Primordial black hole formation during the QCD phase transition

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Primordial black holes with an accurate QCD equation of state
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Comments: 15 pages, 5 figures
Subjects: Cosmology and Nongalactic Astrophysics (astro-ph.CO)

Moriond 21 March 2018 (15 minutes)
3 distinct questions

1. Is DM a new particle, or PBHs? - previous 3 talks
   There are 3 plausible mass ranges (if black hole decay leaves a relic)

2. Were any of the BHs LIGO detected primordial?

3. How can we constrain the primordial power spectrum over a large range of scales?
   We currently measure only ~7 of the expected 50 e folds of inflation
PBH generation

In order for such compact objects to form quickly, the primordial power spectrum needs to be boosted by ~ 7 orders of magnitude above the value observed on large scales. Exactly how much depends on the equation of state and whether the perturbations are Gaussian.
A cosmological coincidence

- PBHs form quickly due to gravitational collapse as soon as the relevant scale enters the horizon (becomes causal)

- For every given mass, there is a corresponding scale and temperature during the early Universe. QCD transition: $t \approx 10^{-6}$ s, $T \approx 200$ MeV, $M \approx 1 M_\odot$, $k \approx 10^7$ Mpc$^{-1}$

- The horizon mass has grown by about 50 orders of magnitude since the end of inflation. The QCD phase transition occurs during the time when LIGO mass PBHs formed.
The QCD phase transition

• As the Universe cools below 1 GeV, strong interactions confine quarks into hadrons and the effective number of relativistic degrees of freedom decreases and $w$ decreases. Borsanyi et al (2016) have recently made the first definitive predictions of this period (to 0.3% accuracy)

• The Hubble volume (horizon) mass ($M_H$) during the peak decrease is about one solar mass. PBHs form with a mass comparable to the horizon mass
The resultant mass function of PBHs

\[ f(M) = \frac{1}{\Omega_{\text{CDM}}} \frac{d\Omega_{\text{PBH}}}{d \ln M_H} \]

\[ f(M) \propto M^{-1/2} e^{-\frac{\delta_c^2}{2\sigma_\delta^2}} \]

- Despite the collapse threshold decreasing by only 10%, PBH formation is boosted by > two orders of magnitude.

- This primarily boosts the number of solar mass PBHs, but also those with the mass LIGO detected.

- For the left plot, approx 10% of DM is made up of ~ solar mass PBHs and 0.1% lies in the LIGO mass range - enough to get the merger rate LIGO detects (neglecting clustering).
  - Sasaki et al. 2016 + Haimoud et al + Chen & Huang ++
Distortions provide general power spectrum constraints!

- Amplitude of power spectrum rather uncertain at $k > 3 \text{ Mpc}^{-1}$
- improved limits at smaller scales can rule out many inflationary models
- CMB spectral distortions would extend our lever arm to $k \sim 10^4 \text{ Mpc}^{-1}$
- very complementary piece of information about early-universe physics

\[ \text{e.g., JC, Khatiri & Sunyaev, 2012; JC, Erickcek & Ben-Dayan, 2012; JC & Jeong, 2013} \]

Slide by Jens Chluba - Ultra compact minihalo constraints are unreliable (Gosenca et al, Delos et al, Nakama et al; all 2017). Spectral distortion constraints are tighter than PBH constraints for $M > 10^3 M_\odot$. Non-Gaussian perturbations can evade these constraints, e.g. Nakama, Carr & Silk 2017
PBH abundance is exponentially sensitive to non-Gaussianity

Local non-Gaussianity (chi-squared)

\[ \zeta = \zeta_g + \frac{3}{5} f_{NL} (\zeta_g^2 - \sigma^2) \]

\[ P_\zeta = 10^{-2} \]

Young and CB 2013

Even a tiny amount of squeezed limit (local) non-Gaussianity correlating standard CMB scales with PBH formation scales will generate large scale DM isocurvature perturbations. This is strongly ruled out by Planck constraints - Tada & Yokoyama 2015, Young & CB 2015
Varying the primordial perturbations

• If the primordial power spectrum is not scale invariant on the relevant scales then the mass function changes, but a peak remains

\[ n_s - 1 = -0.05 \]

\[ n_s - 1 = -0.2 \]
Key points

• The BHs LIGO detected might be astrophysical or primordial
  Bird et al. 2016, Clesse & Garcia-Bellido 2016

• If the initial power spectrum was boosted on scales
  corresponding to LIGO mass BHs, the QCD phase transition
  naturally predicts a much larger population of stellar mass
  PBHs

• Future LIGO observations (+ others) will test this scenario
  and extend our lever arm on inflaiton
Thermal history

Plot by Antony Lewis
Summary

• We have made the first calculation of PBH formation using a realistic equation of state during the QCD phase transition. Uncertainty in PBH formation and the amplitude of the primordial power spectrum dominate over QCD uncertainties for the first time.

• If LIGO did detect PBHs, then there should exist a much larger population of solar mass BHs. These are below the Chandrasekhar mass and hence would be the clearest evidence for PBHs.

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