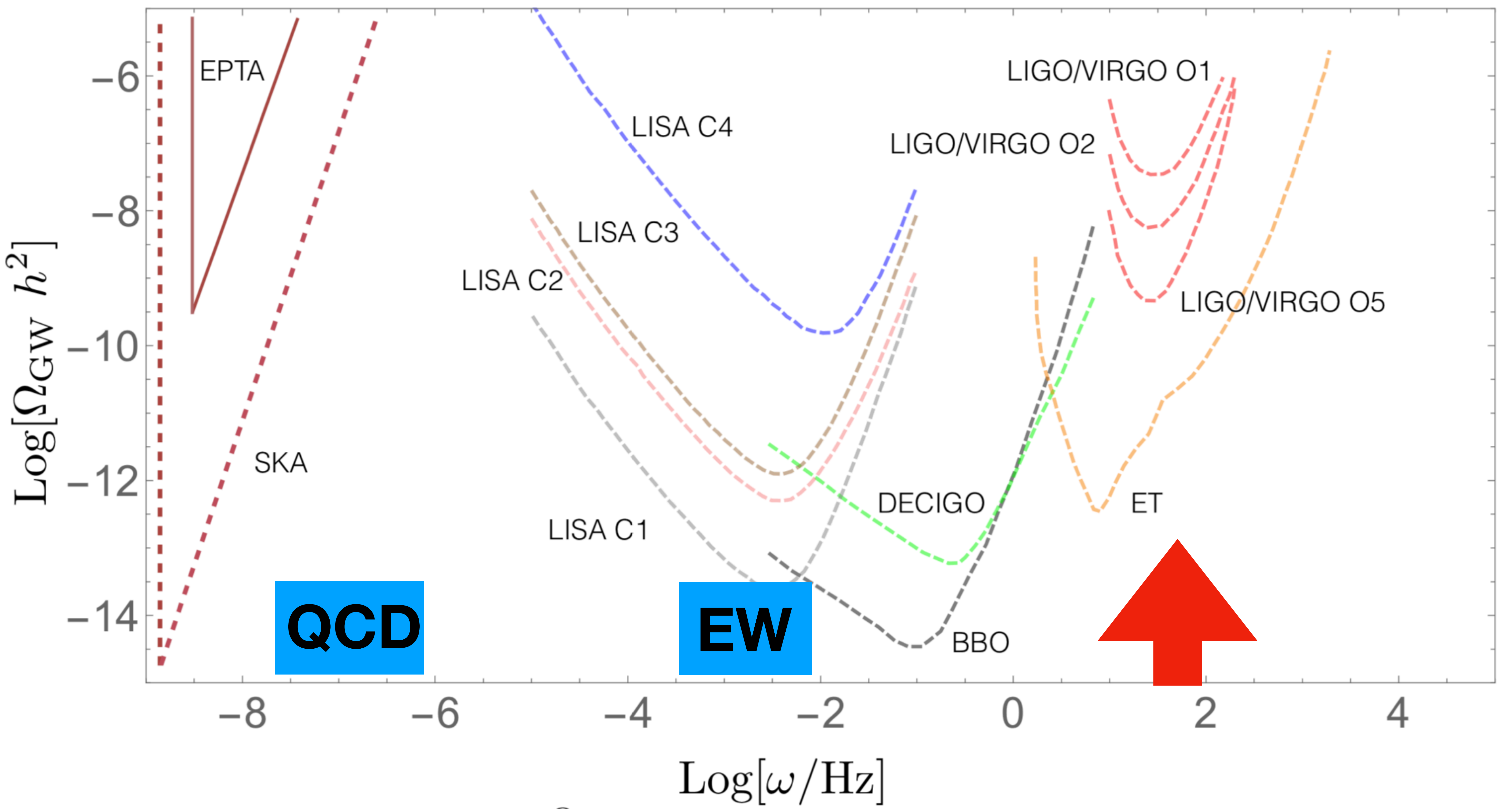
High quality GW relics

Oriol Pujolàs
Institut de Física d’Altes Energies, IFAE
UAB, Barcelona

Theoretical Physics Symposium 2021
The Wolfgang Pauli Centre
8-12 november 2021

GWs

- **LIGO/Virgo/Kagra (and coming): new window, with impressive views!**
- **From HEP perspective: relic stochastic GWB**



GWs

- **LIGO/Virgo/Kagra (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*

Can we probe axion physics with LVK, already??

plan

- Intro

I) GWs from a 1st order Peccei Quinn transition

II) GWs from *heavy axions*

plan

- Intro

I) GWs from *Peccei Quinn bubbles*

II) GWs from *high quality defects*

plan

- Intro

I) GWs from *Peccei Quinn bubbles*

II) GWs from *high quality defects*

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

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

I) GWs from *Peccei Quinn bubbles*

Can the PQ transition be 1st order?

Peccei-Quinn Phase Transition at LIGO

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

and Fabrizio Rompineve[c]

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

arXiv:1912.07587
JHEP 04 (2020) 195

Can the PQ transition be 1st order?

Yes, depending on the type of PQ model

Peccei-Quinn Phase Transition at LIGO

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

and Fabrizio Rompineve[c]

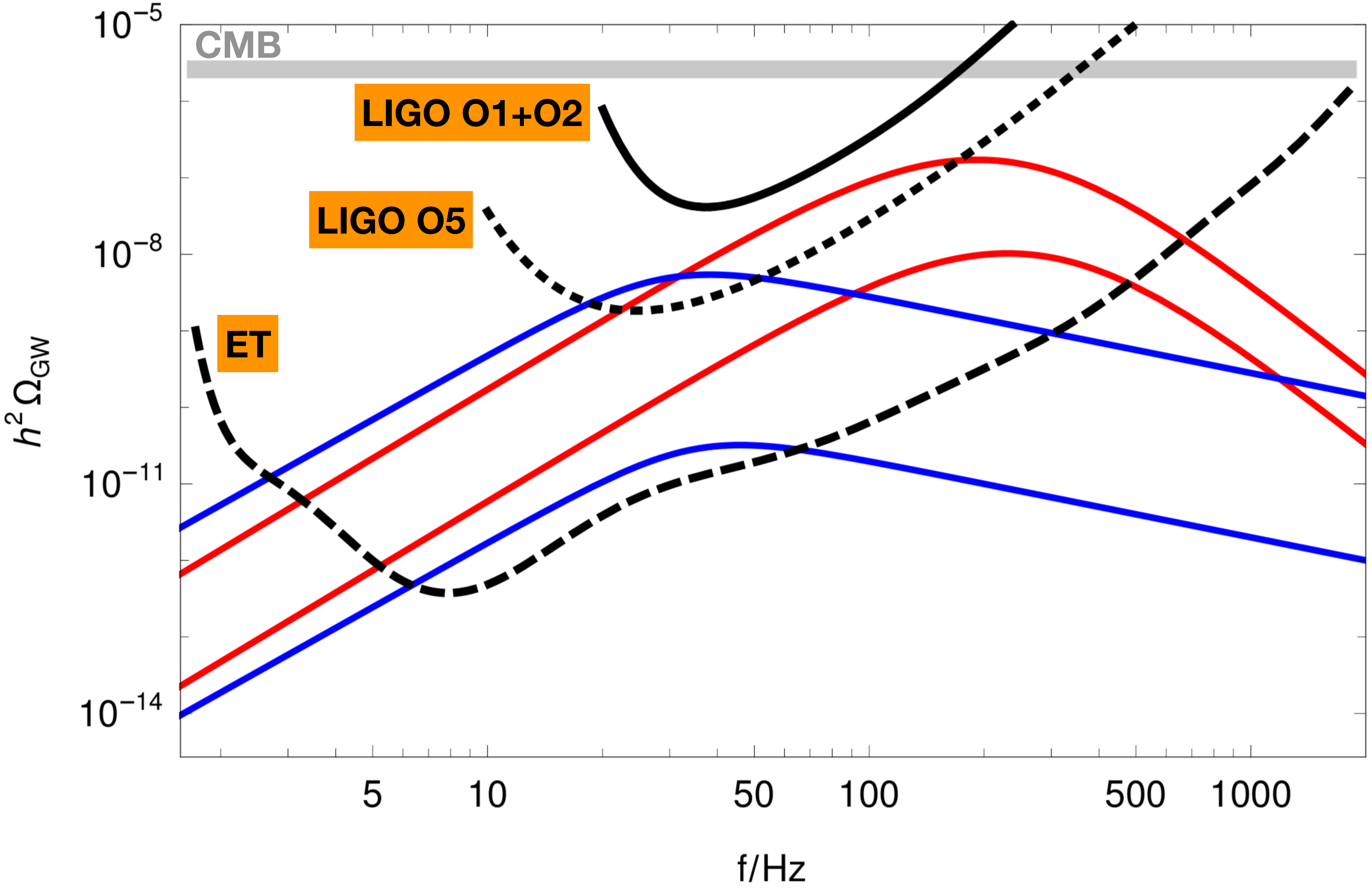
also JHEP 04 (2020) 025
Delle Rose, Panico, Redi, Tesi

arXiv:1912.07587
JHEP 04 (2020) 195

“ABC” of (1st order) cosmological phase transitions

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

1) sensitivity reach to PTs

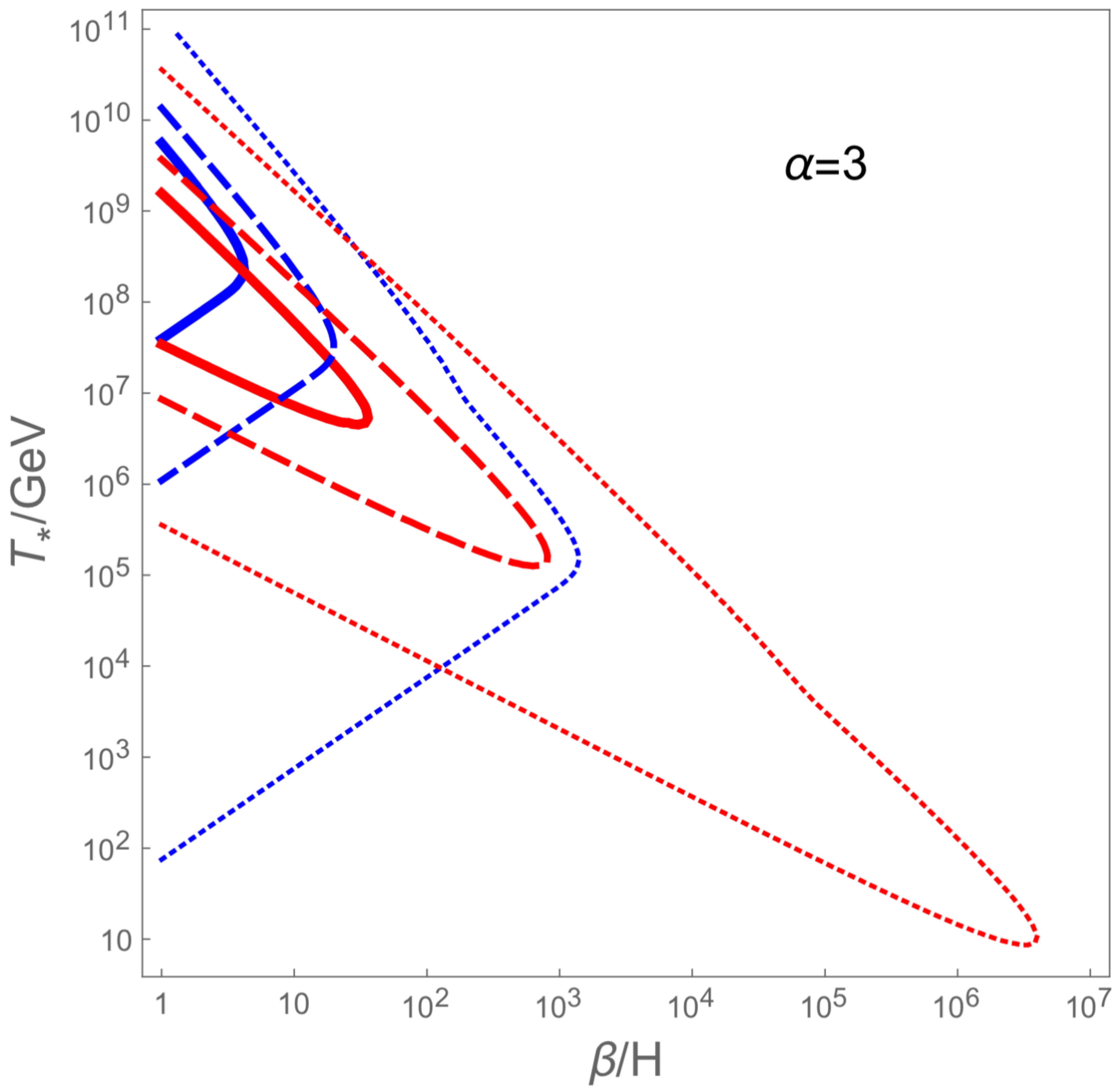


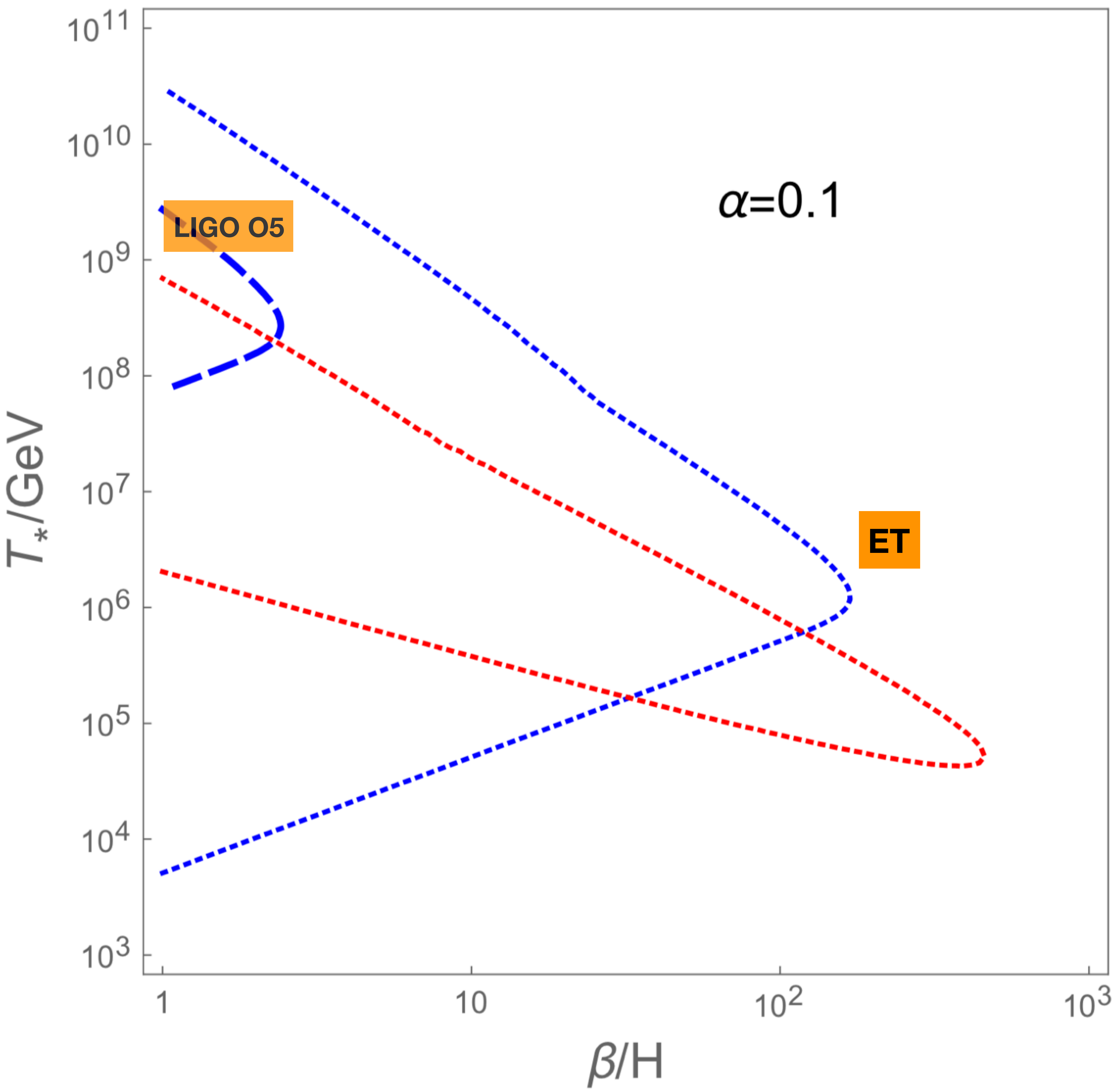
$F_a = 10^8\ GeV\ with\ \alpha \approx 3.5$ $\qquad$ $F_a = 10^9\ GeV\ with\ \alpha \sim 10^6$

1) sensitivity reach to PTs

already ruling-out some parameter space!

(solid lines)





2) Axion models with strong PT

✗

- **KSVZ** (Kim, Shifman, Vainshtein, Zakharov)

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

✓

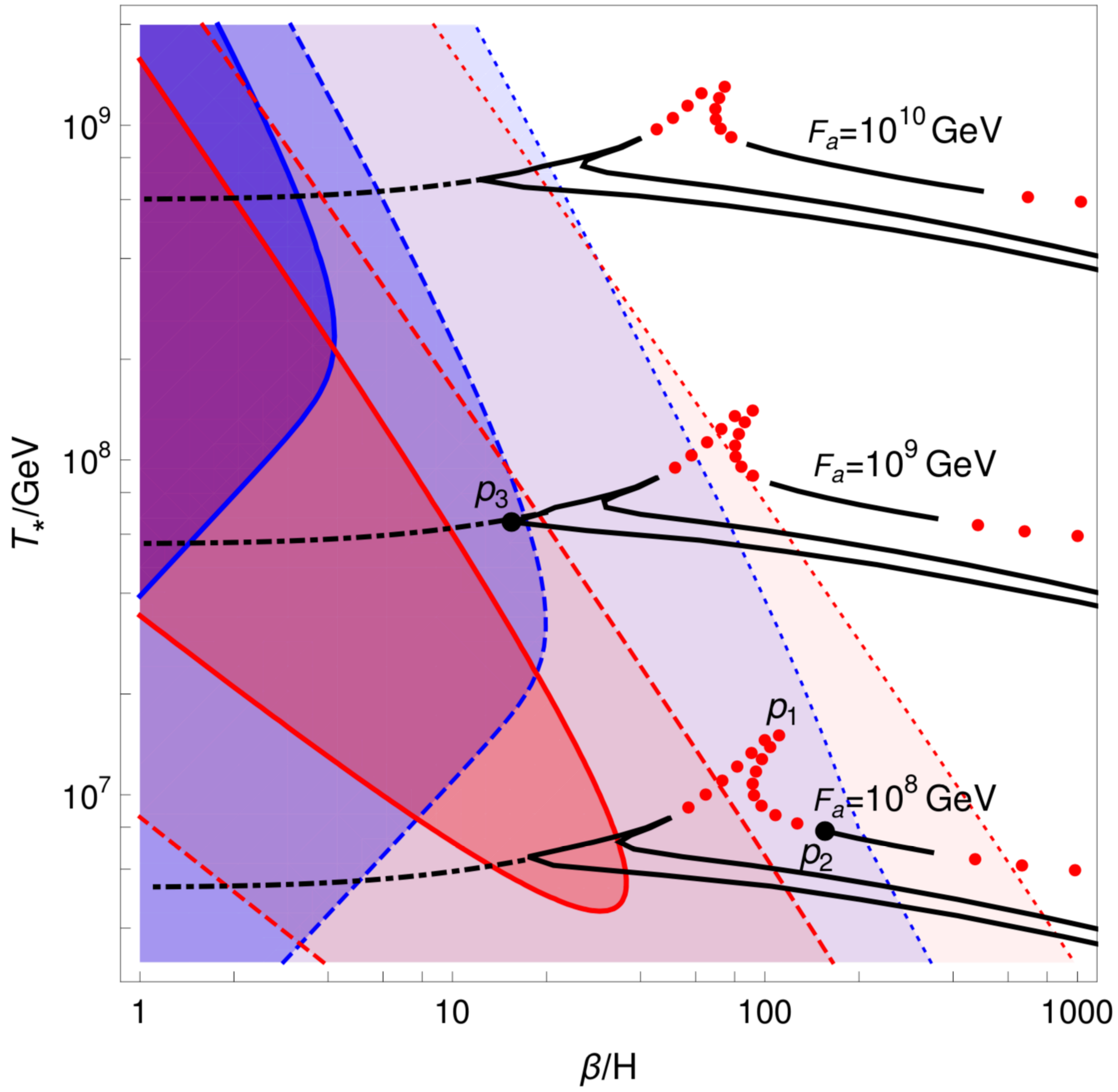
- **DFSZ** (Dine, Fischler, Srednicki, Zhitnitsky)

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

2) Axion models with strong PT

DFSZ can do it !

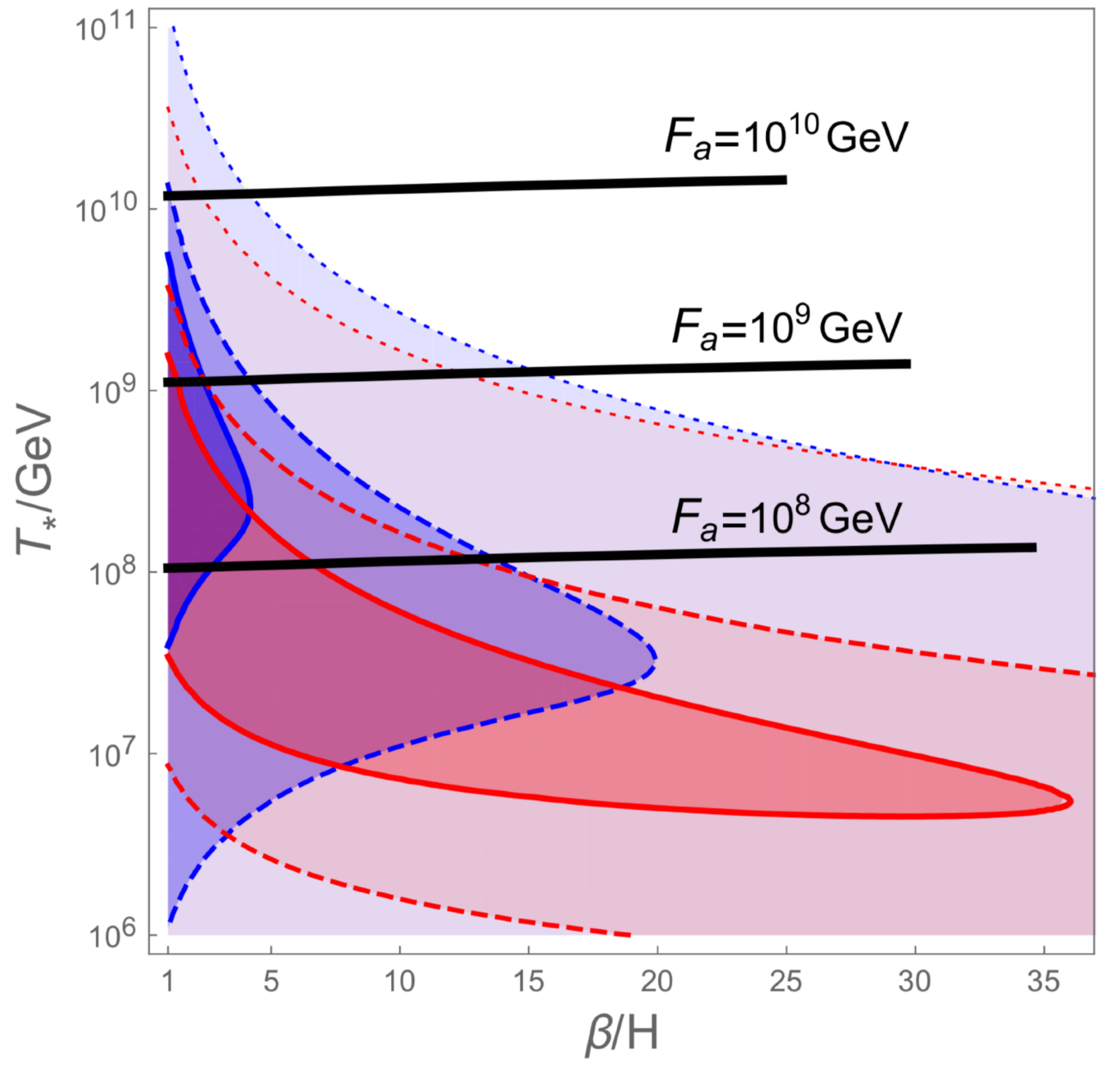
T_* is ~ 1 order of magnitude below F_a



2) Axion models with strong PT

KSVZ/DFSZ can be embedded in larger new physics sectors

- **SUSY version of KSVZ also works**
- **Strong dynamics as well**



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

Phenomenological model (bubble collisions)				
$\Omega_{\rm coll}^{95\%}$ (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 $\Omega_{\rm coll}^{95\%}$(25 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 are already ruled out

Conclusions

- **LIGO/Virgo are sensitive to cosmological phase transitions in the early universe at around** $10^8 GeV$ **— HEP!**
- **Detectable signals arise if sufficient *supercooling*,** $\alpha \gtrsim 1$
- **Prospects for the ET are very good**
- **Very relevant for axion physics: PQ phase transition** $T \sim 10^8 - 10^{12}\ \mathrm{GeV}$
- **Detectable PQ models: DFSZ, strong dynamics, SUSY-KSVZ…**
- **Complementary to other gravitational axion tests from superradiance**

II) GWs from ***high quality defects***

II) GWs from *high quality defects*

High Quality QCD Axion at Gravitational Wave Observatories

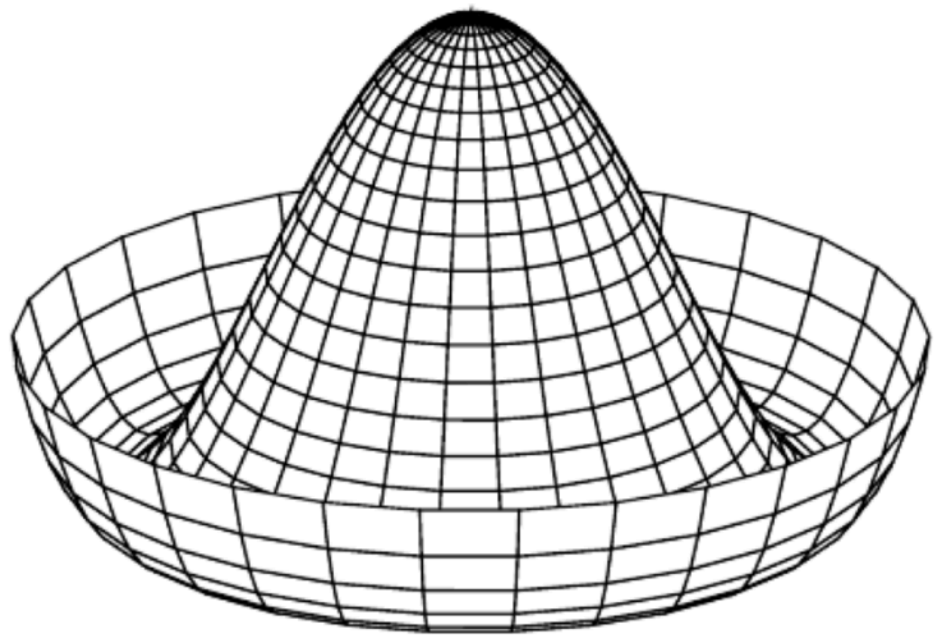
Ricardo Z. Ferreira,[1,*] Alessio Notari,[2,†] Oriol Pujolàs,[1,‡] and Fabrizio Rompineve[3,§]

arXiv:2107.07542

Axionic defects

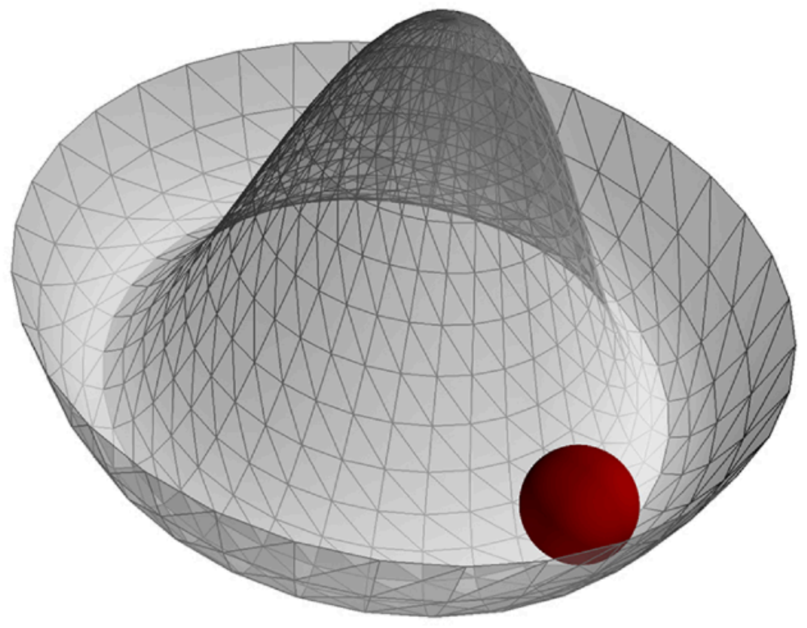
Peccei-Quinn mech: introduce a $U(1)_{PQ}$ symmetry with:

i) SB and



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

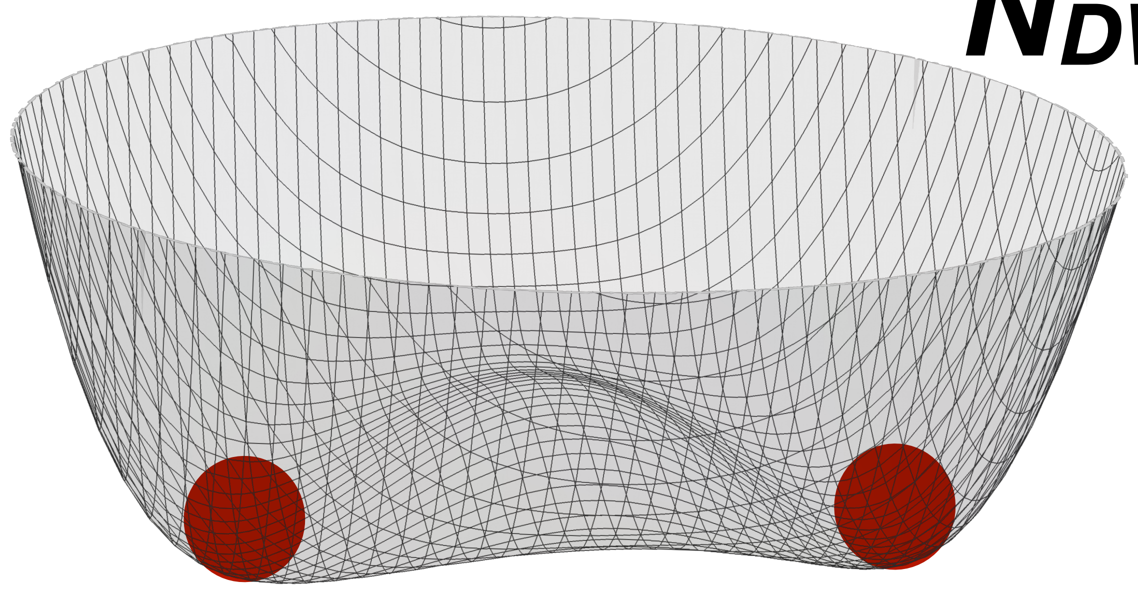
ii) $U(1)_{PQ}\,SU(3)_c\,SU(3)_c$ anomaly



expl. ~~U(1)~~$_{PQ}$ @ $\boldsymbol{\Lambda_{QCD}}$

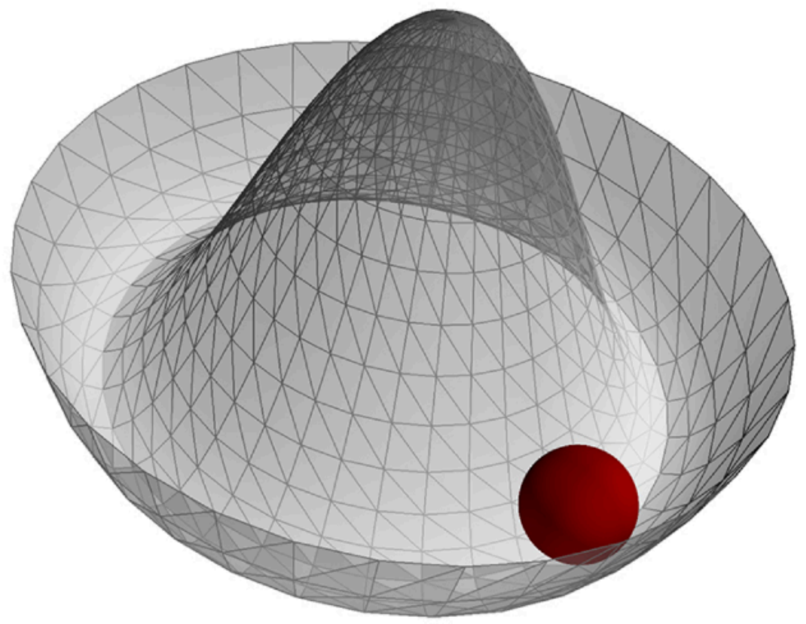
Axionic defects

$N_{DW} = 2$



—> N_{DW} **"Domain wall number"**

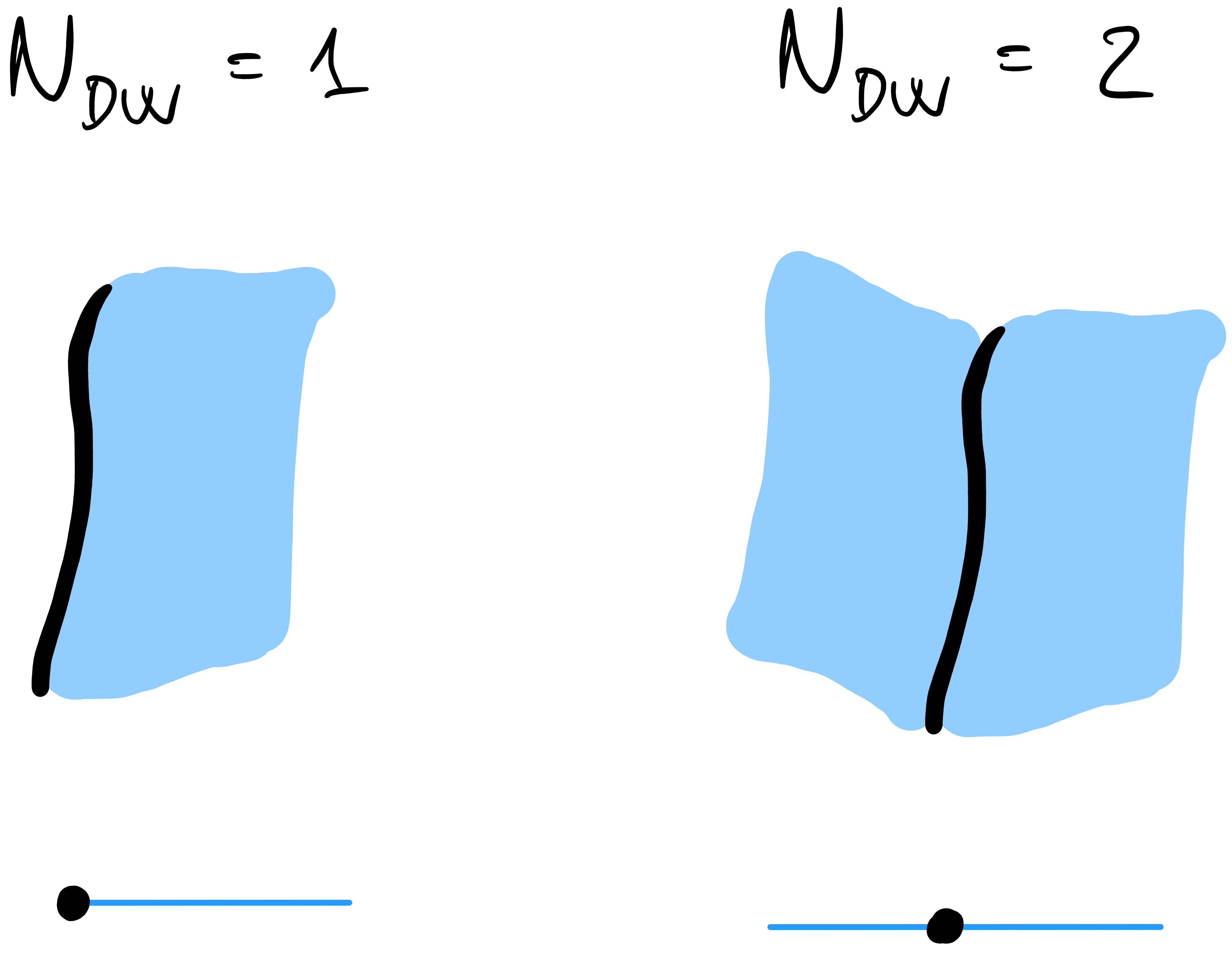
$U(1)_{PQ}$ —> $Z_{N_{DW}}$

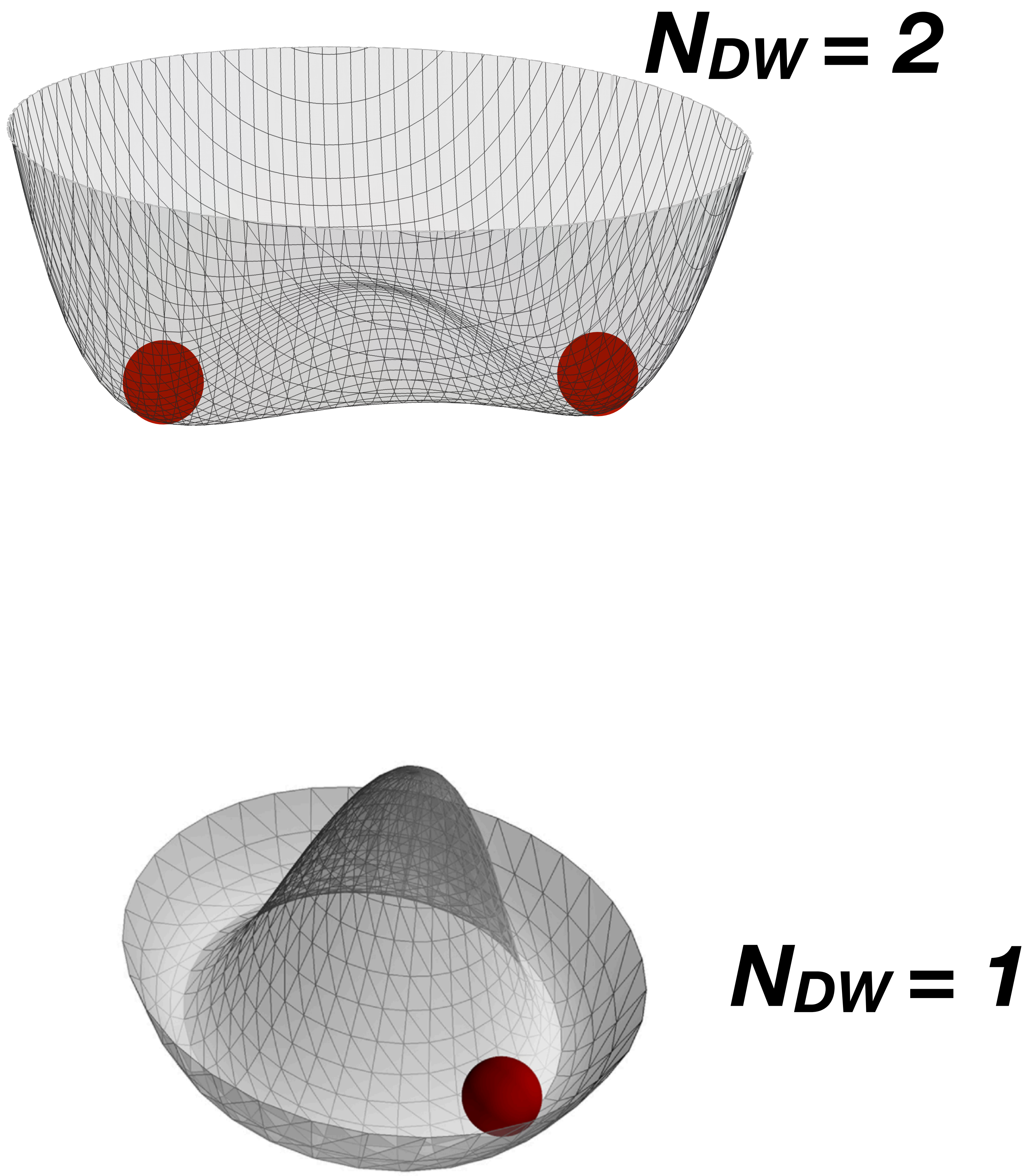


$N_{DW} = 1$

$$V_{QCD}(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(N_{DW}\,\frac{a}{f}\right)\right)$$

Axionic defects





Axion 'quality problem'

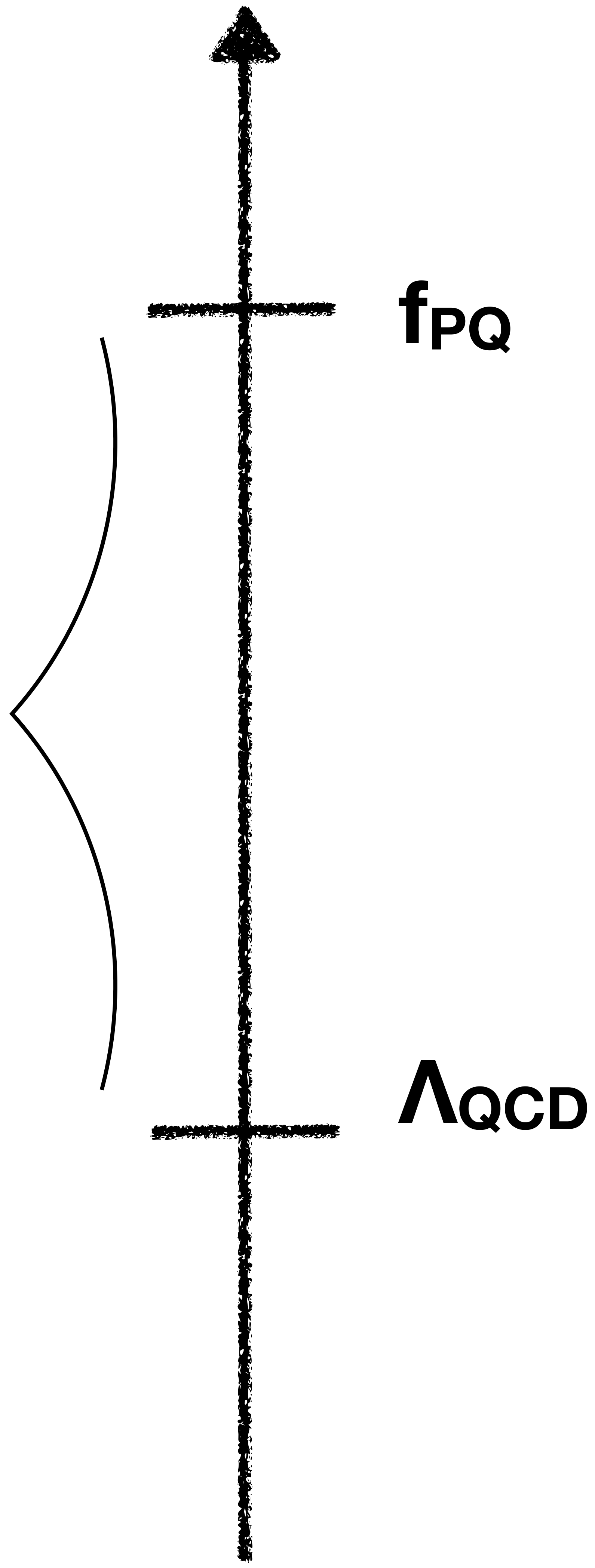
Axion 'quality problem'

Implicitly, only QCD contributes to *V(a)*

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

$$V(a) = \Lambda_{QCD}^4\left(1-\cos(a)\right) + \Lambda_{mis}^4\left(1-\cos(a+\delta)\right)$$

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



Axion 'quality problem'

From the 'PQ-EFT' perspective, misaligned terms

$$c_N \; \frac{\Phi^{4+N}}{M^N}$$

Axion 'quality problem'

From the 'PQ-EFT' perspective, misaligned terms

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

Axion 'quality problem'

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 with large N

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

Axion 'quality problem'

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 with large N

Or $\cancel{PQ}$ is nonperturbative (c_N's exponentially suppressed)

In any case, robustness against this $\cancel{PQ}$ 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:

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

Heavy axions

In practice:

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

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

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

Heavy axions

In practice:

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

$$\Lambda_{mis} \lesssim 10^{-2.5}\Lambda$$

$N_{DW}\,, \quad N'_{DW}$ co-prime

Heavy axions

Heavy => decays quickly

Axions $\neq$ DM

Heavy and weakly coupled => difficult to probe directly!

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 axions

Heavy => decays quickly

Axions $\not\simeq$ DM

Heavy and weakly coupled => difficult to probe directly!

—> cosmology!

Axionic defects (and N_{DW}) play a crucial role

High quality axionic defects

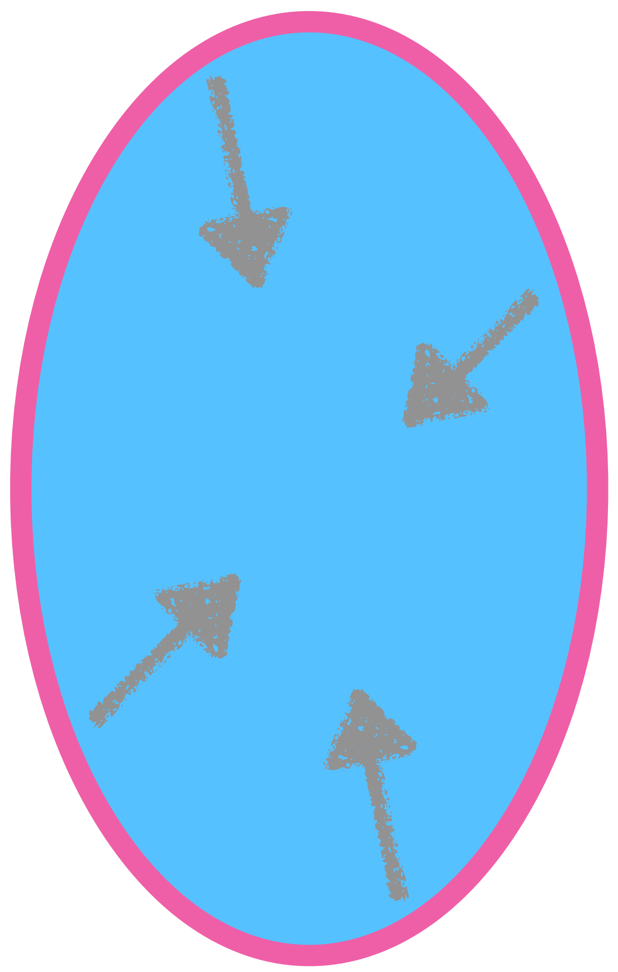
$$\sigma_{DW} \sim m_a f_a^2$$

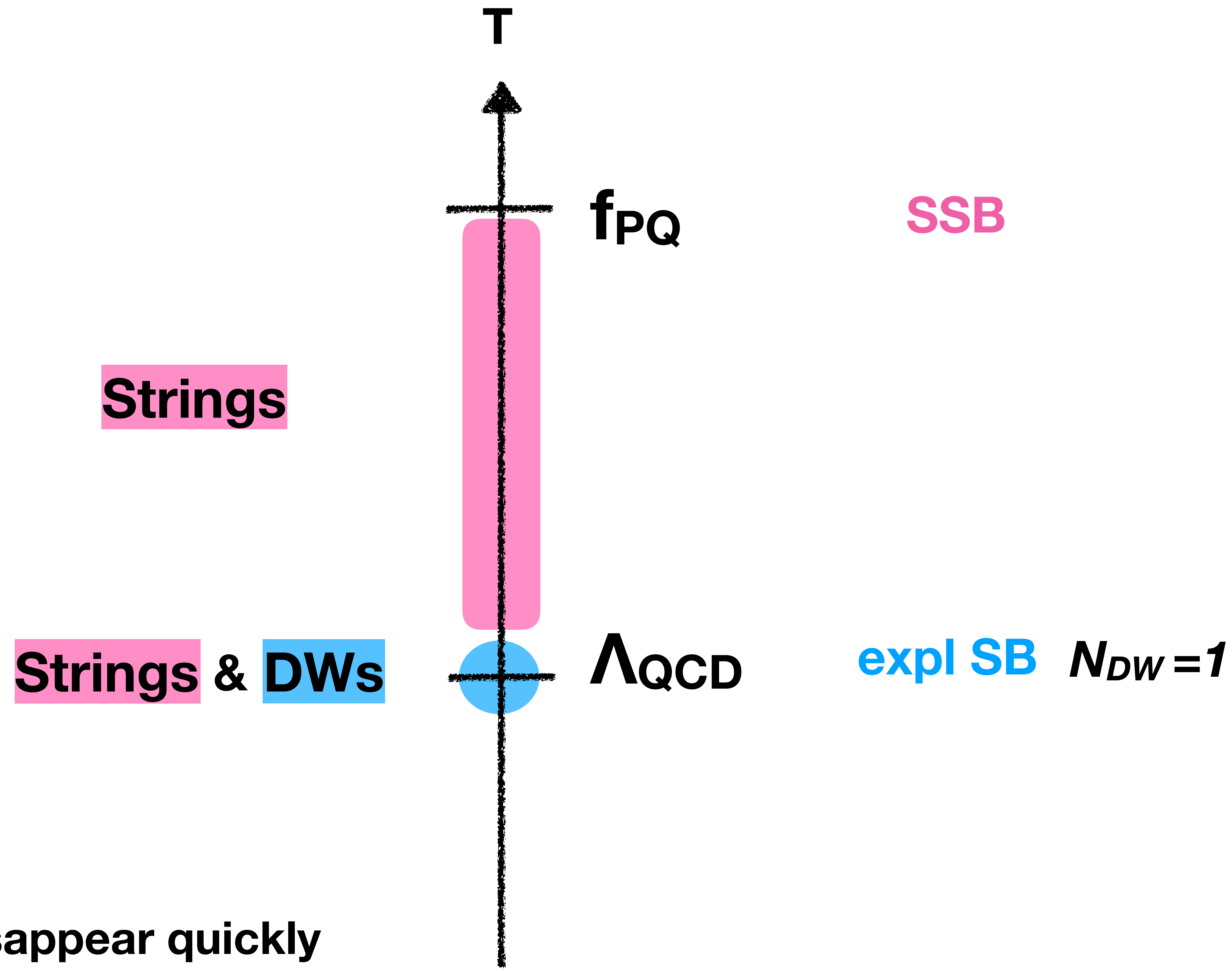
=> DWs are also *heavy*

DW motions induce *strong* GWs

$$\rho_{GW} \sim \frac{\sigma_{DW}^2}{M_P^2}$$

$N_{DW} = 1$

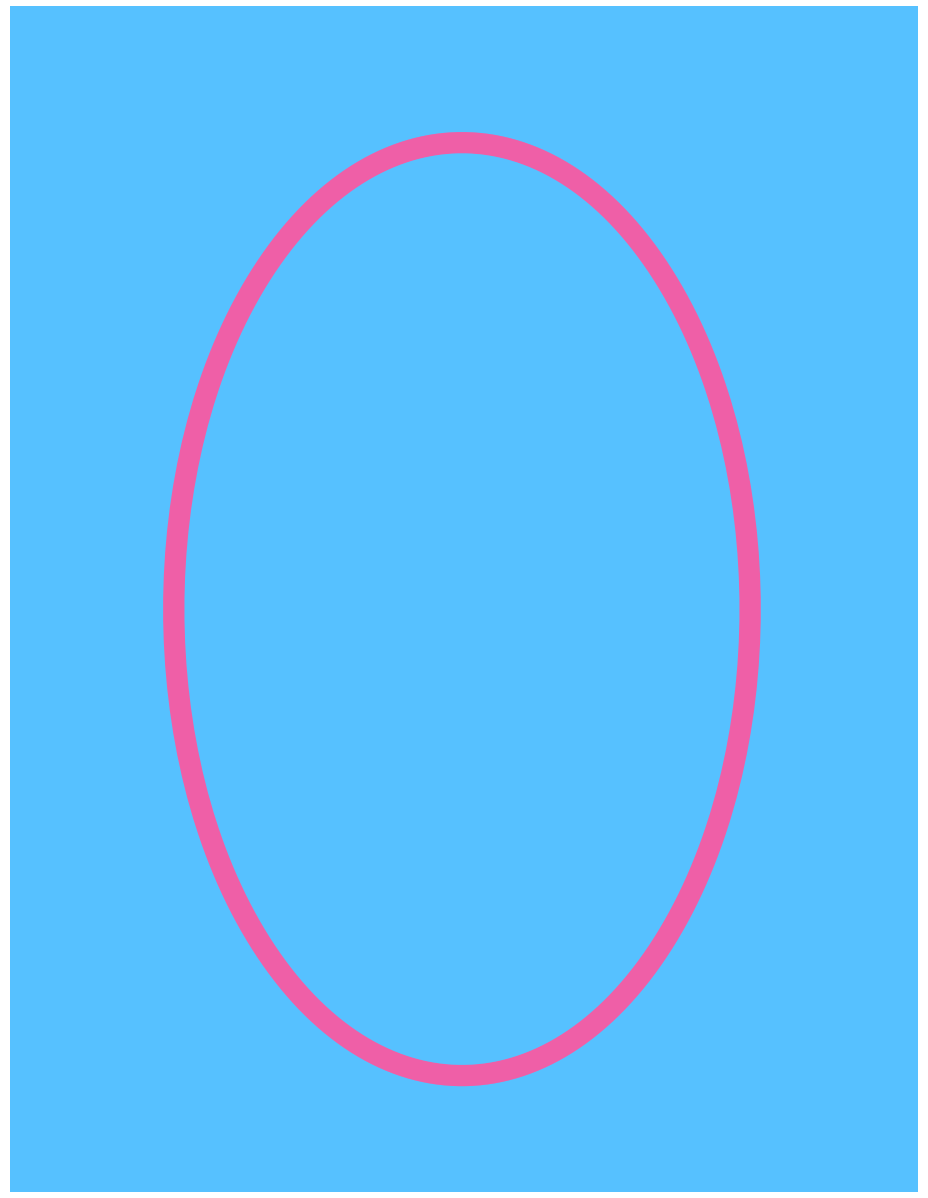


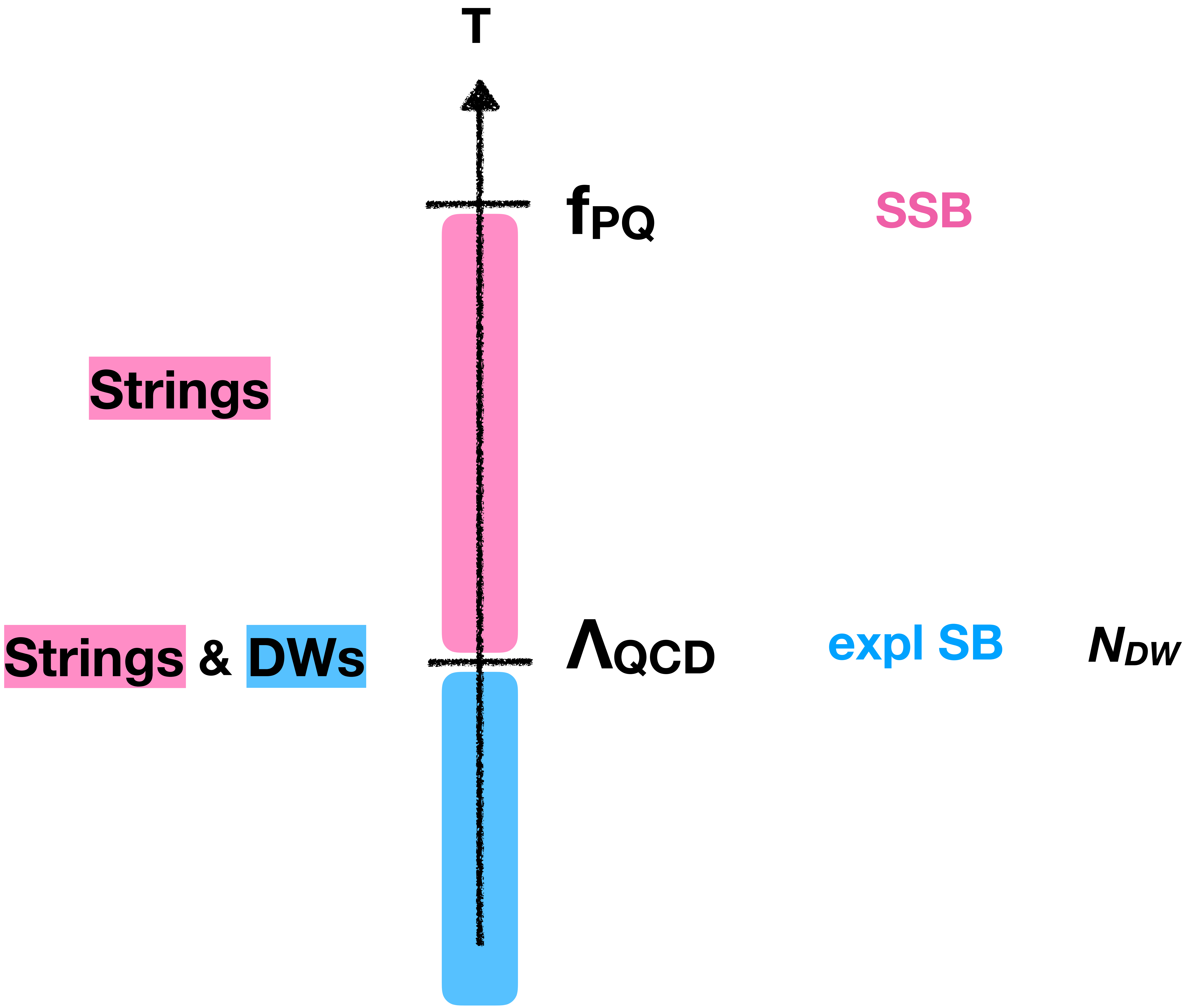


1 DW per string

DWs make the whole network disappear quickly

$N_{DW} > 1$

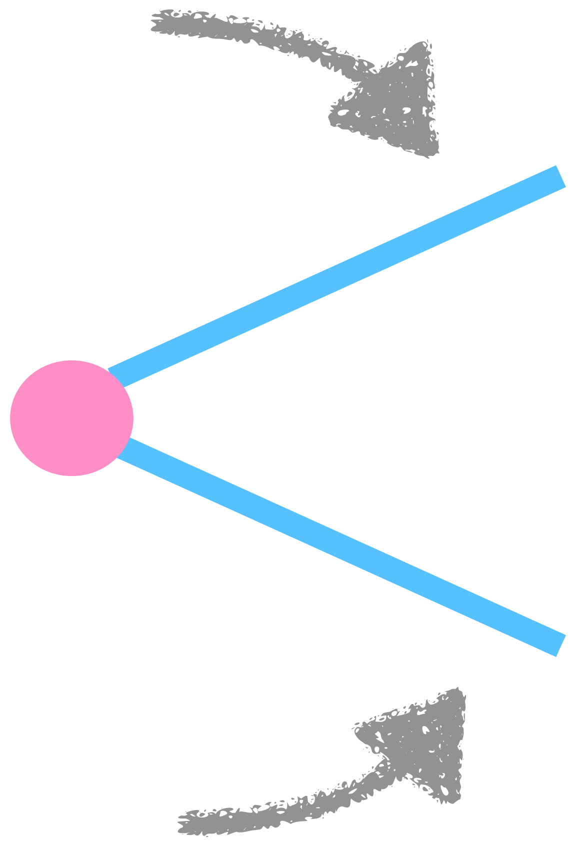




Network stable

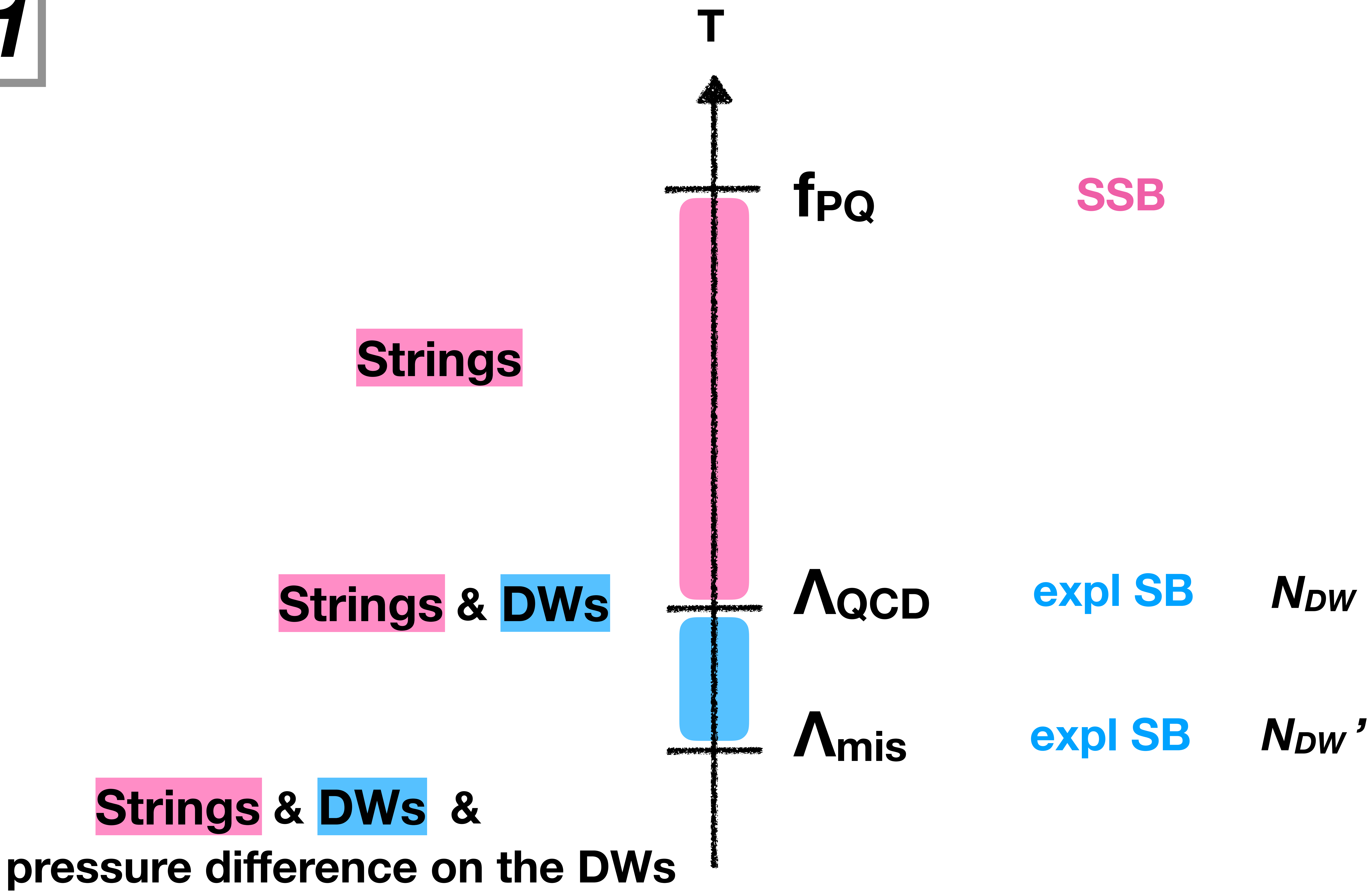
DW problem!

$N_{DW} > 1$

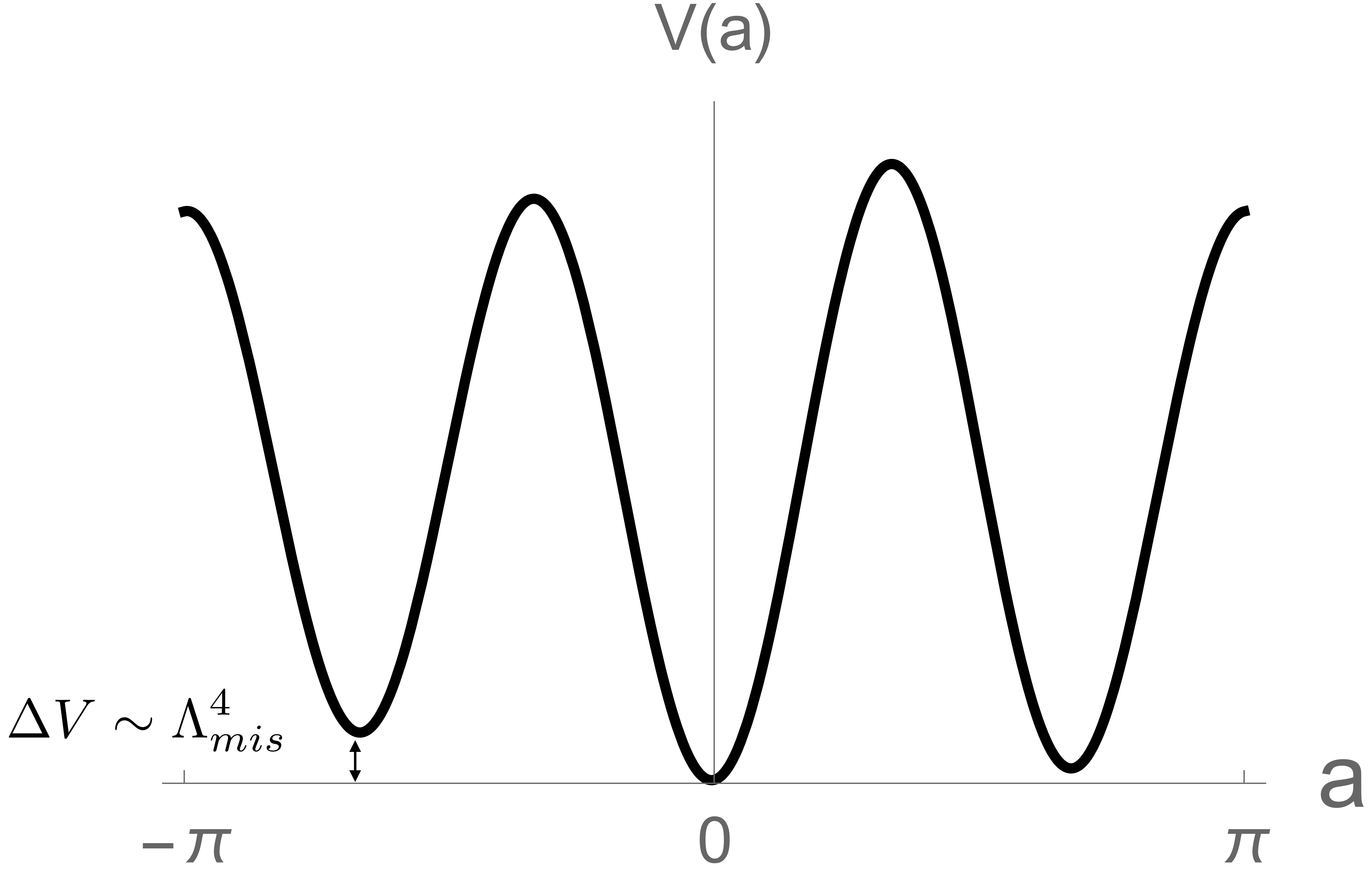


Delayed network anihilation

long DW epoch



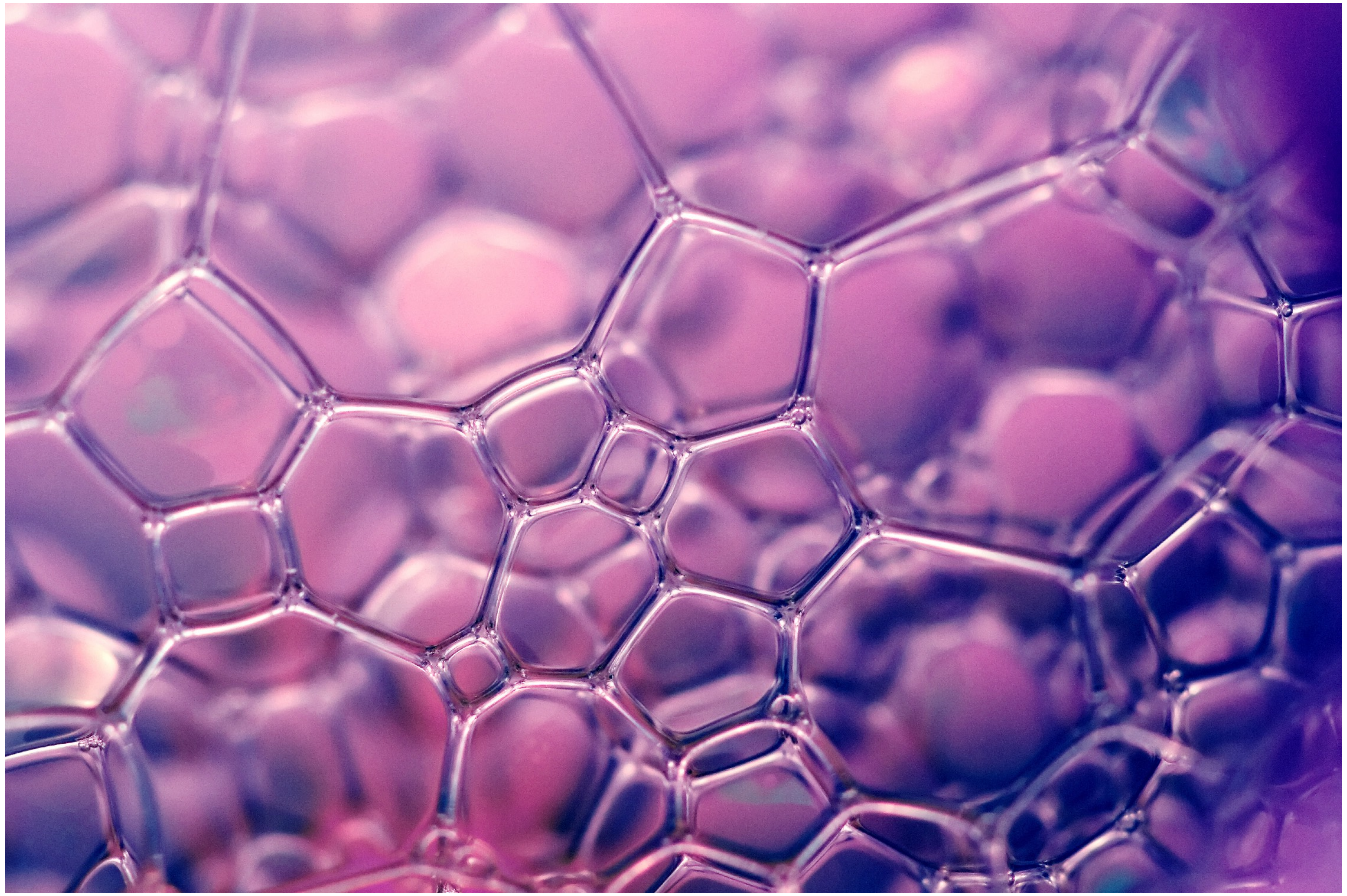
$$V(a) = \Lambda^4\Big(1 - \cos(N_{DW}\ a)\Big) + \Lambda_{mis}^4\Big(1 - \cos(N'_{DW}\ a + \delta)\Big)$$

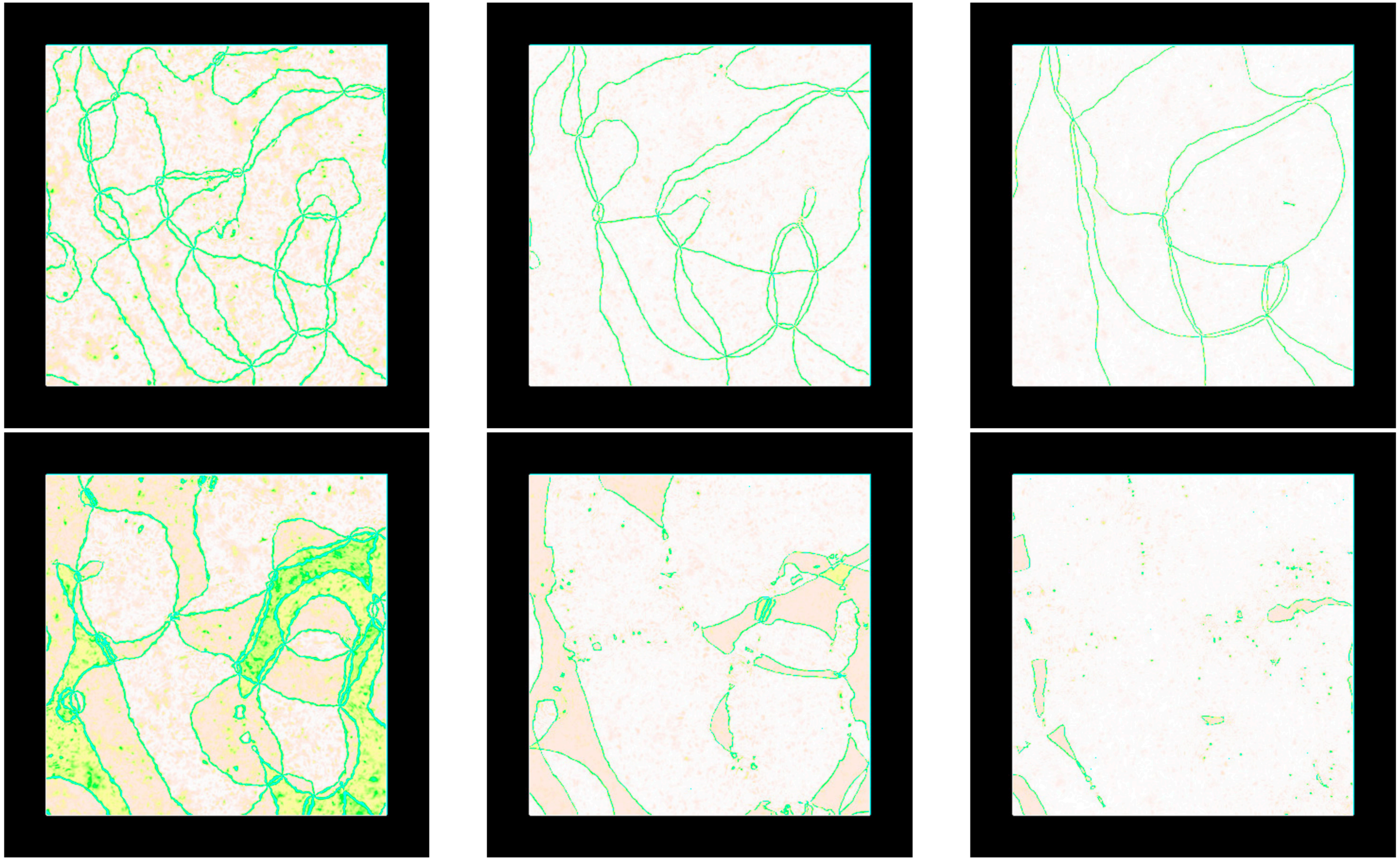


N_{DW} = 3

N_{DW}' = 2

Wall-string network dynamics





(N_{DW}>1)

without Λ_{mis}
network persists

with Λ_{mis}
network annihilates

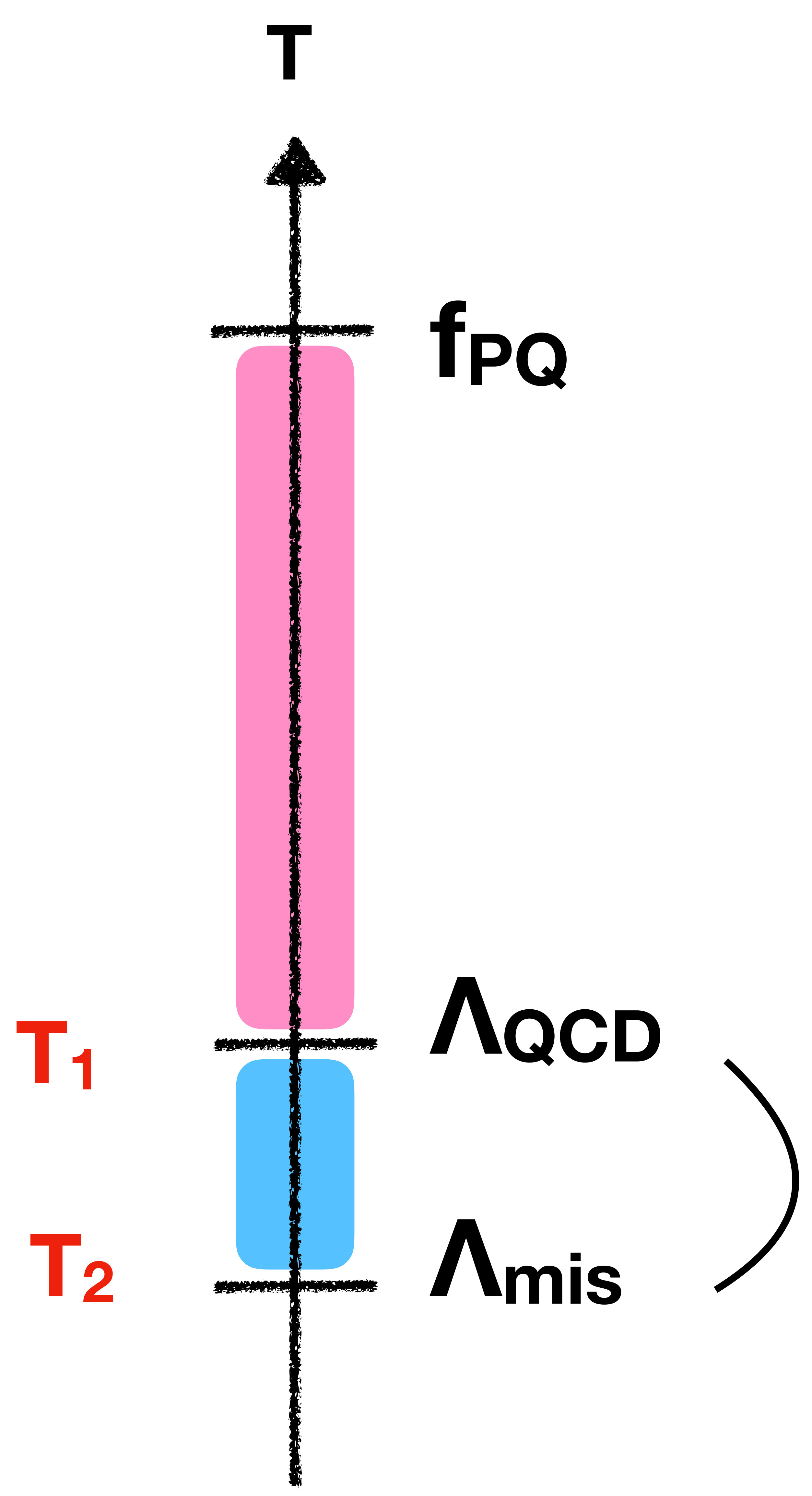
from [Kawasaki et al. '14] $\Delta V \approx 10^{-3} V_{QCD}$

DWs form when

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

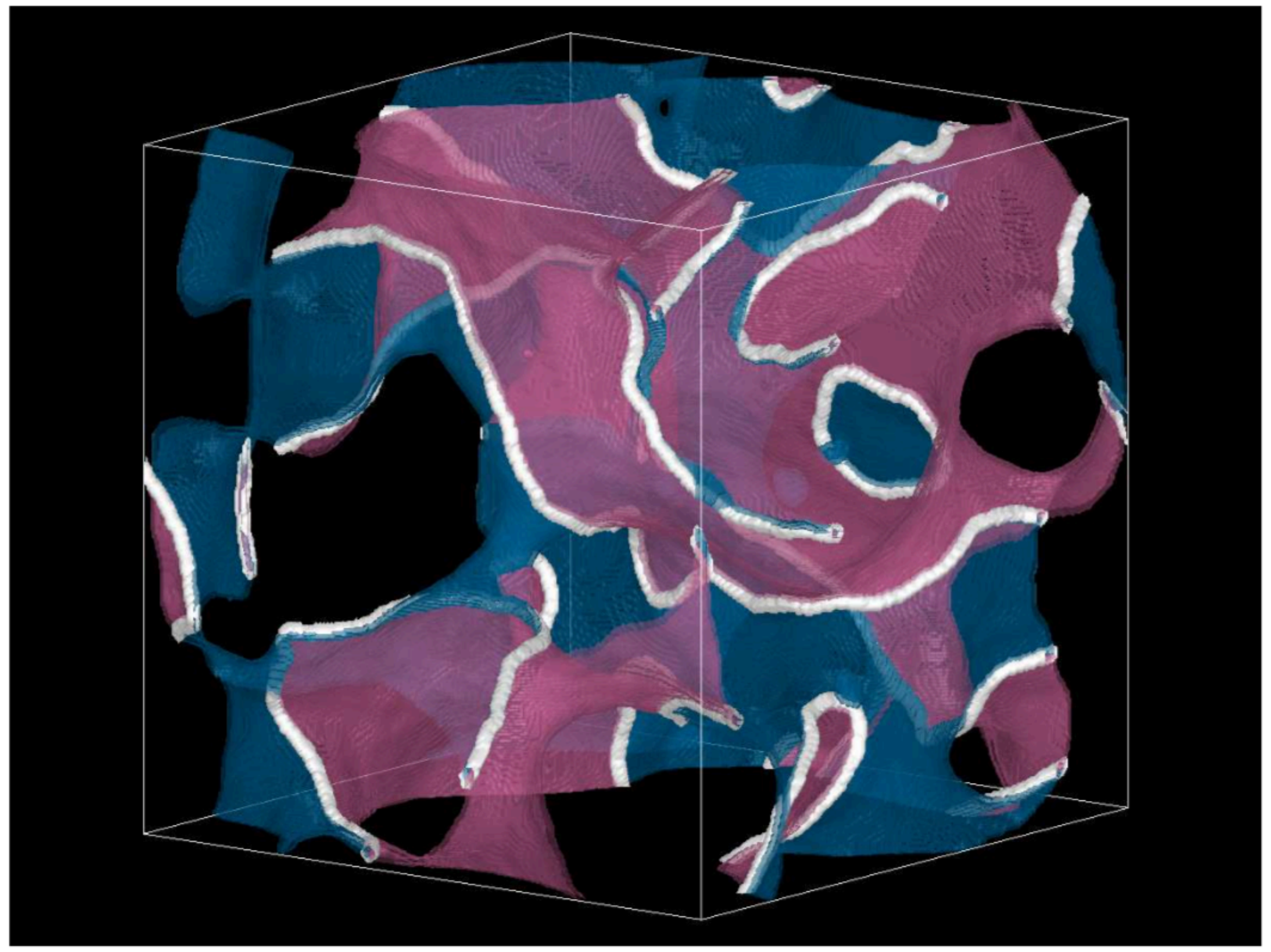
DW+string network ends when

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

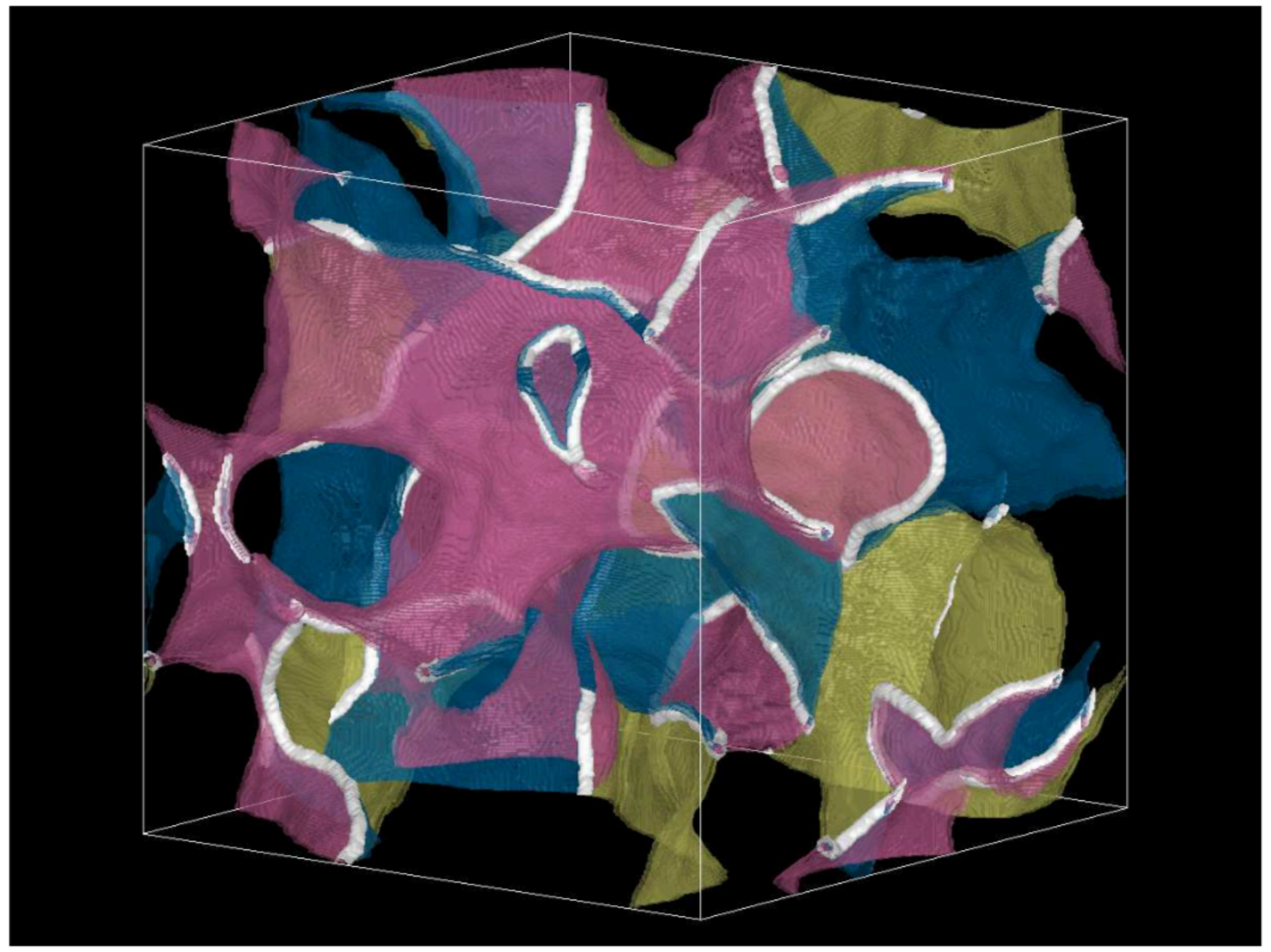


DWs quickly reach *scaling*

$$\rho_{DW} \propto \sigma_{DW} H$$



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

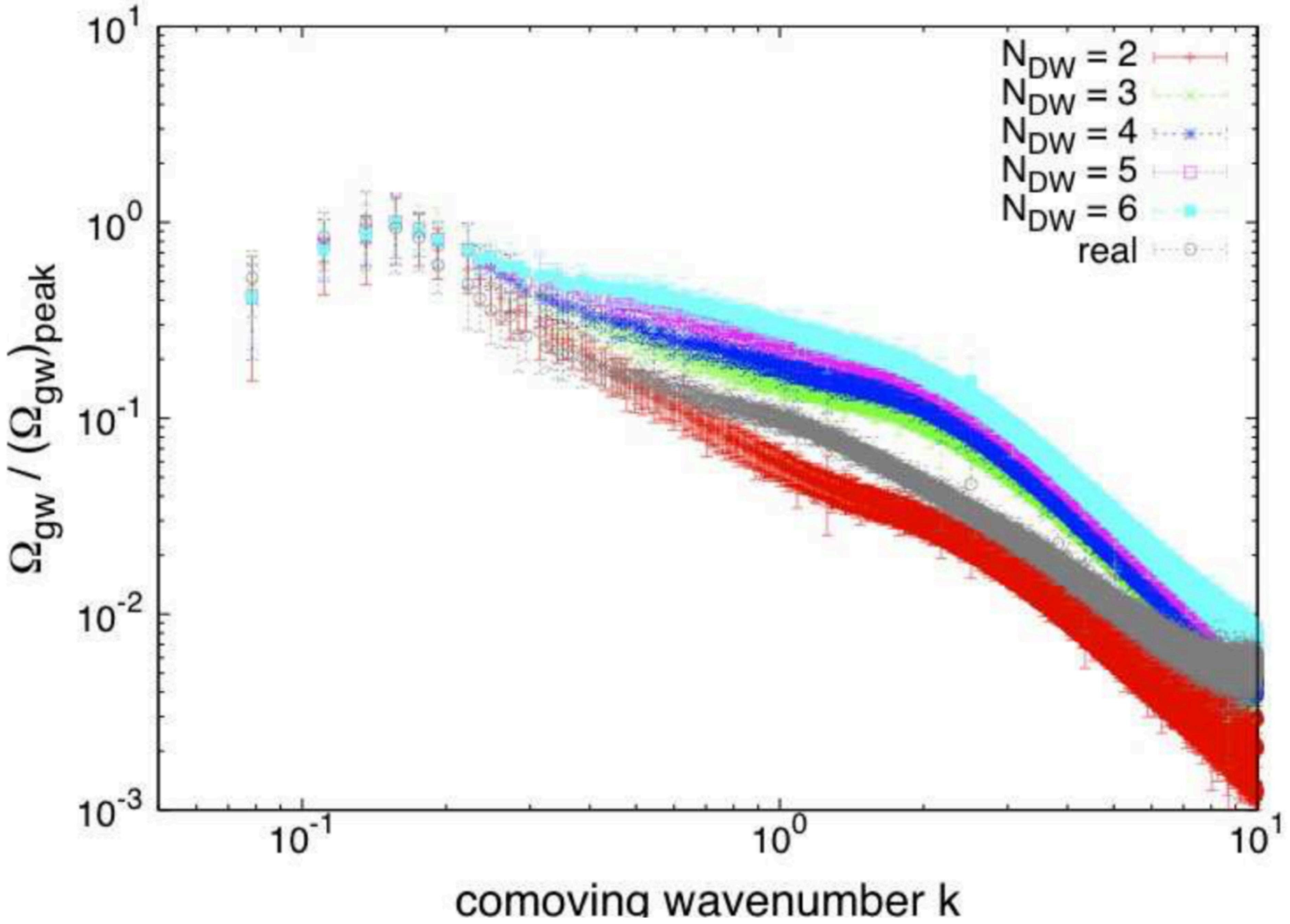


(b) $N_{\rm DW} = 3$

Hiramatsu et al arXiv: 1207.3166

GW spectrum ~ broken power law

w^3 , w^{-1}



Peak in the GW spectrum from network annihilation corresponds to temperature

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

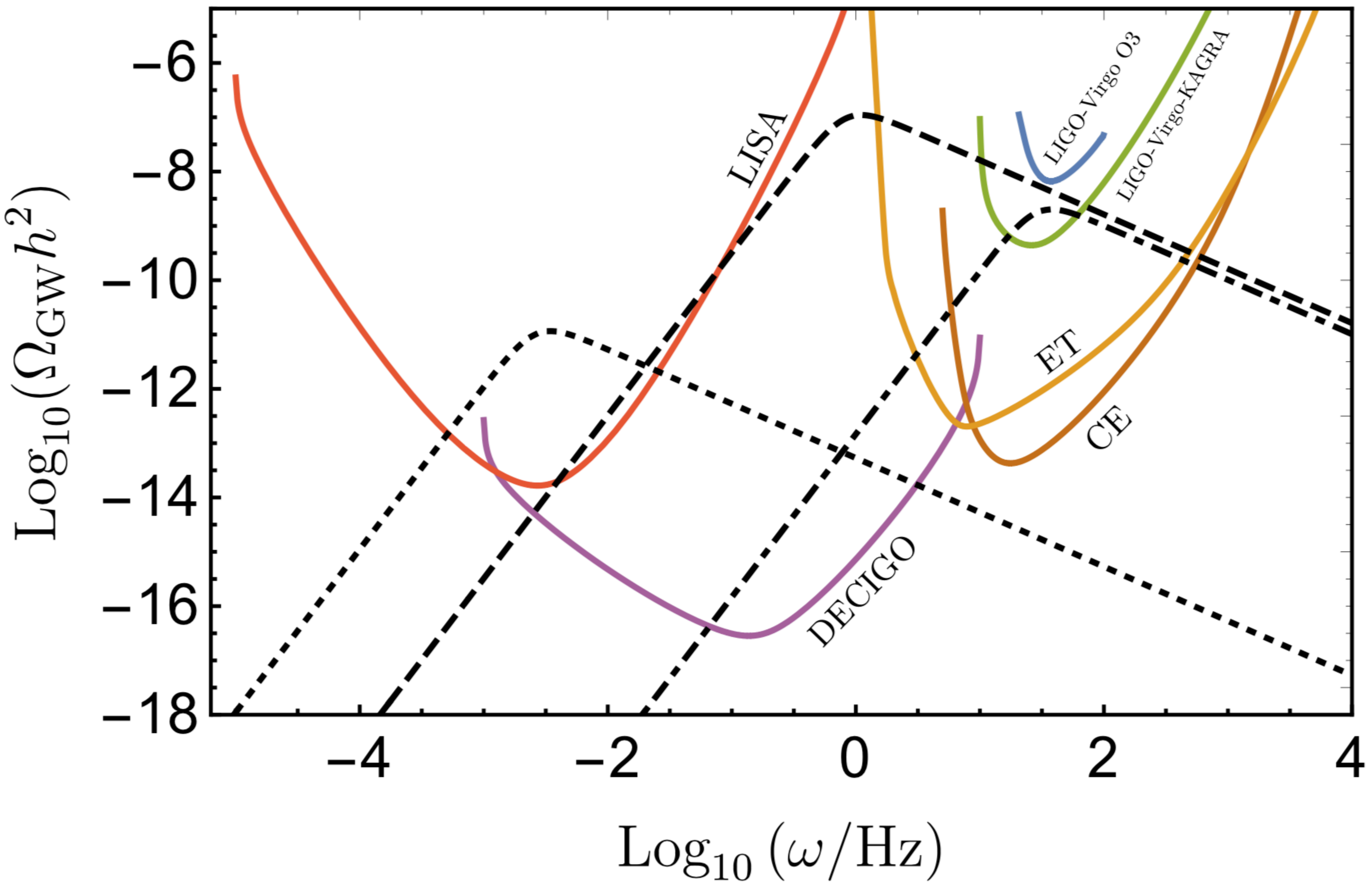
$$r = \Lambda_{mis}/\Lambda_H$$

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

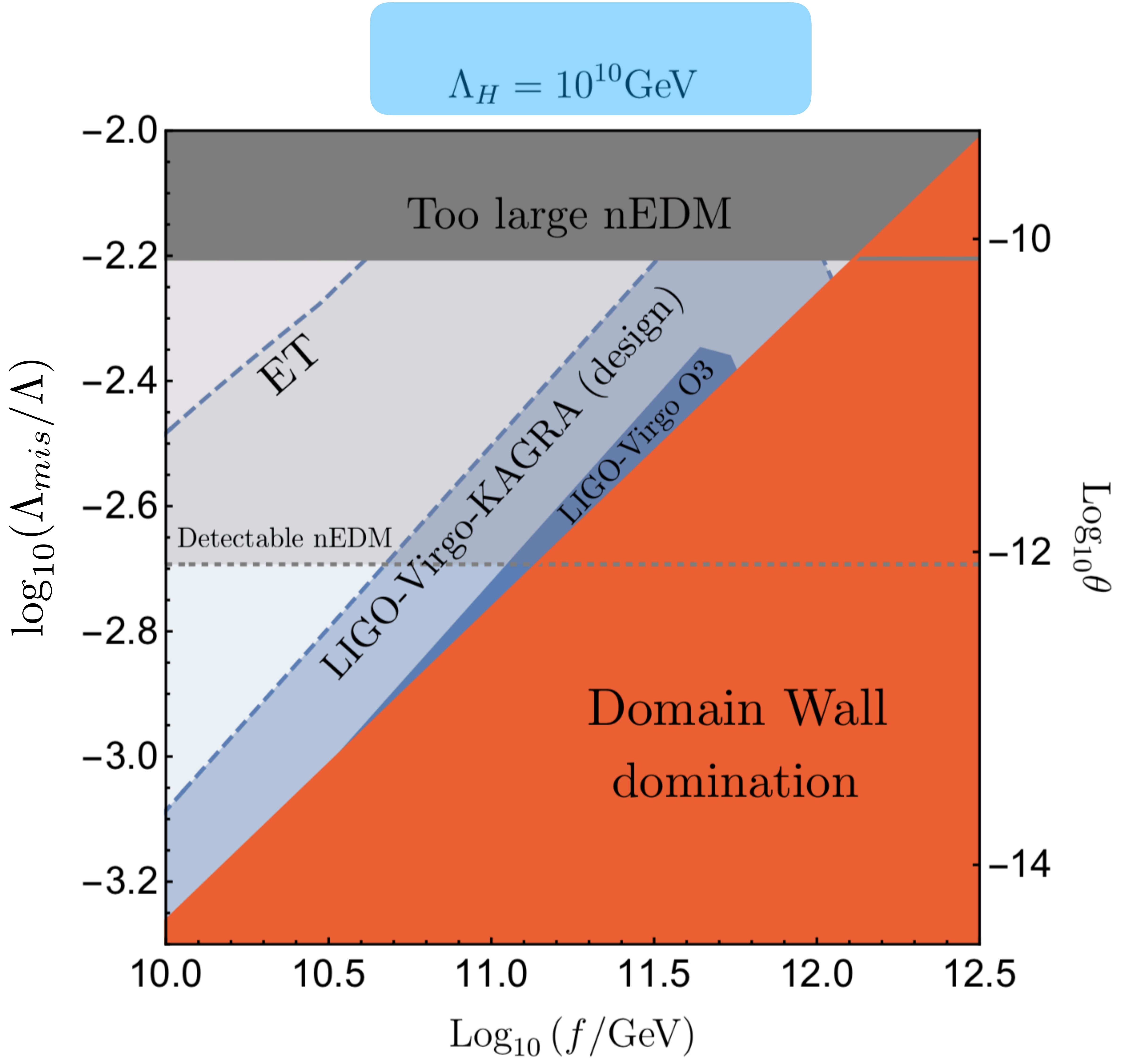
Signal:

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

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

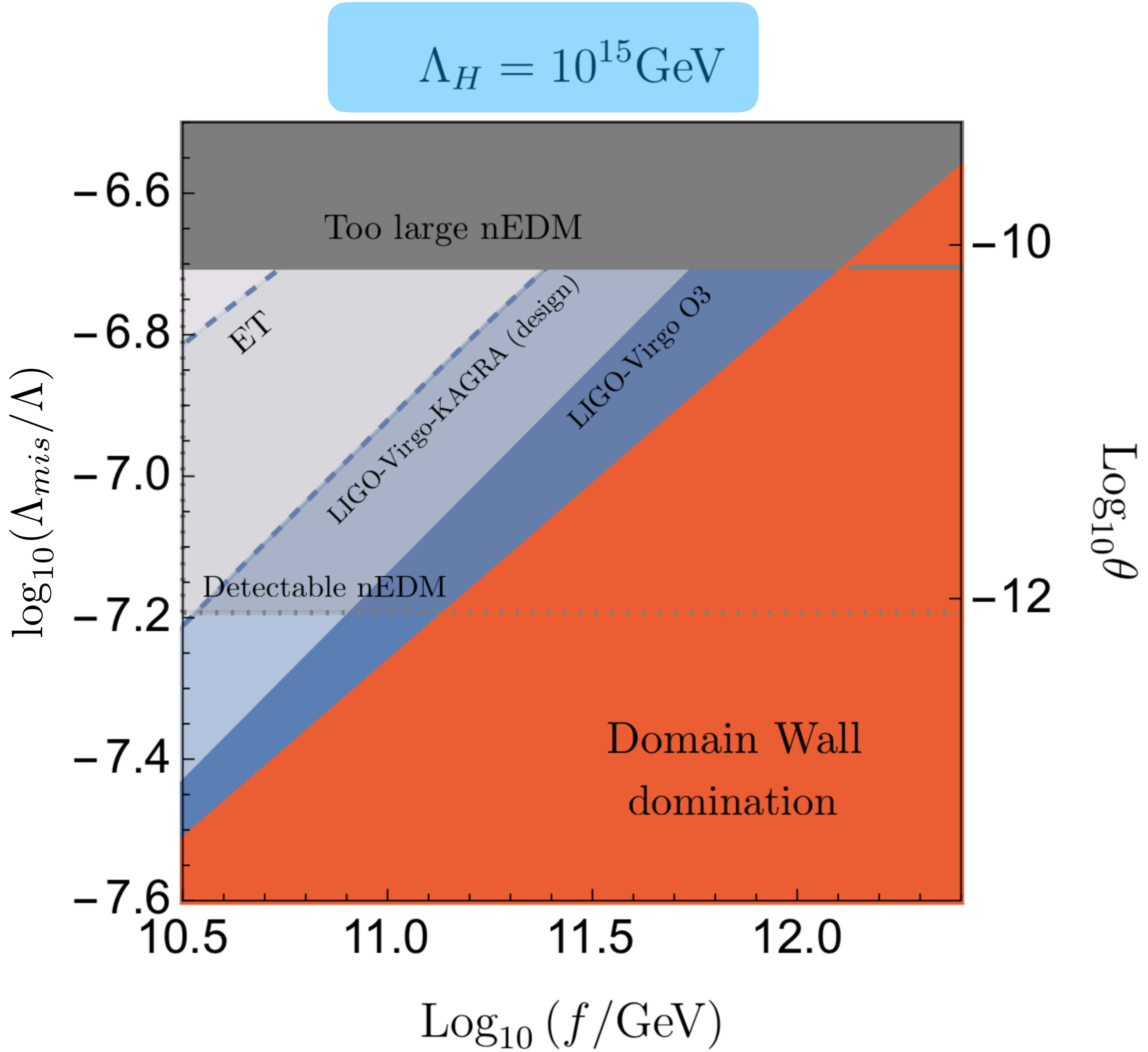


Λ_{mis} =	10^7 GeV	10^{10} GeV	10^{11} GeV
f =	10^{10} GeV	10^{11} GeV	1.6 10^{11} GeV
θ =	8 10^{-13}	8 10^{-13}	1.5 10^{-11}

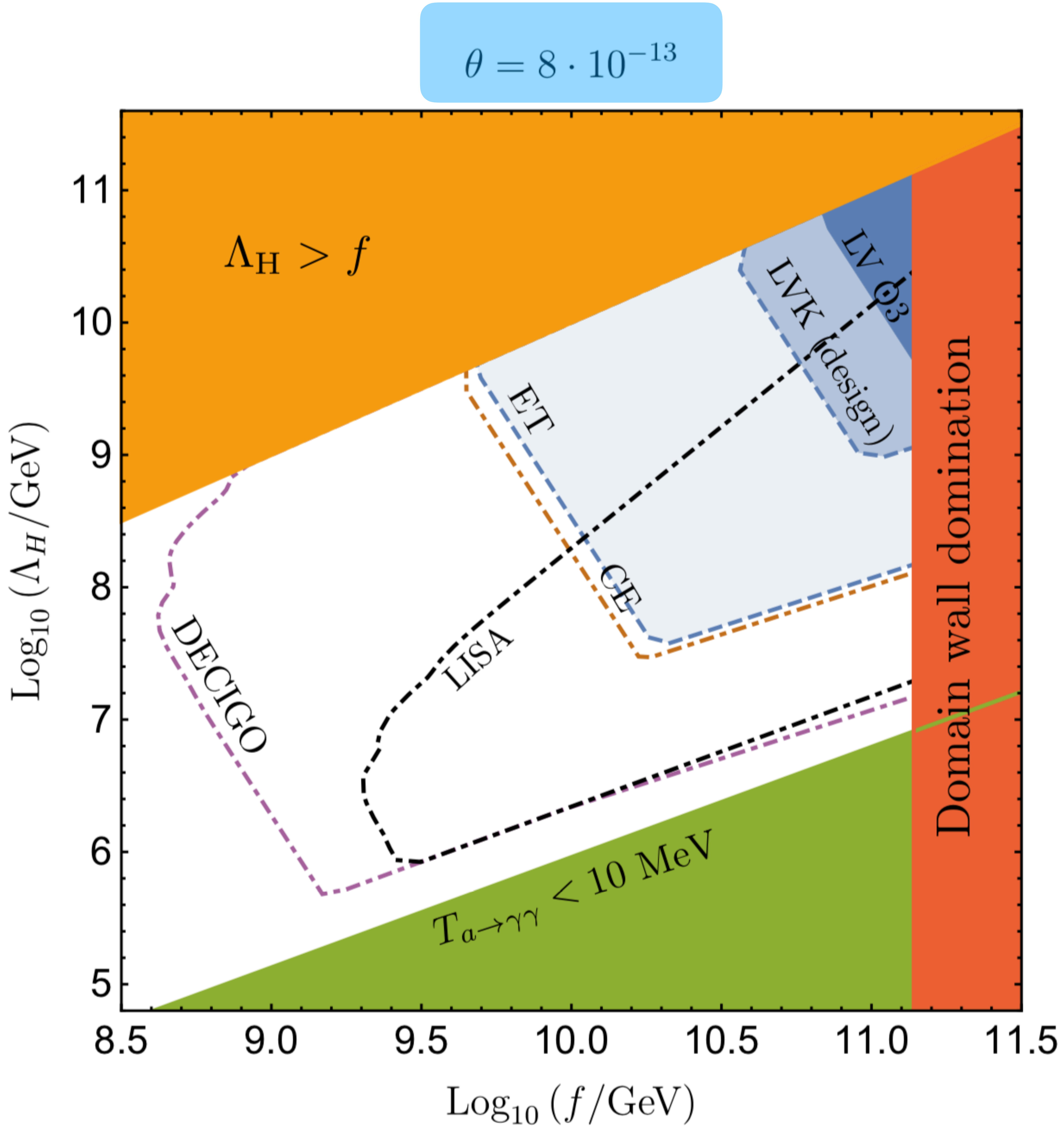


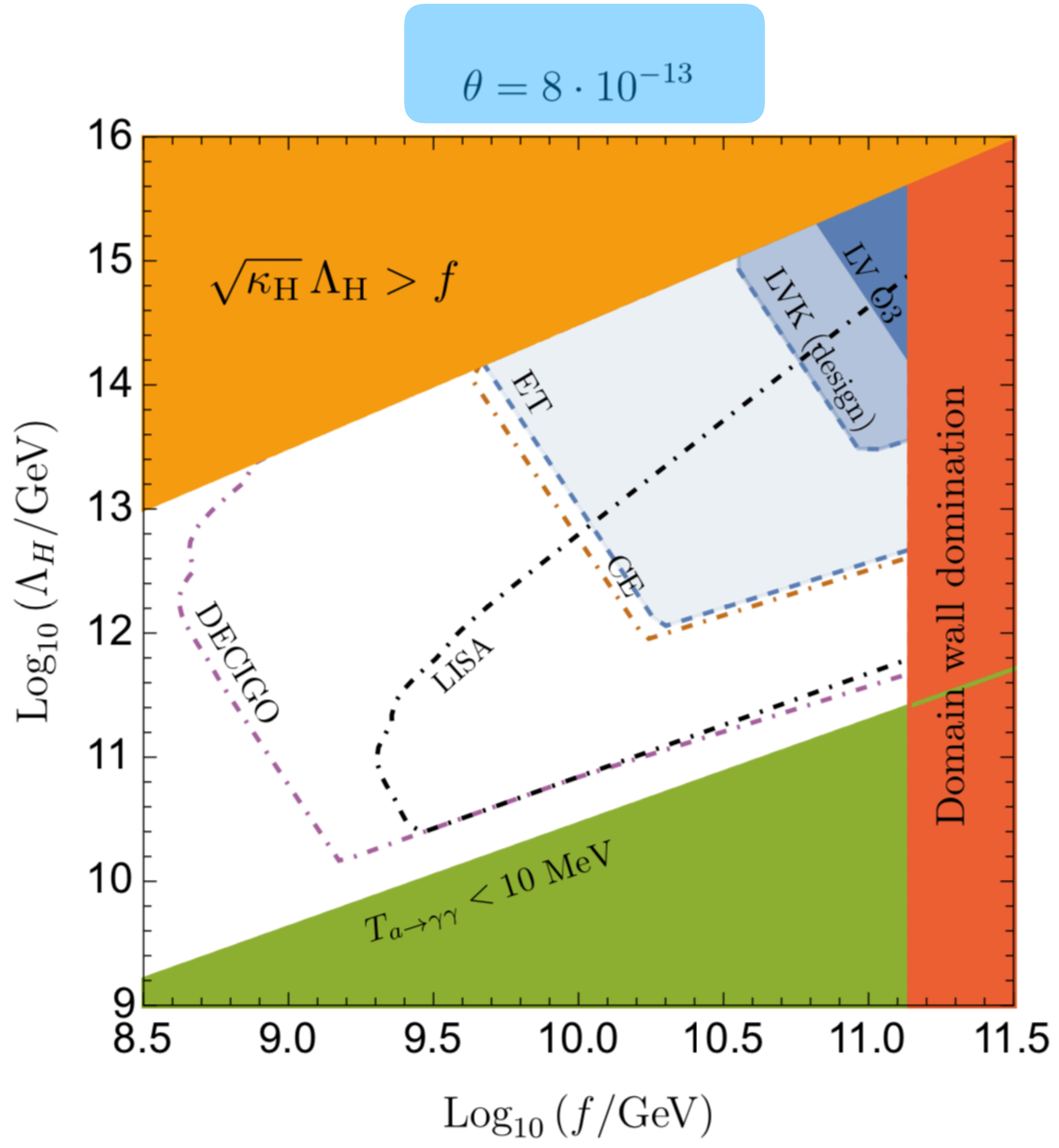
$\Lambda_H = 10^{10}$GeV
Too large nEDM
ET
LIGO-Virgo-KAGRA (design)
LIGO-Virgo O3
Detectable nEDM
Domain Wall domination
$\log_{10}(\Lambda_{mis}/\Lambda)$
$\mathrm{Log}_{10}\theta$
$\mathrm{Log}_{10}(f/\mathrm{GeV})$
−2.0
−2.2
−2.4
−2.6
−2.8
−3.0
−3.2
−10
−12
−14
10.0
10.5
11.0
11.5
12.0
12.5

,



$\Lambda_H = 10^{15}\text{GeV}$
Too large nEDM
ET
LIGO-Virgo-KAGRA (design)
LIGO-Virgo O3
Detectable nEDM
Domain Wall
domination
−6.6
−6.8
−7.0
−7.2
−7.4
−7.6
10.5
11.0
11.5
12.0
−10
−12
$\log_{10}(\Lambda_{mis}/\Lambda)$
$\text{Log}_{10}\,(f/\text{GeV})$
$\text{Log}_{10}\theta$





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.

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

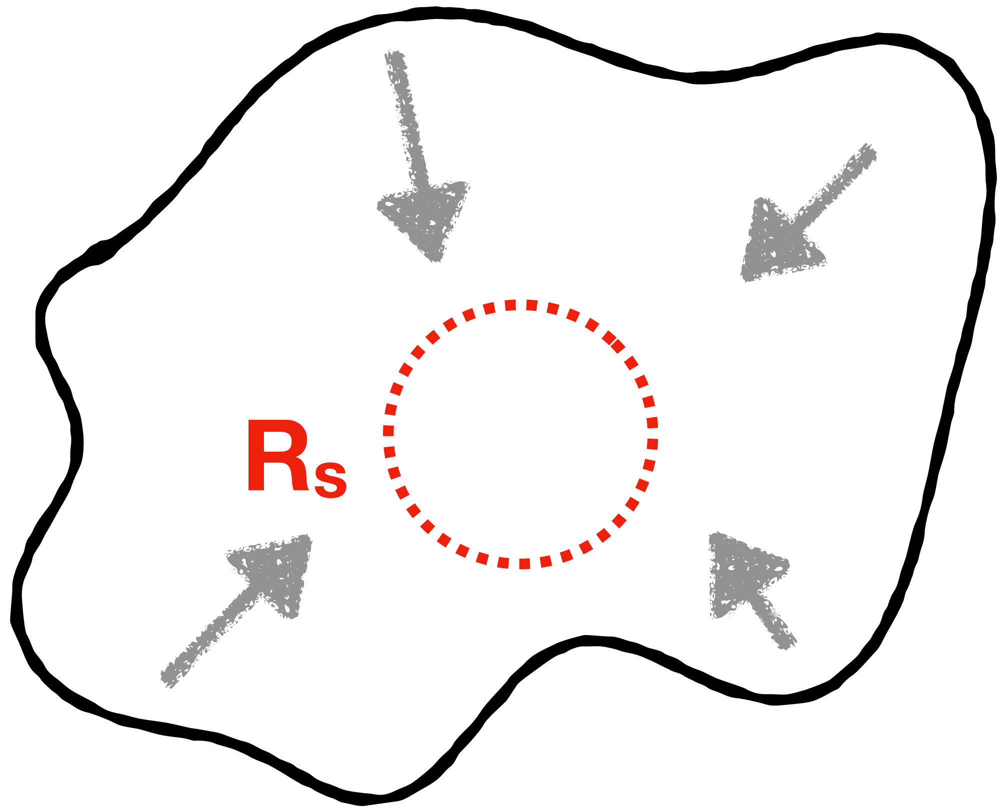
=> some models are already ruled out…

$n_1 = 3 \quad n_2 = -1$

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 aid collapse

σ

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

Thank you

σ

and congratulations, Valery!