Karlsruhe Institute of Technology

Phenomenology of Axion Dark Matter

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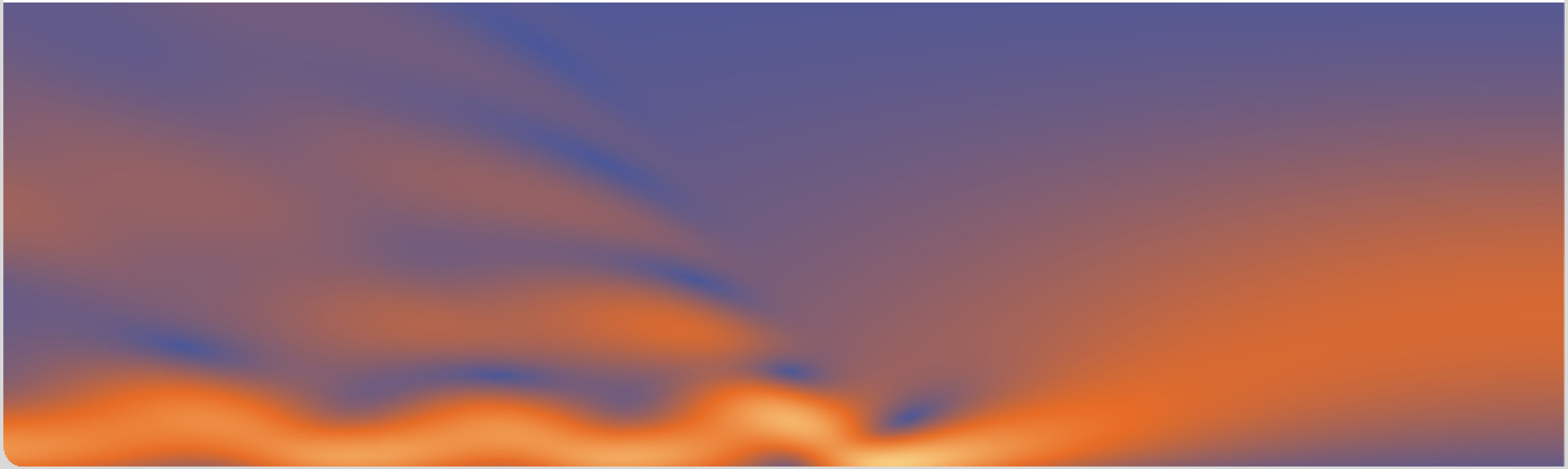


Why do we need axions?

The strong CP problem

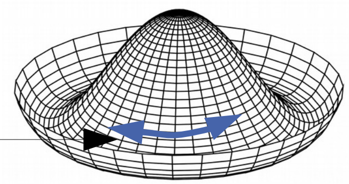
Solution by Peccei and Quinn

- Static $\bar{\theta}$ is promoted to a dynamical variable.
- Goldstone of the spontaneously broken Peccei-Quinn symmetry.
- Potential via non-perturbative effects after QCD phase transition.

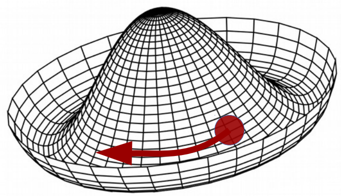
$$\mathcal{L}_{\mathrm{QCD}} \ni \frac{\alpha_S}{8\pi}\bar{\theta} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

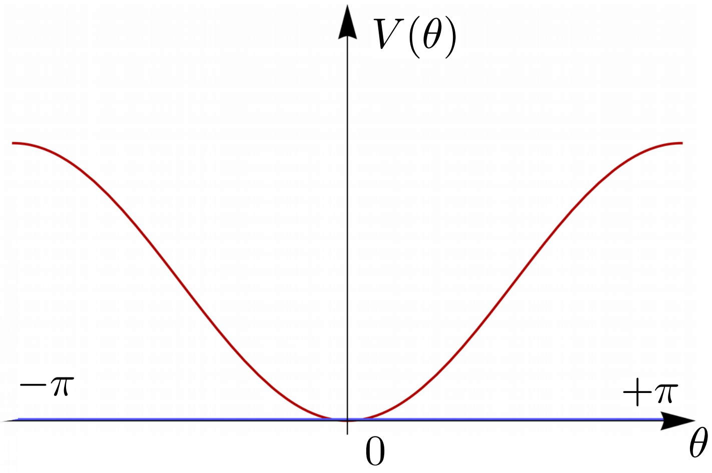
$$\sigma(x) \sim f_{\mathrm{PQ}} \mathrm{e}^{\mathrm{i}a(x)/f_{\mathrm{PQ}}}$$

$$a(x)/f_{\mathrm{PQ}} = \theta_a \in [-\pi, \pi]$$



$$\bar{\theta} \to \theta_a : \quad \frac{\alpha_S}{8\pi}\theta_a G^{\mu\nu}\tilde{G}_{\mu\nu}$$

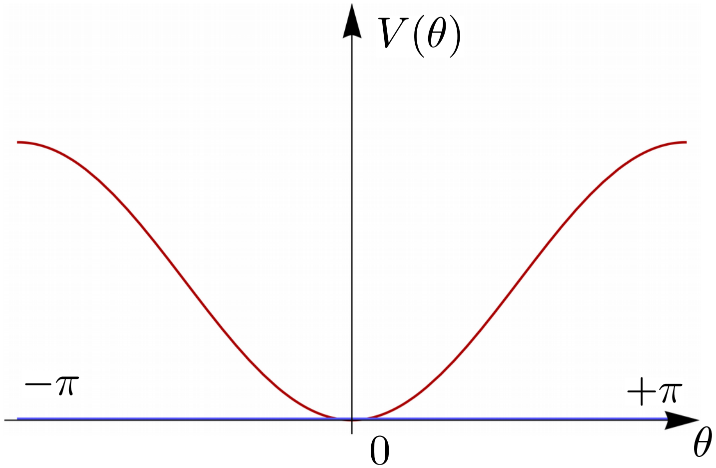




$$m_a \sim m_\pi \frac{f_\pi}{f_{\mathrm{PQ}}} \sim 6\,\mu\mathrm{eV}\frac{10^{12}\,\mathrm{GeV}}{f_{\mathrm{PQ}}}$$

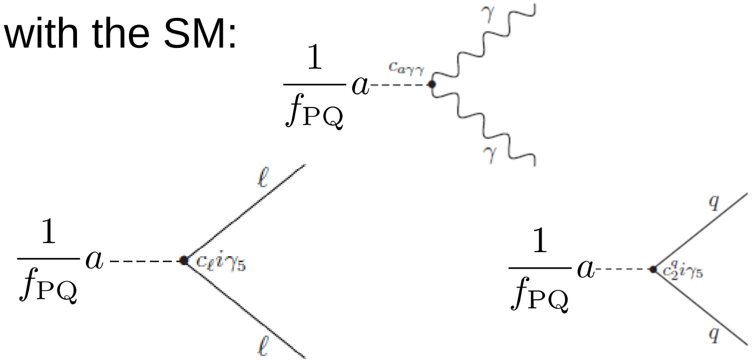
Kalte Dunkle Materie??

The strong CP problem and the axion



Axion mass: $$m_a \sim m_\pi \frac{f_\pi}{f_{\mathrm{PQ}}} \sim 6\,\mathrm{meV}\,\frac{10^9\,\mathrm{GeV}}{f_{\mathrm{PQ}}}$$

Interactions with the SM:



F. Wilczek

Solves the strong CP problem… like my favorite soap.

High breaking scale means very weak interactions.

Dark Matter Candidate!

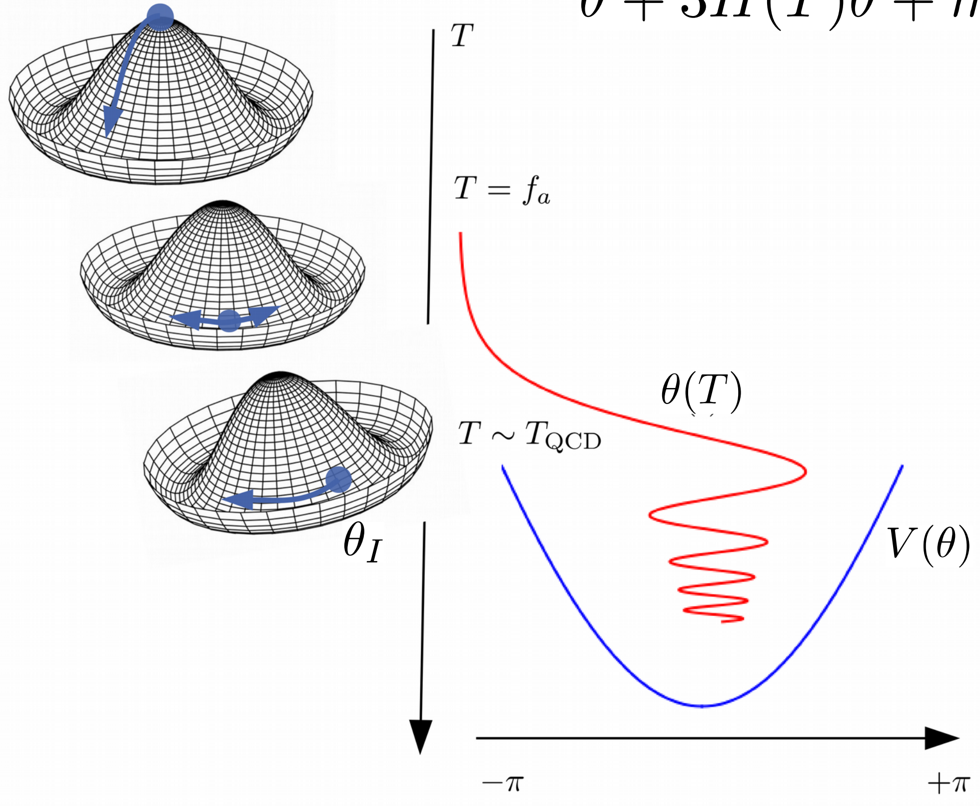
… but extremely light.

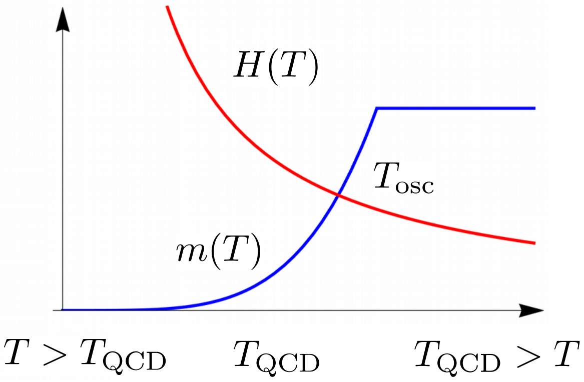
How can axions be cold Dark matter!?

How is axion dark matter produced?

Dark matter via vacuum realignment

$$\ddot{\theta} + 3H(T)\dot{\theta} + m^2(T)\theta = 0$$



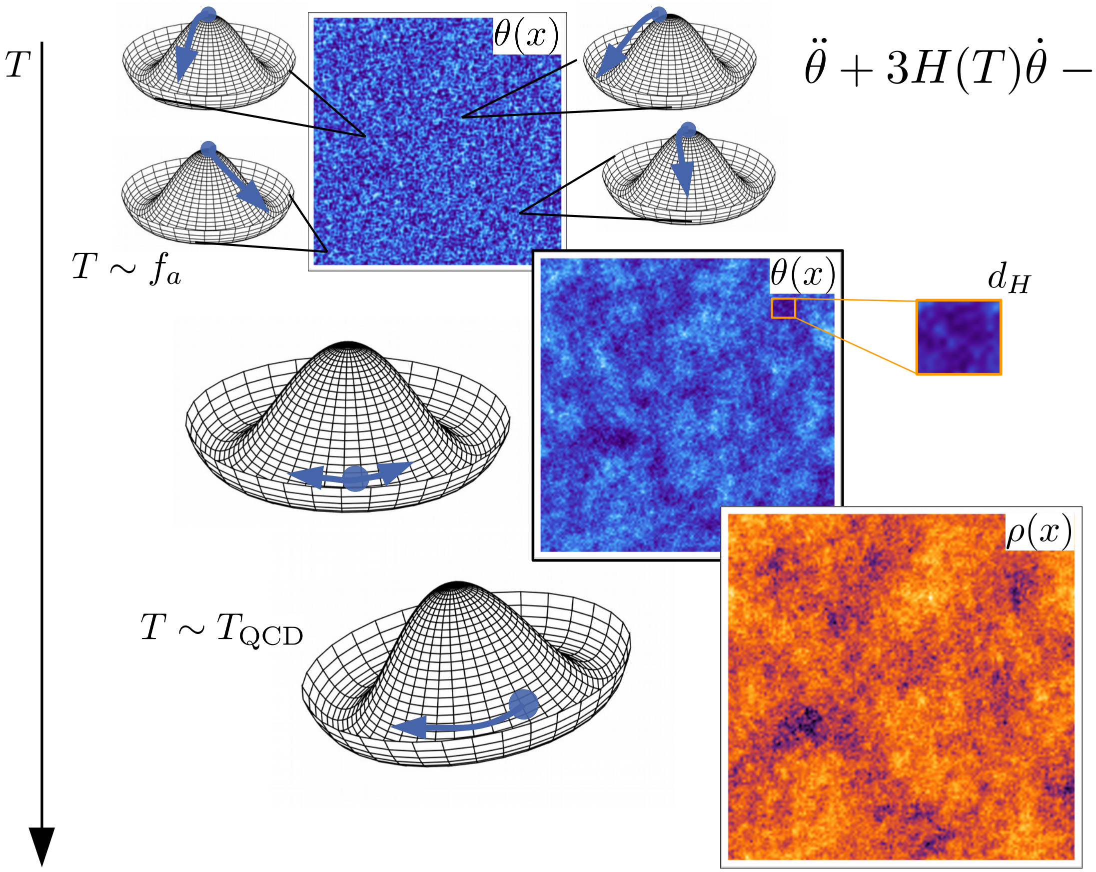


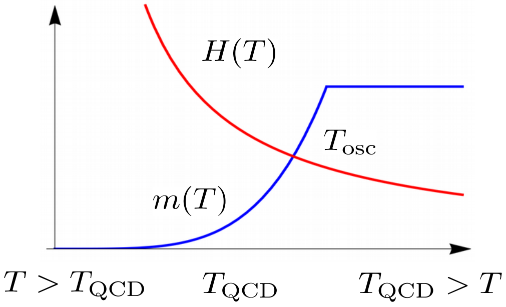
Oscillations around the minimum behave like cold dark matter!

$$\rho_a \sim f_a^2 m_a^2 \theta_I^2 (R(T_{\mathrm{osc}})/R(T))^3$$

Dark matter via vacuum realignment

$$\ddot{\theta} + 3H(T)\dot{\theta} - (\nabla\theta)^2/R^2 + m^2(T)\theta = 0$$





Large fluctuations in the energy density.

Size of the fluctuations:

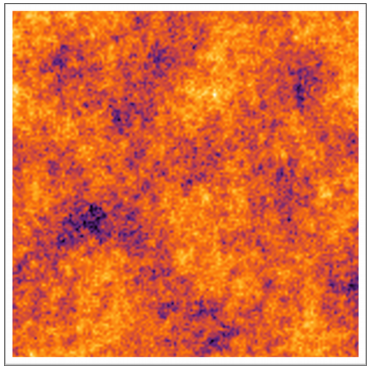
$$\propto d_H(T_{\mathrm{osc}}) \sim 1/H(T_{\mathrm{osc}}) \sim 1/m$$

$$\overline{\rho} \sim f_a^2 m_a^2 \langle \theta_I^2 \rangle (R(T_{\mathrm{osc}})/R(T))^3$$

Interesting phenomenological consequences!

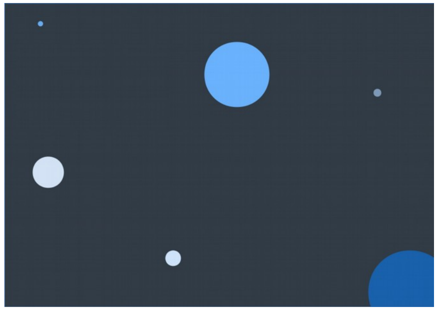
QCD axion: Formation of miniclusters

QCD axion as dark matter: $m_a \sim \mu\mathrm{eV}$



Overdensities can collapse already very early in small gravitationally bound objects. Miniclusters.

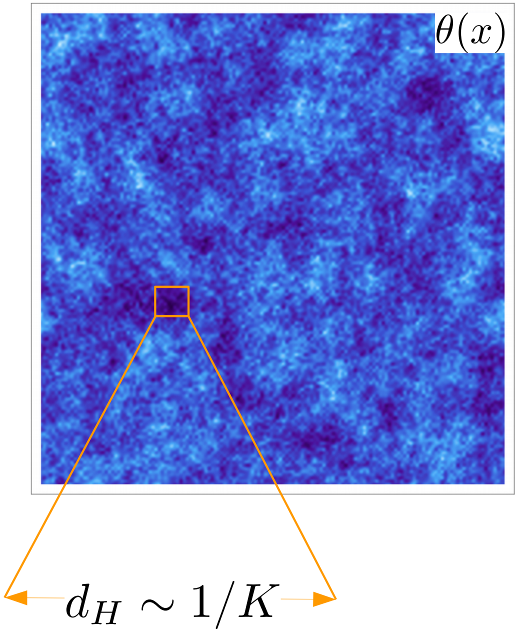
Important consequences for direct detection experiments.



What is the mass, size, and distribution of the miniclusters?

Evolution of the inhomogeneous field

Describing the dynamics with statistical methods and transfer functions.

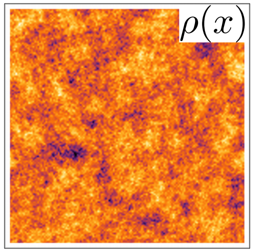


Initial condition:

$$P_\theta \propto \exp\left[-k^2/K^2\right]$$

Solving the equations of motion:

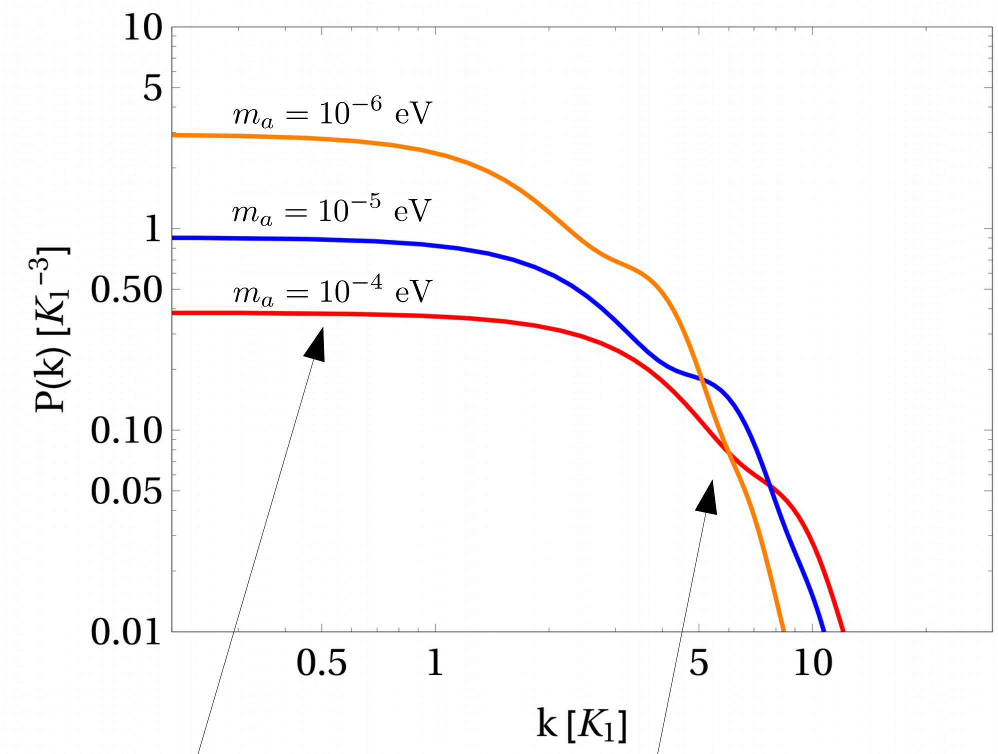
$$\ddot{f}_k + 3H\dot{f}_k + \frac{k^2}{a^2}f_k + m^2(T)f_k = 0$$



Determine the power spectrum of the density fluctuations.

$$\delta = (\rho - \overline{\rho})/\overline{\rho}$$

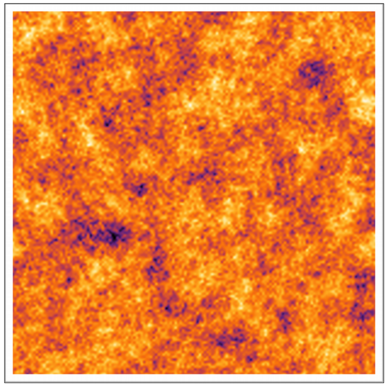
Power spectrum of the density fluctuations



White noise on large scales.

Correlation on small scales.

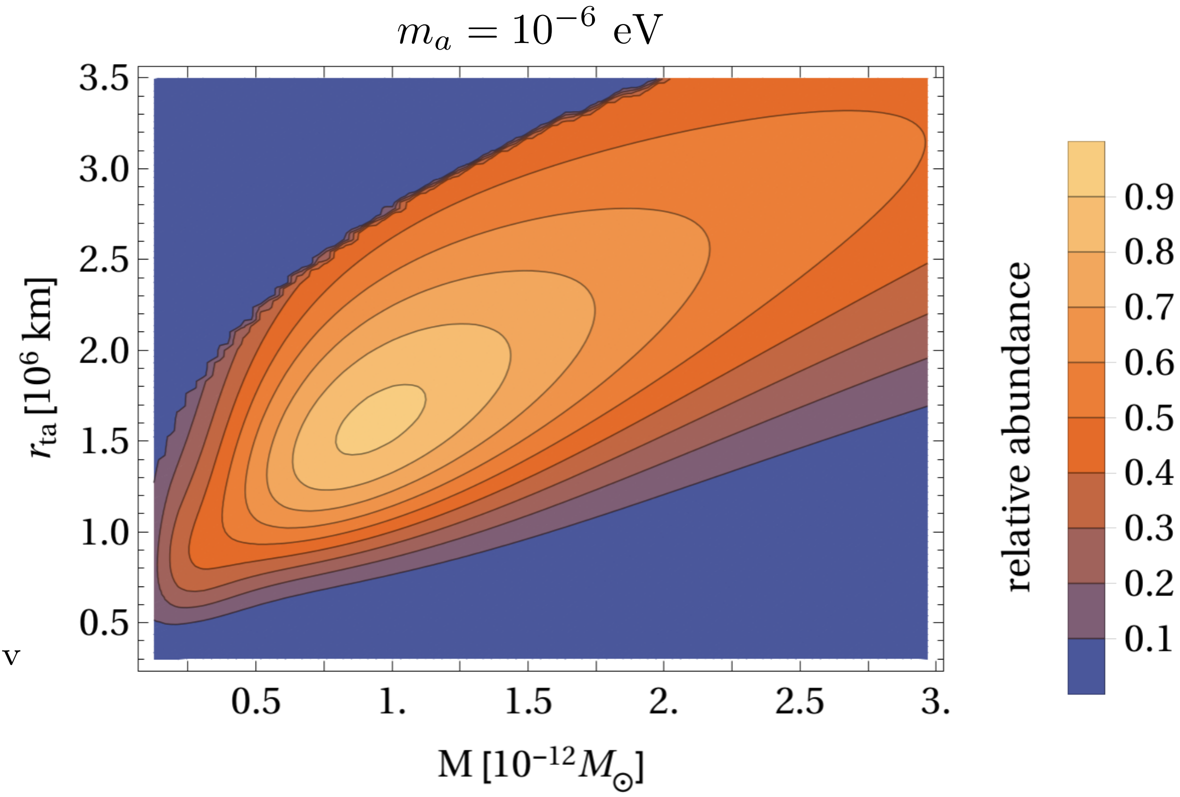
Size of the fluctuations depends on the time the field oscillations commence.



$$L \propto 1/m_a$$

Minicluster mass function

- Decoupling of nonlinear overdensities already in radiation dominated universe.
- Determine distribution of miniclusters.



$$n_a \sim 10^{28}\ \text{cm}^{-3}$$

$$n_{\text{MC}} < 1\ \text{AU}^{-3}$$

$$\nu_{\text{MC}} < 1/\tau_{\text{Univ}}$$

Minicluster mass function

Important input for:

- Direct detection experiments.
- Search for astrophysical signals of miniclusters.
- Further evolution of miniclusters.

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$$n_{\mathrm{MC}} < 1\ \mathrm{AU}^{-3}$$

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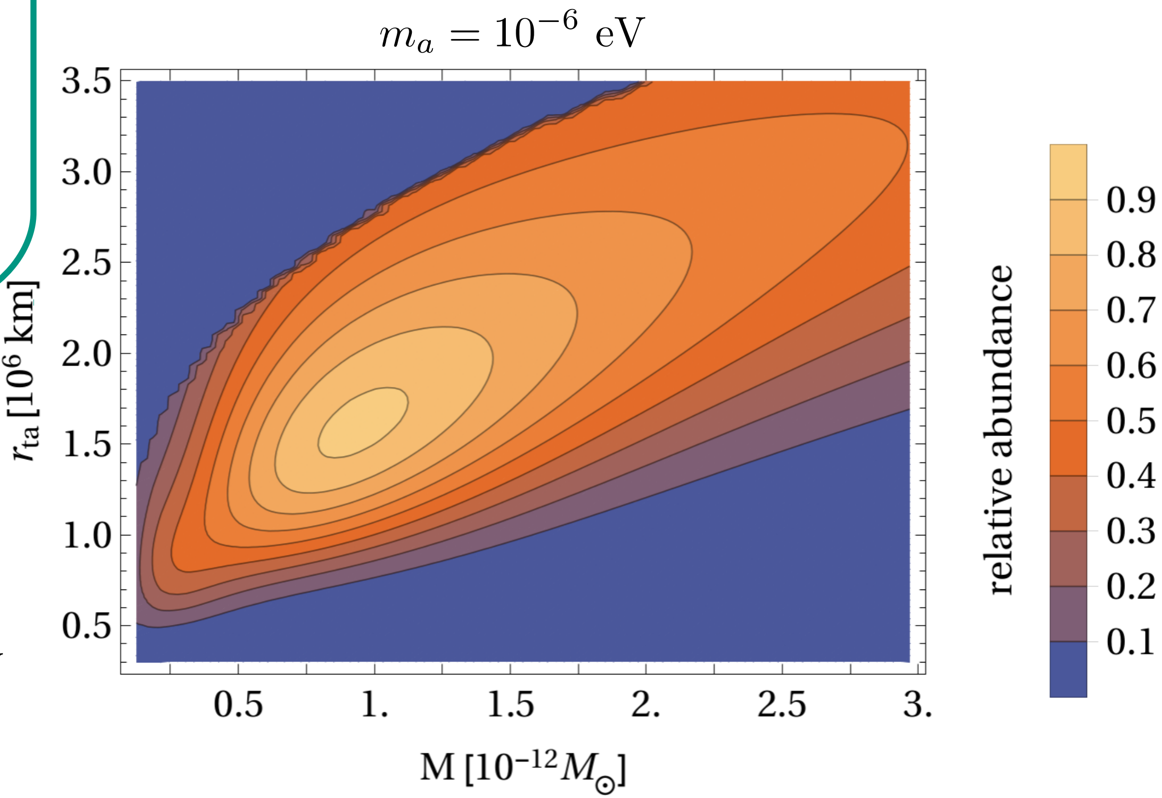


Minicluster collapse in a toy model

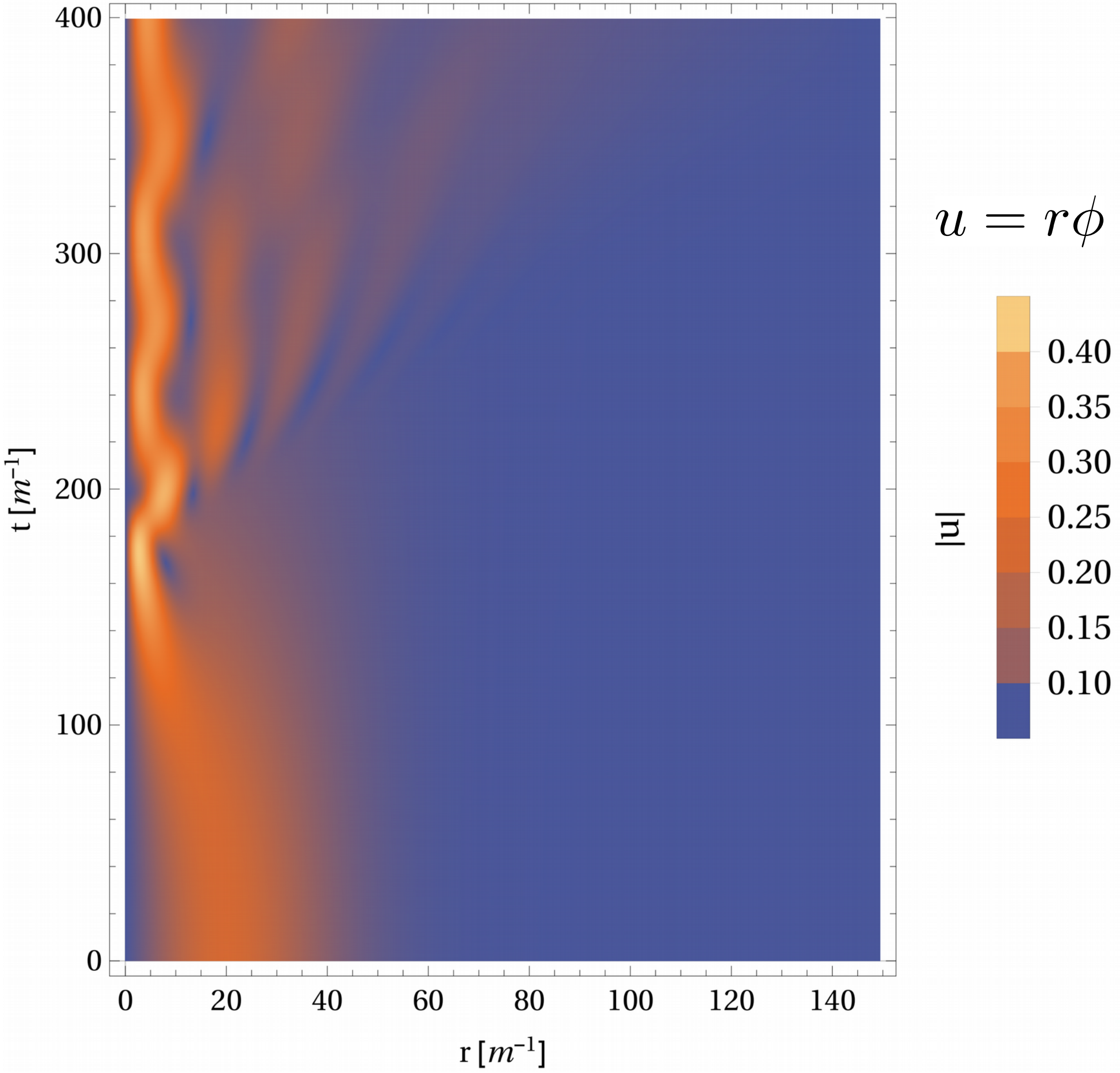
Collapse in virialized
or coherent
configuration?

$$\lambda_{\mathrm{dB}} \sim R_{\mathrm{MC}}$$

Numerical simulation of scalar cloud collapse.

$$\mathrm{i}\partial_t \phi = -\frac{\Delta\phi}{2m} + m\Phi_N \phi$$

$$\Delta\Phi_N = 4\pi G m \phi^* \phi$$



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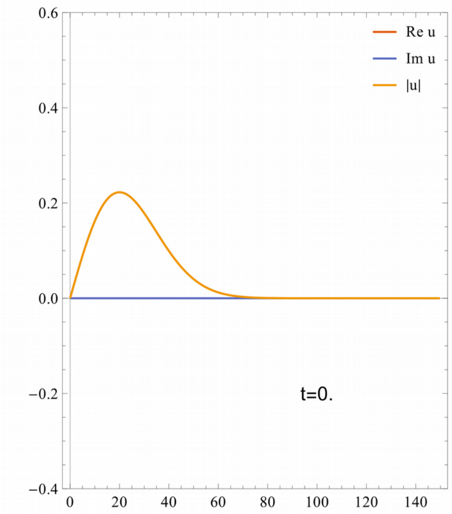
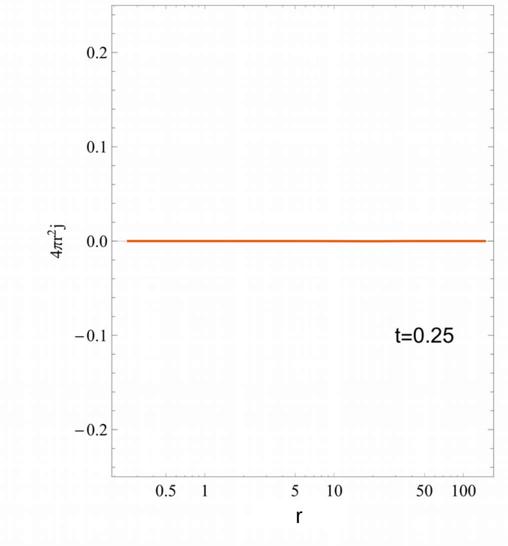
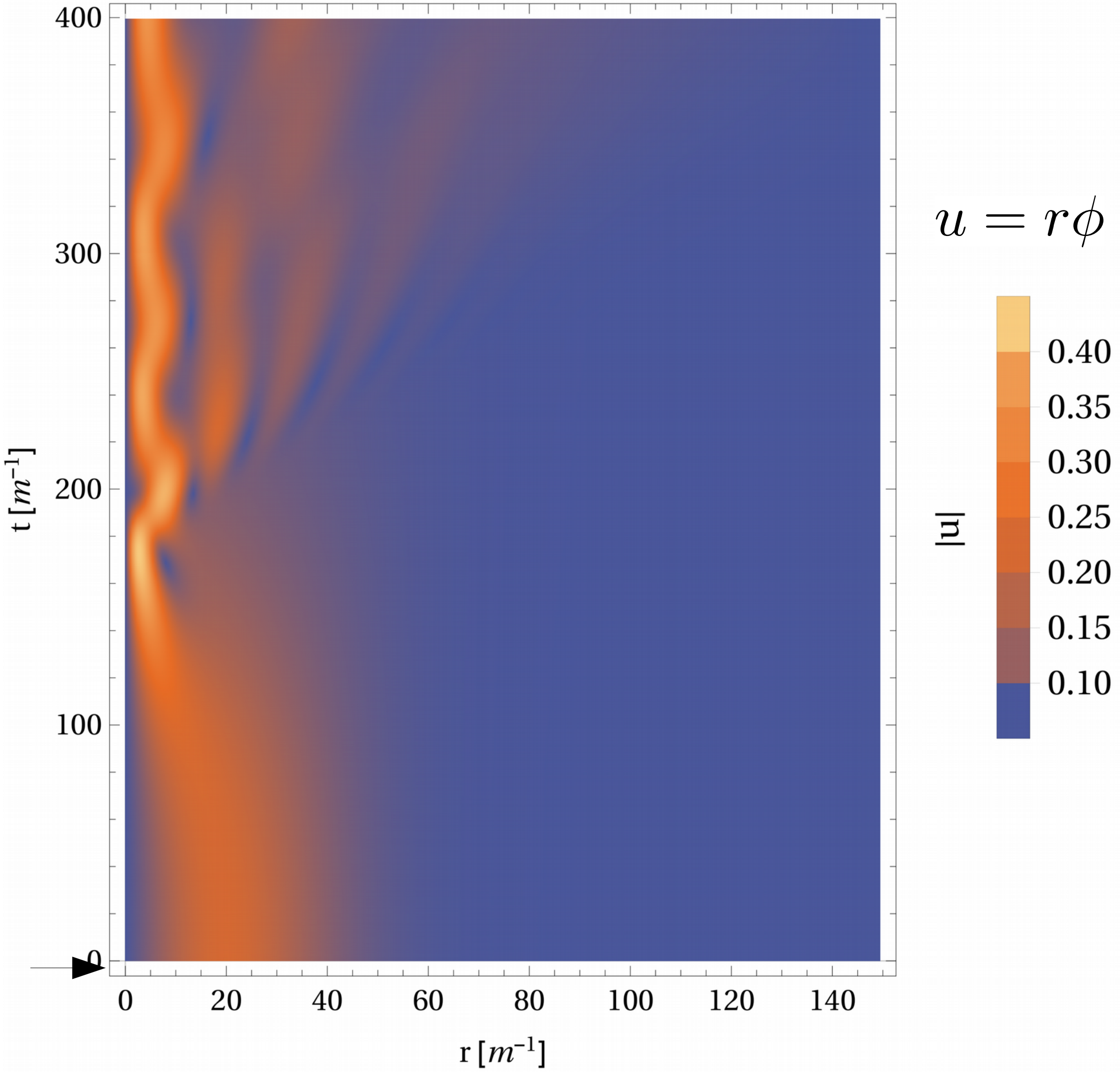
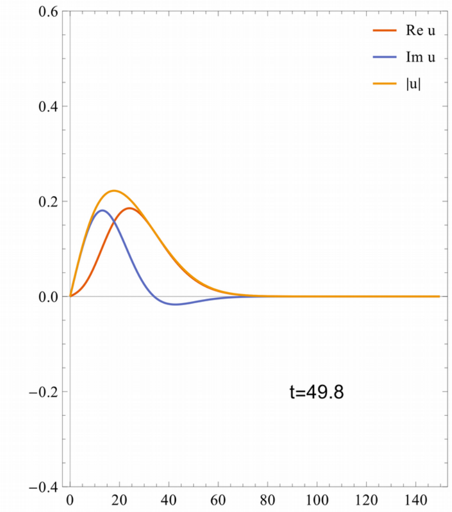


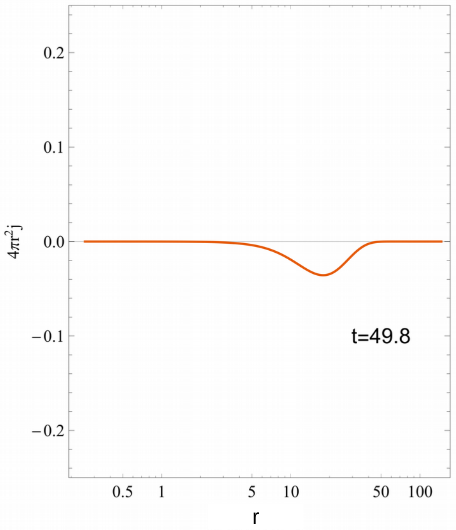


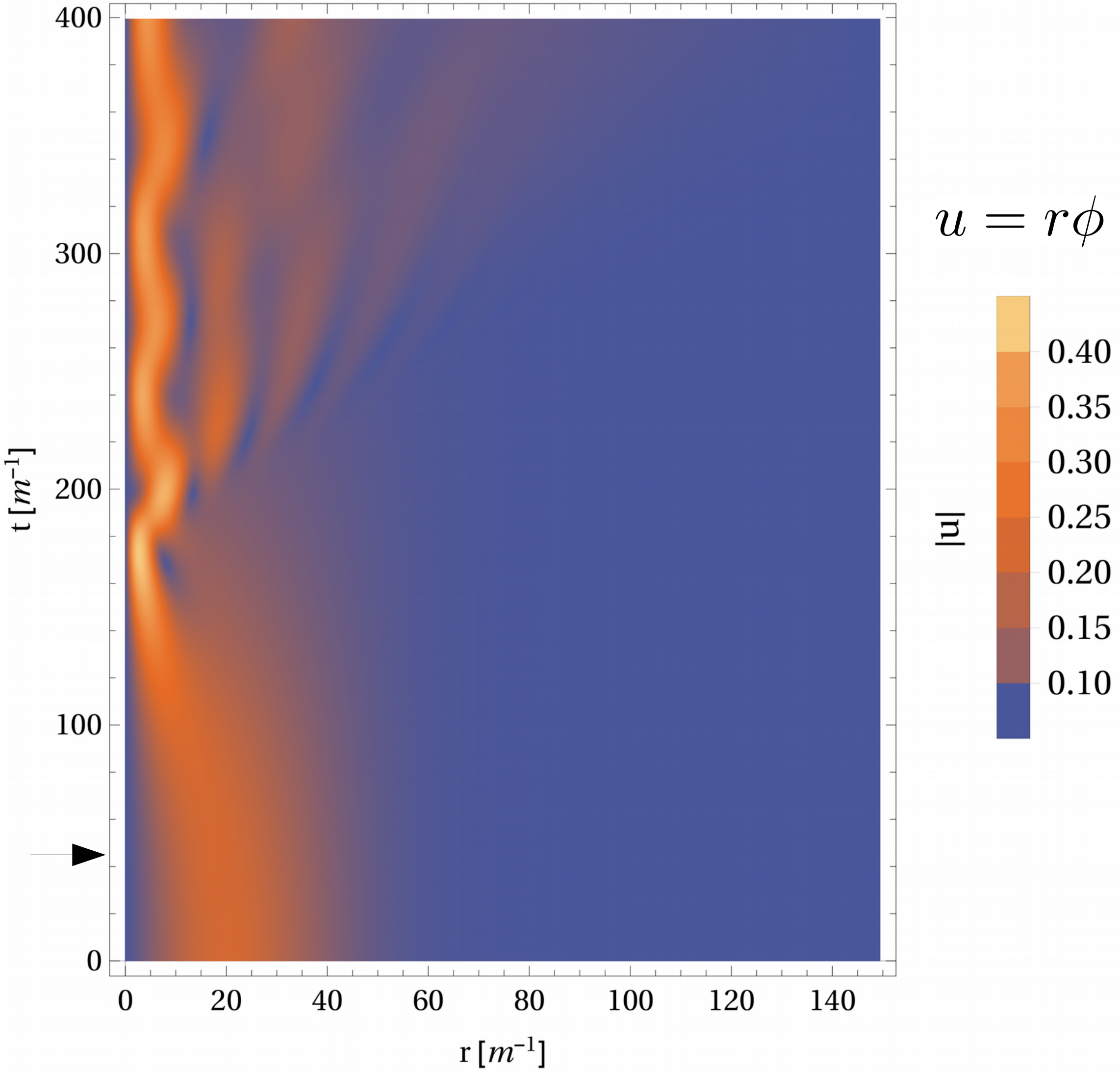


$$u = r\phi$$

Minicluster collapse in a toy model







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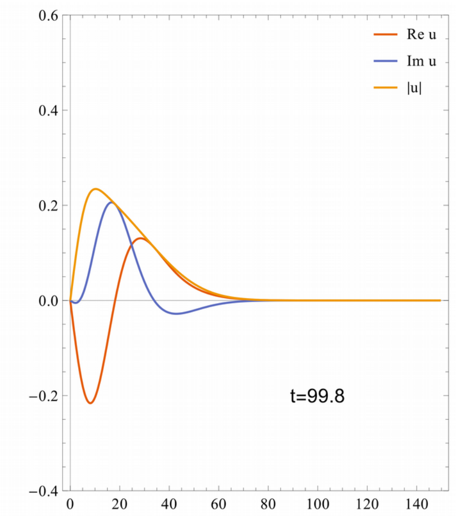

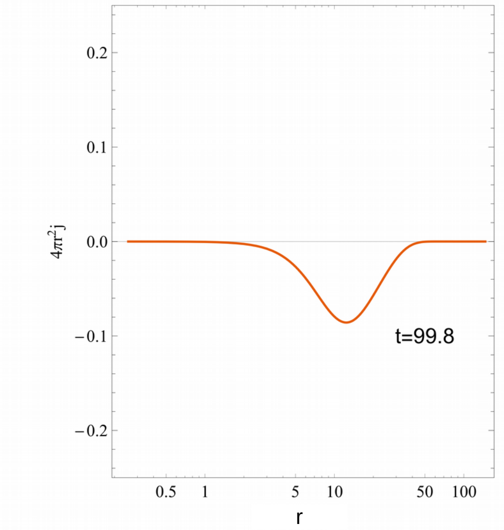

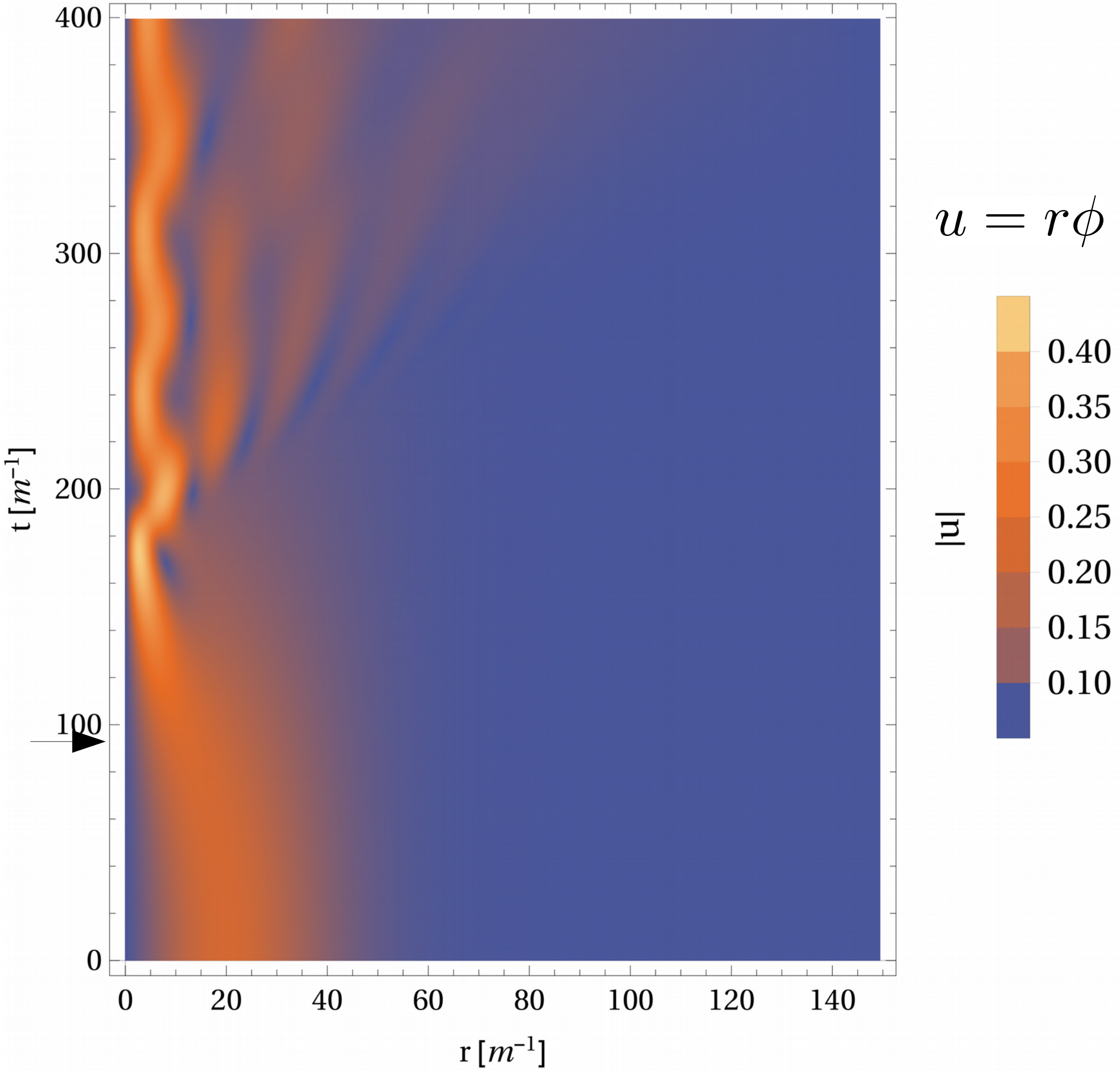

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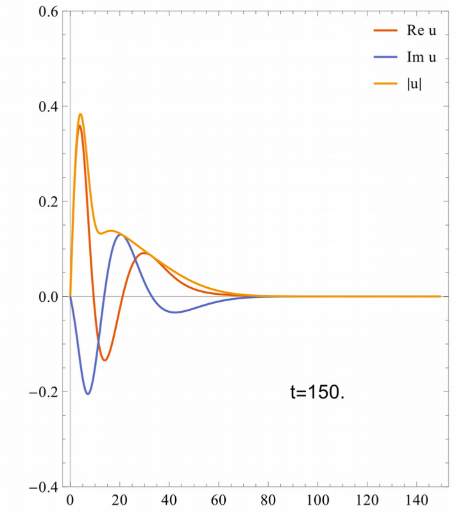

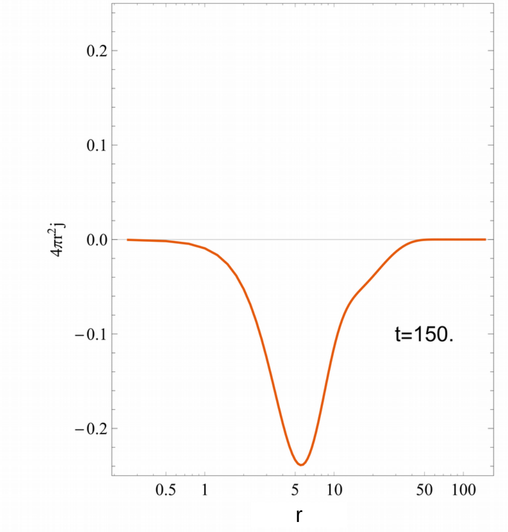

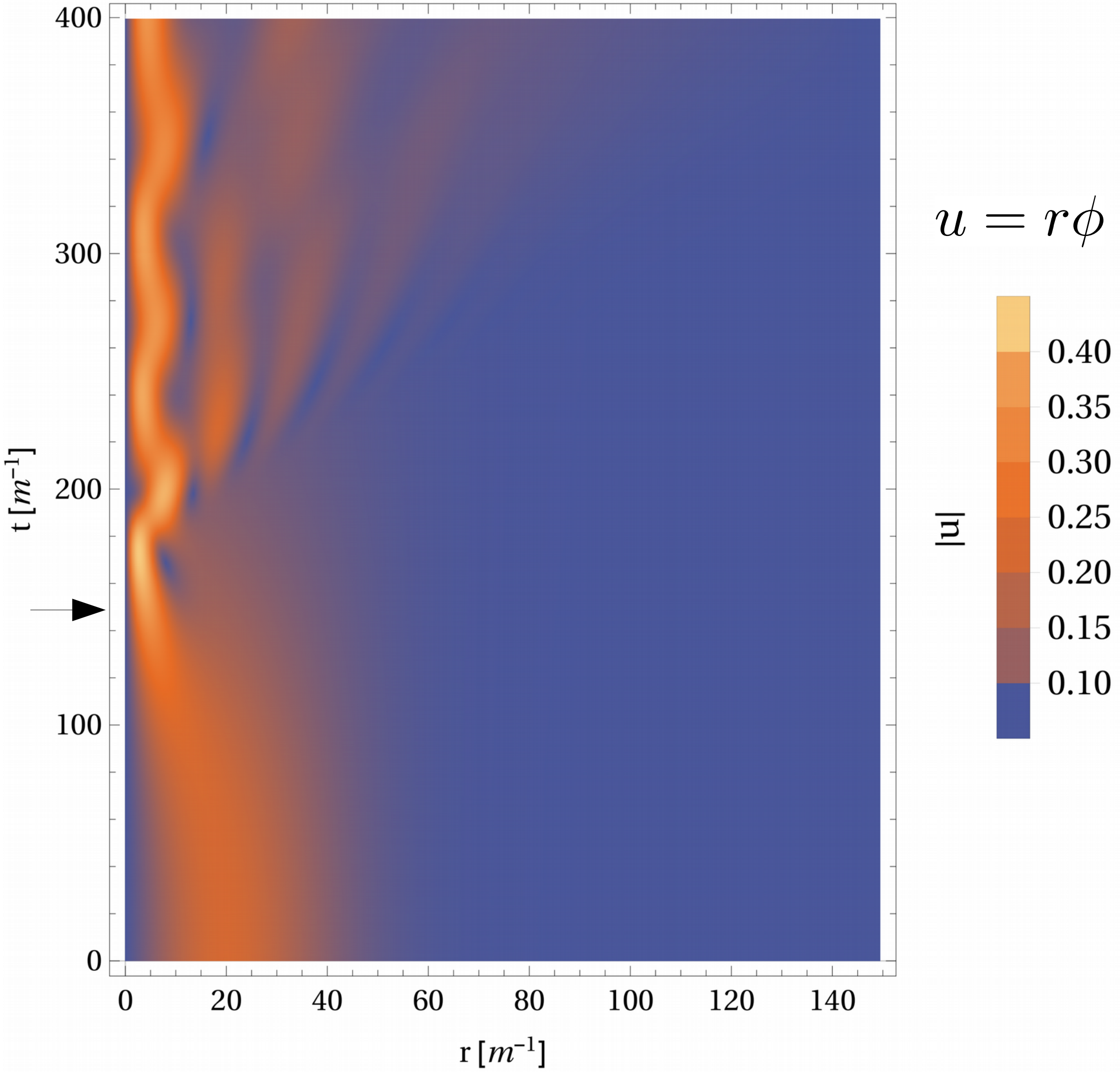

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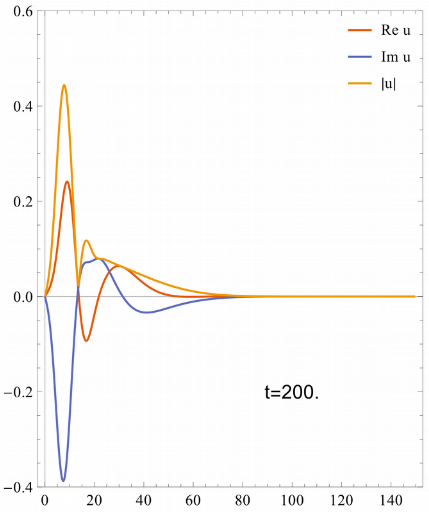

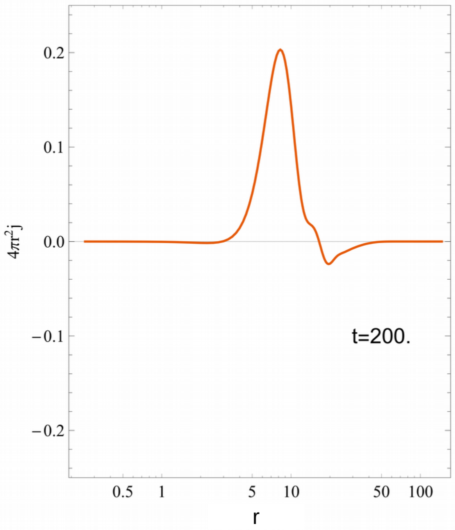

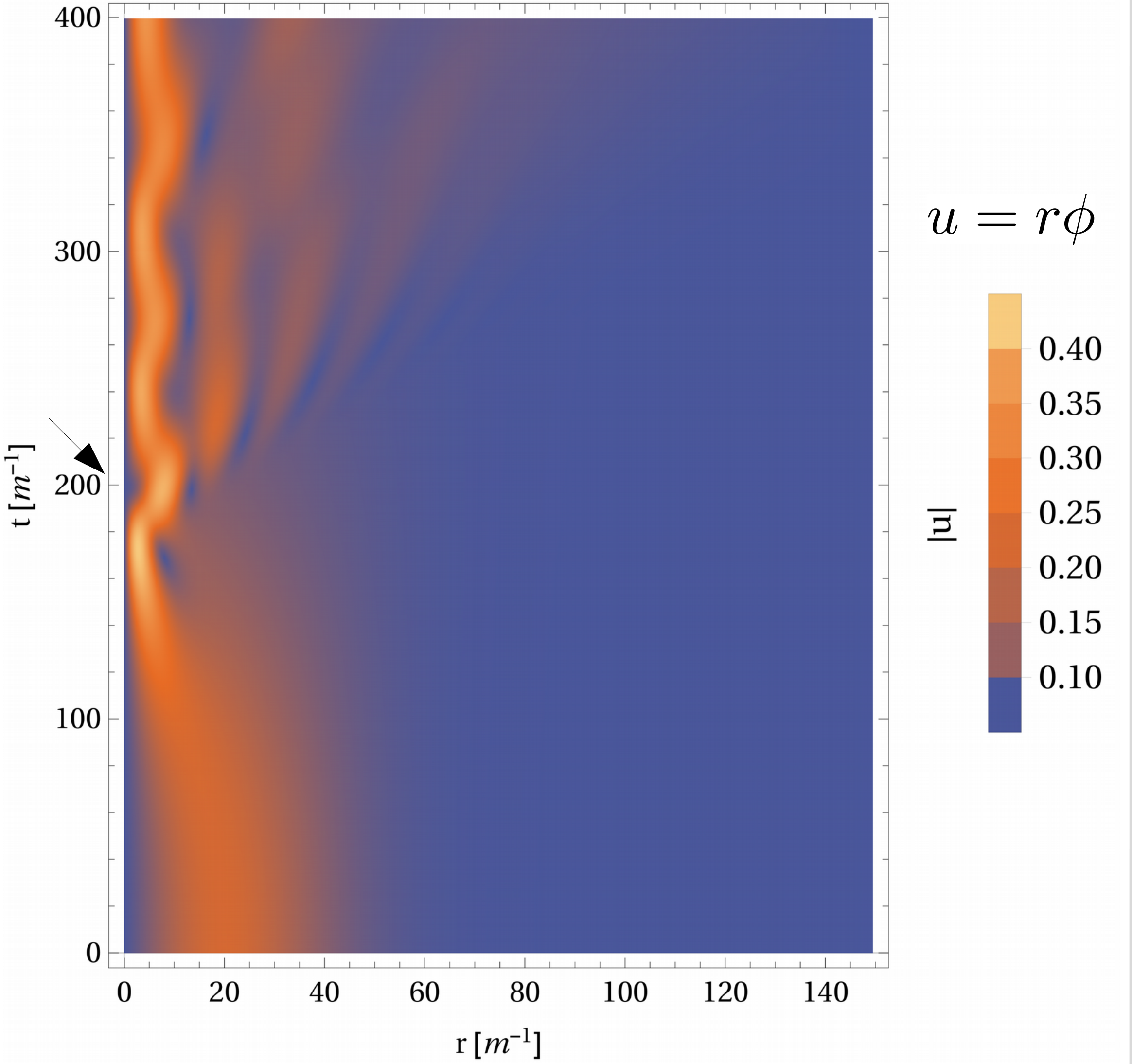

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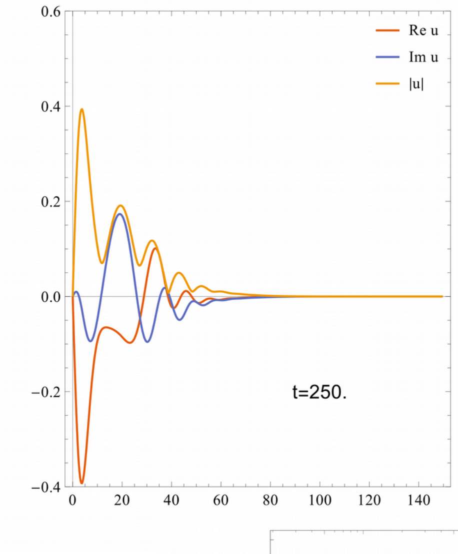

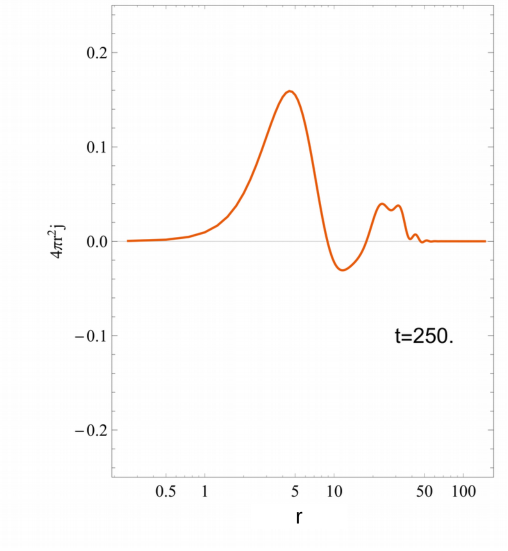

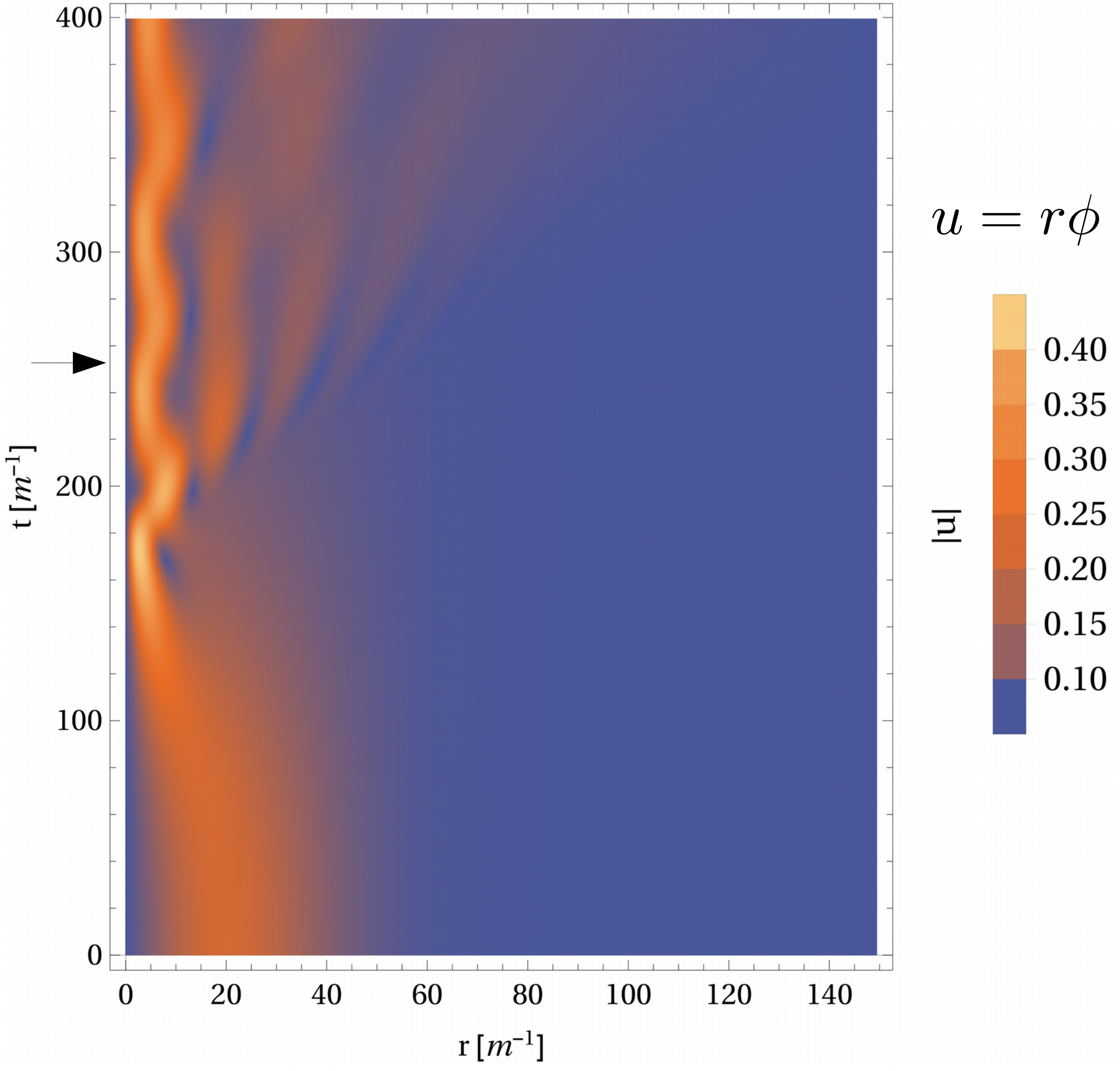

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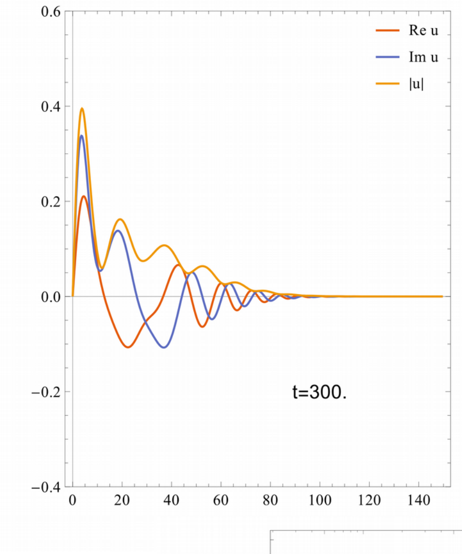

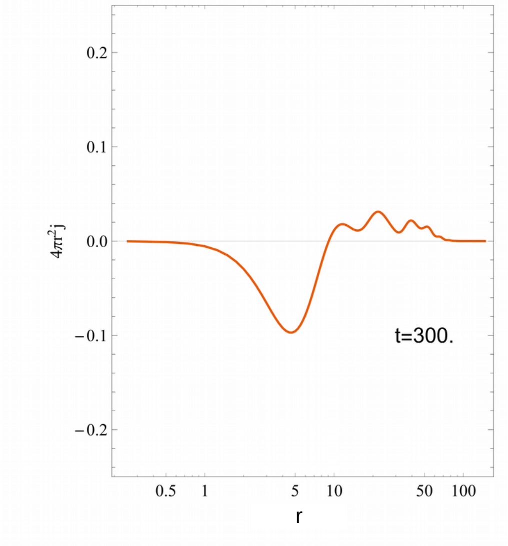

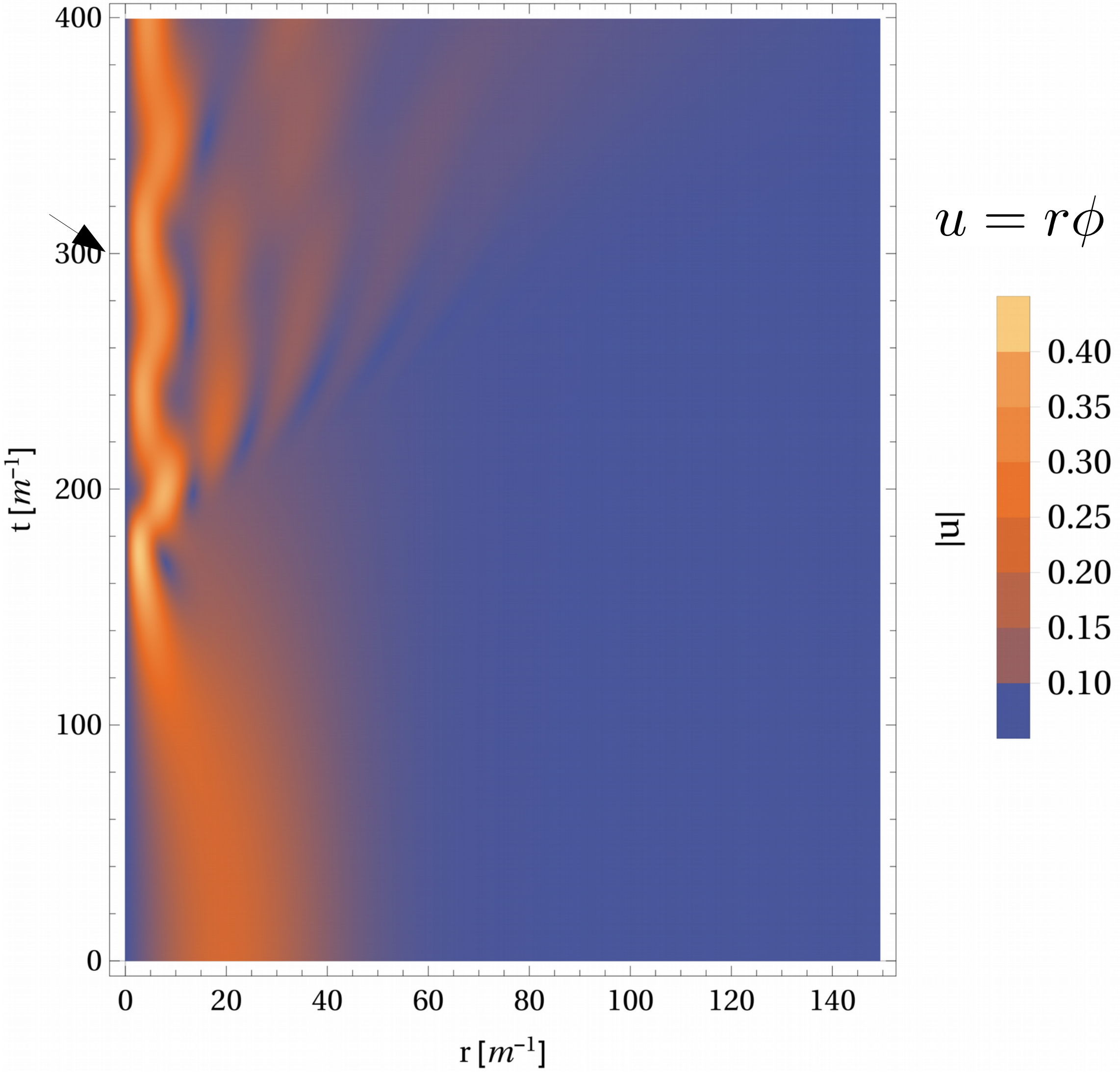

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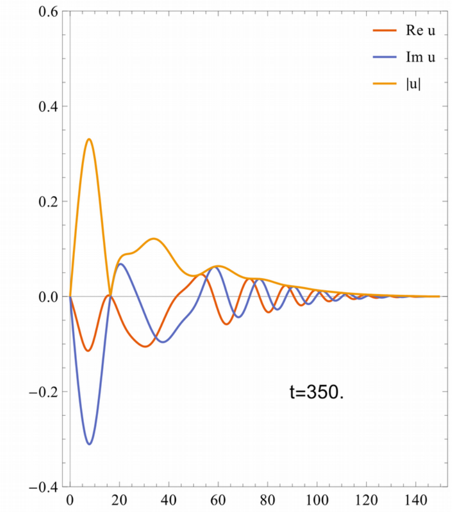
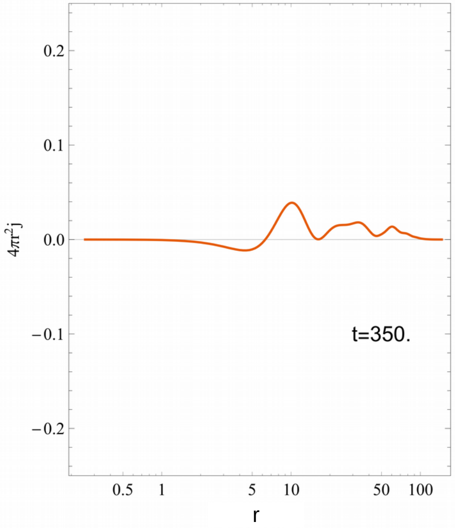
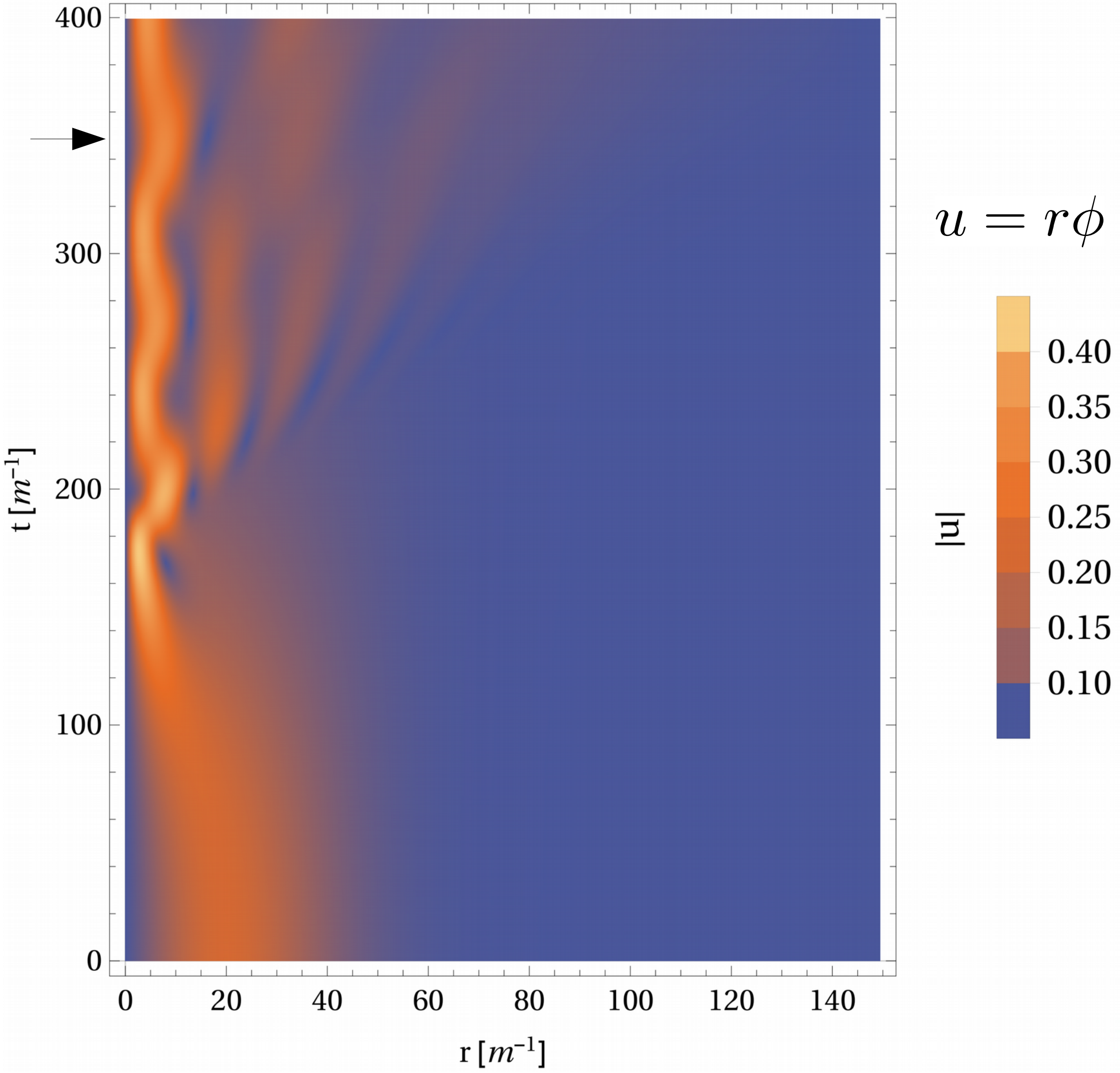
Minicluster collapse in a toy model







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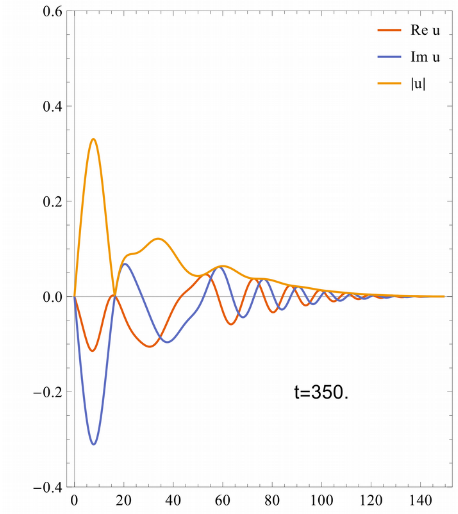

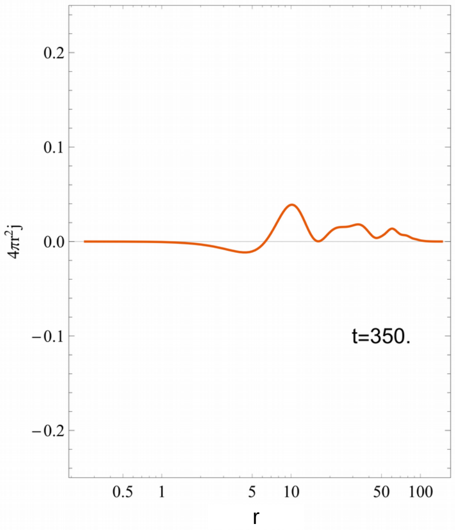

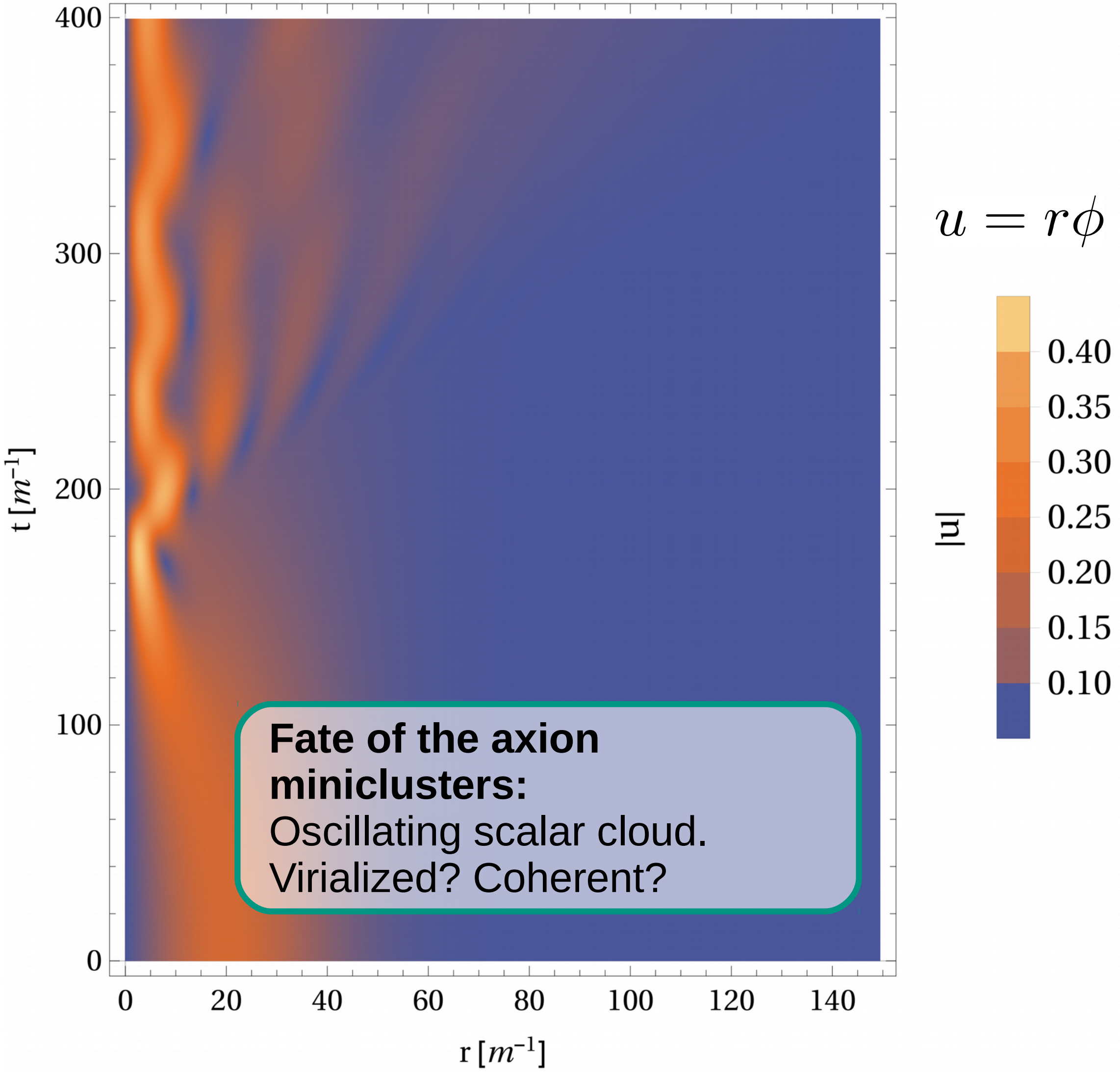

$$u = r\phi$$

Fate of the axion miniclusters:
Oscillating scalar cloud.
Virialized? Coherent?

Conclusion and Outlook

- The axion is a well motivated dark matter candidate.
- Interesting phenomenlogical implications beyond the usual interactions with the Standard Model.
- QCD axion: formation of miniclusters. Understanding their distribution is important for dark matter searches.
- Ultralight ALPs: Minicluster fluctuations have impact on cosmological scales, observable in the CMB. Limits on ALP dark matter masses.

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Thanks for your attention!

Back-Up.