Dernières nouvelles des trous noirs

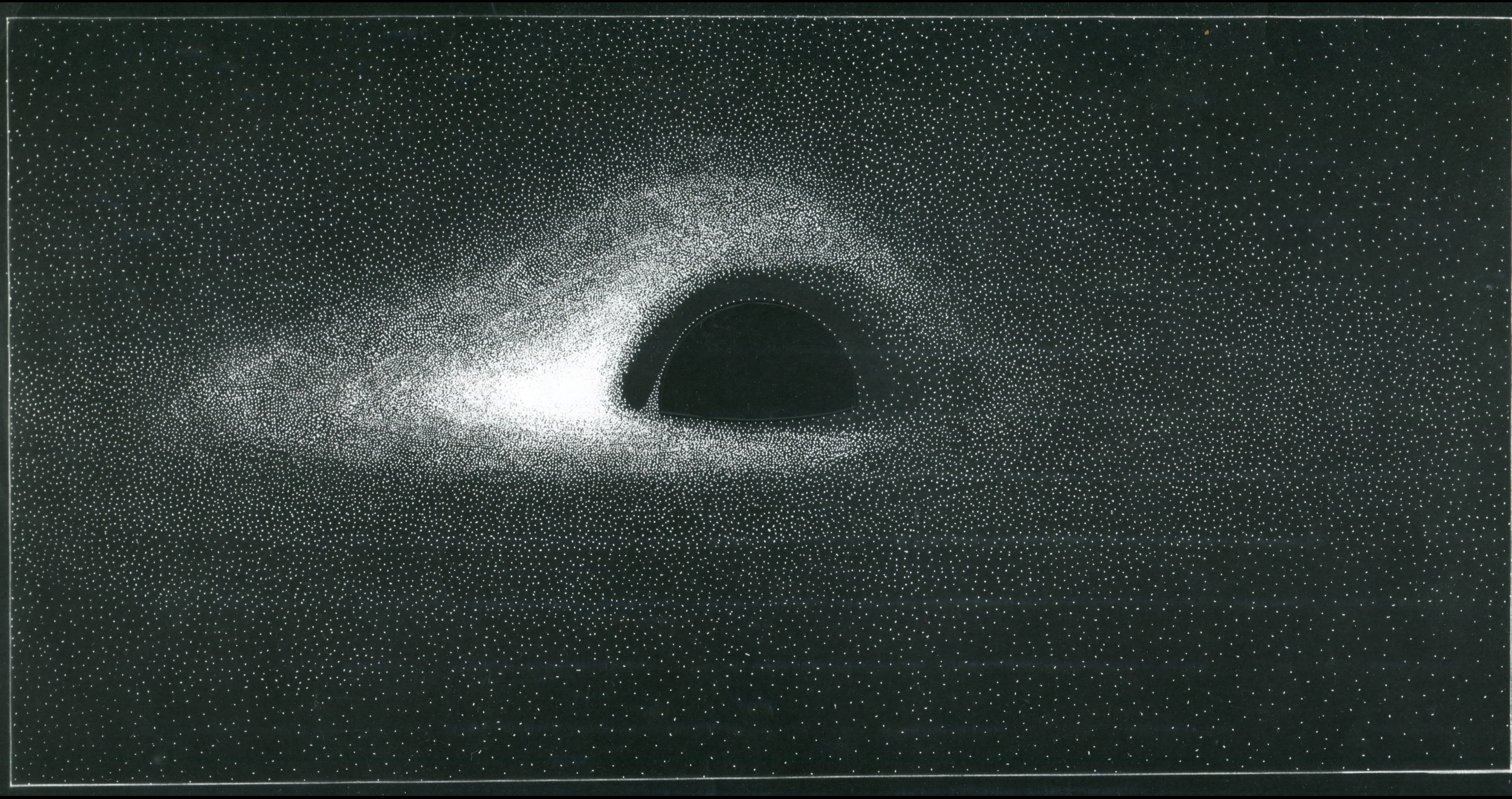
Jean-Pierre Luminet

Laboratoire d'Astrophysique de Marseille (LAM)

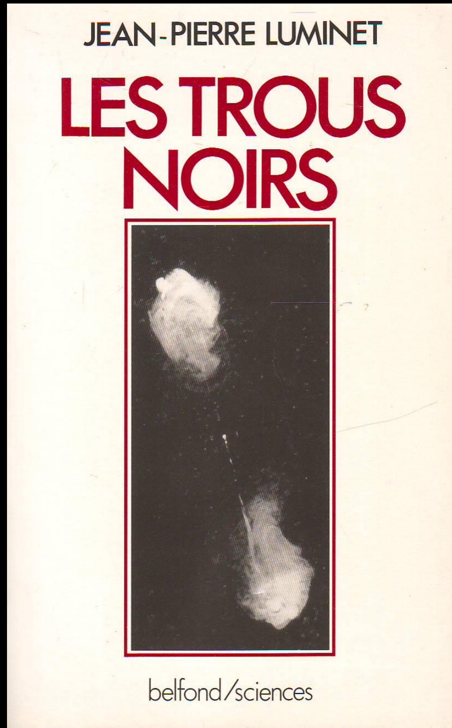
Premières images télescopiques de trous noirs

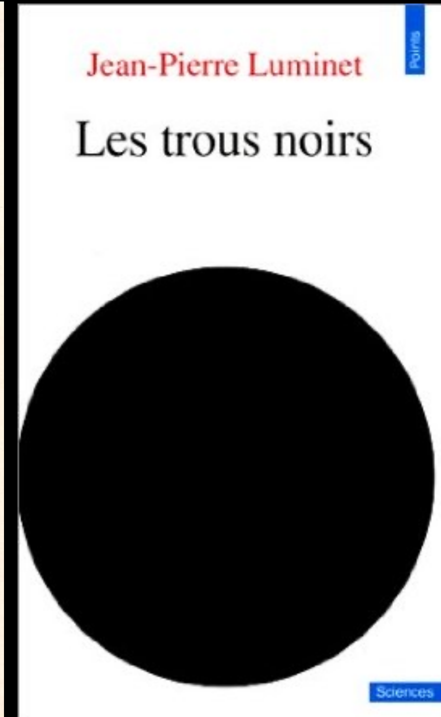
M87*: 10 avril 2019

SgrA*: 12 mai 2022

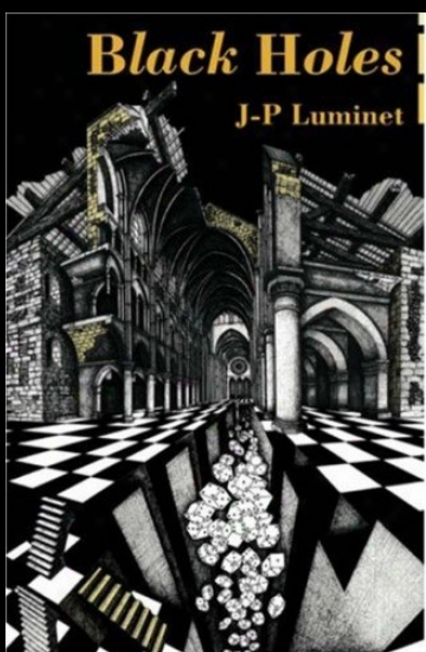


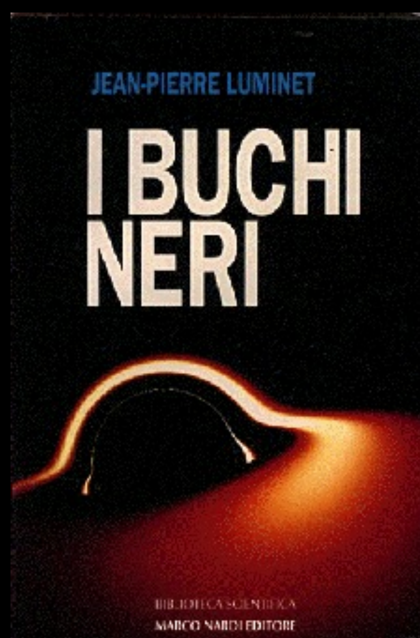
J.-P. Luminet, 1978


JEAN-PIERRE LUMINET
LES TROUS NOIRS
belfond/sciences


Jean-Pierre Luminet
Les trous noirs
Points
Sciences


JEAN-PIERRE LUMINET
Le destin de l'univers
Trous noirs et énergie sombre
Le temps des sciences
fayard


Black Holes
J-P Luminet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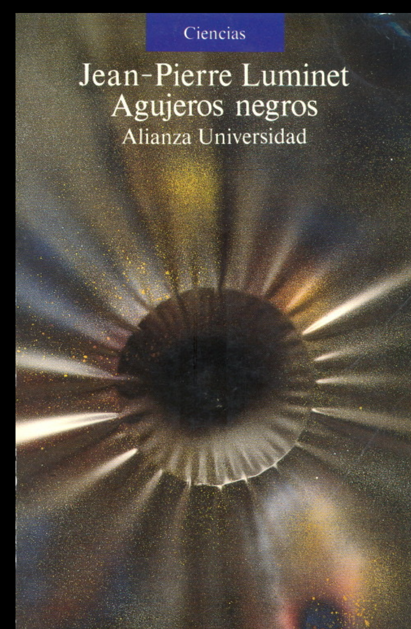
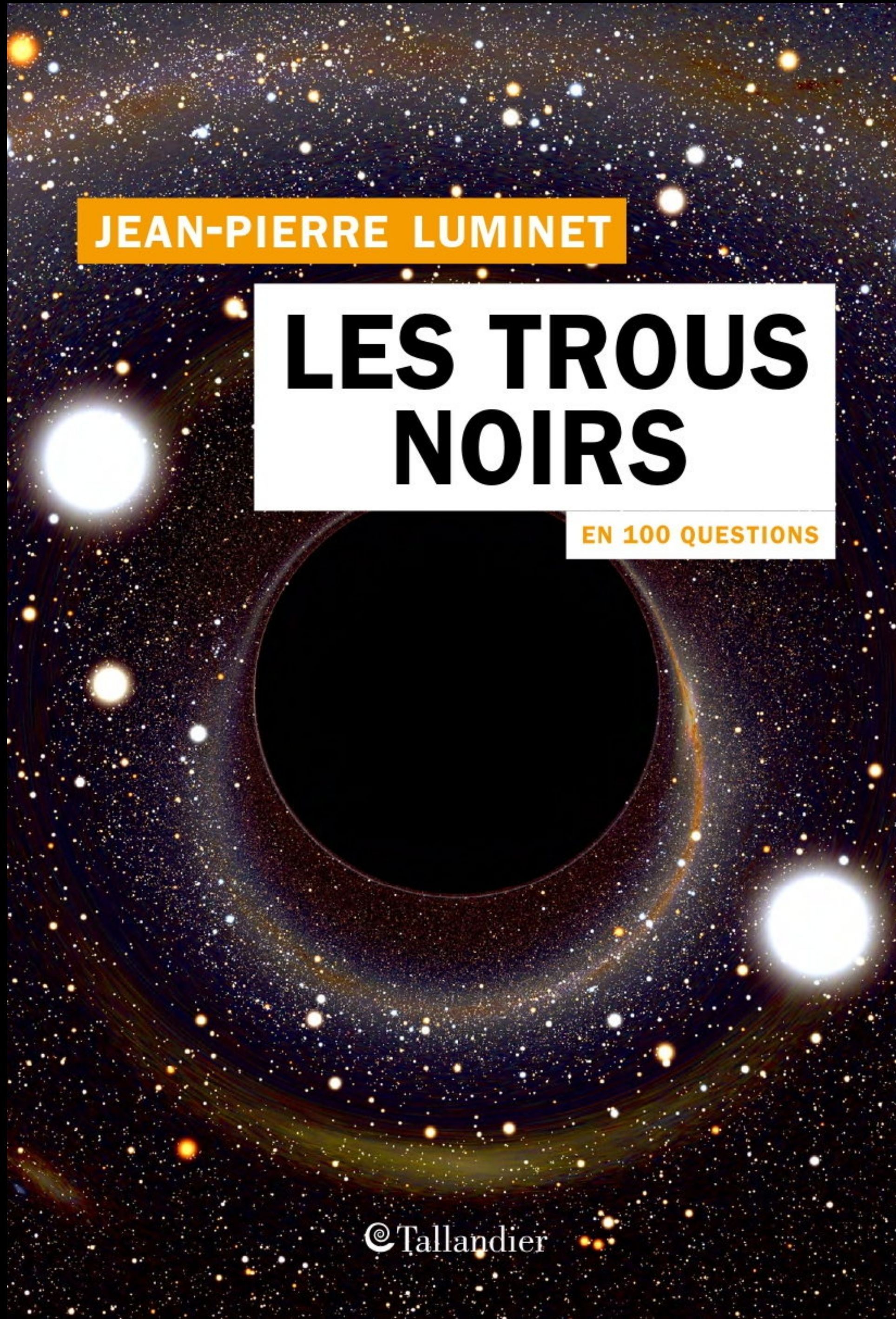

Ciencias
Jean-Pierre Luminet
Agujeros negros
Alianza Universidad


黑洞

JEAN-PIERRE LUMINET

LES TROUS NOIRS

EN 100 QUESTIONS



Tallandier

Léon Dierx : Le Gouffre (1867)

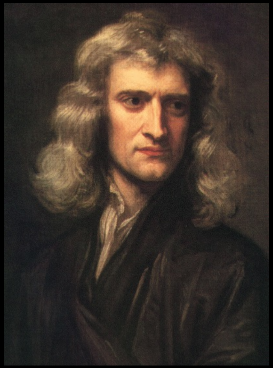
Il est des gouffres noirs dont les bords sont charmants.

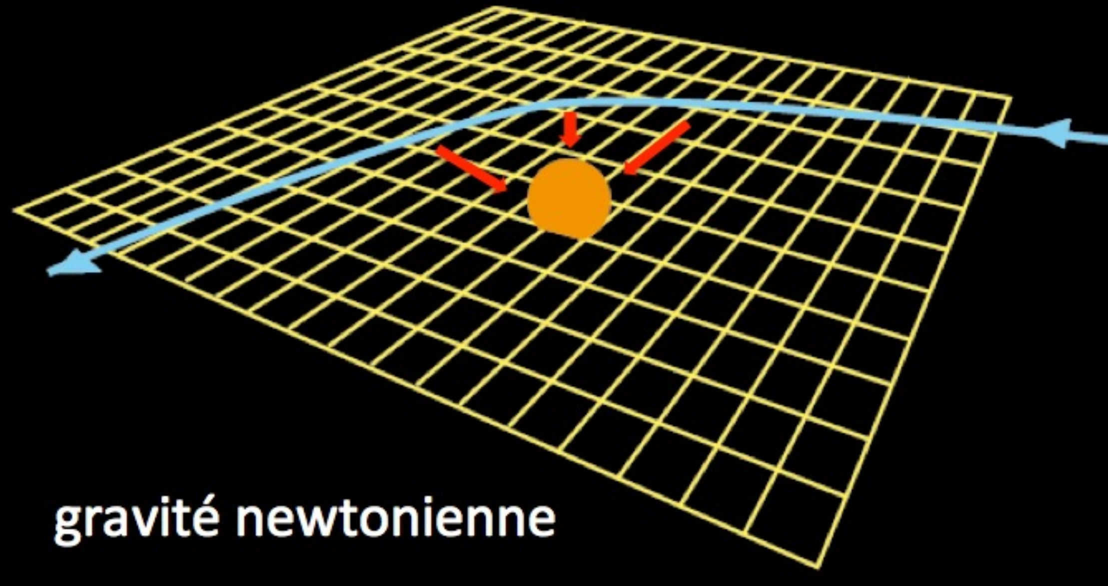
Je sais un gouffre noir sur la verte colline.
Des arbres de senteur l'ombragent en entier,
Et l'on y vient joyeux par le plus gai sentier.
[…] Et pour sonder le creux du soupirail profond,
Pour réveiller l'écho qui dormait sous ces plantes,
J'y fis tomber caillou, pierre et roches branlantes;
Mais comme 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.

Un peu d'histoire …

Théorie de Newton

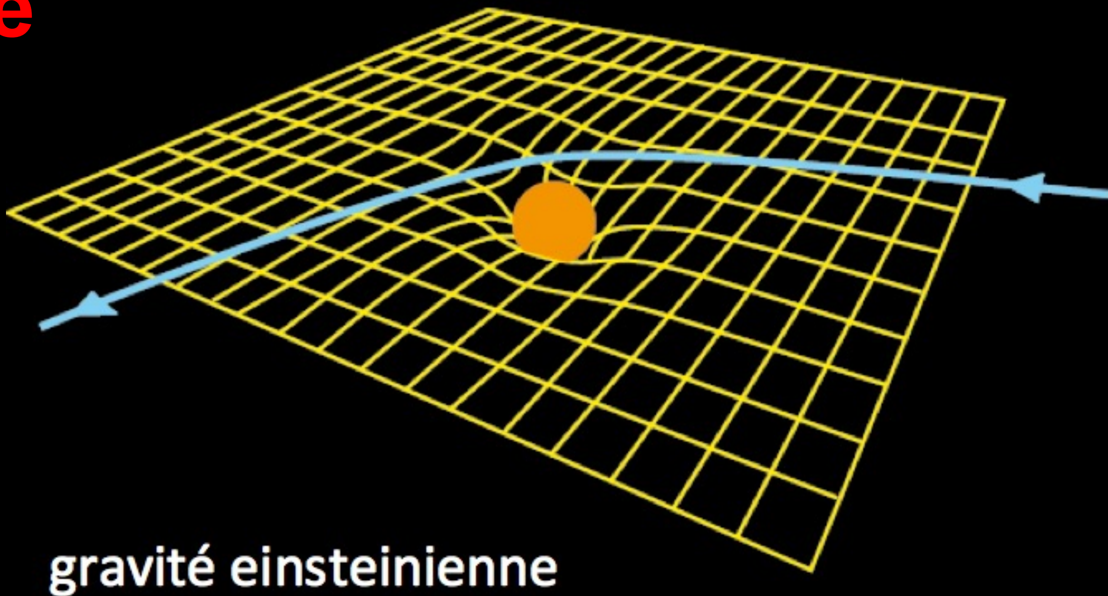
Gravité = Force d'attraction instantanée





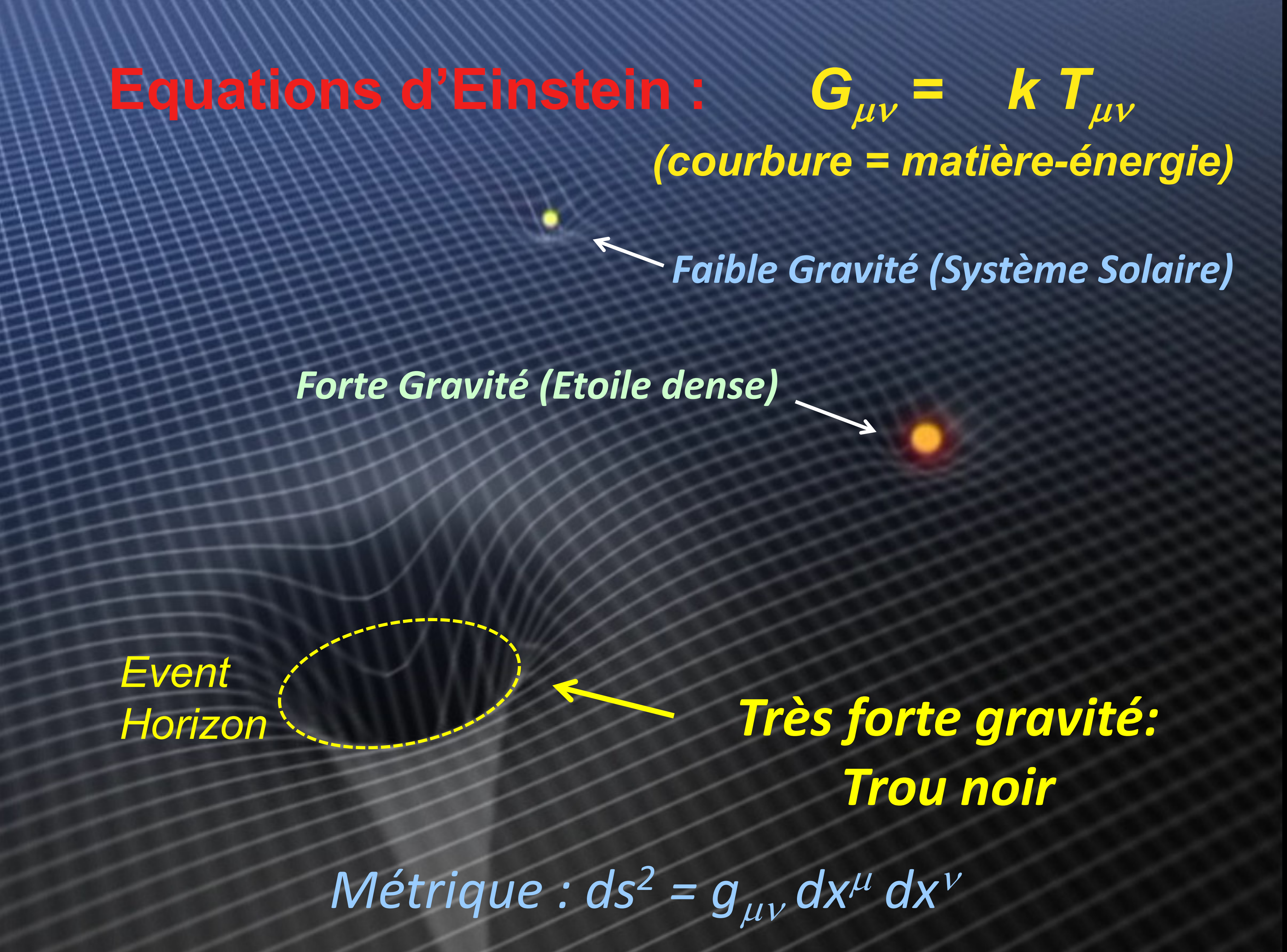
Relativité Générale

Gravité = Courbure de l'espace-temps



Equations d'Einstein : $G_{\mu\nu} = k\, T_{\mu\nu}$

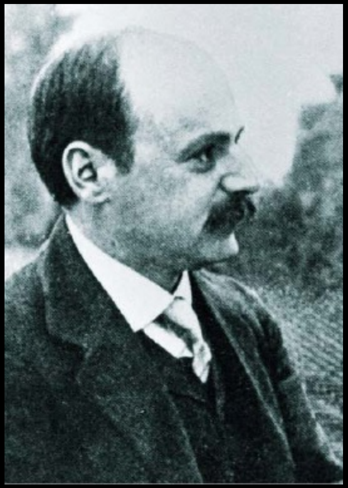
(courbure = matière-énergie)



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

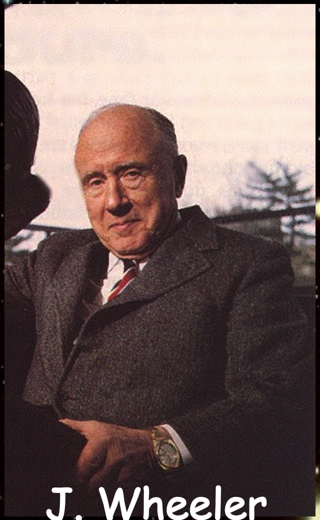
Effondrement gravitationnel

Quelques pères fondateurs

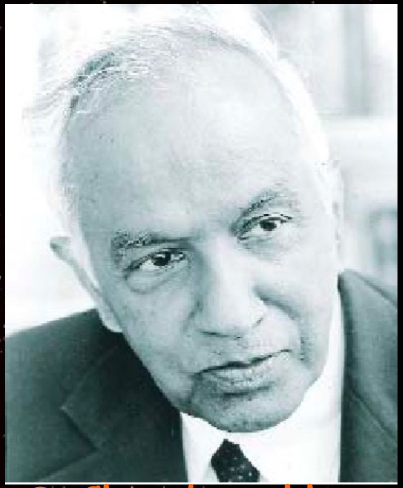


K. Schwarzschild

R. Oppenheimer

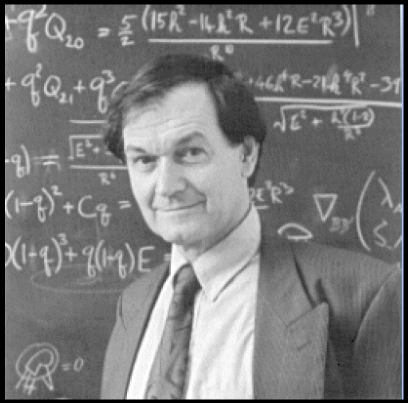


J. Wheeler



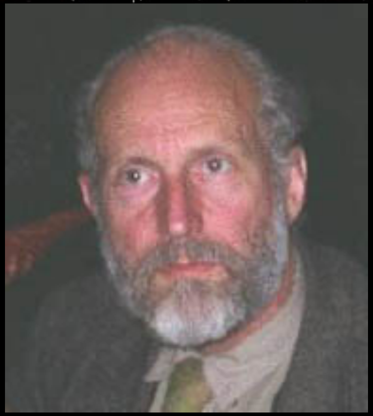
S. Chandrasekhar

K. Thorne



R. Penrose

S. Hawking



B. Carter

Prix Nobel de physique 2020

Le B-A- BA physique

• 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 $\propto 1/M^2$

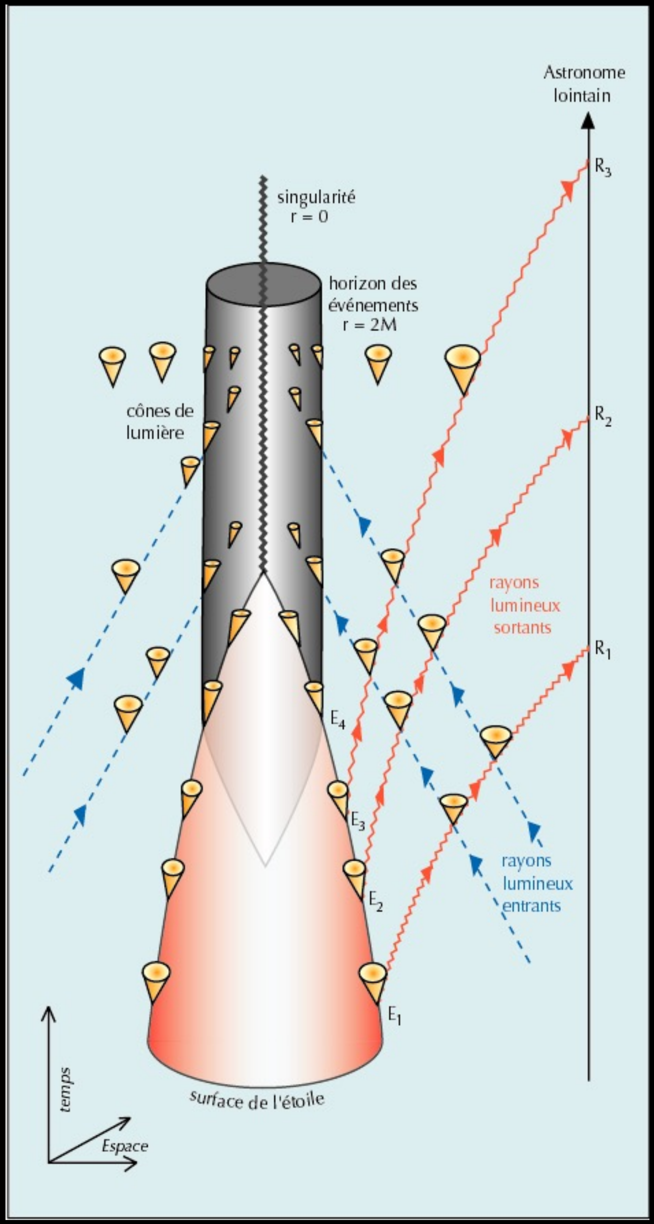
- Pour 10 M_S, $\rho \sim 10^{15}$ g/cm^3
- Pour 10^6 M_S, $\rho \sim 10^3$ g/cm^3
- Pour 10^9 M_S, $\rho \sim 10^{-3}$ g/cm^3

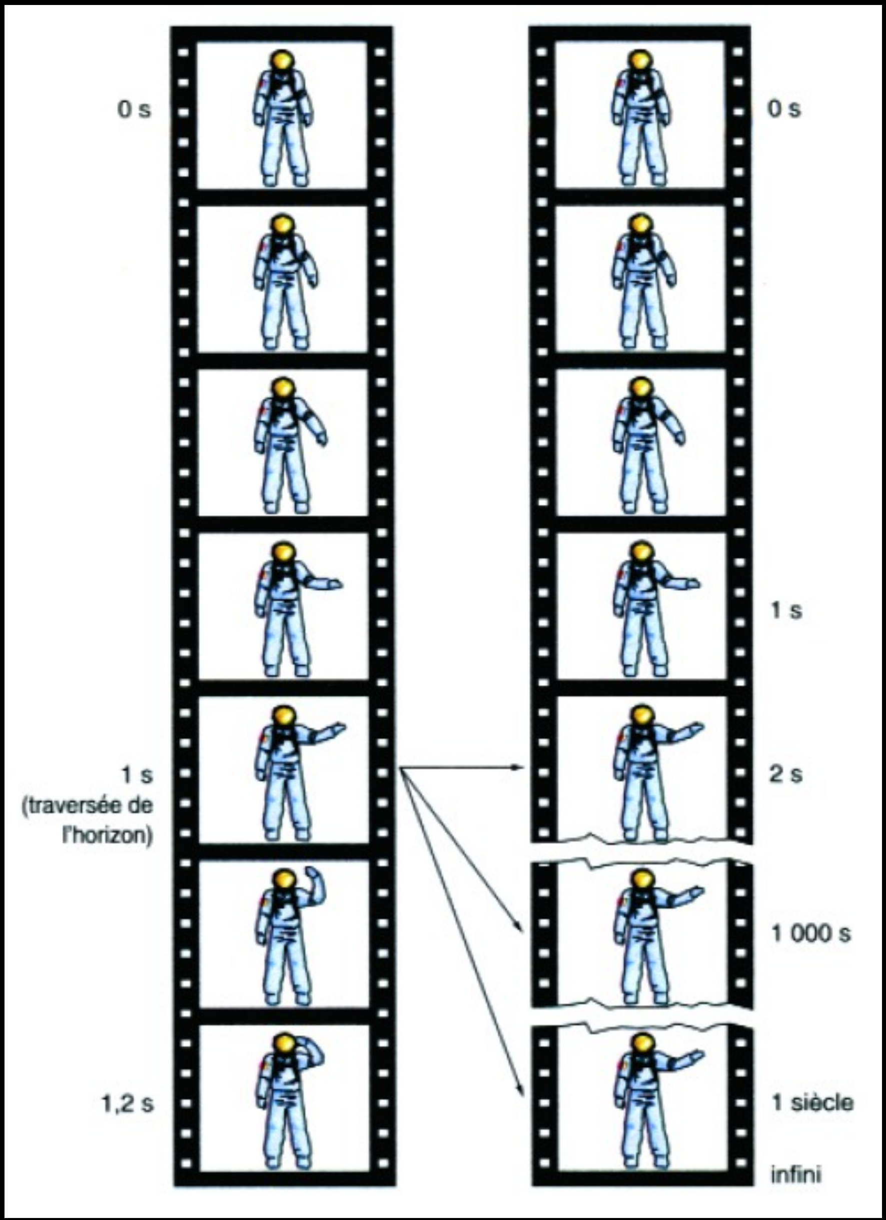
• Un trou noir n'est pas forcément « singulier »

(Singularité = courbure infinie)

RG classique / RG quantique

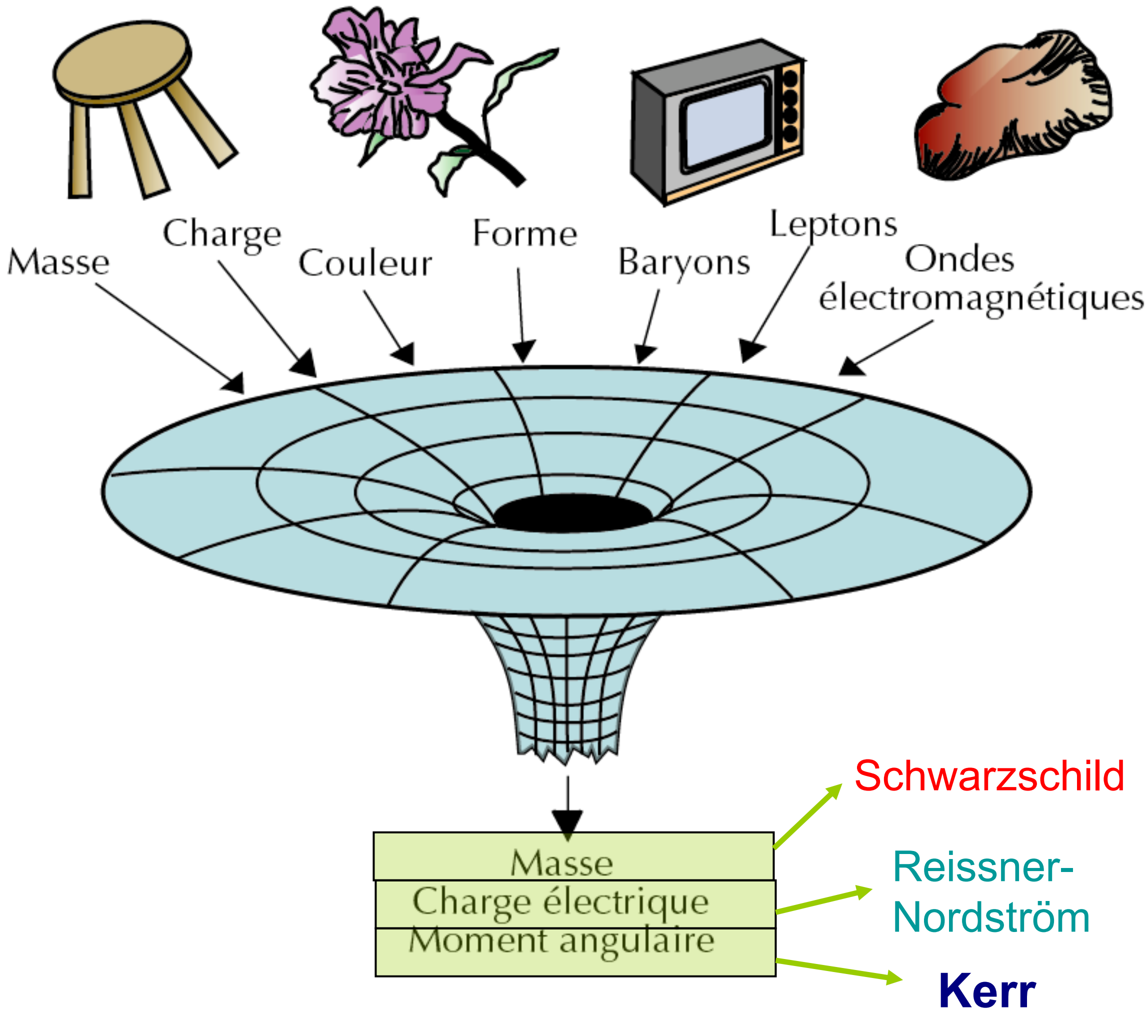
Horizon des événements





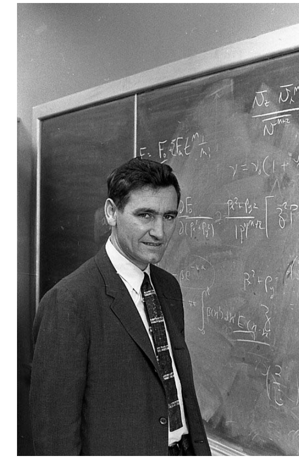
« Un trou noir n'a pas de chevelure »

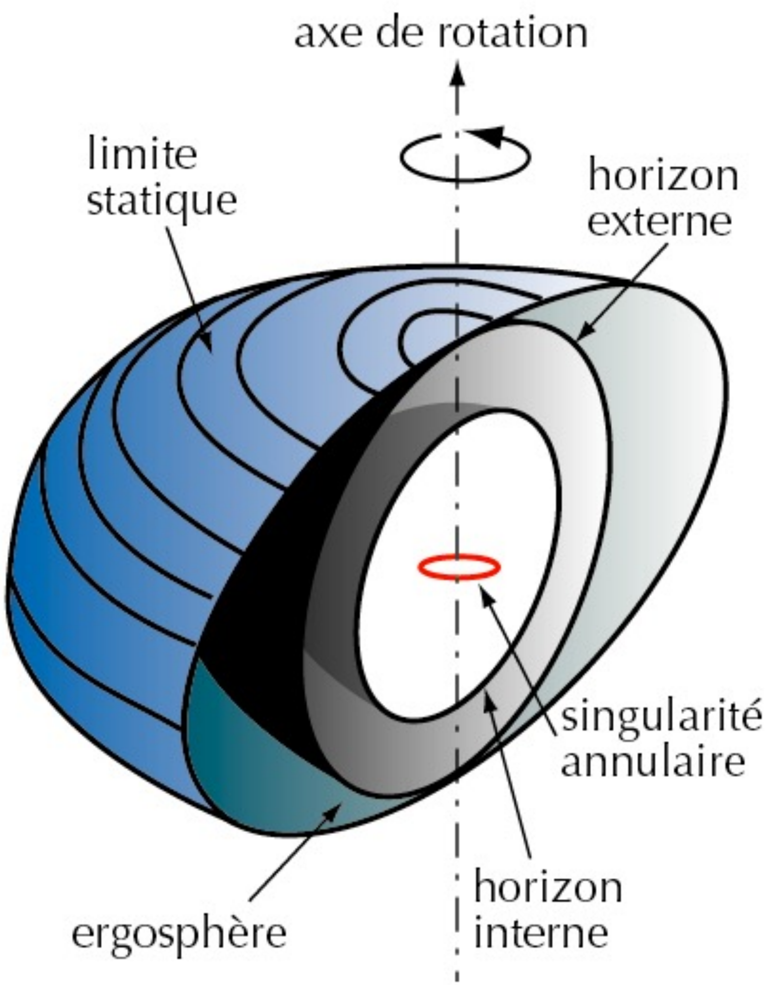
(Théorème de calvitie)



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

Le trou noir en rotation
(Kerr, 1963)





Energie totale :

Energie rotationnelle → Peut être extraite!

Masse irréductible

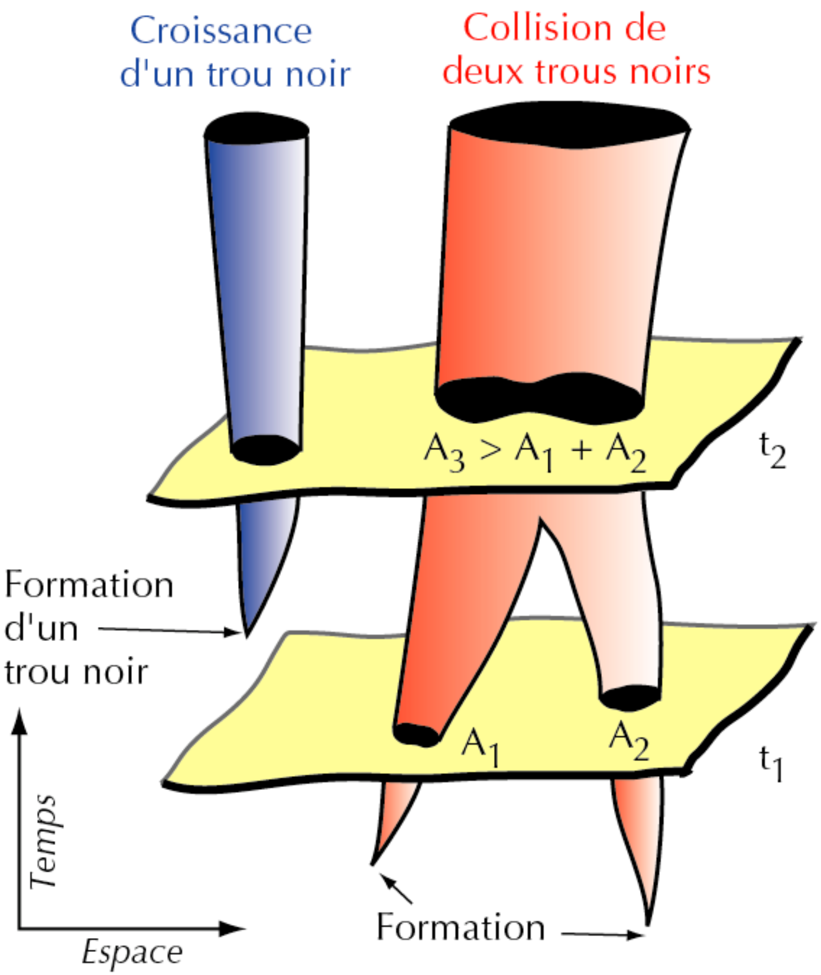
Thermodynamique des trous noirs

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 :

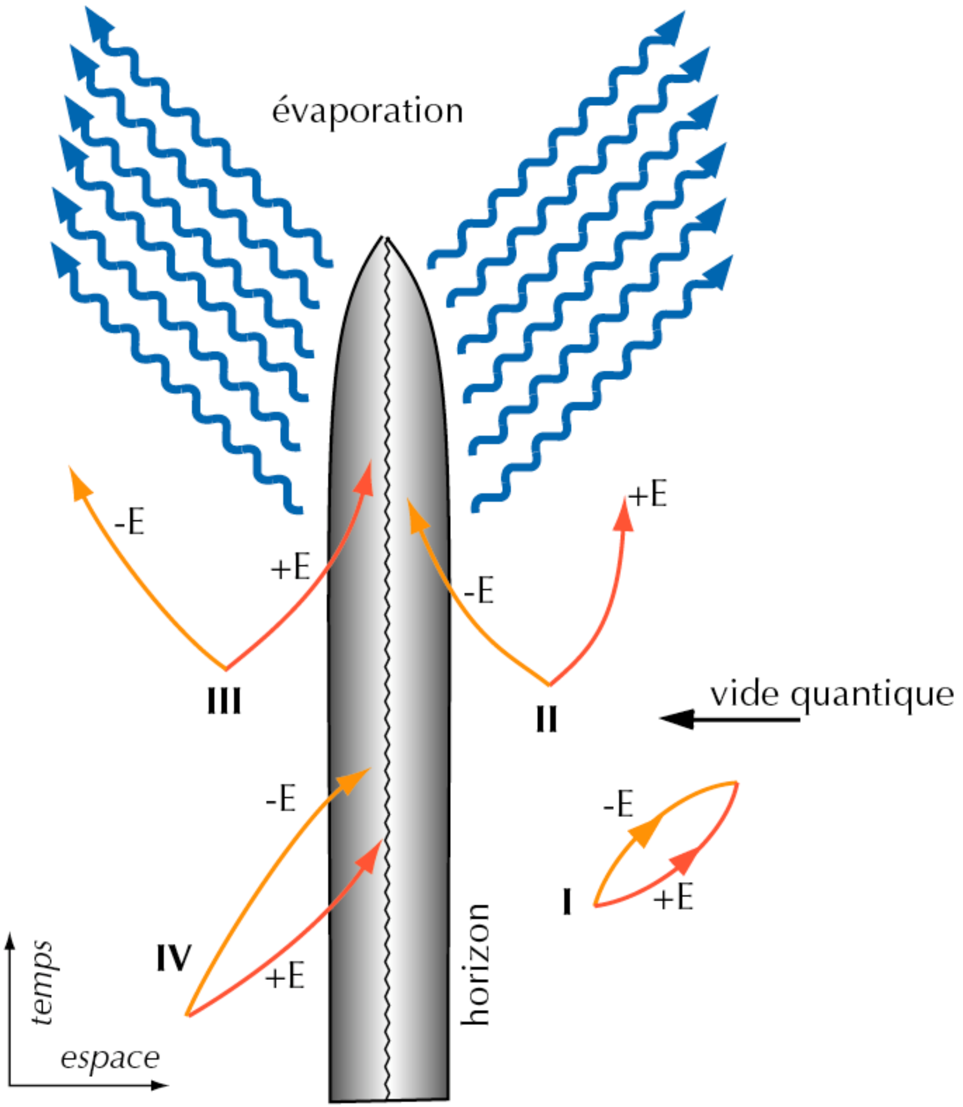
$S = 10^{77} (M/M_S)^2$

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

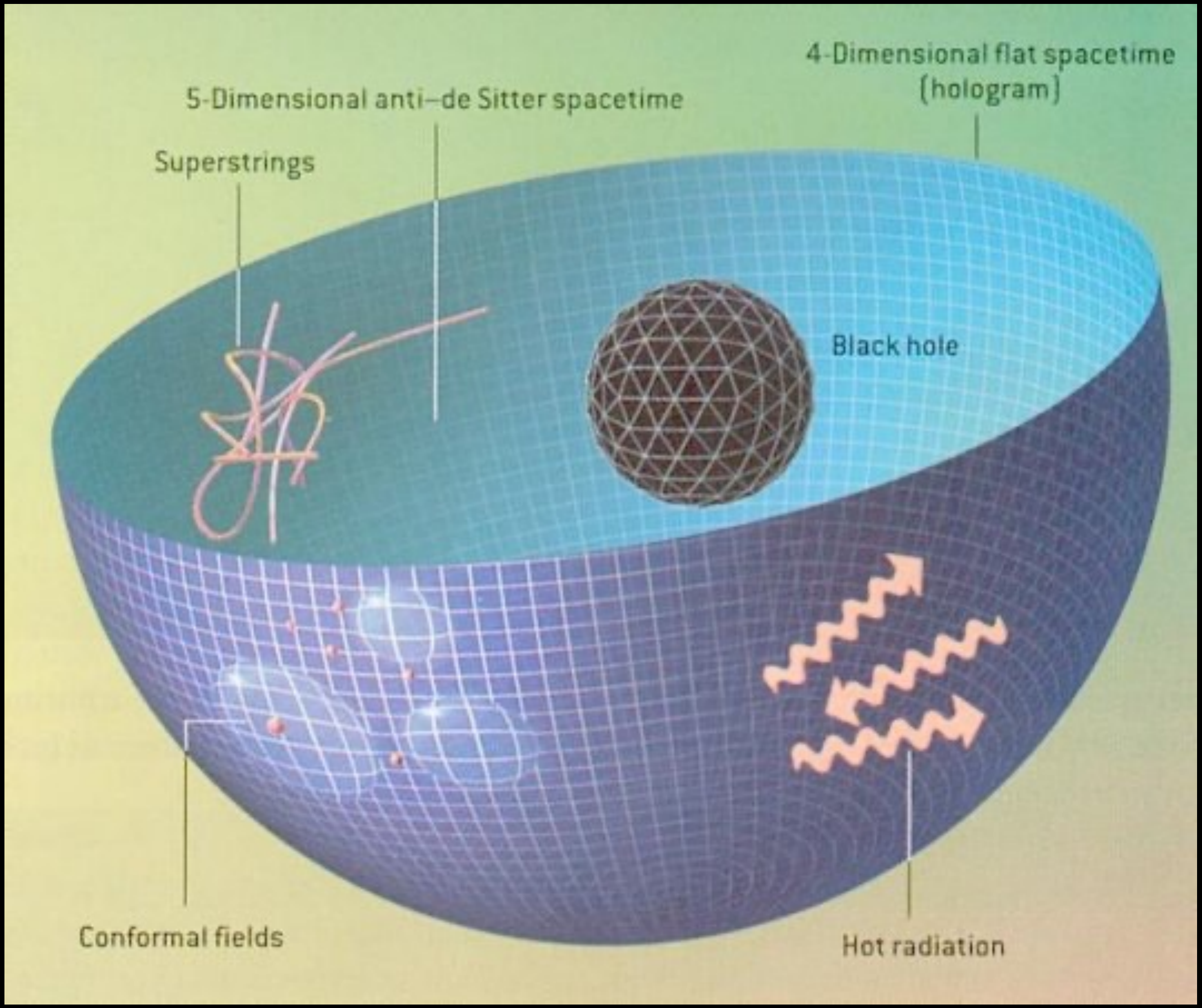
$T(K) = 10^{-7} M_S/M$

⇩

Paradoxe de l'information



Théorie des cordes

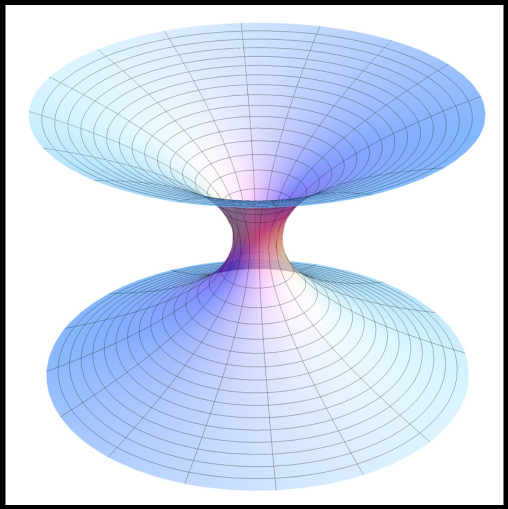


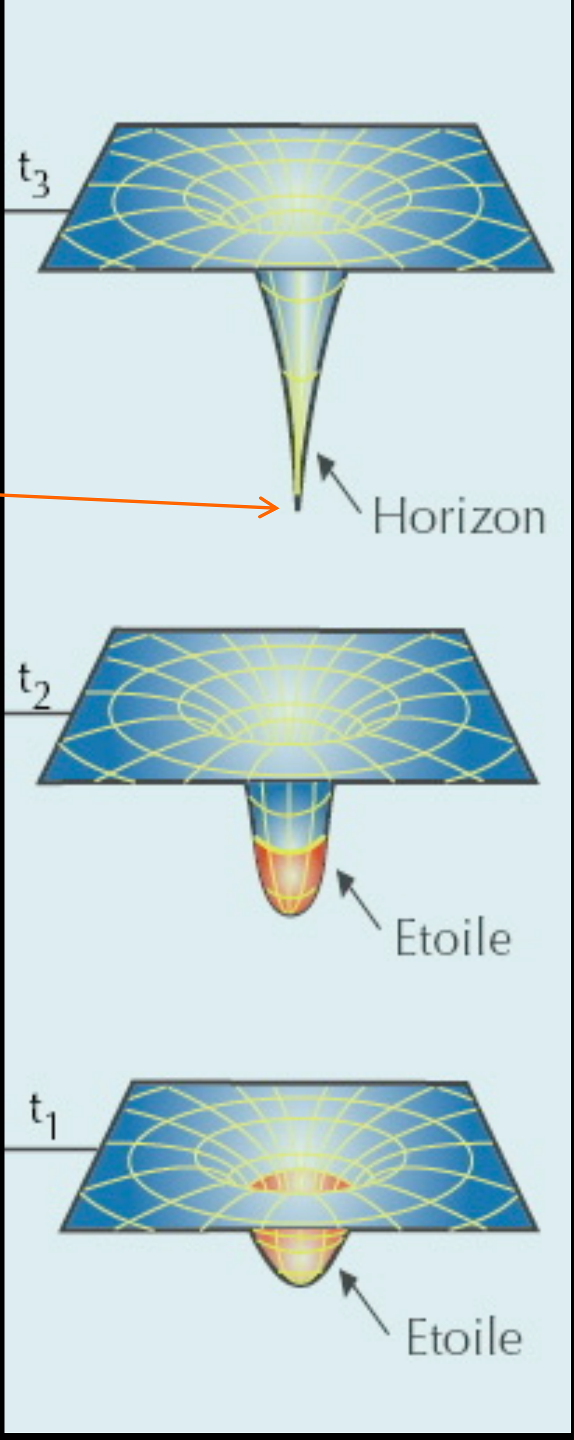
Le trou noir est-il holographique ?

Qu’y a-t-il à l’intérieur ?

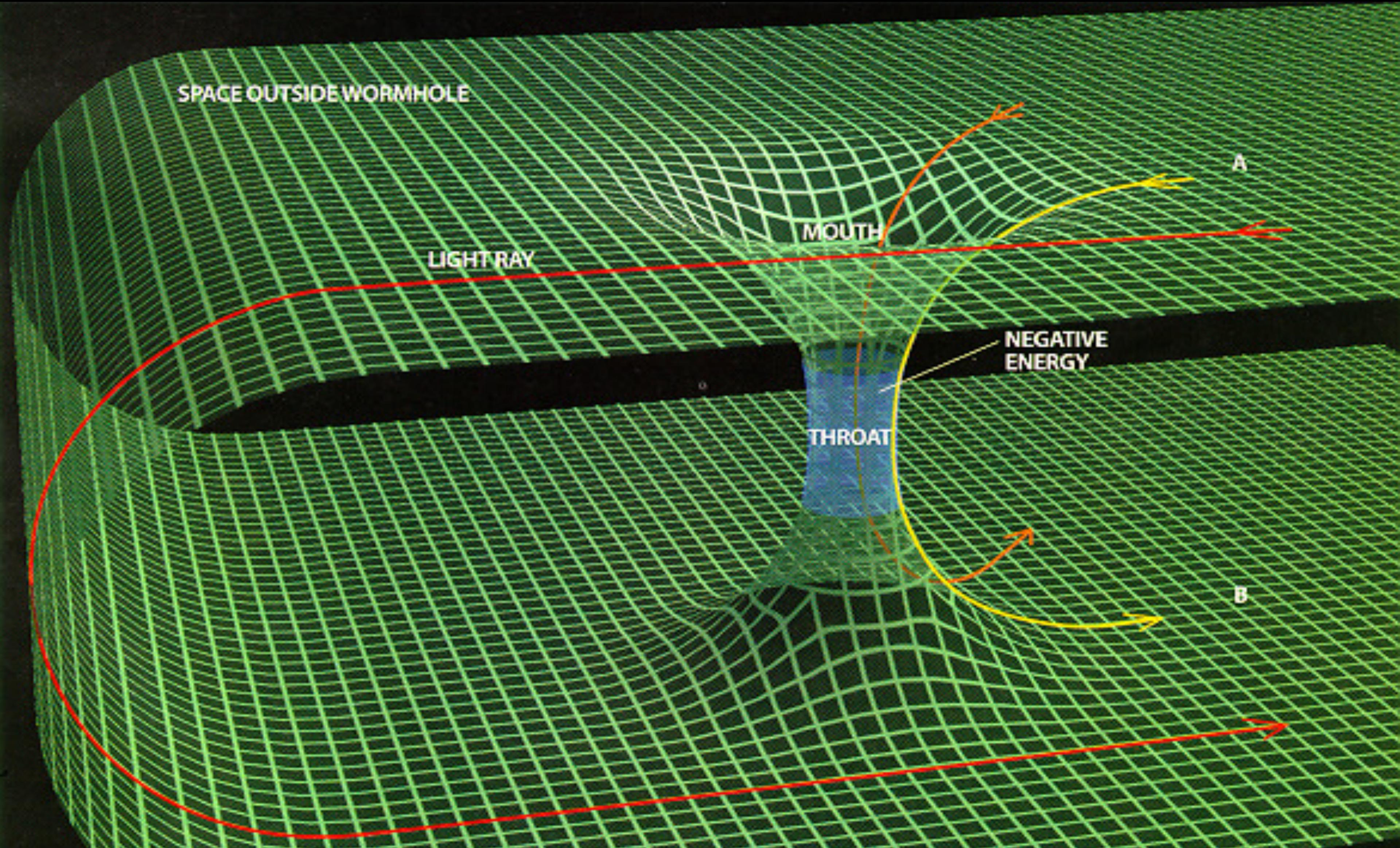
1) Singularité

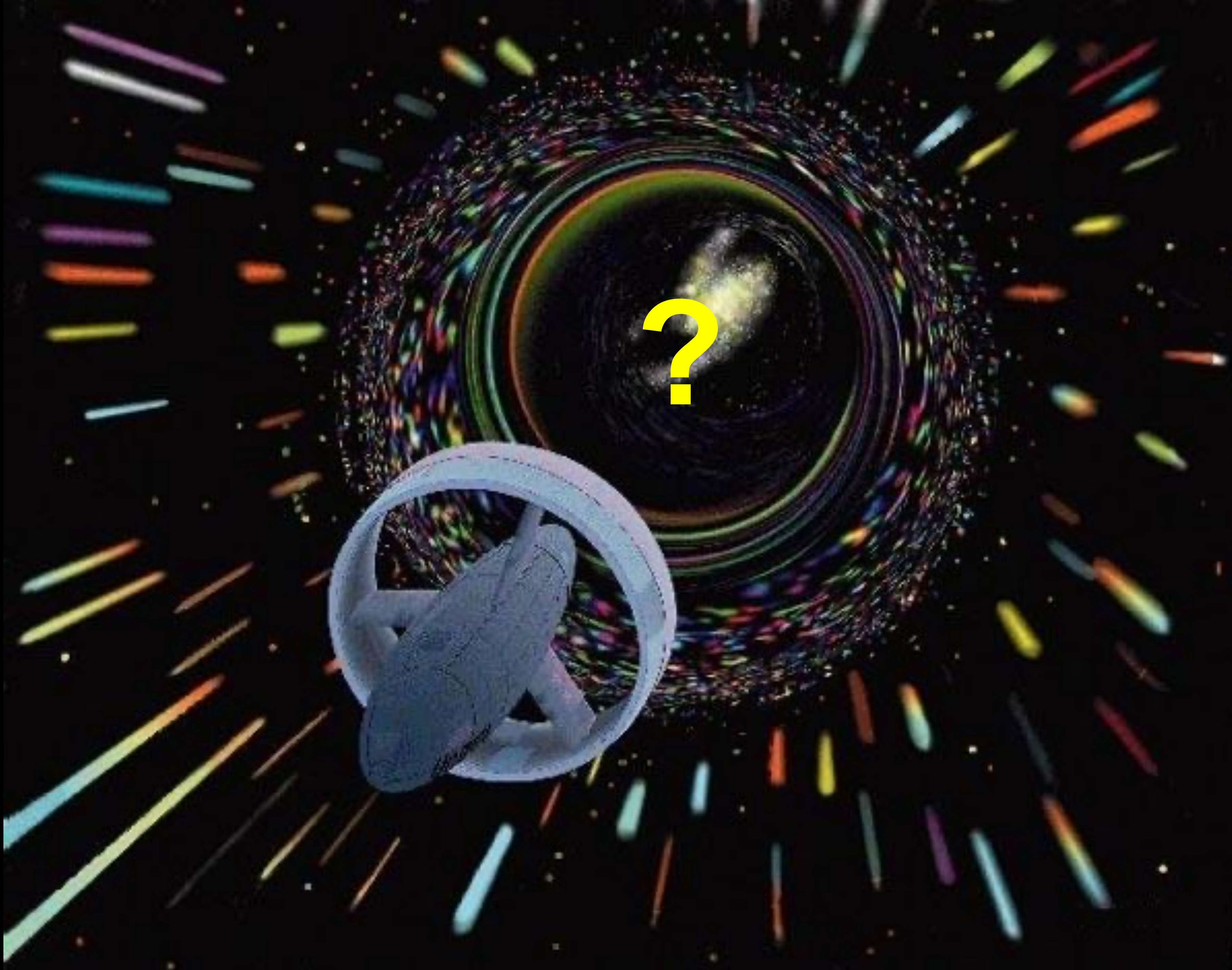
2) Pont d’Einstein-Rosen





La solution « trou de ver »





Les trous noirs astrophysiques

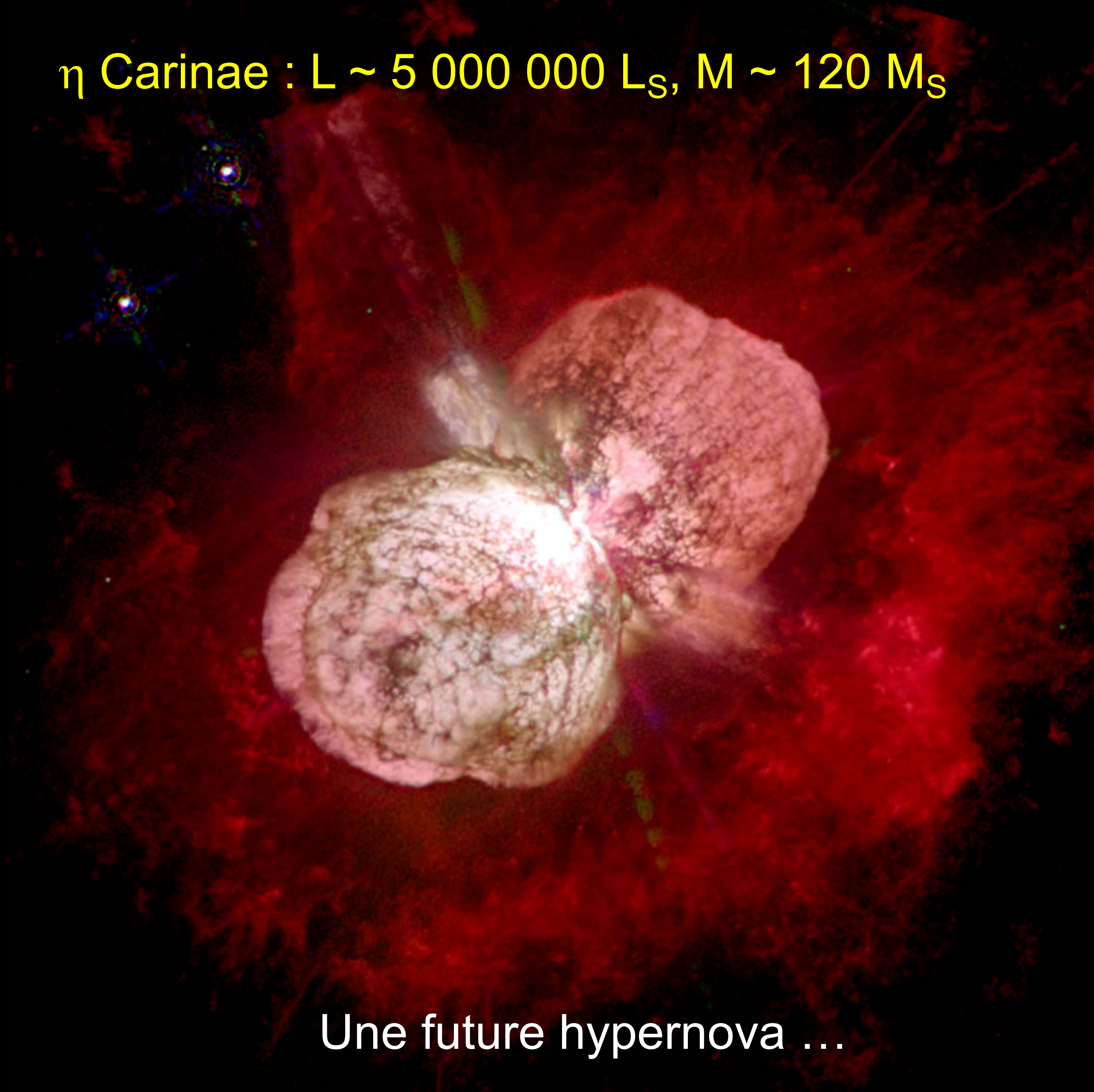
- Trous noirs primordiaux ? $10^{-5}\ g \lesssim M \lesssim 10^{6}\ M_S$
- Trous noirs stellaires $2{,}5\ M_S \lesssim M \lesssim 100\ M_S$
- Trous noirs intermédiaires $10^{3}\ M_S \lesssim M \lesssim 10^{5}\ M_S$
- Trous noirs supermassifs $10^{6}\ M_S \lesssim M \lesssim 10^{10}\ M_S$
- Trous noirs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

Les trous noirs stellaires

Evolution stellaire

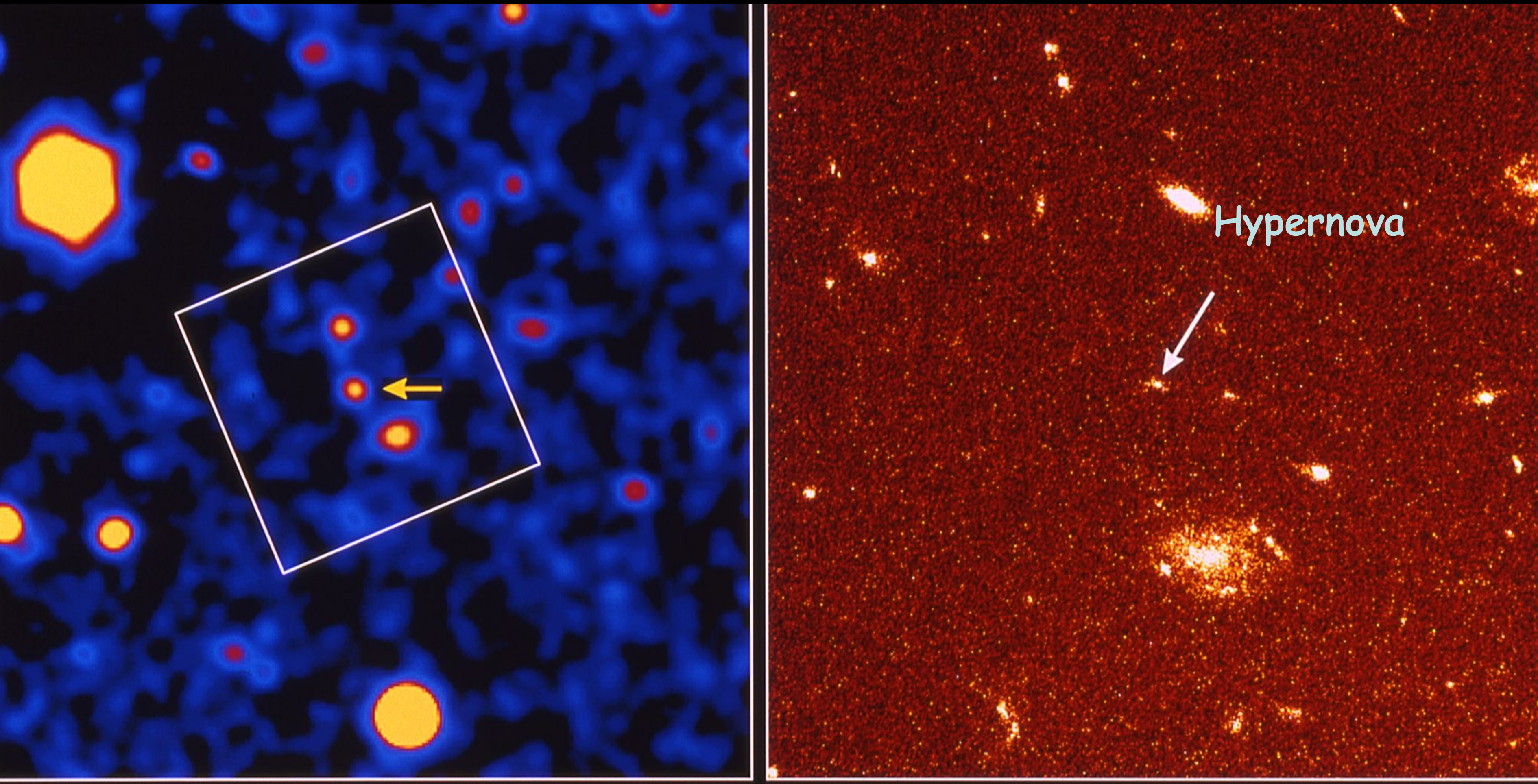
Masse initiale		Résidu compact	%
$M_* \lesssim 8\ M_S$	→	Naine blanche $M_{NB} \leq 1{,}4\ M_S$ (limite de Chandrasekhar)	~ 90
$8\ M_S \lesssim M_* \lesssim 50\ M_S$	→	Etoile à neutrons $M_{EN} \leq 2{,}5\ M_S$ (limite de LOV)	~ 10
$M_* \gtrsim 50\ M_S$	→	Trou noir stellaire $M_{TN} \gtrsim 2{,}5\ M_S$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

η Carinae : L ~ 5 000 000 L_S, M ~ 120 M_S



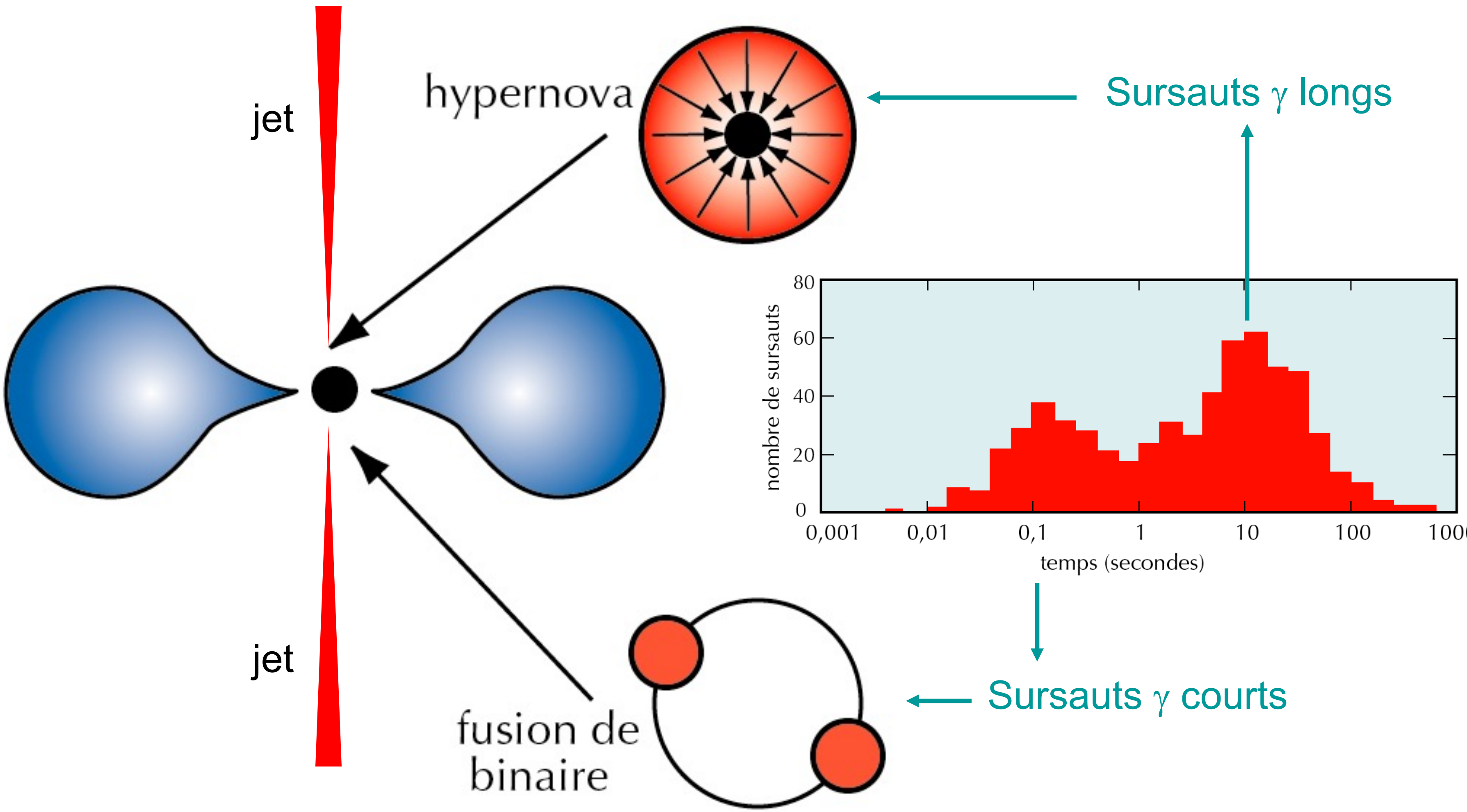
Une future hypernova …

Formation des trous noirs stellaires



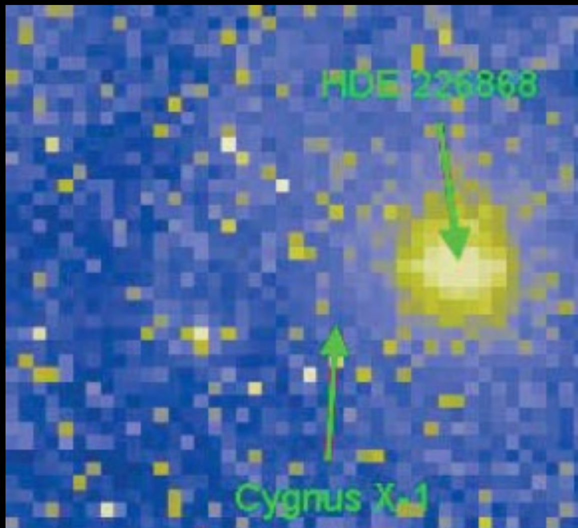
→ Sursauts Gamma

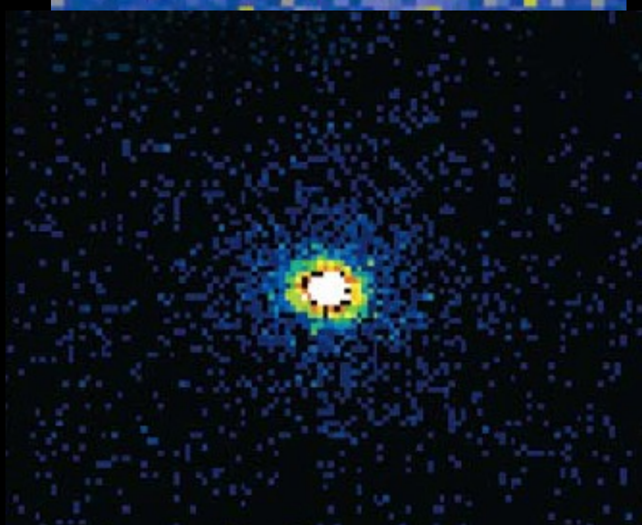
Modélisation des Sursauts Gamma



Détection des trous noirs stellaires

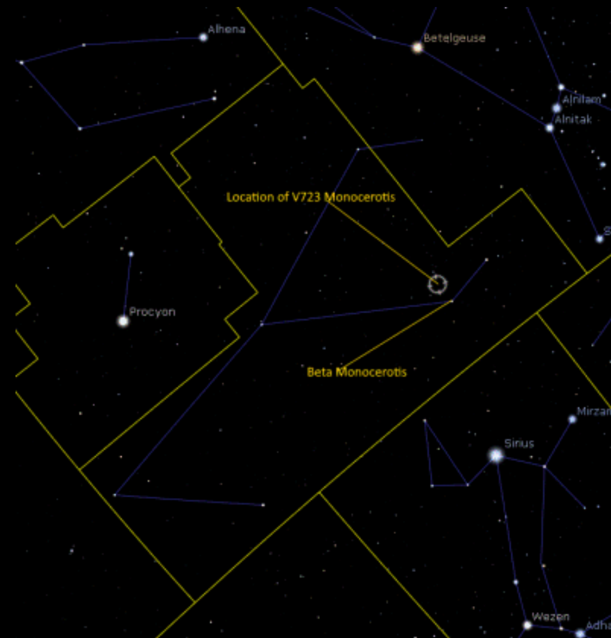
Le premier …





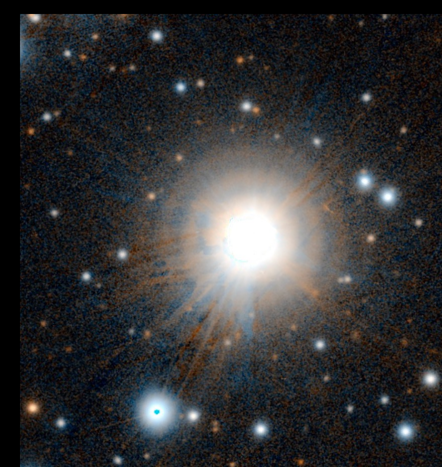
Cygnus X-1
(1971)

Les plus proches …

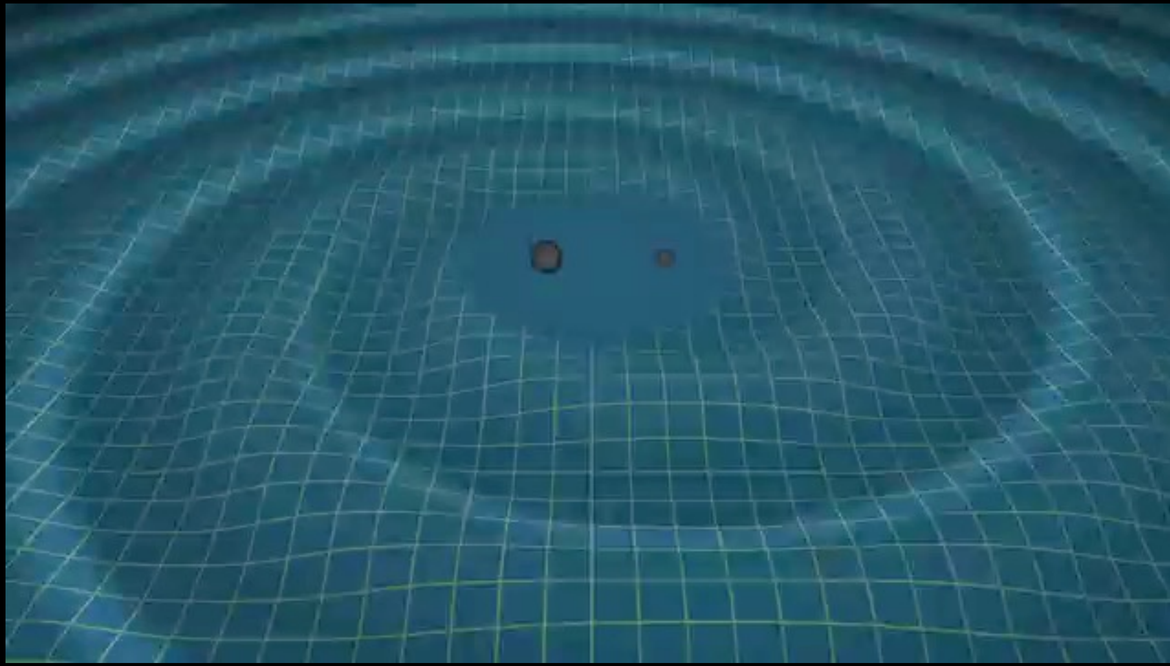


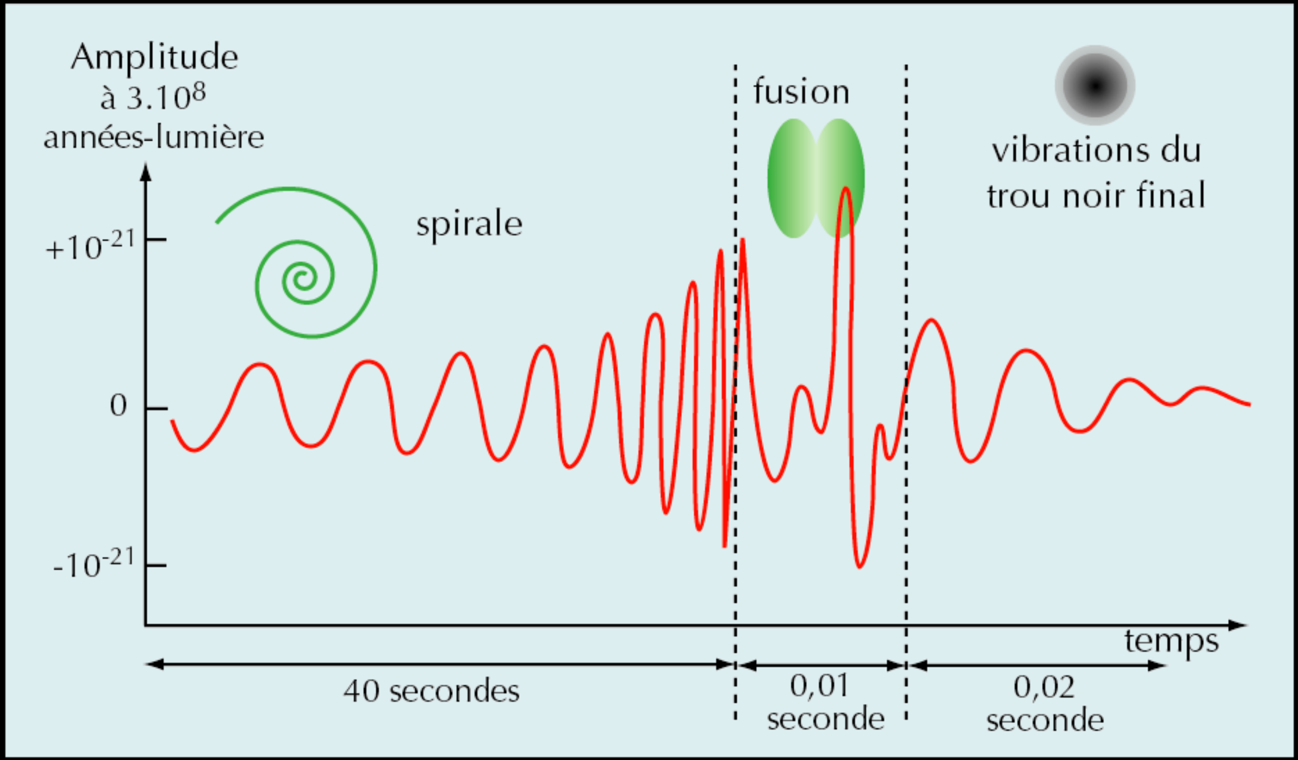
A0620-00 : 3500 a.l.

V723 Mon :
1500 a.l.

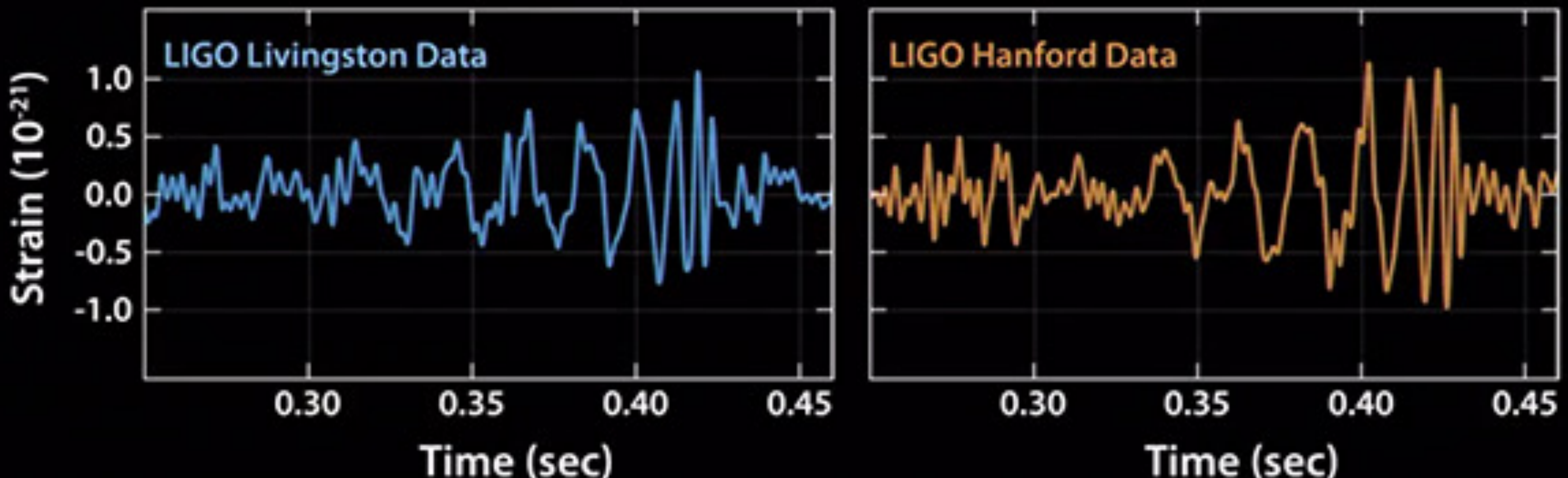


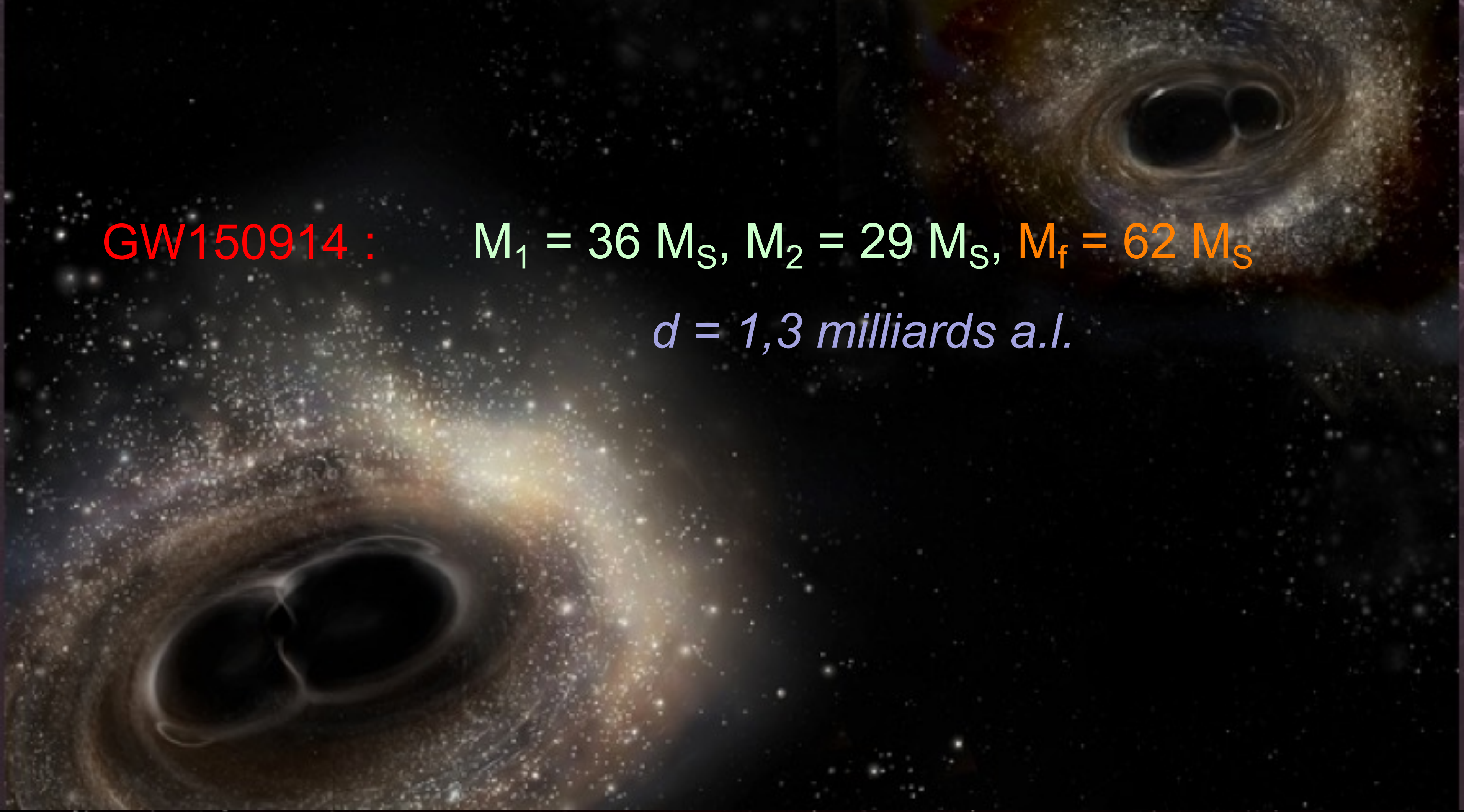
Ondes gravitationnelles





Evénement GW150914





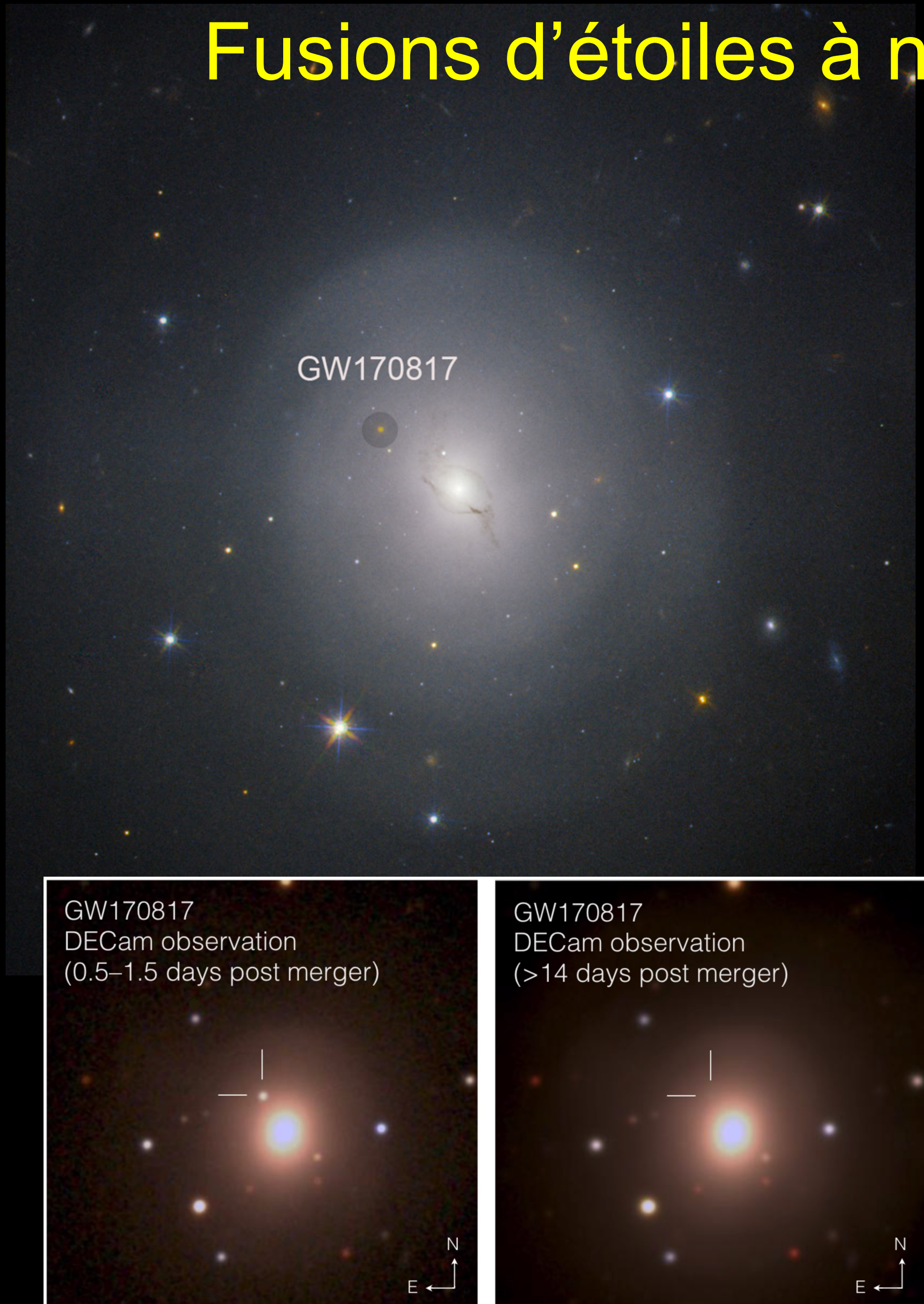
GW150914 : $M_1 = 36\ M_S$, $M_2 = 29\ M_S$, $M_f = 62\ M_S$

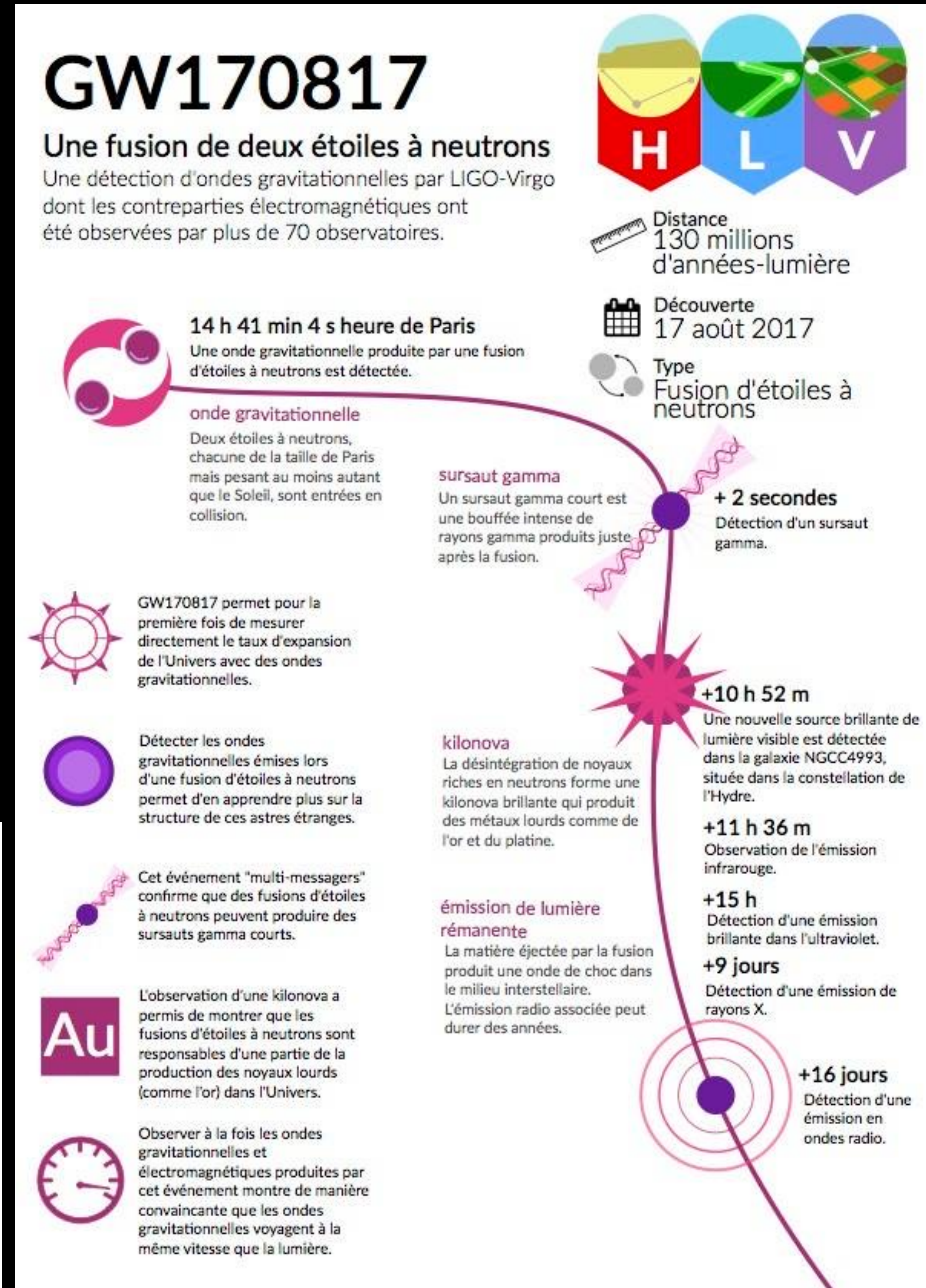
d = 1,3 milliards a.l.

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

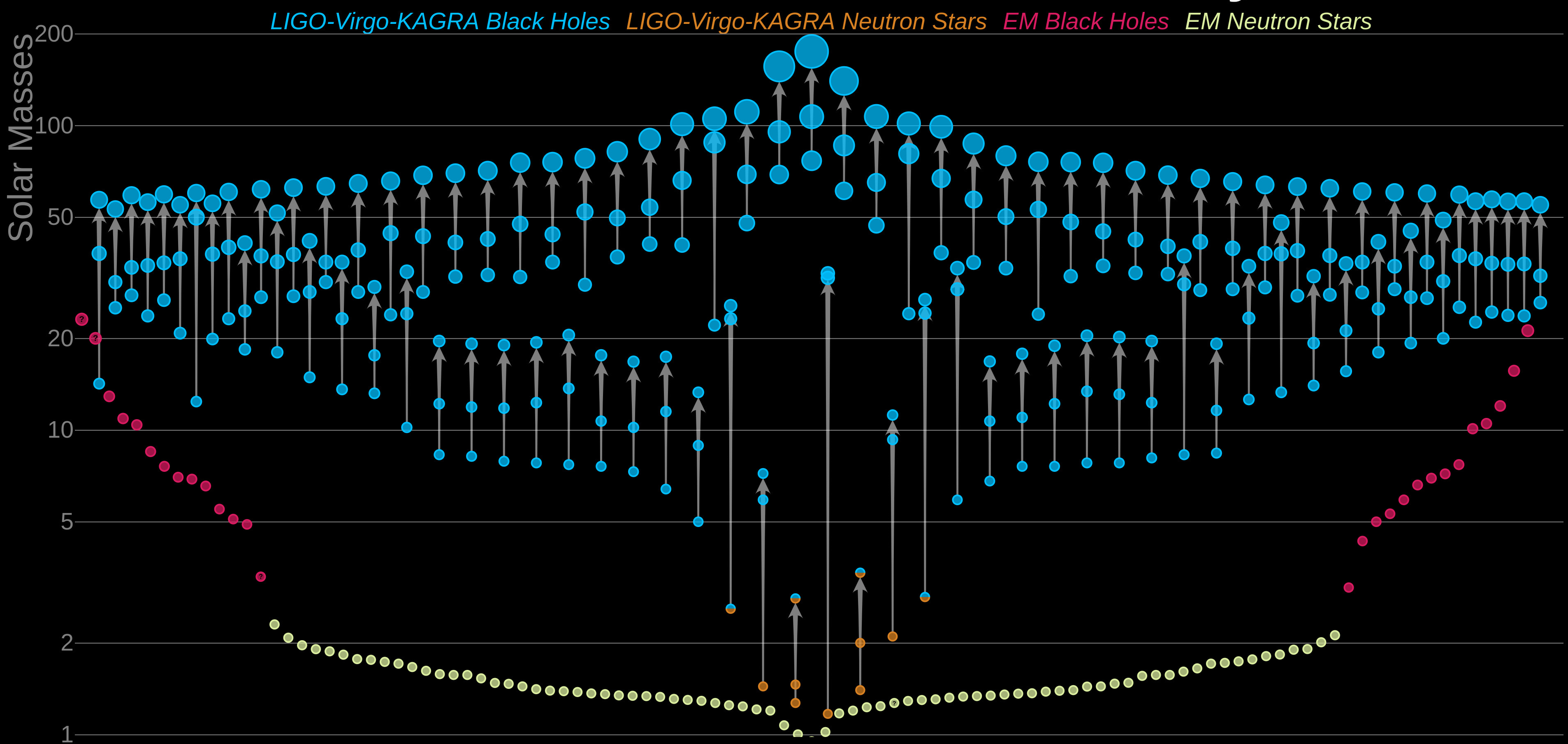
d = 1,4 milliards a.l.

Fusions d'étoiles à neutrons : GW170817





Masses in the Stellar Graveyard

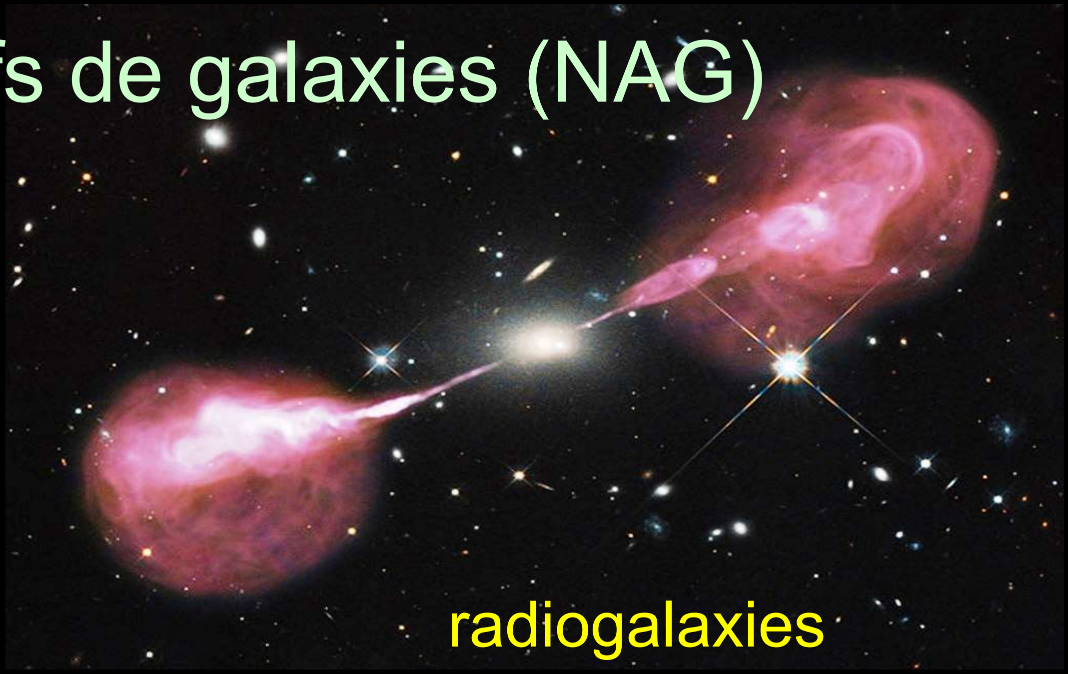


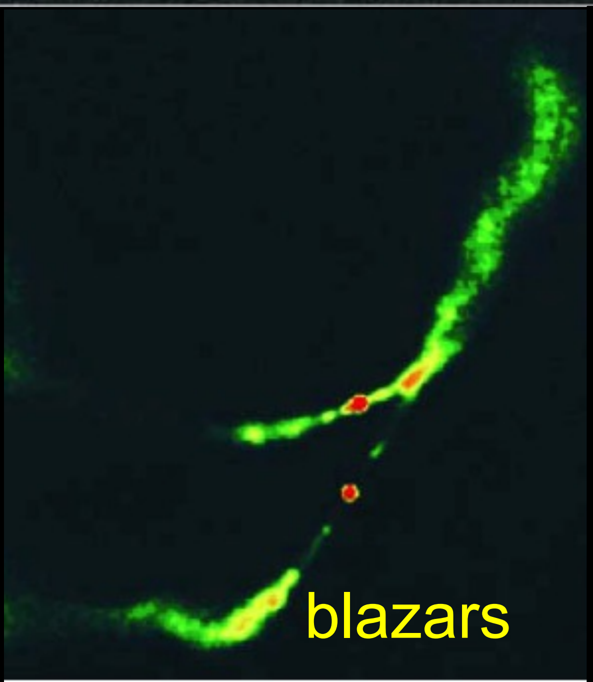
Catalogue GWTC-3 (2021)

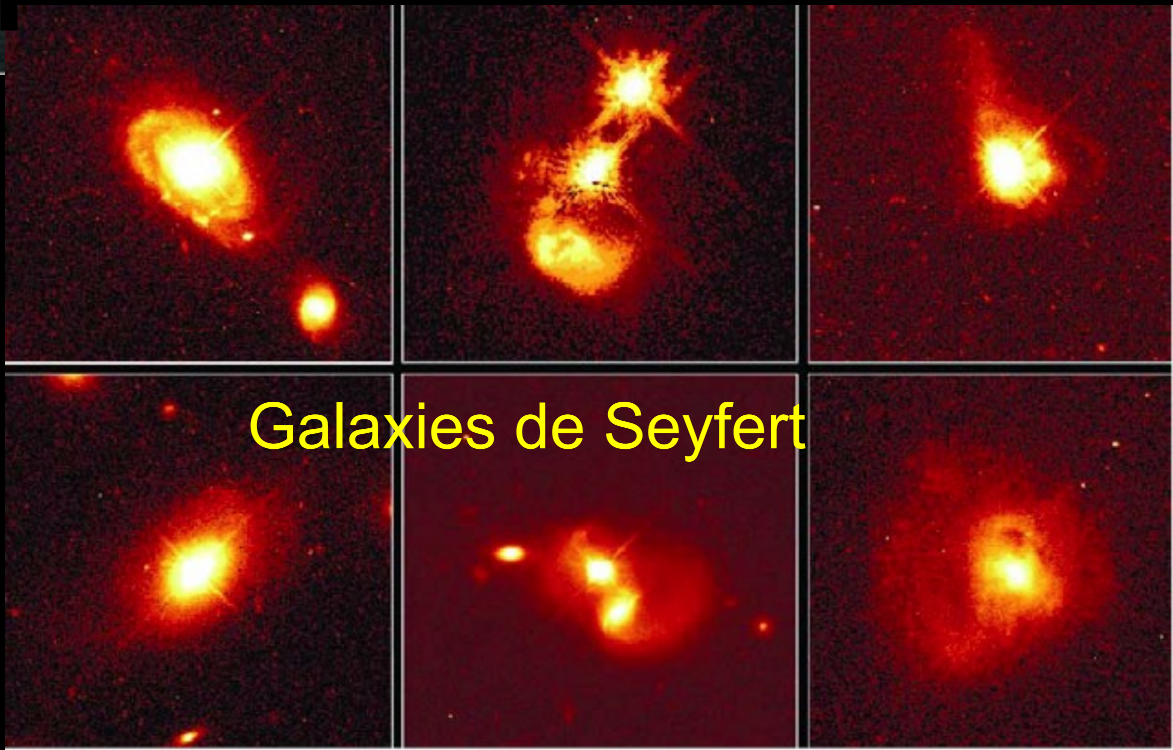
Lacune de masse comblée !

Les trous noirs géants

Noyaux actifs de galaxies (NAG)







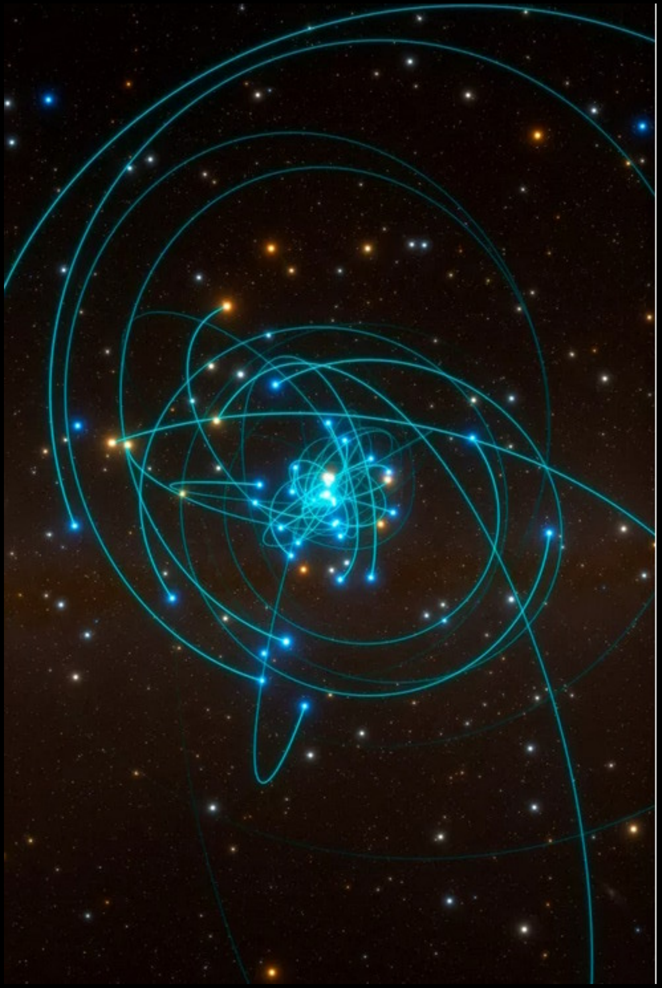
Télescope
Chandra
(rayons X)

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

↓

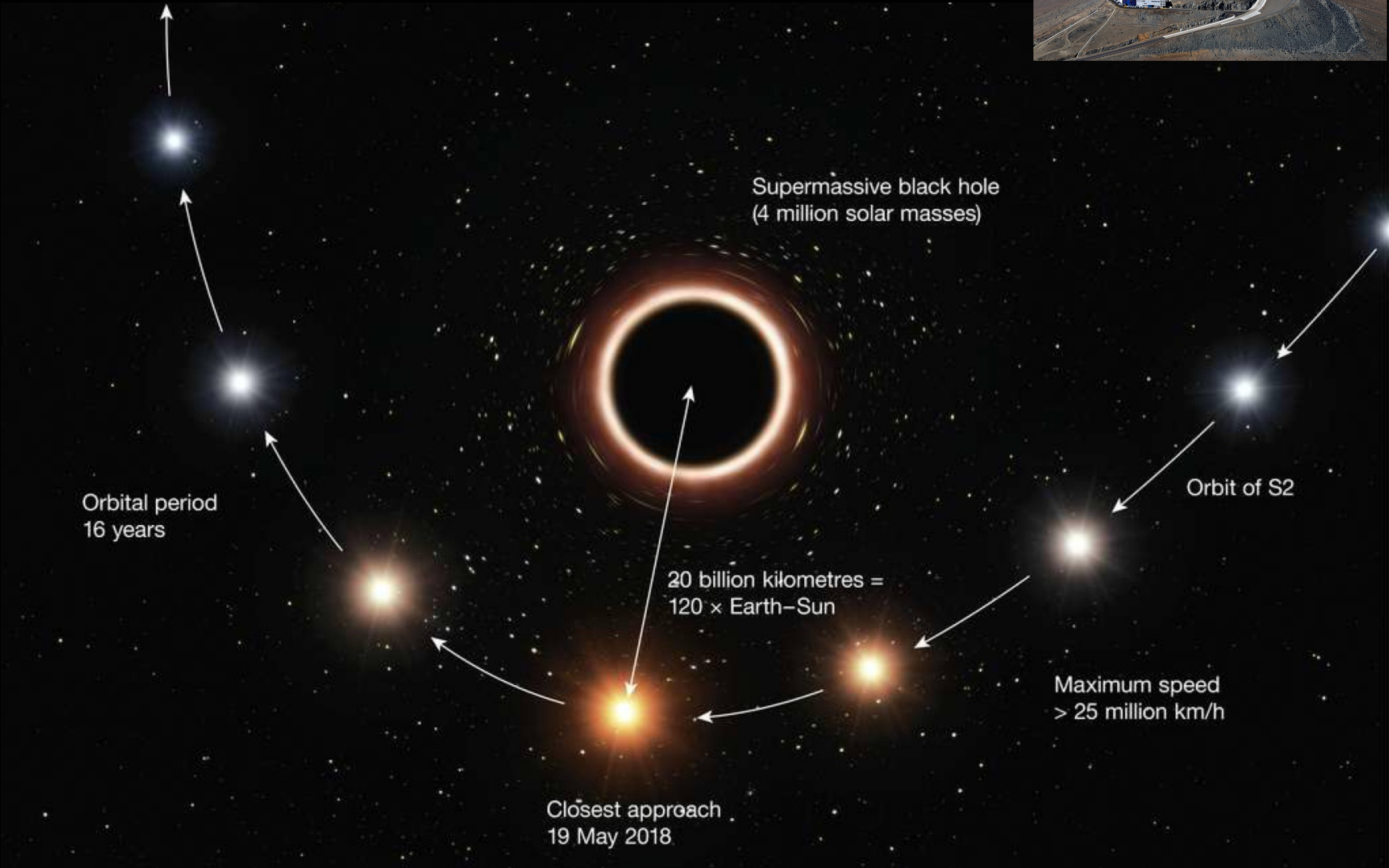
~ 10^9 TNSM !

Sagittarius A* : Le Trou noir Galactique



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

Instrument GRAVITY



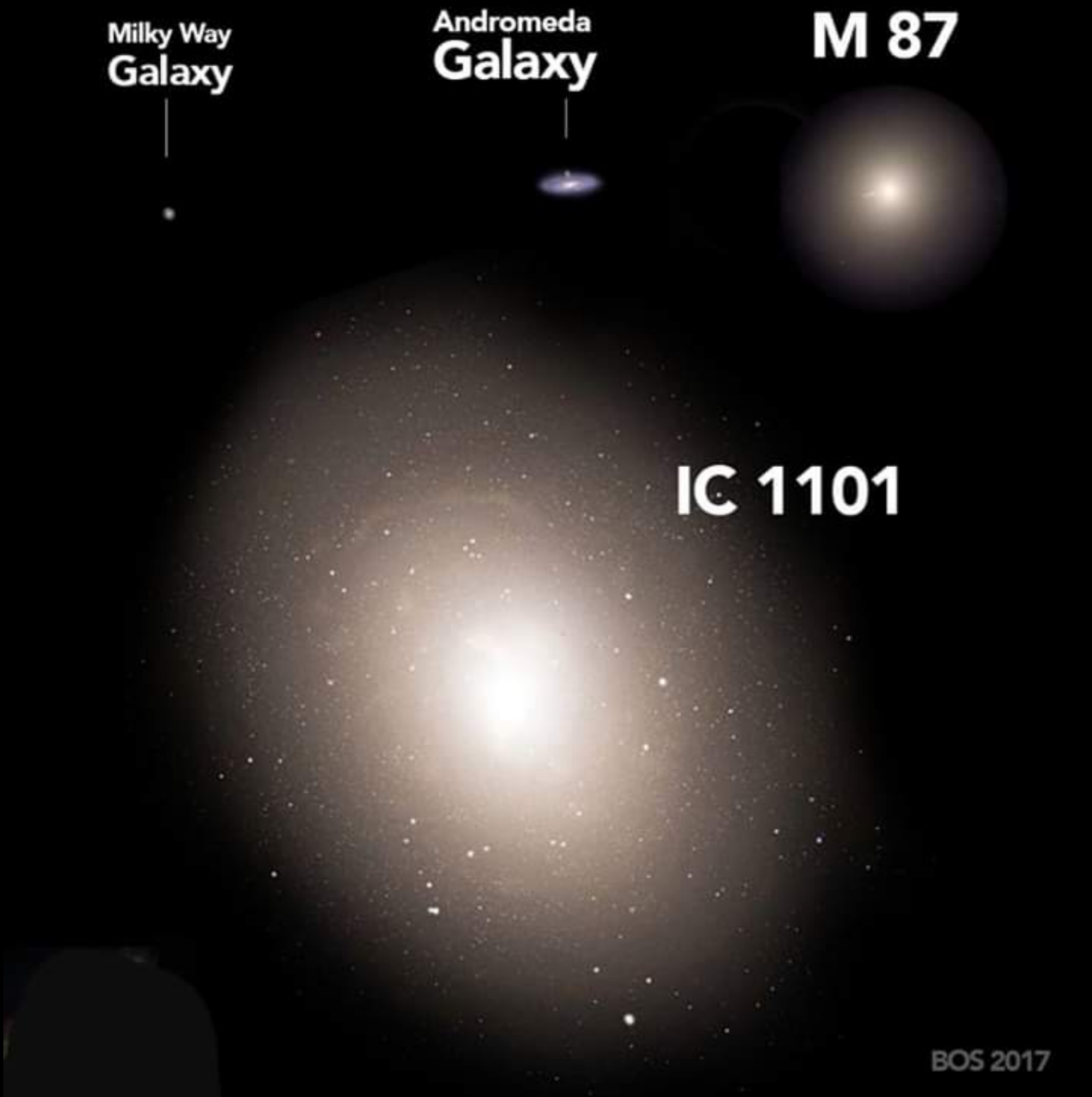
Quasar
TON 618 :

Le plus gros trou noir ultramassif

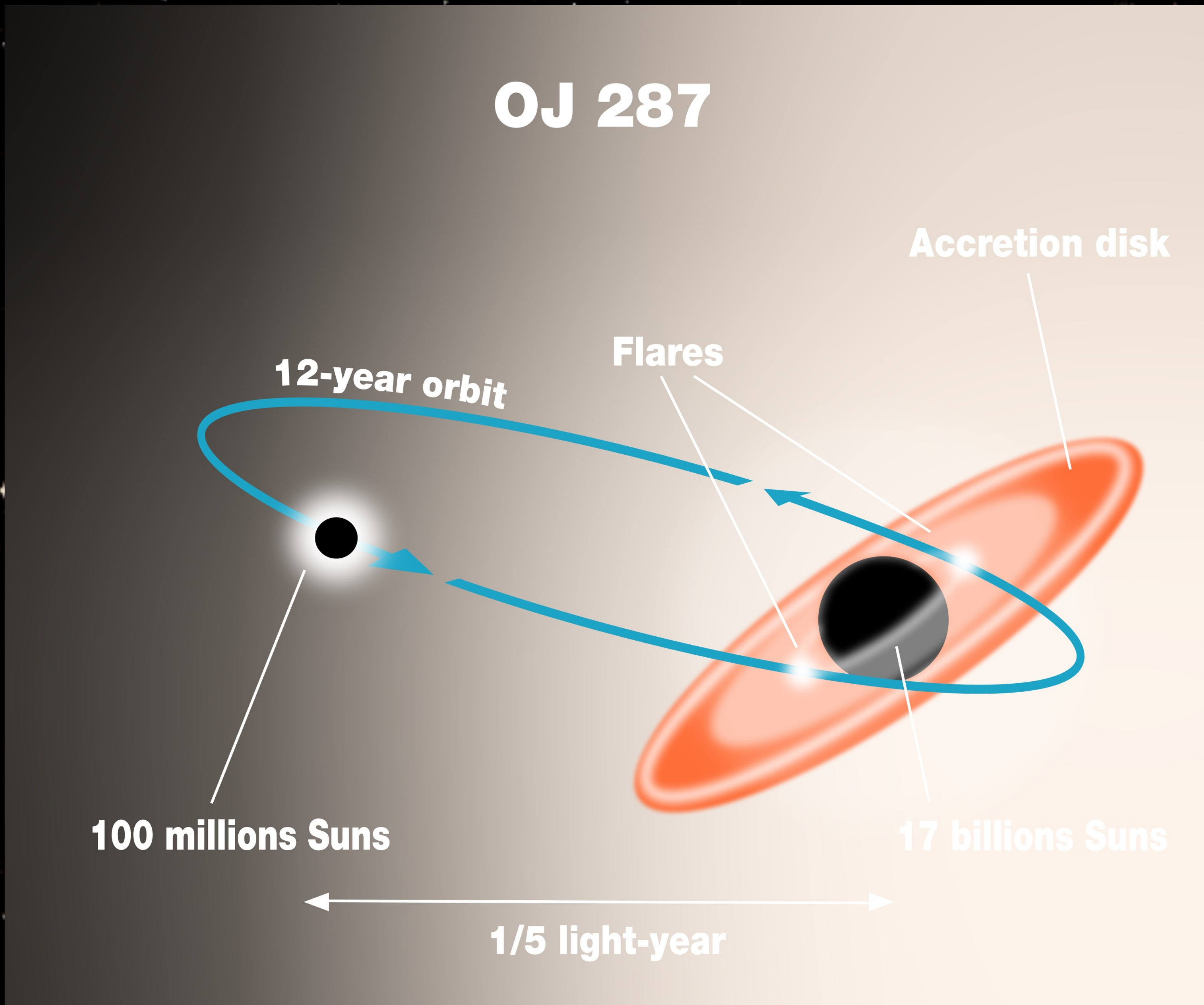
66 milliards M_S

La plus grosse galaxie

TN :
40-100 milliards M_S



Des trous noirs supermassifs binaires !

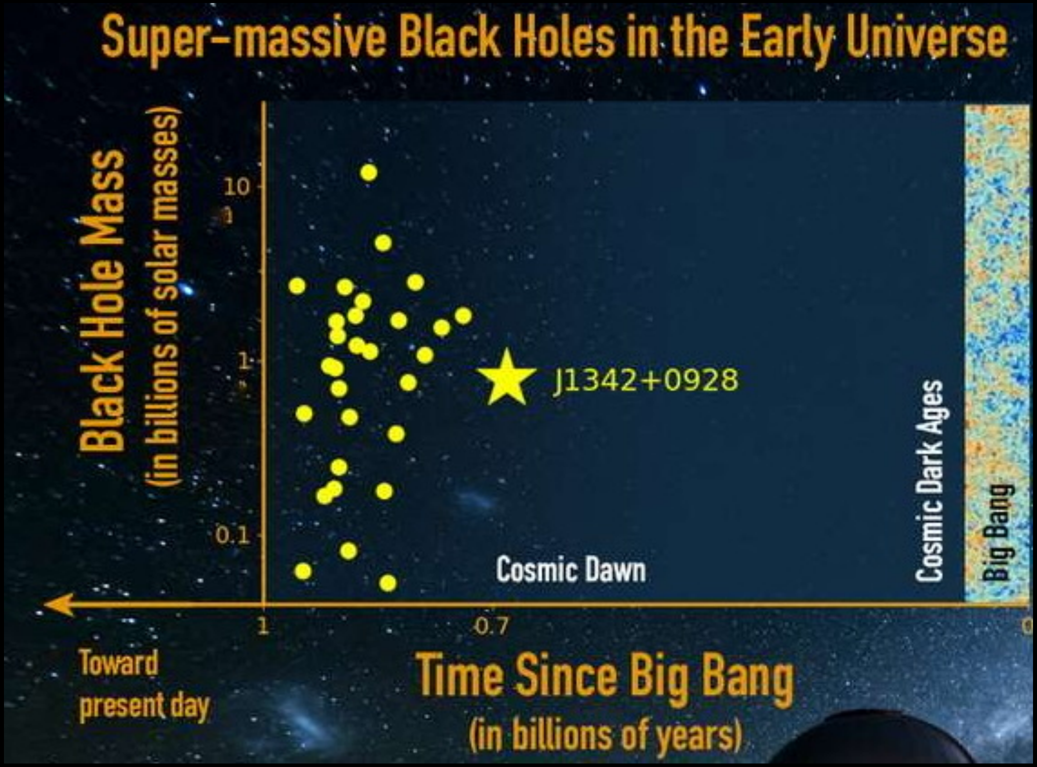


La formation des trous noirs supergéants

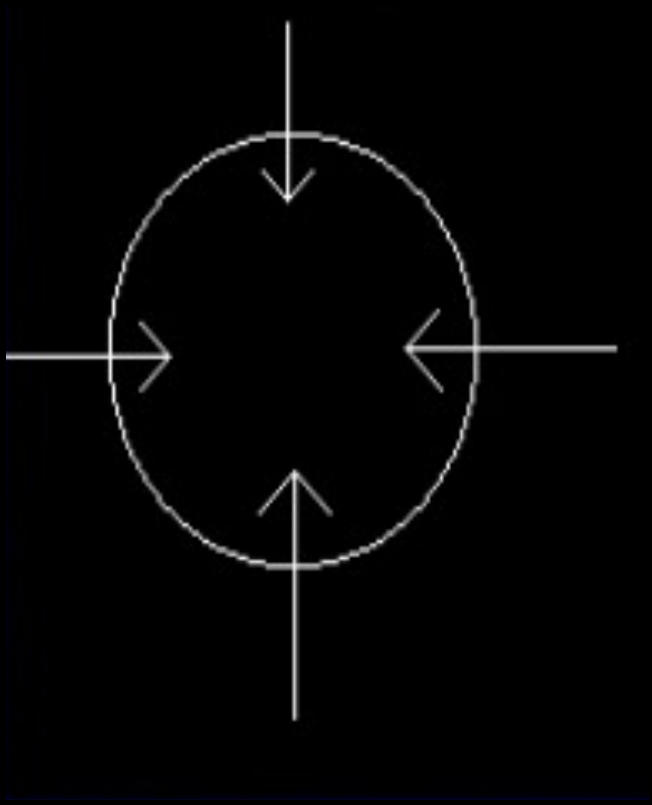
La petite galaxie lenticulaire NGC 1277 a un TN de 5 milliards de Ms: 4 % du total (normalement 0.1%)

J1342+0928 : 1 milliard M_S
700 millions d'années après le BB

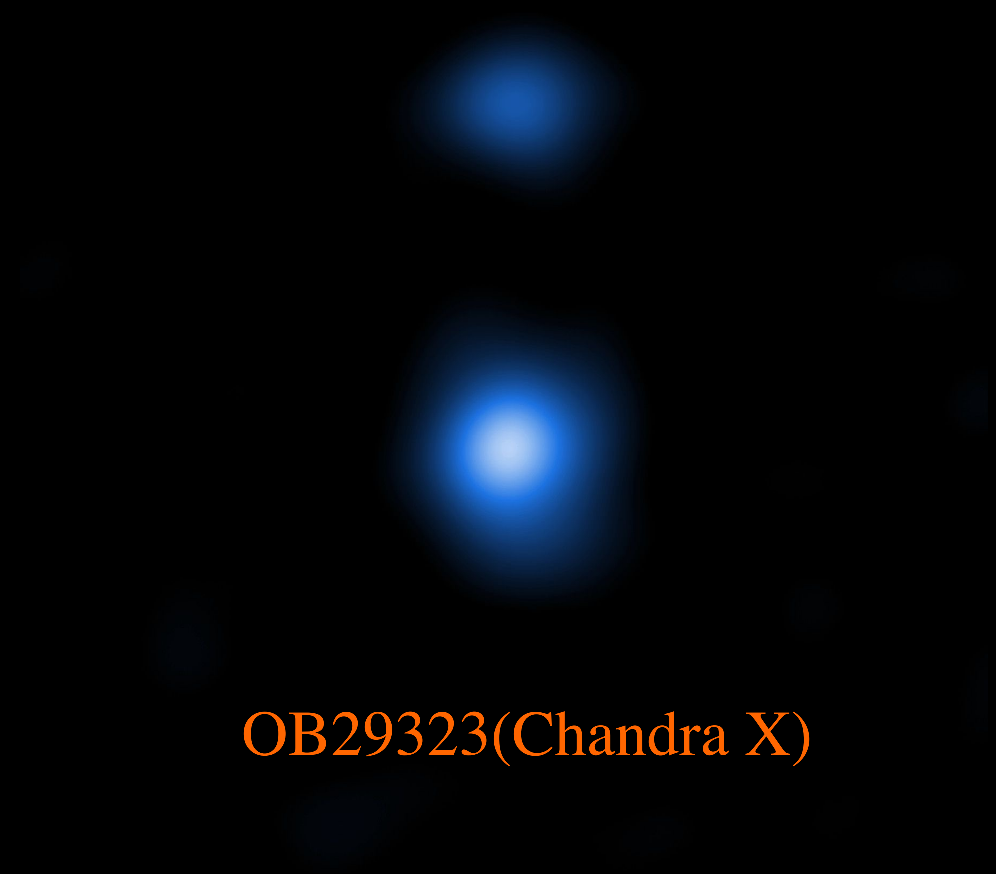
J1007+2115 :1,5 milliards M_S
« Pōniuāʻena »



- Trous noirs primordiaux massifs (< 3 sec)



- Effondrement de grands nuages de gaz

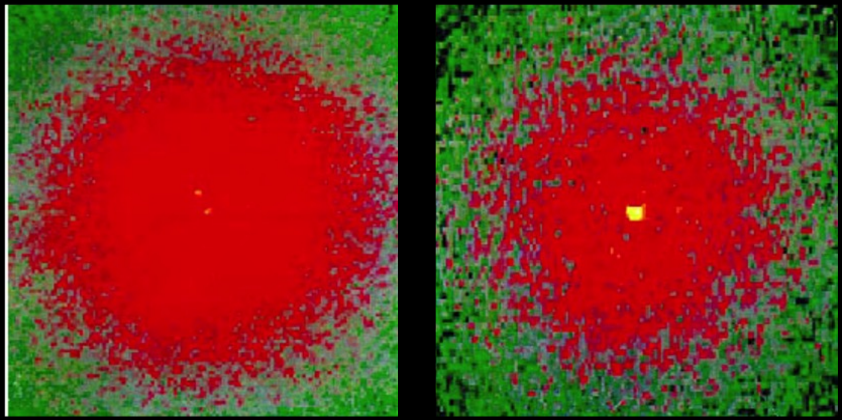


OB29323(Chandra X)

Destruction d'étoiles par les forces de marée

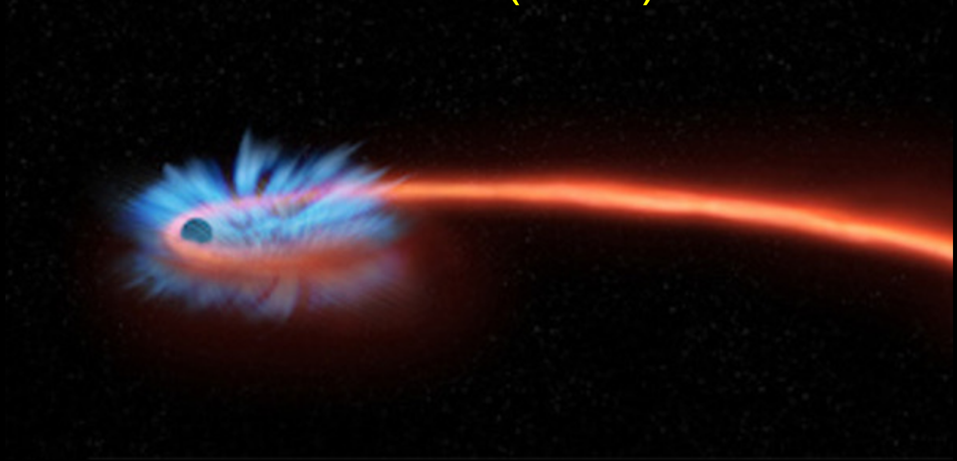
crêpes stellaires flambées (Carter & Luminet, 1982)

NGC 4252 (1995)

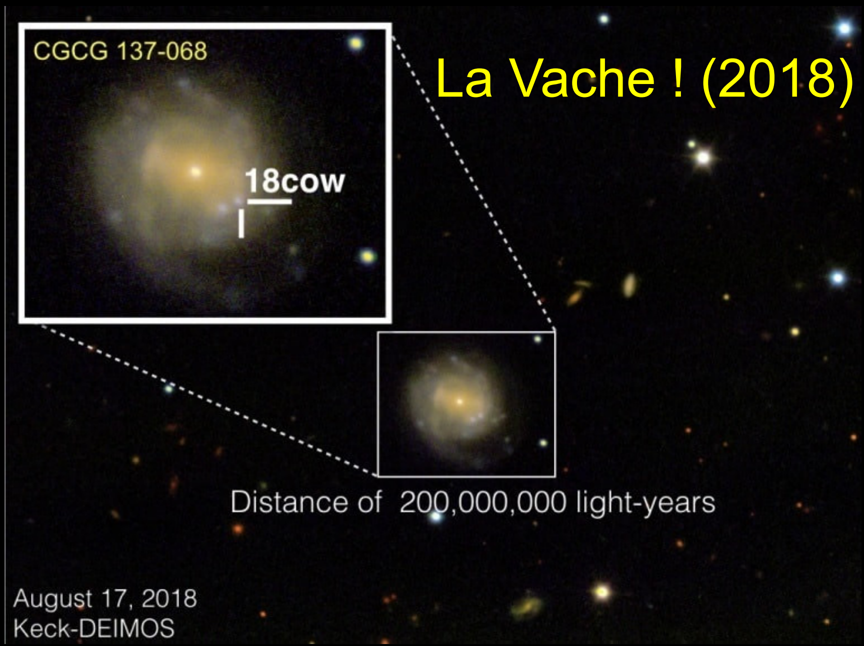


UV-transient (2009)

ASASSN-15lh (2015)



La Vache ! (2018)



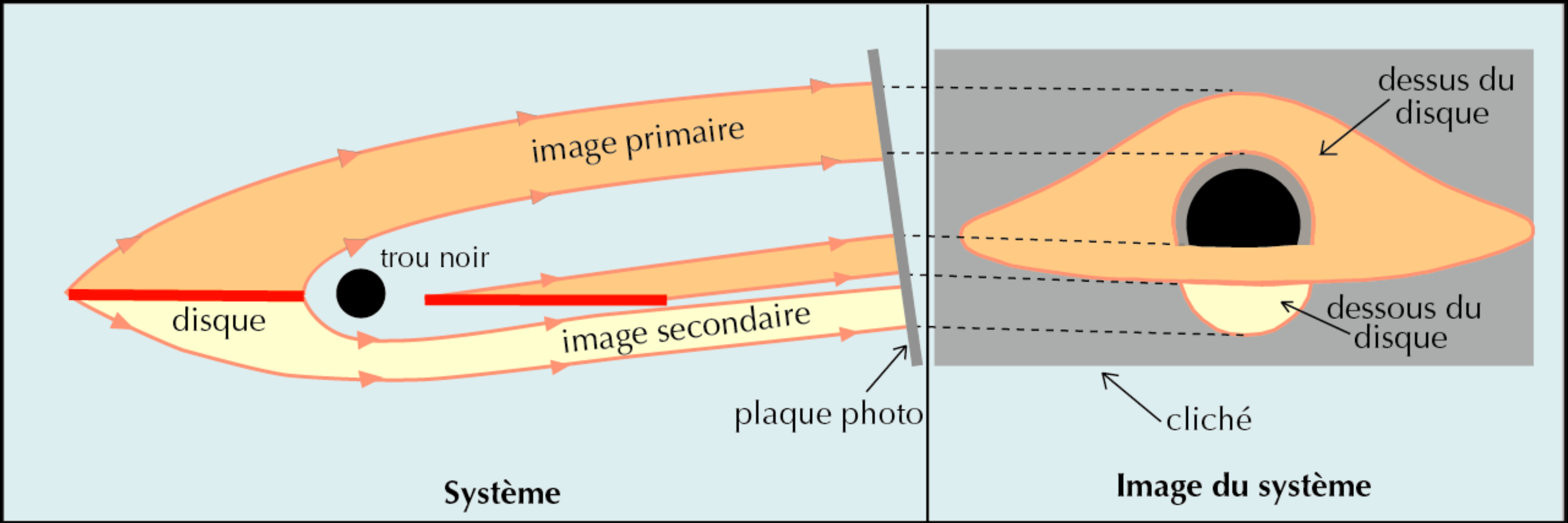
➔ *Destruction de naines blanches par des TNMI…*

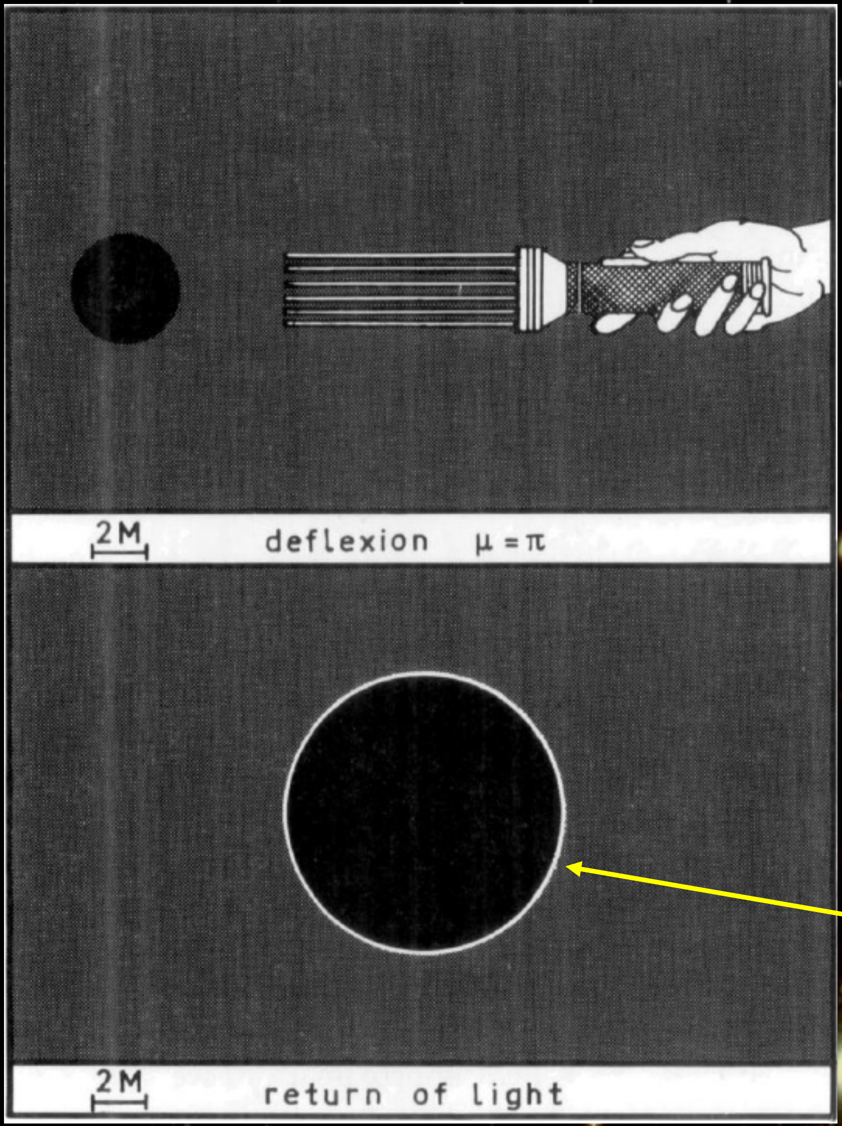
De l’ordinateur au télescope

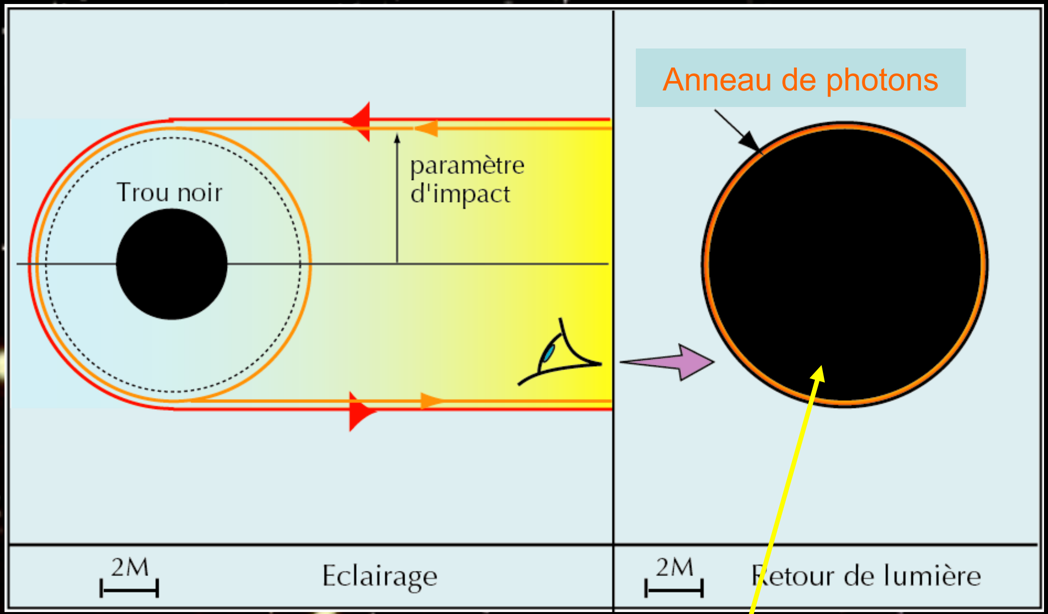
Vues
« d’artiste » :
fausses!

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

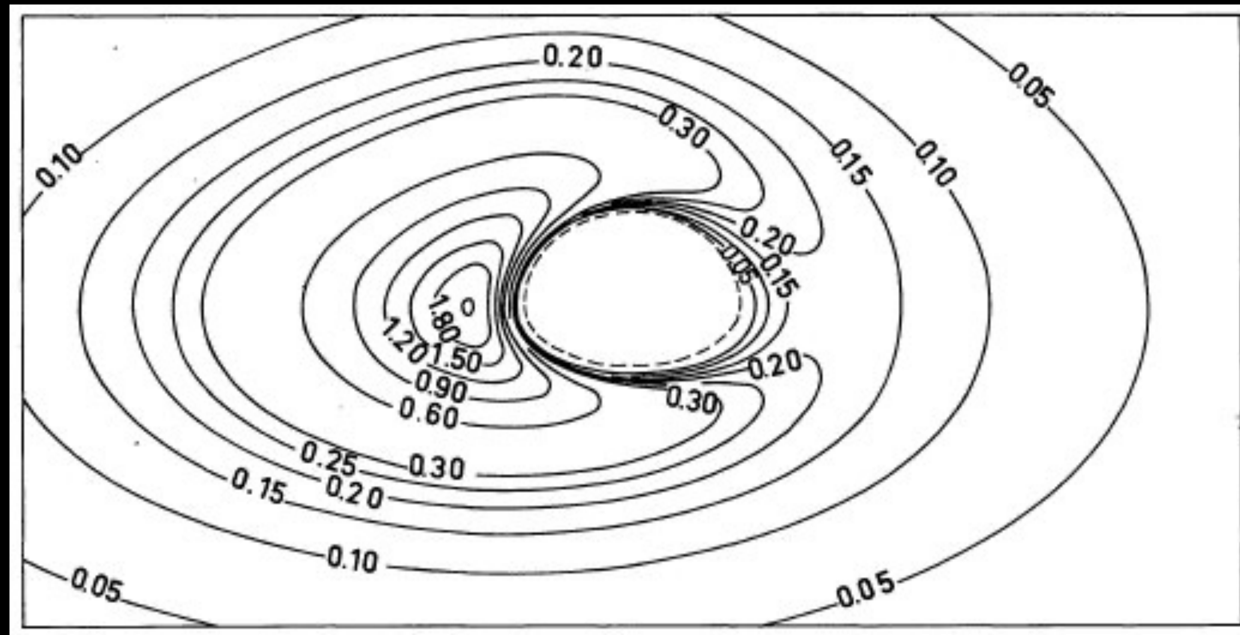
Etape 2 : Modèle relativiste de disque d'accrétion mince

Etape 3 : Décalages spectraux (Einstein, Doppler)

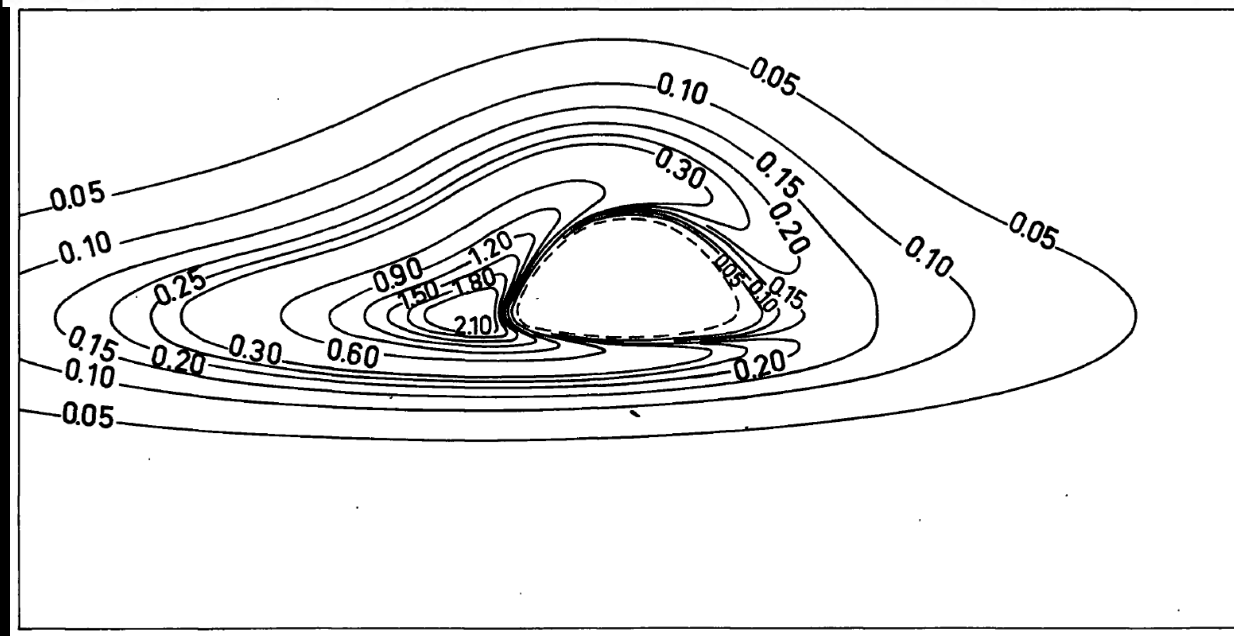
Etape 4 : Flux apparent (bolométrique)

Isophotes

Angle de vue équatorial 30°



Angle de vue équatorial 10°



Astron. Astrophys. 75, 228–235 (1979)

ASTRONOMY AND ASTROPHYSICS

Image of a Spherical Black Hole with Thin Accretion Disk

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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:

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

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:

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

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

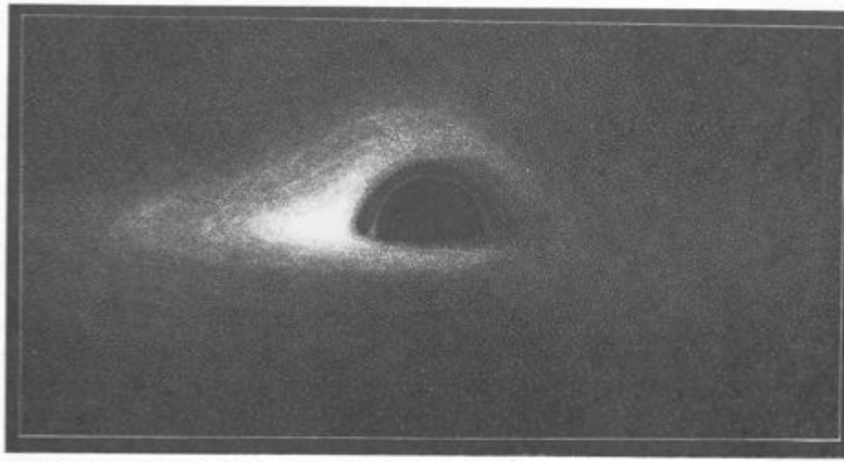


Fig. 11. Simulated photograph of a spherical black hole with thin accretion disk

impact parameter of the visible part of the 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.

References

Cunningham, C.T., Bardeen, J.M.: 1973, *Astrophys. J.* **183**, 237
Darwin, C.: 1959, *Proc. Roy. Soc. London* **A 249**, 180
Eardley, D.M., Press, W.H.: 1975, *Ann. Rev. of Astron. Astrophys.* **13**, 381
Ellis, G.F.R.: 1971, Relativistic Cosmology in *General Relativity and Cosmology*, ed. R. Sachs, Academic Press, New York
Gradshteyn, I.S., Ryzhik, I.W.: 1965, Table of Integral Series and Products, Academic Press, New York
Hagihara, Y.: 1931, *Japan. J. Astron. Geophys.* **8**, 67
Hills, J.G.: 1975, *Nature* **254**, 295
Lightman, A.P., Rees, M.J., Shapiro, S.L.: 1975, Accretion onto compact objects, Lectures at the Enrici Fermi School, Varenna, Italy, July 1975
Lynden-Bell, D.: 1969, *Nature* **223**, 690
Misner, C.W., Thorne, K.S., Wheeler, A.J.: 1973, Gravitation, Freeman, San Francisco
Novikov, I.D., Thorne, K.S.: 1973, in *Black Holes*, Les Houches, ed. DeWitt and DeWitt, Gordon and Breach, New York
Page, D.N., Thorne, K.S.: 1974, *Astrophys. J.* **191**, 499
Prendergast, K.H., Burbidge, G.R.: 1968, *Astrophys. J. Letters* **151**, L 83
Pringle, J.E., Rees, M.J.: 1972, *Astron. Astrophys.* **21**, 1
Pineault, S., Roeder, R.C.: 1977, *Astrophys. J.* **212**, 541
Shakura, N.I., Sunyaev, R.A.: 1973, *Astron. Astrophys.* **24**, 337
Sanchez, N.: 1977, Phys. Rev. **D16**, 937; 1978, to appear
Young, P.J., Westphal, J.A., Kristian, J., Wilson, C.P., Landauer, F.P.: 1978, *Astrophys. J.* **221**, 721

The Final Picture

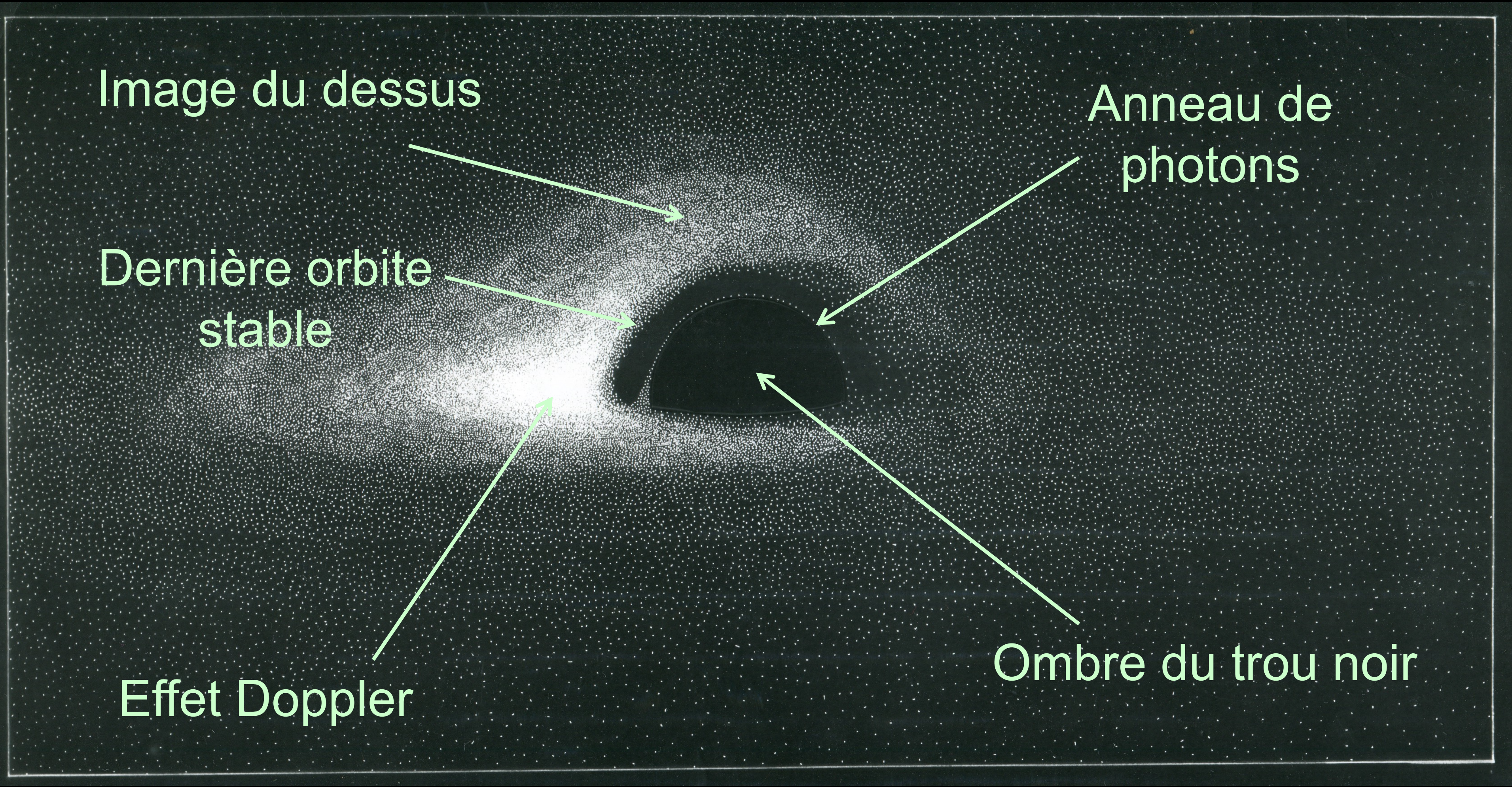
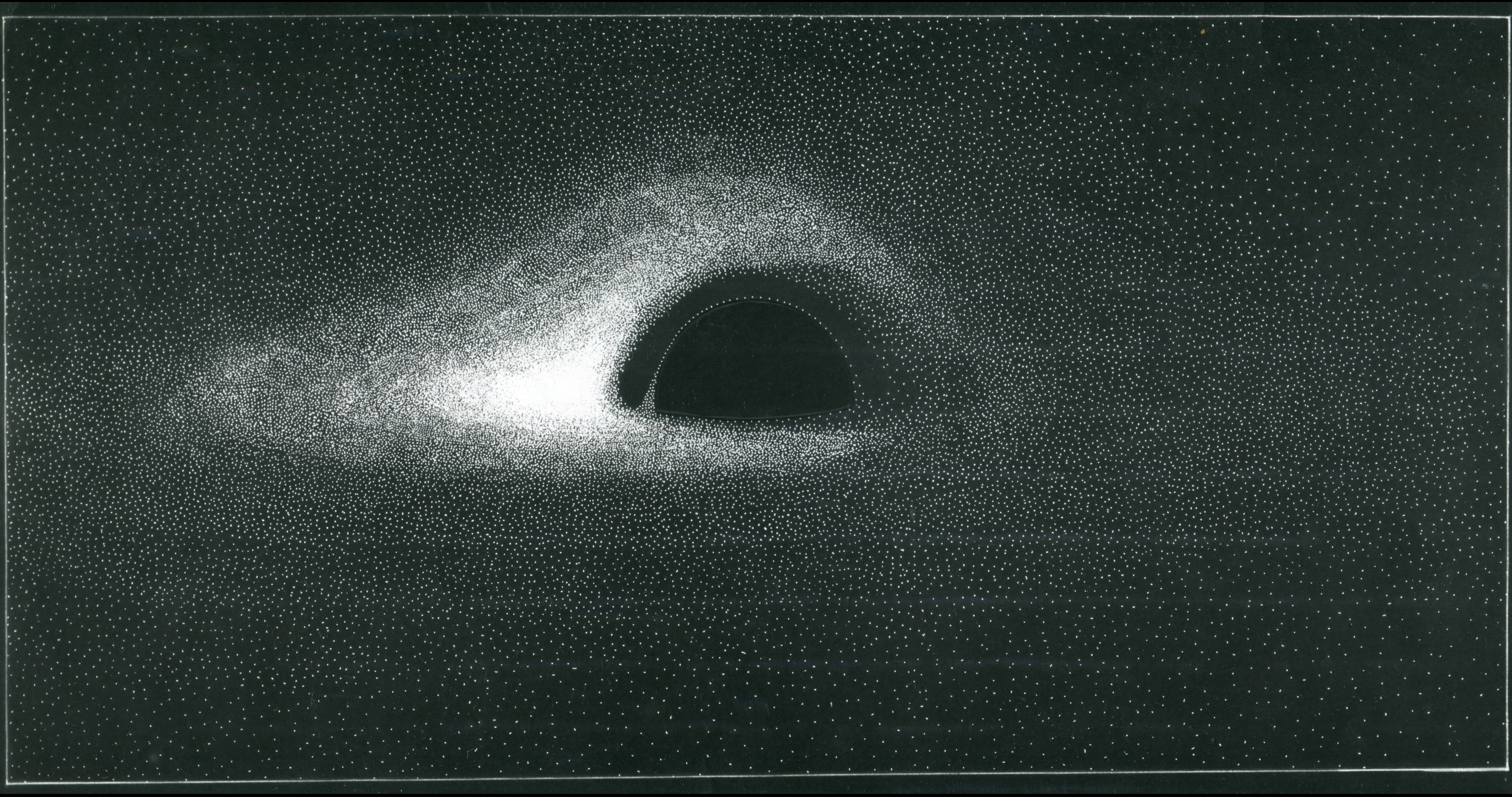


Image of a spherical black hole with thin accretion disk

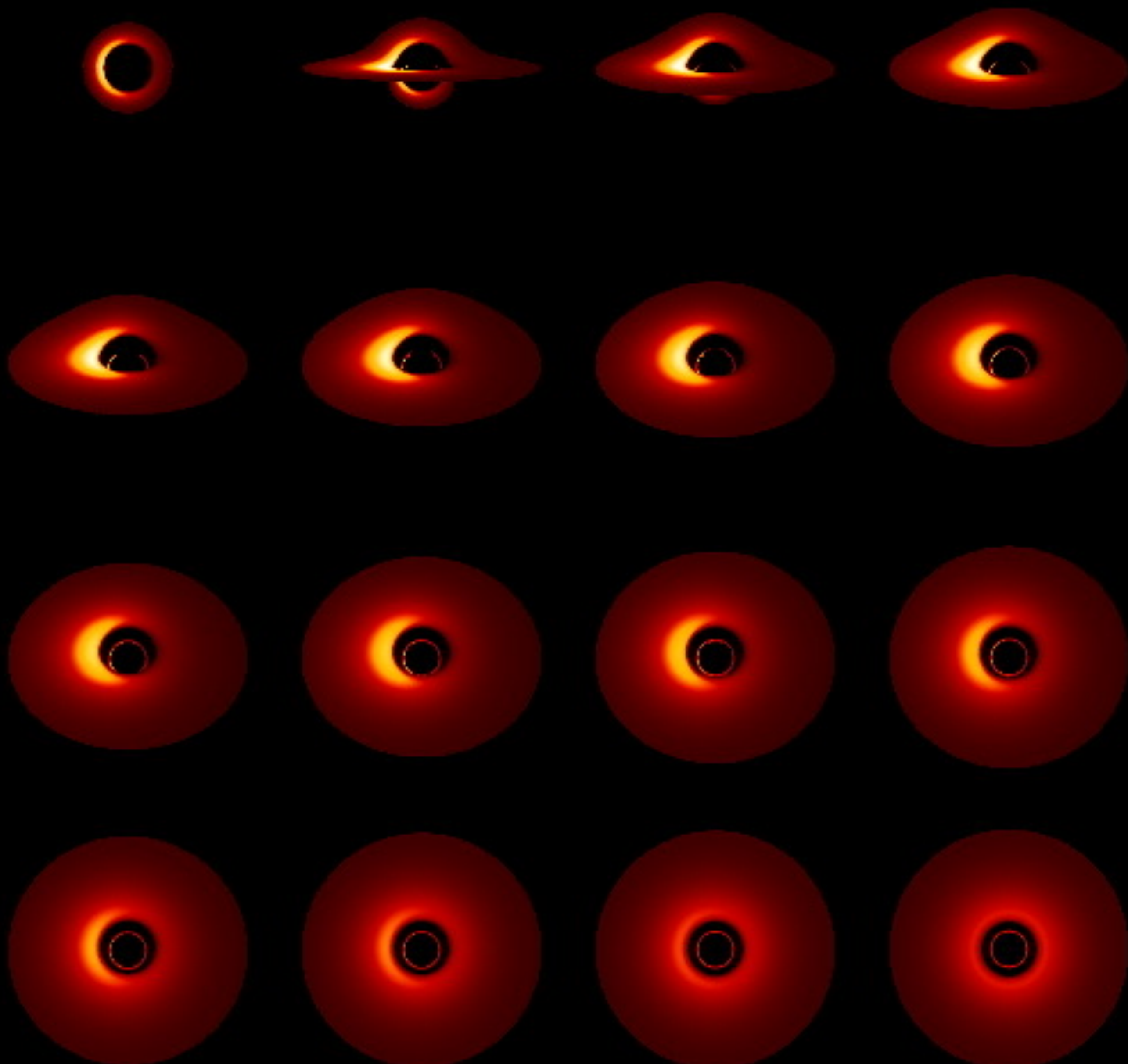
J.-P. Luminet, Astron.Astrophys. **75**, 228 (1979)

A la main!



Nerval !

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

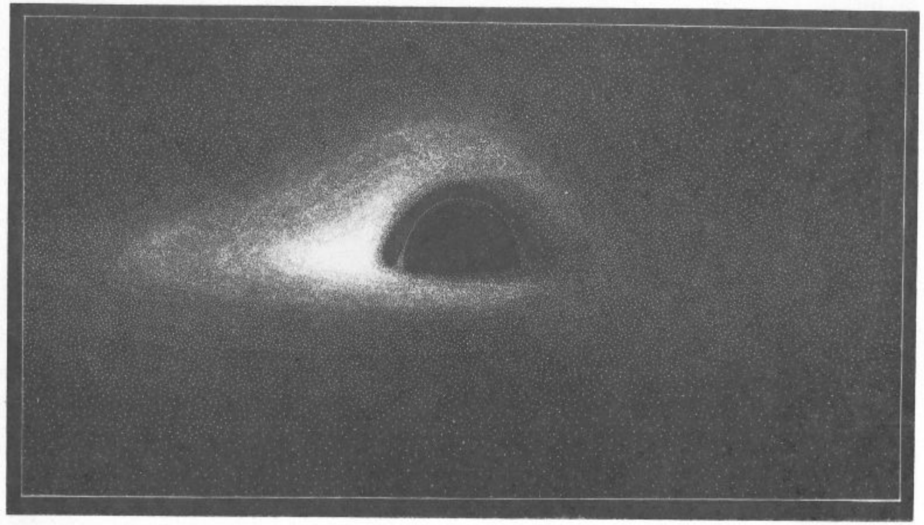


0°- 18°

24°- 42°

48°- 66°

72°- 90°



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Le Trou noir Galactique SgrA*

Masse = 4.10^6 M_S
Diamètre = 25 millions Km

Le Trou noir M87*

Masse = 6.10^9 M_S
Diamètre = 40 milliards Km

D_{app} ~ 35 μarcsec

- Résolution angulaire d'un télescope :

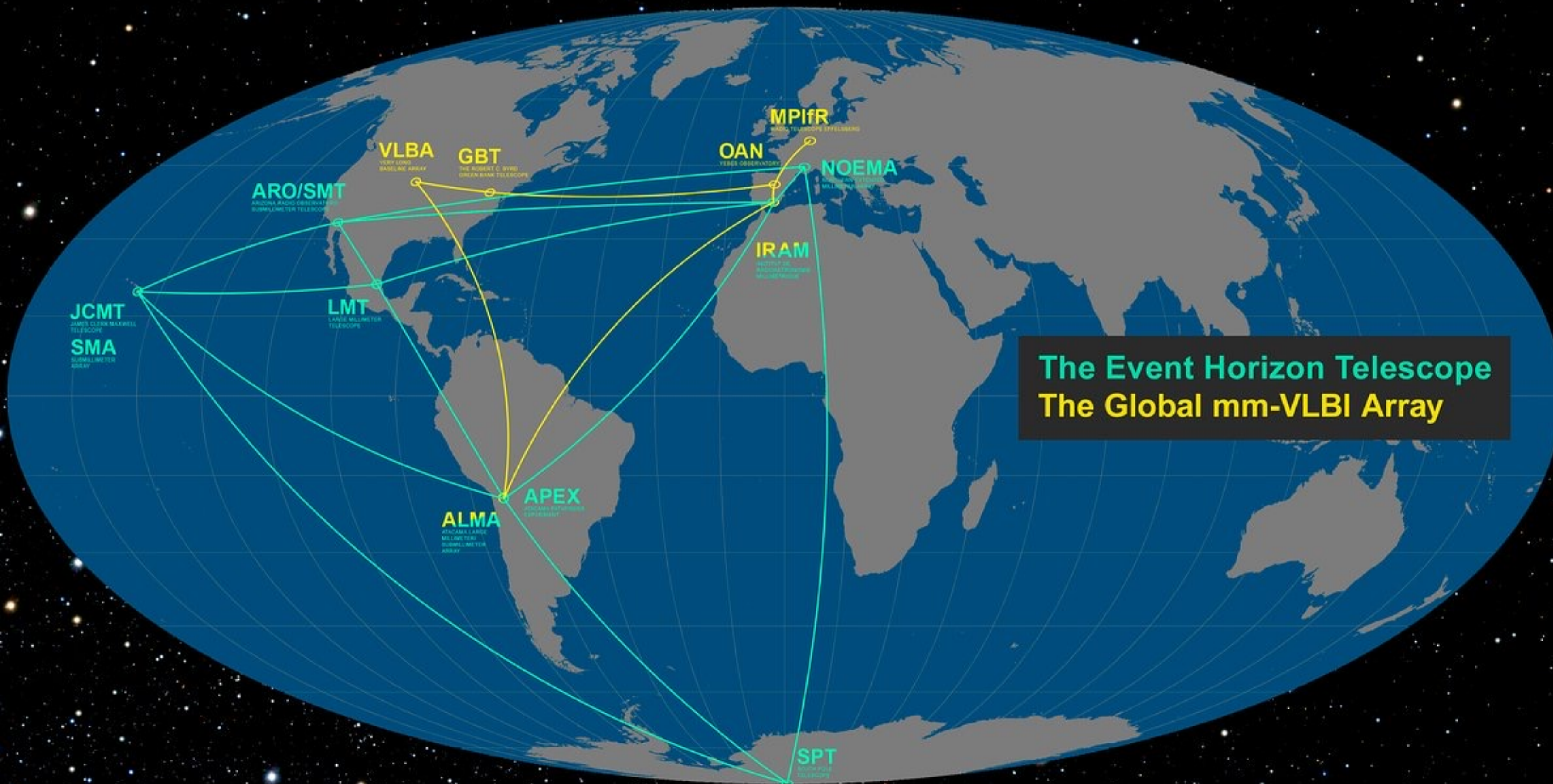
- *proportionnelle à l'ouverture*
- *inversement proportionnelle à la longueur d'onde*

  - 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)

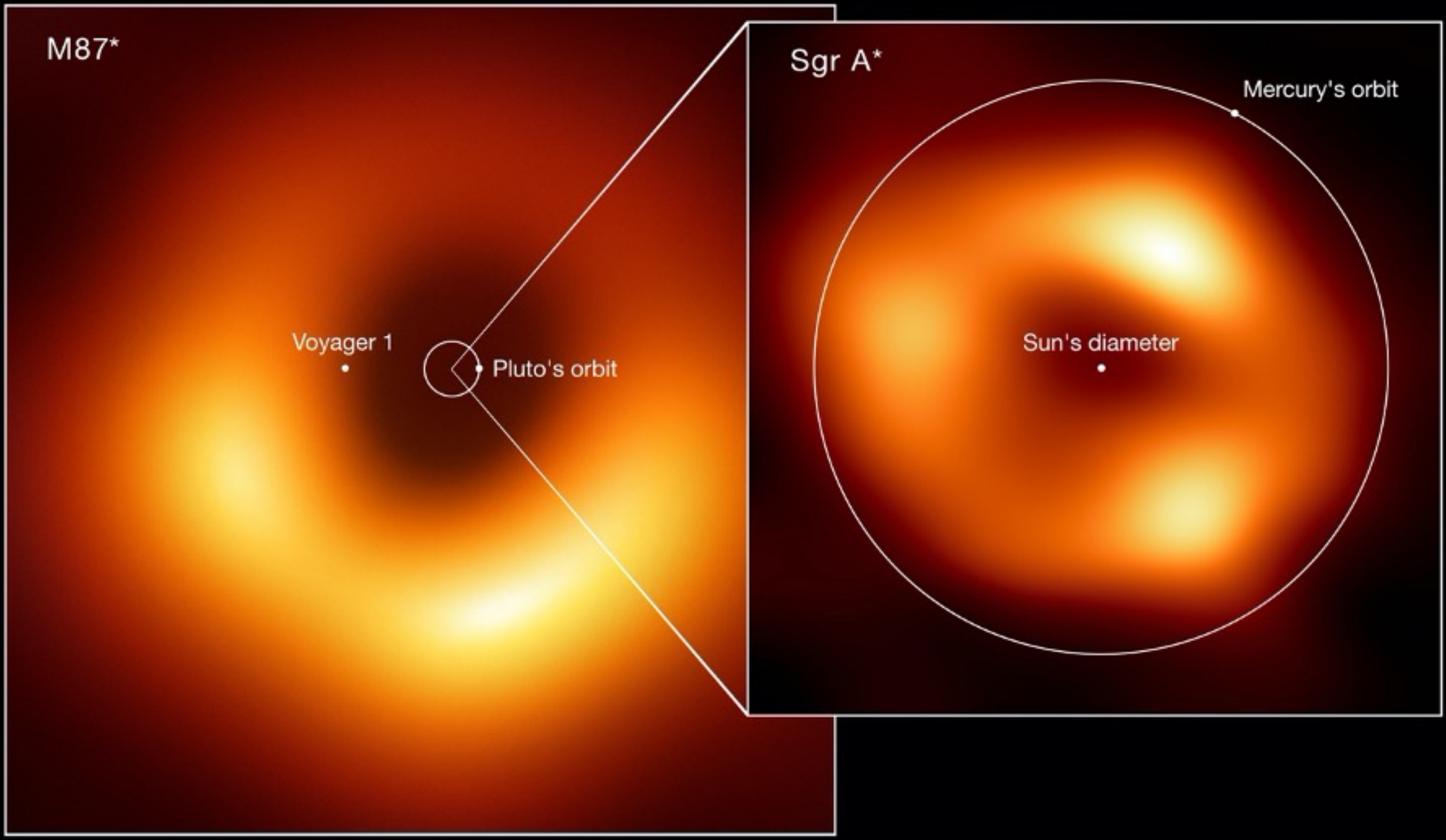


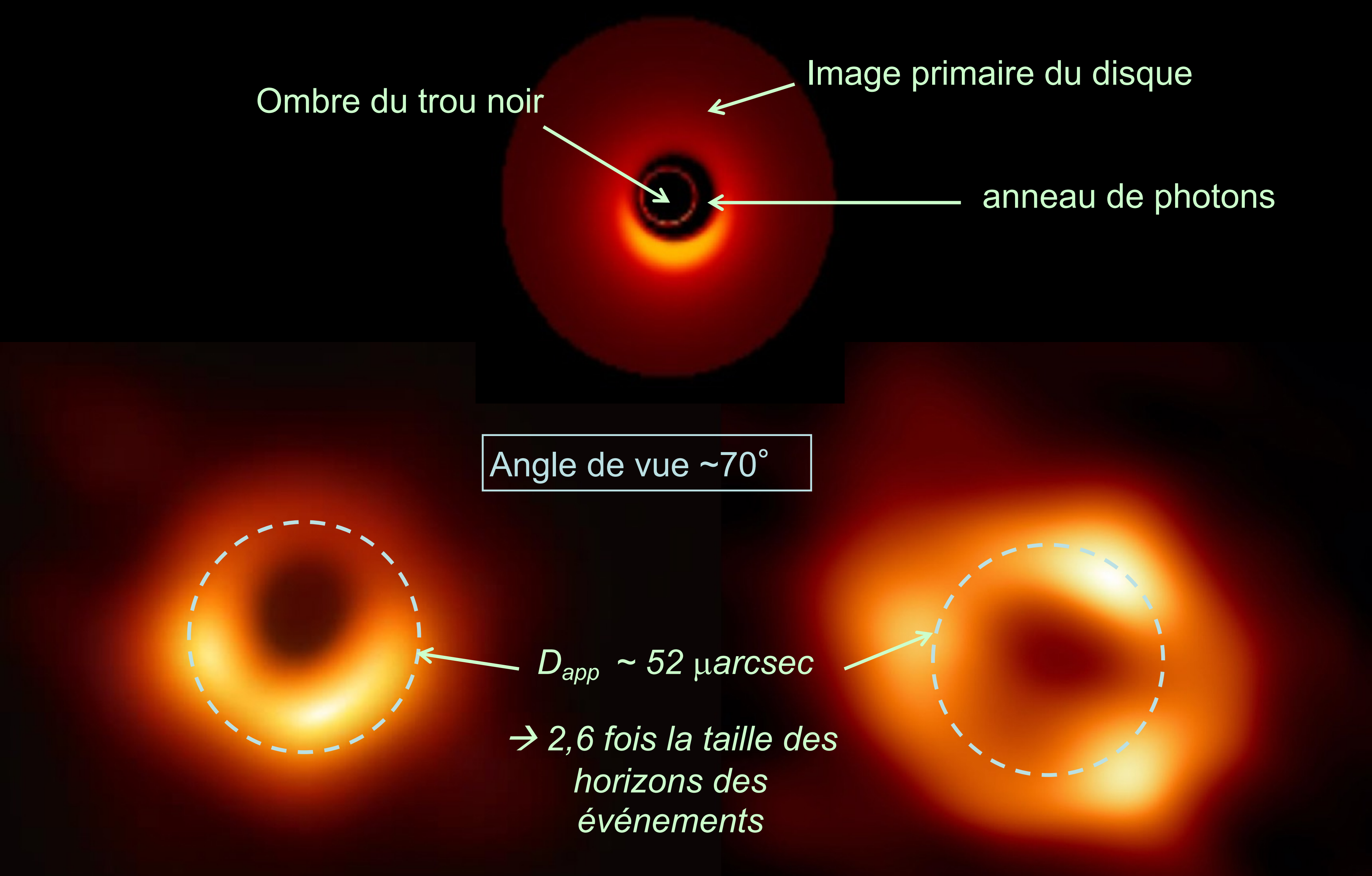
VLBI Résolution : 25 μarcsec

Premières 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



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

- **ALMA** — Atacama Large Millimeter/submillimeter Array — CHAJNANTOR PLATEAU, CHILE
- **APEX** — Atacama Pathfinder EXperiment — CHAJNANTOR PLATEAU, CHILE
- **30-M** — IRAM 30-M Telescope — PICO VELETA, SPAIN
- **JCMT** — James Clerk Maxwell Telescope — MAUNAKEA, HAWAII
- **LMT** — Large Millimeter Telescope — SIERRA NEGRA, MEXICO
- **SMA** — Submillimeter Array — MAUNAKEA, HAWAII
- **SMT** — Submillimeter Telescope — MOUNT GRAHAM, ARIZONA
- **SPT** — South Pole Telescope — SOUTH POLE STATION
- **GLT** — The Greenland Telescope — THULE AIR BASE, GREENLAND, DENMARK

Observing in 2020

- **Kitt Peak** — Kitt Peak 12-meter Telescope — KITT PEAK, ARIZONA, USA
- **NOEMA** — NOEMA Observatory — PLATEAU DE BURE, FRANCE

Merci !