Primordial black holes from axions

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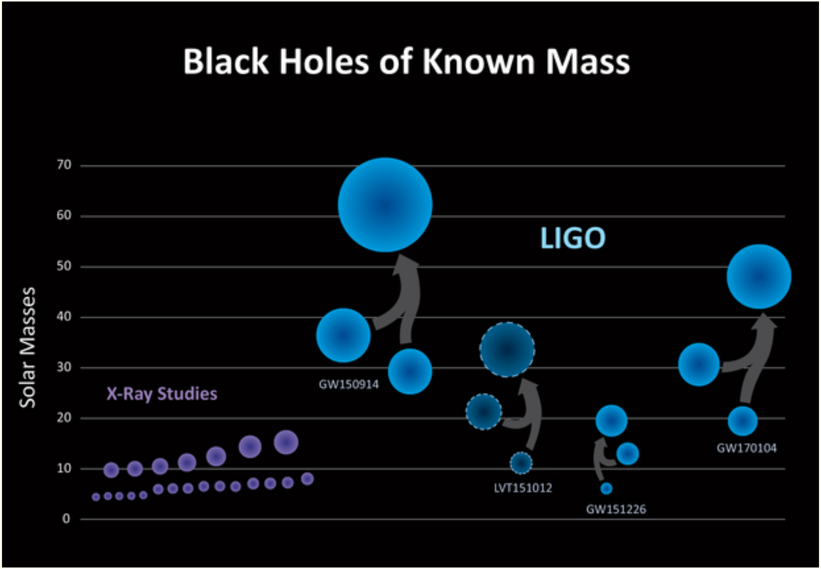
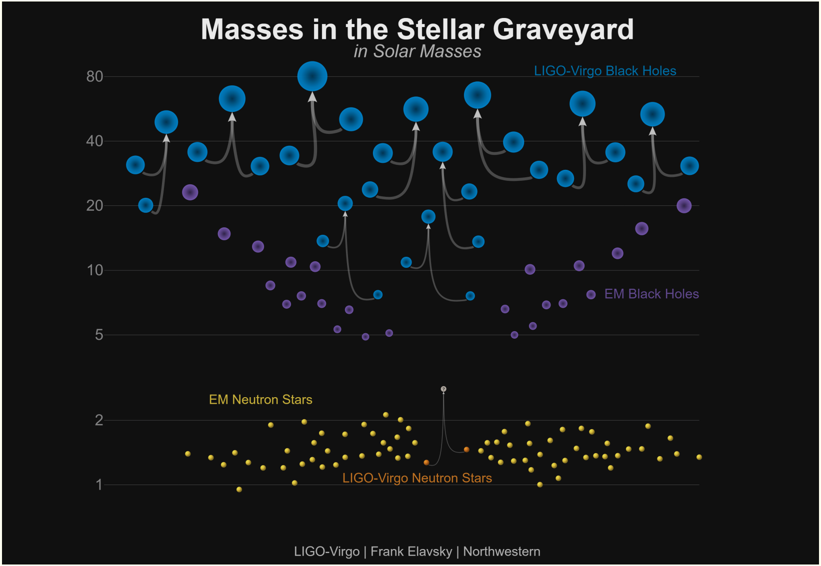
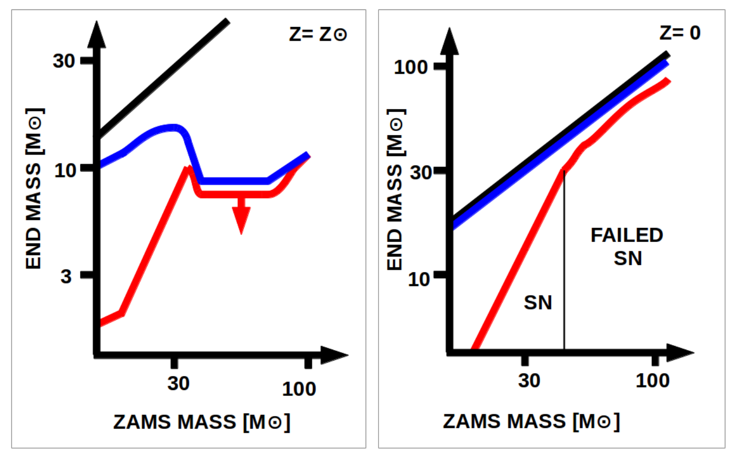

Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
X-Ray Studies
LIGO
GW150914
LVT151012
GW151226
GW170104


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
80
40
20
10
5
2
1
LIGO-Virgo | Frank Elavsky | Northwestern

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.

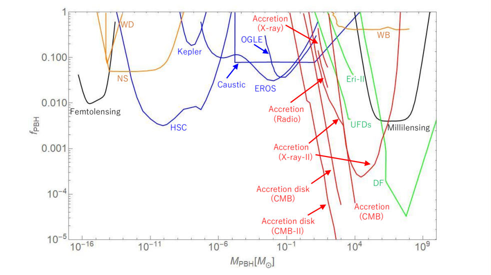
Mapelli, 1809.09130

Another (more massive) puzzle

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

Could they be primordial?

- PBHs could make part (but not all) the DM in the Universe.



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

- Rare Hubble scale perturbations generated during inflation can collapse into BH. If so, the power spectrum should be enhanced by a factor of 10^3 on scales $\ll$ CMB!

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, . . .

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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

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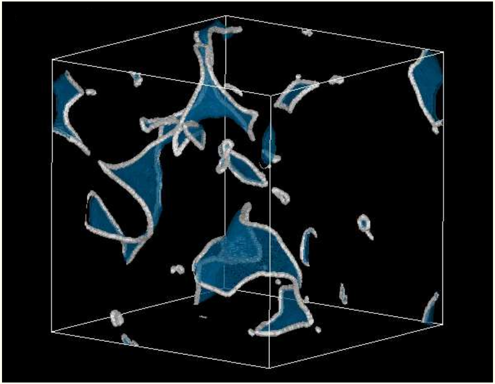
It is crucial that the annihilation of the network proceeds slowly.

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

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

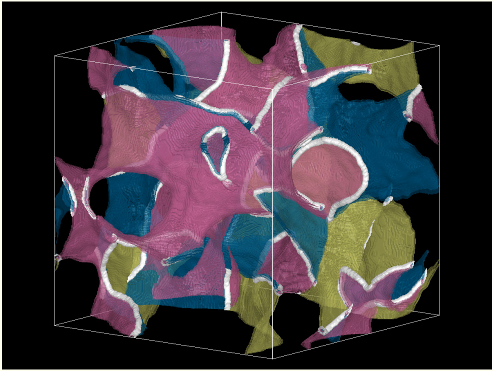
Only one domain wall is attached to each string. Such topological configurations quickly annihilate leaving behind a population of barely relativistic axions.



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

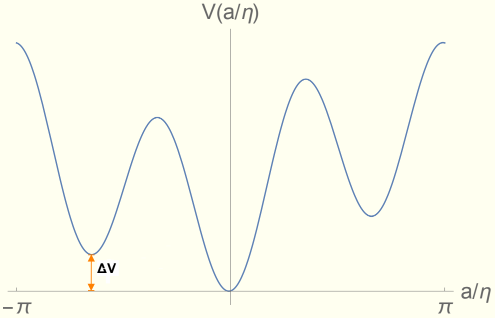
$N_{\mathrm{DW}} > 1$

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 $T_1 \sim T_{\rm QCD}$.
- A closed DW of size R_* may rapidly shrink (if $N_{\rm DW} = 1$) because of its own tension, once $R_* \sim H^{-1} \approx g_{\rm eff}(T_*)^{-1/2} M_p / T_*^2$.
- If $N_{\rm DW} > 1$, 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.

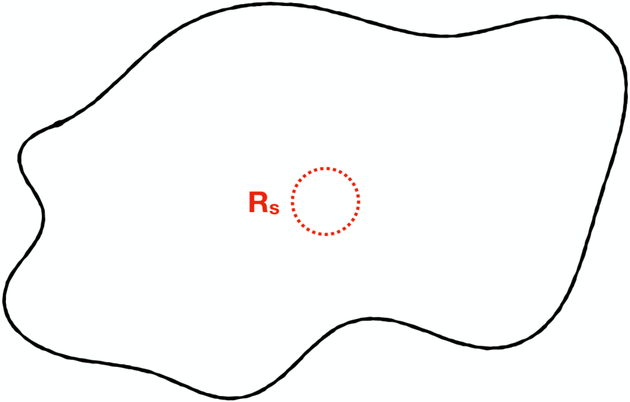
The addition of the bias term misaligns the axion:

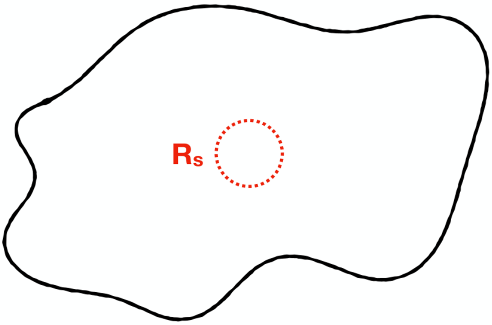
$$\theta_{\rm min} \approx \frac{\mathcal{A}_B^4 N_{\rm DW} \sin\delta}{m^2 N_{\rm DW} F^2 + \mathcal{A}_B^4 \cos\delta} \lesssim 10^{-10}.$$

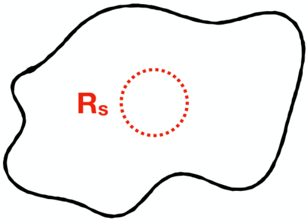
The phase is related to T_2, i.e. the bias,

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

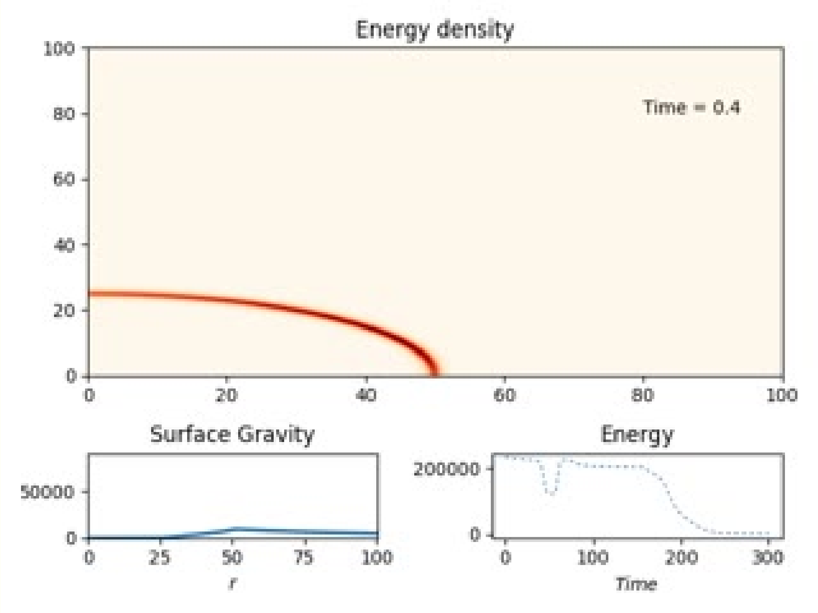
At constant δ, this corresponds to a line in the $\log F - \log T_2$ plane. We would like $\delta \sim 1$.

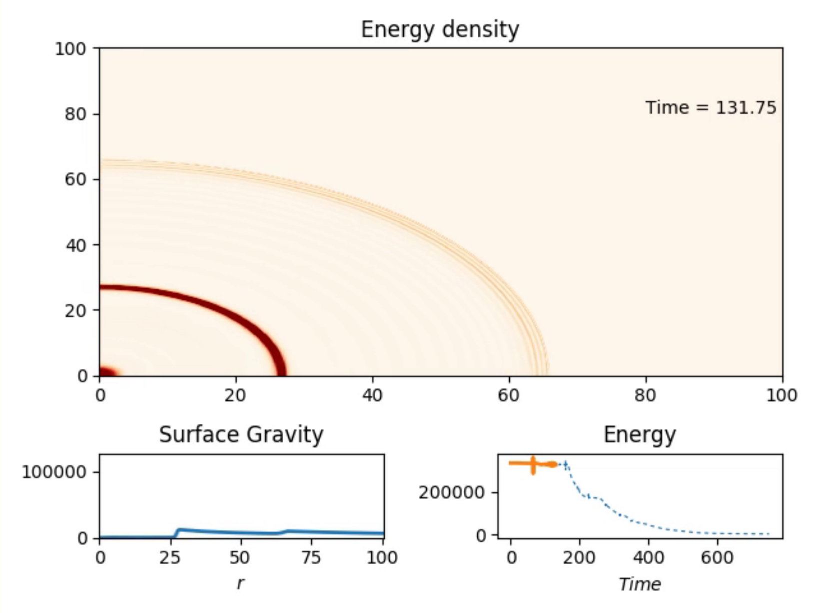

R_s


Rs

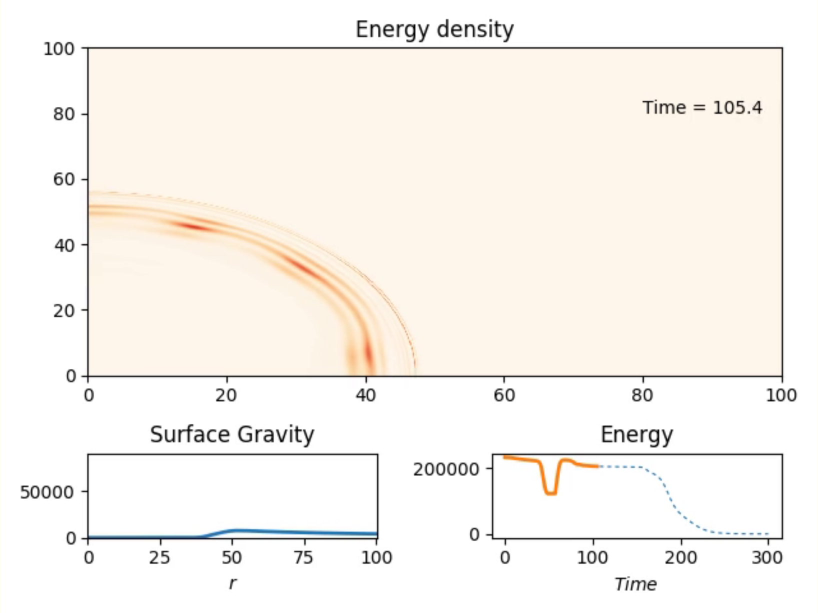

Rs


Rs


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
100
80
60
40
20
0
0
20
40
60
80
100
Surface Gravity
100000
0
0
25
50
75
100
r
Energy
200000
0
0
200
400
600
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:

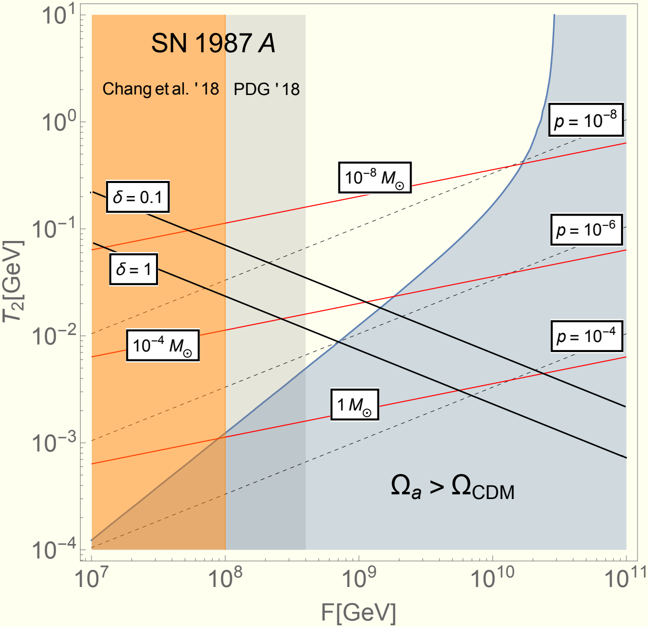
$$p \equiv R_{S,*}/R_* \sim \frac{\sigma H_*^{-1}}{M_p^2} + \frac{\Delta\rho H_*^{-2}}{3M_p^2}$$

$\Rightarrow$ 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
p = 10^−6
p = 10^−4
10^−8 M⊙
10^−4 M⊙
1 M⊙
δ = 0.1
δ = 1
Ωa > ΩCDM
T2[GeV]
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-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!

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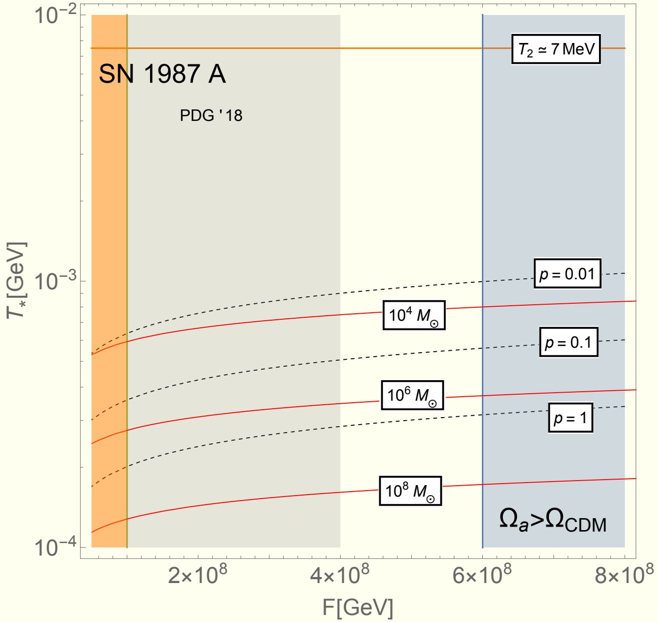

We have not said much about the bias term ...

Planck suppressed operators are unlikely.

A dark gauge sector with $\Lambda_B \sim MeV$ is an interesting possibility.

Conclusions

- LIGO has confirmed the existence of BH binaries that are able to merge within a Hubble time. BHs could be primordial and make up a fraction, but not all, of the DM.
- Axionic topological defects with $N_{\rm DW} > 1$ lead to a new Network Annihilation epoch that can potentially generate PBHs of up to $10^6 M_\odot$.
- This could explain the origin of the SMBHs and influence the formation of LSS.
- 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 $z \sim 10$.