Black Hole Rigidity in General Dimensions

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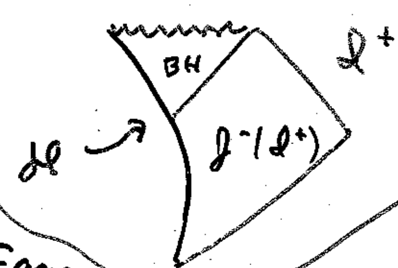
Model Black Hole Rigidity Thm

- let (M^{n+1}, g) be a stationary (not static) Black Hole

There exists a killing field T which is • timelike asymptotically • not surface forming

(M^{n+1}, g) is asympt flat with $\mathcal{I}^+$ & $M^{n+1} \setminus \mathcal{I}^-(\mathcal{I}^+) \neq$ empty



satisfying the Einstein-(?) Eqns together with the conditions $\left\{ \begin{array}{l} \bullet \\ \bullet \\ \bullet \\ \bullet \end{array} \right.$

- The isometry group $\mathcal{G}(M^{n+1}, g)$ includes a 2 Dim Abelian subgroup which $\left\{ \begin{array}{l} \bullet \\ \bullet \\ \bullet \\ \bullet \end{array} \right.$

Importance of BH Rigidity

- Step towards uniqueness

ex 3+1

BH Rigidity $\longrightarrow$ Axisym

$\Longrightarrow$ Kerr

- Surface Gravity:

If $\mathcal{G}(M^{n+1}, g)$ includes generators of $\mathcal{H}$ then

$$\left(\nabla_Y Y - K\, Y\right)\Big|_{\mathcal{H}} = 0$$

defines surface Gravity

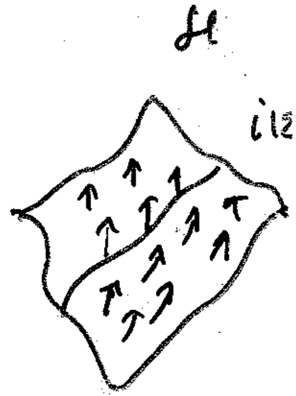
$\Longrightarrow$ BH Thermo

a real theorem:

3+1 Black Hole Rigidity (Hawking-Ellis, Chrusciel)

- Let (M^{3+1}, g) be a stationary (not static) BH
  satisfying the vacuum Einstein eqns
  or the Einstein-Maxwell eqns

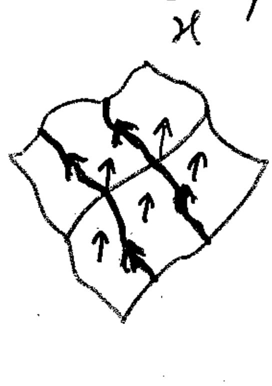
  together with the conditions
  - analytic
  - $\mathcal{H} = \Sigma^2 \times \mathbb{R}$ ← connected component
    (Σ^2 compact)
  - there exists
    $i : \Sigma^2 \to \mathcal{H}$
    such that $i(\Sigma^2)$ spacelike
    T transverse to $i(\Sigma^2)$



- The isometry group $\mathcal{G}(M^{3+1}, g)$
  includes $S^1 \times \mathbb{R}$ subgroup

  which acts freely on the **generators** of $\mathcal{H}$

So there is a killing field <u>tangent to generators</u>

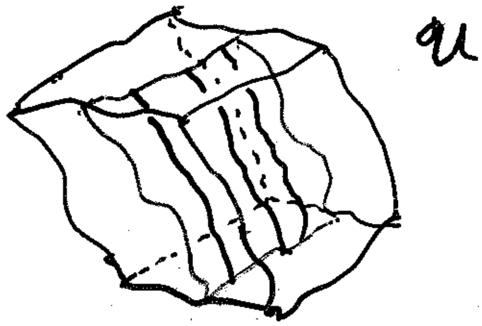


Proof Sketch of 3+1 BH Rigidity Thm

following ideas of Chrusciel

A] Transformation into Compact Horizon Problem

- Consider neighborhood $\mathcal{U}$ of BH Horizon $\mathcal{H}$



- Recall

  Thm (Hawking-Ellis)

  $\mathcal{H} = \partial(\mathcal{J}^-(\mathscr{I}^+))$ is

  - 3 dim null hypersurface
  - ruled by congruence of null generators
  - $\Sigma^2 \times \mathbb{R} = S^2 \times \mathbb{R}$

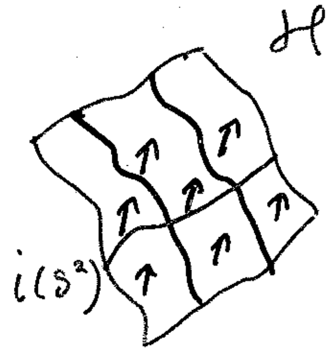
    presuming that Σ^2 is compact

- Note that

  T (Killing field of stationarity) is

  - tangent to $\mathcal{H}$
    (since T preserves geometry)
  - not tangent to generators of $\mathcal{H}$
    (Thm of Sudarsky-Wald
    relies on
    - stationary not static
    - asympt timelike

• transverse to $i(S^2)$



- Compactification

Claim

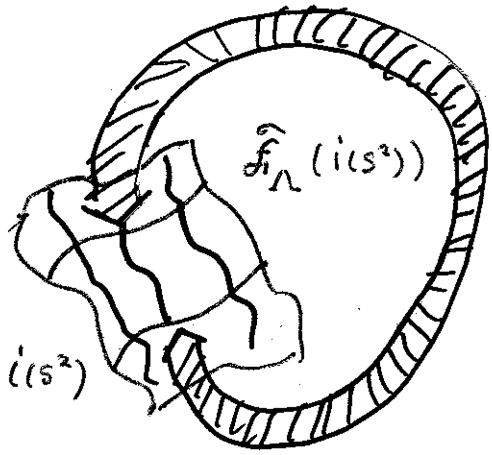
Let $\hat{\mathcal{F}}_\lambda$ be flow of T

$\exists \Lambda$ s.t.

if identify

$\hat{\mathcal{F}}_\Lambda(i(S^2)) \leftrightarrow i(S^2)$

then generators <u>close</u>



Pf of Claim

Since flow on S^2 has fixed points

$\hat{\mathcal{F}}_\lambda$ is λ-angle rotation

so

$\lambda = \Lambda \leftrightarrow$ rotate by 2π !

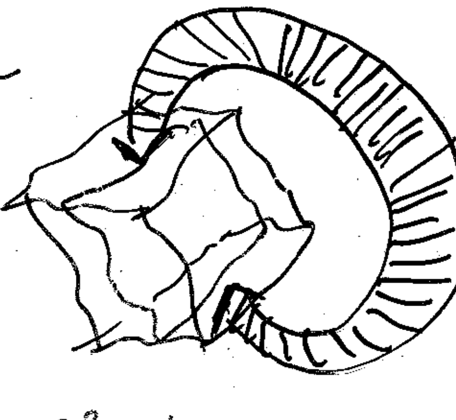
- Extend identification into $\mathcal{U}$

$\Rightarrow$ New spacetime

$(\hat{M}^{3+1}, \hat{g})$

with <u>compact</u>

null hypersurface $\hat{\mathcal{H}}$ "$S^2 \times S^1$"



ready to

B] Apply Compact Null Hypersurface Thm

- Thm (Moncrief - I)

  Let (M^{3+1}, g) be
  - soln of vac Eintein or Einstein - Maxwell
  - analytic

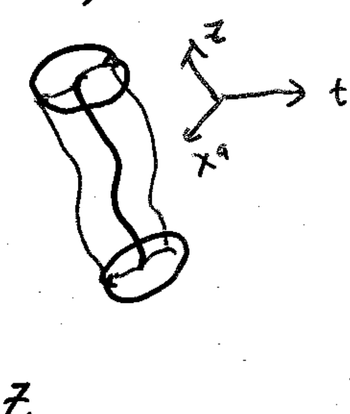
  Assume $\exists$
  $$N^3 \hookrightarrow M^{3+1}$$
  - analytic embedded 3 submfd
  - null
  - compact
  - closed generators

  The isometry group $\mathcal{G}(M^{3+1}, g)$ contains
  S^1 subgroup acting tangent to generators of N

- Idea of Proof
  - Set up Gaussian Null coords in tubes

  $$g = 2\,dt\,dz + \phi\,dz^2 + 2\beta_a\,dx^a dz + \mu_{ab}\,dx^a dx^b$$

  with
  $$\phi|_N = 0$$
  $$\beta|_N = 0$$



  - Show
  $$\mu_{ab}|_N \text{ independent of } z$$

  Pf
  Hawking Ellis argument based on Raychaudhuri Shear Eq

$\Rightarrow g|_{\mathcal{H}}$ independent of z.

- Show $\exists$ new set of Gaussian Null Coords with $\partial_t \phi|_{\mathcal{H}} = K$ constant

Pf

Solving Ricatti Eqn

Note:
This is where (t, z, x^a) are adjust so that $\frac{\partial}{\partial z}$ is KV

Verify:

$$\frac{d^2 z}{d\lambda^2} - \frac{K}{2}\left(\frac{dz}{d\lambda}\right)^2 = 0$$ geodesic eqn for generators

$\Rightarrow K$ is surface gravity

$=0$ generators complete to future & pa

$\neq 0$ generators complete only to future

- Show

$$\partial_t^{(m)}\phi,\ \partial_t^{(m)}\beta_a,\ (\partial_t)^m \mu_{ab}$$

all indep of z

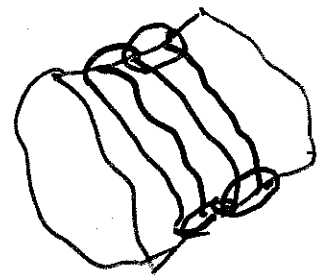
Pf

Induction using Einstein Eqs

- Extend $\frac{\partial}{\partial z}$ as Killing field into Tube (off $\mathcal{H}$)

Use Cauchy-Kowaleskaya ← Analyticity needed

• Patch Killing Vector Field from Tubes



C] UnWrap Back to Black Hole

¿ What Changes from 3+1 BH Rigidity Proof to n+1 BH Rigidity Proof

- Can still compactify $\mathcal{H}$
- But cannot compactify generally with closed generators

$\Rightarrow$ n+1 version of Compact Null Hypersurface Thm does not do the job

$\Rrightarrow$ Need Compact Null Hypersurface Thm with Non Closed Generators

Just developed by Moncrief - I if have T symmetry

n+1 Black Hole Rigidity (Moncrief-I, Hollands-Ishibashi-Wald)

Let (M^{n+1}, g) $n \geq 3$ be a stationary (not static) BH satisfying vacuum Einstein together with the conditions

- analytic
- $\mathcal{H} = \Sigma^{n-1} \times \mathbb{R}$
  compact
- there exists
  $i : \Sigma^{n-1} \to \mathcal{H}$
  such that $i(\Sigma^{n-1})$ spacelike
  T transverse to $i(\Sigma^{n-1})$
- generators complete to past
  incomplete to future — New

The isometry group $\mathcal{G}(M^{n+1}, g)$ includes 2 dim subgroup acting freely on the generators

Proof Sketch of $n+1$ BH Rigidity Thm

A] Transformation into Compact Horizon Problem

Same, except

Σ^{n-1} generally not S^2

$\longrightarrow$ generally no fixed pts for $\tilde{\mathcal{F}}_\lambda$

$\Longrightarrow$ generally non closed generators

rely on

B] Non Closed Generator Compact Null Hypersurface (with KV $\uparrow$) Thm

- Thm

Let (M^{n+1}, g) be

- soln of vac Einstein
- analytic

Assume

- $\exists\ N^n \hookrightarrow M^{n+1}$
  - * analytic embedding
  - * null
  - * compact $\Sigma^{n-1} \times S^1$
  - * non closed generators

    generically

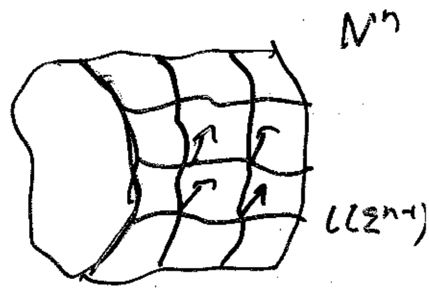
  - * generators complete to past
    incomplete to future.

- $\exists$ Killing Vector field T
  transverse to some compact section $i(\Sigma^{n-1}) \subset N$

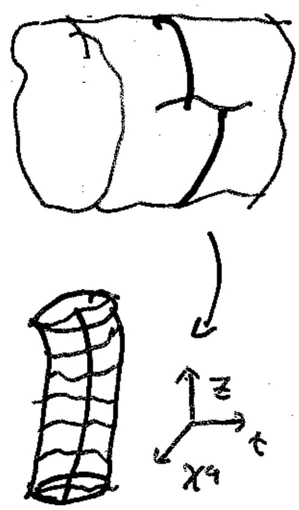
The isometry group $\mathcal{G}(M^{n+1}, g)$ contains
a T^2 subgroup acting tangent to generators of N^n

- Idea of Proof

- Foliate N^n
  using $i(\Sigma^{n-1})$
  & flow of T
  $\rightarrow$ spacelike slices of N^n



- Set up Gaussian Null Coordinates
  $\Rightarrow$ Same as for closed generators
  except at transition



$$g = 2\,dt\,dz + \phi\,dz^2 + 2\beta_a\,dx^a\,dz + \mu_{ab}\,dx^a dx^b$$

$a, b \in \{1, \dots n-1\}$

with $\phi|_N = 0$

$\beta|_N = 0$

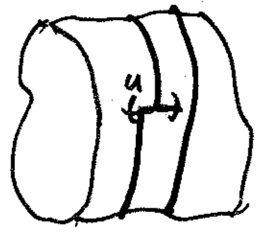
- Show $\mu_{ab}|_N$ indep of z

Pf

As for 3+1

- Control Generator Orbits via

Poincaré Recurrence



~ Let $\{\psi_\lambda : M \to M \mid \lambda \in \mathbb{R}\}$ be 1-param family of volume-preserving diffeos of compact M

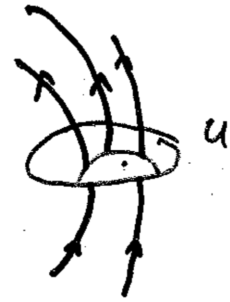
~ For any $p \in M$ & any $\lambda_0 > 0$ & any nbhd U of p $\exists\, j \in \mathbb{N}$ s.t.

$$\psi_{j\lambda_0}(p) \in U$$

$\Rightarrow$ The orbit returns arbitrarily close (eventually)

Note:

Preservation of $\mu_{ab}\, dx^a dx^b$ geometry along flow



$\Rightarrow T^k \times \mathbb{R}$ tubes as closure of flow

- Construct Candidate Killing Field

Let ∂_z be tangent to generators

Set $Y = w\,\partial_z$ on N in tube

$$w(z,x^a) = \frac{k}{2}\int_z^\infty d\rho \, \exp\left[-\int_z^\rho \tfrac{1}{2}\,\partial_t \phi(\zeta,x^a)\,d\zeta\right]$$

Integration along generator starting at (z,x^a)

* Claim

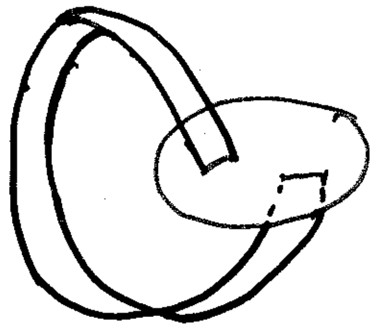
- For the null generator starting at (z,x^a) with tangent vector Y the future affine length is k regardless of (z,x^a)
- The function w is analytic
- The vector field Y extends to a Killing field

- Pf of Claim
  - uniform affine length → calc'n
  - analyticity is difficult
  - Killing field verification is just like closed generator case once analyticity is verified

★ Verifying Analyticity of u

2 stages

* Continuity & Differentiability via Ribbon Arguments:



$\Rightarrow$ Compare integrals

$$\int -\tfrac{1}{2}\partial_t \phi$$

along neighboring gens starting at nearby points

<u>using</u> <u>Stokes</u> <u>on</u> <u>the</u> <u>ribbon</u>

with 1-form

$$\eta = -\tfrac{1}{2}\partial_t \phi$$

$$d\eta = 0$$

$$\Rightarrow \int \omega - \int \omega = \int \omega - \int \omega$$

* Analyticity via

- complexify
  "Grauert Tubes"
- construct sequence

$$u_j(z, x^a) = \frac{k}{2}\int_z^{j\ \text{trecurrence}} d\rho\ \exp[\ \text{etc}\ ]$$

in <u>complex</u>

- show seq is Cauchy via Ribbons

↑ fol'n useful here

- Use Banachness of $\mathbb{C}$ analytic

$\Rightarrow u = \lim u_j$ is analytic

- Verify Y is Killing field
  - Show

    $$\mathcal{L}_Y(\partial_t^{(m)}\phi) \qquad \mathcal{L}_Y(\partial_t^{(m)}\beta_a) \qquad \mathcal{L}_Y(\partial_t^{(m)}\mu_{ab})$$

    all vanish
  - Extend off N into tube via Cauchy-Kowalaskaya
  - Patch tubes

C] Unwrap Back to Black Hole

To Do:

- Complete write up
- Remove condition on generator completeness
- Add nonvacuum fields
- Remove analyticity
- Prove
  Non Closed Generator Compact Null Horizon Thm
  with no assumed Killing Field