

# Advanced GR : Conserved charges & black hole thermodynamics

Dec. 2021

- **goal** : advanced topics w/ view towards current research
  - assume good working knowledge of GR
  - review, if necessary, the notion of diffeomorphism, Einstein's eqns, black hole solutions (Schwarzschild, Kerr) and their properties

**Outline** : 2 main directions

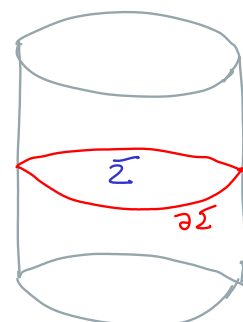
## A. Conserved charges in gauge theories (start today)

- learn how to compute cons. charges (e.g. charge, energy, ang. mom.) in (in principle) arbitrary spacetimes using the **covariant phase space formalism** ← powerful & covariant ⇒ general
- **!** in a **gauge theory** (local, rather than global symmetries  $\varepsilon(\kappa)$  including GR), the cons. charges are **not** given as integrals of a local current, but instead they are **quasi-local** (associated w/ a subregion in spt.)

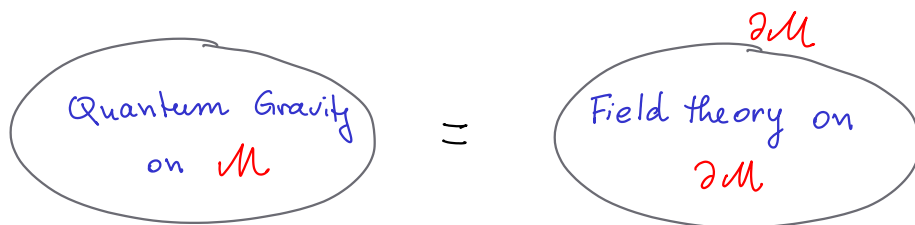
$$J_{\text{Noether}}^{\mu} = 0 + \nabla_{\nu} K^{\mu\nu} \quad \leftarrow \text{antisymm}$$

$\uparrow$   
on-shell

$$Q = \int_{\partial\Sigma} d^{d-2}x K^{tr}$$



- notice that  $Q \neq 0$  iff gauge parameter falls off slowly enough for the boundary contribution to be non-zero  $\Rightarrow$  in gauge theories, including GR, symmetries are **asymptotic symmetries**
- asympt. symmetries are **true** symmetries; they act non-trivially on phase space (even though gauge transf.  $\leftrightarrow$  redundancies of description, **large** gauge transformations are not).
- very interesting applications to **holography**



asympt. symm in gravity  $\leftrightarrow$  symmetries of the field theory

$\hookrightarrow$  examples :  $AdS_3$  & Minkowski $_4$  (time permitting)

## B. Black hole thermodynamics

- very deep & fundamental relation between **gravitation**, **thermodyn** & **quantum theory**
- responsible for breakthrough in quantum gravity (holography)
- recent developments (QG  $\Leftrightarrow$  quantum info) are heavily based on this older subject of b.h. thermodynamics ('70's)

## Plan

### ①. The four laws of black hole mechanics

- laws obeyed by geometric quantities associated to black holes that bear a remarkable mathematical resemblance to the laws of thermodynamics

- general proof & generalization due to Wald - Iyer  $S_{BH} = \frac{A_H}{4G} + (\dots)$

② Converse of the 1<sup>st</sup> law : if entropy  $\propto$  area  $\Rightarrow$  Einstein eqns  
(Jacobson)

$\Rightarrow$  gravity not fundamental, but emergent

③ Geometry & the laws of entanglement dynamics (time permitting)