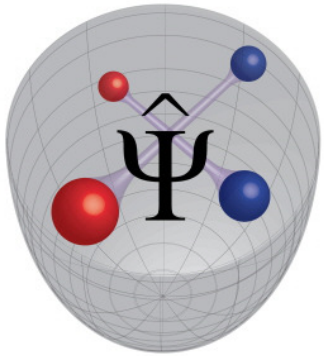
Quantum many-body analogue black-holes and analogue cosmology

Uwe R. Fischer

Seoul National University

Group: Theory of Cold Atoms



June 27, 2025, RQI-N 15, Napoli

Why Quantum Simulation of Curved Spacetimes with Many-Body Systems?

Key Importance: Observability of Fundamental QFT Effects

eg Hawking Temperature of Astrophysical Black Holes
(solar mass BH: $T_H \sim 60$ nK)

Unobservable on Top of CMB

First Observations
of Hawking Radiation

Nature & Nature Physics, 2016, 2019 & 2021
[Steinhauer Group Technion]

Cosmological QFT Effects Observable

Science 2013 [Chin Group Chicago]

PRX 2018 [Campbell Group Maryland]

Nature 2022 [Oberthaler Group Heidelberg]

Quantum Many-Body Black Holes

Steinhauer BEC Experiments:

Swees Blue-Detuned Trapping Potential Jump Through Condensate to Create BH in Essentially 1D Gas

$\Rightarrow$ Highly Nonequilibrium State (At Least Initially)

Basic Question We Addressed:

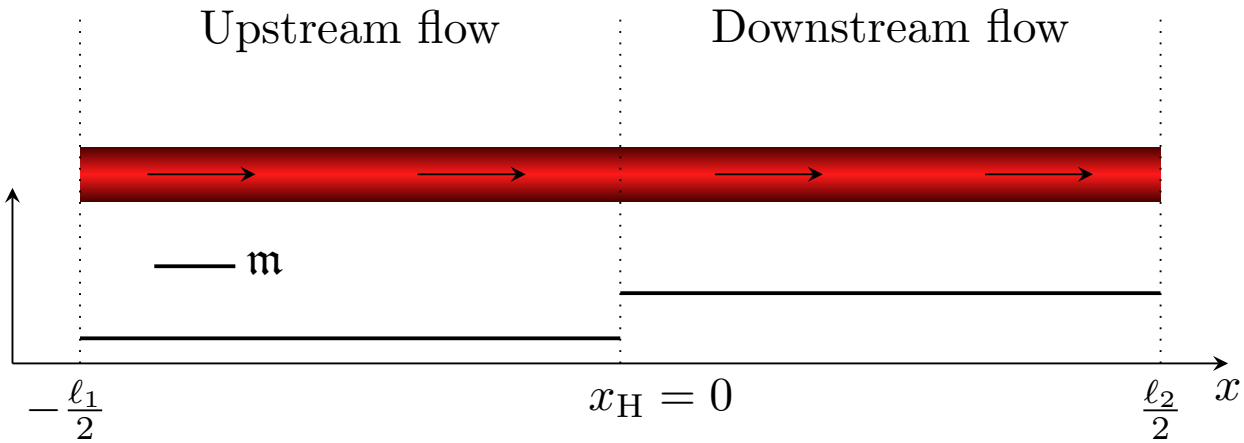
Does Finite-Size Stationary Black Hole Exist in 1D?

Note: Hohenberg Theorem Rules Out Size $\ell \to \infty$ in 1D

[Phase Fluctuations Growing Without Bound, Destroy BEC]

Our Setup

Finite Size Condensate With Source and Drain



Creation of Horizon:

Interaction Coupling Constant $g = g_{1\rm D}$ Jump at $x_{\rm H} = 0$

Source (at $-\ell_1/2$) and Drain (at $\ell_2/2$)

$\Rightarrow$ Create Steady State of Single Black Hole

Else **Black**–White Hole Pair Unavoidable

(For Steady Circulating State, by Topology on the Torus)

Diagnostic Tool of Bogoliubov:

Take Bogoliubov Expansion of Bosonic Field Operator
(v: Constant Flow Speed)

$$\hat{\Psi}(t,x) = e^{-i\mu t + ivx}[\sqrt{\rho} + \hat{\psi}(t,x)]$$

Quantum Depletion (:= Number of Particles Not in Condensate)

$$\delta\rho = \langle \hat{\psi}^\dagger \hat{\psi} \rangle$$

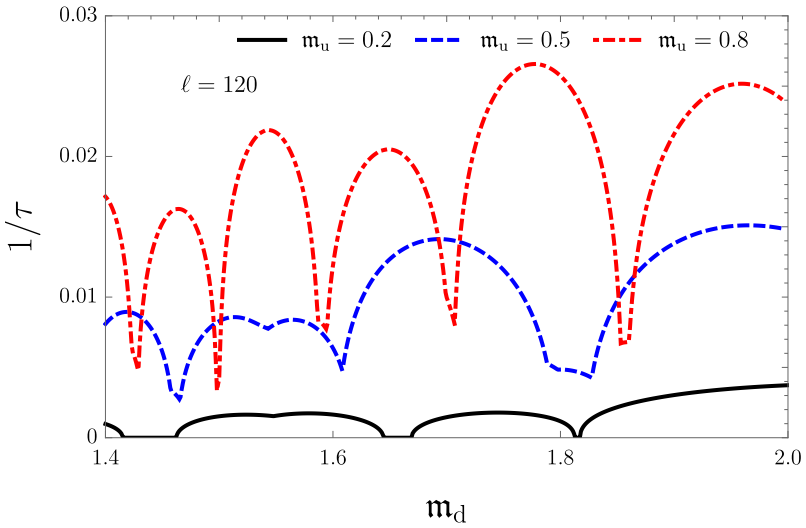
Should be Suitably "Small" $\delta\rho \ll \rho$

Then Bogoliubov Approach Consistent

[By Convention We Kept $\delta\rho/\rho \leq 10\,\%$ (Typically $3\,\%$)]

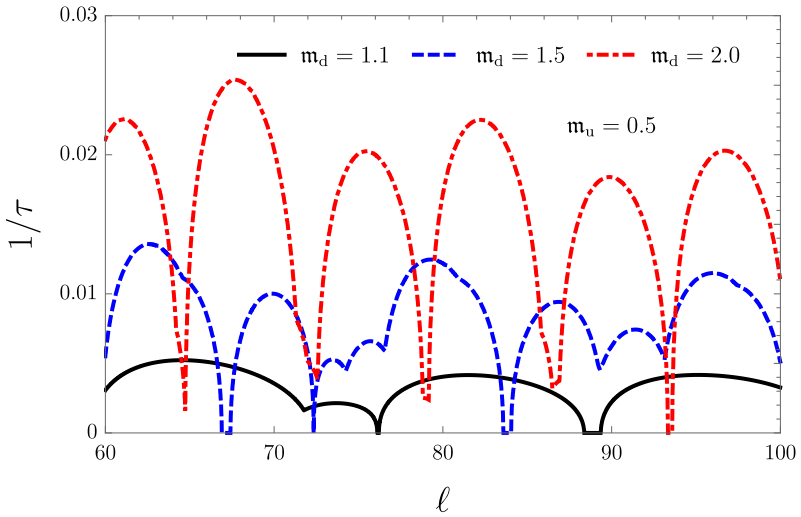
Finite BH Lifetime from Spectrum

$$\tau = \frac{1}{2\mathrm{Im}\ \Omega_{\max}} \qquad [\Omega_{\max}\text{: Largest Im Part Excitation}]$$



Downstream Mach Number

$\mathfrak{m}_\mathrm{d} := v/c_\mathrm{d}$



Total Size ℓ

$\Rightarrow$ Irregular Behavior but also **Stability Windows**

Quench Preparation of Black Hole

Spectrum Gives Generally Unstable Quantum Modes
in BH Configuration

$\Rightarrow$ Start from Horizonless Configuration in the Quasi-1D Box

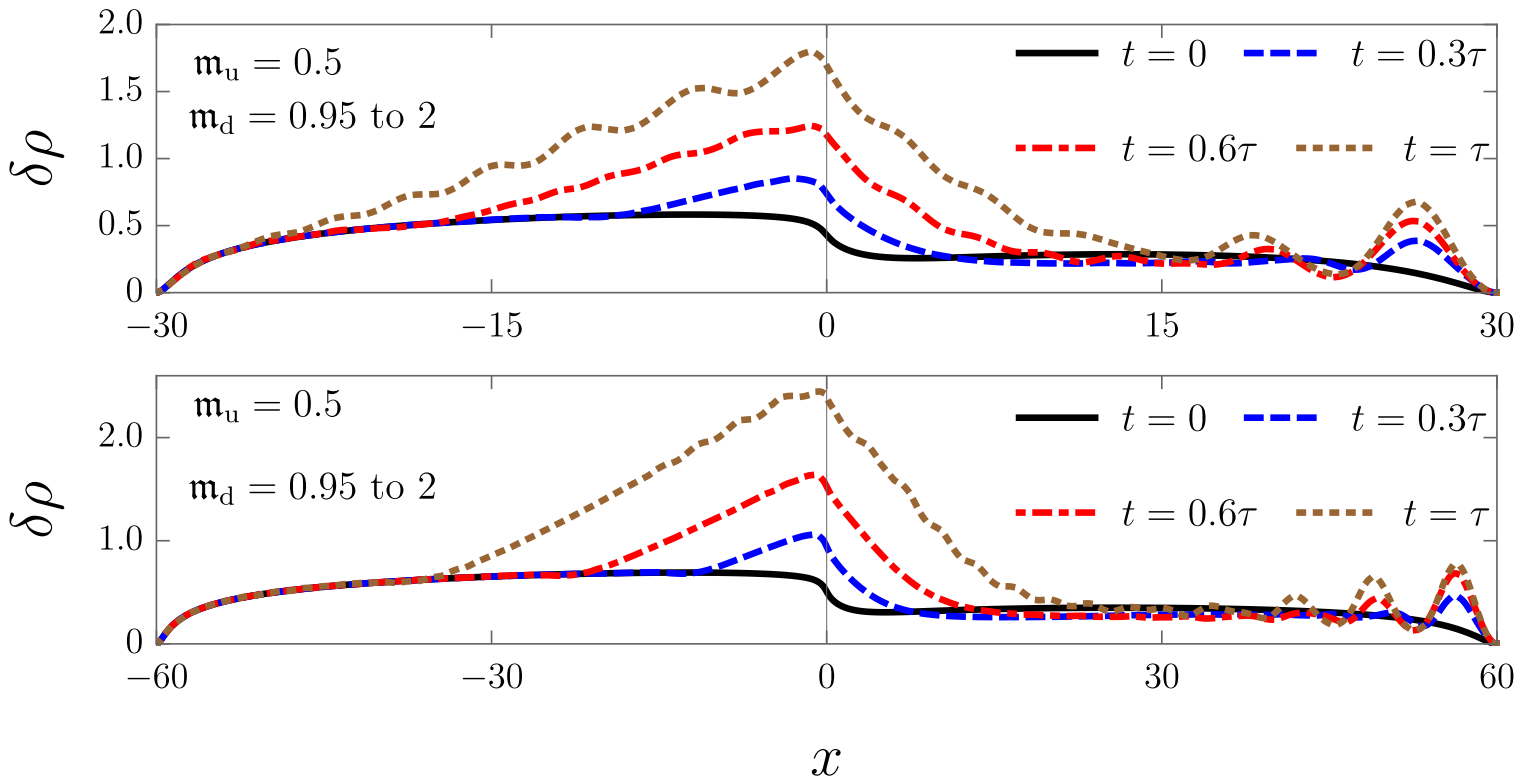
Advantage:

Initial Quasiparticle Vacuum Well Defined Without Sonic Horizon

No Issues with Vacuum in Presence of Instabilities!

Then Compute Depletion $\delta\rho = \delta\rho(t)$

Hawking Radiation Buildup in Upstream Depletion

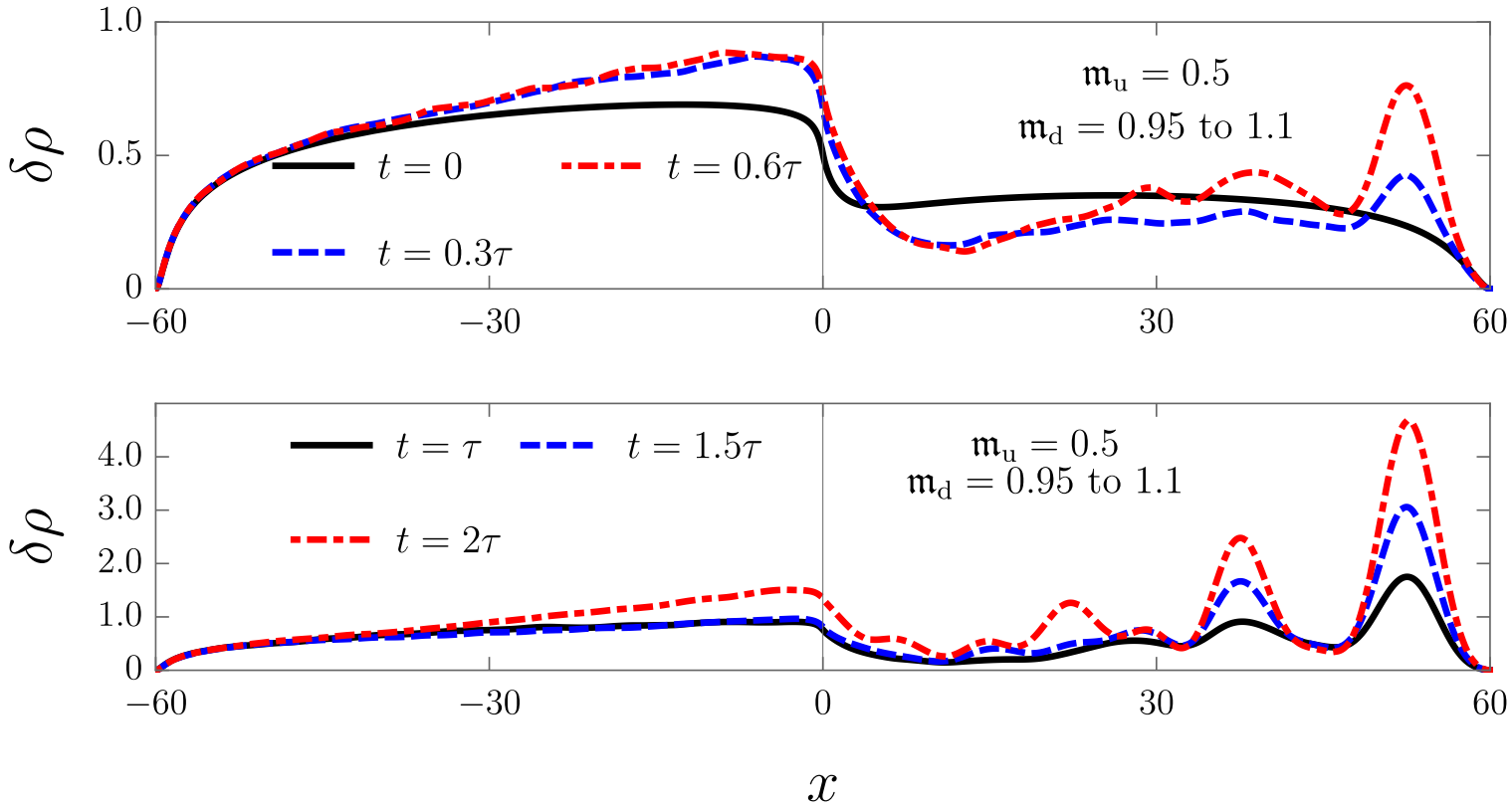


Quantum Depletion "Shock Front" Outside of Horizon Builds Up

Signature of Hawking Radiation

And... Oscillations Downstream (Inside Black Hole) Emerge!

Less Deep Quench

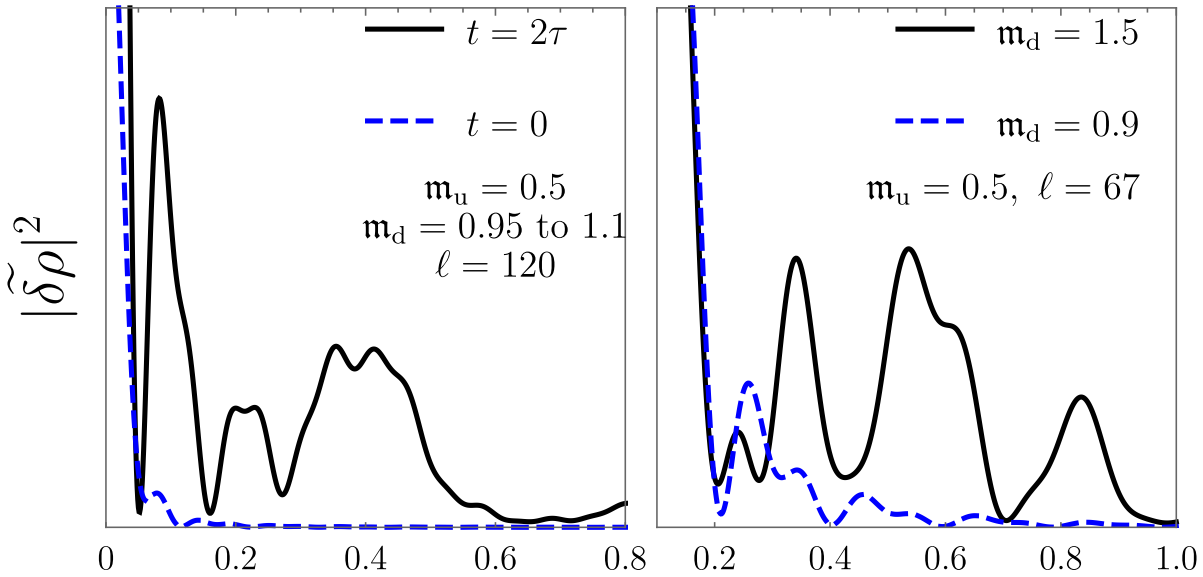


$\Rightarrow$ Oscillations have Relatively Higher Amplitude

Detection Tool of Horizon Emergence:

Power Spectrum of Quantum Depletion

[Measured for 3D Gas: Hadzibabic Group, PRL **119** (2017)]



Unstable BH (Finite τ) Stable BH ($\tau \to \infty$)

Note: Depletion $\Leftrightarrow$ First-Order Correlations

Usual HR Signature: Weak Density-Density Correlations

Ribeiro, Baak & URF, PRD **105** (2022)

Analogue Quantum Cosmology

S M Chandran & URF

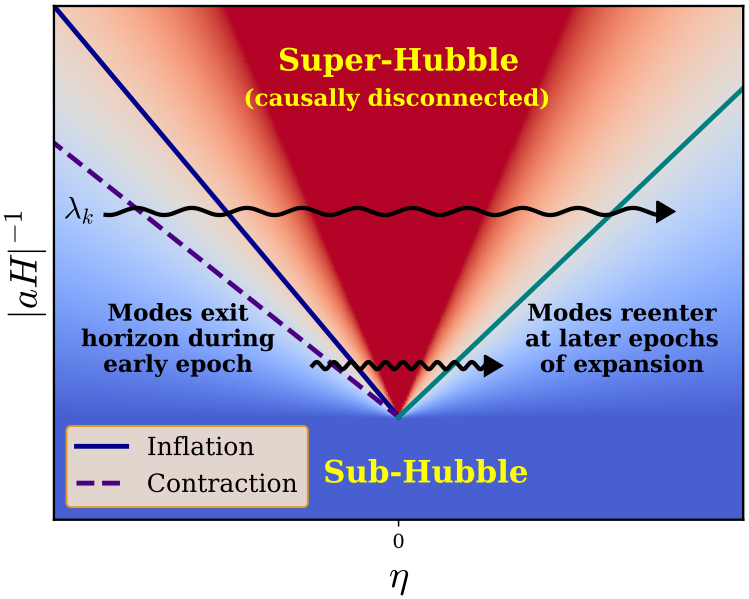
arXiv:2506.02719v2 [gr-qc] (10th June, 2025)

Cosmological Expansion-Contraction Power Spectrum Duality:

Same Scale-Invariant Power Spectrum for Inflation and Bounce

Wands PRD **60** (1999)

However: Duality Holds Only in Lorentz-Invariant Theories!

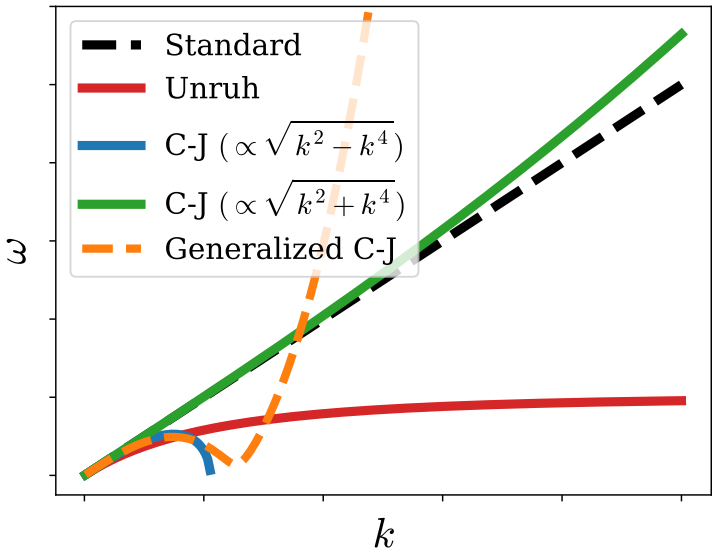


Cosmological Trans-Planckian Dispersion Modiification

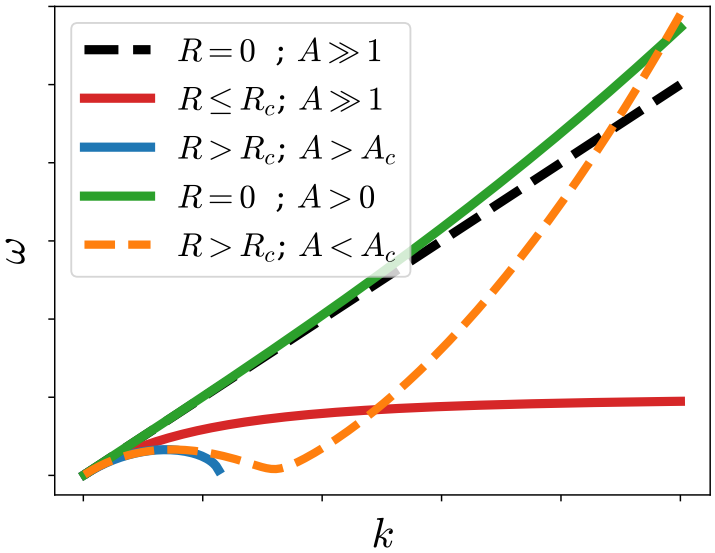
Microscopic Control in Dipolar (+ Contact) Quantum Gas

for Previously Ad Hoc Trans-Planckian Dispersions

Brandenberger, Martin, Niemeyer, Kempf, Parentani...



Cosmology

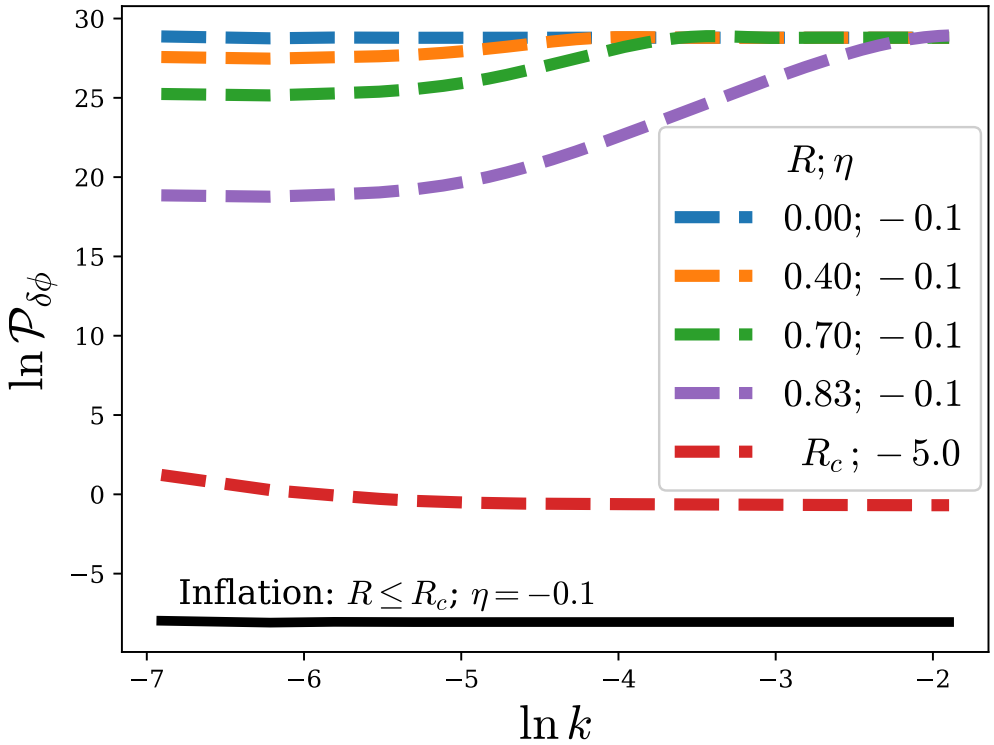


Dipolar BEC

"Unruh Flat-Band" Dispersion:

Dipolar and Contact Couplings Identical!

Trans-Planckian Modification: Duality Broken



Blue Tilt

However: "Unruh Flat-Band" Dispersion: Red Tilt!

Result:

- Power-Spectrum-Indistinguishable Inflation and Bounce (Wands Duality)

Result:

- Power-Spectrum-Indistinguishable Inflation and Bounce (Wands Duality)
- Become Distinguishable due to Trans-Planckian Dispersion

Result:

- Power-Spectrum-Indistinguishable Inflation and Bounce (Wands Duality)
- Become Distinguishable due to Trans-Planckian Dispersion
- Currently Realizable in Dipolar Bose-Einstein Condensates (eg Erbium and Dysprosium)

Chandran & URF

arXiv:2506.02719v2 [gr-qc] (10th June, 2025)