Black hole as a supercollider

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Plan of talk

Energy in the centre of mass frame and its growth

From particular metrics to generic rotating and charged black holes

Strong and weak versions of effect

Kinematic explanation

Geometric explanation

Collisions near inner horizon, role of bifurcation point

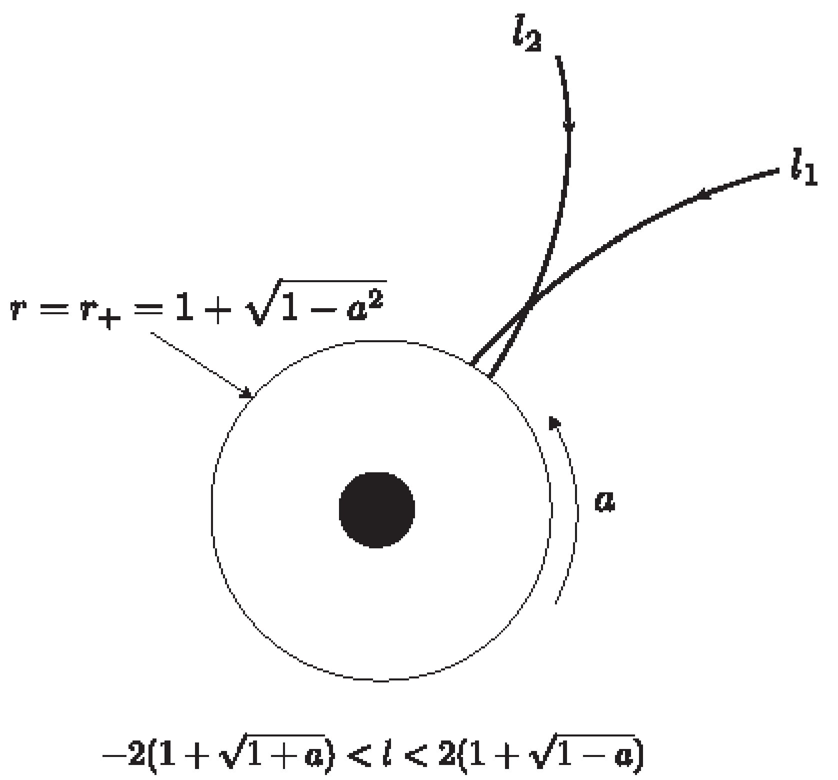


FIG. 1. Schematic picture of two particles falling into a black hole with angular momentum a (per unit black hole mass) and colliding near the horizon. The allowed range of l for geodesics falling into the black hole is also given.

Banados, Silk, West

Energy in centre of mass frame

$$(E_{\mathrm{c.m.}}, 0, 0, 0) = mu^i_{(1)} + mu^i_{(2)},$$

$$u^i u_i = 1$$

$$E_{\mathrm{c.m.}} = m\sqrt{2}\sqrt{1 + u^i_{(1)}u_{(2)i}}$$

$$E^2_{cm} = \left|P_m P^m\right|$$

Total momentum $P_m = p^{(1)}{}_m + p^{(2)}{}_m$

Schwarzschild metric (a=0)

Schwarzschild

$$E_{cm} = 2m\sqrt{5}$$

Baushev 2008

No effect

Kerr (rotation)

Reissner-Nordstrom (charge)

Kerr metric

Kerr

$$(E_{\rm c.m.}^{\rm Kerr})^2 = \frac{2m_0^2}{r(r^2 - 2r + a^2)}[2a^2(1 + r) - 2a(l_2 + l_1) - l_2 l_1(-2 + r) + 2(-1 + r)r^2 - \sqrt{2(a - l_2)^2 - l_2^2 r + 2r^2}\sqrt{2(a - l_1)^2 - l_1^2 r + 2r^2}].$$

On horizon both numerator and denominator=0

Extremal case: a=1

$$E_{\rm c.m.}^{\rm Kerr}(r \to r_+) = \sqrt{2}m_0\sqrt{\frac{l_2 - 2}{l_1 - 2} + \frac{l_1 - 2}{l_2 - 2}},$$

critical value $l = 2$

BSW: extremal Kerr
Grib and Pavlov: also nonextremal

O. Z.: generic rotating, charged (even for radial motion)

BSW effect (2009): both particles move towards horizon, needs fine-tuning between energy and momentum

T. Piran and J. Shanam, PRD 1977

1 particle moves away from horizon, no fine-tuning required

Extremal versus nonextremal

Problems with attaining extremality, a=0,998 (Thorne)

Jacobson et al, Berti at al: difficulties in realization

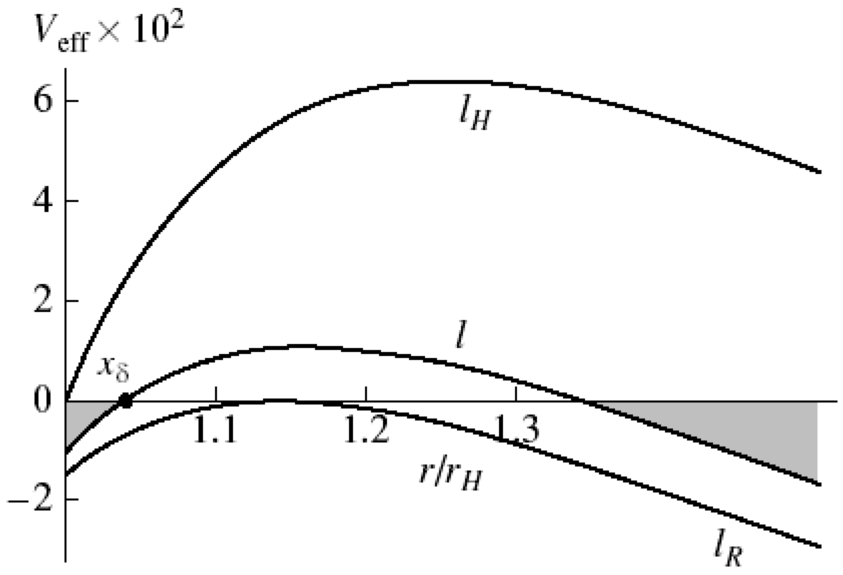
Grib and Pavlov: nonextremal Kerr

Extremal case: collision near horizon   proper time diverges

10^3 larger than that of the LHC one must wait only $\approx 10^8$ s.

$$E_{\text{c.m.}} \approx \frac{m}{\sqrt{\delta}} \sqrt{\frac{2(l_H - l_2)}{1 - \sqrt{1 - A^2}}}$$

$$l_1 = l_H - \delta,$$



The effective potential for $A = 0.95$ and $l_R \approx 2.45$, $l = 2.5$, $l_H \approx 2.76$. Allowed zones for $l = 2.5$ are shown by the gray color.

Multiple scattering (Grib and Pavlov)

$$-2\left(1+\sqrt{1+A}\right) = l_L \leq l \leq l_R$$
$$= 2\left(1+\sqrt{1-A}\right).$$

$$l_H - l_R = 2\frac{\sqrt{1-A}}{A}\left(\sqrt{1-A}+\sqrt{1+A}-A\right)$$
$$\approx 2(\sqrt{2}-1)\sqrt{\epsilon}, \quad \epsilon \to 0. \quad ($$

$$A = 1 - e$$

Acceleration of particles as universal property of rotating black holes

O. Z., PRD 2010

Role of horizon

Universality of black hole physics

Unified approach to nonextremal versus extremal black holes

$$ds^2 = -N^2 dt^2 + g_{\phi\phi}(d\phi - \omega dt)^2 + dl^2 + g_{zz} dz^2.$$

equatorial plane $\theta = \frac{\pi}{2}$ $(z = 0)$ is a symmetry one.

$u_0 \equiv -E$ $u_\phi \equiv L$ conserved quantities

Integrals of geodesic equations

$$g_{mn} u^m u^n = -1$$

$$\dot{t} = u^0 = \frac{E - \omega L}{N^2}$$

$$\dot{\phi} = \frac{L}{g_{\phi\phi}} + \frac{(-\omega^2 L + E\omega)}{N^2}$$

$$\dot{l}^2 = \frac{(E - \omega L)^2}{N^2} - \delta - \frac{L^2}{g_{\phi\phi}}.$$

$\delta = 1$ for timelike

$$E_{CM} = \sqrt{2} m_0 \sqrt{1 - g_{\mu\nu} U^{\mu}_{(1)} U^{\nu}_{(2)}}$$

$$\frac{E_{cm}^2}{2m^2} = c + 1 - Y, \; c = \frac{X}{N^2}$$

$$X = X_1 X_2 - Z_1 Z_2,$$

$$X_i \equiv E_i - \omega L_i,$$

$$Z_i = \sqrt{(E_i - \omega L_i)^2 - N^2 b_i}, \; b_i = 1 + \frac{L_i^2}{g_{\phi\phi}},$$

$$Y = \frac{L_1 L_2}{g_{\phi\phi}}.$$

Different limiting transitions

1) Let, for generic L_i, one approaches the horizon, so $N \to 0$.

$$\left(\frac{E_{cm}^2}{2m^2}\right)_H = 1 + \frac{b_{1(H)}(L_{2(H)} - L_2)}{2(L_{1H} - L_1)} + \frac{b_{2(H)}(L_{(1)H} - L_1)}{2(L_{2(H)} - L_2)} - \frac{L_1 L_2}{(g_{\phi\phi})_H}, \; L_{i(H)} \equiv \frac{E_i}{\omega_H}$$

$$L_1 = L_{1(H)}(1-\varepsilon), \; \varepsilon \ll 1, \; L_2 \neq L_{2(H)}$$

$$\left(\frac{E_{cm}^2}{2m^2}\right)_H \approx \frac{b_{1(H)}(L_{2(H)} - L_2)}{2L_{1(H)}\varepsilon}.$$

$$\lim_{L_1 \to L_{1(H)}} \lim_{N \to 0} E_{cm} = \infty.$$

2) Let us take $L_1 \to L_{1(H)}$ first and, then, consider the limit $N \to 0$.

2a) Nonextremal case

It follows from the finiteness of the geometrical scalars

$R \qquad R_{mn} R^{mn}$

$$\omega = \omega_H + BN^2 + ...$$

One cannot reach horizon. Of no interest

2b)

$$\omega = \omega_H - B_1 N + B_2 N^2 + ...$$

Kerr: $B_1 = M^{-1}$

$$\frac{E_{cm}^2}{2m^2} \approx \frac{(E_2 - \omega_H L_2)}{N}[B_1 \frac{E_1}{\omega_H} - \sqrt{(\frac{E_1^2}{\omega_H^2} B_1^2 - b_1)}].$$

$$\lim_{N \to 0} \lim_{L_1 \to L_{1(H)}} E_{cm} = \infty.$$

$L = L_{(H)}$

Proper time to approach horizon:

$$\tau \sim \int \frac{dlN}{Z} \sim l \to \infty$$

$$\Delta\phi \approx \frac{EB_1}{\sqrt{(\frac{E^2}{\omega_H^2} B_1^2 - b_1)}} \int \frac{dl}{N}$$

$$N \approx N_0 \exp(-Al)$$

$$\Delta\phi \to \infty.$$

limits $\varepsilon \to 0$ and $N \to 0$.

3) Small but nonzero ε and N

$Z^2 \geq 0$

$$0 \leq N \leq \frac{E\varepsilon}{\sqrt{b_H}}.$$

4) $L_1 = L_{1(H)}, L_2 = L_{2(H)}$.

Either horizon (nonextremal) is unreachable or E is finite (extremal).

Agreement with results for Kerr metric

$$g_{00}=-(1-\frac{2M}{r}),\ g_{0\phi}=-\frac{2Ma}{r},\ g_{\phi\phi}=r^2+a^2+\frac{2Ma^2}{r},\ \omega=-\frac{g_{0\phi}}{g_{\phi\phi}}.$$

$$N^2=\frac{(r-r_H)(r-r_C)}{r^2+a^2+\frac{2M}{r}a^2},$$

where r is the Boyer-Lindquist coordinate, $r_H=M+\sqrt{M^2-a^2}$, $r_C=M-\sqrt{M^2-a^2}$

horizon value $\omega_H=\frac{a}{2Mr_H}$

$$\left(\frac{E_{cm}}{2m}\right)_H=\sqrt{1+\frac{M(l_1-l_2)^2}{2r_C(l_1-l_H)(l_2-l_H)}}$$

$$0 \leq r - r_H \leq \frac{a^2\varepsilon^2}{r_H\sqrt{1 - \frac{a^2}{M^2}}}$$

$$l_{(H)} = \frac{2r_H}{a}$$

$$l = \frac{L}{M}$$

$$\frac{E_{cm}^2}{2m^2} \approx \frac{(2 - l_2)}{2N}(2 - \sqrt{2}).$$

$$l_H = 2$$

$$\Delta\phi \approx \frac{M\sqrt{2}}{r-M} \rightarrow \infty$$

Acceleration of particles by nonrotating charged black holes

O. Z. JETP Letters 2010

Role of rotation $L_1 = \frac{E_1}{\omega_H}$ If $\omega_H \to 0$, $L_1 \to \infty$,

Angular momentum versus charge

Reissner-Nordström

Pure radial motion

not only $\omega_H = 0$ but also $L_1 = L_2 = 0$ for both colliding particles

particles charged, nongeodesic motion

$$ds^2 = -dt^2 f + \frac{dr^2}{f} + r^2 d\omega^2$$

$$f = 1 - \frac{2M}{r} + \frac{Q^2}{r^2}$$

$$mu^0 = m\dot{t} = \frac{1}{f}(E - \frac{qQ}{r}),$$

$$m^2\dot{r}^2 = (E - \frac{qQ}{r})^2 - m^2 f.$$

$$\frac{E_{cm}^2}{2m^2} = 1 + \frac{X_1 X_2 - Z_1 Z_2}{f m^2}$$

$$X_i = E_i - \frac{q_i Q}{r},\ Z_i = \sqrt{X_i^2 - m^2 f}.$$

1) Let $f \to 0$. Then, we obtain from the (5), (6) that

$$\frac{E^2_{cm(H)}}{2m^2} = 1 + \frac{1}{2}\left[\frac{q_{2(H)} - q_2}{q_{1(H)} - q_1} + \frac{q_{1(H)} - q_{11}}{q_{2(H)} - q_{22}}\right]$$

$$q_{i(H)} \equiv \frac{E_i r_H}{Q}$$

$$r_H = M + \sqrt{M^2 - Q^2} \geq Q$$

$$q_{(H)} > E.$$

If particle comes from infinity, $E \geq m$

$$q_{(H)} > m.$$

"overcharged"

If, say, $q_1 = q_{1(H)}(1-\delta)$ with $\delta \ll 1$ and $q_2 \neq q_{2(H)}$, the energy $E_{cm(H)} \sim \frac{1}{\sqrt{\delta}}$ can be made as large as one likes. Thus, we have that

$$\lim_{q_1 \to q_{1(H)}} \lim_{r \to r_H} E_{cm} = \infty.$$

2) Let now $q_1 = q_{1(H)}$ from the very beginning, $q_2 \neq q_{2(H)}$.

Nonextremal horizon unreachable

Extremal horizon

$$\frac{E_{cm}^2}{2m^2} = 1 + \frac{X_{2(H)}}{m^2(1-\frac{r_H}{r})}[E_1 - \sqrt{(E_1^2 - m^2)}] + O((1-\frac{r_H}{r})).$$

$$\lim_{r \to r_H} \lim_{q_1 \to q_{1(H)}} E_{cm} = \infty.$$

3) $q_1 = q_{1(H)},\ q_2 = q_{2(H)}$

Effect is absent

LIMITING TRANSITIONS FOR TIME AND CONDITIONS OF COLLISION

1) E(center of mass) tends to infinity
2) Collision does occur

Particle 1 starts at t=0, r=r(initial)

Particle 2 starts at the later moment $t = t_0 > 0$ from the same point

Collision on horizon

$$t_0 = t_1 - t_2 > 0,\ t_1 = \int_{r_f}^{r_i} \frac{dr X_1}{f\sqrt{X_1^2 - m^2 f}},\ t_2 = \int_{r_f}^{r_i} \frac{dr X_2}{f\sqrt{X_2^2 - m^2 f}}.$$

Kinematic explanation

$$E^2_{\rm c.m.} = -(p_1^\mu + p_2^\mu)(p_{1\mu} + p_{2\mu}) = m_1^2 + m_2^2 - 2m_1 m_2 u_1^\mu u_{2\mu}.$$

$$\gamma = -u_1^\mu u_{2\mu} = \frac{1}{\sqrt{1-w^2}}$$

BSW effect occurs if $w \rightarrow 1$

w is relative velocity

$$w^2 = 1 - \frac{(1-v_1^2)(1-v_2^2)}{[1 - v_1 v_2(\vec{n}_1\vec{n}_2)]^2}.$$

$$\vec{v}_1 = v_1 \vec{n}_1$$

The most interesting case: $v_1 < 1,$ $v_2 \rightarrow 1$

Collision of rapid particle with target

$$ds^2 = -N^2dt^2 + g_{\phi\phi}(d\phi - \omega dt)^2 + dl^2 + g_{zz}dz^2.$$

Attached to observer

$$h_{(0)\mu} = -N(1, 0, 0, 0),$$
$$h_{(1)\mu} = (0, 1, 0, 0),$$
$$h_{(2)\mu} = \sqrt{g_{zz}}(0, 0, 0, 1),$$
$$h_{(3)\mu} = \sqrt{g_{\phi\phi}}(-\omega, 0, 0, 1).$$

$$-u_\mu h^\mu_{(0)} = \frac{E - \omega L}{N},$$
$$u_\mu h^\mu_{(3)} = \frac{L}{\sqrt{g_{\phi\phi}}}.$$

If

$$V_m = h_{m(0)}$$

then

$$V_m x^{(3)m} = 0$$

ZAMO

$$v^{(i)} = v_{(i)} = \frac{u^\mu h_{\mu(i)}}{-u^\mu h_{\mu(0)}}.$$

$$E - \omega L = \frac{N}{\sqrt{1 - v^2}},$$

Horizon limit $\quad N \to 0$

1) Usual particle, $\quad E \neq w_+ L \quad v \to 1$

2) Critical particle $\quad E = w_+ L \quad v \to v_0 < 1$

Collision between massive and massless particles (electron and photon)

$$E - wL = NE_{kin}$$

$$E_{kin} = \frac{m}{\sqrt{1 - V^2}}$$

E_{kin} Measured by local observer

E conserved

Usual: $V \to 1$ $E_{kin} \to \infty$

Critical: $V \to V_+ < 1$

E_{kin} finite

$$n_0 - wL = nN$$

n Measured by local observer

n_0 conserved

Usual: $n \to \infty$

Critical: n finite

Play of two factors: Doppler effect (DE) and gravitational blue shift (GB)

Case 1: Electron is critical, photon is usual	Finite redshift - DE . GB infinite Effect exists
Case 2: Electron is usual, photon is critical	DE infinite, GB finite Effect exists
Case 3: Both particles are critical	DE and GB finite, no effect
4. Case 4: Both particles are usual	Infinite DE compensated by infinite GB Outcome is finite, no effect

Ultimate manifestation of kinematic nature of BSW effect: target at rest

$$ds^2 = -f dt^2 + \frac{dr^2}{f} + r^2 d\Omega^2$$

$$f = 1 - \frac{2m}{r} + \frac{Q^2}{r^2} - \frac{\Lambda r^2}{3},$$

$$\varphi = \frac{Q}{r}$$

Radial motion

$$m^2 \dot{r}^2 = -V_{eff} = X^2 - m^2 f.$$

$$X = E - q\varphi.$$

d
i
a

Equilibrium

$$V_{eff}(r_0) = 0.$$

$$V'_{eff}(r_0) = 0$$

perpetual turning point

Analogue of innermost stable orbit in Kerr metric

$$V''_{eff}(r_0) = 0.$$

We are interested in points near horizon

$$-\frac{1}{2}V'_{eff}(r_0) = m\sqrt{f(r_0)}\frac{qQ}{r_0^2} - \frac{m^2}{2}f'(r_0).$$

Nonextremal: surface gravity $k = \frac{f'(r_+)}{2} \neq 0$

On the horizon $V'_{eff}(r_0) \to -m^2\kappa$

No such points

Near-extremal

$\kappa \ll Dx.$

$x = r_0 - r_+$

$x^3 \approx H^3 \kappa^2,$

$$H^3 = \frac{3r_+^3}{4(-\Lambda)(1 - 2\Lambda r_+^2)}$$

$\Lambda < 0$

Collisions with unbound energies

$$\frac{E_{c.m.}^2}{2m^2} = 1 + \frac{X_1 X_2 - Z_1 Z_2}{f m^2}$$

where

$$Z_i = \sqrt{X_i^2 - m^2 f},\ i = 1, 2.$$

$$Z_1 = 0$$

$$\frac{E^2}{2m^2} = 1 + \frac{X_2}{m\sqrt{f}}$$

$$E_{c.m.} \approx \sqrt{2mX_2} A \kappa^{-\frac{1}{3}}$$

2 particles, nonlocal picture

Role of gravity: to diminish velocity,

Acceleration due to deceleration!

KINEMATIC CENSORSHIP

1) Collision on horizon of extremal Kerr: infinite proper time

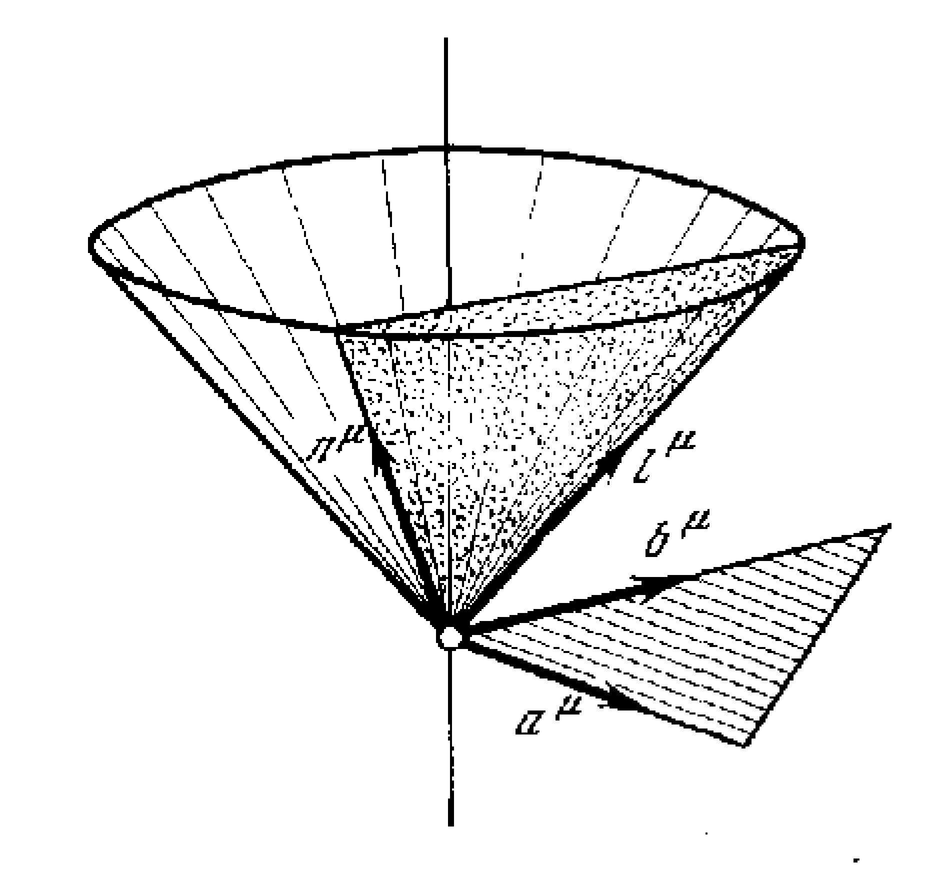
2) Now: if we take the limit of zero surface gravity or take extremal horizon from the very beginning: no timelike trajectory on lightlike surface

Geometric explanation

$$g_{\alpha\beta} = -l_\alpha N_\beta - l_\beta N_\alpha + \sigma_{\alpha\beta}$$

lightlike vectors l^μ, N^μ

spacelike vectors a^μ, b^μ orthogonal to them



Four-velocity

$$u_i^\mu = \frac{l^\mu}{2\alpha_i} + \alpha_i N^\mu + s_i^\mu,\ s_i^\mu = A_i a^\mu + B_i b^\mu$$

$$-(u_1 u_2) = \frac{1}{2}\left(\frac{\alpha_1}{\alpha_2} + \frac{\alpha_2}{\alpha_1}\right) - (s_1 s_2).$$

$$E_{c.m.}^2 = m_1^2 + m_2^2 + m_1 m_2\left[\frac{\alpha_1}{\alpha_2} + \frac{\alpha_2}{\alpha_1} - 2(s_1 s_2)\right].$$

Case 1
always

$a = 0$

For head-on collision
means that particle
cannot cross horizon

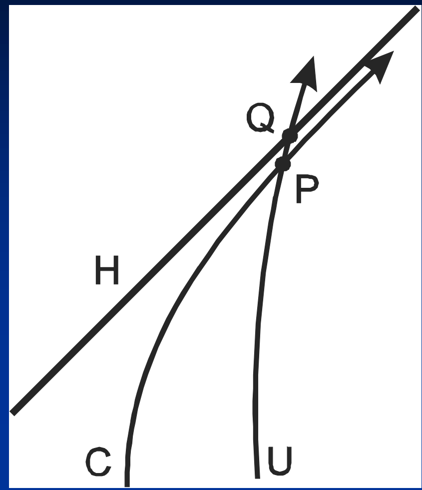
Case 2
Special condition

Case 2

$$\alpha_1 \to 0$$

$$E^2_{c.m.} \to \infty.$$

Now, special condition



Kruskal-like coordinates

$$ds^2 = -C dX dY + \gamma_{ab} dx^a dx^b$$

$$Cu^X u^Y = 1$$

$$u^X \sim \alpha \to 0.$$

$$\tau \sim -\ln X \to \infty$$

Reissner-Nordstrom

Case 1

$$\alpha = \frac{X - Z}{m}$$

$$Z = \sqrt{X^2 - m^2 N^2}$$

$$X = E - \frac{qQ}{r}$$

On the horizon $Z = X_H$

$a \rightarrow 0$

on horizon always

Case 2

$$\alpha_H = \frac{2X_H}{m} > 0$$

On horizon

Special condition

BSW effect versus Penrose process

What energy can be observed at infinity?

1) Radial motion in RN metric

$$ds^2 = -N^2 dt^2 + \frac{dr^2}{N^2} + r^2(d\theta^2 + d\phi^2 \sin^2\theta).$$

$$u^\mu_{(i)} = \frac{l^\mu}{2\alpha_i} + \beta_i N^\mu,$$

$$\alpha_i = \frac{X_i - \varepsilon_i Z_i}{m_i}, \; X_i \equiv E_i - q_i\varphi,$$

$$Z_i = \sqrt{X_i^2 - m_i^2 N^2},$$

$$m(\alpha_1 + \alpha_2) = \mu(\alpha_3 + \alpha_4),$$
$$m(\frac{1}{\alpha_1} + \frac{1}{\alpha_2}) = \mu(\frac{1}{\alpha_3} + \frac{1}{\alpha_4}).$$

Outging particles

$$a = \frac{X - Z}{m} \qquad Z = \sqrt{X^2 - m^2 N^2}$$

near horizon, $a \to 0$ autmatically

$$\alpha_4 \approx \frac{\mu_4}{m}\alpha_1$$

1) BSW effect, $a_1 \to 0$

$$m \le E < \frac{m^2}{E_1 + \sqrt{E_1^2 - m^2}}$$

2) Special situation: usual particles collide and produce light particles

$$E_4 > E$$

$$\sqrt{\frac{2N(\cosh\gamma_1 + \cosh\gamma_2)}{\alpha_1}} m < \mu \ll m.$$

$$N \ll 1$$

$$E_i = m \cosh g_i$$

Rotating black holes

$$ds^2 = -N^2 dt^2 + g_{\phi\phi}(d\phi - \omega dt)^2 + dn^2 + g_{zz} dz^2$$

$$X = \frac{E - \omega m L}{m}$$

Critical particle: $E = w_H m L$

Now,

near horizon

$$Z = N\sqrt{B_1^2 L^2 - (1 + \frac{L^2}{g^H_{\phi\phi}})} + O(N^2),$$

$$\omega = \omega_H - B_1 N + O(N^2)$$

$$E_4 \approx E_1 \frac{1 - \sqrt{1 - \frac{1}{B_1^2 g_{\phi\phi}^H}}}{1 + \sqrt{1 - \frac{1}{B_1^2 g_{\phi\phi}^H}}} < E_1.$$

Extremal Kerr metric

$$E_4 \approx E_1 \frac{2 - \sqrt{3}}{2 + \sqrt{3}} \approx 0.07\ E_1.$$

Complimentarity

BSW effect: large energy in CM frame near horizon, modest energy at infinity

Finite energy in CM frame near horizon but large energy at infinity

Circular orbits and acceleration of particles by near-extremal dirty rotating black holes: general approach

Circular orbits in astrophysics. Kerr metric (Bardeen et al, 1972)

BSW effect: critical particle. Natural realization near horizon

ISCO innermost stable orbit

MBO marginally bound orbit

PhO photon orbit

$$ds^2 = -N^2dt^2 + g_{\phi\phi}(d\phi - \omega dt)^2 + dl^2 + g_{zz}dz^2.$$

$$N^2\dot{l}^2 \equiv -V_{eff} = (E - \omega L)^2 - bN^2,\ b = (\gamma + \frac{L^2}{g_{\phi\phi}}).$$

$$dl = \frac{d\rho}{N}.$$

$$V_{eff}(\rho_0) = 0,$$
$$\frac{dV_{eff}}{d\rho}(\rho_0) = 0$$

For nonextremal BH

$$-\frac{1}{2}\frac{dV_{eff}}{d\rho} \rightarrow -b_+\kappa \neq 0$$

No orbits near horizon

Near extremal, small surface gravity

ISCO

$$\frac{d^2V_{eff}(\rho_0)}{d\rho^2} = 0.$$

$$x = \rho_0 - \rho_+$$

$$x : k^{2/3}$$

MBO

E=m

$$x : k$$

PhO

$$x : k$$

PROPER DISTANCE.

$\rho \approx \rho_+$ Between horizon and MBO or PhO,

Proper distance is finite

Between horizon and ISCO, $l : \ln\frac{1}{k}$

Two scenarios of collisions

O –scenario. Collision on circular near-horizon orbit

H – scenario Collision on horizon with participation of particle that plunged to horizon from circular orbit

	O - version	H - version
ISCO	$E_{c.m.} \sim k^{-1/3}$	$E_{c.m.} \sim k^{-1/3}$
MBO, PhO	$E_{c.m.} \sim k^{-1/2}$	

Universality

Collisions on inner horizon

Again, one of two particle should be critical. Then, the following cases are possible

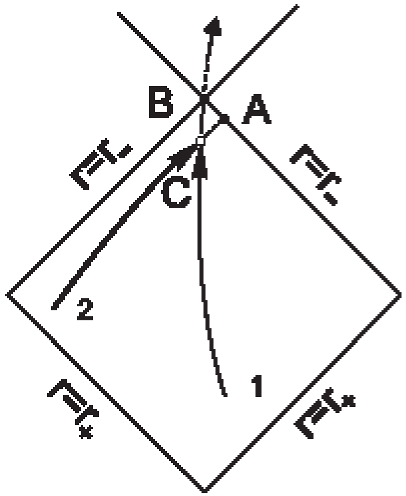


FIG. 2. The weak version of the BSW effect. Near-horizon collision between critical particle 1 and usual one 2.

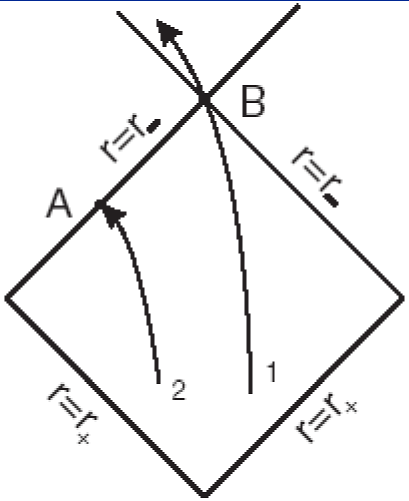


FIG. 1. Impossibility of the strong version of the BSW effect. The critical particle 1 passes through the bifurcation point whereas a usual one 2 hits the left horizon.

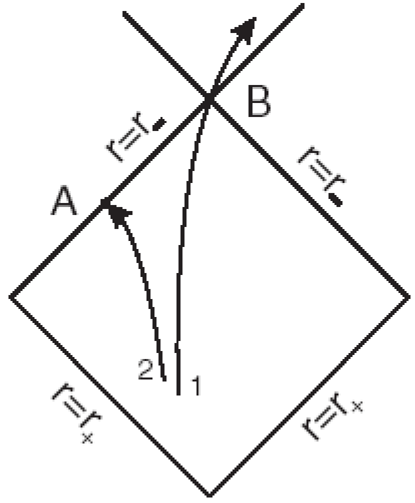


FIG. 3. Impossibility of the strong version of the PS effect. The critical particle 1 passes through the bifurcation point, whereas a usual one 2 hits the left horizon.

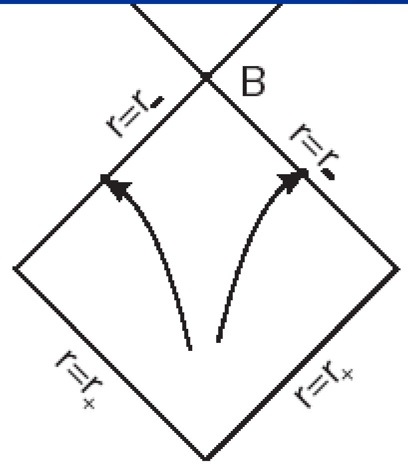


FIG. 4. Impossibility of the strong version of the PS effect. Two usual particles hit different branches of the horizon.

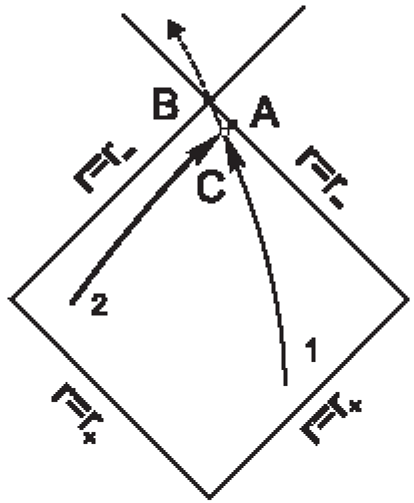


FIG. 5. The weak version of the PS effect. Near-horizon collision between critical particle 1 and usual one 2.

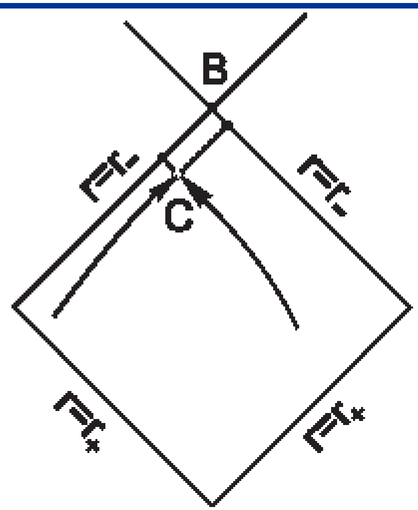


FIG. 6. The weak version of the PS effect. Collision between two usual particles near the left horizon.

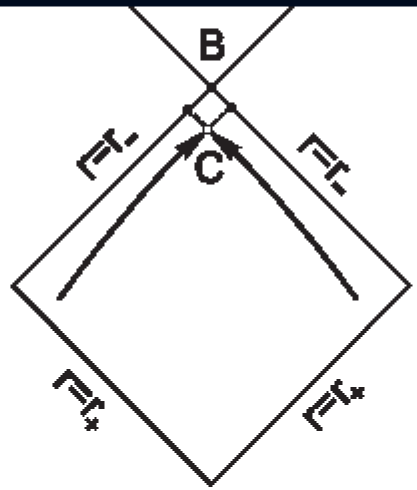


FIG. 7. The weak version of the PS effect. Collision between two usual particles near the bifurcation point.

Kinematic censorship

Summary and conclusions

Main ingredients of the effect:

1) event horizon,

2) critical particle

Universality of effect

Rotating and charged BH – universal property

Extremal BH. Kinematic censorship: infinite proper time

Nonextremal BH: multiple scattering, narrow near-horizon strip

Kinematic explanation: in terms of relative velocity

Geometric explanation: local light cone

Potential applications: Probe of Planck scale, properties of galaxy nuclei, etc.

Thank you!