Extremal black holes in dynamical Chern-Simons gravity

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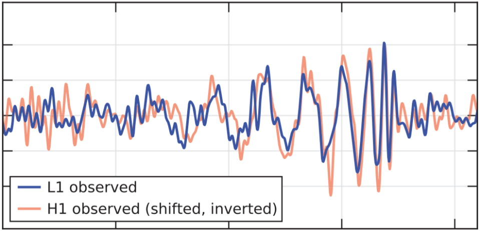
[arXiv:1512.05453]

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?

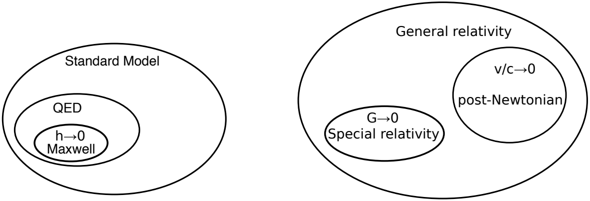
Chern-Simons = GR + pseudo-scalar + interaction

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

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

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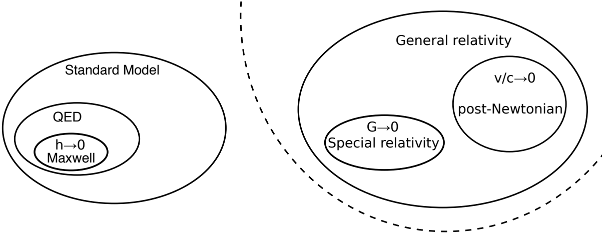

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Decoupling limit

Theory is GR + ε × deformation. Expand everything in ε

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

$$\Box_{\mathrm{GR}}\vartheta^{(1)} = \mathsf{Src}[g_{\mathrm{GR}}]$$

- ε^2: Deformation to metric

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

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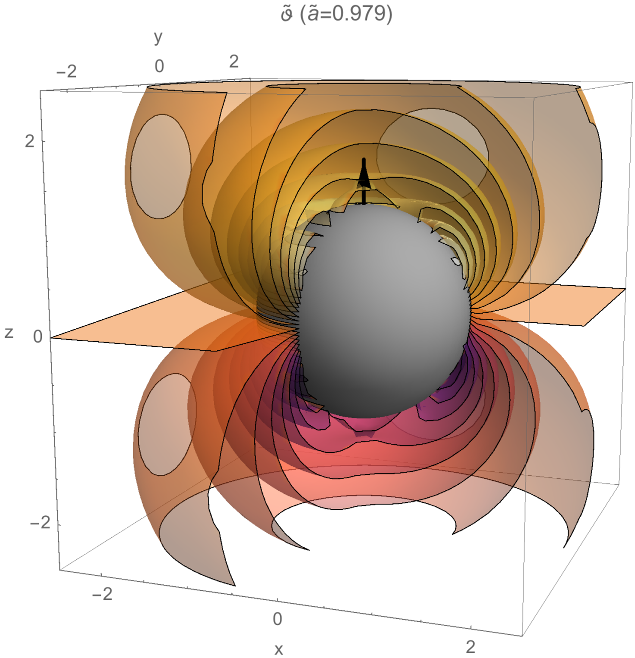
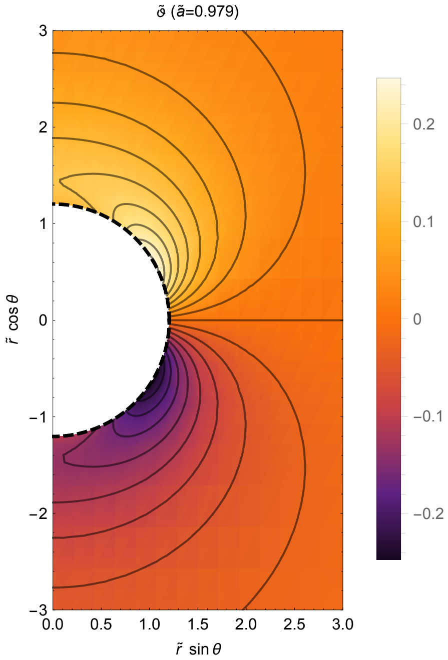
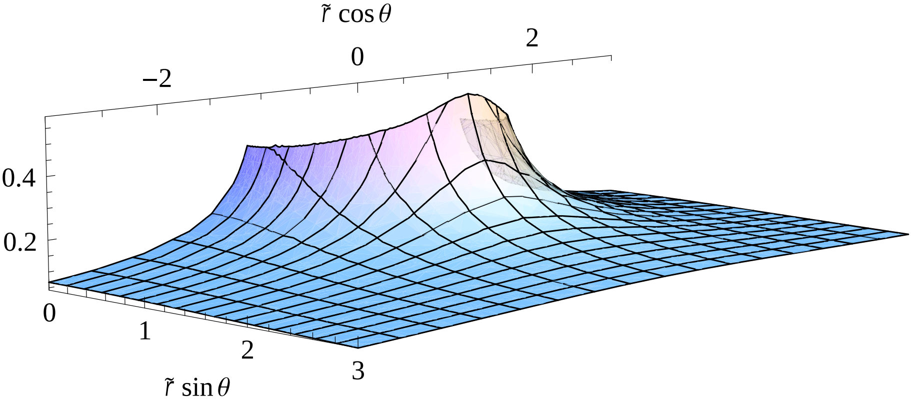
Black holes in dCS

- $a = 0$ (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 $a \to M$
- Analytics for $a = M$?



$\tilde{\vartheta}$ ($\tilde{a}$=0.979)
y
−2
0
2
z
2
0
−2
x
−2
0
2

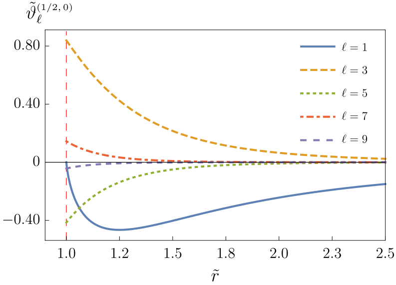

$\tilde{\vartheta}$ ($\tilde{a}$=0.979)
$\tilde{r}\cos\theta$
$\tilde{r}\sin\theta$
3
2
1
0
−1
−2
−3
0.0
0.5
1.0
1.5
2.0
2.5
3.0
0.2
0.1
0
−0.1
−0.2


r̃ cos θ
−2
0
2
0.4
0.2
0
1
2
3
r̃ sin θ

What we did in [arXiv:1512.05453]

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

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



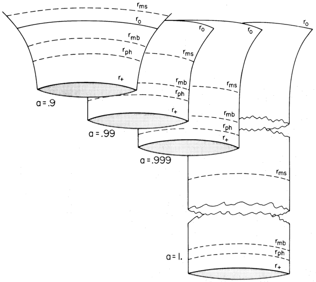
- Exponential convergence

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

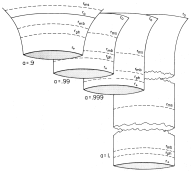
$$
\begin{aligned}
\vartheta &= -\frac{2c(-7+2c^2+c^4)}{(1+c^2)^3} - 4\arctan c \\
\mathsf{tr}h^{\mathrm{Def}} &= \frac{4(301+482c^2+7526c^4+7120c^6+3221c^8+566c^{10})}{105(1+c^2)^6} \\
&\quad - 24i\arctan(c)\arctan\left(\frac{-i+c}{i+c}\right) - \frac{3944}{105}\operatorname{arctanh}(c^2) \\
&\quad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

where $c = \cos\theta$

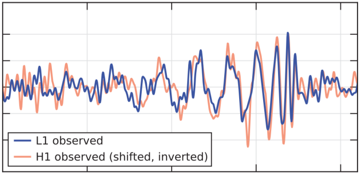
What does it mean?

- Confirmed conjectured divergence at Kerr horizon for $a \to M$
- 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

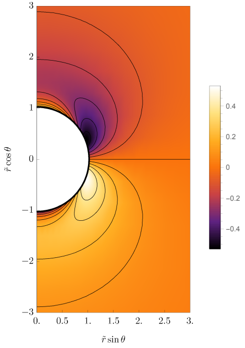
What's next?



- 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]

Bonus slides!

Equations to solve

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

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

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

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

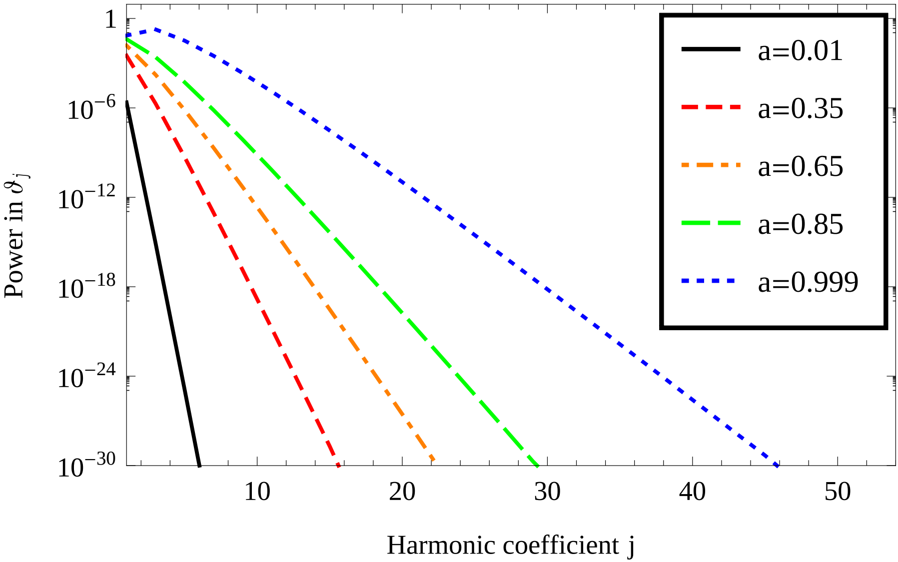
Numerical approach

- 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")

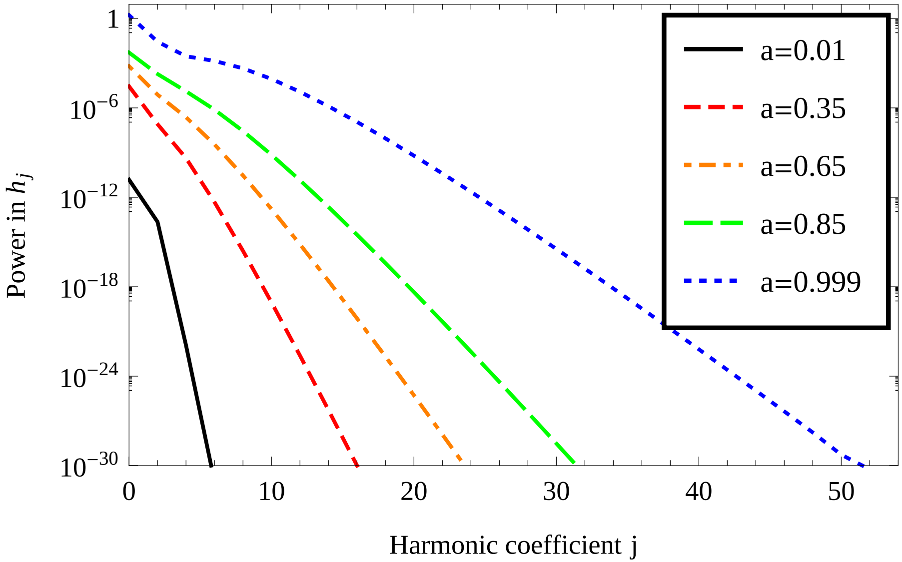
Numerical approach

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

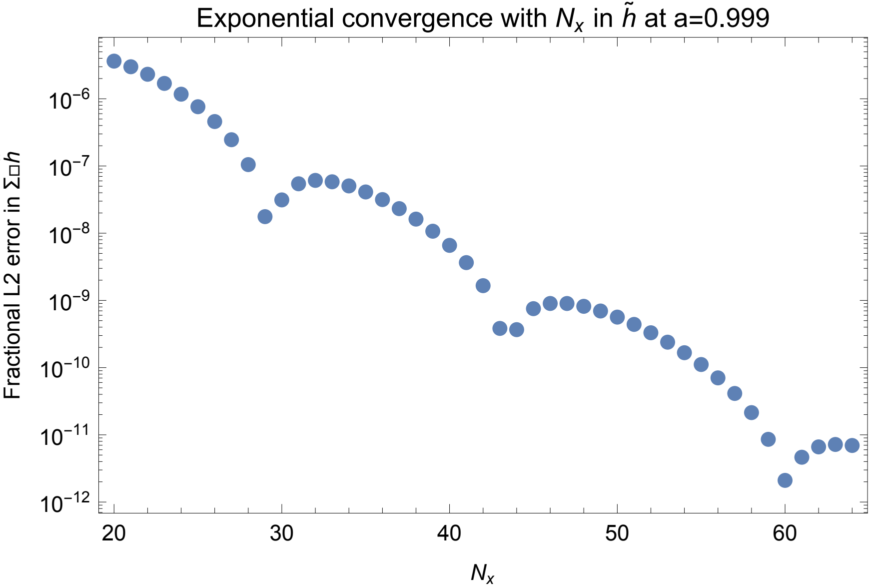
Exponential convergence



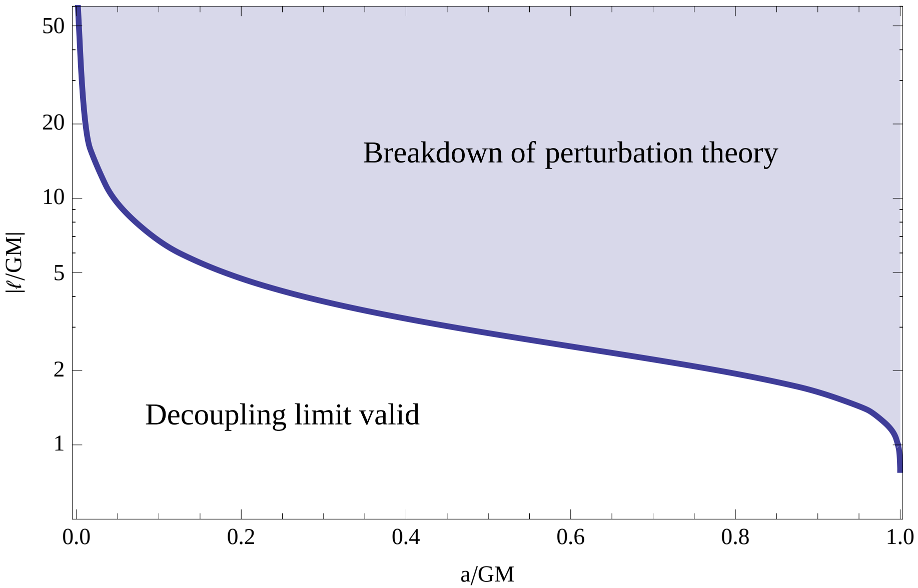
Exponential convergence



Exponential convergence

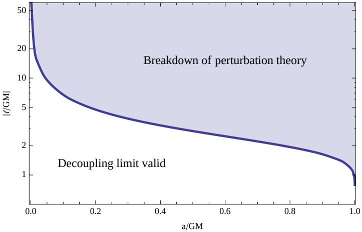


Regime of validity



Forecasting bounds

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



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

- Better by 10^7 than Solar System bounds