Strong cosmic censorship in de Sitter spacetime

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Based on:

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1801.09694 (PRD) & 1808.02895 (JHEP) & 1808.04832 (CQG)

The vacuum of the Universe IV, *Barcelona* June 2019

Outline:

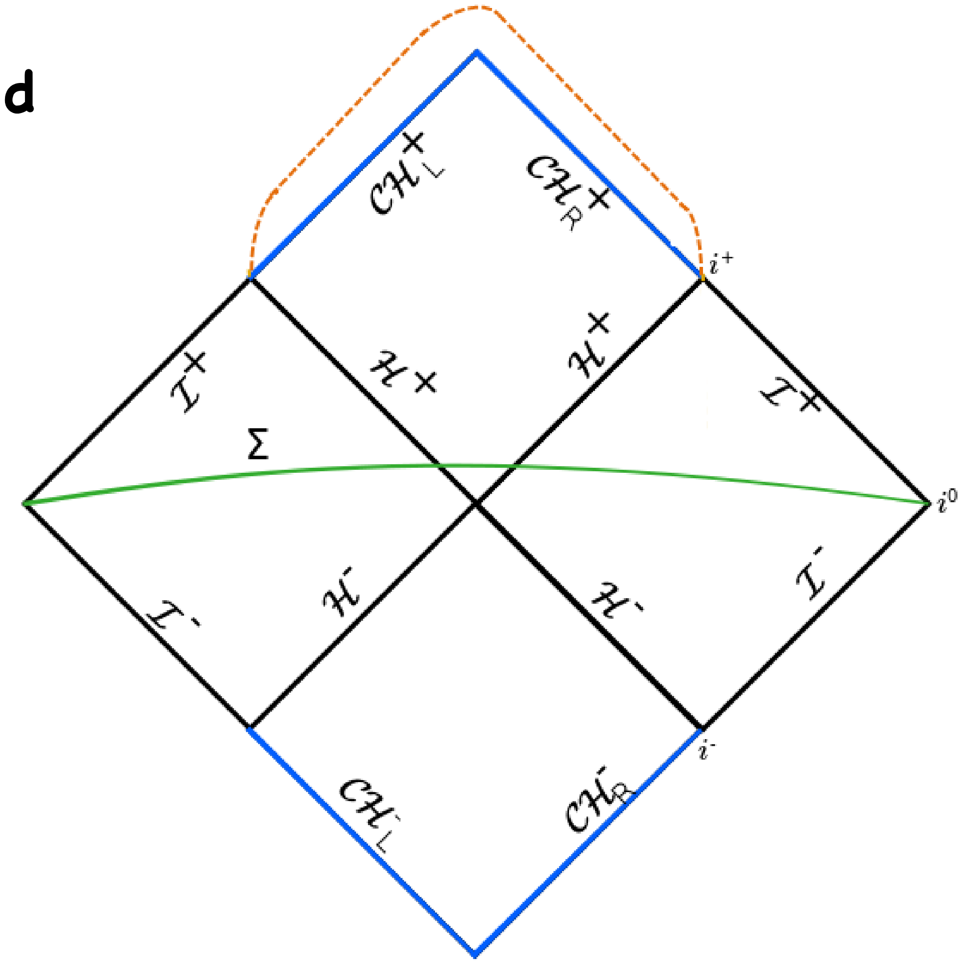
1. Strong Cosmic censorship with $\Lambda = 0$
2. Strong Cosmic censorship with $\Lambda > 0$
3. Quantum effects

1. Strong Cosmic censorship with $\Lambda = 0$

➞ Black holes with Λ = 0

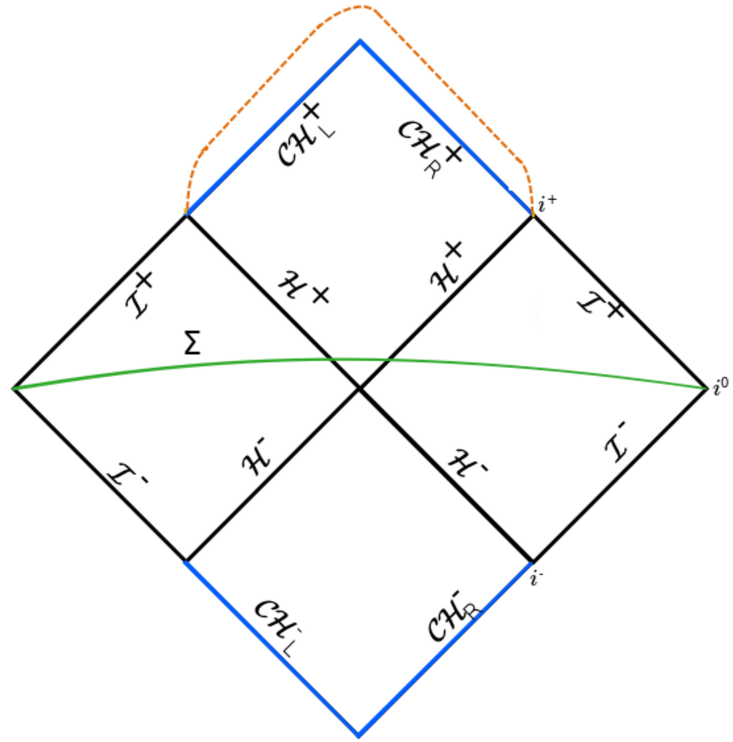
- Consider **Einstein-Maxwell theory with** Λ **= 0.**
- **Reissner-Nordström** black hole (charged non-rotating BH).
  Kerr BH (rotating, uncharged BH)

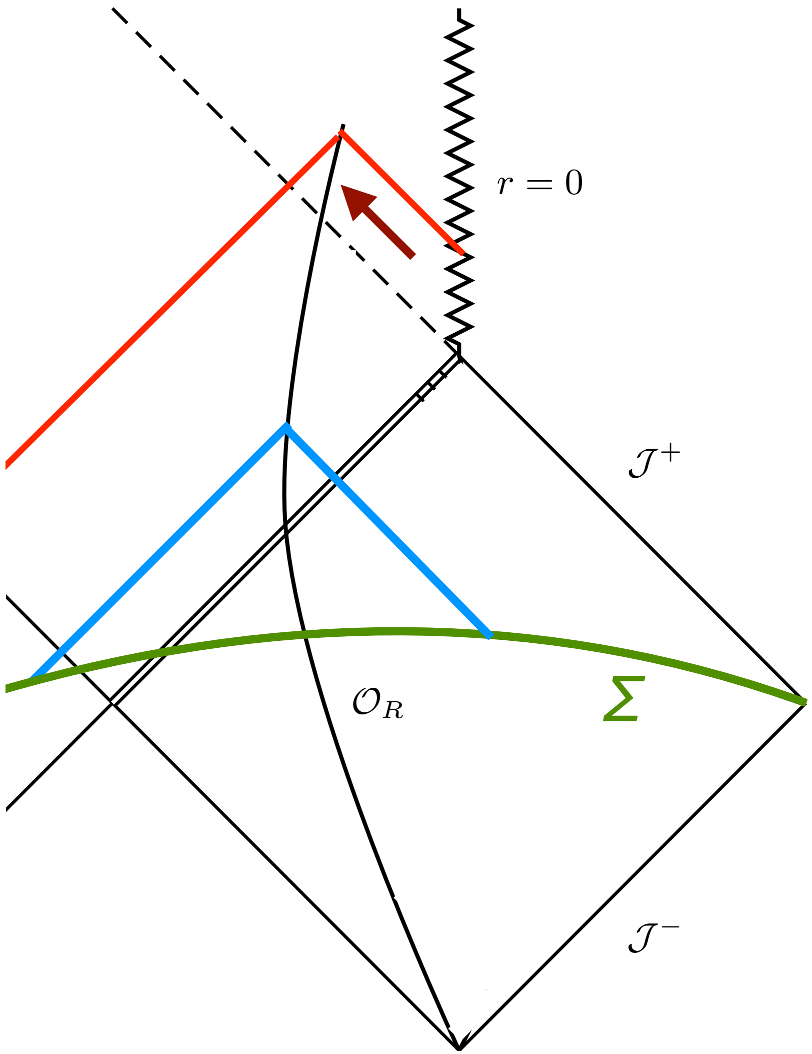
- Both solutions **can be smoothly extended across a horizon** H^+ inside the BH.



- Inner horizon is a **Cauchy horizon** $CH_{L,R}{}^{+}$:

  a **boundary** to the region of spacetime in which **physics** can be **predicted** from **initial data prescribed on a surface Σ**.



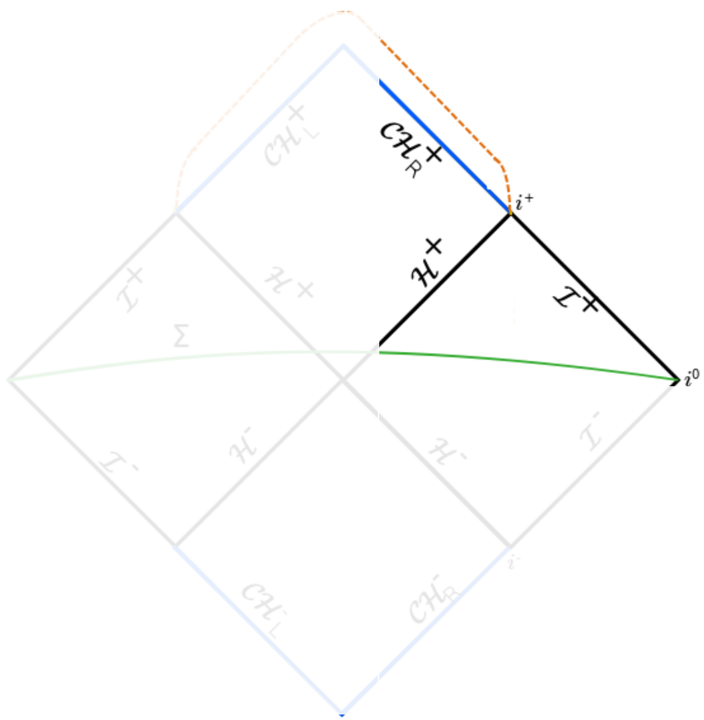


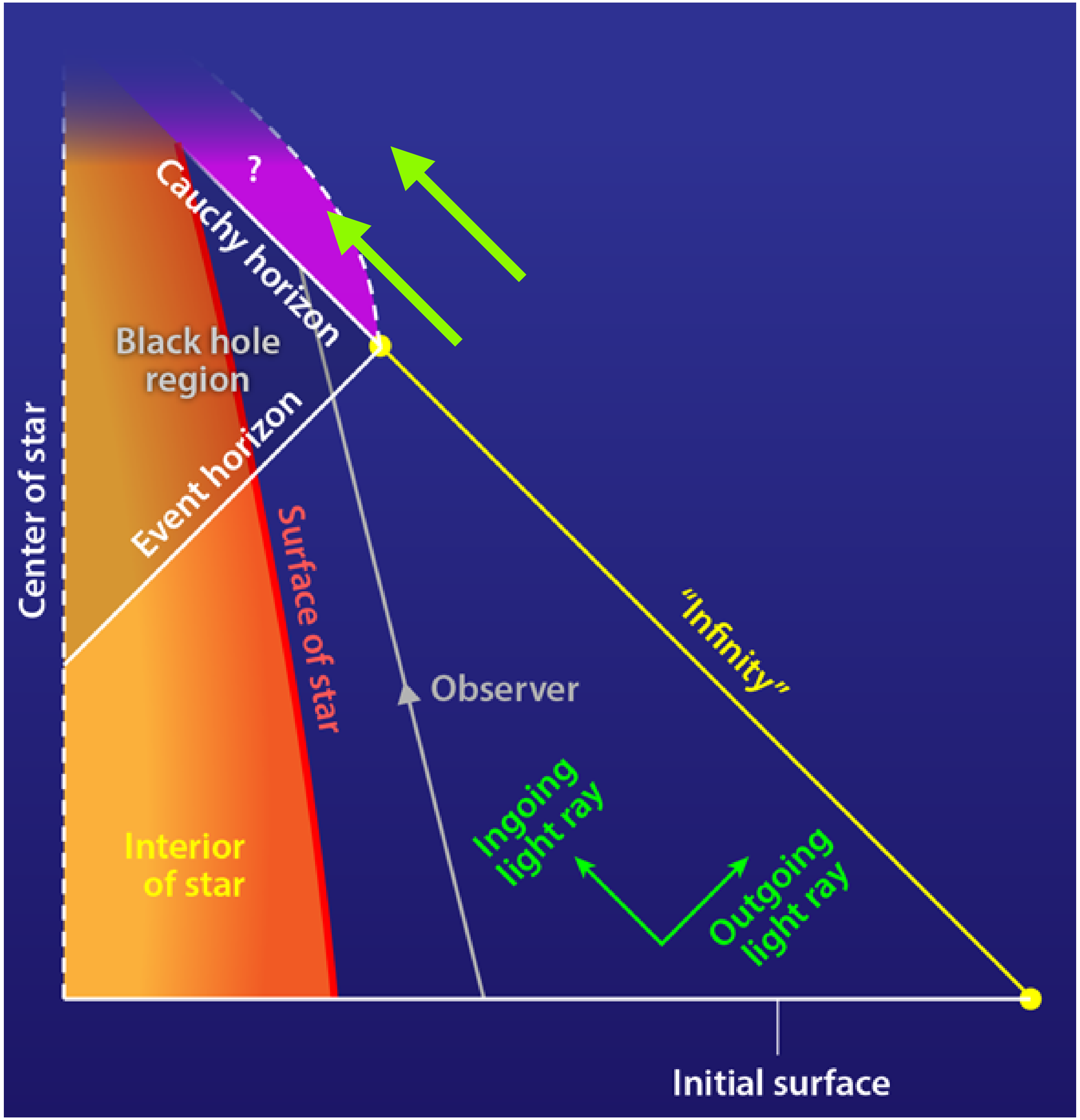
- Solution **beyond** the Cauchy horizon is ***NOT*** **determined by initial data on Σ**.

There are **infinitely** many **ways** of smoothly **extending** the solution **across** the **Cauchy** horizon.

- Interested in the ``*right*`` **Cauchy horizon** CH_R^+

  because **early time section** of this is expected to be present in a **BH formed from collapse**.





→ **we have a problem ...**

- **Newtonian physics, Maxwell theory, Yang-Mills, Schrödinger equation:**

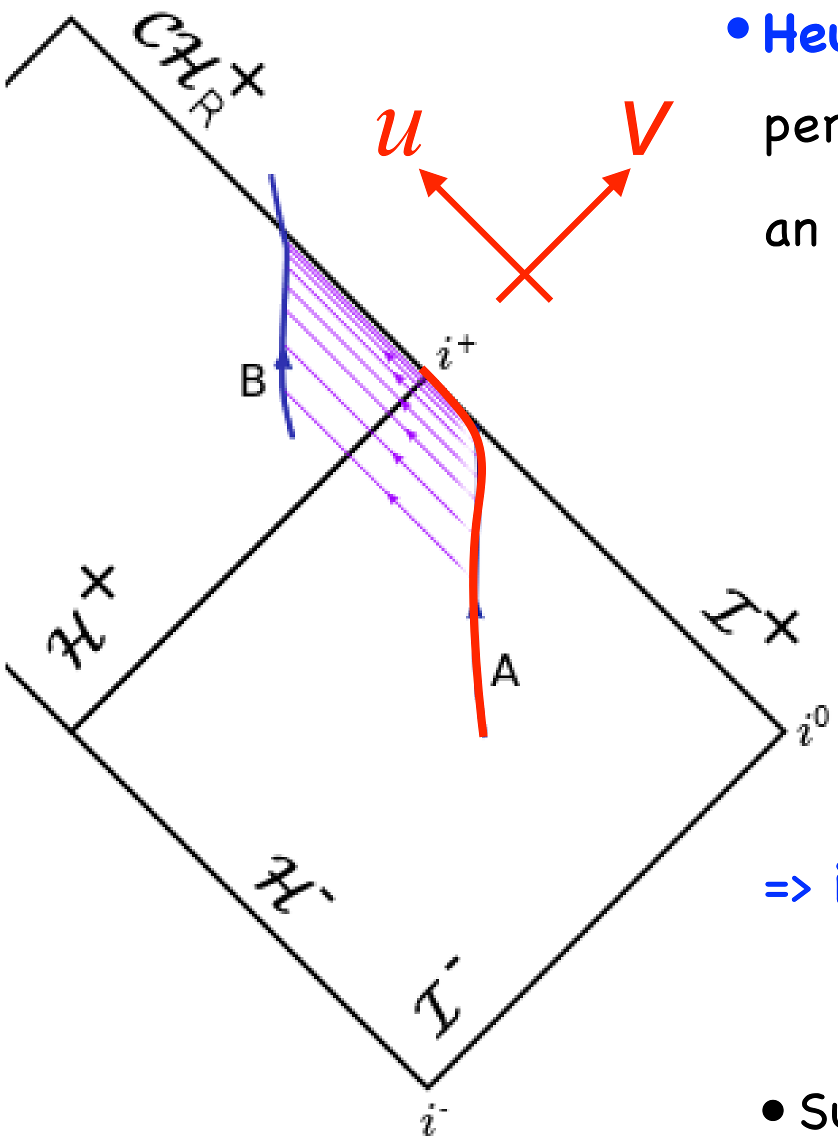
  solution **determined** globally **from initial data:** can **predict** future

- **BUT** in **GR** we **can smoothly extend a solution**

  into a region of spacetime which **canNOT** be **predicted from initial data !**

This is a **worrying failure of determinism** in physics.

- **Penrose: Cauchy horizon should be unstable!** This **would restore predictability!**



- **Heuristics:**

  perturbations entering from outside the BH experience an **infinite blue-shift** at the right Cauchy horizon.

$$\frac{\nu_B}{\nu_A} = \frac{\Delta\tau_A}{\Delta\tau_B} \sim e^{\kappa_- v} \quad \text{as} \quad \begin{array}{l} r \to r_- \\ v \to \infty \end{array}$$

$v = t + r_*$: ingoing Eddington-Finkelstein time

=> **infinite energy densities** observed at the $\mathbf{CH_R^+}$

- Suggests there will be a **large backreaction at the Cauchy horizon,** perhaps **causing** it to be **replaced by a singularity**

→ Strong cosmic censorship conjecture (Penrose 70's)

[aka Very SCC or C^0 version]

- Consider complete, asymptotically flat initial data for the Einstein-Maxwell eqns.

  Then **generically** (generic initial data) the resulting

  solution cannot be extended (continuously) across a Cauchy horizon

  (the maximal Cauchy development of a two-ended Σ is inextendible**)**

- If correct, this conjecture **restores predictability**

  without invoking poorly understood physics

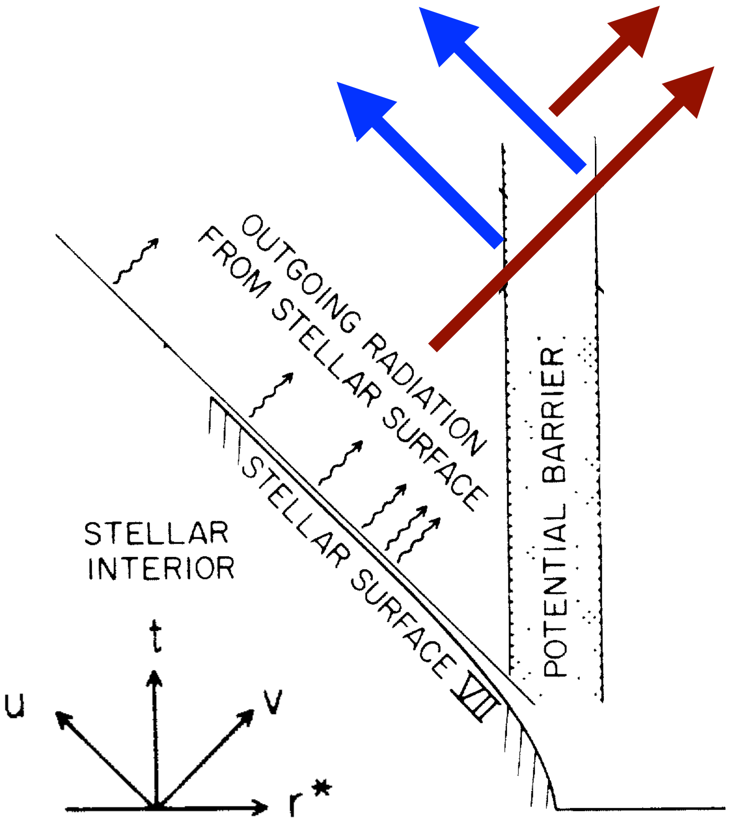
  (e.g. backreaction of quantum effects).

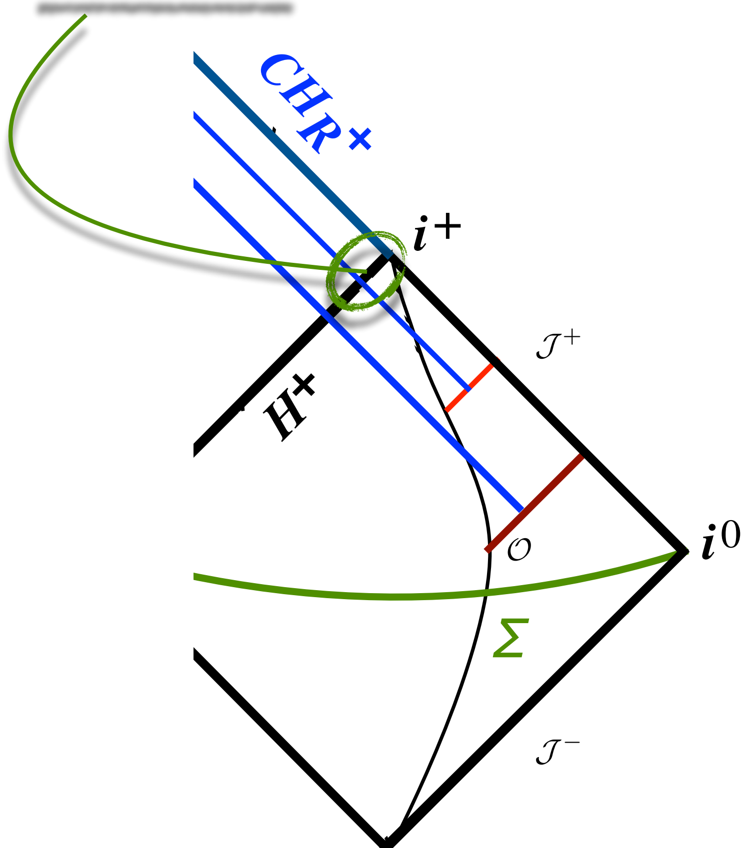
- **NOT** related to Penrose's **weak cosmic censorship** conjecture:

  "naked singularities don't form from collapse"

→ Evidence for the conjecture: linear

- Consider linear **perturbations of RN BHs:**
  massless scalar (or linearized gravito-electromagnetic perturbations).
- Take **initial data compactly supported on** Σ.
- Perturbations outside BH exhibit **power-law decay** ("**late time tails**") [Price 72]
- This is **slow enough** to **trigger the blue-shift instability** at the Cauchy horizon
- Inverse-power law tail of grav. collapse **provides initial data** for **internal problem**





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- **Result:**
  - **gradient of scalar diverges** at Cauchy horizon.
  - **Energy density** measured by **observer crossing CH** is **divergent**:

$$\rho = T_{\mu\nu} u^\mu u^\nu$$

=> **Expect large backreaction** on **metric.**

[McNamara (1978) Chandrasekhar & Hartle (1982)]

→ Evidence for the conjecture: nonlinear

[Poisson-Israel (1990), Ori (1991)]

"Null dust" model (charged Vaidya with infalling null dust):

- **Backreaction** causes the

  invariant "Hawking mass" to **diverge** at the Cauchy horizon ("**mass inflation**").

  => **Energy density** $\rho = T_{ab}\, u^a u^b$ measured by free-falling observer also **diverges**.

  => **Cauchy horizon** becomes **singular**, in agreement with conjecture.

- **However**: the metric can be **continuously extended across Cauchy horizon**

  (so the Cauchy horizon can still be defined).

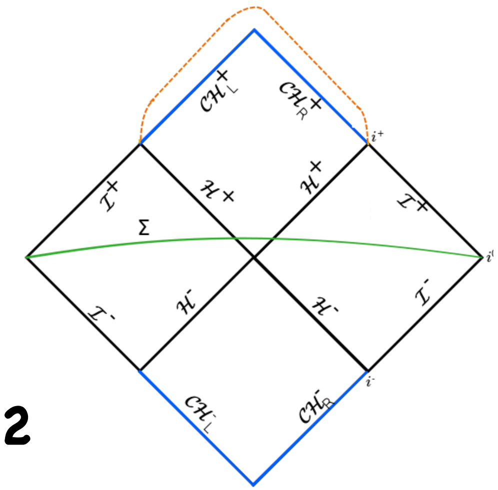
  => the **singularity** at CH_R^+ **is null** at least at "early time".

(Maybe) NOT what Penrose had in mind !

→ Rigorous results: RN

[Dafermos (2003, 2012), Luk & Oh (2017)]

- Spherically symmetric Einstein-Maxwell coupled to massless (neutral) scalar field Φ
  Consider **nonlinear** perturbations of RN solution by Φ.



- Take compactly supported initial data for Φ on **two-ended** Σ.

  Then the **(nonlinear) solution** can be **continuously** & globally

  extended across a Cauchy horizon.

- Generically, if $|\partial_v \Phi|_{\mathcal{H}^+} \geq C v^{-p} \ \ (p > 1)$, the extension is **not C2** at the Cauchy horizon.

  => Cauchy horizon is a **weak null singularity**.

- **If** we **only** specify data for Φ in **one asymptotically flat region** then above statements **apply** to the **"early time" part of the "right" Cauchy horizon** CH_R^+.

- **Effectively proves "mass inflation"**

→ Rigorous results: Kerr

Kerr: [Dafermos & Luk (2017)]

if (nonlinear) gravitational perturbations decay along the $\mathcal{H}^{+}$ at the expected inverse power-law rate

then the **perturbed solution** can be **continuously extended** across a Cauchy horizon at early time.

→ Crossing the Cauchy horizon

- **Summary so far:**

  a perturbed RN BH solution be can **continuously extended across a CH**

  (i.e. Penrose's C^0 version of SCC is false)

  but the extension is **not** in C^2, i.e., the **CH is a curvature singularity**.

  => Great! **Predictability is restored!**

- Not so fast! **Ori (1991)** ... **a twist in the story:**

– Consider an (**extended**) observer approaching the CH.

  The **total tidal distortion** felt by this observer can **remain bounded!**

– So **what happens** to such an observer?

– To answer this question, one must **specify:**

  what is the **matter field content of** the observer & their **EOM**.

If these EOM still **"make sense" at the CH** then we **still** have a **problem** with **predictability**! (i.e. CH has singularity but **observer survives its crossing**)

→ Weak solutions

- KEY question: What it the **minimal regularity** required to **make sense of EOM?**
- Can make sense of solutions **less regular than C^2** as **weak solutions**.

  Example: **shocks** in compressible perfect fluid.

– Scalar field Φ: $\Box\Phi = 0.$
– Treat this as a $\mathbf{1^{st}}$ **order** perturbation, **sourcing** a $\mathbf{2^{nd}}$ **order** metric pert $h^{(2)}_{\mu\nu}$. One has:

$$\mathcal{L}\, h^{(2)}_{\mu\nu} = 8\pi\, T_{\mu\nu}[\Phi] \qquad \sim \qquad \nabla^2\, h^{(2)}_{\mu\nu} = 8\pi\, T_{\mu\nu}[\Phi]\,. \qquad \textbf{(1)}$$

Well defined if $h^{(2)}_{\mu\nu}$ **twice continuously differentiable** (of class C^2) and Φ of class C^1.

– Multiply (1) by a smooth, compactly supported, symmetric tensor, $\psi^{\mu\nu}$ & integrate by parts:

$$\int d^4x\sqrt{-g}\left(-\nabla h^{(2)}_{\mu\nu}\nabla\psi^{\mu\nu} - 8\pi\psi^{\mu\nu}T_{\mu\nu}\right) = 0 \qquad \textbf{(2)}$$

Keypoint: Can have Φ, $h^{(2)}_{\mu\nu}$ **obeying** (2) (if C^1) but, **if** $h^{(2)}_{\mu\nu}$ **not** C^2, (1) **is not obeyed**

- If (2) is obeyed for *any* $\psi^{\mu\nu}$ $\Longrightarrow$ we have a **weak solution** of **original** Einstein eqn (1)

→ Weak solutions

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- If (2) is obeyed for *any* $\psi^{\mu\nu}$ $\Longrightarrow$ we have a **weak solution** of **original** Einstein eqn (1)
- **EOM** (2) **"makes sense"**, if terms involving Φ are **finite**

  $\Rightarrow$ **require that Φ belongs to Sobolev space H^1_{loc}** :
  space of functions Φ s.t. for any smooth compactly supported function ψ,
  $(\hat{\Phi}^2 + \partial_\mu\hat{\Phi}\partial_\mu\hat{\Phi})$ **is integrable** (where $\hat{\Phi} \equiv \psi\Phi$).

locally square integrable: $\psi\Phi$ is square integrable

→ Christodoulou's formulation of SCC

- **Criterion for weak solutions** of the **full nonlinear** **vacuum** **Einstein equation:**

A **weak solution** of the Einstein equation $[T[\Phi] \to T\big[(h^{(1)})^2, (\partial h^{(1)})^2\big]$

must have **locally square integrable (H^1_{loc})** **Christoffel symbols** in some chart.

- **Christodoulou's version** of the **SCC conjecture** (2009):

generically, it is **not** possible to **extend** the maximal Cauchy development

across the Cauchy Horizon

as a **weak metric solution of EOM** (=> also not C^2)

- If correct then generically there is **no way** of **extending** beyond the CH

in such a way that **(at least the weak version of) EOM are satisfied** there

=> predictability restored!

- This version of the conjecture is **believed** to be **true** with Λ **= 0**.

→ Summary so far ($\Lambda = 0$)

- Different SCC versions distinguished by **smoothness level** required at Cauchy CH_R
- In order of **decreasing strength**:
  - **C^0 version (Very SCC):** generically **no continuous** extension exists across **CH**
    => singularity exists before Cauchy horizon forms.
    ⇓
  - **Christodoulou version:** generically **no weak** extension (with H^1_{loc} Christoffel symb.)
    => Cauchy surface is a weak null singularity.
    ⇓
  - **C^2 version:** generically **no** C^2 extension.
- For **Einstein-Maxwell(-massless scalar)** theory, with $\Lambda = 0$:
  - **C^0 version** is **false** [proof by Christodoulou; Dafermos-Luk]
  - **Christodoulou** version **believed** to be **true** [proof for Einstein-scalar: Dafermos-Rothman; Luk-Oh]
  - Strong evidence that **C^2 version** is **true**.

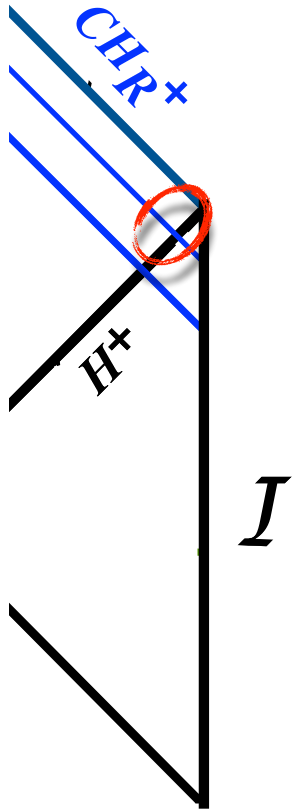
2. Strong Cosmic censorship with $\Lambda > 0$

→ The cosmological constant: $\Lambda < 0$ (AdS)

- Λ **< 0:** perturbations outside an **AdS_4** BH **decay** very slowly ($\sim 1/(\log t)^{\#}$), i.e. more slowly than power-law decay of Λ=0 [Holzegel-Smulevici (2013)].

- This is **likely to** strengthen the instability of the **Cauchy horizon**.

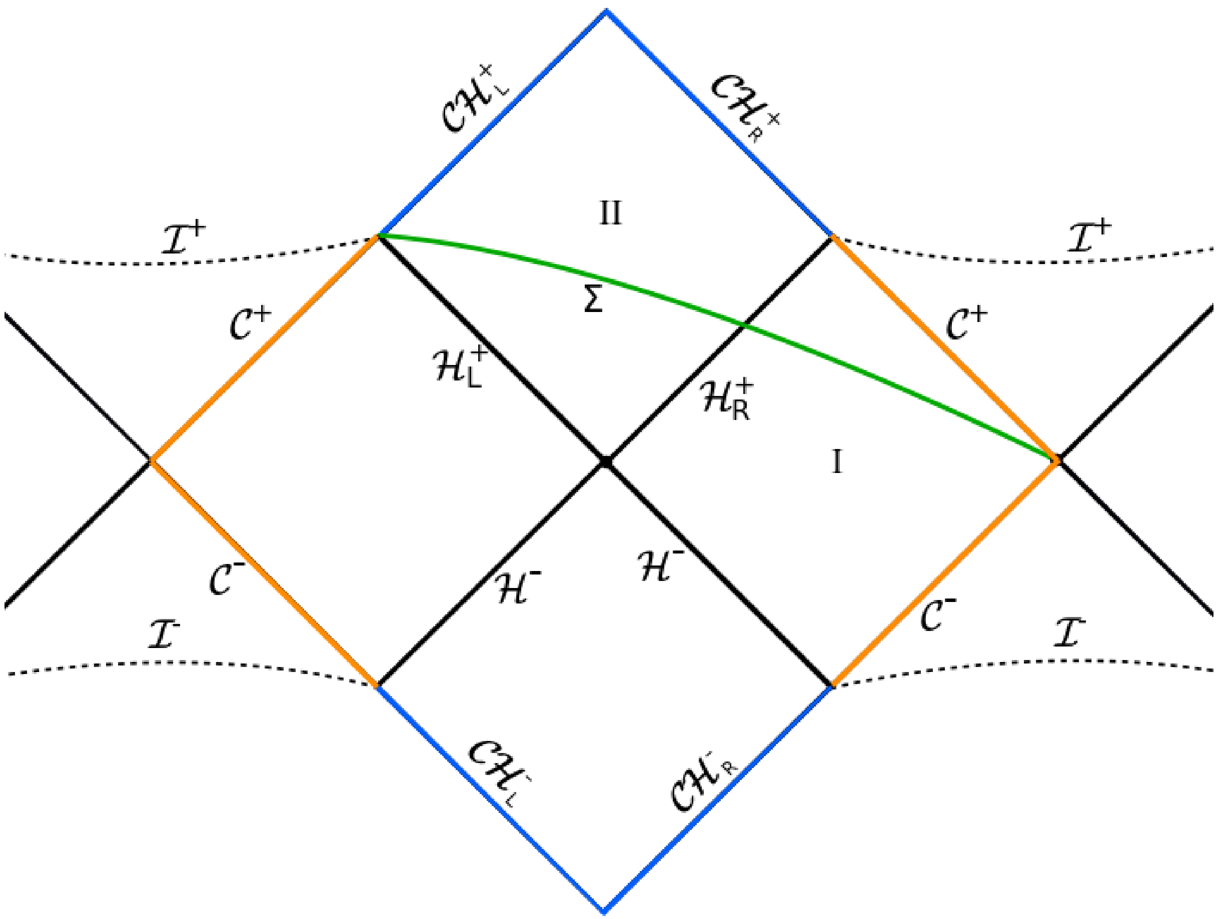
  => Christodoulou version of SCC expected to be true.



- **But** (surprisingly) C^0 version still false [Kehle (2018)]

→ The cosmological constant Λ > 0 (de Sitter)

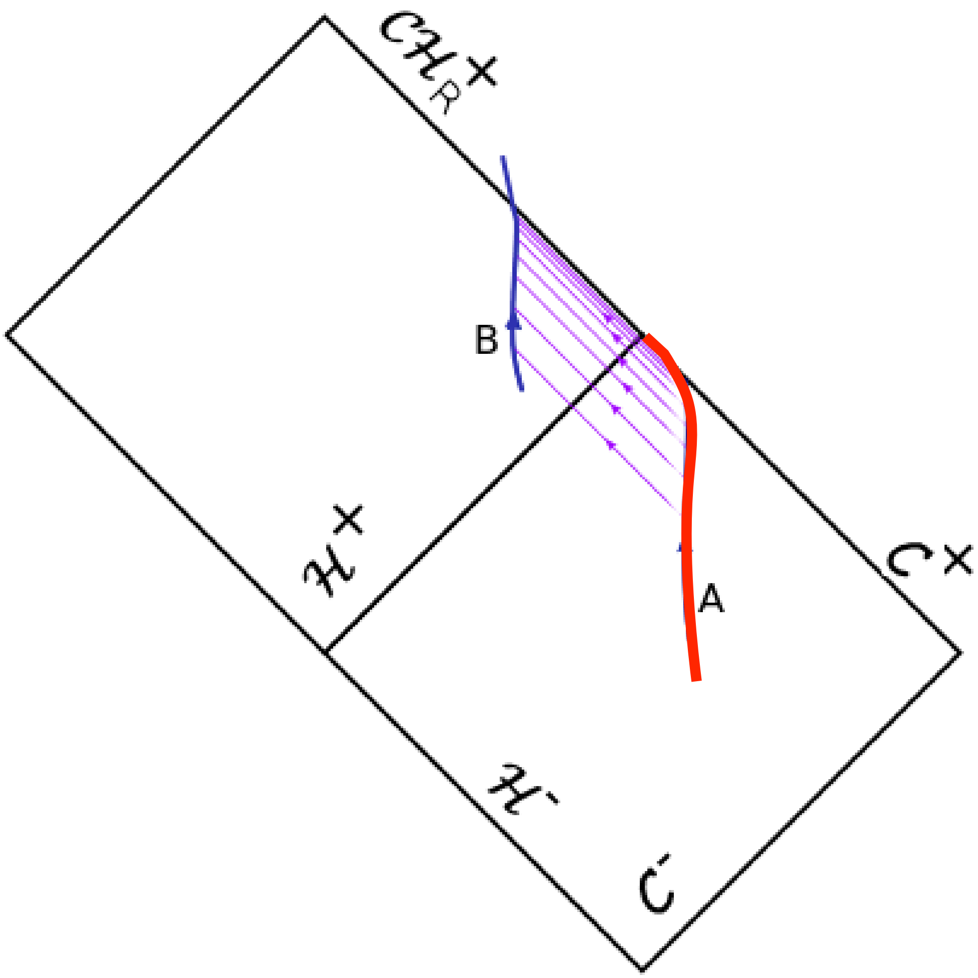
Onwards, assume Λ **> 0**: we now have a **cosmological horizon** $\mathcal{C}^{+,-}$.



→ Blue vs red shift competition

- **Perturbations entering H+** at **late time** have to **climb out** of the **potential well** associated with the **cosmological horizon**, suffering a **red-shift**.

- This **competes** with **blue-shift at Cauchy horizon**: **which effect wins ?**



→ Mellor-Moss (1990)

- Perturbations of Reissner-Nordstrom-de Sitter (RNdS) **decay very fastly (exp)!**

- They argued that **late time decay** of linear perturbations outside the BH is **determined** by the **slowest decaying quasinormal mode** (damped oscillation).

- **Quasinormal mode:** solution with time dependence $\mathbf{e}^{-i\,\omega\,t}$ smooth on future event horizon $\mathbf{H^+}$ and future cosmological horizon $\mathbf{C^+}$. ω is complex with $\mathrm{Im}(\omega) < 0$.

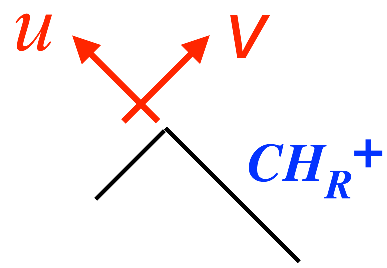
- Define **spectral gap** α to be the **minimum value of** $-\mathrm{Im}(\omega)$

  So **generic** perturbations **decay exponentially** in time as $e^{-\alpha\,t}$,

  (in contrast with power-law decay for $\Lambda = 0$)

- **Does this decay trigger the blue-shift instability** of Cauchy horizon CH_R^+ ?

- Introduce **double null coordinates (U, V)** so that **Cauchy** horizon is at **V = 0** with **BH interior** in **V < 0**.



- MM showed that **near Cauchy horizon**,

  generic **linear perturbations** are **proportional** to **$(-V)^\beta$** with

$$\beta = \frac{\alpha}{\kappa_-}$$

  κ_- is the (positive) **surface gravity** of the **Cauchy horizon**

- So **gradient** of perturbation $\partial\Phi \sim (-V)^{\beta-1}$ **blows up** at Cauchy horizon **if $\beta<1$**

- MM showed (numerically) that most RNdS BHs have $\beta<1$.

  => **backreaction** causes curvature to **blow up** at the **Cauchy horizon**

  => good, **C^2 version of SCC is obeyed**.

- But MM also claimed that near-extremal RN holes have $\beta > 1$.

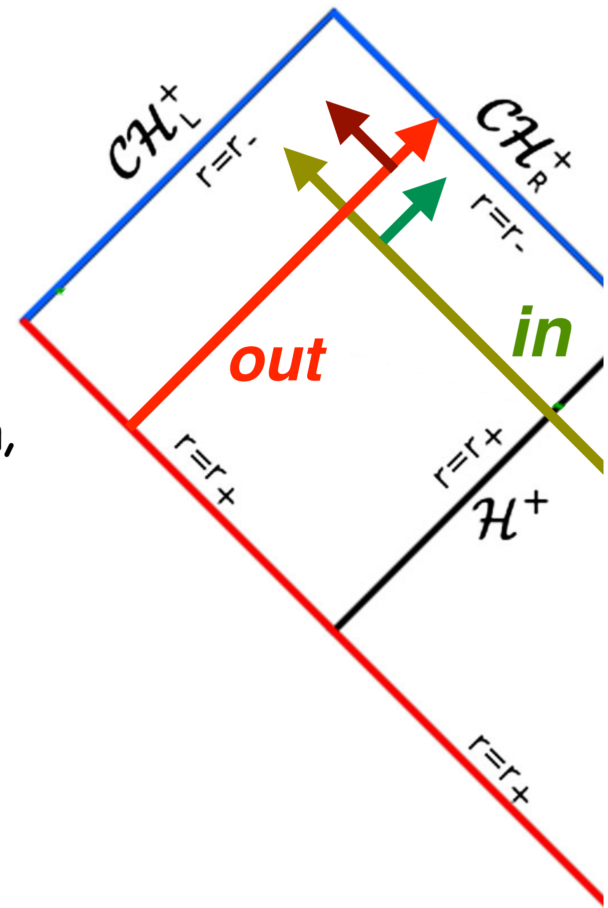
  If correct, this **would** entail a **violation** of the **C^2 version of SCC** !!!

→ Confusion

- [Brady, Moss & Myers **"Cosmic censorship: as strong as ever"** (1998)]:

  argued that the **MM** analysis **overlooks**

  the effect of **outgoing radiation** inside the hole.



- BMM <u>**claimed**</u> that **backscattering** of such radiation

  would always have a **large effect at** the **Cauchy** horizon,

  restoring the **C^2 version of SCC** for $\Lambda > 0$.

- It turns out that the **BMM argument has a problem:**

  we showed that their **initial** perturbation

  is <u>**not**</u> **smooth (not even C^1)** at the **event horizon !**

[OD, Reall, Santos 1808.02895]

However, main conclusions correct!!! —> see **rough** Dafermos & Shlapentokh-Rothman (2018) <u>**later**</u>

→ Recent developments

- [Hintz & Vasy (2015)]

  For smooth initial perturbations,

  HV have (mathematically) proved that the **behaviour** of **linear perturbations** **at** the **Cauchy horizon**

  is **indeed determined** by **quasinormal modes**,

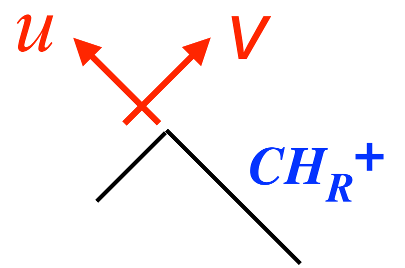
  as originally claimed by Mellor-Moss.

- Therefore:

  – **C^2 version respected iff** $\beta < 1$

  – If nonlinearities behave as expected then
  Christodoulou version of SCC is respected iff $\beta < 1/2$

is $\beta < 1/2$? [later slide]



- **Origin of critical** $\beta \equiv -\frac{\text{Im}(\omega)}{\kappa_-} = \frac{1}{2}$ **?**

– Near $\mathcal{CH}_R^+$, **QNM** is **sum** of **two independent** solutions (u: outgoing EF time):

$$\Phi\Big|_{\mathcal{CH}_R^+} = A\,\Phi^{(1)} + B\,\Phi^{(2)} \quad \text{with} \begin{cases} \Phi^{(1)} = e^{-i\omega u} Y_\ell(\theta) \hat{R}^{(1)}_{\omega\ell}(r) \\ \Phi^{(2)} = e^{-i\omega u} Y_\ell(\theta) (r - r_-)^{i\omega/\kappa_-} \hat{R}^{(2)}_{\omega\ell}(r) \end{cases}$$

[$\hat{R}^{(1,2)}_{\omega\ell}(r_-) \neq 0$ and smooth]

$\text{Im}(\omega) < 0 \;\; \Rightarrow \;\; \Phi^{(2)}(r_-) = 0$ **BUT** $\Phi^{(2)}$ is **not** smooth at $r = r_-$.

NO reason for $B = 0$ $\Rightarrow$ **regularity of QNM** is determined by the **non-smooth** $\Phi^{(2)}$.

– ***What is the condition for $\Phi^{(2)}$ to be locally square integrable?***

$\Phi^{(2)} \sim (r - r_-)^p$ with $p = i\omega/\kappa_-$ $\Rightarrow \partial_r \Phi^{(2)} \sim (r - r_-)^{p-1}$

which is square integrable $\left(\int \left(\partial_r \Phi^{(2)}\right)^2$ **finite**$\right)$ **iff** $2(\beta - 1) > -1$ where $\beta = \text{Re}(p)$.

$\Longrightarrow$ **QNM** $\in H^1_{\text{loc}}$ **at** $\mathcal{CH}_R^+$ **iff** $\beta \equiv -\frac{\text{Im}(\omega)}{\kappa_-} > \frac{1}{2}$ $\longrightarrow$ Christodoulou's SCC may be violated

- Therefore:
  - if $\exists$ a QNM with $\beta < 1/2$ => Φ cannot be extended across CH_R^+ in H^1_{loc} => **SCC ok**
  - if **all** QNM have $\beta > 1/2$ => **SCC** may be **violated**

- **[Cardoso, Costa, Destounis, Hintz & Jansen (2017)]:**

  careful numerical study of massless scalar field QNMs of RNdS.
  - Calculate slowest-decaying QNMs to determine β
  - Found that **near-extremal RNdS holes** have $1/2 < \beta < 1$

    => so massless scalar perturbations

    violate the Christodoulou version but not the **C^2 version of SCC.**

- Very recently: numerical confirmation that this is true with **backreaction**, in **spherical** symmetry. **[Cardoso et al (2018)]**

→ Our work: RNdS

[OD, Reall, Santos 1808.02895]

- We studied linearized (coupled) **gravitational-electromagnetic** perturb of RNdS

- We found that **near-extremal** RNdS BHs **always** have $\beta > 2$

- Hence, in **pure** Einstein-Maxwell theory, **not only** is the

  Christodoulou's version of SCC violated but **so is the C^2 version !!!**

- **In fact**, generic perturbations are C^r at the Cauchy horizon,

  where r can be **made arbitrarily large**

  by making the **BH sufficiently near-extremal** & **sufficiently large** (in units of Λ)

.

- So **SCC** is **very badly violated** in **Einstein-Maxwell** theory with $\Lambda > 0$ **!!!**

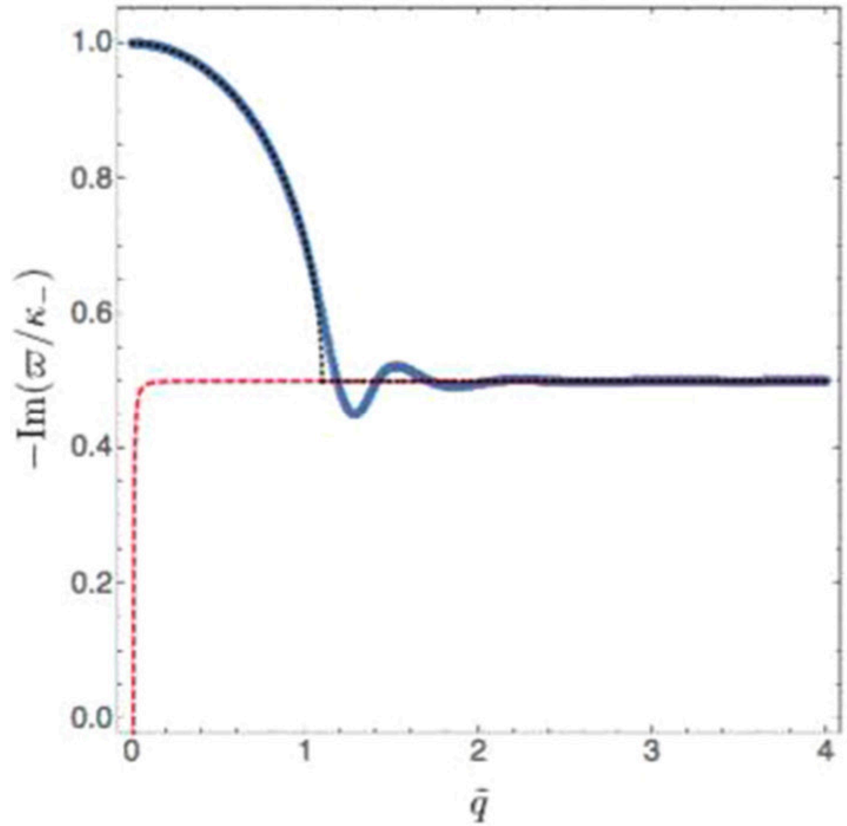
→ Our work: Adding charged matter to RNdS

- In **Einstein-Maxwell(-uncharged scalar)** theory,

  it is **impossible** to **form** a **RNdS black hole**: **no charged matter**.

- So **add** a **charged scalar field.**
- **Our results:**

  [OD, Reall, Santos, 1808.04832]



for **"physical" (large) values of charge,**

β is **very close** to **1/2** BUT oscillates around 1/2 as **BH** approaches extremality

=> **Christodoulou's** version of **SCC is violated** (β > 1/2).

- [see also Hod (2018), Cardoso et al (2018)]: β **> 1/2 not seen**

  because not close enough to extremality

→ Our work: Kerr dS

- $\Lambda > 0$ is our **Universe**. But near-extremal **RNdS** black holes are **unphysical**:

  highly charged BHs don't exist in **Nature!**

- **RN** is often regarded as a **toy model for Kerr within spherical symmetry**.

- **So is there a violation of SCC for near-extremal Kerr-dS ?**

- We studied **QNMs with large angular momentum**, i.e., $\Phi \propto e^{im\varphi}$, $|m| \gg 1$,

  both for **scalar field** and **gravitational** perturbations.

- In this limit, the modes can be calculated using **geometric optics**,

  i.e., **looking** at **null geodesics**.

- **Ingoing/outgoing boundary conditions** at the **event/cosmological horizons**

  ↔ **null geodesics** which do **not cross** any **horizons to the past**.

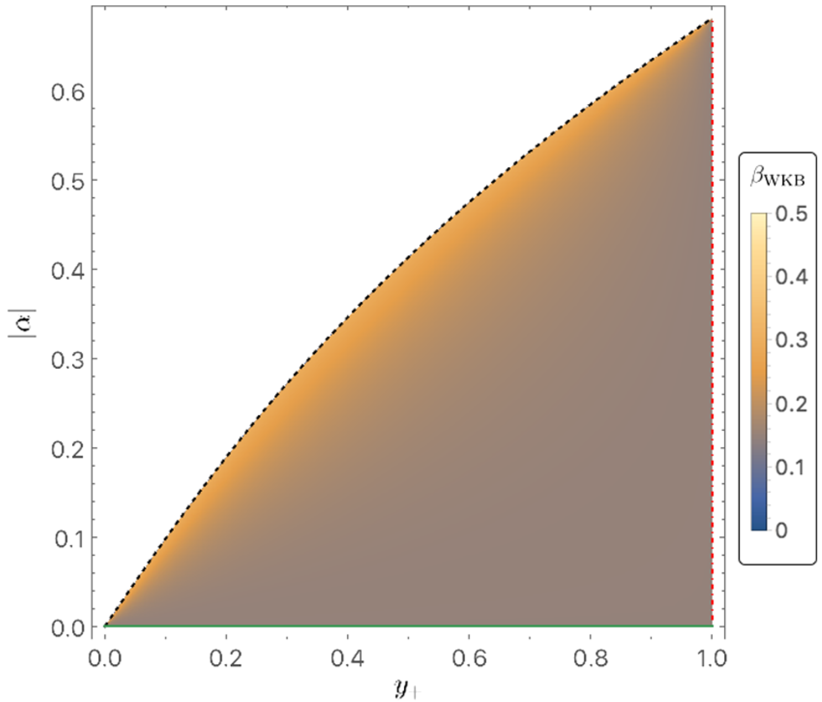
→ Our work: Kerr dS

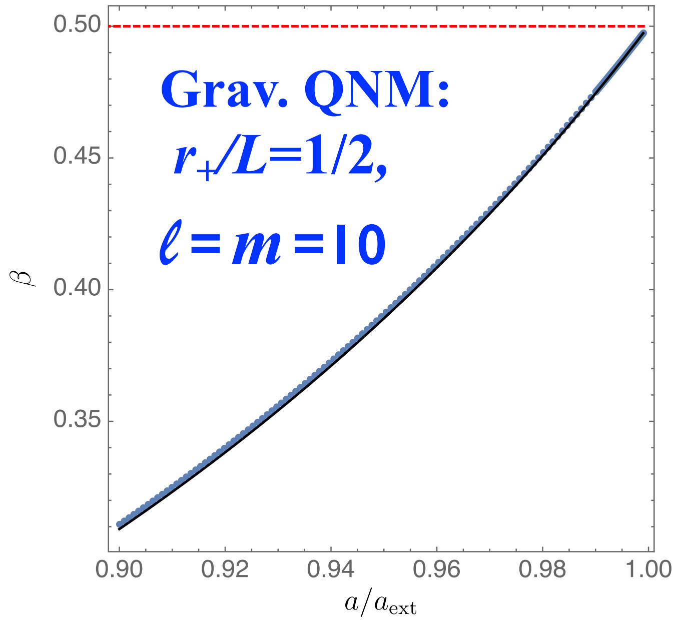
[OD, Eperon, Reall, Santos, 1801.09694]

- The **photon sphere** consists of null geodesics which **remain forever** at **fixed r**.
- These are **unstable trajectories:**

  the **decay rate when perturbed** fixes the **imaginary part** of **associated QNM**.
- From such trajectories we can place an **upper bound** on β: $\beta < 1/2$
- Thus **Christodoulou's** version of **SCC** is **respected** by **Kerr-dS !!!**
- So when Λ **> 0**, Christodoulou's SCC is **respected** in **pure Einstein** gravity

  BUT violated in **Einstein-Maxwell** theory.





→ Taking the rough with the smooth

- **How** do we **rescue SCC** in Einstein-**Maxwell** theory with $\Lambda > 0$?

- So far we've considered perturbations arising from **smooth initial data**.

- [Dafermos & Shlapentokh-Rothman (2018)]: consider **rough initial data**.

  => **Late time behaviour** is no **longer dictated** by **quasinormal modes**.

- The **smoothness** of the **solution** (in the sense of **Sobolev** spaces)

  generically **gets worse** at the **Cauchy horizon**.

(In fact this is precisely what **happens** in the **earlier** argument of **Brady, Moss, Myers**!)

[OD, Reall, Santos 1808.02895]

- A **generic** perturbation arising from

  initial data with the **minimum acceptable** level of **smoothness** will not **have**

  this minimum acceptable level of **smoothness** at the **Cauchy** horizon.

3. Quantum effects

→ Quantum effects: theory with charged particles

- $\Lambda \leq 0$: **Christodoulou's version of SCC** appears to be **true**

  so we do **not** need to invoke quantum effects to restore predictability.

- **$\Lambda > 0$: do quantum effects help?**

- **If** theory **contains** **charged particles**: RNdS BH can **radiate** them & **lose** its **charge**

- This does not depend on the mass of the particles:

  redshifted away at cosmological horizon!

- So **Hawking radiation** will **drive BH away from extremality** => **SCC** is **saved**.

→ Quantum effects: theory with NO charged particles

- Now consider RNdS in <u>**pure**</u> Einstein-Maxwell theory (<u>**no**</u> charged matter).

- We have **Hawking radiation** of **photons** and **gravitons**
  from both the BH horizon and the cosmological horizon.

- This will **drive a RNdS BH away from extremality** towards a "**lukewarm**" solution
  (for which the two horizons have **equal temperatures**)

- **BUT** such BHs are **still close enough** to **extremality**
  to **violate Christodoulou's version of SCC** (but not C^2 version).

→ Quantum effects: theory with NO charged particles

- Expect the **quantum state** of the **fields** to **approach**

  the **Hartle-Hawking** (thermal) state at **late time**.

- It would be interesting to **calculate** $\langle T_{\mu\nu} \rangle$ in this **HH state**

  near the **Cauchy** horizon of a **lukewarm** BH.

- **Does** $\langle T_{\mu\nu} \rangle$ **diverge** at the Cauchy horizon **sufficiently rapidly**

  to ensure that $G_{\mu\nu} = 8\pi \langle T_{\mu\nu} \rangle$ **cannot be satisfied** there, **even weakly?**

- **If so** then **predictability** would be **enforced** by **vacuum polarization**.

- Calculations in a **2d toy model** show that

  $\langle T_{\mu\nu} \rangle$ **does diverge** at a Cauchy horizon. **[Birrell & Davies 1977]**

  – The **4d case** is much **harder!**

  $\langle T_{\mu\nu} \rangle$ has only been calculated outside a lukewarm RNdS black hole.

  [Winstanley & Young (2007), Breen & Ottewill (2010)]

→ Summary

- **Strong cosmic censorship:** physics should be predictable from initial data!

- Very likely to be **true** for $\Lambda \leq 0$.
  True for **pure Einstein** theory with $\Lambda > 0$.

- **Badly** (very! not even C^2) violated in **pure Einstein-Maxwell** theory with $\Lambda > 0$
  unless we allow **rough** initial data.

- Opportunity for quantum effects to save the day?

- Further reading:
  — **OD, Felicity Eperon, Harvey Reall, Jorge Santos**
  1801.09694 (PRD) & 1808.02895 (JHEP) & 1808.04832 (CQG)
  — **Mihalis Dafermos' website**