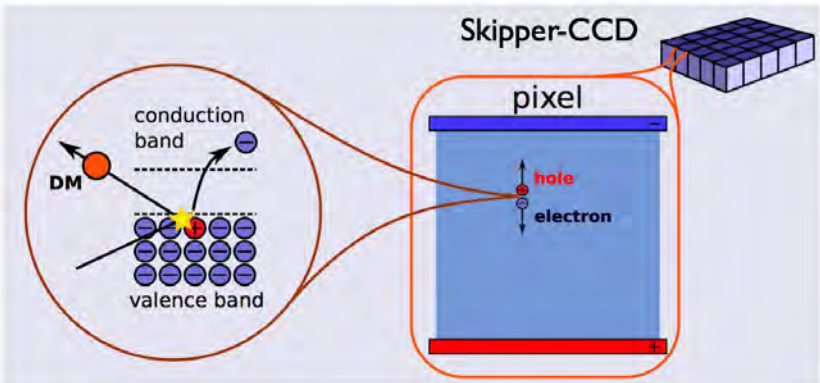
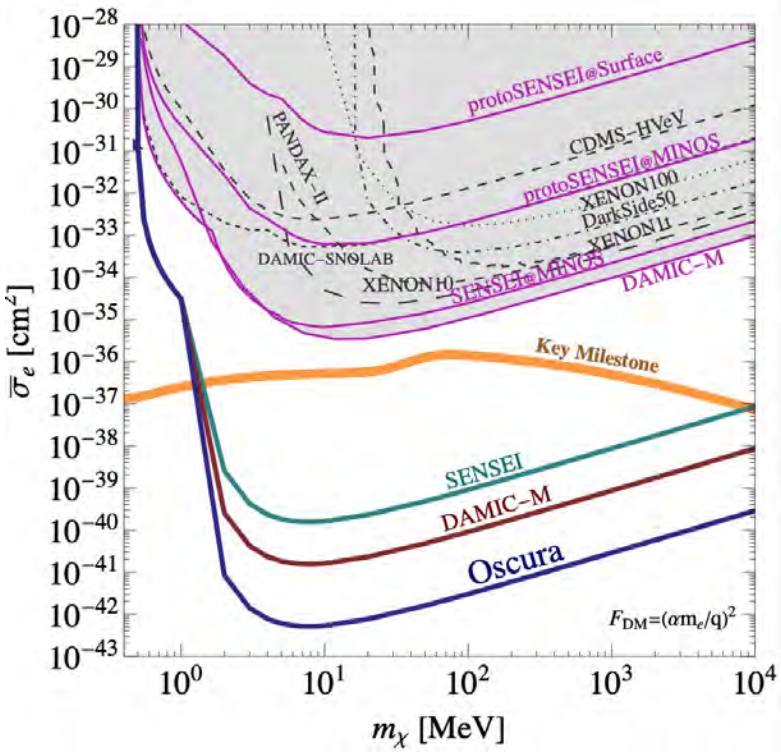
Graciela Gelmini-UCLA

Experiment dedicated to LightDM An example:

SENSEI/DAMIC-M/Oscura: Detection concept



DM would create one or a few electrons in a pixel



AXIONS- ALPs

For QCD axions:
the mass m_a is related to the spontaneous U(1) symmetry breaking scale f_a,

$$m_a = \frac{\sqrt{m_u m_d} m_\pi}{(m_u + m_d) f_\pi f_a} \simeq 6.3 \text{ eV} \left(\frac{10^6 \text{GeV}}{f_a} \right)$$

there is a coupling with gluons

$$L_{agg} = \frac{\alpha_s}{8\pi} \frac{a_{\text{phys.}}}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

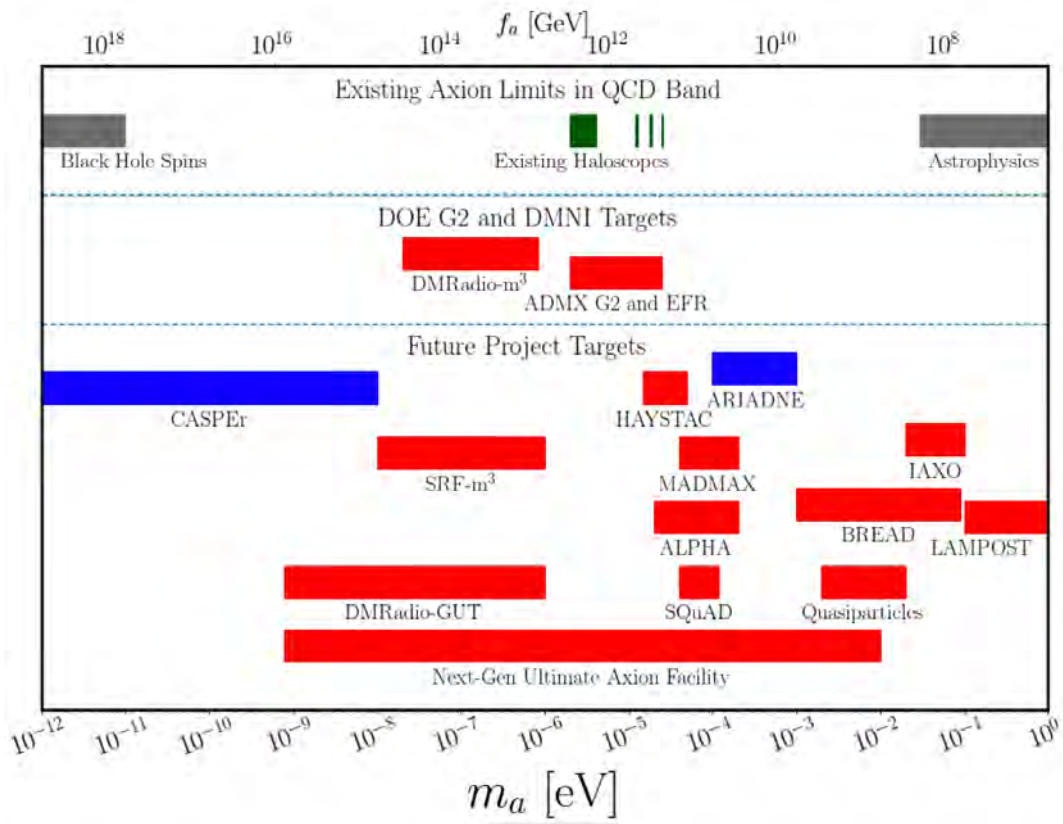
and several models of different types (Shifman, Vainshtein, Zakharov (SVZ) and Dine, Fischler, Srednicki and Zhitnisky (DFSZ)) produce different coupling of a with γ's and fermions.

$$L_{a\gamma\gamma} = \frac{\alpha}{4\pi} K_{a\gamma\gamma} \frac{a_{\text{phys.}}}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad L_{aff} = \frac{C_f}{2 f_a} \bar{\psi}_f \gamma^\mu \gamma^5 \psi_f \partial_\mu a_{\text{phys.}}$$

For ALPs: m_a and f_a are independent, and each coupling may or not exist.

AXIONS- ALPs searches In the context of QCD axion models

From "Feebly-Interacting Particles: FIPs 2022 Workshop Report," 2305.01715



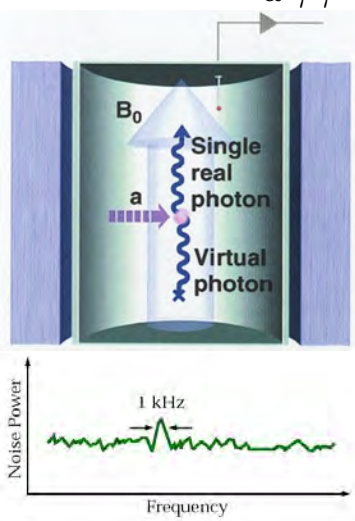
For axions coupled to photons: existing in green, projects in red, astrophysics limits in gray; coupled to gluons, future in blue.

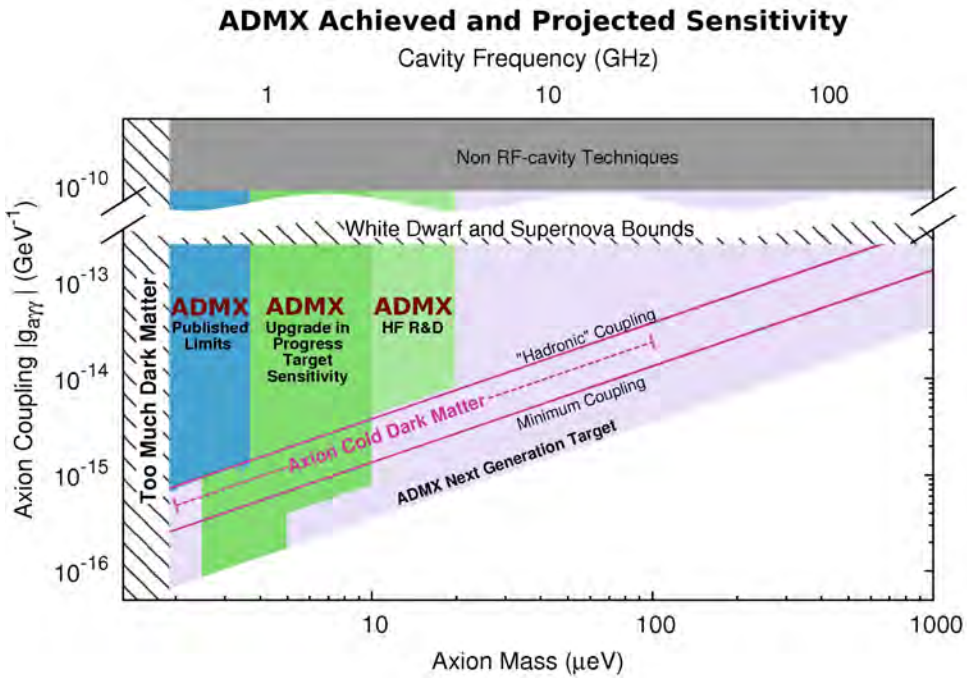
Tradicional axions searches in resonant cavities: ADMX

the Axion DM eXperiment P. Sikivie in 1983 proposed searches for resonant axion-photon conversion $a\gamma \to \gamma$, for m_a = resonant frequency of a cavity (works for 1μeV $\leq$ m $\leq$ 1 meV)

ADMX (Axion DM eXperiment)

Microwave cavity: $g_{a\gamma\gamma}$





New idea ALPHA the Axion Longitudinal Plasma HAloscope Consortium

Based on the new concept of wire metamaterials, with tunable plasma frequency

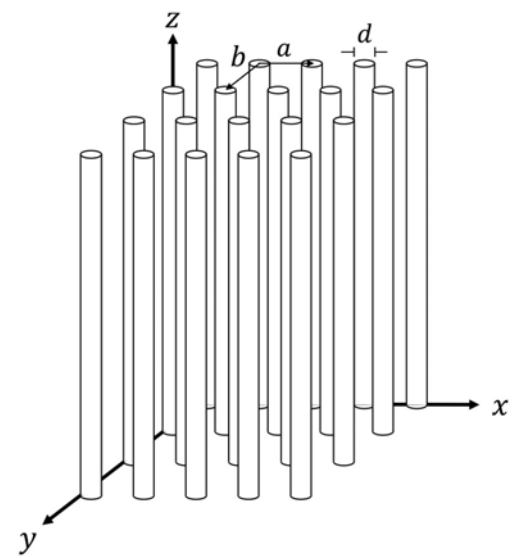
Lawson, Millar, Pancaldi, Vitagliano and Wilczek Phys. Rev. Lett. 123 (2019) 141802

—In a plasma, photons acquire an effective mass, the plasma frequency ω_p, and a longitudinal component, the "longitudinal plasmon" (actually a wave in the electron density).

—In a magnetic field, axions passing though the plasma would absorb a photon and produce another, $a\gamma \to \gamma$. The production rate has a large resonance enhancement when $m_a = \omega_p$.

$$\frac{\omega_p^2}{c^2} = \frac{2\pi}{ab}\left[\log\left(\frac{\sqrt{a\,b}}{\pi\,d}\right) + F\left(\frac{a}{b}\right)\right]^{-1}$$

$$F(u) = -\frac{\log u}{2} + \sum_{n=1}^{\infty}\left(\frac{\coth(\pi n u) - 1}{n}\right) + \frac{\pi u}{6}$$



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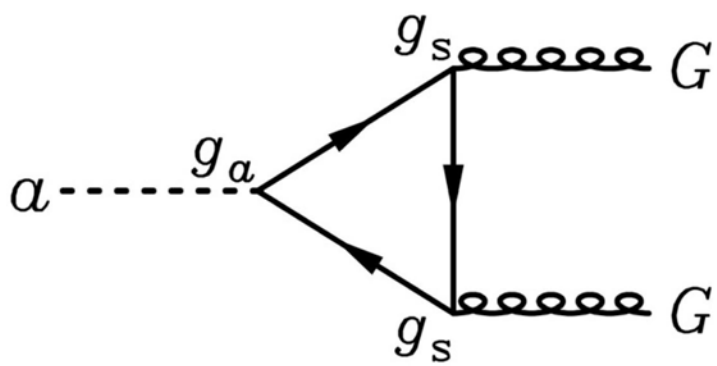
EXTRA: Old slides on Axions/ALPs

Non thermal mechanism: boson condensate formation

AXIONS are hypothetical pseudo-Goldstone Bosons (Wilczek 1978, Weinberg 1978) associated with the spontaneous breaking of an axial U(1) symmetry (Peccei-Queen 1977) of quarks (and optionally of leptons too) at a scale f_a (given by the VEV of a scale field) thus coupled through the chiral triangular anomaly to gluons. The coupling with photons is model dependent (as is that with leptons).



The PQ symmetry is the only viable solution of the "strong-CP" problem of QCD proposed so far.(See e.g. reviews by Peccei and Raffelt on axions)

AXIONS: The Lagrangian of QCD includes a CP violating term

$$L_{QCD} = \theta_{QCD} \frac{g^2}{32\pi^2} G_a^{\mu\nu} \ \ \tilde{G}_{a\mu\nu}$$

Besides, the quark mass matrix is in general complex

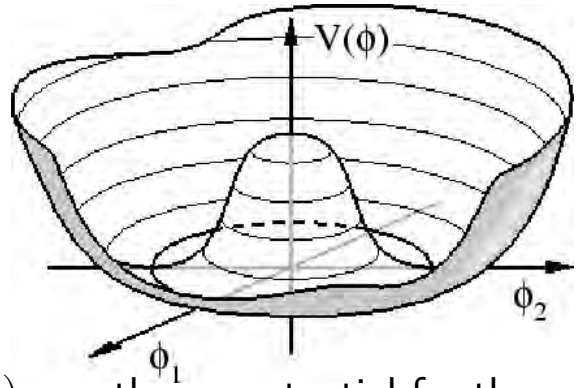
$$L_{\rm Mass} = \bar{q}_{iR} M_{ij} q_{jL} + h.c.$$

A $U(1)_A$, namely one which rotates right and left handed fields separately change the θ value is necessary to diagonalize it

$$-\pi \leq \bar{\theta} = \theta + arg\ detM \leq \pi$$

The experimental limit on the neutron electric moment $d_n \simeq e\theta m_q/M_N^2$ implies $\bar{\theta} < 10^{-11}$! The strong CP problem is why is this $\bar{\theta}$ angle, coming from the strong and weak interactions, so small?.

AXIONS: The only viable solution of the "strong-CP" problem of QCD proposed so far is to augment the SM to make the Lagrangian invariant under a global chiral symmetry $U(1)_{PQ}$ (Peccei-Queen 1977) spontaneously broken at a high scale f_a, whose Goldstone boson is the AXION a (Wilczek 1978, Weinberg 1978)

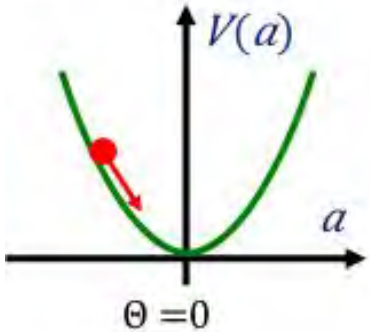


so that now

$$\bar{\theta} + \frac{< a >}{f_a}$$

Effects of the QCD anomaly generates an explicit breaking of $U(1)_{PQ}$, thus a potential for the field a,

$$V_{\rm eff} \sim cos\left(\bar{\theta} + \frac{< a >}{f_a}\right) = cos(\theta)$$



whose minimum is at $< a >= -f_a/\bar{\theta}$, i.e. $\theta = 0$ thus the Lagrangian in terms of $a_{\rm phys} = a - < a >$ no longer has a CP violating θ-term. CP - symmetry is dynamically restored

AXIONS: In this minimum the axion has mass (generic prediction)

$$m_a = \frac{\sqrt{m_u m_d} m_\pi}{(m_u + m_d) f_\pi f_a} \simeq 6.3 \text{ eV} \left(\frac{10^6 \text{GeV}}{f_a} \right)$$

and a coupling with gluons (generic prediction)

$$L_{agg} = \frac{\alpha_s}{8\pi} \frac{a_{\text{phys.}}}{f_a} G^{\mu\nu} \tilde{G}_{\mu\nu}$$

Several models: Shifman, Vainshtein, Zakharov (SVZ) and Dine, Fischler, Srednicki and Zhitnisky (DFSZ) produce different coupling of a with γ's and fermions.

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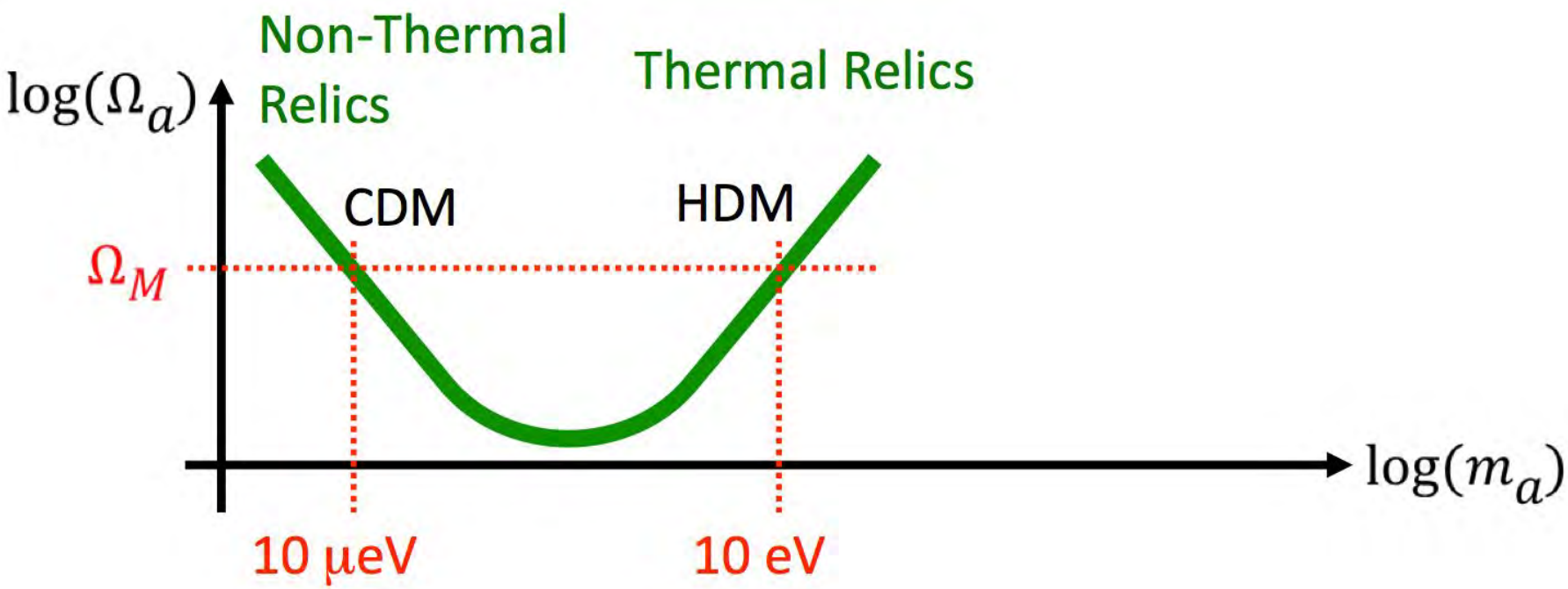
AXIONS can be HDM or CDM

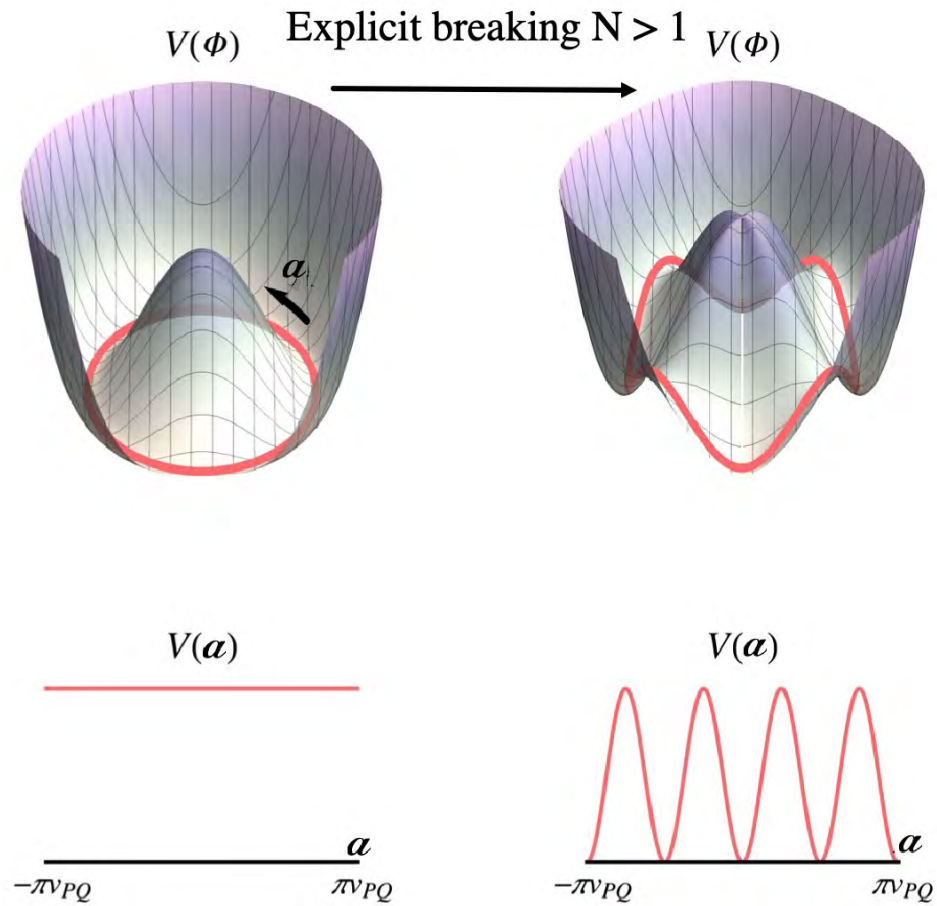


HDM when produced thermally for "large" m_a (large enough coupling with pions $a\pi\pi\pi$)
CDM produced as a Bose-Einstein condensate (very small coupling)

ALPs as CDM

- Nambu Goldstone Boson (NBG) due to a U(1) global symmetry spontaneously broken at a scale V is the field component a along the orbit of degenerate minima $\phi = Ve^{\theta}$, phase $\theta = a/V$.

- The symmetry is also explicitly broken at a scale $v << V$- leads to one $(N = 1)$ or more $(N > 1)$ true minima along the previous orbit of degenerate minima (discrete symmetry Z_N) gives mass to the pseudo-NGB $m_a \simeq v^2/V$.



(Fig. adapted from Armengaud et al 1904.09155)

Many particle models of this type

- Original axion model (Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)
  $U(1)_{PQ}$ - Explicit breaking due to QCD instanton effects $V > v \simeq \Lambda_{\rm QCD}$, $N = 6$

- Invisible axion (also called QCD axion) models (Kim 1979; Shifman, Vainshtein and Zakharov 1980; Zhitnitsky 1980; Dine, Fischler and Srednicki 1981)
  $U(1)_{PQ}$ - Explicit breaking due to QCD instanton effects $V >> v \simeq \Lambda_{\rm QCD}$,
  KSVZ $N = 1$ or $N > 1$, DFSZ $N = 6$.

- Generic axion-like particle (ALP) models (Jaeckel and Ringwald 2010)
  Ad-hoc $U(1)$ and explicit breaking for ALPs to be dark matter $V >> v$, $N = 1$ or $N > 1$

- Singlet Majoron models (Chikashige, Mohapatra and Peccei 1981; Rothstein, Babu and Seckel 1993; Gu, Ma and Sarkar 2010)
  $U(1)_L$ - Explicit breaking due to gravitational effects, $N = 1$ or $N > 1$

- ...

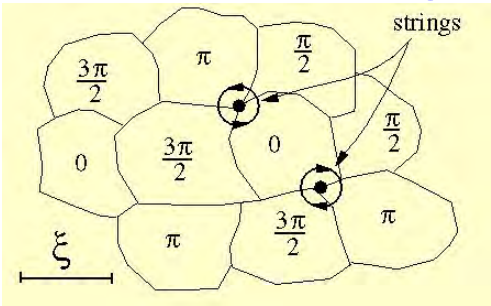
Complex cosmology

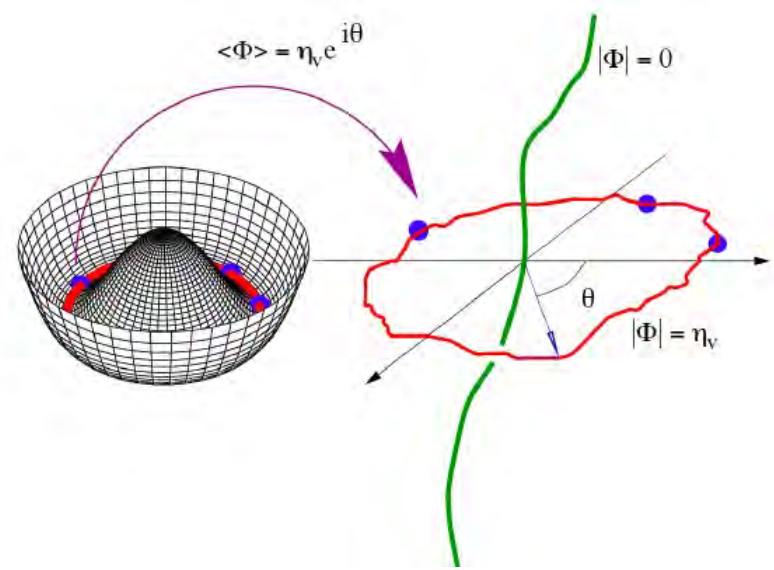
- Spontaneous breaking at scale V: creates domains with different field phase.

If inflation happens after, at end of inflation the Universe is in only one domain.

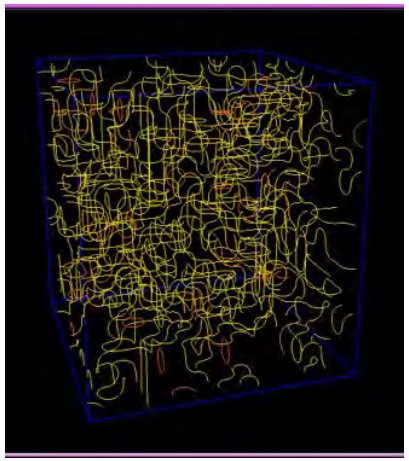
- In a post-inflation scenario cosmic strings appear

(Kibble Mechanism 1976)





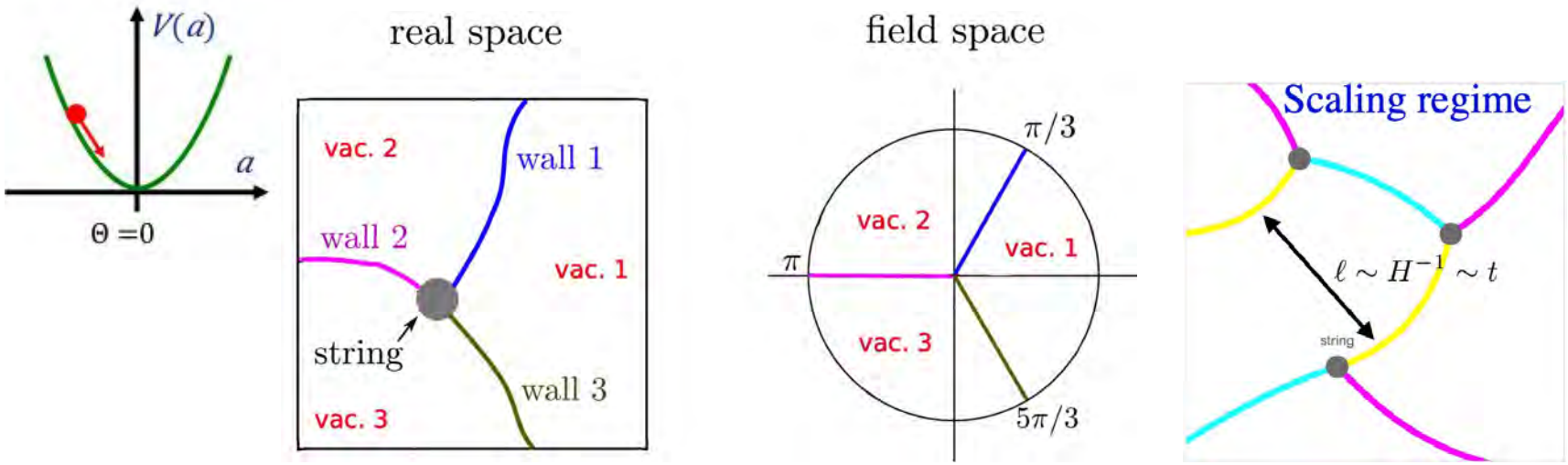
constituting a string system



Complex cosmology

Eq. of motion $\ddot{a} + 3H\dot{a} + V(a)' = 0$, $V = (m_a^2 a^2)/2$ damped oscillator.

- Field is driven towards closest Z_N minimum when $3H \simeq m_a \simeq v^2/V$ ($t \simeq$ oscillation period m_a^{-1}): cosmic walls appear joined to the strings. E.g. for $N = 3$



- N=1 unstable system: "ribbons" bounded by strings shrink and annihilate fast

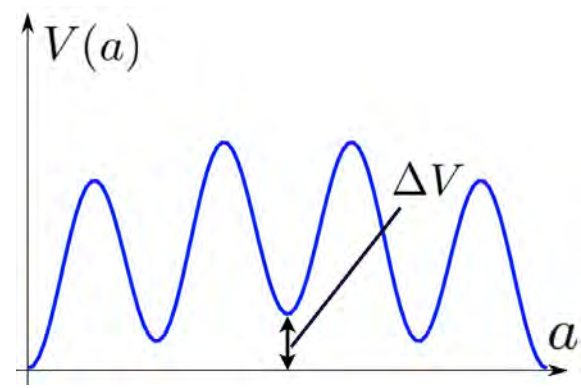
- N>1 stable string-wall system: each string attached to N walls - Soon reaches a "scaling regime" in which linear size $\simeq$ cosmic horizon t (Press, Ryden, Spergel 1989)

Complex cosmology of $N > 1$ stable wall system

- Energy density of system $\rho_{\text{wall system}} \simeq \sigma/t$ ($\sigma \simeq v^2 V$: energy per unit area), while for radiation or matter domination $\rho \sim 1/t^2$ decrease faster with time. Thus stable walls would get to dominate the energy density of the Universe, leading to an unacceptable cosmology.

- Zeldovic, Kobzarev and Okun (1974) realized this problem and proposed as solution: a small breaking of the Z_N so that only one true vacuum remains.

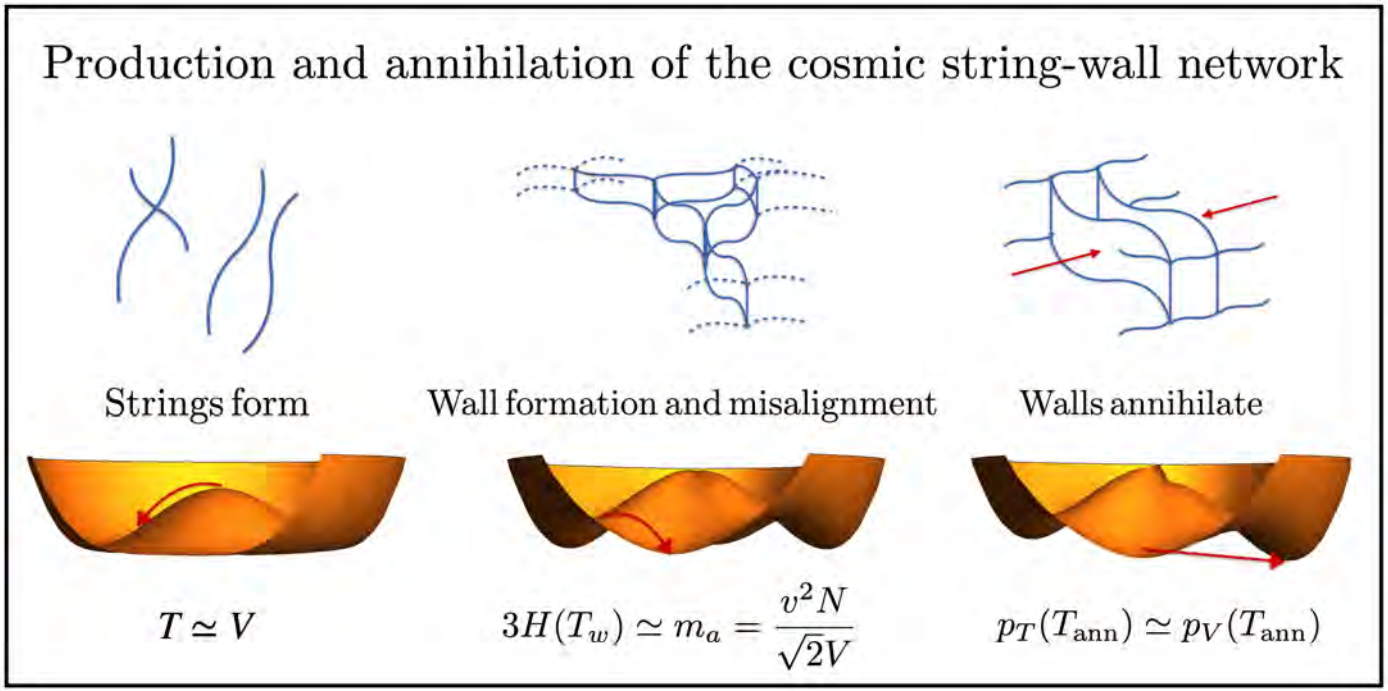
- This introduces a "bias", i.e. an energy difference or volume pressure $\Delta V = p_V \simeq V_{\text{bias}}$ between the false and the true vacua.



- Initially $V_{\text{bias}} \ll p_T \simeq \sigma/t$, the tension pressure.

- As p_T decreases with time, when $V_{\text{bias}} \simeq \sigma/t$, walls accelerate away from the true vacuum leading to the annihilation of the string-wall system: $t_{\text{ann}} \simeq \sigma/V_{\text{bias}}$

Complex cosmology of $N > 1$ stable wall system



ALP production in pre-inflation models: misalignment.

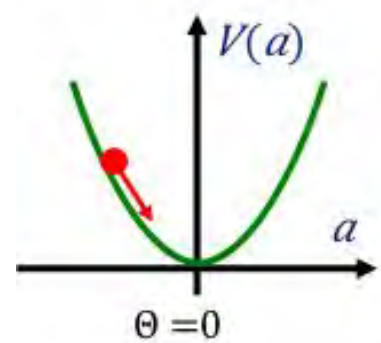
In post-inflation models via three mechanisms:1)- misalignment, 2)- emission by strings and 3)- emission by the string-walls (only if N>1)

AXIONS as CDM via misalignment

Coherently oscillating field scenario, QCD parameters and temperature dependent m_a imply (Bae, Huh & Kim, 0806.0497)

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

θ_i is the initial value of a in our patch of the Universe.
If inflation happens after the PQ symmetry spontaneous breaking, there is only one value



If axions account for the whole of the DM $\Omega_a h^2 = 0.11$

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

$\theta_i \simeq 1$ implies $f_a \simeq 10^{12}$ GeV "classic window"
$\theta_i < 1$ implies $f_a > 10^{12}$ GeV " anthropic window" (e.g. $f_a \simeq 10^{16}$ GeV for $\theta_i \simeq 0.003$)

But also AXIONs could be a subdominant component of the CDM.

A scalar field oscillating in a quadratic potential behaves as CDM

The equation of motion of a spatially homogeneous scalar field in the expanding Universe is

$$\ddot{\phi} + 3H\dot{\phi} + V(\phi)' = 0$$

which for $V = (m^2\phi^2)/2$ becomes

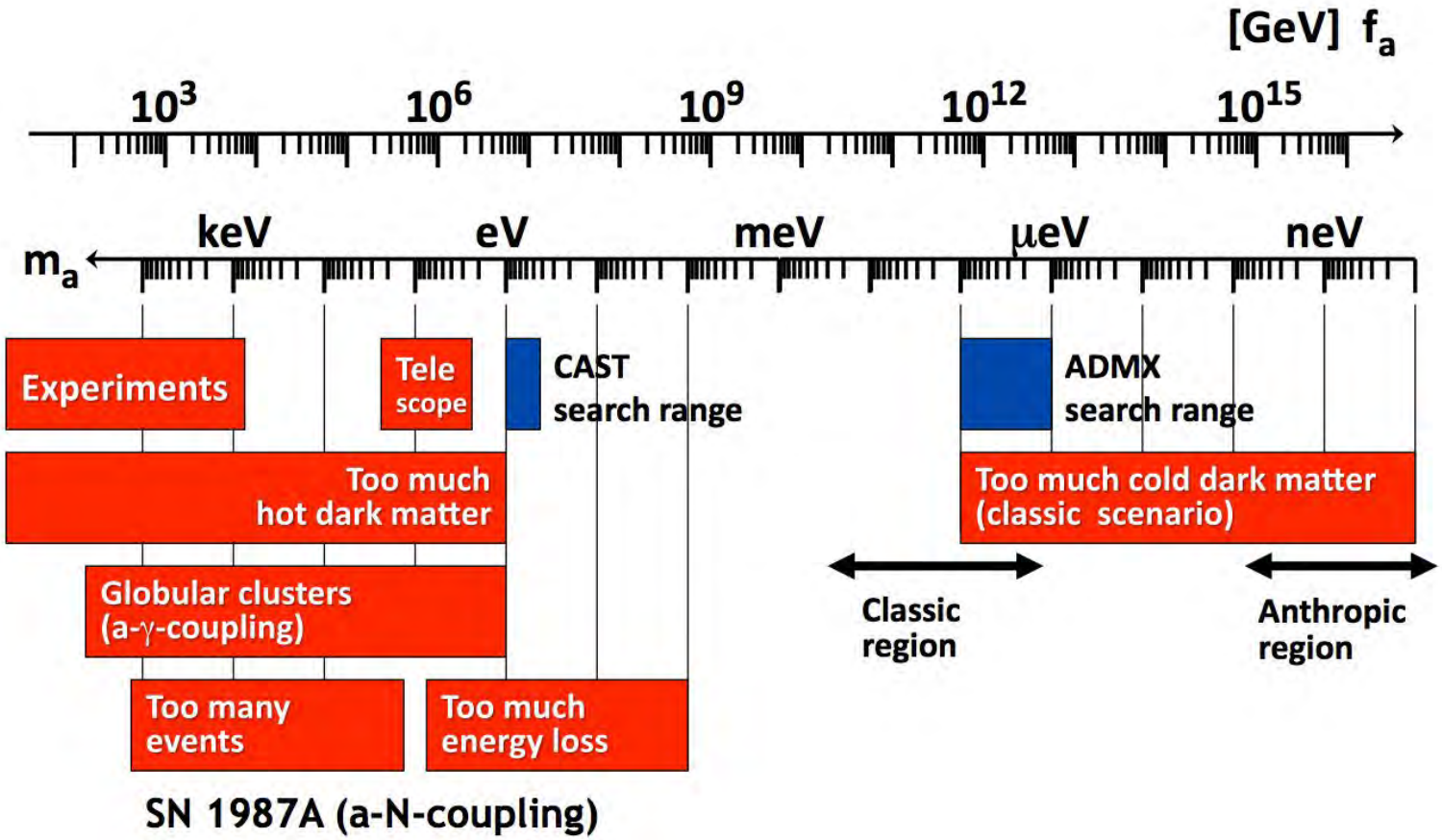
$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

The energy density of this field is $\rho = \dot{\phi}^2/2 + V(\phi)$. As in any harmonic oscillator the average of the kinetic and of the potential energies over one period are equal: $< \dot{\phi}^2/2 >=< (m^2/2\phi^2)/2 >$. Thus $\rho =< \dot{\phi}^2 > + < m^2/2\phi^2 >$. Taking the derivative of this expression and $m = m(T)$ to be a slowly varying function of time, we get

$$\dot{\rho} = [< (\dot{m}/m) > -3H]$$

which has as solution $\rho = const.m/a^3$ (a is the scale factor of the Universe and H=$\dot{a}/a$). This has the same form as for matter: $\rho_{\rm matter} = n\ m/a^3$.

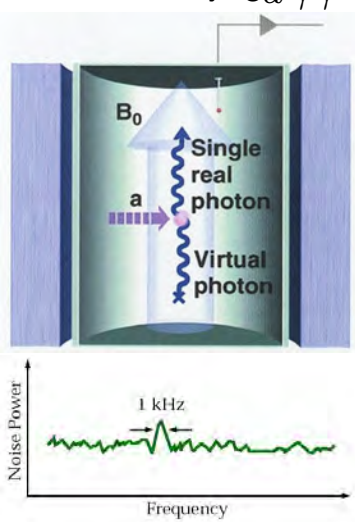
AXIONS Many bounds- fig. from Raffelt- 2011

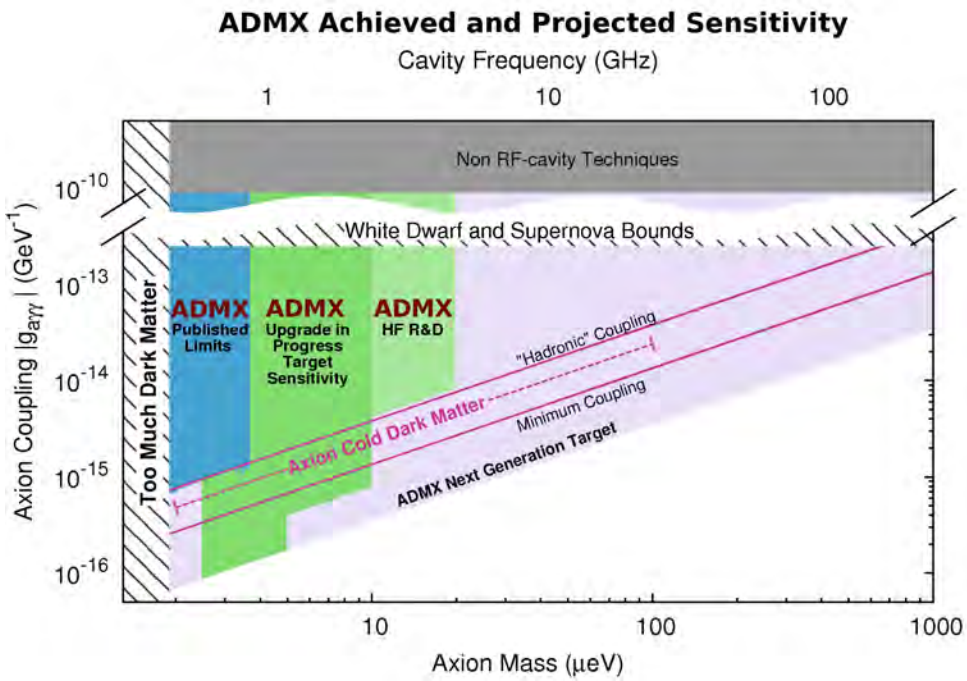


AXIONS as CDM using the axion coupling to photons (model dependent) (Sikivie 1983) ADMX best experiment for the "good CDM candidate range" 1μeV $\leq$ m $\leq$ 1 meV

ADMX (Axion DM eXperiment)

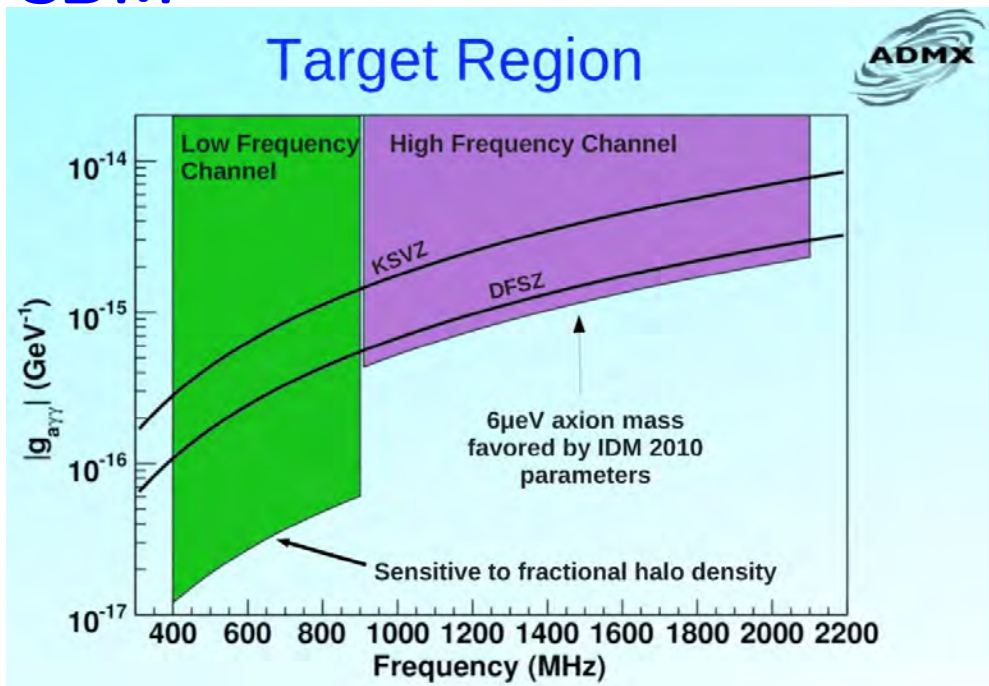
Microwave cavity: $g_{a\gamma\gamma}$





ADMX Phase II-"definitive" axion dark matter search (L. Rosenberg 2013) to start soon

AXIONS as CDM



But vertical axis $\sim \sqrt{Rate} \sim \sqrt{\Omega_a g_{a\gamma\gamma}^2} \sim \theta_i K_{a\gamma\gamma} m_a^{0.4}$ so bound applies to this product of parameters and the coupling $K_{a\gamma\gamma}$ is highly model dependent.

AXIONS as CDM in the "anthropic window" using the model independent axion coupling to gluons, Graham & Rajendran (1101.2691, 1306.6088, 1306.6089) proposed to measure a time varying electric neutron moment as the axion field oscillates. Recall $d_n \sim \theta$ and $\theta(t) = a(t)/f_a$

$$d_n = g_d a \simeq 10^{-16}\ \theta_i\ cos(m_a t)\ \ \mathrm{e\ cm}$$

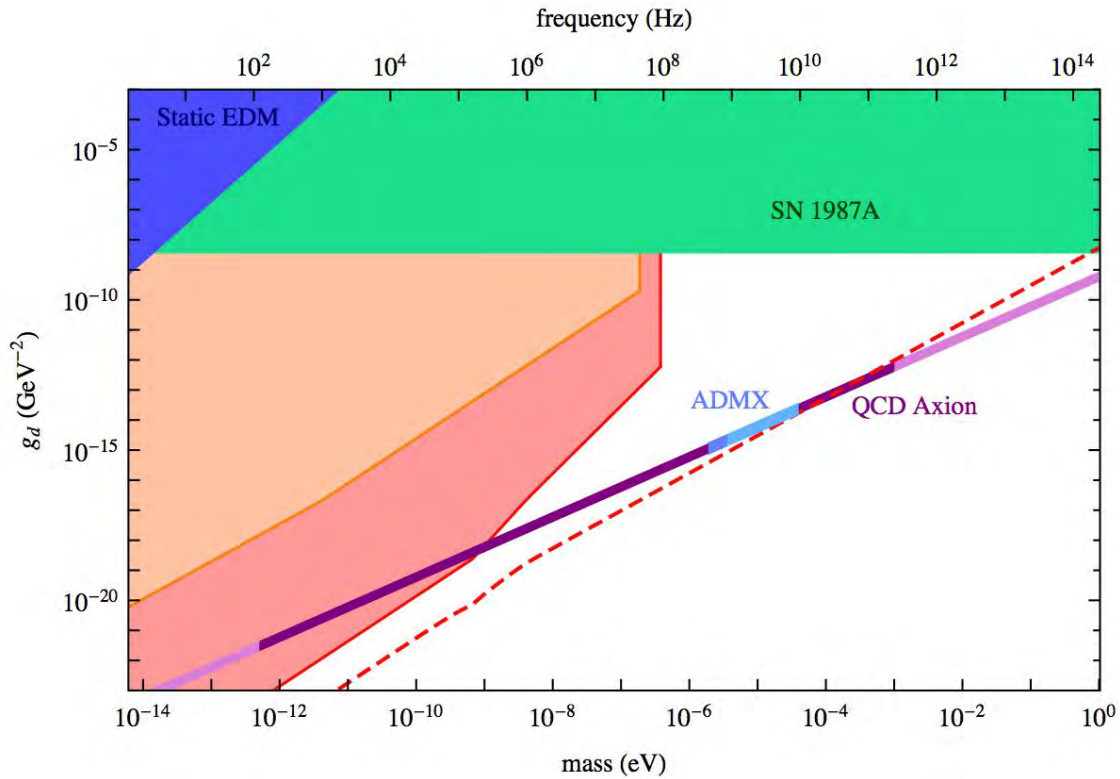
Experimental limit on static EDM $d_n < 0.63 \times 10^{-25}$ e-cm (observation last ≥ 1 second)

Also valid for Axion-Like Particles (ALPs)

For kHz-GHz, precession of nuclear spins in electric fields changes the magnetization of a sample of material, which could be observed with precision magnetometry.

AXIONS as CDM in the "anthropic window": CASPEr

(Cosmic Axion Spin Precession Experiment) from Budker, et al 1306.6089



Solid pink and orange: sensitivity regions for phase 1 and 2 proposals, set by magnetometer noise

- red dashed line: limit from magnetization noise

AXIONS in non-Standard Pre-BBN Cosmologies

allow for different combination of parameter. Example: the initial misalignment angle θ_i as a function of the Peccei-Quinn scale f_a for the axion to be 100% of the CDM in standard cosmology (black solid line), kination cosmology with transition to standard at 4MeV (red dotted line), 300MeV (green dot-dashed line) or 700MeV (blue dashed line).

from Visinelli and Gondolo 0912.00