

Extremal black holes in dynamical Chern-Simons gravity

Leo C. Stein (TAPIR, Caltech)
with Robert McNees (Loyola University Chicago)
and Nicolás Yunes (Montana State University)

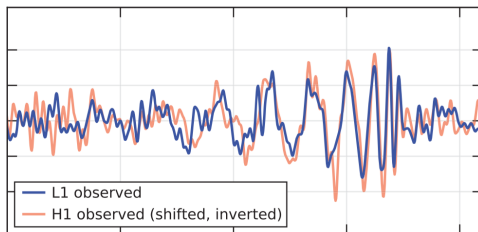


April APS Meeting 2016

[[arXiv:1512.05453](https://arxiv.org/abs/1512.05453)]

Squad goals

- 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** (BBH)
 - Parametric vs. non-parametric. Know what we're looking for?
- Only have binary black hole mergers in GR! Some ideas.

Modest goals

- Short term: Shapes of black holes in beyond-GR theories
- Necessary step before dynamics of black holes
- Our work: BHs in dynamical Chern-Simons gravity

What is dynamical Chern-Simons gravity?

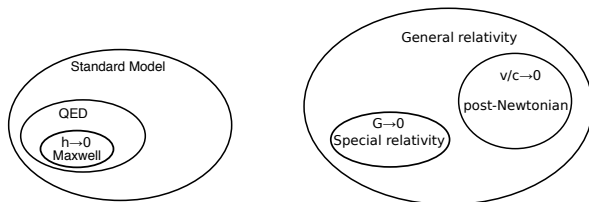
Chern-Simons = GR + pseudo-scalar + interaction

$$S = \int d^4x \sqrt{-g} \left[\frac{m_{\text{pl}}^2}{2} R - \frac{1}{2} (\partial\vartheta)^2 + \frac{m_{\text{pl}}}{8} \ell^2 \vartheta {}^*RR \right]$$

Anomaly cancellation, low-E string theory, LQG... (see Nico's review)

Why study dynamical Chern-Simons gravity?

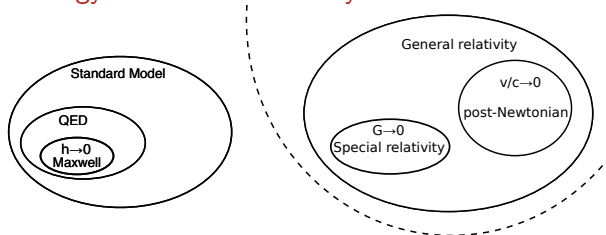
- *Don't* think dCS is fundamental theory (see Delsate+Hilditch+Witek)
- GR is a low-energy effective field theory



- Lowest-order EFT with parity-odd ϑ , shift symmetry (long range)
- Phenomenology unique from other R^2 (e.g. Einstein-dilaton-Gauss-Bonnet)
- Only decoupling limit makes sense

Why study dynamical Chern-Simons gravity?

- *Don't* think dCS is fundamental theory (see Delsate+Hilditch+Witek)
- GR is a low-energy effective field theory



- Lowest-order EFT with parity-odd ϑ , shift symmetry (long range)
- Phenomenology unique from other R^2 (e.g. Einstein-dilaton-Gauss-Bonnet)
- Only decoupling limit makes sense

Decoupling limit

Theory is GR + $\varepsilon \times$ deformation. Expand everything in ε

- ε^0 : Vacuum GR
- ε^1 : Unfreeze new degrees of freedom

$$\square_{\text{GR}} \vartheta^{(1)} = \text{Src}[g_{\text{GR}}]$$

- ε^2 : Deformation to metric

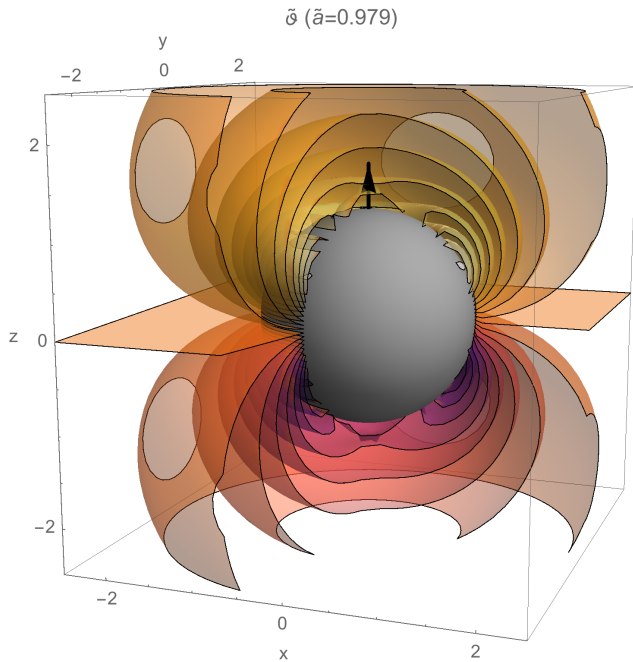
$$G_{ab}^{(1)}[h^{(2)}] = \text{Src}_{ab}[\vartheta^{(1)}, g_{\text{GR}}]$$

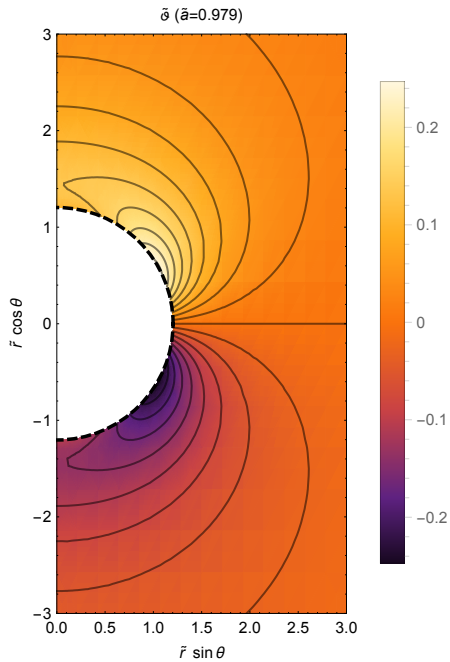
Modest goals

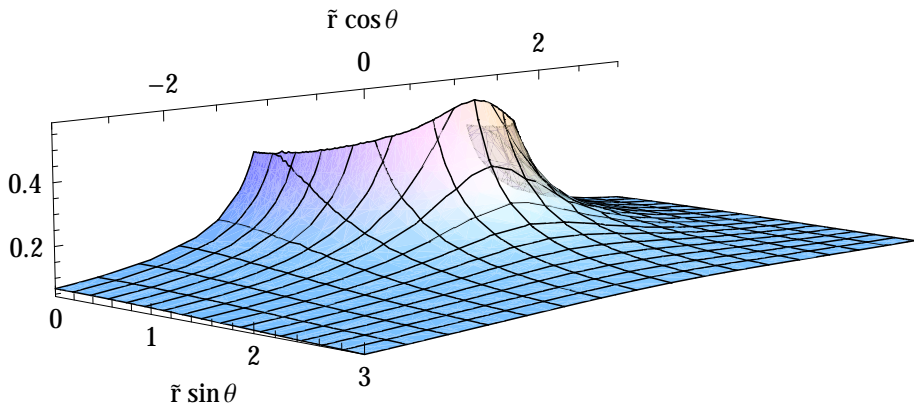
- Short term: Shapes of black holes in beyond-GR theories
- Necessary step before dynamics of black holes
- Our work: BHs in dynamical Chern-Simons gravity

Black holes in dCS

- $a = 0$ (Schwarzschild) is exact solution with $\vartheta = 0$
- Analytically known solutions in decoupling limit
 - $a \ll M$ limit up to $\mathcal{O}(a^2)$, valid $\forall r$ (see Yunes+Pretorius, Yagi+Yunes+Tanaka)
 - $r \gg M$ limit for $l = 1$, valid $\forall a$ (see Yagi+Yunes+Tanaka)
- Numerical solutions for scalar sector $\forall r, a < M$
Phys. Rev. D 90, 044061 (2014) [arXiv:1407.2350]
- Conjectured divergence at $a \rightarrow M$
- Analytics for $a = M$?



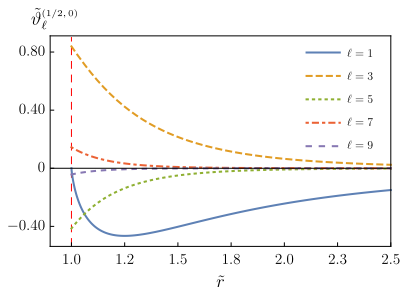




What we did in [arXiv:1512.05453]

- Equations simplify for $a = M$
- **Analytic** scalar field solution for ϑ_ℓ

$$\vartheta_\ell(r) = (\text{polyn.}, \text{roots}, \text{logs}, \text{inv. trig})(r, \ell)$$



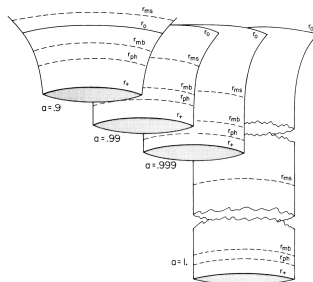
- Exponential convergence

What we did in [arXiv:1512.05453]

- Metric tensor deformation is hard
- Tensor deformation = **trace** + grad vect + transverse tracefree
- Formal solution for trace of metric deformation (gauge dependent)
- **Monopole $\ell = 0$ diverges on Kerr horizon!**

Fresh results

- Near-horizon extremal Kerr (NHEK) (Sam's and Niels' talks)
- Zoom in on horizon region



- Acquire enhanced symmetry group $SL(2, \mathbb{R}) \times U(1)$

Fresh results

- NHEK allows to find horizon solution analytically

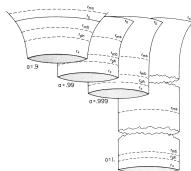
$$\begin{aligned}\vartheta &= -\frac{2c(-7 + 2c^2 + c^4)}{(1 + c^2)^3} - 4 \arctan c \\ \text{tr} h^{\text{Def}} &= \frac{4(301 + 482c^2 + 7526c^4 + 7120c^6 + 3221c^8 + 566c^{10})}{105(1 + c^2)^6} \\ &\quad - 24i \arctan(c) \arctan\left(\frac{-i + c}{i + c}\right) - \frac{3944}{105} \operatorname{arctanh}(c^2) \\ &\quad + 6i \operatorname{Li}_2\left(-\frac{1 + ic}{i + c}\right) - 6i \operatorname{Li}_2\left(\frac{1 + ic}{i + c}\right)\end{aligned}$$

where $c = \cos \theta$

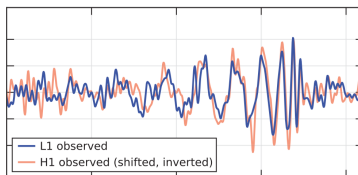
What does it mean?

- Confirmed conjectured divergence at Kerr horizon for $a \rightarrow M$
- New conjecture: divergence hidden behind **deformed horizon**
- Need full metric to locate
- Or: extremality condition may be shifted away from $a = M$
- Constraints from observations of rapidly spinning BHs

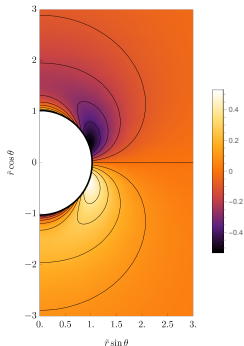
What's next?



- Understand NHEK solution
- Find full metric tensor solutions analytically (extremal)
- Numerical metric tensor solutions (all a)
- Correction to BH thermo from dCS
- Observables: Accretion disk, black hole shadow
- Binary black hole merger in decoupling limit (with Maria Okounkova)



- Goal: Want to test GR in dynamical strong-field, BBH.
Need to understand merger in deformations of theory.
- First: Must understand deformation to Kerr when theory deformed
- Previous work: Computed dCS scalar deformation to Kerr numerically
- This work: Computed scalar deformation to extremal Kerr *analytically*



Details in [\[arXiv:1512.05453\]](https://arxiv.org/abs/1512.05453)

Bonus slides!

Equations to solve

$$S = \int d^4x \sqrt{-g} \left[\frac{m_{\text{pl}}^2}{2} R - \frac{1}{2} (\partial\vartheta)^2 + \frac{m_{\text{pl}}}{8} \ell^2 \vartheta {}^*RR \right]$$

$$\square\vartheta = -\frac{m_{\text{pl}}}{8} \ell^2 {}^*RR$$

$$m_{\text{pl}}^2 G_{ab} + m_{\text{pl}} \ell^2 C_{ab} = T_{ab}^{(m)} + T_{ab}^{(\vartheta)}$$

- $g^{ab}C_{ab} = 0$

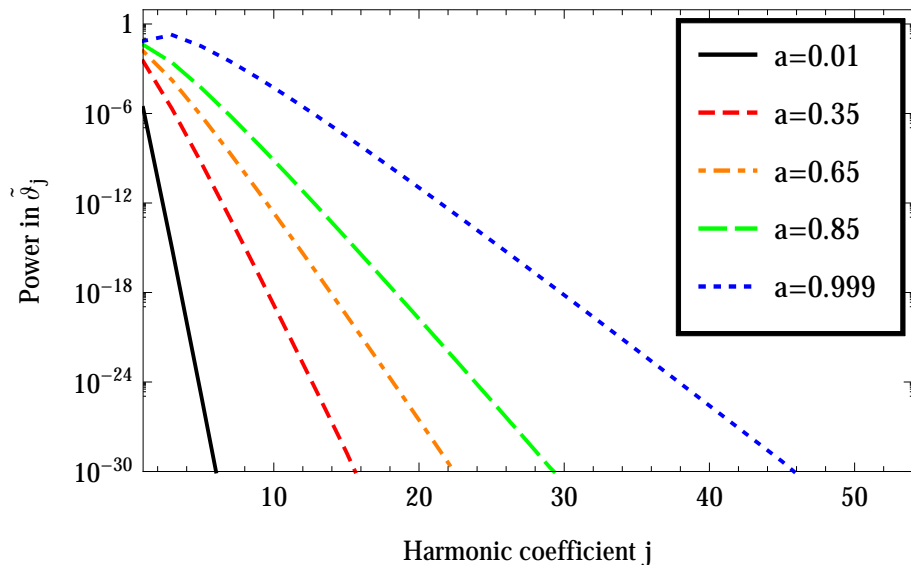
Numerical approach

- Elliptic PDE. Could solve hyperbolic, parabolic, relaxation scheme
- Numerical separation of variables. Each j mode is an ODE.
- Compactify r
- Pseudospectral collocation method
- Directly solve discrete ODE operator (“numerical Green’s function”)

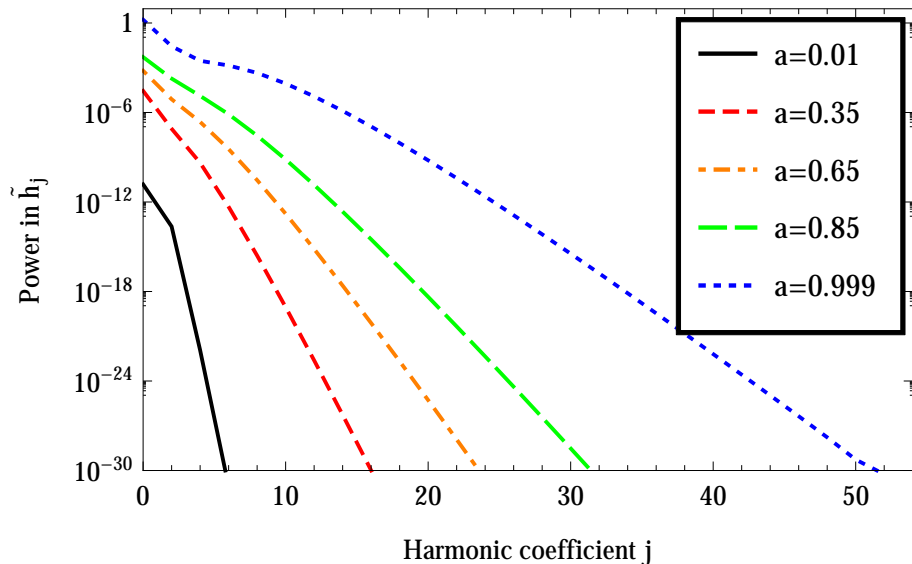
Numerical approach

- For each a , find $\vartheta(r, \theta; a)$, compute $(\partial\vartheta)^2$, find $h^{\text{def}}(r, \theta; a)$
- Evaluate $\max |h^{\text{def}}|$ and find regime of validity

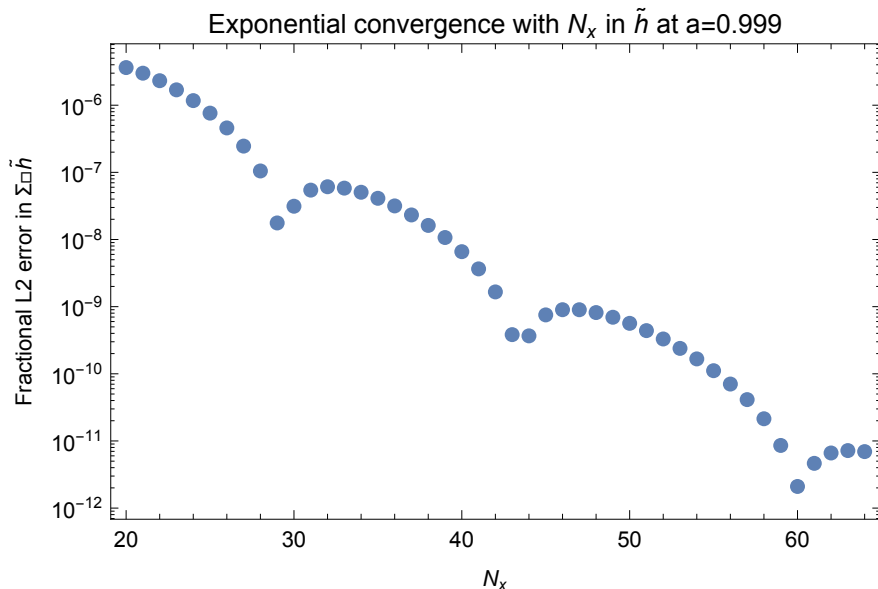
Exponential convergence



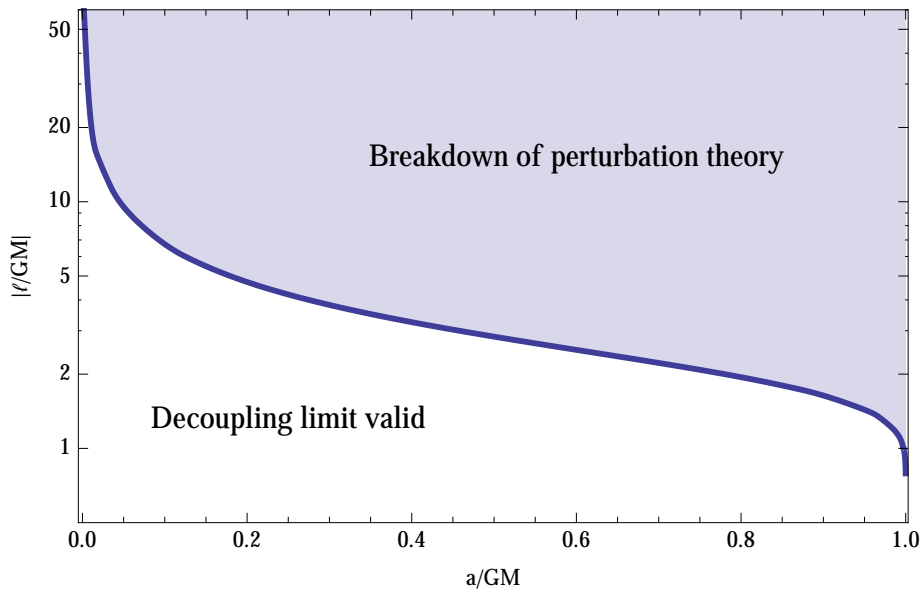
Exponential convergence



Exponential convergence

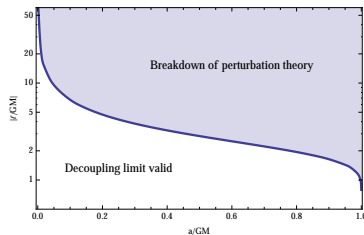


Regime of validity



Forecasting bounds

- Observation of BH indistinguishable from GR predictions
- Size of ℓ correction below breakdown (caveat: cancellation)
- GRO J1655–40: $M = 6.30 \pm 0.27 M_{\odot}$, $\tilde{a} \approx 0.65\text{--}0.75$



$$\Rightarrow \ell \lesssim 22\text{km}$$

- Better by 10^7 than Solar System bounds