Preheating with Gauge Fields and Non-linear Gravity

Ryn Grutkoski ’21 and Tom Giblin

Department of Physics, Kenyon College, Gambier, OH 43022

Background

Big Bang cosmology comes from the predictions of Einstein’s equations, a set of differential equations that determine how the Universe evolves. The only solution to these mathematical equations tells us that the Universe has a finite age and a hot, dense beginning. This model is consistent with many of our observations, but it has some major inconsistencies with the Universe we observe today [1].

These problems can be resolved with an early period of exponential expansion, known as inflation. While inflation resolves many issues, it introduces questions of its own. One challenge has been that the energy that drove inflation must be transferred to the particles that make up the Standard Model. This process of transferring energy is known as reheating.

The addition of non-linear effects to affect transition faster is known as preheating. A new way to attain radiation-domination is by gauge-preheating, in which gauge fields are the fields that undergo preheating. These can be more efficient and are guaranteed to produce a radiation-dominated Universe [2-5].

Multiple Gauge Fields

If the inflaton is coupled to more than one gauge field, it can decay into multiple particles. In this case, the energy density of the Universe would be split between different gauge fields which—if they are not coupled to each other—would become different populations of particles in the late Universe. In this case, a lot of energy from the inflaton could end up in a particle (or multiple particles) that wouldn’t interact with the Standard Model providing a novel and intriguing dark matter candidate.

Using GABE, which evolves fields on a lattice, I simulated preheating with multiple gauge fields coupled to the inflaton. I used both dilatonic and axial-like couplings, $W(\phi) = e^{\phi/M}$ and $X(\phi) = \frac{\phi}{M}$, respectively.

With multiple gauge fields, one preheats quickly and efficiently, while the other does not gain as much energy, but could be a candidate for generating the dark sector.

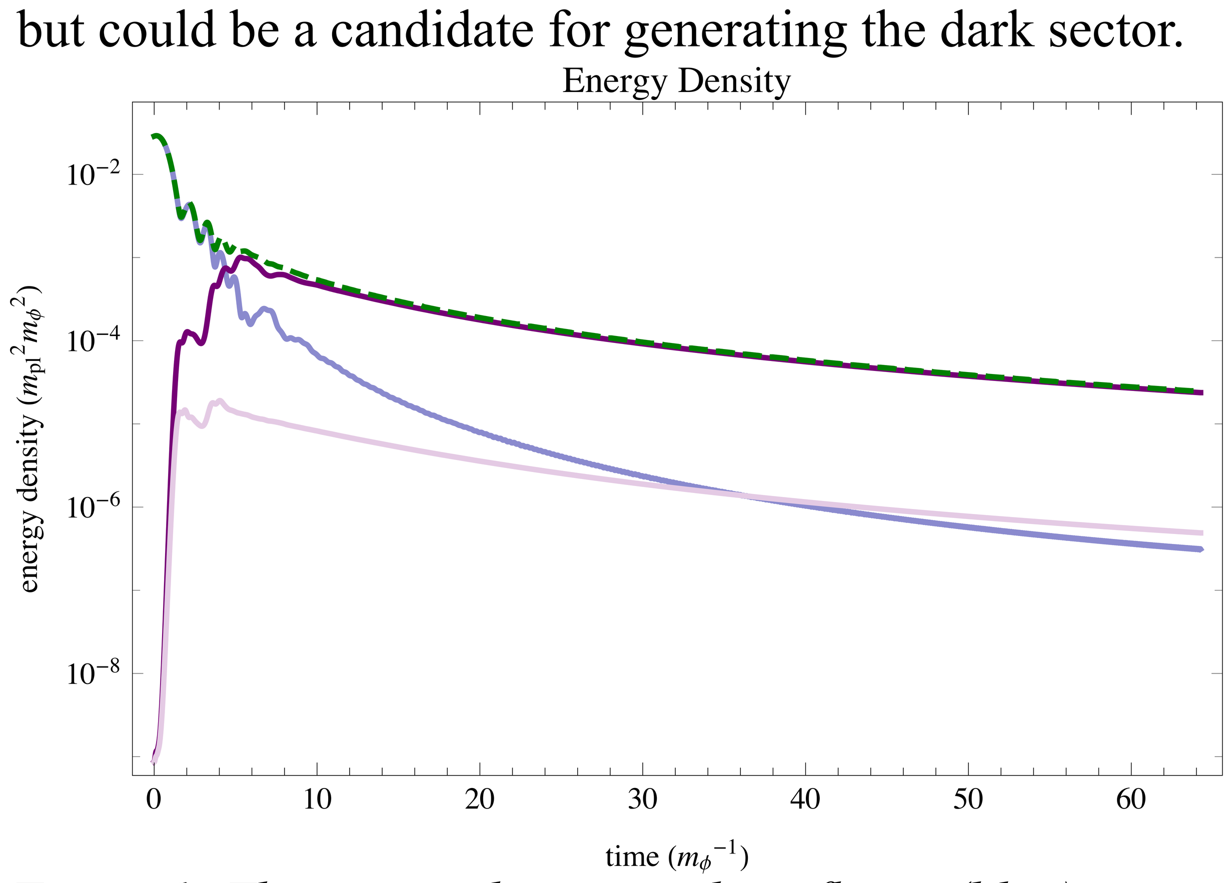

Figure 1: The energy density in the inflaton (blue), gauge field with $M_W = .015$, $M_X = .02$ (dark purple), gauge field with $M_W = .04$, $M_X = .015$ (light purple), and total energy density (green, dashed). $m_\phi = 10^{-6}$ *for the simulation.*

Abstract

Big Bang cosmology is a consequence of Einstein’s equations and the cosmological principle—and is consistent with many of our observations. However, standard Big Bang cosmology has some inconsistencies with the Universe we observe today, which are solved by a period of inflation. At the same time, the end of inflation is messy, with no unique mathematical model to get to the Universe we observe today. A better understanding of reheating can help us to better understand the particle physics present at those high energies. Here, I’ll discuss preheating with multiple gauge fields as a possible model of reheating and the characteristics of such a model, why the effects of local gravity might be important, and how we will have to deal with those effects.

Newtonian Potential and Local Gravity

Gauge preheating is fast and violent, taking place on the scale of $\mathcal{H}$. Because of the scale on which gauge preheating takes place, the possibility exists that local gravity becomes important. With perturbations, the line element of the FLRW metric becomes

$$ds^2 = -(1+2\Phi)dt + (1-2\Phi)a^2(dx^2+dy^2+dz^2)$$

where Φ is the Newtonian gravitational potential and is calculated based off of the density perturbation at each point. When Φ becomes a significant fraction of .5, then this linearized perturbed metric breaks down.

To probe this, I added a function to calculate the Newtonian potential, working in momentum space before inverse Fourier transforming back to position space.

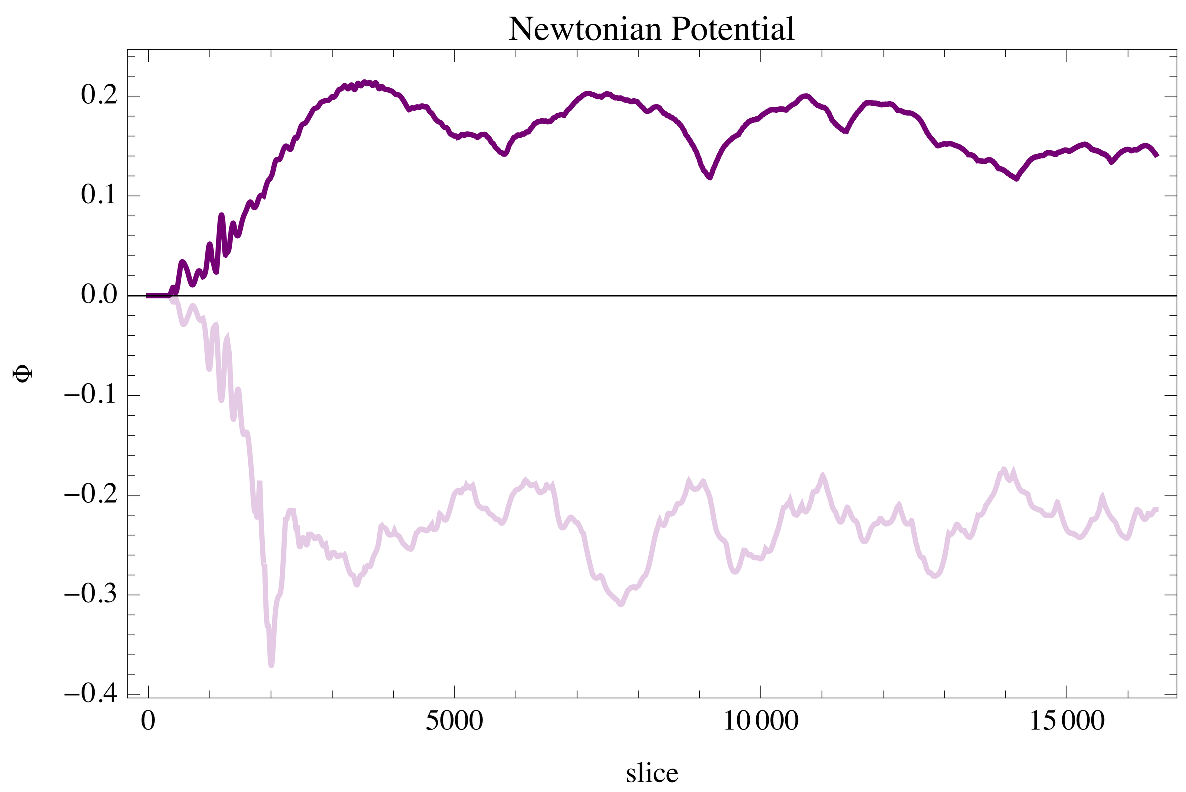

Figure 2: The minimum (dark purple) and maximum (light purple) of the Newtonian potential on each output slice, with the minimum getting as low as -.37 and the maximum reaching around .21

The size the Newtonian potential reaches indicates that it could be entering invalid regimes. To check this, I added perturbations to the equations of motion using the Newtonian potential.

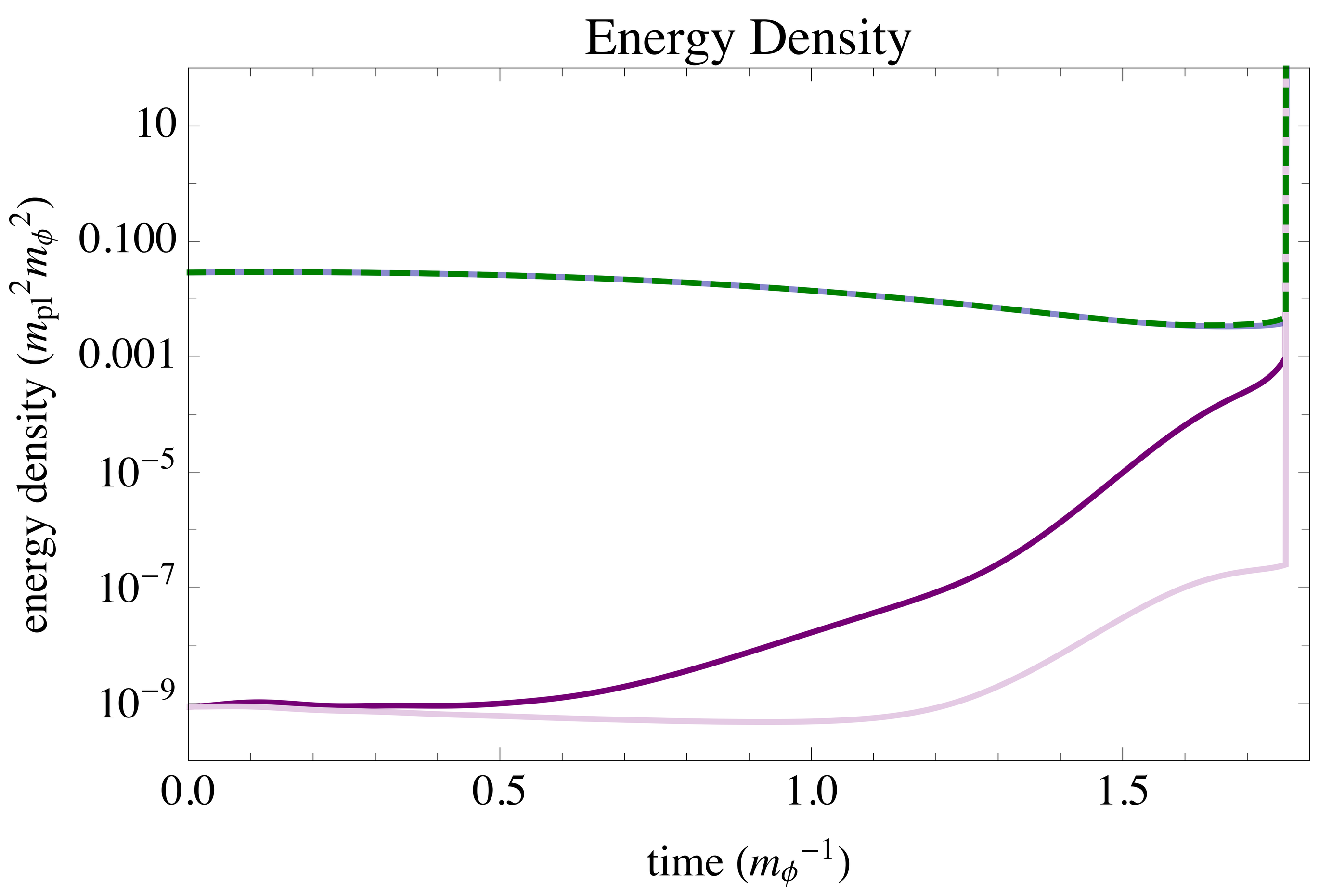

Figure 3: Energy density in the inflaton (blue), gauge field with $M_W = .015$, $M_X = .02$ (dark purple), gauge field with $M_W = .025$, $M_X = .015$ (light purple), and total energy density (green, dashed). $m_\phi = 10^{-6}$ *for the simulation.*

Fully Non-linear Gravity

Because the Newtonian potential does get large, it means that linearization cannot be used to study the effects of gravity during gauge-preheating. If you try to use linearized gravity, things crash. So to investigate the effects of gravity, it will be necessary to study the phenomena of gauge preheating in fully non-linear gravity, using BSSN.

Studying the gauge preheating in BSSN is important because it will provide the opportunity to look for such phenomena as primordial black holes, which could provide ways to constrain preheating models. However, non-linear gravity means full general relativity. And that means long, complicated equations…

The above is just the equation of motion for a scalar field. However, to study gauge fields in the context of preheating, it will be necessary to deal with one scalar field coupled to a vector field (the gauge field). Due to the way we evolve the gauge fields, a separate equation of motion is needed for each component (time, x, y, and z) of the gauge field. This further complicates the equations of motion that will need to be calculated and then implemented into the code. Furthermore, tricks will need to be used in order to promote numerical stability of the evolution in fully non-linear gravity.

References

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