black hole radiation: horizon avoidance and firewalls

2017.07.06 15:10
RQI-N

Daniel Terno

Department of Physics & Astronomy

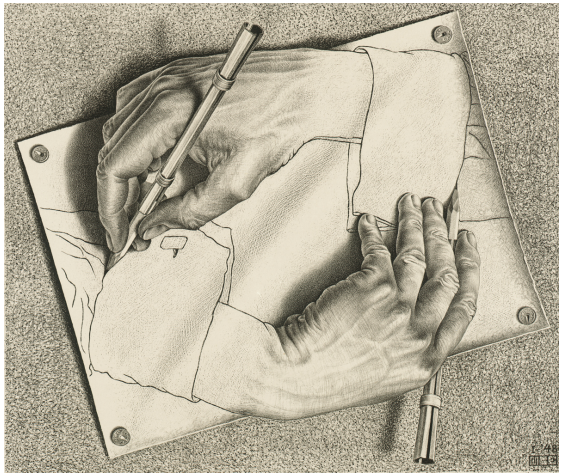
MACQUARIE University

京都大学 KYOTO UNIVERSITY

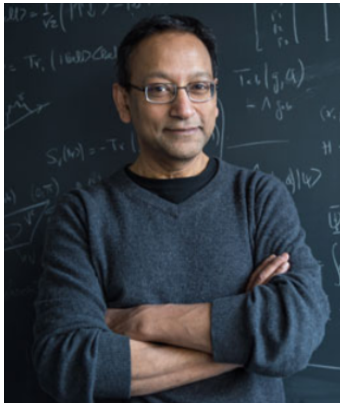
YITP YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH UNITED STATES AIR FORCE

collaborators

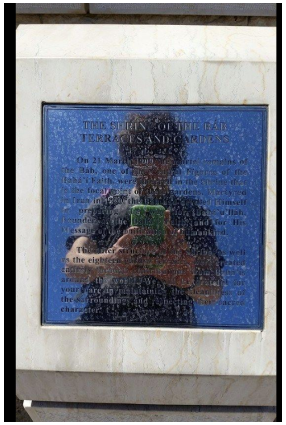


Valentina Baccetti



Viqar Husain

Robb Mann



Ian Nagle

Referee A

references

- VB, RBM, DRT, *Do event horizons exist?* , arXiv: 1706.01180 (2017)
- VB, RBM, DRT, *Horizon avoidance in spherically-symmetric collapse*, arXiv:1703.09369 (2017).
- VB, RBM, DRT, *Effects of evaporation on gravitational collapse*, arXiv:1610.07839 (2016).
- VB, VH, DRT, *The information recovery problem*, Entropy **19**,17 (2017).

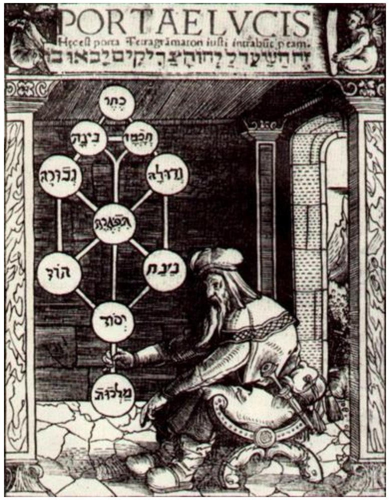
- Mann, *Black Holes: Thermodynamics, Information, and Firewalls* (Springer, New York, 2015)
- Harlow, Rev. Mod Phys. **88**, 015002 (2016)
- Unruh and Wald, arXiv:1703.02140 (2017)
- Marolf, arXiv:1703.02143 (2017)

units:

$$h = c = G = k_B = 1$$

signature: -+++

a view from foundations: paradoxes of QM



Ingredients:

1. Classical ideas/assumptions/results
2. Quantum features/results
3. Combine and try to obtain probability distributions that satisfy all of (1) & (2)

Outcome:

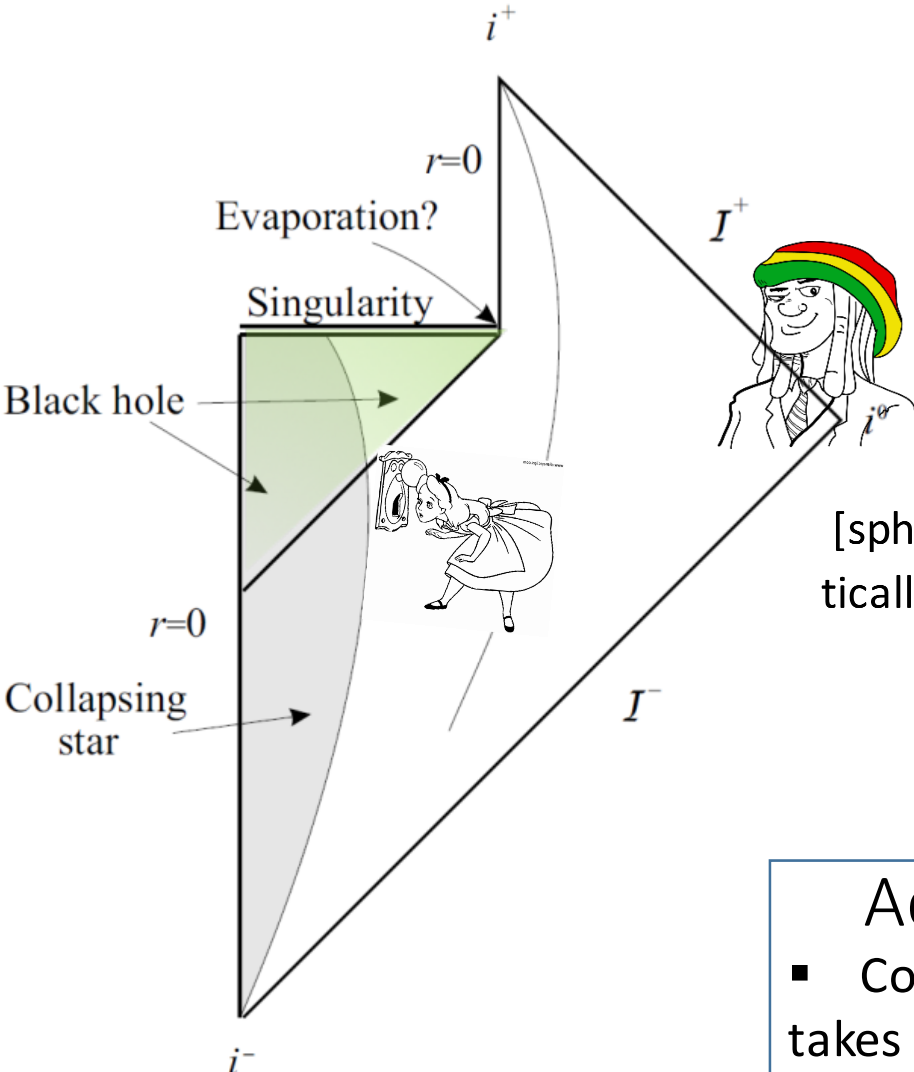
❖ Contradiction

❖ Contradiction
(before all QM results are used)

Examples:

- EPR: Bell-CHSH; KS, wave-particle
- BH info loss, firewall

making of the info loss paradox



Ingredients

GR: horizon, mass-area relation
QFTc: radiation

Why is it a paradox?

GR: deterministic
[spherically-symmetric collapse on a asympto-tically flat background: Hamiltonian evolution]

Unruh, Phys. Rev. D **14**, 870 (1976).
VH and DRT, Phys. Rev. D **81**, 044039 (2010)

QM►*QFT*: unitary

Whose paradox?

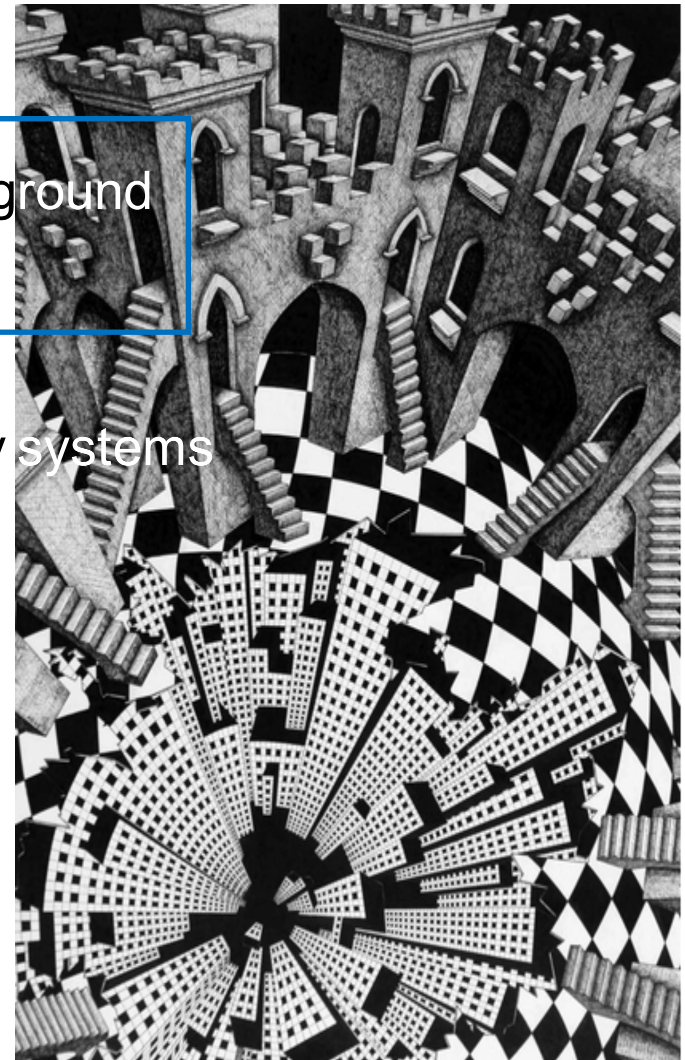
Additional causality issue:

- Collapse (i.e. event horizon crossing) takes an infinite amount of time
- Radiation (that needs a horizon?) evaporates a BH in finite amount of time

logic of the analysis

Hierarchy of models

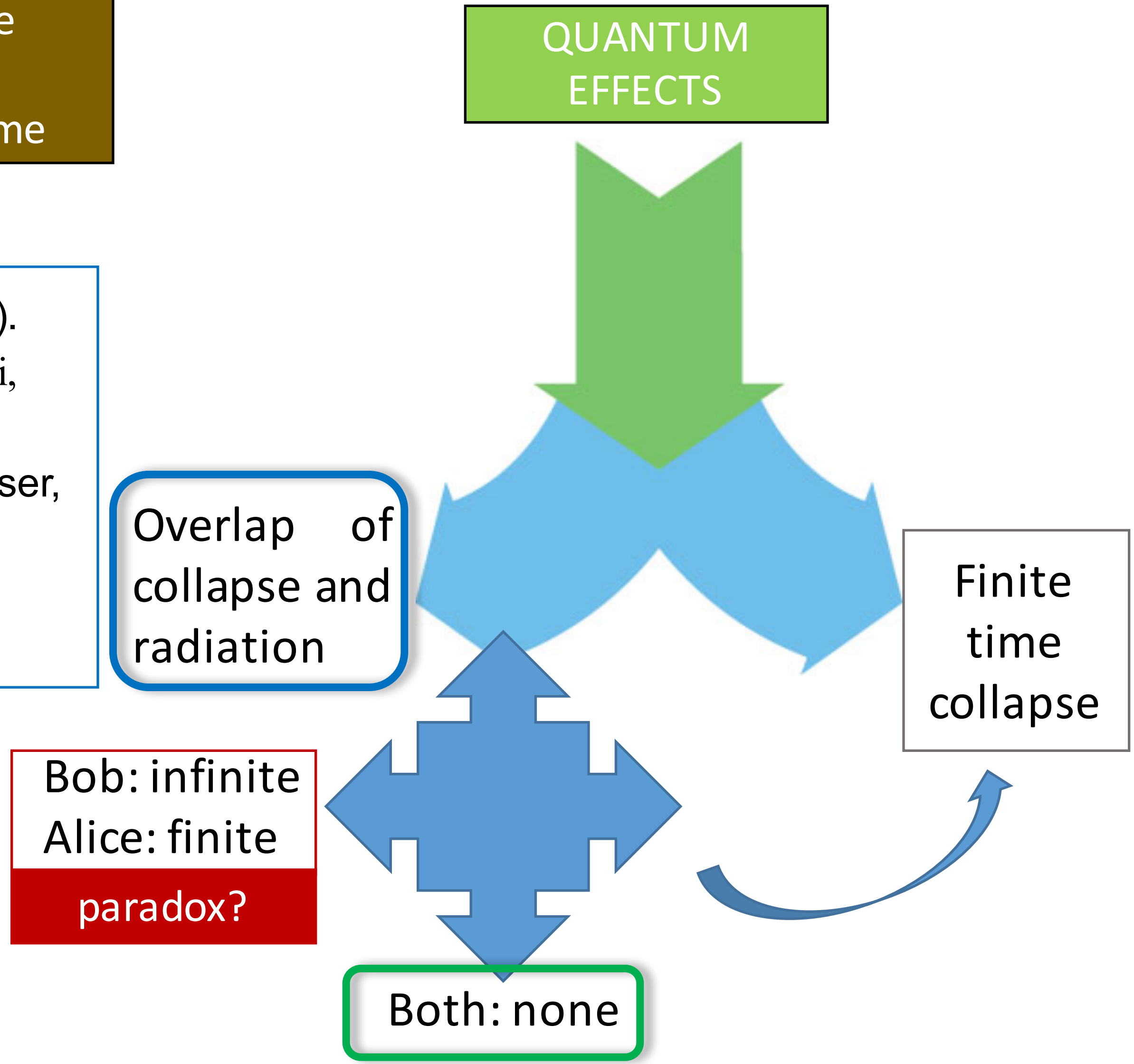
- quantum field theory on a curved background
- semiclassical gravity
- semiclassical stochastic gravity
- effective field theories of matter-gravity systems
- full theory of quantum gravity

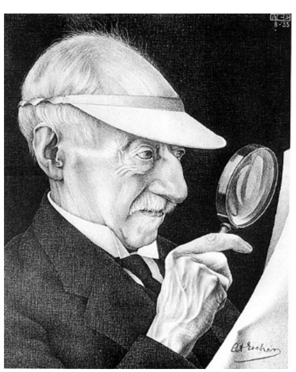


logic of causality

Collapse takes infinite Bob's time
Collapse takes finite Alice's time
Evaporation takes finite Bob's time

- Gerlach, PRD **14**, 1479 (1976).
- Alberghi, Casadio, Vacca, Venturi, PRD **64**, 104012 (2001).
- Barcelo, Liberati, Sonego, Visser, CQG **23**, 5341 (2006)
- Vachaspati, Stojkovic, Kraus, PRD **76**, 024005 (2007).





logic of the analysis: four assumptions

1. The classical spacetime structure is still meaningful and is described by a metric $g_{\mu\nu}$.

2. Classical concepts, such as trajectory, event horizon or singularity can be used.

3. The collapse leads to a pre-Hawking radiation

4. The metric is modified by quantum effects. The resulting curvature satisfies the semiclassical equation

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = 8\pi \langle \hat{T}_{\mu\nu} \rangle \qquad \langle \hat{T}_{\mu\nu} \rangle = \frac{2}{\sqrt{-g}} \frac{\delta W}{\delta g^{\mu\nu}}$$

- Paranjape and Padmanabhan,
  Phys. Rev. D **80**, 044011 (2009)

goals & tools

Self-consistency of the semiclassical theory

- ➢ possibility of the horizon avoidance (no finite proper time crossing)?

Classical horizon obtains its physical status because of the finite proper time crossing (co-moving/in-falling Alice).

Quantum-affected horizon should be tested in the same way

- ➢ massive shells, etc

Summary

Massive thin shells + spherical symmetry + arbitrary shell stress-energy + generic metric outside + *D* spacetime dimensions

The Schwarzschild radius is not crossed.
There are no trapped surfaces.
The shell is at a certain sub-Planckian distance from the would-be horizon that depends only on the mass and evaporation rate

Mechanism of avoidance: depends on what is the evaporating metric

A. Regularized firewall
B. Deceleration

Oppenheimer-Snyder dust ball (can interact with radiation) + no shell crossing

The Schwarzschild radius is not crossed.

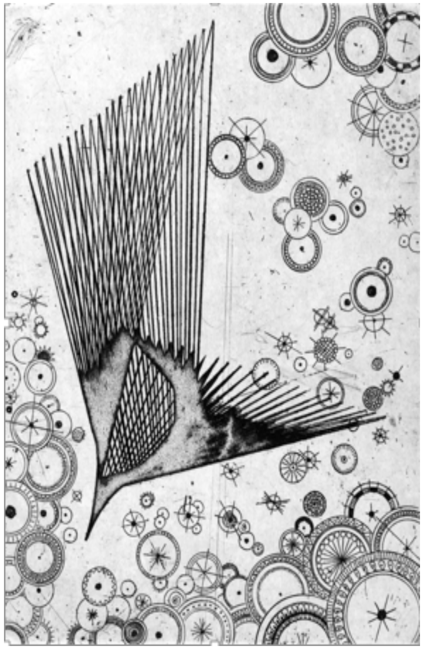
Summary

Rotating thin massive shell +Vaidya-Kerr outside (near region)

The Schwarzschild radius is not crossed.
The shell is deformed and the sub-Planckian distance from the would-be horizon depends on the mass, evaporation rate and latitude.

OUTLINE

- ❑ Coordinates, shells and collapse
- ❑ Horizon avoidance
- ❑ Opportunities & questions



PART 1

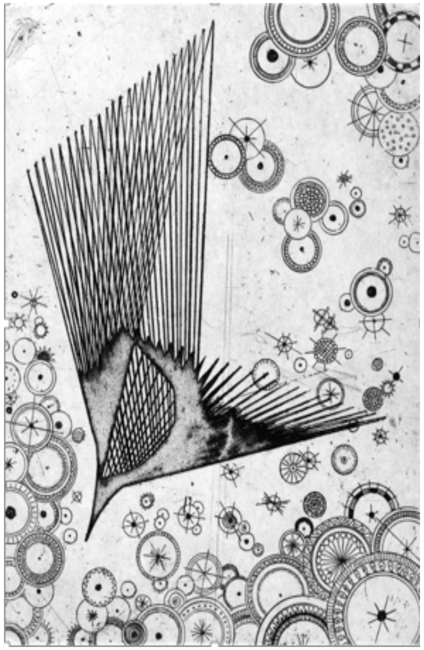
Coordinates, classical shells & collapse

Null coordinates

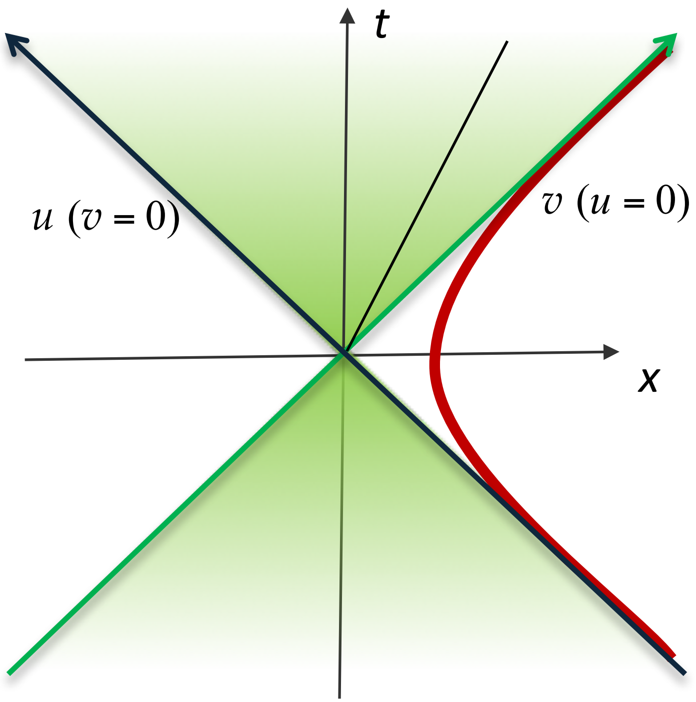
Carter-Penrose diagrams

Collapse of the shells

Collapse with Eddington-Finkelstein



COORDINATES



- Minkowski

$$ds^2 = -dt^2 + dr^2 + r^2 d\Omega^2$$

Retarded/outgoing $u = t - r$

Advanced/ingoing $v = t + r$

$$ds^2 = -du\,dv + r^2 d\Omega^2$$
$$= -du\,dv + \tfrac{1}{4}(u-v)^2 d\Omega^2$$
$$= -du^2 - 2du\,dr + r^2 d\Omega$$

INFINITY

- ❑ Finite infinites

$$\tilde{g}_{\mu\nu} = \omega^2 \eta_{\mu\nu}$$

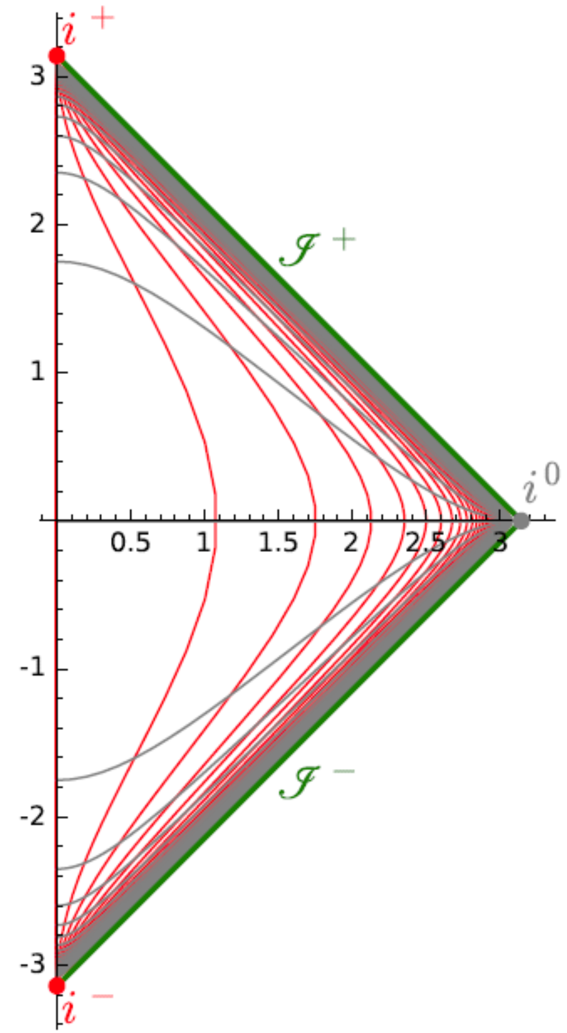
Conformal transfomation ♦ regular metric

$$u = t - r \qquad U = \arctan u$$
$$v = t + r \qquad V = \arctan v$$

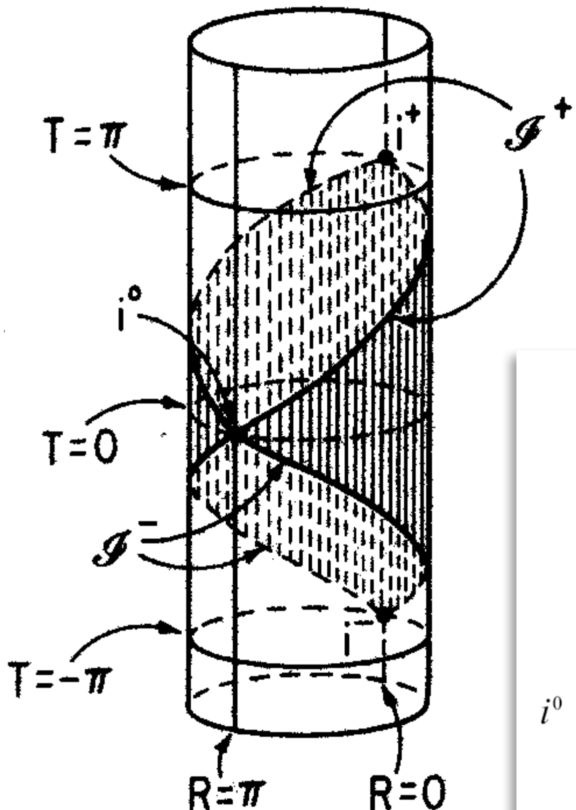
$$T = V + U$$
$$R = V - U$$

$$d\tilde{s}^2 = dT^2 - dR^2 - \sin^2 R d\Omega^2$$
$$-\pi \le T \pm R \le \pi$$
$$R \ge 0$$

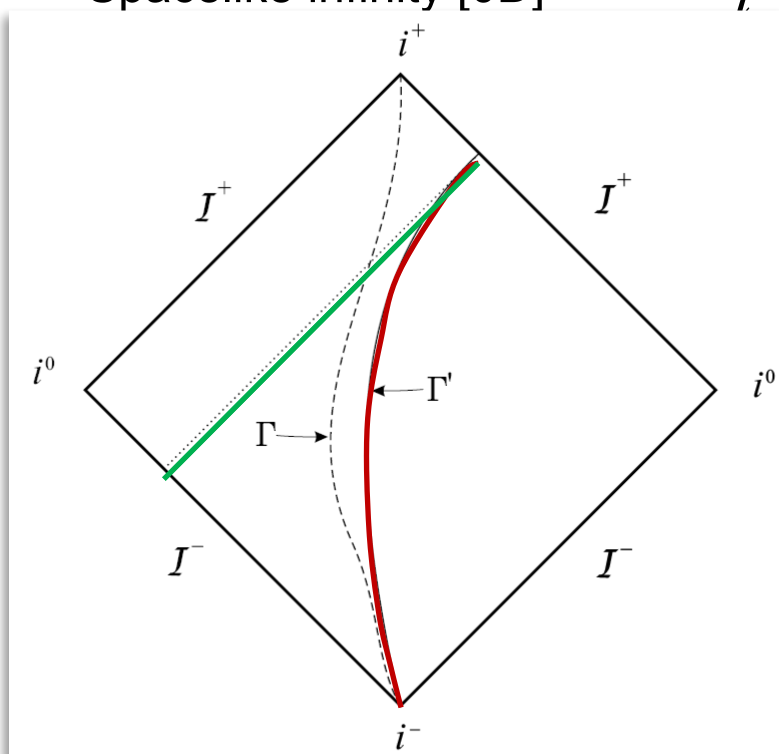
$$\omega^2 = 4\frac{(1+u^2)}{(1+v^2)}$$

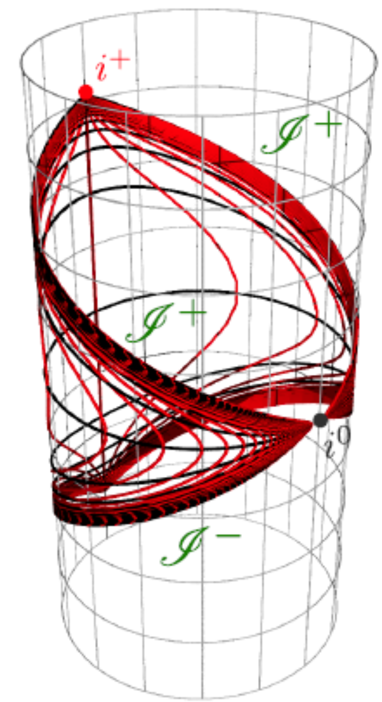


INFINITY



Past timelike infinity [0D]	i^-	$R=0, T=-\pi$
Future timilike infinity [0D]	i^+	$R=0, T=\pi$
Past null infinity [3D]	I^-	$T=R-\pi$
Future null infinity [3D]	I^+	$T=-R+\pi$
Spacelike infinity [0D]	i^0	$T=0, R=\pi$





SCHWARZSCHILD

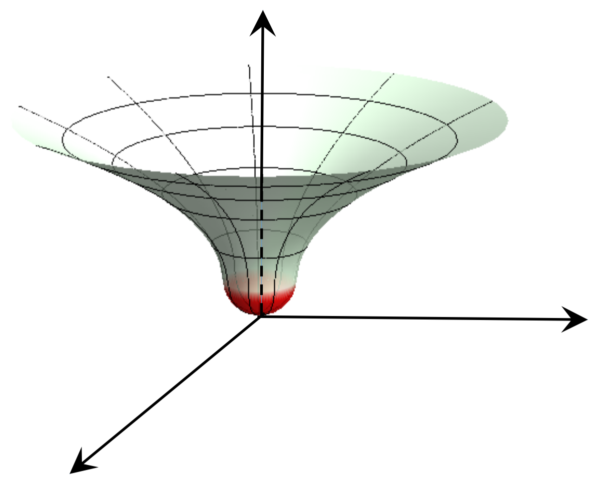
- General spherically-symmetric spacetime

$$ds^2 = -f(r,t)dt^2 + g(r,t)dr^2 + r^2 d\Omega^2$$

- Static, vacuum: Schwarzschild

$$f = 1 - C/r \qquad C = r_g = \frac{2GM}{c^2}$$

$$g = 1/f$$



◊ circumference: $2\pi r$

◊ proper time interval of a static observer: $\Delta\tau = \sqrt{1 - r_g/r}\,\Delta t$

◊ physical time at infinity (@Bob): t

◊ coordinate singularity | horizon: $r = r_g$

SCHWARZSCHID

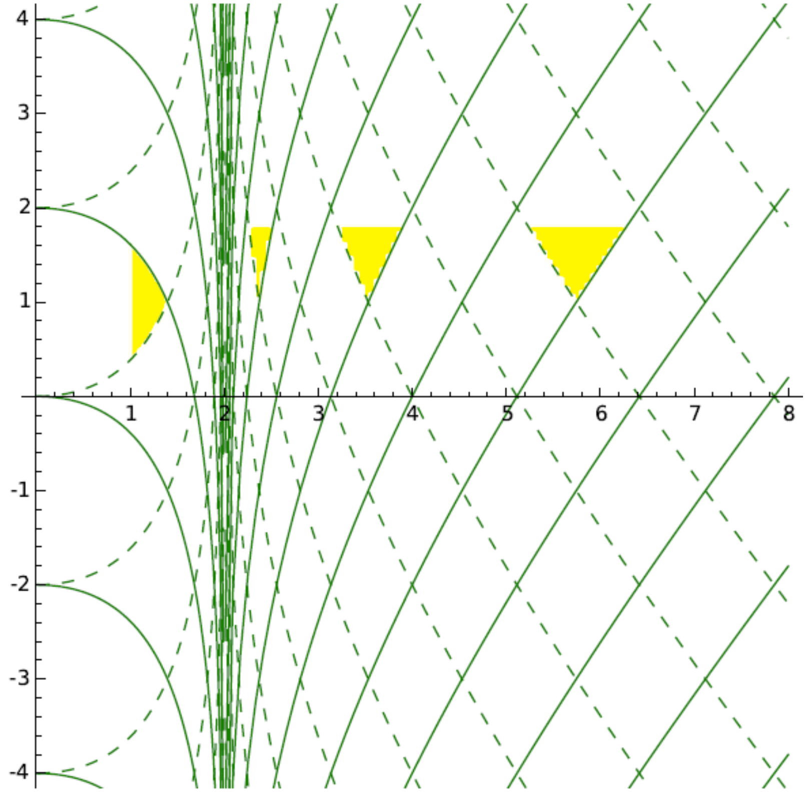
- Radial photons

$$ds^2 = 0 \qquad dt = \pm \frac{dr}{1 - r_g / r}$$

◊ incoming radial photon:

travel time to $r = r_g$: infinity

$$t - r - r_g \log(1 - r_g / r) = \text{const}$$



- Radial massive particles

◊ travel time to horizon:
infinite Δt, finite $\Delta \tau$

SCHWARZSCHID

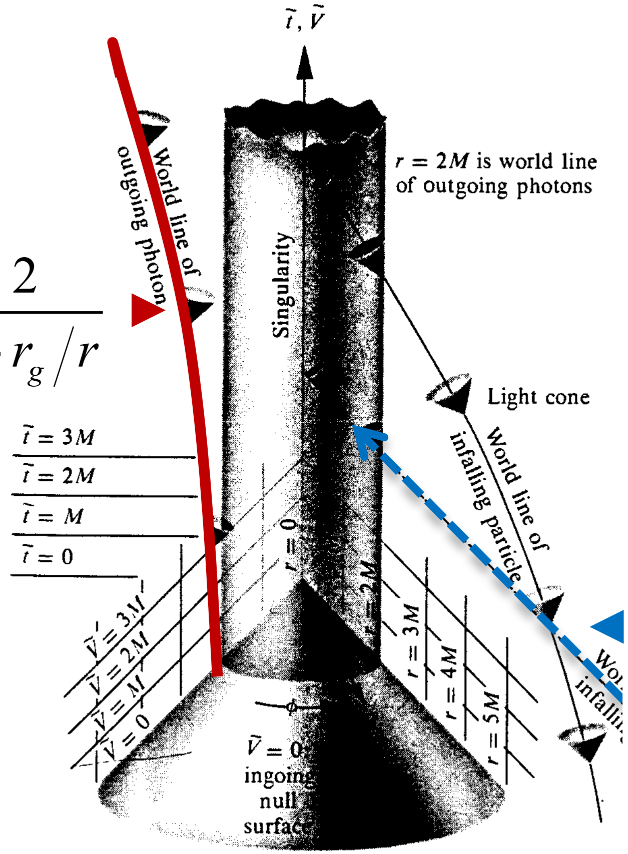
Eddington-Finkelstein

$$r^* \equiv r + r_g \log|r_g/r - 1|$$

$$v \equiv t + r^*$$

$$\frac{dv}{dr} = \frac{2}{1 - r_g/r}$$

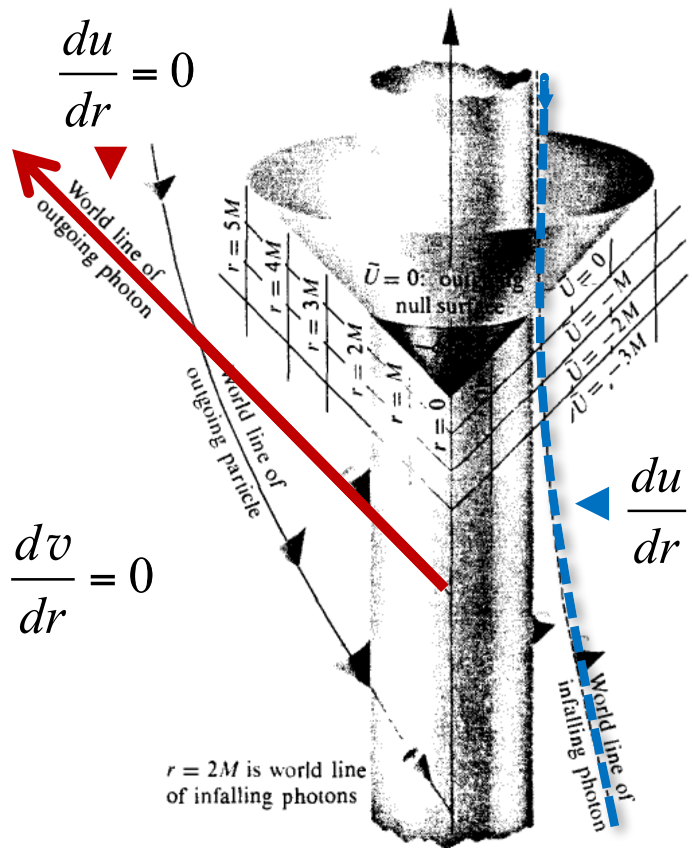
$$\frac{dv}{dr} = 0$$



$$u \equiv t - r^*$$

$$\frac{du}{dr} = 0$$

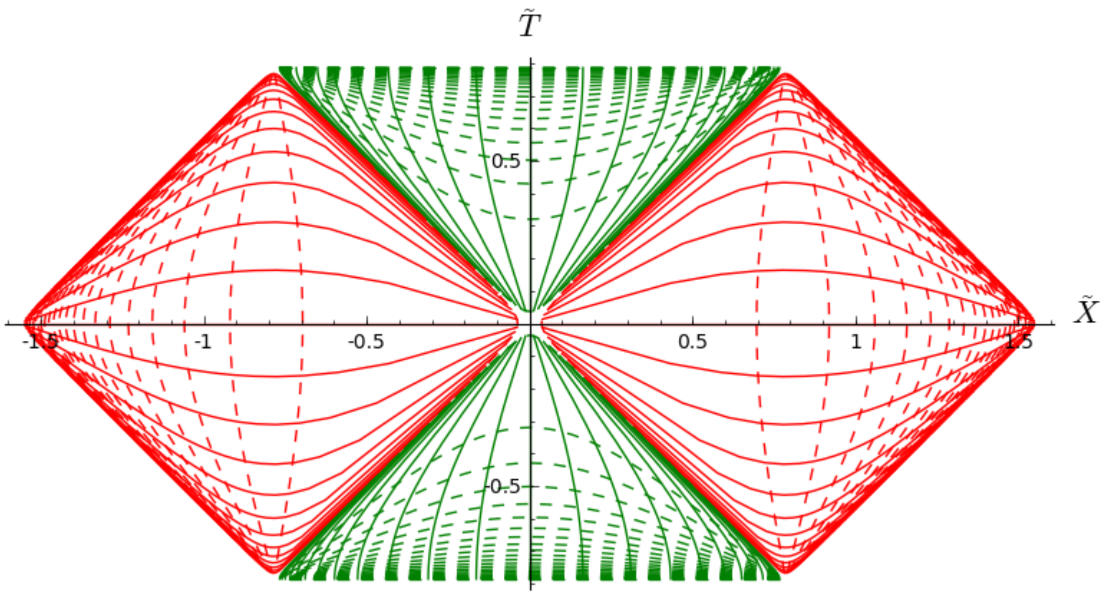
$$\frac{du}{dr} = -\frac{2}{1 - r_g/r}$$

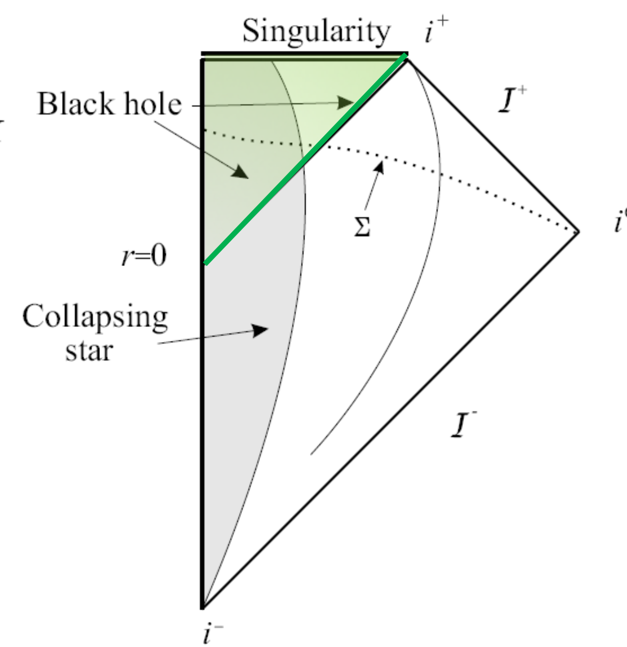


SCHWARZSCHID

Kruskal | Carter-Penrose

u, v → U, V → T, R +max extension





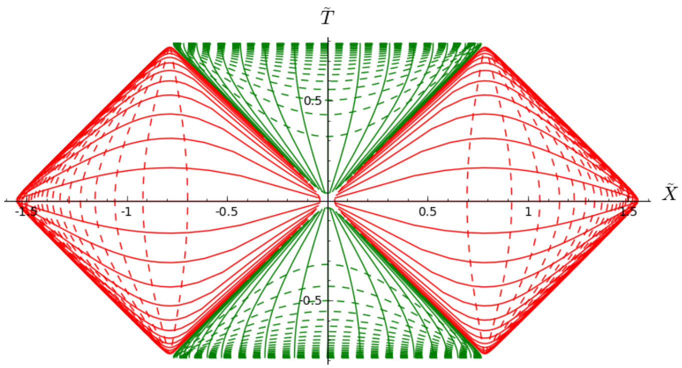
Black hole: $\mathcal{B} = \mathcal{M} - \text{Past}(\mathcal{I}^+)$

Horizon area $A = 4\pi r_g^2 = 16\pi M^2$

HAWKING

◊ Surface gravity: the force per unit mass as measured at infinity, to keep the observer stationary just outside the horizon

Schwarzschild: $\kappa = 1/2r_g = 1/4M$



❖ Black body temperature

$$T = \frac{\kappa}{2\pi}\frac{\hbar c^3}{G k_B}$$

❖ Evaporation

$$\dot{M} \propto -T^4 A \propto M^{-2}$$

$$M = (1 - t/t_E)^{1/3} M_0,$$

$$t_E \propto M_0^3$$

THIN SHELL

classical

- Description

Surface metric, extrinsic curvature

- Characterization

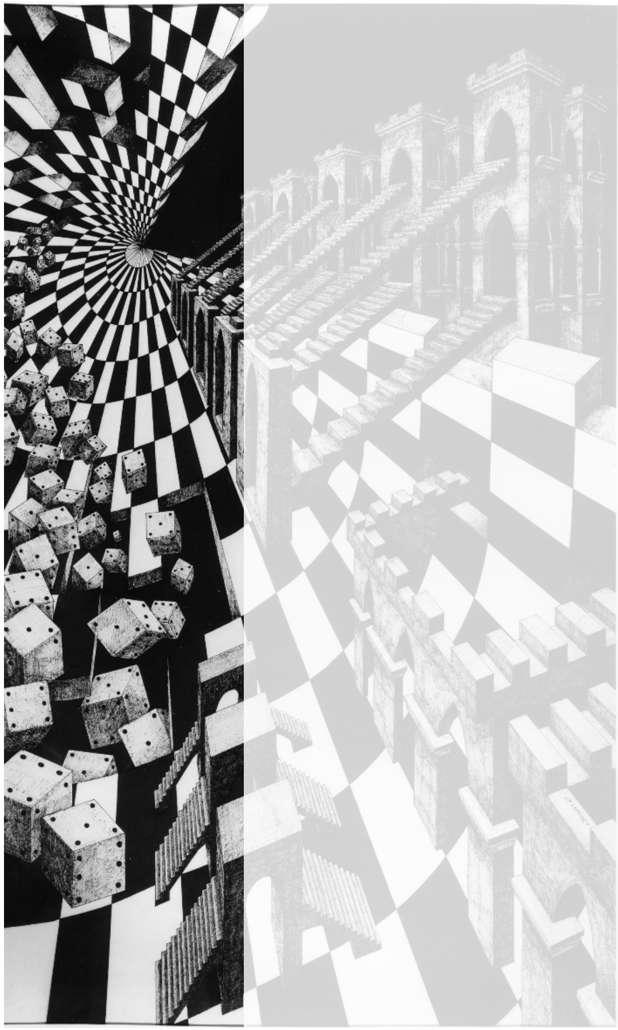
Singular stress-energy tensor

- Dynamics

Minkowski inside, Schwarzschild outside

- Solution

Travel time to horizon:
infinite Δt, finite $\Delta \tau$

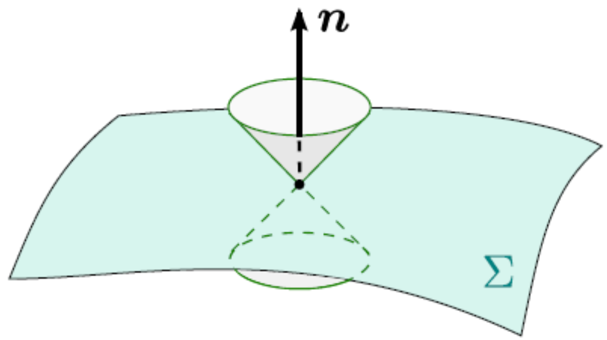


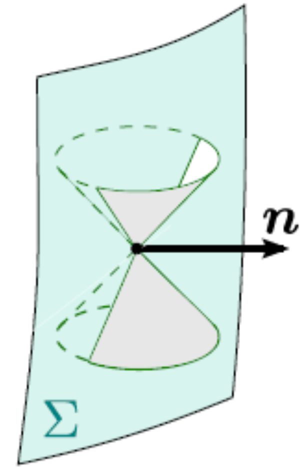
THIN SHELL

description

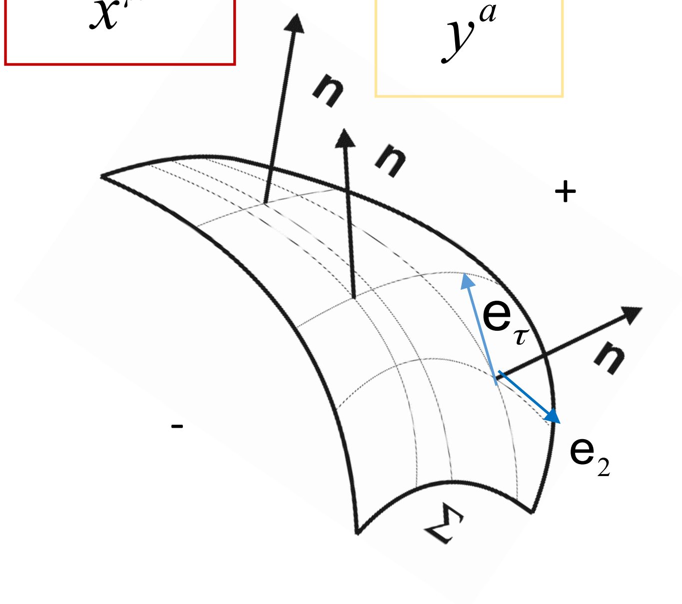
Surface in space(time): $\Phi(x^\mu) = 0$

$$\mathrm{n}^2 = \varepsilon = \pm 1, 0$$





spacetime	surface
x^μ	y^a



basis

$$e_a^\mu = \frac{\partial x^\mu}{\partial y^a}$$

$$\mathrm{n} \cdot \mathrm{e} = 0$$

$$A^\mu \rightarrow A_a = A^\mu e_{a\mu}$$

$$g_{\mu\nu} \rightarrow h_{ab} = g_{\mu\nu} e_a^\mu e_b^\nu$$

THIN SHELL

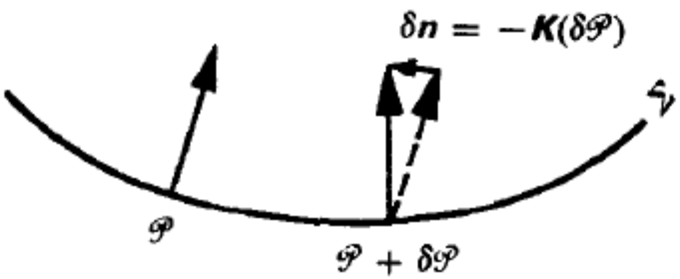
description & characterisation

- 1st junction condition $g_{\mu\nu} \rightarrow h_{ab}$

$$g_{\mu\nu}\Big|_{\Sigma^+} \rightarrow h_{ab} \leftarrow g_{\mu\nu}\Big|_{\Sigma^-}$$

- Extrinsic curvature

$$n^{\mu}_{;a} = -\varepsilon K^{b}_{a} e^{\mu}_{b}$$



Extrinsic curvature

$$K_{ab} := n_{\alpha;\beta} e^{\alpha}_{a} e^{\beta}_{b} \equiv K_{ba}$$

$$A^{\mu}_{;b} = A^{\mu}_{;\nu} e^{\nu}_{b} \equiv A^{a}_{|b} e^{\mu}_{a} - \varepsilon A^{a} K_{ab} n^{\mu}$$

- 2nd junction condition

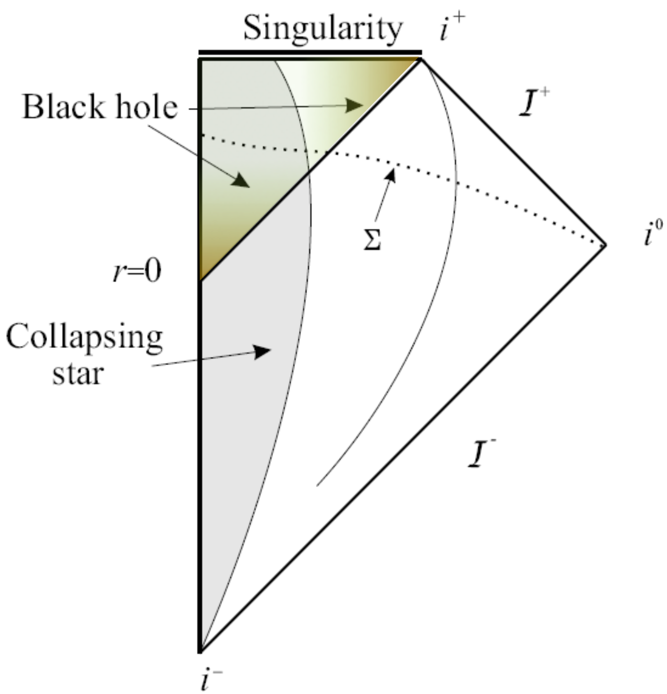
$$[K_{ab}] := K^{+}_{ab} - K^{-}_{ab}$$

$$S_{ab} = -\frac{1}{8\pi}([K_{ab}] - K[h_{ab}])$$

$$R_{\mu\nu} - \tfrac{1}{2} R g_{\mu\nu} = 8\pi T^{\mu\nu}$$

THIN SHELL

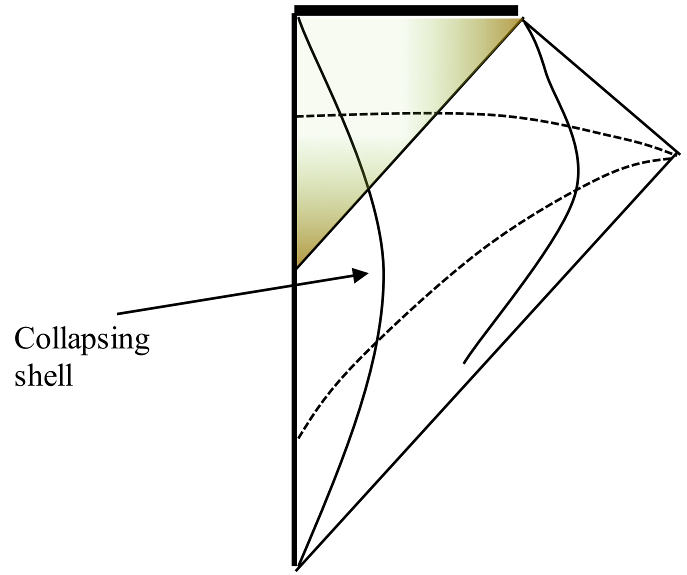
dynamics



Horizon crossing:
finite proper time

- Model:

spherical symmetry,
thin dust shell



Minkowski inside,
Schwarzschild outside

THIN SHELL

dynamics

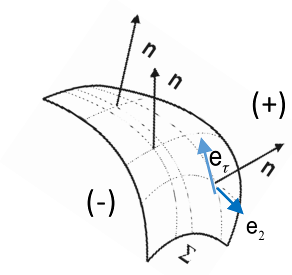
(+) Schwarzschild | Eddington-Finkelstein

$$ds_+^2 = -f(r_+)dt_+^2 + f(r_+)^{-1}dr_+^2 + r_+^2 d\Omega,$$
$$= -f(r_+)du_+^2 - 2du_+ dr_+ + r_+^2 d\Omega_{D-}$$

$$f = 1 - C/r$$

(-) Minkowski

$$ds_-^2 = -dt_-^2 + dr_-^2 + r_-^2 d\Omega$$



Tracing the shell $T(\tau), R(\tau)$ $U(\tau), R(\tau)$

$$F(R,T) = f\left(r = R(\tau), t = T(\tau)\right)$$

Surface coordinates: $y^a = (\tau, \theta, \varphi)$

Making the shell

Surface stress-energy tensor

$$S^{ab} = \sigma v^a v^b = \sigma \delta_\tau^a \delta_\tau^b,$$

THIN SHELL

dynamics

Junction conditions, etc

$$ds_\Sigma^2 = h_{ab}dy^a dy^b = -d\tau^2 + R^2 d\Omega$$

$$\dot{T}_+ = \sqrt{F + \dot{R}^2}/F$$

$$\dot{U}_+ = \frac{-\dot{R} + \sqrt{F + \dot{R}^2}}{F}$$

$$R_- = R_+ = R$$

$$S_{ab} = -\frac{1}{8\pi}([K_{ab}] - K[h_{ab}])$$

Simplifications + substitutions

THIN SHELL EQUATION

$$\mathcal{D}(R) := \frac{2\ddot{R} + F'}{2\sqrt{F + \dot{R}^2}} - \frac{\ddot{R}}{\sqrt{1 + \dot{R}^2}} + \frac{\sqrt{F + \dot{R}^2} - \sqrt{1 + \dot{R}^2}}{R} = 0$$

$$\tau(R)$$

Horizon crossing

$$\tau\left(R = r_g\right) < \infty$$

PART 2

HORIZON AVOIDANCE

Logic

Exterior metric

Examples & plots

General case: firewall or deceleration?

THIN SHELL

evaporation

- ❑ Logic: assumptions 1-4 hold

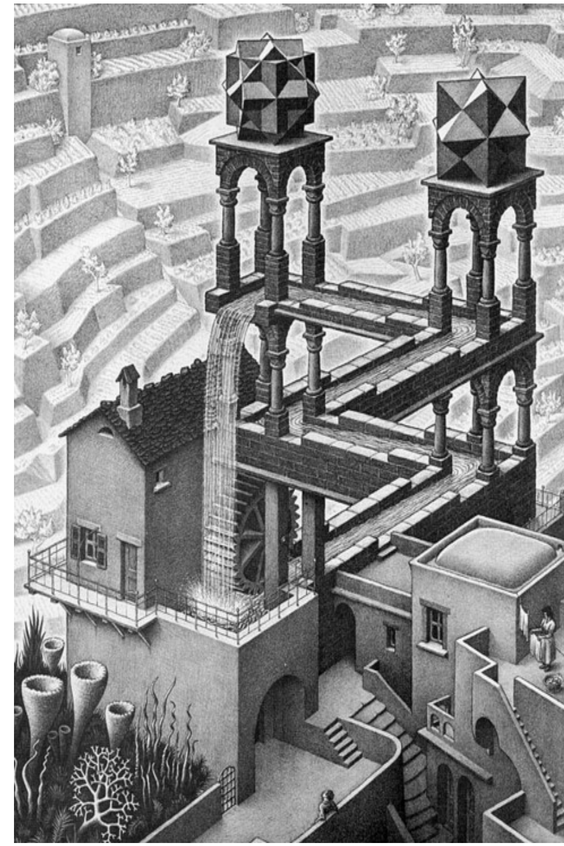
- ❑ Question: what happens to the shell?

  Is it still true?

  $$\tau_*\Big(R = r_g(\tau_*)\Big) < \infty$$

- ❑ Problem: no agreed outside metric for evaporating collapsing shell

- ❑ Solution: use spherical symmetry [+..]



SPHERICAL SYMMETRY

general metric & examples

shell's trajectory $\left(U(\tau), R(\tau)\right)$

$r_g(u) \equiv C(u, r_g(u))$

EF coordinates outside

$$ds^2 = -e^{2h(u,r)} f(u,r) du^2 - 2e^{h(u,r)} du dr + r^2 d\Omega$$

outgoing Vaidya

$$ds_+^2 = -f(r,u)du^2 - 2du dr + r^2 d\Omega$$

$$f = 1 - C(u)/r \qquad dC/du < 0$$

$$f =: 1 - C(u,r)/r$$

$x := R - r_g$

Standard coordinates outside

$$ds^2 = -k(t,r)^2 f(t,r) dt^2 + f(t,r)^{-1} dr^2 + r^2 d\Omega$$

retarded Schwarzs-child

$$ds^2 = -\tilde{f}(t,r)dt^2 + \tilde{f}(t,r)^{-1} dr^2 + r^2 d\Omega$$

$$\frac{dr}{dt} = 1 - C(\tilde{t})/r \qquad \tilde{f}(t,r) = 1 - C(\tilde{t})/r \equiv f(\tilde{t}, r)$$

shell's trajectory $\left(T(\tau), R(\tau)\right)$

$r_g(t) \equiv C(t, r_g(t))$

THIN SHELL

Vaidya

$$ds_+^2 = -f(r,u)du^2 - 2dudr + r^2 d\Omega$$

$$F = 1 - C(U)/R$$

$$\dot{U}_+ = \frac{-\dot{R} + \sqrt{F + \dot{R}^2}}{F}$$

THIN SHELL EQUATION

$$\mathcal{D}(R) - F_U \dot{U}\left(\frac{\dot{R}}{2F\sqrt{F+\dot{R}^2}} - \frac{1}{2F}\right) = 0$$

The gap to monitor: $x(\tau) := R(\tau) - r_g\left(U(\tau)\right)$

Asymptotics : $\dot{U} \approx -2\dot{R}/F \approx -2\dot{R}C/x$

$$\ddot{R} \approx 4\dot{R}^4 \frac{C}{x^2}\frac{dC}{dU}.$$

Acceleration of the collapse

THIN SHELL

Vaidya

$$\dot{x} = \dot{R}\left(1 - \frac{2C}{x}\left|\frac{dC}{dU}\right|\right) = |\dot{R}|\left(\frac{\epsilon_*(\tau)}{x} - 1\right) \qquad \varepsilon_* := 2C\left|\frac{dC}{du}\right|$$

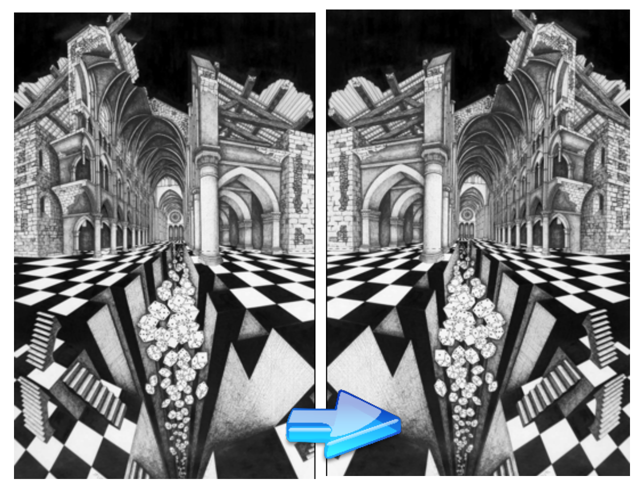
Once the gap is smaller than ε_* it starts increasing!

Tame firewall

$$8\pi T_{uu} = -\frac{1}{r^2}\frac{dC}{du}, \quad \rho = T_{\mu\nu}v^\mu v^\nu,$$

$$\rho \approx \frac{1}{2\pi}\left|\frac{dC}{dU}\right|\frac{\dot{R}^2}{x^2}.$$

$$\ddot{R} \approx \frac{\dot{R}^4}{CC_U}$$



THIN SHELL

Retarded Schwarzschild

$$ds^2 = -\tilde{f}(t,r)dt^2 + \tilde{f}(t,r)^{-1}dr^2 + r^2 d\Omega$$

$$\frac{dr}{dt} = 1 - C(\tilde{t})/r \qquad \tilde{f}(t,r) = 1 - C(\tilde{t})/r \equiv f(\tilde{t},r)$$

THIN SHELL EQUATION

$$\mathcal{D}(R) - \frac{F_T \dot{R}}{F^2} = 0$$

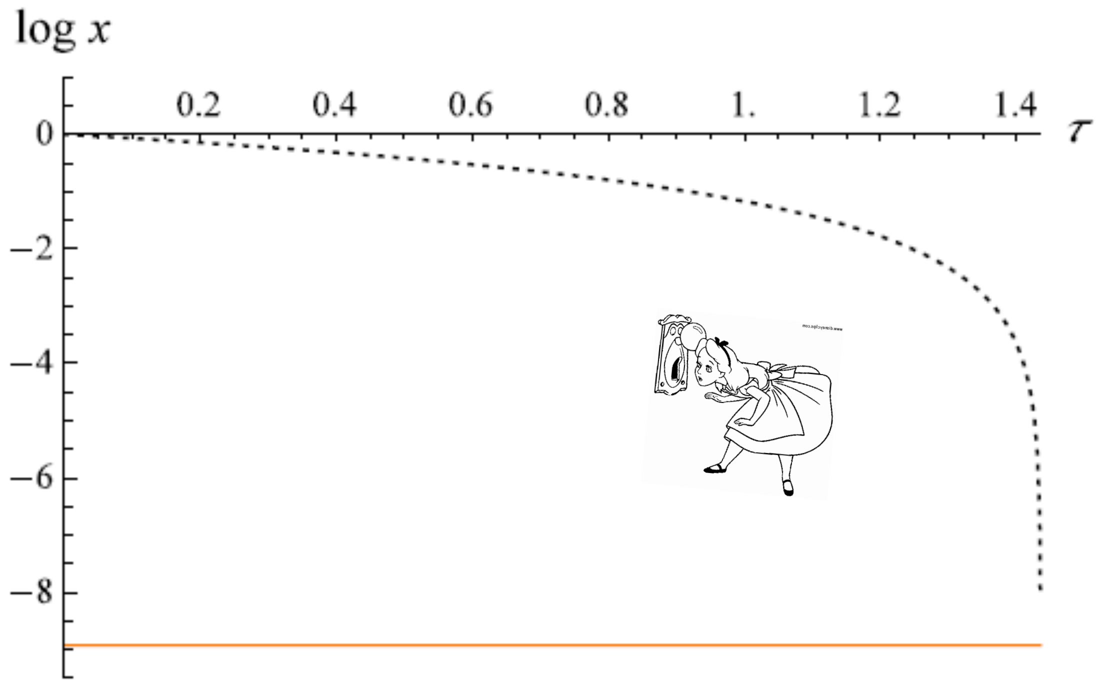
$$\frac{dC}{dt} = \frac{8\times 8}{15{,}360\pi}\frac{1}{C^2}$$

Switch on when $R=\varepsilon$

THIN SHELL

Retarded Schwarzschild

$$
\begin{cases}
\ddot{R} \approx -\dfrac{\dot{R}^4}{3\kappa C x^2} \\
\dot{C} \approx \dfrac{\dot{R}}{3\kappa C^2 x}
\end{cases}
$$



Initial data: $C_0 = 10, R_0 = 100, \dot{R}_0 = 0$

$\varepsilon = 1$

qualitative:
Dragan, arXiv:1610.07839 (2010).

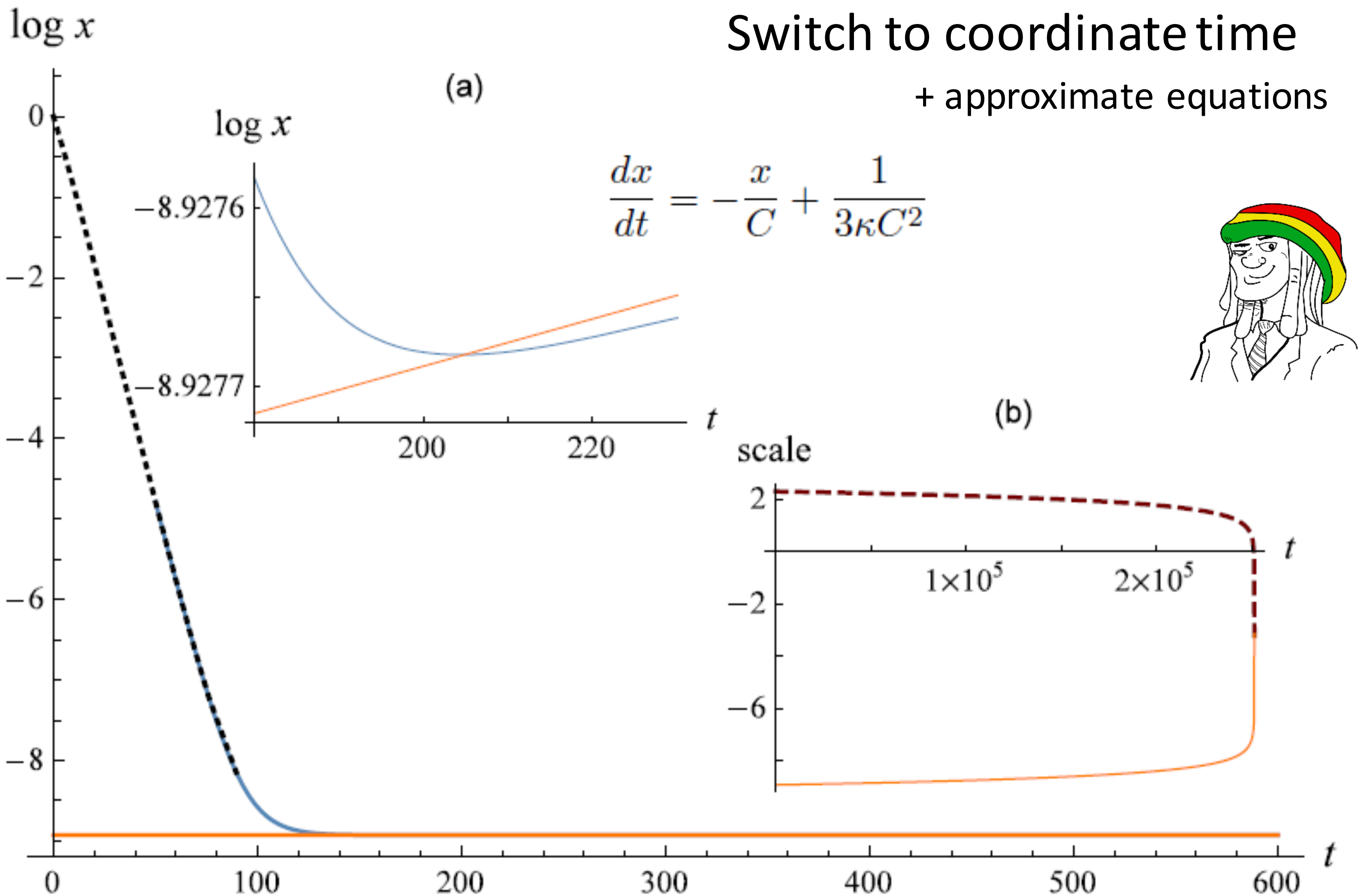
THIN SHELL

Retarded Schwarzschild

Switch to coordinate time

+ approximate equations

$$\frac{dx}{dt} = -\frac{x}{C} + \frac{1}{3\kappa C^2}$$



SPHERICAL SYMMETRY

general metric in EF coordinates

$$ds^2 = -e^{2h(u,r)} f(u,r) du^2 - 2e^{h(u,r)} du dr + r^2 d\Omega$$

Assumptions:

$f =: 1 - C(u,r)/r$

(i) $0 \le C < \infty$ with $C(u, r) > 0$ for $u < u_E < \infty$, and $\partial C / \partial u < 0$ as long as $C > 0$

(ii) $h(u, r)$ is continuous

(iii) the metric has only one coordinate singularity, namely an (infinite red-shift) surface $f(u, r) = 0$

$$r_g \equiv C\left(u, r_g(u)\right)$$

Consequences:

$$C(u,r) = r_g(u) + w(u,r)\left(r - r_g(u)\right)$$

$w(u,r) \le 1$ etc

SPHERICAL SYMMETRY

general metric: horizon avoidance

A slight change of the formulas,
the same conclusions

$$\dot{U} > \frac{2r_g}{\bar{E}(1-W)} \frac{|\dot{R}|}{x}$$

$$\dot{x} = \dot{R} - \dot{r}_g\big(U(\tau)\big) > \dot{R}(1 - \epsilon_*/x)$$

$$\epsilon_* = \frac{2}{\bar{E}} \frac{r_g}{1-W} \left| \frac{dr_g}{dU} \right|$$

$$\bar{E} := e^{h(U,R)}$$

SPHERICAL SYMMETRY

firewall or deceleration?

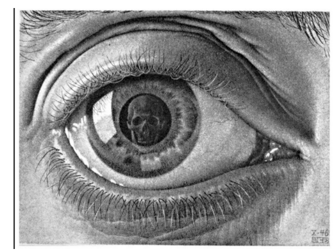
Positivity of the shell's surface density + freedom of initial conditions:

$\bar{E} > \sqrt{F}$

$$\bar{E} > \sqrt{\frac{F+\dot{R}^2}{1+\dot{R}^2}} \approx 1 - \frac{C}{2R\dot{R}^2} \approx 1 - \frac{1}{2\dot{R}^2}$$

Asymptotics:

$$\ddot{R} \propto \underbrace{[\pm]}_{\text{metric}} \text{mass} \times \text{rate} \, \frac{\dot{R}^2}{x^2}$$



Collapse accelerates = there is a firewall $\left(\ddot{R} < 0\right)$ only if

$$\bar{E}(U, r_g(U)) < \sqrt{1+\frac{1}{\dot{R}^2}} \approx 1 + \frac{1}{2\dot{R}^2}$$

$\bar{E} = e^{h(U,R)}$

ROTATING SHELL

outgoing Kerr-Vaidya outside

Warning: may be inconsistent if extended all the way to infinity
Needs a consistent treatment of the angular momentum

The best coordinates to work are Janis-Newman

$(u, r, \theta, \tilde{\phi})$

$$-g_{\mu\nu} = \begin{pmatrix} 1 - 2Mr/\rho^2 & 1 & 0 & 2aMr\sin^2\theta/\rho^2 \\ 1 & 0 & 0 & -a\sin^2\theta \\ 0 & 0 & -\rho^2 & 0 \\ 2aMr\sin^2\theta/\rho^2 & -a\sin^2\theta & 0 & -\Sigma^2\sin^2\theta/\rho^2 \end{pmatrix}$$

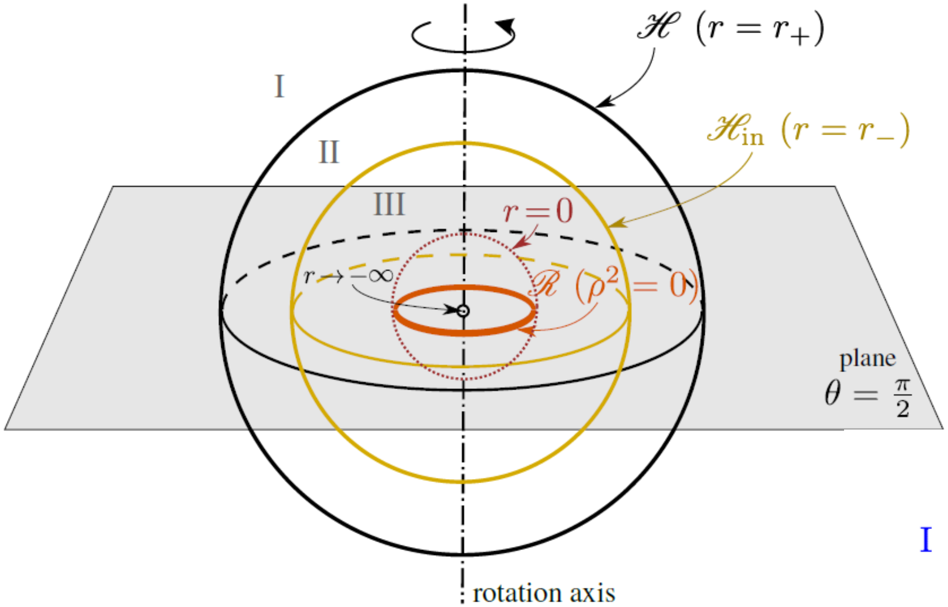
The functions are the same as in Boyer-Lindquist

$$\rho^2 = r^2 + a^2\cos^2\theta, \qquad \Delta = r^2 - 2Mr + a^2, \qquad \Sigma^2 = (r^2 + a^2)^2 - a^2\Delta\sin^2\theta$$

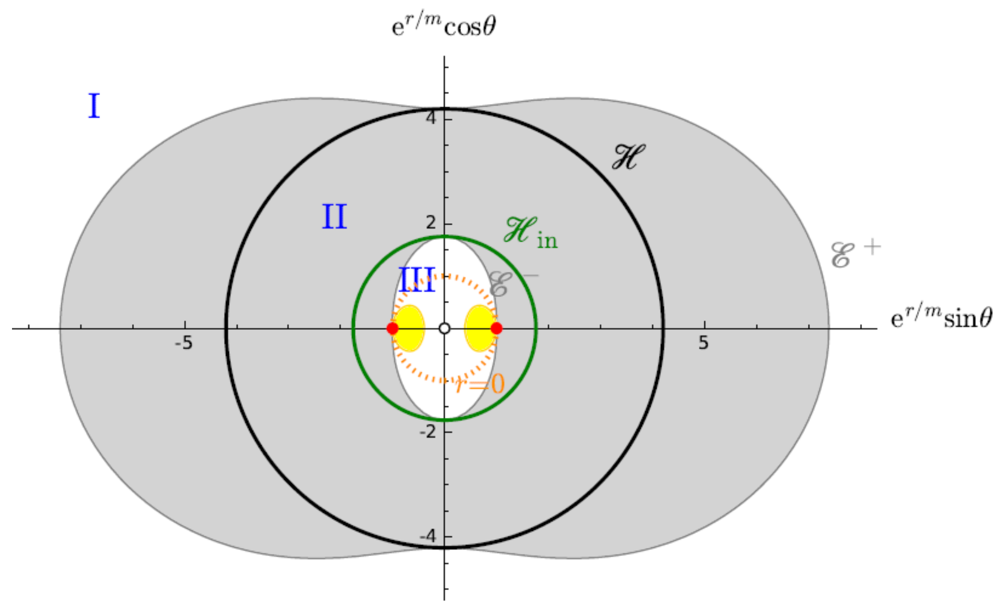
Retarded EF coordinate	New azimuthal coordinate
$du = dt - \frac{r^2 + a^2}{\Delta} dr$	$d\tilde{\phi} = d\phi - \frac{a}{\Delta} dr$

ROTATING SHELL

Some elements of Kerr geometry



$$r_+ = M + \sqrt{M^2 - a^2}$$



ROTATING SHELL

outgoing Kerr-Vaidya outside

- Physics (and shape) can depend on longitude, so parametrize by the initial θ_0

- There are symmetries, but all the components of four velocity may be non-zero

$$v_{\theta_0}{}^{\mu} = (\dot{T}_{\theta_0}, \dot{R}_{\theta_0}, \dot{\Theta}_{\theta_0}, \Omega_{\theta_0}\dot{T}_{\theta_0})$$

$$\tilde{v}^{\mu}_{\theta_0} = (\dot{U}_{\theta_0}, \dot{R}_{\theta_0}, \dot{\Theta}_{\theta_0}, \Omega_{\theta_0}\dot{U}_{\theta_0} + (\omega(R^2_{\theta_0} + a^2) - a)/\Delta_{\theta_0})\dot{R}_{\theta_0})$$

Assymptotics: assuming that $\dot{\Theta}, \Omega$ are finite

$$\dot{U}_{\theta_0} = f(M, a, \theta_0)|\dot{R}_{\theta_0,\tau}|/x_{\theta_0} + \ldots$$

f is a horribly-looking function

ROTATING SHELL

outgoing Kerr-Vaidya outside

$$x_{\theta_0} = R_{\theta_0} - r_+$$

$$\dot{x}_{\theta_0} = \dot{R}_{\theta_0}\big(1 - \epsilon_{\theta_0}(\tau)/x_{\theta_0}(\tau)\big)$$

$$\epsilon_{\theta_0}(\tau) = -\left.\frac{dr_+}{du}\right|_{\Sigma_{\theta_0}} f\big(M(U(\tau)), a(U(\tau)), \theta_0\big)$$

PART 3

Opportunities & questions

Known

Known unknowns

Context

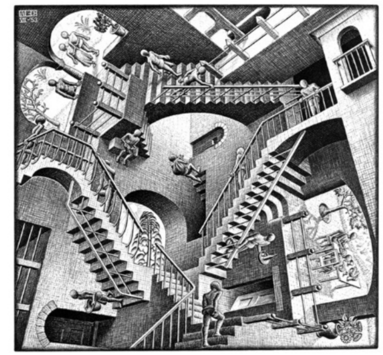
Unknown unknowns

KNOWN

- Thin massive shell:

  collapse & evaporation without horizon

  Generic spherical-symmetric metric
  Arbitrary dimension D>3+1
  Works for a shell collapsing on a core
  Possibility of a firewall or deceleration



- Thin massive rotating dust shell:

  collapse & evaporation without horizon

  Kerr-Vaidya

- Dust ball (Oppenheimer-Snyder):

  collapse & evaporation without horizon

  Generic spherical-symmetric metric

†Ashtekar and Bojowald, Class. Quant. Grav **22**, 3349 (2005).
Stephens, 't Hooft, and Whiting, Class. Quant. Grav. **11**, 621 (1994)

KNOWN UNKNOWNS & CONJECTURES

- ❑ Is the horizon avoidance generic?
- ❑ Which stress-energy tensor to use?
- ❑ Can we have the exceptional metric?
- ❑ Trapped surfaces?
- ❑ What happens at the next level [semiclassical stochastic gravity]?

CONTEXT

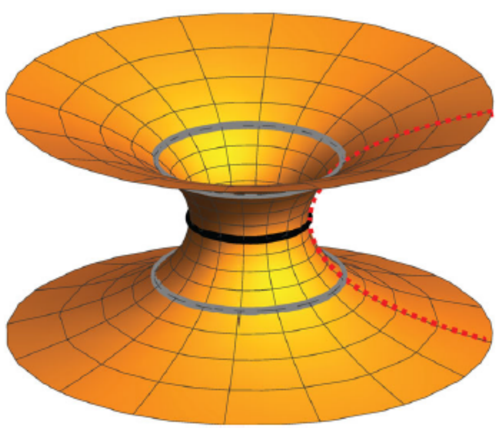
- Absence of the event horizon is consistent with arguments that quantum effects destroy it.
- No info loss in the semiclassical theory: it is consistent
  The paradox goes the way of the paradoxes of QM

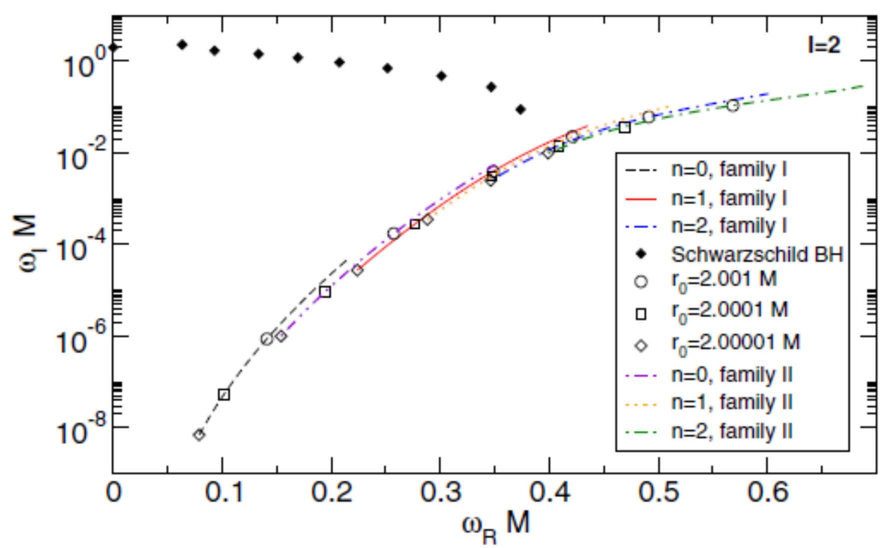
†Brustein, Fortschr. Phys. **62**, 255 (2014)

- Observability? May be…

The first reaction: no, just the standard classical GR

But





Cardoso, Franzin, and Pani,
Phys. Rev. Let. **116**, 171101 (2016)

UNKNOWN UNKNOWNS

- How quantum correlations get distributed between the tripartite system of gravity/early modes/late modes?

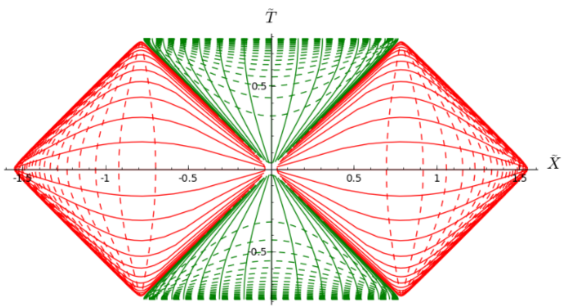
- Bekenstein-Hawking black hole entropy is $S_{BH} = A/4$.

If event horizons do not correspond to asymptotically reachable states of collapsing matter, what are the thermodynamic properties of the resulting ultra-compact objects?

thanks

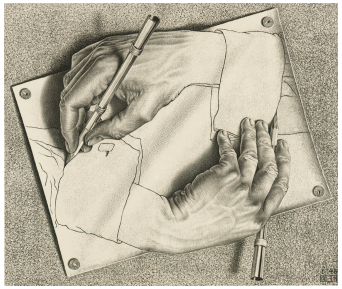
● Bernard Kay ● Stefano Liberati ● Paolo Pani ● Tanmay Vachaspati
● Yuki Yokokura ● Dieter Zeh ■ Sabine Hossenfelder

picture credits



É. Gourgoulhon

J.-P. Luminet



M. C. Esher