Information loss problem and a ‘black hole’ model with a closed apparent horizon

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S.W. Hawking , “Information Preservation and Weather Forecasting for Black Holes”, Jan 22, 2014e-Print: [**arXiv:1401.5761**]

“The absence of event horizons mean that **there are no black holes** – in the sense of regimes from which light can't escape to infinity. “

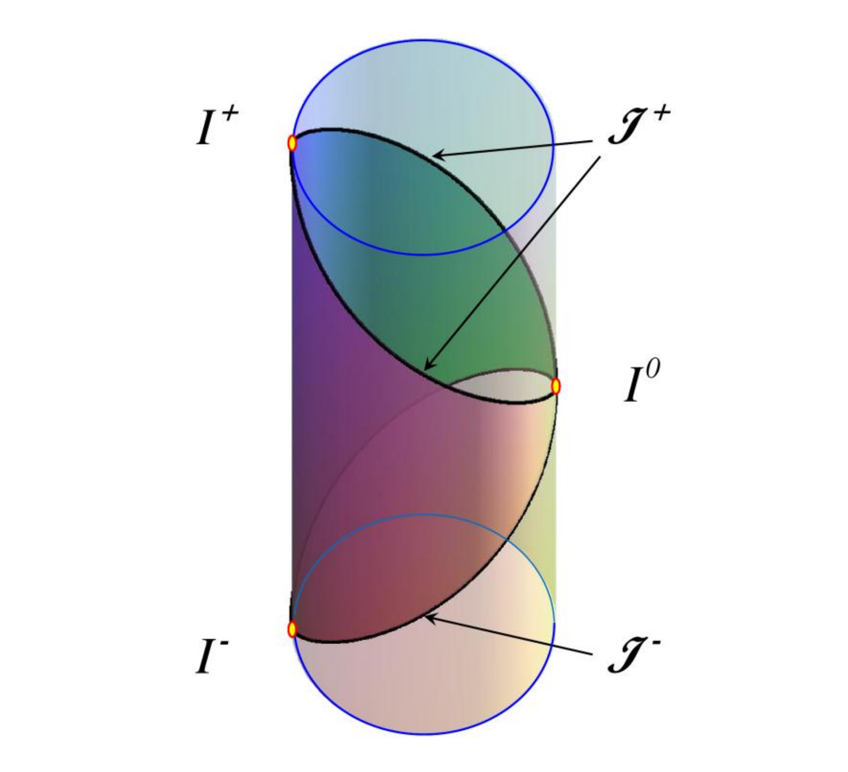
http://tyumen-time.ru/news/video/662/ (21.04.2014)

Владимир Путин: “Прекратились разговоры, что бесполезно вкладывать средства в сельское хозяйство, в село. **Пресловутое словосочетание «черная дыра», мне кажется, уже ушло в прошлое.”**

“Notorious phrase "black hole", it seems to me, already gone into the past “

Do black holes exist?

Black Hole Definition



$$ds^2 = -dT^2 + dR^2 + R^2 d\omega^2$$

$$T \pm R = \tan\frac{\psi \pm \xi}{2}$$

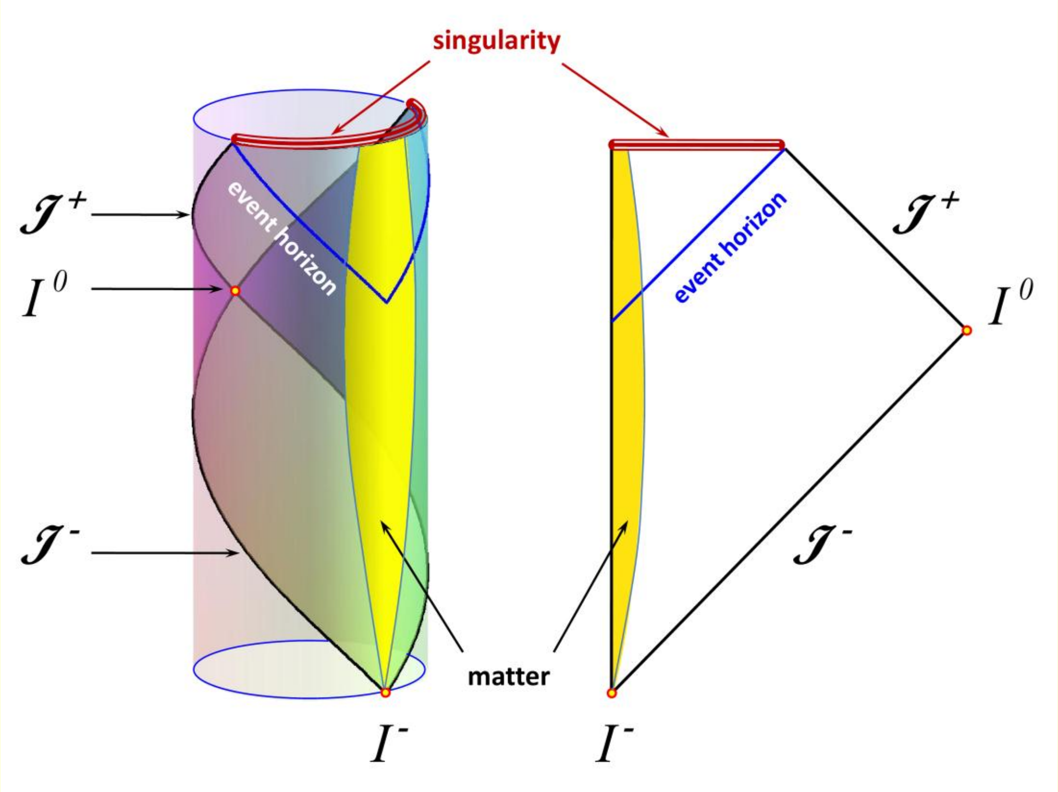
$$ds^2 = \Omega^{-2} dS^2$$

$$dS^2 = -d\psi^2 + d\xi^2 + \sin^2\xi\, d\omega^2$$

$$\Omega = 2\cos\frac{\psi+\xi}{2}\cos\frac{\psi-\xi}{2}$$

For Minkowski ST:

Future (I^+) and past (I^-) null infinities are regular null surfaces in metric dS^2, the boundaries of ST

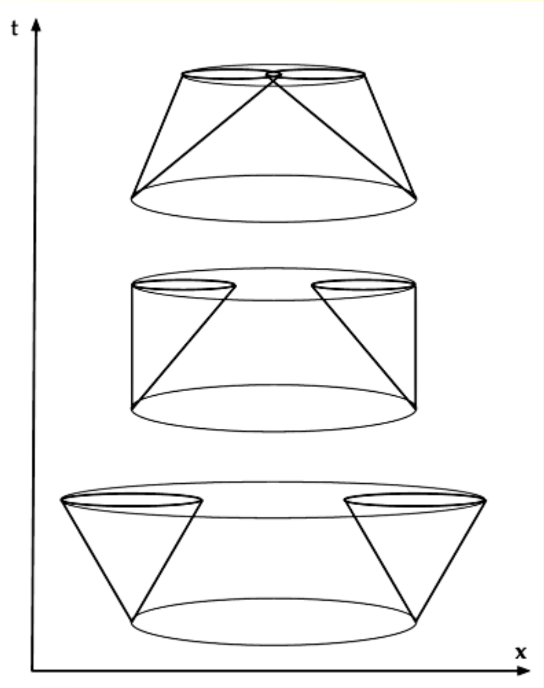


Penrose (1963+): Asymptotically flat ST is a ST which has the same asymptotic structure as the Minkowski space and which is either vacuum at infinity, or the stress-energy tensor falls down there rapidly enough. The boundary of the domain, `visible' from the infinity, $\dot{J}^-(I^+)$, is called the event horizon. The ST region inside the event horizon is called a black hole.

This definition assumes that one should know (or predict) global future evolution of the ST, so that he/she can decide whether the light can escape from the inner domain and reach a distant observer sometime in future. This definition allows one to prove very powerful theorems about global properties of black holes. For example their surface area never decreases and generically the EH is null. These and other similar results are based on the assumption that some version of the energy condition is satisfied. E.g. the weak energy condition:

$$T_{\mu\nu} l^{\mu} l^{\nu} \geq 0$$

`Quasi-local definition' of BH: Apparent horizon



A compact smooth surface *B* is called a trapped surface if both, in- and out-going null surfaces, orthogonal to *B*, are non-expanding .

A trapped region is a region inside *B*.

A boundary of all trapped regions is called an apparent horizon.

In a ST obeying the null-energy condition the apparent horizon lies inside (or coincides with) the true event horizon.

In classical physics in order to prove the existence of a BH (in an exact mathematical sense) it is not necessary to wait infinite time, but it is sufficient to check the existence of the trapped surface `now'.

In quantum physics (or in `exotic' theories) the energy conditions could be violated. An example is an evaporating black hole (negative energy flux through the horizon reduces its mass). It is possible, in principle, that the apparent horizon exists, but there is no event horizon.

Penrose theorem:

Trapped surface + WEC → singularity

(geodesic incompleteness)

If a black hole completely disappears as a result of its quantum evaporation one has the Information Loss Puzzle

Information Loss Puzzle

$$\begin{pmatrix}\text{Pure}\\ \text{state}\end{pmatrix} \overset{\text{Collapse}}{\Rightarrow} \begin{pmatrix}\text{Black}\\ \text{hole}\end{pmatrix} \overset{\text{Evaporation}}{\Rightarrow} \begin{pmatrix}\text{Thermal}\\ \text{radiation}\end{pmatrix}$$

If an initial pure state evolves into a mixed state, described by the density matrix, the unitarity of quantum evolution is lost. The unitarity is a basic principle of the quantum mechanics. Does it mean that

Gravity + Quantum Mechanics= Inconsistent theory ?

Main ways out:

1. Quantum mechanics is still valid on a causal evolution of the initial Cauchy surface, but after evaporation an external observer has access only to a part of the system;
2. Information gradually leaks out during the evaporation process;
3. Information is collected in a small mass remnant;
4. Entanglement is immediately broken between the infalling particle and the outgoing particle. A falling observer will see a \`firewall', when he/she crosses the horizon. This "resolution" requires a violation of Einstein's equivalence principle,

5 No internal singularity, closed apparent horizon

Black hole model with a closed apparent horizon

"Spherically symmetric collapse in quantum gravity"
V.P. Frolov and G.A. Vilkovisky, Physics Lett. B, 106, **1981**, pp. 307–313

Abstract: The problem of classical singularities is revised on the basis of the quantum-gravity effective equations. We find a simple rule for establishing the Birkhoff theorem in spherically symmetric problems. All exact solutions of the lagrangian with $C^2_{\alpha\beta\gamma\sigma}$ are obtained. Spherically symmetric collapse of the thin null shell of mass M is considered in the framework of a local theory describing vacuum polarization effects. The boundary-value problem is set and the asymptotic solution is obtained. It is found that the shell collapses to $r = 0$ without the rise of a singularity, and begins expanding. The global behaviour of the solution is obtained for small M. **For large *M* it is conjectured that the event horizon does not form, and the apparent horizon is closed. An object forms, possessing the observable properties of a black hole, but living a finite time.**

Static spherically symmetric ST

$$ds^2 = -f\ dt^2 + g\ dr^2 + r^2 d\omega^2$$

is locally Euclidean at $r = 0$ iff

$$g = 1 + Cr^2 + \ldots \Rightarrow (\nabla r)^2 = g^{-1} = 1 - Cr^2 + \ldots$$

$$\frac{1-(\nabla r)^2}{r^2} \sim \text{curvature.}$$

If the AH crosses the center $r = 0$, ST has a curvature singularity there.

In a BH with a regular interior (1) either the AH is closed (2) or its inner and outer branches do not intersect

Other publications on regular BH models with closed apparent horizons

T. A. Roman and P.G. Bergmann (1983);
P. Bolashenko and V.F. (1986)
S. N. Solodukhin, (1999);
S. A. Hayward (2006);
S. Ansoldi (2008),
C. Bambi, D. Malafarina, L. Modesto (2013)
V. N. Lukas and V. N. Strokov (2013)
C. Rovelli and F. Vidotto (2014);

D.I. Kazakov, S.N. Solodukhin (1993)
P. Hajicek (2002);
D. Grumiller (2003, 2004;
J. Ziprick and G. Kunstatter (2010)

For discussion of models with closed apparent horizon see also the book by V.F. and Novikov “Black Hole Physics” (1998), and references therein.

Other types of regular BH models: Universe(s) creation inside a BH

V.F., Markov, Mukhanov:
"Through A Black Hole Into A New Universe?" Phys.Lett. B216 (1989) 272-276;
"Black Holes As Possible Sources Of Closed and Semiclosed Worlds" , IC/88/91. May 1988. Phys.Rev. D41 (1990) 383**;**
Barrabes and V. F., "How many new worlds are inside a black hole?" Phys.Rev. D53 (1996) 3215

Buonanno, Damour, Veneziano, "Pre- big bang bubbles from the gravitational instability of generic string vacua", Nucl.Phys. B543 (1999) 275-320:.

Smolin, "*The Life of the Cosmos*" , 1997:

V. Rubakov,
V. Lukash et. all

Main goal of this talk is to illustrate generic features of models with a closed apparent horizon

Main assumptions of the model

Spacetime with a geometry $g_{\mu\nu}$ satisfying modified gravitational equations;

Limiting curvature conjecture (Markov 1982, 1984);

Geometry differes from the classical one in the domains, where (curvature) $\sim l_{Pl}^{-2} \Rightarrow r < r_0 = l_{Pl}(r_S / l_{Pl})^{1/3}$;

Hawking radiation to the infinity is accompanied by negative energy flux through the horizon, which slowly reduces the black hole's mass;

Null fluid approximation for incoming and outgoing energy fluxes;

This massive shell approximation for the region near the horizon, where massless quanta are created.

$$dS^2 = -f dV^2 + 2dV\,dr + r^2 d\omega^2,$$

$$f = 1 - \frac{2M(v) r^2}{r^3 + 2M(v) b^2}.$$

When $b \to 0$ one has Vaidya metric

$$f = 1 - \frac{2M(v)}{r} \Rightarrow T_{\mu\nu} = \frac{\dot{M}}{4\pi r^2} V_{,\mu} V_{,\nu}$$

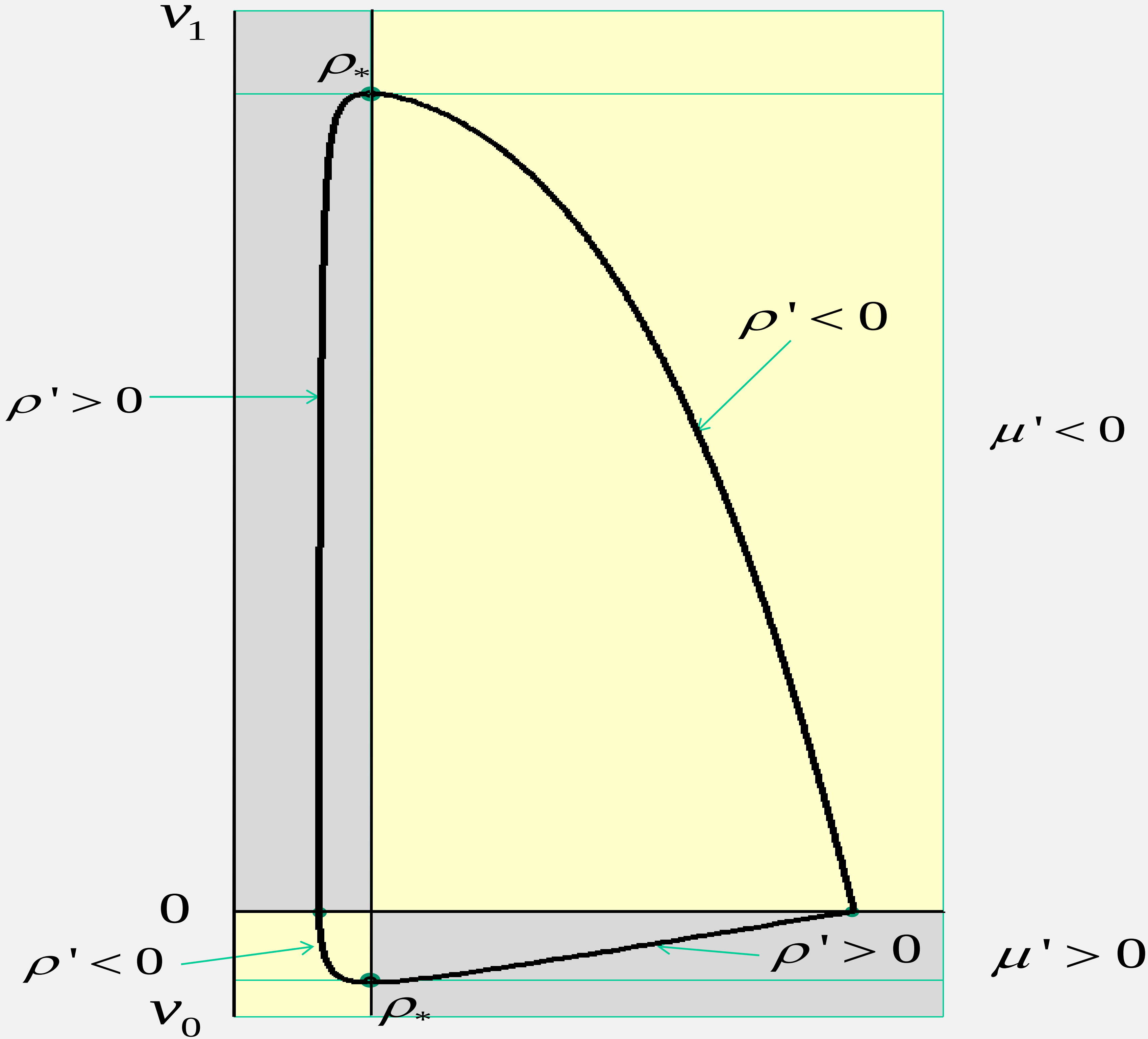
Use `Plankian scale parameter' b to transform the metric into its dimensionless form

$$dS^2 = b^2 ds^2, \quad ds^2 = -f dv^2 + 2dv\, d\rho + \rho^2 d\omega^2,$$

$$f = 1 - \frac{2\mu(v)\rho^2}{\rho^3 + 2\mu(v)}.$$

In the limit $\rho \to 0$ one has $f \sim 1 - \rho^2$ and the (curvature)$^2 \sim 1$

Apparent horizon: $(\nabla\rho) = f = 0$



v_1
ρ_*
$\rho' < 0$
$\rho' > 0$
$\mu' < 0$
0
$\rho' < 0$
$\rho' > 0$
$\mu' > 0$
v_0
ρ_*

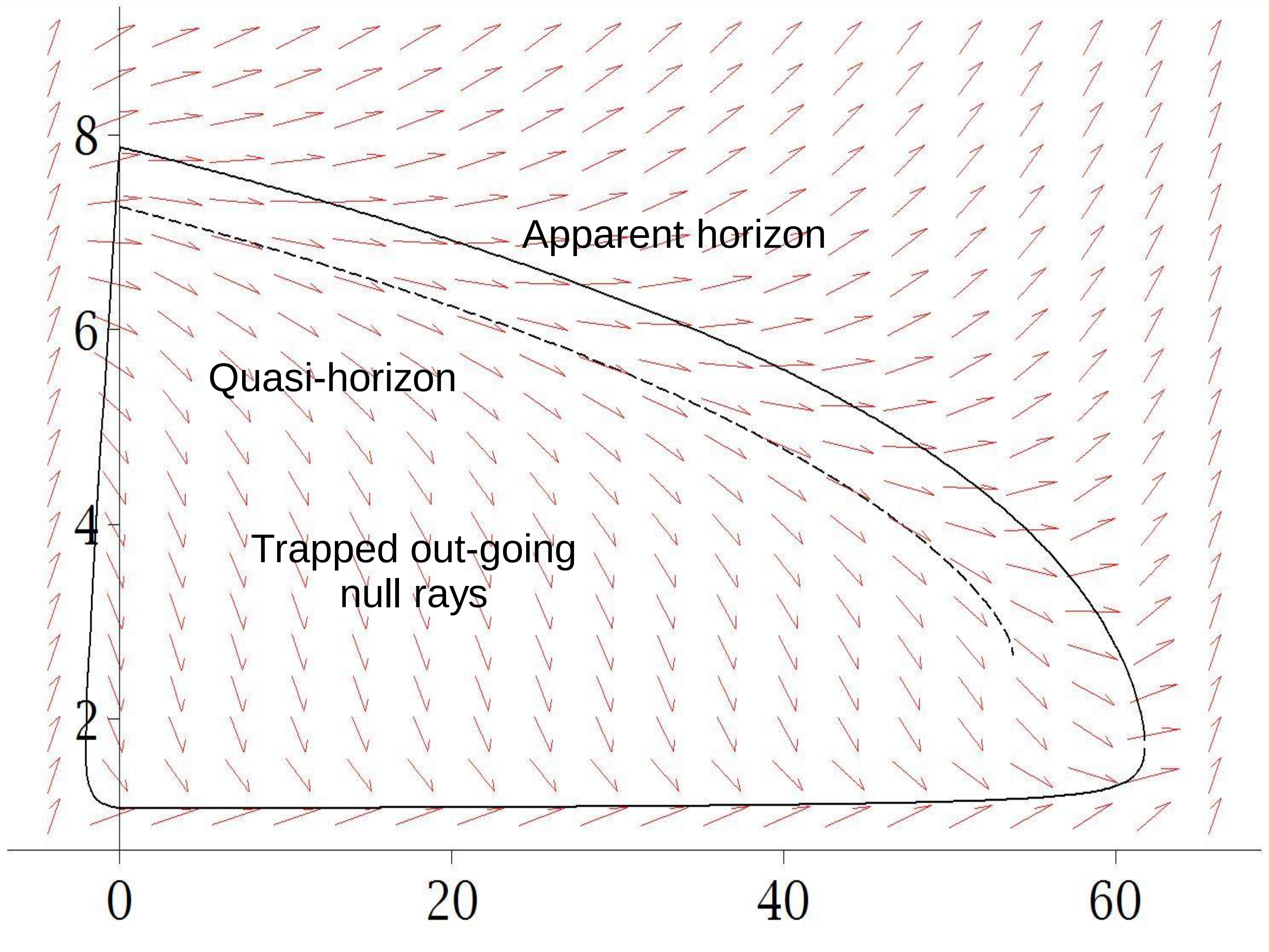
$\mu_* = \dfrac{3\sqrt{3}}{4}$ is the minimal mass of the black hole.

(BH formation is the 1st order `phase transition'

V.F. & Vilkovisky, 1979)

Simplest model: $\mu^3 = \mu_0^3 - v, \text{ for } v > 0,$

$\mu = \mu_0(1 - v/v_0), \text{ for } v_0 < v < 0$

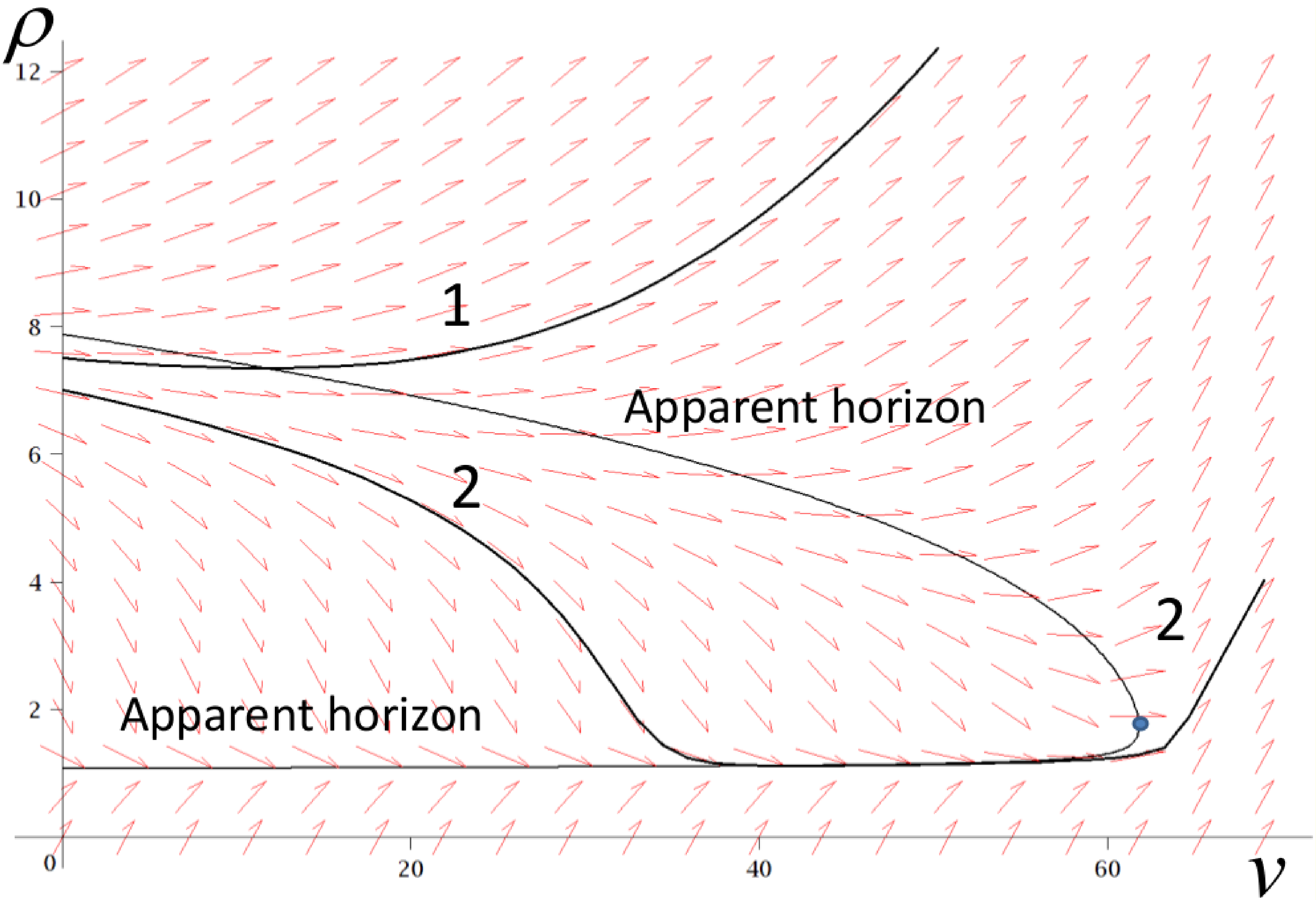

8
6
4
2
0
20
40
60
Apparent horizon
Quasi-horizon
Trapped out-going
null rays

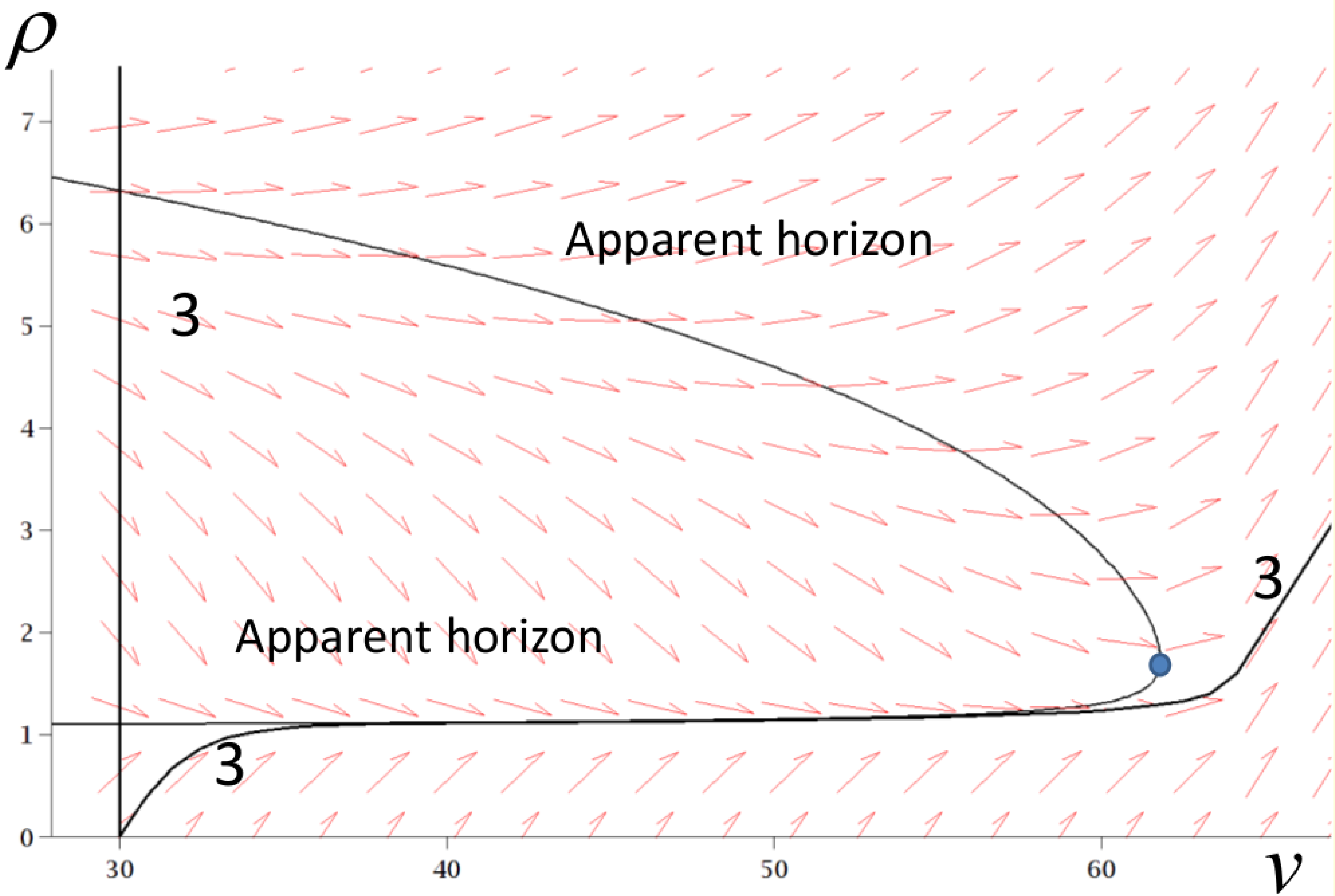
Quasi-horizon

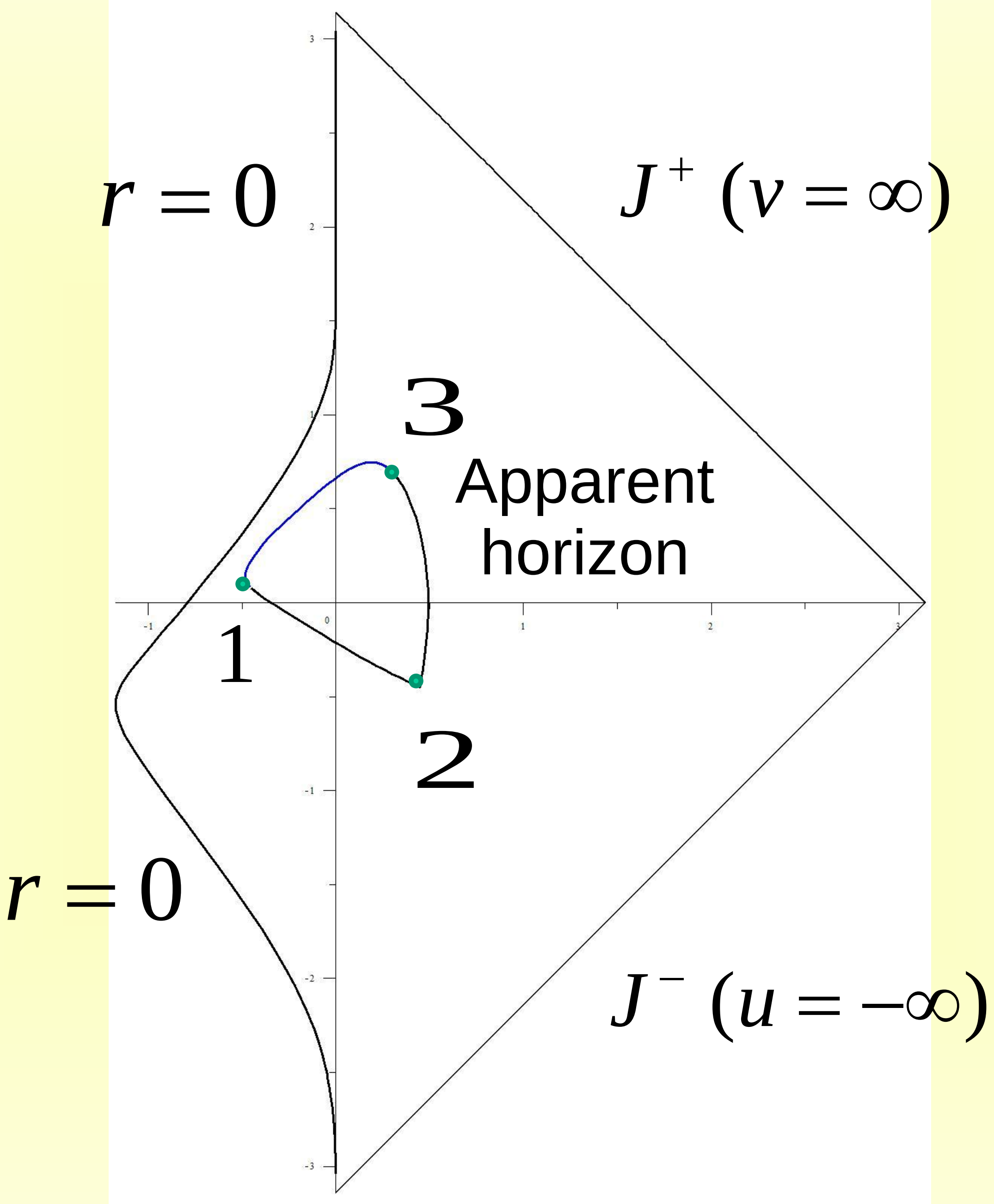
Radial out-going null rays: $\dfrac{d\rho}{dv} = \dfrac{1}{2} f$

Quasi-horizon: $\dfrac{d^2\rho}{dv^2} = 0 \Rightarrow 2\partial_v f + f\partial_\rho f = 0$

Equivalent definition: $(\nabla f)^2 = 0$


ρ
12
10
8
6
4
2
0
20
40
60
v
1
2
2
Apparent horizon
Apparent horizon


ρ
7
6
5
4
3
2
1
0
30
40
50
60
v
Apparent horizon
Apparent horizon
3
3
3


$r = 0$
$J^+ \ (v = \infty)$
3
Apparent
horizon
1
2
$r = 0$
$J^- \ (u = -\infty)$

Frequency shift

The `surface gravity' of the inner horizon is negative: $\kappa \approx -b^{-1} \Rightarrow$ large blue shift:

$$\omega \sim \omega_0 \exp((V - V_0)/b)$$

Summary

1. Validity of the approximation $g_{\mu\nu} = \langle \hat{g}_{\mu\nu} \rangle$;
2. Gravity as an emergent theory;
3. Analogue of the trans-Planckian problem;
4. Inverse Hawking process;
5. Quasi-horizon