NEHOP 2025
New Horizons in Primordial Black Hole Physics

Queen Mary
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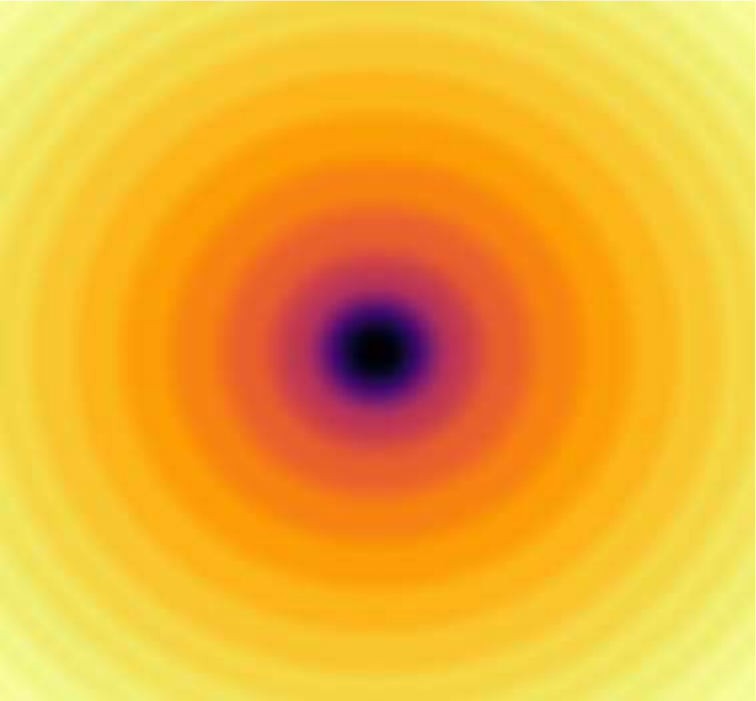
Primordial Black Hole Formation: Scalar Field Dominated Universe



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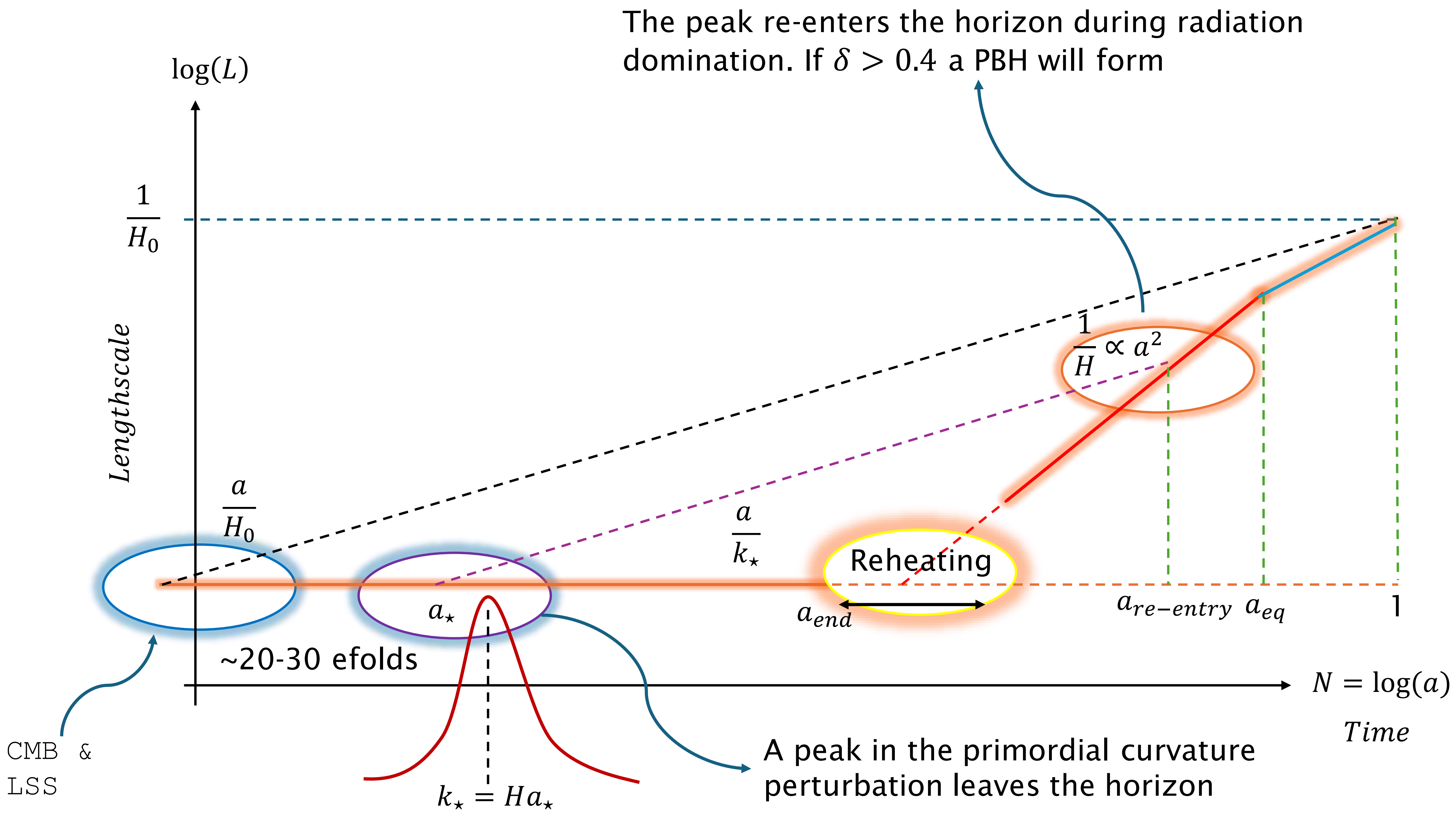
arXiv:2504.02600

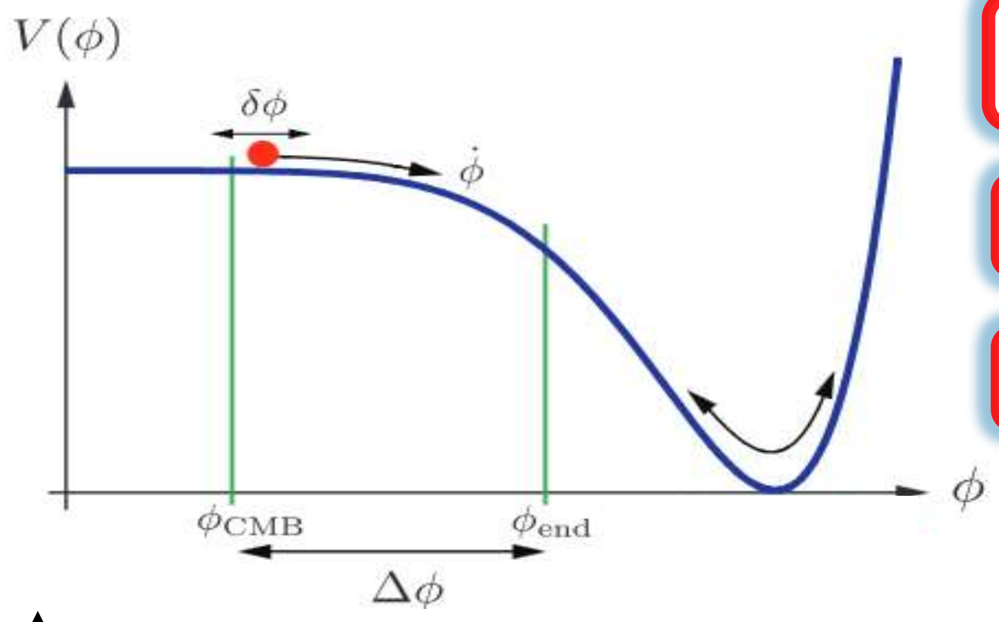
In collaboration with Luis Padilla, David Mulryne and Juan Carlos Hidalgo

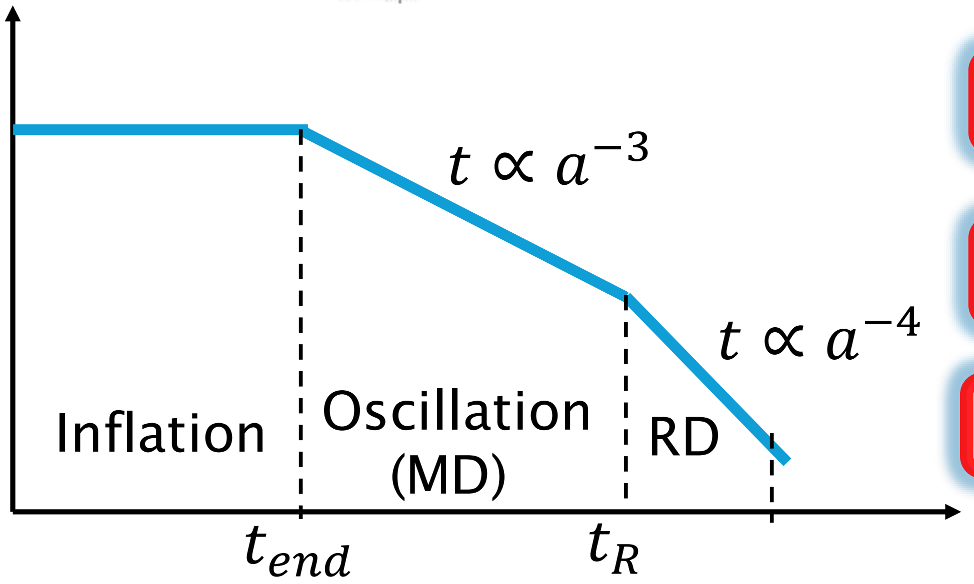


The peak re-enters the horizon during radiation domination. If $\delta > 0.4$ a PBH will form
$\log(L)$
$\frac{1}{H_0}$
Lengthscale
$\frac{1}{H} \propto a^2$
$\frac{a}{H_0}$
$\frac{a}{k_\star}$
Reheating
$a_\star$
a_{end}
$a_{re-entry}$
a_{eq}
1
~20-30 efolds
$N = \log(a)$
Time
CMB & LSS
$k_\star = Ha_\star$
A peak in the primordial curvature perturbation leaves the horizon

Carr, et al., (2018)

Slow Reheating after Inflation





Graph modified from Baumann TASI

$$V(\varphi) = \frac{1}{2}m^2\varphi^2$$

$$\Gamma \ll H$$

$$2m \gg 3H$$

$$w \approx 0$$

$$< P_\varphi > = 0$$

$$\rho \propto a^{-3}$$

Early Matter/Scalar field Dominated Period!

- We expect that T_R occurs at low energy scales compared to inflation: $10^{14}\ GeV$
- T_R can be as low as the scale of BBN: $10\ MeV$

Consider a scenario where reheating could have lasted over a few *e*-folds

Motivation

- The fluctuations that are of importance for PBH formation are found on the tail of the fluctuation distribution

PBH formation is enhanced during eras of softened equations of state

- PBH formation during SR has been carried out assuming a dust-like behaviour for the governing scalar field

Neglects the inherent wave-like dynamics and oscillatory behaviour of the scalar field

Question: Does the perfect fluid approximation for an oscillating scalar field remain valid for defining the collapse of a perturbation to a PBH?

The goal: To address the above question through a fully relativistic numerical treatment of the evolution of the oscillating scalar field.

Numerical Setup

- Assume spherical symmetry*
- The energy momentum tensor:

$$T_{\mu\nu} = (\rho + P)u_\mu u_\nu + P g_{\mu\nu} - g_{\mu\nu}\left(\frac{1}{2}\partial_\sigma\varphi\partial^\sigma\varphi + V(\varphi)\right) + \partial_\mu\varphi\partial_\nu\varphi$$

- Select the comoving gauge of the fluid: $v^i = 0$

- Misner Sharp Formalism:

$$ds^2 = -e^{2\phi}dt^2 + e^\lambda dA^2 + R^2 d\Omega^2$$

Derive and solve the Einstein-Klein-Gordon equations

Spherical Symmetry

Guzman, Urena-Lopez (2006)
Leibling, Palenzuela (2012)
Seidel, Suen (1994)

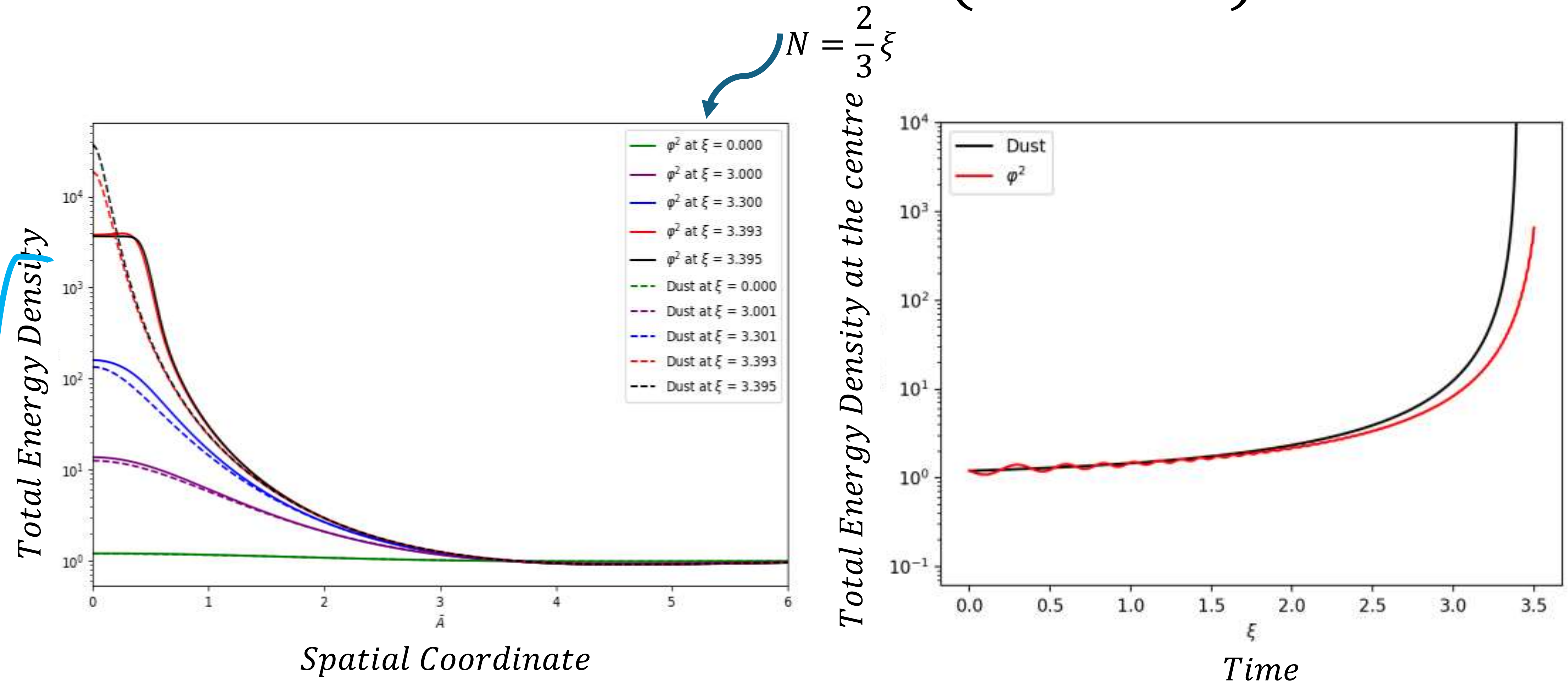
- Within spherical symmetry, it has been shown that the wave-like behaviour can prevent the collapse of large fluctuations and allow for Solitonic- and halo-like configurations

Effective "wave-like" Pressure

- Spherical symmetry is relatively easy to generalise:

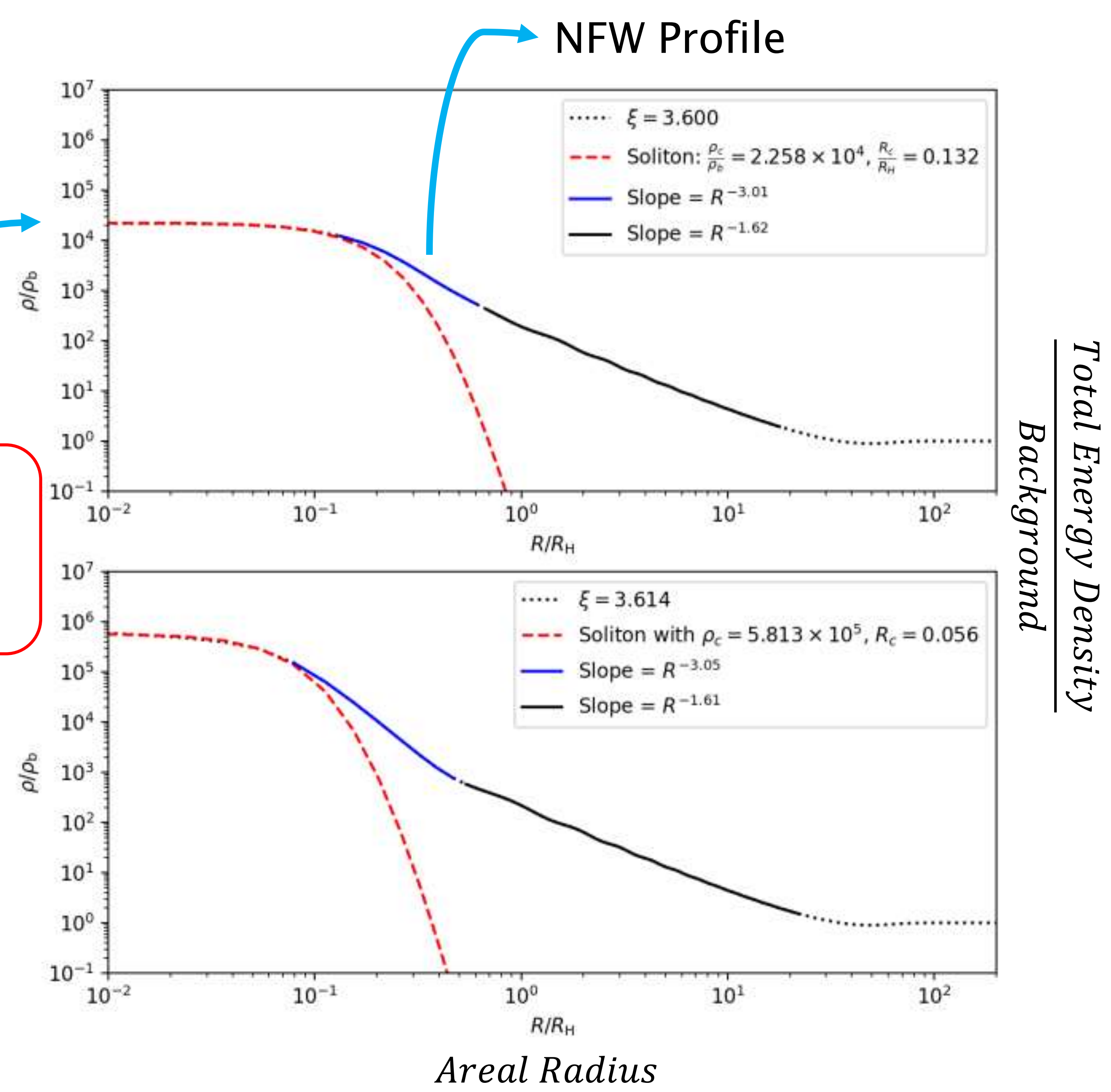
Any scalar field + fluid

Numerical Results ($\delta = 0.45$)



Expected signature of the pressure exerted by the wave-like nature of the scalar field

$$\rho(R) = \frac{\rho_c}{\left(1 + 0.091\left(\frac{R}{R_c}\right)^2\right)^8}$$

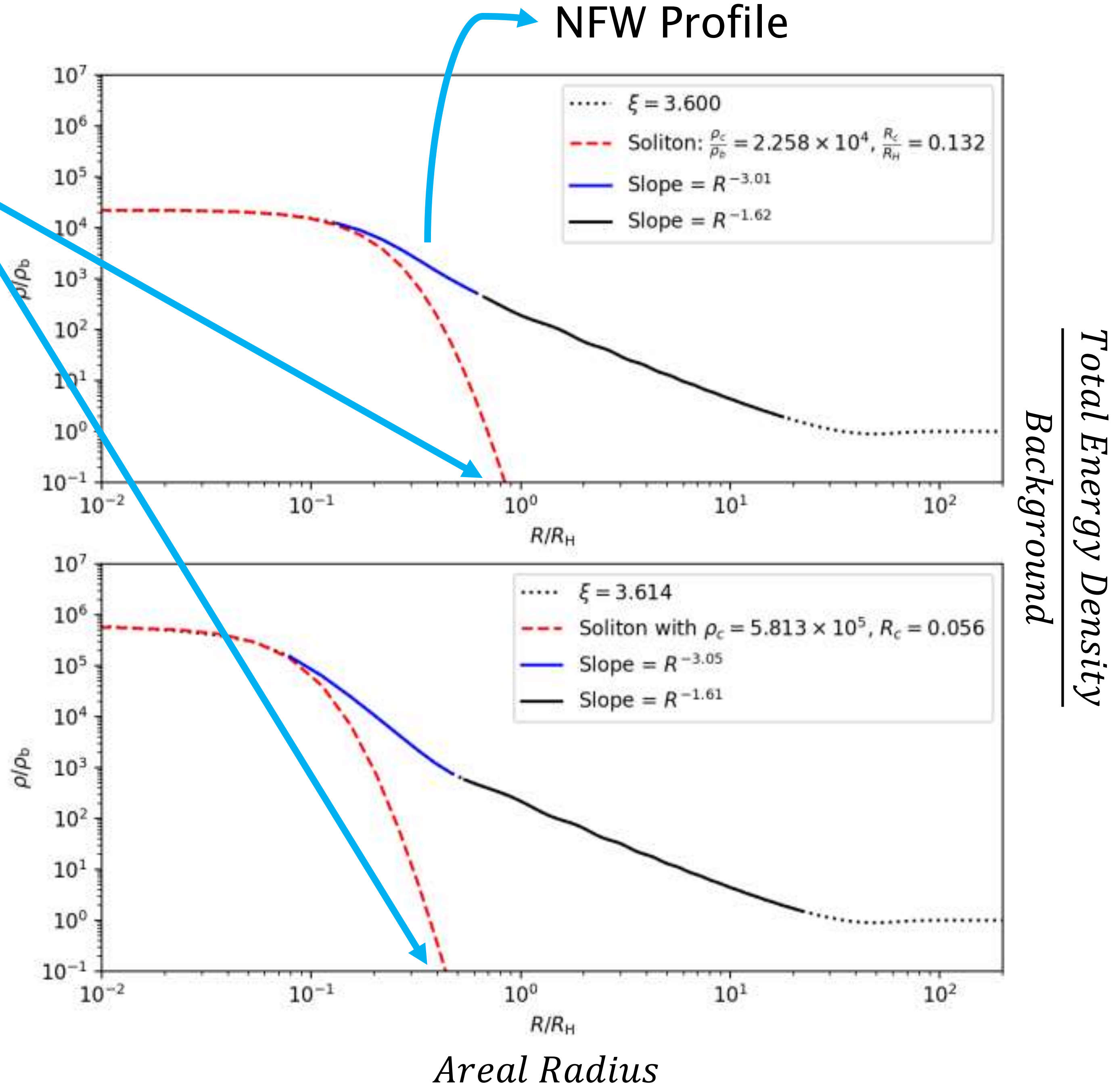


*intermediate phase

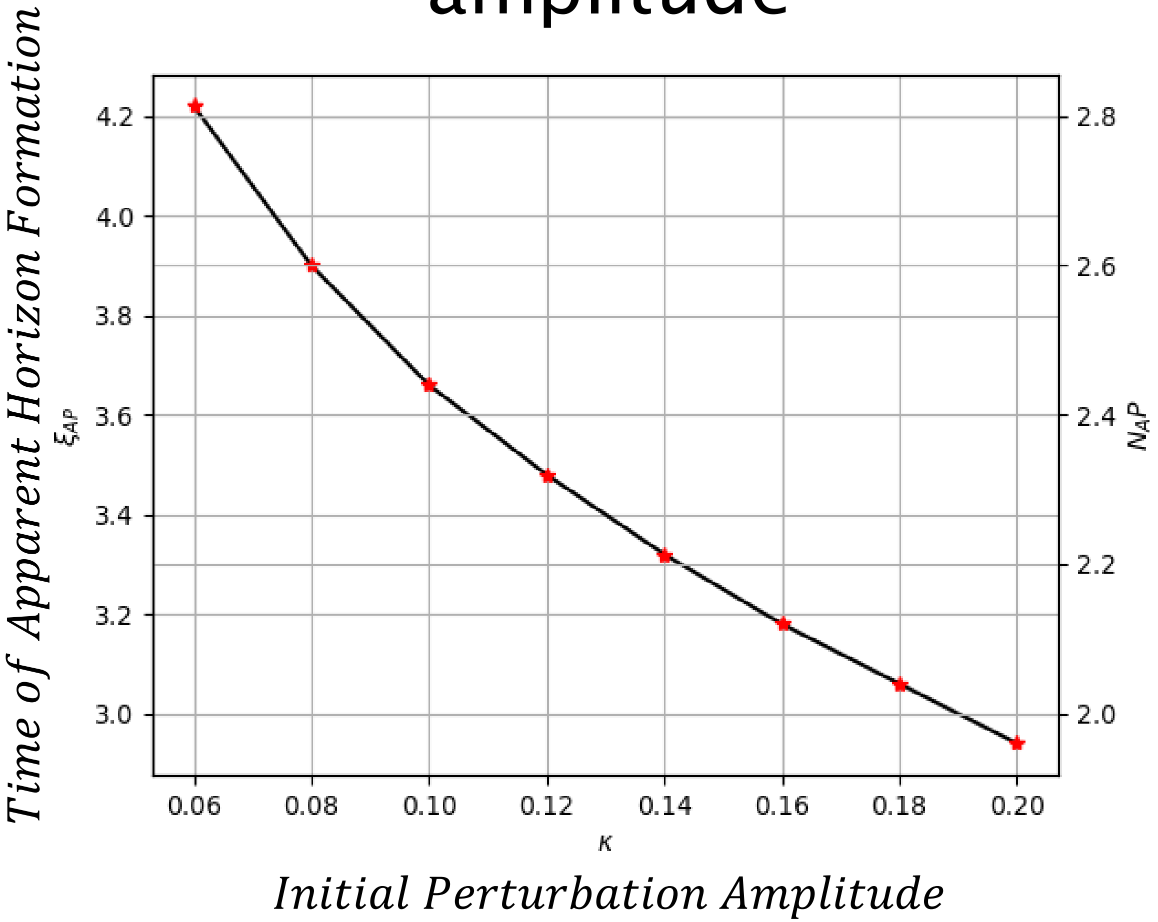
Soliton transforms over time

$M_{sol} \propto R_{1/2}^{-1}$

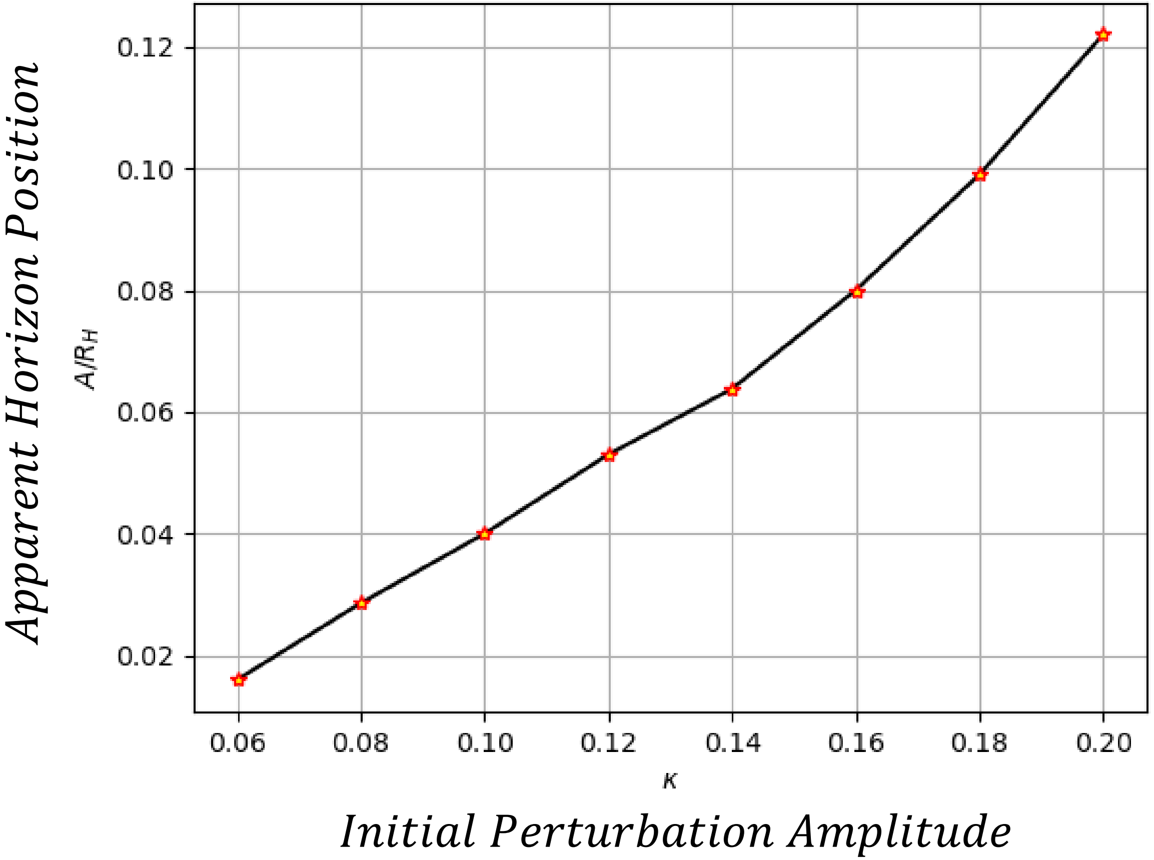
This profile has been reported in Newtonian Limit but has **<u>not yet been confirmed</u>** in GR



Time of Apparent Horizon formation against initial amplitude



Size of Apparent Horizon formation against initial



Conclusion

- We find that the quadratic potential case deviates significantly from dust-like behaviour at collapse
- Our simulations indicate that perturbations experience an effective wave-like pressure that counteracts gravitational collapse
- The behaviour of the perturbations we evolved suggests that PBH formation may be significantly altered in this scenario, with a reasonable possibility that stable solitonic/virialized structures could emerge as the outcome of gravitational collapse for some initial conditions.

Future Work

- We have a code that can evolve a perfect fluid plus multiple uncoupled scalar fields:
  - Scalar fields with zero-energy false vacua and negative true vacua
  - Higgs Potential
  - N-Inflation Models

- Extend the scalar field dominated scenarios: PBH abundances, Dark Matter fraction, the PBH importance into the Radiation Era

Thank you!

Back up slides

- The Schrodinger-Poisson equations

$$i\hbar\partial_t\psi = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + m\Psi\psi \qquad \nabla^2\Psi = \frac{4\pi G}{a}(\rho - \langle\rho\rangle)$$

Reformulated into Quantum Hydrodynamics equations

Madelung-Bohm Formalism

$$\partial_t \boldsymbol{v} + \frac{1}{a^2}(\boldsymbol{v}\nabla)\boldsymbol{v} + \nabla\Psi + \nabla Q = 0 \qquad \partial_t\rho + \frac{1}{a^2}\nabla(\rho\boldsymbol{v}) = 0$$

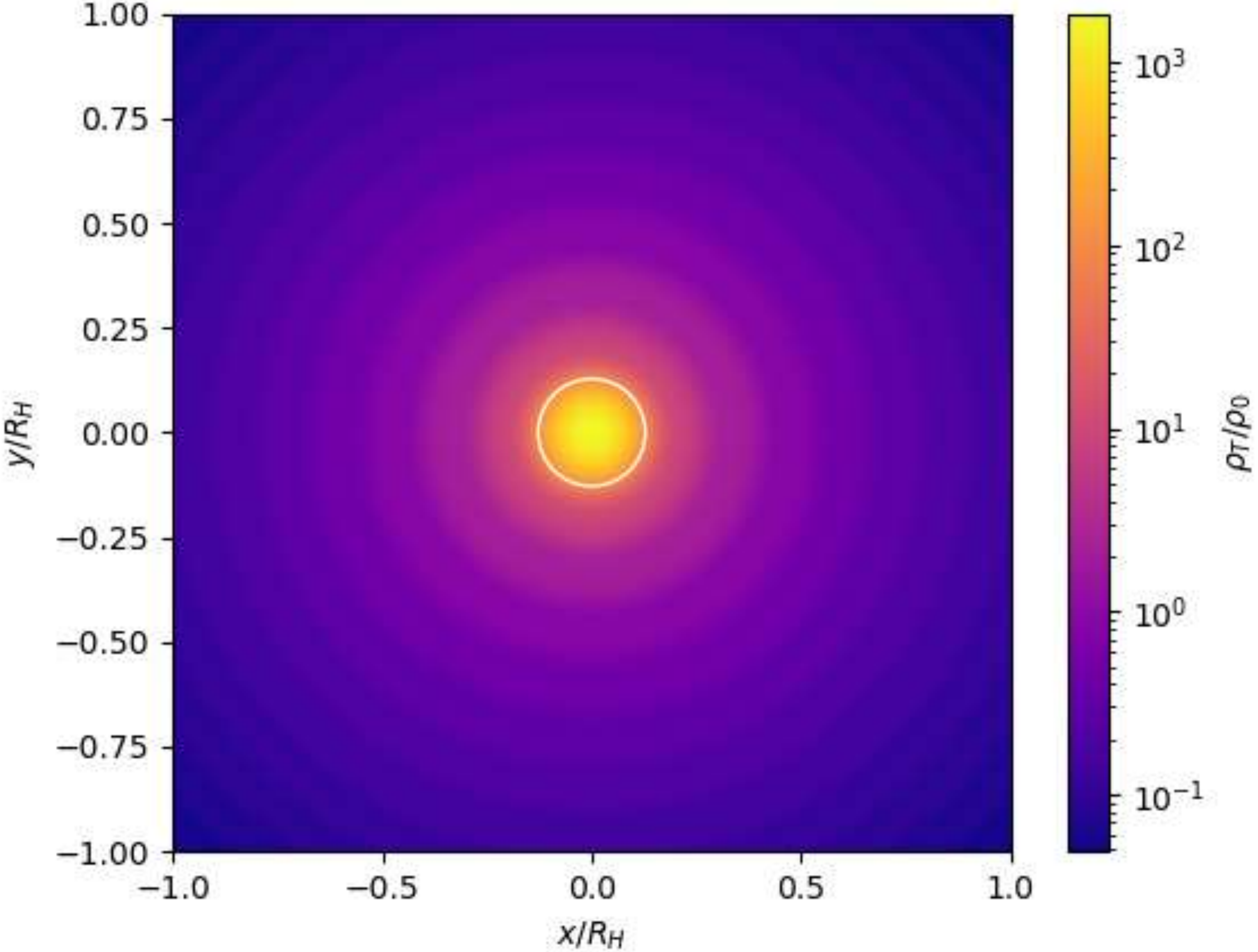
$L \sim \lambda_{dB}$ $\quad \lambda \equiv \frac{\hbar}{mv}$

Quantum Pressure Term: arising from the KE term in the SP equations

$$Q = -\frac{\hbar}{2m^2a^2}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}$$

If $L \gg \lambda_{dB}$: dust-like

Quantum “force” opposing gravitational collapse



1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
y/R_H
−1.0
−0.5
0.0
0.5
1.0
x/R_H
10^3
10^2
10^1
10^0
10^{-1}
ρ_T/ρ_0