Title: GWs from high-quality axionic defects

Speakers: Oriol Pujolas

Series: Particle Physics

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Abstract: The axion solution to the strong CP problem has many virtues but it suffers from the so-called quality problem. This problem is avoided in heavy axion realizations which, however, are harder to probe experimentally. I will show how generic heavy axion models can be tested in current and future gravitational wave (GW) observatories, due to the cosmological GW background produced by the axionic topological defects. Moreover, the resulting GW signal is correlated with a sizable strong CP phase, within reach of upcoming neutron electric dipole moment measurements.

Zoom link: https://pitp.zoom.us/j/99150077172?pwd=UWhkZVdzV2lCQittWXVtMnludXBkUT09

GWs from high-quality axionic defects

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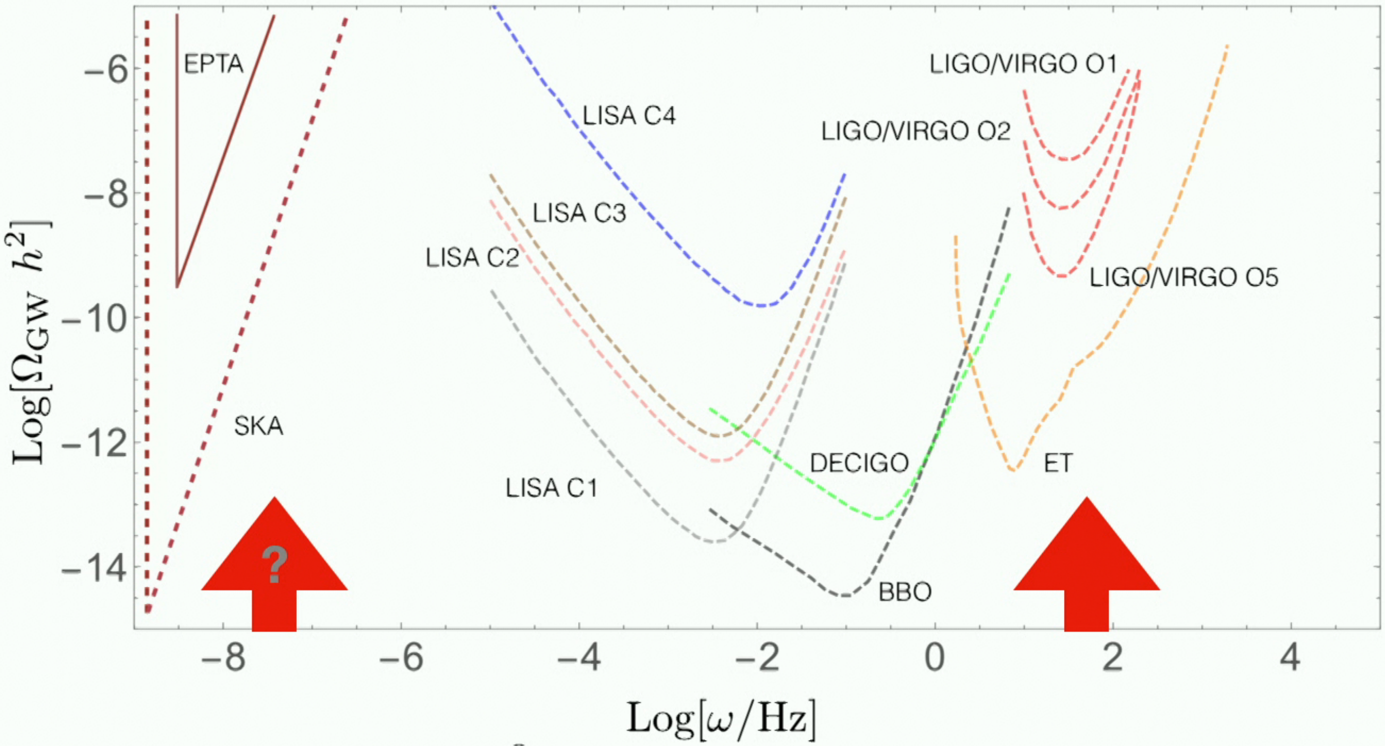
GWs

- **LIGO/Virgo/Kagra, PTAs (and coming): new window, with impressive views!**



GWs

- **LIGO/Virgo/Kagra, PTAs (and coming): new window, with impressive views!**
- **From HEP perspective: relic stochastic GWB**
- **E.g., LVK sensitive to cosmological phase transitions at *$T \sim 10^8$ GeV***

—> close to a *usual suspect*: Peccei-Quinn scale, *10^9 — 10^{11} GeV*

plan

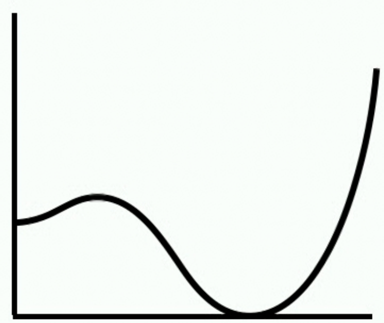
I) GWs from a 1st order Peccei Quinn transition

II) GWs from strings & domain walls in heavy axions

→ post-inflationary P̸Q̸ — most constrained, but *still* viable

10^9 GeV < f_a < 10^{11} GeV

I) GWs from a 1st order Peccei Quinn transition



Peccei-Quinn Phase Transition at LIGO

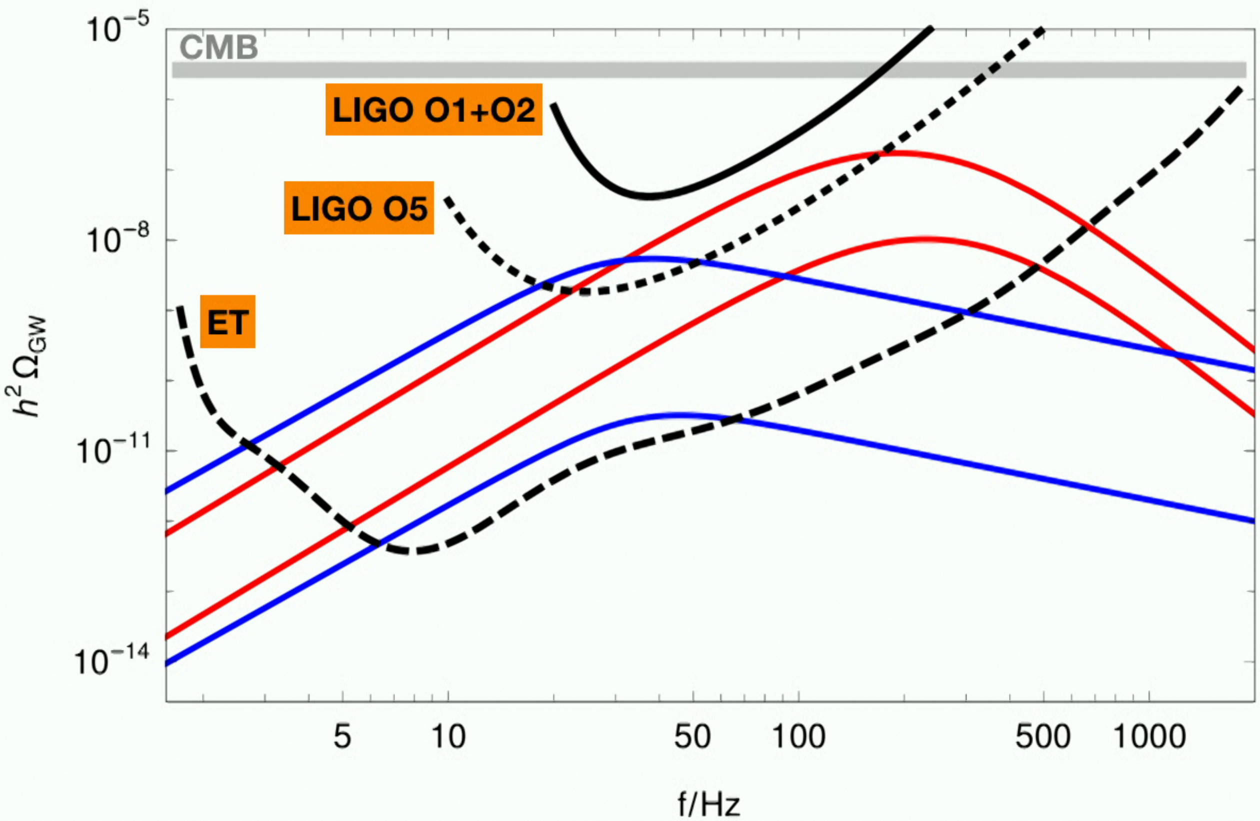
Benedict von Harling[a], Alex Pomarol[a,b], Oriol Pujolàs[a]

and Fabrizio Rompineve[c]

arXiv:1912.07587
JHEP 04 (2020) 195

also:
arXiv:1912.06139
JHEP 04 (2020) 025
Delle Rose, Panico, Redi, Tesi

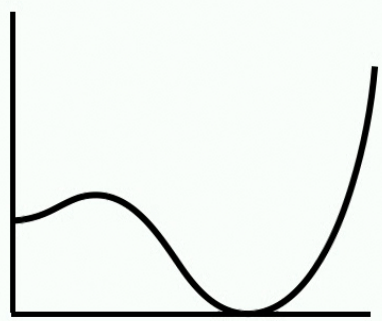
Are there axion models with strong enough 1st order transition to lead to detectable GWs at LVK?



$F_a = 10^8\ GeV\ with\ \alpha \approx 3.5$ $\qquad$ $F_a = 10^9\ GeV\ with\ \alpha \sim 10^6$

"ABC" of (1st order) cosmological phase transitions

$\alpha = \frac{\Delta V}{\rho_\gamma(T_n)}$	latent heat (~strength)
$\beta = \frac{\dot{\Gamma}}{\Gamma}\Big\rvert_{T_n}$	inverse duration
$\Gamma = \mathcal{A}\, e^{-S_B}$	nucleation rate
T_n	nucleation temperature
T_*	transition completed



Axion models with strong PT:

✗ • **KSVZ** (Kim, Shifman, Vainshtein, Zakharov)

=> ***extra heavy quarks with PQ-charge***

✓ • **DFSZ** (Dine, Fischler, Srednicki, Zhitnitsky)

=> ***extra Higgs doublet with PQ-charge***

$$V = \lambda_\phi(|\Phi|^2 - f^2/2)^2 + |H_1|^2(\kappa_1|\Phi|^2 - \mu_1^2) + |H_2|^2(\kappa_2|\Phi|^2 + \mu_2^2) - (\kappa_3\Phi^n H_1 H_2 + h.c.)$$
$$+ \lambda_1|H_1|^4 + \lambda_2|H_2|^4 + \lambda_3|H_1 H_2|^2 + \lambda_4|H_1|^2|H_2|^2 \,,$$

DFSZ type models give strong PT

when close to scale invariant

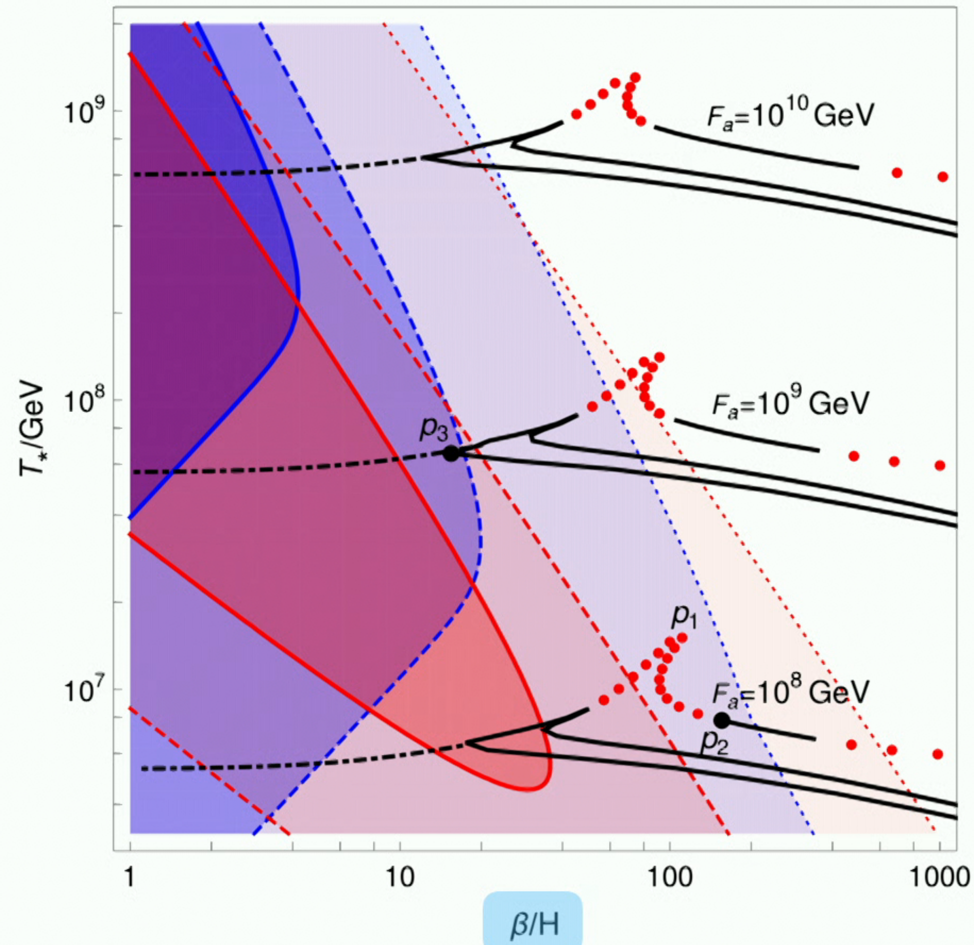
$$\mu_2^2, \lambda_\phi f^2 \ll f^2$$

$$V = \frac{1}{4}\lambda_\phi(\phi)\phi^4$$

$$T_* \simeq 0.1\sqrt{\kappa_2}\, F_a$$

T_* **is ~ 1 order of magnitude below** F_a

(solid black line: $\alpha > 3$)

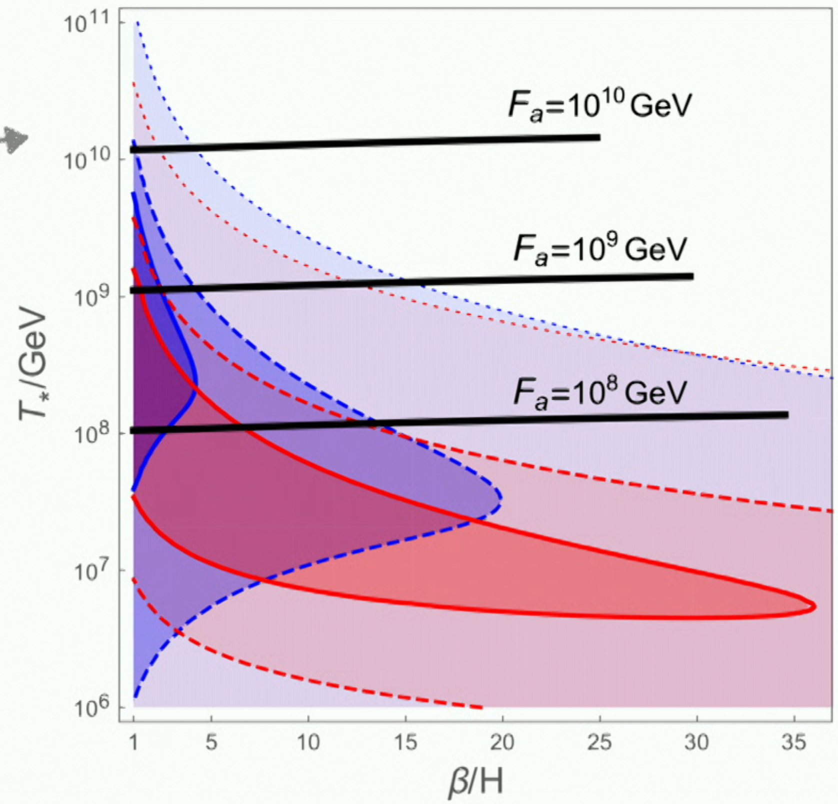


KSVZ/DFSZ can be embedded in larger new physics sectors

- **SUSY version of KSVZ**
- **Strong dynamics**

both of them also lead to strong PTs

already ruling-out some parameter space!



LIGO/Virgo search on SGWB from 1st order phase transitions:

Phys.Rev.Lett. 126 (2021) 15, 151301
arXiv:2102.01714

Phenomenological model (bubble collisions)				
$\Omega^{95\%}_{\rm coll}$ (25 Hz)				
$\beta/H_{\rm pt} \setminus T_{\rm pt}$	10^7 GeV	10^8 GeV	10^9 GeV	10^{10} GeV
1	1.0×10^{-8}	8.4×10^{-9}	5.0×10^{-9}	–
10	4.0×10^{-9}	6.3×10^{-9}	–	–

TABLE III: The 95% CL upper limits on $\Omega^{95\%}_{\rm coll}(25\ {\rm Hz})$ for fixed values of $\beta/H_{\rm pt}$ and $T_{\rm pt}$, and $v_{\rm w} = \kappa_\phi = 1$. The dashed lines denote no sensitivity for exclusion.

=> some models start to getting ruled out already

Conclusions

- **LIGO/Virgo are sensitive to cosmological phase transitions in the early universe at around $10^8 GeV$ – HEP!**
- **Relevant for axion physics: we can tell whether PQ phase transition was strong!**
- **LVK are sensitive to PQ models close to scale invariant (Coleman-Weinberg): DFSZ, strong dynamics, SUSY-KSVZ…**
- **Prospects for the CE & ET are promising**
- **Complementary to other gravitational axion tests, superradiance**

II) GWs from strings & domain walls in heavy axions

II) GWs from strings & domain walls in heavy axions

High Quality QCD Axion at Gravitational Wave Observatories

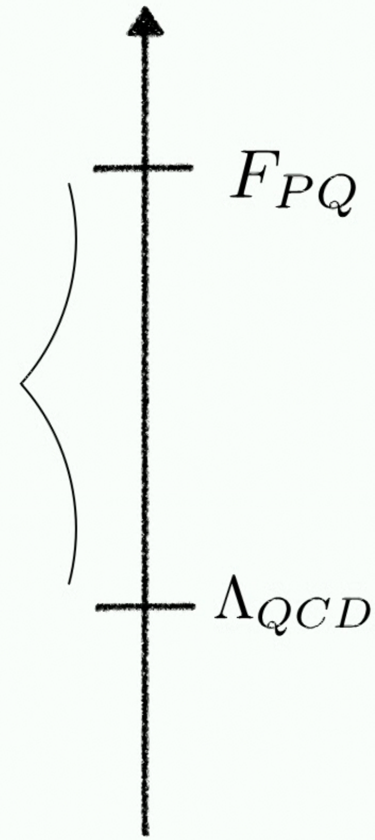
Ricardo Z. Ferreira,[1,*] Alessio Notari,[2,†] Oriol Pujolàs,[1,‡] and Fabrizio Rompineve[3,§]

arXiv:2107.07542 **Phys.Rev.Lett. 128 (2022) 14, 141101**

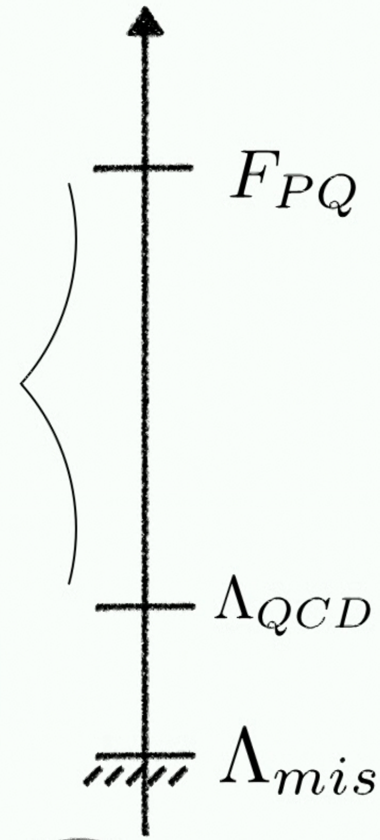
Axion *quality problem*

Axion solution to the strong CP problem (aka, Peccei-Quinn mechanism): only QCD contributes to *V(a)*

Solution can be spoiled by *any* other "misaligned" sector



Axion *quality problem*



Axion solution to the strong CP problem (aka, Peccei-Quinn mechanism): only QCD contributes to *V(a)*

Solution can be spoiled by *any* other "misaligned" sector

$$V(a) = \Lambda^4_{QCD}\Big(1 - \cos(a)\Big) + \Lambda^4_{mis}\Big(1 - \cos(a+\delta)\Big)$$

strong CP solved <=> $\Delta\theta = \sin\delta \, \frac{\Lambda^4_{mis}}{\Lambda^4_{QCD}} \lesssim 10^{-10}$

From the 'PQ-EFT' perspective, misaligned terms

$$c_N \frac{\Phi^{4+N}}{M^N} \quad \rightarrow \quad \Lambda_{mis} = c_N^{1/4} \left(\frac{f}{M}\right)^{N/4} \lesssim 10^{-2.5} \Lambda_{QCD}$$

Either first nonzero c_N has large N

Or $\not{PQ}$ is nonperturbative (c_N's exponentially suppressed)

In any case, robustness against this $\not{PQ}$ is desirable —> push "Λ_{QCD}" up *Heavy axion*

Heavy axions

SM extended with (or embedded into) new sector with $\Lambda \gg \Lambda_{QCD}$

$$V(a) = \left[\Lambda_{QCD}^4 + \Lambda^4\right]\left(1 - \cos(a)\right)$$

- ***Mirror SM with softly broken Z_2***
- ***Small instantons***
- ***Color - Dark Color unification***

Heavy axions

In practice:

$$V(a) = \Lambda^4\Big(1 - \cos(N_{DW}\ a)\Big) + \Lambda^4_{mis}\Big(1 - \cos(N'_{DW}\ a + \delta)\Big)$$

$$f_a m_a = \Lambda^2 \gg \Lambda^2_{QCD}$$

$$m_a \simeq 10^8\ \text{GeV}\left(\frac{10^{12}\ \text{GeV}}{f}\right)\left(\frac{\Lambda_{\text{H}}}{10^{10}\ \text{GeV}}\right)^2$$

Heavy axions

Heavy => decays quickly

Axions $\neq$ DM

Heavy and weakly coupled => difficult to probe directly!

presence of the misaligned sector => $\theta \neq 0$

improving precision in neutron EDM d_n

nEDM@SNS (1908.09937) –> $\Delta\theta \gtrsim 10^{-12}$

pEDM (2007.10332) –> $\Delta\theta \gtrsim 10^{-13}$

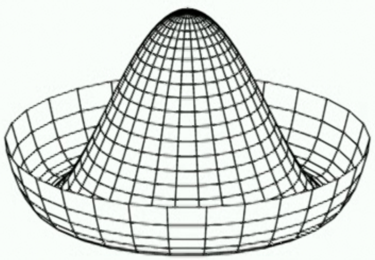
Heavy axionic defects

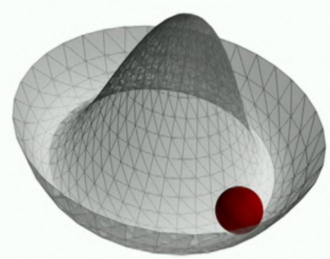
$\sigma_{DW} \sim m_a f_a^2$ => **DWs are also *heavy***

DW motion induces *strong* GWs $\rho_{GW} \sim \frac{\sigma_{DW}^2}{M_P^2}$

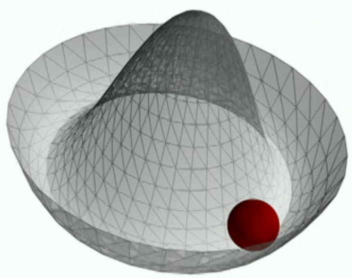
Axionic defects

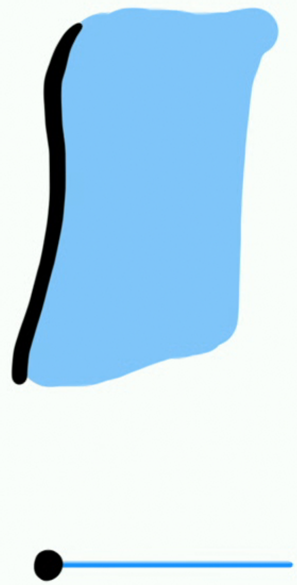
Peccei-Quinn mech: introduce a $U(1)_{PQ}$ symmetry with 2 properties:

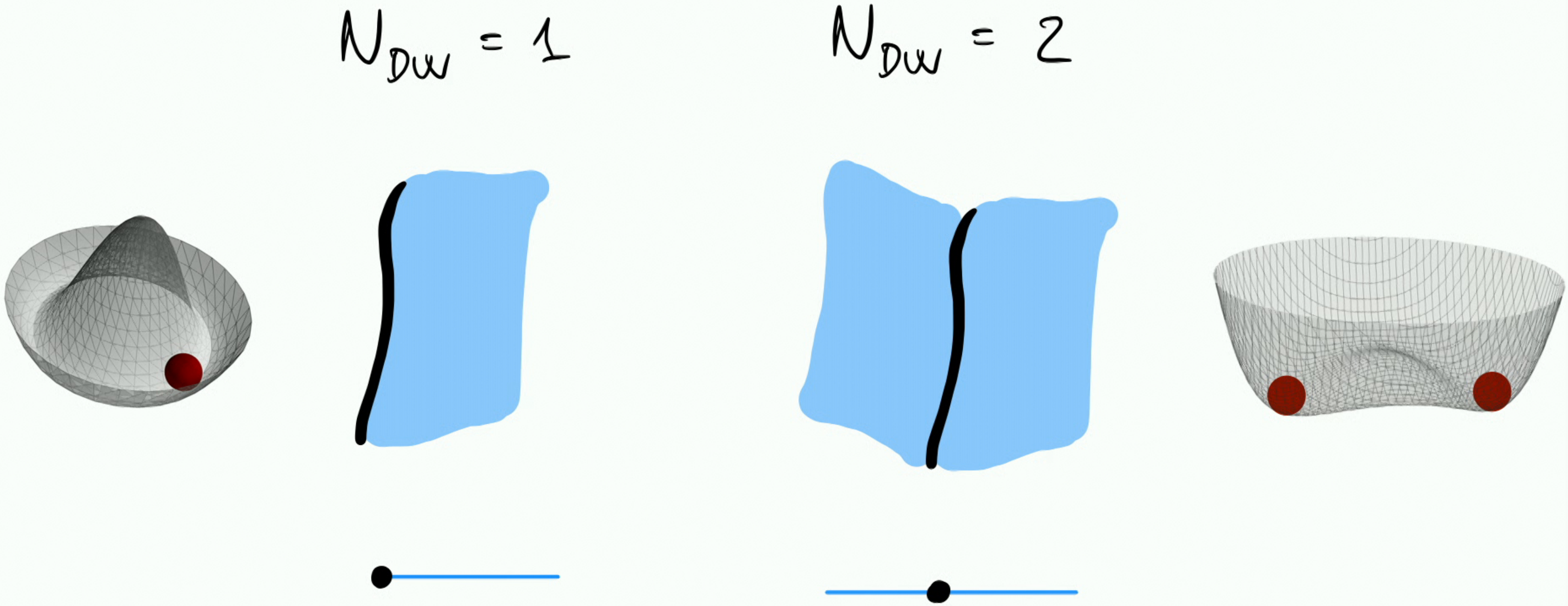
1) SB, i.e.:  spont. $\cancel{U(1)}_{PQ}$ @ f_a

2) $U(1)_{PQ}$ $SU(3)_c$ $SU(3)_c$ anomaly  expl. $\cancel{U(1)}_{PQ}$ @ Λ_{QCD}

$N_{DW} = 1$



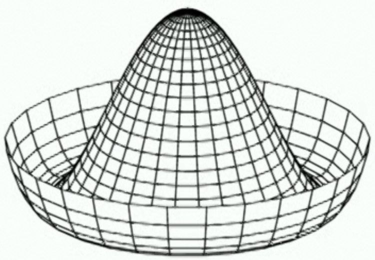



$N_{DW} = 1$
$N_{DW} = 2$

Axionic defects

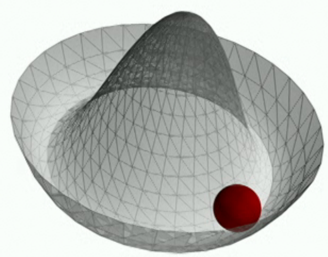
Peccei-Quinn mech: introduce a $U(1)_{PQ}$ symmetry with 2 properties:

1) SB, i.e.:



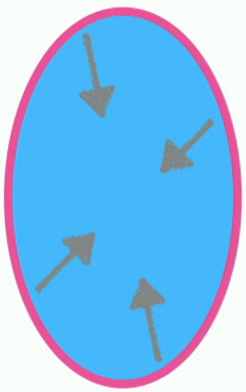
spont. ~~U(1)~~$_{PQ}$ @ f_a

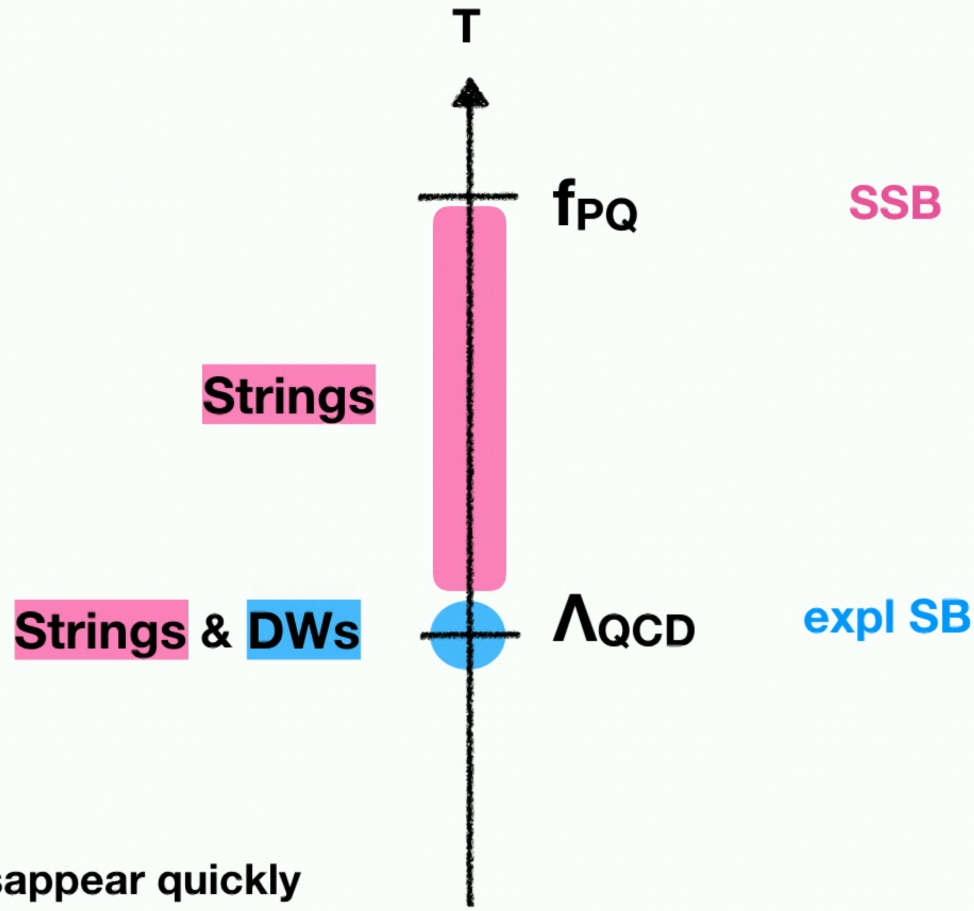
2) $U(1)_{PQ}\,SU(3)_c\,SU(3)_c$ anomaly



expl. ~~U(1)~~$_{PQ}$ @ Λ_{QCD}

$N_{DW} = 1$

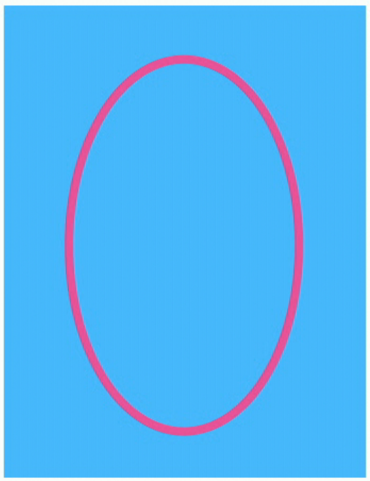


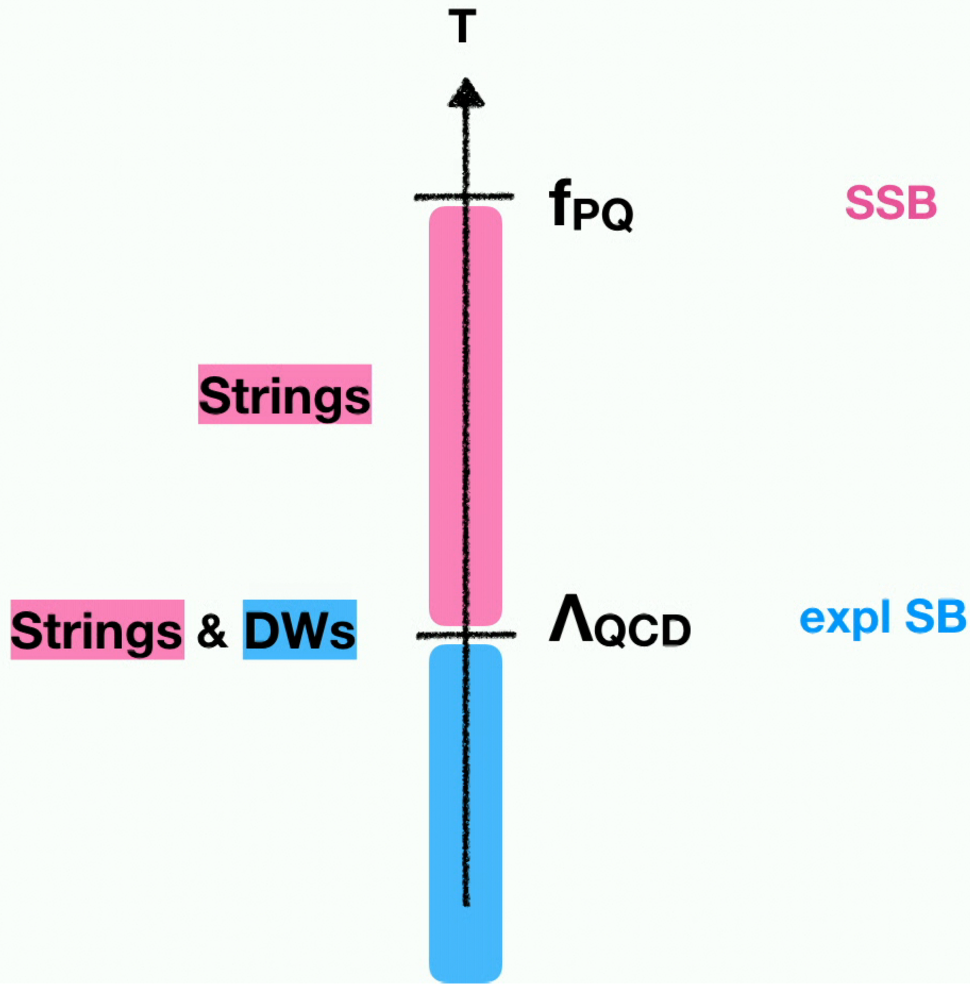


1 DW per string

DWs make the whole network disappear quickly

$N_{DW} > 1$

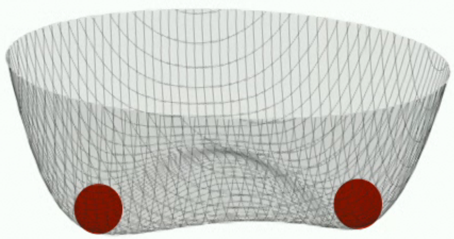


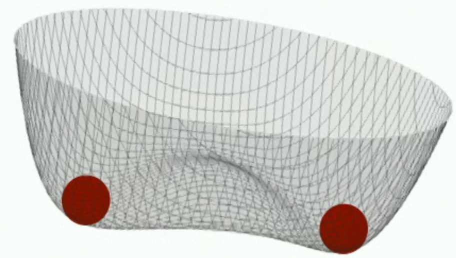


Network is stable

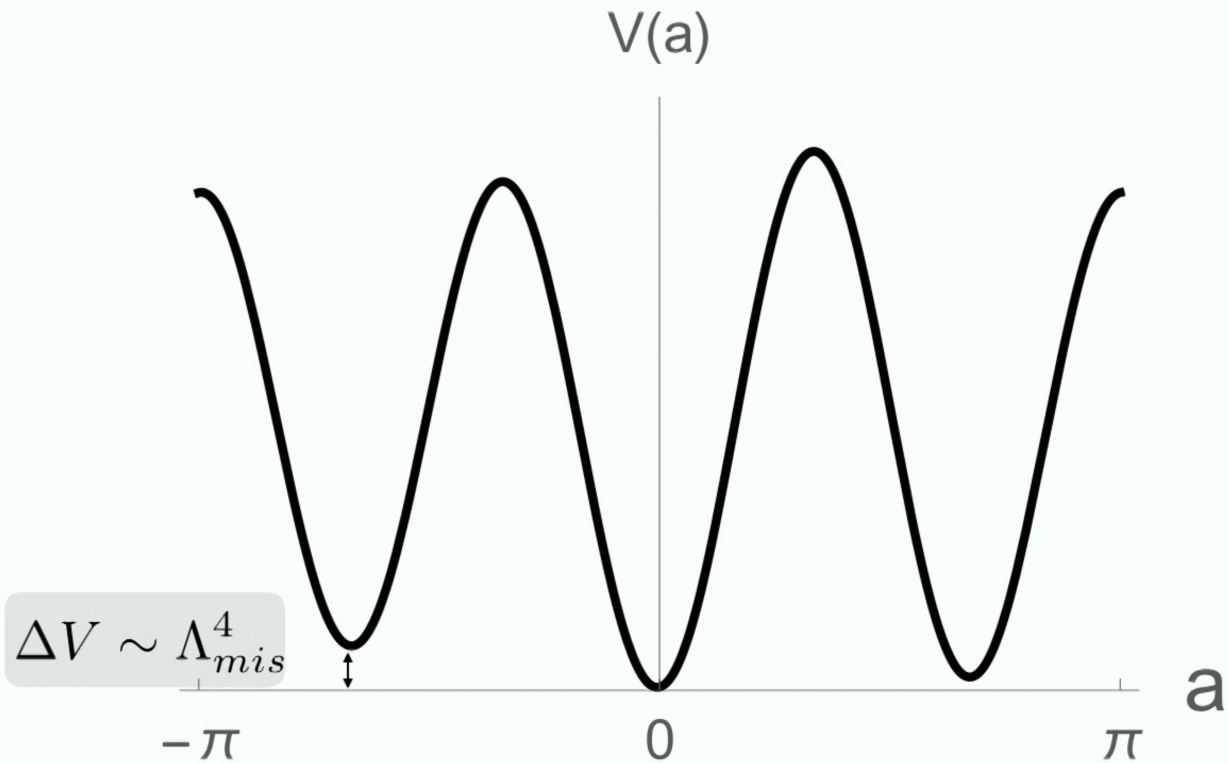
=> DW problem!

the misaligned contributions (which motivate heavy axions) come to rescue the N_{DW}>1 case





$$V(a) = \Lambda^4\Big(1 - \cos(N_{DW}\ a)\Big) + \Lambda^4_{mis}\Big(1 - \cos(N'_{DW}\ a + \delta)\Big)$$



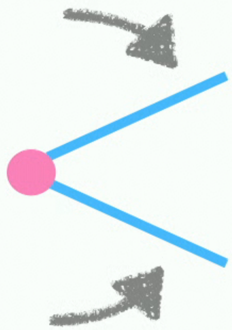
$N_{DW} = 3$

$N_{DW}' = 2$

$r = \Lambda_{mis}/\Lambda_H$

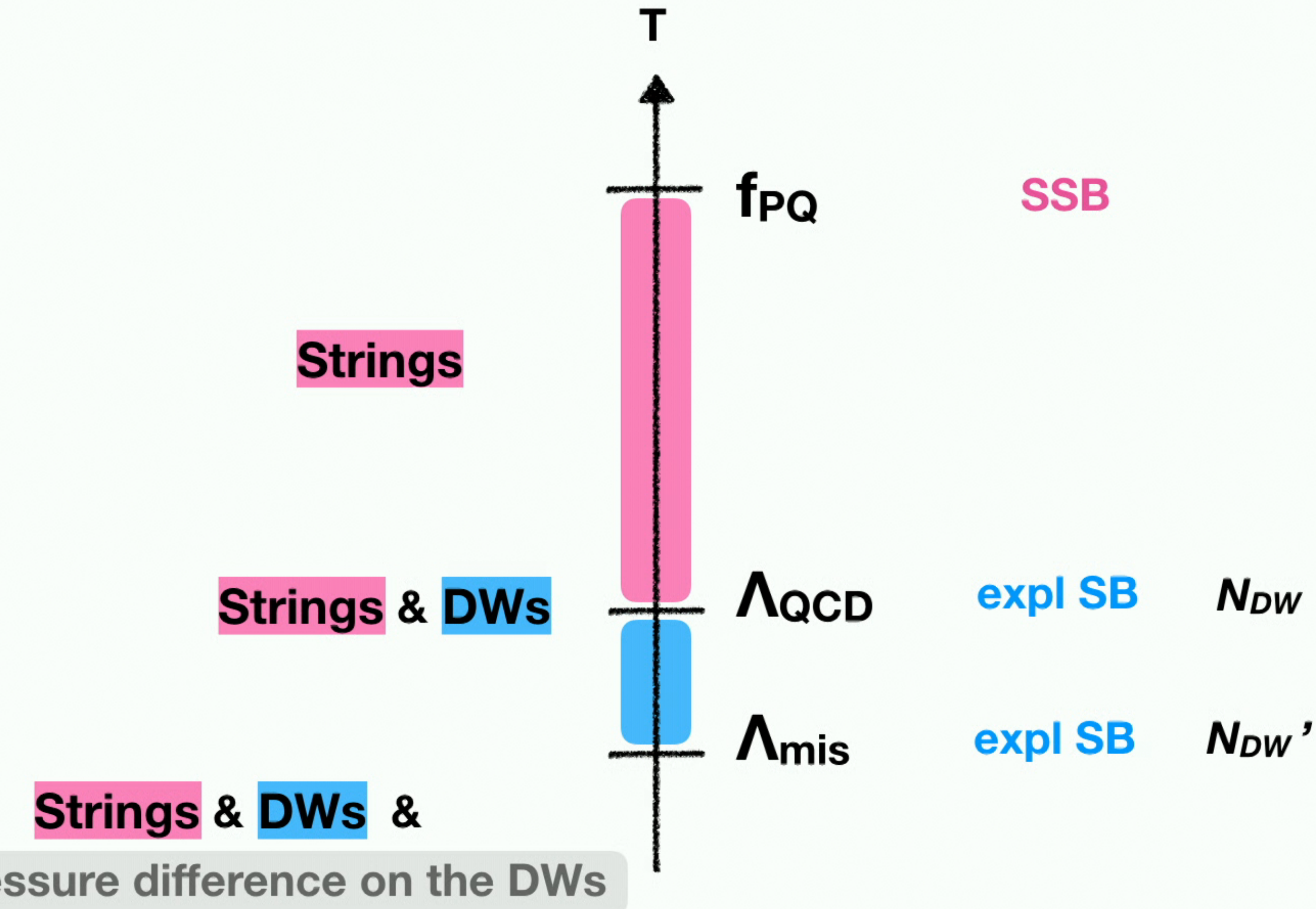
$\sim \theta^{1/4}$

$N_{DW} > 1$



Delayed network anihilation

long DW epoch



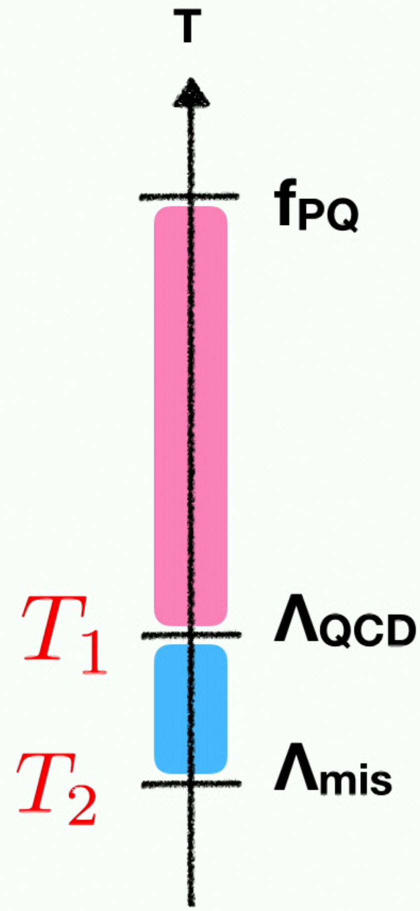
$N_{DW} > 1$

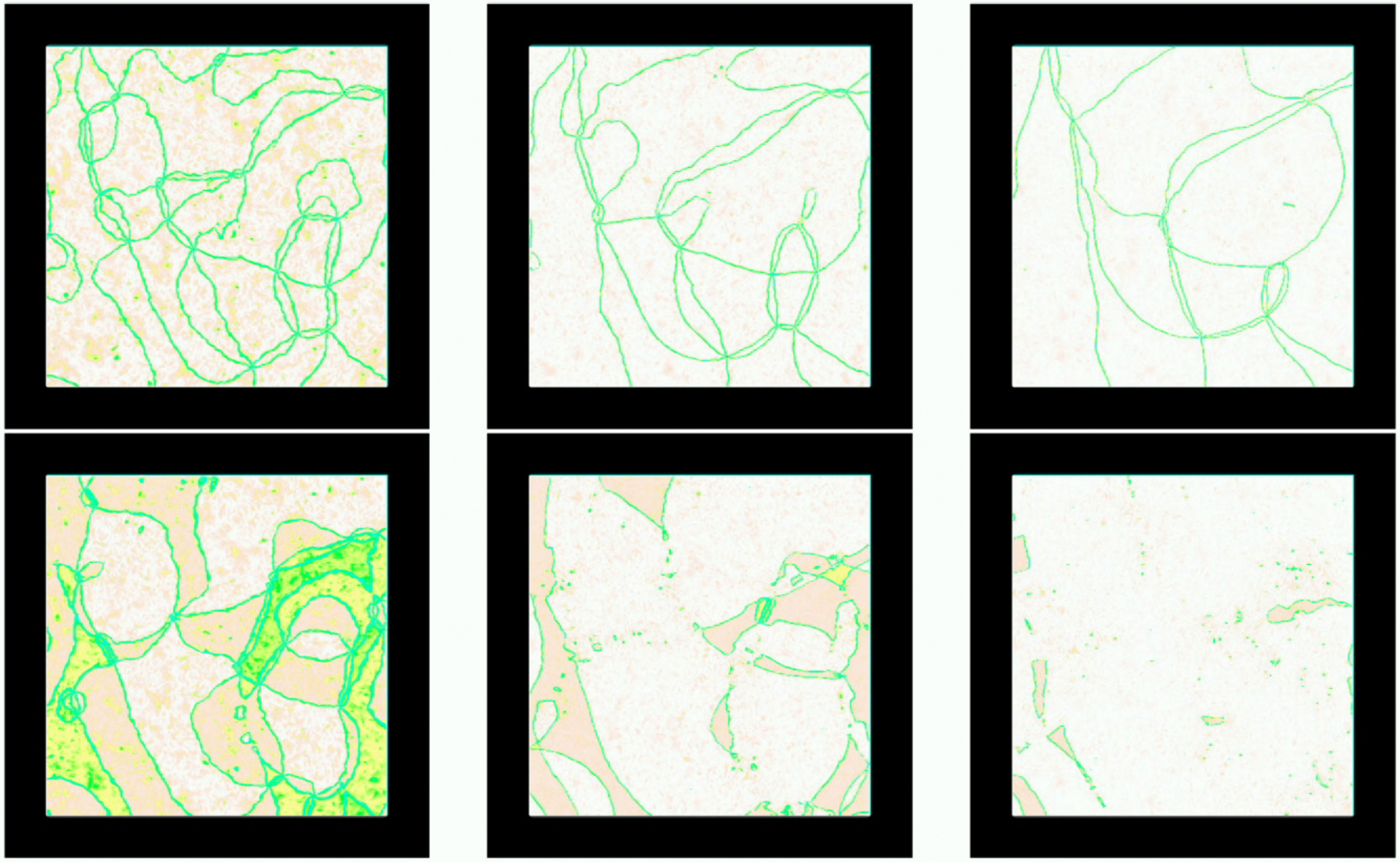
DWs form when

$$3H(T_1) = m_a(T_1)$$

DW+string network ends when

$$a_{DW} = \frac{\Delta V}{\sigma} \sim H(T_2)$$



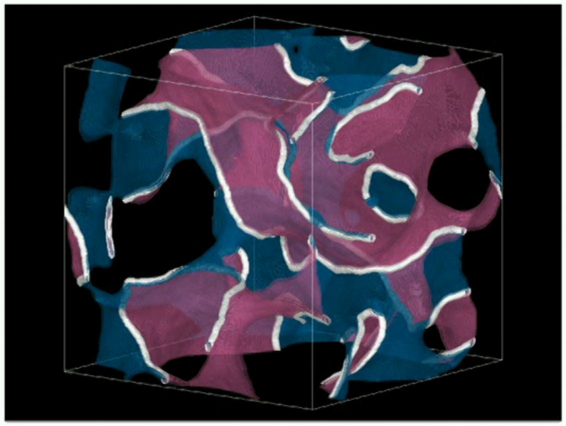


(N_{DW}>1)

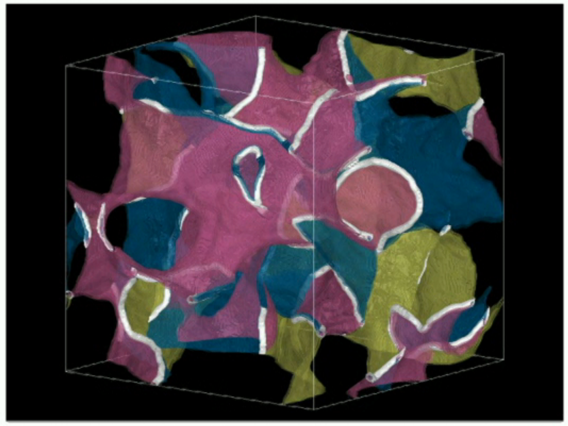
without Λ_{mis} : the network persists

with Λ_{mis} the network annihilates

from [Kawasaki et al. '14] $\Delta V \approx 10^{-3} V_{QCD}$



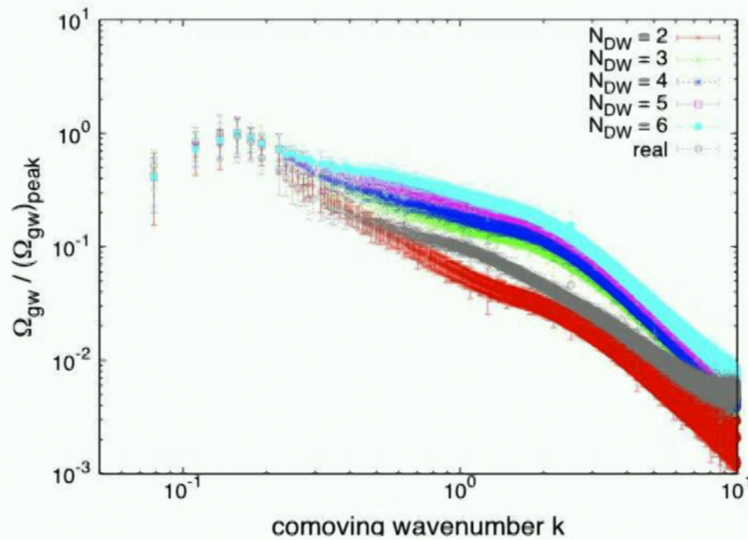
(a) $N_{\rm DW} = 2$



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

Hiramatsu et al arXiv: 1207.3166

$$\Omega_{\rm gw}(\omega) = \Omega_{\rm gw}(\omega_{\rm peak}) \frac{4}{\left(\frac{\omega}{\omega_{\rm peak}}\right)^{-3} + 3\left(\frac{\omega}{\omega_{\rm peak}}\right)}$$



The peak in the GW spectrum ~ from network annihilation time, i.e.,

$$T_2 \simeq \frac{10^7\text{GeV}}{\sqrt{\kappa_\text{H}}}\sqrt{\frac{10^{12}\text{GeV}}{f}}\left(\frac{\Lambda_\text{H}}{10^{10}\text{GeV}}\right)\left(\frac{r}{0.005}\right)^2$$

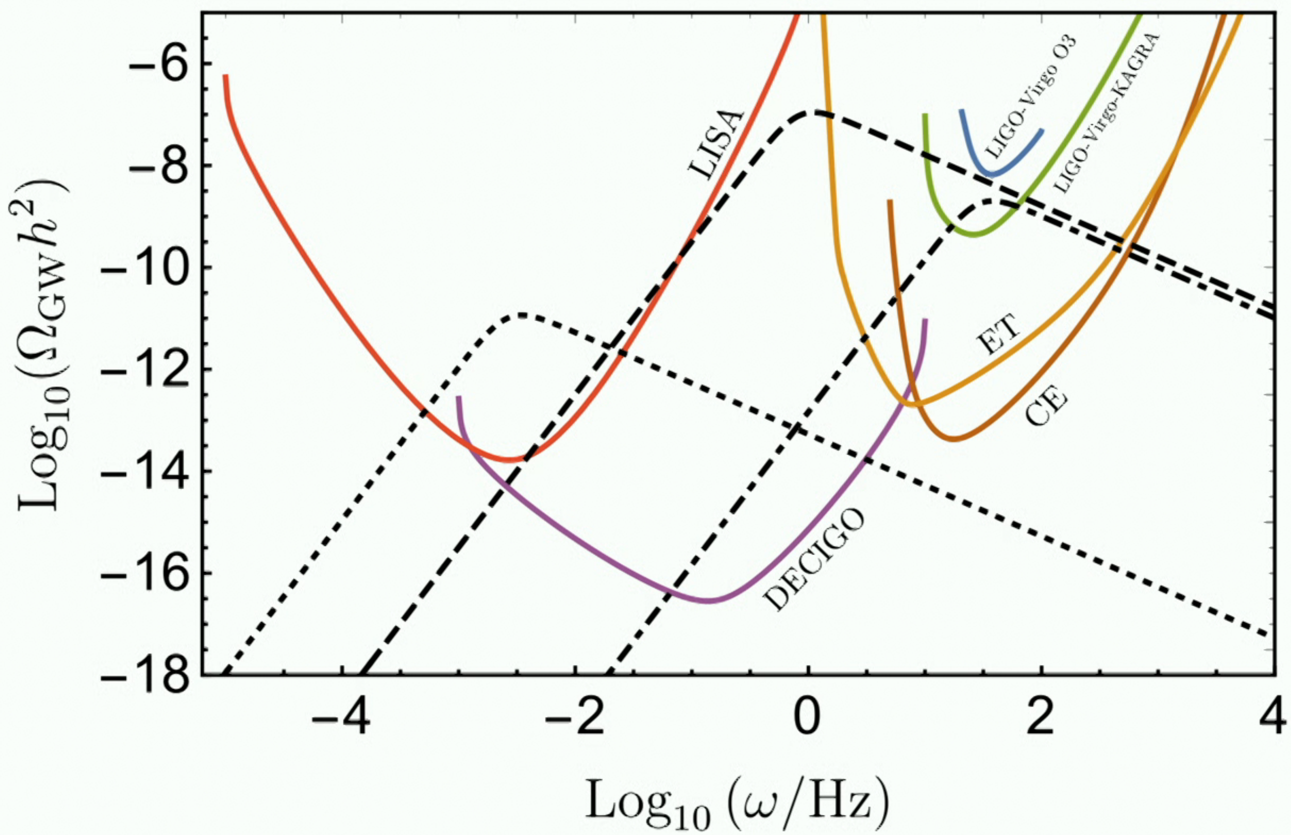
$$r = \Lambda_{mis}/\Lambda_H \sim \theta^{1/4}$$

Signal:

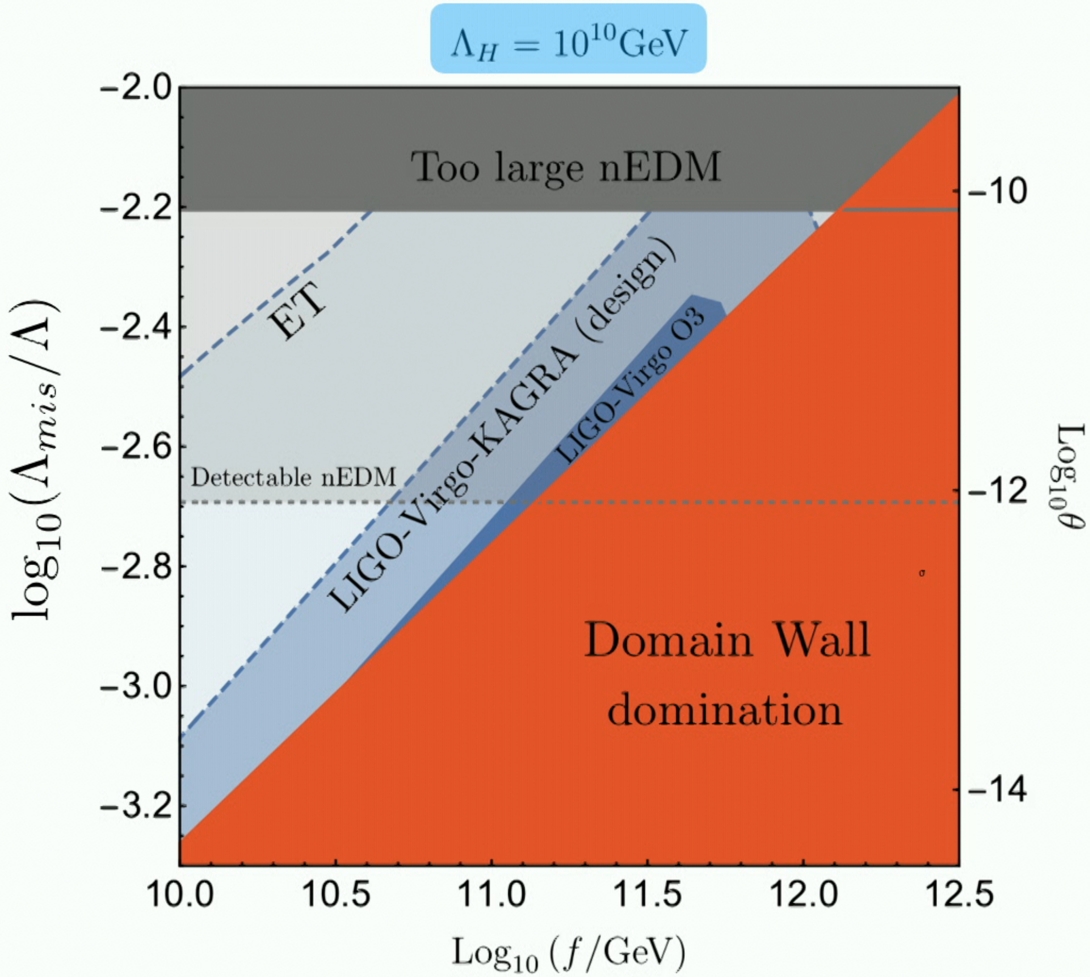
$$\omega_\text{peak} \simeq \frac{5\ \text{Hz}}{\sqrt{\kappa_\text{H}}}\left(\frac{r}{0.005}\right)^2\left(\frac{\Lambda_\text{H}}{10^{10}\text{GeV}}\right)\sqrt{\frac{10^{11}\text{GeV}}{f}}\,.$$

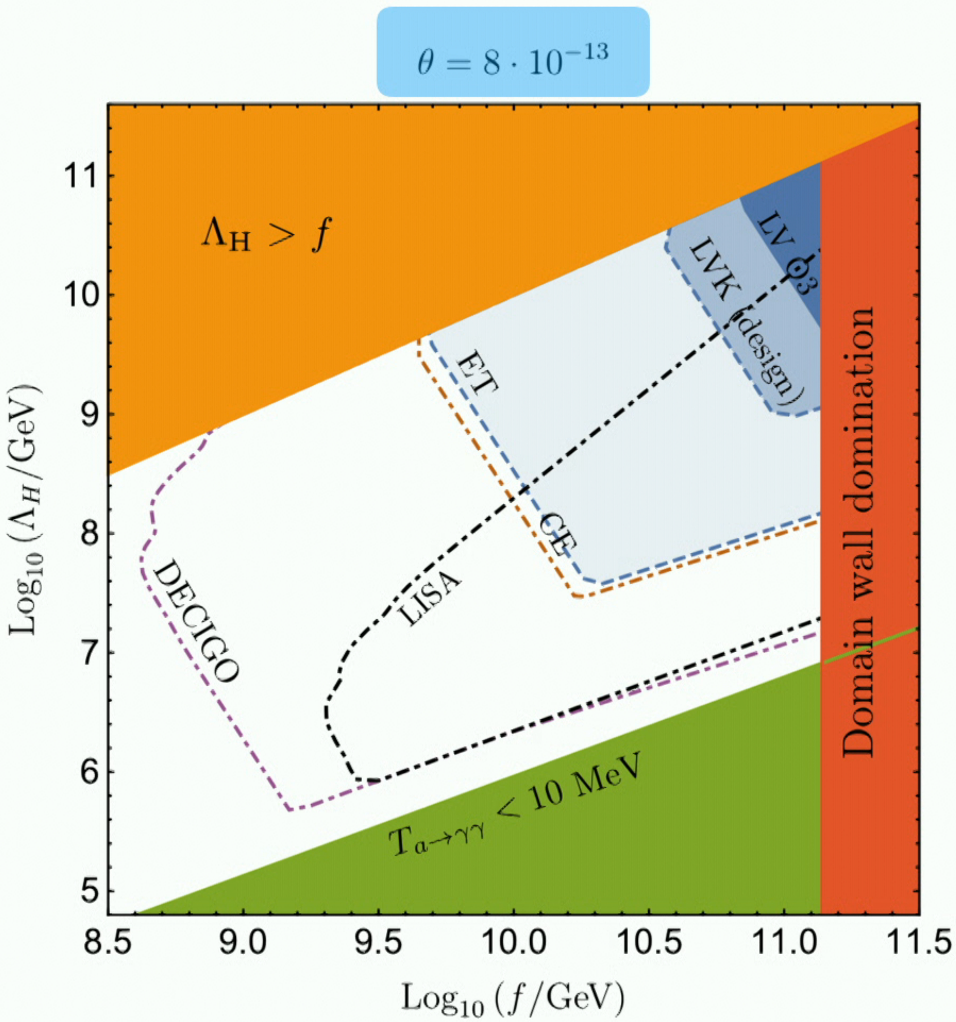
$$\Omega_{GW} \sim 10^{-7}\left(\frac{\rho_{DW}}{\rho_{rad}}\right)^2_{T=T_2}$$

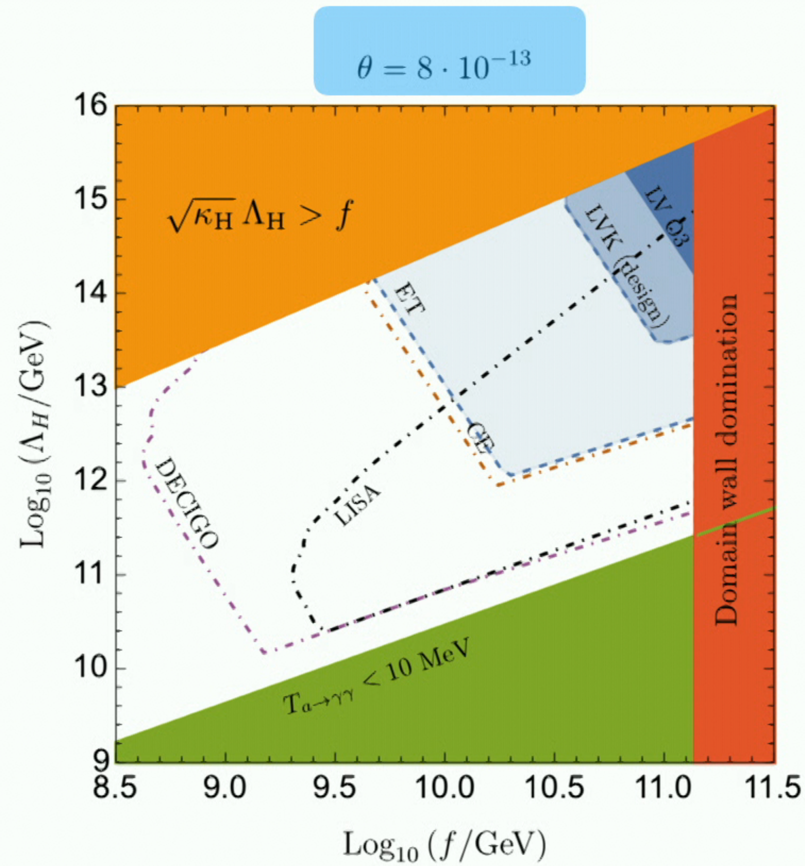
$(\ \Lambda^4 \equiv \kappa_H^2 \Lambda_H^4\ )$



Λ_H =	10^7 GeV	10^{10} GeV	10^{11} GeV
f =	10^{10} GeV	3 10^{11} GeV	1.6 10^{11} GeV
θ =	2 10^{-12}	9 10^{-11}	1.2 10^{-11}


$\Lambda_H = 10^{10}$GeV
Too large nEDM
ET
LIGO-Virgo-KAGRA (design)
LIGO-Virgo O3
Detectable nEDM
Domain Wall domination
$\log_{10}(\Lambda_{mis}/\Lambda)$
$\mathrm{Log}_{10}\theta$
$\mathrm{Log}_{10}(f/\mathrm{GeV})$
-2.0
-2.2
-2.4
-2.6
-2.8
-3.0
-3.2
-10
-12
-14
10.0
10.5
11.0
11.5
12.0
12.5





with $\kappa_H = 10^{-9}$.

$$\Lambda^4 \equiv \kappa_H^2 \Lambda_H^4$$

Phys.Rev.Lett. 126 (2021) 15, 151301
arXiv:2102.01714

Broken power law model			
	$f_* = 1\,\mathrm{Hz}$	$f_* = 25\,\mathrm{Hz}$	$f_* = 200\,\mathrm{Hz}$
$n_2 = -1$	3.3×10^{-7}	3.5×10^{-8}	2.8×10^{-7}
$n_2 = -2$	8.2×10^{-6}	6.0×10^{-8}	3.7×10^{-7}
$n_2 = -4$	5.2×10^{-5}	1.8×10^{-7}	3.7×10^{-7}

TABLE II: Upper limits for the energy density amplitude, $\Omega_*^{95\%}$, in the broken power law model for fixed values of the peak frequency, f_*, and negative power law index, n_2.

$$\Omega_{\rm bpl}(f) = \Omega_* \left(\frac{f}{f_*}\right)^{n_1} \left[1 + \left(\frac{f}{f_*}\right)^{\Delta}\right]^{(n_2 - n_1)/\Delta}$$

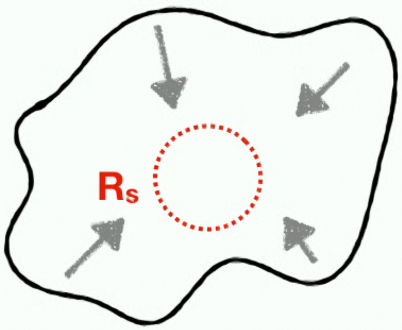
$n_1 = 3 \quad n_2 = -1$

=> some models are already constrained…

Primordial Black Holes

The same network collapse can lead to PBHs

Ferrer Masso Panico OP Rompineve
Phys.Rev.Lett. 122 (2019) 10, 101301
1807.01707



Tension & pressure helps collapse

Collapse condition $$R_S = \frac{\sigma}{H^2 M_P^2} \gtrsim \frac{1}{H}$$

coincides with DW domination

near DW domination region, PBHs are expected

Conclusions

Heavy axion models naturally contain long DW epoch — very different from bubbles

DW network collapse generates strong GW signal (and PBHs)

Combined signature both in GWs and in nEDM

LIGO/Virgo/KAGRA are already testing interesting axion models!

LVK = extremely high-energy machines

Better simulations of bubble collisions and string/wall networks are needed to chart the excluded parameter space