Title: Weak Cosmic Censorship in Einstein-Scalar theory in flat 4D

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Series: Strong Gravity

Date: November 21, 2019 - 1:00 PM

URL: http://pirsa.org/19110127

Abstract: We present a plausible counterexample to the weak cosmic censorship conjecture in four-dimensional Einstein-Scalar theory with asymptotically flat boundary conditions. Our setup stems from the analysis of the massive Klein-Gordon equation on a fixed Kerr black hole background. In particular, we construct the quasinormal spectrum numerically, and analytically in the WKB approximation, then go on to compute its backreaction on the Kerr geometry. In the regime of parameters where the analytic and numerical techniques overlap we find perfect agreement. We give strong evidence for the existence of a nonlinear instability at late times.

Introduction
○○

Weak Cosmic Censorship Conjecture (WCCC)
○○○○

Setup
○○○○○○○○

So what happens with the scalar clouds?
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Weak Cosmic Censorship in Einstein-Scalar theory in flat 4D

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November 21, 2019

arXiv:1906.11257

Introduction   Weak Cosmic Censorship Conjecture (WCCC)   Setup   So what happens with the scalar clouds?

OO   OOOO   OOOOOOOO   OOOO

Table of Contents

Introduction

♦ Massive scalar fields in a Kerr background superradiate.

Introduction

- ◆ Massive scalar fields in a Kerr background superradiate.
  - For any black hole rotation and scalar mass a superradiant mode exists

- ◆ With time modes stabilise one by one and form quasi-bound states - scalar clouds around the BH

- ◆ Gravitational waves emission is not efficient enough to prevent cascading towards higher mode-numbers.

- ◆ The system evolves to a Schwarzschild BH emersed in a very slowly decaying massive scalar field, which we expect is a non-linearly unstable configuration

Definition

Weak Cosmic Censhorship Conjecture (WCCC)

Let (Σ, h_{ab}, K_{ab}) be a geodesically complete, asymptotically flat, initial data set. Let the matter fields obey hyperbolic equations and satisfy the dominant energy condtition. Then **generically** the maximal development of this initial data is an asymptotically flat spacetime (in particular it has complete $\mathcal{I}^+$) that is strongly asymptotically predictable.

Introduction   Weak Cosmic Censorship Conjecture (WCCC)   Setup   So what happens with the scalar clouds?

○○   ○●○○   ○○○○○○○○   ○○○○

Definition

In simpler terms: Starting from generic initial data, WCCC forbids the formation of naked singularities - singularities in causal contact with future null infinity.

Counterexamples

Higher Dimensions

♦ Black Strings in 5D (2010) - Lehner, Pretorius [LP10]

♦ Black Rings in flat 5D (2016) - Figueras, Markus Kunesch, Tunyasuvunakool [FKT16]

♦ Axisymmetric ultraspinning instability of Myers-Perry black holes in flat 6D (2017) - Figueras, Markus Kunesch, Tunyasuvunakool, Lehner [FKLT17]

Counterexamples

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Fine-tuned 4D

♦ Critical collapse in spherical symmetry (1993) - Choptuik [Cho93, Chr94]

♦ Critical collapse, no symmetry assumptions (2018) - Deppe, Kidder, Scheel, Teukolsky [DKST19]

Introduction
○○

Weak Cosmic Censorship Conjecture (WCCC)
○○○●

Setup
○○○○○○○○

So what happens with the scalar clouds?
○○○○

Violation in 4D AdS

♦ Einstein gravity with negative Λ coupled to a Maxwell field [HSW16, CS17]

- Flat boundary with an electric potential profile

Violation in 4D AdS

♦ Einstein gravity with negative Λ coupled to a Maxwell field [HSW16, CS17]

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♦ Constant amplitude $\rightarrow$ static, zero temperature solutions up to a certain maximum value - then naked singularities.

♦ Start from vanishing potential and slowly increase its amplitude past the maximum $\rightarrow$ violation of WCCC [CS17]

... and resolution

♦ Include charged scalar fields as motivated by the Weak Gravity Conjecture [AHMNV07, CHS18]

♦ The static solutions become unstable to developing scalar hair and new hairy solutions emerge, which are regular past the maximum amplitude from before.

Table of Contents

Introduction
○○

Weak Cosmic Censorship Conjecture (WCCC)
○○○○

Setup
○●○○○○○○

So what happens with the scalar clouds?
○○○○

Einstein-Klein-Gordon system

Einstein gravity minimally coupled to a real massive scalar

$$S = \int_{\mathcal{M}} \mathrm{d}^4 x \sqrt{-g} \left(\frac{R}{16\,\pi\,G} - \nabla_a \psi \nabla^a \psi - \mu^2\,\psi^2 \right).$$

Linearised analysis

♦ Massive scalar field perturbations on a fixed Kerr background

♦ Ansatz: $\psi = \mathrm{Re}\big[e^{-i\,\omega\,t + i\,m\,\phi}\,R(r)\,S(\theta)\big]$, $\omega \in \mathbb{C}$, $m \in \mathbb{Z}$

♦ Equation of motion: $\Box\psi = \mu^2\psi$

♦ Presence of superradiant scattering
[SR14, CSR17, ZE79, Det80]

Introduction
○○

Weak Cosmic Censorship Conjecture (WCCC)
○○○○

Setup
○○●○○○○○

So what happens with the scalar clouds?
○○○○

Superradiance

Wave analog of the Penrose process - extraction of energy from the black hole by throwing matter in

E_0

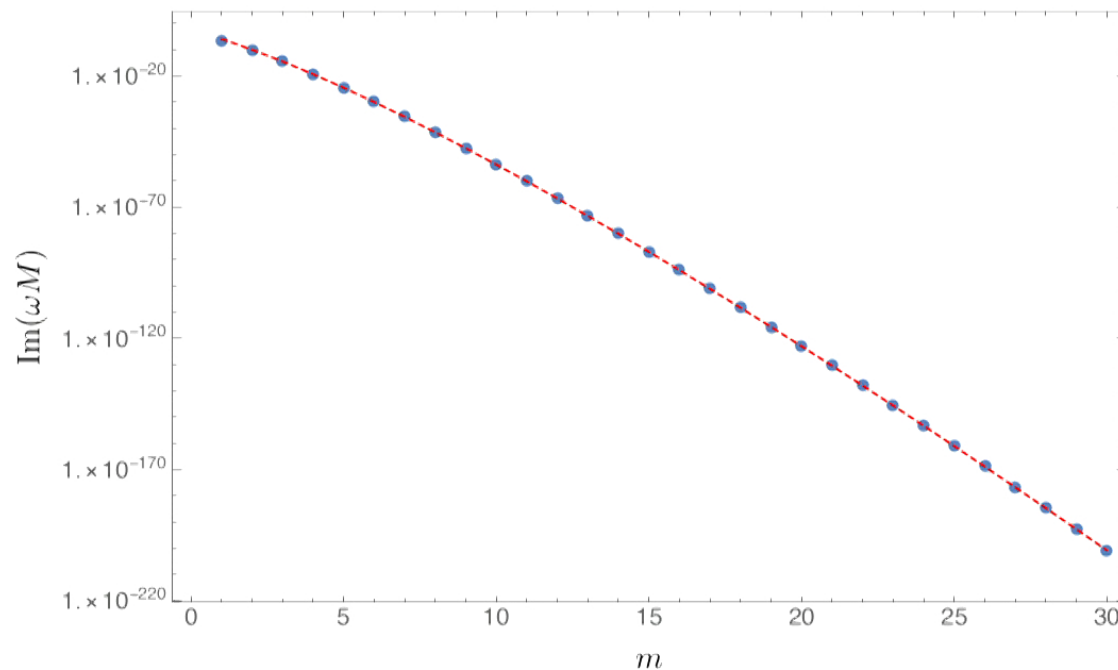Ergosphere

$E_1 < 0$

$E_2 > E_0$
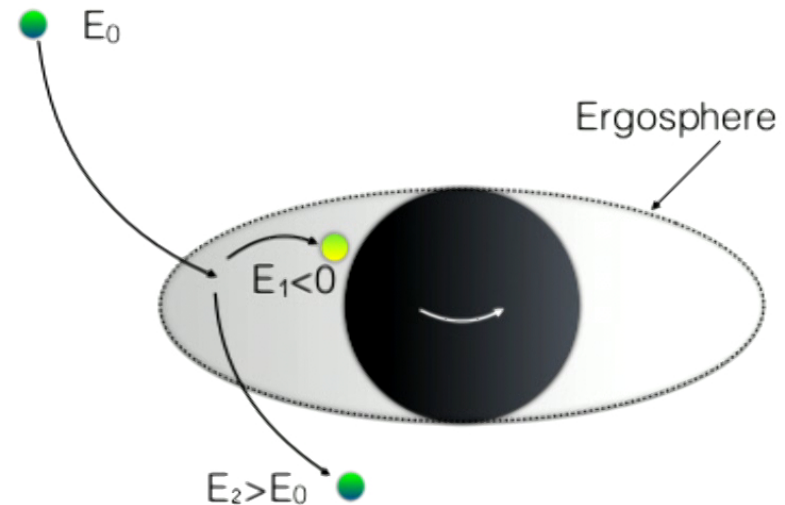
Elly Leiderschneider, Tsvi Piran, arXiv:1501.01984

Unstable modes

WKB expansion for large $\ell = m$ in far-away and near-horizon region followed by matching produces

$$\omega_I = f_1(\tilde{a}, \tilde{\mu})\, \ell^{N-\frac{9}{2}} \sinh\left[\frac{2\,\pi(\tilde{a}\,\ell - \tilde{\mu}(1 + \tilde{a}^2))}{1 - \tilde{a}^2}\right] \exp\left[-4\ell \log \ell + \mathcal{O}(\ell)\right].$$

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♦ For **any** scalar field mass μ and **any** nonzero black hole spin a superradiant mode **exists** ($\ell = \ell_\star \equiv \lceil \mu/\Omega_K \rceil$)

♦ The timescales on which the modes evolve suggest that they do so independently

Trapping and scalar clouds

♦ Due to the mass of the scalar field a trapping region exists.

Introduction
OO

Weak Cosmic Censorship Conjecture (WCCC)
OOOO

Setup
OOOOO●OOO

So what happens with the scalar clouds?
OOOO

Trapping and scalar clouds

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Trapping region
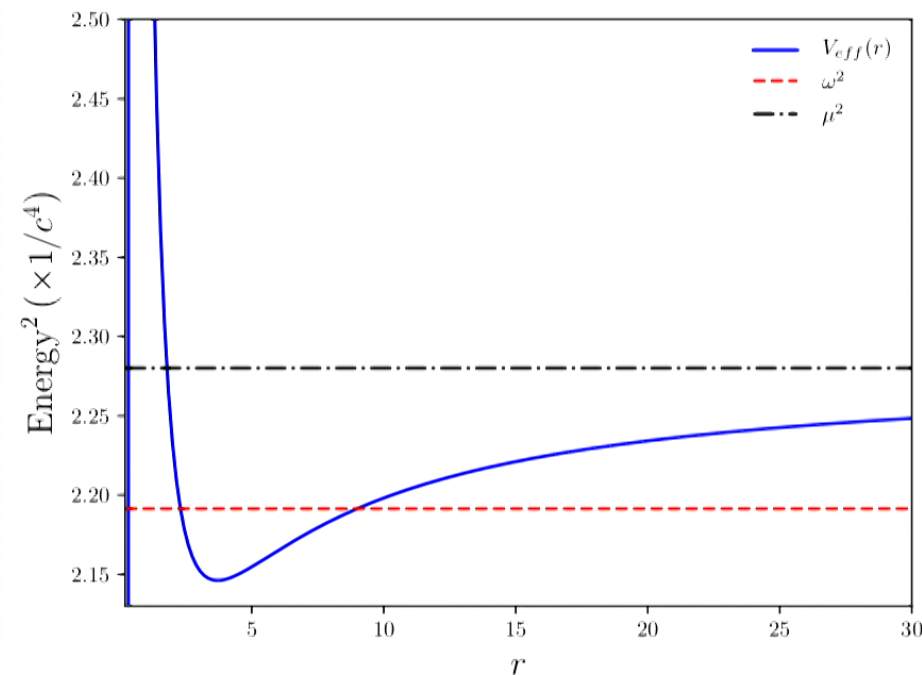
Trapping and scalar clouds

♦ Due to the mass of the scalar field a trapping region exists.

♦ Scalar modes get localised there $\rightarrow$ at onset of superradiance scalar clouds (bound states of the scalar field) emerge.

Introduction
OO

Weak Cosmic Censorship Conjecture (WCCC)
OOOO

Setup
OOOOO●OOO

So what happens with the scalar clouds?
OOOO

Trapping and scalar clouds

- ◆ Due to the mass of the scalar field a trapping region exists.
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- ◆ Real field - scalar clouds disperse through gravitational wave (GW) emission

Trapping and scalar clouds

- ◆ Due to the mass of the scalar field a trapping region exists.
- ◆ Scalar modes get localised there $\rightarrow$ at onset of superradiance scalar clouds (bound states of the scalar field) emerge.
- ◆ Real field - scalar clouds disperse through gravitational wave (GW) emission

Does the emission of gravitational waves by the clouds prevent the cascade towards higher m-modes?

Gravitational Wave emission

♦ Treat the scalar clouds as perturbing matter sources and solve Teukolsky's equation [Teu73]

$$\mathcal{D}\,\psi_4 = 4\,\pi\,T_4$$

♦ The rate of emitted gravitational radiation is given by

$$\frac{d^2 E_s}{dt\,d\Omega} = \lim_{r \to \infty} \frac{r^2}{4\,\pi\,\omega_{gw}^2}|\psi_4|^2, \quad P_E = \frac{\mathrm{d}E_s}{\mathrm{d}t}\left(\frac{M}{\mathcal{M}_s}\right)^2,$$

$$\mathcal{M}_s = \int_{r_+}^{+\infty}\int_0^{\pi}\int_0^{2\pi}\sqrt{-g}\,T^t{}_t\,\mathrm{d}\phi\,\mathrm{d}\theta\,\mathrm{d}r$$

♦ Superradiance proceeds on an exponential scale - $e^{\omega_I t}$

Introduction
○○

Weak Cosmic Censorship Conjecture (WCCC)
○○○○

Setup
○○○○○●○○

So what happens with the scalar clouds?
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Gravitational Wave emission

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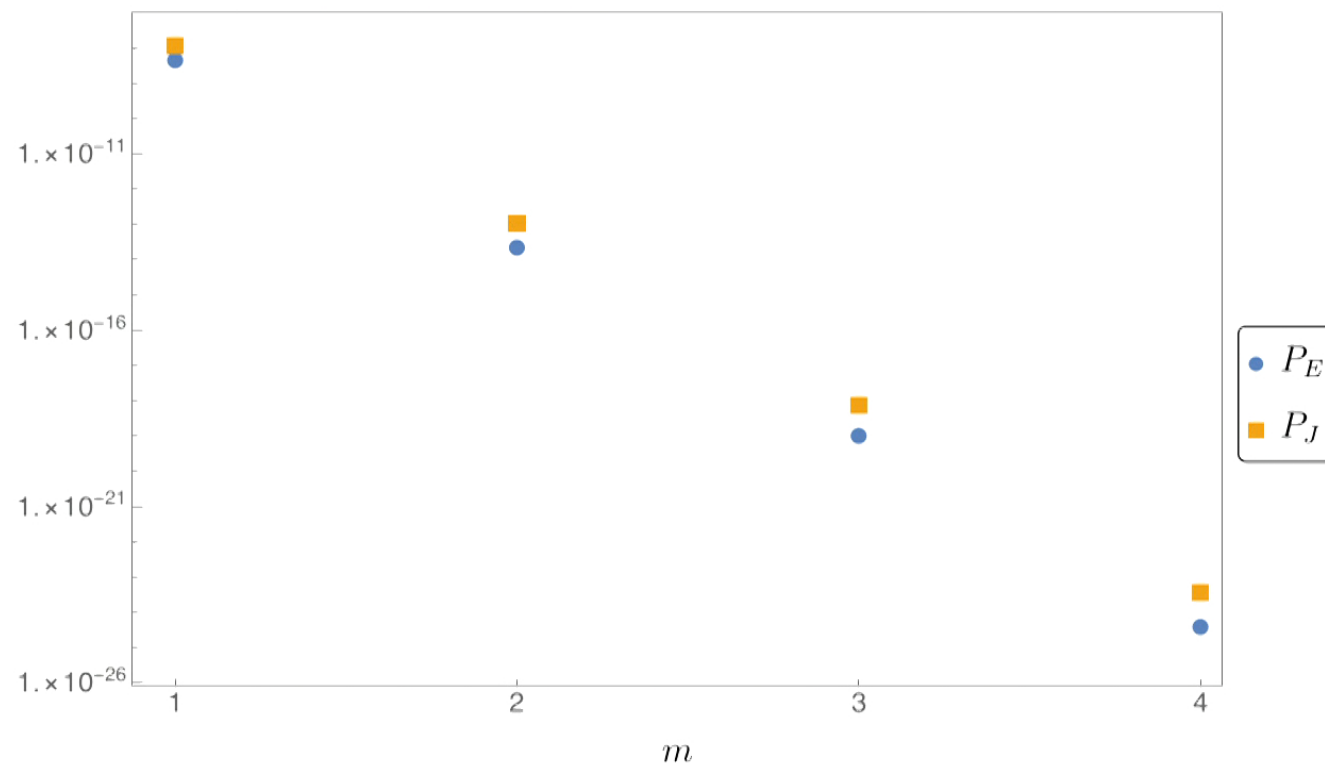
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◆ Superradiance proceeds on an exponential scale - $e^{\omega_I t}$
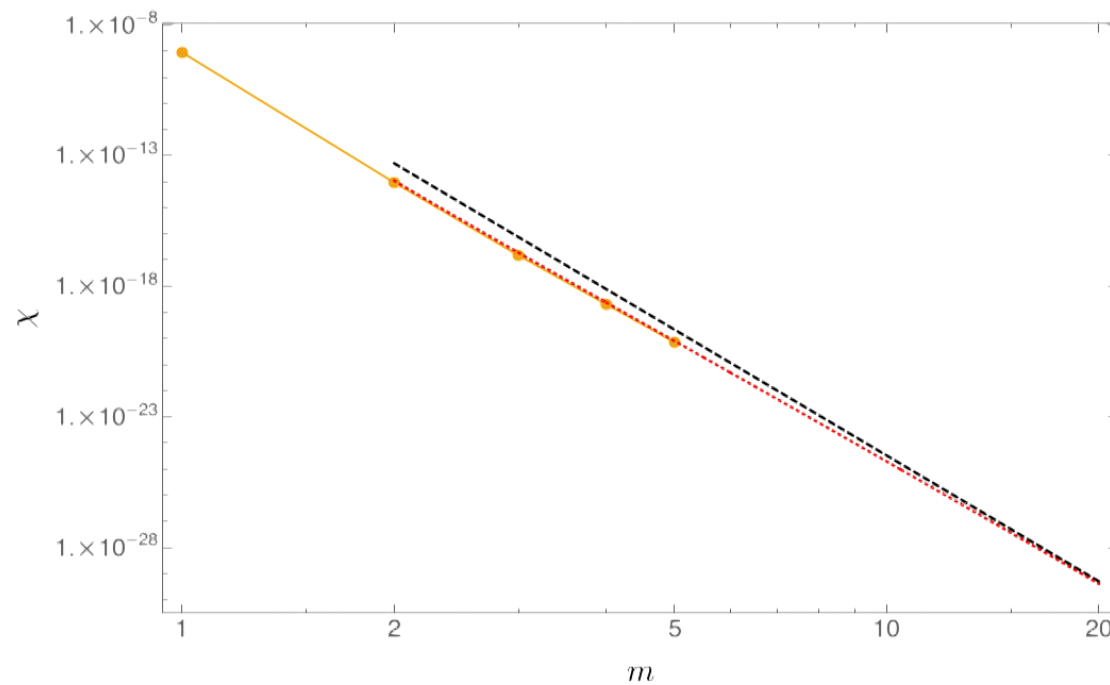◆ We want to know whether $\frac{dE_s}{dt}$ decreases as a function of m

Gravitational Wave emission

Curvature

The NP scalar $\psi_4 = C_{abcd}\, n^a \bar{m}^b n^c \bar{m}^d$ gives us a way of measuring spacetime curvature

$$\chi \equiv \max_{r,\theta} \left(|\psi_4|^2 / \mathcal{M}_s^2 \right)$$

Introduction
○○

Weak Cosmic Censorship Conjecture (WCCC)
○○○○

Setup
○○○○○○○○

So what happens with the scalar clouds?
○●○○

So what happens with the scalar clouds?

◆ Given a spinning BH and a scalar field of *any* mass μ, we can always find a superradiant mode

◆ Consider initial data for the Einstein-Scalar system

◆ Late time dynamics will be controlled by the $\ell = m$ superradiant modes of the scalar field

$$\psi(t, r, \theta, \phi) = \text{Re}\left[\sum_{\ell=0}^{+\infty} a_\ell e^{-i\omega_\ell t + i\ell\phi} R_{\omega_\ell \ell \ell}(r) S_{\omega_\ell \ell \ell}(\theta)\right] ,$$

- These decouple given our results for the growth rate

Introduction
○○

Weak Cosmic Censorship Conjecture (WCCC)
○○○○

Setup
○○○○○○○○

So what happens with the scalar clouds?
○○●○

Schwarzschild surrounded by scalar clouds

$a \to 0$ in our formula for the superradiant growth reduces to the correct result for massive scalar perturbations on Schwarzschild.

$$\tilde{\omega}_{I,\tilde{a}=0} \sim -e^{-4\ell \log \ell}.$$

◆ Corresponds to late time decay of the perturbations **slower** than $1/\log t$ [ERS16, Kei16]

◆ This is considered indicative of the development of a non-linear instability in the system

Introduction
○○

Weak Cosmic Censorship Conjecture (WCCC)
○○○○

Setup
○○○○○○○○

So what happens with the scalar clouds?
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