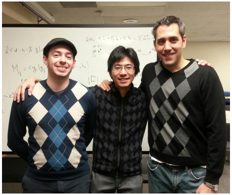
Preface

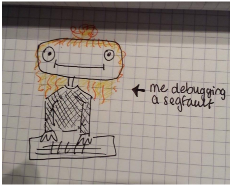
Thanks: CIERA, organizers, everyone here at 9am

Happy birthday, Laura!

Wayne Zhao



Me, Kent Yagi, Nico Yunes



Maria (Masha) Okounkova

Many other colleagues, SXS Collaboration, taxpayers

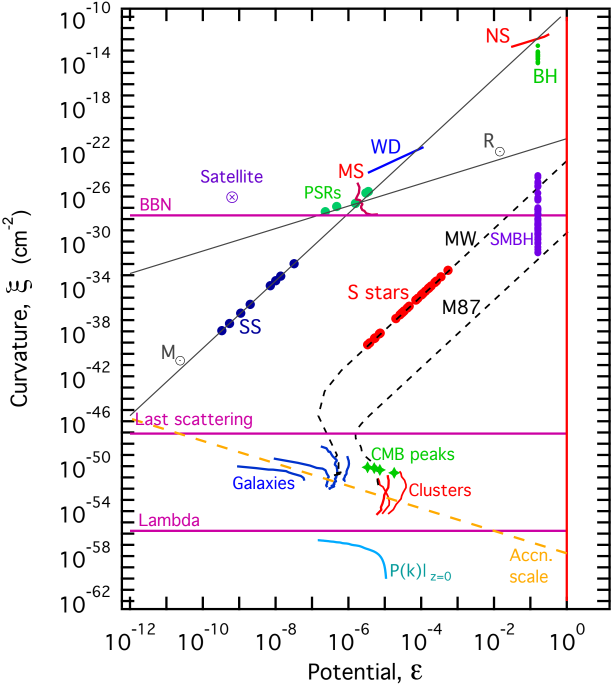
Binary black hole mergers: Beyond general relativity

Leo C. Stein (TAPIR, Caltech)

FF2016@CIERA — 2016 Sep. 2

Motivation

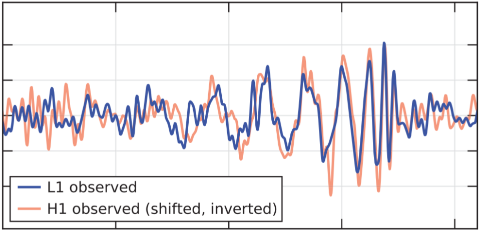
1. General relativity successful but incomplete
   - GR+QM=new physics (e.g. BH information paradox)
   - Expect GR is low-energy EFT
   - Planck scale phenomena? Other scales?
2. Ask nature
   - So far, only weak-field precision tests
   - Lots of theories $\approx$ GR
   - Need to explore strong-field
     - Strong curvature • non-linear



NS
BH
WD
R⊙
MS
Satellite
PSRs
BBN
MW
SMBH
S stars
M87
SS
M⊙
Last scattering
CMB peaks
Galaxies
Clusters
Lambda
P(k)| z=0
Accn. scale
Curvature, ξ (cm⁻²)
Potential, ε

Vision

- Before this year: precision tests of GR in weak field
- Now: first direct measurements of dynamical, strong field regime



- Future: precision tests of GR in the strong field
  - $\Longrightarrow$ Black hole binary merger

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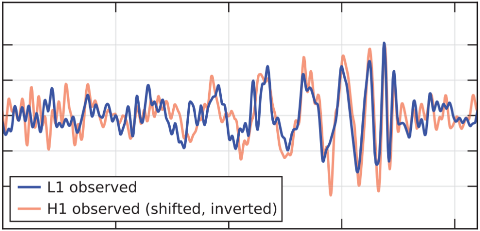
- Now: first direct measurements of dynamical, strong field regime



- Future: precision tests of GR in the strong field
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Question: How to perform precision tests of GR in strong field?

How to perform precision tests

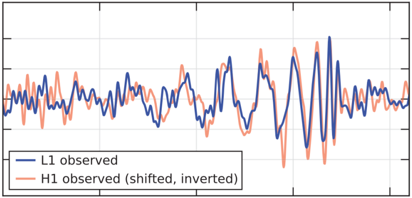
- Two approaches: theory-specific and theory-agnostic
- Agnostic: parameterize, e.g. PPN, PPE

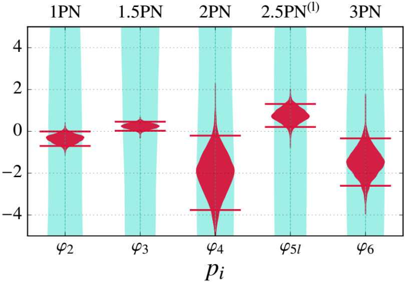
Parameterized post-Einstein framework

- Insert power-law corrections to amplitude and phase ($u^3 \equiv \pi \mathcal{M} f$)

$$\tilde{h}(f) = \tilde{h}_{GR}(f) \times (1 + \alpha u^a) \times \exp[i\beta u^b]$$

- Parameters: (α, a, β, b)
- Inspired by post-Newtonian calculations in beyond-GR theories





How to perform precision tests

- Two approaches: theory-specific and theory-agnostic
- Agnostic: parameterize, e.g. PPN, PPE
- Want more powerful parameterization
- Don't know how to parameterize in strong-field!
- Need guidance from specific theories

How to perform precision tests

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Problem: Only simulated BBH mergers in GR!

The problem

- Only have BBH mergers in GR, some scalar-tensor
- Recall BBH in S-T is identical to GR (unless funny boundaries)

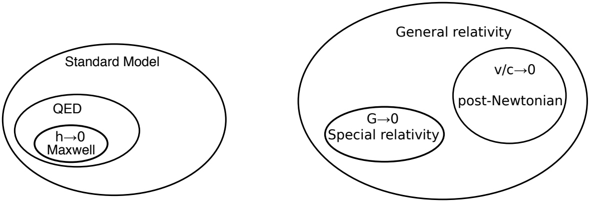
From Lehner+Pretorius 2014:

> redshifts of $z \simeq 20$ with a SNR ≥ 10. For a recent review see Seoane et al. (2013).] Compounding the problem, despite the large number of proposed alternatives or modifications to general relativity (see, for example, Will 1993, 2006), almost none have yet been presented that (*a*) are consistent with general relativity in the regimes where it is well tested, (*b*) predict observable deviations in the dynamical strong field relevant to vacuum mergers, and (*c*) possess a classically well-posed initial value problem to be amenable to numerical solution in the strong field. The notable exceptions are a subset of scalar tensor theories, though these require a time-varying cosmological scalar field for binary black hole systems (Horbatsch & Burgess 2012) or one or more neutron stars in the merger (see Section 5). Thus there is little guidance on what reasonable strong-field deviations one might expect. Proposed solutions to (at least partially) circumvent these problems include the parameterized post-Einsteinian and related frameworks (Yunes & Pretorius

- Don't know if other theories have good initial value problem
  Example: Delsate+ PRD **91**, 024027, dynamical Chern-Simons
- But wait—title of this talk!

The solution

- Treat every theory as an effective field theory (EFT)
- Already do this for GR. Valid below some scale
- Theory only needs to be approximate, approximately well-posed



- Example: weak force below EWSB scale (lose unitarity above)

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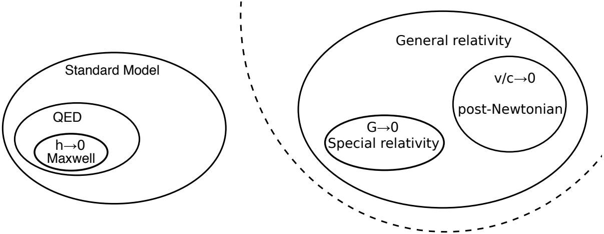

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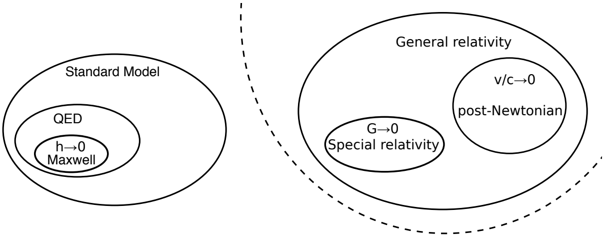
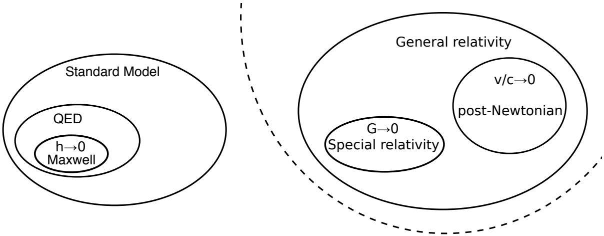
The solution



- Same should happen in gravity EFT:
  lose predictivity (bad initial value problem) above some scale
- Theory valid below cutoff $\Lambda \gg E$. Must recover GR for $\Lambda \to \infty$.
- Assume weak coupling, use perturbation theory

The solution



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Example: Dynamical Chern-Simons gravity

What is dynamical Chern-Simons gravity?

- Chern-Simons = GR + pseudo-scalar + interaction

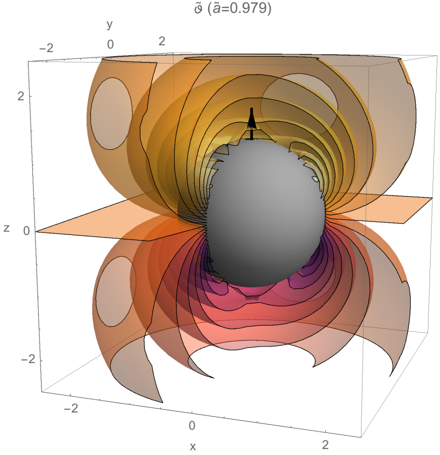
$$S = \int d^4x\sqrt{-g}\left[R - \frac{1}{2}(\partial\vartheta)^2 + \varepsilon\,\vartheta\ {}^*RR\right]$$

$$\Box\vartheta = \varepsilon\,{}^*RR\,, \qquad G_{ab} + \varepsilon\,C_{ab}[\partial\vartheta\partial^3 g] = T_{ab}$$

- Anomaly cancellation, low-E string theory, LQG...
(see Nico's review Phys. Rept. **480** (2009) 1-55)
- Lowest-order EFT with parity-odd ϑ, shift symmetry (long range)
- Phenomenology unique from other R^2
(e.g. Einstein-dilaton-Gauss-Bonnet)

Black holes in dCS

- $a = 0$ (Schwarzschild) is exact solution with $\vartheta = 0$
- Rotating BHs have dipole+ scalar hair



LCS, PRD **90** 044061 (2014) [arXiv:1407.2350]

Black holes in dCS

- $a = 0$ (Schwarzschild) is exact solution with $\vartheta = 0$
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  LCS, PRD **90** 044061 (2014) [arXiv:1407.2350]
- Post-Newtonian of BBH inspiral in
  PRD **85** 064022 (2012) [arXiv:1110.5950]
- More updated phenomenology in
  CQG **32** 243001 (2015) [arXiv:1501.07274]

Back to problem and solution

- DCS had principal part $\partial^3 g$ coming from C_{ab} tensor. *Probably* not well-posed, Delsate+ PRD **91**, 024027.
- Theory is GR $+ \varepsilon \times$ deformation. Expand everything in ε
- ~~Derivation~~
- At every order in ε, principal part is Princ$[G_{ab}]$

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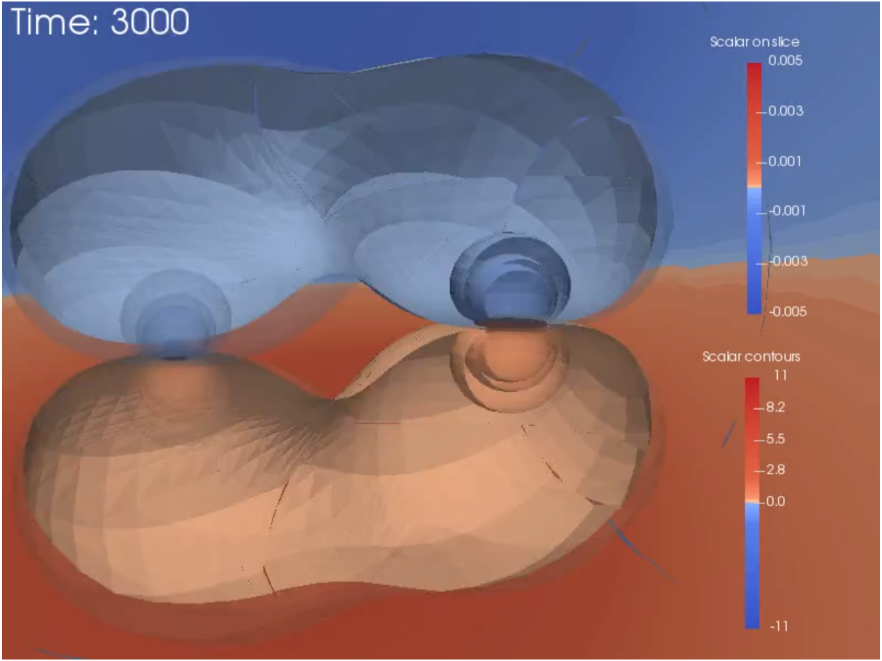
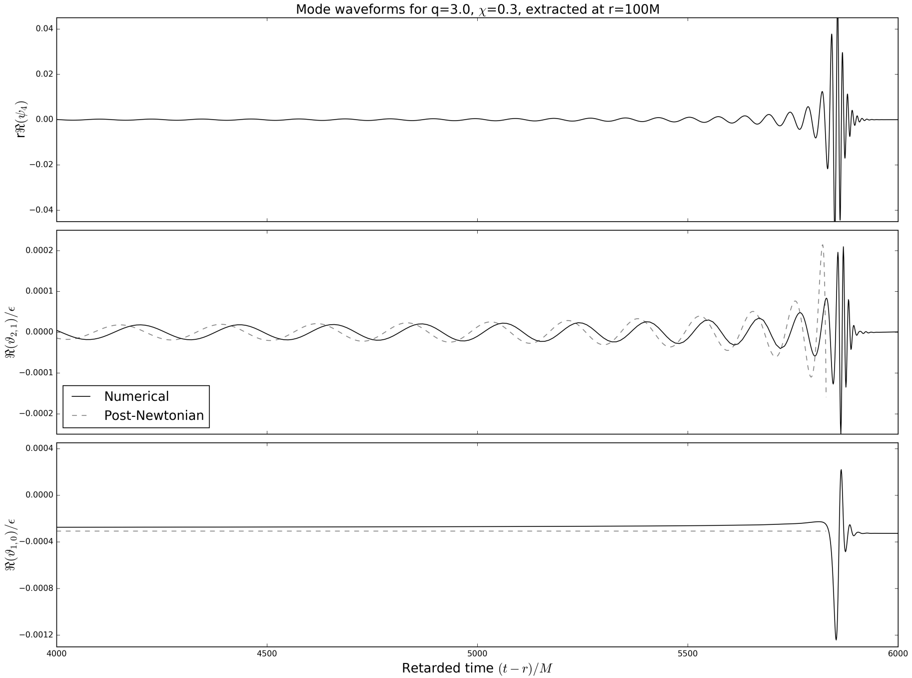
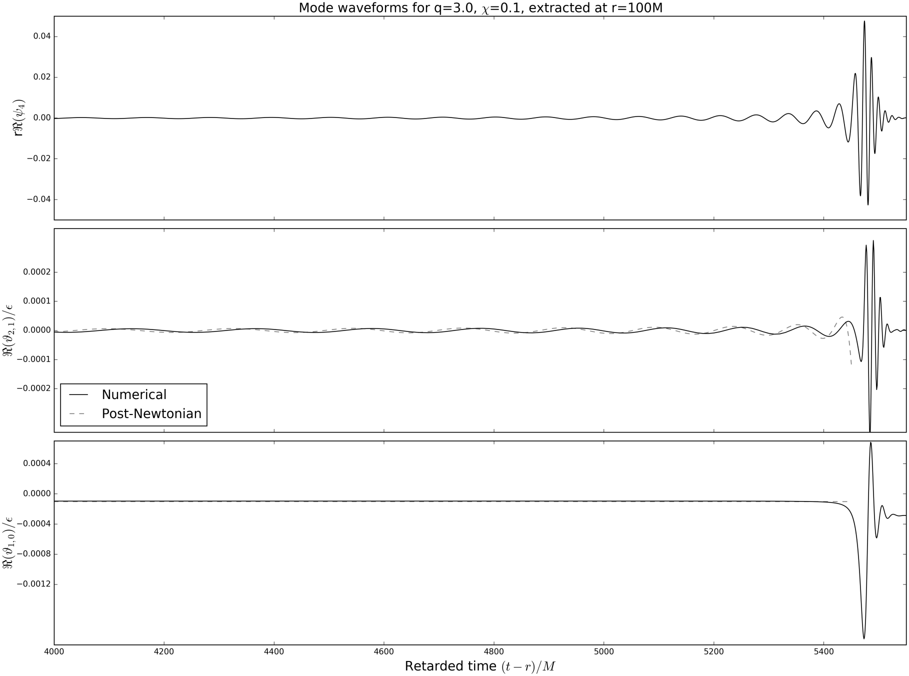
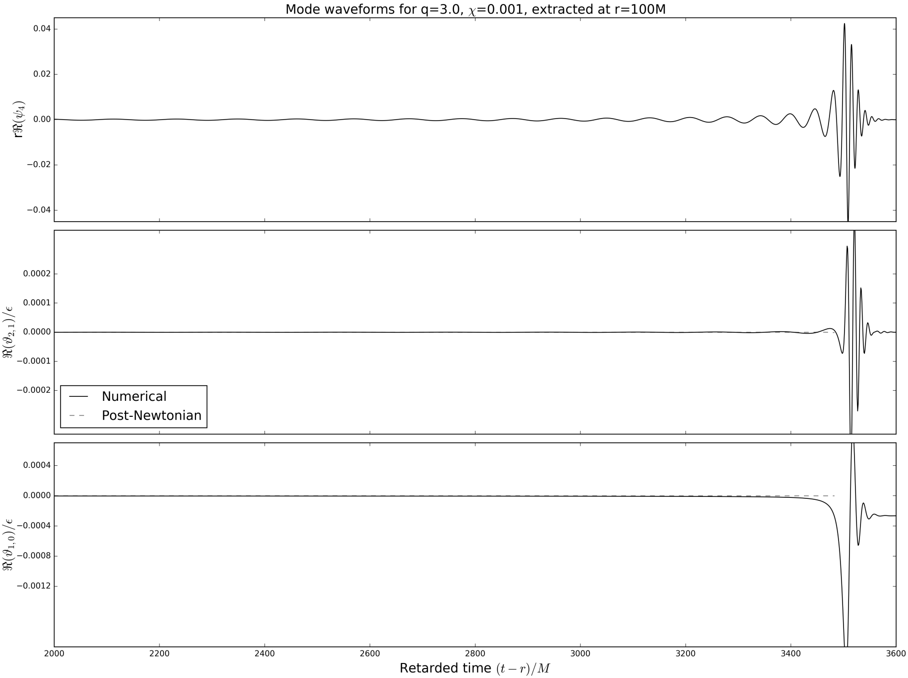
Background dynamics are well-posed $\Longrightarrow$ perturbations well-posed

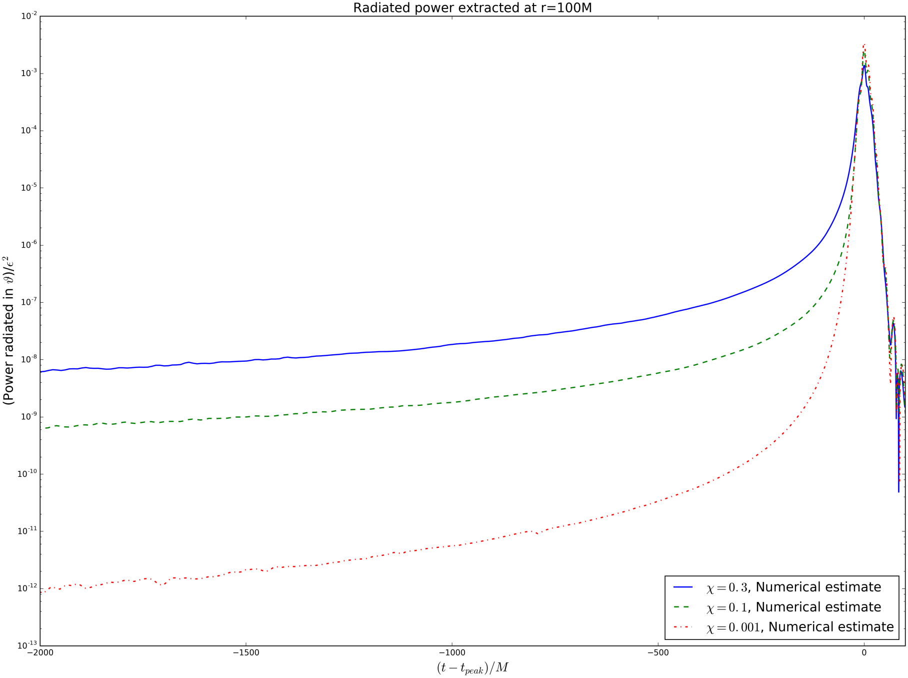

Time: 3000
Scalar on slice
0.005
0.003
0.001
-0.001
-0.003
-0.005
Scalar contours
11
8.2
5.5
2.8
0.0
-11



Mode waveforms for q=3.0, χ=0.3, extracted at r=100M
$r\Re(\psi_4)$
0.04
0.02
0.00
−0.02
−0.04
$\Re(\vartheta_{2,1})/\epsilon$
0.0002
0.0001
0.0000
−0.0001
−0.0002
Numerical
Post-Newtonian
$\Re(\vartheta_{1,0})/\epsilon$
0.0004
0.0000
−0.0004
−0.0008
−0.0012
4000
4500
5000
5500
6000
Retarded time $(t-r)/M$


Mode waveforms for q=3.0, χ=0.1, extracted at r=100M
$r\Re(\psi_4)$
0.04
0.02
0.00
−0.02
−0.04
$\Re(\vartheta_{2,1})/\epsilon$
0.0002
0.0001
0.0000
−0.0001
−0.0002
Numerical
Post-Newtonian
$\Re(\vartheta_{1,0})/\epsilon$
0.0004
0.0000
−0.0004
−0.0008
−0.0012
4000
4200
4400
4600
4800
5000
5200
5400
Retarded time $(t-r)/M$


Mode waveforms for q=3.0, χ=0.001, extracted at r=100M
r$\Re(\psi_4)$
$\Re(\vartheta_{2,1})/\epsilon$
$\Re(\vartheta_{1,0})/\epsilon$
Numerical
Post-Newtonian
Retarded time $(t-r)/M$



Radiated power extracted at r=100M
(Power radiated in ϑ)/ϵ^2
$(t-t_{peak})/M$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
−2000
−1500
−1000
−500
0
$\chi = 0.3$, Numerical estimate
$\chi = 0.1$, Numerical estimate
$\chi = 0.001$, Numerical estimate

The Plan

- Do $\mathcal{O}(\varepsilon^2)$ perturbations numerically
- Lots of phenomenology studies in dynamical Chern-Simons
- Method is generic—apply to other theories.
  Next up: Einstein-dilaton-Gauss-Bonnet
- Understand regime of validity of weak-coupling limit
- Build (surrogate model) parameter estimation code, constrain specific theories
- Provide guidance to build parameterized models

The TAKE AWAY™

- General relativity must be incomplete
- Want precision tests of GR in strong-field
  $\implies$ Binary black hole mergers
- Parametric (theory-agnostic) tests are nice but lack guidance
- Need detailed observational predictions from beyond-GR theories
- Most theories: don't know about initial value problem
- Effective field theory gives solution:
  - weak-coupling limit
  - perturbation theory about general relativity solution
- Gives well-posed initial value problem
- First binary black hole mergers in dynamical Chern-Simons gravity
- Lots more to do!