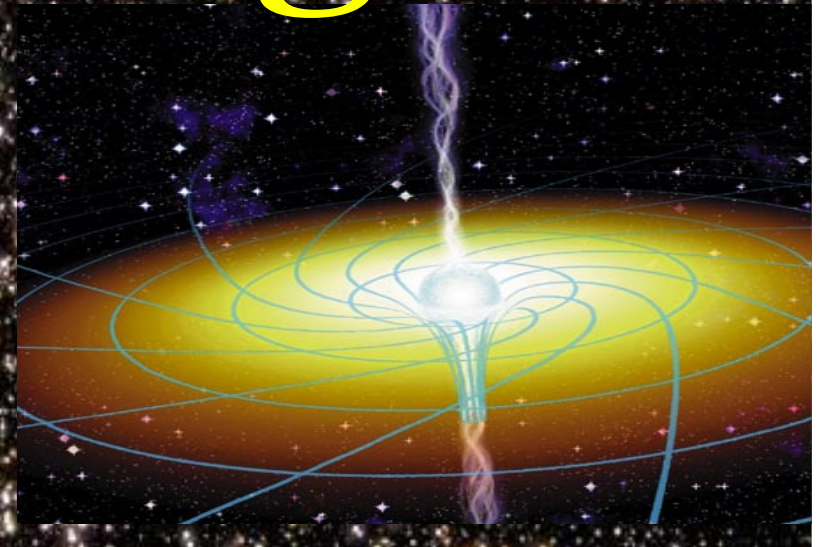


# Buracos Negros

## 1. BNs em Relatividade Geral



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**Universidade de Barcelona**

**&**

**Centro de Física do Porto (Univ. Porto)**

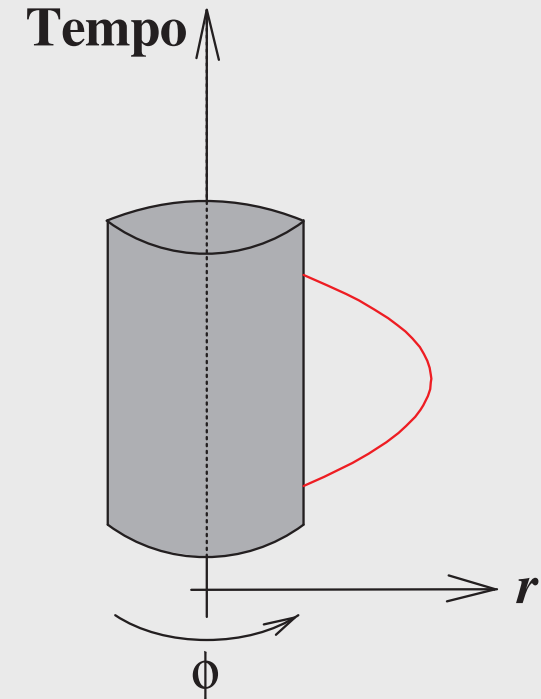
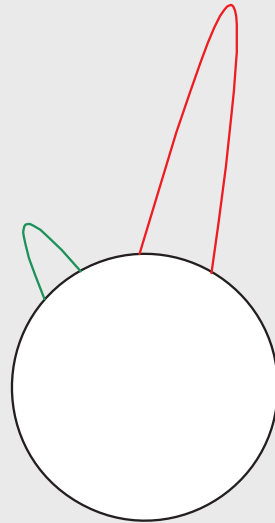
**4<sup>a</sup> EAG**



# Conceito Newtoniano de Buraco Negro

Tudo o que sobe cai de seguida.... se

$$v < v_{\text{esc}} \sim 11 \text{ Km / s}$$



$$\frac{1}{2} m v_{\text{esc}}^2 - \frac{GMm}{r} = 0$$

$$\rightarrow v_{\text{esc}} = c$$

$$r_+ = \frac{2GM}{c^2}$$

$$M_{\text{sol}} \Rightarrow r_+ \sim 3 \text{ Km}$$

$$M_{\text{Terra}} \Rightarrow r_+ \sim 1 \text{ cm}$$

## Teoria Gravitação de Newton

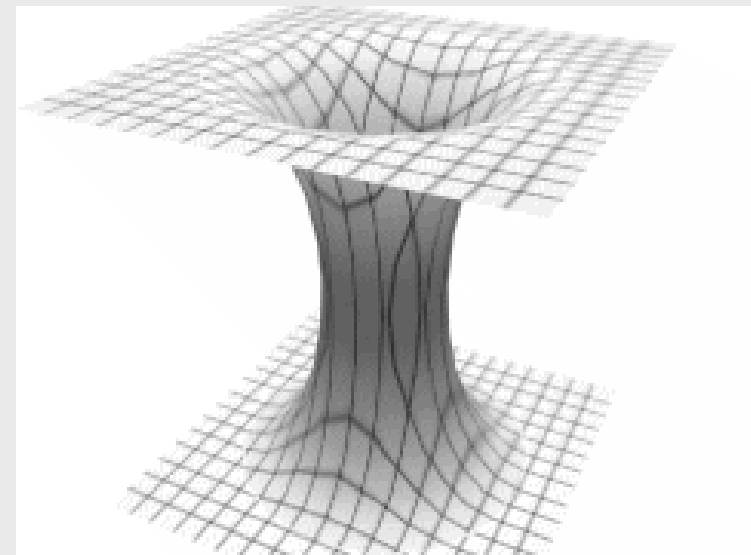
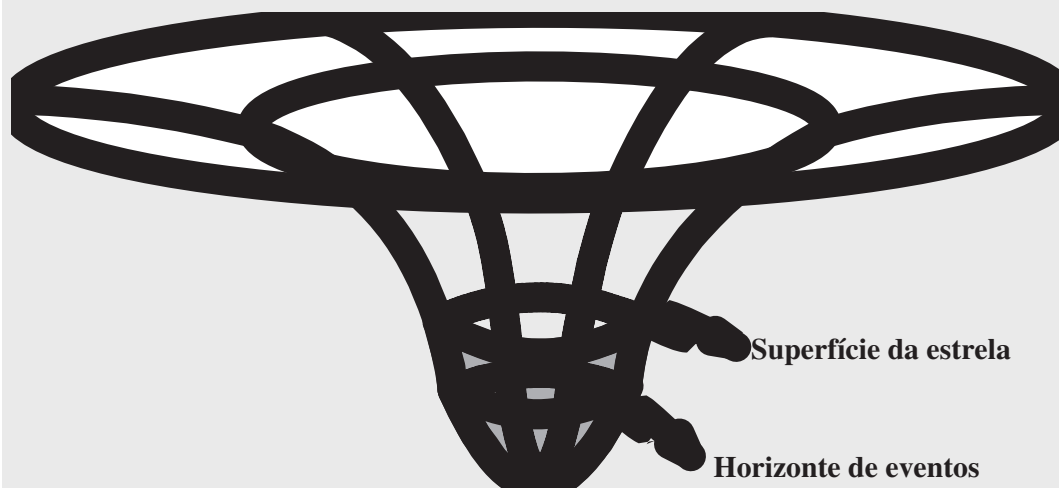
Teoria de Newton não obedece à Relatividade Restrita.

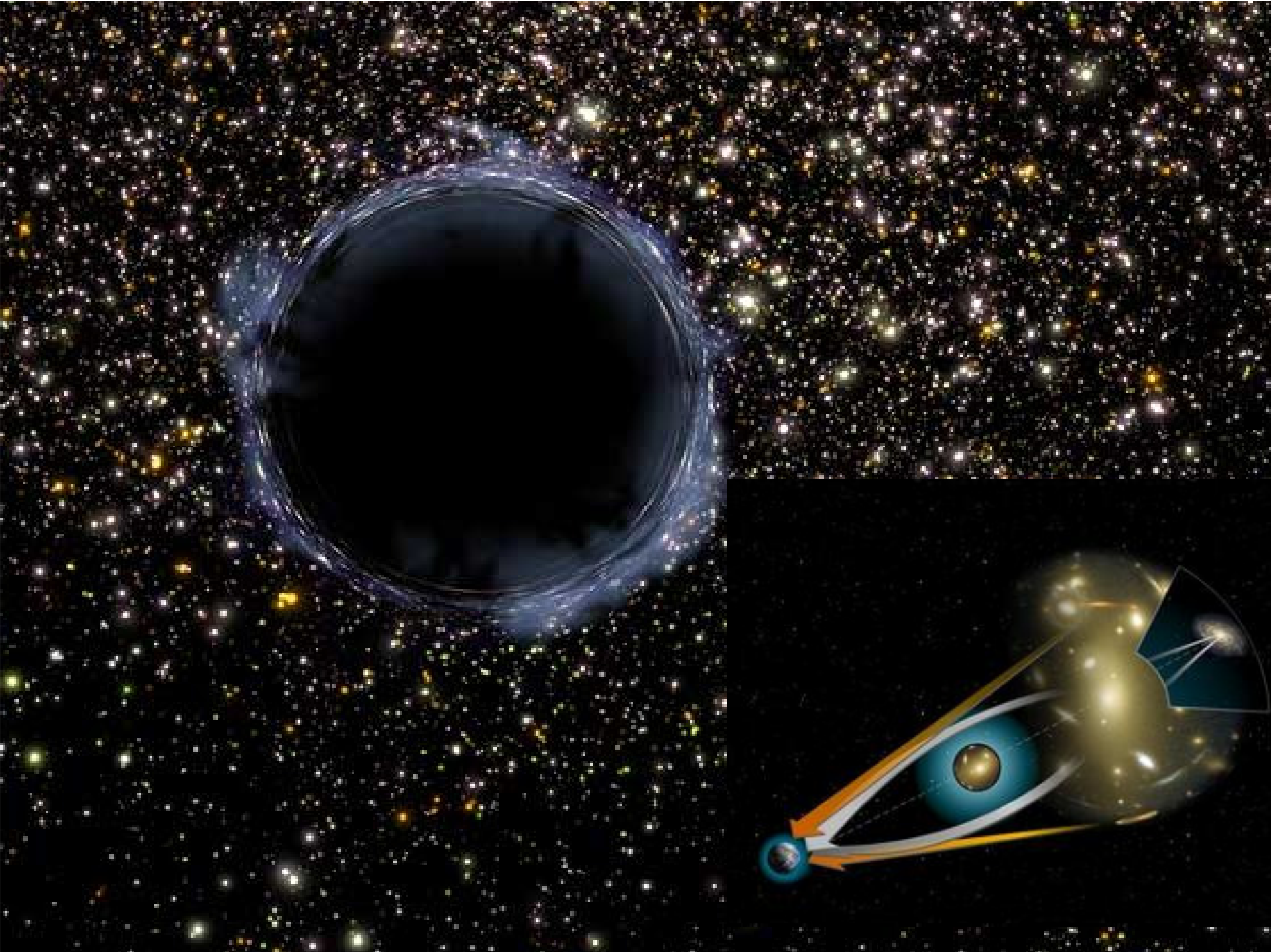
Força Gravit. é proporcional à posição instantânea dos corpos

## Teoria Gravitação de Einstein: Relatividade Geral

**Equações de Einstein:**

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \quad (\text{Curvatura na Geometria} \leftrightarrow \text{Energia})$$





# Buraco Negro na Relatividade Geral

## Geometria curva: deformação do espaço

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \quad (\text{Curvatura na Geometria} \leftrightarrow \text{Energia})$$

**Solução Plana (ausência massas/energia) (Minkowski, 1905) :**

$$ds^2 = -c^2 dt^2 + dr^2 + r^2 (d\theta^2 + \text{sen}^2 \theta d\phi^2)$$



$$ds^2 = -c^2 dt^2 + dx^2 + dy^2 + dz^2$$

**Solução (Massa esfericamente distribuída) (Schwarzschild, 1917) :**

$$ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 + \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 + r^2 (d\theta^2 + \text{sen}^2 \theta d\phi^2)$$

Potencial Newtoniano

Constantes  $G, c$

$R_{\text{sup}} > r_+ \rightarrow$  Estrela

$R_{\text{sup}} < r_+ \rightarrow$  Buraco Negro

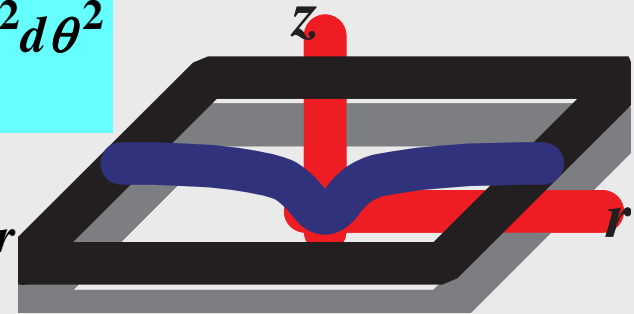
$t = \text{const.}$

$\phi = \text{const.}$

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 + r^2 d\theta^2$$

$$d\bar{s}^2 = dz^2 + dr^2 + r^2 d\theta^2 \quad \Leftrightarrow \quad d\bar{s}^2 = \left[1 + \left(\frac{dz}{dr}\right)^2\right] dr^2 + r^2 d\theta^2$$

$$ds^2 = d\bar{s}^2 \rightarrow \left(\frac{dz}{dr}\right)^2 + 1 = \left(1 - \frac{2Gm}{c^2 r}\right)^{-1} \rightarrow z(r) = \int_0^r \left(\frac{r}{2m(r)} - 1\right)^{\frac{1}{2}} dr$$



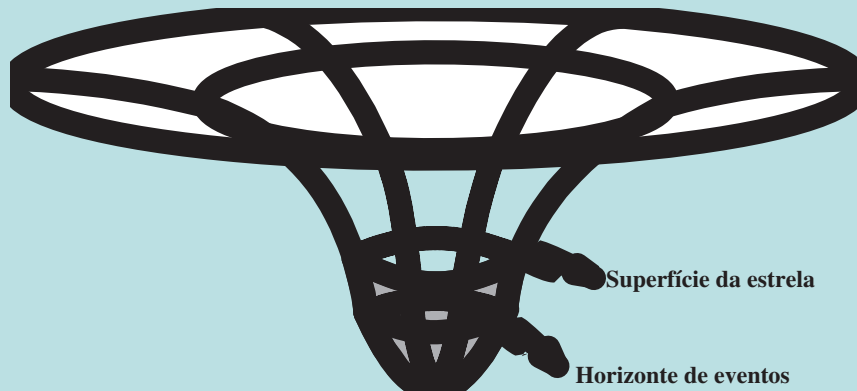
### Estrela:

Exterior da Estrela

$$z^2(r) = 8Mr - 16M^2$$

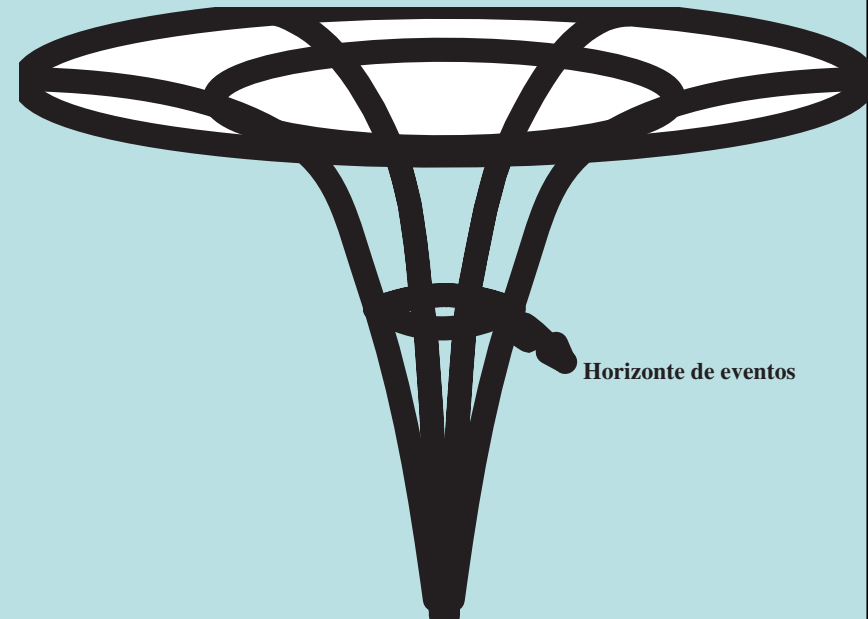
Interior da Estrela (se  $\rho = \text{const.}$ )

$$[a - z(r)]^2 + r^2 = a^2, \quad a^2 \equiv 3\pi\rho/8$$



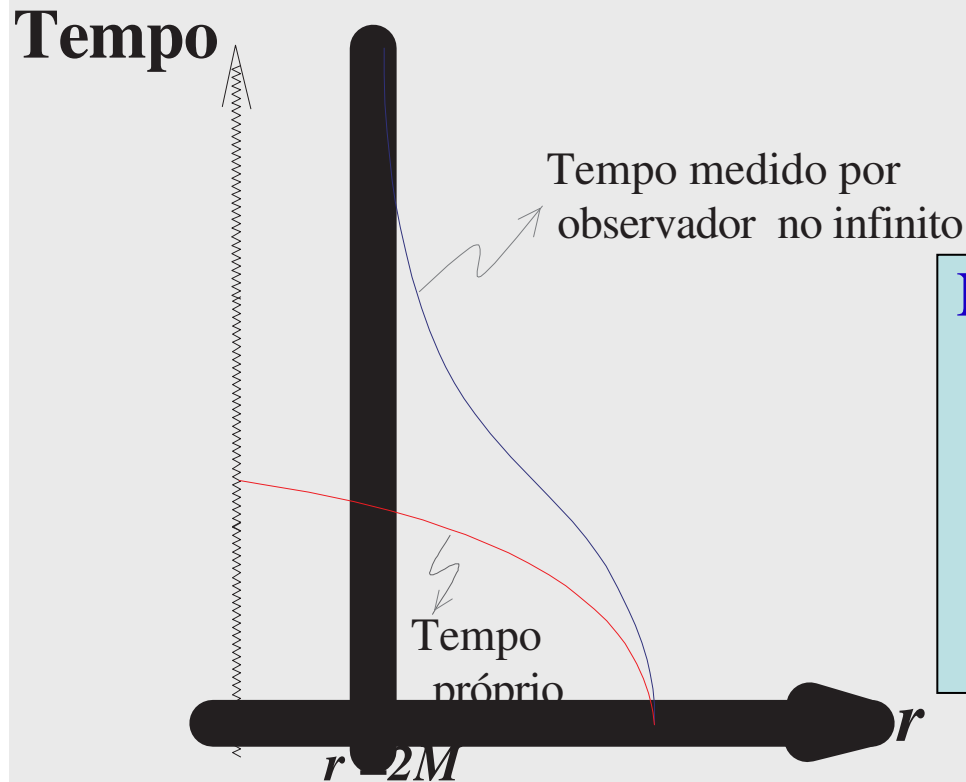
### Buraco Negro:

$$z^2(r) = 8Mr - 16M^2$$



# Geometria curva: deformação do tempo

## Queda livre de um corpo



Na Relatividade Restrita:

$$d\tau = (1 - v^2 / c^2)^{1/2} dt$$

No Buraco Negro:

$$ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 + \dots$$

$$d\tau = \left(1 - \frac{2GM}{c^2 r}\right)^{1/2} dt$$

Tempo próprio

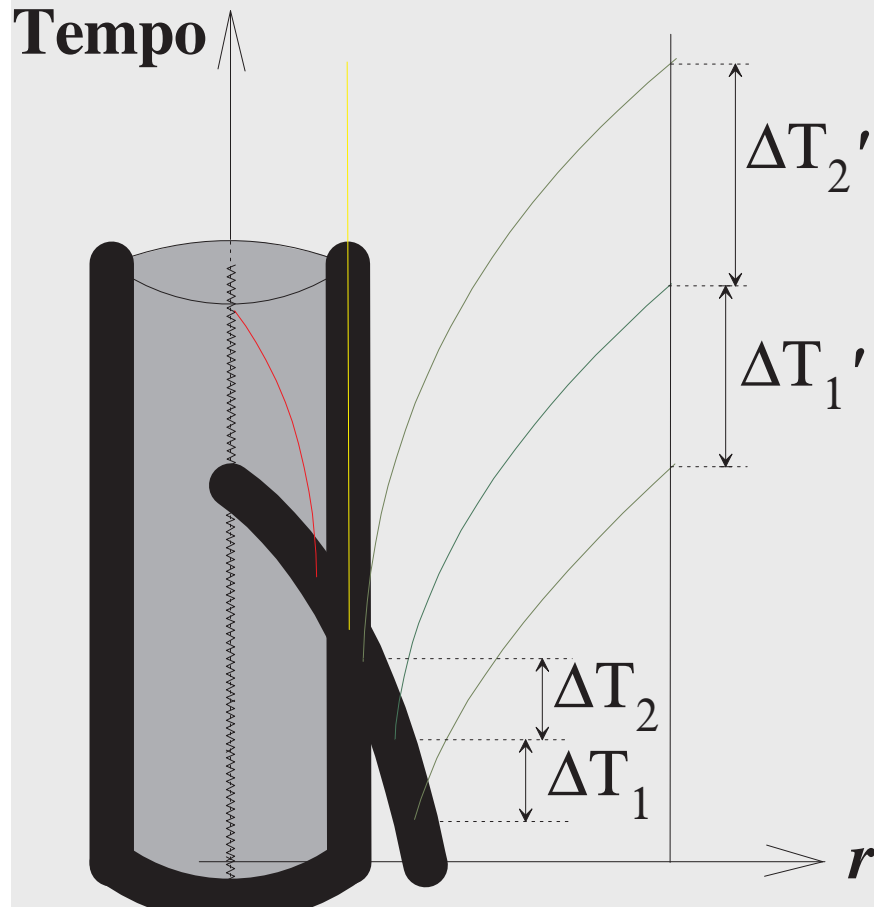
Tempo do Observador  
no Infinito

$$r \rightarrow r_+ : \Delta\tau = \left(1 - \frac{2GM}{c^2 r_+}\right) \Delta t = 0 \times \infty$$



# Geometria curva: deformação do tempo

## Queda livre de um corpo



No espaço plano:

$$ds^2 = -c^2 dt^2 + dr^2 + \dots$$

**Luz :**  $\frac{dr}{dt} = c \rightarrow ds = 0$

No Buraco Negro:

$$ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 + \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 + \dots$$

$$ds = 0 \rightarrow \frac{c dt}{dr} = \pm \left(1 - \frac{2GM}{c^2 r}\right)^{-1/2}$$

$$r = \infty \rightarrow \frac{cdt}{dr} = 1$$

$$r > 2M \rightarrow \frac{cdt}{dr} > 1 : t \uparrow, r \uparrow$$

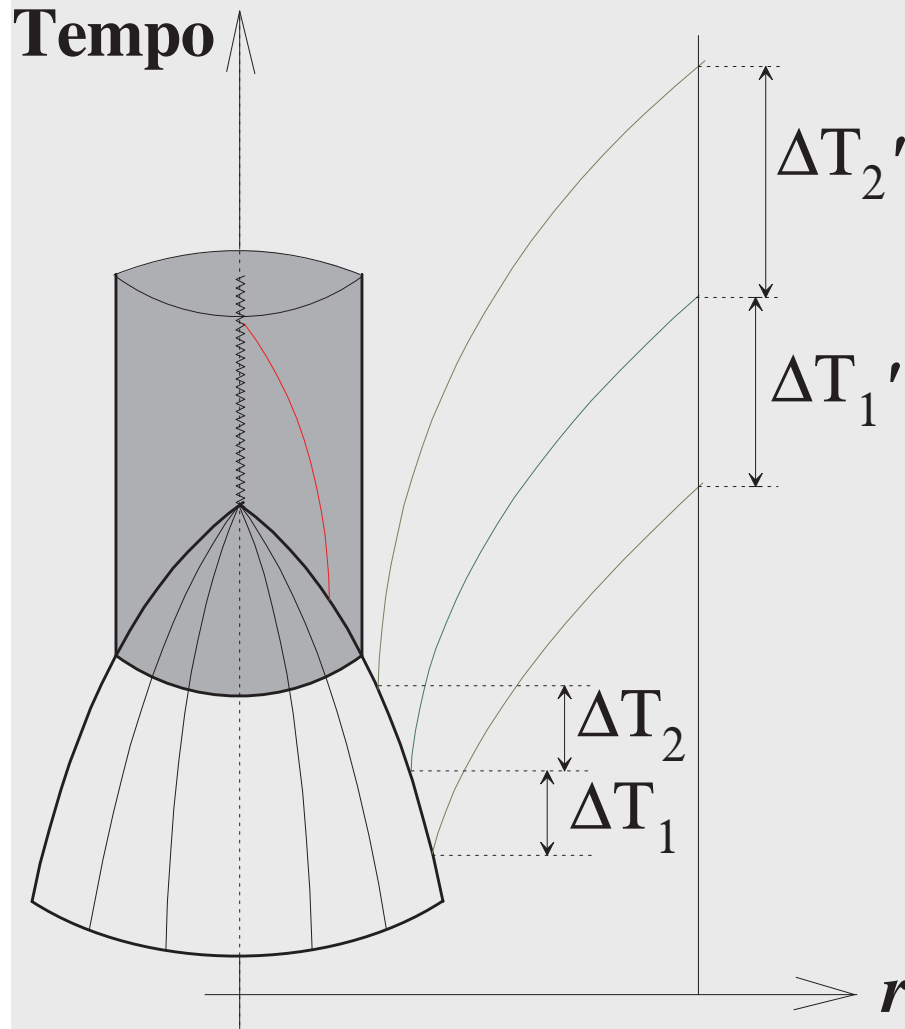
$$r = 2M \rightarrow \frac{cdt}{dr} = \infty : t \uparrow, r = \text{const}$$

$$r < 2M \rightarrow \frac{cdt}{dr} < 0 : t \uparrow, r \downarrow$$

**Nada consegue escapar de  $r < 2M$  para  $r > 2M$**

# Colapso gravitacional de uma estrela massiva

Não deveríamos ver a estrela eternamente em colapso e a brilhar eternamente ?!



1. N° fotões recebidos diminui c/ tempo

2.  $\nu = \frac{1}{T} \searrow \Rightarrow E_\gamma = h\nu \searrow$

$$L \propto \exp\left(-\frac{1}{3\sqrt{3}} \frac{1}{M} t\right)$$

$$\tau = 3\sqrt{3}M \approx 10^{-5} \frac{M}{M_{sol}} \text{ segundos}$$

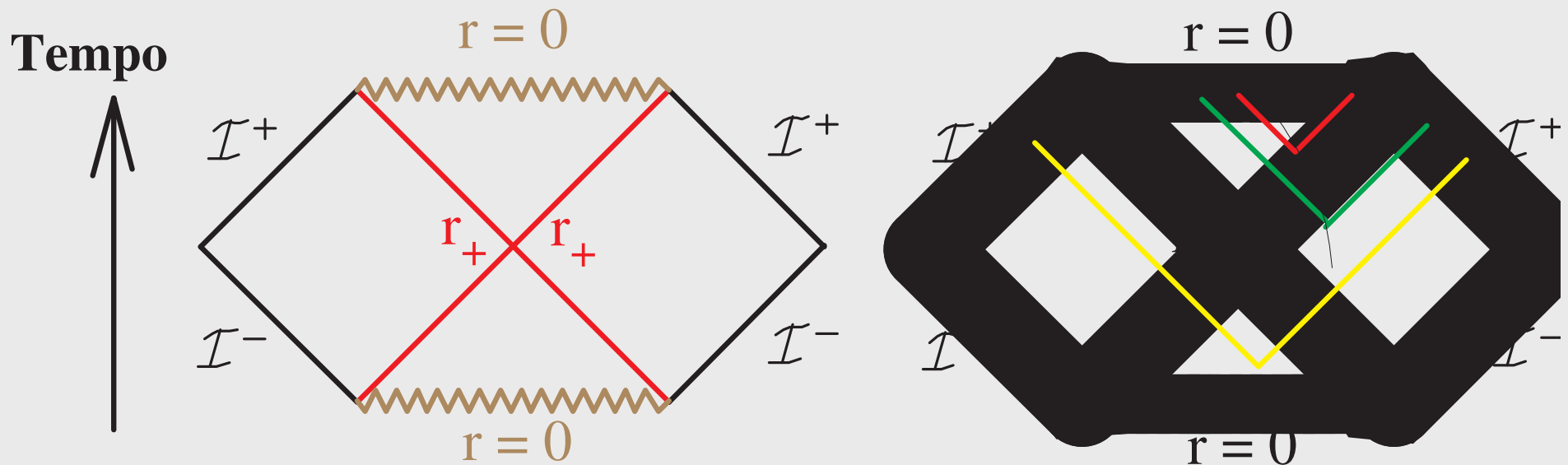
Uma vez iniciado o colapso, rapidamente o objecto fica invisível !

$$\frac{dr}{dt} = c \left( 1 - \frac{2GM}{c^2 r} \right) \neq c \quad ?!$$

Transformação de coordenadas tal que no novo sistema a luz se mova com velocidade  $c$

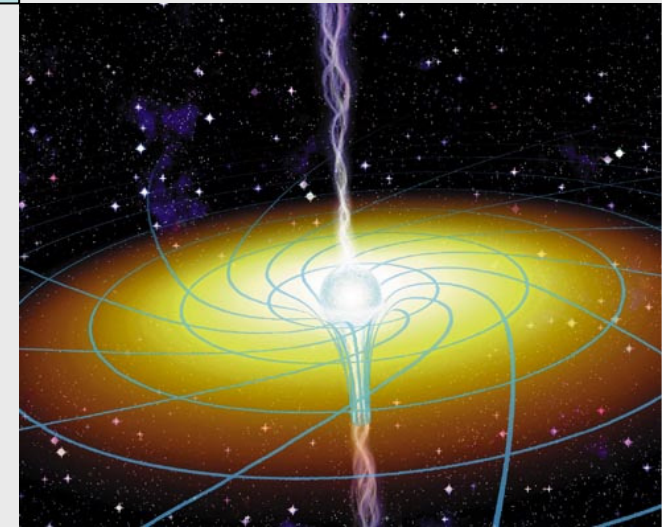
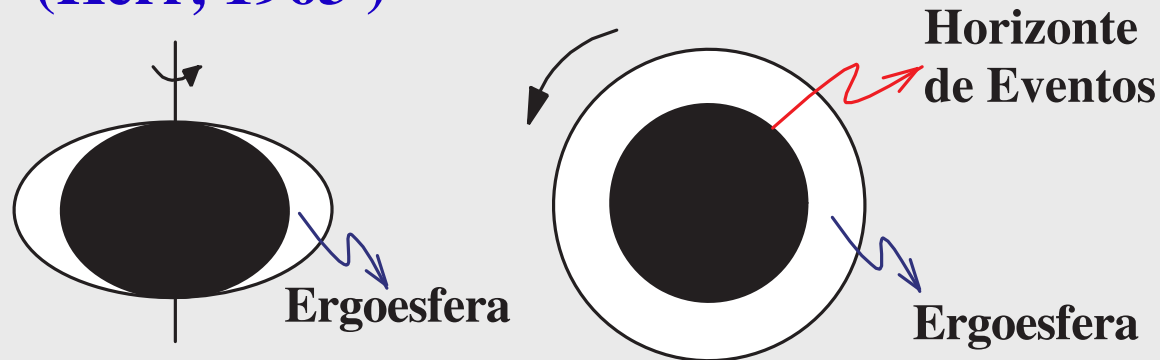


### Diagrama causal de Finkelstein, Kruskal, Carter, Penrose:



# Buraco Negro com Rotação

- (Kerr, 1963 )



→ Existe Rotação Máxima do BN:  $J \leq \frac{G}{c} M^2$

→ Na ergoesfera todos os objectos movem-se no sentido de rotação do BN

- (Kerr-Newman, 1965 ) : BN com carga e rotação

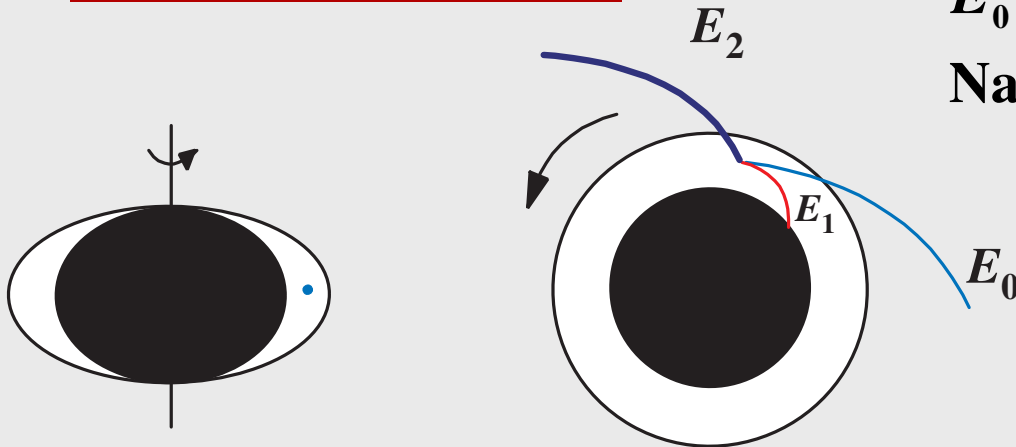
→ Os BNs não têm cabelo! (Wheeler )

**Bilhete de Identidade:**  $M, J, Q$

As propriedades do BN não dependem da forma como o construímos!

# Extracção de Energia de um Buraco Negro com Rotação

## Processo de Penrose

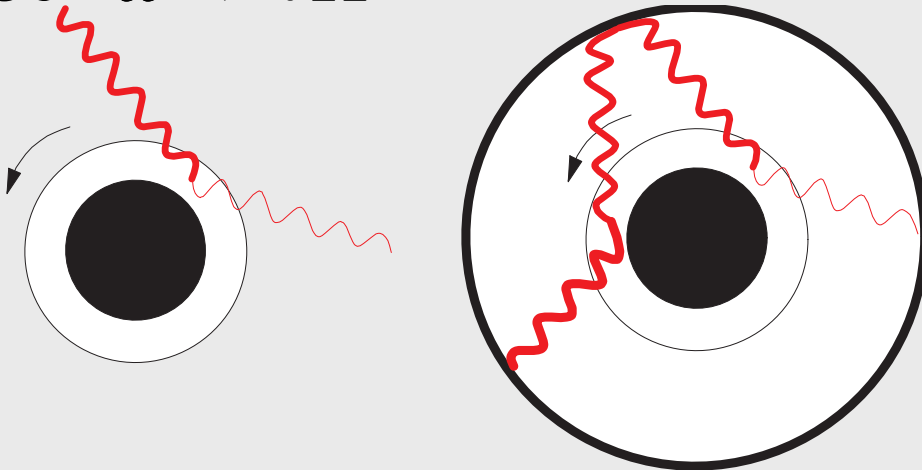


$$E_0 = E_1 + E_2$$

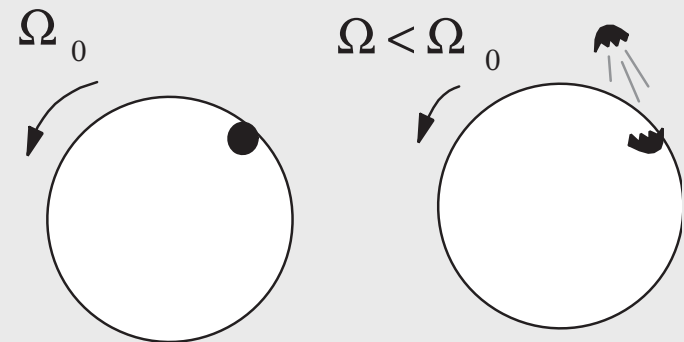
Na ergoesfera :  $E_1 < 0 \rightarrow E_2 > E_1$  !

## Superradiância de ondas

Se  $\omega < m\Omega$



Zel'dovich, Starobinsky;  
Press, Teukolsky;  
Cardoso, Dias, Lemos, Yoshida



$$E_f > E_0$$

**Bomba de Buraco Negro !**

# Formação de Buracos Negros

- **Colapso Gravitacional**
- **Buracos Negros Primordiais**
- **Criação Quântica de Buracos Negros num Campo Externo**

## → Colapso Gravitacional

### História:

1930: Massa Máxima de Anã Branca (Chandraseckar)

1932: Neutrão e especulação de Estrela Neutrões (Zwicky)

1939: Colapso esfera homogênea s/ pressão conduz  $\rho=00$  (Oppenheimer, Snyder)

1960: Colapso Gravitacional conduz a BN (Wheeler)

1967: Descoberta de Pulsar

1968: Nasce termo “Buraco Negro” (Wheeler)

→ Massa Máxima de Anã Branca (Chandraseckar) :  $1.4M_{\text{sol}}$

→ Massa Máxima de Estrela de Neutrões (Oppenheimer, Volkoff) :  $2 - 3 M_{\text{sol}}$

Acima destes valores a pressão de degenerescência não consegue impedir o colapso gravitacional e forma-se BN

→ 
$$\begin{cases} M_{\text{inicial}} < 8M_{\text{sol}} & \rightarrow \text{Anã Branca} \\ 8M_{\text{sol}} < M_{\text{inicial}} < 45M_{\text{sol}} & \rightarrow \text{Estrela de Neutrões} \\ M_{\text{inicial}} > 45M_{\text{sol}} & \rightarrow \text{Buraco Negro} \end{cases}$$

→ **Buracos Negros Primordiais** (Novikov, Zel'dovich (1967), Hawking, 1971)

Fluctuações na densidade do Universo Primordial podem ter conduzido  
à formação de BNs:

Energia Gravitacional  $\geq$  Energia Interna (de pressão)

$$\frac{G M^2}{R} \geq P R^3 \xrightarrow{P \approx \rho c^2} R \leq \frac{G M}{c^2}$$

→ Dimensão da flutuação

$$\rho \approx G^{-1} t^{-2}$$

$$M = \rho V \sim \rho R^3$$

$$M \approx \frac{c^3}{G} t \approx 10^{38} t$$

$$\begin{cases} t = 10^{-43} s \rightarrow M \approx 10^{-5} g \\ t = 10^{-4} s \rightarrow M \approx M_{\text{sol}} \\ t = 100 s \rightarrow M \approx 10^8 M_{\text{sol}} \end{cases}$$

→ **Mini BNs deviam estar “explodindo” em raios-gama**

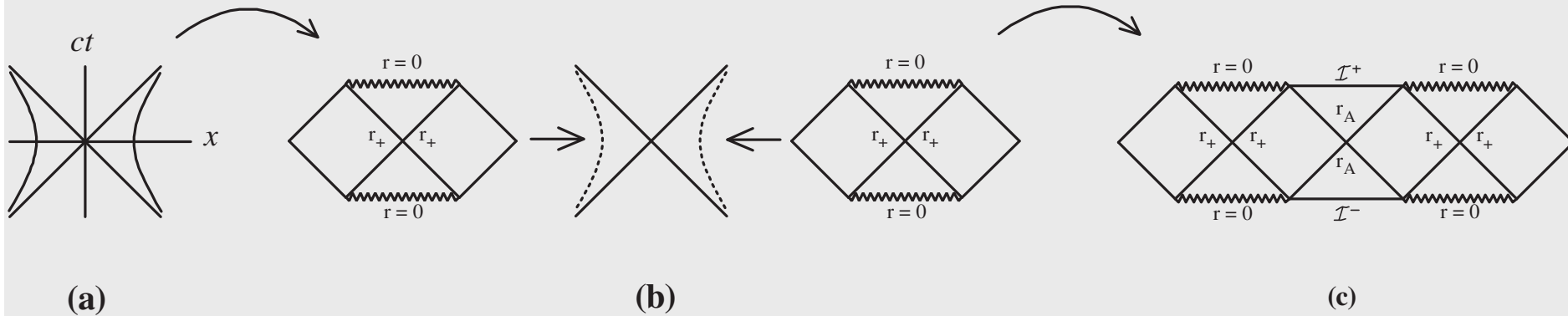
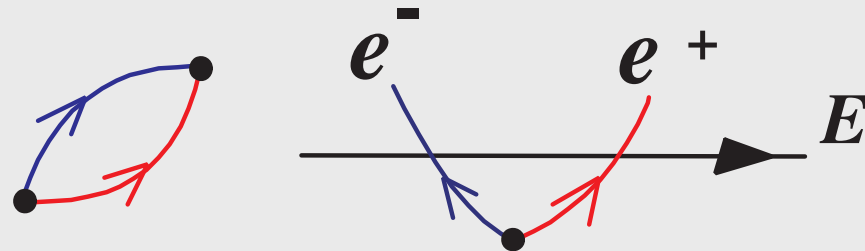
→ **Galáxias de Núcleo Activo parecem conter um BN supermassivo**



# Criação Quântica de Buracos Negros num Campo Externo

→ Análogo Gravitacional do processo de Schwinger (Gibbons, 1991)

→ Processo de criação de Schwinger (1951)



$$x = at^2$$

$$x^2 - c^2t^2 = \frac{1}{a^2}$$



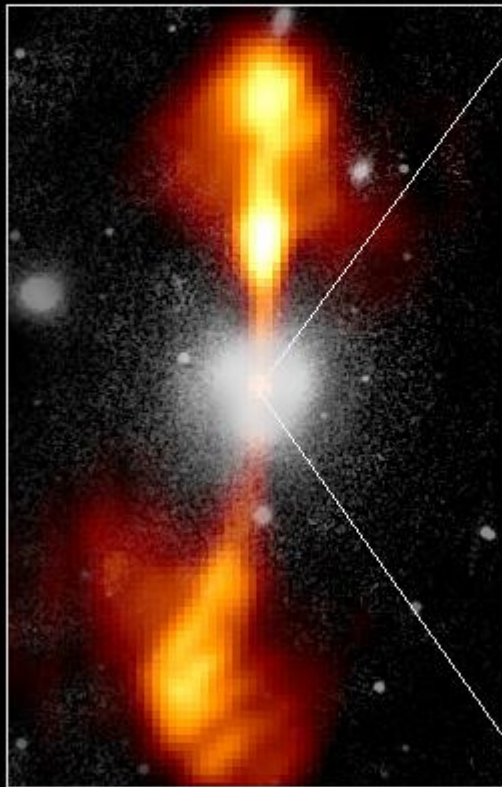


# Buraco Negro no núcleo da Galáxia NGC 4261

## Core of Galaxy NGC 4261

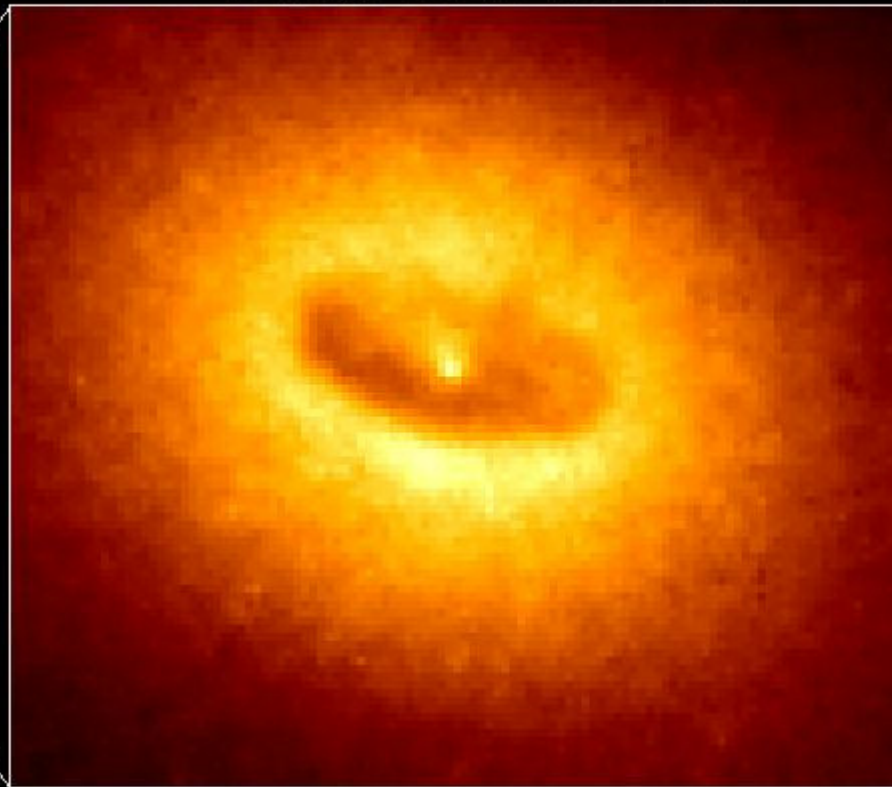
Hubble Space Telescope  
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image



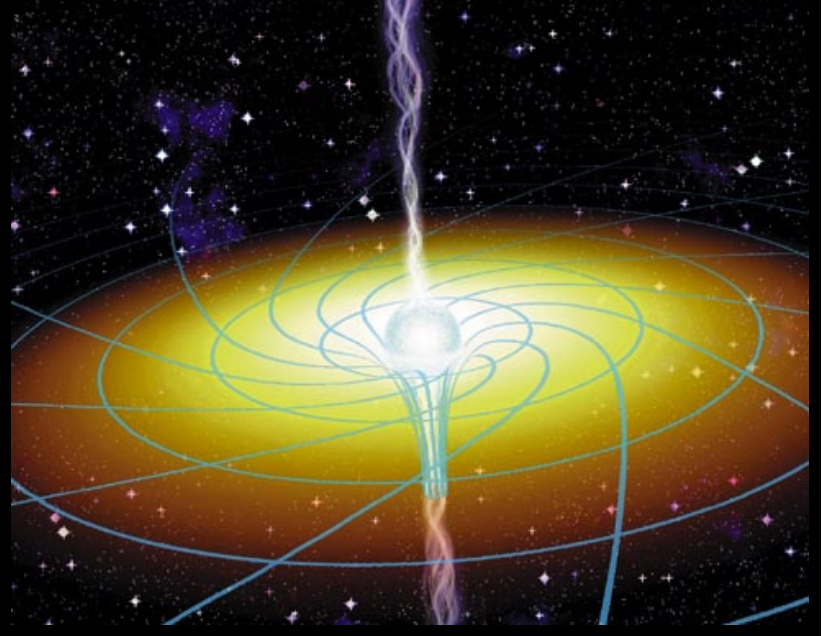
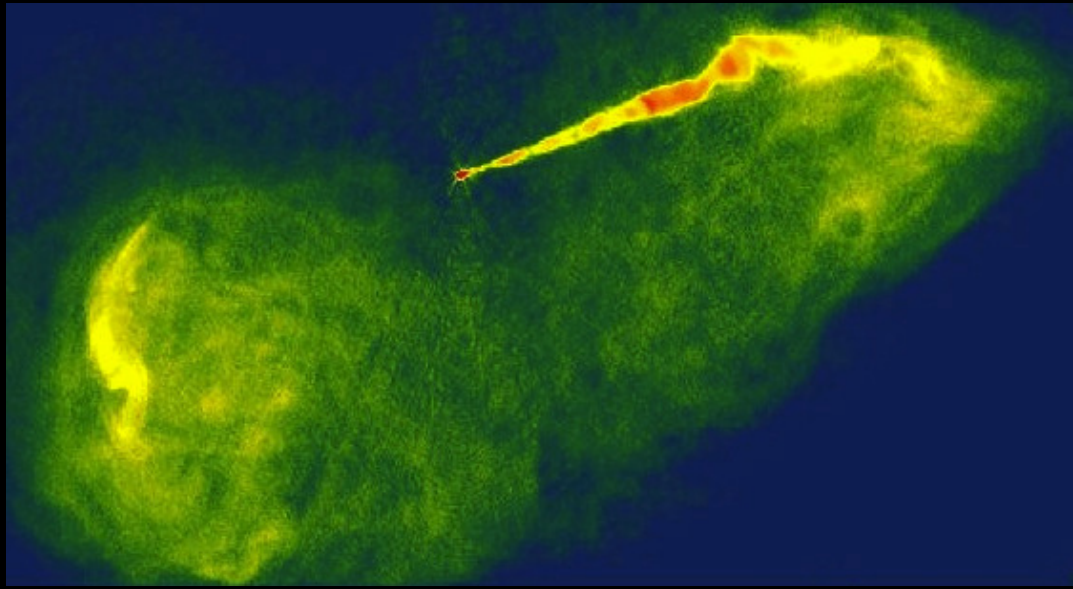
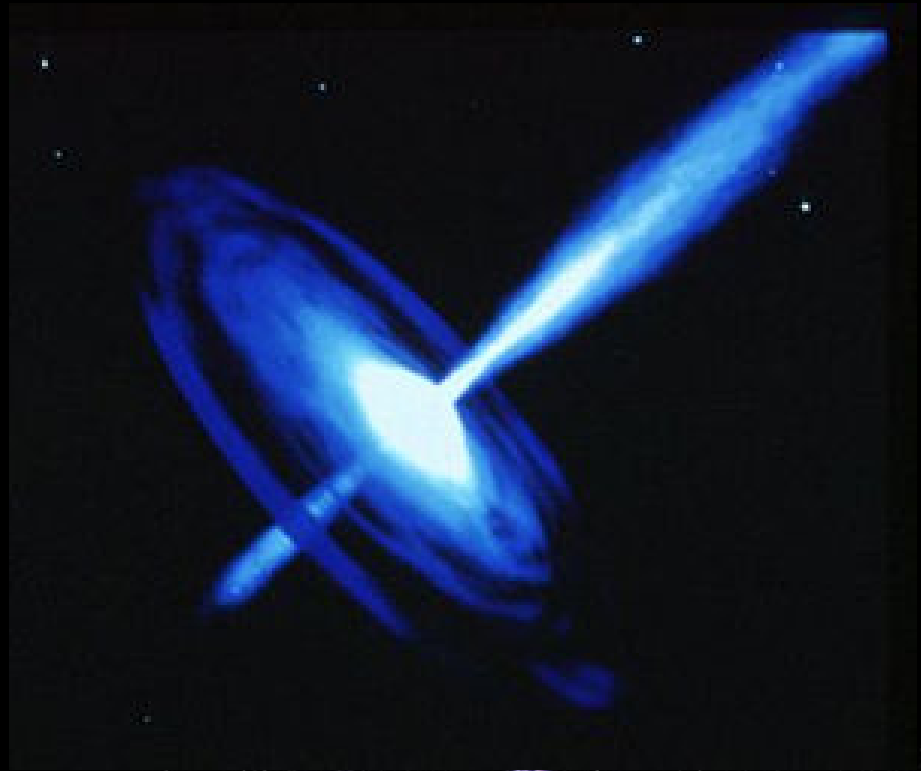
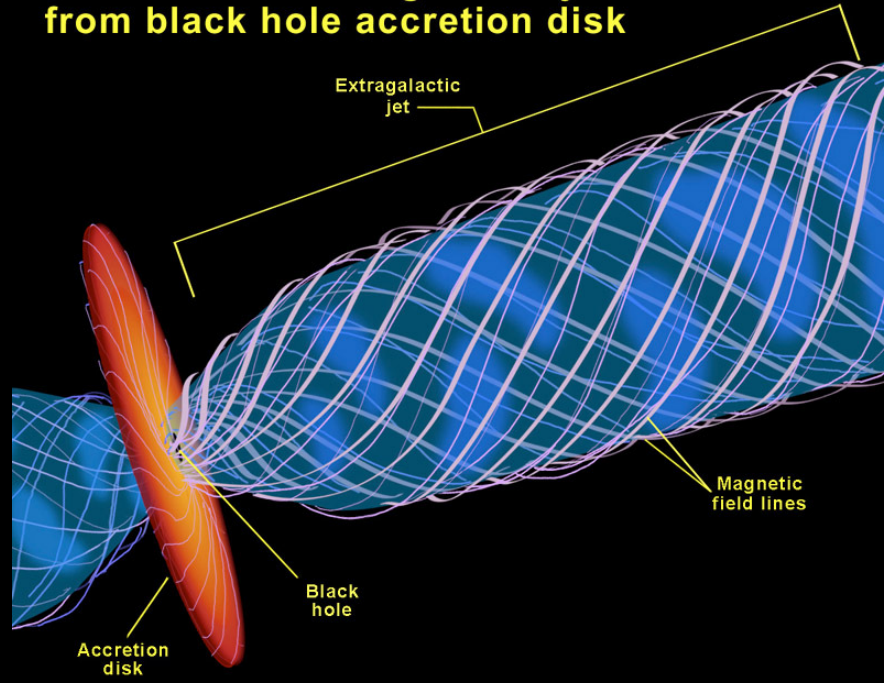
380 Arc Seconds  
88,000 LIGHT-YEARS

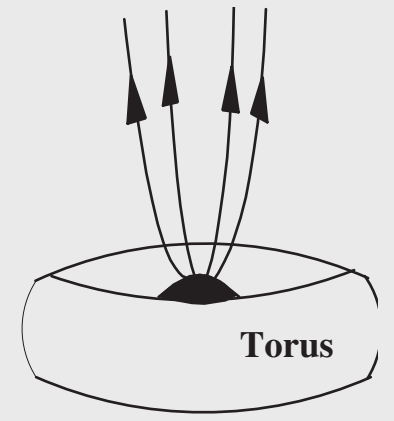
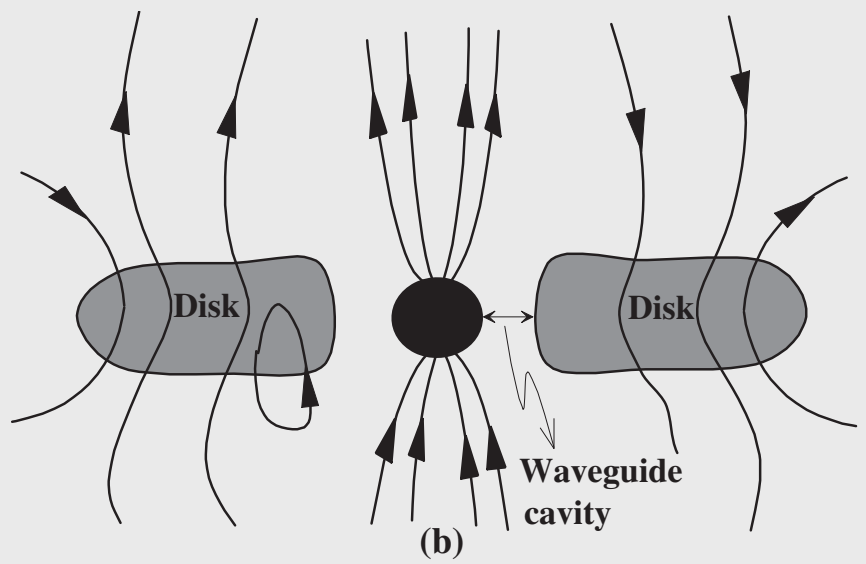
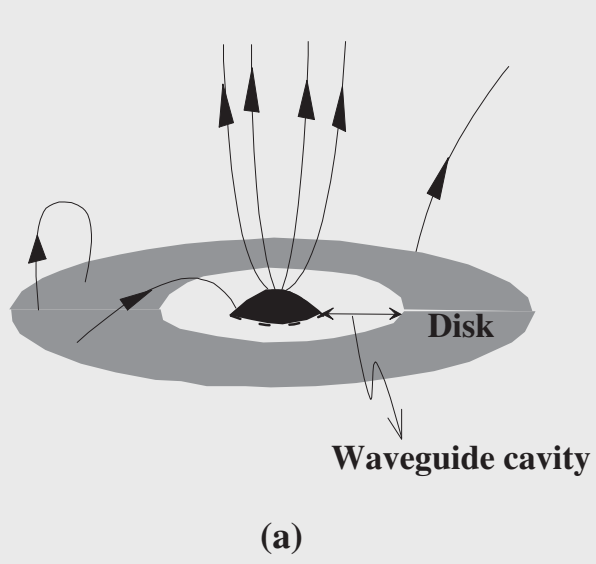
HST Image of a Gas and Dust Disk



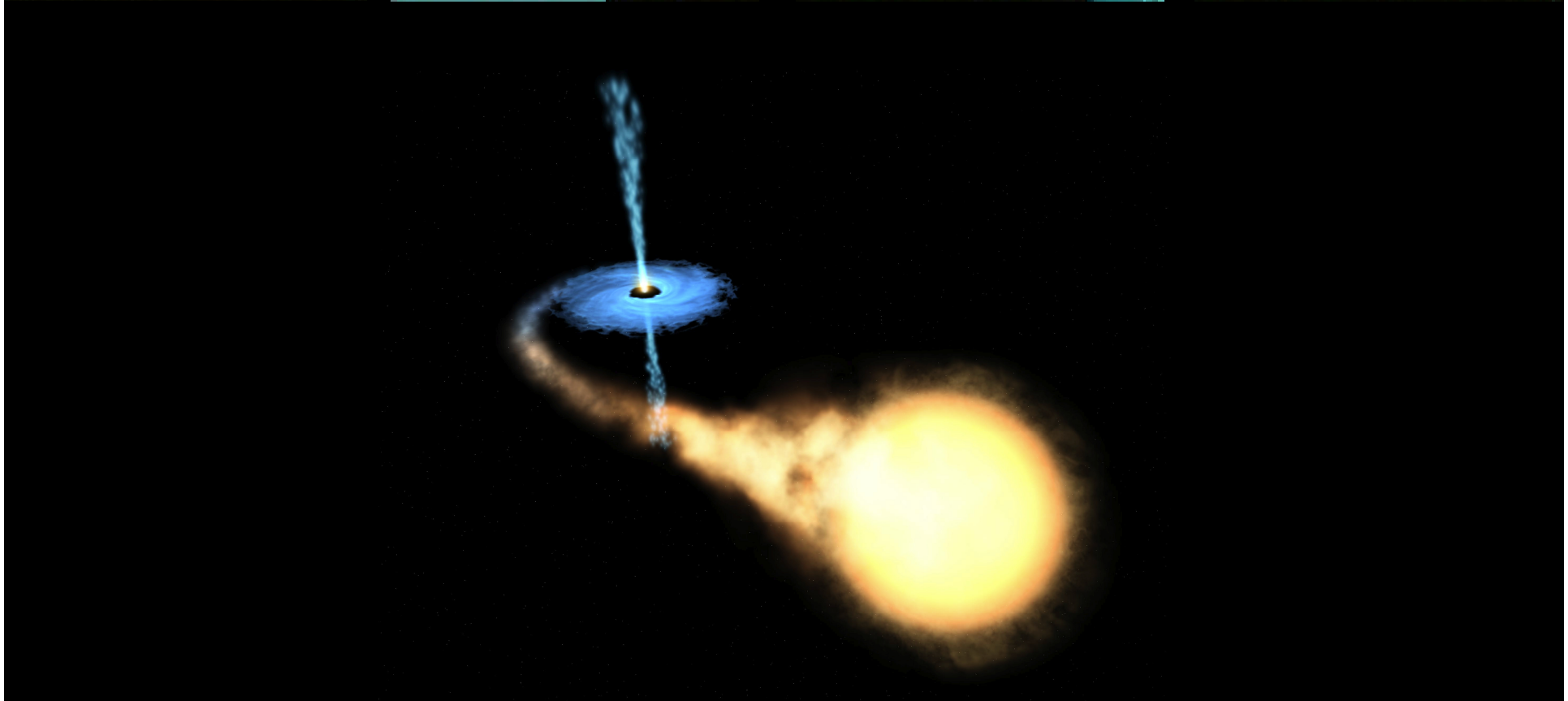
17 Arc Seconds  
400 LIGHT-YEARS

# Formation of extragalactic jets from black hole accretion disk

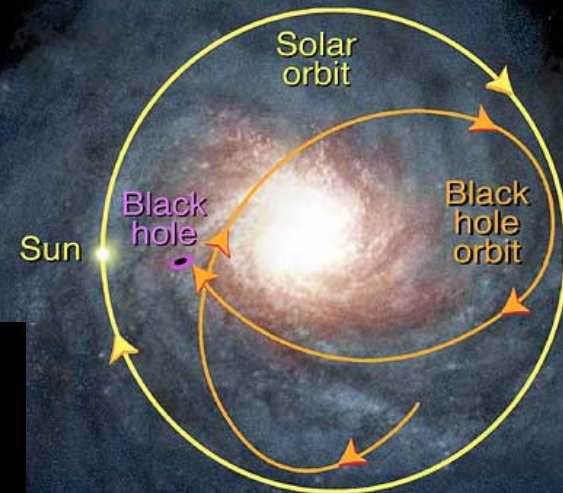




# Sistema Binário de Raios-X

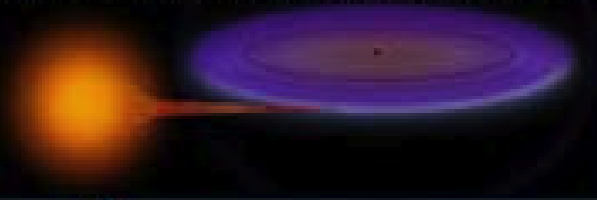


This is the path of a runaway black hole, called GRO J1655-4, believed to have been catapulted from a supernova explosion long ago. Both our Sun and the black hole orbit the center of our Milky Way galaxy.



## Black hole's wild ride through the Milky Way

The black hole, liberated from a globular cluster some 7 billion years ago, has been cannibalizing its companion star ever since.



Edge-on view of orbit



**XTE J1118+480**

$$M = 7 M_0$$

$$v = 145 \text{ km/s}$$

Artist's conception of the Milky Way



## Estrela de Neutrões.

Morte de estrelas com  $10 M_{\text{sol}} < \text{massa} < 45 M_{\text{sol}}$



Massa máxima estrelas de neutrões: 3 Msol

**Neutron Star RX J185635-3754**

HST • WFPC2

NASA and F. Walter (State University of New York at Stony Brook) • STScI-PRC00-35

Formada numa supernova visível a olho nú por chineses no ano 1000 a.c

30 000 000 000 mais densa que o aço. Velocidade: 100 x  $V_{\text{som}}$