Scalar fields and primordial black holes

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Chameleon gravity

-There are conceptual issues with a cosmological constant.

-Scalar field theories can explain the universe's accelerated expansion.

-These fields are coupled to matter, but we haven't detected a "fifth force" in the solar system.

-Chameleon scalar field couplings depend on the local matter density.

Equations of motion

-The addition of a scalar field leads to a modified action.

-Varying the Einstein-Hilbert action with respect to the inverse metric, we get the Einstein field equations.

-We can get the scalar field equation of motion in a similar fashion.

$$S = \int \mathrm{d}^4x\sqrt{-g_*}\left[\frac{M_{\mathrm{pl}}^2}{2}R_*\right] + S_m[\tilde{g}_{\mu\nu}, \psi_m]$$

$$\Big\downarrow \ \frac{\delta}{\delta g_{\mu\nu}}$$

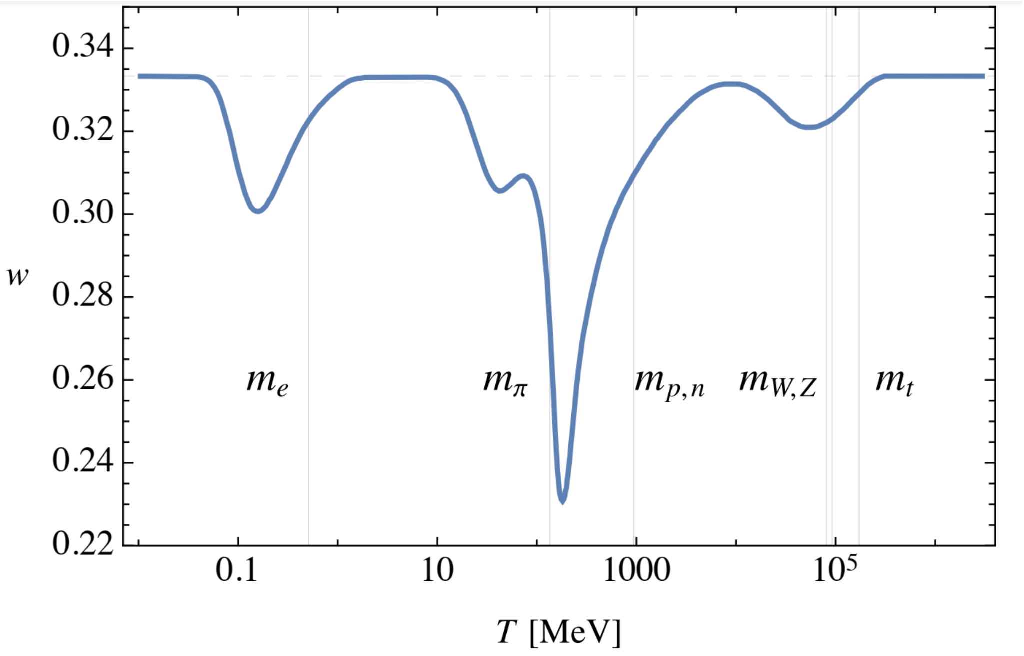
$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

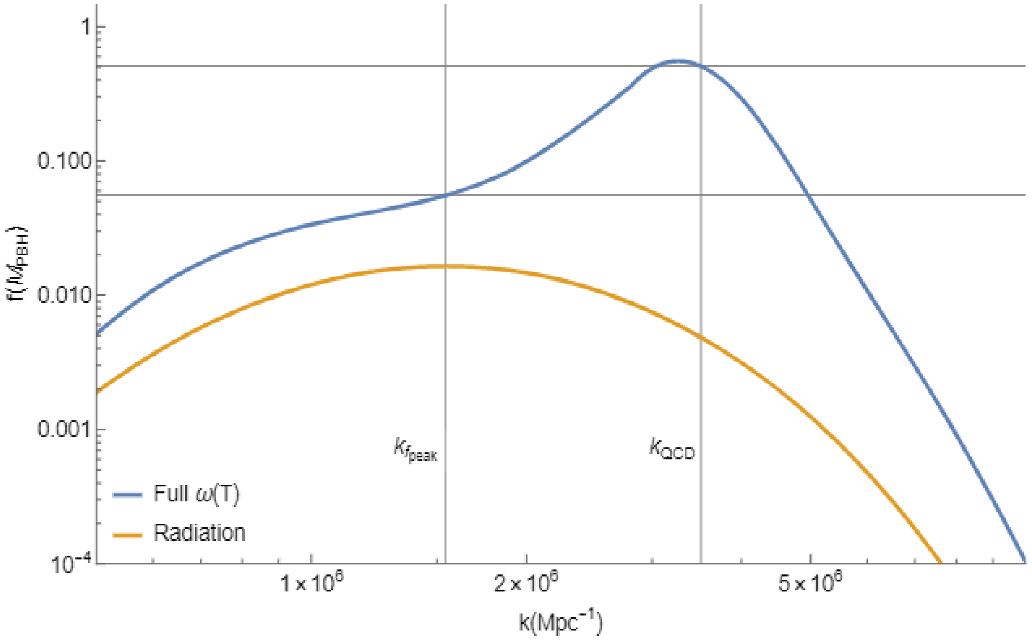
$$S = \int \mathrm{d}^4x\sqrt{-g_*}\left[\frac{M_{\mathrm{pl}}^2}{2}R_* - \frac{1}{2}(\nabla_*\phi)^2 - V(\phi)\right] + S_m[\tilde{g}_{\mu\nu}, \psi_m]$$

$$\Big\downarrow \ \frac{\delta}{\delta \phi}$$

$$\ddot{\phi} + 3H_*\dot{\phi} = -\frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi} - \frac{\beta}{M_{\mathrm{pl}}}\rho_*(1-3\omega)$$

https://arxiv.org/pdf/1906.08217





Early universe equation of state and PBHs

-Thermodynamic properties of the primordial plasma in the SM have been calculated precisely.

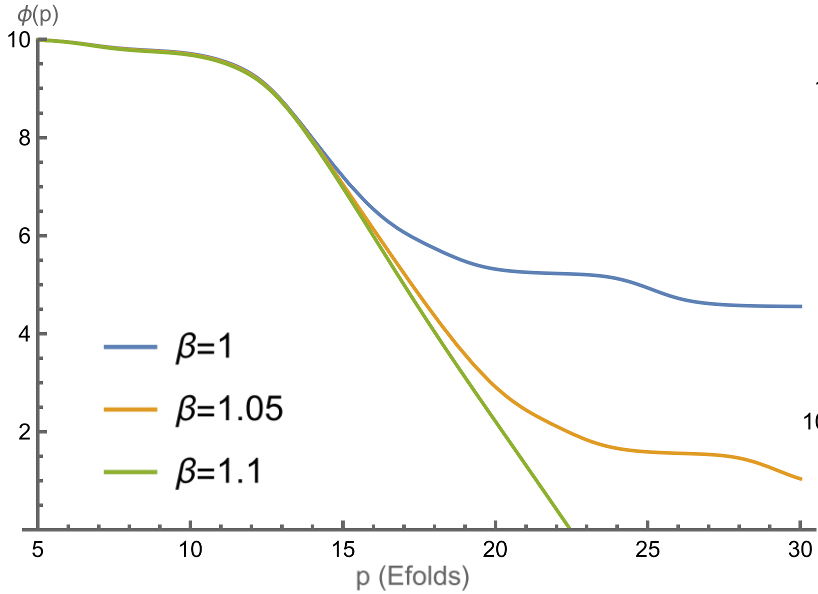
-When the universe's temperature drops below a particle's rest energy, it will decouple.

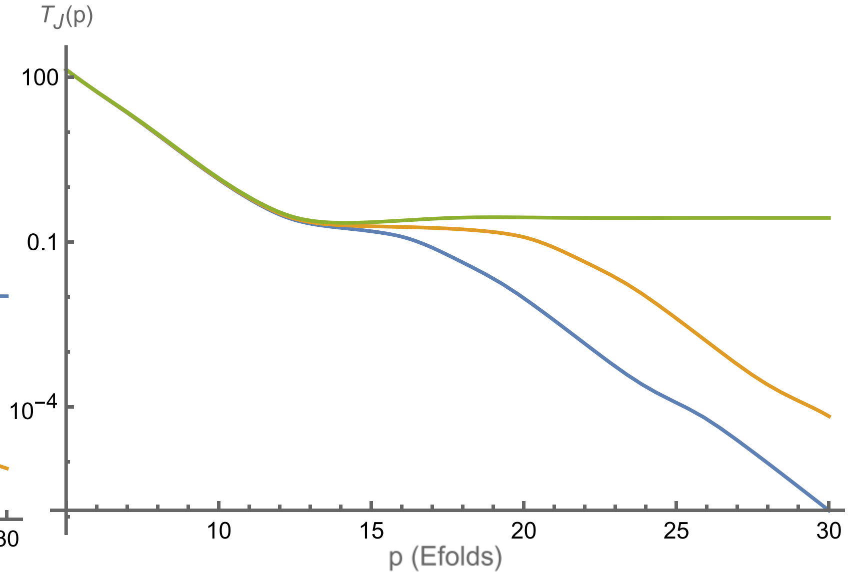
-Particles decoupling lead to reductions in the equation of state.

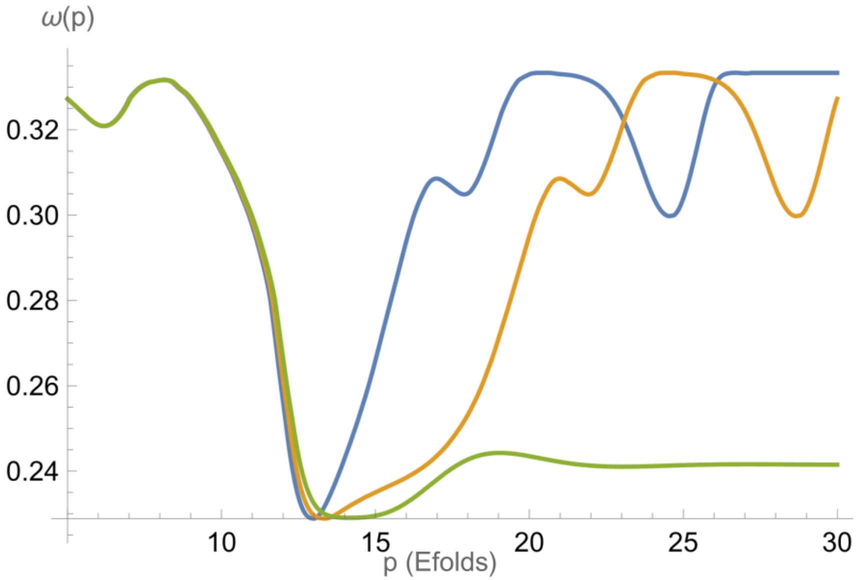
-PBH formation is exponentially sensitive to these changes.

Chameleon trajectories

-Standard model phase transitions “kick” chameleon down its potential.
-Due to the conformal coupling, the plasma temperature now depends on the scalar field.
-As the field rolls, the temperature evolution slows down.
-This leads to extended periods of reduced equation of state.

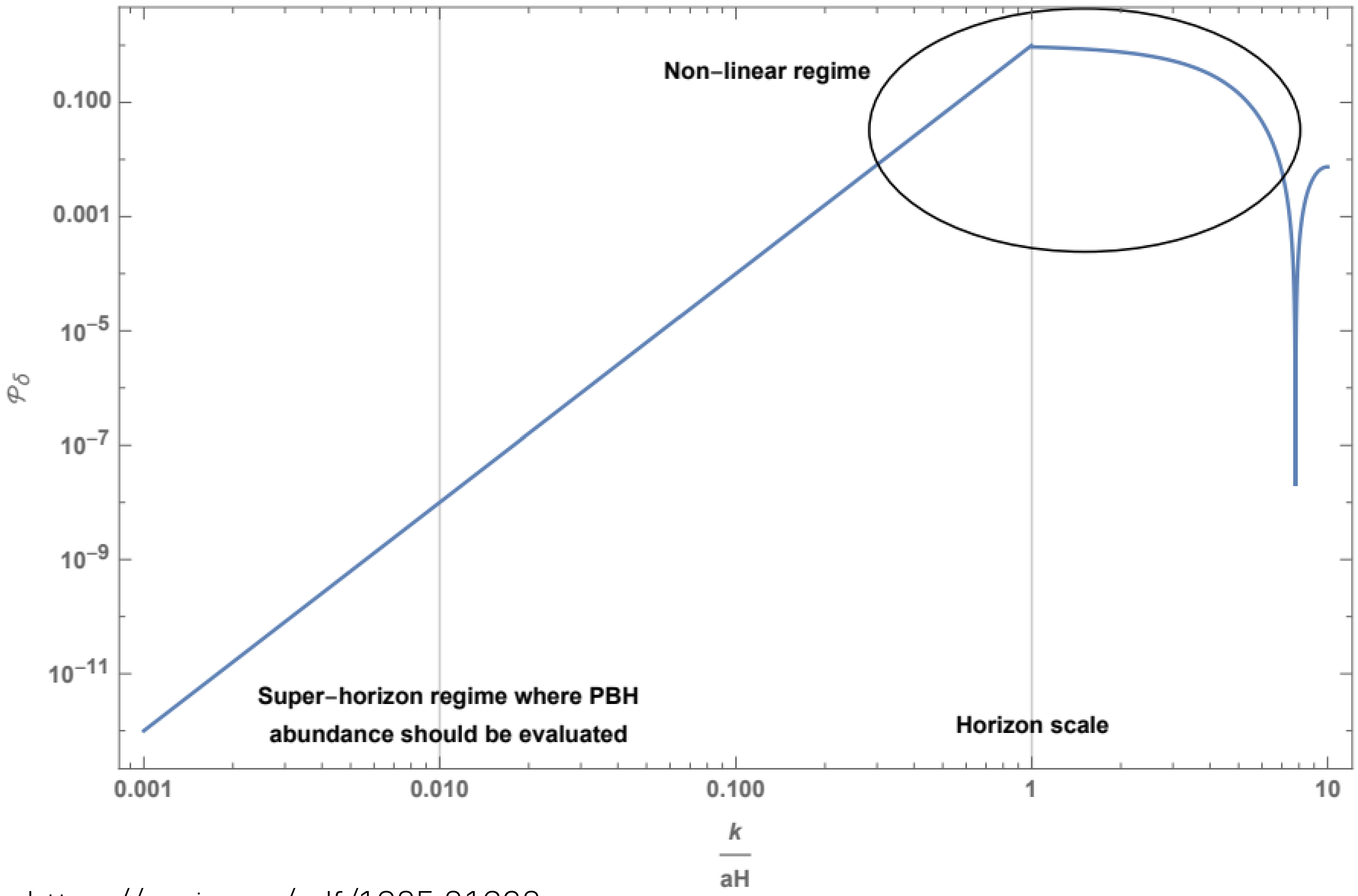






Jeans analysis

- One way of describing gravitational collapse is via the Jean's criterion.
- The idea is that, when the free-fall time is less than the sound-crossing time, gravity overcomes pressure forces. The Jeans length is the associated length scale.
- Bernard Carr used this criterion to estimate the threshold of collapse of a PBH.
- In the standard scenario, the Jean's length is the same as the horizon scale, meaning that PBHs form at horizon-entry.

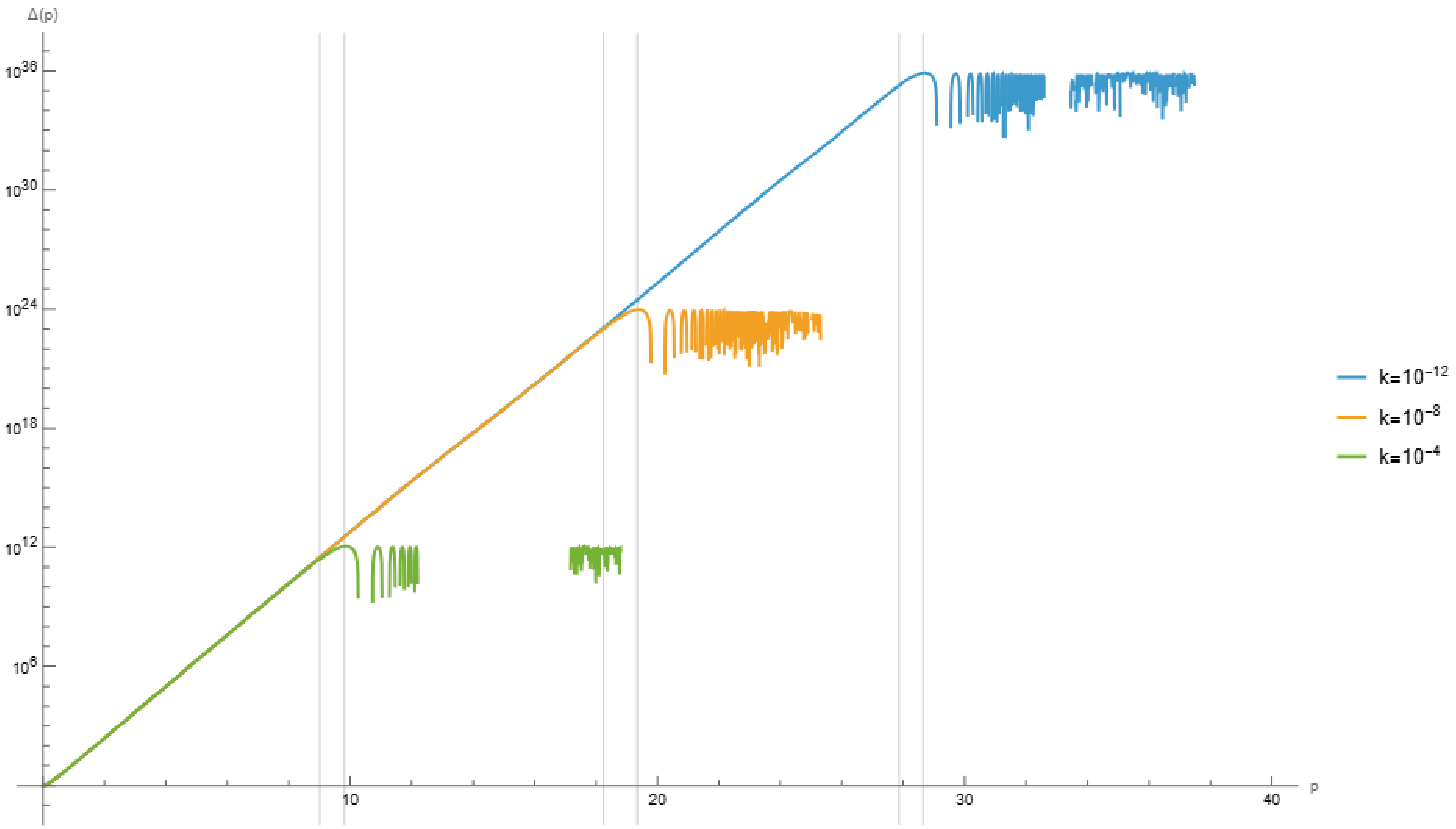


https://arxiv.org/pdf/1905.01230

Standard density evolution

- This is the evolution of the PPS of the density perturbation.
- After horizon re-entry, there is oscillatory behaviour as perturbations are smoothed out by gravity and pressure forces.

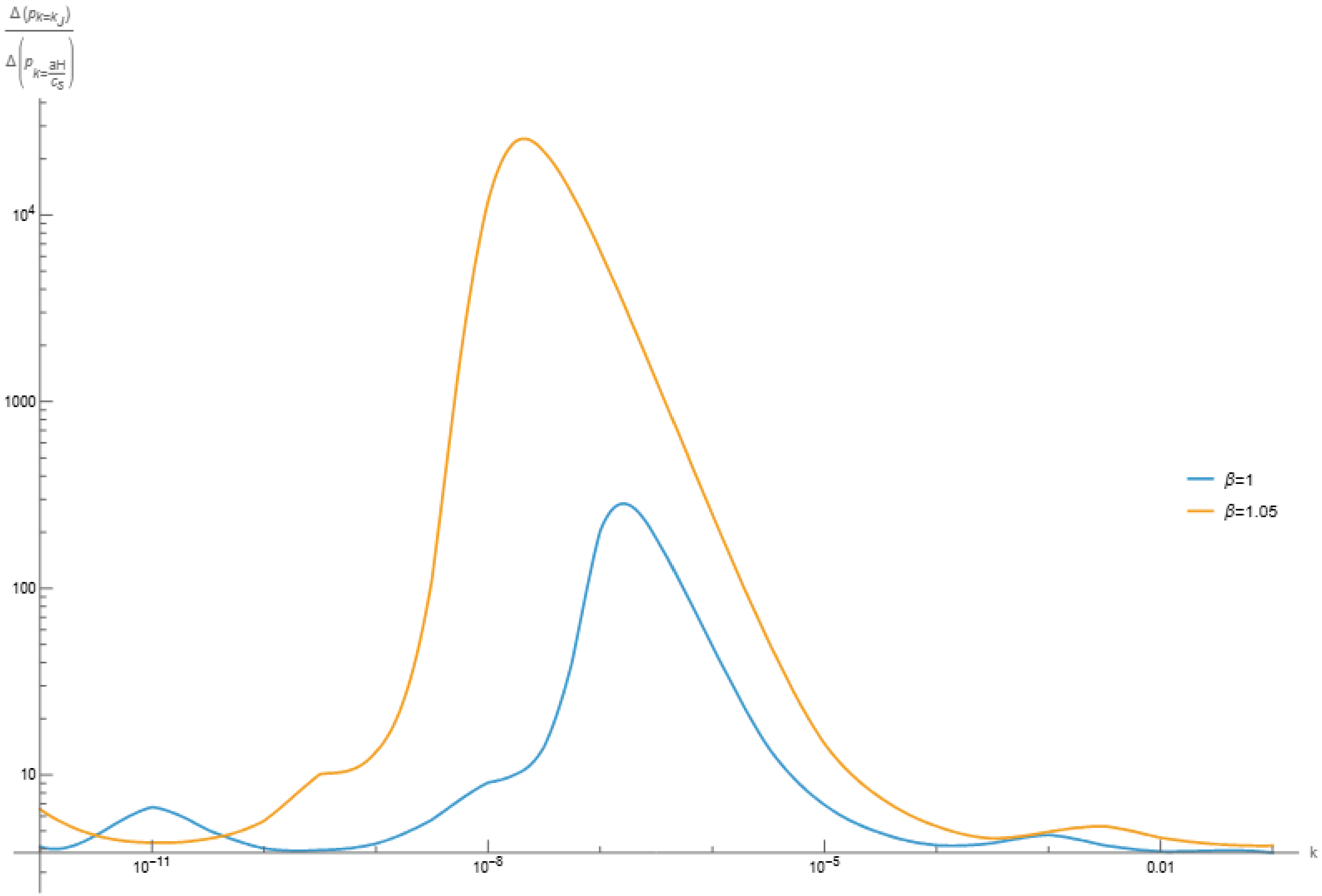
Jeans analysis in modified gravity



- In modified gravity, there are changes in the gravitational force laws caused by mixing with the scalar field.
- This results in a renormalisation of the Jeans scale that is no longer equal to the horizon scale.
- Importantly, we can see that the Jeans scale is now larger than the horizon scale!

PBH implications

- We see that, upon horizon re-entry, a density perturbation may have a relatively large amount of growth before it hits the Jeans scale.
- This can result in a large decrease in the threshold for collapse!



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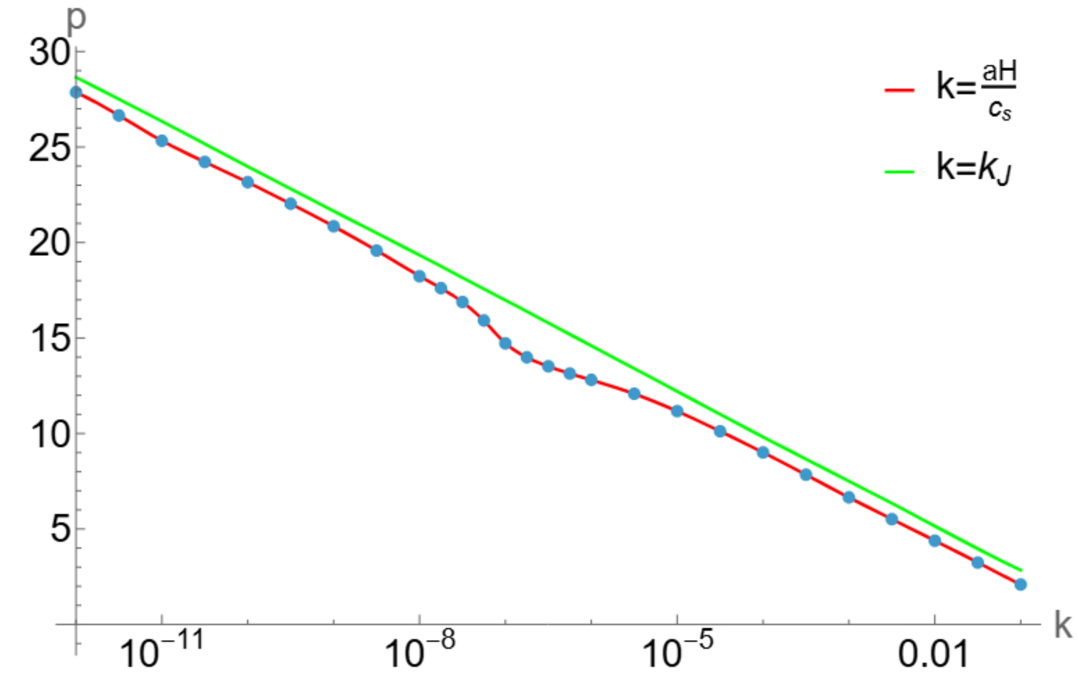
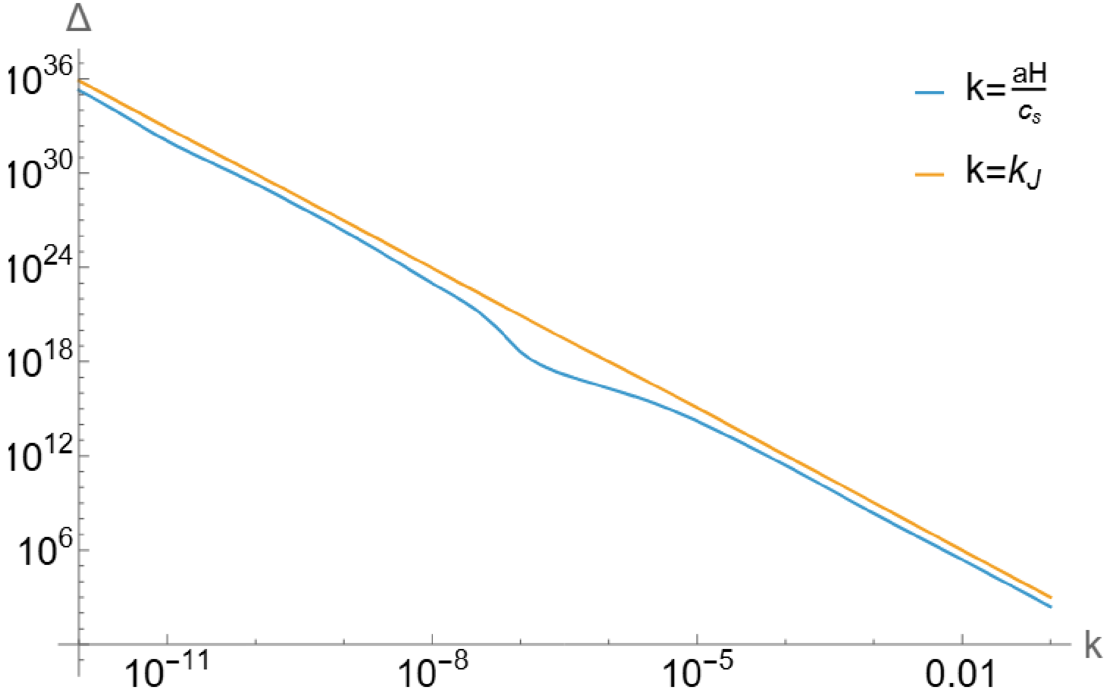
Conclusions

-There may be more scalar fields in the universe than we know (Higgs, inflaton(?)).

-If coupled to matter, these fields will have implications for the thermodynamics of the early universe, which PBHs are extremely sensitive to.

-Scalar fields may also have many other implications relevant for PBHs, such as a modification to the Jeans length.





Modified density perturbation evolution

- Whilst the scalar field is rolling, it's kinetic energy leads to an increase in the Hubble rate.
- The larger the Hubble rate, the quicker modes will re-enter the horizon.
- We track the value of the density perturbation at the two scales of interest.

Horizon mass

$$M_H(T_J) = \frac{4}{3}\pi\rho(T_J)\frac{1}{H(T_J)^3}$$

$$= \frac{4}{3}\pi\left(\frac{30}{\pi^2}\frac{1}{g_{*\rho}(T_J)}\right)^{1/2}\frac{1}{T_J^2}e^{-2\beta\varphi(T_J)}\left(3 - \frac{\left(\frac{d\varphi}{dT_J}\frac{dT_J}{dp}\right)^2}{2}\right)^{3/2}$$

-Due to additional energy in the universe, the horizon mass also changes with a scalar field.

-PBHs masses are often approximated to be the same as the horizon, at the point of formation.