

The background of the slide is a visualization of gravitational waves. It features a grid of blue lines that warp and ripple in concentric, circular patterns, representing the curvature of spacetime. Two dark, circular objects are visible in the center, likely representing black holes or neutron stars that have just merged, creating the source of the gravitational waves.

# Gravitational wave signals of early universe axion dynamics

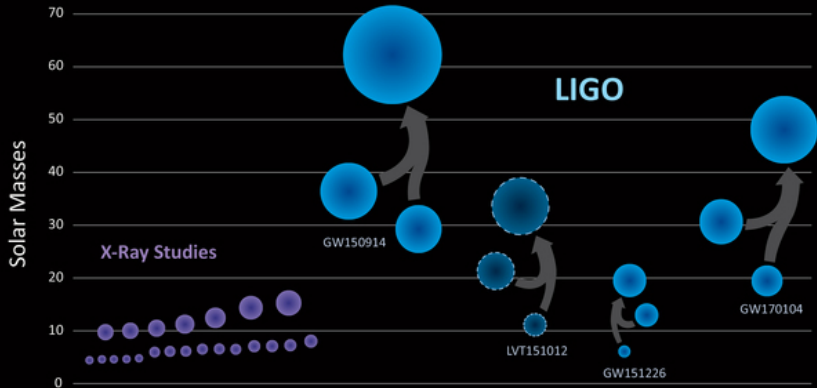
Francesc Ferrer, Washington University in St. Louis

✉ [ferrer@wustl.edu](mailto:ferrer@wustl.edu)

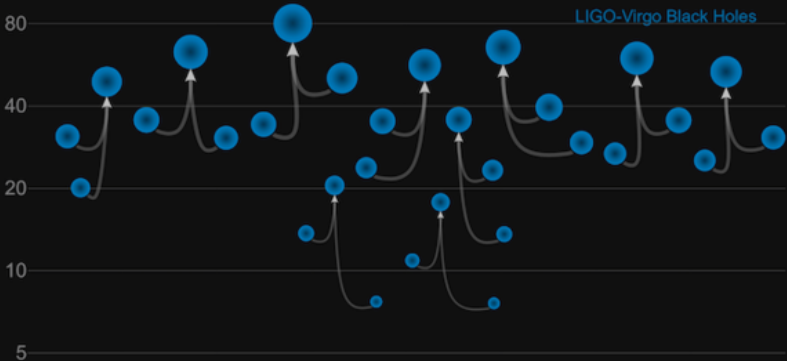
HKUST - IAS. Hong Kong, January 9, 2020.

# OVERVIEW AND MOTIVATION

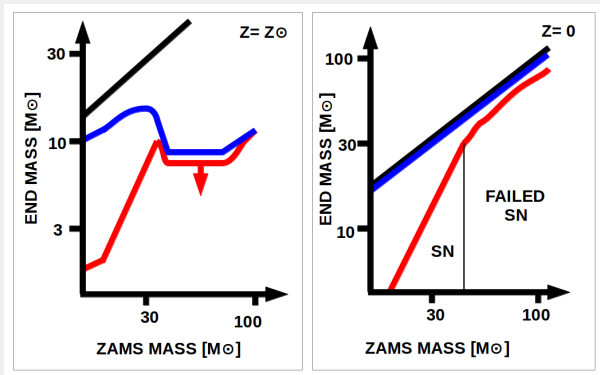
# Black Holes of Known Mass



Solar Mass



# UNEXPECTED/SURPRISING?

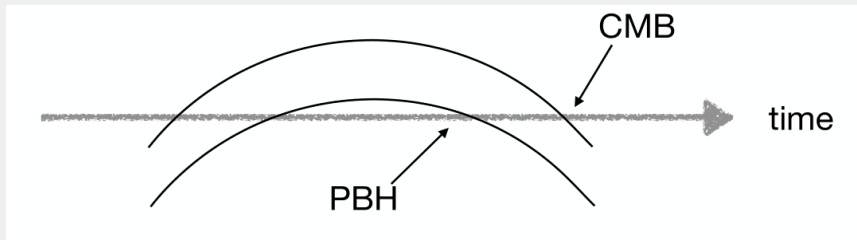


- Most astrophysical models predict  $M \gtrsim 20 M_{\odot}$ . But, larger BHs can result from metal-free stars.

Mapelli, 1809.09130

- The LIGO/Virgo horizon is  $z \sim 0.1 - 0.2$ , but third-generation ground-based GW detectors (e.g. Einstein Telescope) will be able to observe mergers up to  $z \sim 10$ .

# COULD THEY BE PRIMORDIAL?

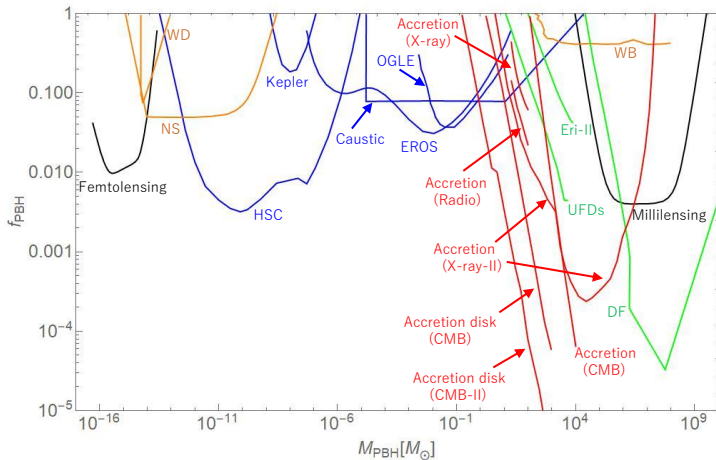


Rare Hubble scale perturbations can collapse into BHs:

$$\beta \approx \text{erfc} \left( \frac{\delta_c}{\sqrt{2}\sigma} \right)$$

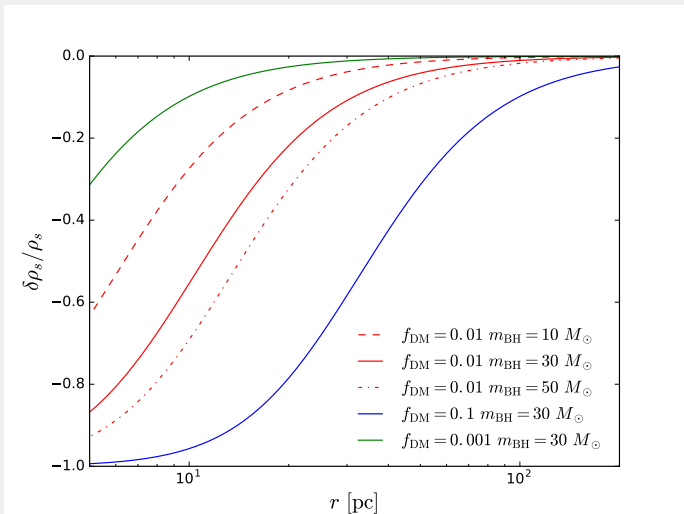
B.J. Carr & S.W. Hawking, MNRAS 1974; S. Bird et al, 1603.00464; S. Clesse & J. García-Bellido, 1603.05234; M. Sasaki et al. 1603.08338

# CONSTRAINTS



Sasaki *et al.* CQG 35 (2018) 063001

# PBHs ARE NOT EXACTLY CDM



T.D. Brandt, ApJ 2016; Koushiappas & Loeb, 1704.01668

## ANOTHER (MORE MASSIVE) PUZZLE



SMBHs reaching  $\gtrsim 10^{10} M_{\odot}$  are present in the centers of most massive galaxies, even at large redshifts.

## 1 Overview and motivation

## 2 Could LIGO detect axions?

- PBHs from QCD axion dynamics

FF, E. Massó, G. Panico, O. Pujolàs & F. Rompineve, 1807.01707, PRL 2019

- GWs from a phase transition at the PQ scale

B. Dev, FF, Y. Zhang & Y. Zhang, 1905.00891, JCAP 2019

## 3 Conclusions

# COULD LIGO DETECT AXIONS?

## 1 Overview and motivation

## 2 Could LIGO detect axions?

### ■ PBHs from QCD axion dynamics

FF, E. Massó, G. Panico, O. Pujolàs & F. Rompineve, 1807.01707, PRL 2019

### ■ GWs from a phase transition at the PQ scale

B. Dev, FF, Y. Zhang & Y. Zhang, 1905.00891, JCAP 2019

## 3 Conclusions

# ALTERNATIVE MECHANISMS TO INFLATION?

Phase transitions in the early universe provide a potential avenue: Several violent phenomena naturally occur that can assist in generating large overdensities that gravitationally collapse into BHs: bubble collisions, topological defects, . . .

- We will consider axionic string-wall networks.
- PQ symmetry is broken after inflation: the axion takes different values in different regions and the network is formed when the axion gets its mass, around the QCD phase transition.

F.F., E. Massó, G. Panico, O. Pujolàs & F. Rompineve, 1807.01707, PRL 2019

Eventually, the network has to decay. Otherwise, the energy density would be quickly dominated by domain walls.

The collapse of closed domain walls, which belong to the hybrid string-wall network can lead to the formation of PBHs.

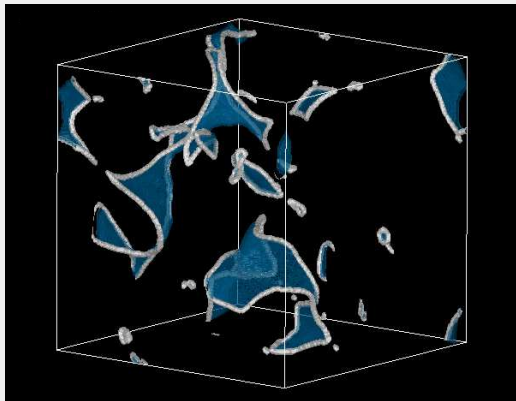
T. Vachaspati, 1706.03868

It is crucial that the annihilation of the network proceeds slowly.

- This mechanism does not rely on (nor complicate) the physics of inflation.
- GW astronomy can potentially probe the physics of axions.

$$N_{\text{DW}} = 1$$

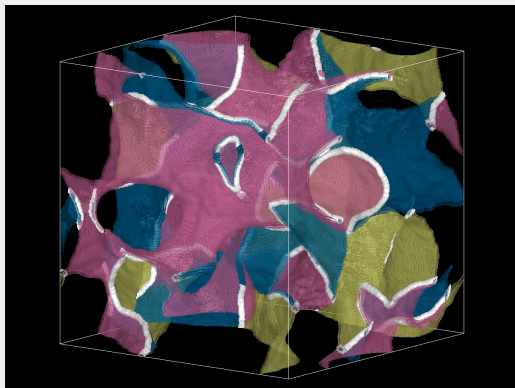
Only one domain wall is attached to each string. Such topological configurations quickly annihilate leaving behind a population of barely relativistic axions.



T. Hiramatsu, *et al.*, PRD 85, 105020 (2012)

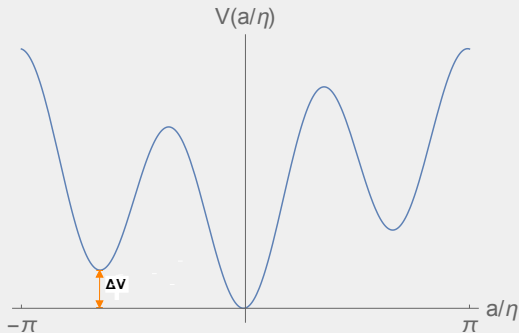
$$N_{\text{DW}} > 1$$

There are  $N_{\text{DW}}$  domain walls attached to every string, each one pulling in a different direction. The network can actually be stable, and dominate the universe.



# DW PROBLEM?

Lift the degeneracy of axionic vacua by introducing a bias term (dark QCD?). The energy difference between the different minima acts as a pressure force on the corresponding domain walls.



Once the Hubble length becomes comparable to the closed wall size  $R_*$ , the DW rapidly shrinks because of its own tension.

- This occurs at  $T_*$ , defined by:

$$R_* \sim H^{-1} \approx g_{\text{eff}}(T_*)^{-1/2} M_{\rho} / T_*^2.$$

- The total collapsing mass has two contributions:

$$M_* = 4\pi\sigma R_*^2 + \frac{4}{3}\pi\Delta\rho R_*^3 \approx 4\pi\sigma H_*^{-2} + \frac{4}{3}\pi\Delta\rho H_*^{-3}$$

If  $N_{\text{DW}} > 1$ , then  $\Delta\rho > 0$ .

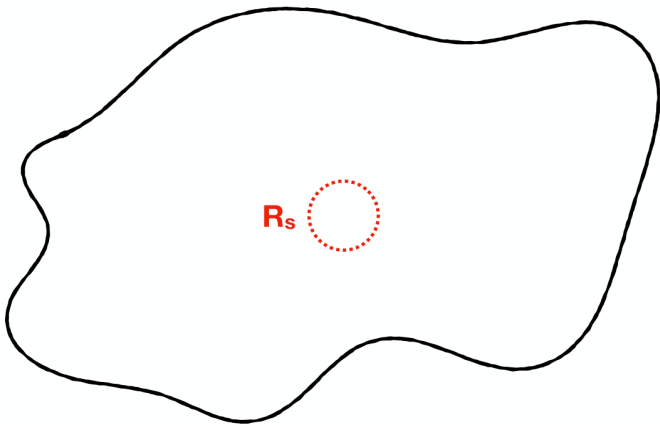
# SCHWARZSCHILD RADIUS OF THE DW

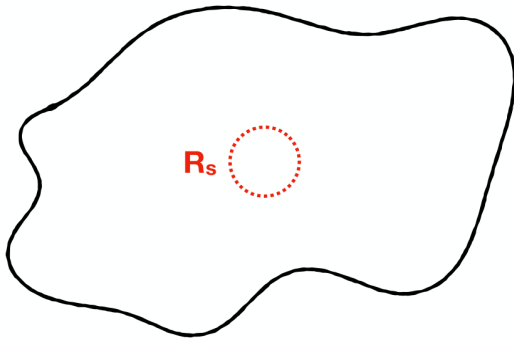
The ratio of the Schwarzschild radius of the collapsing DW to its initial size  $R_*$  is an important parameter:

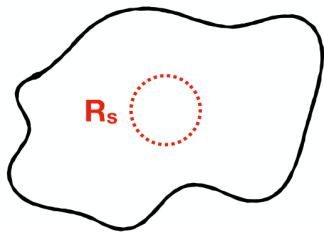
$$p \equiv R_S/R_* \sim \frac{2G_N M_*}{H_*^{-1}} \sim \frac{\sigma H_*^{-1}}{M_p^2} + \frac{\Delta\rho H_*^{-2}}{3M_p^2}.$$

If  $p$  is close to 1 the DW rapidly enters  $R_S$  and forms a BH. Otherwise the wall has to contract significantly making it unlikely to form a BH. This is the *figure of merit* for PBH formation.

(Deviations from spherical symmetry, radiation friction during collapse can partly modify this picture.)

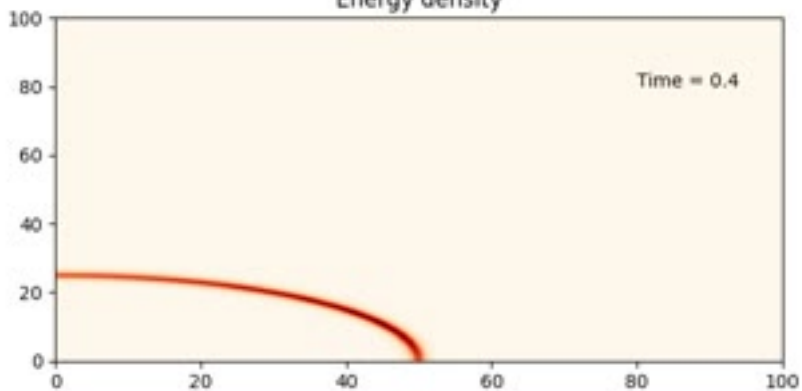




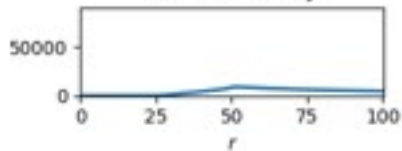




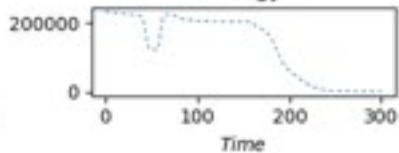
## Energy density



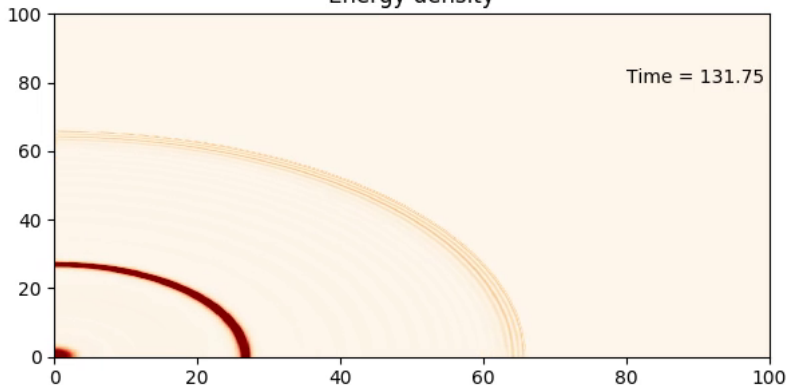
## Surface Gravity



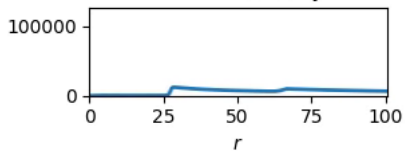
## Energy



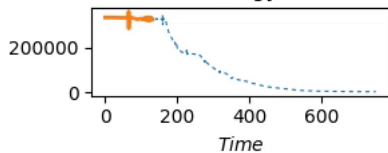
## Energy density



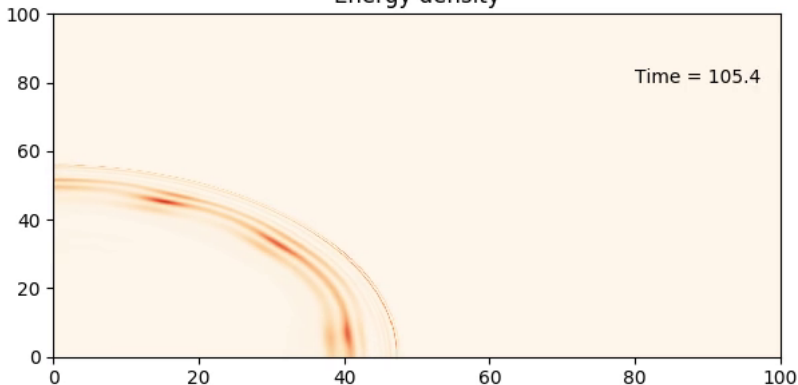
## Surface Gravity



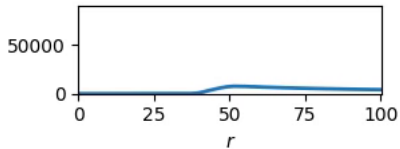
## Energy



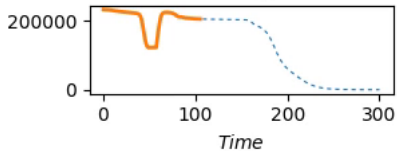
# Energy density



## Surface Gravity



## Energy



Two regimes:

- When the tension dominates,  $M_* \sim T_*^{-4}$  and  $p \sim T^{-2}$ .
- When the energy density dominates,  $M_* \sim T_*^{-6}$  and  $p \sim T^{-4}$ .

The duration of the hybrid network has a huge impact: as the temperature decreases it becomes more likely to form a black hole, and heavier black holes result from DWs which collapse later.

Long-lived string-wall networks are essential. This requires multiple DWs attached to each string.

As soon as the axion obtains its potential from nonperturbative QCD effects domain walls become relevant. This occurs at a temperature

$$3H(T_1) = m(T_1) \Rightarrow T_1 \sim \text{GeV}.$$

At around the same time, the homogeneous component of the axion field starts to oscillate and generates CDM. If  $N_{\text{DW}} > 1$ , the network is stable, but a bias term can be added to avoid the DW problem:

$$V_B(a) = \mathcal{A}_B^4 \left[ 1 - \cos \left( \frac{a}{f} + \delta \right) \right].$$

There is now an energy difference  $\Delta\rho \approx \mathcal{A}_B^4$ , which balances the tension until

$$\sigma \approx \mathcal{A}_B^4 H^{-1} \Rightarrow T_2 \sim \sqrt{M_P \Delta\rho \sigma}$$

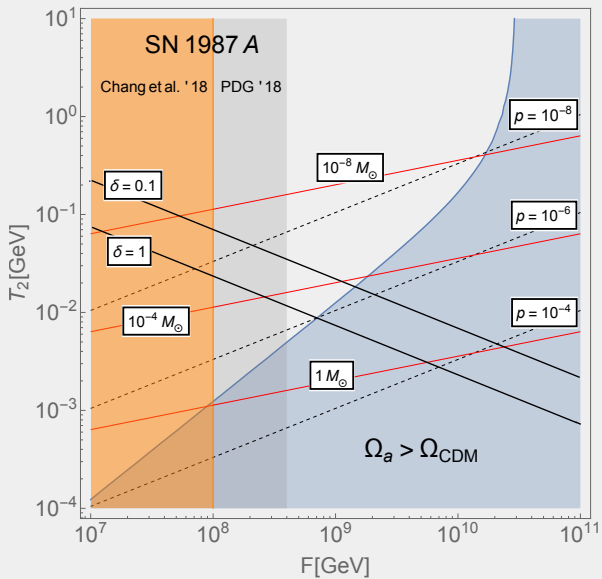
Crucial points:

- There can be a significant separation between  $T_1$  and  $T_2$ .
- Closed structures surrounding regions with energy  $\mathcal{A}_B^4$  can exist.

The addition of the bias term misaligns the axion:

$$\theta_{\min} \approx \frac{\mathcal{A}_B^4 N_{DW} \sin \delta}{m^2 N_{DW} F^2 + \mathcal{A}_B^4 \cos \delta} \lesssim 10^{-10}.$$

The phase is related to  $T_2$  through  $\mathcal{A}_B$ . At constant  $\delta$ , this corresponds to a line in the  $\log F - \log T_2$  plane. We would like  $\delta \sim 1$ .



- For the QCD axion we find an interesting region around

$$f_a \sim 10^9 \text{ GeV.}$$

PBHs of mass  $10^{-4} M_\odot$  can form with  $p \sim 10^{-6}$ .

- For generic ALPs we can reach larger probabilities  $p \sim 10^{-3}$  in scenarios where

$$T_2 \sim \text{keV.}$$

Interestingly much larger BHs,  $\lesssim 10^8 M_\odot$  could be formed.

Most of the axionic string-wall network disappears at  $T_2$ , which is when the vacuum contribution starts dominating, and both  $\rho$  and  $M_*$  increase steeply.

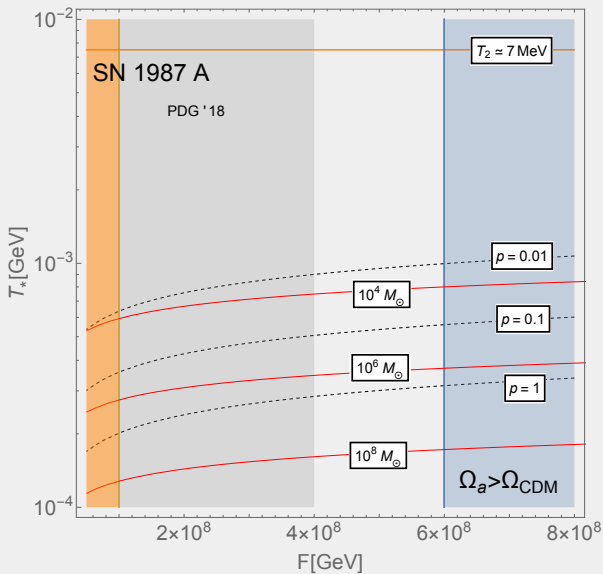
But, 1 – 10% of the walls survive until  $\sim 0.1 T_2$ , when:

- $\rho \sim 1$
- $M_* \sim 10^6 M_\odot$

Hence, a fraction  $f \sim 10^{-6}$  of the DM end up forming SMBHs!  
Also influence LSS.

B. Carr & J. Silk, 1801.00672

# LATE COLLAPSES



- Planck suppressed operators are unlikely.
- A dark gauge sector with  $\Lambda_B \sim MeV$  is an interesting possibility.

A. Caputo & M. Reig, 1905.13116

## 1 Overview and motivation

## 2 Could LIGO detect axions?

### ■ PBHs from QCD axion dynamics

FF, E. Massó, G. Panico, O. Pujolàs & F. Rompineve, 1807.01707, PRL 2019

### ■ GWs from a phase transition at the PQ scale

B. Dev, FF, Y. Zhang & Y. Zhang, 1905.00891, JCAP 2019

## 3 Conclusions

We will now consider generic pNGB resulting from a U(1) symmetry spontaneously broken at a scale  $f_a (\gg v_{ew})$ .

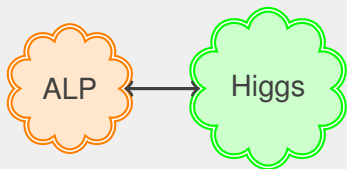
Couplings to SM particles are suppressed by inverse powers of  $f_a$ .

$$\Phi(x) = \frac{1}{\sqrt{2}} [f_a + \phi(x)] e^{ia(x)/f_a}$$

mass  $\sim f_a$       very light

For low-energy phenomenology,  $\phi$  is integrated out and ignored. We will look at the dynamics of  $\phi$  around the  $f_a$  scale and find that it can provide additional constraints on the ALP model.

Consider a non-zero coupling



Then, the phase transition at the scale  $f_a$  could be strongly first-order and produce a stochastic GWs.

$$\mathcal{V}_0 = -\mu^2|H|^2 + \lambda|H|^4 + \kappa|\Phi|^2|H|^2 + \lambda_a \left( |\Phi|^2 - \frac{1}{2}f_a^2 \right)^2 .$$

In terms of the real scalar field components,

$$\mathcal{V}_0(\phi, h) = \frac{\lambda_a}{4} \left( \phi^2 - f_a^2 \right)^2 + \frac{\kappa}{4} \phi^2 h^2 - \frac{\mu^2}{2} h^2 + \frac{\lambda}{4} h^4$$

# FIRST ORDER PHASE TRANSITION

A FOPT along the  $\phi$  direction while maintaining the VEV of  $h$  equal to zero, can occur if:

$$\mu^2 \leq \frac{2\lambda\lambda_a}{\kappa} f_a^2$$

We will choose  $\mu$  that saturates the identity and ignore the dependence of the effective potential on  $h$ .

The radiative contribution of the scalar to the Higgs mass has to be cancelled out in a UV complete escenario (e.g. by vector-like fermions at the  $\mu$ -scale).

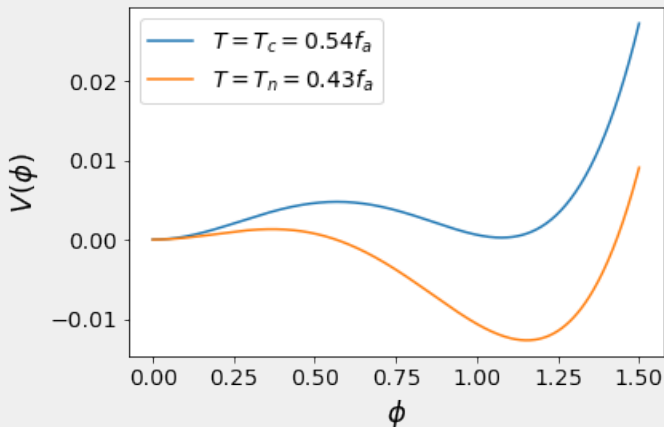
For related ideas & extensions, see also

Delle Rose, Panico, Redi & Tesi 1912.06139

von Harling, Pomarol, Pujolas & Rompineve 1912.07587

# FIRST ORDER PHASE TRANSITION

Fixing  $f_a$ , scan the region  $(\kappa, \lambda_a)$  to find where a FOPT can take place.



$$h^2\Omega_{\text{GW}} \simeq h^2\Omega_\phi + h^2\Omega_{\text{SW}} + h^2\Omega_{\text{MHD}}$$

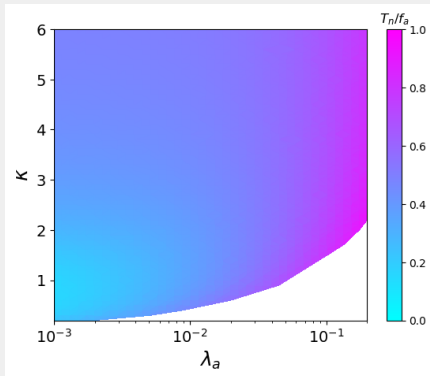
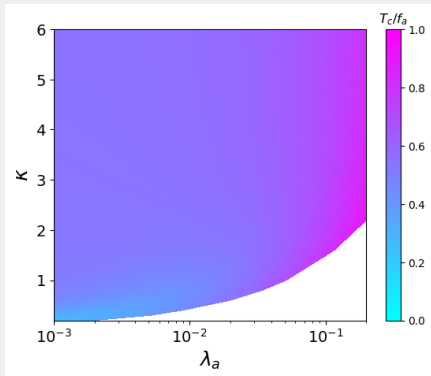
C. Caprini et al. 1910.13125

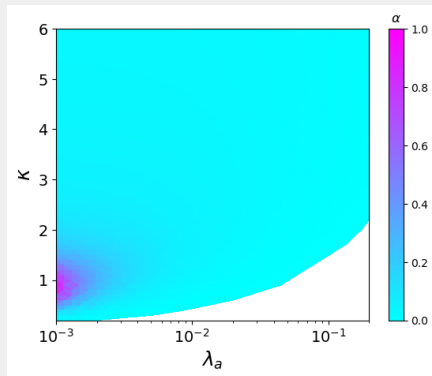
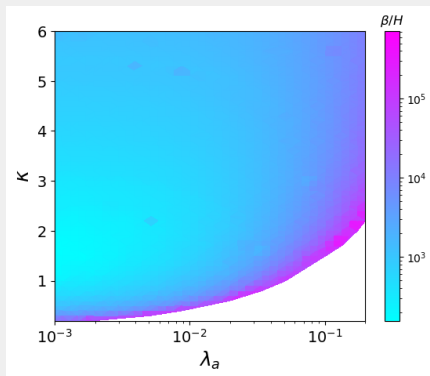
Input quantities to be calculated from our model parameters:

- Ratio  $\alpha$  of vacuum energy density released in the PT to radiation.
- Rate of the PT,  $\beta/H_*$ .
- Latent heat fractions for each of the three processes.
- Bubble wall velocity.

In the phenomenologically relevant cases, the bubble wall collision and sound wave contributions dominate.

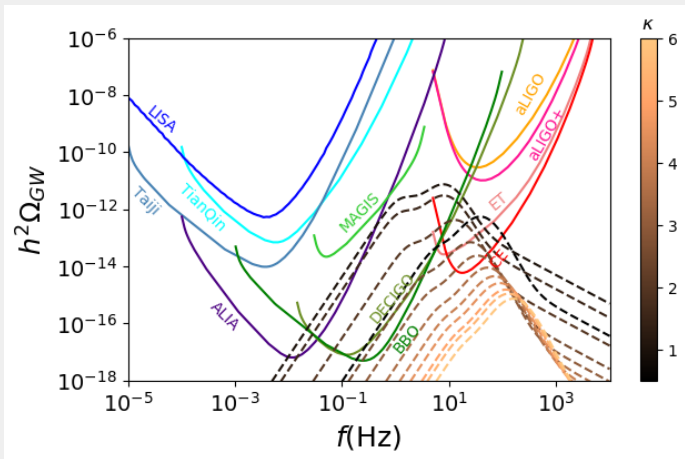
Consider  $10^3 \text{ GeV} \leq f_a \leq 10^8 \text{ GeV}$ .



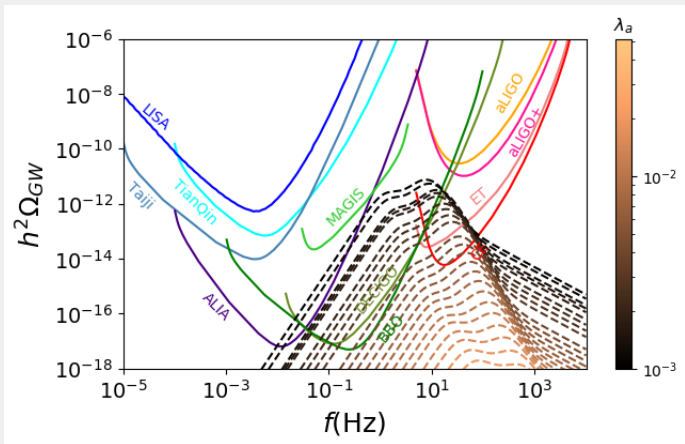


A sizeable GW signal can be generated for large  $\alpha$  and small  $\beta$ .  
When  $\kappa \approx 1$  &  $\lambda_a \approx 10^{-3}$  it reaches  $h^2 \Omega_{\text{GW}} \approx 10^{-12}$ .

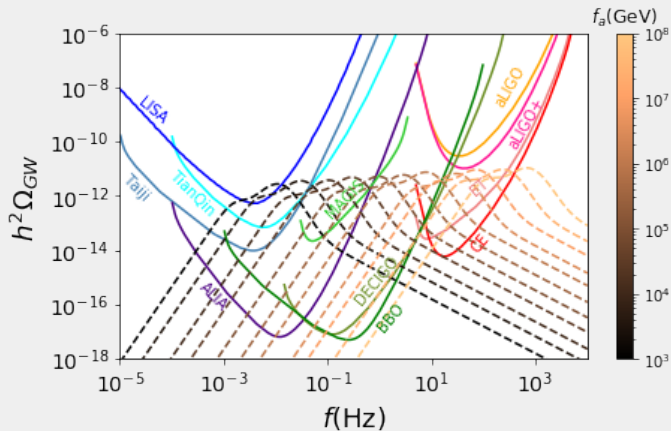
# DETECTION PROSPECTS



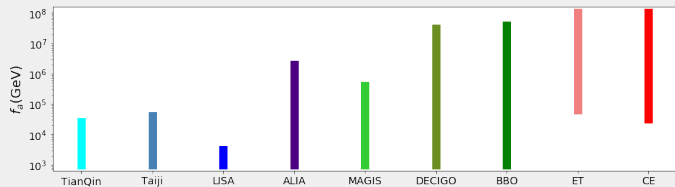
# DETECTION PROSPECTS



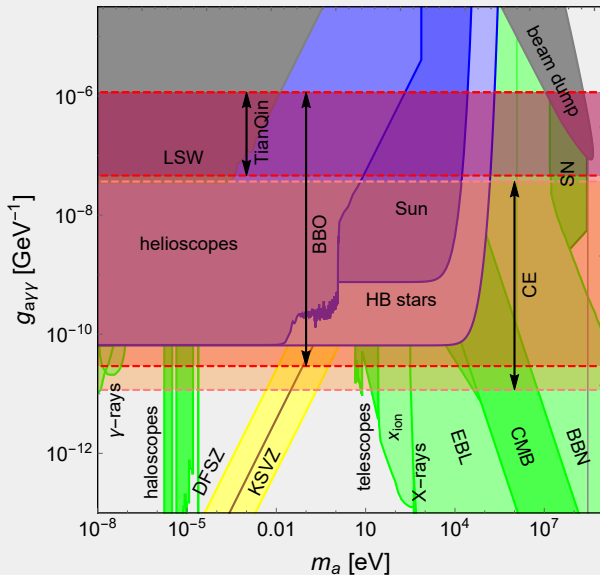
# DETECTION PROSPECTS



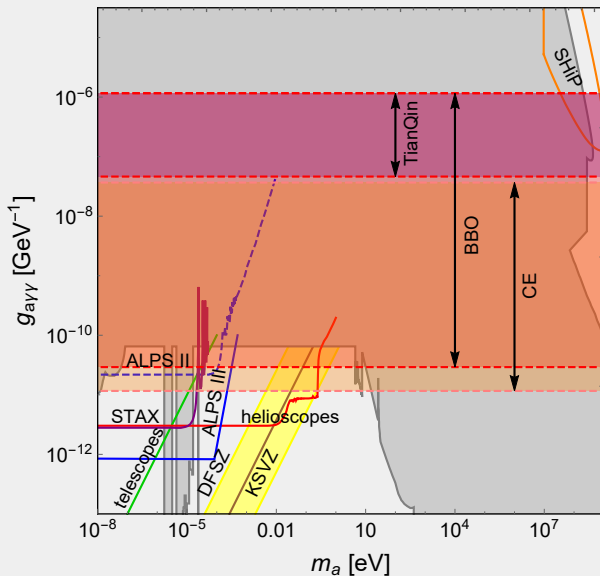
# DETECTION PROSPECTS



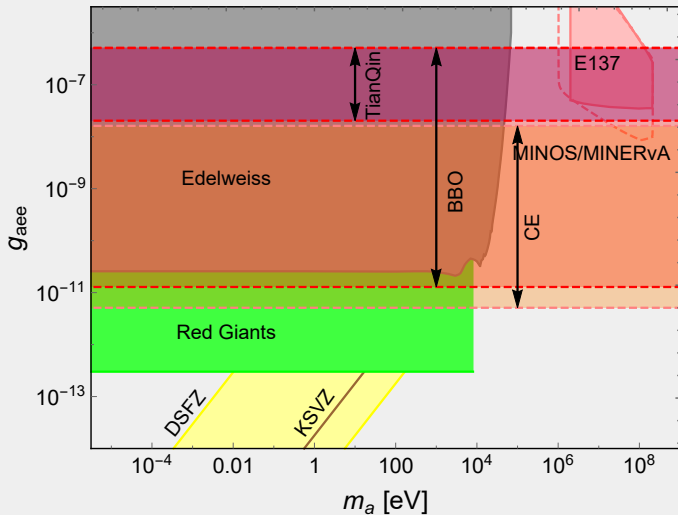
# COMPARISON WITH OTHER ALP CONSTRAINTS



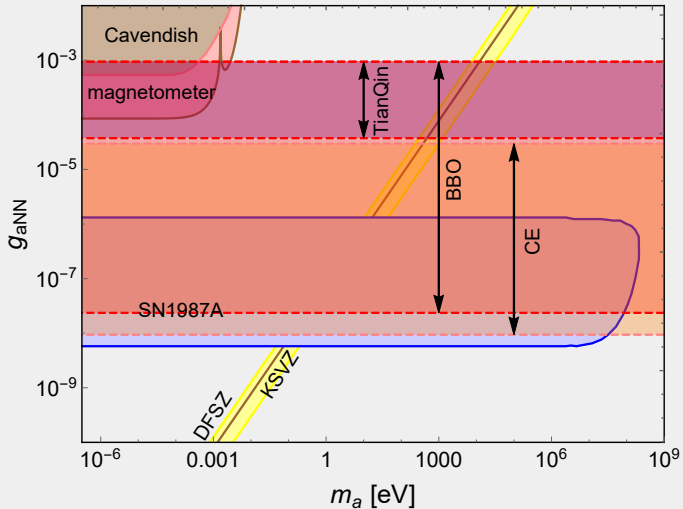
# COMPARISON WITH OTHER ALP CONSTRAINTS



# COMPARISON WITH OTHER ALP CONSTRAINTS



# COMPARISON WITH OTHER ALP CONSTRAINTS



# CONCLUSIONS

# CONCLUSIONS

- The observed LIGO BHs masses  $\gtrsim 20M_{\odot}$  are unexpectedly large to result from stellar evolution considerations, and could be hinting at PBHs.
- Axionic topological defects with  $N_{\text{DW}} > 1$  lead to a new *Network Annihilation epoch* that can potentially generate PBHs of up to  $10^6 M_{\odot}$ , and that can be tested by LISA.
- A FOPT at the PQ scale could take place in some ALP models. The GW signal strength could be as large as  $h^2 \Omega_{\text{GW}} \sim 10^{-12}$ , within reach of next generation GW observatories.