Un siècle de Relativité Générale ...

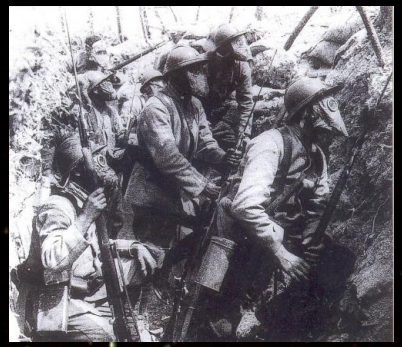
J.-P. Luminet

L.A.M. marseille

CPT Marseille

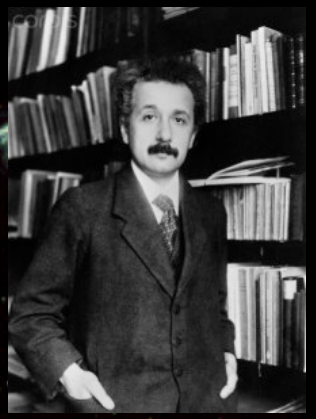
& LUTH Paris

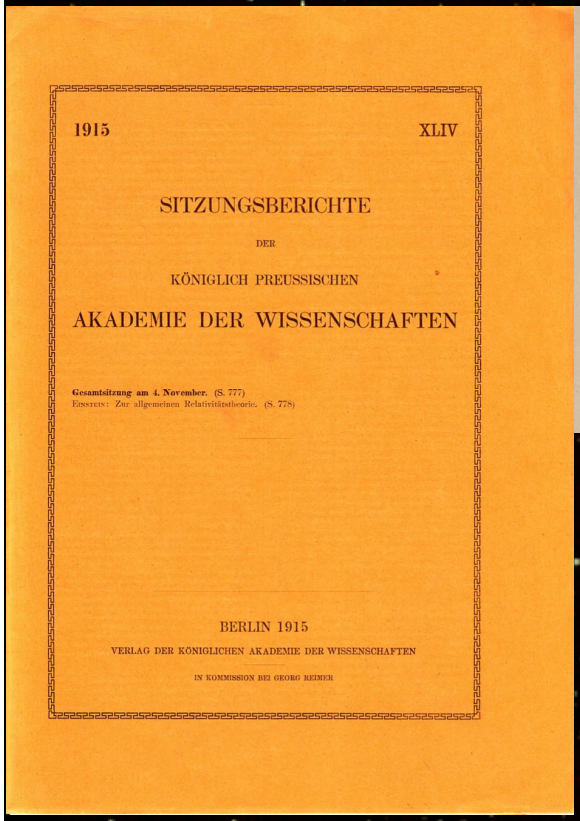
Congrès UdPPC, octobre 2015



C'était il y a un siècle

....





1915 XLIV

SITZUNGSBERICHTE

DER

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN

Gesamtsitzung am 4. November. (S. 777)
Einstein: Zur allgemeinen Relativitätstheorie. (S. 778)

BERLIN 1915

VERLAG DER KÖNIGLICHEN AKADEMIE DER WISSENSCHAFTEN

IN KOMMISSION BEI GEORG REIMER

4 novembre 1915

844 Sitzung der physikalisch-mathematischen Klasse vom 25. November 1915

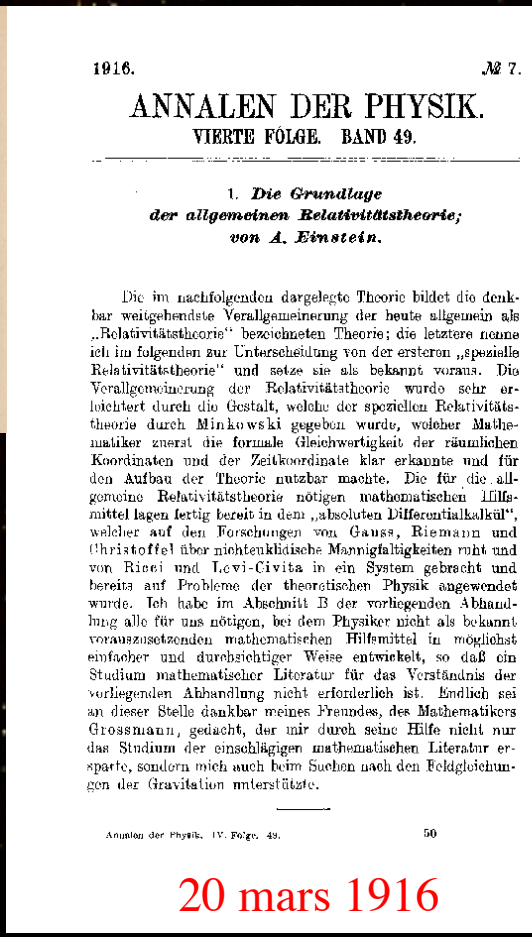
Die Feldgleichungen der Gravitation.

Von A. Einstein.

In zwei vor kurzem erschienenen Mitteilungen[1] habe ich gezeigt, wie man zu Feldgleichungen der Gravitation gelangen kann, die dem Postulat allgemeiner Relativität entsprechen, d. h. die in ihrer allgemeinen Fassung beliebigen Substitutionen der Raumzeitvariabeln gegenüber kovariant sind.

Der Entwicklungsgang war dabei folgender. Zunächst fand ich Gleichungen, welche die Newtonsche Theorie als Näherung enthalten

25 novembre 1915



1916. № 7.

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 49.

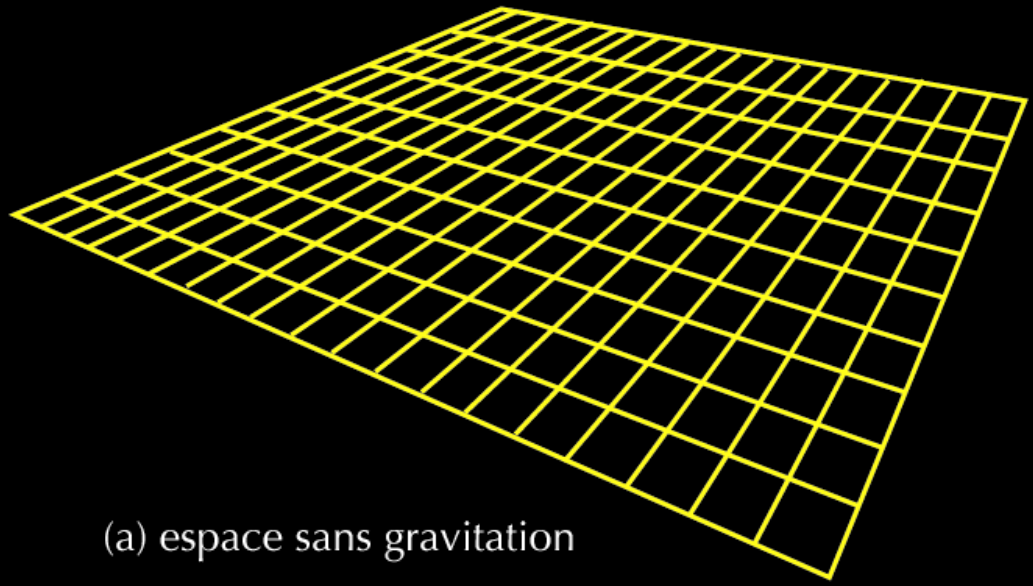
1. ***Die Grundlage der allgemeinen Relativitätstheorie; von A. Einstein.***

Die im nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich im folgenden zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung der Relativitätstheorie wurde sehr erleichtert durch die Gestalt, welche der speziellen Relativitätstheorie durch Minkowski gegeben wurde, welcher Mathematiker zuerst die formale Gleichwertigkeit der räumlichen Koordinaten und der Zeitkoordinate klar erkannte und für den Aufbau der Theorie nutzbar machte. Die für die allgemeine Relativitätstheorie nötigen mathematischen Hilfsmittel lagen fertig bereit in dem „absoluten Differentialkalkül", welcher auf den Forschungen von Gauss, Riemann und Christoffel über nichteuklidische Mannigfaltigkeiten ruht und von Ricci und Levi-Civita in ein System gebracht und bereits auf Probleme der theoretischen Physik angewendet wurde. Ich habe im Abschnitt B der vorliegenden Abhandlung alle für uns nötigen, bei dem Physiker nicht als bekannt vorauszusetzenden mathematischen Hilfsmittel in möglichst einfacher und durchsichtiger Weise entwickelt, so daß ein Studium mathematischer Literatur für das Verständnis der vorliegenden Abhandlung nicht erforderlich ist. Endlich sei an dieser Stelle dankbar meines Freundes, des Mathematikers Grossmann, gedacht, der mir durch seine Hilfe nicht nur das Studium der einschlägigen mathematischen Literatur ersparte, sondern mich auch beim Suchen nach den Feldgleichungen der Gravitation unterstützte.

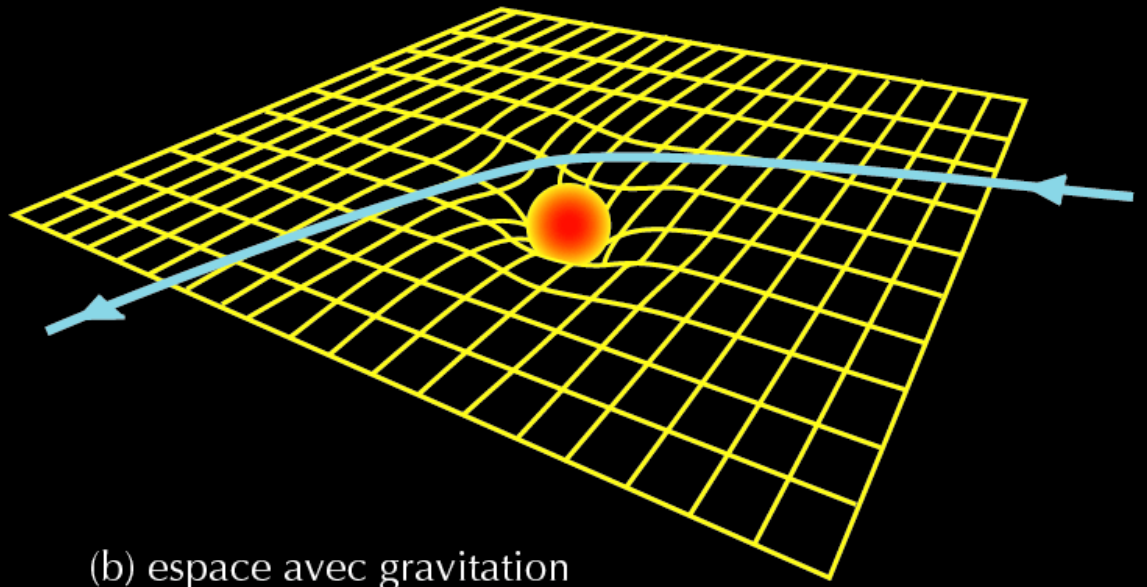
Annalen der Physik. IV. Folge. 49. 50

20 mars 1916

Relativité Générale : Gravitation = Courbure de l'espace-temps



(a) espace sans gravitation

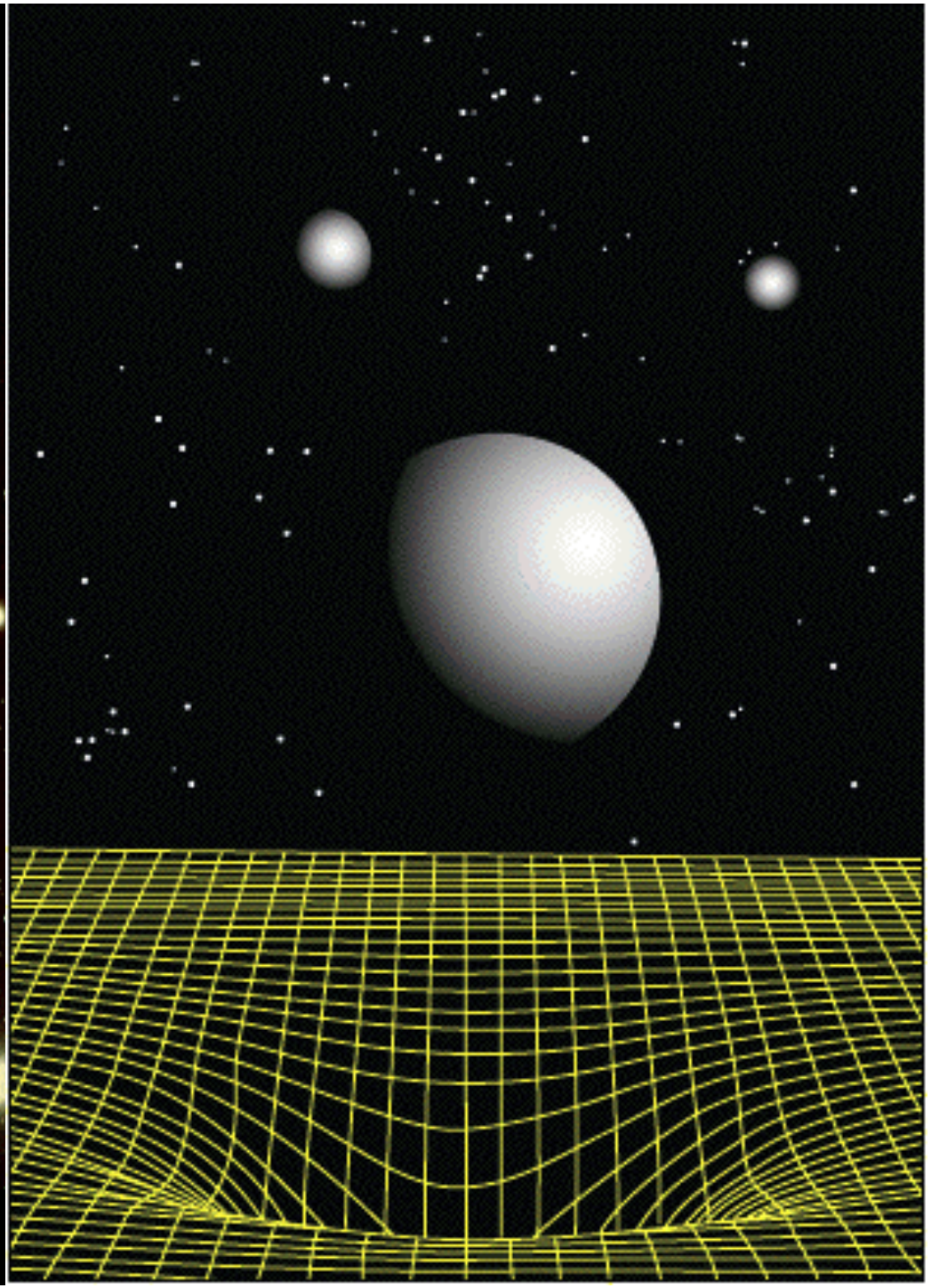


(b) espace avec gravitation

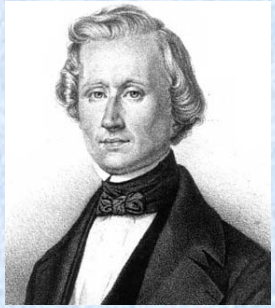
Equations d'Einstein :

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

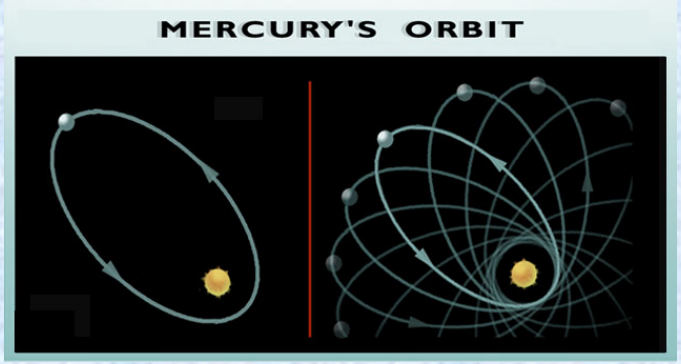
courbure = matière-énergie



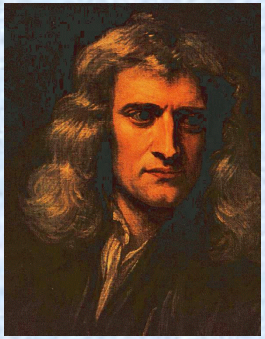
Succès 1 : explication de l'avance du périhélie de Mercure



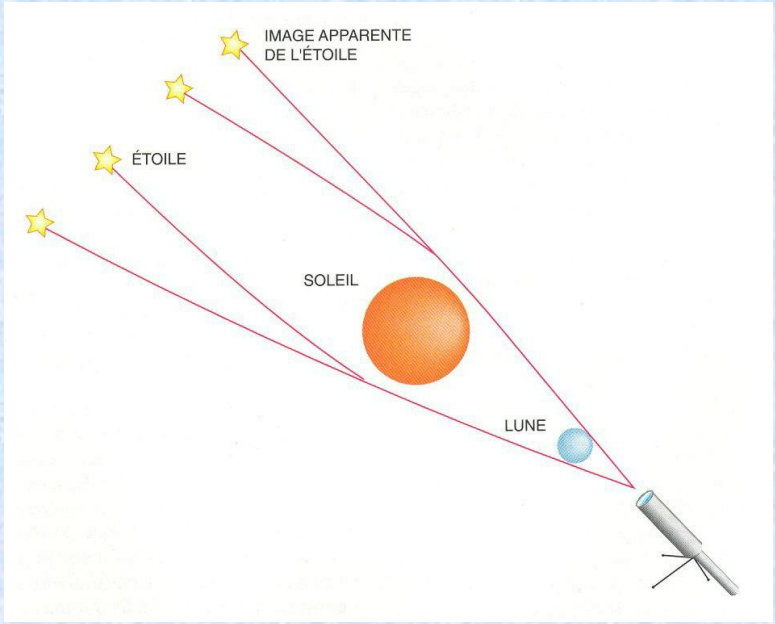
Le Verrier



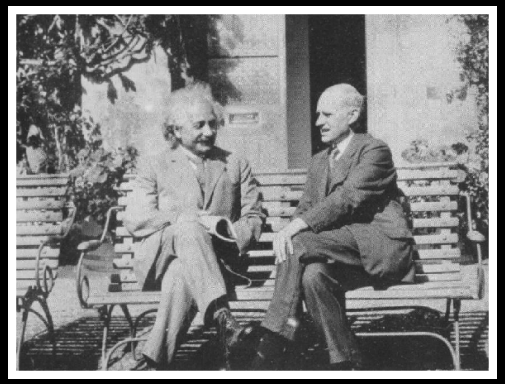
Succès 2 : déviation des rayons lumineux



Newton



L'éclipse du 29 mai 1919



IGHTS ALL ASKEW IN THE HEAVENS
Special Cable to THE NEW YORK TIMES.
New York Times (1857); Nov 10, 1919; ProQuest Historical Newspapers The New York Times (1851 - 2004)
pg. 17

LIGHTS ALL ASKEW IN THE HEAVENS

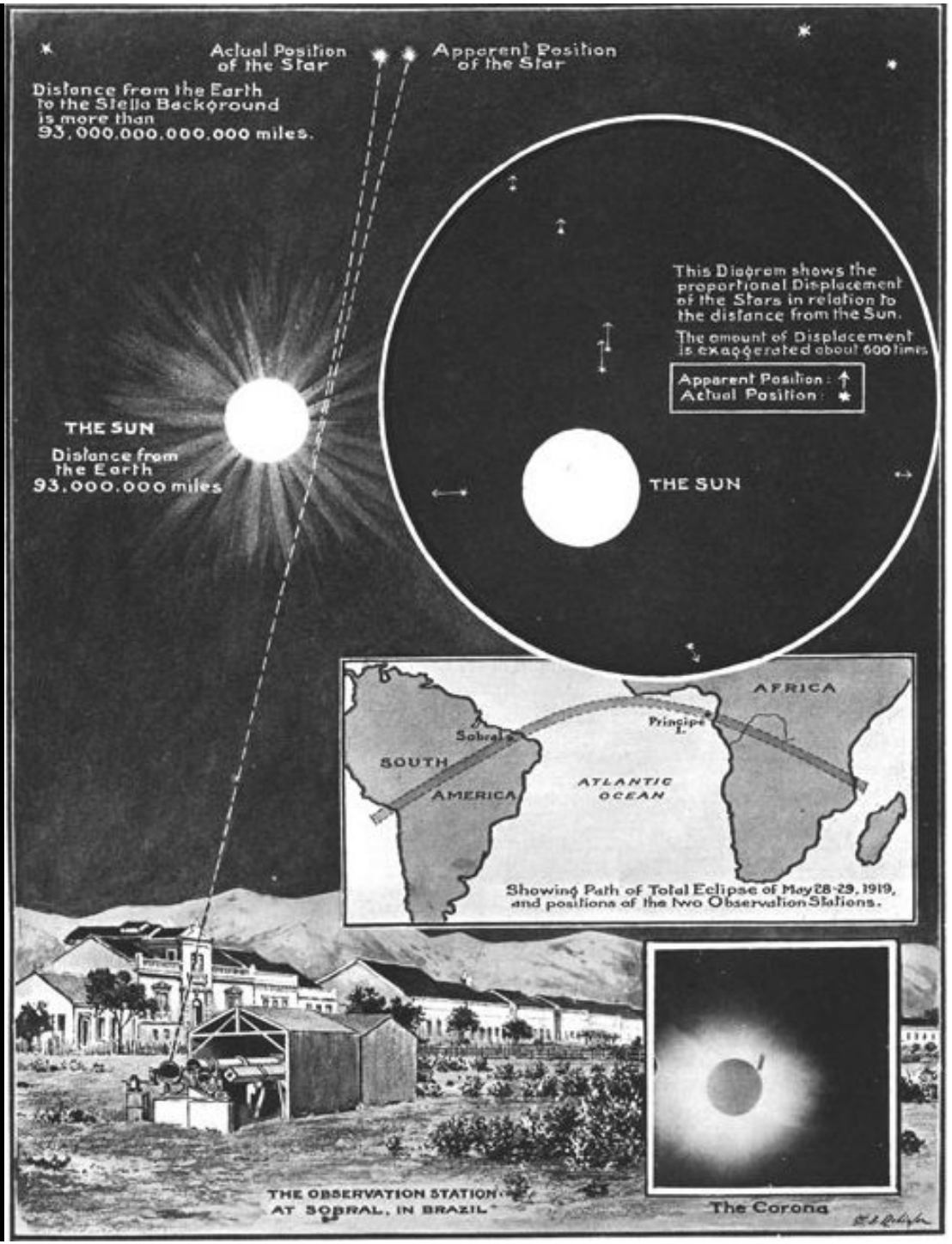
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

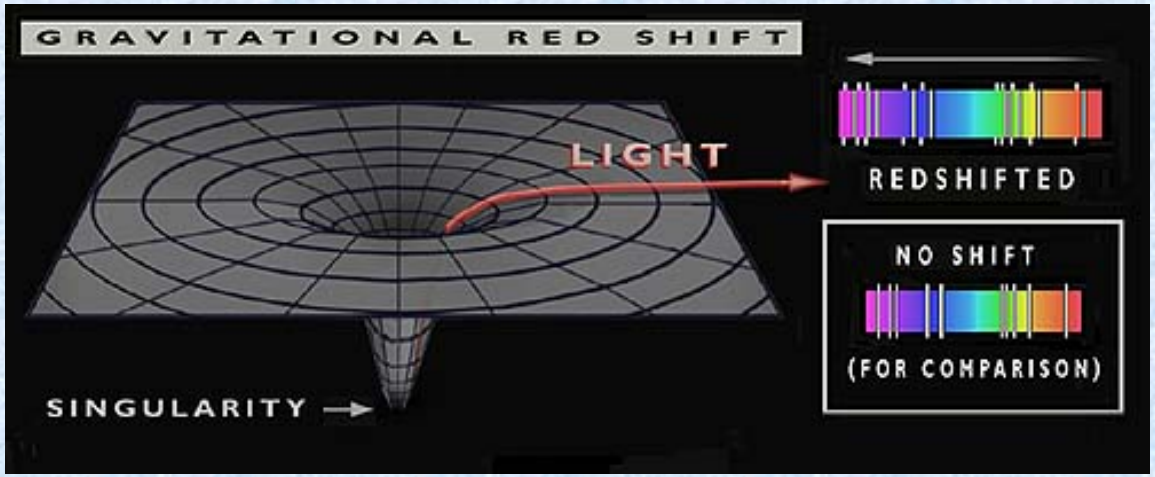
Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

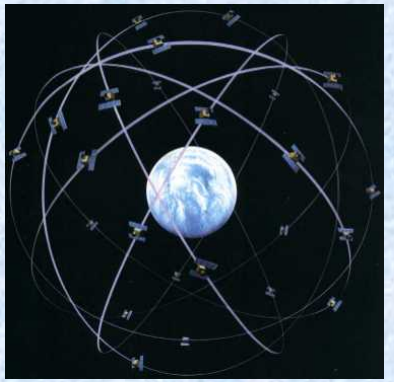
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.



Succès 3 : Décalage vers le rouge gravitationnel

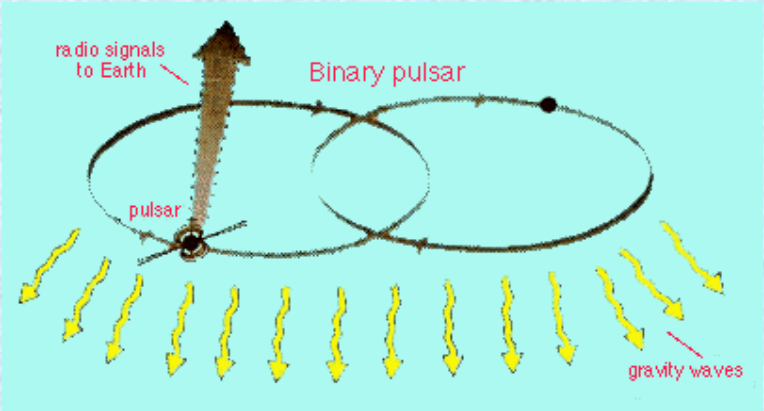


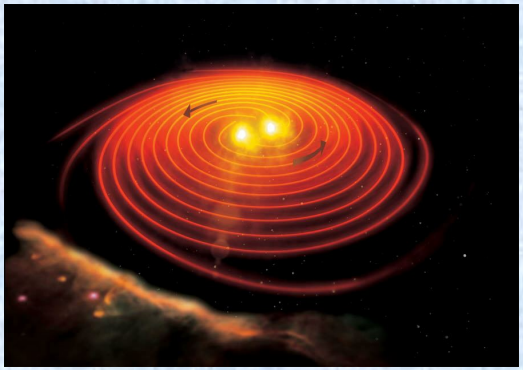
Vessot/Levine



GPS

Succès 4 : Emission d'ondes gravitationnelles





Hulse

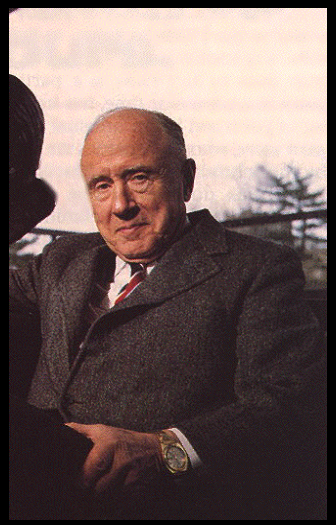
Taylor

Problème 1
effondrement gravitationnel

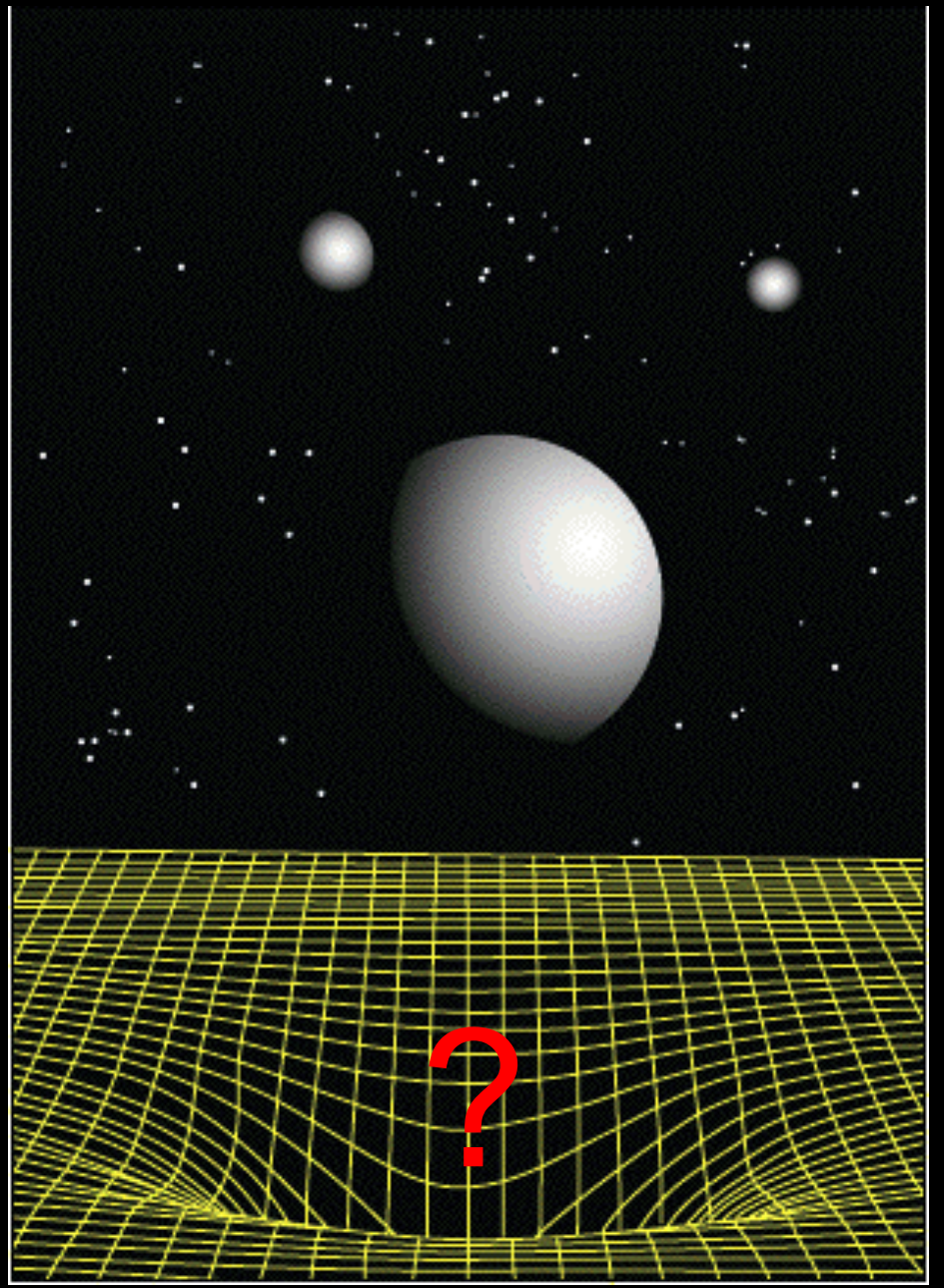
K. Schwarzschild

S. Chandrasekhar

R. Oppenheimer



J. Wheeler

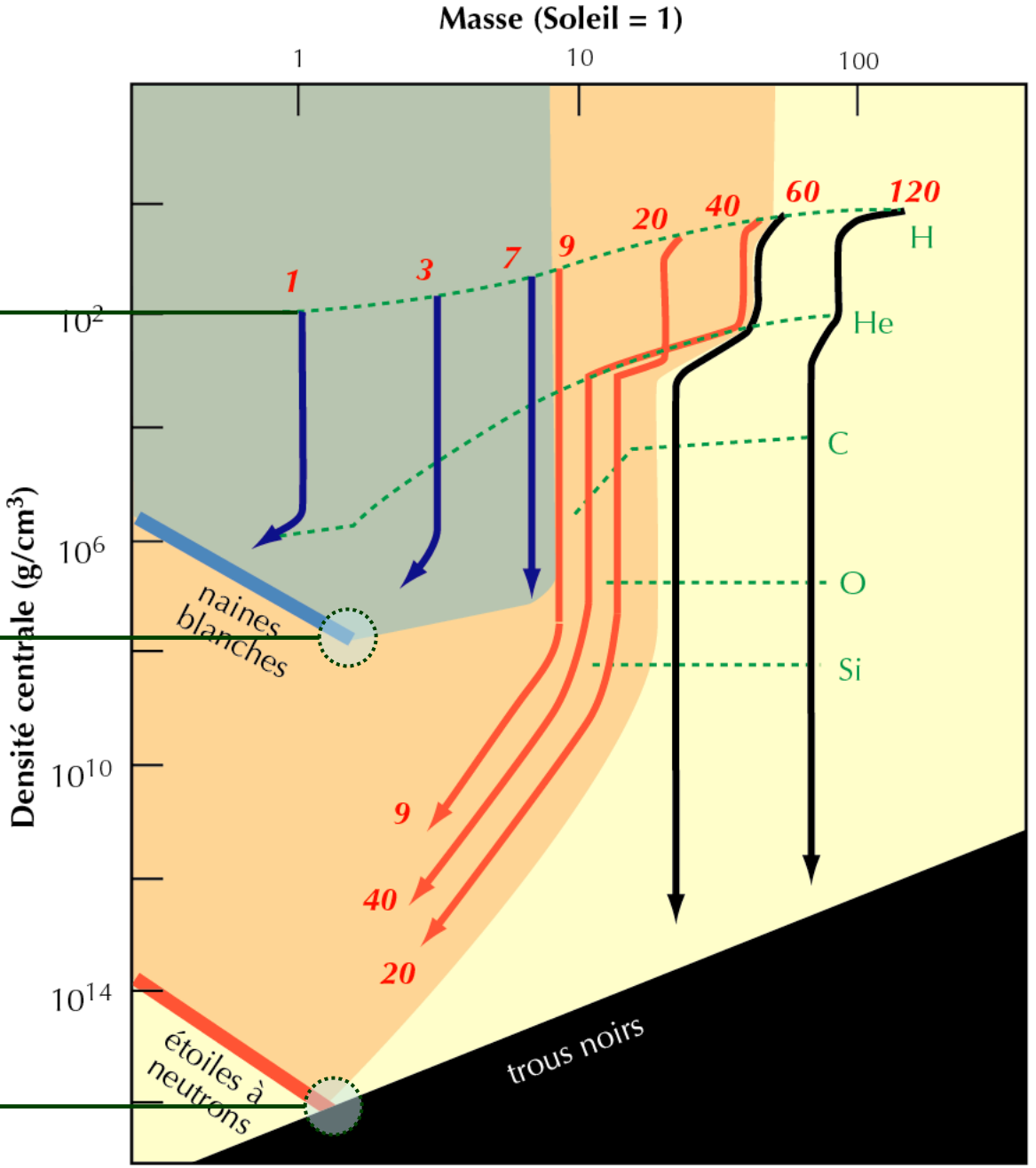


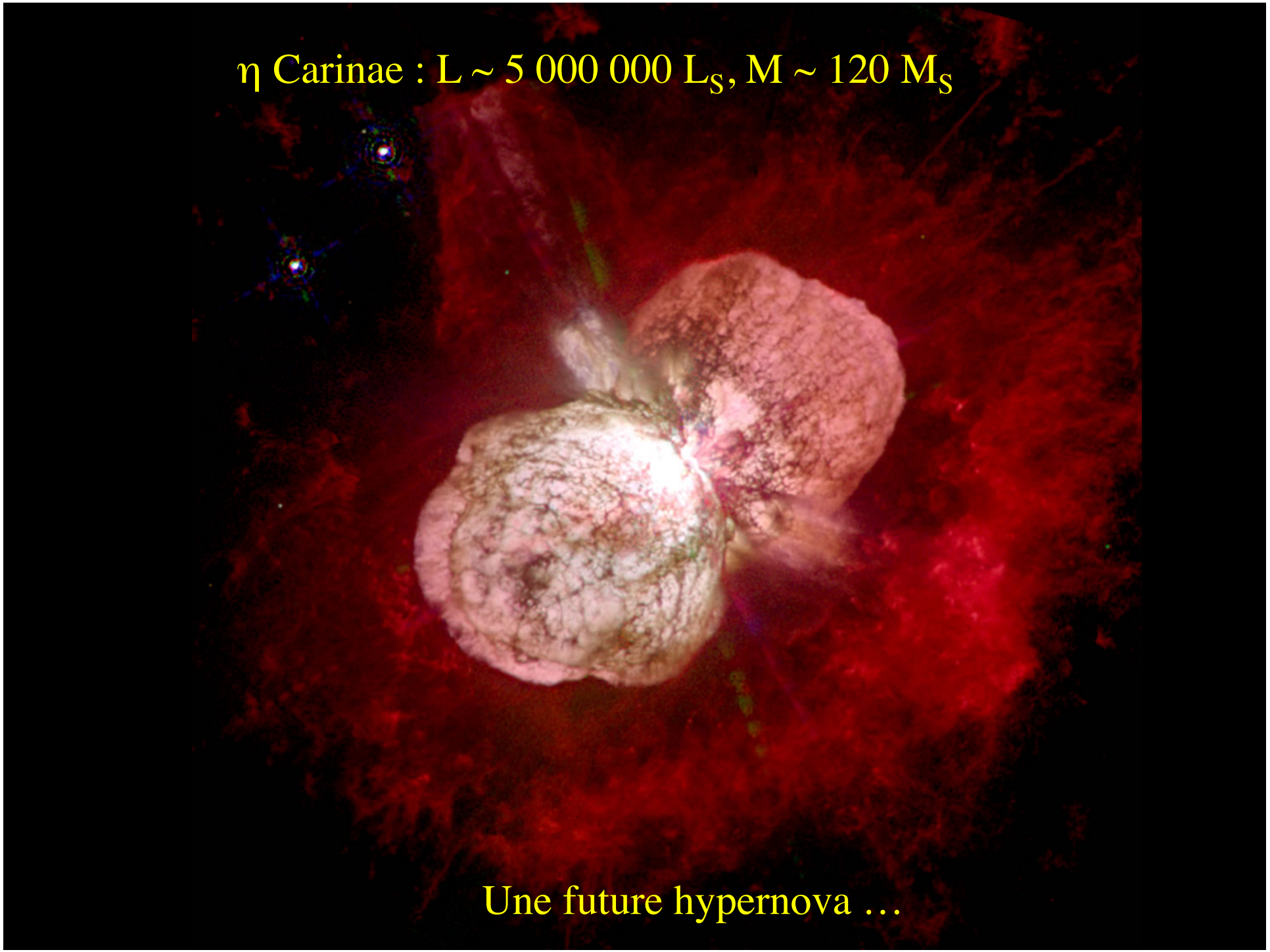
Evolution stellaire

Masse initiale

Limite de Chandrasekhar 1,4 M_S

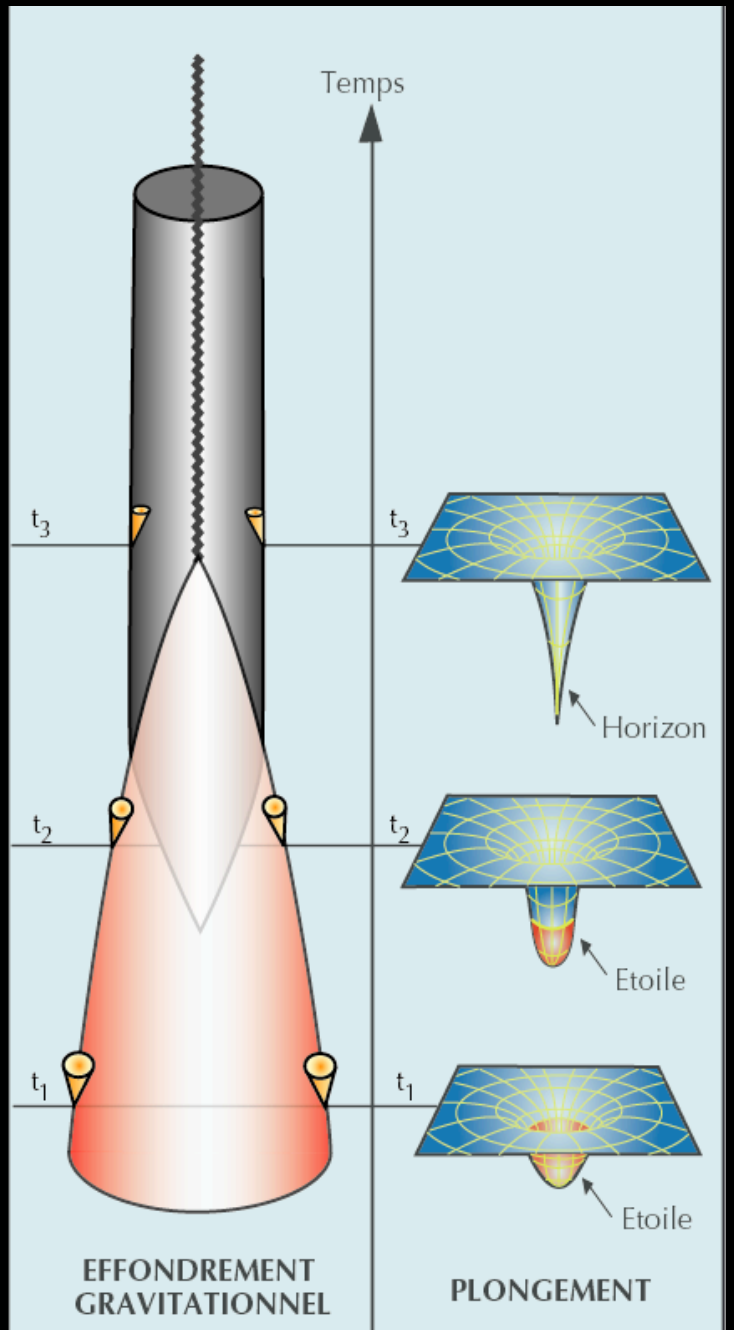
Limite de LOV ≤ 3 M_S

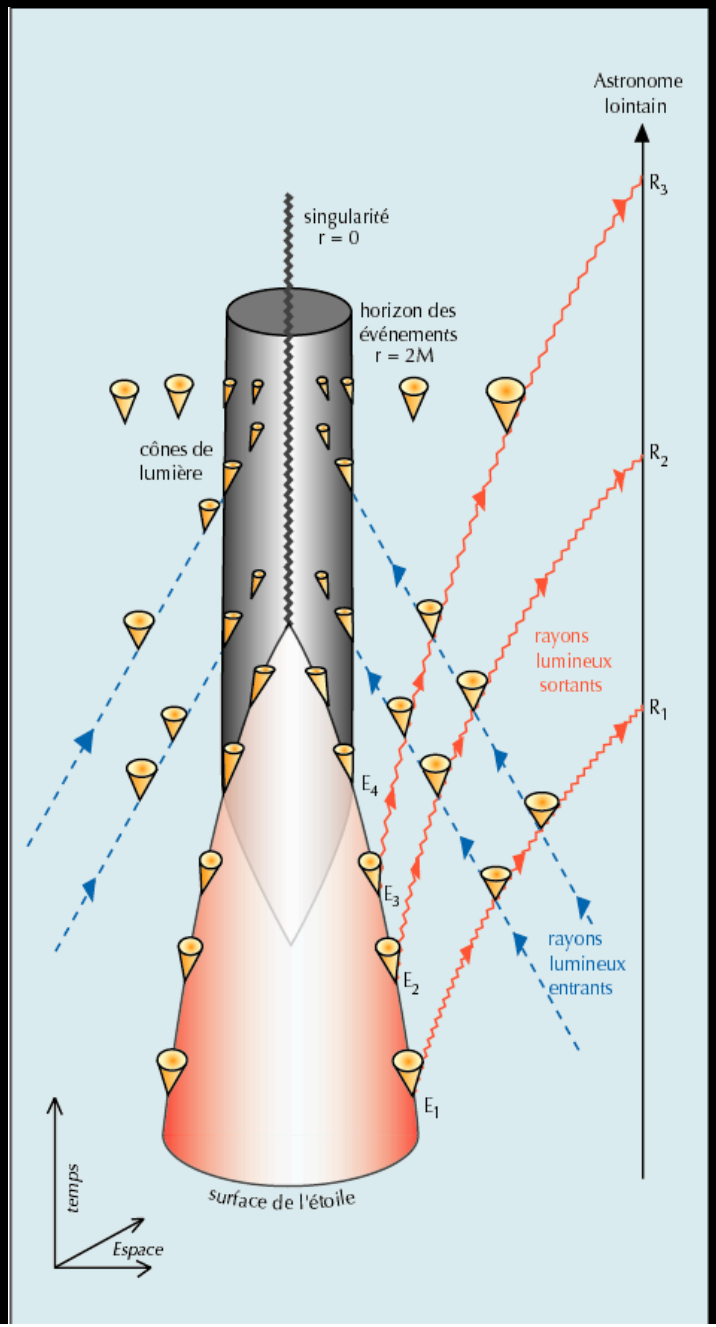



η Carinae : L ~ 5 000 000 L_S, M ~ 120 M_S
Une future hypernova …

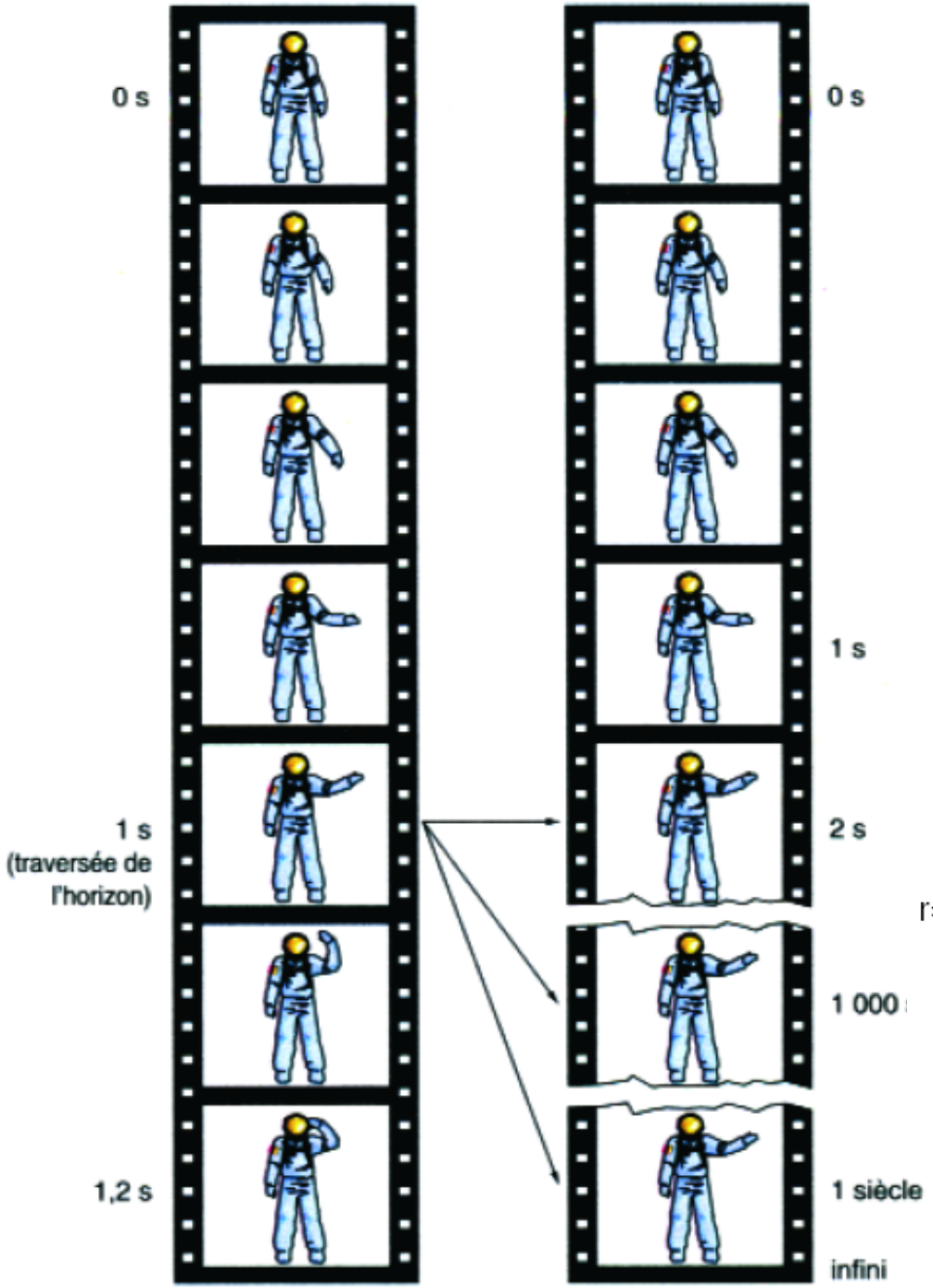

Si $M_* > 45\ M_S$
TROU NOIR !

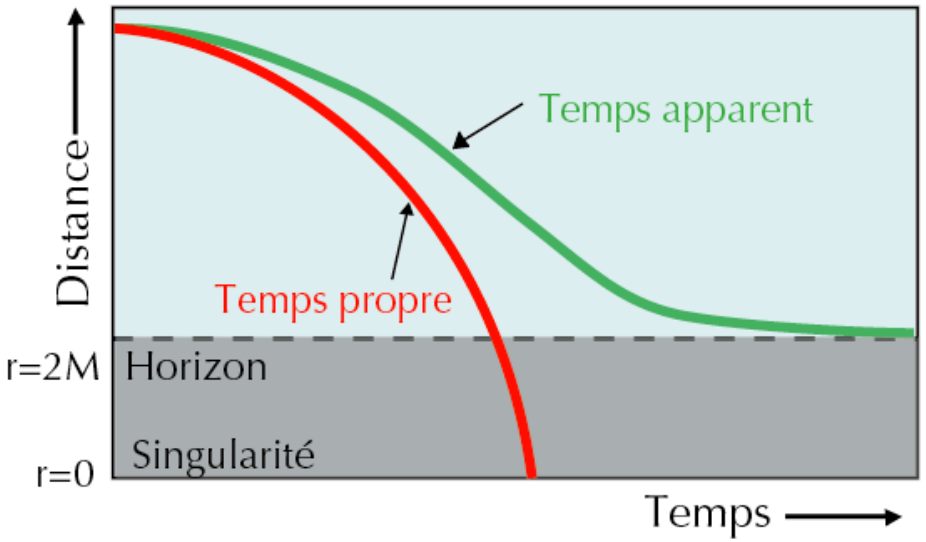
Trou noir de Schwarzschild



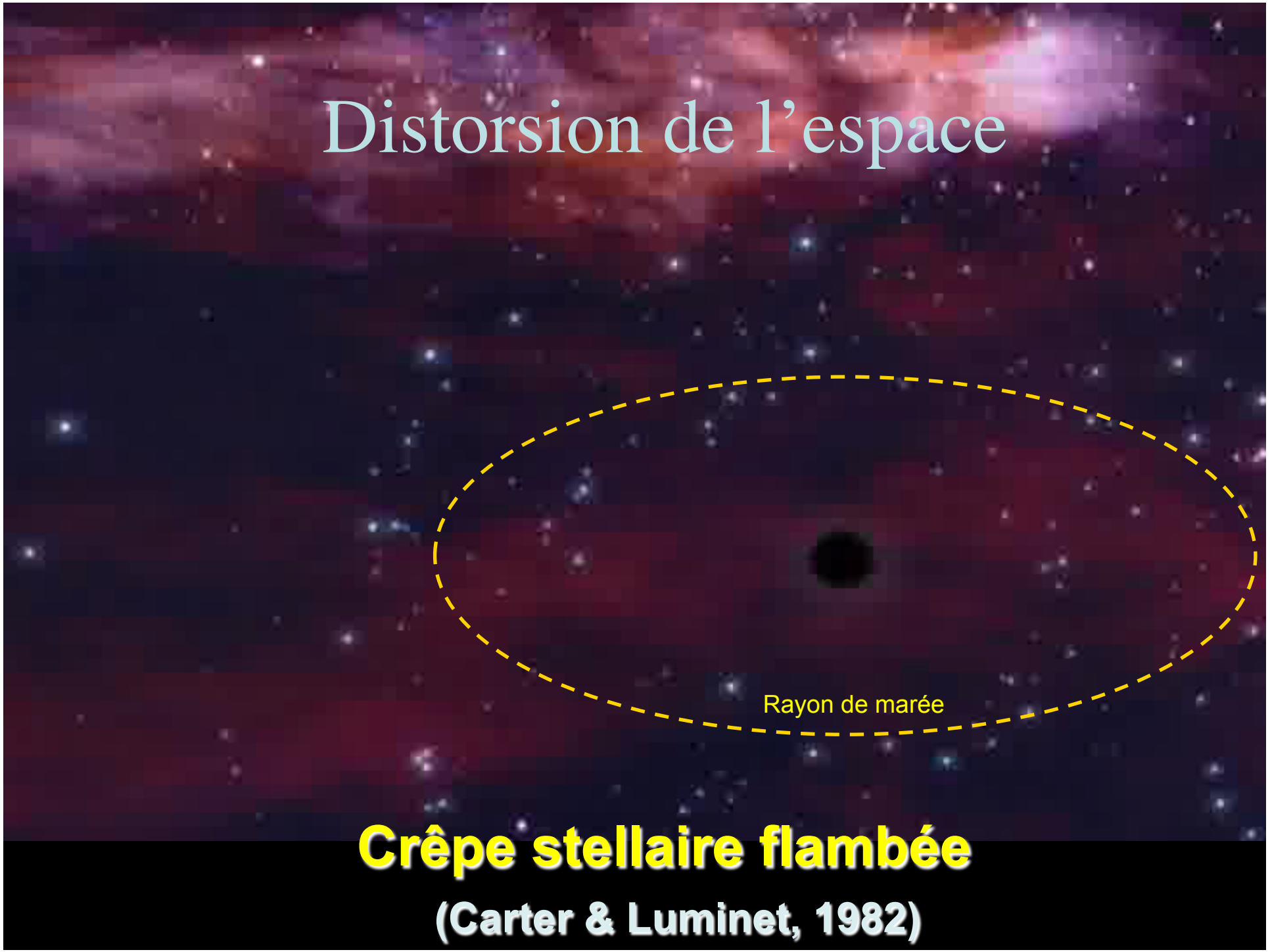


Distorsion du temps





Distorsion de l'espace



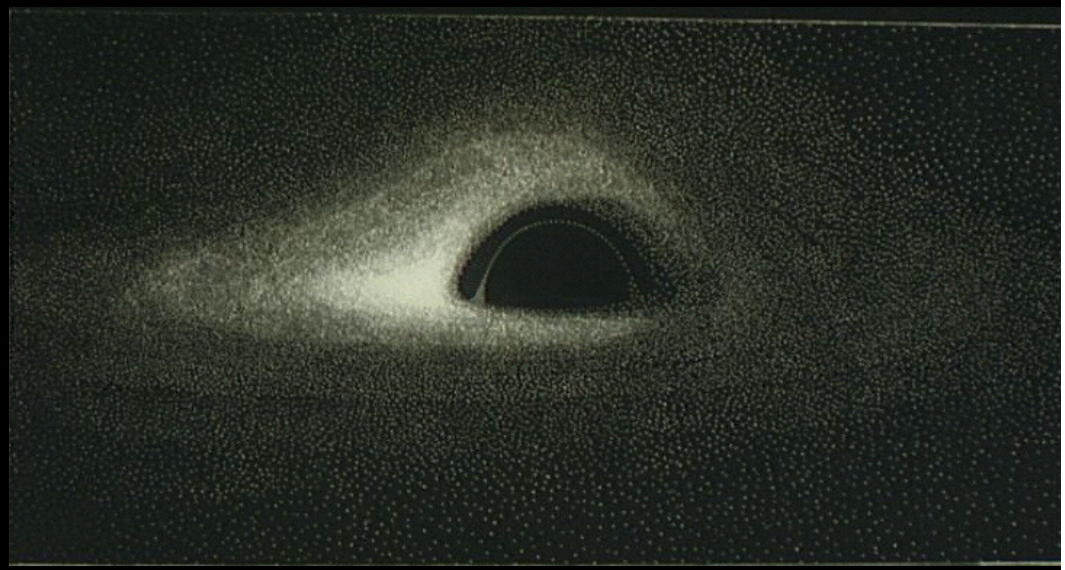
Crêpe stellaire flambée

(Carter & Luminet, 1982)

Visualisation des Trous Noirs

J.-P. Luminet

Astron. Astrophys. (1979)



J.-A. Marck

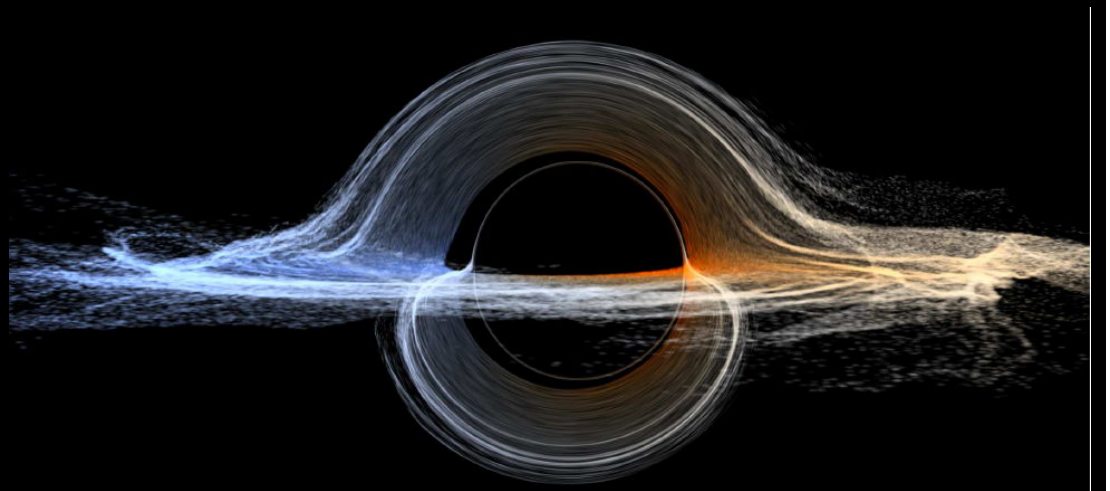
Class. Quant. Grav. (1996)

Thorne et al.

Film Interstellar (2014)

Thorne et al.

Class. Quantum Grav (2014)



Objet « non effondré »

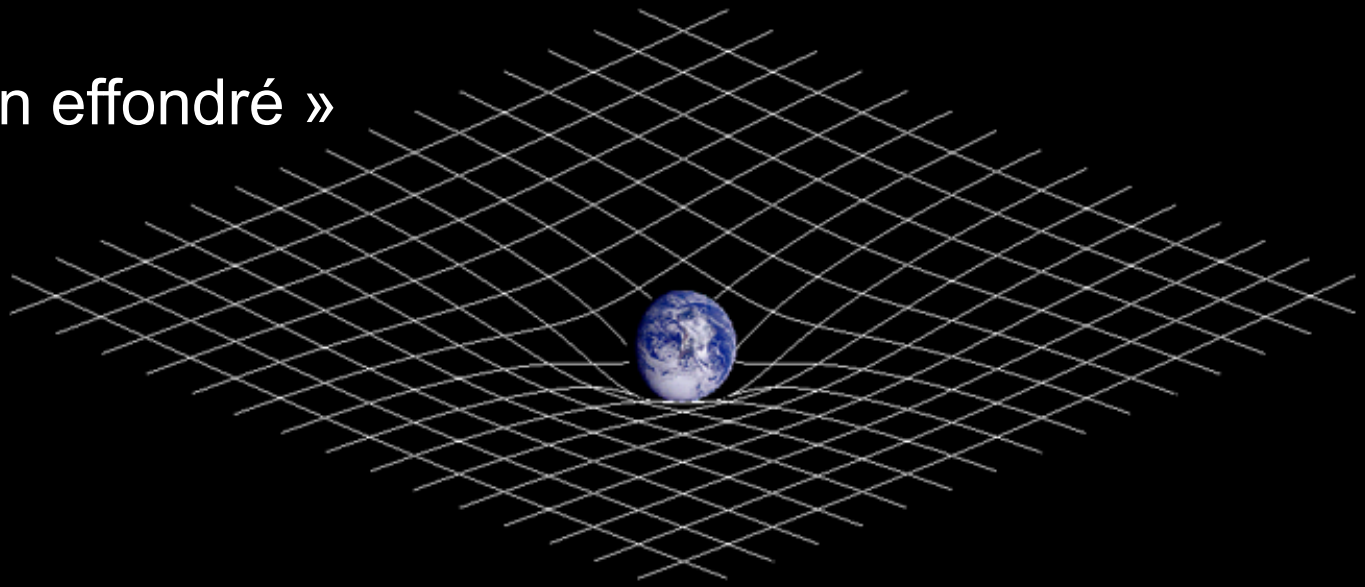
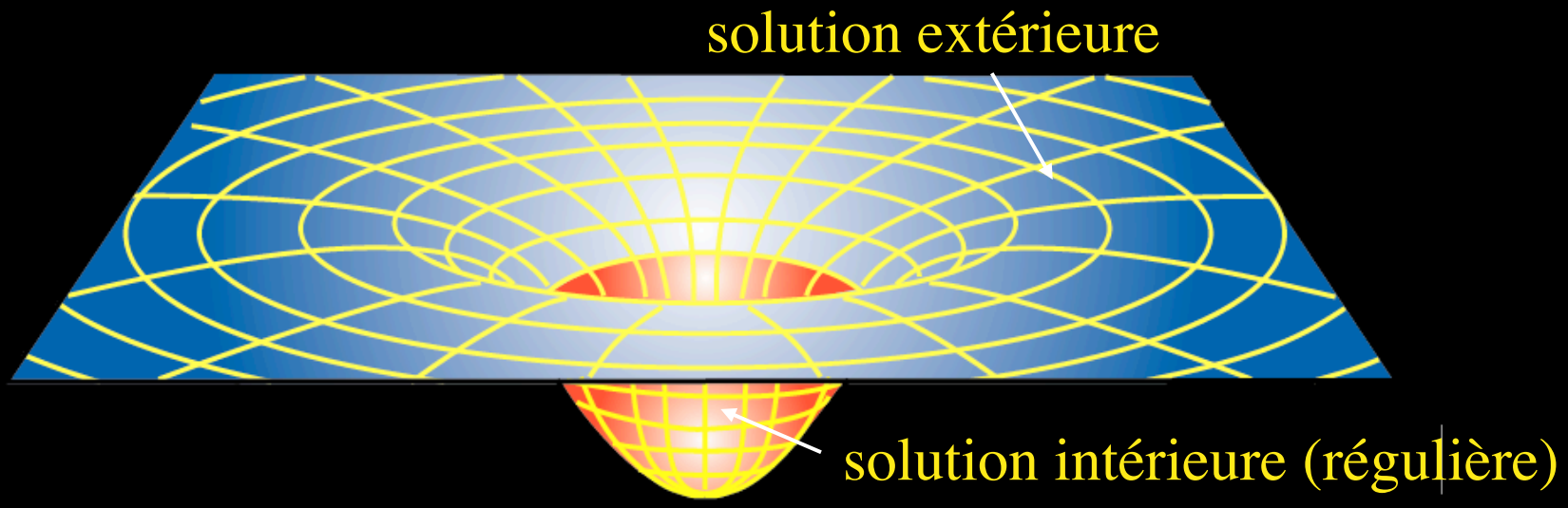
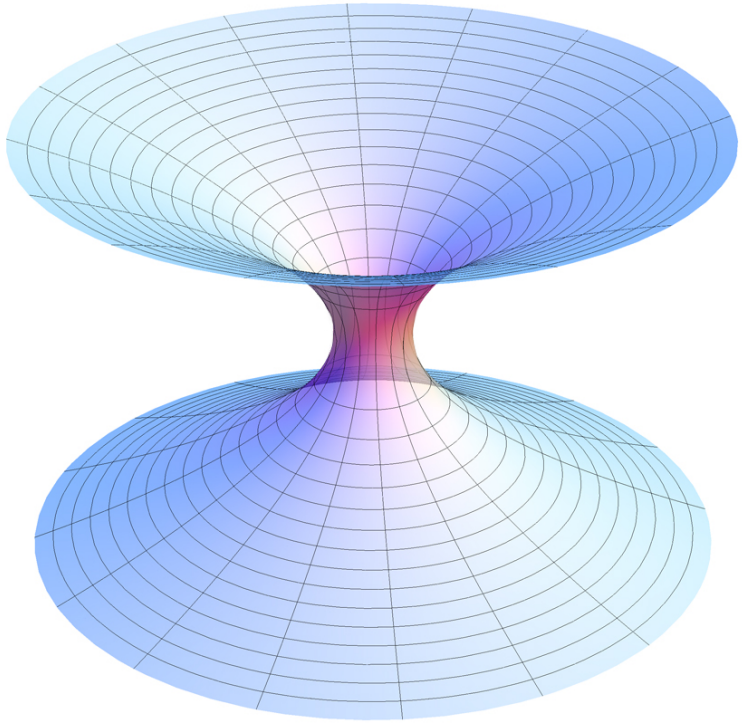


Diagramme de plongement

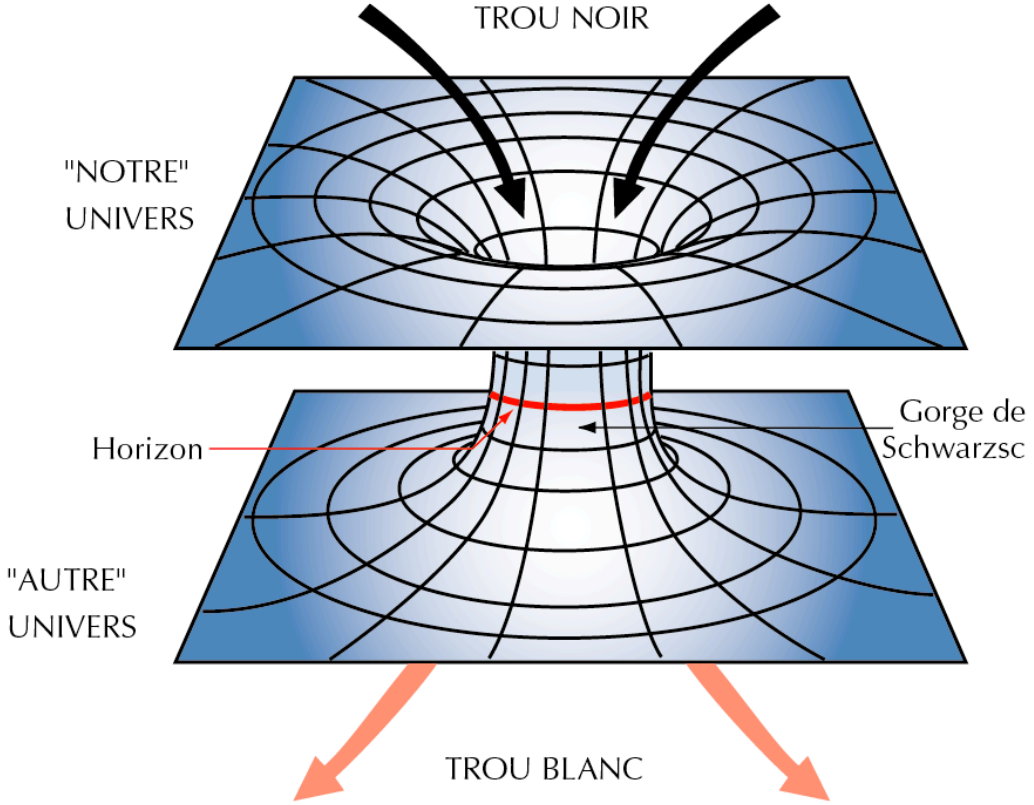


Trou noir de Schwarzschild

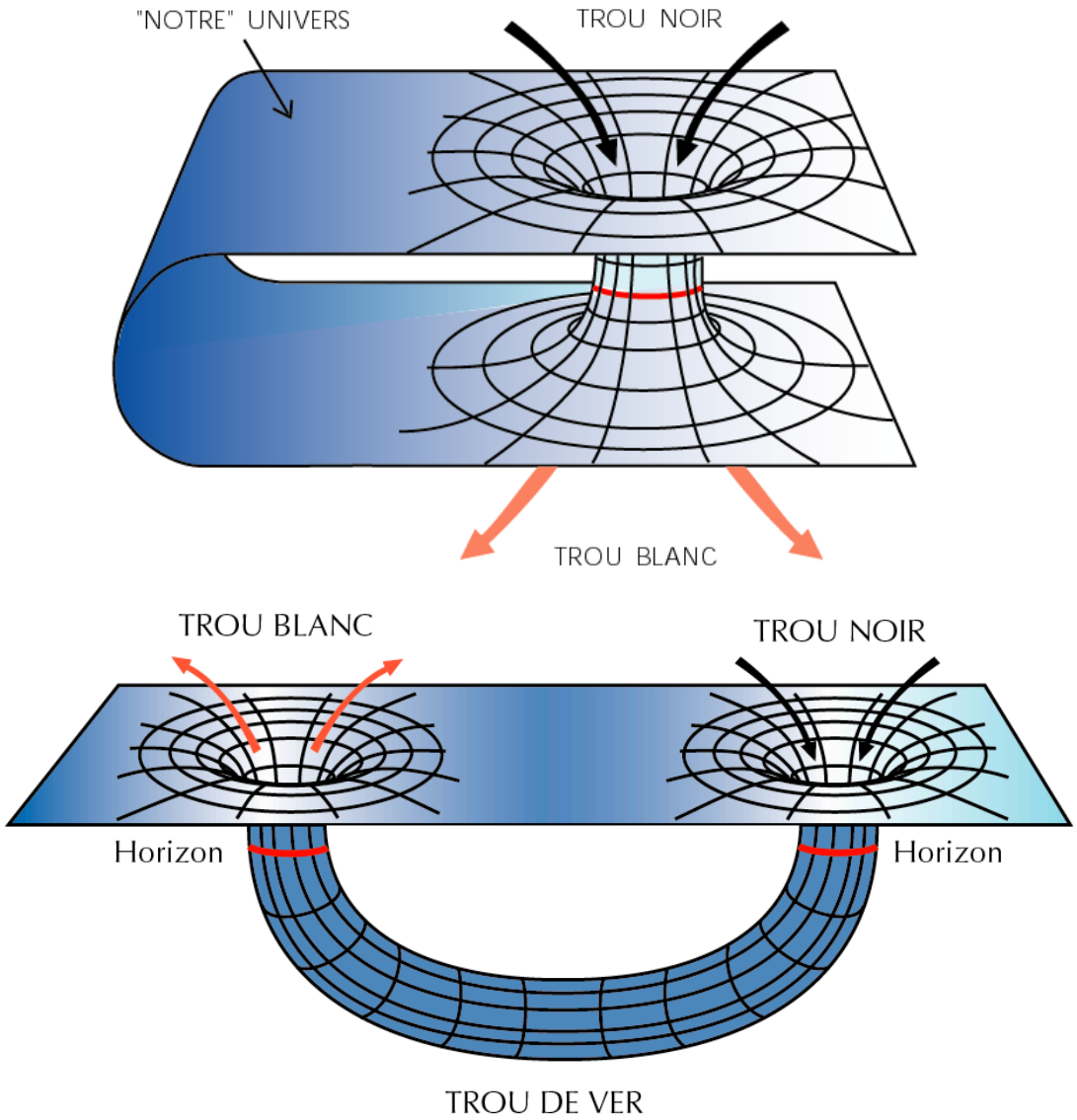
Paraboloïde de Flamm (1916)



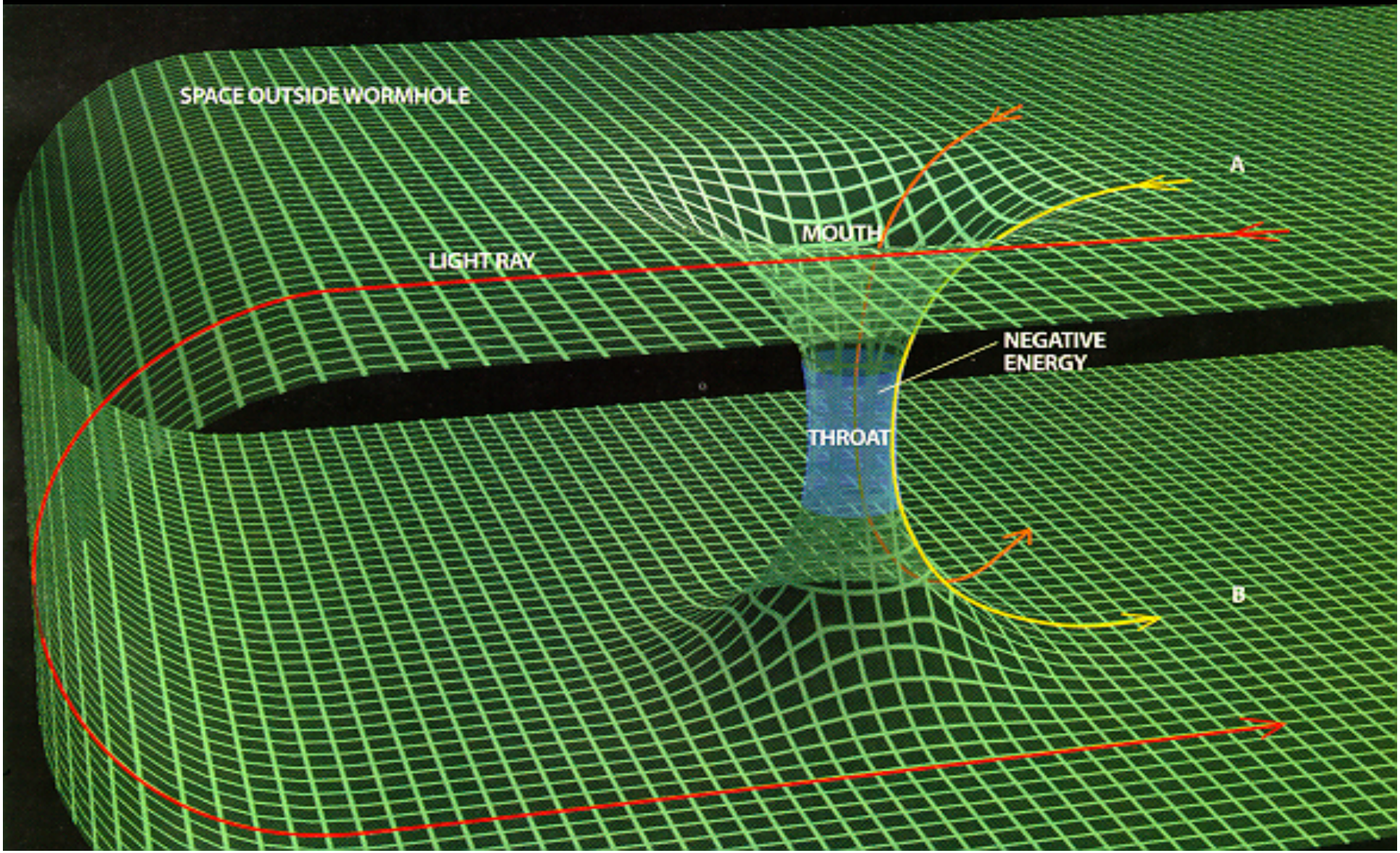
Pont d'Einstein-Rosen (1935)

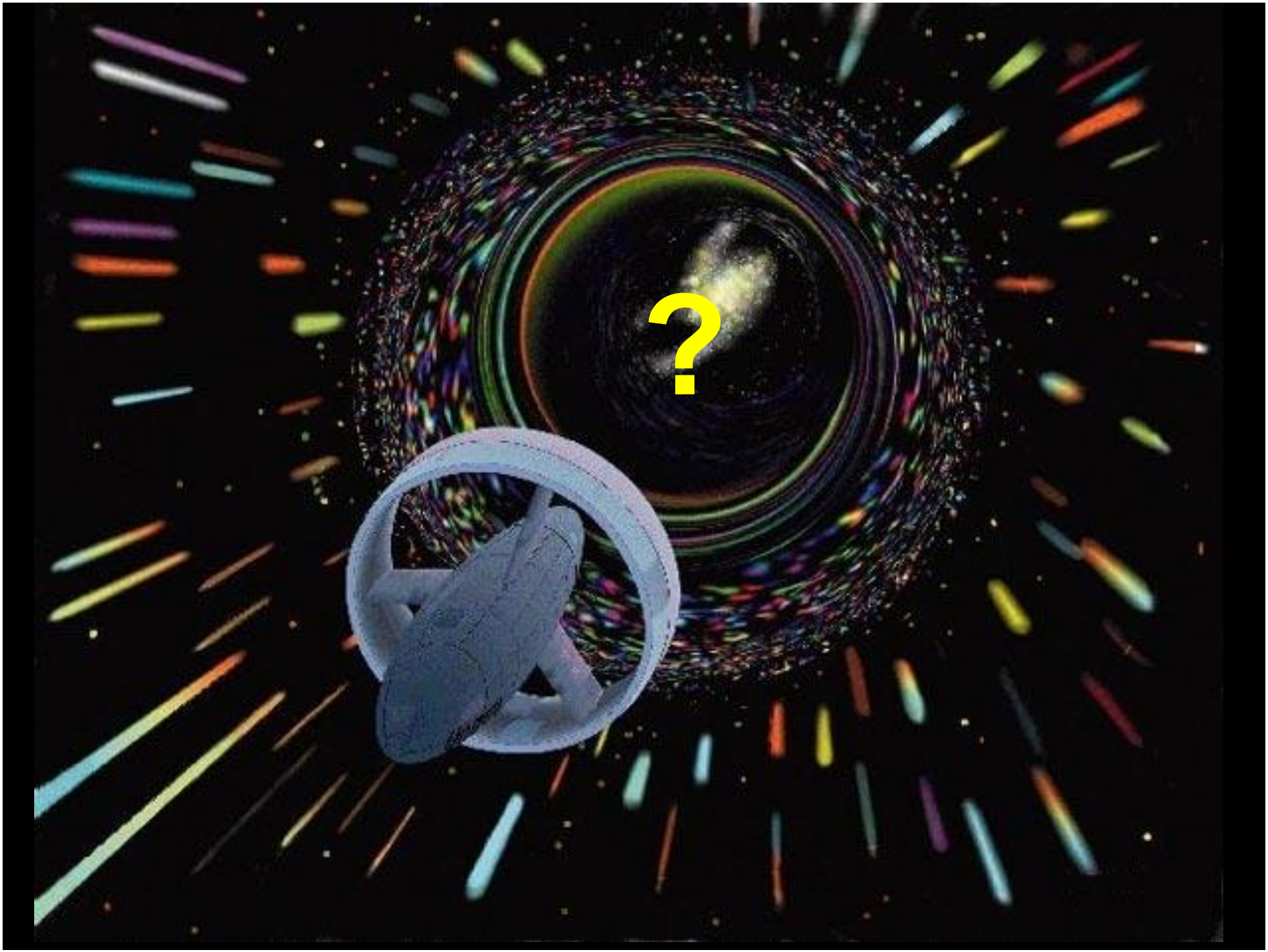


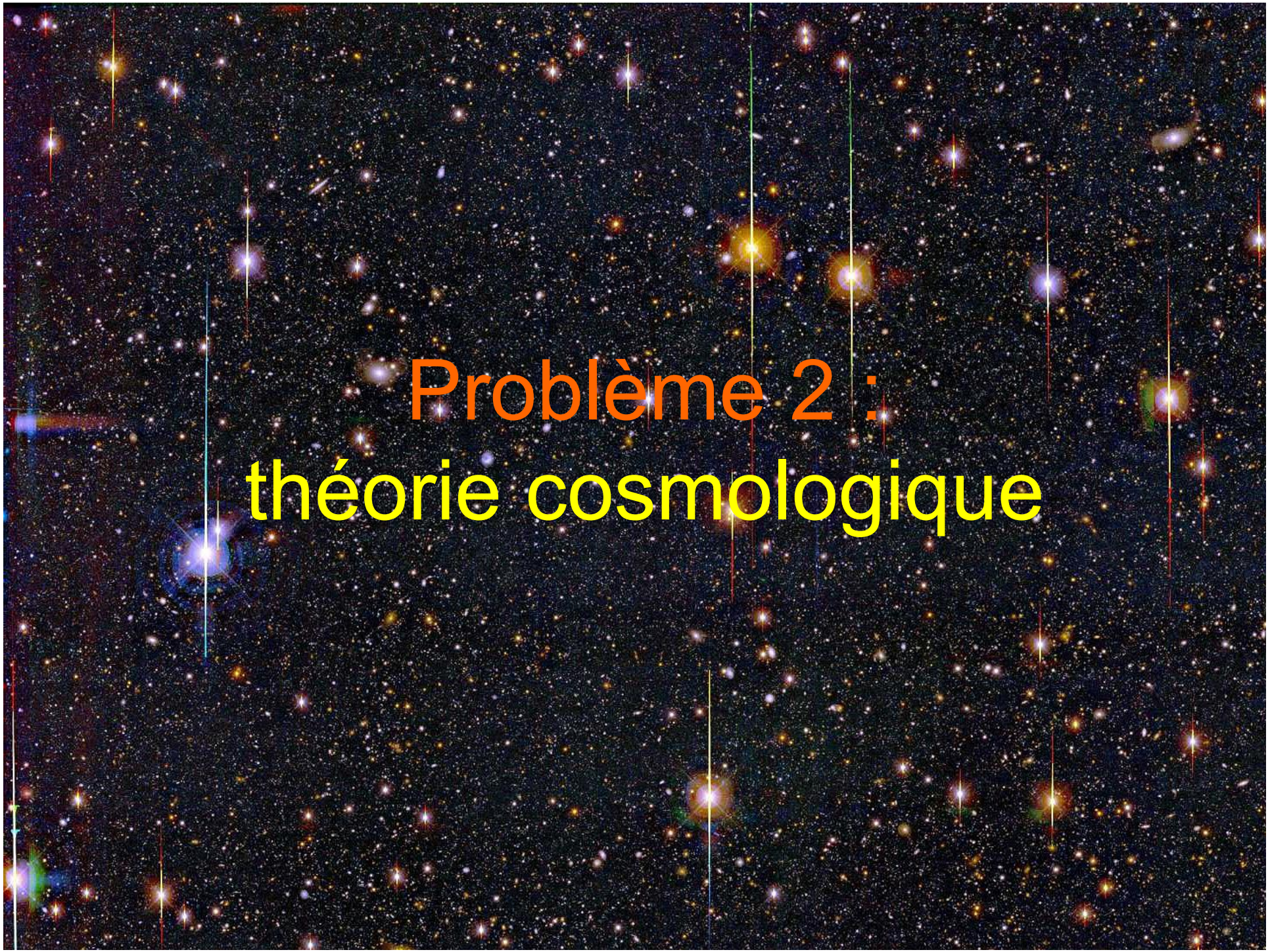
Trou de ver (Wheeler 1967)



Des raccourcis de l'espace-temps !





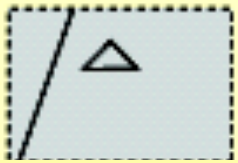

Problème 2 :
théorie cosmologique

Homogénéité

\+ isotropie

=>

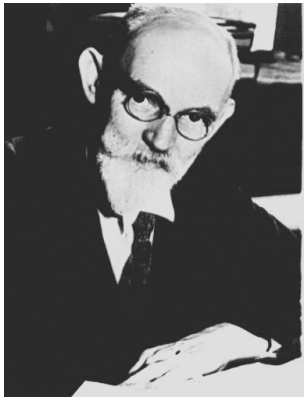
courbure spatiale constante

courbure	
K > 0  espace sphérique	fini (sans bord)
K = 0  espace Euclidien	fini ou infini
K < 0  espace hyperbolique	fini ou infini

1917 : Einstein calcule le premier modèle cosmologique relativiste

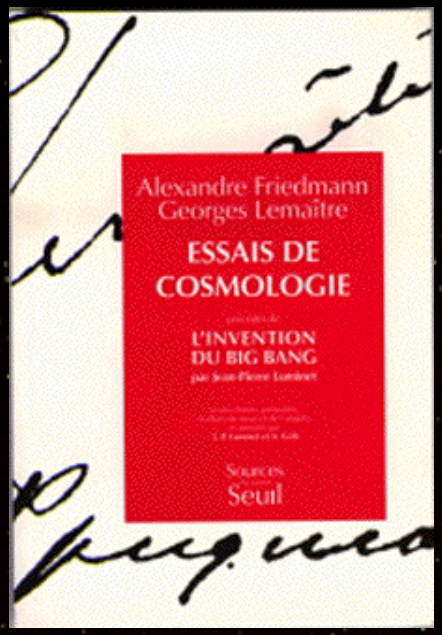
- Courbure : +1 (hypersphère de rayon R)
- Matière : ρ = constante
- **Modèle statique**
- Constante cosmologique: : $\lambda = 1/R^2$

$$G_{ij} = k\,T_{ij} \quad \Rightarrow \quad G_{ij} + \lambda\,\gamma_{ij} = k\,T_{ij}$$

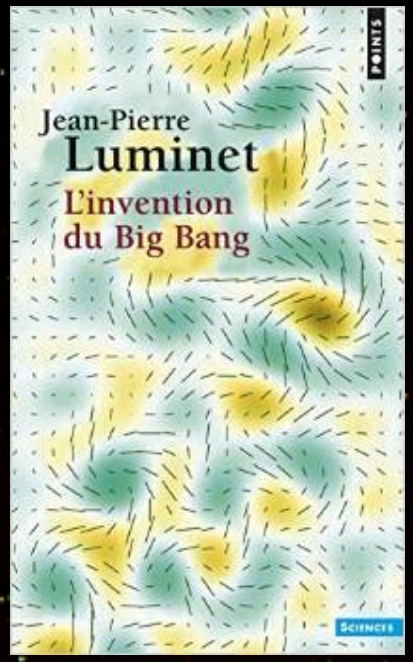


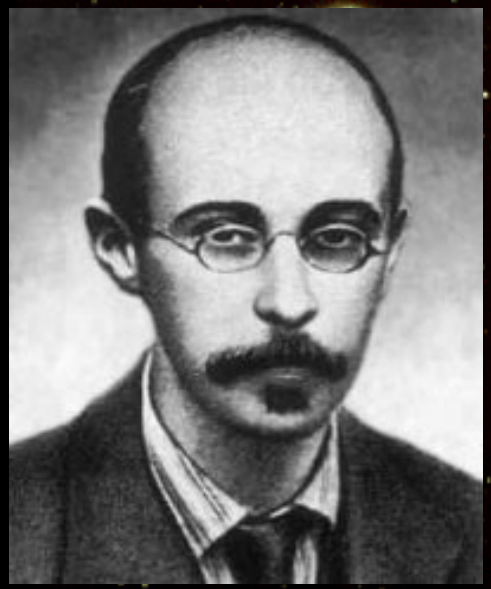
1917 : De Sitter calcule le second modèle cosmologique relativiste

- Matière **: espace vide**
- Constante cosmologique : $\lambda = 3/R^2$
- **Modèle statique** (mais la c. c. simule une expansion accélérée de l'espace)



LES INVENTEURS DU BIG BANG





Friedmann

Lemaître

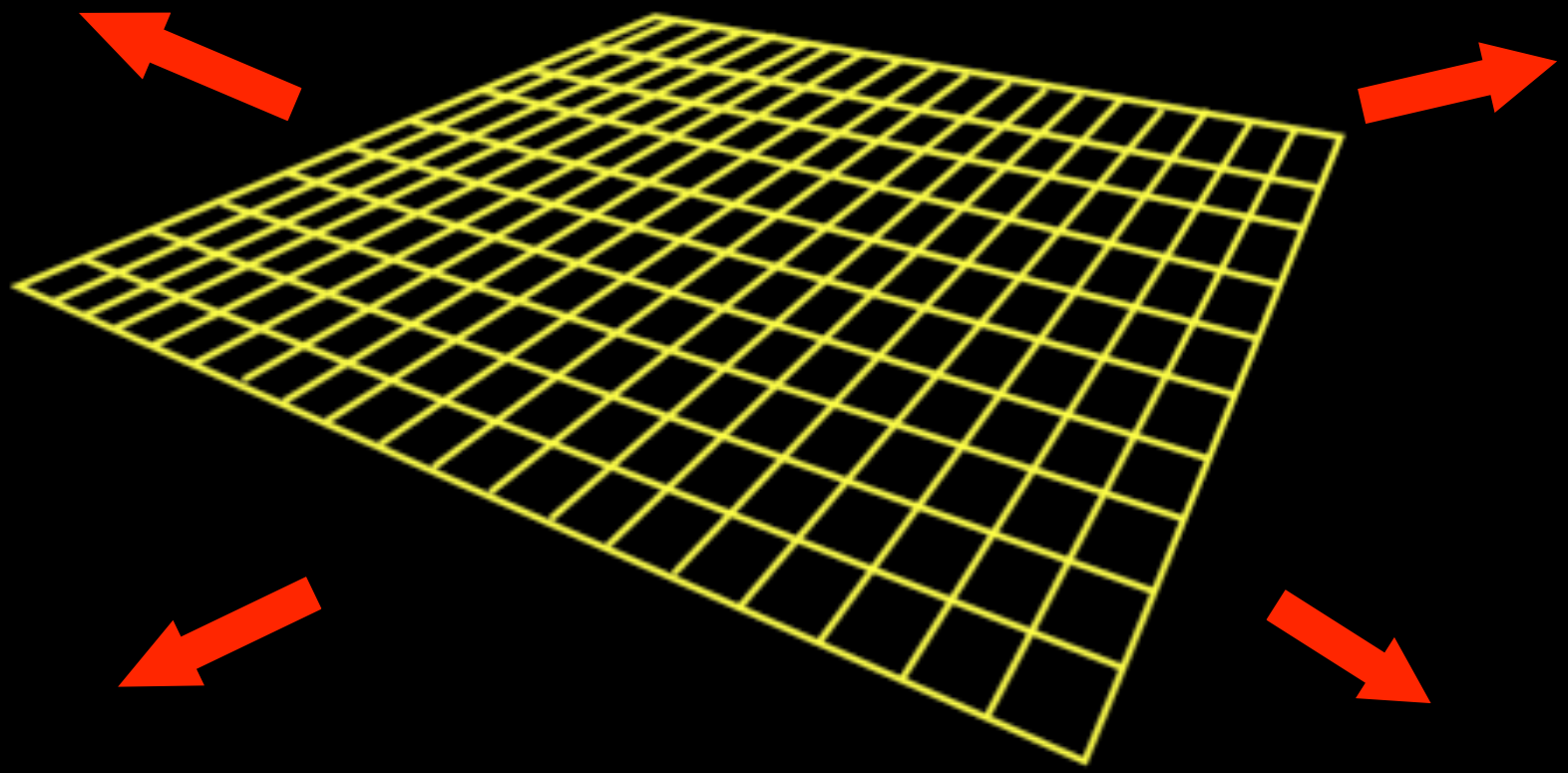
Hubble

Gamow

Courbure de l'espace-temps

→ Univers Dynamique !

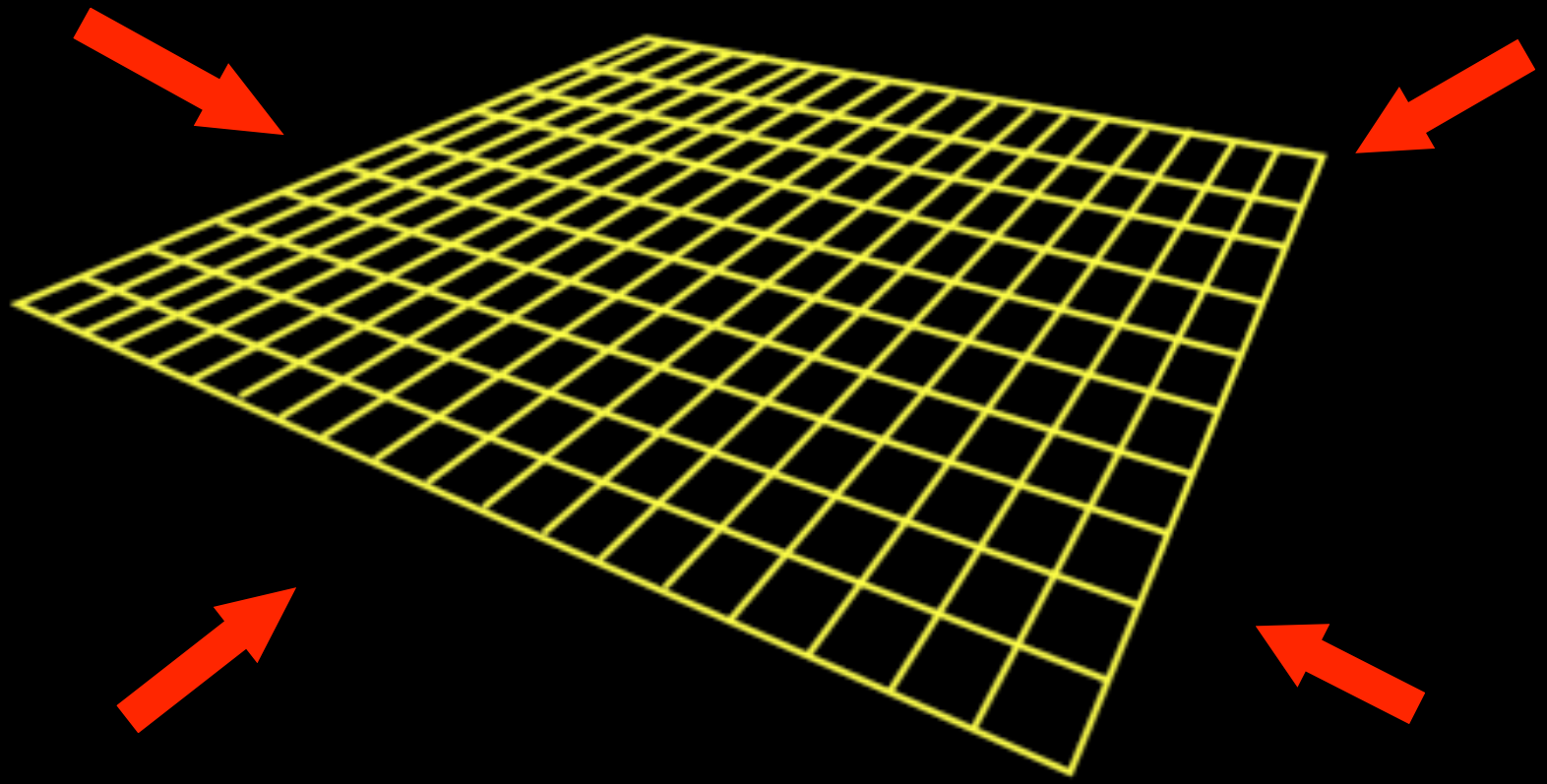
Expansion

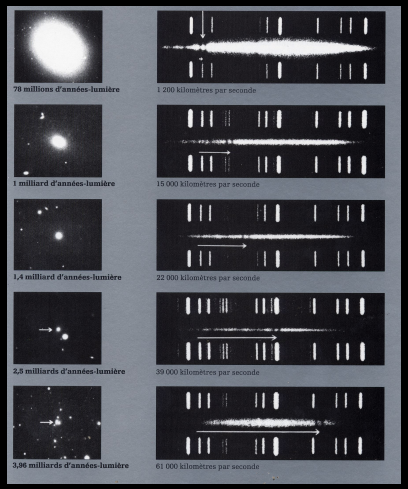


Courbure de l'espace-temps

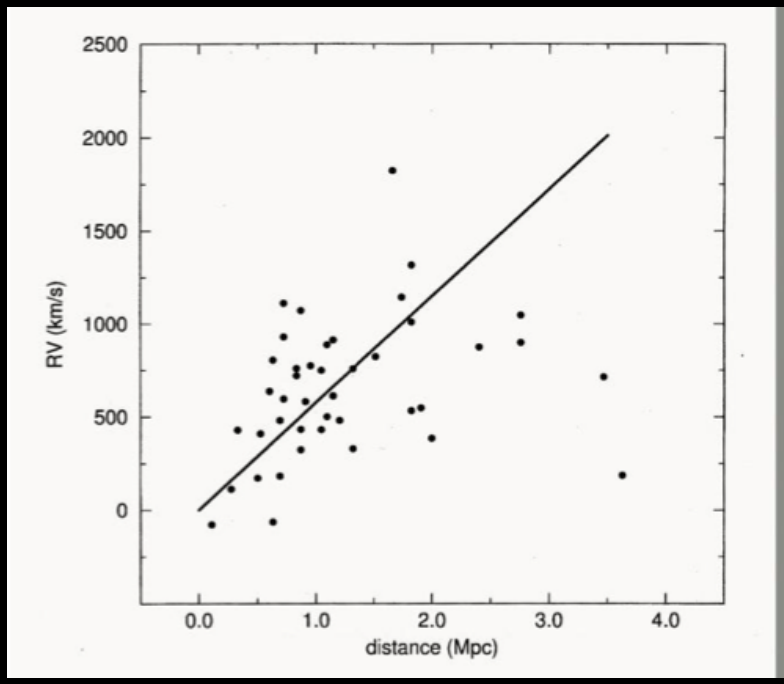
→ Univers Dynamique !

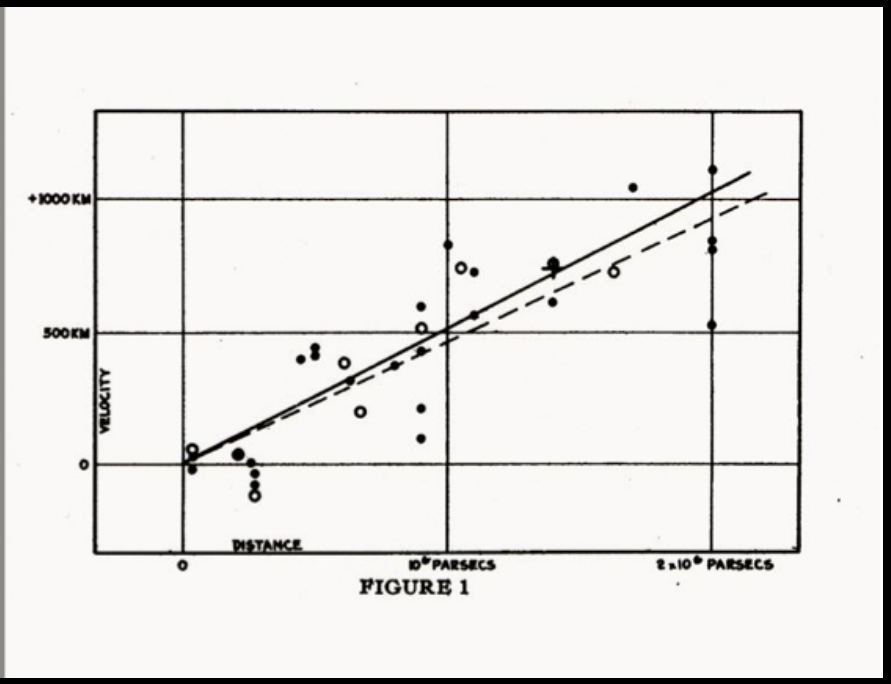
Contraction





Expansion de l'Univers et « loi de Hubble »

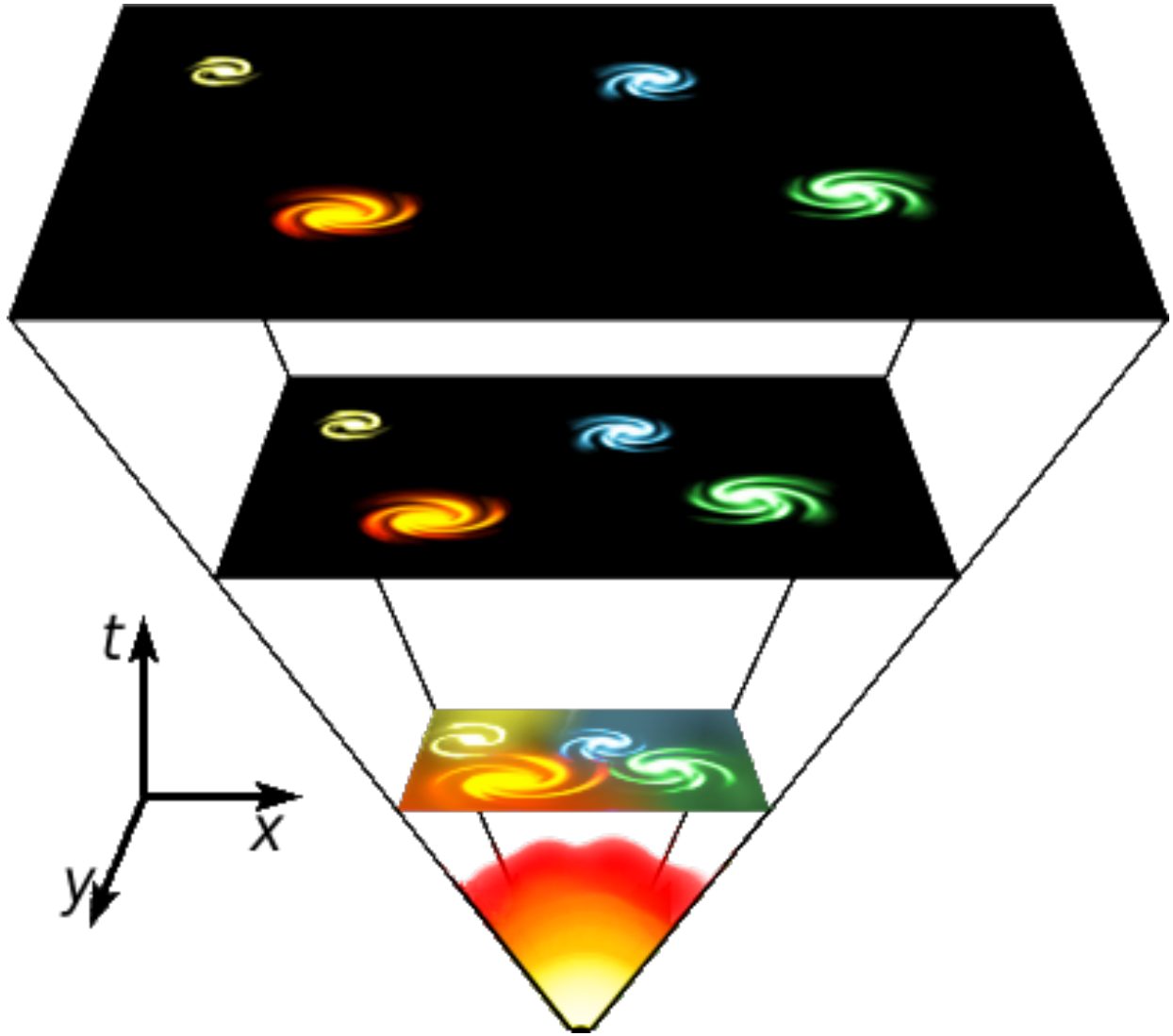




Lemaître 1927, H=575 km/s/Mpc

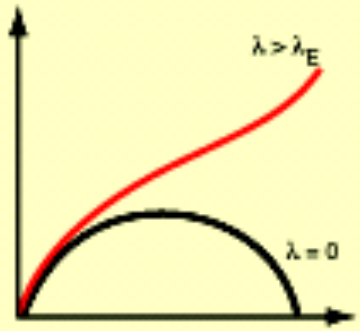
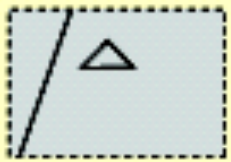
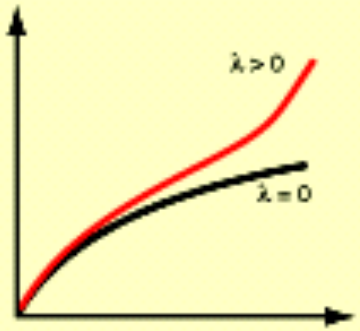
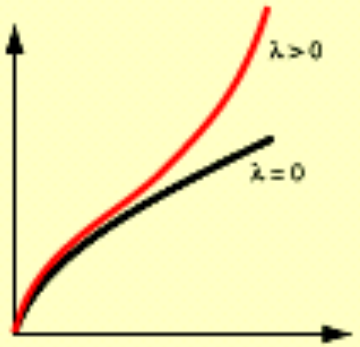
Hubble 1929, H=530 km/s/Mpc

L'Univers est en expansion

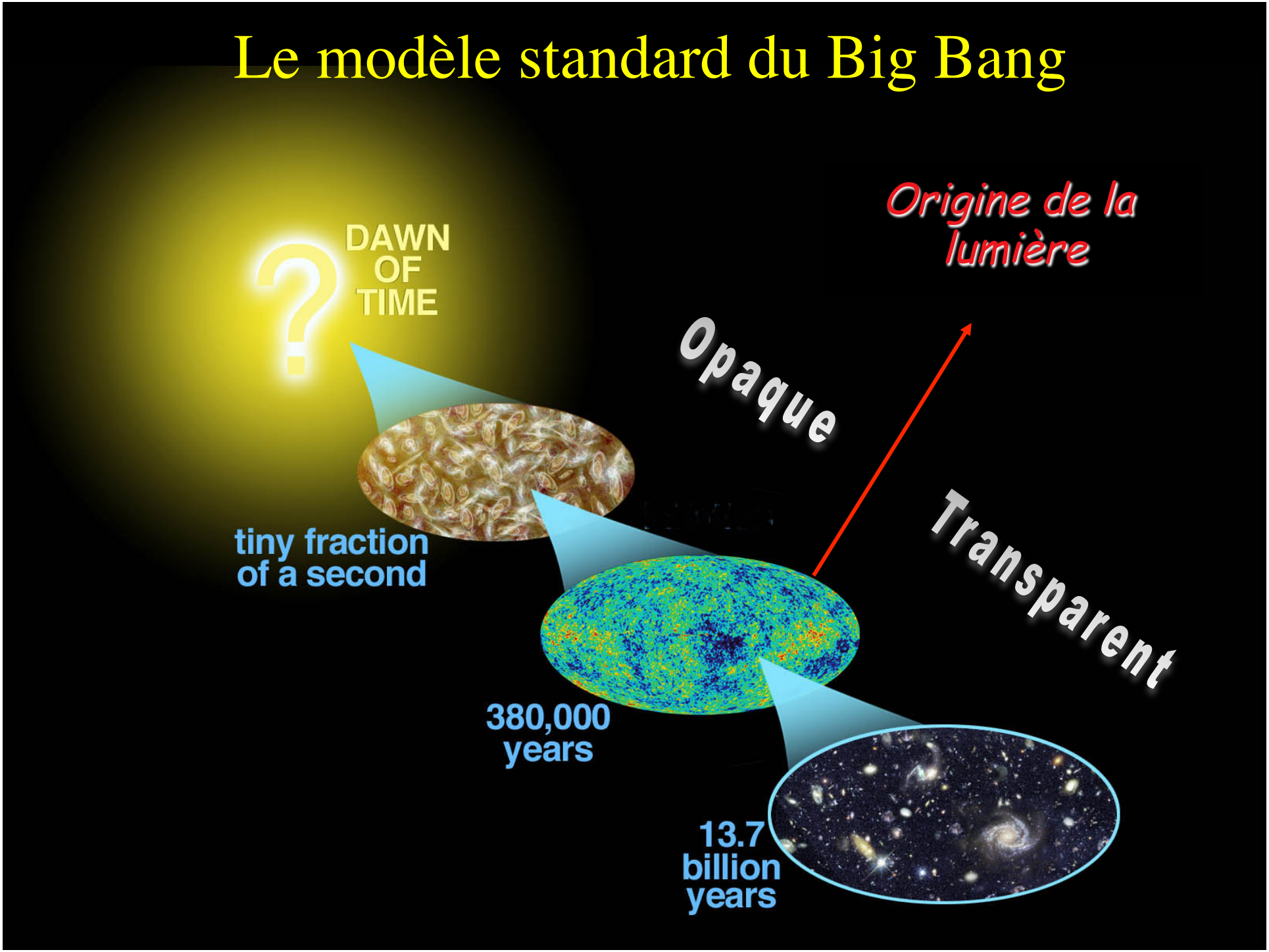


Big Bang

Modèles de Friedmann-Lemaître

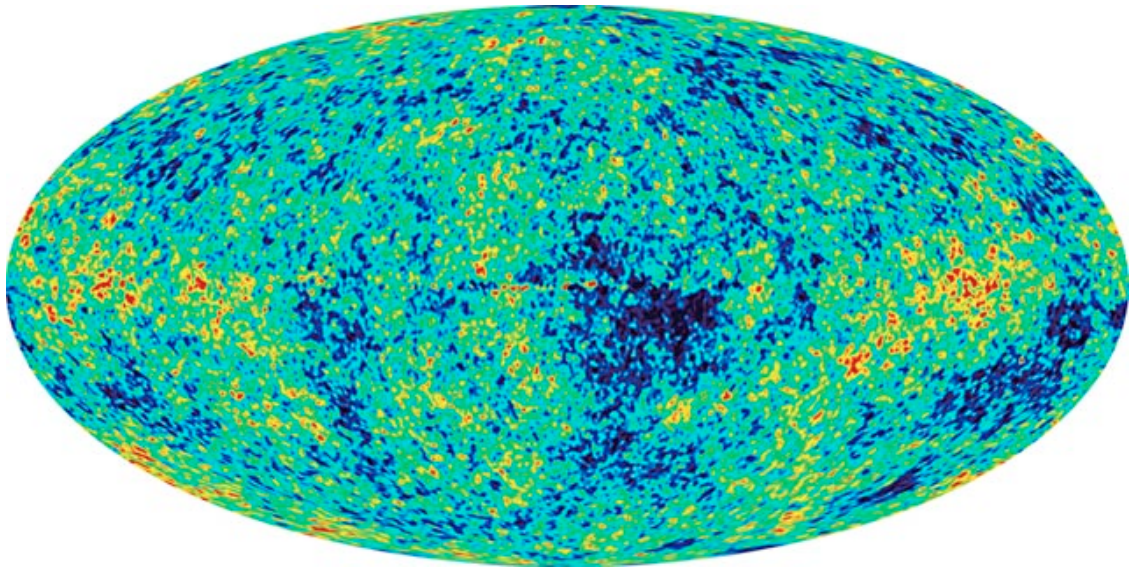
	courbure	dynamique	destin
$\Omega>1$	K > 0  elliptique		ouvert si λ grand fermé
$\Omega=1$	K = 0  Euclidien		ouvert
$\Omega<1$	K < 0  hyperbolique		ouvert

Le modèle standard du Big Bang

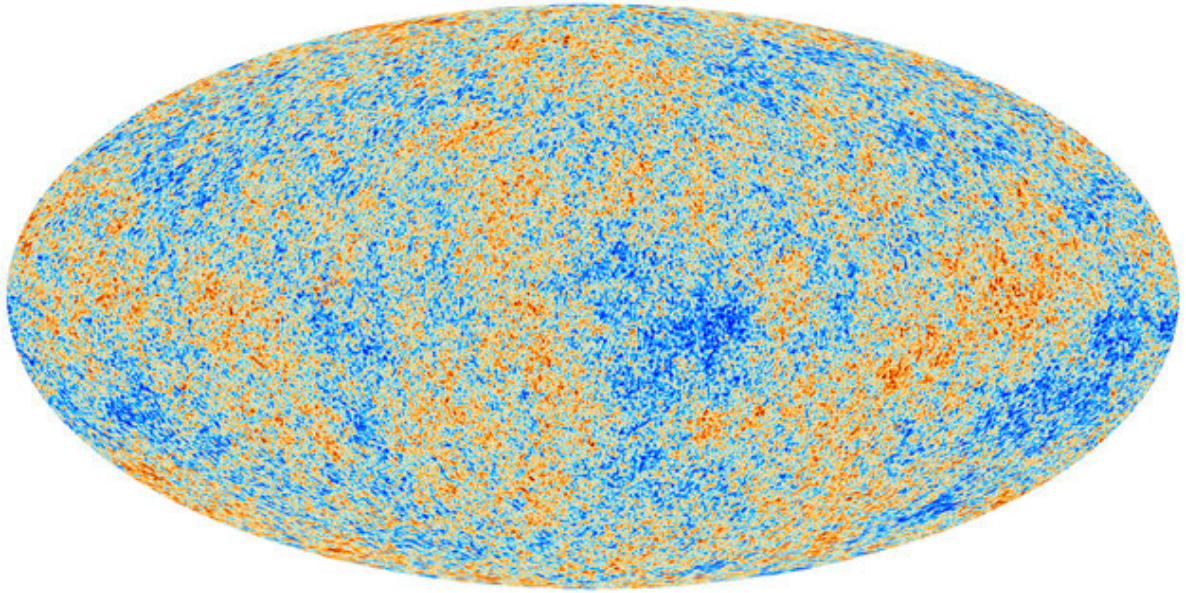


Anisotropies du rayonnement fossile

WMAP
2003

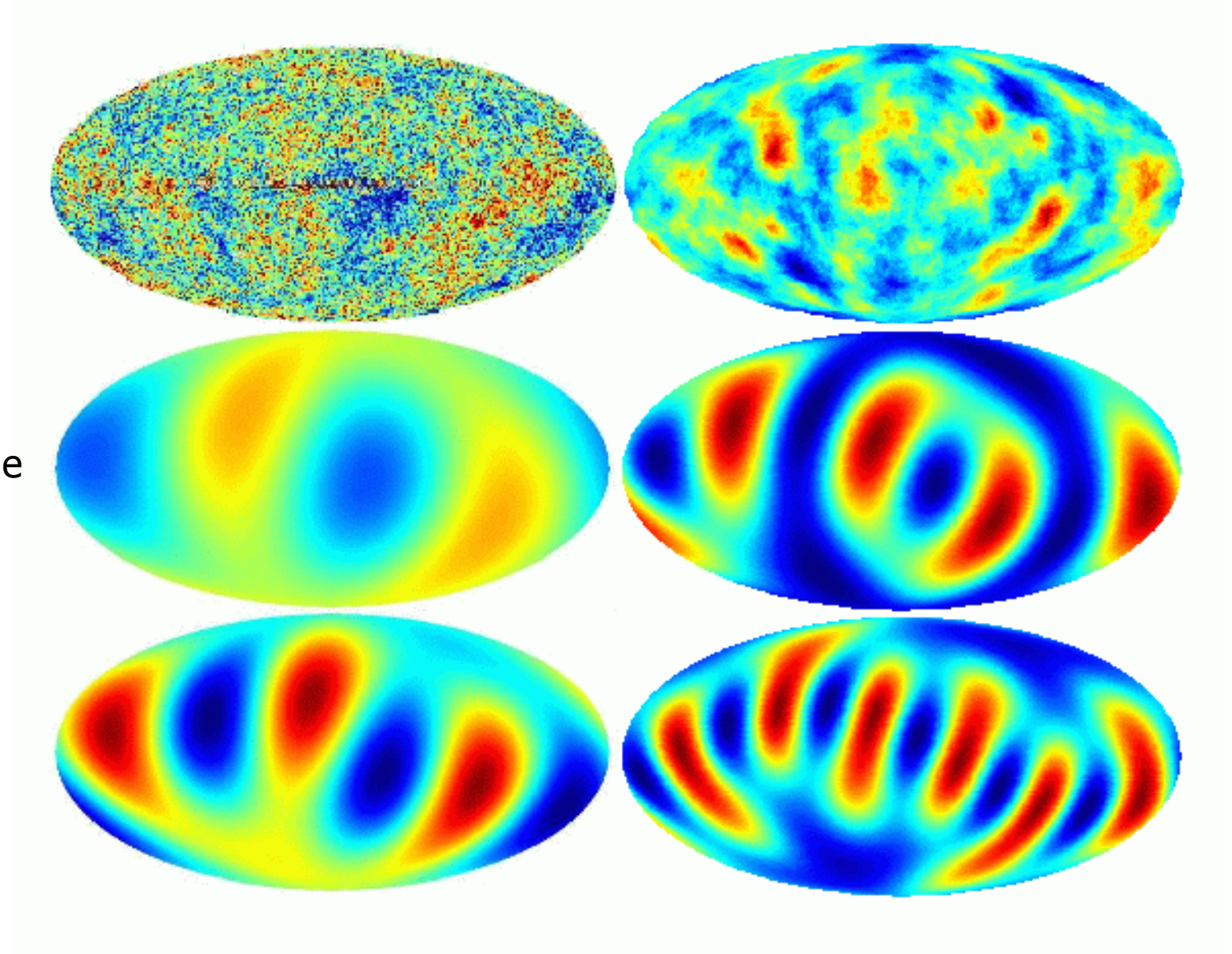


Planck
2013



Les harmoniques cosmiques

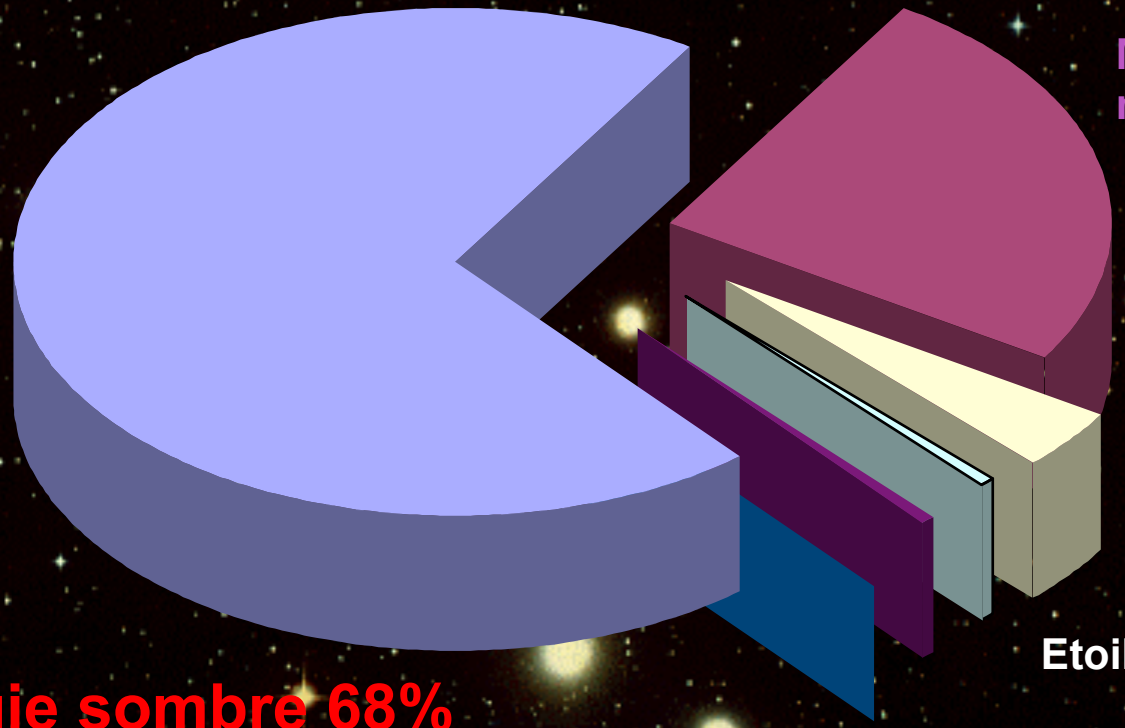
Quadrupole



Âge de l'Univers

13,81 milliards d'années

La composition de l'Univers



Matière noire non atomique 27%

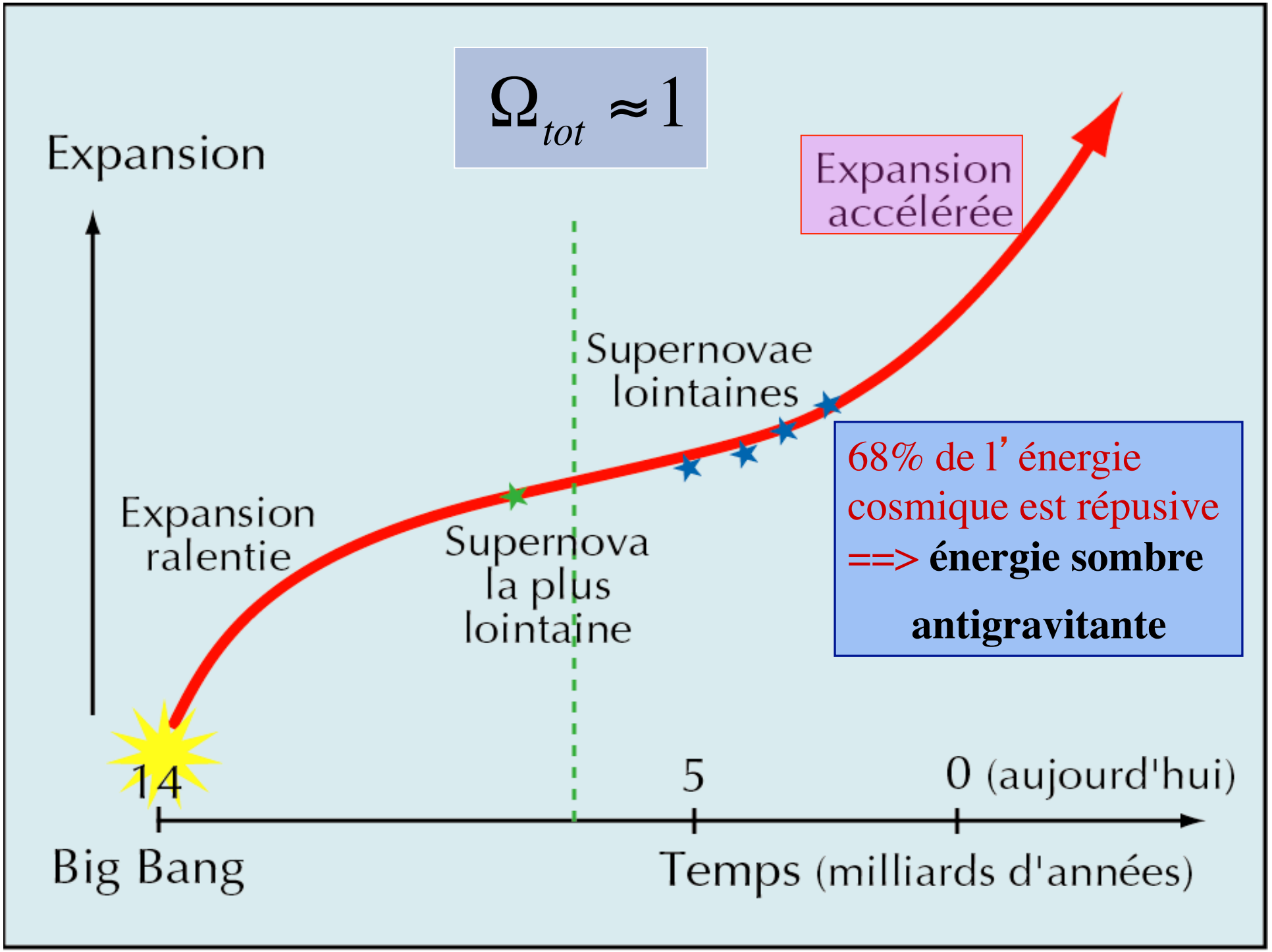
Matière noire atomique 4%

Etoiles, gaz visible 0.5%

Neutrinos 0,5%

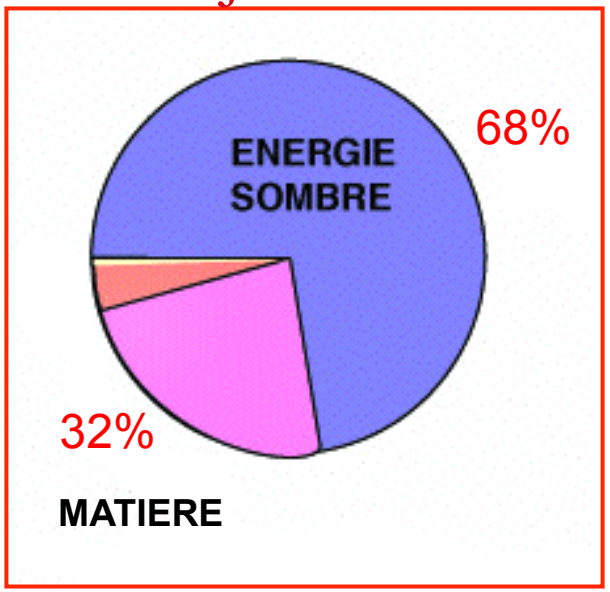
Lumière 0,05%

Energie sombre 68%

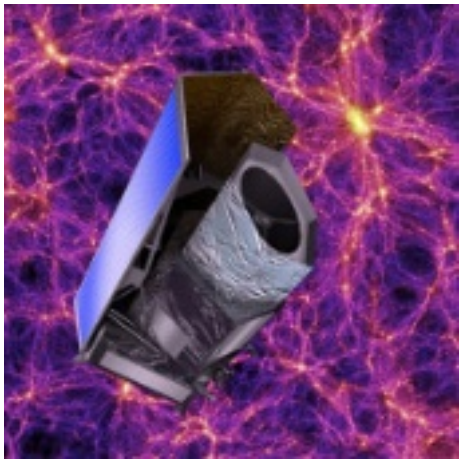

$\Omega_{tot} \approx 1$
Expansion
Expansion accélérée
Supernovae lointaines
Expansion ralentie
Supernova la plus lointaine
68% de l'énergie cosmique est répusive ==> énergie sombre antigravitante
14
5
0 (aujourd'hui)
Big Bang
Temps (milliards d'années)

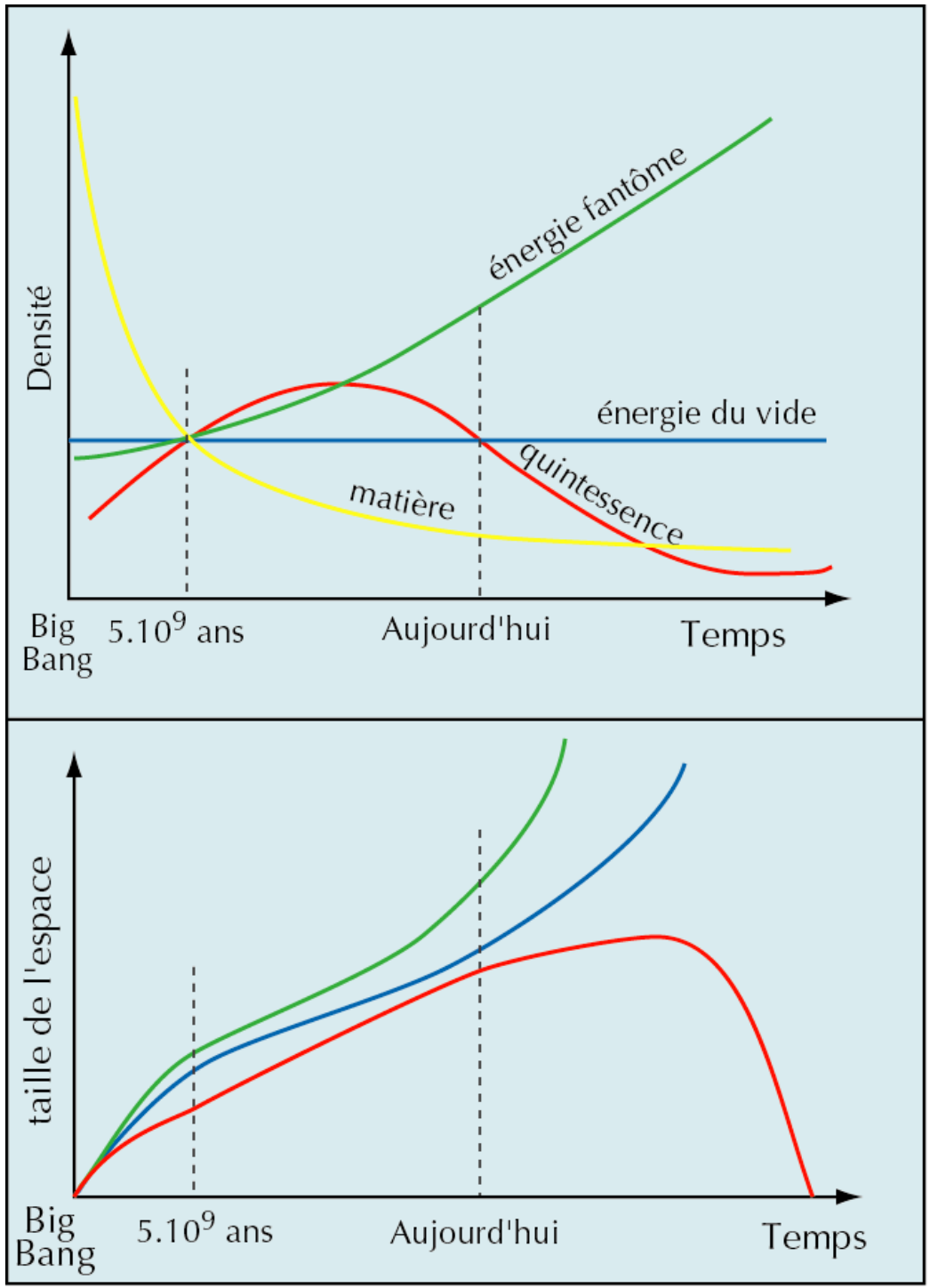
Quel futur pour l'Univers ?

aujourd'hui:



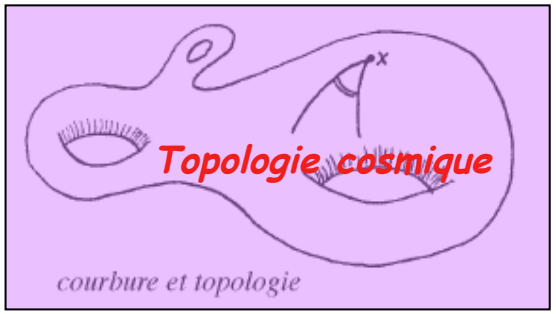
Mission Euclid 2020





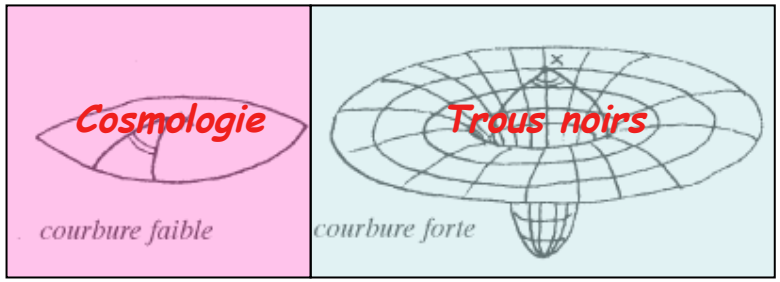
Au-delà de la Relativité générale…

Niveau 1



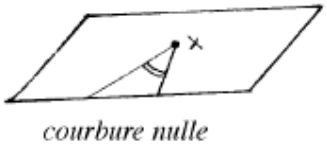
Topologie cosmique

Niveau 2



Relativité générale, cosmologie

Niveau 3

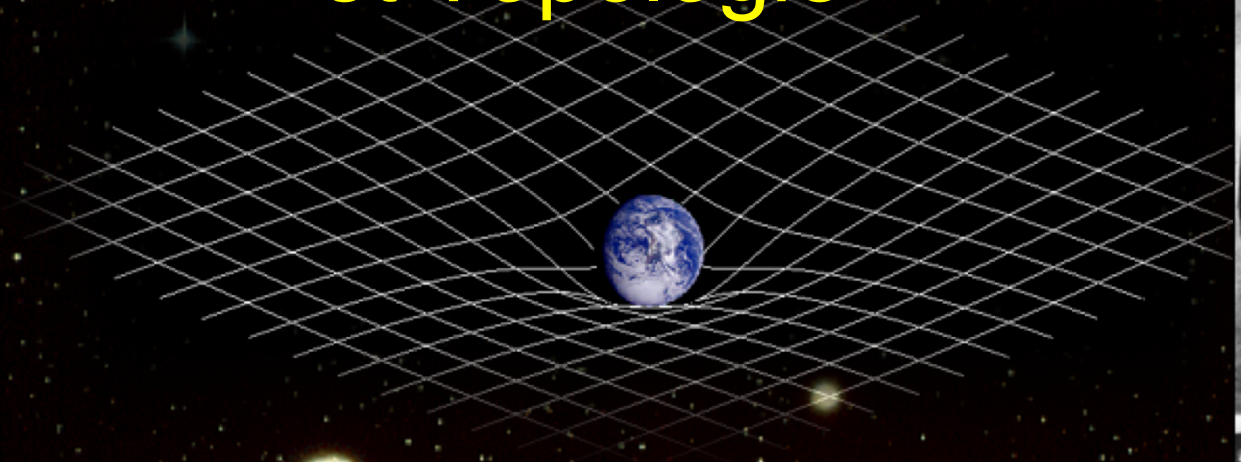


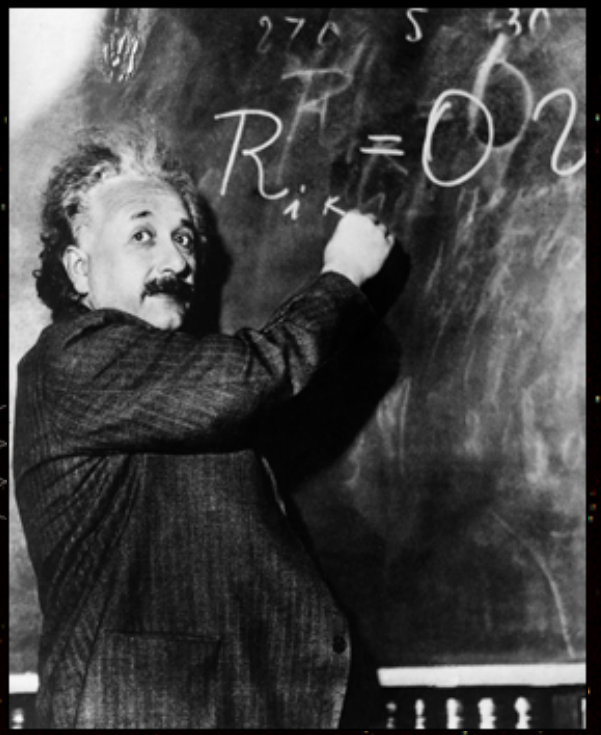
Mécanique classique, Relativité restreinte

Niveau 4

Gravitation quantique, Théories d'unification

Relativité générale et Topologie



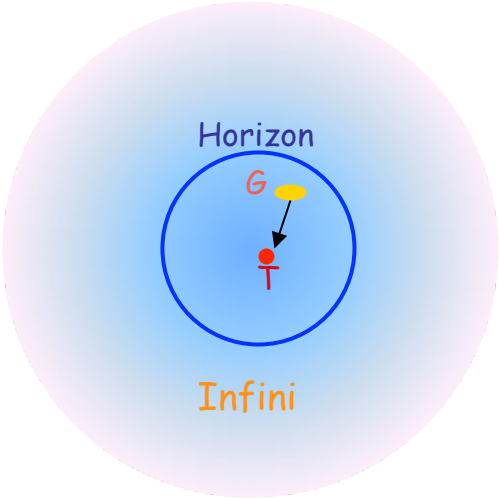


$$G_{\mu\nu} = k\, T_{\mu\nu}$$

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

La métrique de l'espace-temps ne détermine pas ses propriétés globales !

Quelle est la taille et la forme de l'Univers ?

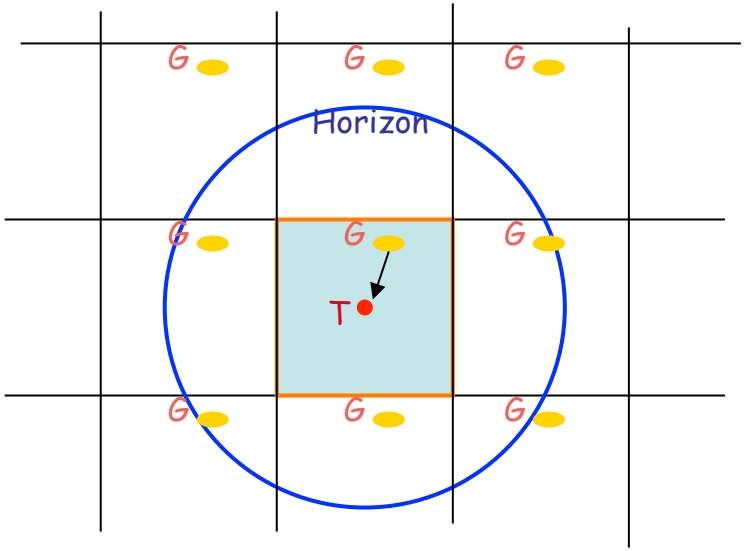


Hypothèse 1

L'univers réel est infini

Hypothèse 2

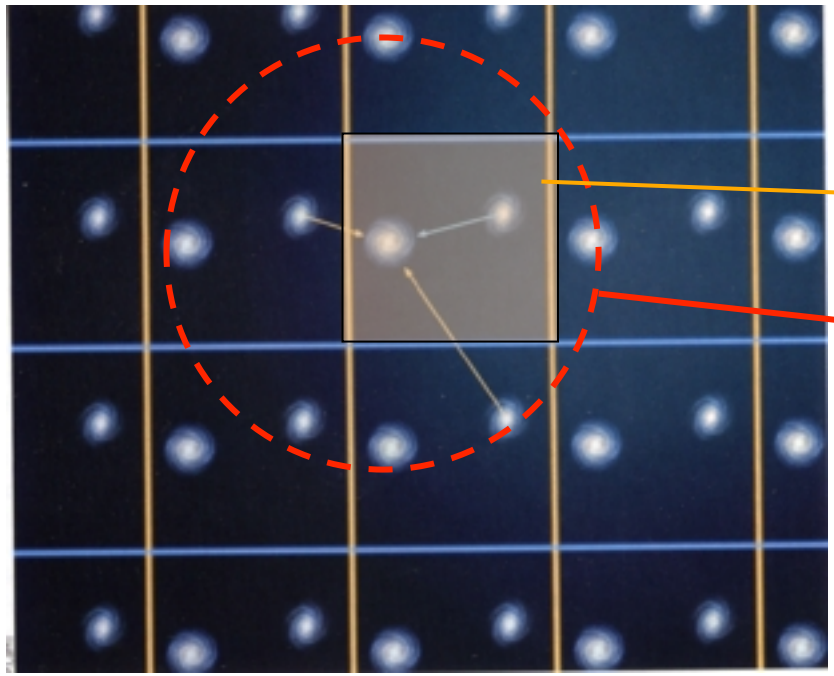
L'univers est fini (sans bord) mais plus grand que l'univers visible



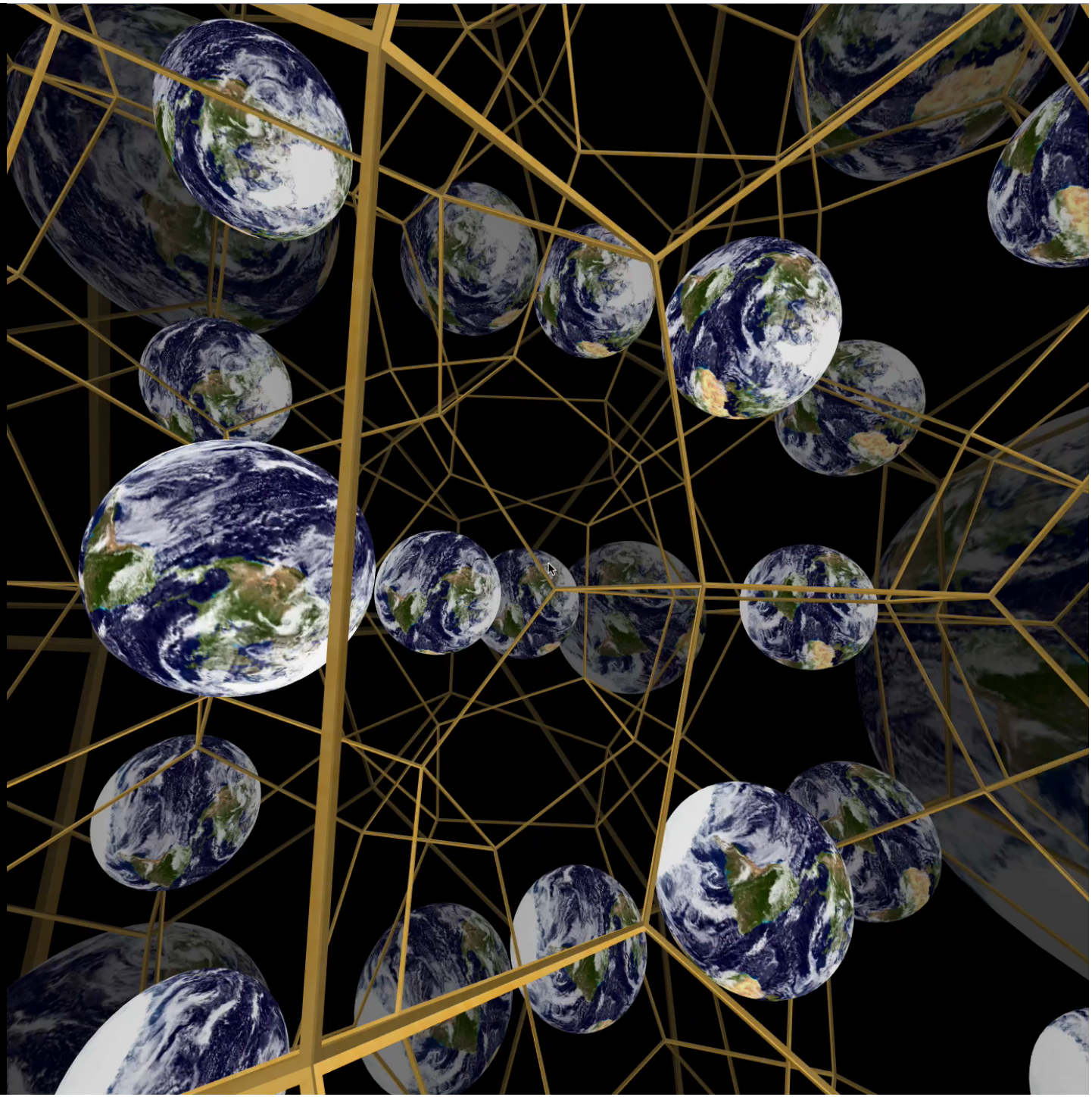
Hypothèse 3

L'univers est fini (sans bord) et plus petit que l'univers visible

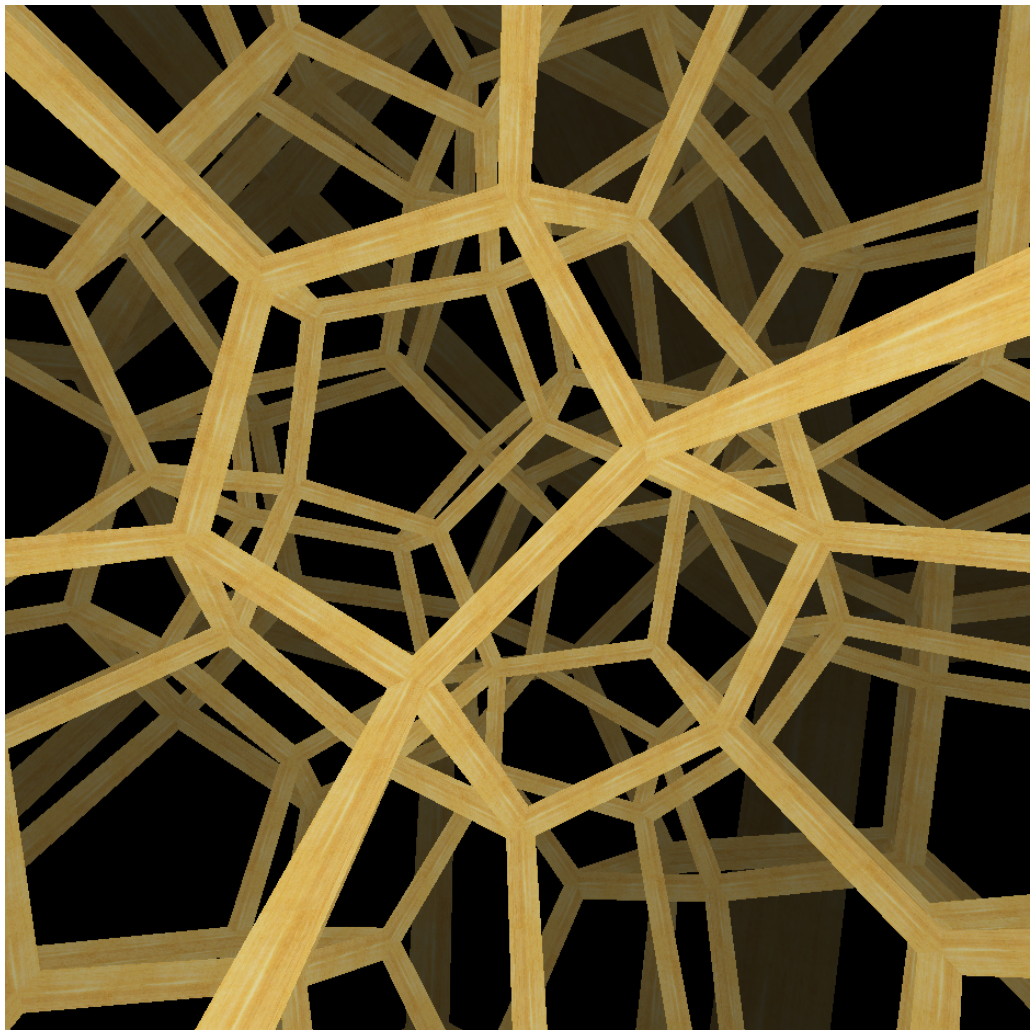
Effet de mirage topologique



Curved Spaces Program

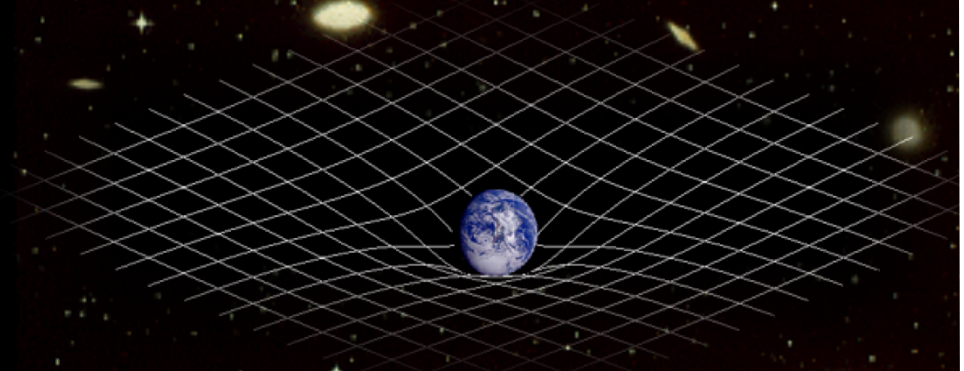


Espace dodécaédrique de Poincaré



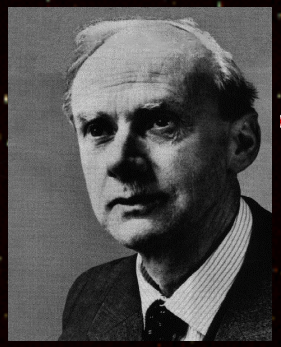
Luminet et al. (2003)

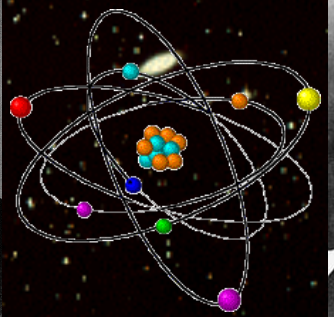
Relativité générale



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

Mécanique quantique

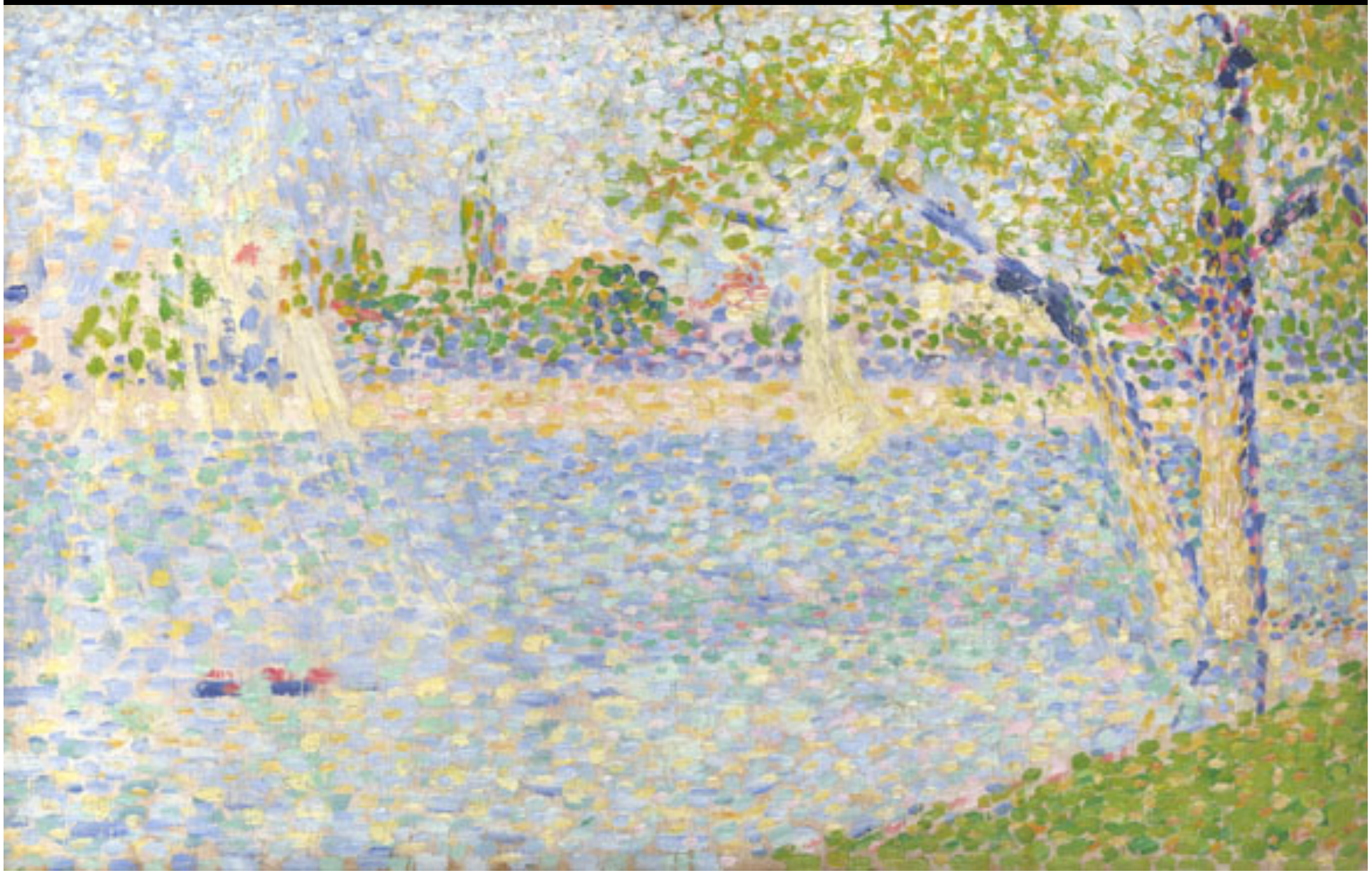




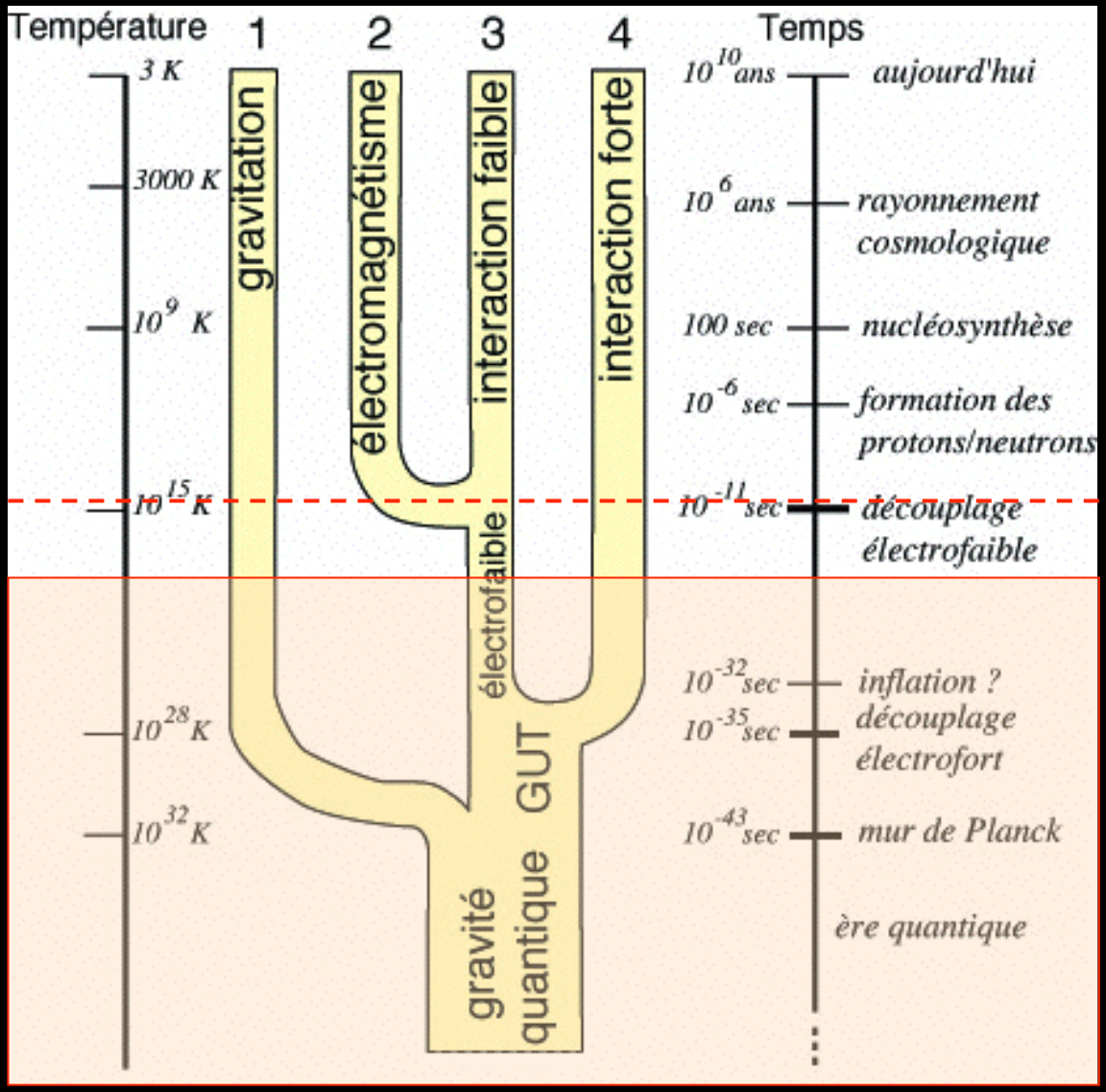
$$ih\partial/\partial t\,|\Psi> = H\,|\Psi>$$

Relativité générale

Mécanique quantique



Unification des interactions fondamentales



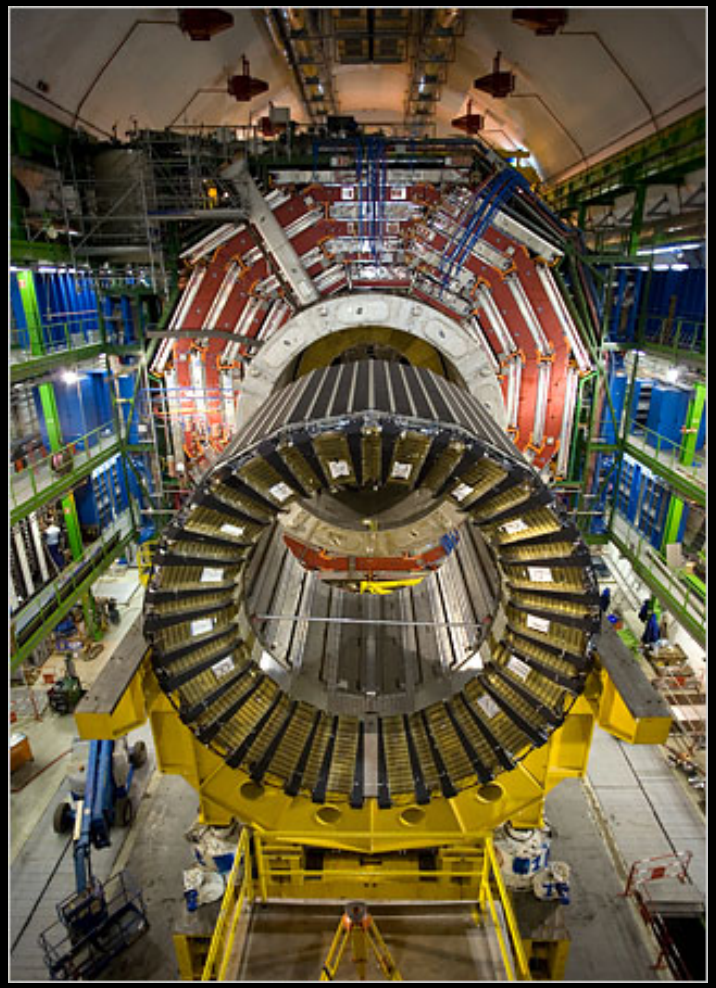
Expériences CERN

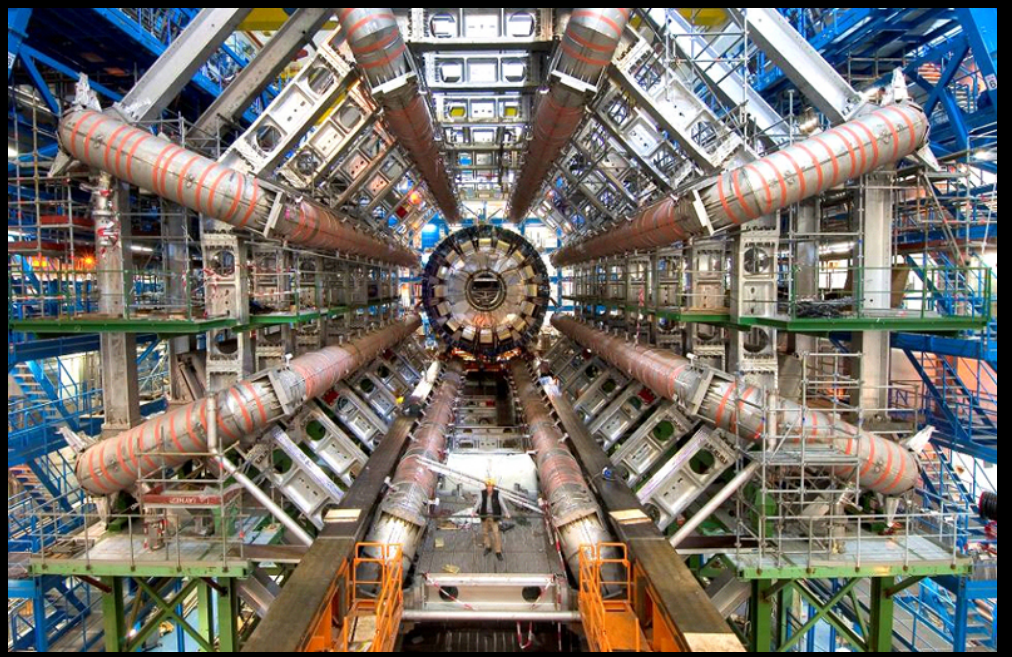
modèle standard

Modèles théoriques

Limites de la physique

LHC (CERN)





Solutions ?

Réduire la géométrie aux champs

Supercordes

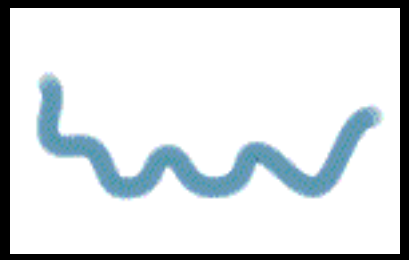
branes

Réduire les champs à la géométrie

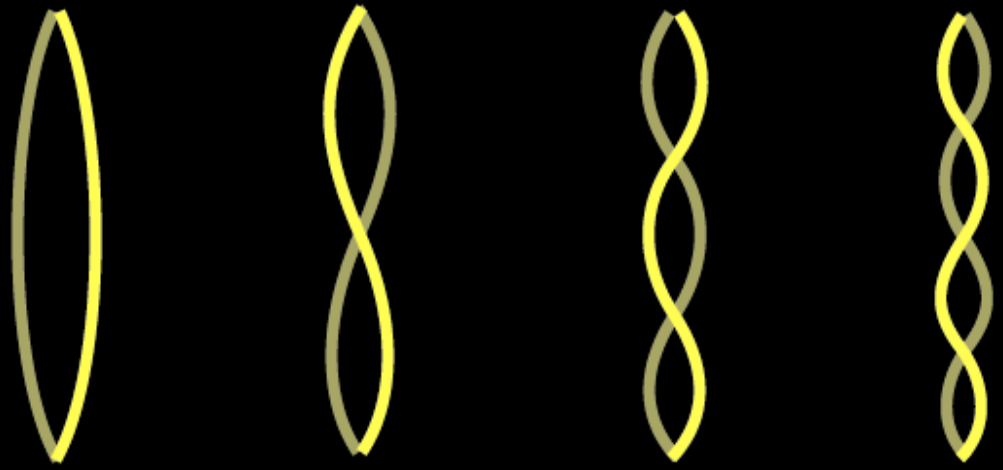
Gravité quantique à boucles

Théorie des cordes

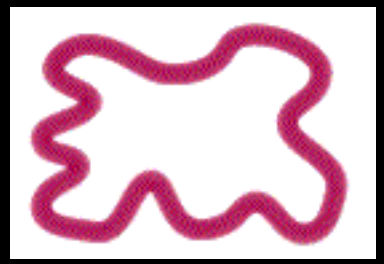
taille ~10^{-33} cm



cordes ouvertes



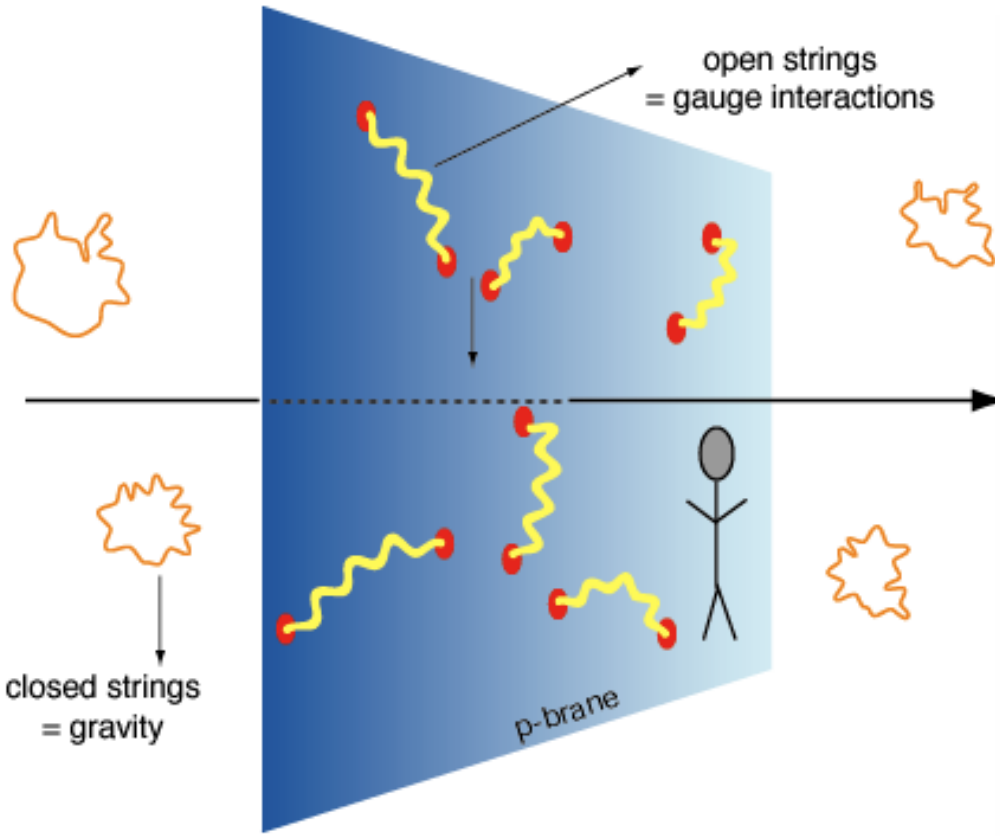
cordes fermées

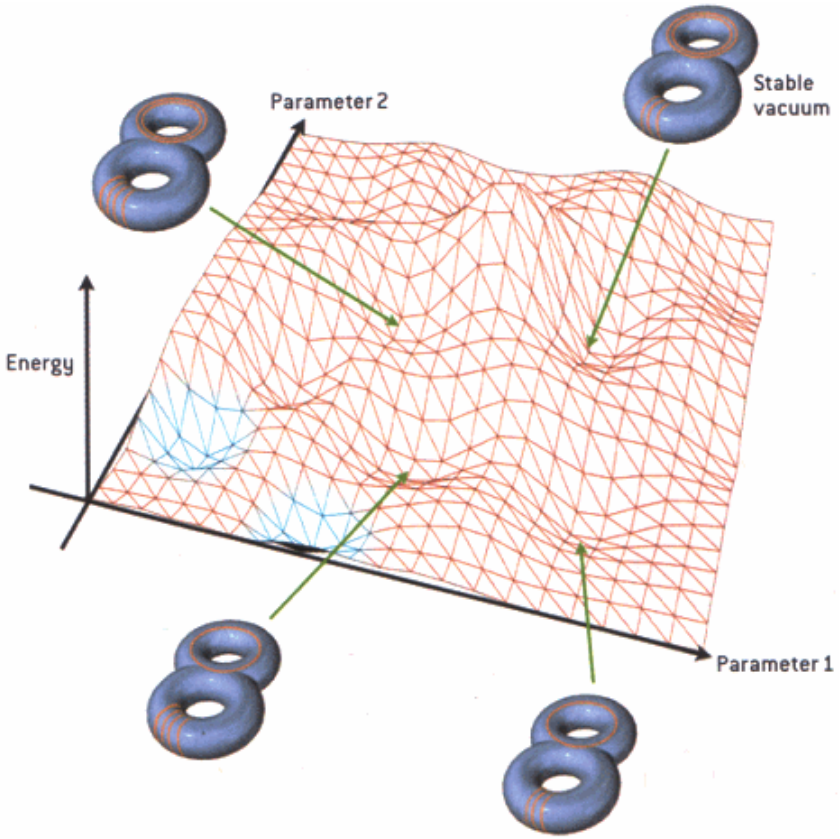


Théorie des cordes

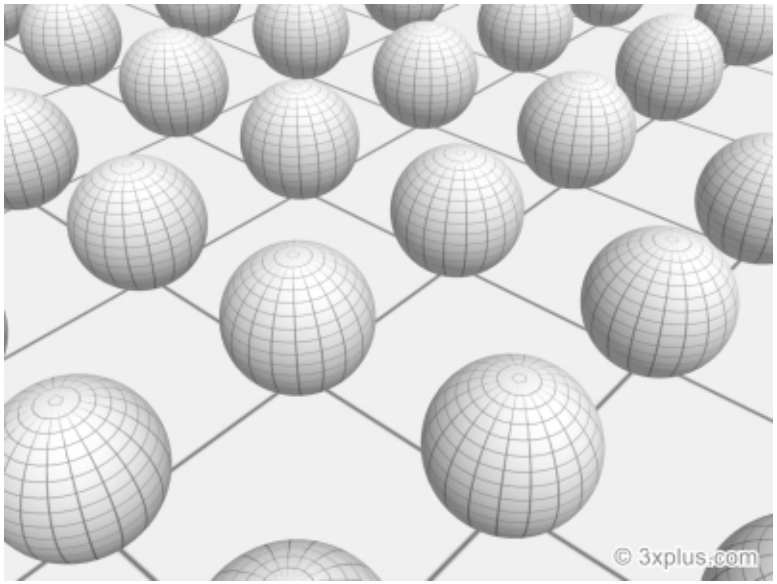
Prix à payer 1 :
Dimensions supplémentaires

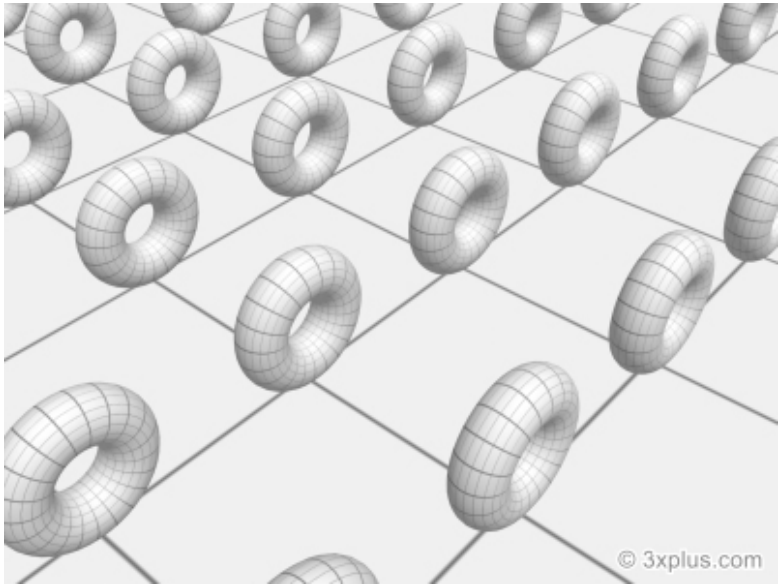
Prix à payer 2 :
10^{500} solutions

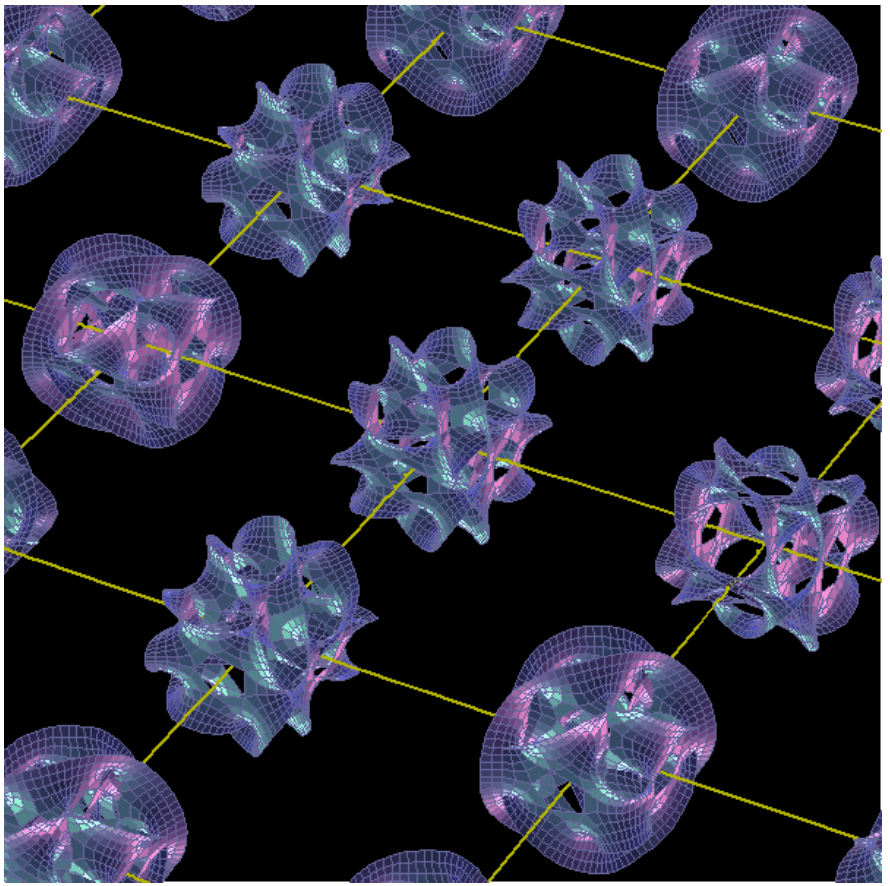




Théories des cordes





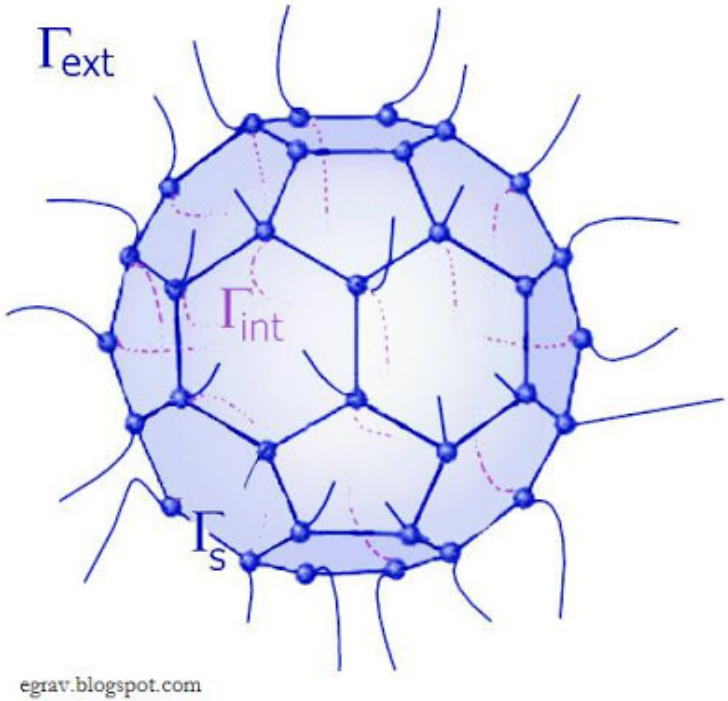


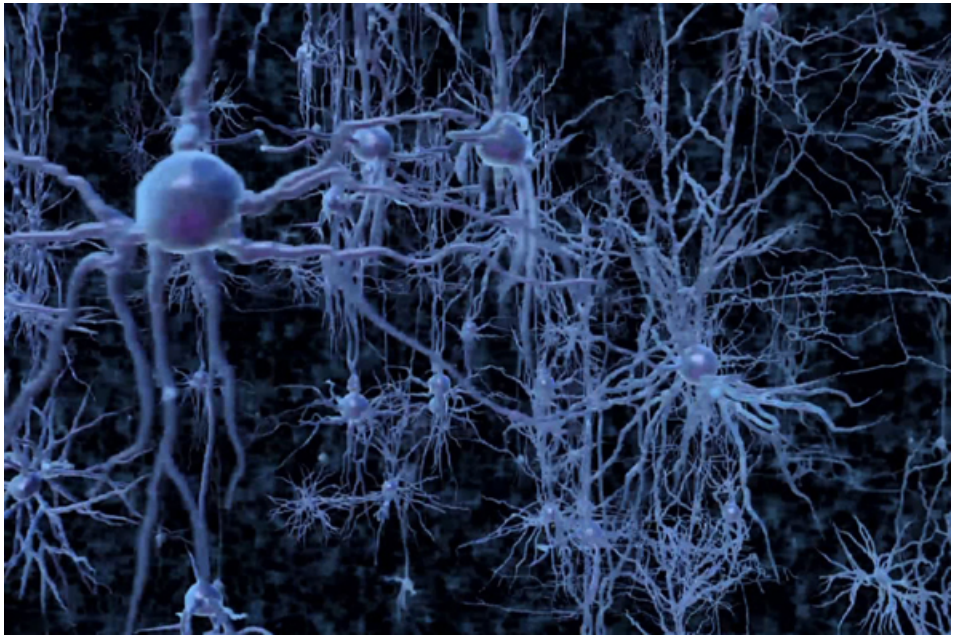
La topologie des espaces de Calabi-Yau engendre

les familles de particules.

Gravité quantique à boucles

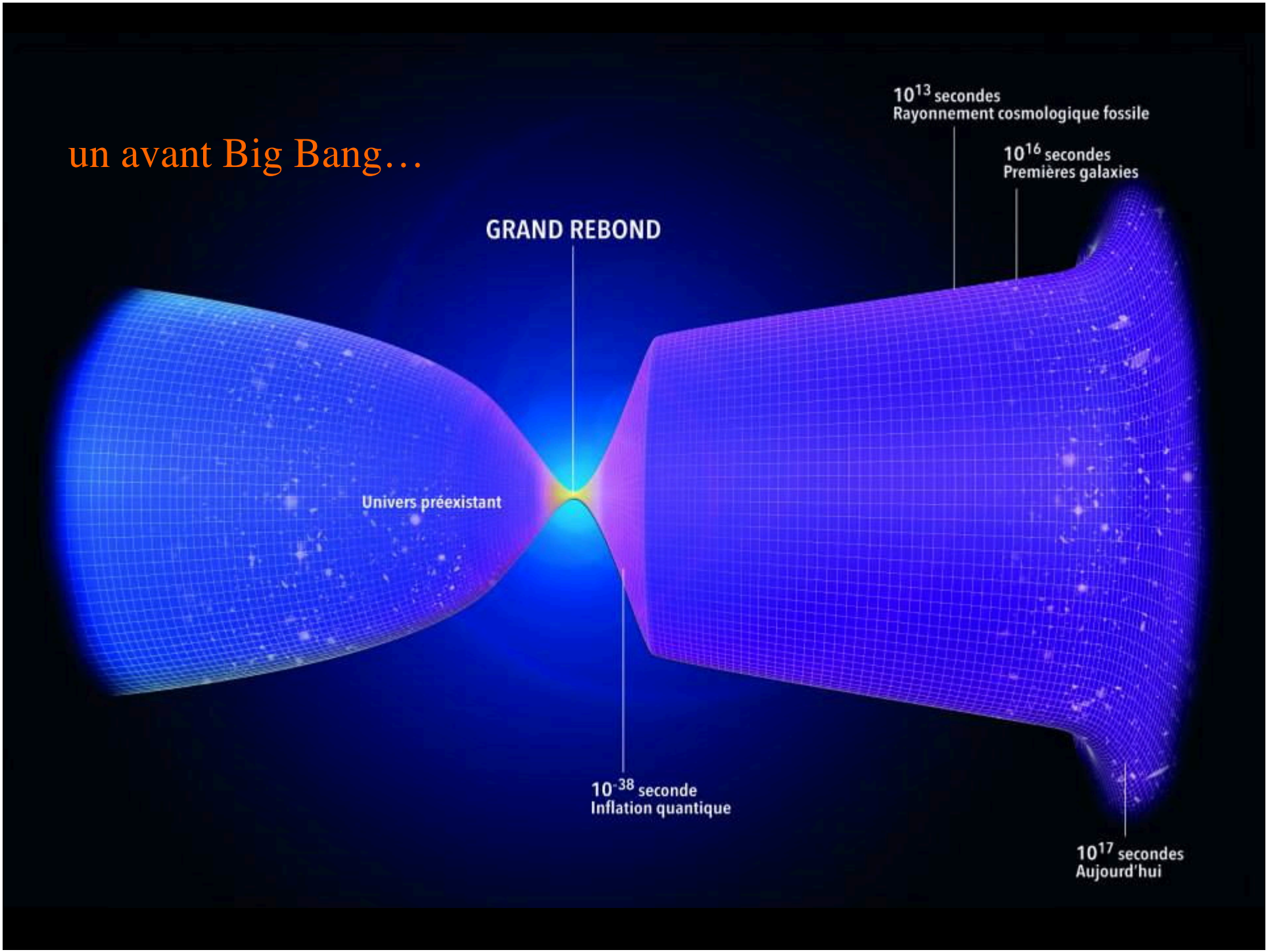
Atomes d'espace : vol ~ 10^{-99} cm^3



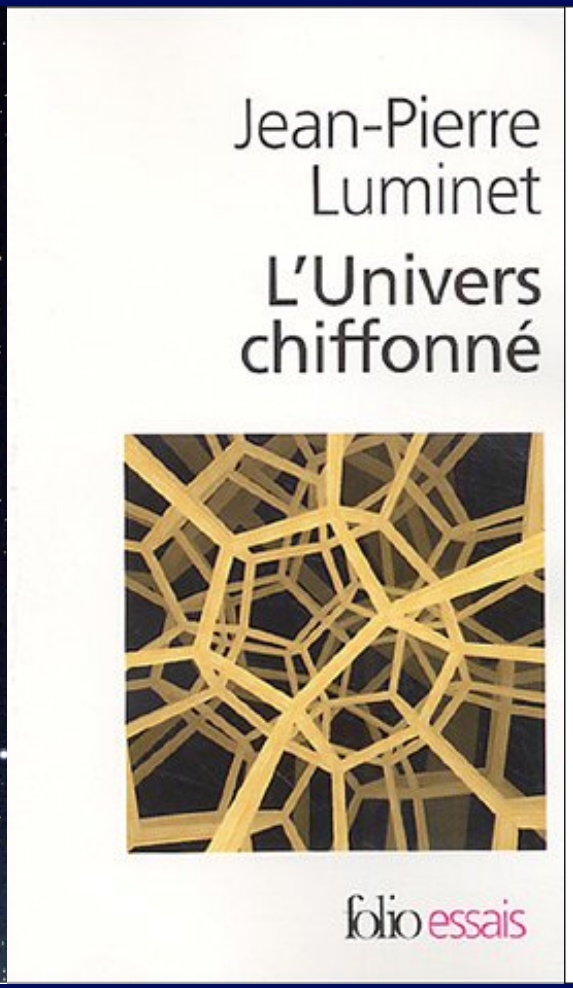


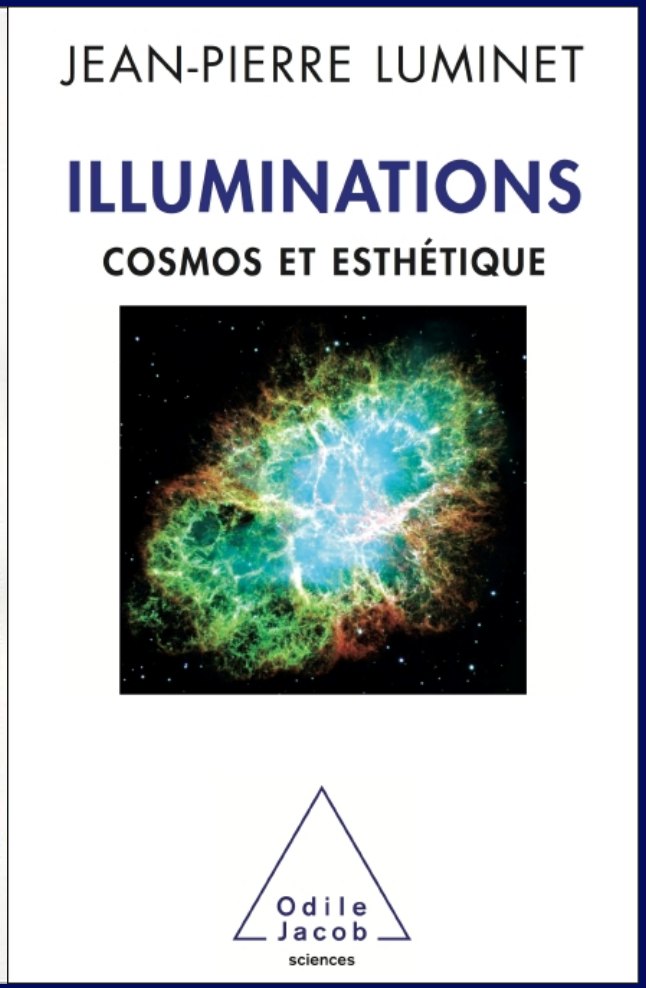
Formalisme : Réseaux de spins

un avant Big Bang…




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


Jean-Pierre Luminet
L'Univers chiffonné
folio essais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ILLUMINATIONS
COSMOS ET ESTHÉTIQUE
Odile Jacob
sciences