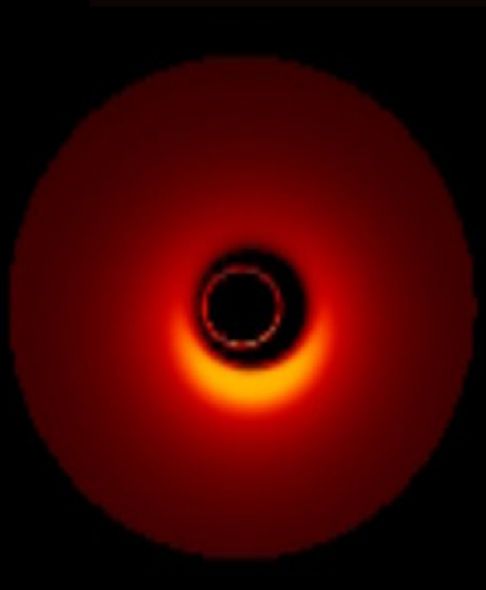
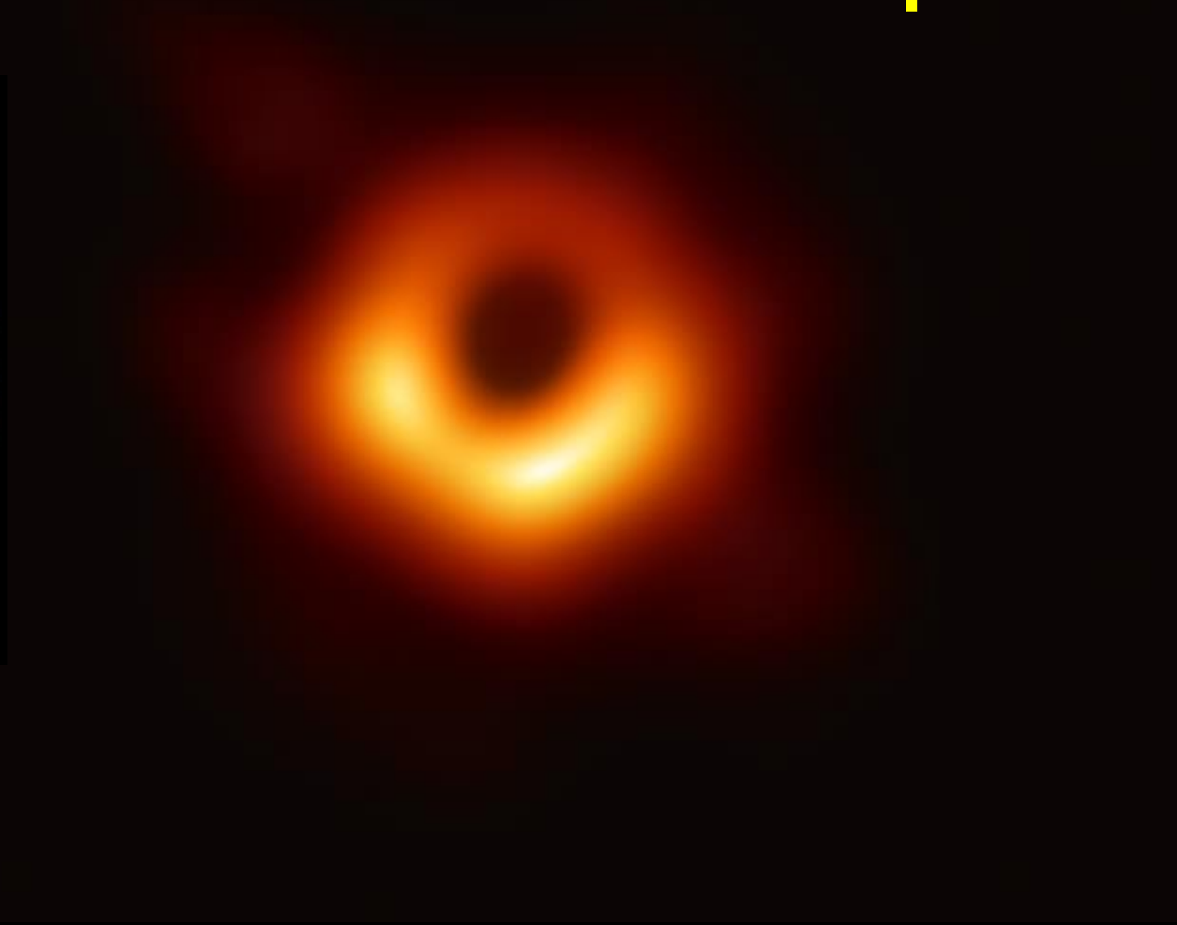
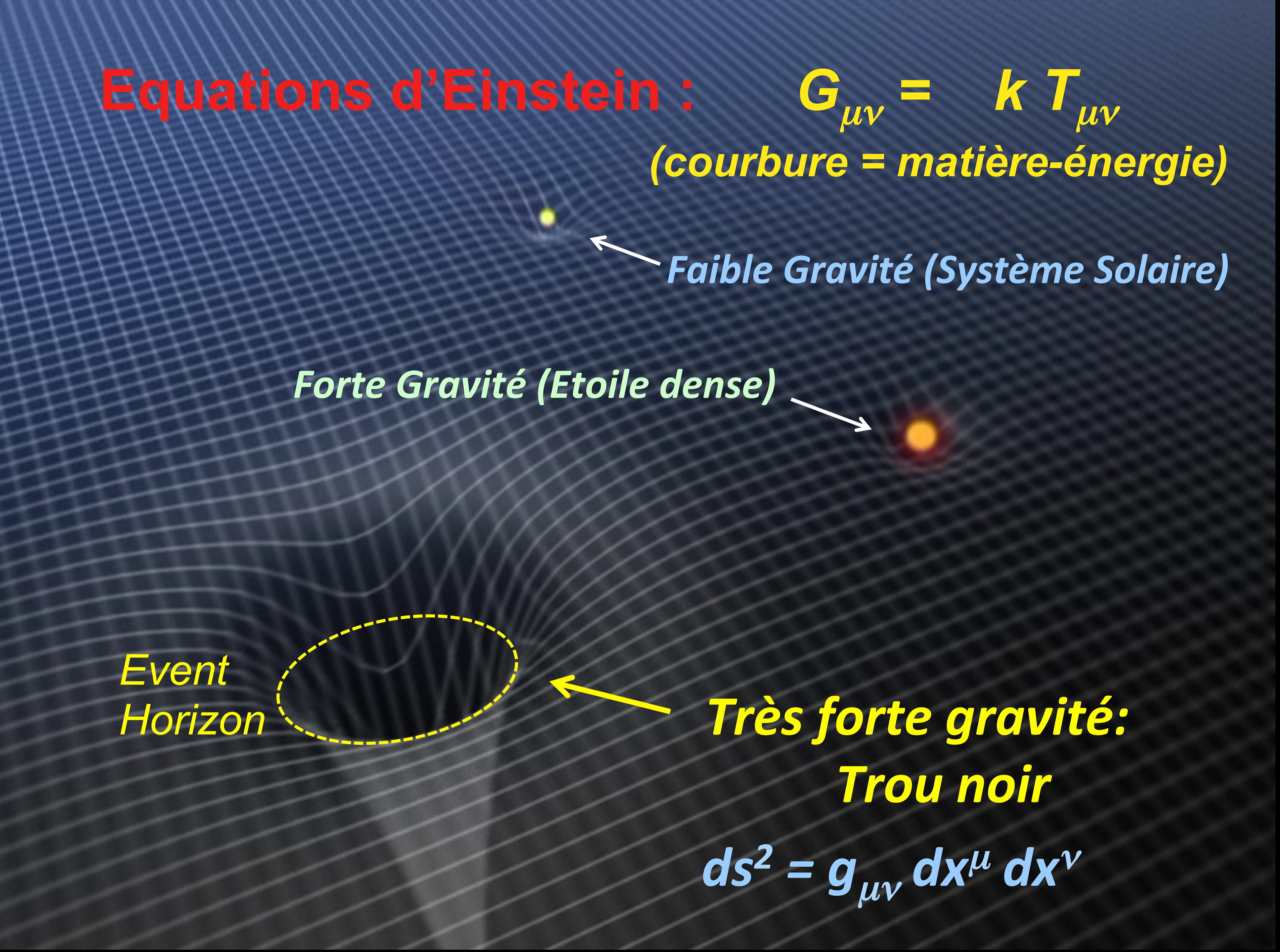
Voir les trous noirs :
de l’ordinateur au télescope





CPPM – janvier 2020

Jean-Pierre Luminet


Equations d'Einstein : $G_{\mu\nu} = k\, T_{\mu\nu}$
(courbure = matière-énergie)
Faible Gravité (Système Solaire)
Forte Gravité (Etoile dense)
Event Horizon
Très forte gravité: Trou noir
$ds^2 = g_{\mu\nu}\, dx^{\mu}\, dx^{\nu}$

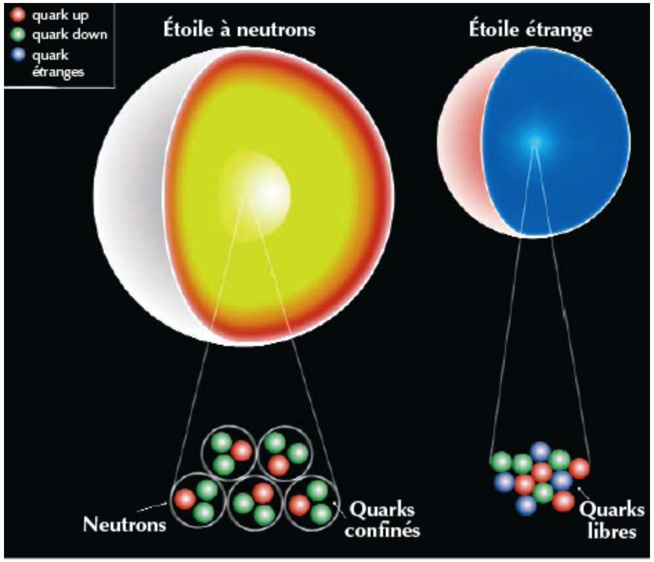
Effondrement gravitationnel

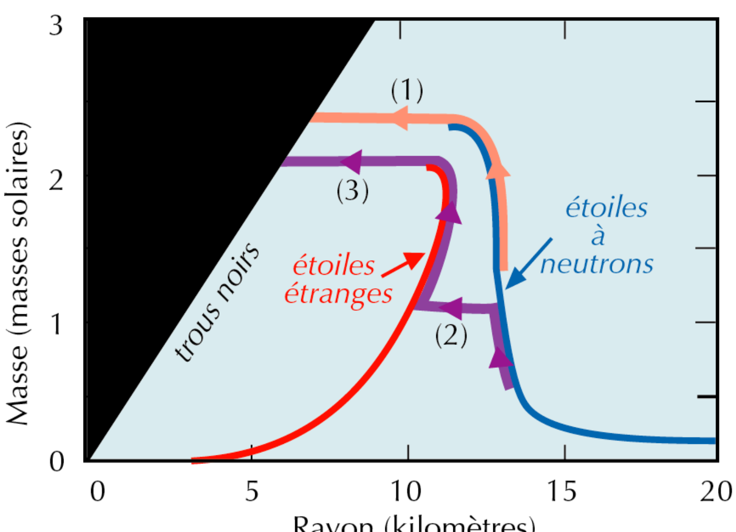
si $M_{cœur*} > 3\ M_S$

TROU NOIR !

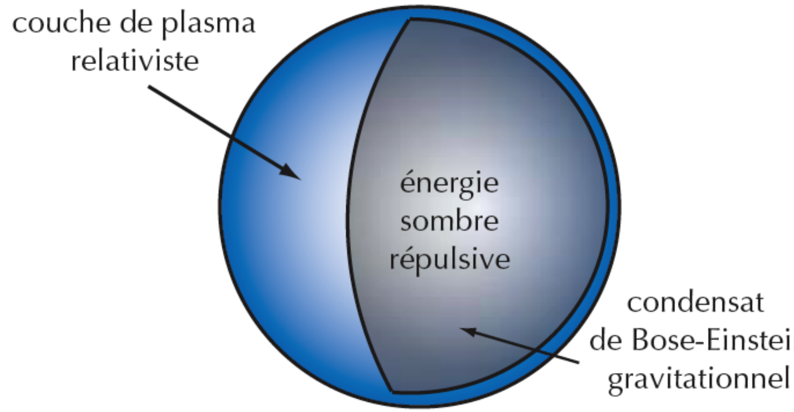
Alternatives au trou noir ?

Etoiles à quarks

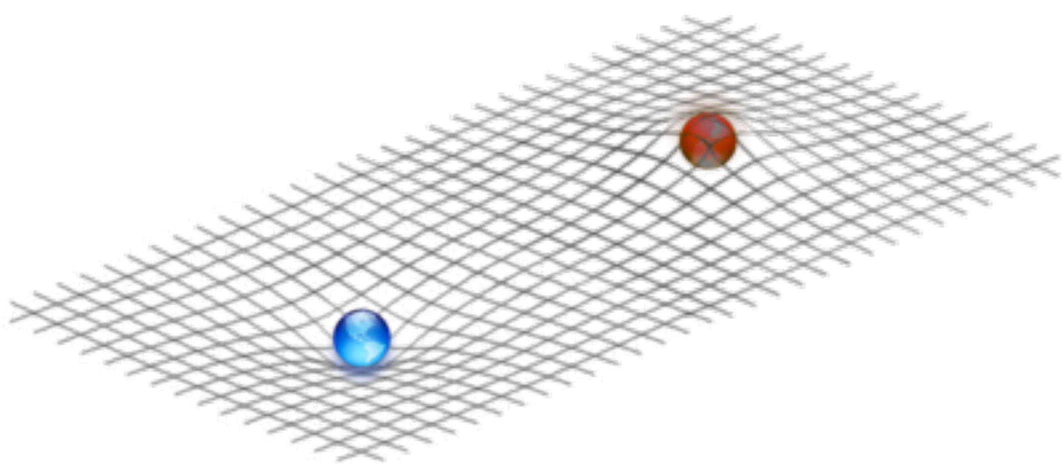




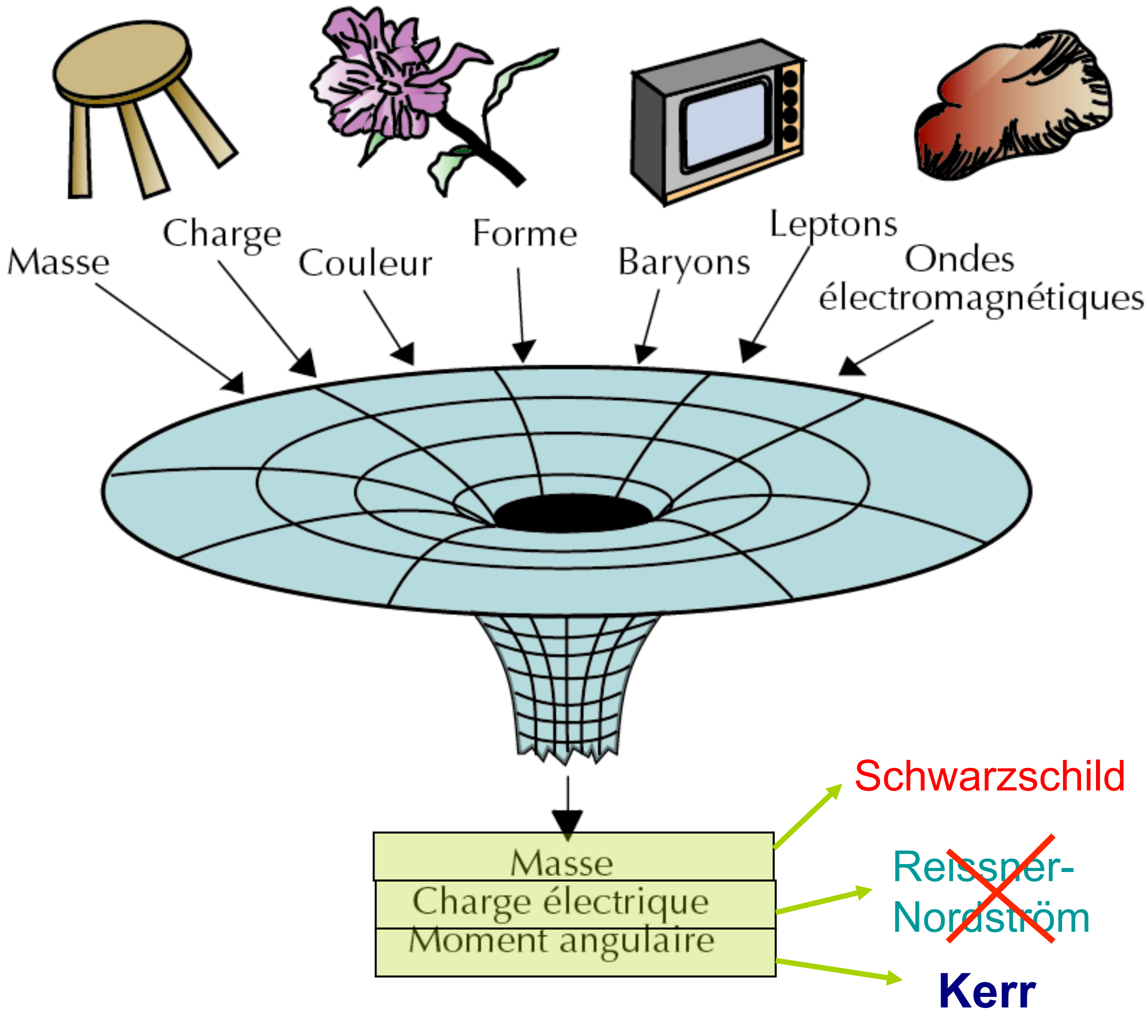
Gravastars



Théorie bimétrique modèle Janus



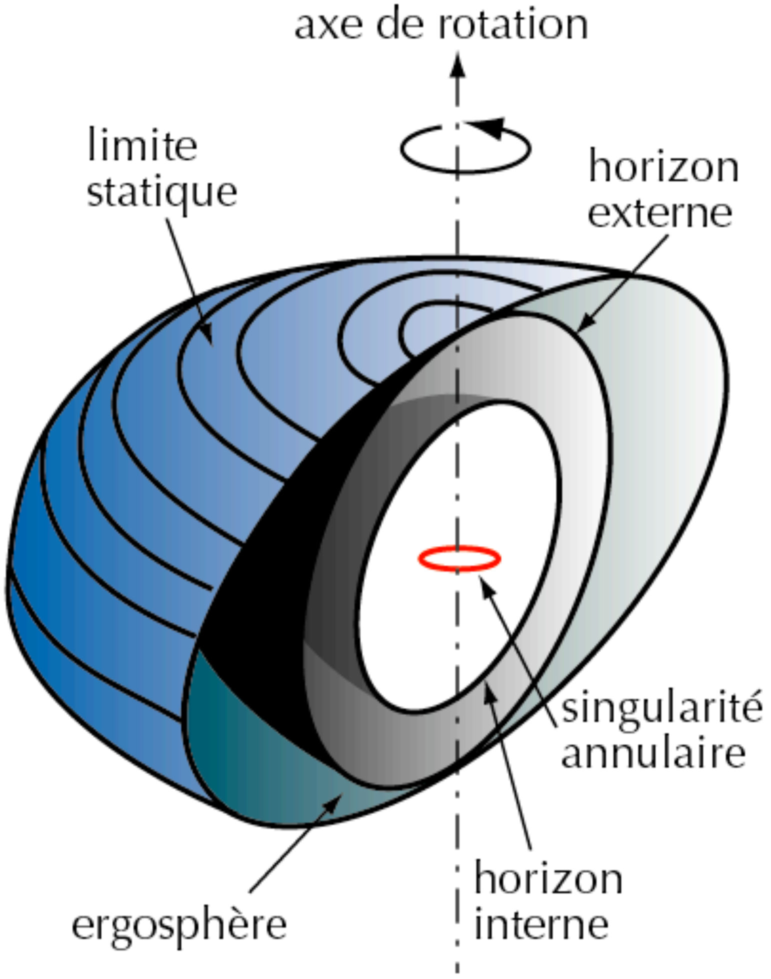
Conjecture « No hair » (Zeldovich, Novikov, Wheeler, 1960's)

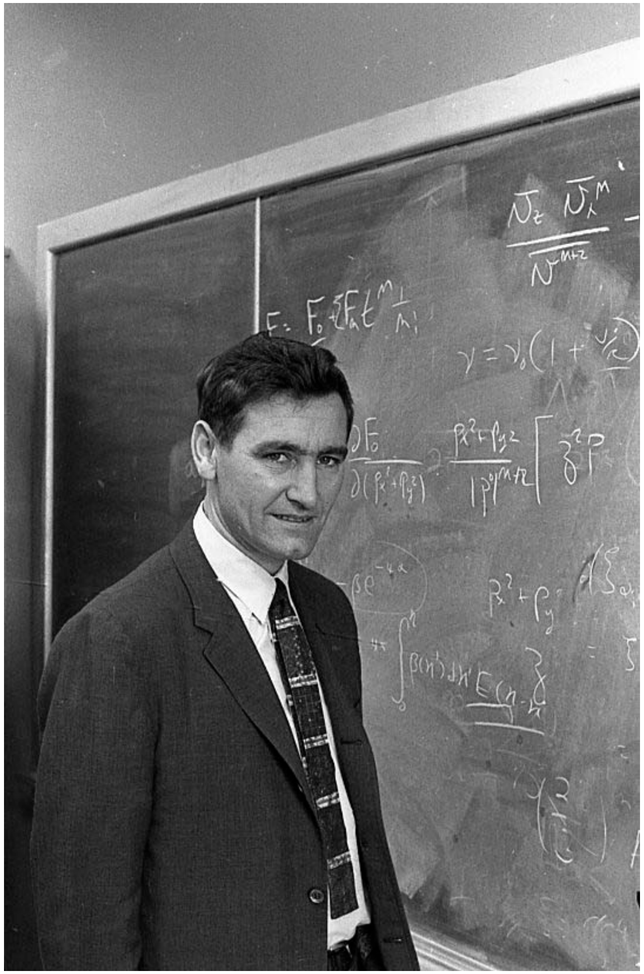


Théorème d'unicité (Carter, Hawking, Israël, 1970's)

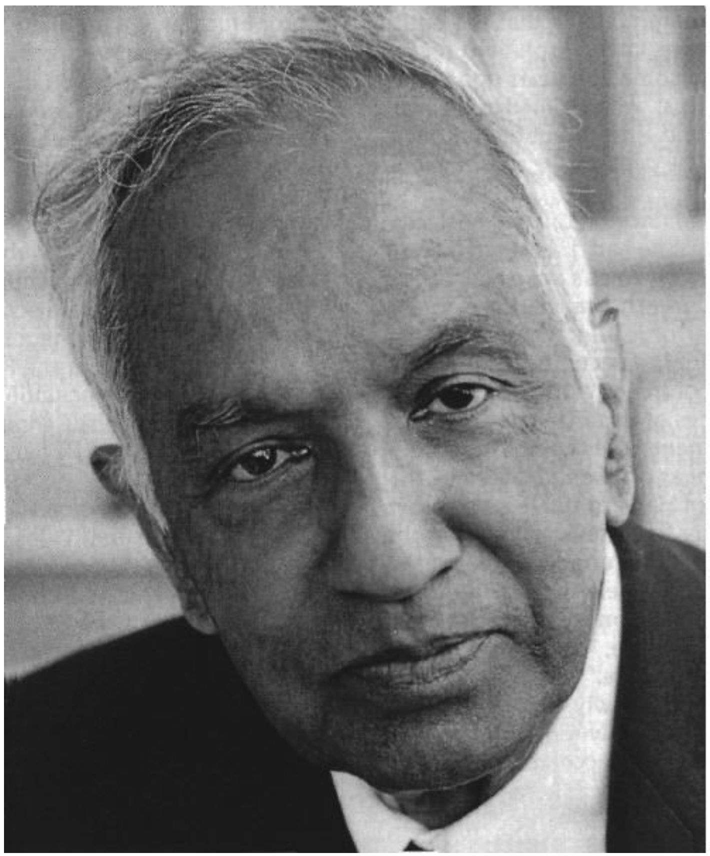
Le trou noir en rotation
(Kerr, 1963)

(a,M) avec a < M





S. Chandrasekhar
(Prix Nobel 1983)



« De toute ma vie de scientifique, longue de quarante-cinq ans, ma plus intense expérience a été de réaliser que la solution exacte aux équations d'Einstein de la relativité générale découverte par le mathématicien néo-zélandais Roy Kerr fournit une représentation absolument exacte d'une quantité innombrable de trous noirs qui peuplent l'univers. Ce frisson ressenti devant la beauté, le fait incroyable qu'une découverte résultant d'une recherche d'esthétique en mathématiques trouve son reflet exact dans la Nature, me persuade que la beauté est ce à quoi l'esprit humain est sensible dans ce qu'il a de plus fondamental et de plus profond. »

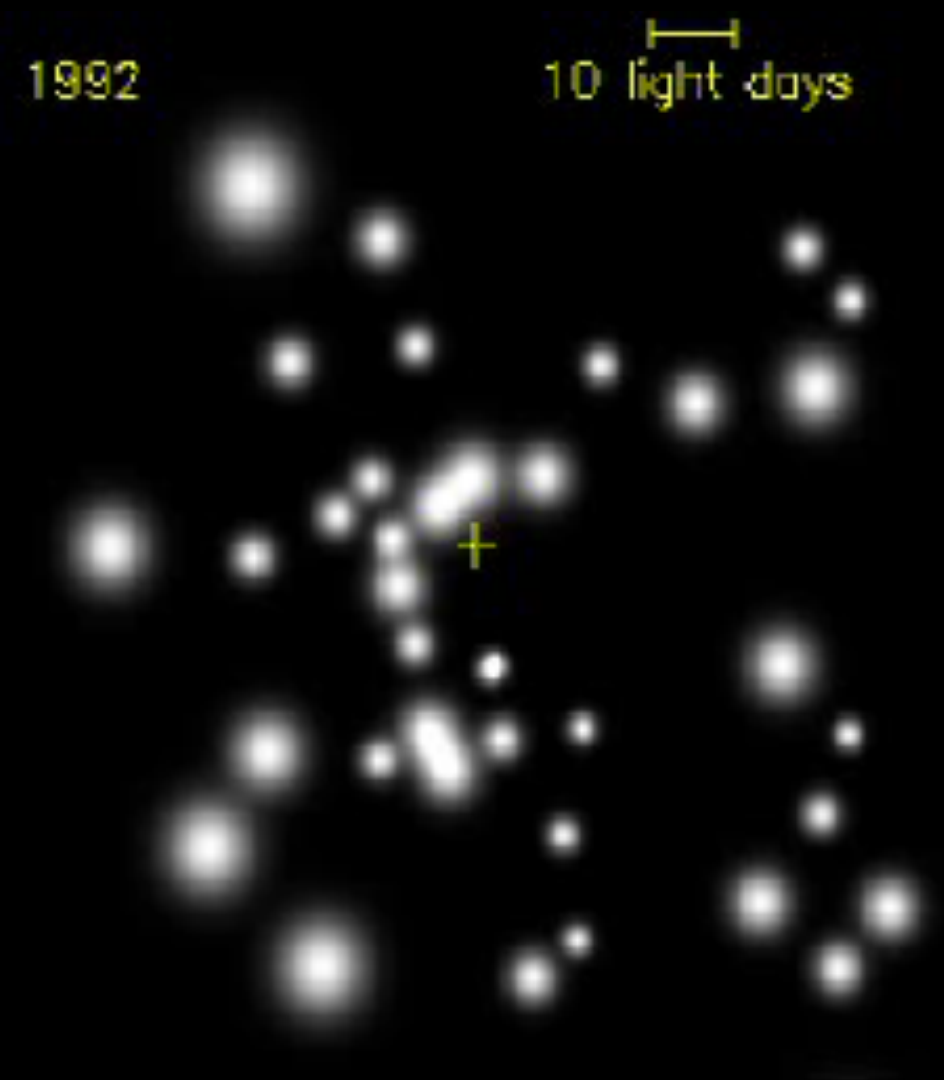

Signatures
indirectes

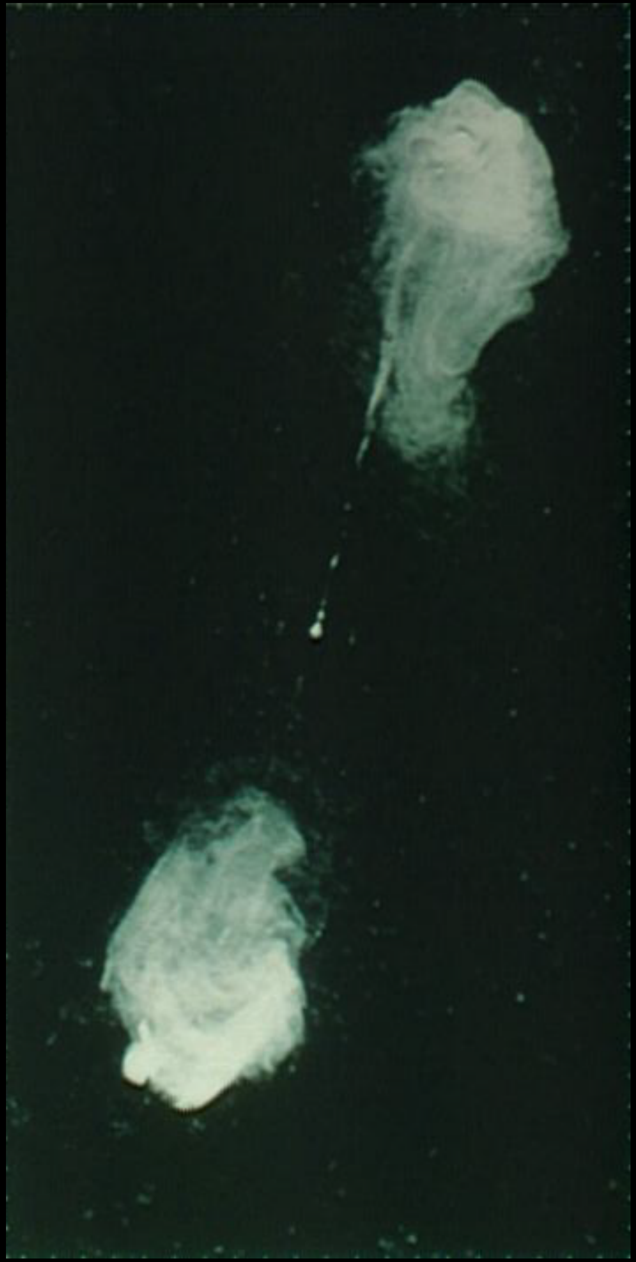
Détection des trous noirs stellaires

$(3\ M_S < M < 100\ M_S)$

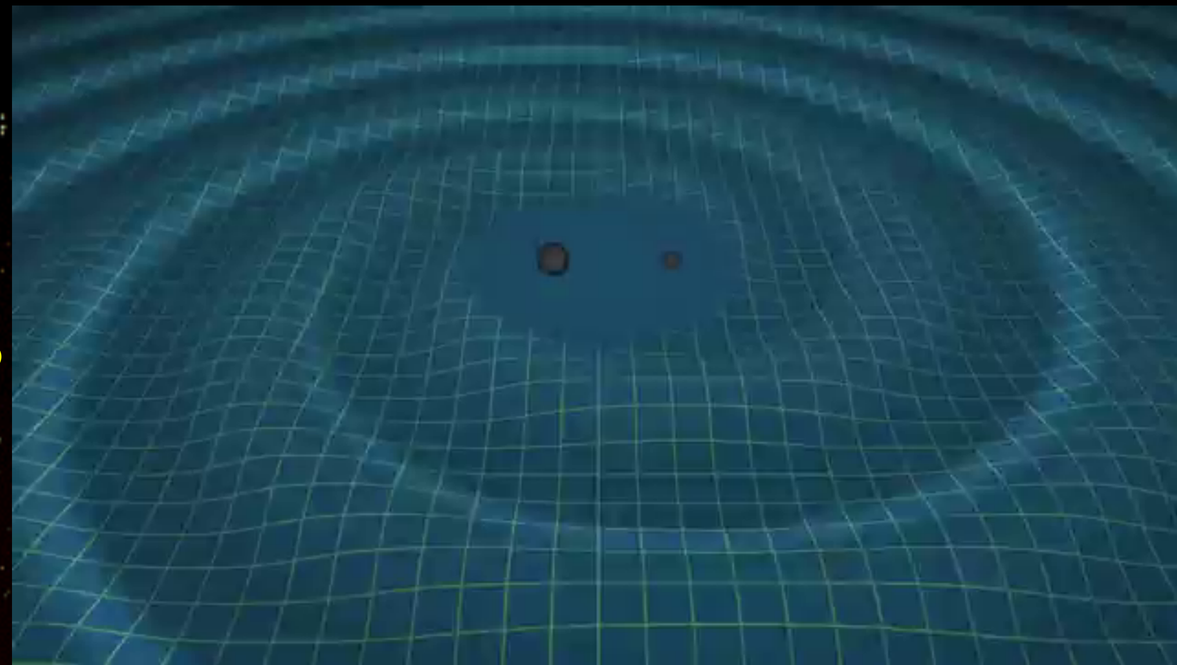
Source X binaire

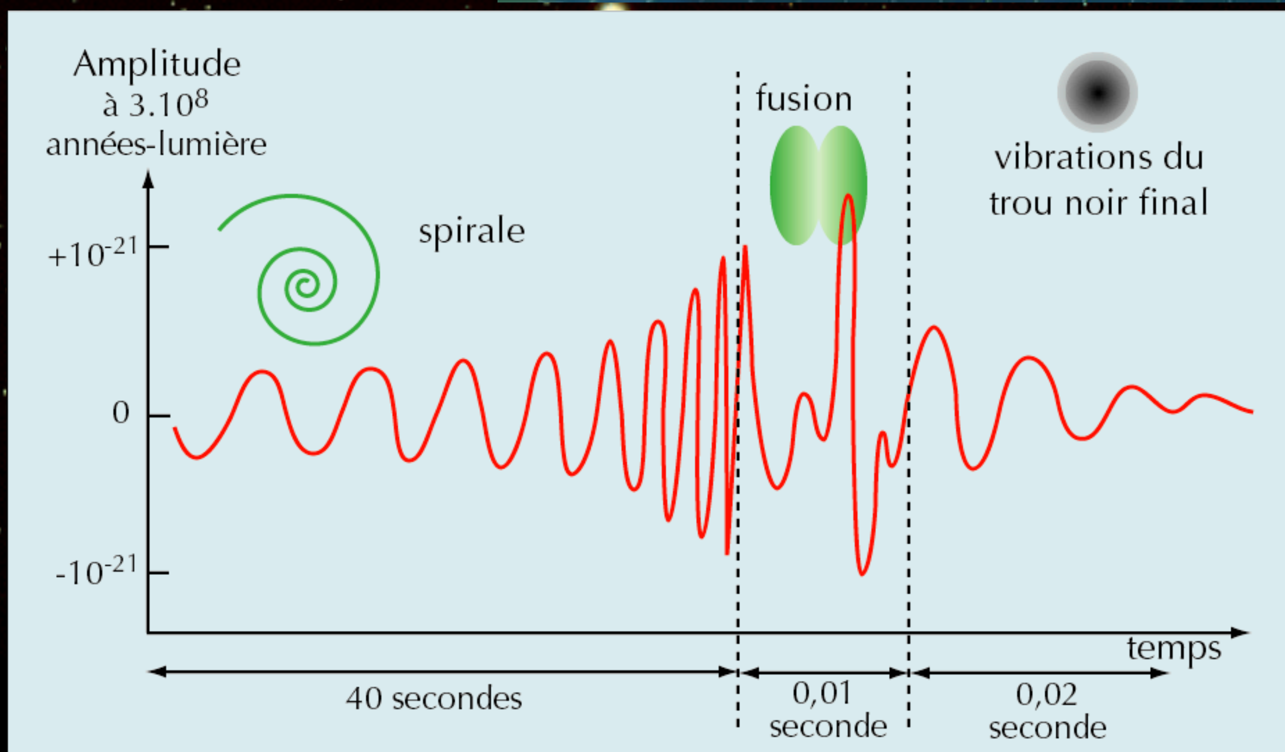
Trous noirs supermassifs (M > 10^6 M_S)



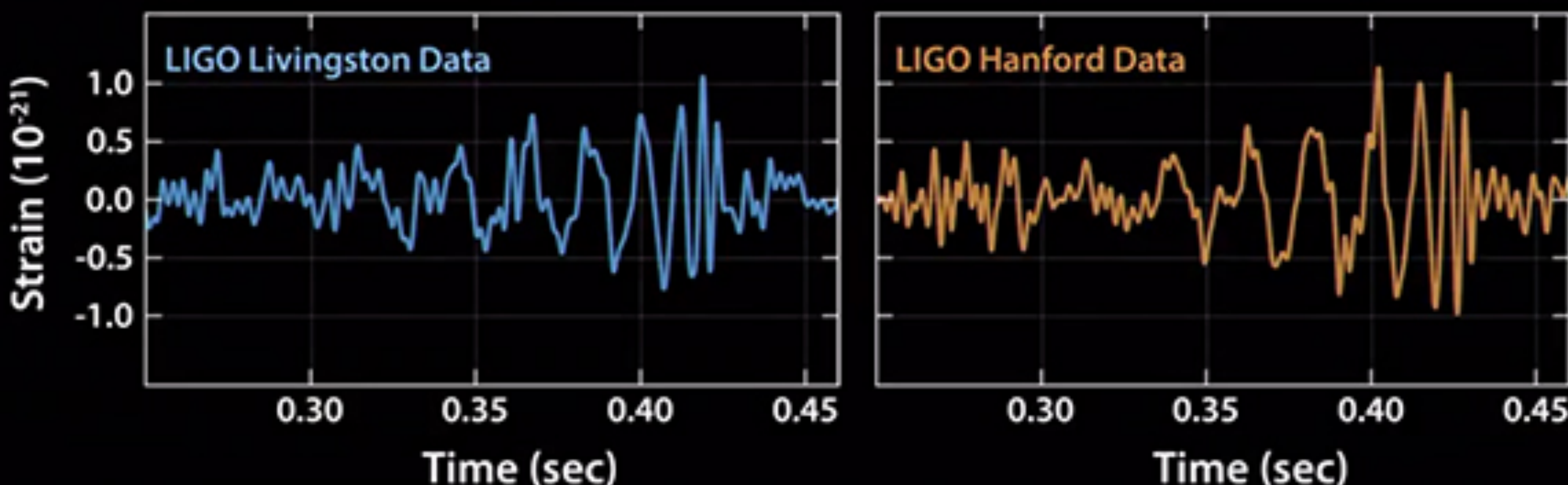


Ondes gravitationnelles



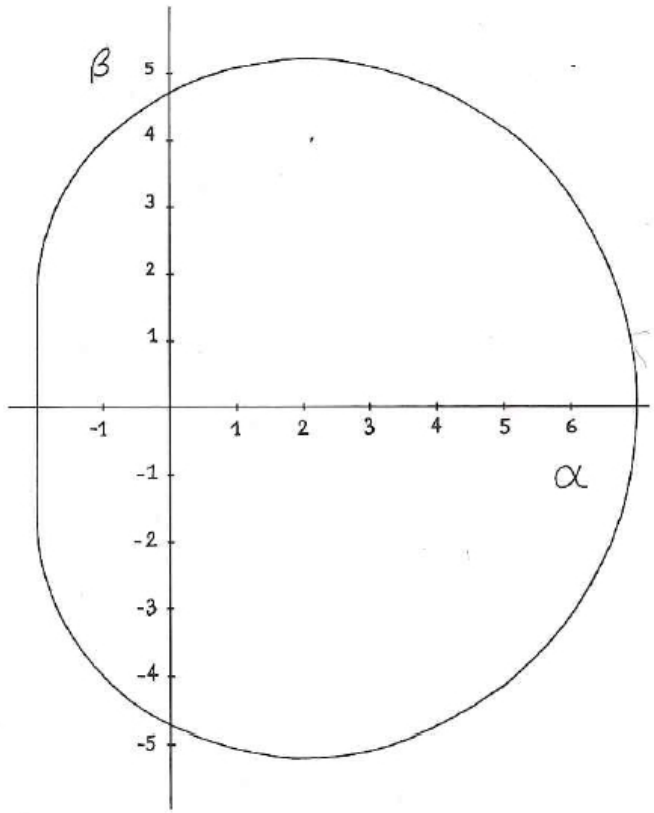


Evénement GW150914

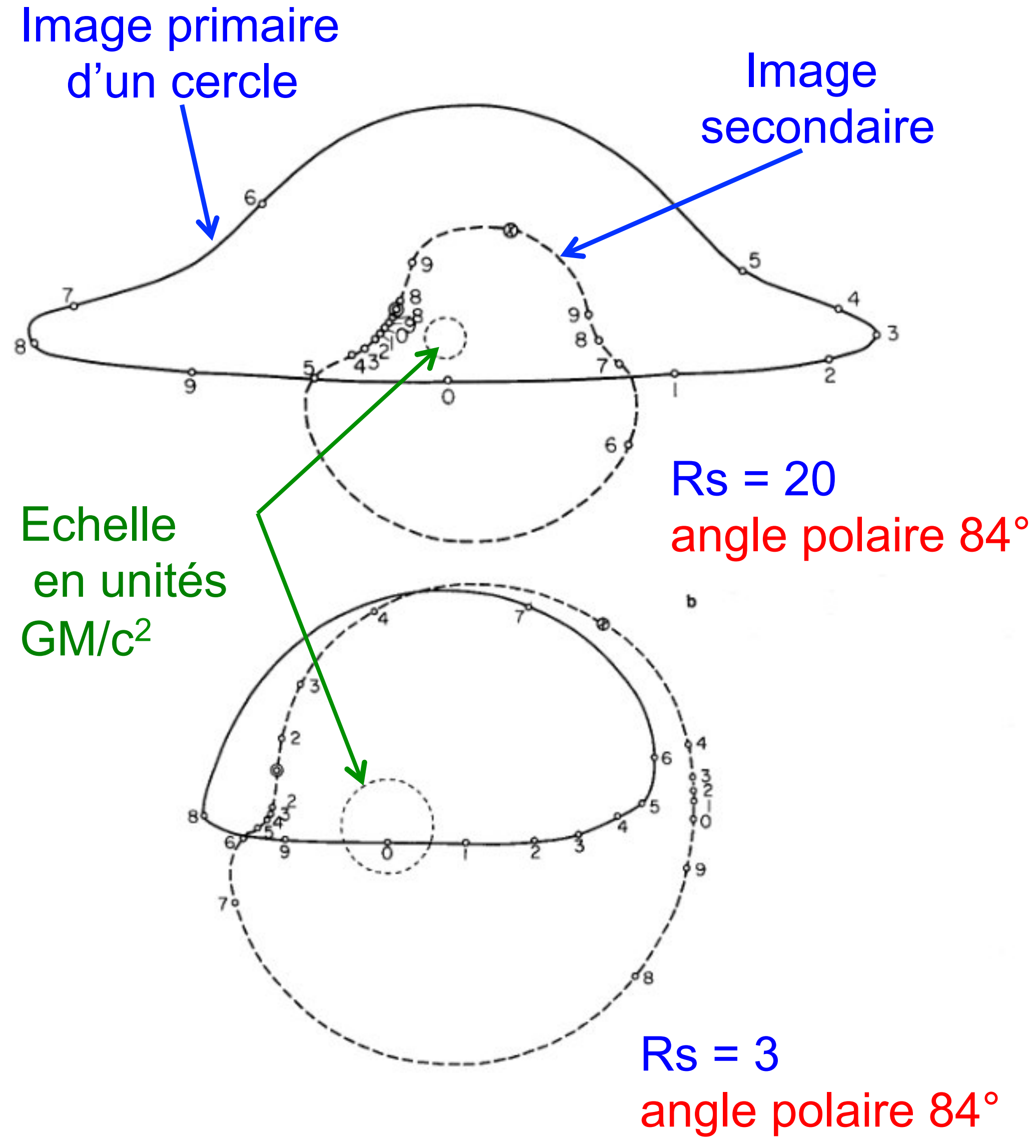



Voir l'ombre d'un
trou noir !

Premiers calculs en géométrie de Kerr



Contour apparent d'un trou noir de Kerr extrême (a=0.998M)
(Bardeen 1972)

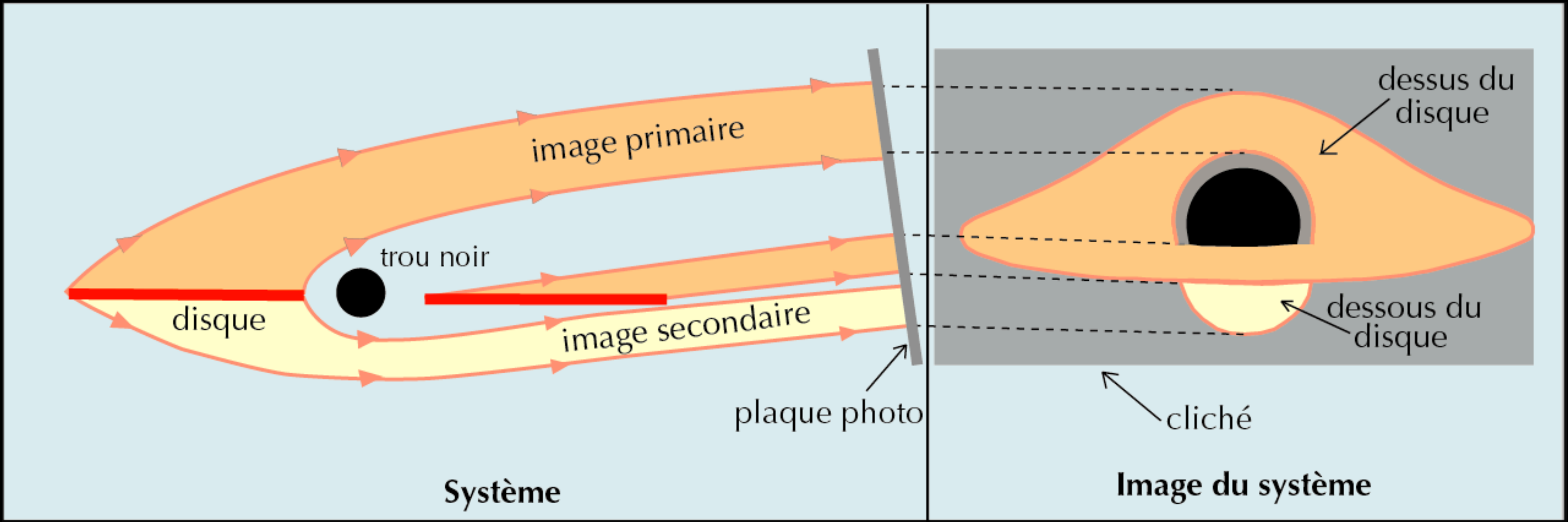


Forme d'une orbite stellaire circulaire
(Cunningham & Bardeen 1973)

Image d'anneaux circulaires lumineux autour d'un astre sphérique

Espace-temps plat
(Saturne)

Espace-temps courbe
(trou noir statique)



Astron. Astrophys. 75, 228–235 (1979)

ASTRONOMY AND ASTROPHYSICS

Image of a Spherical Black Hole with Thin Accretion Disk

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Received July 13, 1978

Summary. Black hole accretion disks are currently a topic of widespread interest in astrophysics and are supposed to play an important role in a number of high-energy situations. The present paper contains an investigation of the optical appearance of a spherical black hole surrounded by thin accretion disk. Isoradial curves corresponding to photons emitted at constant radius from the hole as seen by a distant observer in arbitrary direction have been plotted, as well as spectral shifts arising from gravitational and Doppler shifts. By the results of Page and Thorne (1974) the relative intrinsic intensity of radiation emitted by the disk at a given radius is a known function of the radius only, so that it is possible to calculate the exact distribution of observed bolometric flux. Direct and secundary images are plotted and the strong asymmetry in the flux distribution due to the rotation of the disk is exhibited. Finally a simulated photograph is constructed, valid for black holes of any mass accreting matter at any moderate rate.

Key words: black holes – accretion disks – geometrical optics

1. Introduction

The aim of the present paper is to provide a reply to the question that many people ask themselves about the optical appearance of a black hole.

In order to be visible a black hole has of course to be illuminated, like any ordinary body. One of the simplest possibilities would be for the black hole to be illuminated by a distant localized source which in practise might be a companion star in a loosely bound binary system. A more interesting and observationally important possibility is that in which the light source is provided by an emitting accretion disk around the black hole, such as may occur in a tight binary system with overflow from the primary, and perhaps also on a much larger scale in a dense galactic nucleus. The general problem of the optical appearance of black holes is related to the analysis of trajectories in the gravitational field of black holes. For a spherical, static, electrical field-free black hole (whose external space-time geometry is described by the Schwarzschild metric) this problem is already well known (Hagihara, 1931; Darwin, 1959; for a summary, see Misner et al., 1973 [MTW]). In Sect. 2 we give only a brief outline of it with basic equations, trying to point out the major features which will appear later. All our calculations are done in the geometrical optics approximation (for a study of wave-aspects, see Sanchez, 1977). In Sect. 3 we calculate the apparent shape of circular rings orbiting a non-rotating black hole and the results are depicted in Figs. 5–6. In Sect. 4 we recall the standard analysis by Novikov and Thorne (1973) of the problem of energy release by a thin accretion disk in a general astrophysical context, focusing attention more particularly on the analytic solution for the surface distribution of energy release that was derived by Page and Thorne (1974) in the limiting case of a sufficiently low accretion rate. In terms of this idealized (but in appropriate circumstances, realistic) model, we calculate the distribution of bolometric flux as seen by distant observers at various angles above the plane of the disk (Figs. 9–11).

2. Image of a Bare Black Hole

Before analyzing the general problem of a spherical black hole surrounded by an emitting accretion disk, it is instructive to investigate a more simple case in which all the dynamics are already contained, namely the problem of the return of light from a bare black hole illuminated by a light beam projected by a distant source. It is conceptually interesting to calculate the precise apparent pattern of the reflected light, since some of the main characteristic features of the general geometrical optics problem are illustrated thereby.

The Schwarzschild metric for a static pure vacuum black hole may be written as:

$$ds^2 = -\left(1-\frac{2M}{r}\right)dt^2 + \left(1-\frac{2M}{r}\right)^{-1}dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\phi^2) \qquad (1)$$

where r, θ, and ϕ are spherical coordinates and the unit system is chosen such that $G=c=1$. M is the relativistic mass of the hole (which has the dimensions of length). In this standard coordinate system the horizon forming the surface of the hole is located at the Schwarzschild radius $r_s = 2M$.

One can take advantage of the spherical symmetry to choose the "equatorial" plane $\theta = \pi/2$ so as to contain any particular photon trajectory under consideration. The trajectories will then satisfy the differential equation:

$$\left\{\frac{1}{r^2}\left(\frac{dr}{d\phi}\right)\right\}^2 + \frac{1}{r^2}\left(1-\frac{2M}{r}\right) = 1/b^2. \qquad (2)$$

The second term in the left member can be interpreted as an effective potential $V(r)$, in analogy with the non-relativistic mechanics. The motion does not depend on the photon energy E and on its angular momentum L separately, but only on the ratio $L/E = b$, which is the impact parameter at infinity.

Let the observer be in a direction fixed by the polar angle ϕ_0 in the Schwarzschild metric, at a radius $r_0 \gg M$. The rays emitted by a distant source of light and deflected by the black hole intersect the observer's detector (for example a photographic plate) at a

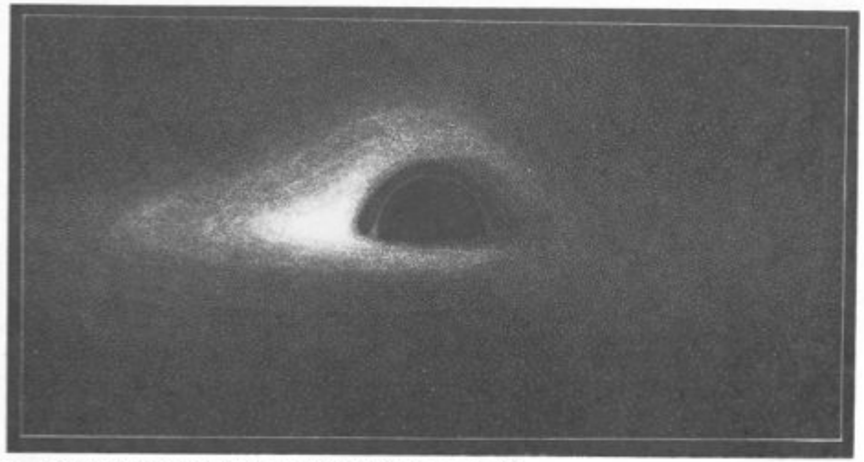

Fig. 11. Simulated photograph of a spherical black hole with thin accretion disk

impact parameter of the visible part of the secundary image) in Eqs. (15) and (19).

The results are taken into account in Fig. 11, which represents the final result of this paper, namely a simulated "bolometric photography" of a static black hole with thin accretion disk.

Figures 9–11 are valid for a large number of black hole situations, i.e. black holes with any mass accreting matter at any rate sufficiently far below the Eddington limit. Thus our picture could represent many relatively weak sources, such as for instance the supermassive black hole whose existence in the nucleus of M 87 has been suggested recently by Young et al. (1978).

It is important to point out that for more spectacular sources such as quasars and Seyfert galaxies, the theory has not yet been developed enough to provide reliable models that could be visualized analogously.

Acknowledgements. I am greatly endebted to B. Carter for help and encouragement; I am grateful to J. Diaz Alonso and N. Sanchez for fruitful discussions.

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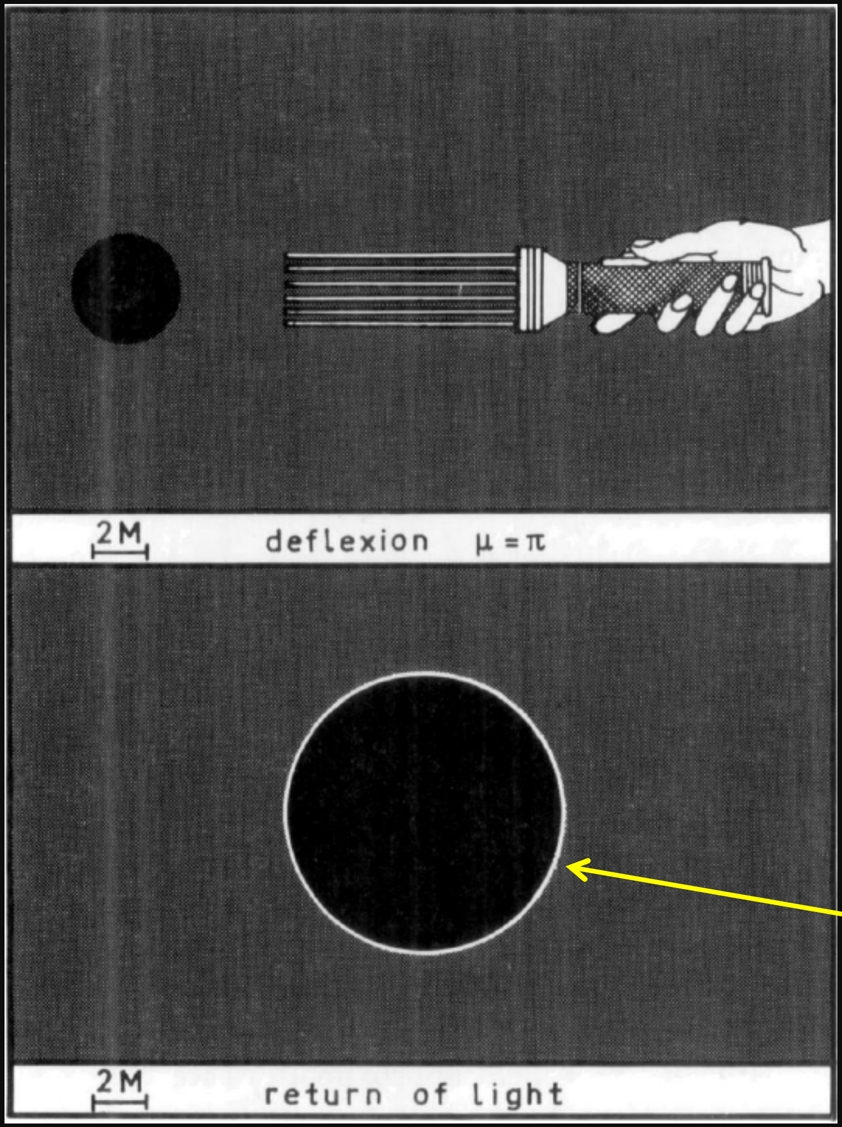
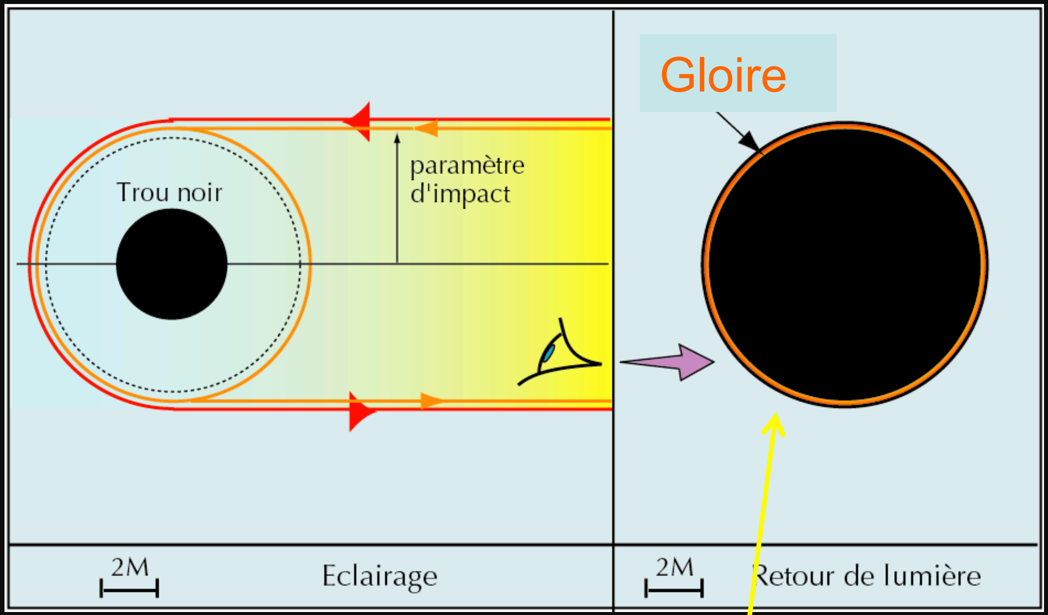
Young, P.J., Westphal, J.A., Kristian, J., Wilson, C.P., Landauer, F.P.: 1978, *Astrophys. J.* **221**, 721





Ombre d'un trou noir
de Schwarzschild
et anneau de photons

Facteur d'agrandissement $\sqrt{27}/2 \sim 2.6$

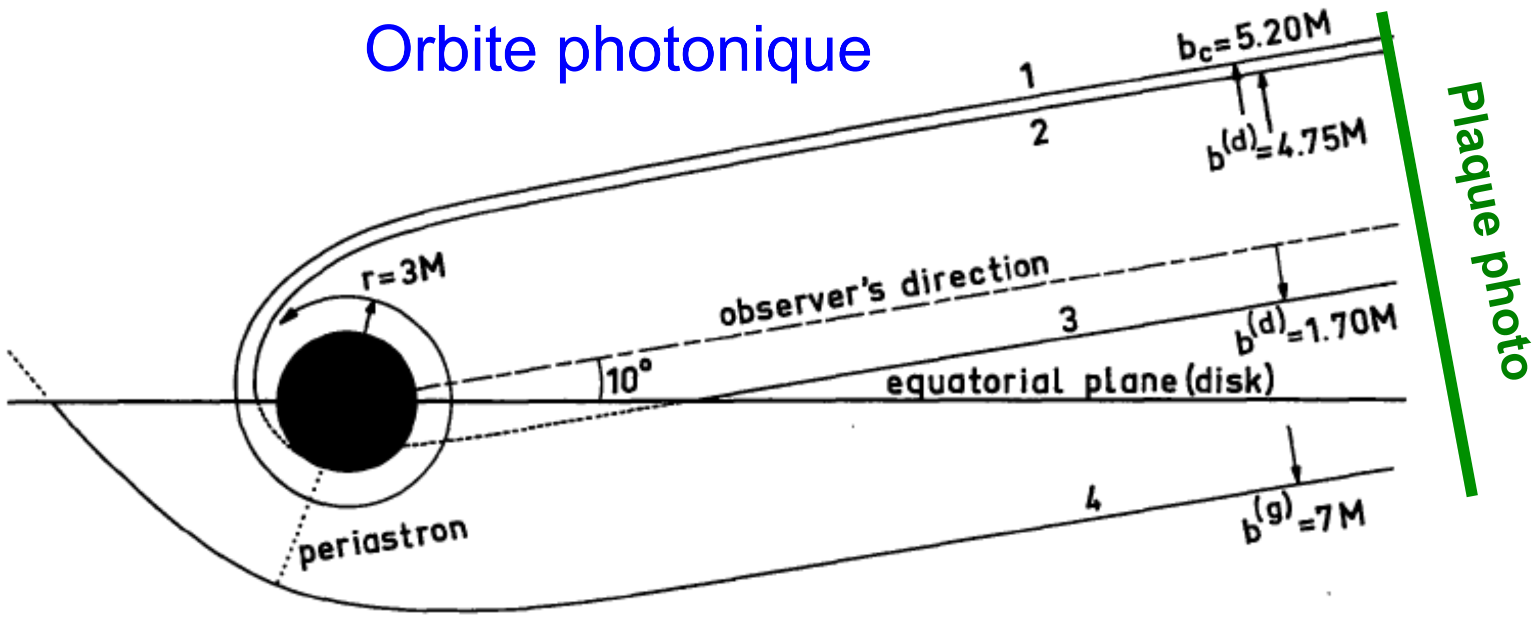
Etape 1 : Intégration des trajectoires des photons

$$ds^2 = -\left(1-\frac{2M}{r}\right)dt^2 + \left(1-\frac{2M}{r}\right)^{-1}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

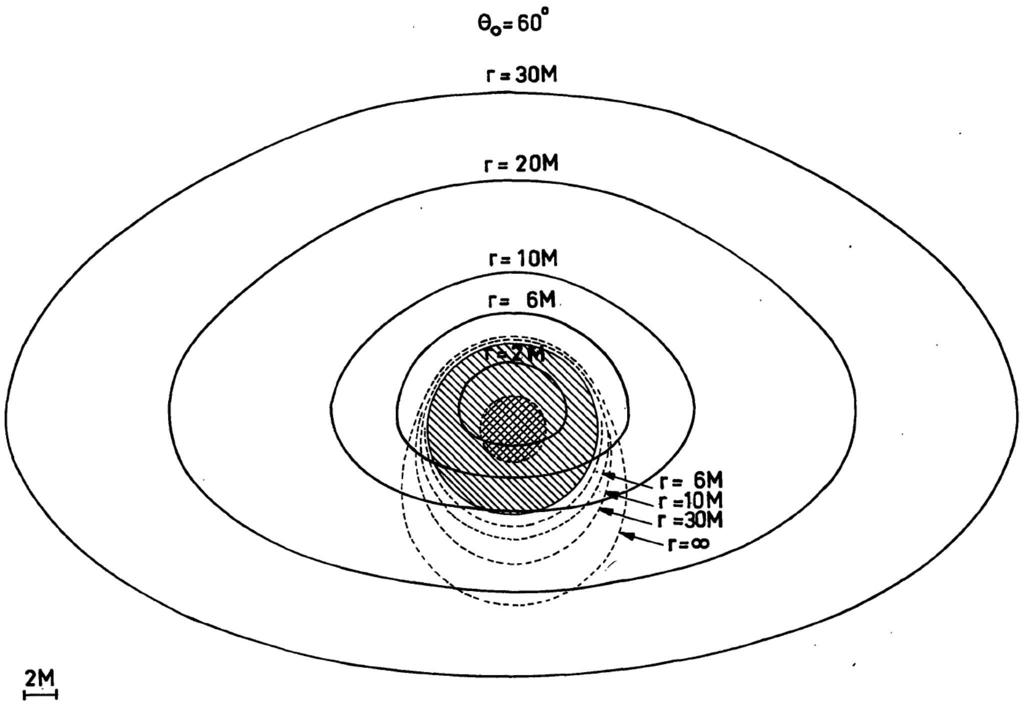
Métrique de Schwarzschild

$$\left\{\frac{1}{r^2}\left(\frac{dr}{d\phi}\right)\right\}^2 + \frac{1}{r^2}\left(1-\frac{2M}{r}\right) = 1/b^2 \longrightarrow$$ Parameter d'impact

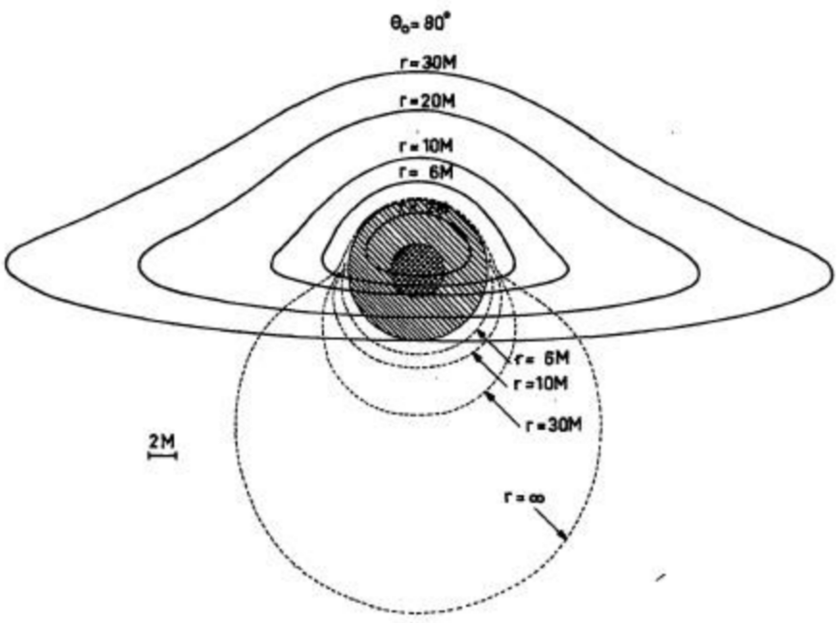
Orbite photonique



Courbes isoradiales



Angle de vue équatorial 30°



Angle de vue équatorial 10°

Etape 2 : Modèle relativiste de disque d'accrétion mince (Page & Thorne, 1974)

Flux Intrinsèque :

$$F_S = \frac{3\,M\,\dot{M}}{8\pi}\,\frac{1}{(r^* - 3)\,r^{*5/2}}\left[\sqrt{r^*} - \sqrt{6} + \frac{\sqrt{3}}{3}\,\mathrm{Log}\left\{\frac{(\sqrt{r^*} + \sqrt{3})\,(\sqrt{6} - \sqrt{3})}{(\sqrt{r^*} - \sqrt{3})\,(\sqrt{6} + \sqrt{3})}\right\}\right]$$

Taux d'accrétion   r/M

F_S est maximum à r* ~9.55

Etape 3 : Décalages spectraux (Einstein, Doppler)

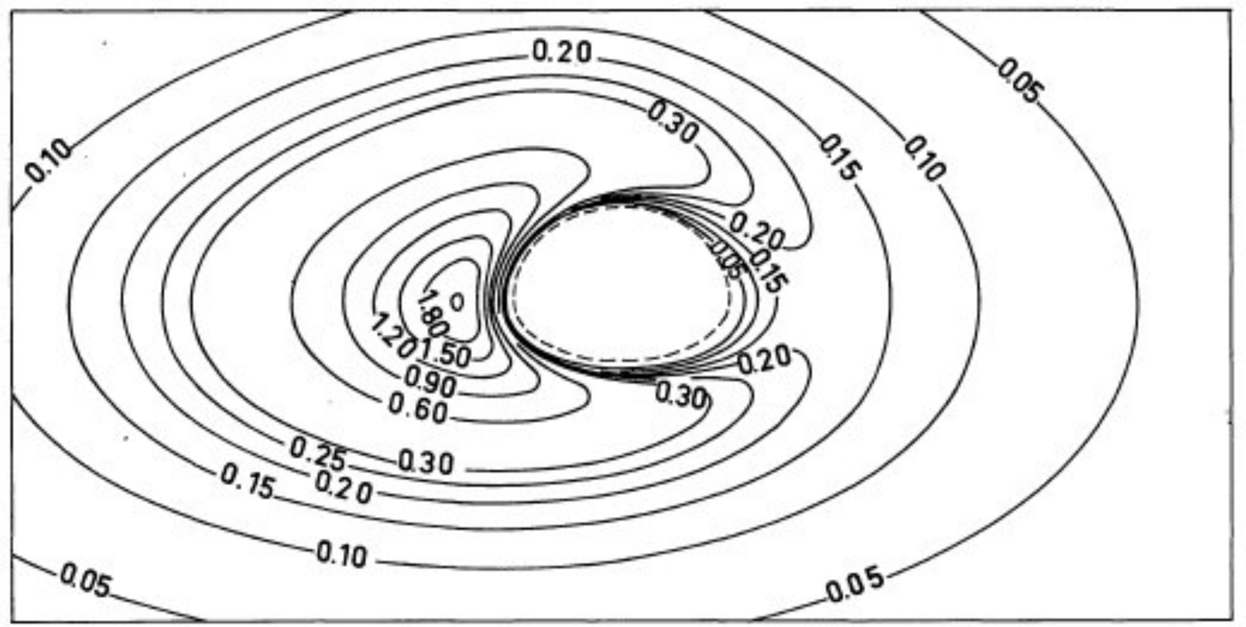
$$1 + z = (1 - 3\,M/r)^{-1/2}\,(1 + (M/r^3)^{1/2} b \sin\theta_0 \sin\alpha).$$

Etape 4 : Flux apparent (bolométrique)

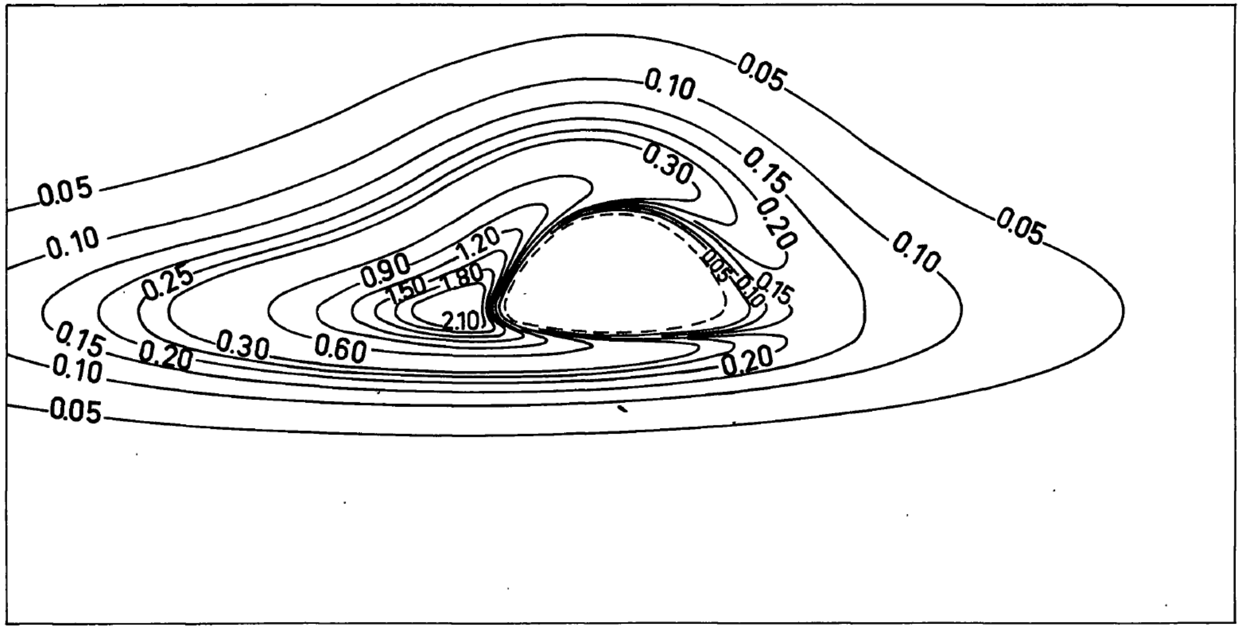
$$F_0 = F_S/(1+z)^4$$

Isophotes

Angle de vue équatorial 30°



Angle de vue équatorial 10°



The Final Picture

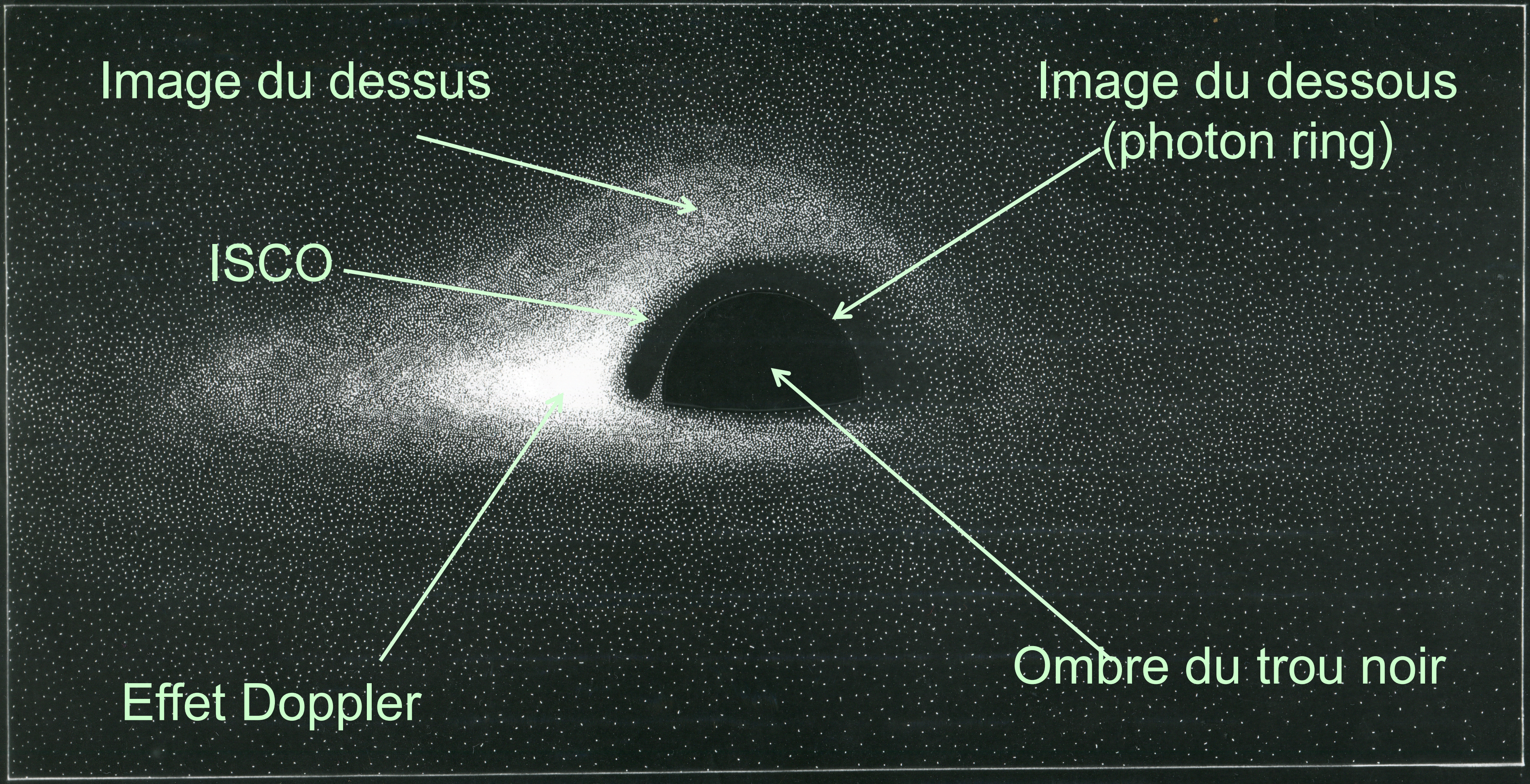
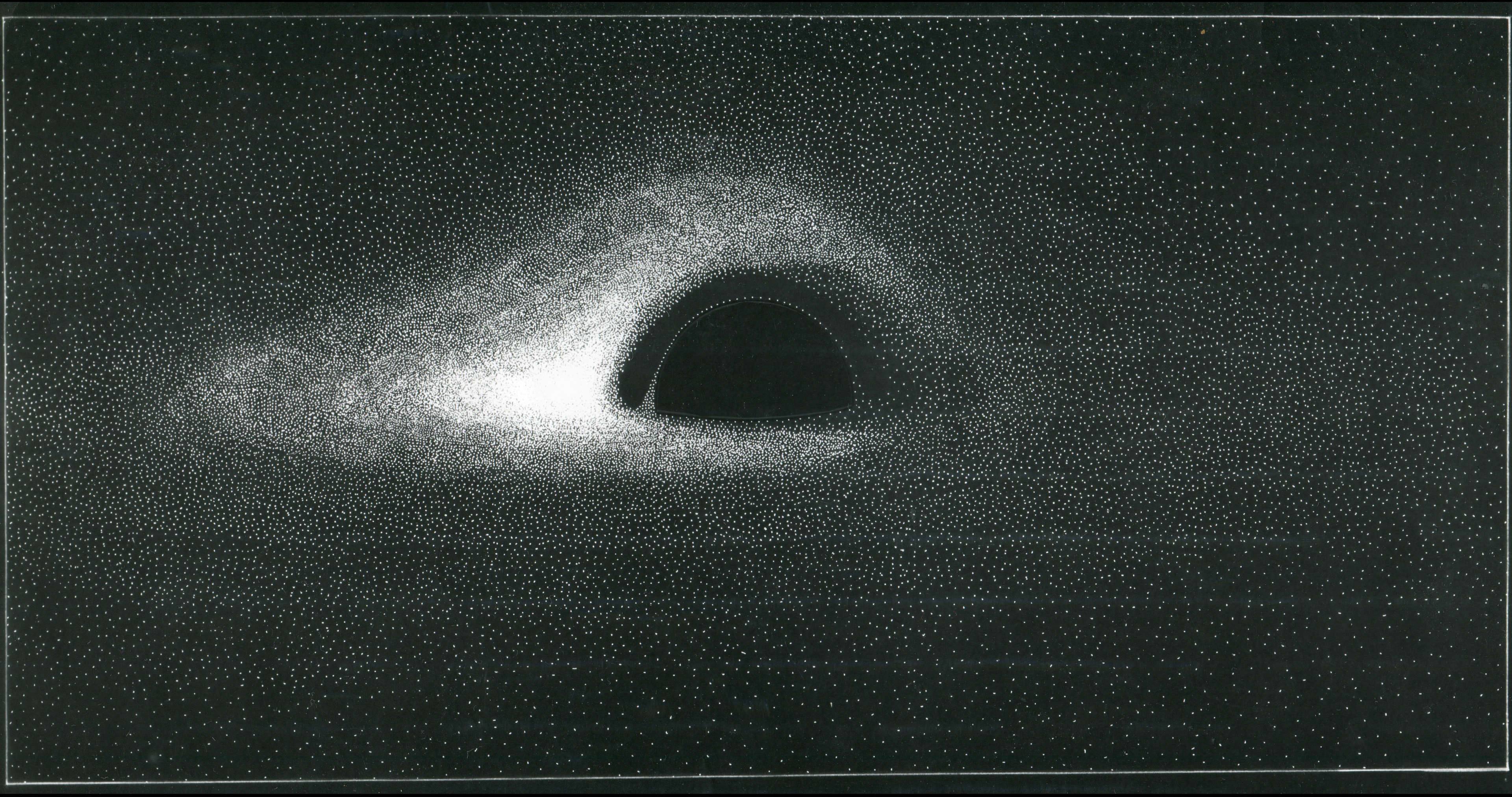


Image of a spherical black hole with thin accretion disk

J.-P. Luminet, Astron.Astrophys. **75**, 228 (1979)

A la main!



Les trous noirs : maelströms cosmiques

par B. Carter et J.P. Luminet

■ Parmi les objectifs de l'astrophysique, un des plus prisés par les néophytes est la recherche des trous noirs. Aucune observation irréfutable n'a encore été réalisée à ce jour... et nombreux sont maintenant ceux qui associent cette idée à un mythe.

■ Et pourtant Laplace, à la fin du XVIII^e siècle avait déjà imaginé qu'un astre puisse être totalement invisible. Mais c'était aller à l'encontre de la théorie ondulatoire de la lumière qui se développa solidement pendant le siècle suivant. C'est à l'aube du XX^e siècle qu'Einstein proposa la théorie corpusculaire de la lumière et établit ainsi l'influence obligatoire de la gravitation sur les particules de lumière, les photons. De là, à imaginer un corps céleste suffisamment massif pour que les rayons lumineux eux-mêmes ne puissent s'en échapper... C'est l'histoire que rapportent ici les auteurs.

Brandon Carter et Jean-Pierre Luminet sont membres du groupe d'astrophysique relativiste à l'observatoire de Paris-Meudon ; le premier auteur est maître de recherche au CNRS.

■ L'expérience de tous les jours avait appris à nos ancêtres préhistoriques qu'un caillou lancé en l'air retombe toujours (s'il ne rencontre aucun obstacle), et cela quelle que soit la force du bras l'ayant lancé. Ils ne se doutaient probablement pas que leurs lointains descendants parviendraient à projeter dans l'espace des fusées de plusieurs tonnes capables d'échapper définitivement à l'attraction terrestre.

En fait, que ce soit une fusée ou un simple caillou, n'importe quel projectile peut être lancé hors d'atteinte du champ gravitationnel terrestre si sa vitesse initiale est suffisamment grande. Le lecteur aura reconnu le concept familier de *vitesse de libération*. Celle-ci est de 11 km/s pour la Terre, mais elle peut être calculée indépendamment de tout projectile pour n'importe quelle autre planète ou n'importe quelle étoile. Le raisonnement est le suivant : pour qu'un projectile de masse m échappe au champ gravitationnel d'un grand corps de masse M — disons une planète — il faut que son énergie cinétique $\frac{1}{2} mv^2$ (où v est la vitesse du projectile) soit plus grande que son énergie potentielle gravitationnelle $\frac{GMm}{R}$ (où G est la constante de la gravitation universelle, R le rayon de la planète). La vitesse de libération v_c s'obtient donc en égalant ces deux énergies, c'est-à-dire

$$v_c = \sqrt{\frac{2GM}{R}}.$$

Ainsi, plus une planète ou une étoile est massive, plus la vitesse nécessaire pour s'en échapper doit être grande. Pour le Soleil, elle atteint 620 km/s, pour une étoile dense comme une naine blanche elle dépasse plusieurs milliers de km/s.

L'idée du « trou noir » trouve sa source dans ce concept de vitesse de libération et remonte à l'« Exposition du système du monde », publié en 1796 et dont l'auteur était le célèbre mathématicien et astronome français Pierre-Simon de Laplace. On reste aujourd'hui encore confondu par l'audace intellectuelle de cet homme hors du commun, qui osa répondre à Napoléon à propos de Dieu : « Sire, je n'avais pas besoin de cette hypothèse. » Laplace avait en effet remarqué que si un astre était suffisamment grand pour qu'à sa surface la vitesse de libération dépasse la vitesse de la lumière c = 300 000 km/s, en supposant de plus que la lumière est composée de petits corpuscules obéissant aux lois ordinaires de la gravitation, alors cet astre serait

Novembre 1978

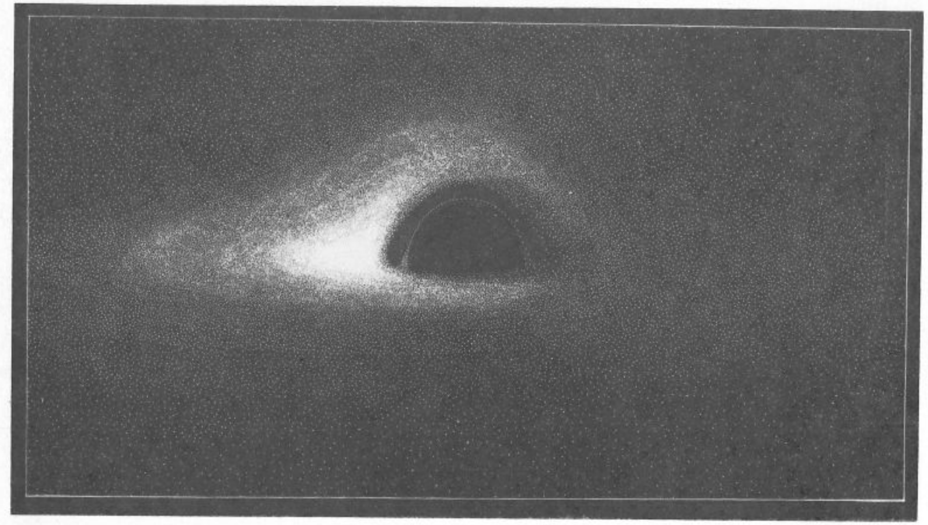


Fig. 11. Simulated photograph of a spherical black hole with thin accretion disk

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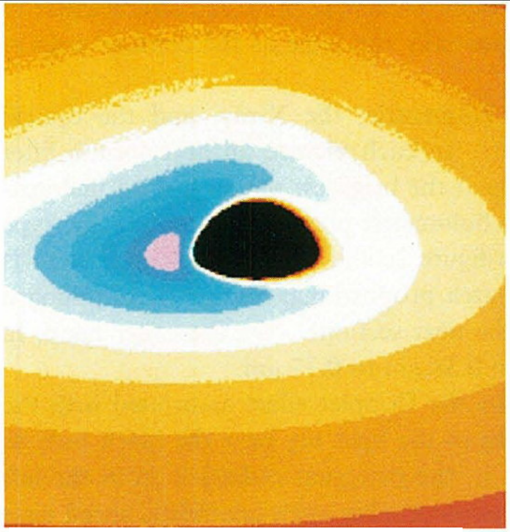
Janvier 1979

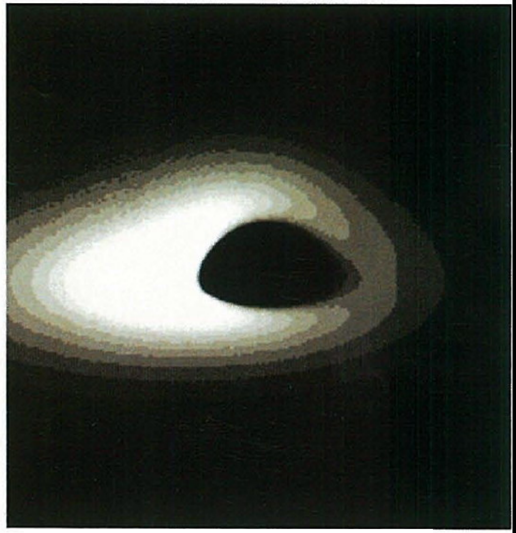
Premières images en couleurs (Fukue & Yokohama 1988)

Trou noir de Schwarzschild de masse stellaire

$T_{max} = 10^7 K$

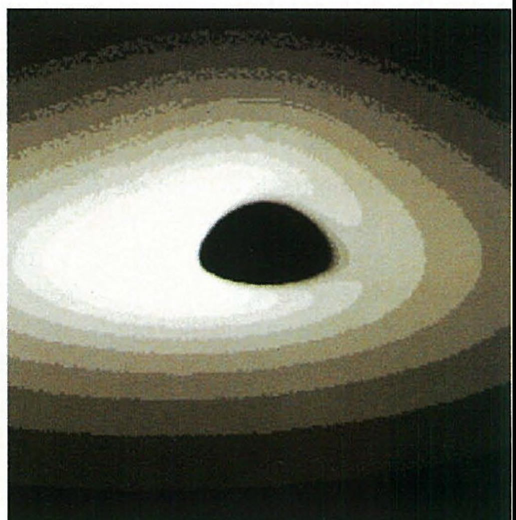


Fausses couleurs

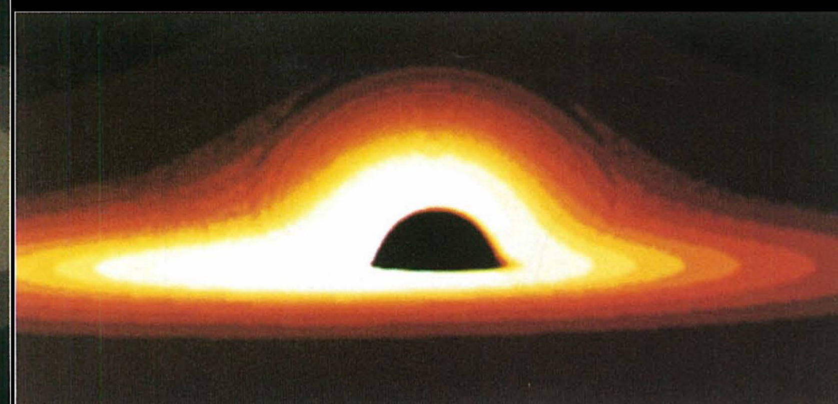


Bolométrique

En rayons X

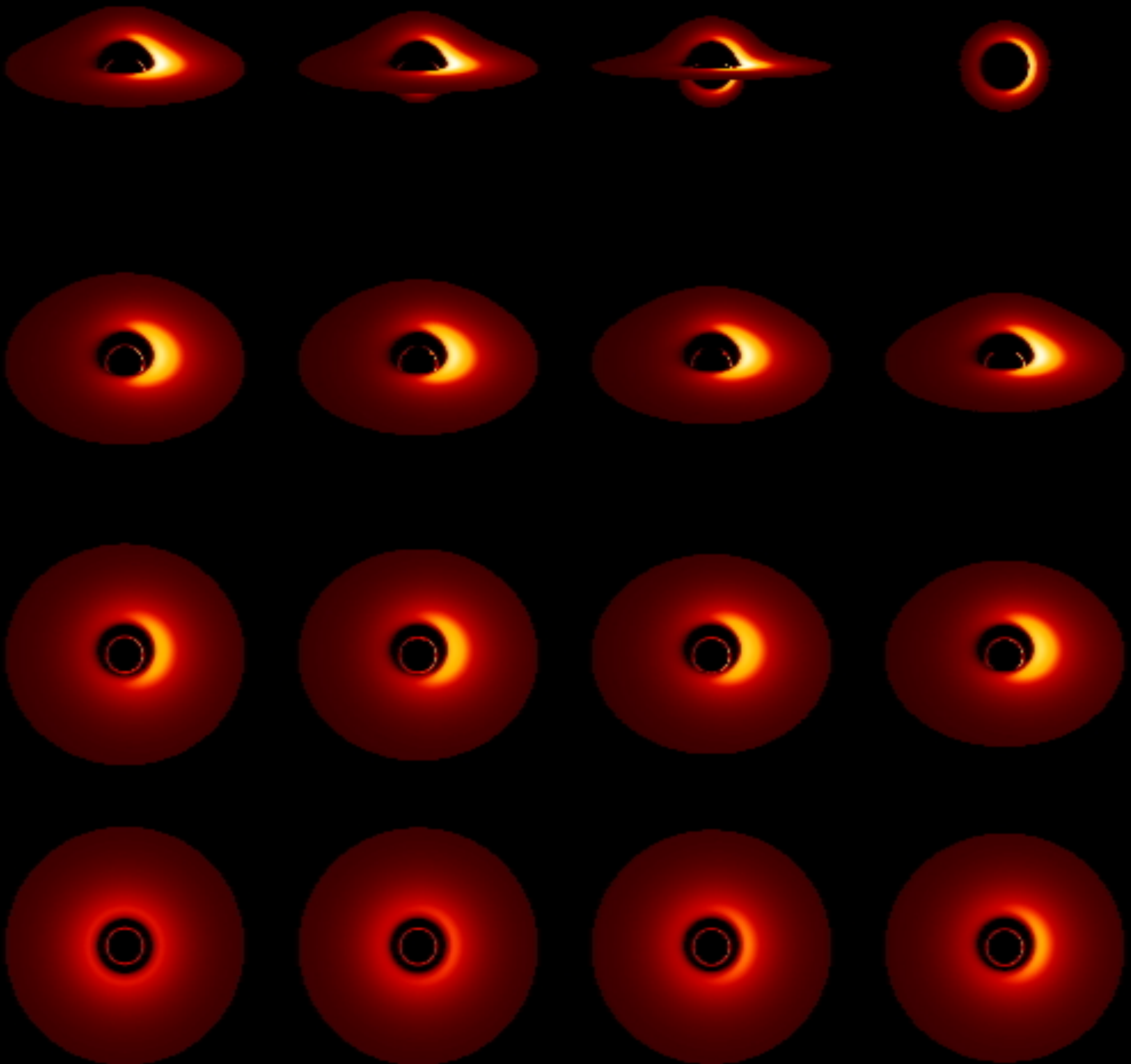


Optique



Trou noir de Schwarzschild supermassif

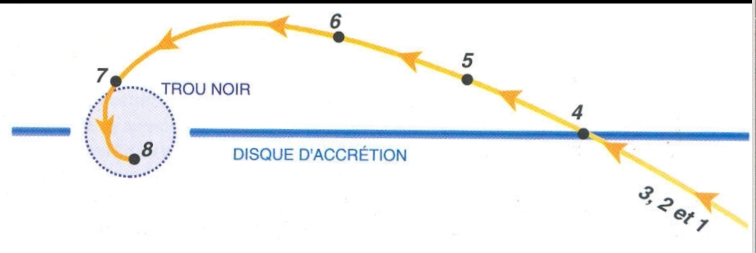
Premières images à tous angles de vue

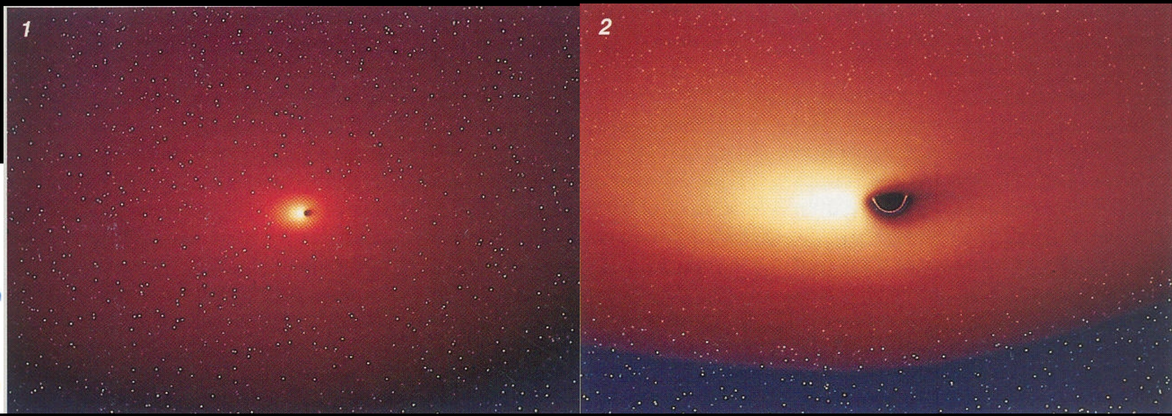


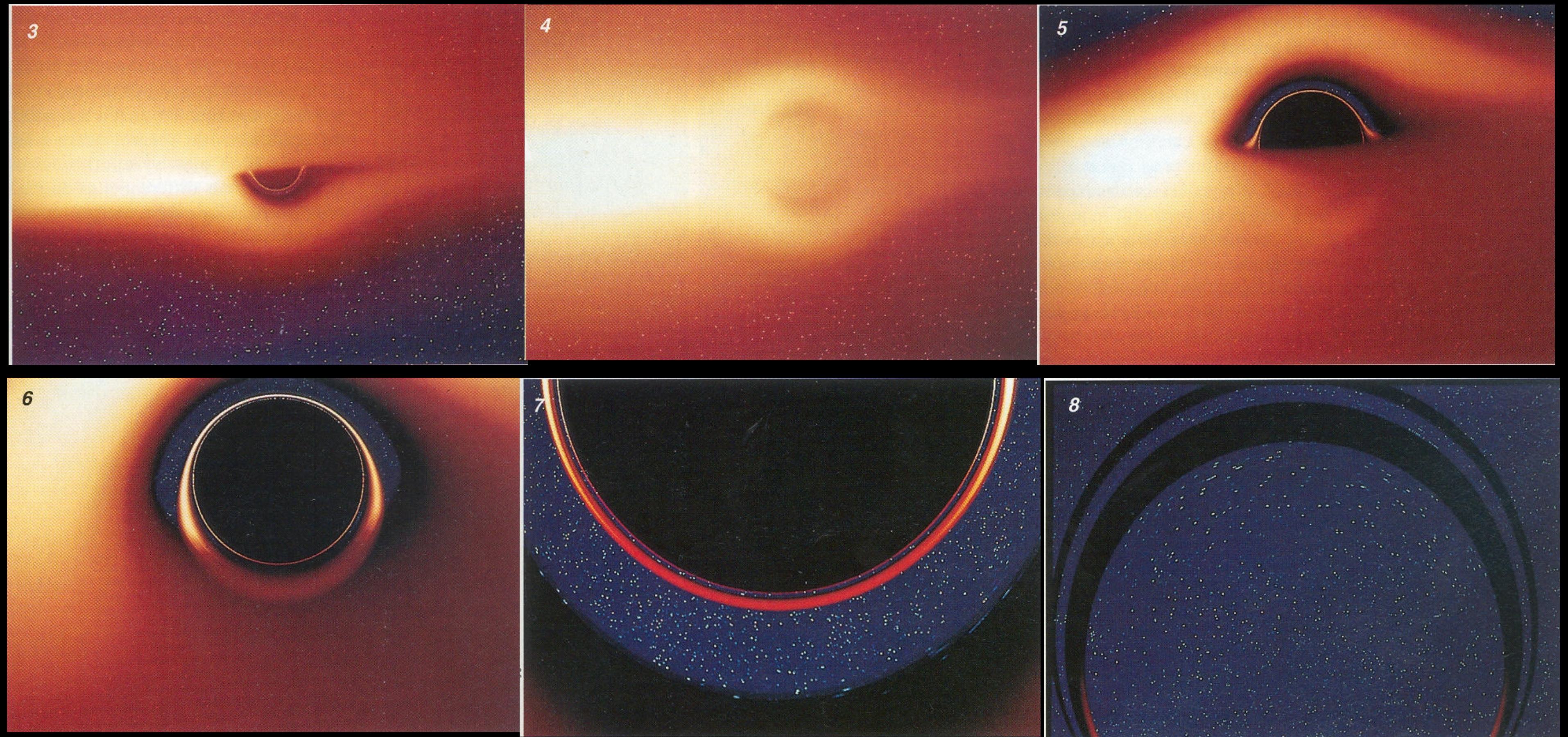
J.A.Marck/JPL
1989
(non publié)

Image en fausses couleurs du disque d’accrétion autour d’une trou noir de Schwarschild avec angle de vue 7° (Marck, 1991)

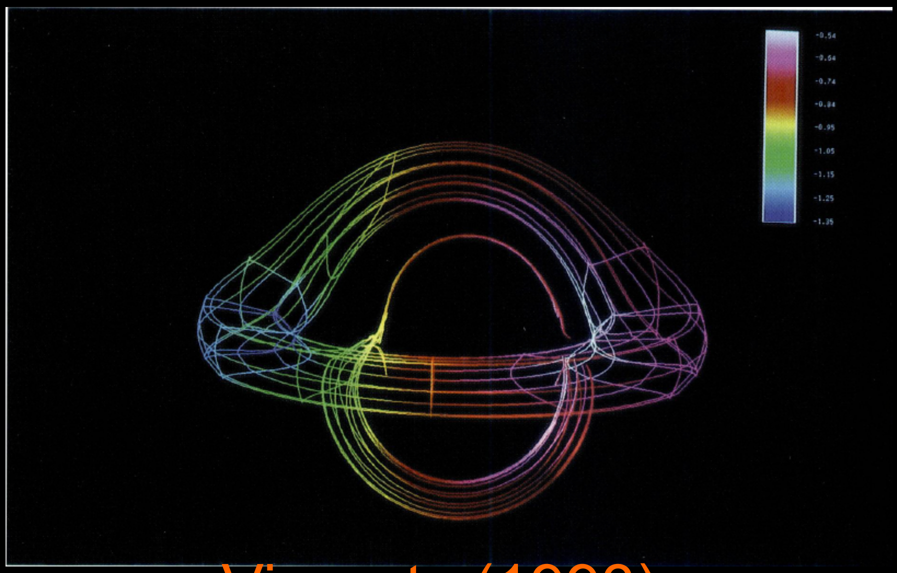
Vol dans un trou noir de Schwarzschild
(Marck, 1993)



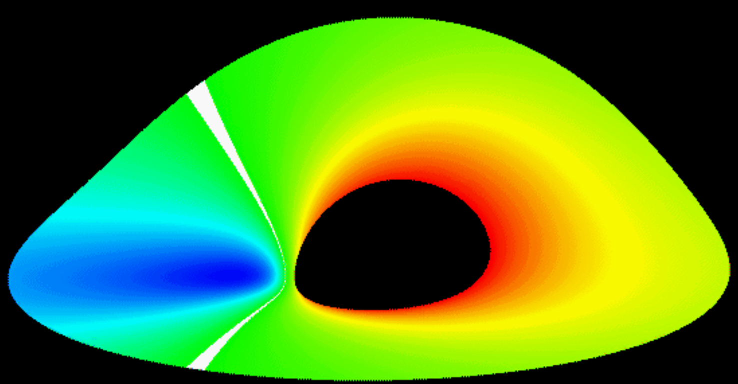




Premiers calculs de disque d'accrétion pour lesTN de Kerr

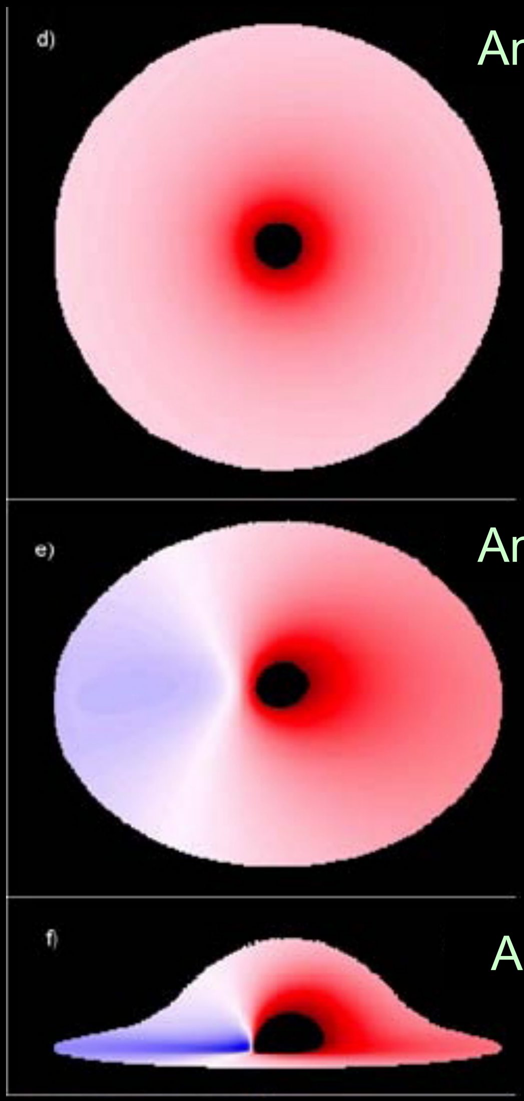


Viergutz (1993)



Angle 15°

Bromley (1997)



Angle 85°

Angle 45°

Angle 5°

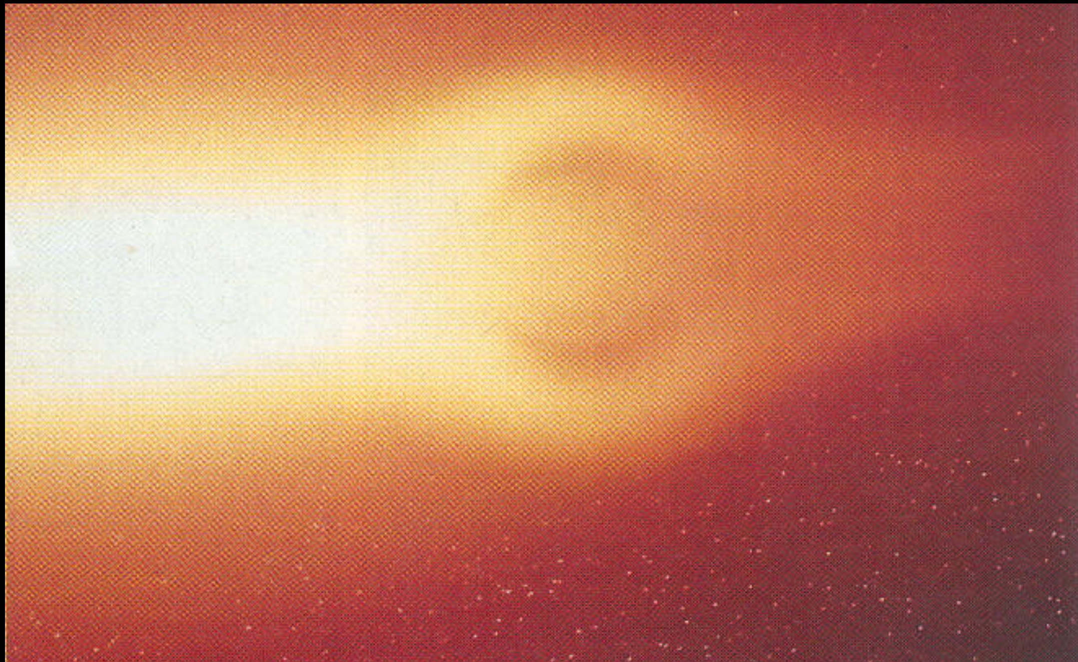
Fanton et al. (1997)

Thorne et al.

Film Interstellar (2014)

J.-P. Luminet & J.-A. Marck

Pour la Science (1997)



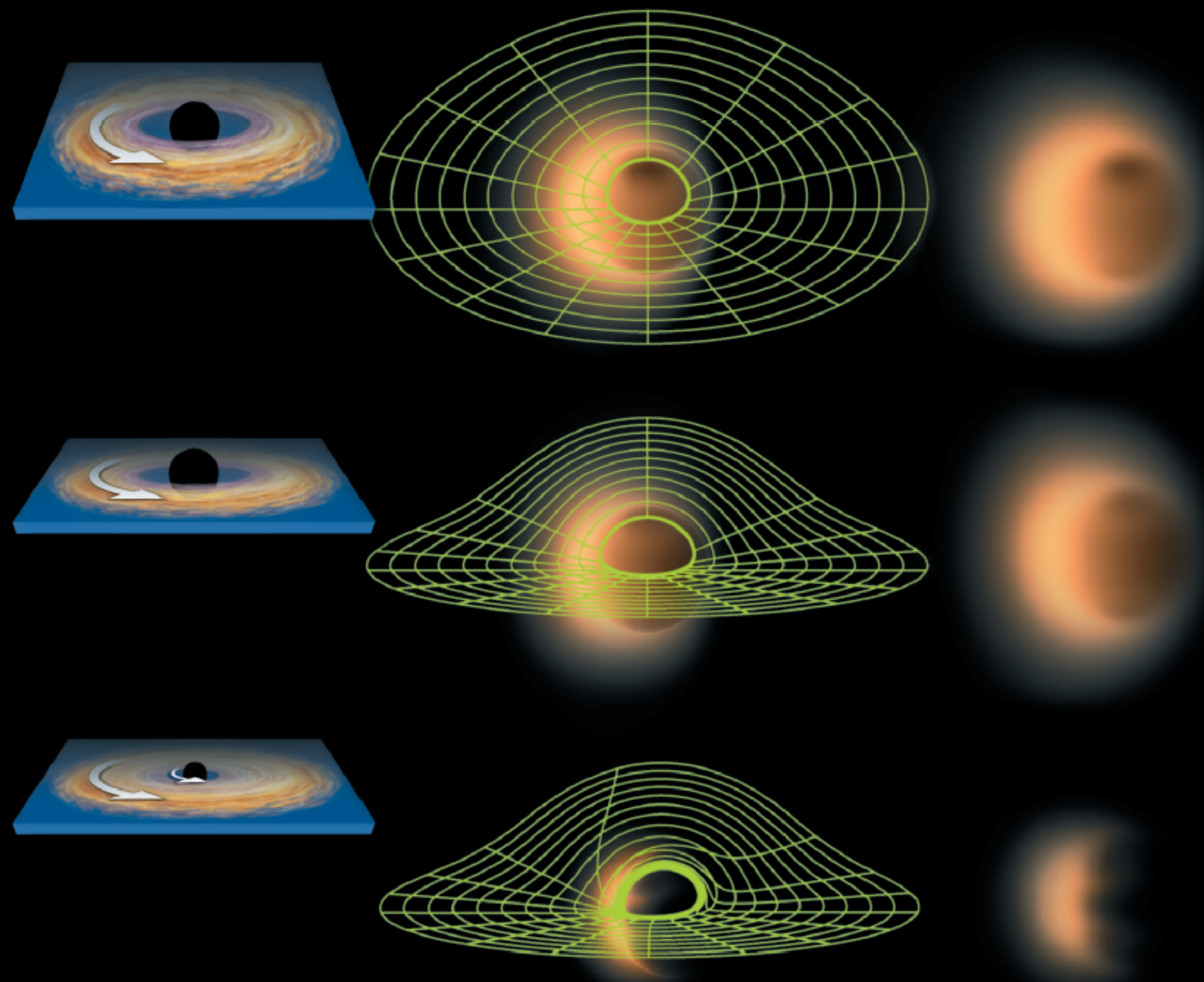
Démarrage des projets VLBI/EHT…

(Falcke & Melia 2000, Doeleman 2001)

TN statique
angle de vue 30°

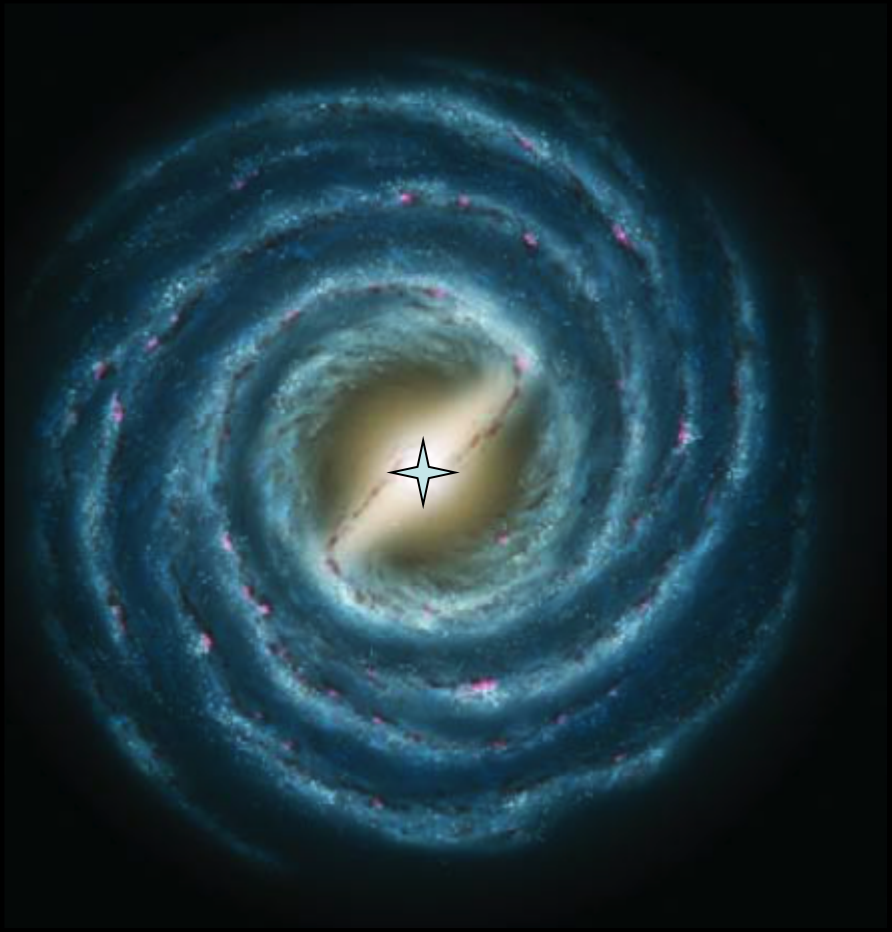
TN statique
angle de vue 10°

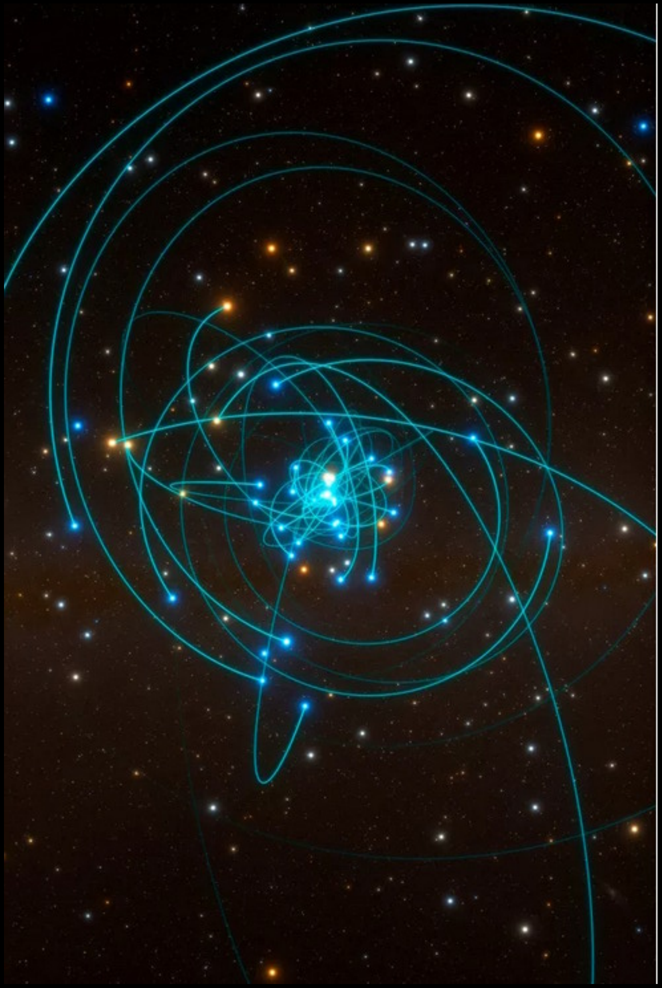
TN de Kerr
angle de vue 10°



Broderick & Loeb, SciAm 2009

Le Trou noir Galactique





Masse = 4 000 000 masses solaires
Diamètre = 25 000 000 Km

M87

Distance :
50 millions a.l.

Trou noir M87*

Masse :
6 milliards M_S

Diamètre :
40 milliards km

Voir Sagittarius A* / M87*?

$R_S \sim 3$ km M/M_S

D_{SagA^*} ~ 25 millions km à 26 000 a.l.
D_{M87^*} ~ 40 milliards km à 50 millions a.l.

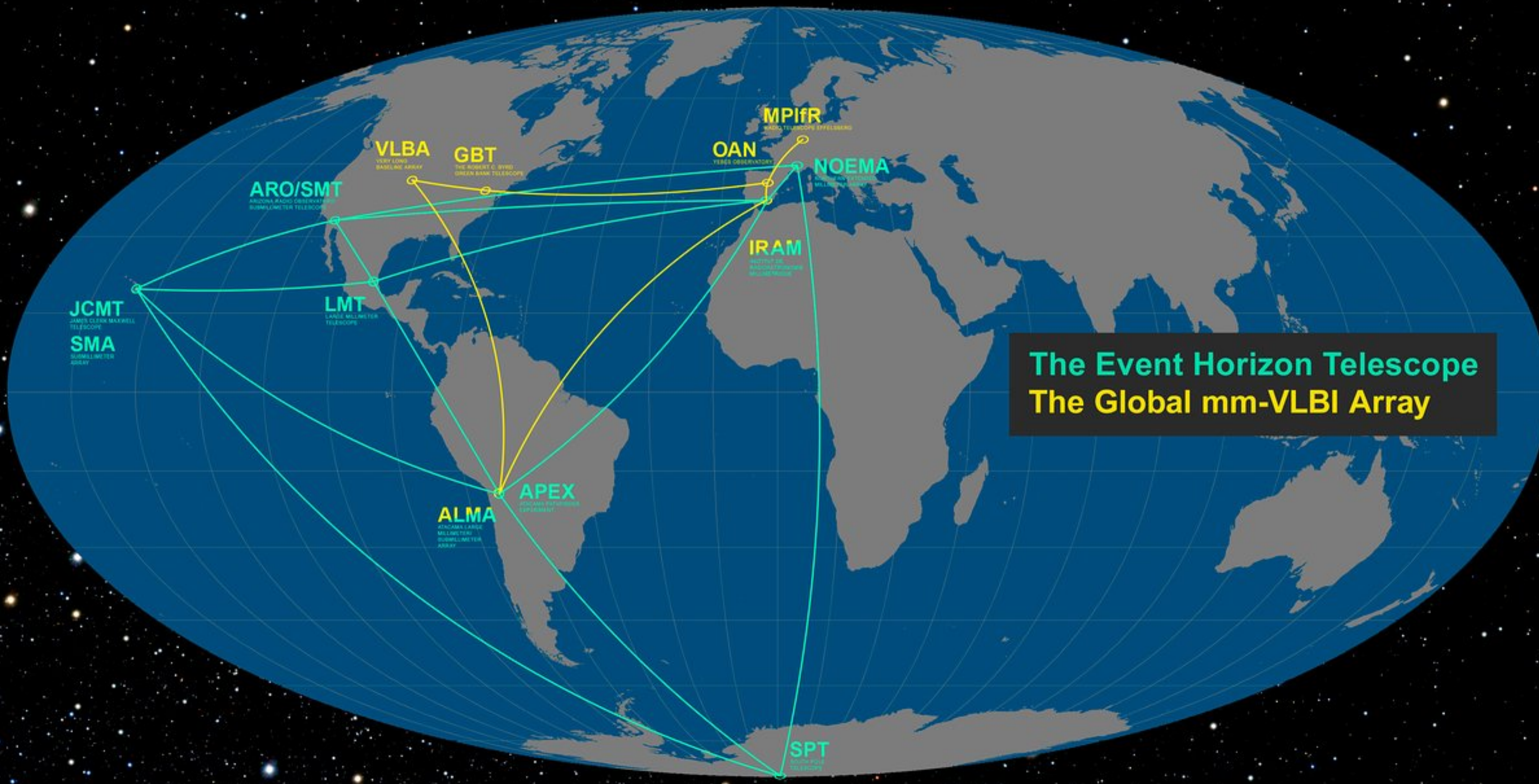
$D_{app} \sim 50\ \mu arcsec$

- Résolution angulaire d'un télescope :
  - *proportionnelle à l'ouverture*
  - *inversement proportionnelle à la longueur d'onde*
- Les C.G. sont presque transparents aux λ millimétriques

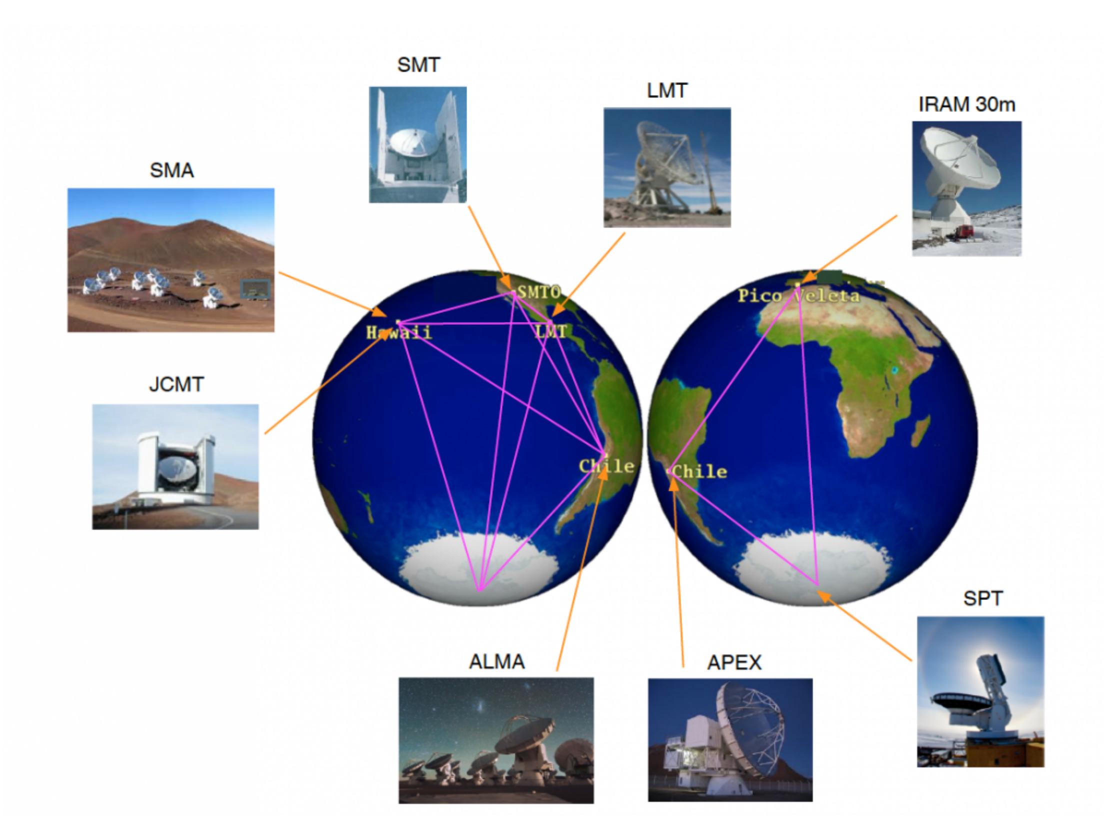
Un réseau VLBI de 10 000 km à 1.3 mmλ peut résoudre 25μ*arcsec !*

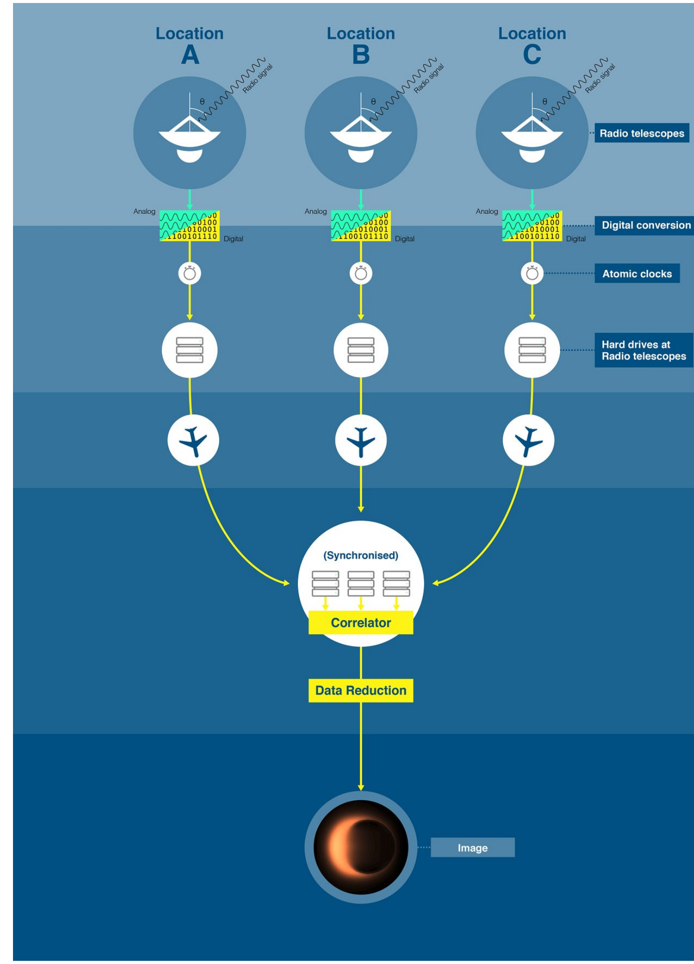
➔Event Horizon Telescope (EHT) Consortium

(Doeleman et al., 2008)



VLBI Résolution : 25 μarcsec

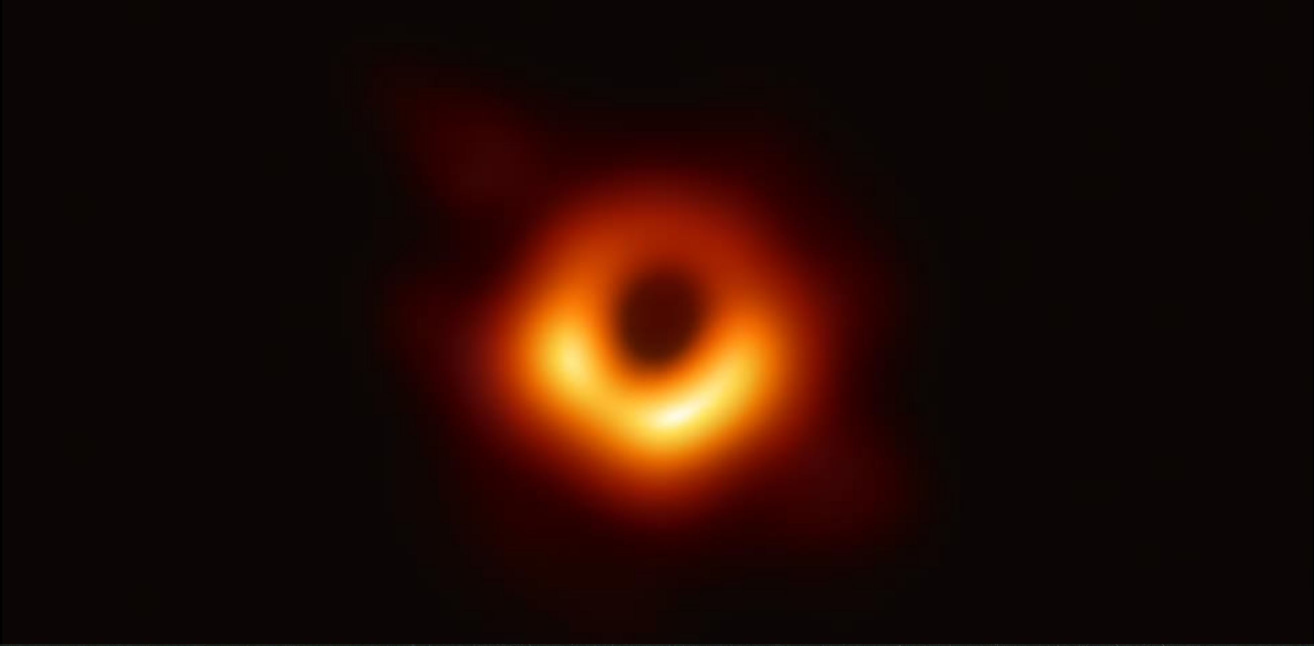


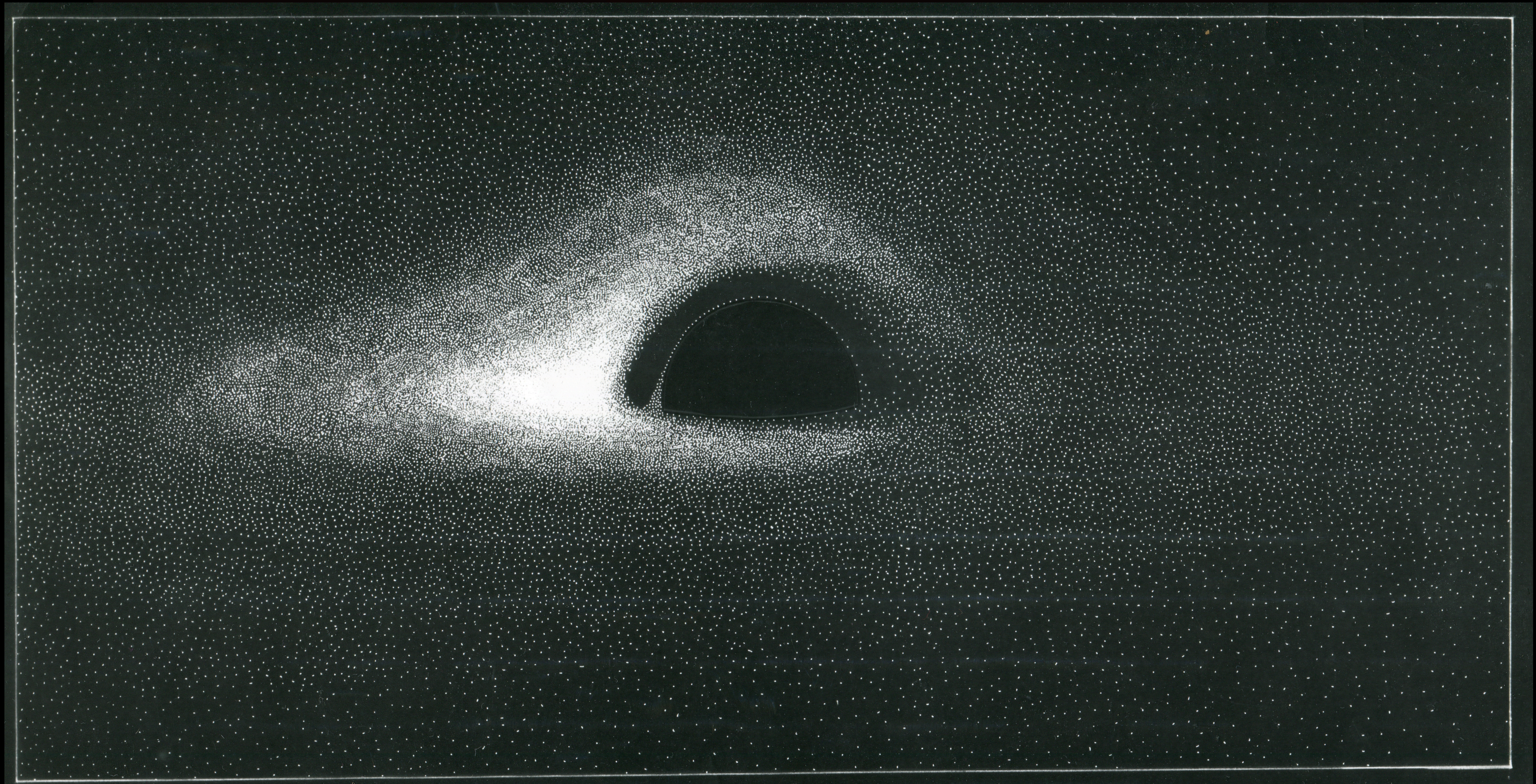


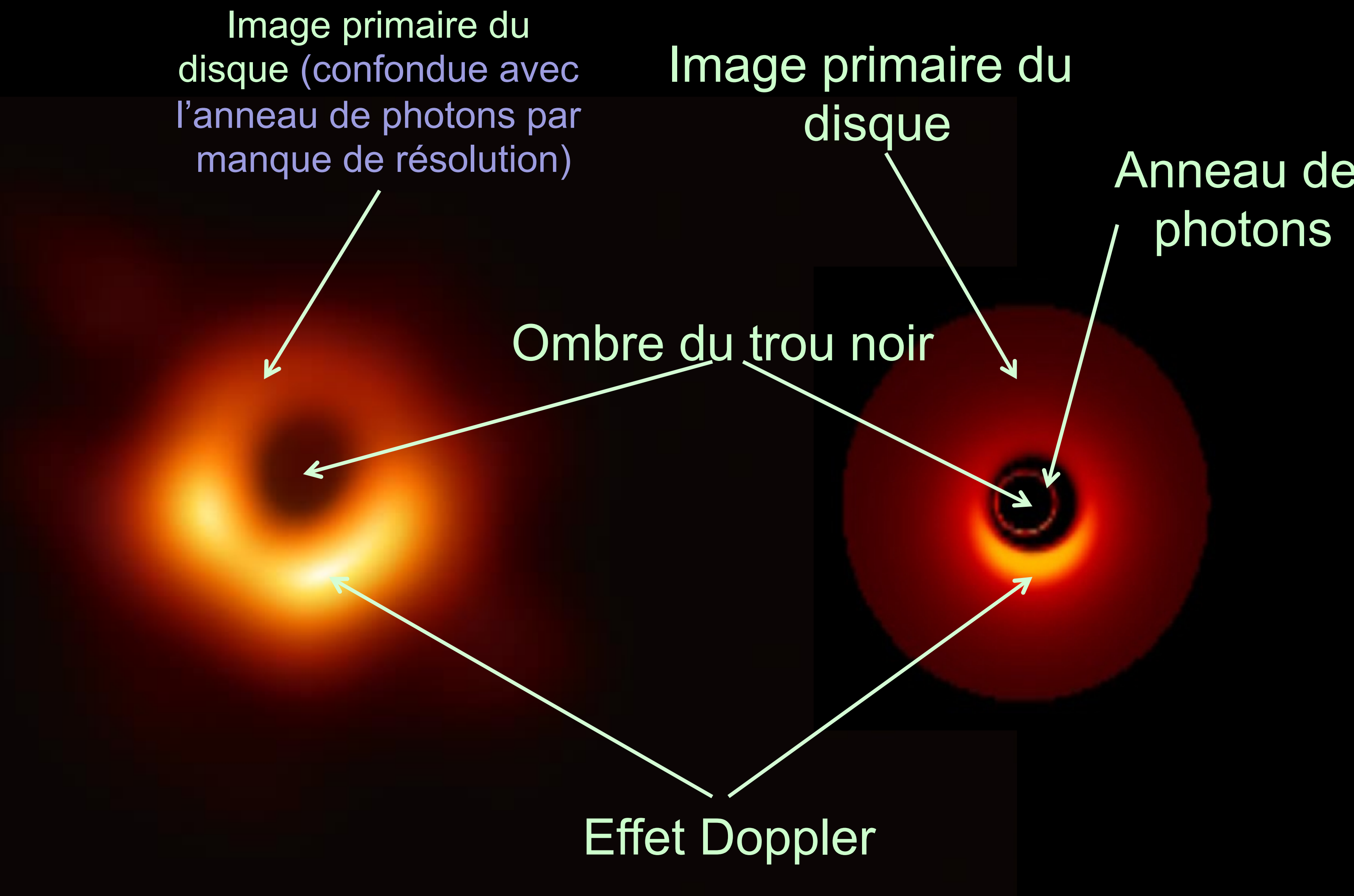
- Premières observations : 5 jours en avril 2017 (SgrA* / M87*)
- 20 petabytes de données (à une fréquence de 10^{-10} sec)
- Traitement des données sur les supercalculateurs du MIT et MPI Bonn

Première image télescopique de M87* : 10 avril 2019

[redacted] [redacted]



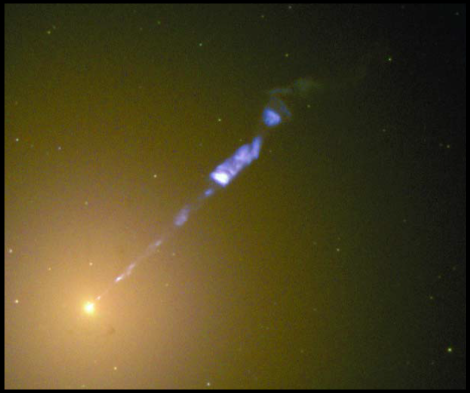




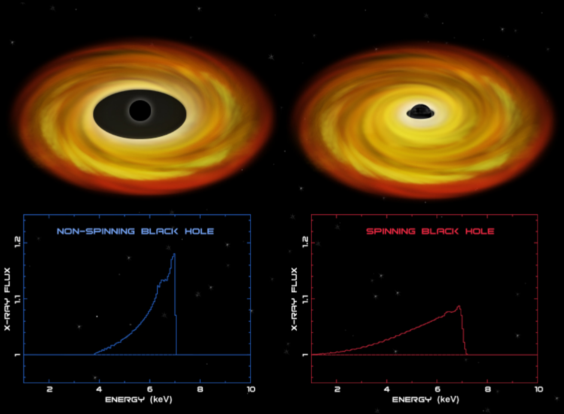
M87* par l'EHT

Simulation numérique de 1989

Aussi :



• Variabilité du champ magnétique
➔ Mécanisme des jets



• Recherche de signaux périodiques
➔ orbites de points chauds dans le disque d'accrétion (influence du spin)

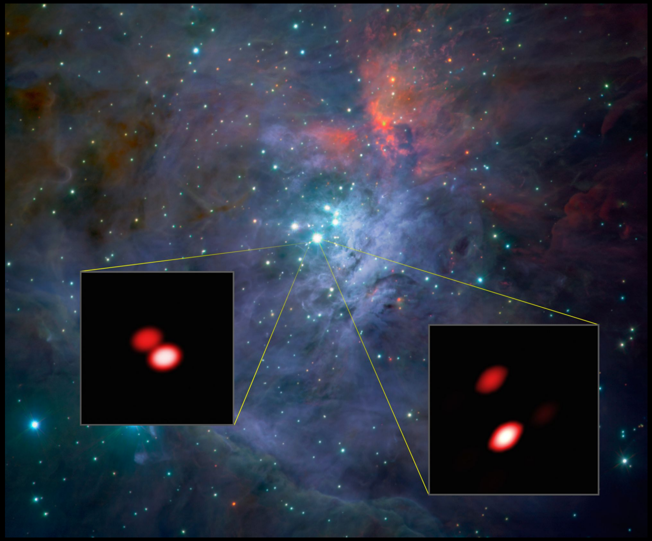
A venir :

• Addition de nouvelles stations radio
• Extension à 0.87 mm

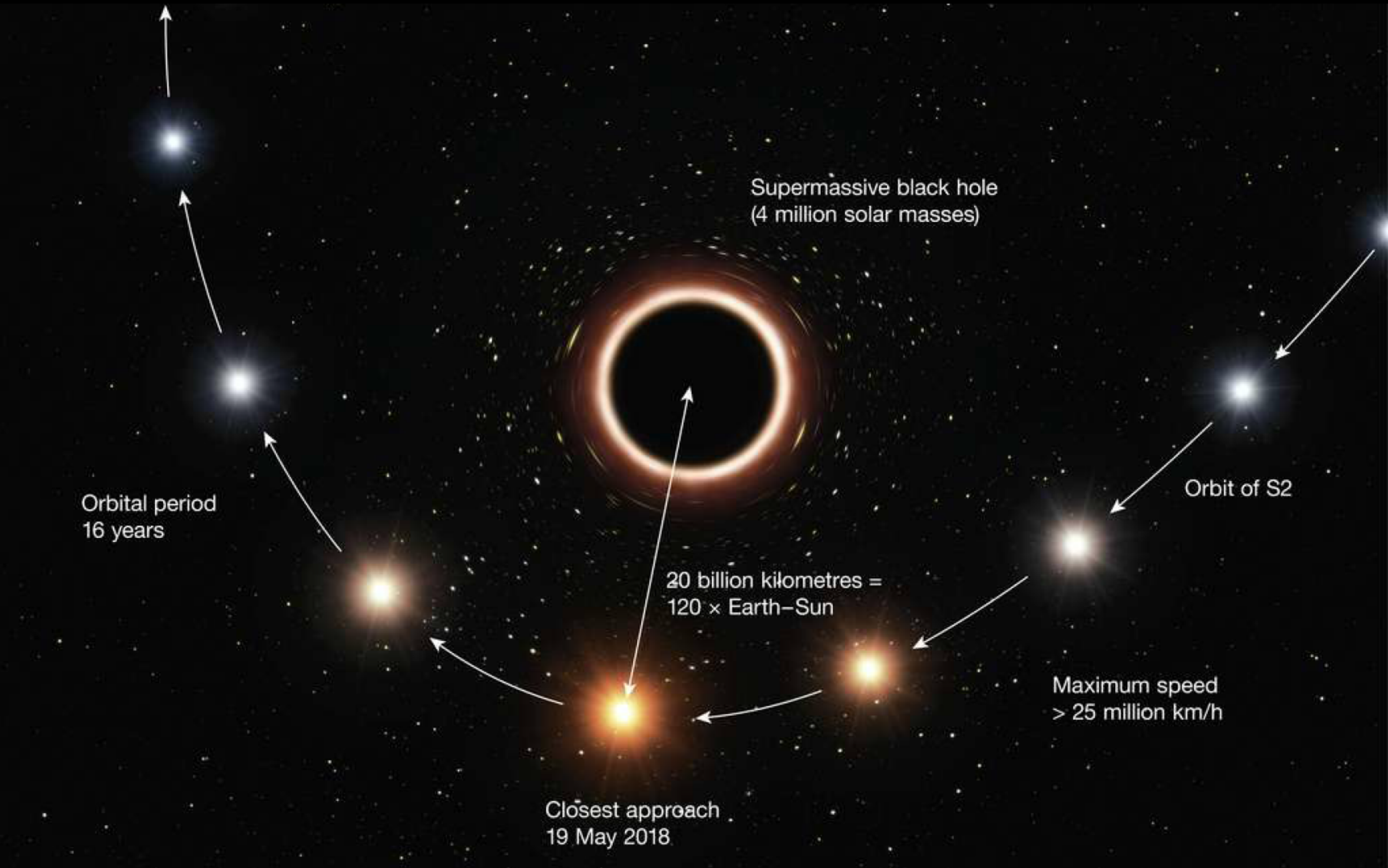
www.eventhorizontelescope.org

Instrument GRAVITY (2016)

Interférométrie optique-IR
~ Ø 200 mètres !

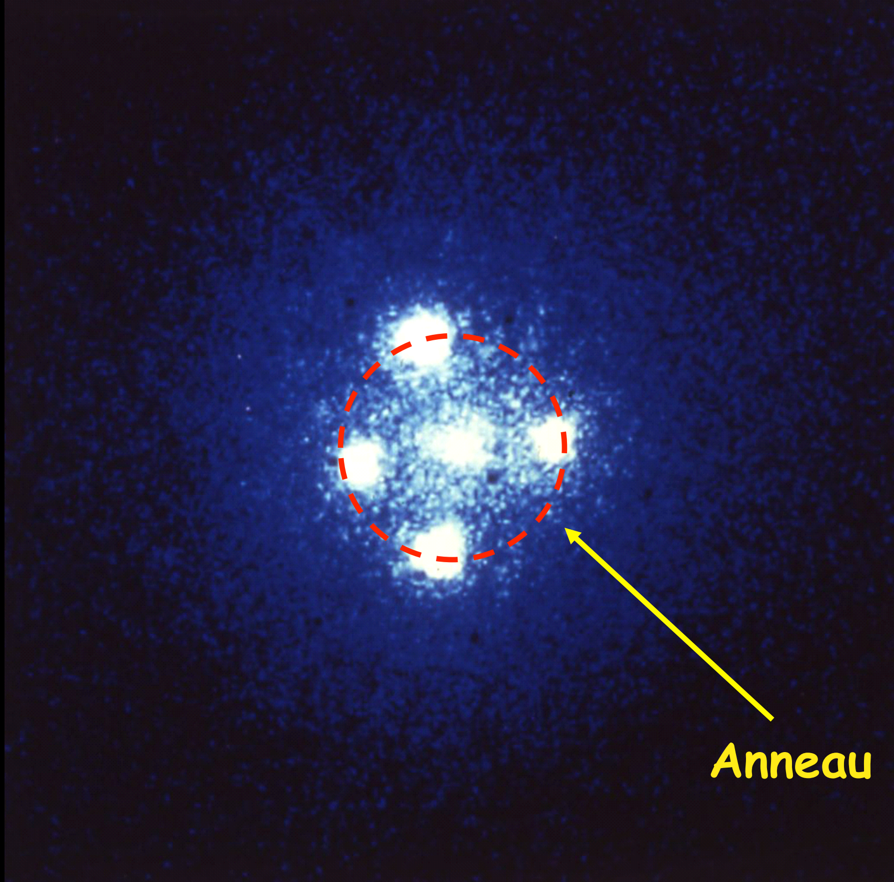


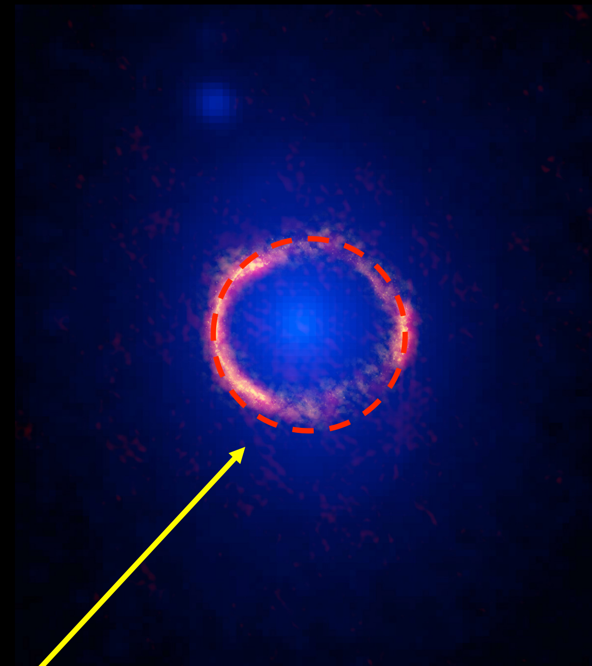
Résolution :
4 milliarcsec


Supermassive black hole
(4 million solar masses)
Orbital period
16 years
Orbit of S2
20 billion kilometres =
120 × Earth–Sun
Maximum speed
> 25 million km/h
Closest approach
19 May 2018

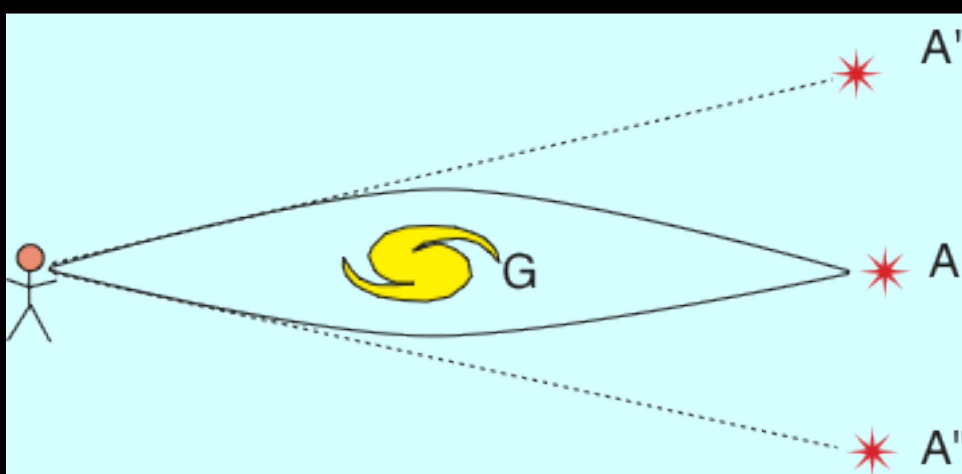
Trou noir :

Qu'y a-t-il derrière ?



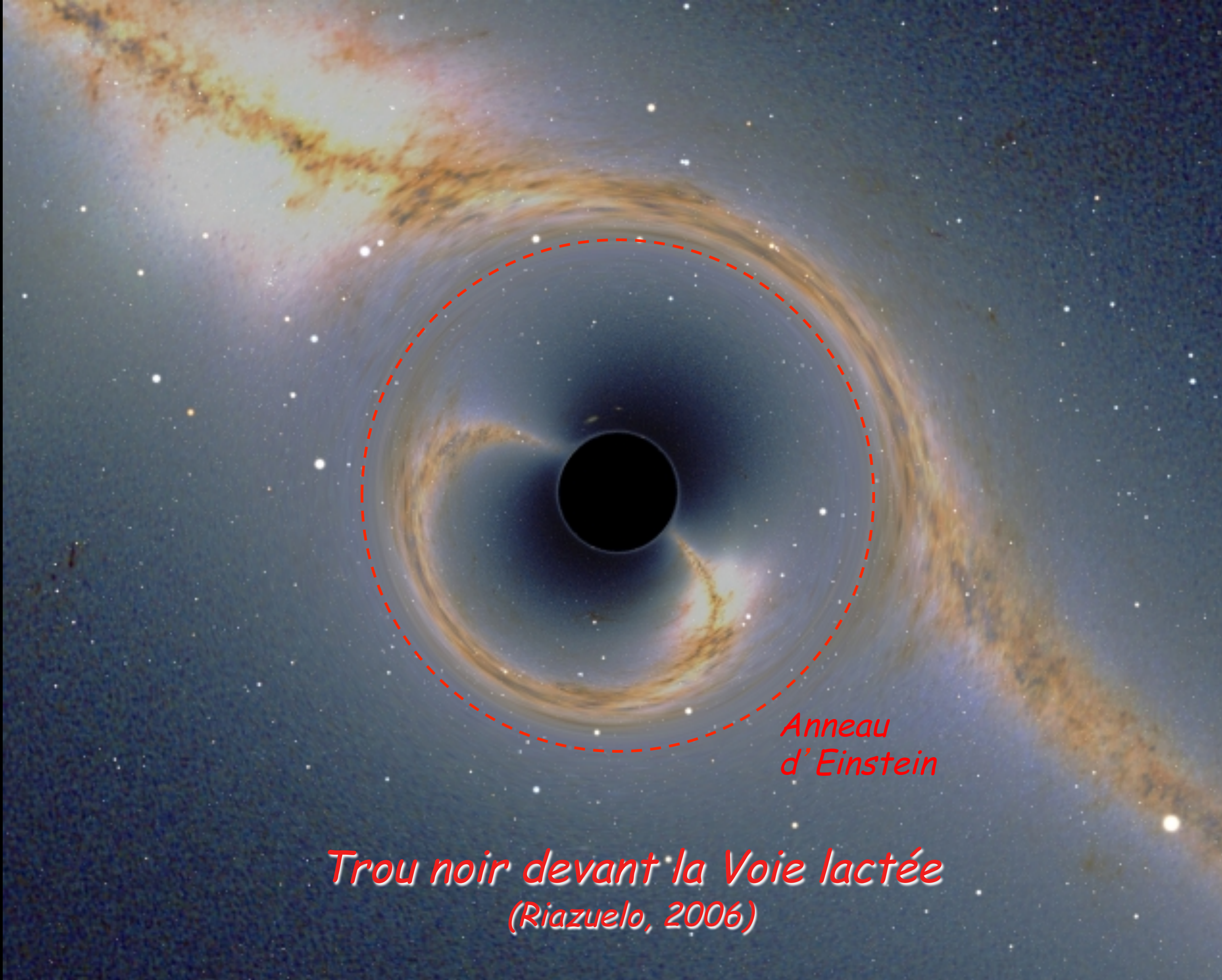


Anneau d' Einstein



Mirage Gravitationnel


Effet de mirage gravitationnel

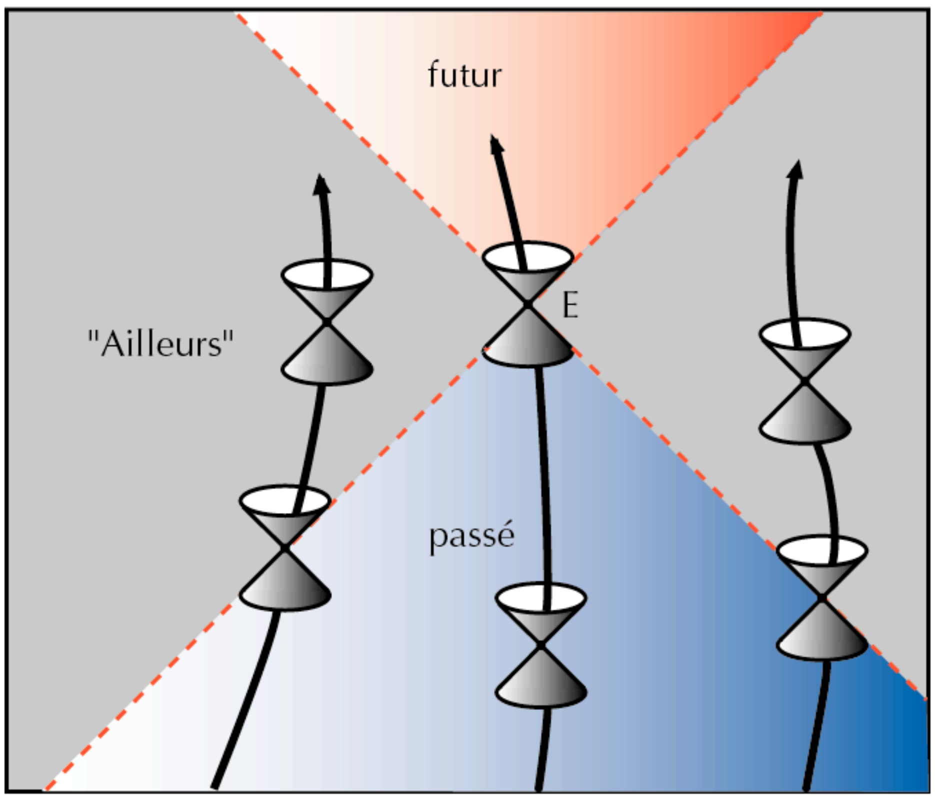


Trou noir devant la Voie lactée
(Riazuelo, 2006)

Voyage dans un trou noir de Kerr

Les cônes de lumière

Espace-temps plat (Poincaré- Minkowski)



Espace-temps courbe

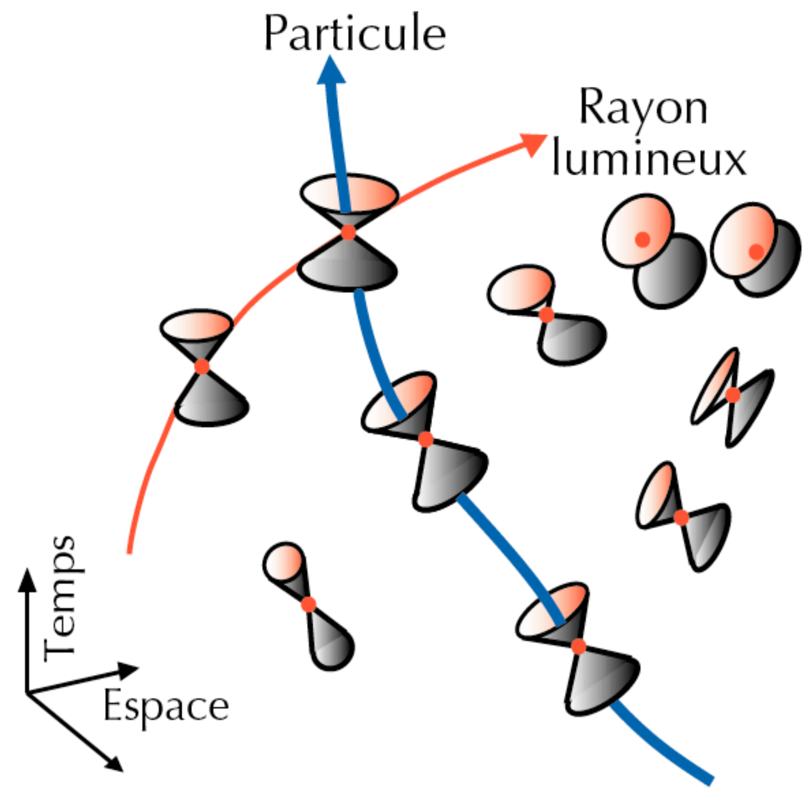


Diagramme de Penrose de l'espace-temps de Minkowski

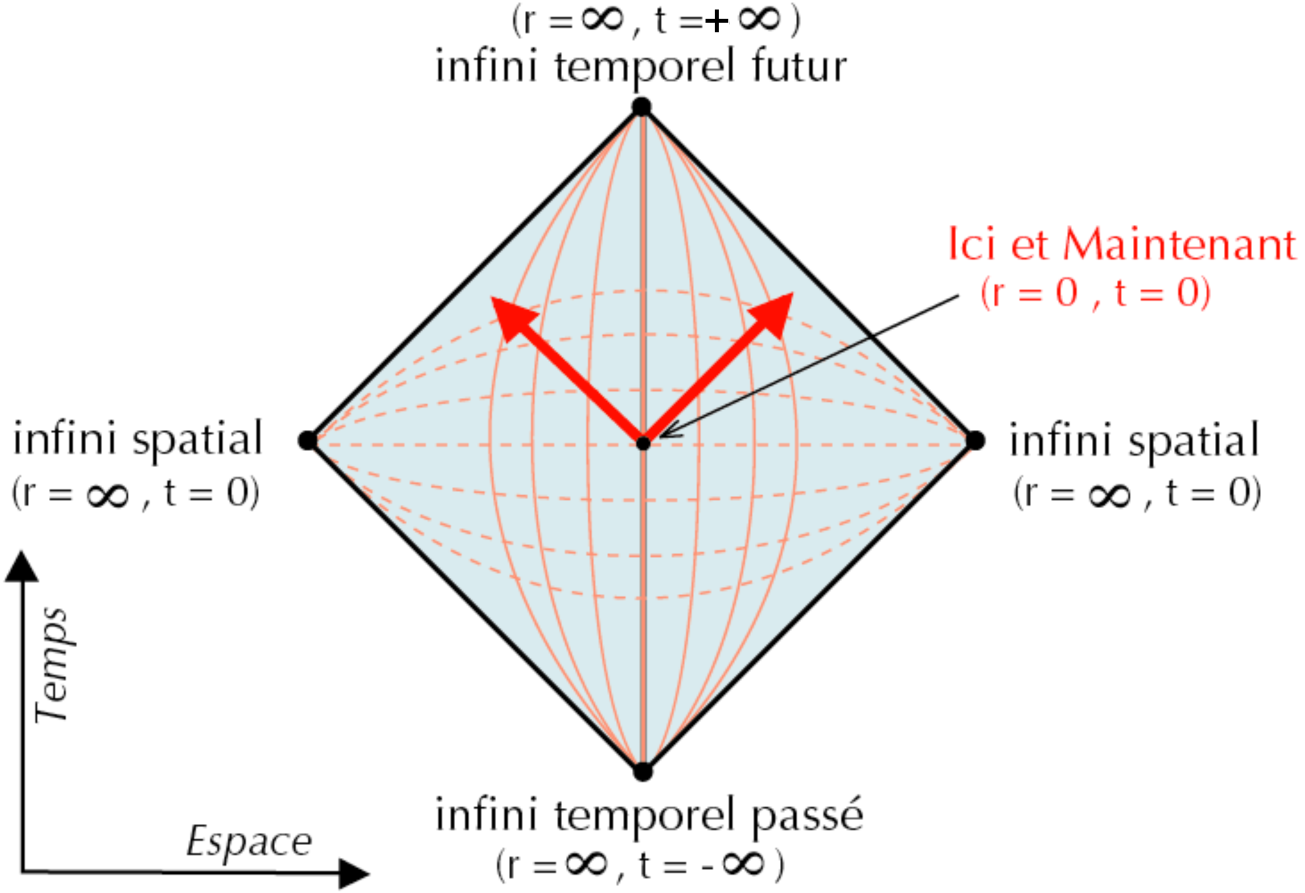


Diagramme de Penrose de l' espace-temps de Schwarzschild

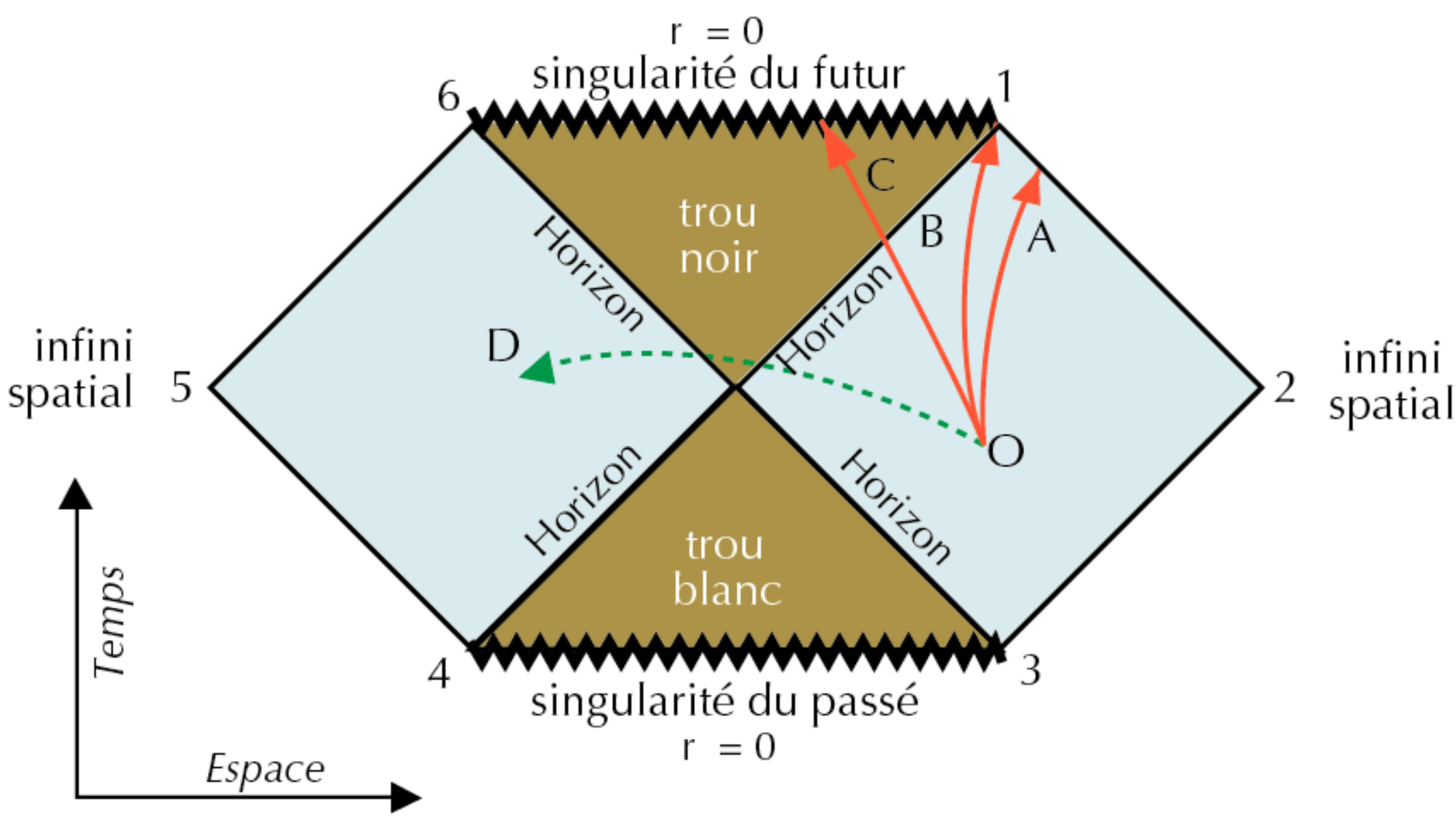
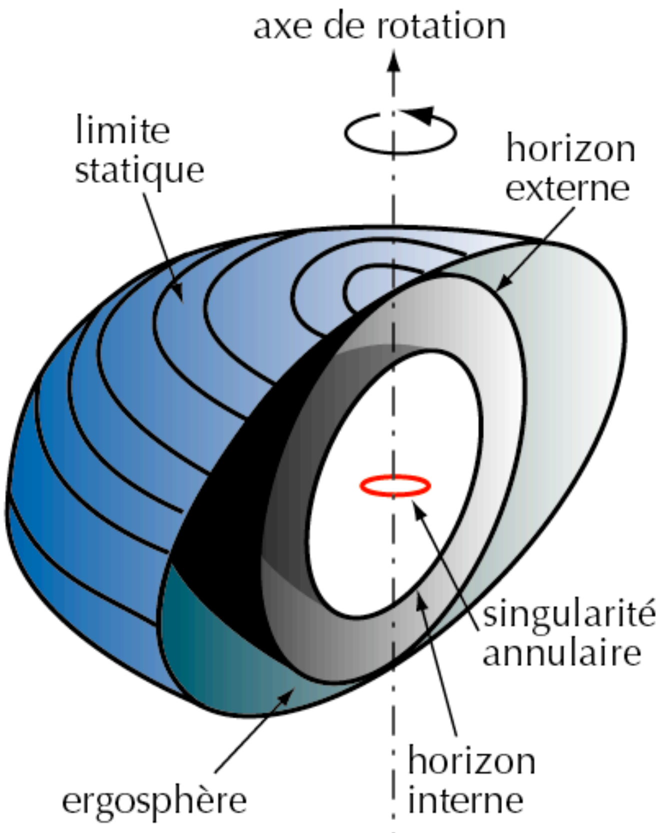
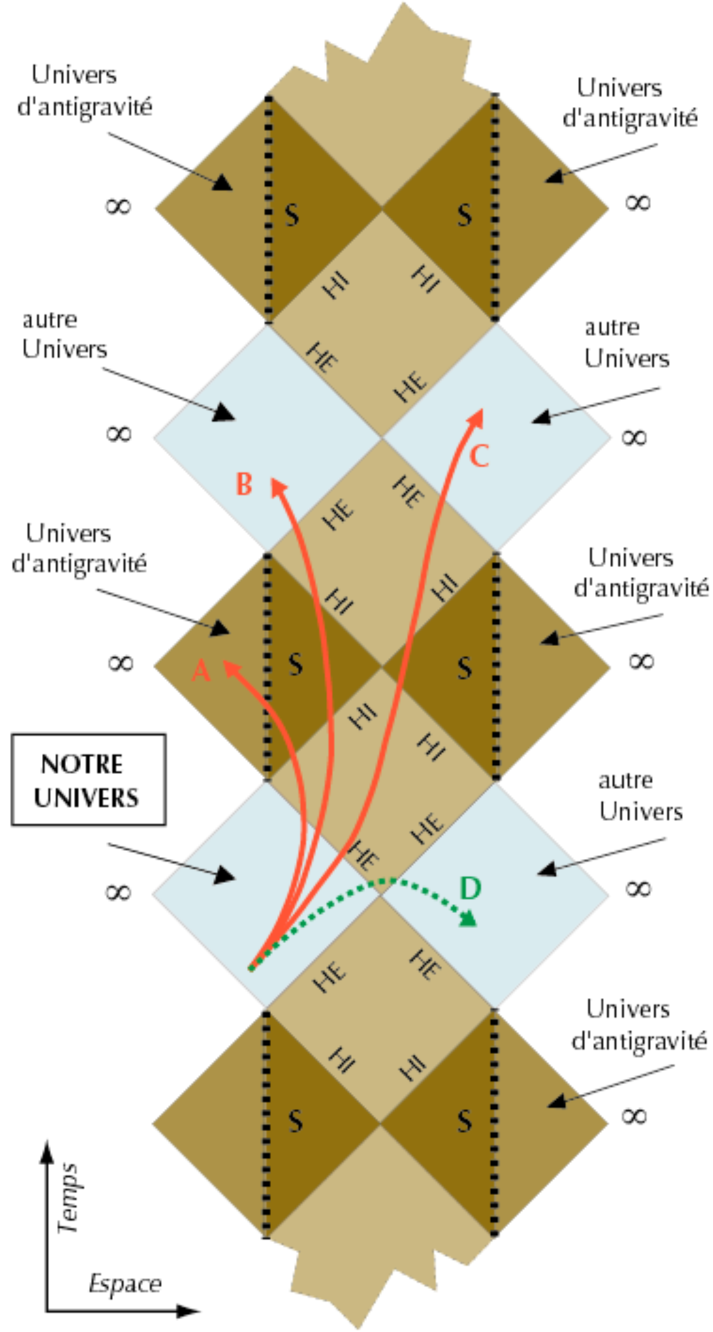
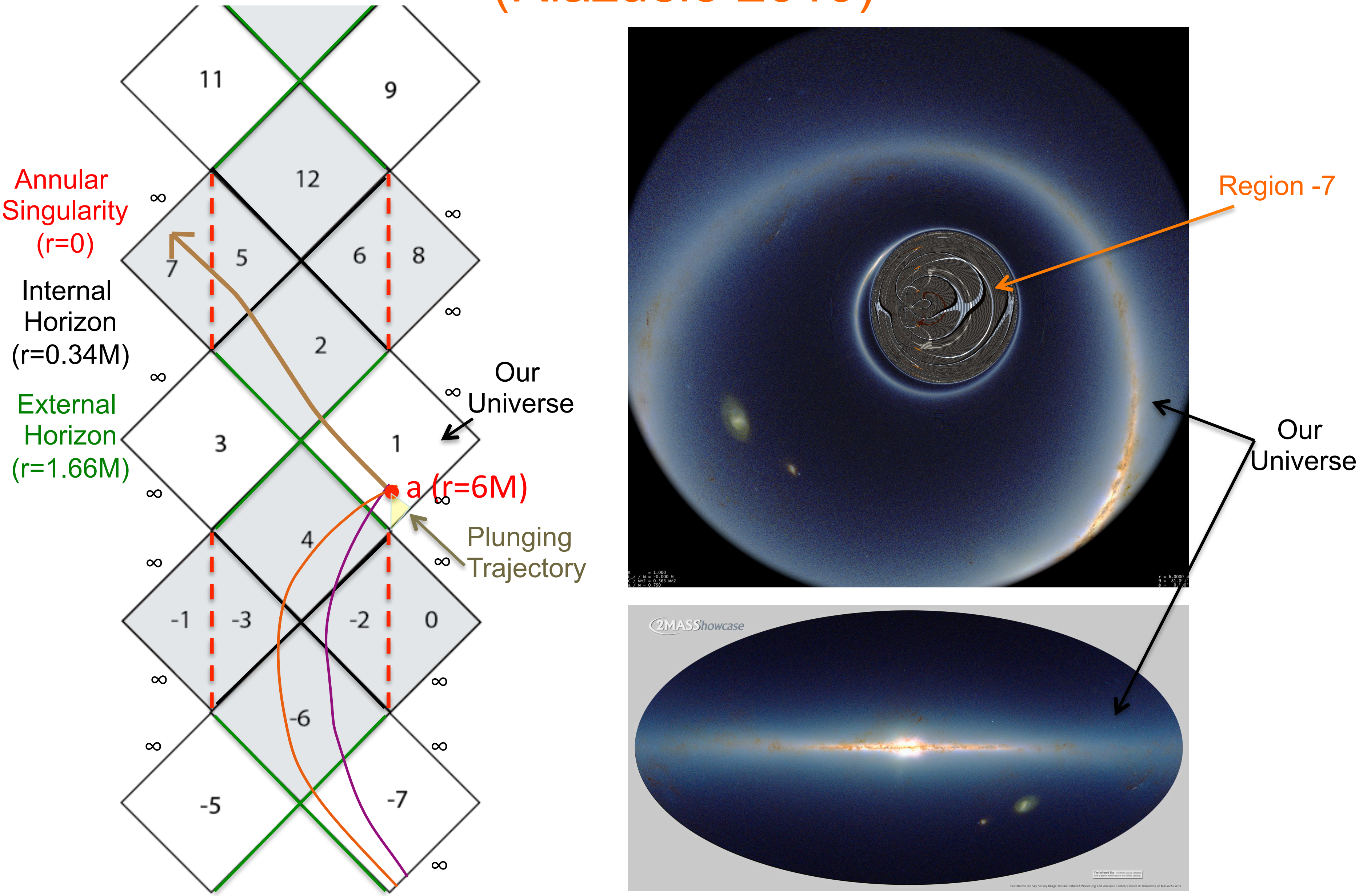


Diagramme de Penrose-Carter de l'espace-temps de Kerr



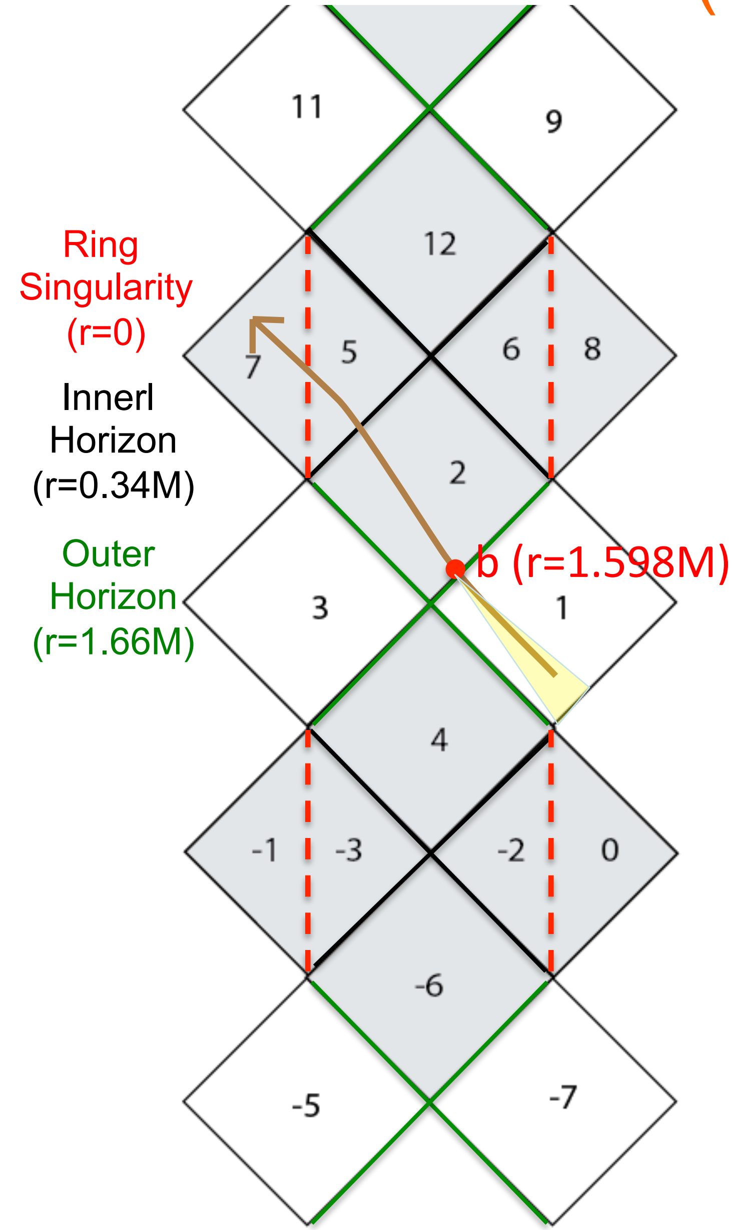


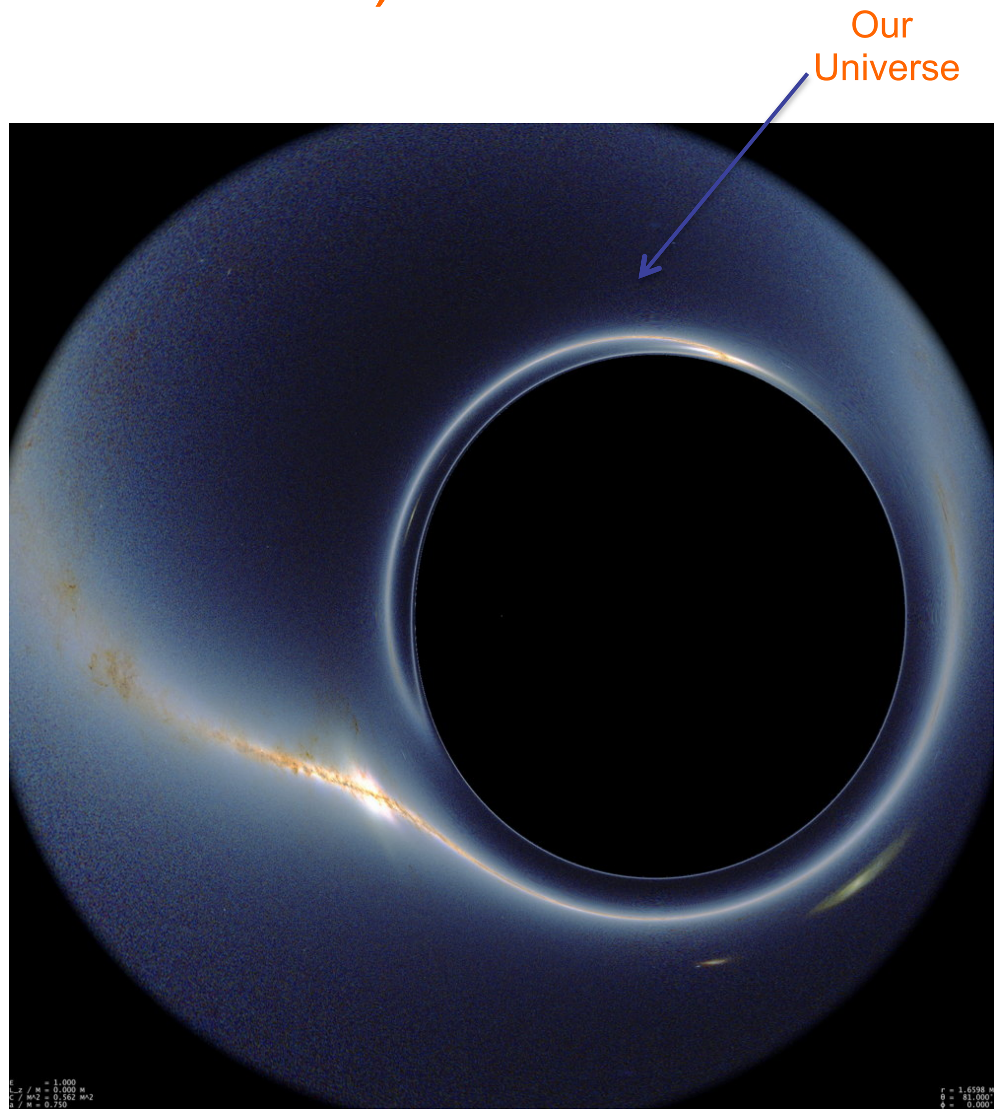
Flight into a Kerr Black Hole (a= 0.75 M)
(Riazuelo 2019)



Flight into a Kerr Black Hole (a= 0.75 M)

(Riazuelo 2019)

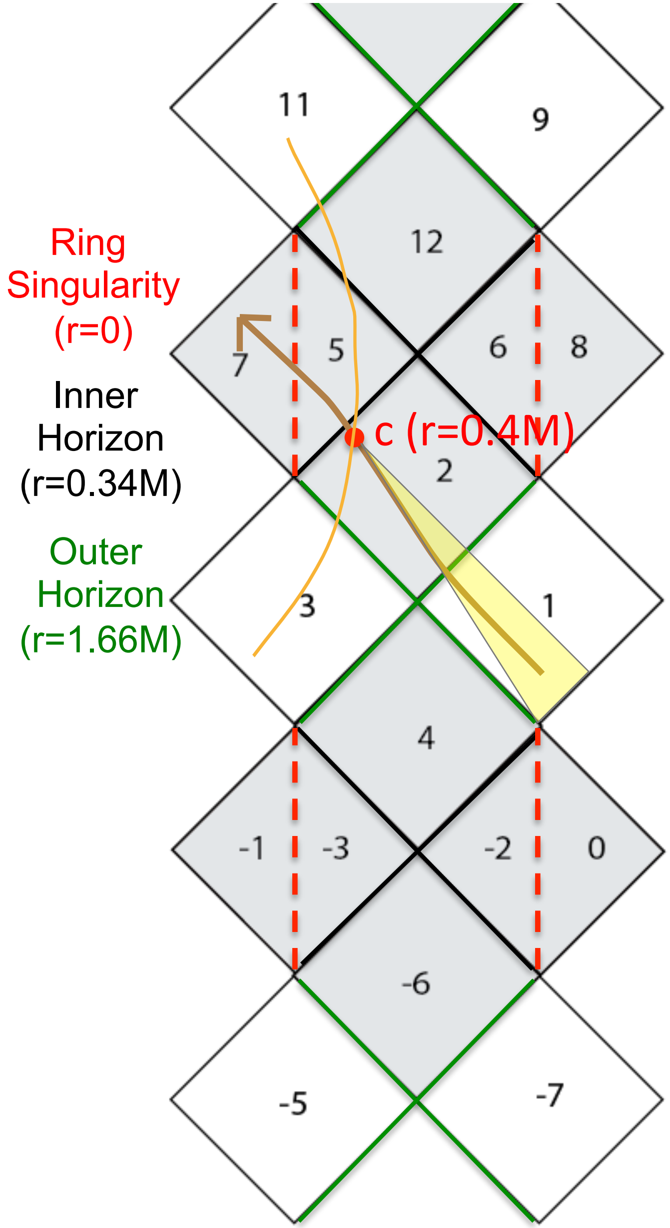


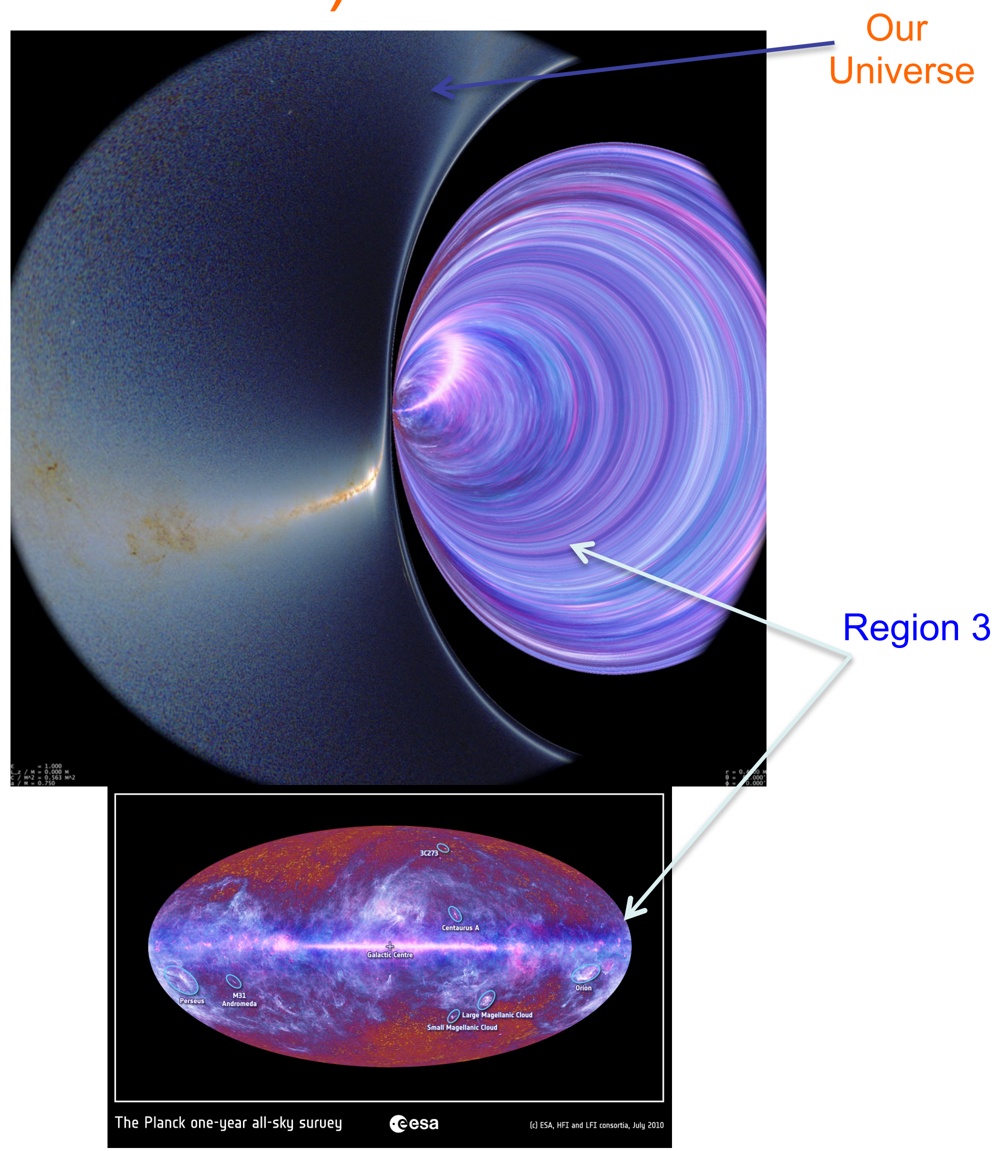


What we see in b

Flight into a Kerr Black Hole (a= 0.75 M)

(Riazuelo 2019)

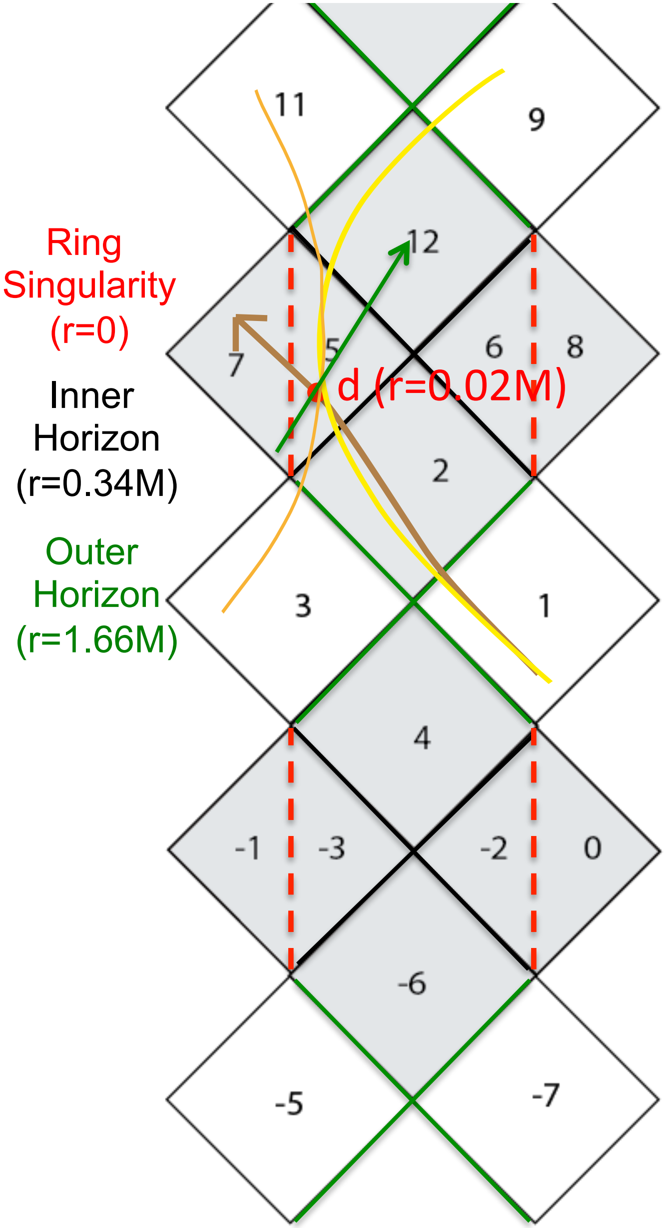


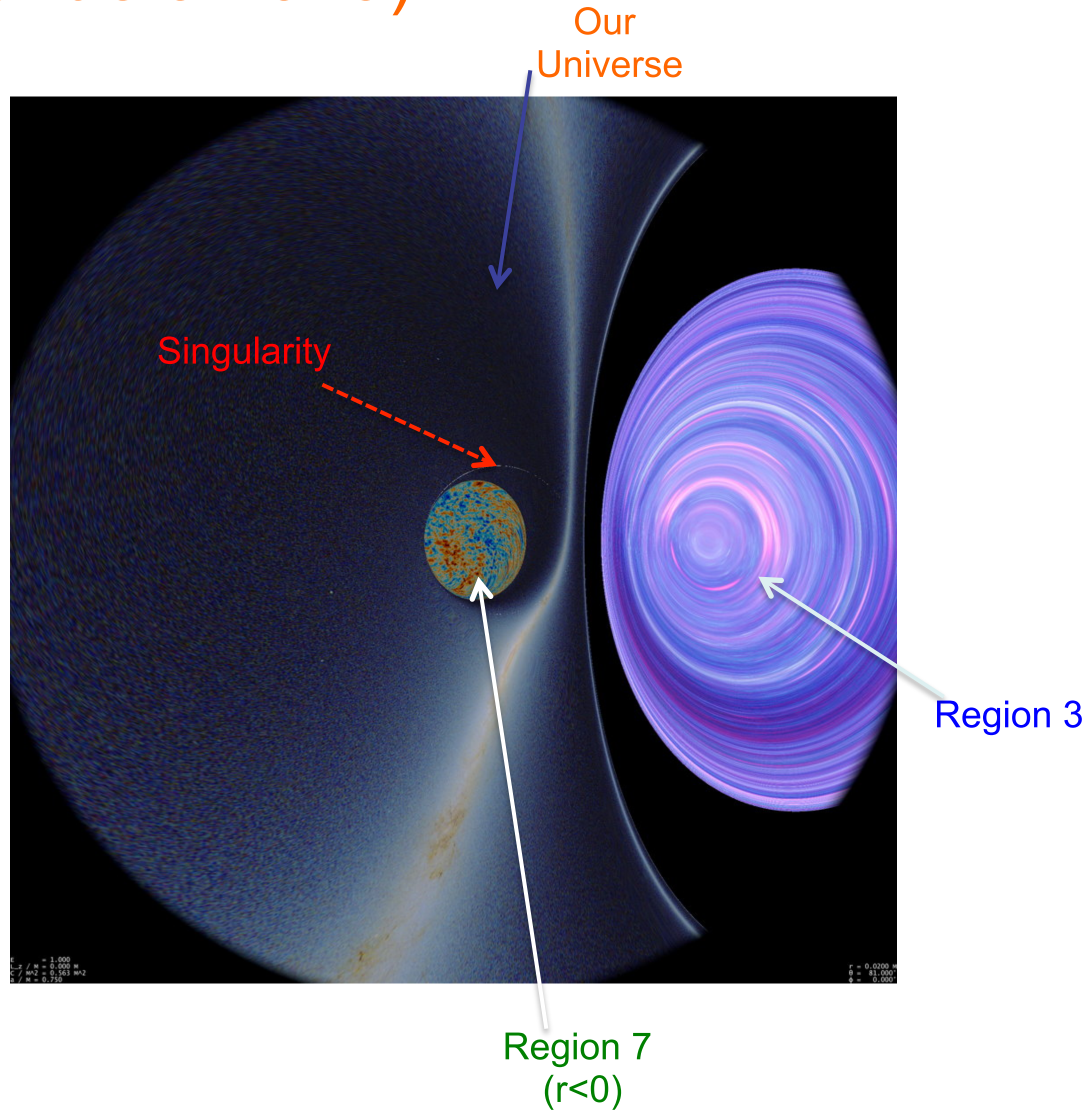


What we see in c

Flight into a Kerr Black Hole (a= 0.75 M)

(Riazuelo 2019)





What we see in d

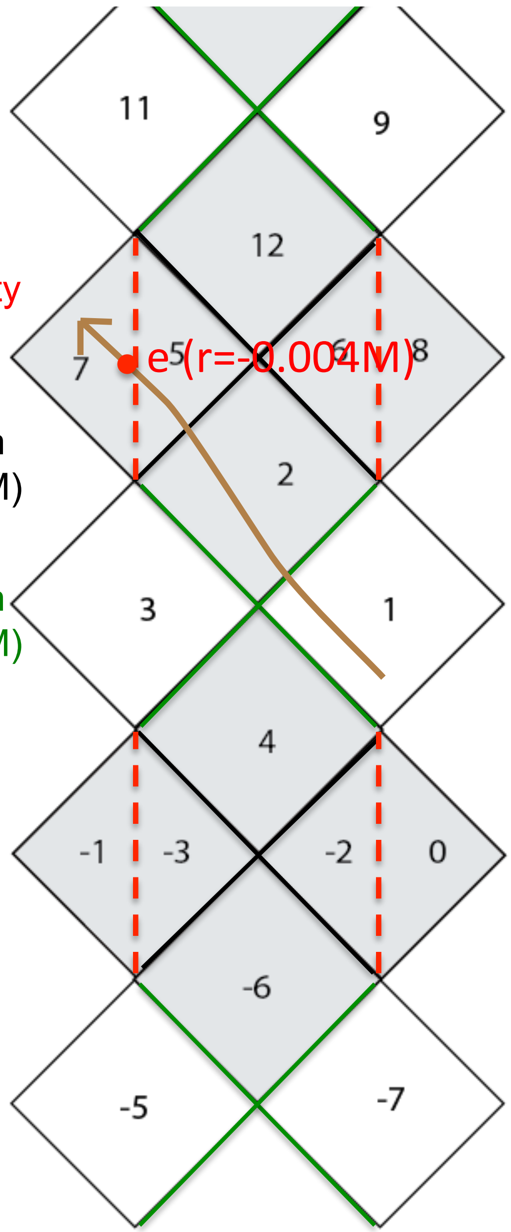
Flight into a Kerr Black Hole (a= 0.75 M)

(Riazuelo 2019)

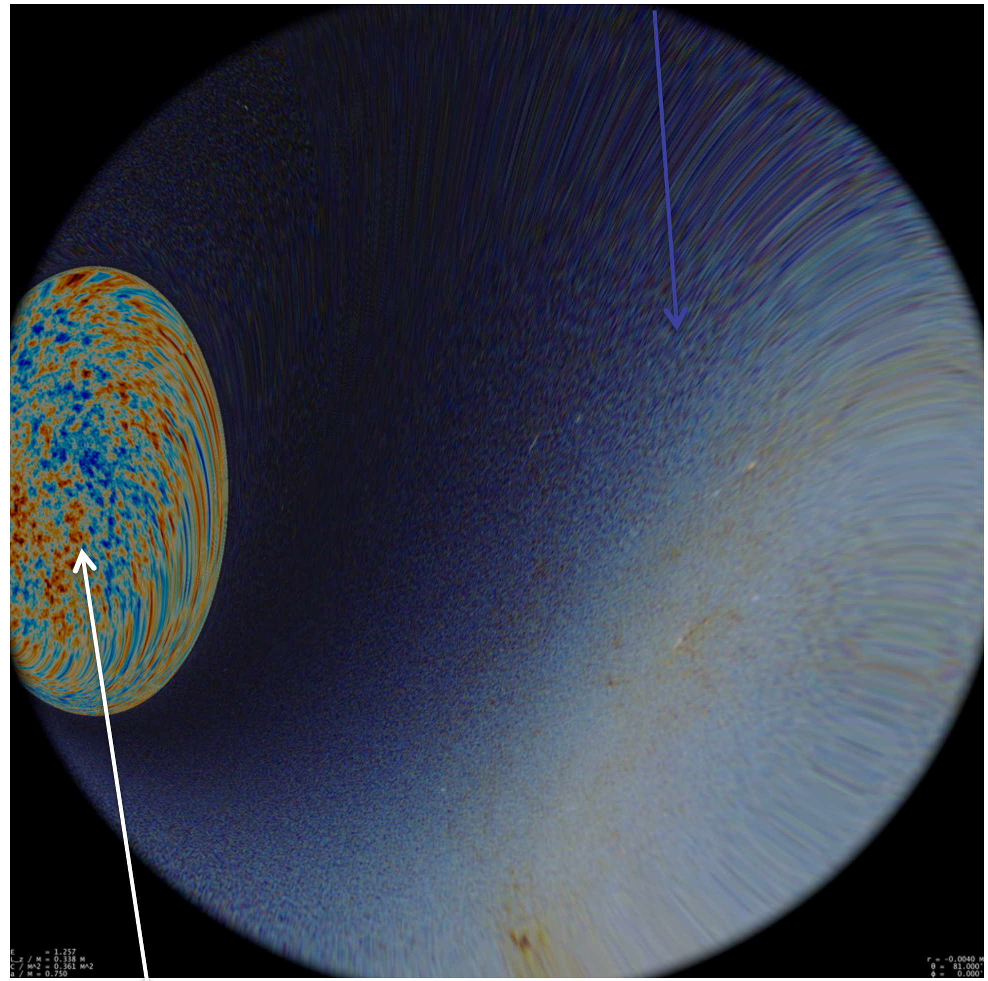
Ring Singularity (r=0)

Inner Horizon (r=0.34M)

Outer Horizon (r=1.66M)



Our Universe (region 1)

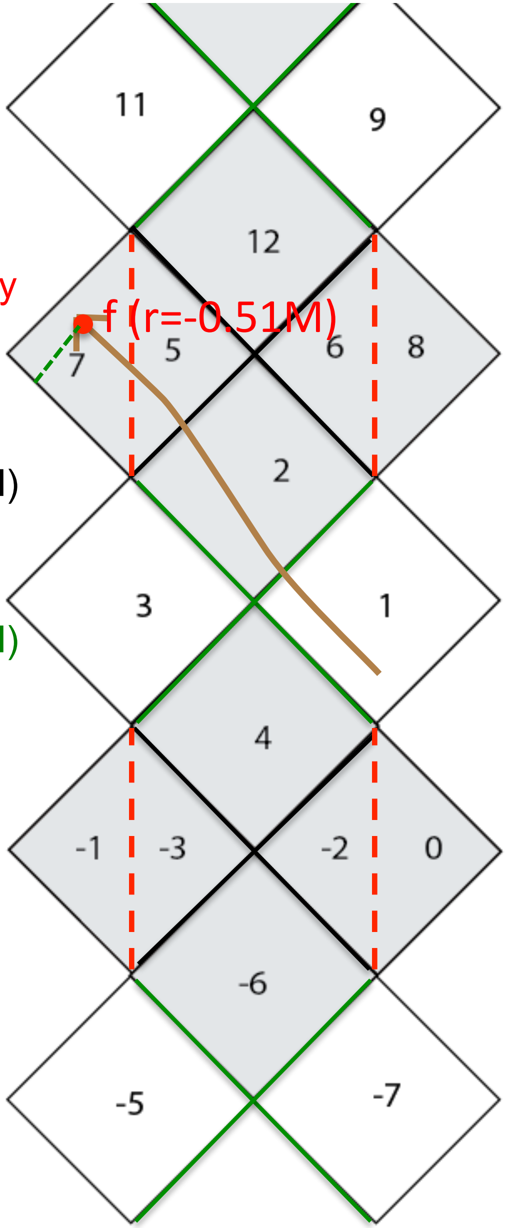


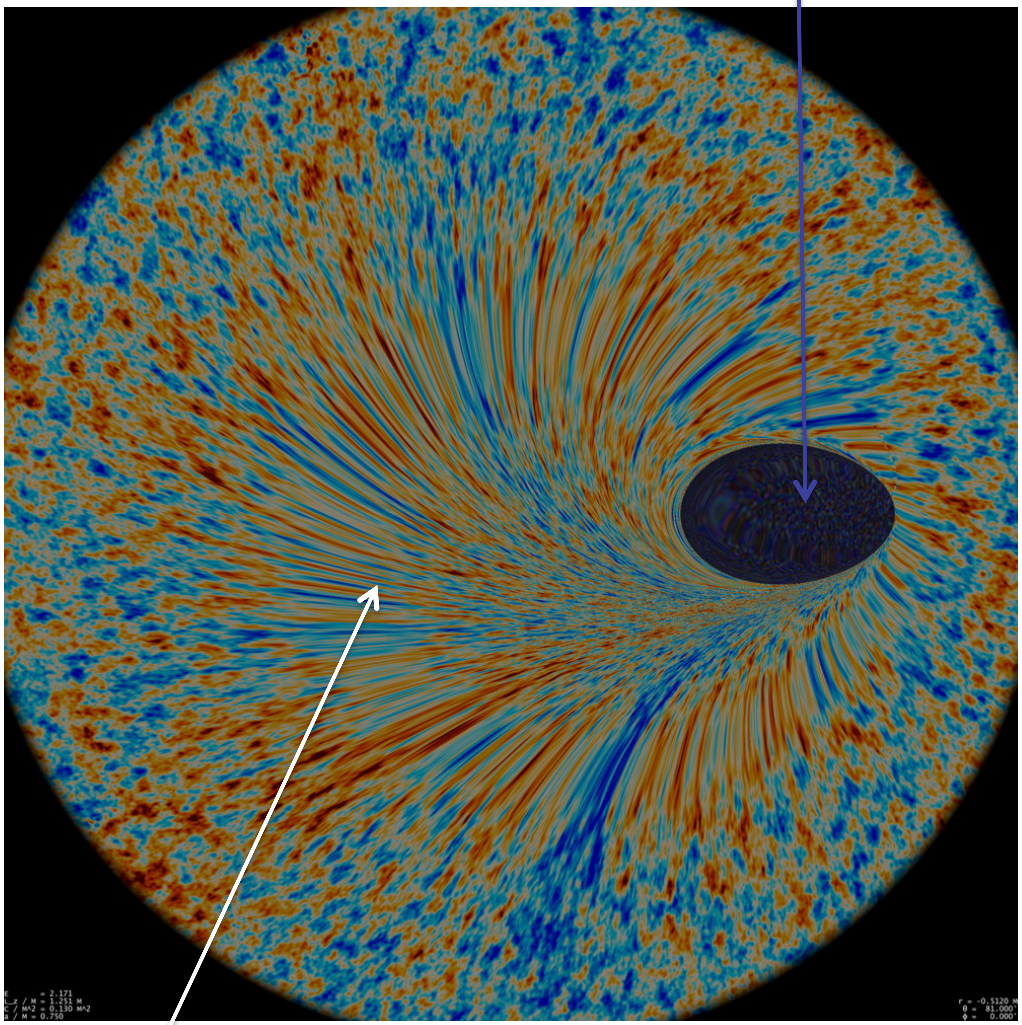
Region 7 (r<0)

What we see in e

Flight into a Kerr Black Hole (a= 0.75 M)

(Riazuelo 2019)





What we see in f

Merci !