salvatore ribisi @ XXV SIGRAV conference
CPT - Marseille 07/09/2023

LIGHT-CONE THERMODYNAMICS

purification of the Minkowski vacuum

based on arXiv:2307.12031
in collaboration with Alejandro Perez

BLACK-HOLE THERMODYNAMICS

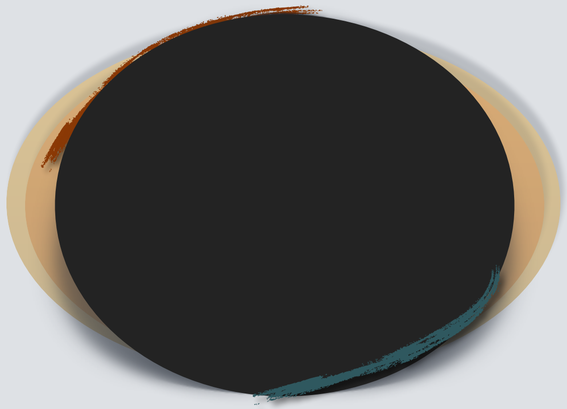
J M Bardeen, B Carter, and S W Hawking. **The four laws of black hole mechanics.** *Commun.Math.Phys.* 31 (1973) 161-170

0. constant surface gravity κ along the horizon for stationary black holes

1. under small perturbations,
$$\delta M = \frac{\kappa}{8\pi}\delta A + \Omega \delta J + \Phi \delta Q$$

2. $\Delta A \geq 0$

3. extremal black holes ($\kappa = 0$) cannot be obtained by a finite sequence of processes from non-extremal ones



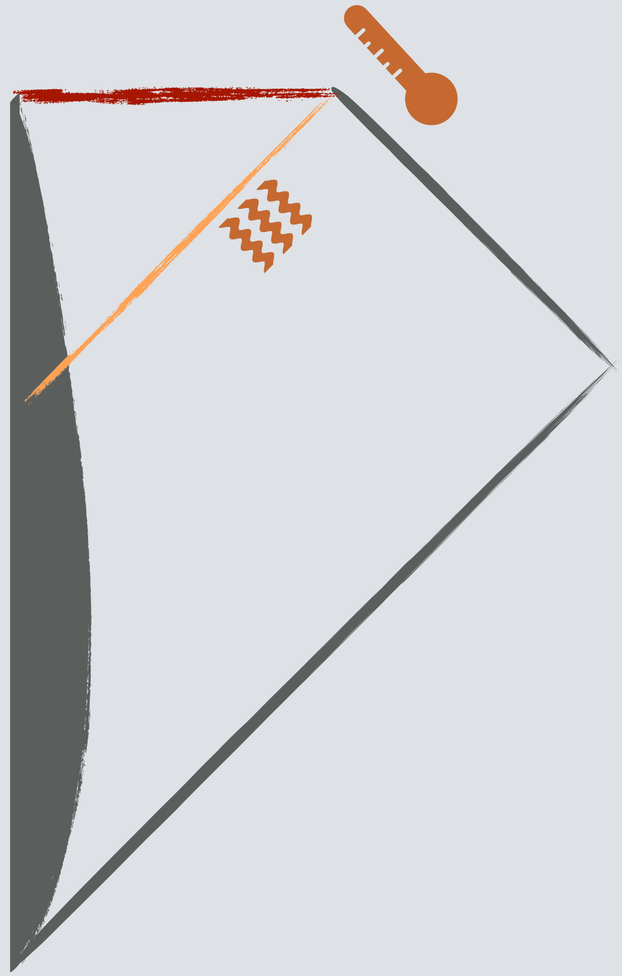
BLACK-HOLE THERMODYNAMICS

S W Hawking. **Particle Creation by Black Holes.**
Commun.Math.Phys. 43 (1975) 199-220

once ***Quantum Field Theory*** is taken into account, the analogy gets stronger

Hawking radiation has

- $T = \kappa/2\pi$
- $S = A/4$



LIGHT-CONE THERMODYNAMICS

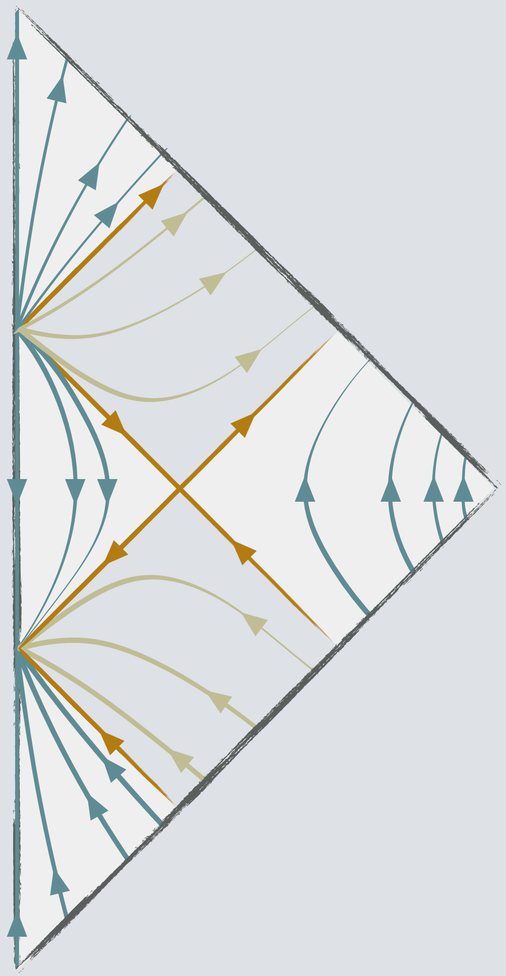
T De Lorenzo and A Perez. Light Cone Thermodynamics.
Phys. Rev. D, 97(4):044052, 2018

radial Conformal Killing Fields of Minkowski spacetime (**MCKF**) ξ given by

$$\xi^a = \kappa \left(\frac{v^2 - r_H^2}{2r_H} \left(\frac{\partial}{\partial v} \right)^a + \frac{u^2 - r_H^2}{2r_H} \left(\frac{\partial}{\partial u} \right)^a \right)$$

such that $\mathcal{L}_\xi \eta_{ab} \propto \eta_{ab}$

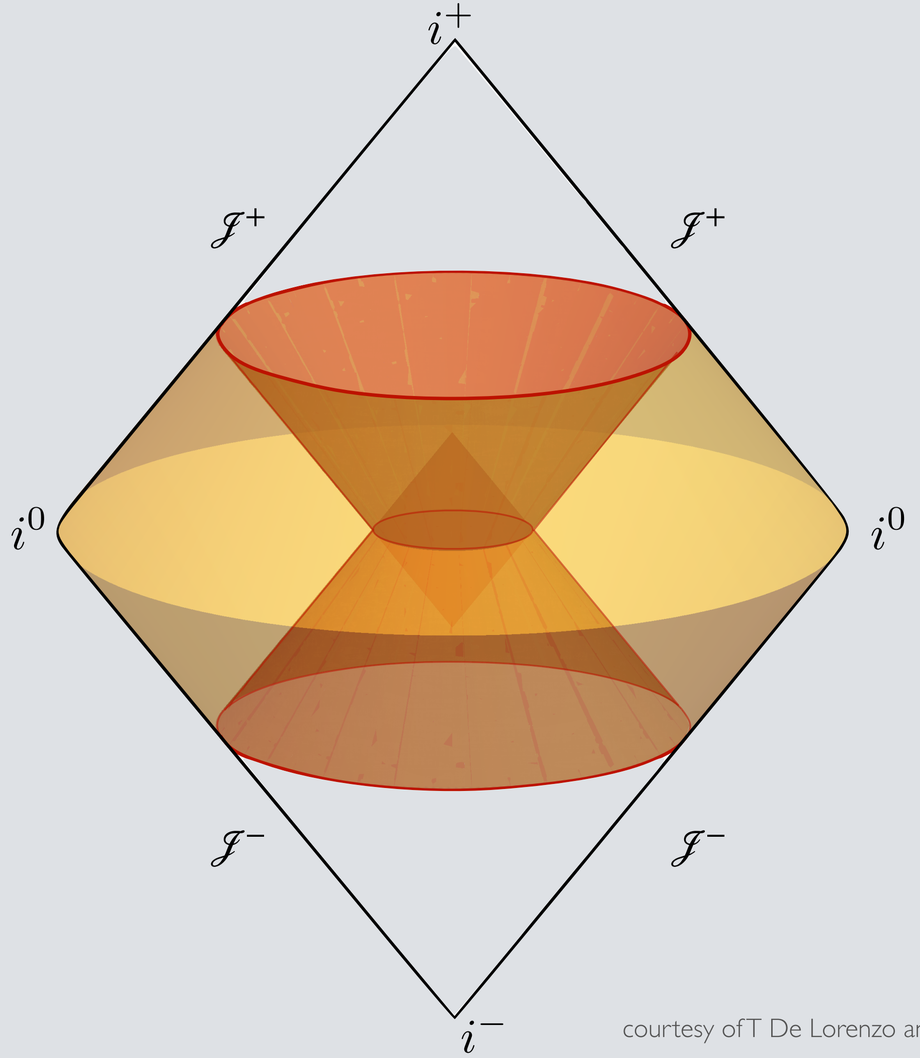
the **MCKF** divides spacetime into six regions



LIGHT-CONE THERMODYNAMICS

T De Lorenzo and A Perez. Light Cone Thermodynamics.
Phys. Rev. D, 97(4):044052, 2018

- MCKFs define conformal Killing horizons
- same topology as black-hole horizons $S^2 \times \mathbb{R}$
- bifurcate horizons, with MCFKs vanishing on a 2-sphere of radius r_H
- they separate events in spacetime as in a Reissner-Nordström black hole



courtesy of T De Lorenzo and A Perez

LIGHT-CONE THERMODYNAMICS

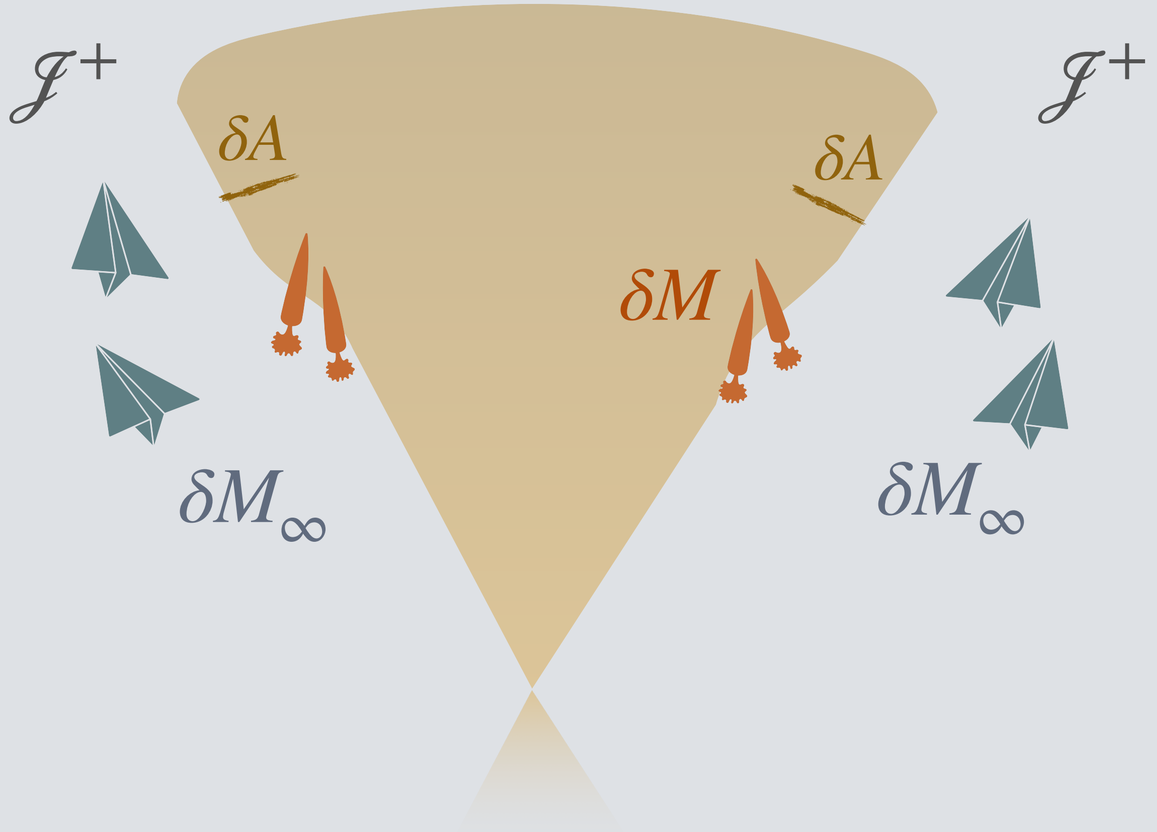
T De Lorenzo and A Perez. Light Cone Thermodynamics.
Phys. Rev. D, 97(4):044052, 2018

0. generalized constant surface gravity κ on the conformal Killing horizon

1. under conformally-invariant matter perturbations $\delta M = \frac{\kappa}{8\pi}\delta A + \delta M_\infty$

2. $\Delta A \geq 0$

3. extremal radial **MCKFs** have vanishing "temperature" and vanishing "entropy"



QUANTUM FIELD THEORY

A Perez and SR. *Light-cone thermodynamics: purification of the Minkowski vacuum.* arXiv:2307.12031

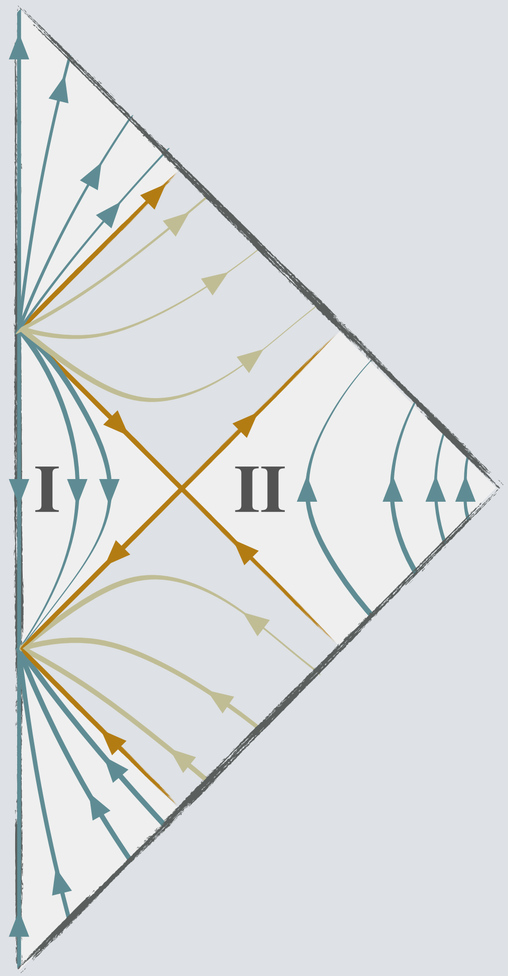
conformally invariant Klein-Gordon (**KG**) equation

$$\left(\nabla^{\mu}\nabla_{\mu} - \frac{1}{6}R\right)\phi = 0$$

we define the vacuum in terms of the radial **MCKF** in the regions where it's timelike

$$a_{\mathrm{I}}\,|0\rangle_{\xi} = 0 \qquad\qquad a_{\mathrm{II}}\,|0\rangle_{\xi} = 0$$

to express the Minkowski vacuum in terms of these modes it is crucial to study analytic properties of solutions of the **KG** equation on the light cone



UNRUH EFFECT FOR MCKF

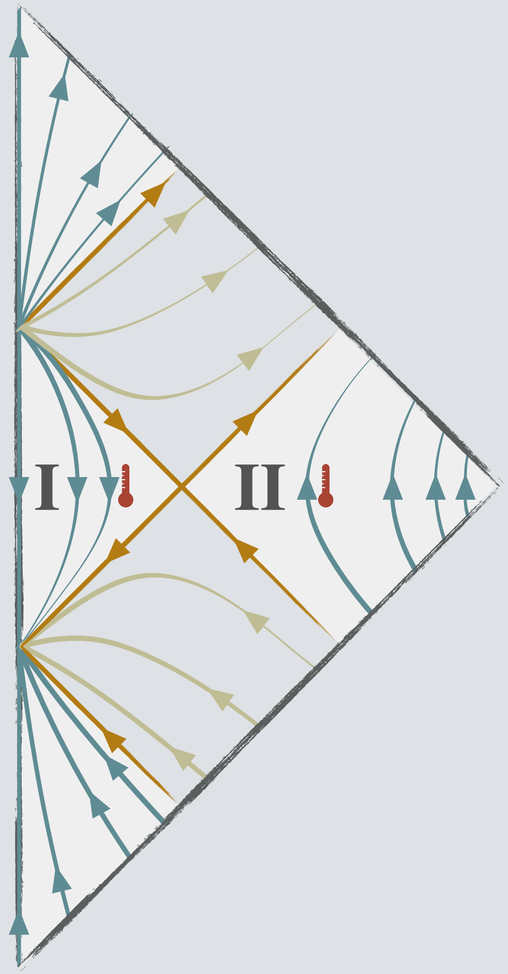
A Perez and SR. *Light-cone thermodynamics: purification of the Minkowski vacuum.* arXiv:2307.12031

this decomposition is given by

$$U\left|0\right\rangle_M = \prod_i \left(\sum_{n=0}^{\infty} e^{-\frac{n\pi\omega_i}{\kappa}} \left|n,\omega_i\right\rangle_{\mathrm{I}} \otimes \left|n,\omega_i\right\rangle_{\mathrm{II}} \right)$$

the surface gravity κ is indeed a physical temperature, as detected by conformally-invariant thermometers following the radial **MCKF**.

the laws of light-cone thermodynamics become actual thermodynamical laws, with temperature $\kappa/2\pi$ and entropy $S = A/4$.



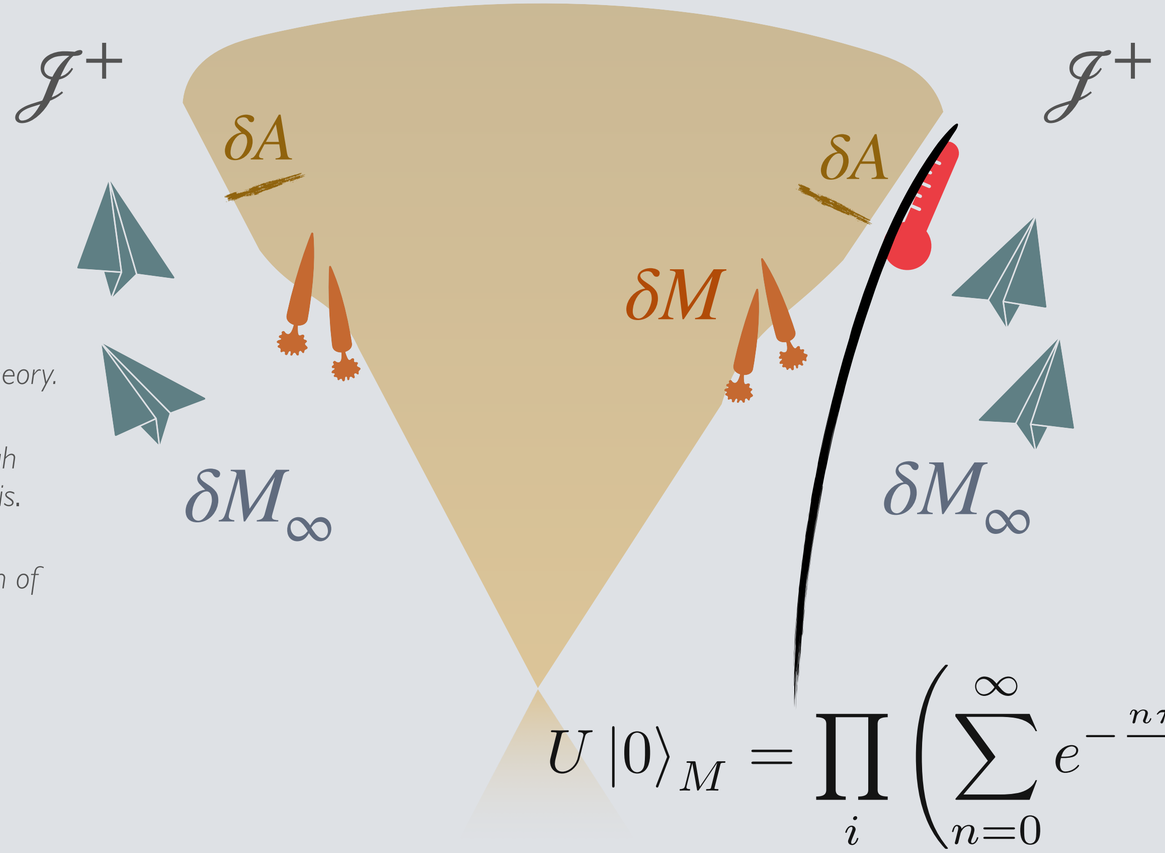
A Perez and SR. *Light-cone thermodynamics: purification of the Minkowski vacuum.* arXiv:2307.12031

T De Lorenzo and A Perez. *Light Cone Thermodynamics.* Phys. Rev. D, 97(4):044052, 2018

P D Hislop and R Longo. *Modular Structure of the Local Algebras associated with the Free Massless Scalar Field Theory.* Commun. Math. Phys. 84 (1982) 71

P Martinetti and C Rovelli. *Diamond's temperature: Unruh effect for bounded trajectories and thermal time hypothesis.* Class. Quant. Grav. 20 (2003) 4919-4932

H Casini, M Huerta and R C Myers. *Towards a derivation of holographic entanglement entropy.* JHEP 05 (2011) 036



$$U\,|0\rangle_M = \prod_i \left(\sum_{n=0}^{\infty} e^{-\frac{n\pi\omega_i}{\kappa}}\ |n,\omega_i\rangle_{\mathrm{I}} \otimes |n,\omega_i\rangle_{\mathrm{II}} \right)$$

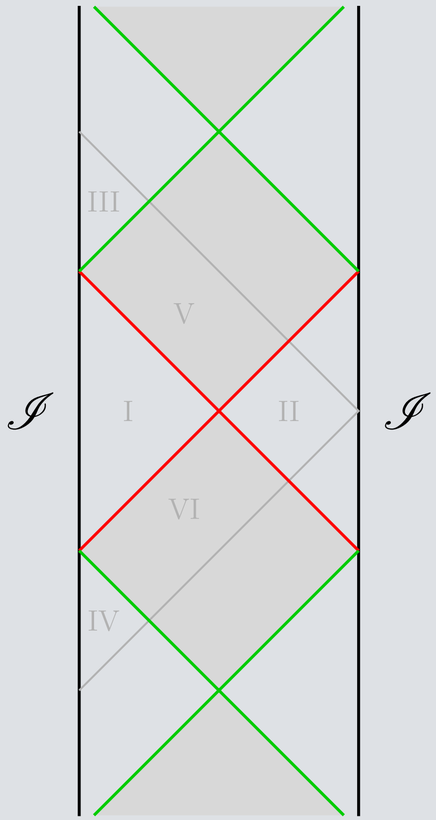
AGNEDD'E SUCU E FINÌ U VATTÌU

or

THANK YOU FOR YOUR ATTENTION

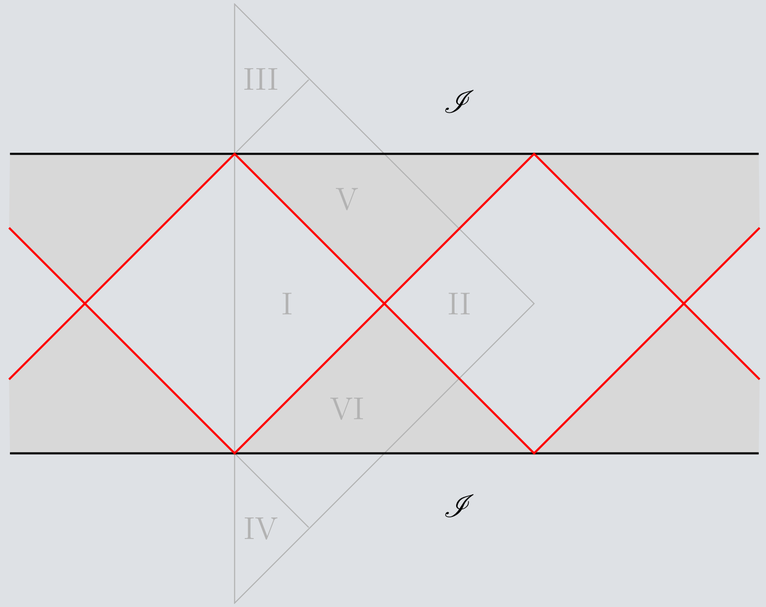
VERY GOOD QUESTION

T De Lorenzo and A Perez. Light Cone Black Holes. Phys. Rev. D, 99(6):065009, 2019



near-horizon
near-extremal RN

- under a family of conformal transformations, the radial **MCKFs** become actual Killing fields
- some of these geometries describe black-hole or cosmological solutions
- because of the conformal invariance of the Klein-Gordon inner product, most results naturally extend to these spacetimes



deSitter
spacetime

courtesy of T De Lorenzo and A Perez