Title: Aspects of Rotating Black Holes in Dynamical Chern-Simons Gravity

Speakers: Leah Jenks

Series: Cosmology & Gravitation

Date: December 16, 2021 - 1:00 PM

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Abstract: In this talk I will give an overview of recent and ongoing work regarding rotating black holes in dynamical Chern-Simons (dCS) gravity. dCS gravity is a well motivated modified theory of gravity which has been extensively studied in gravitational and cosmological contexts. I will first discuss unique geometric structures, `the Chern-Simons caps,' which slowly rotating black holes in dCS gravity were recently found to possess. Motivated by the dCS caps, I will then discuss superradiance in the context of slowly rotating dCS black holes and show that there are corrections to the usual solution for a Kerr black hole. Lastly, I will comment on the observable implications for these corrections and point towards avenues for future work.

Zoom Link: https://pitp.zoom.us/j/95228483630?pwd=dWk1c3p5dUU3RXJrNEhIT2M3Tk1Kdz09

Aspects of Rotating Black Holes in Dynamical Chern-Simons Gravity

Leah Jenks
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arXiv:2104.00019 (PRD), arXiv:2201.XXXX
S. Alexander, G. Gabadadze, LJ, N. Yunes

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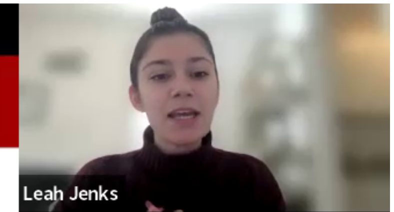
Perimeter Institute Strong Gravity & Cosmology Seminar
December 16, 2021



Overview and Main Takeaways

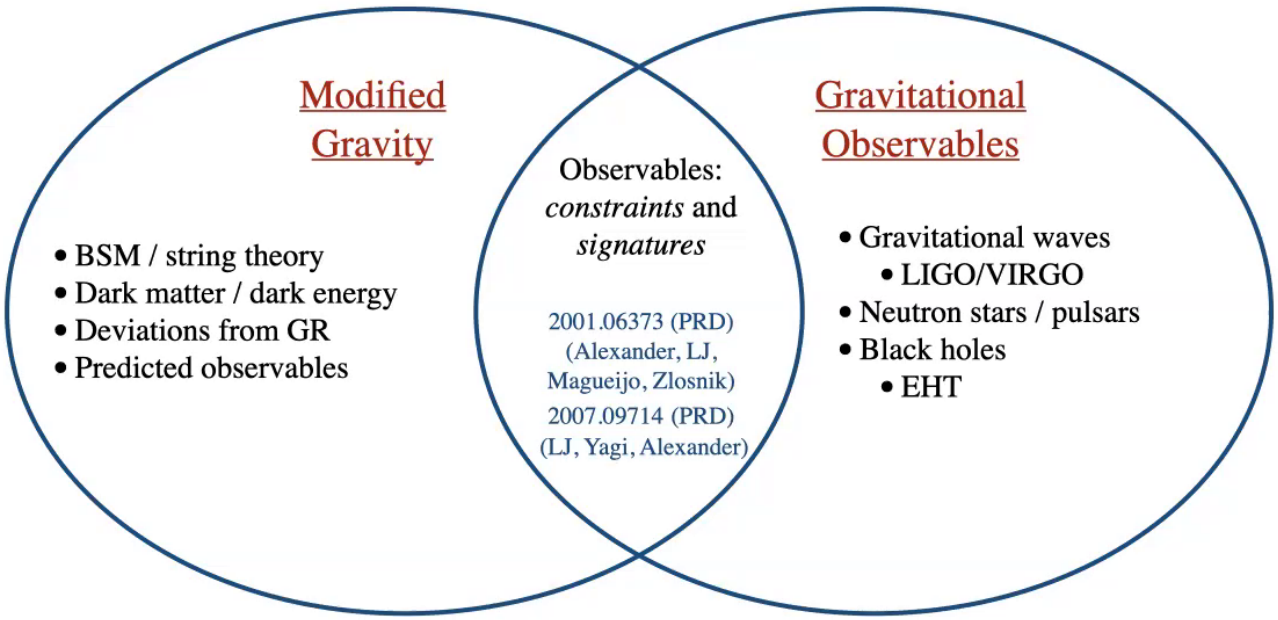
Main Takeaways:

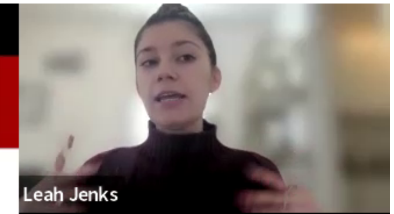
1. Dynamical Chern-Simons gravity (dCS) is a well-motivated theory with promising cosmological and gravitational implications

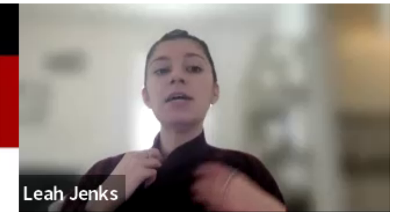
2. dCS black holes possess unique geometric structures — the 'dCS caps' which may provide novel insights into deviations from GR

3. Superradiance induced by dCS black holes deviates from GR and has potential observable consequences

Big Picture

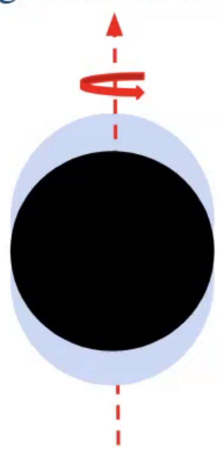

Modified Gravity
• BSM / string theory
• Dark matter / dark energy
• Deviations from GR
• Predicted observables
Observables: *constraints* and *signatures*
2001.06373 (PRD) (Alexander, LJ, Magueijo, Zlosnik)
2007.09714 (PRD) (LJ, Yagi, Alexander)
Gravitational Observables
• Gravitational waves
• LIGO/VIRGO
• Neutron stars / pulsars
• Black holes
• EHT


Leah Jenks



Essential Physics

dCS caps: Chern-Simons pseudo scalar interaction induces non-standard behavior - analogy to angular momentum



Superradiance: unstable modes in a radiative system - analogy to driven resonance in harmonic oscillator

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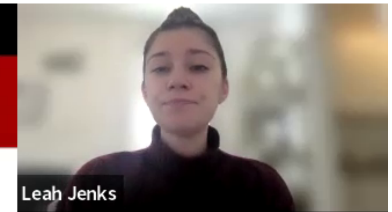
dCS Gravity: Motivations

- Chern-Simons term arises in string theory and effective field theory
  - Green-Schwarz mechanism (Green & Schwarz, 1984)
  - EFT of inflation (Weinberg, 2008)
- dCS gravity intrinsically includes an axion-like particle
- Cosmological, gravitational, and particle physics implications

dCS Gravity: Action



Jackiw & Pi 2003,
Alexander & Yunes 2007+

$$S_{\rm vac} = \int d^4x\sqrt{-g}\left[\kappa R + \frac{\alpha}{4}\vartheta\ {}^*R\,R - \frac{1}{2}\left(\nabla_a\vartheta\right)\left(\nabla^a\vartheta\right)\right]$$

Modified Einstein Eq.

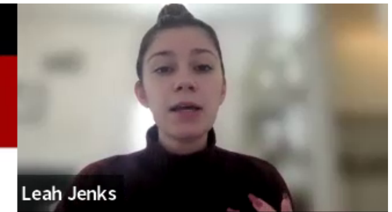
$$G_{ab} + \frac{\alpha}{\kappa}C_{ab} = \frac{1}{2\kappa}T_{ab}$$

$$C^{ab} = \left(\nabla_c\vartheta\right)\ \epsilon^{cde(a}\nabla_e R^{b)}{}_d + \left(\nabla_c\nabla_d\vartheta\right)\ {}^*R^{d(ab)c}$$

Pseudo-scalar EoM

$$\Box\vartheta = -\frac{\alpha}{4\kappa}\ {}^*R\,R$$

dCS Gravity: Effective Field Theory



We can write the dCS action as:

$$S = \int d^4x \sqrt{-g} \left[\kappa R + \frac{\sigma}{4\mu} \, {}^*R \, R - \frac{1}{2} \left(\nabla_a \sigma \right) \left(\nabla^a \sigma \right) \right]$$

In principle, we have an infinite sum of higher dimensional terms

- Truncate the series at the first term
- We never reach the scale at which dCS breaks down
- $\mu \ll M_{pl}$, highly unconstrained from observations

dCS Gravity: Slowly Rotating Solution

Yunes & Pretorius 2009, Yagi, Yunes & Tanaka 2012, Maselli, et al. 2017

$$ds^2 = ds_{\mathrm{K}}^2 + \frac{5}{4}\zeta M \chi \frac{M^4}{r^4}\left(1 + \frac{12}{7}\frac{M}{r} + \frac{27}{10}\frac{M^2}{r^2}\right)\sin^2\theta dt d\phi$$

$$\vartheta = \frac{5}{8}\alpha\chi\frac{\cos\theta}{r^2}\left(1 + 2\frac{M}{r} + \frac{18}{5}\frac{M^2}{r^2}\right)$$

Deviations from Kerr

$$r_{\pm} = r_{\pm,\mathrm{K}} \mp \frac{915}{28672} M\zeta\chi^2$$

$$r_{\mathrm{ergo}} = r_{\mathrm{ergo,K}} - \frac{915}{28672} M\zeta\chi^2\left(1 + \frac{2836}{915}\sin^2\theta\right)$$

dCS Gravity: Effective Field Theory

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$$S = \int d^4x\sqrt{-g}\left[\kappa R + \frac{\sigma}{4\mu}\ {}^{*}R\,R - \frac{1}{2}\left(\nabla_a\sigma\right)\left(\nabla^a\sigma\right)\right]$$

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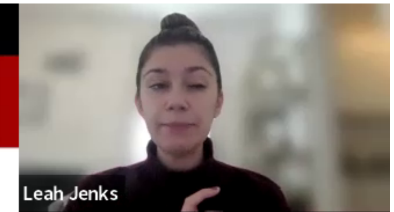
dCS Gravity: Slowly Rotating Solution



Yunes & Pretorius 2009,
Yagi, Yunes & Tanaka 2012,
Maselli, et al. 2017

$$ds^2 = ds^2_{\mathrm{K}} + \frac{5}{4}\zeta M \chi \frac{M^4}{r^4}\left(1 + \frac{12}{7}\frac{M}{r} + \frac{27}{10}\frac{M^2}{r^2}\right)\sin^2\theta dt d\phi$$

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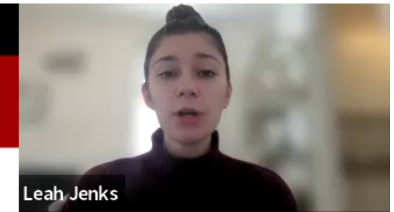
The Chern-Simons Caps: Motivations

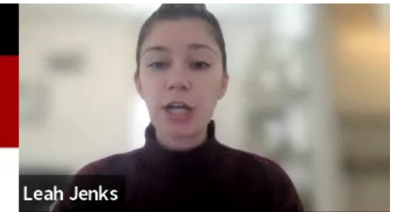


Recall: $$R_{ab} = 8\pi\bar{T}_{ab} - 16\pi\alpha C_{ab}$$

Geodesic focusing: $$R_{ab}u^a u^b > 0$$

dCS gravity naturally has the structure to violate the focusing theorem!

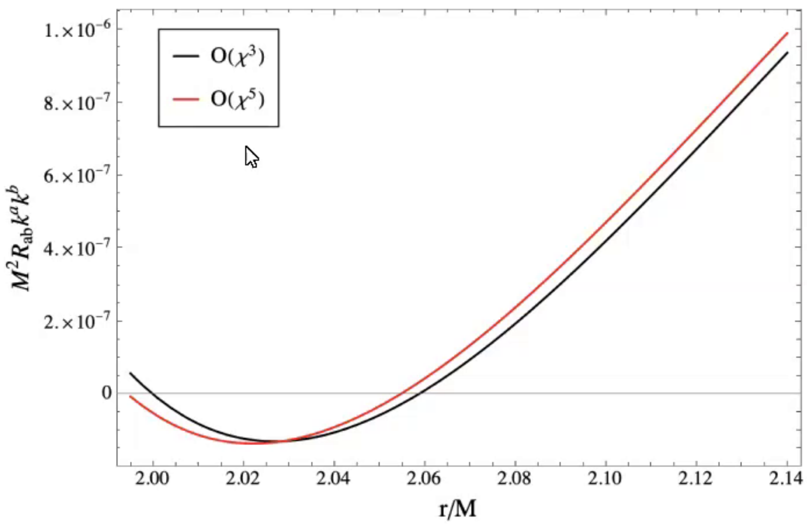
The Chern-Simons Caps: Geodesic Focusing

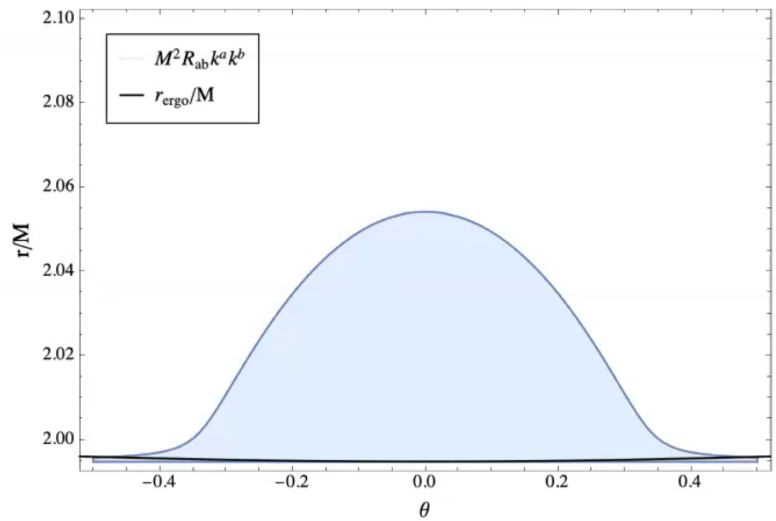


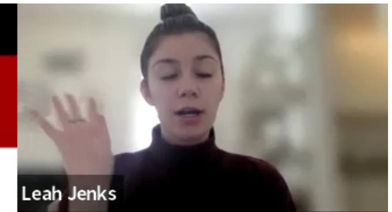
Consider a stationary timelike observer in the slowly rotating dCS spacetime:

$$R_{ab}\, k^a_{\rm st} k^b_{\rm st} = \frac{45}{4}\,\zeta\chi^2\, f\,\frac{\gamma^8}{M^2}\left[1 + 2c_\theta^2 + \frac{40\gamma}{15}\left(1 + \frac{3}{4}c_\theta^2\right)\right.$$
$$\left. + 6\gamma^2\left(1 + \frac{1}{3}c_\theta^2\right) - \frac{312}{5}\gamma^3 c_\theta^2\right] + \mathcal{O}(\zeta\chi^4)$$

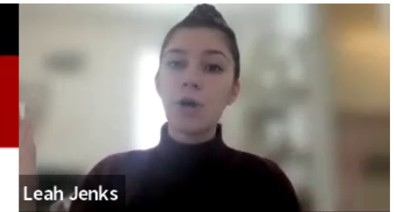
The Chern-Simons Caps: Geometry



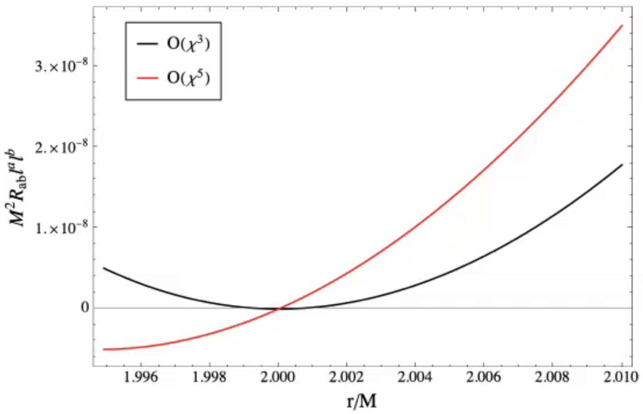


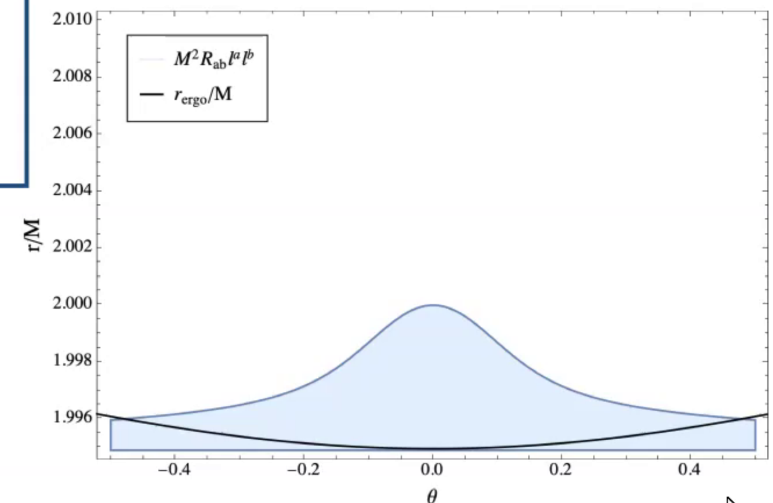


The Chern-Simons Caps: Radial Null Geodesics



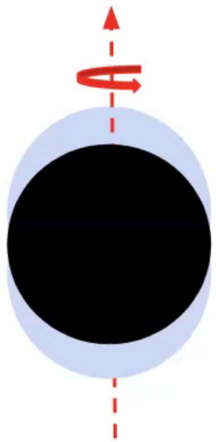
$$R_{ab}\, l^a l^b = \frac{25}{32}\,\zeta\chi^2\, f\,\frac{\gamma^6}{M^2}\left[c_\theta^2 + 4\gamma c_\theta^2 + \frac{72}{5}\gamma^2\left(1+\frac{43}{24}c_\theta^2\right) + \frac{192}{5}\gamma^3\left(1+\frac{13}{32}c_\theta^2\right) + \frac{432}{5}\gamma^4\left(1-\frac{1}{15}c_\theta^2\right) - \frac{19872}{25}\gamma^5 c_\theta^2\right] + \mathcal{O}(\zeta\chi^4)\,,$$

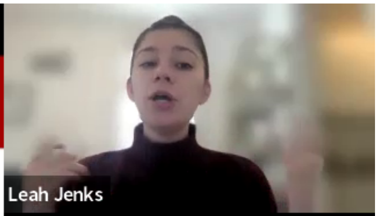




The Chern-Simons Caps: Implications

- Condition for Hawking-Penrose singularity theorem is violated
- Energy condition of the effective energy-momentum tensor
- Behavior of matter close to dCS black holes





Superradiance in dCS Gravity: Motivations

- Scalar field amplified by rotation of black hole (Black hole bomb - Press & Teukolsky, 1972)
- "String Axiverse" - Arvanitaki et al., 2009 +
- Extended to vectors (eg East & Pretorius, 2017, East 2017 +, Baryakhtar et al., 2017) and tensors (eg Brito, 2020)

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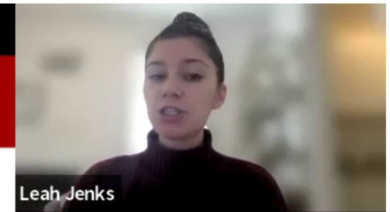
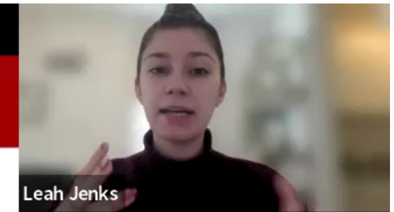


Superradiance in GR



Massive scalar field on a Kerr black hole background:

$$(\Box_{\rm K} - \mu^2)\varphi_{\rm K}(t, r, \theta, \phi) = 0$$

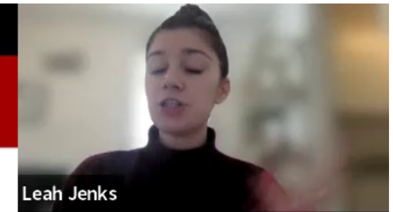
Detweiler limit: $\omega M \ll 1, \mu M \ll 1$ (Detweiler, 1980):

$$\varphi_{\ell,m} = e^{-i\omega_{\rm K} t} e^{im\phi} S_\ell(\theta) R_\ell(r)$$

Frequency spectrum: ℓ=1, m=1:

$$\mathrm{Im}(\omega_{\rm K}) = \mu \left(\frac{\rm a}{\rm M}\right) \frac{(\mu \rm M)^8}{24}$$

Superradiance in dCS Gravity: Setup

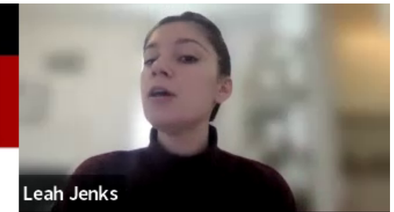


Theory: dCS gravity + scalar field

$$S = S_{\mathrm{EH}} + S_{\mathrm{dCS}} + S_{\vartheta} + S_{\varphi}$$

$$S_{\varphi} = \int d^4x \sqrt{-g} \left[-\frac{1}{2} g^{ab} \nabla_a \varphi \nabla_b \varphi - \frac{1}{2} \mu^2 \varphi^2 \right]$$

Superradiance in dCS Gravity



Klein-Gordon Equation up to $\mathcal{O}(\zeta\chi^2)$

$$(\Box_{\mathrm{K}} + \Box_{\mathrm{dCS}} - \mu^2)\varphi = 0$$

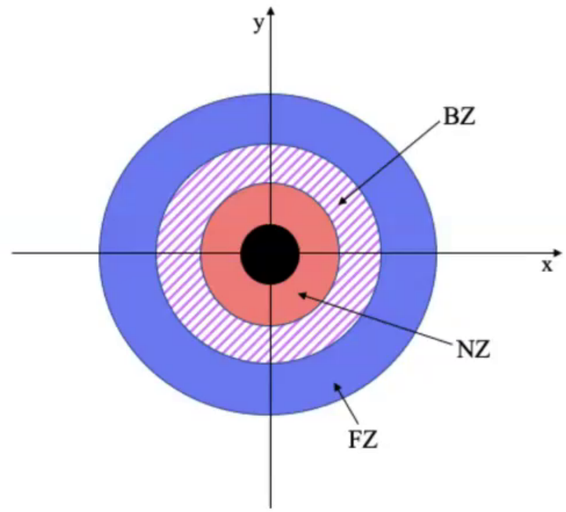
Ansatz with $\omega M \ll 1, \mu M \ll 1$

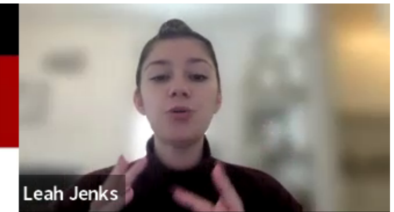
$$\varphi_{\ell,m} \propto e^{-i\omega_\ell t} e^{im\phi} P_\ell^m(\cos\theta) f^0_{\ell,m}(r) + e^{im\phi}\zeta\chi^2 \Big(e^{-i\omega_\ell t} P_\ell^m(\cos\theta)\tilde{f}^{\mathrm{dCS}}_{\ell,m}(r)$$

$$+ e^{-i\omega_{\ell+2} t} P_{\ell+2}^m(\cos\theta)\tilde{f}^{\mathrm{dCS}}_{\ell+2,m}(r) + e^{-i\omega_{\ell-2} t} P_{\ell-2}^m(\cos\theta)\tilde{f}^{\mathrm{dCS}}_{\ell-2,m}(r) \Big)$$

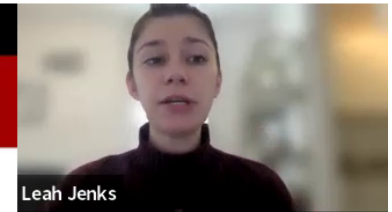
Asymptotic Matching

- Far zone: r >> M
- Near zone: r-r_H << max(ℓ/ω, ℓ/μ)
- Buffer zone: r >> M,
  r-r_H << min(ℓ/ω, ℓ/μ)





Near zone metric resummation



dCS metric has spurious divergences at Schwarzschild and Kerr horizons, so we need to resum:

1) Resummed metric identically reduces to original metric when expanded in small $\chi \ll 1$
2) Each component remains finite everywhere outside the dCS horizon

$$\bar{\Delta} = \Delta + \frac{915}{14336} M \zeta \chi^2$$

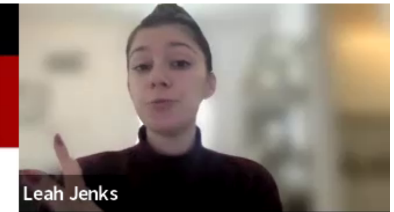
$$\delta g_{rr} = \frac{915}{14336} \frac{M^2 r^2 \zeta \chi^2}{\bar{\Delta}^2}$$

$$\delta g_{tt} = \frac{915}{14336} \frac{M^2 \chi^2 \zeta}{r^2}$$

$$g_{rr,\text{resum}} = g_{rr,\text{K}}(\Delta \to \bar{\Delta}) + g_{rr,\text{dCS}}(f \to \bar{\Delta}/r^2) + \delta g_{rr}$$

$$g_{tt,\text{resum}} = g_{tt,\text{K}}(\Delta \to \bar{\Delta}) + g_{tt,\text{dCS}}(f \to \bar{\Delta}/r^2) + \delta g_{tt}$$

Superradiance in dCS Gravity: Frequencies



Frequency spectrum:

- ℓ, ℓ+2 maximized for ℓ=1, m=1
- ℓ-2 maximized for ℓ=3, m=1

ℓ =1

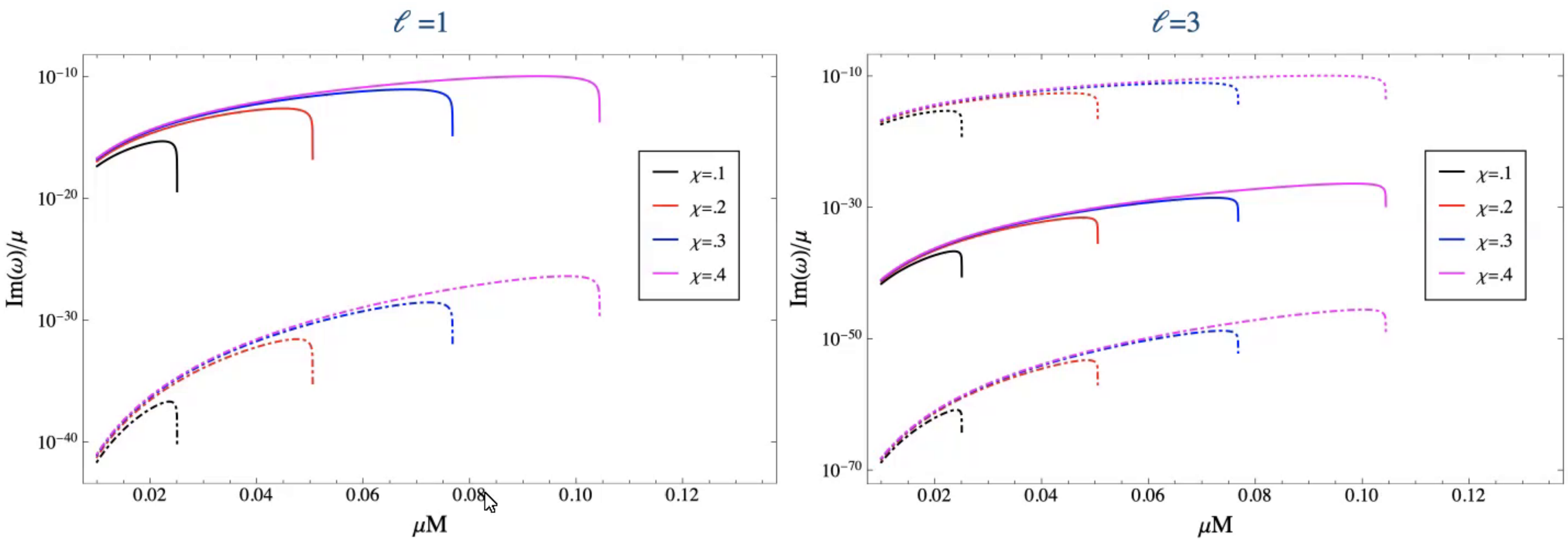
$$\mathrm{Im}(\omega_\ell) \approx \mu \frac{(\mu \mathrm{M})^8}{24} (\chi - 2\mu \mathrm{r}_+)$$

$$\mathrm{Im}(\omega_{\ell+2}) \approx \mu \frac{(\mu \mathrm{M})^{16}}{129024000} (\chi - 2\mu \mathrm{r}_+)$$

ℓ = 3

$$\mathrm{Im}(\omega_{\ell-2}) \approx \mu \frac{(\mu \mathrm{M})^8}{24} (\chi - 2\mu \mathrm{r}_+)$$

Superradiance in dCS Gravity: Frequency Spectrum



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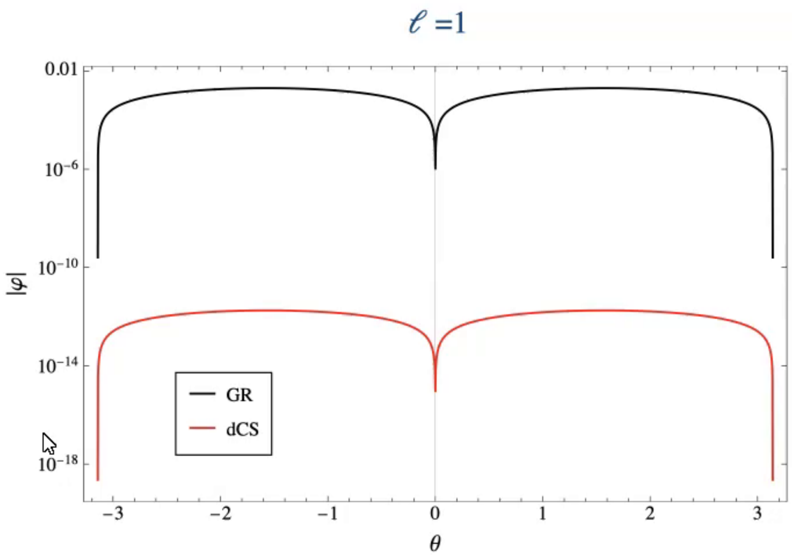
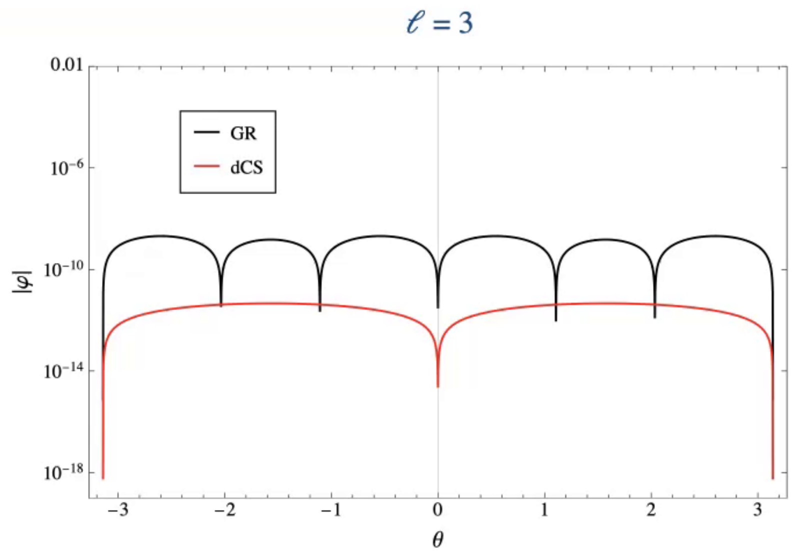
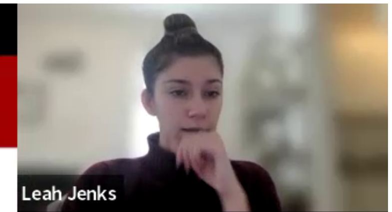
Superradiance in dCS Gravity: Angular Dependence

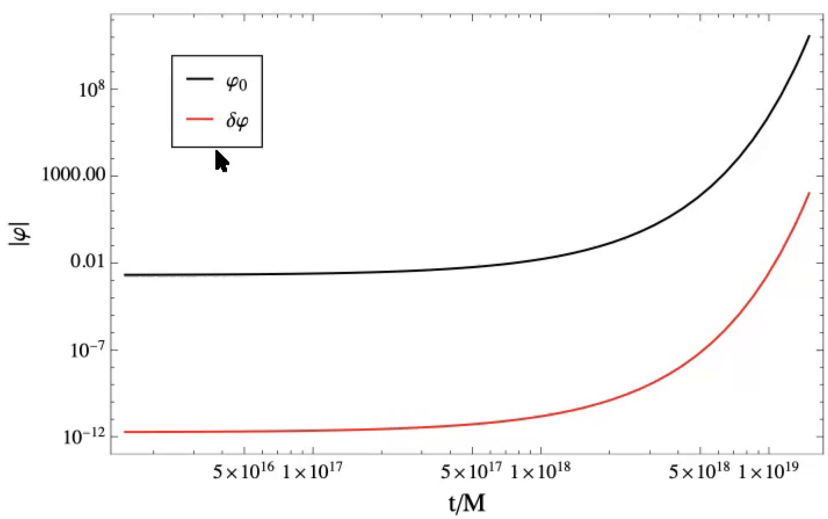




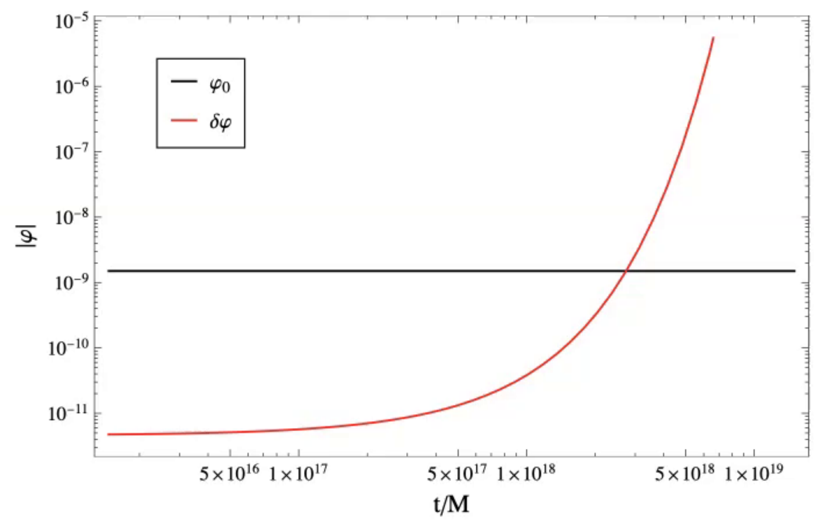
Superradiance in dCS Gravity: Time Evolution



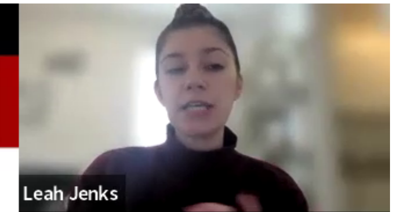
$\ell = 1$



$\ell = 3$



Superradiance in dCS Gravity: Observables & Future Work

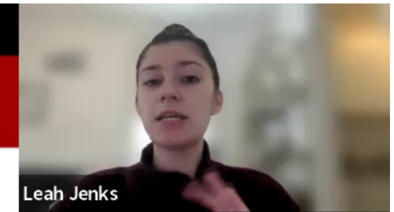


Observables:

- Black hole spin-down (Arvanitaki et al., 2009, Arvanitaki & Dubovsky, 2010 +)
  - Regge plane constraints
- Gravitational wave emission (Arvanitaki et al., 2009, Arvanitaki & Dubovsky, 2010 +)
- EHT observations (eg Davoudiasl & Denton, 2019)

Event Horizon Telescope

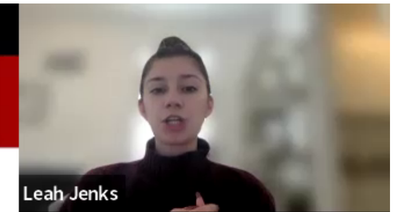
Superradiance in dCS Gravity: Observables & Future Work



Fermionic Superradiance in dCS?

- Fermions do NOT super radiate in GR - Unruh 1974
- Potential for presence of caps and dCS scalar to evade this - unlikely
- Potential for induced superradiance
  - Analogy to fermion preheating (Green & Kofman, 1998)
  - Analogy to induced EM superradiance (Boskovic et al., 2018)

Summary & Conclusions



- dCS gravity provides a vast background to search for observations of modified gravity
- The dCS caps may provide a window into observable signatures
- Superradiance in dCS gravity is distinct from GR, leads to small corrections in the scalar profile
- More work is necessary!

Thank you!