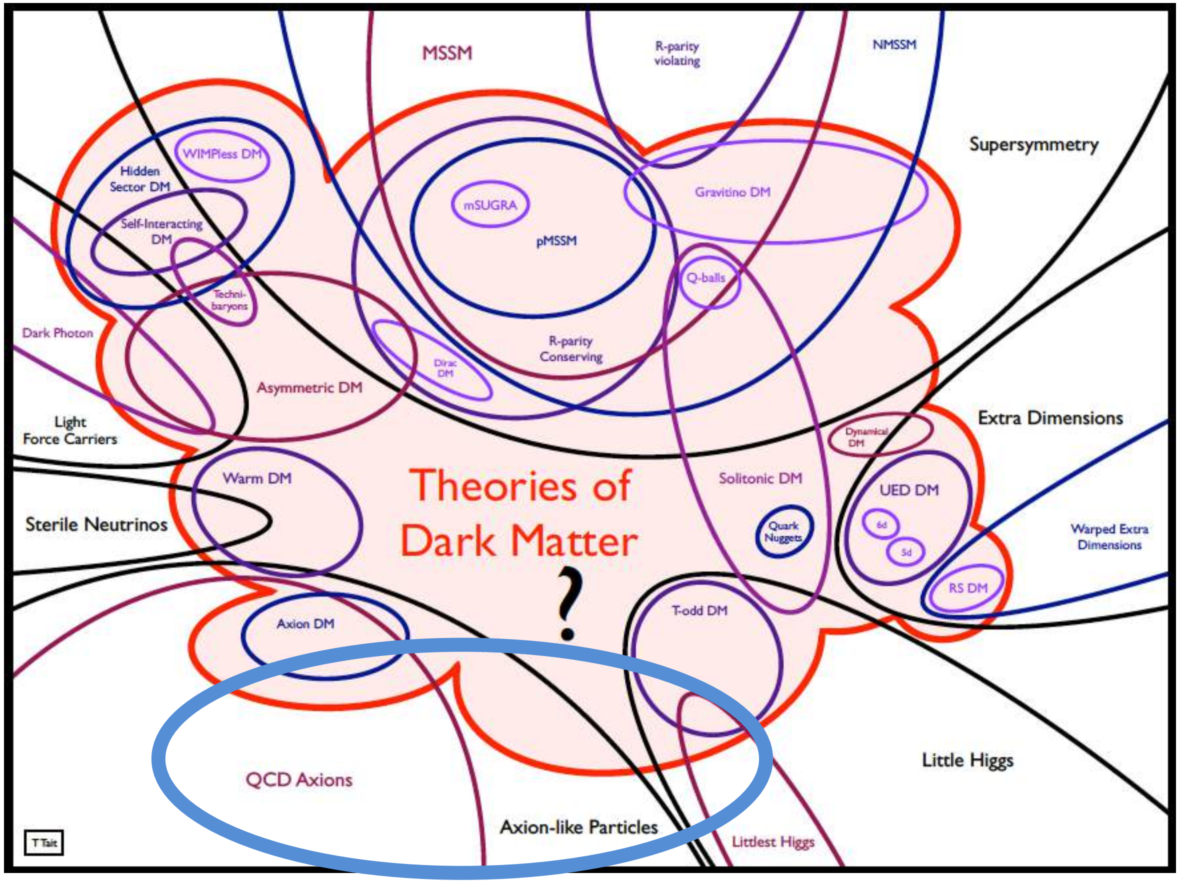
Ruling out light axions: The writing is on the wall

Subir sarkar

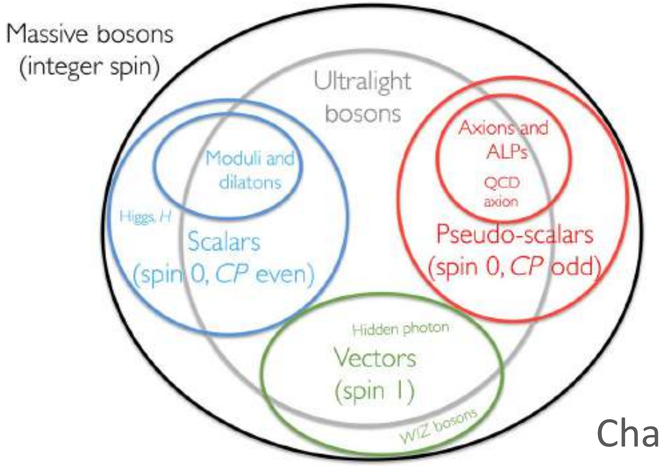
We revisit the domain wall problem for QCD axion models with more than one quark charged under the Peccei-Quinn symmetry. Symmetry breaking during or after inflation results in the formation of a domain wall network which would cause cosmic catastrophe if it comes to dominate the Universe. The network may be made unstable by invoking a ‘tilt’ in the axion potential due to Planck scale suppressed non-renormalisable operators. Alternatively the random walk of the axion field during inflation can generate a ‘bias’ favouring one of the degenerate vacuua, but we find that this mechanism is in practice irrelevant. Consideration of the axion abundance generated by the decay of the wall network then requires the Peccei-Quinn scale to be rather low – thus **ruling out e.g. the DFSZ axion with mass below ~60 meV**, where most experimental searches are in fact focussed. [arXiv:2211.14635]

Advances in Astroparticle Physics & Cosmology, SINP Kolkata, 23-27 Jan 2023

As dark matter WIMPs have proved to be elusive, so interest has grown in axions …



Courtesey: Tim Tait



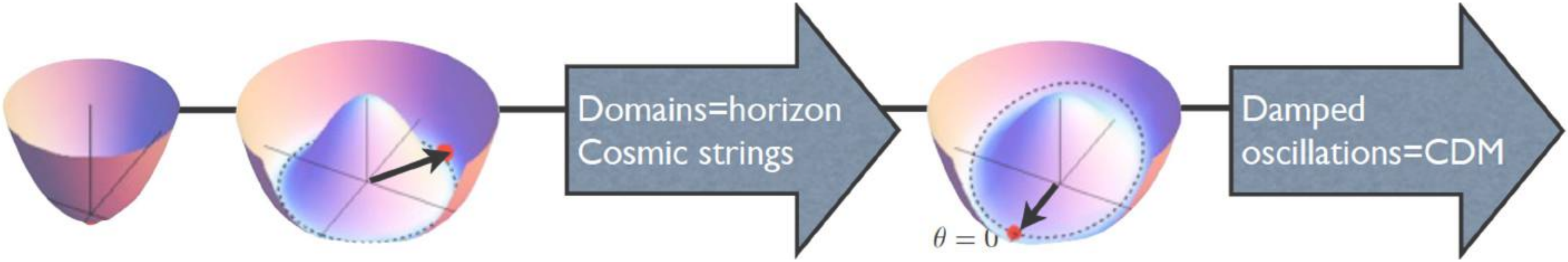
Chadha-Day *et al*, *Sci.Adv.***8**:abj361,2022

AXION DARK MATTER

$$\mathcal{L}_{\rm eff} = F^2 + \bar{\Psi}\, \not{D}\Psi + \bar{\Psi}\Psi\Phi + (D\Phi)^2 + \Phi^2 \quad \boxed{+\theta_{\rm QCD} F\tilde{F}}$$

The SM admits a term which would lead to *CP* violation in strong interactions, hence an (unobserved) electric dipole moment for neutrons ⇒ requires $\theta_{\rm QCD} < 10^{-10}$

To achieve this without fine-tuning, $\theta_{\rm QCD}$ must be made a dynamical parameter, through the introduction of a new $U(1)_{\text{Peccei-Quinn}}$ symmetry which must be broken … the resulting (pseudo) Nambu-Goldstone boson is the QCD **axion** which subsequently gets a mass via mixing with the pion: $m_a = m_\pi\, (f_\pi/f_{\rm PQ}) \sim 5.6$ eV $(10^6\, \text{GeV}/\, f_{\rm PQ})$


Domains=horizon
Cosmic strings

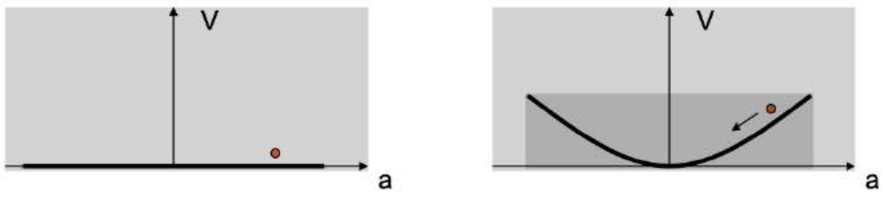
Damped
oscillations=CDM

Courtesey: Javier Redondo

When the temperature drops to $\Lambda_{\rm QCD}$ the axion potential turns on and the coherent oscillations of relic axions contain energy density that behaves like *cold* dark matter with $\Omega_a h^2 \sim 10^{11}$ GeV$/f_{\rm PQ}$, so this requires $f_{\rm PQ} \sim 10^{10\text{-}12}$ GeV ⇒ $m_a \sim 10^{-6}$–10^{-4} eV

Experimental searches for axions are therefore focussed on this mass range, however the above argument has ignored the contribution from the topological defects that form in the axion field

Axion production by vacuum realignment



$T \geq 1\,\mathrm{GeV}$ $T \leq 1\,\mathrm{GeV}$

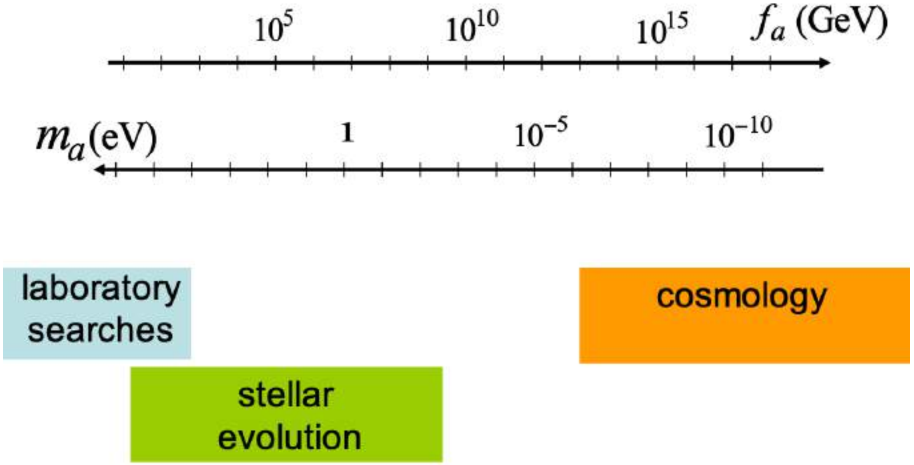
$$n_a(t_1) \simeq \frac{1}{2} m_a(t_1) a(t_1)^2 \simeq \frac{1}{2t_1} f_a^2 \alpha(t_1)^2$$

initial misalignment angle

$$\rho_a(t_1) \simeq m_a n_a(t_1) \left(\frac{R_1}{R_0}\right)^3 \propto m_a^{-\frac{7}{6}}$$

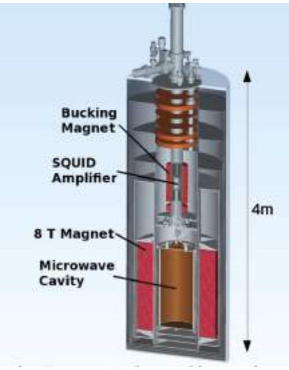
Axions produced by vacuum realignment are cold dark matter

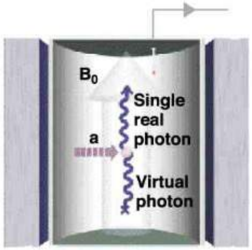
Axion constraints

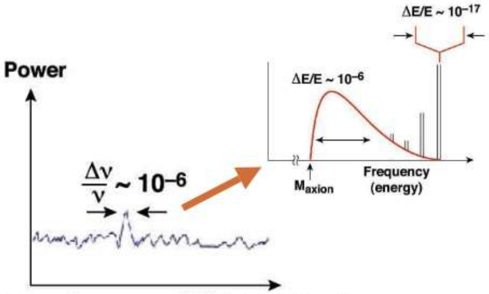


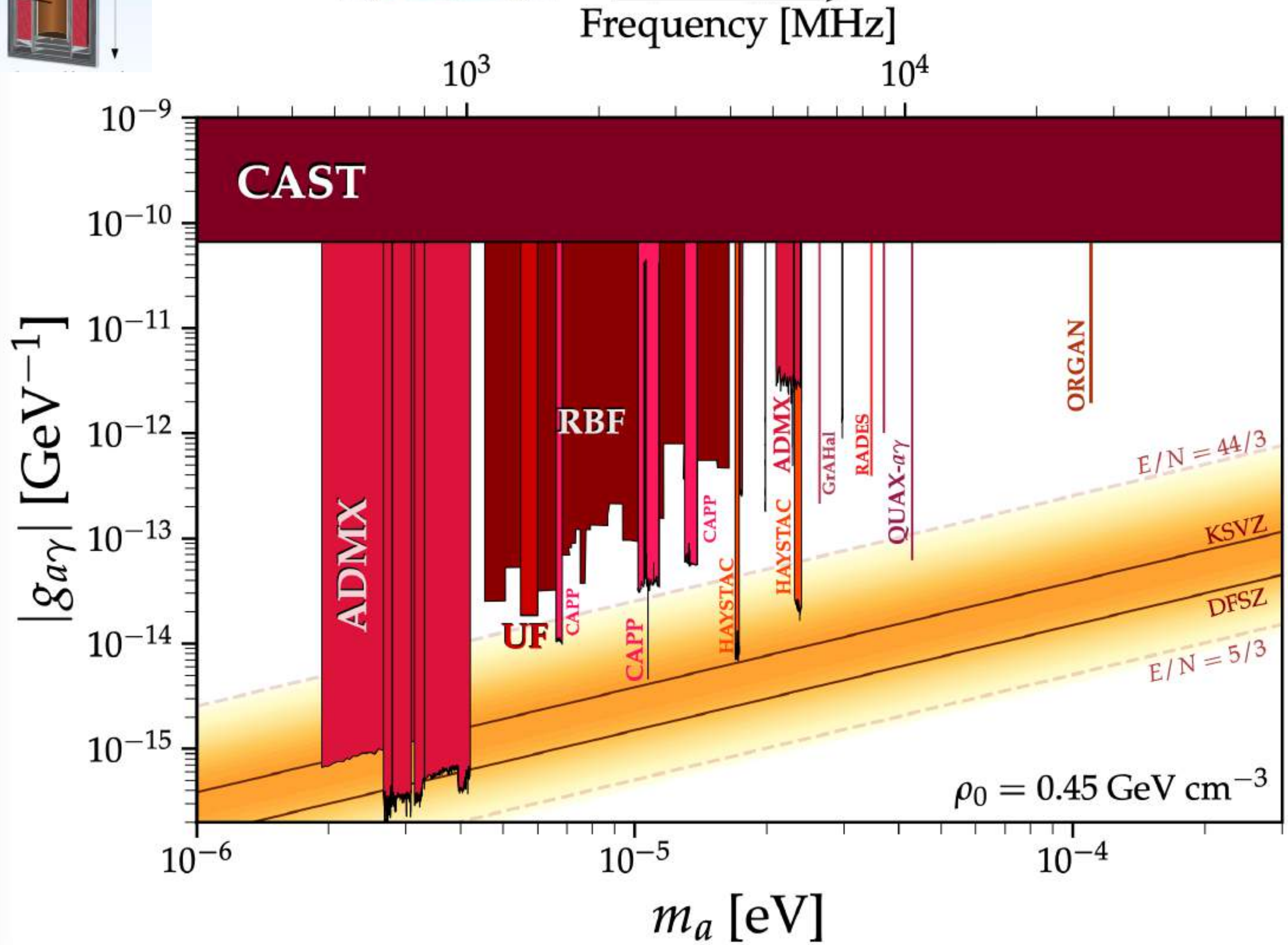
Courtesey: Pierre Sikivie

LIMITS ON AXION-PHOTON COUPLING FROM RF CAVITY EXPERIMENTS

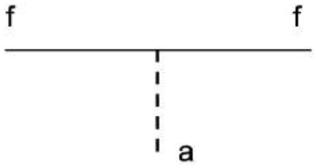




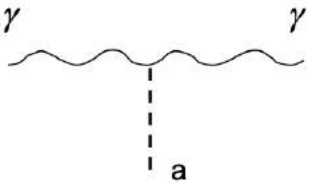




C. O'Hare, https://doi.org/10.5281/



$$\mathcal{L}_{a\bar{f}f} = i g_f \frac{a}{f_a} \bar{f}\gamma_5 f$$



$$\mathcal{L}_{a\gamma\gamma} = g_\gamma \frac{a}{f_a} \vec{E}\cdot\vec{B}$$

g_γ = 0.97 in KSVZ model
0.36 in DFSZ model

The axion *always* couples to two photons (through the anomaly) but may or may not couple to fermions depending on how it arises in the underlying particle physics model.

1) **KSVZ**: Only a scalar field σ with $f_a = \langle\sigma\rangle \gg v_F$, and a superheavy quark Q with $M_Q \sim f_a$ carry PQ charge i.e. $N = 1$

The KSVZ axion does not interact with leptons – *only* with light quarks

2) **DFSZ**: Adds a scalar field σ which carries PQ charge, with $f_a = \langle\sigma\rangle \gg v_F$, i.e. $N > 1$

The DFSZ axion interacts with *both* leptons and quarks and is thus more general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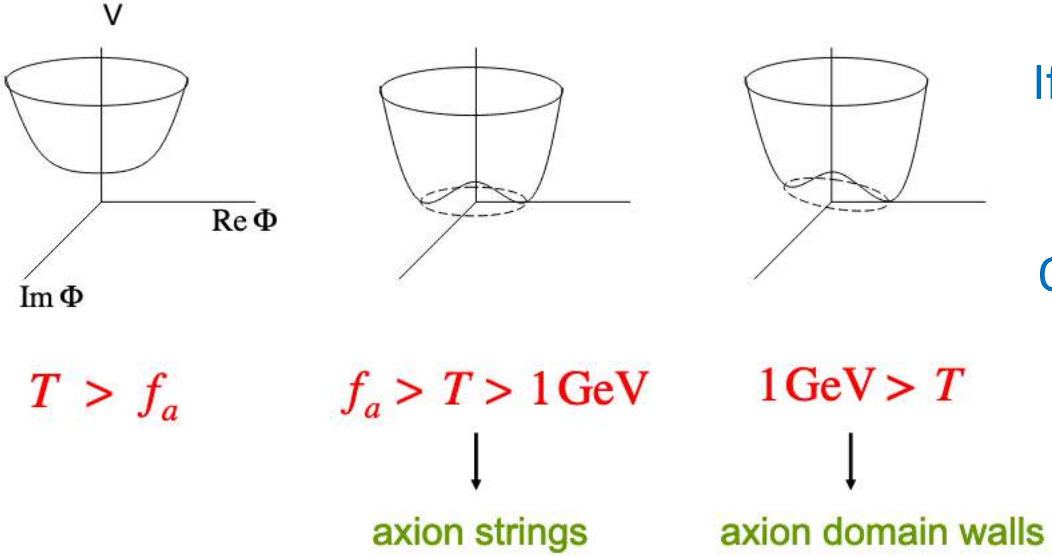


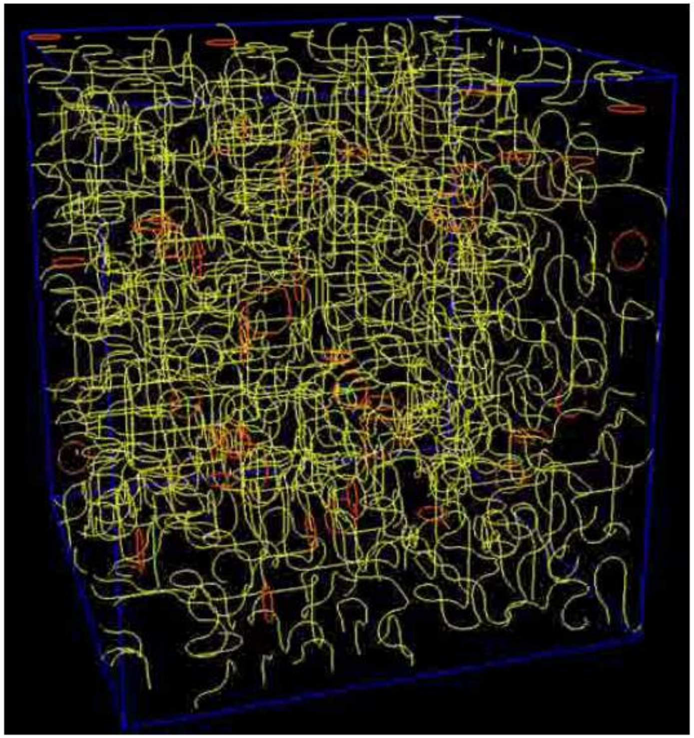
$T > f_a$

$f_a > T > 1\,\mathrm{GeV}$ ↓ axion strings

$1\,\mathrm{GeV} > T$ ↓ axion domain walls

If there are $N > 1$ quarks charged under $U(1)_{\mathrm{PQ}}$, then the Z_N symmetry leads to the formation of domain walls at the QCD scale … their energy density scales as $\rho_{\mathrm{wall}} \propto R^{-2}$ (*cf.* $\rho_{\mathrm{m}} \propto R^{-3}$, $\rho_{\mathrm{r}} \propto R^{-4}$) so they *must* decay soon afterwards

Sikivie, *PRL* 48:1156,1982



String interactions are complicated, understood by numerical simulations

String energy density follows a scaling law

$$\rho_{\mathrm{strings}} \simeq \xi \mu H^2$$

$$10^3 > \xi > 1$$

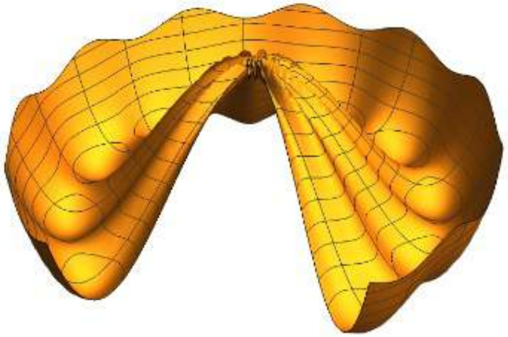
Equivalent to ξ strings per Hubble volume

Network is dominated by infinitely long strings with structure at scale 1/H

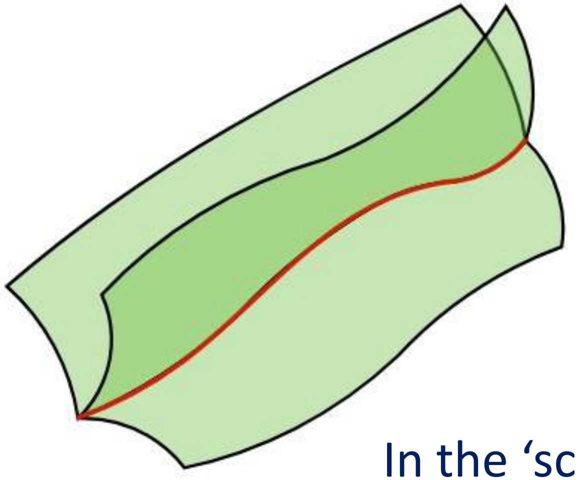
For massless axions:
Once formed, there are always a few strings per Hubble

Axions radiated from the string network contribute ~25% more DM (O'Hare et al, arXiv:2112.05117)

$U(1) \rightarrow \mathbb{Z}_N$



$$V(a) = m_a^2 f_{\mathrm{PQ}}^2 \left[1 - \cos(N_{\mathrm{DW}}\, a)\right]$$

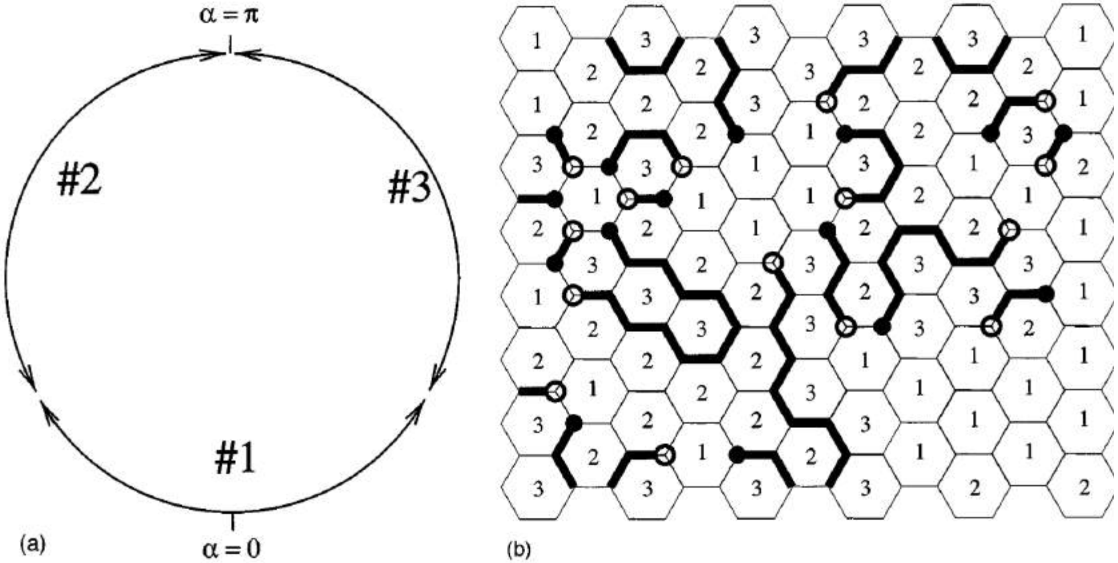


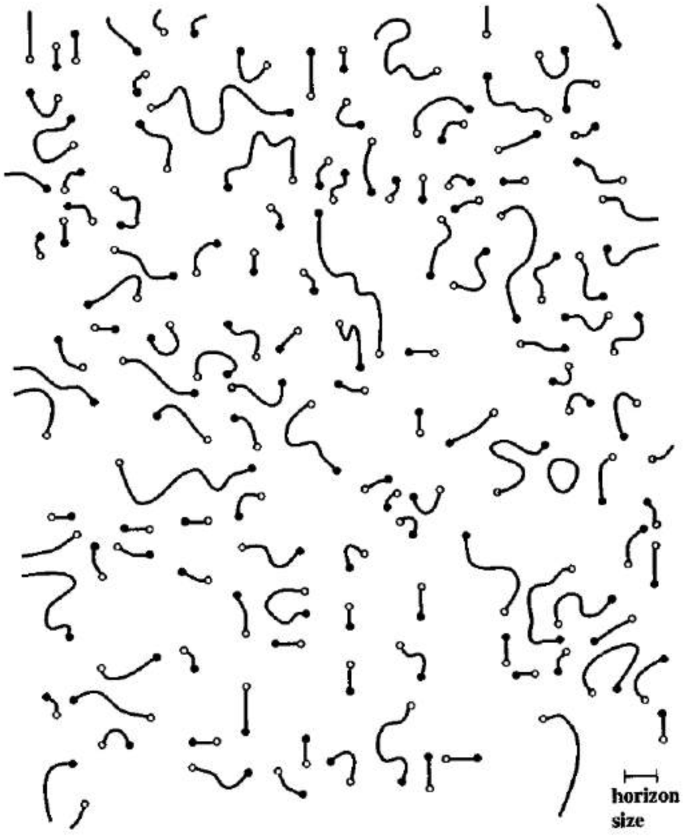
In the ‘scaling’ regime, there is $O(1)$ wall per Hubble volume

When $H < m_a$, domain walls ending on strings form

$N_{\mathrm{DW}} = 1$ String network disappears soon after

$N_{\mathrm{DW}} > 1$ String/domain wall network survives





Chang *et al*, *Phys.Rev.*D59:023505,1998

However discrete (global) symmetries are *violated* by quantum gravity effects …
This will induce a 'tilt' in the potential due to Planck scale suppressed operators

$$\delta V_{M_{\rm Pl}} = \frac{|g|\, e^{i\delta}}{M_{\rm Pl}^{2m+n-4}}\, |\phi|^{2m}\, \phi^n$$

$\Rightarrow V(a) = \mu\,[1 - \cos\,(n\,a + \delta)]$, where

$\mu \equiv |g|\; (M_{\rm Pl}/m_a)^2\; (f_{\rm PQ}/\sqrt{2}M_{\rm Pl})^{2m+n-2}$

Larsson, S.S. & White, *Phys.Rev.***D55**:5129,1997

Our numerical simulations showed that there is an *exponential* fall-off from the network 'scaling regime'

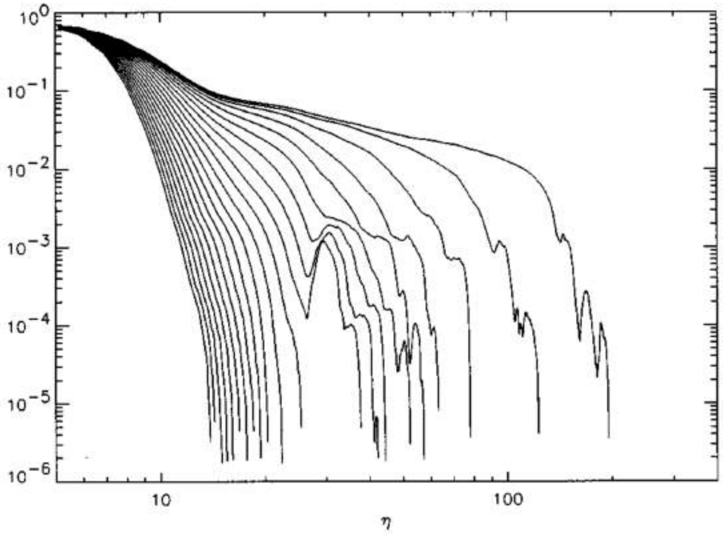
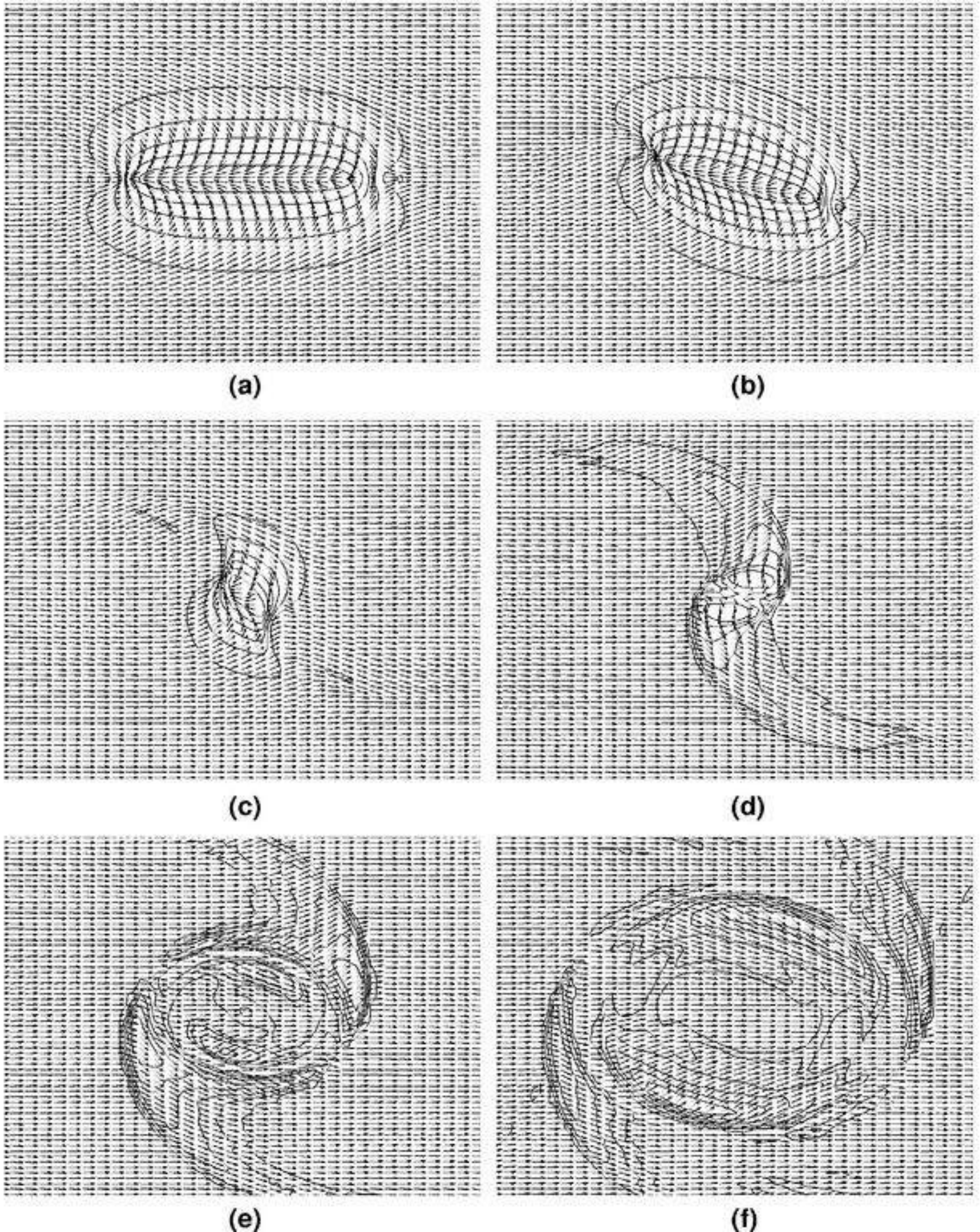


FIG. 2. Comoving area against conformal time in three dimensions, with the pressure μ in the range $0-0.2$.

Abel, White & S.S., *Nucl.Phys.***B454**:663,1995

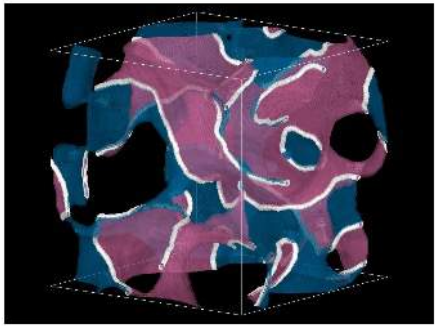
The wall network will then collapse, thus averting cosmological disaster
… the higher the 'tilt' the sooner can this happen (e.g. before BBN)



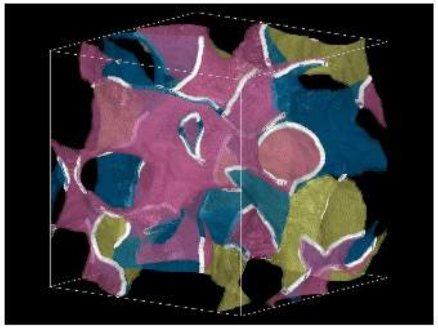
Domain wall bounded by string decaying into axion radiation

Chang *et al*, *Phys.Rev.*D59:023505,1998

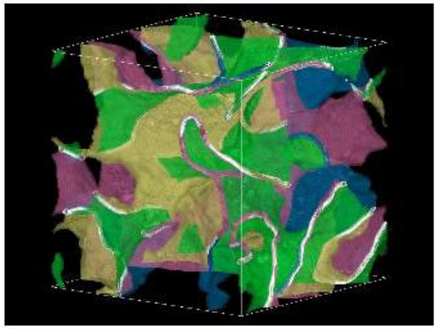
Detailed numerical simulations of the collapse of the domain wall network and the radiated spectrum of axions (and gravitational waves)



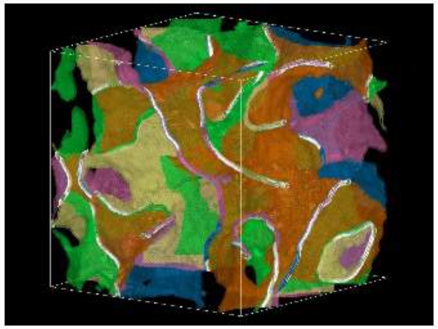
(a) $N_{\rm DW} = 2$



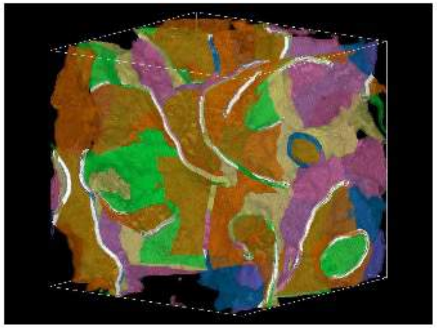
(b) $N_{\rm DW} = 3$



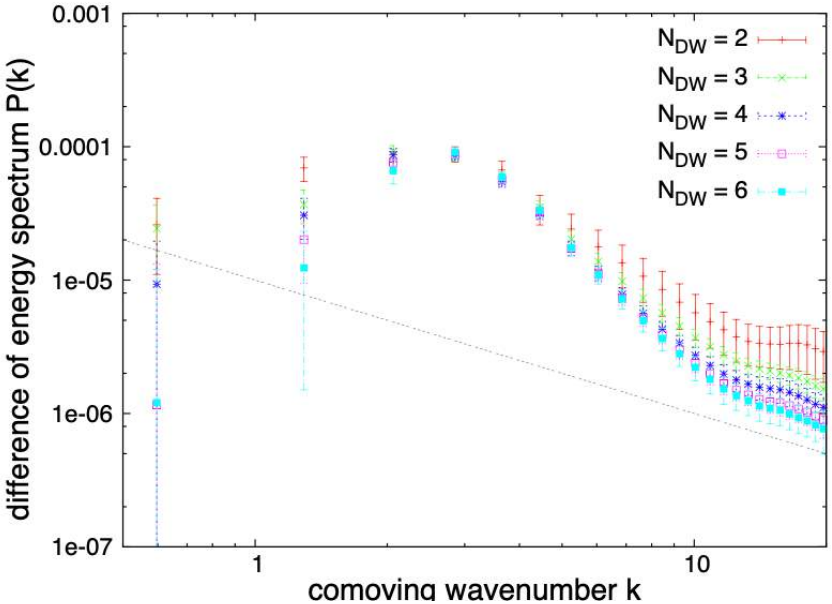
(c) $N_{\rm DW} = 4$

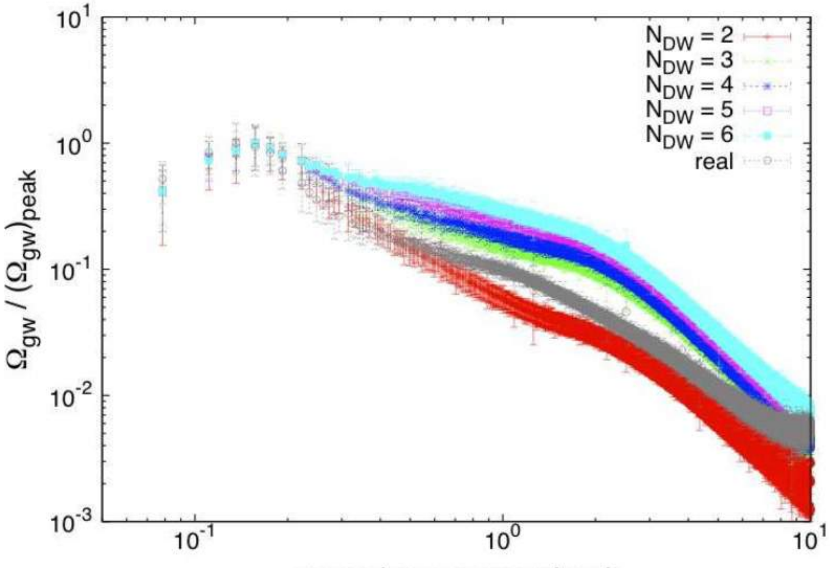


(d) $N_{\rm DW} = 5$



(e) $N_{\rm DW} = 6$





Hiramitsu, Kawasaki, Saikawa & Sekiguchi, JCAP **01**:001,2013

The decay of the wall network generates axions which are initially relativistic, but subsequently turn non-relativistic when $T \sim m_a$, effectively acting as *hot* dark matter

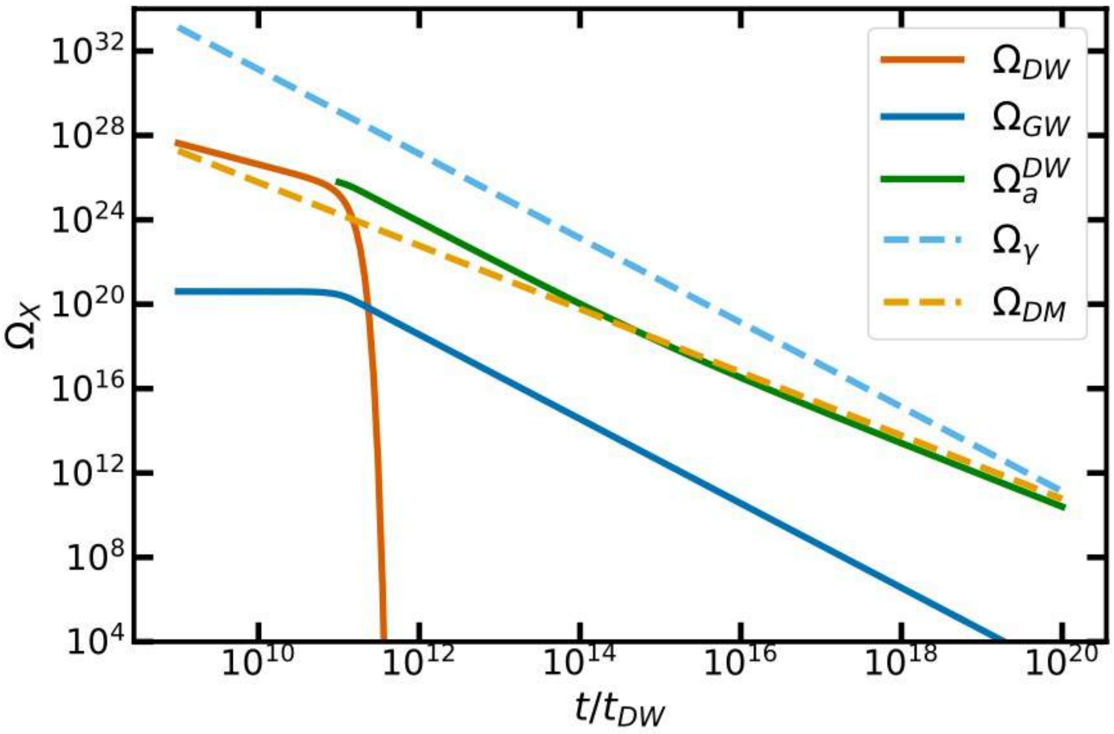
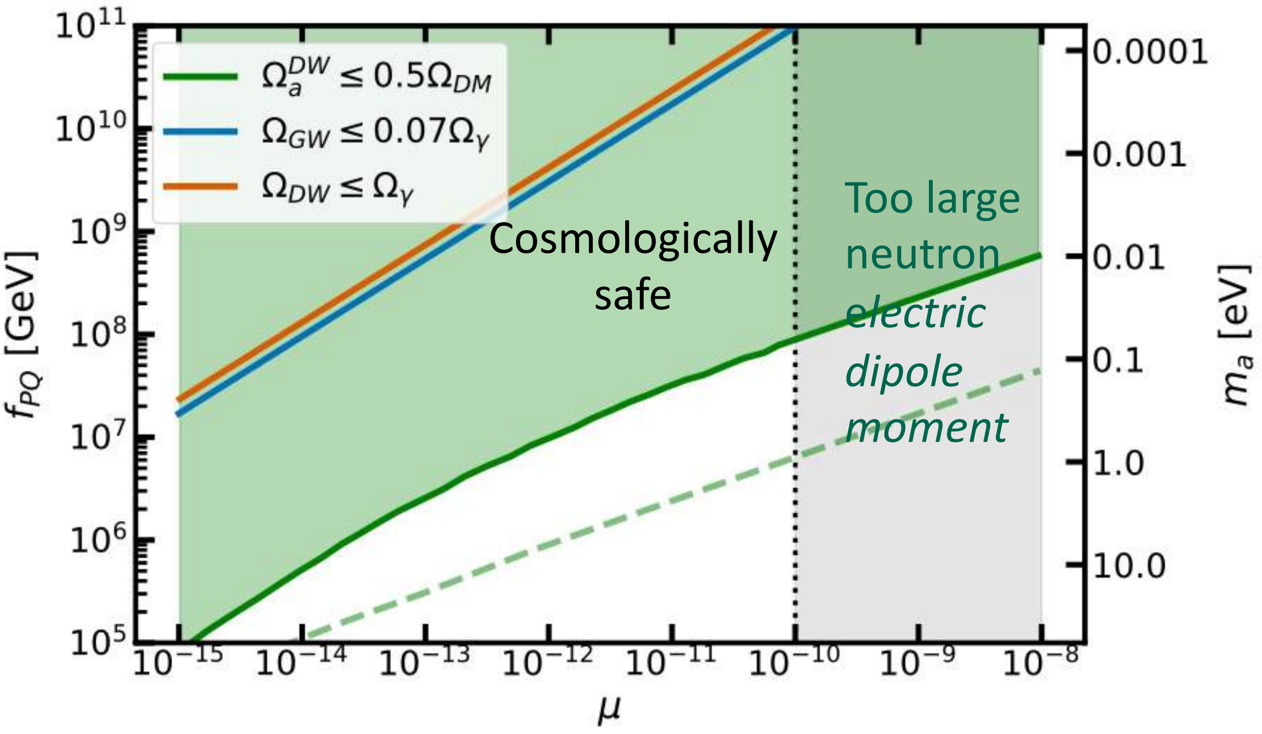


Figure 2: Evolution of various components of the energy density with time (in units of $t_{\rm DW} = m_a^{-1}$), for a tilt parameter $\mu = 10^{-11}$ and $f_{\rm PQ} = 2.7 \times 10^7$ GeV. The dashed blue (orange) line indicates the usual radiation (dark matter) content. The brown line indicates the axion domain walls which decay at $t_{\rm dec} \sim t_{\rm DW}/\mu$, and the blue and green lines correspond to their decay products, respectively gravitational waves and axions (taking $K = 100$). The latter turn non-relativistic at $t_{\rm nr} \sim t_{\rm dec} K^2$ and are taken to contribute half of the present dark matter abundance, the rest coming from the misalignment mechanism.

Beyer & S.S., arXiv:2211.14635

This requires the walls to decay essentially **as soon as they are born (**at $T \sim \Lambda_{\rm QCD}$) in order that the decay axions do not contribute more than a fraction $x_a \sim 0.5$ of the DM

But if the ‘tilt’ is large enough to make the wall network decay cosmologically safe, the breaking of the $\mathbb{Z}_N$ symmetry can violate the neutron EDM limit: $\langle\theta\rangle < 10^{-10}$!



Beyer & S.S., arXiv:2211.14635

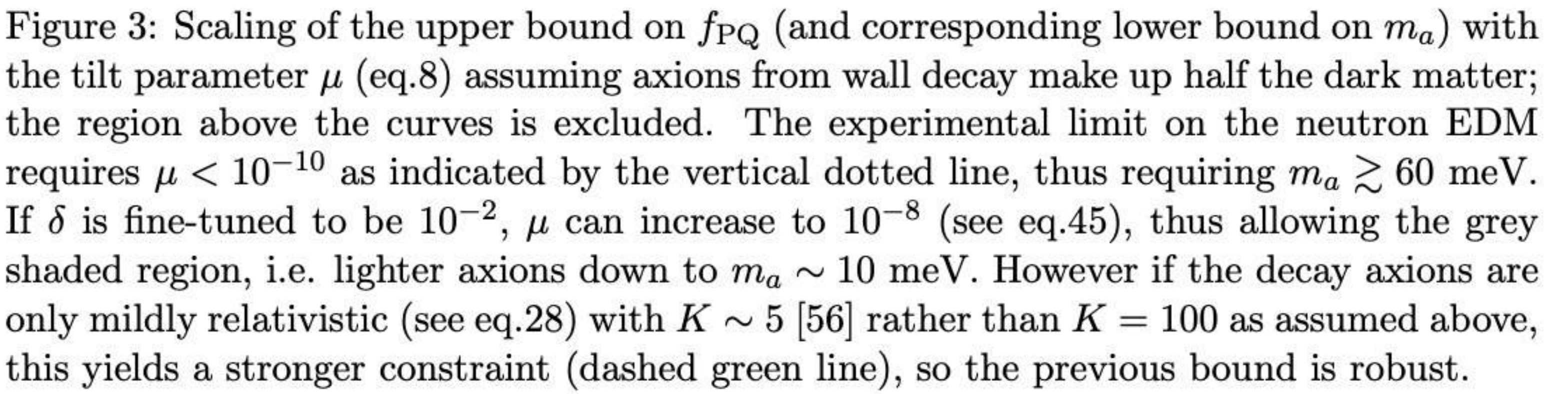


Figure 3: Scaling of the upper bound on $f_{\rm PQ}$ (and corresponding lower bound on m_a) with the tilt parameter μ (eq.8) assuming axions from wall decay make up half the dark matter; the region above the curves is excluded. The experimental limit on the neutron EDM requires $\mu < 10^{-10}$ as indicated by the vertical dotted line, thus requiring $m_a \gtrsim 60$ meV. If δ is fine-tuned to be 10^{-2}, μ can increase to 10^{-8} (see eq.45), thus allowing the grey shaded region, i.e. lighter axions down to $m_a \sim 10$ meV. However if the decay axions are only mildly relativistic (see eq.28) with $K \sim 5$ [56] rather than $K = 100$ as assumed above, this yields a stronger constraint (dashed green line), so the previous bound is robust.

This implies an *upper* limit on $f_{\rm PQ} < 10^8\,\mathrm{GeV}\,(x_a/0.5)^{-6/7} \Rightarrow m_a > 60\,\mathrm{meV}$

The ‘tilt’ solution to the axion domain wall problem is therefore severely constrained

$$\boxed{\frac{\log\left(1.6\times 10^{-91} N_{\rm DW}/n\right)}{\log\left(f_{\rm PQ}/\sqrt{2}M_{\rm Pl}\right)} < 2m+n < 1+\frac{\log\left(1.2\times 10^{-83}\right)}{\log\left(f_{\rm PQ}/\sqrt{2}M_{\rm Pl}\right)}}$$

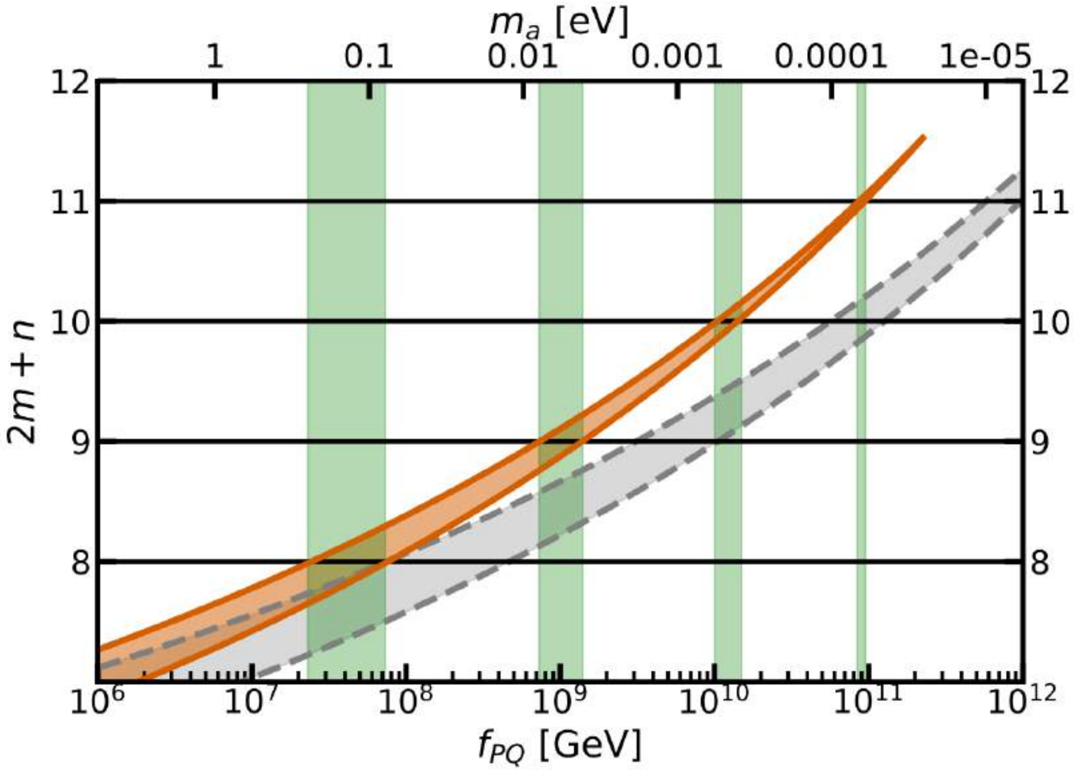
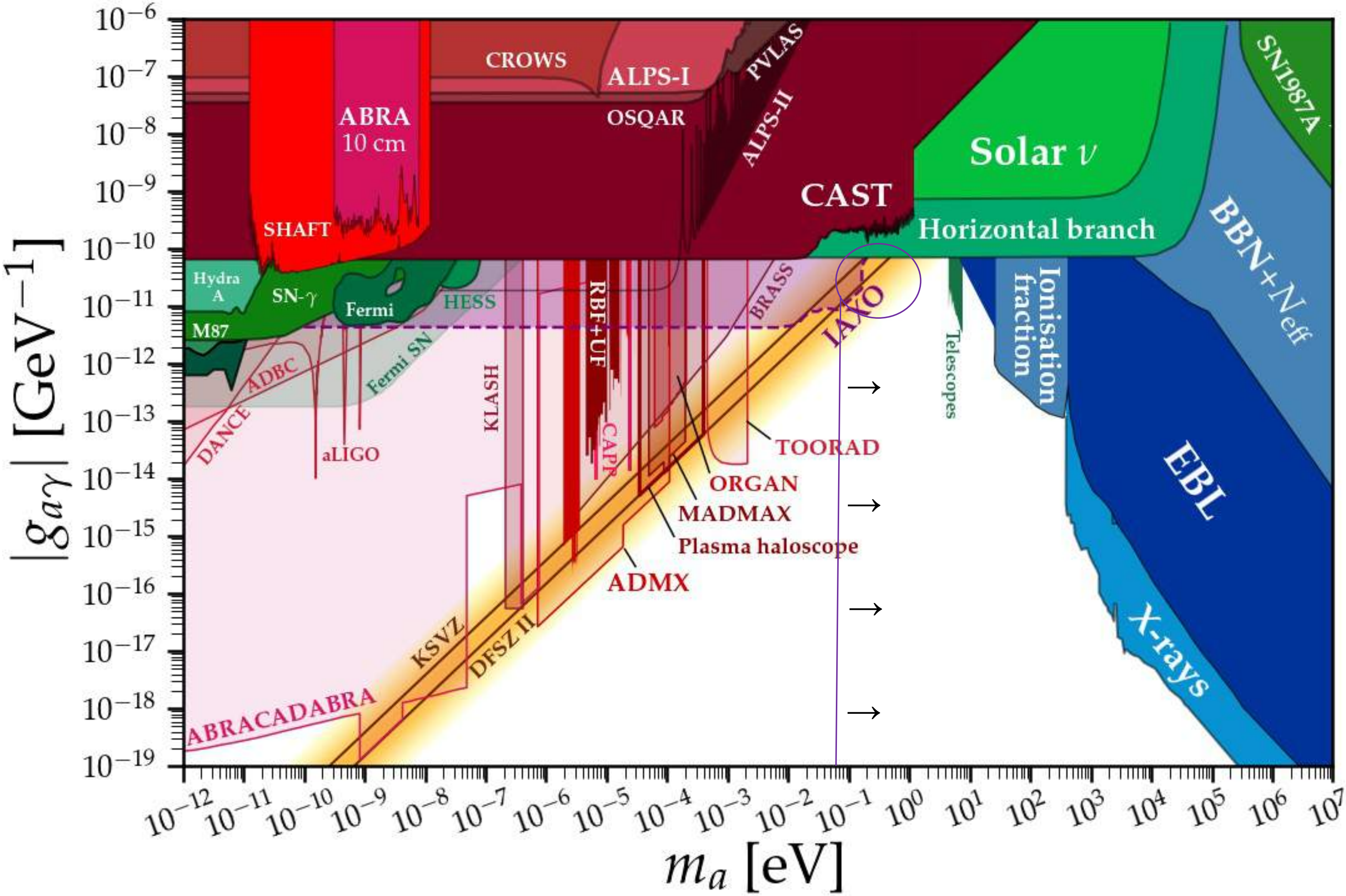


Figure 1: The dimension $2m+n$ of Planck scale suppressed non-renormalisable operators required to solve the axion domain wall problem, versus the Peccei-Quinn scale $f_{\rm PQ}$. The orange shaded region is allowed by the inequalities (17) derived in the text. The plot ends at $f_{\rm PQ} \sim 10^{11}\,{\rm GeV}\,N_{\rm DW}/n$ above which there is no solution. Moreover $2m+n$ must be an integer — which further restricts $f_{\rm PQ}$ to the green vertical bands. The grey shaded region (bounded by dashed lines) illustrates the mild relaxation of the constraint when the coupling $|g|$ and phase δ of the tilt operator are both fine-tuned to be 10^{-2}.

Beyer & S.S., arXiv:2211.14635

LIMITS & PROJECTIONS ON AXIONS (AND ALPs)



C. O'Hare, https://doi.org/10.5281/

Our bound strengthens case for experiments which probe QCD axion mass of ~ 0.1-1 eV

SUMMARY

- QCD axion models (DFSZ) where the Peccei-Quinn symmetry breaks after inflation have a potential problem with the formation of domain walls

- The domain wall network will come to dominate the Universe leading to (power-law) inflation with no end … i.e. an unacceptable cosmology

- The problem can be solved by evoking non-renormalizable, Planck scale suppressed operators (arising from quantum gravity) which violate the discrete global symmetry – the domain wall network will then decay

- However this generates an (unobserved) electric dipole moment of the neutron, hence such 'tilt' of the potential is phenomenologically restricted

- The opposing constraints then require that $f_{\mathrm{PQ}} < 10^8\,\mathrm{GeV} \Rightarrow m_a > 60\,\mathrm{meV}$

- Direct experiments targeting the axion mass range $\sim$ 0.1-1 eV* are thus necessary, e.g. using X-ray lasers (Beyer *et al*, *Phys.Rev.*D105:035031,2022)

*Such axions are supposedly excluded by SN1987a but may in fact account for observations of anomalous stellar cooling (Gianotti *et al*. *JCAP* **10**:010,2017)