

Preface

Thanks: CIERA, organizers, everyone here at 9am



Happy birthday, Laura!



Me, Kent Yagi, Nico Yunes



Wayne Zhao



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

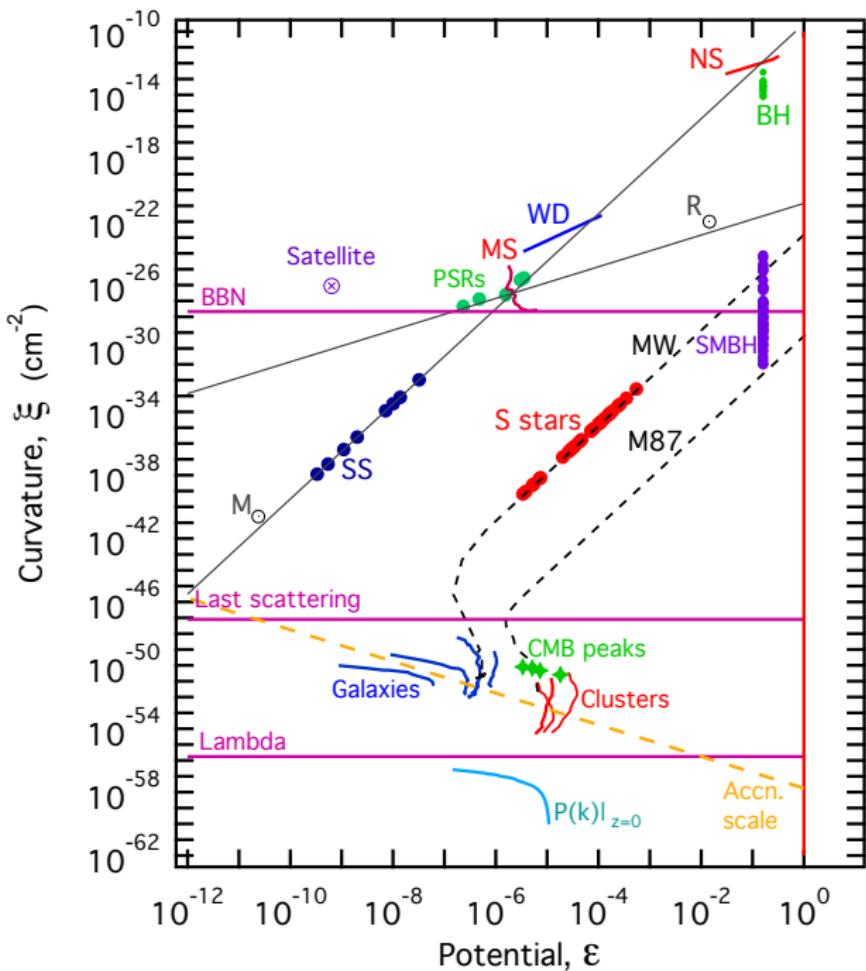
Motivation

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?

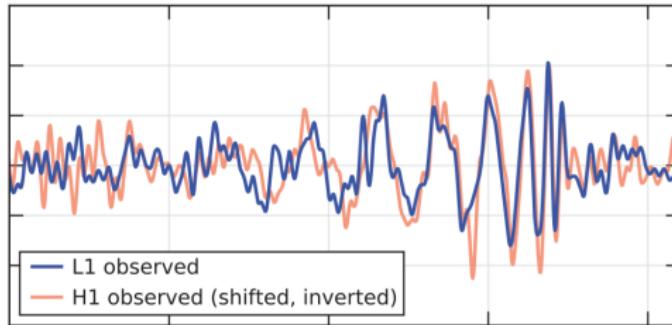
② Ask nature

- So far, only weak-field precision tests
- Lots of theories \approx GR
- Need to explore strong-field
 - Strong curvature • non-linear



Vision

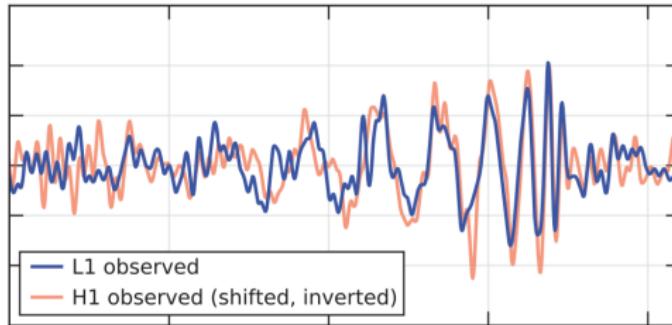
- Before this year: precision tests of GR in weak field
- Now: first direct measurements of dynamical, strong field regime



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

Vision

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

How to perform precision tests

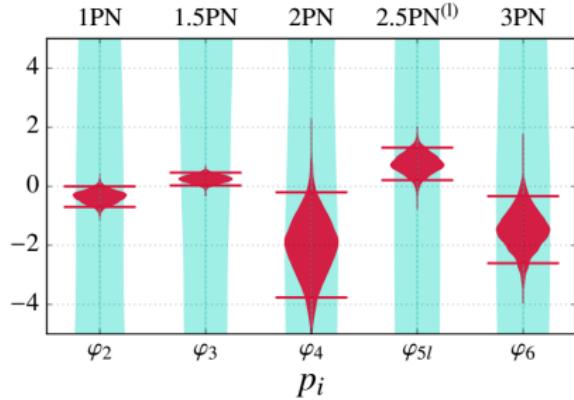
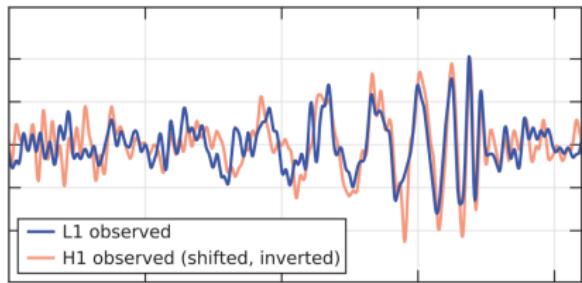
- Two approaches: theory-specific and theory-agnostic
- Agnostic: **parameterize**, e.g. PPN, PPE

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

- Two approaches: theory-specific and theory-agnostic
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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)

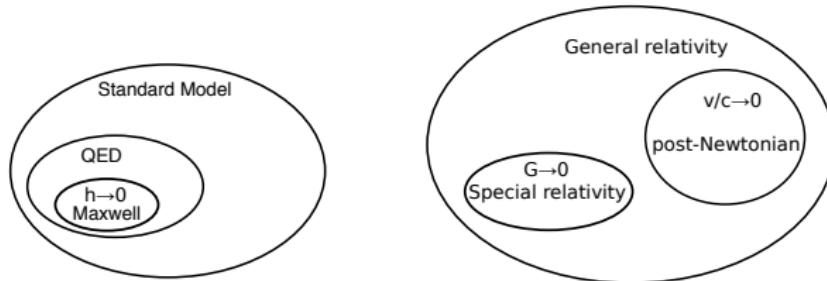
From Lehner+Pretorius 2014:

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 2009, 2010, 2011; Delsate et al. 2012).

- 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

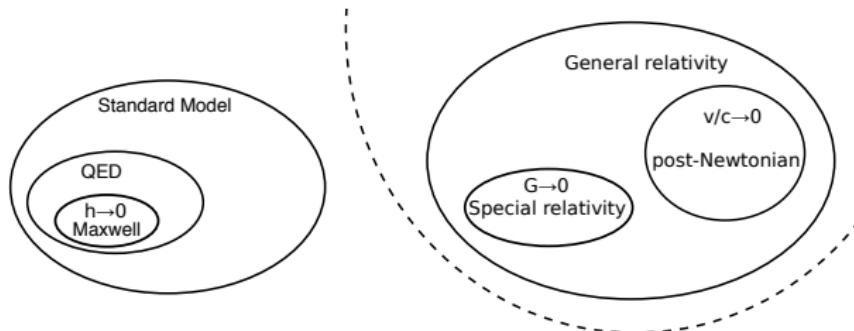
- Treat every theory as an **effective field theory** (EFT)
- Already do this for GR. **Valid** below some scale
- Theory only needs to be **approximate**, approximately well-posed



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

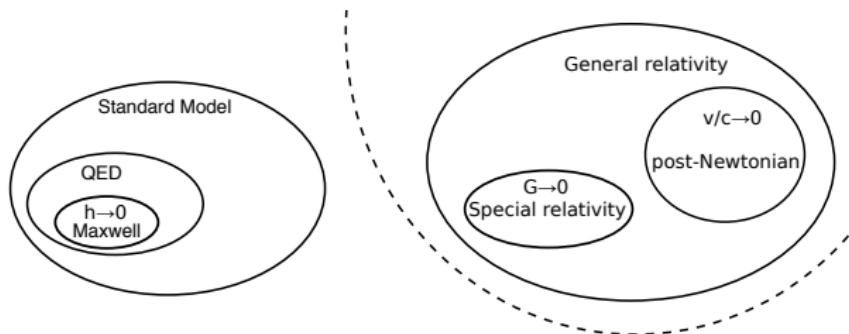
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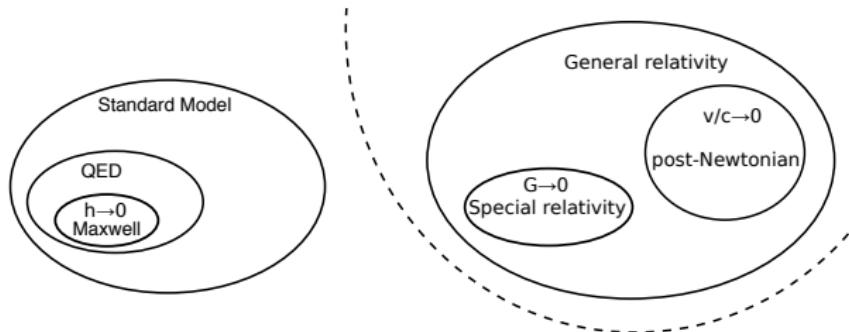
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The solution



- 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 $\Lambda \rightarrow \infty$.
- Assume **weak coupling**, use **perturbation theory**

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Example: Dynamical Chern-Simons gravity

What is dynamical Chern-Simons gravity?

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

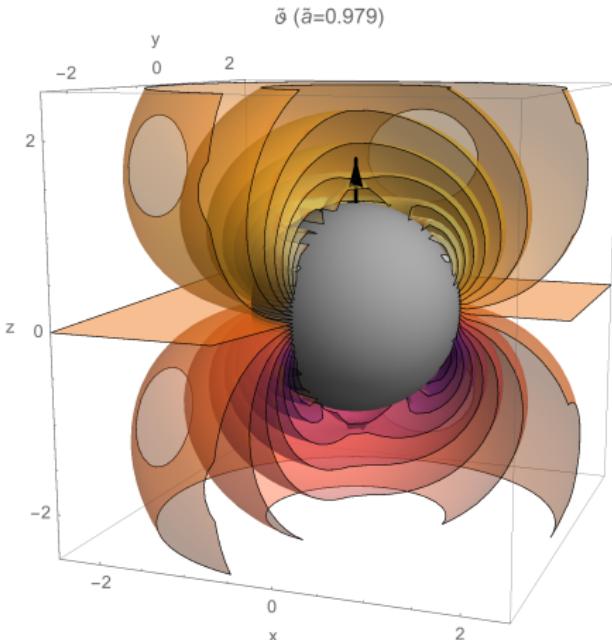
$$S = \int d^4x \sqrt{-g} \left[R - \frac{1}{2}(\partial\vartheta)^2 + \varepsilon \vartheta {}^*RR \right]$$

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

- 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]

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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

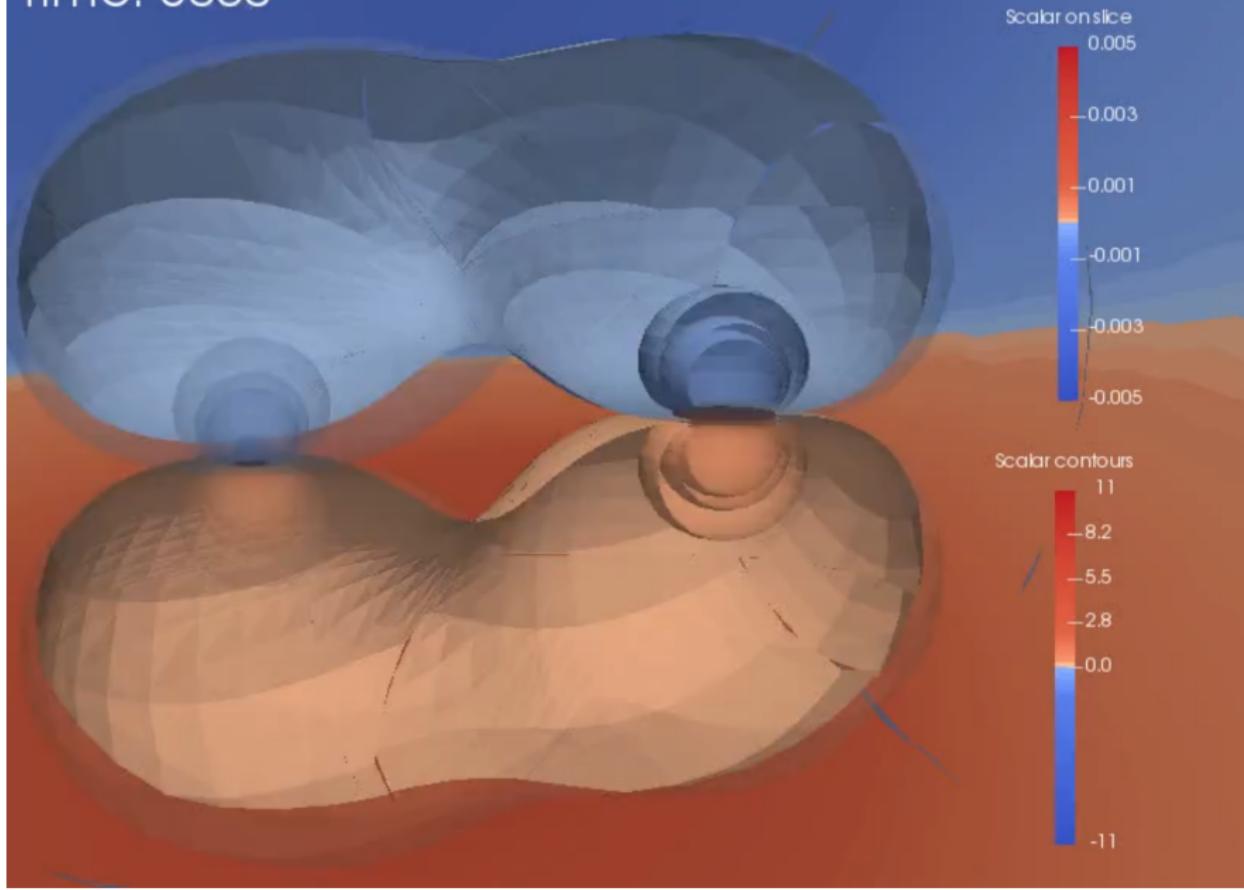
- DCS had principal part $\partial^3 g$ coming from C_{ab} tensor. *Probably* not well-posed, Delsate+ PRD **91**, 024027.
- Theory is GR + $\varepsilon \times$ deformation. Expand everything in ε
- Derivation
- At every order in ε , principal part is Princ[G_{ab}]

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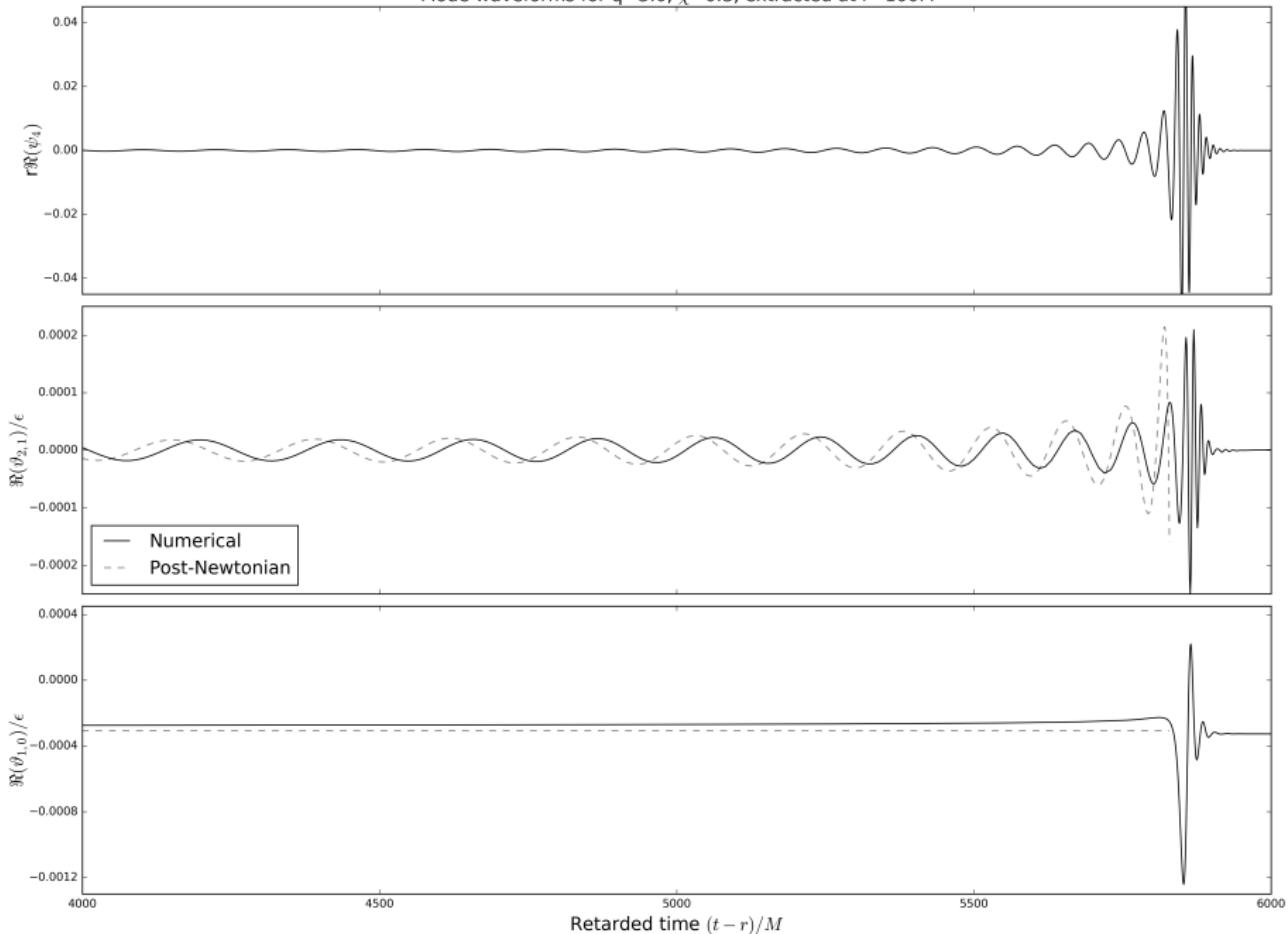
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Background dynamics are well-posed \implies perturbations well-posed

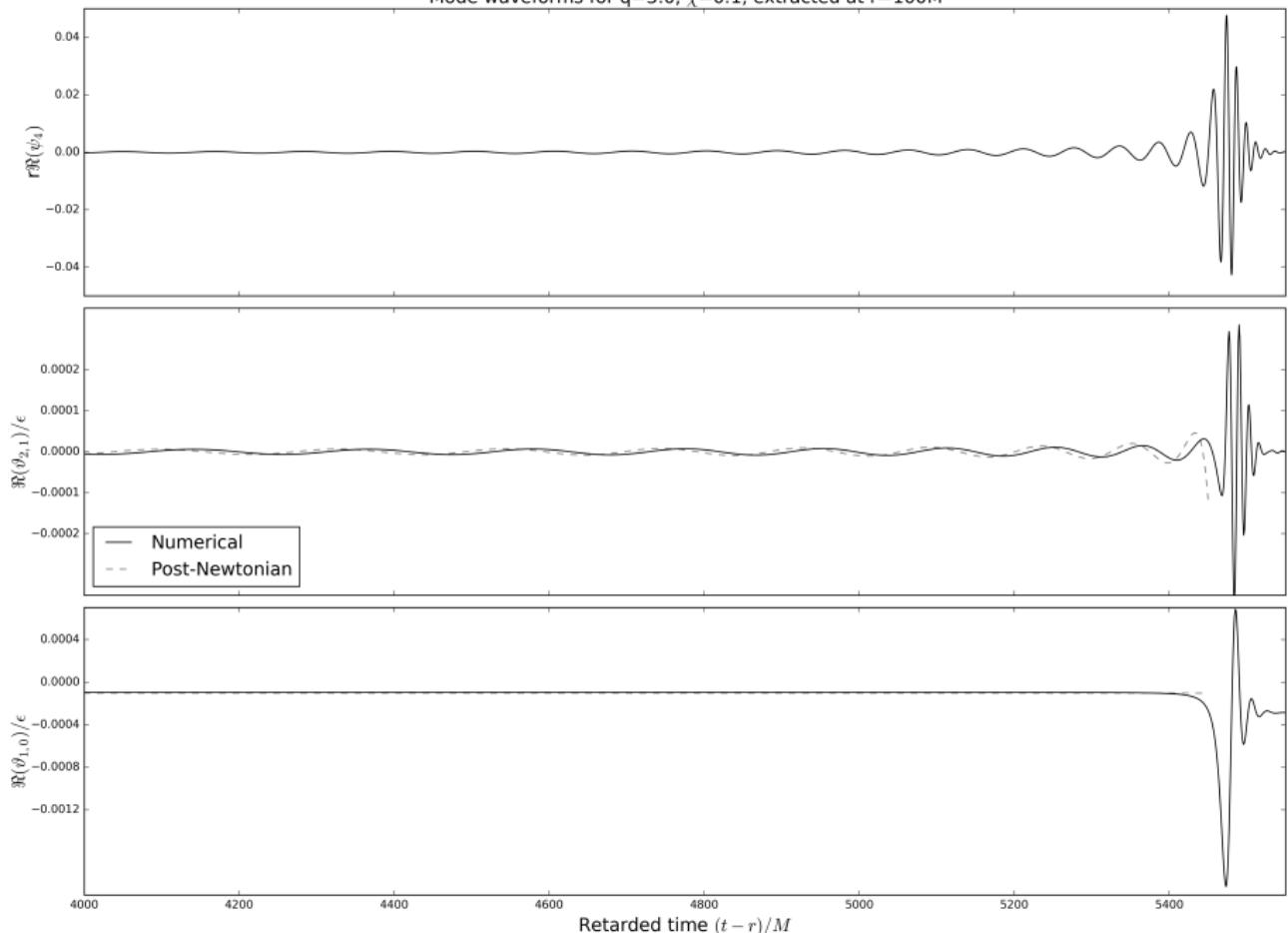
Time: 3000



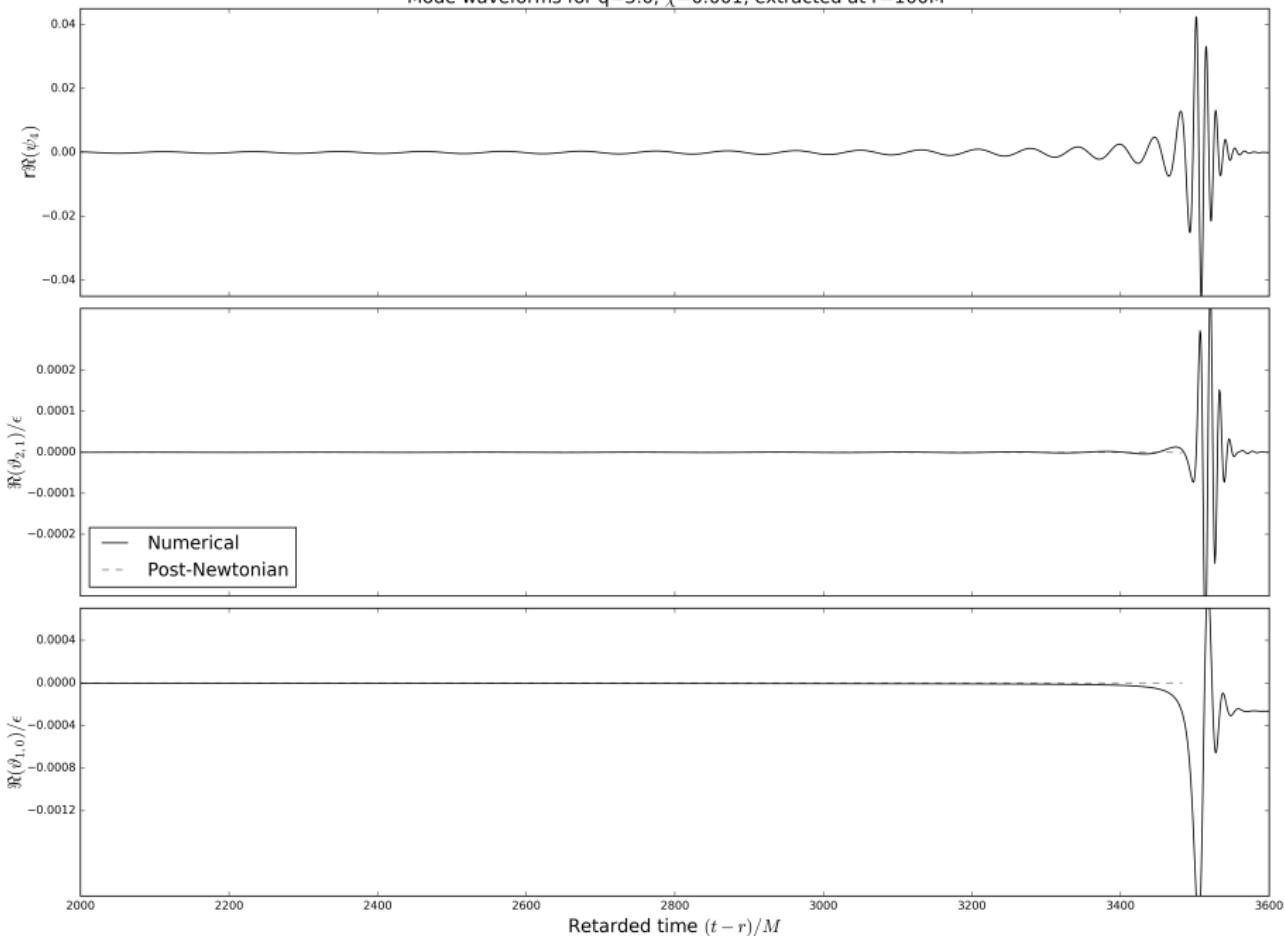
Mode waveforms for $q=3.0$, $\chi=0.3$, extracted at $r=100M$



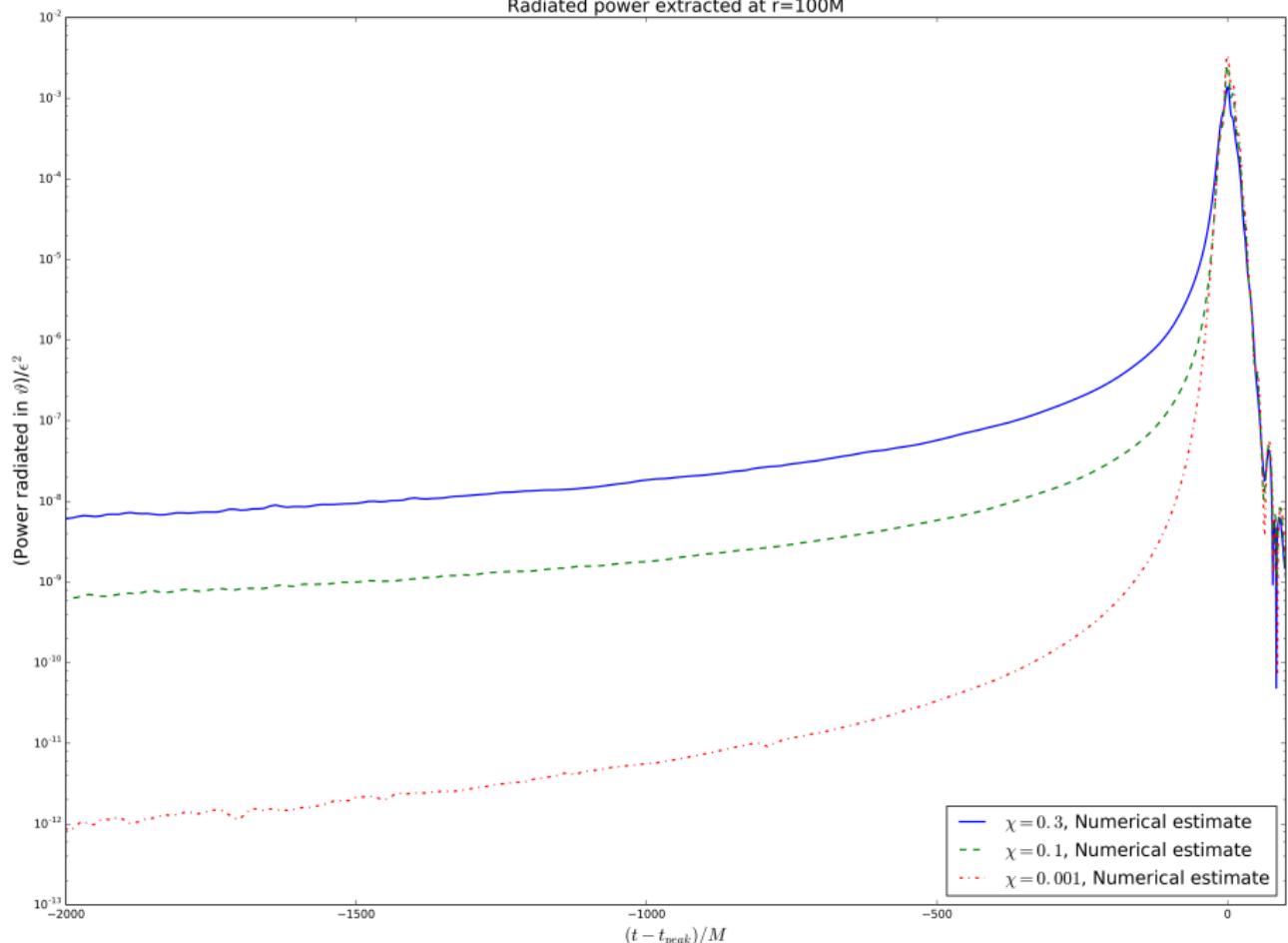
Mode waveforms for $q=3.0$, $\chi=0.1$, extracted at $r=100M$



Mode waveforms for $q=3.0$, $\chi=0.001$, extracted at $r=100M$



Radiated power extracted at $r=100M$



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

- 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!