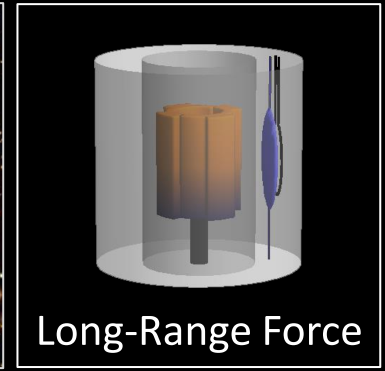

Milli-eV Frontier of Axion Physics

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

Milli-eV frontier reloaded

PHYSICAL REVIEW D **84,** 103008 (2011)

The meV mass frontier of axion physics

Georg G. Raffelt,[1] Javier Redondo,[1] and Nicolas Viaux Maira[2]

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(Received 7 September 2011; published 29 November 2011)

We explore consequences of the idea that the cooling speed of white dwarfs can be interpreted in terms of axion emission. In this case, the Yukawa coupling to electrons has to be $g_{ae} \sim 1 \times 10^{-13}$, corresponding to an axion mass of a few meV. Axions then provide only a small fraction of the cosmic cold dark matter, whereas core-collapse supernovae release a large fraction of their energy in the form of axions. We estimate the diffuse supernova axion background in the Universe, consisting of 30 MeV-range a… a radiation density comparable to the extragalactic background light. The diff… background would be challenging to detect. However, axions with… be accessible in a next-generation axion helioscope.

DOI: 10.1103/PhysRevD.84.10300…

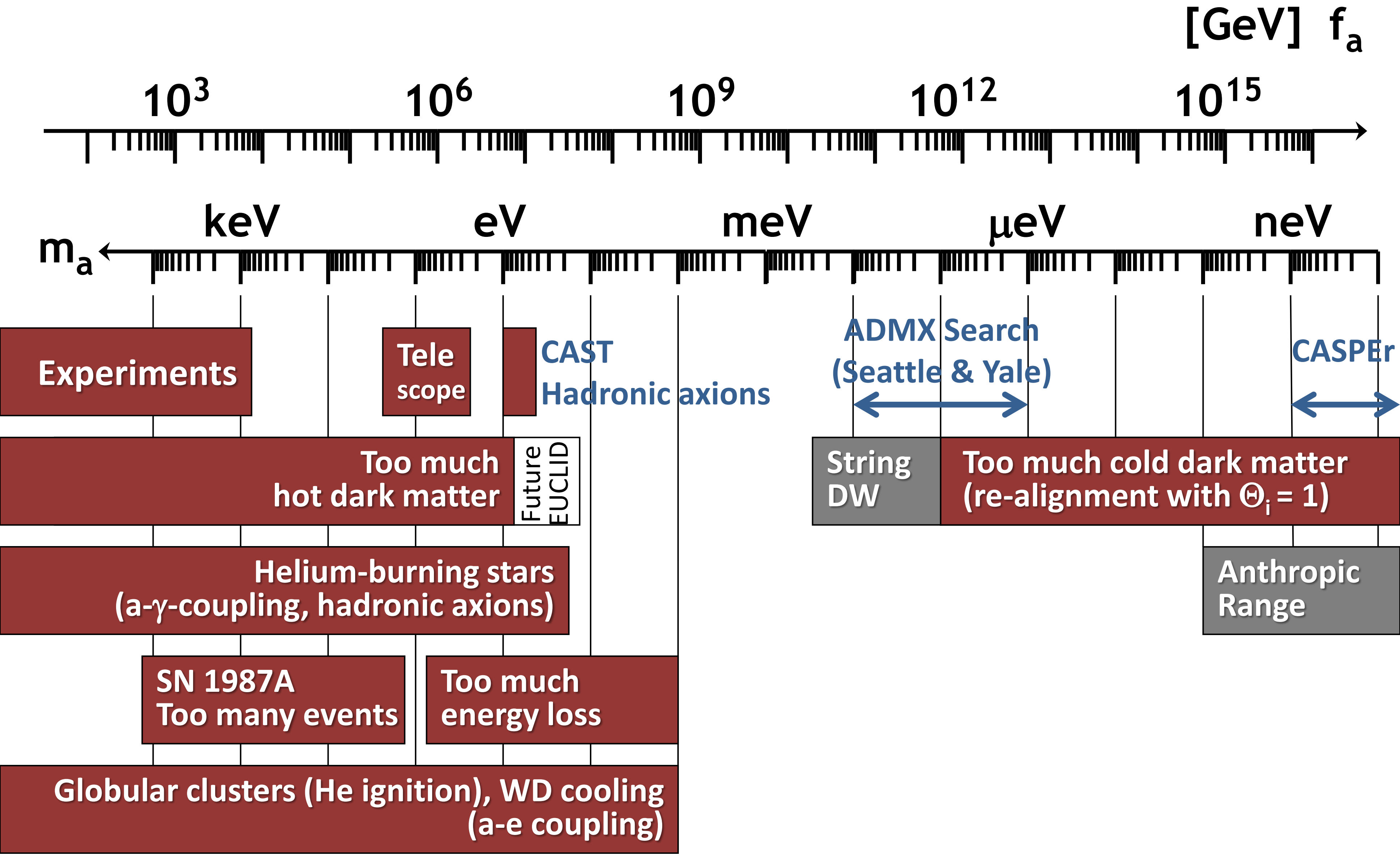
…haps … the absence of … the QCD vacuum structure … …oidable consequence is the existence of …axion, the Nambu-Goldstone boson of a new $U(1)_{PQ}$ symmetry. Axions acquire a mass $m_a \sim m_\pi f_\pi / f_a$ by their mixing with neutral mesons, where $m_\pi = 135$ MeV and $f_\pi = 92$ MeV are the pion mass and decay constant, and f_a is a large energy scale related to the spontaneous breaking of $U(1)_{PQ}$. Axions generically interact with hadrons and photons. They may also interact with charged leptons, the DFSZ model [4] being a generic case. All interactions are suppressed by f_a^{-1}, so for large f_a, axions are both very …

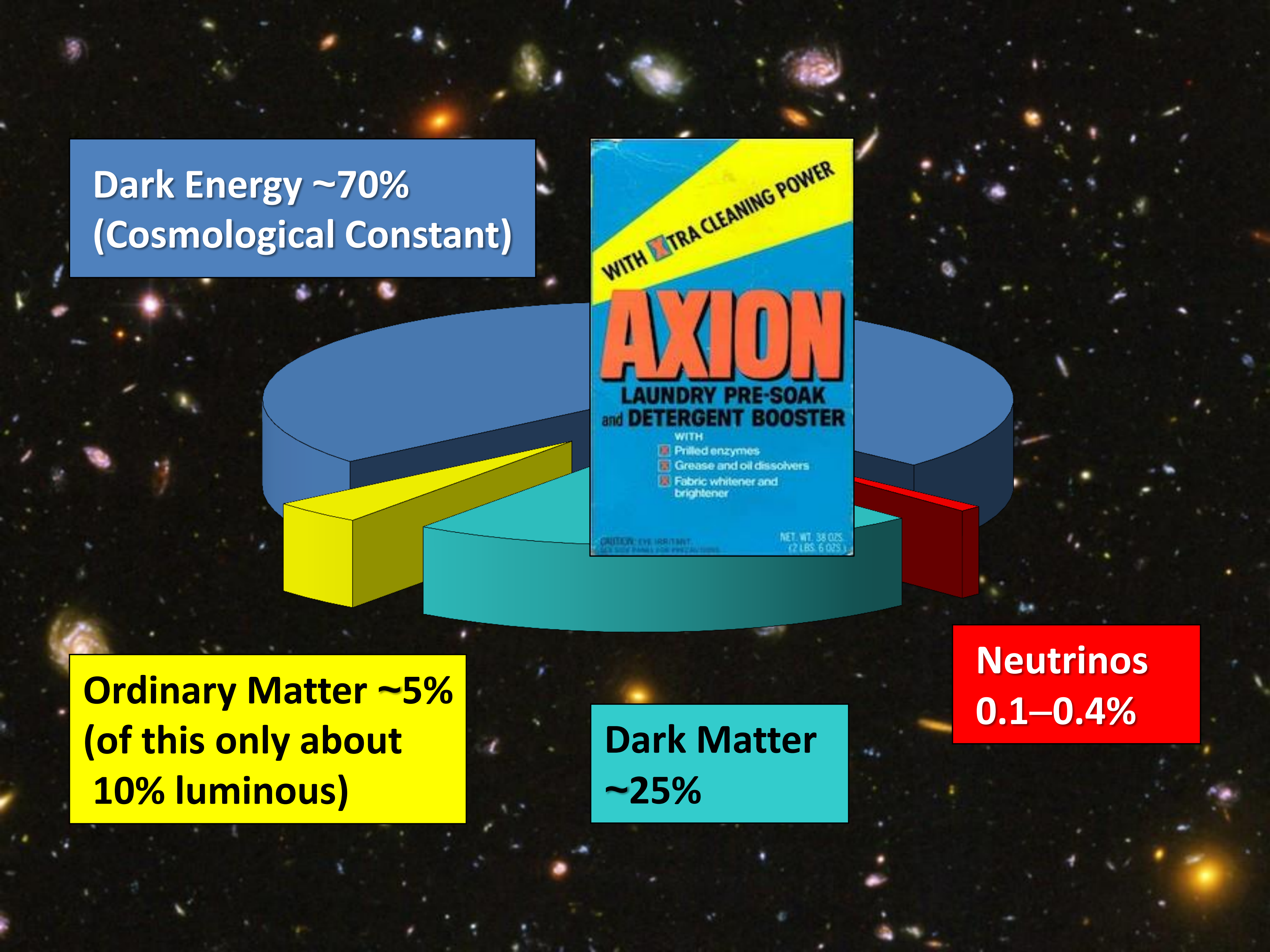
…sity could correspond to m_a as large as a few 100 μeV [9]. Either way, meV-mass axions provide only a subdominant CDM component.

II. COOLING OF COMPACT STARS

The most restrictive astrophysical limits on those axion models that couple to charged leptons arise from WDs. An early study used the WD cooling speed, as manifested in their luminosity function, to derive a limit on the axion-electron coupling of $g_{ae} \lesssim 4 \times 10^{-13}$ [10]. In the early 1990s, it became possible to test the cooling speed of pulsating WDs, the class of ZZ Ceti stars, by their measured period decrease $\dot{P}/P$. In particular, the star G117-B15A was cooling too fast, an effect that could be …

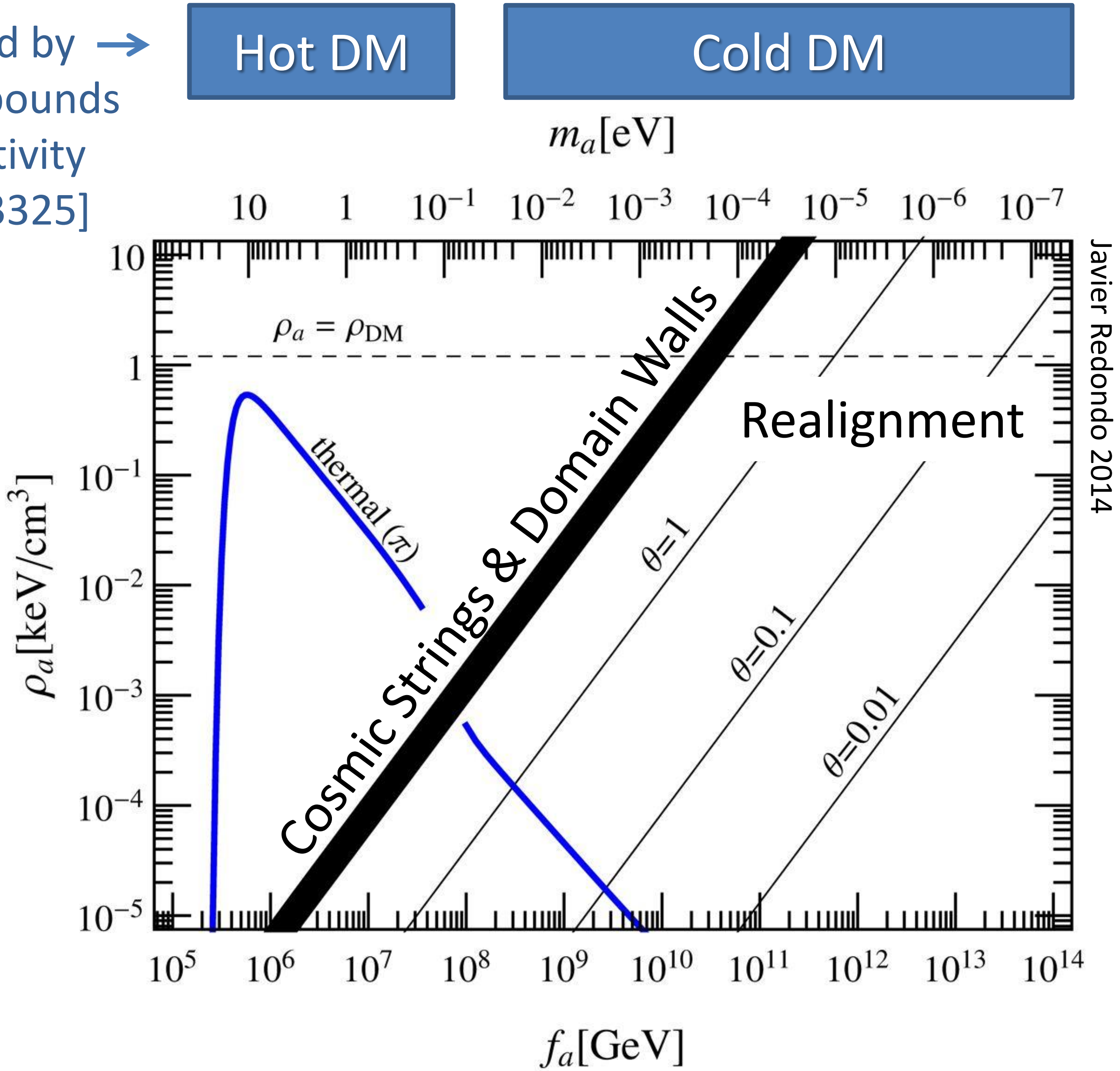
Axion Bounds and Searches




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
Ordinary Matter ~5%
(of this only about
10% luminous)
Dark Matter
~25%
Neutrinos
0.1–0.4%

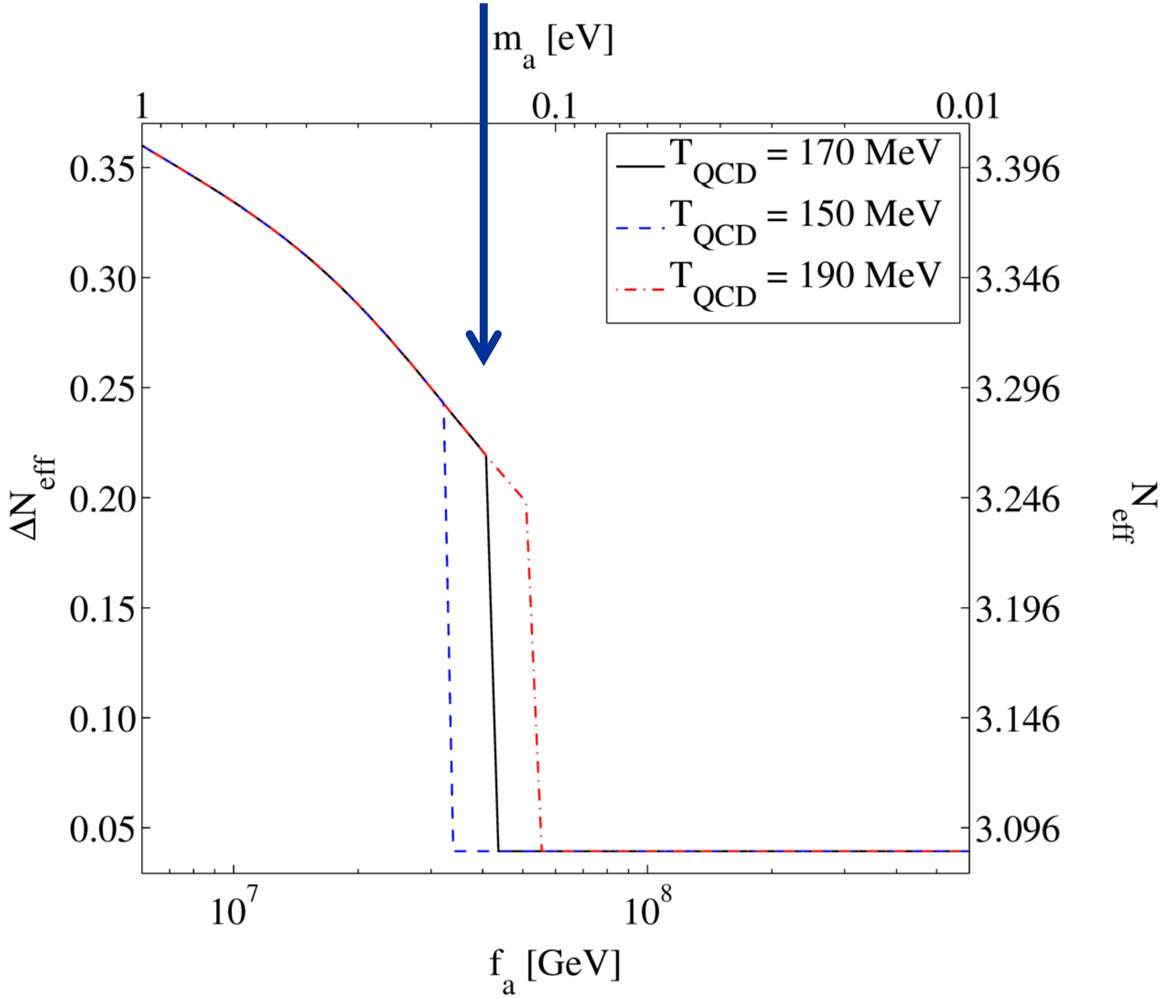
Axion Dark Matter Density

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



Thermal Axion Density and EUCLID Sensitivity

Hot dark matter sensitivity of future surveys (EUCLID) is around minimal m_ν
Can probe axions down to $m_a \sim 0.15\ \mathrm{eV}$

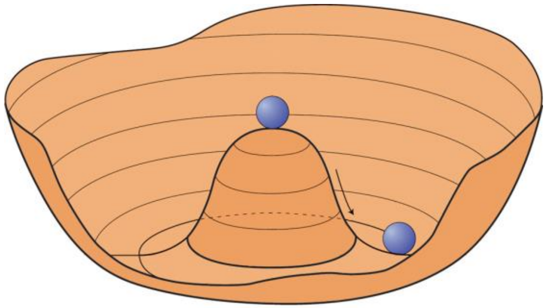


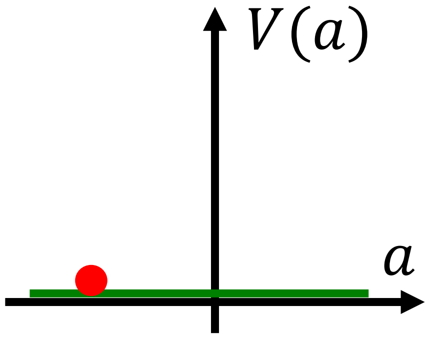
Archidiacono, Basse, Hamann, Hannestad, Raffelt & Wong, arXiv:1502.03325

Creation of Cosmological Axions by Re-alignment

$T \sim f_a$ (very early universe)

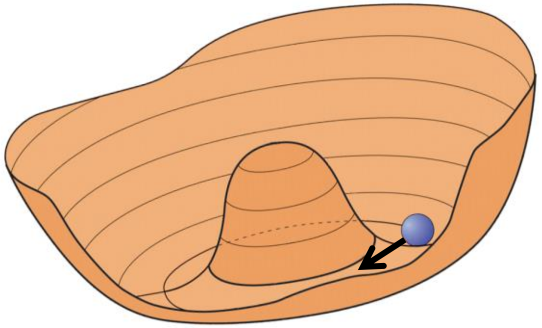
- $U_{PQ}(1)$ spontaneously broken
- Higgs field settles in "Mexican hat"
- Axion field sits fixed at $a_i = \Theta_i f_a$

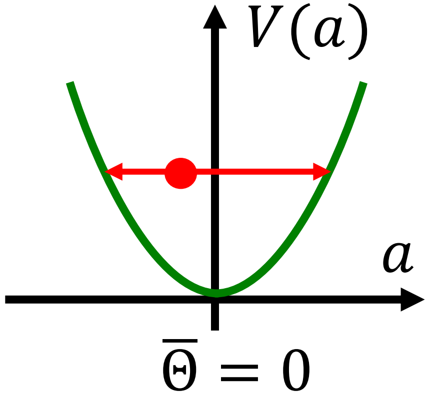




$T \sim 1$ GeV ($H \sim 10^{-9}$ eV)

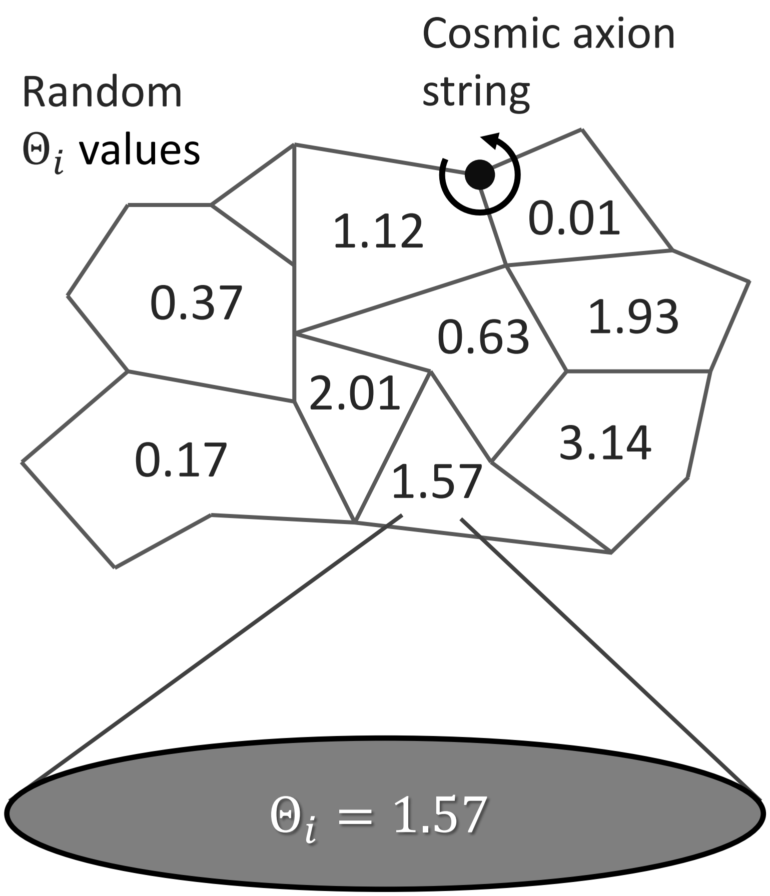
- Axion mass turns on quickly by thermal instanton gas
- Field starts oscillating when $m_a \gtrsim 3H$
- Classical field oscillations (axions at rest)





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

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

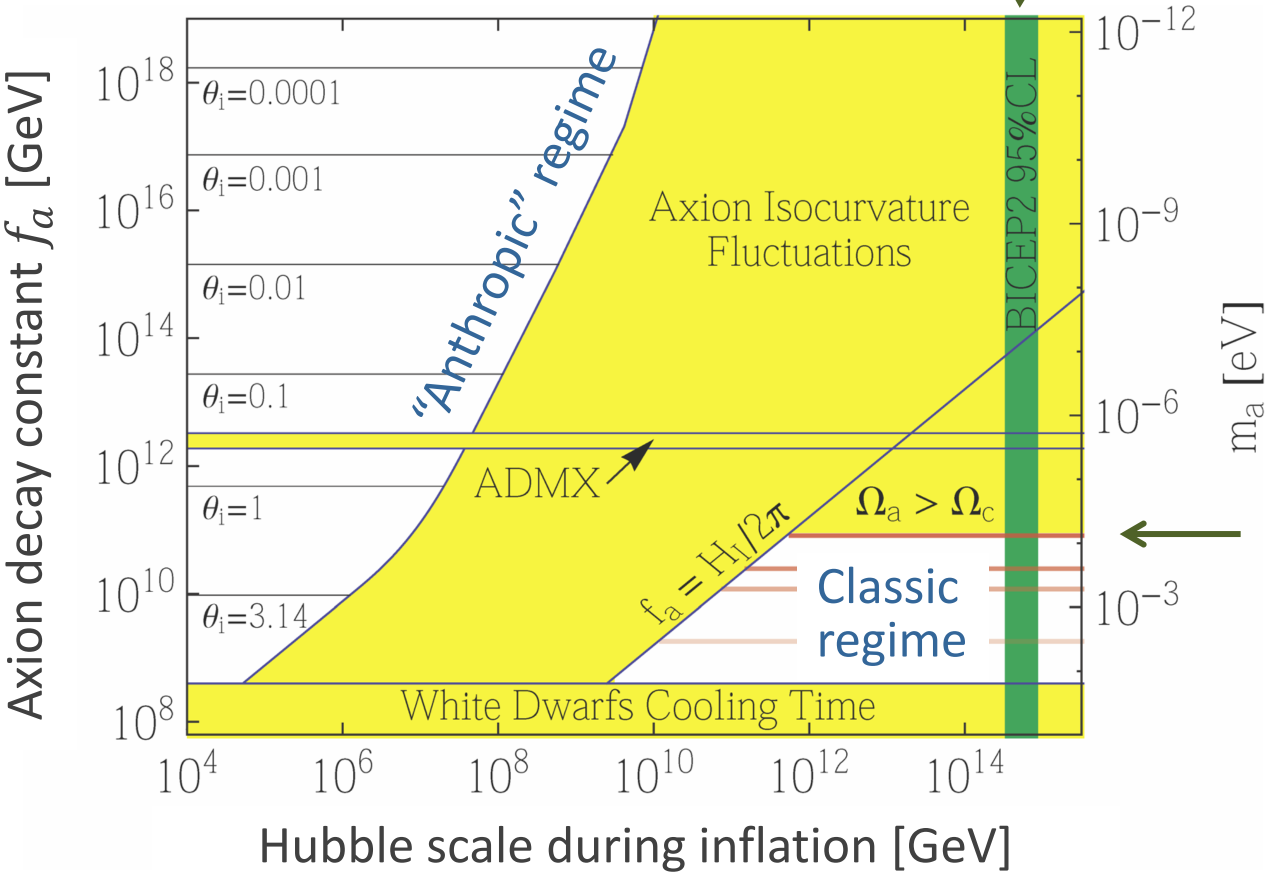
Scenario 2

- 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

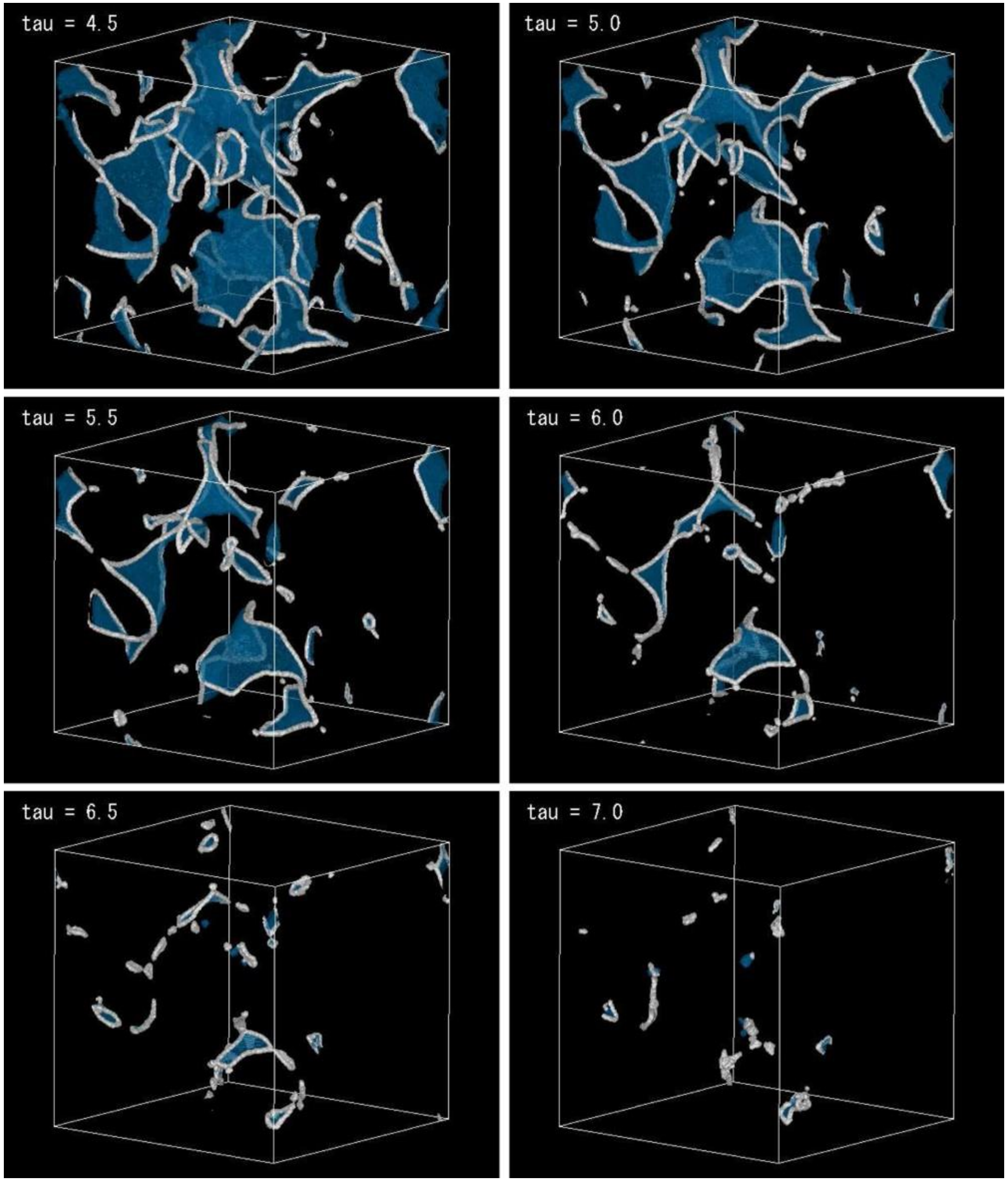
B-modes in CMB would exclude
"anthropic" regime of large f_a



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

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

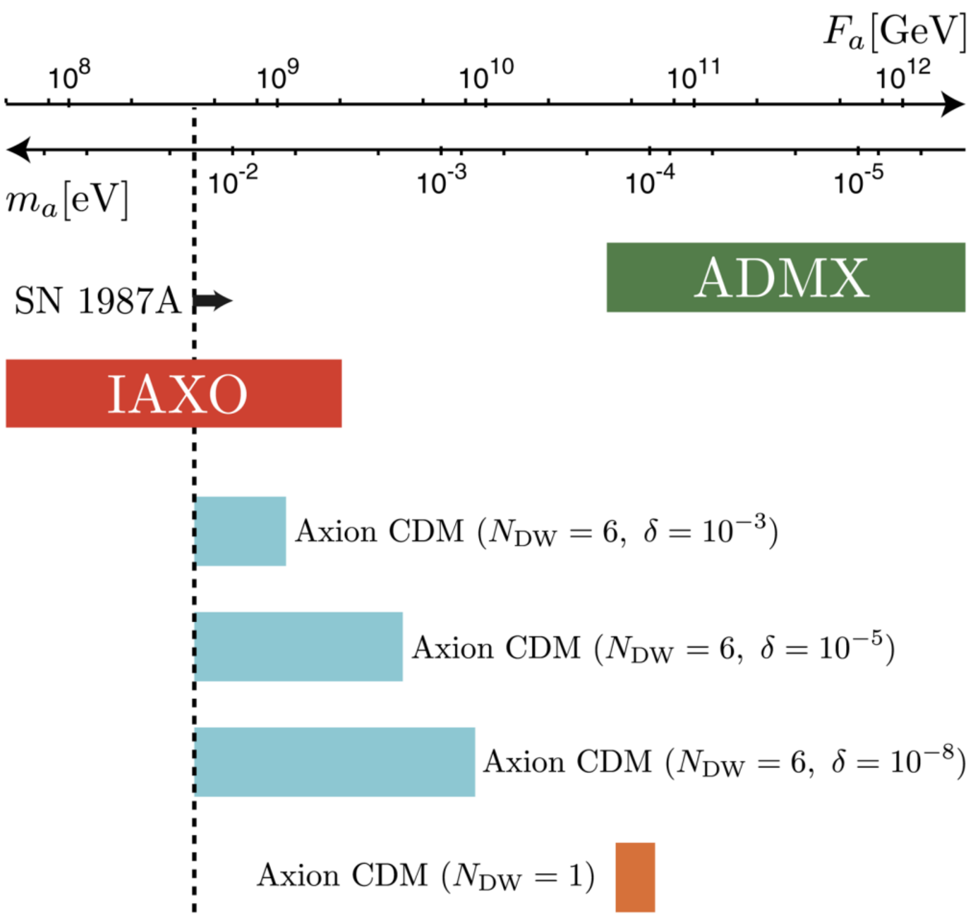
Kawasaki, Saikawa & Sekiguchi, arXiv:1412.0789 (PRD 2015)

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

Historical Neutrino Dark Matter Lessons

Early 1980s

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

Status 2015

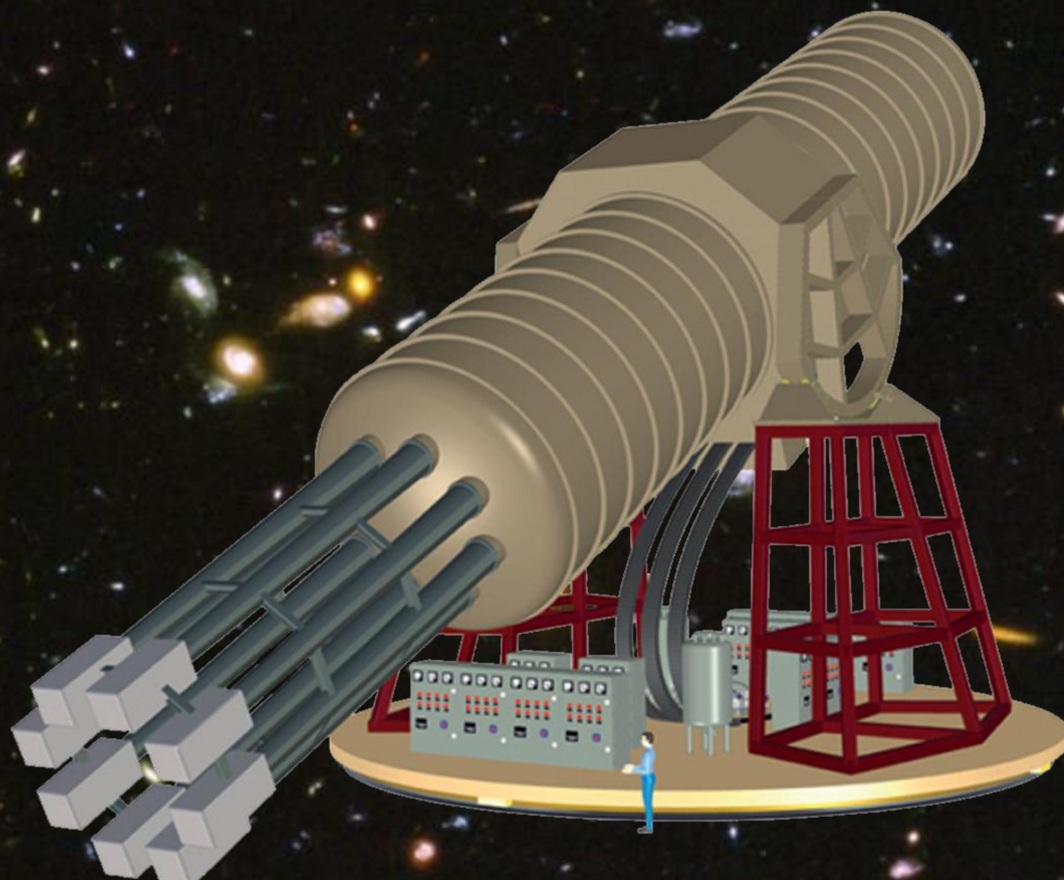
- 70% of gravitating "mass" is dark energy
- Dark matter must be mostly "cold" (structure formation)
- Neutrinos have sub-eV masses (oscillations, cosmo limits)
- Sub-dominant dark matter component

History does not always repeat itself, but …

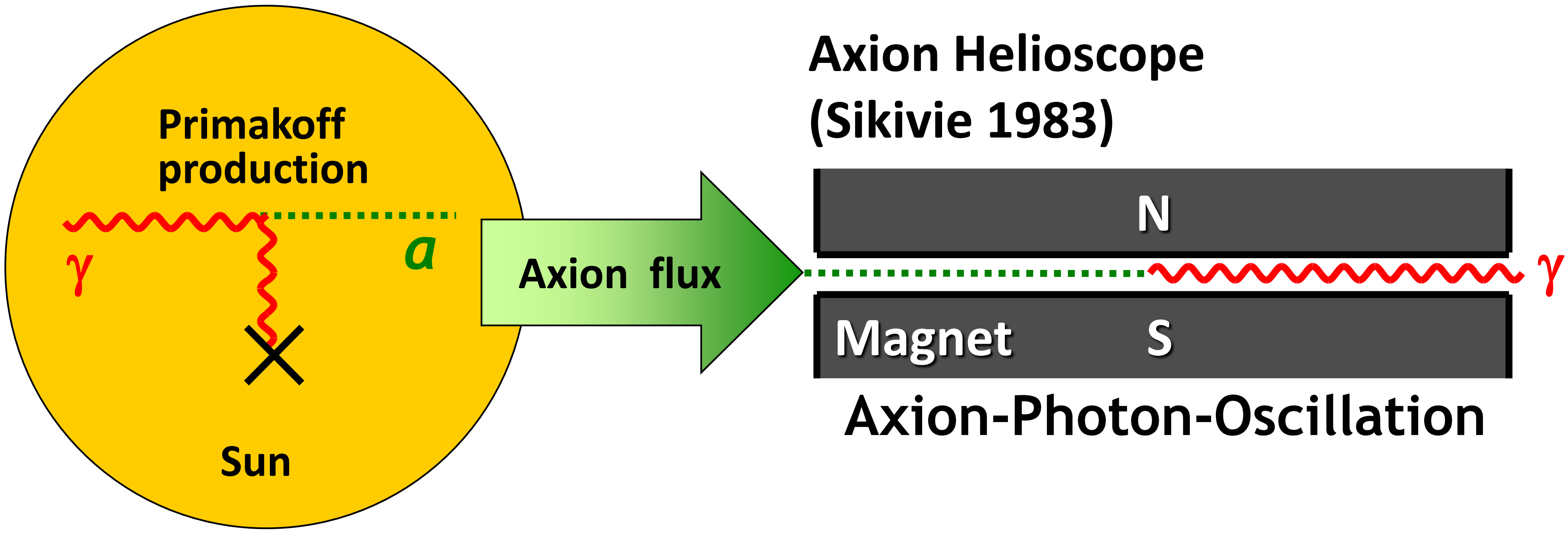
- If axions (or similar) exist, MUST be ALL of dark matter?

International Axion Observatory (IAXO)

To boldly go where no man has gone before
(in axion parameter space)

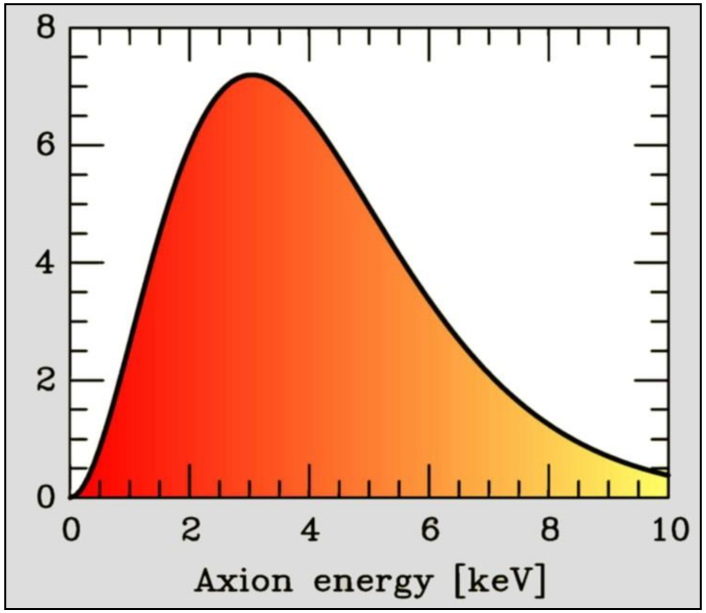


Search for Solar Axions



Axion Helioscope
(Sikivie 1983)

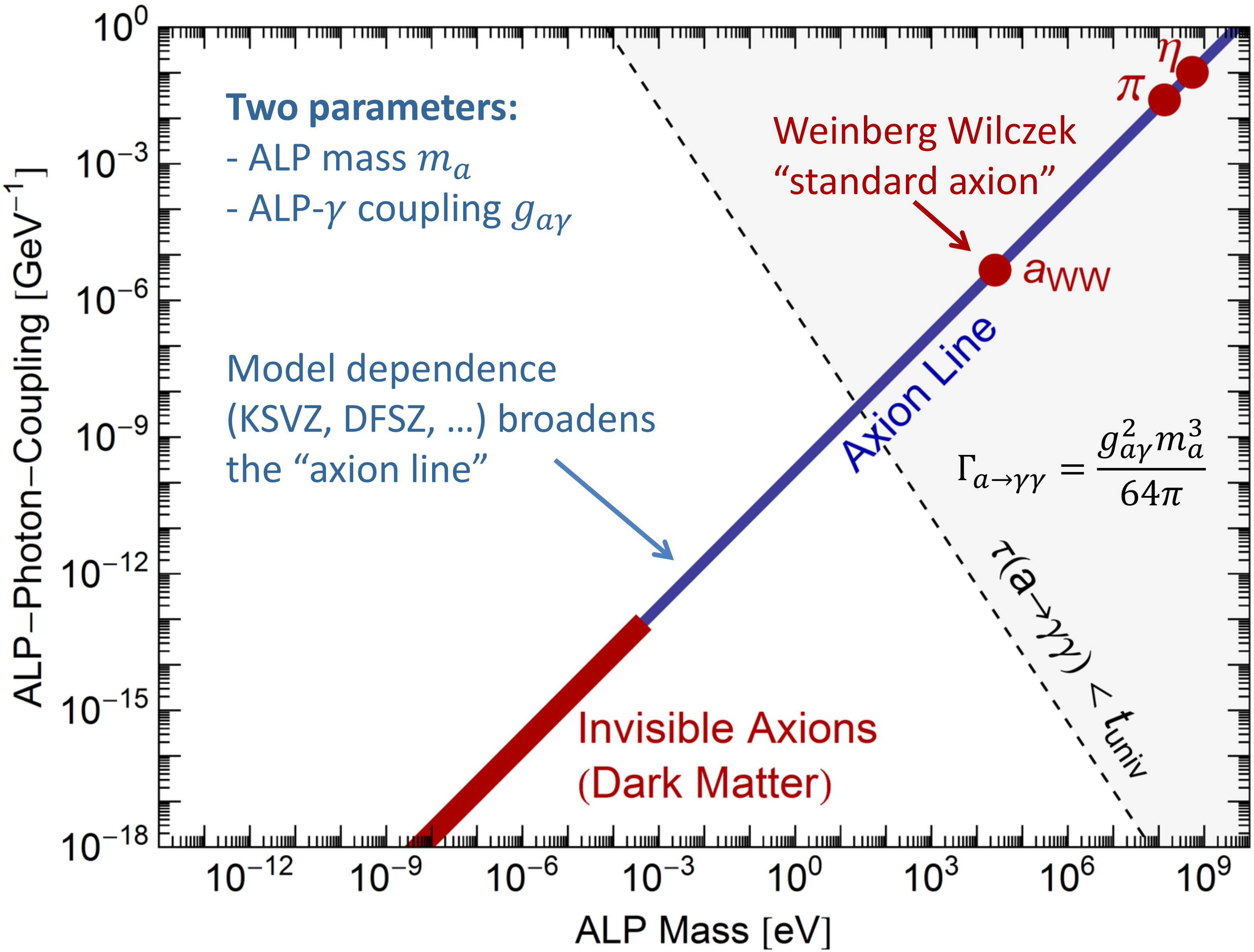
Axion-Photon-Oscillation



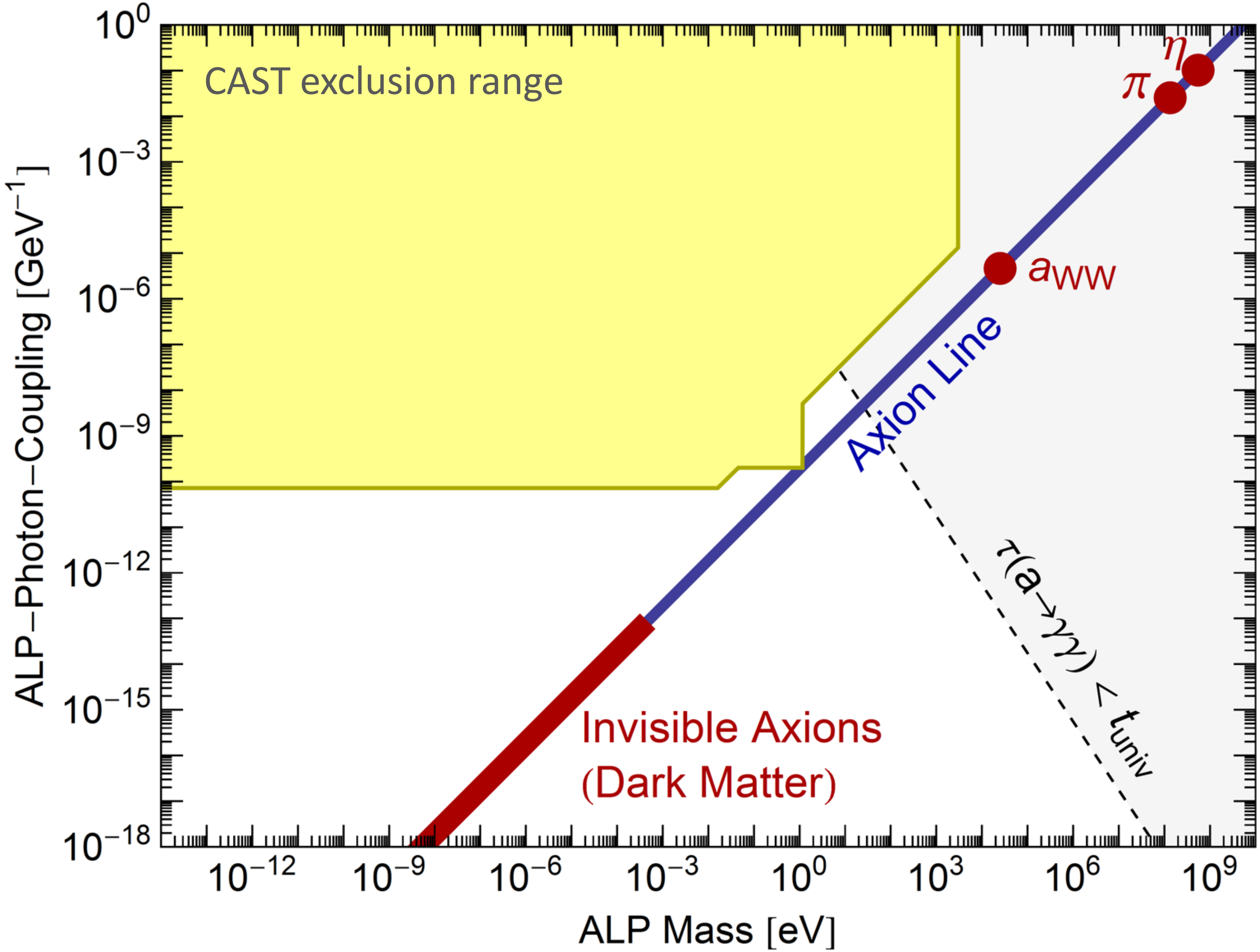
- Tokyo Axion Helioscope (“Sumico”) (Results since 1998, up again 2008)
- CERN Axion Solar Telescope (CAST) (Data since 2003)

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

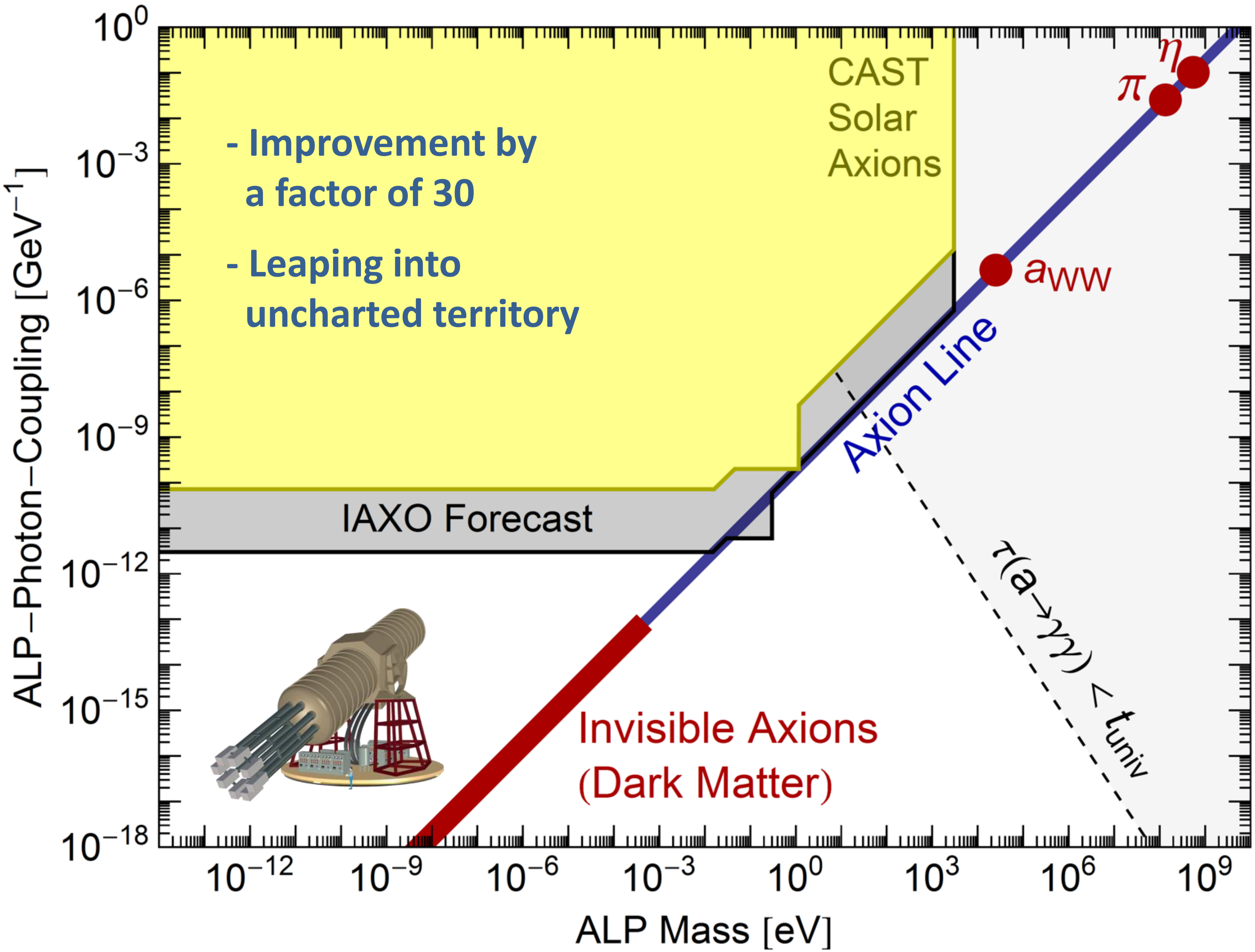
Parameter Space for Axion-Like Particles (ALPs)



Parameter Space for Axion-Like Particles (ALPs)



Parameter Space for Axion-Like Particles (ALPs)



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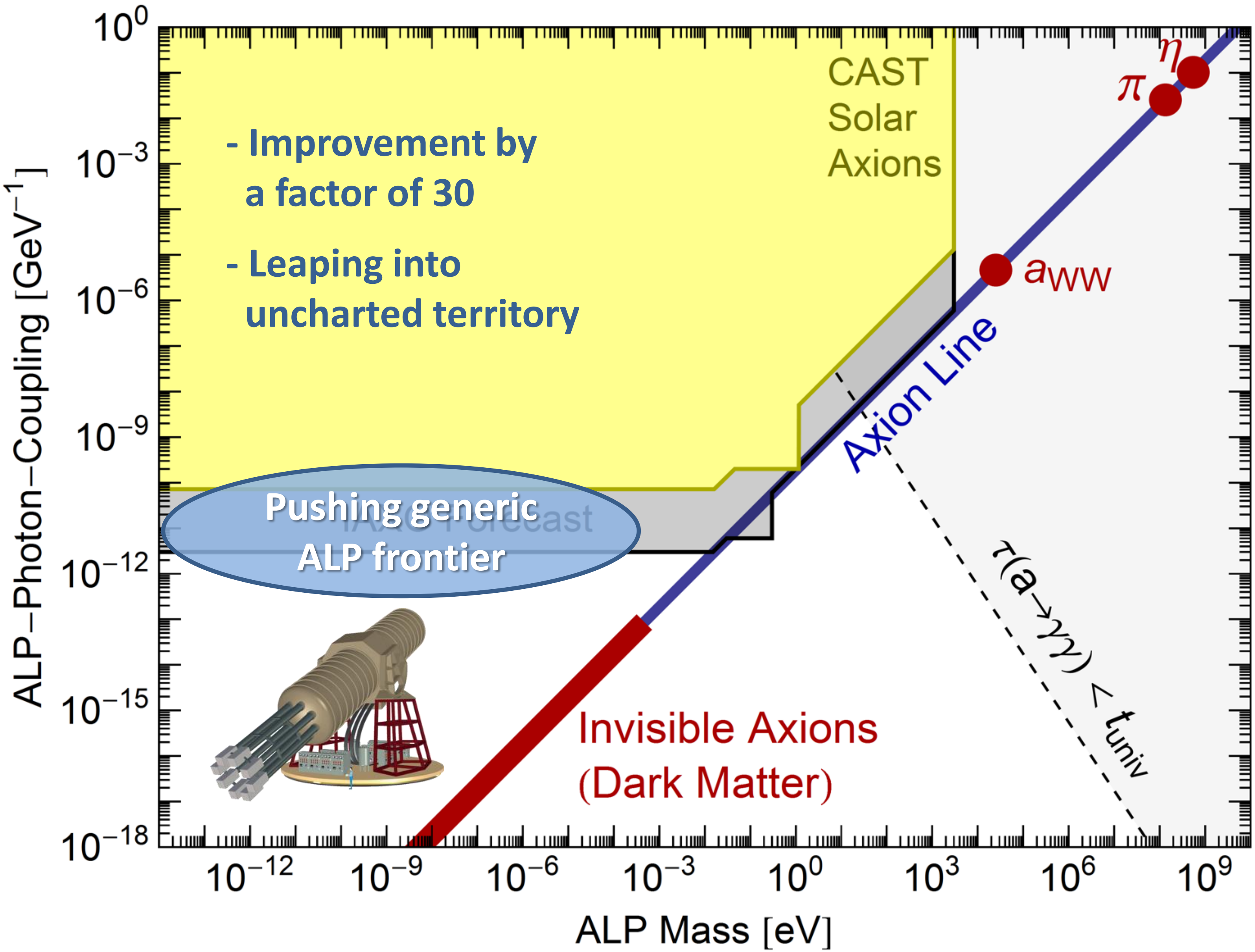
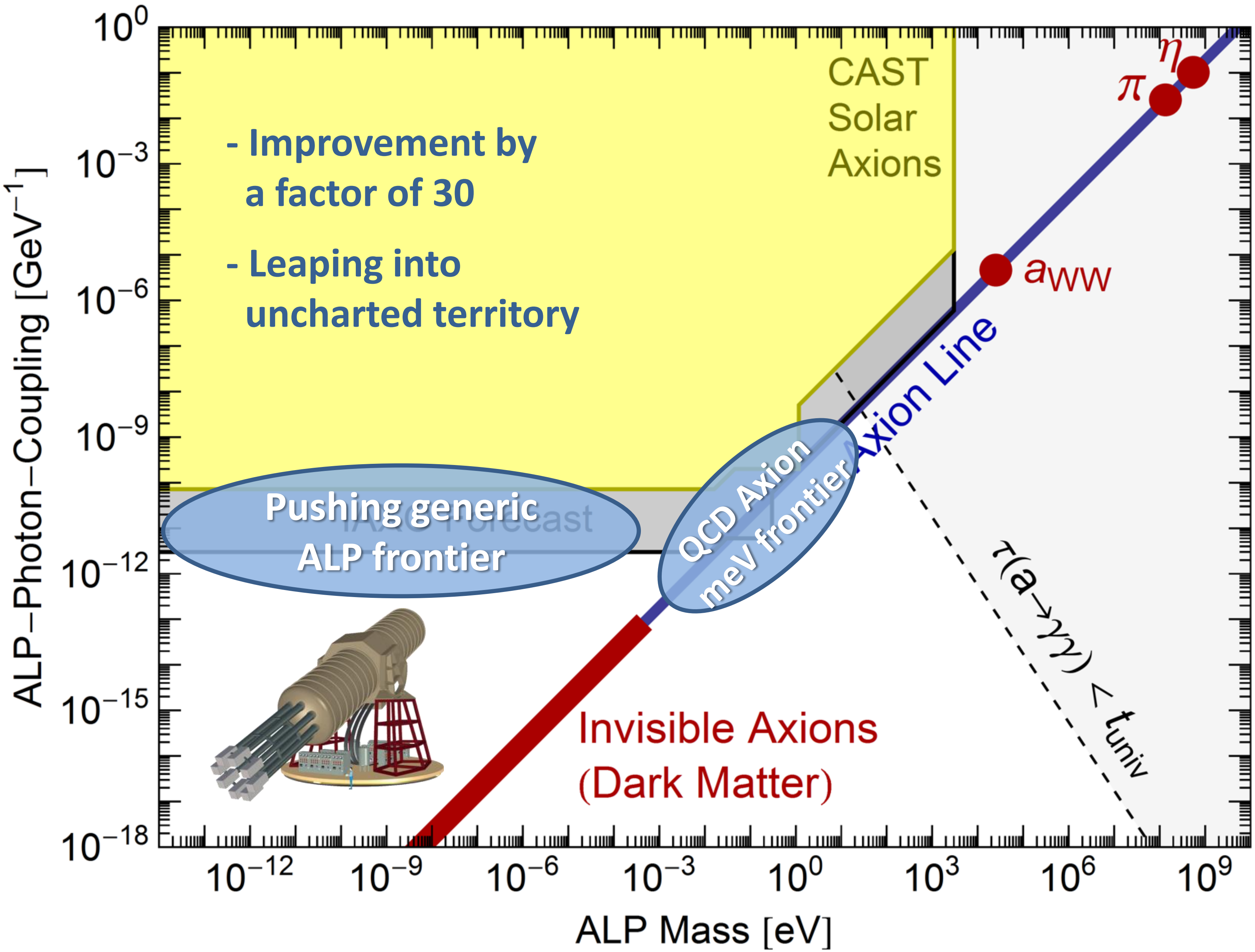
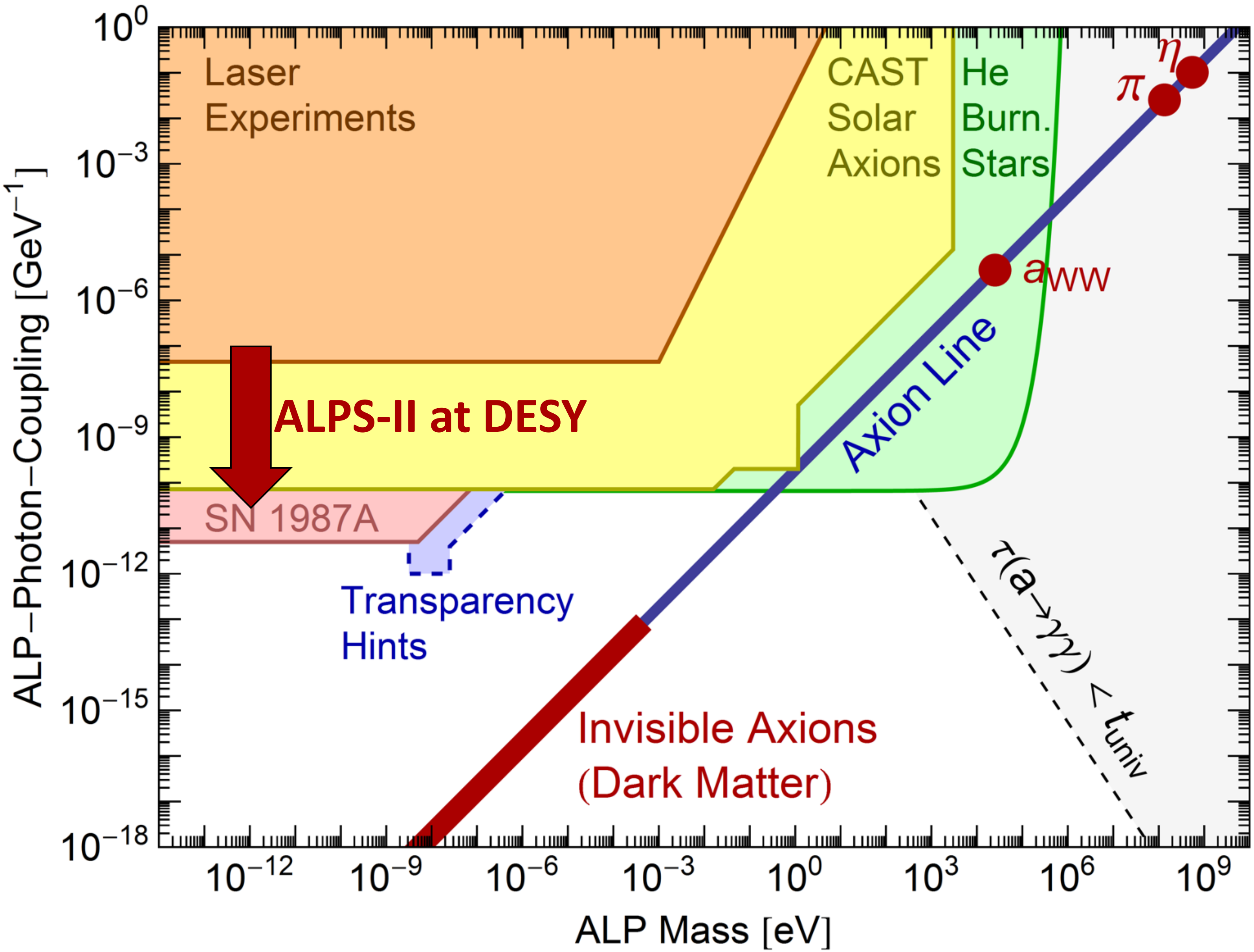


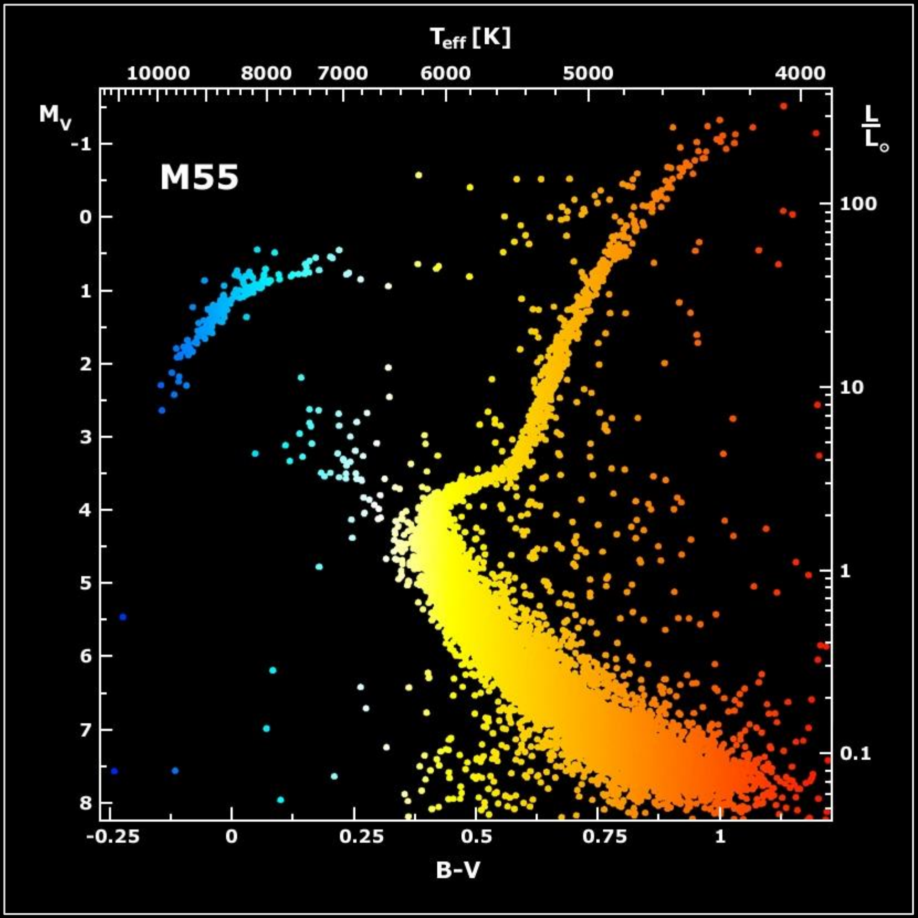
Parameter Space for Axion-Like Particles (ALPs)



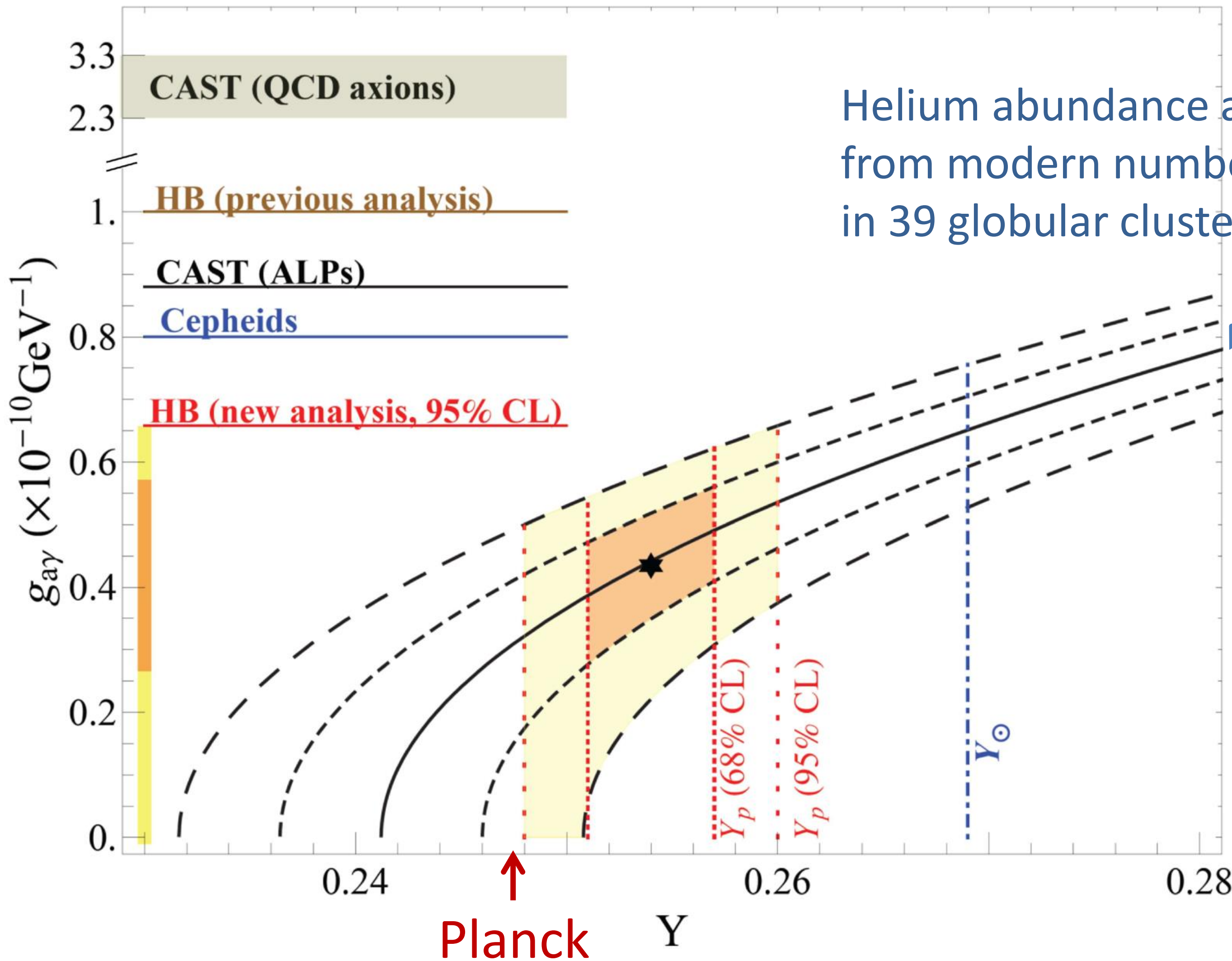
Parameter Space for Axion-Like Particles (ALPs)



Galactic Globular Clusters



New ALP Limit from Globular Clusters



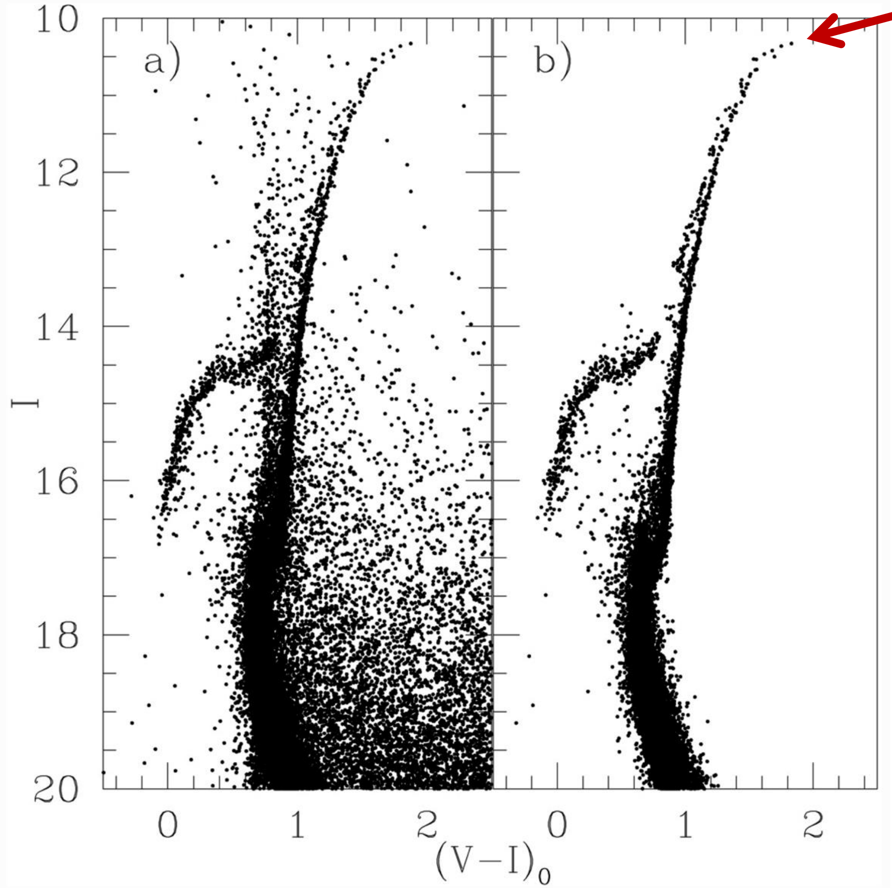
Helium abundance and energy loss rate from modern number counts HB/RGB in 39 globular clusters

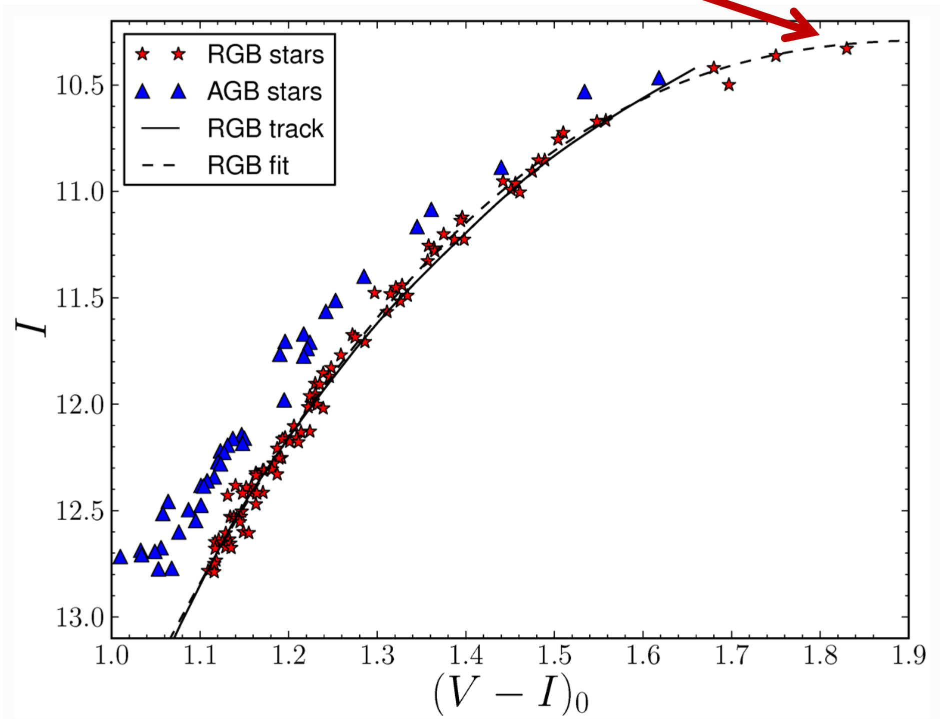
Planck

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

Color-Magnitude Diagram of Globular Cluster M5

Brightest red giant
measures nonstandard energy loss





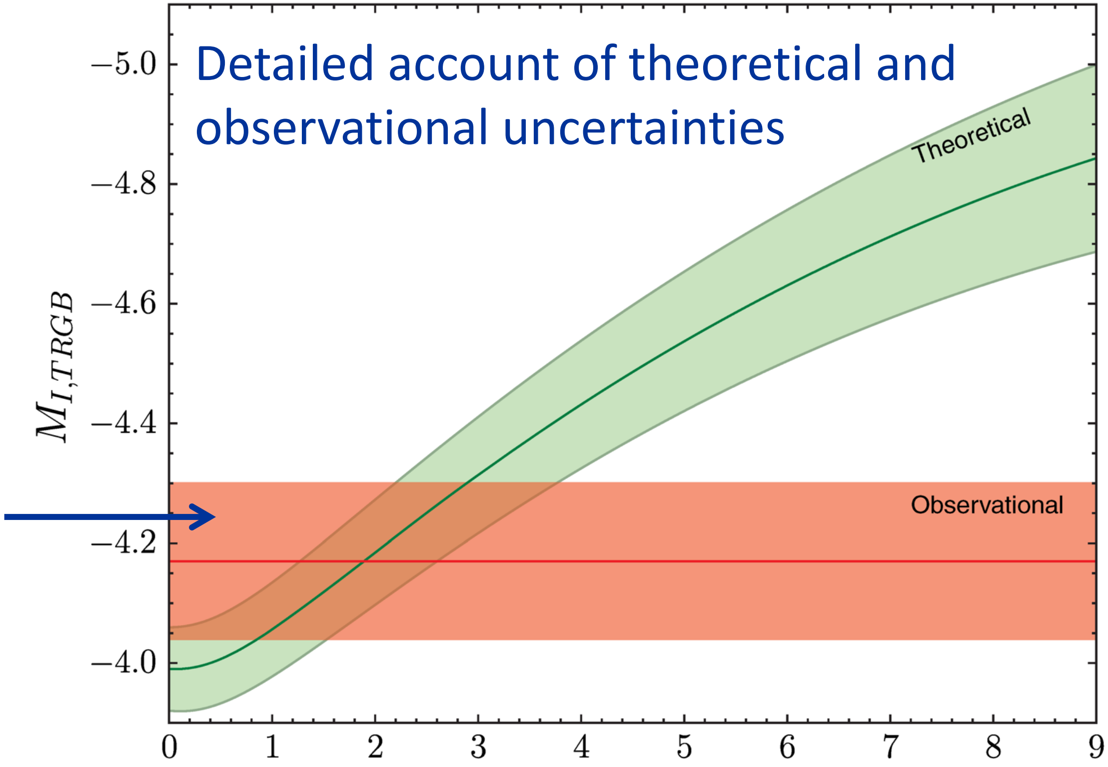
CMD (a) before and (b) after cleaning

CMD of brightest 2.5 mag of RGB

Viaux, Catelan, Stetson, Raffelt, Redondo, Valcarce & Weiss, arXiv:1308.4627

Limits on Axion-Electron Coupling from GC M5

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



Axion-electron Yukawa $g_{ae} \times 10^{13}$

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

Limit on axion-electron Yukawa

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

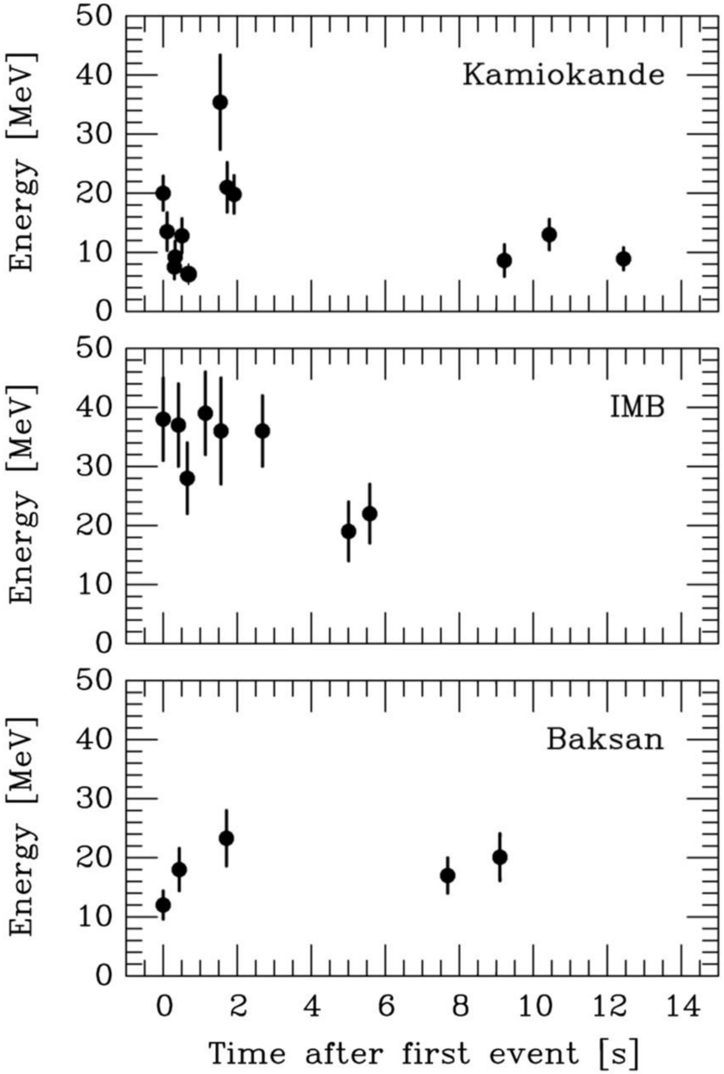
Mass limit in DFSZ model

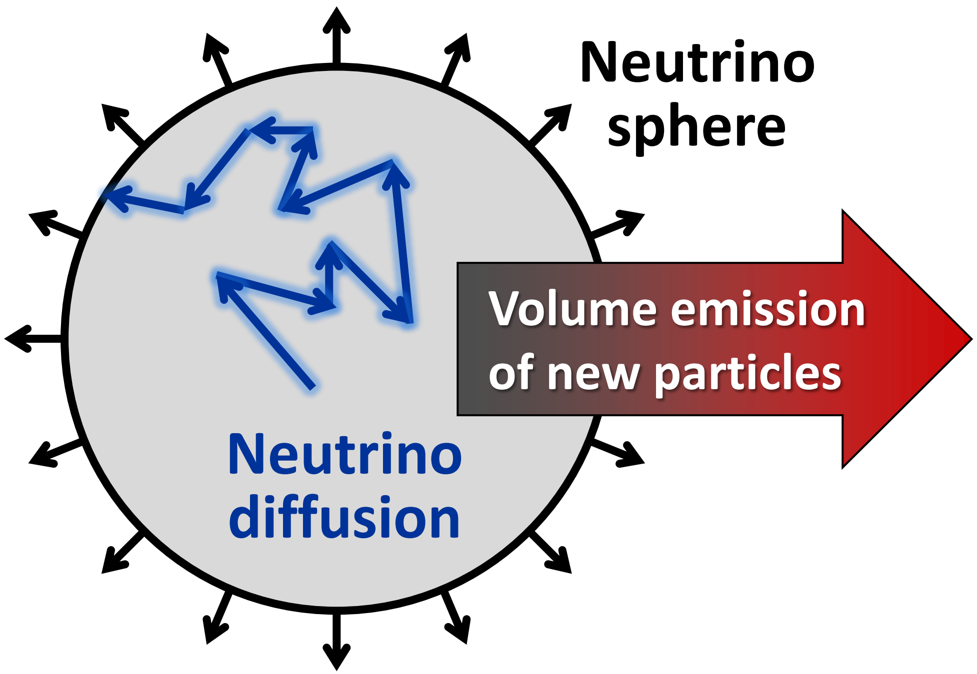
$$m_a \cos^2\beta < \begin{cases} 9.3\ \mathrm{meV} & (68\%\ \mathrm{CL}) \\ 15.4\ \mathrm{meV} & (95\%\ \mathrm{CL}) \end{cases}$$

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.)

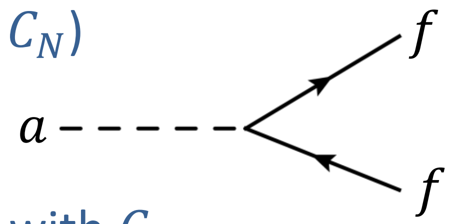
Late-time signal most sensitive observable

Axion-Nucleon Couplings

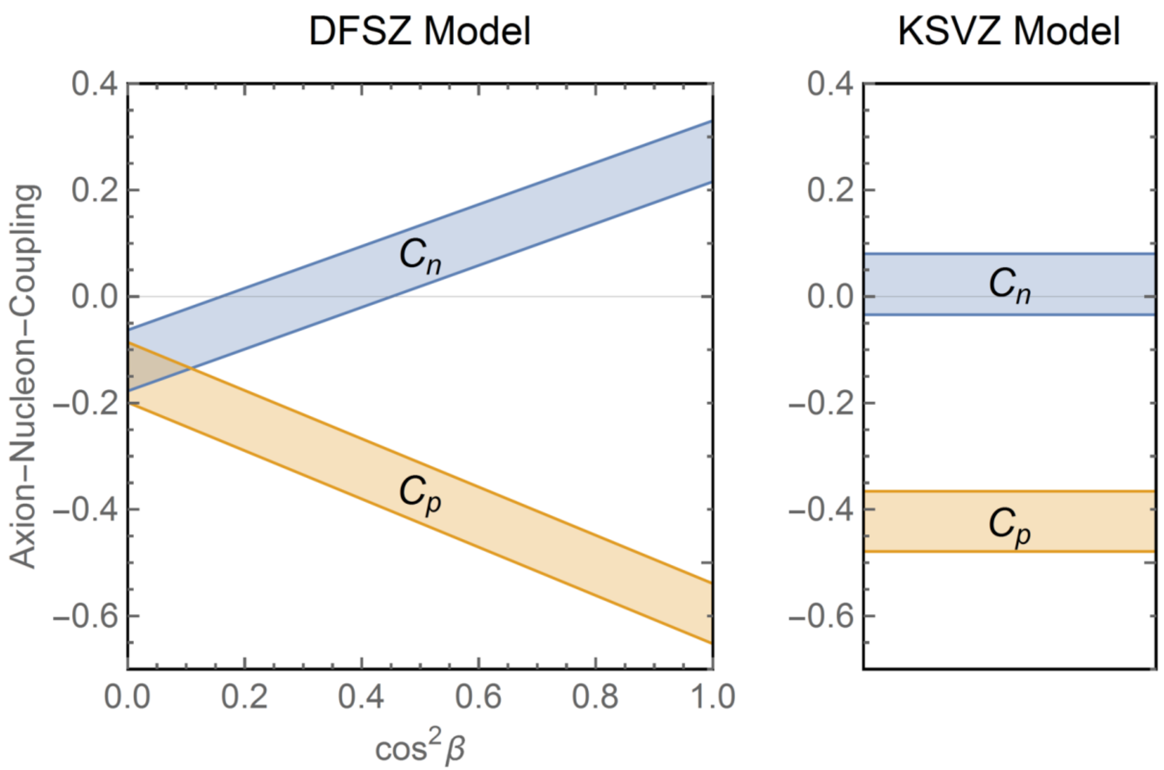
Axion-nucleon coupling (model-dependent numerical factors C_N)

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

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



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



Uncertainty mostly from

$$z = \frac{m_u}{m_d} = 0.38 \ldots 0.58$$

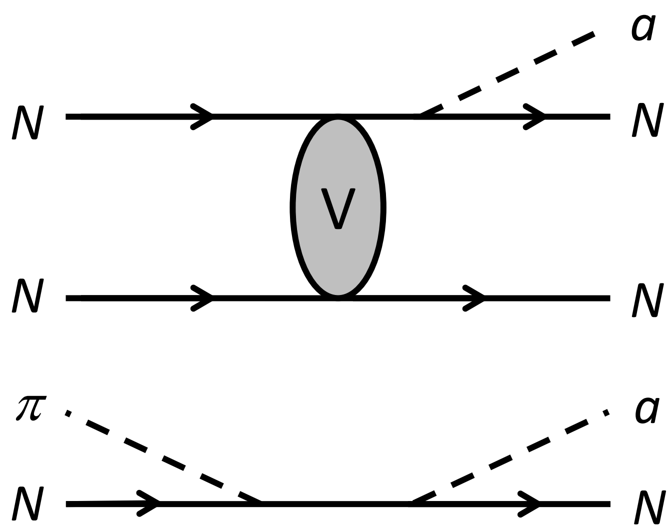
Coupling to neutron could be very small!

Axion Emission in a Nuclear Medium

Axion-nucleon coupling

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

- axial-vector structure
- spin-interaction



Bremsstrahlung

Free pions for some conditions?

Difficulties include:

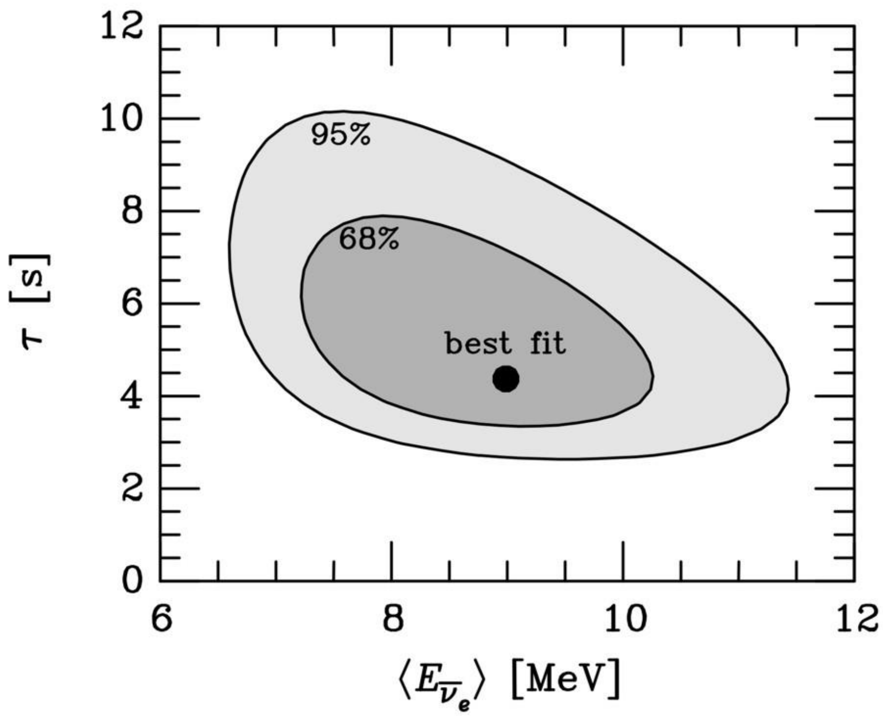
- Realistic nucleon-nucleon interaction potential for spin-dependent part (even in vacuum)
- Many-body effects (effective mass, spin-spin correlations ...)
- Axion couplings in the nuclear medium (axial current!)
- Multiple-scattering effects:
  - Frequency of NN collisions exceeds typical axion energy: $\tau_{\rm coll}^{-1} > E_a$
  - Expect LPM-type destructive interference effects

$\rightarrow$ **Need proton and neutron dynamical spin structure function in SN medium**

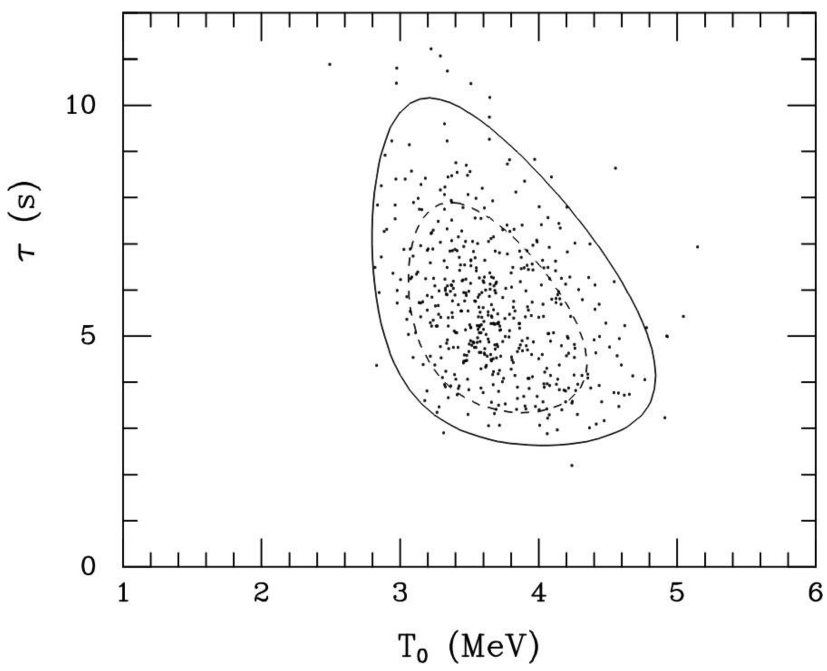
Cooling Time Scale

Exponential cooling model: $T = T_0\, e^{-t/4\tau}$, constant radius, $L = L_0\, e^{-t/\tau}$

Fit parameters are T_0, τ, radius, 3 offset times for KII, IMB & BST detectors



Loredo and Lamb
Unpublished preprint 1995

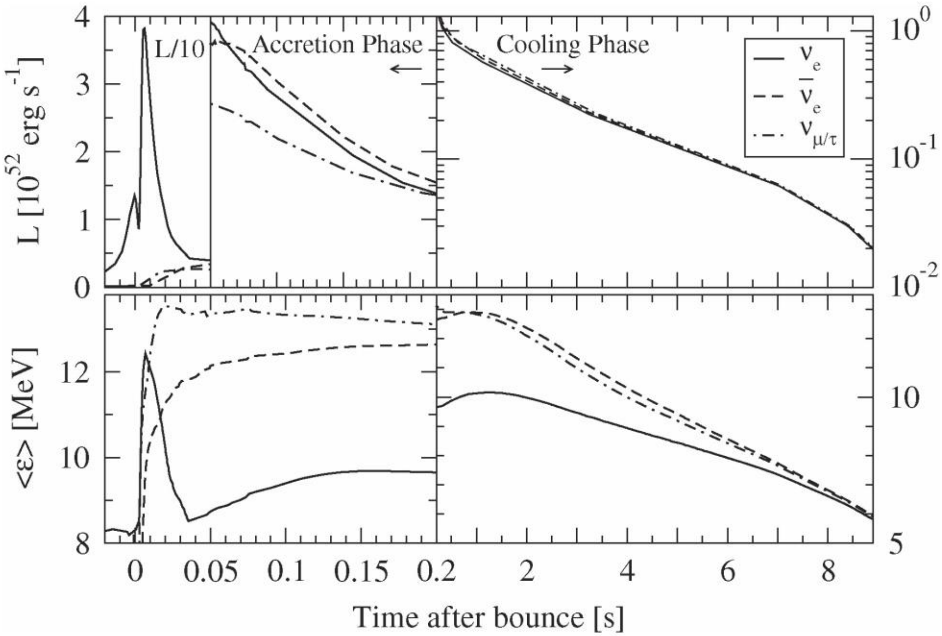


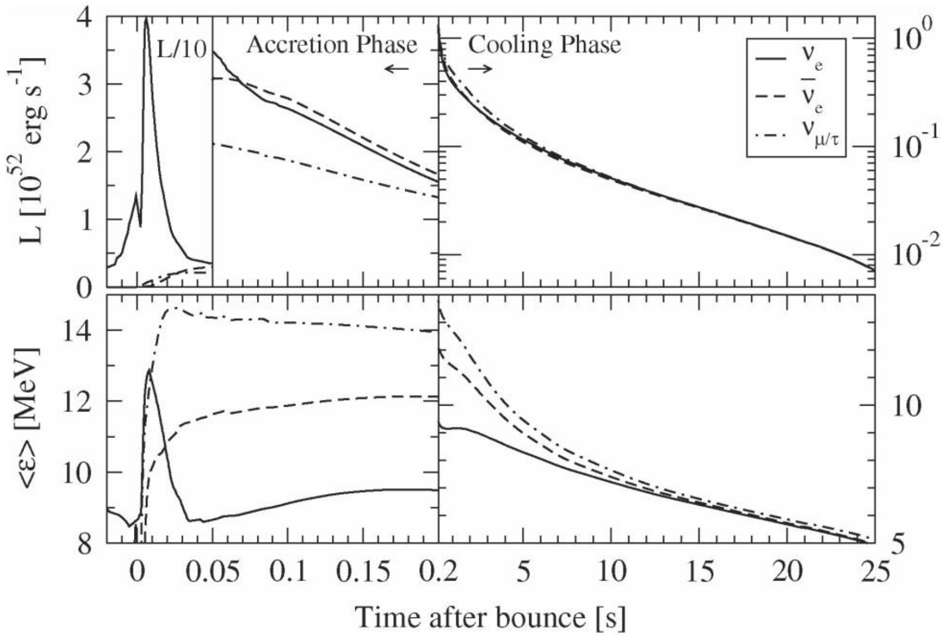
Loredo and Lamb, Bayesian analysis
astro-ph/0107260

Long-Term Cooling of EC SN (Garching 2009)

Neutrino opacities with strong NN correlations and nucleon recoil in neutrino-nucleon scattering.
Exponential cooling with $\tau = 2.6\ s$
Barely allowed by SN 1987A

Neutrino opacities without these effects (~ Basel case?)
Much longer cooling times

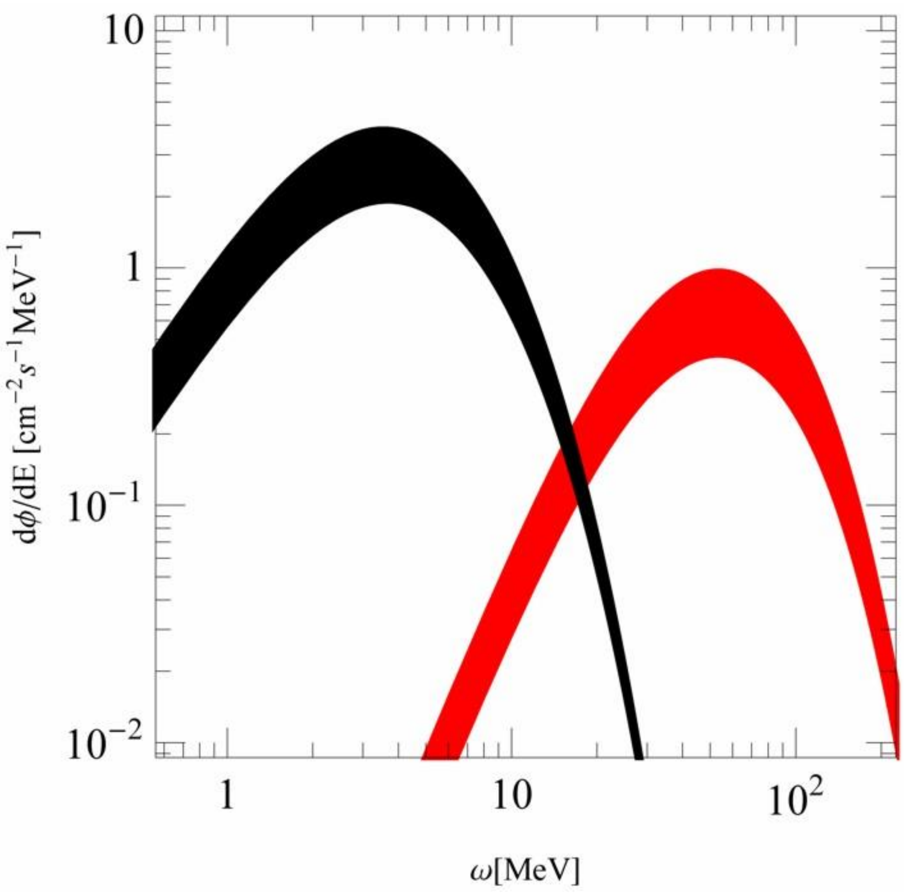




L. Hüdepohl et al. (Garching Group), arXiv:0912.0260

Diffuse Supernova Axion Background (DSAB)

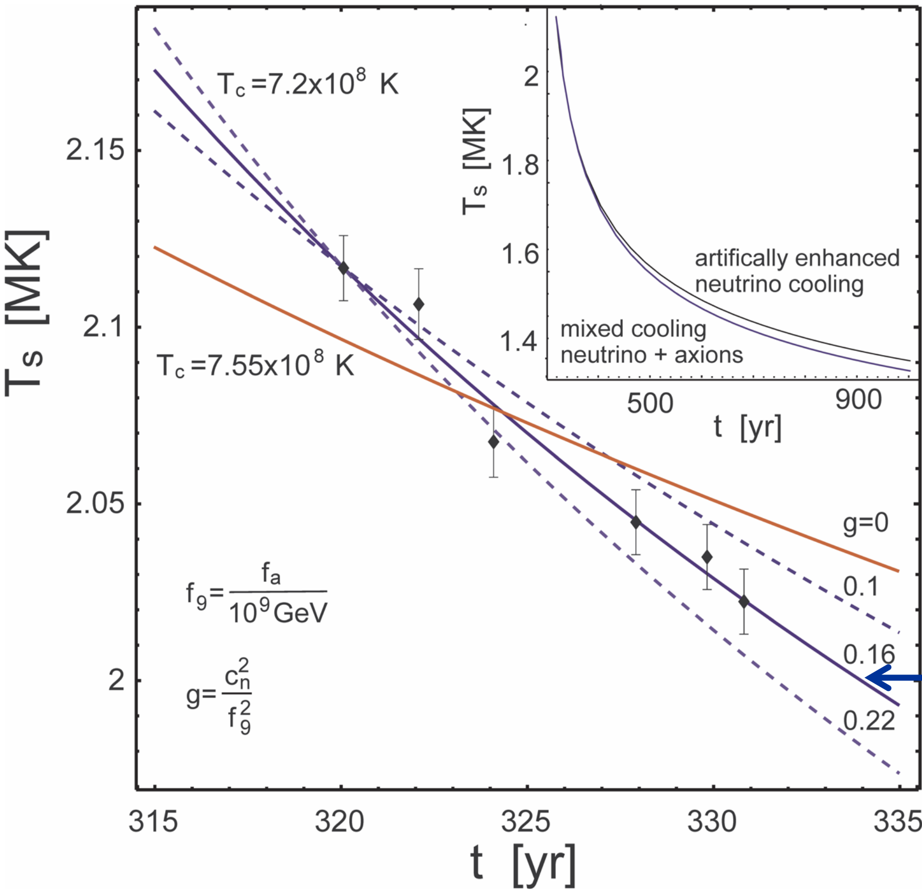
- Neutrinos from all core-collapse SNe comparable to photons from all stars
- Diffuse Supernova Neutrino Background (DSNB) similar energy density as extra-galactic background light (EBL), approx 10% of CMB energy density
- DSNB probably next astro neutrinos to be measured



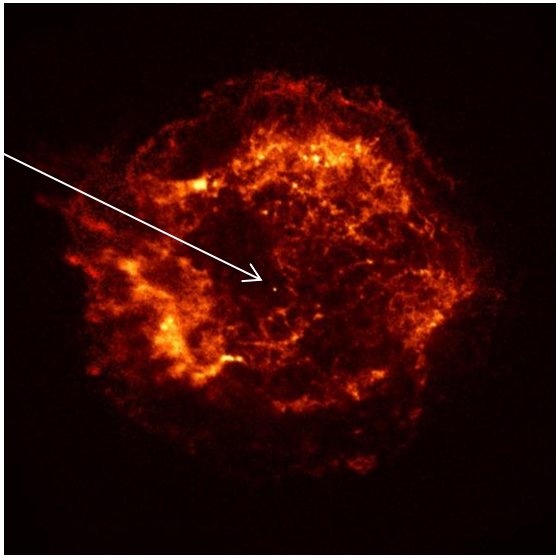
- Axions with m_a near SN 1987A energy-loss limit
- Provide DSAB with comparable energy density as DSNB and EBL
- No obvious detection channel

Raffelt, Redondo & Viaux
arXiv:1110.6397

Cooling of Neutron Star in Cas A



Chandra x-ray image of non-pulsar compact remnant



$C_n m_a \sim 2.4$ meV

Measured surface temperature over 10 years reveals unusually fast cooling rate

- Neutron Cooper pair breaking and formation (PBF) as neutrino emission process?
- Evidence for extra cooling (by axions)?

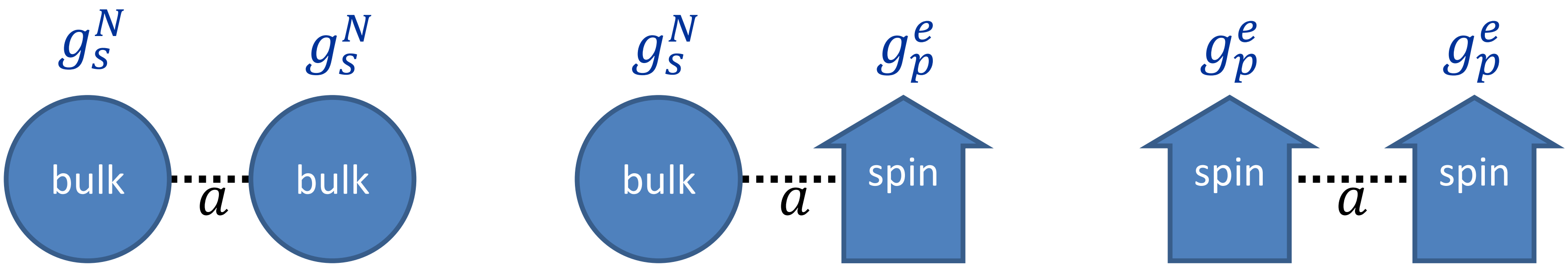
Leinson, arXiv:1405.6873

PHYSICAL REVIEW D VOLUME 30, NUMBER 1 1 JULY 1984

New macroscopic forces?

J. E. Moody* and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(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 $(g_s^N)^2$

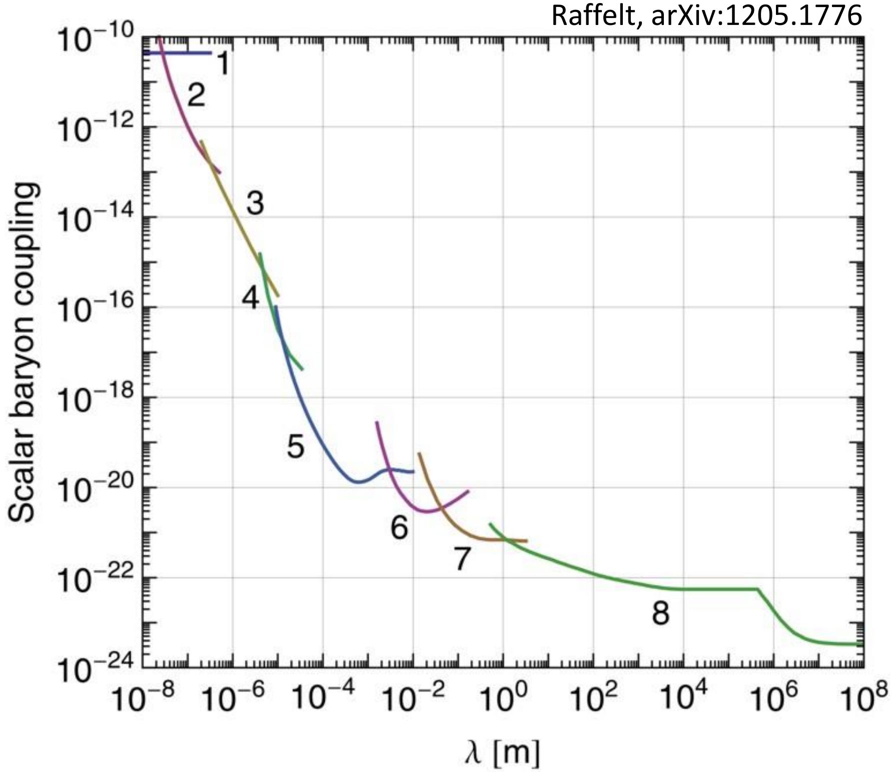
Torsion balance using
polarized electron spins
Axion couplings $g_s^N g_p^e$
T-violating force

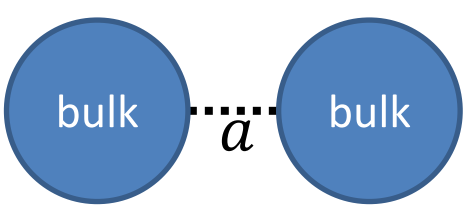
Spin-spin forces
hard to measure
Axion couplings $(g_s^e)^2$

Long-Range Force Experiments

Long-range force limits from tests of Newton's law and equivalence principle (Mostly from Eöt-Wash Group, Seattle)

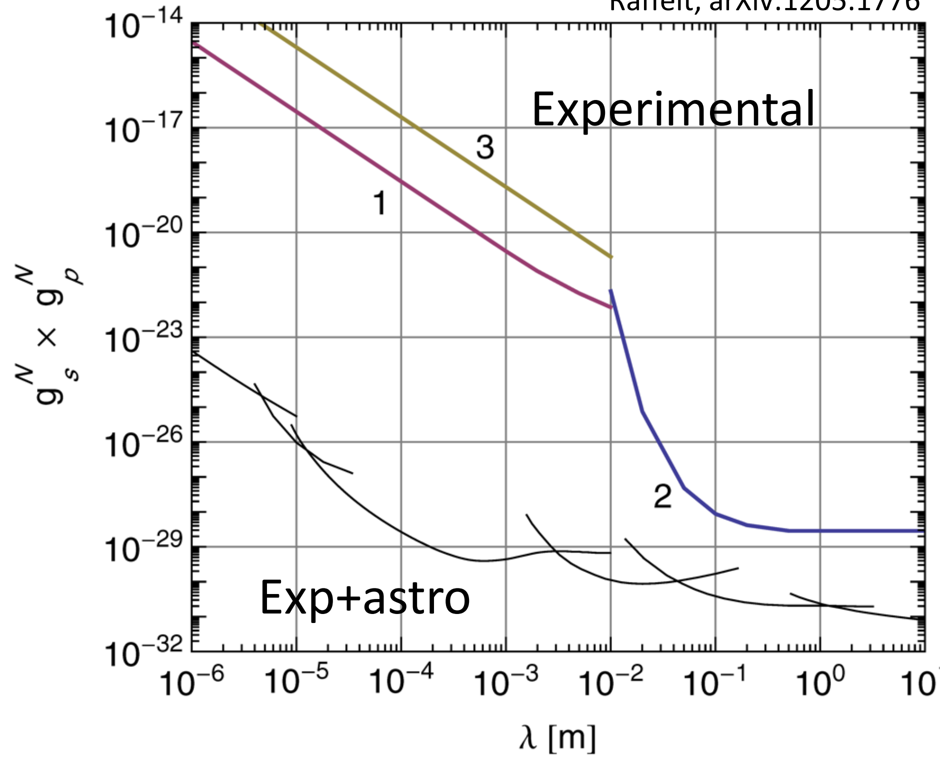
Raffelt, arXiv:1205.1776

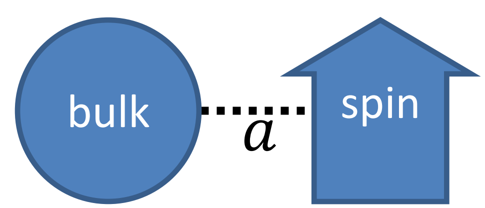




Limits from long-range g_s^N limits times astrophysical g_p^N limits, compared with direct $g_s^N g_p^N$ constraints

Raffelt, arXiv:1205.1776





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

Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance

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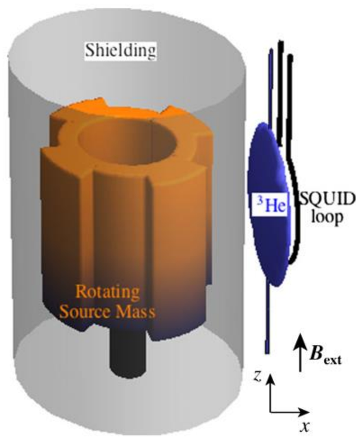

FIG. 1 (color online). A source mass consisting of a segmented cylinder with n sections is rotated around its axis of symmetry at frequency ω_{rot}, which results in a resonance between the frequency $\omega = n\omega_{rot}$ at which the segments pass near the sample and the resonant frequency $2\vec{\mu}_N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

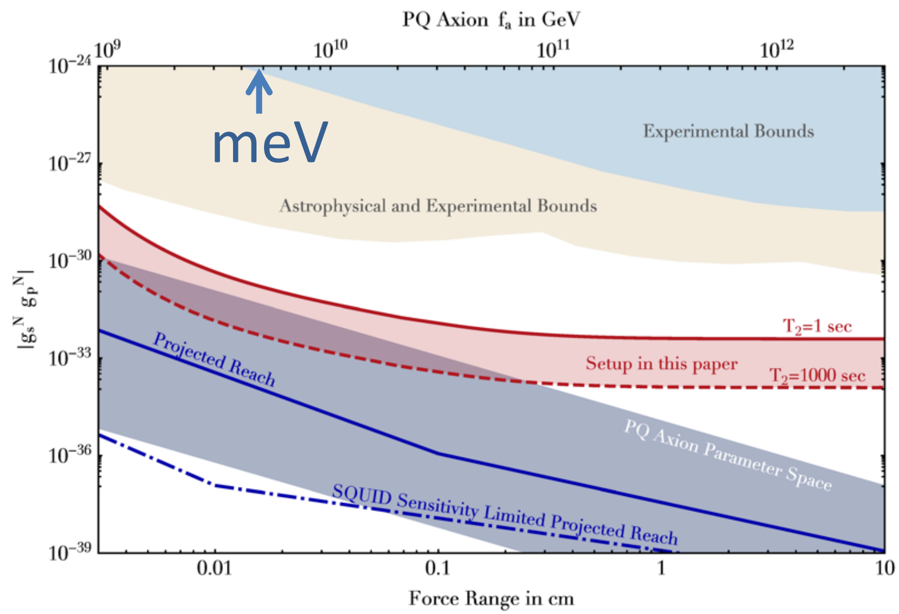

FIG. 2 (color online). Projected reach for monopole-dipole axion mediated interactions.

ARIADNE: Axion Resonant InterAction DetectioN Experiment

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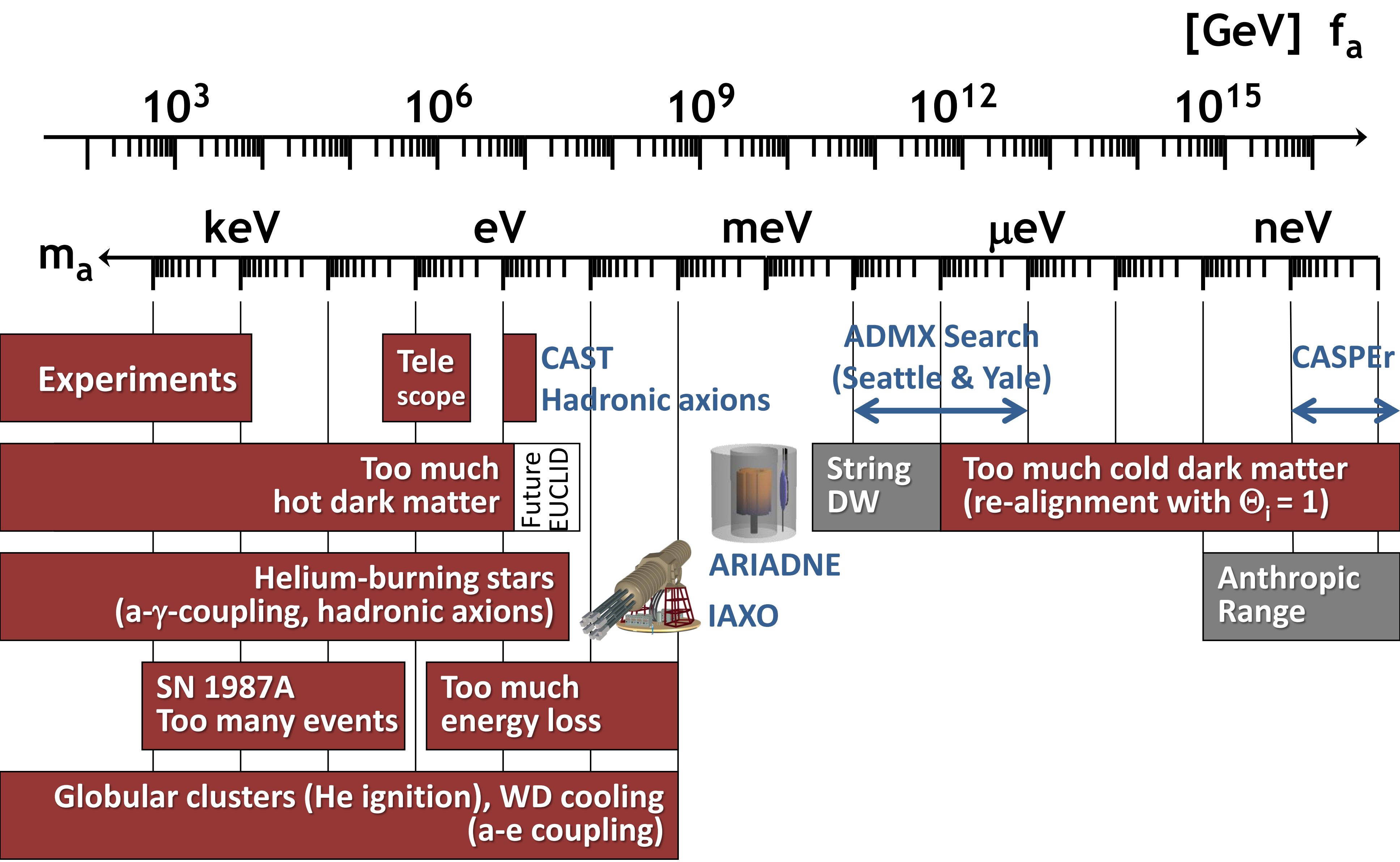
Axion Bounds and Searches



Milli-eV range quite relevant for axion searches