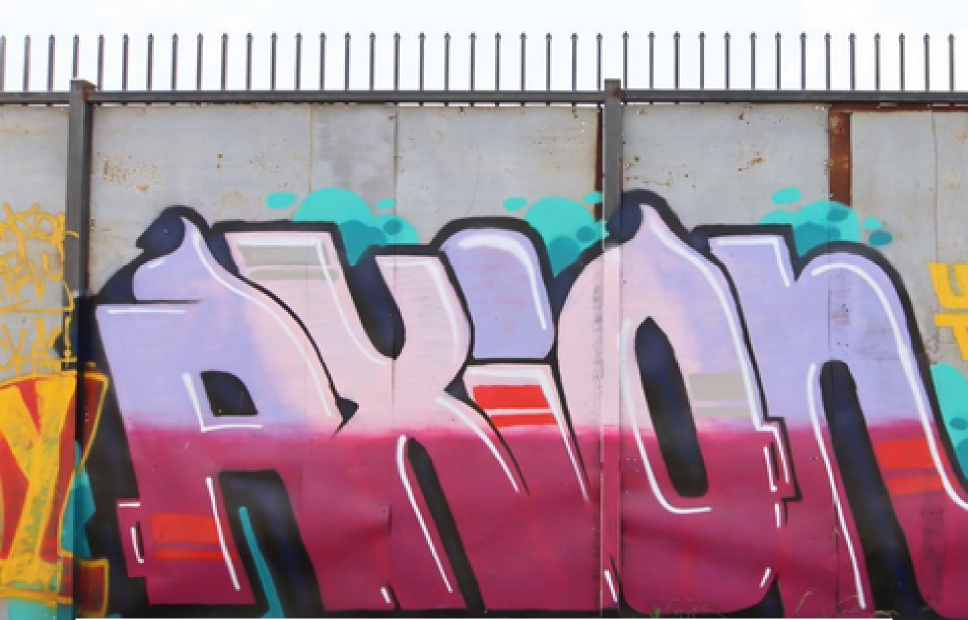


Francesc Ferrer, Washington University in St. Louis
SubirFest – Oxford, Sep 13, 2023

PHYSICAL REVIEW D **67**, 103005 (2003)

Clustering of ultrahigh energy cosmic rays and their sources

N. W. Evans
Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 OHA, United Kingdom

F. Ferrer and S. Sarkar
Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom
(Received 23 December 2002; published 22 May 2003)

The sky distribution of cosmic rays with energies above the "GZK cutoff" holds important clues to their origin. The AGASA data, although consistent with isotropy overall, shows evidence for small-angle clustering, and it has been argued that such clusters are aligned with BL Lacertae objects, implicating these as the sources. It has also been suggested that such clusters can arise if the cosmic rays come from the decays of very massive relic particles in the galactic halo, due to the expected clumping of cold dark matter. We examine these claims and show that both are, in fact, unjustified.

PHYSICAL REVIEW D **69**, 128302 (2004)

Reply to "Comment on 'Clustering of ultrahigh energy cosmic rays and their sources'"

N. W. Evans,[1] F. Ferrer,[2] and S. Sarkar[2]

[1] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 OHA, United Kingdom*

[2] *Theoretical Physics, University of Oxford, 1 Keble Road, Oxford OX1 3NP, United Kingdom*

(Received 2 March 2004; published 30 June 2004)

We reiterate that there is no evidence that BL Lacs are sources of ultrahigh energy cosmic rays.

DOI: 10.1103/PhysRevD.69.128302 PACS number(s): 98.70.Sa

Tinyakov and Tkachev (TT) [1] have claimed that "BL Lacertae are sources of the observed ultrahigh energy cosmic rays" (UHECRs). They considered a set of 39 UHECRs with $E > 4.8 \times 10^{19}$ eV observed by the Akeno Giant Air Shower Array (AGASA) and 26 UHECRs with $E > 2.4 \times 10^{19}$ eV ob-

considered. Therefore we reassert that there is no justification for ascribing any significance to coincidences between Yakutsk events and BL Lacs within 2.5°.

To demonstrate this quantitatively we have calculated the autocorrelation functions of the selected AGASA and

Why axions?

- Well-motivated: strong CP-problem, promising DM candidates, …
- Broad experimental program based on $g_{a\gamma\gamma}$: axions transform into photons in external magnetic fields (and vice versa), …
- Less constrained ALPs naturally appear in UV completions of the SM.
- Rich early universe phenomenology.

OUTLINE

Introduction

Why axions?

- Well-motivated: strong CP-problem, promising DM candidate, …
- Broad experimental program based on $g_{a\gamma\gamma}$: axions transform into photons in external magnetic fields (and vice versa), …
- Less constrained ALPs naturally appear in UV completions of the SM.
- Rich early universe phenomenology.

The theta term:

$$\mathcal{L}_{\text{QCD}} \supset \theta \frac{g_3^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu},$$

where $0 \leq \theta \leq 2\pi$ violates CP. E.g. it predicts a neutron electric dipole moment

$$d_e \sim \bar{\theta} \times 10^{-15} \text{ e-cm},$$

but experimentally $d_e \lesssim 3 \times 10^{-25}$ e-cm, so $\bar{\theta} \lesssim 10^{-10}$ should be tiny. Why?

The solution: the PQ axion

- Couple a pseudoscalar field to $G\tilde{G}$:

$$\theta = \mathcal{C} a / f_a .$$

- The axion field has a shift symmetry $a \to a +$ const, only derivatives $\partial_\mu a$ appear in the action.
- Non-perturbative QCD instanton effects generate a potential that is minimized at $a = 0$ (mod $2\pi / N_{DW}$), which dynamically solves the strong CP problem.

Axion properties

In typical UV completions the axion appears as the Goldstone boson of a global $U(1)$ PQ-symmetry, which is spontaneously broken at some high-energy scale f_a.
The PQ-symmetry is explicitly broken by quantum effects (instantons) that emerge at Λ_{QCD} and induce a mass:

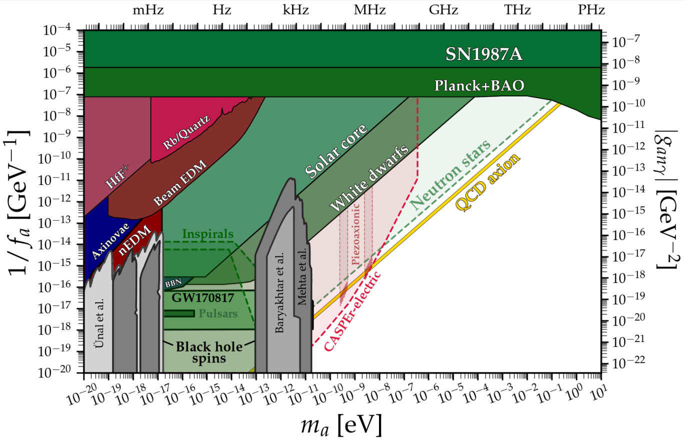
$$m_{a,QCD} \sim \Lambda_{QCD}^2/f_a \approx 6 \times 10^{-6}\ \mathrm{eV}\left(\frac{10^{12}\ \mathrm{GeV}}{f_a/\mathcal{C}}\right).$$

At low energies, axions can have model dependent couplings to SM particles:

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - m_a^2 a^2 - \sum_{e,p,n} g_{aff}\partial_\mu(a)\bar{\psi}\gamma^\mu\gamma_5\psi - \frac{1}{4}g_{a\gamma\gamma}aF\tilde{F} + \ldots$$

where the couplings are suppressed by a large energy scale, $\propto 1/f_a$.

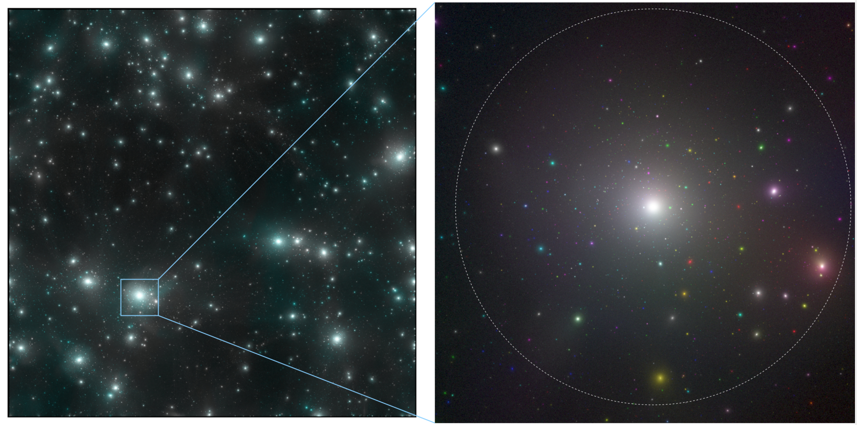
AXIONS AND ALPS



Ciaran O'Hare, https://doi.org/10.5281/zenodo.3932430

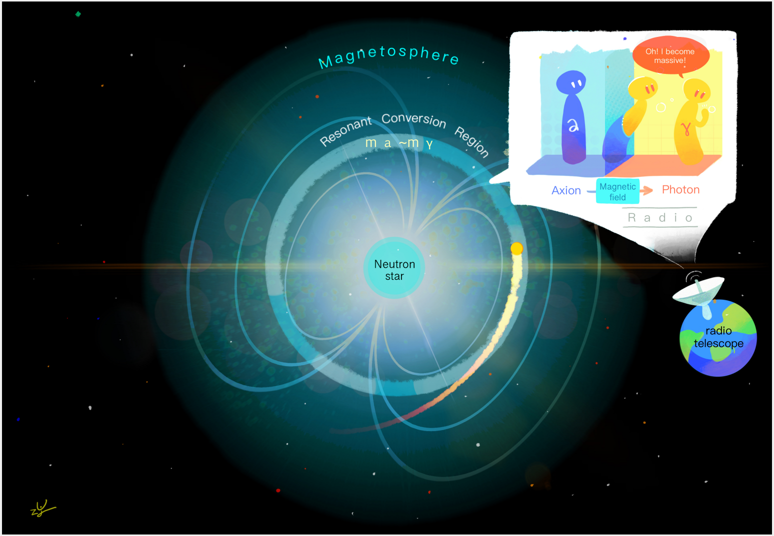
QCD axions can be DM for $m_a \sim 10^{-5} - 10^{-3}$ eV.

Axion miniclusters



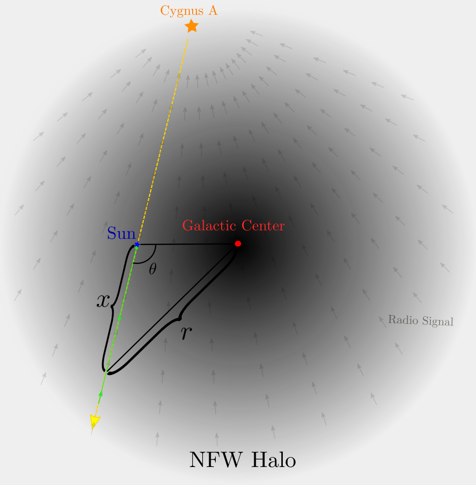
Eggenmeier et al 1911.09417

FRBs



Izawaki PRD 2015; Raby PRD 2016; Pshirkov IJMPD 2017; Buckley, Dev, FF, Huang PRD 2021

GEGENSCHEIN



Ghosh,Salvadó,Miralda-Escudé 20; Witte et al. 21; Arza and Sikivie 21; Sun et al 21; Buen-Abad et al 21

Dangerous walls

SciPost Physics Submission

Ruling out light axions: the writing is on the wall

Konstantin A. Beyer* and Subir Sarkar

Rudolf Peierls Centre for Theoretical Physics, Parks Road, Oxford OX1 3PU, UK
(*Current address: konstantin.beyer@mpi-hd.mpg.de)

2 May 2023

Abstract

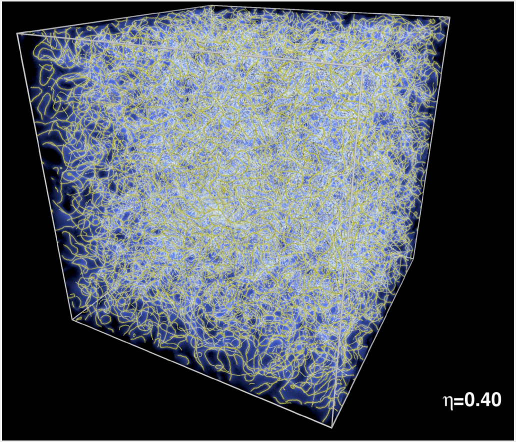
We revisit the domain wall problem for QCD axion models with more than one quark charged under the Peccei-Quinn symmetry. Symmetry breaking during or after inflation results in the formation of a domain wall network which would cause cosmic catastrophe if it comes to dominate the Universe. The network 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 vacua, but we find that this mechanism is in practice


UNO
TKO

COSMOLOGICAL EVOLUTION II: STRING NETWORK

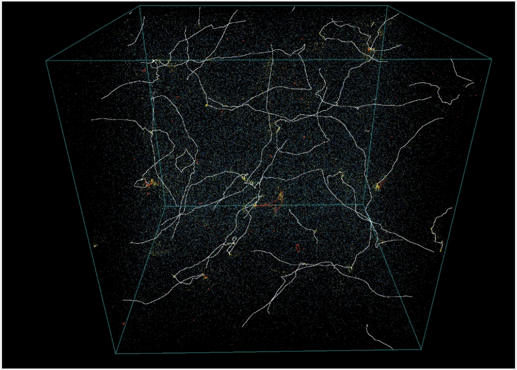
The breaking of the global U(1) symmetry will lead to the formation of a network of cosmic strings.

Kibble 76



Buschmann, Foster & Safdi 20

The network enters a scaling regime, where loops are produced that decay into axions.

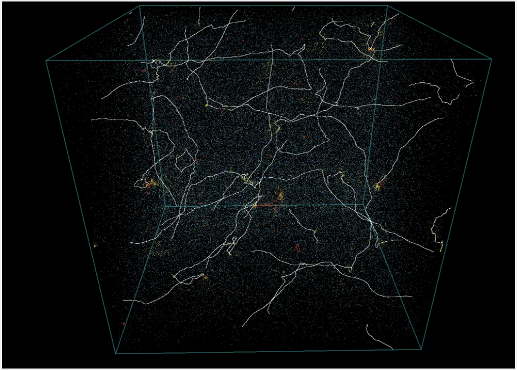


Vachaspati, Pogosian & Steer 15

.

Network evolution

The network enters a scaling regime, where loops are produced that decay into axions.



Vachaspati, Pogosian & Steer 15

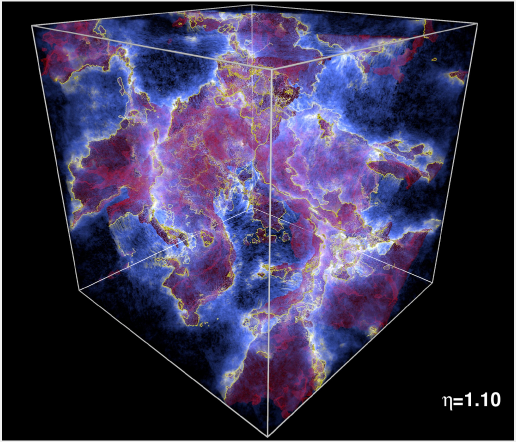
Although logarithmic deviations from scaling have been observed.

Gorgetto, Hardy & Villadoro 18

Cosmological evolution III: QCD PT

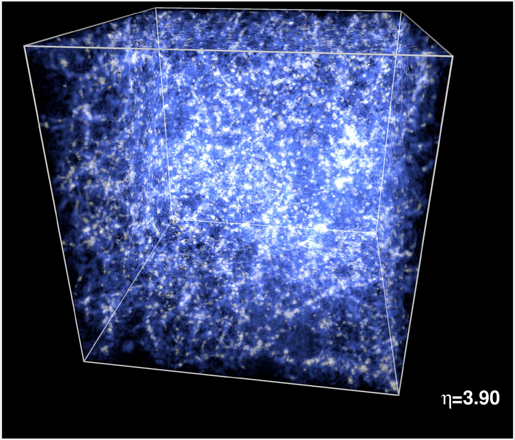
At the QCD phase transition, instanton effects generate the axion potential and domain walls appear.

Vilenkin & Everett 82



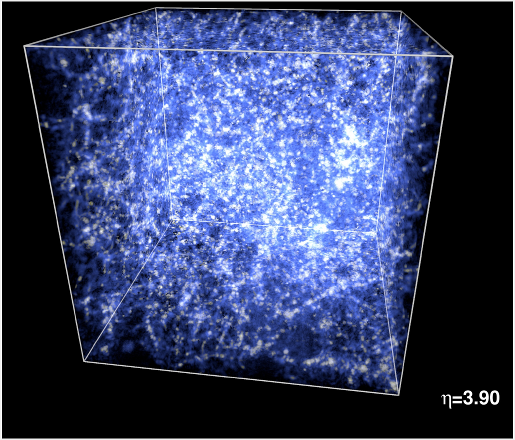
Buschmann, Foster & Safdi 20

The network quickly annihilates into axions due to string and DW tension.



Buschmann, Foster & Safdi 20

The network quickly annihilates into axions due to string and DW tension.

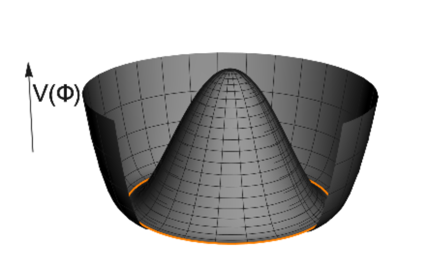


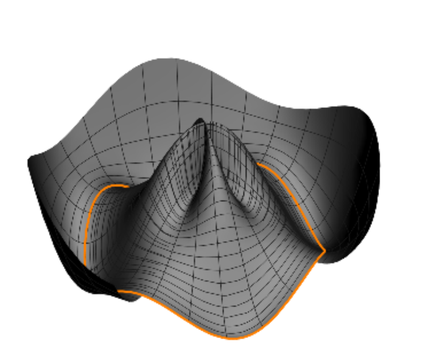
Buschmann, Foster & Safdi 20

Except...

Long-lived networks

If $N_{DW} > 1$ the network is stable!

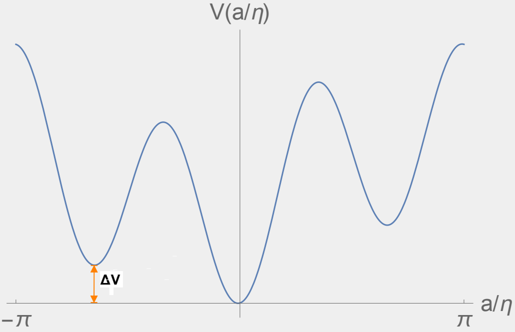




Chadha-Day, Ellis, Marsh 21

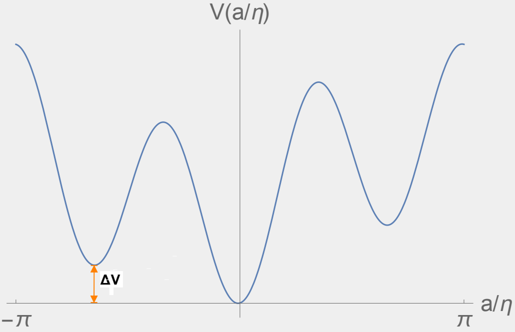
DW problem?

Lift the degeneracy of axionic vacua by introducing a bias term (dark QCD?). The energy difference between the different minima acts as a pressure force on the corresponding domain walls.



DW PROBLEM?

Lift the degeneracy of axionic vacua by introducing a bias term (dark QCD?). The energy difference between the different minima acts as a pressure force on the corresponding domain walls.



But, for ultra-light ALPs, the walls are so light that they could still exist today.

Walls can be trendy too

And? Can we dectect it?

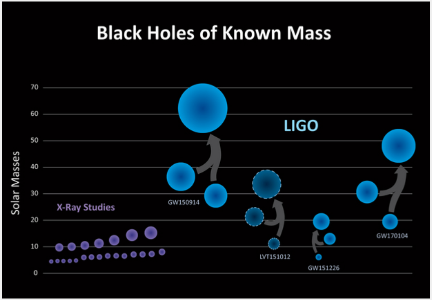
- For the QCD axion it could produce PBHs.

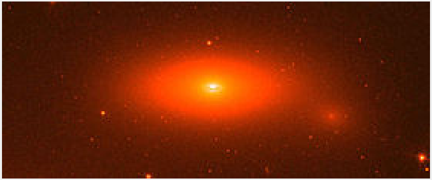
FF, E. Massó, G. Panico, O. Pujolàs, F. Rompineve, PRL 122, 101301 (2019)

- For ultra-light axions it can leave imprints in the CMB.

Agrawal, Hook & Huang 20; Jain, Hagimoto, Long & Amin 22

Non-astrophysical BHs?





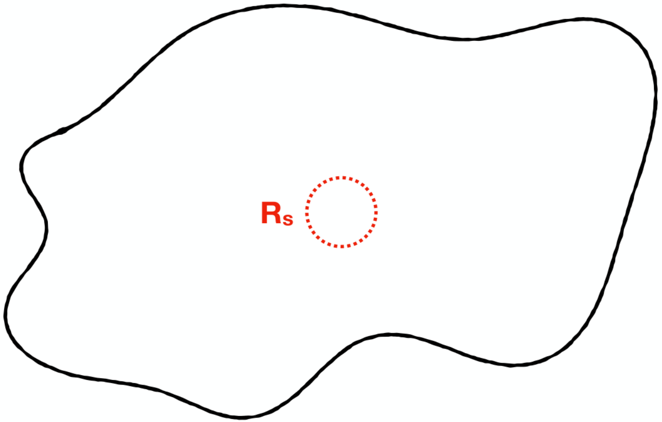
PBHs from string-wall defects

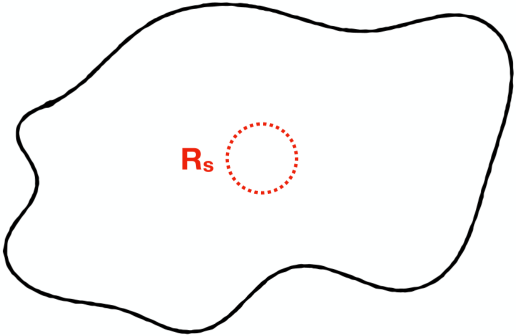
A closed DW of size R_* will rapidly shrink because of its own tension, once $R_* \sim H^{-1} \approx g_{\rm eff}(T_*)^{-1/2} M_p / T_*^2$.

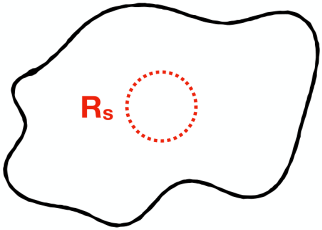
Its mass has contributions from the wall tension and from any difference in energy density between the two regions separated by the DW:

enddisplaymath $\Rightarrow$ Heavier black holes form from DW which collapse later in cosmological history.

FORMING THE BLACK HOLE




R_s


Rs

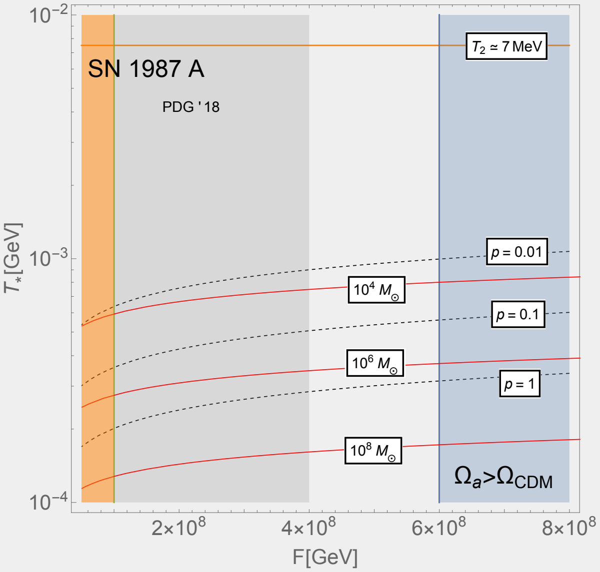
But, $1 - 10\%$ of the walls survive until $\sim 0.1 T_2$, when:

- $p \sim 1$
- $M_* \sim 10^6 M_\odot$

$\Rightarrow$ A fraction $f \sim 10^{-6}$ of the DM end up forming SMBHs!

B. Carr & J. Silk, 1801.00672

LATE COLLAPSES



At $T \sim f_a$, the global PQ is spontaneously broken. Is there any indication that it took place?

- If the transition is strongly first order it could generate stochastic gravitational waves.
- If 10^3 GeV $\lesssim f_a \lesssim 10^8$ GeV, the GW frequency falls in the range of LIGO and several proposed future observatories.

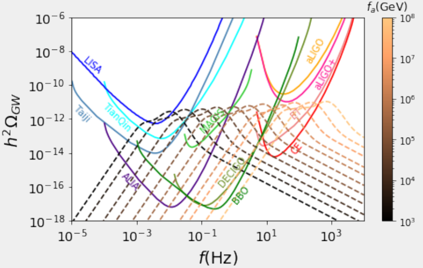
Let us consider a KSVZ-like axion model:

$$\mathcal{V}_{\prime} = -\mu^2|H|^2 + \lambda|H|^4 + \kappa|\Phi|^2|H|^2 + \lambda_a\left(|\Phi|^2 - f_a^2/2\right)^2.$$

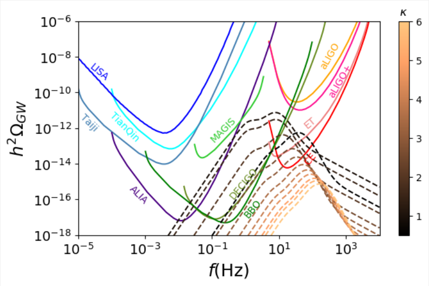
B. Dev, FF, Y. Zhang & Y. Zhang, JCAP (2019)

GW DETECTION PROSPECTS

$10^3\,\mathrm{GeV} < f_a < 10^6\,\mathrm{GeV}, \kappa = 1, \lambda_a = 0.001$



$0.001 < \lambda_a < 0.2, \kappa = 1, f_a = 10^6\,\mathrm{GeV}$



The PT in our scenario is not strong enough for LIGO, but it could be detected in the future. Stronger GW backgrounds are generated for Coleman-Weinberg-type symmetry breaking which leads to supercooling (Von Harling, Pomarol, Pujolàs & Rompineve, JHEP 20; Delle Rose, Panico, Redi & Tesi, JHEP 20).

Conclusions

Axions are well motivated DM candidate, with a rich phenomenology. However, Subir warns us that we must be careful when embedding axions in a particle physics model.

- If $f_a < H_{\mathrm{inf}}$, we generically expect an additional contribution to the relic density from the decay of topological defects. At a minimum, this shifts the target mass that experiments should focus.
- Once tamed by Subir, we gain access to a wealth of measurable relics: PBHs of up to $10^6 M_\odot$, stochastic waves that are being mapped by PTA, ...
- For lighter ALPs, the CS-DW network could be present after recombination. Interesting signals could be imprinted in the CMB.

CONCLUSIONS

Axions are well motivated DM candidate, with a rich phenomenology. However, Subir warns us that we must be careful when embedding axions in a particle physics model.

- If $f_a < H_{\text{inf}}$, we generically expect an additional contribution to the relic density from the decay of topological defects. At a minimum, this shifts the target mass that experiments should focus.
- Once tamed by Subir, we gain access to a wealth of measurable relics: PBHs of up to $10^6 M_\odot$, stochastic waves that are being mapped by PTA, ...
- For lighter ALPs, the CS-DW network could be present after recombination. Interesting signals could be imprinted in the CMB.

Per molts anys, Subir!