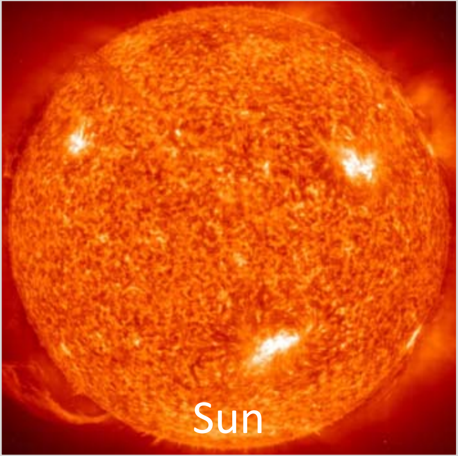

Sun

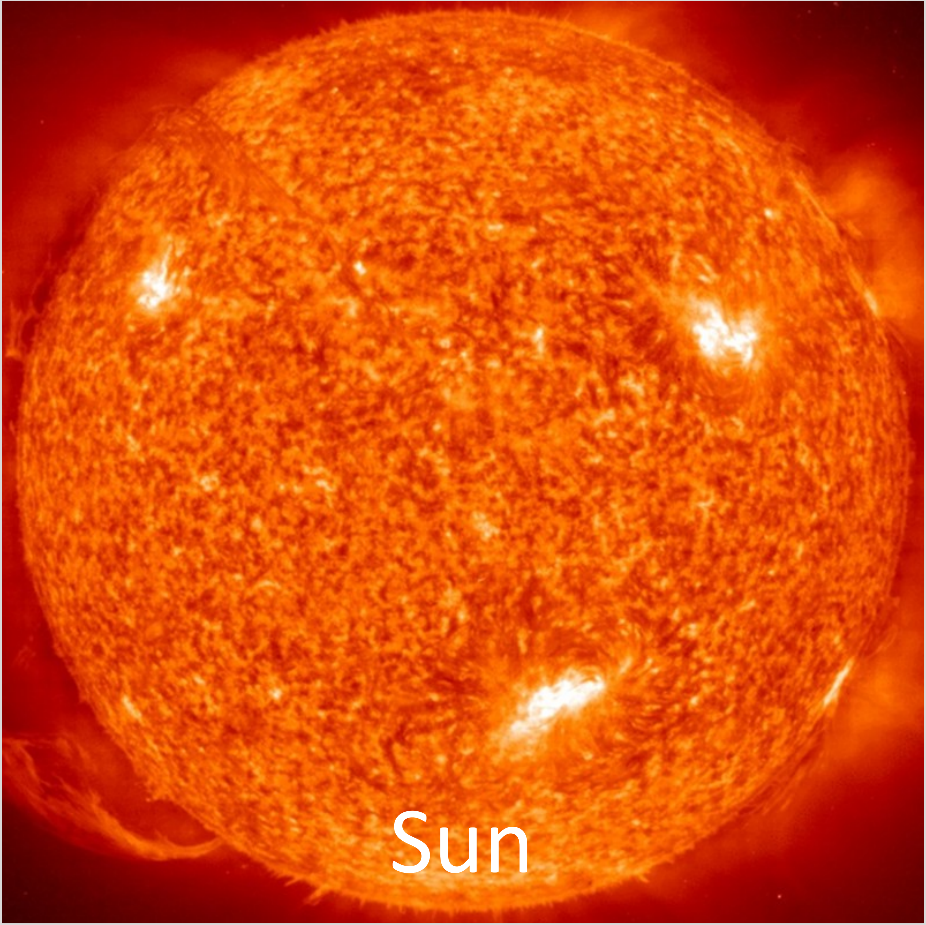

Globular Cluster


Supernova 1987A


Dark Matter

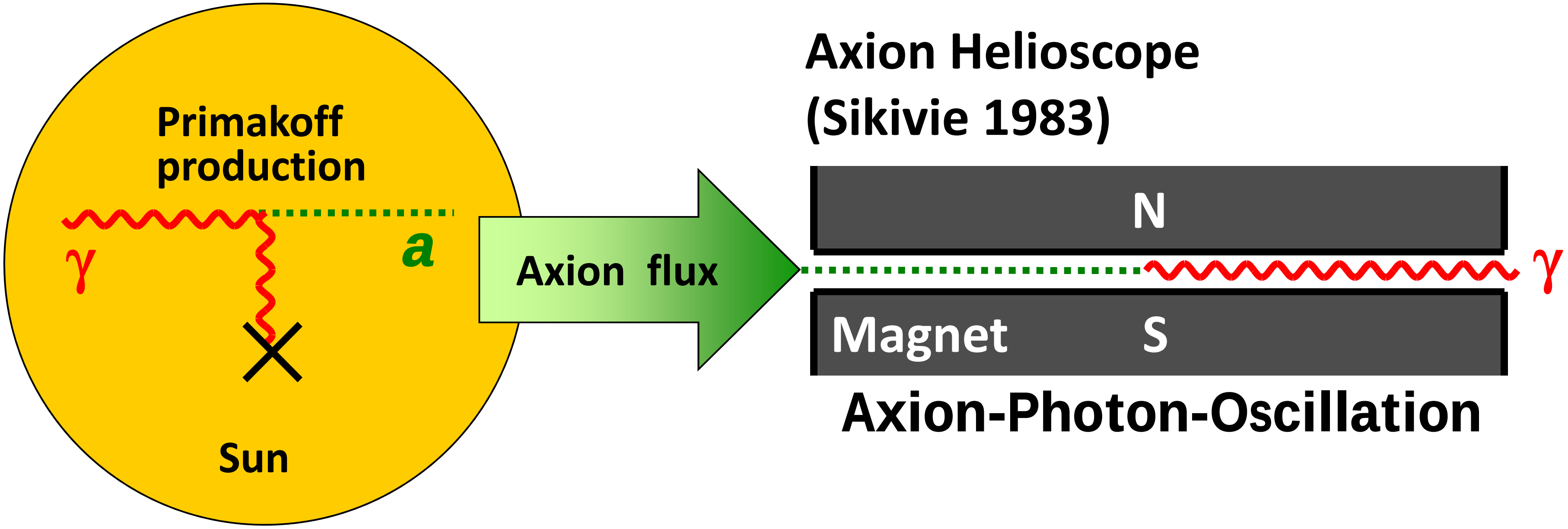
Astrophysical and Cosmological Axion Limits

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



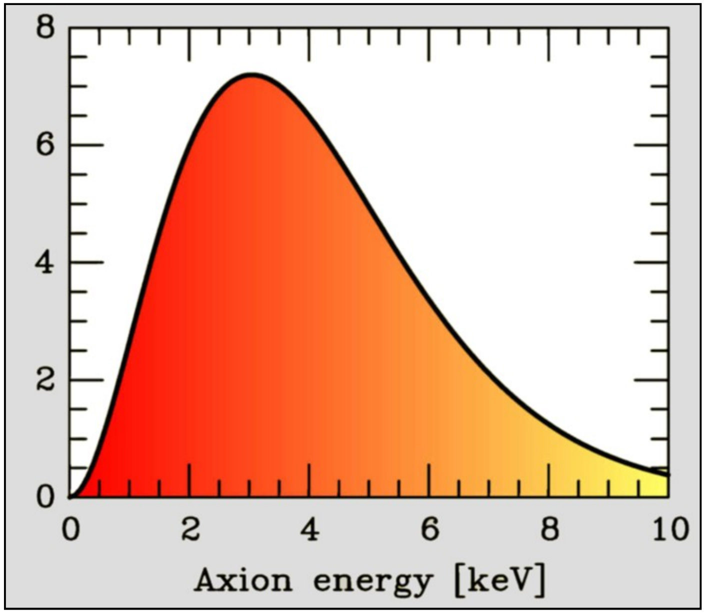
Solar Axions

Search for Solar Axions



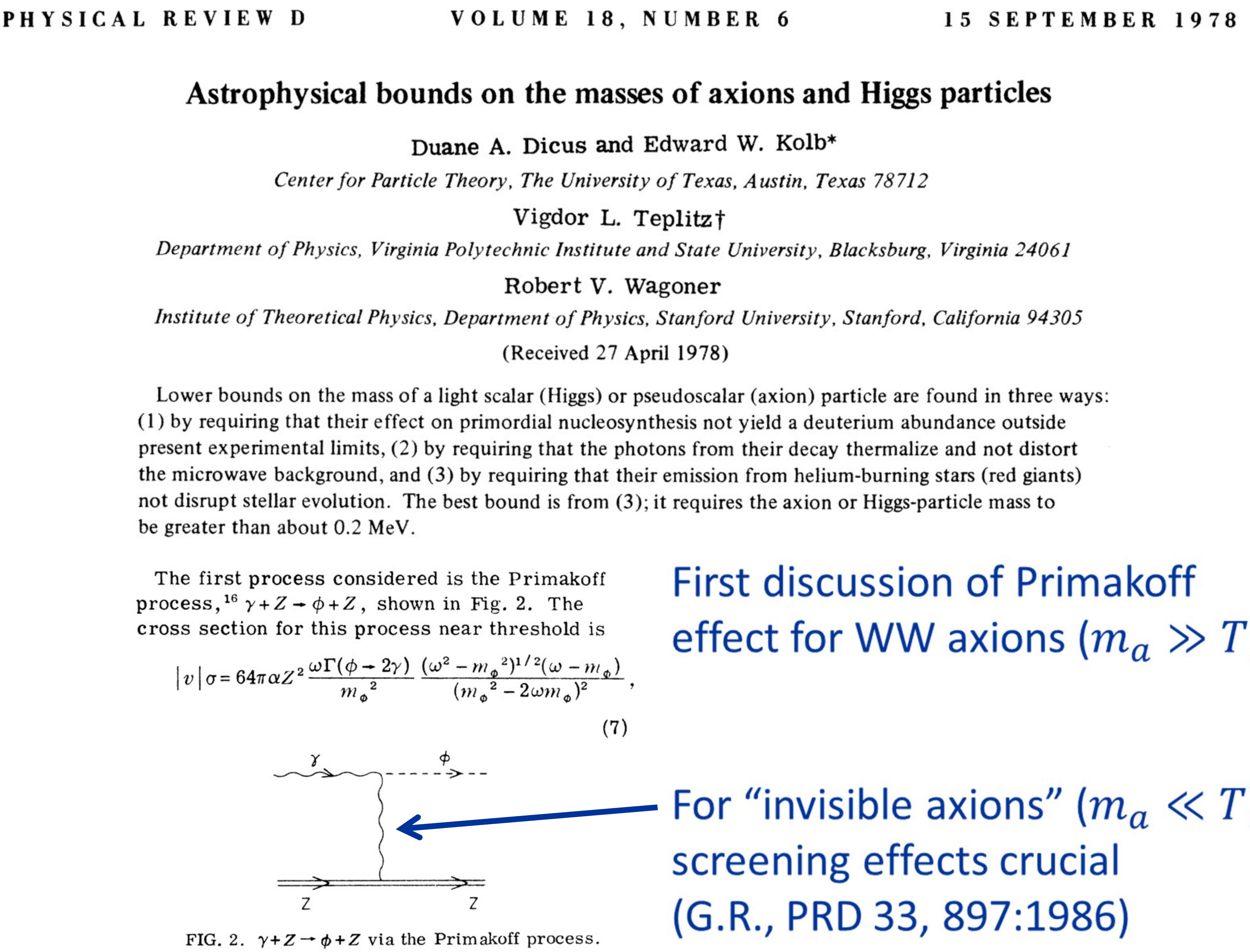
Axion Helioscope (Sikivie 1983)

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 ...)



PHYSICAL REVIEW D VOLUME 18, NUMBER 6 15 SEPTEMBER 1978

Astrophysical bounds on the masses of axions and Higgs particles

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

(Received 27 April 1978)

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

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

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

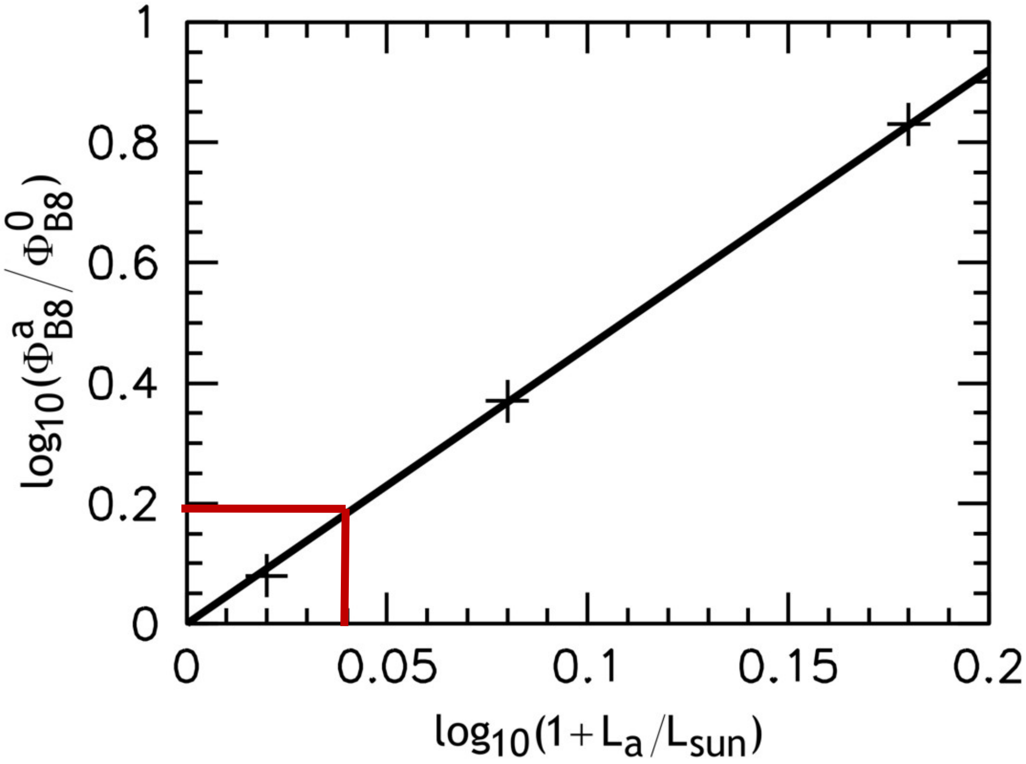
FIG. 2. $\gamma + Z \to \phi + Z$ via the Primakoff process.

First discussion of Primakoff effect for WW axions ($m_a \gg T$)

For “invisible axions” ($m_a \ll T$) screening effects crucial (G.R., PRD 33, 897:1986)

Solar Neutrino Limit on Solar Energy Losses

Self-consistent models of the present-day Sun provide a simple power-law connection between a new energy loss L_a (e.g. axions) and the all-flavor solar neutrino flux from the B8 reaction as measured by SNO



$$\Phi^a_{\mathrm{B8}} = \Phi^0_{\mathrm{B8}} \left(\frac{L_\odot + L_a}{L_\odot}\right)^{4.6}$$

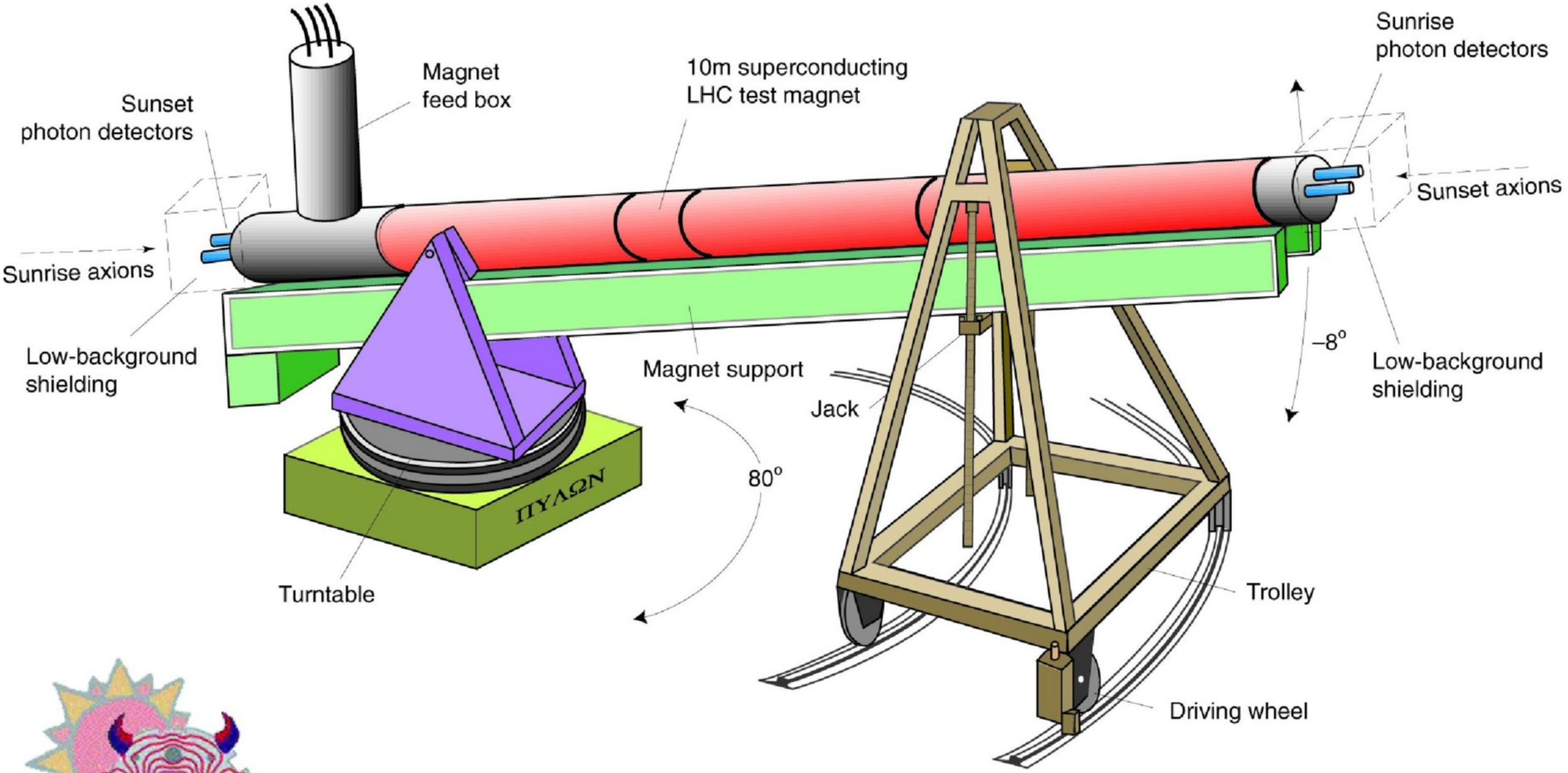
Solar model prediction and SNO measurements imply roughly

$$L_a \lesssim 0.1\, L_\odot$$

Gondolo & Raffelt, arXiv:0807.2926

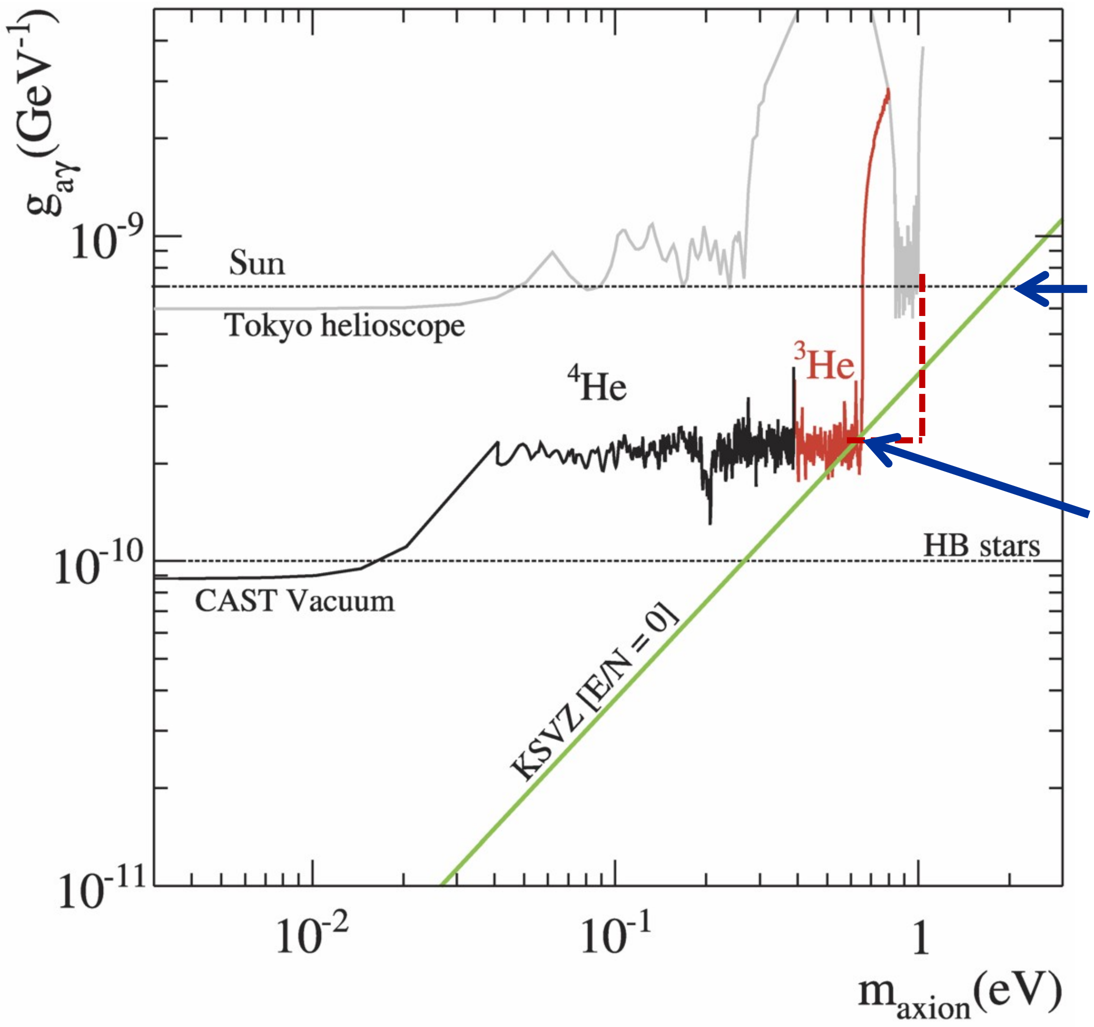
Schlattl, Weiss & Raffelt, hep-ph/9807476

LHC Magnet Mounted as a Telescope to Follow the Sun



Cern **A**xion **S**olar **T**elescope

Helioscope Limits

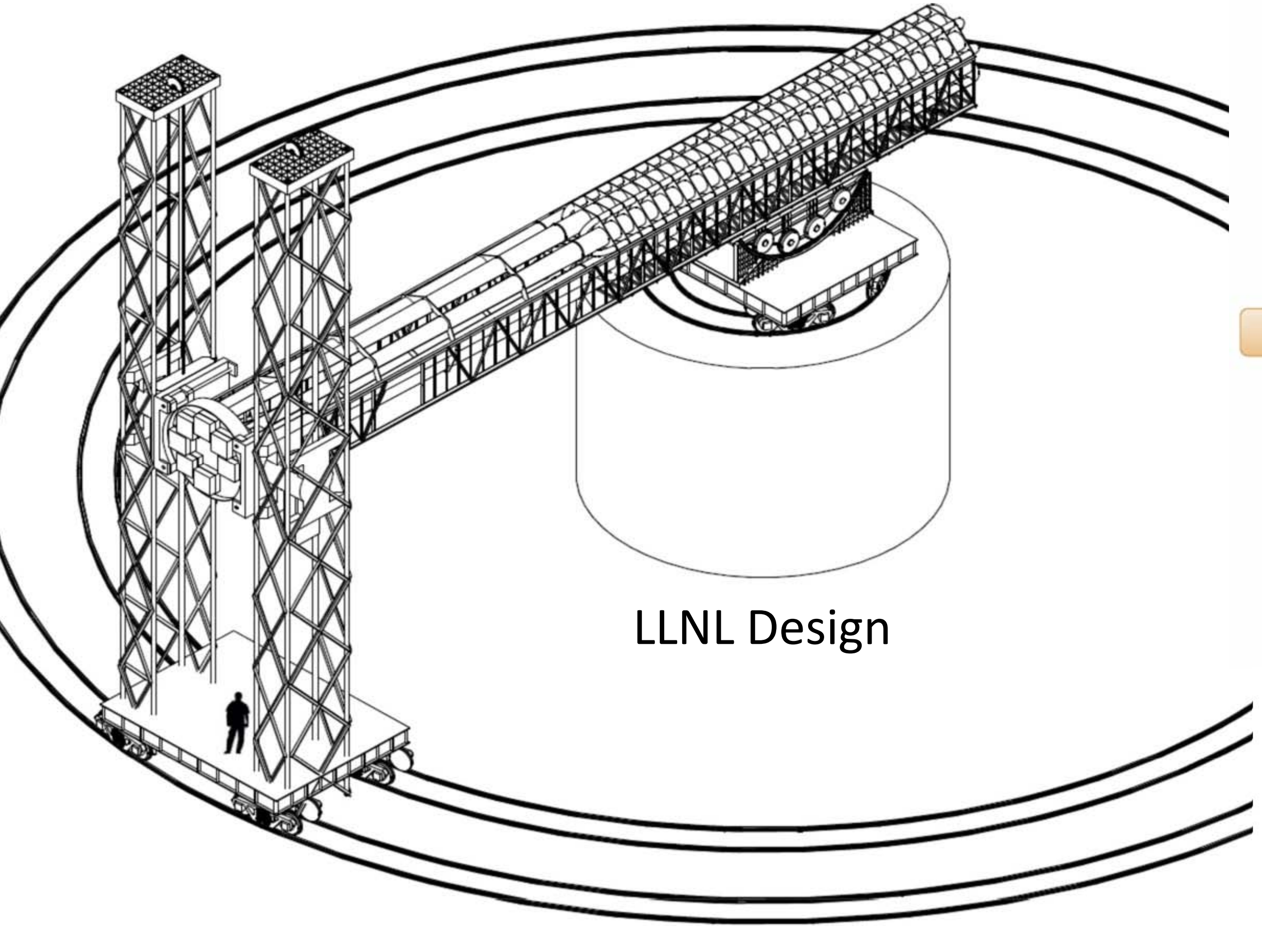


Solar neutrino limit

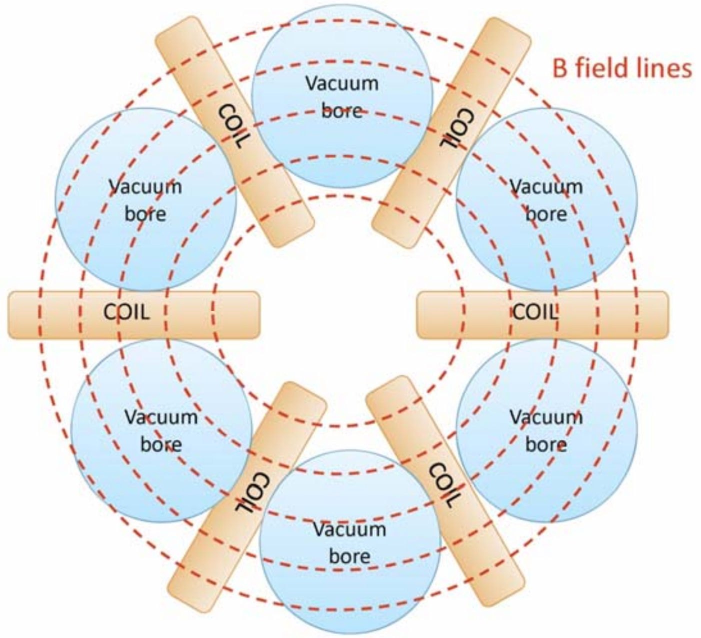
First experimental crossing of the KSVZ line

CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): JCAP 0902 (2009) 008
CAST-II results (He-3 filling, range 1): PRL 107 (2011) 261302

Next Generation Axion Helioscope (IAXO)

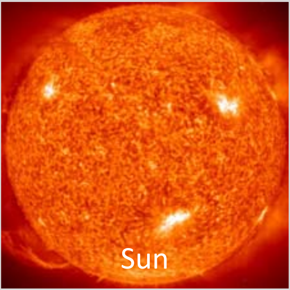


LLNL Design



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

Irastorza et al., "Towards a new generation axion helioscope", arXiv:1103.5334


Sun

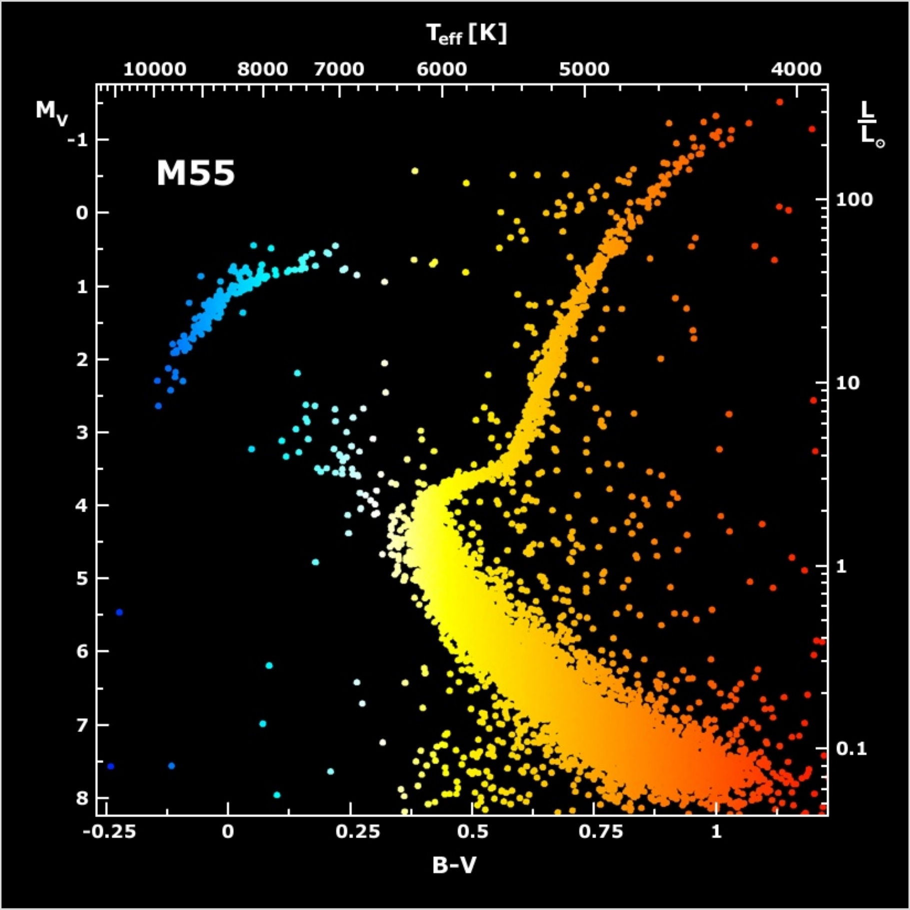

Globular Cluster


Supernova 1987A

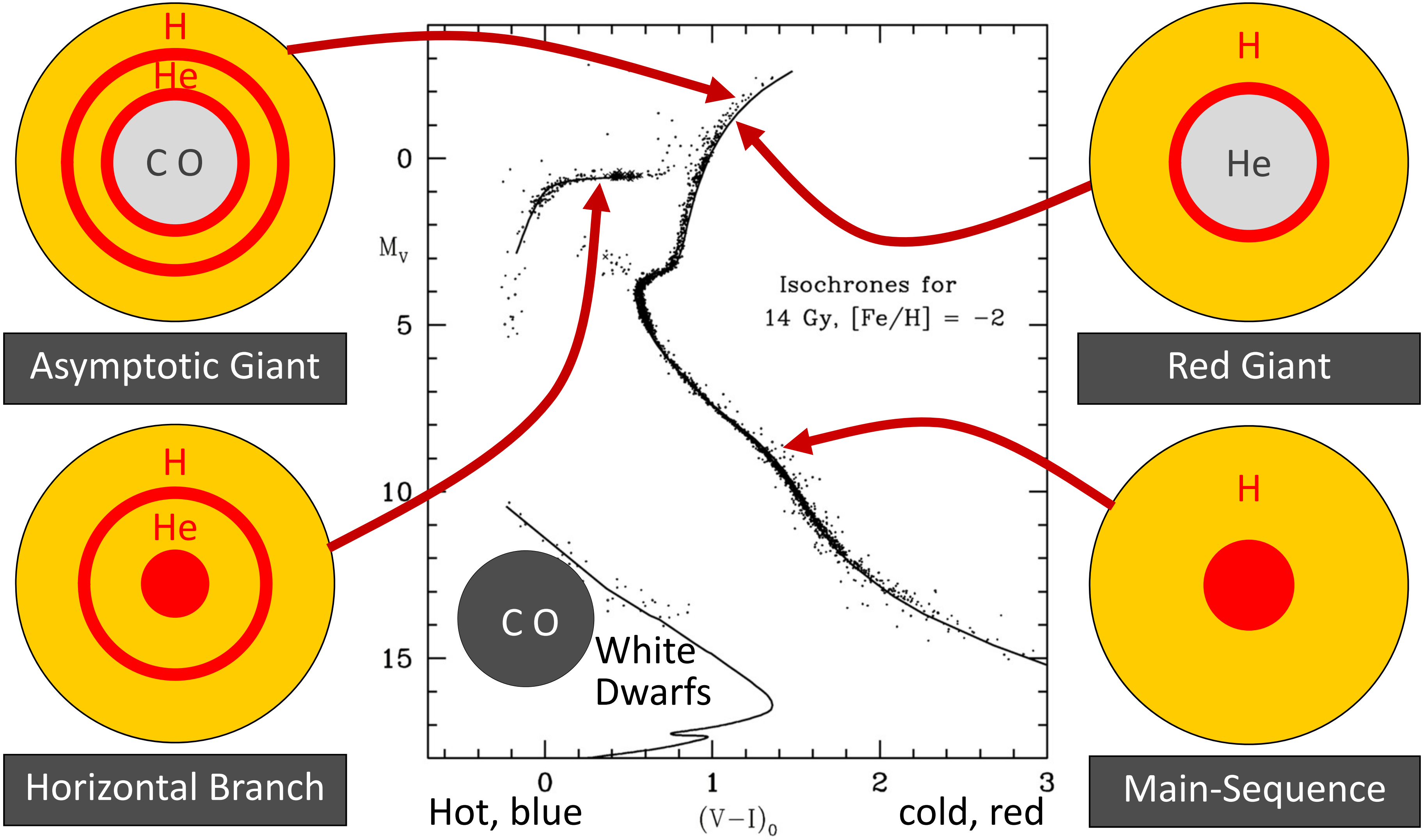

Dark Matter

Axions from Normal Stars

Galactic Globular Cluster M55



Color-Magnitude Diagram for Globular Clusters



Asymptotic Giant

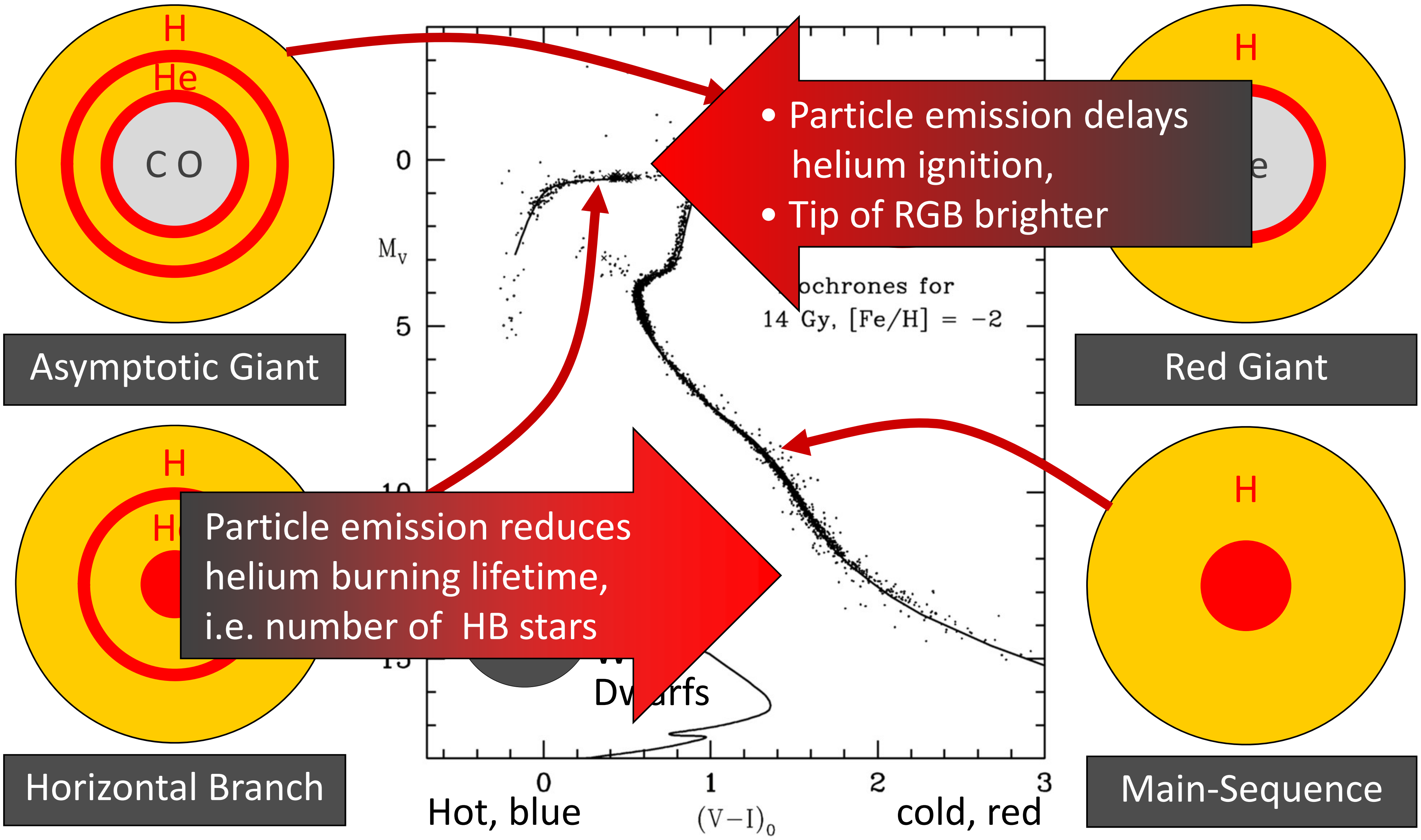
Horizontal Branch

Red Giant

Main-Sequence

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters



- Particle emission delays helium ignition,
- Tip of RGB brighter

Asymptotic Giant

Red Giant

Particle emission reduces helium burning lifetime, i.e. number of HB stars

Horizontal Branch

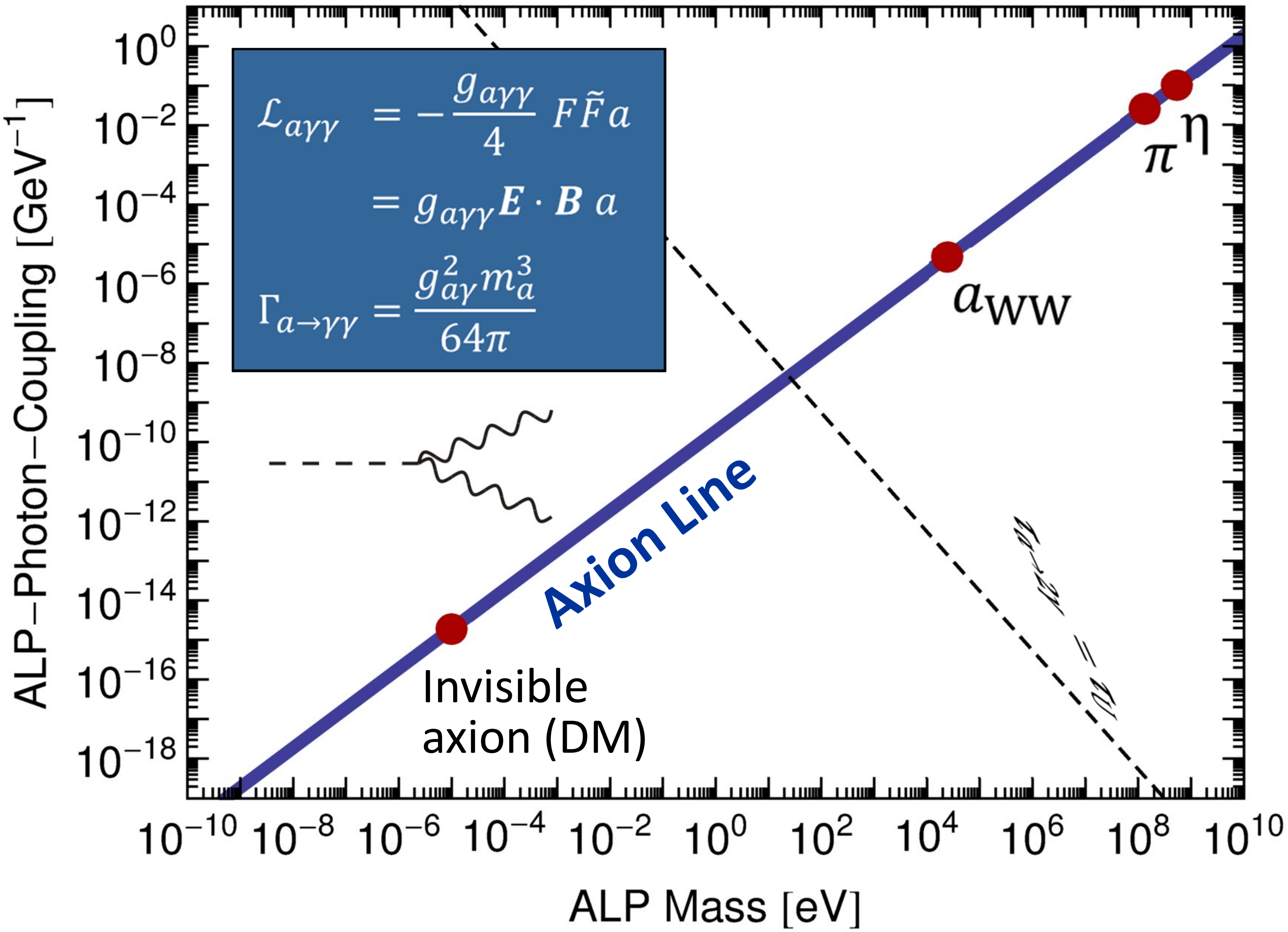
Main-Sequence

Hot, blue

cold, red

Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

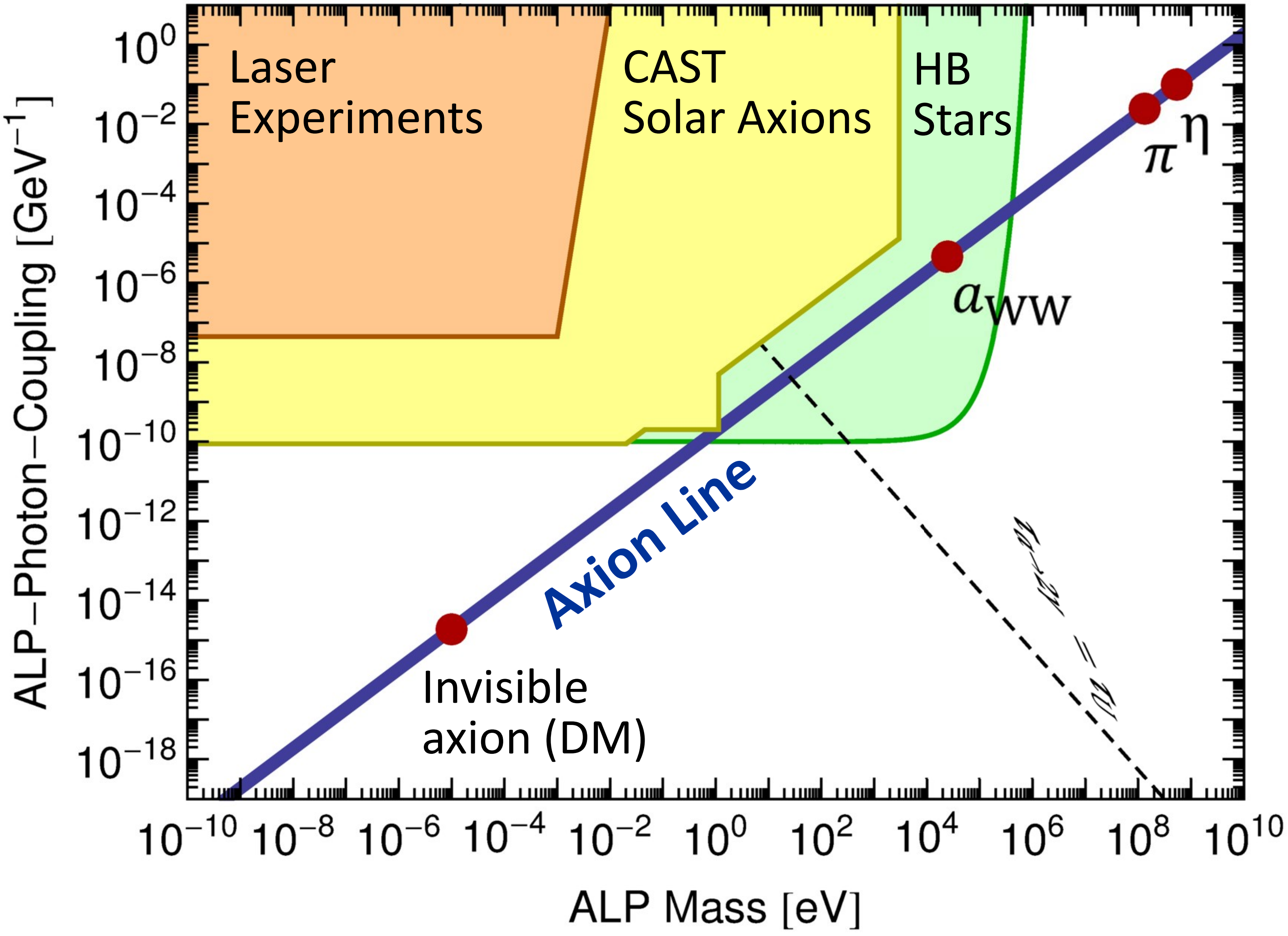
Parameter Space for Axion-Like Particles (ALPs)



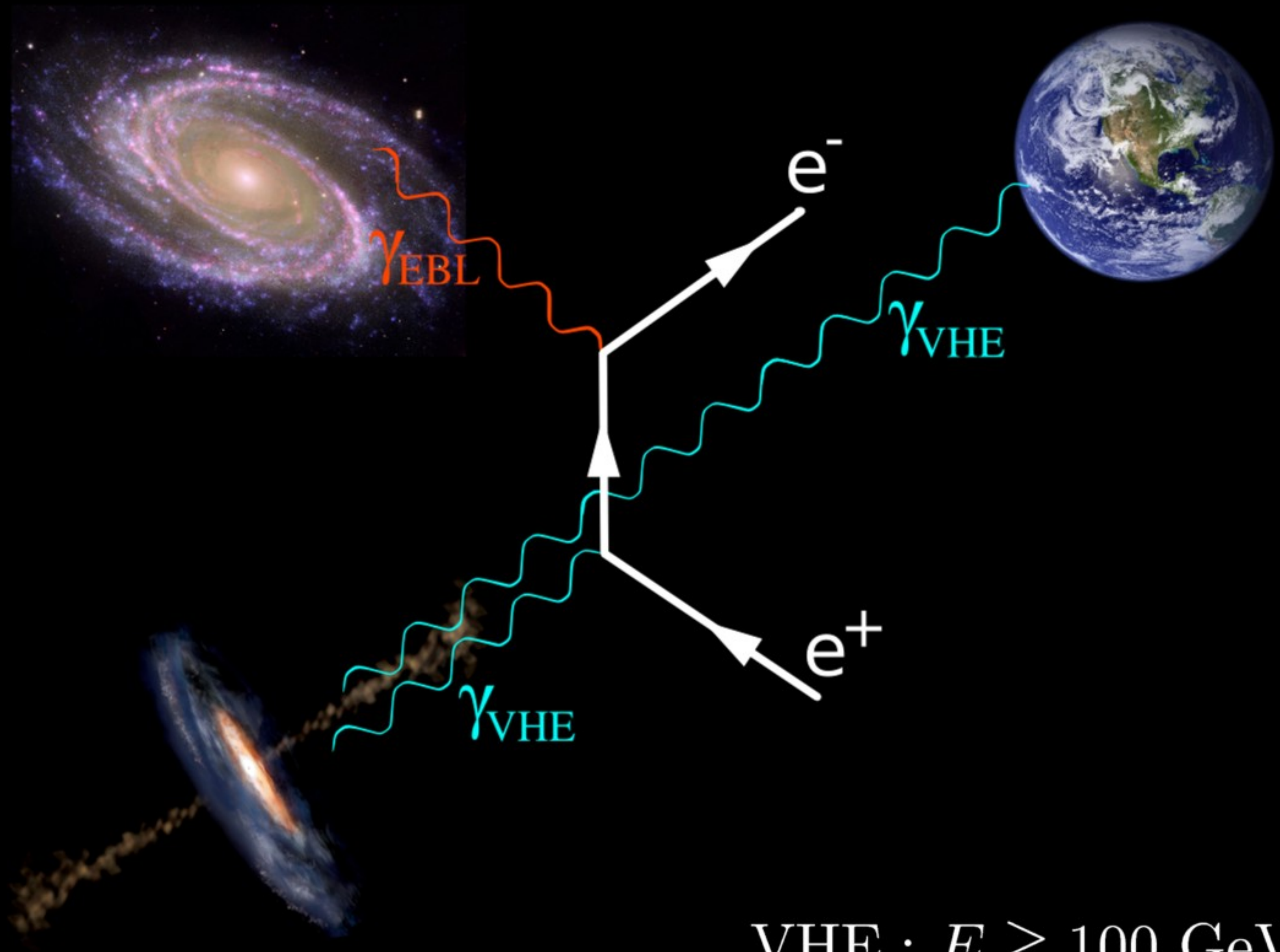
$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} F\tilde{F}a = g_{a\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}\,a$$

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

Parameter Space for Axion-Like Particles



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

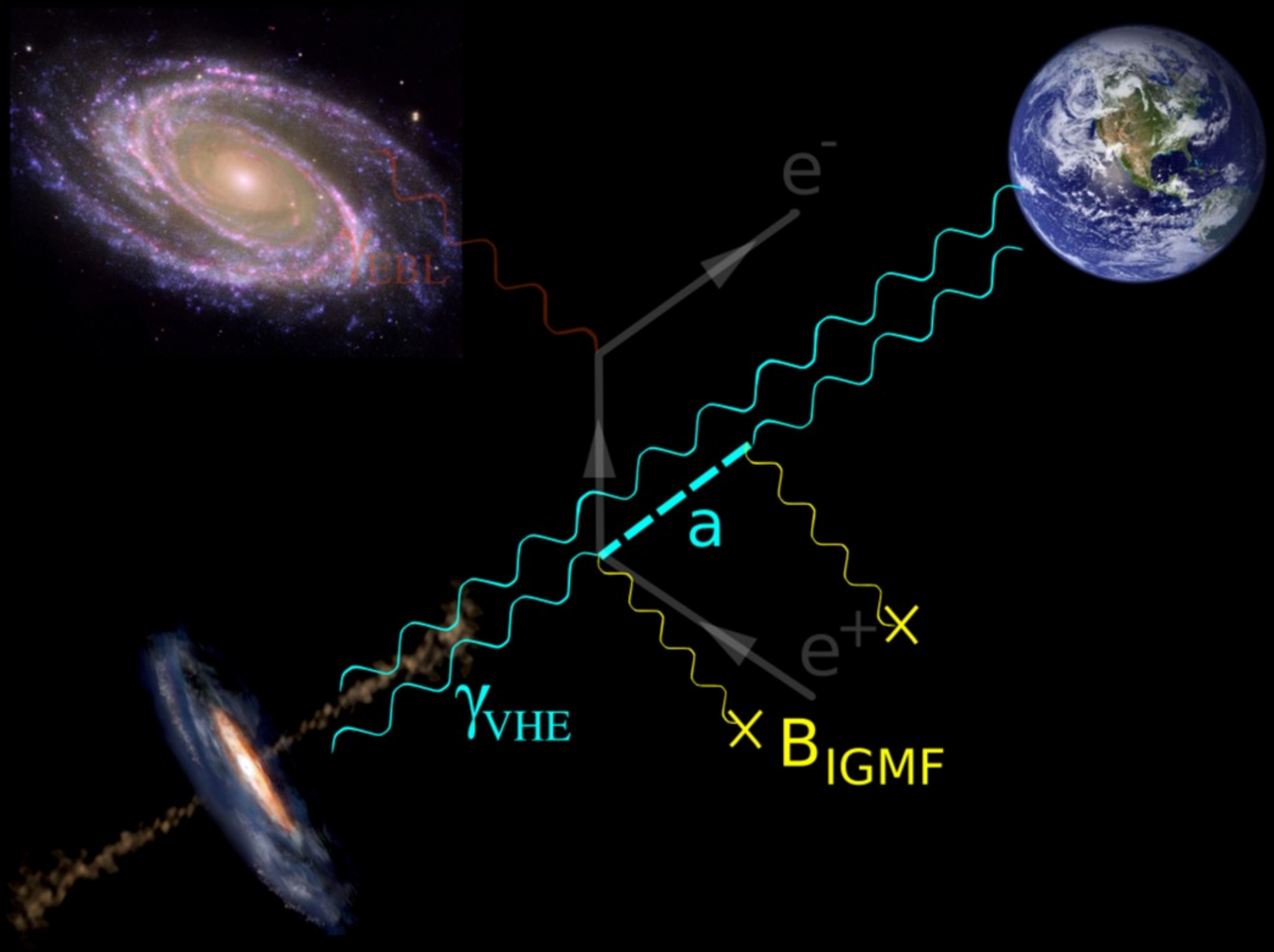
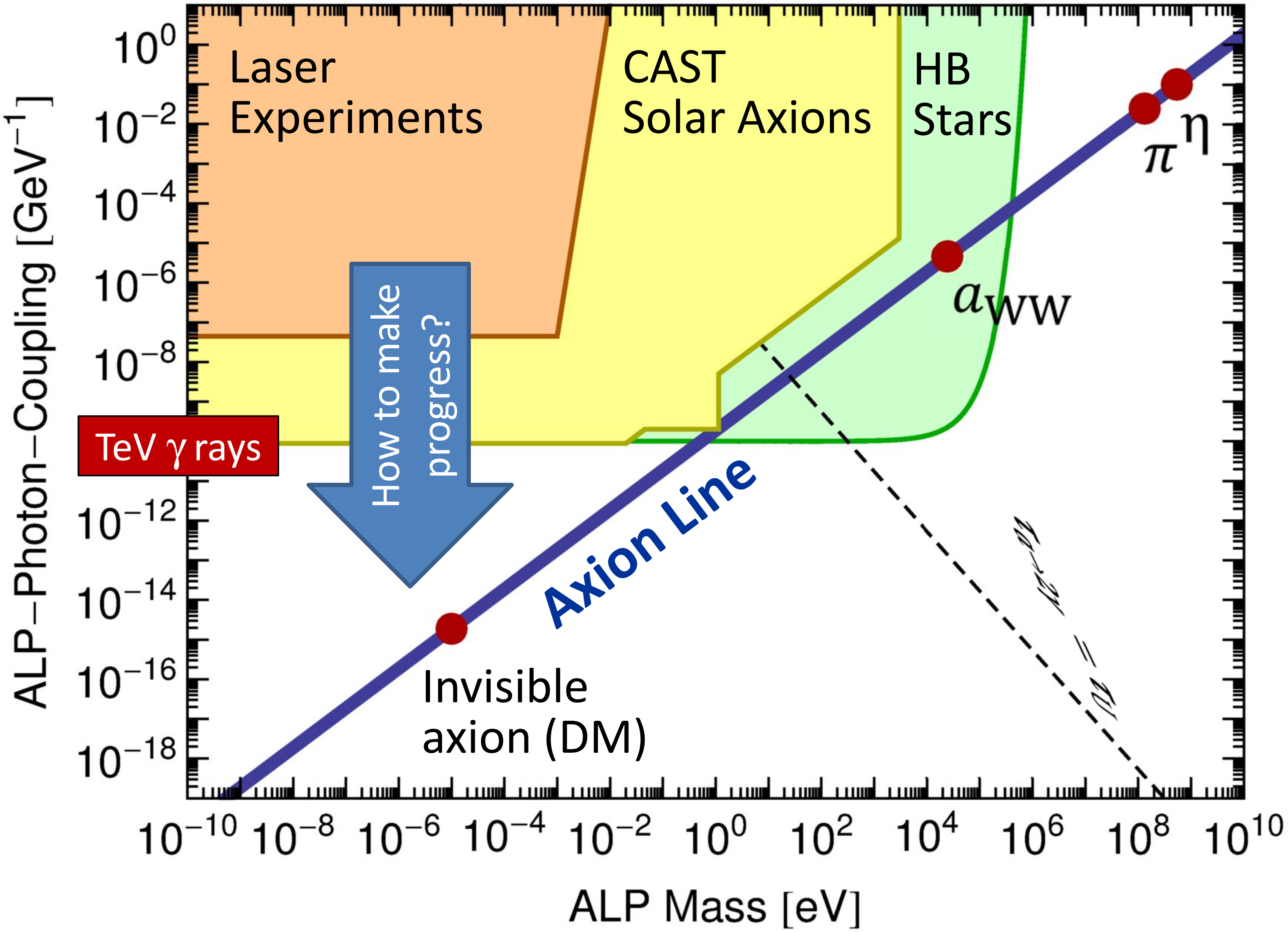


Figure from a talk by Manuel Meyer (Univ. Hamburg)

Parameter Space for Axion-Like Particles




Sun


Globular Cluster


Supernova 1987A


Dark Matter

SN 1987A Neutrino Signal

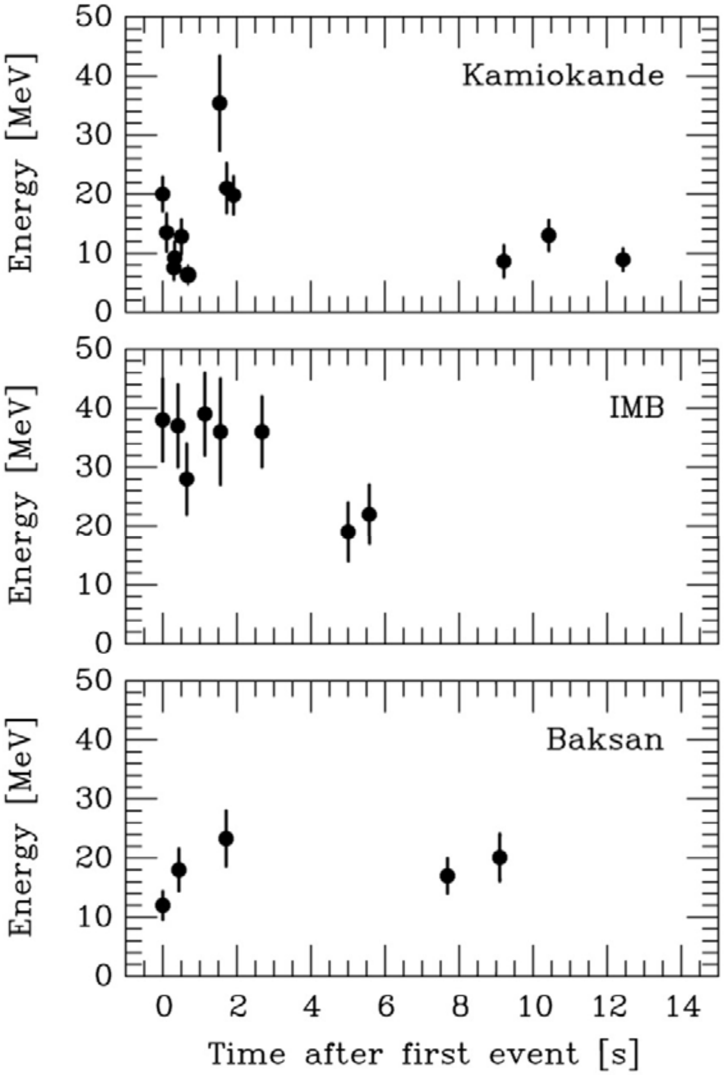
Sanduleak –69 202

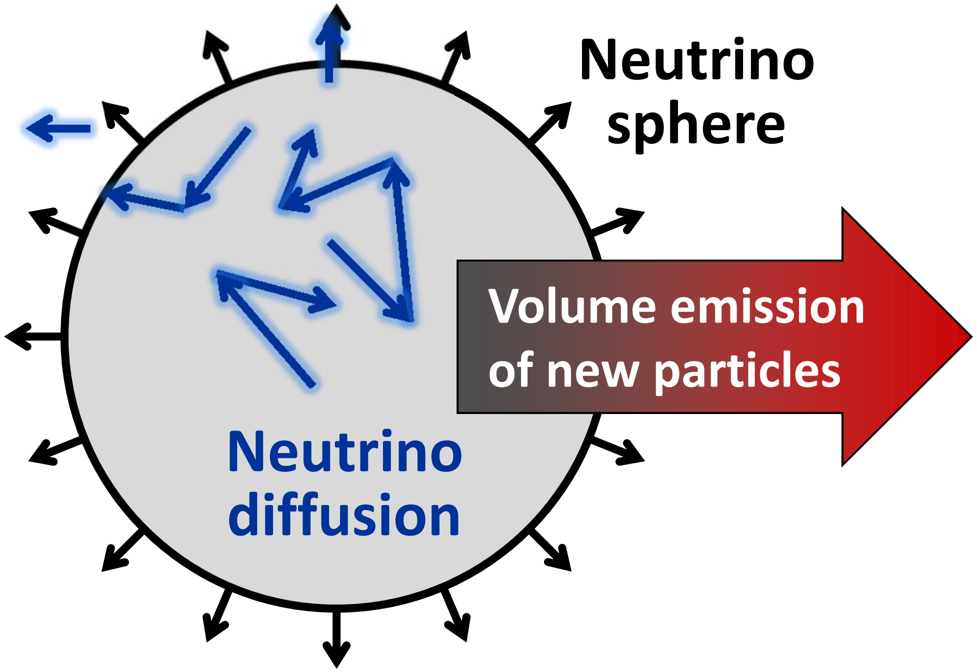
Supernova 1987A

23 February 1987

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal



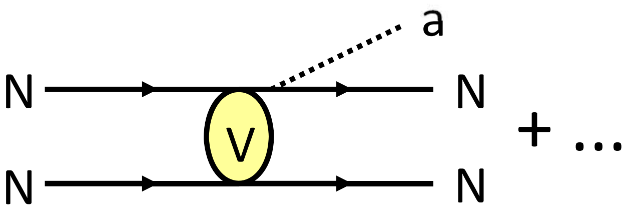


Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axion Emission from a Nuclear Medium

Axion-nucleon interaction: $\mathcal{L}_{\text{int}} = \frac{C_N}{2f_a}\,\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a = \frac{C_N}{2f_a}J_\mu^A\partial_a^\mu$



Nucleon-Nucleon
Bremsstrahlung

Energy-loss rate (erg cm^{-3} s^{-1})

$$Q = \int d\Gamma_a \int d\Gamma_{\text{Nucleons}} |\mathcal{M}|^2 \omega \quad \text{(axion energy } \omega\text{)}$$

$$= \left(\frac{C_N}{2f_a}\right)^2 \frac{n_B}{4\pi^2}\int_0^\infty d\omega\,\omega^4 S(-\omega)$$

Dynamical structure function, in nonrelativistic limit correlator of nucleon spin density operator

$$S(\omega,k) = \frac{4}{3n_B}\int_{-\infty}^{+\infty} dt\, e^{i\omega t}\,\langle\boldsymbol{\sigma}(t,k)\cdot\boldsymbol{\sigma}(0,k)\rangle$$

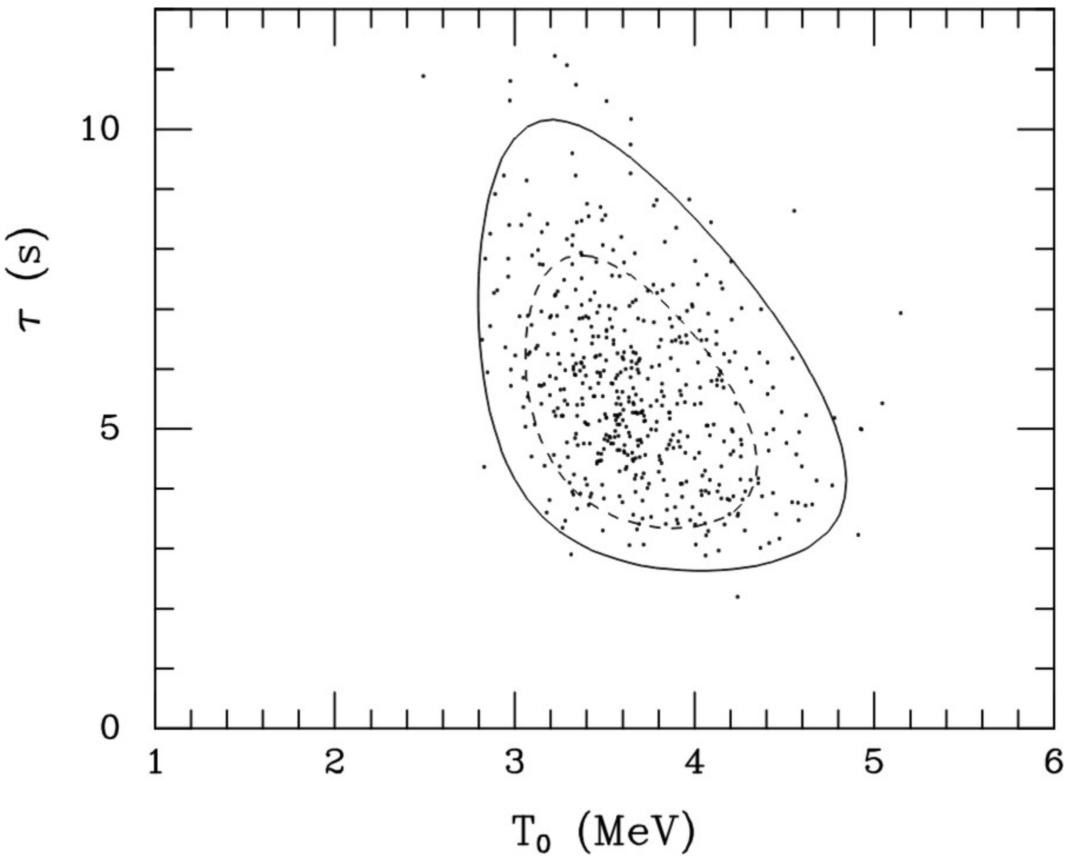
Early calculations using one-pion exchange potential without many body effects or multiple-scattering effects over-estimated emission rate, see e.g.

- Janka, Keil, Raffelt & Seckel, PRL 76:2621,1996.
- Hanhart, Phillips & Reddy, PLB 499:9, 2001.
- Bacca, Hally, Liebendörfer, Perego, Pethick & Schwenk, arXiv:1112.5185 (2011).

Cooling Time Scale

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

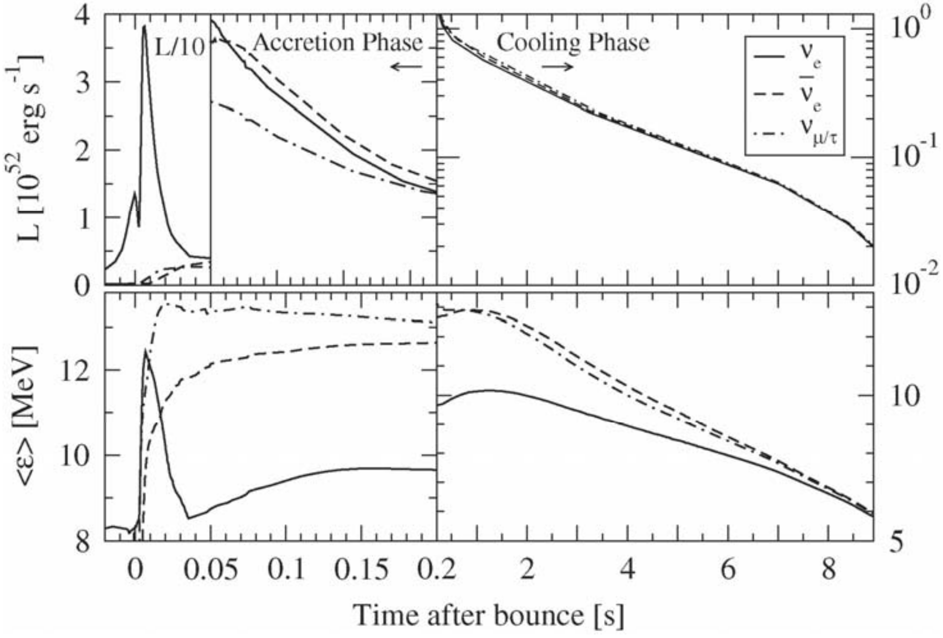
Fit parameters are T_0, τ, radius, 3 offset times for KII, IMB & BST detectors



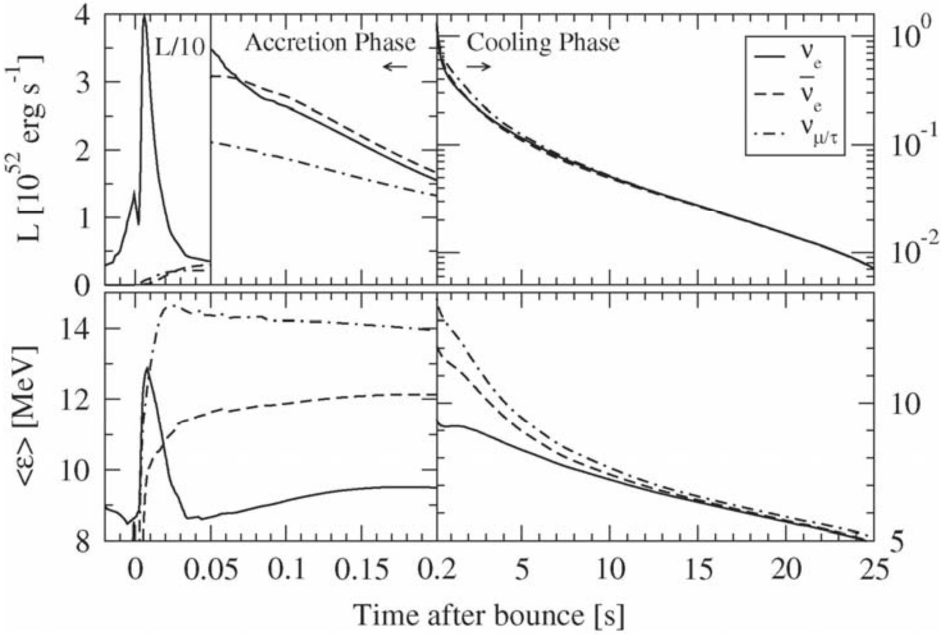
Loredo and Lamb, Bayesian analysis
astro-ph/0107260

Long-Term Cooling of EC SN (Garching 2009)

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

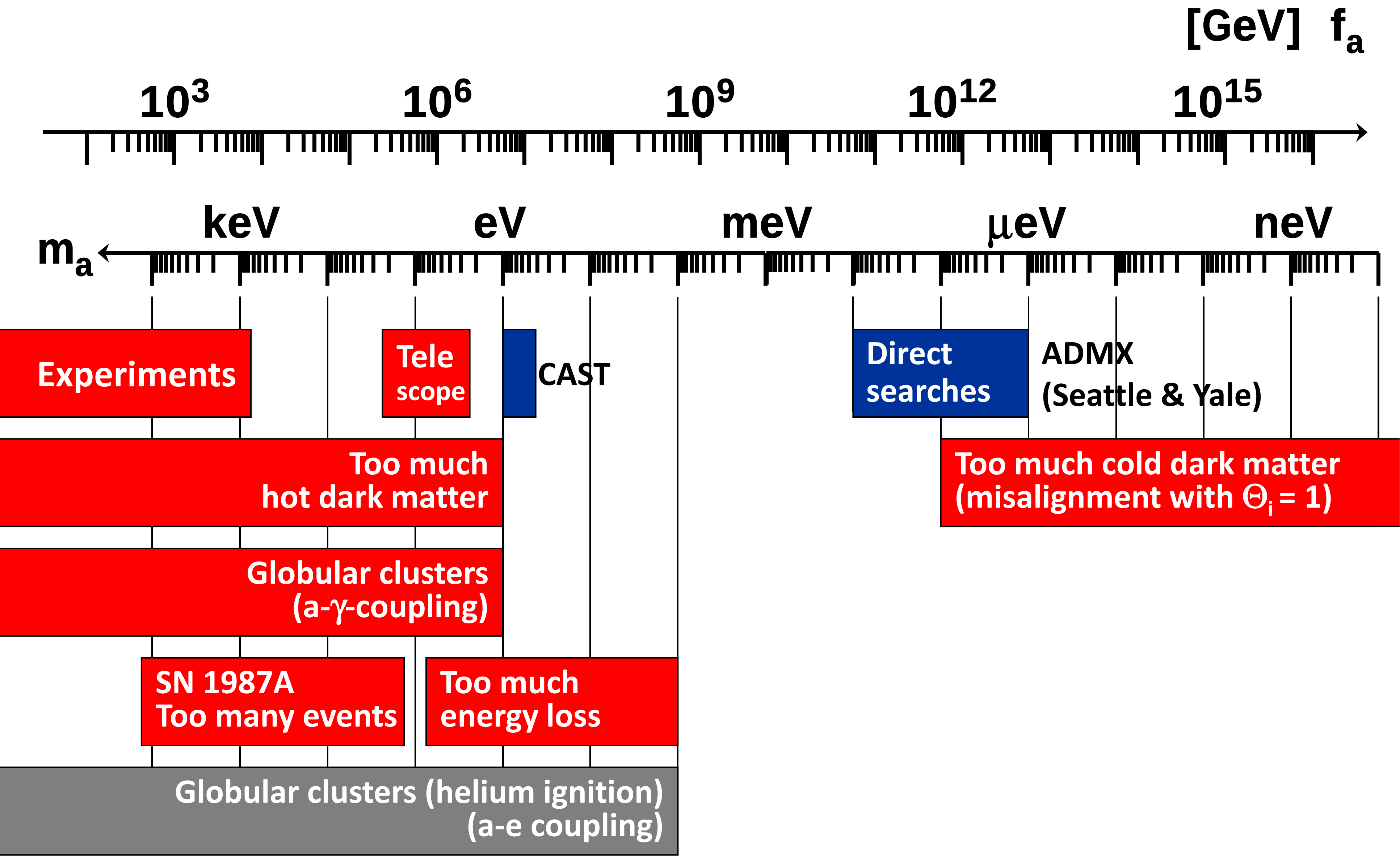


Neutrino opacities without these effects (~ Basel case?)
Much longer cooling times



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

Axion Bounds and Searches



Experiments

Tele scope

CAST

Direct searches

ADMX (Seattle & Yale)

Too much hot dark matter

Too much cold dark matter (misalignment with $\Theta_i = 1$)

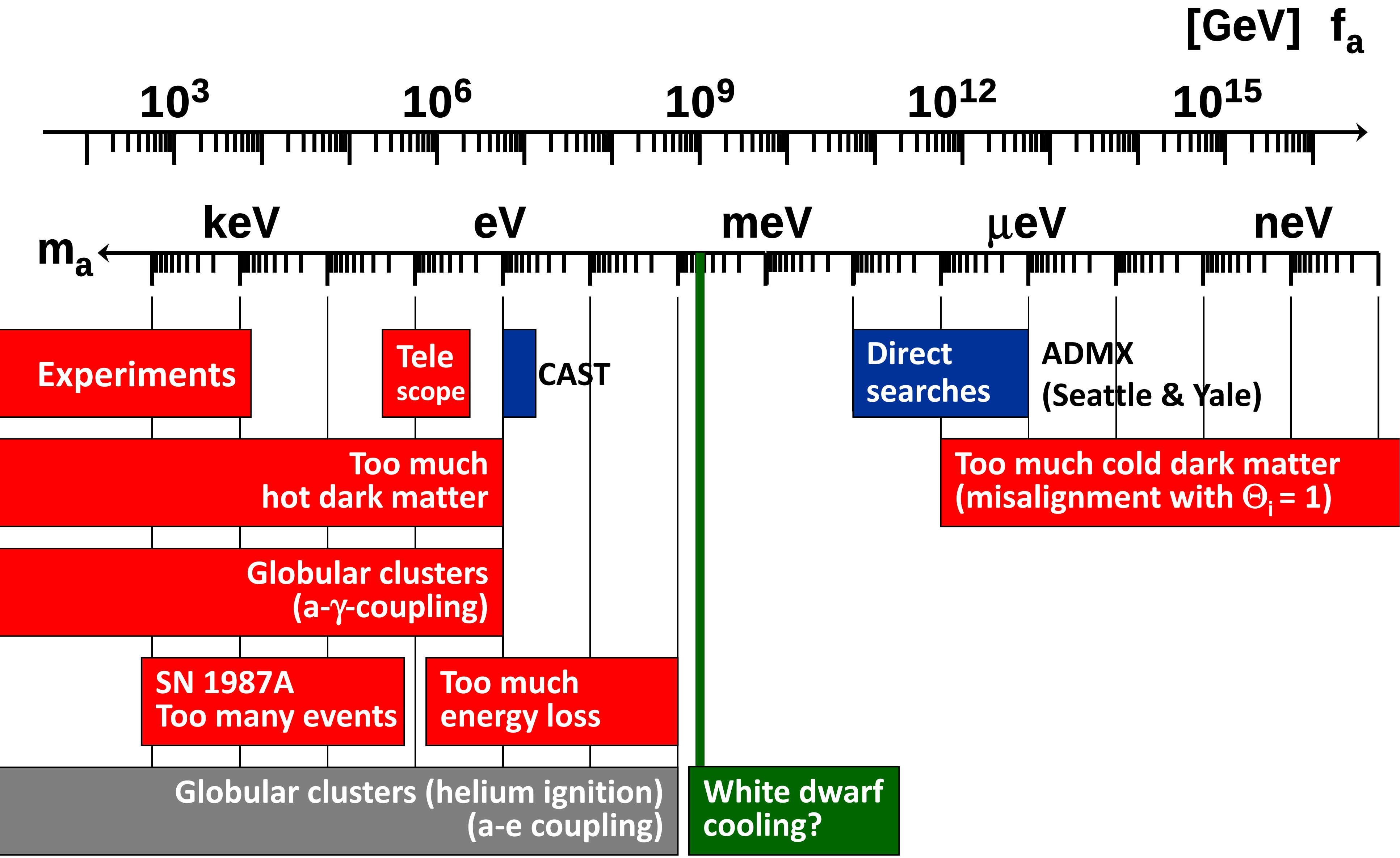
Globular clusters (a-γ-coupling)

SN 1987A Too many events

Too much energy loss

Globular clusters (helium ignition) (a-e coupling)

Axion Bounds and Searches



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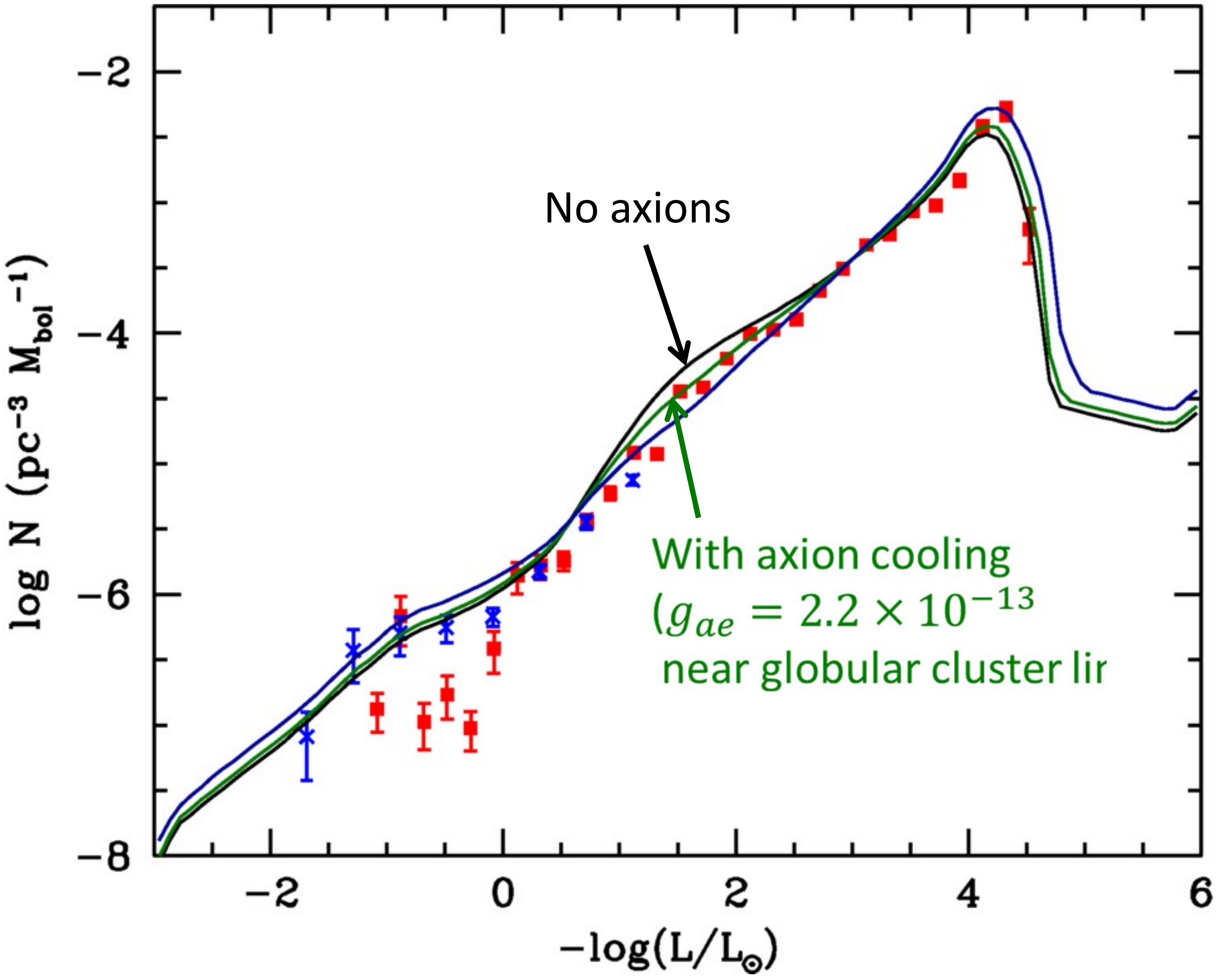
White dwarf cooling?

Do White Dwarfs Need Axion Cooling?



With axion cooling ($g_{ae} = 2.2 \times 10^{-13}$

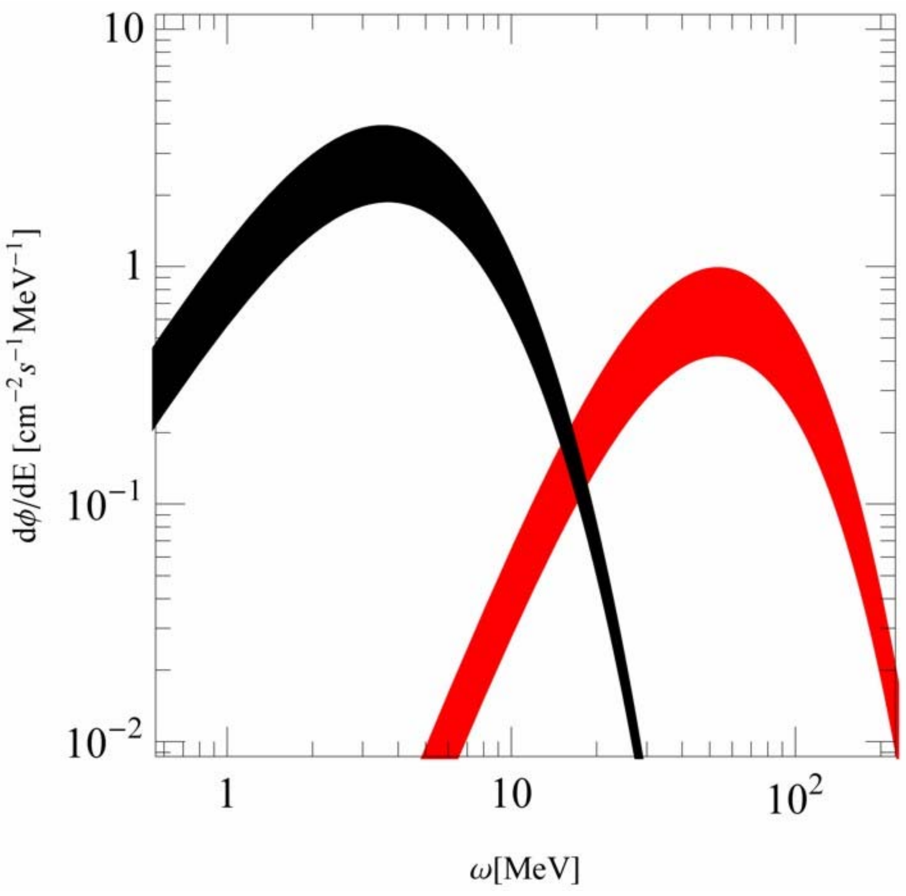
near globular cluster lir

White dwarf luminosity function (number of WDs per brightness interval)

Isern et al., arXiv:1204.3565

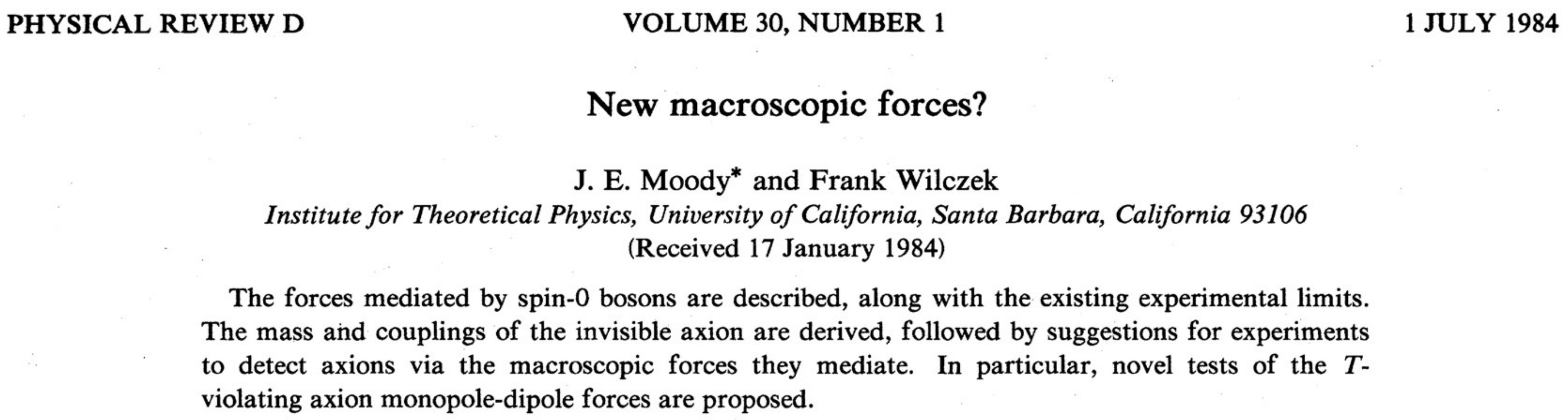
Diffuse Supernova Axion Background (DSAB)

- 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 $m_a \sim 10$ meV near SN 1987A energy-loss limit
- Provide DSAB with compable energy density as DSNB and EBL
- No obvious detection channel

Raffelt, Redondo & Viaux
work in progress (2011)

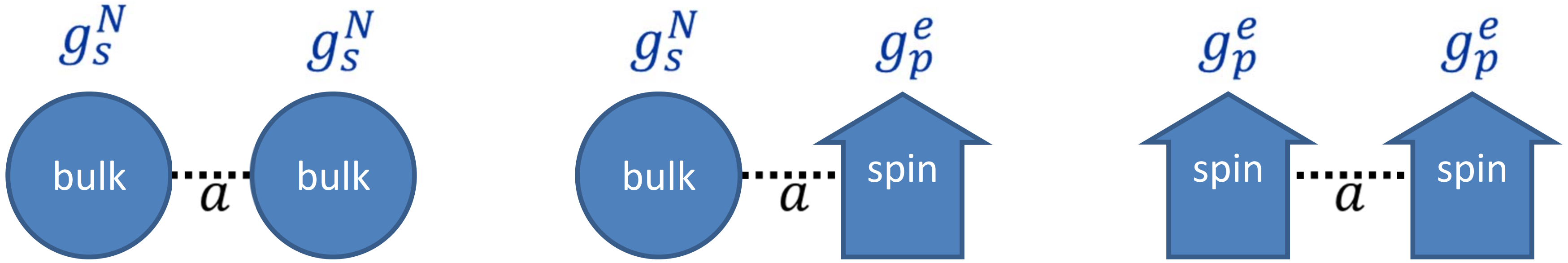


PHYSICAL REVIEW D VOLUME 30, NUMBER 1 1 JULY 1984

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 $(g_s^N)^2$

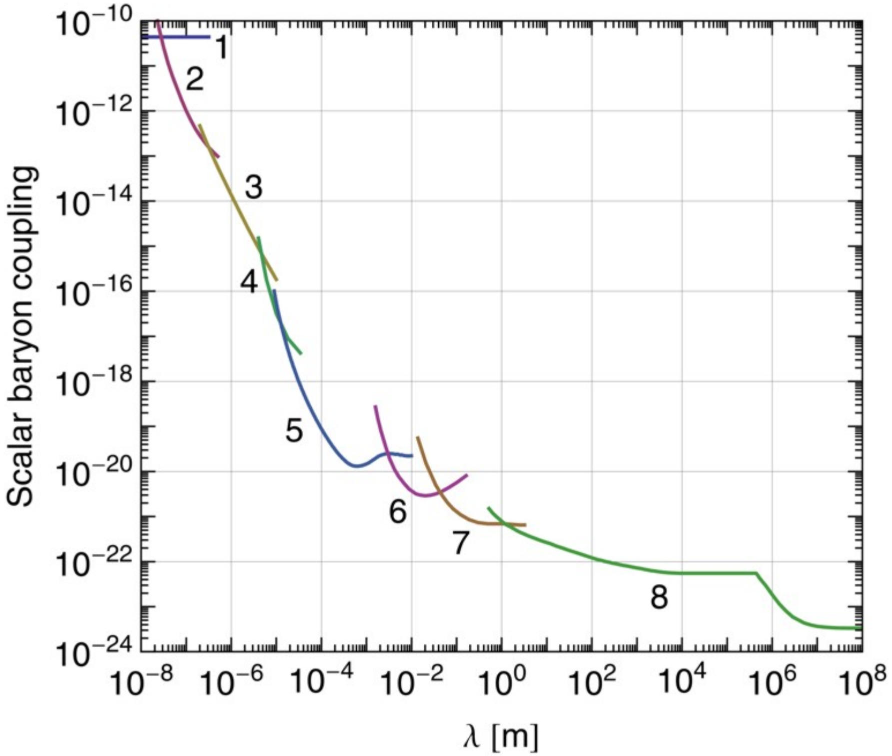
Torsion balance using
polarized electron spins
Axion couplings $g_s^N g_p^e$
T-violating force

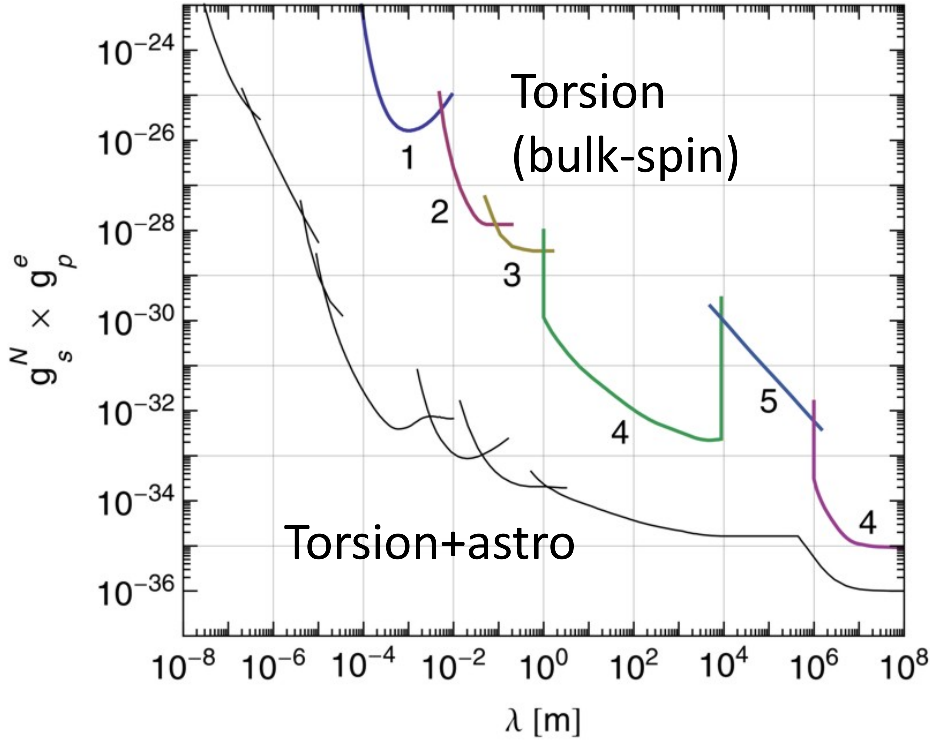
Spin-spin forces
hard to measure
Axion couplings $(g_s^e)^2$

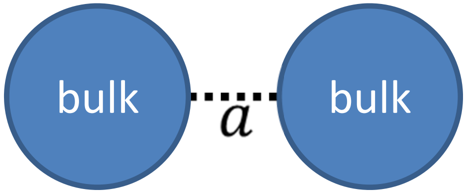
Long-Range Force Experiments

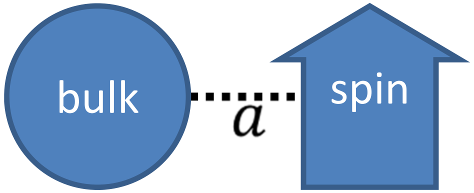
Long-range force limits from tests of Newton's law and equivalence principle (Mostly from Eöt-Wash Group, Seattle)

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

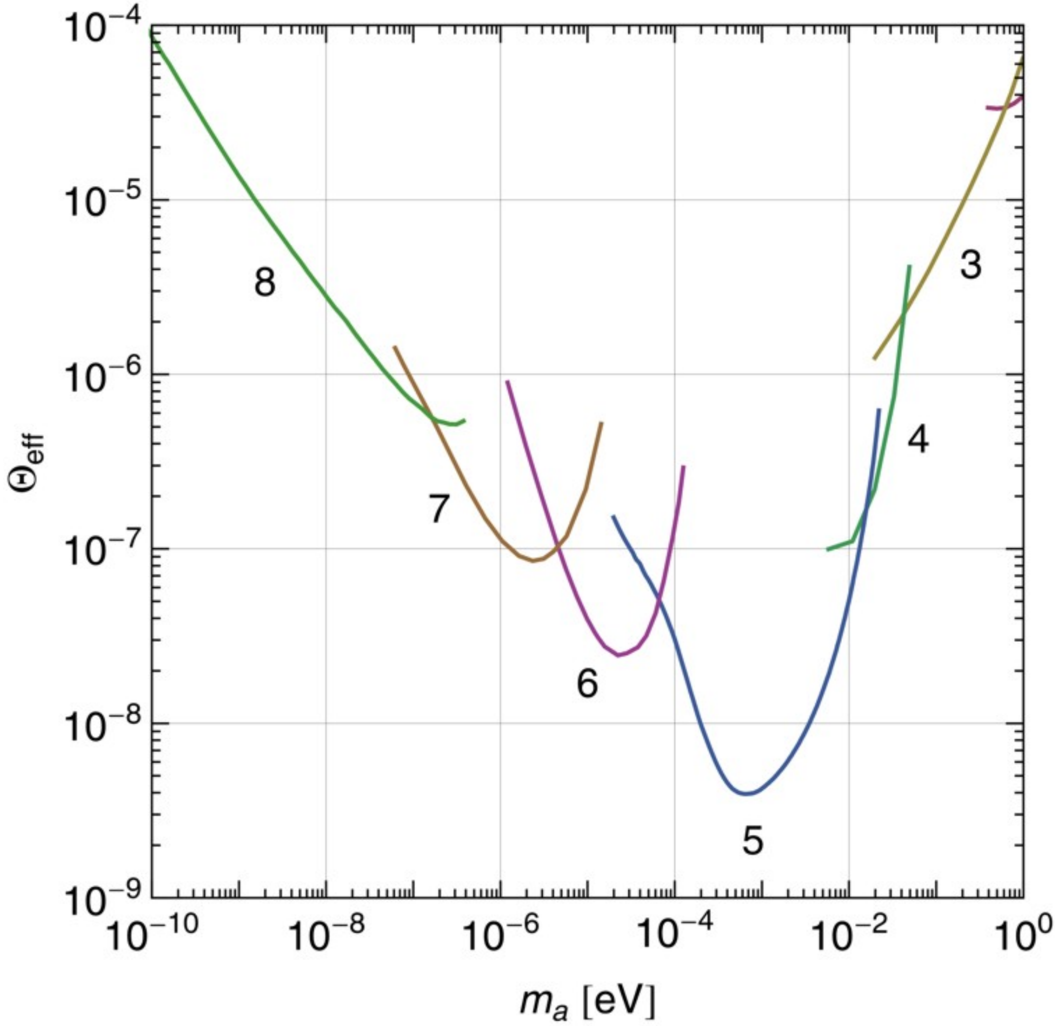








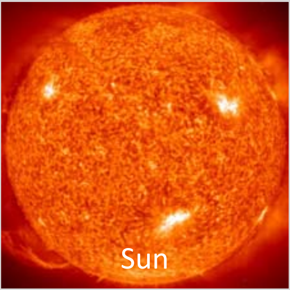
Limits on CP Violation from Long-Range Forces



Assume axion scalar CP-violating force with nucleons

$$g_s^N = \Theta_{\rm eff}\frac{f_\pi}{f_a} \sim \Theta_{\rm eff}\frac{m_a}{m_\pi}$$

Eöt-Wash constraint provides best limit around $m_a \sim 1\,\text{meV}$


Sun


Globular Cluster

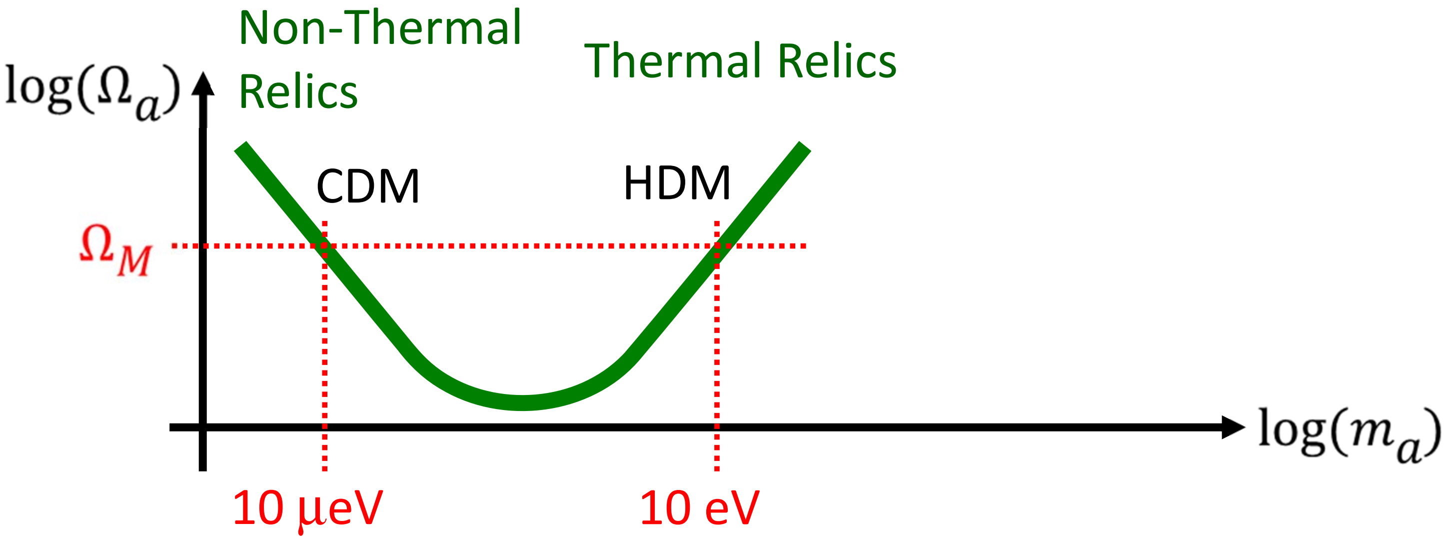

Supernova 1987A


Dark Matter

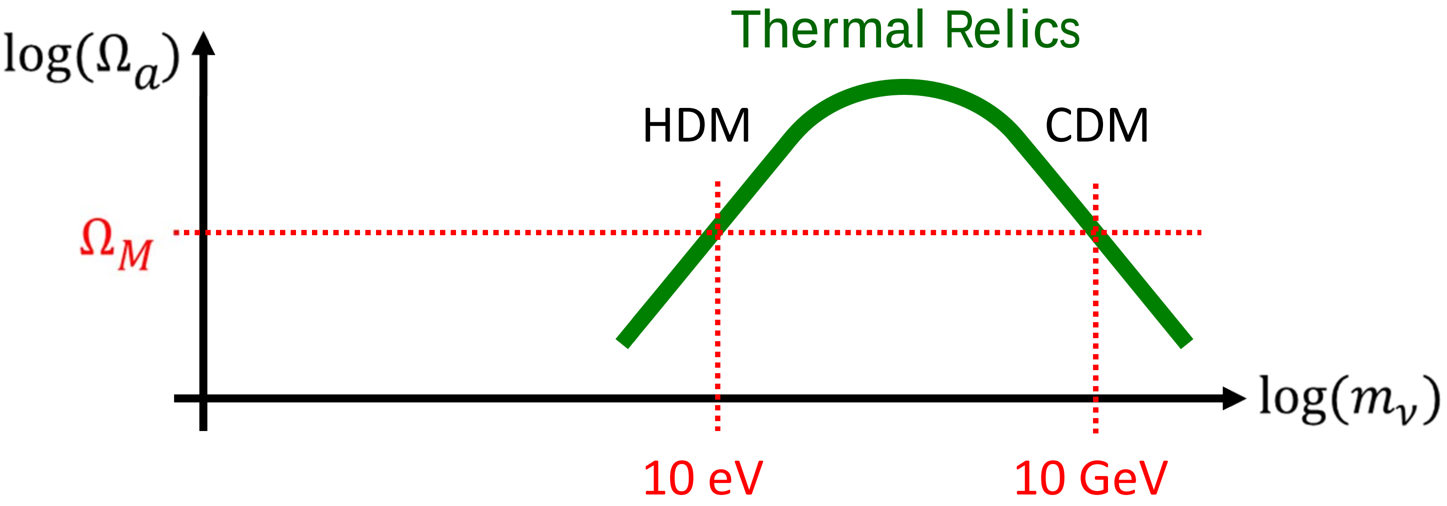
Cosmological Constraints

Lee-Weinberg Curve for Neutrinos and Axions

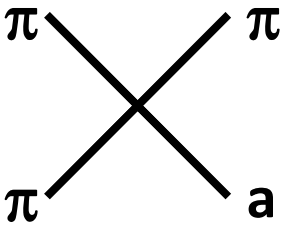
Axions



Neutrinos
& WIMPs

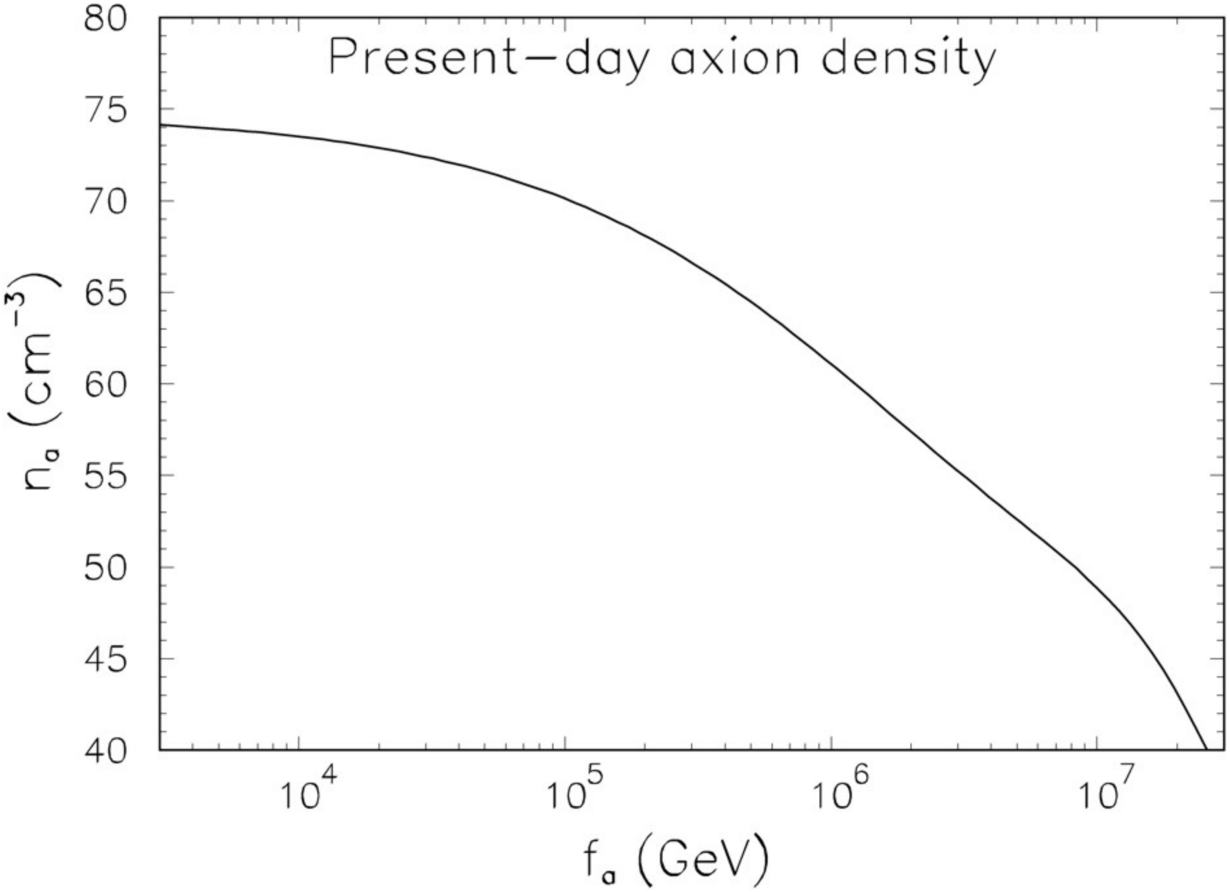


Axion Hot Dark Matter from Thermalization after $\Lambda_{\rm QCD}$



$$L_{a\pi} = \frac{C_{a\pi}}{f_a f_\pi}\left(\pi^0\pi^+\partial_\mu\pi^- + \pi^0\pi^-\partial_\mu\pi^+ - 2\pi^+\pi^-\partial_\mu\pi^0\right)\partial^\mu a$$

Chang & Choi, PLB 316 (1993) 51



Hannestad, Mirizzi & Raffelt, hep-ph/0504059

Neutrino and Axion Hot Dark Matter Limits

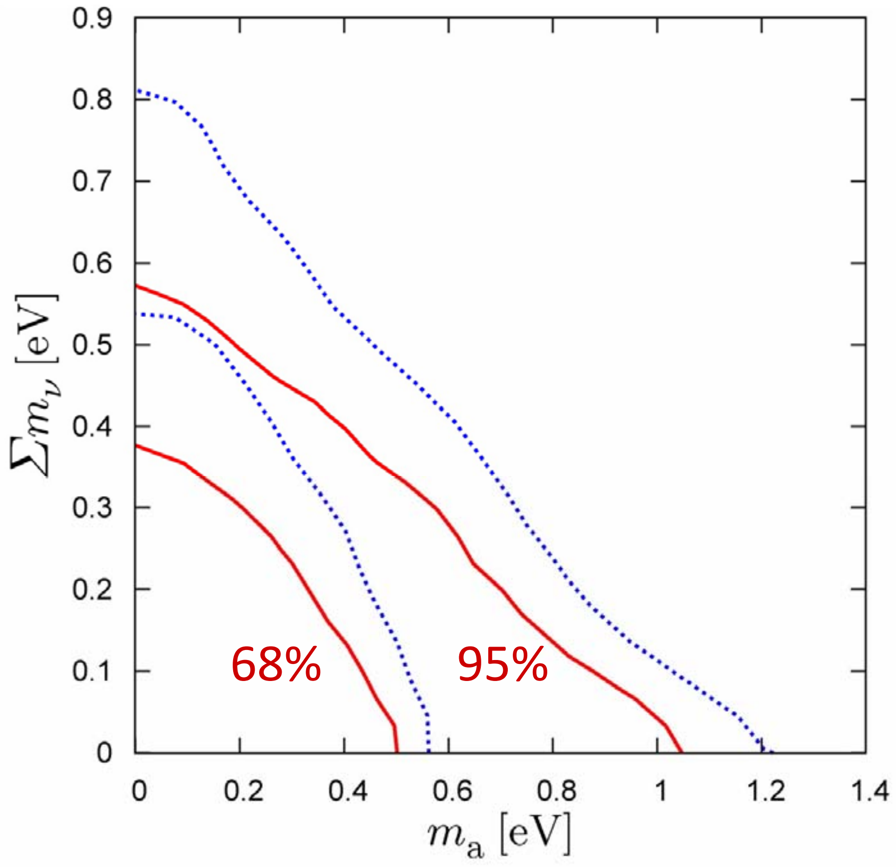


Figure 1. 2D marginal 68% and 95% contours in the $\sum m_\nu$–m_a plane. The blue lines correspond to our results using CMB+HPS, and the red lines using CMB+HPS+HST.

Credible regions for neutrino plus axion hot dark matter
(WMAP-7, SDSS, HST)
Hannestad, Mirizzi, Raffelt & Wong
[arXiv:1004.0695]

Marginalizing over neutrino hot dark matter component

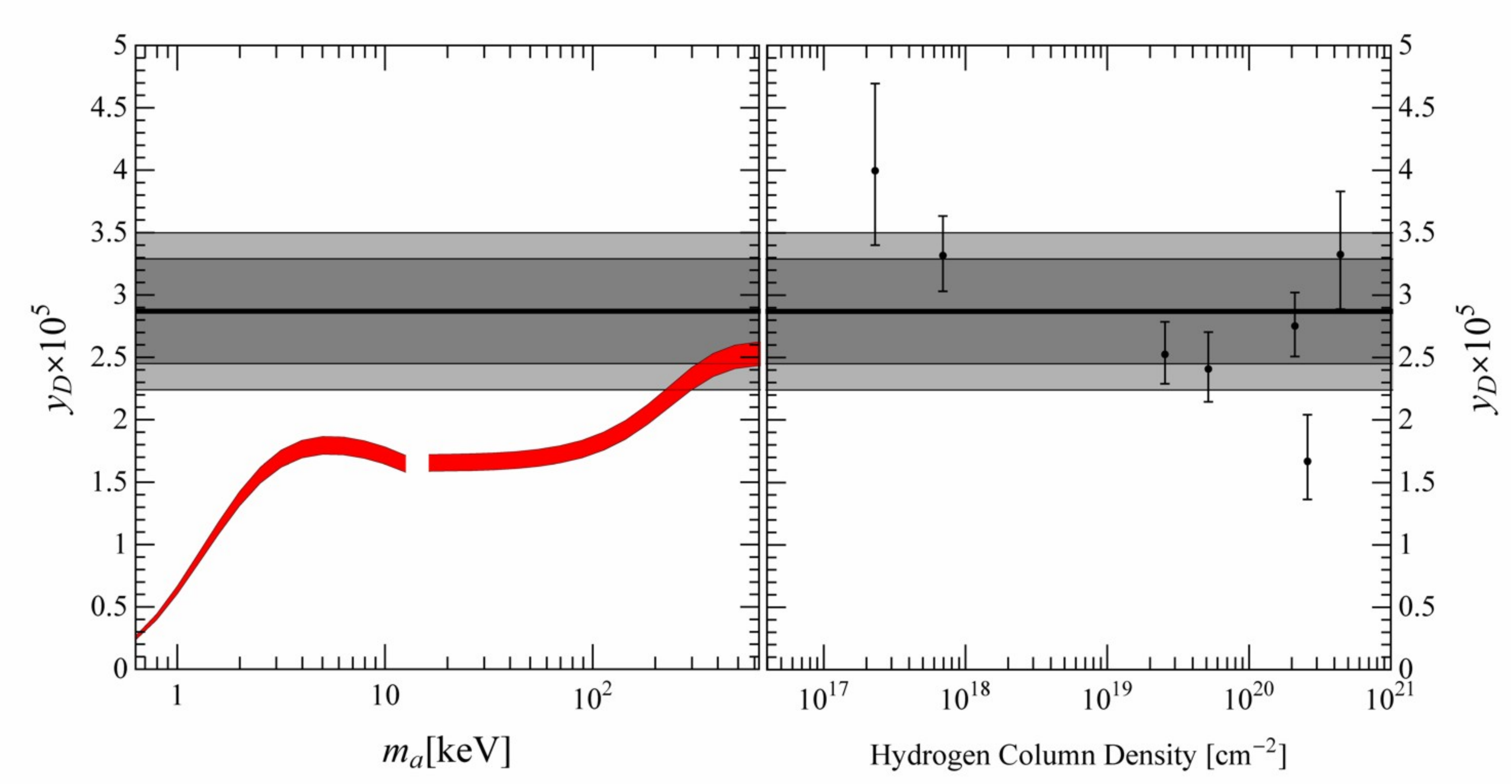
$$m_a < 0.7\ \text{eV}\ \ (95\%\ \text{CL})$$

Assuming no axions

$$\sum m_\nu < 0.4\ \text{eV}\ \ (95\%\ \text{CL})$$

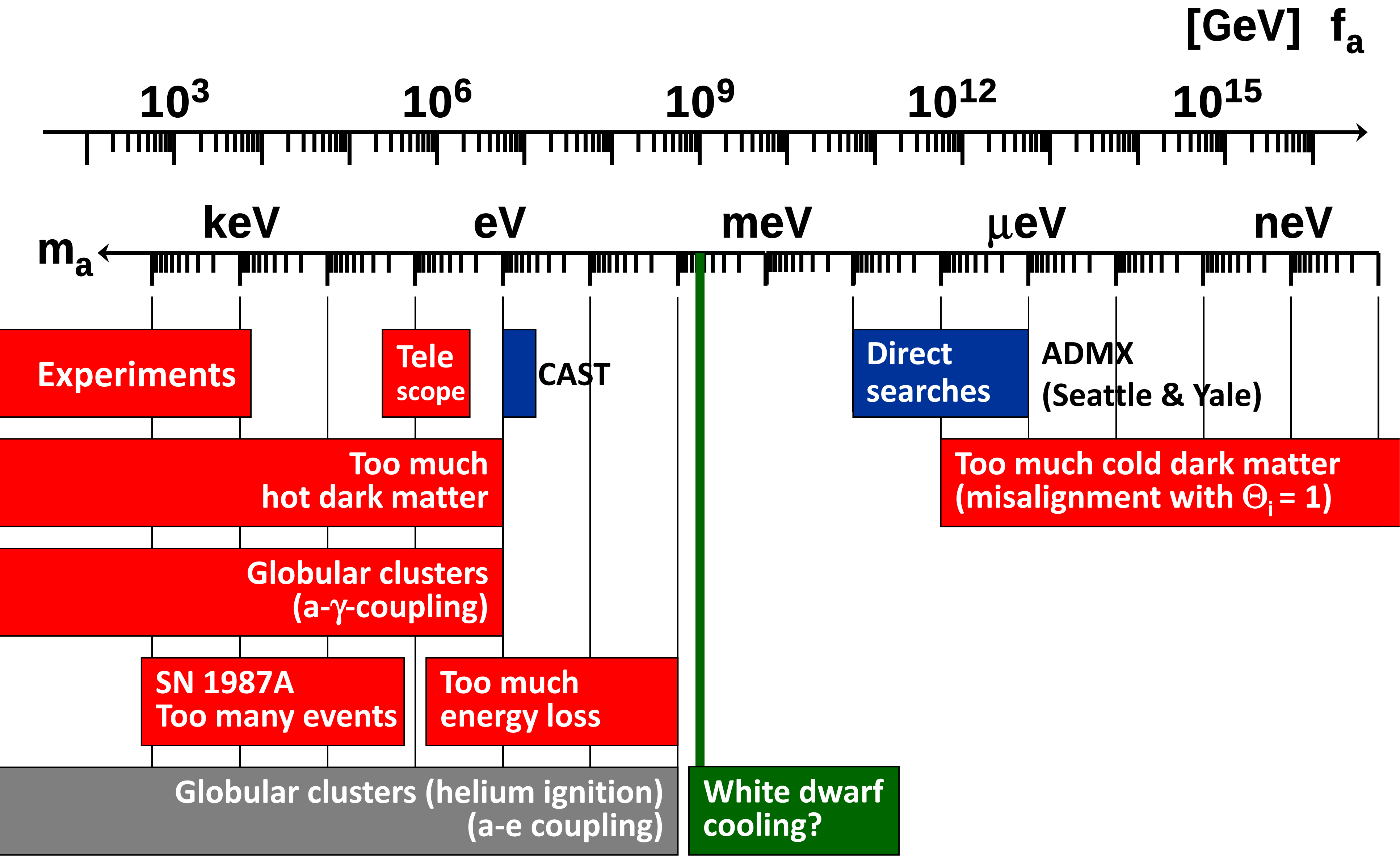
BBN limits on sub-MeV mass axions

- Axions essentially in thermal equilibrium throughout BBN
- e^+e^- annihilation partly heats axions → missing photons
- Reduced photon/baryon fraction during BBN
- Reduced deuterium abundance, using WMAP baryon fraction



Cadamuro, Hannestad, Raffelt & Redondo, arXiv:1011.3694 (JCAP)

Axion Bounds and Searches



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Direct searches

ADMX (Seattle & Yale)

Too much hot dark matter

Too much cold dark matter (misalignment with $\Theta_i = 1$)

Globular clusters (a-γ-coupling)

SN 1987A Too many events

Too much energy loss

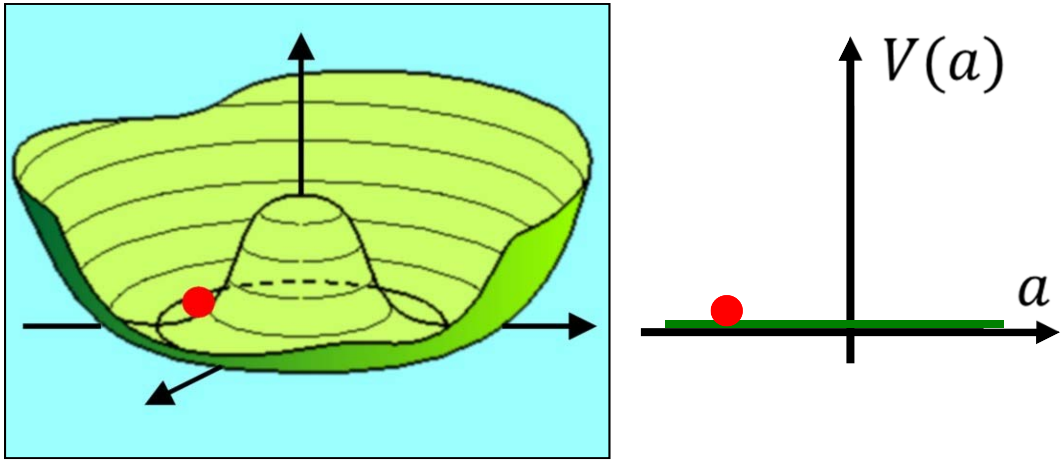
Globular clusters (helium ignition) (a-e coupling)

White dwarf cooling?

Creation of Cosmological Axions

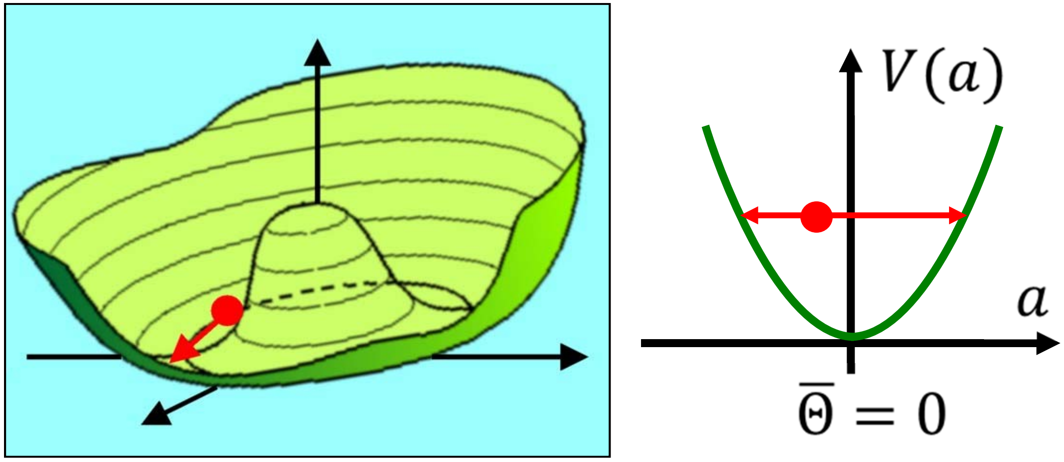
$T \sim f_a$ (very early universe)

- $U_{PQ}(1)$ 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

Cosmic Axion Density

Modern values for QCD parameters and temperature-dependent axion mass imply (Bae, Huh & Kim, arXiv:0806.0497)

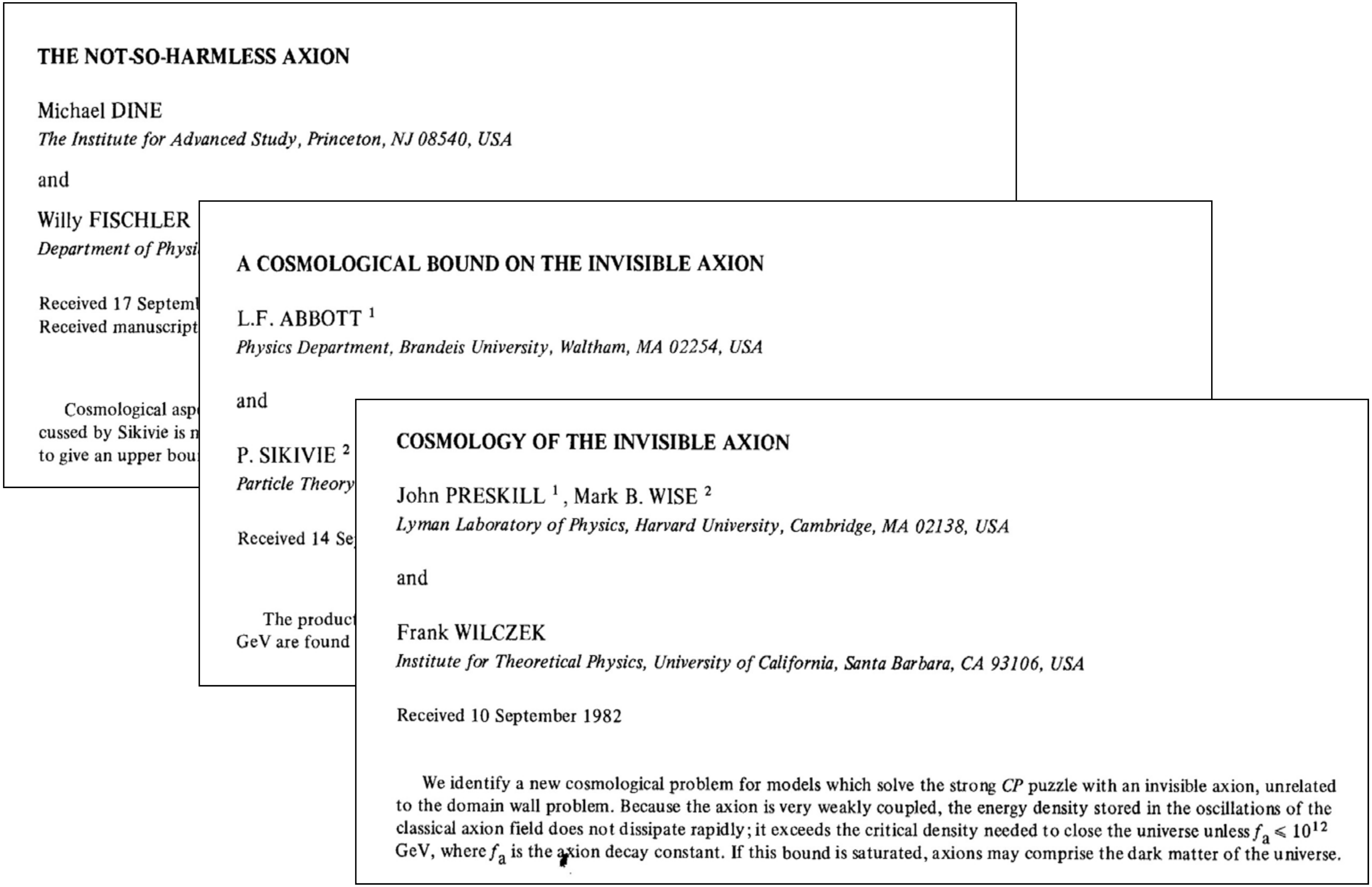
$$\Omega_a h^2 = 0.195\,\Theta_\mathrm{i}^2 \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.184} = 0.105\,\Theta_\mathrm{i}^2 \left(\frac{10\ \mu\mathrm{eV}}{m_a}\right)^{1.184}$$

If axions provide the cold dark matter: $\Omega_a h^2 = 0.11$

$$\Theta_\mathrm{i} = 0.75 \left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)^{0.592} = 1.0 \left(\frac{m_a}{10\ \mu\mathrm{eV}}\right)^{0.592}$$

- $\Theta_\mathrm{i} \sim 1$ implies $f_a \sim 10^{12}$ GeV and $m_a \sim 10\ \mu\mathrm{eV}$ ("classic window")
- $f_a \sim 10^{16}$ GeV (GUT scale) or larger (string inspired) requires $\Theta_\mathrm{i} \lesssim 0.003$ ("anthropic window")

Axion Cosmology in PLB 120 (1983)



THE NOT-SO-HARMLESS AXION

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Received 17 Septem
Received manuscript

Cosmological asp
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A COSMOLOGICAL BOUND ON THE INVISIBLE AXION

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Particle Theory

Received 14 Se

The product
GeV are found

COSMOLOGY OF THE INVISIBLE AXION

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and

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

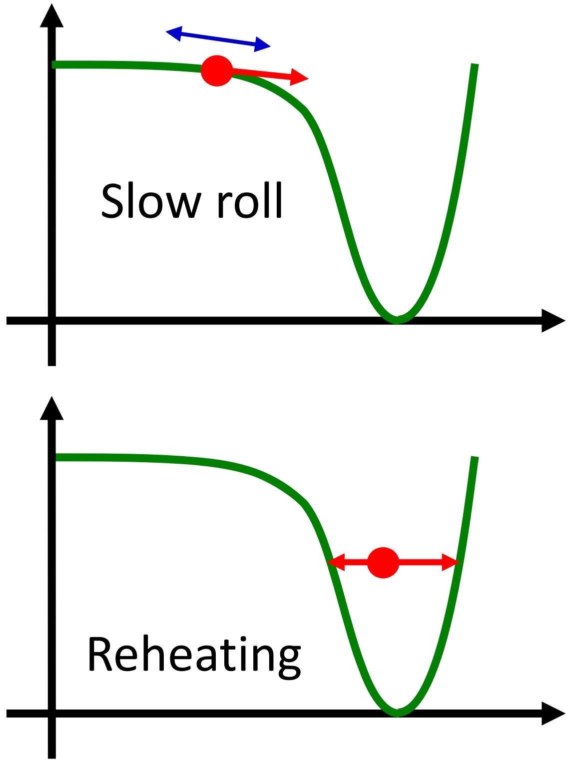
Received 10 September 1982

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.

Creation of Adiabatic vs. Isocurvature Perturbations

Inflaton field

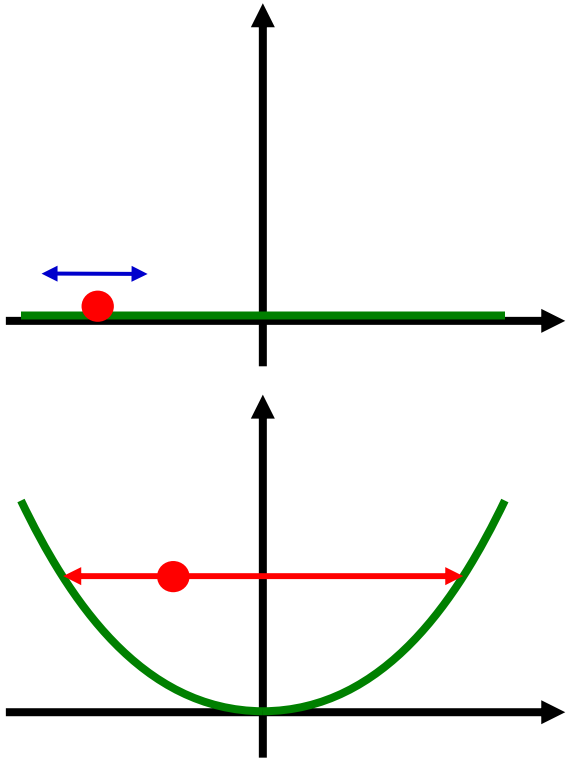
De Sitter expansion imprints
scale invariant fluctuations



Inflaton decay → matter & radiation
Both fluctuate the same:
Adiabatic fluctuations

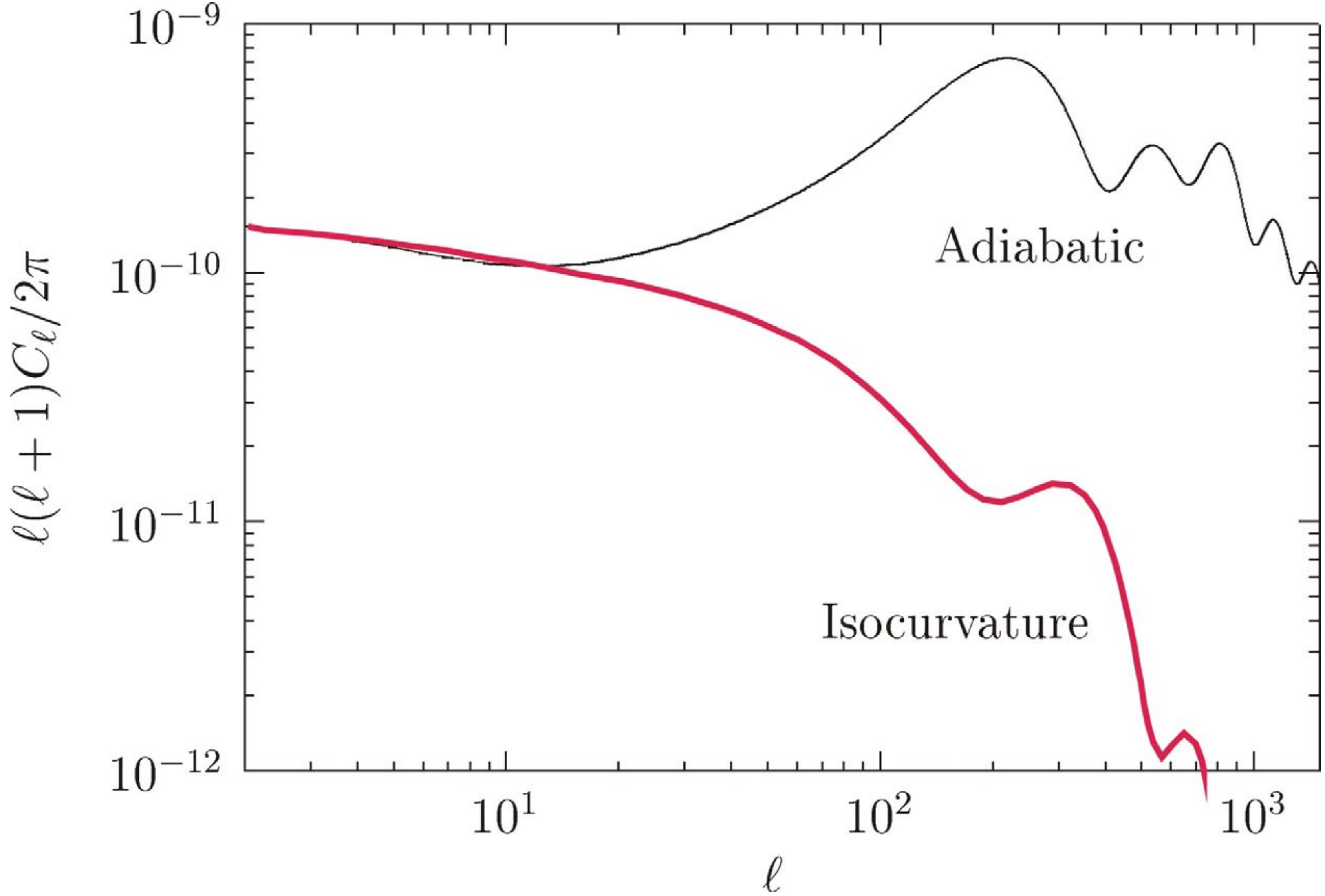
Axion field

De Sitter expansion imprints
scale invariant fluctuations



Inflaton decay → radiation
Axion field oscillates late → matter
Matter fluctuates relative to radiation:
Entropy fluctuations

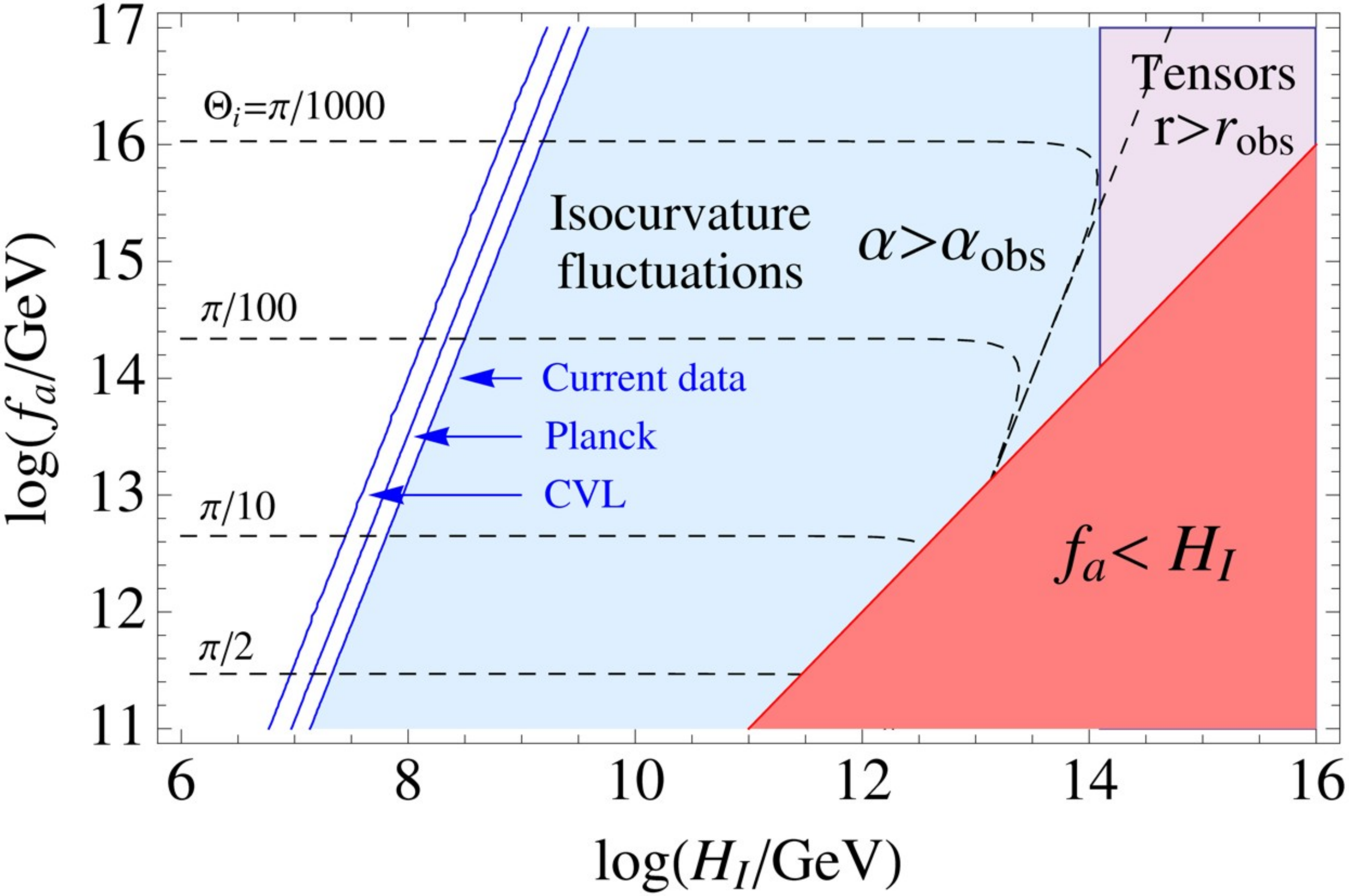
Adiabatic vs. Isocurvature Temperature Fluctuations



Adapted from Fox, Pierce & Thomas, hep-th/0409059

Isocurvature Forecast

Hubble scale during inflation



Axion decay constant

Hamann, Hannestad, Raffelt & Wong, arXiv:0904.0647

Cold Axion Populations

Case 1
Inflation after PQ symmetry breaking

Homogeneous mode oscillates after

$$T \lesssim \Lambda_{\mathrm{QCD}}$$

Dependence on initial misalignment angle $\Omega_a \propto \Theta_{\mathrm{i}}^2$

Dark matter density a cosmic random number (“environmental parameter”)

- Isocurvature fluctuations from large quantum fluctuations of massless axion field created during inflation
- Strong CMB bounds on isocurvature fluctuations
- Scale of inflation required to be small

Case 2
Reheating restores PQ symmetry

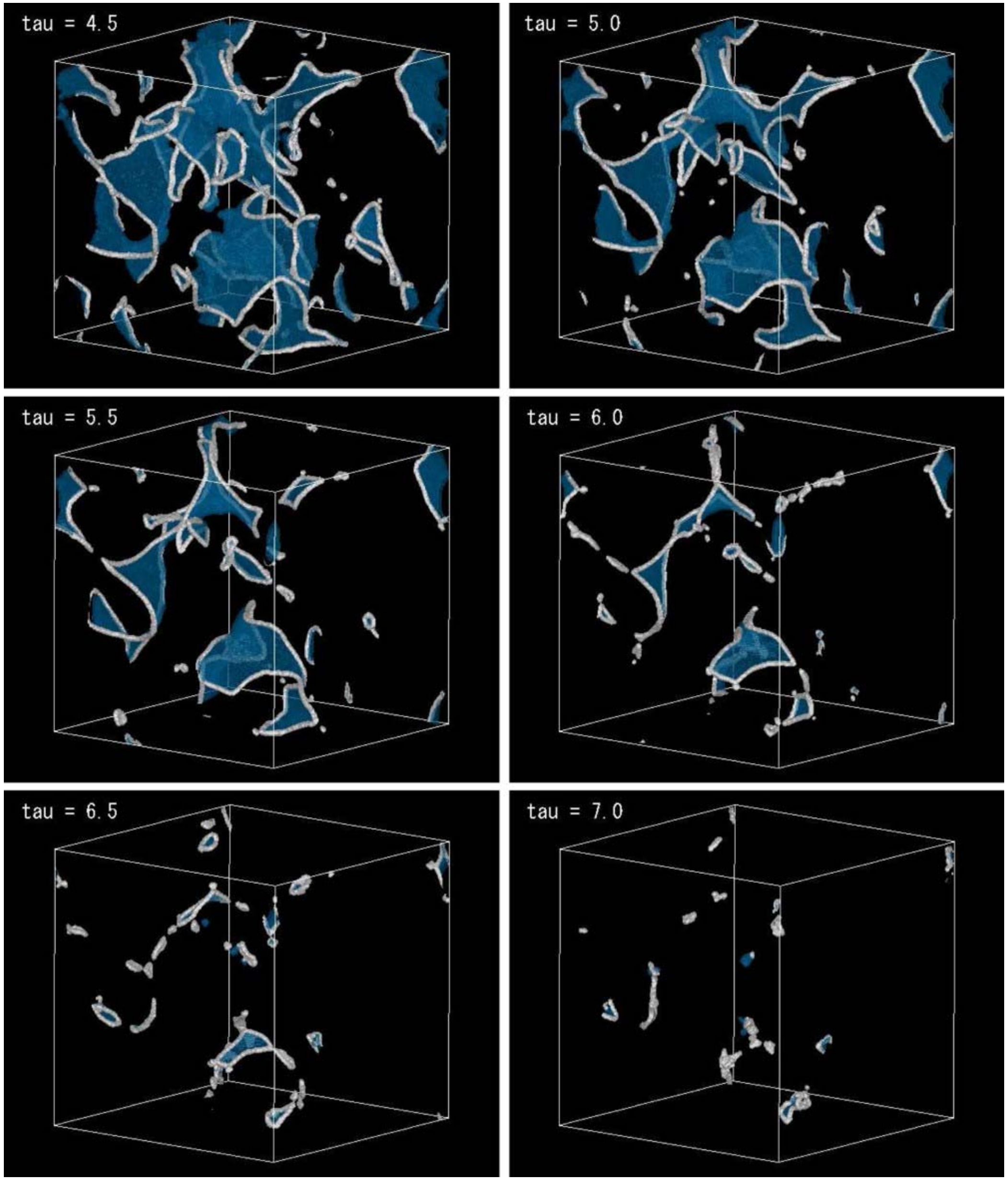
- Cosmic strings of broken $\mathrm{U_{PQ}(1)}$ form by Kibble mechanism
- Radiate long-wavelength axions
- Ω_a independent of initial conditions
- $N = 1$ or else domain wall problem

Inhomogeneities of axion field large, self-couplings lead to formation of mini-clusters

Typical properties

- Mass $\sim 10^{-12}\,M_{\mathrm{sun}}$
- Radius $\sim 10^{10}$ cm
- Mass fraction up to several 10%

Axion Production by Domain Wall and String Decay



Recent numerical studies of collapse of string-domain wall system

$$\Omega_a h^2 = (16 \pm 6)\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19} \times \left(\frac{g_{*,1}}{70}\right)^{-0.41}\left(\frac{\Lambda}{400\ \mathrm{MeV}}\right)$$

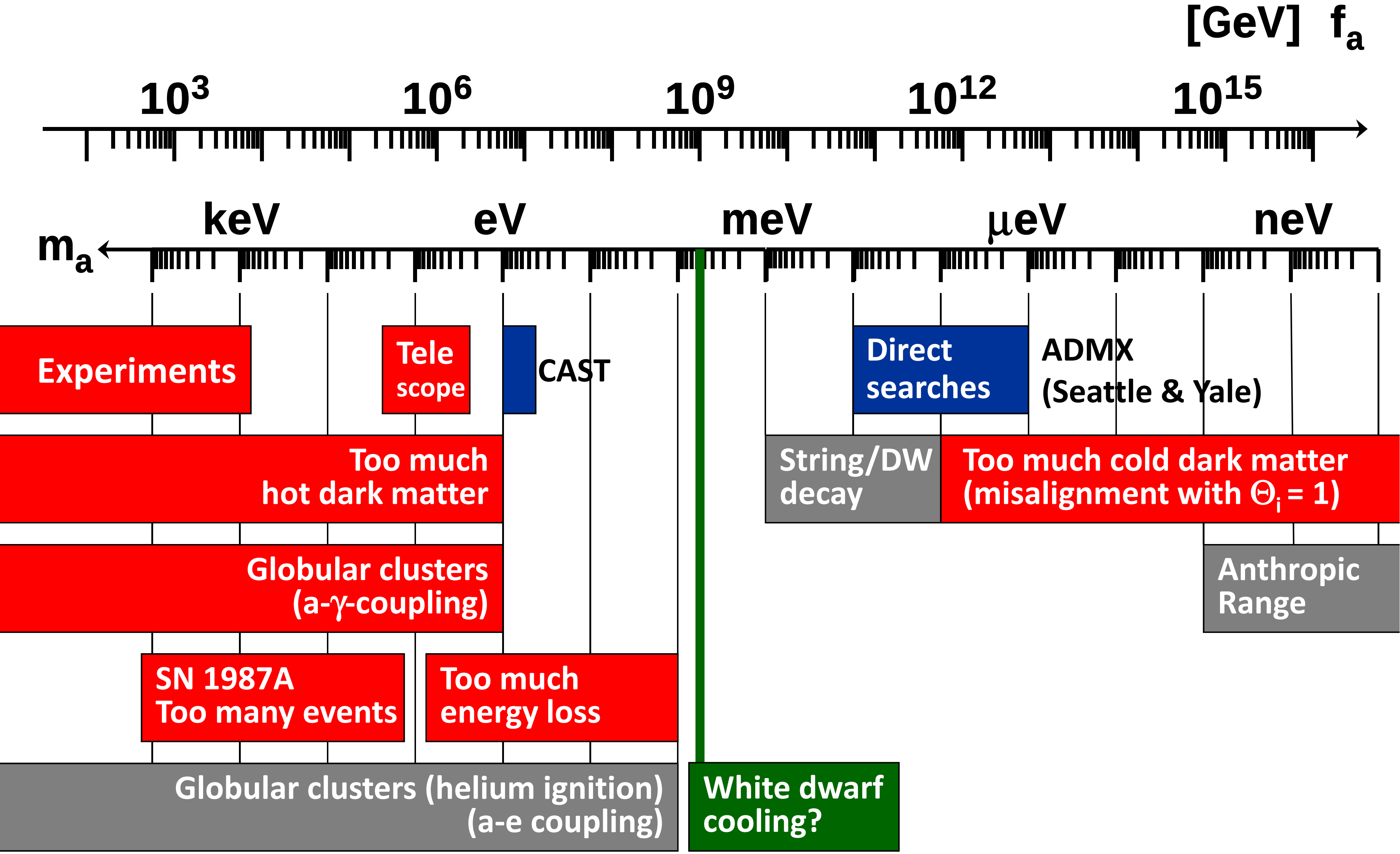
Implies a CDM axion mass of

$$m_a \sim 1\ \mathrm{meV}$$

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

Remains to be confirmed, interpretation of numerical studies not entirely straightforward

Axion Bounds and Searches



Experiments

Tele scope

CAST

Direct searches

ADMX (Seattle & Yale)

Too much hot dark matter

String/DW decay

Too much cold dark matter (misalignment with $\Theta_i = 1$)

Globular clusters (a-γ-coupling)

Anthropic Range

SN 1987A Too many events

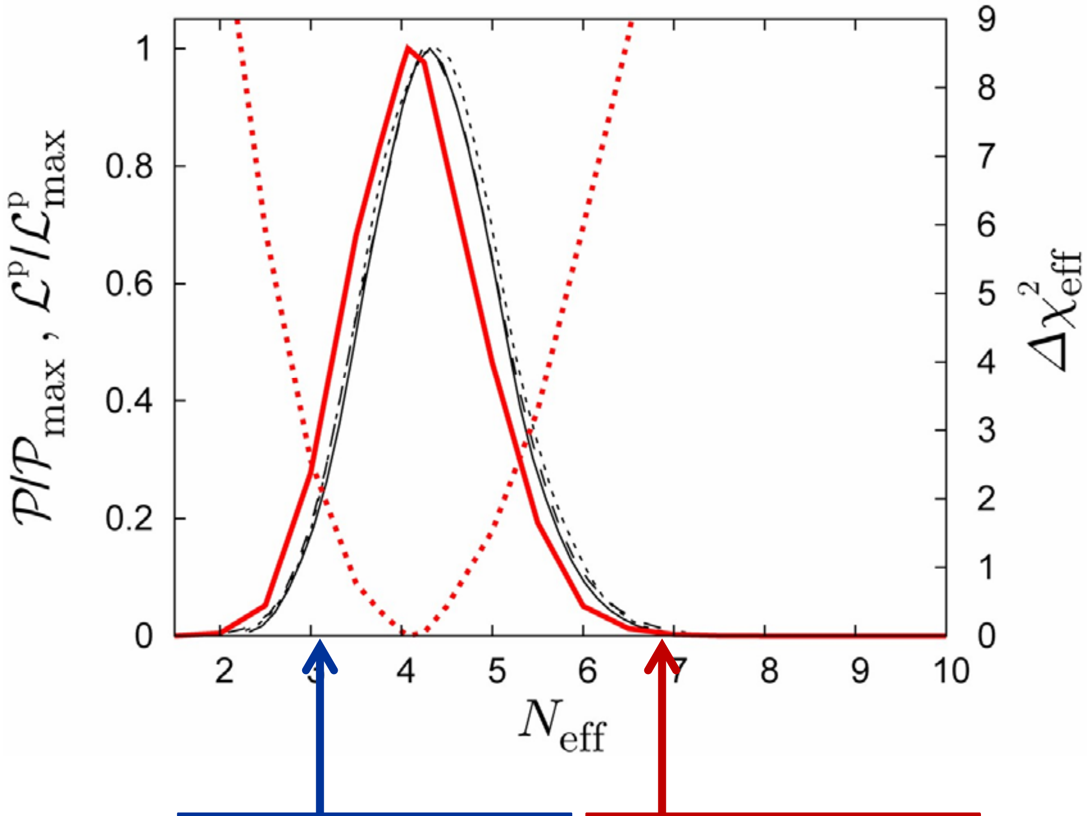
Too much energy loss

Globular clusters (helium ignition) (a-e coupling)

White dwarf cooling?

Excluding CDM Axions With Radiation Density?

Cosmic radiation density derived from data of WMAP-7+ACT+HST (Hamann, arXiv:1110.4271), PLANCK will settle (Paper expected Jan 2013)



$N_{\rm eff} = 3.046$

$N_{\rm eff} = 6.77$

CDM axions reaching thermal equilibrium with photons after BBN?

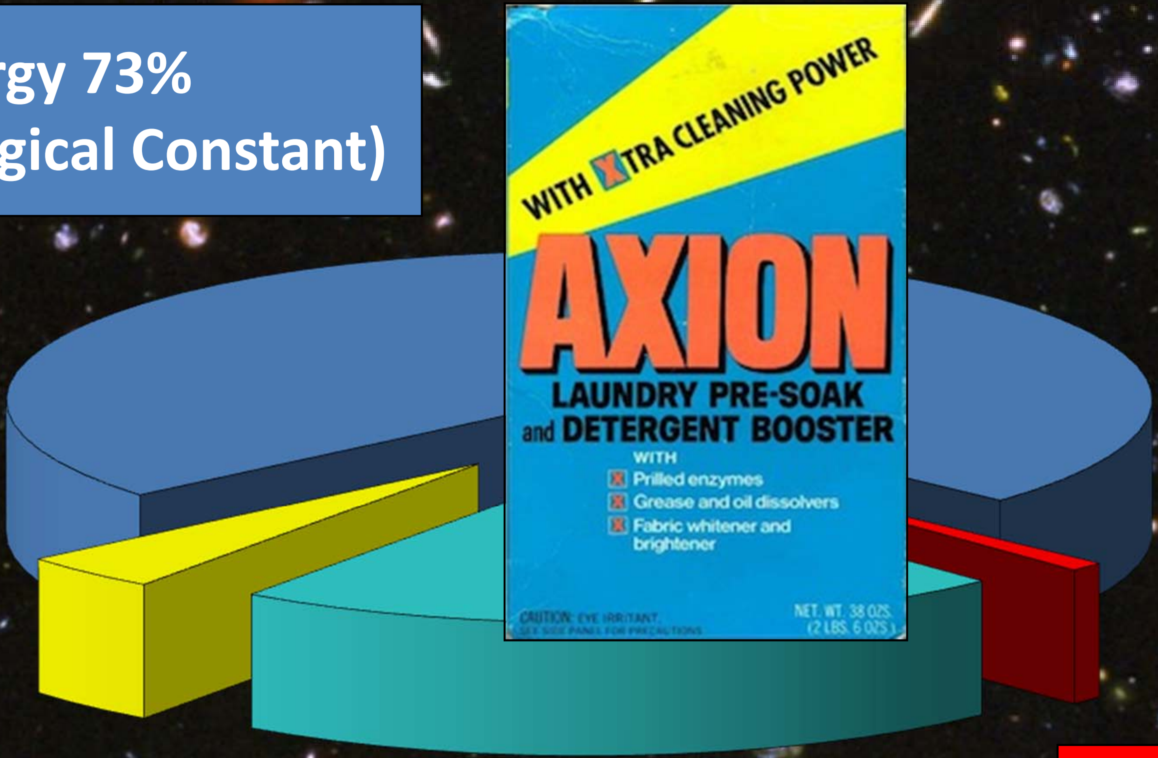
Sucks up photons, increases effective neutrino density.

(Erken, Sikivie, Tam & Yang arXiv:1104.4507, PRL 2012)

CDM axions excluded?

My opinion: Doubts about axion-photon thermalization.

Dark Energy 73%
(Cosmological Constant)



Ordinary Matter 4%
(of this only about
10% luminous)

Dark Matter
23%

Neutrinos
0.1–2%