The Role of Gravity During Preheating

Tom Giblin
February 5, 2020
From Inflation to the Hot Big Bang
KITP; University of California, Santa Barbara

1511.01105, 1511.01106,
1608.04403, 1907.10601
(among others)

work published with Chi Tian,
James Mertens Glenn Starkman,
and Avery Tishue

Work With

- For the Late Universe (not preheating)

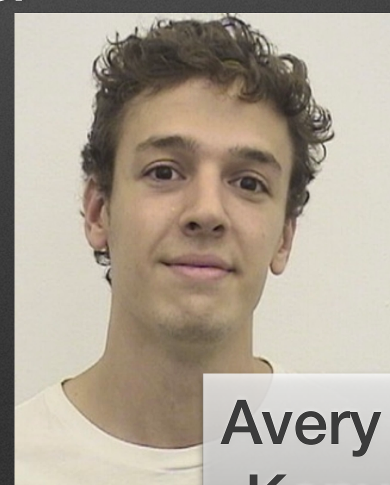
Jim Mertens
York/PI

Glenn Starkman
Case Western

Chi Tian
Case Western

- For the Early Universe (preheating)

Kathryn Grutkoski
Kenyon ‘21



Avery Tishue
Kenyon ‘18

My group at Kenyon

related to stuff we're talking about here

Gwyneth Phillips '20 Rand Burnette '21

Schrödinger-Poisson Systems

Allegra Fass '21

Modified Gravity and Compact Objects

Ericka Florio '22

Mary Gerhardinger '22

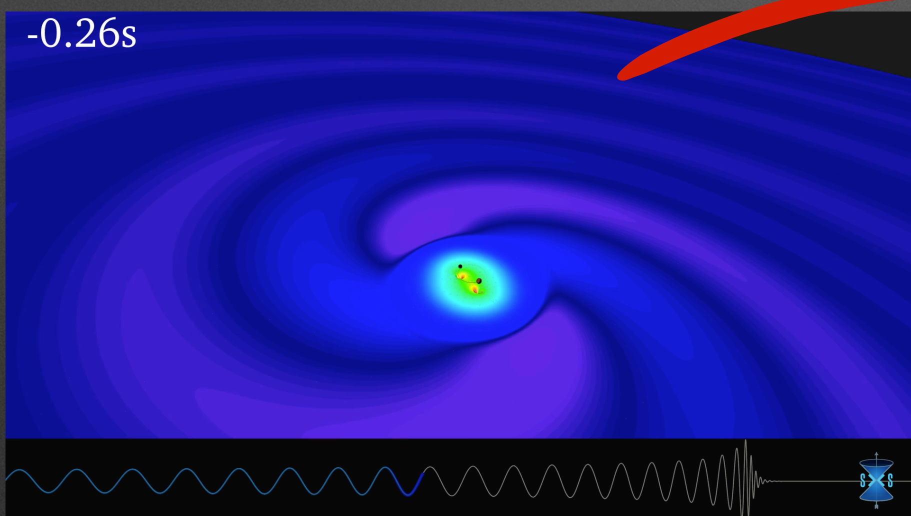
Preheating, EMDE, Early Dark Energy

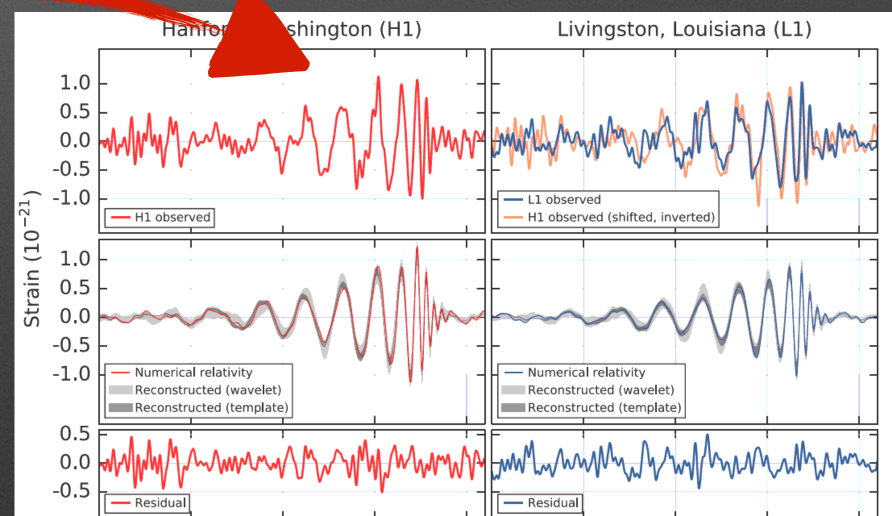
Gravity

- General Relativity appears to be one heck of a theory

Gravity

- An example:
  - Two black holes collide*
  - General Relativity *predicts*** a signal
  - We measure the signal***





*where'd the come from? See many other talks
**Many contributors, this analysis from Simulating Extreme Space-time (not me)
**LIGO: Phys. Rev. Lett. 116, 061102 (absolutely not me)

Unfortunately

- No one seemed to tell the Universe

According to General Relativity here's what happened (mathematically speaking)

The Universe today is a combination of Matter and Radiation (mostly matter)

The Universe cools enough to be transparent

Because matter dilutes slower than radiation, the earlier Universe was more radiation than matter

In the distant past, the Universe was very very dense

mathematically speaking, the model ends (begins) with a zero-volume, t=0.

According to Concordance Cosmology here's what happened (mathematically speaking)

Dark Energy Dominated Universe (expansion of the universes seems to be accelerating)

The Universe today is a combination of Matter and Radiation (mostly matter)

PLUS Dark matter

The Universe cools enough to be transparent

Because matter dilutes slower than radiation, the earlier Universe was more radiation than matter

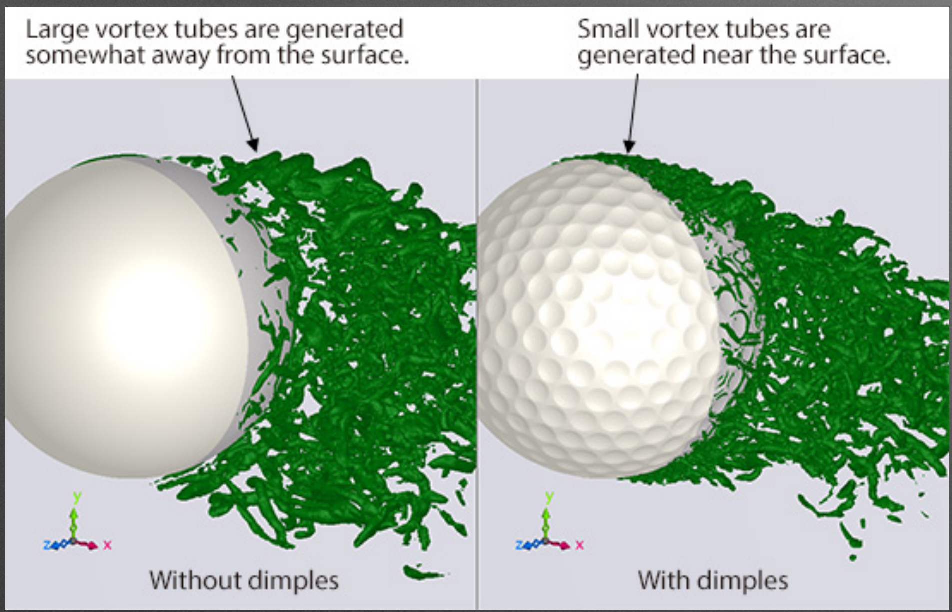
In the distant past, the Universe was very very dense

Inflation? Ekpyrosis? Bubbles? Gnomes?

The Main Point: Gravity is Non-Linear

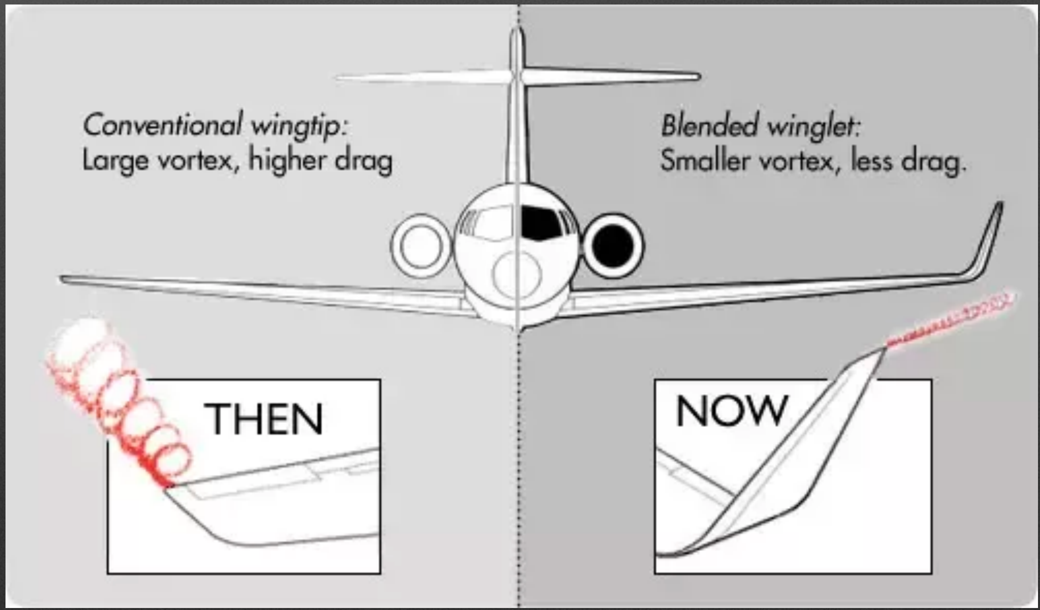
- Being "non-linear" is *more* that just "not being small"
- We like to *separate scales* when doing physics problems (e.g. what happens here, stays here)
  - Non-linear physics can mix up scales - power transferred between scales through *cascades* or *inverse-cascades*

Sometimes things that look like Perturbations



Takao Itami
https://www.cradle-cfd.com/

Anas Maaz
https://www.quora.com/



The Main Question:
For the Universe,
does it matter?

Averaging

- Generally a Hubble Volume is taken to be the region over which we do averaging — we all agree that different Hubble patches could have different expansion rates (causality, right?)

$$H^{-3} \approx (4000\,\mathrm{Mpc})^3$$

- Yet there is structure at (just) smaller scales
  - Galaxy Clusters $\sim 1 - 10\,\mathrm{Mpc}$
  - Inter-Cluster Distances $\sim 50\,\mathrm{Mpc}$

Scales at Reheating

- Generally a Hubble Volume is taken to be the region over which we do averaging — we all agree that different Hubble patches could have different expansion rates (causality, right?)

$$H^{-1} \propto \mathcal{O}(1) \times \frac{m_{\rm pl}^2}{m^2 \phi_0^2} = \mathcal{O}(1) \times m^{-1}$$

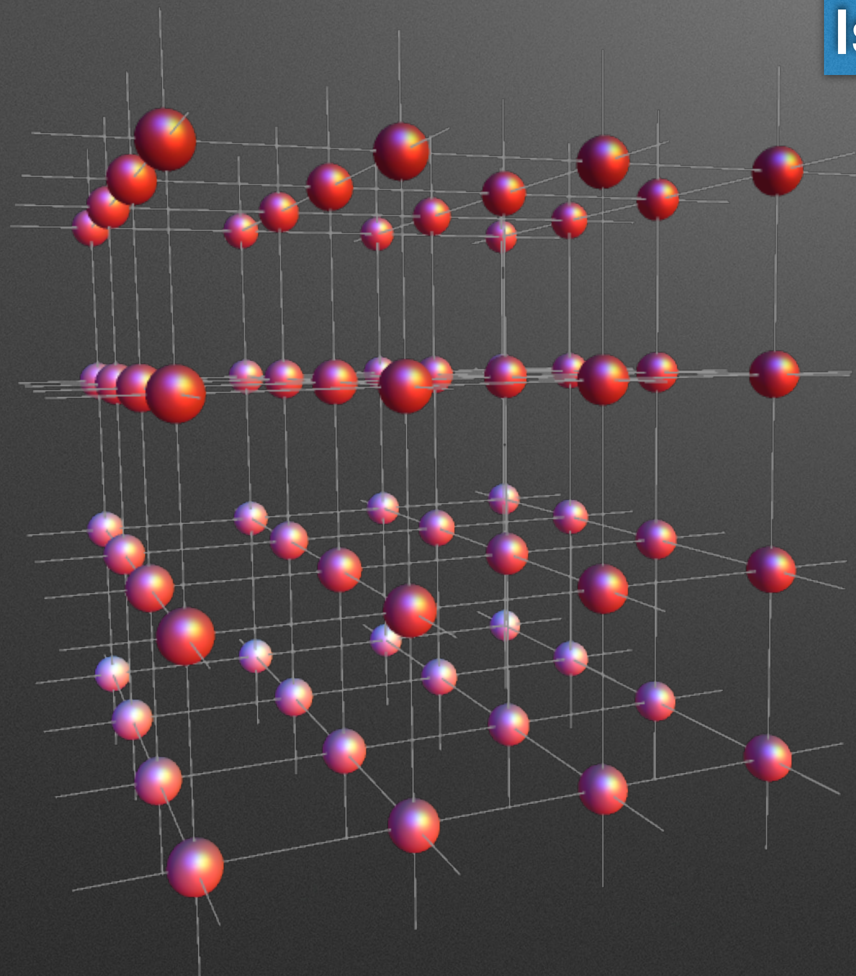
- YET: we talk about things at scales around this
  - Oscillons
  - Tachyonic/Parametric Resonance

$$\Big\} \; k \propto \mathcal{O}(1) \times m^{-1}$$

Can non-linear physics help explain the great mysteries of the Universe?

We want to investigate

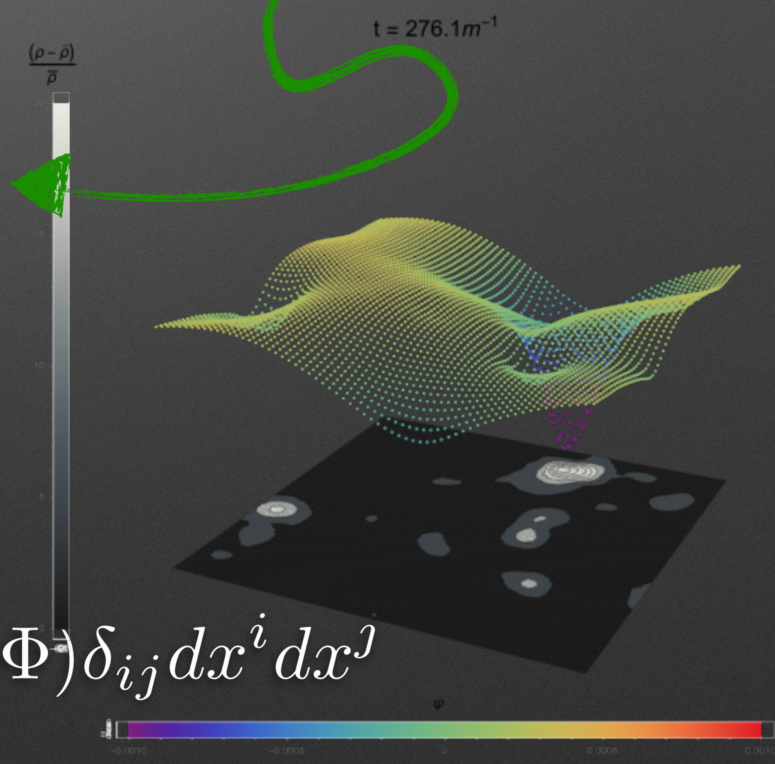
GABE:
Scalar Fields (Gravitational Waves)
Isotropic and Homogeneous evolution



We want to investigate

GABE:
Scalar Fields (Gravitational Waves)
Isotropic and Homogeneous evolution

NewtGABE:
Newtonian Gravity
Scalar Fields
Newtonian Potential + back reaction



$$ds^2 = -(1+2\Phi)dt^2 + a^2(t)(1-2\Phi)\delta_{ij}dx^i dx^j$$

Our first go

- Perturbation theory, of course!

$$ds^2 = -\left(1+2\Phi\right)dt^2 + a^2\left(1-2\Phi\right)\left[dx^2+dy^2+dz^2\right],$$

- Which gives us an equation of motion for the field

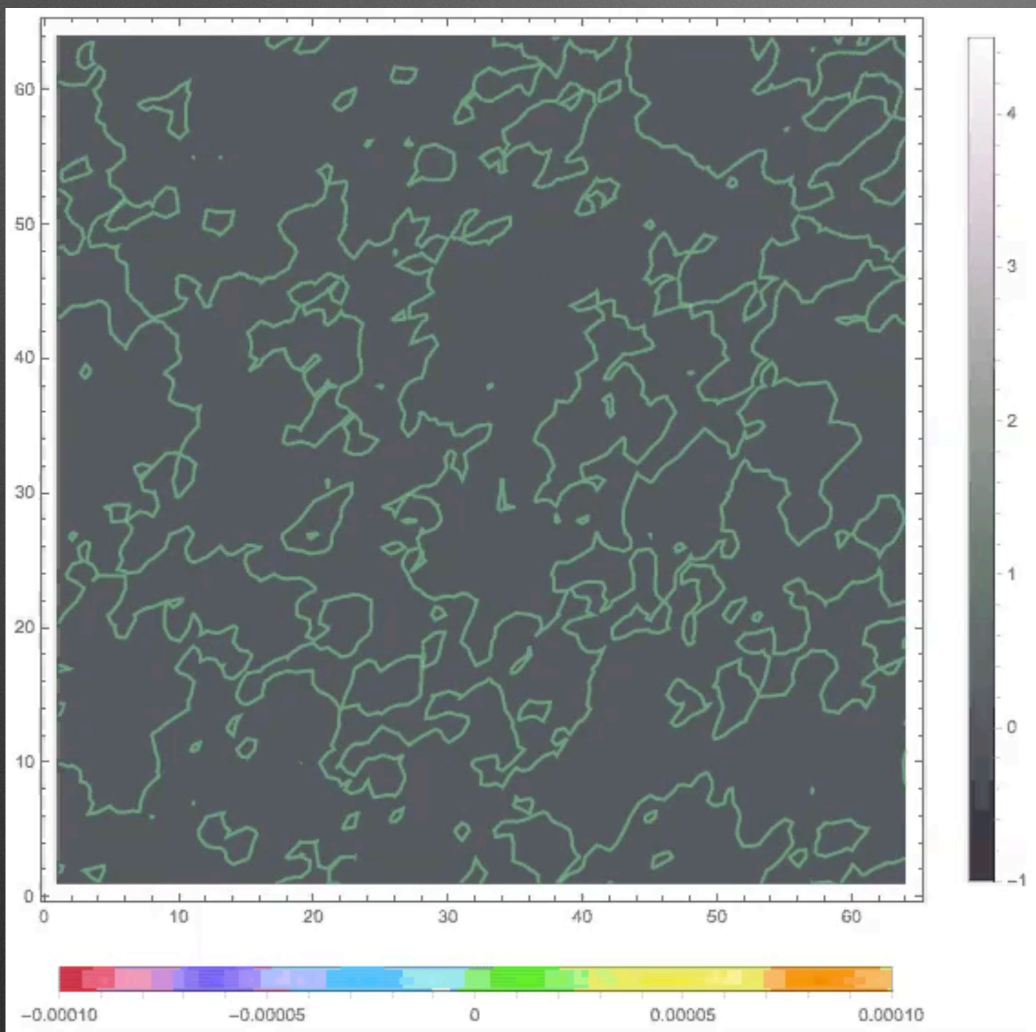
$$\ddot{\phi} = -3H\dot{\phi} + 4\dot{\phi}\dot{\Phi} + \left(1+4\Phi\right)\frac{\nabla^2\phi}{a^2} - \left(1+2\Phi\right)\frac{\partial V}{\partial\phi}$$

- and an equation to satisfy for the Newtonian potential

$$\nabla^2\Phi - 3a^2 H\left(\dot{\Phi} + H\Phi\right) = \frac{4\pi a^2}{m_{\rm pl}^2}\delta\rho$$

$$-k^2\tilde{\Phi} - 3a^2 H\left(\dot{\tilde{\Phi}} + H\tilde{\Phi}\right) = \frac{4\pi a^2}{m_{\rm pl}^2}\left(2\Phi\rho_0 + \delta\rho\right).$$

Other things to look for?



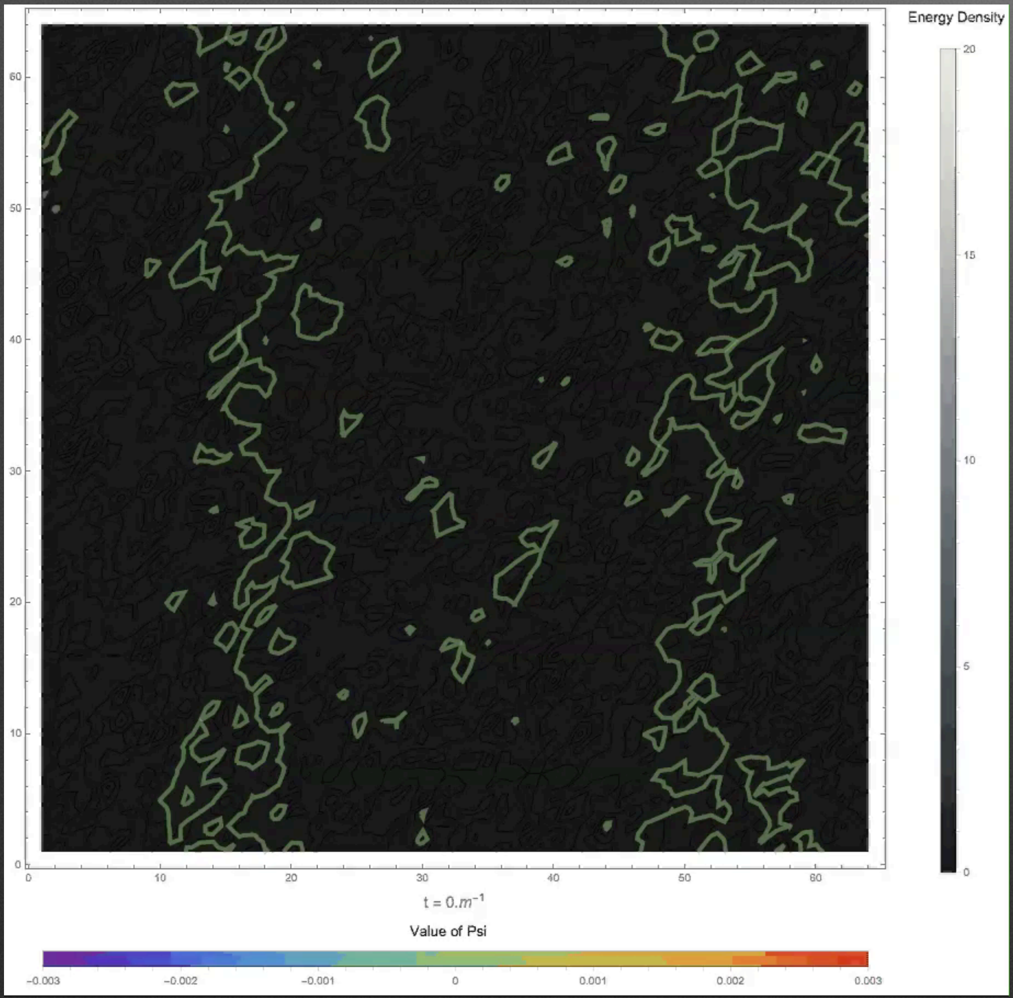
Φ

$\delta\rho/\rho$

- Gravitational back reaction
- Preheating produces gravitational inhomogeneities

Or Oscillons….

- Non-topological structures that come from (slightly open) inflationary potentials



We want to investigate

GABE:
Scalar Fields (Gravitational Waves)
Isotropic and Homogeneous evolution

NewtGABE:
Newtonian Gravity
Scalar Fields
Newtonian Potential + back reaction

GabeREL:
Scalar Fields/Fluids
Full Numerical Relativity

What you would *like* to do

- Write down the most general form of the metric,

$$g_{\mu\nu} = \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{01} & g_{11} & g_{12} & g_{13} \\ g_{02} & g_{12} & g_{22} & g_{23} \\ g_{03} & g_{13} & g_{23} & g_{33} \end{pmatrix}$$

- Plug it into Einstein's Equations

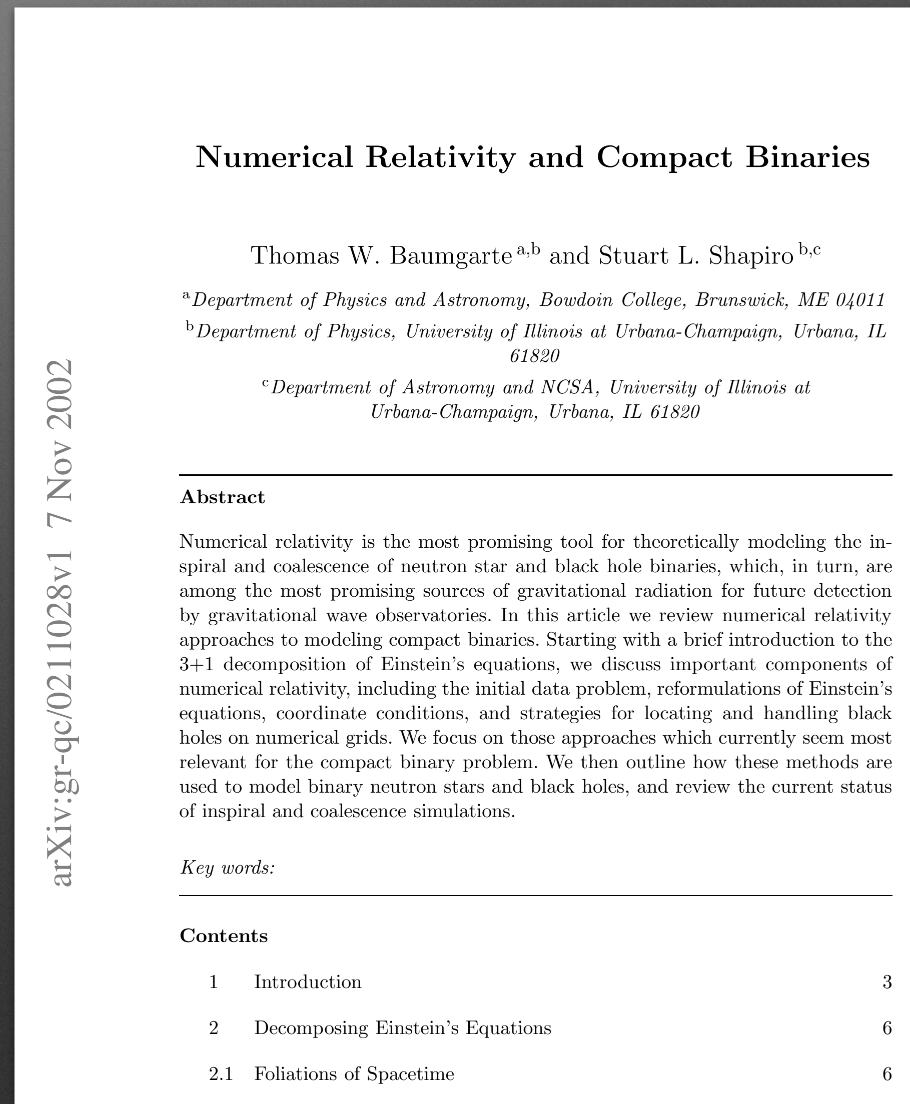
$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$$

- Solve the system of second order differential equations (subject to your gauge-constraints)

```
In[9]:= SetDirectory[NotebookDirectory[]];

In[10]:= << GREAT.m

GREAT functions are: IMetric, Christoffel,
  Riemann, Ricci, SCurvature, EinsteinTensor, SqRicci, SqRiemann.

Enter 'helpGREAT' for this list of functions

In[11]:= (metric = {{g00[x0, x1, x2, x3], g01[x0, x1, x2, x3], g02[x0, x1, x2, x3],
      g03[x0, x1, x2, x3]}, {g01[x0, x1, x2, x3], g11[x0, x1, x2, x3],
      g12[x0, x1, x2, x3], g03[x0, x1, x2, x3]},
     {g02[x0, x1, x2, x3], g12[x0, x1, x2, x3], g22[x0, x1, x2, x3],
      g23[x0, x1, x2, x3]}, {g03[x0, x1, x2, x3], g13[x0, x1, x2, x3],
      g23[x0, x1, x2, x3], g33[x0, x1, x2, x3]}}) // MatrixForm

Out[11]//MatrixForm=
( g00[x0, x1, x2, x3]  g01[x0, x1, x2, x3]  g02[x0, x1, x2, x3]  g03[x0, x1, x2, x3] )
( g01[x0, x1, x2, x3]  g11[x0, x1, x2, x3]  g12[x0, x1, x2, x3]  g03[x0, x1, x2, x3] )
( g02[x0, x1, x2, x3]  g12[x0, x1, x2, x3]  g22[x0, x1, x2, x3]  g23[x0, x1, x2, x3] )
( g03[x0, x1, x2, x3]  g13[x0, x1, x2, x3]  g23[x0, x1, x2, x3]  g33[x0, x1, x2, x3] )

In[12]:= coords = {x0, x1, x2, x3}

Out[12]= {x0, x1, x2, x3}

In[13]:= EinsteinTensor[metric, coords]
```

What can we do?

- You can do a little better by making gauge choices that reduce the number of parameters or (re)parameterize so that you have nice equations for.. some.. of them…
- Even then they are extremely difficult to numerically stabilize



arXiv:gr-qc/0211028v1 7 Nov 2002

Numerical Relativity and Compact Binaries

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Abstract

Numerical relativity is the most promising tool for theoretically modeling the inspiral and coalescence of neutron star and black hole binaries, which, in turn, are among the most promising sources of gravitational radiation for future detection by gravitational wave observatories. In this article we review numerical relativity approaches to modeling compact binaries. Starting with a brief introduction to the 3+1 decomposition of Einstein's equations, we discuss important components of numerical relativity, including the initial data problem, reformulations of Einstein's equations, coordinate conditions, and strategies for locating and handling black holes on numerical grids. We focus on those approaches which currently seem most relevant for the compact binary problem. We then outline how these methods are used to model binary neutron stars and black holes, and review the current status of inspiral and coalescence simulations.

Key words:

Contents

What we have to do…

- Luckily there are a set of new approaches. We use the most common of these: the BSSN formalism.
- It is based on the ADM metric decomposition

$$g_{\mu\nu} = \begin{pmatrix} -\alpha^2 + \gamma_{lk}\beta^l\beta^k & \beta_i \\ \beta_j & \gamma_{ij} \end{pmatrix}$$

- We we introduce more parameters than (minimally) necessary so that the equations are easier to solve

In Cosmology

- We can fix the gauge (we will give up being able to create black holes, as well as some other concessions) to focus on spatial slices

- We can then track the spatial 3-metric

$$\gamma_{ij} = e^{4\phi}\bar{\gamma}_{ij}$$

- as well as the extrinsic curvature

$$K_{ij} = e^{4\phi}\bar{A}_{ij} + \frac{1}{3}\gamma_{ij}K$$

In Cosmology

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In Cosmology

- We can fix the gauge (we will give up being able to create black holes, as well as some other concessions) to focus on spatial slices

- We can then track the spatial 3-metric

Think of this as keeping track of the size of local volumes

$$\gamma_{ij} = e^{4\phi}\bar{\gamma}_{ij}$$

- as well as the extrinsic curvature

Think of this as measuring the local expansion rate

$$K_{ij} = e^{4\phi}\bar{A}_{ij} + \frac{1}{3}\gamma_{ij}K$$

$$\partial_t \phi = -\bar{\gamma}_{ij} rac16 \alpha K + \beta^i \partial_i \phi + \frac{1}{6} \partial_i \beta^i$$

$$\partial_t \bar{\gamma}_{ij} = -2\alpha \tilde{A}_{ij} + \beta^k \partial_k \tilde{A}_{ij} + \bar{\gamma}_{ik} \partial_j \beta^k + \bar{\gamma}_{kj} \partial_i \beta^k - \frac{2}{3} \bar{\gamma}_{ij} \partial_K \beta^k$$

$$\partial_t K = \gamma^{ij} D_j D_i \alpha + \alpha \left(\tilde{A}_{ij} \tilde{A}_{ij} u + \frac{1}{3} K^2 \right) + 4\pi\alpha (\rho + S) + \beta^i \partial_i K$$

$$\partial_t \tilde{A}_{ij} = e^{-4\phi} \left(-D_j D_i \alpha + \alpha (R_{ij} - 8\pi S_{ij})\right)^{TF} + \alpha \left(K \tilde{A}_{ij} - 2 \tilde{A}_{il} \tilde{A}^l_j \right) + \beta^k \partial_k \tilde{A}_{ij} + \tilde{A}_{ik} \partial_j \beta^k + \tilde{A}_{kj} \partial_i \beta^k - \frac{2}{3} \tilde{A}_{ij} \partial_k \beta^k$$

$$\partial_t \bar{\Gamma}^I = -2 \tilde{A}_{ij} \partial_j \alpha + 2\alpha \left(\bar{\Gamma}^i_{jk} \tilde{A}^{kj} - \frac{2}{3} \bar{\gamma}^{ij} \partial_j K - 8\pi \bar{\gamma}^{ij} S_j + 6 \tilde{A}^{ij} \partial_j \phi \right) + \beta^j \partial_j \bar{\Gamma}^i - \bar{\Gamma}^j \partial_j \beta^i + \frac{2}{3} \bar{\Gamma}^i \partial_j \beta^j + \frac{1}{3} \bar{\gamma}^{li} \partial_l \partial_j \beta^j + \bar{\gamma}^{lj} \partial_j \partial_l \beta^i$$

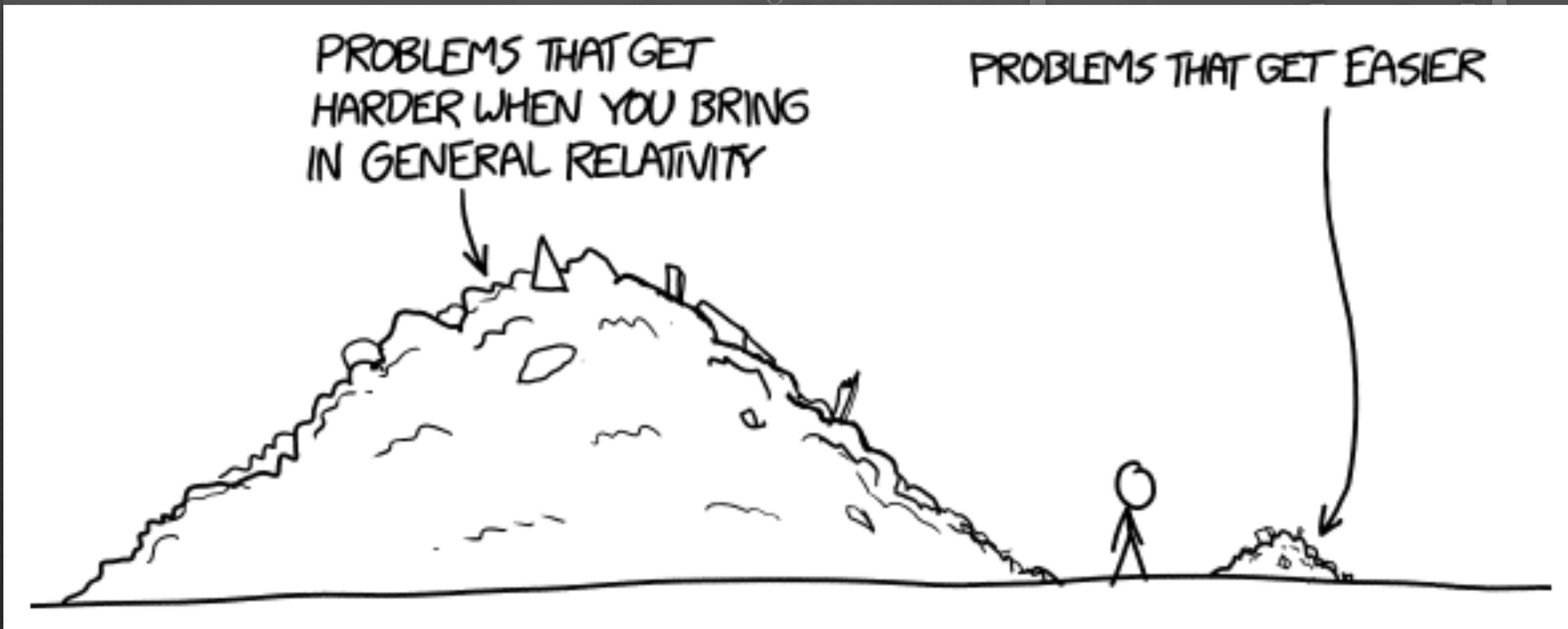
Importantly

These variables have well-behaved differential equations and *are a complete description of GR without dimensional reductions or simplifications*

The POWER is in the redundancy of the equations of motion

$$
\partial_t \bar{\Gamma}^i = -2\tilde{A}^{ij}\partial_j \alpha + 2\alpha(\bar{\Gamma}^i_{jk}\tilde{A}^{kj} - \frac{2}{3}\bar{\gamma}^{ij}\partial_j K
- 8\pi\bar{\gamma}^{ij}S_j + 6\tilde{A}^{ij}\partial_j\phi) + \beta^j\partial_j\bar{\Gamma}^i
- \bar{\Gamma}^j\partial_j\beta^i + \frac{2}{3}\bar{\Gamma}^i\partial_j\beta^j + \frac{1}{3}\bar{\gamma}^{li}\partial_l\partial_j\beta^j
+ \bar{\gamma}^{lj}\partial_j\partial_l\beta^i
$$

$$\partial_t \phi = -\bar{\gamma}_{ij} rac16 \alpha K + \beta^i \partial_i \phi + \frac{1}{6} \partial_i \beta^i$$



$$+ A_{ik} \partial_j \beta^k + A_{kj} \partial_i \beta^k - \frac{}{3} A_{ij} \partial_k \beta^k$$

```
In[•]:= eom = 1/sqrtg0 * (D[sqrtg0 *
      (gupper0[[1, 1]] * D[ϕ[t, x, y, z]
        gupper0[[1, 3]] * D[ϕ[t, x, y, z
     t] + D[sqrtg0 * (gupper0[[2, 1]] * D
        gupper0[[2, 2]] * D[ϕ[t, x, y, z
        gupper0[[2, 4]] * D[ϕ[t, x, y, z
      (gupper0[[3, 1]] * D[ϕ[t, x, y, z]
        gupper0[[3, 3]] * D[ϕ[t, x, y, z
    y] + D[sqrtg0 * (gupper0[[4, 1]] * D
        gupper0[[4, 2]] * D[ϕ[t, x, y, z
        gupper0[[4, 4]] * D[ϕ[t, x, y, z
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```
Out[•]=
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 (2 √
 √(-γxx
 large output

In[•]:= FullSimplify
Out[•]= (γxy[x, y, z]
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```
(-γyy^(0,1,0)[x, y, z] ϕ^(0,0,1,0)[t, x, y, z] + 2 γyy[x, y, z]
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γxz[x, y, z]^2 (γxx[x, y, z] γ
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ϕ^(0,0,1,0)[t, x, y, z] - γzz[x, y, z]
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4 γyz[x, y, z] ϕ^(0,0,1,1)[t, x, y, z
2 γzz[x, y, z] γxy^(0,1,0)[x, y, z] ϕ^(0,1
γzz[x, y, z] γyy^(1,0,0)[x, y, z] ϕ^(0,1,0
4 γyz[x, y, z] γyz^(1,0,0)[x, y, z] ϕ^(0,1
2 γxy[x, y, z] (2 γxy^(0,0,1)[x, y, z] ϕ
z] ϕ^(0,0,1,0)[t, x, y, z] + γzz^(0,
6 γyz[x, y, z] ϕ^(0,1,0,1)[t, x, y, z
2 γyz[x, y, z]^2 ϕ^(0,2,0,0)[t, x, y, z])
(γxx^(0,0,1)[x, y, z] ϕ^(0,0,0,1)[t, x, y, z]
```

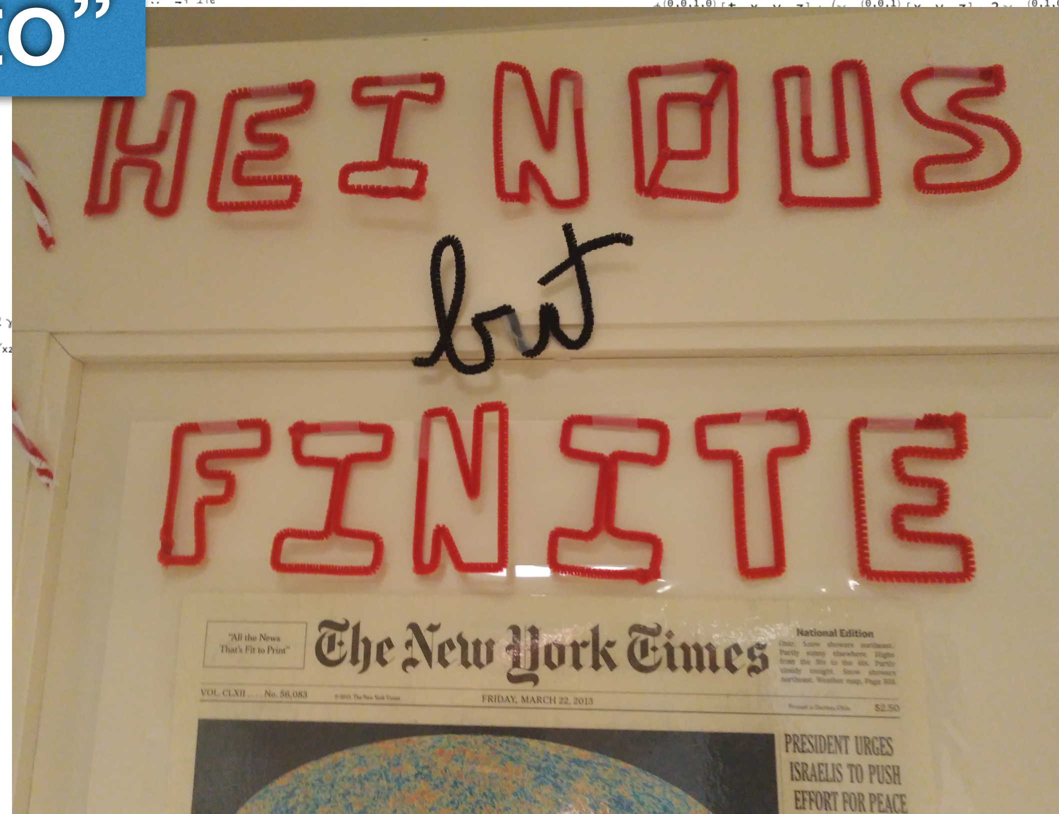
```
γzz^(1,0,0)[x, y, z] ϕ^(0,1,0,0)[t, x, y, z] + γzz[x, y, z] ϕ^(0,2,0,0)[t, x, y, z])) -
γxy[x, y, z]^2 (γzz[x, y, z] (γxx[x, y, z] ((γyy^(0,0,1)[x, y, z] - 2 γyz^(0,1,0)[x, y, z])
ϕ^(0,0,0,1)[t, x, y, z] + (-2 γyz^(0,0,1)[x, y, z] + γzz^(0,1,0)[x, y, z])
ϕ^(0,0,1,0)[t, x, y, z] + 2 γzz[x, y, z] ϕ^(0,0,2,0)[t, x, y, z]) +
2 γzz[x, y, z] (γxx^(0,1,0)[x, y, z] ϕ^(0,0,1,0)[t, x, y, z] +
γyy^(1,0,0)[x, y, z] ϕ^(0,1,0,0)[t, x, y, z])) + γyz[x, y, z] (γxx[x, y, z]
((2 γyz^(0,0,1)[x, y, z] + γzz^(0,1,0)[x, y, z]) ϕ^(0,0,0,1)[t, x, y, z] + γzz^(0,0,1)[
x, y, z] ϕ^(0,0,1,0)[t, x, y, z] - 4 γzz[x, y, z] ϕ^(0,0,1,1)[t, x, y, z]) -
2 γzz[x, y, z] (γxx^(0,1,0)[x, y, z] ϕ^(0,0,0,1)[t, x, y, z] + γxx^(0,0,1)[x,
y, z] ϕ^(0,0,1,0)[t, x, y, z] + 2 γyz^(1,0,0)[x, y, z] ϕ^(0,1,0,0)[t, x, y, z])) +
γyz[x, y, z]^2 ((γxx^(0,0,1)[x, y, z] + 2 γxz^(1,0,0)[x, y, z]) ϕ^(0,0,0,1)[t, x, y, z] -
2 γxx[x, y, z] ϕ^(0,0,0,2)[t, x, y, z] + (2 γxz^(0,0,1)[x, y, z] + γzz^(1,0,0)[x, y, z])
```



```
y, z] - 2 (γxy^(0,0,1)[x, y, z] - γxz^(0,1,0)[x, y, z] + γyz^(1,0,0)[x, y, z])
ϕ^(0,0,1,0)[t, x, y, z] + (γyy^(0,0,1)[x, y, z] - 2 γyz^(0,1,0)[x, y, z])
ϕ^(0,1,0,0)[t, x, y, z]) - 4 γyz[x, y, z]^2 ϕ^(0,1,0,1)[t, x, y, z] +
γyz[x, y, z] (2 (γxy^(0,0,1)[x, y, z] + γxz^(0,1,0)[x, y, z] + γyz^(1,0,0)[x, y, z])
ϕ^(0,0,0,1)[t, x, y, z] + (2 γxz^(0,0,1)[x, y, z] + γzz^(1,0,0)[x, y, z])
ϕ^(0,0,1,0)[t, x, y, z] + (2 γyz^(0,0,1)[x, y, z] + γzz^(0,1,0)[x, y, z])
ϕ^(0,1,0,0)[t, x, y, z] - 4 γzz[x, y, z] ϕ^(0,1,1,0)[t, x, y, z]))) +
γxy[x, y, z] (γxx[x, y, z] (γzz[x, y, z] (γyy^(0,1,0)[x, y, z] ϕ^(0,0,0,1)[t, x, y, z] +
(γyy^(0,0,1)[x, y, z] + 2 γyz^(0,1,0)[x, y, z]) ϕ^(0,0,1,0)[t, x, y, z]) +
12 γyz[x, y, z]^2 ϕ^(0,0,1,1)[t, x, y, z] - 4 γyz[x, y, z]
(γyy^(0,0,1)[x, y, z] ϕ^(0,0,0,1)[t, x, y, z] + γzz^(0,1,0)[x, y, z]
ϕ^(0,0,1,0)[t, x, y, z] + γzz[x, y, z] ϕ^(0,0,2,0)[t, x, y, z])) +
γyz[x, y, z] (-4 γzz[x, y, z] (γxx^(0,1,0)[x, y, z] ϕ^(0,0,1,0)[t, x, y, z] +
γyy^(1,0,0)[x, y, z] ϕ^(0,1,0,0)[t, x, y, z]) + γyz[x, y, z]
((3 γxx^(0,1,0)[x, y, z] - 2 γxy^(1,0,0)[x, y, z]) ϕ^(0,0,0,1)[t, x, y, z] +
(3 γxx^(0,0,1)[x, y, z] - 2 γxz^(1,0,0)[x, y, z]) ϕ^(0,0,1,0)[t, x, y, z] -
2 (γxy^(0,0,1)[x, y, z] + γxz^(0,1,0)[x, y, z] - 3 γyz^(1,0,0)[x, y, z])
ϕ^(0,1,0,0)[t, x, y, z]) + 4 γyz[x, y, z]^2 ϕ^(0,2,0,0)[t, x, y, z]) +
γyy[x, y, z] (γxx[x, y, z] ((2 γyz^(0,0,1)[x, y, z] + γzz^(0,1,0)[x, y, z])
ϕ^(0,0,0,1)[t, x, y, z] + γzz^(0,0,1)[x, y, z] ϕ^(0,0,1,0)[t, x, y, z] -
4 γzz[x, y, z] ϕ^(0,0,1,1)[t, x, y, z]) + γzz[x, y, z]
((γxx^(0,1,0)[x, y, z] + 2 γxy^(1,0,0)[x, y, z]) ϕ^(0,0,0,1)[t, x, y, z] +
(γxx^(0,0,1)[x, y, z] + 2 γxz^(1,0,0)[x, y, z]) ϕ^(0,0,1,0)[t, x, y, z] +
2 (γxy^(0,0,1)[x, y, z] + γxz^(0,1,0)[x, y, z] + γyz^(1,0,0)[x, y, z]) ϕ^(0,1,0,0)[
t, x, y, z]) - 4 γyz[x, y, z] (γxx^(0,0,1)[x, y, z] ϕ^(0,0,0,1)[t, x, y, z] +
γxx[x, y, z] ϕ^(0,0,0,2)[t, x, y, z] + γzz^(1,0,0)[x, y, z]
ϕ^(0,1,0,0)[t, x, y, z] + γzz[x, y, z] ϕ^(0,2,0,0)[t, x, y, z]))))) /
(2 (γxz[x, y, z]^2 γyy[x, y, z] - 2 γxy[x, y, z] γxz[x, y, z] γyz[x, y, z] +
γxy[x, y, z]^2 γzz[x, y, z] +
γxx[x, y, z] (γyz[x, y, z]^2 - γyy[x, y, z] γzz[x, y, z]))^2) +
α^(1,0,0,0)[t, x, y, z] ϕ^(1,0,0,0)[t, x, y, z] / α[t, x, y, z]^3 -
ϕ^(2,0,0,0)[t, x, y, z] / α[t, x, y, z]^2
```

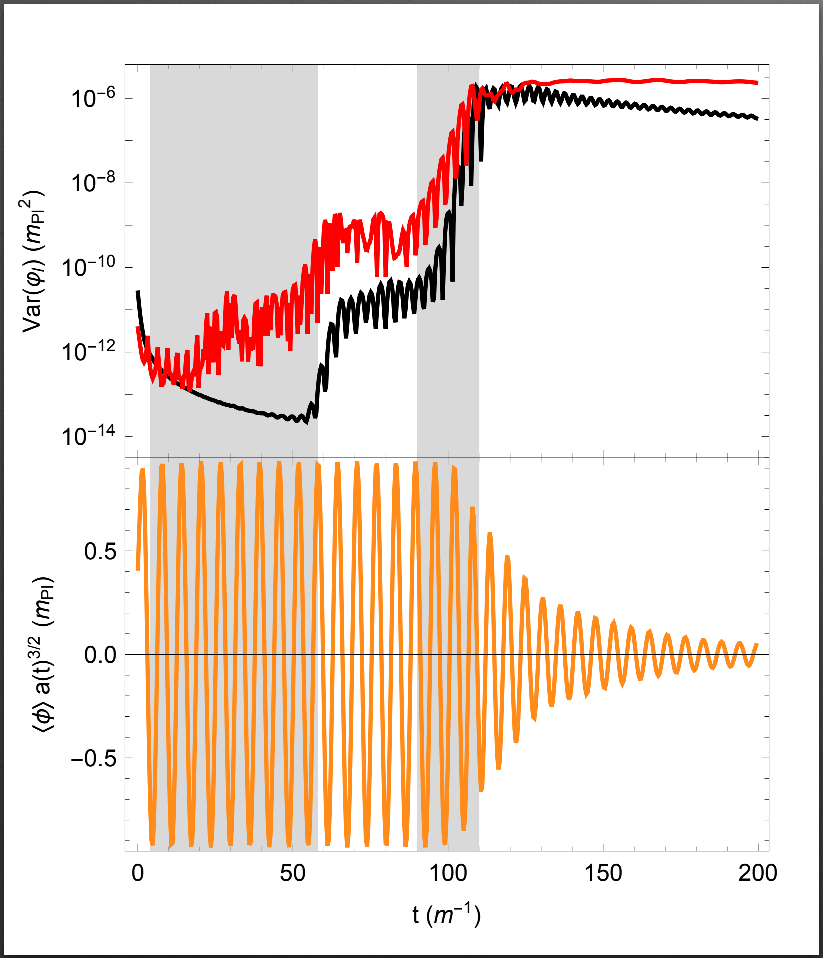
```
In[•]:= teom = 1/sqrtg0 * (D[sqrtg0 * (gupper0[[1, 1]] * D[ϕ[t, x, y, z], t] +
      gupper0[[1, 2]] * D[ϕ[t, x, y, z], x] + gupper0[[1, 3]] * D[ϕ[t, x, y, z], y] +
      gupper0[[1, 4]] * D[ϕ[t, x, y, z], z]), t]) == 0;
```

Sort of our "Group Motto"



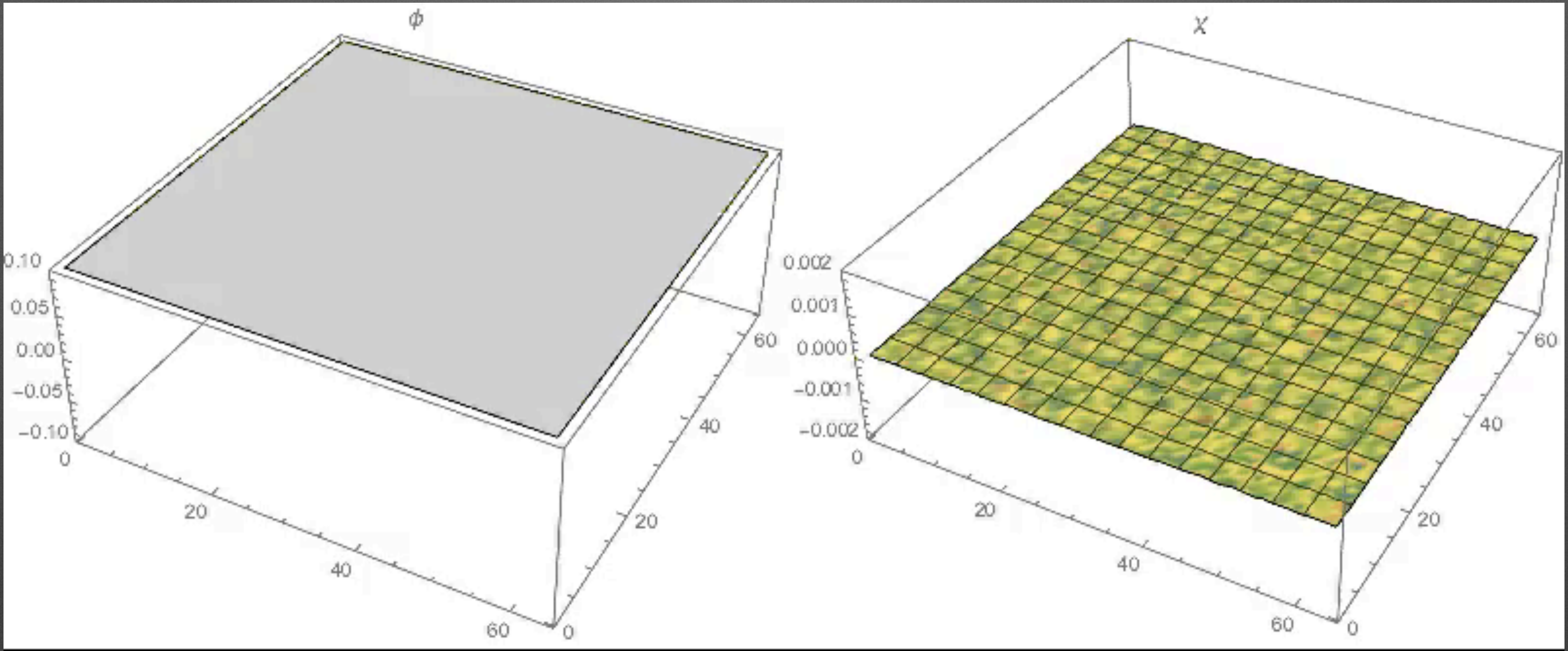

```
teom = 1/sqrtg0 * (D[sqrtg0 * (gupper0[[1, 1]] * D[ϕ[t, x, y, z], t] +
    gupper0[[1, 2]] * D[ϕ[t, x, y, z], x] + gupper0[[1, 3]] * D[ϕ[t, x, y, z], y] +
    gupper0[[1, 4]] * D[ϕ[t, x, y, z], z]), t]) == 0;
```

Our First Test: Preheating

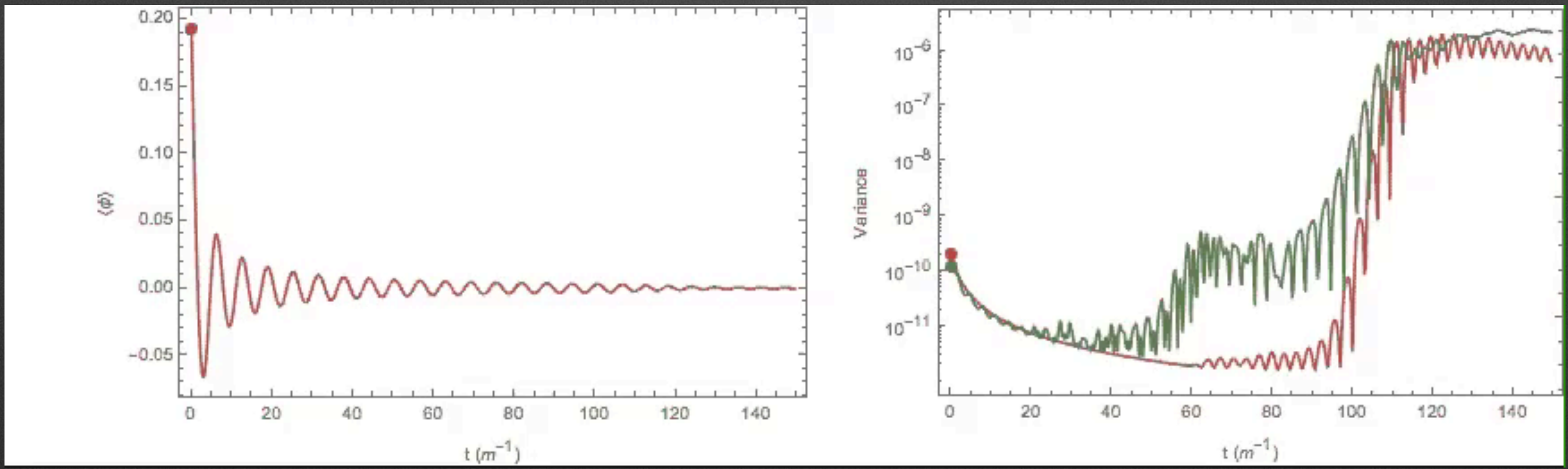


The Inflationary field is coupled to a second "matter" field

Non-linear interactions case the energy to be transferred quickly and violently.



ϕ
χ



⟨ϕ⟩
t (m^{-1})
Variance
t (m^{-1})

Two Predictions

- The process never happens when you take gravity into account: the universe fragments immediately and black holes form. The end of times begin shortly after inflation

- The resonance proce
create primordial bla

Delayed Reheating and the Breakdown of Coherent Oscillations

1003.3011

Richard Easther, Raphael Flauger, and James B. Gilmore [1]

[1] *Department of Physics,*
Yale University,
New Haven, CT 06520, USA

1003.3011

Two Predictions

- The process never happens when you take gravity into … and … rtly after

Lighting the Dark: The Evolution of the Post-Inflationary Universe

Nathan Musoke,[1,*] Shaun Hotchkiss,[1,†] and Richard Easther[1,‡]

[1] *Department of Physics, The University of Auckland, Private Bag 92019, Auckland, New Zealand*

(Dated: September 26, 2019)

In simple inflationary cosmological scenarios the near-exponential growth can be followed by a long period in which the Universe is dominated by the oscillating inflaton condensate. The condensate is initially almost homogeneous, but perturbations grow gravitationally, eventually fragmenting the condensate if it is not disrupted more quickly by resonance or prompt reheating. We show that the gravitational fragmentation of the condensate is well-described by the Schrödinger-Poisson … show that large overdensities form quickly after the onset … ion of this phase of nonlinear dynamics in the very early … m of the inflationary power spectrum and the dark matter … coupled to the inflaton.

1909.11678
PLUS AN EXCITING
TALK TOMORROW

… Breakdown
… tions

… mes B. Gilmore [1]

[1] *Department of Physics,*
Yale University,
New Haven, CT 06520, USA

1003.3011

Two Predictions

Primordial black holes from the preheating instability

Jérôme Martin,[a] Theodoros Papanikolaou,[b] Vincent Vennin[b,a]

[a]Institut d'Astrophysique de Paris, UMR 7095-CNRS, Université Pierre et Marie Curie, 98bis boulevard Arago, 75014 Paris, France
[b]Laboratoire Astroparticule et Cosmologie, Université Denis Diderot Paris 7, 75013 Paris, France

E-mail: jmartin@iap.fr, theodoros.papanikolaou@apc.univ-paris7.fr, vincent.vennin@apc.univ-paris7.fr

1907.04236

- T… ake gravity into a… liately and b… gin shortly after in…
- The resonance process *itself* is strong enough to create primordial black holes.

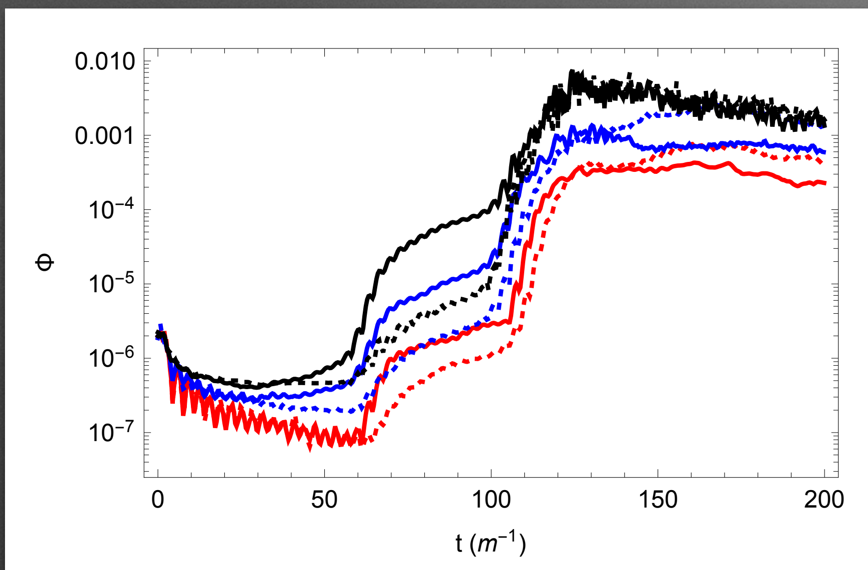
Two Predictions

- The process never happens when you take gravity into account: the universe fragments immediately and black holes form. The end of times begin shortly after inflation

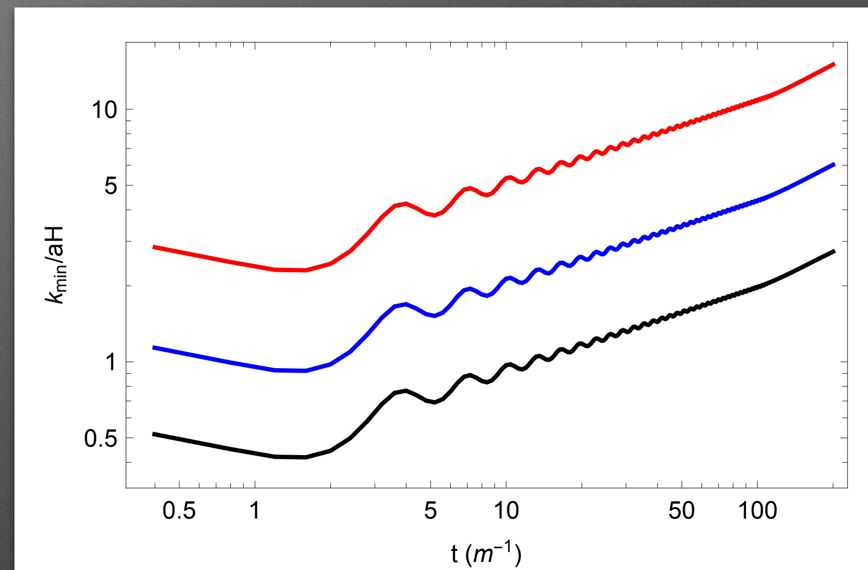
- The resonar
create primc

What do we learn by looking at the Newtonian Potential

For “reasonable” box sizes



How big/small does the Newtonian potential get?



The ratio of the Hubble horizon to the *longest* wavelength in the box

red: 2 m^{-1}, blue: 5 m^{-1}

black: 11 m^{-1}

Can we capture the details?

From perturbation Theory

$$ds^2 = -(1+2\Phi)dt^2 + 2a(t)B_{,i}dx^i dt + a^2(t)\left[(1-2\Psi)\delta_{ij} + 2\partial_i\partial_j E\right]dx^i dx^j$$

$$\Phi_B \equiv \Phi - \frac{d}{dt}\left[a^2\left(\dot{E} - \frac{B}{a}\right)\right]$$

$$\Psi_B \equiv \Psi + Ha^2\left(\dot{E} - \frac{B}{a}\right)$$

Comparing to BSSN

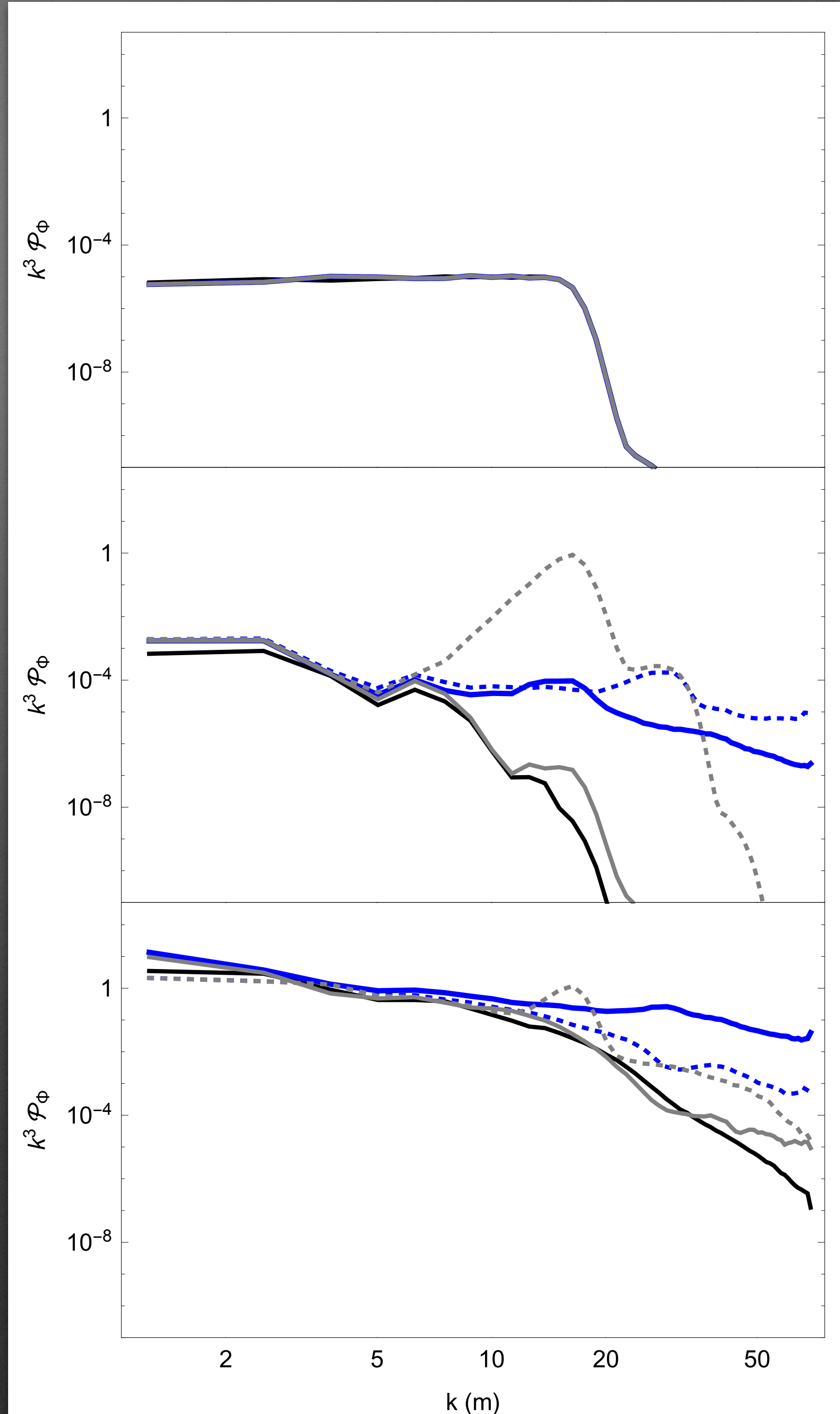
$$\tilde{E} = -\frac{1}{k^2}\left[\frac{3}{4}\frac{k_i k_j}{k^2}\frac{\tilde{\gamma}_{ij}}{a^2} - \frac{1}{4}\frac{\tilde{\gamma}_{ii}}{a^2}\right]$$

$$\tilde{B} = -\frac{1}{a}\frac{ik_j\tilde{\beta}_j}{k^2}$$

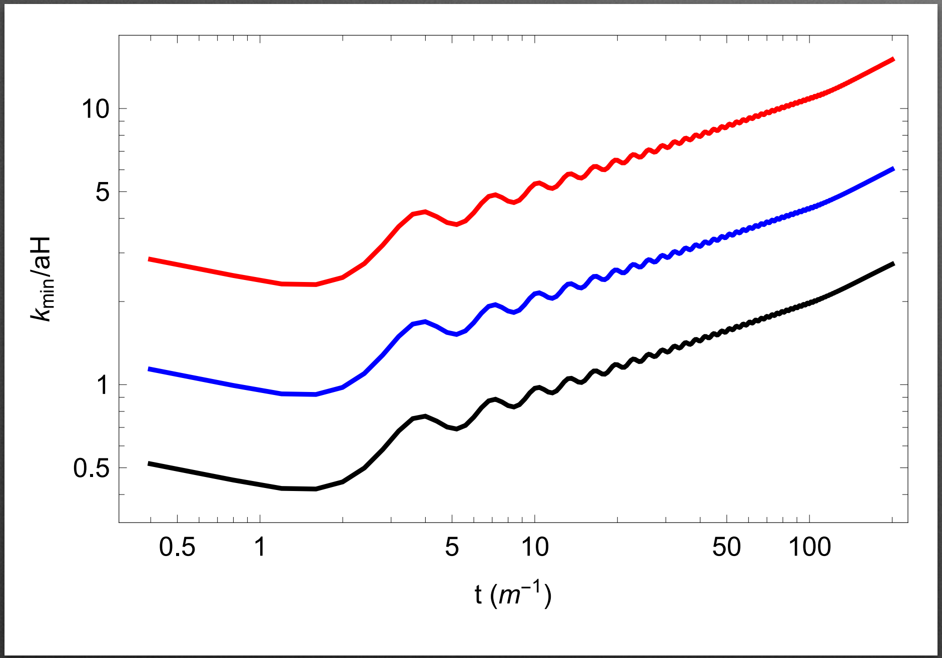
$$\Phi = \alpha - 1$$

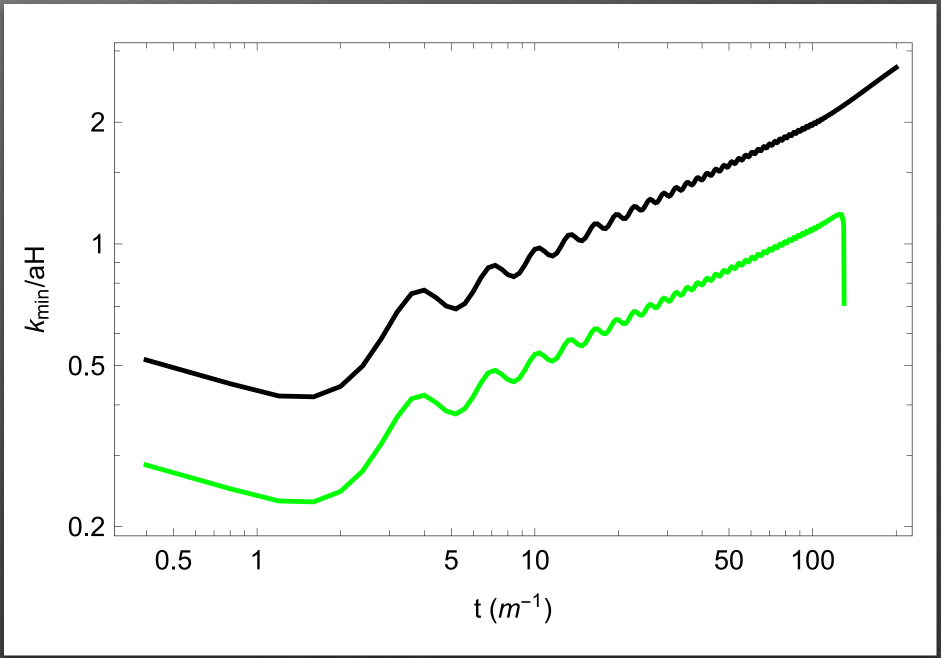
$$\tilde{\Psi} = \frac{1}{4}\left[\frac{k_i k_j}{k^2}\frac{\tilde{\gamma}_{ij}}{a^2} - \frac{\tilde{\gamma}_{ii}}{a^2}\right]$$

Details in 1907.10601



As we approach larger (box) sizes





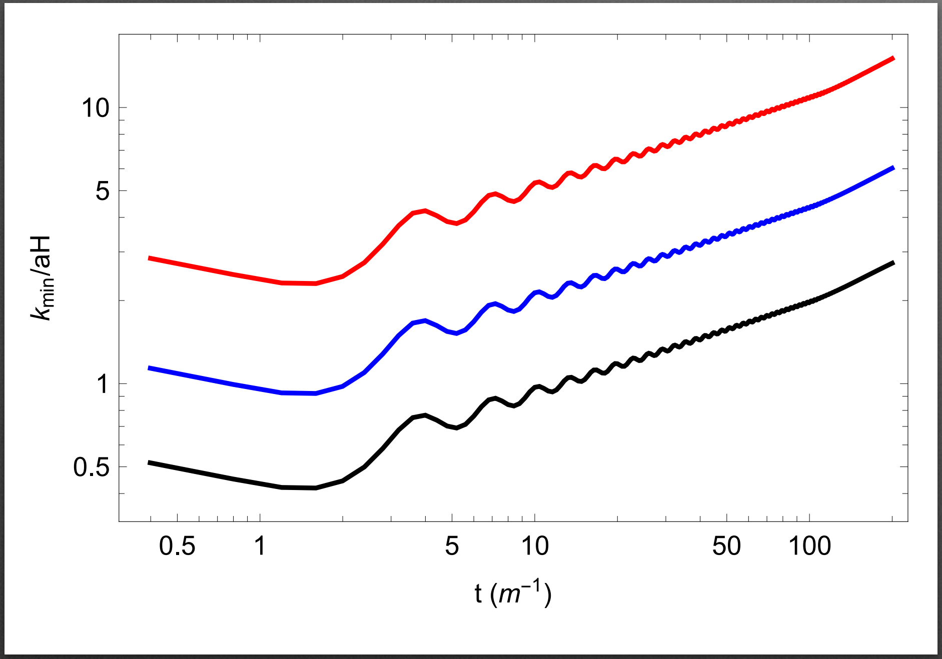
red: 2 m^{-1}

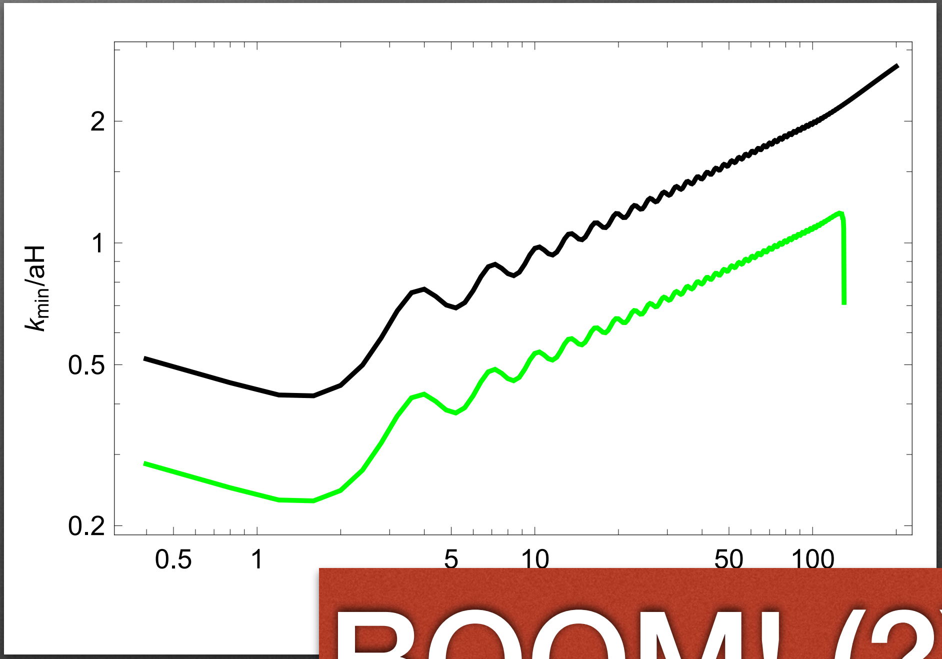
blue: 5 m^{-1}

black: 11 m^{-1}

green: 20 m^{-1}

As we approach larger (box) sizes





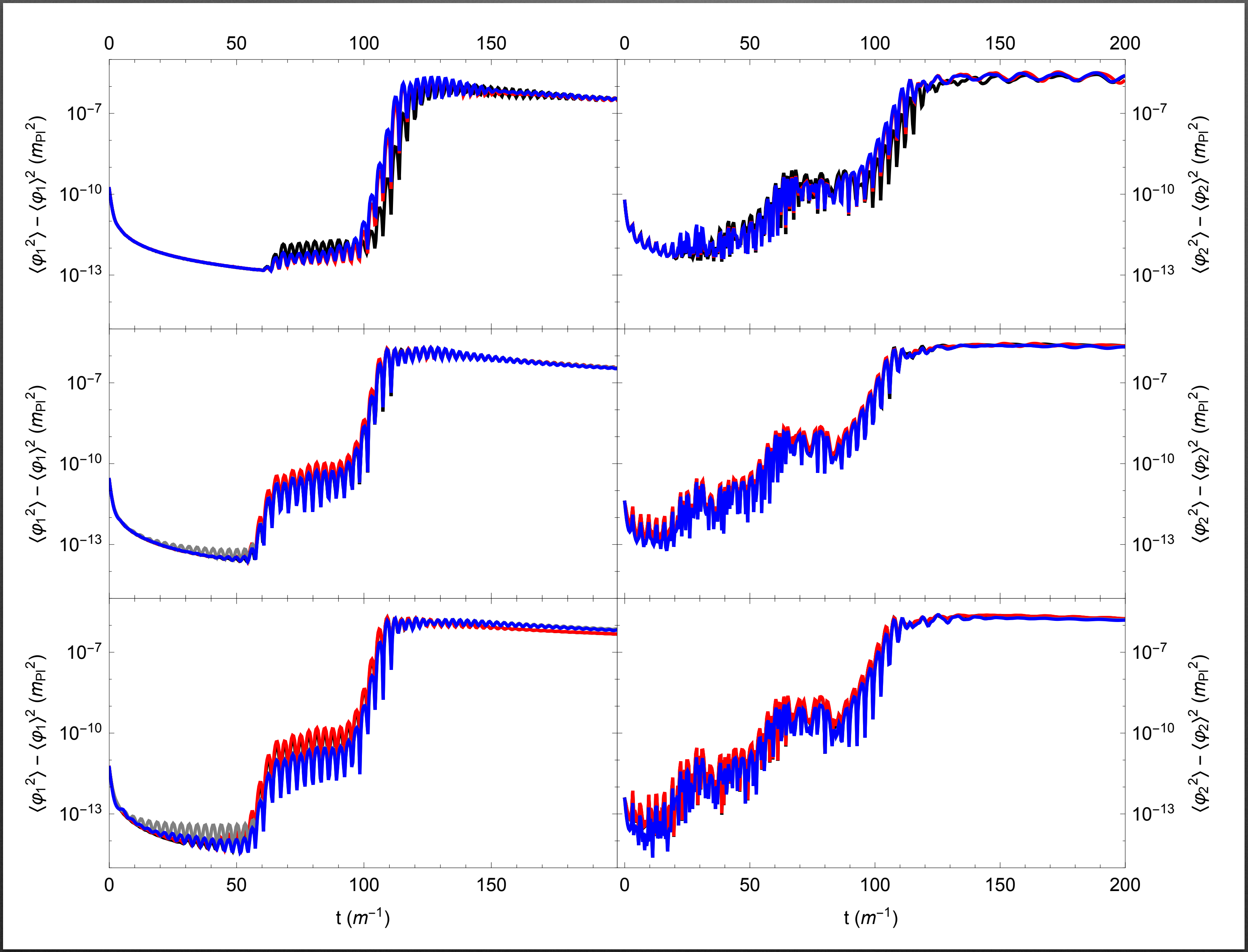
BOOM! (?)

red: 2 m^{-1}

blue: 5 m^{-1}

black: 11 m^{-1}

green: 20 m^{-1}



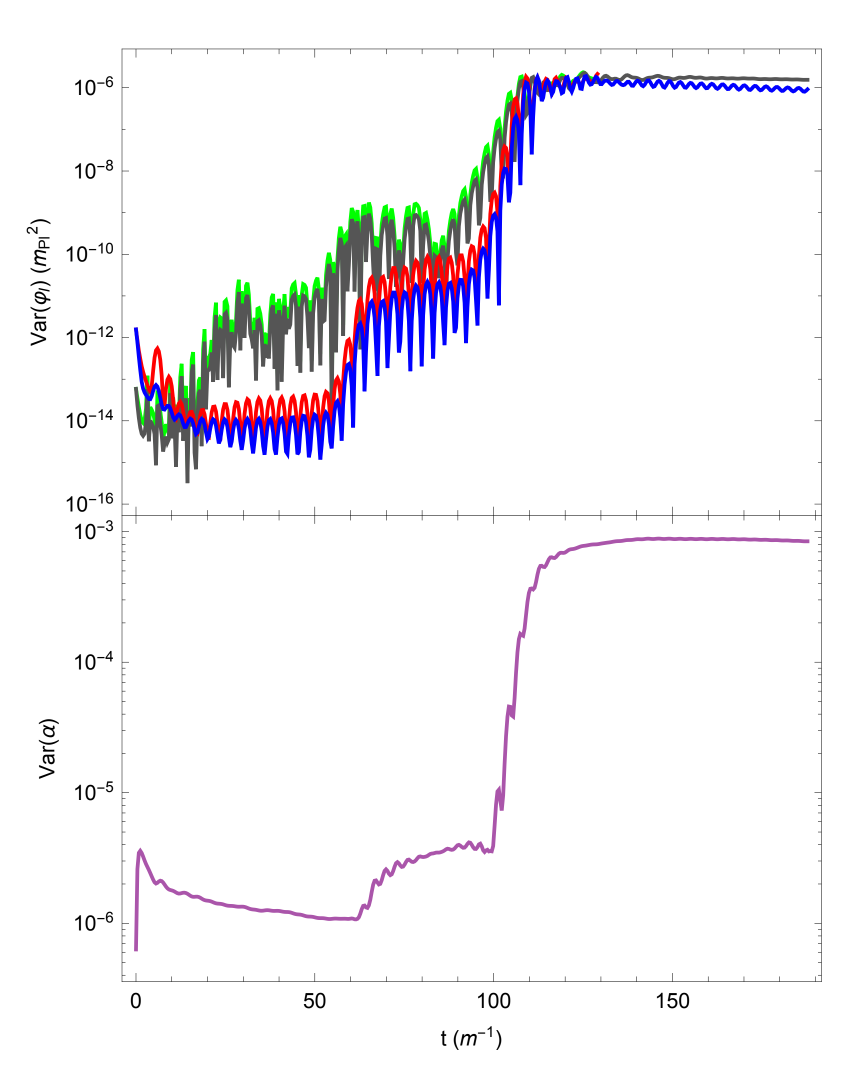
$L = 2\,m^{-1}$

$L = 5\,m^{-1}$

$L = 11\,m^{-1}$

Black = FLRW, Grey = Perturbative, Blue = BSSN

For the big box

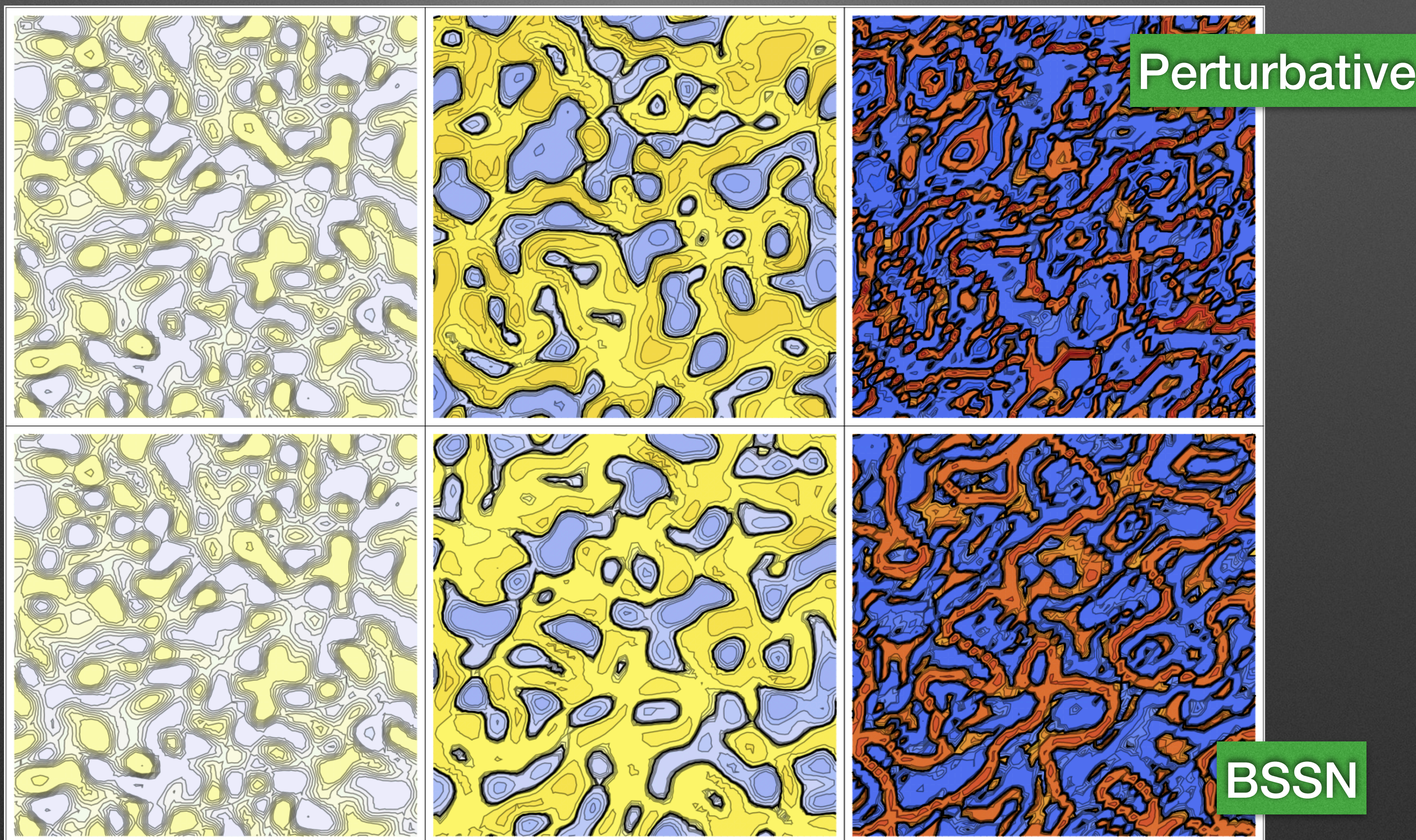


Red: inflaton Perturbative
Blue: inflaton BSSN

Green: decay field Perturbative
Black: decay field BSSN

The *variance* of the lapse does not show departures from homogeneity that indicate back hole formation

How do they look

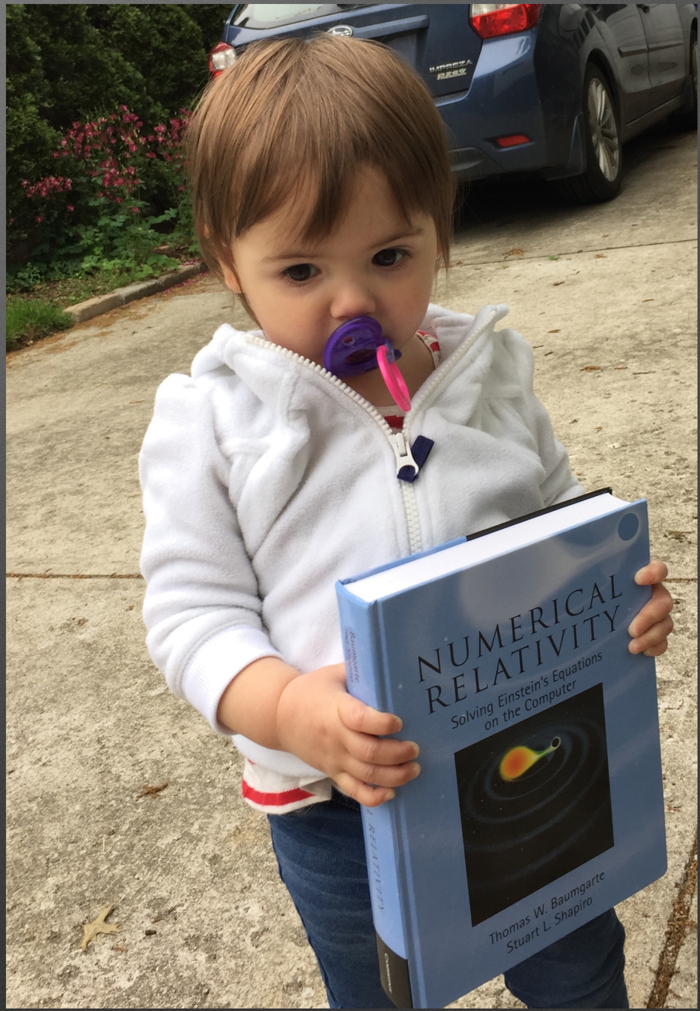


So there's no need to panic

- In these cases: non-linear physics seems to be a friend, not a foe
- But there's still *much* left in parameter space: e.g. we know that collapse will happen

Your Take-home

- The next step in understanding the Universe is hard
  - Physics is non-linear
  - You have to ask the right questions
  - You need to interpret the answers correctly
- We need new, bold, creative, insightful, original and diverse ideas to answer these questions

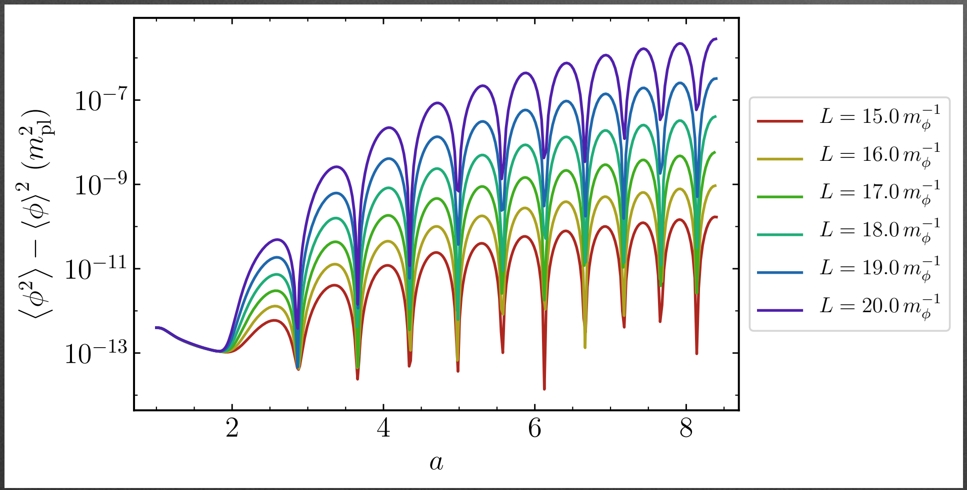


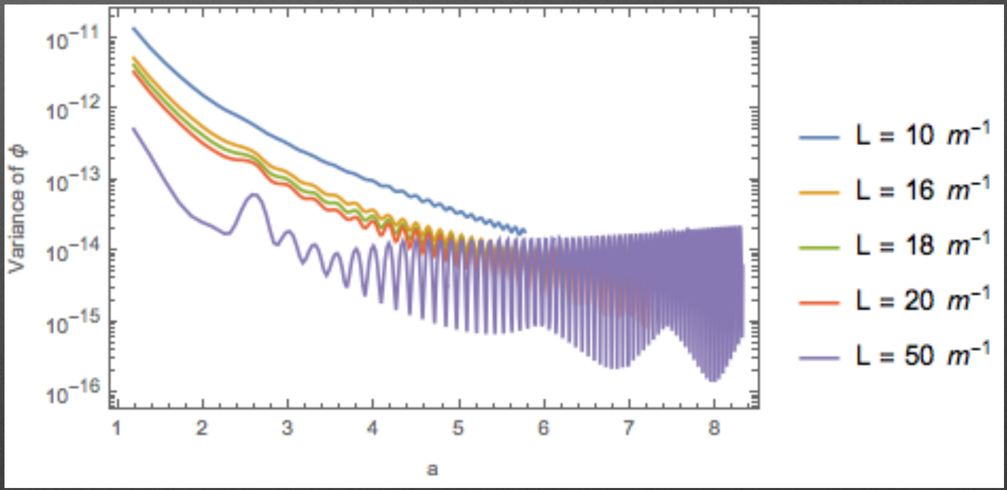
Fin

Comments on Fragmentation

A test with a single field

- A single, massive, scalar in the presence of gravity
- Can we go beyond perturbation theory?



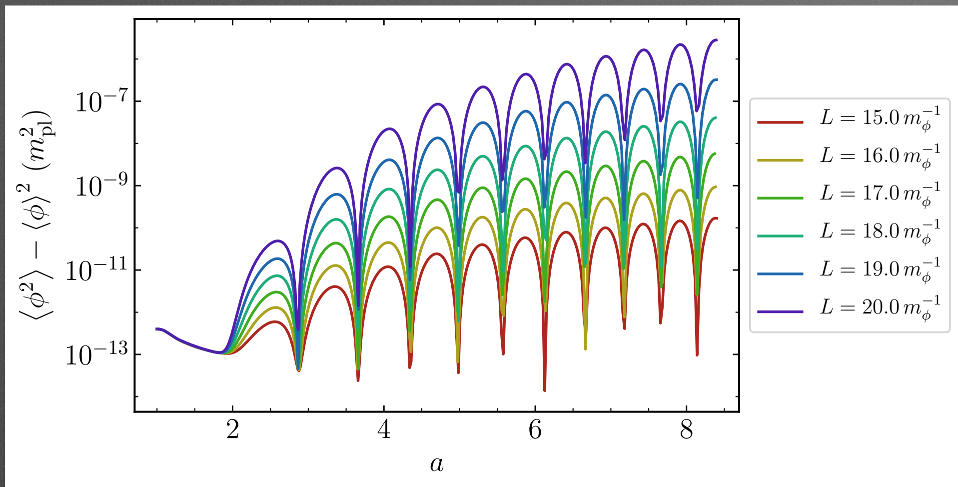


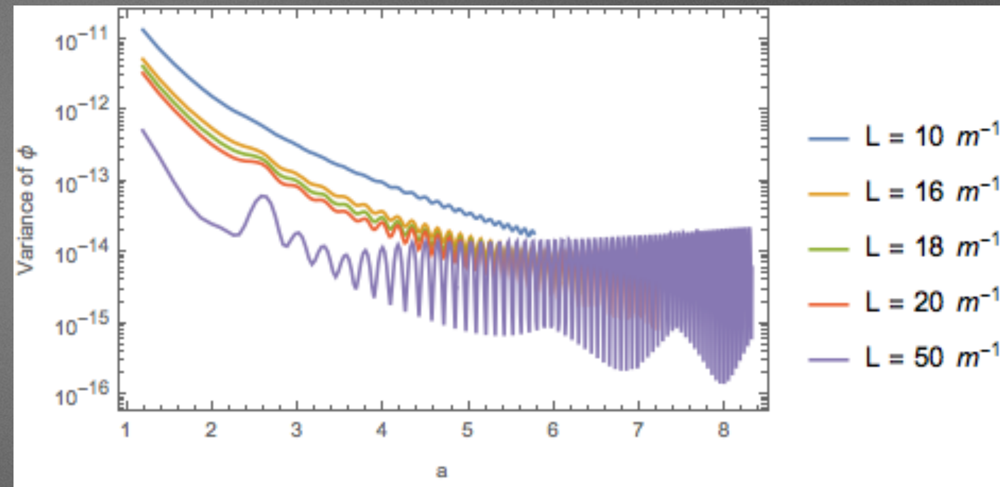
Linearized gravity

BSSN

$$m = 10^{-6}\, m_{\rm pl}$$

Field variances

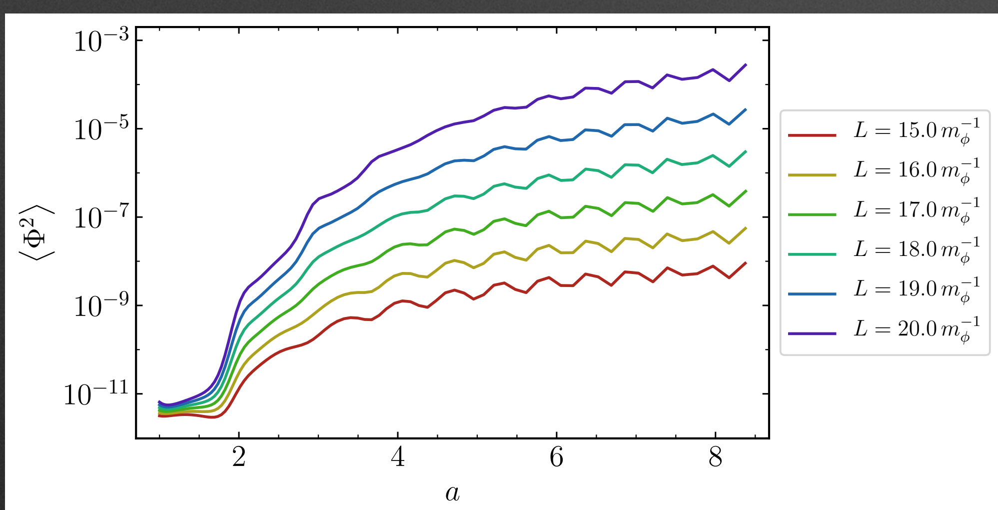


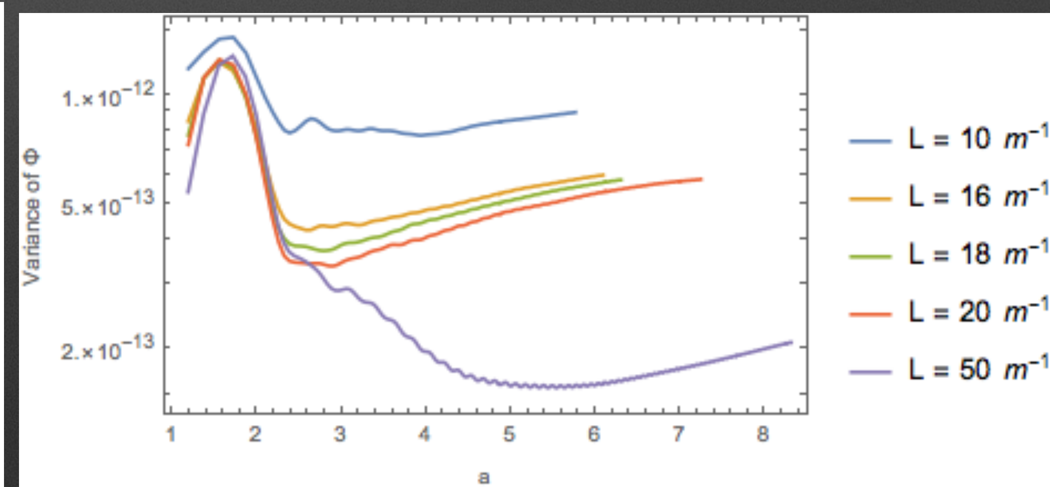


Linearized gravity

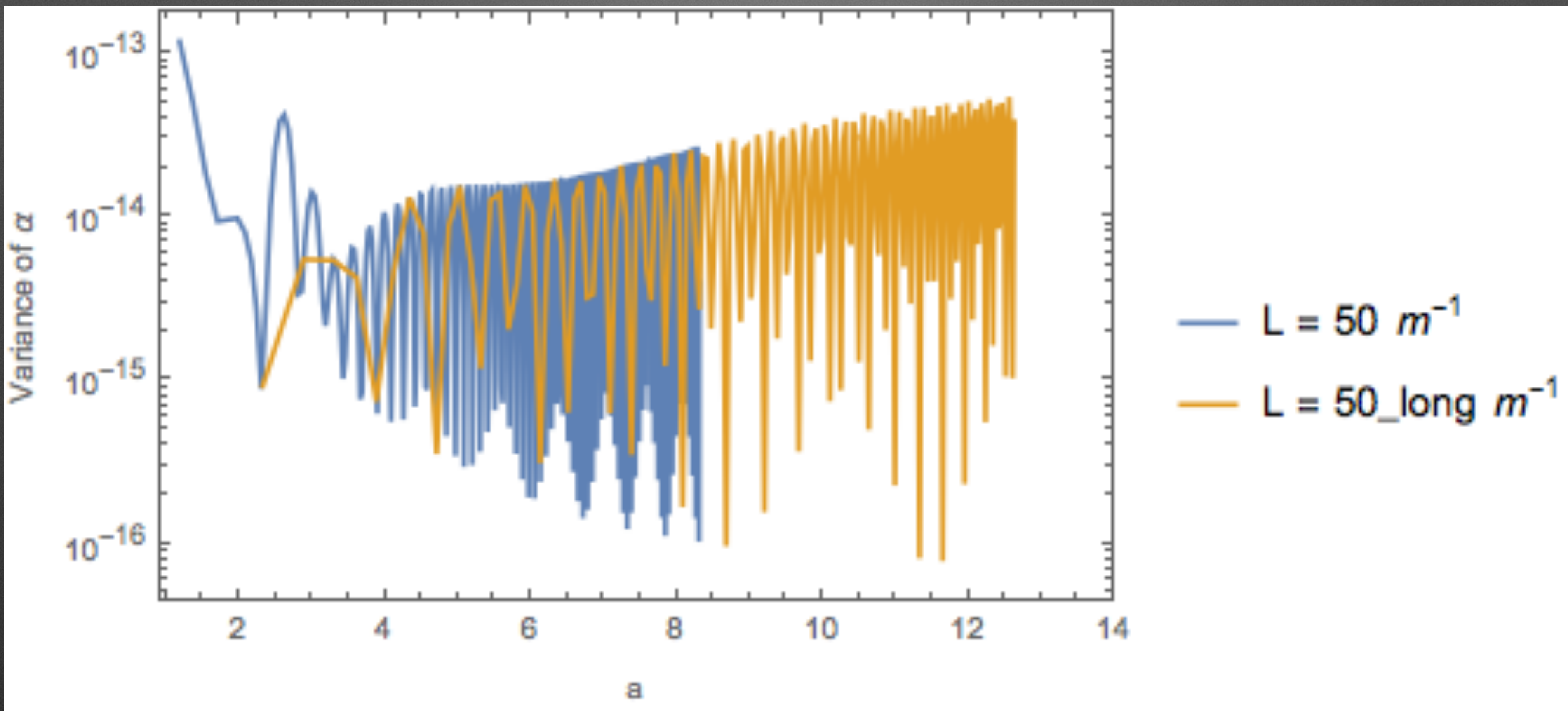
BSSN

Variance of the Newtonian/one of the Bardeen Potentials



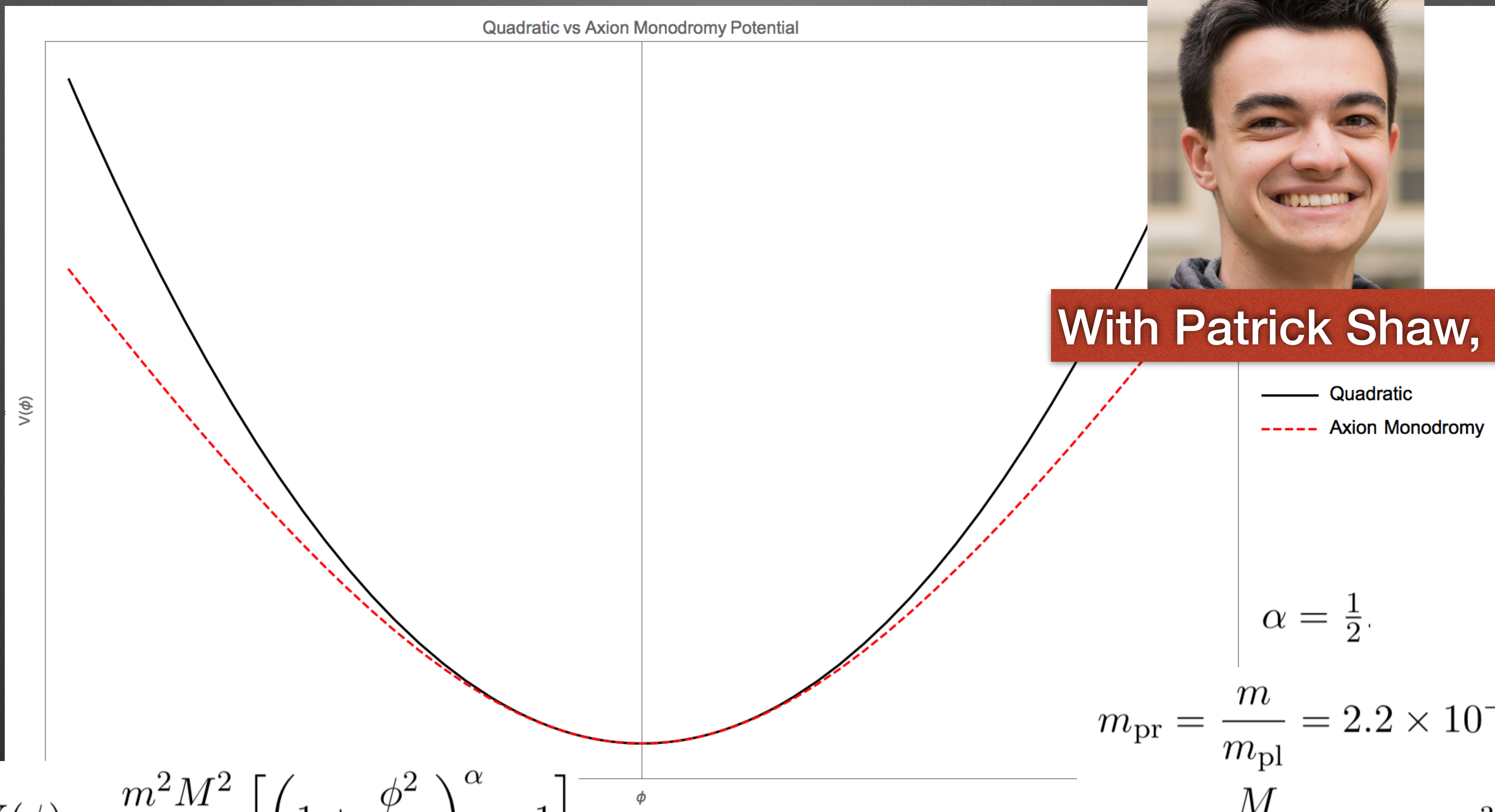


BIGGER BOXES



Comments on Oscillons

Oscillons in Monodromy



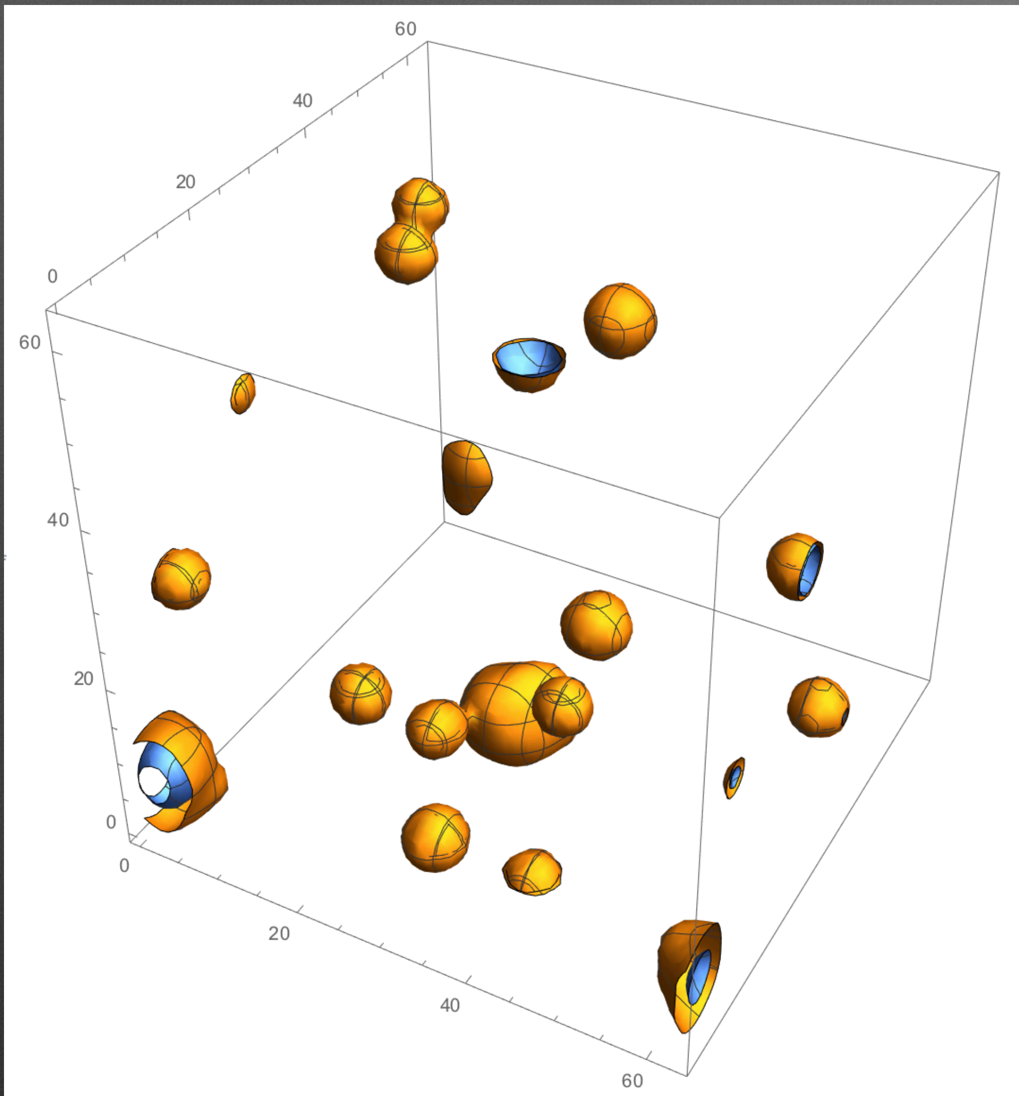
With Patrick Shaw, ‘19

$$\alpha = \frac{1}{2}.$$

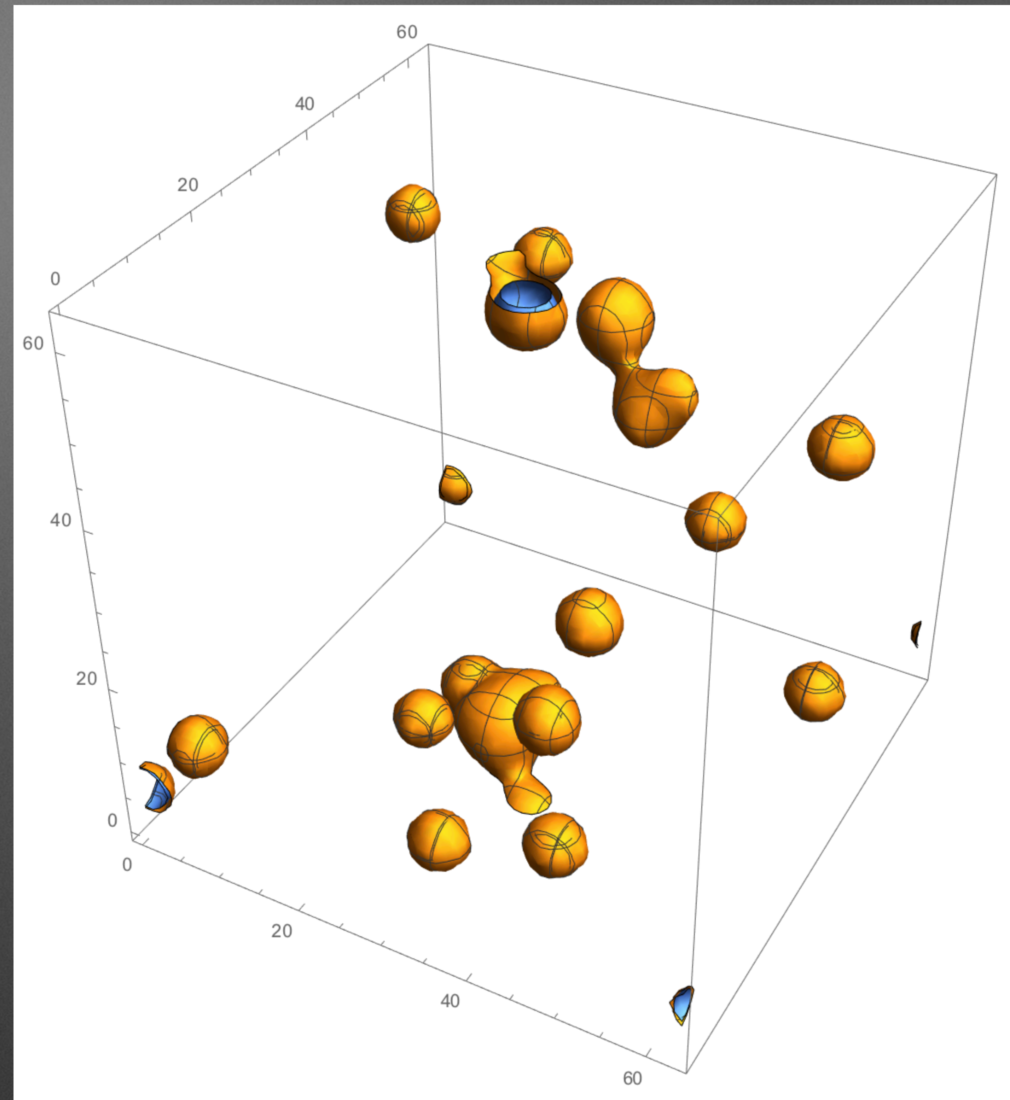
$$m_{\rm pr} = \frac{m}{m_{\rm pl}} = 2.2 \times 10^{-5},$$

$$M_{\rm pr} = \frac{M}{m_{\rm pl}} = 4 \times 10^{-3}.$$

$$V(\phi) = \frac{m^2 M^2}{2\alpha}\left[\left(1 + \frac{\phi^2}{M^2}\right)^{\alpha} - 1\right]$$

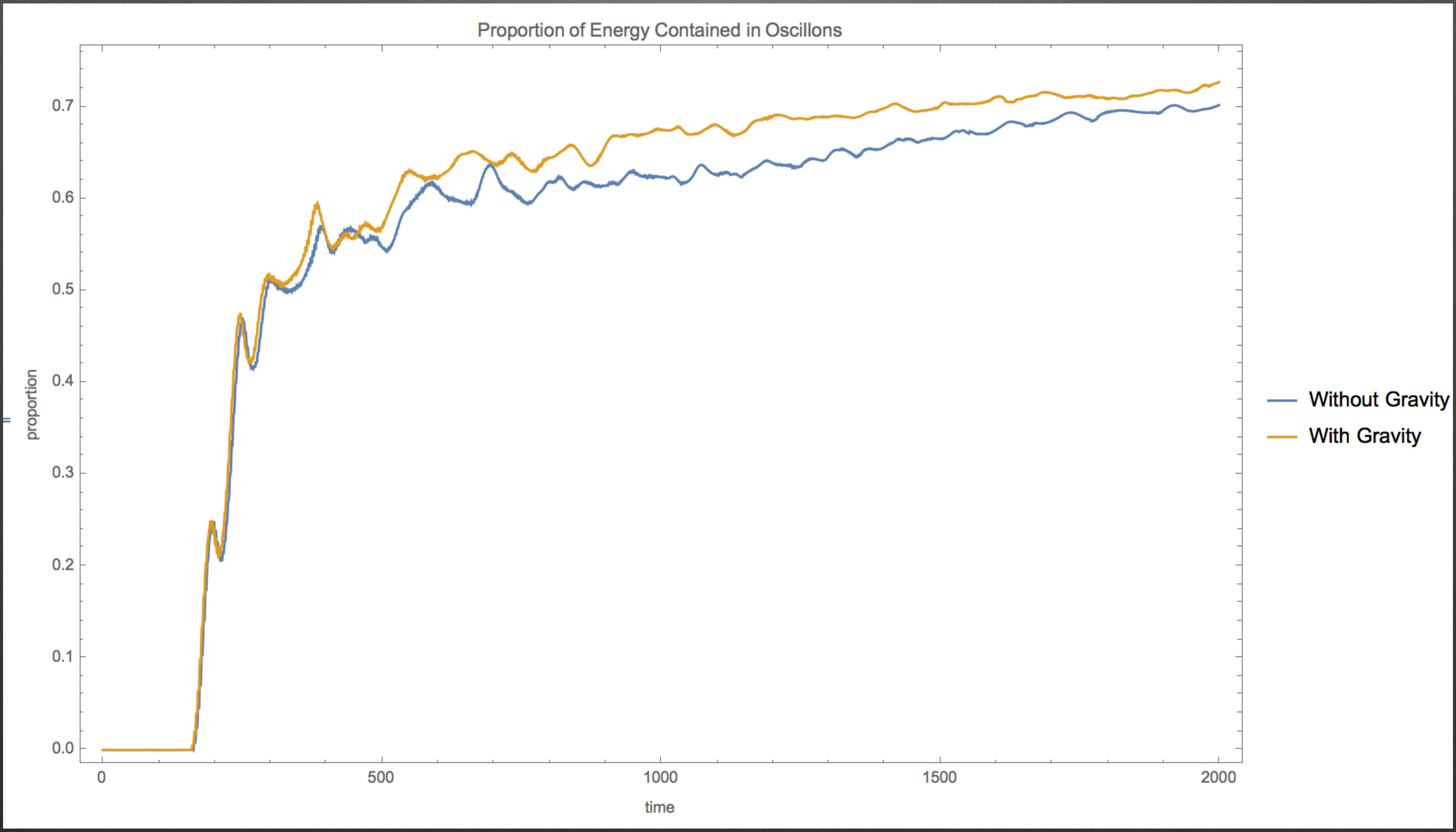


No Gravity



Linear Gravity

There is is a slight difference in the TOTAL energy in Oscillons



But the Newtonian Potential is still small