Quality tests for the Heavy QCD Axion

Ricardo Z. Ferreira

arXiv:2107.07542
w/ A. Notari, O. Pujolas, F. Rompineve

Vanilla QCD axion

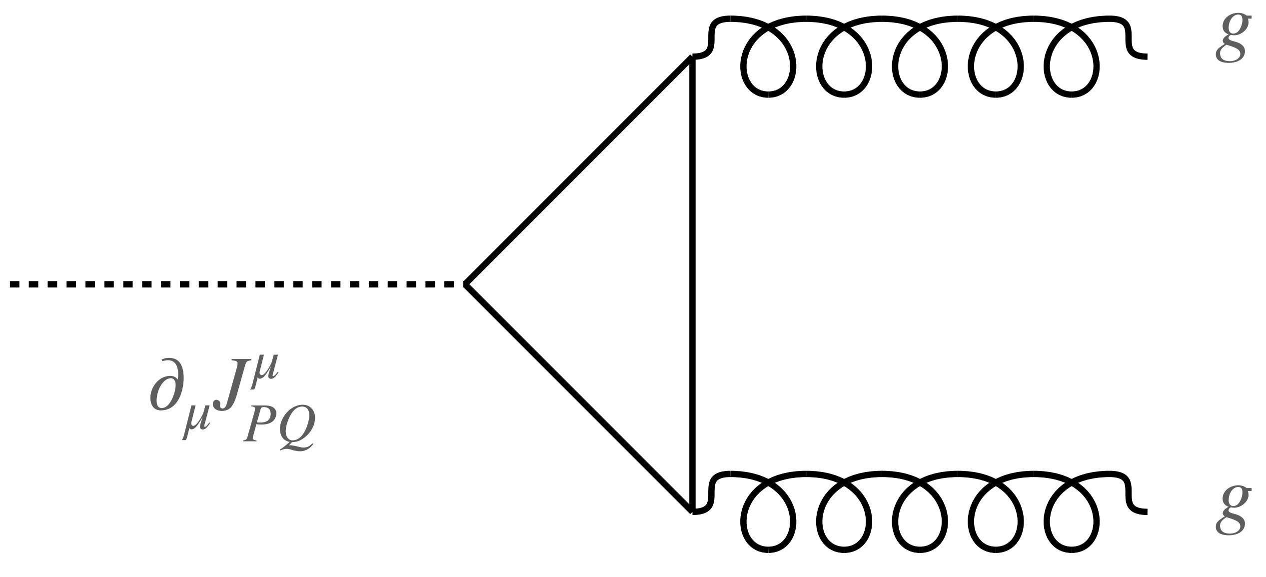
Strong CP problem: $\theta_{SM} < 10^{-10}$ *?*

- *Peccei-Quinn solution:* $\theta\, G\tilde{G} \quad \rightarrow \quad \frac{a}{f} G\tilde{G}$

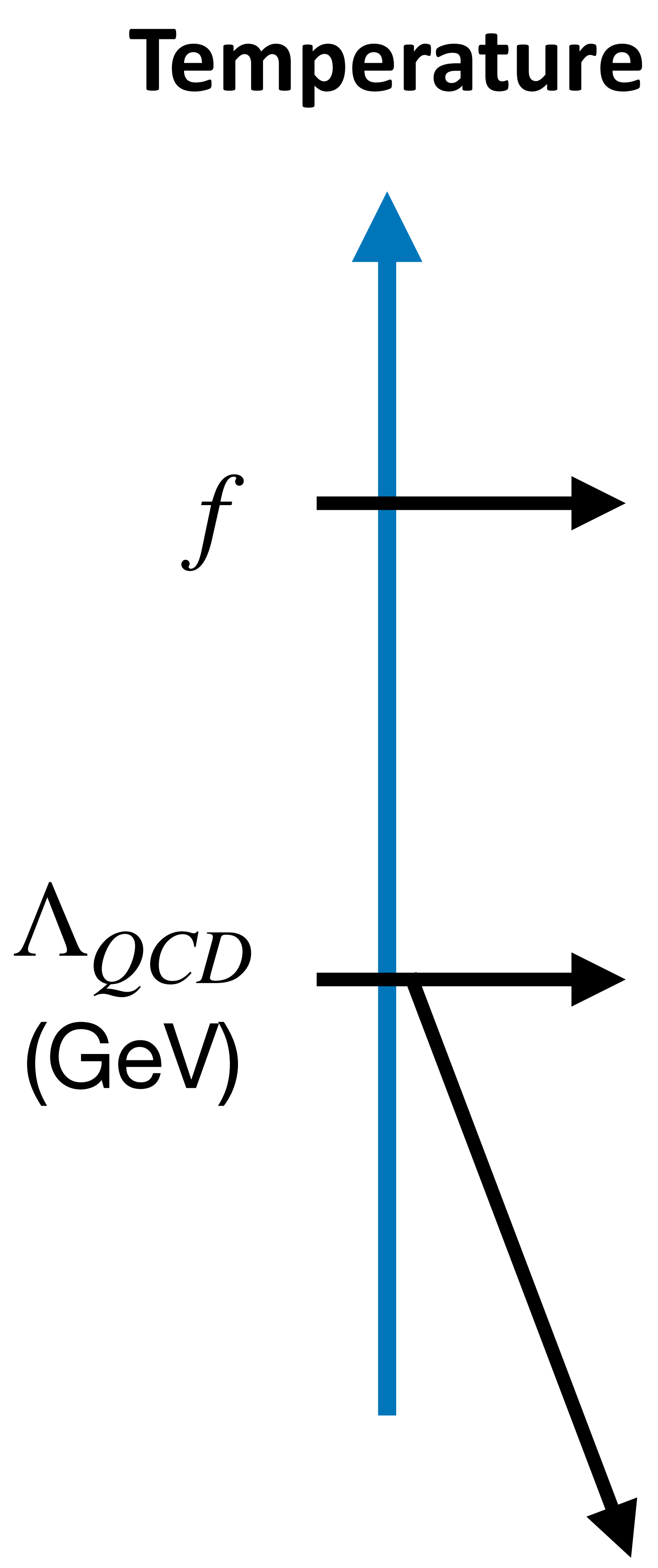
  $\longrightarrow$ Oscillates and decays to 0

[Peccei-Quinn 77',
Weinberg 78', Wilczek 78']

- *How?*
  Complex scalar + U(1) global symmetry
  - *Spontaneously broken* at $T \sim f \;\rightarrow\;$ *Axion is the GB*
  - *Anomalous* wrt QCD: $\partial_\mu J^\mu_{PQ} \propto N_{DW}\, G\tilde{G}$



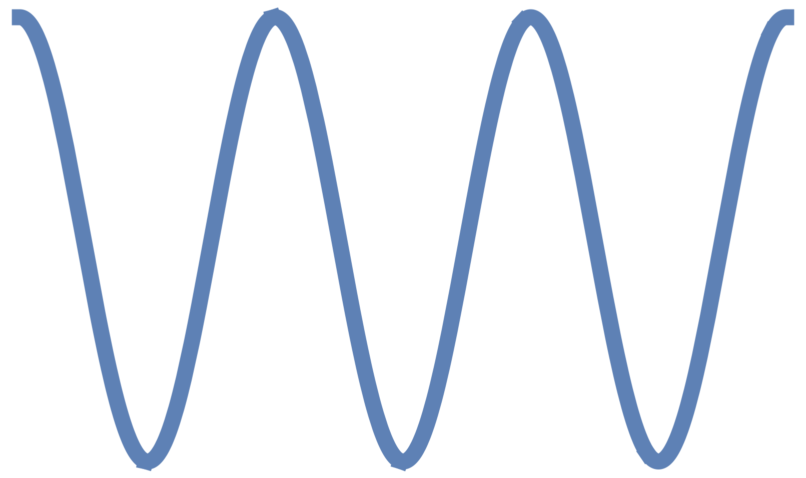
Cosmological evolution



- Axion takes random values.
  Network of **cosmic strings** is formed

- **QCD non-perturbative effects** break axion shift symmetry $(U(1) \to \mathbb{Z}_{N_{DW}})$

$$V \sim \Lambda_{QCD}^4 \cos\left(\underset{f}{\left(\frac{N_{DW}}{v_{PQ}}\right)} a\right),$$

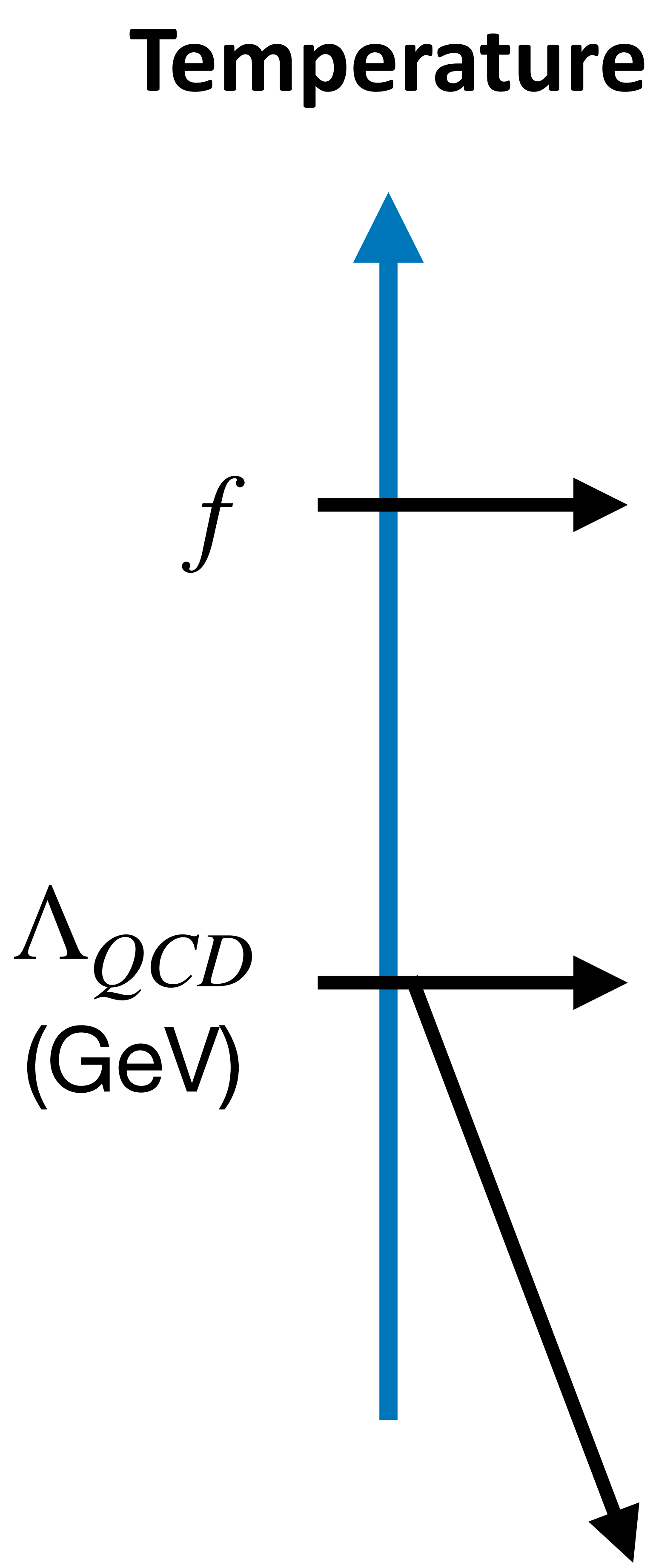


N_{DW} degenerate vacua.

- **Domain Walls** are formed with tension

$$\sigma = 8\, m_a\, f^2, \qquad \begin{cases} N_{DW} = 1 \text{ (unstable)} \\ N_{DW} > 1 \text{ (stable)} \end{cases}$$

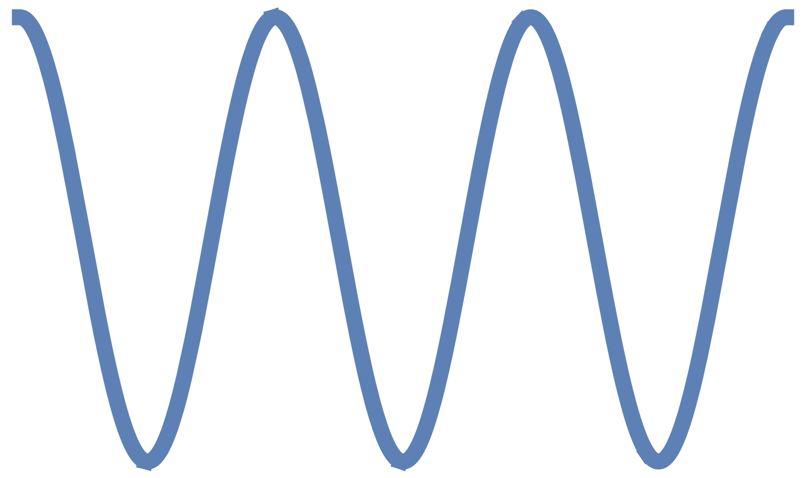
Cosmological evolution



- Axion takes random values.
  Network of **cosmic strings** is formed

- **QCD non-perturbative effects** break axion shift symmetry $(U(1) \to \mathbb{Z}_{N_{DW}})$

$$V \sim \Lambda_{QCD}^4 \cos\left(\underbrace{\frac{N_{DW}}{v_{PQ}}}_{f} a\right),$$



N_{DW} degenerate vacua.

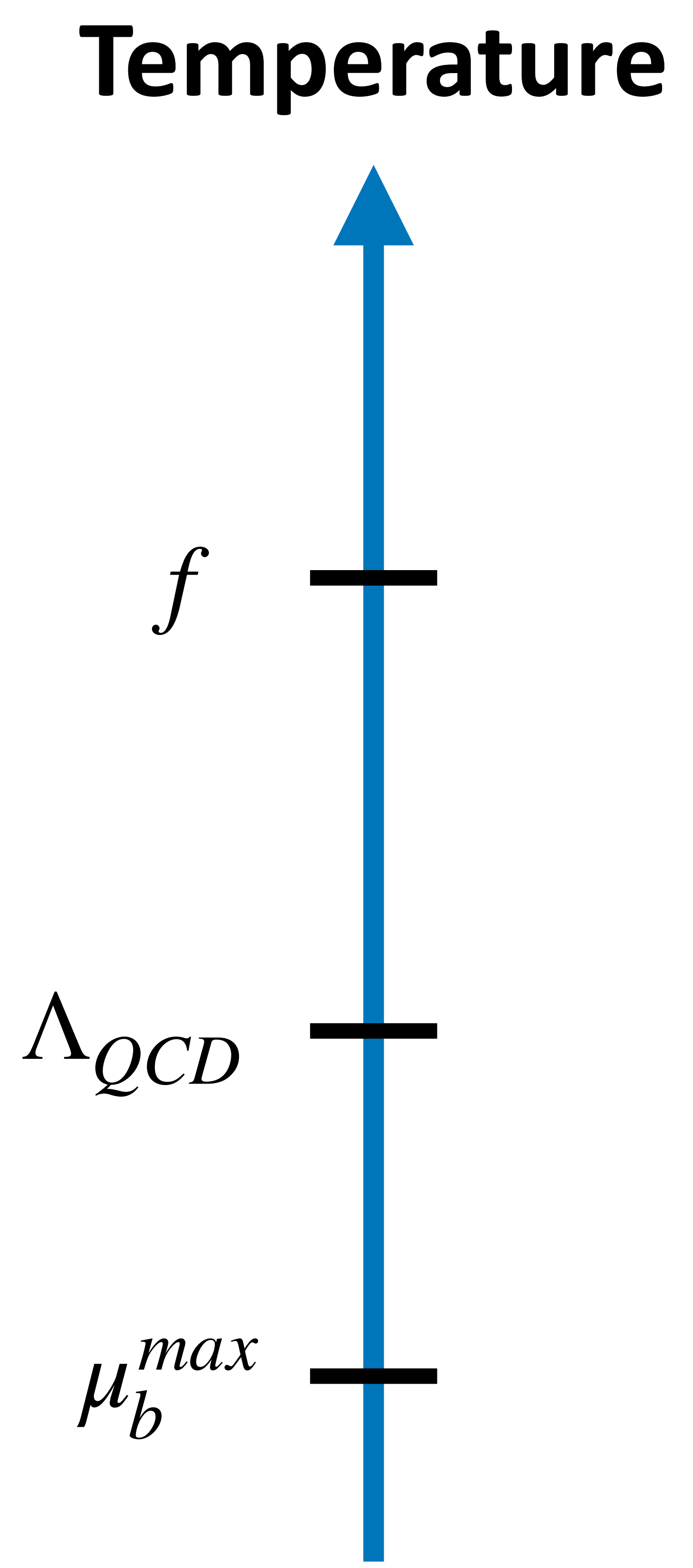
- **Domain Walls** are formed with tension

$$\sigma = 8\, m_a\, f^2, \qquad \begin{cases} N_{DW} = 1 \text{ (unstable)} \\ \boxed{N_{DW} > 1 \text{ (stable)}} \end{cases}$$

$\rho_{DW} \sim \sigma H$
Redshifts slower radiation
Domain Wall problem

[Georgi et al. 81’, Holdom et al. 82’, Dine et al. 86’, Kamionkowski et al. 92’, Holman et al. 92’, Barr et al. 92’, Ghigna et al. 92’,…]

Quality Assessment



PQ symmetry needs to be of **high quality**:

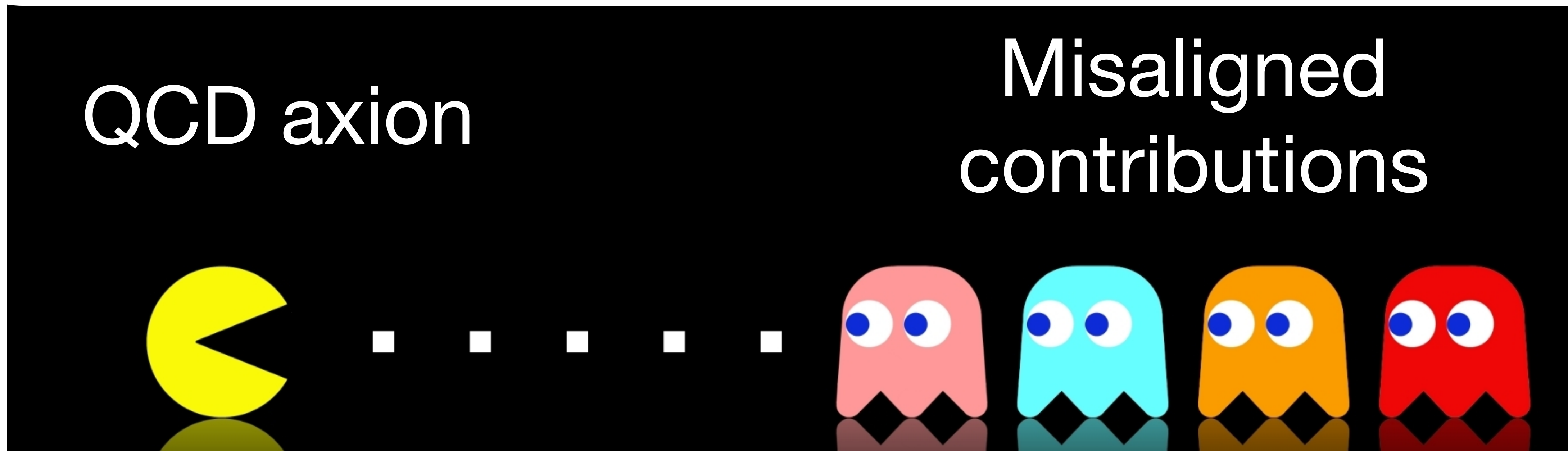
- Additional $\cancel{PQ}$ are in general **misaligned** $(\delta_i \sim 1)$

$$V_{misaligned} = \sum_i \mu_{b,i}^4 \, cos\left(\frac{N_{b,i}}{v_{PQ}} a + \delta_i\right)$$

  and **spoil** axion solution if $\mu_b \gtrsim 10$ MeV.

- … but can **solve DW problem** if $N_{b,i} = 1$ or co-prime with N_{DW}

Examples:
- Confining (QCD-like) gauge sectors
- Non-perturbative effects
- Higher dimensional operators
- Gravity



Heavy QCD axion

- **Large** $\Lambda_H \gg \Lambda_{QCD}$, **aligned** $\cancel{PQ}$ terms **shield** misaligned contributions:

$$V \sim (\Lambda_{QCD}^4 + \Lambda_H^4) \cos\left(\frac{N_{DW}}{v_{PQ}} a\right)$$

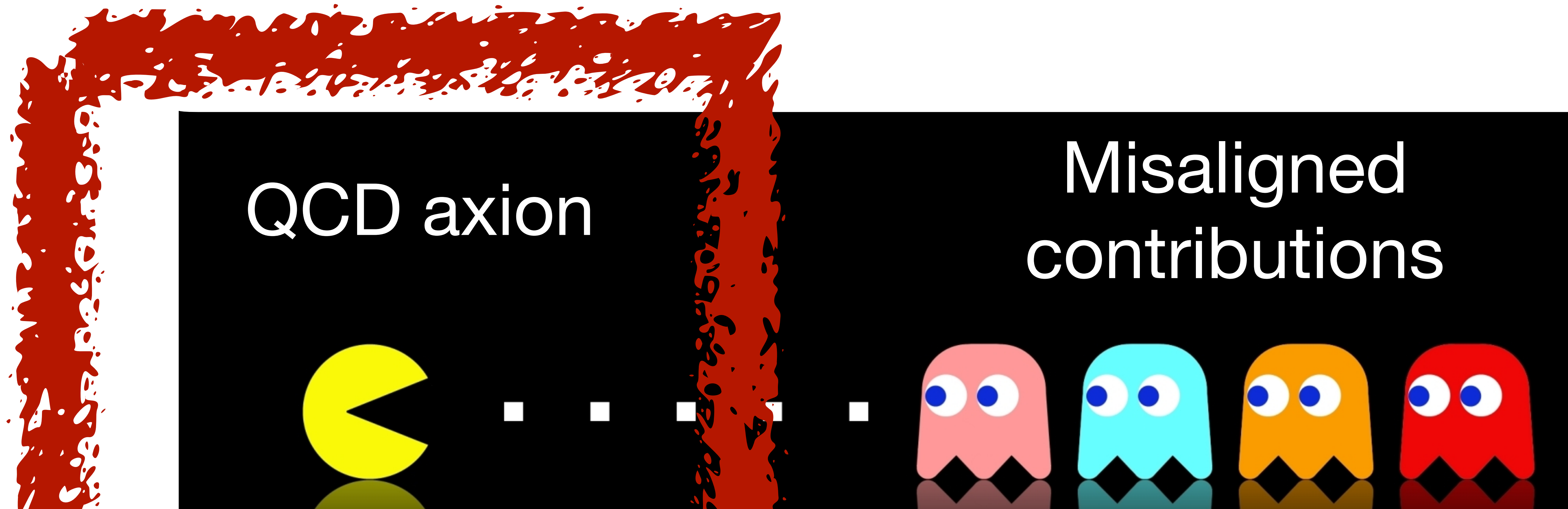
Examples:
- QCD strongly coupled at high energies;
- Z_2 symmetry;
- additional gauge group with unification

[Holdom et al. 82’, …, Berezhiani et al. 01’…, Tye et al. 81’, …]

- But **no relics…** axion decays to gluons very early

$$T_{a\to gg} \simeq 10^7 \text{ GeV } \alpha_s \left(\frac{\Lambda_H}{10^{10} \text{ GeV}}\right)^3 \left(\frac{10^{12} \text{ GeV}}{f}\right)^{\frac{5}{2}}$$

Quality improvement!



How can we test it?

DWs: form **earlier** $(T \sim \Lambda_H)$, **larger tension** $(\sigma = 8 m_a f^2)$

misaligned contributions

Large

→ DW Network is **short lived**

→ **Sizeable correction** to θ_{SM}

$$\Delta\theta \sim r^4\,, \qquad r \equiv \mu_b/\Lambda_H$$

(**probed at n(p)EDM** experiments)

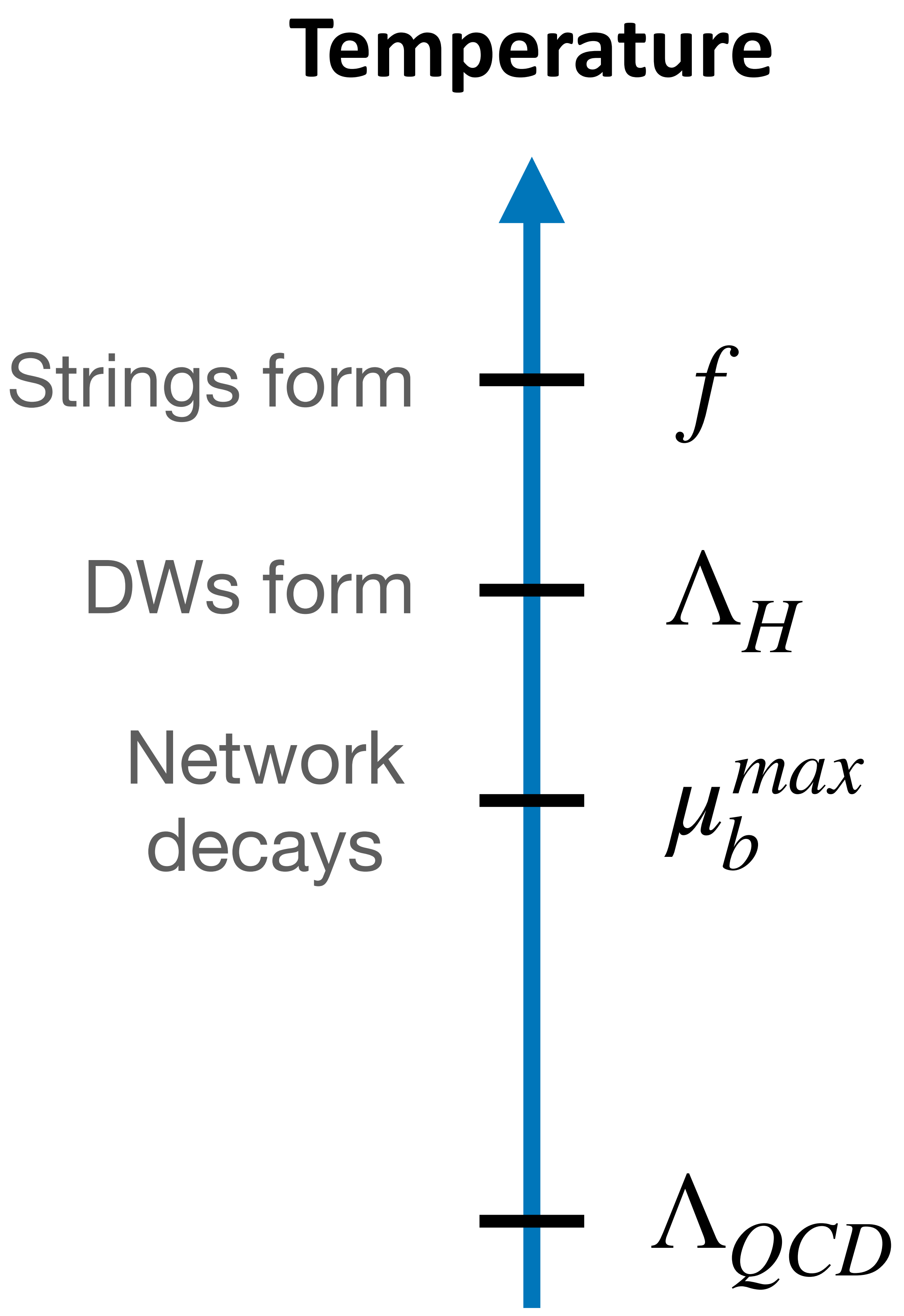
Small

→ DW Network is **long lived**

→ DW **energy density** becomes **large**

$$\left.\frac{\rho_{\text{dw}}}{\rho_{\text{rad}}}\right|_{T=T_{ann}} \simeq 0.1 \left(\frac{f}{10^{11}\ \text{GeV}}\right)^2 \left(\frac{0.003}{r}\right)^4$$

(**large GW production**)



[**RZF**, Notari, Pujòlas, Rompineve 21']

Network annihilation $\rightarrow$ Stochastic GW signal

[Vilenkin 81';
RZF, A.Notari, O. Pujolas, F. Rompineve **21'**]

- **Amplitude**

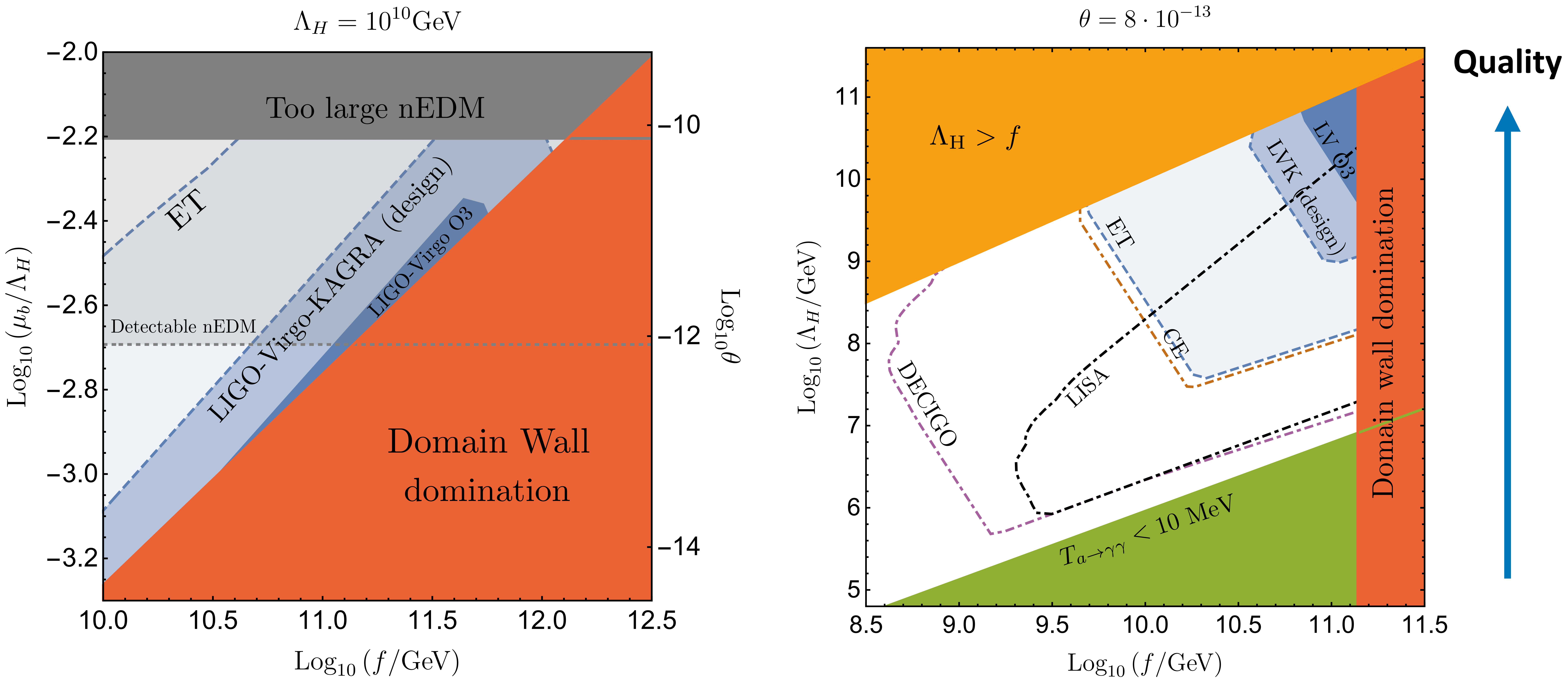
$$\rho_{\text{gw}}(T_{\text{ann}}) \sim \frac{\sigma^2}{8\pi M_p^2} \qquad \rightarrow \qquad \Omega_{\text{gw}} h^2 \simeq 10^{-6} \left(\frac{\rho_{\text{dw}}}{\rho_{\text{rad}}} \right)^2_{T=T_{ann}}$$

- **Peak frequency**

$$\omega_{\text{peak}} \simeq 5 \text{ Hz} \left(\frac{r}{0.005} \right)^2 \left(\frac{\Lambda_H}{10^{10}\,\text{GeV}} \right) \left(\frac{10^{11}\text{ GeV}}{f} \right)^{1/2} \quad , \qquad \begin{cases} \omega^3, & \omega \ll \omega_{peak} \\ \omega^{-1}, & \omega \gg \omega_{peak} \end{cases}$$

[Hiramatsu et al. 13']

Results

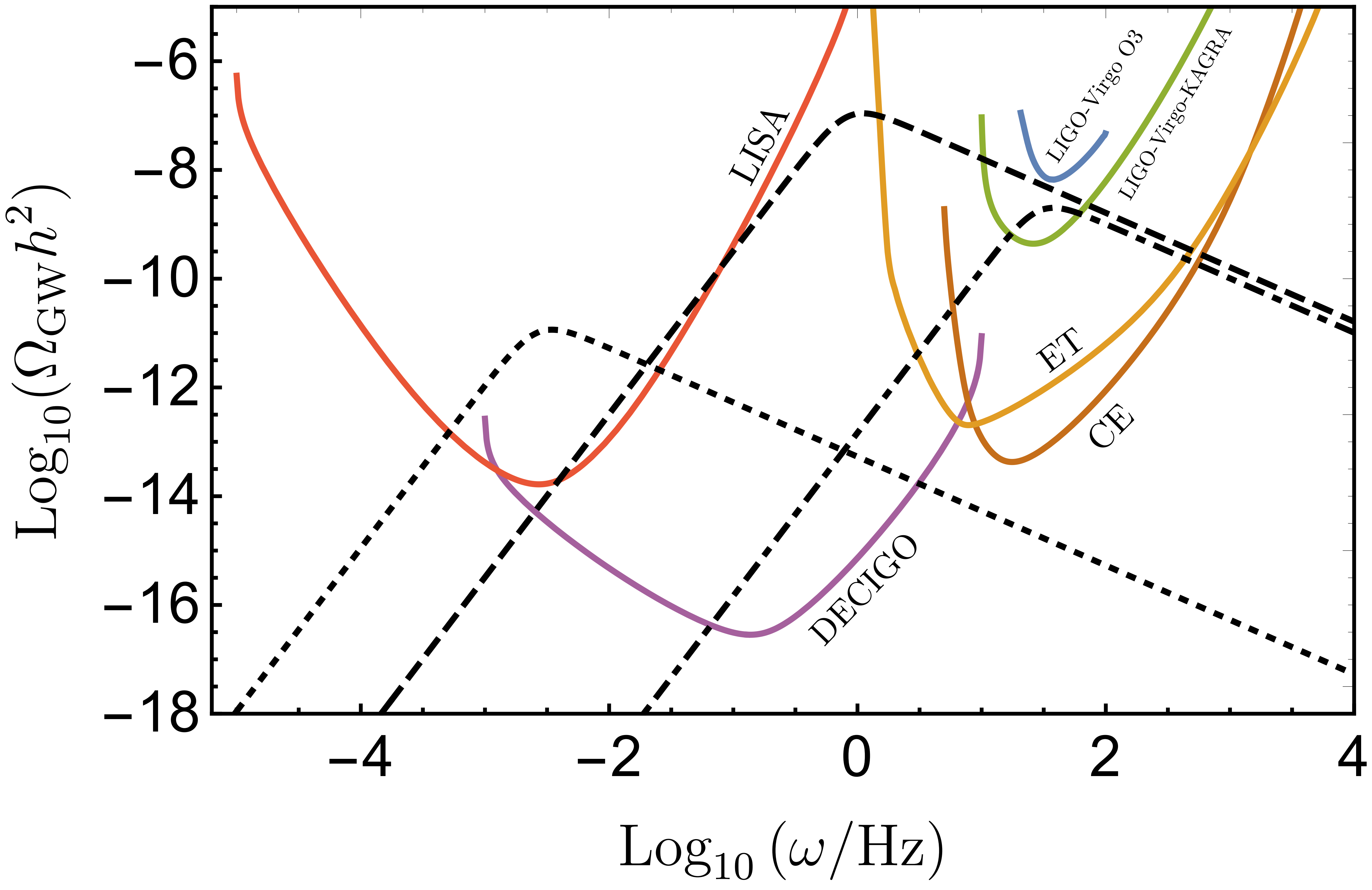


$\Lambda_H = 10^{10}$GeV
Too large nEDM
ET
LIGO-Virgo-KAGRA (design)
LIGO-Virgo O3
Detectable nEDM
Domain Wall domination
$\mathrm{Log}_{10}(\mu_b/\Lambda_H)$
$\mathrm{Log}_{10}\theta$
$\mathrm{Log}_{10}(f/\mathrm{GeV})$
−2.0
−2.2
−2.4
−2.6
−2.8
−3.0
−3.2
−10
−12
−14
10.0
10.5
11.0
11.5
12.0
12.5
$\theta = 8 \cdot 10^{-13}$
$\Lambda_\mathrm{H} > f$
LV O3
LVK (design)
ET
CE
LISA
DECIGO
$T_{a\to\gamma\gamma} < 10$ MeV
Domain wall domination
$\mathrm{Log}_{10}(\Lambda_H/\mathrm{GeV})$
$\mathrm{Log}_{10}(f/\mathrm{GeV})$
11
10
9
8
7
6
5
8.5
9.0
9.5
10.0
10.5
11.0
11.5
Quality

Conclusions

- Heavy QCD axion models can be tested with (current!) GW observatories. Correlated signals at n(p)EDM experiments would be a smoking gun.
- Future work:
  lower Λ_H to explain nanoGrav, PBH from the network collapse, improved simulations, …
- More generally, these models are a good testbed to probe the breaking of global symmetries.

Spectrum



[**RZF**, Notari, Pujòlas, Rompineve 21']
[Hiramatsu et al. 13']

- - - - $\Lambda_{\mathrm{H}} = 10^{10}$ GeV, $f \simeq 10^{11}$ GeV, $\Delta\theta \simeq 8 \cdot 10^{-13}$

········ $\Lambda_{\mathrm{H}} = 10^{7}$GeV, $f \simeq 2.5 \cdot 10^{10}$ GeV, $\Delta\theta \simeq 8 \cdot 10^{-13}$

-·-·- $\Lambda_{\mathrm{H}} = 10^{11}$ GeV, $f \simeq 1.6 \cdot 10^{11}$ GeV, $\Delta\theta \simeq 1.5 \cdot 10^{-11}$