Primordial Black Holes from the QCD axion

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IFAE Barcelona

based on: Francesc Ferrer, Eduard Massó, Giuliano Panico, Oriol Pujolàs and FR, **arXiv:1807.01707**

IFAE 25 years 1991-2016 Institut de Física d'Altes Energies

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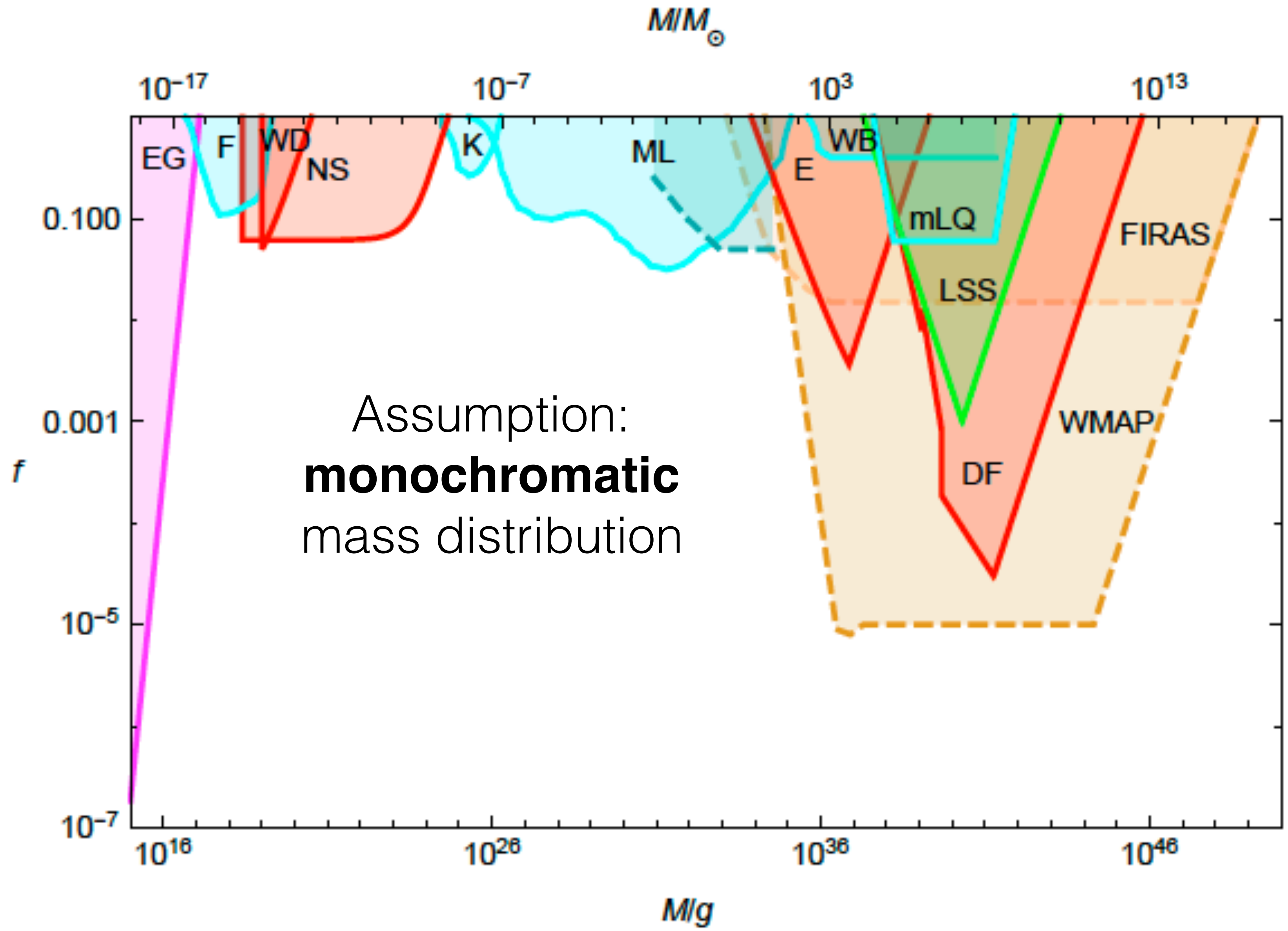
PBHs as DM

- **Interest**: alternative, traditionally **astrophysical**, DM candidate.

However:

$$f \equiv \frac{\Omega_{PBH}}{\Omega_{DM}}$$



Taken from: Carr et al., arXiv:1607.06077

Interest in heavy BHs

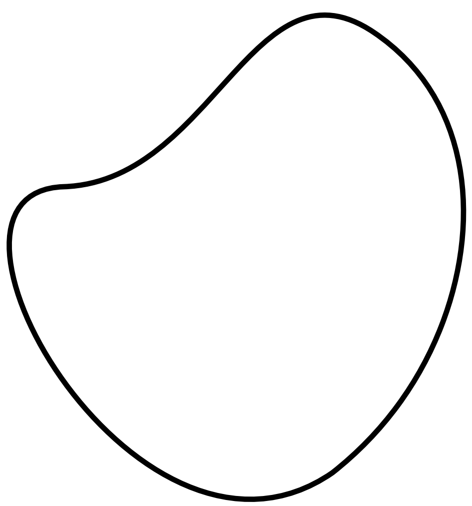
- We (can) hear them! (LIGO-LISA-etc)
- We "see" them! (Super-Massive BHs at the centre of galaxies, maybe primordial?)
- **Small fraction** of **very heavy (** $\gtrsim 10^5 M_\odot$ **)** PBHs: helps in generation of cosmological structures *and* may alleviate problems of CDM on sub-galactic scales! **(Clesse et al. ´15, Carr and Silk ´18)**.

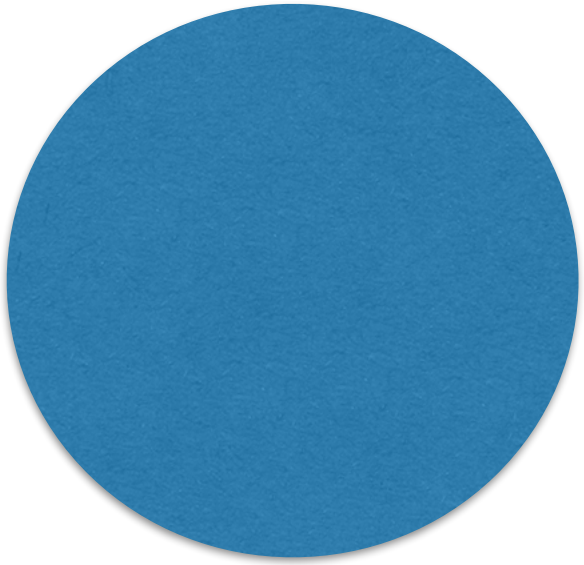
Focus of this talk

- **Most studied** formation mechanism: **gravitational** collapse of density fluctuations from **Inflation**.

- **Alternative** formation mechanism: collapse of topological defects in the early Universe.

- **Examples**: strings (Vilenkin ´81, …), domain walls (Khlopov ´05,…, Deng et al. ´17).





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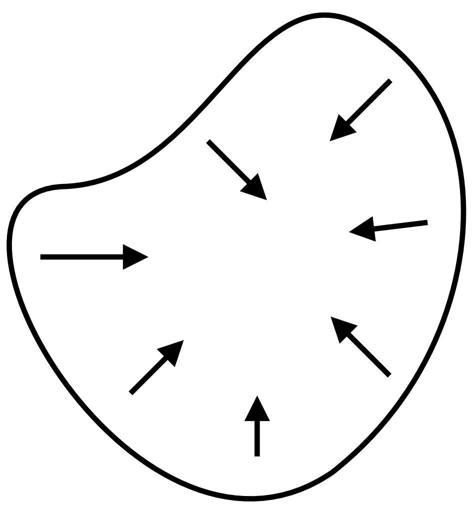

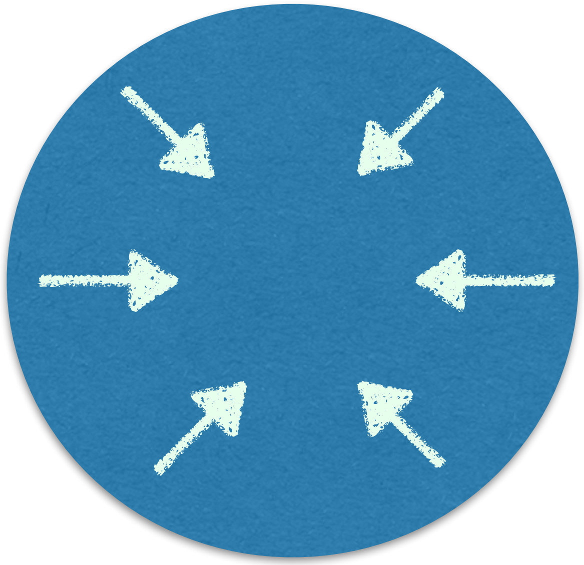

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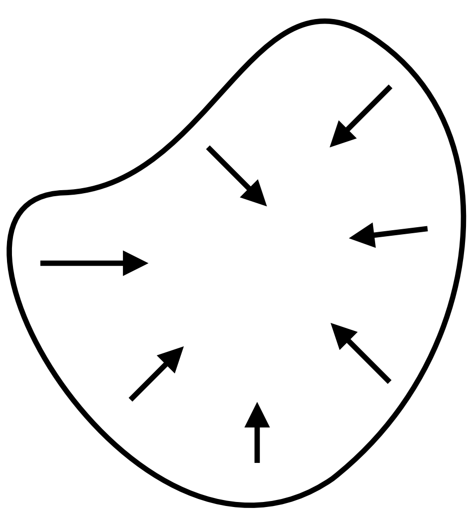
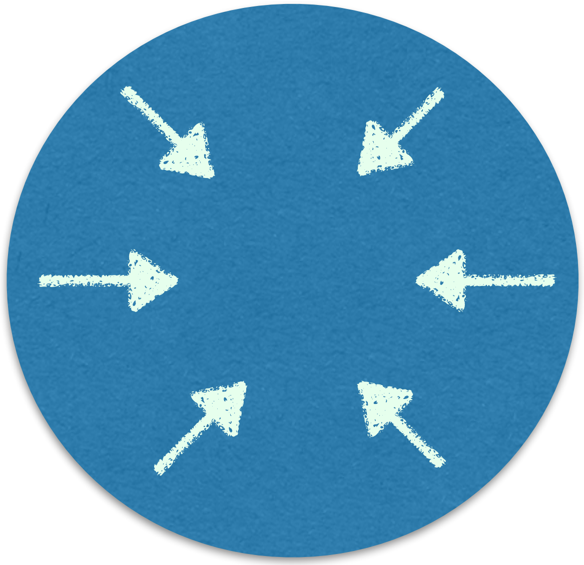
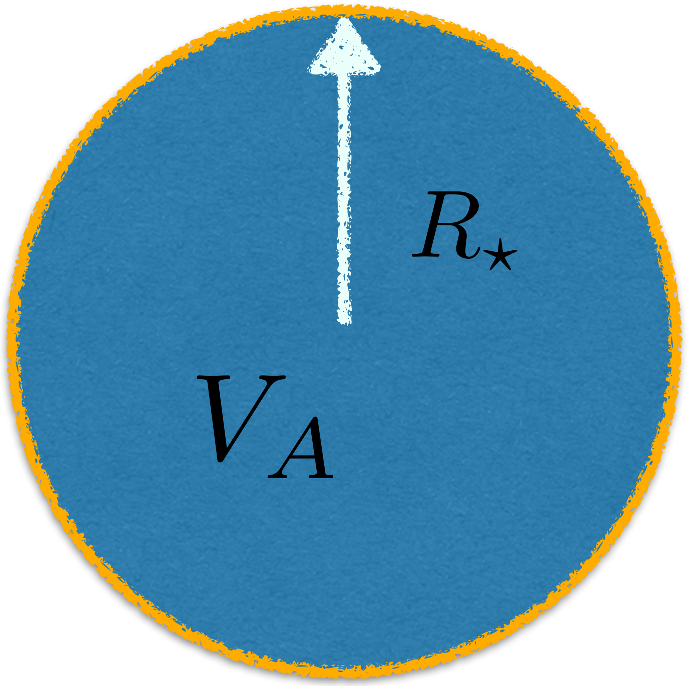




→ Collapse driven by **tension**!

PBHs from domain walls (DWs)

$V_B \lesssim V_A$



σ

Wall **tension**

- DW collapses once

$$H_\star^{-1} \equiv H^{-1}(T_\star) \sim R_\star$$

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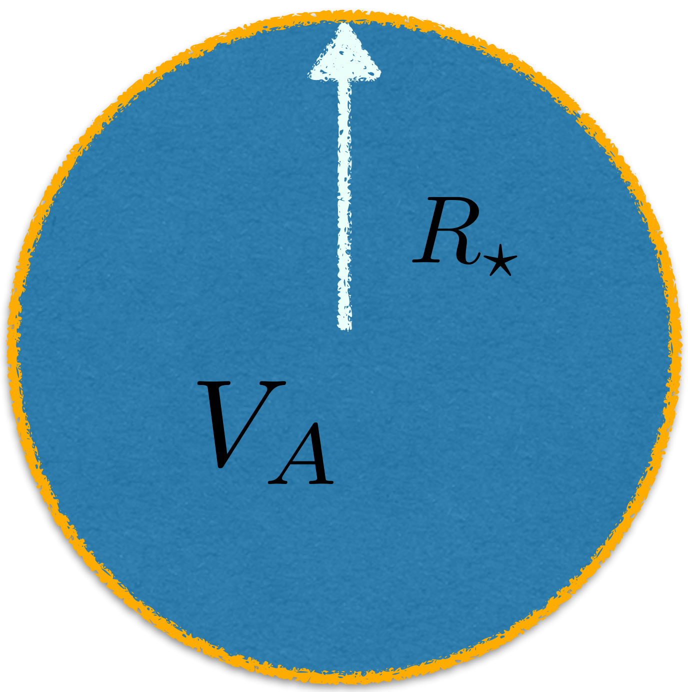

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- Collapsing **mass**

$$M_\star \simeq 4\pi\sigma H_\star^{-2} + \frac{4}{3}\pi\Delta V \; H_\star^{-3}$$

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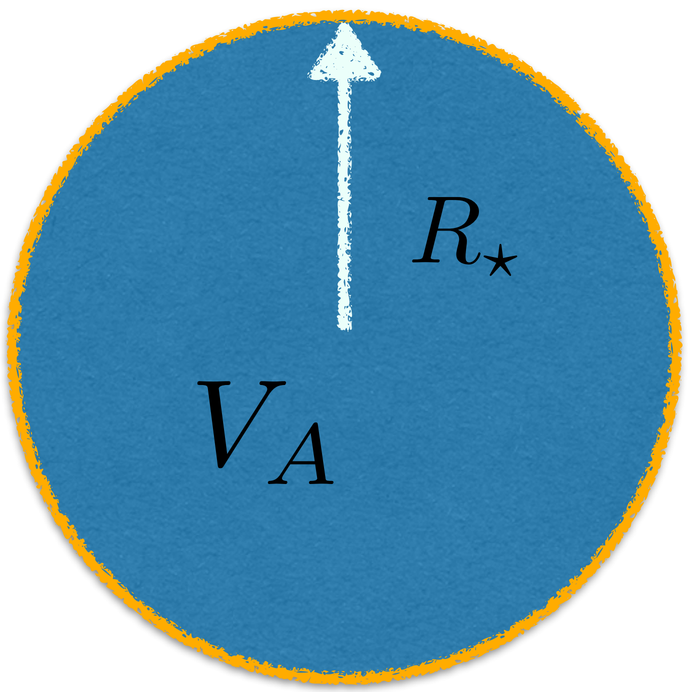

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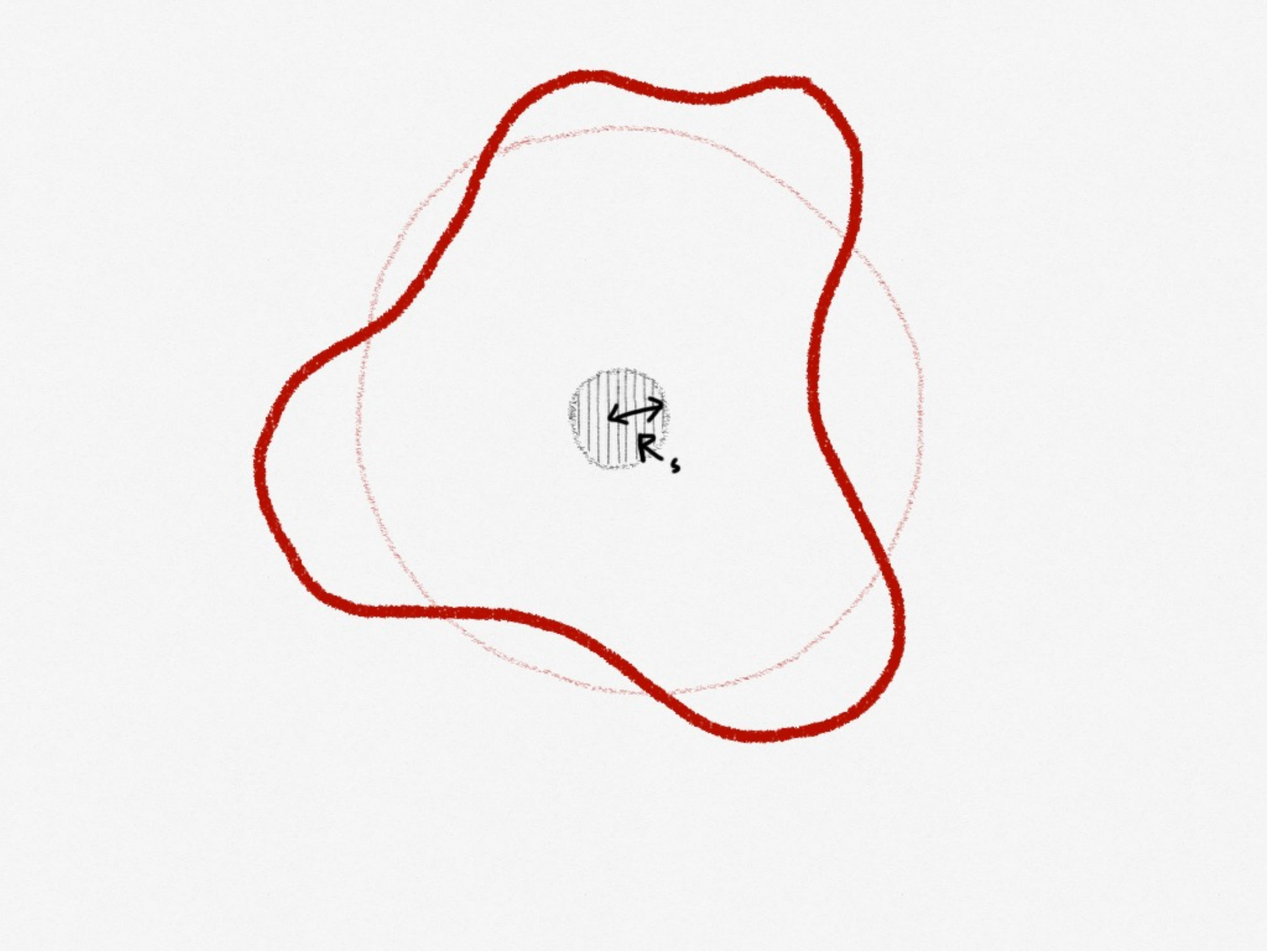
$\sim T_\star^{-4}$ $\qquad$ $\sim T_\star^{-6}$

Figure of merit



Pictures by P. Baratella

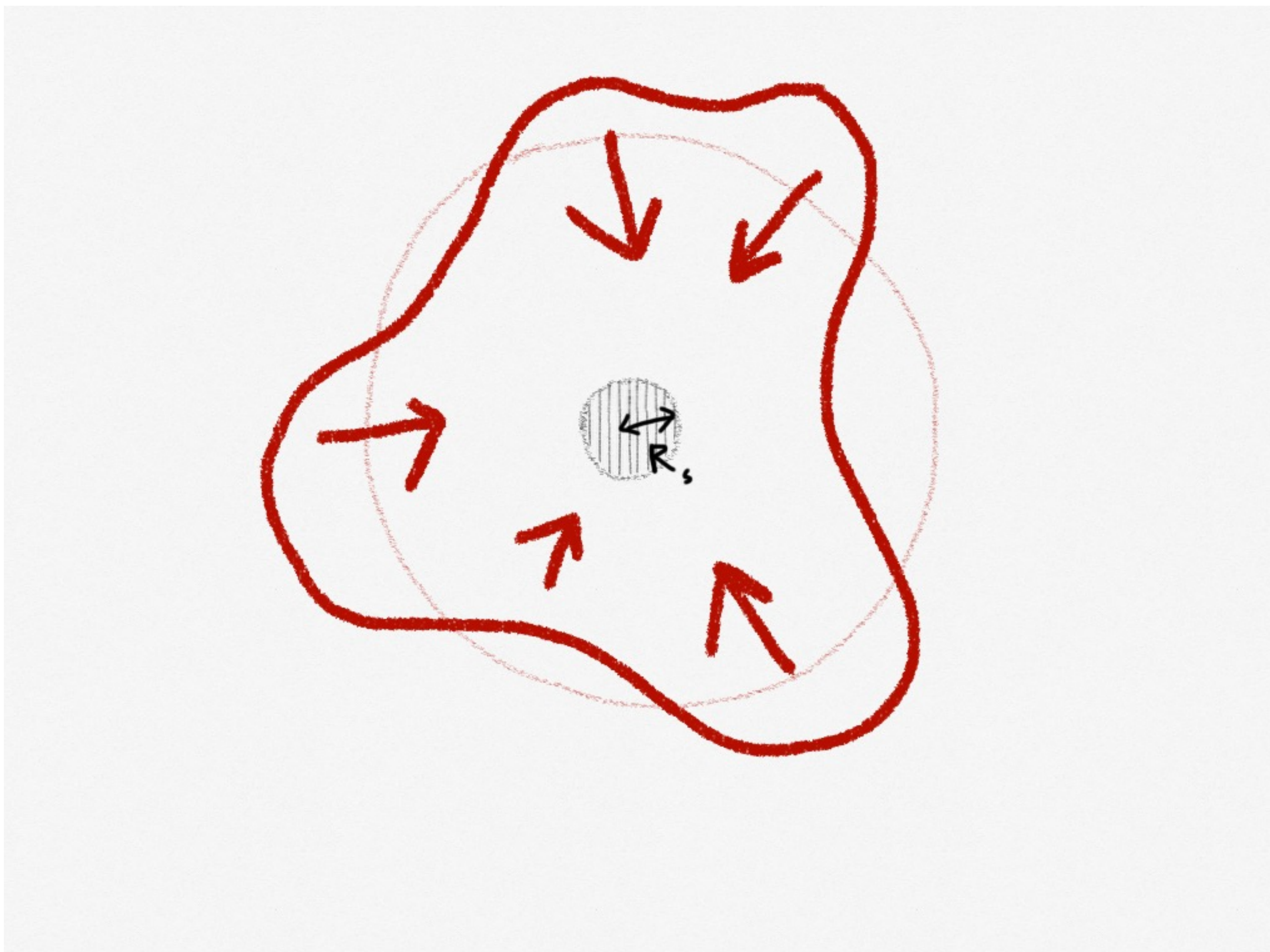
$$p \equiv \frac{R_S}{R_\star} \sim \frac{2G_N M_\star}{H_\star^{-1}}$$

$$\sim \frac{\sigma H_\star^{-1}}{M_p^2} + \frac{\Delta V H_\star^{-2}}{3M_p^2}$$

$$\downarrow \qquad\qquad \downarrow$$

$$\sim T_\star^{-2} \qquad \sim T_\star^{-4}$$

Figure of merit



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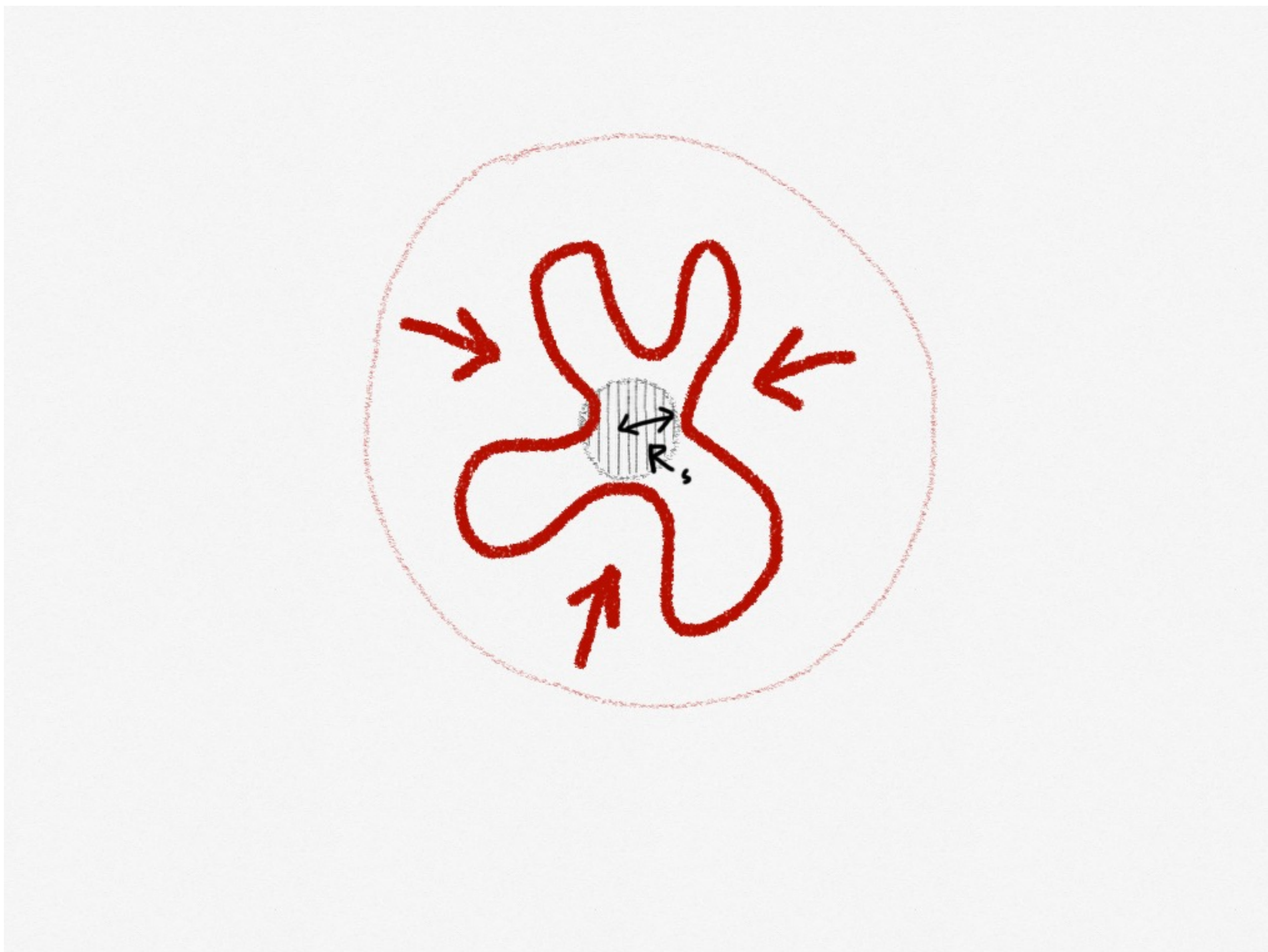

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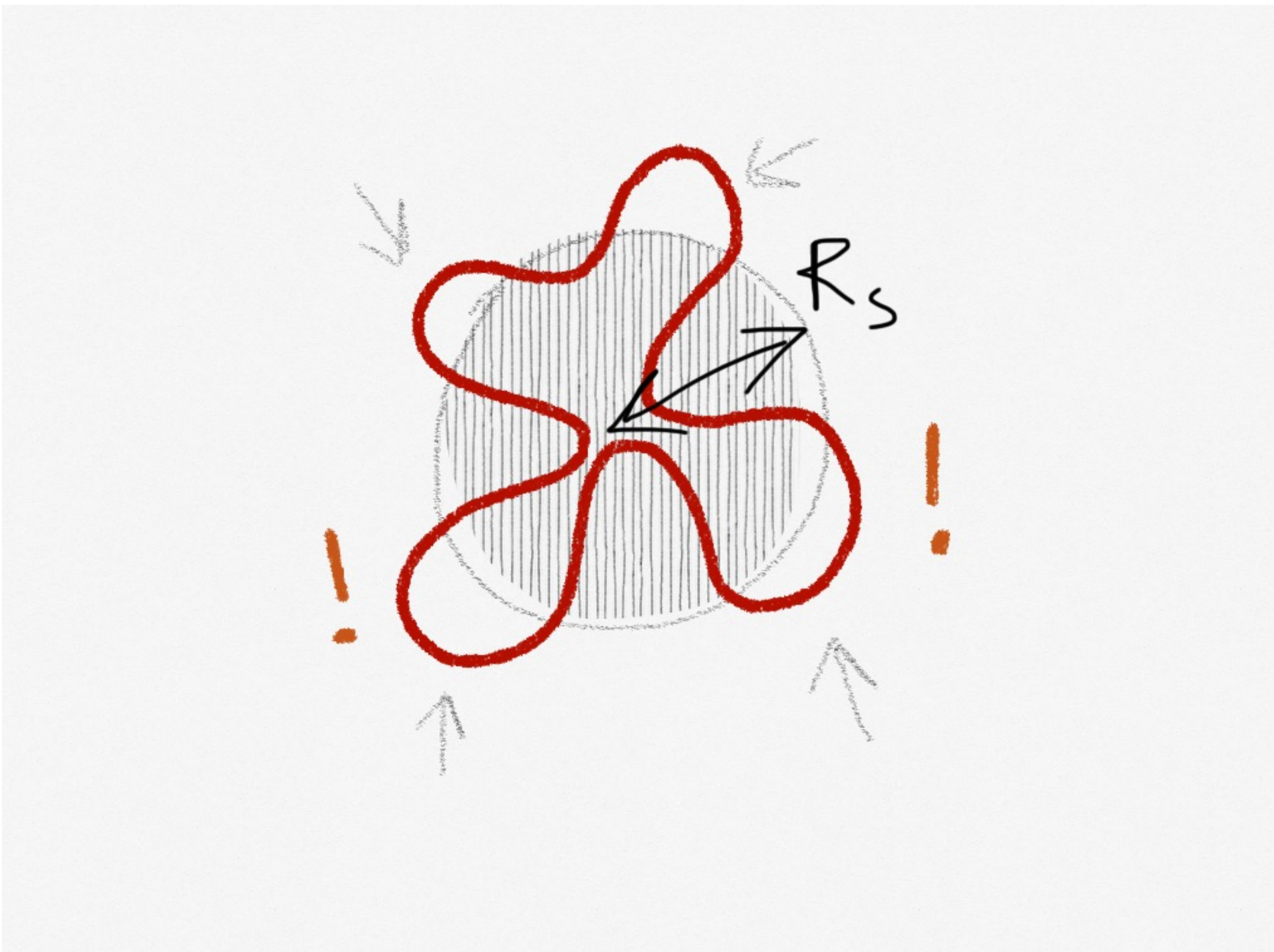

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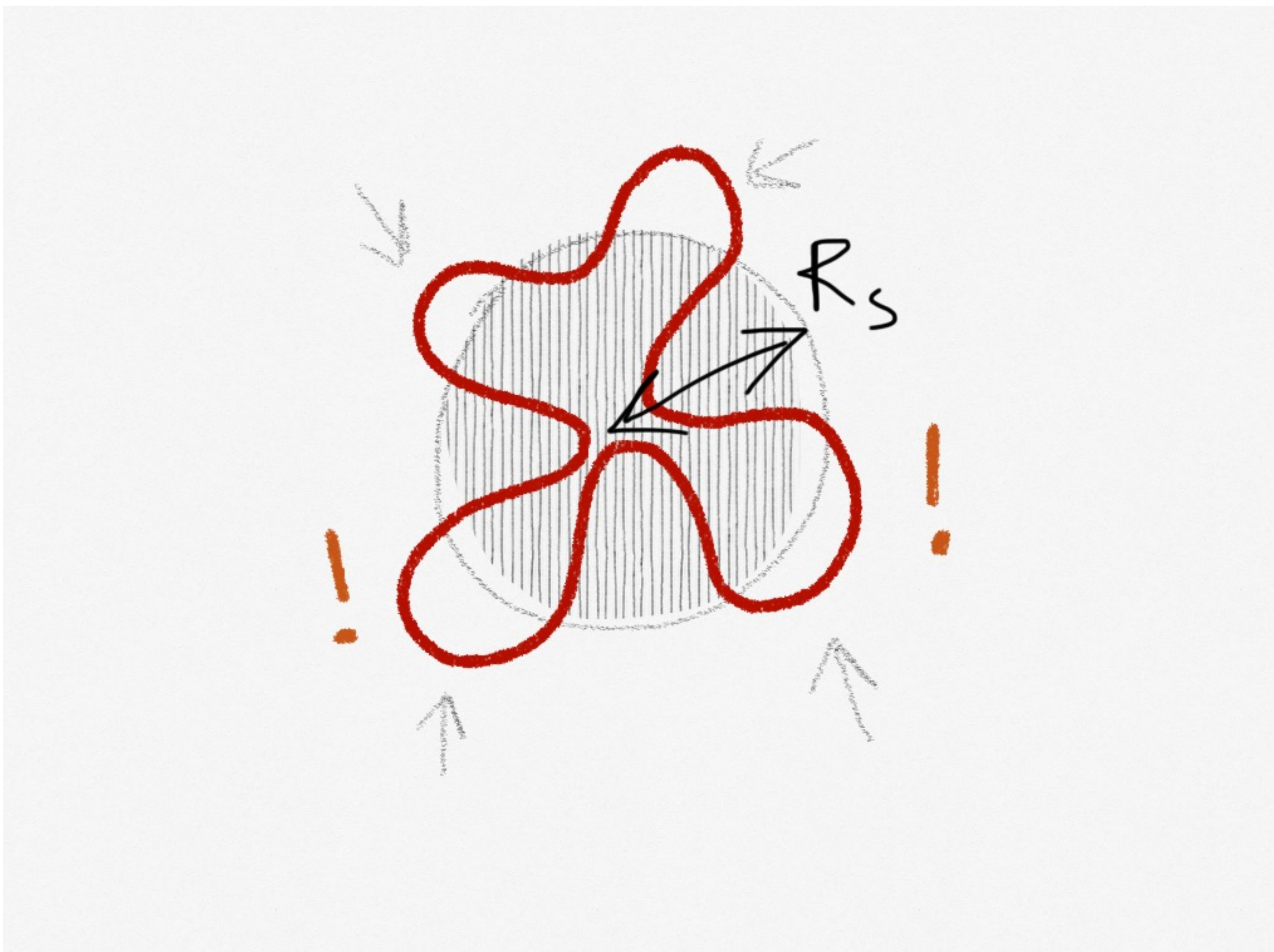

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PBHs more likely to form (p~0.1) if collapse occurs late!

Focus of this talk

- **New here**: PBH formation from **axionic** hybrid string-domain wall **network**.

- Framework: **QCD axion** with domain wall number >1 (**DFSZ** and generalisations of **KSVZ**, see **Vachaspati ´17** for =1 case).

$$\mathcal{L}_a \supset -N_{DW} \frac{a(t, \mathbf{x})}{v} \int d^3x G_{\mu\nu} \tilde{G}^{\mu\nu}$$

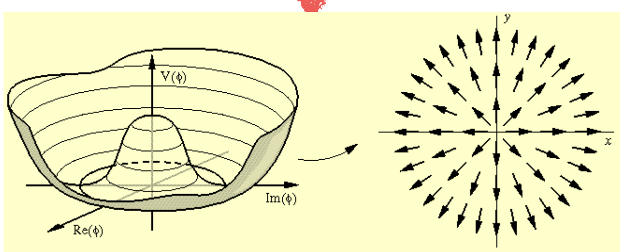
- Mechanism is **independent** of inflation!

- DM made of **axions** and **heavy PBHs**!

Defects of the QCD axion

Defects of the QCD axion

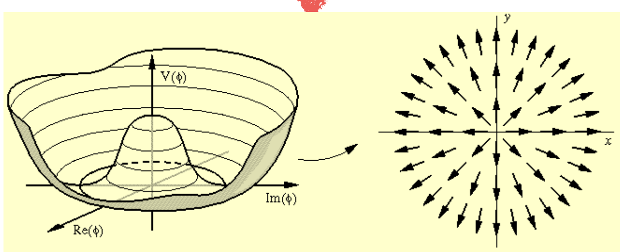
T_{RH} $T_{\not{\mathrm{P}}\mathrm{Q}} = v$



Strings

Defects of the QCD axion

$T_{\rm RH}$ $T_{\not{\rm PQ}} = v$ $T_1 \sim {\rm GeV} : 3H(T_1) = m(T_1)$



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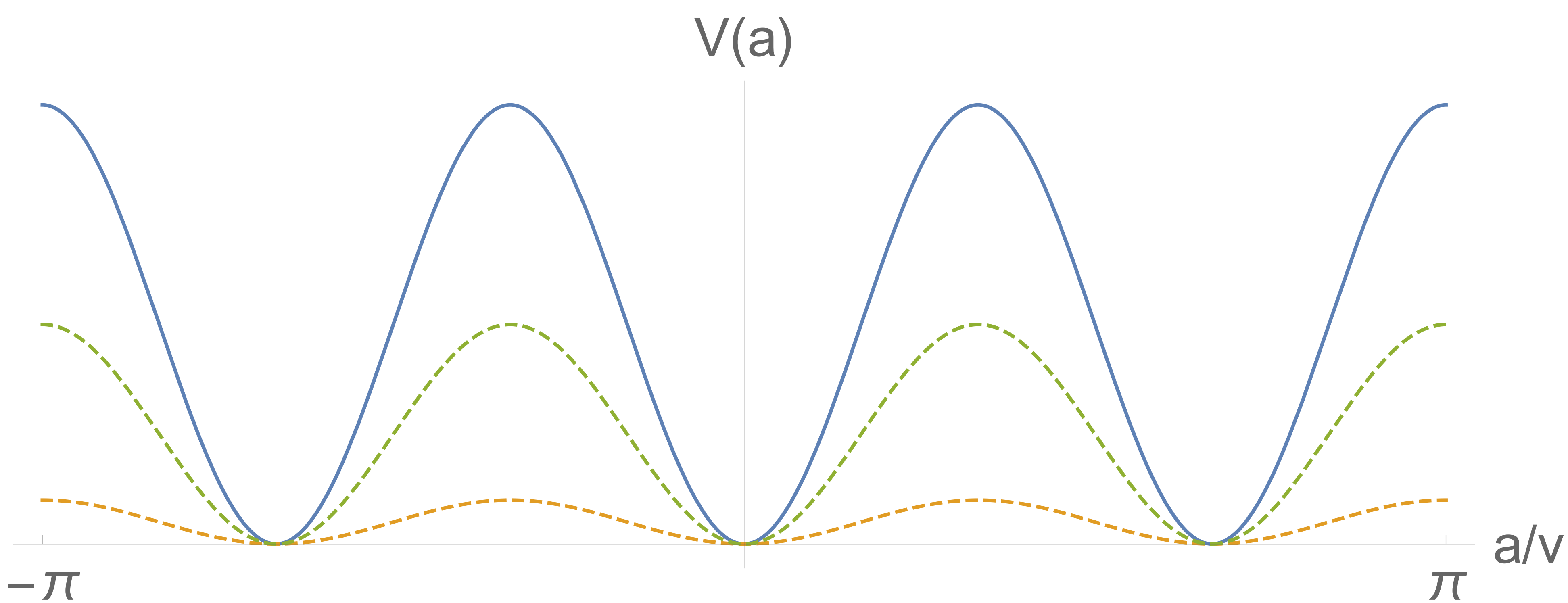
DWs



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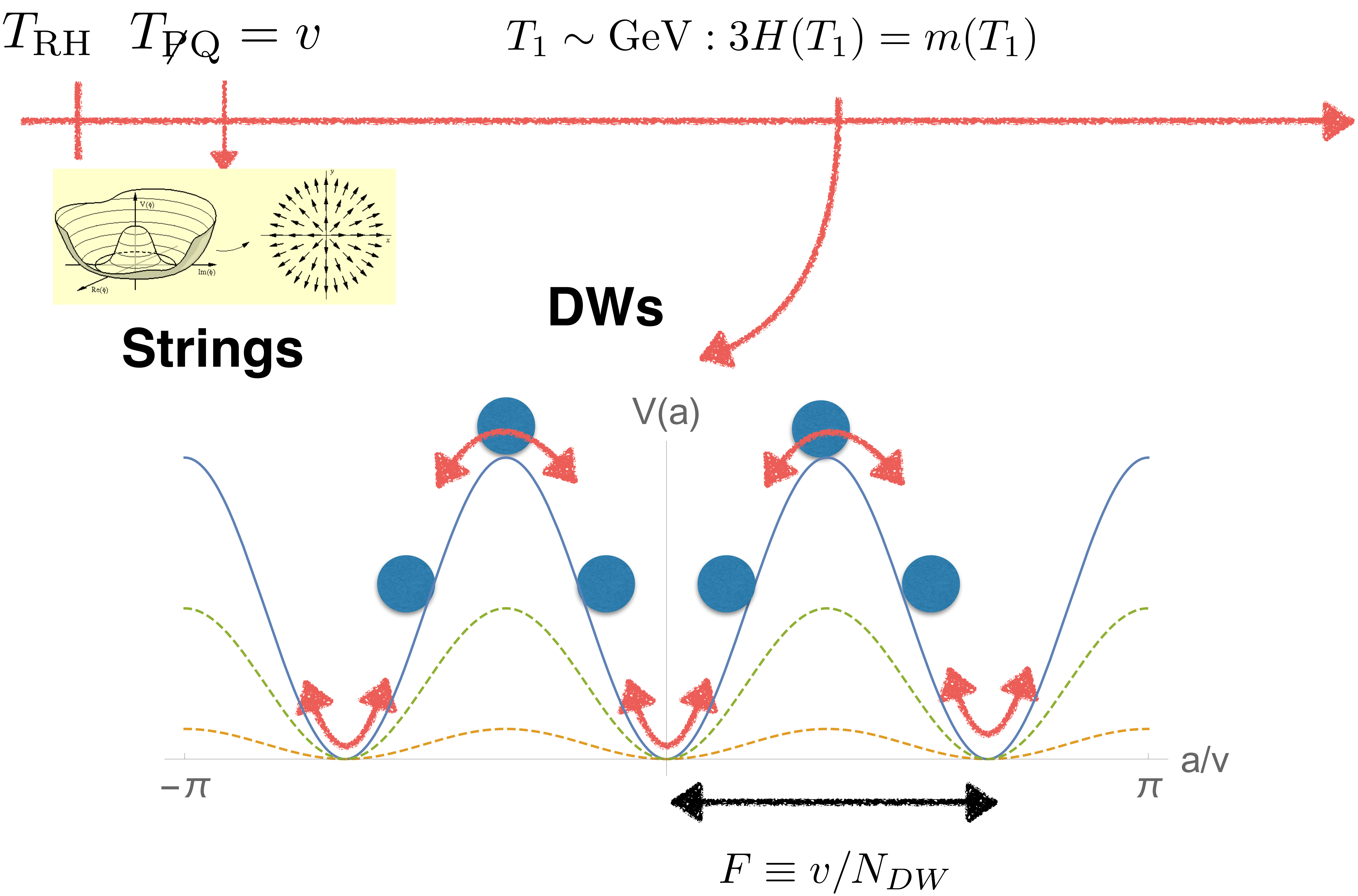
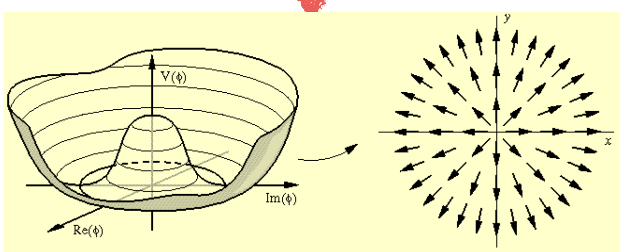


Defects of the QCD axion

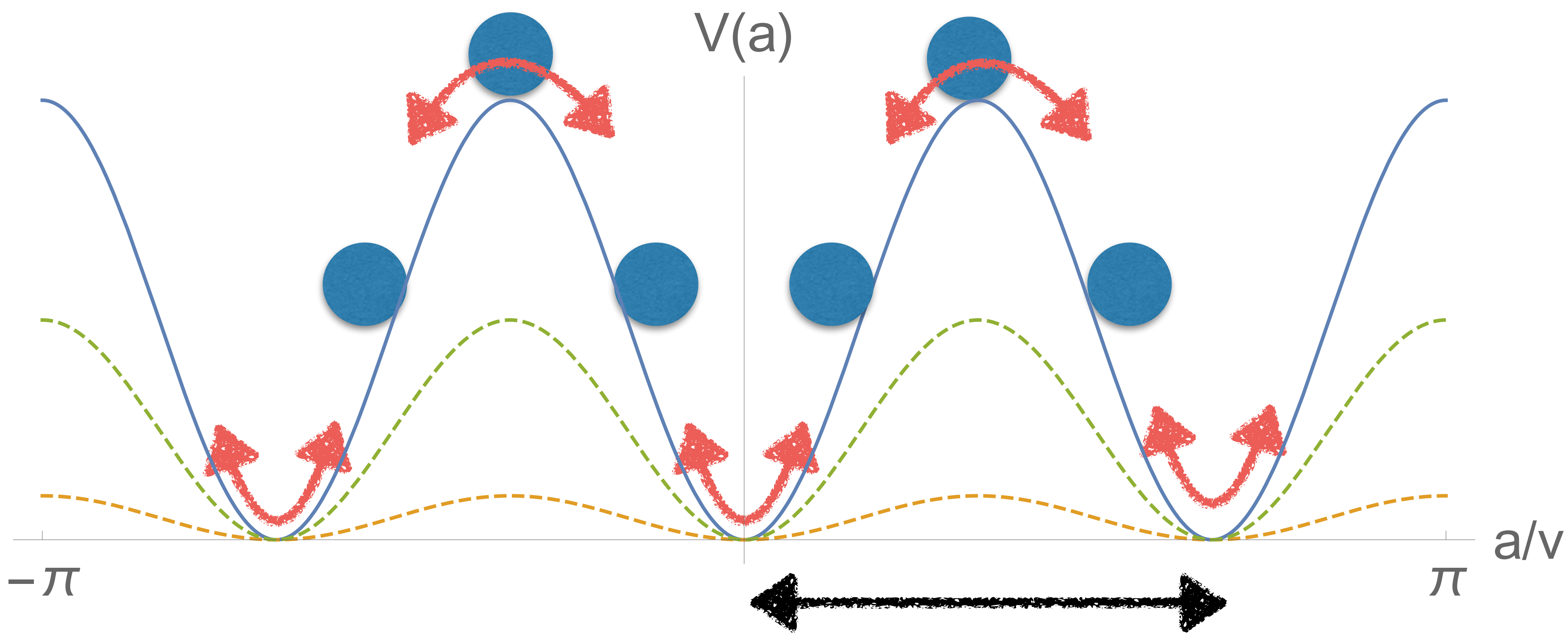
T_{RH} $T_{\not{P}\mathrm{Q}} = v$ $T_1 \sim \mathrm{GeV} : 3H(T_1) = m(T_1)$ T_2



Strings

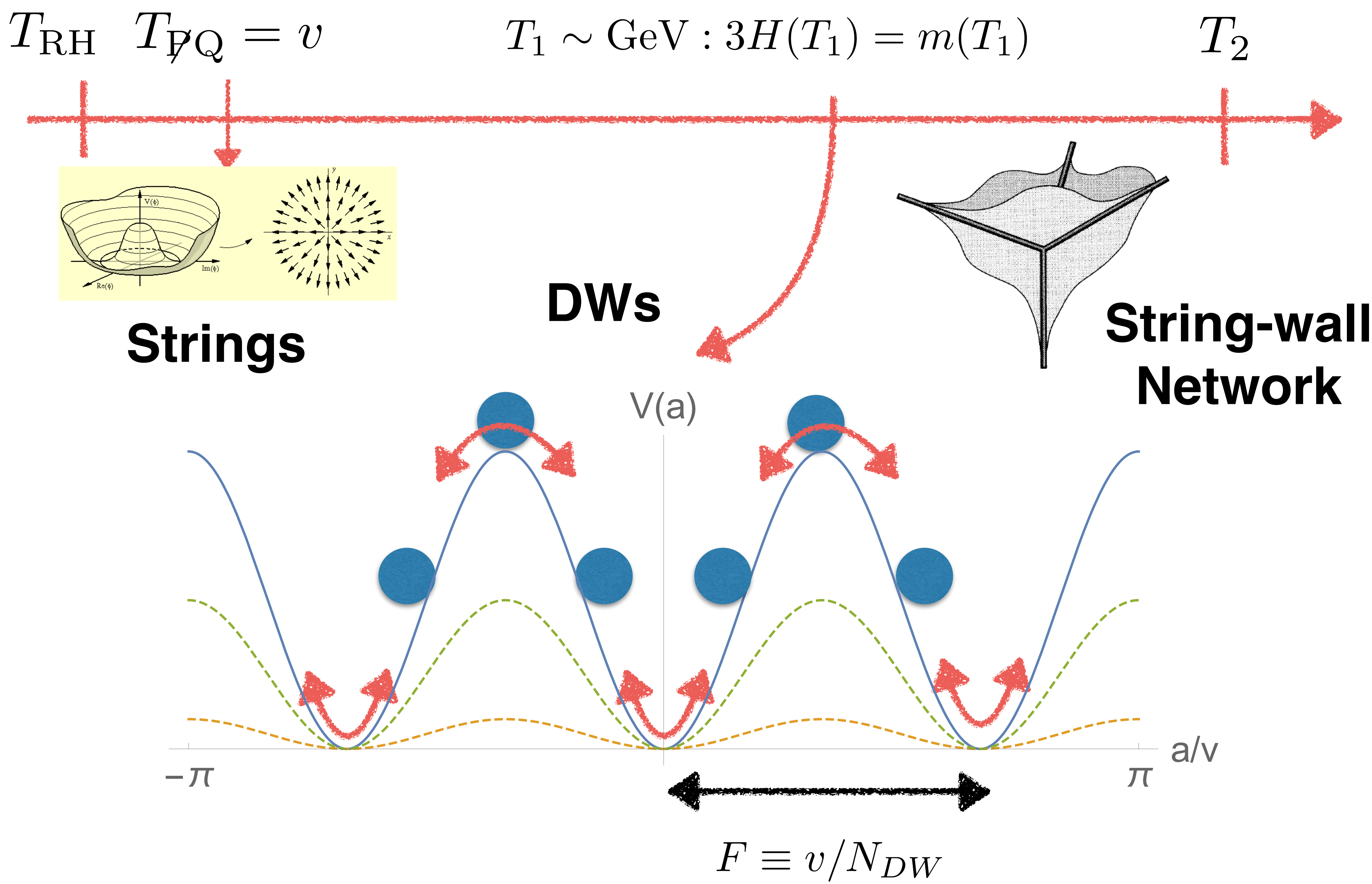
Network:
each string attached to N_{DW} walls

DWs



$F \equiv v/N_{DW}$

Defects of the QCD axion



QCD axion with $N_{DW} > 1$

- $N_{\rm DW} = 1$: network is **unstable**, rapidly decays.
- $N_{DW} > 1$: network is **stable, DW problem!**

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Way out:
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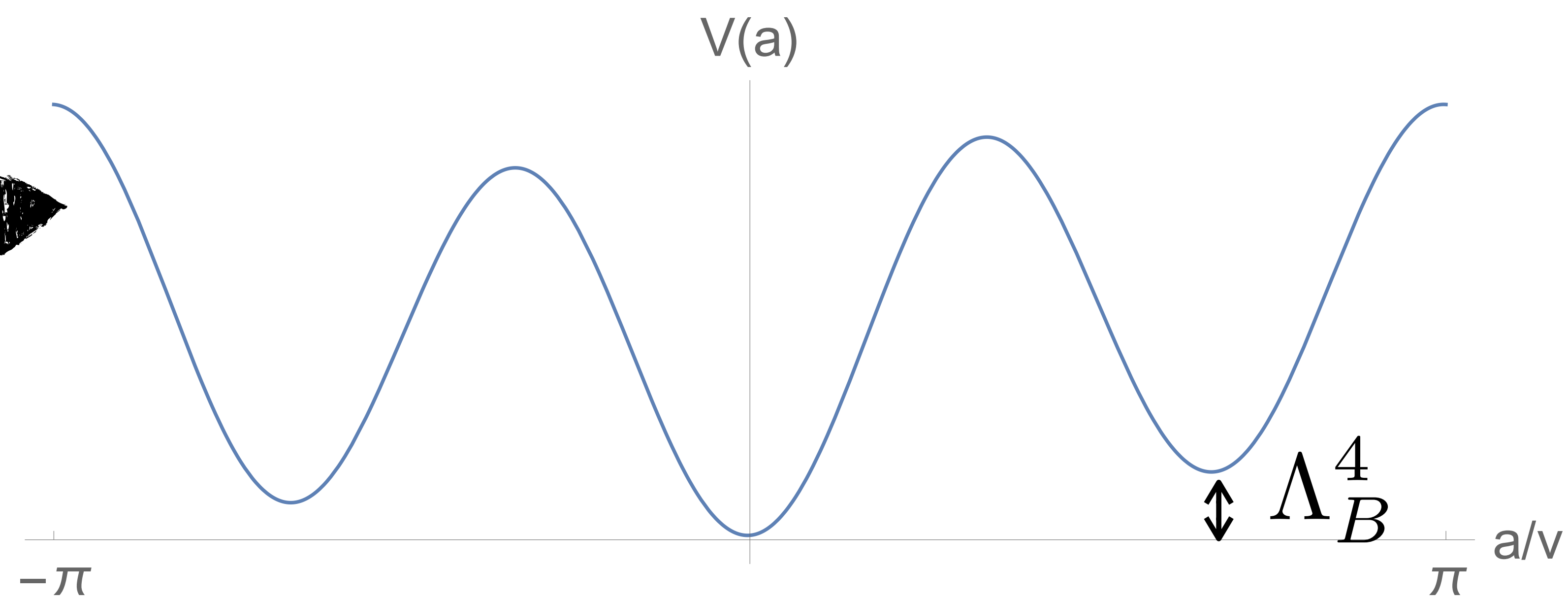

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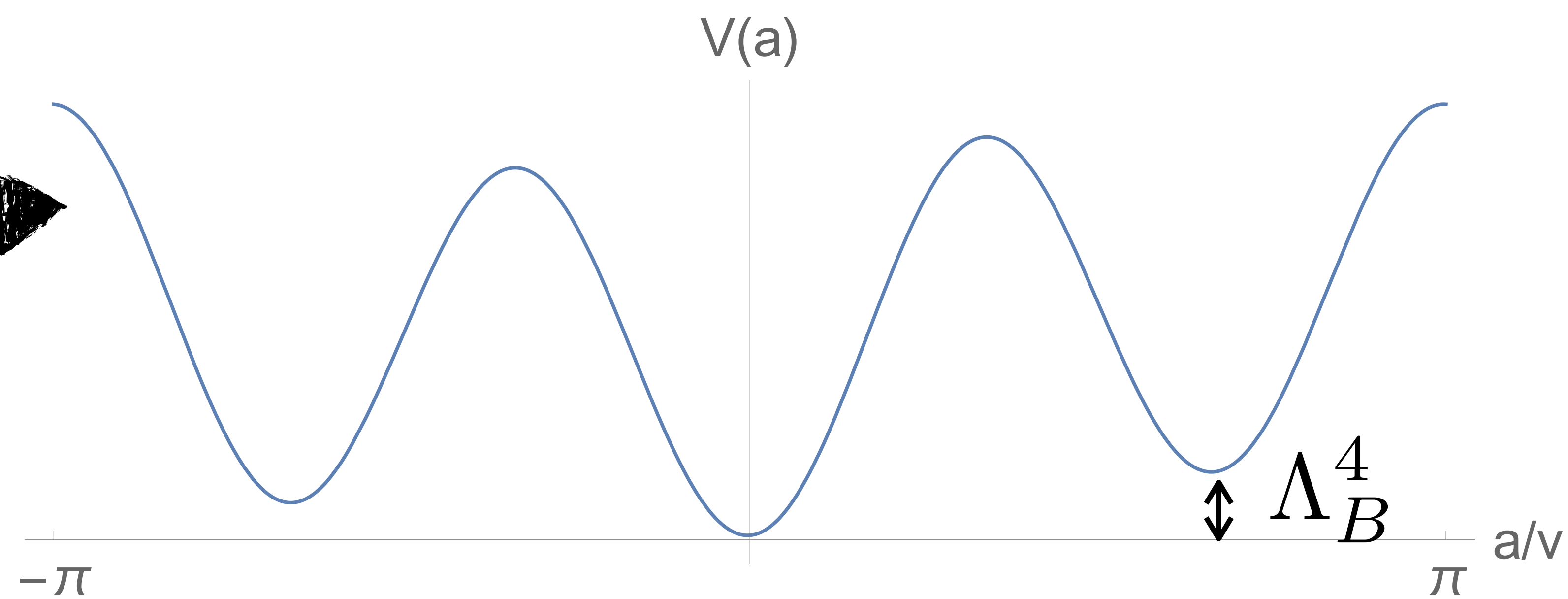

Way out:
add **bias** term

Network starts **decaying** when balance between tension and pressure is achieved!

$$T_2 \simeq \sqrt{\frac{M_p \Lambda_B^4}{\sigma}} < T_1$$

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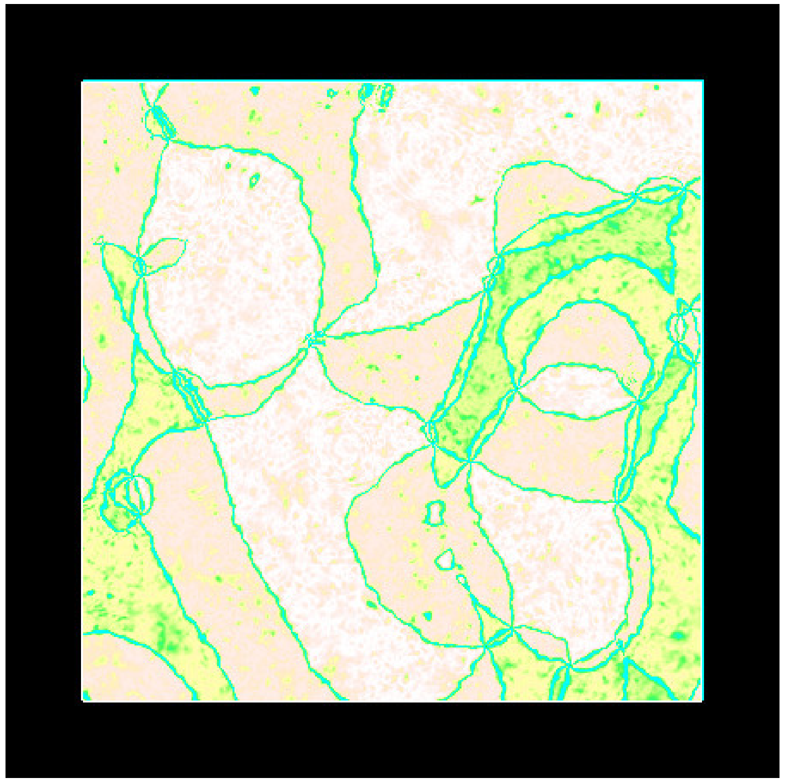

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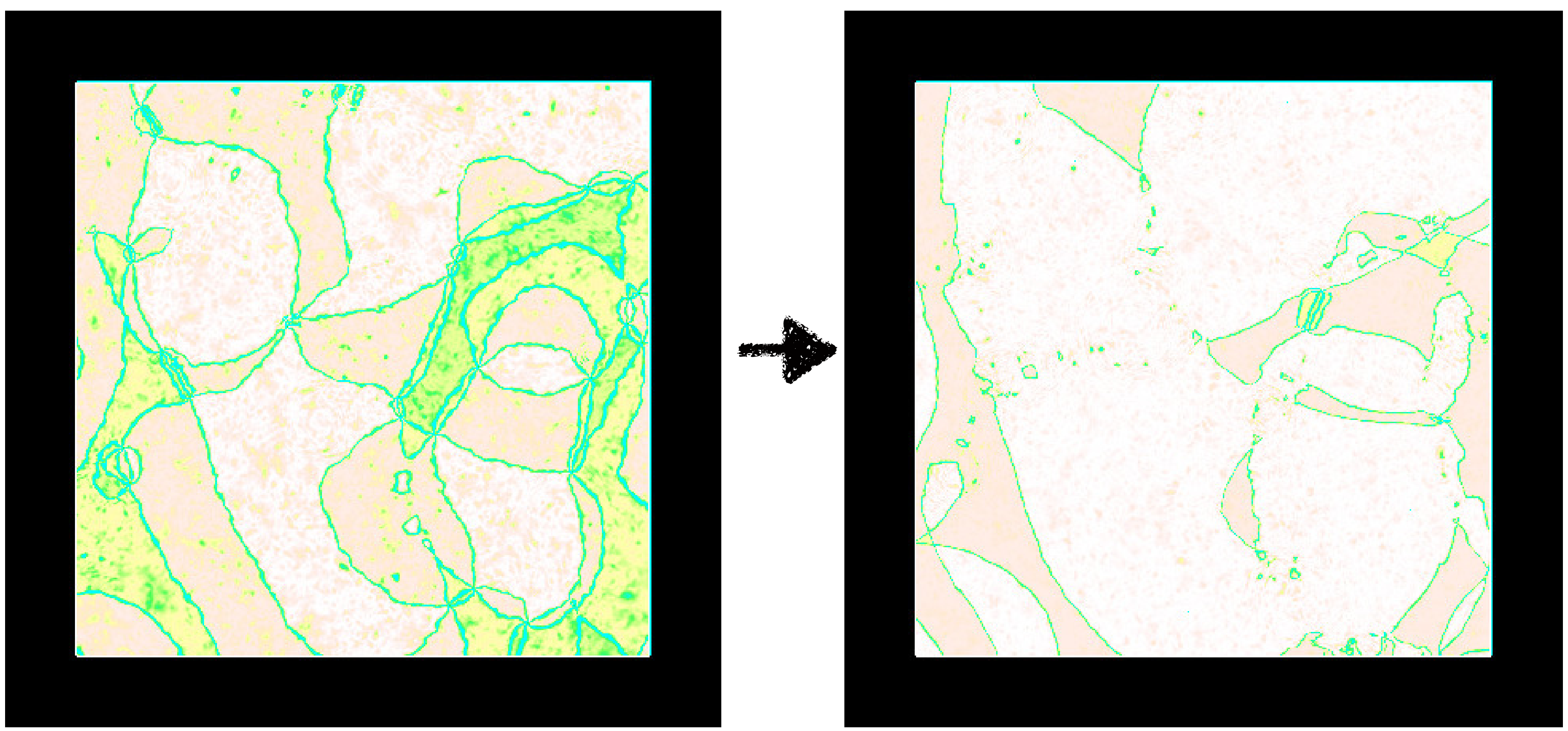

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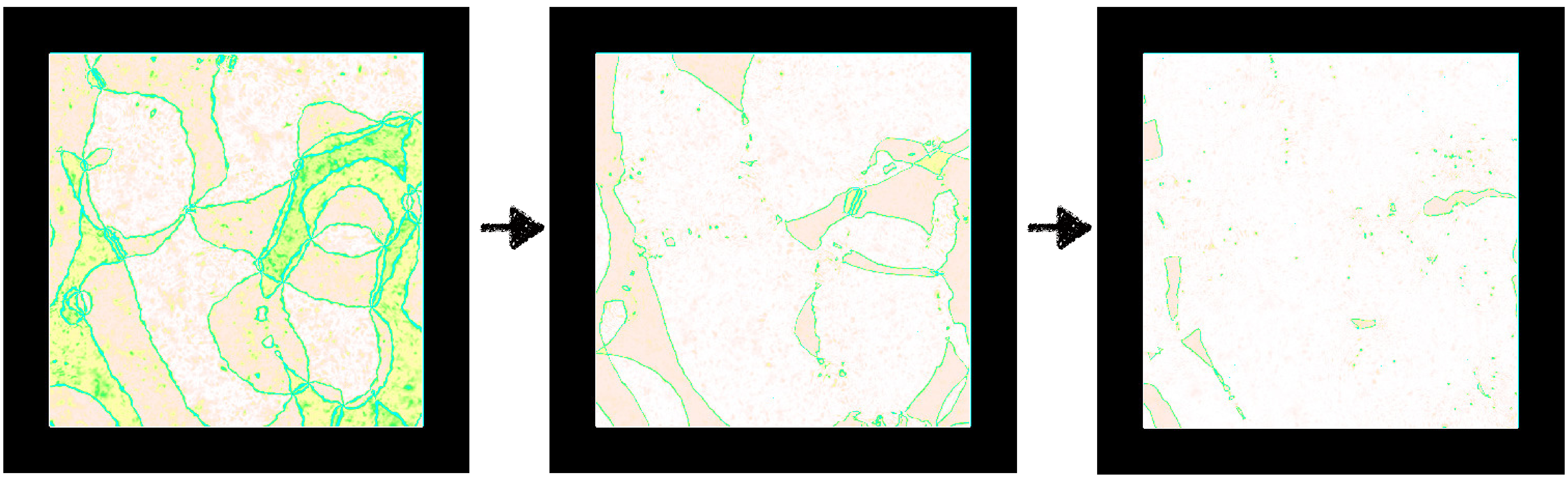

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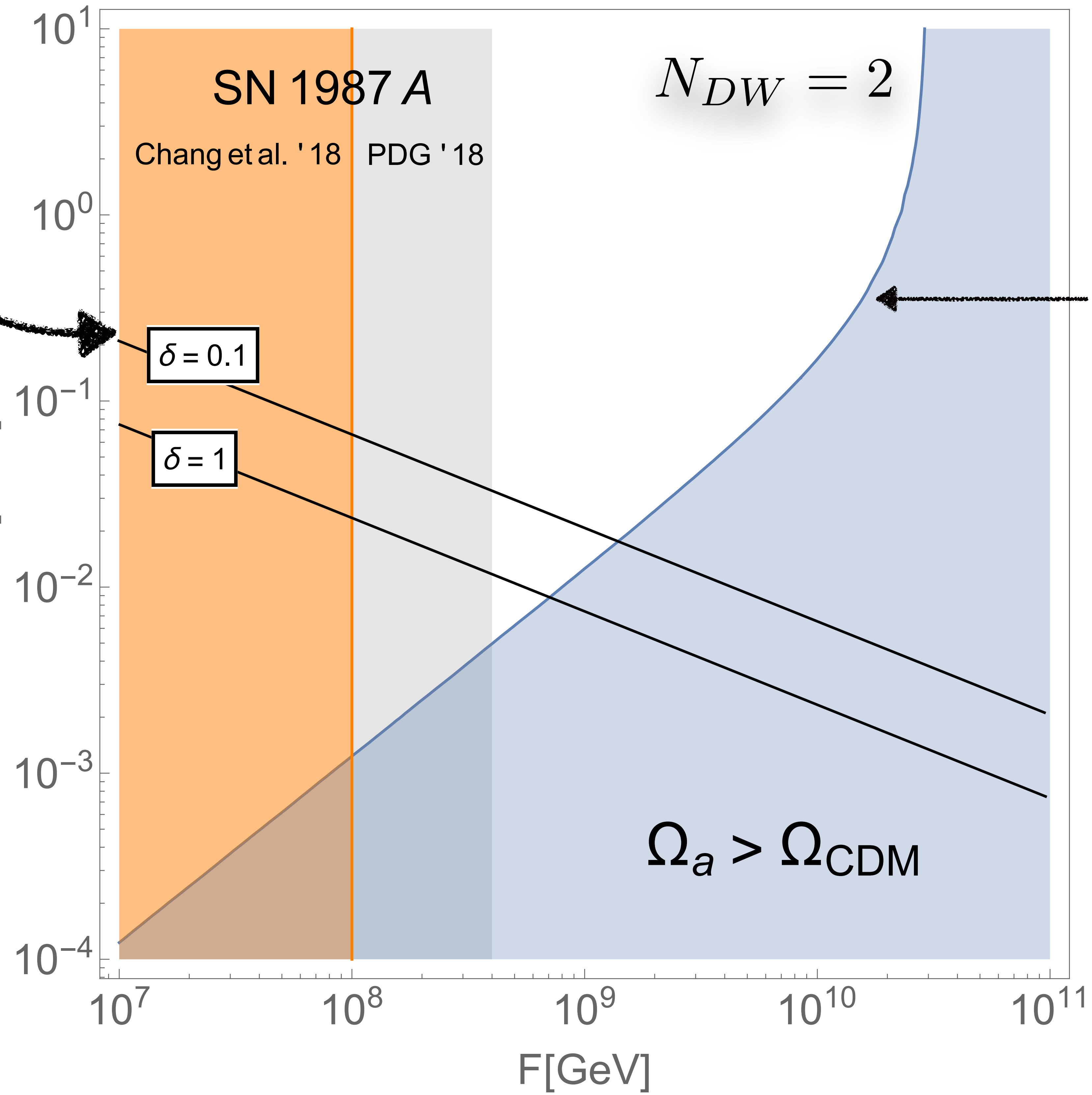
Axion DM with $N_{DW} > 1$

Largest bias offset to keep CP conserving minimum



$$\Omega_a = \Omega_{\rm mis} + \Omega_{\rm strings} + \Omega_{\rm NW}$$

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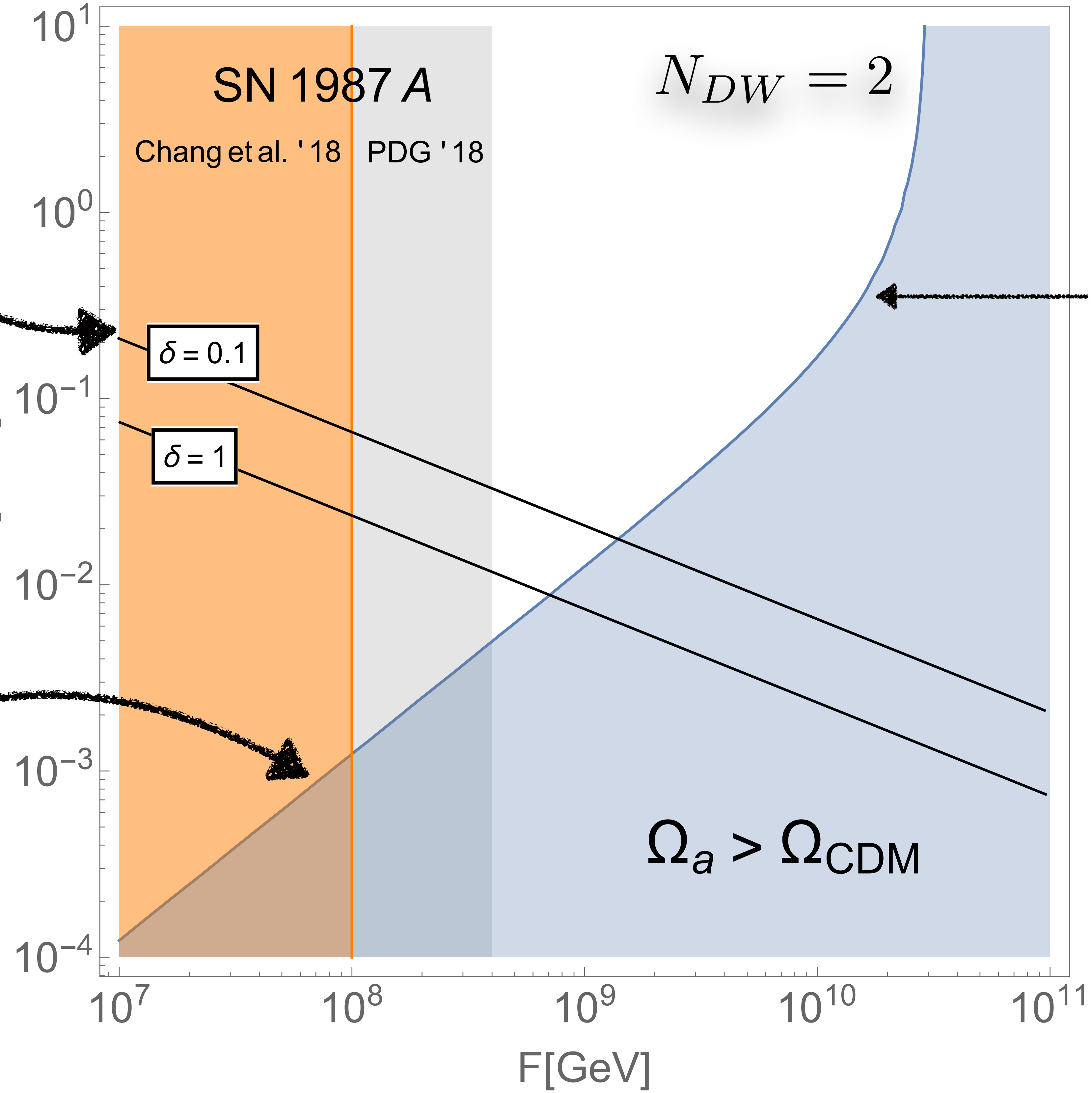
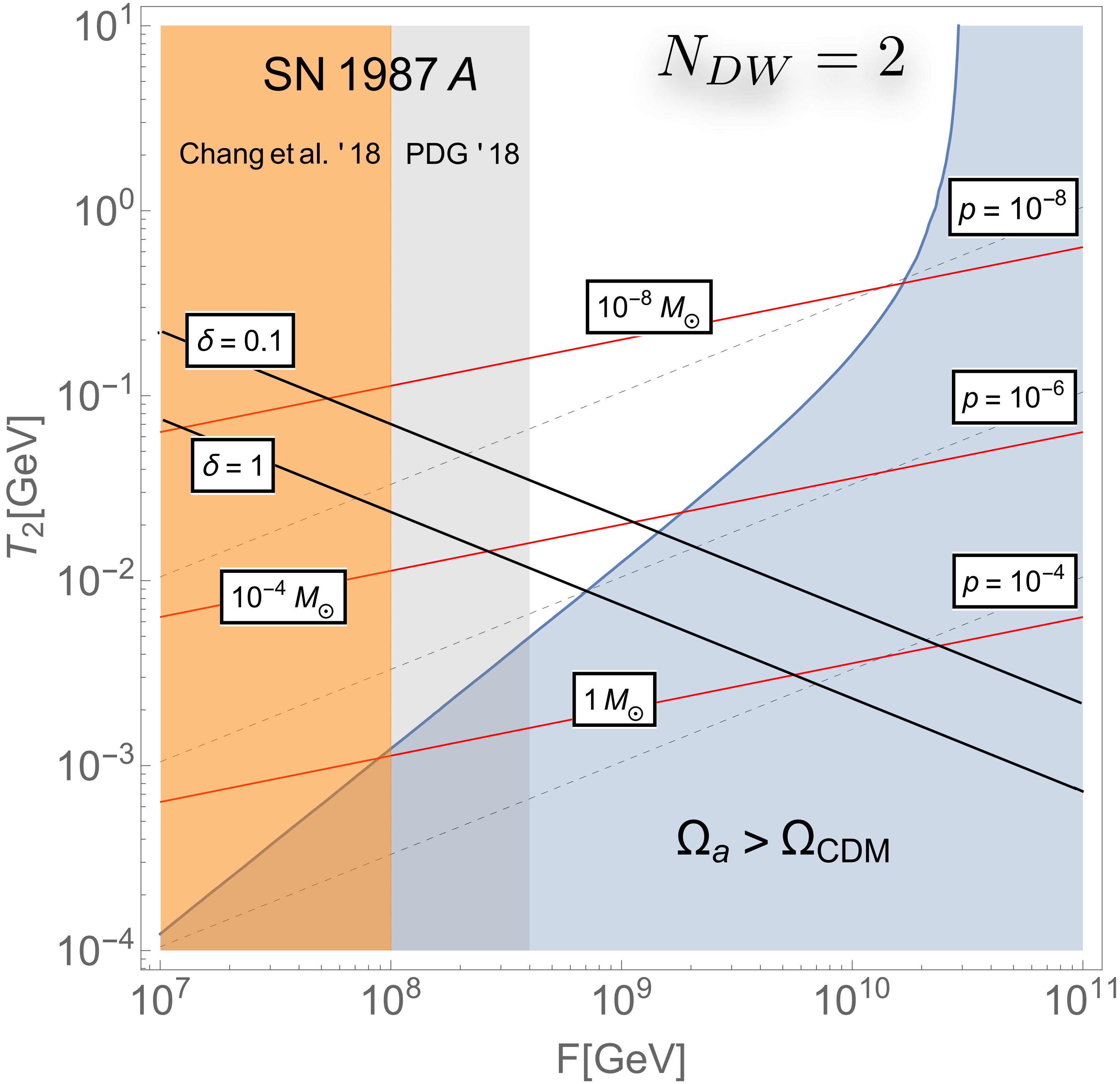


$$\Omega_a = \Omega_{\text{mis}} + \Omega_{\text{strings}} + \Omega_{\text{NW}}$$

Criterium to numerically fix T_2: only 10% of network survives **1412.0789**

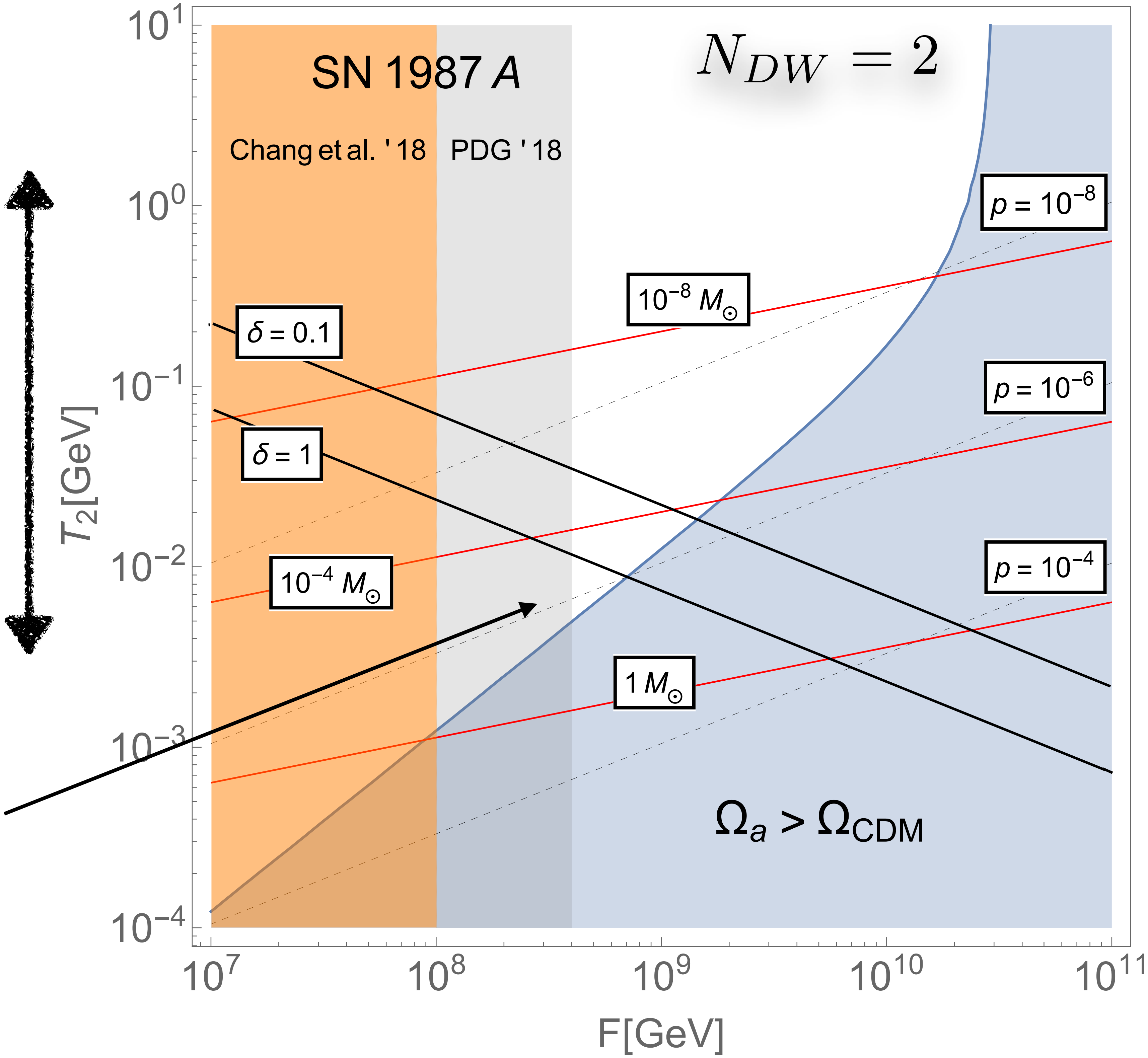
PBHs from closed walls in the network collapsing at T_2



PBHs from closed walls in the network collapsing at T_2

Advantage of $N_{DW} > 1$!

Still small p!



Late collapses

- **However**: still around 10% of the network leftover at T_2!

- For walls collapsing **after $\mathbf{T_2}$**, volume contribution dominates:

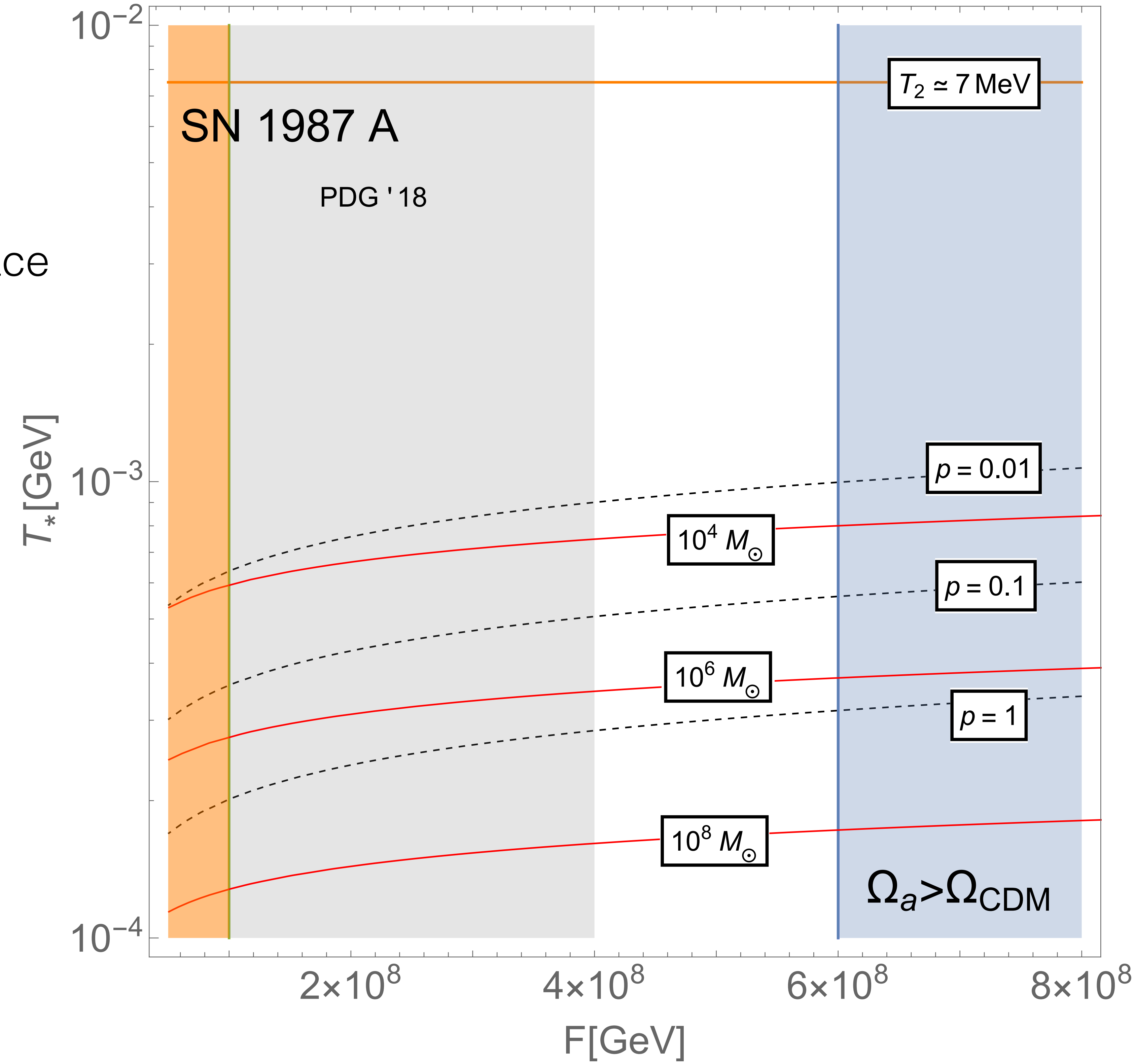
$$p \sim T_\star^{-4}, \;\; M_\star \sim T_\star^{-6}$$

- Need only one order of magnitude in T to reach

$$p \gtrsim 0.1$$

Collapse after T_2

Example in the lower corner of parameter space



Collapse after T_2

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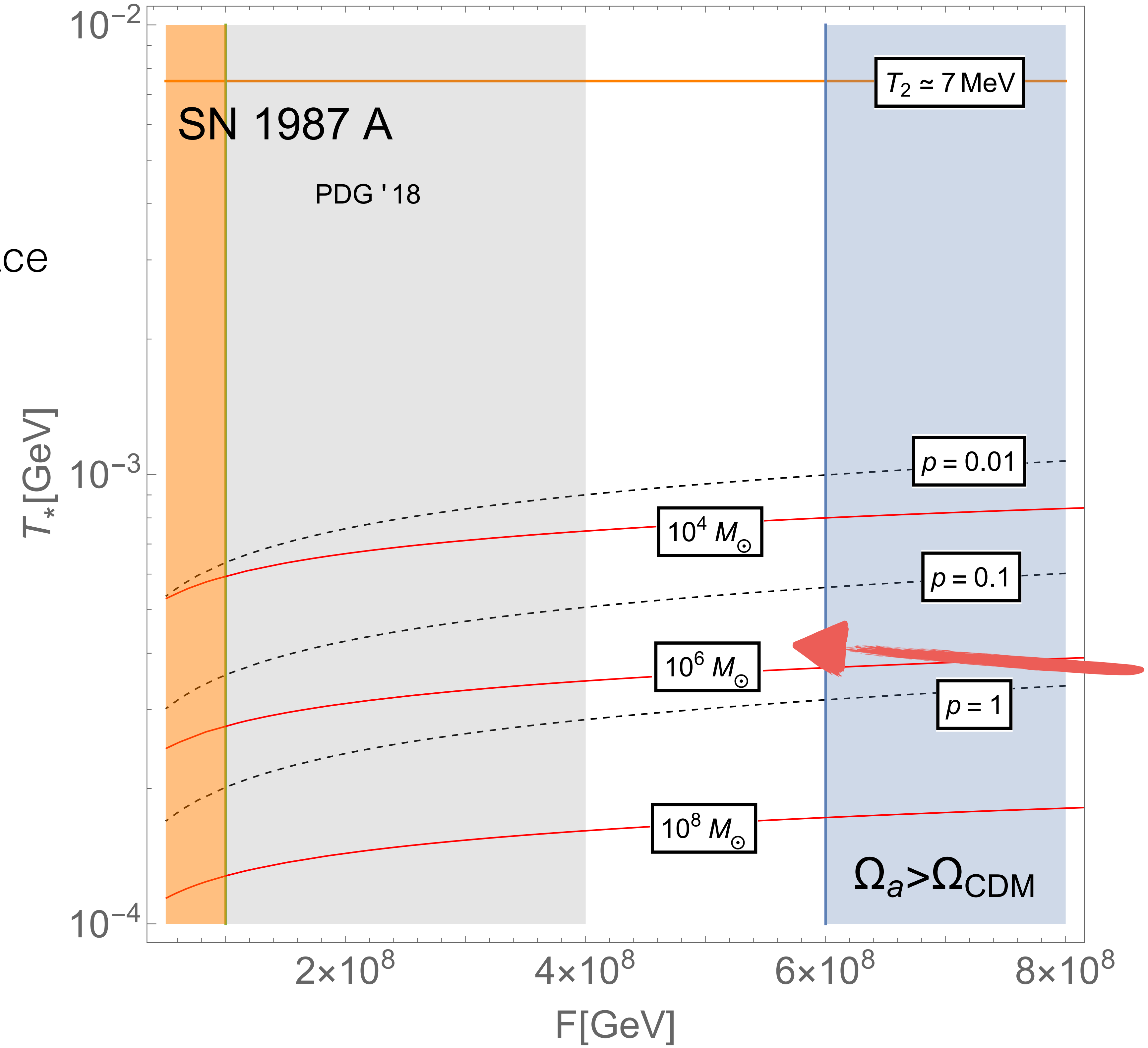


Likely to
form
Heavy
PBHs!

PBH fraction

- Reasonable expectation:

$$f \sim p^N \times \frac{\rho_{nw}(T_\star)}{\rho_{CDM}(T_\star)}$$

Collapse of single structure

Decay of the whole network

- N takes into account *asphericities*, *ang. momentum* etc. For large p, expect $N \sim O(1)$.

- After T_2 , network is dominated by bias term

$$\rho_{\rm nw} = P_{\rm nw} \Lambda_B^4$$

Surviving fraction of the network

PBH fraction

- **For detailed estimate**: need numerical simulations!
- For **simplicity,** assume

$$P_{nw} \sim \left(\frac{T_2}{T_\star} \right)^{-\alpha}$$

- Simulations of Kawasaki et al. ´14 suggest $\alpha \approx 7$.
- For N=2, f peaks at $\sim 10^{-6}$!

Conclusions

- **QCD axion** models with $N_{DW} > 1$ are characterised by **long-lived** string-domain walls network.
- Under reasonable expectations, $M \sim 10^4 - 10^7 M_\odot$ PBHs can be obtained from the collapse of closed structures in the **network**.
- **Small fraction**, $f \gtrsim 10^{-6}$. DM **dominantly** made of axion quanta.
- Preferred region of axion parameter space

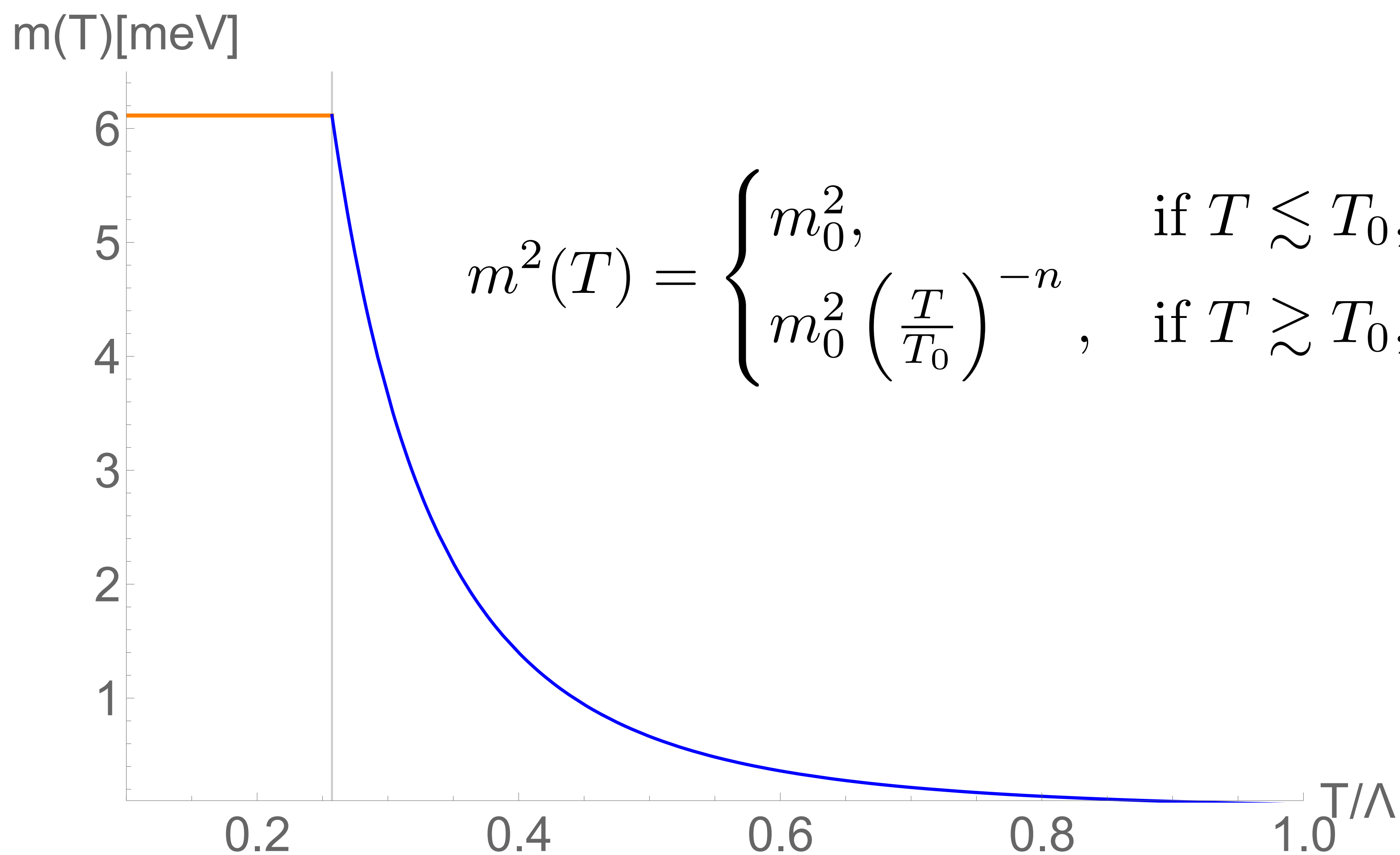
$$F \lesssim 10^9 \text{ GeV} \Rightarrow m \gtrsim \text{ meV}$$

To be explored at:
IAXO, TASTE, ARIADNE, ALPSII, …

Outlook: bias term from dark QCD? Details of collapse?

Backup

Axion mass



$$m^2(T) = \begin{cases} m_0^2, & \text{if } T \lesssim T_0, \\ m_0^2 \left(\frac{T}{T_0}\right)^{-n}, & \text{if } T \gtrsim T_0, \end{cases}$$

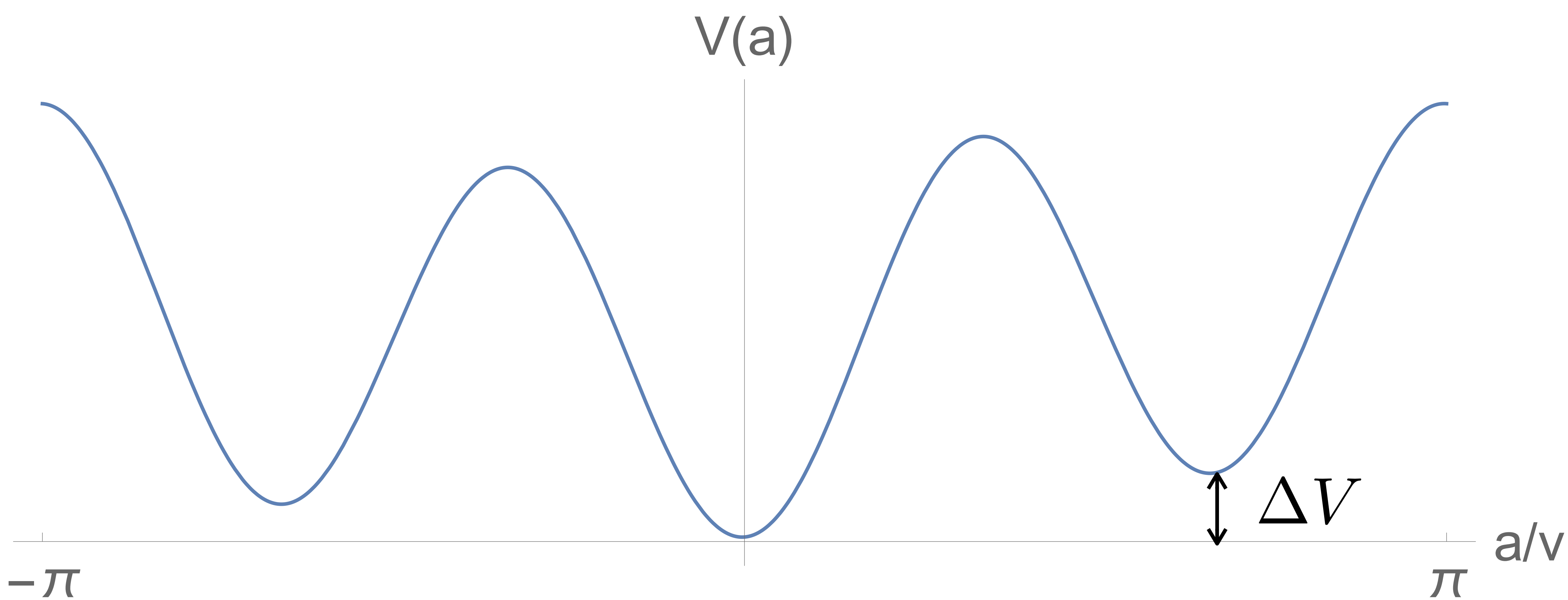
Parameters determined from Dilute Instanton Gas Approximation (High T, Wantz et al.´10) and Lattice (Borsanyi et al.´16)

$$n \approx 7, \; T_0 \approx 100 \text{ MeV}$$

see Bonati et al.´16 for deviations

Bias term

- $N_{DW} > 1$: $\rho_{nw} \sim a^{-2} \longrightarrow$ domain wall problem!
- Need to lift degeneracy of vacua



$\longrightarrow$ Add: $V_B = \Lambda_B^4 \left[1 - \cos\left(\frac{a}{v} + \delta\right)\right]$

Bias from dark QCD

- Consider dark QCD without light quarks confining below T_2 and coupled to the QCD axion.
- Induce temperature-dependent bias term.

$$\Delta V(T) \simeq m_B(T)^2 F^2$$

- Increases with decreasing temperature!
- Large p achieved faster! Possibly larger fraction of PBHs with smaller masses!

Axion relic abundance

$$\Omega_{\rm mis}h^2 \simeq B_n \sqrt{c_0}\, c_T^{-\frac{1}{4+n}} \left(\frac{F}{10^9\ {\rm GeV}}\right)^{\frac{6+n}{4+n}} \left(\frac{g_{\rm eff}(T_1)}{80}\right)^{-\frac{6+n}{2(4+n)}} \left(\frac{\Lambda_{QCD}}{400\ {\rm MeV}}\right)$$

$$\Omega_{\rm strings}h^2 \simeq C_n \left(\frac{F}{10^9\ {\rm GeV}}\right)^{\frac{6+n}{4+n}} \left(\frac{g_{\rm eff}(T_1)}{80}\right)^{-\frac{2+n}{2(4+n)}} \left(\frac{\Lambda_{QCD}}{400\ {\rm MeV}}\right)$$

$$\Omega_{\rm nw}h^2 \simeq 0.14 \times \left(\frac{F}{10^9\ {\rm GeV}}\right) \left(\frac{\Lambda_{QCD}}{400\ {\rm MeV}}\right)^2 \left(\frac{g_{\rm eff}(T_2)}{10.75}\right)^{-1/4} \left(\frac{10\ {\rm MeV}}{T_2}\right)$$