High energy collisions near black holes and super-Penrose process

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“Standard” Penrose process

Decay of particle $$0 \rightarrow 1 + 2$$

$$E_0 = E_1 + E_2 \qquad E_2 < 0 \qquad E_1 > E_0$$

Efficiency $$\eta = \frac{E_1 - E_0}{E_0}$$

ergoregion

Collisional Penrose process

$$1 + 2 \rightarrow 3 + 4$$

Two different kinds of energy

Killing energy $E = -p_\mu \xi^\mu$ ξ^μ Killing vector

E conserved, integral of motion since metric is static or stationary

Energy in the CM frame $E_{c.m.}$

not conserved. Moreover, it is defined in one point only.
point of collision

BSW process

Unbound energy in the centre of mass (CM) frame

$E_{c.m.}$ versus E Killiing energy measured at infinity

Even in spite of unbound $E_{c.m.}$

E Is typically quite modest

Equatorial plane

Kerr Excess less than 50 % Mejer et al, 2012
Harada et al 2012

Dirty black holes OZ 2012

Dirty = surrounded ny matter, NOT Kerr BH

Standard scenario.
Particles 1 and 2 fall from infinity, collide
Particle 4 falls into a BH, particle 3 moves to infinity
Either particle 3 moves immediately after colliison towards BH and bounces or moves to inifnity at once

Particle 1 is fine-tuned (critical)

Particle 2 is not fine-tuned (usual)

From analysis of conservation laws:
Particle 3 is critical or near-critical, particle 4 is usual

J. Schnittman (2014)

Partcile 1 moves from BH, head-on collision with particle 2

Amplification, factor about 14

Kerr, numerics

Particle 1 is critical

Harada et al 2015

Kerr, analytically

Particle 1 (moves from BH) is usual

Unbound efficiency (super-Penrose process)

E. Berti, R. Brito and V. Cardoso, 2015 — Kerr, numerics

O. Z. 2015 — Dirty BH, analytically

Near horizon, particle should move towards BH

White holes (Grib and Pavlov 2014)

or special scenario n case of BH

We can try to prepare required state (usual particle moving from BH)

Is it possible ot obtain it as a result of previous collision?

Full scenario

Step 1. Particle 1 and 2 fall from infinity and collide near BH

Step 2. They produce usual particle 3

Step 3. Particle 3 collides with particle 4 falling from inifnity (head-on collision)

Result: particle 5 with unbound energy moving to infinity

One of particle falling from infinity has to have mass (N is lapse funciton)

$m_2 = O(N^{-2})$ Kerr metric, E. Leiderschneider and T. Piran 2015

General approach (O.Z., 2015)

$$ds^2 = -N^2 dt^2 + g_\phi (d\phi - \omega dt)^2 + \frac{dr^2}{A} + g_\theta d\theta^2,$$

Equatorial plane, redefine radial coordinate

Effective metric

$$ds^2 = -N^2 dt^2 + g_\phi (d\phi - \omega dt)^2 + \frac{dr^2}{N^2}$$

Geodesic particles

$$m\dot{t} = \frac{X}{N^2}, \qquad m\dot{\phi} = \frac{L}{g_\phi} + \frac{\omega X}{N^2}, \qquad m\dot{r} = \sigma Z,$$

$$X = E - \omega L, \qquad Z = \sqrt{X^2 - N^2\left(m^2 + \frac{L^2}{g_\phi}\right)},$$

Forward-in-time condition $X \geq 0$ $\sigma = \pm 1$

$X_H > 0$ usual

"H" horizon, "c" collision

$X_H = 0$ critical

$X_H \neq 0$ but small near-critical $X_H = O(N_c)$

Conservation laws

$E_{in} = E_{fin}$ $L_{in} = L_{fin}$ Consequence: $X_{in} = X_{fin}$

Let p particles collide and produce q new particles.

$$\sum_{i=1}^{p} \sigma_i Z_i = \sum_{k=1}^{q} \sigma_k Z_k.$$ radial momentum

Conservation laws + forward-in-time conditions

Near-horizon limit, $N_c \to 0$

Statement. If in the initial configuration usual outgoing particles are absent, they cannot appear after collision.

Previous statement applis to case with finite masses, etc.

If we relax this condition, it is possible to obtain a usual outgoing Particle, provided

$m_2 = O(N^{-2})$ Generalizes observation of E. Leiderschneider and T. Piran

Attempt to find loophole

Fractional degrees allow $X = O(N^s)$ $0 < s < 1$

Inconsistent with conservaiton laws

List of possibilities (how to achieve SP process)

Collision with a supermassive particle

Collision near past horizons (white holes)

Collisions with (near)critical particles

Scenarios with collisions inside ergoregion but NOT near horizon

Scenario for getting unbound energy in CM

Grib and Pavlov 2013 Kerr, OZ 2013 generalized

Negative large angular momentum of one particle

What about SP ?

Yes, possible (O.Z. 2015)

Again the quesiton how to create paticle with large negative L

Is it possible from preceding collisions with finite energies and momenta?

No, impossible

$$E_1 + E_2 = E_3 + E_4 \qquad L_1 + L_2 = L_3 + L_4$$

$$X > 0$$

$E_3 > 0$ and large $\qquad E_4 < 0$ and large

$L_4 < 0 \qquad |L_4|$ large

L_3 large positive

$$X_1 + X_2 = X_3 + X_4$$ All X finite

$$Z = \sqrt{X^2 - N^2\left(m^2 + \frac{L^2}{g_\phi}\right)},$$ X is finite but $L \rightarrow \infty$

impossible

No black holes, other mechanisms

Naked singularities OZ 2014, Harada and Patil 2015

Now there is no problem with usual particle.

Pased ob scenario suggested by Patil and Joshi

Particle moves from inifnity, reflects from potential barrier and collides with another particle moving from infinity

Simplest case: RN

$m < e$ but m close to e

Ker: m<a but m close to a

Collision near would-be horizon

Rapid rotation

Three relevant quantities that control high energetic process

N $\quad L$ $\quad \omega$

1) $N \to 0$ Proximity to horizon

2) $L \to -\infty$ Not near horizon, ergoregion

3) $\omega \to \infty$ absence of horizon

Case 3 Teo wormhole

N. Tsukamoto and C. Bambi (2015)

Now, there is no problem with preparing of usual outgoing particle

Collision of two identical particles

$$E_{max} = E_1 + s, \qquad s = \frac{Q\sqrt{g_\phi}}{N}\sqrt{B}, \; B = 1 - \frac{\mu^2 N^2}{\beta},$$

$$Q = \omega E_1 - \frac{L_1 g_{00}}{g_\phi}. \qquad \beta = X_1^2 - \frac{N^2 L_1^2}{g_\phi}.$$

When $N \to 0$ $E_{max} \to \infty$

Admits generalization to collision of different particles

Interesting feature: energy in CM frame and E are not related directly

Possible scenarios in which

$E \gg E_{c.m.}$ Noticed before for the Teo wormhole

N. Tsukamoto and C. Bambi (2015)

Described results apply to geodesic particles in rotating spacetimes

Electrically charged particles interacting with charged BH

SP possible OZ 2012
Confirmed by Harata et al 2013

Open question: interaction with other field

Thank you!