Evolution of gauge invariant scalar perturbations from inflation to reheating (storytime edition)

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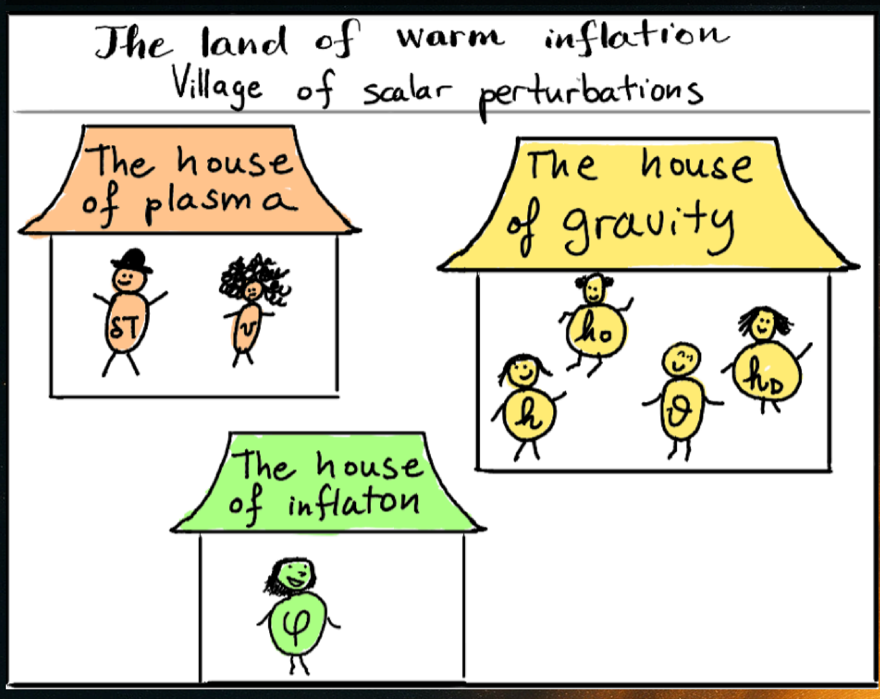
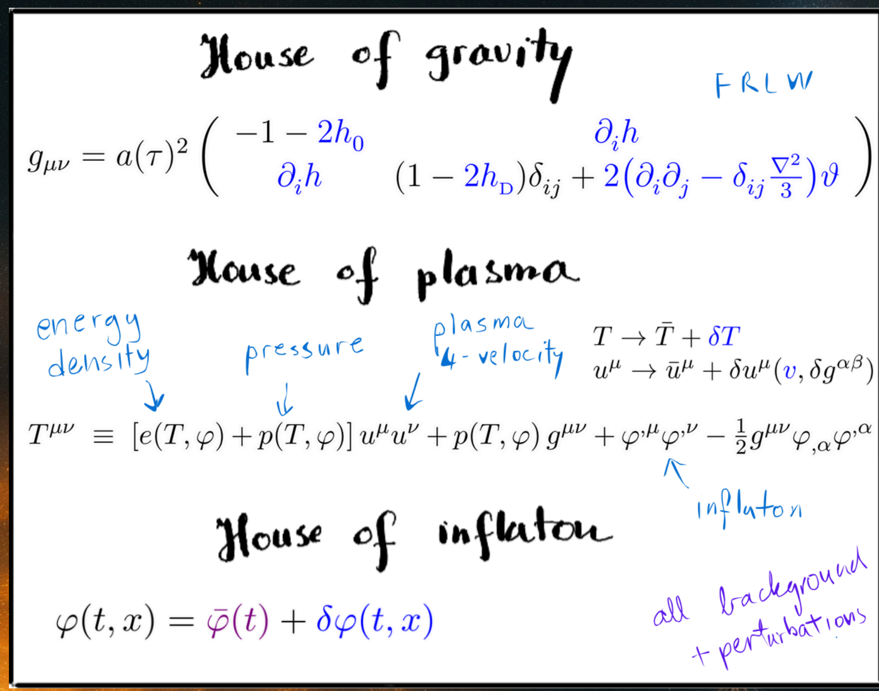
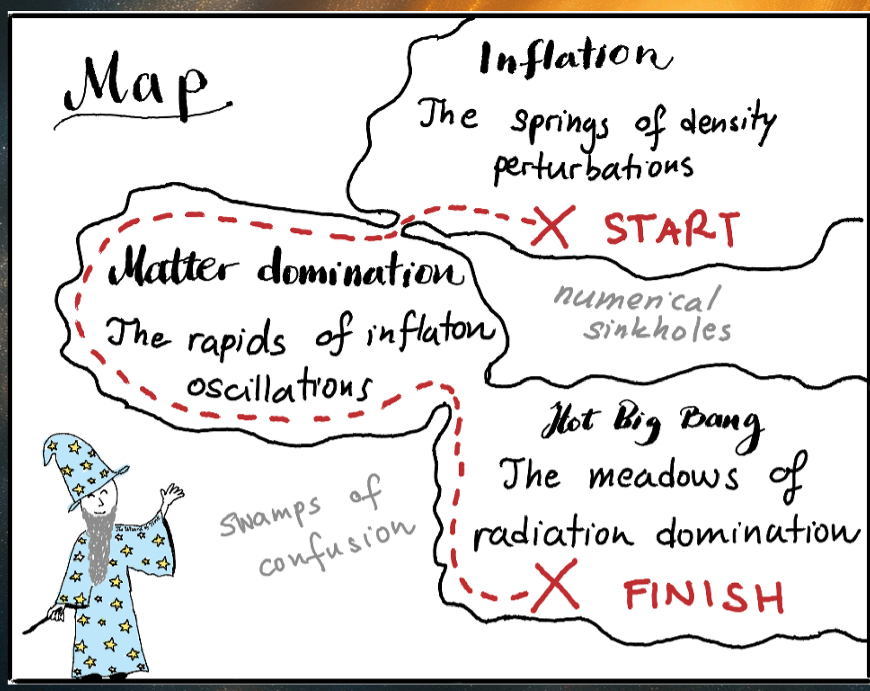
Once upon a time, in the vacuum of the early universe during inflation, quantum energy fluctuations were generated. They quickly evolved and assumed identities of the inflaton, plasma, or the spacetime metric.



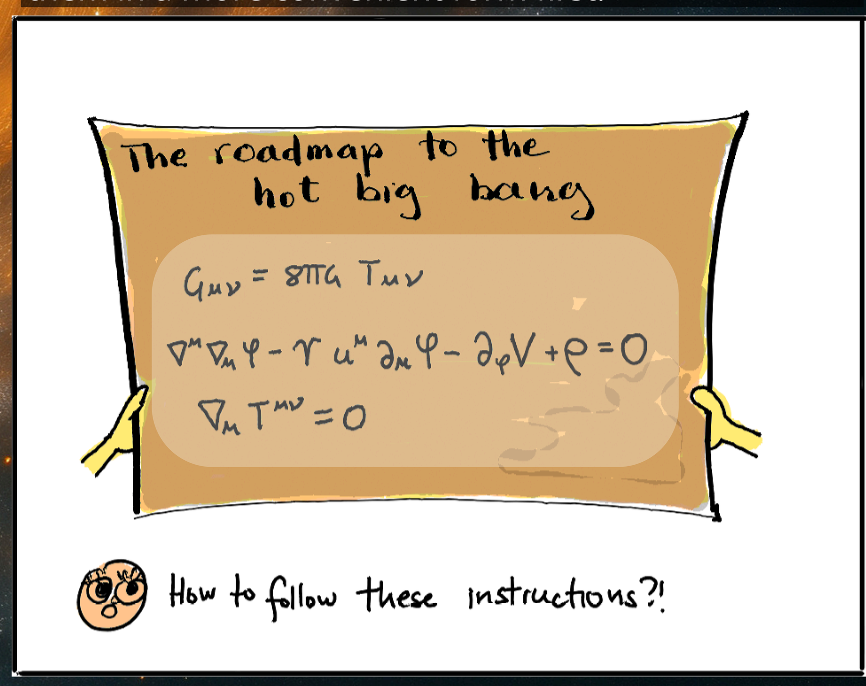
To understand the nature of scalar perturbations, we provide their family trees for your convenience.



The perturbations were approached by the Wizard of Time. He sent them off on a journey to the "Hot Big Bang", to the beginning of the radiation domination. He gave them a map...

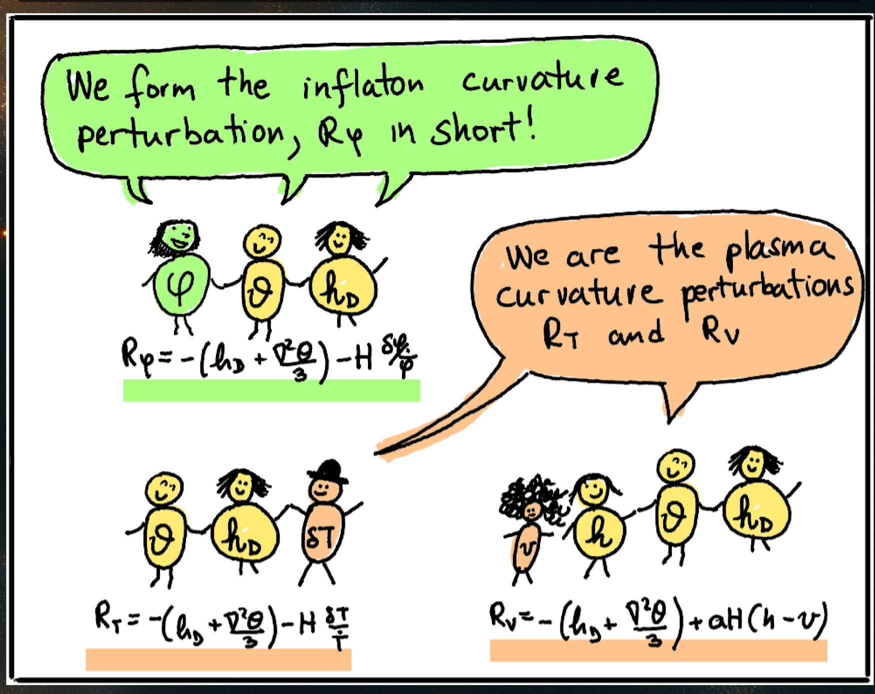


...together with a set of instructions, equations that would guide them on their journey. The equations were very compact. The perturbations knew that in order to follow the equations, they needed to rewrite them in a more convenient form first.

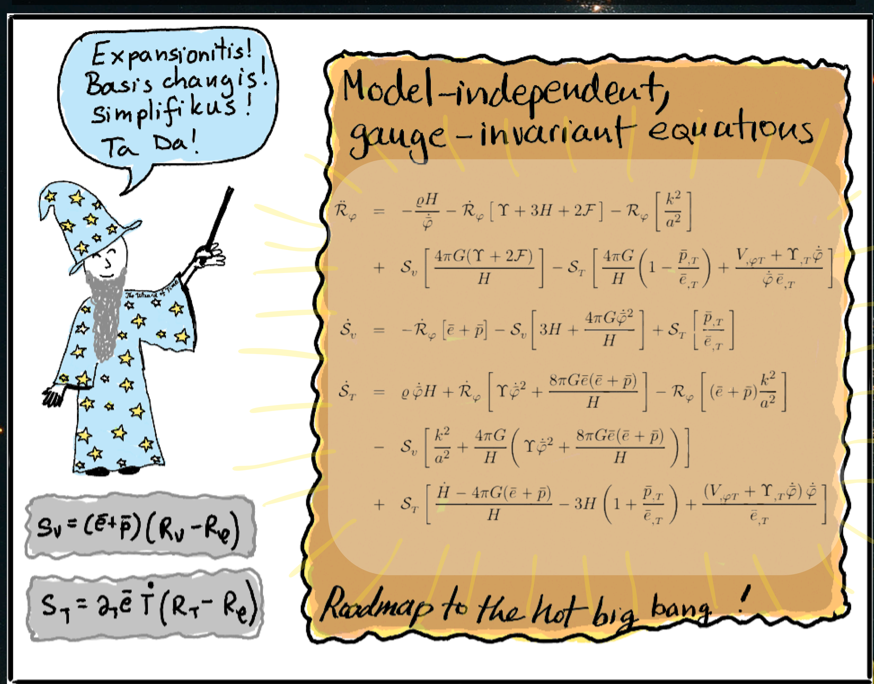


The Wizard agreed to help, but he first imposed some conditions on the travel.

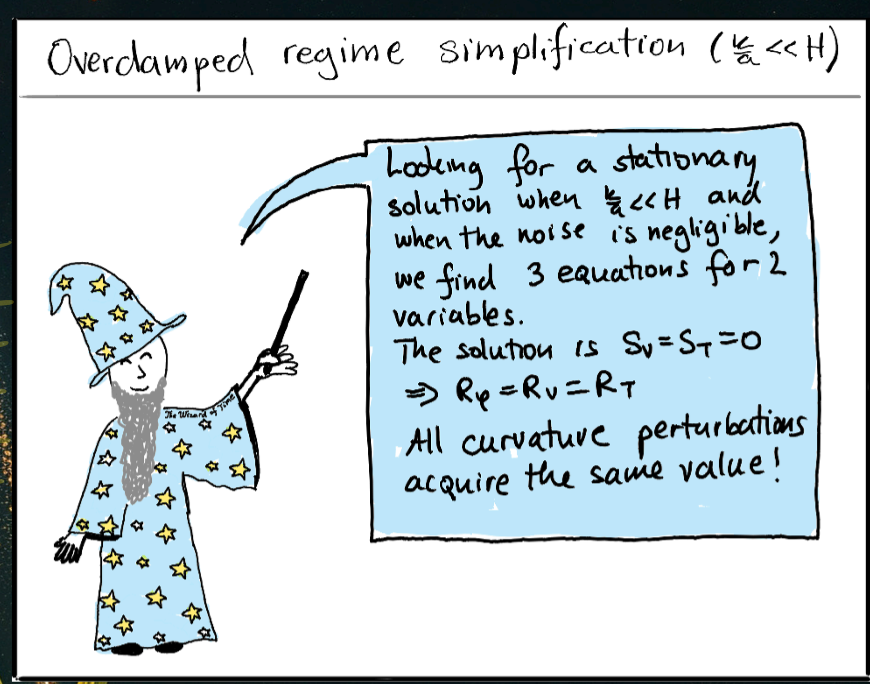
Exploiting 2 scalar gauge parameters, the 7 perturbations rearranged themselves into 5 gauge-invariant combinations. Here 3 are shown, the other 2 could be Bardeen potentials. They play no role in our equations (they decoupled from the rest).



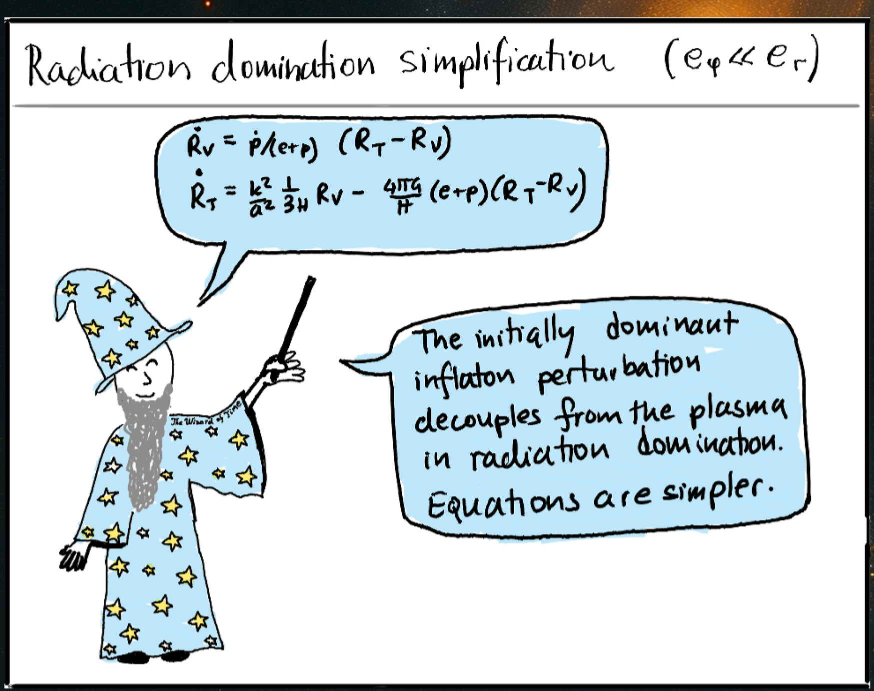
The compact roadmap equations could now be rewritten in a useful way. Expanding the equations to the linear order, performing a change of basis, expressing the equations in terms of the comoving momentum k, and skillfully simplifying gets us to...:



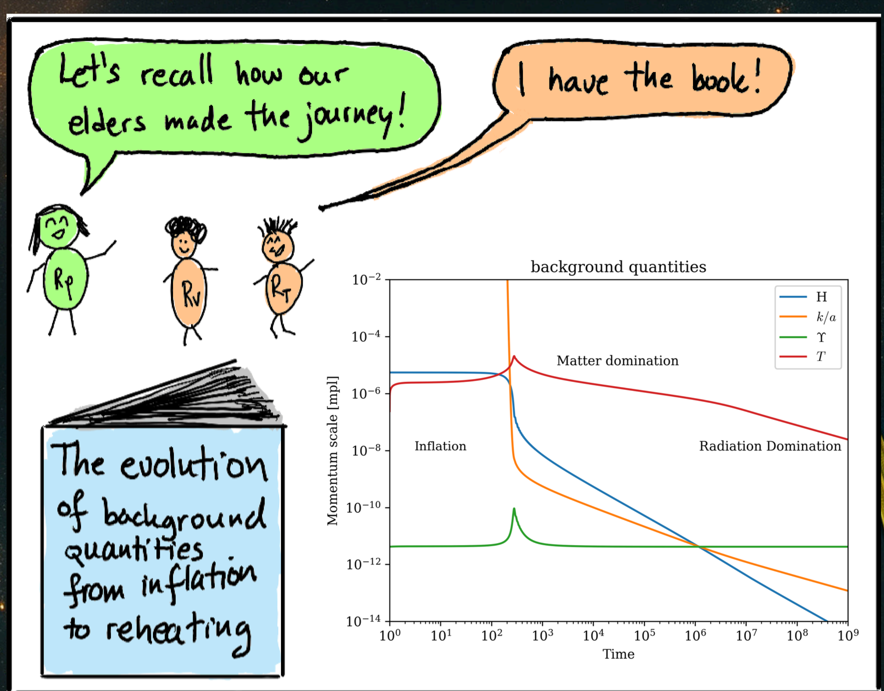
General, model-independent, gauge invariant equations valid beyond the regime of slow roll were derived! To understand them better, one could look in specific regimes where the equations simplify.

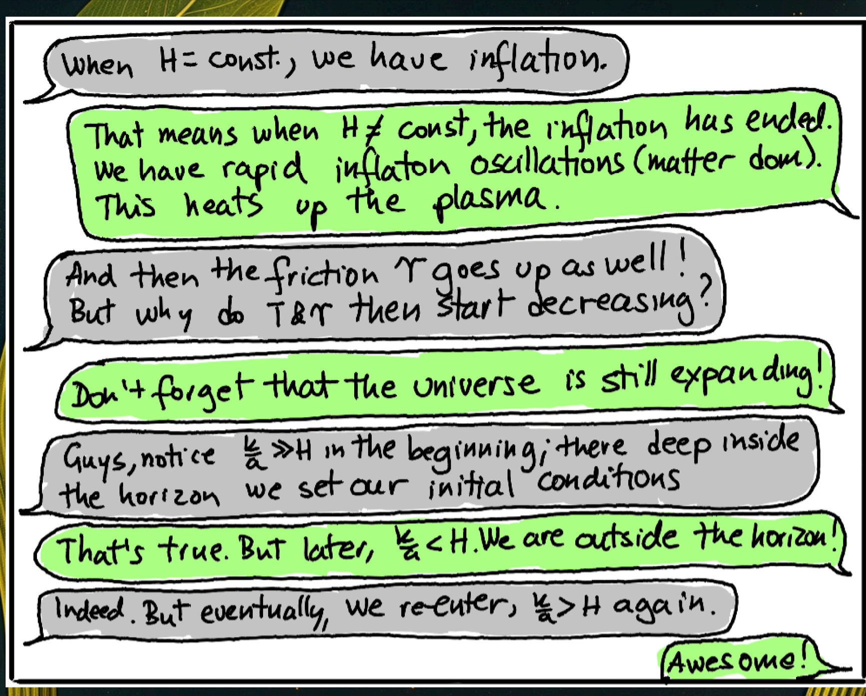


During radiation domination, inflaton no longer influences the plasma.

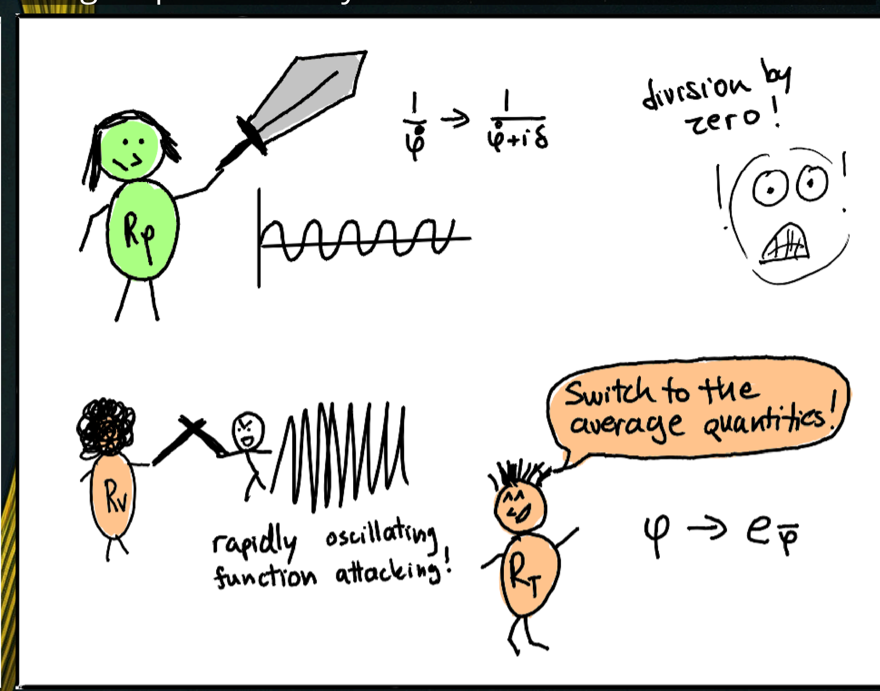


Before solving the first order equations, it is insightful to first understand what happens on the background level.

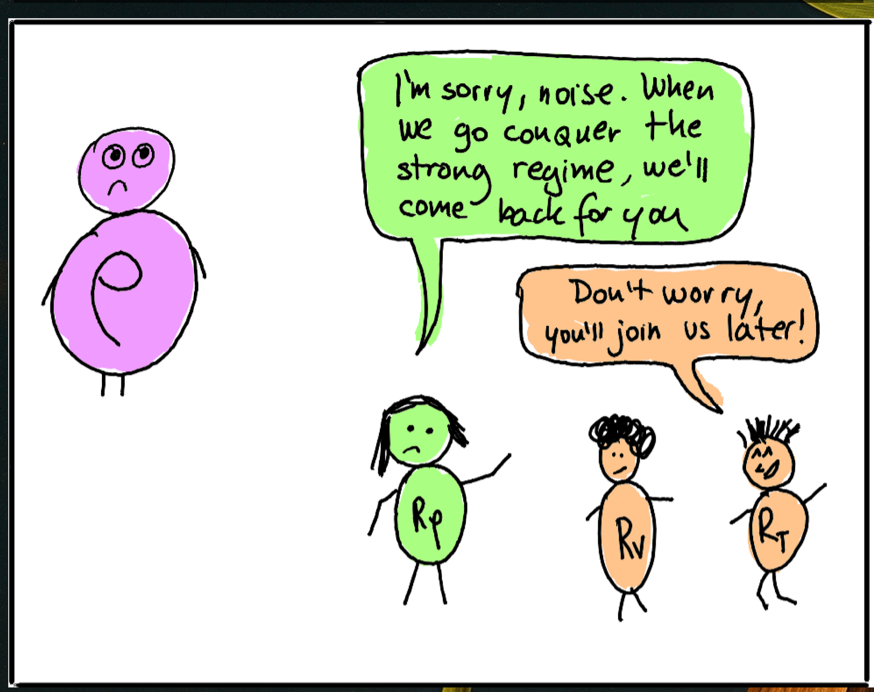




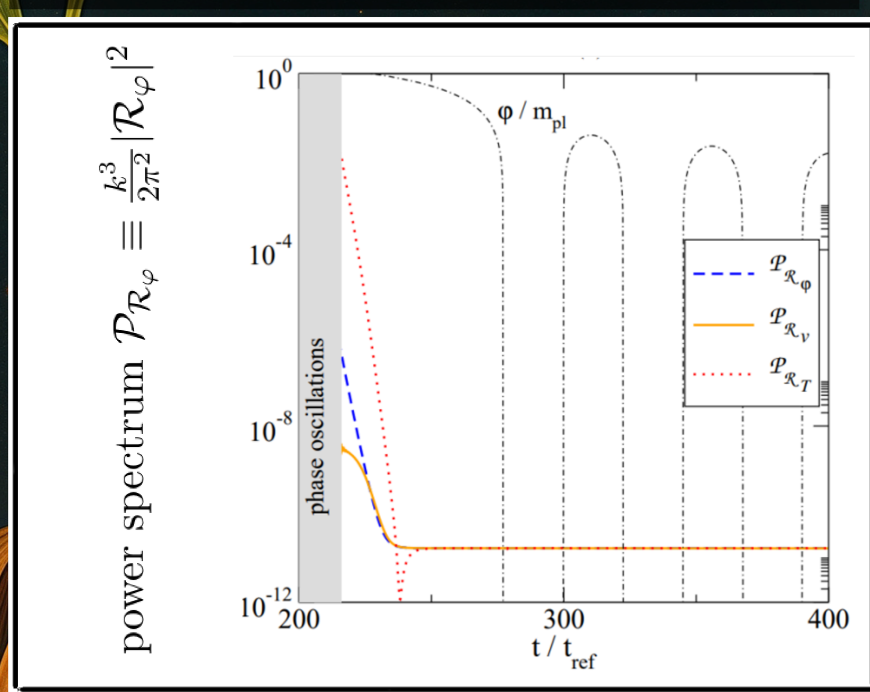
Our heroes set out on the journey to solve the full equations numerically. They successfully overcame the dangers presented by the Numerical sinkholes.



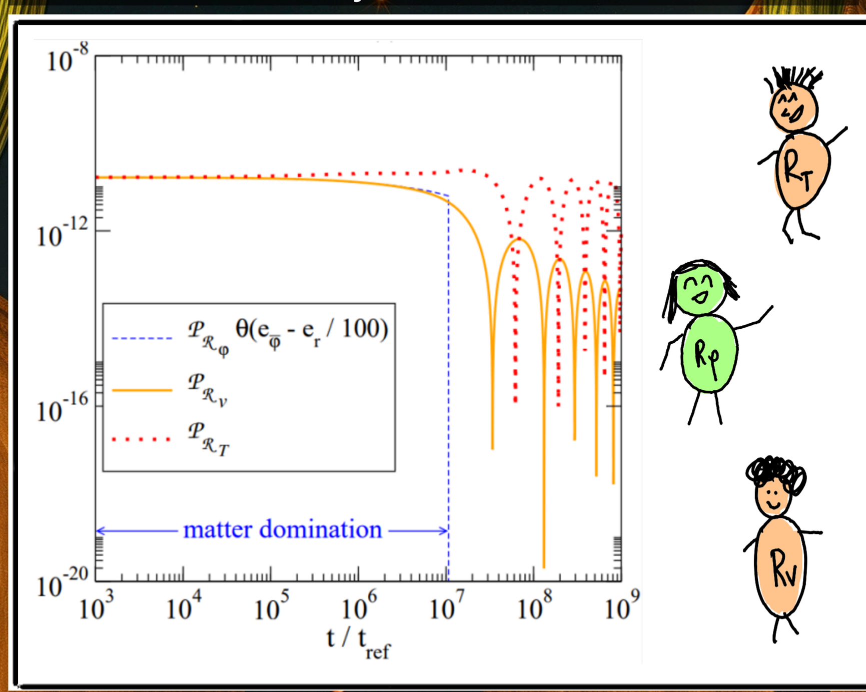
Here, the noise was neglected (weak regime). When exploring the strong regime, the influence of the noise on the solution will be carefully studied.



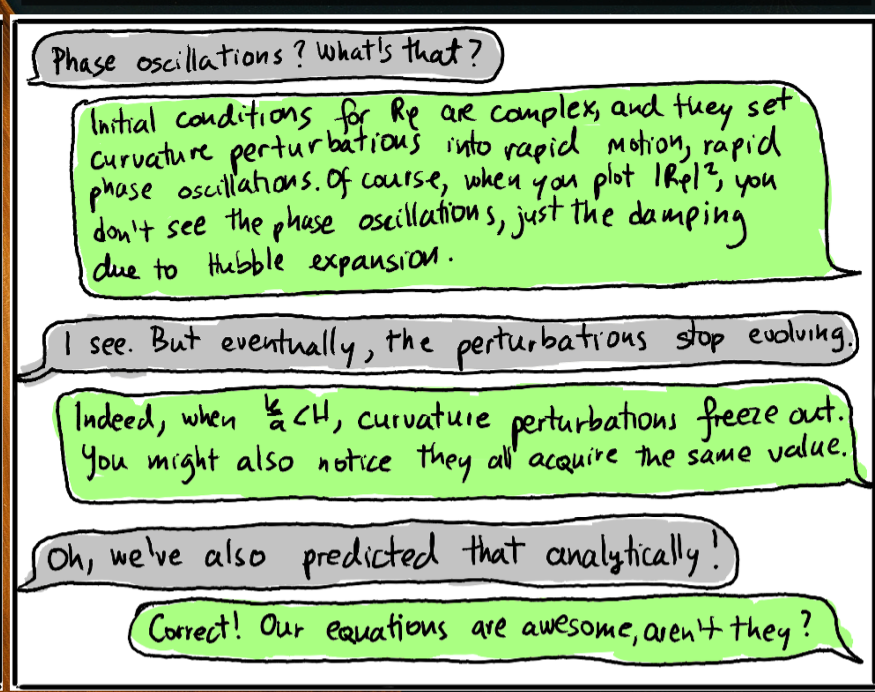
Finally, our gauge invariant heroes reached their destination, radiation domination. Hurray! Their journey is presented in terms of the power spectrum.



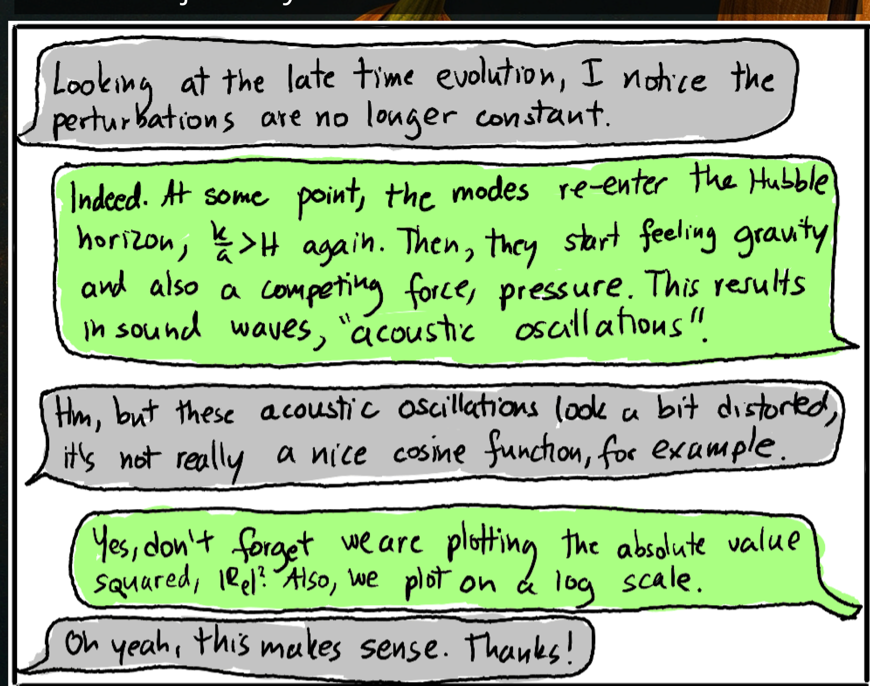
The left plot shows the evolution at early times (see freeze out). The right plot shows the evolution at late times (horizon re-entry, acoustic oscillations).



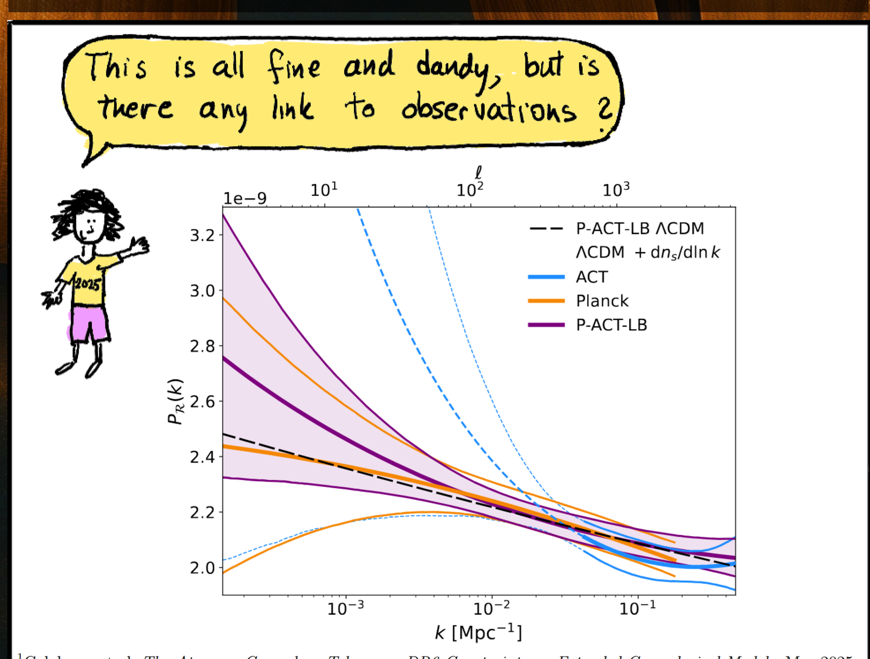
The proud curvature perturbations happily shared the details of their journey with their friends...



...what a journey!

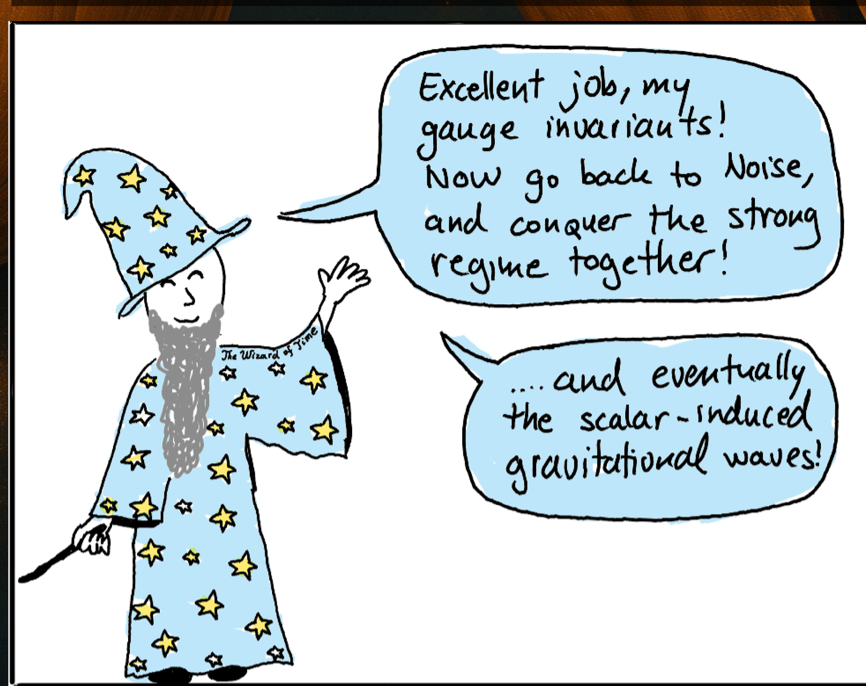


Connection to the data?



[1] Calabrese et al. The Atacama Cosmology Telescope: DR6 Constraints on Extended Cosmological Models, Mar 2025

Next steps?



Terms and Conditions

By reading the poster, you understand that:

- We assumed plasma to be thermal
- To provide a full numerical solution, the following benchmarks were chosen:

natural inflation[2]: $V = m^2 f_a^2[1 - \cos(\frac{\varphi}{f_a})]$

$f_a = 1.25\, m_{pl}$, $m = 1.09 \times 10^{-6}\, m_{pl}$

weakly coupled Yang-Mills plasma:

$e_r = \frac{g_* \pi^2 T^4}{30}$, $p_r = \frac{g_* \pi^2 T^4}{90}$, $g_* = 16$

friction coefficient:[3]

$\Upsilon = \frac{\kappa_T (\pi T)^3 + \kappa_m m^3}{(4\pi)^2 f_a^2}$ κ_T: thermal scattering, κ_m: vacuum decays

easy illustration values: $\kappa_T = 10^6$, $\kappa_m = 10^{10}$

[2] Freese et al. Phys. Rev. Lett. 65, 3233 (1990)
[3] Laine et al. J. High Energ. Phys. 2022, 126 (2022)

based on: https://arxiv.org/abs/2407.17074

CosmoFONDUE, 10.-13.6.2025, Geneva