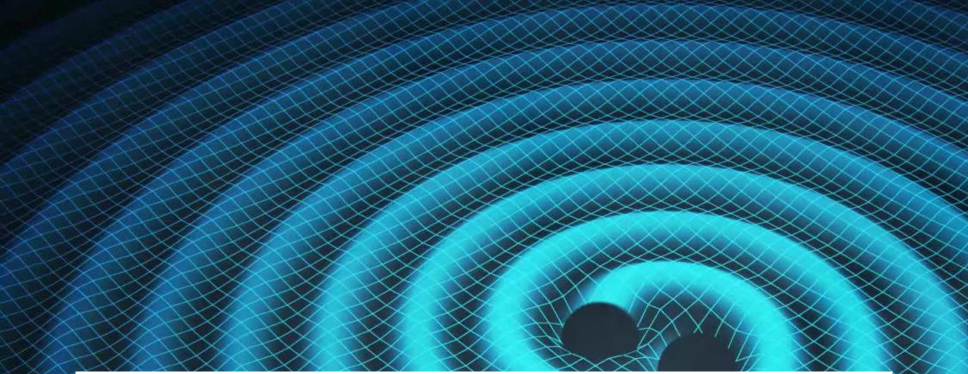


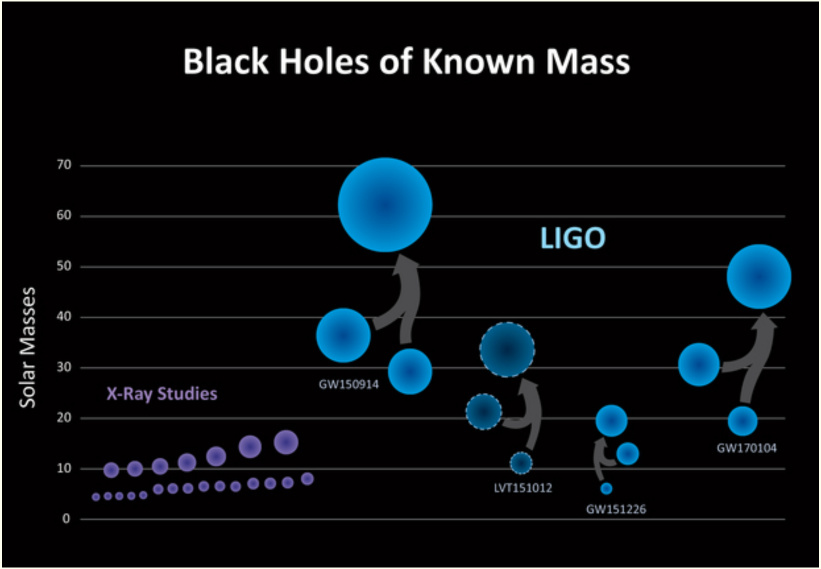
Primordial black holes as dark matter

Francesc Ferrer, Washington University in St. Louis

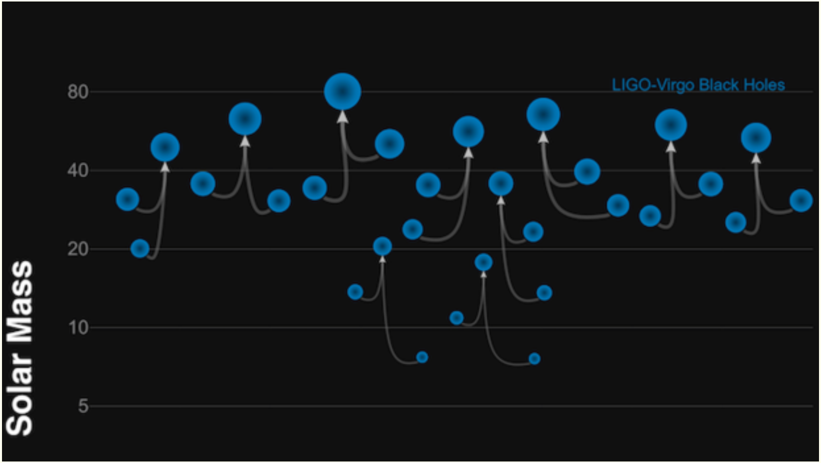
✉ ferrer@wustl.edu

Next frontiers in the search for DM.

August 29, 2019. GGI, Firenze.

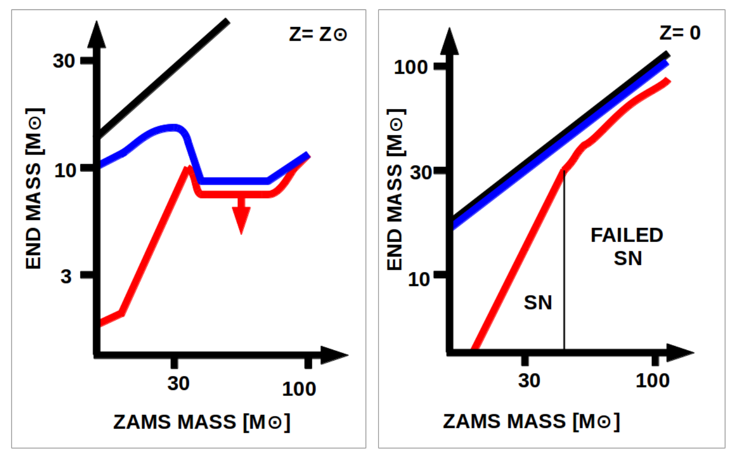


Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
LIGO
X-Ray Studies
GW150914
LVT151012
GW151226
GW170104



LIGO-Virgo Black Holes
80
40
20
10
5
Solar Mass

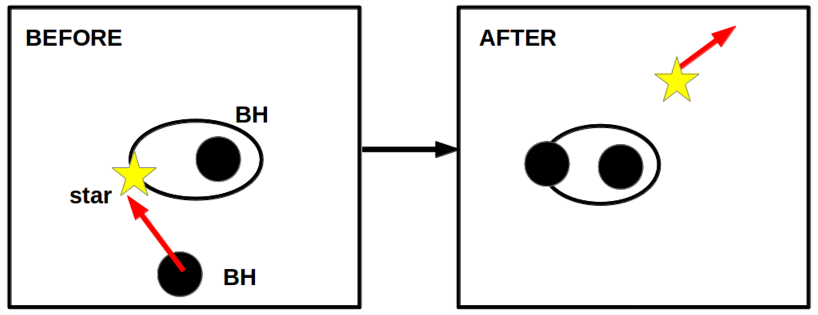
Unexpected/surprising?



Most astrophysical models did not predict BHs with $M \gtrsim 20M_{\odot}$. But, large BHs masses can be generated from $\geq 40M_{\odot}$ metal-free stars undergoing direct collapse.

Mapelli, 1809.09130

How are binaries formed?



Could work in young star clusters or in nuclear star clusters surrounding SMBHs. Unlike isolated binaries, spins are misaligned/isotropic. But, three body encounters (necessary to harden the binary) can eject the system.

The astrophysical picture is largely incomplete:

- The formation channels of merging BH binaries are still uncertain. Major simplifications are adopted in dynamical simulations, and the statistics about BHs in young star clusters is small.
- A global picture of the BH merger history as a function of redshift is missing.

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 binary mergers up to $z \sim 10$.

Another (more massive) puzzle

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

Outline

Overview and motivation

PBHs as dark matter

Could LIGO detect axions?

- PBHs from QCD axion dynamics

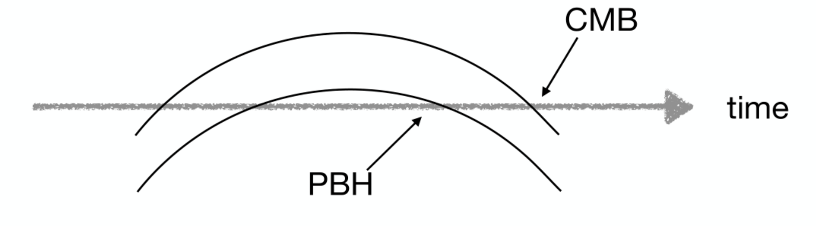
  FF, E. Massó, G. Panico, O. Pujolàs & F. Rompineve, 1807.01707

- GWs from a phase transition at the PQ scale

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

Conclusions

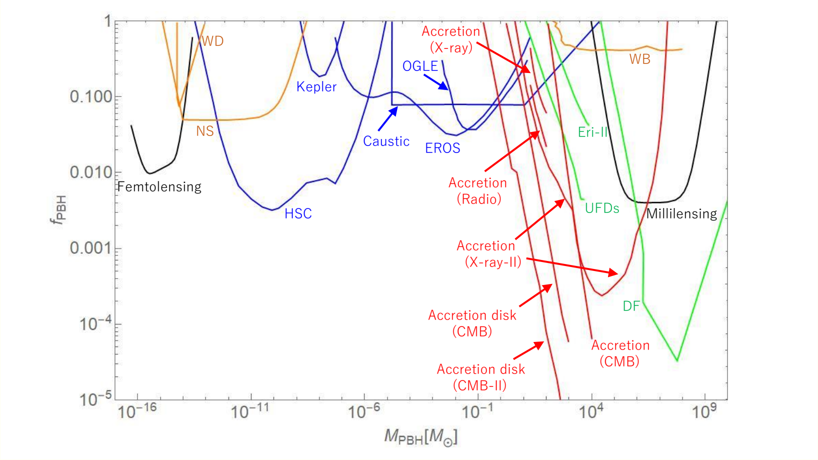
Could they be primordial?



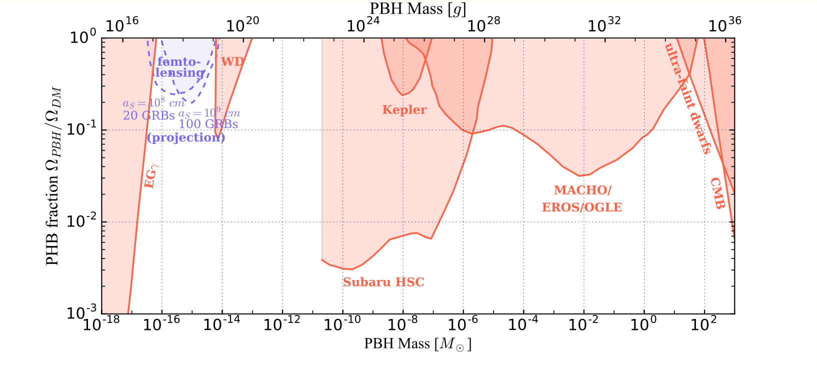
Rare Hubble scale perturbations can collapse into BHs:

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

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

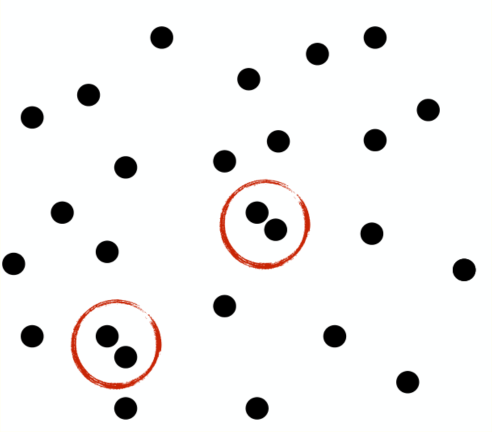


Sasaki *et al.* CQG 35 (2018) 063001



Katz *et al.* 1807.11495

Binary formation



PBHs are randomly distributed, but some pairs are close enough to decouple from Hubble flow.

Nakamura, Sasaki, Tanaka & Thorne, 1997

Most of the BH pairs that merge today form in the early universe, deep in the radiation era. Pairs form due to the chance proximity of PHB pairs and merge on a time-scale:

$$t_{merge} = \frac{3c^5}{170 G_N^3} \frac{a^4 (1 - e^2)^{7/2}}{M_{pbh}^3}$$

Several processes (torques due to other BHs, encounters with other BHs, DM spikes around PBHs, ...) influence the merger rate that is measured by LIGO.
Clustering might substantially change the picture.

Ali-Haïmoud, Kovetz & Kamionkowski, 1709.06576

Kavanagh, Gaggero & Bertone, 1805.09034

Pair formation in present day halos

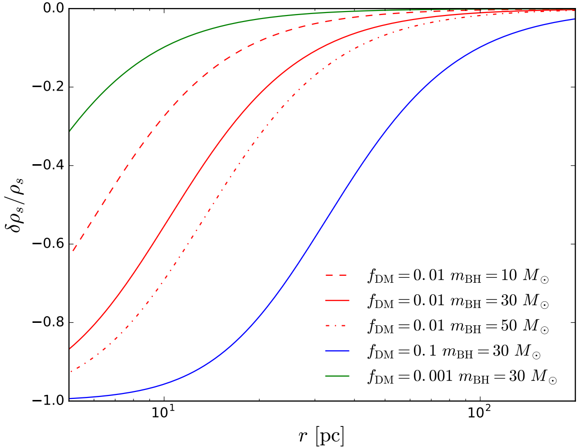
Binary BHs can also form in present day halos from GW emission. These binaries are very tight and highly eccentric so that they coalesce within a very short timescale. In principle this population gives a subdominant contribution to the LIGO observed events, but:

- PBHs could be clumped around SMBH spikes
- Merger rates could be boosted
- The cross-section is strongly velocity dependent,

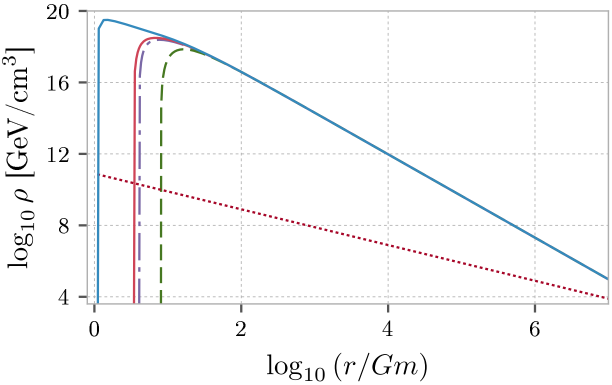
$$\sigma \propto v_{\rm rel}^{-18/7}$$

FF & A. Medeiros, 1810.xxxx

PBHs are not exactly CDM



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



FF, A. Medeiros & C.M. Will, 1707.06302

Outline

Alternative mechanisms?

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, . . .

Alternative mechanisms?

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.

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

Cosmological evolution

Important distinction whether PQ symmetry is broken before or after inflation:

- Pre-inflationary PQ breaking $\rightarrow$ the axion has a single uniform initial value a_i within the observable universe.
- In the post-inflationary case the axion takes different values in different regions.

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In the latter case when the axion gets its mass, around the QCD phase transition, *a hybrid string-domain wall network is formed.*

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.

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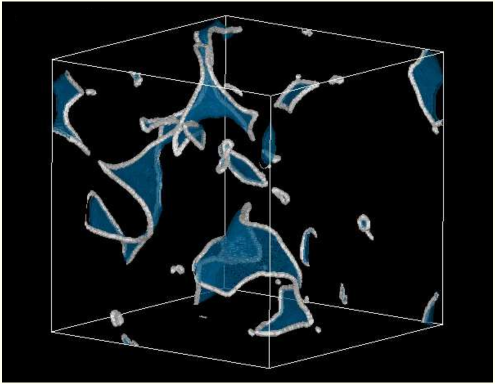
T. Vachaspati, 1706.03868

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.

$N_{\rm DW} = 1$

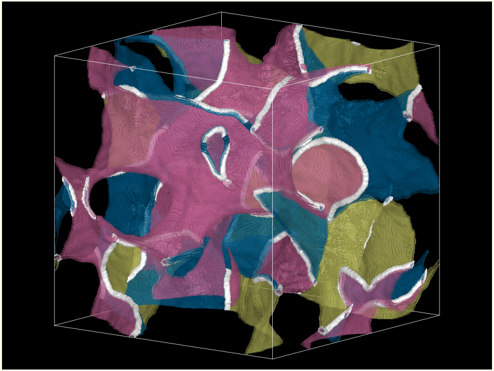
Only one domain wall is attached to each string. Such topological configurations quickly annihilate leaving behind a population of barely relativistic axions.



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

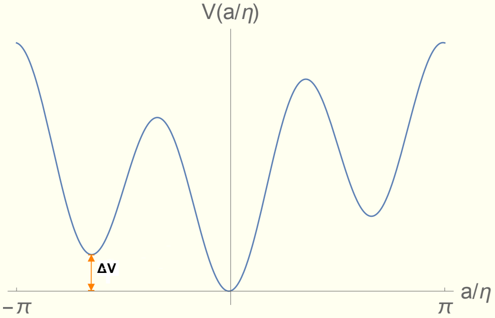
$N_{\mathrm{DW}} > 1$

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



T. Hiramatsu, *et al.*, JCAP 1301 (2013) 001

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.



- The domain walls are created at $T_1 \sim T_{\text{QCD}}$.
- A closed DW of size R_* may rapidly shrink (if $N_{\text{DW}} = 1$) because of its own tension, once $R_* \sim H^{-1} \approx g_{\text{eff}}(T_*)^{-1/2} M_p / T_*^2$.
- If $N_{\text{DW}} > 1$, the annihilation occurs at $T_2 > T_*$ set by $\dfrac{\Delta V}{\sigma}$. There can be a significant separation between formation T_1 and T_2.

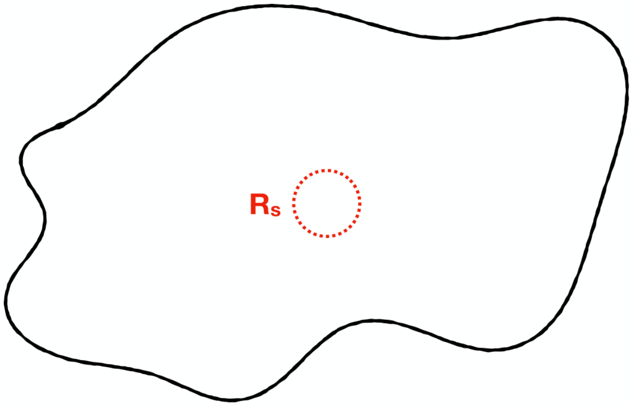
The addition of the bias term misaligns the axion:

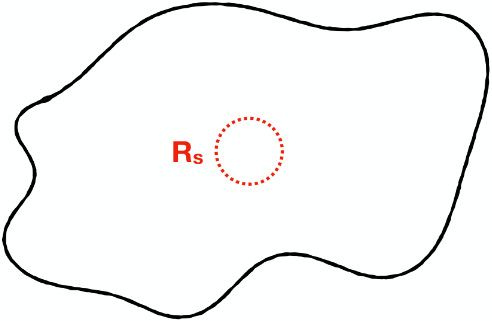
$$\theta_{\text{min}} \approx \frac{\mathcal{A}_B^4 N_{\text{DW}} \sin\delta}{m^2 N_{\text{DW}} F^2 + \mathcal{A}_B^4 \cos\delta} \lesssim 10^{-10}.$$

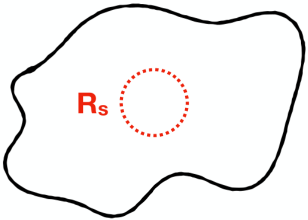
The phase is related to T_2, i.e. the bias,

$$\mathcal{A}_B^4 \sim T_2^2 \sigma / M_P.$$

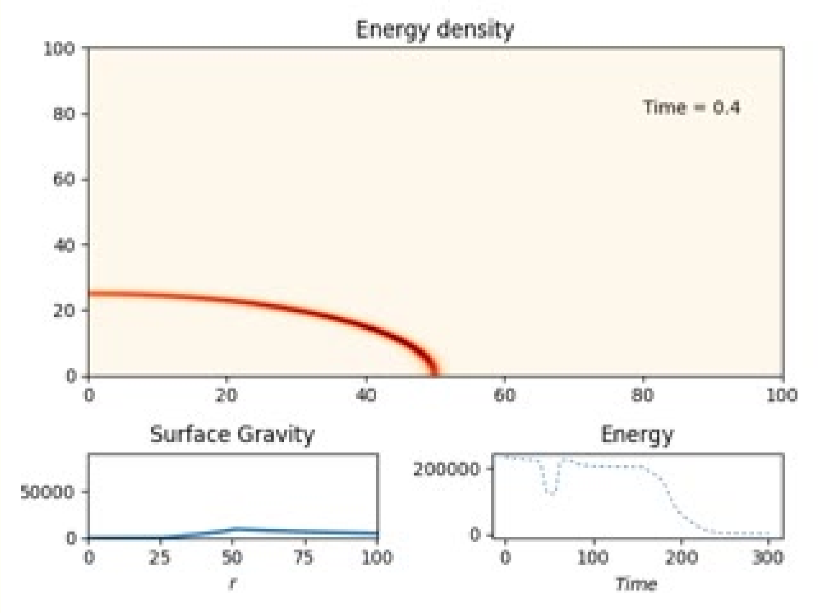
At constant δ, this corresponds to a line in the $\log F - \log T_2$ plane. We would like $\delta \sim 1$.


Rs

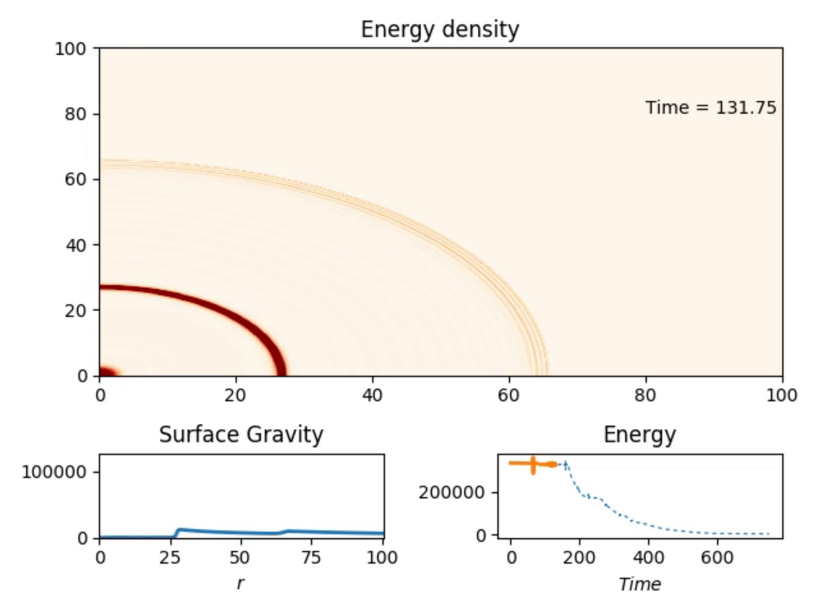

Rs

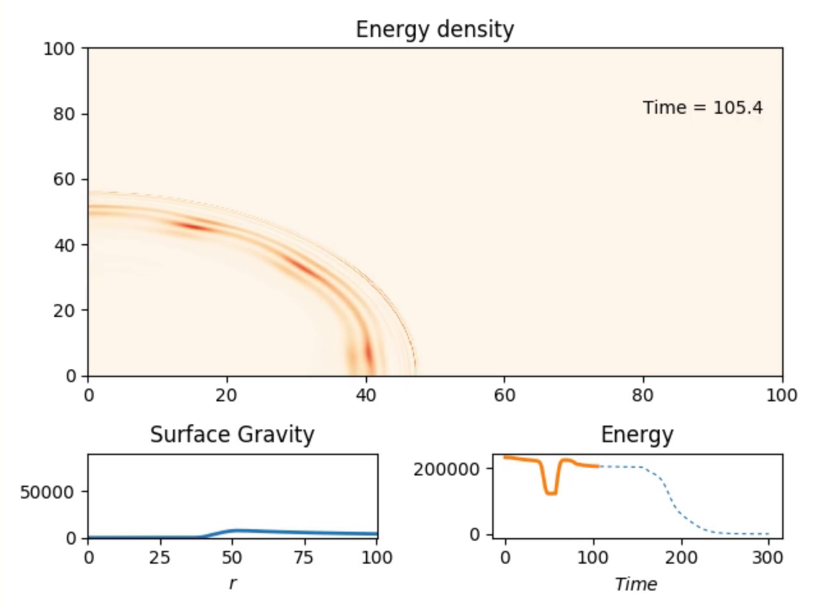

Rs


R_s



Energy density
Time = 0.4
100
80
60
40
20
0
0
20
40
60
80
100
Surface Gravity
50000
0
0
25
50
75
100
r
Energy
200000
0
0
100
200
300
Time


Energy density
Time = 131.75
Surface Gravity
r
Energy
Time



Energy density
Time = 105.4
100
80
60
40
20
0
0
20
40
60
80
100
Surface Gravity
50000
0
0
25
50
75
100
r
Energy
200000
0
0
100
200
300
Time

PBHs from string-wall defects

A closed DW of size R_* will rapidly shrink because of its own tension, once $R_* \sim H^{-1} \approx g_{\rm eff}(T_*)^{-1/2} M_p / T_*^2$.
Its mass has contributions from the wall tension and from any difference in energy density between the two regions separated by the DW:

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

$\Rightarrow$ Heavier black holes form from DW which collapse later in cosmological history.

The Schwarzschild radius of the collapsing defect is $R_{S,*} = 2G_N M_*$, and the *figure of merit* for PBH formation is:

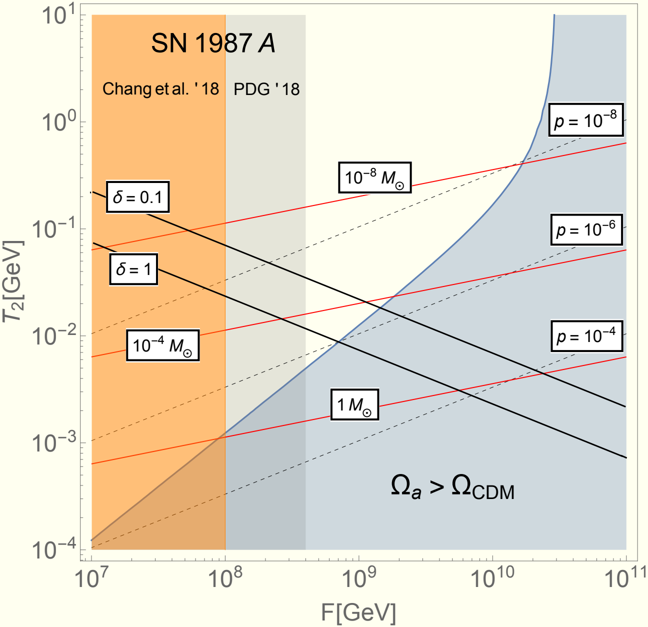
$$p \equiv R_{S,*}/R_* \sim \frac{\sigma H_*^{-1}}{M_p^2} + \frac{\Delta\rho H_*^{-2}}{3M_p^2}$$

$\Rightarrow$ As the temperature decreases it becomes more likely to form a black hole.

Two regimes:

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

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



SN 1987 A
Chang et al. '18
PDG '18
$p = 10^{-8}$
$10^{-8}\ M_\odot$
$\delta = 0.1$
$\delta = 1$
$p = 10^{-6}$
$10^{-4}\ M_\odot$
$p = 10^{-4}$
$1\ M_\odot$
$\Omega_a > \Omega_{CDM}$
T_2[GeV]
F[GeV]

Axion-QCD vs ALPs

- 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.

B. Carr & J. Silk, 1801.00672

Late collapses

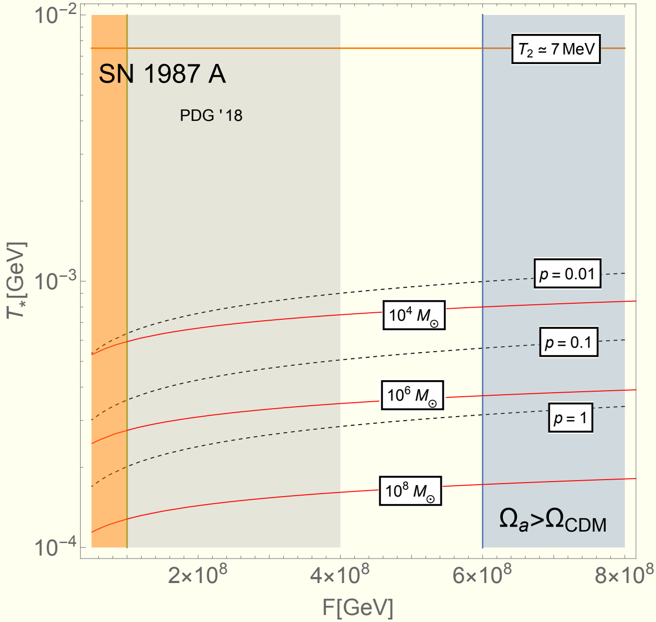
Most of the axionic string-wall network disappears at T_2, which is when the vacuum contribution starts dominating, and both p and M_* increase steeply.
But, $1 - 10\%$ of the walls survive until $\sim 0.1\,T_2$, when:

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

$\Rightarrow$ A fraction $f \sim 10^{-6}$ of the DM end up forming SMBHs!

B. Carr & J. Silk, 1801.00672

Late collapses



We have not said much about the bias term . . .
Planck suppressed operators are unlikely.
A dark gauge sector with $\Lambda_B \sim MeV$ is an interesting possibility.

A. Caputo & M. Reig, 1905.13116

Or it might not be needed after all..

Stojkovic, Freese & Starkman, hep-ph/0505026

Outline

Overview and motivation

PBHs as dark matter

Could LIGO detect axions?

PBHs from QCD axion dynamics

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

GWs from a phase transition at the PQ scale

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

Conclusions

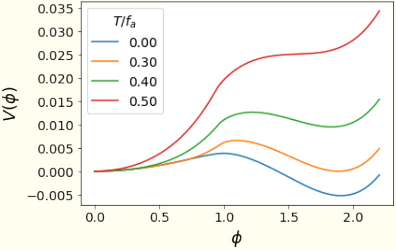
Model

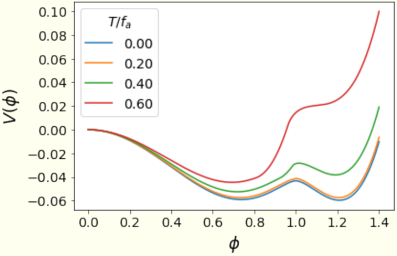
$$\mathcal{V}_0 \; = \; -\mu^2|H|^2 + \lambda|H|^4 + \kappa|\Phi|^2|H|^2 + \lambda_a\left(|\Phi|^2 - \frac{1}{2}f_a^2\right)^2 \; .$$

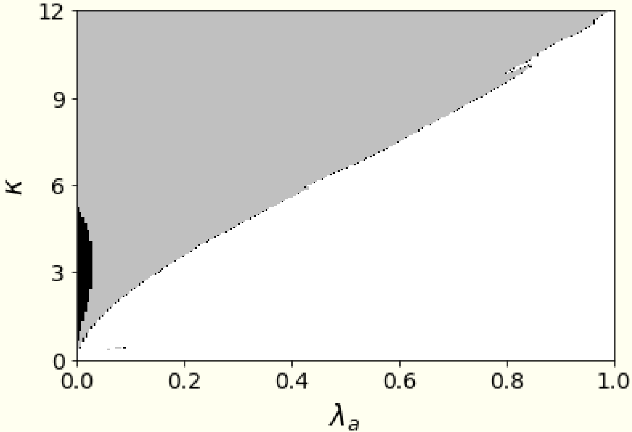
- f_a, κ and λ_a are free parameters.
- To obtain the observed Higgs mass, $\mu^2 \approx \kappa f_a^2/2$.

Phase transition

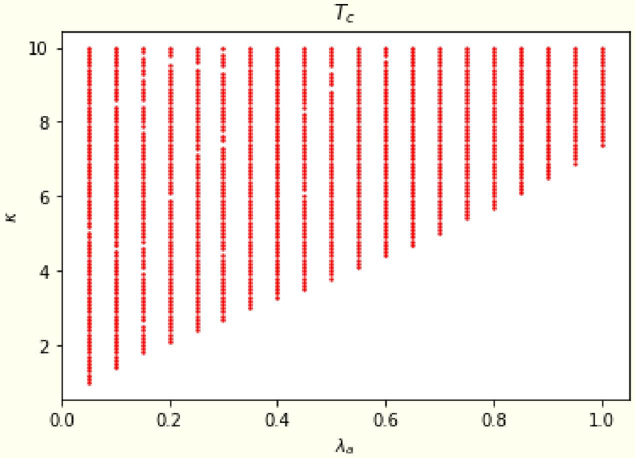
Fixing f_a, scan the region (κ, λ_a) to find where a FOPT can take place.







12
9
6
3
0
κ
0.0
0.2
0.4
0.6
0.8
1.0
λ_a


T_c
10
8
6
4
2
κ
0.0
0.2
0.4
0.6
0.8
1.0
λ_a

Gravitational wave production

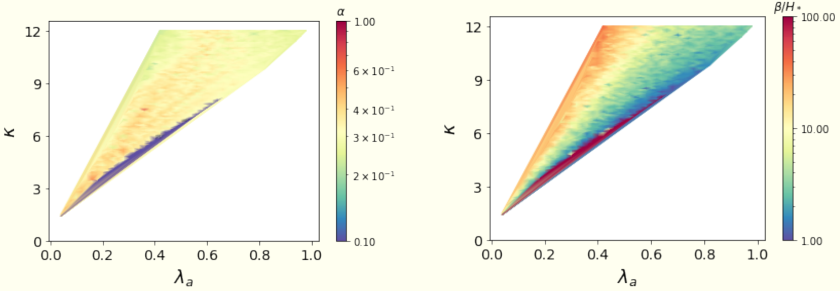
$$h^2\Omega_{\mathrm{GW}} \simeq h^2\Omega_\phi + h^2\Omega_{\mathrm{SW}} + h^2\Omega_{\mathrm{MHD}}\,.$$

C. Caprini et al. 1512.06239

Input quantities to be calculated from our model parameters:

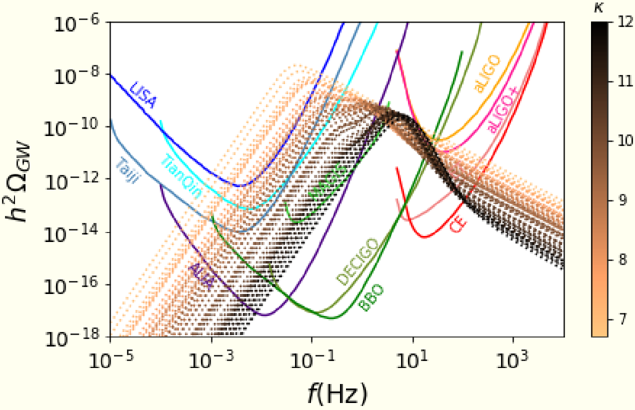
- Ratio α of vacuum energy density released in the PT to radiation.
- Rate of the PT, β/H_*.
- Latent heat fractions for each of the three processes.
- Bubble wall velocity.

In the phenomenologically relevant cases, the bubble wall collision contribution dominates.

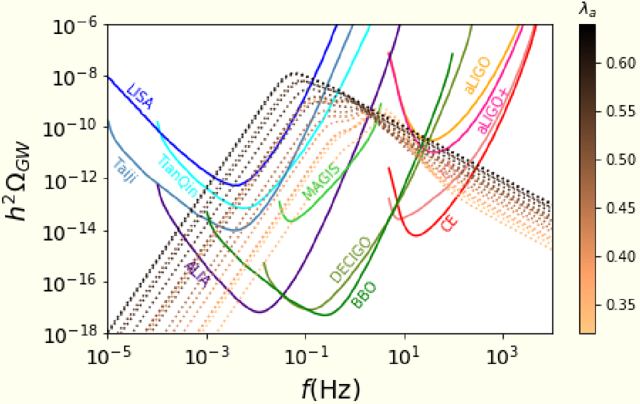


α
1.00
6 × 10⁻¹
4 × 10⁻¹
3 × 10⁻¹
2 × 10⁻¹
0.10
κ
λ_a
β/H_*
100.00
10.00
1.00
κ
λ_a

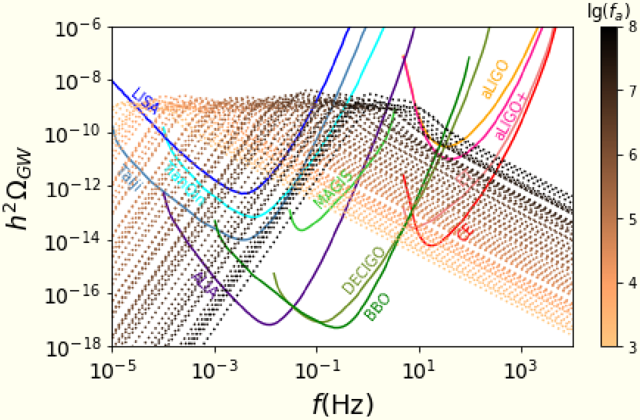
Detection prospects



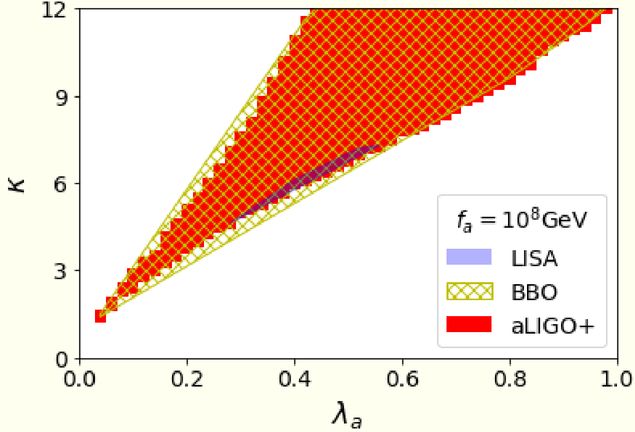
Detection prospects



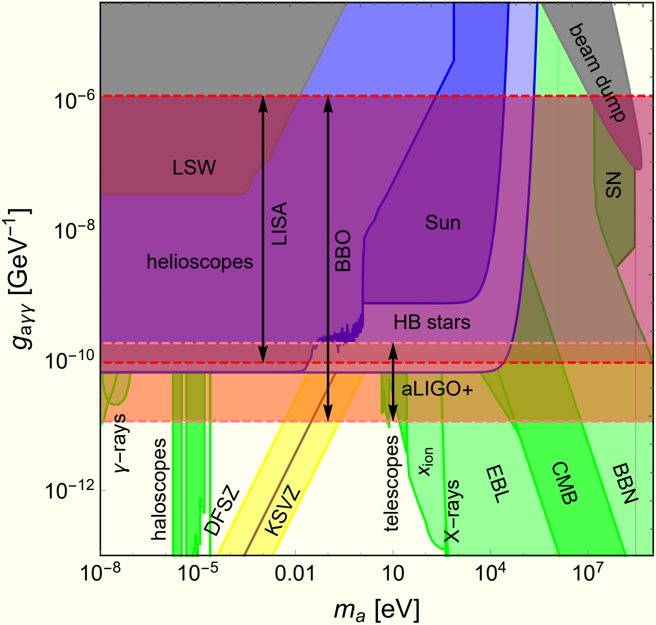
Detection prospects



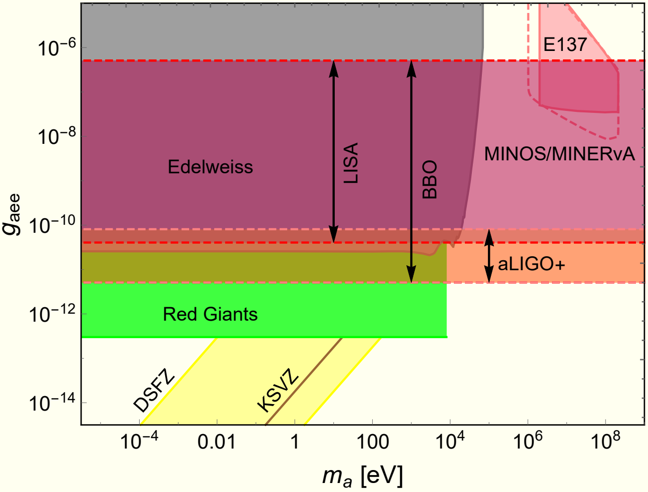
Detection prospects



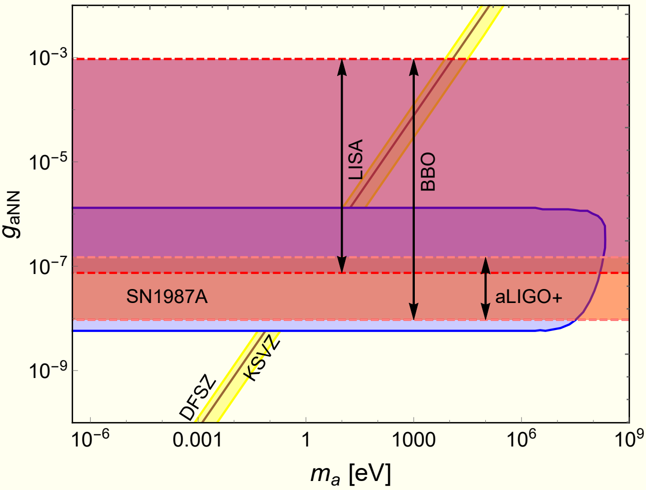
Comparison with other ALP constraints



Comparison with other ALP constraints



Comparison with other ALP constraints



Conclusions

- LIGO has confirmed the existence of BH binaries that are able to merge within a Hubble time.
- The observed BHs mass $\gtrsim 20M_\odot$ is somewhat surprising from the astrophysics point of view. A fraction, but not all, of the DM could be made of black holes.
- Axionic topological defects with $N_{\rm DW} > 1$ lead to a new Network Annihilation epoch that can potentially generate PBHs of up to $10^6 M_\odot$, and 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 $h^2\Omega_{\rm GW} \sim 10^{-8}$, within reach of aLIGO+.