

Dernières nouvelles des trous noirs

A central black hole is depicted as a dark, circular void. It is surrounded by a glowing, multi-layered accretion disk that emits light in shades of blue, green, and yellow. The background is a deep blue space filled with numerous stars of varying sizes and colors, including white, yellow, and orange. A faint, glowing orange and yellow nebula or galaxy structure is visible in the upper left quadrant.

JEAN-PIERRE LUMINET

LABORATOIRE D'ASTROPHYSIQUE DE
MARSEILLE (LAM)

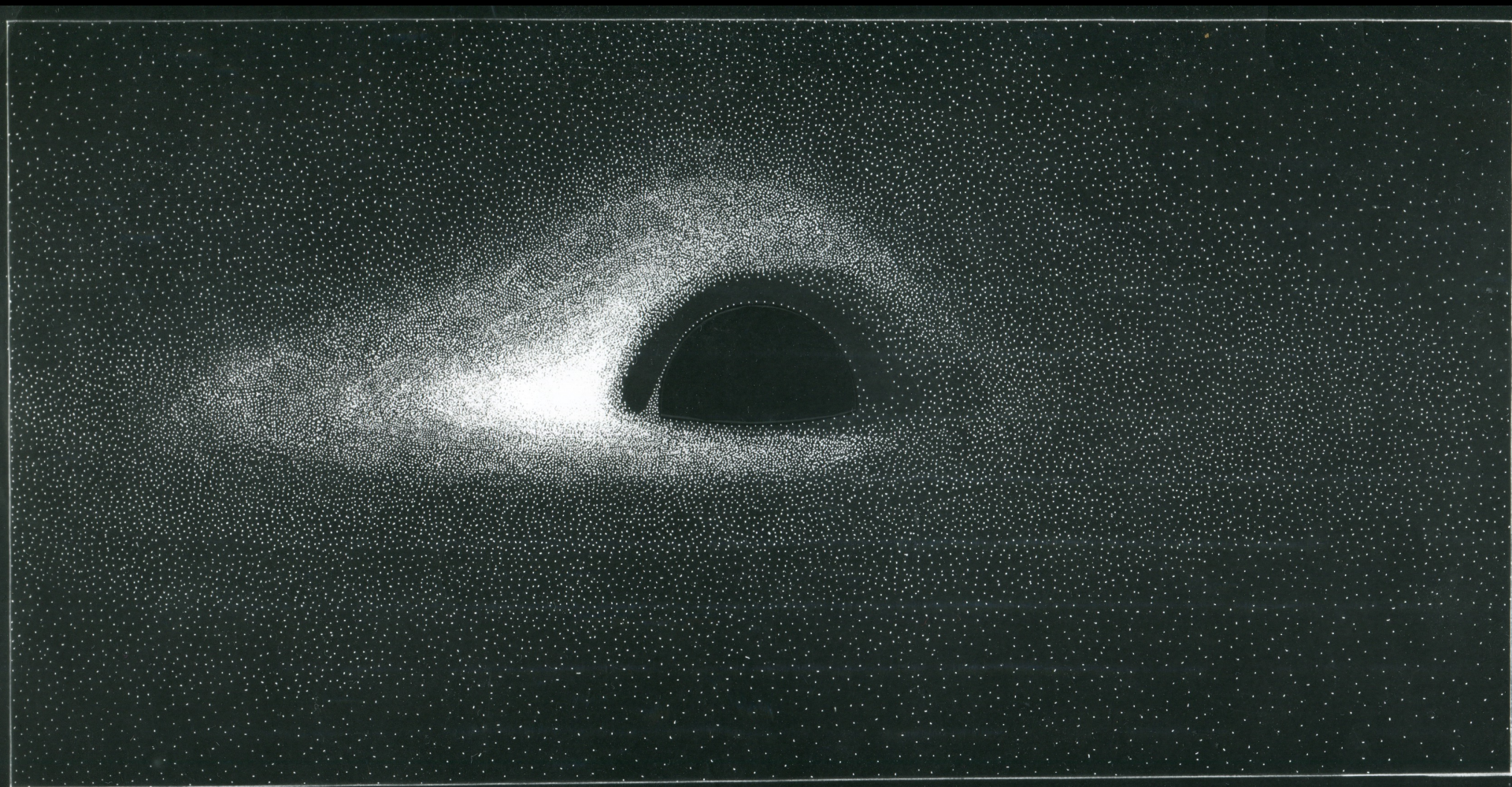
Premières images télescopiques de trous noirs



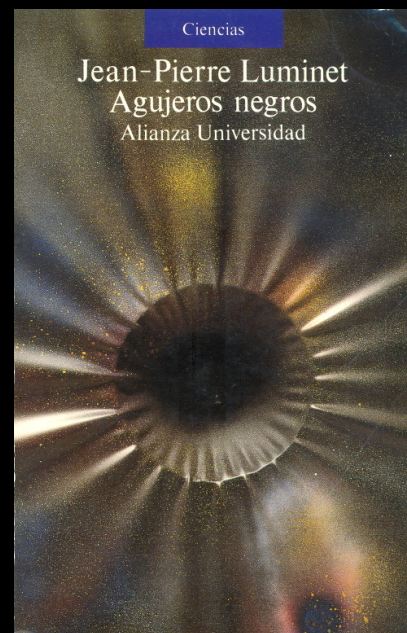
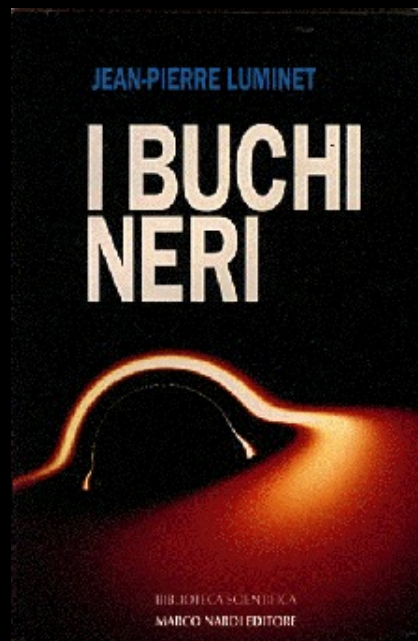
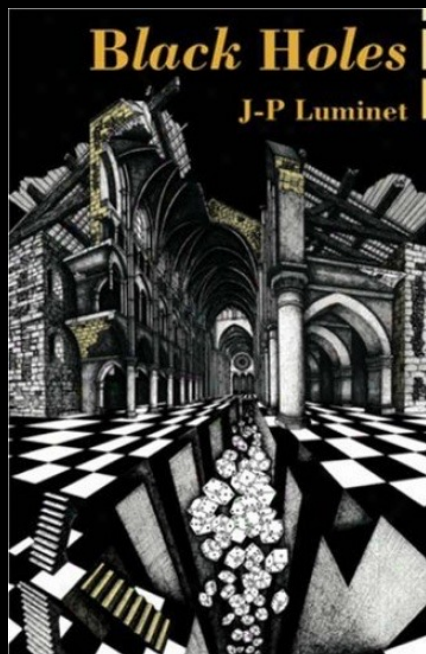
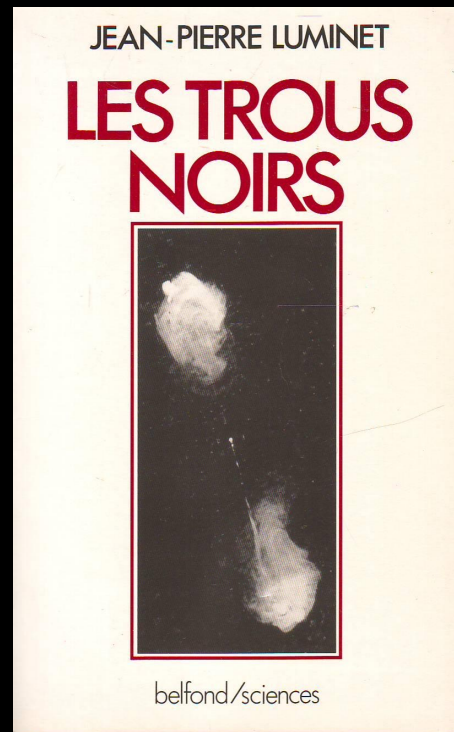
M87*: 10 avril 2019



SgrA*: 12 mai 2022



J.-P. Luminet, 1978





JEAN-PIERRE LUMINET

LES TROUS NOIRS

EN 100 QUESTIONS

©Tallandier

Léon Dierx : Le Gouffre (1867)



Il est des gouffres noirs dont les bords sont charmants.

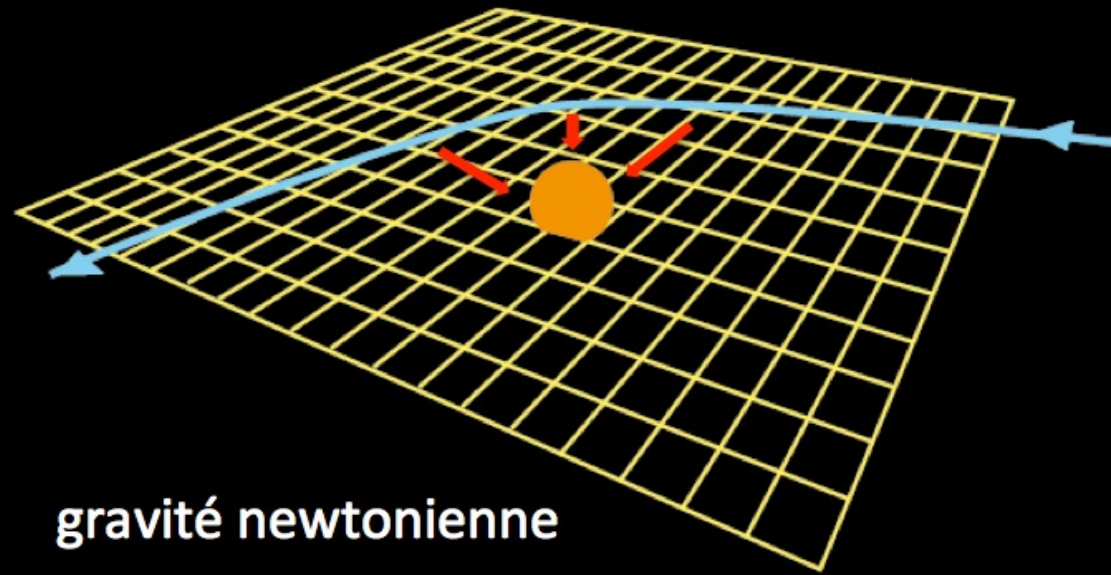
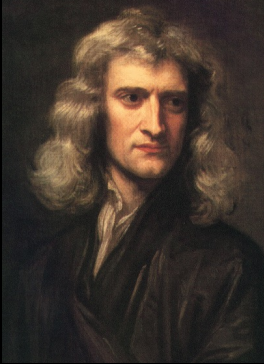
Je sais un gouffre noir sur la verte colline.
Des arbres de senteur l'ombragent en entier,
Et l'on y vient joyeux par le plus gai sentier.
[...] Et pour sonder le creux du soupirail profond,
Pour réveiller l'écho qui dormait sous ces plantes,
J'y fis tomber caillou, pierre et roches branlantes;
Mais comme au néant même en qui rien ne répond,
Tout s'abîmait. Nul bruit ne monta des ténèbres,
Un horrible frisson de pâleur et de froid
M'envahit tout à coup. Et je m'enfuis tout droit,
Souffleté par le vent des mystères funèbres.

A blue-toned image of a hand holding a pen nib, with the text "Un peu d'histoire ..." overlaid in yellow. The background is a dark blue gradient, and the hand and pen nib are rendered in a lighter blue, almost white, color. The pen nib is pointing downwards, and the hand is positioned to hold it. The text is centered horizontally and vertically.

Un peu d'histoire ...

Théorie de Newton

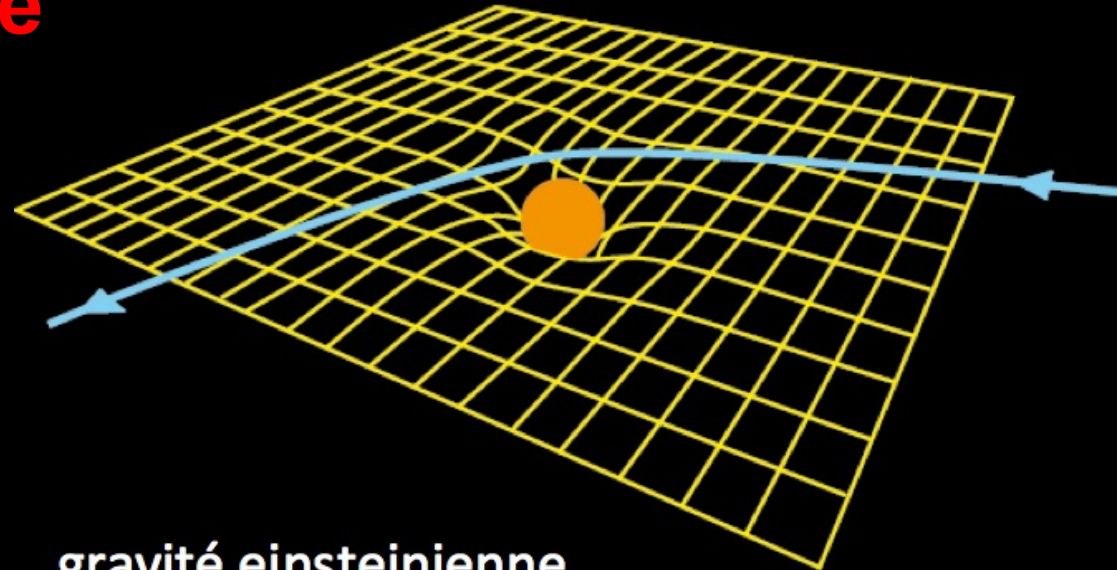
*Gravité = Force
d'attraction instantanée*



gravité newtonienne

Relativité Générale

*Gravité = Courbure de
l'espace-temps*



gravité einsteinienne

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**

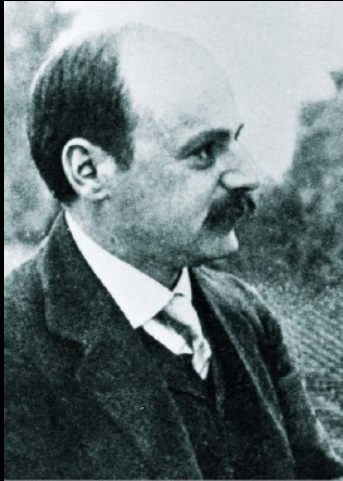
Métrieque : $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

Effondrement gravitationnel

TROU NOIR



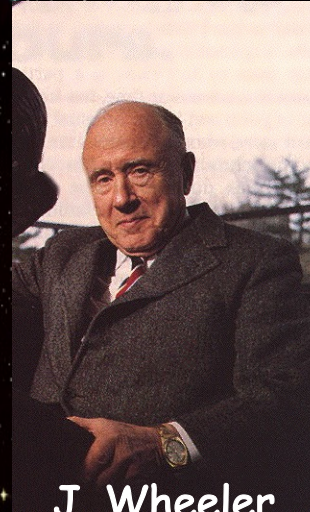
Quelques pères fondateurs



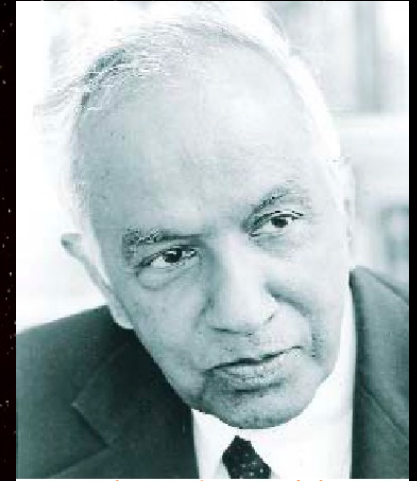
K. Schwarzschild



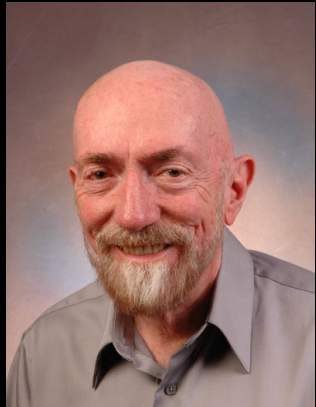
R. Oppenheimer



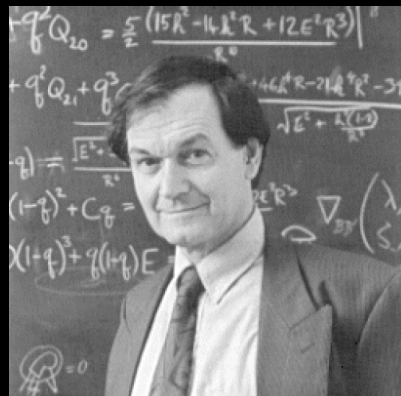
J. Wheeler



S. Chandrasekhar



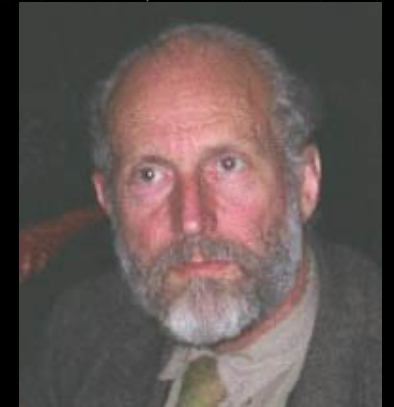
K. Thorne



R. Penrose

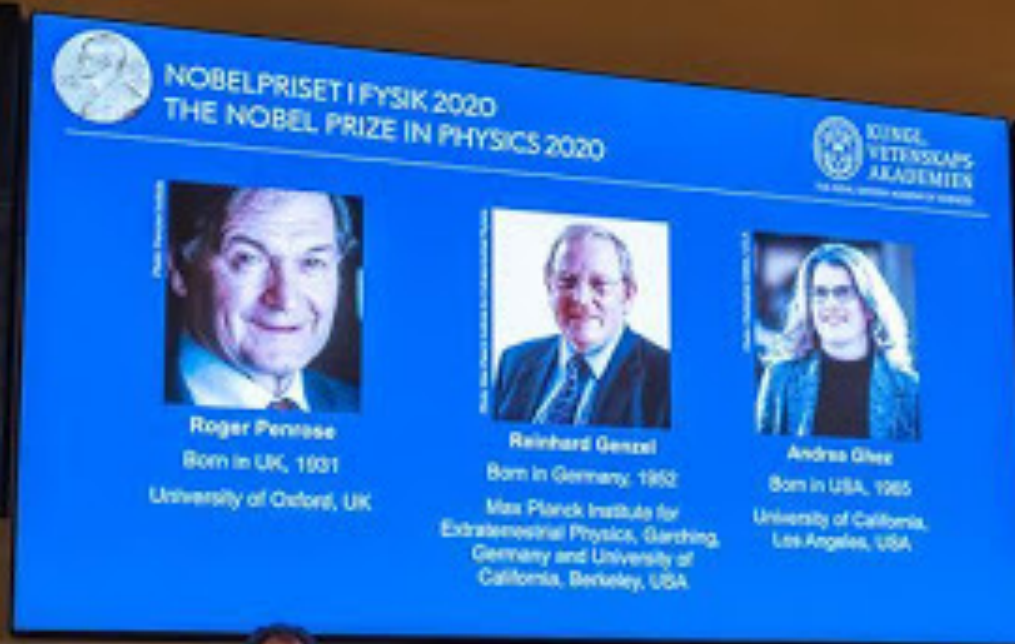


S. Hawking



B. Carter




Prix Nobel de physique 2020



The image shows a large blue screen displaying the announcement for the Nobel Prize in Physics 2020. At the top left is the Nobel Prize logo. The text reads "NOBELPRISET I FYSIK 2020" and "THE NOBEL PRIZE IN PHYSICS 2020". On the top right is the logo of the Royal Swedish Academy of Sciences. Below this, three portraits of the laureates are shown, each with their name and affiliation.

NOBELPRISET I FYSIK 2020
THE NOBEL PRIZE IN PHYSICS 2020

KUNGL. VETENSKAPS AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Portrait	Name	Birth	Institution
	Roger Penrose	Born in UK, 1931	University of Oxford, UK
	Reinhard Genzel	Born in Germany, 1952	Max Planck Institute for Extraterrestrial Physics, Garching, Germany and University of California, Berkeley, USA
	Andrea Ghez	Born in USA, 1965	University of California, Los Angeles, USA

KUNGL. VETENSKAPS AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

KUNGL. VETENSKAPS AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Le B-A- BA physique

A blue-toned image of a wine glass with a glowing effect, serving as a background for the text. The glass is centered and has a bright, circular glow at its base, which fades into the surrounding blue background. The text "Le B-A- BA physique" is overlaid in a bright yellow color.

- Un trou noir n'est pas forcément « petit »

Rayon critique de Schwarzschild:

$$R_S = 2GM/c^2 \sim 3 \text{ km } M/M_S$$

- Un trou noir n'est pas forcément « dense »

masse volumique moyenne $\propto 1/M^2$

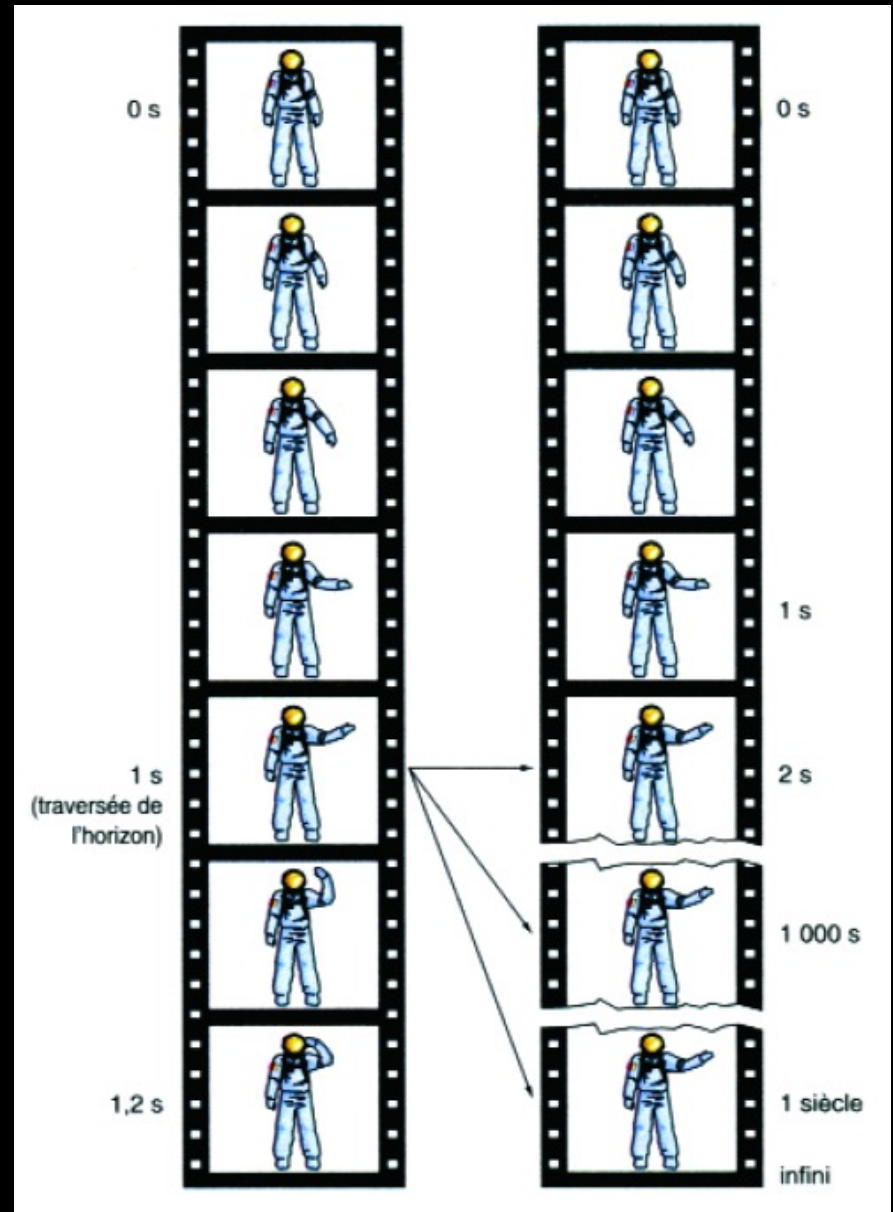
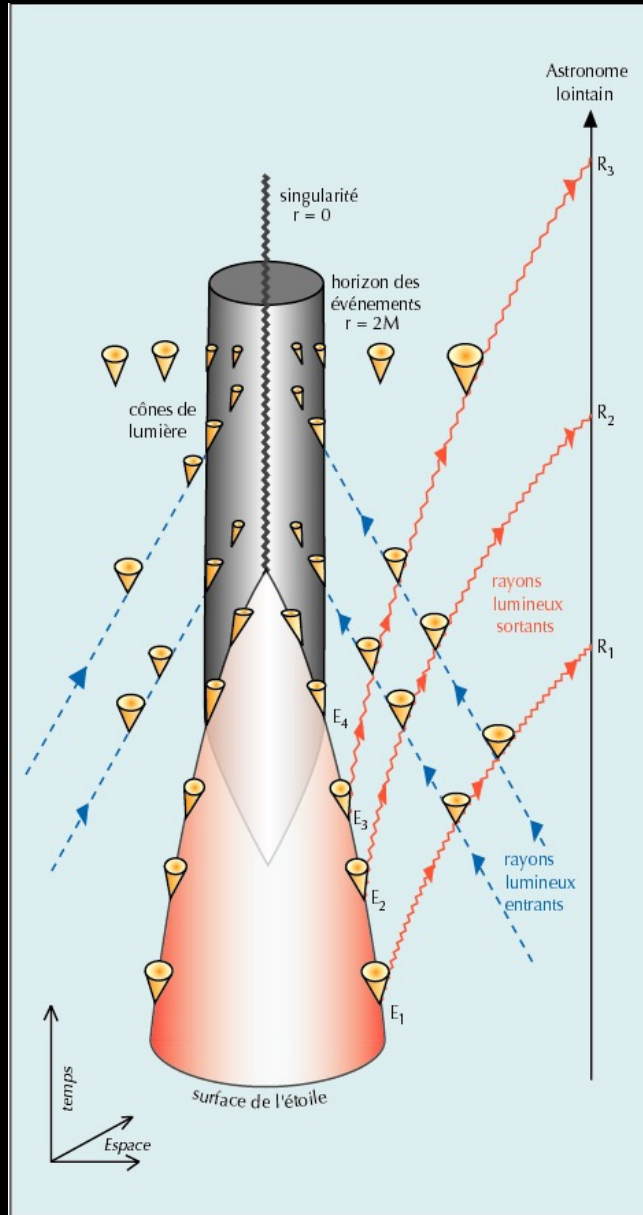
- Pour $10 M_S$, $\rho \sim 10^{15} \text{ g/cm}^3$
- Pour $10^6 M_S$, $\rho \sim 10^3 \text{ g/cm}^3$
- Pour $10^9 M_S$, $\rho \sim 10^{-3} \text{ g/cm}^3$

- Un trou noir n'est pas forcément « singulier »

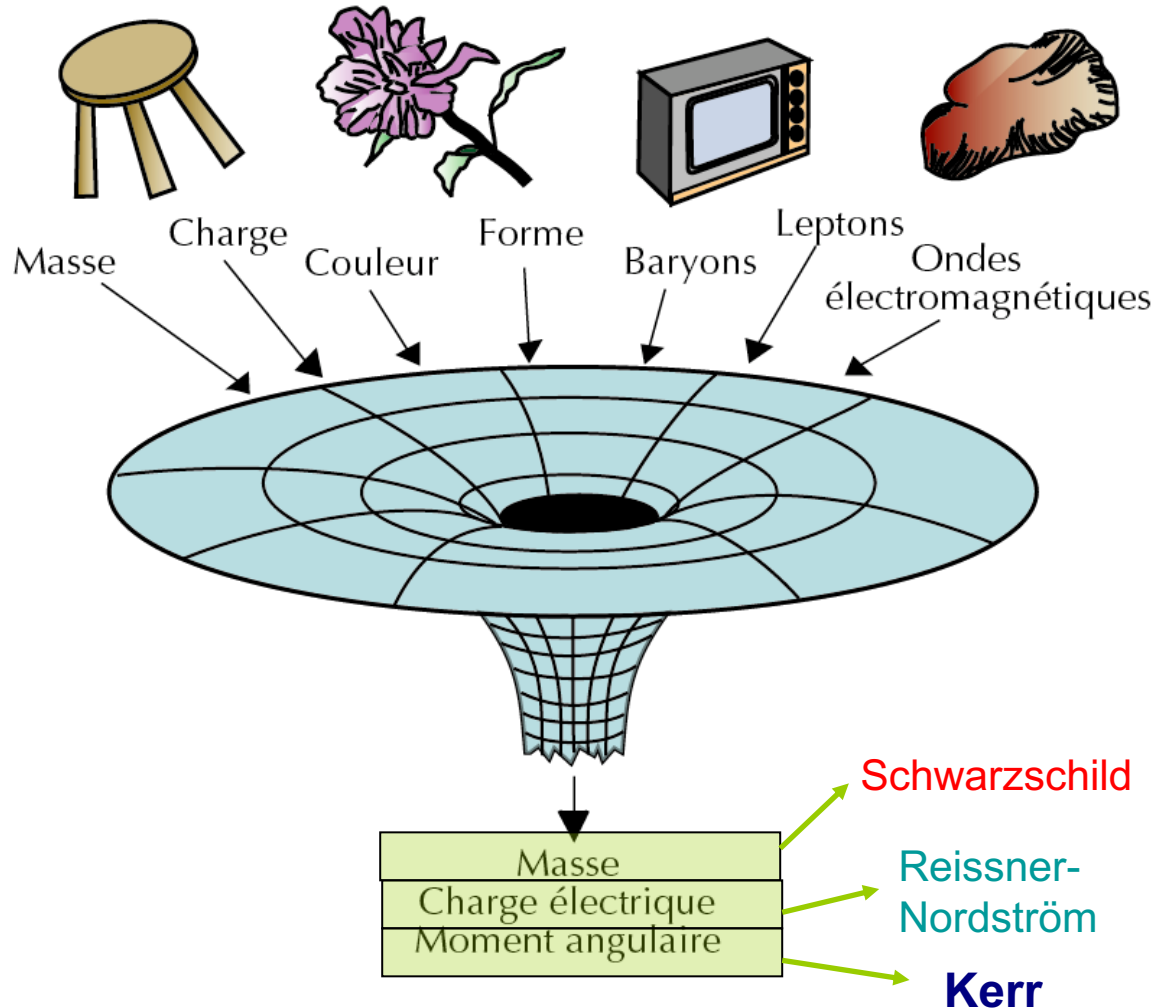
(Singularité = courbure infinie)

RG classique / RG quantique

Horizon des événements

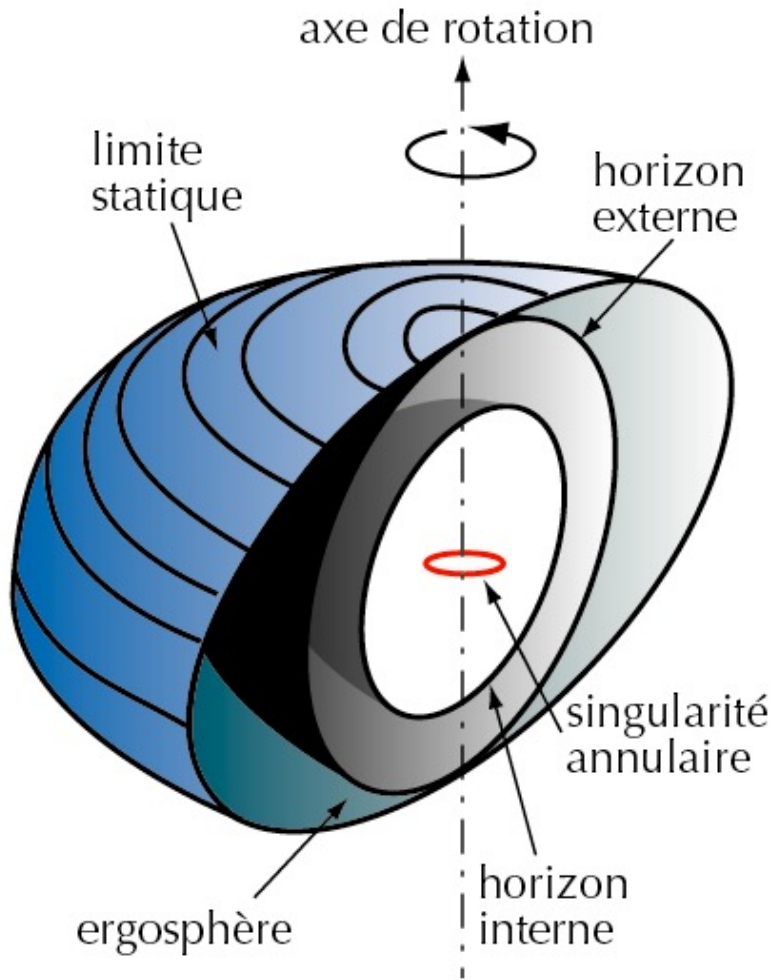
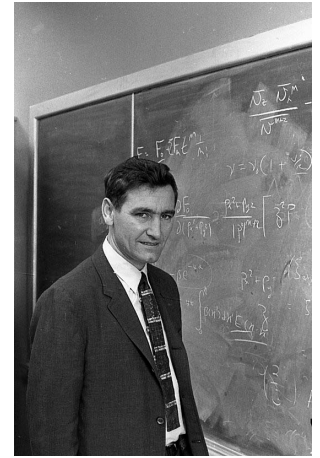


« Un trou noir n'a pas de chevelure » (Théorème de calvitie)



➔ *Enorme Perte d'information pour l'univers extérieur !*

Le trou noir en rotation (Kerr, 1963)



Energie totale :

Energie
rotationnelle

Masse
irréductible

Peut être extraite!

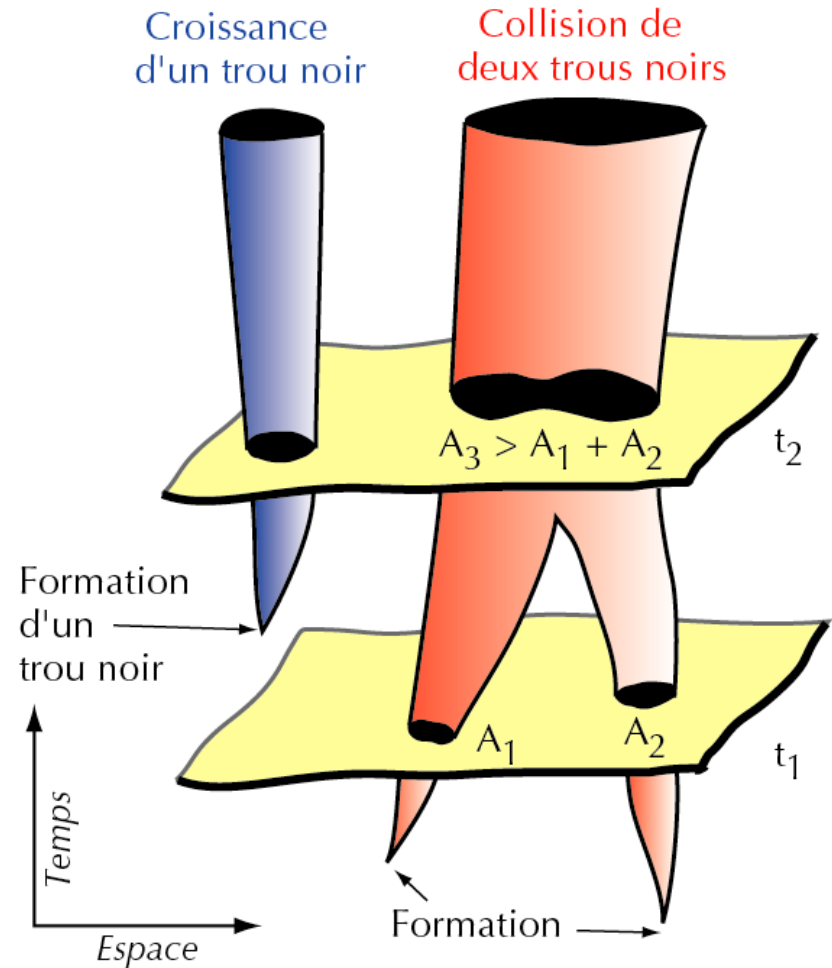
Thermodynamique des trous noirs

aire \propto entropie

$$S = A/4$$

température \propto
gravité de surface

$$T = g/2\pi$$



$$dA > 0$$

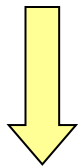
Evaporation quantique des trous noirs & Rayonnement Hawking

→ Les trous noirs ont une gigantesque entropie :

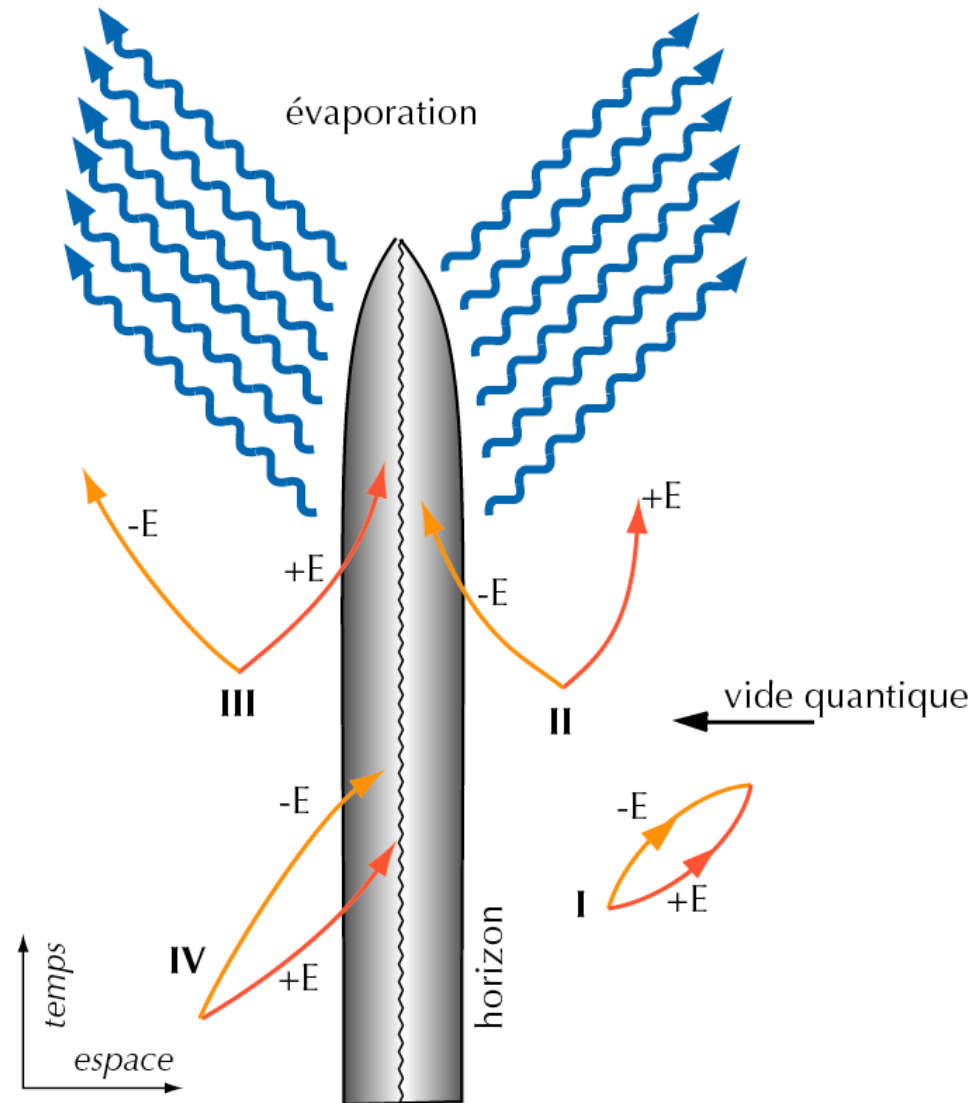
$$S = 10^{77} (M/M_S)^2$$

→ Les trous noirs rayonnent comme un corps noir de température :

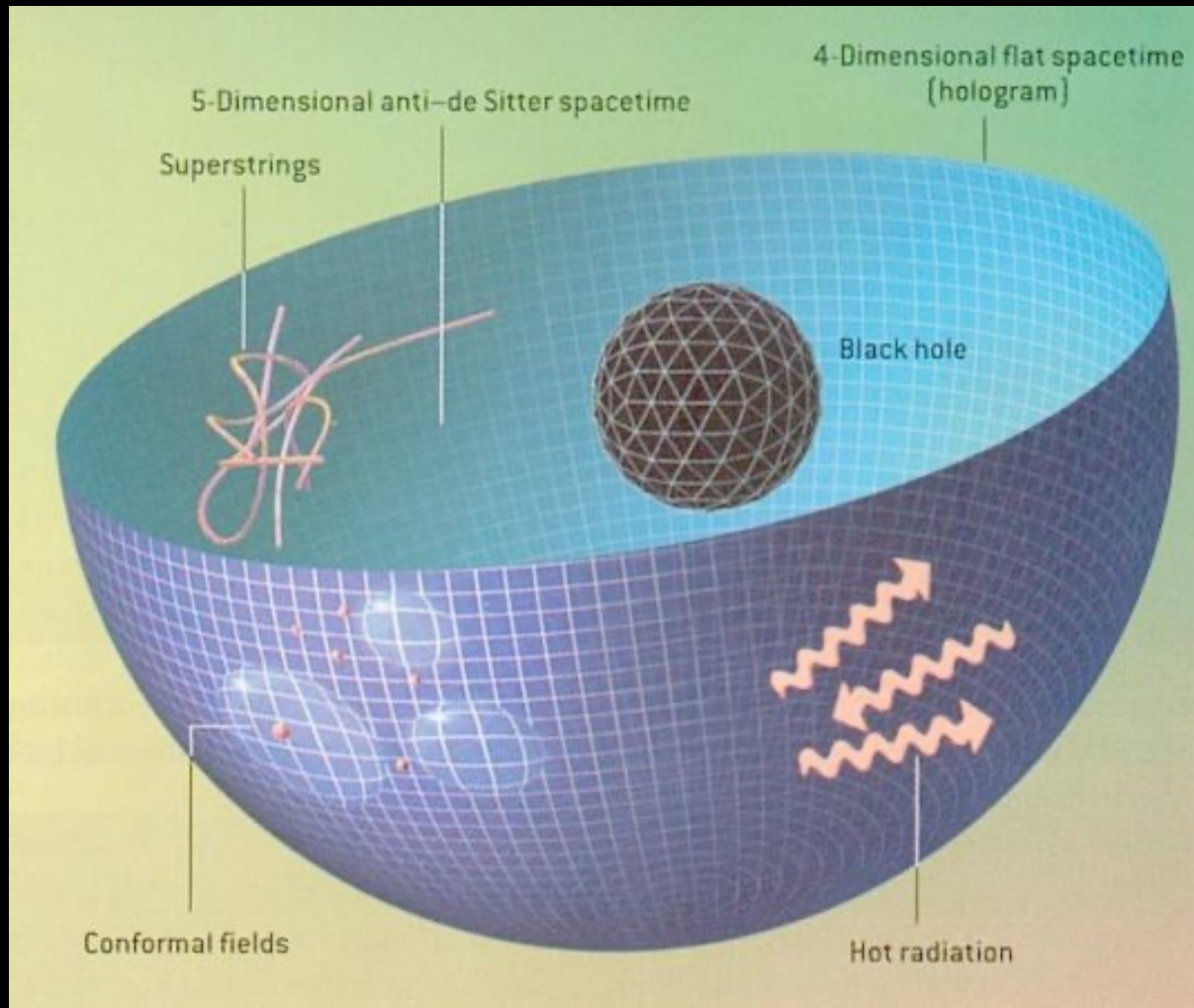
$$T(K) = 10^{-7} M_S/M$$



Paradoxe de l'information



Théorie des cordes

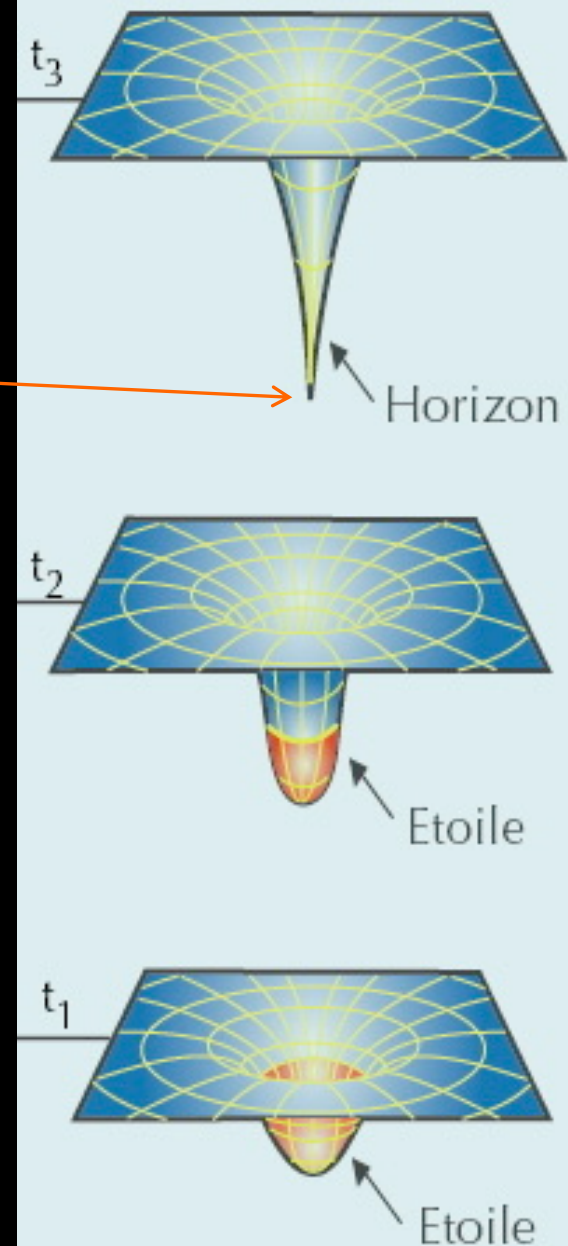
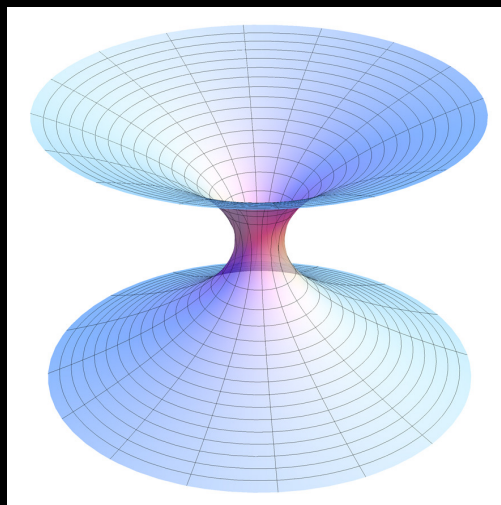


Le trou noir est-il holographique ?

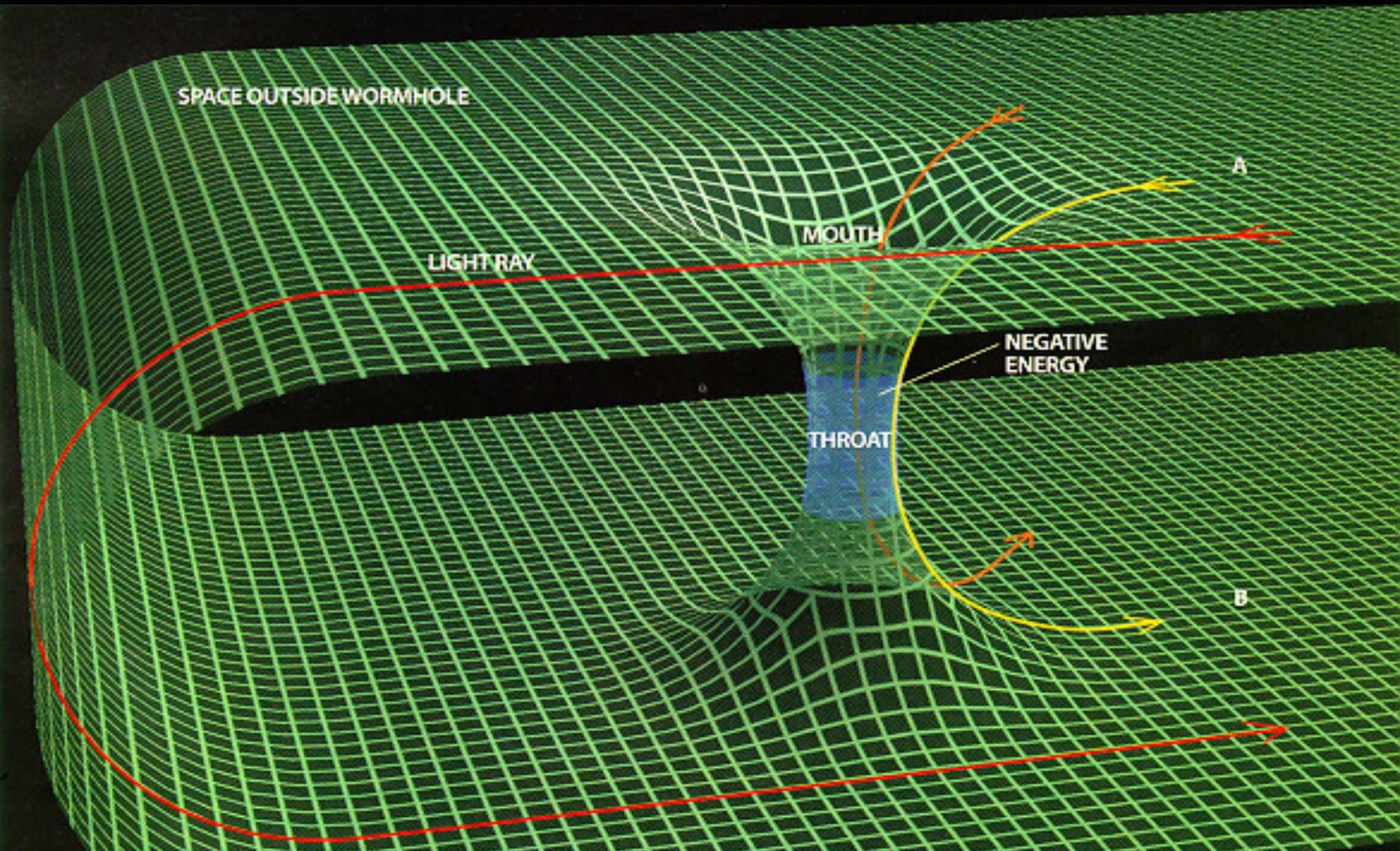
Qu'y a-t-il à l'intérieur ?

1) Singularité

2) Pont d'Einstein-Rosen



La solution « trou de ver »





Les trous noirs astrophysiques

- Trous noirs primordiaux ? $10^{-5} g \lesssim M \lesssim 10^6 M_S$
- Trous noirs stellaires $2,5 M_S \lesssim M \lesssim 100 M_S$
- Trous noirs intermédiaires $10^3 M_S \lesssim M \lesssim 10^5 M_S$
- Trous noirs supermassifs $10^6 M_S \lesssim M \lesssim 10^{10} M_S$
- Trous noirs ultramassifs $M \gtrsim 10^{10} M_S$
- Trou noir univers?

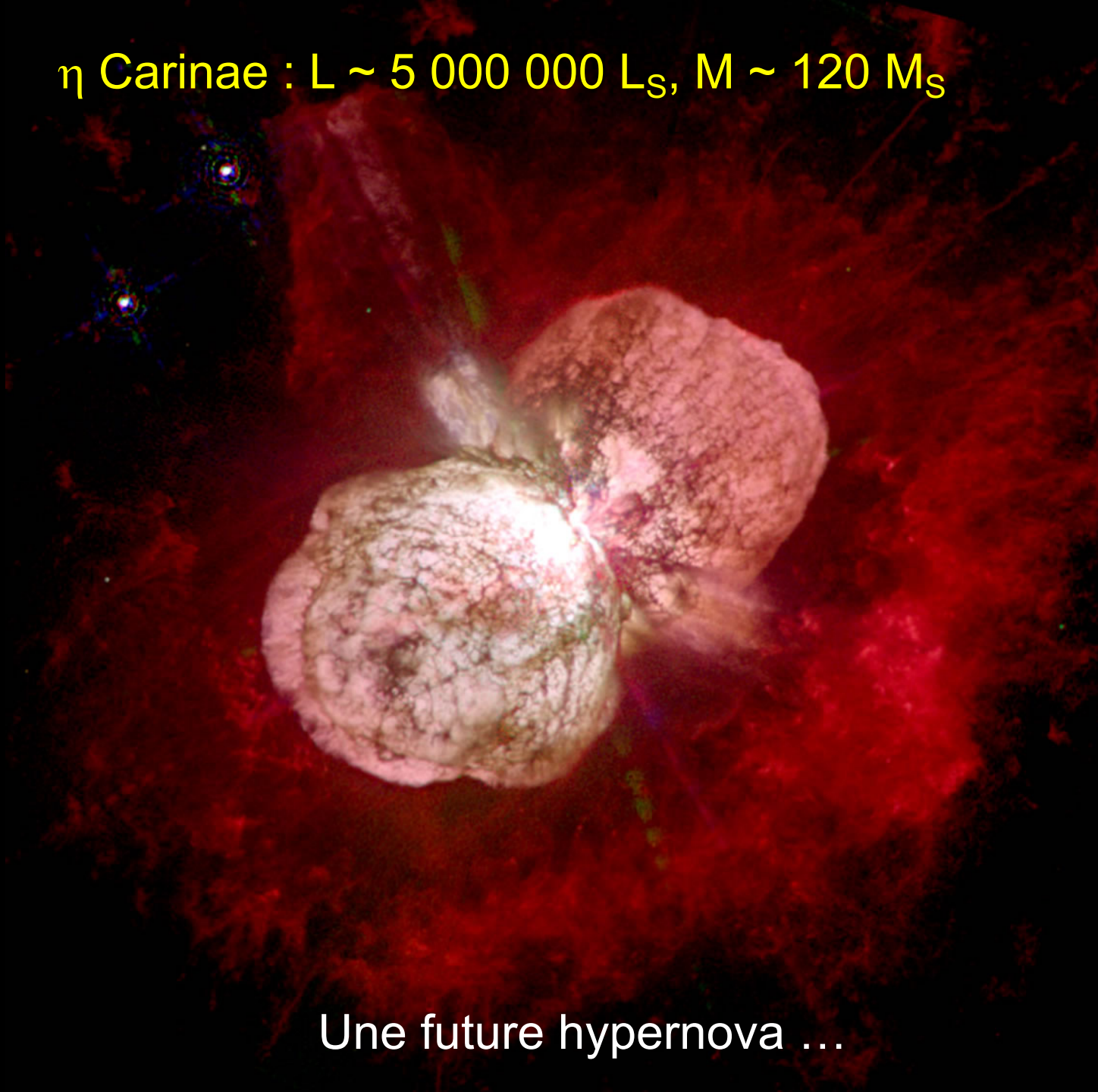
A blue-toned visualization of a stellar black hole. The image shows a central dark region (the event horizon) surrounded by a bright, glowing accretion disk. The light from the disk is distorted by the strong gravity of the black hole, creating a lensing effect that makes the disk appear to curve and stretch. The overall appearance is that of a funnel of light being drawn into a central point.

Les trous noirs stellaires

Evolution stellaire

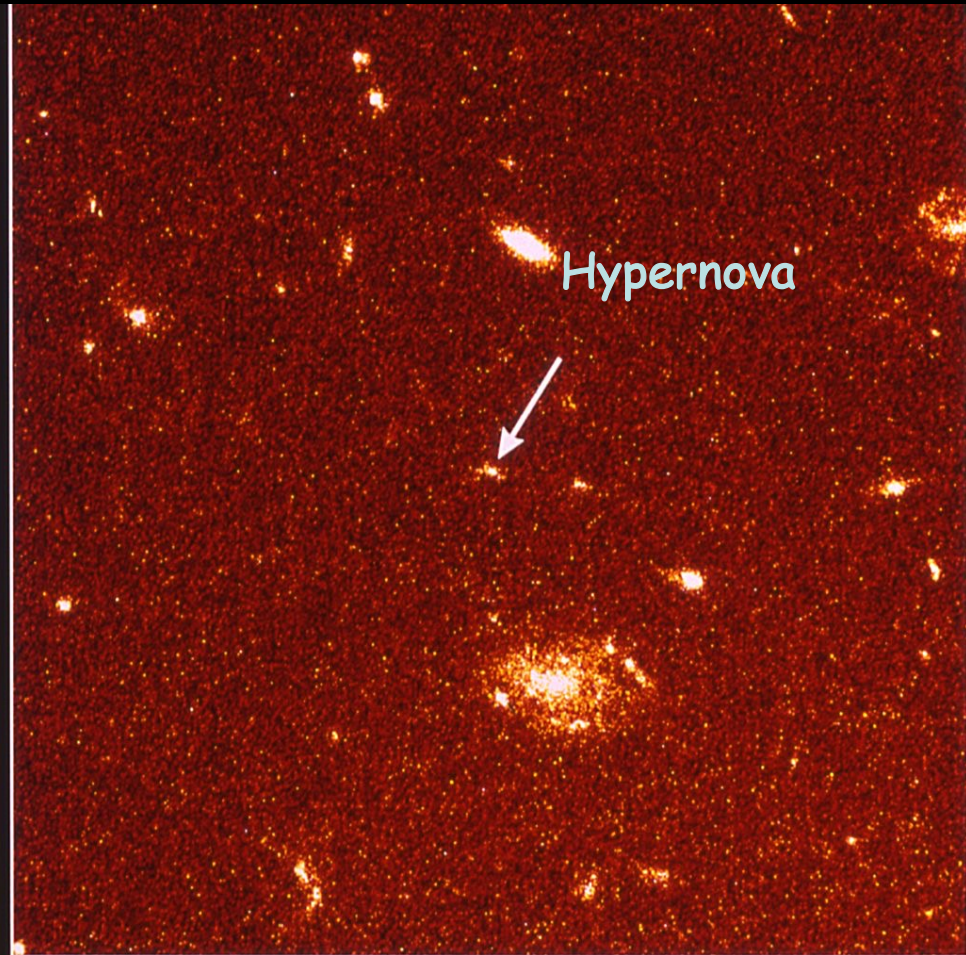
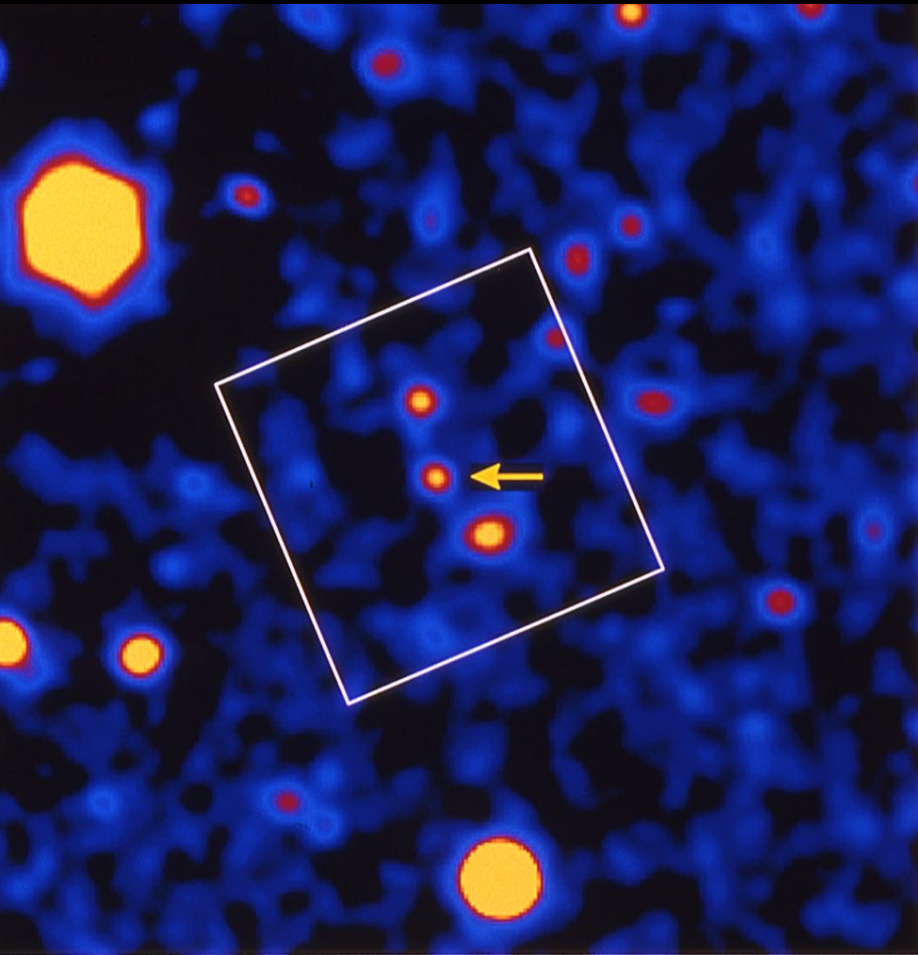
Masse initiale	Résidu compact	%
$M_* \lesssim 8 M_S$	→ Naine blanche $M_{NB} \leq 1,4 M_S$ (limite de Chandrasekhar)	~ 90
$8 M_S \lesssim M_* \lesssim 50 M_S$	→ Etoile à neutrons $M_{EN} \leq 2,5 M_S$ (limite de LOV)	~ 10
$M_* \gtrsim 50 M_S$	→ Trou noir stellaire $M_{TN} \gtrsim 2,5 M_S$	~ 10^{-4}

η Carinae : $L \sim 5\,000\,000 L_{\odot}$, $M \sim 120 M_{\odot}$



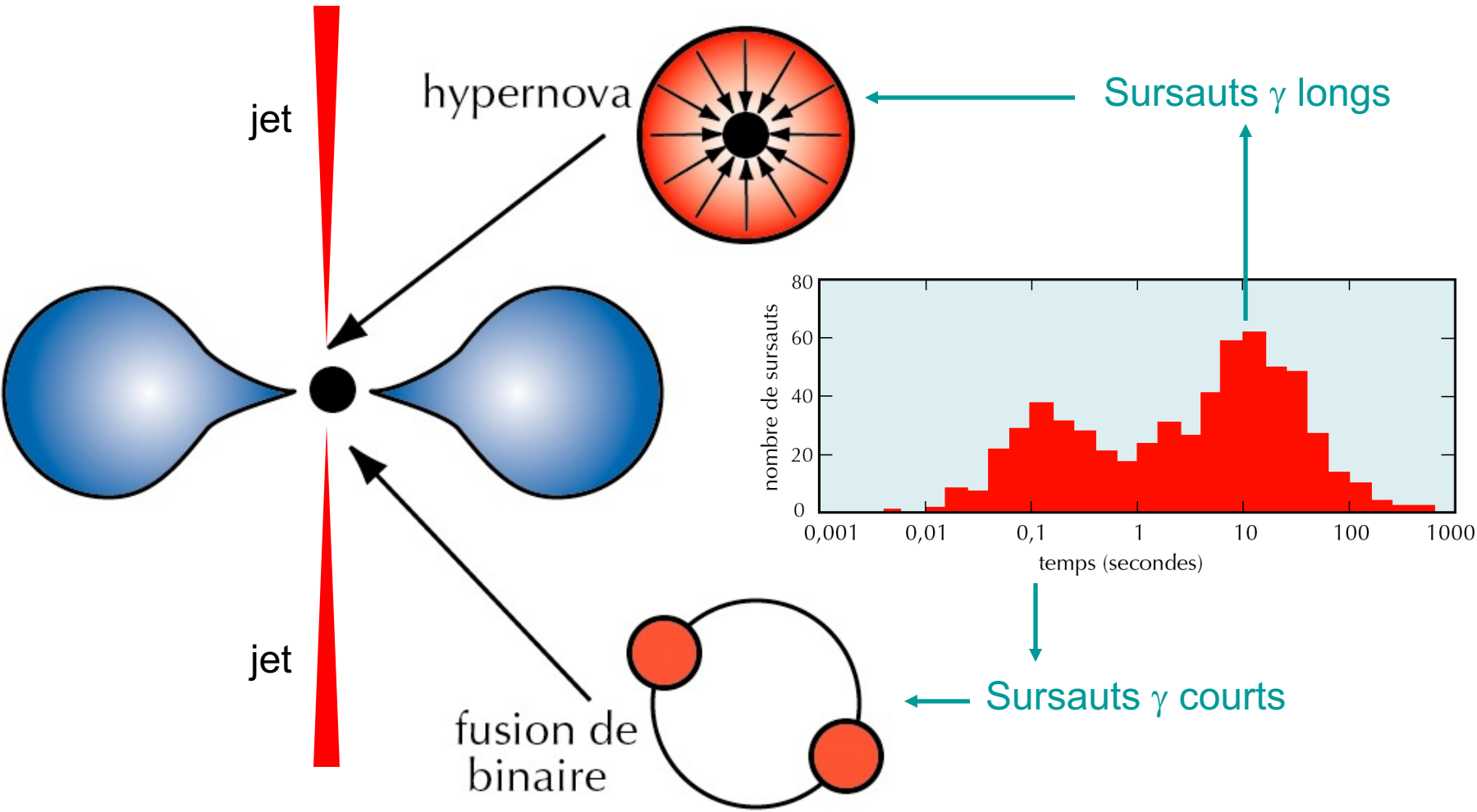
Une future hypernova ...

Formation des trous noirs stellaires



→ Sursauts Gamma

Modélisation des Sursauts Gamma

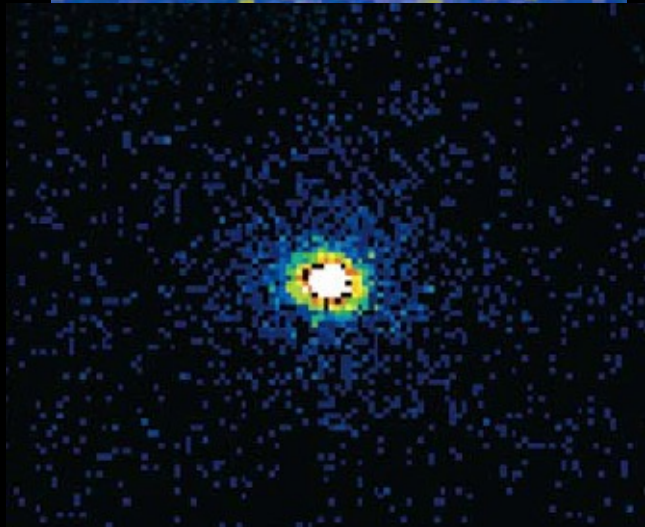
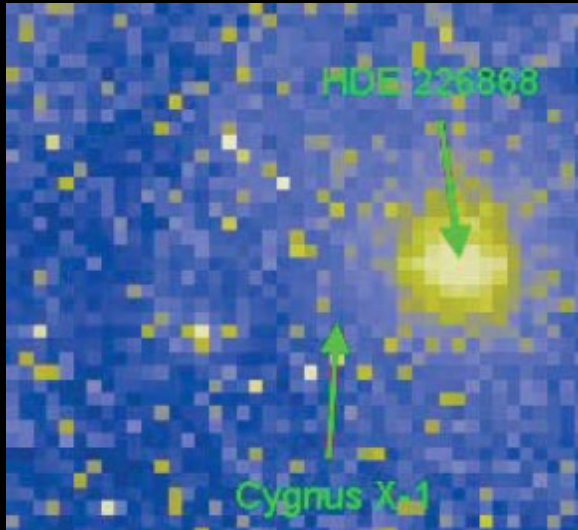


Détection des trous noirs stellaires



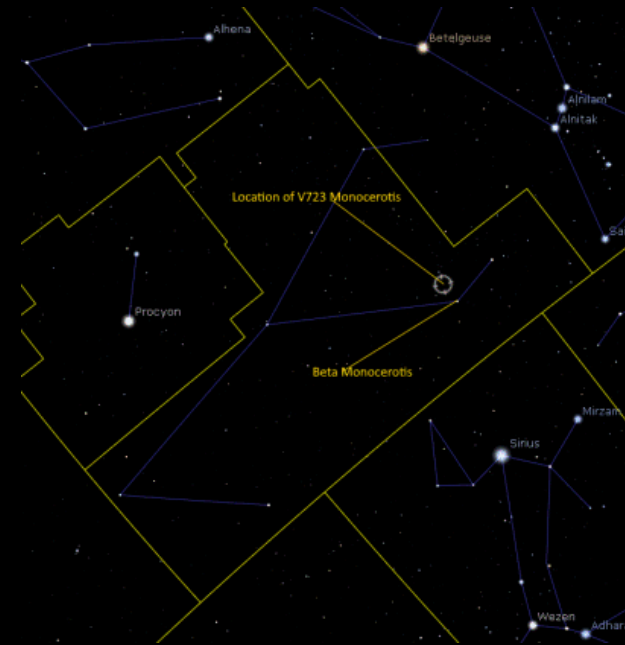
Source X binaire

Le premier ...



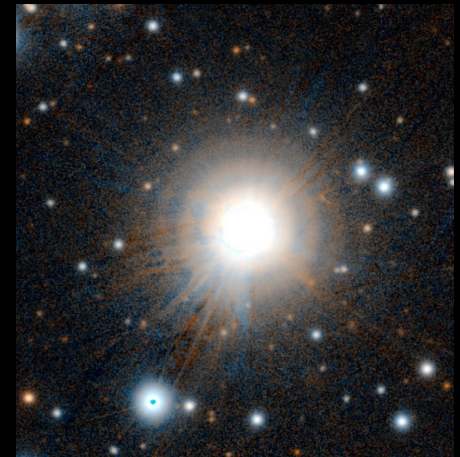
Cygnus X-1
(1971)

Les plus proches ...

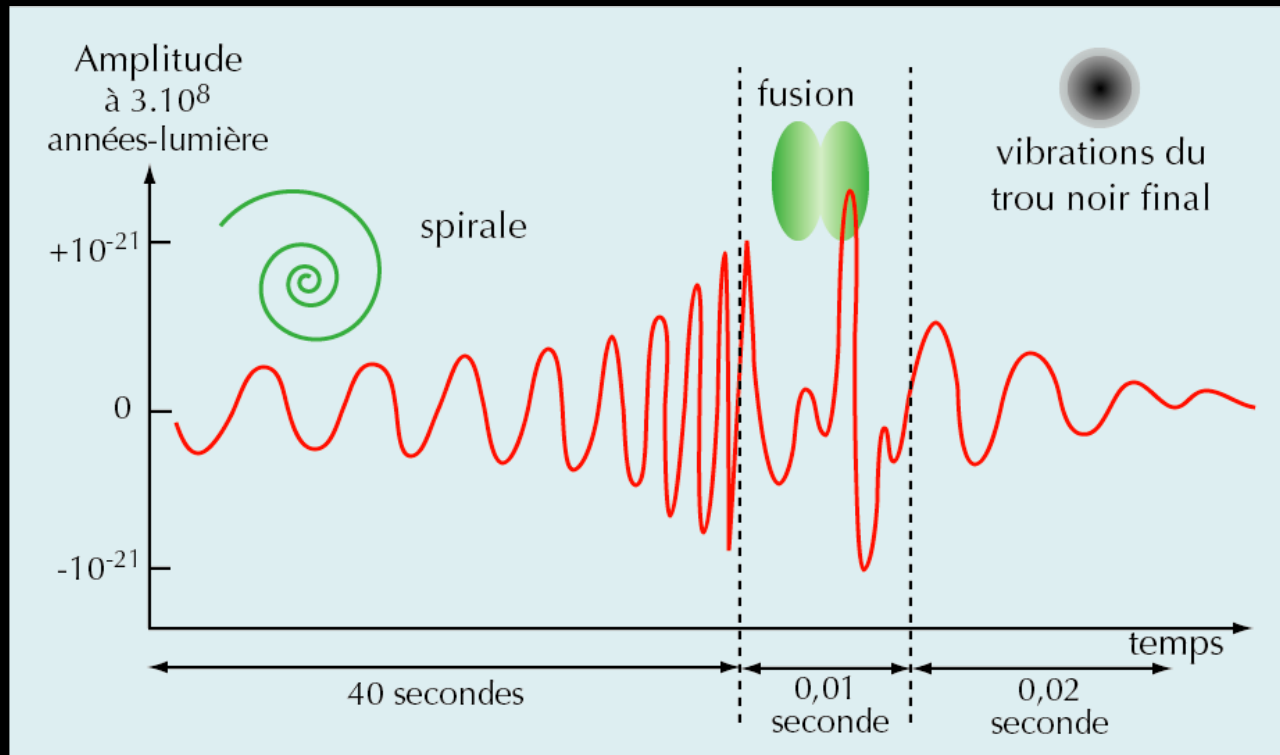
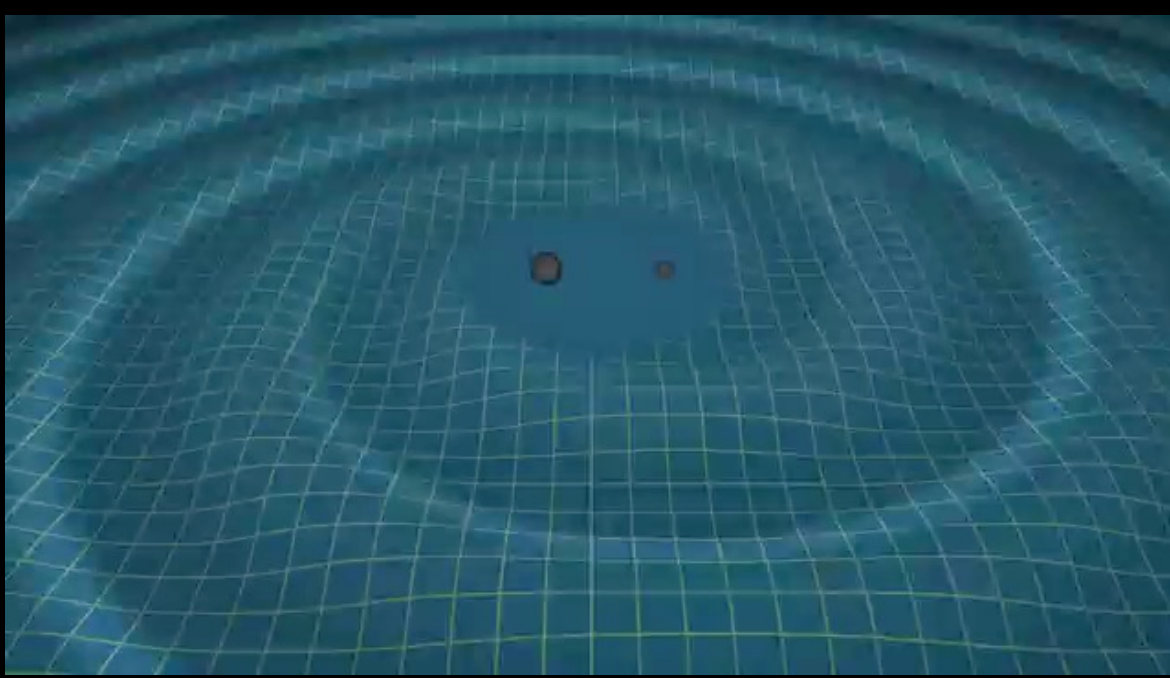


A0620-00 : 3500 a.l.

V723 Mon :
1500 a.l.

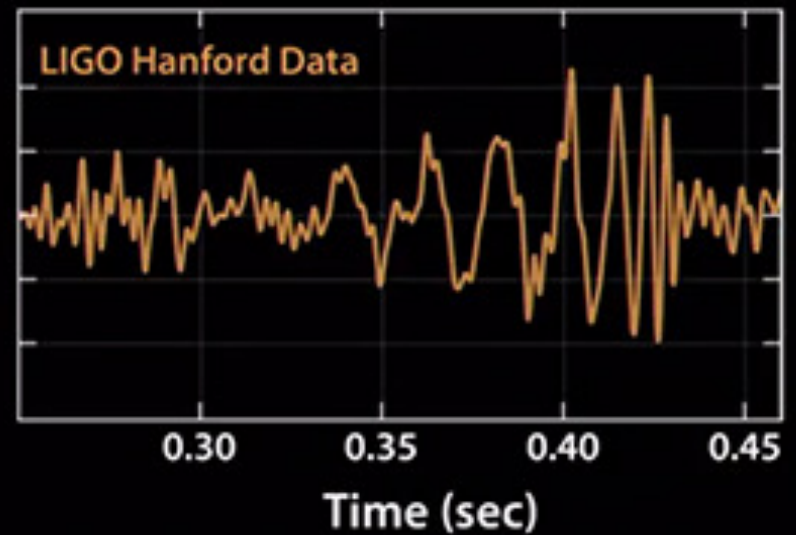
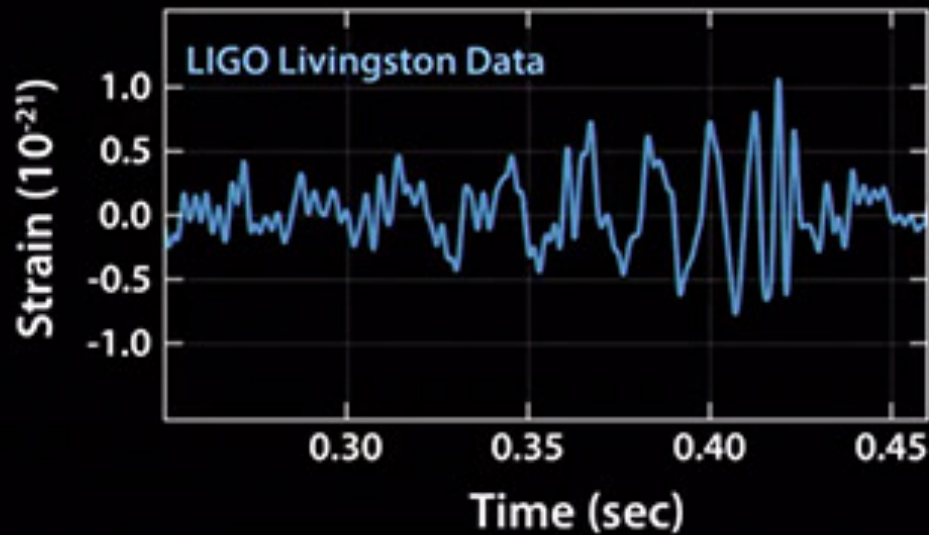


Ondes gravitationnelles





Evénement GW150914





GW150914 : $M_1 = 36 M_S$, $M_2 = 29 M_S$, $M_f = 62 M_S$

d = 1,3 milliards a.l.

GW151226 : $M_1 = 14 M_S$, $M_2 = 8 M_S$, $M_f = 21 M_S$

d = 1,4 milliards a.l.

Fusions d'étoiles à neutrons : GW170817

GW170817

GW170817
DECam observation
(0.5–1.5 days post merger)

GW170817
DECam observation
(>14 days post merger)

GW170817

Une fusion de deux étoiles à neutrons

Une détection d'ondes gravitationnelles par LIGO-Virgo dont les contreparties électromagnétiques ont été observées par plus de 70 observatoires.



Distance
130 millions
d'années-lumière

Découverte
17 août 2017

Type
Fusion d'étoiles à
neutrons



14 h 41 min 4 s heure de Paris

Une onde gravitationnelle produite par une fusion d'étoiles à neutrons est détectée.

onde gravitationnelle

Deux étoiles à neutrons, chacune de la taille de Paris mais pesant au moins autant que le Soleil, sont entrées en collision.

sursaut gamma

Un sursaut gamma court est une bouffée intense de rayons gamma produits juste après la fusion.

+ 2 secondes

Détection d'un sursaut gamma.



GW170817 permet pour la première fois de mesurer directement le taux d'expansion de l'Univers avec des ondes gravitationnelles.



Détecter les ondes gravitationnelles émises lors d'une fusion d'étoiles à neutrons permet d'en apprendre plus sur la structure de ces astres étranges.



Cet événement "multi-messagers" confirme que des fusions d'étoiles à neutrons peuvent produire des sursauts gamma courts.



L'observation d'une kilonova a permis de montrer que les fusions d'étoiles à neutrons sont responsables d'une partie de la production des noyaux lourds (comme l'or) dans l'Univers.



Observer à la fois les ondes gravitationnelles et électromagnétiques produites par cet événement montre de manière convaincante que les ondes gravitationnelles voyagent à la même vitesse que la lumière.

kilonova

La désintégration de noyaux riches en neutrons forme une kilonova brillante qui produit des métaux lourds comme de l'or et du platine.

+10 h 52 m

Une nouvelle source brillante de lumière visible est détectée dans la galaxie NGCC4993, située dans la constellation de l'Hydre.

+11 h 36 m

Observation de l'émission infrarouge.

+15 h

Détection d'une émission brillante dans l'ultraviolet.

+9 jours

Détection d'une émission de rayons X.

émission de lumière rémanente

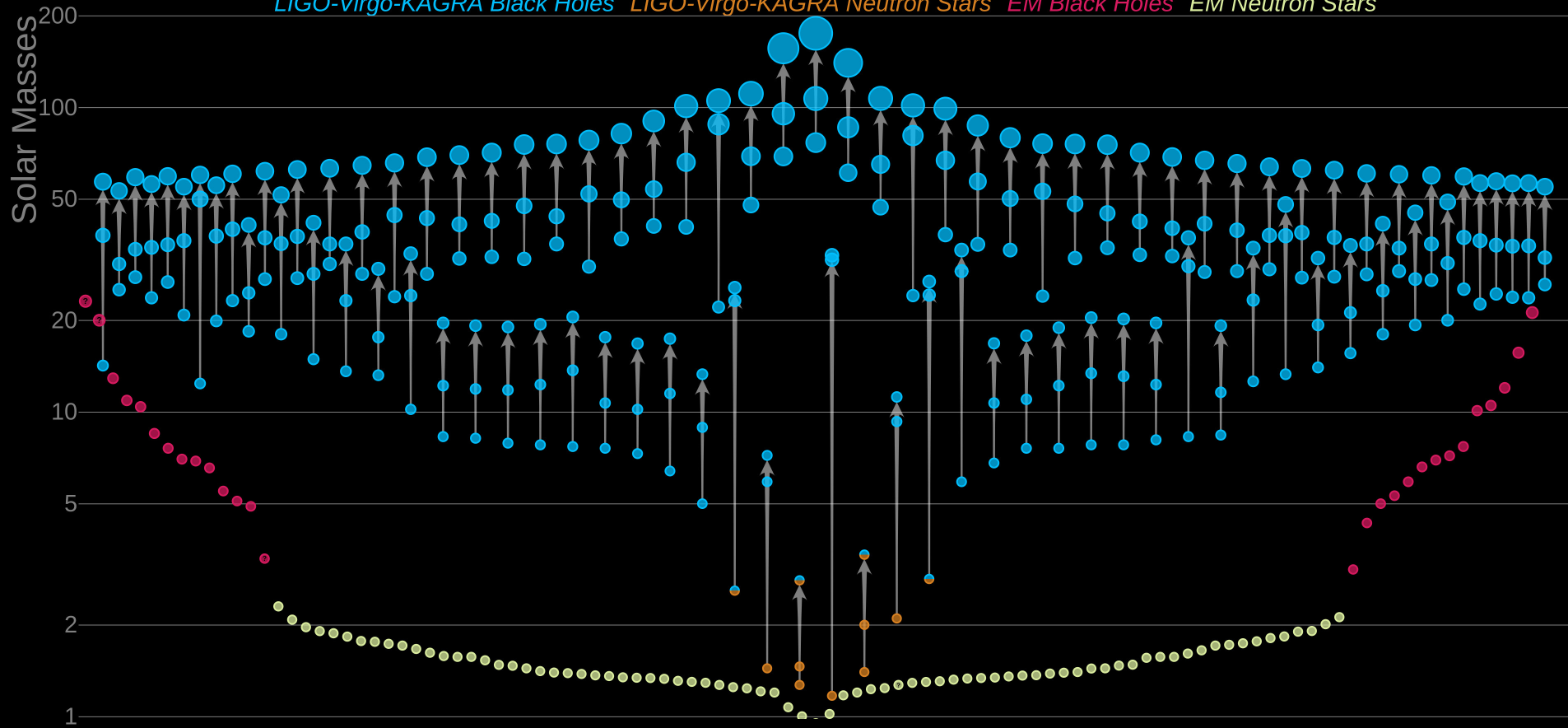
La matière éjectée par la fusion produit une onde de choc dans le milieu interstellaire. L'émission radio associée peut durer des années.

+16 jours

Détection d'une émission en ondes radio.

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes LIGO-Virgo-KAGRA Neutron Stars EM Black Holes EM Neutron Stars



Catalogue GWTC-3 (2021) n

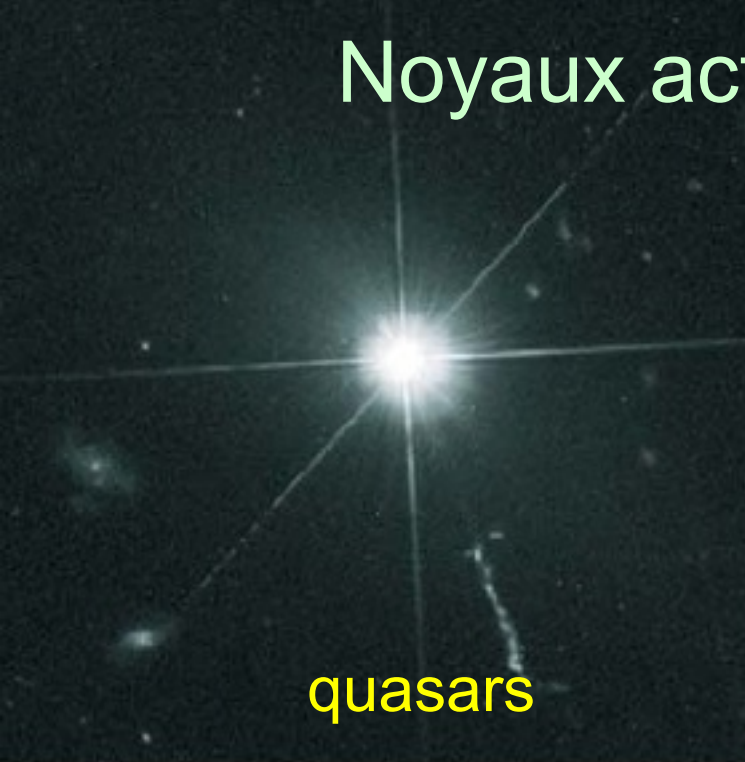


Lacune de masse comblée !

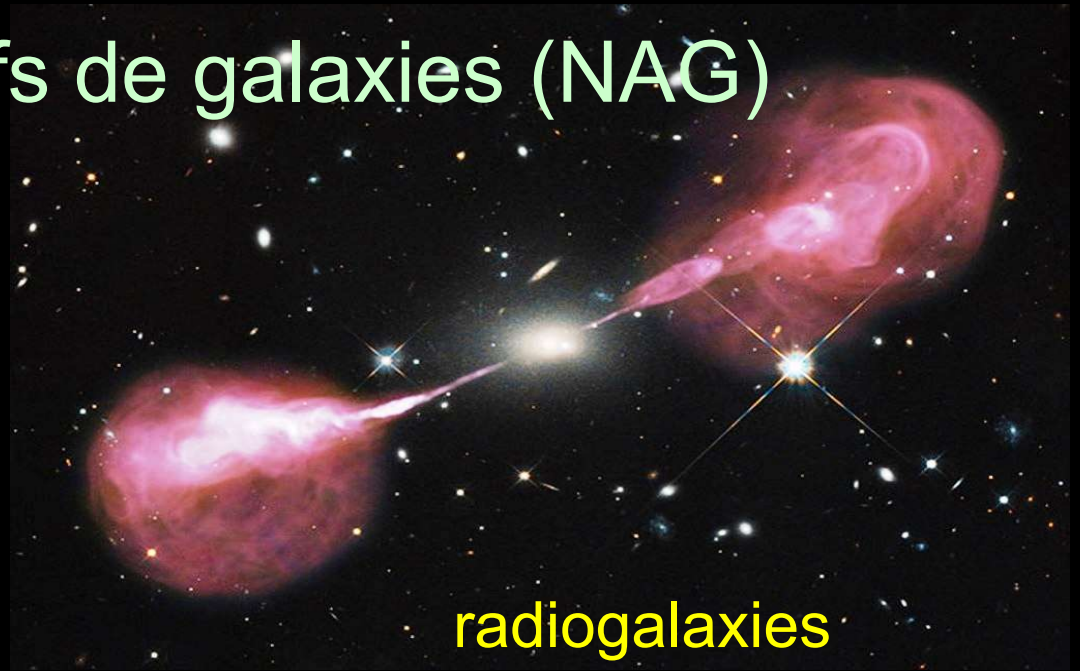
Les trous noirs géants

A blue-toned visualization of a black hole's event horizon and accretion disk. The central region is dark, surrounded by a bright, glowing ring of light representing the event horizon. Below this ring, a vertical, funnel-shaped structure extends downwards, representing the accretion disk. The entire scene is set against a dark blue background with a subtle, concentric ripple pattern.

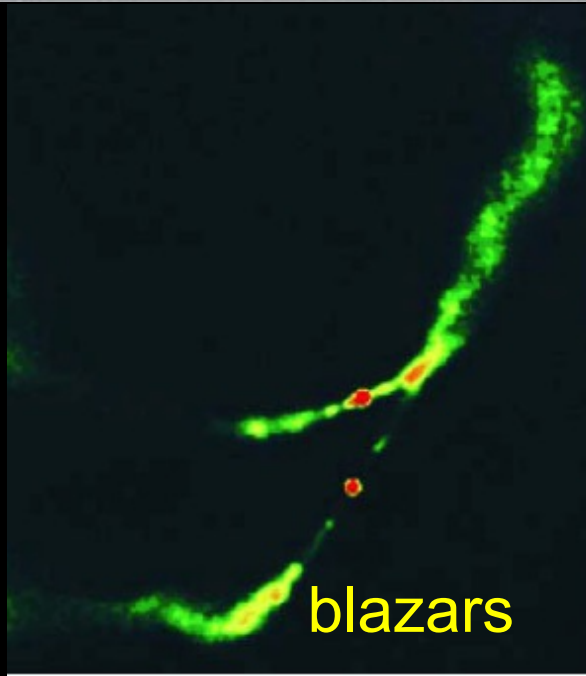
Noyaux actifs de galaxies (NAG)



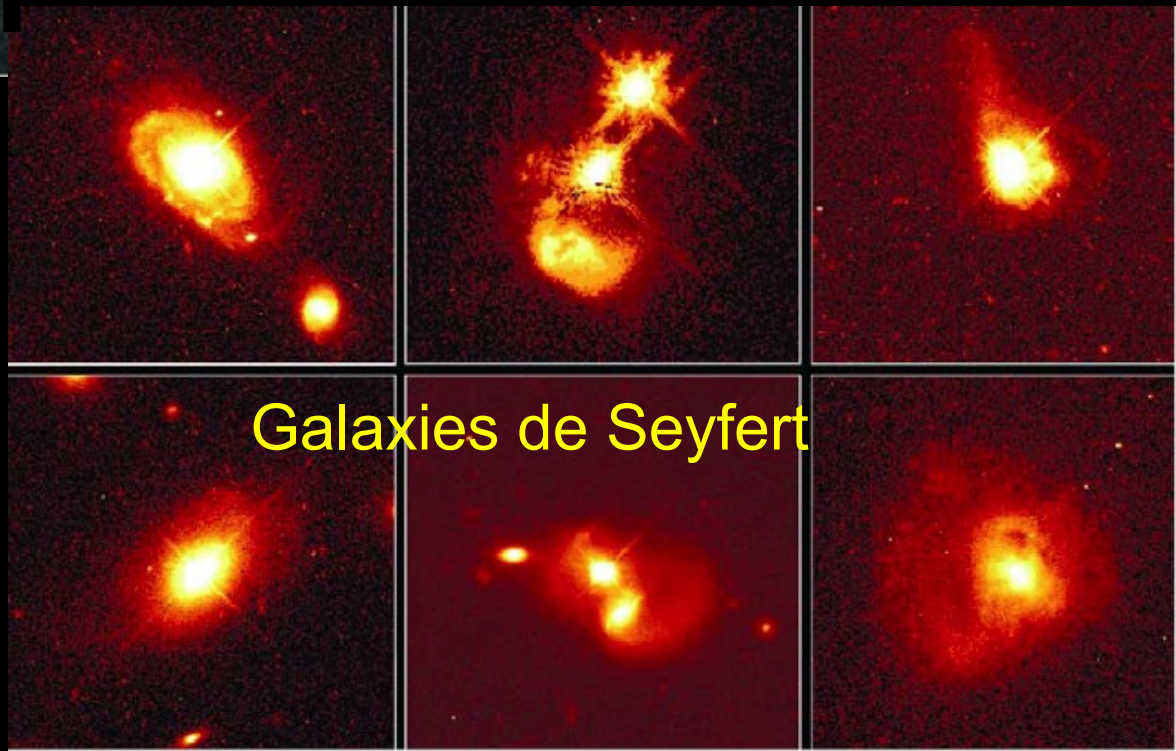
quasars



radiogalaxies



blazars



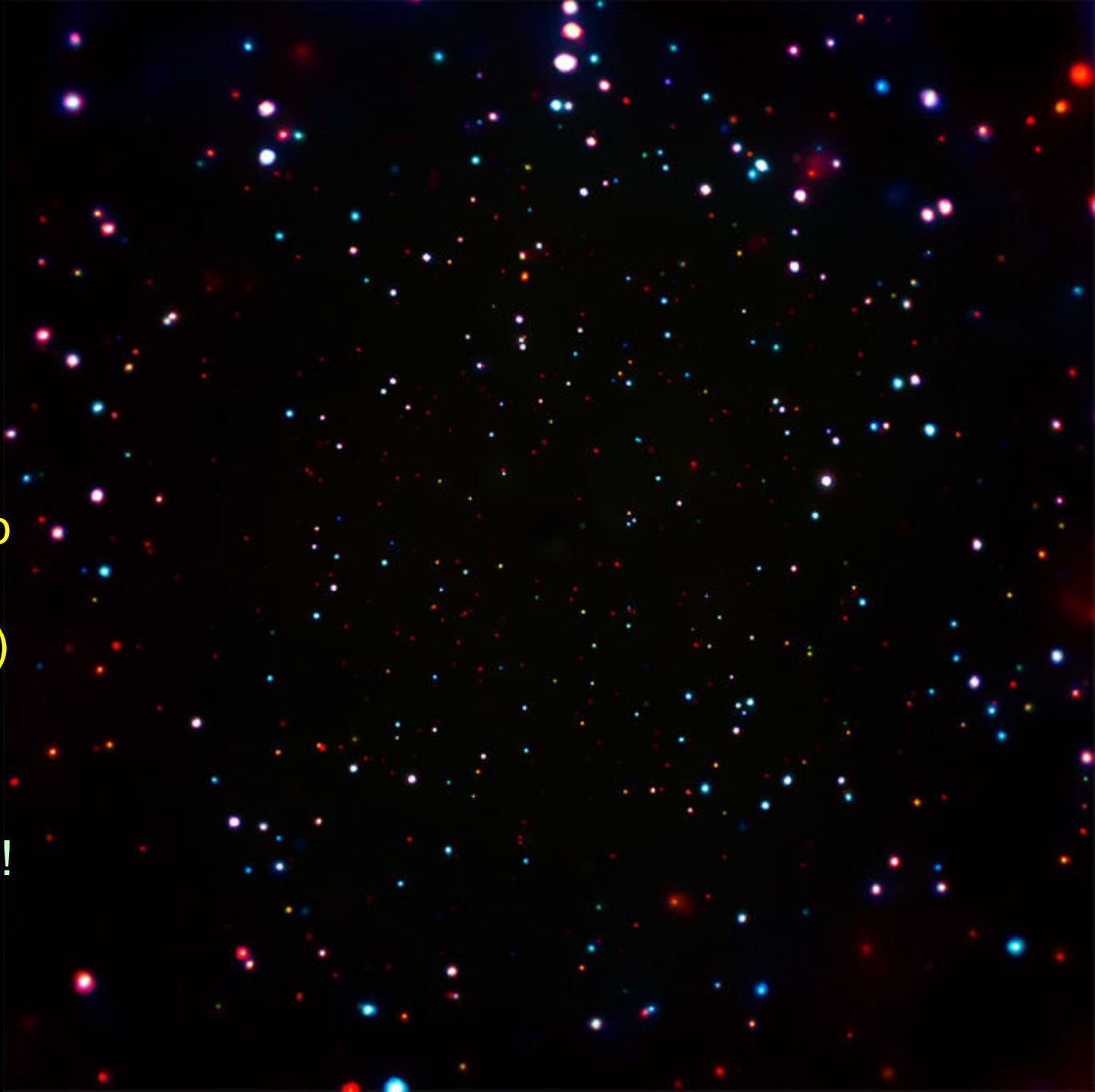
Galaxies de Seyfert

Télescope
Chandra
(rayons X)

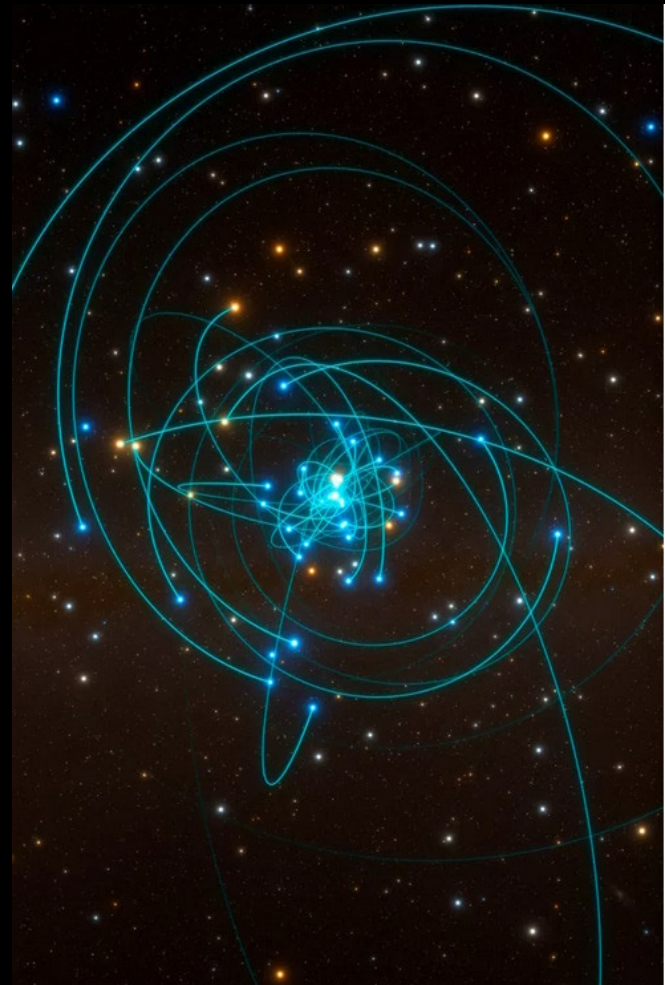
5000 TNSM
dans un champ
de 30'
(~ pleine Lune)



~ 10^9 TNSM !

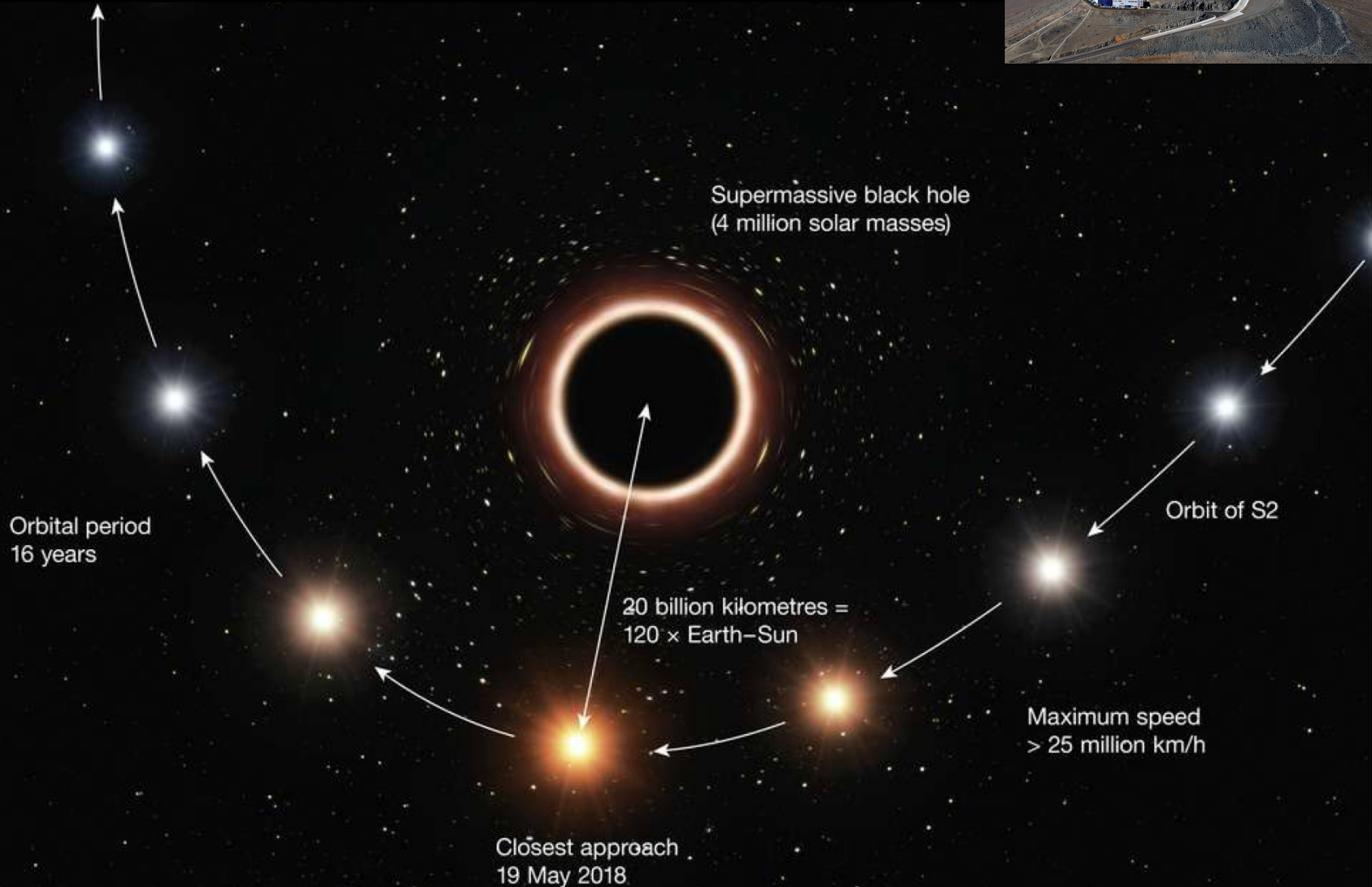


Sagittarius A* : Le Trou noir Galactique



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

Instrument GRAVITY



Quasar
TON 618 :

Le plus gros
trou noir
ultramassif

66 milliards
 M_{S}

TON 618
2606 AU Diameter.


Solar system, approx. 80 AU diameter.

La plus
grosse
galaxie

TN :
40-100
milliards M_{\odot}

Milky Way
Galaxy

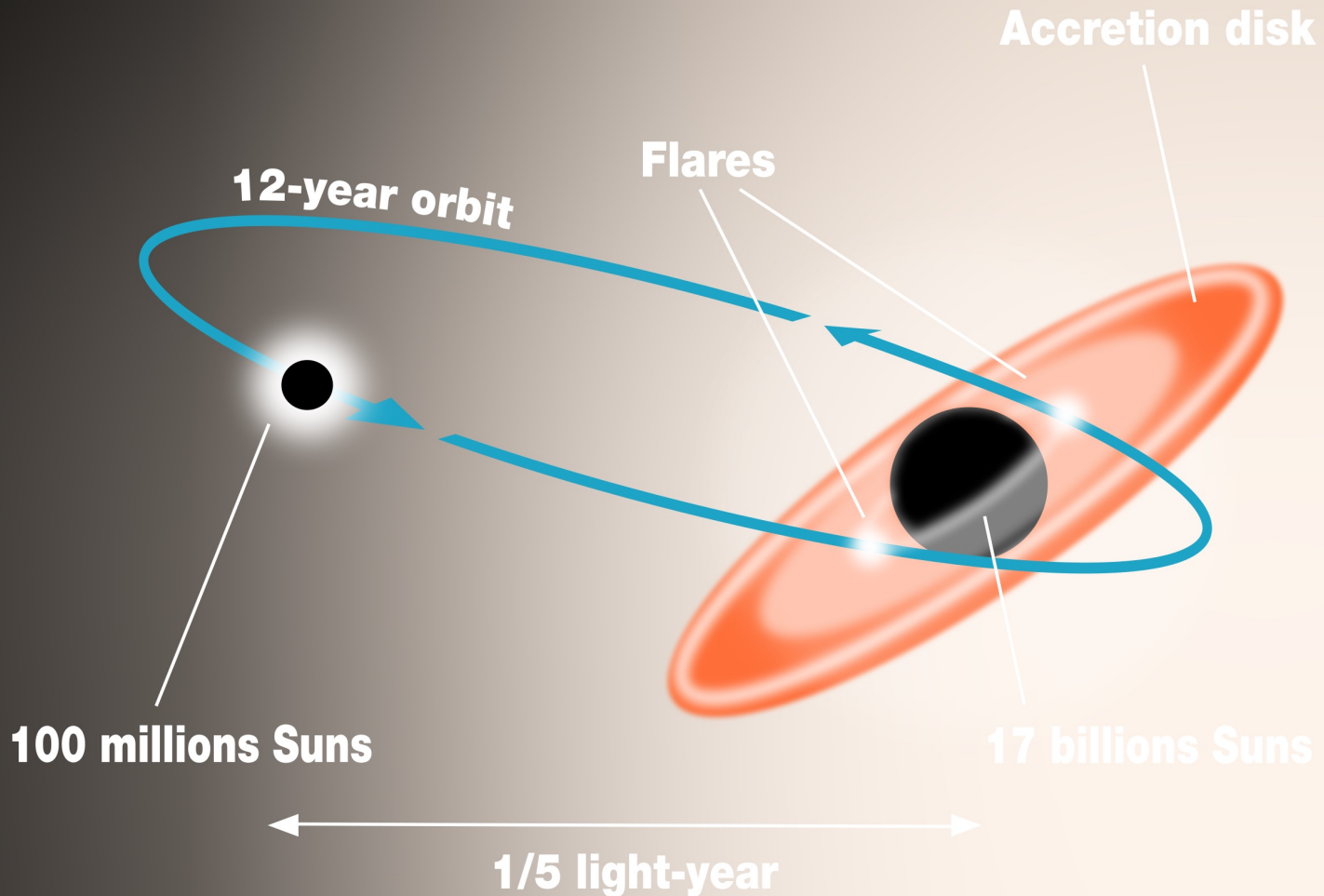
Andromeda
Galaxy

M 87

IC 1101

Des trous noirs supermassifs binaires !

OJ 287



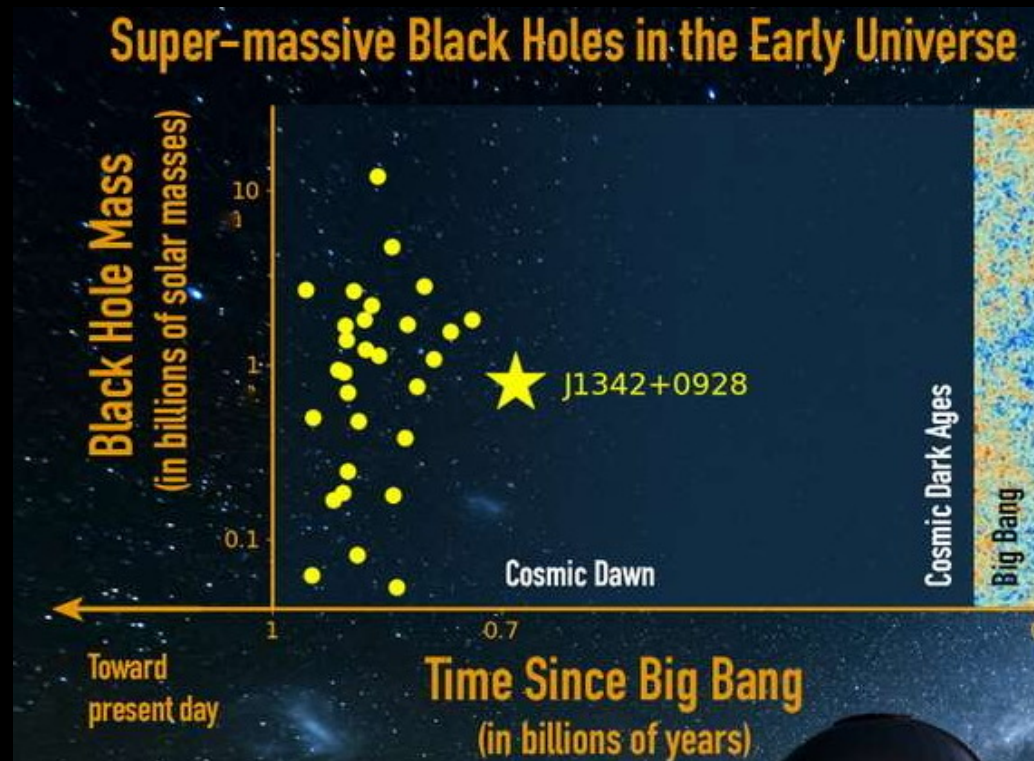
La formation des trous noirs supergéants



La petite galaxie lenticulaire NGC 1277 a un TN de 5 milliards de M_{\odot} : 4 % du total (normalement 0.1%)

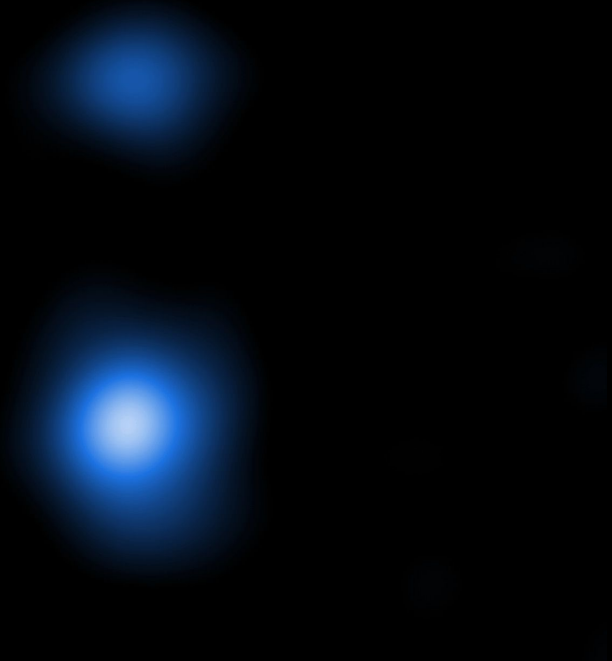
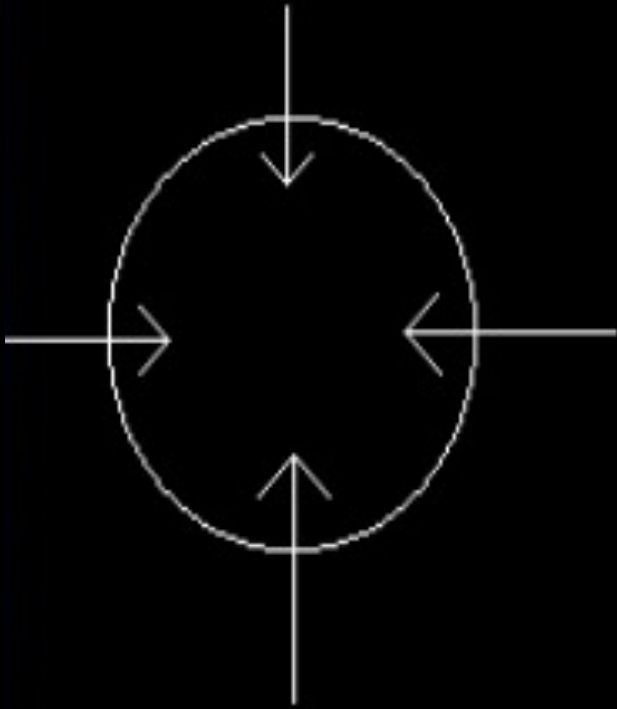
J1342+0928 : 1 milliard M_{\odot}
700 millions d'années après le BB

J1007+2115 : 1,5 milliards M_{\odot}
« Pōniuā'ena »



- Trous noirs primordiaux massifs (< 3 sec)

- Effondrement de grands nuages de gaz



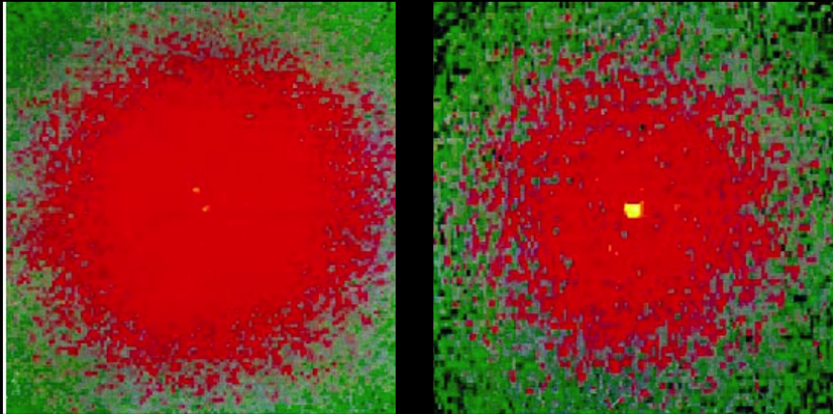
OB29323(Chandra X)

Destruction d'étoiles par les forces de marée

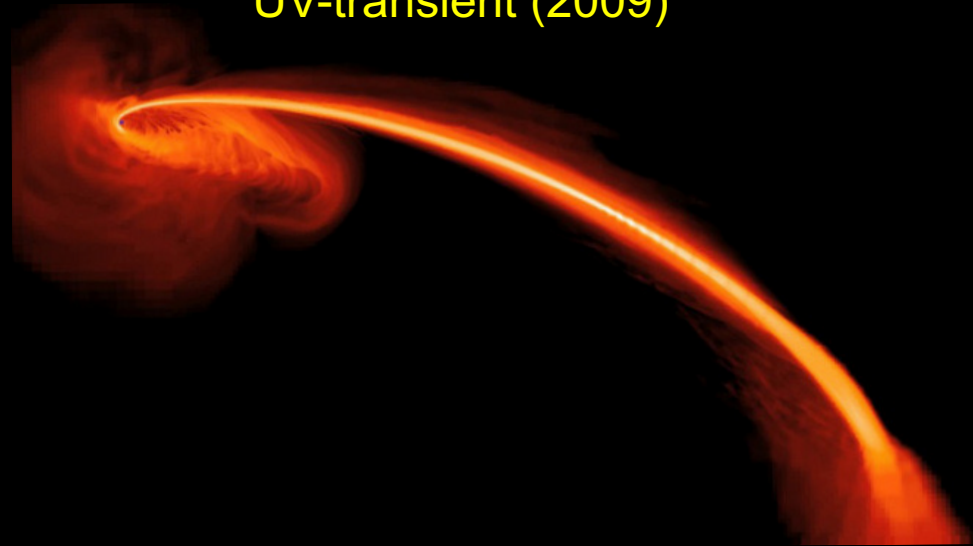


crêpes stellaires flambées (Carter & Luminet, 1982)

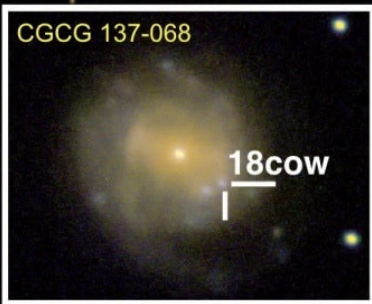
NGC 4252 (1995)



UV-transient (2009)



ASASSN-15lh (2015)



La Vache ! (2018)



Distance of 200,000,000 light-years

August 17, 2018
Keck-DEIMOS

➔ *Destruction de naines blanches par des TNMI...*

De l'ordinateur au téléscope



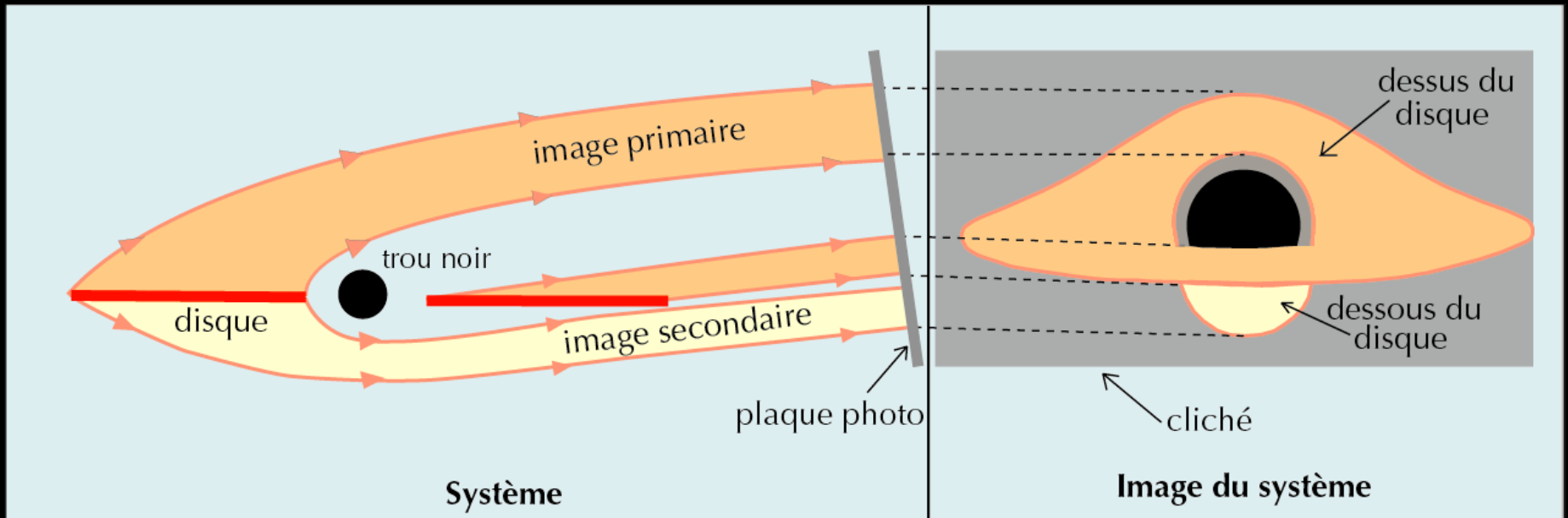
Vues
« d'artiste » :
fausses!

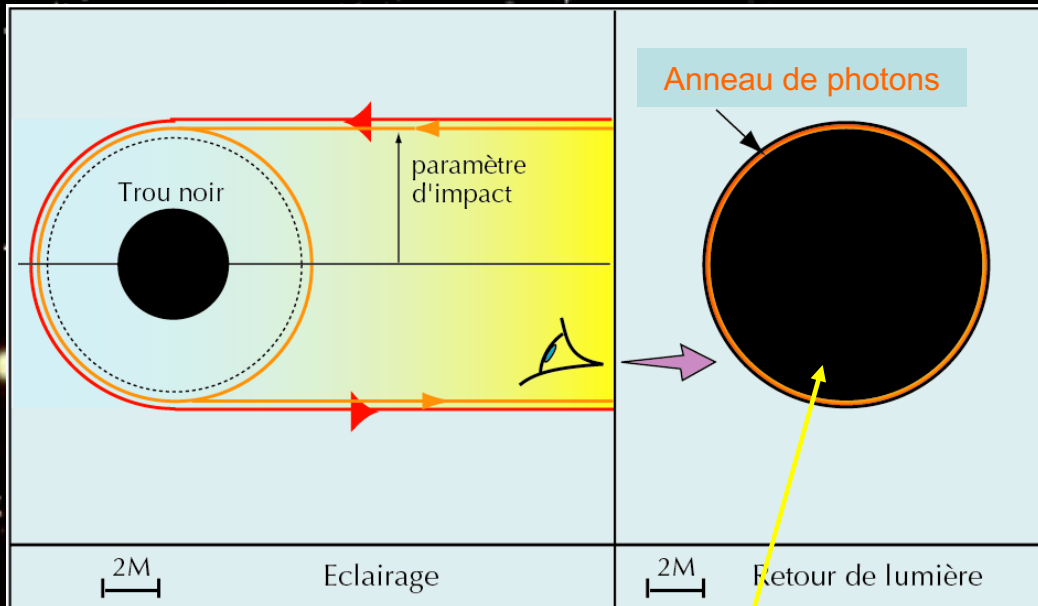
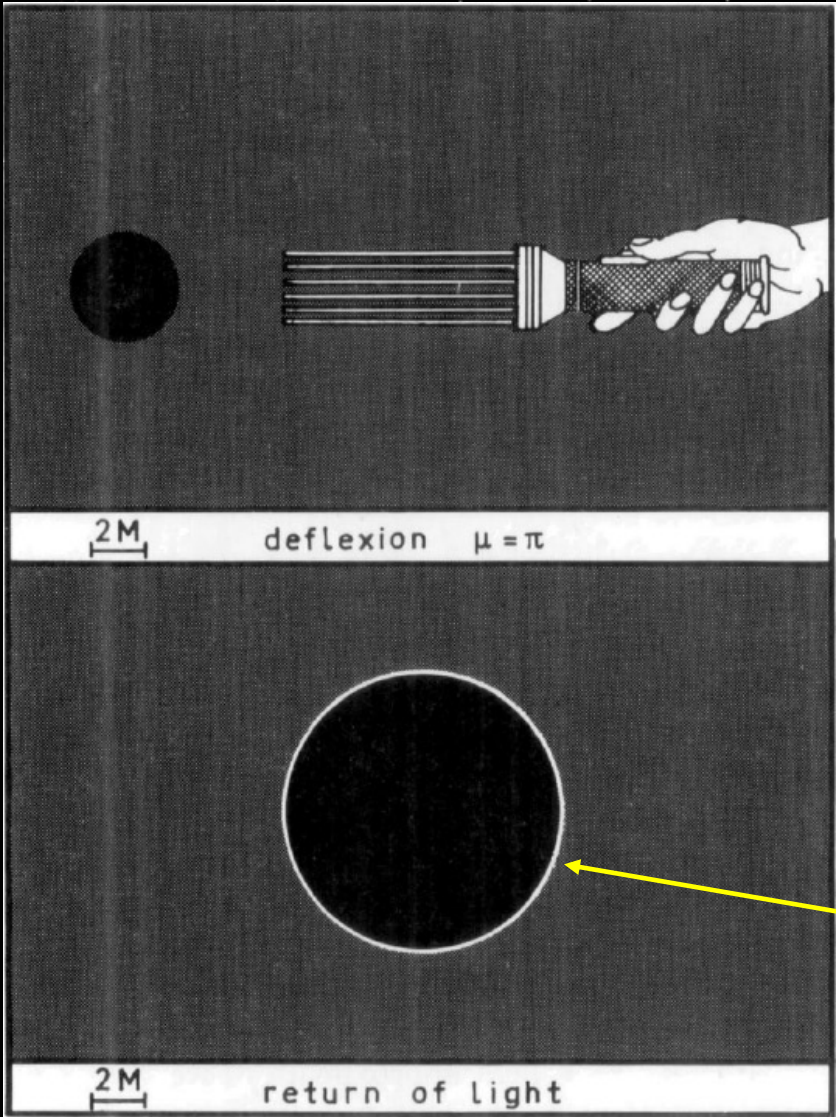


Espace-temps newtonien



Espace-temps einsteinien





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 dans la métrique de Schwarzschild

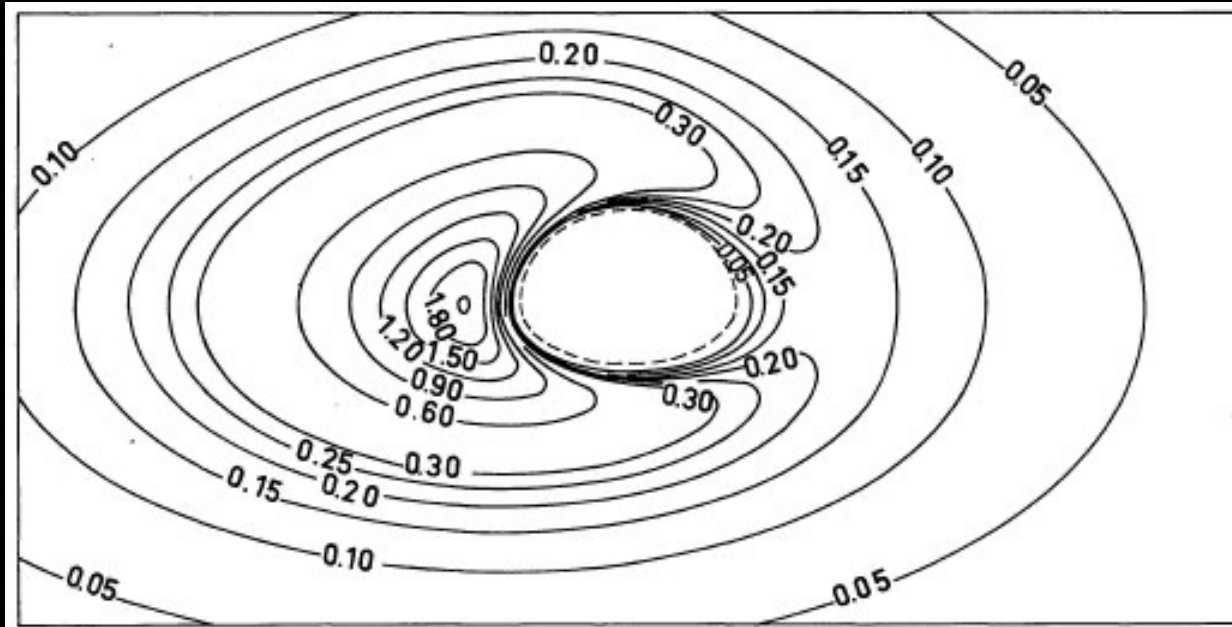
Etape 2 : Modèle relativiste de disque d'accrétion mince

Etape 3 : Décalages spectraux (Einstein, Doppler)

Etape 4 : Flux apparent (bolométrique)

Isophotes

Angle de vue équatorial
 30°



Angle de vue équatorial
 10°

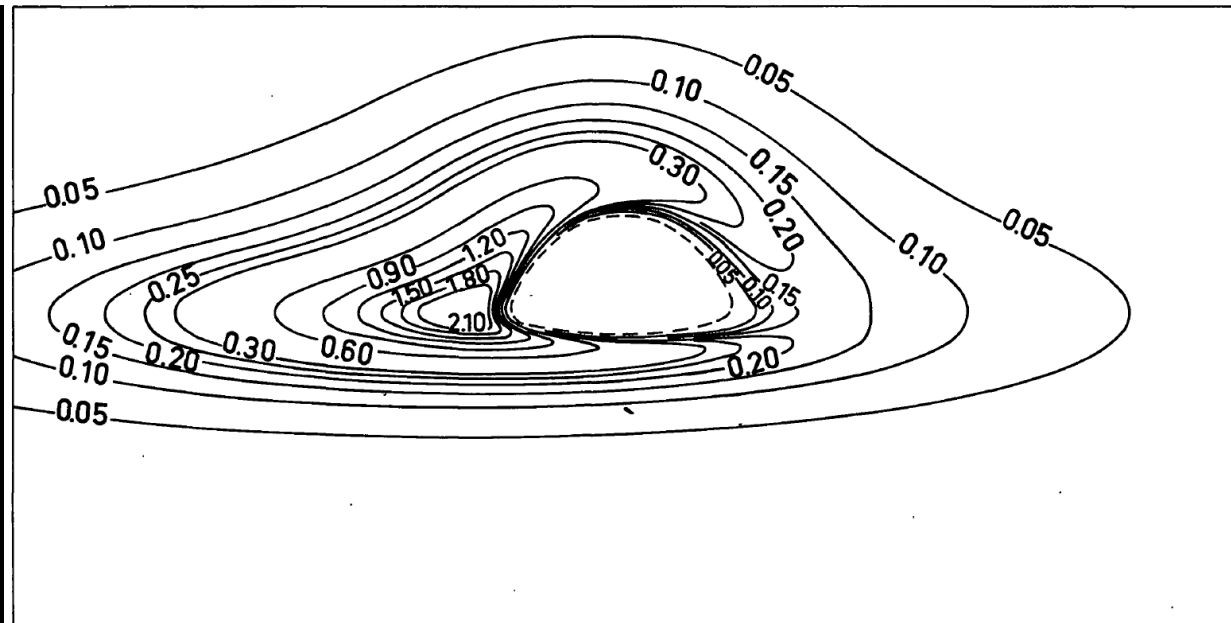


Image of a Spherical Black Hole with Thin Accretion Disk

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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 secondary 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, 1939; 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:

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

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:

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

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

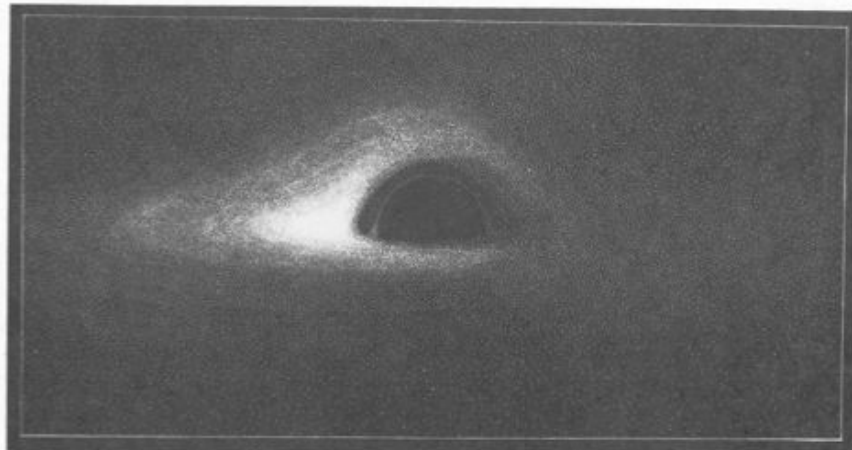


Fig. 11. Simulated photograph of a spherical black hole with thin accretion disk

impact parameter of the visible part of the secondary 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.

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The Final Picture

Image du dessus

Anneau de photons

Dernière orbite stable

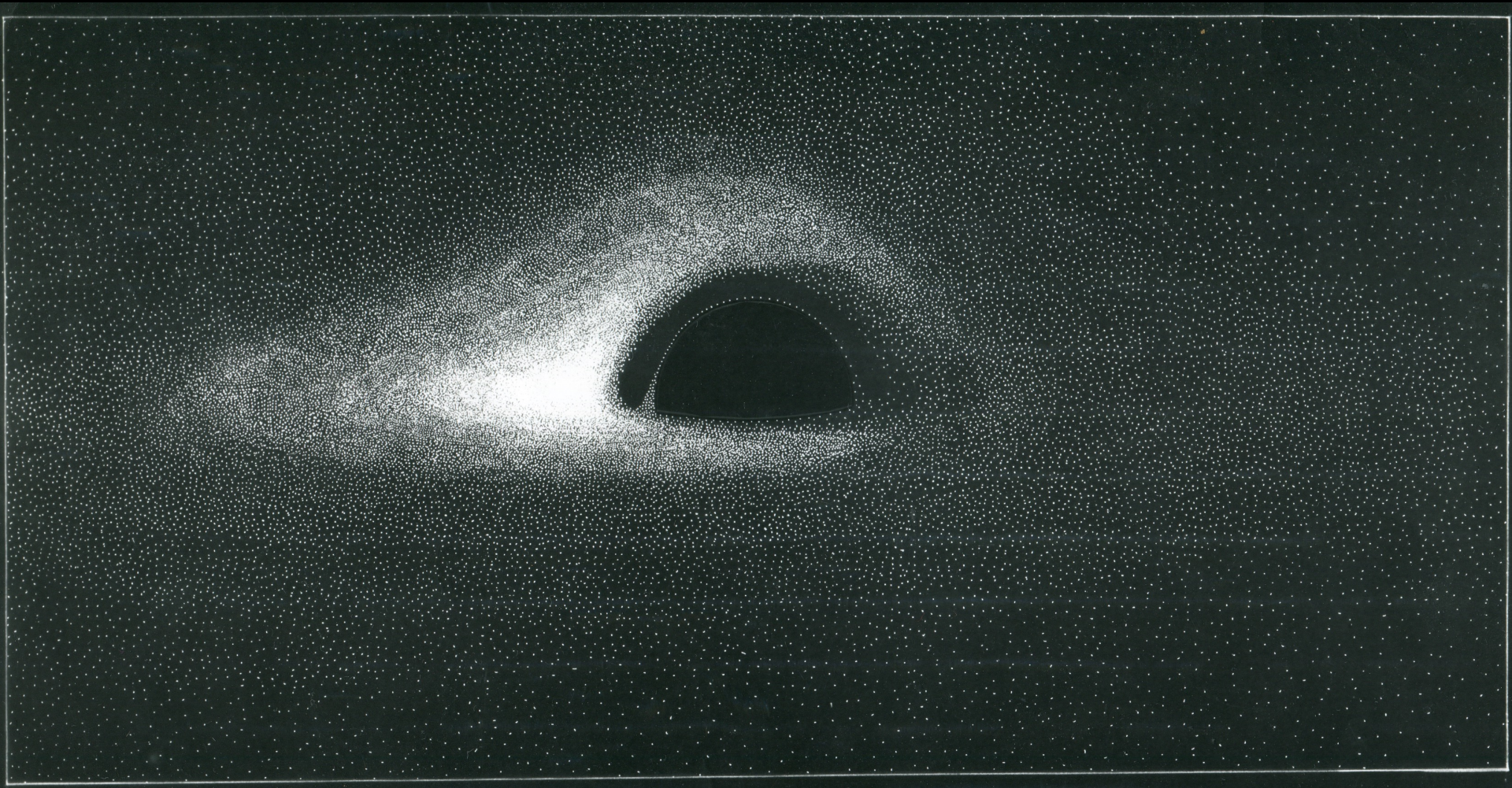
Effet Doppler

Ombre du trou noir

Image of a spherical black hole with thin accretion disk

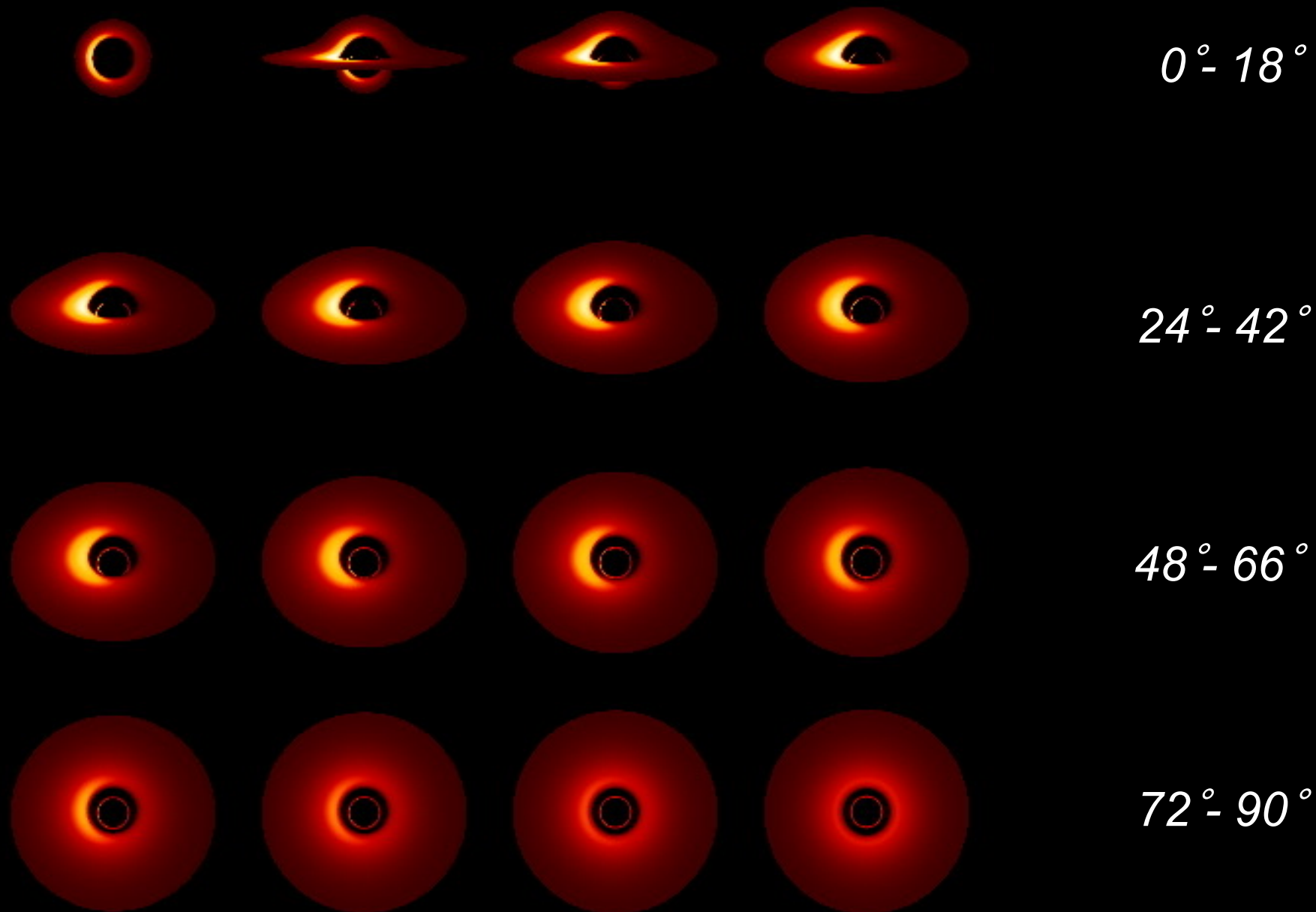
J.-P. Luminet, *Astron.Astrophys.* **75**, 228 (1979)

A la main!



Nerval !

Premières images à tous angles de vue (JAM/JPL 1989)



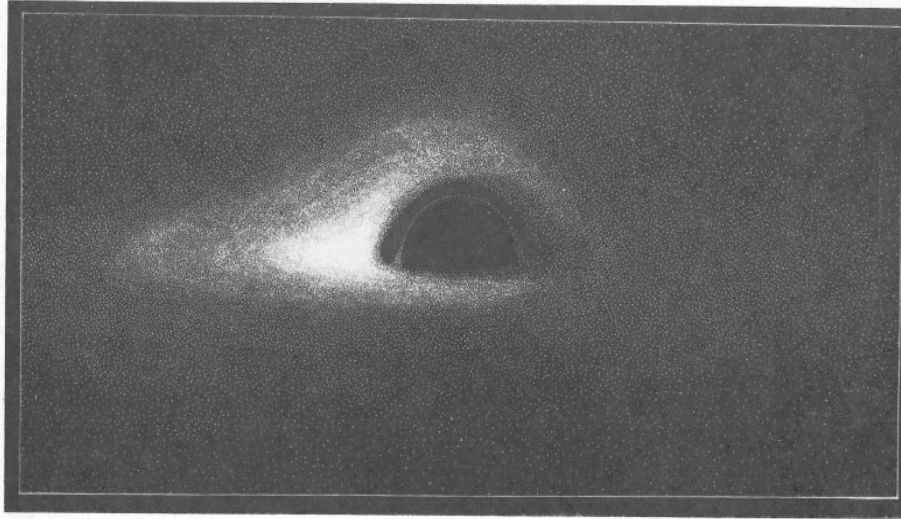


Fig. 11. Simulated photograph of a spherical black hole with thin accretion disk

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.

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Le Trou noir Galactique SgrA*



Masse = $4 \cdot 10^6 M_{\odot}$
Diamètre = 25 millions Km

Le Trou noir M87*



Masse = $6 \cdot 10^9 M_{\odot}$
Diamètre = 40 milliards Km

Sgr A*
27000 light-years away

M87*
55000000 light-years away

$D_{app} \sim 35 \mu\text{arcsec}$

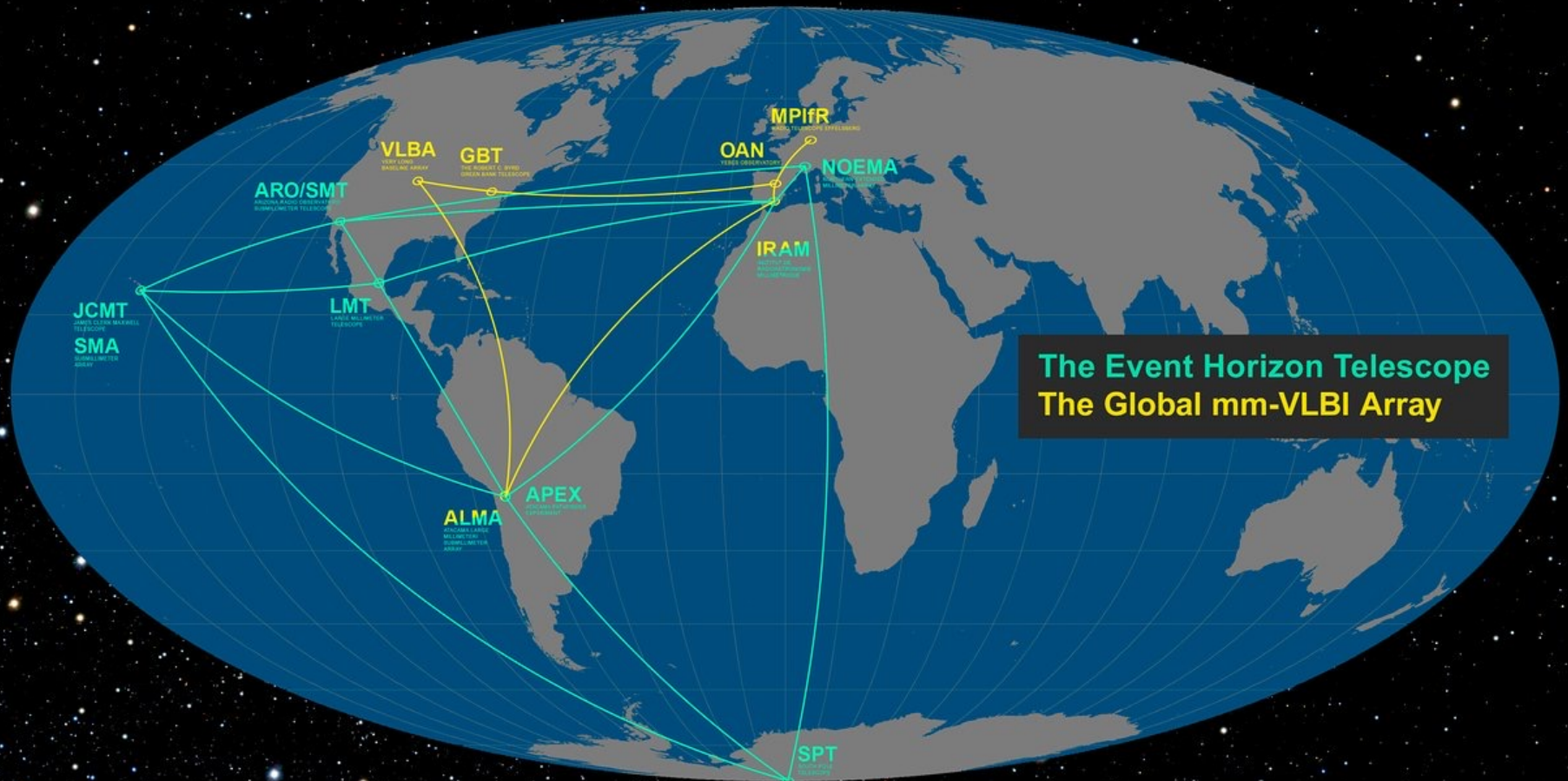
• Résolution angulaire d'un télescope :

- *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 mm λ peut résoudre 25 μarcsec !

→ Event Horizon Telescope (EHT) Consortium

(Doeleman et al., 2008)



VLBI Résolution : $25 \mu\text{arcsec}$

Premières images télescopiques de trous noirs



M87*: 10 avril 2019



SgrA*: 12 mai 2022

M87*

Voyager 1

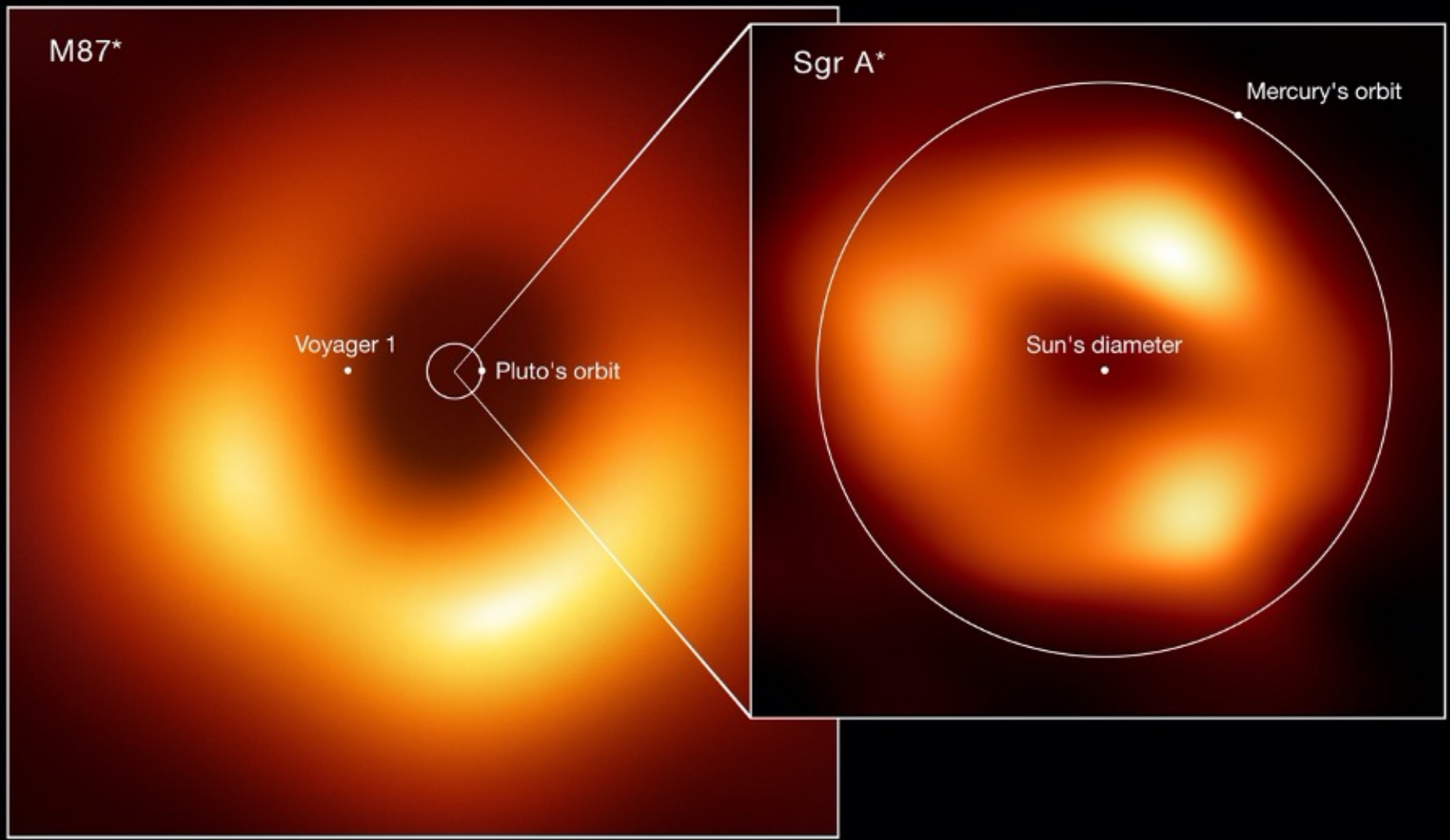


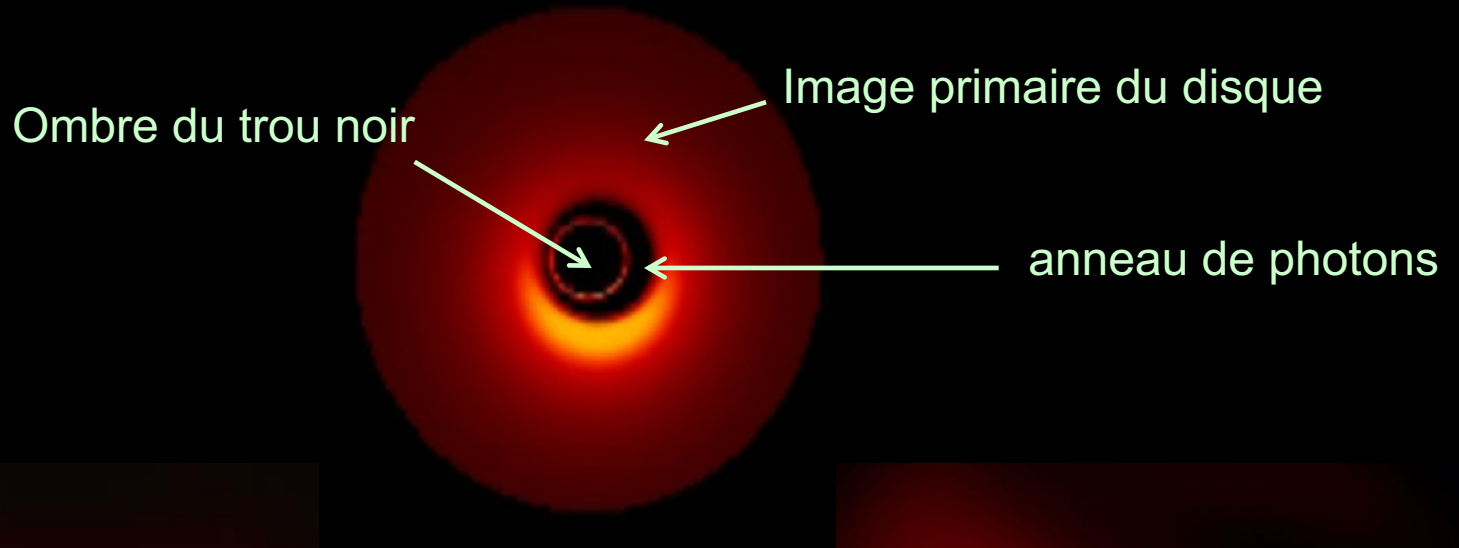
Pluto's orbit

Sgr A*

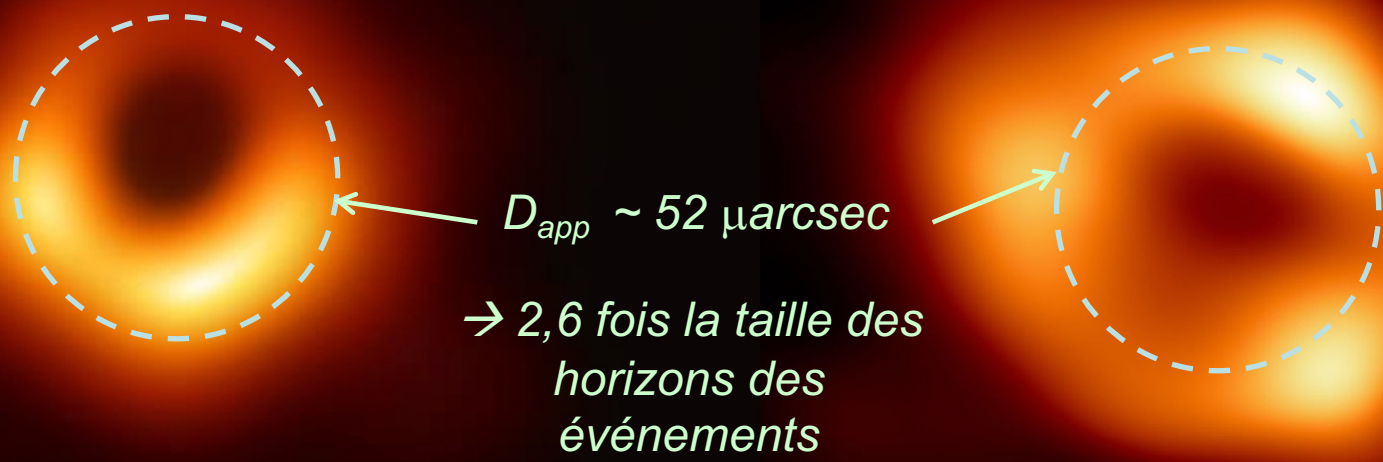
Mercury's orbit

Sun's diameter





Angle de vue $\sim 70^\circ$



À la résolution de l'EHT, l'image primaire du disque est superposée à l'anneau de photons

Event Horizon Telescope (EHT)

A Global Network of Radio Telescopes

2018 Observatories



Observing
in 2020



Merci !

On t'entend pas J-P,
ça coupe !



Jules