Primordial Black Holes from Axions?

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Cosmological Probes of BSM - Benasque May 10, 2018

work in collaboration with
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Outline

1 Motivation.

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2. Axionic string-wall networks.

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3 PBHs from the QCD Axion and from Axion-Like Particles (ALPs).

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3 PBHs from the QCD Axion and from Axion-Like Particles (ALPs).

4 Summary and conclusions.

Motivation

- Nature of DM remains mysterious. see tomorrow's talks.
- Some well-motivated *particle physics* candidates (many others on the market)
  1. **WIMPs**: motivated by the WIMP miracle and by SUSY solution to hierarchy problem. Currently under experimental pressure (no WIMP + no low scale SUSY).
  2. **Axions**: motivated by strong CP problem (QCD) and ubiquitous in String Theory. Only very small region of parameter space currently probed (ADMX), more to come!.
- Recent LIGO observations of $O(10)M_{\odot}$ BHs revive interest in traditionally astrophysical candidate: **Primordial Black Holes (PBHs)** see morning talks.
- Even if $\rho_{PBH}/\rho_{CDM} \ll 1$, PBHs can be seeds of cosmic structures [Carr, Silk '18]

- Conventional connection with particle physics: PBHs generated from **gravitational** collapse of inflationary overdensities.

- Gravitationally collapsing horizon-size overdensity would generate a PBH of mass

$$M_H \approx \frac{4}{3}\pi\frac{\rho}{H^3} = \frac{4}{3}\pi\frac{M_p^2}{H} \simeq \left(\frac{100\text{ MeV}}{T}\right)^2 M_\odot,$$

$\Rightarrow$ PBHs of given mass require large overdensities re-entering at some $T \rightarrow$ need to **complicate** inflationary picture.

- **Broad motivation of this talk**: Can PBHs be generated by dynamics which occurs directly at T_{QCD}, **not tied to inflation**?

$\rightarrow$ Coincidence: T_{QCD} also sets the axion DM abundance from the misalignment mechanism.

Spoiler

- **Basic idea of this talk**: generate PBHs from the collapse of axionic domain walls [see also Deng et al.'16, Vachaspati '17].
- **Collapse** driven by **tension** of the domain wall, **not** gravitational!
- Independent from physics of inflation.

$\rightarrow$ **Alternative** particle physics approach to PBHsDM.

- **Remark**: will mainly use parameters of the QCD axion, but same mechanism can occur for general Axion-Like-Particles (ALPs).

Part 1

Axionic String-Wall Networks

Phases and Defects of the (QCD) Axion

- **Focus**: PQ symmetry broken **after** inflation.

1 At $T_{P\!\!\!/Q} = \eta$, a complex scalar field Φ with potential

$$V(\Phi) = \frac{\lambda}{4}\left(|\Phi|^2 - \eta^2\right)^2,$$

acquires a VEV $\Phi \simeq \eta e^{ia/\eta}$ which spontaneously breaks $U(1)_{PQ}$.

→ **Strings** form at $T_{P\!\!\!/Q}$, around which $\Delta a = 2\pi\eta$.

- Scaling regime $\rho_{string} \simeq \mu_{string} H^2 \sim a(t)^{-4}$, where μ_{string} is the string tension.
- Strings radiate axions from $T_{P\!\!\!/Q}$ down to T_{QCD}.

Phases and Defects of the (QCD) Axion

→ Non-perturbative (QCD instantons) effects induce a potential for a

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

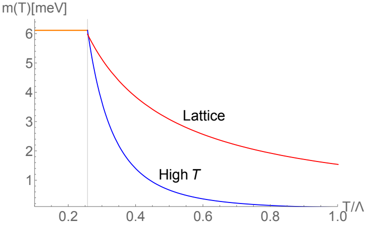
with periodicity $F = \eta/N_{DW}$.

→ $N_{DW} \equiv$ number of physically inequivalent vacua in the domain $[-\eta, \eta]$.

→ $N_{DW} \equiv$ color anomaly, e.g.

- KSVZ: $N_{DW} = 1$ in simplest case, $N_{DW} > 1$ with more generations of heavy fermions.
- DSFZ: $N_{DW} = 6$ in simplest case other values possible [see e.g. Monday's talk by Ziegler].

Temperature Dependence of the Axion Mass



$$T \lesssim 10^2\text{MeV} \;\; m^2(T) = c_T \frac{\Lambda_{QCD}^4}{F^2}\left(\frac{T}{\Lambda_{QCD}}\right)^{-n}$$

$$T \gtrsim 10^2\text{MeV} \;\; m^2(T) = c_0 \frac{\Lambda_{QCD}^4}{F^2}$$

Theoretical uncertainties on parameters

- High T DIGA-based calculation: $n \approx 7, c_T \approx 10^{-7}, c_0 \approx 10^{-3}$ [Wantz, Shellard '10] .
- Preliminary lattice calculations hint at $n \approx 2, c_T \approx 10^{-4}$ [see Grilli di Cortona et al. '15 and refs therein].

Phases and Defects of the (QCD) Axion

2 The axion is frozen because of Hubble friction until $3H(T_1) \simeq m(T_1)$.

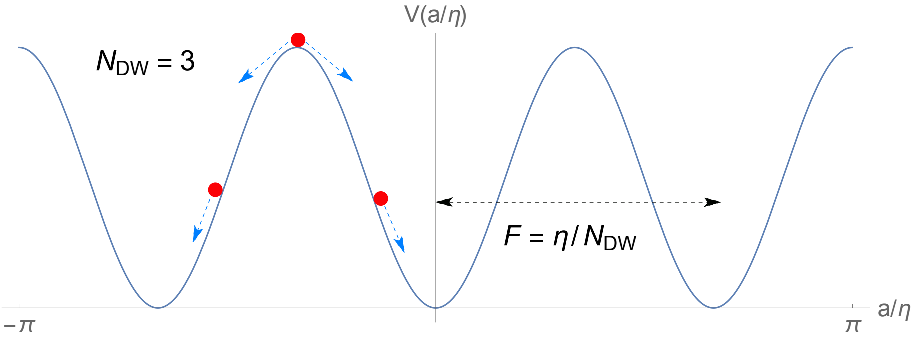
- At $T_1 \approx 1-6$ GeV the axion oscillates and behaves as CDM$\rightarrow$ *Misalignment mechanism*.

$\Rightarrow$ Oscillation occur around any of the N_{DW} vacua $\Rightarrow$ Domain walls form!

- Each string gets attached to N_{DW} domain walls$\Rightarrow$ String-Wall Network is formed

  $\mathbf{N_{DW} = 1}$: Strings cut holes in DWs $\Rightarrow$ Network disappears rapidly after T_1.

  $\mathbf{N_{DW} > 1}$: DWs are pulling each string from different directions $\Rightarrow$ Network is stable.

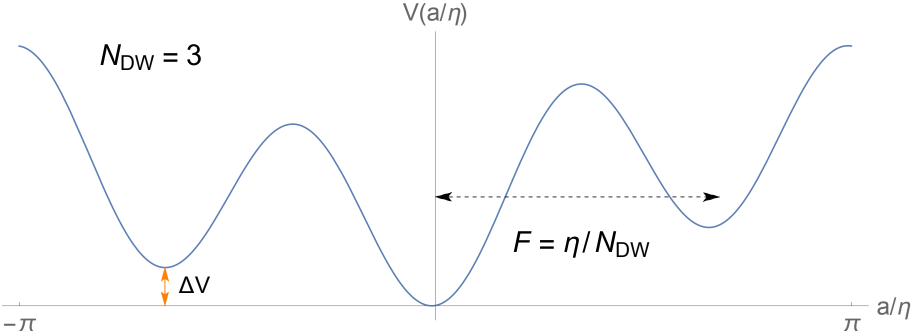


- Stable network enters scaling regime: $\rho_{DW} \sim \sigma H \sim a^{-2}$

$\Rightarrow$ Network overcloses the Universe!

- Here $\sigma \simeq 8mF^2$ is the DW tension.

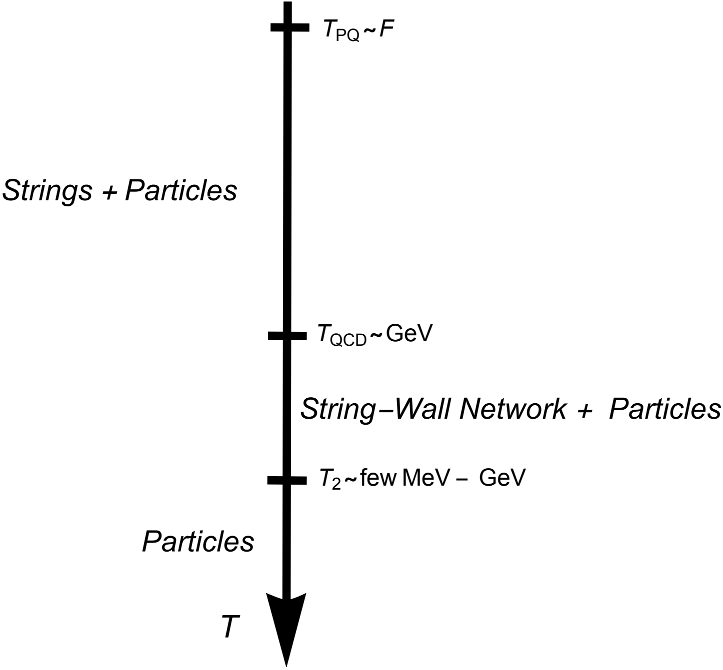
→ Need to lift degeneracy of the vacua and induce network annihilation

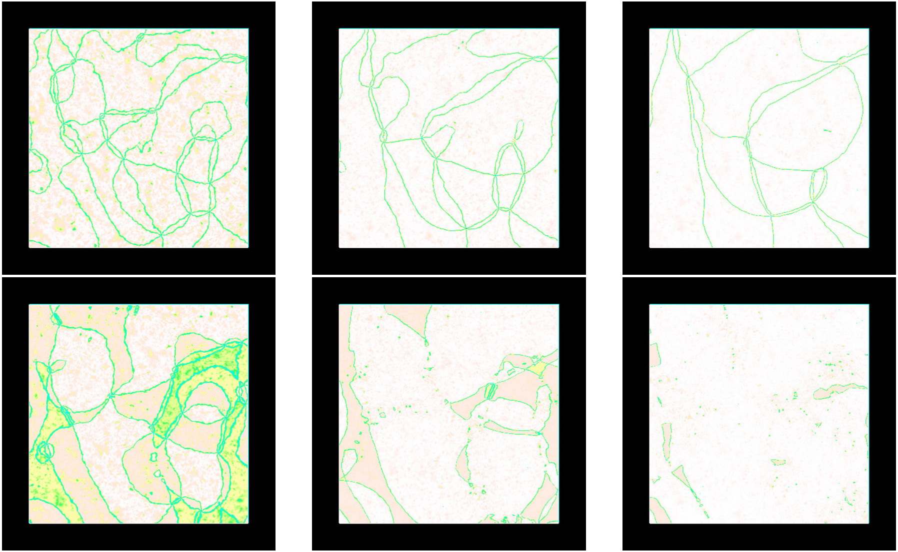


- Can be achieved by adding

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

- Network annihilates at $T_2 \sim \sqrt{\frac{M_p \sigma}{\Lambda_B^4}}$.

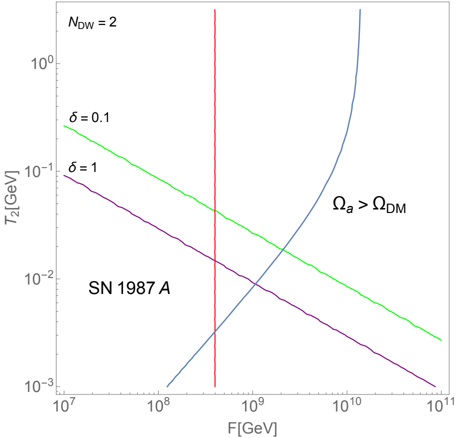

$T_{PQ} \sim F$
Strings + Particles
$T_{QCD} \sim$ GeV
String–Wall Network + Particles
$T_2 \sim$ few MeV – GeV
Particles
T



Figures taken from [Kawasaki et al. '14]

1st row: $\Delta V = 0$, 2nd row: $\Delta V \approx 10^{-3} V_{QCD}$

Axion Dark Matter with $N_{DW} > 1$



Numerical parameters taken from Kawasaki et al. '14 (pure scaling).

Uncertainties can enlarge untuned region of parameter space.

Take Home Messages from Part 1

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Question for Part 2

Can (a fraction of) $\Omega_{a,DW}$ be made of PBHs?

Part 2

Primordial Black Holes from String-Wall Networks

Mechanism

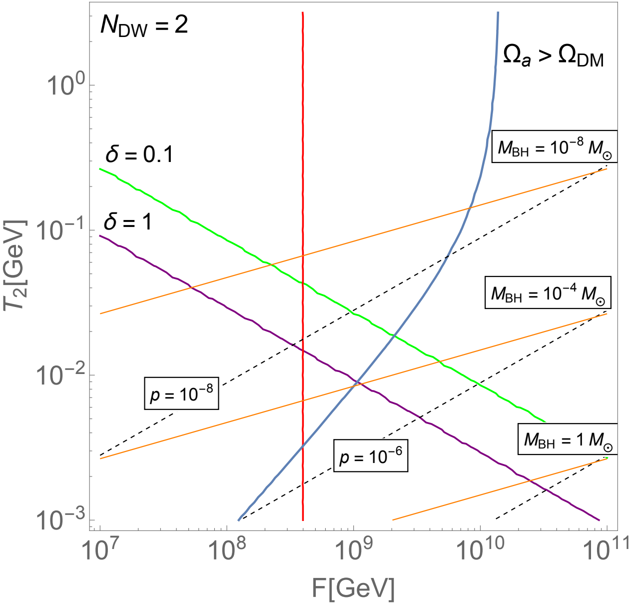
- Consider a closed domain wall entering the horizon at $T_\star$ with radius $R_0 \sim H^{-1}(T_\star)$.
- It starts collapsing immediately under the action of its own tension.
- First consider spherical DW without loss of energy $\rightarrow$ BH would form if DW allowed to shrink to R_s.
- Mass of the BH

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

- Figure of merit

$$p = \frac{R_s}{H^{-1}(T)} = \frac{\sigma H(T_2)}{M_p^2 H(T_2)^2} = \frac{3\rho_{DW}}{\rho_{tot}}$$

$\rightarrow$ Larger p and M_{BH} if DWs collapse at the end of long NA epoch!



→ Figure of merit is small for the QCD axion!

- Realistic setup: no reason for DWs to be spherical see however [Deng et al.'16, Garriga's talk] for nucleation of spherical DWs.

- Expect asphericities of size $\sim H^{-1}(T)$. First assume that they remain constant during collapse (see [Widrow '89] for thin wall analysis).

$\rightarrow$ The smaller p, the smaller the probability of producing PBHs!

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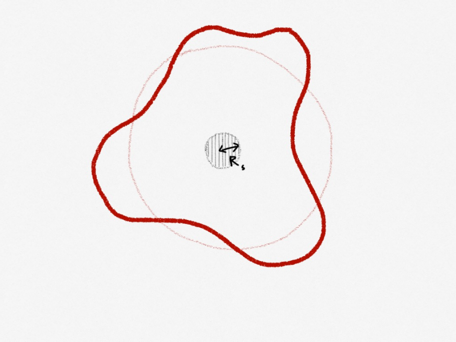

artistic rendition by P. Baratella

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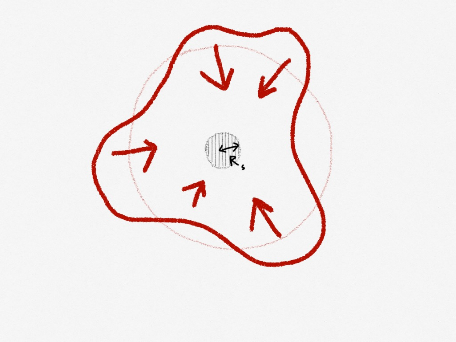

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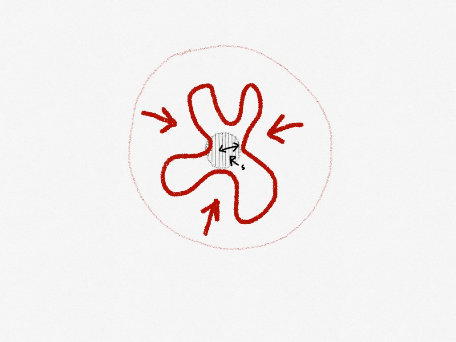

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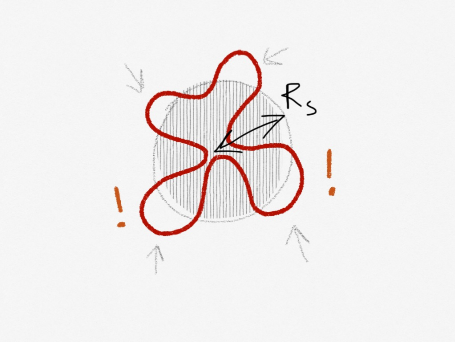

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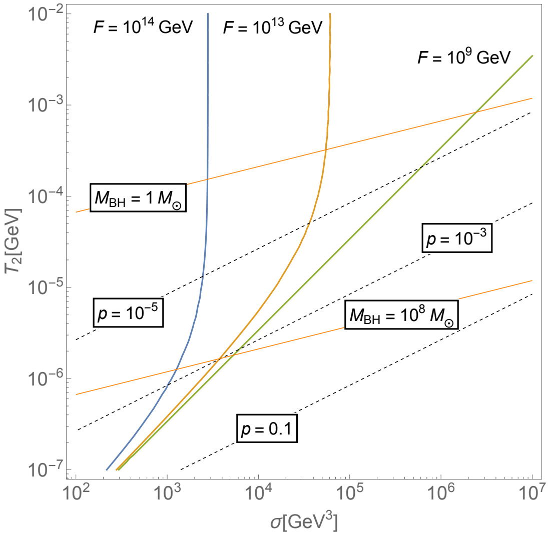
$\rightarrow$ The smaller p, the smaller the probability of producing PBHs!

But

1. Are asphericities reduced during the collapse?
2. What about generic ALP?
3. Also, what about avoiding SN bounds? see e.g. Monday's talk by Ziegler

Option 2: the ALP case (assuming same T dependence as QCD, $N_{DW} = 2$)



$\rightarrow$ R_s/H^{-1} larger by 4 orders of magnitude!

$\rightarrow$ Much heavier PBHs (up to upper bound)!

Option 1: Look at Physics of DW Collapse

- Thin Wall (Nambu-Goto) analysis shows that low l asphericities remain approximately constant during collapse [Widrow '89]

→ However, axionic DWs are in fact radiating axion quanta as they shrink

$$\mathcal{L}_{DW} = -\sigma \int_{DW} \sqrt{g} + e \int_{DW} A_3$$

Can think of as some friction on the DW motion.

→ **Idea**: can this smoothen the shape of the DW?

→ Similar in a sense to interaction of DW with thermal plasma, where exponential suppression of asphericities is observed [see Garriga et al '92 for strings].

→ Currently trying to understand analytically (Thin Wall+Friction) and numerically (Thick Wall) reduction of asphericities!

1. DW starts radiating at $R_\star \sim (R_0 m)^{2/3} m^{-1}$ [Widrow '89].
2. DW collapses until $R_{min} \sim (R_0 m)^{-2/3} m^{-1}$, then bounces [Vachaspati'17].

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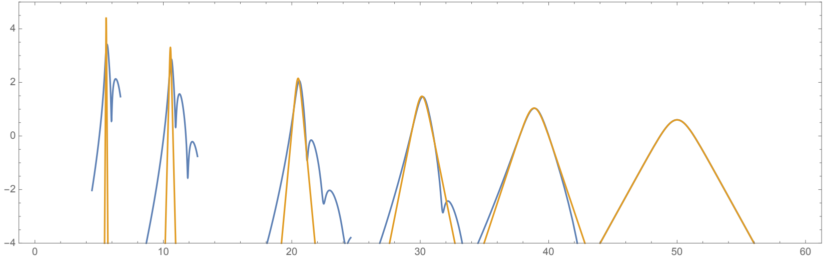

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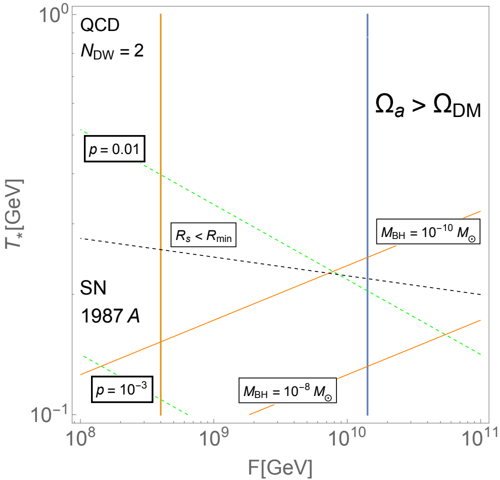
→ Best Case Scenario: asphericities are very suppressed by axion radiation from $R_\star$ to R_s.

- Figure of merit then given by $p = R_\star / H^{-1} \simeq (R_0 m)^{-1/3} m^{-1} \sim T^{2/3}$.

⇒ p larger for DWs which collapse **earlier** in the NA epoch!

→ However, cannot be too early, otherwise $R_s < R_{min}$ and BH cannot form.

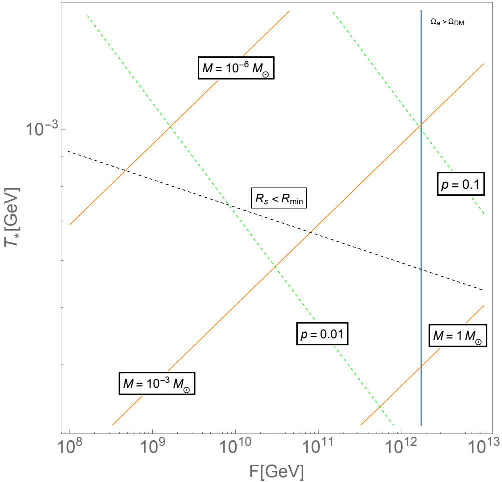


- Here $T_\star$ = T at which given DW in the network starts to collapse.

$\rightarrow$ Figure of merit improves by 5 orders of magnitude!

- Region above dashed black line is disfavored $\rightarrow N_{DW} = 1$ problematic for PBHs.

The ALP case with friction, $N_{DW} = 2$



Very interesting values of p and M_{BH}!

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4. Naive figure of merit for QCD is small, BH mass for ALP is large!
5. Under investigation: suppression of **asphericities** via radiation of axions.
6. If so, then both QCD axion and ALP are very interesting light PBHs generators!
7. Final PBH **fraction**? Associated cosmo signatures (**GWs**, . . .)?

Thanks for your attention!