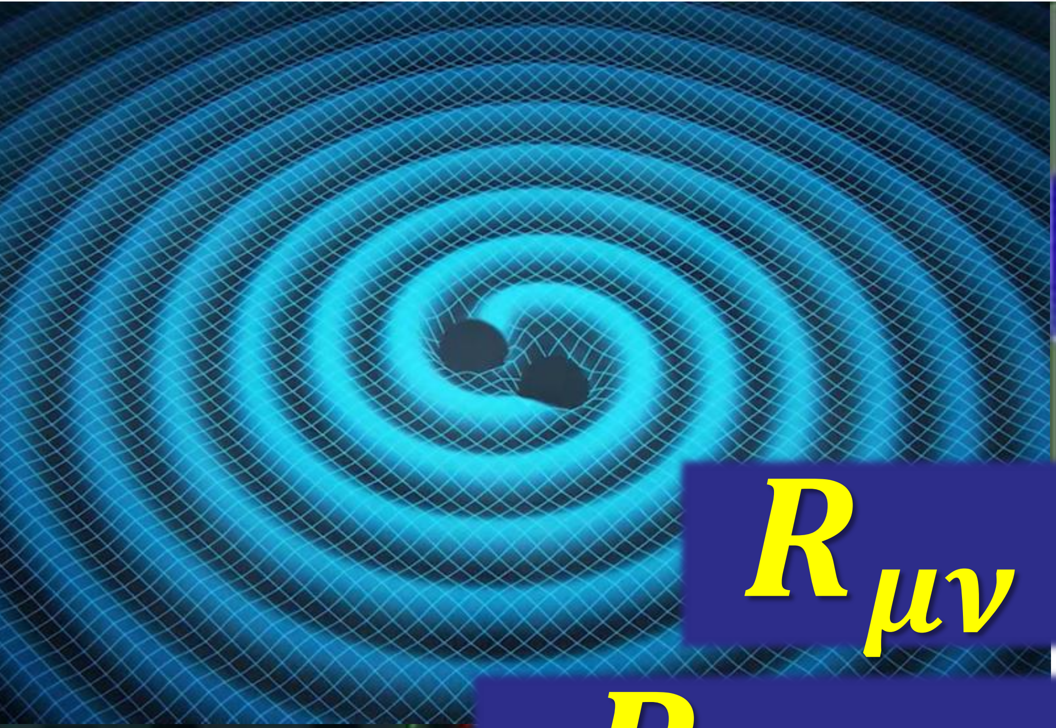
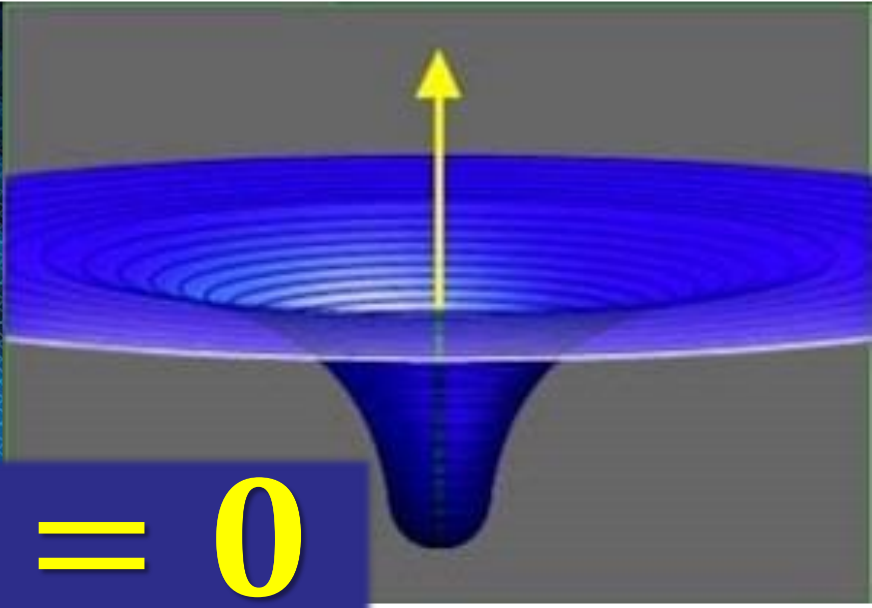
Black holes in the 1/D expansion

Roberto Emparan

ICREA & U. Barcelona (& YITP Kyoto)

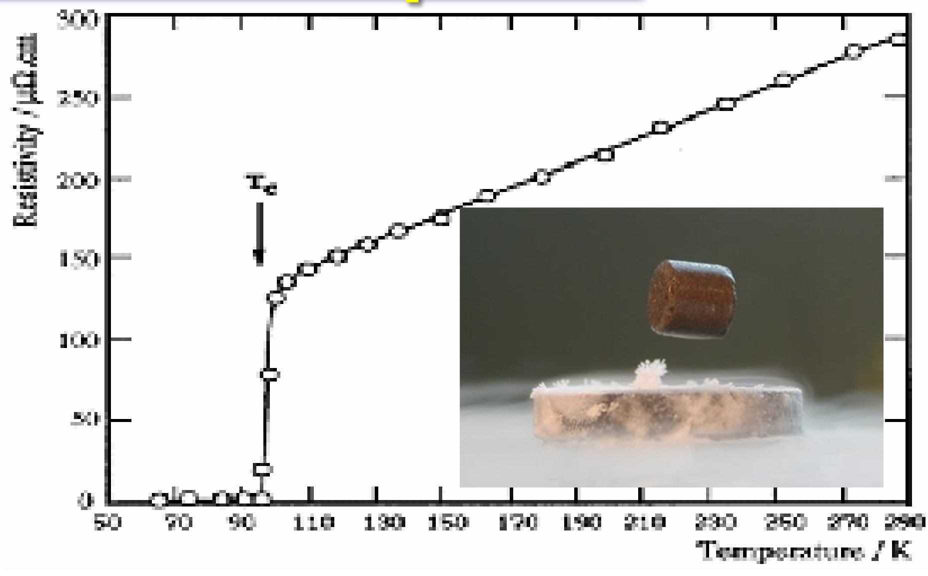
w/ Tetsuya Shiromizu, Ryotaku Suzuki,
Kentaro Tanabe, Takahiro Tanaka





$$R_{\mu\nu} = 0$$

$$R_{\mu\nu} = -\Lambda g_{\mu\nu}$$



A dimensionless, adjustable parameter
is a good thing to have
for studying a theory

Quantum ElectroDynamics

Perturb around $e^2 = 0$

Quantum GluoDynamics

SU(3) Yang-Mills theory

No parameter?

Quantum GluoDynamics

SU(**N**) Yang-Mills theory

parameter!

What dimensionless parameter in

$$R_{\mu\nu} = \Lambda \, g_{\mu\nu}?$$

$$R_{\mu\nu} = \Lambda\, g_{\mu\nu}$$

$$\mu, \nu = 0, \ldots, \boldsymbol{D} - 1$$

?

YM $\leftrightsquigarrow$ Quantum GR

$SU(N \to \infty)$ $SO(D \to \infty, 1)$

Quantum GR: SO(**D**-1,1) local Lorentz group

graviton polarizations grows with D

BUT:

No topological expansion of Feynman diagrams

No arrangement into worldsheets

Strominger 1981

Bjerrum-Bohr 2004

Even worse: UV behavior infinitely bad

YM
SU($N \to \infty$)

$\leftrightsquigarrow$

Quantum GR
SO ($D \to \infty$,1)

Classical General Relativity

D-diml Einstein's theory

Well-defined for all D

Many problems can be formulated keeping D arbitrary

→ D = continuous parameter

→ expand in 1/D

Kol et al

RE+Suzuki+Tanabe

Classical General Relativity

D-diml Einstein's theory

Large D

keeps essential physics of D=4

∃ black holes

∃ gravitational waves

simplifies the theory

reformulation in terms of other variables?

BH in *D* dimensions

$$ds^2 = -\left(1 - \left(\frac{r_0}{r}\right)^{D-3}\right)dt^2 + \frac{dr^2}{1 - \left(\frac{r_0}{r}\right)^{D-3}} + r^2 d\Omega_{D-2}$$

Localization of interactions

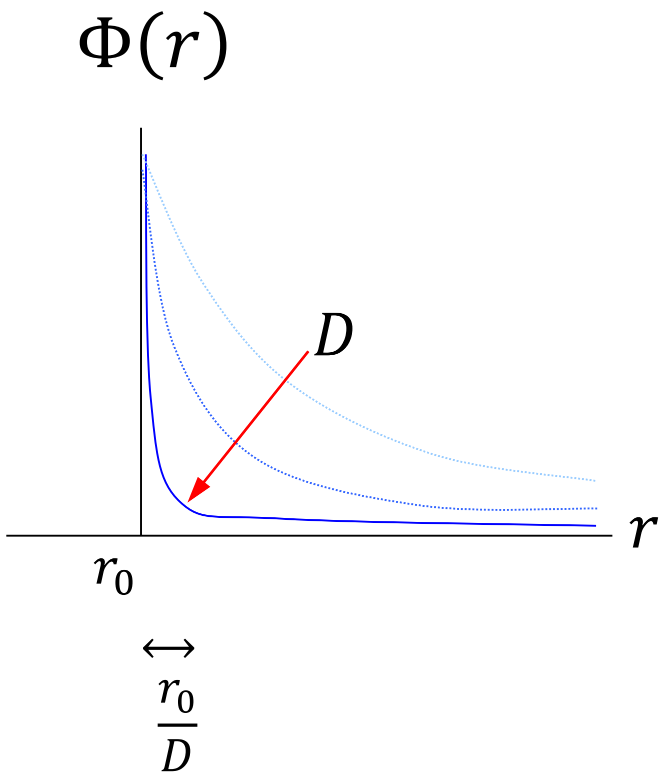
Large potential gradient:

$$\Phi(r) \sim \left(\frac{r_0}{r}\right)^{D-3}$$

$$\nabla\Phi\Big|_{r_0} \sim D/r_0$$

$\Longrightarrow$ Hierarchy of scales

$$\frac{r_0}{D} \ll r_0$$



Fixed $r > r_0$ $\quad D \to \infty$

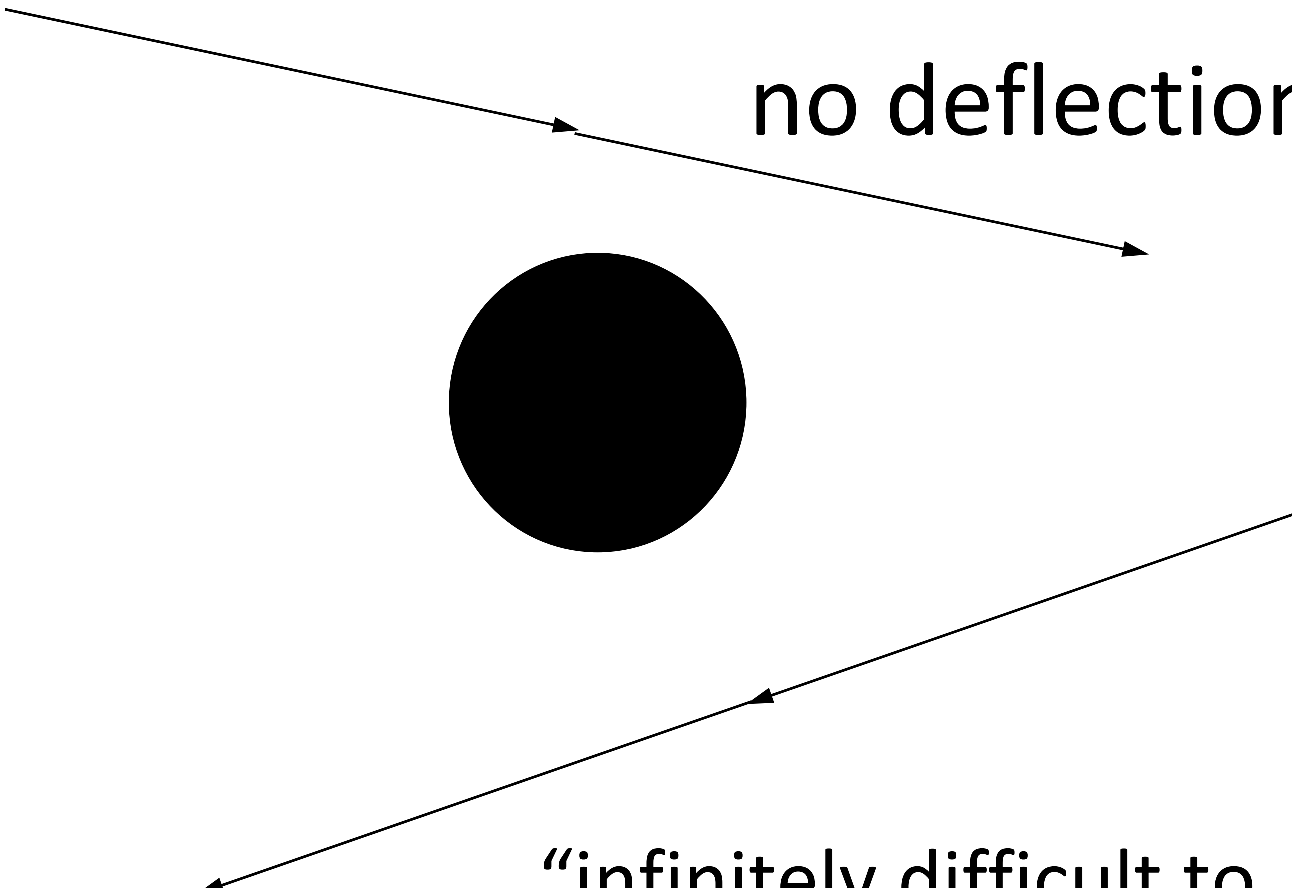
$$1 - \left(\frac{r_0}{r}\right)^{D-3} \to 1$$

$$ds^2 \to -dt^2 + dr^2 + r^2 d\Omega_{D-2}$$

Flat, empty space at $r > r_0$

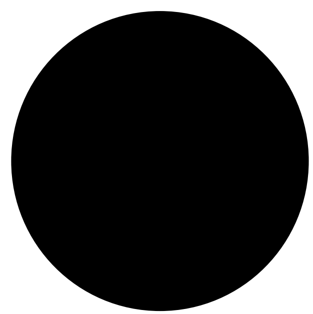
“**Far-zone**” limit

Black Hole scattering:
no deflection



"infinitely difficult to
catch a line of force"

Black Hole scattering



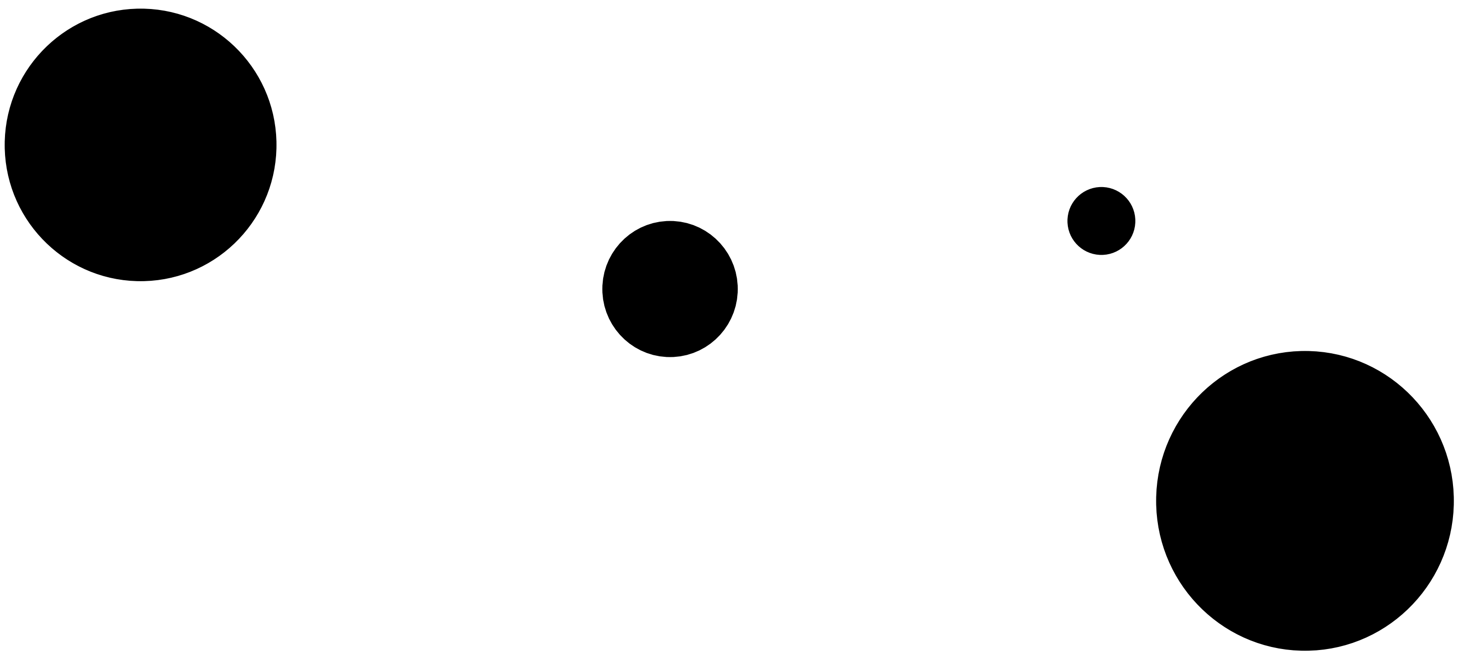
No absorption of waves

with wavelength

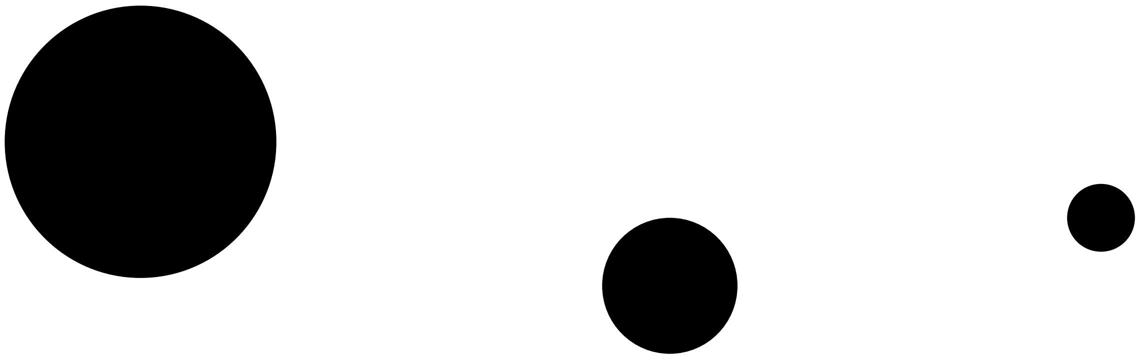
$\lambda \sim r_0$

Perfect reflection

No interaction



Holes cut out in Minkowski space

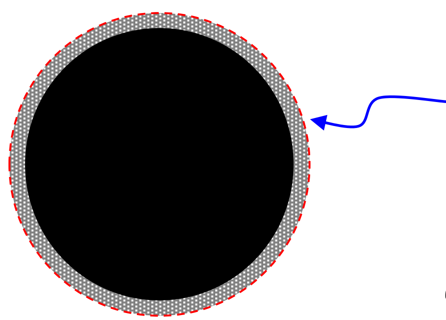


We are keeping length scales $\sim r_0$ finite as we send $D \to \infty$

“**Far-zone**” limit

Now take a limit that does *not* *trivialize* the gravitational field

$$\left(\frac{r_0}{r}\right)^{D-3} = \mathcal{O}(1) \iff r - r_0 < \frac{r_0}{D}$$



$$r - r_0 \sim \frac{r_0}{D}$$

“**Near-horizon**” limit

Near-horizon geometry

$$ds^2 = -\left(1 - \left(\frac{r_0}{r}\right)^{D-3}\right)dt^2 + \frac{dr^2}{1 - \left(\frac{r_0}{r}\right)^{D-3}} + r^2 d\Omega_{D-2}$$

$$\left.\begin{aligned} \left(\frac{r}{r_0}\right)^{D-3} &= \cosh^2\rho \\ t_{near} &= \frac{D}{2r_0} t \end{aligned}\right\} \text{finite as } D \to \infty$$

Near-horizon geometry

2d string bh

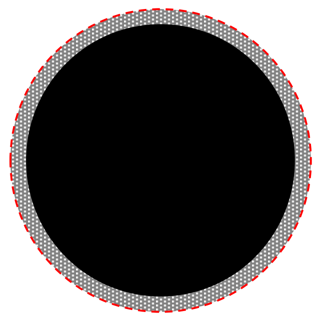
$$ds^2_{nh} \to \frac{4r_0^2}{D^2}\left(-\tanh^2\rho\ dt^2_{near} + d\rho^2\right)$$

$$+\, r_0^2\,(\cosh\rho)^{4/D}\, d\Omega^2_{D-2}$$

Soda 1993

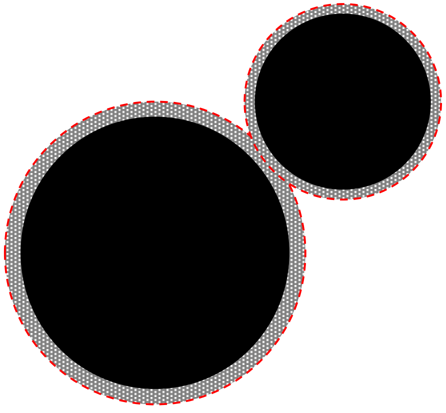
Grumiller et al 2002

Physics at $\sim r_0/D$ close to the horizon is *not* trivial



Perfect absorption
of waves with
$\lambda \sim r_0/D$
$\omega \sim D/r_0$

"**Near-horizon**" dynamics



Not an exact solution

Non-trivial interaction

"**Near-horizon**" dynamics

Near-horizon universality

2d string bh = near-horizon geometry of **all neutral non-extremal bhs**

rotation = local boost

(along horizon)

cosmo const = 2d bh mass-shift

Large D Effective Theory

Solve near-horizon equations

integrate-out short-distance dynamics

→ Boundary conds for far-zone fields

Long-distance effective theory

Black hole perturbations ✓

all analytic

Scattering

Quasinormal modes

Ultraspinning instability

Holographic superconductors

Full non-linear GR ✓

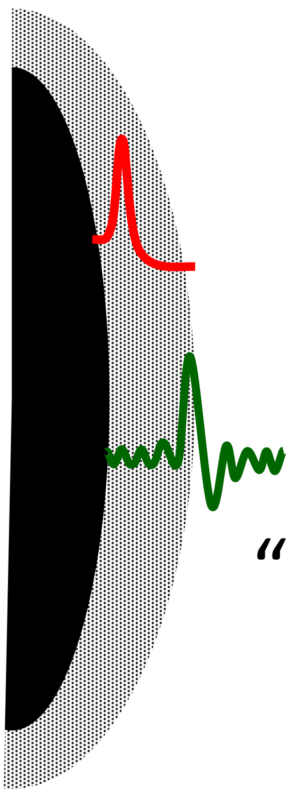
General theory of static black holes: ***Soap-film*** theory

Black droplets

simple ODE

Non-uniform black strings

BH excitations (quasinormal modes)



"Decoupled" normalizable states

very few modes: $\mathcal{O}(D^0)$

slow modes $\omega \sim D^0/r_0$

non-universal

"Non-decoupled" non-normalizable states

most modes: $\mathcal{O}(D^2)$

fast modes $\omega \sim D/r_0$

universal

BH perturbations: How accurate?

Small expansion parameter: $\frac{1}{D-3}$

not quite good for $D = 4$ ...

BH perturbations: How accurate?

Small expansion parameter: $\frac{1}{D-3}$

not quite good for $D = 4$ ...

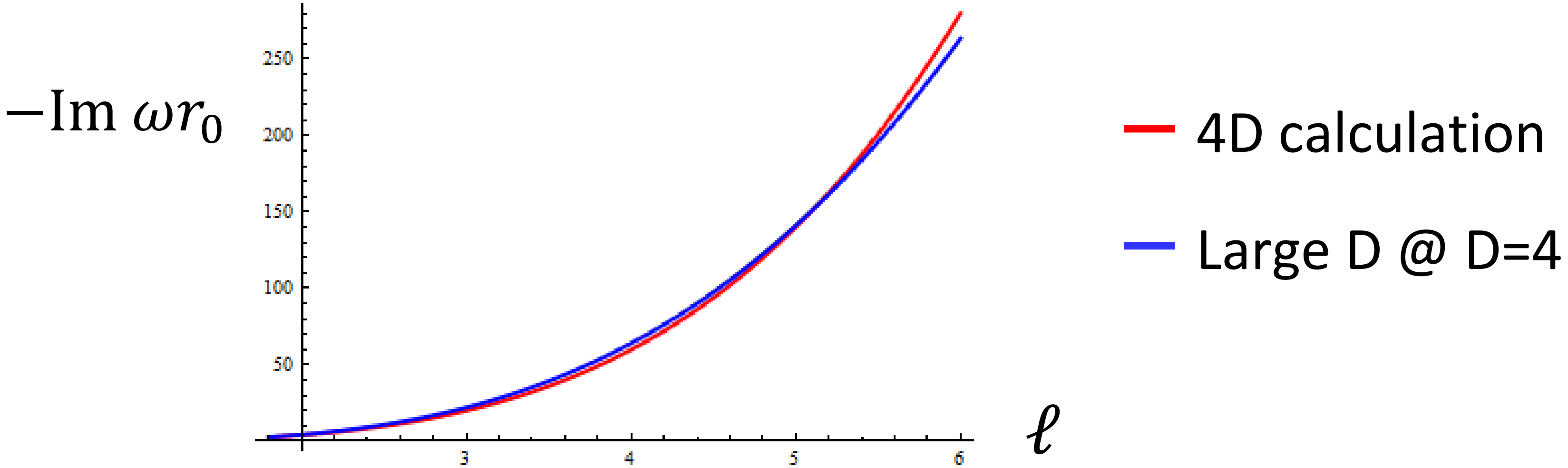
But it seems to be $\frac{1}{\mathbf{2}(D-3)}$

not *so* bad in $D = 4$, if we can compute higher orders

(in AdS: $\frac{1}{2(D-1)}$)

Quite accurate

Quasinormal frequency in $D = 4$ (vector-type)

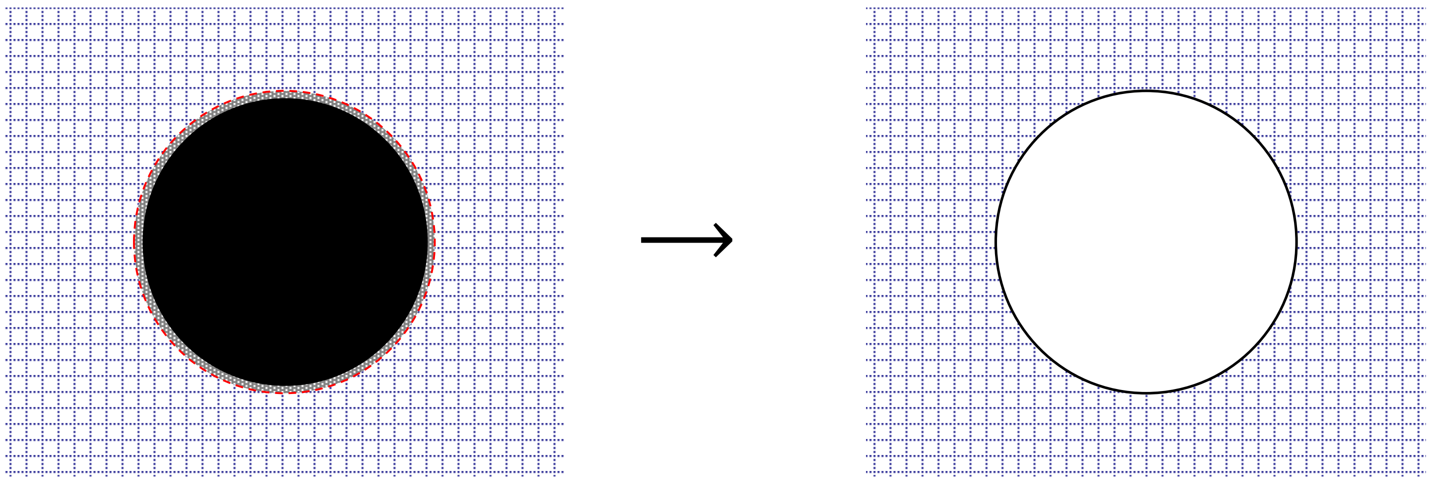


Calculation up to $\frac{1}{D^3}$ yields 6% accuracy in $D = 4$

$$6\% = \frac{1}{\left(2(D-3)\right)^4}\Big|_{D=4}$$

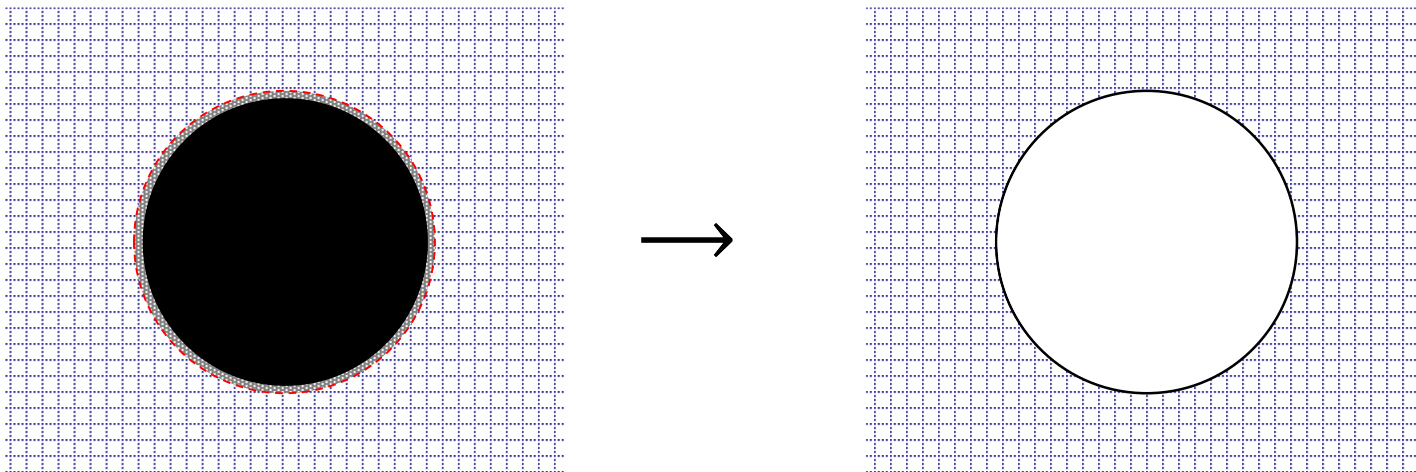
Fully non-linear GR @ large D

Large-D ⇒ neat separation bh / background



Replace bh ⟶ surface in background

What eqs determine this surface?



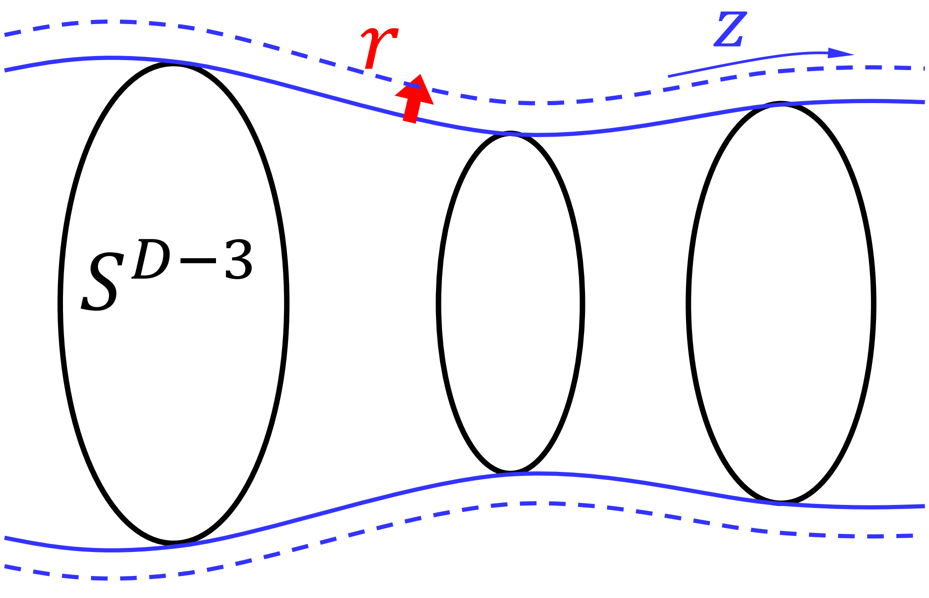
Derive them by solving Einstein’s eqs

in near-horizon zone

Gradient hierarchy

Gradients ⊥ Horizon: $\partial_r \sim D$

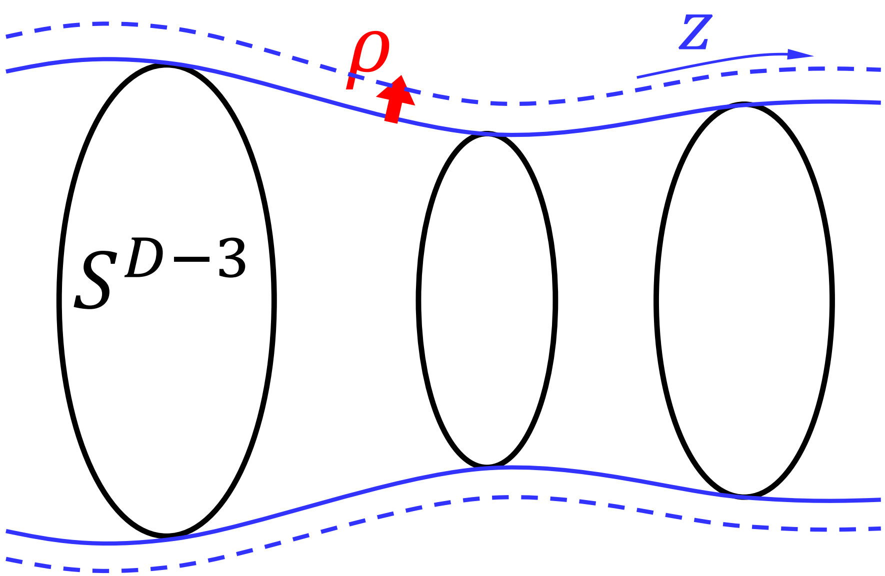
Gradients ∥ Horizon: $\partial_z \sim 1$



Static geometry: large D ansatz

$$ds^2 = N^2(z)\frac{d\rho^2}{D^2} + g_{\Omega\Omega}(\rho, z)d\Omega_{D-3}$$

$$+g_{tt}(\rho, z)dt^2 + g_{zz}(\rho, z)dz^2$$



Solve radial Einstein's eqs (w/ horizon at $\rho = 0$)

$$ds^2 = N^2(z)\frac{d\rho^2}{D^2} + g_{\Omega\Omega}(\rho, z)d\Omega_{D-3}$$

$$+g_{tt}(\rho, z)dt^2 + g_{zz}(\rho, z)dz^2$$

Recall: near-horizon bh

$$ds^2 = r_0^2\left(-\tanh^2\rho\, dt^2 + \frac{d\rho^2}{D^2}\right) + dz^2 +$$

$$r_0^2\,(\cosh\rho)^{4/D}\, d\Omega_{D-3}$$

Solve radial Einstein's eqs (w/ horizon at $\rho = 0$)

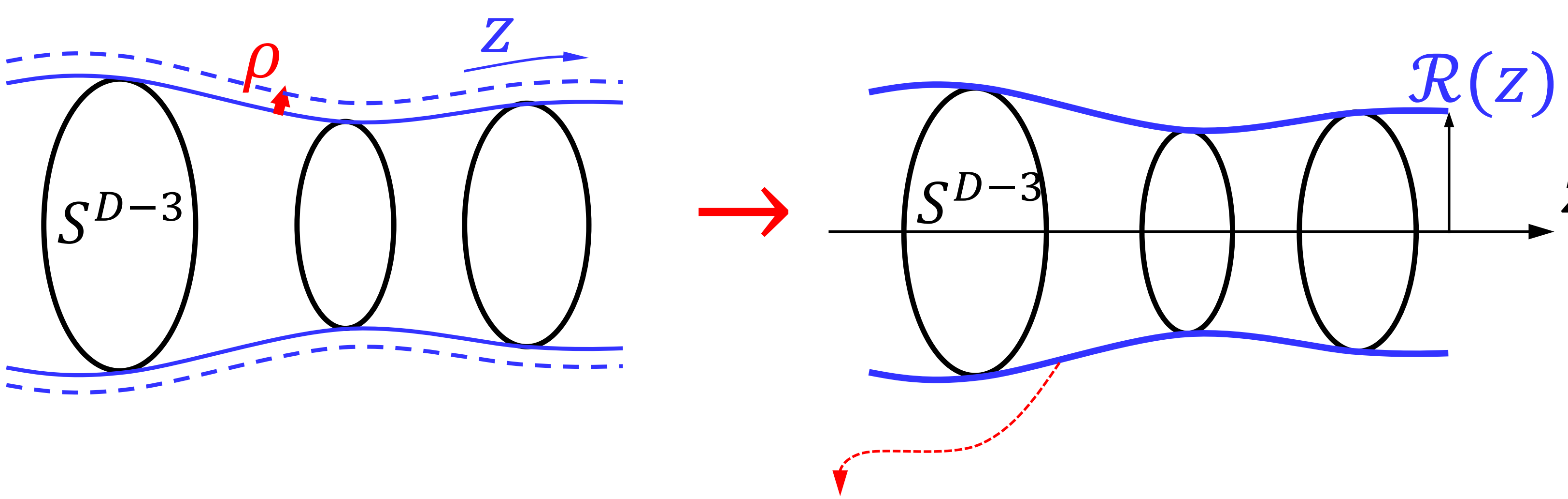
$\Rightarrow$ Modulation along z of near-horizon geometry

$$ds^2 = N^2(z)\left(-\tanh^2\rho\, dt^2 + \frac{d\rho^2}{D^2}\right) + f(\rho, z)dz^2 + \mathcal{R}^2(z)\,(\cosh\rho)^{4/D}\, d\Omega_{D-3}$$

$N(z)$: local redshift

$\mathcal{R}(z)$: radius of S^{D-3}

Black hole replaced by effective membrane embedded in background



Induced metric:

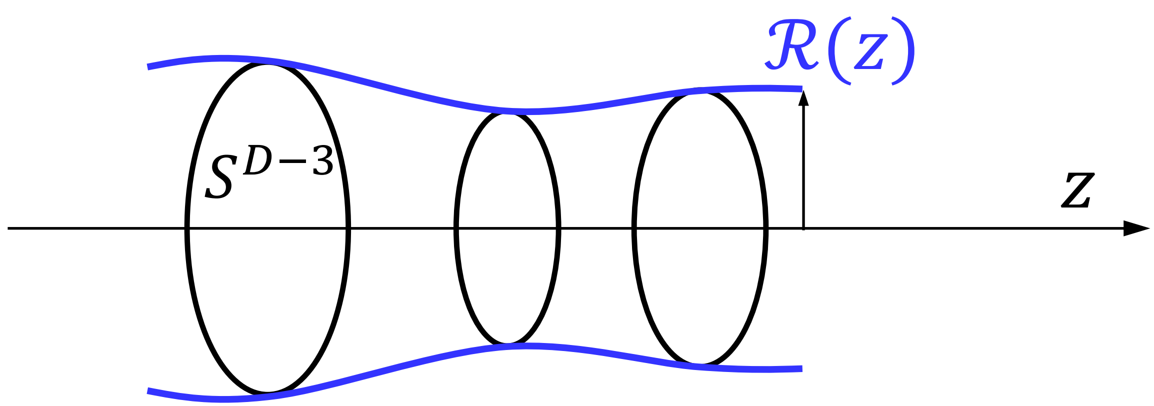
$$ds^2\Big|_h = -N^2(z)dt^2 + dz^2 + \mathcal{R}^2(z)d\Omega_{D-3}$$

Einstein vector-constraint in ρ:

$$\sqrt{-g_{tt}}K = \text{const}$$

K = mean curvature of ‘horizon surface’

$$ds^2\Big|_h = g_{tt}(z)dt^2 + dz^2 + \mathcal{R}^2(z)d\Omega_{D-3}$$



Soap-film equation (redshifted)

$$\sqrt{-g_{tt}}K = \mathrm{const}$$

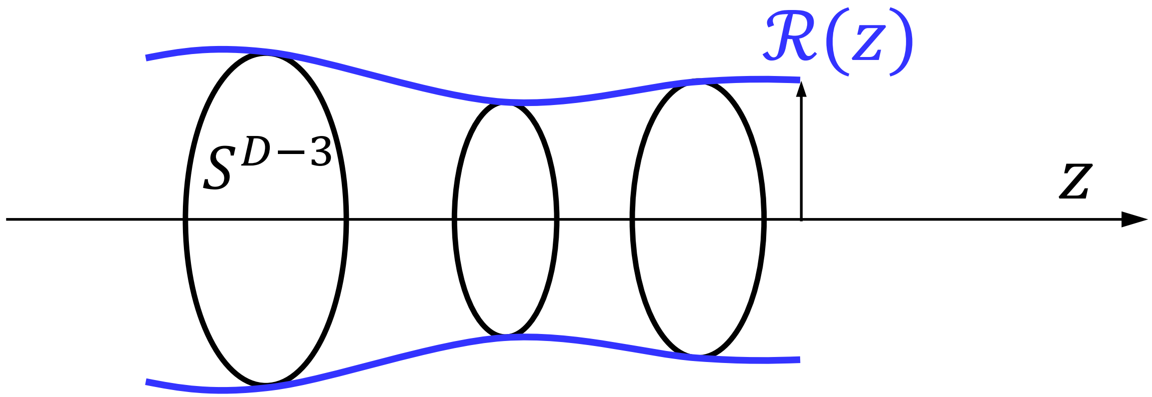
Valid up to NLO in 1/D (but *not* at NNLO)

Some applications

Soap bubble in Minkowski

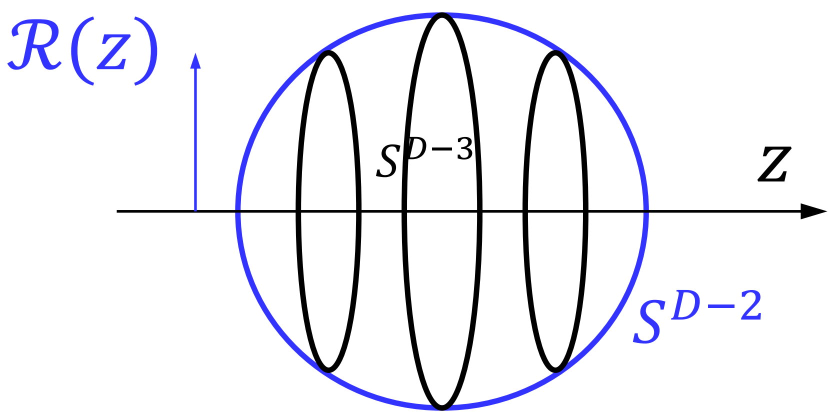
$$ds^2 = -dt^2 + dz^2 + dr^2 + r^2 d\Omega_{D-3}$$

$$r = \mathcal{R}(z)$$



Soap bubble in Minkowski = Schw BH

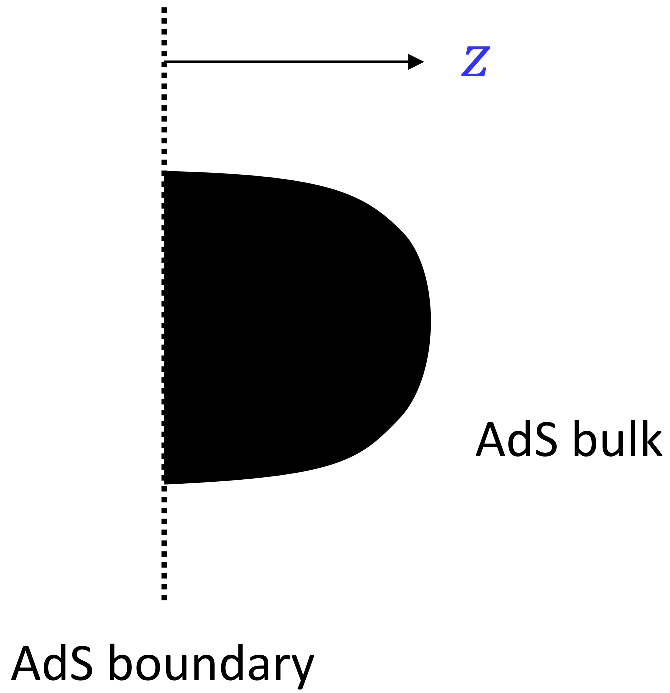
$$\sqrt{-g_{tt}}K = \text{const} \;\Rightarrow\; \mathcal{R}'^2 + \mathcal{R}^2 = 1$$



$$\Rightarrow \mathcal{R}(z) = \sin z$$

Black droplets

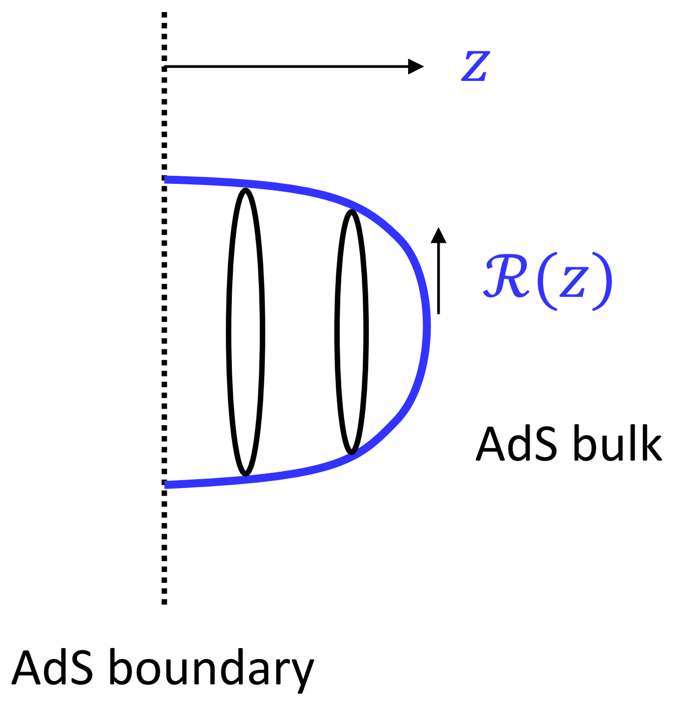
Black hole at boundary of AdS



dual to CFT in BH background

Numerical solution:

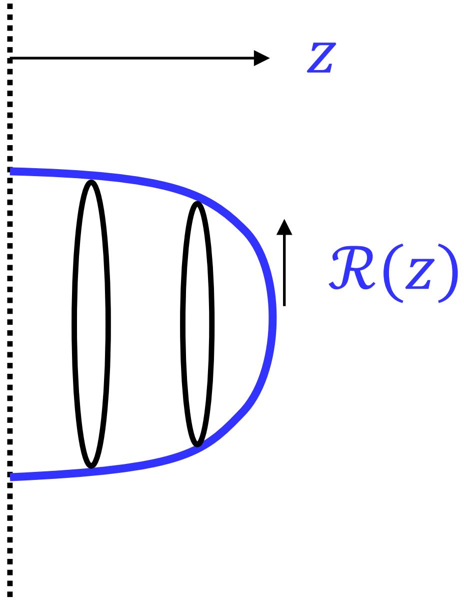
Figueras+Lucietti+Wiseman



z
$\mathcal{R}(z)$
AdS bulk
AdS boundary

$$\sqrt{-g_{tt}}K = \text{const}$$

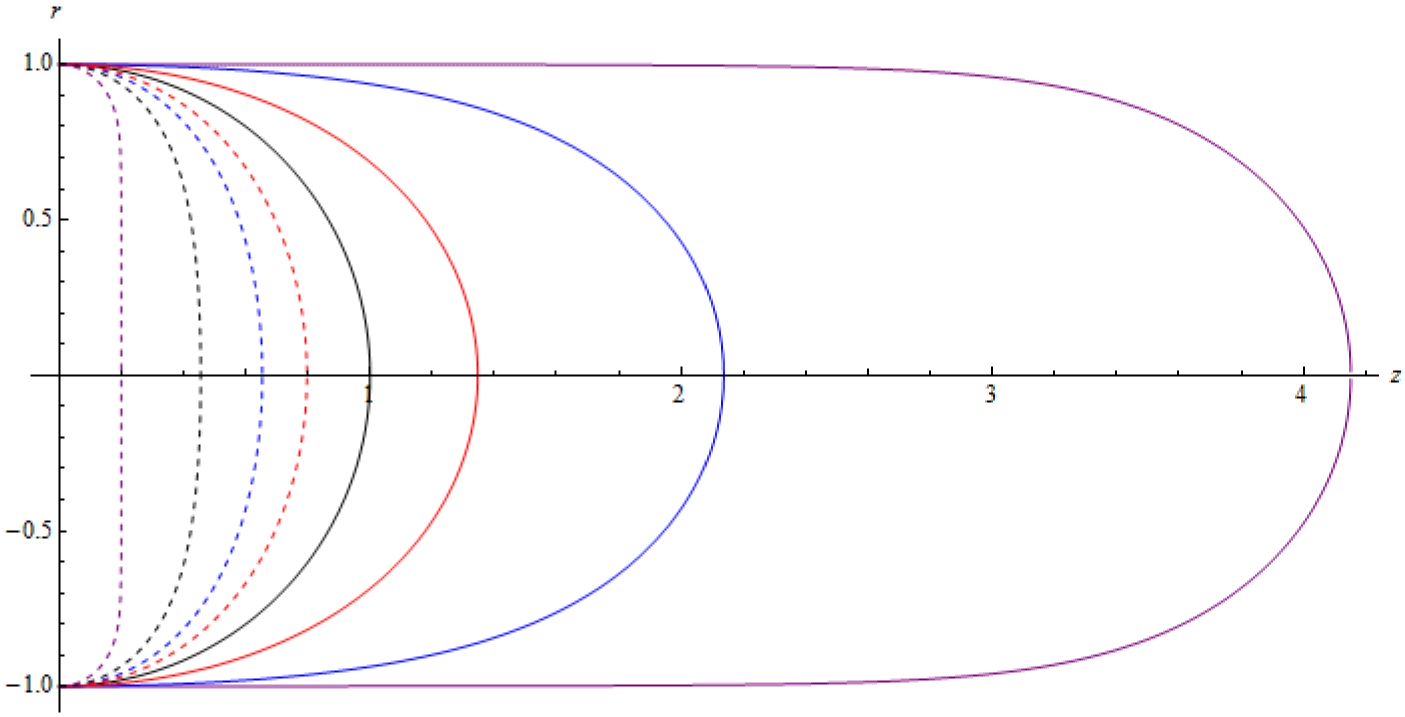
$$\Rightarrow \mathcal{R}(z)' = -\frac{z}{\mathcal{R}(z)} \frac{1 \pm \sqrt{z^2 + \mathcal{R}(z)^2(1-z^2)}}{1-z^2}$$



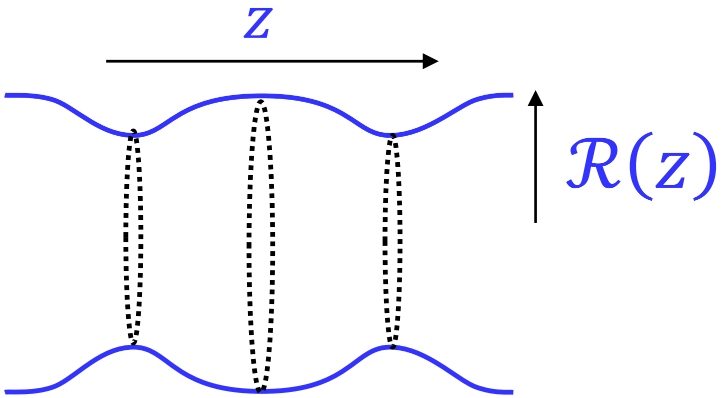
Numerical code

```
zmin = 0.000001;
zmax = 0.67;
r0 = .5;
NDSolve[{r'[z] == -z/r[z] (1 - Sqrt[r[z]^2 + z^2 (1 - r[z]^2)])/(1 - z^2), r[zmin] == r0}, r, {z, zmin, zmax}]
```

Black droplets

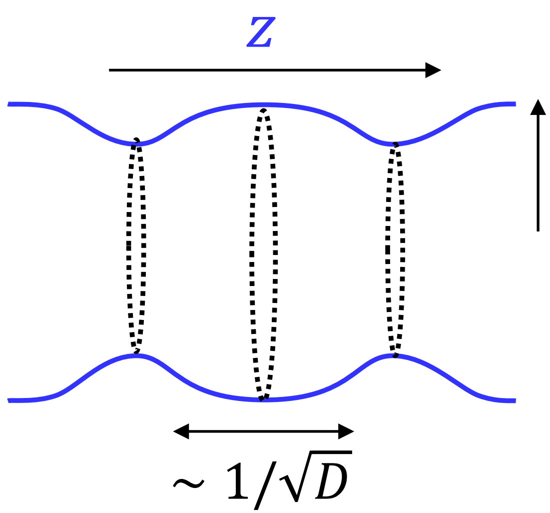


Non-uniform black strings



Numerical solution: *Wiseman*

Non-uniform black strings



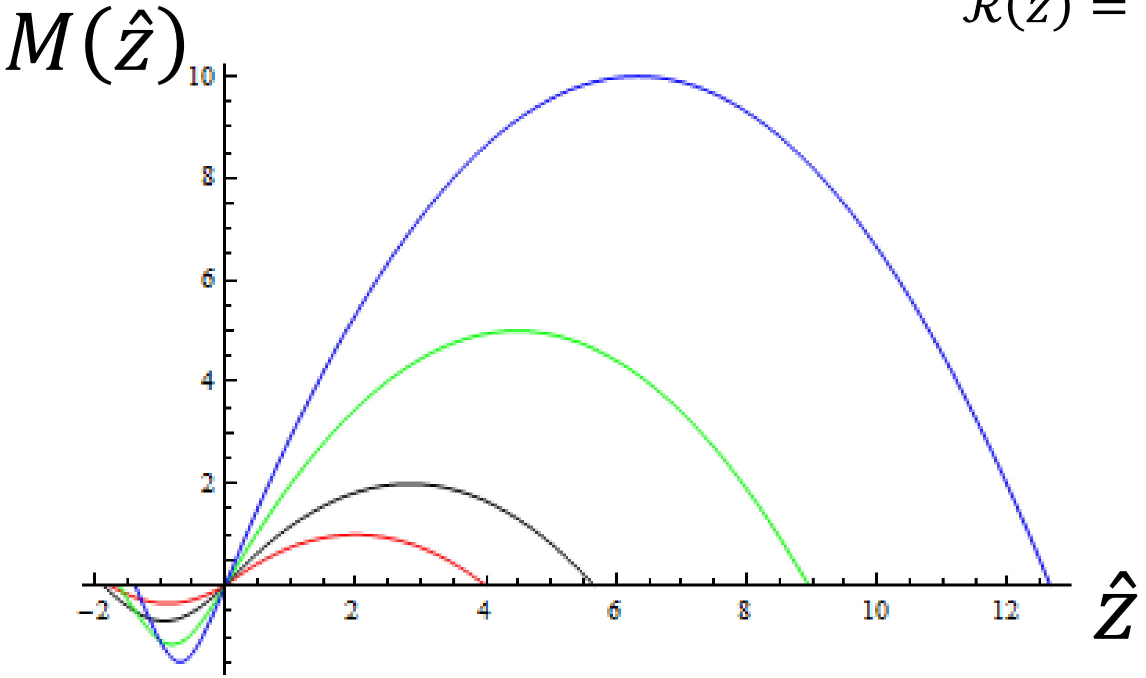
$$\mathcal{R}(z) = 1 + \frac{2M(z)}{D}$$

$$K = \mathrm{const}$$

$$\Longrightarrow \; M'' + M'^2 + M = \mathrm{const}$$

Non-uniform black strings

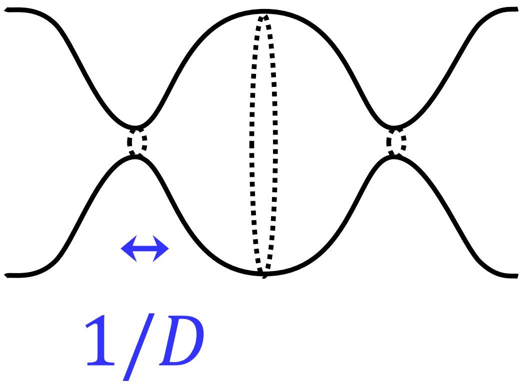
$$\mathcal{R}(z) = 1 + \frac{2M(z)}{D}$$



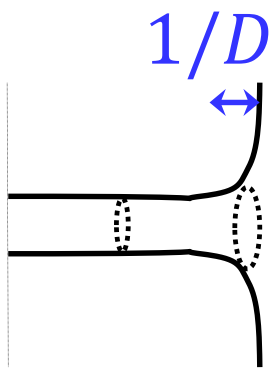
Limitations

1/D expansion breaks down when $\partial_z \sim D$

- Highly non-uniform black strings



- AdS black funnels



In progress

Extensions of $\sqrt{-g_{tt}}\, K = \mathrm{const}$

Charged black holes

Rotating black holes

(Time-evolving black holes)

Conclusions

1/D: it works

(not obvious beforehand!)

Static black holes are soap bubbles

up to NLO in $1/D$,

& possibly redshifted

Can we reformulate GR

around $D \to \infty$,

with black holes as

basic (extended) objects?

Quantum effects?

Dimensionful scale:

$$L_{Planck} = (G\hbar)^{\frac{1}{D-2}}$$

Quantum effects governed by $\frac{r_0}{L_{Planck}}$

If $\frac{r_0}{L_{Planck}} \sim D^0$ the bh is fully quantum:

Entropy $\rightarrow 0$

Temperature $\rightarrow \infty$

Evaporation lifetime $\rightarrow 0$

But other scalings are possible

Scaling $\frac{r_0}{L_{Planck}}$ with D:

how large are the black holes,

which quantum effects are finite at large D

Finite entropy: $r_0/L_{Planck} \sim D^{1/2}$

Finite temperature: $r_0/L_{Planck} \sim D$

Finite energy of Hawking radn: $r_0/L_{Planck} \sim D^2$

Near-horizon limits

vs

Decoupling limits

Near-horizon geometries

Well-defined limiting geometry

Requires small parameter→scale separation

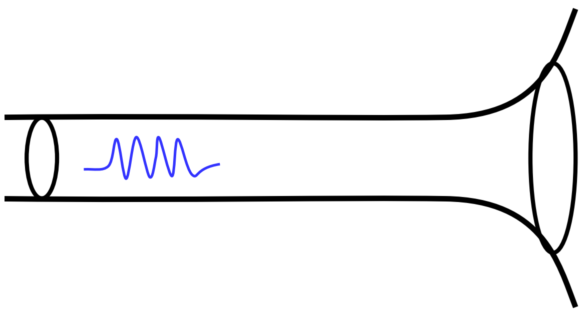
Well known: **(near-)extremal black holes**

small near-extremality parameter

$$\frac{\sqrt{M^2 - Q^2}}{M}, \qquad \frac{\sqrt{M^4 - J^2}}{M^2} \ll 1$$

(Near-)Extremal black holes

Throat geometries near-horizon

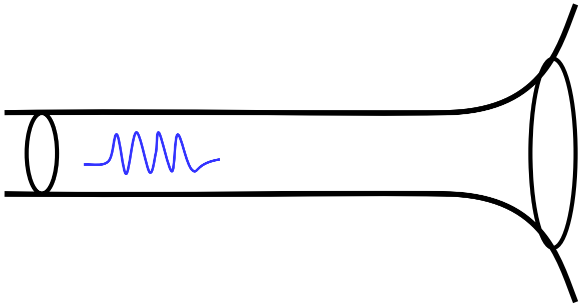


throat supports
"decoupled" dynamics

e.g. AdS/CFT decoupling limit

(Near-)Extremal black holes

Decoupled dynamics:



finite-frequency excitations that are normalizable in n-h geometry

Is the large D limit a decoupling limit?

Is the large D limit
a decoupling limit?

No

Perturbative BH dynamics @ large D

is concentrated close to the horizon

States can be characterized in terms of their properties within N-H geometry

- normalizable states
- non-normalizable states
- BF bound-violating states

but N-H geometry is **not long** throat

$$ds^2_{nh} = \frac{4r_0^2}{D^2}\left(-\tanh^2\rho \;\, dt^2_{near} + d\rho^2\right) + r_0^2 d\Omega^2_{D-2}$$

small extent $\propto r_0/D$

crossed very quickly $t_{near} = \frac{D}{2r_0} t$

Most excitations *not* trapped within: non-decoupled