Black hole formation in a contracting universe

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Based on work with **Robert Brandenberger** (McGill U.)

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ΛCDM parameters

Parameter	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02242 ± 0.00014
$\Omega_c h^2$	0.11933 ± 0.00091
$100\theta_{MC}$	1.04101 ± 0.00029
τ	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.047 ± 0.014
n_s	0.9665 ± 0.0038

Planck18 [1807.06209]

- $\alpha_s \equiv dn_s/d\ln k = -0.004 \pm 0.013$, $r < 0.065$ $(95\,\%)$
- $f_{NL}^{local} = 0.8 \pm 5.0$, $f_{NL}^{equil} = -4 \pm 43$, $f_{NL}^{ortho} = -26 \pm 21$ Planck15 [1502.01592]
- Many inflation models can give you those numbers

But inflation is not the only possibility!

- Ekpyrotic cosmology (contraction with $p = w\rho$, $w \gg 1$) Khoury *et al.* [hep-th/0103239], Ijjas *et al.* [1404.1265], Lehners & Wilson-Ewing [1507.08112], Fertig *et al.* [1607.05663]

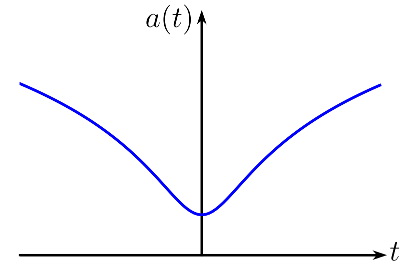
$$n_{\mathrm{s}} \sim 0.97\,,\ \alpha_{\mathrm{s}} \sim \mathcal{O}(-10^{-3})\,,\ r \approx 0\,,\ |f_{\mathrm{NL}}| \sim \mathcal{O}(1) - \mathcal{O}(10)$$

- String gas cosmology (quasi-static, thermal) Brandenberger & Vafa ['89], Chen *et al.* [0712.2477], Brandenberger *et al.* [1403.4927], Brandenberger [1505.02381]

$$n_{\mathrm{s}} < 1\,,\ r \ll 1\,,\ |f_{\mathrm{NL}}| \ll 1\,,\ n_{\mathrm{t}} \approx 1 - n_{\mathrm{s}} > 0$$

- And other scenarios See review: Brandenberger & Peter [1603.05834]

Bouncing Cosmology



- Many alternatives are 'bouncing' scenarios: the Big Bang is replaced by a bounce, before which the Universe was contracting
- Can we find generic predictions or imprints of a contracting Universe before the Big Bang/bounce?
- Take a minimal assumption: consider a contracting universe with matter as we know it today (i.e., dust, radiation, etc.)

Hydrodynamical fluid in a contracting universe

- Energy density and pressure:

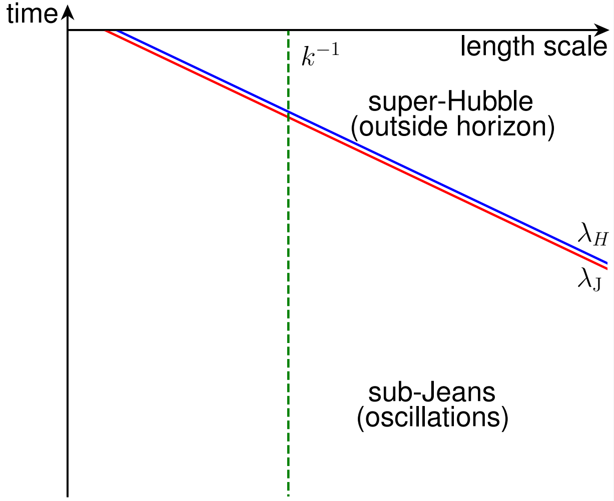
$$\rho(t,\boldsymbol{x}) = \bar{\rho}(t) + \delta\rho(t,\boldsymbol{x})\,, \qquad p(t,\boldsymbol{x}) = \bar{p}(t) + \delta p(t,\boldsymbol{x})$$

$$\bar{p} = w\bar{\rho}\,, \qquad \delta p = c_{\mathrm{s}}\delta\rho\ (\text{constant entropy})\,, \qquad c = 1$$

- Dust: $w = c_{\mathrm{s}}^2 \ll 1$; radiation $w = c_{\mathrm{s}}^2 = 1/3$
- Density contrast in Fourier space: $\delta_k \equiv \delta\rho_k/\bar{\rho}$
- Jeans scale: $k_{\mathrm{J}} \equiv \sqrt{4\pi G_{\mathrm{N}}\bar{\rho}/c_{\mathrm{s}}}$, $\lambda_{\mathrm{J}} \sim 1/k_{\mathrm{J}}$
- Sub-Jeans scales $(\lambda < \lambda_{\mathrm{J}}) \implies$ oscillations ($\delta_k(t) \sim e^{\pm i c_{\mathrm{s}} k t}$)
- Super-Jeans scales $(\lambda > \lambda_{\mathrm{J}}) \implies$ gravitational instability ($\delta_k(t) \nearrow$)
- Can this lead to black holes?

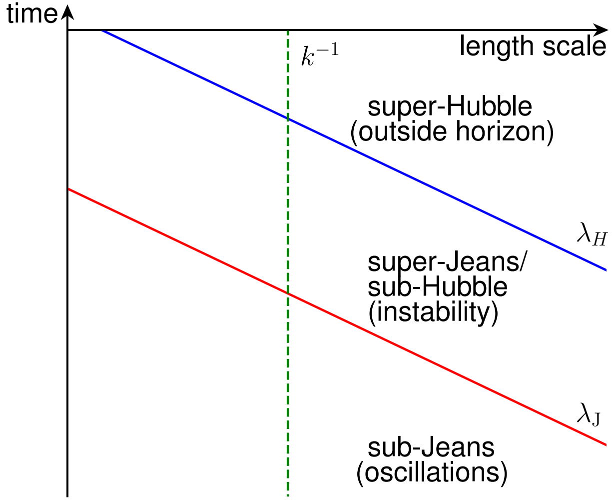
Jeans and Hubble scales

- Jeans radius: $\lambda_{\rm J} = c_{\rm s}(a|H|)^{-1}$; Hubble radius: $\lambda_H = (a|H|)^{-1}$
- Radiation $\implies c_{\rm s}^2 = 1/3 \implies \lambda_{\rm J} \sim \lambda_H$



Jeans and Hubble scales

- Jeans radius: $\lambda_\mathrm{J} = c_\mathrm{s}(a|H|)^{-1}$; Hubble radius: $\lambda_H = (a|H|)^{-1}$
- Dust $\implies c_\mathrm{s}^2 \ll 1 \implies \lambda_\mathrm{J} \ll \lambda_H$



Black hole formation probability

- Specify initial conditions (e.g., quantum vacuum, thermal state, etc.) $\longrightarrow$ get full solution for $\delta_k(t)$ by solving the linearized Einstein equations

- Probability of black hole formation (Press-Schechter formalism):

$$\mathrm{Prob}(R,t) = \sqrt{\frac{2}{\pi}}\frac{1}{\sigma}\int_{\delta_\mathrm{c}}^{\infty}\mathrm{d}\delta\ e^{-\delta^2/2\sigma^2}\,,$$

$$\sigma^2(R,t) = \frac{1}{2\pi^2}\int_0^{\infty}\mathrm{d}k\,k^2W^2(kR)|\delta_k(t)|^2\,,$$

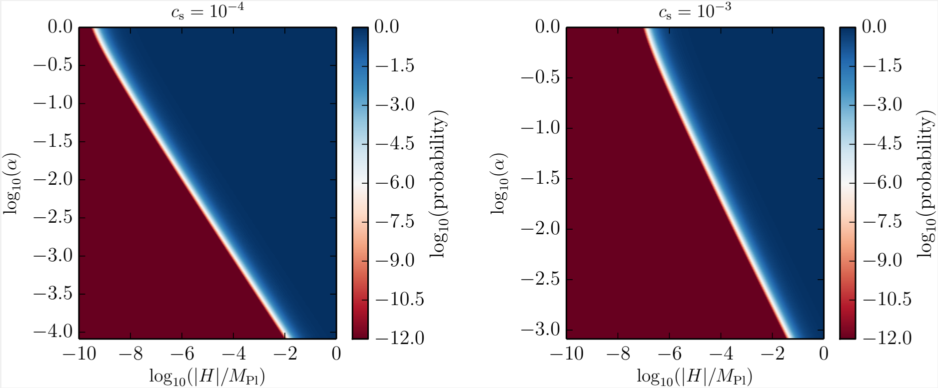
$$W(kR) = \mathrm{Window\ function}$$

- High probability when $\sigma \gtrsim \delta_\mathrm{c}$

Black hole formation probability

- Starting with a quantum vacuum JQ & Brandenberger [1609.02556]

$$\alpha \equiv R_{\rm BH}/|H|^{-1}$$

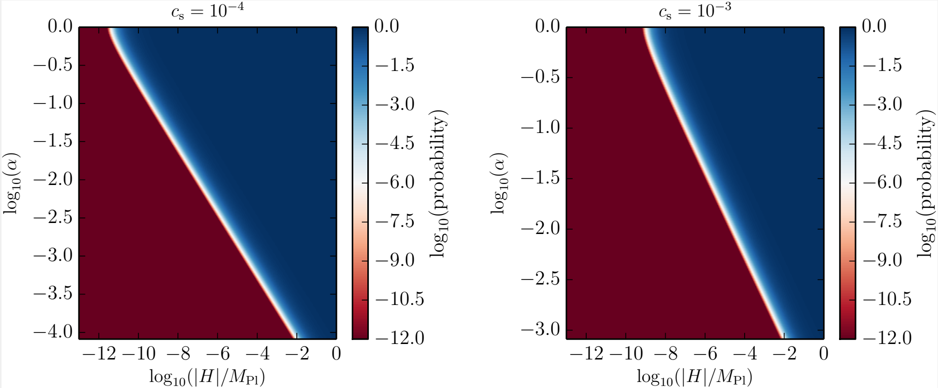


dust, super-Jeans/sub-Hubble: $|\delta_k(t)|^2 \sim k^{-3} c_s^{-5} H(t)^2$

Black hole formation probability

- Starting with a thermal state at $|H_{\rm ini}| = 10^{-16}\ M_{\rm Pl}$ JQ & Brandenberger [1609.02556]

$$\alpha \equiv R_{\rm BH}/|H|^{-1}$$



Implications and discussion

- If a long-enough phase of dust-dominated contraction lasts, Hubble-size black holes form well before Planckian densities: $R_{\rm BH} \sim c_{\rm s}^{-5/2} \ell_{\rm Pl}$ (quantum); $R_{\rm BH} \sim c_{\rm s}^{-18/5} \ell_{\rm Pl}$ (thermal) JQ & Brandenberger [1609.02556]

- E.g. (quantum initial conditions):
  $c_{\rm s} = 10^{-10} \implies R_{\rm BH} \sim 10^{25}\,\ell_{\rm Pl} \sim 10^{-10}\,{\rm m}$,
  $M_{\rm BH} \sim 10^{20}\,{\rm g} \sim 10^{-13}\,M_\odot \longrightarrow$ primordial black hole?

- E.g. 2: $c_{\rm s} = 10^{-5} \implies R_{\rm BH} \sim 10^{12}\,\ell_{\rm Pl} \sim 10^{-23}\,{\rm m}$, $M_{\rm BH} \sim 10^{7}\,{\rm g} \longrightarrow$ evaporated black hole remnant?

- Harder to form black holes if $c_{\rm s}$ increases (e.g., no radiation black holes before Planckian densities)

- But easier to form black holes if there are structures already in the Universe (rather than just a quantum vacuum)

Outlook

- First estimate of black hole formation in a contracting universe $\longrightarrow$ analysis could be refined
- Can black holes pass through a bounce? Carr *et al.* [1104.3796, 1402.1437, 1701.05750, 1704.02919]
- If so, one can use observations to constrain bouncing cosmological models Chen *et al.* [1609.02571]
- Could there be specific gravitational wave signals? Barrau *et al.* [1711.05301]
- Also, could black holes play a role in the bounce itself? E.g., black holes at the string scale Mathur [0803.3727], Masoumi [1505.06787], JQ *et al.* [1809.01658]

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