Title: Numerical black holes in dynamical Chern-Simons gravity

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Abstract: <p>This talk will explore the applications of the computing power of numerical relativity to gravitational theories beyond general relativity. Specifically, I will consider dynamical Chern-Simons gravity, which has roots in string theory and loop quantum gravity. I will discuss our formalism and efforts to simulate binary black holes in this theory to generate waveforms LIGO and LISA. Additionally, I will discuss the generation of numerical black hole solutions in this theory, and applications to probing black hole shadows with the Event Horizon Telescope. </p>

NUMERICAL BLACK HOLES IN DYNAMICAL CHERN-SIMONS GRAVITY

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PERIMETER INSTITUTE SEPT 2018 1

OUTLINE

- BBH mergers in dCS I: Scalar Field [MO, Stein, et al. 2017]
- Numerical BH initial data and shadows in dCS
  [MO et al 2018. in prep]
- \+ evolving metric perturbations

MOTIVATIONS FOR DCS

GR nonrenormalizable → use effective field theory $\mathcal{L}_{\rm EH}$ only the first term

Low-energy realization of string theory [Polchinski98, Moura+Schiappa07]

Loop quantum gravity [Taveras+Yunes08, Mercuri+Taveras09]

Cancels gravitational anomalies in chiral theories in curved spacetime including Green-Schwartz [Delbourgo+Salam72, Eguchi+Freund76, Alvarez-Gaume+Witten84, Green+Schwarz84, Polchinski98]

Alexander+Yunes09

DCS EQUATIONS OF MOTION

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

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

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

$$C \supset \partial\partial\partial g$$

WELL-POSED IVP?

Delsate+15

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WHAT SHOULD WE DO?

GR is well-posed → perturb around GR

$$g_{ab} = g_{ab}^{\mathrm{GR}} + \sum_{k=1}^{\infty} \varepsilon^k h_{ab}^{(k)} \qquad \vartheta = \sum_{k=0}^{\infty} \varepsilon^k \vartheta^{(k)}$$

↓

Plug into EOM, collect powers

ORDER REDUCTION SCHEME

$$g_{ab} = g_{ab}^{\mathrm{GR}} + \sum_{k=1}^{\infty} \varepsilon^k h_{ab}^{(k)} \qquad \vartheta = \sum_{k=0}^{\infty} \varepsilon^k \vartheta^{(k)}$$

ε^0 $\quad G_{ab}^{(0)} = 0 \qquad \square^{(0)} \vartheta^{(0)} = 0 \to \vartheta^{(0)} = 0$

ε^1 $\quad G_{ab}^{(1)}[h^{(1)}] = 0 \to h_{ab}^{(1)} = 0 \qquad \square^{(0)} \vartheta^{(1)} = \frac{m_{\mathrm{pl}}}{8} l^2 ({}^*RR)^{(0)}$

ε^2 $\quad h_{ab}^{(2)}$ has source

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WHAT WE KNOW ABOUT BH IN DCS

Schwarzschild ✓ Kerr ✗ Pretorius+09

Slow-rotation approx: ϑ around isolated BH dipole Stein14

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WHAT WE KNOW ABOUT DCS BBH FROM PN

Scalar field dipole moment

Yagi+12

$$\mu_A^i = -\frac{5}{2}\frac{m_{\rm pl}\ell^2}{8}\chi_A^i$$

* Dipoles going around each other

↓

quadrupolar radiation

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WHAT WE KNOW ABOUT DCS BBH FROM PN

- $(l, l-1)$ modes dominant
- $l = 1$ varies on spin-precession timescale, non-rad
- No monopolar radiation

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ORDER REDUCTION SCHEME

$$g_{ab} = g_{ab}^{\mathrm{GR}} + \sum_{k=1}^{\infty} \varepsilon^k h_{ab}^{(k)} \qquad \vartheta = \sum_{k=0}^{\infty} \varepsilon^k \vartheta^{(k)}$$

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ε^2 $\quad h_{ab}^{(2)}$ has source

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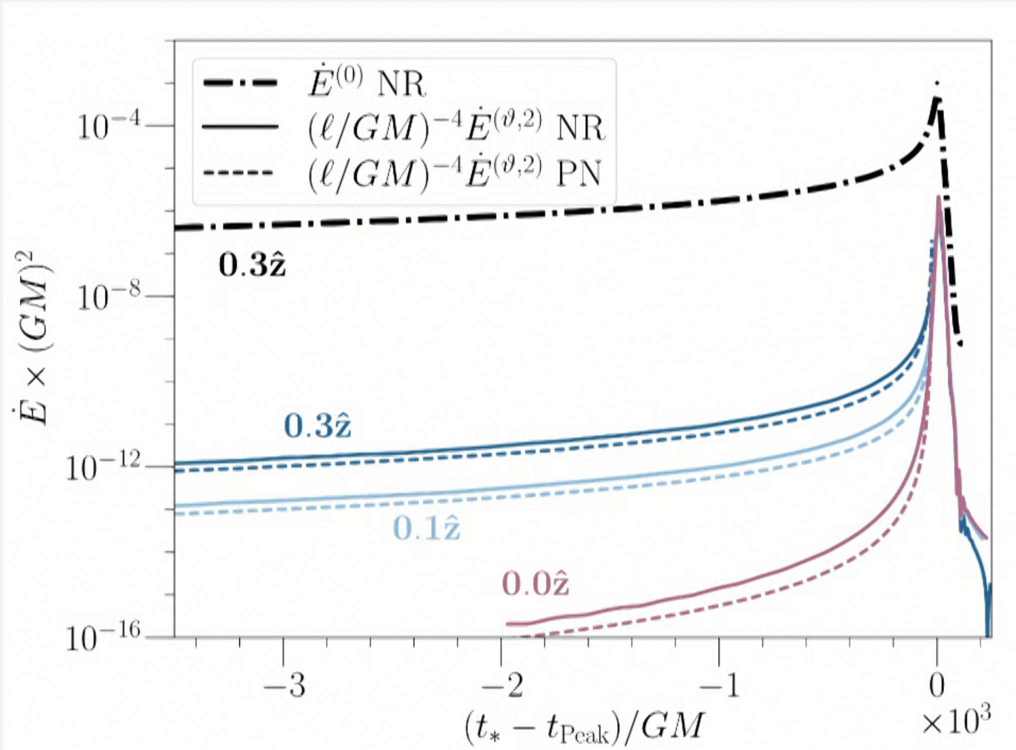
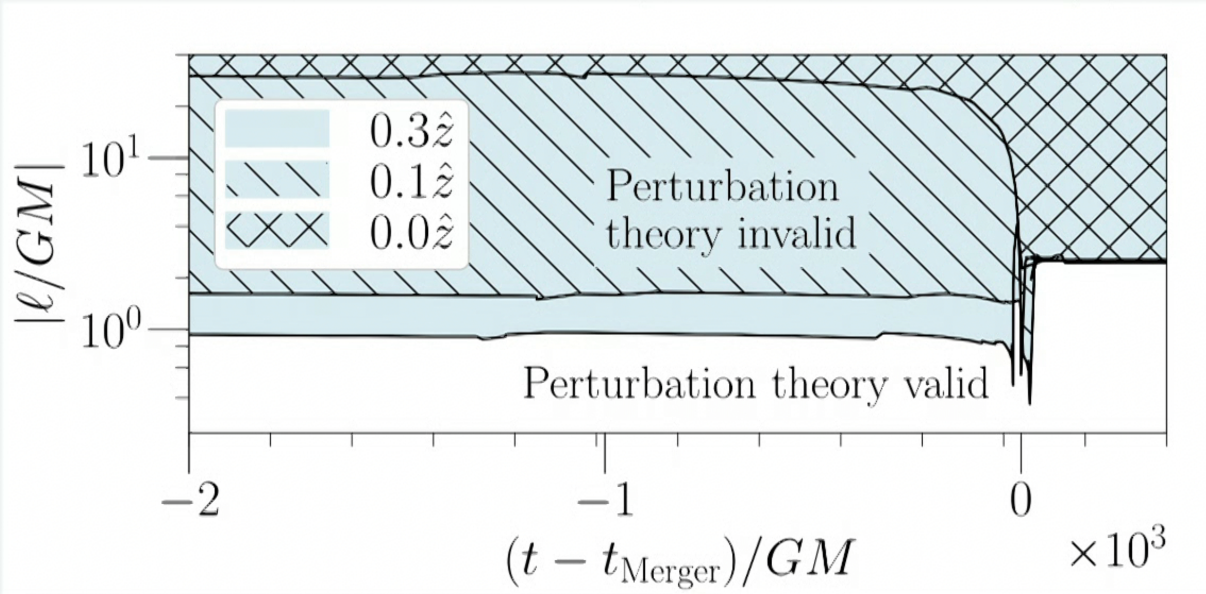
ENERGY FLUXES



REGIME OF VALIDITY

$$g_{ab} = g_{ab}^{(0)} + \frac{\varepsilon^2}{2} h_{ab}^{(2)} + \mathcal{O}(\varepsilon^3) \quad \Rightarrow \quad (\ell/GM)^2_{\max} \sim 0.14 \left(\sqrt{\frac{\left\| g_{ab}^{(0)} \right\|}{\left\| h_{ab}^{(2)} \right\|}} \right)_{\min}$$



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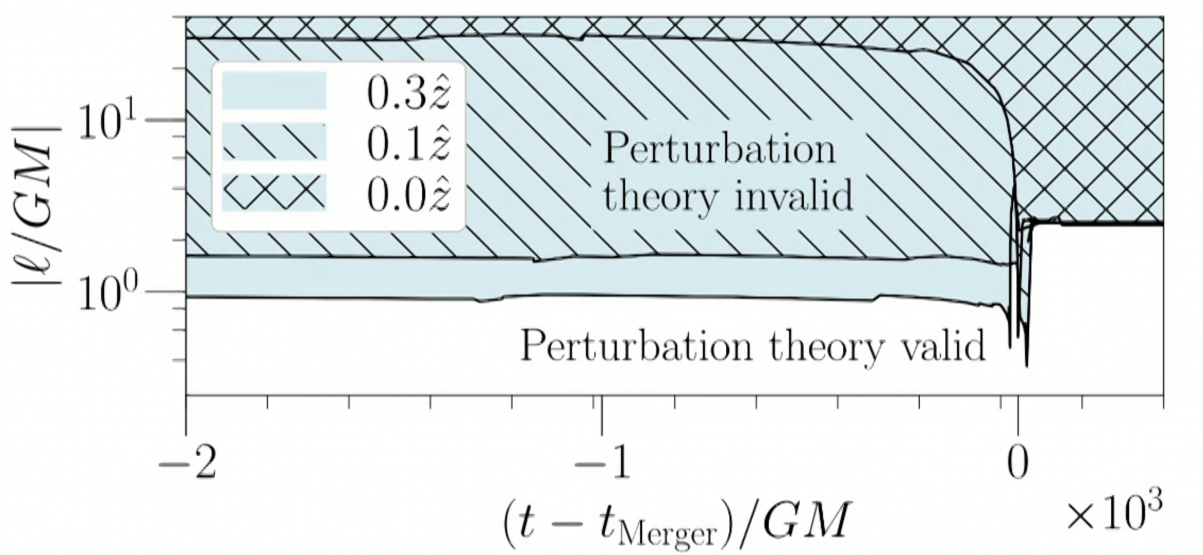
REGIME OF VALIDITY

$$g_{ab} = g^{(0)}_{ab} + \frac{\varepsilon^2}{2} h^{(2)}_{ab} + \mathcal{O}(\varepsilon^3) \Rightarrow (\ell/GM)^2_{\max} \sim 0.14 \left(\sqrt{\frac{\left\| g^{(0)}_{ab} \right\|}{\left\| h^{(2)}_{ab} \right\|}} \right)_{\min}$$



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DEPHASING

dCS waveform phase will differ from GR

Estimate this!

$$\phi = \phi^{\mathrm{GR}} + \varepsilon \Delta\phi + \mathcal{O}(\varepsilon^2)$$

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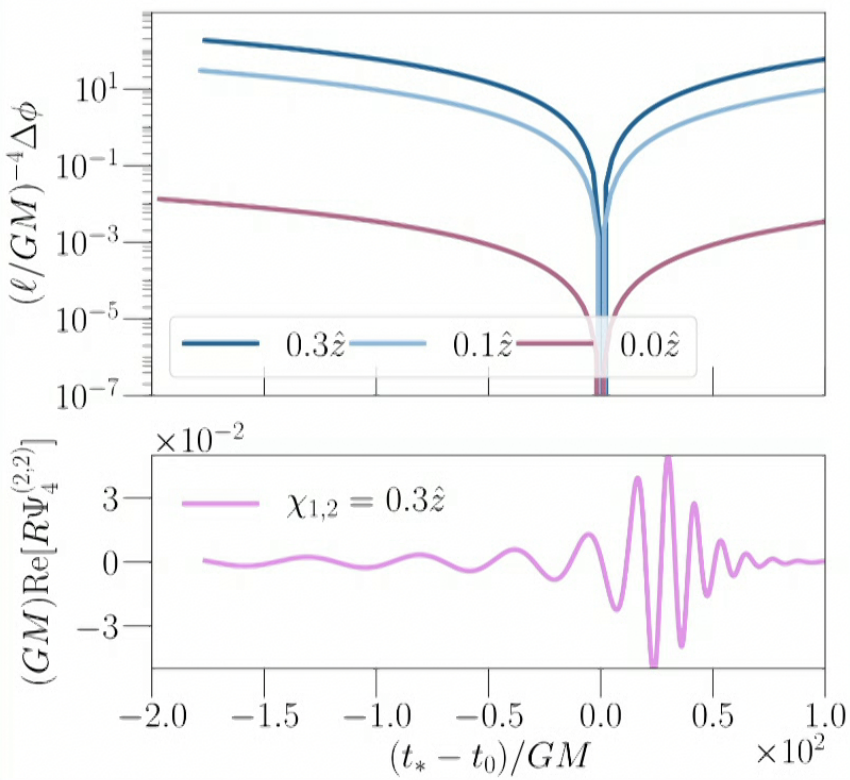
DEPHASING

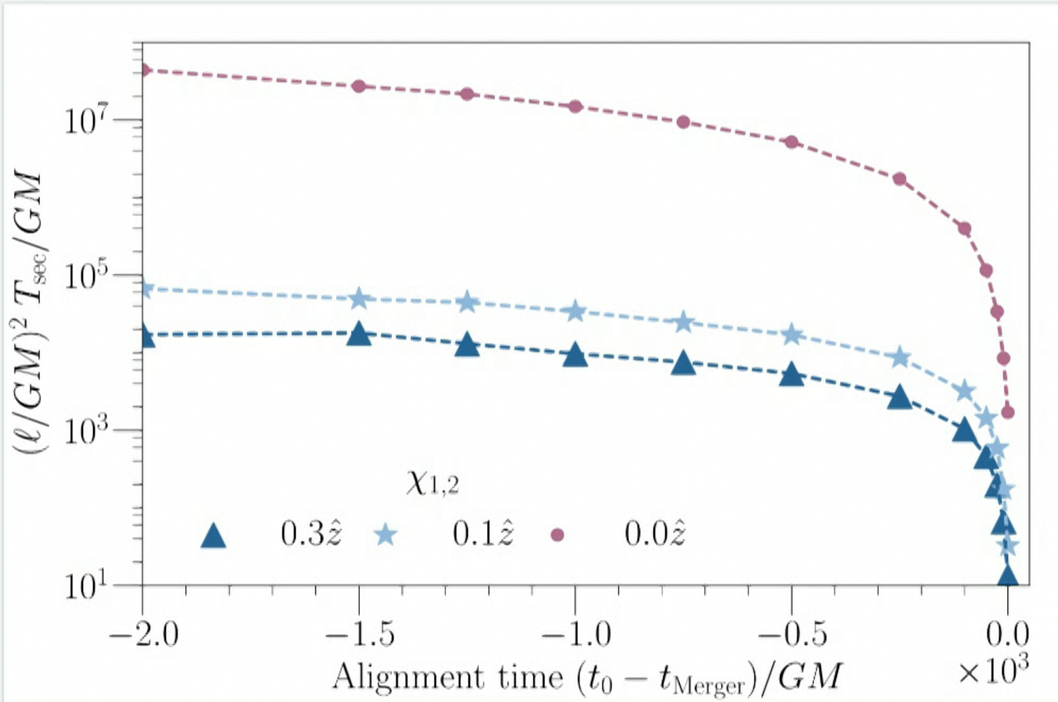
$$\Delta\phi \approx A(t - t_0) + B(t - t_0)^2$$

$$\Delta\phi = \frac{1}{2}(t - t_0)^2 \left.\frac{d\Delta\omega}{dt}\right|_{t_0}$$



DEPHASING

How long to accumulate a radian of phase difference?



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PARAMETER BOUNDS

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

What are the current bounds?

Gravity Probe B + LAGEOS satellites $\ell \lesssim 10^8$ km Ali-Haïmoud+11

Projected PN waveforms $\ell \lesssim (10 - 100)$ km Yagi+12

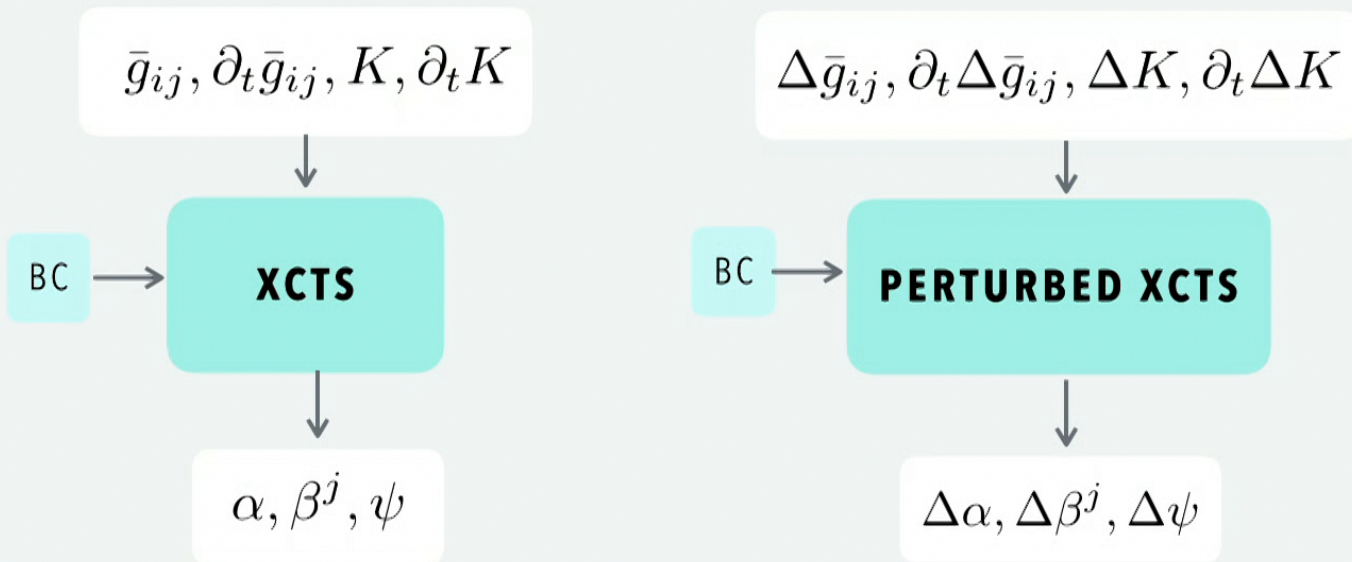
THE NEXT STEP

ε^0 $\quad G_{ab}^{(0)} = 0$ $\qquad \square^{(0)}\vartheta^{(0)} = 0 \rightarrow \vartheta^{(0)} = 0$

ε^1 $\quad \square^{(0)} h_{ab}^{(1)} = 0 \rightarrow h_{ab}^{(1)} = 0$ $\qquad \square^{(0)}\vartheta^{(1)} = \frac{m_{\rm pl}}{8} l^2 ({}^*RR)^{(0)}$

ε^2 $\quad h_{ab}^{(2)}$ has source

METRIC PERTURBATION INITIAL DATA



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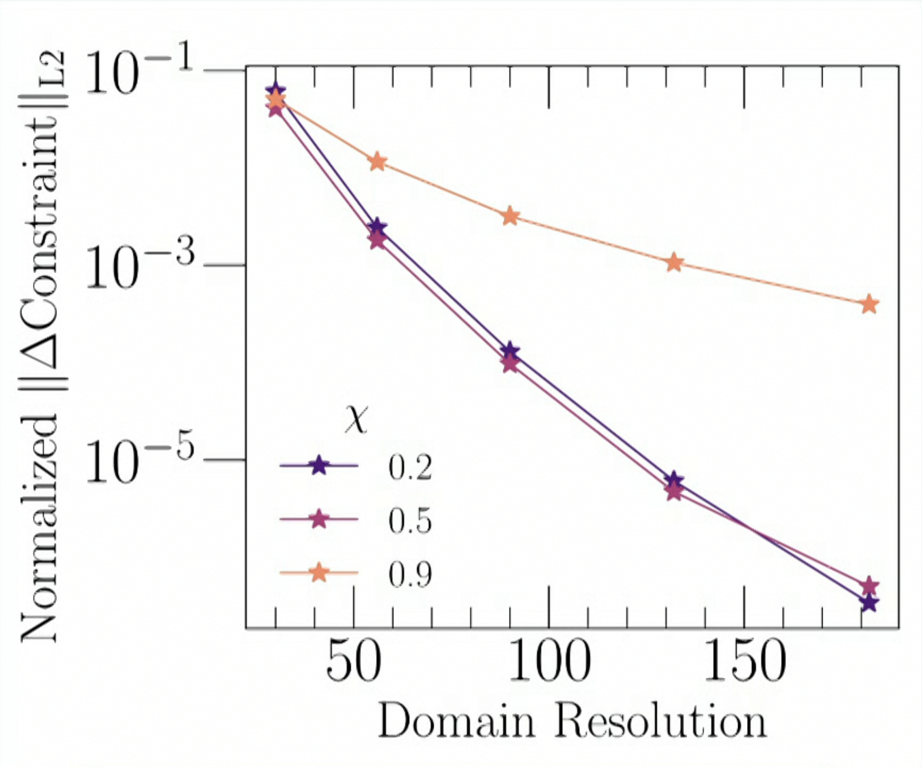
GENERATE DCS INITIAL DATA



+ stationary

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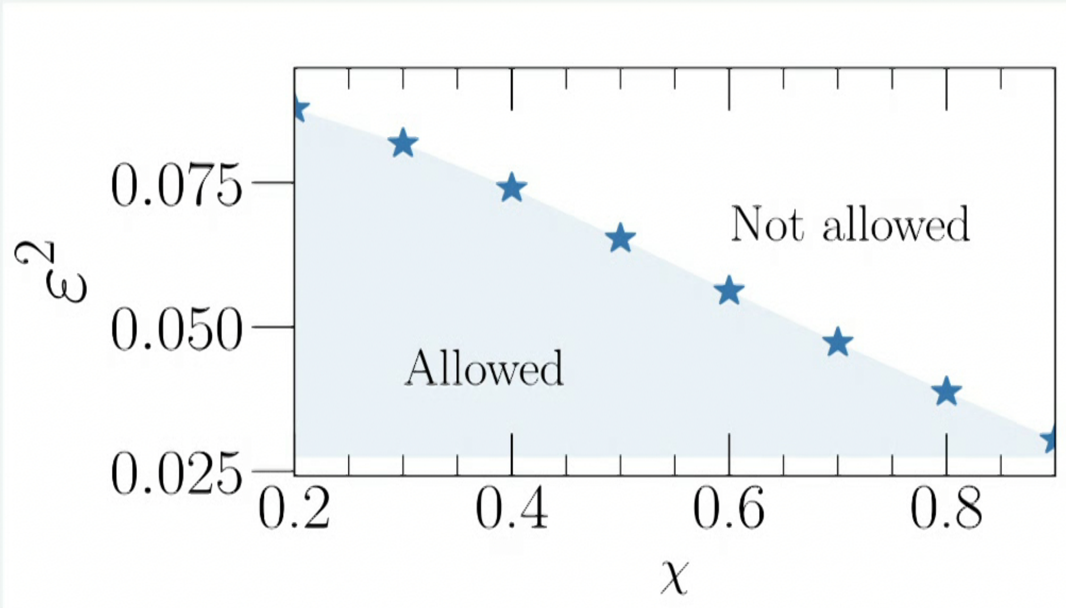
Generalization to binary case

REGIME OF VALIDITY

$$\psi_{ab} \rightarrow \psi_{ab} + \varepsilon^2 \Delta\psi_{ab}$$



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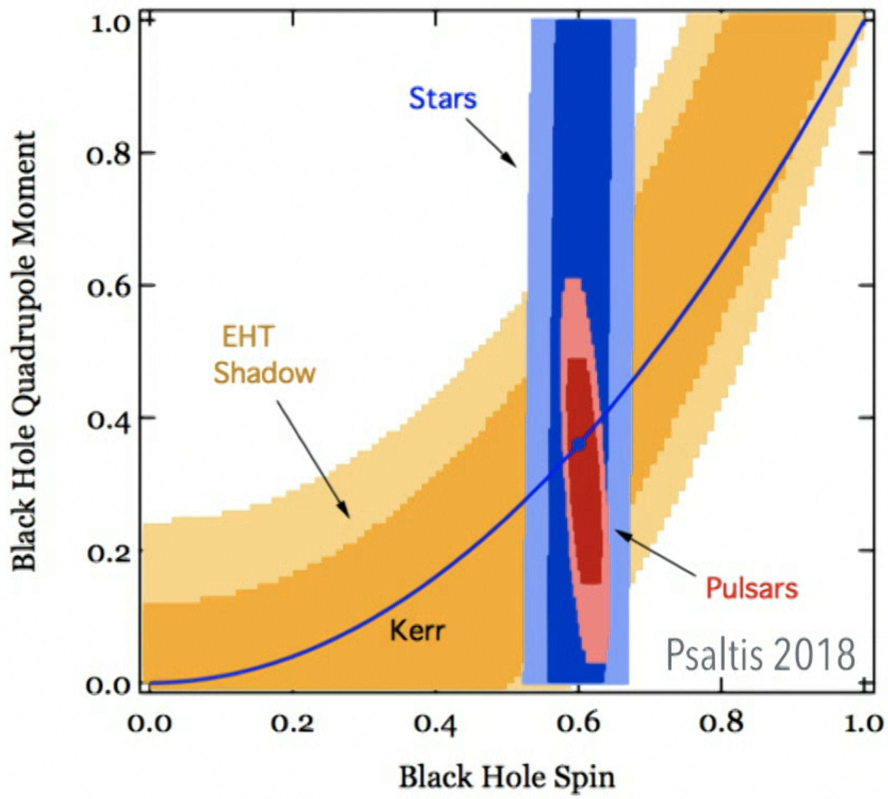
EVENT HORIZON TELESCOPE



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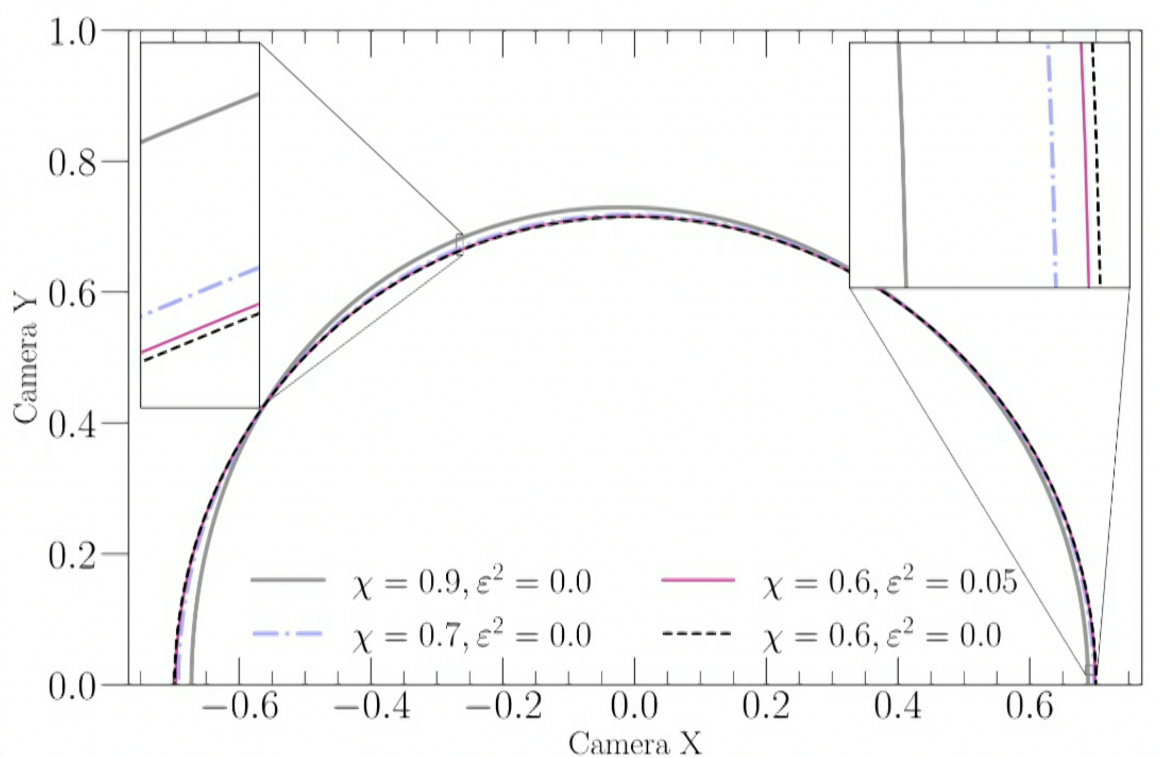
BLACK HOLE SHADOWS IN DCS

$$\psi_{ab} \rightarrow \psi_{ab} + \varepsilon^2 \Delta\psi_{ab}$$



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PUTTING IT ALL TOGETHER

$\Delta\bar{g}_{ij}, \partial_t \Delta\bar{g}_{ij}, \Delta K, \partial_t \Delta K$

↓

BC → **PERTURBED XCTS**

↓

$\Delta\alpha, \Delta\beta^j, \Delta\psi$ STATIONARY

+ Metric perturbation evolution