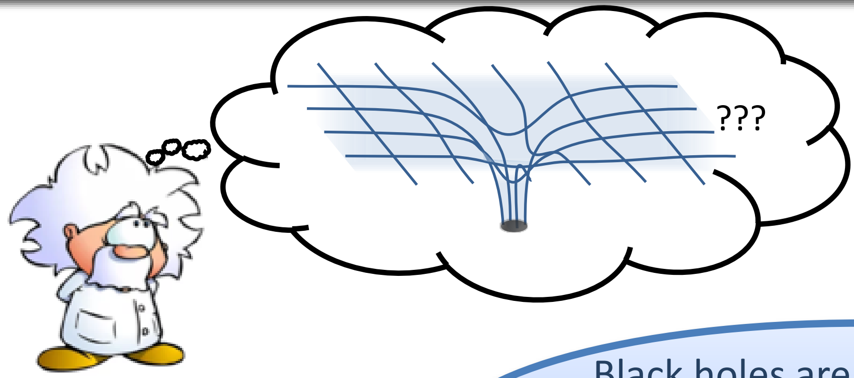
Geometric Resolution of Schwarzschild Horizon

GGI Workshop,

April 19 2023

Pierre Heidmann

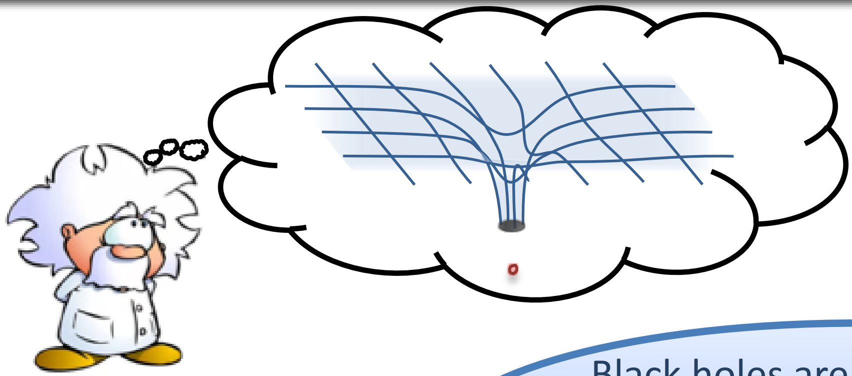
Black Hole Puzzles



Black holes are at the center of

theoretical conflicts between

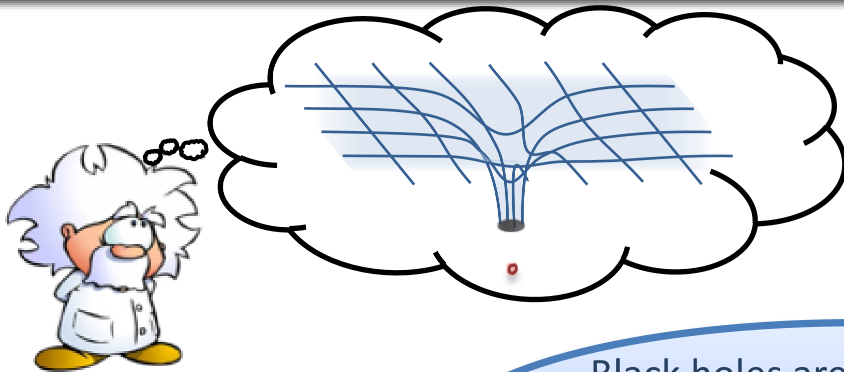
GR and QM



Black holes are at the center of **theoretical conflicts** between **GR and QM**

Singularity

Black Hole Puzzles

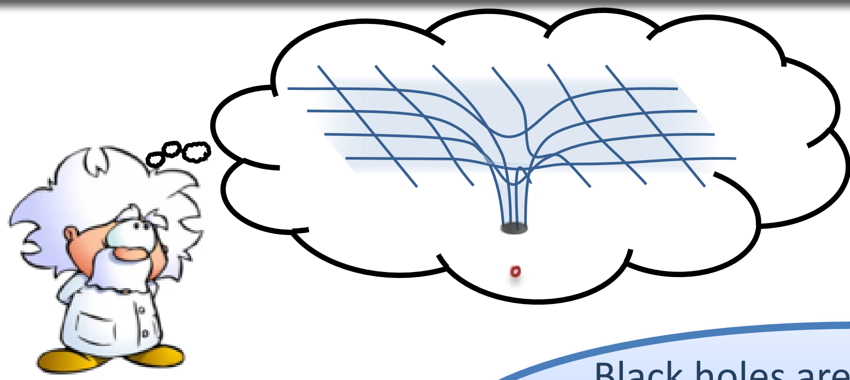


Black holes are at the center of **theoretical conflicts** between **GR and QM**

Singularity

Horizon ⇒ Information Paradox

Black Hole Puzzles

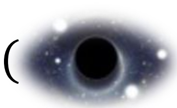


Black holes are at the center of **theoretical conflicts** between **GR and QM**

Singularity

Horizon ⇒ Information Paradox

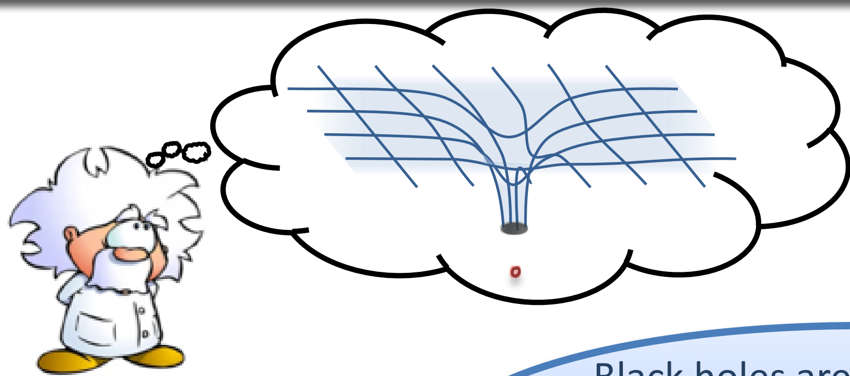
Microscopic Description of BH entropy

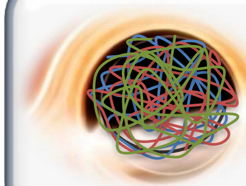
$\# \, states$ () $\gg$ $\# \, states$ ( )

$(e^{10^{90}})$ $(e^{10^{88}})$

!

Black Hole Puzzles





<u>Black Hole:</u>
Quantum Gravitational Phase of Matter?

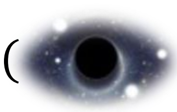
New Quant. Grav. States!

Black holes are at the center of **theoretical conflicts** between **GR and QM**

Singularity

Horizon ⇒ Information Paradox

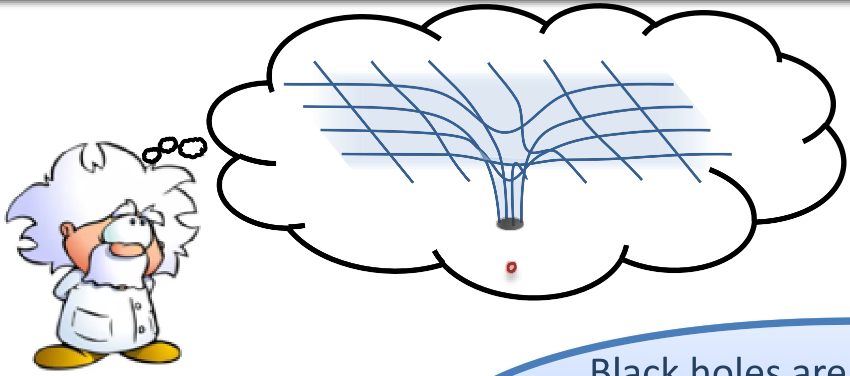
Microscopic Description of BH entropy

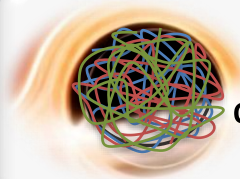
$\# \, states$ () $\gg$ $\# \, states$ ( )

$(e^{10^{90}})$ $(e^{10^{88}})$

!

Black Hole Puzzles





Black Hole:

Quantum Gravitational Phase of Matter?

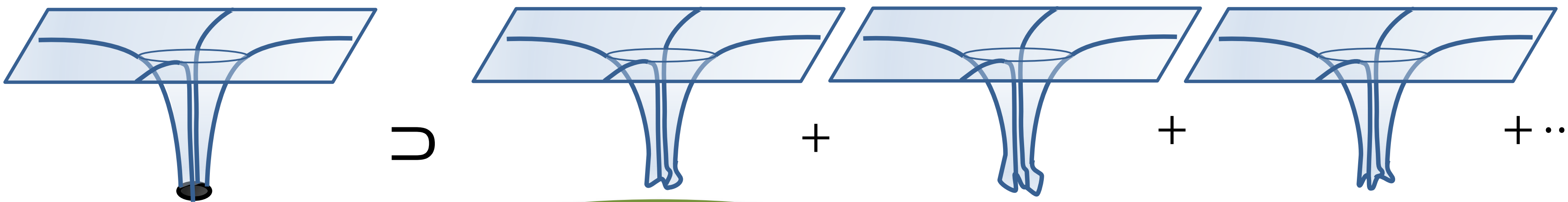
New Quant. Grav. States!

Black holes are at the center of **theoretical conflicts** between **GR and QM**

- **Singularity**
- **Horizon** ⇒ Information Paradox
- **Microscopic** Description of BH entropy

What are the **new degrees of freedom from Quantum Gravity** that make black holes?

Supersymmetric Paradigm



Part of the e^S **microstates of SUSY BH** can be described by **Gravitational Solitons**

Coherent states of quantum gravity

Resolve the singularity & horizon into **smooth microstructure**

Topological deformations

Extra compact dimensions

EM Flux

Do **coherent QG states** extend beyond supersymmetry? Can they resolve **horizons of non-extremal BH**?

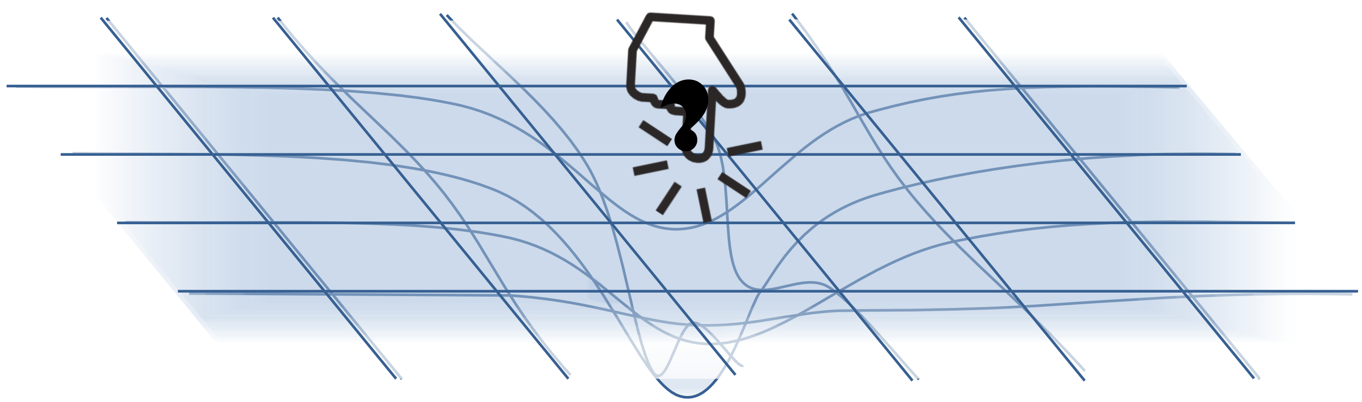
1. Vacuum solitons in gravity
2. Charged solitons in gravity
3. Solitons that resolve Schwarzschild horizon
4. Some gravitational properties

On Solitons in Gravity

- <u>Soliton:</u>
  - ``perpetual'' state of a non-linear theory
  - ~ fundamental particle but regular
- <u>Existence in 4d General Relativity?</u> Serini 1918, Einstein, Pauli '41, Breitenlohner, Maison, Gibbons '87
  - $S = \int d^4x \sqrt{-g}\, R$
  - Smooth & horizonless
  - Pure deformation of spacetimes
  - Finite energy & stable

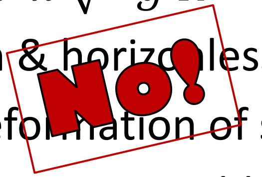
On Solitons in Gravity

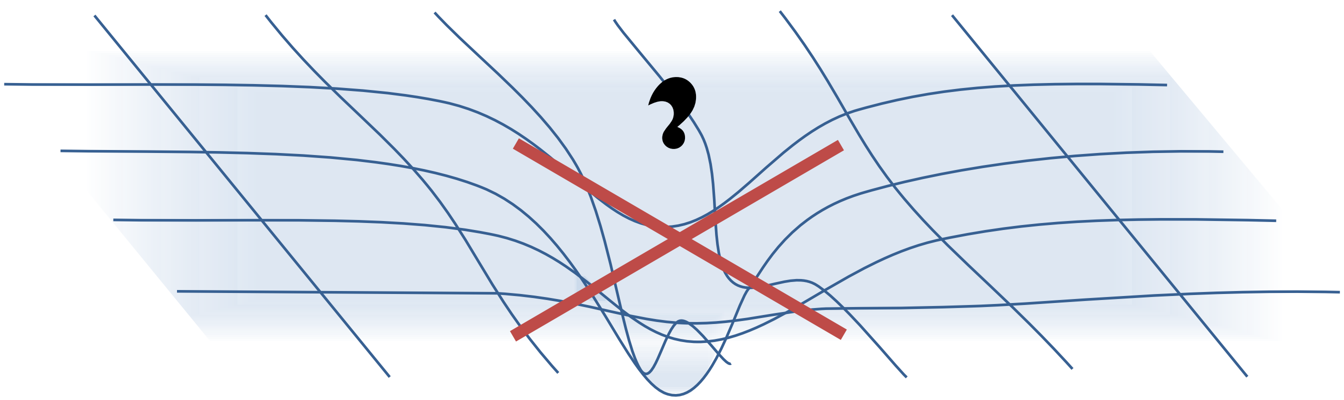
- <u>Soliton:</u>
  - ``perpetual'' state of a non-linear theory
  - ~ fundamental particle but regular
- <u>Existence in 4d General Relativity?</u> Serini 1918, Einstein, Pauli '41, Breitenlohner, Maison, Gibbons '87
  - $S = \int d^4x \sqrt{-g}\, R$
  - Smooth & horizonless
  - Pure deformation of spacetimes
  - Finite energy & stable



On Solitons in Gravity

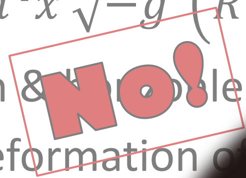
- <u>Soliton:</u>
  - ``perpetual'' state of a non-linear theory
  - $\sim$ fundamental particle but regular
- <u>Existence in 4d General Relativity?</u> Serini 1918, Einstein, Pauli '41, Breitenlohner, Maison, Gibbons '87
  - $S = \int d^4x \sqrt{-g}\, R$
  - Smooth & horizonless
  - Pure deformation of spacetimes
  - Finite energy & stable



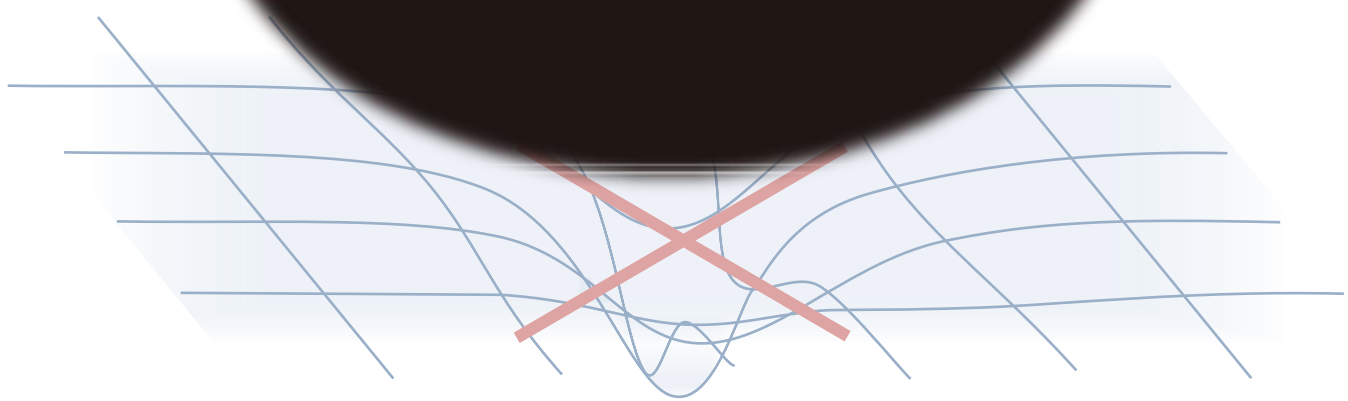


On Solitons in General Relativity

- <u>Soliton:</u>
  - ``perpetual'' state of a non-linear theory
  - ~ fundamental particle but regular
- <u>Existence in 4d General Relativity?</u> Serini 1918, Einstein, Pauli '41, Breitenlohner, Maison, Gibbons '87
  - $S = \int d^4x \sqrt{-g} \left(R - \frac{1}{4}F^2\right)$
  - Smooth & [illegible]less
  - Pure deformation of
  - Finite energy & s

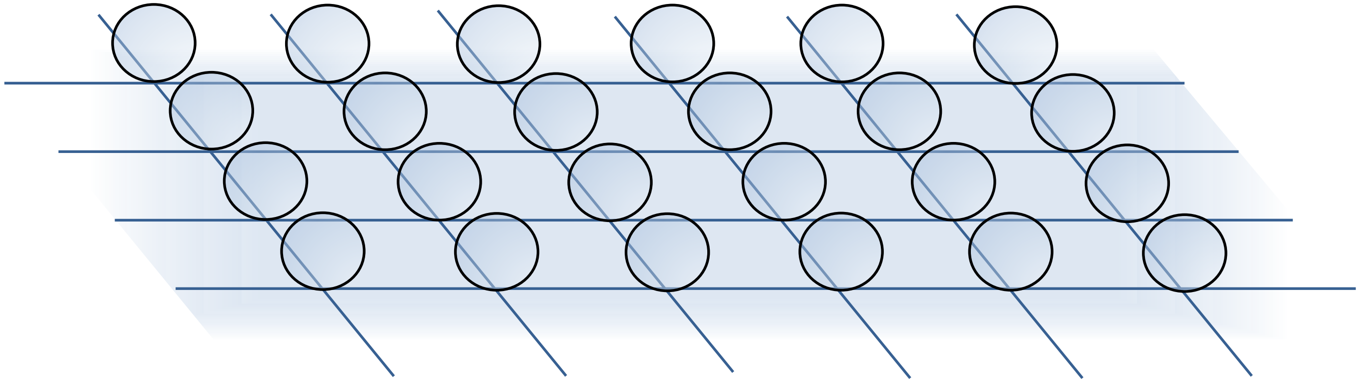


No-go Theor[illegible]ns *in 4d GR*

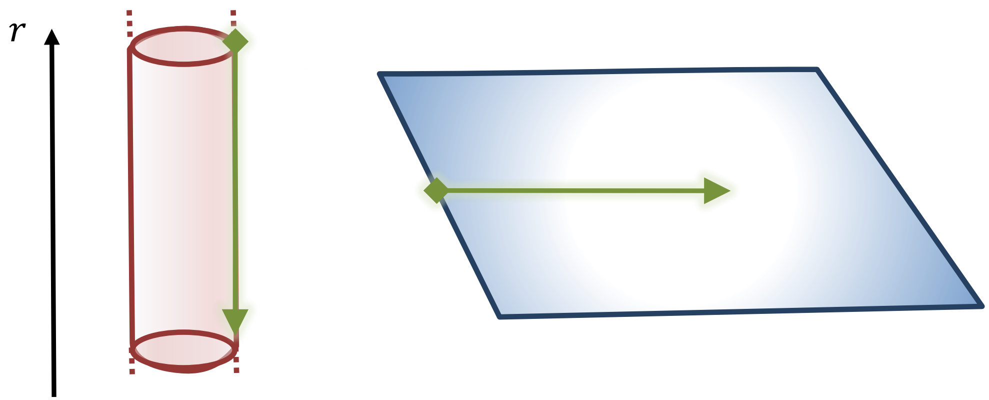


Solitons with extra compact dimensions

- <u>Gravity with extra compact dimensions:</u>
  - 4d spacetime + a compact dimension in vacuum
  - Deformation of the circle ⇒ Deformation of the 4d spacetime
  - **Topological Soliton:** <u>state of gravity</u> produced by the degeneracy of the circle

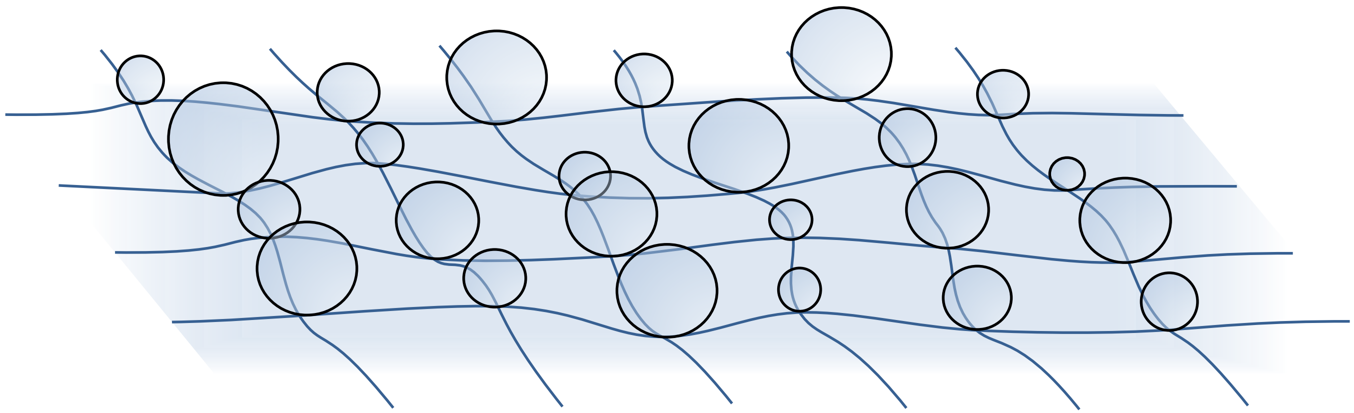


=

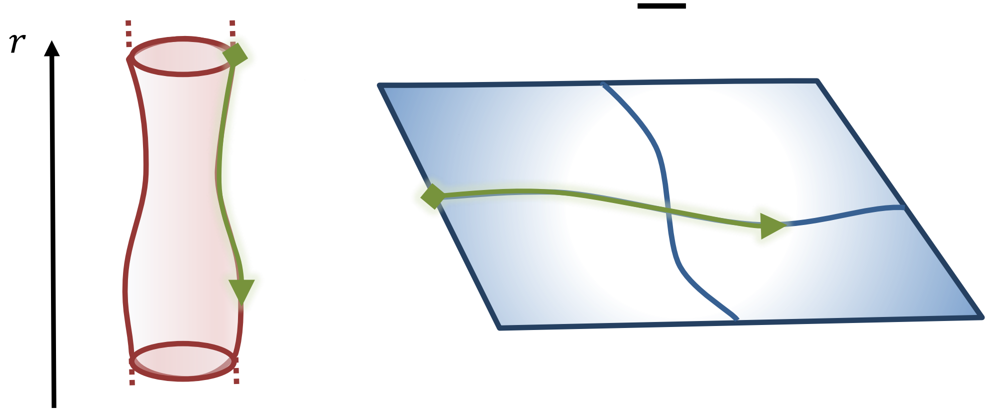


Solitons with extra compact dimensions

- Gravity with extra compact dimensions:
  - 4d spacetime + a compact dimension in vacuum
  - Deformation of the circle ⇒ Deformation of the 4d spacetime
  - **Topological Soliton:** state of gravity produced by the degeneracy of the circle

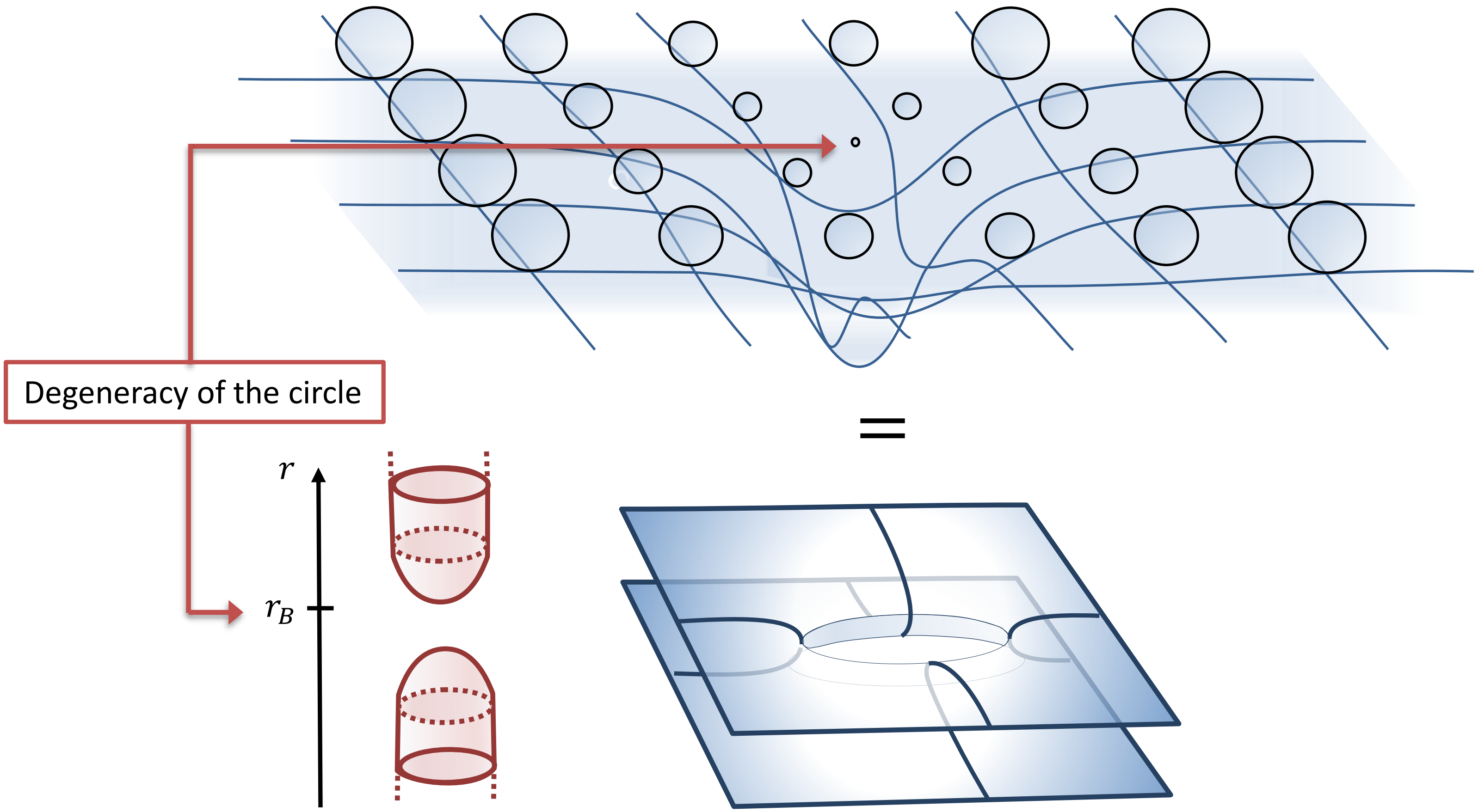


$=$



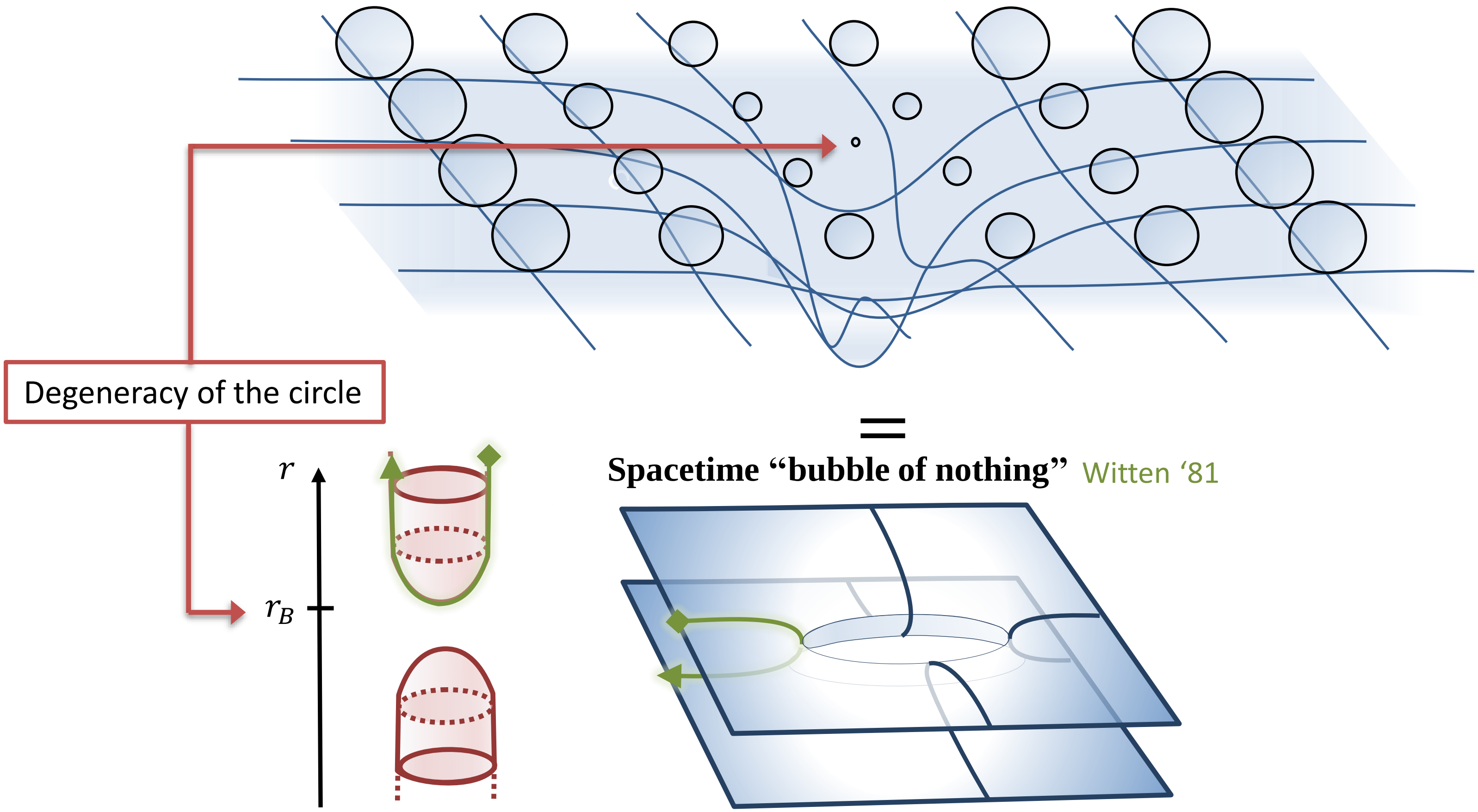
Solitons with extra compact dimensions

- <u>Gravity with extra compact dimensions:</u>
  - 4d spacetime + a compact dimension in vacuum
  - Deformation of the circle ⇒ Deformation of the 4d spacetime
  - **Topological Soliton:** <u>state of gravity</u> produced by the degeneracy of the circle



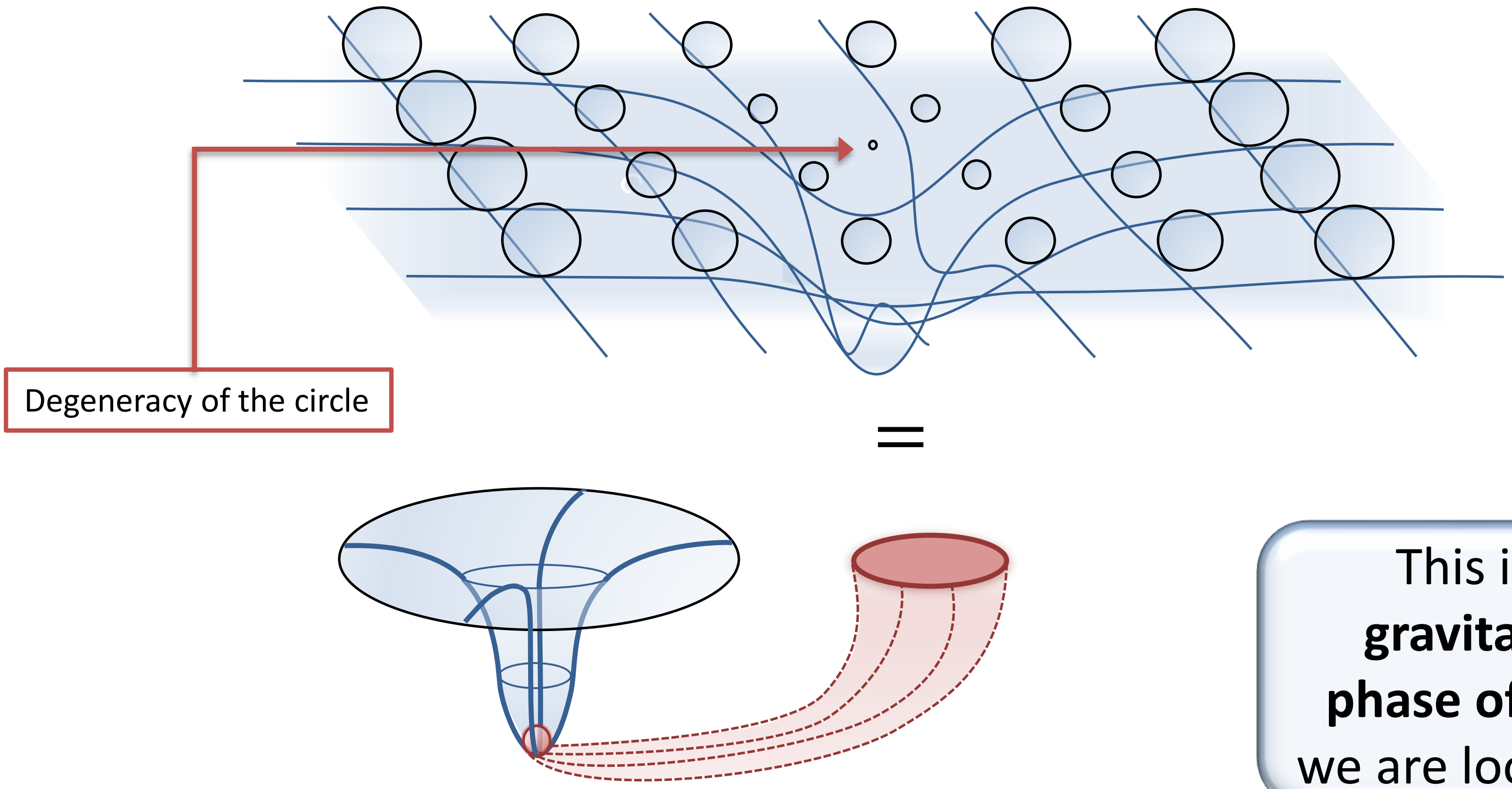
Solitons with extra compact dimensions

- <u>Gravity with extra compact dimensions:</u>
  - 4d spacetime + a compact dimension in vacuum
  - Deformation of the circle ⇒ Deformation of the 4d spacetime
  - **Topological Soliton:** <u>state of gravity</u> produced by the degeneracy of the circle



Solitons with extra compact dimensions

- <u>Gravity with extra compact dimensions:</u>
  - 4d spacetime + a compact dimension in vacuum
  - Deformation of the circle ⇒ Deformation of the 4d spacetime
  - **Topological Soliton:** <u>state of gravity</u> produced by the degeneracy of the circle



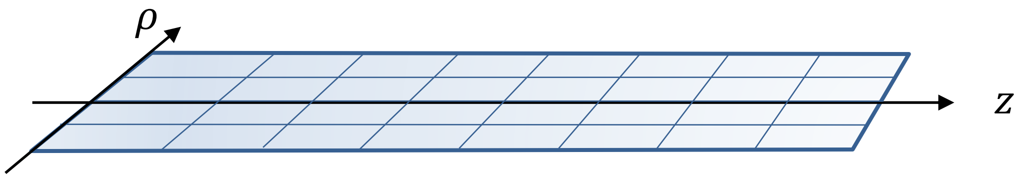
This is the **gravitational phase of matter** we are looking for!

Solution Generating Technique

- Challenge: **Einstein equations**
- Weyl formalism in 4d GR: Weyl 1917

$$ds_4^2 = -W_0\,dt^2 + \frac{1}{W_0}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right]$$

- Generalized Weyl formalism Emparan, Reall '02



Solution Generating Technique

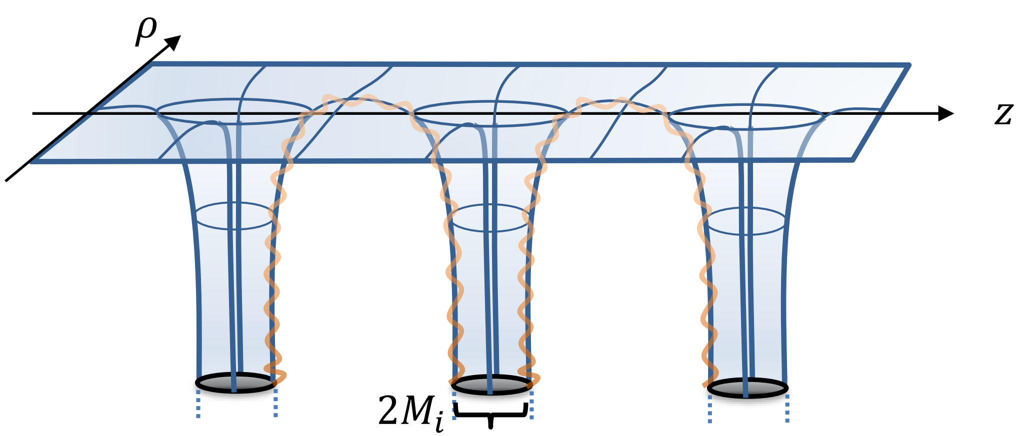
- <u>Challenge:</u> **Einstein equations**
- Weyl formalism in 4d GR: Weyl 1917

$$ds_4^2 = -W_0\, dt^2 + \frac{1}{W_0}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] \Rightarrow$$

Linear Einstein Equations!

$$W_0 = \prod_i \left(1 - \frac{2M_i}{r_i(\rho, z)}\right)$$

- Generalized Weyl formalism Emparan, Reall '02 Bah, PH '20



Solution Generating Technique

- <u>Challenge:</u> **Einstein equations**
- Weyl formalism in 4d GR: Weyl 1917

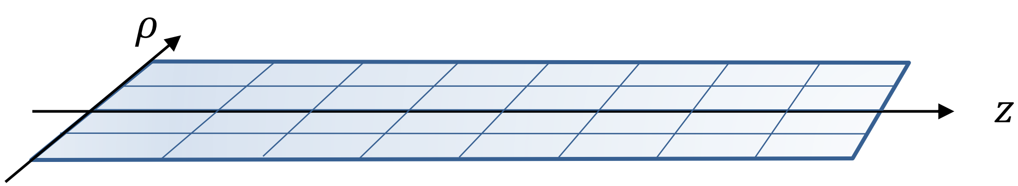
$$ds_4^2 = -W_0\,dt^2 + \frac{1}{W_0}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] \;\Rightarrow$$

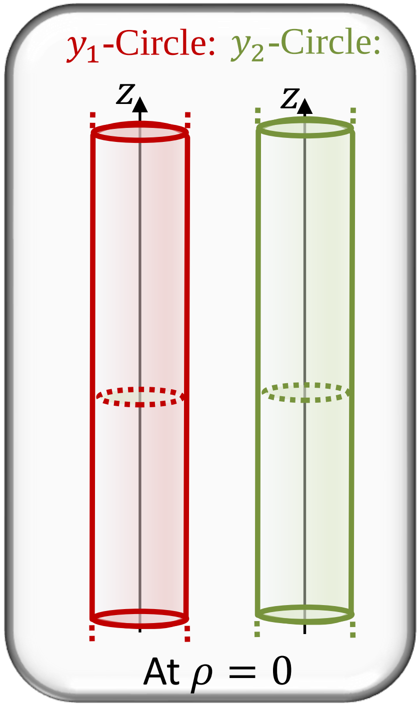
Linear Einstein Equations!

$$W_\Lambda = \prod_i \left(1 - \frac{2M_i}{r_i(\rho,z)}\right)^{D_i^{(\Lambda)}}$$

- Generalized Weyl formalism Emparan, Reall '02 Bah, PH '20

$$ds_D^2 = -W_0\,dt^2 + \frac{1}{\prod W_\Lambda}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] + \sum_I W_I\,dy_I^2$$





Solution Generating Technique

- <u>Challenge:</u> **Einstein equations**
- Weyl formalism in 4d GR: Weyl 1917

$$ds_4^2 = -W_0\, dt^2 + \frac{1}{W_0}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] \Rightarrow$$

Linear Einstein Equations!

$$W_\Lambda = \prod_i \left(1 - \frac{2M_i}{r_i(\rho, z)}\right)^{D_i^{(\Lambda)}}$$

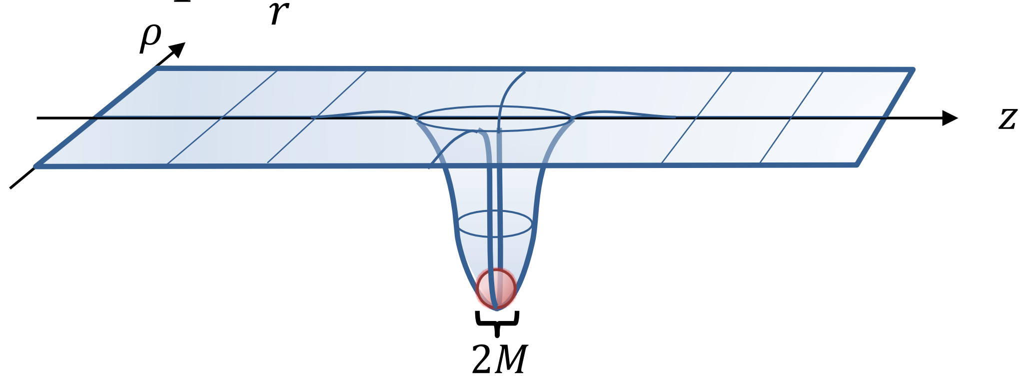
- Generalized Weyl formalism Emparan, Reall '02 Bah, PH '20

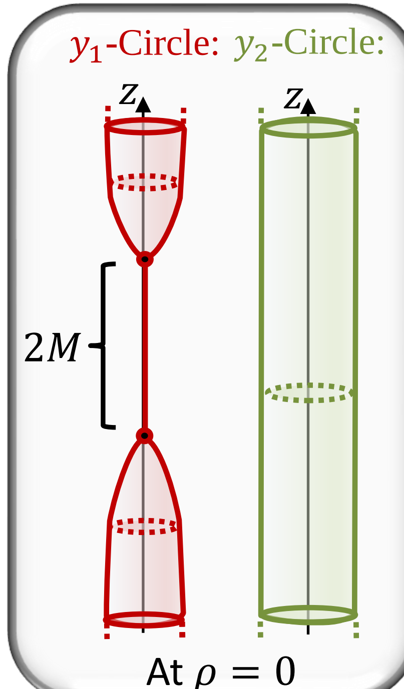
$$ds_D^2 = -W_0\, dt^2 + \frac{1}{\prod W_\Lambda}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] + \sum_I W_I\, dy_I^2$$

Contains the bubble of nothing

Regularity: $2M = R_{y_1}$

$$ds_D^2 = -dt^2 + \frac{dr^2}{1 - \frac{2M}{r}} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2) + \left(1 - \frac{2M}{r}\right) dy_1^2 + \cdots$$





Solution Generating Technique

- <u>Challenge:</u> **Einstein equations**
- Weyl formalism in 4d GR: Weyl 1917

$$ds_4^2 = -W_0\, dt^2 + \frac{1}{W_0}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] \Rightarrow$$

Linear Einstein Equations!

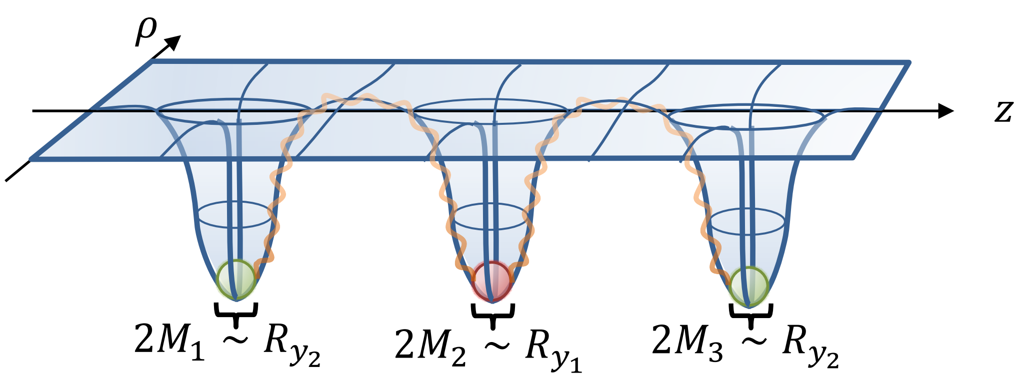
$$W_\Lambda = \prod_i \left(1 - \frac{2M_i}{r_i(\rho,z)}\right)^{D_i^{(\Lambda)}}$$

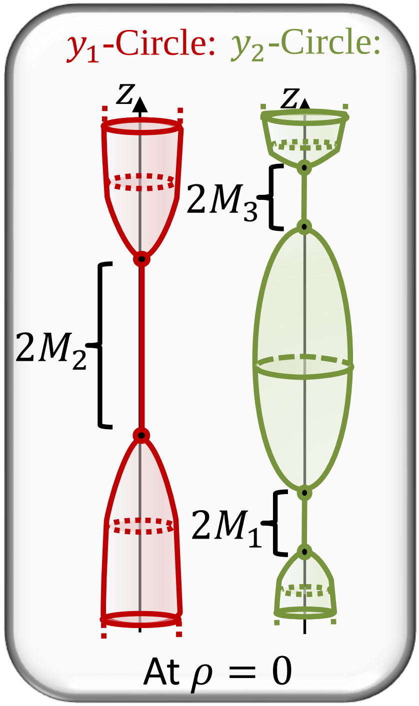
- Generalized Weyl formalism Emparan, Reall '02 Bah, PH '20

$$ds_D^2 = -W_0\, dt^2 + \frac{1}{\prod W_\Lambda}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] + \sum_I W_I\, dy_I^2$$

Contains the bubble of nothing

Bound states of bubbles





Solution Generating Technique

- <u>Challenge:</u> **Einstein equations**
- Weyl formalism in 4d GR: Weyl 1917

$$ds_4^2 = -W_0\, dt^2 + \frac{1}{W_0}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] \Rightarrow$$

Linear Einstein Equations!

$$W_\Lambda = \prod_i \left(1 - \frac{2M_i}{r_i(\rho,z)}\right)^{D_i^{(\Lambda)}}$$

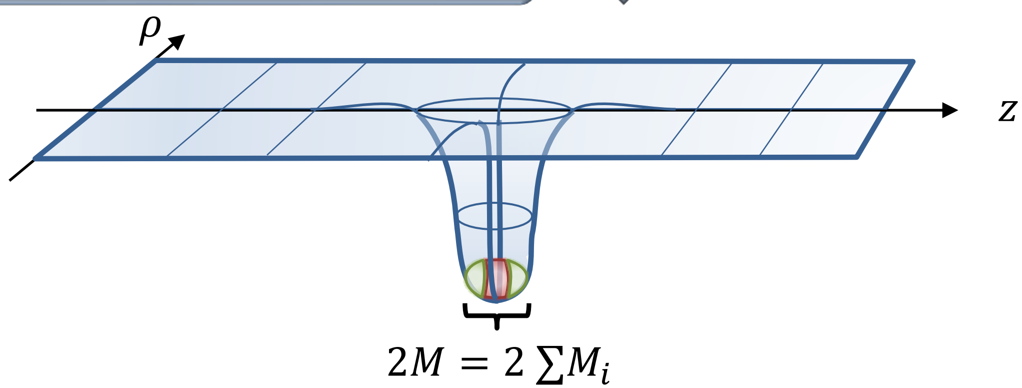
- Generalized Weyl formalism Emparan, Reall '02 Bah, PH '20

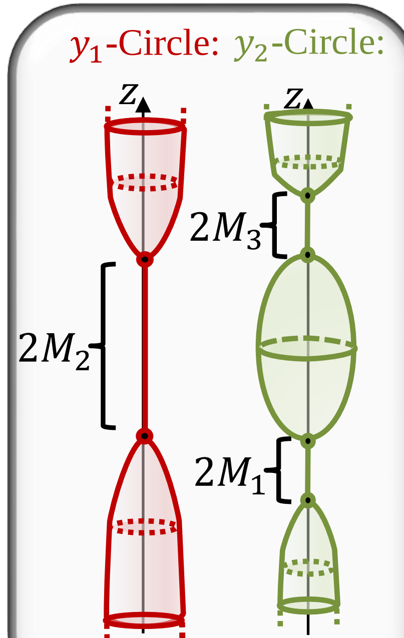
$$ds_D^2 = -W_0\, dt^2 + \frac{1}{\prod W_\Lambda}\left[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2\right] + \sum_I W_I\, dy_I^2$$

Contains the bubble of nothing

Bound states of bubbles

Smooth bound states of bubbles





Vacuum Topological Solitons

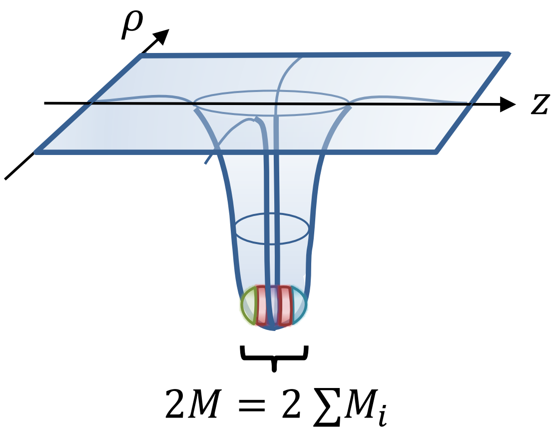
- Class of **Vacuum Topological Solitons** induced by the degeneracy of compact directions Bah, PH '20

$$ds_D^2 = -dt^2 + H\left[\frac{dr^2}{1-\frac{2M}{r}} + r^2 d\theta^2\right] + r^2 \sin^2\theta\, d\phi^2 + \sum_I \prod_{i=1}^{N} \left(1 - \frac{2M_i}{r_i}\right)^{D_i^{(\Lambda)}} dy_I^2 \qquad D_i^{(\Lambda)} = 0 \text{ or } 1.$$

H: accounts for **interaction between internal bubbles** of different kinds

M_i: Sizes of internal bubbles constrained by ***bubble equations*** in terms of **radii of extra dimensions R_{y_I}**

- Reduction to 4d: **Singular BH with scalars** of mass $\frac{1}{2}M = \frac{1}{2}\sum M_i$



Vacuum Topological Solitons

- Class of **Vacuum Topological Solitons** induced by the degeneracy of compact directions Bah, PH '20 '21

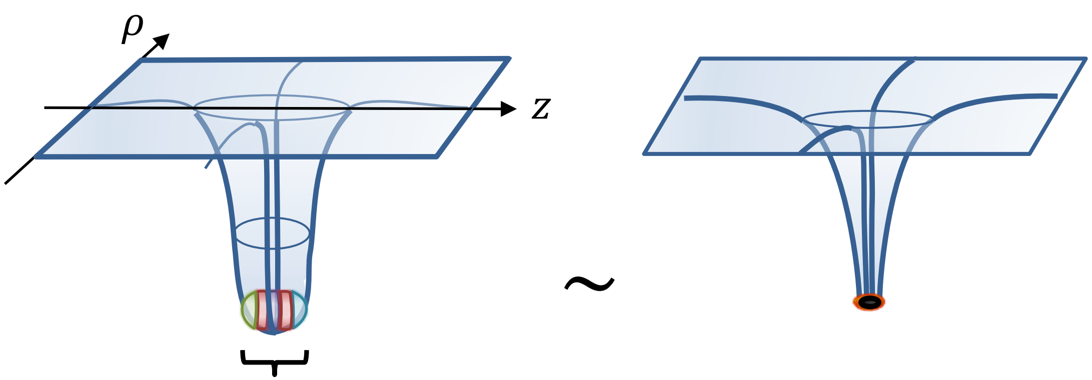
$$ds_D^2 = -dt^2 + H\left[\frac{dr^2}{1-\frac{2M}{r}} + r^2 d\theta^2\right] + r^2 \sin^2\theta\, d\phi^2 + \sum_I \prod_{i=1}^{N} \left(1 - \frac{2M_i}{r_i}\right)^{D_i^{(\Lambda)}} dy_I^2 \qquad D_i^{(\Lambda)} = 0 \text{ or } 1.$$

H accounts for **interaction between internal bubbles** of different kinds

$2M_i$: Sizes of internal bubbles constrained by ***bubble equations*** in terms of **radii of extra dimensions R_{y_I}**

- Reduction to 4d: **Singular BH with scalars** of mass $\frac{1}{2}M = \frac{1}{2}\sum M_i$

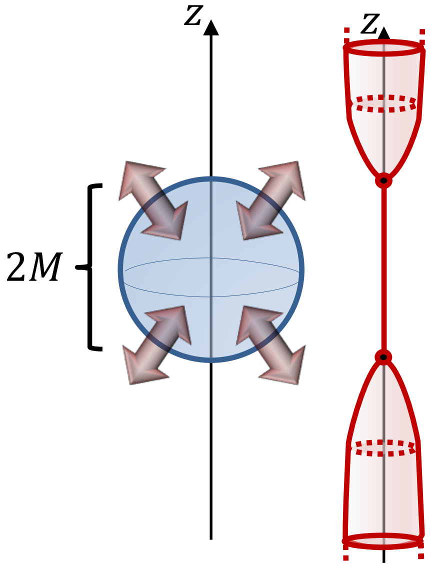
$$ds_4^2 = \sqrt{1-\frac{2M}{r}}\left[-dt^2 + H\left[\frac{dr^2}{1-\frac{2M}{r}} + r^2 d\theta^2\right] + r^2 \sin^2\theta\, d\phi^2\right] \quad + \text{ bunch of } \textbf{scalar fields}$$

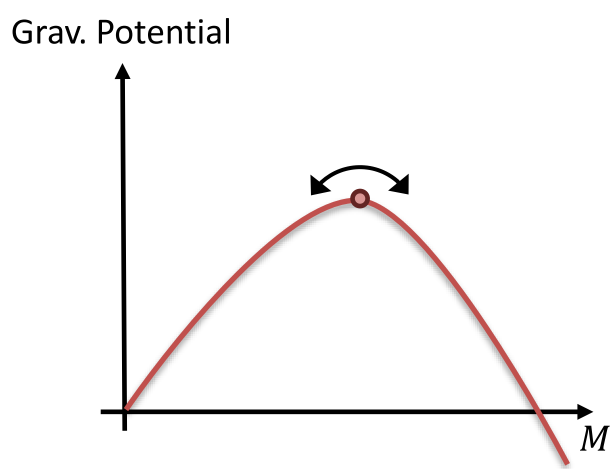


$2M = 2\sum M_i$

Instability of Vacuum Solitons

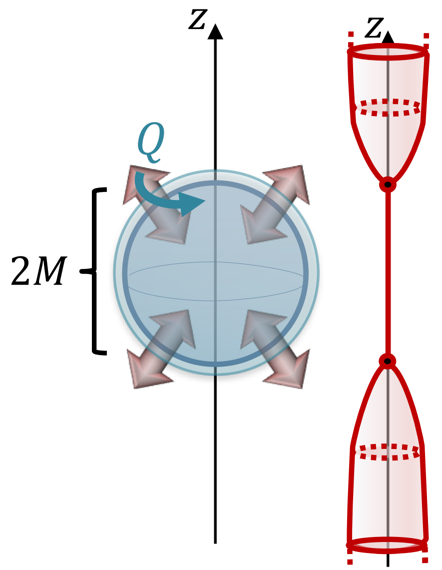
- <u>But… Stability issue!</u> Witten '81, Gross, Perry, Yaffe '82
  - Bubble of nothing mediates the decay of Kaluza-Klein vacuum spacetimes: it **grows indefinitely or collapses**
  - Another ingredient is required…

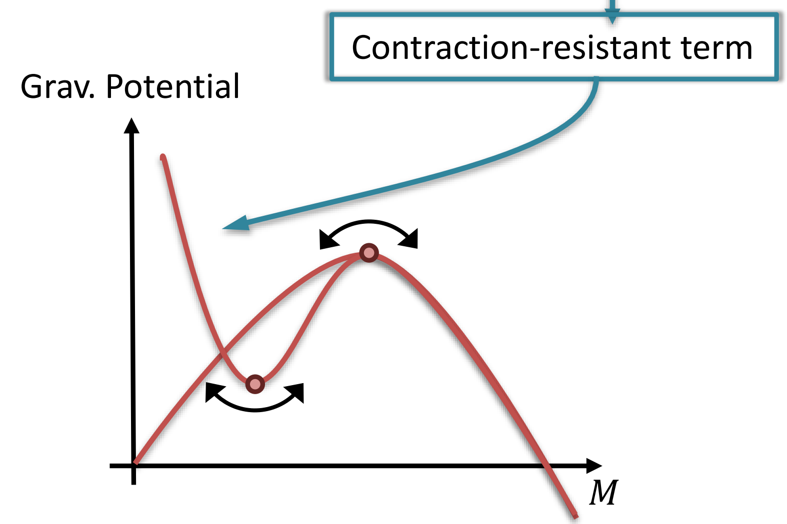




Instability of Vacuum Solitons

- <u>But… Stability issue!</u> Witten '81, Gross, Perry, Yaffe '82
  - Bubble of nothing mediates the decay of Kaluza-Klein vacuum spacetimes: it **grows indefinitely or collapses**
  - Another ingredient is required: **Electromagnetic flux!** $\rightarrow$ $E_{flux} \sim \int F^2 \sim \frac{Q^2}{r^2}$





<u>Expectation:</u> meta-stable **Gravitational Solitons** with compact dimensions and EM flux could exist!

<u>Question:</u> Can we actually construct them? What is their physics?

1. Vacuum solitons in gravity

2. Charged solitons in gravity

3. Solitons that resolve Schwarzschild horizon

4. Some gravitational properties

Electrostatic Ernst Formalism in 4d

- <u>Challenge:</u> **Einstein Maxwell equations**
- Electrostatic Ernst formalism in 4d: Ernst '68

$$ds_4^2 = -\frac{1}{Z}\,dt^2 + Z[e^{2\nu}(d\rho^2 + dz^2) + \rho^2 d\phi^2]$$
$$F = dA \wedge dt$$

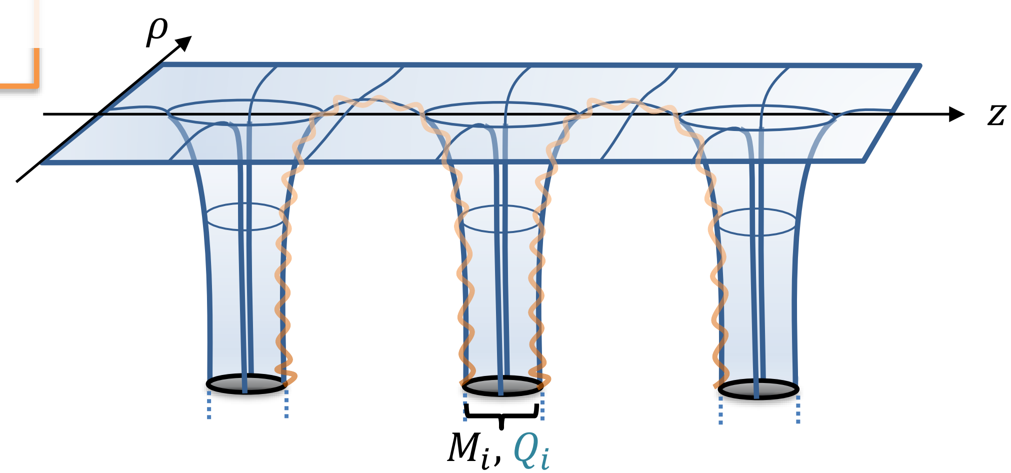
$\Rightarrow$ Non-linear Ernst equations but **integrable**!

- Solution-generating techniques:
  - <u>Inverse scattering:</u> Generic solutions with **an arbitrary number of sources** (BH here) induced by a mass parameter M_i and a charge Q_i Ruiz, Manko, Martin '95
  - <u>Charged Weyl:</u> **Linear** solutions for an arbitrary number of sources with $M_i/Q_i = cst$ Bah, PH '20, '21

$$Z = \frac{e^b W^{-1} - e^{-b} W}{2\sinh b}, \qquad A = \frac{\sqrt{1+\sinh^2 b\, Z^2}}{Z}$$

$$W_\Lambda = \prod_i \left(1 - \frac{2M_i}{r_i}\right)$$

charge-to-mass ratio $M_i/Q_i = \cosh b$:
- $b \to \infty$ vacuum limit
- $b \to 0$ extremal limit



Generalized Ernst Formalism

- Classification of frameworks that **decompose into set of Ernst Equations:**

PH '21

  - **M-theory** on $T^6 \times S^1$ with M2-M2-M2-KKm flux
  - **Type IIB** on $T^4 \times S^1 \times S^1$ with D1-D5-P-KKm flux

⋮

  - D1-D5 system on $S^1 \times S^1$ and rigid T^4

$$ds_6^2 = \frac{1}{\sqrt{Z_{D1} Z_{D5}}} \left[-W_1\, dt^2 + \frac{dy_1^2}{W_1} \right] + \sqrt{Z_{D1} Z_{D5}} \left[\frac{1}{W_2} \left[e^{2\nu} (d\rho^2 + dz^2) + \rho^2 d\phi^2 \right] + W_2\, dy_2^2 \right],$$

$$F_3 = d\left[H_{D5}\, d\phi \wedge dy_2 - A_{D1}\, dt \wedge dy_1 \right],$$

Sector (Z_{D1}, A_{D1})

Sector (Z_{D5}, H_{D5})

→ Ernst equations

Sector W_1

Sector W_2

→ Weyl equations

→ Solve each sector independently and build **Topological Solitons**

Bah, PH '20, '21, '22, '23; PH '21;
Bah, Weck, PH '22

A Topological Star

- Source the previous framework by **a single charged bubble** Bah, PH PRL '20

- The metric: $r_B > r_S$

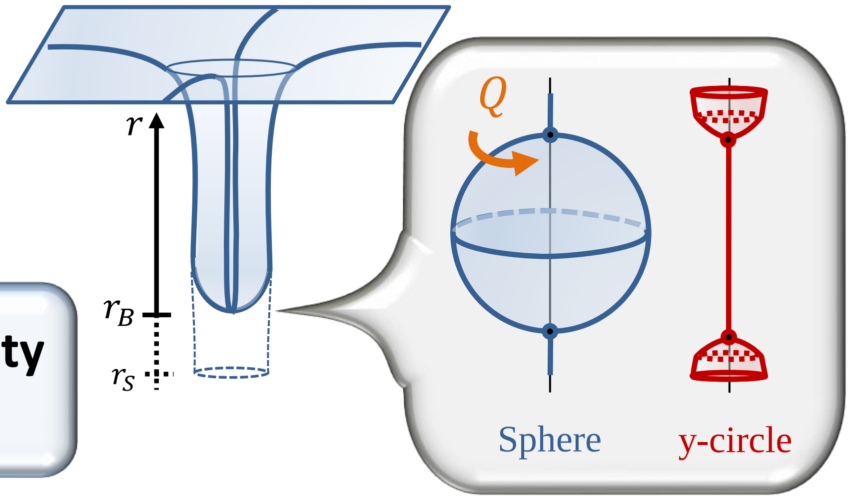
$$ds^2 = -\left(1-\frac{r_S}{r}\right)dt^2 + \underbrace{\left(1-\frac{r_B}{r}\right)dy^2}_{\text{Extra Dimension}} + \frac{dr^2}{\left(1-\frac{r_S}{r}\right)\left(1-\frac{r_B}{r}\right)} + \underbrace{r^2[d\theta^2 + \sin^2\theta\, d\phi^2]}_{\text{Sphere}}$$

- Soliton is located at $r = r_B$ and carries **D1-D5 charges** $Q = \sqrt{3 r_S r_B}$

- **Regularity** $\Rightarrow$ $r_B, r_S \sim R_y$ (Extra dimension size)

- $R_y \sim 10^3 \ell_P \Rightarrow \begin{cases} \text{Mass} \sim 10^{21} \text{ protons} \\ \quad \sim 10^{-36} M_\odot \\ \text{Size}, r_B \sim 10^{-23}\, r_{proton} \end{cases}$

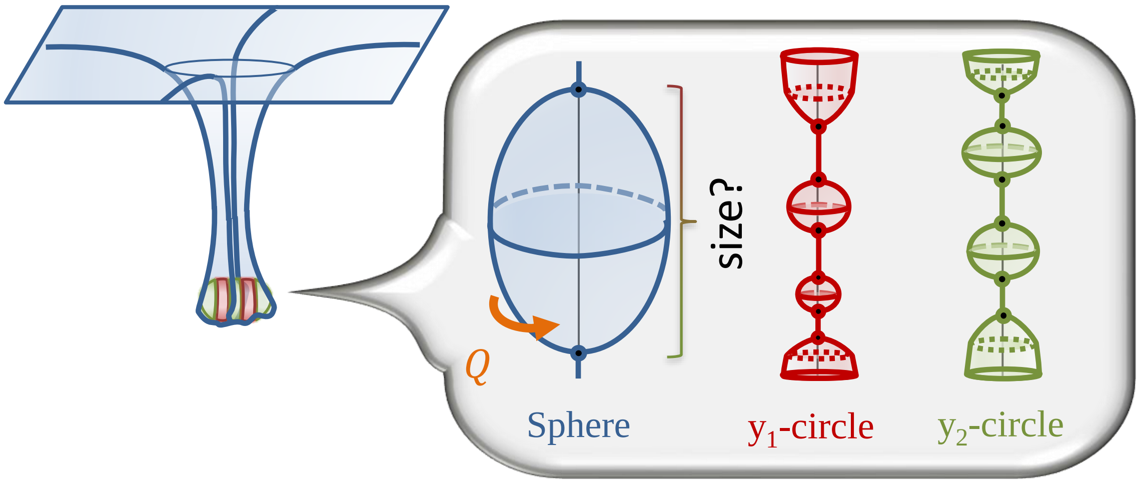
Topological star ~ **Topological Particle of Gravity**
How to make **macroscopic solitons**?



Bubble Bag Ends

- **Bound states** of topological stars **using at least two extra dimensions**

Bah, PH ’20, ’21, ‘22; PH ‘21



- Use the Charged Weyl Formalism to **solve EOM analytically with a linear ansatz**
- Smooth bound states of N topological stars with $Q = M/\cosh b$
  - Size $\sim N^{1/4}\,R_y \rightarrow$ **macroscopic**!
  - **Like non-extremal black holes + singular scalars** in 4d but **free from singularities and horizons** in 6d!
  - Clear origin as M2-M2-M2 or D1-D5-KKm non-supersymmetric bubbling geometries

Bubble Bag Ends

Bah, PH '21

$$ds_6^2 = \frac{1}{\mathcal{Z}_1}\left[-dt^2 + U_1 dy_1^2\right] + \frac{U_2\,\mathcal{Z}_1}{\mathcal{Z}_0}\left(dy_2 + H_0\,d\phi\right)^2 + \frac{\mathcal{Z}_0\mathcal{Z}_1}{U_1U_2}\left[e^{2\nu}\,\left(d\rho^2+dz^2\right) + \rho^2 d\phi^2\right],$$
$$F_3 = dH_1 \wedge d\phi \wedge dy_2 \,+\, dT_1 \,\wedge\, dt \,\wedge\, dy_1\,, \tag{2.14}$$

where the quantities,[8] which are independent of the gauge fields, are given by

$$U_1 \,=\, \prod_{i=1}^{N+1}\left(1 - \frac{2M_{2i-1}}{r_+^{(2i-1)} + r_-^{(2i-1)} + M_{2i-1}}\right), \qquad U_2 \,=\, \prod_{i=1}^{N}\left(1 - \frac{2M_{2i}}{r_+^{(2i)} + r_-^{(2i)} + M_{2i}}\right),$$
$$e^{2\nu} \,=\, \frac{E_{-+}^{(1,n)}}{\sqrt{E_{++}^{(n,n)}E_{--}^{(1,1)}}}\prod_{i=1}^{N}\prod_{j=1}^{N+1}\sqrt{\frac{E_{--}^{(2i,2j-1)}E_{++}^{(2i,2j-1)}}{E_{-+}^{(2i,2j-1)}E_{+-}^{(2i,2j-1)}}}\,, \tag{2.15}$$

and the ones depending on the gauge fields are

$$\mathcal{Z}_0 \,=\, \frac{e^{b_0} - e^{-b_0}\,U_1\,{U_2}^2}{2\,\sinh b_0}\,, \qquad \mathcal{Z}_1 \,=\, \frac{e^{b_1} - e^{-b_1}\,U_1}{2\,\sinh b_1}\,,$$
$$H_0 \,=\, \frac{1}{2\sinh b_0}\left[r_-^{(1)} - r_+^{(2N+1)} + \sum_{i=1}^{N}(r_-^{(2i)} - r_+^{(2i)})\right], \tag{2.16}$$
$$H_1 \,=\, \frac{1}{2\sinh b_1}\sum_{i=1}^{N+1}(r_-^{(2i-1)} - r_+^{(2i-1)})\,, \quad T_1 \,=\, -\sinh b_1\,\frac{e^{b_1} + e^{-b_1}\,U_1}{e^{b_1} - e^{-b_1}\,U_1}\,,$$

We define the distances to the endpoints $r_\pm^{(i)}$ and the generating functions $E_{\pm\pm}^{(i,j)}$ such as

$$r_\pm^{(i)} \equiv \sqrt{\rho^2 + \left(z - z_i^\pm\right)^2}\,, \qquad E_{\pm\pm}^{(i,j)} \equiv r_\pm^{(i)} r_\pm^{(j)} + \left(z - z_i^\pm\right)\left(z - z_j^\pm\right) + \rho^2, \tag{2.10}$$

But…. The geometries still have non-zero total charges

1. Vacuum solitons in gravity

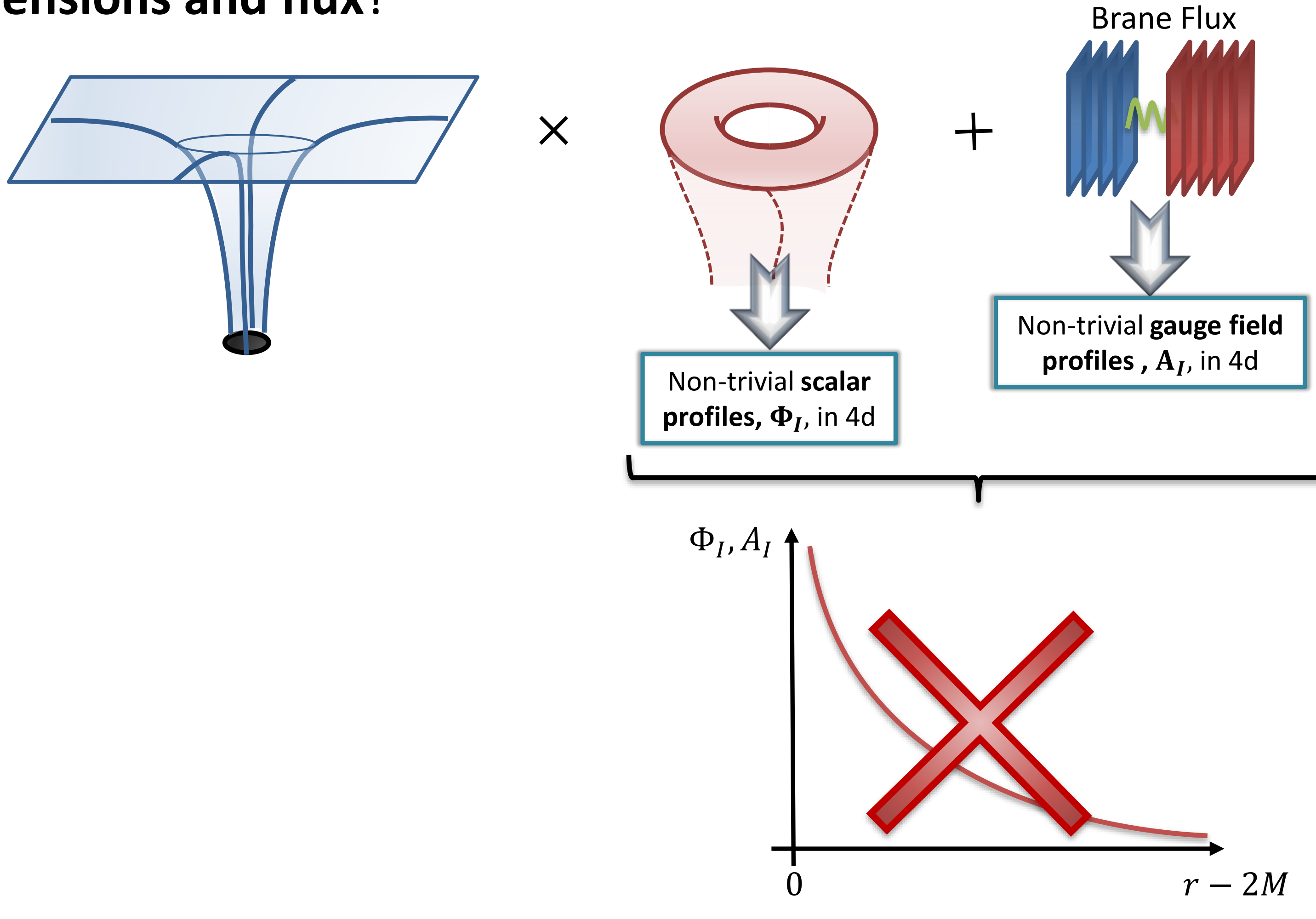
2. Charged solitons in gravity

3. Solitons that resolve Schwarzschild horizon

4. Some gravitational properties

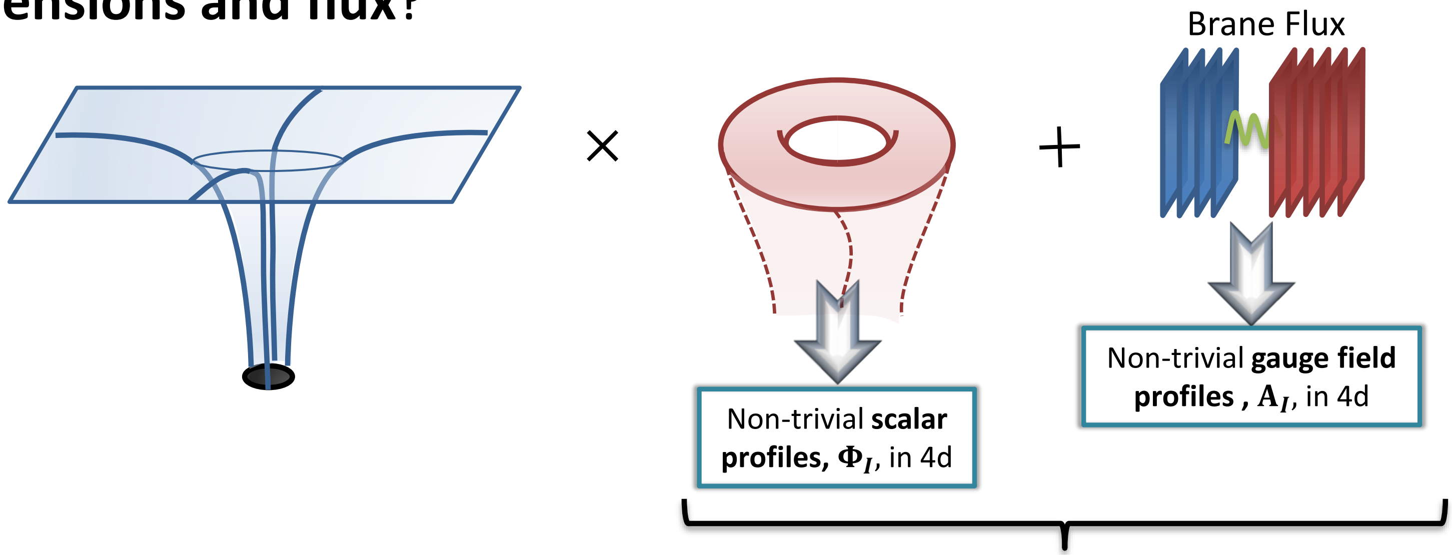
Resolving Schwarzschild?

- How to **resolve Schwarzschild** arbitrarily close to its horizon using **extra dimensions and flux**?



Resolving Schwarzschild?

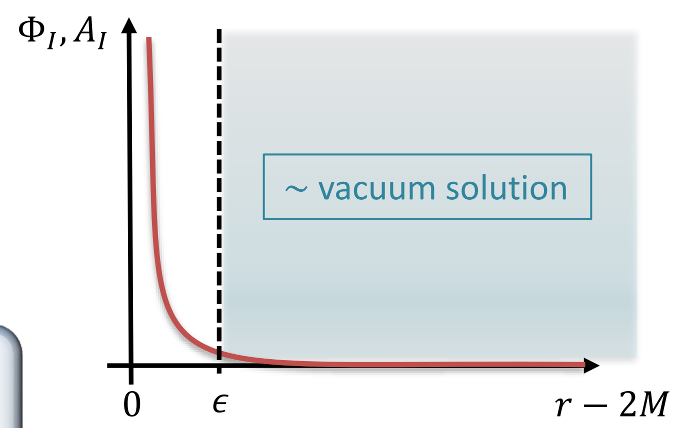
- How to **resolve Schwarzschild** arbitrarily close to its horizon using **extra dimensions and flux**?



- Extremal SUSY BH have already scalar and gauge field tails

$$\Phi_I, A_I \sim 1 + \frac{\alpha}{r} \quad \rightarrow \quad 1 + \sum_i \frac{\alpha_i}{r_i}$$

How to proceed for Schwarzschild?



Bah, PH '23

Schwarzschild Scalarwalls

- **Schwarzschild Scalarwalls**: Schwarzschild black hole with a backreacted singular scalar field Bah, PH '23

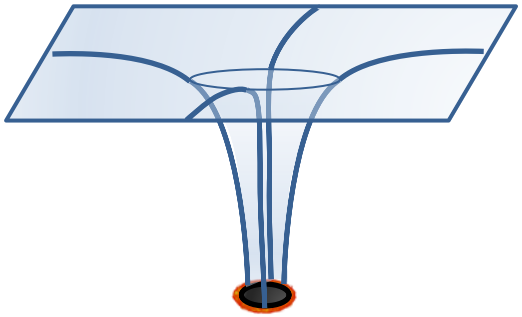
$$ds_4^2 = -\left(1-\frac{2M}{r}\right)dt^2 + H(r,\theta)\left[\frac{dr^2}{\left(1-\frac{2M}{r}\right)} + r^2 d\theta^2\right] + r^2 \sin^2\theta \, d\phi^2,$$

$$e^{-\Phi} = 1 - \frac{2M}{r}, \qquad H(r,\theta) = \left(1 + \frac{M^2 \sin^2\theta}{r(r-2M)}\right)^{-1}$$

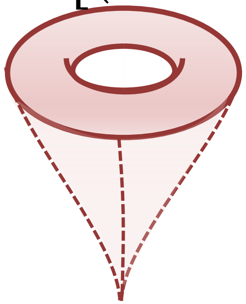
- Embedding in M-theory on T^7 as **a vacuum solution with T^7 deformations**

$$ds_{11}^2 = \left(1-\frac{2M}{r}\right)^{\frac{2}{3}} [-dt^2 + dy_0^2 + dy_1^2 + dy_2^2] + \left(1-\frac{2M}{r}\right)^{-\frac{1}{3}} ds(T^4)^2$$

$$+\left(1-\frac{2M}{r}\right)^{-\frac{1}{3}}\left[H(r,\theta)\left[\frac{dr^2}{\left(1-\frac{2M}{r}\right)} + r^2 d\theta^2\right] + r^2\sin^2\theta \, d\phi^2\right],$$



×



Can we resolve the $r = 2M$ singular horizon?

Geometric Resolution

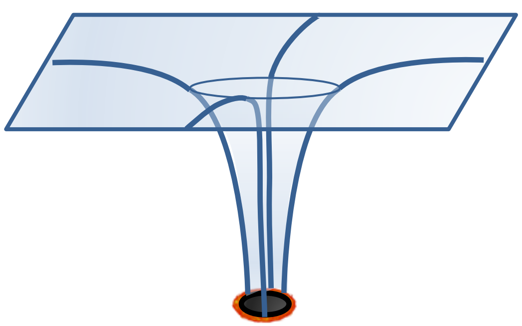
- **Step 1:** blowing up a **bubble of nothing** of size $\ell \sim 2M$
- **Step 2:** add $(\ell/2)^2 \sim M^2$ **M2 branes and anti-M2 branes at the poles**
- **Step 3:** Replace the poles by **small bubbles of size σ** supported by the same M2 brane flux

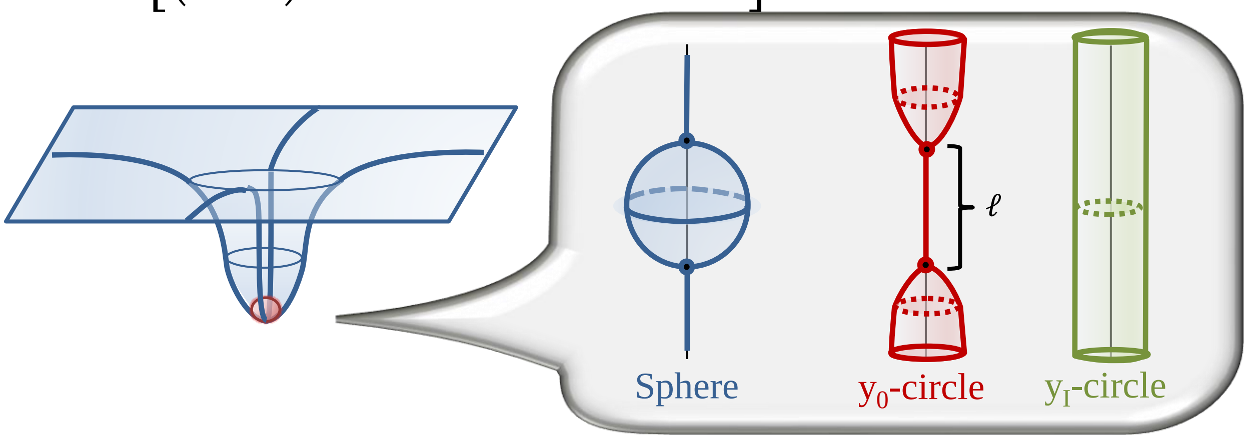
$$ds_{11}^2 = [-dt^2 + ds(T^6)^2] + \left(1-\frac{\ell}{r}\right)dy_0^2 + \left[\frac{dr^2}{\left(1-\frac{\ell}{r}\right)} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2\right]$$

Red. on T^7

$$ds_4^2 = -\sqrt{1-\frac{\ell}{r}}\, dt^2 + \sqrt{1-\frac{\ell}{r}}\left[\frac{dr^2}{\left(1-\frac{\ell}{r}\right)} + r^2 d\theta^2 + r^2 \sin^2\theta \, d\phi^2\right]$$

+ scalar $\sim 1 - \frac{\ell}{r}$





Geometric Resolution

- **Step 1:** blowing up a bubble of nothing of size $\ell \sim 2M$
- **Step 2:** add $(\ell/2)^2 \sim M^2$ M2 branes and anti-M2 branes at the poles
- **Step 3:** Replace the poles by small bubbles supported by the same M2 brane flux

$Z \sim \left(1-\frac{\ell}{r}\right)^{-1}$ for $r \gtrsim 2M + R_{y_0}$

$$ds_{11}^2 = Z^{-\frac{2}{3}}[-dt^2 + dy_1^2 + dy_2^2] + Z^{\frac{1}{3}}\left[\left(1-\frac{\ell}{r}\right)dy_0^2 + ds(T^4)^2\right]$$
$$+ Z^{\frac{1}{3}}\left[H\left[\frac{dr^2}{\left(1-\frac{\ell}{r}\right)} + r^2 d\theta^2\right] + r^2 \sin^2\theta \, d\phi^2\right],$$

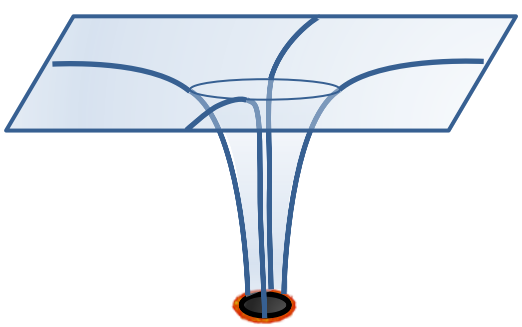
$$F_4 = dA \wedge dt \wedge dy_1 \wedge dy_2$$

$A \sim 0$ for $r \gtrsim 2M + R_{y_0}$

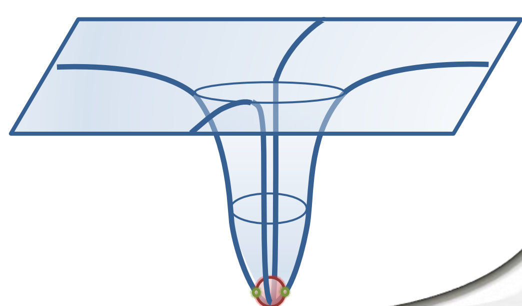
Red. on T^7

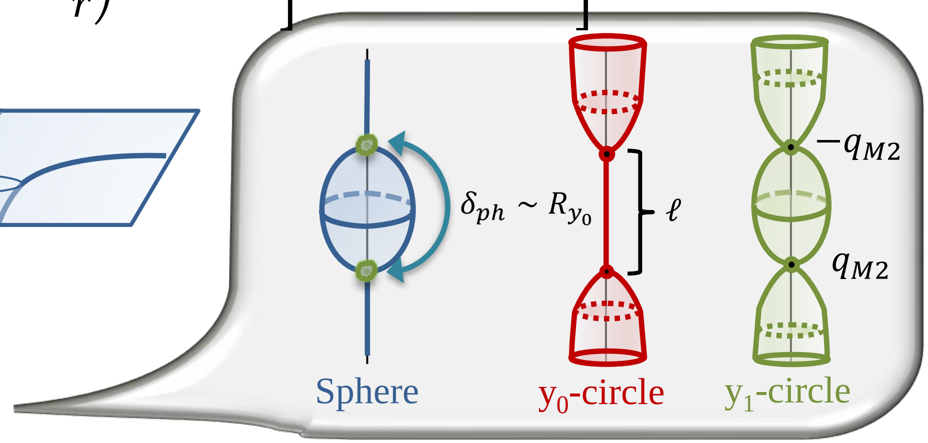
$$ds_4^2 = -\sqrt{\frac{1-\frac{\ell}{r}}{Z}}\,dt^2 + \sqrt{Z\left(1-\frac{\ell}{r}\right)}\left[H\left[\frac{dr^2}{\left(1-\frac{\ell}{r}\right)} + r^2 d\theta^2\right] + r^2\sin^2\theta \, d\phi^2\right]$$

+ scalars



$\sim$



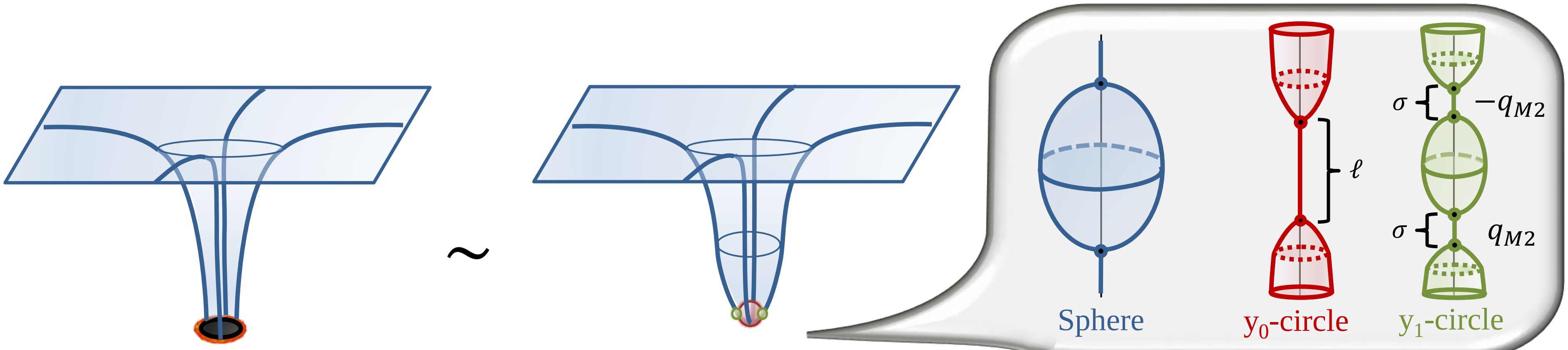


Geometric Resolution

- **Step 1:** blowing up a bubble of nothing of size $\ell \sim 2M$
- **Step 2:** add $(\ell/2)^2 \sim M^2$ M2 branes and anti-M2 branes at the poles
- **Step 3:** Replace the poles by small bubbles supported by the same M2 brane flux

$$ds_{11}^2 = Z^{-\frac{2}{3}}\left[-dt^2 + \left(1-\frac{\sigma}{r_1}\right)\left(1-\frac{\sigma}{r_3}\right)dy_1^2 + dy_2^2\right] + Z^{\frac{1}{3}}\left[\left(1-\frac{\ell}{r_2}\right)dy_0^2 + ds(T^4)^2\right]$$
$$+ Z^{\frac{1}{3}}\left[H\left[\frac{dr^2}{\left(1-\frac{\ell+2\sigma}{r}\right)} + r^2 d\theta^2\right] + r^2\sin^2\theta\, d\phi^2\right], \qquad F_4 = dA \wedge dt \wedge dy_1 \wedge dy_2$$

First example of topological solitons that resolve the horizon of a Schwarzschild black hole + a scalar tail



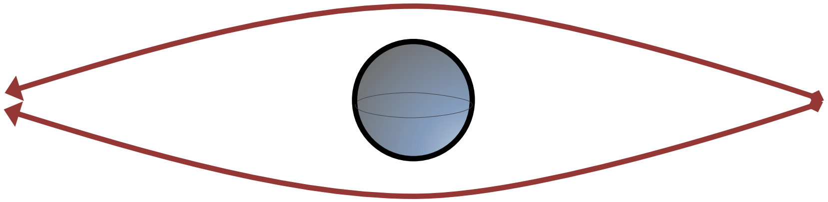
1. Vacuum solitons in gravity
2. Charged solitons in gravity
3. Solitons that resolve Schwarzschild horizon
4. Some gravitational properties

Lensing and Gravitational Wave Signatures

- **Two experiments** allow to probe the near-environment of black holes.

What are the **gravitational characteristics of topological solitons** compared to those of a black hole?

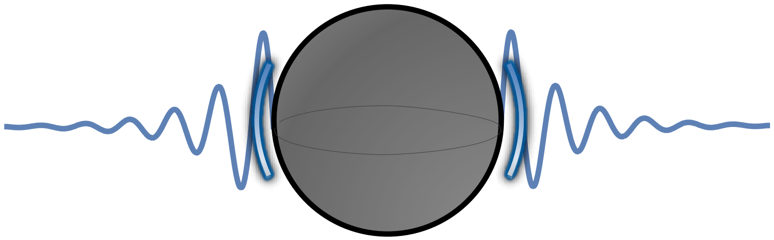
1. Gravitational lensing:



BH and TS do not emit light but **scatter light rays**

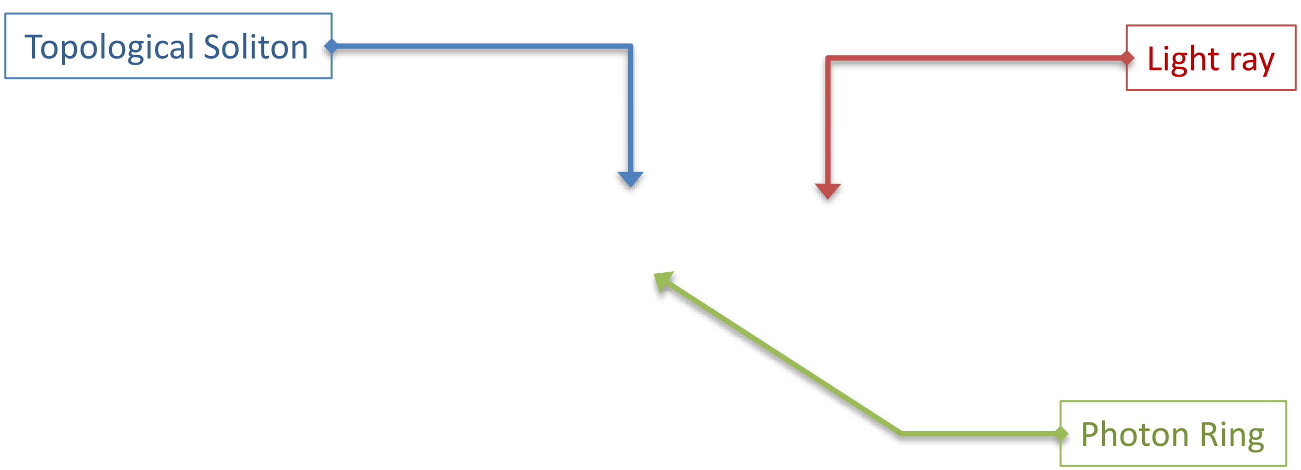
2. Gravitational wave emission:

After the gravitational merger, the final state relaxes by emitting a **ringdown gravitational wave signal**.



Gravitational Lensing and Imaging

- Topological Soliton → **intense spacetime deformation ⇒ intense lensing**
- Photons follow **geodesic trajectories**
- Like black holes, they are circumscribed by an **photon ring (~ shadow)** where light can be trapped.
- However, incoming photons do not fall into a horizon **(≠ shadow)** but **bounce on the soliton after a chaotic trajectory**



Bah, Berti, PH '22

Imaging Topological Solitons

- <u>What do Topological solitons look like in the sky?</u>

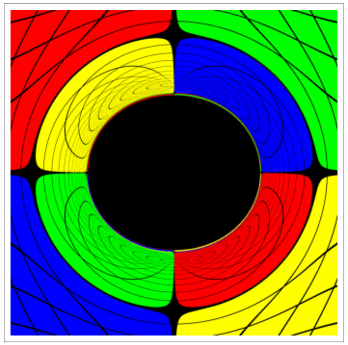
Bah, Berti, PH '22

1. Build a ray tracing code
2. Shoot 10^6 light rays from a celestial sphere
3. Reconstruct the picture as seen from a distant observer

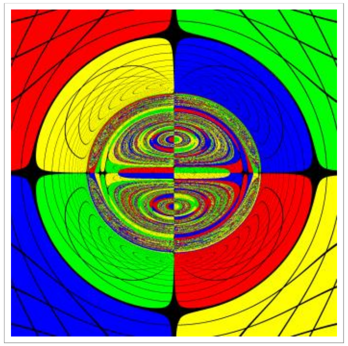
<u>Flat Space:</u>

<u>Schwarzschild:</u>

<u>Schw. Scalarwall:</u>



<u>Smooth resolution:</u>



Photon Rings **match with Schwarzschild Shadow** in size and scattering properties

Imaging Topological Solitons

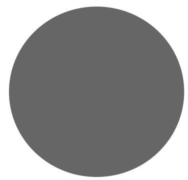
- Use a **star patch** for more ``arty'' imaging   Bah, Berti, PH '22
- Incoming light endures **high redshift and chaotic trajectories**
  → intensity should be suppressed beyond the probe limit

Flat Space:

Schwarzschild:

Schw. Scalarwall:

Smooth resolution:



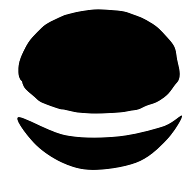
Imaging Topological Solitons

- Imaging from a **bright accretion disk** → ~EHT Bah, Berti, PH '22

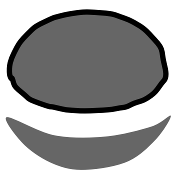
Flat Space:

Schwarzschild:

Schw. Scalarwall:



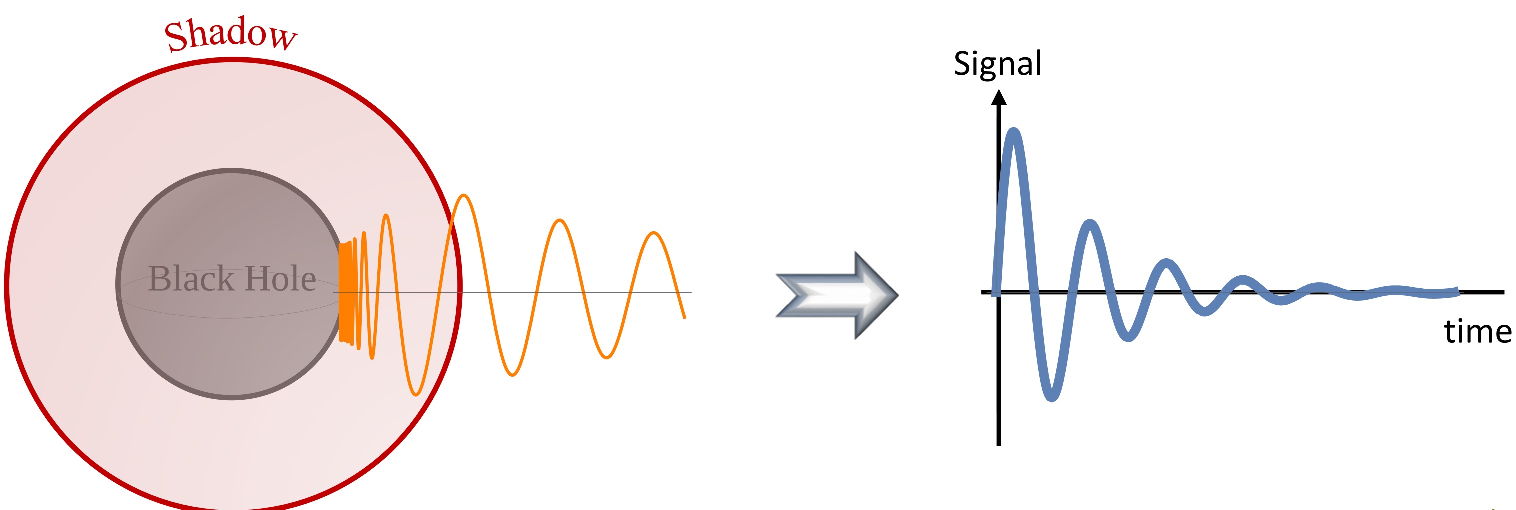
Smooth resolution:



Expectation:
blurred and faded cloud should emerge from inside the shadow

Gravitational Wave Signal

- Gravitational waves are governed by **quasi-normal**
- Static black hole: **modes localize at the shadow** and **determined by its scattering properties**
- Topological solitons replace the horizon by **stable photon rings**. How does it affect quasi-normal modes?
    - Fundamental modes **localize at the microstructure**
    - Black hole modes are part of the spectrum
      but **cavity effect on their decay time**



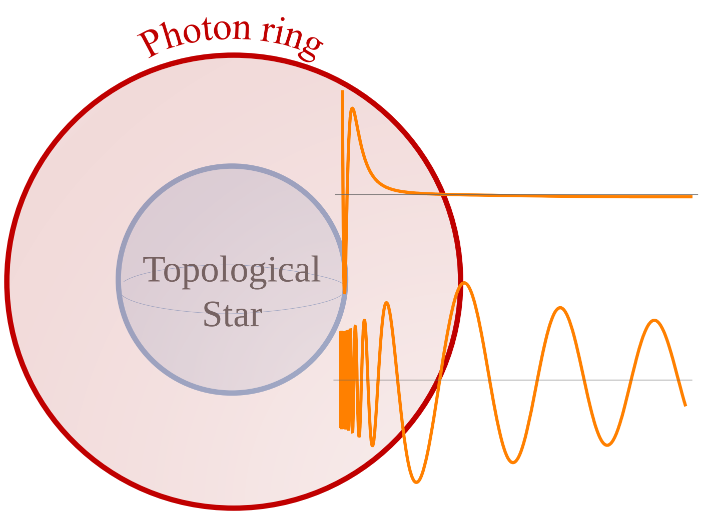
Bah, Berti, Speeney, PH '23

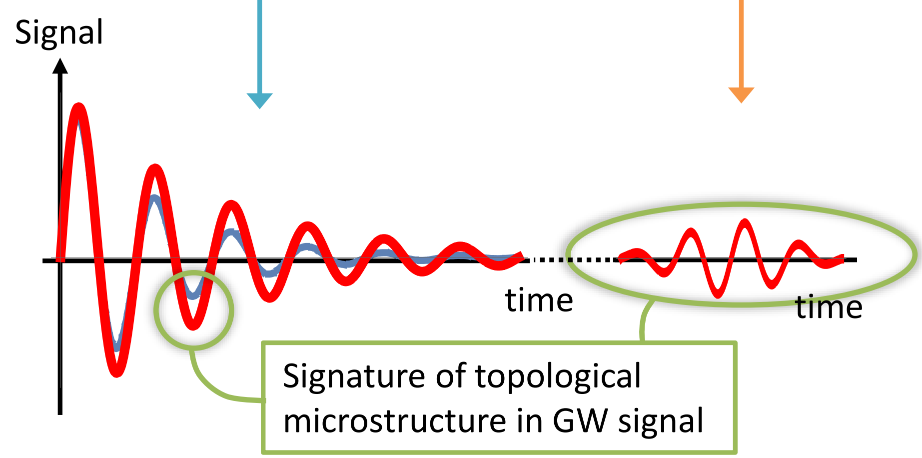
Gravitational Wave Signal

- Gravitational waves are governed by **quasi-normal**
- Static black hole: **modes localize at the shadow** and **determined by its scattering properties**
- Topological solitons replace the horizon by **stable photon rings**. How does it affect quasi-normal modes?
  - Fundamental modes **localize at the microstructure**
  - Black hole modes are part of the spectrum but **cavity effect on their decay time**

Echoes in the long-term signal

Short-term signal is identical to black hole signal but with a **damping tail**





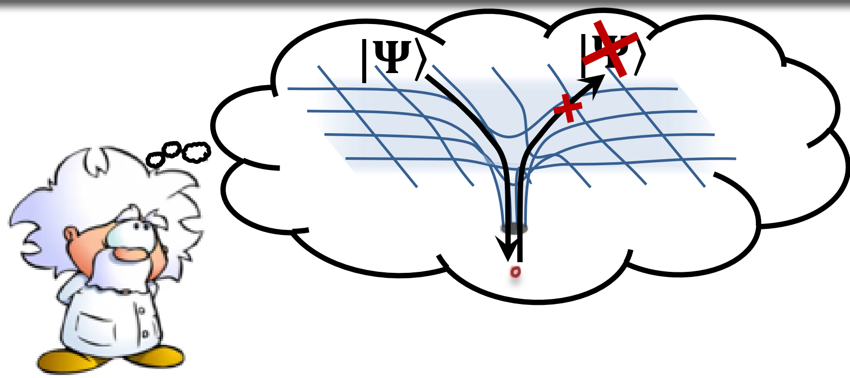
Bah, Berti, Speeney, PH ’23

Conclusion and Outlook

- Fundamental states of Quantum Gravity that manifest as **Topological Solitons in Gravity exist**. Their **phenomenology** and **fundamental role open a window into new astrophysics and black hole physics.**
- Solitons in Anti-de Sitter spacetimes and application to **holography**? Bah, PH '22; Houppe, PH '22
- General phase space of topological solitons? Spinning solitons? Chern-Simons interactions?
- Physical observables for future experiments? Bah, Berti, PH '22; Bah, Berti, Speeney, PH '23
- General aspect of stability and existence? Bah, Dey, PH '21

  Nucleation in the early universe (dark matter?) or late stage of matter collapse (BH)?

Black Hole Puzzles

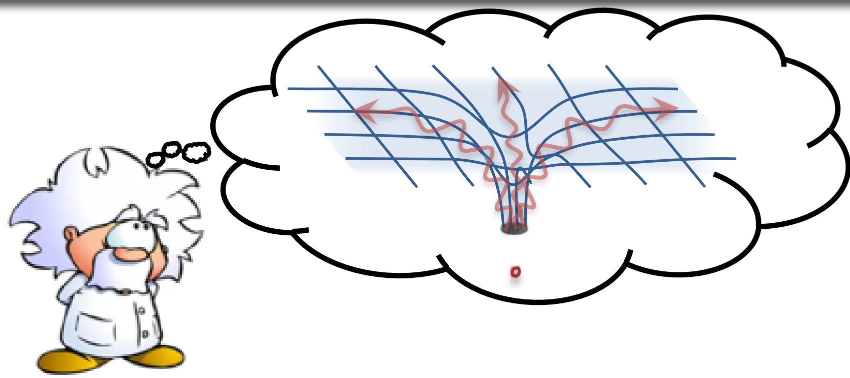


Black holes are at the center of **theoretical conflicts** between **GR and QM**

Singularity

Horizon ⇒ Information Paradox

Black Hole Puzzles



Black holes are at the center of **theoretical conflicts** between **GR and QM**

Singularity

Horizon ⇒ Information Paradox

Black Hole Puzzles