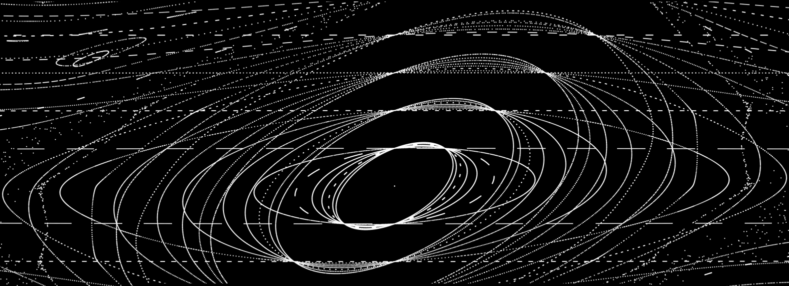
Causal structure of black hole evaporation.



Joe Schindler

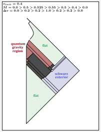
UCSC Physics

November 2016

Goal:

Show this diagram

(true penrose diagram for bh formation and evaporation)

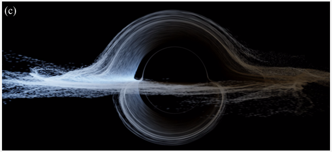


and convince you that you care.

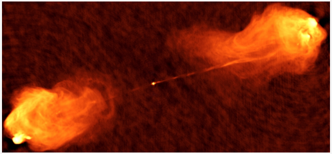
Step 1:
Context

What is a black hole?

Astrophysical black holes.

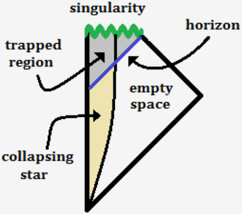


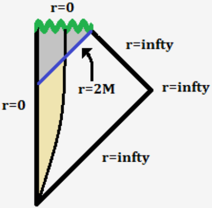
(Gargantua, Thorne 2015)



(Cyg A, NRAO via Narayan 2015)

Theoretical black hole spacetimes.

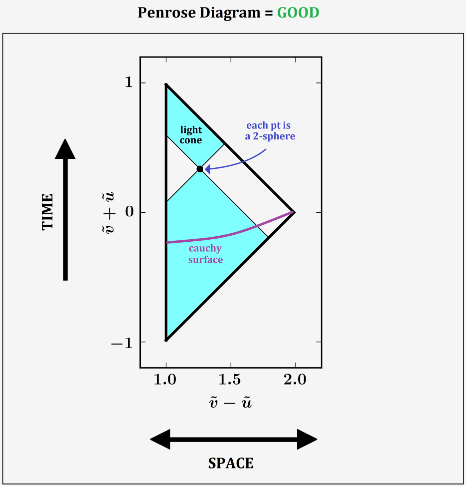




Key feature: Trapped region leading to extreme curvature.

Penrose diagrams.

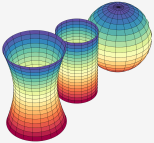
Visualizing a spacetime:



Everything you need to know about GR.

- **spacetime** = manifold (w/ one timelike dimension)
- **metric** ($g_{\mu\nu}$) encodes geometry:

$ds^2 = dx^2 + dy^2$ (flat plane)	$ds^2 = R^2\,(d\theta^2 + \sin^2\theta\, d\phi^2)$ (sphere)	$ds^2 = -dt^2 + dr^2 + r^2\, d\Omega^2$ (flat spacetime)



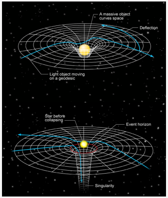
(Wikimedia Commons)

- **lightcones** determine causal structure
- **gravity** from coupled matter+metric eqns:

$$S = S_{\text{grav}} + S_{\text{matter}}$$

- **curvature** relates to matter content, partly through $G_{ab} = 8\pi T_{ab}$.

total curvature	=	ricci part	+	traceless part
(R_{abcd})	$\to$	(G_{ab})	,	(C_{abcd})



(Nastase 2009)

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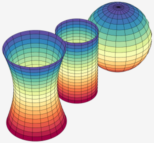

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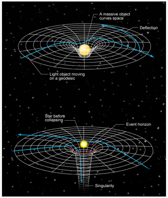

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(flat plane)	(sphere)	(flat spacetime)

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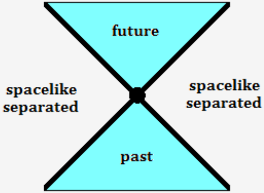

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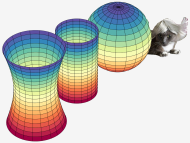

(Wikimedia Commons)

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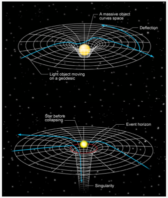

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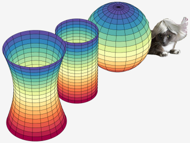

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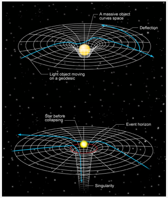
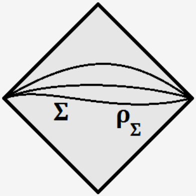
total curvature	=	ricci part	+	traceless part
(R_{abcd})	$\rightarrow$	(G_{ab})	,	(C_{abcd})
		local matter		waves and distant sources

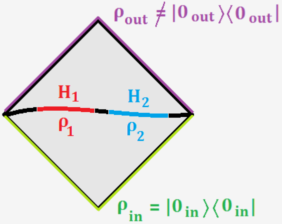


(Nastase 2009)

QFT IN CS.

- **density matrix**, pure states, mixed states
- each **cauchy surface** has a density matrix on its **hilbert space**
- HS is tensor product of local DOFs
- definition of **particles/vacuum not unique**
- classical wave basis ⇔ fock basis
- semi-classical limit from $\langle T_{\mu\nu} \rangle$
- locally flat ⇒ locally standard QFT



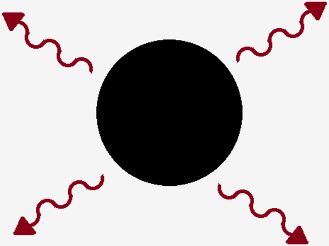


Step 2:
Motivation

Motivation.

black holes evaporate by emitting (approximately) thermal radiation

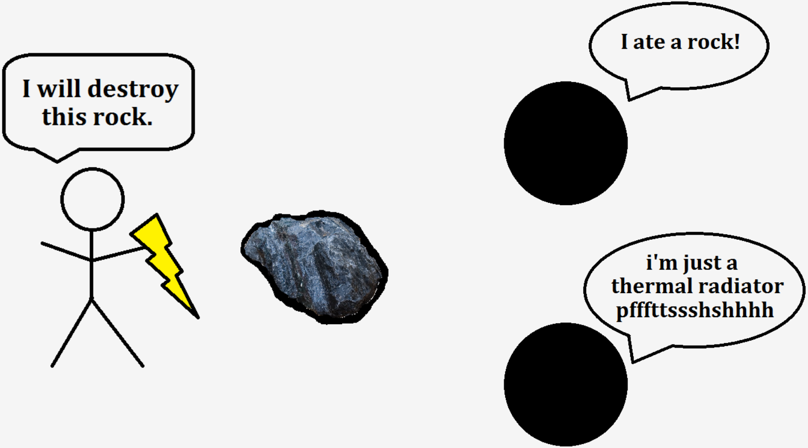
$(T \propto 1/M)$



stuff goes in $\Rightarrow$ hawking radiation comes out

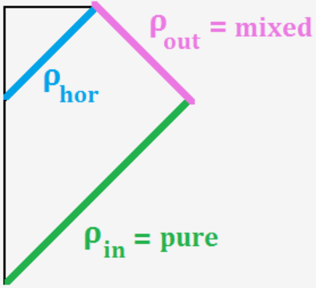
Motivation.

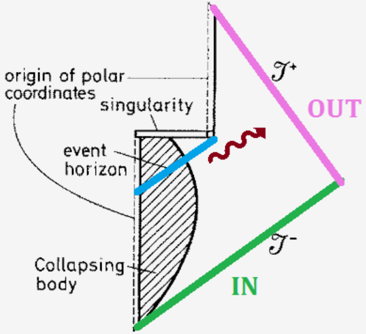
- "information paradox"?



Motivation.

- not well posed

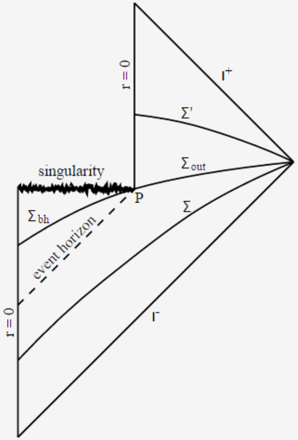




(Hawking 1975 + annotation)

Motivation.

- doesn't correspond to any spacetime
- no cauchy surface
- everything happens at the bad point (P)
- singularity?
- general: no fake diagram contains any unknown information
- conclusion: not very useful (or worse!)
- goal: explicitly construct evaporating bh spacetime and compute diagram



(1993)

Step 3:

Explicitly Computed Penrose Diagrams

Algorithm.

New algorithm computes any diagram of the form

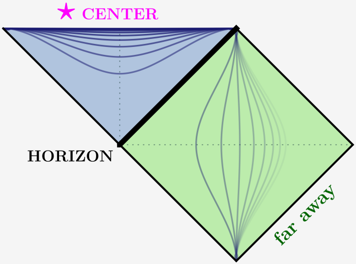
$$ds^2 = -f(r)\,dt^2 + f(r)^{-1}\,dr^2 + r^2\,d\Omega^2\ .$$

(Mink, Schwarz, R-N, dS, AdS, Ax-Kerr-Newm, Hayward, S-dS, S-AdS, ...)

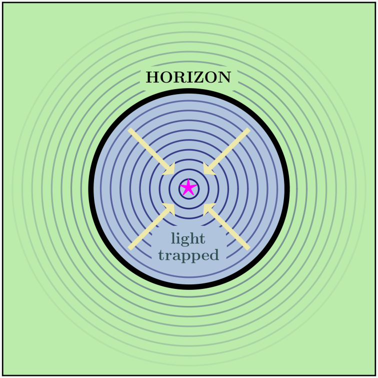
- numerically computable with any number of horizons
- metric analytic across horizons
- slightly expands class of known diagrams

Schwarzschild BH.

penrose diagram



coordinate "time" slice



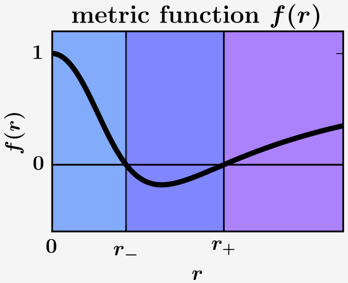
"schwarzschild radius" $R = \frac{2GM}{c^2}$

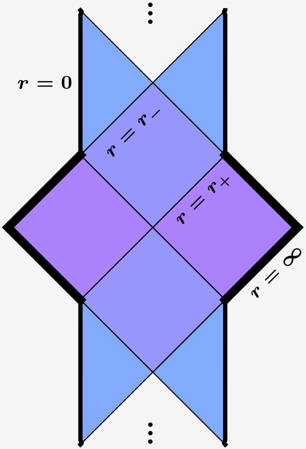
Strongly spherically symmetric spacetimes.

- **function** $f(r)$ **specifies metric**

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

- **horizons** where $f = 0$
- **maximal extension** vs. collapse/evap





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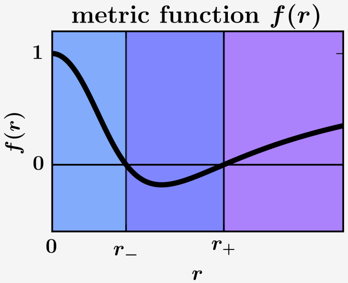
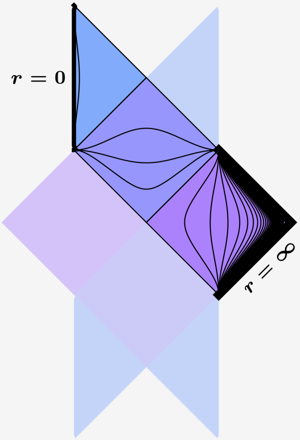
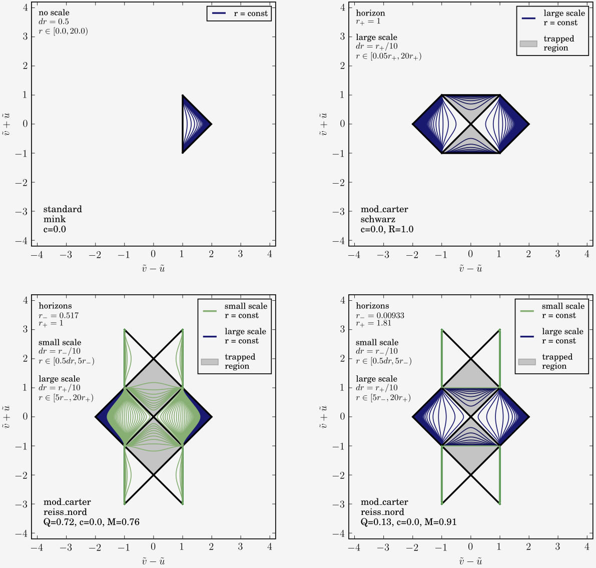


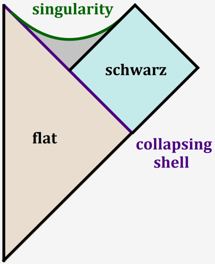


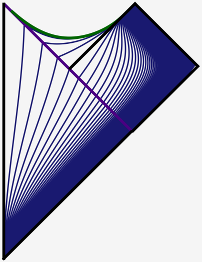
Penrose diagrams.



Shell collapse.

standard eternal bh from shell collapse





(well-defined piecewise junction yields a matter shell)

Step 4:
Non-Singular Black Holes

SINGULARITY?

singularities:

- infinite curvature and density ... point mass
- classical GR breaks down
- remove w/ curvature cutoff?

removing singularity is restrictive:

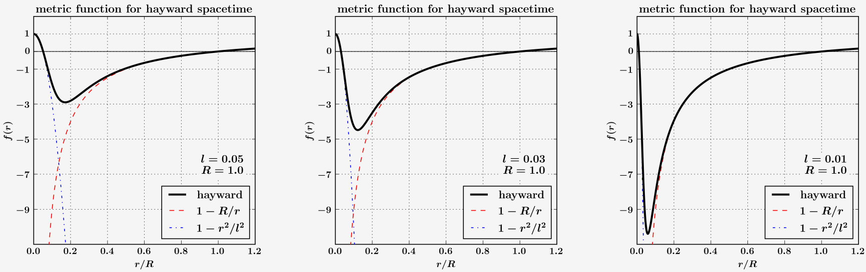
- $r = 0$ must be timelike (inner horizon forms)
- for strong spherical symmetry: $f(r) \sim 1 + O(r^2)$ as $r \to 0$

why?

- keep curvature finite
- well-defined cartesian coordinates
- topological reasons

Non-singular BH.

Hayward spacetime: $f(r) = 1 - \dfrac{Rr^2}{r^3 + Rl^2}$



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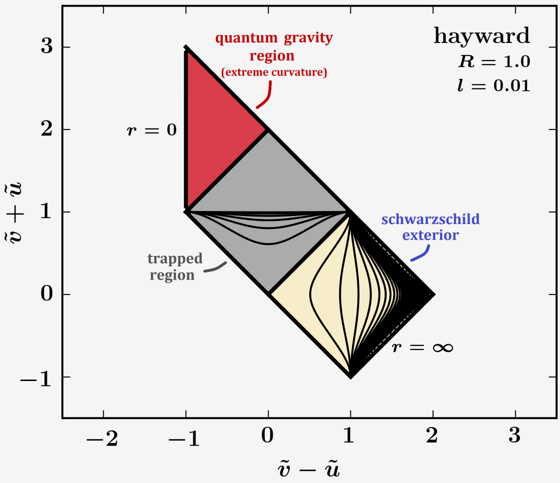
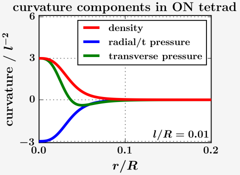
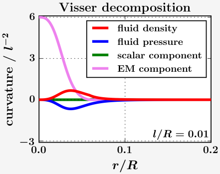
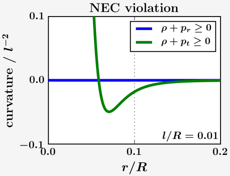
Non-singular BH.

Hayward spacetime:



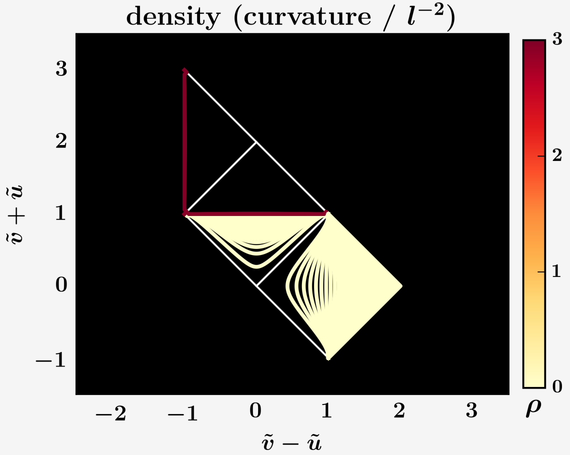


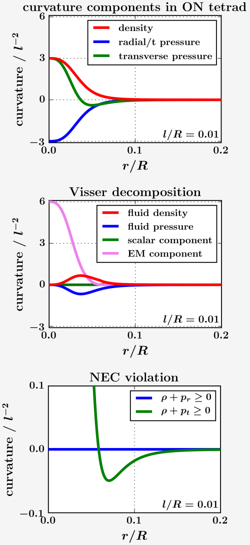




Non-singular BH.

Hayward spacetime:





Step 5:
BH Evaporation

Black Holes Radiate.

Orders of magnitude for BH evaporation:

mass (M)	**radius** ($R \propto M$)	**temp** ($T \propto 1/M$)	**lifetime** ($t \propto M^3$)
$M_{SMBH} \approx 10^{38}$ kg	1 au	10^{-6} nK	10^{81} GYr
$M_{sun} \approx 10^{30}$ kg	1 km	100 nK	10^{57} GYr
$M_{earth} \approx 10^{24}$ kg	1 mm	100 mK	10^{39} GYr
$M_{yaks} \approx 10^{9}$ kg	proton	10^{14} K (EWSB)	1000 Yr
$M_{antmegacolony} \approx 10^{5.5}$ kg	tiny	10^{17} K	1 s
$M_{planck} \approx 10^{-8}$ kg	$2\ l_p$	10^{30} K (GUT)	10^{-40} s

Simple blackbody spectrum.

Evaporation.

evidence for bh evaporation:

- classical bh thermodynamics

$$dM = \frac{\kappa}{8\pi}\, dA + \Omega\, dJ + \Phi\, dQ$$

- particle creation derivation
- euclidean “magic” thermal derivation
- particle tunneling models
- vacuum stress tensor derivation
- and more! (wiki derivation, rindler info derivation, AdS/CFT)

Evaporation.

evidence for bh evaporation:

- classical bh thermodynamics – suggestive

$$dM = \frac{\kappa}{8\pi}\, dA + \Omega\, dJ + \Phi\, dQ$$

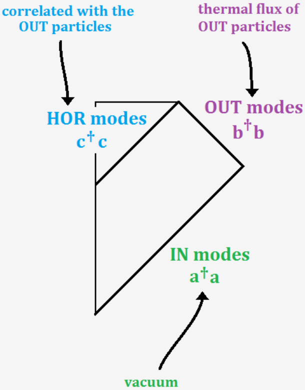
- particle creation derivation
  – doesn't require bh
- euclidean "magic" thermal derivation
  – doesn't require bh
- particle tunneling models
  – negative energy?
- vacuum stress tensor derivation
  – distinguishes bh from flat space
- and more! (wiki derivation, rindler info derivation, AdS/CFT)

Evaporation.

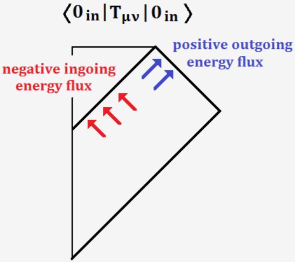
- many closely intertwined derivations
- no single, clear, physical picture
  (does a clear semiclassical description exist? we think yes)
- deep relation to entropy

Most important dynamical derivations.

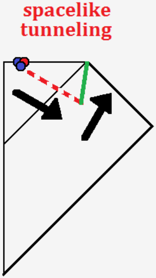
particle creation



vacuum stress tensor

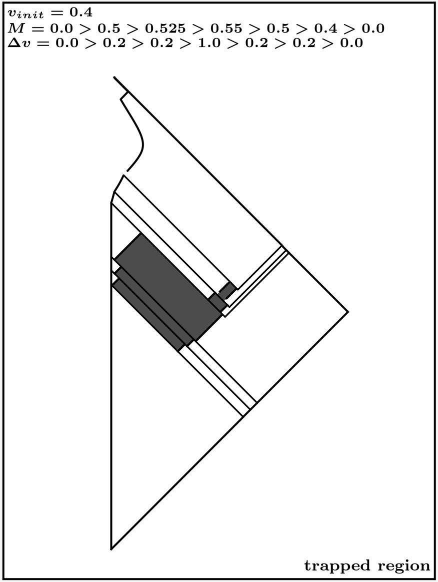


tunneling

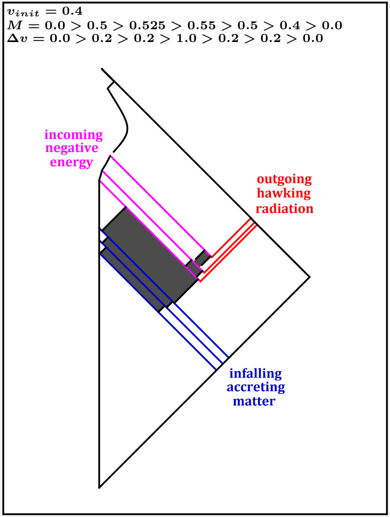


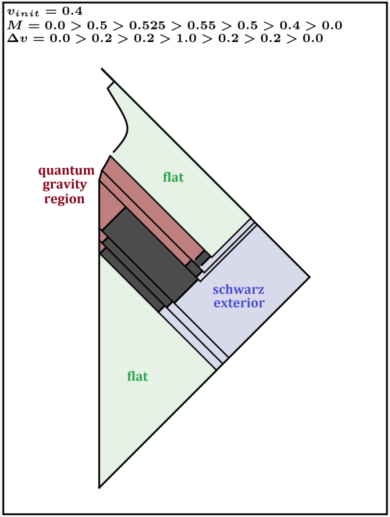
And now for the grand finale…

Formation and evaporation.



Formation and evaporation.





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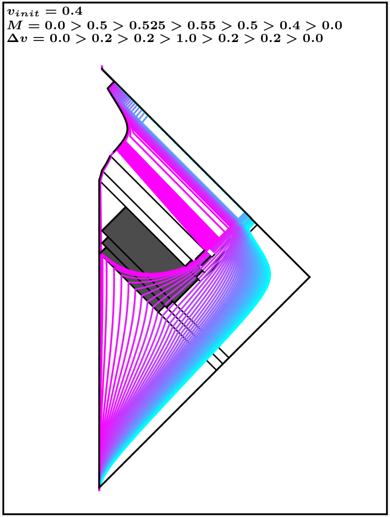
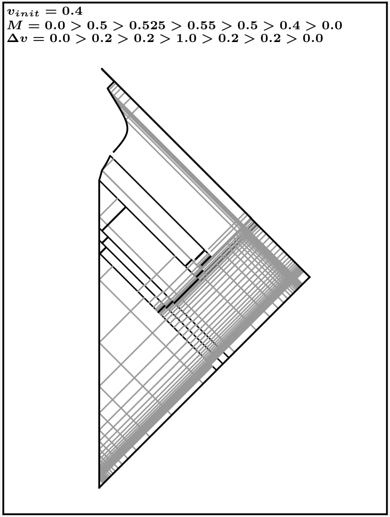




What now?

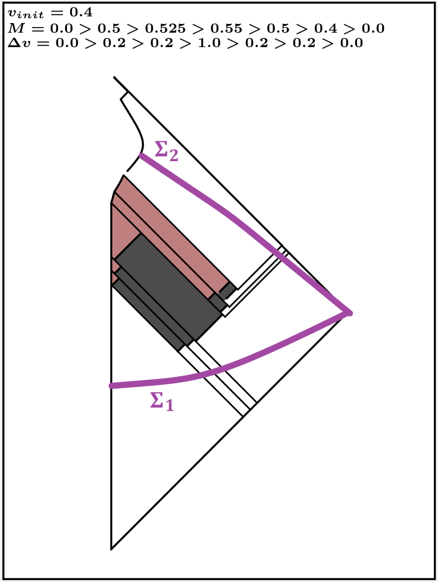
Upcoming papers...

- algorithm and the new basic diagrams
- f/e diagrams in asymptotically flat and asymptotically dS space w/ and w/o singularity
- more after do below

Things to do...

- put in correct $M(v)$, and extend to dS
- calculate junction $G^{\mu}{}_{\nu}$ and compare to spacelike tunneling
- repeat Hawking effect derivations in these backgrounds and demonstrate self-consistency
- rotating regular bh projections?
- back to roots: entropy, local causal diamond description, stretched horizon description... using new perspectives
- ...

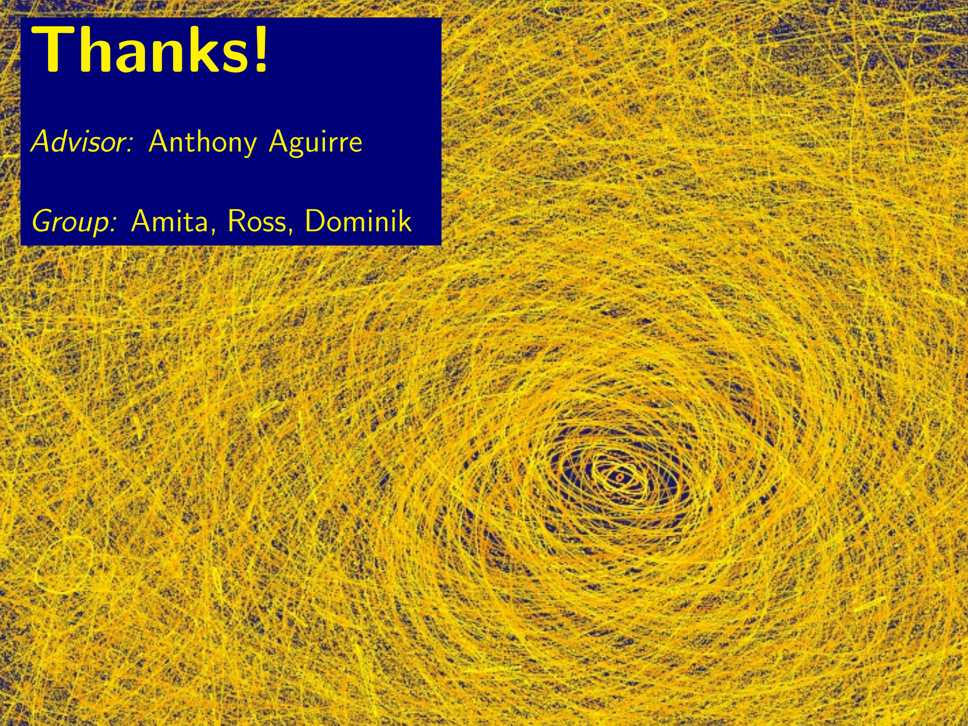
A sendoff.


$v_{init} = 0.4$
$M = 0.0 > 0.5 > 0.525 > 0.55 > 0.5 > 0.4 > 0.0$
$\Delta v = 0.0 > 0.2 > 0.2 > 1.0 > 0.2 > 0.2 > 0.0$
Σ_2
Σ_1

Thanks!

Advisor: Anthony Aguirre

Group: Amita, Ross, Dominik



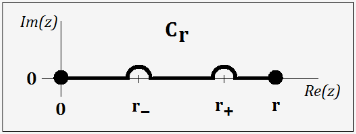
Extra Slides

ALGORITHM.

- require only that $f(r_0) = 0 \Longrightarrow f$ analytic at r_0

- double-null coords from

$$r_*(r) = \int_{C_r} \frac{dz}{f(z)}$$

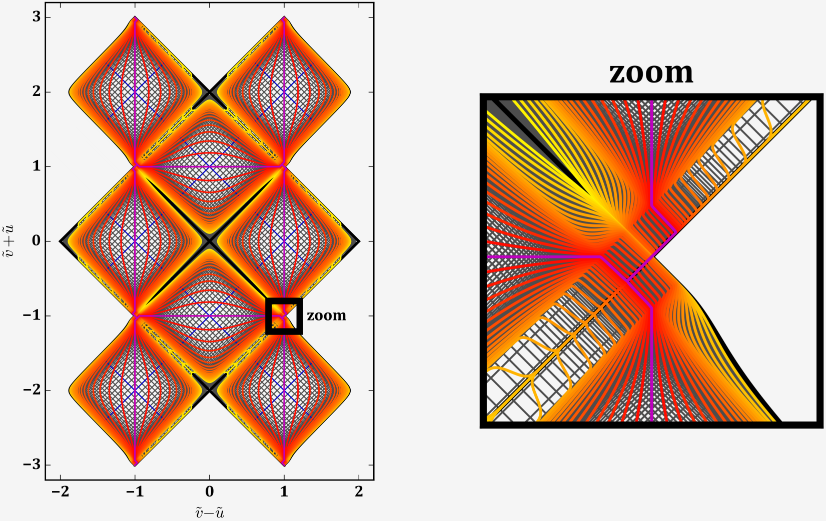


- target metric is **analytic at horizons**

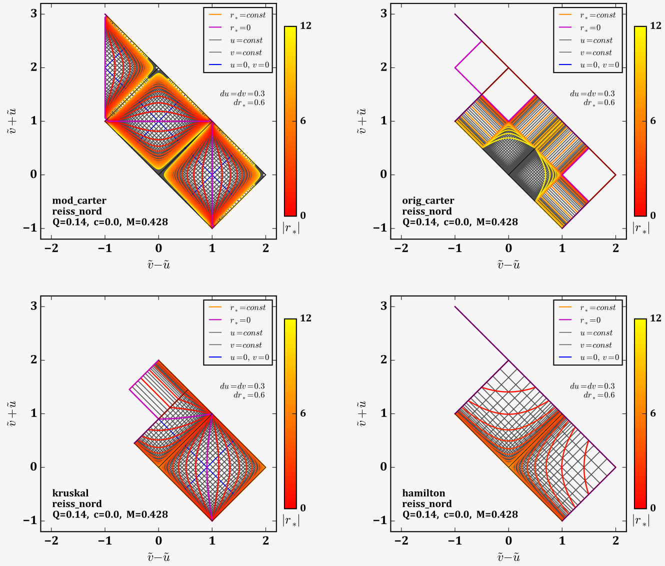
$$ds^2 = -\frac{4\pi^2 \, |f(r)|}{e^{kr_*(r)}} \; G_u(u,k) \; G_v(v,k) \; d\bar{u} d\bar{v} + r^2 d\Omega^2$$

- trivially extended to any number of horizons

Detail view.

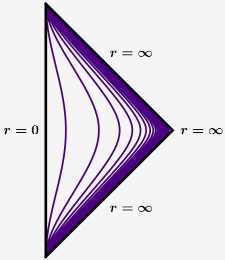


Alternative methods.

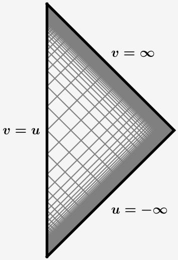


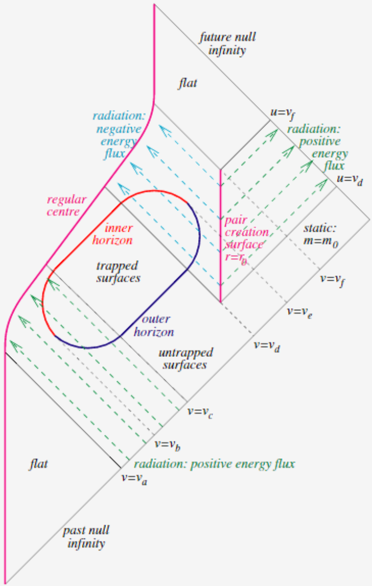
Minkowski Space.

lines of constant radius



lines of constant u,v





(Hayward 2006)