Primordial black hole Dark matter: Part-1

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Black Holes from the Big Bang could be the Dark Matter


INTERNATIONAL
MOTHER
LANGUAGE
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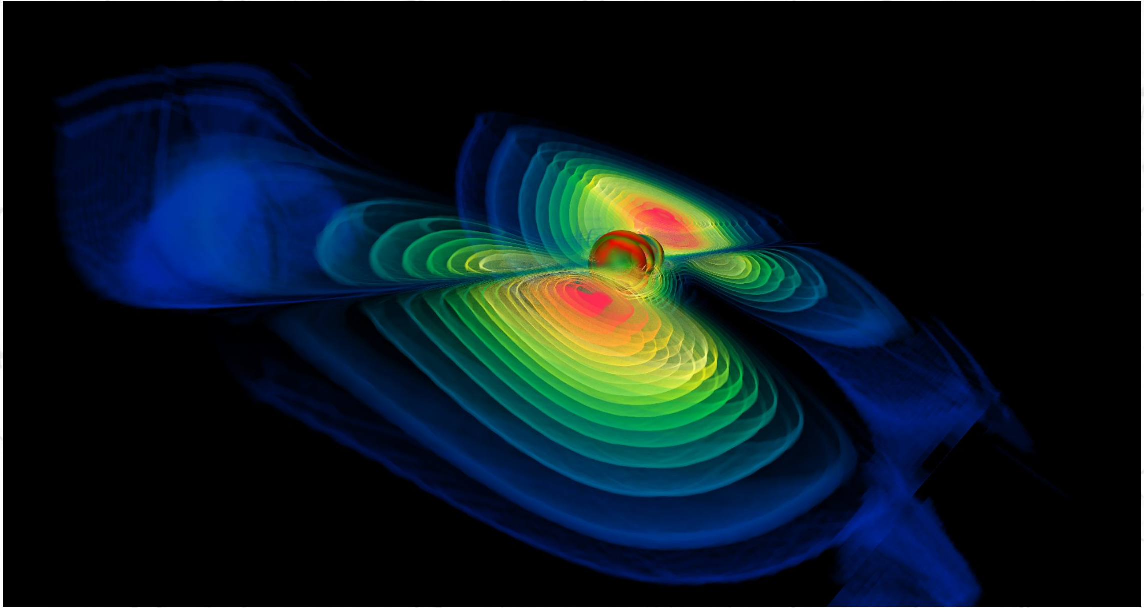
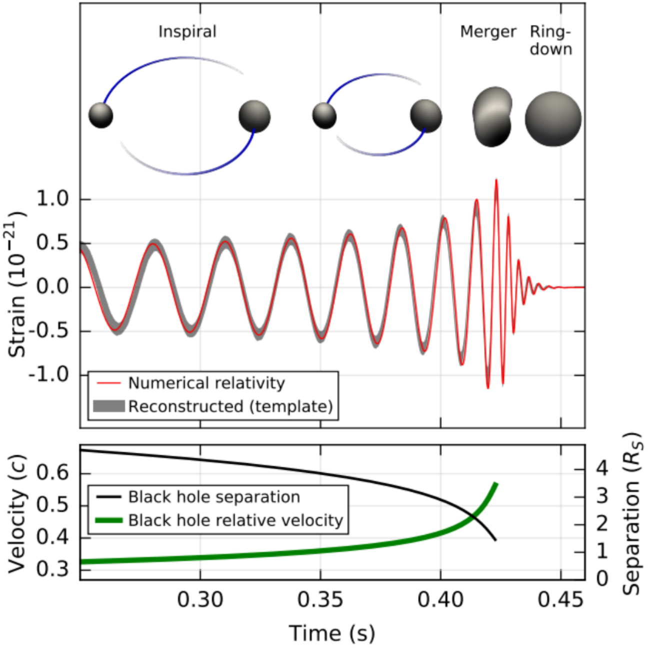
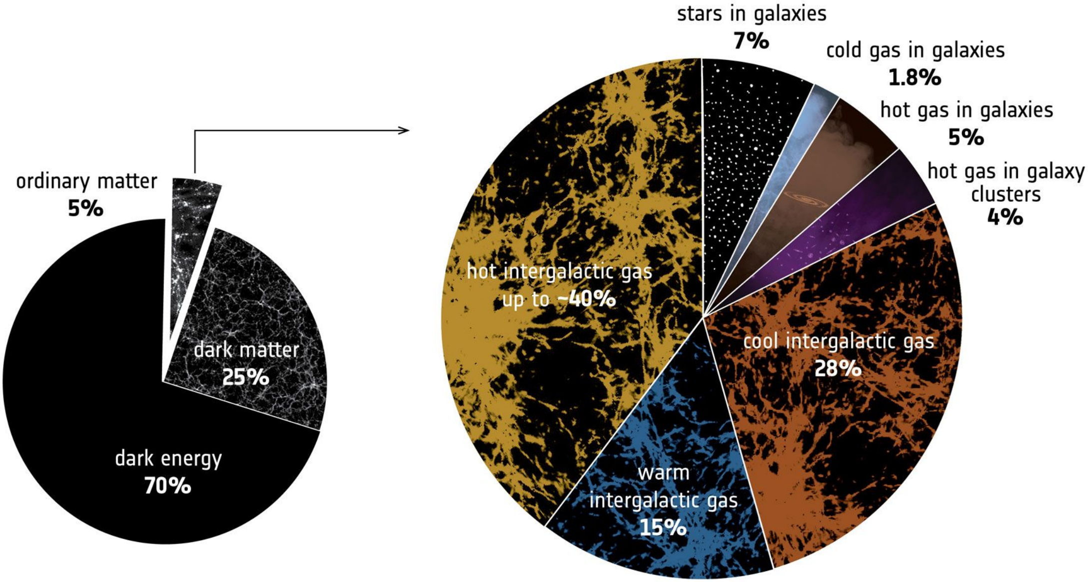
21 FEBRUARY




Inspiral
Merger
Ring-
down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

Primordial Black Hole
https://wiki2.org/en/Primordial_black_hole

- Primordial black hole (also abbreviated as PBH) is a hypothetical type of black hole that formed soon after the Big Bang. In the early universe, high densities and heterogeneous conditions could have led sufficiently dense regions to undergo gravitational collapse, forming black holes. Yakov Borisovich Zel'dovich and Igor Dmitriyevich Novikov in 1966 first proposed the existence of such black holes. The theory behind their origins was first studied in depth by Stephen Hawking in 1971. Since primordial black holes did not form from stellar gravitational collapse, their masses can be far below stellar mass (c. 2×10^{30} kg). The essential ingredient for the formation of a primordial black hole is a fluctuation in the density of the Universe.


ordinary matter
5%
dark matter
25%
dark energy
70%
stars in galaxies
7%
cold gas in galaxies
1.8%
hot gas in galaxies
5%
hot gas in galaxy clusters
4%
hot intergalactic gas up to ~40%
cool intergalactic gas
28%
warm intergalactic gas
15%

Dark matter remains dark

- Dark matter - which has never been directly observed - is thought to constitute the majority of matter in the universe and act as the unseen scaffolding upon which galaxies form and develop.
- Physicists have spent years testing a variety of dark matter candidates, including hypothetical particles such as sterile neutrinos, Weakly Interacting Massive Particles (WIMPS), and axions.

Dark matter remains dark

- With the dark matter problem about to wrap itself up with a bow and no observations suggesting otherwise, primordial black holes became an academic backwater.
  "One senior cosmologist kind of ridiculed me for working on that," said Jedamzik, who traces his own interest back to the 1990s.
  "So I stopped that because I needed to have a permanent position."

Primordial Black Hole Dark Matter and the LIGO/Virgo observations

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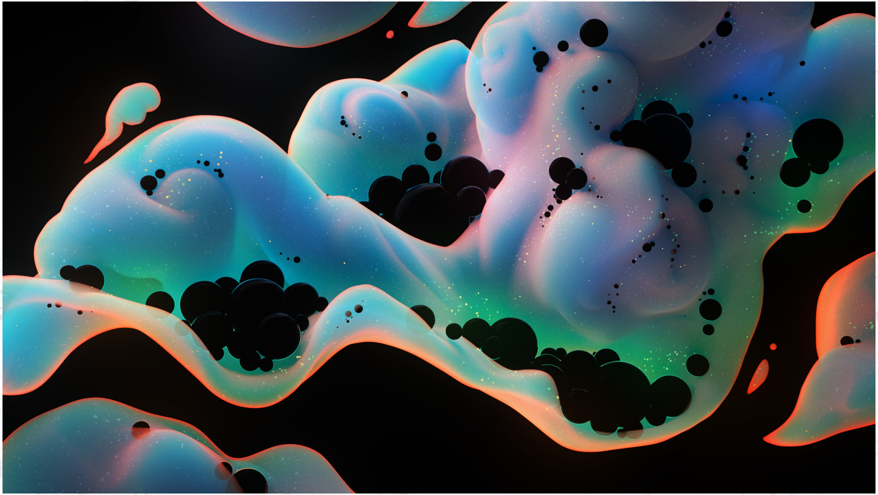
The LIGO/Virgo collaboration have by now detected the mergers of ten black hole binaries via the emission of gravitational radiation. The hypothesis that these black holes have formed during the cosmic QCD epoch and make up all of the cosmic dark matter, has been rejected by many authors reasoning that, among other constraints, primordial black hole (PBH) dark matter would lead to orders of magnitude larger merger rates than observed. We revisit the calculation of the present PBH merger rate. Solar mass PBHs form clusters at fairly high redshifts, which evaporate at lower redshifts. We consider in detail the evolution of binary properties in such clusters due to three-body interactions between the two PBH binary members and a third by-passing PBH, for the first time, by full numerical integration. A Monte-Carlo analysis shows that formerly predicted merger rates are reduced by orders of magnitude due to such interactions. The natural prediction of PBH dark matter formed during the QCD epoch yields a pronounced peak around $1M_\odot$ with a small mass fraction of PBHs on a shoulder around $30M_\odot$, dictated by the well-determined equation of state during the QCD epoch. We employ this fact to make a tentative prediction of the merger rate of $\sim 30M_\odot$ PBH binaries, and find it very close to that determined by LIGO/Virgo. Furthermore we show that current LIGO/Virgo limits on the existence of $\sim M_\odot$ binaries do not exclude QCD PBHs to make up all of the cosmic dark matter. Neither do constraints on QCD PBHs from the stochastic gravitational background, pre-recombination accretion, or dwarf galaxies pose a problem. Microlensing constraints on QCD PBHs should be re-investigated. We caution, however, in this numerically challenging problem some possibly relevant effects could not be treated.

Physicists argue that Black Holes from the Big Bang could be the Dark Matter

- It was an old idea of Stephen Hawking:
  Unseen "primordial" black holes might be the hidden dark matter. It fell out of favor for decades, but a new series of studies has shown how the theory can work.

- *Bernard John Carr (1976).
  Primordial black holes (PhD thesis).
  University of Cambridge.*

Important idea



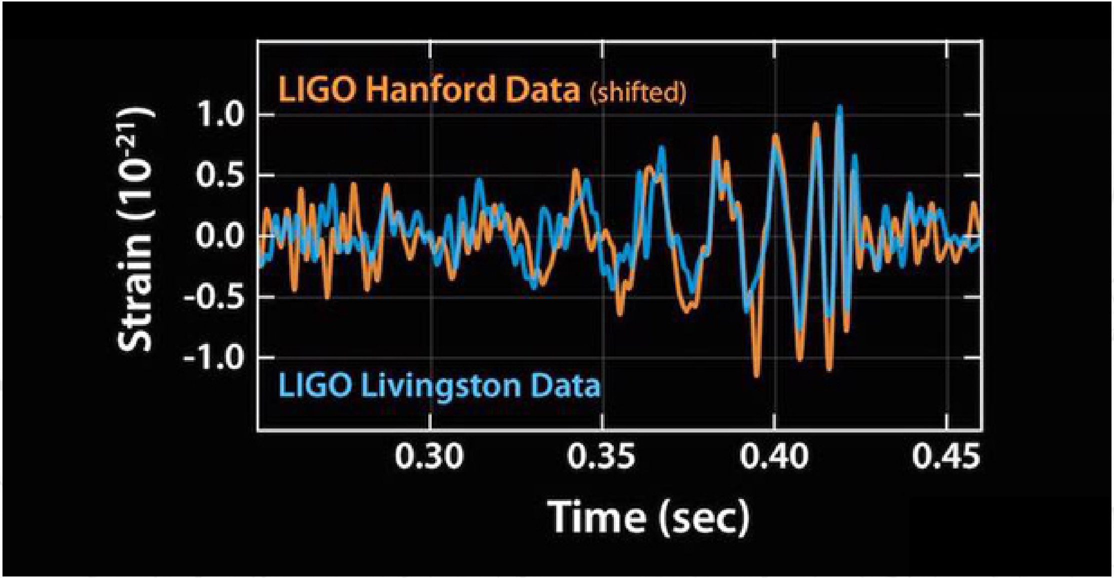
Primordial black holes would cluster in distinct clumps throughout the universe. Relatively large black holes would be surrounded by much smaller ones.

Black holes are elegant and simple, and possibly lurking in deep, dark places all around us.

- The first gravitational waves thrummed through detectors at the Laser Interferometer Gravitational-Wave Observatory (LIGO) in September 2015.

- Previously, the largest star-size black holes had topped out at around 20 times the mass of the sun. These new ones were about 30 solar masses each - not inconceivable, but odd.

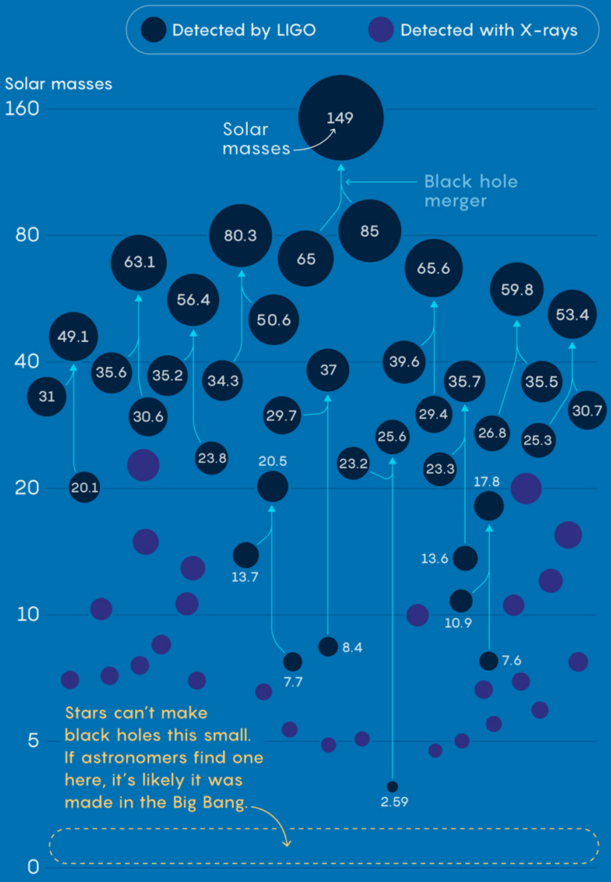
- *B.P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116, 061102 (2016).*

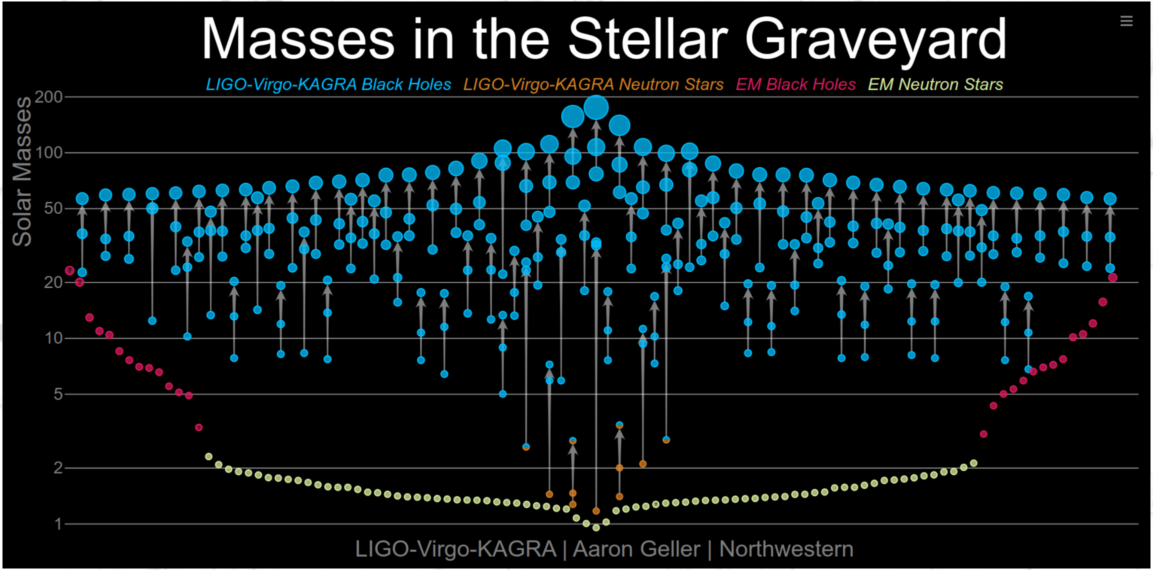


The first gravitational wave signal was observed seven milliseconds apart on 14 September 2015 at Advanced LIGO's Hanford and Livingston detectors.

The Black Holes We Know

Before 2015, all star-size black holes were discovered with X-ray telescopes. These black holes appeared to be limited to about 20 solar masses. LIGO has now observed the collisions of many larger specimens. If primordial black holes exist, many should be in this larger range; others should have masses smaller than our sun.





Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

arXiv:1603.00464: Did LIGO detect dark matter?, Yacine Ali-Haïmoud et al.

- If two BHs in a galactic halo pass sufficiently close, they radiate enough energy in gravitational waves to become gravitationally bound. The bound BHs will rapidly spiral inward due to the emission of gravitational radiation and ultimately merge.
- PBH mergers are likely to be distributed spatially more like dark matter than luminous matter and have no electromagnetic/neutrino counterparts.
- They may be distinguished from mergers of BHs from more traditional astrophysical sources through the observed mass spectrum, their high ellipticities, or their stochastic gravitational-wave background.

arXiv:1603.00464: Did LIGO detect dark matter?, Yacine Ali-Haïmoud et al.

- Consider two PBHs approaching each other on a hyperbolic orbit with some impact parameter and relative velocity $v_{\rm pbh}$. As the PBHs near each other, they produce a time-varying quadrupole moment and thus GW emission. The PBH pair becomes gravitationally bound if the GW emission exceeds the initial kinetic energy. The cross section for this process is:

$$\sigma = \pi \left(\frac{85\,\pi}{3}\right)^{2/7} R_s^2 \left(\frac{v_{\rm pbh}}{c}\right)^{-18/7} = 1.37 \times 10^{-14}\, M_{30}^2\, v_{\rm pbh-200}^{-18/7}\, {\rm pc}^2,$$

where $M_{\rm pbh}$ is the PBH mass, and M_{30} the PBH mass in units of $30\,M_\odot$, $R_s = 2GM_{\rm pbh}/c^2$ is its Schwarzschild radius, $v_{\rm pbh}$ is the relative velocity of two PBHs, and $v_{\rm pbh-200}$ is this velocity in units of 200 km sec^{-1}.

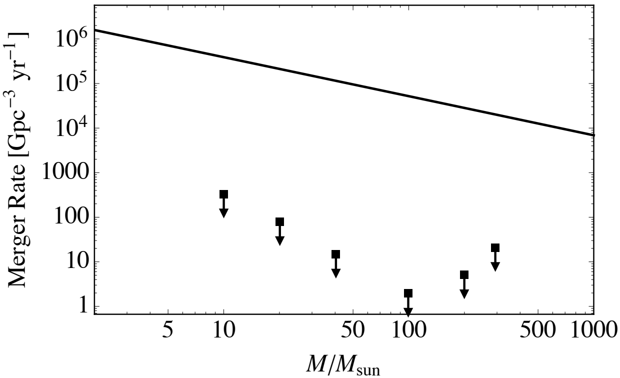
arXiv:1603.00464: Did LIGO detect dark matter?, Yacine Ali-Haïmoud et al.

- They consider the possibility that the black-hole (BH) binary detected by LIGO may be a signature of dark matter, within a window for masses $20\,M_\odot \lesssim M_{\rm bh} \lesssim 100\,M_\odot$ where primordial black holes (PBHs) may constitute dark matter.
- Next generation experiments will be invaluable in performing PBH's GW waveforms with initial high ellipticity exhibited by higher frequency harmonics due to elongated orbit and low-frequency stochastic background.
- These ellipticities become unobservably small by the time the inspiral enters the LIGO band, but they may be detectable in future experiments.

arXiv:1709.06576: The merger rate of primordial-black-hole binaries, Yacine Ali-Haïmoud et al.

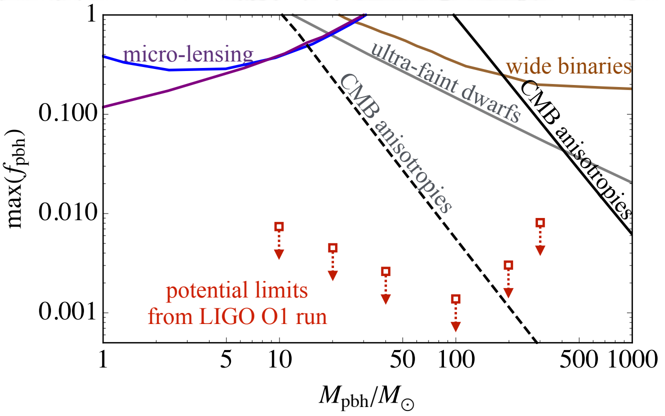
- If binaries formed in the early Universe survive to the present time, as suggested by our analytic estimates, they dominate the total PBH merger rate.
- This merger rate would be orders of magnitude larger than LIGO's current upper limits if PBHs make a significant fraction of the dark matter.

arXiv:1709.06576: The merger rate of primordial-black-hole binaries, Yacine Ali-Haïmoud et al.



Merger rate of PBH binaries if they make up all of the dark matter, and provided PBH binaries are not significantly perturbed between formation and merger (solid line).

arXiv:1709.06576: The merger rate of primordial-black-hole binaries, Yacine Ali-Haïmoud et al.



Upper bounds on the fraction of dark matter in PBHs as a function of their mass.

arXiv:1904.02129: Primordial black holes from the QCD epoch: Linking dark matter, baryogenesis and anthropic selection, Bernard Carr et al.

- If primordial black holes (PBHs) formed at the quark-hadron epoch, their mass must be close to the Chandrasekhar limit, this also being the characteristic mass of stars. If they provide the dark matter (DM), the collapse fraction must be of order the cosmological baryon-to-photon ratio $\sim 10^{-9}$, which suggests a scenario in which a baryon asymmetry is produced efficiently in the outgoing shock around each PBH and then propagates to the rest of the Universe.

arXiv:2110.02821: Primordial Black Holes as Dark Matter Candidates, Bernard Carr et al.

Collapse at the Quantum Chromodynamics Phase Transition

- The mass of a PBH forming at the QCD epoch is

$$M \approx 0.9 \left(\frac{\gamma}{0.2}\right)\left(\frac{g_*}{10}\right)^{-1/2}\left(\frac{\xi}{5}\right)^2 M_\odot \,,$$

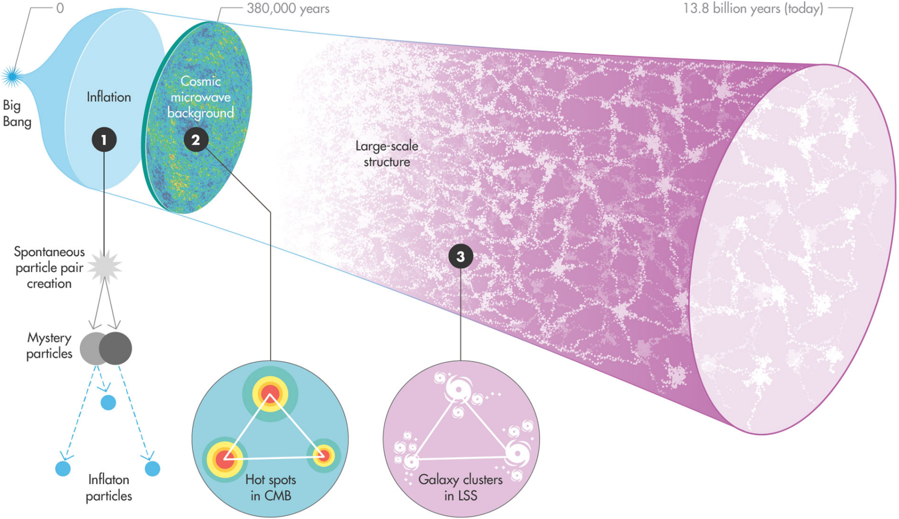
where g_* is normalised appropriately and $\xi \equiv M_{\rm Pl}/(k_{\rm B}\,T) \approx 5$ is the ratio of the proton mass to the QCD phase-transition temperature. This is necessarily close to the Chandrasekhar mass. Since all stars have a mass in the range $(0.1 - 10)$ times this, it has the interesting consequence that dark and visible objects have comparable masses.

arXiv:2108.09471: Primordial Black Holes from Confinement, Dvali et al.

- However, *Dvali et al.* have a scenario which combines inflation with quark confinement to form PBHs somewhat smaller than the mass given by this Equation.

TRIANGLES IN THE SKY

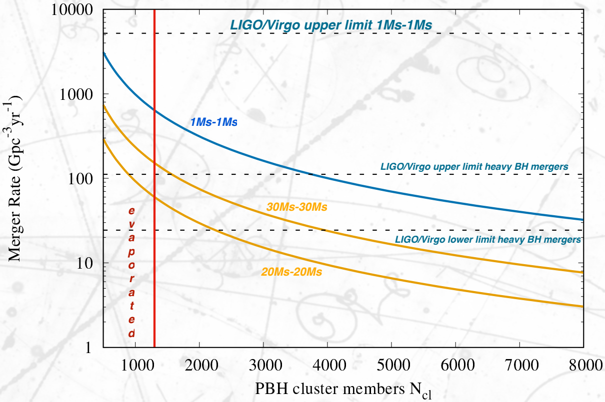
According to the theory of cosmic inflation, pairs of particles spontaneously surfaced throughout the primordial universe. Some pairs decayed into three "inflaton" particles, producing triangular configurations that expanded into arrangements of cosmological structures that are visible today. Triangles may appear as correlations between three hot spots in the 2-D cosmic microwave background (CMB), or between three galaxy clusters in the 3-D large-scale structure (LSS). These triangles and other shapes reveal the types and relationships of particles that existed during inflation.



arXiv:2006.11172: Primordial Black Hole Dark Matter and the LIGO/Virgo observations, Karsten Jedamzik

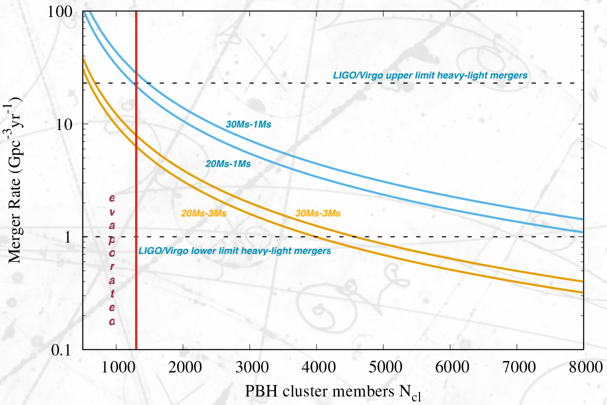
- The natural prediction of PBH dark matter formed during the QCD epoch yields a pronounced peak around $1M_{\odot}$ with a small mass fraction of PBHs on a shoulder around $30M_{\odot}$, dictated by the well-determined equation of state during the QCD epoch.
- The tentative prediction of the merger rate of $\sim 30M_{\odot}$ PBH binaries, is very close to that determined by LIGO/Virgo.

arXiv:2007.03565: Evidence for primordial black hole dark matter from LIGO/Virgo merger rates, Karsten Jedamzik



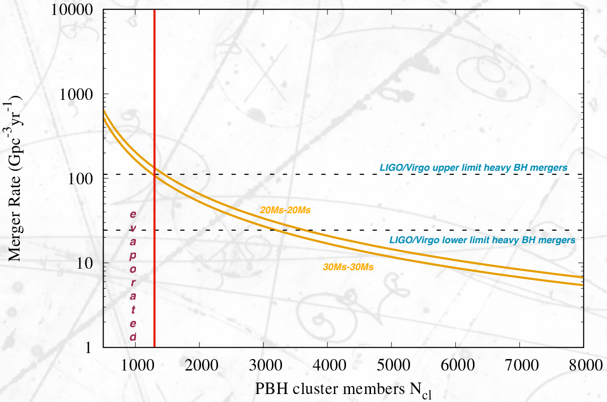
The predicted current merger rates of two equal mass PBHs as a function of the number of PBH cluster members N_{cl} they reside in today.

arXiv:2007.03565: Evidence for primordial black hole dark matter from LIGO/Virgo merger rates, Karsten Jedamzik



Merger rates of light PBHs with heavy PBH.

arXiv:2007.03565: Evidence for primordial black hole dark matter from LIGO/Virgo merger rates, Karsten Jedamzik



Merger rates for inflationary perturbations with a peak on the QCD scale. Where PBH formation during the QCD epoch with an inflationary peak.

Next parts

- The simulations were performed under the assumption of a first order transition.
- Now any softening of the equation state, as for example during higher-order transitions, or annihilation phases, such as the e^+e^- annihilation phase what will happen?
- With the advancements of lattice gauge simulations it was possible to derive the zero chemical potential QCD equation of state with high precision.
- Many more ...