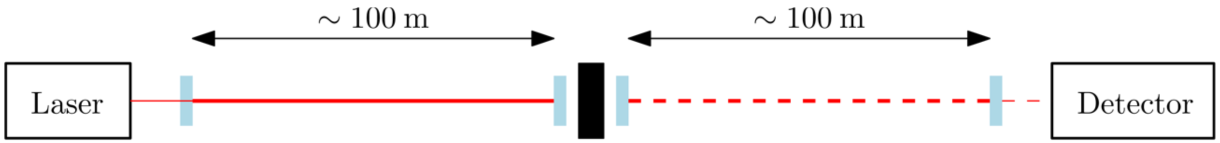
(a) ALPS-I

ALPS-I (finished)



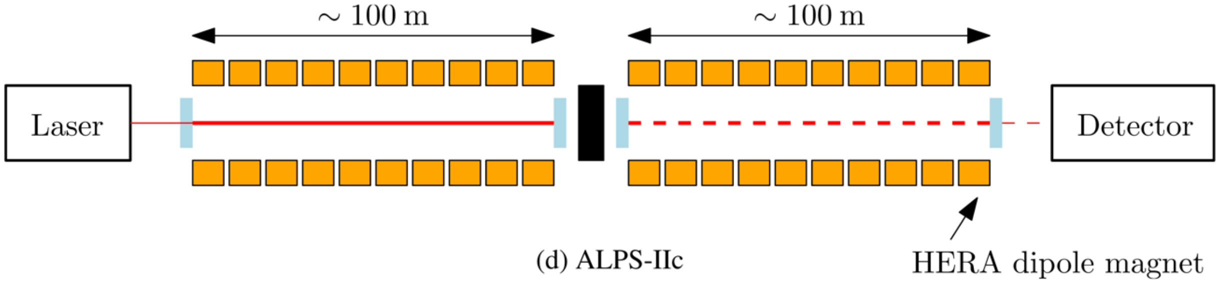
(b) ALPS-IIa

ALPS-IIa (2014)



(c) ALPS-IIb

ALPS-IIb (2015)

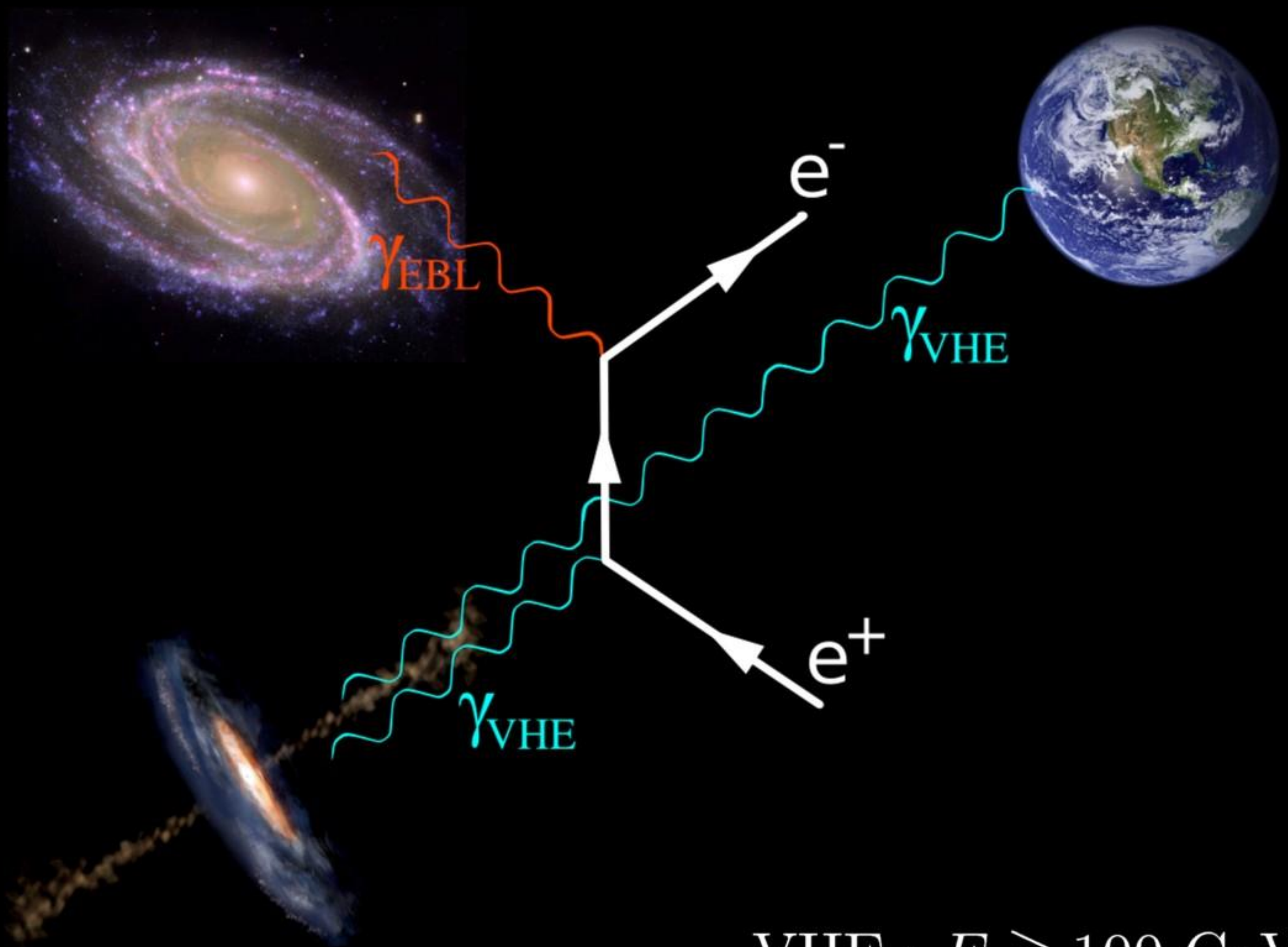


(d) ALPS-IIc

ALPS-IIc (2017)

ALPS-II Technical Design Report, arXiv:1302.5647

Shining TeV Gamma Rays through the Universe



$$\mathrm{VHE} : E \gtrsim 100\ \mathrm{GeV}$$

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

Shining TeV Gamma Rays through the Universe

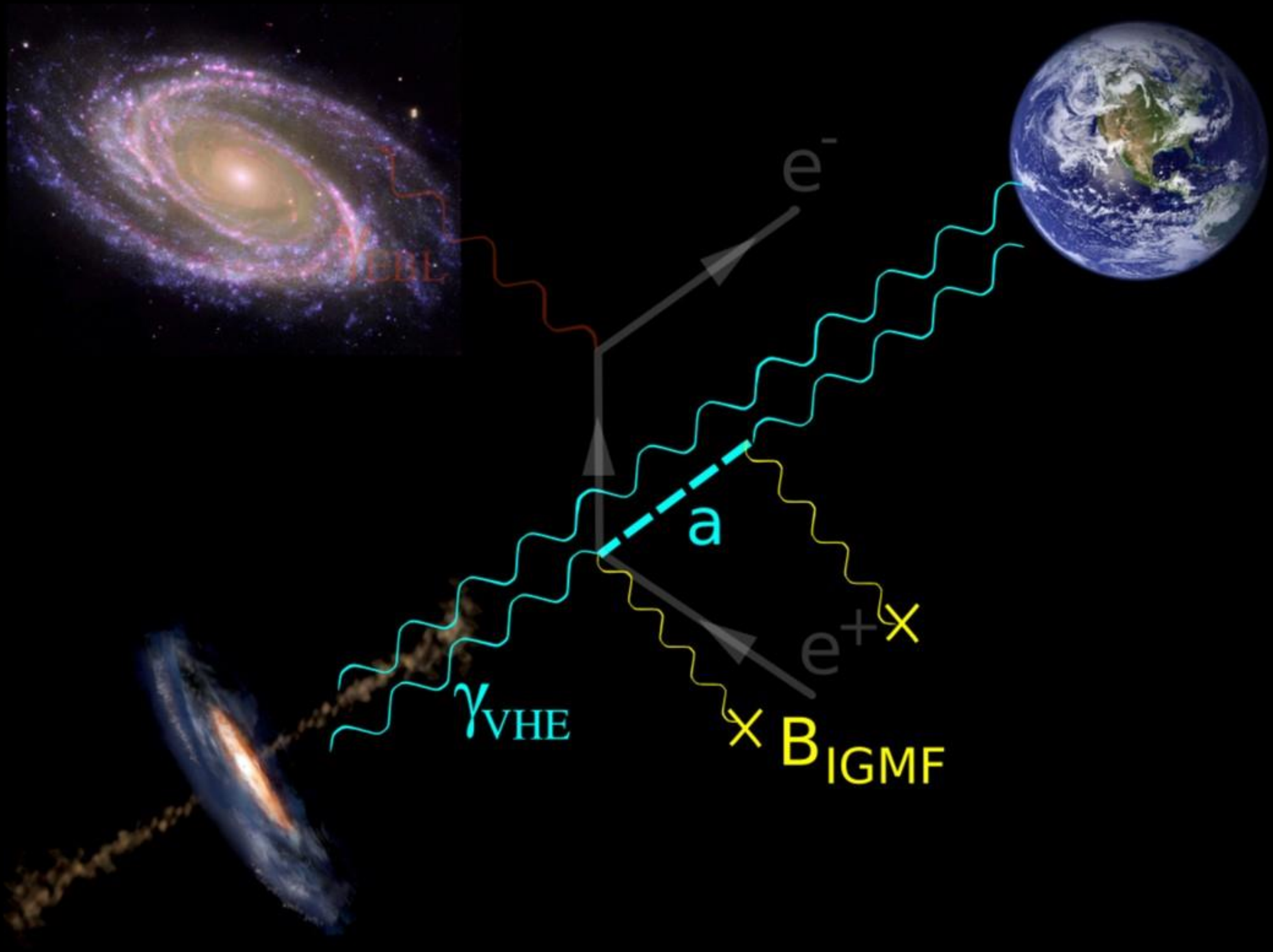
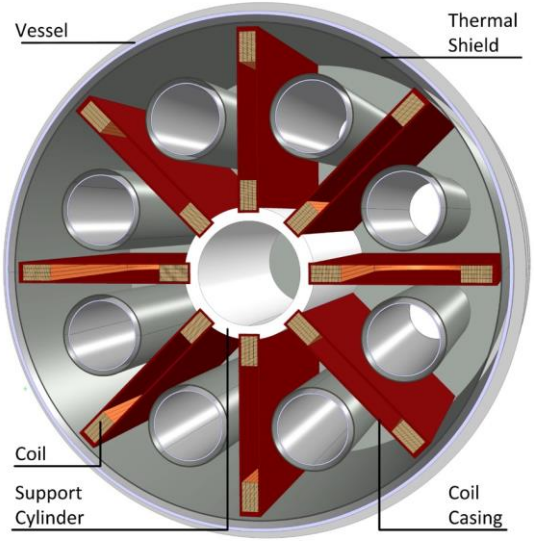
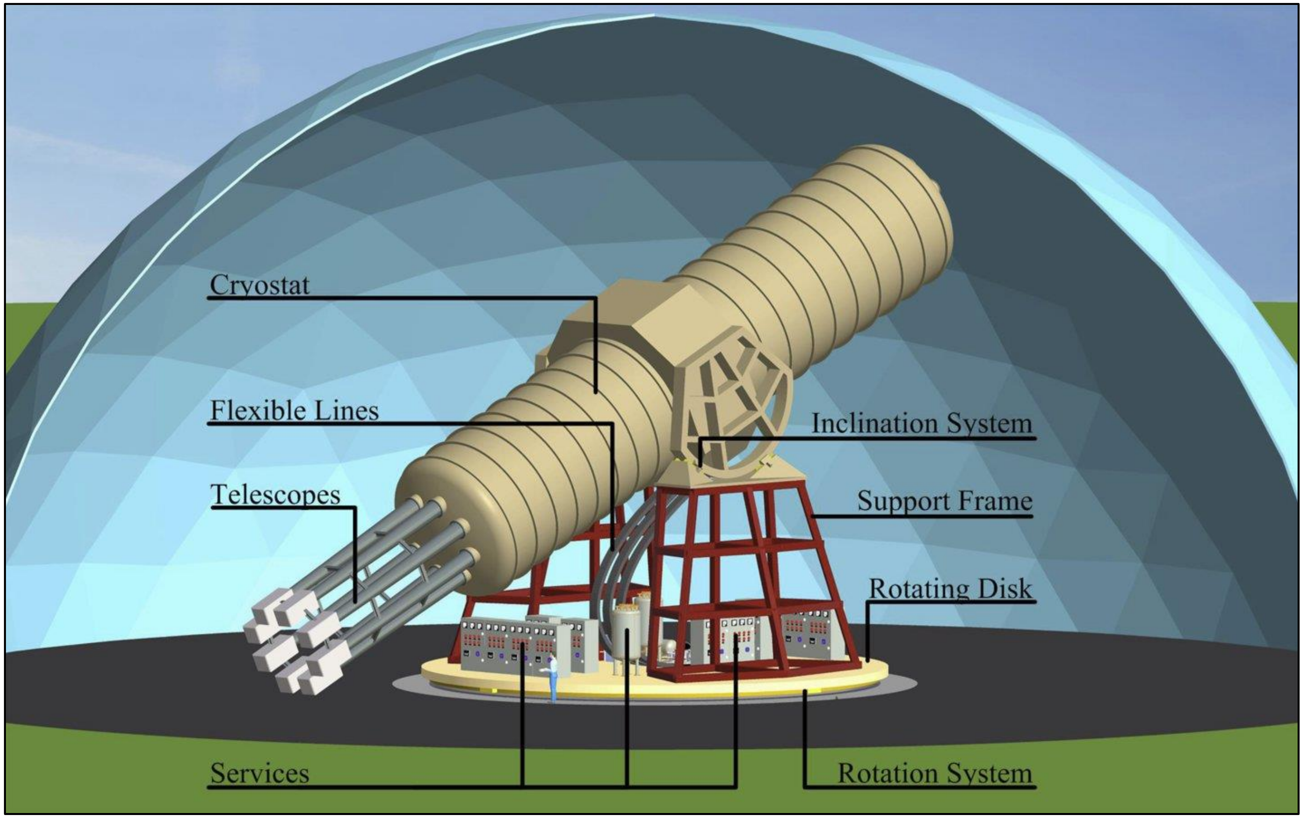


Figure from a talk by Manuel Meyer (Univ. Hamburg)

Next Generation Axion Helioscope (IAXO) at CERN

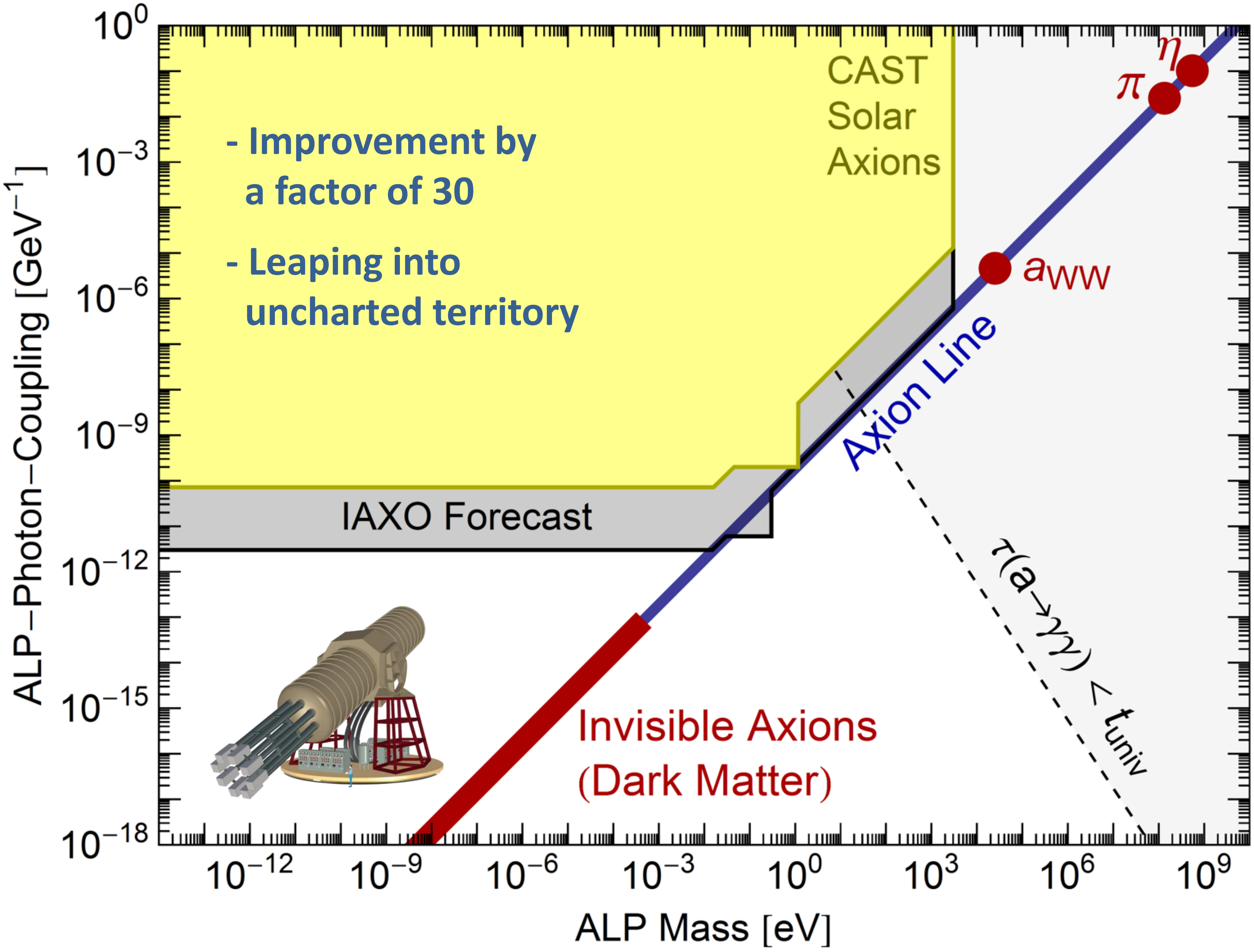




Need new magnet w/
– Much bigger aperture: $\sim 1\ \mathrm{m}^2$ per bore
– Lighter (no iron yoke)
– Bores at T_{room}

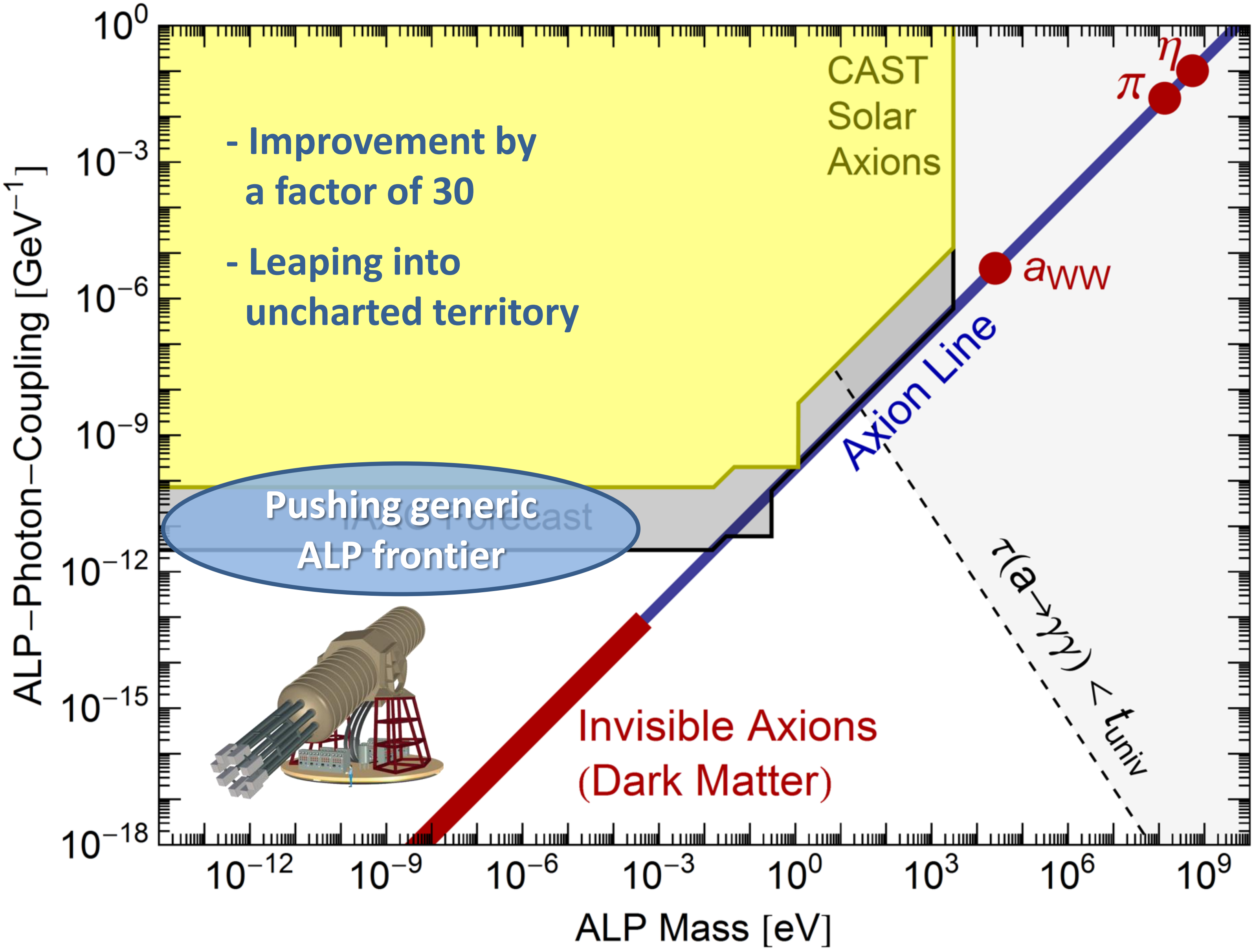
- Irastorza et al.: Towards a new generation axion helioscope, arXiv:1103.5334
- Armengaud et al.: Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233

Parameter Space for Axion-Like Particles (ALPs)



- Improvement by a factor of 30
- Leaping into uncharted territory

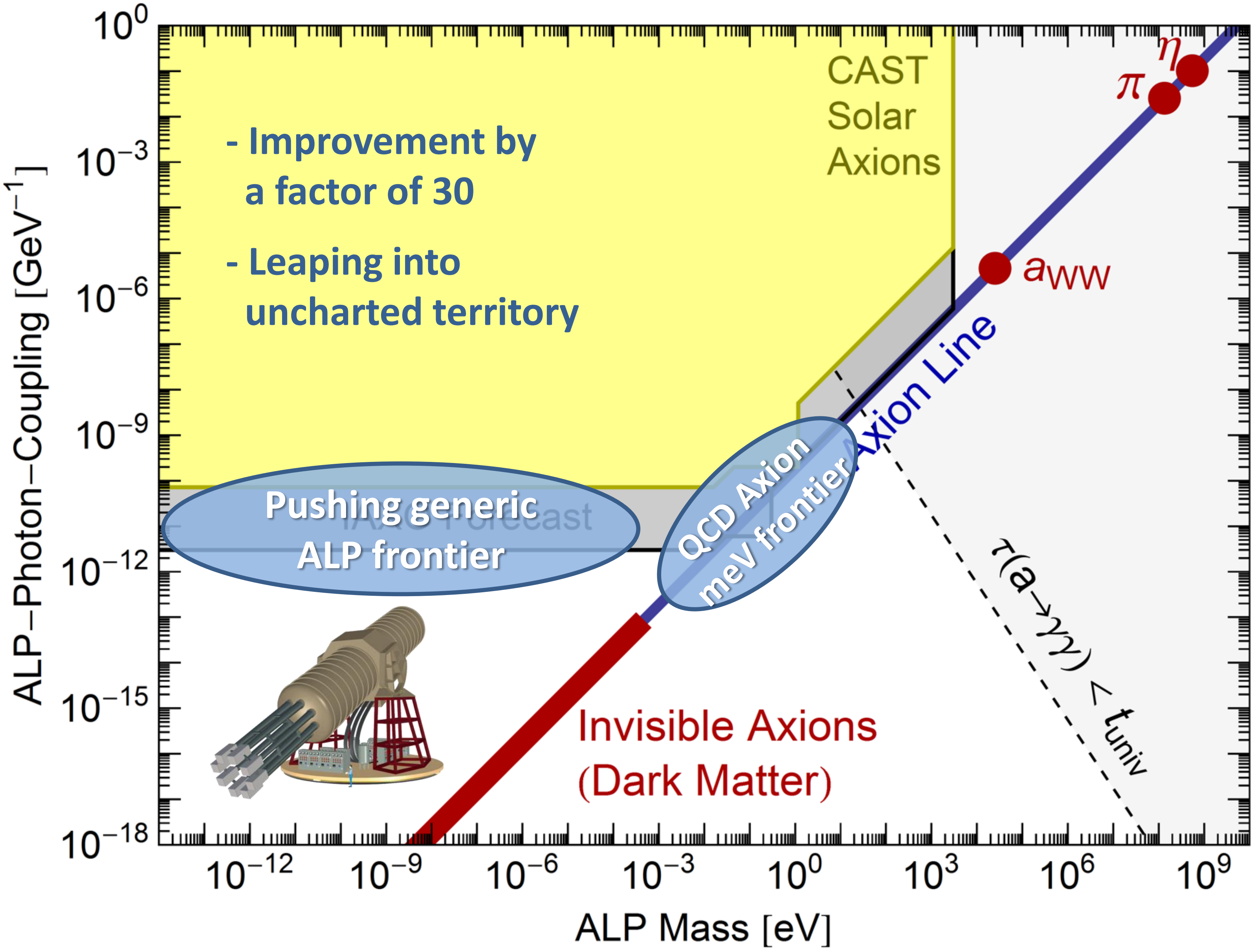
Parameter Space for Axion-Like Particles (ALPs)



- Improvement by a factor of 30
- Leaping into uncharted territory

Pushing generic ALP frontier

Parameter Space for Axion-Like Particles (ALPs)

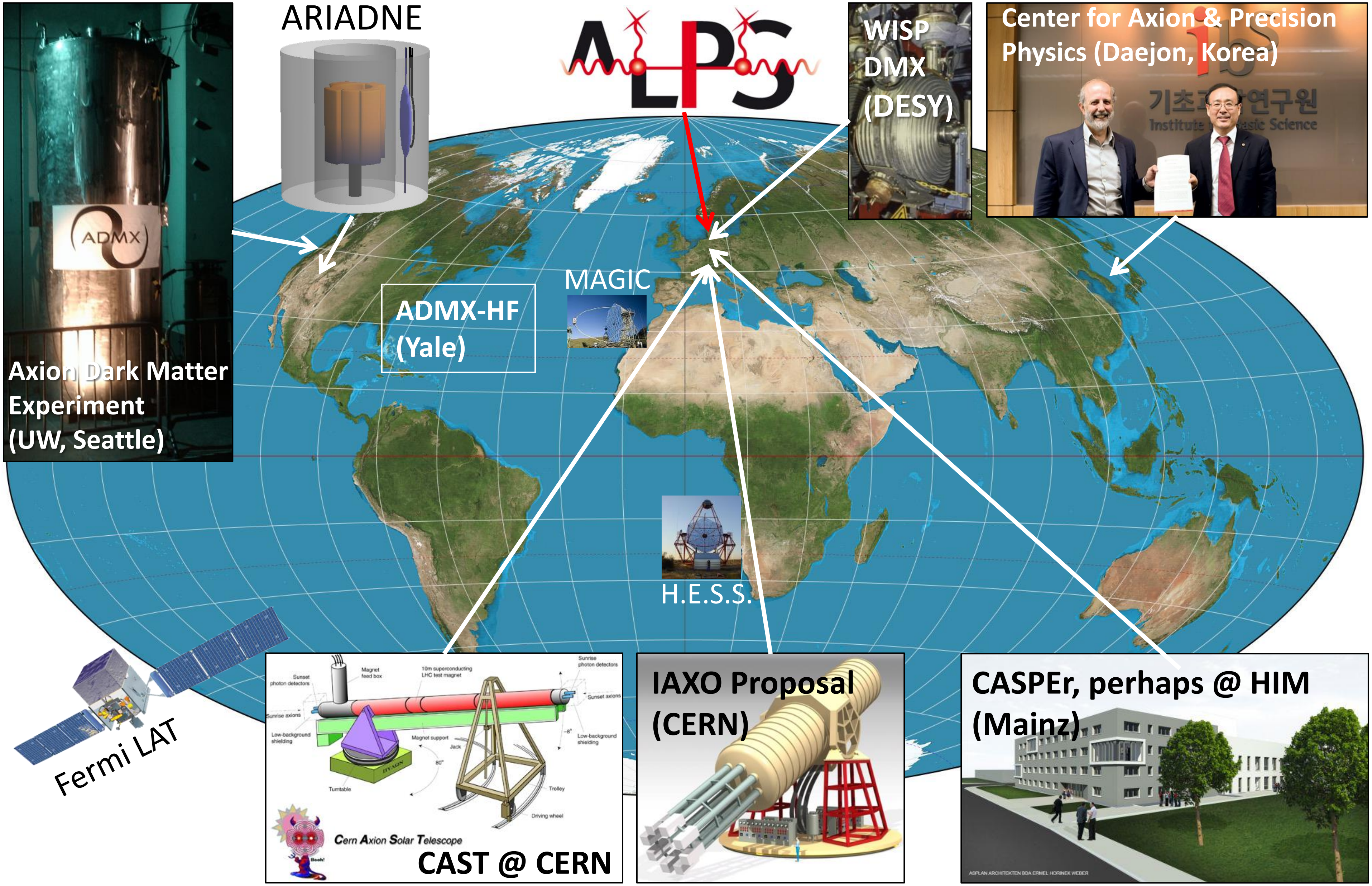


- Improvement by a factor of 30
- Leaping into uncharted territory

Pushing generic ALP frontier

QCD Axion meV frontier

Axion and Axion-Like Particle Searches



ARIADNE

ALPS

WISP DMX (DESY)

Center for Axion & Precision Physics (Daejon, Korea)

MAGIC

ADMX-HF (Yale)

Axion Dark Matter Experiment (UW, Seattle)

H.E.S.S.

Fermi LAT

Cern Axion Solar Telescope

CAST @ CERN

IAXO Proposal (CERN)

CASPEr, perhaps @ HIM (Mainz)

Dow Jones Index for Axions: The Rally Continues

inSPIRE: Citation of Peccei-Quinn papers or title axion or axino