Gravitational wave signatures of axionic domain walls

Ricardo Z. Ferreira
(IFAE, Barcelona)

Based on:
***Phys.Rev.Lett.* 128 (2022) 14, 141101 & arXiv:2204.04228**
with A.Notari, O.Pujolàs, F. Rompineve

Institute for High Energy Physics

Outline

1. Networks of topological defects:

   - Domain Walls and Gravitational waves

2. Domain Walls in axionic models:

   - The heavy QCD axion case

3. Hints at pulsar timing arrays?

4. Conclusion

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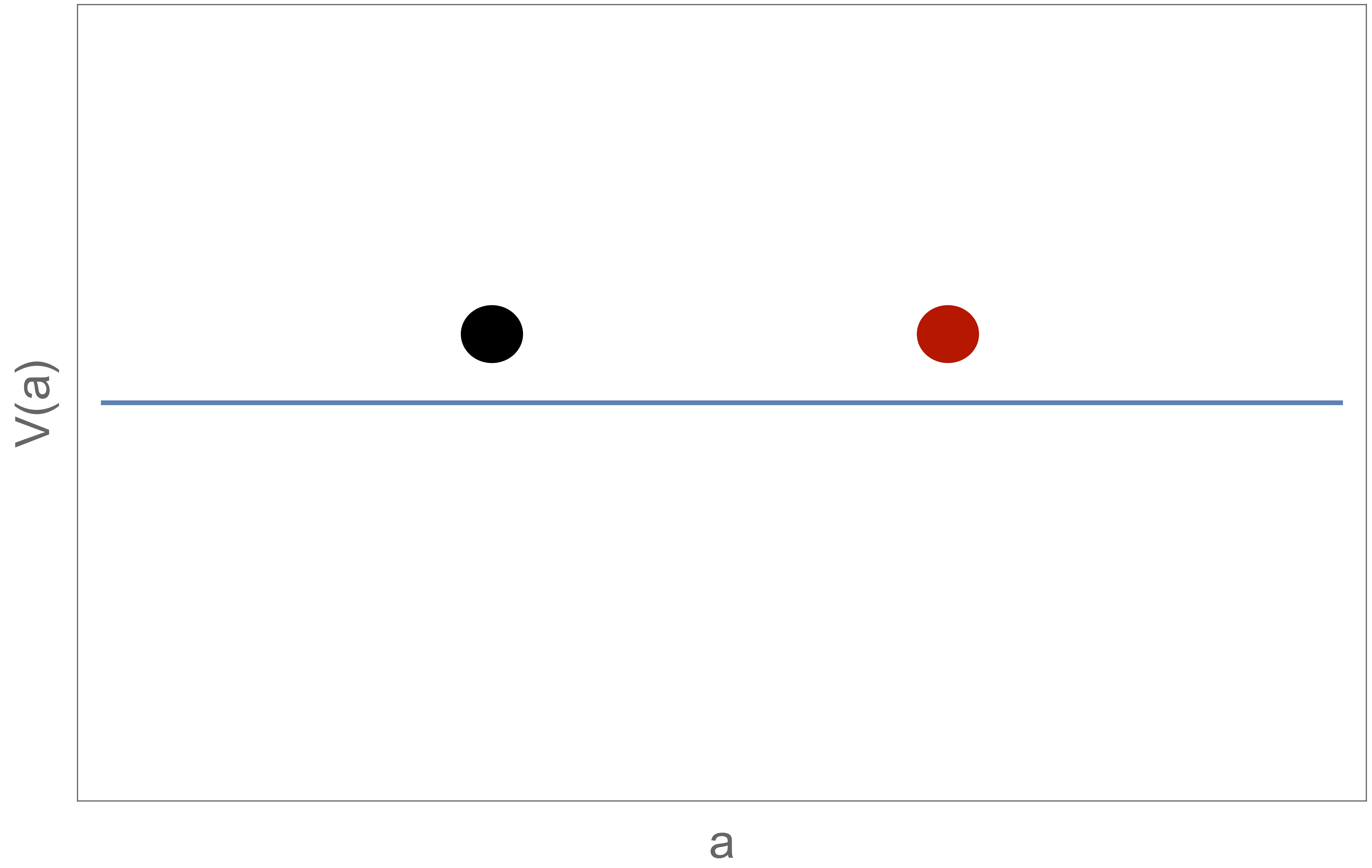
Topological defects in the early universe

Formation mechanism:

- **Spontaneous breaking** of a global/local symmetry group G at critical temperature T
- If the vacuum manifold of G is **non-trivial** → formation of topological defects:
  - **Domain Wall** (G = discrete symmetry, e.g Z_N)
  - **Cosmic strings** (G = U(1) symmetry)
  - **Monopoles, Textures,** …
- Examples: ferromagnetic materials, liquid crystals, **early universe**, etc.

Domain Walls



- $T > T_c$,

  scalar field takes random values over $[0, 2\pi]$

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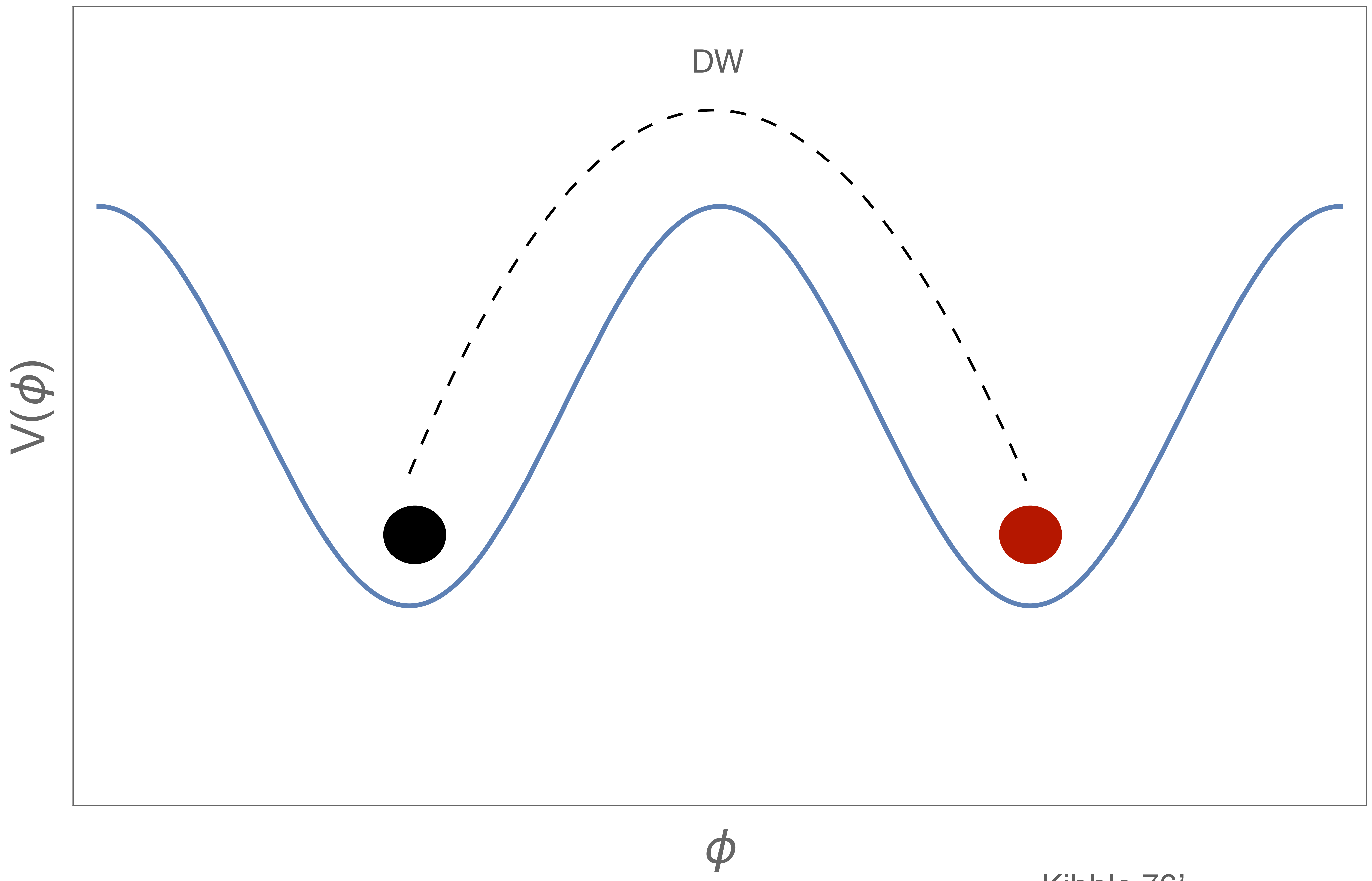
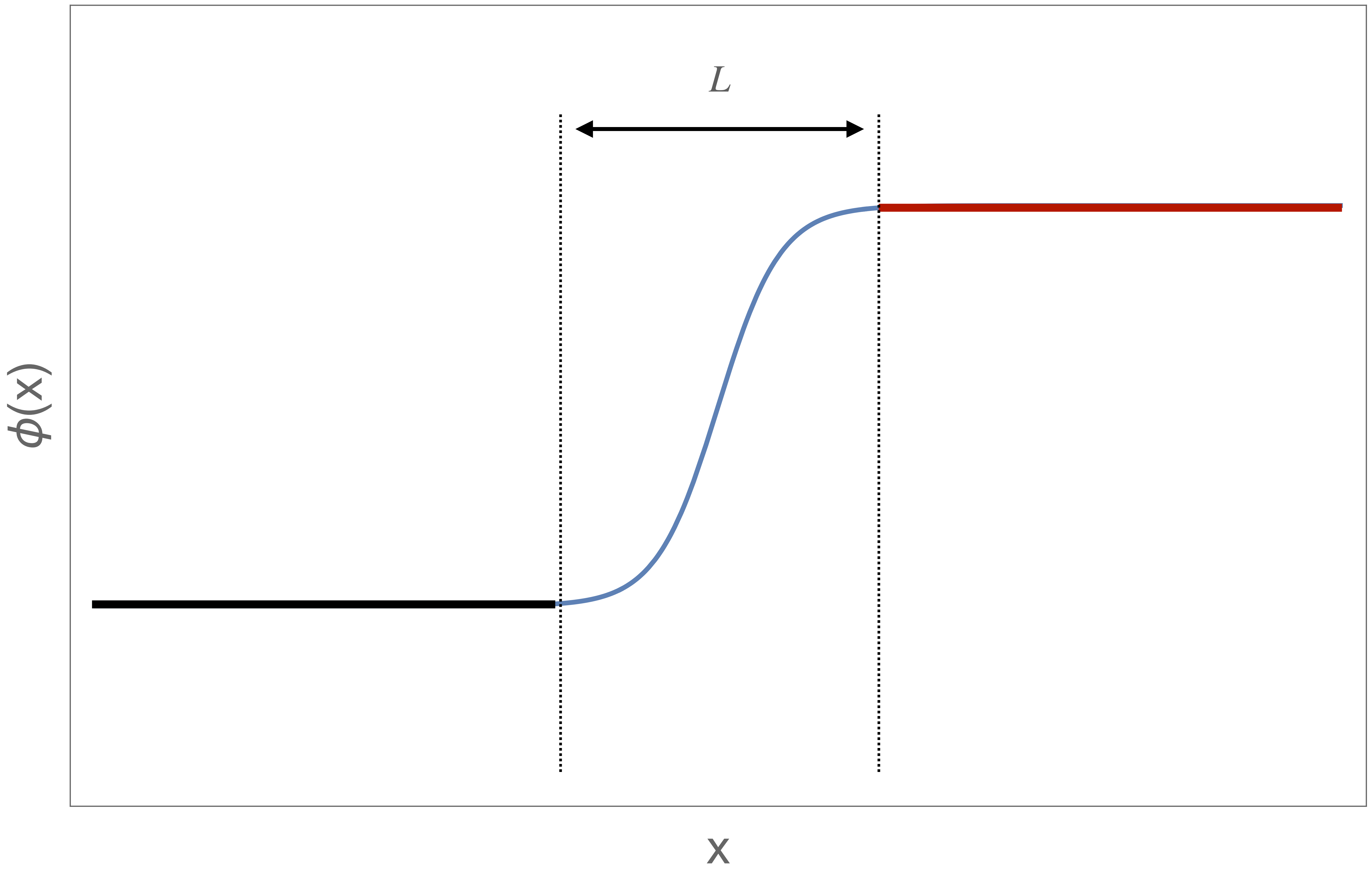


Kibble 76'

- At T_c, scalar field potential (e.g. instant) grows quickly.
- Different regions of the universe trapped in the different minima (Kibble mechanism).
- Domain wall = field configuration connecting two different minima.

Domain Walls



- Energy is localised in space (wall).

- Domain walls are characterized by:

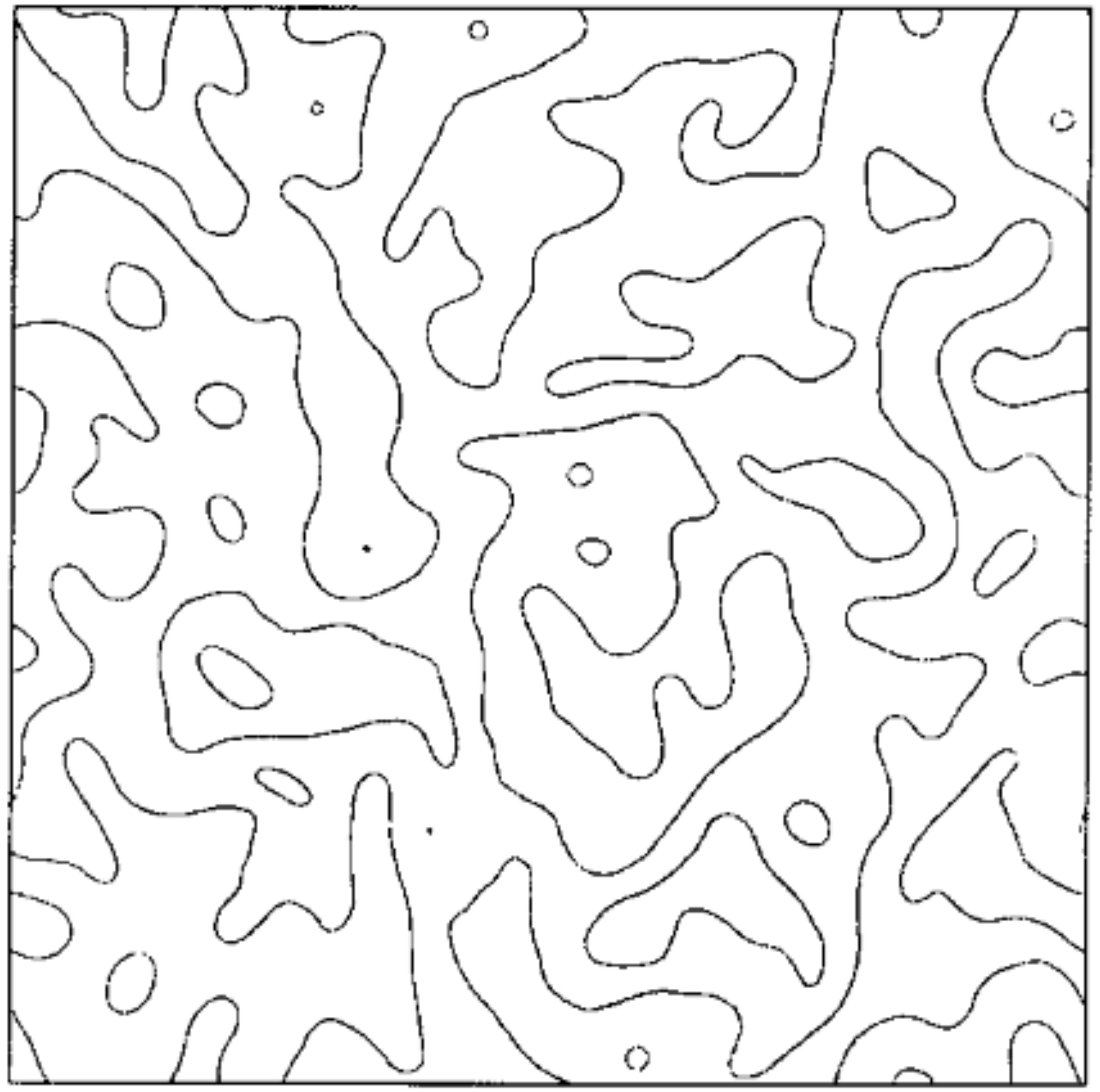
  width,

  $L \sim 1/m_\phi$

  tension,

  $$\sigma = \int \phi'(x)^2\, dx \sim m_\phi \, \langle \phi \rangle^2$$

Network formation and the scaling regime



Press et al. 89'

- Network of DWs is formed:
  - **Large scales (super-horizon)**: Frozen by Hubble friction.
  - **Small scales (sub-horizon):** DWs self-accelerate due to its tension, collide and intersect leading to **dissipation**.

- Attractor solutions - **the scaling regime:**

  ~ 1 wall per horizon with curvature $R \sim 1/H$.

⚠ Domain Wall problem ⚠

- **Energy density** in the network

$$\rho_{network} \sim \rho_{DW} = c\,\sigma\,H$$

, c~O(1)~average DW per Hubble patch (model dependent)

$\rightarrow$ **redshifts very slowly** ($\propto H$) and tends to **dominate** the universe.
$\rightarrow$ DW domination **incompatible with observations.**

Unless…

1. **DWs annihilate** before dominating.
   (e.g. symmetry restoration, discrete symmetry is not exact)

   Vilenkin 81', Sikivie 82',…

2. DW **tension is small enough** ($\sigma \lesssim 1$ MeV).
   Network still irrelevant today.

   Zeldovich 76'

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Gravitational waves from DW networks

- Rough estimation:
  Most of the energy is in **Hubble sized walls** with **curvature** $R \sim H^{-1}$:

  - **Energy** and **quadrupole**

$$E_{dw} \sim \sigma R^2 = \sigma H^{-2} \qquad \rightarrow \qquad Q_{ij} \sim E_{dw} R^2 \sim \sigma H^{-4}$$

Hiramatsu et al. 2013'

  - **Quadrupole formula,**

$$P_{GW} = G \dddot{Q}_{ij}^2 \sim G \sigma^2 H^{-2} \qquad \rightarrow \qquad \rho_{GW} \sim \frac{P_{GW}\, t}{Vol} \sim P_{GW} H^2 \sim G \sigma^2$$

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✔ Verified by numerical simulations

Hiramatsu et al. 2013’

Gravitational waves from DW networks

- DWs relevance **grows over time** ($\alpha = \rho_{DW}/\rho_{tot}$ is growing).

- **Abundance today** mostly depends on α at the time of annihilation:

$$\Omega_{GW}(k)h^2 = \frac{1}{\rho_{tot}}\frac{d\rho_{GW}}{d\log k} = 10^{-10}\epsilon\left(\frac{10.75}{g_*}\right)^{1/3}\left(\frac{\alpha_{ann}}{0.01}\right)^2 S(k)$$

Hiramatsu et al. 2013'
RZF, Notari, Pujolas, Rompineve 21',22'

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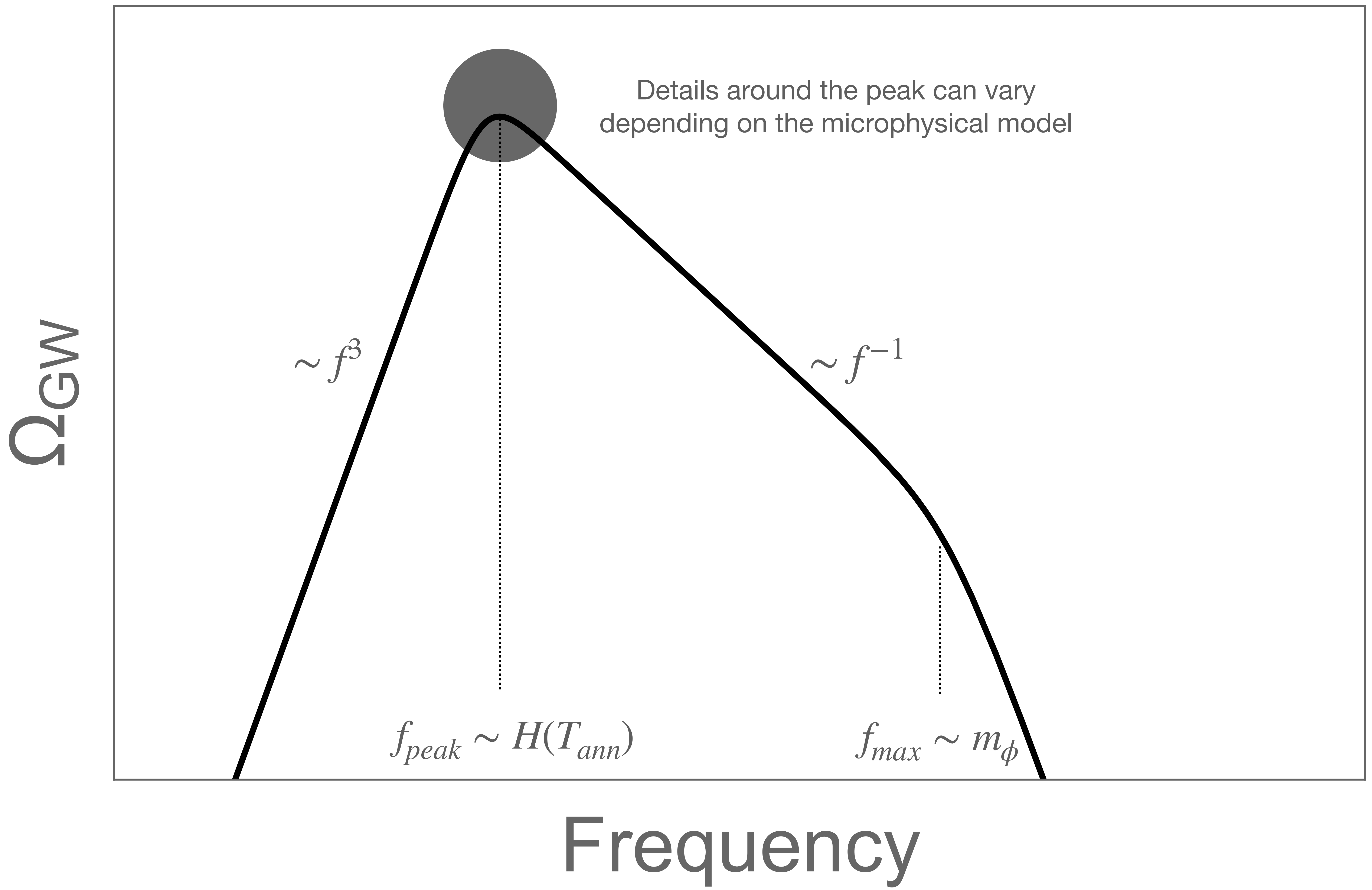
★ **Within sensitivity of current detectors** if network constitutes more than $\mathcal{O}(1\%)$ of the energy budget at T_{ann}.

Spectral shape



- Signal peaks at scales corresponding to the Hubble horizon at T_{ann}

$$f_{peak} = H(T_{ann})$$

Hiramatsu et al. 2013’

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Domain Walls in axionic models

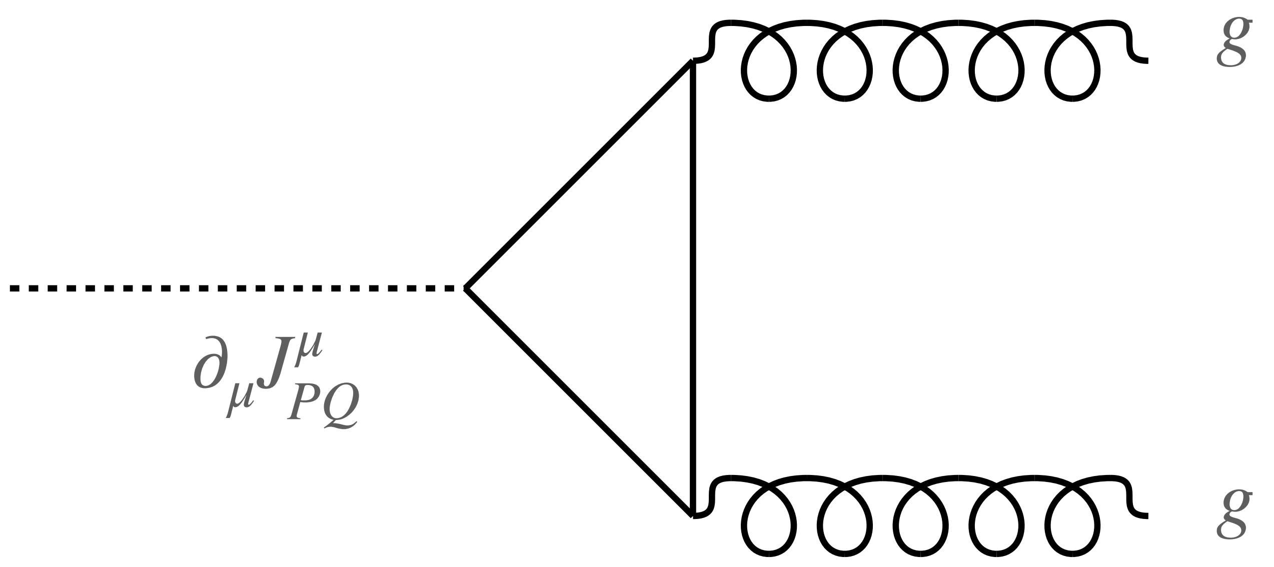
Where do they come from?

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

- (Effective PQ) U(1) global symmetry:

  # *Spontaneously broken* at $T \sim f$ $\rightarrow$ *Axion is the GB*

  # *Anomalous (e.g. wrt* QCD): $\partial_\mu J^\mu_{PQ} \propto N_{DW}\, G\tilde{G}$



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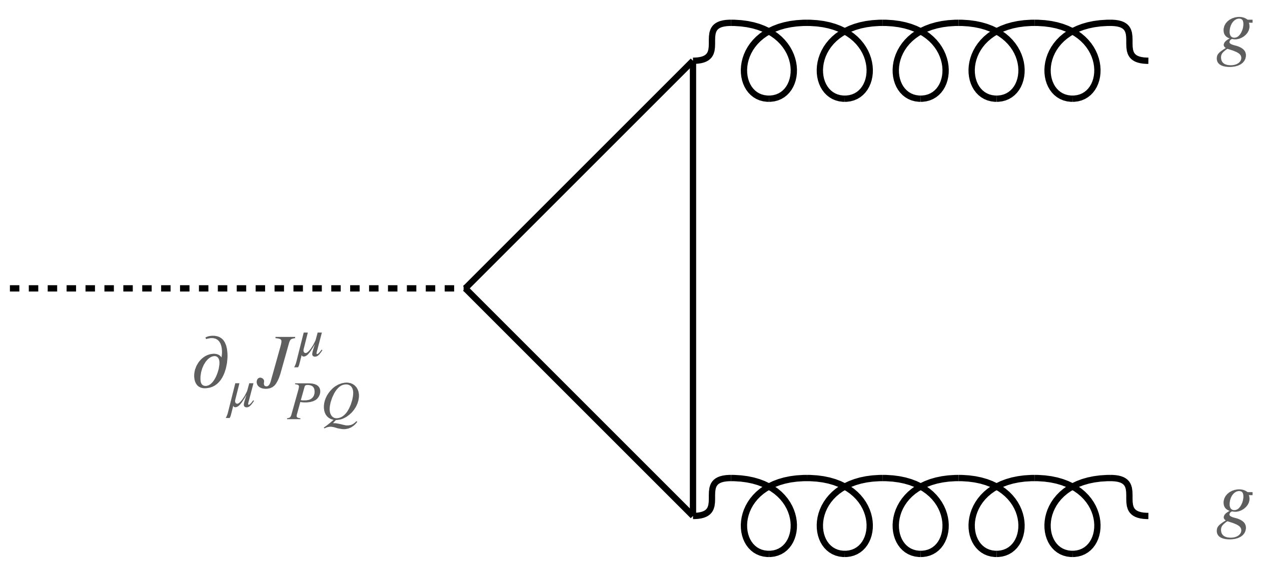


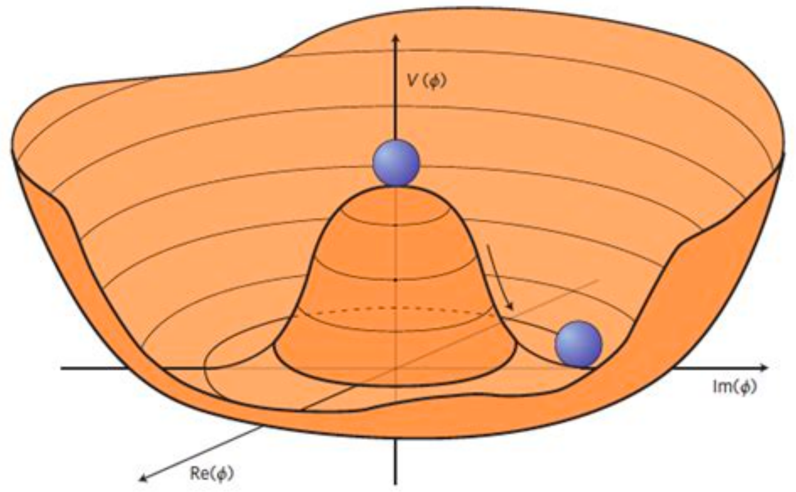
$$N_{DW} = 2 \sum dim(rep) \times \text{dynkin index} \times Q_{U(1)} = \begin{cases} 1, & \text{KSVZ} \\ 6, & \text{DFSZ} \end{cases}$$

DWs are common to axionic models (even in the vanilla QCD axion)

Cosmological evolution

Temperature

f → $\cancel{U(1)}$, axion takes random values $[0,2\pi)$.
Network* of **cosmic strings.**



* Symmetry broken after inflation

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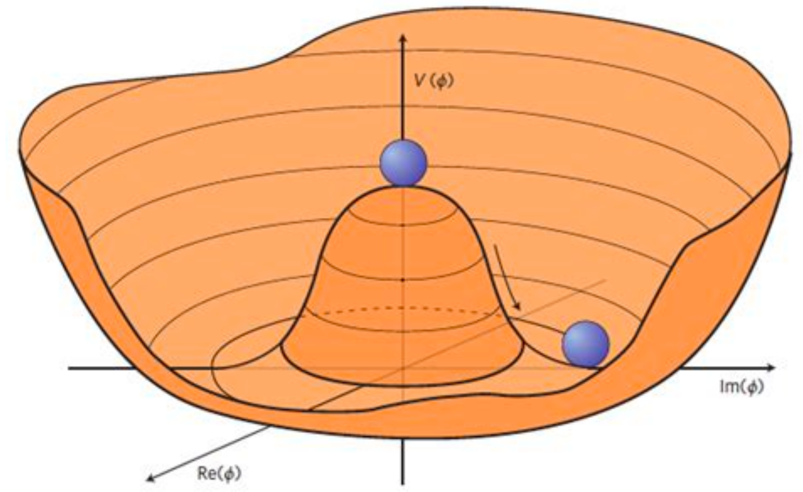
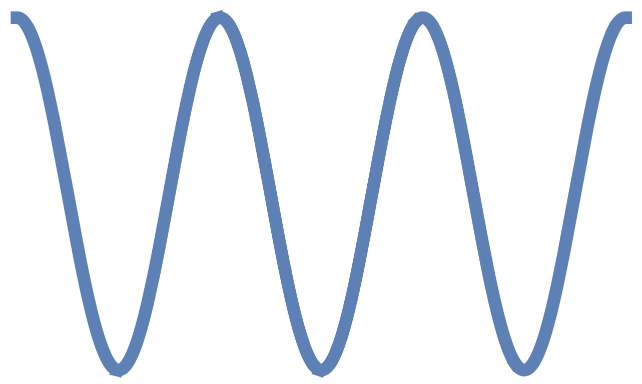


$H(T) \sim m_a$
(DWs form) → Shift-symmetry softly broken $(U(1) \to \mathbb{Z}_{N_{DW}})$:
(explicitly or via non-perturbative effects)



$V_a \sim \Lambda^4 \cos\left(N_{DW}\, a/f\right)$

DW number

[Kibble 76',
Kibble, Lazarides, Shafi 82',
Vilenkin, Everett 82']

[Pictures taken from M. Jain+ 2022]

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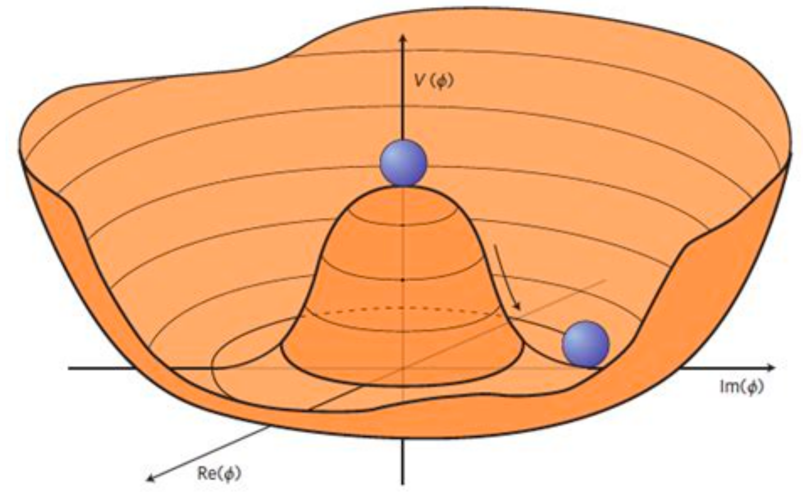

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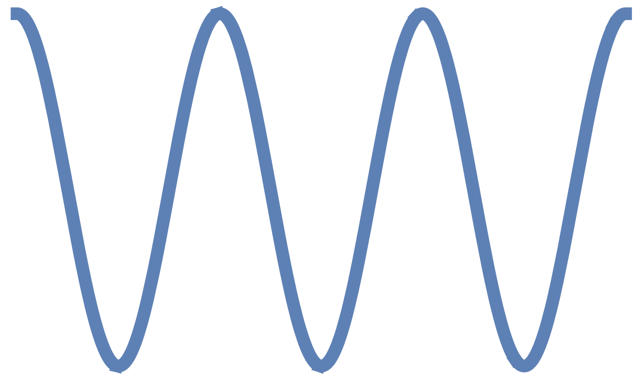

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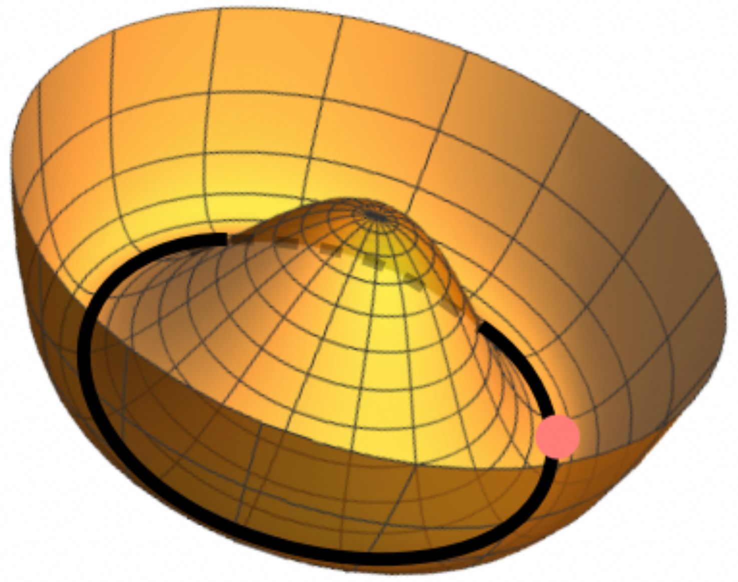
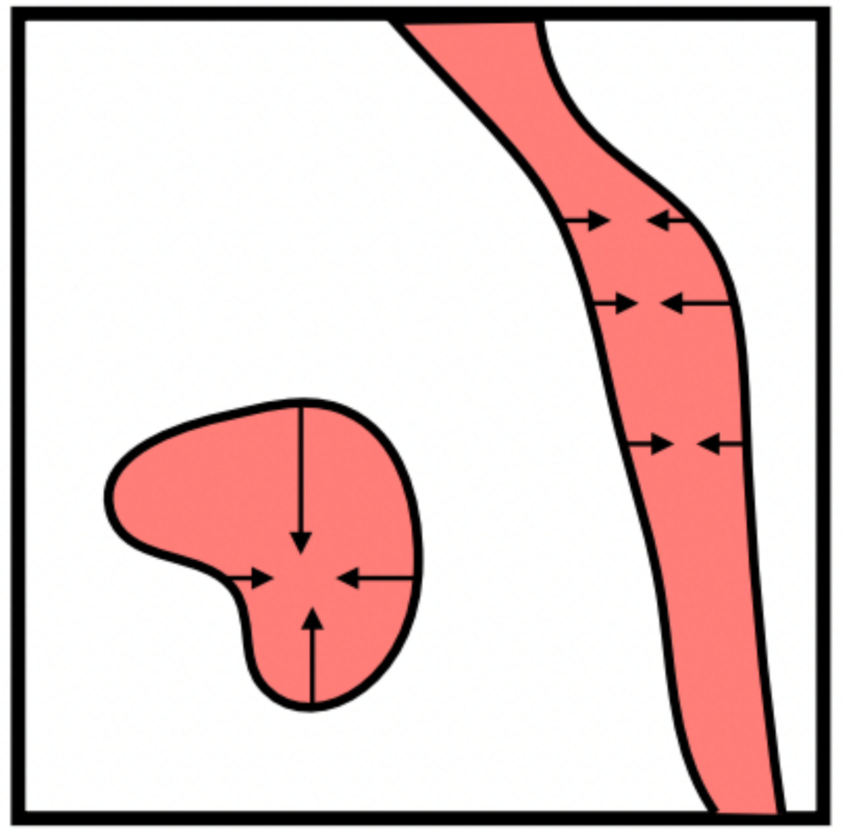
Network of **string-DWs** with tension

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





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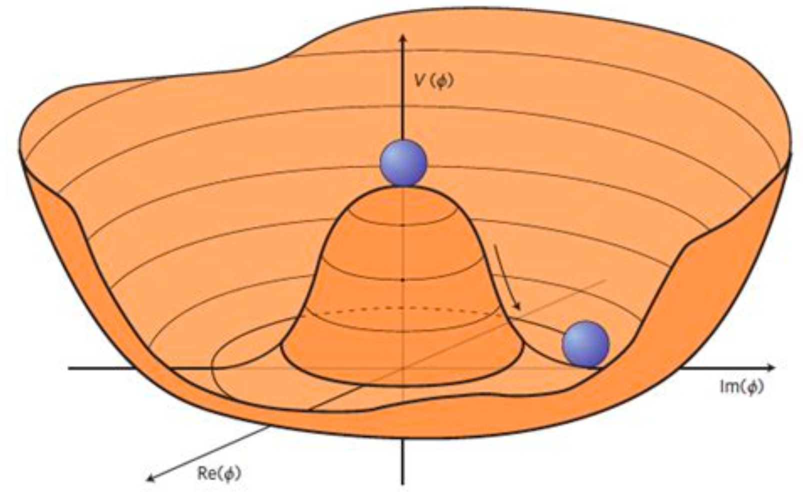

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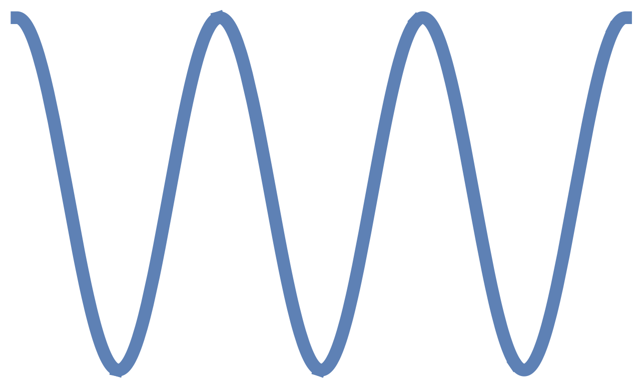

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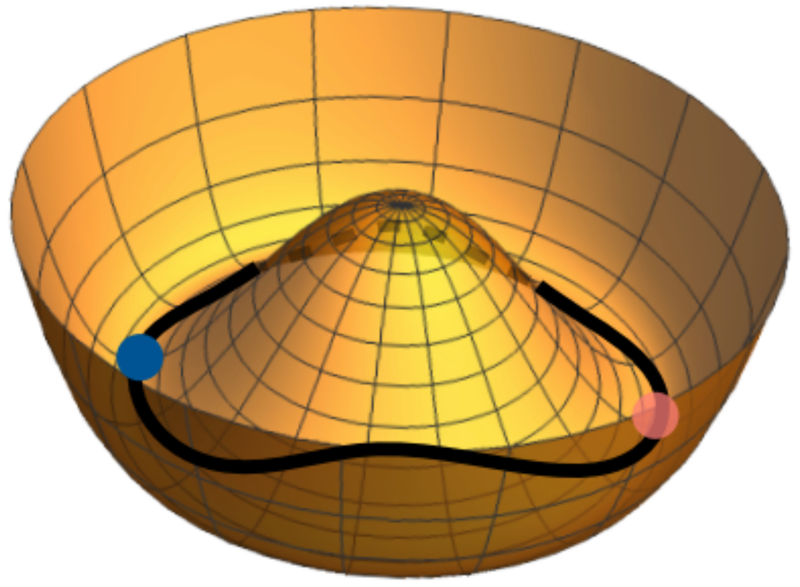

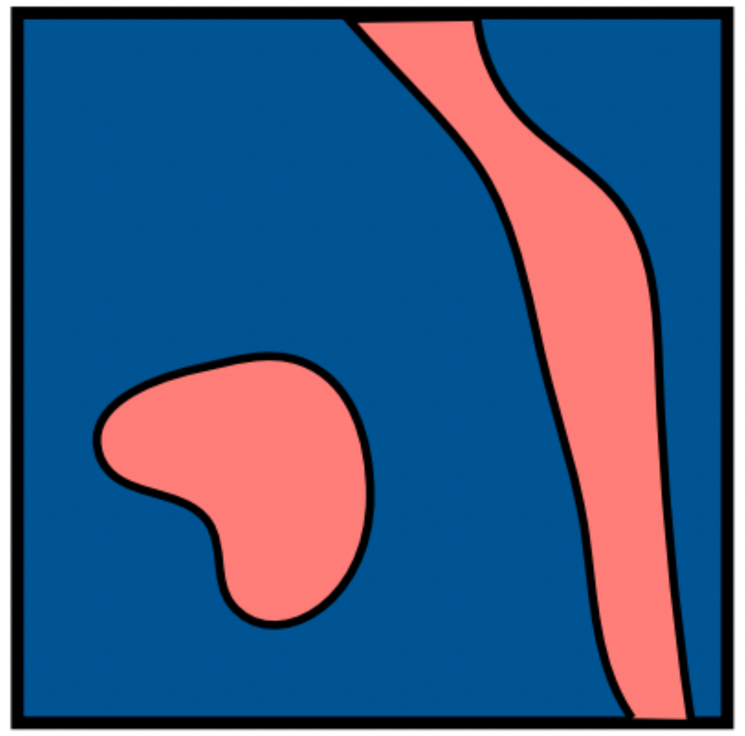

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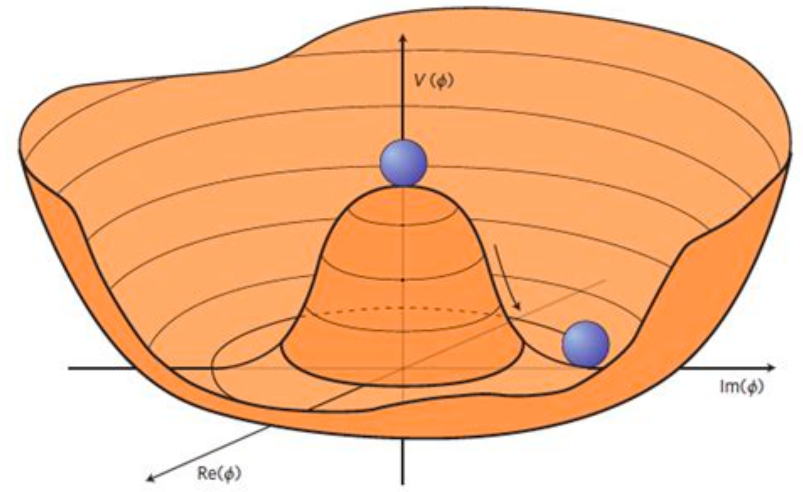

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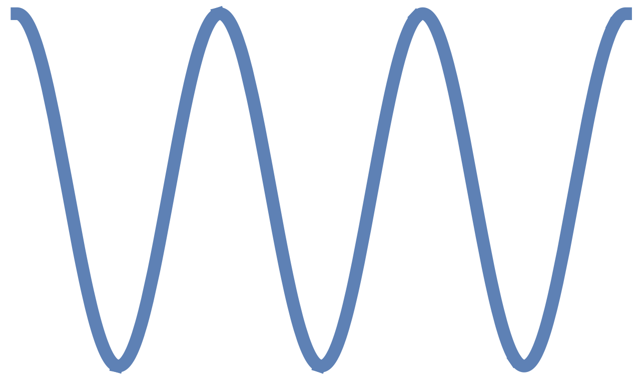

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⚠ **Domain Wall problem**

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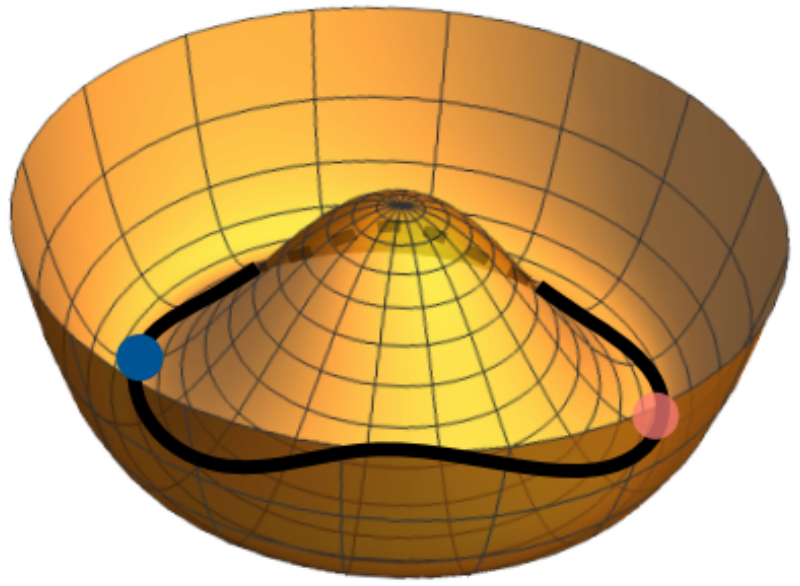

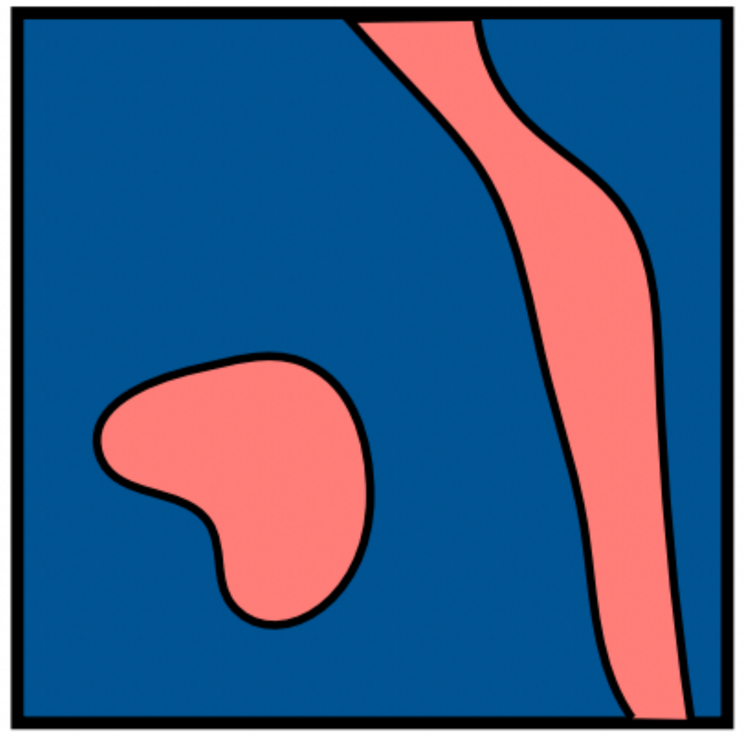

[Kibble 76',
Kibble, Lazarides, Shafi 82',
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[Pictures taken from M. Jain+ 2022]

Vanilla QCD axion case

DFSZ-like axion has stable DWs that form around T~GeV.

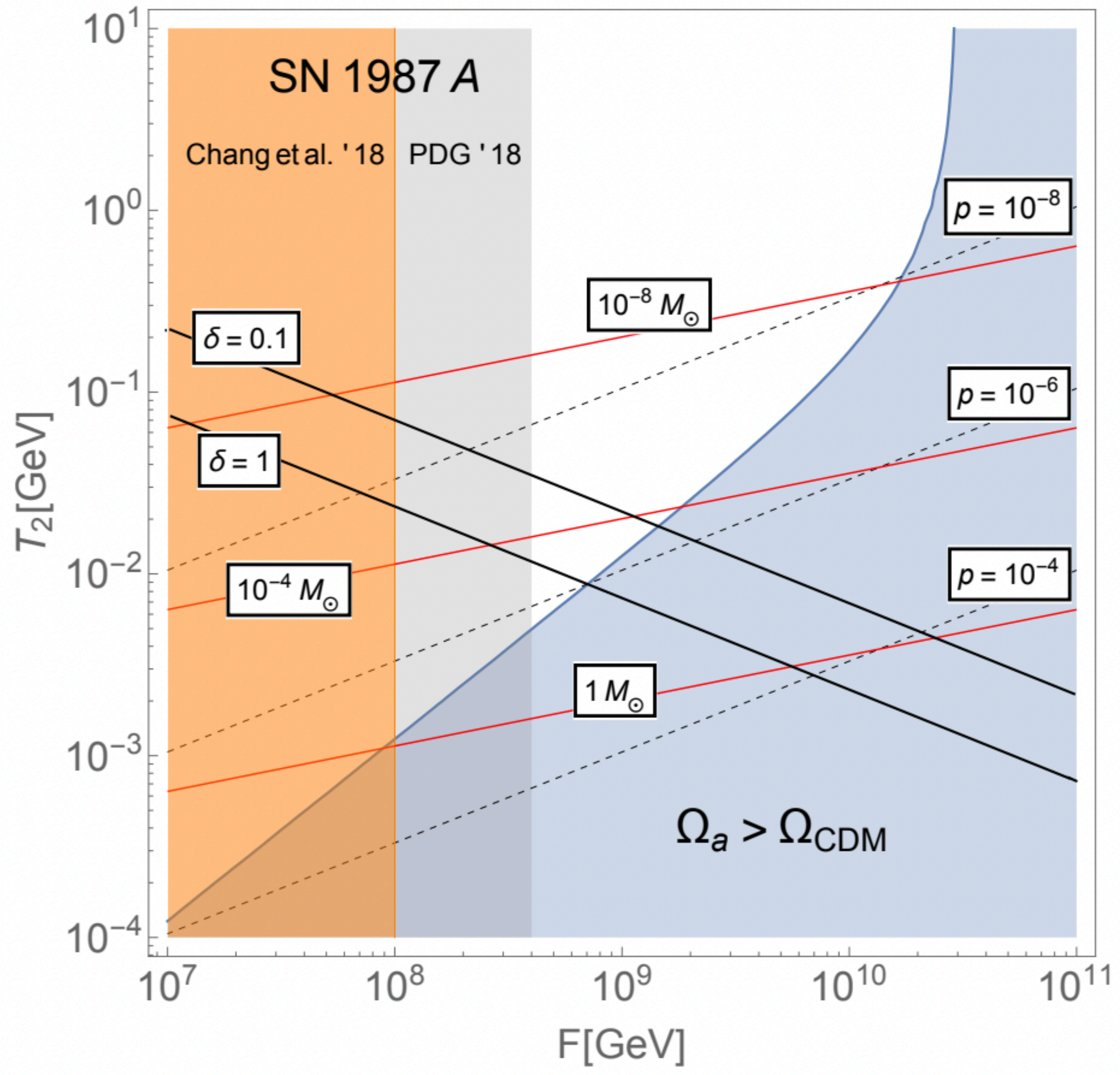
- Need for **"Bias" contribution** to axion potential to break Z_N (and the DWs)

$$V_{bias} \sim \Lambda_b^4 \cos\left(\frac{a}{f} + \delta\right)$$

[Sikivie 82']

- Bias in general misaligned ($\delta \sim 1$) and so **dangerous:**
  - **Large bias** → corrections to θ_{SM} : $\Delta\theta_{SM} \sim r^4, \quad r \equiv V_b/\Lambda$
  - **Small bias** → DWs annihilate late → large contributions to Ω_a

[Kawasaki+ 14', Ferrer et al. 18']



[Ferrer et al. 18']

But… not much parameter space available due to SN constraint.

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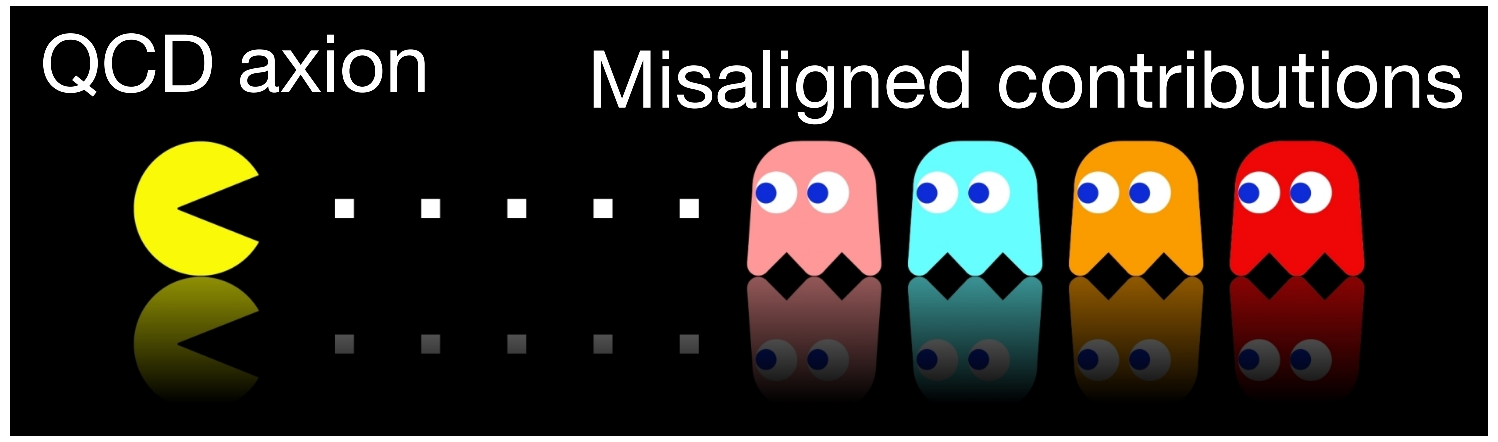
The Heavy QCD axion

- **Motivation:** ‘Quality problem’

(Bias) PQ breaking terms can spoil solution to strong CP problem.

$\Rightarrow$ PQ symmetry needs to be of **high quality.**



[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’,…]

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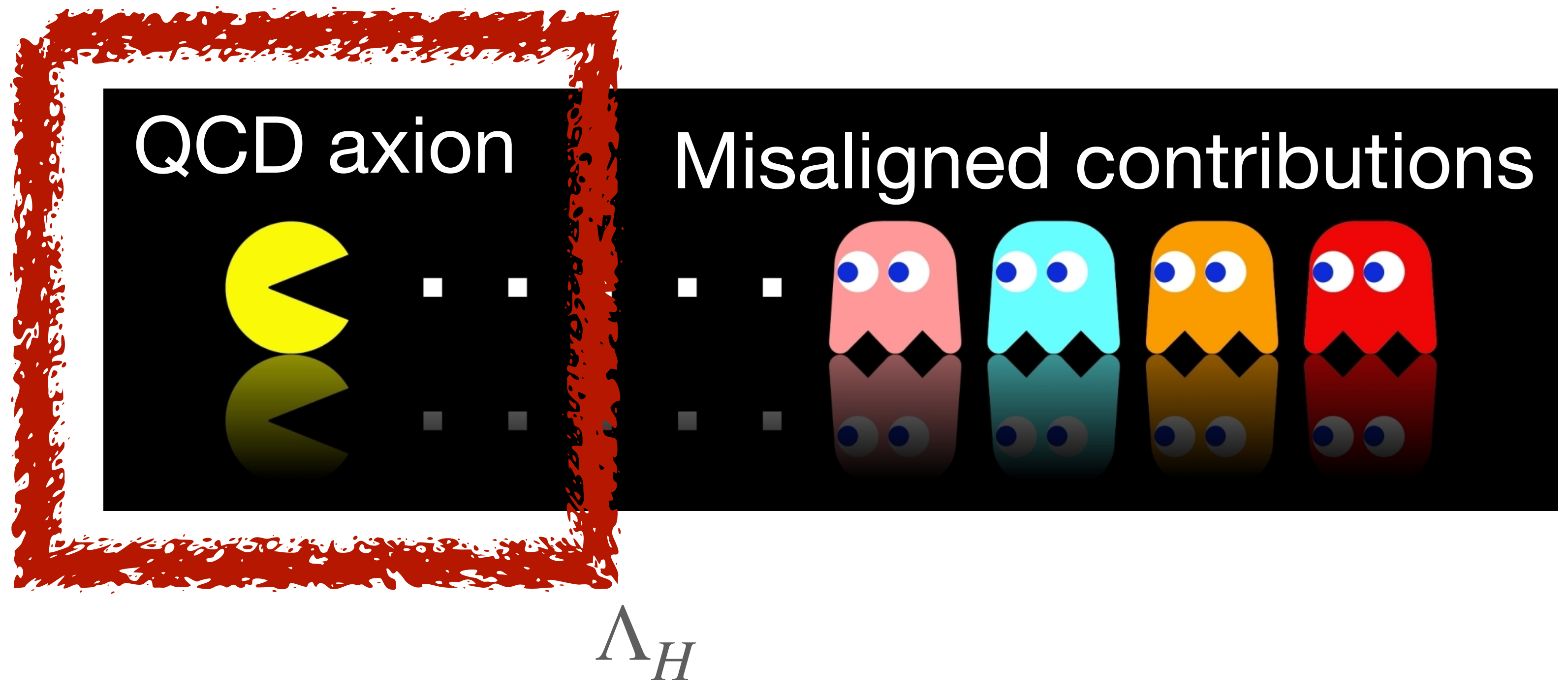


- **Improved quality:**

QCD axion coupled to heavier sector ($\Lambda_H \gg \Lambda_{QCD}$),
aligned with QCD.

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

- Examples: [see Julien's talk]
  - *small instantons,*
  strong coupling effects at high energies;
  - Z_2 symmetry;
  - additional gauge group with unification heavier

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

How can we test it?

Heavy QCD has no relics but…
DWs are more relevant: form **earlier** $(T \sim \Lambda_H)$, **larger tension** $(\sigma = 8 m_a f^2)$

Bias contributions

Large

→ DW Network is **short lived**

→ **Sizeable correction** to θ_{SM}

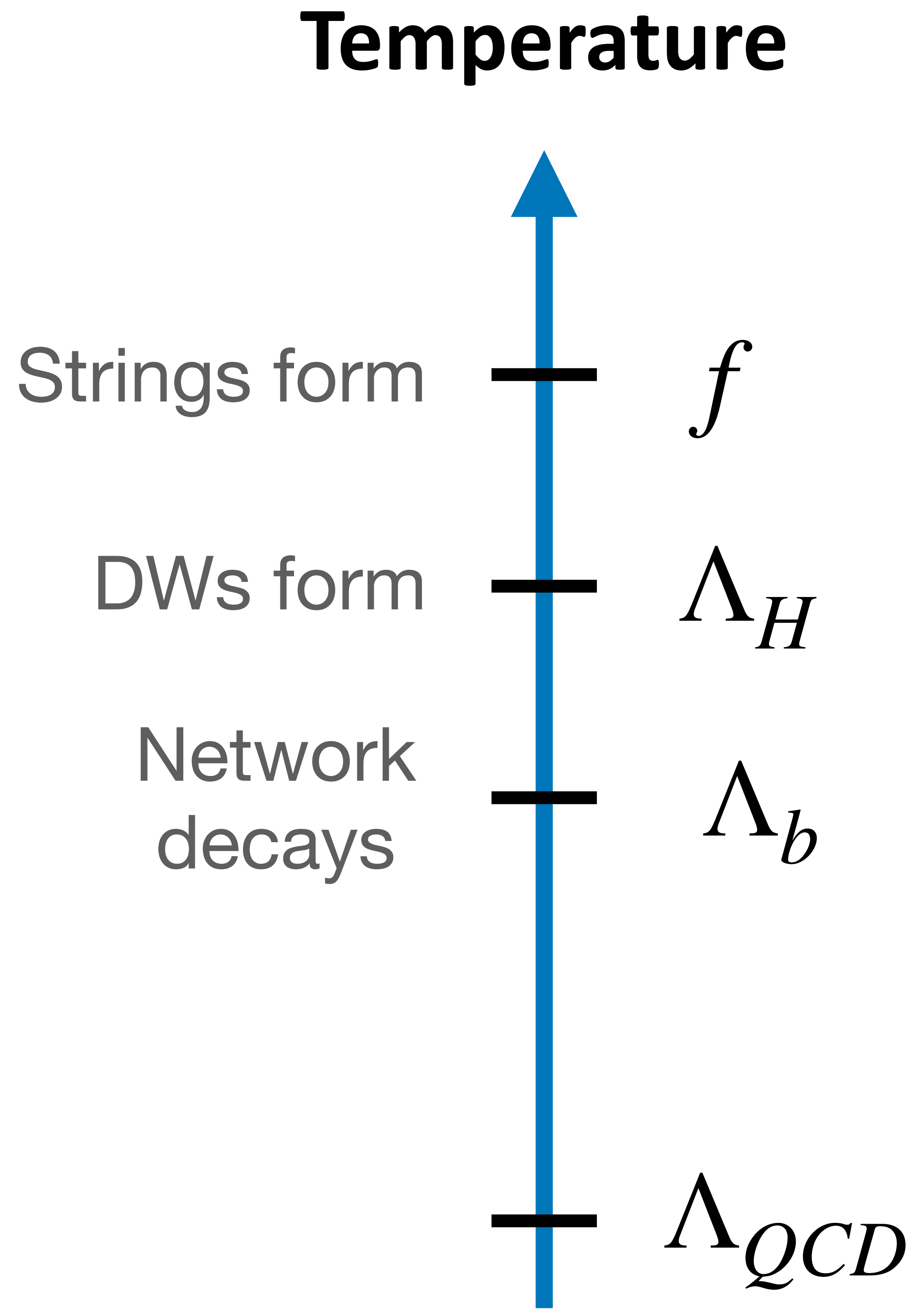
(**probed at n(p)EDM** experiments)

Small

→ DW Network is **long lived**

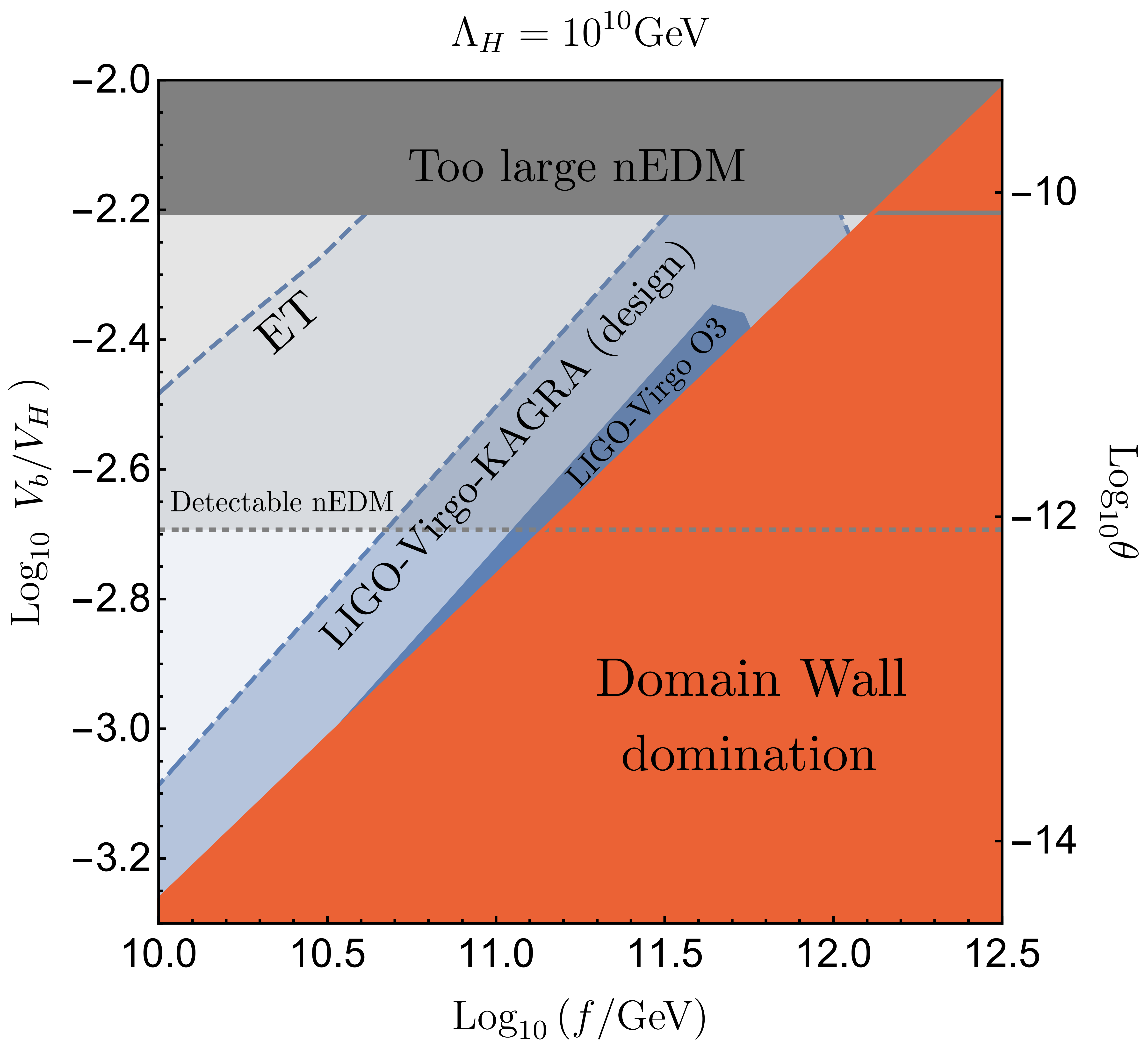
→ DW **energy density** becomes **large**

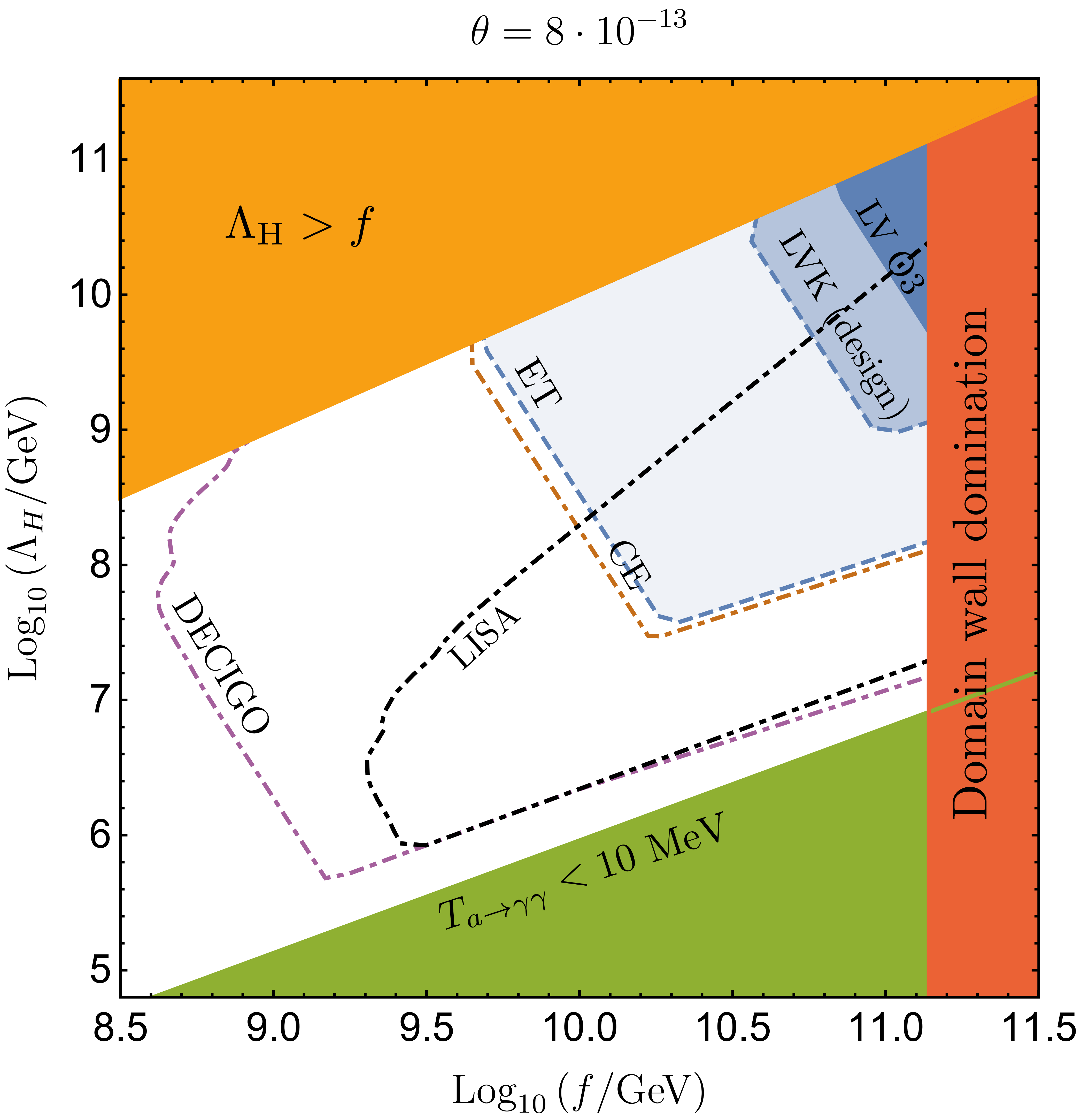
(**detectable GWs**)

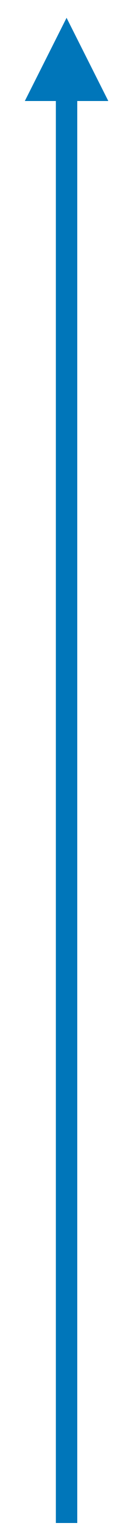


[**RZF**, Notari, Pujòlas, Rompineve 21']

Results







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

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Hints of DWs at PTAs?

- **Pulsar Timing Array (PTA) observatories** (EPTA, NANOGrav, PPTA) found **evidence** for a signal in the time residuals.

  - Can be explained by a **stochastic GW background**.

  - Compatible with signal from **supermassive BH binaries.**

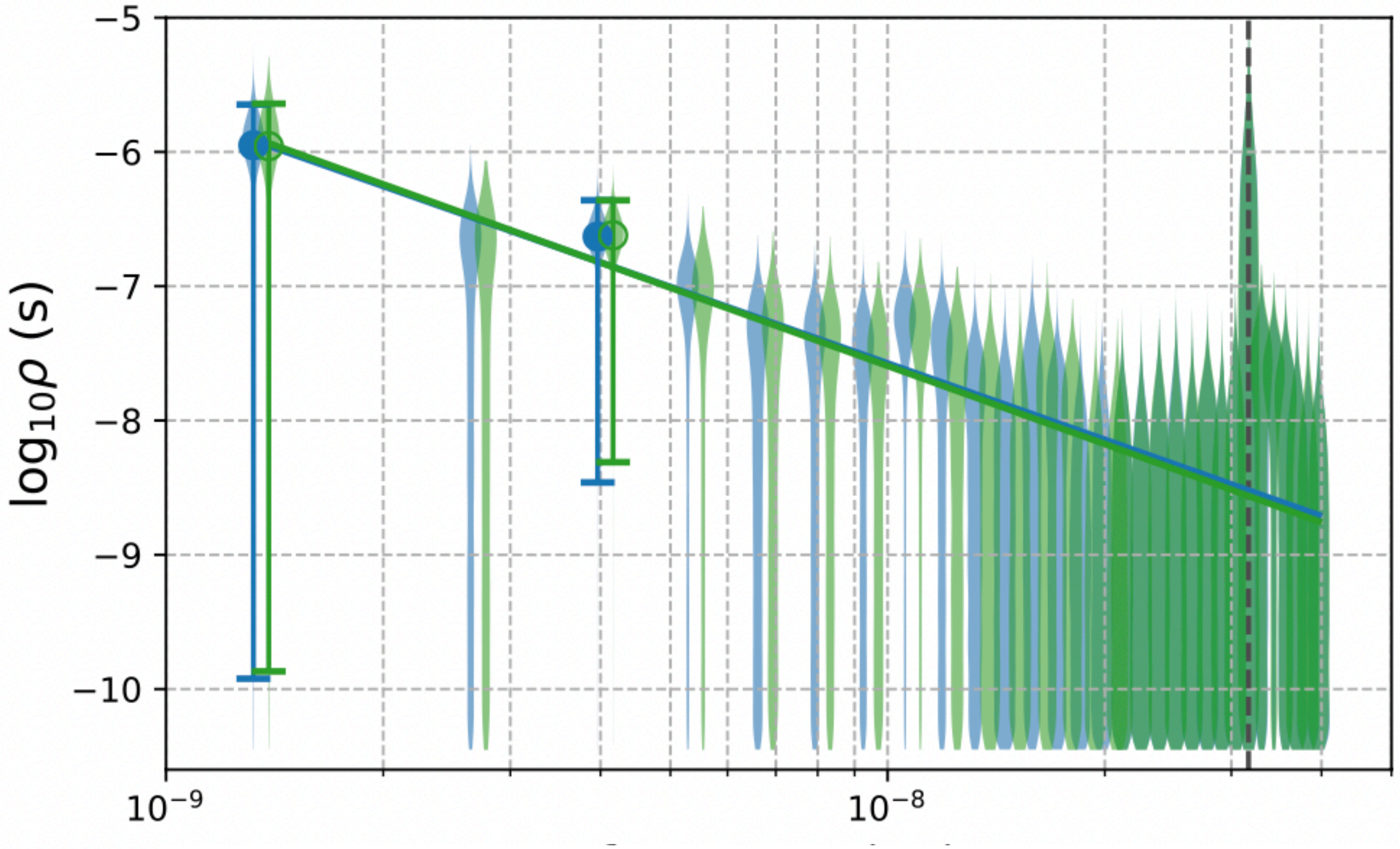
  - Early universe explanation also possible: **Domains walls?**

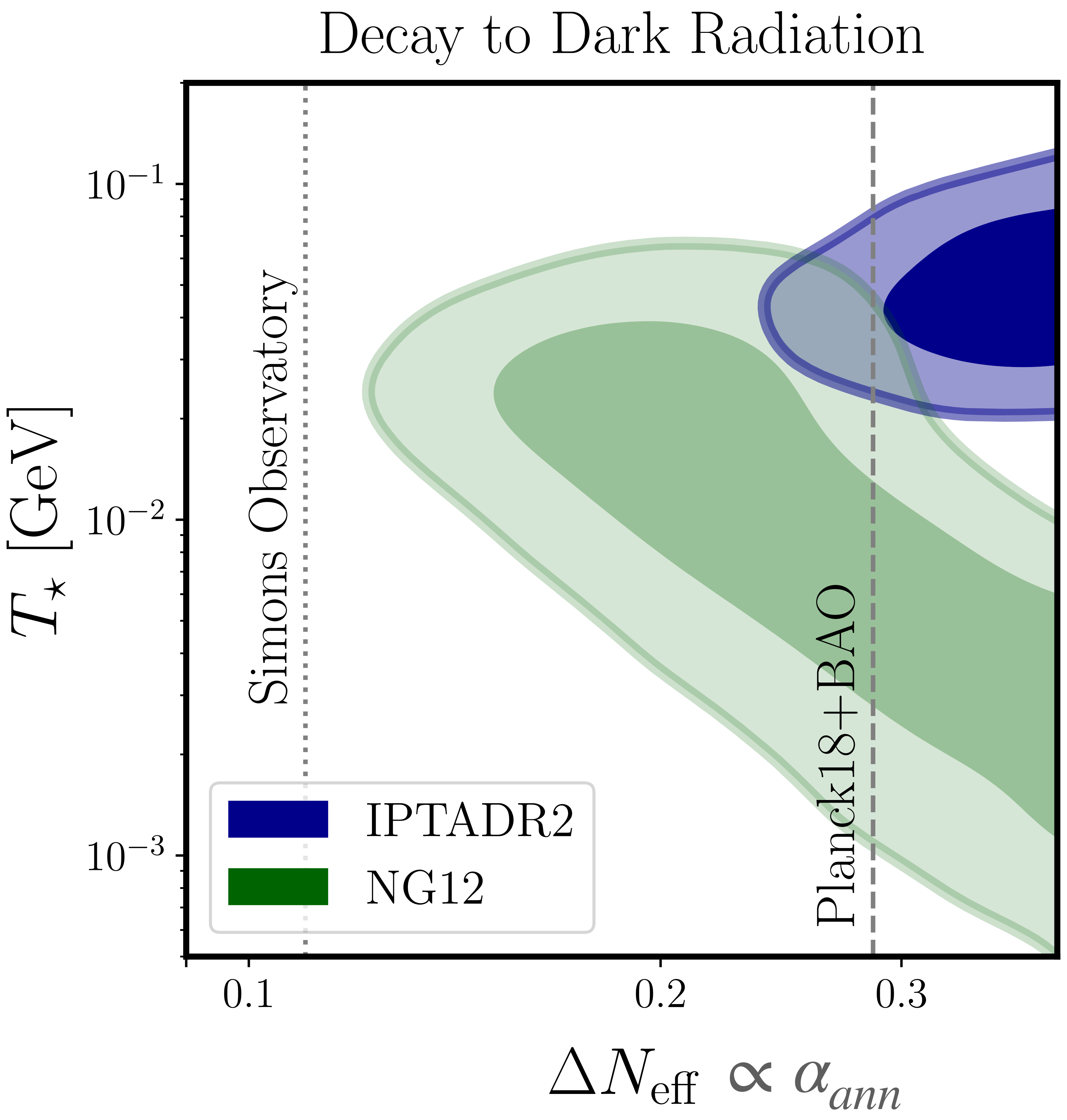
[**RZF,** F. Rompineve, A. Notari, O. Pujolàs, 22']

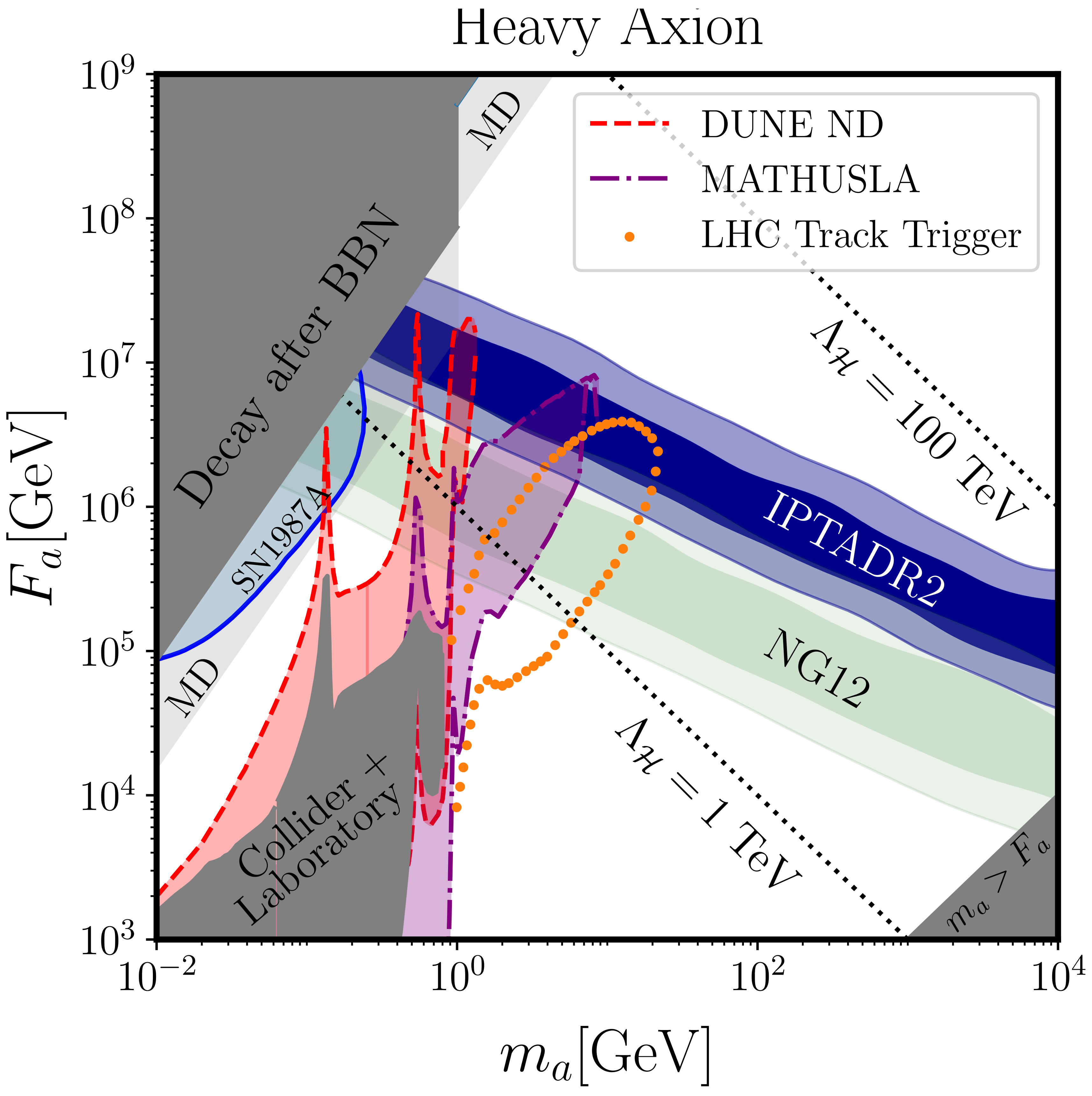
(Other options: 1st order PT, cosmic strings.)

[Bian+ 20', Craig+ 20', Chiang+ 20', Sakharov 21', Wang 22']

EPTA collaboration 21'







- Network of DWs with σ**~(40-100 TeV)**^{3}, T_{ann}**~20-50 MeV** provide a **good fit** to both datasets (as good as SMBH binaries).

[**RZF,** F. Rompineve, A. Notari, O. Pujolàs, 22']

- But **network remnants are dangerous**:

  - **Decay to dark radiation** will be fully probes with **future CMB surveys**!
  - **Decay to SM (e.g. Heavy QCD axion)** brings additional collider signatures.

Conclusions

- **Domain walls** are the outcome of many extensions of the SM (e.g. axionic models). Their **tendency for domination** leads to **strong cosmological signals.**

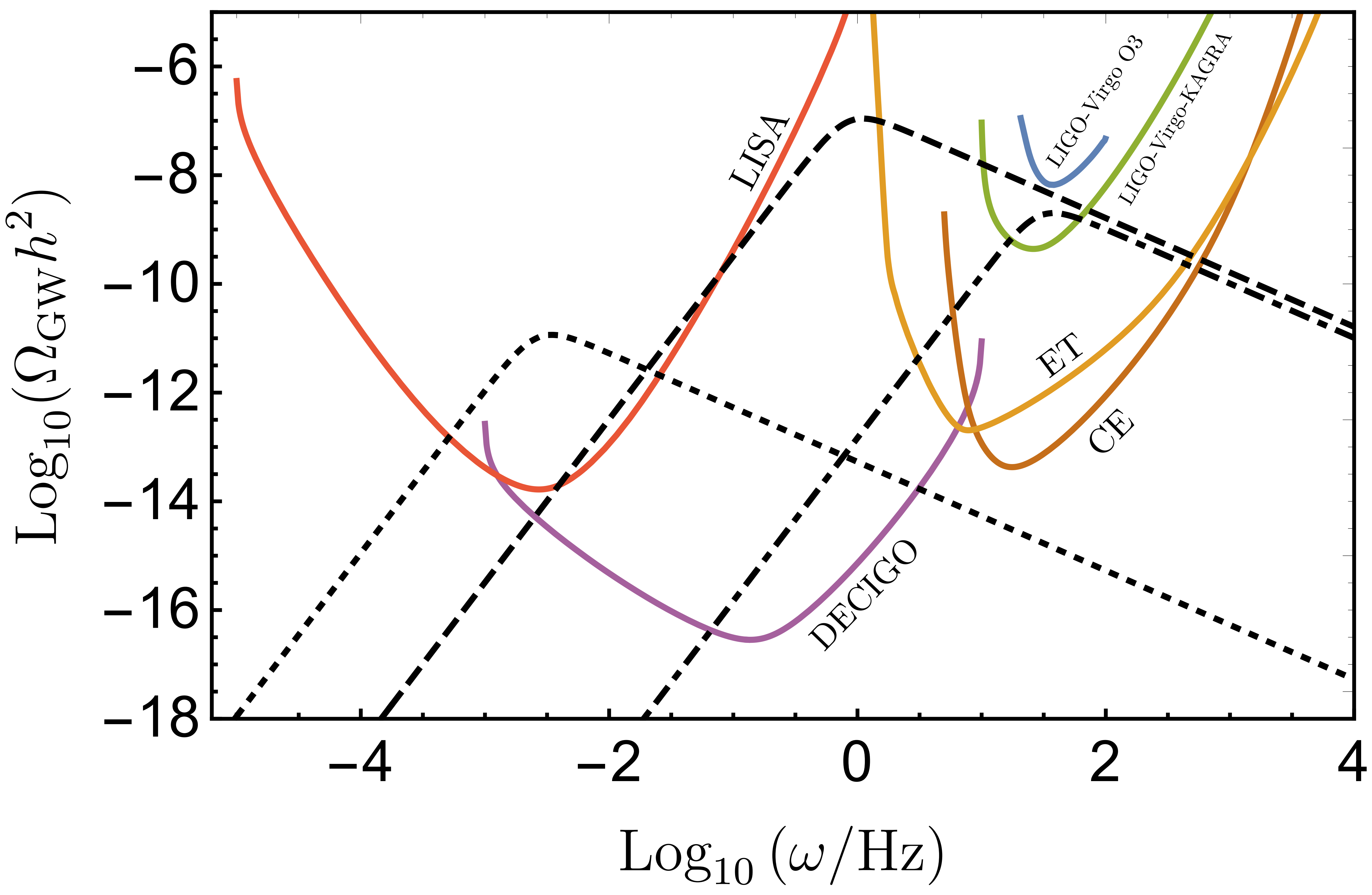
- The **Heavy QCD axion** leads to a **very predictive GW+EDM signal** that is already being probed at LIGO.

- **PTA observatories** have found **evidence** for a time delays.
  DW interpretation brings other cosmological or laboratory signatures that allow to distinguish from other onterpretations.

- Better **numerical simulations** of DW networks needed to improve the modelling of the GW signal.

Extra slides

Spectrum

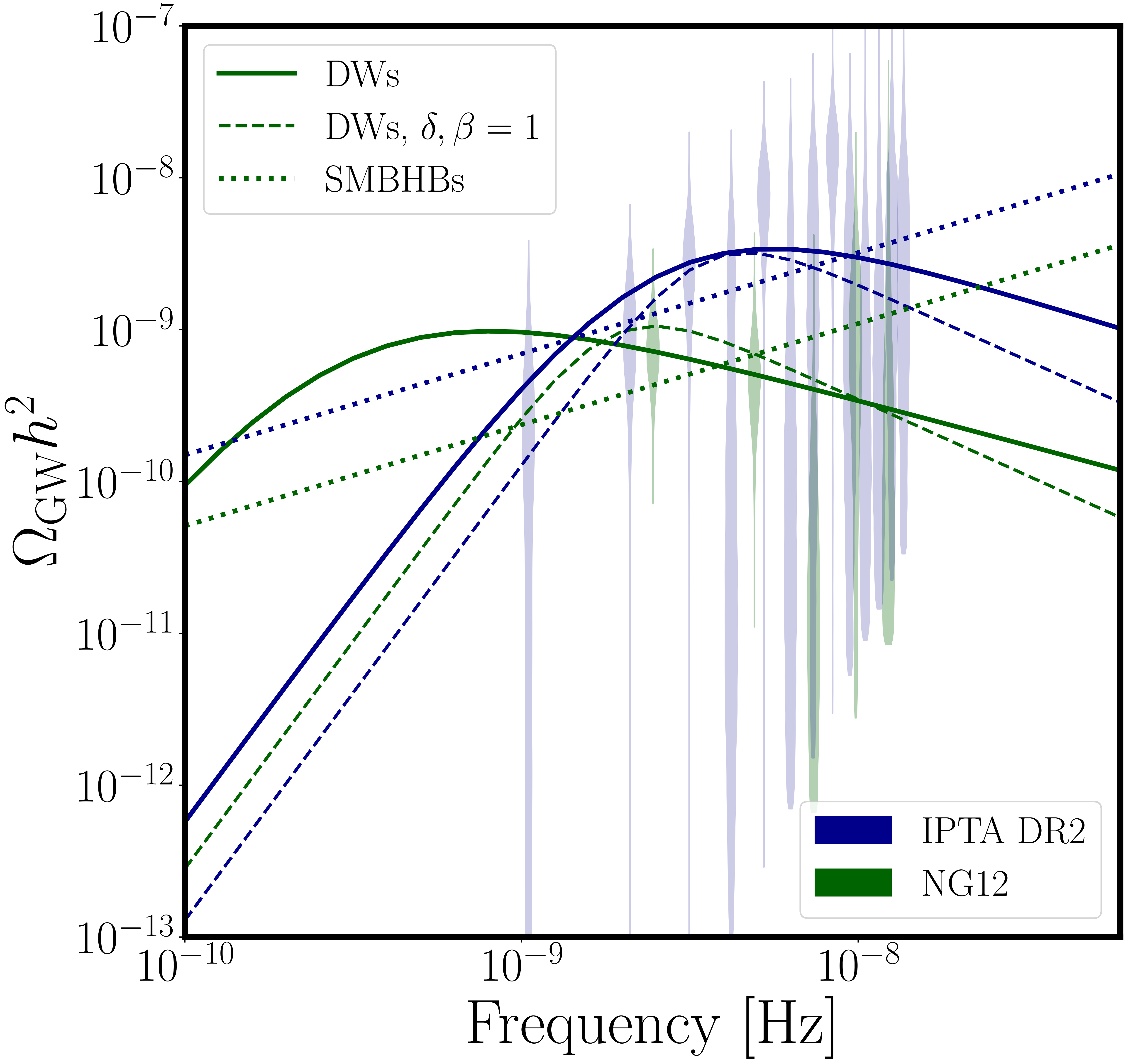


[**RZF**, Notari, Pujòlas, Rompineve 21']
[Hiramatsu et al. 13']

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



DWs
DWs, $\delta, \beta = 1$
SMBHBs
IPTA DR2
NG12
$\Omega_{\rm GW} h^2$
Frequency [Hz]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-10}
10^{-9}
10^{-8}