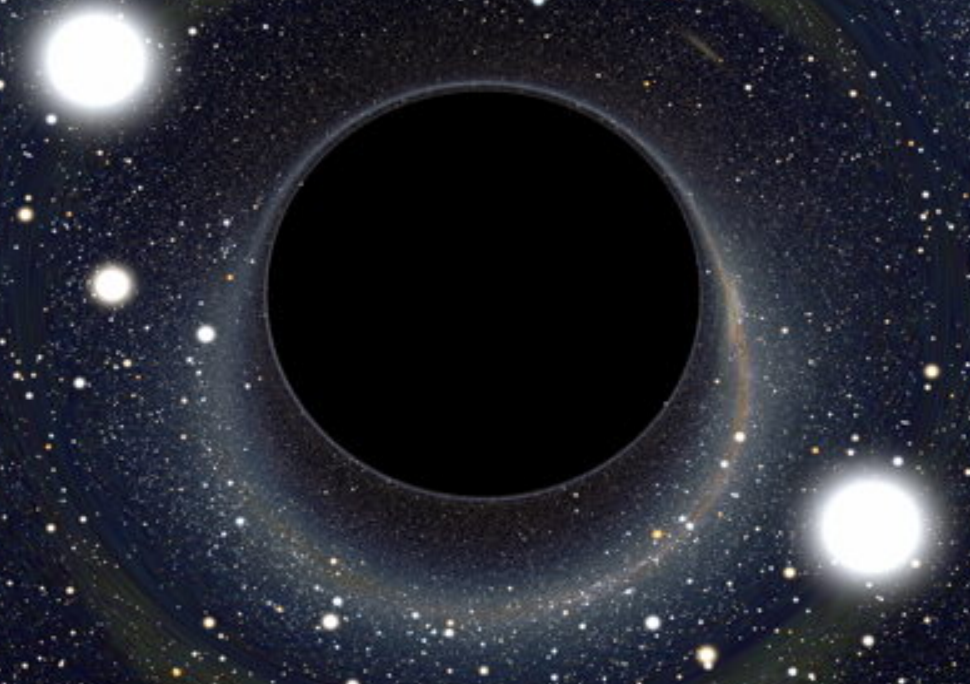
Carter's Inspirations :

from BKL conjecture to stellar pancakes

Personal Memories1975-1986



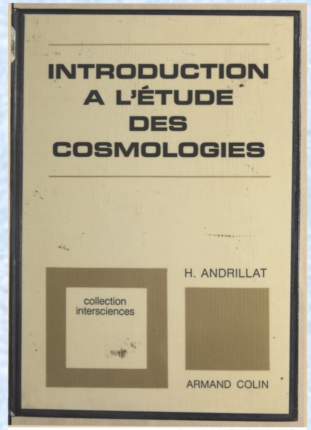
Jean-Pierre Luminet

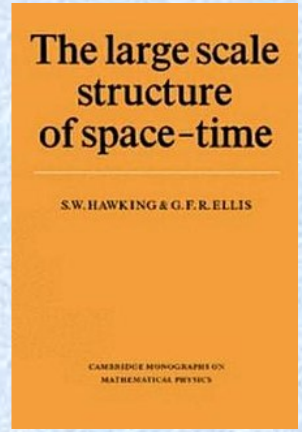
Laboratoire d'Astrophysique de Marseille

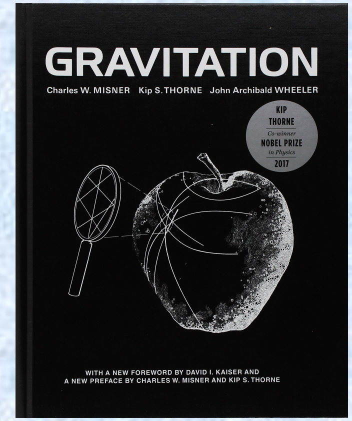
Cartet's Fest, Paris 2022


BKL Singularities

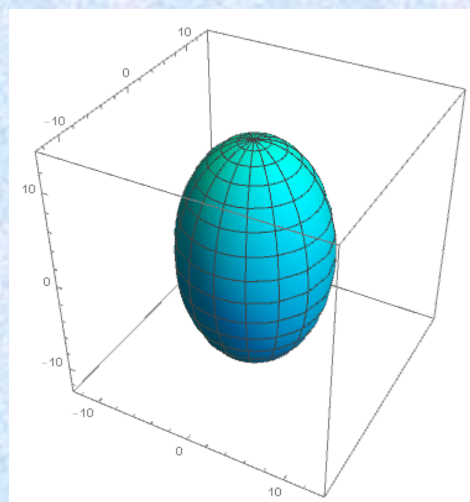
Prof. Henri Andrillat





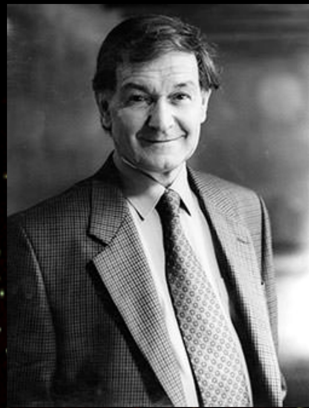


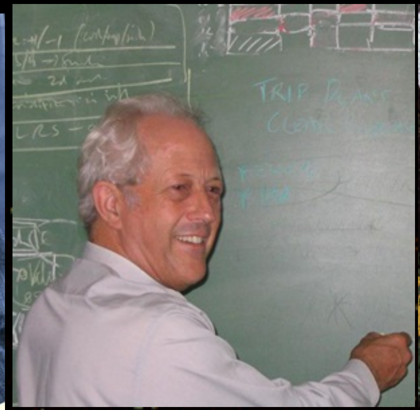
June 1975



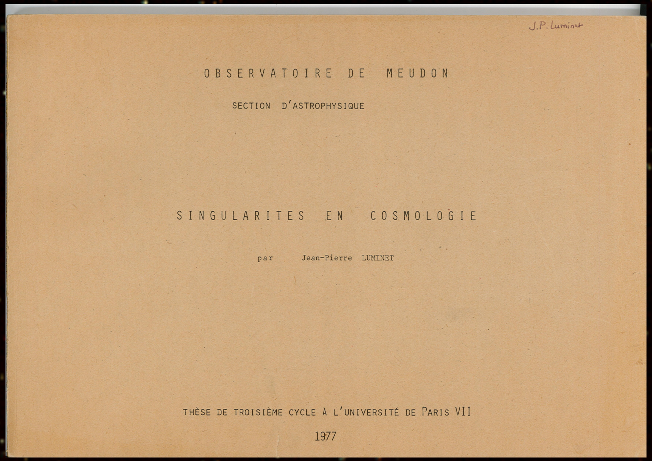
BKL conjecture

Meudon Observatory





D.A.M.T.P.



J.P. Luminet

OBSERVATOIRE DE MEUDON

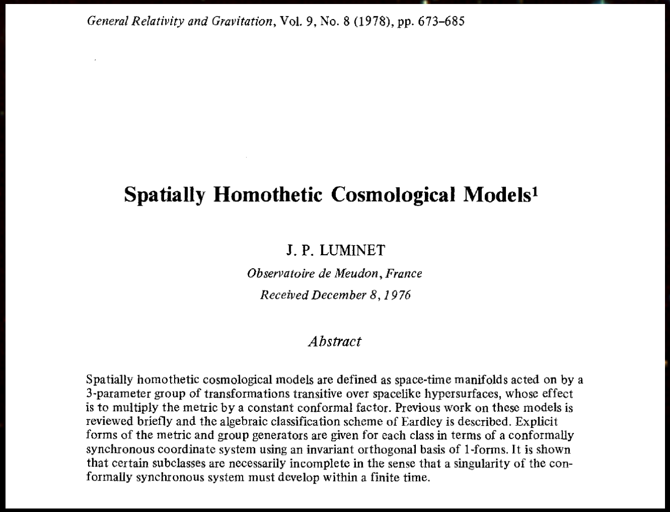
SECTION D'ASTROPHYSIQUE

SINGULARITES EN COSMOLOGIE

par Jean-Pierre LUMINET

THÈSE DE TROISIÈME CYCLE À L'UNIVERSITÉ DE PARIS VII

1977



General Relativity and Gravitation, Vol. 9, No. 8 (1978), pp. 673–685

Spatially Homothetic Cosmological Models[1]

J. P. LUMINET

Observatoire de Meudon, France

Received December 8, 1976

Abstract

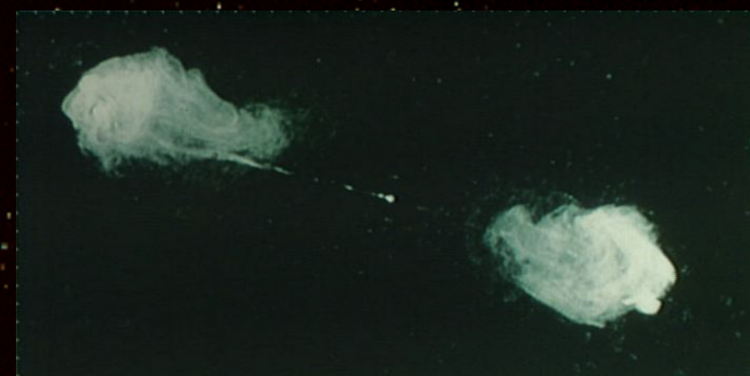
Spatially homothetic cosmological models are defined as space-time manifolds acted on by a 3-parameter group of transformations transitive over spacelike hypersurfaces, whose effect is to multiply the metric by a constant conformal factor. Previous work on these models is reviewed briefly and the algebraic classification scheme of Eardley is described. Explicit forms of the metric and group generators are given for each class in terms of a conformally synchronous coordinate system using an invariant orthogonal basis of 1-forms. It is shown that certain subclasses are necessarily incomplete in the sense that a singularity of the conformally synchronous system must develop within a finite time.


Seeing Black Holes…

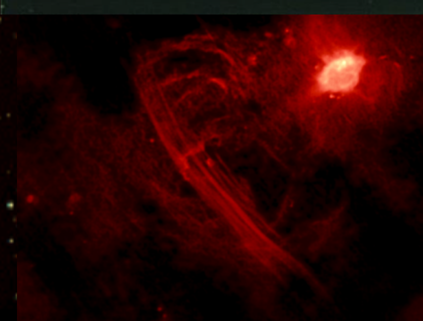
In the 1970's, only very indirect evidence for black hole existence

- Binary X-ray sources for stellar mass BH (Uhuru, 1971)

- Energetic considerations for quasars and AGN (Lynden-Bell & Rees, 1971)



- Compact radio source SgrA* for massive BH (Balick et al., 1974)



Astron. Astrophys. 75, 228–235 (1979)

ASTRONOMY AND ASTROPHYSICS

Image of a Spherical Black Hole with Thin Accretion Disk

J.-P. Luminet

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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:

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

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 ... and on its angular mom... $L/E = b$, which is the im...

Let the observer be ... in the Schwarzschild m... by a distant source of lig... the observer's detector ...

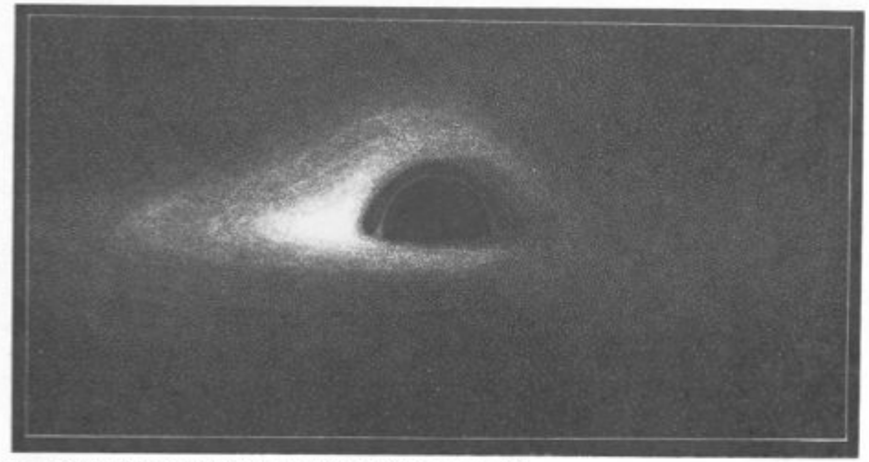

Fig. 11. Simulated photograph of a spherical black hole with thin accretion disk

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

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Prendergast, K.H., Burbidge, G.R.: 1968, *Astrophys. J. Letters* **151**, L 83
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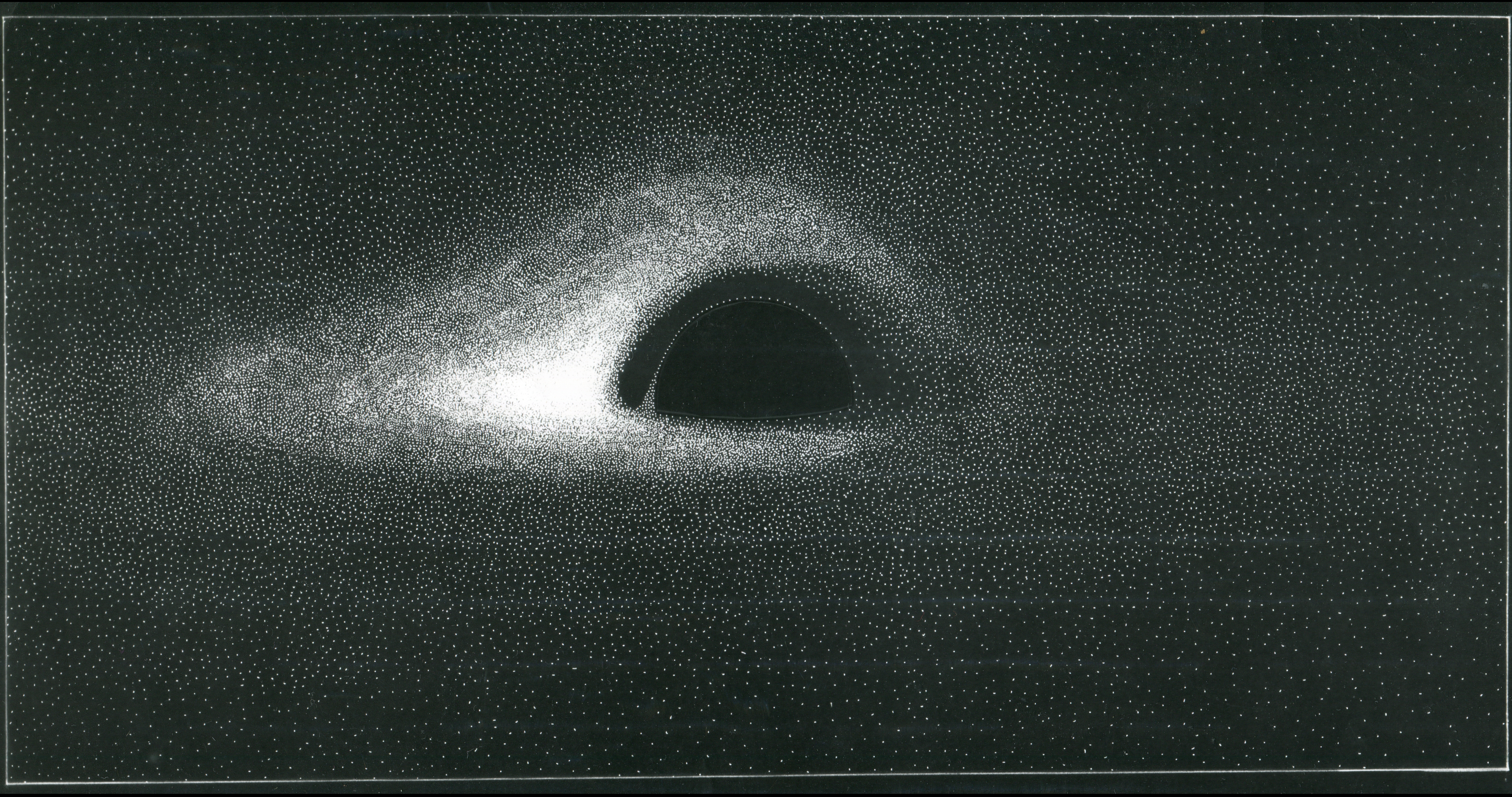
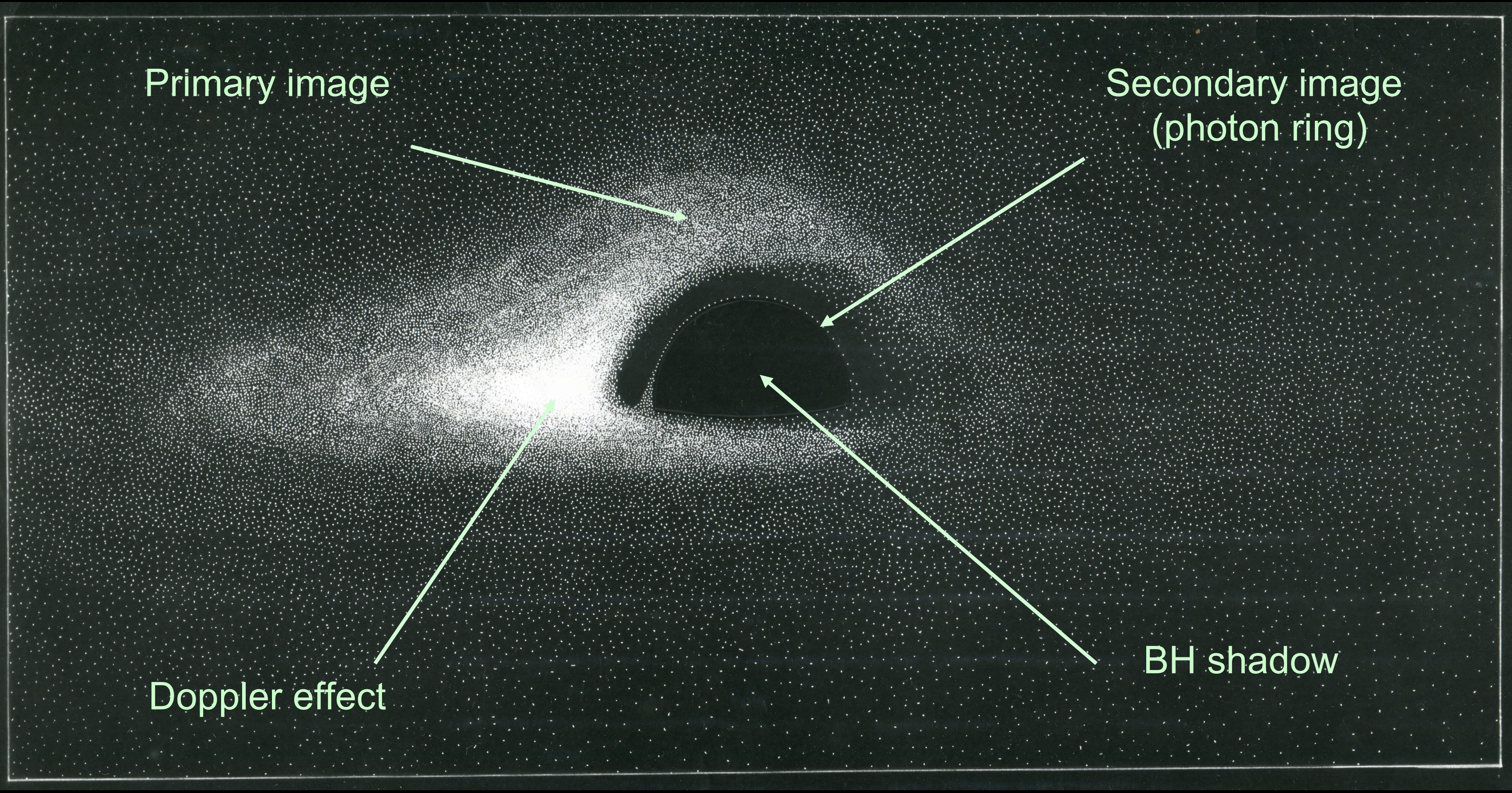
Image of a spherical black hole with thin accretion disk

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

The Final Picture



The Final Picture



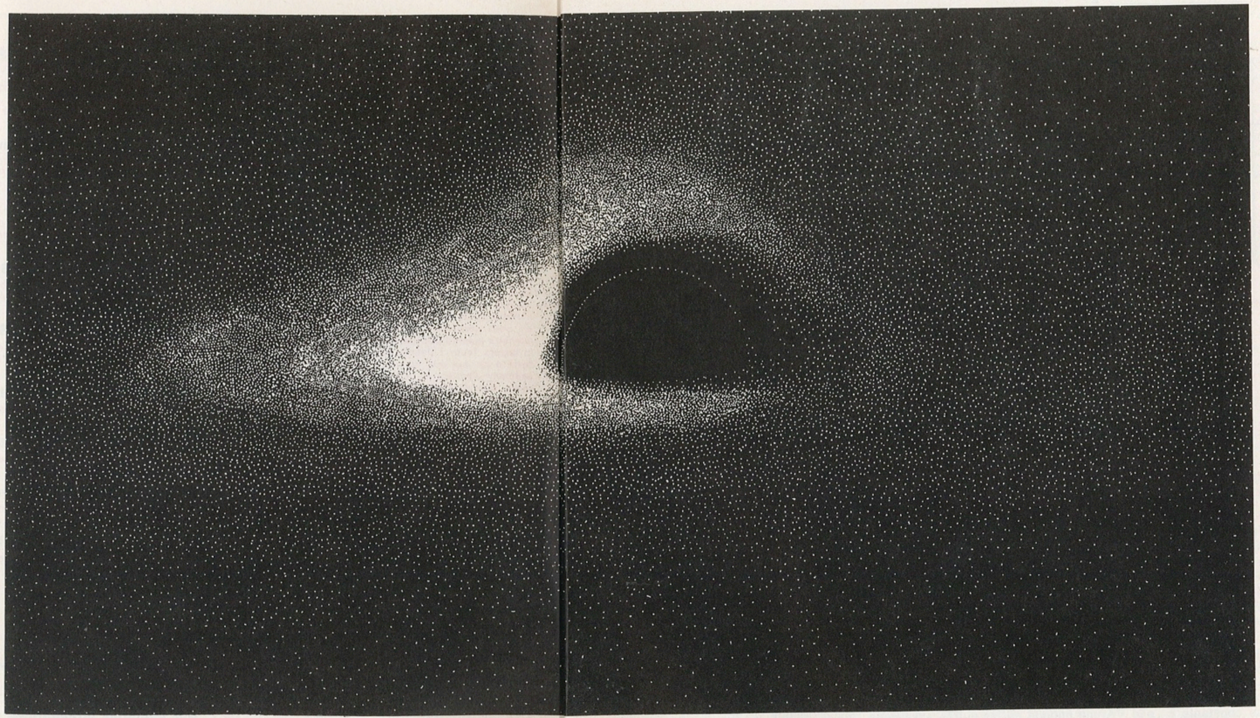
BOLOMETRIC (ALL WAVELENGTHS INTEGRATED)

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.



Apparence photographique réelle d'un trou noir sphérique entouré d'un disque d'accrétion mince, d'après les calculs de J.P. Luminet. [4]
Comme dans la figure précédente, on suppose que le trou noir est vu de loin dans une direction inclinée de 10° au-dessus du plan équatorial. On notera que la moitié seulement de l'image secondaire est visible au-dessus du trou noir, l'autre moitié étant cachée par l'image primaire (le disque étant opaque). Selon D.N. Page et K.S. Thorne, [7] l'intensité relative intrinsèque du rayonnement émis par le disque n'est fonction que de la distance r au trou noir (avec un maximum vers r = 10M), et les contours r = constante ont la forme indiquée sur la figure 7. Mais l'intensité apparente du disque est très modifiée par rapport à l'intensité intrinsèque en raison des effets de décalage des fréquences : « vers le rouge » en cas de ralentissement, « vers le bleu » dans le cas contraire. Comme Einstein l'avait déjà remarqué, le champ gravitationnel en tant que tel donne toujours lieu à un ralentissement (« décalage vers le rouge gravitationnel »), mais dans notre cas il faut ajouter un effet Doppler, dû à la vitesse de rotation extrêmement grande des parties intérieures du disque. C'est la superposition de ces deux effets qui donne l'apparence dissymétrique à l'image. Le sens de rotation du disque a été choisi de telle sorte que la matière s'approche dans la direction d'observation dans la partie gauche de l'image et s'en éloigne dans la partie droite. Lorsque la matière s'éloigne, le ralentissement Doppler s'ajoute au ralentissement gravitationnel, ce qui explique le très fort affaiblissement dans la partie droite. Par contre, dans la partie gauche, les deux effets tendent à s'annuler, ce qui permet à l'image de garder à peu près son intensité intrinsèque.

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Luminet
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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 totalement invisible, puisque les rayons lumineux eux-mêmes ne pourraient pas s'en échapper ! Un tel astre obscur, appelé cent cinquante ans plus tard *trou noir*, serait nécessairement confiné à l'intérieur d'un rayon critique donné par $R_c = 2GM/c^2$.

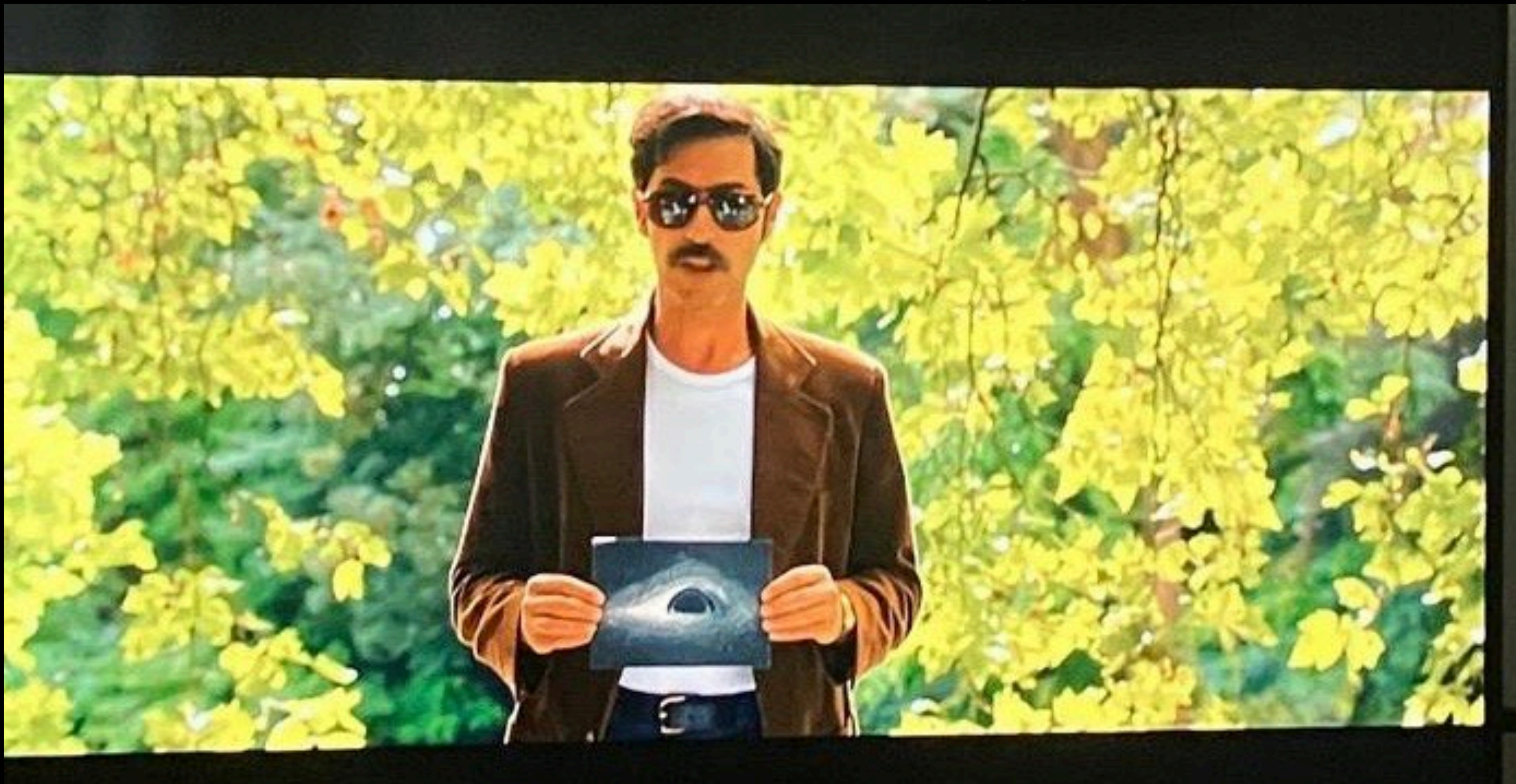
Comment Einstein réhabilita Laplace.

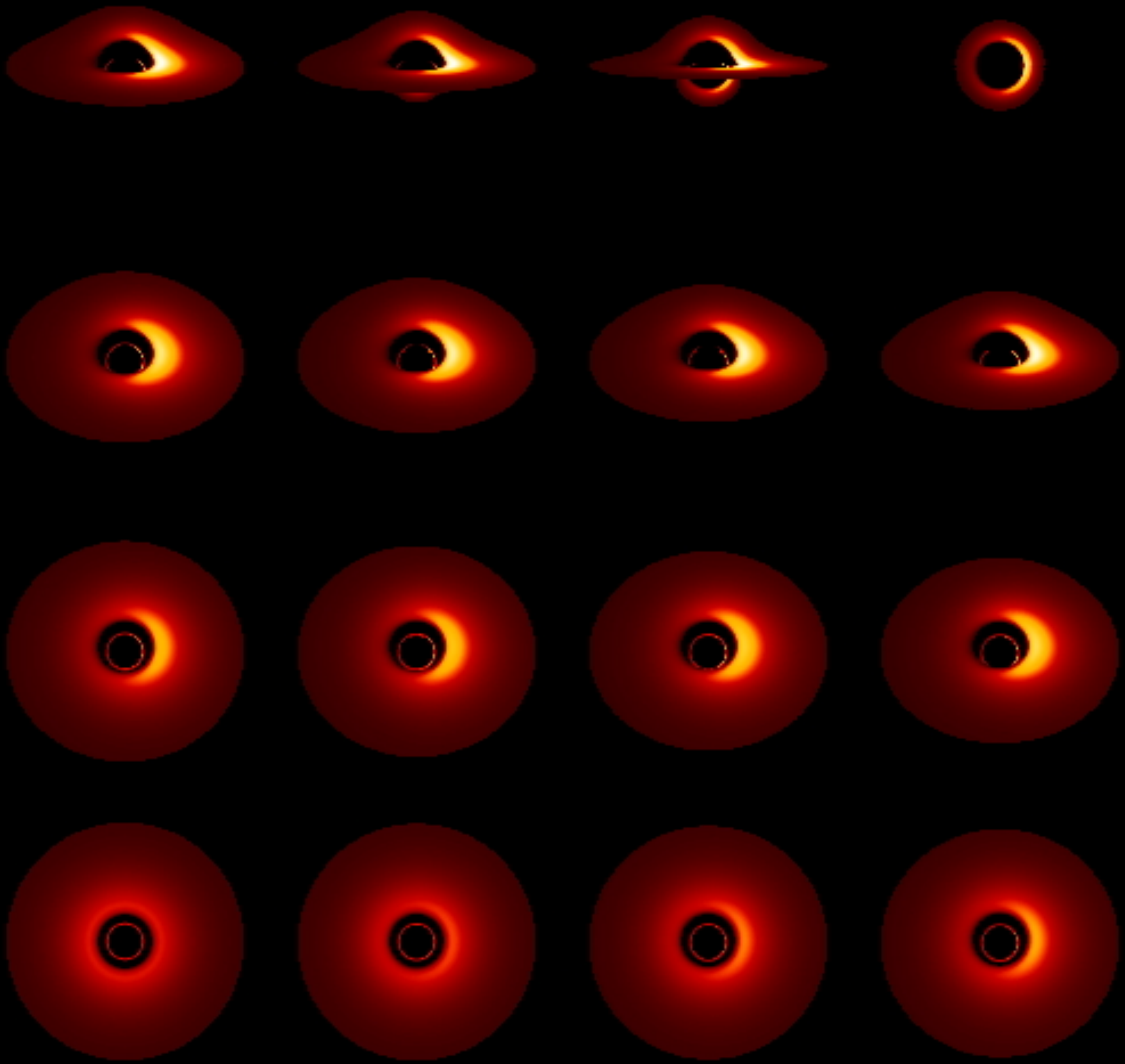
Les spéculations de Laplace étaient beaucoup trop en avance sur leur temps pour être prises au sérieux par ses contemporains. Tout au long du XIX^e^ siècle, la théorie *ondulatoire* de la lumière se développa tant et si bien que la possibilité que la lumière pût être influencée par la gravitation, comme la matière ordinaire, ne fut même pas envisagée. Il fallut attendre Einstein pour qu'à l'aube du XX^e^ siècle, les principes entrevus prophétiquement par Laplace soient à nouveau projetés dans le champ des spéculations de la physique théorique et expérimentale.

Déjà, Max Planck avait émis l'idée révolutionnaire selon laquelle les ondes électromagnétiques (et la lumière en particulier) ne pouvaient être rayonnées ou absorbées que sous forme de grains discrets appelés *quantas*, d'énergie $E = h\nu$ (où h est la constante de Planck et ν la fréquence de l'onde). Einstein fut le premier à développer cette idée jusque dans sa conclusion logique : ces « quantas » peuvent être assimilés à de véritables corpuscules — connus aujourd'hui sous le nom de *photons* — dont l'énergie est donnée précisément par la formule de Planck. Ce fut une étape clé dans la formulation moderne de la mécanique quantique, dans laquelle les théories corpusculaire et ondulatoire ne sont plus considérées comme étant exclusives l'une de l'autre, mais sont deux modes complémentaires permettant de visualiser un phénomène dont la nature duelle fondamentale ne peut se conceptualiser rigoureusement qu'au moyen de mathématiques très sophistiquées.

En même temps qu'il ressuscitait la théorie corpusculaire de la matière, Einstein proposait la célèbre théorie de la relativité restreinte, selon laquelle la vitesse de la lumière constitue une limite absolue qu'aucune particule physique ne peut franchir. Etant donné les accords remarquables entre cette théorie et toutes les expériences *locales* sur la propagation de la lumière, les physiciens de l'époque acceptèrent la relativité restreinte comme la théorie de base sur laquelle toutes les autres théories devaient s'ajuster. Or, Einstein lui-même n'était pas satisfait de sa propre théorie, percevant une inadéquation fondamentale entre le principe

French TV Series « OVNI(s) - 2022





J.A.Marck
1989
(unpublished)

Colored image of a Schwarschild black hole accretion disk with inclination angle 7° (Marck, 1991)

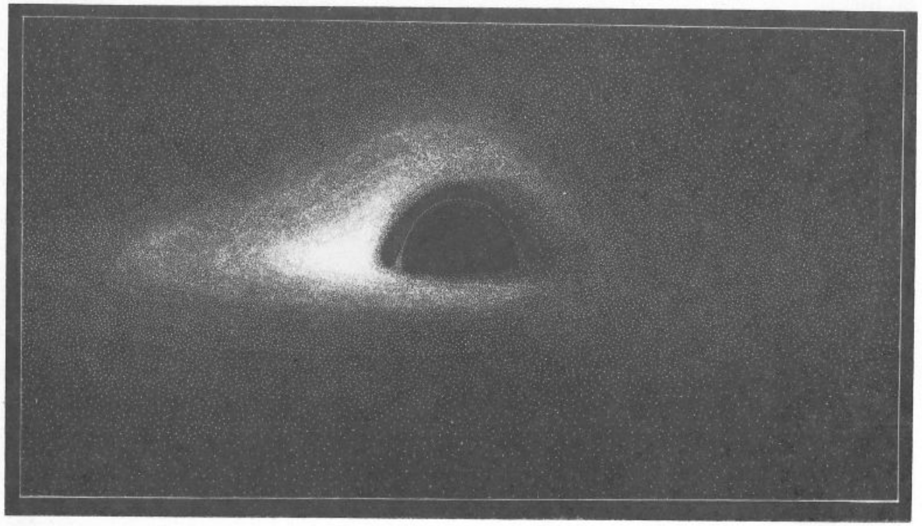


Fig. 11. Simulated photograph of a spherical black hole with thin accretion disk

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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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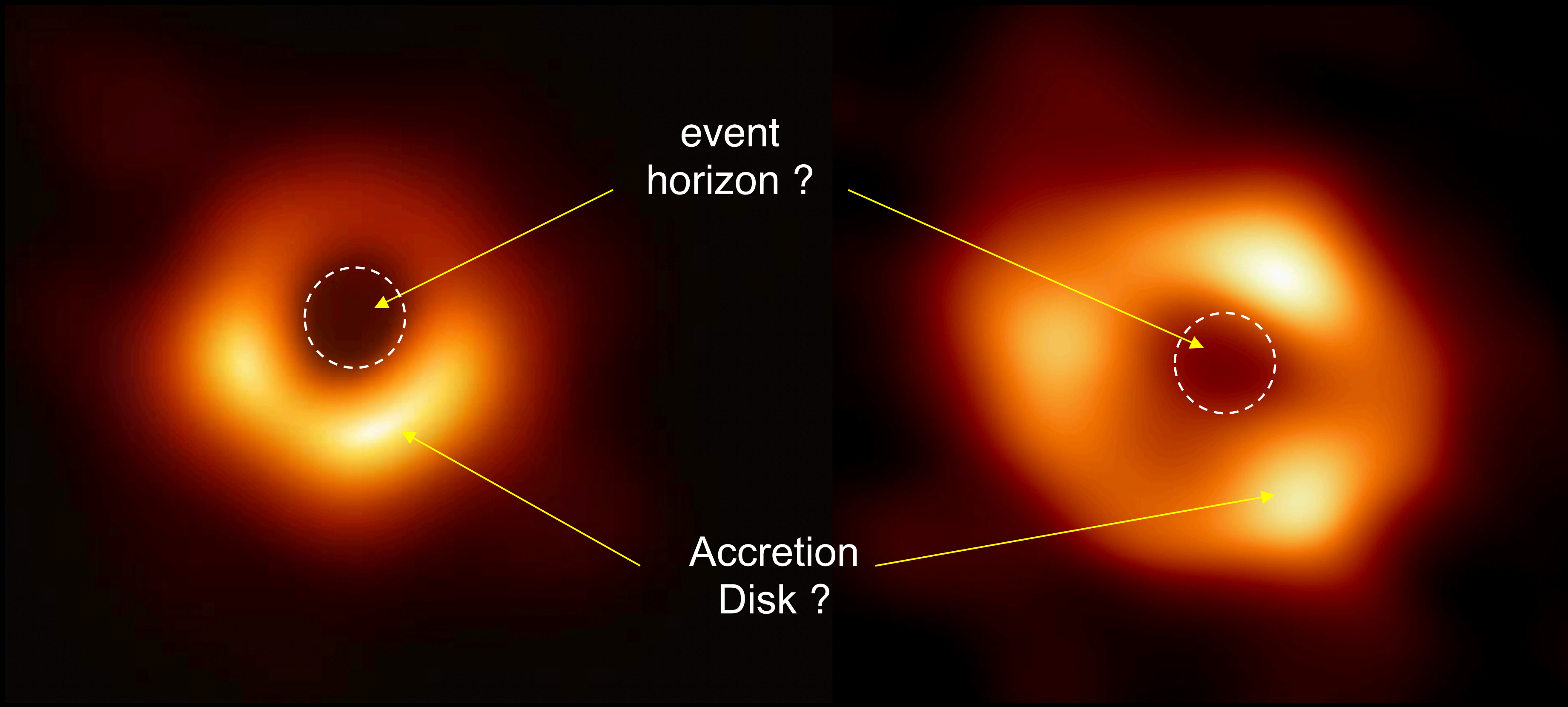
First telescopic images of supermassive black holes by the EHT

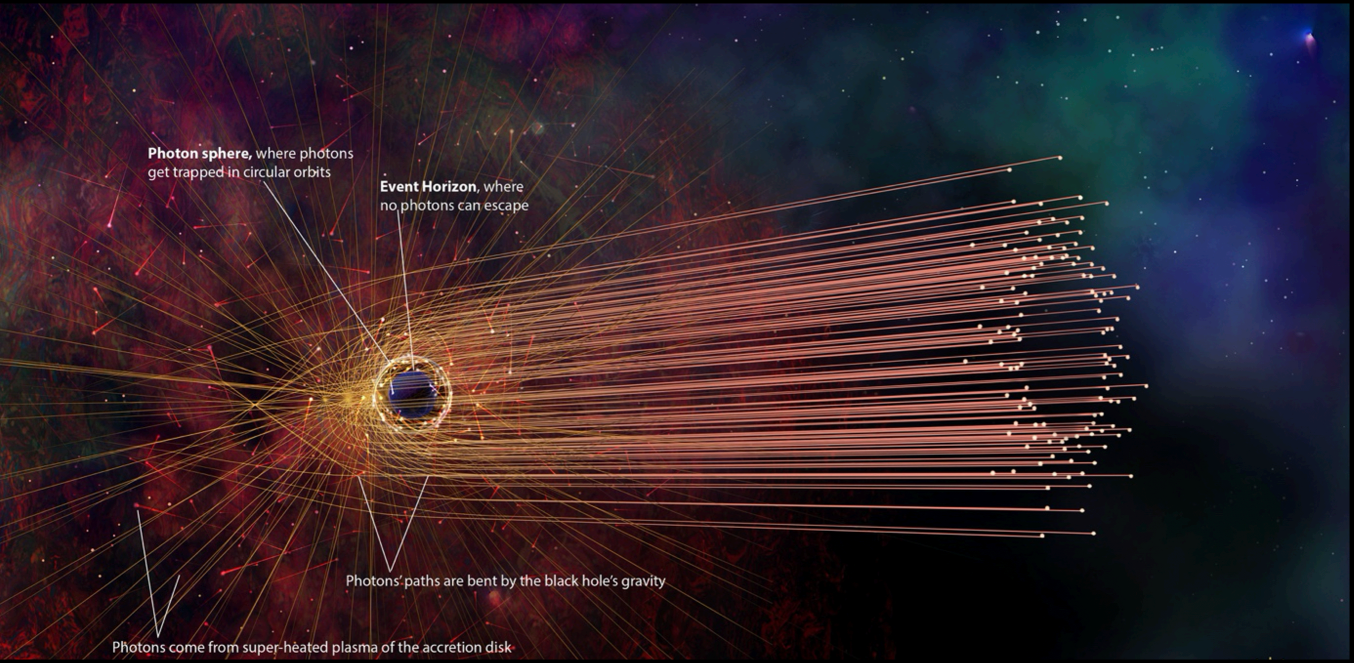


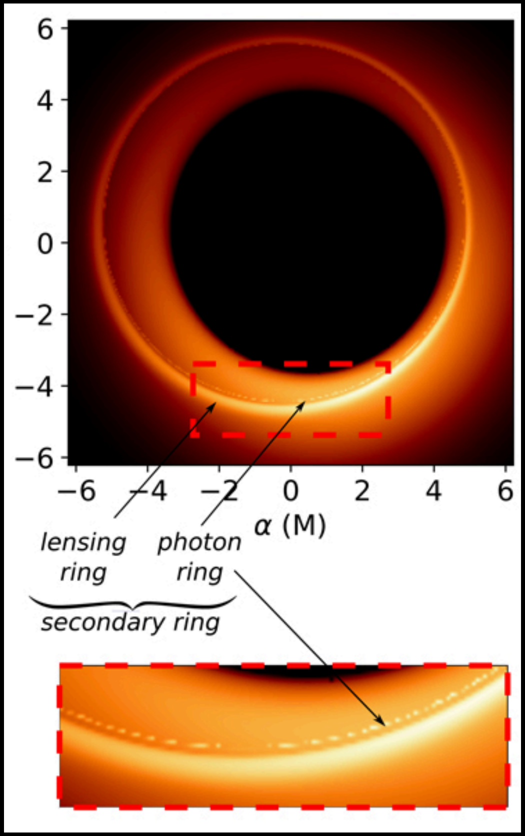
M87*: 10 april 2019

SgrA*: 12 may 2022

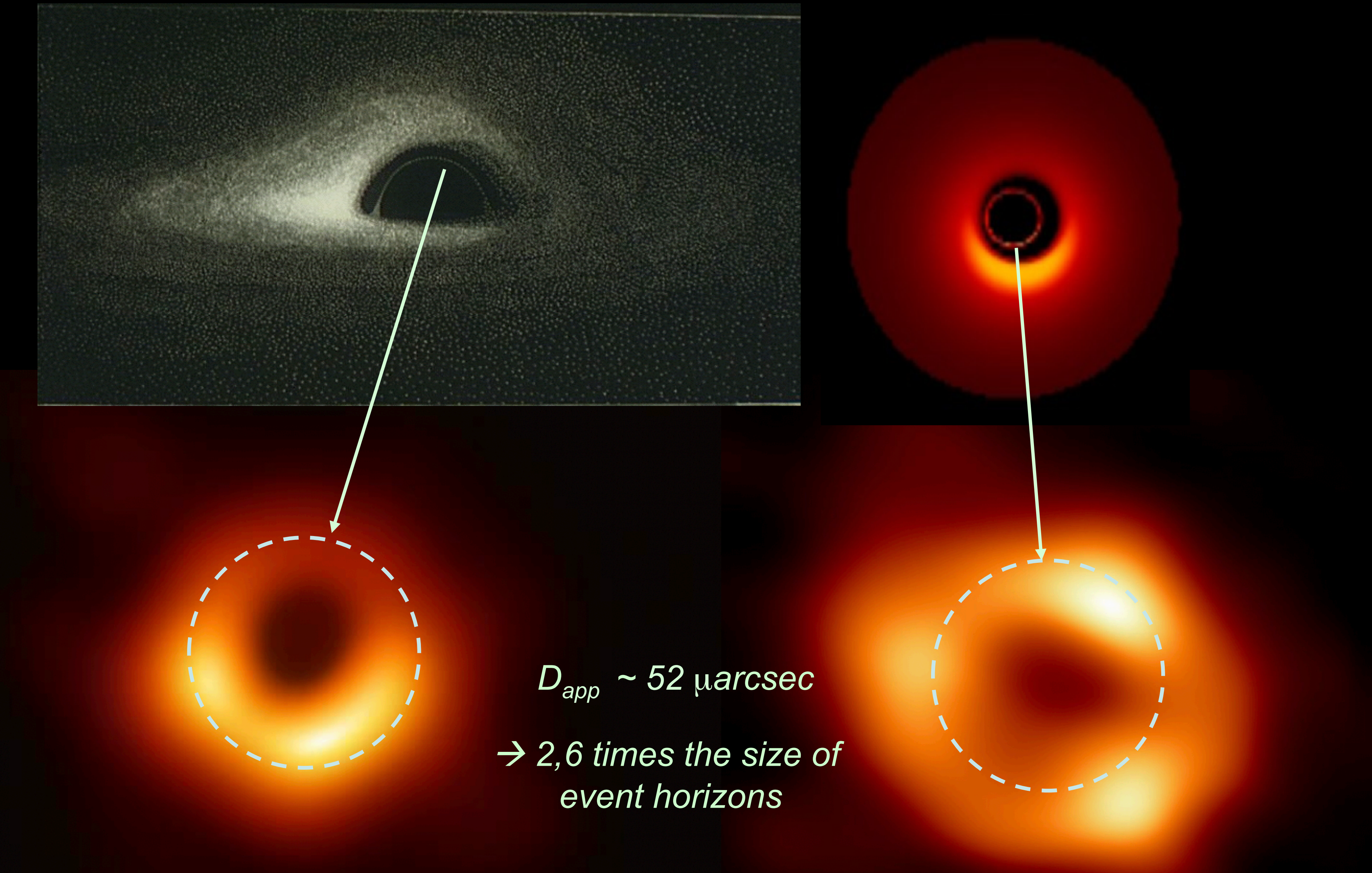
Caution…

EHT image is monochromatic (λ= 1.3 mm)
➔ At this wavelength the accretion disks emit little, the luminosity is dominated by the photon ring





F. Vincent, 2021



D_{app} ~ 52 μarcsec

→ *2,6 times the size of event horizons*

At EHT resolution, the photon ring appears as a thick ring instead of a thin one

Tidal Disruption Events…

Brandon Carter

From Wikipedia, the free encyclopedia

Brandon Carter, FRS (born 1942) is an Australian theoretical physicist, best known for his work on the properties of black holes and for being the first to name and employ the anthropic principle in its contemporary form. He is a researcher at the Meudon campus of the Laboratoire Univers et Théories, part of the CNRS.

Biography [edit]

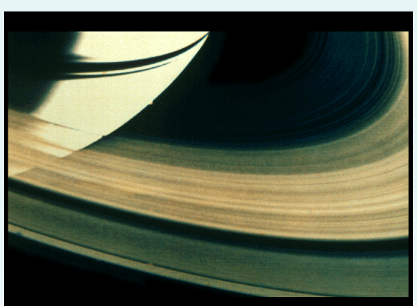
Carter studied at the University of Cambridge under Dennis Sciama. He found the exact solution of the geodesic equations for the Kerr/Newman electrovacuum solution, and the maximal analytic extension of this solution. In the process, he discovered the extraordinary *fourth constant of motion* and the Killing–Yano tensor. Together with Werner Israel and Stephen Hawking, he proved partially the no-hair theorem in general relativity, stating that all stationary black holes are completely characterized by mass, charge, and angular momentum. In 1982 with astrophysicist Jean-Pierre Luminet, he invented the concept of tidal disruption event (TDE), namely the destruction of a star passing in the vicinity of a supermassive black hole. They showed that this phenomenon could result in the violent destruction of the star in the form of a "stellar pancake", causing a reactivation of nuclear reactions in the core of the star in the stage of its maximum compression.

Tidal Disruption Basics

Incompressible homogeneous bodies in static field (planet-satellite couple in circular orbit)

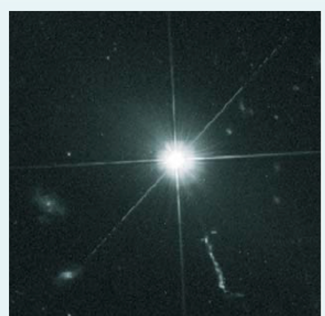
Roche limit (1847)

$$R_T = 2.45\, R_* \left(\frac{M_\cdot}{M_*}\right)^{1/3}$$



Tidal disruption of stars by black holes could explain NAG (1975)

(ony if $M_H < M_{Hills}$)

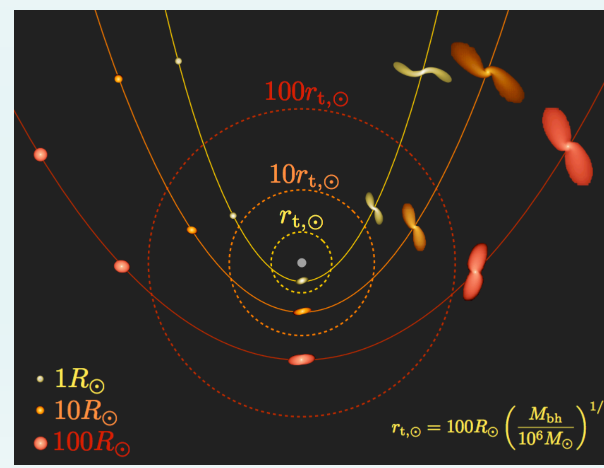


Carter, Luminet et al. (1982-1989) :

« affine » star model

First numerical calculations for compressible bodies in dynamical tidal field

(star-BH encounters in parabolic orbit)



Nature Vol. 296 18 March 1982

ARTICLES

Pancake detonation of stars by black holes in galactic nuclei

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Recent efforts to understand exotic phenomena in galactic nuclei commonly postulate the presence of a massive black hole accreting gas produced by tidal or collisional disruption of stars. For black holes in the mass range 10^4–$10^7 M_\odot$, individual stars penetrating well inside the Roche radius will undergo compression to a short-lived pancake configuration very similar to that produced by a high velocity symmetric collision of the kind likely to occur in the neighbourhood of black holes in the higher mass range $\gtrsim 10^9 M_\odot$. Thermonuclear energy release ensuing in the more extreme events may be sufficient to modify substantially the working of the entire accretion process.

0028-0836/82/110211—04$01.00

MANY of the most plausible models for explaining spectacular energy release phenomena in galactic nuclei are based on the release of gravitational energy by gas accreting on to a very massive central black hole[1]. A likely mechanism[2] for providing the gas necessary to fuel such a model would be the breakup of ordinary stars, either by the Roche tidal effect in the case of a black hole with mass M below the Hills'[3] limit, $M \lesssim 10^8 M_\odot$, or else by the effect of collisions in the case of a more massive black hole with a sufficiently dense surrounding star cluster. Gas release by tidal or collisional breakup (as well as by mechanisms such as supernovae and ordinary stellar winds) may also be important at other relatively quiescent stages in the history of a galactic nucleus containing a black hole, that is at times when the most observationally spectacular phenomena (such as quasars) are absent.

This article draws attention to a neglected effect which could be significant in many situations where tidal or collisional disruption occurs, namely that in the more extreme events (which may constitute a not negligible fraction of the total) the disruption will be preceded by a short-lived phase of high compression to a roughly pancake shaped configuration in which the density and temperature may rise enough to detonate effectively some significant fraction of the available thermonuclear fuel.

A very flat pancake type configuration will be formed briefly by any nearly head-on collision between roughly similar stars at very high relative velocities (analogous pancake formation being experimentally familiar in the microscopic context of very high energy proton–proton collision). We have in mind in particular the kind of event that is likely to occur near a black hole with the very large mass $M \gtrsim 10^9 M_\odot$ that is thought[4] to be necessary to account for the most extreme quasar phenomena. Beyond 0.1 pc from such an object, typical stellar collisions will have velocities $\gtrsim 10^4$ km s^{-1}, thus exceeding by a factor $\beta \gtrsim 10$ the minimum of the order of 10^3 km s^{-1} needed for disruption. Detailed studies of high velocity ($\gtrsim 10^4$ km s^{-1}) collisions will require an elaborate hydrodynamic treatment, with allowance for shocks, of the kind already available[5] for the intermediate velocity ($\approx 10^3$ km s^{-1}) collisions in which a moderate degree of flattening is already present. However, a preliminary idea of the effects to be expected may be obtained from consideration of the simpler but otherwise very similar configuration that arises during tidal disruption of a single star, whose evolution can be followed approximately[6,7] in terms only of ordinary differential equations using an adiabatic affine star model which, although highly idealized, can, nevertheless, be expected to provide a qualitatively valid description of the behaviour of the stellar core before, if not after the instant of maximum compression.

The phenomena of tidal disruption of a self gravitating body passing within the Roche radius

$$R_R \approx M^{1/3} \rho_*^{-1/3} \qquad (1)$$

(where ρ_* is its characteristic central density) has been studied for over a century, but mainly in terms of an incompressible fluid model. It does not seem to have been realized that adequate allowance for compressibility leads to the prediction that a star penetrating deeply within the Roche radius will pass through a phase of compression to a highly flattened pancake configuration, closely similar, in both spatial and temporal characteristics, to that produced by a symmetric collision involving a pair of stars. It turns out that the effect of a collision with stellar velocities exceeding the central characteristic velocity (which is a few hundreds of km s^{-1} for a typical main sequence star) by a factor of the order of β can be roughly simulated by a single star following an orbit that penetrates to within a pericentre radius R_p given in order of magnitude by

$$\beta \approx R_R / R_p \qquad (2)$$

(a value β of the order of 10 thus being sufficient to reproduce the effect of a collision with relative velocity of the order of 10^4 km s^{-1}). Not only can the study of thermonuclear reactions in such a tidally produced pancake give a first rough indication of what may occur in a high velocity stellar collision, but it would also appear to be an astrophysically interesting phenomenon in its own right in the context of a black hole in the moderate mass range $10^4 M_\odot$ to $10^7 M_\odot$ for which it is possible to obtain a large value of β without the star either being penetrated by or swallowed by the black hole. The potential importance of this phenomenon stems from the fact that deep penetration is much less improbable than would be expected from purely geometric considerations. Just as the probability of high velocity collisions deep in the potential well of an $M \gtrsim 10^9 M_\odot$ black hole is enhanced far above what would be proportional to the corresponding volume (by an amount whose exact calculation is difficult) in consequence of the well known cusp effect in the stellar density distribution (see ref. 8), so, similarly, the probability of penetration of an individual star deep within the tidal field of a more moderate sized black hole will also be much higher than would be deduced from the corresponding purely geometrical cross-section, by an amount that can be relatively easily estimated from the characteristics of the individual approximately parabolic orbit. We conclude that the fraction of all tidally disrupted stars with penetration factor exceeding a given value β will be of the order of magnitude of β^{-1}.

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Astron. Astrophys. 121, 97–113 (1983)

ASTRONOMY AND ASTROPHYSICS

Tidal compression of a star by a large black hole

I. Mechanical evolution and nuclear energy release by proton capture

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Summary. The gross qualitative behaviour of a star plunging deeply within the Roche tidal radius, R_R, of a large black hole to a pericentre radius $\beta^{-1} R_R$, with $\beta \gtrsim 3$, is examined using a simplified affine star model whose evolution is canonically determined by a Lagrangian formalism. In Phase I, for $R \gtrsim R_R$, the star remains in only slightly distorted self-gravitating quasi-equilibrium, but in Phase II its particles undergo approximately free fall in the strong external tidal field within the Roche radius. In Phase III the compression is halted and reversed by the build-up of pressure in a highly flattened pancake configuration, in which adiabatic heating raises the temperature to a maximum given in most cases by $\Theta_m \approx \beta^2 \Theta_*$ where Θ_* is the equilibrium core temperature. In Phase IV the matter expands again in approximately free fall, and in Phase V, as the star moves outside the Roche radius, pressure and self-gravitational forces again come into play. For stars rich in intermediate weight elements, nuclear energy release by proton capture in Phase III is shown to be important. Consideration of the more spectacular possibility of helium detonation is postponed until Part II.

Key words: black hole – nuclei of galaxies – nucleosynthesis

1. Introduction

The purpose of the present work is to describe the qualitative outlines of the mechanism whereby a star that penetrates deeply, by a large factor β say, within the Roche tidal radius of a sufficiently compact and massive body can undergo compression to a highly flattened but short lived pancake configuration in the plane of its orbit, thereby raising its core temperature Θ from an equilibrium value Θ_* to a maximum that in most cases will be given by

$$\Theta_m \approx \beta^2 \Theta_* \qquad (1.1)$$

and as a result possibly detonating part of the available nuclear fuel. We have already (Carter and Luminet, 1982) drawn attention to the likely importance of this phenomenon for understanding the evolution of active galactic nuclei on the assumption that the compact central body is a massive black hole. In the present article we shall not be concerned with the collective effects resulting from the explosive disruption of a large number of stars, but will limit our attention essentially to the mechanical behaviour of an individual star during the critical period, lasting at most about an hour, during which the greater part of the nuclear energy release takes place. As a concrete example we shall consider here only the simplest relevant reaction process, namely accelerated proton capture by intermediate weight elements: it is shown in the final section that (although negligible for Population II stars) this process can easily liberate a potentially very important energy from any main sequence stars whose constitution is at least as rich as that of Population I stars in the solar neighbourhood [a condition whose likelihood is suggested by the known tendency for metallicity in galaxies to increase towards the nucleus, see e.g. Pagel and Edmunds (1981)]. We shall postpone until a subsequent paper the consideration of the much more violent, but also more complicated chain of reactions, that may be set off in rather more restricted circumstances by detonation of the helium content ($\gtrsim 25\%$ by weight) in smaller stars via the triple-α process. We shall also refrain from any attempt to consider the potentially observable effects on a longer timescale (days or weeks) resulting from the transfer of energy to, and its radiation from, the outer envelope regions of the star.

The plan of the present article is as follows. After discussing the difference between the present investigation and various previous studies of tidal disruption of stars by black holes in Sect. 2, we go on in Sect. 3 to introduce an idealized affine star model whose internal configuration is described in terms of just nine parameters (the components of a 3×3 deformation matrix) and governed by a canonically defined Lagrangian function. The resulting equations of motion are the same as those obtained from the tensor virial theorem (see Chandrasekhar, 1969) by expanding in powers of distance from the centre of the star, and as such have already been used to allow for compressibility in a relativistic tidal field by Lattimer and Schramm (1976) (albeit in the context of neutron stars in almost circular orbits, for which the effects of compression are of minor importance compared with those in the context of ordinary stars in plunging orbits as considered here). Although it is probably adequate for describing the massive core of the star during the early stages of tidal disruption, the affine model cannot deal with the diffuse outer layers, nor with the radiation transfer that will become important at late stages. It may however be used for a very rough description of the effects of nuclear energy generation during the phase of maximum compression, using the formalism that is set up in Sect. 4. This formalism is illustrated here by application to the particularly simple cases in which the equation of state can be treated as *polytropic* (for small main sequence stars subject even to very high compression, and for medium mass main sequence stars subject to moderate compression, it will be a good approximation to take the equation of state to be that of an ordinary non relativistic polytrope with adiabatic index $\gamma = 5/3$).

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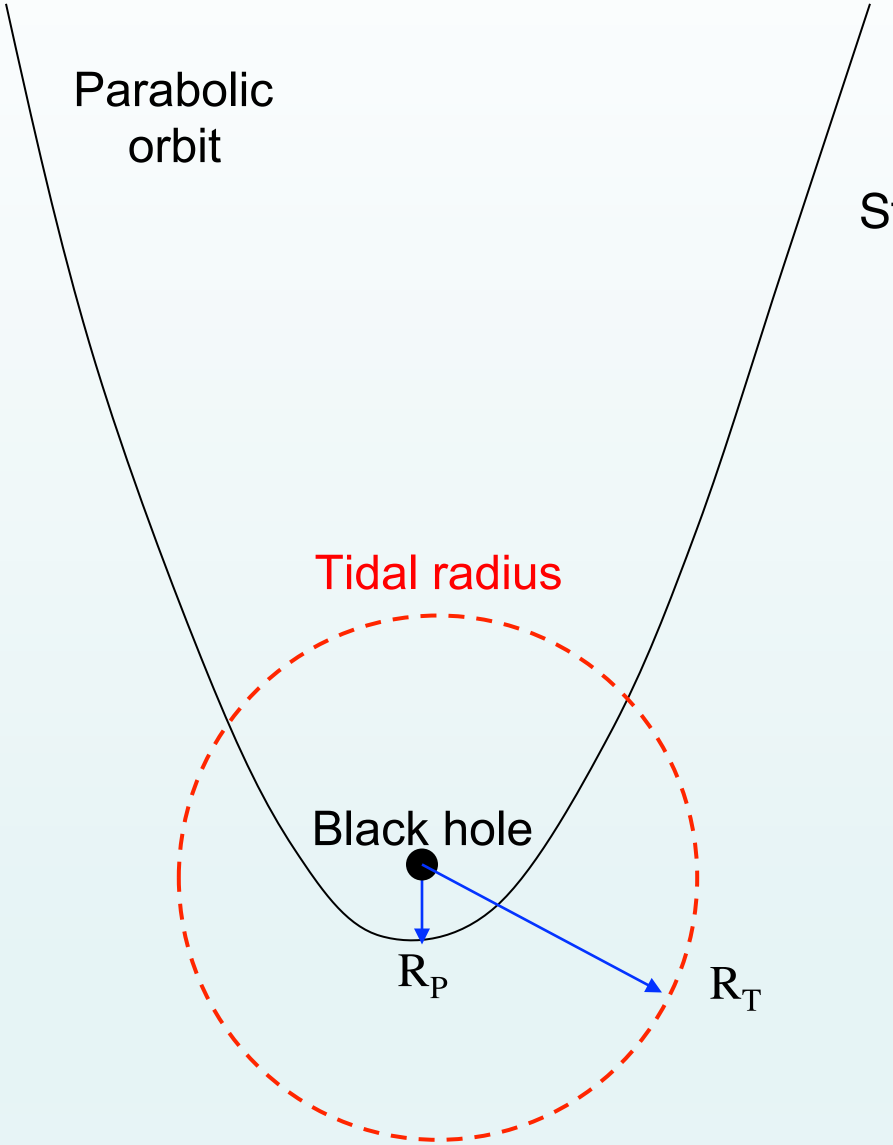
Astron. Astrophys. 1983

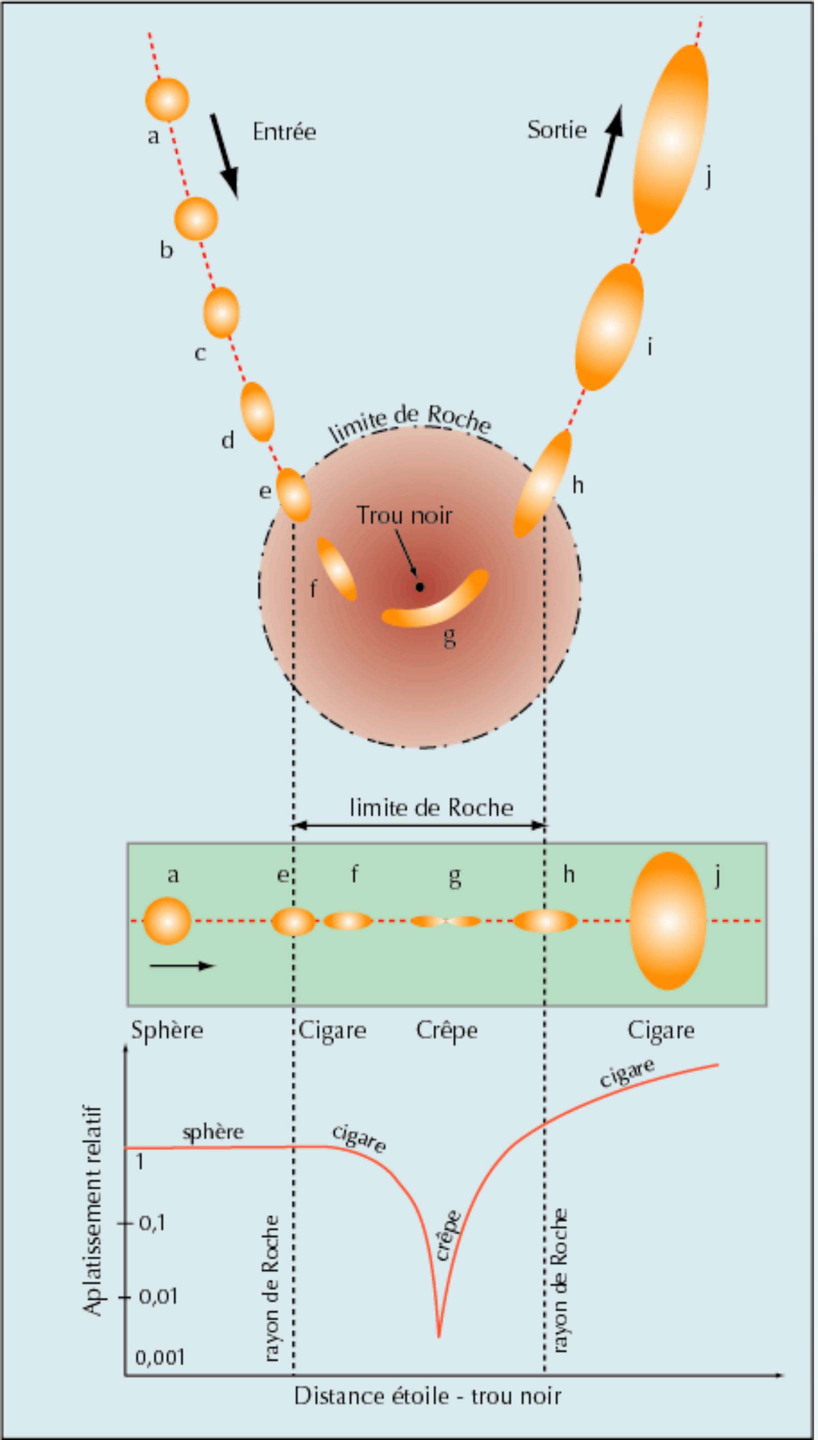


Strength of the Tidal Encounter :

penetration factor

(CL, Nature 1982)

$$\beta \equiv \frac{R_T}{R_p}$$



The Pancake Effect

(Carter & Luminet, *Nature*, 1982)

Max. compression and heating strongly dependent from β :

$\rho_{max} \sim \beta^3 \rho_*$ — 10^6 g/cm^3

$\beta = 10$

$T_{max} \sim \beta^2 T_*$ ⇒ 10^9 K

$\Delta\tau_{max} \sim \beta^{-4} \tau_*$ — 0.1 sec

⇓

Conditions required for
explosive stellar disruption

Mechanics of the affine star model

M.N.R.A.S. 1985

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Summary. In a recent pioneering study of the phenomena occurring when a star is disrupted by passage through the tidal field of a large black hole, it was found convenient to make use of a simplified affine star model (described in

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DYNAMICS OF AN AFFINE STAR MODEL IN A BLACK HOLE TIDAL FIELD

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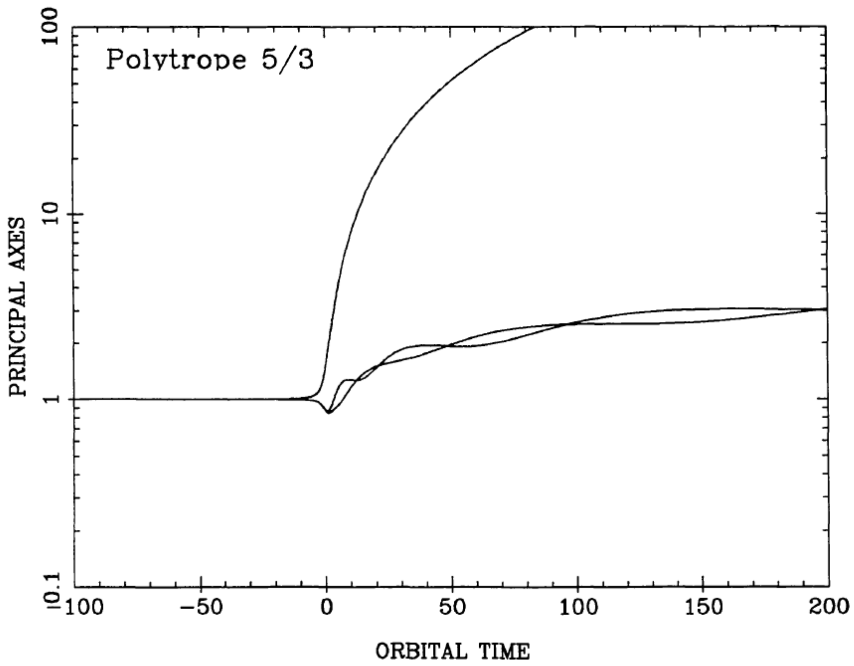
Received 1985 May 13; accepted 1985 December 2

ABSTRACT

It has recently been shown that the tidal disruption of a star moving in a deeply plunging orbit in the field of a large black hole such as may occur in an active galactic nucleus can most conveniently be studied in a first approximation using a simple affine star model. Preliminary investigations have shown that the (positive) nuclear energy released during a short-lived phase of compression to a highly flattened pancake configuration can more than counterbalance the (negative) self-binding energy of the original stellar configuration, so that instead of ending up weakly bound to the central black hole (as had been supposed in earlier studies based on a less realistic incompressible model) the gas may ultimately be blown out with net positive energy.

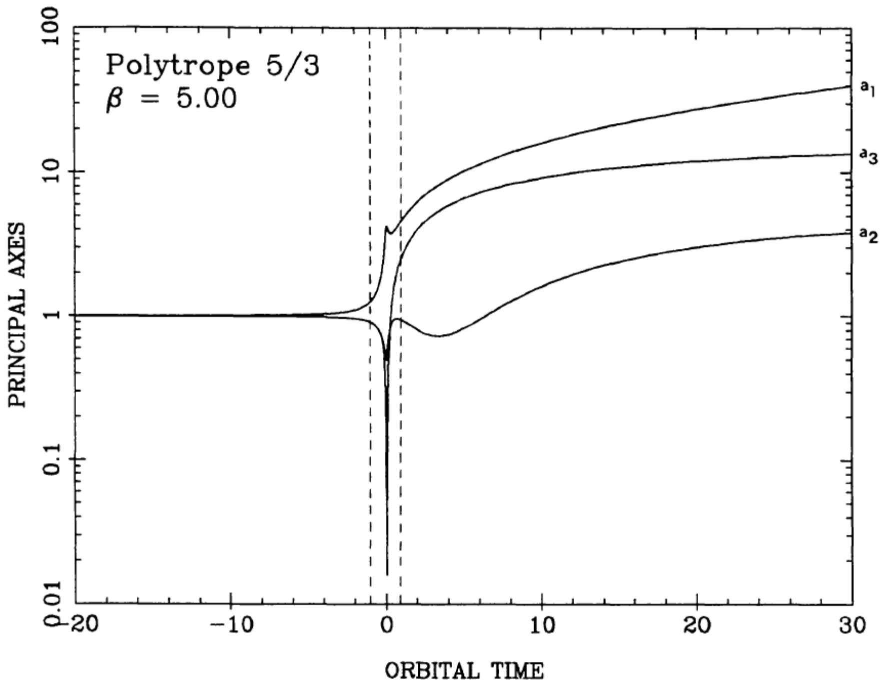
Disruption process in the ellipsoidal model

Slight penetration
($\beta < 3$)

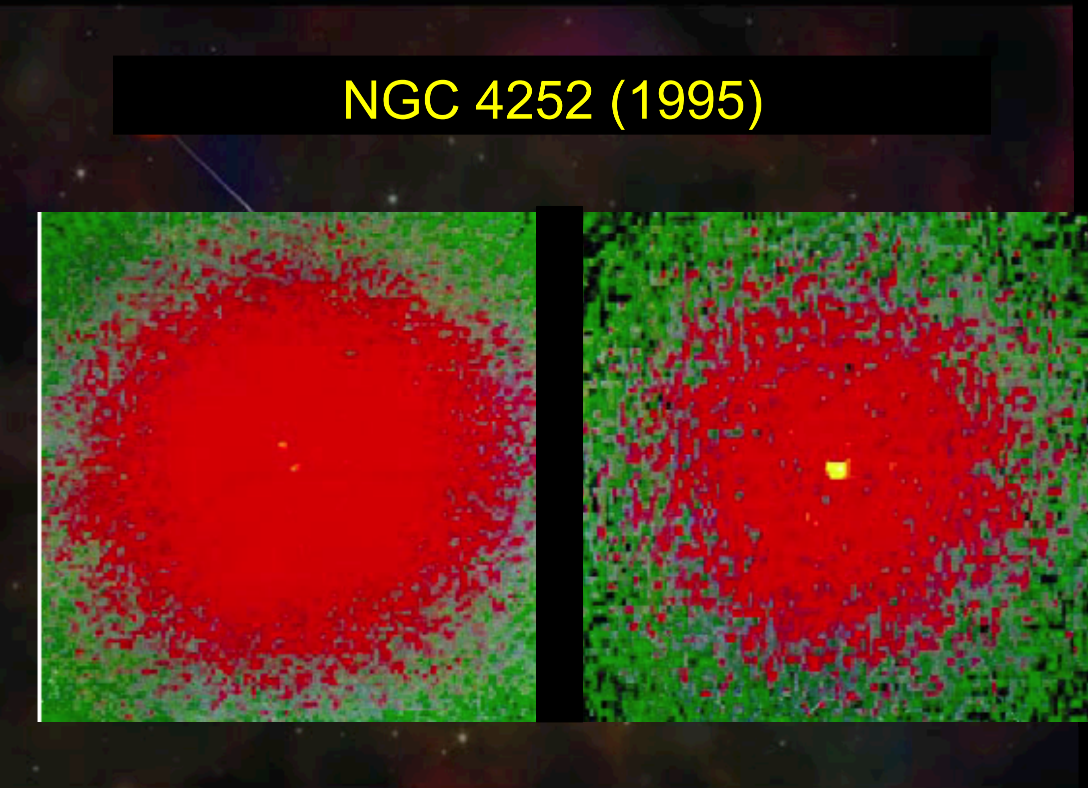


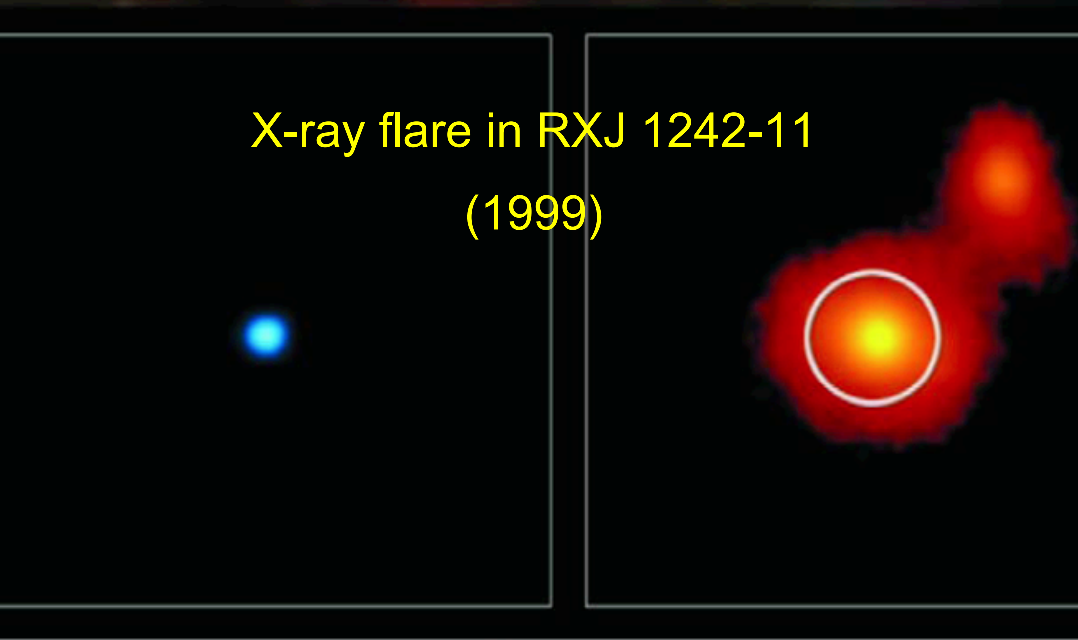
« cigar-like » configuration

Deep penetration
($\beta > 3$)



« pancake » configuration

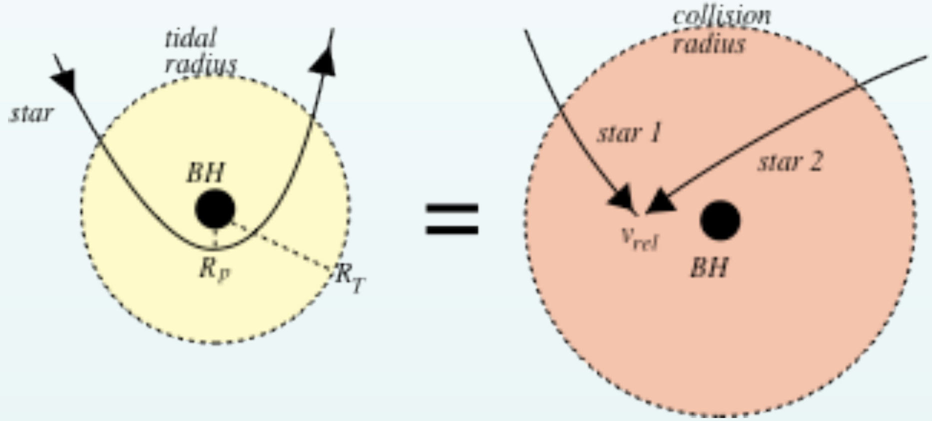

NGC 4252 (1995)


X-ray flare in RXJ 1242-11
(1999)


UV-transient
(ROTSE telescope 2009)
SPACE SCIENCES SERIES OF ISSI
The Tidal Disruption of Stars by Massive Black Holes
Peter G. Jonker · Iair Arcavi
E. Sterl Phinney · Elena M. Rossi
Nicholas C. Stone · Sjoert van Velzen
Editors
Springer

Disruptive star-star collisions by SMBH

Around a 10^9 M_S black hole, the typical collisional velocities are > 5000 km/s within a distance 0.1 pc from the black hole



$\beta = R_T/R_p$

crushing factor

$\beta = v_{coll}/v^*$

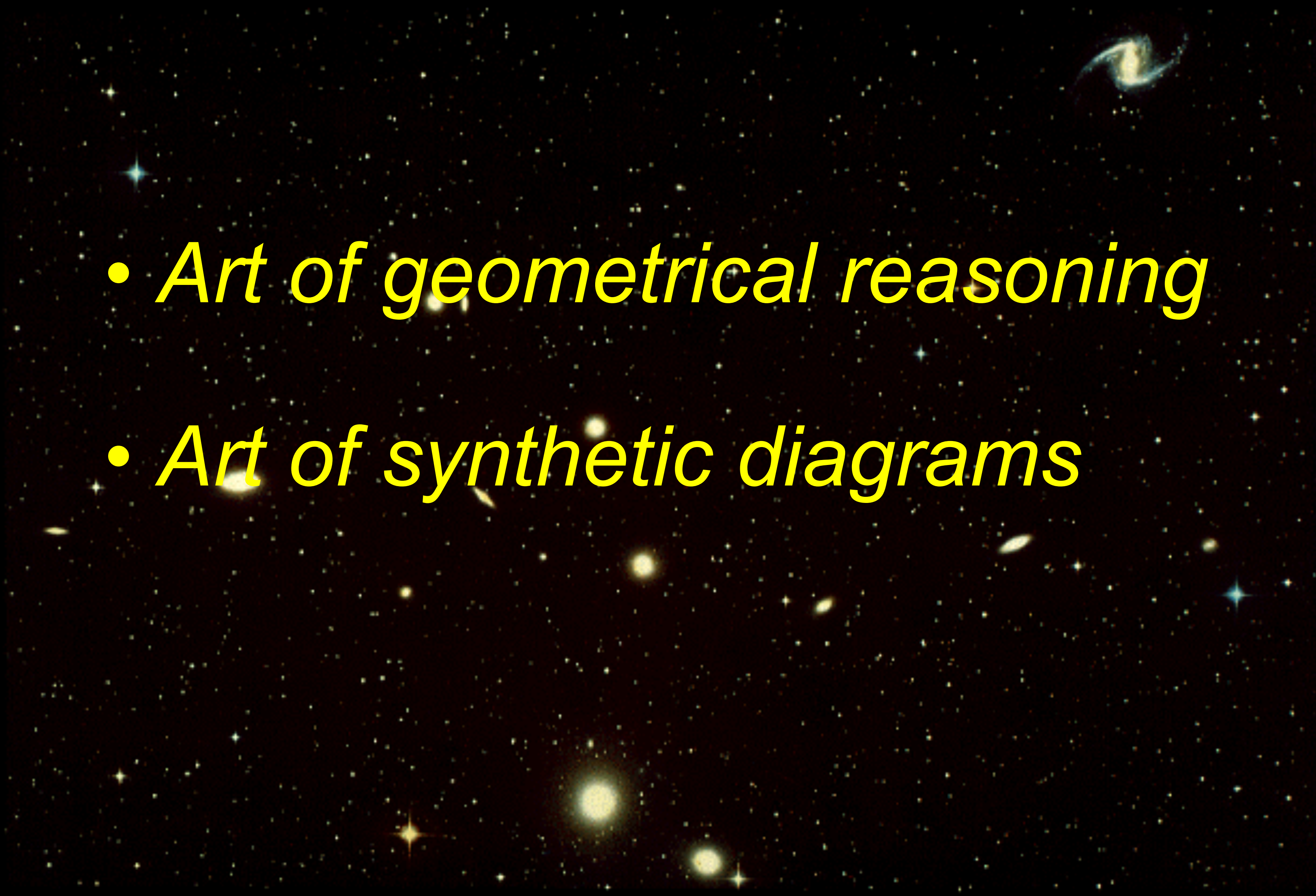
Massive BH (10^4 - 10^8 M_S)

(CL 1982)

Supermassive BH > 10^8 M_S

Galactic Nuclei, AGN

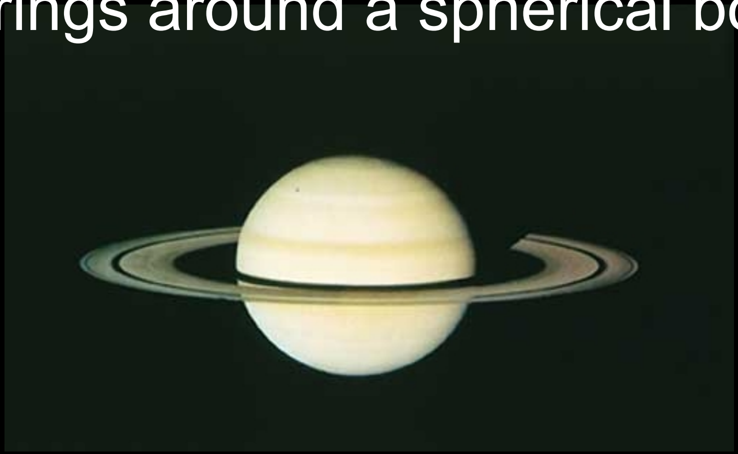
Blazars, Giant ellipticals



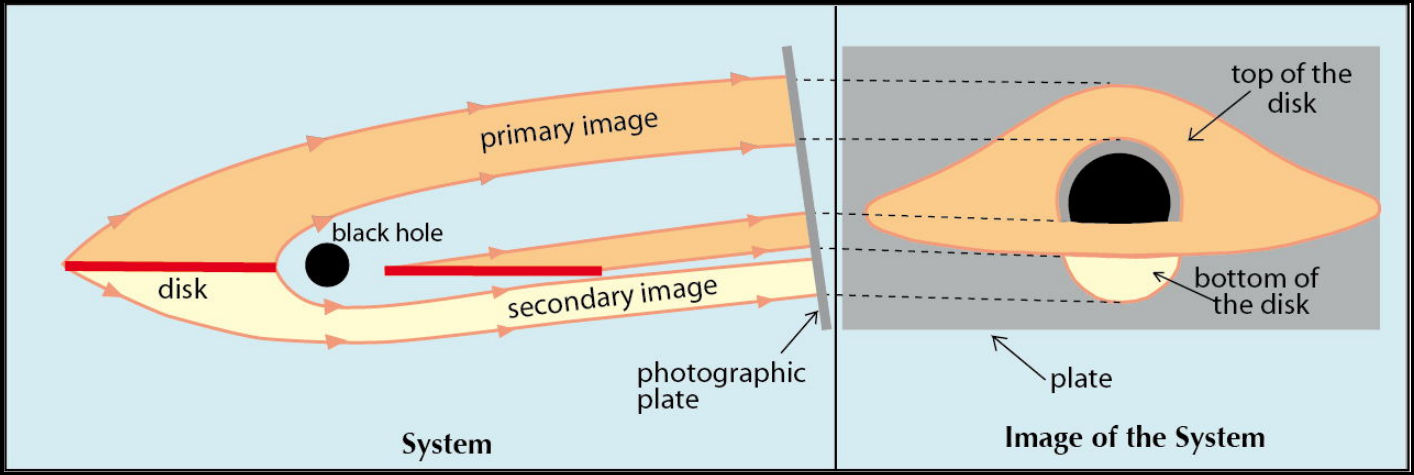
- *Art of geometrical reasoning*
- *Art of synthetic diagrams*

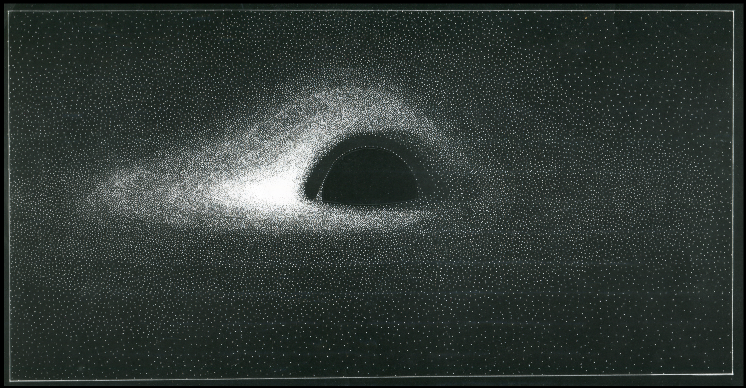
Image of circular luminous rings around a spherical body

Flat spacetime

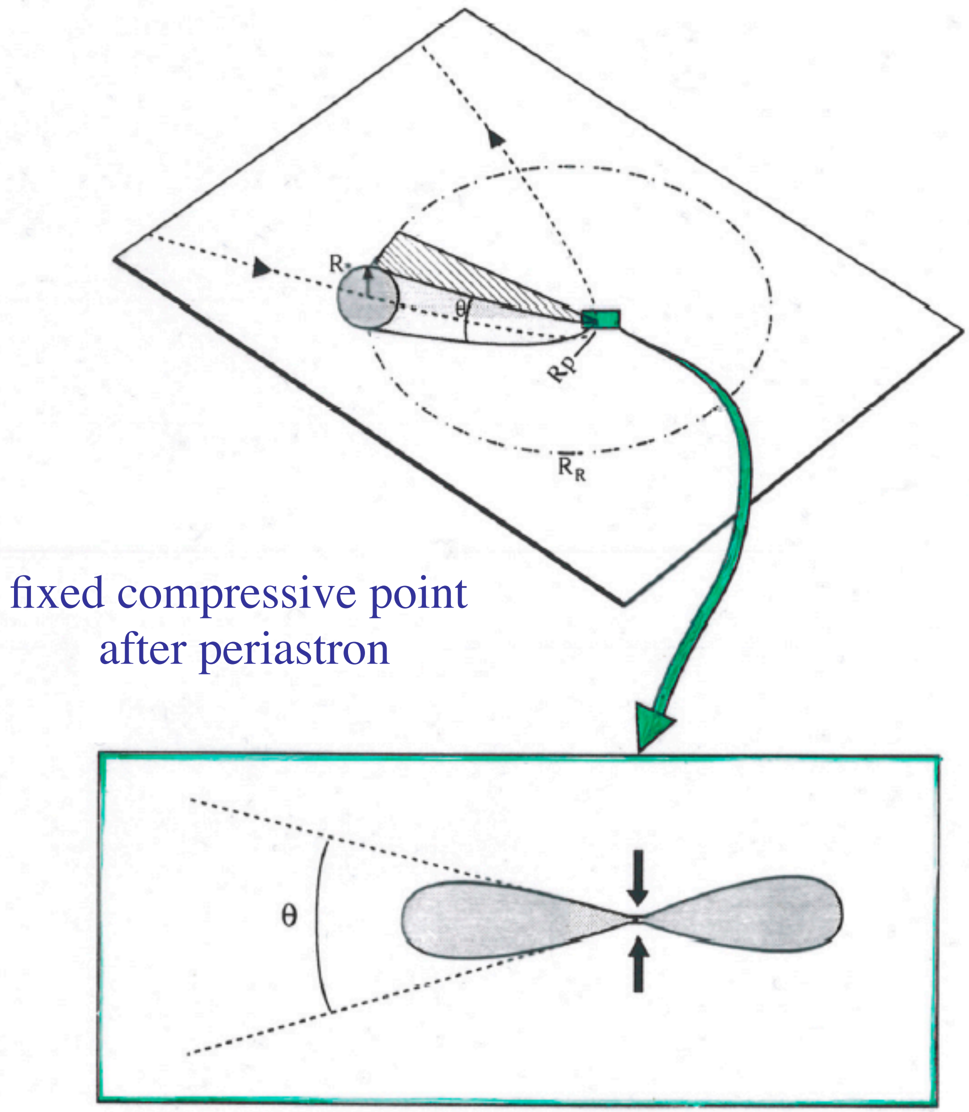


Curved spacetime (black hole)



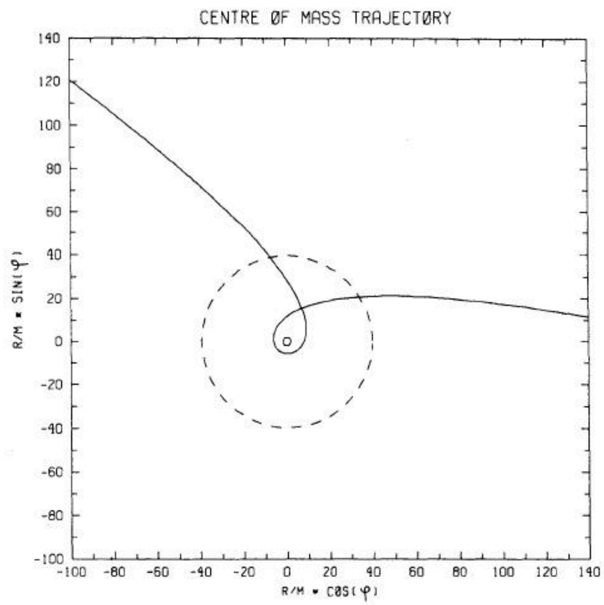


The « Rolling Mill » Effect

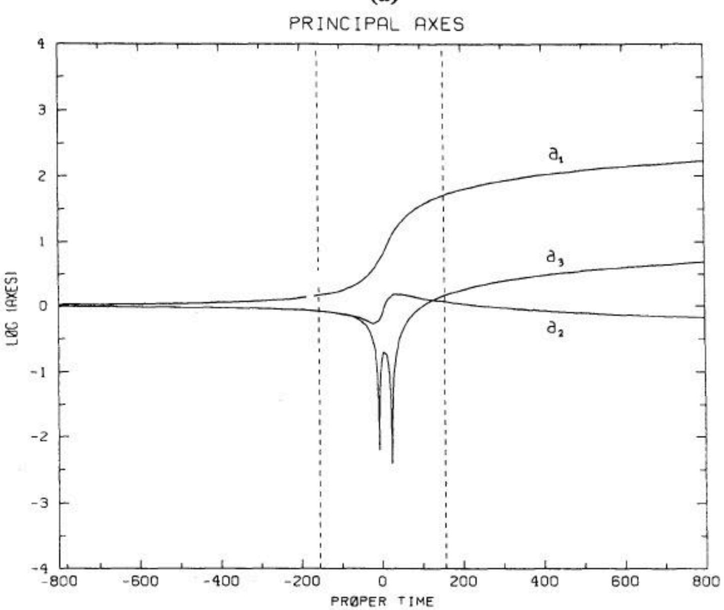


Relativistic tidal field

Tid



(a)



(b)

Double point inside the tidal radius

⇒ Several compressions

Mon. Not. R. astr. Soc. (1985) **212**, 57–75

Tidal squeezing of stars by Schwarzschild black holes

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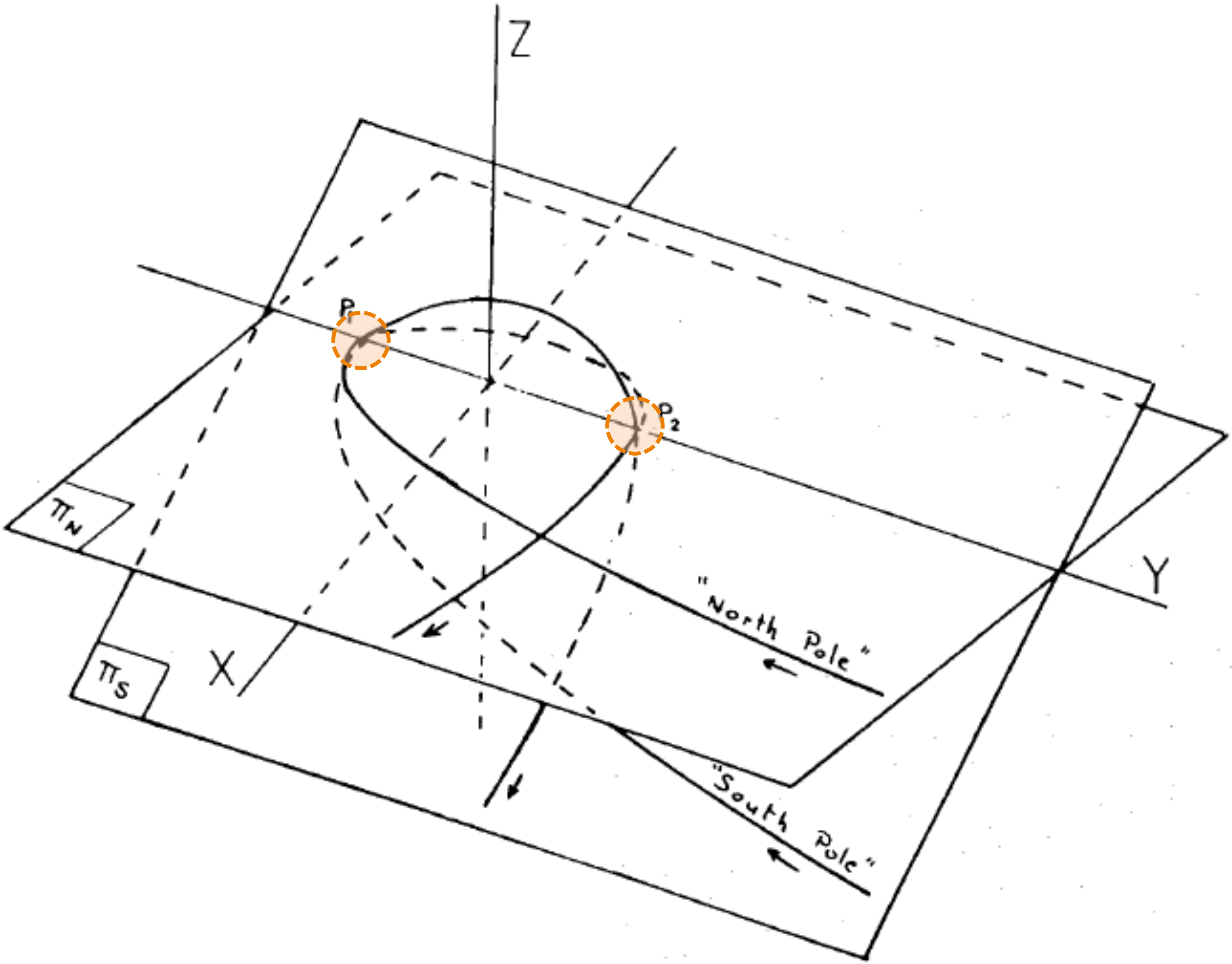
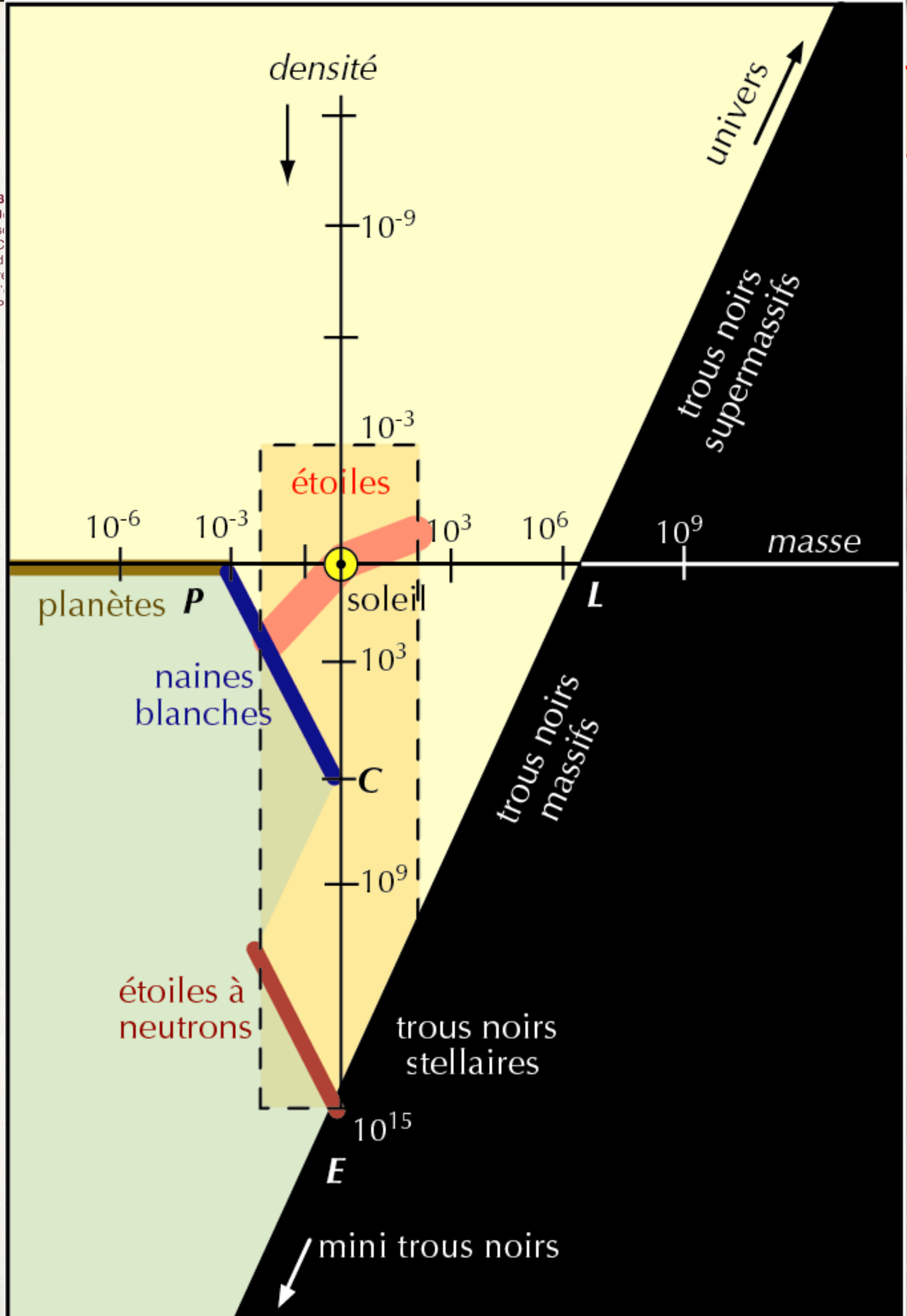
Summary. We present a relativistic generalization of the problem of tidal disruption of a star deeply plunging within the Roche radius of a massive Schwarzschild black hole, on the basis of the affine star model developed by Carter & Luminet in a Newtonian context. We show that new specific relativistic effects occur. In particular, tidal compression acting on the direction orthogonal to the orbital plane of the star may induce formation of many successive strong squeezings of the star when the periastron of its orbit is sufficiently close to the horizon of the black hole. Illustrative numerical results are displayed in last section.


Z
X
Y
P_1
P_2
π_N
π_S
"North Pole"
"South Pole"



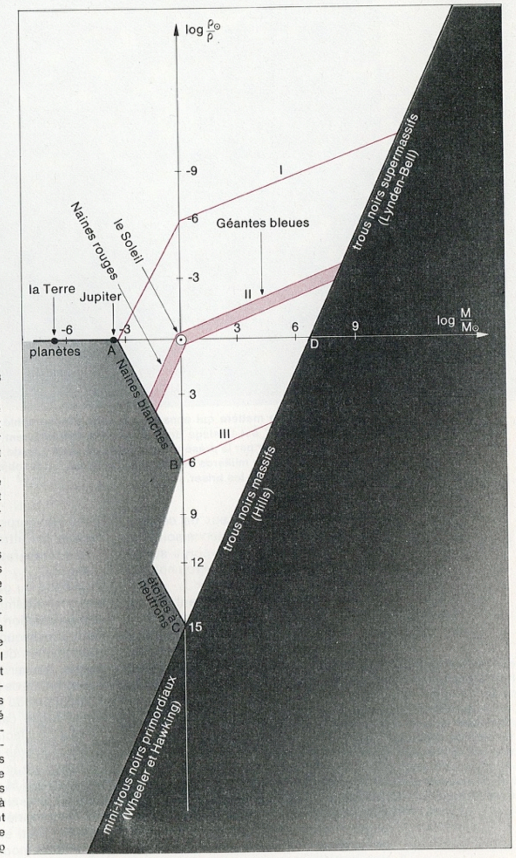
Mass-density diagram of celestial bodies

1. Le diagramme masse-densité des corps célestes

■ Les relations que l'on veut calculer entre la masse et la densité des différents types de corps astronomiques peuvent être reportées sous forme de courbes sur un même diagramme (voir figure). Ces courbes délimitent une zone blanche, seule accessible aux étoiles ordinaires. Une droite le traverse, délimitant la zone des trous noirs (sombre). Sur les axes, on porte, en coordonnées logarithmiques, la masse M et la densité ϱ de l'objet, en unités de masse et de densité solaires, $M_\odot$ et $\rho_\odot$.

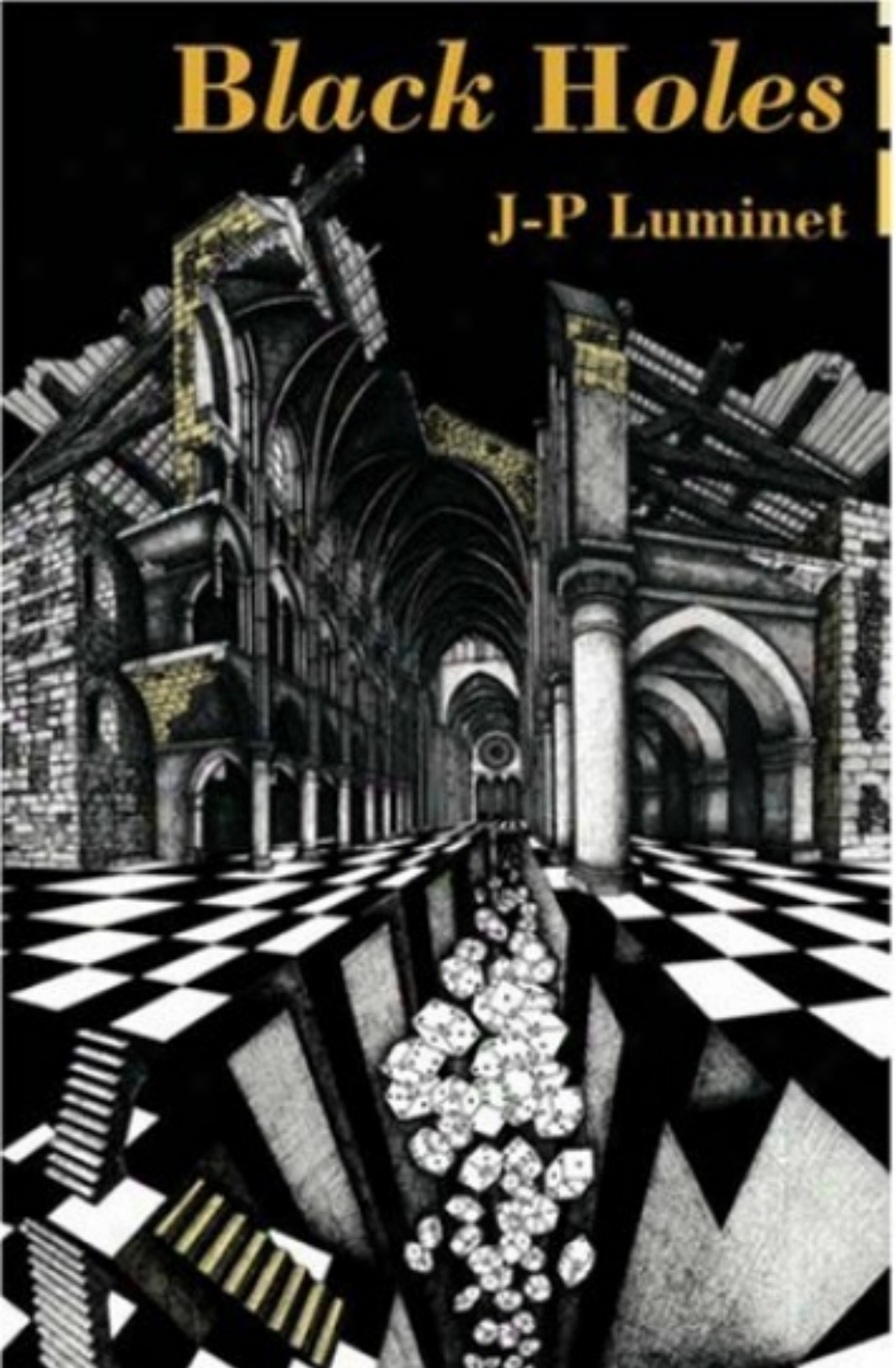
La genèse des courbes tracées sur le diagramme peut être retracée rapidement.

Il existe des formules très simples donnant, à un ordre de grandeur près, les masses et les densités caractéristiques de la plupart des espèces d'objets astronomiques, en fonction seulement de quelques constantes fondamentales de la physique. On montre ainsi que la densité de la matière froide ordinaire ne dépend pas de la masse de l'objet. Ceci cesse d'être valable pour les masses plus grandes que la limite de Fowler (A), égale à 10^{-3} $M_\odot$, soit à peu près la masse de Jupiter. Au-dessus de cette masse, les forces de compression gravitationnelle donnent lieu à des états plus denses, occupés par les naines blanches, dont la densité est proportionnelle au carré de la masse (AB). Cette expression cesse à son tour d'être valable lorsque les pressions deviennent assez grandes pour conférer aux électrons des vitesses relativistes ; ce phénomène a lieu à partir de la limite de Chandrasekhar (B). Bien qu'il n'y ait pas d'états d'équilibre froids significativement plus massifs que cette limite, il en existe de beaucoup plus denses, occupés par les étoiles à neutrons. Leur existence découle de la possibilité de comprimer la matière jusqu'à ce que les électrons se combinent avec les protons. Le nouvel état est constitué presque exclusivement de neutrons, avec des densités supérieures à celle des noyaux atomiques (10^{13}—10^{15} g/cm²). Lorsque la densité devient suffisante, il y a finalement formation d'un trou noir à la limite de Landau-Oppenheimer-Volkoff (C). Toutes ces courbes déterminent la frontière d'une région en grisé, inaccessible dans les conditions astronomiques ordinaires à cause des effets répulsifs qui découlent du principe de Pauli. En ce qui concerne les trous noirs, la relation entre M et ϱ s'obtient immédiatement en écrivant que la vitesse de libération à la surface d'un trou noir est égale à la vitesse de la lumière. Cette formule n'a aucune limitation et la droite représentative, qui traverse tout le diagramme, délimite la région sombre interdite aux corps astronomiques ordinaires. La ligne des trous noirs coupe l'axe horizontal des densités à la limite de Laplace (D), qui correspond aux caractéristiques du trou noir que Laplace avait envisagé : 10^7 $M_\odot$, $1\rho_\odot$. Cette limite



joue un rôle essentiel dans les modèles de trous noirs géants dans les noyaux galactiques.

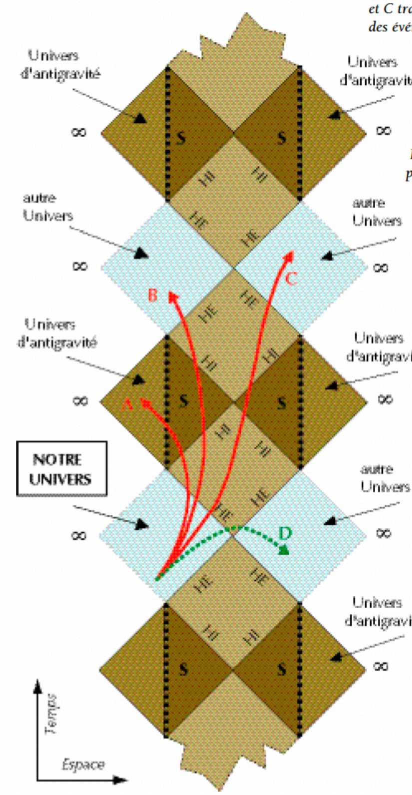
Les objets soutenus par une pression thermique sont nécessairement confinés dans la région blanche du diagramme. Les lignes « rouges » du diagramme correspondent à des objets chauds, à trois températures caractéristiques particulièrement importantes : d'une part l'énergie minimale pour qu'il y ait ionisation de la matière (I), puis l'énergie nécessaire pour qu'il y ait des réactions thermonucléaires (II), enfin l'énergie au-delà de laquelle les effets relativistes (tels que création de paires électron-positron) deviennent importants, ce qui donne lieu à toutes sortes d'instabilités (III).



qui seraient assez imprudents pour naviguer exactement dans le plan équatorial du trou noir. Mis à part le danger des forces de marée, ils peuvent la frôler d'aussi près qu'ils veulent sans la toucher, ils peuvent même la voir si des signaux lumineux en sortent.

Quant à l'« autre côté » de la singularité, c'est un morceau d'espace-temps spatialement infini, dans lequel les distances sont « négatives ». Cette apparente absurdité s'interprète par une inversion du caractère attractif de la gravitation. Celle-ci deviendrait ***répulsive***, forçant ainsi la matière à s'éloigner indéfiniment de la singularité.

La richesse structurelle du trou noir en rotation ouvre des perspectives d'exploration passionnantes. Sur la figure, la trajectoire A montre la possibilité d'explorer l'univers d'antigravité situé de l'autre côté de la singularité. Les trajectoires B et C prouvent qu'il est théoriquement possible de pénétrer à l'intérieur du trou noir – de préférence suffisamment massif, afin de ne pas être déchiqueté par les forces de marée –, de survoler l'anneau singulier et de ressortir du trou pour déboucher dans d'autres univers extérieurs. Enfin, la trajectoire D est interdite car elle sort du cône de lumière… Il existe quand même un feuillet de l'espace-temps qui ne peut pas être exploré !



distances y étant « négatives », elle s'interprète comme un univers d'antigravité. La singularité est orientée verticalement et en traits discontinus, signifiant qu'elle peut être évitée et que l'on peut passer au travers. Pour naviguer dans l'espace-temps du trou noir en rotation, la seule règle est de ne pas s'écarter de plus de 45 degrés de la verticale. Diverses trajectoires partant de l'univers extérieur (« notre » univers) et traversant le trou noir sont montrées. La trajectoire A passe à travers la singularité annulaire et explore l'univers d'antigravité. Les trajectoires B et C traversent quatre horizons des événements et ressortent du trou noir dans un autre univers. La trajectoire D en vert est interdite car elle voyage plus vite que la lumière. Il est mathématiquement permis d'identifier les « autres » univers avec notre univers, mais l'opération donne lieu à des paradoxes temporels.

La machine à remonter le temps

Le bon sens, quoi qu'il fasse, ne peut manquer de se laisser surprendre à l'occasion. Le but de la science est de lui épargner cette surprise.
Bertrand Russell

Tandis que la carte de Kruskal montrait que le trou de ver de Schwarzschild (ou pont d'Einstein-Rosen) est infranchissable, le jeu de Penrose suggère que le trou


Thank you
Brandon !