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Timothy R. Scully

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Reheating the universe

Timothy R. Scully '15 and Professor John T. Giblin, Jr.
Department of Physics, Kenyon College, Gambier, OH

Abstract

With the recent findings of BICEP2, inflation seems to be the most compelling explanation for the expansion of the universe. Alone, the rapid expansion of the universe would result in a much lower temperature than necessary for nucleosynthesis. To counteract this temperature discrepancy, we introduce reheating, a process of thermalizing the universe after inflation. Normally, most toy models simply use scalar fields to produce reheating. By coupling gauge fields to a scalar inflaton, however, parametric resonance and tachyonic dynamics may be introduced into an inflationary model. The introduction of the gauge fields provides a much more efficient mechanism through which radiative energy that would otherwise be trapped in the inflaton's potential can be released. In addition to being more efficient at reheating, gauge fields add more plausibility to the model as gauge fields prove to be underlying factors in most of physics. Specifically, we studied Abelian gauge fields with U(1) symmetry. Using our Grid and Bubble Evolver (GABE), a lattice evolving program, we parameterize the coupling constant between the gauge and scalar fields. This parameterization allows us to probe for the most efficient reheating.

Gauge Fields

After the cooling caused by inflation, there needs to be a process that can release the energy stored in the inflation, effectively reheating the universe through radiation. The most likely and most testable mechanisms for reheating come from already observed phenomena. Because of its near ubiquitous appearance in fundamental physics, gauge theory could provide an effective yet simple mechanism for reheating. Gauge theory plays an integral part of physics as the gauge symmetries involved, whether conserved and broken, define the Standard Model and the fundamental forces. In general, a gauge field refers to a vector field that obeys a gauge theory where the Lagrangian is invariant under any transformation. The most familiar gauge field is the magnetic vector potential (A) used in electromagnetism. Introducing gauge theory requires some revisions to typical operations. For example fermion fields are coupled to gauge fields via a covariant derivative. The covariant derivative is defined by

$$D_\mu = \partial_\mu + igA_\mu .$$

Introducing this covariant derivative likewise requires reworking of the Lagrangian

$$\begin{aligned} \mathcal{L}_{int} &= i\frac{g}{2}\phi^T A_\mu^T \partial^\mu \phi + i\frac{g}{2}(\partial_\mu \phi)^T A^\mu \phi - \frac{g^2}{2}(A_\mu \phi)^T A^\mu \phi \\ &= -\frac{1}{2}\text{Tr}(F^{\mu\nu} F_{\mu\nu}) . \end{aligned}$$

In these equations, the variable g serves as a coupling constant, determining the overall strength of the interaction between the scalar and gauge field. By parameterizing this coupling constant, we can explore the correlation between the strength of the fields' coupling and how efficiently the energy from the scalar field is released and radiated, possibly paving the way for nucleosynthesis.

GABE

The process of evolving large fields and their properties requires great computational power. To study the evolution and interaction of the gauge and scalar fields, a program called Grid and Bubble Evolver (GABE) was used. GABE uses a second order Runge-Kutta method to calculate field values at all points in a lattice. For this model, a 256^3 point cubic lattice was used. With GABE, the fields are evolved according each field's unique equation of motion.

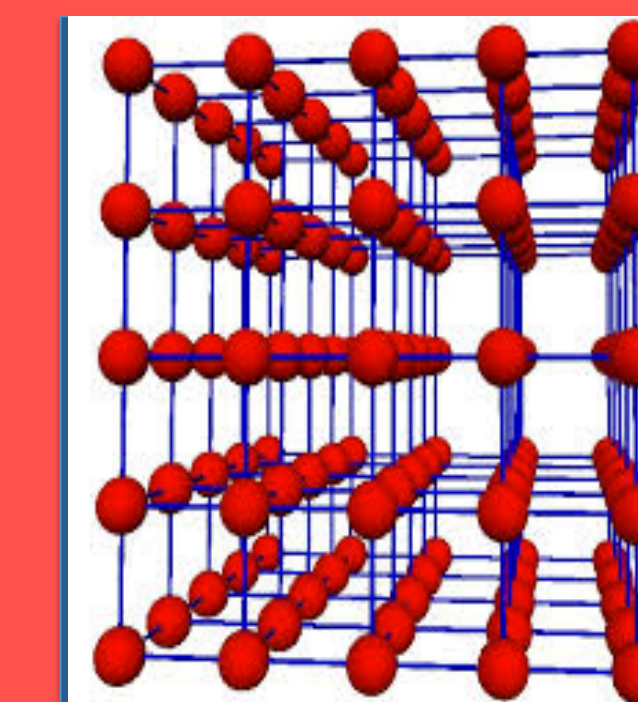


Fig 3. Cubic lattice visualization.

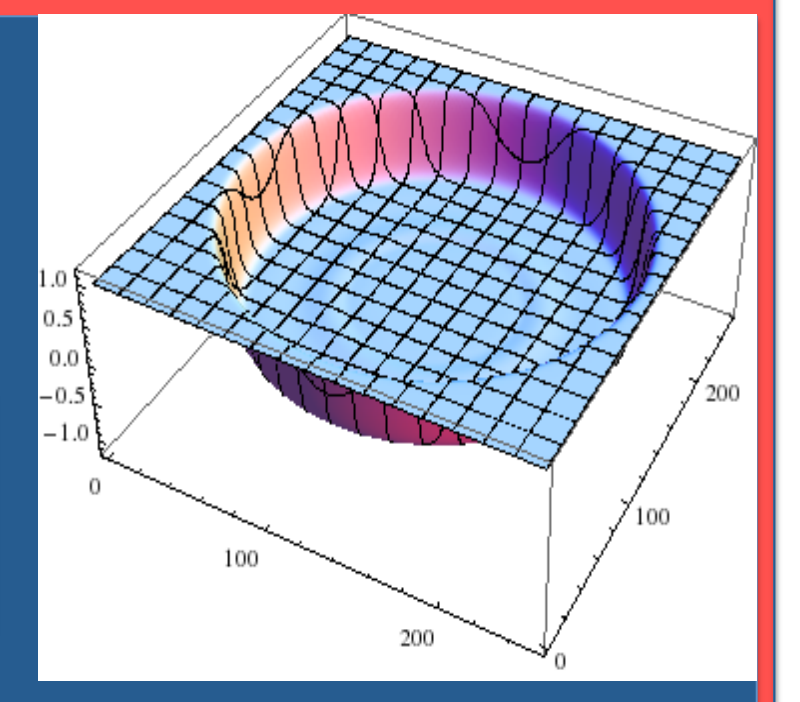


Fig 4. Bubble nucleated in GABE.

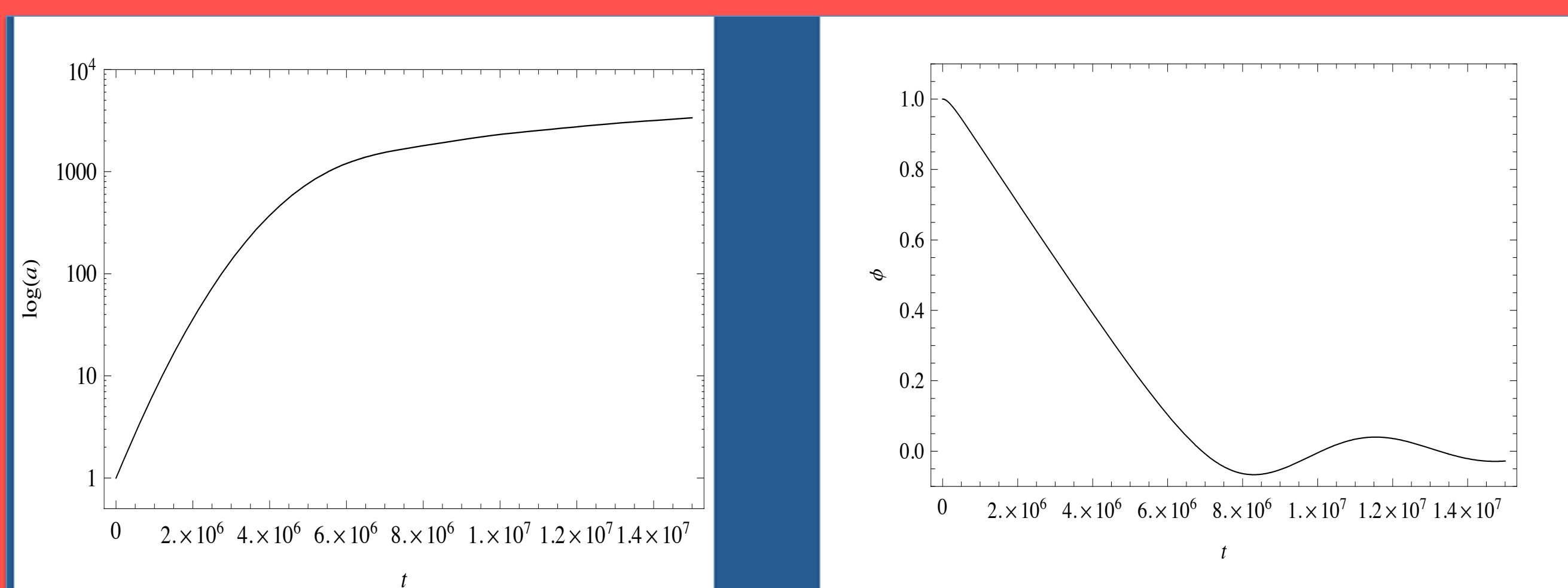


Fig 1. Plot of Scale Factor

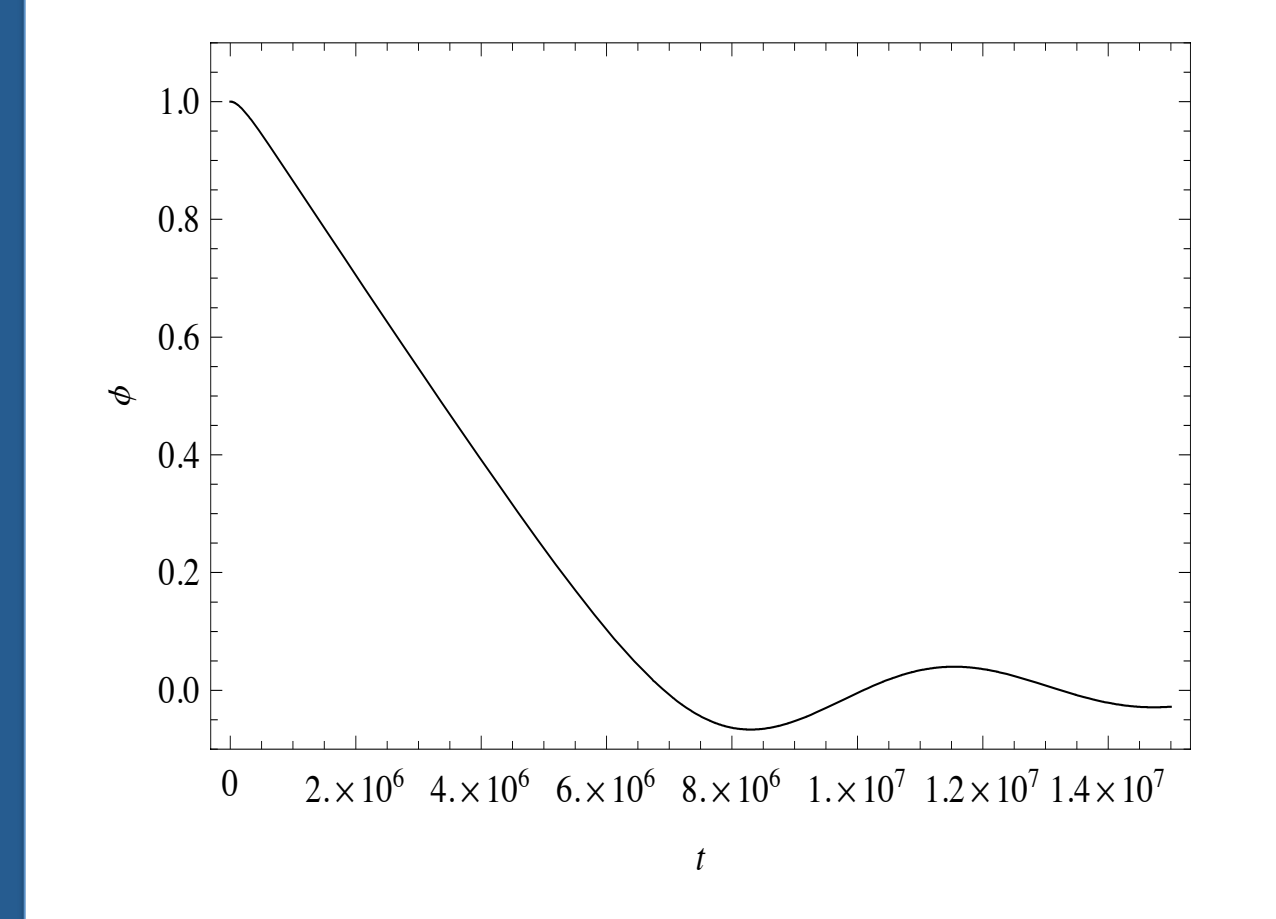


Fig 2. Plot of Inflaton

Results

With the correct coupling, the energy of the scalar field can be radiated with great efficiency. At its most efficient parameterization, a coupling constant of 45, our model shows that about 90% of the energy in the universe will be radiation. This radiation dominant universe provides a reheating scenario in which sufficient energy for nucleosynthesis is released from the scalar field. With the ability to nucleosynthesize through reheating, the cooling caused by inflation can easily be overcome, posing no threats to the development of today's universe.

Our Model

Through its enormous rate of expansion, inflation answers many questions of physics with one succinct theory. Introducing inflation to the study of cosmology brings about one small problem: the Universe is left with an extremely low energy density afterward. Our model consists of a scalar field, powering inflation, and an Abelian gauge field obeying U(1) symmetry, the same type of gauge field and symmetry that define the properties of electromagnetism. By using this gauge field we move beyond toy models of reheating. We investigate whether this more fundamental and familiar model can produce the same non-linear effects needed for reheating since the inflaton alone cannot create a Universe hot enough for nucleosynthesis. As the inflaton decays (see Fig 2.), we monitor if sufficient energy is transferred to the gauge fields. Our inflaton has a potential defined as

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

and obeys the Klein Gordon equation of motion

$$\square\phi = \frac{-\partial V(\phi)}{\partial\phi} .$$

The gauge field obeys the gauge choice ($\partial_i A_i = 0$) resulting in the equations of motion following

$$-\partial_0^2 A_j + \partial^2 A_j = \frac{\lambda}{f}\epsilon_{ijk}\partial_0\phi\partial_i A_k .$$

Initialization

If we examine the gauge field in Fourier space we can decompose it onto its two circularly polarized modes. This decomposition allows us to find the spectrum of each mode at the end of inflation. Although the initial modes are strongly polarized, the final state may or may not be; the inclusion of these modes adds testability to the project. We define the gauge field using these modes and their corresponding polarization vectors

$$\vec{A} = A_+\vec{\epsilon}_+ + A_-\vec{\epsilon}_- .$$

These polarization vectors describe the helicity and phase of the modes and are both perpendicular to k . After Fourier transformation, the equation of motion becomes

$$\left(\partial_u^2 - \frac{1}{4} \mp i\frac{\theta}{u}\right) A_k^\pm = 0$$

The solution to this equation are a set of confluent hypergeometric functions called Whittaker functions. Unfortunately, the Whittaker functions are not well-integrated into C. In order to initialize the modes we were able to create an easily programmable and accurate fit to the Whittaker functions, demonstrated in the plots below.

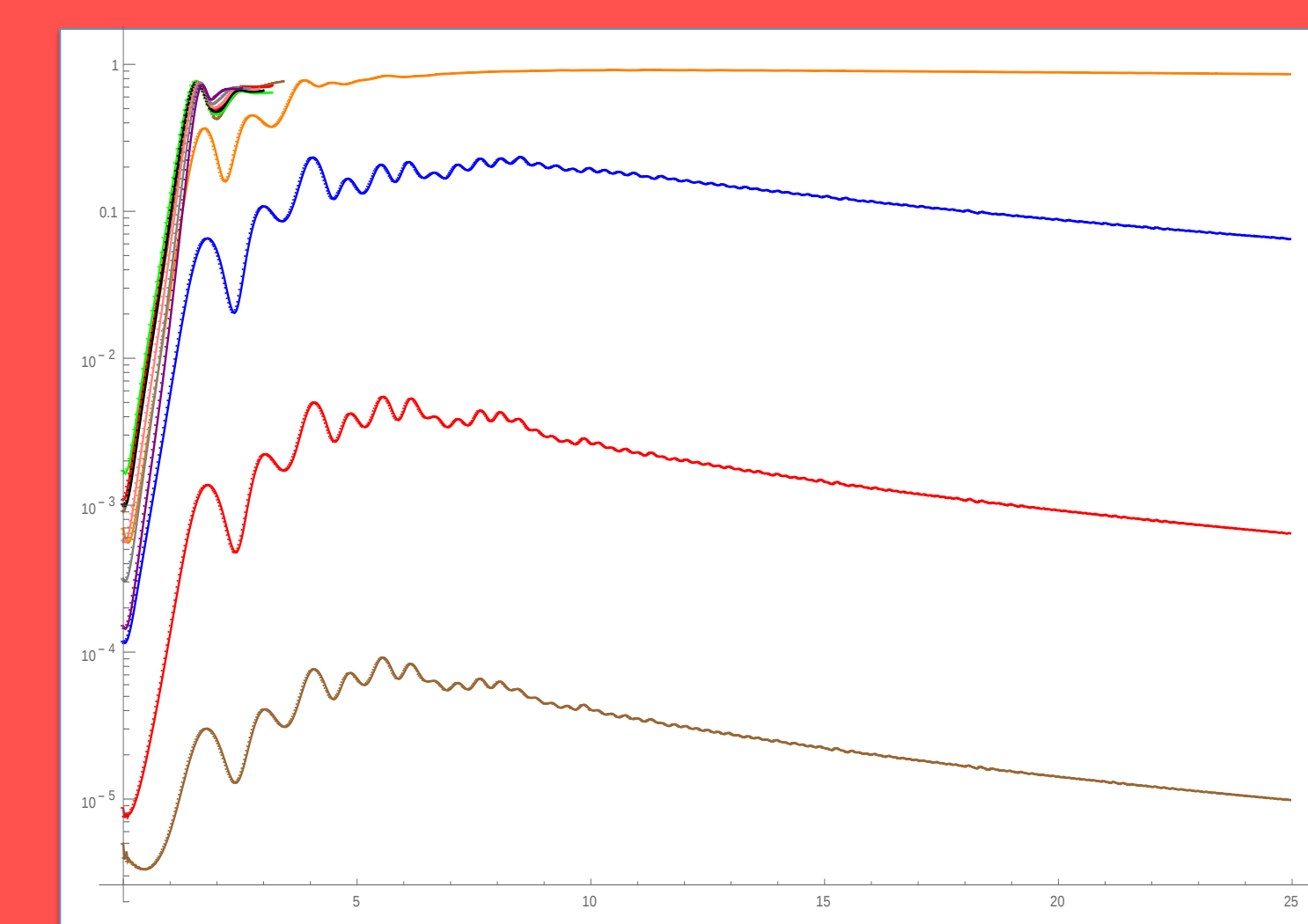


Fig 5. Ratio of Radiation Energy and Total Energy v. time (The most efficient coupling (45) is in orange. The longest time ranges are the least-valued couplings.)

Future Work

The near future of this project includes studying the monodramatic case. Ultimately, we would like to couple the scalar field to a non-Abelian gauge field with SU(2) symmetry, the symmetry that defines the weak interaction.

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References

- [1] Giblin, John T. "Using Observation to Constrain Early Universe Cosmology." Diss. Yale University, 2008. Print.
- [2] Neil Barnaby, Enrico Pajer, Marco Peloso. "Gauge Field Production in Axion Inflation: Consequences for Monodromy, non-Gaussianity in the CMB, and Gravitational Waves at Interferometers." [arXiv:1110.3327]
- [3] Zee, A. Quantum Field Theory in a Nutshell. Second ed. Princeton, NJ: Princeton UP, 2003. Print.
- [4] Lattice image. http://www.umbc.edu/hpcreu/2010/projects/images_team1/sid_cell_cube.jpg

