Black Hole Dark Matter

Menu:

1st) Primordial BH generalities
2nd) Presentation of a recent work
3rd) Discussion

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Physics at the LHC and Beyond, CERN, 3/8/2018

0) Motivation

1) Observational constraints

2) Formation mechanisms

0) Motivation

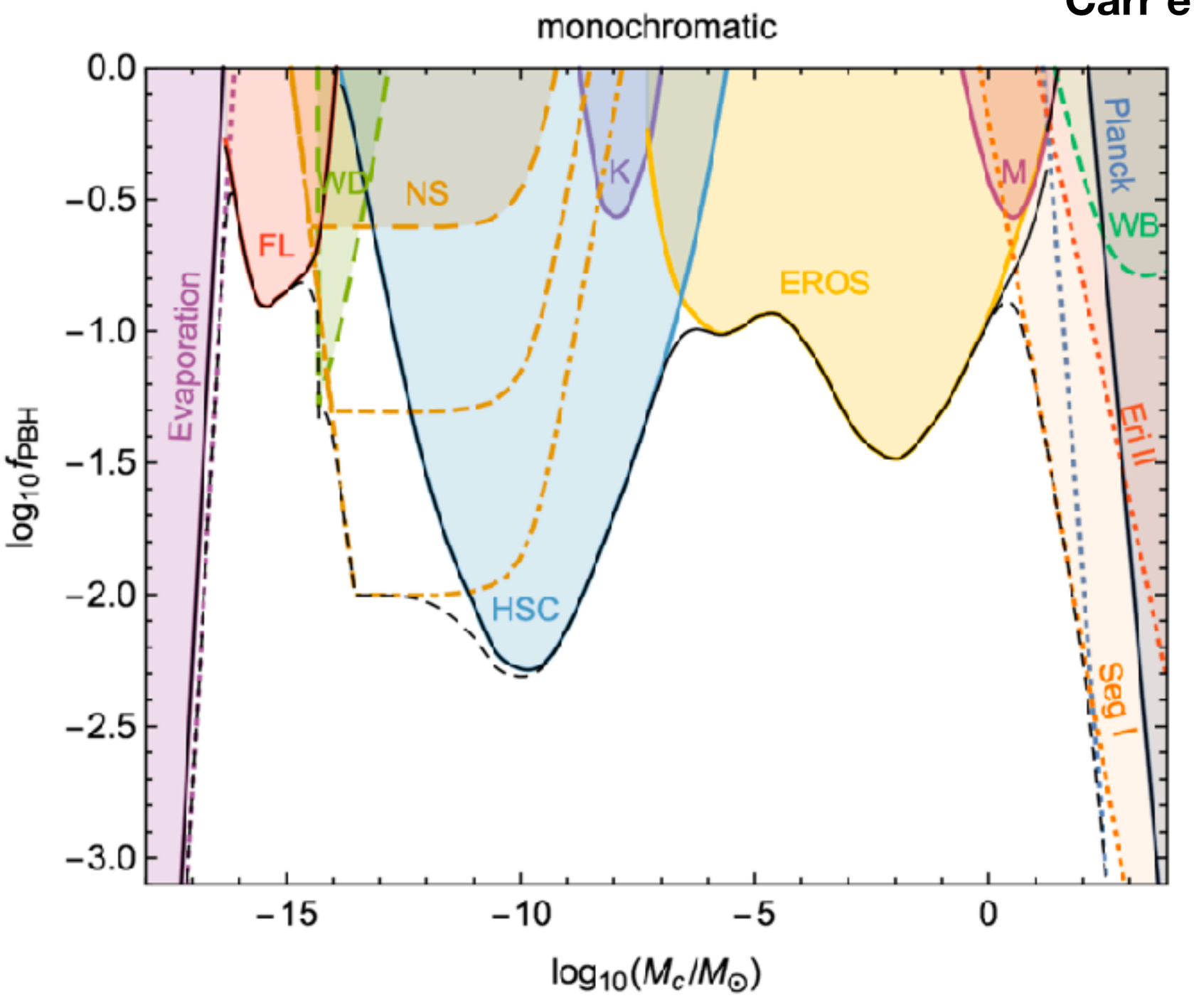
DM — SMBHs — LIGO merger events — indirect probe of HEP

1) Observational constraints

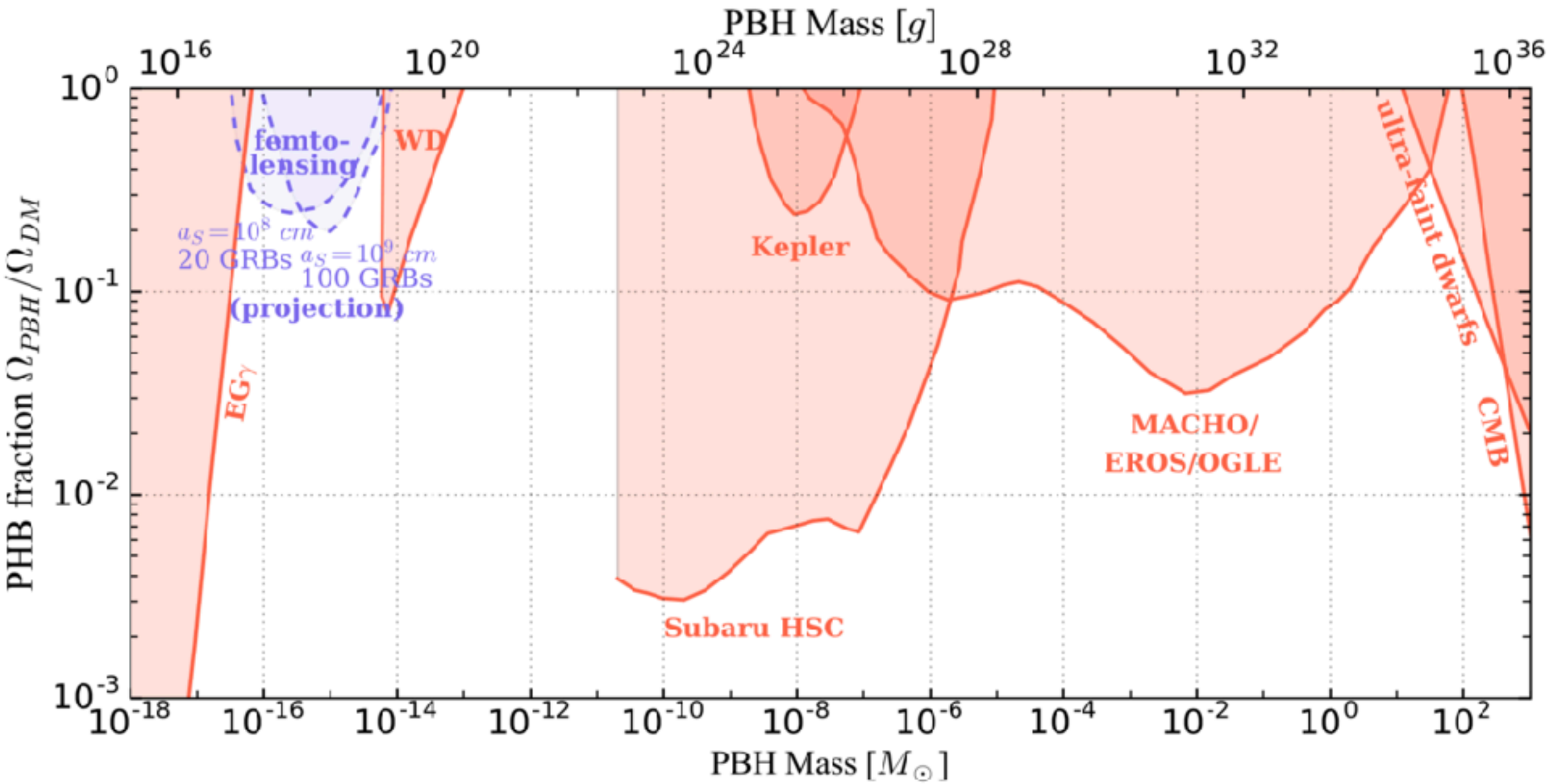
2) Formation mechanisms

Constraints

Carr et al, 1705.05567



Constraints



Katz et al, arXiv:1807.11495

0) Motivation

DM — SMBHs — LIGO merger events — indirect probe of HEP

1) Observational constraints

Many types — strongly depend on M & on the ‘mass function’ —

100% of DM in BHs possible? — *still debated*

2) Formation mechanisms

0) Motivation

DM — SMBHs — LIGO merger events — indirect probe of HEP

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Many types — strongly depend on M & on the ‘mass function’ —

100% of DM in BHs possible? — *still debated*

2) Formation mechanisms

Based on inflation

The most studied

Not based on inflation

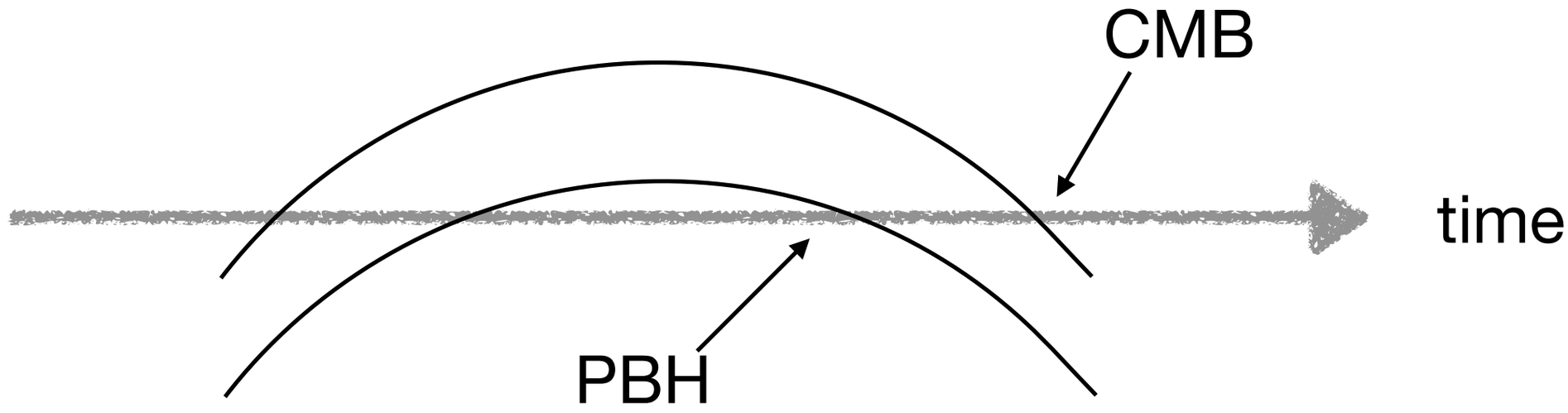
Several potential candidates, mostly cosmological phase transitions:
1) Bubble collisions 2) collapse of topological defects 3) pressure reduction

Plan

- **PBHs from inflation**
- **PBHs from axions**

PBHs from inflation

Vanilla option: from inflation.



Large overdensities $\delta > \delta_c$ collapse into a **BH**

PBHs from inflation

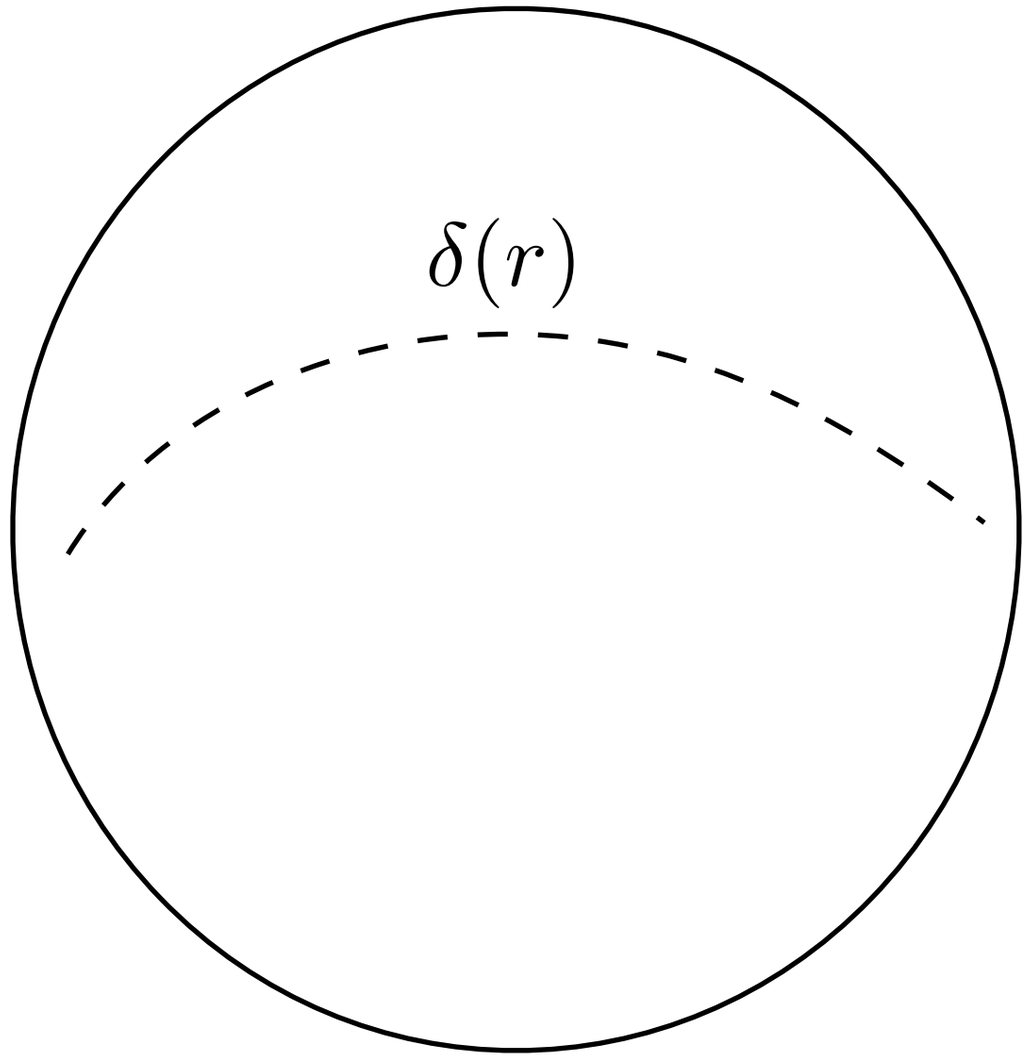
Vanilla option: from inflation.

‘critical’ collapse

$$M \sim M_{horizon}(\delta - \delta_c)^{\gamma}$$

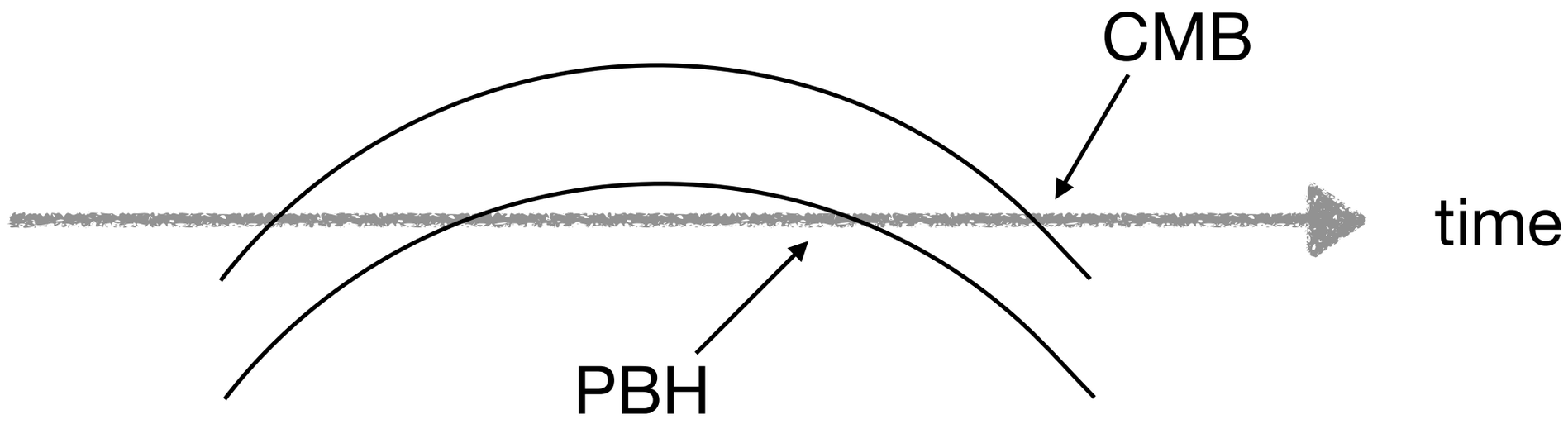
$$\delta = \frac{\delta\rho}{\rho}$$

$$\delta_c \sim 1/3$$



PBHs from inflation

Vanilla option: from inflation.



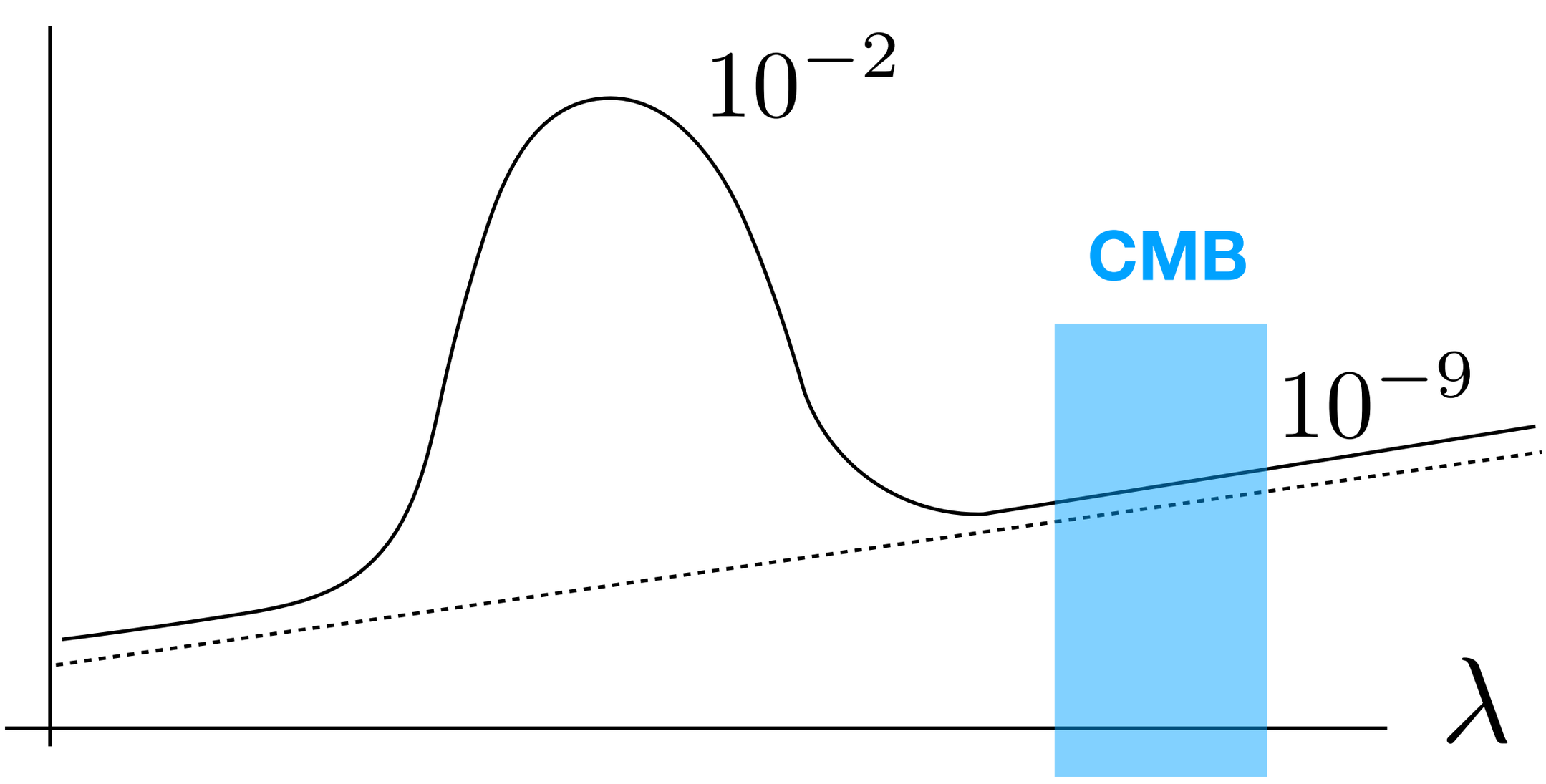
$$\text{fraction} \sim \text{Exp}\left(-\frac{\delta_c^2}{\mathcal{P}}\right)$$

$$M \sim \left(\frac{100\,\text{MeV}}{T}\right)^2 M_\odot$$

assuming Gaussian distribution

PBHs from inflation

Power spectrum must be enhanced at scales << CMB by factor **10^7**



PBHs from inflation

Power spectrum must be enhanced at scales << CMB by factor 10^7

Is it possible NOT to ask anything on inflation??

Primordial Black Holes from axionic defects

arXiv:1807.01707

with:

Francesc Ferrer, Eduard Massó, Giuliano Panico & Fabrizio Rompineve

Summary of the mechanism

QCD axion models with PQ scale < inflation scale => network of topological defects

The axionic Strings get attached to Domain Walls at ~ QCD epoch (and anihilate the network)

The later the DW ‘enter’ the horizon, the bigger they are => more likely to collapse into a BH

The effects is strongest for $N_{DW} > 1$

Axions

Strong CP problem

2 sources of CP violation in the SM:

$$\frac{\alpha_s}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \theta_{\mathrm{QCD}} \qquad Arg[Det[M_q]]$$

Required for the $\eta - \eta'$ meson mass splitting

Neutron electic dipole moment

$$d_n < 3 \times 10^{-26} \mathrm{ecm}$$

$$\theta_{\mathbf{tot}} < 0.7 \times 10^{-11}$$

Strong CP problem

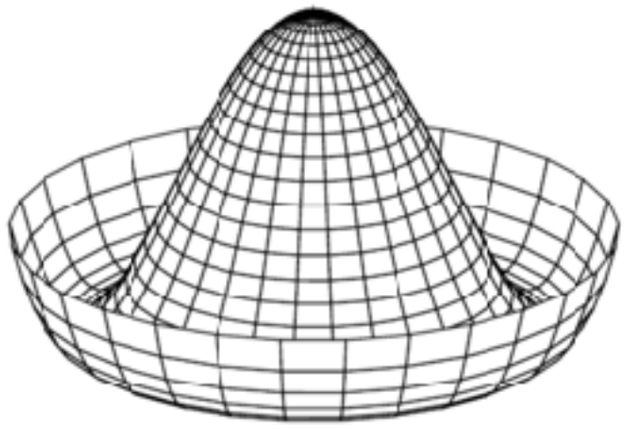
- Axion solution = dynamical/cosmological relaxation

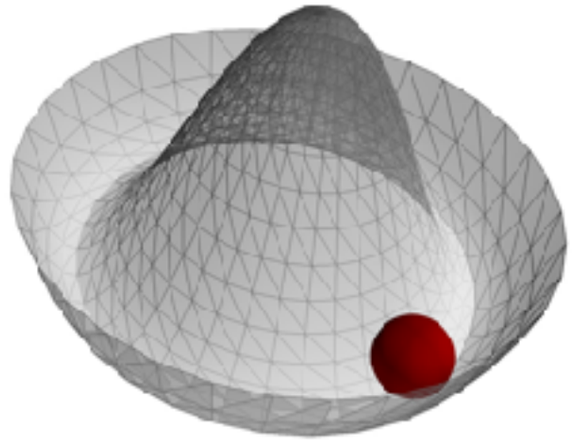
  - Introduce global *Peccei-Quinn* symm, $U(1)_A$

$$\Phi = \rho\, e^{i\, a/f}$$

- $U(1)_A$ is spontaneously broken at $\langle \Phi \rangle = f$
- Explicitly (but mildly) broken by QCD

Solution





$$V(\Phi) = \lambda(|\Phi|^2 - \eta^2)^2 \qquad + \varepsilon\Phi + h.c.$$

$$\Phi m_q \langle \bar{q}\, q \rangle + h.c.$$

At low energies,

$$V(a,T) = m^2(T)\, f^2 \left[1 - \cos\left(a / f\right)\right]$$

Bonus 1: Dark Matter candidate

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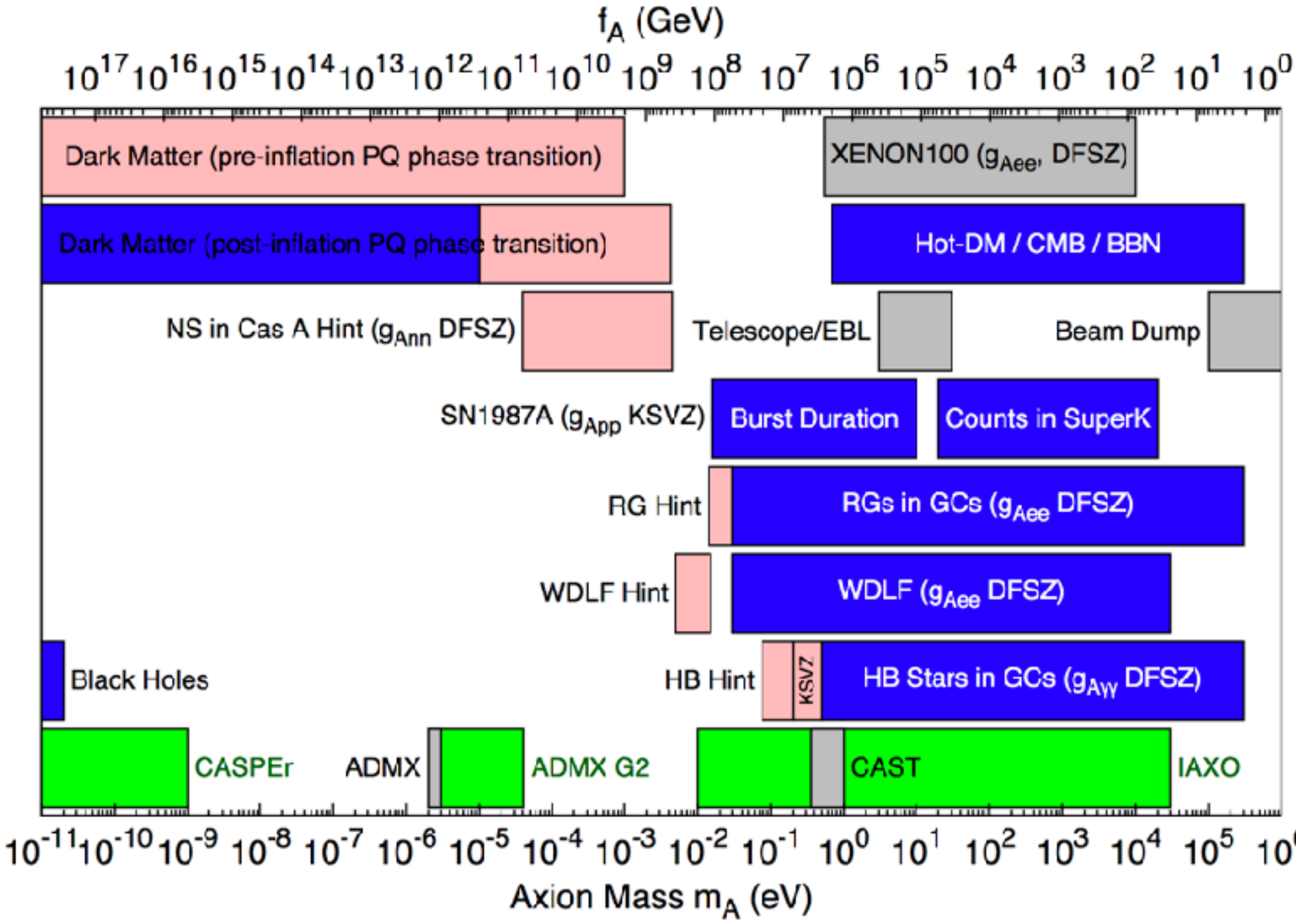
Focus on the most constrained case,

$$f < T_{reh}$$



Bonus 2: topological defects generated

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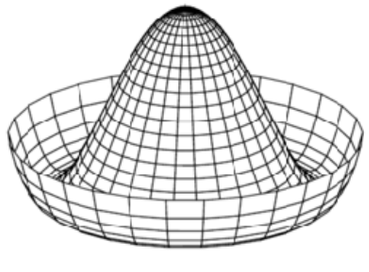
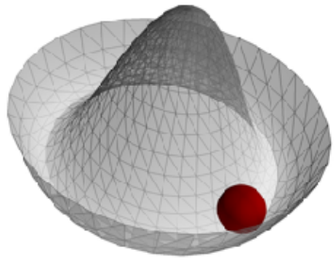
global Strings are formed

(SSB of $U(1)_{PQ}$)



Domain Walls formed, *bounded by* Strings

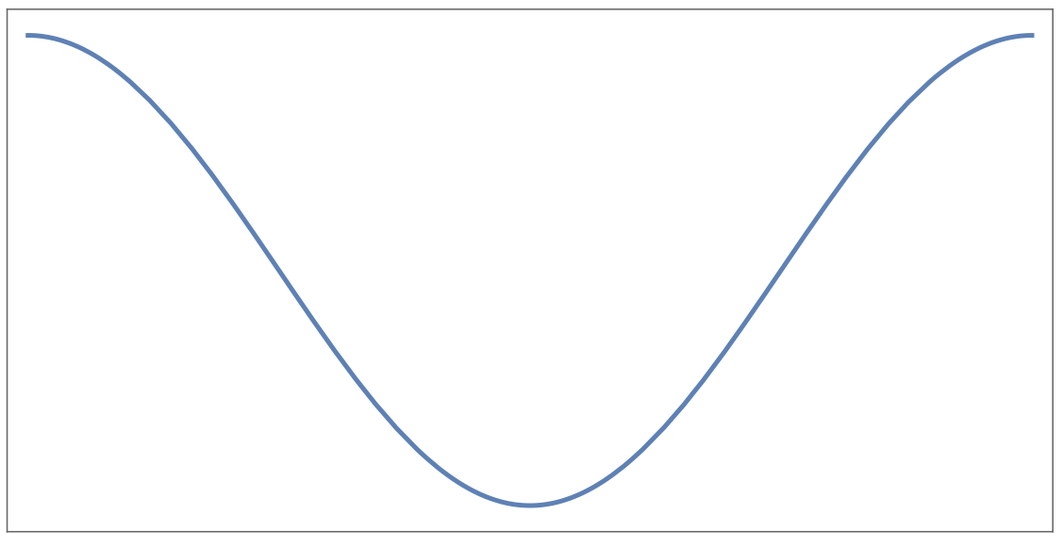


Bonus 2: topological defects generated

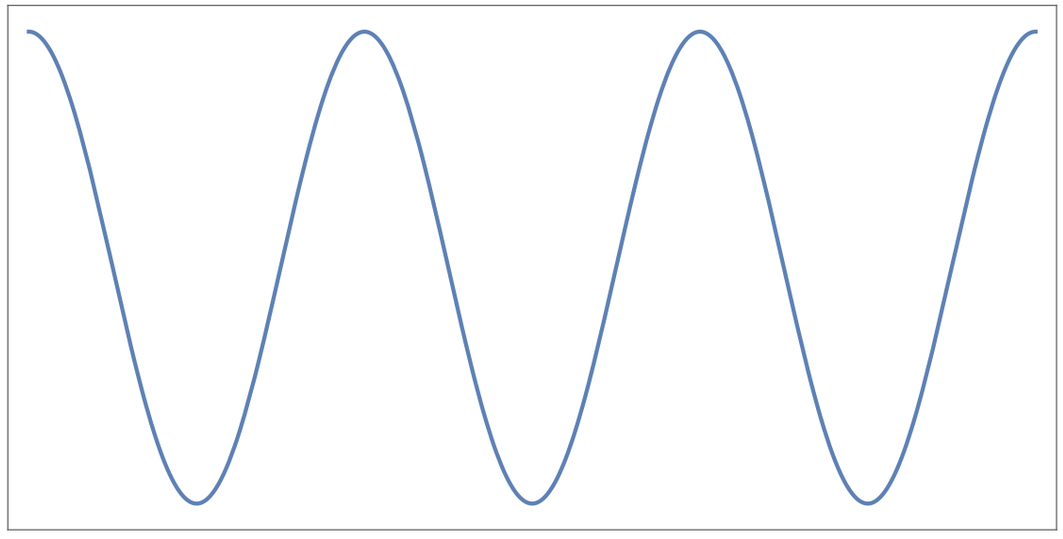
Very sensitive to the
"Domain Wall Number" N_{DW} ~ number of PQ-charged quarks

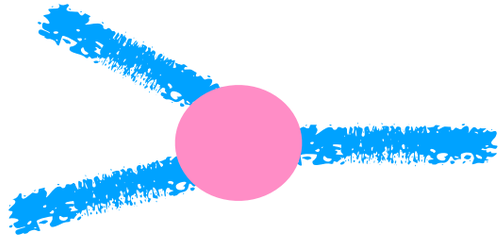
$$V(a,T) = \frac{m^2(T)\eta^2}{N_{DW}^2}\left[1-\cos\left(\frac{a}{\eta}N_{DW}\right)\right]$$

$N_{DW} = 1$

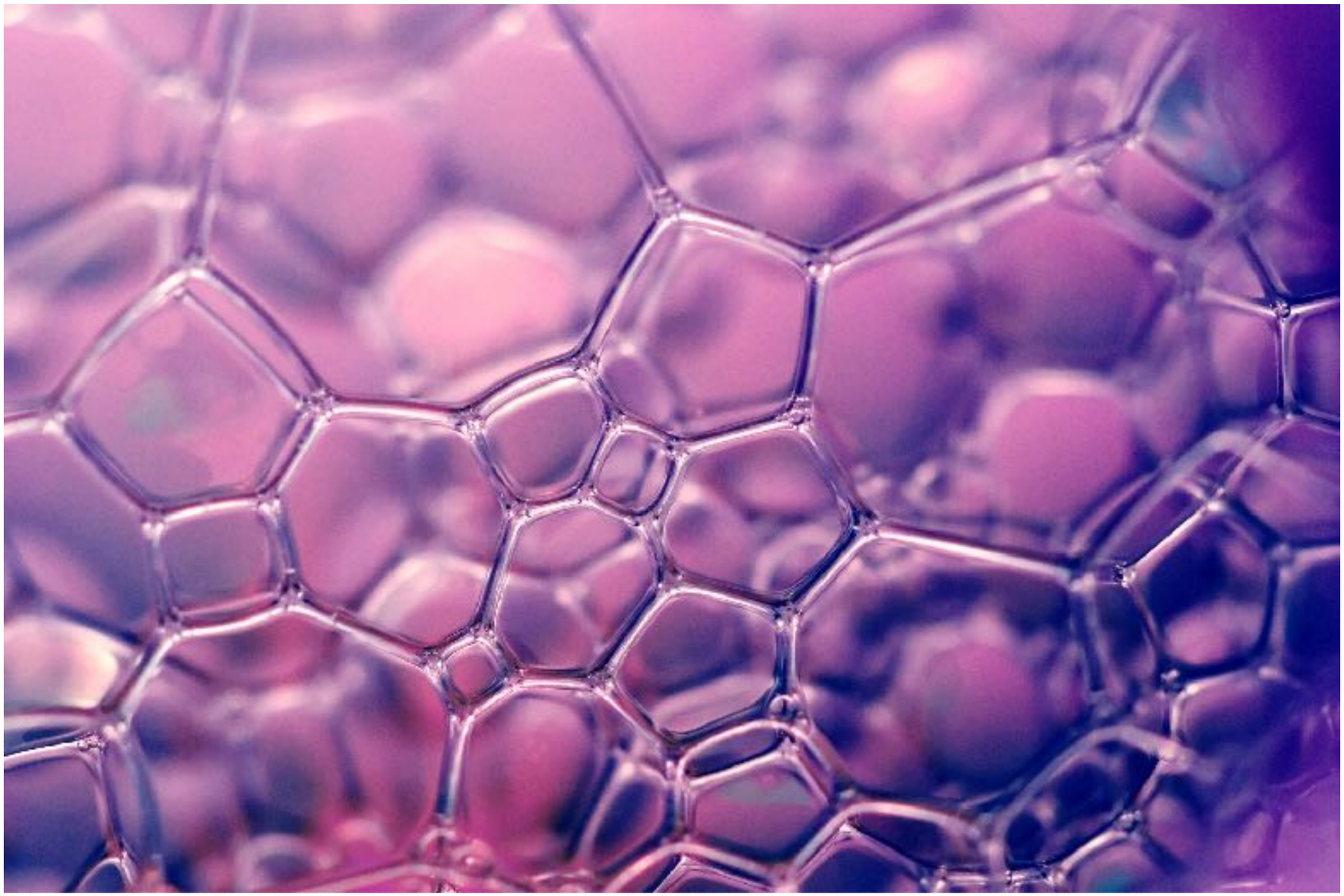


$N_{DW} = 3$





Wall-string Network

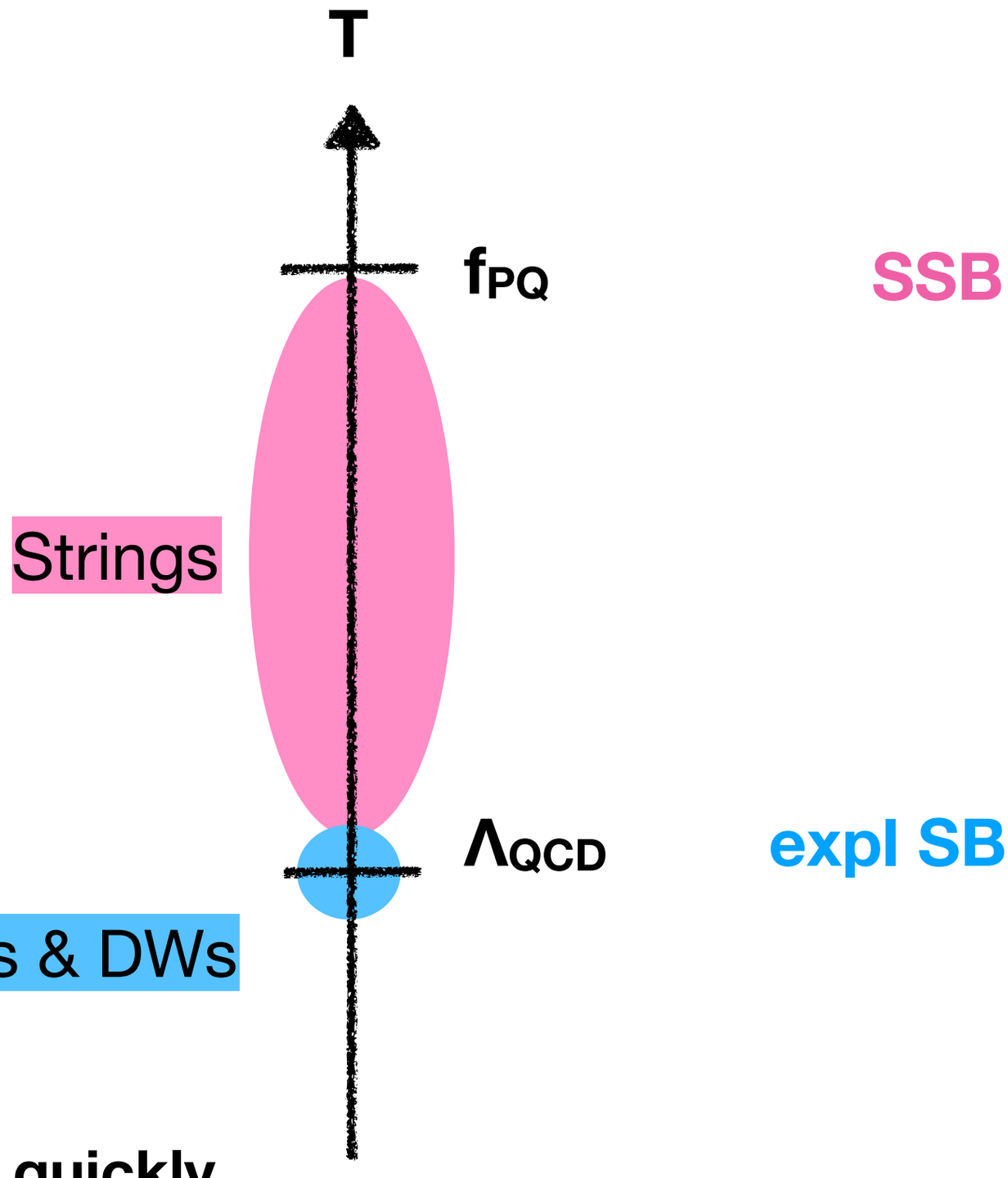


Network dynamics

$N_{DW} = 1$

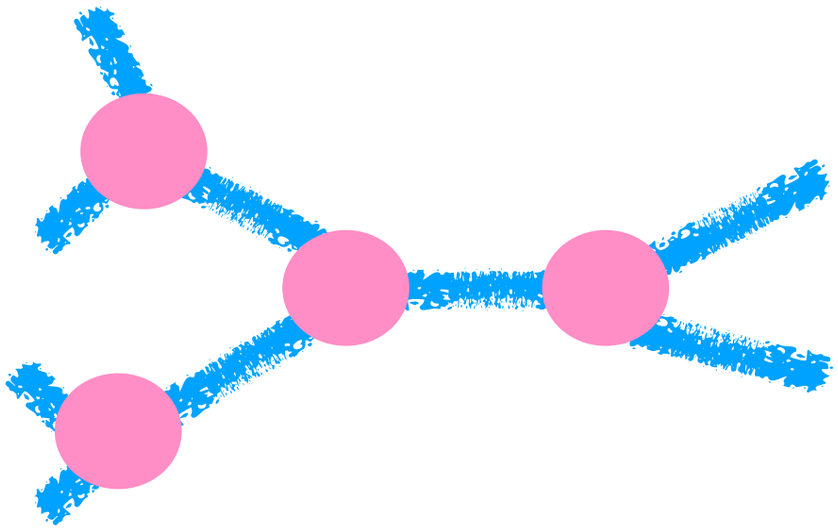
1 DW per string

=> network unstable, it disappears quickly
(but no BHs…)



Network dynamics

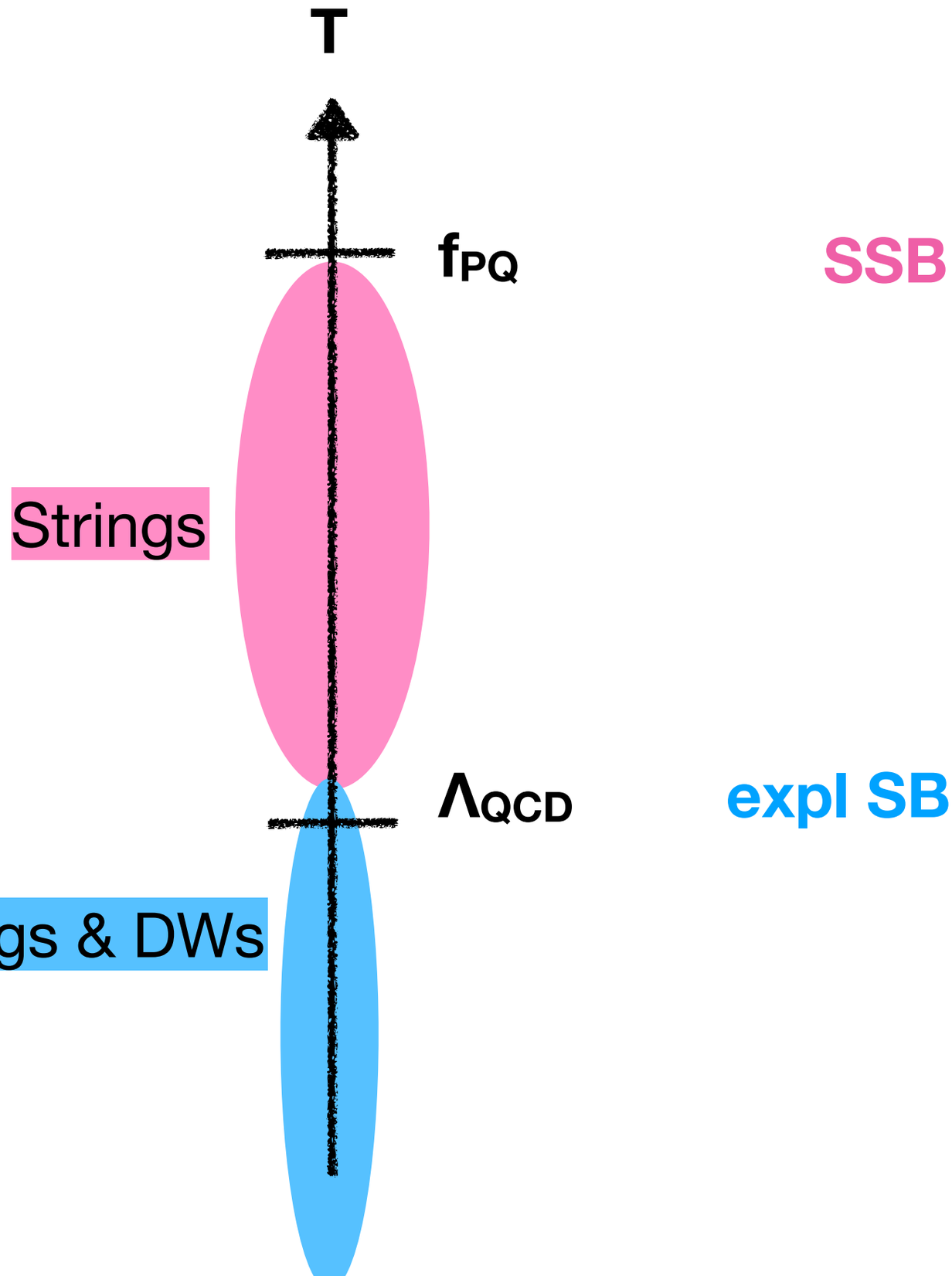
$N_{DW} > 1$



=> Network is stable

=> DW problem!

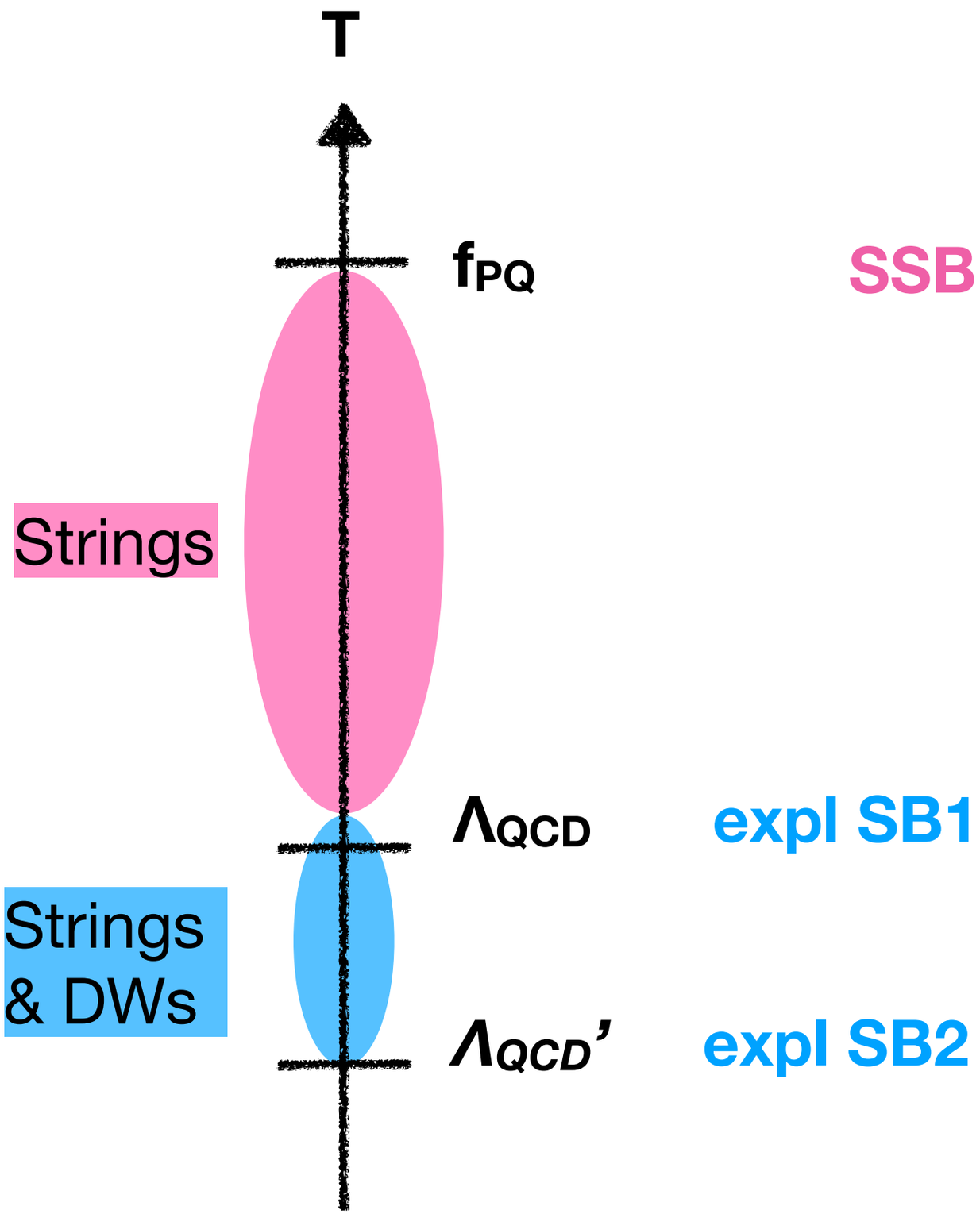
=> Must break Z_N !!



Network dynamics

$N_{DW} > 1$

$$U(1) \to \mathbb{Z}_N \to 1$$



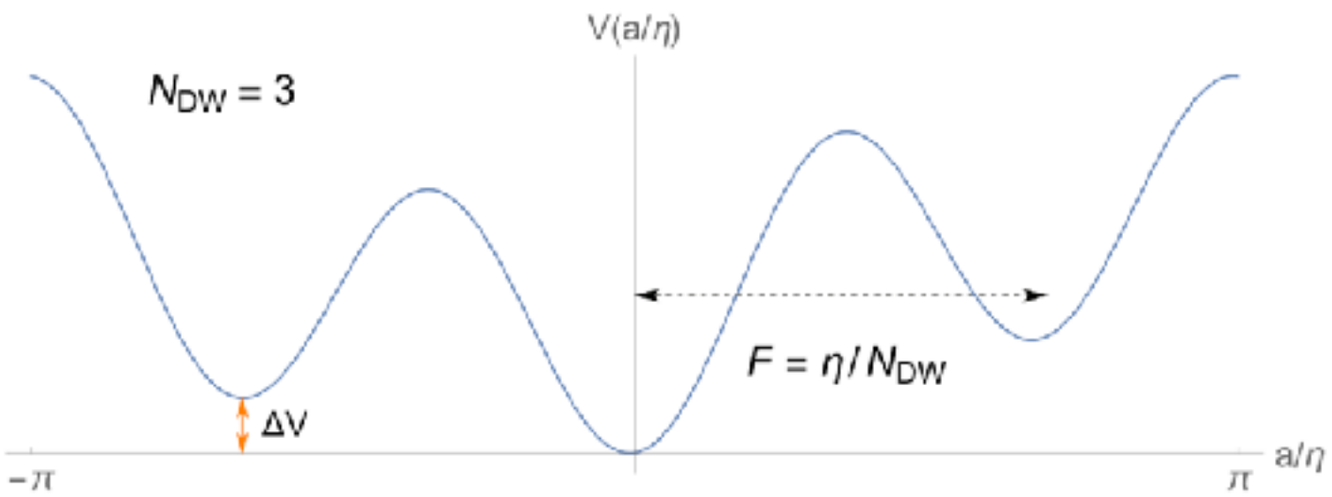
String-DW network epoch { Strings & DWs

We require

$N_{DW} > 1$

'bias'

$$V(a,T) = \frac{m^2(T)\eta^2}{N_{DW}^2}\left[1-\cos\left(\frac{a}{\eta}N_{DW}\right)\right] + \Lambda_B^4\left[1-\cos\left(\frac{a}{\eta}+\delta\right)\right]$$



One additional parameter, Λ_{QCD},

(assume $\delta = O(1)$)

Network dynamics

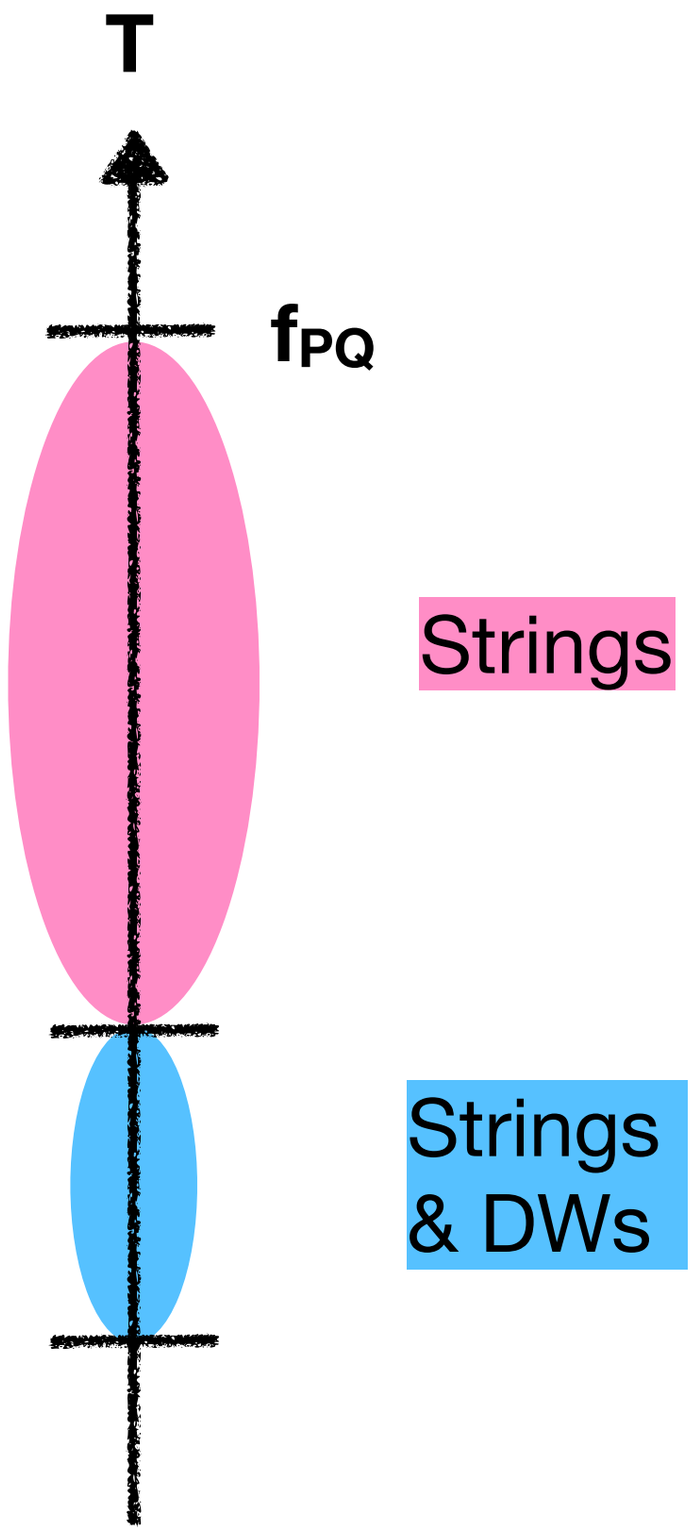
$N_{DW} > 1$

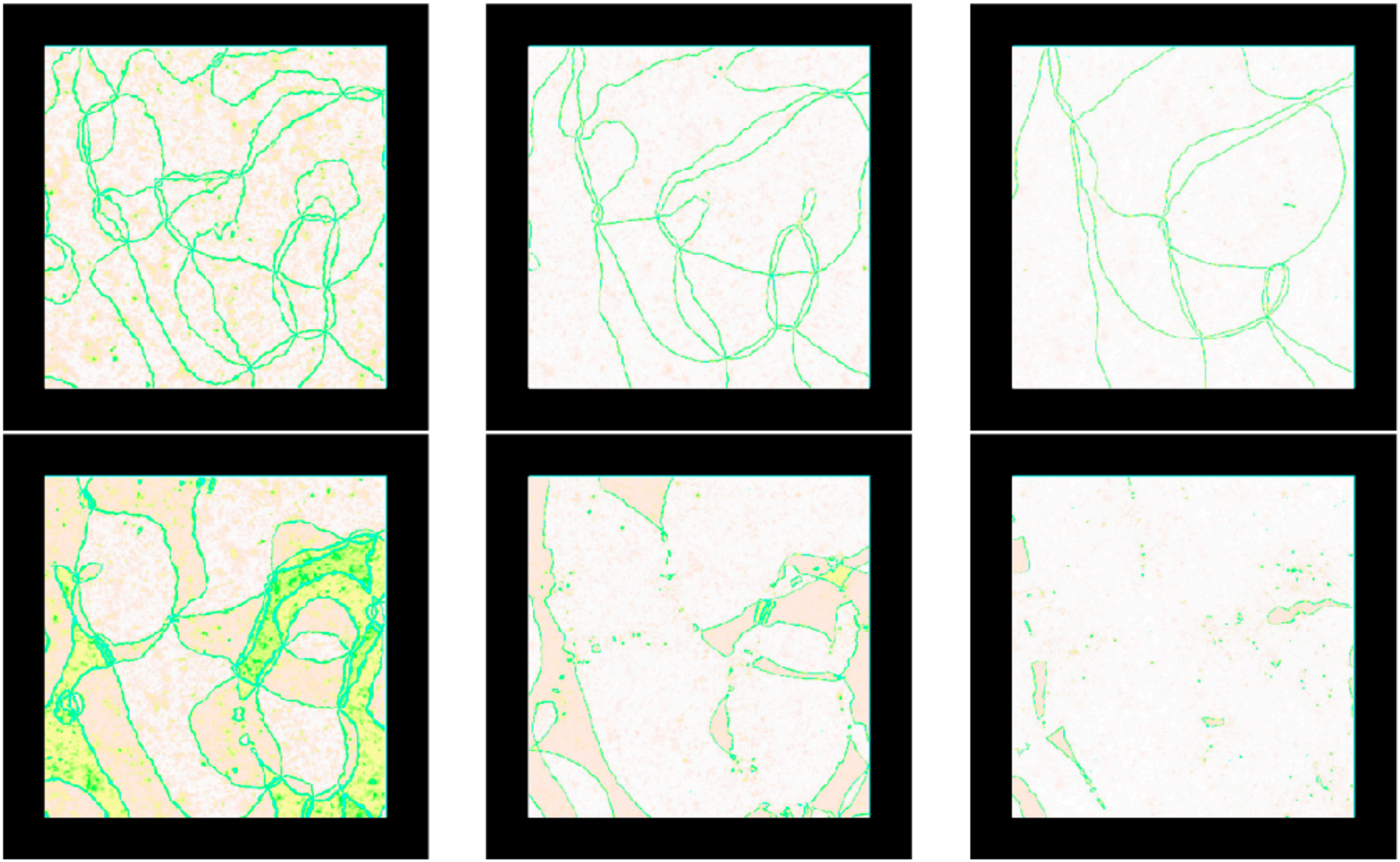
DWs form when

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

DW+string network ends when

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





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

See also
1806.04677
1806.05566

SN 1987 *A*

Chang et al. '18

PDG '18

$\delta = 0.1$

$\delta = 1$

$\Omega_a > \Omega_{\rm CDM}$

T_2[GeV] (Λ_{QCD}')

F[GeV]

10^{1} 10^{0} 10^{-1} 10^{-2} 10^{-3} 10^{-4}

10^{7} 10^{8} 10^{9} 10^{10} 10^{11}

=> Axion models with $N_{DW} > 1$ contain a

LONG NETWORK ANIHILATION EPOCH

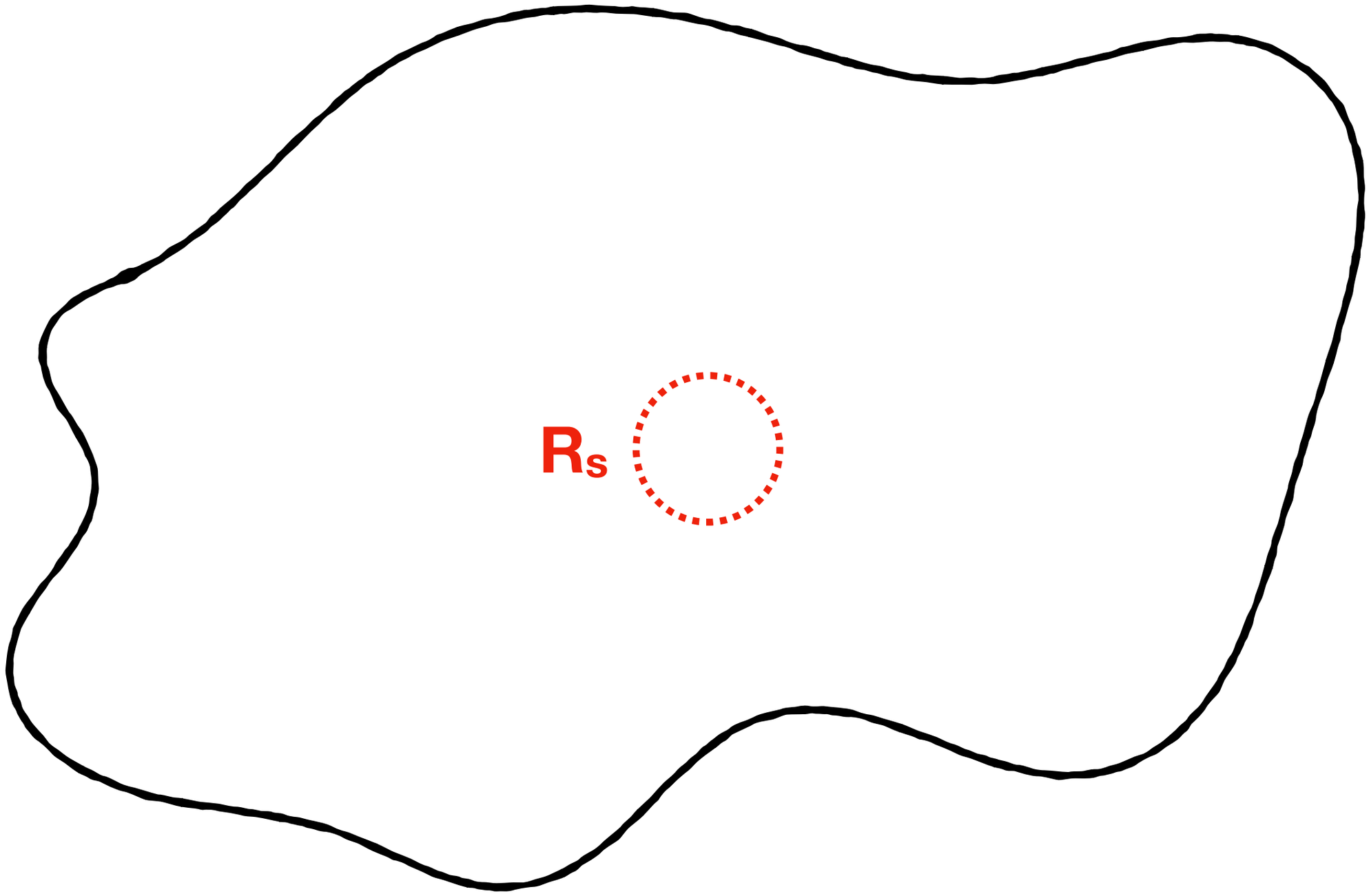
Q) **Does this lead to BH formation?**

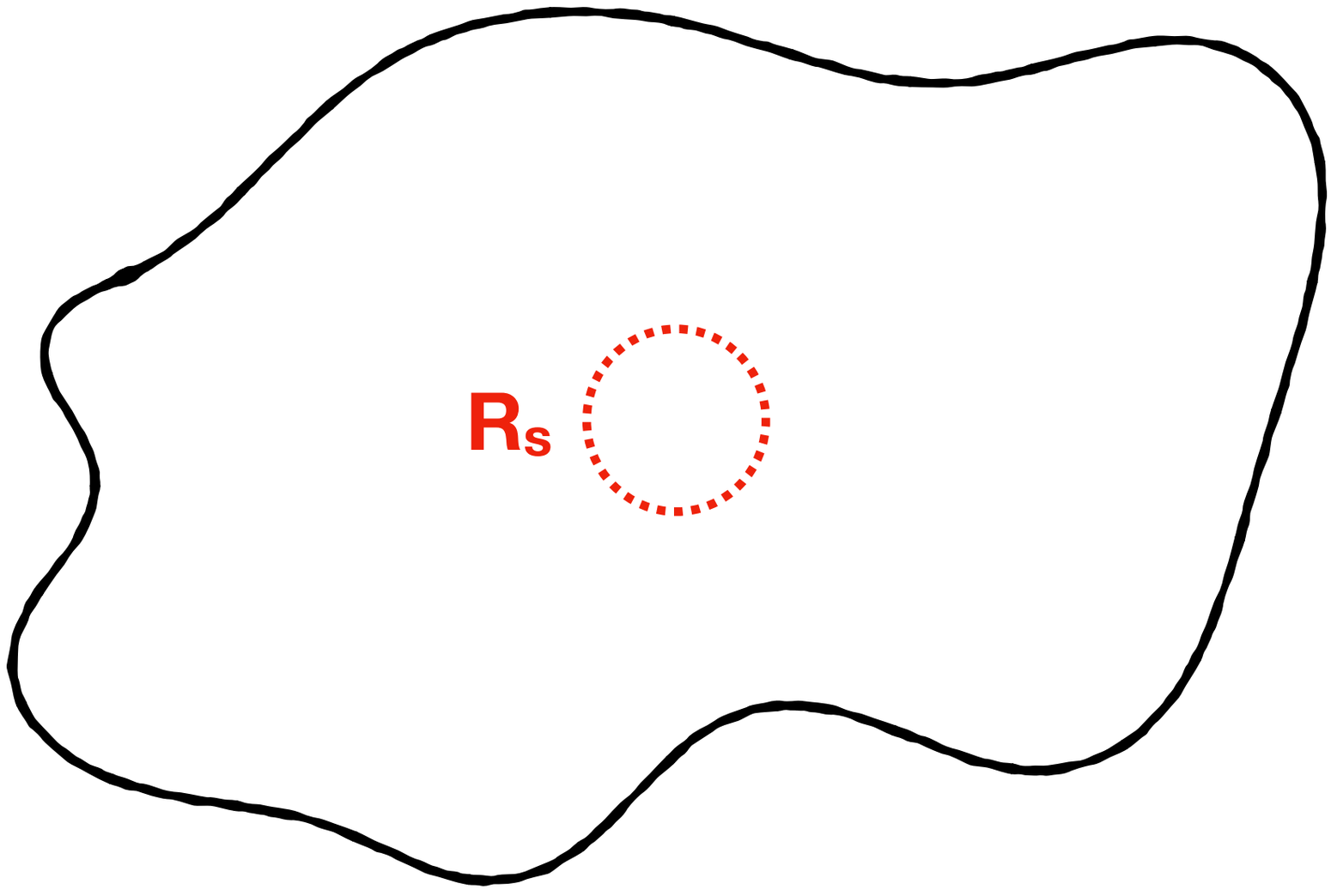
To make some progress we study a simpler (but related) problem:

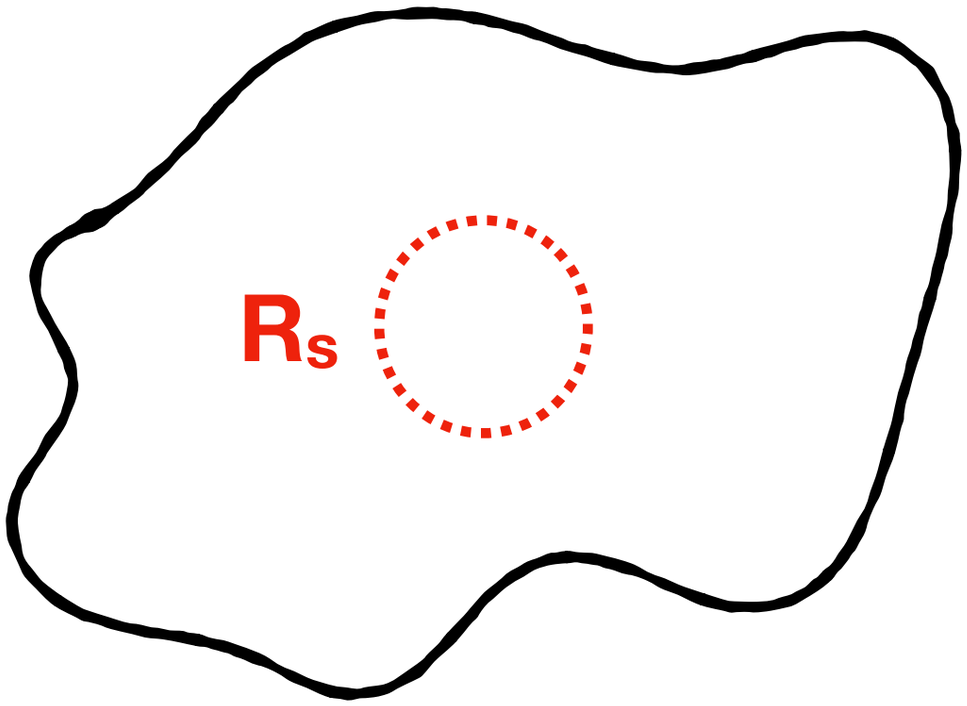
Collapse of a single closed DW with initial size ~ horizon

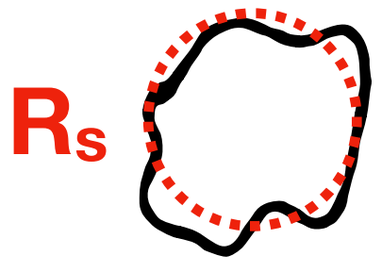
(which are ‘entering the horizon’ during all the network anihilation era)

Domain wall collapse

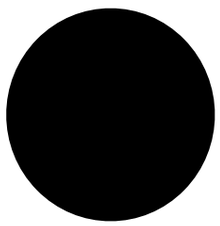

Rs


R_S


Rs


Rs

BH!



Mass

If BHs formed at all, then

$$M_{BH} \simeq 4\pi\sigma H^{-2}(T) \simeq 10^{-4} M_\odot \left(\frac{F}{10^9\ \text{GeV}}\right)\left(\frac{10\ \text{MeV}}{T}\right)^4$$

Formation criterium:

DW size < its own Shwarzschild radius

$$R_{DW} \lesssim R_{Schw}$$

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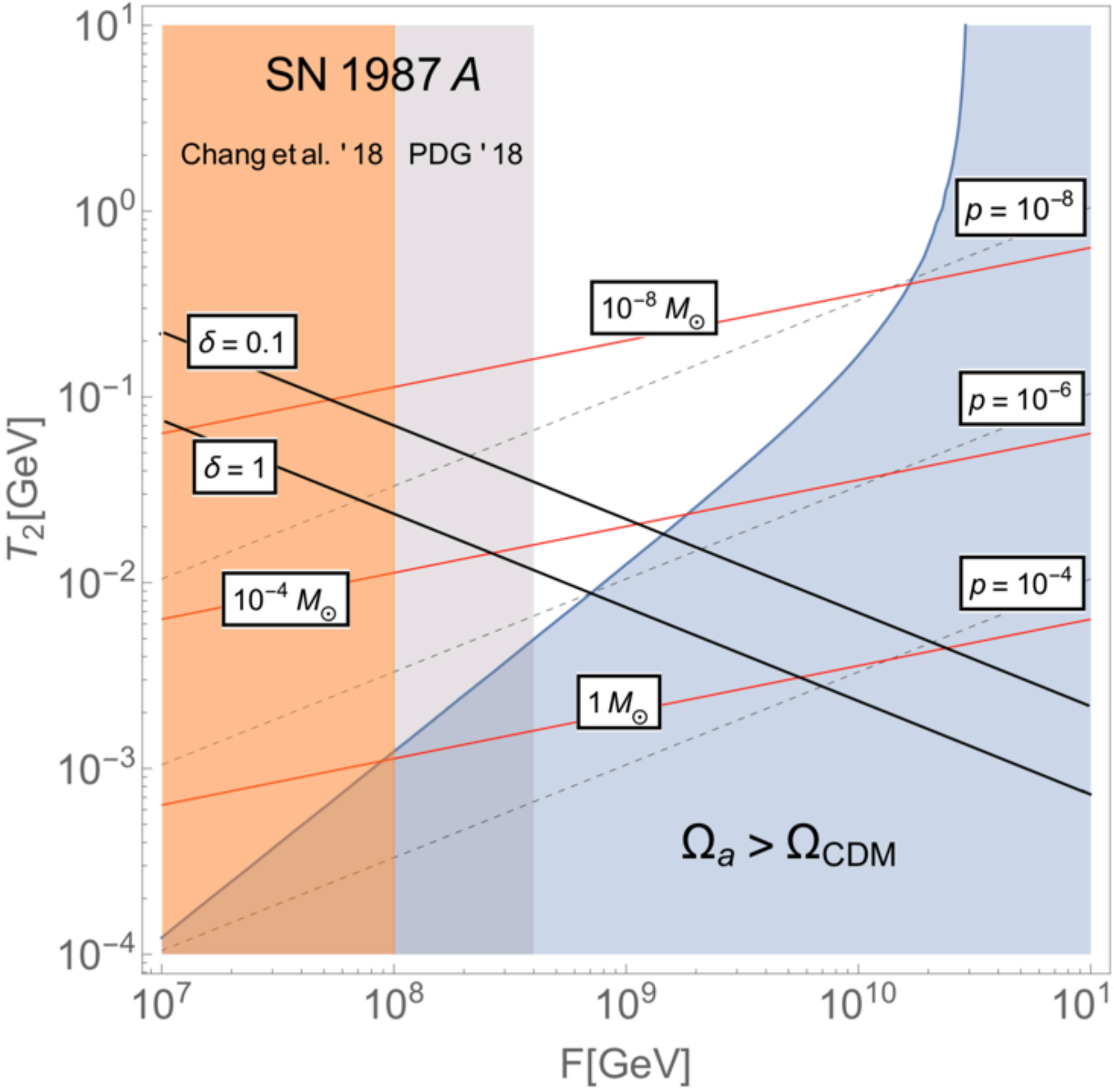
DW size < its own Shwarzschild radius

$$R_{DW} \lesssim R_{Schw}$$

$$H^{-1} \qquad\qquad \sim H^{-2}\,\frac{\sigma}{M_P^2}$$

(More easily satisfied for DWs entering later)

F.O.M. $p = R_S\, H$



F.O.M.

$p = R_S H$

For closed walls with size ~ horizon at T_2

Bias is important

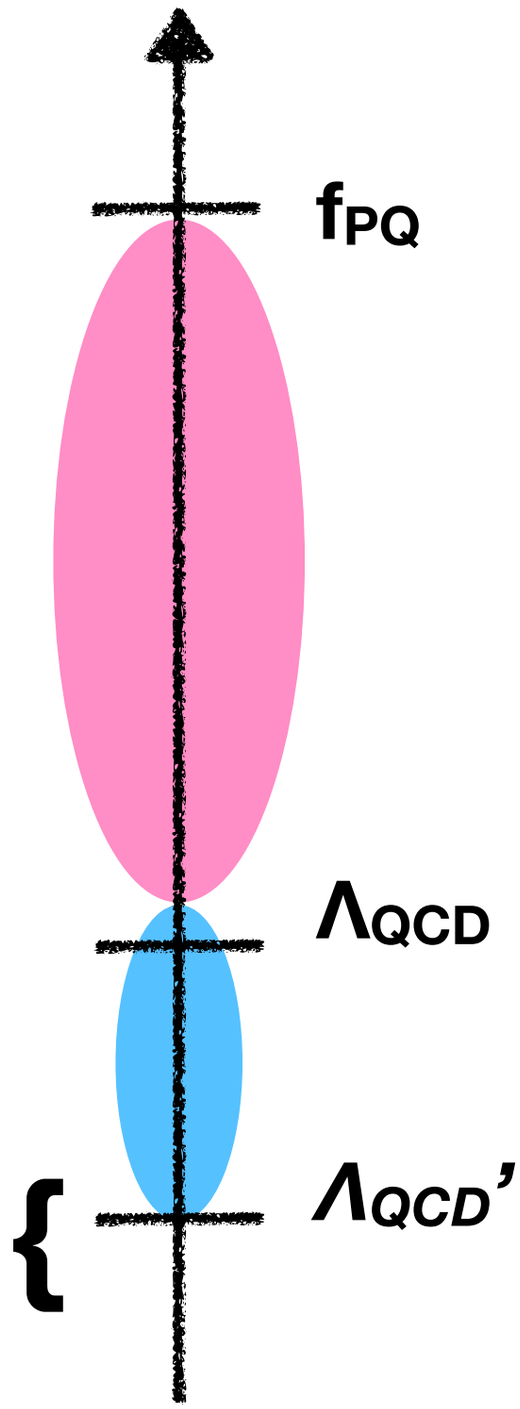
$$M \sim \sigma R^2 + \Delta V R^3$$

- **The anihilation epoch doesn't have a sharp end**

- **For 'late birds', the BH mass is dominated by bias term, and M scales like volume**

$$M \sim \frac{\Delta V \ M_P^3}{T^6} \qquad\qquad R_S H \sim \frac{\Delta V}{T^4}$$

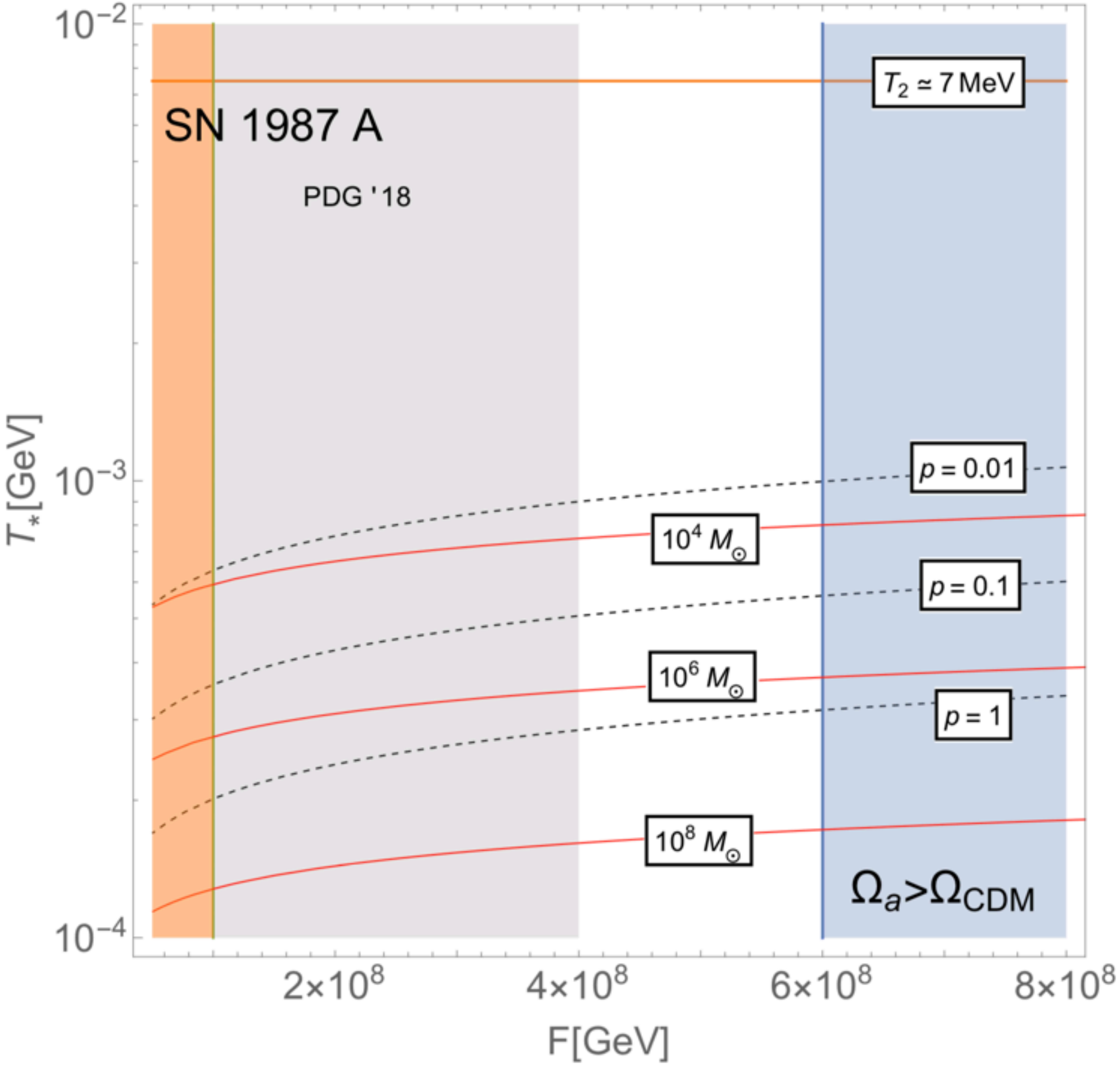
- **There is a (small but nonzero) fraction of DWs present below T_2**

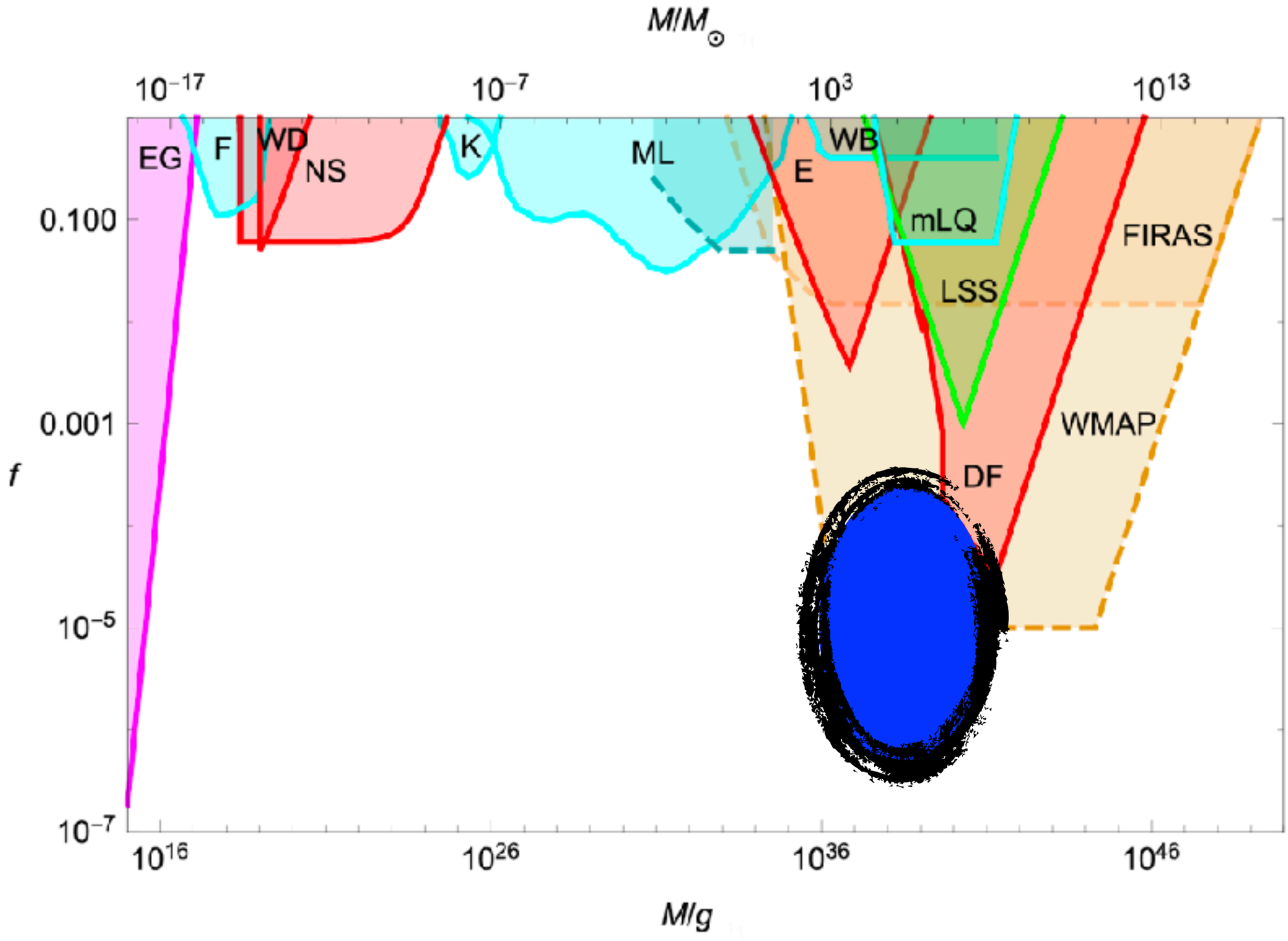


QCD axion

Late-birds

Heavy BHs easily formed!




$M/M_\odot$
10^{-17}
10^{-7}
10^{3}
10^{13}
EG
F
WD
NS
K
ML
E
WB
mLQ
LSS
FIRAS
WMAP
DF
0.100
0.001
10^{-5}
10^{-7}
f
10^{16}
10^{26}
10^{36}
10^{46}
M/g

Primordial Black Holes as Seeds for Cosmic Structures

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if the SMBHs are themselves primordial, they might play a role in generating galaxies, either on account of their gravitational Coulomb effect [21] or through the Poisson fluctuations in their number density [22]. In the latter case, they would need to have an initial mass of at least $10^6 M_\odot$ but their contribution to the dark matter density need only be 10^{-5}. Such large

Conclusions

- **Axionic String-Wall Network collapse (with $N_{DW}>1$) is a PBH formation mechanism — *not tied to inflation!***

- **For the QCD axion with m_a~*meV* —> M_{PBH} ~ 10^6 $M_\odot$**

- **Fraction depends strongly on DW+string network collapse details — a problem worth studying more closely**

- **In this mechanism PBHs are a fraction of DM naturally**

- It can be extrapolated (ALP) to other scales & mass ranges

Discussion

0) Motivation

DM — SMBHs — LIGO merger events — indirect probe of HEP

Perhaps only with BSM?

1) Observational constraints

Many types — strongly depend on M & on the 'mass function' —

100% of DM in BHs possible? — *still debated*

Is < 100% interesting? Depends on existence of models that provide that

2) Formation mechanisms

Based on inflation

The most studied — criticisms: i) *ad hoc* — ii) very high energies

Not based on inflation

Several potential candidates, mostly cosmological phase transitions

PBH (non-)observation can give hints on BSM physics

Thank you!