Title: The mass-inflation phenomenon in the asymptotic safety scenario

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Abstract:

The mass-inflation phenomenon in the AS scenario

Alfio Bonanno – INAF, Catania

Outline of the talk

- Motivation
- CH instability
- Mass-inflation singularity
- Flow equations around WF and AS FP
- An explicit QG modified solution

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- Extension of the ST beyond the CH
- Conclusions

"Gravitational collapse is the greatest crisis of physics of all time."

J.A.Wheeler

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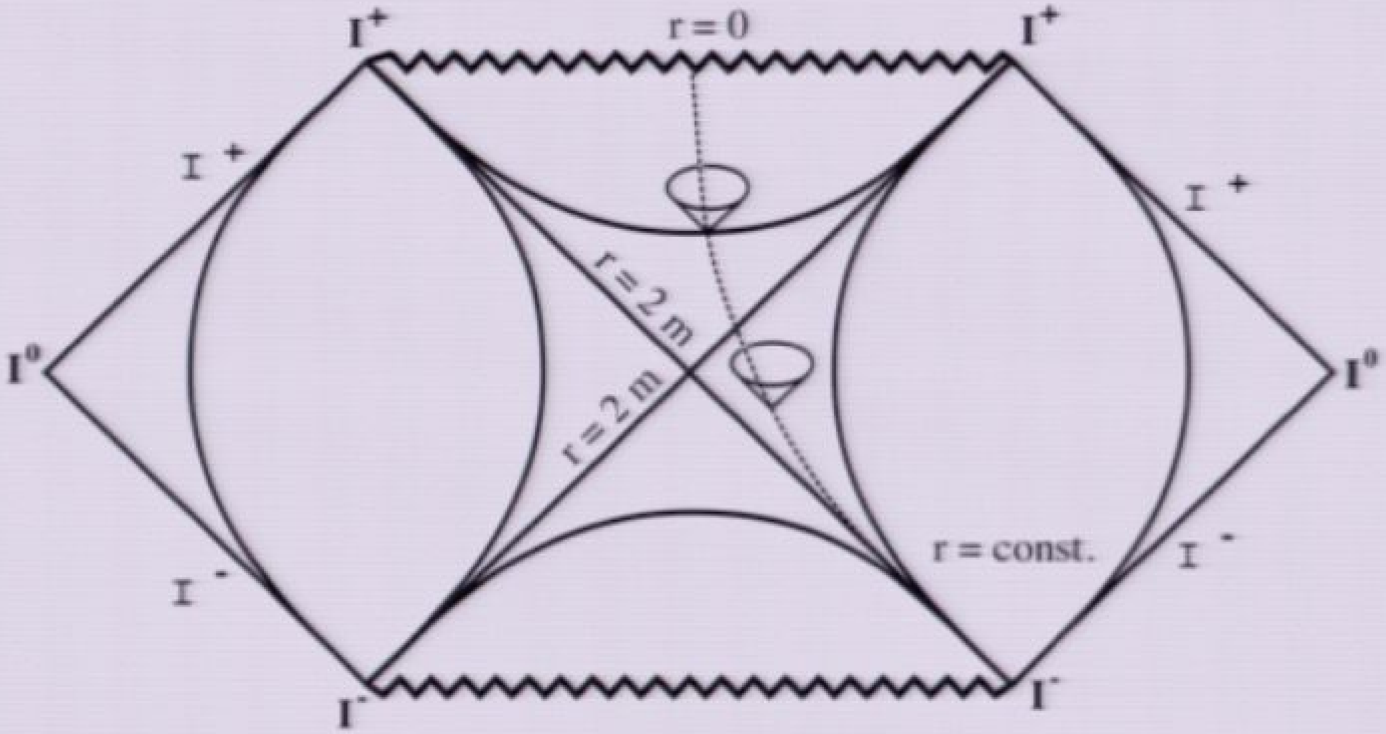
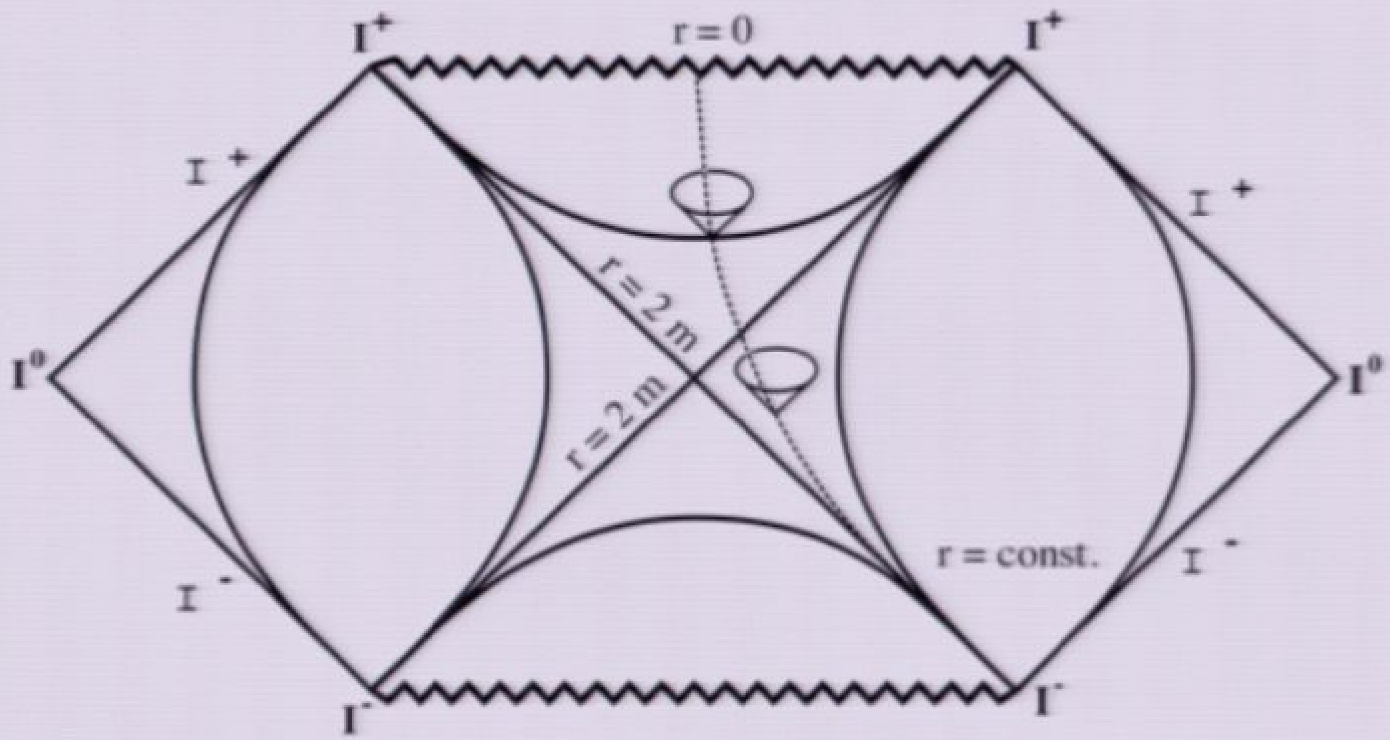
- What is happening?

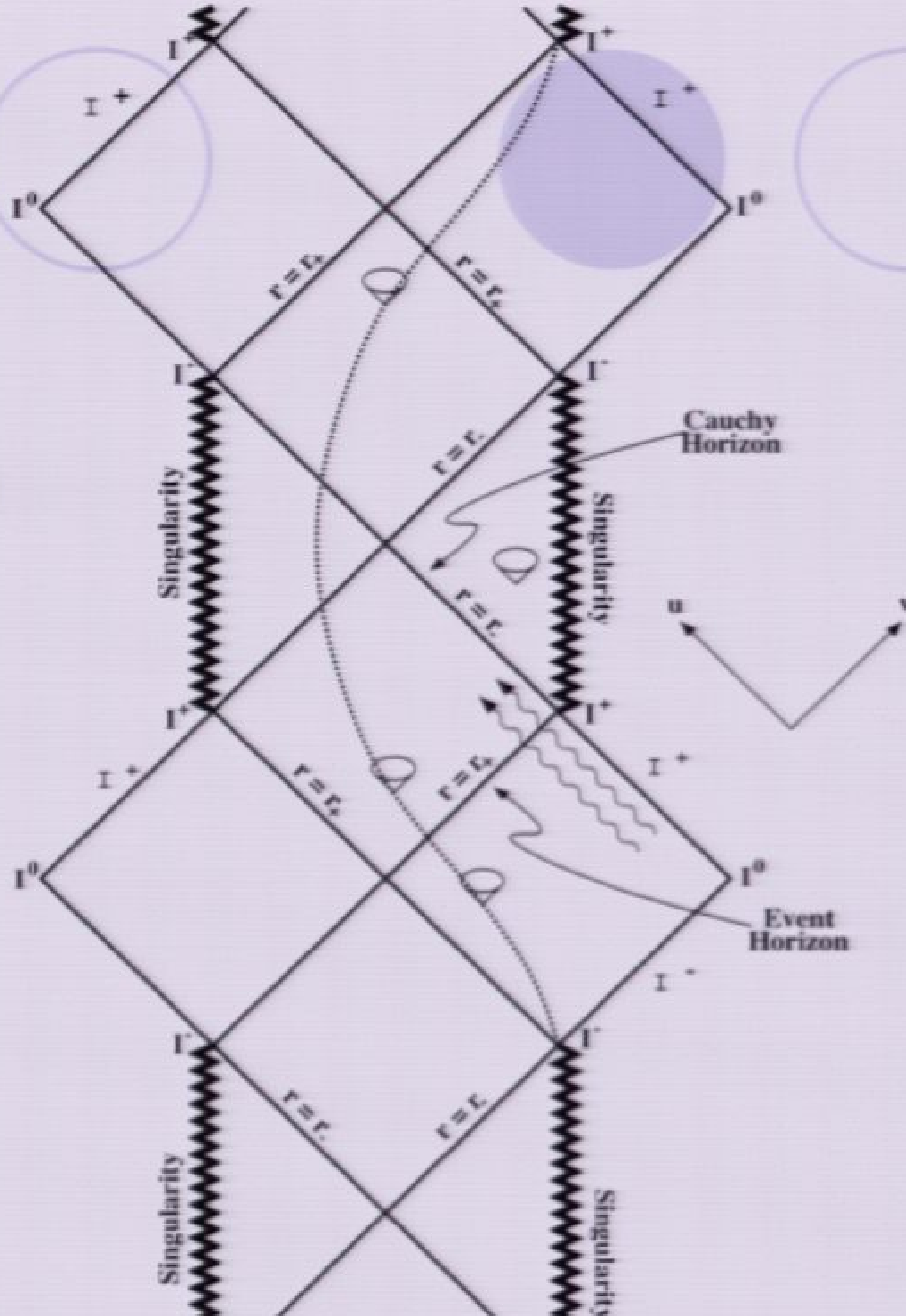


I⁺
r = 0
I⁺
I ⁺
I ⁺
r = 2 m
I⁰
I⁰
r = 2 m
r = const.
I ⁻
I ⁻
I⁻
I⁻

Schwarzschild static BH



electric charge!



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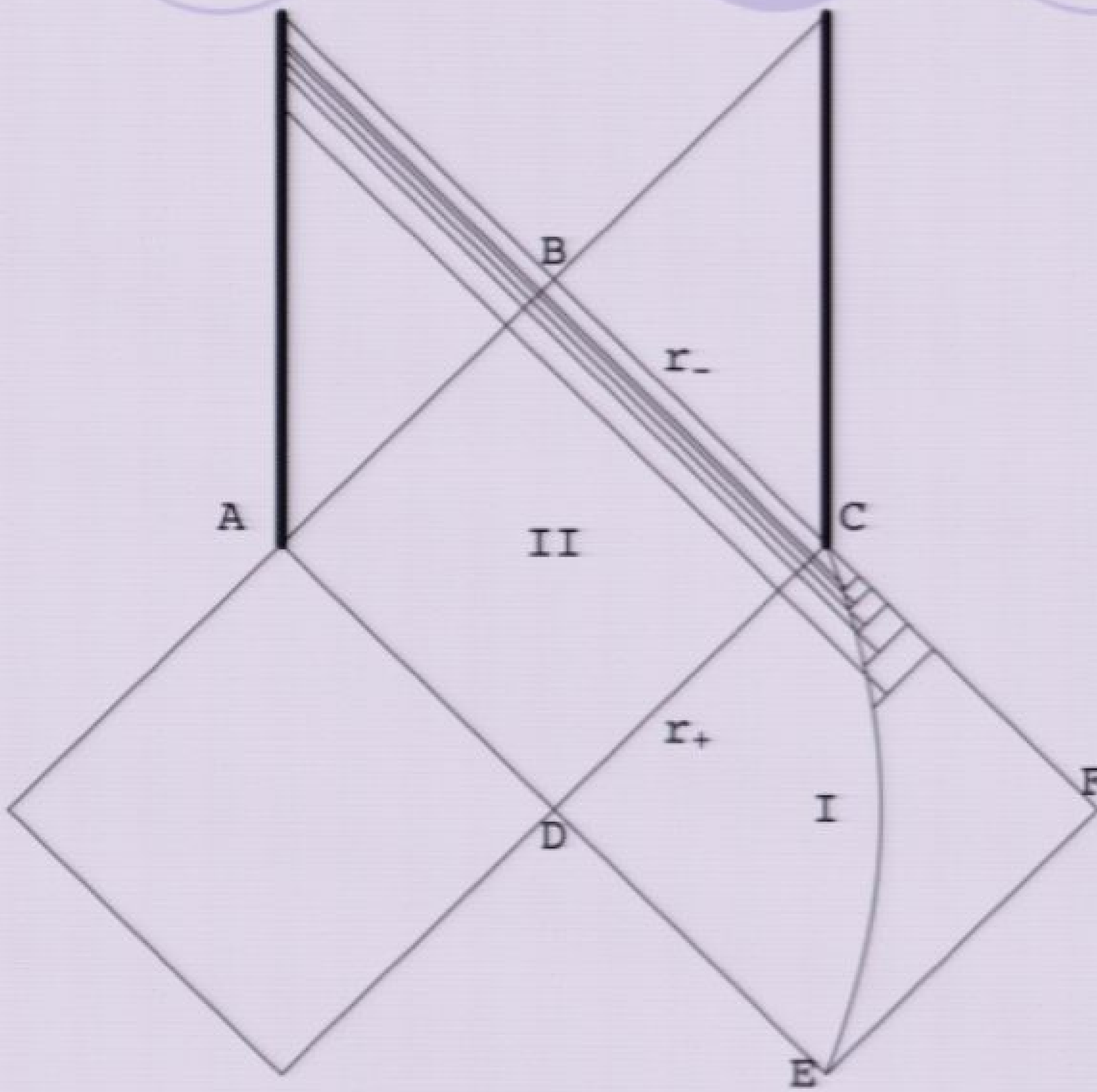
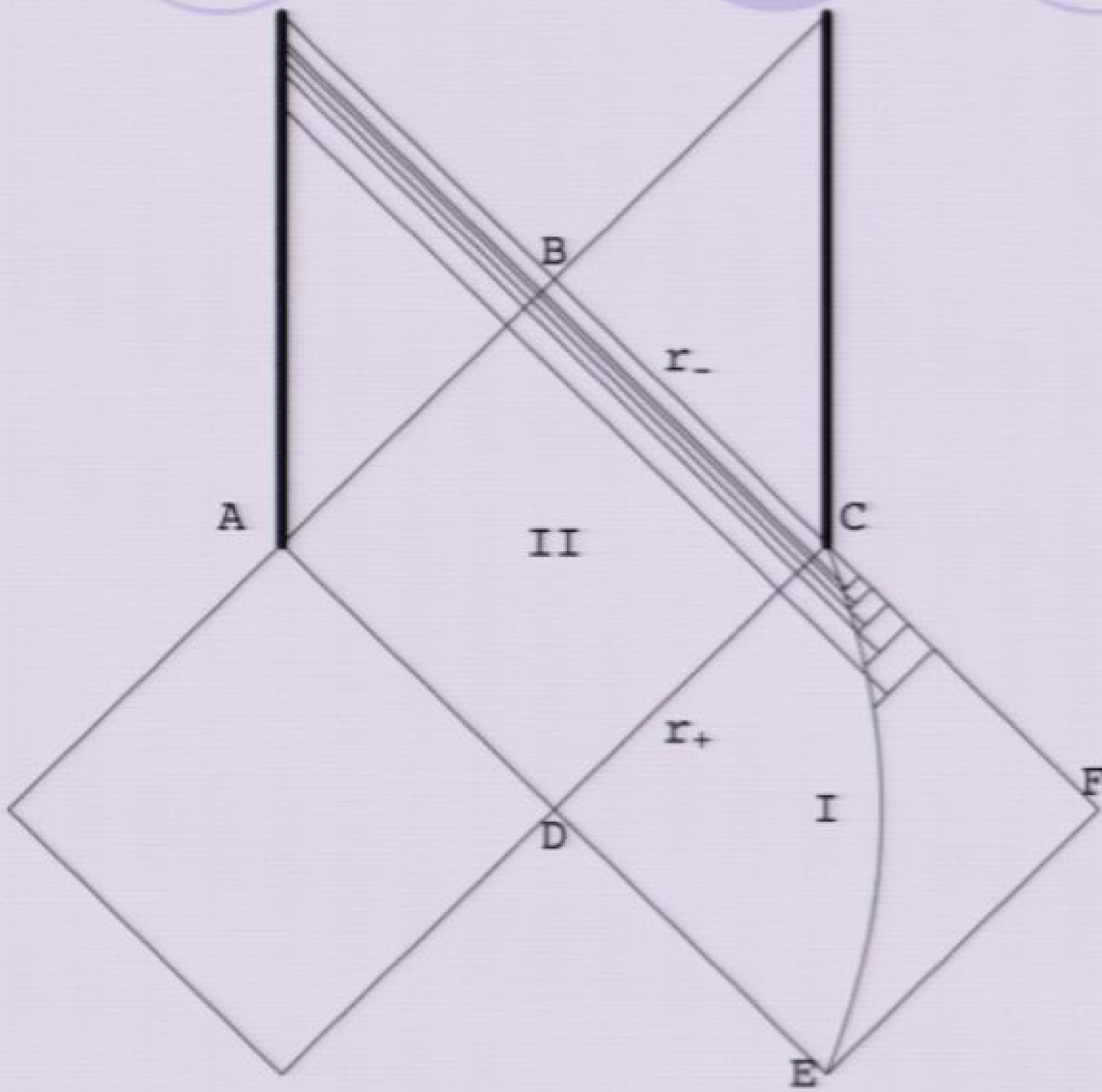


A Cauchy Horizon appears



Consider a geodesic of an observer which is crossing the CH

$$\dot{r}^2 = E^2 - f(r), \quad \dot{v} = [E - (E^2 - f(r))]^{1/2}/f(r)$$

$$\dot{r} \simeq -|E|, \quad \dot{v} \simeq -2|E|/f(r), \quad dr/dv \simeq \frac{1}{2}f(r)$$

Thus

$$\dot{v} \simeq |E|e^{\kappa v}$$

Measured energy due to infalling radiation

$$\rho = T_{\alpha\beta}u^{\alpha}u^{\beta} = T_{vv}\dot{v}^2 = \frac{|E|^2}{4\pi r^2}L(v)e^{2\kappa v}$$

as $v \rightarrow \infty$

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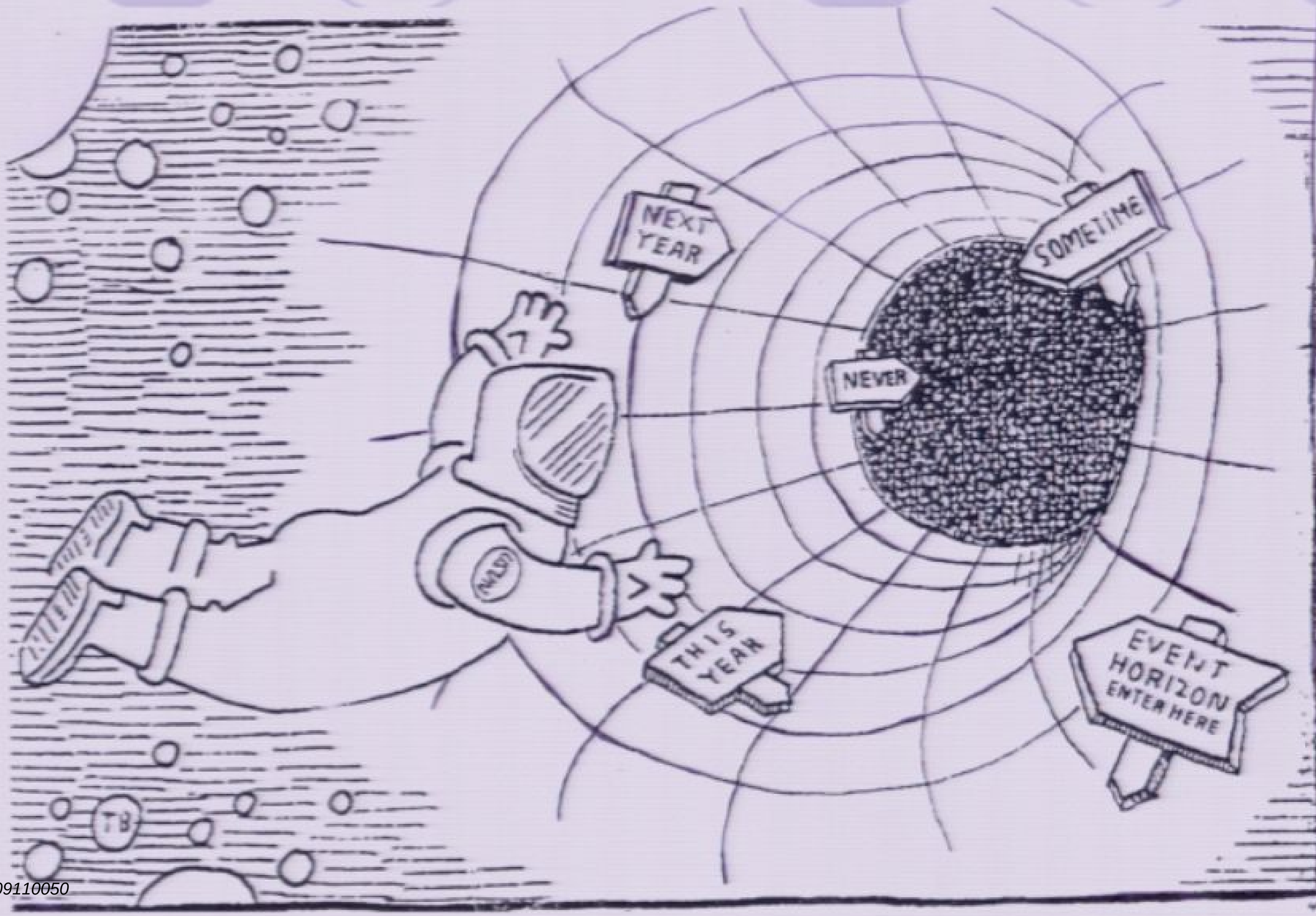
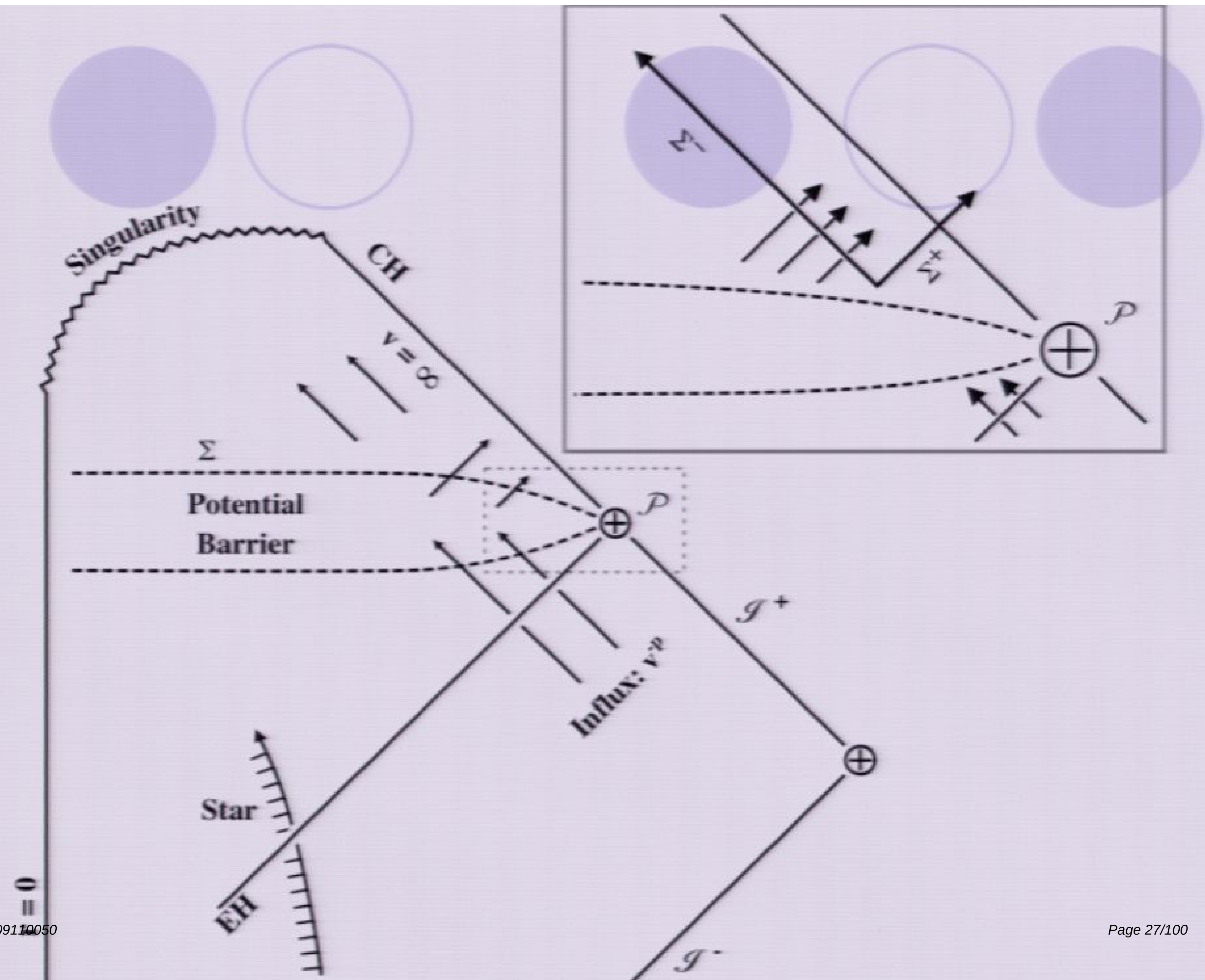
- Very difficult problem due to its non-linear nature!

A journey into a BH




Singularity
CH
v = ∞
Σ
Potential
Barrier
𝒫
𝒥⁺
Influx: v^p
Star
EH
𝒥⁻
Σ⁻
Σ⁺
𝒫

Old and new work

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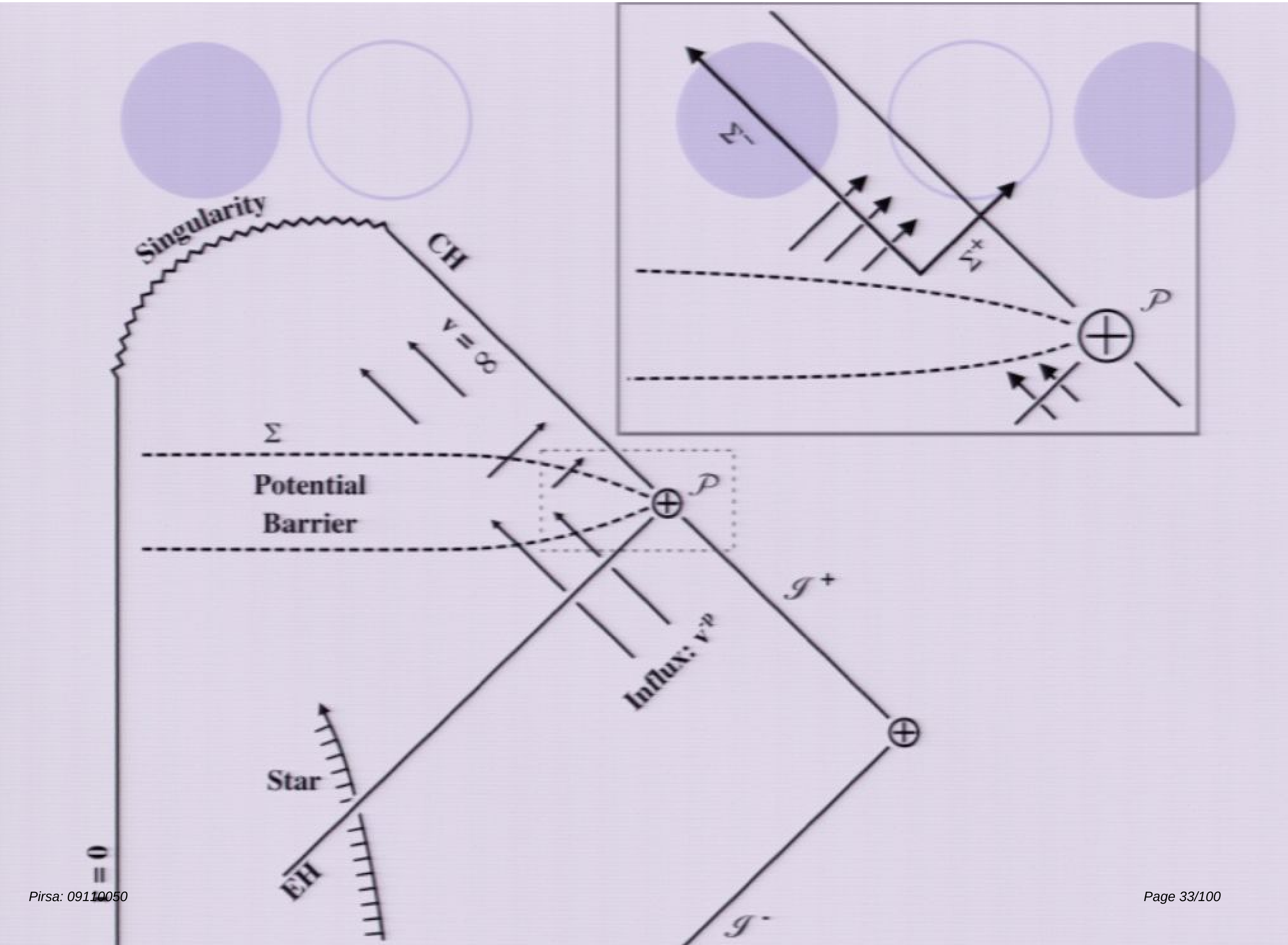

Singularity
CH
$v = \infty$
Σ
Potential
Barrier
$\mathcal{P}$
$\mathscr{I}^+$
Influx: v^{-p}
Star
EH
$\mathscr{I}^-$
Σ^-
Σ^+
$\mathcal{P}$

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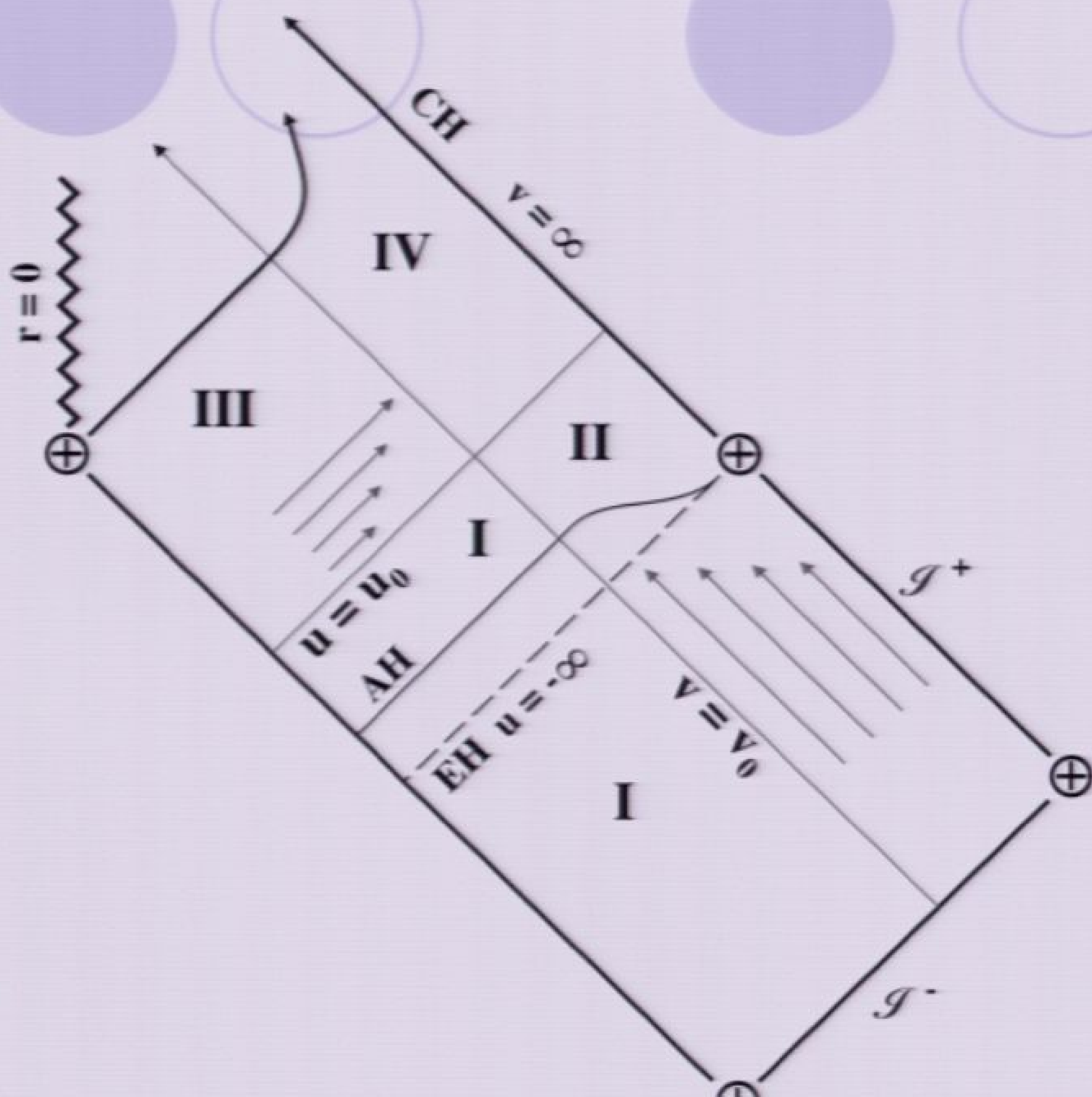
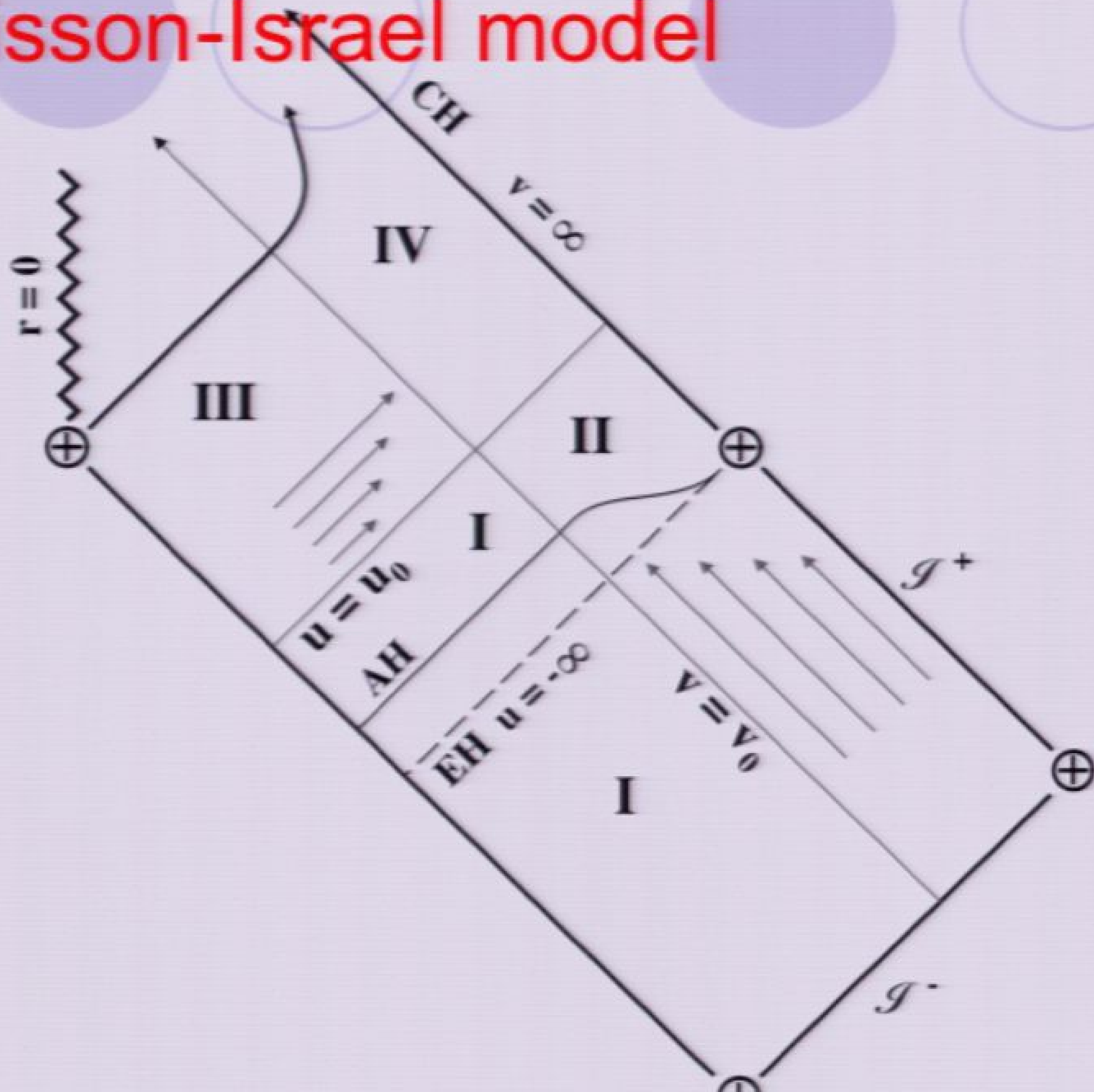
- … Renewed interest in this problem


CH
v = ∞
IV
r = 0
III
II
I
u = u₀
AH
u = -∞
EH
v = v₀
I
𝒥⁺
𝒥⁻

Poisson-Israel model



In the original mass inflation analysis by Poisson-Israel, a null crossflow stress tensor was used to model the gravitational radiation. The stress tensor for null crossflowing radiation can be written as

$$T_{\alpha\beta} = \frac{L_{in}(V)}{4\pi r^2}\partial_\alpha V \partial_\beta V + \frac{L_{out}(U)}{4\pi r^2}\partial_\alpha U \partial_\beta U \quad (1)$$

which satisfies the conservation equations and has $P = T = 0$. The conservation equations force L_{in} (L_{out}) to be a function only of V (U).

In the Kruskal coordinate V, the Price power-law tail has the form

$$L_{in}(V) = \frac{dm_{in}}{dv}(\frac{dv}{dV})^2 = \frac{\beta}{(-\kappa_- V)^2}(-\ln(-\kappa_- V))^{-p}.$$

As the Cauchy horizon is approached, in the limit $V \to 0_-$, L_{in} diverges and the source term in the wave equation for m diverges as well.

The integral solution for the mass function is

$$m(U,V) = \int_{U_1}^{U}\int_{V_1}^{V} r'^{-1}e^{-\lambda'}L_{in}(V')L_{out}(U')dU'dV' + m_{in}(V) + m_{out}(U) - m_1$$

The gravitational wave tail influx is turned on at advanced time V_1 and the outflux is assumed to be switched on at the advanced time U_1, which is behind the event horizon The divergence of $L_{in}(V')dV'$ leads to mass inflation with the mass function behaving as

$$m \sim \frac{1}{(-V)ln(-V)^p}, \;\; V \to 0_-$$

thus $R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta} \sim m^2 \to \infty$

A strong (curvature) singularity develops at Cauchy Horizon!

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A strong (curvature) singularity develops at Cauchy Horizon!

- Spacetime just “ends” there!
- QG effects “cure” the singularity
- Spacetime can still be classically extended as we do in fluid mechanics when shock develops

Quantum Effect and recent works

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- First attempt: semiclassical approach (Anderson, et al PRL 1993)

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- Can the Asymptotic safety scenario halt the Mass -Inflation?
- Encode the running of G into the Einstein Equations

RG improvement of dynamical eqs:

Le Chatelier-Braun Principle (1884, 1888): "Every physical system in stable equilibrium under the influence of an external force (a change in an environmental property A) which tends to alter an intensive characteristic B of the system (temperature, pressure, concentration, number density of molecules, etc.) every where or just in some parts. Can only experience interior changes--the secondary effect---in some other parameter of state C of the system, usually extensive (entropy, volume, number of particles of a specific kind, etc.) producing a current (or flow) that causes a feedback effect B of opposite sign to that resulting from the exterior force.

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- Insert this trajectory into the FE

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- Only valid near the CH below the inner potential barrier

We need a RG trajectory near the NGFP

- Insert this trajectory into the FE
- Only valid near the CH below the inner potential barrier
- Compute the new mass function

Proper-time flow equation for gravity

A.B. & M.Reuter, JHEP, 2005

$$\partial_t \hat{S}_k[g,\bar{g}] = -\frac{1}{2}\mathrm{Tr}\int_0^\infty \frac{ds}{s}\,\partial_t f_k^m(s)\left[\exp(-s\hat{S}_k^{(2)}) - 2\exp(-sS_{\mathrm{gh}}^{(2)})\right]$$

$$f_k^m(s) = \frac{\Gamma(m+1, Zsk^2) - \Gamma(m+1, Zs\Lambda^2)}{\Gamma(m+1)}$$

This is not “exact” at the level of the general functional equation, but local truncations work VERY well!

m	η	m	η
1	0.0653	11	0.0365
2	0.0507	12	0.0362
3	0.0452	13	0.0360
4	0.0423	14	0.0358
5	0.0405	15	0.0356
6	0.0393	16	0.0354
7	0.0385	17	0.0353
8	0.0378	20	0.0350
9	0.0373	30	0.0343
10	0.0369	40	0.0340

The anomalous dimension η at the Wilson-Fisher fixed point. Note: R. Guida and J. Zinn-Justin, (1998) find $\eta = 0.0335$ from seven loop pt in $D = 3$

A.B. & D.Zappala', (2001), Phys.Lett.B.

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$$\partial_t g = \beta_g(g,\lambda) \equiv [d-2+\eta_N]g \quad \text{(1a)}$$

$$\partial_t \lambda = \beta_\lambda(g,\lambda) \quad \text{(1b)}$$

The anomalous dimension $\eta_N \equiv -\partial_t \ln Z_{Nk}$ is given by

$$\eta_N = 8(4\pi)^{1-\frac{d}{2}}\Big[\frac{d(7-5d)}{24}(1-2\lambda)^{\frac{d}{2}-m-2} - \frac{d+6}{6}\Big] g \frac{\Gamma(m+2-\frac{d}{2})}{\Gamma(m+1)}$$

and the beta-function of λ reads

$$\beta_\lambda = -(2-\eta_N)\lambda + 4(4\pi)^{1-\frac{d}{2}}\Big[\frac{d(d+1)}{4}(1-2\lambda)^{\frac{d}{2}-m-1} - d\Big] g \frac{\Gamma(m+1-\frac{d}{2})}{\Gamma(m+1)}$$

Beta-functions

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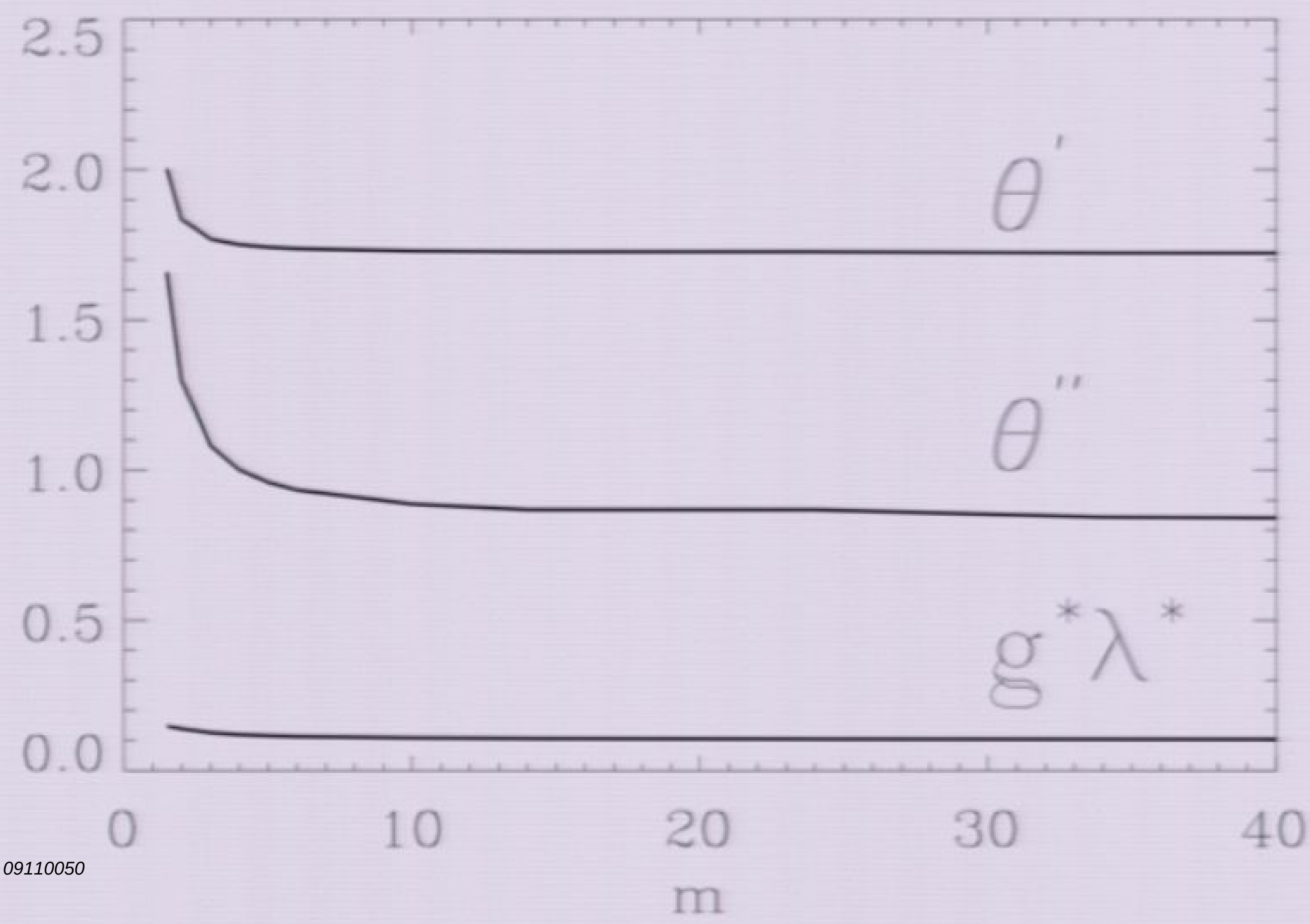
Critical exponents

m	g_*	λ_*	$\lambda_* g_*$	θ'	θ''
3/2	0.763	0.192	0.147	2.000	1.658
2	1.663	0.118	0.138	1.834	1.230
3	1.890	0.066	0.125	1.769	1.081
4	2.589	0.046	0.119	1.750	1.001
5	3.281	0.035	0.115	1.742	0.959
6	3.970	0.028	0.113	1.737	0.934
10	6.718	0.016	0.108	1.729	0.886
40	27.271	0.0038	0.103	1.722	0.840



2.5
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
m
θ'
θ''
$g^*\lambda^*$

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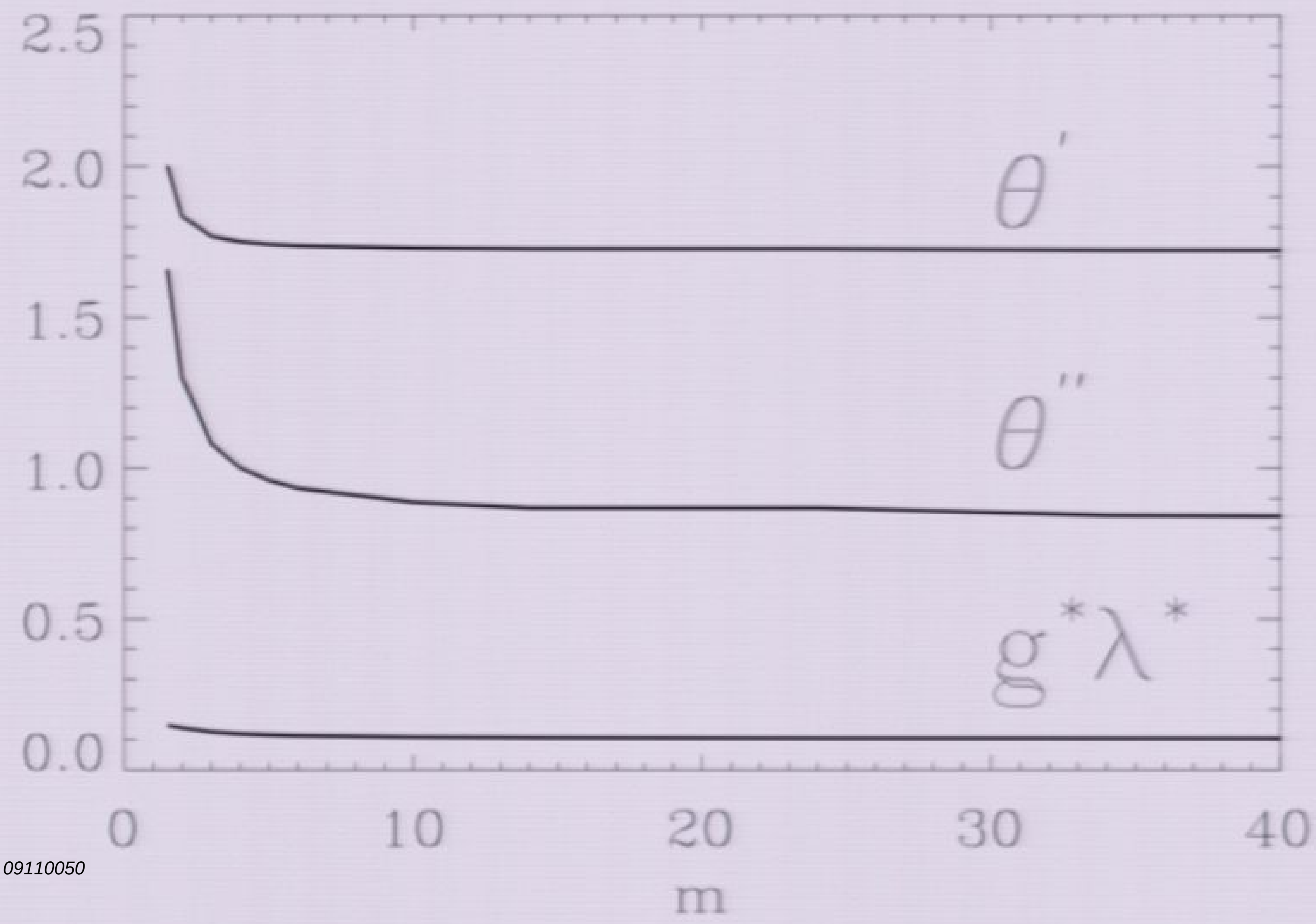

Explicit solution for g-running

$$\eta = -\frac{4}{3} 2^{-d} \pi^{1-\frac{d}{2}} (-3d + 5d^2 + 24)$$

$$g(t) = -\frac{d-2}{\eta - (d-2)\, C_0\, e^{-(d-2)t}}$$

Assume cutoff-id:

$$k^2 = |\Psi_2|$$

Coulombian component of the Weyl curvature!

oved FE

Use coordinates x^a $(a, b = 0, 1)$ on the radial two-spaces (θ, ϕ) = *const* and the function $r(x^a)$ that measures the area of those two-spheres whose line element is $r^2 d\Omega^2$. The metric element is then

$$ds^2 = g_{ab} dx^a dx^b + r^2 d\Omega^2$$

By defining the scalar fields $f(x^a), m(x^a)$ and

$$-2\kappa(x^a) = \frac{\partial f}{\partial r}, \quad f = 1 - \frac{2M}{r} + \frac{e^2}{r^2}$$

RG improved FE

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The RG improved FE become

$$r_{;ab} + \kappa g_{ab} = -4\pi G_k r(T_{ab} - g_{ab}T)$$

$$R - 2\partial_r \kappa = 8\pi G_k (T - 2P)$$

where the static electro-magnetic field is generated by a charge of strength e and T_{ab} is the stress-energy tensor of the matter field whose two-dimensional trace is T and tangential pressure is P.

Dynamical equation for M

Vave-equation for the mass function

$$\Box M = -16\pi^2 r^3 G_k^2 T_{ab} T^{ab} + 8\pi G_k f(P - T)$$
$$+4\pi r^2 G_k \kappa T - 4\pi r^2 G_k r_{,a} T^{,a}$$

vhere

$$G_k = \frac{G_N}{1 + cM(U,V)}$$

Asymptotic solution valid near CH

QG correction

$$M \sim \frac{1}{(-V)^{1/3}\ln(-V)^p}$$

Classical behavior

$$M \sim \frac{1}{(-V)\ln(-V)^p}$$

As a consequence :

$$R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta} \sim M^2 \qquad (1)$$

is now integrable along V !

Strength of the CH singularity

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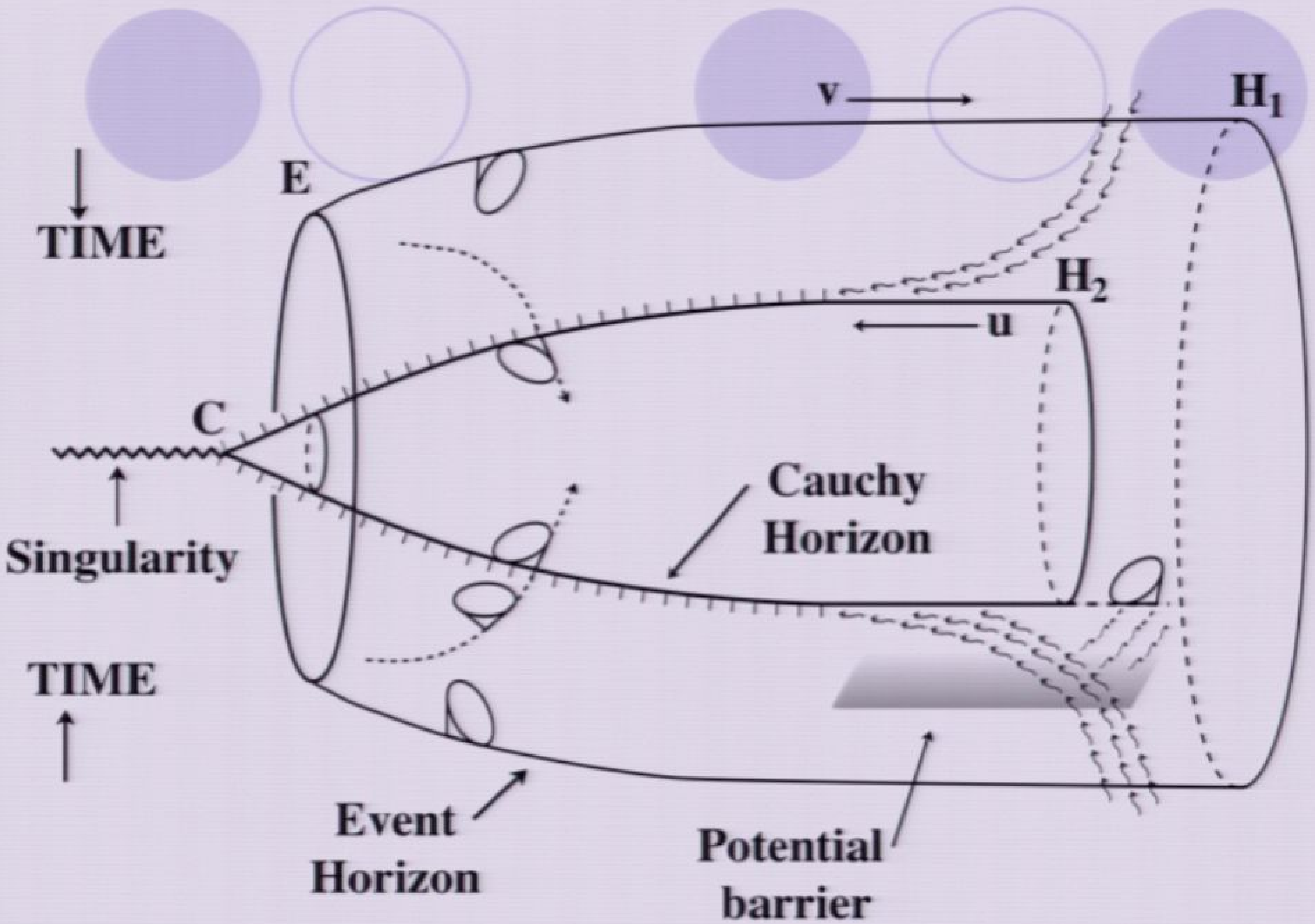
Strength of the CH singularity

- The tidal acceleration diverges at CH
- But the tidal acceleration integrated along the infalling geodesic does not diverge at CH
- This is in sharp contrast with the original PI model where only the physical distortion of the infalling body would be finite at CH
- Do we predict a C1 (unique) continuation of the classical spacetime along the CH?



TIME
v
H1
E
H2
u
C
Singularity
Cauchy Horizon
TIME
Event Horizon
Potential barrier

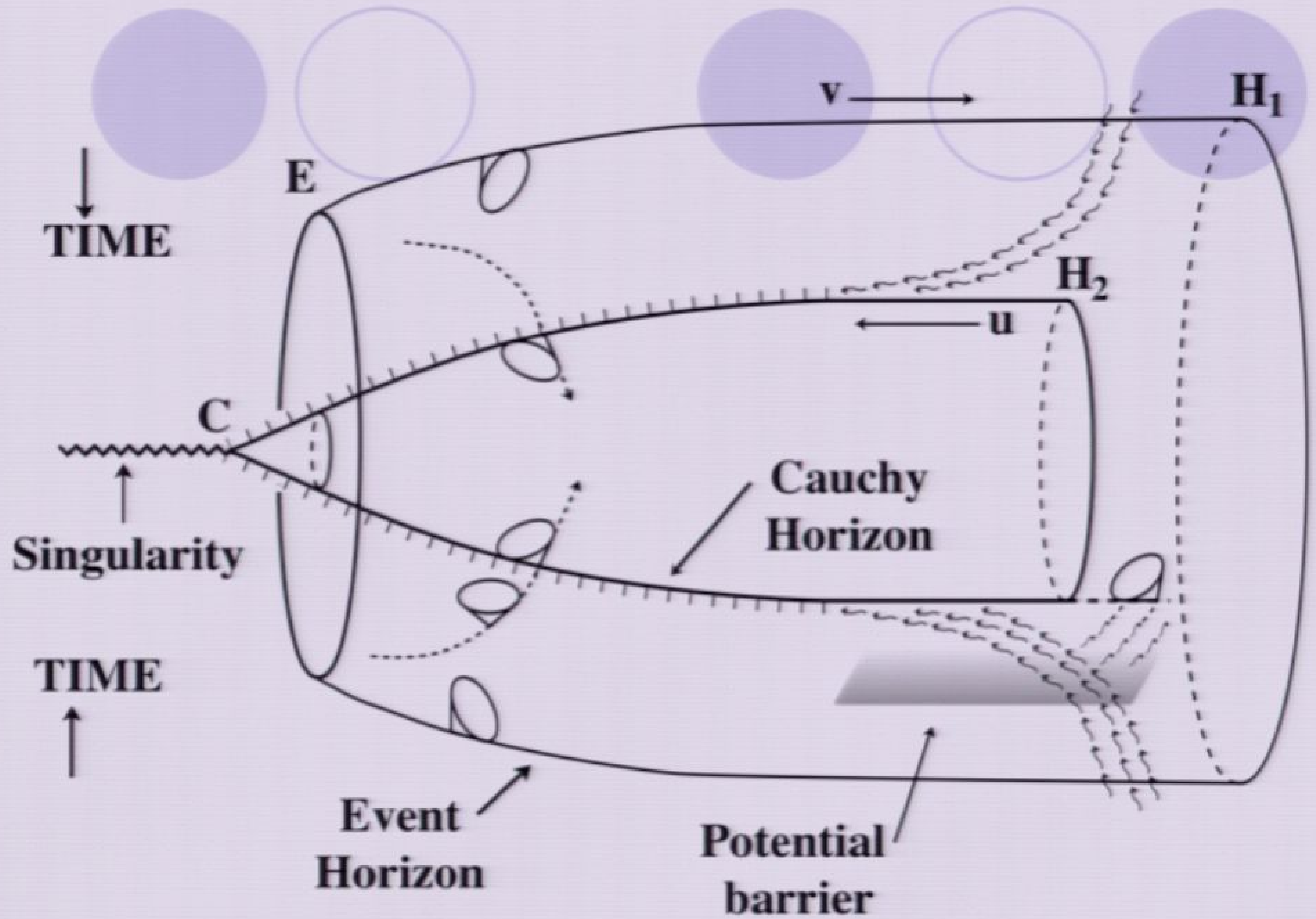
In terms of lightlike coordinates U, V the minimally-coupled wave equation is

$$r\varphi_{UV} + r_U\varphi_V + r_V\varphi_U = 0$$

for a spherisymmetric massless field $\varphi(U, V)$.

The Einstein equations now appear as

$$\begin{aligned} m_U &= -4\pi r^2 e^{-2\sigma}\varphi_U^2 r_V, \\ r_{UU} &- 2\sigma_U r_U = -4\pi r\varphi_U^2, \\ (r^2)_{UV} &= -e^{2\sigma}\left(1 - e^2/r^2\right), \\ \sigma_{UV} &= (e^{2\sigma}/r^3)(m - e^2/r) - 4\pi\,\varphi_U\,\varphi_V \end{aligned}$$


v
H$_1$
E
TIME
H$_2$
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Cauchy
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Singularity
TIME
Event
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barrier

Minimally coupled field

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for a spherisymmetric massless field $\varphi(U, V)$.

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$$\begin{aligned} m_U &= -4\pi r^2 e^{-2\sigma}\varphi_U^2 r_V, \\ r_{UU} &- 2\sigma_U r_U = -4\pi r\varphi_U^2, \\ (r^2)_{UV} &= -e^{2\sigma}\left(1 - e^2/r^2\right), \\ \sigma_{UV} &= (e^{2\sigma}/r^3)(m - e^2/r) - 4\pi\,\varphi_U\,\varphi_V \end{aligned}$$

Define functions $a(U), b(V)$ by setting their derivatives $\dot{a}, \dot{b}$ equal respectively to $\varphi_U\mid_b$, $\varphi_V\mid_b$, the values on the underside of the inner potential barrier. Define further functions $A(U), B(V)$ by $\ddot{A} = 4\pi r_0^2 \dot{a}^2, \ddot{B} = 4\pi r_0^2 \dot{b}^2$, with the boundary conditions $A(-\infty) = B(0) = 0$. Then

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\begin{aligned}
\varphi &= a(U) + b(V) \\
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r^2 &= r_s^2(U,V) - 2A(U) - 2B(V), \\
\sigma &= \sigma_s(U,V) + r_0^{-4} A(U)B(V), \\
m &= m_0 + (\kappa_0^2/r_0)\dot{A}(U)\dot{B}(V)
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Subscript s refers to the static RN solution (mass m_0, inner-horizon radius r_0) which forms the final exterior state. The general conditions for the validity of the approximation,

$$\dot{A}^2 \ll \ddot{A}, \quad \dot{B}^2 \ll \ddot{B},$$

are satisfied in the situation of interest to us:

$$\begin{array}{l} A \sim [\ln(-U)]^{-(p-1)}, \\ B \sim \mid -\ln(-V) \mid^{-(p-1)} \end{array} \; (U \to -\infty,\; V \to -0).$$

These expressions confirm that the metric components $e^{2\sigma}$, r^2 (though not their derivatives) are regular and approach the RN values toward the past end of CH.

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