Primordial black holes formed in the matter-dominated era

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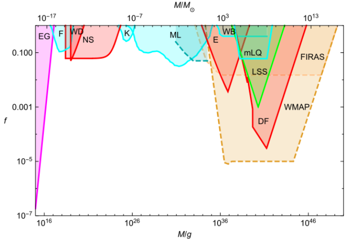
This talk is based on the collaboration:

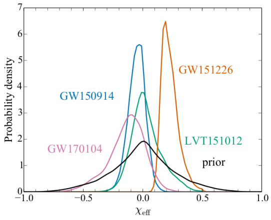
- Harada, Yoo (Nagoya), Kohri (KEK), Nakao (OCU) & Jhingan (YGU), 1609.01588
- Harada, Yoo, Kohri, & Nakao, 1707.03595

Primordial black hole (PBH)

- PBH = Black hole formed in the early Universe
  - Probe into the early Universe and high-energy physics. γ-rays, X-rays, DM and GWs. (Carr et al. (2010), Carr et al. (2016))
  - LIGO BBHs may be of primordial origin. (Sasaki et al. (2016), Bird et al. (2016), Clesse & Garcia-Bellido (2017))
  - BH spins have attracted great attention. (e.g. McClintock (2011), Abbott et al. (2017))



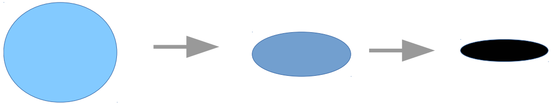
(a) Carr et al. (2016)



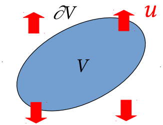
(b) LIGO Collaboration (2017)

PBH formation in the matter-dominated (MD) era

- Pioneered by Khlopov & Polnarev (1980). Early MD phase scenarios such as inflaton oscillations, phase transitions, and superheavy metastable particles.
- If pressure is negligible, nonspherical effects play crucial roles.
  - The triaxial collapse of dust leads to a “pancake” singularity. (Lin, Mestel & Shu (1965), Zeldovich (1969))



  - The effect of angular momentum may halt gravitational collapse or spin the formed PBHs. (Peebles (1969), Catelan & Theuns (1996))



Zeldovich approximation

- Zeldovich approximation (ZA) (1969)
  Extrapolate the Lagrangian perturbation theory in the linear order in Newtonian gravity to the nonlinear regime.

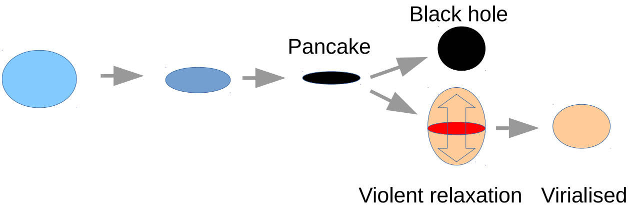
$$r_i = a(t)q_i + b(t)p_i(q_j),$$

  where $b(t) \propto a^2(t)$ denotes a linearly growing mode.
- We can take the coordinates in which

$$\frac{\partial p_i}{\partial q_j} = \mathrm{diag}(-\alpha, -\beta, -\gamma).$$

- We assume that α, β and γ are constant over the smoothing scale and normalise b so that $b/a = 1$ at horizon entry $t = t_H$ of the scale.

Application of the hoop conjecture



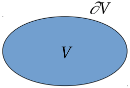
- Hoop conjecture (Thorne 1972): A BH forms if and only if the circumference C of a mass M satisfies $C \lesssim 4\pi GM/c^2$.
- Then, we obtain a BH criterion for the pancake collapse.

$$h(\alpha,\beta,\gamma) := \frac{C}{4\pi Gm/c^2} = \frac{2}{\pi}\frac{\alpha-\gamma}{\alpha^2}E\left(\sqrt{1-\left(\frac{\alpha-\beta}{\alpha-\gamma}\right)^2}\right) \lesssim 1,$$

where $E(e)$ is the complete elliptic integral of the second kind.

Spin angular momentum

- Region V: to collapse in the future



- Angular momentum with respect to the COM in the Eulerian coordinates

$$\mathbf{L} = \rho_0 a^4 \left(\int_V \mathbf{x} \times \mathbf{u} d^3\mathbf{x} + \int_V \mathbf{x}\delta \times \mathbf{u} d^3\mathbf{x} - \frac{1}{V} \int_V \mathbf{x}\delta d^3\mathbf{x} \times \int_V \mathbf{u} d^3\mathbf{x} \right),$$

where $\mathbf{x} := \mathbf{r}/a$, $\mathbf{u} := aD\mathbf{x}/Dt$, $\delta := (\rho - \rho_0)/\rho_0$, and $\psi := \Psi - \Psi_0$.

- Linearly growing mode of perturbation

$$\delta_1 = \sum_{\mathbf{k}} \hat{\delta}_{1,\mathbf{k}}(t) e^{i\mathbf{k}\cdot\mathbf{x}}, \; \psi_1 = \sum_{\mathbf{k}} \hat{\psi}_{1,\mathbf{k}}(t) e^{i\mathbf{k}\cdot\mathbf{x}}, \; \mathbf{u}_1 = \sum_{\mathbf{k}} \hat{\mathbf{u}}_{1,\mathbf{k}}(t) e^{i\mathbf{k}\cdot\mathbf{x}},$$

where $\hat{\delta}_{1,\mathbf{k}} = A_{\mathbf{k}} t^{2/3}, \; \hat{\psi}_{1,\mathbf{k}} = -\frac{2}{3}\frac{a_0^2}{k^2} A_{\mathbf{k}}, \; \hat{\mathbf{u}}_{1,\mathbf{k}} = i a_0 \frac{\mathbf{k}}{k^2} \frac{2}{3} A_{\mathbf{k}} t^{1/3}.$

1st-order effect

$$\mathbf{L} = \rho_0 a^4 \left(\int_V \mathbf{x} \times \mathbf{u} d^3\mathbf{x} + \int_V \mathbf{x}\delta \times \mathbf{u} d^3\mathbf{x} - \frac{1}{V} \int_V \mathbf{x}\delta d^3\mathbf{x} \times \int_V \mathbf{u} d^3\mathbf{x} \right)$$

- If ∂V is not a sphere, the 1st term contribution grows as $\propto a \cdot \mathbf{u} \propto t$.
- For an ellipsoid with axes (A_1, A_2, A_3),

$$\langle \mathbf{L}^2_{(1)} \rangle^{1/2} \simeq \frac{2}{5\sqrt{15}} q \frac{MR^2}{t} \langle \delta^2 \rangle^{1/2},$$

where $r_0 := (A_1 A_2 A_3)^{1/3}$, $R := a(t) r_0$, q is a nondimensional reduced quadrupole moment, and δ is the averaged density perturbation. (Cf. Catelan & Theuns 1996)

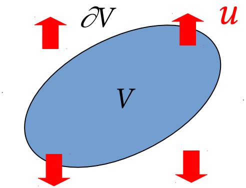


Figure: The 1st-order effect can grow if ∂V is not a sphere.

2nd-order effect

$$\mathbf{L} = \rho_0 a^4 \left(\int_V \mathbf{x} \times \mathbf{u} d^3\mathbf{x} + \int_V \mathbf{x}\delta \times \mathbf{u} d^3\mathbf{x} - \frac{1}{V} \int_V \mathbf{x}\delta d^3\mathbf{x} \times \int_V \mathbf{u} d^3\mathbf{x} \right)$$

- Even if ∂V is a sphere, the remaining contribution grows as 1st order × 1st order $\propto a \cdot \delta \cdot \mathbf{u} \propto t^{5/3}$.

$$\langle \mathbf{L}_{(2)}^2 \rangle^{1/2} = \frac{2}{15} \mathcal{I} \frac{MR^2}{t} \langle \delta^2 \rangle,$$

where $R := a(t) r_0$ and we can assume $\mathcal{I} = O(1)$. (Cf. Peebles 1969)

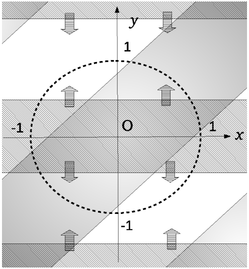


Figure: The 2nd-order effect can grow due to the mode coupling.

The application of the Kerr bound

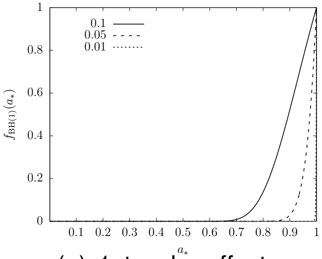
- Time evolution of V and angular momentum
  - Horizon entry ($t = t_H$): $ar_0 = cH^{-1}$, $\delta_H := \delta(t_H)$, $\sigma_H := \langle \delta_H^2 \rangle^{1/2}$
  - Turn around ($t = t_m$): $\delta(t_m) = 1$, typically $t_m = t_H \sigma_H^{-3/2}$
  - $a_* := L/(GM^2/c)$ at $t = t_m$

$$\langle a_{*(1)}^2 \rangle^{1/2} = \frac{2}{5}\sqrt{\frac{3}{5}} q \sigma_H^{-1/2}, \langle a_{*(2)}^2 \rangle^{1/2} = \frac{2}{5} \mathcal{I} \sigma_H^{-1/2}$$

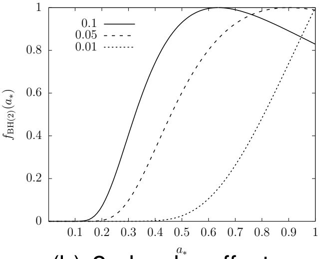
  - For $t > t_m$, the evolution of V decouples from the cosmological expansion and hence a_* is kept almost constant.
- Consequences
  - Typically $\langle a_*^2 \rangle^{1/2} \gtrsim 1$ if $\sigma_H \lesssim 0.1$. This contrasts with small spins ($a_* \lesssim 0.4$) of PBHs formed in the RD era. (Chiba & Yokoyama (2017))
  - a_* is typically too large for direct collapse to a BH.

Spin distribution

- Spin distribution of PBHs formed in the MD era



(a) 1st-order effect



(b) 2nd-order effect

Figure: A Gaussian distribution assumed for the density perturbation. Each curve labelled with σ_H.

- The region with smaller δ_H has larger a_*. There appears a threshold δ_{th} below which the angular momentum halts the collapse to a BH.

PBH production probability

- Triple integral for production probability β_0

$$\beta_0 \simeq \int_0^\infty d\alpha \int_{-\infty}^{\alpha} d\beta \int_{-\infty}^{\beta} d\gamma\, \theta[\delta_H(\alpha,\beta,\gamma) - \delta_{\rm th}]\theta[1 - h(\alpha,\beta,\gamma)] w(\alpha,\beta,\gamma),$$

where we use $w(\alpha,\beta,\gamma)$ given by Doroshkevich (1970).

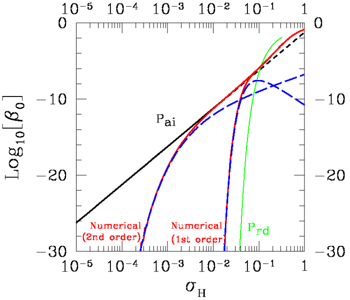


Figure: The red lines are due to both angular momentum and anisotropy. The black solid line is solely due to anisotropy.

Discussion of PBH production probability

- Semianalytic estimate (black dashed line and blue dashed line)

$$\beta_0 \simeq \begin{cases} 2\times 10^{-6} f_q(q_c)\mathcal{I}^6\sigma_H^2 \exp\left[-0.15\dfrac{\mathcal{I}^{4/3}}{\sigma_H^{2/3}}\right] & \text{(2nd-order effect)} \\ 3\times 10^{-14}\dfrac{q^{18}}{\sigma_H^4}\exp\left[-0.0046\dfrac{q^4}{\sigma_H^2}\right] & \text{(1st-order effect)} \\ 0.05556\sigma_H^5 & \text{(anisotropic effect)} \end{cases}$$

  where $f_q(q_c)$: the fraction of regions with $q < q_c = O(\sigma_H^{1/3})$.
- The density fluctuation σ_H can be written in terms of the power spectrum $P_\zeta(k)$ of the curvature perturbation ζ as

$$\sigma_H^2 \simeq \left(\frac{2}{5}\right)^2 P_\zeta(k_{BH}).$$

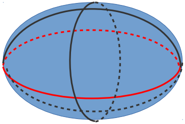
Summary

- PBHs may form not only in the RD era but also in the (early) MD era from primordial cosmological fluctuations.
- In the MD era, the effect of anisotropy gives $\beta_0 \simeq 0.05556\sigma_H^5$, while the effect of angular momentum gives further suppression for the smaller values of σ_H.
- PBHs formed in the MD era mostly have large spins ($a_* \simeq 1$) in contrast to the small spins ($a_* \lesssim 0.4$) of PBHs formed in the RD era.

Anisotropic collapse in the ZA

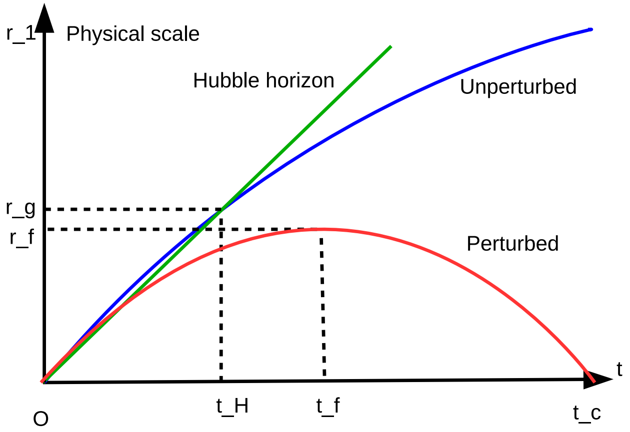
- The triaxial ellipsoid of a Lagrangian ball (assumption)

$$\begin{cases} r_1 = (a - \alpha b)q \\ r_2 = (a - \beta b)q \\ r_3 = (a - \gamma b)q \end{cases}$$



- Evolution of the collapsing region:
  - Horizon entry ($t = t_H$): $a(t_H)q = cH^{-1}(t_H) = r_g := 2Gm/c^2$.
  - Maximum expansion ($t = t_f$): $\dot{r}_1(t_f) = 0$ giving $r_f := r_1(t_f) = r_g/(4\alpha)$.
  - Pancake singularity ($t = t_c$): $r_1(t_c) = 0$ giving $a(t_c)q = 4r_f = r_g/\alpha$.

Evolution of the perturbation



Application of the Kerr bound

- Technical assumption

$$|\mathbf{L}_{(1)}| \simeq \frac{2}{5\sqrt{15}} q \frac{MR^2}{t} \delta, \ |\mathbf{L}_{(2)}| \simeq \frac{2}{15} \mathcal{I} \frac{MR^2}{t} \langle \delta^2 \rangle^{1/2} \delta.$$

- The above assumption implies

$$a_{*(1)} = \frac{2}{5}\sqrt{\frac{3}{5}} q \delta_H^{-1/2}, \ \ a_{*(2)} = \frac{2}{5} \mathcal{I} \sigma_H \delta_H^{-3/2}, \ \ a_* = \max(a_{*(1)}, a_{*(2)}).$$

- The Kerr bound $a_* \leq 1$ gives a threshold $\delta_{\rm th}$ for δ_H, where

$$\delta_{\rm th} = \max(\delta_{\rm th(1)}, \delta_{\rm th(2)}), \ \ \delta_{\rm th(1)} := \frac{3 \cdot 2^2}{5^3} q^2, \ \ \delta_{\rm th(2)} := \left(\frac{2}{5} \mathcal{I} \sigma_H \right)^{2/3}.$$