Black Hole Jets

Elene Katsadze

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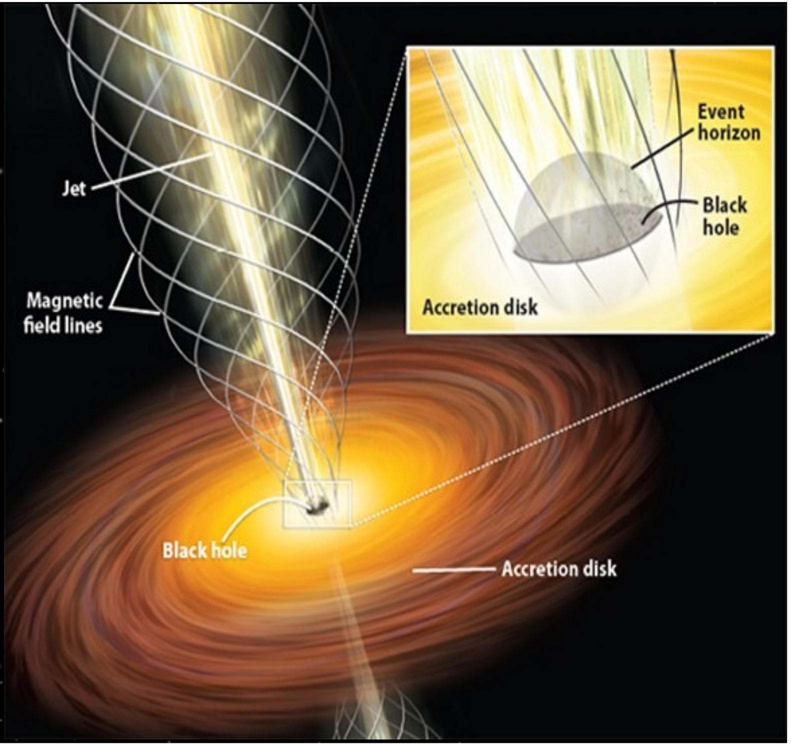
01 Introduction

"Curious Straight Ray" - Heber Curtis (1918)

M87 Galaxy Jet

1. Accretion Disk
2. Spinning Black Hole
3. Strong Magnetic Field



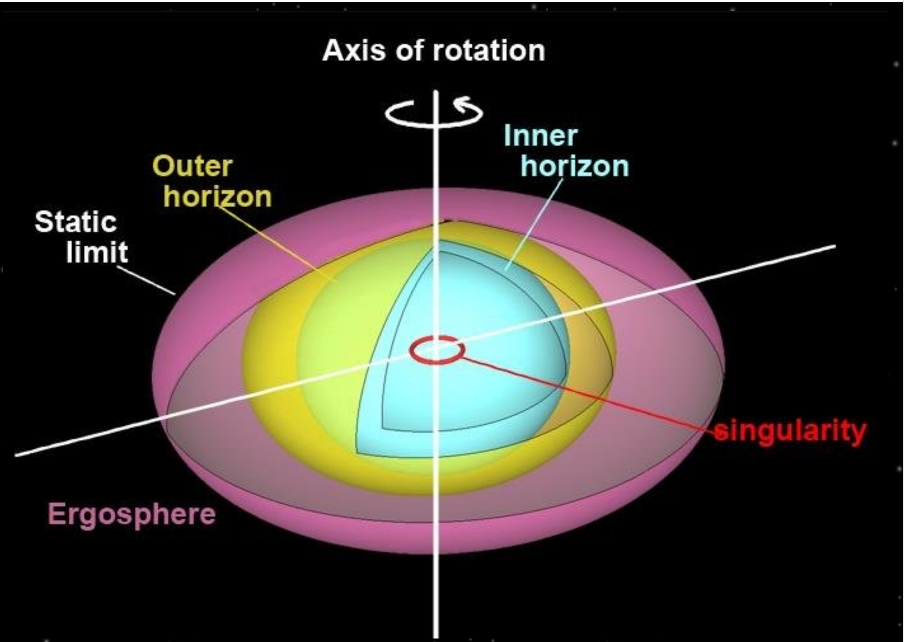
Spinning Black Holes

Mass: M

Angular Momentum: J

(Kerr Parameter: $a = J/M$)

Charge: $Q \sim 0$



Kerr Metric in the equatorial plane in Boyer-Lindquist coordinates (t, r, θ, φ):

G=c=1

$$d\tau^2 = \left(1 - \frac{2M}{r}\right) dt^2 + \frac{4Ma}{r} dt d\varphi - \frac{dr^2}{1-\frac{2M}{r}+\frac{a^2}{r^2}} - \left(1 + \frac{a^2}{r^2} + \frac{2Ma^2}{r^3}\right) r^2 d\varphi^2 \qquad (1)$$

Assume: a=1, $R^2 = r^2 + M^2 + \frac{2M}{r^3}$

$$d\tau^2 = \left(1 - \frac{2M}{r}\right) dt^2 + \frac{4M}{r} dt d\varphi - \frac{dr^2}{\left(1-\frac{2M}{r}\right)^2} - R^2 d\varphi^2 \qquad (2)$$

02 Penrose Process

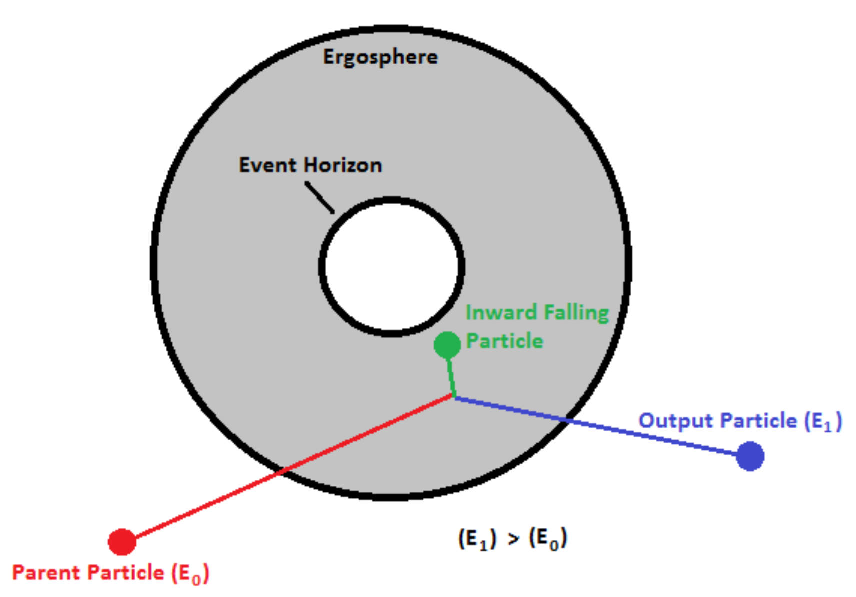
[Roger Penrose, 1969]

Total Energy E/m:

$$\frac{E}{m} = \left(1 - \frac{2M}{r}\right)\frac{dt}{d\tau} + \frac{2M^2}{r}\frac{d\varphi}{d\tau} \tag{2}$$

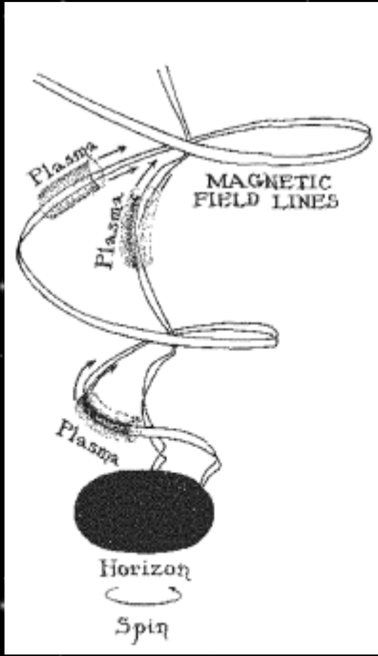
Condition for negative energy:

$$R\,\frac{d\varphi}{d\tau} < R\,\frac{2M - r}{2M^2} \tag{3}$$



Efficiency – 20.7% [Chandrasekhar, 1983]

03 Blandford-Znajek Mechanism



[Blandford-Znajek,1977]

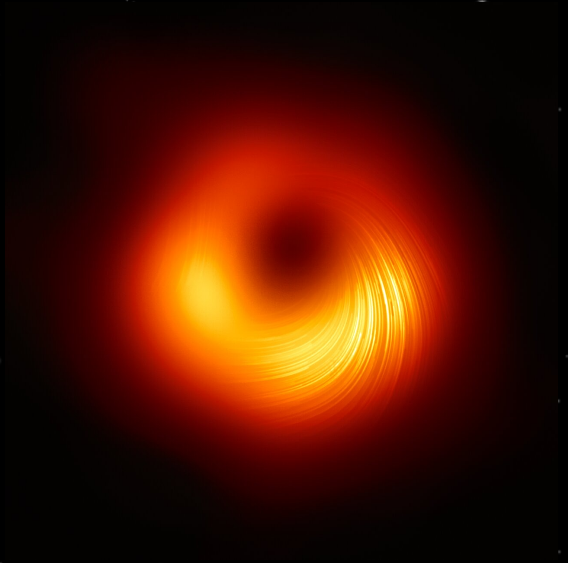
Force-Free Condition: $F_{\mu\alpha}j^{\alpha} = 0$ (4)

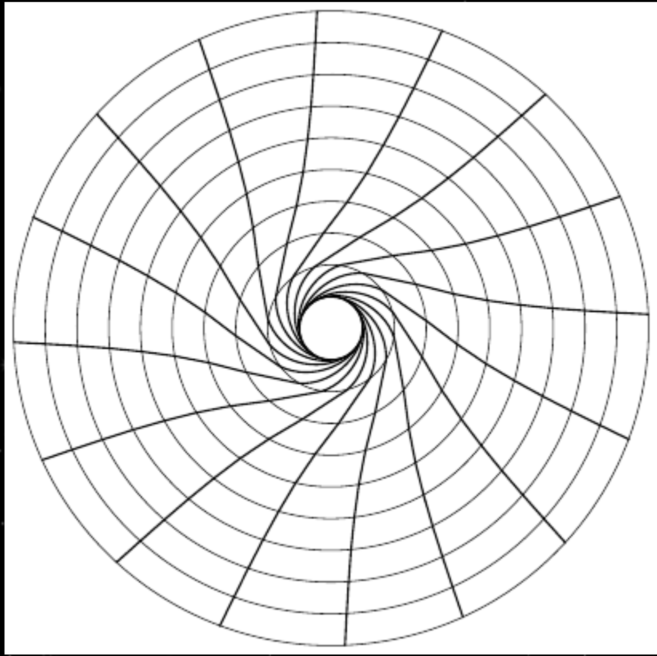
Where $F_{\mu\alpha}$ - Electromagnetic Field Tensor

Force-Free Electrodynamics (FFE):

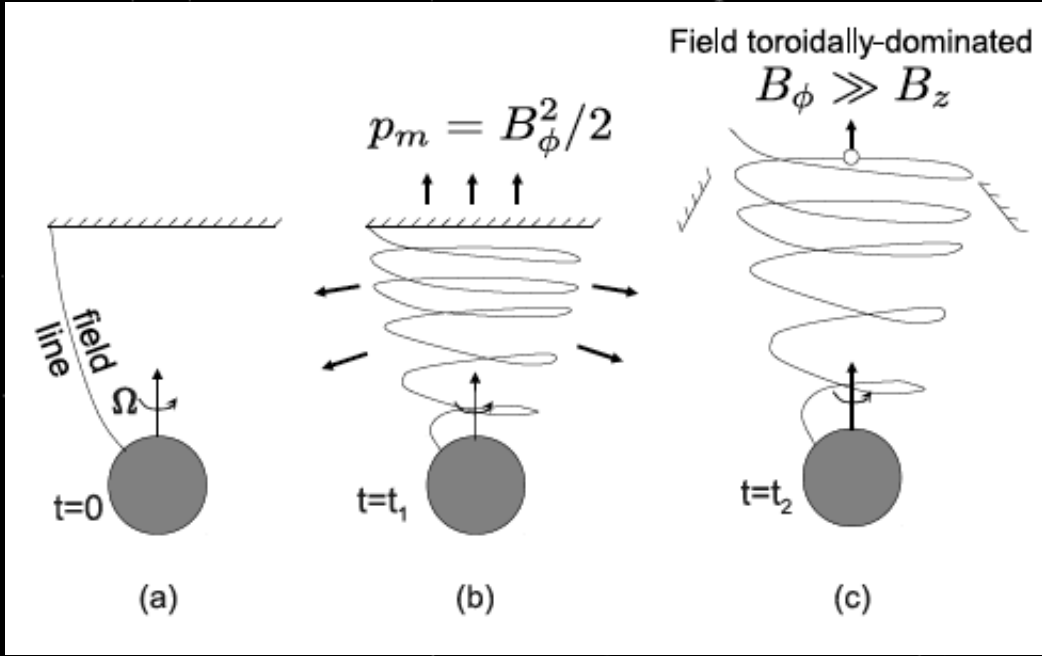
$F_{\mu\alpha}\nabla_{\alpha}F^{\mu\alpha} = 0.$, $\nabla_{[\alpha}F_{\upsilon\lambda]} = 0$ (5)

$\frac{d\boldsymbol{B}}{dt} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B})$ (6)





Frame Dragging



BZ Mechanism

04

Conclusion

Extracting rotational energy from a Kerr hole, where spin of the BH is powering the process.

Problem of Penrose process:
- Requires the breakup (spontaneous fission) of particles at relativistic speeds in opposite directions

Resources:

- *R. Penrose, "Gravitational Collapse: The Role of General Relativity", 1969*
- *R. D. Blandford and R. L. Znajek, "Electromagnetic extraction of energy from Kerr black holes", 1977*
- *Dennis V. Perepelitsa, "Spinning Black Hole Energetics", 2007*

THANK YOU!