

A black hole is depicted at the center, surrounded by a glowing accretion disk. The background is a dense field of stars of various colors (white, yellow, orange, blue) against a dark blue space. The title text is overlaid on the upper part of the image.

# Les trous noirs: physique & astrophysique

JEAN-PIERRE LUMINET

LABORATOIRE D'ASTROPHYSIQUE DE  
MARSEILLE (LAM)

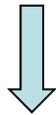
& OBSERVATOIRE DE PARIS (LUTH)

Collège de France 2015

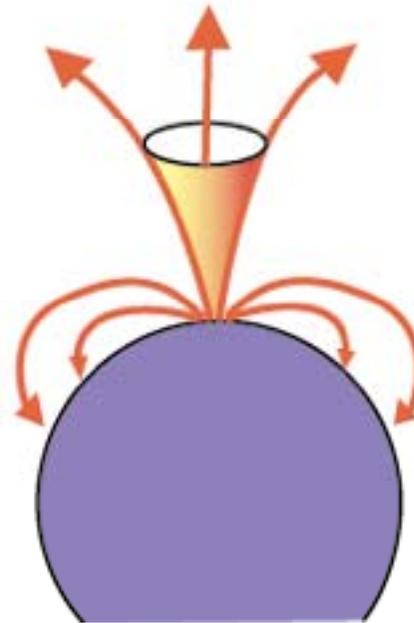
# Gravitation newtonienne

*Michell 1784, Laplace 1796*

Vitesse de libération >  
300 000 km/s



**astre invisible**



***Exemple : densité du soleil, 500 fois son rayon***

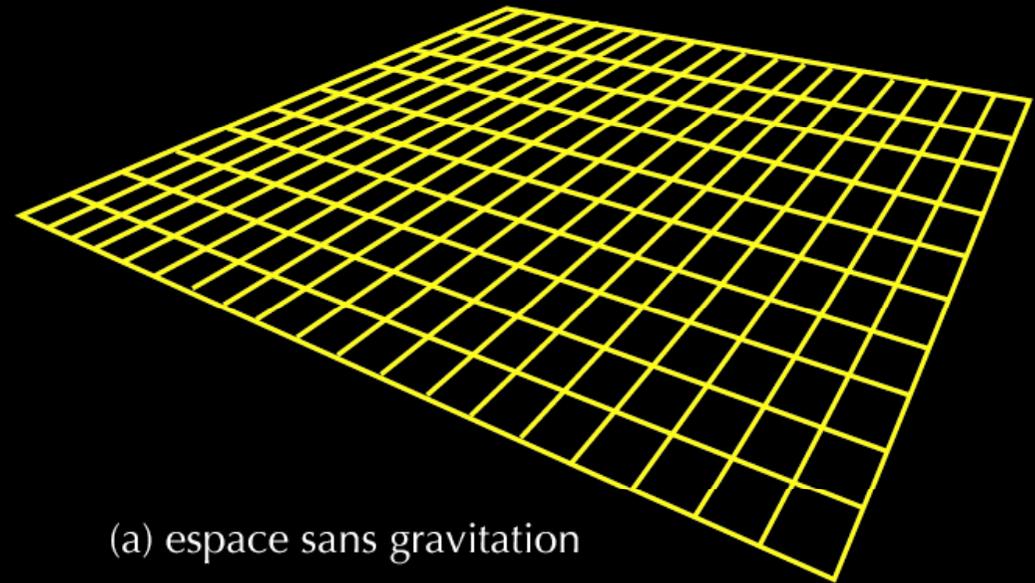
formule générale (Schwarzschild 1917):

$$R_{\text{crit}} \sim 3 \text{ km } M/M_{\text{S}}$$

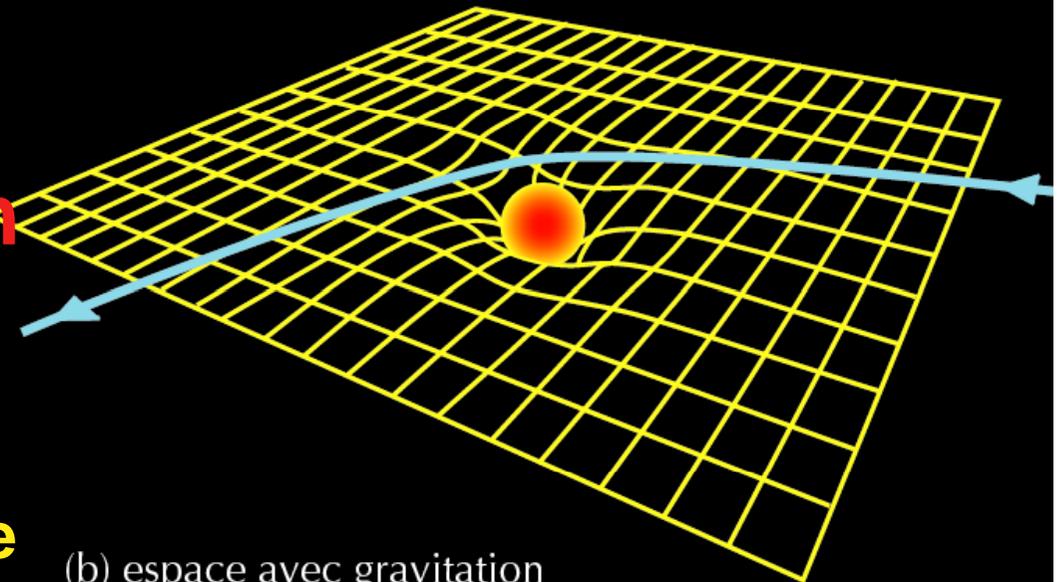
# Relativité Générale

(25 novembre 1915)

## Espace-temps courbe



(a) espace sans gravitation



(b) espace avec gravitation

Equations d'Einstein

:

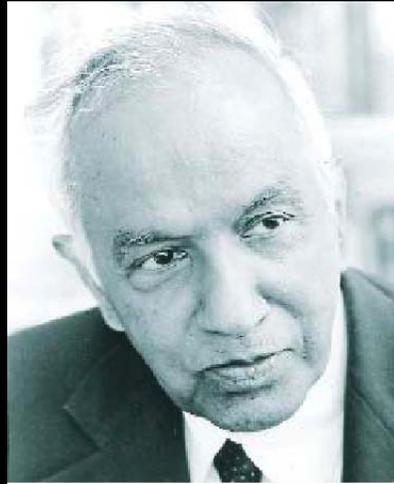
$$G_{\mu\nu} = k T_{\mu\nu}$$

courbure = matière-énergie

# Effondrement gravitationnel



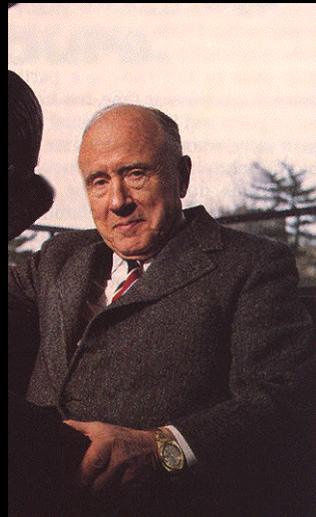
K. Schwarzschild



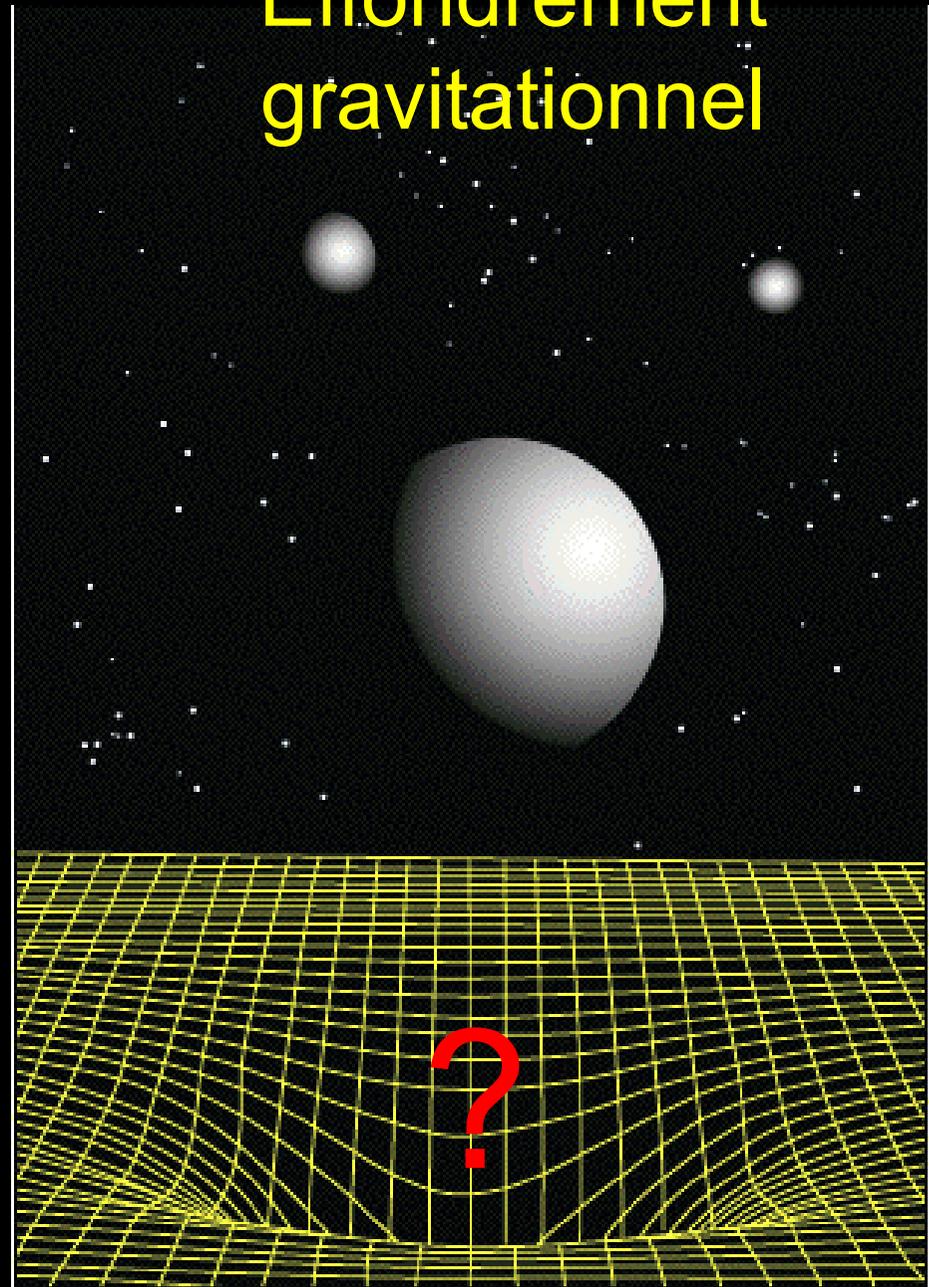
S. Chandrasekhar

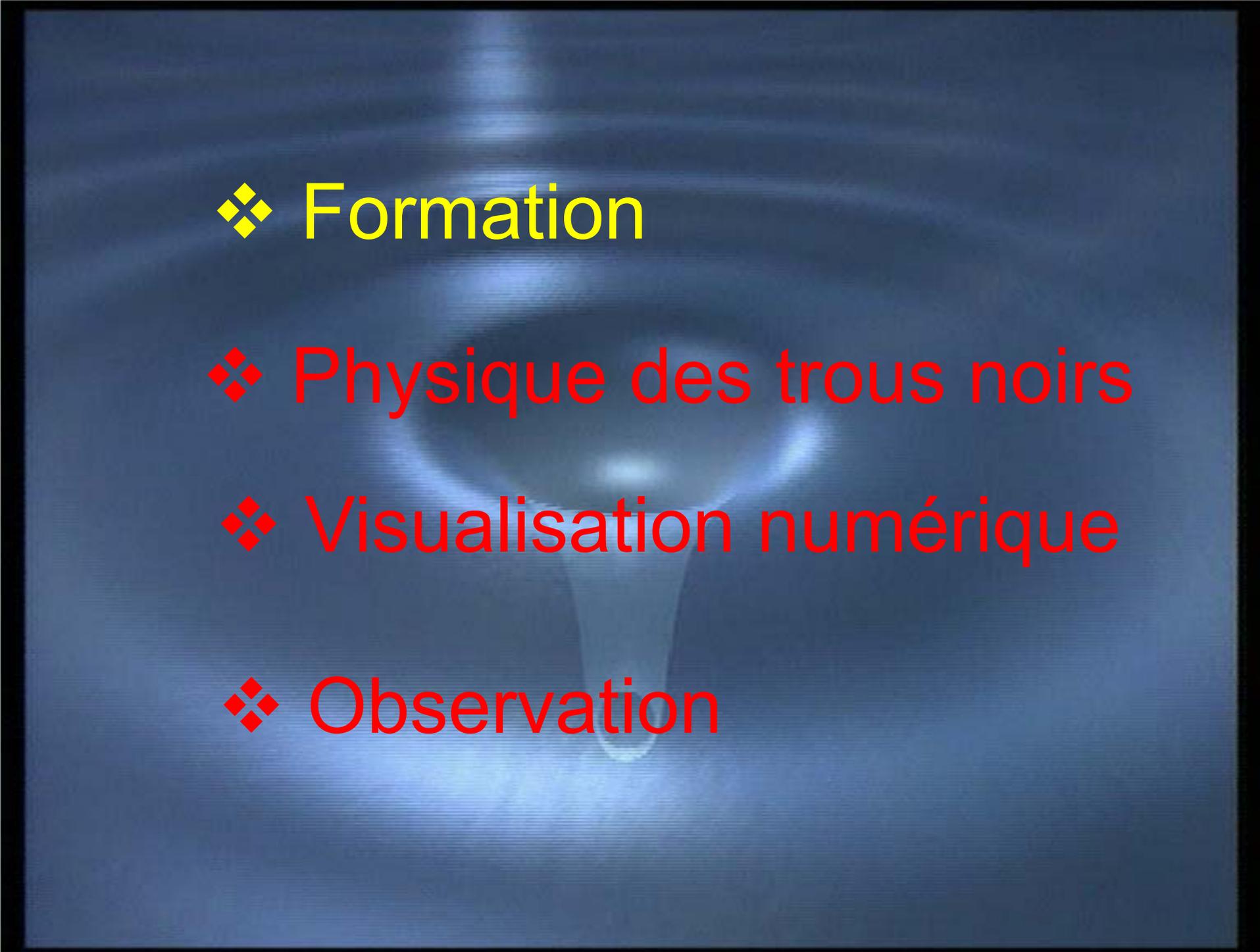


R. Oppenheimer



J. Wheeler





❖ Formation

❖ Physique des trous noirs

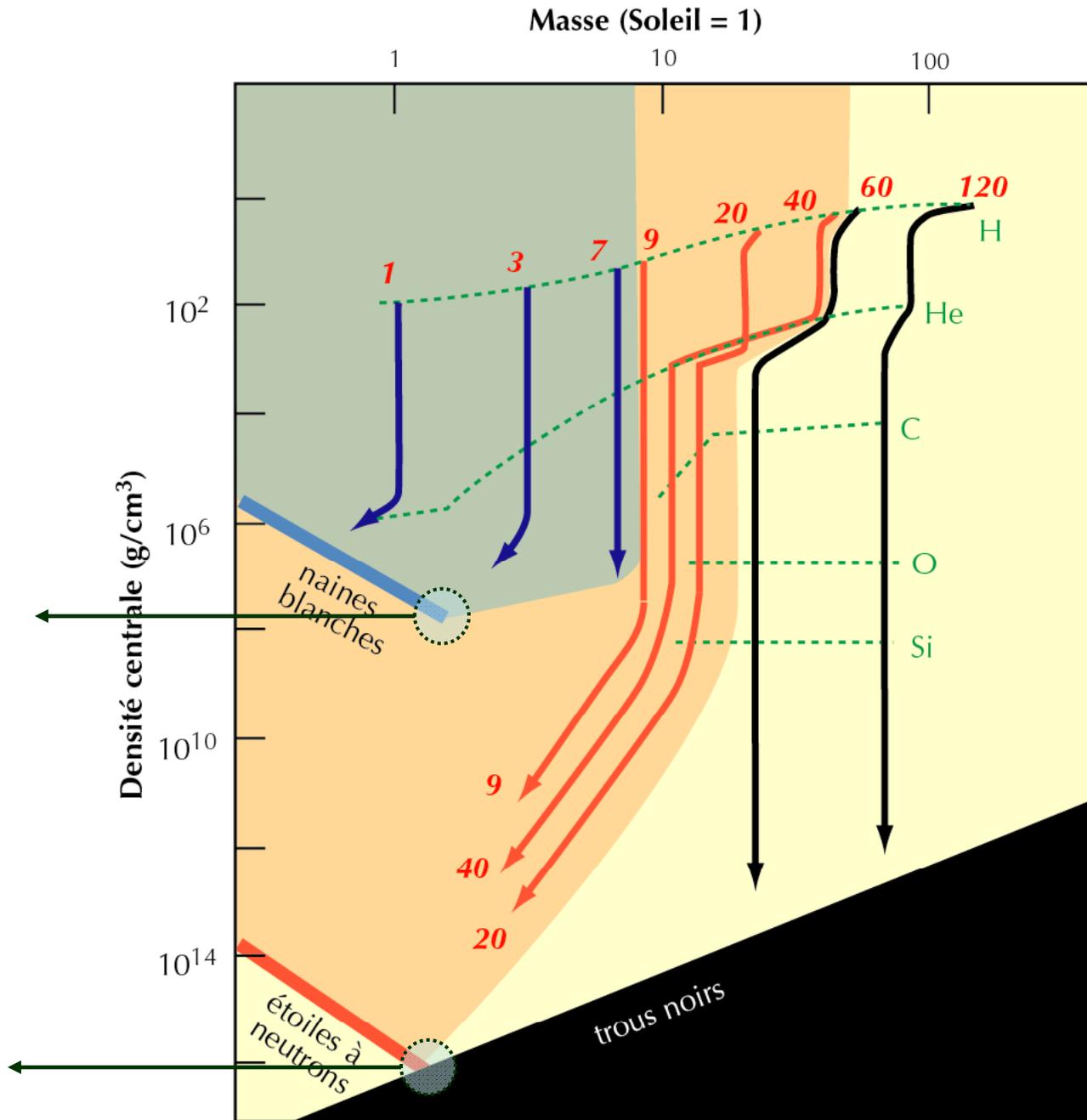
❖ Visualisation numérique

❖ Observation

# Etats « froids »

Limite de Chandrasekhar  
 $1,4 M_{\odot}$

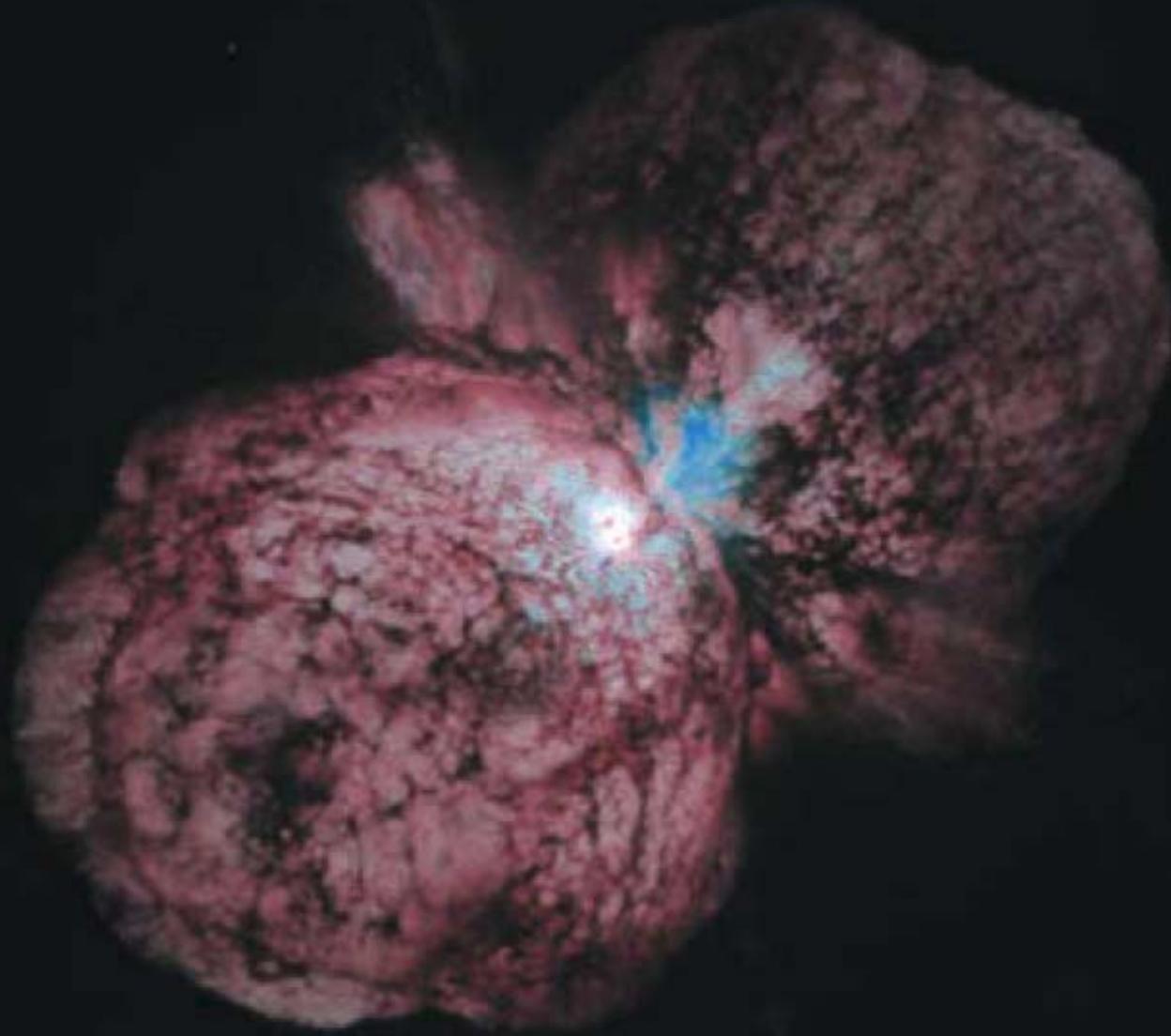
Limite de LOV  
 $\leq 3 M_{\odot}$



Si  $M_* > 40 M_S$

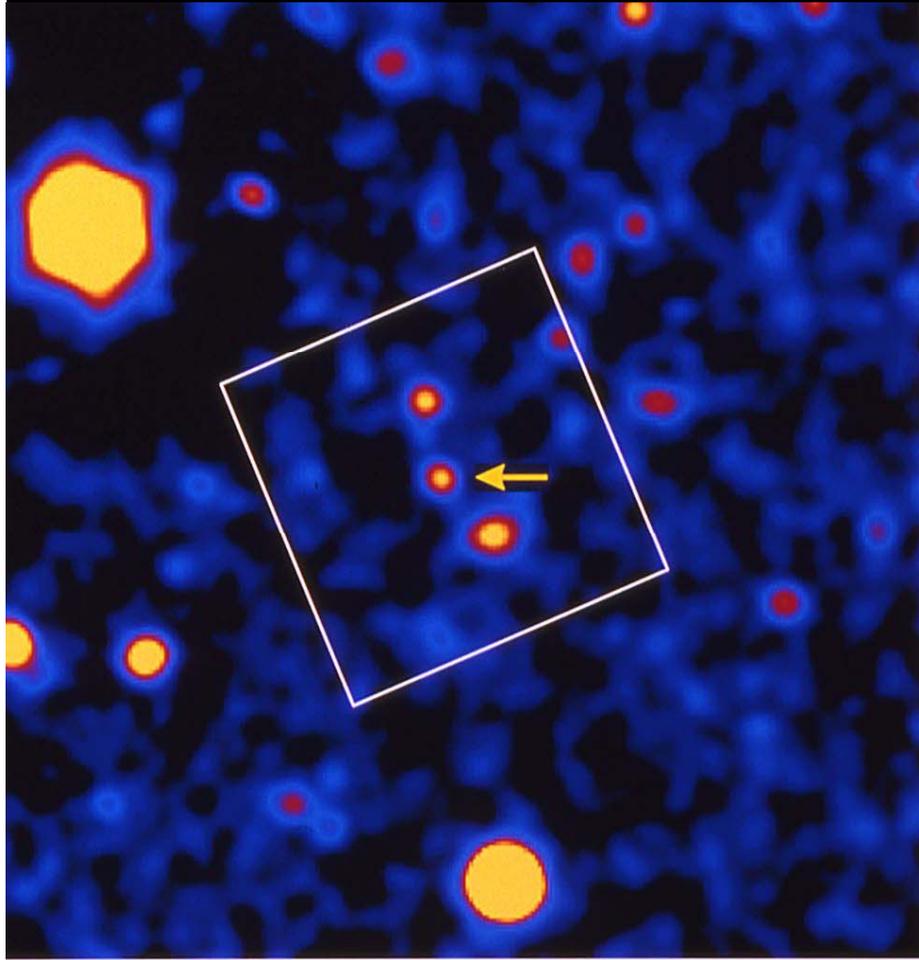
***TROU NOIR !***

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

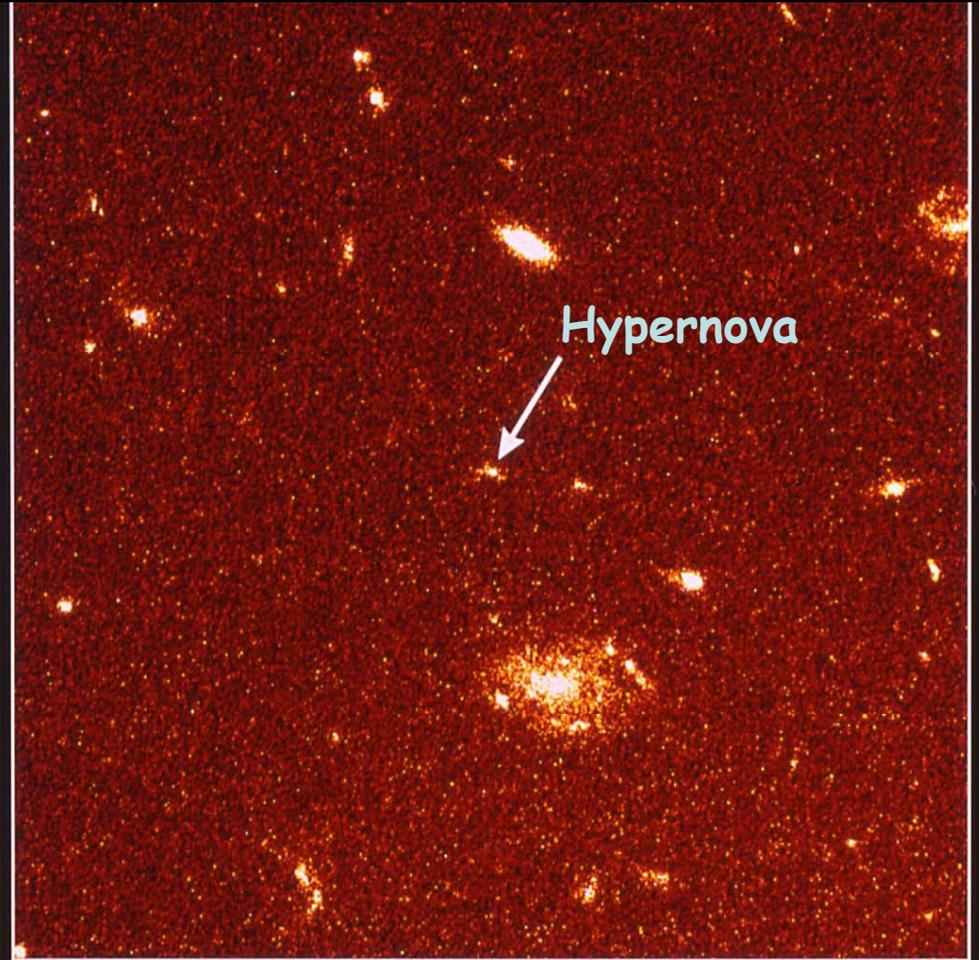


Une future hypernova ...

# Sursaut Gamma 971 214

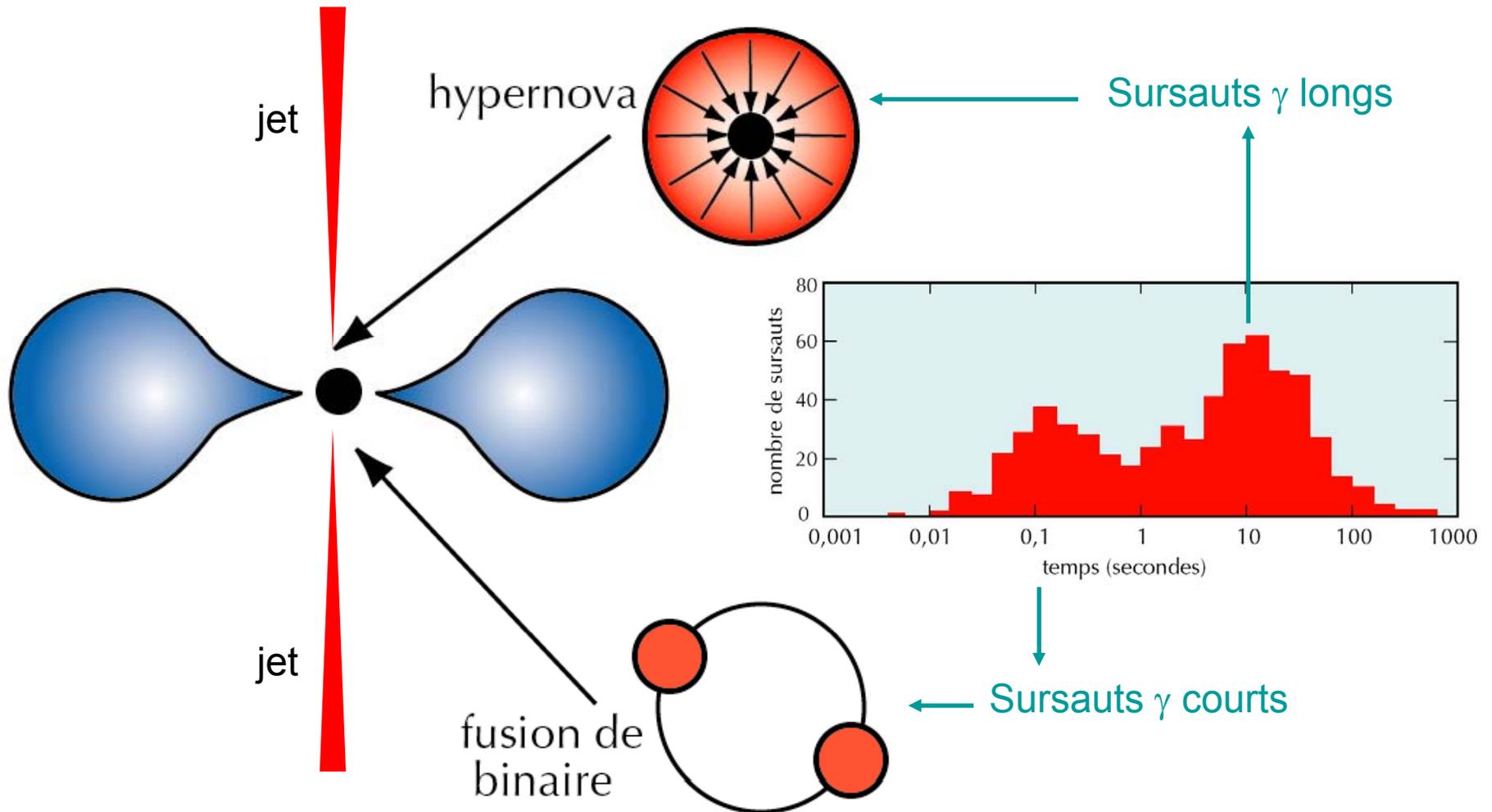


Keck • December 1997

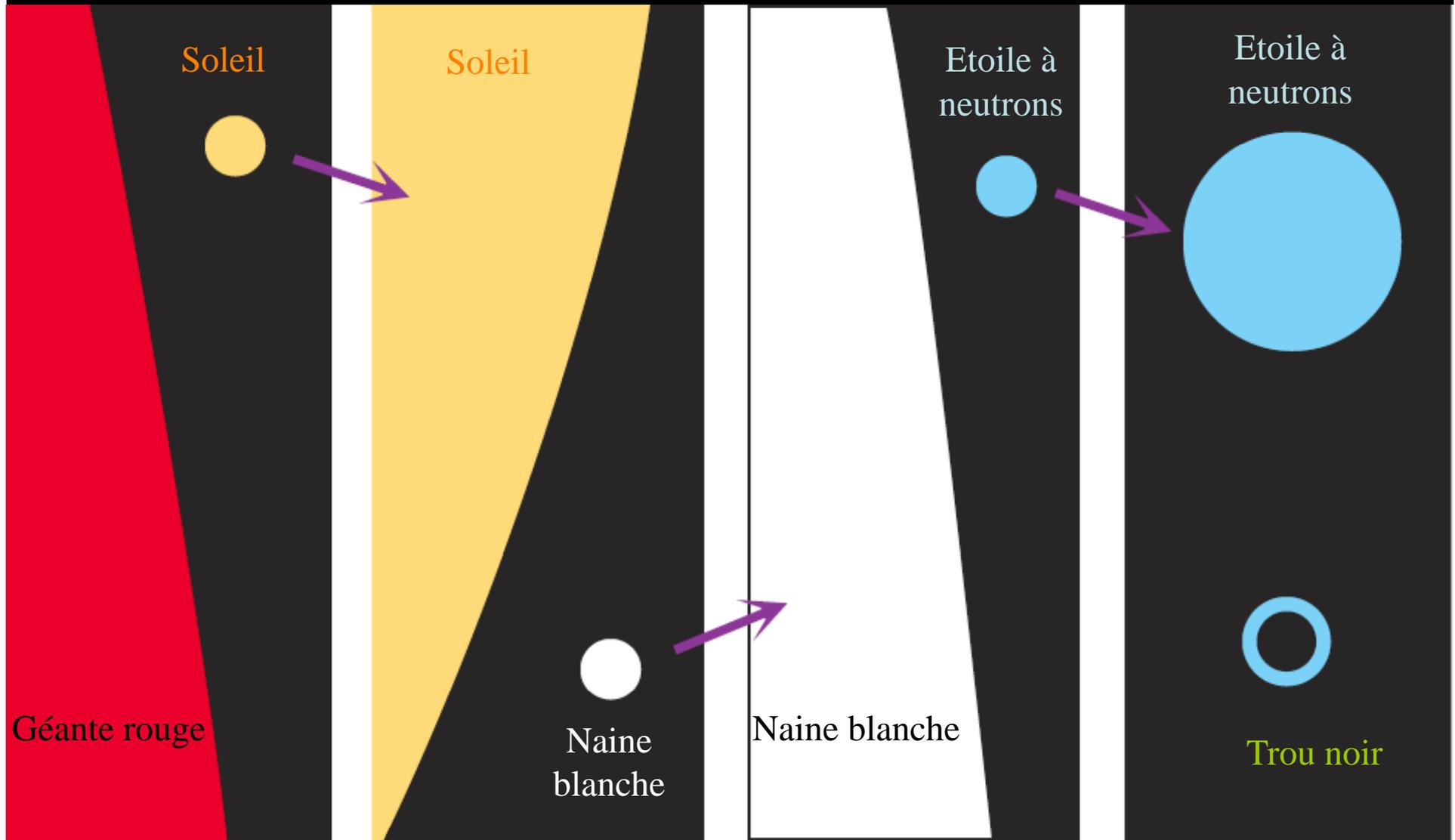


HST/STIS • February 1998

# Modélisation des Sursauts Gamma



# Tailles comparées des étoiles de $1 M_{\odot}$



$$R_s = 2GM/c^2 \sim 3 \text{ km } M/M_{\odot}$$

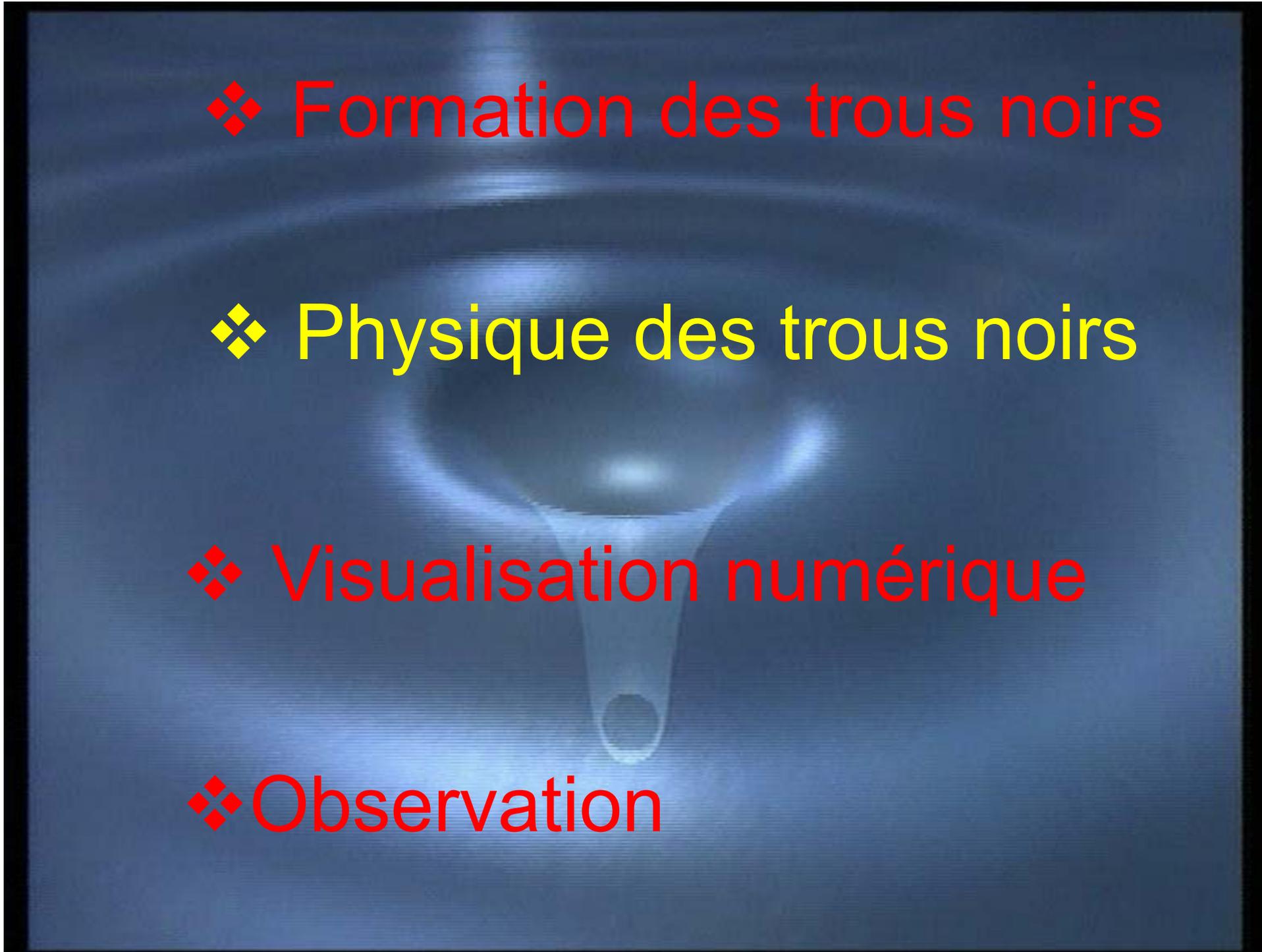
Un trou noir n'est pas  
nécessairement « dense » :

*masse volumique moyenne  $1/M^2$*

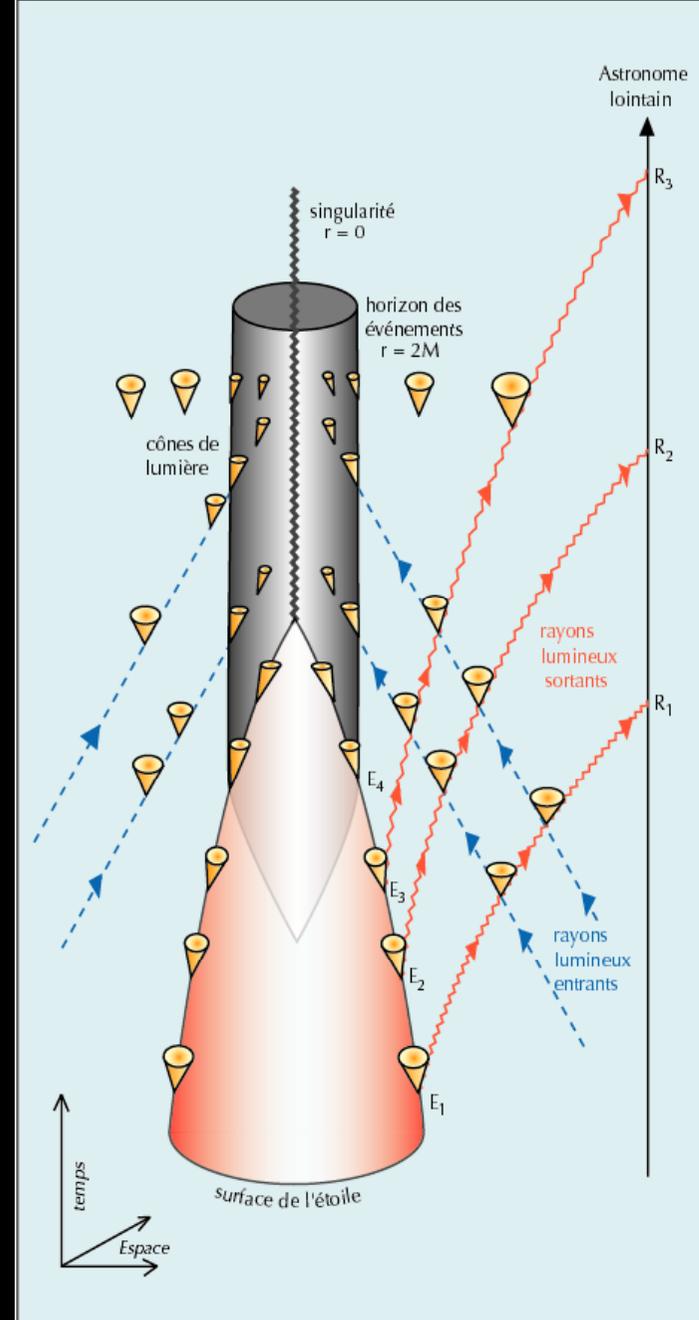
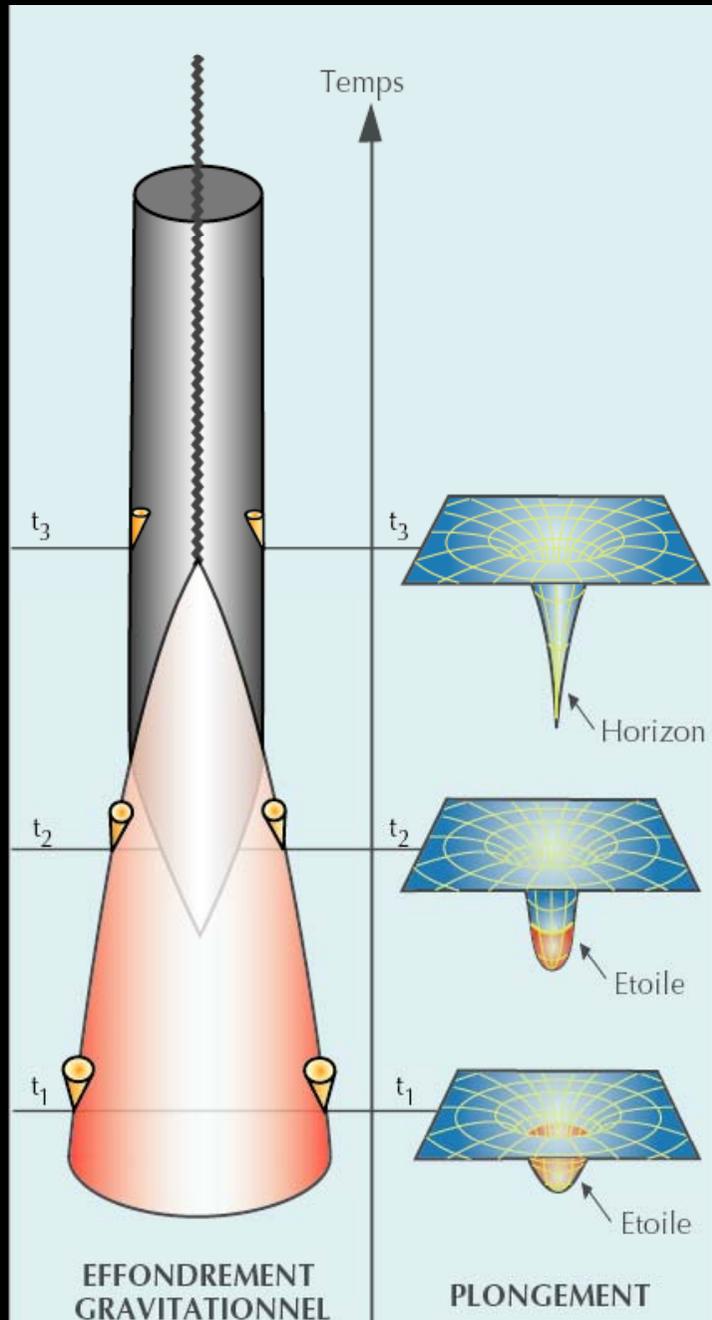
- Pour  $10 M_{\odot}$ ,  $\rho \sim 10^{15} \text{ g/cm}^3$
- Pour  $10^6 M_{\odot}$ ,  $\rho \sim 10^3 \text{ g/cm}^3$
- Pour  $10^9 M_{\odot}$ ,  $\rho \sim 10^{-3} \text{ g/cm}^3$

Un trou noir est un objet ***compact***

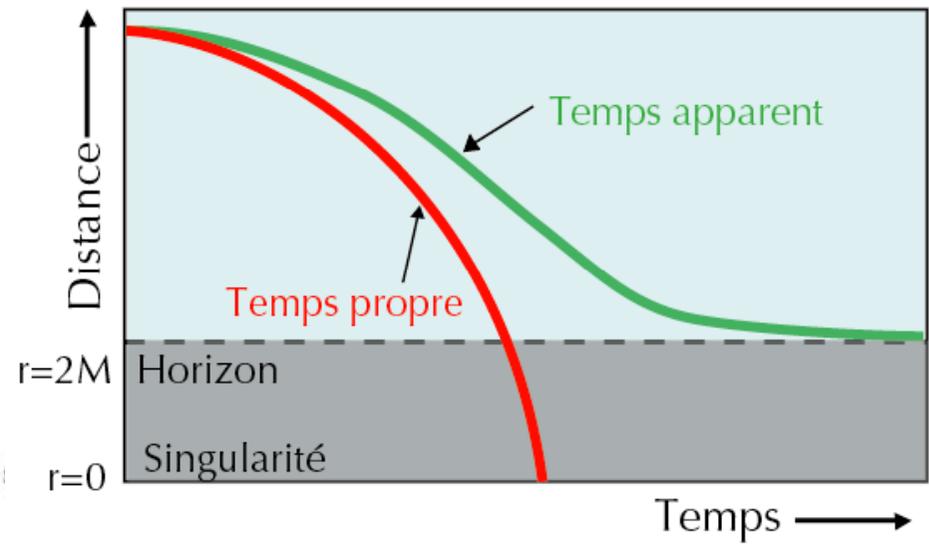
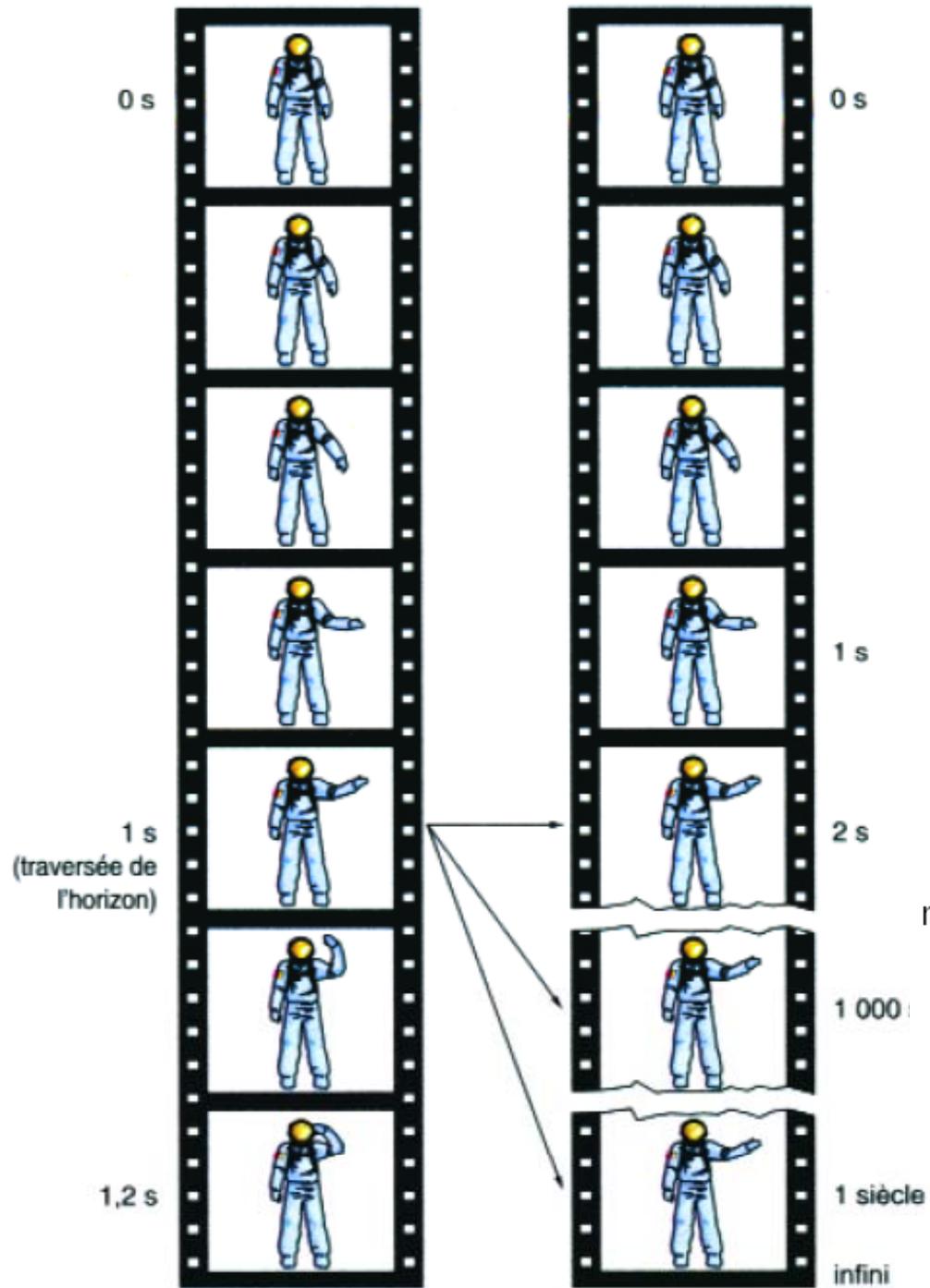
*Taille réelle/Taille critique  $\sim 1$*

- 
- ❖ Formation des trous noirs
  - ❖ Physique des trous noirs
  - ❖ Visualisation numérique
  - ❖ Observation

# Effondrement sphérique (Schwarzschild)

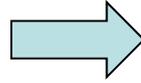


# Gel du temps

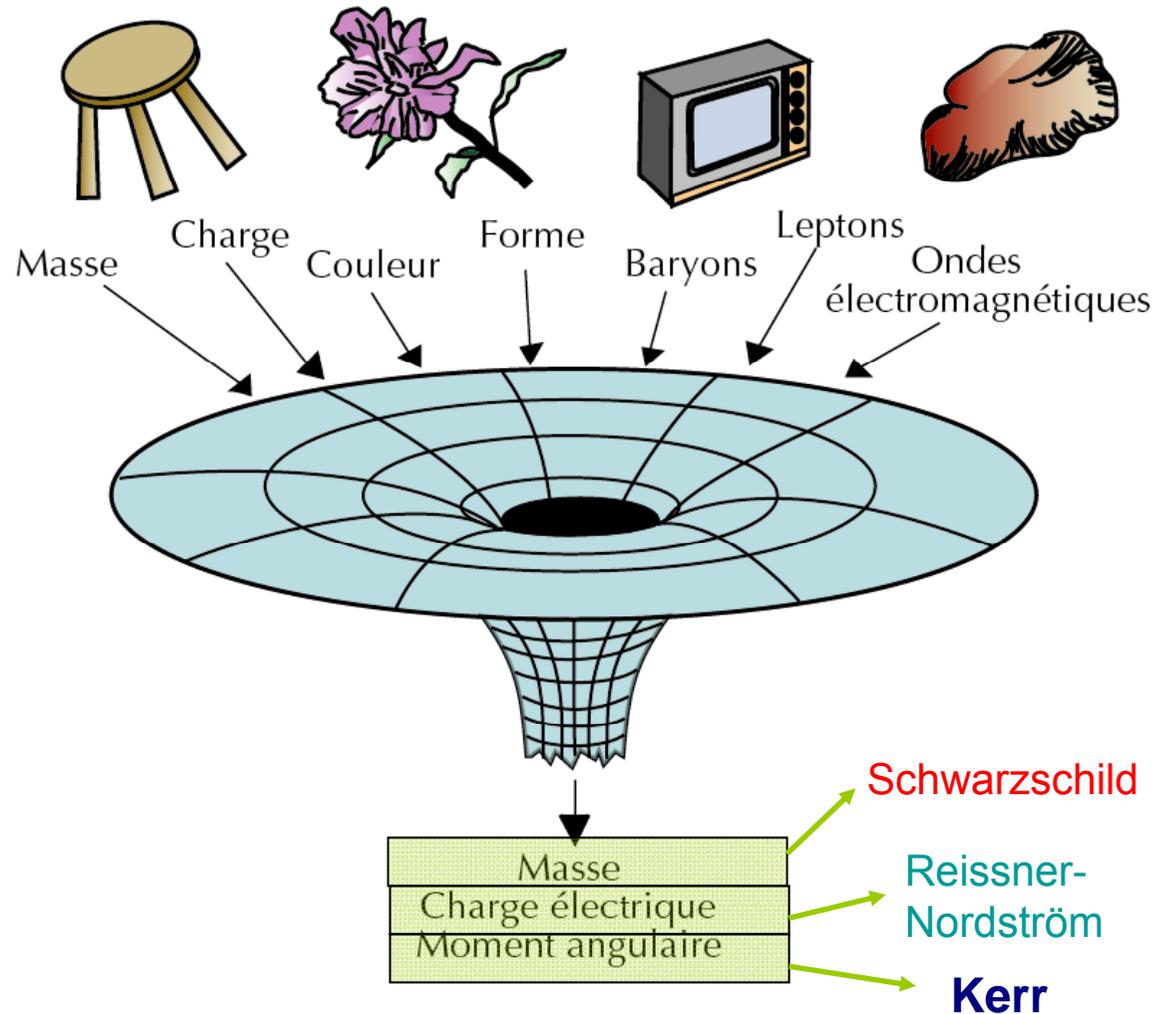
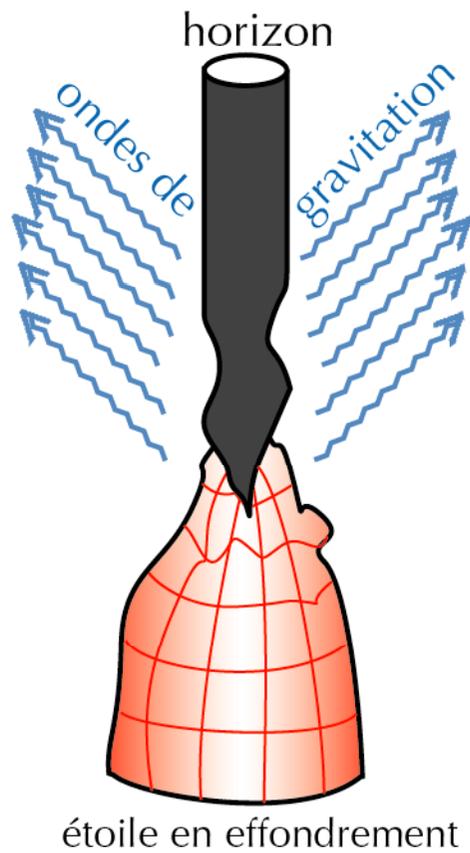


# Effondrement non sphérique

Ondes gravitationnelles



Théorème « No hair »



# Le trou noir de Kerr

(J,M) avec  $J < M^2$

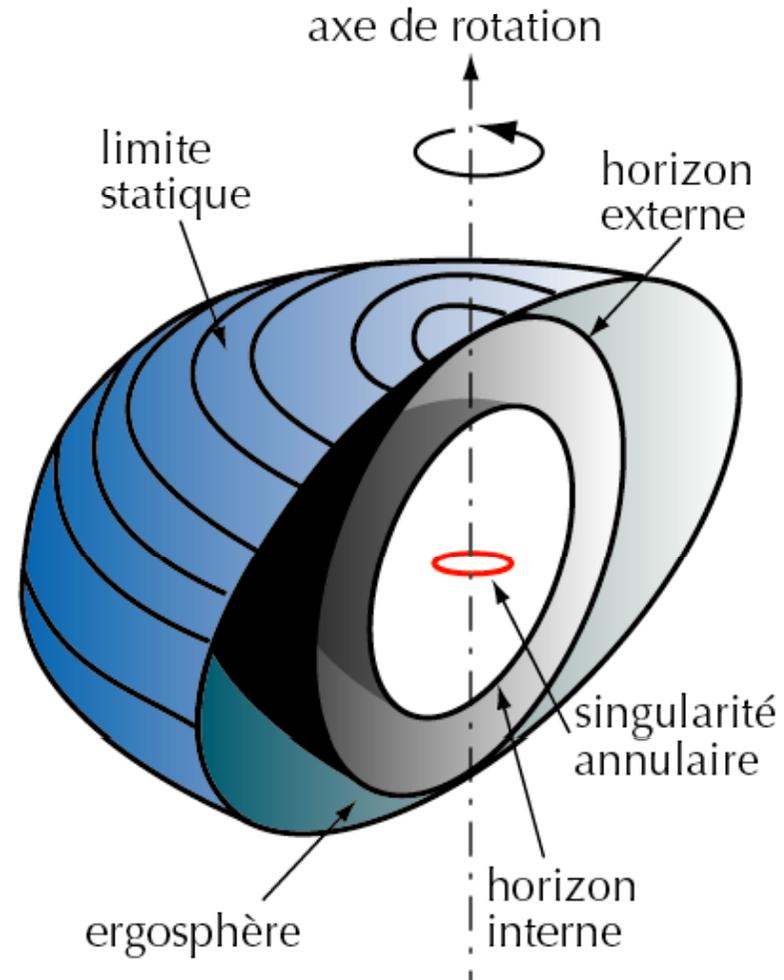
Energie totale :

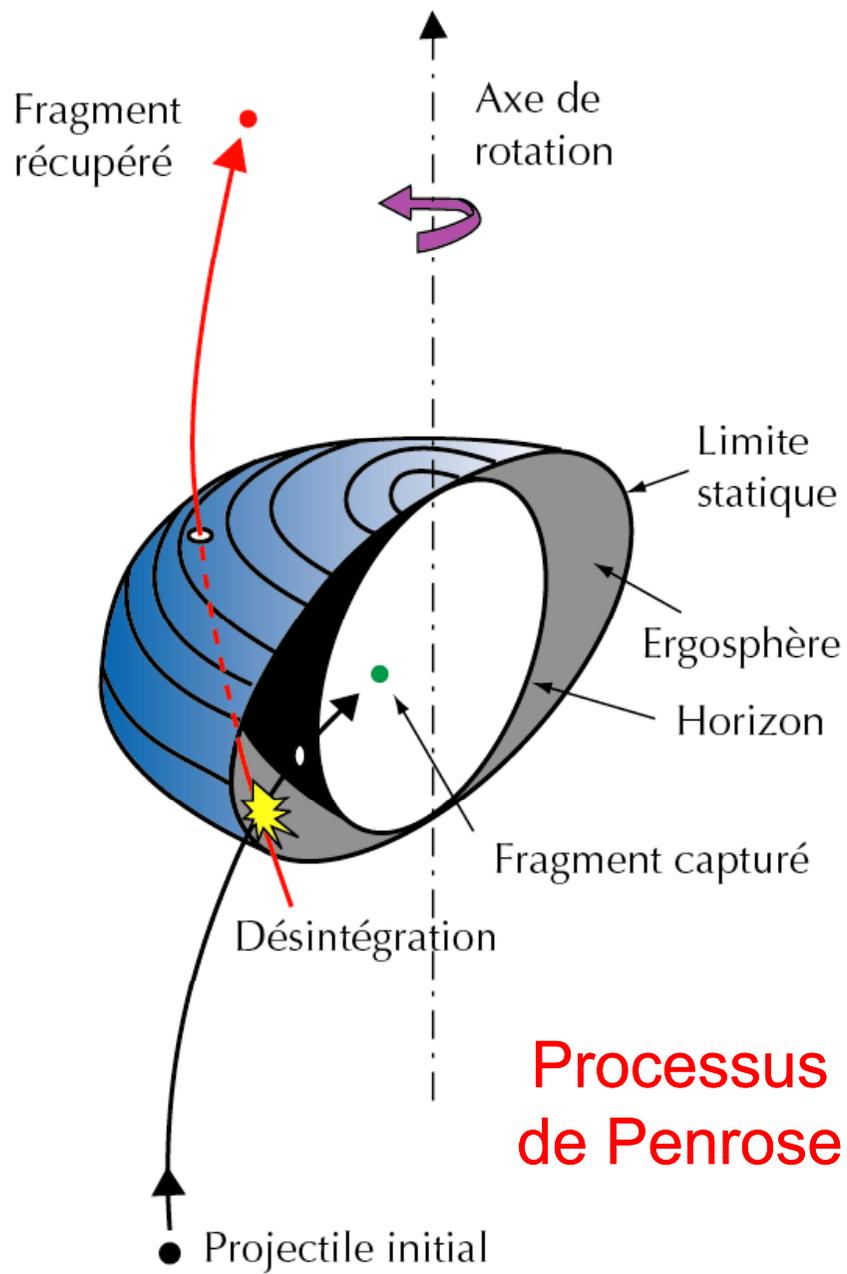
$$M^2 = J^2/4M_{ir}^2 + M_{ir}^2$$

↓  
Energie  
rotationnelle

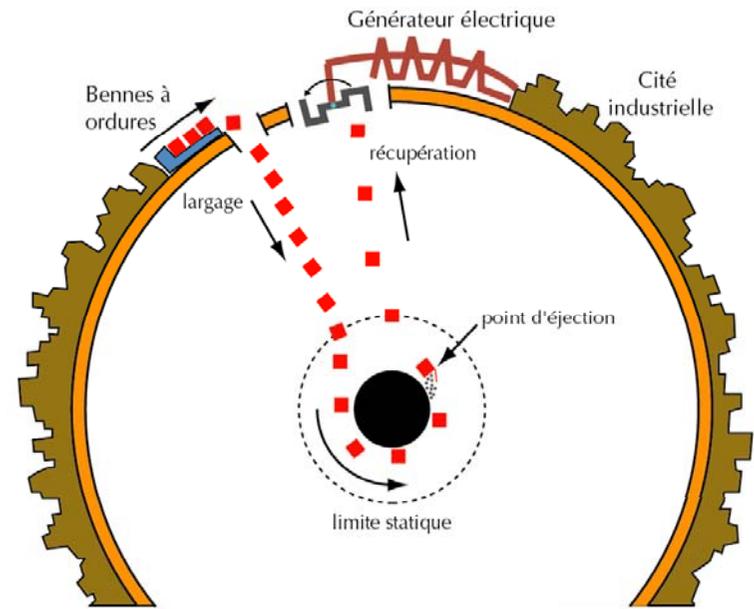
↓  
Masse  
irréductible

↓  
Peut être extraite



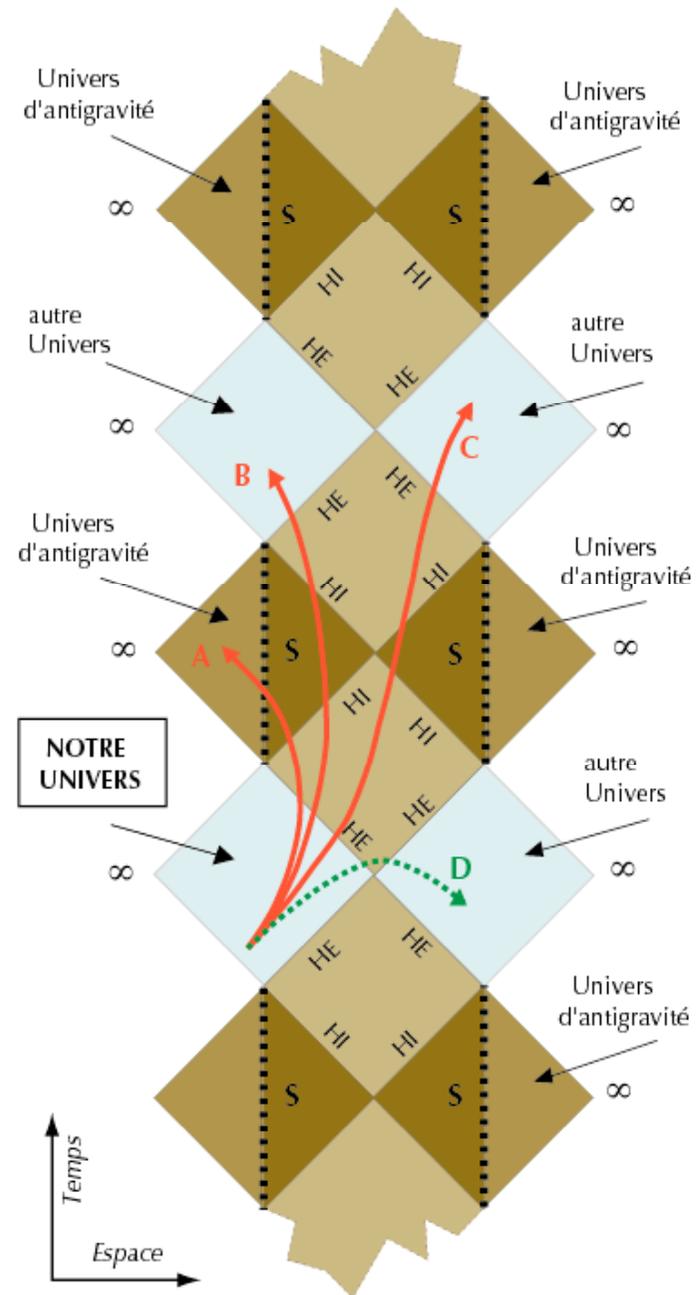
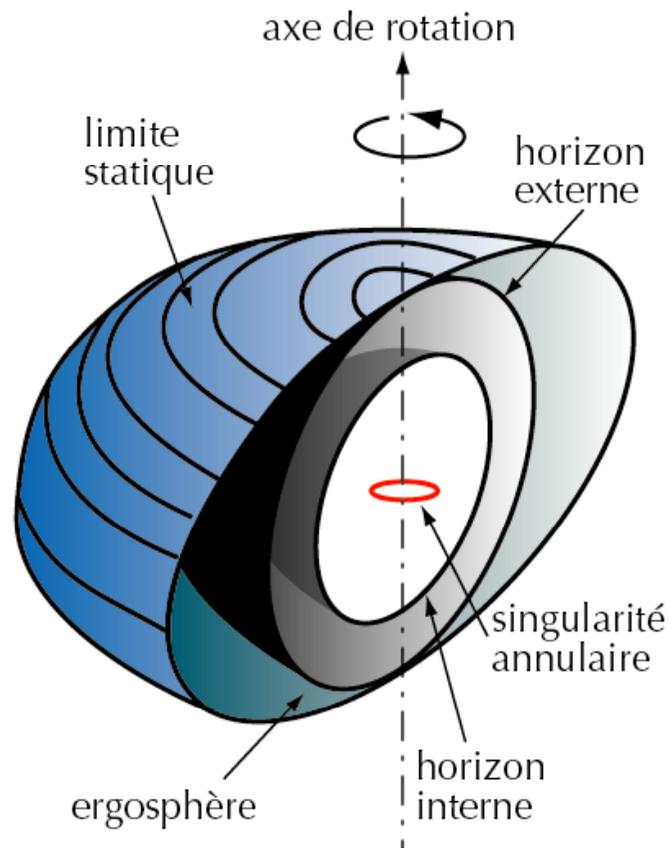


**Processus de Penrose**



**jusqu'à 29%**

# Trou noir & Trou de ver



# Thermodynamique des trous noirs

aire entropie ?

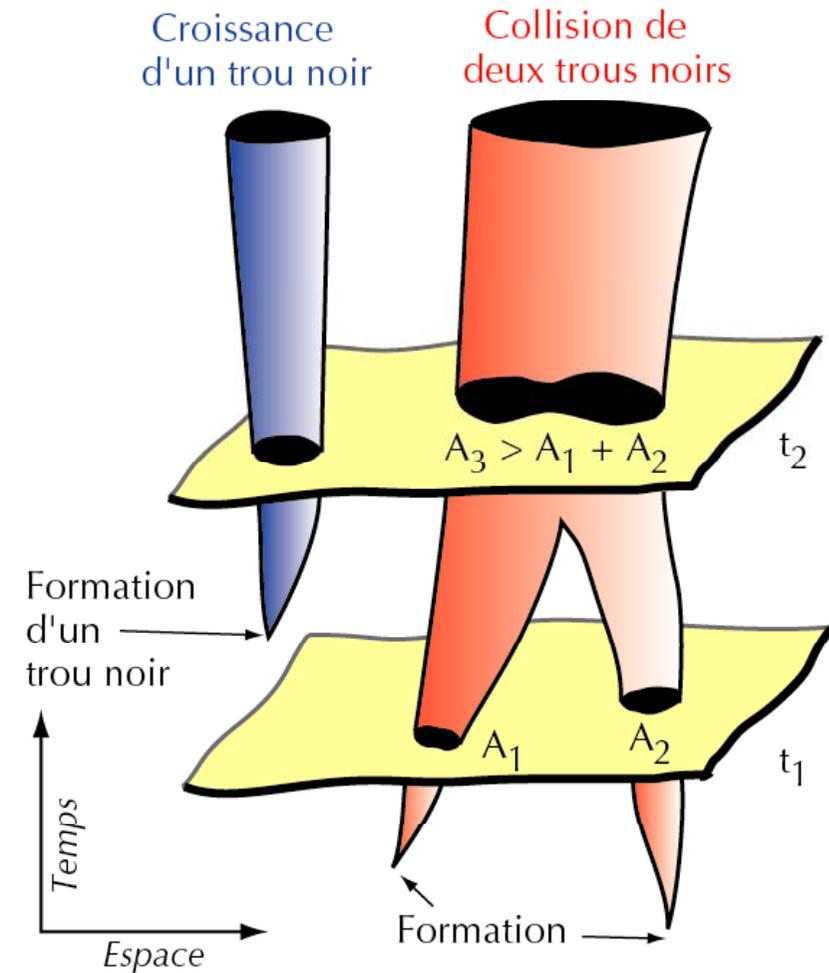
$$S = A/4$$

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

température gravité  
de surface ?

$$T = g/2\pi$$

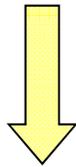
$$T(K) = 10^{-7} M_S/M$$



$$dA > 0$$

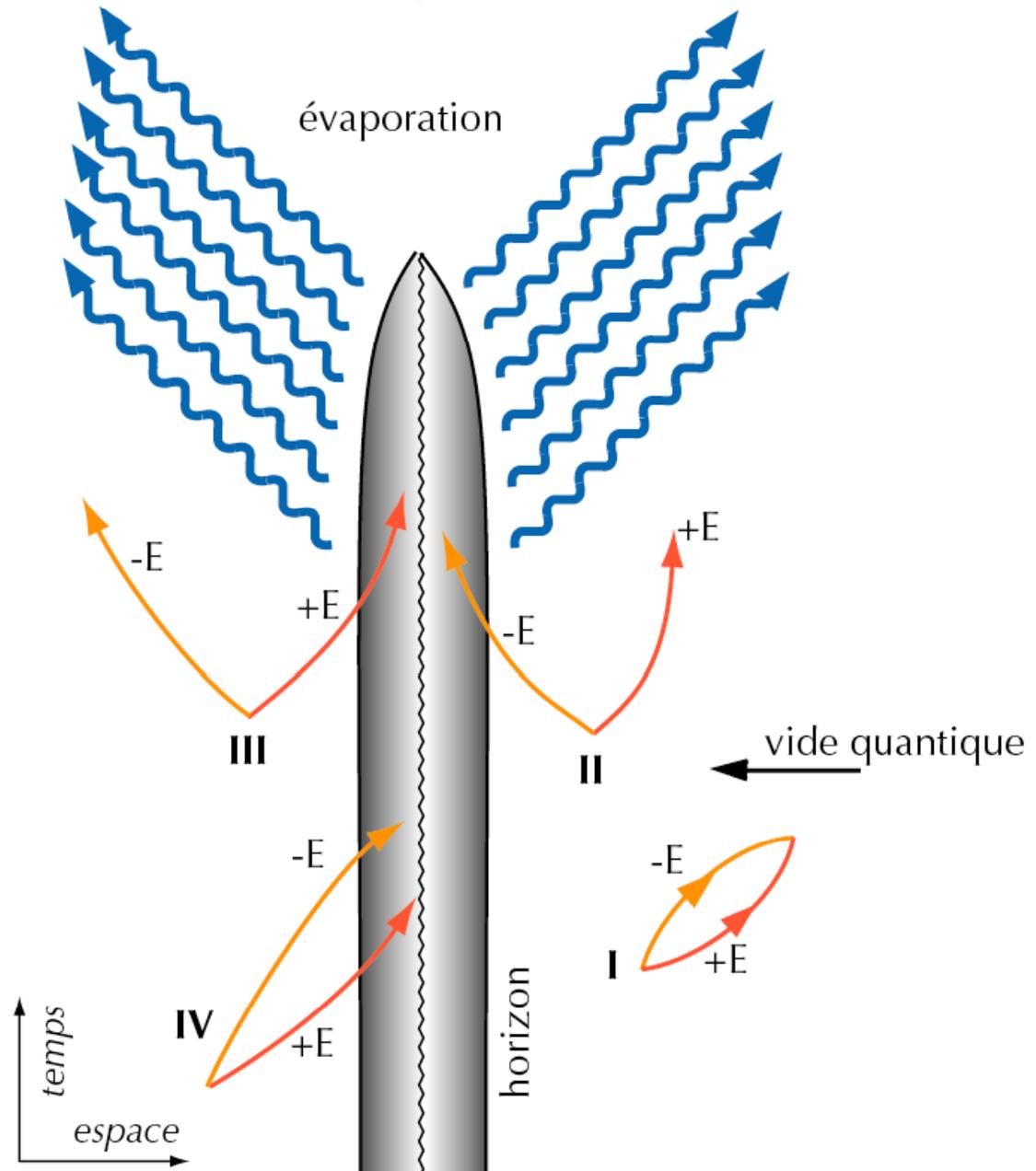
# Evaporation quantique des mini- trous noirs

( $M < 10^{15}$  g)

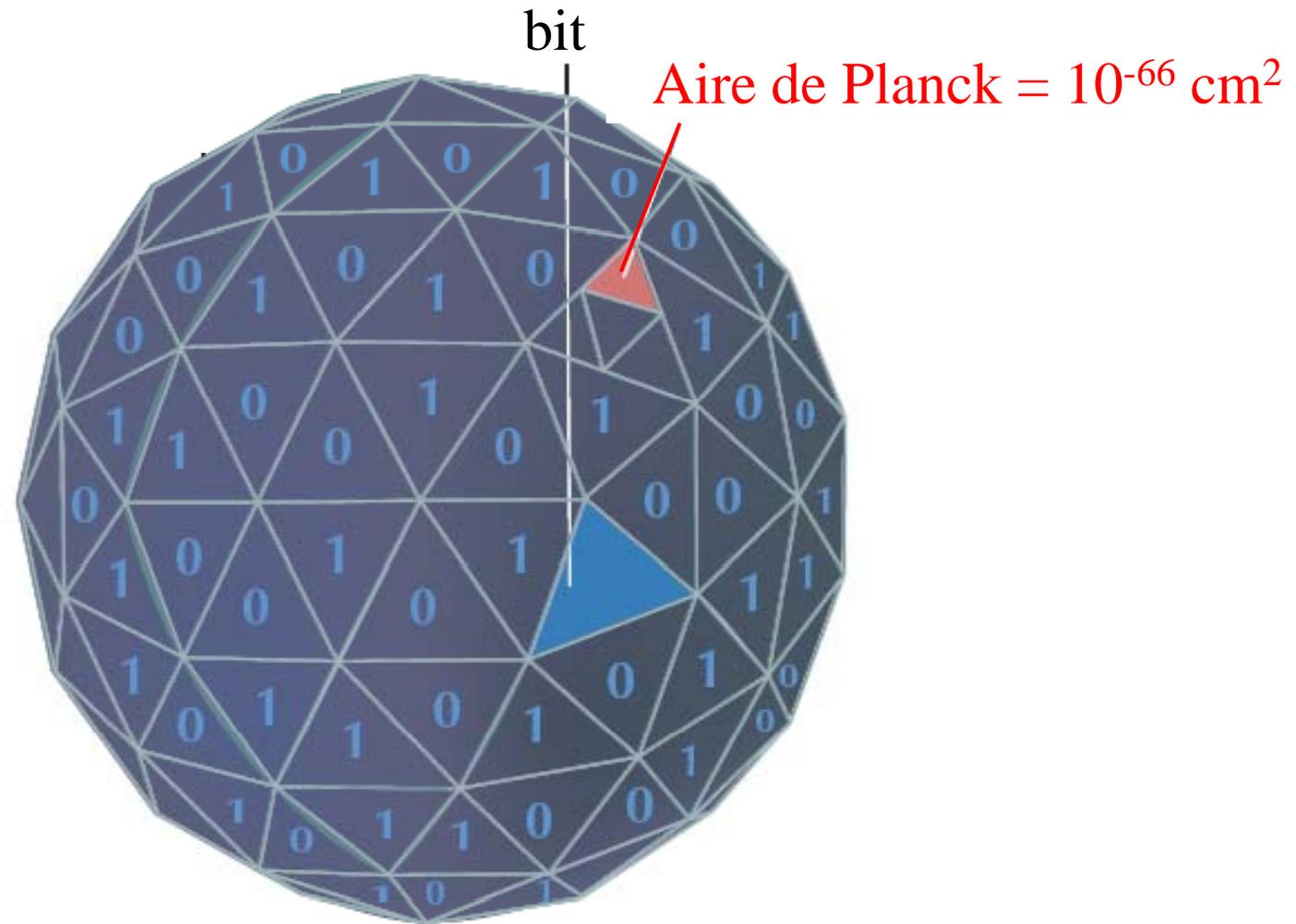


Paradoxe de  
l'information  
(unitarité)

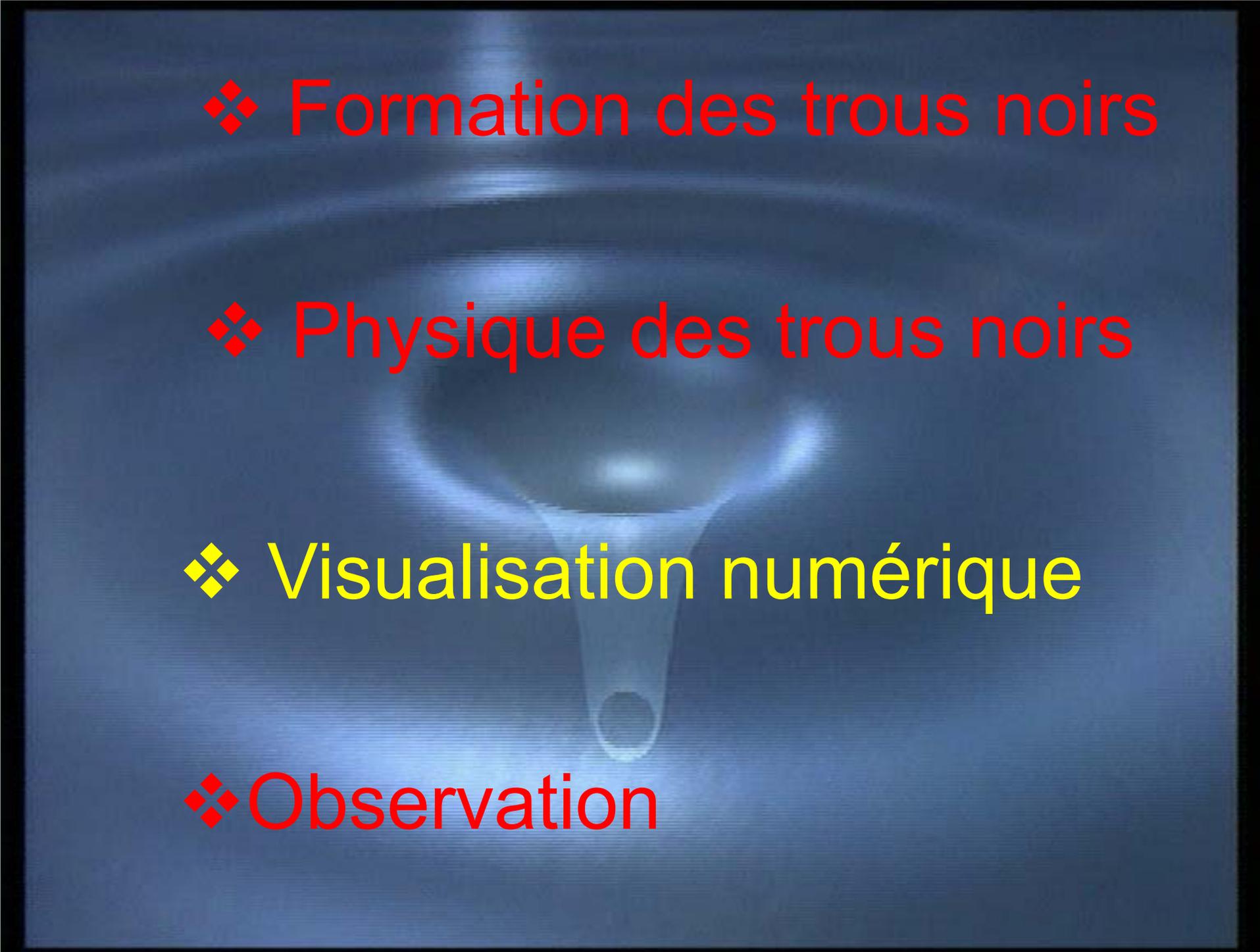
Hawking, 1975



# Le trou noir est-il holographique ?



→  $S = A/4$

- 
- ❖ Formation des trous noirs
  - ❖ Physique des trous noirs
  - ❖ Visualisation numérique
  - ❖ Observation

J.-P. Luminet

*Astron. Astrophys.* **75**, 228-  
235 (1979)

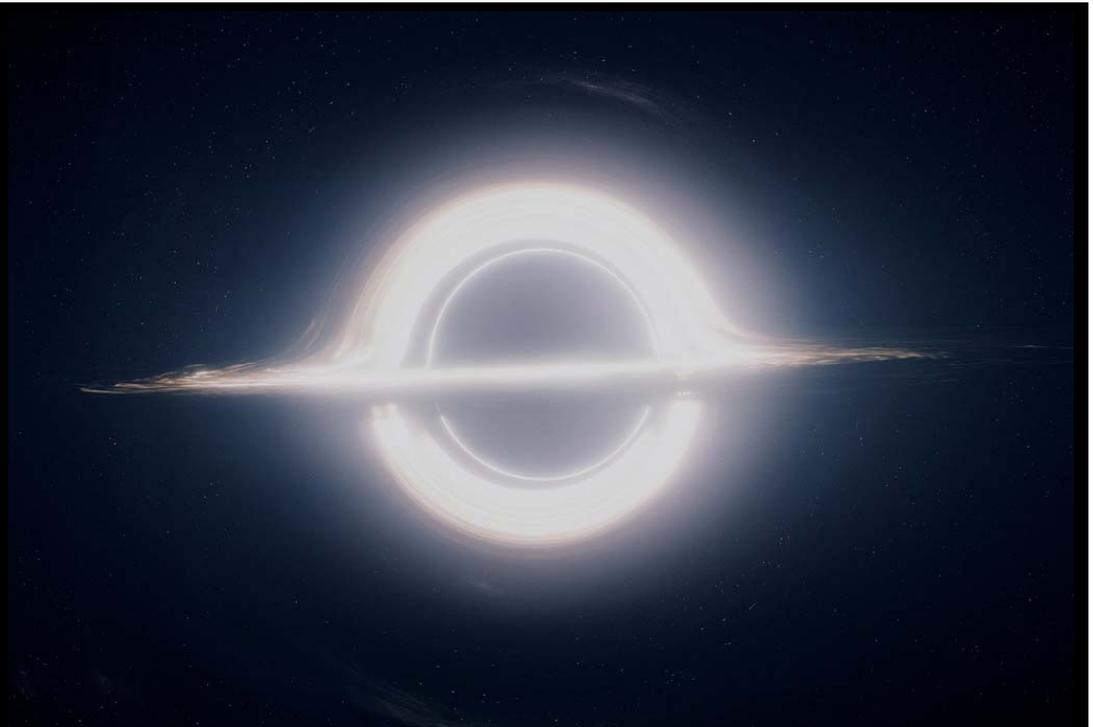


J.-A. Marck

*Class. Quant. Grav.* **13**,  
393-402 (1996)



Thorne et al.  
Interstellar (2014)

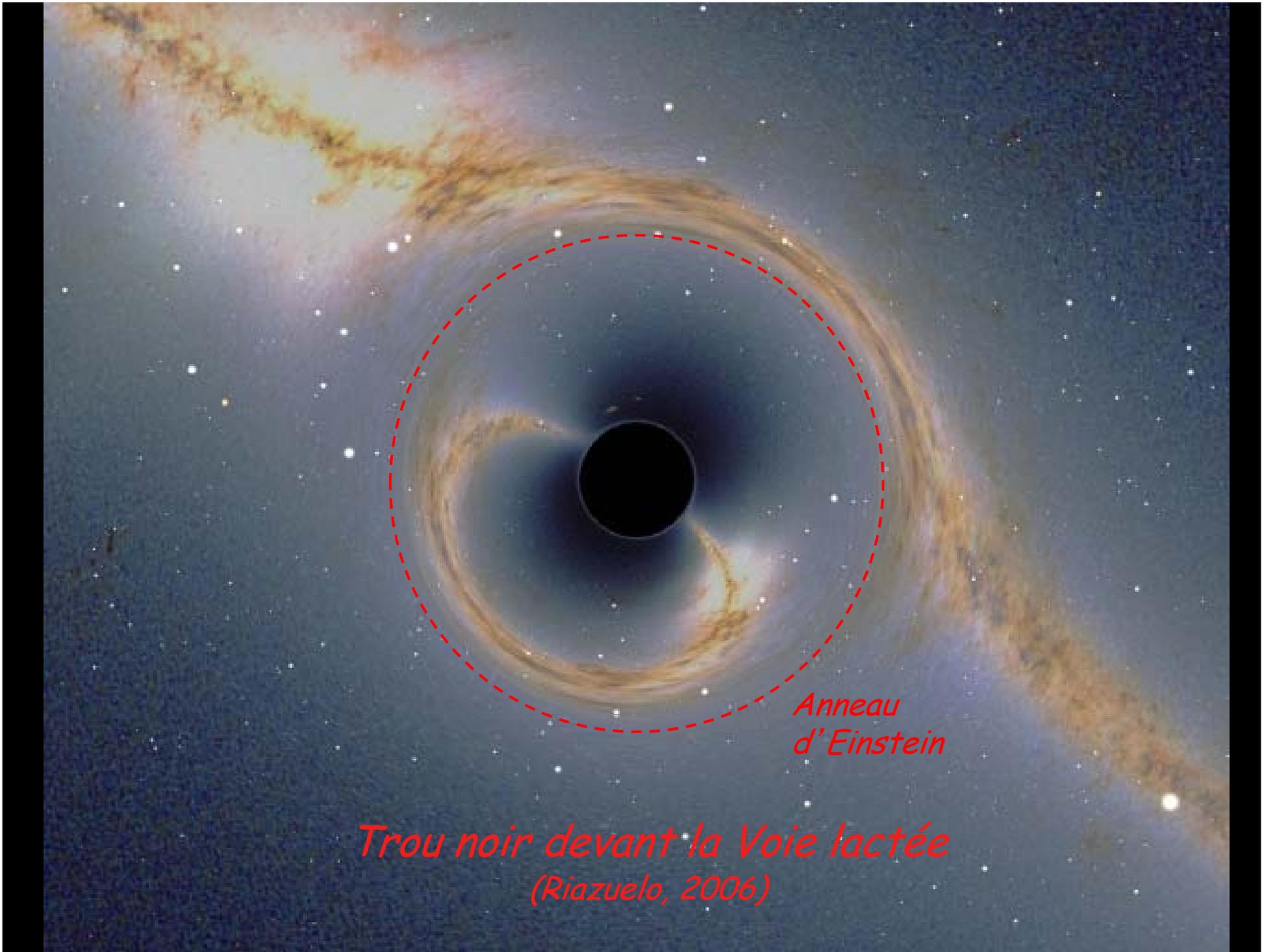


J.-P. Luminet & J.-A. Marck  
Pour la Science (1997)





*Effet de mirage gravitationnel*



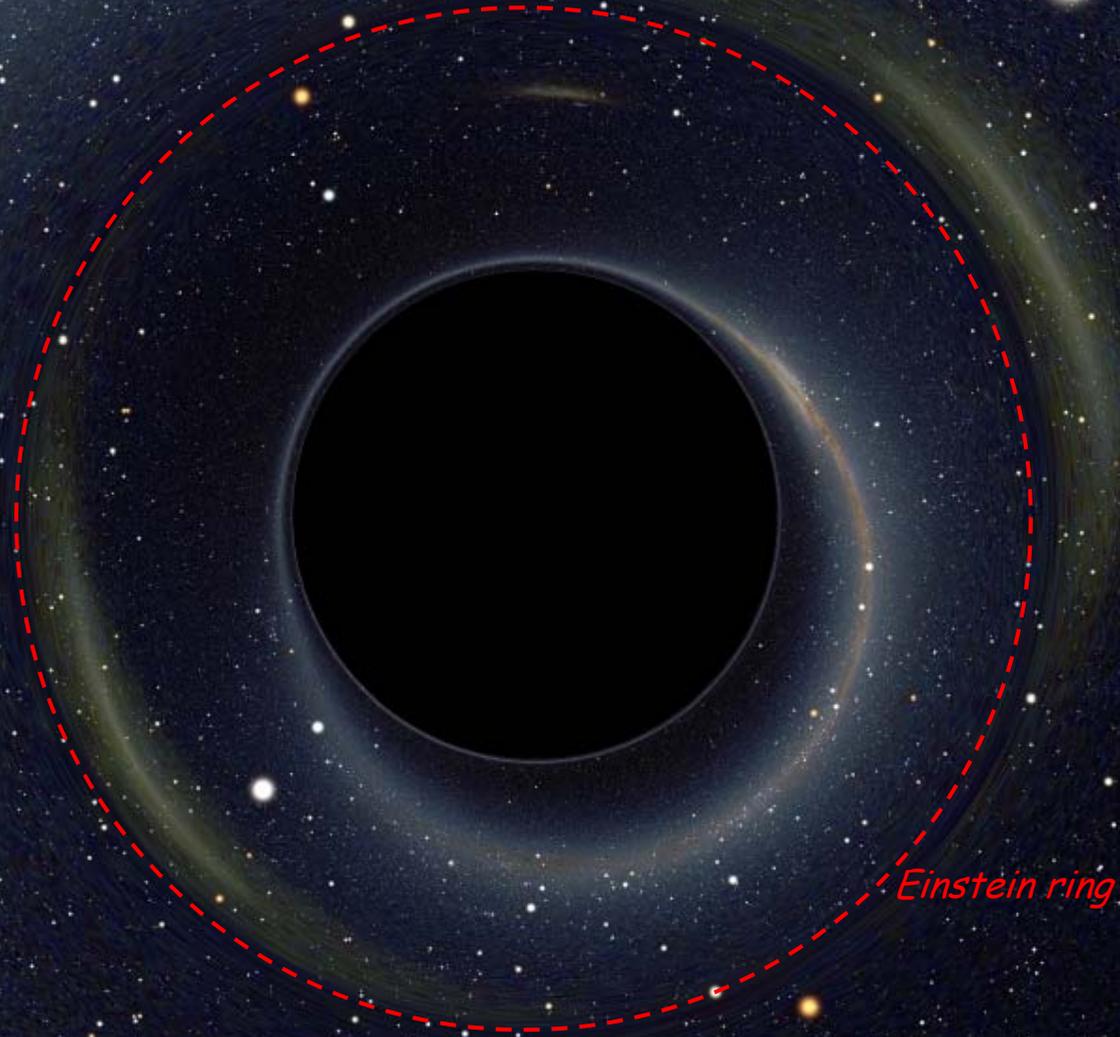
*Anneau  
d'Einstein*

*Trou noir devant la Voie lactée  
(Riazuelo, 2006)*

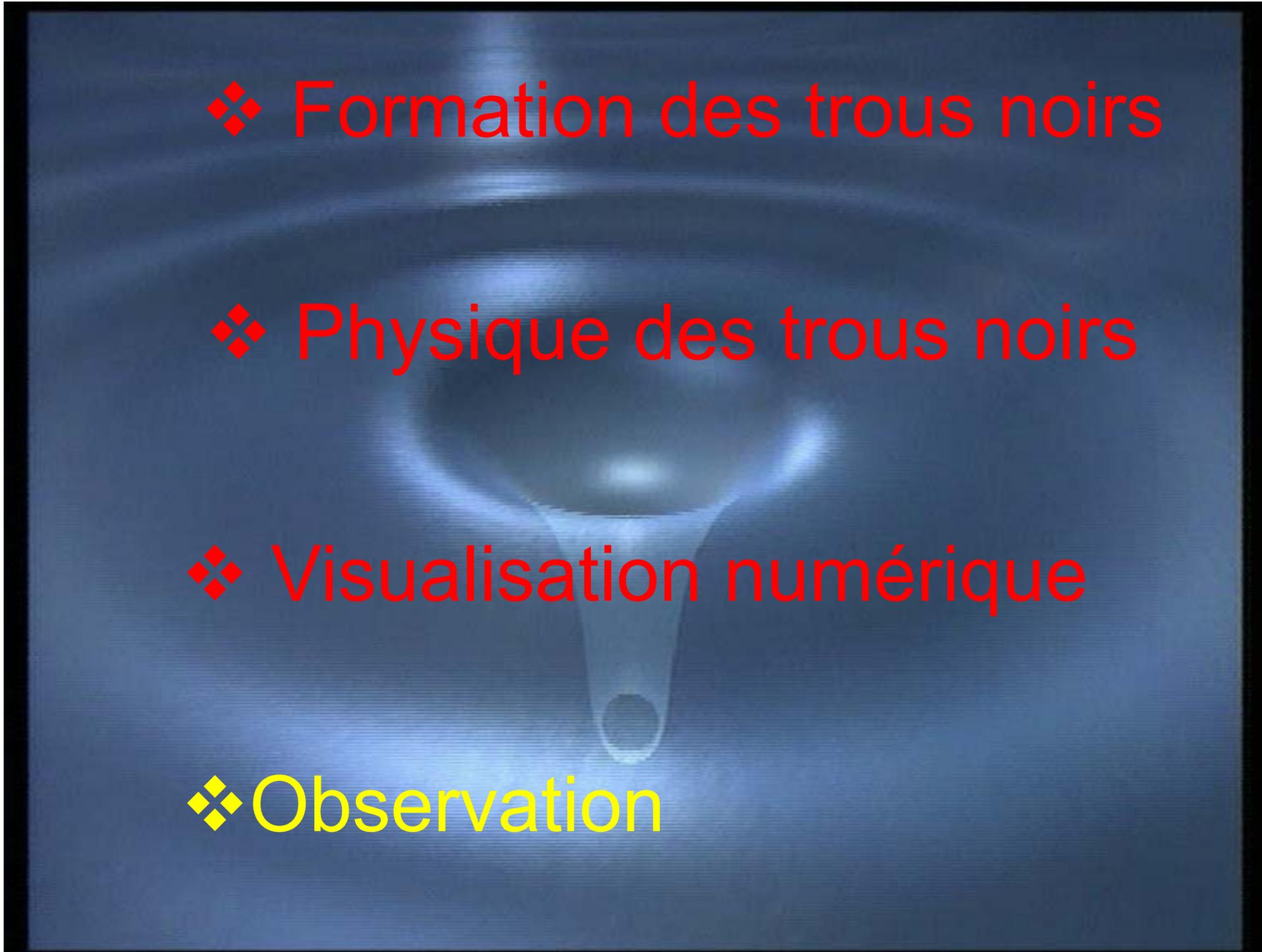


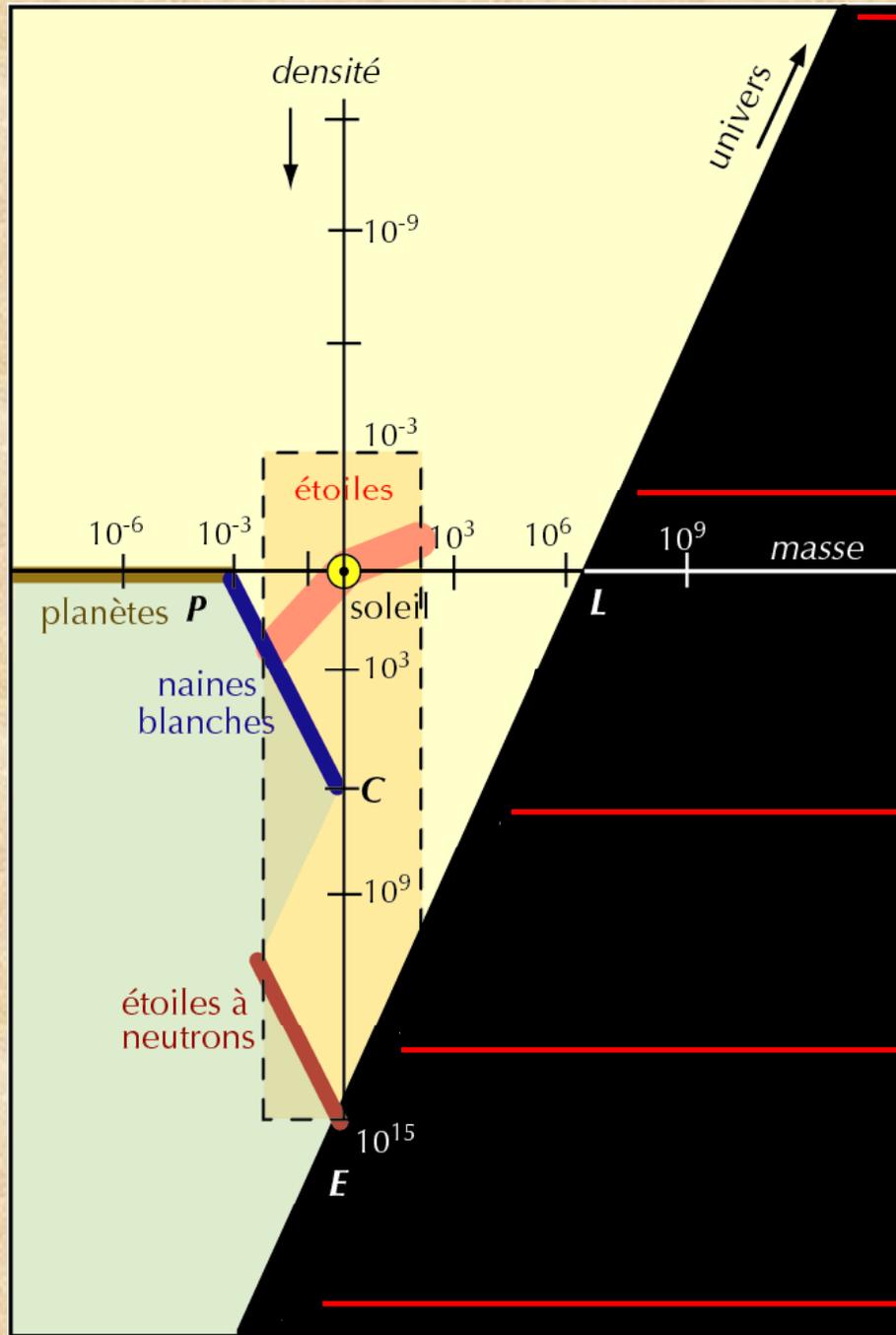
*Trou noir devant les Nuages de Magellan*

*(A. Riazuelo, 2006)*



*Einstein ring*

- 
- ❖ Formation des trous noirs
  - ❖ Physique des trous noirs
  - ❖ Visualisation numérique
  - ❖ Observation



Trou noir Univers?

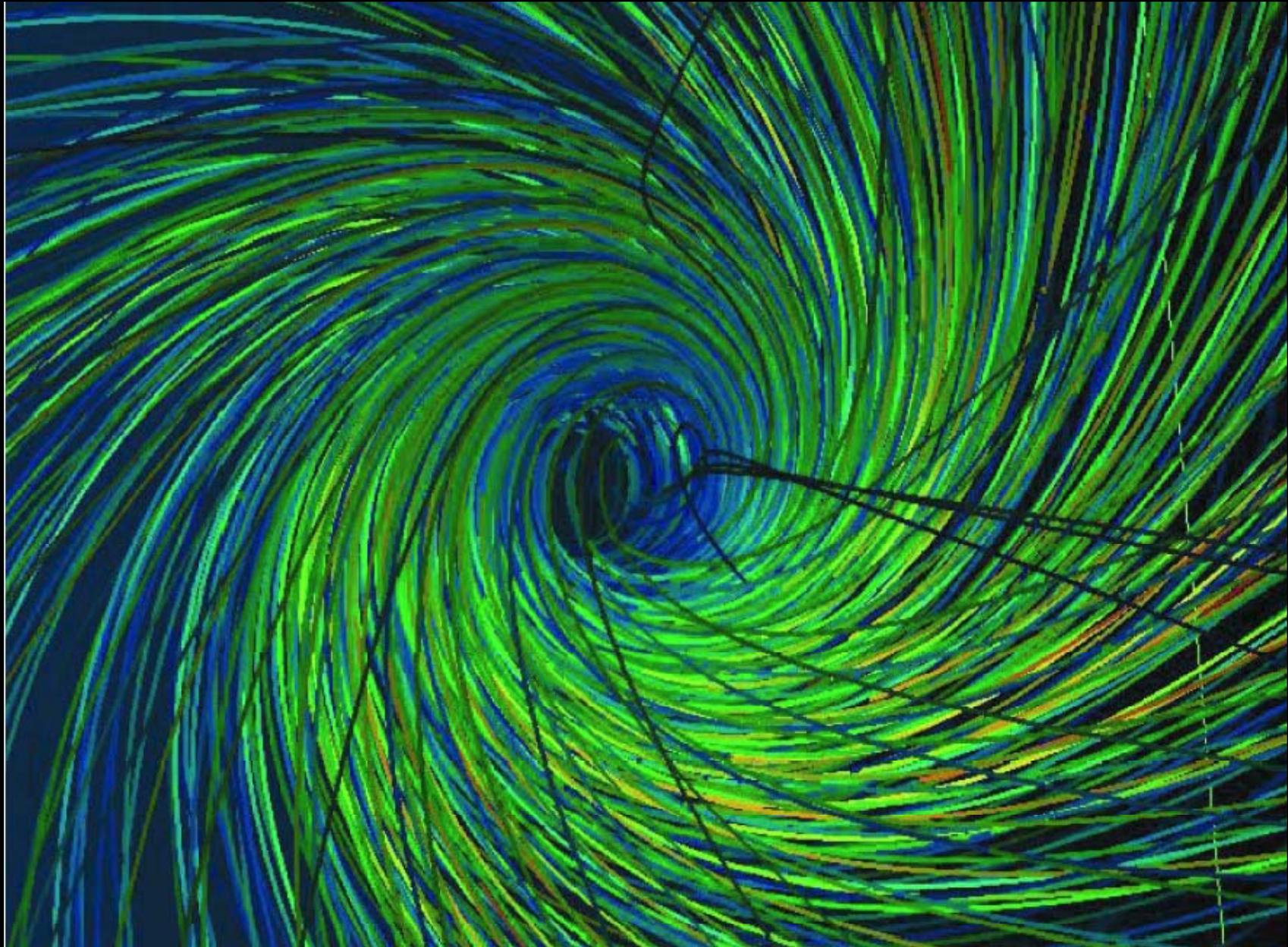
Trous noirs géants

Trous noirs intermédiaires

Trous noirs stellaires

Mini-trous noirs

# Détection des mini-trous noirs ( $M < 10^{15}$ g)



# Détection des trous noirs stellaires

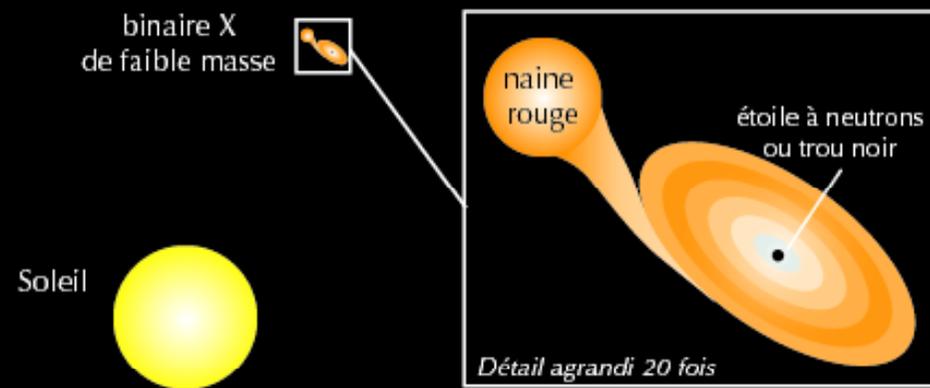
$(3 M_{\odot} < M < 100 M_{\odot})$

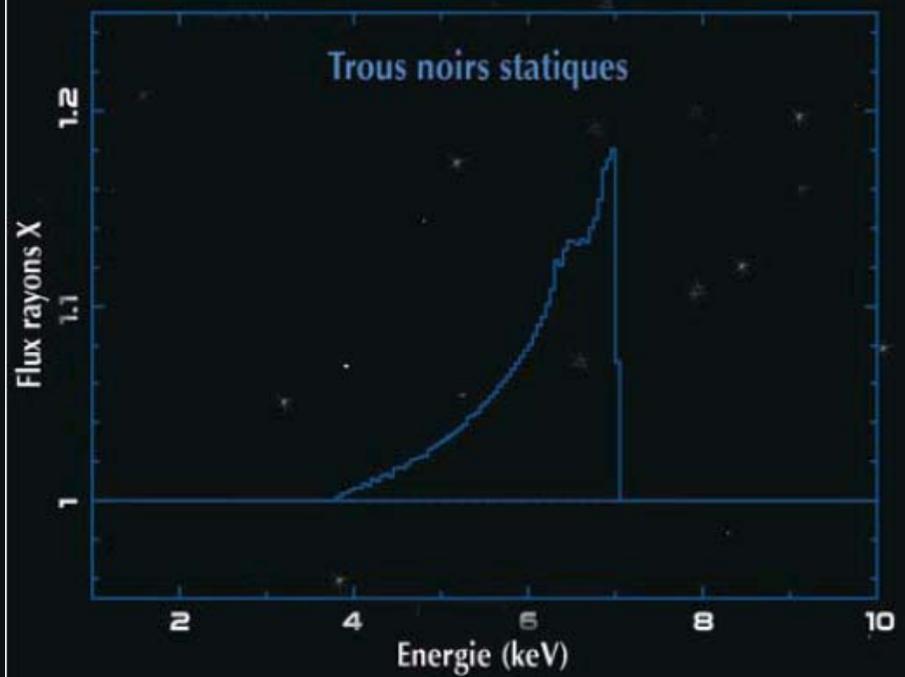
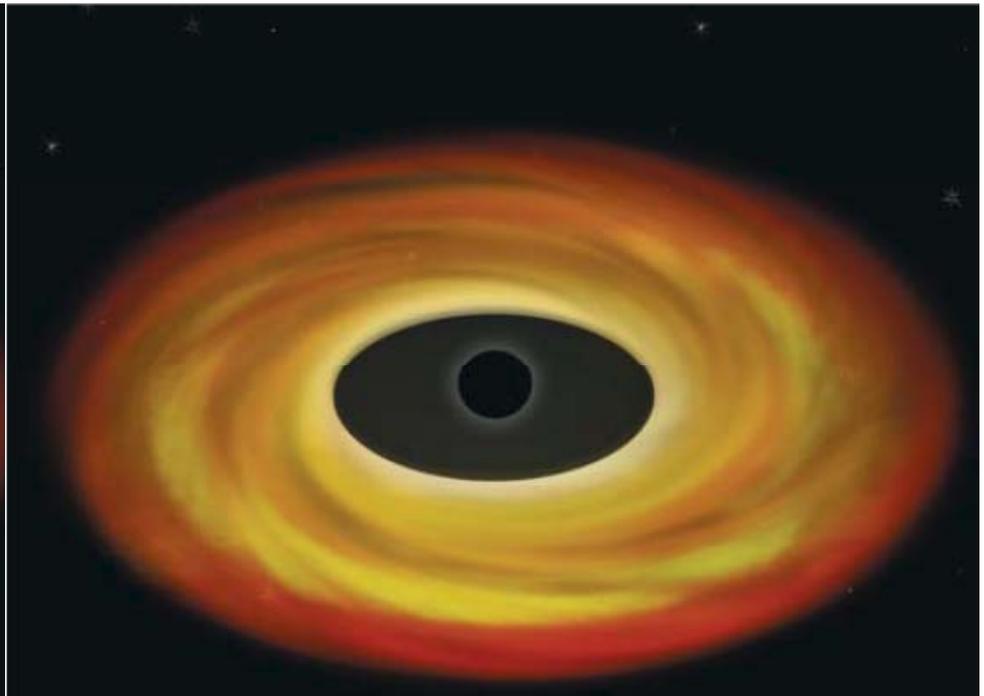
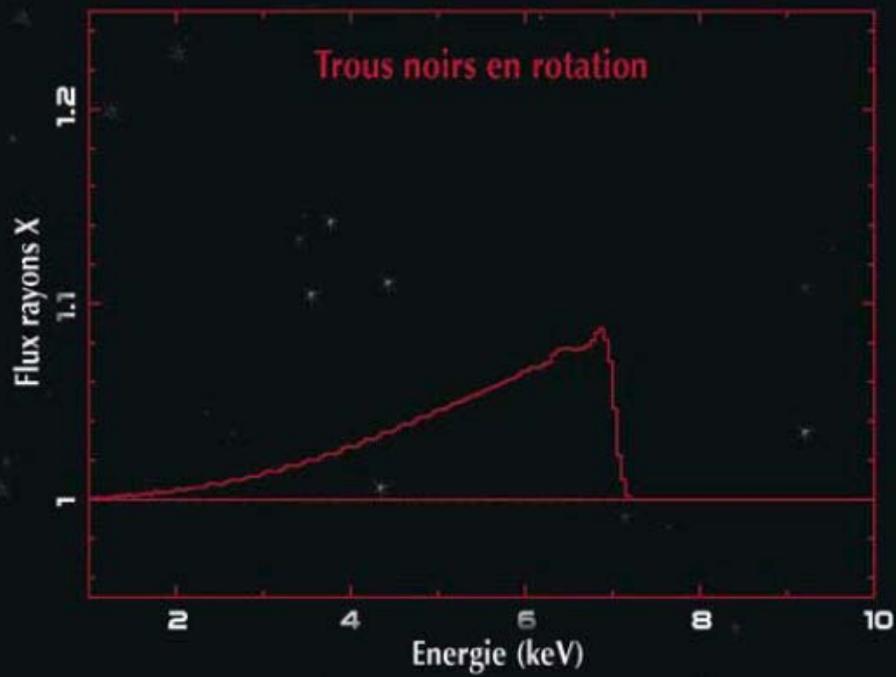


## Binaires X de grande masse (HMXB)



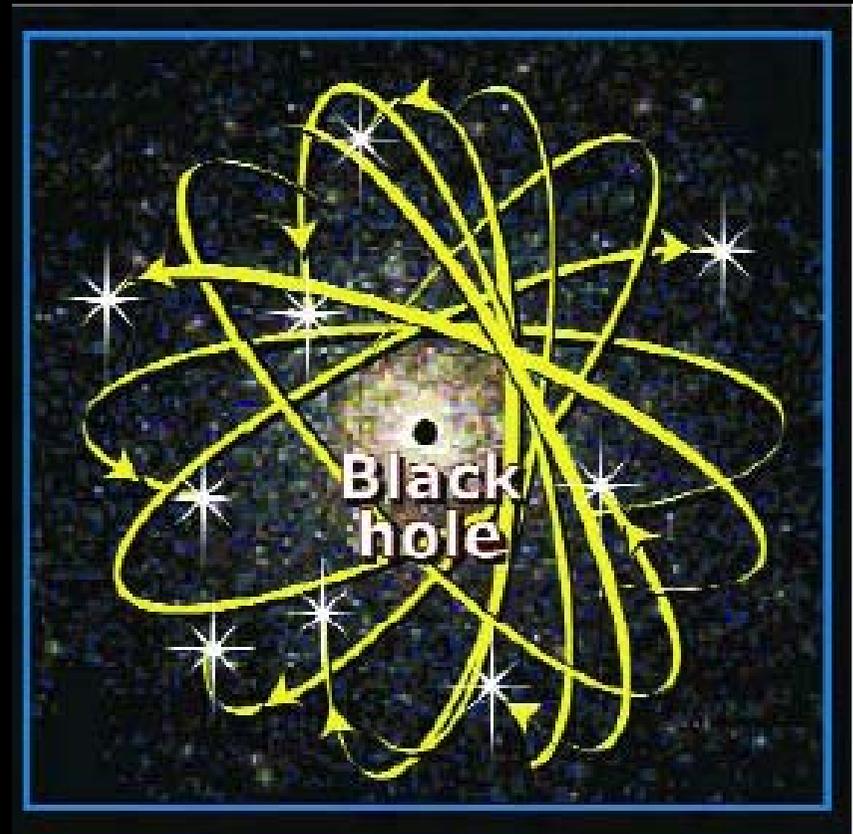
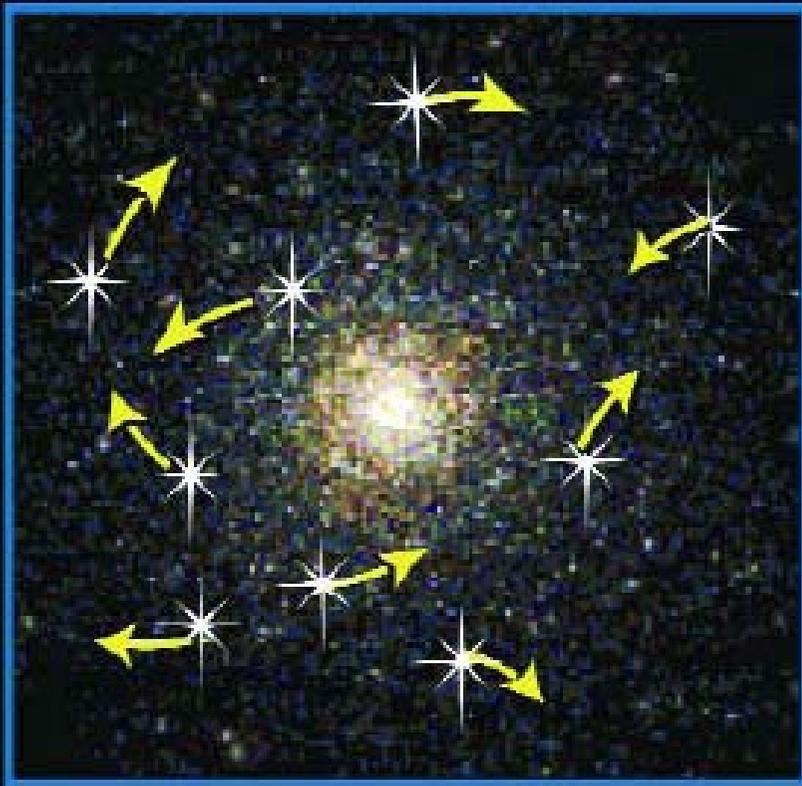
## Binaires X de faible masse (LMXB)





# Détection des trous noirs intermédiaires

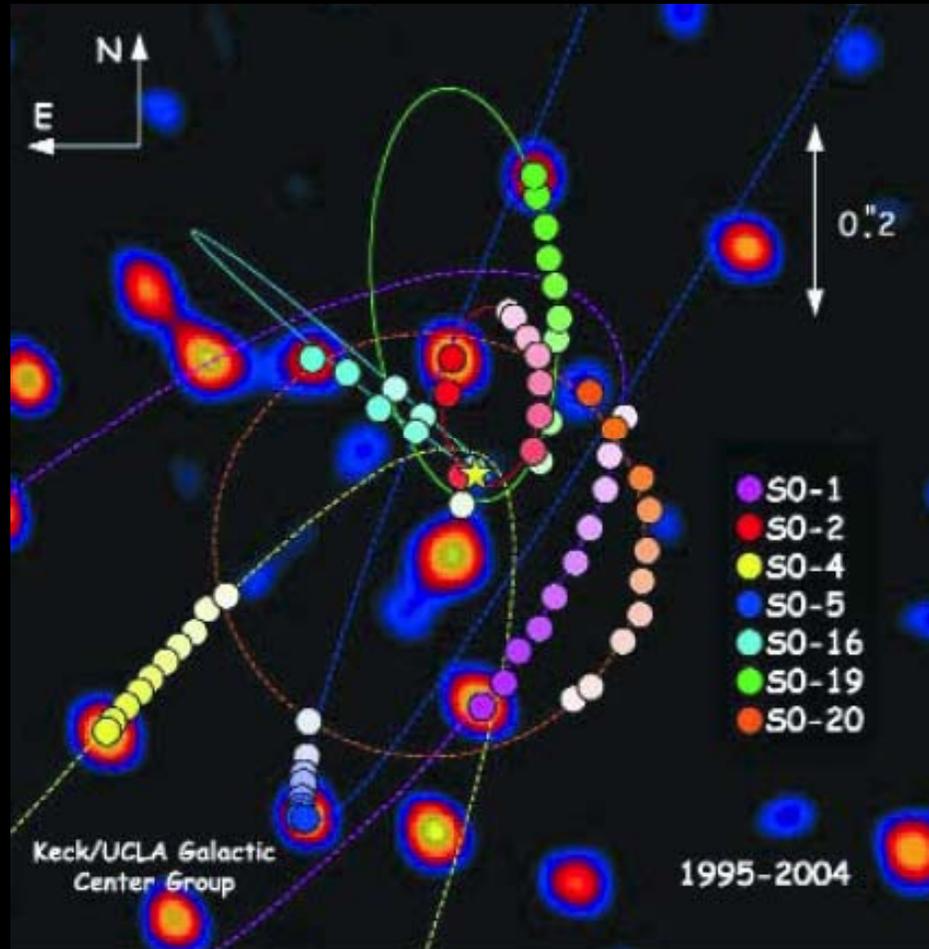
$(300 M_{\odot} < M < 10\,000 M_{\odot})$



# Le Trou noir Galactique

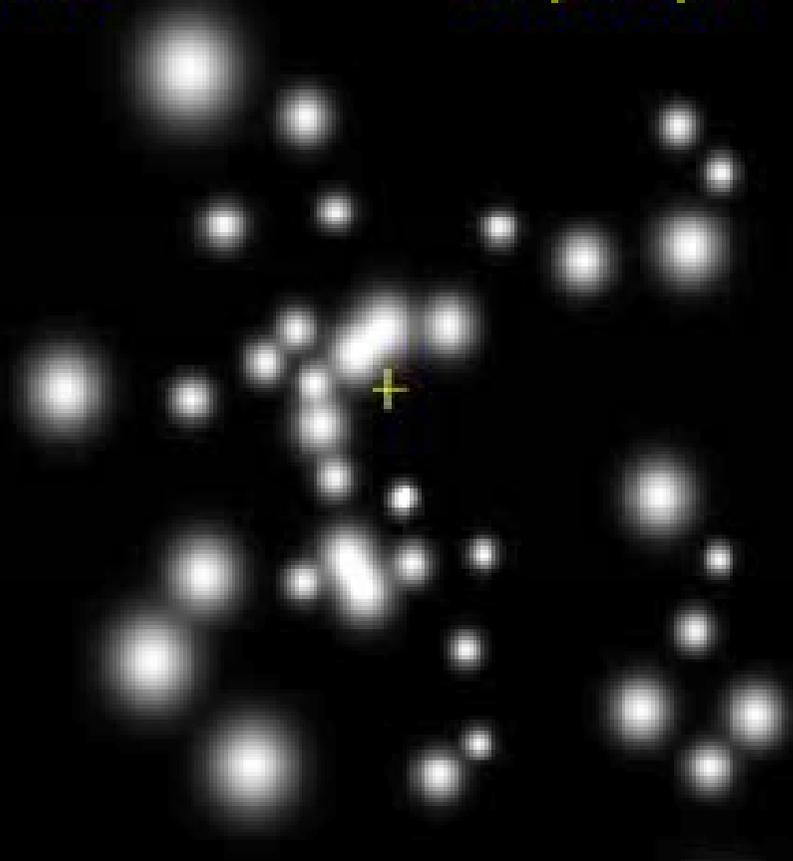


# Sagittarius A\*



1992

10 light days



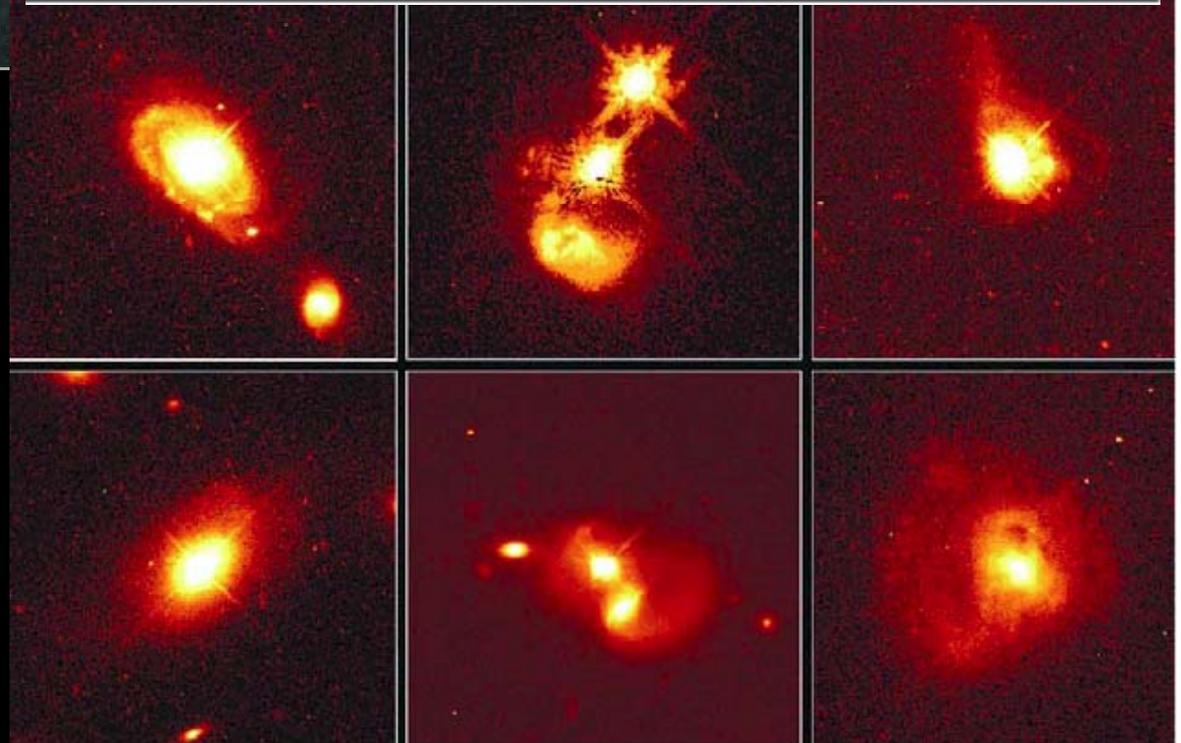
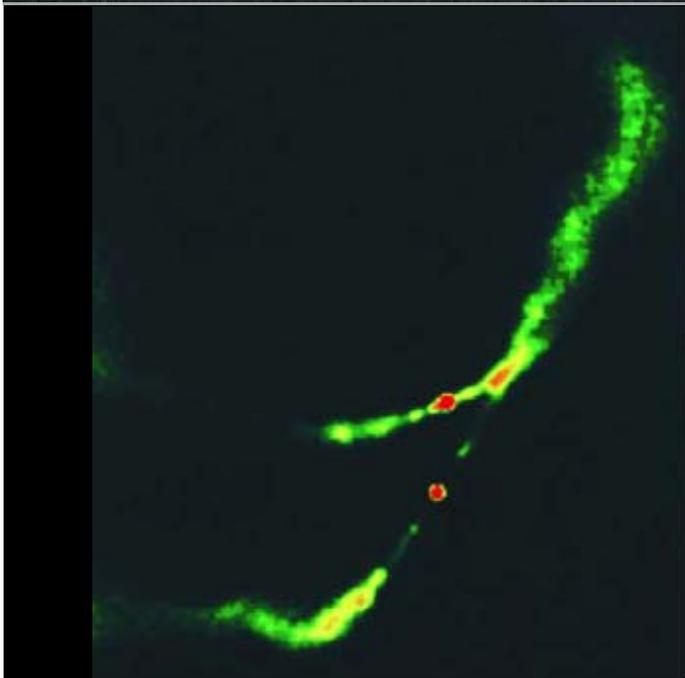
Masse  $M = 4\,000\,000$  masses solaires

# Détection des trous noirs supermassifs

( $M > 10^6 M_{\odot}$ )

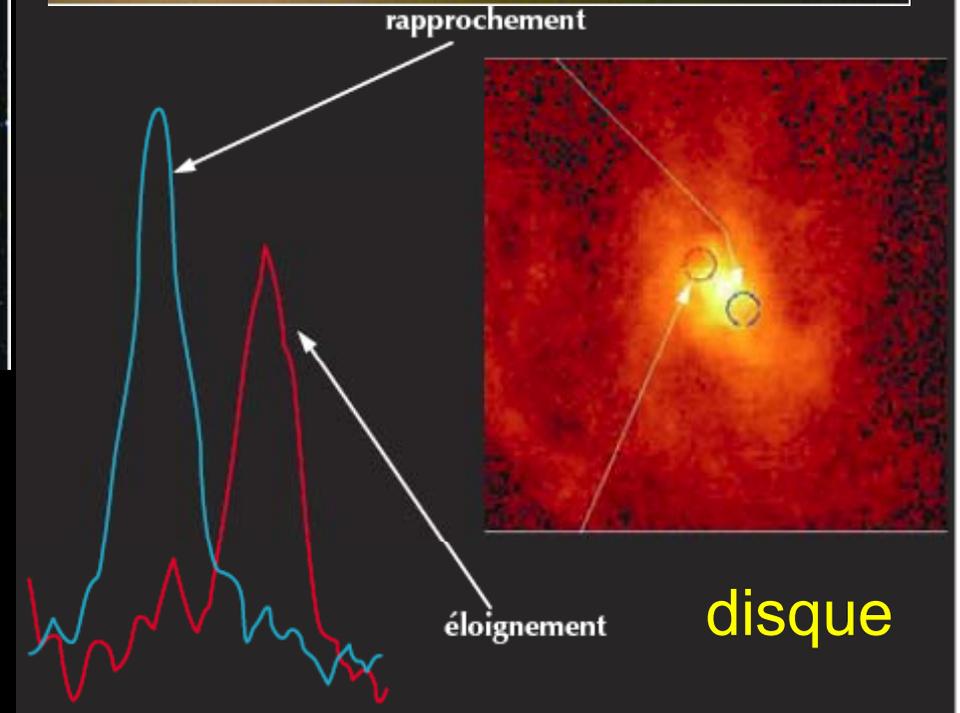
quasars

radiogalaxies



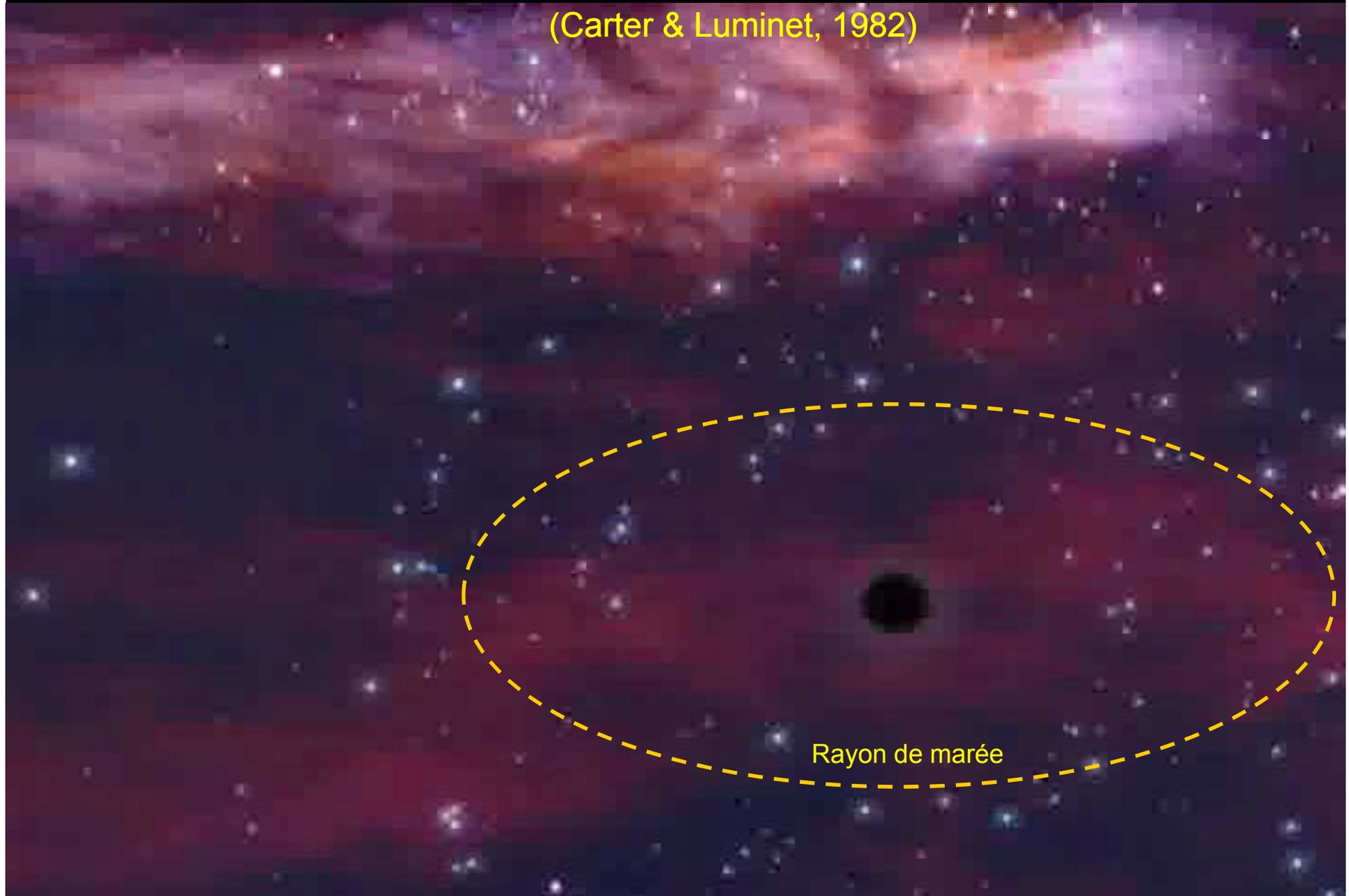


M 87 :  
 $M_{\text{tn}} \sim 3 \times 10^9 M_{\text{S}}$



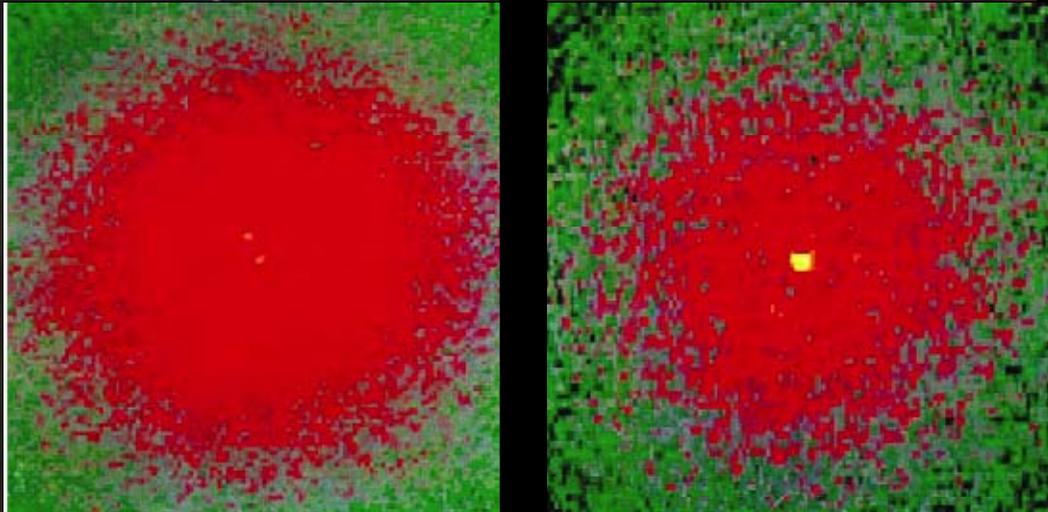
# Les crêpes stellaires flambées

(Carter & Luminet, 1982)



Rayon de marée

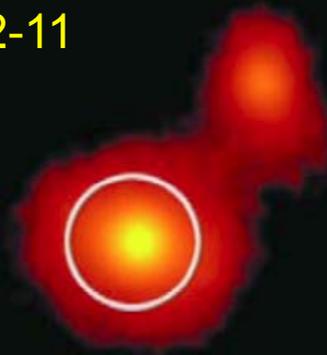
NGC 4252 (1995)



UV-transient  
(ROTSE telescope 2009)



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



# Les trous noirs « supergéants »



La petite galaxie lenticulaire  
NGC 1277 a un TN de 17  
milliards de Ms: 14 % du total  
(normalement 0.1%)

Le « record » : S5 0014+81  
40 milliards de masses solaires

J0100+2802

12 milliards de masses solaires  
daté d'à peine 900 millions  
d'années après le big bang

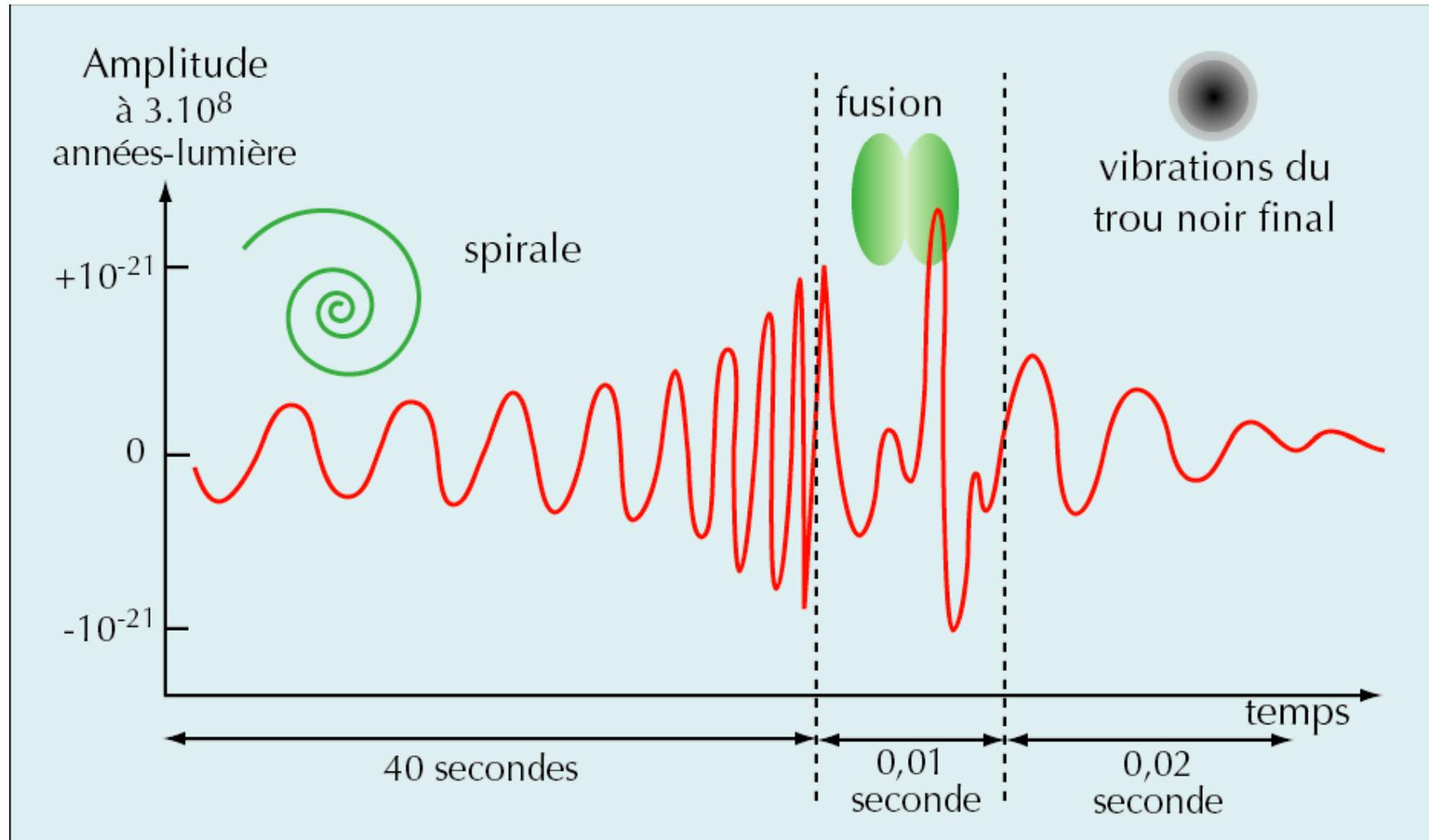


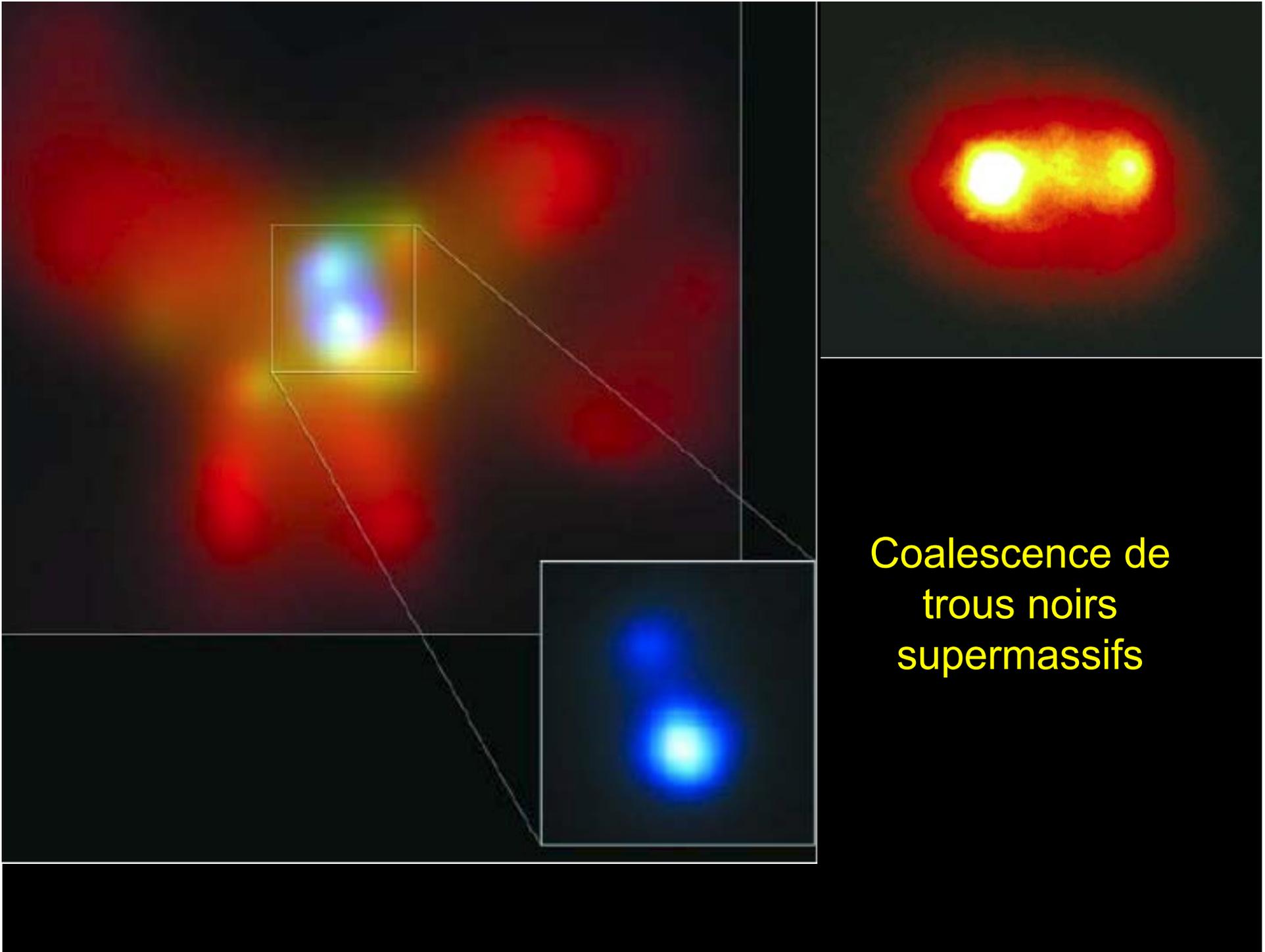


## Détecteur d'ondes gravitationnelles



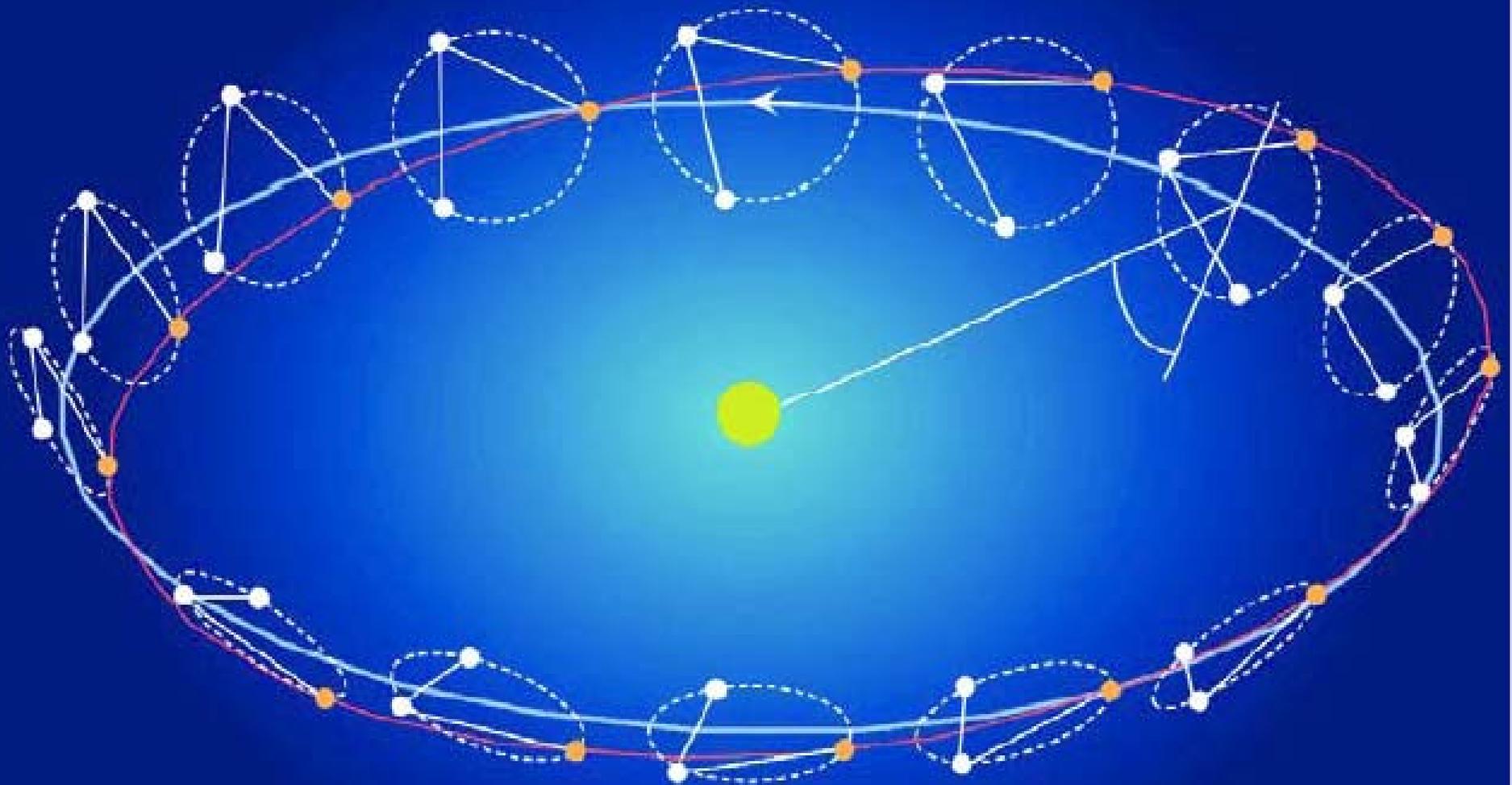
# Signal gravitationnel émis par une coalescence





Coalescence de  
trous noirs  
supermassifs

# evolved Laser Interferometer Space Antenna (projet eLISA)



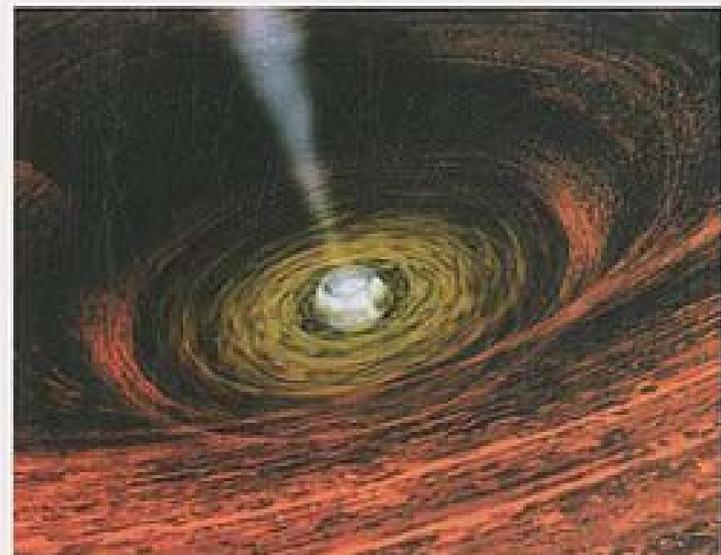
JEAN-PIERRE LUMINET

# Le destin de l'univers

Trous noirs  
et énergie sombre

*Le temps des sciences* **fayard**

Jean-Pierre  
Luminet  
Le Destin  
de l'Univers



folio **essais**