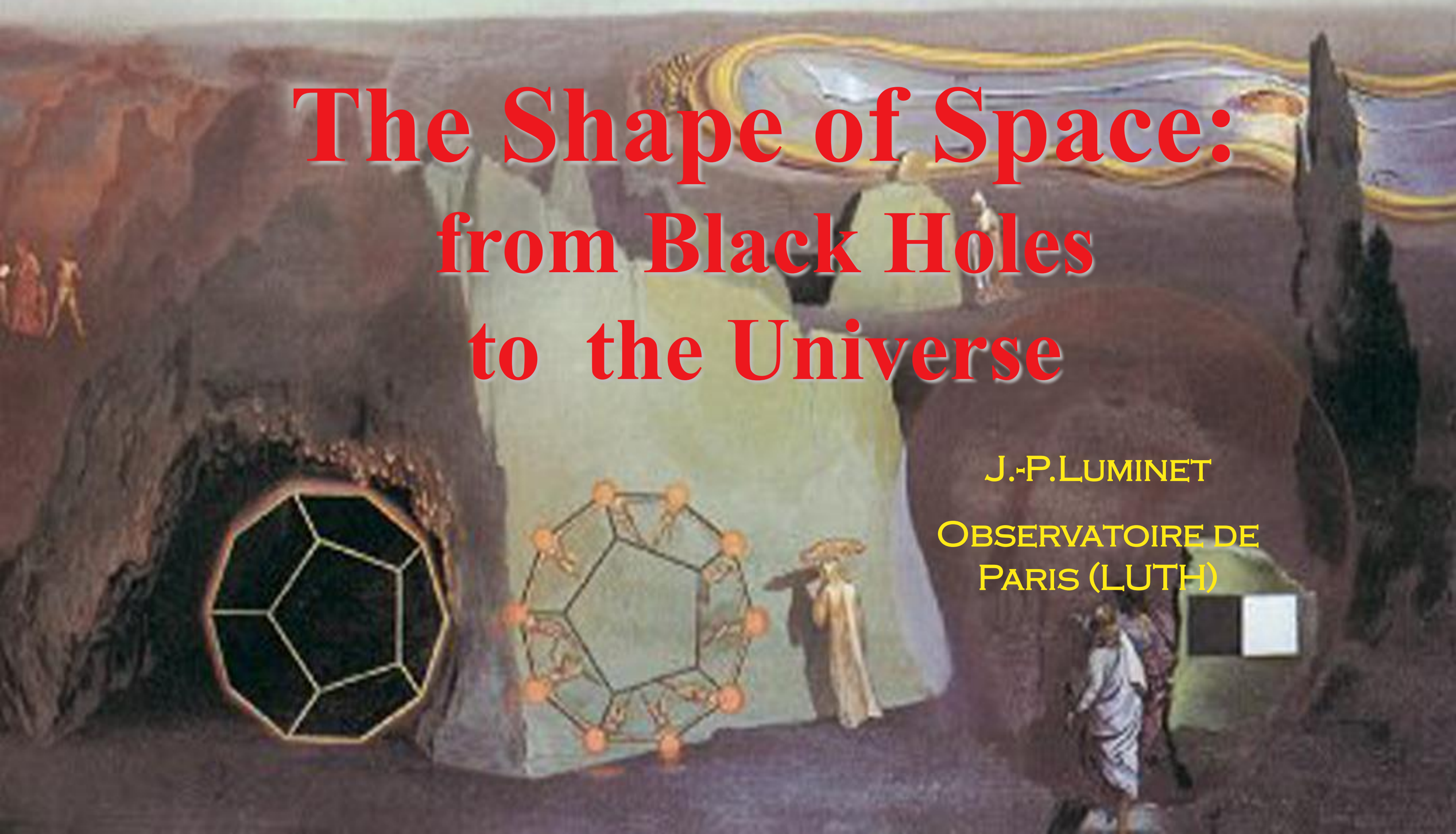
Imaging in Space and Time

28/8-1/9 2006 Brijuni

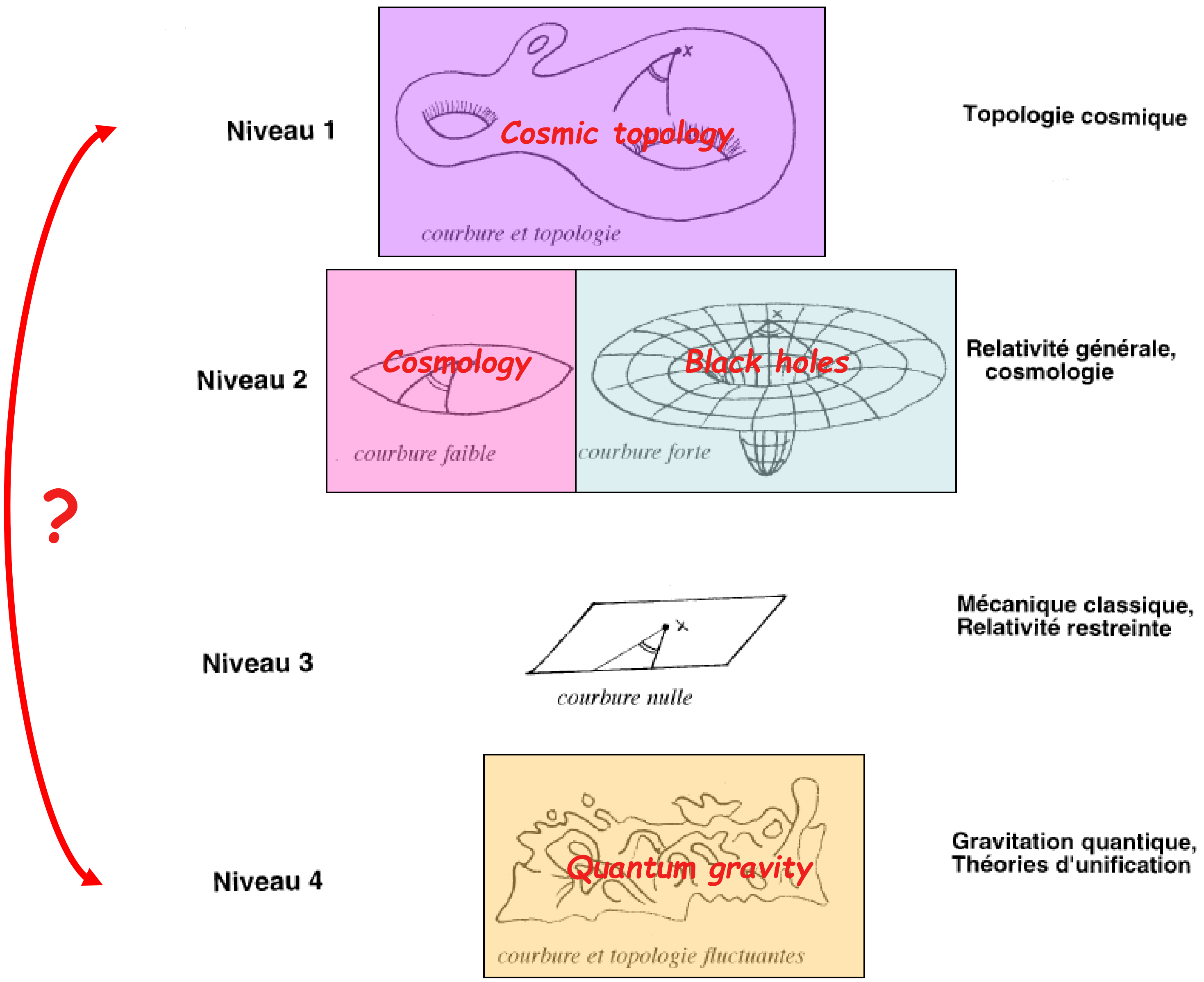
The Shape of Space: from Black Holes to the Universe

J.-P.Luminet

Observatoire de Paris (LUTH)



4 levels of geometry



General Relativity

$$G_{ij} = k\ T_{ij}$$

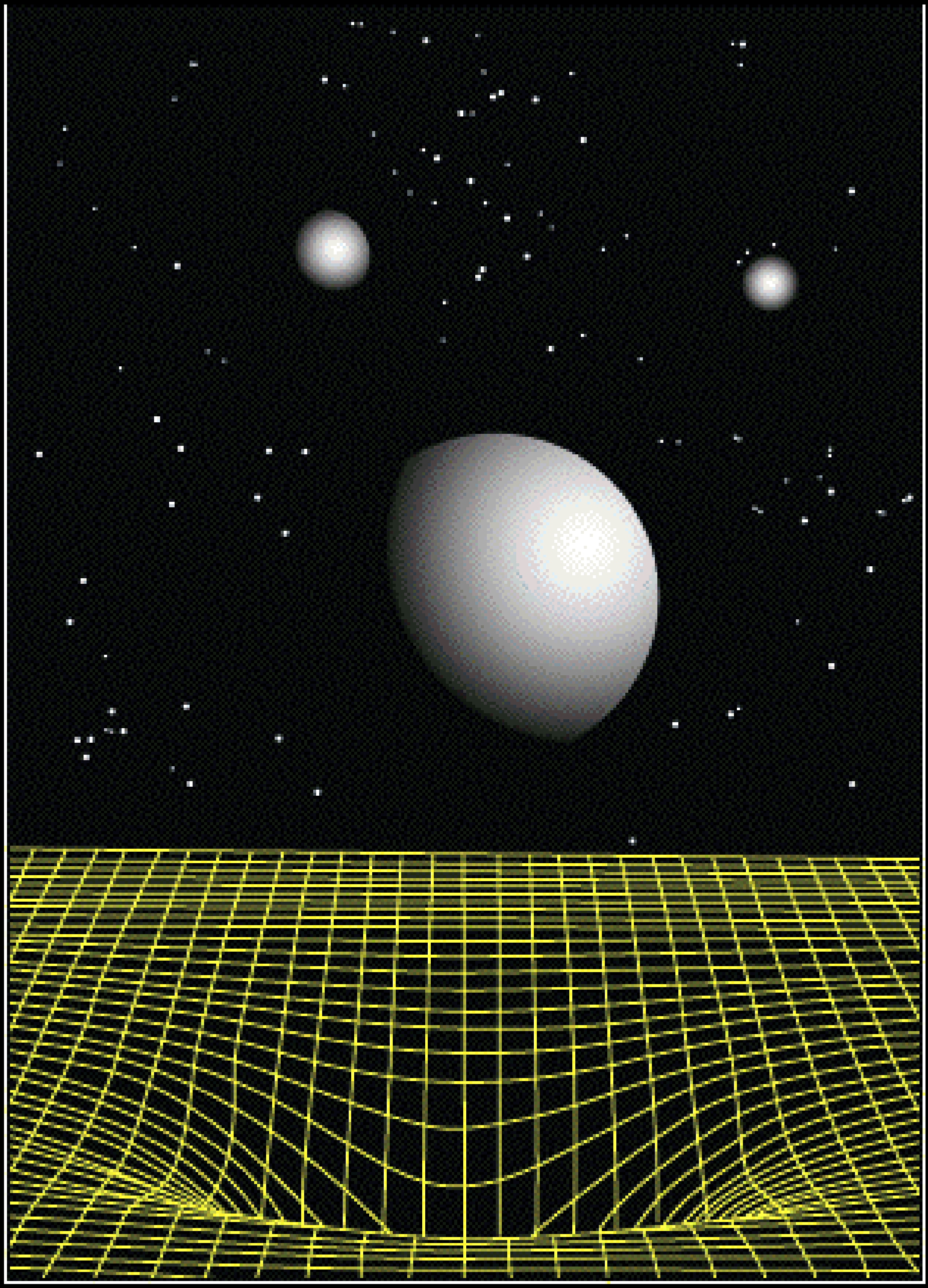
geometry = matter-energy

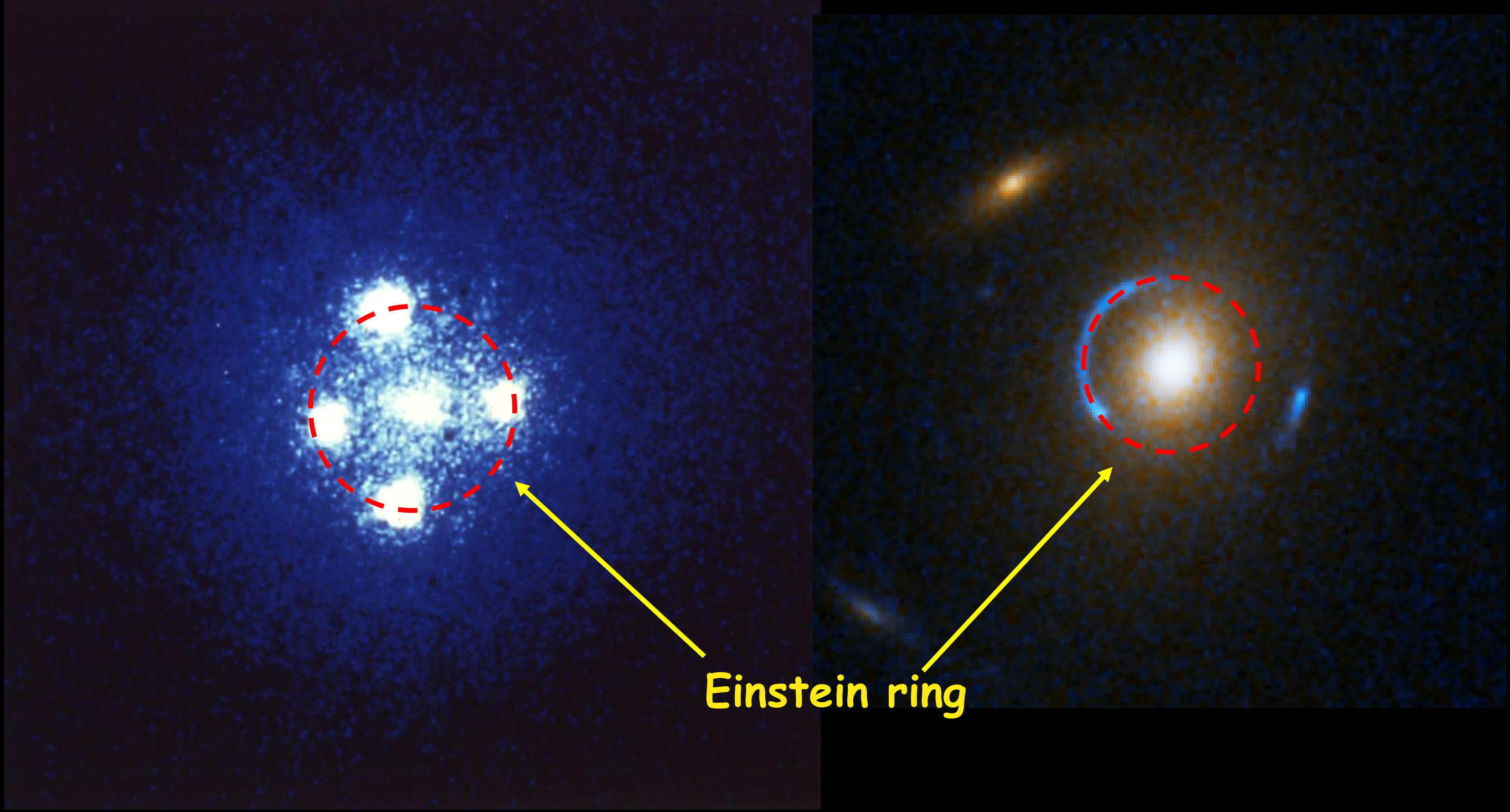
↓

$$ds^2 = g_{ij}\ dx^i x^j$$

spacetime metric

gravity =
spacetime curvature





Gravitational lensing

If $M_* > 30\ M_S$

Imaging Black Holes

Newtonian spacetime

curved spacetime

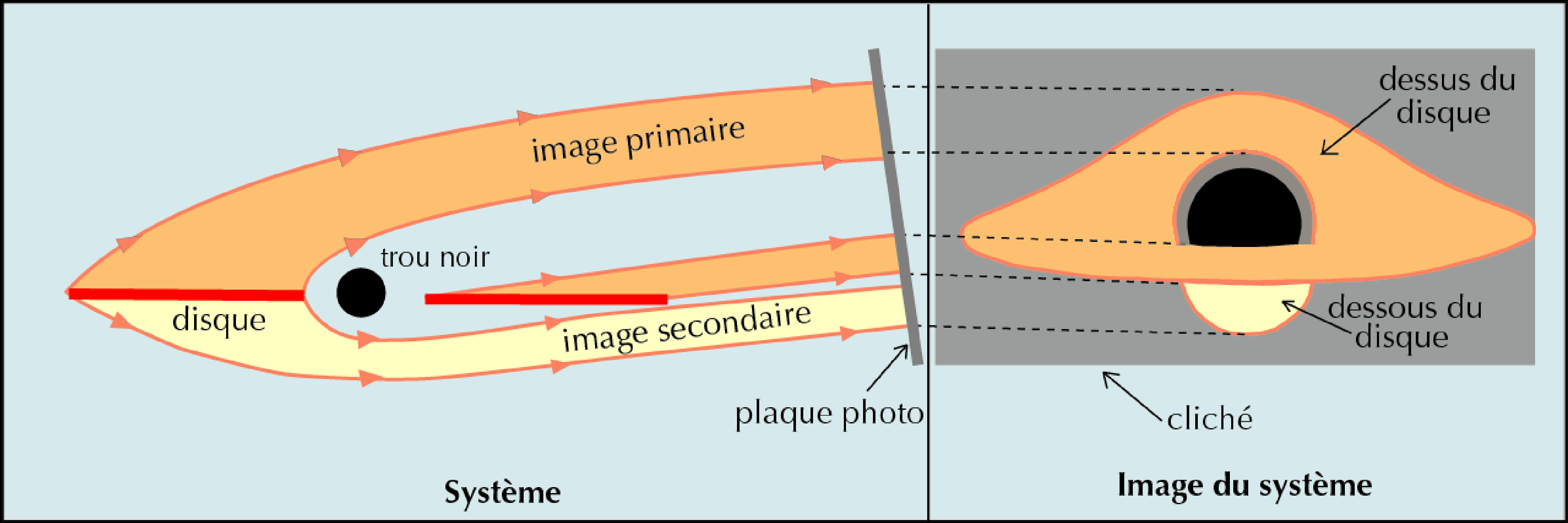
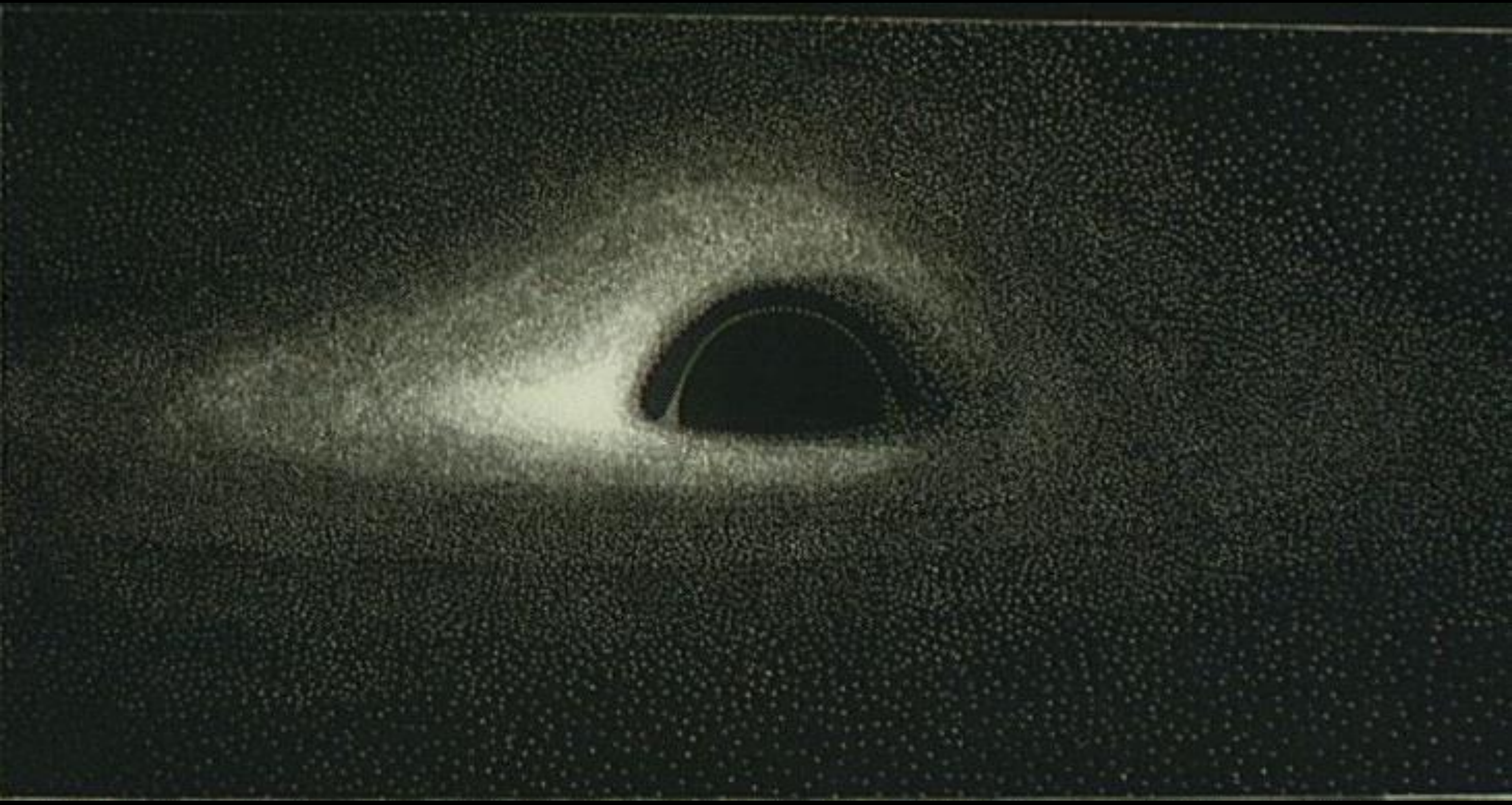


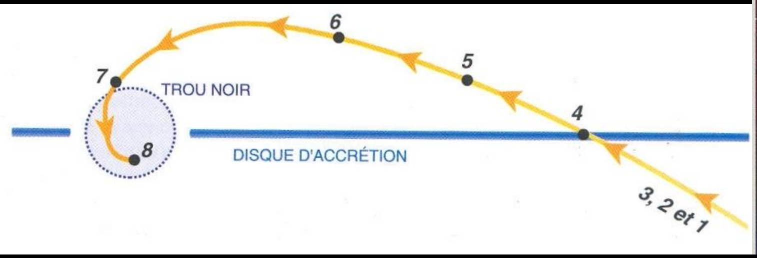
Image of a spherical black hole with thin accretion disk

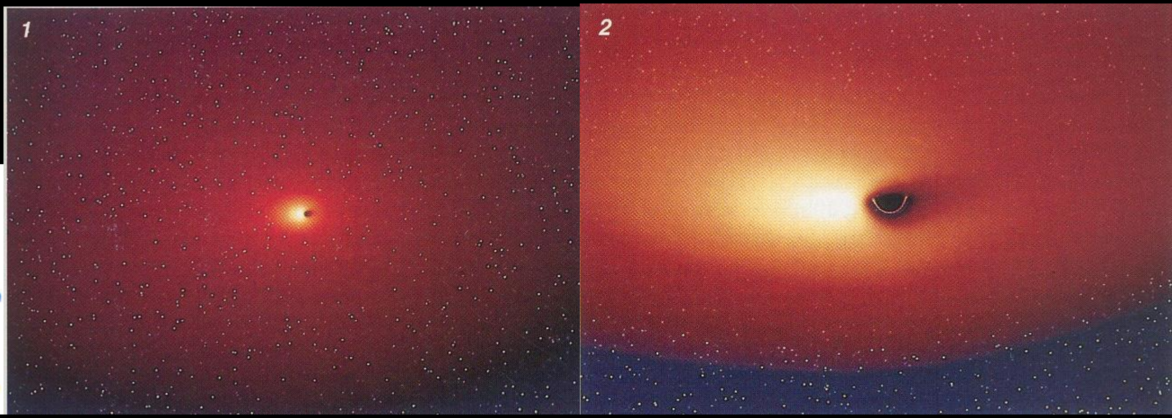
(J.-P. Luminet, 1979)

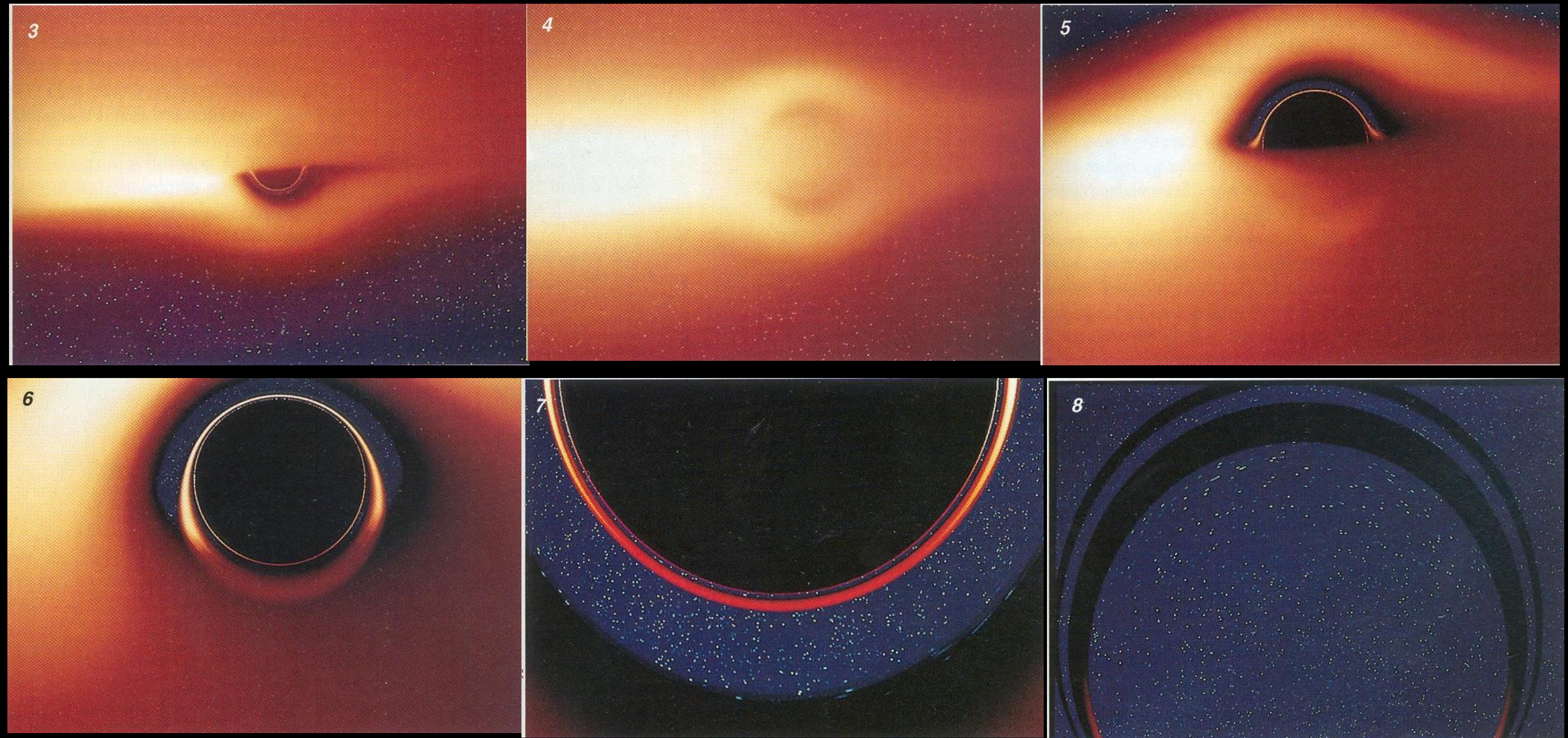


Flight into a black hole

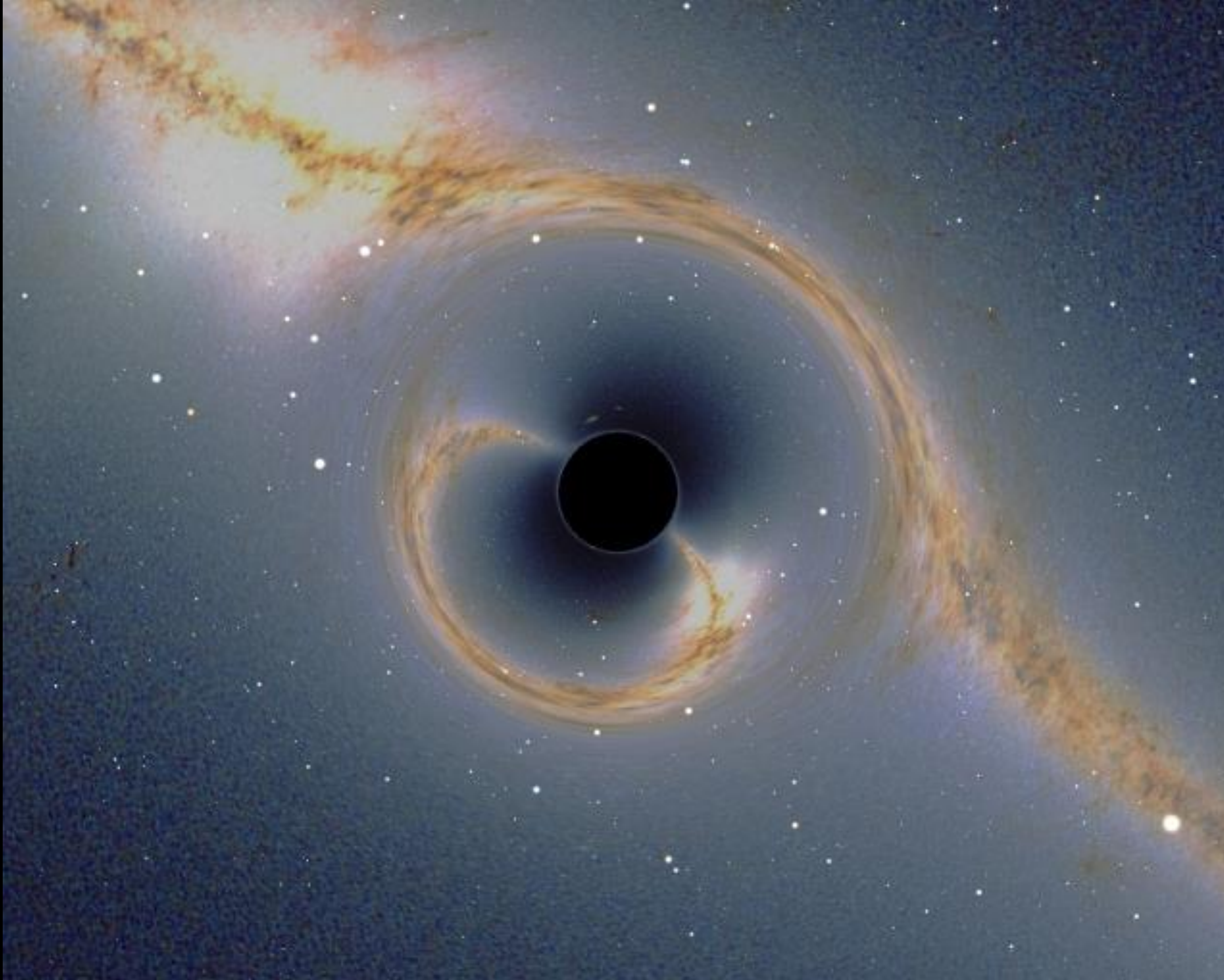
(J.A.Marck, 1993)

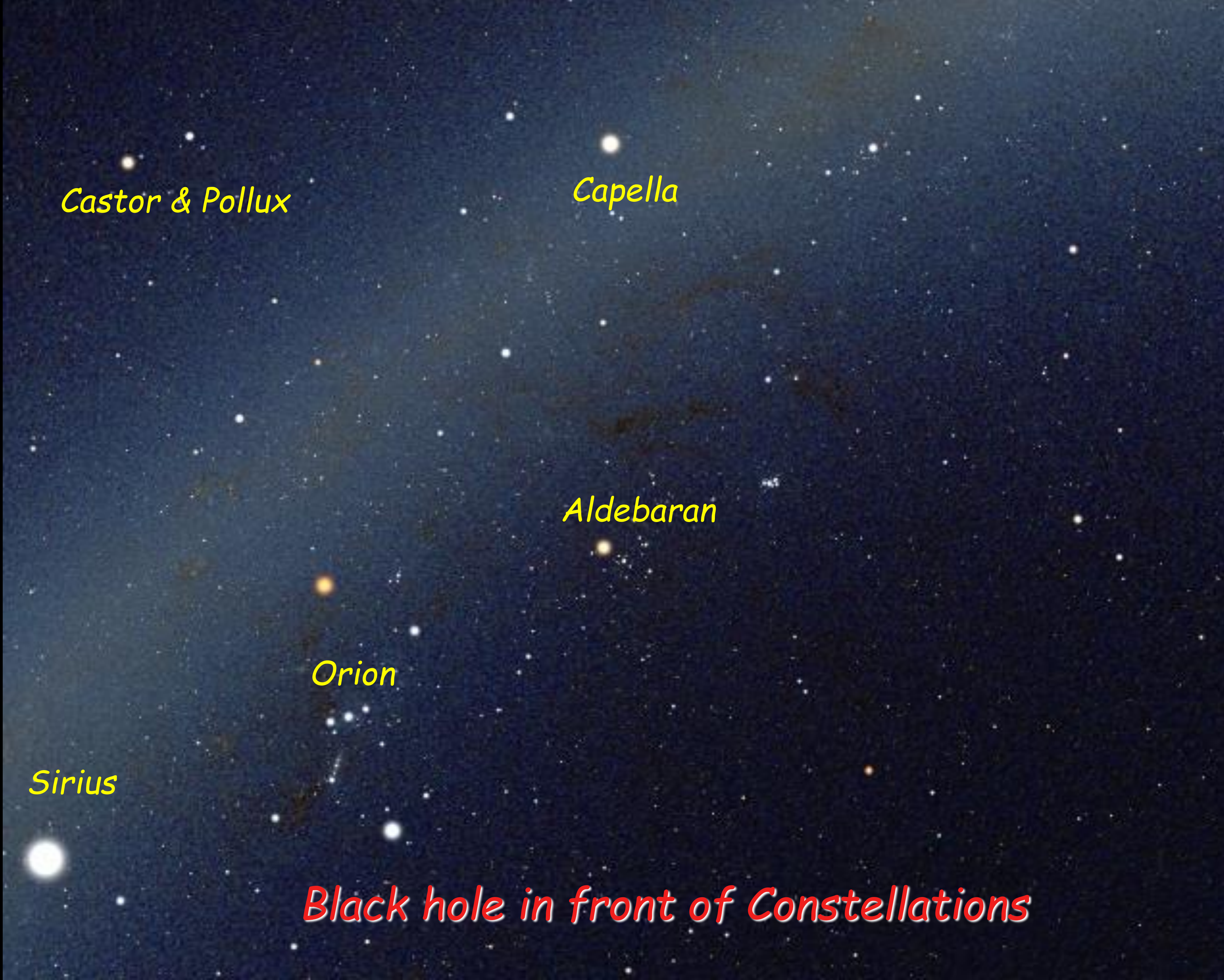






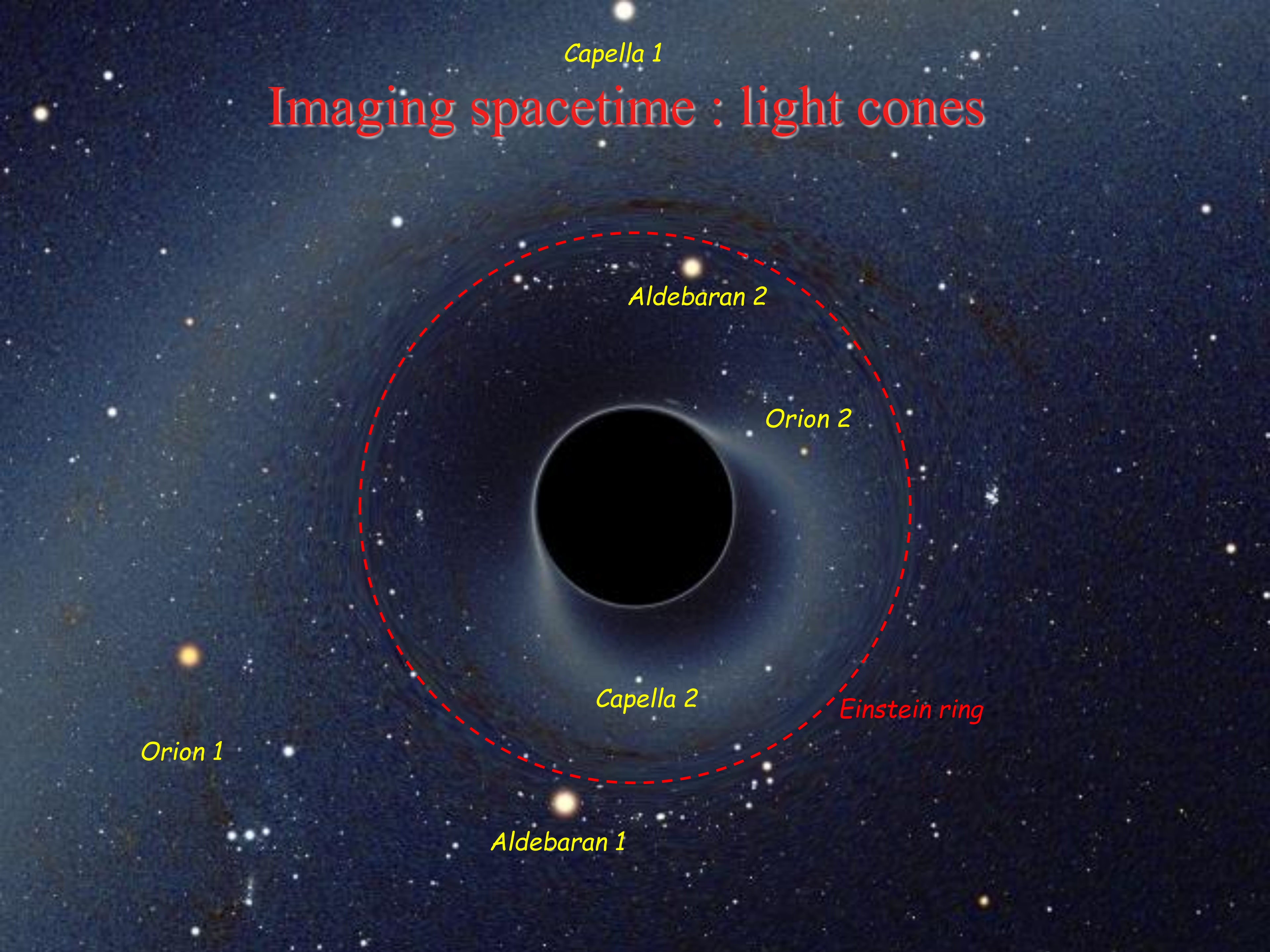
Black hole in front of Milky Way
(Riazuelo, 2006)

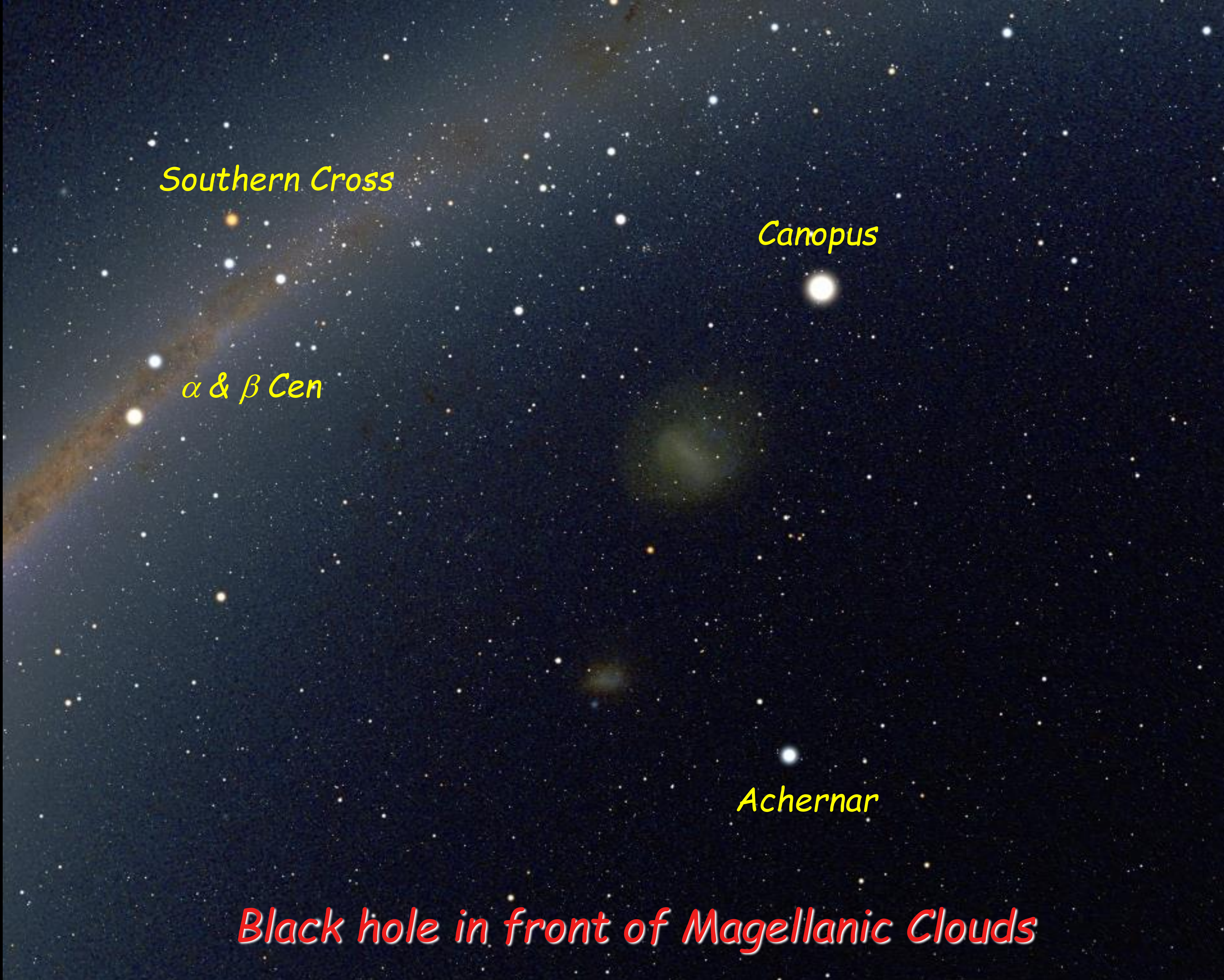




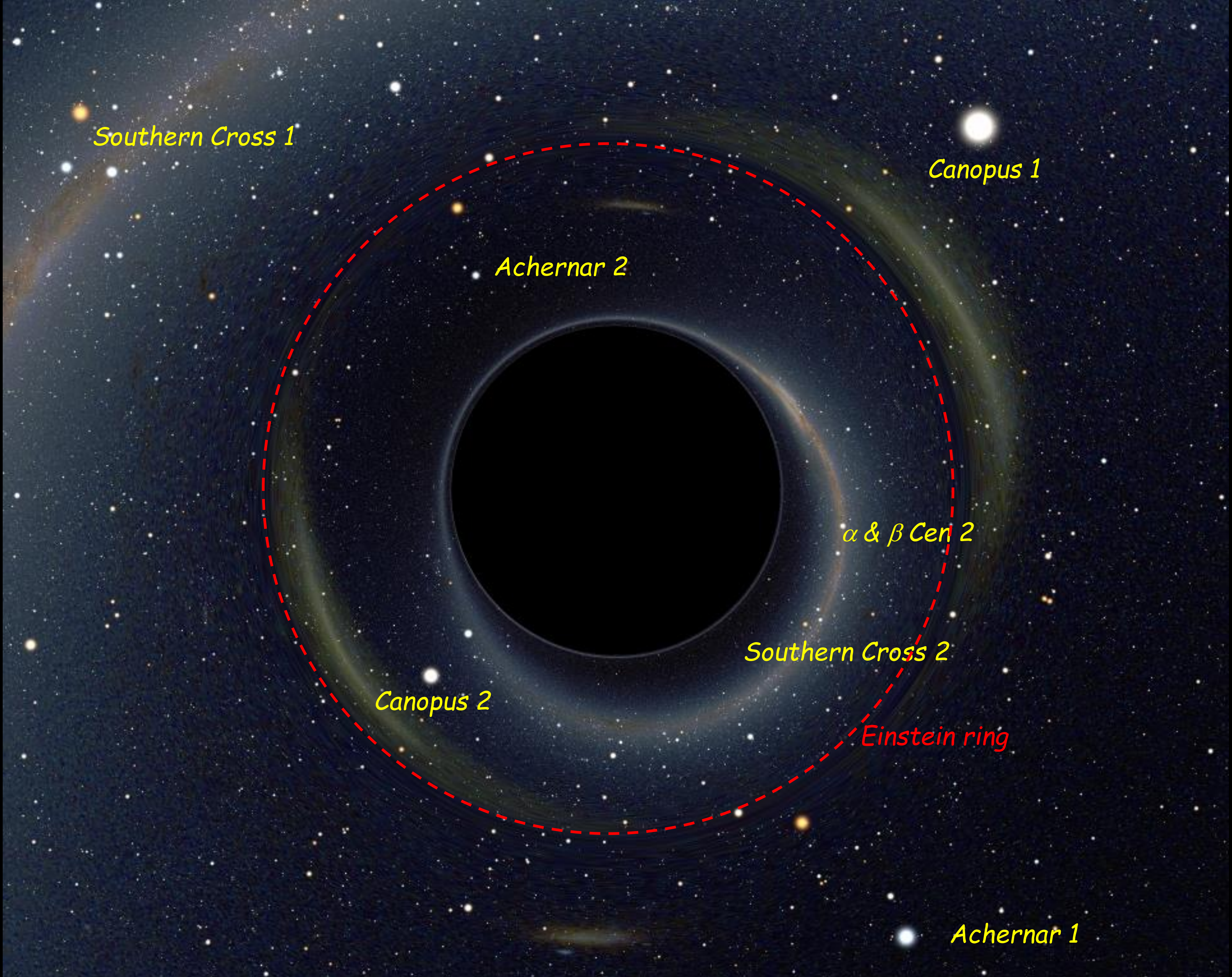
Castor & Pollux
Capella
Aldebaran
Orion
Sirius
Black hole in front of Constellations

Imaging spacetime : light cones

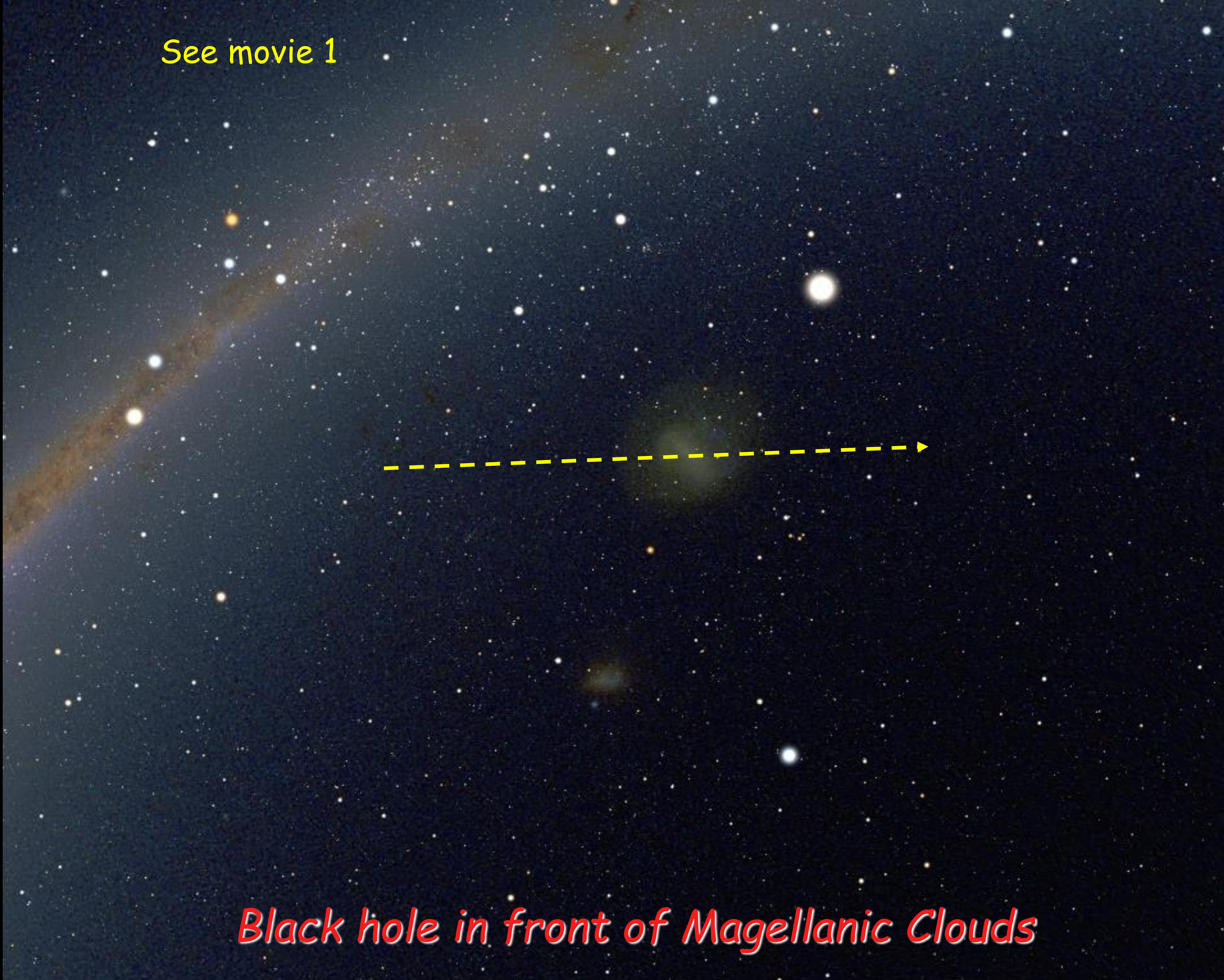




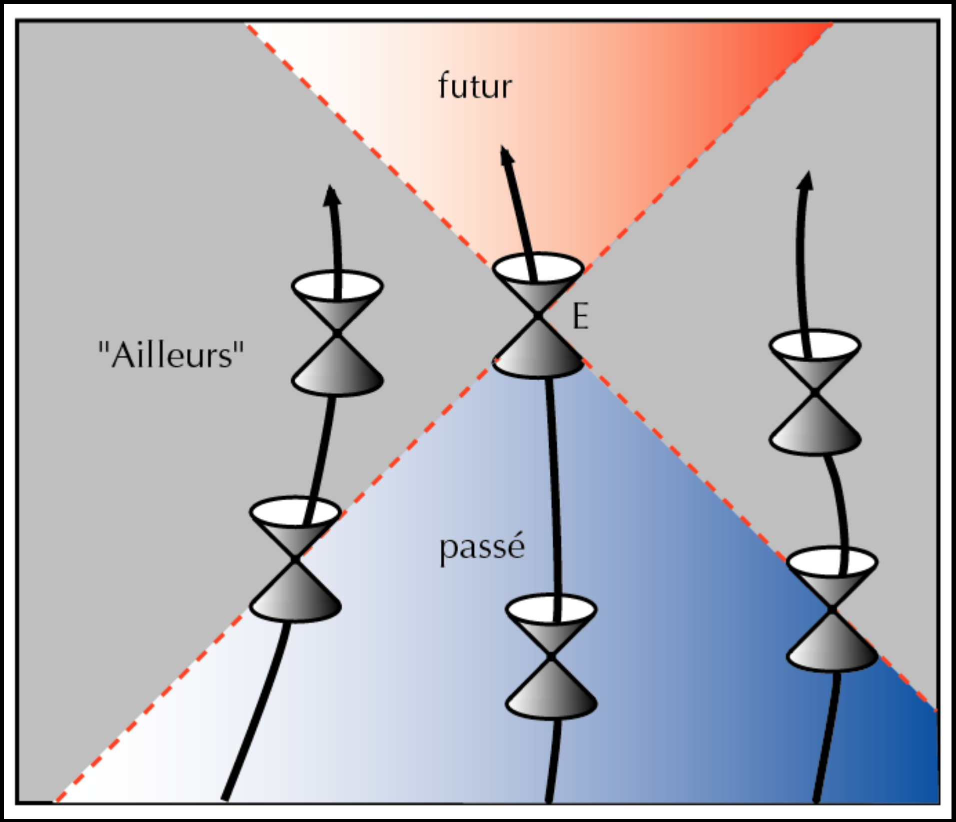
Southern Cross
Canopus
α & β Cen
Achernar
Black hole in front of Magellanic Clouds



Southern Cross 1
Canopus 1
Achernar 2
α & β Cen 2
Southern Cross 2
Canopus 2
Einstein ring
Achernar 1

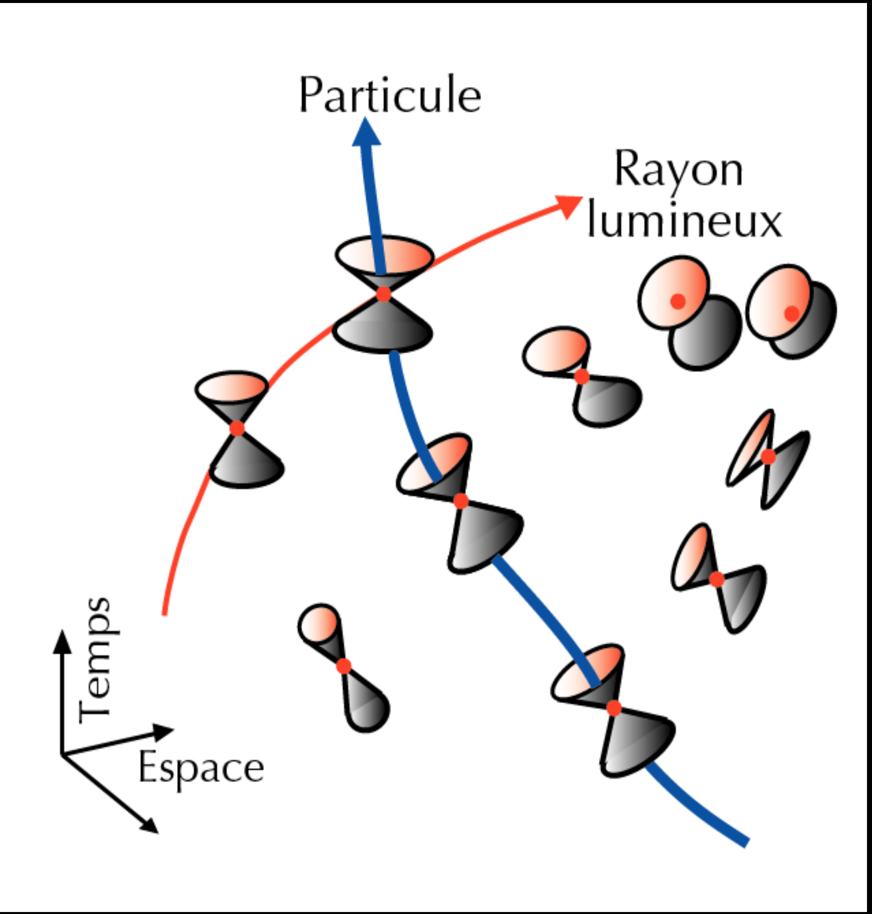

See movie 1
Black hole in front of Magellanic Clouds

Imaging spacetime : light cones



Flat (Minskowski) spacetime

Curved spacetime

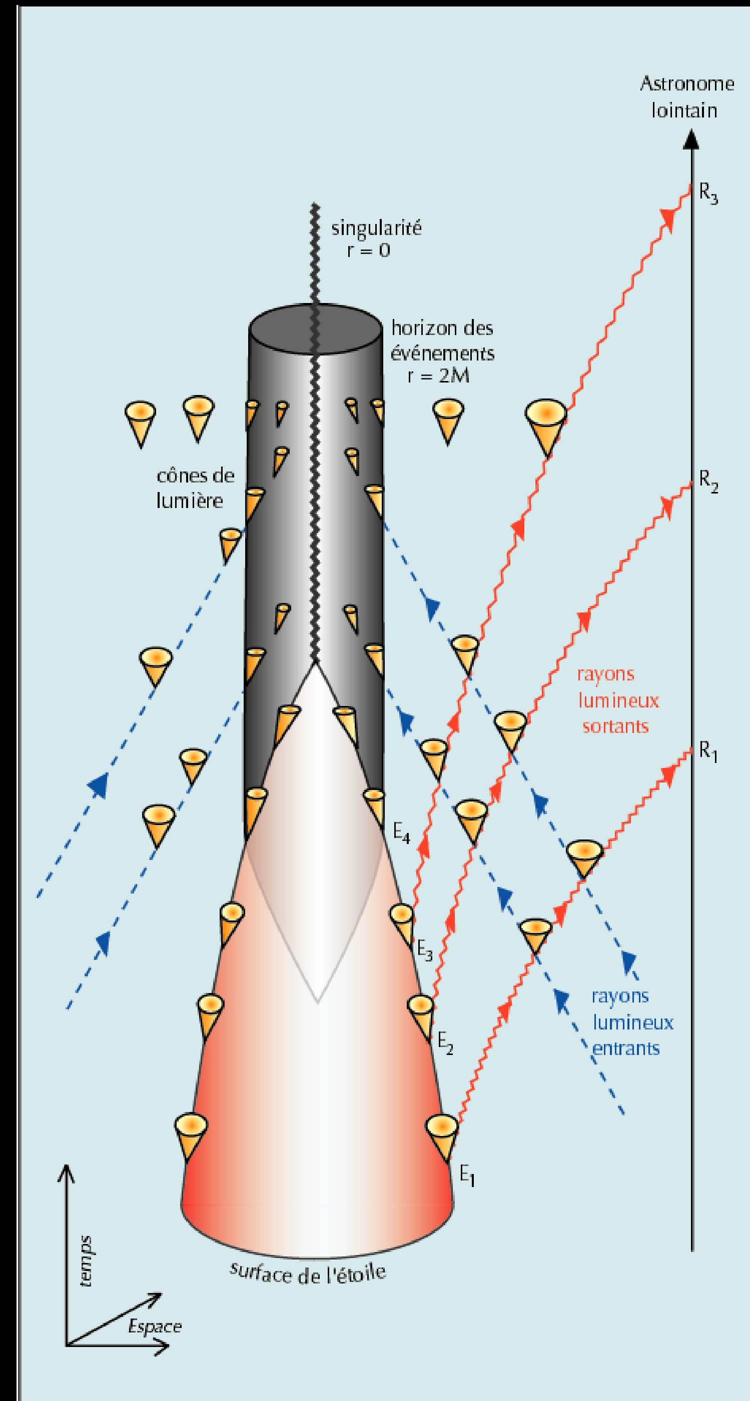


Gravitational collapse to a Schwarzschild black hole

metric:

Schwarzschild radius:

→ Event horizon

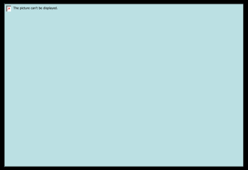


Embedding

Step 1: Schwarzschild metric outside mass M (G=c=1) :

Step 2: Equatorial section

Time section

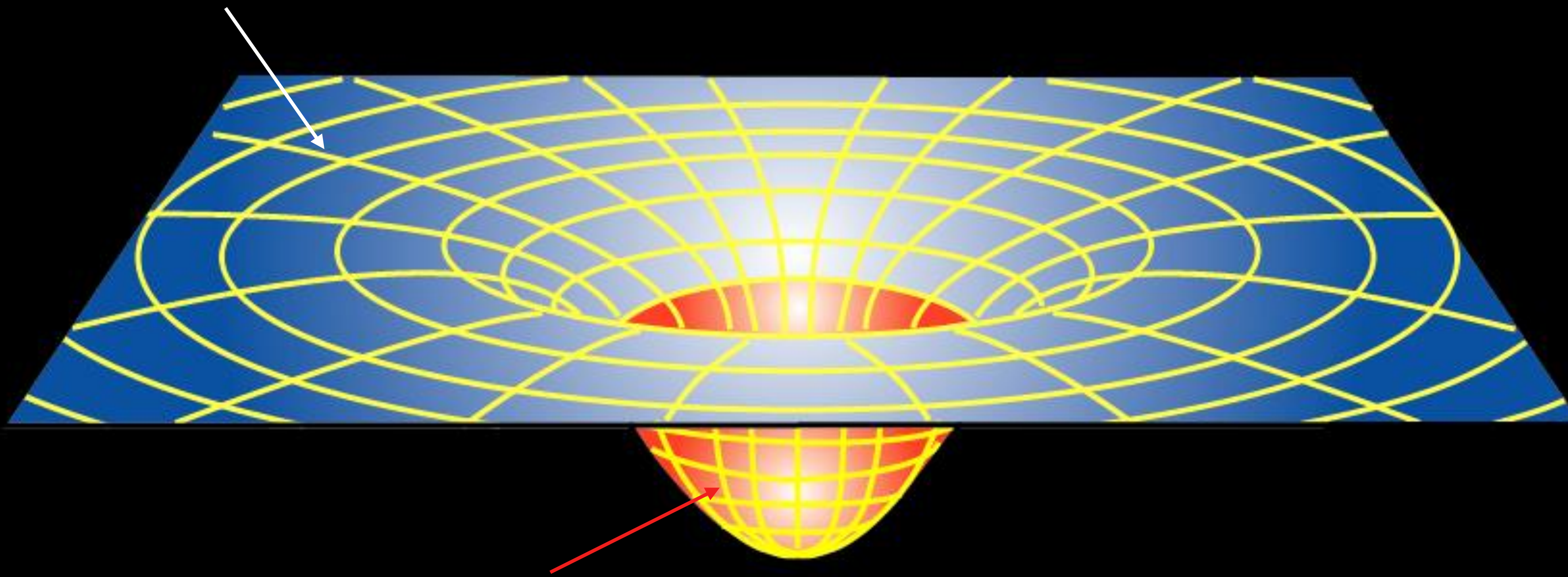


Curved 2-geometry:

Step 3: Embedding in 3D Euclidian space

Result for ordinary star ($R_* > 2M$)

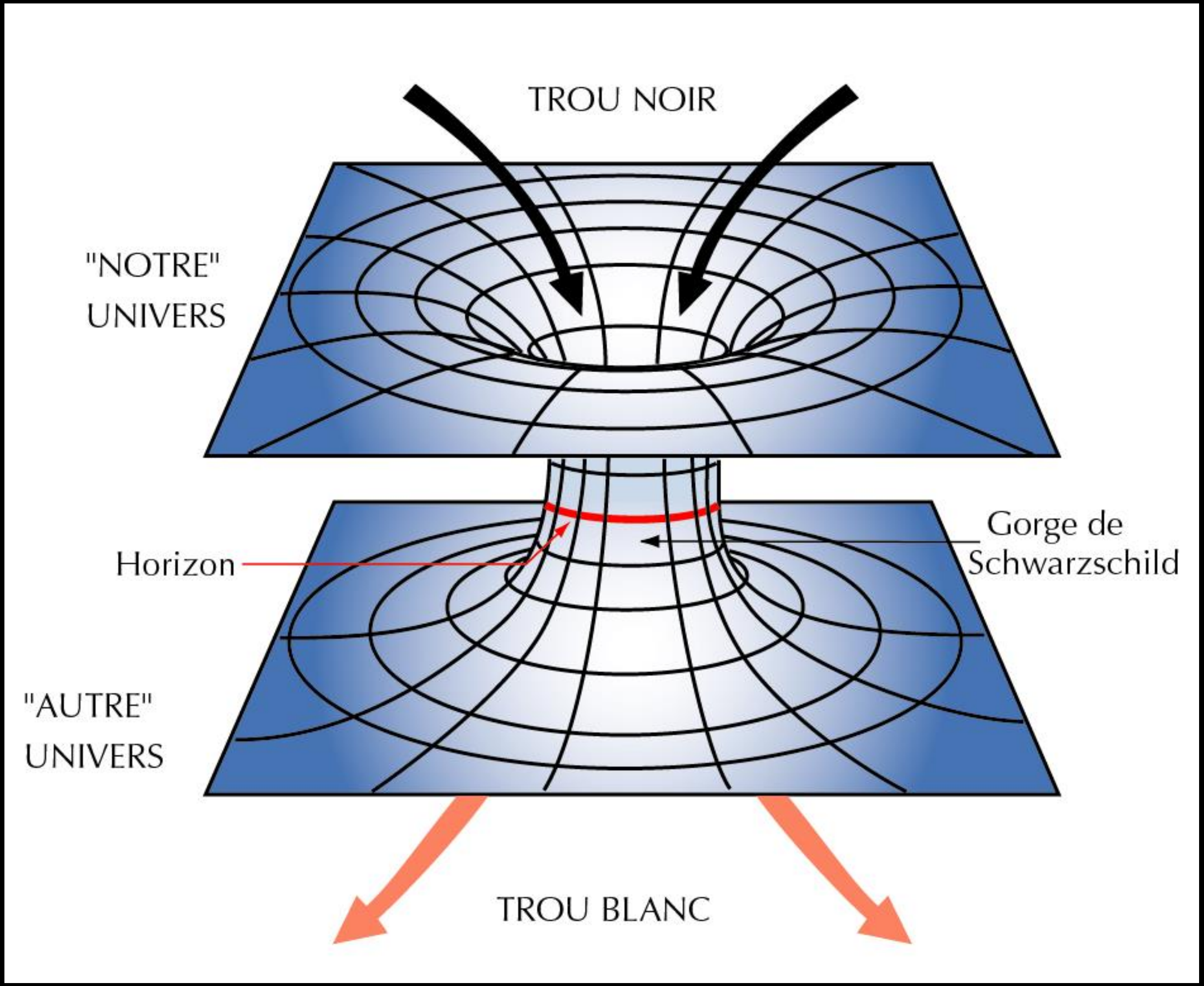
Outer solution (asymptotically flat)



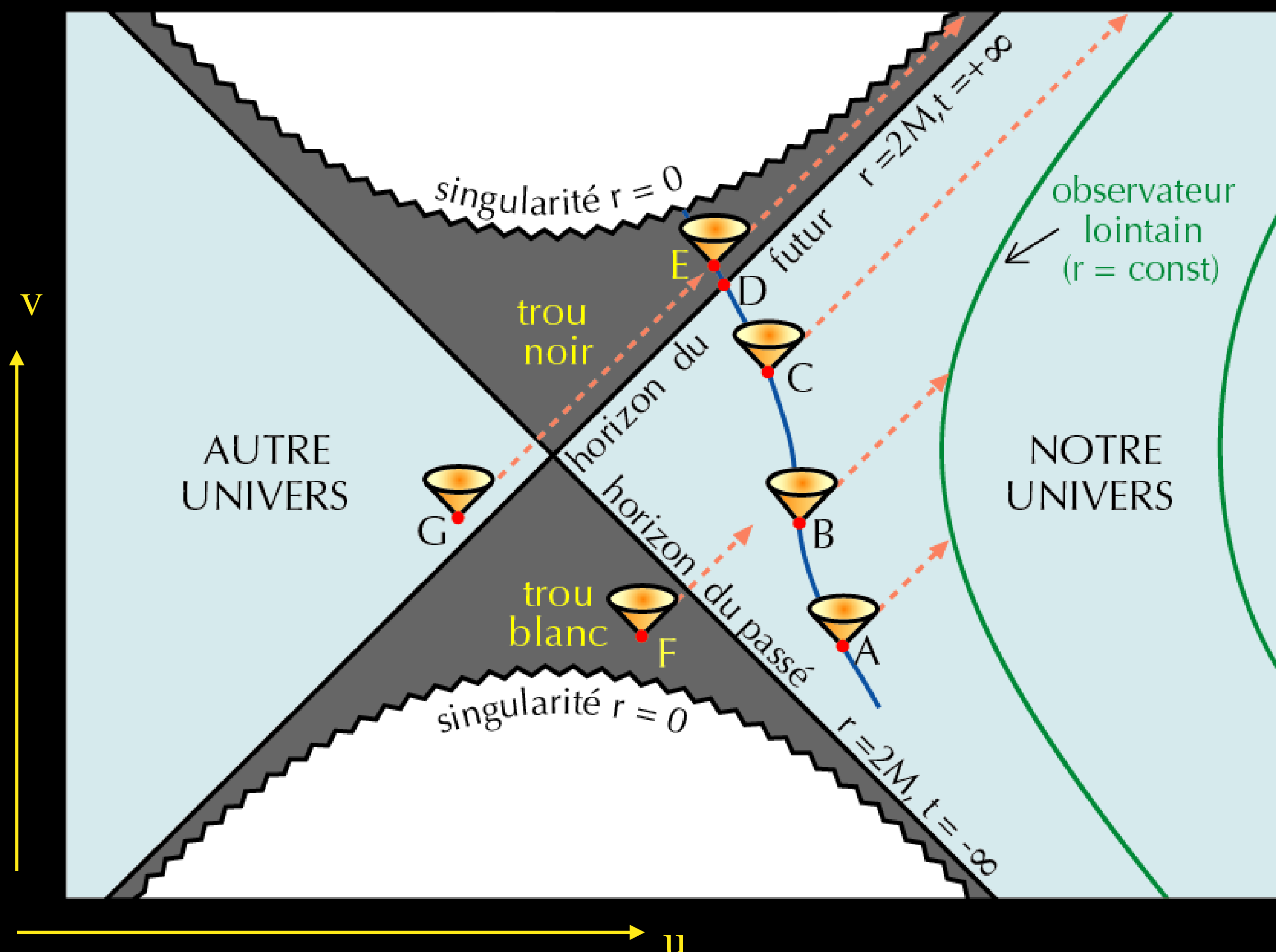
Inner solution (regular)

Result for black hole

Outer solution only
(Flamm paraboloid)



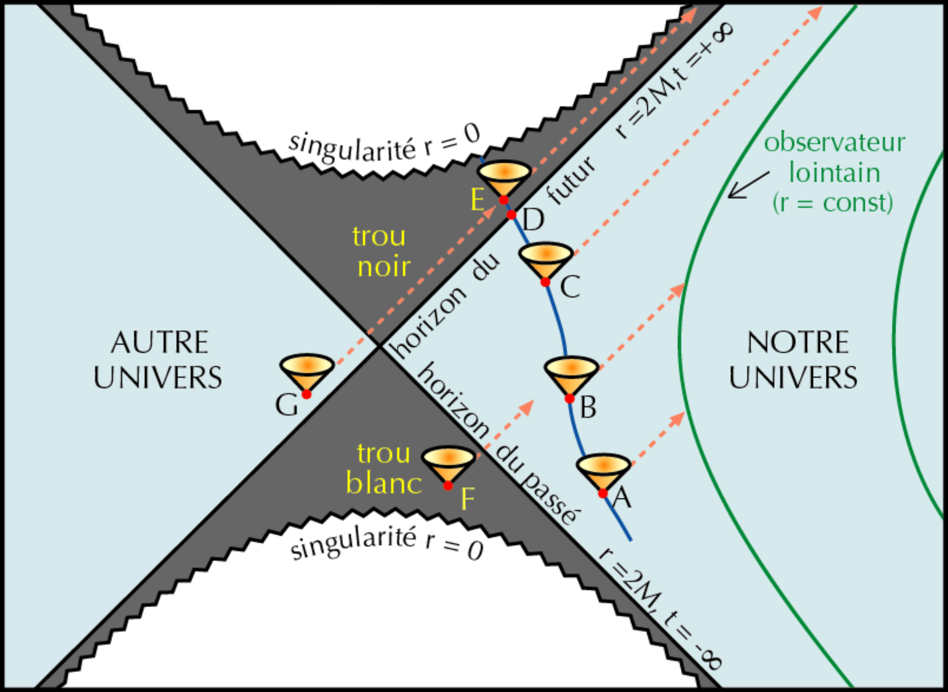
Spherical black hole in Kruskal coordinates

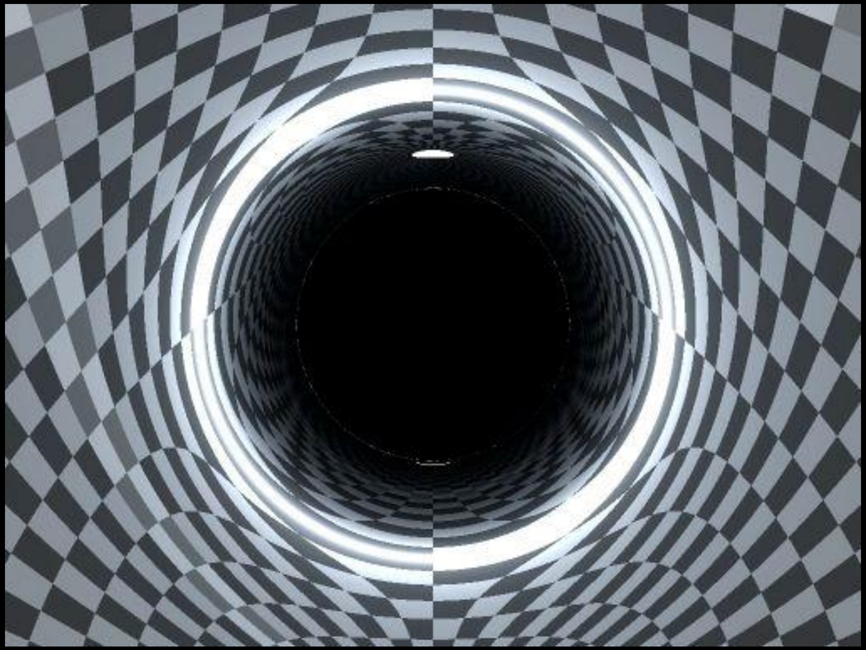


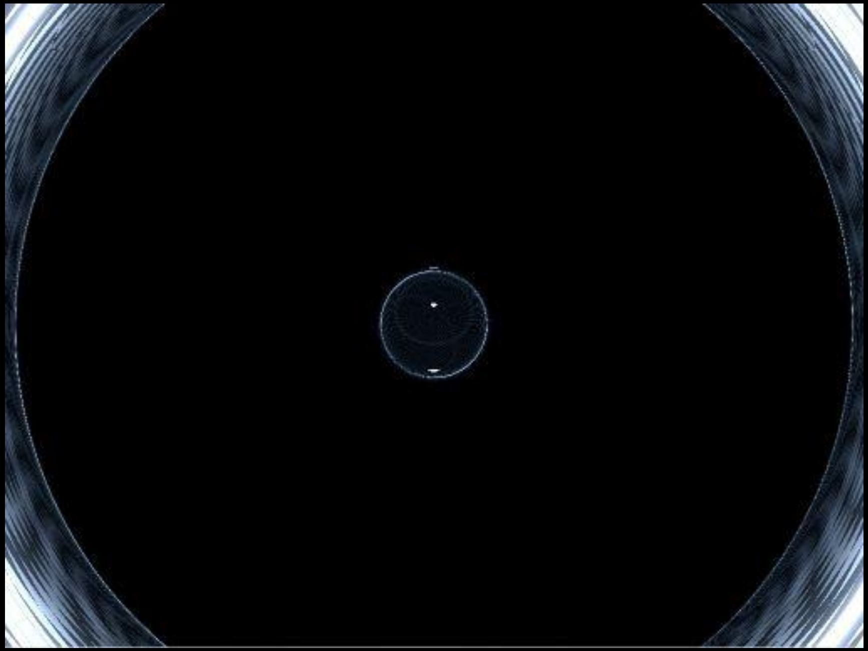
Flight into a static black hole

Radial photons

(A.Riazuelo, 2006)



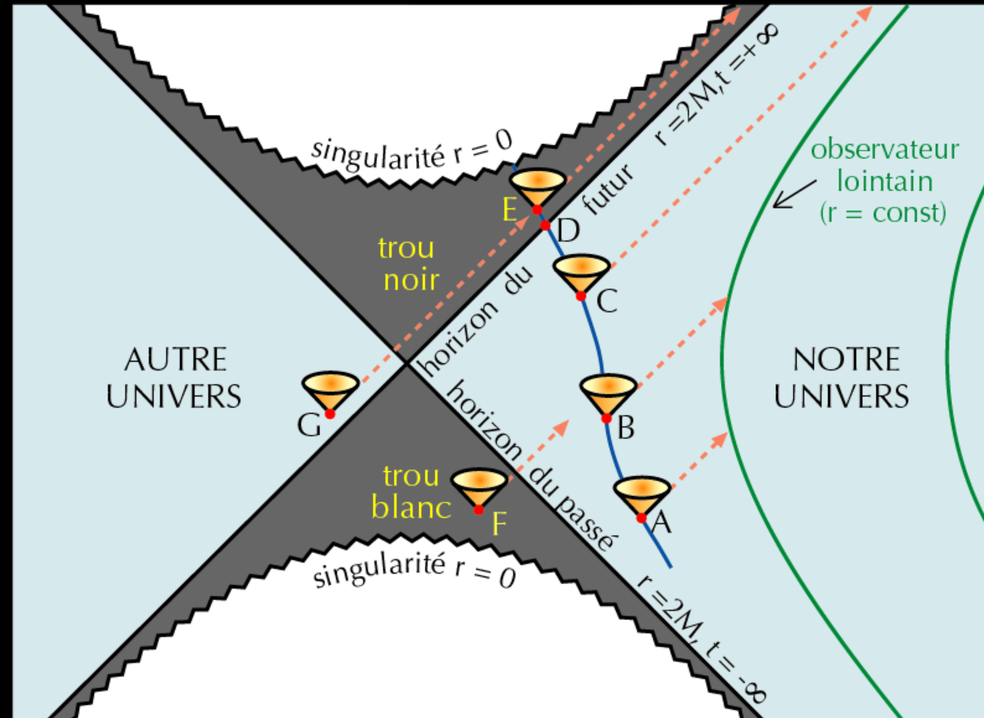


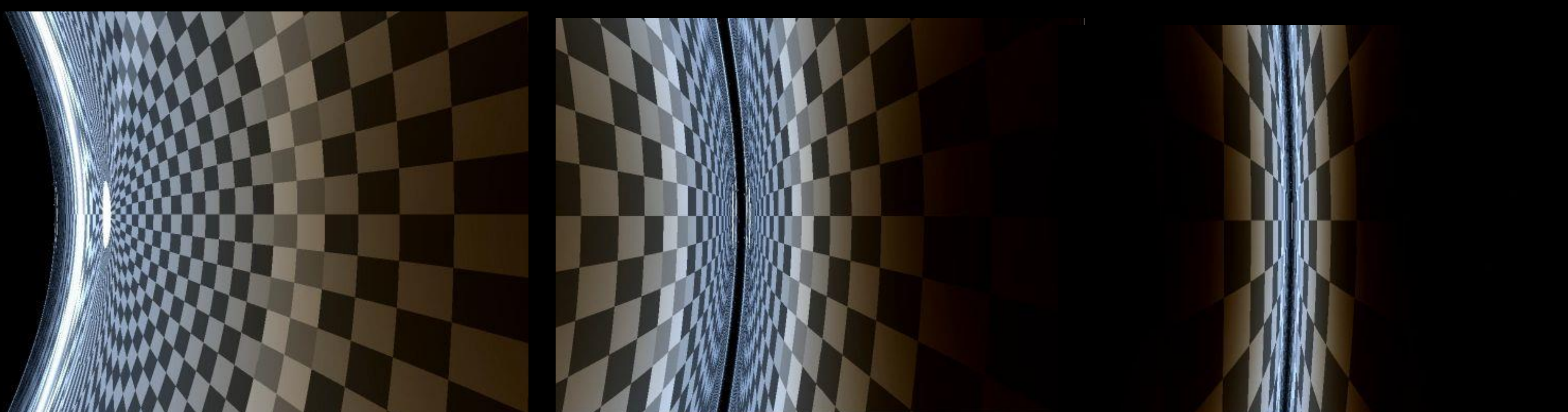


See movie 1

Flight into a static black hole 2

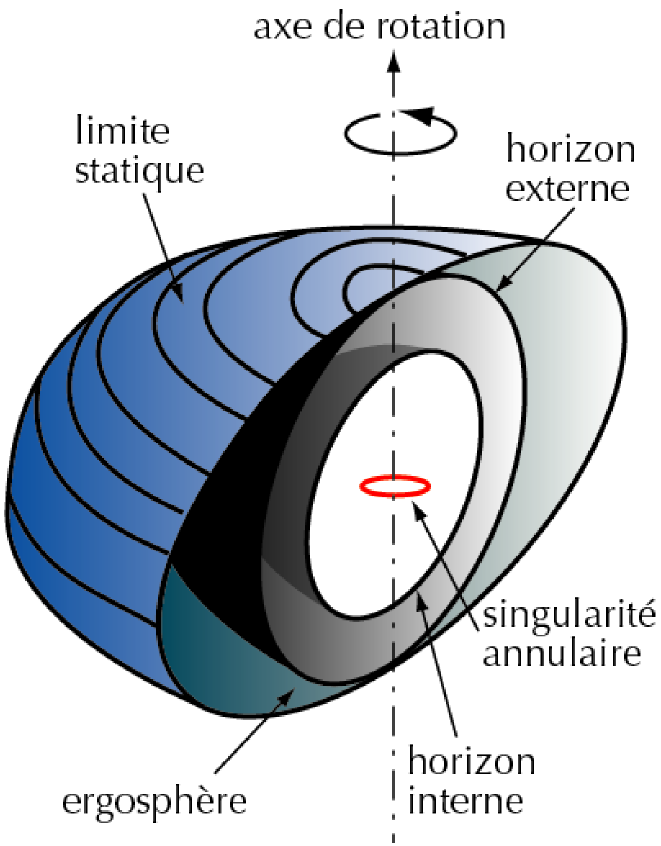
Non-radial photons



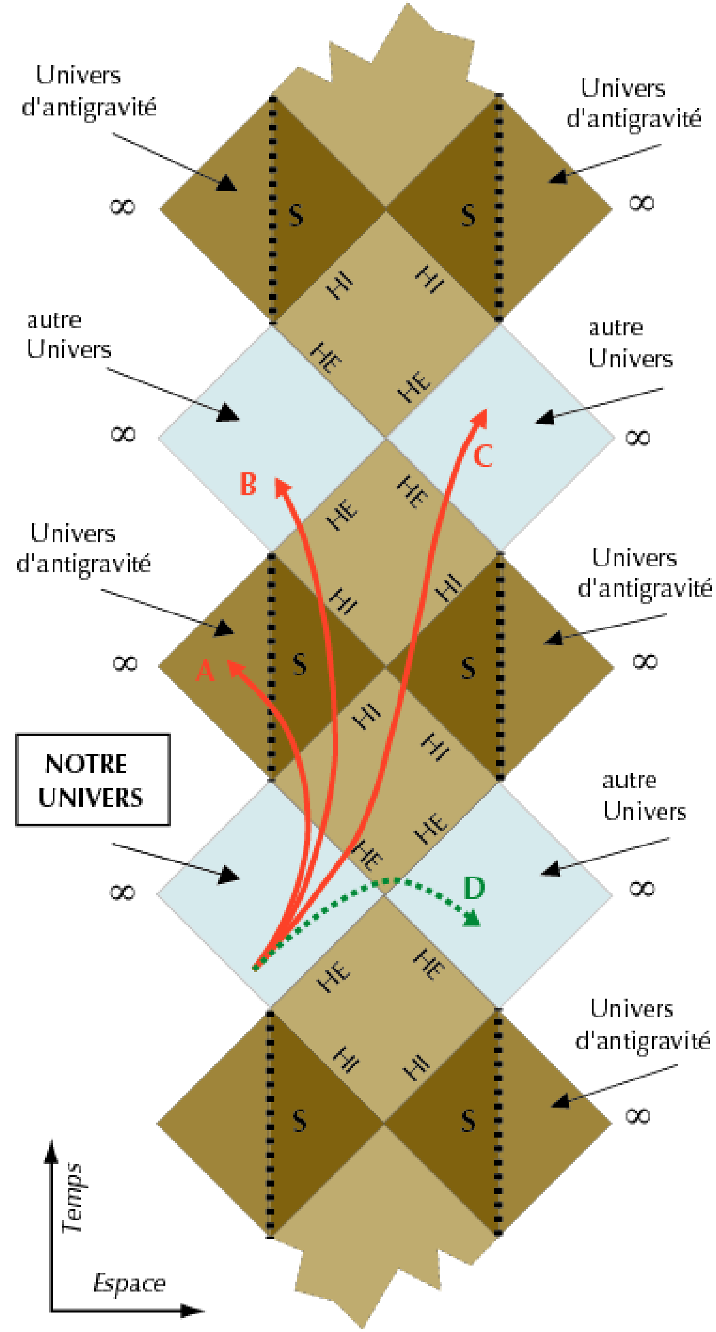


See movie 2

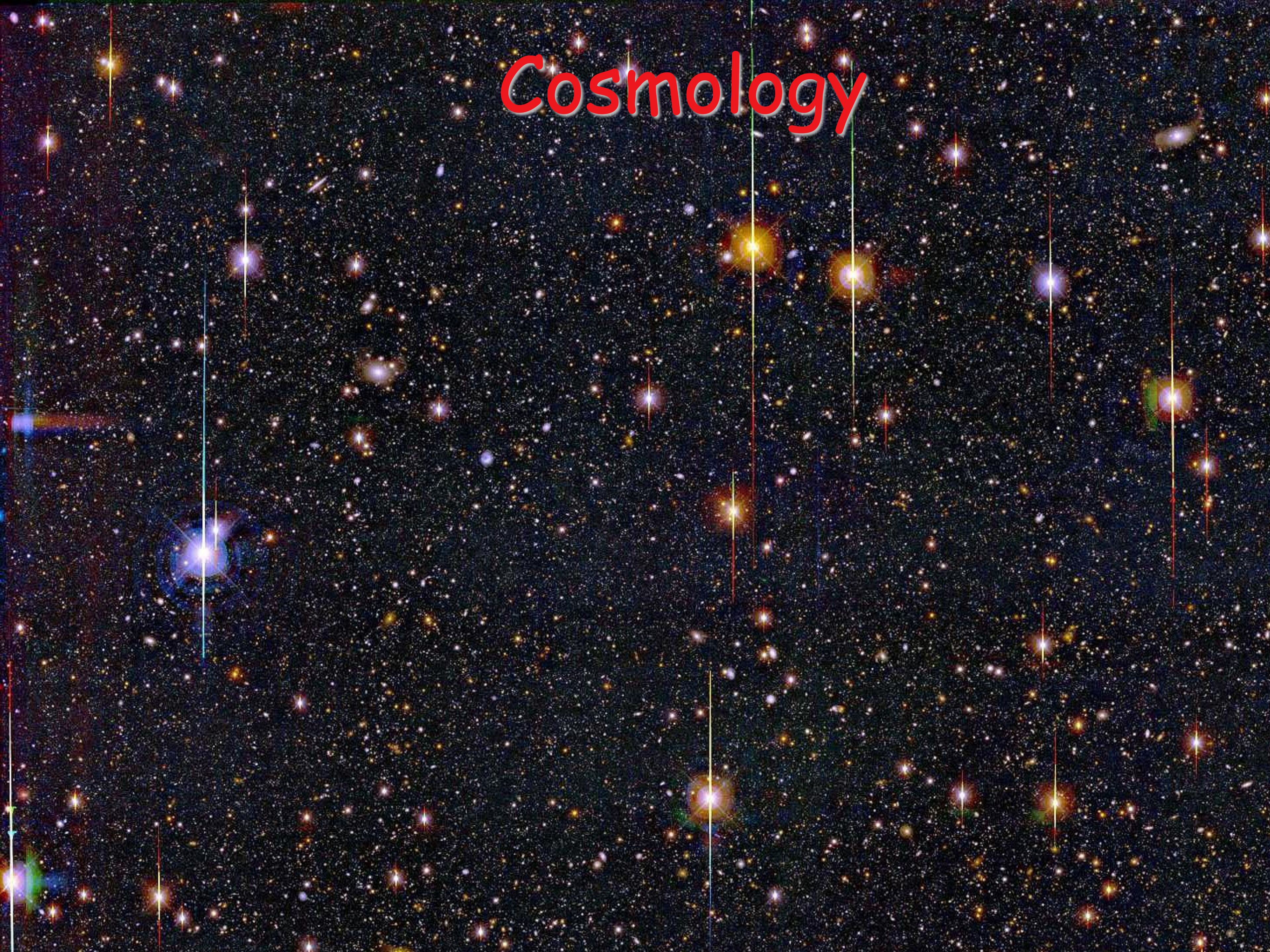
Flight into a Kerr (rotating) black hole



no movie yet!



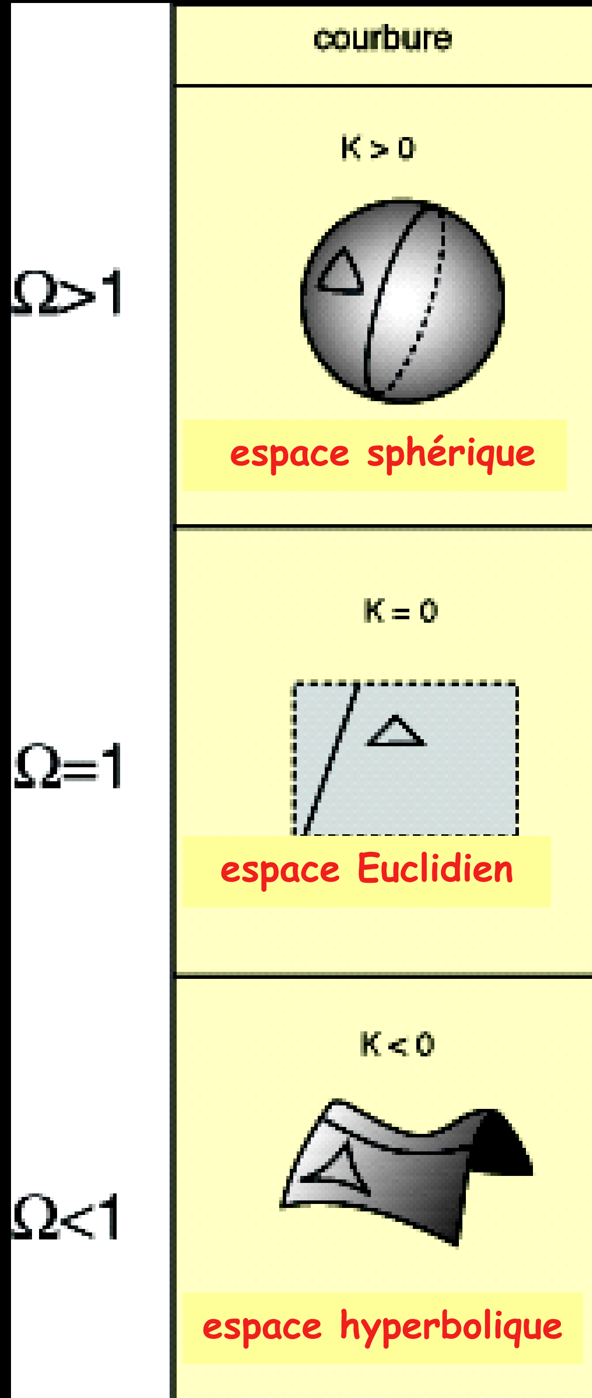
Cosmology



Homogeneity

=>

constant space curvature !

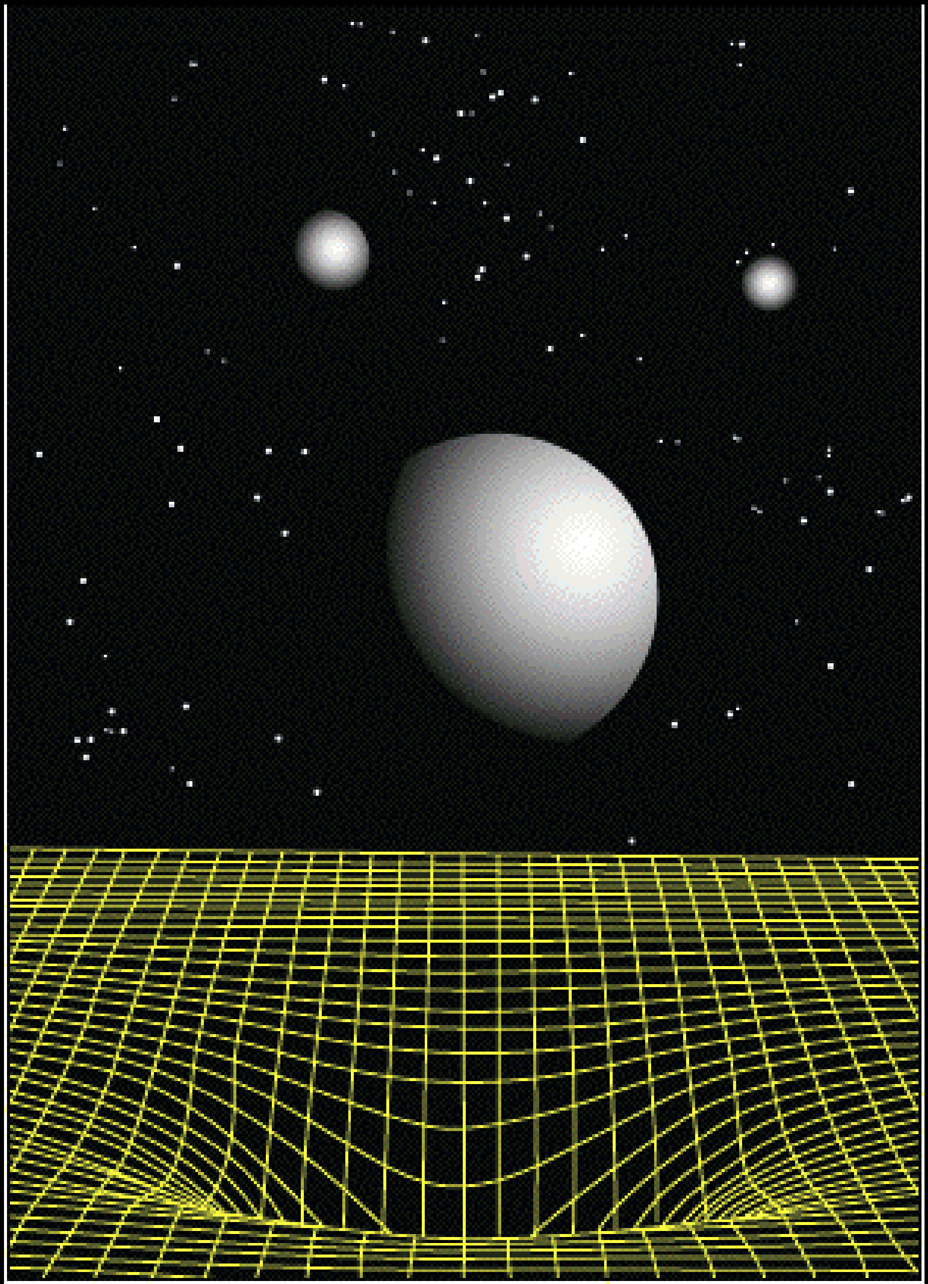


finite (no edge)

finite or infinite

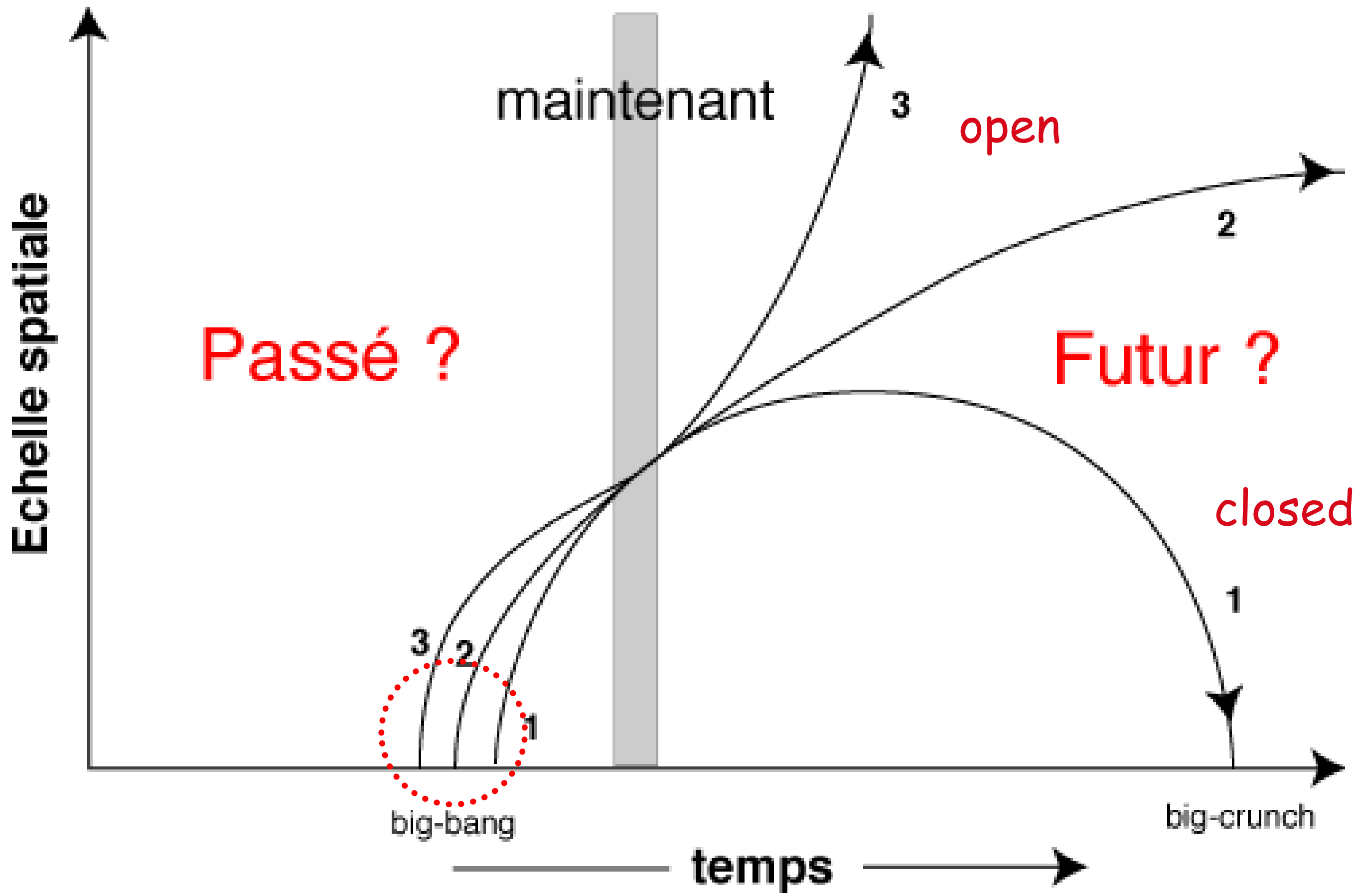
finite or infinite

Space-time curvature ==> a dynamical universe !

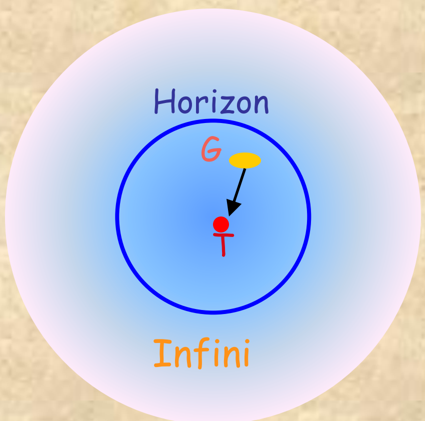


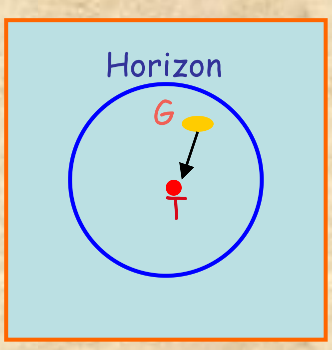
Expansion

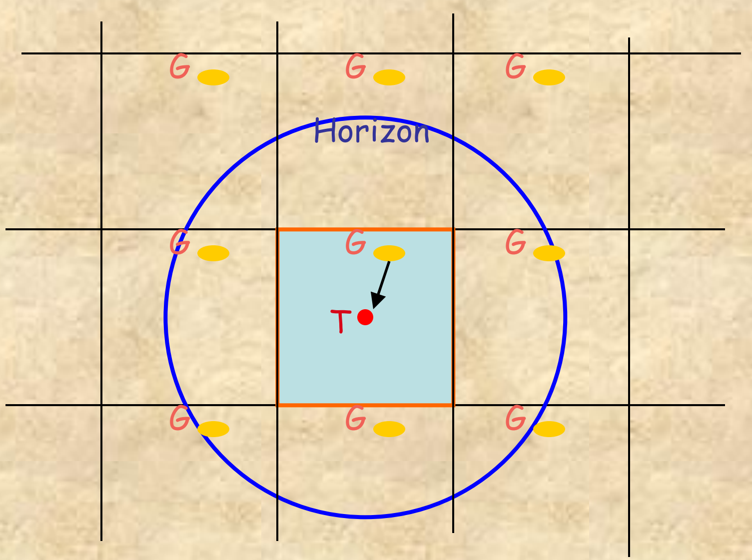
Big bang models



What is the size and shape of space ?







Not testable
(only L >> R_h)

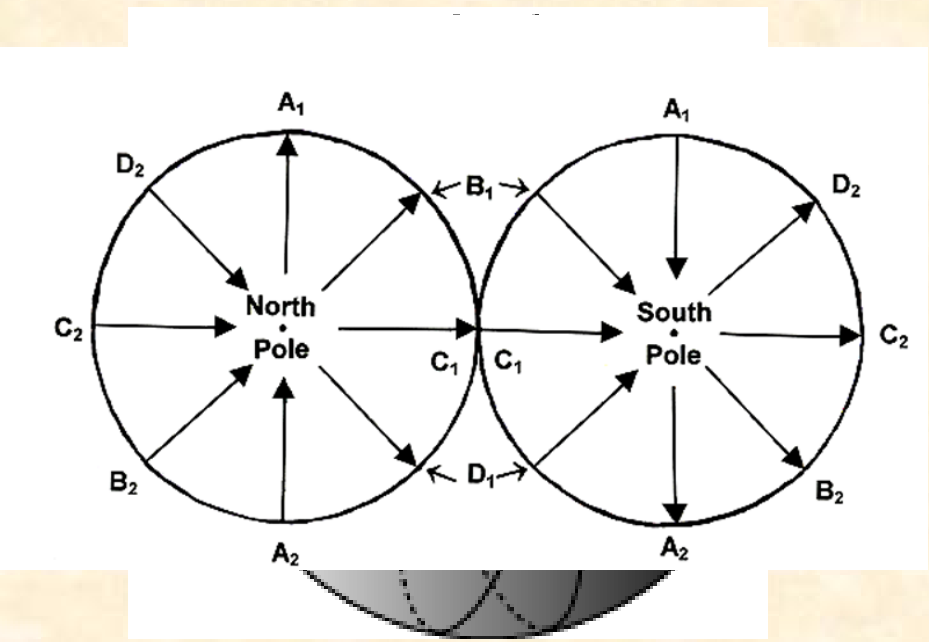
May be testable •
if L >~ R_h

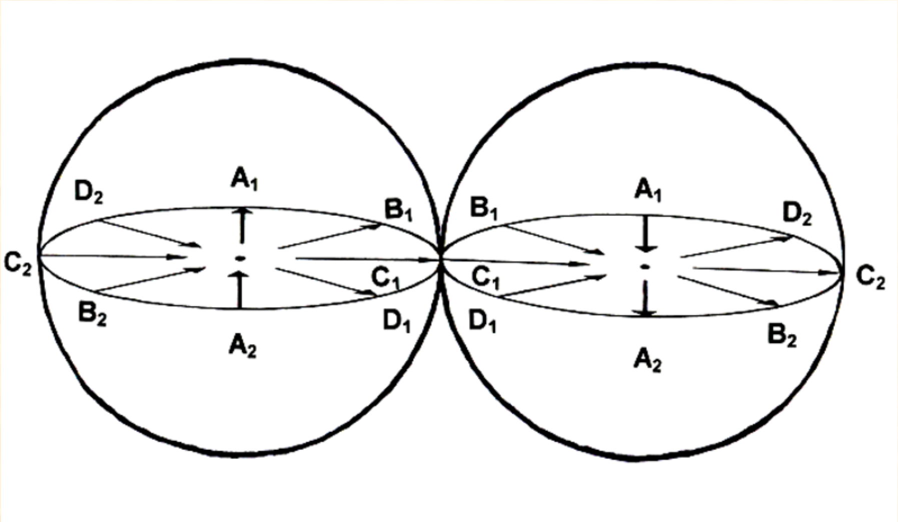
Testable
• topological lensing

Think finite space without edge

Sphere = 2D Surface
finite area, no edge

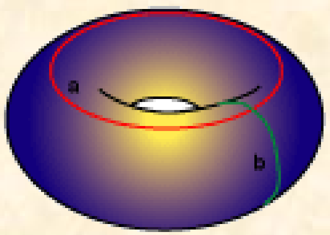
Hypersphere = 3D space
finite volume, no edge

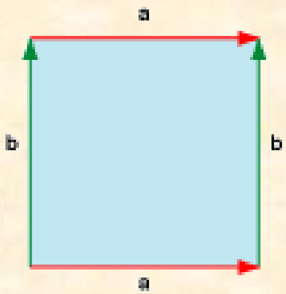


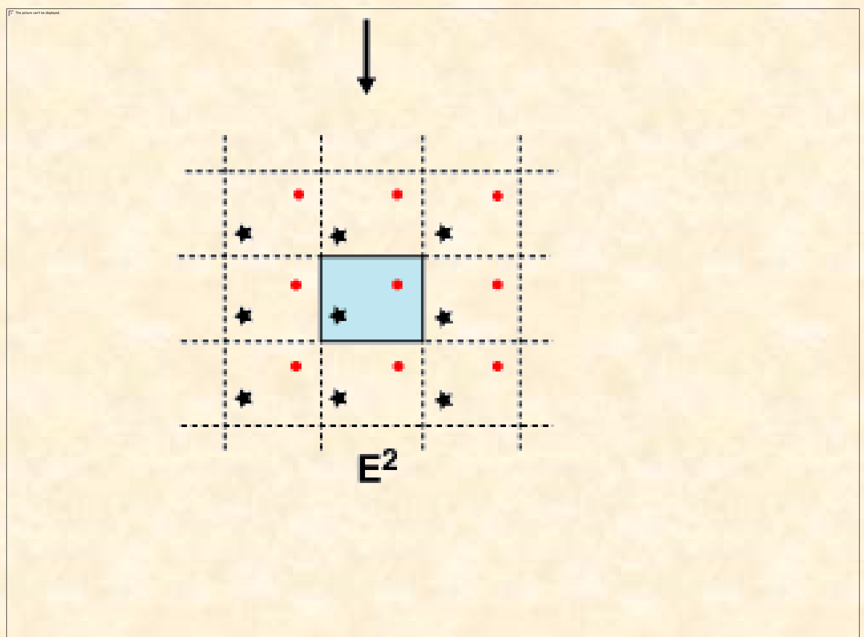


A finite flat space without a boundary

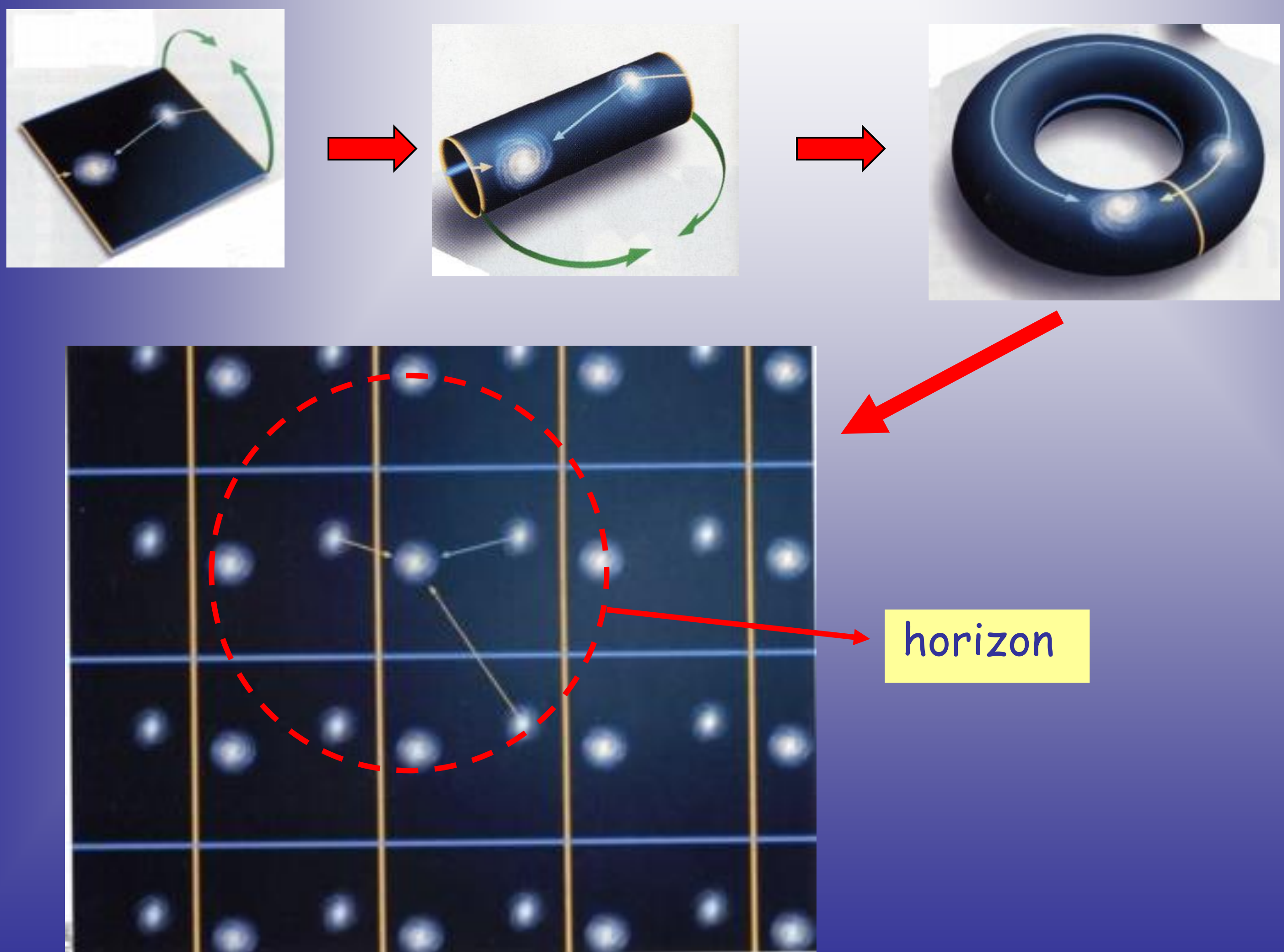
- Torus



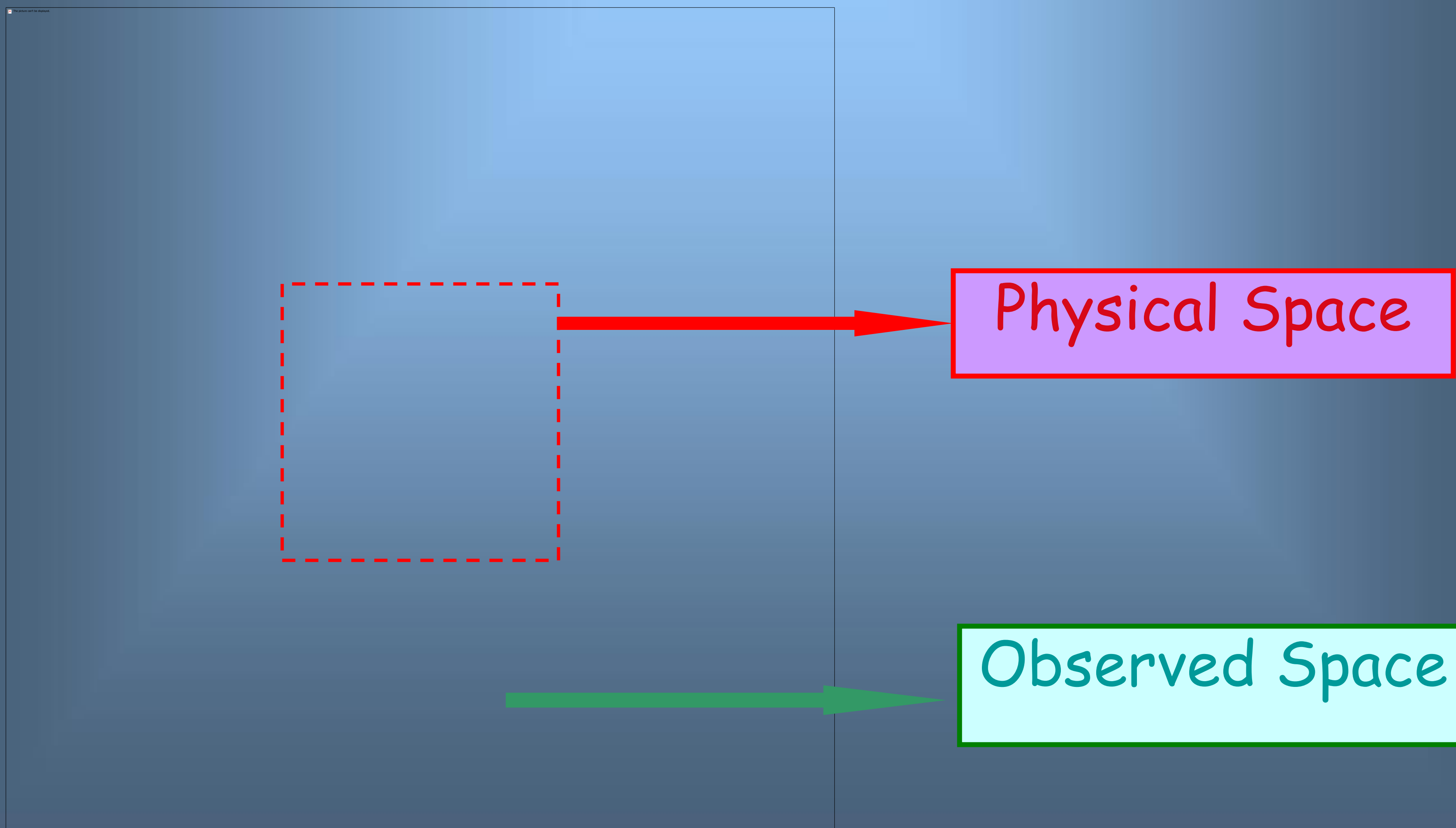




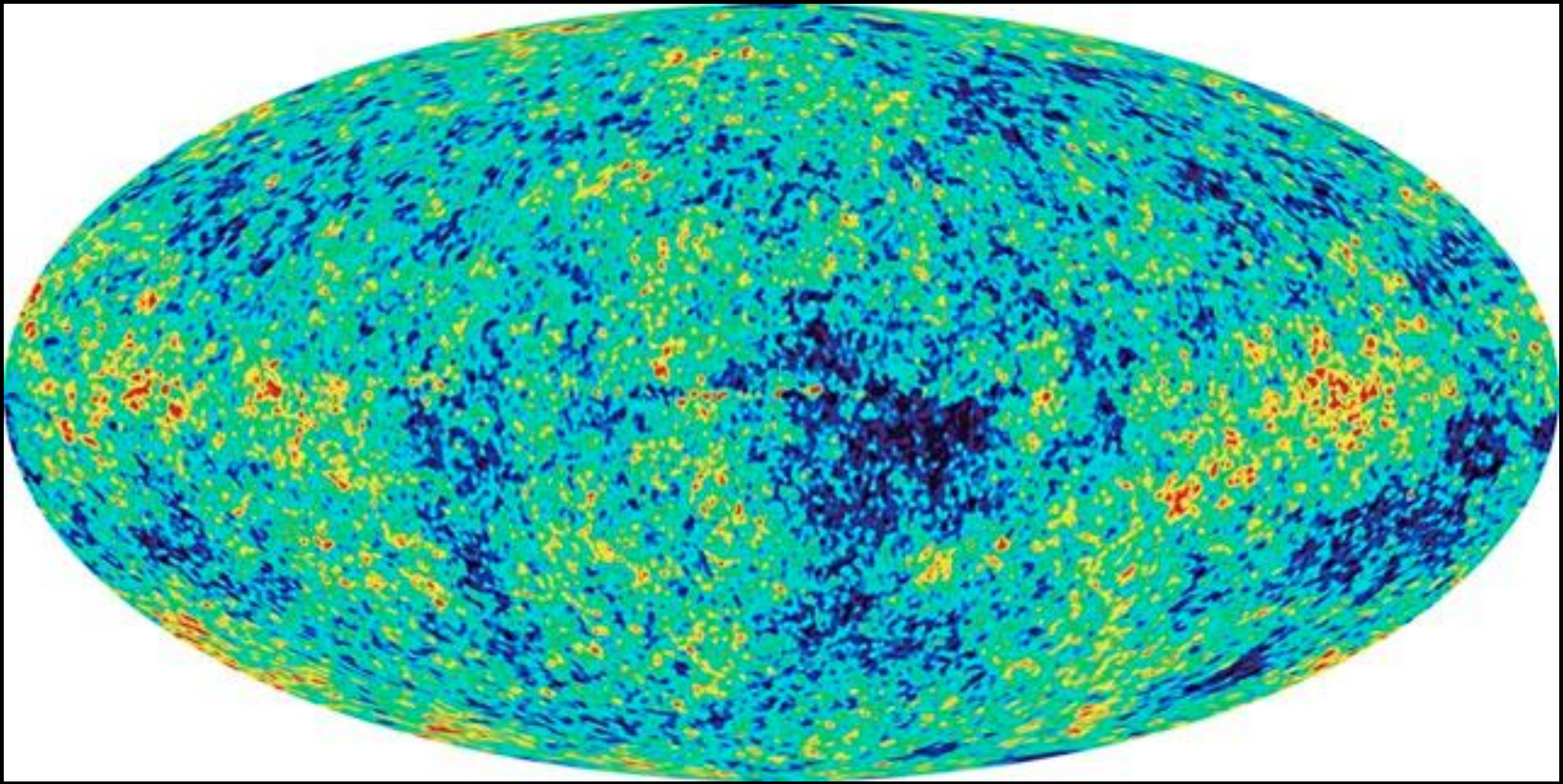
Topological lens effect



Hypertorus


The picture can't be displayed.
Physical Space
Observed Space

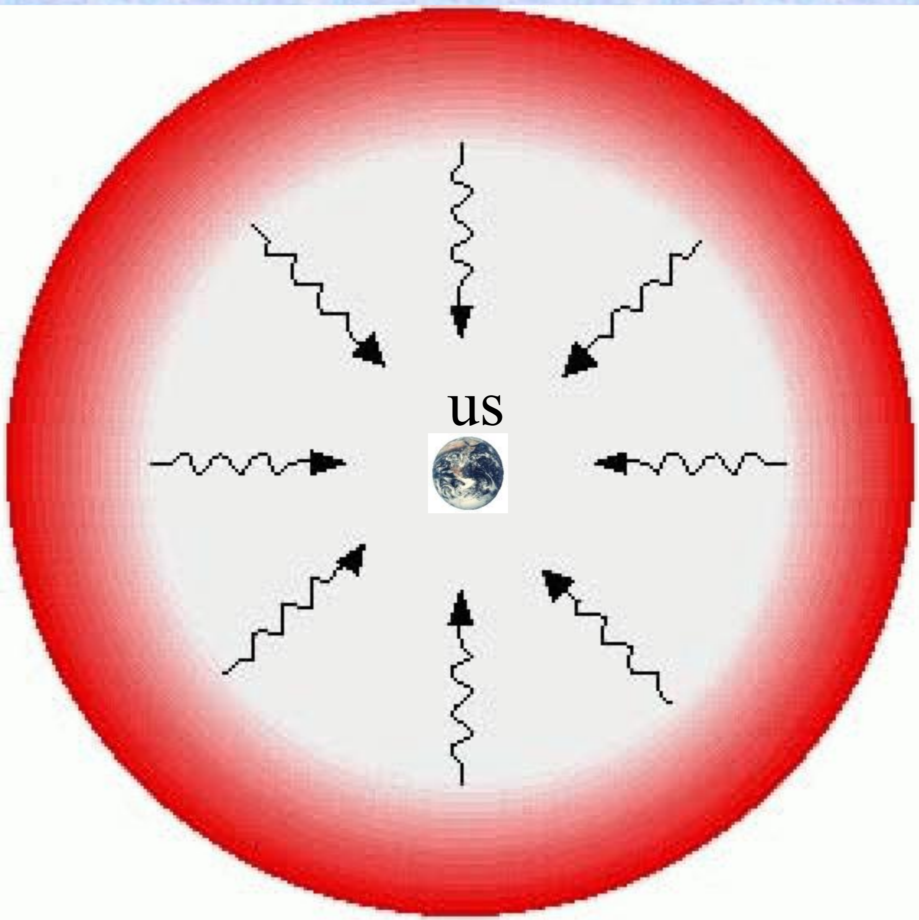
Cosmic Microwave Background

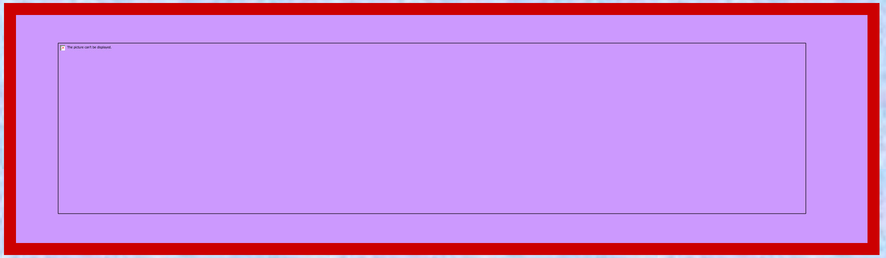


The universe as a cosmic « drumhead »

Cosmic Microwave Background

Observed on a 2-sphere



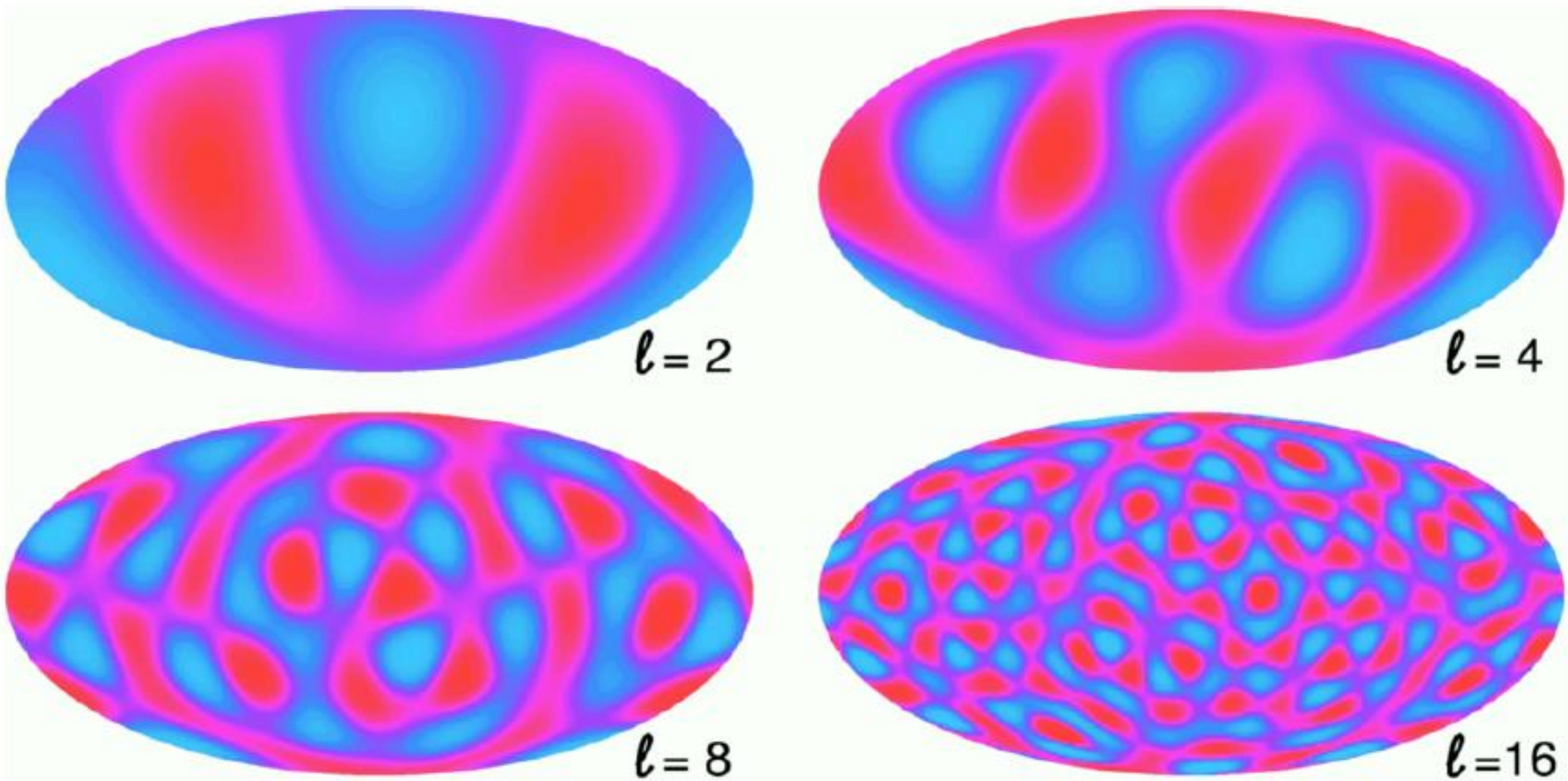


Spherical harmonics

Multipole moments

The CMB multipoles

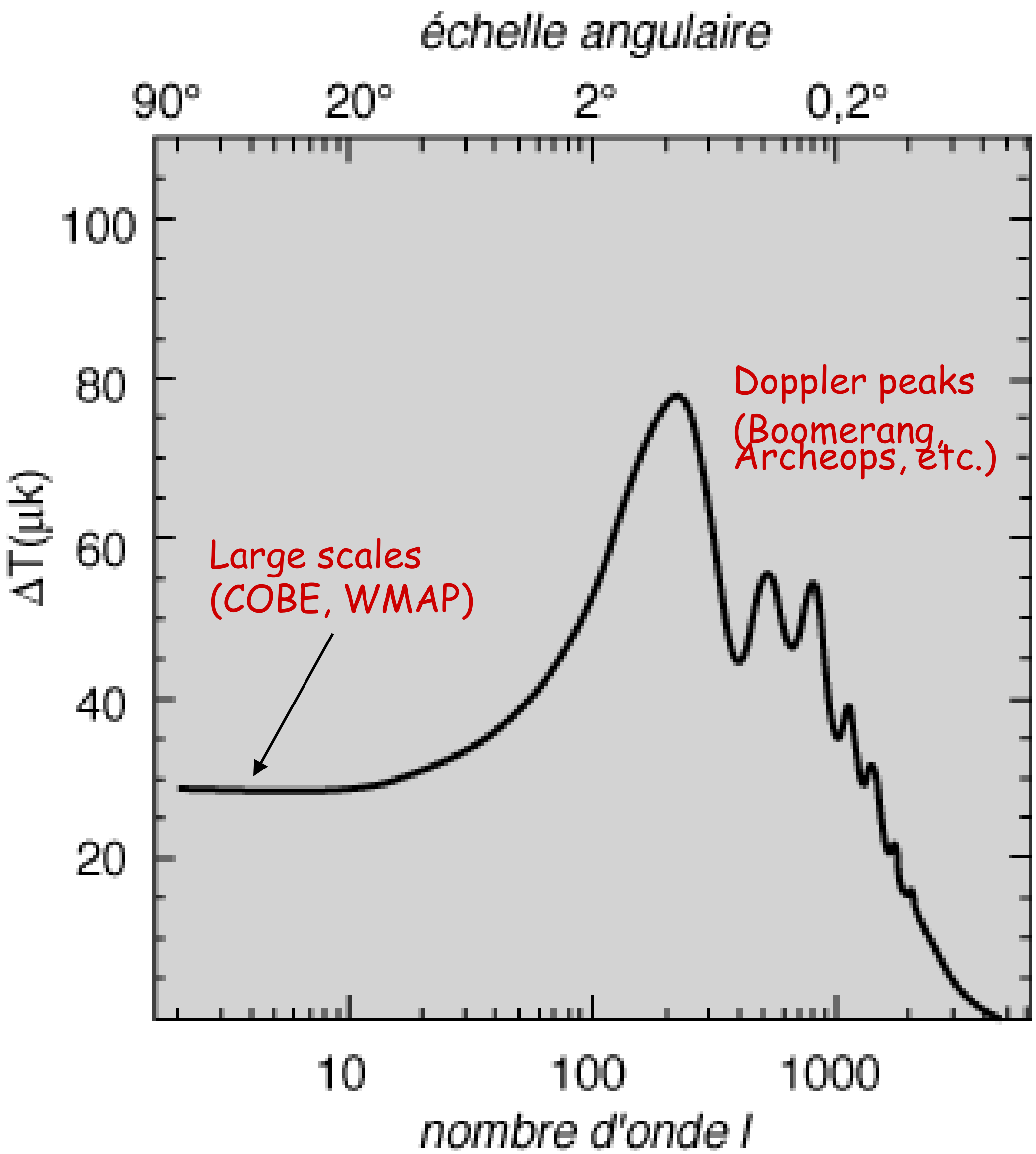
Quadrupole



Power spectrum

$\delta T_l^2 = l(l+1)C_l/2\pi$

$l = 180°/\theta$



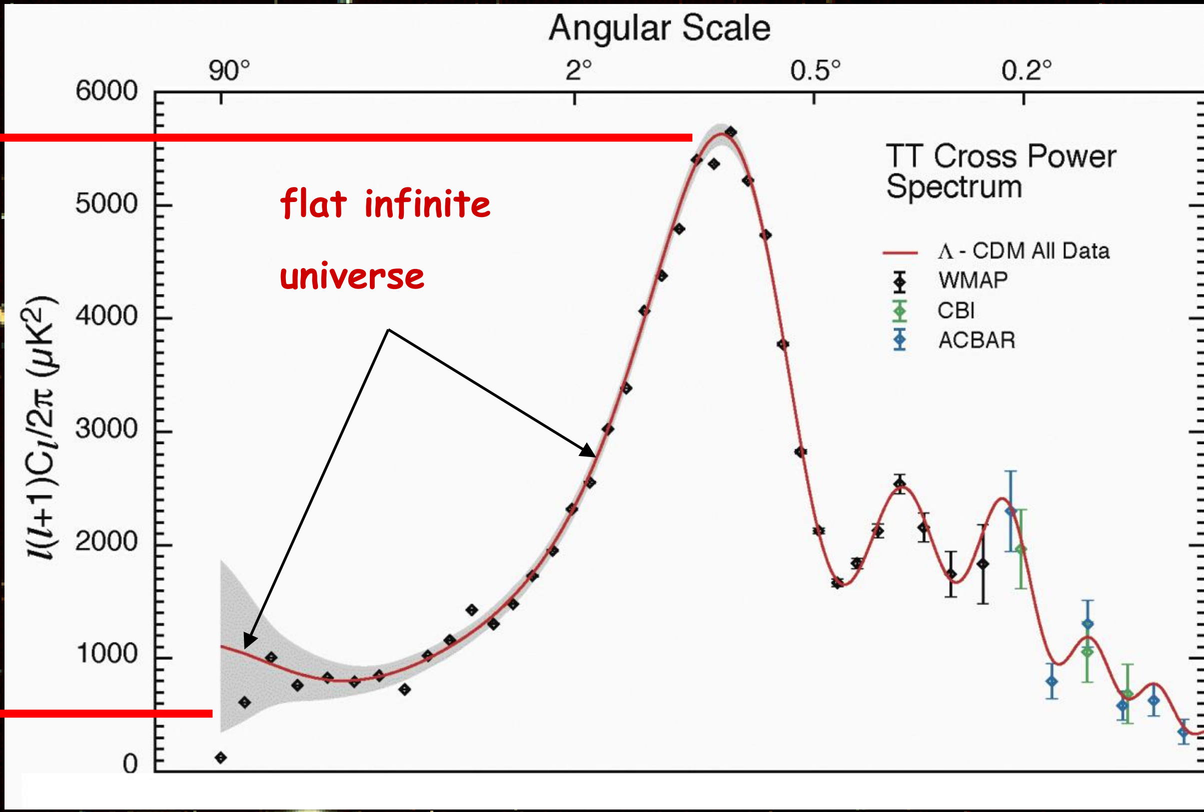
WMAP power spectrum

(2003- 2006)

- Universe seems to be positively curved

$\Omega_{\square\square\square} = 1.02 \pm 0.02$

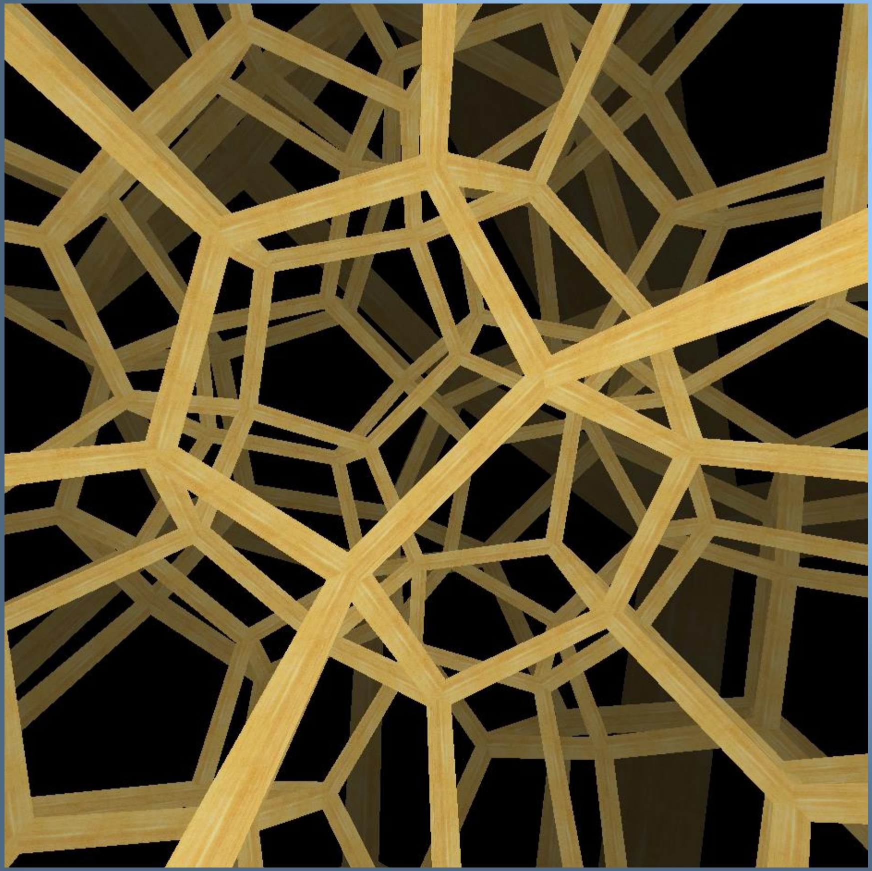
- Lack of power at large scales $(> 60°)$



Space might be finite with a special shape!

Poincaré Dodecahedral Space

FP : 12 faces regular dodecahedron



S^3/I^*

120 copies tessellate S^3

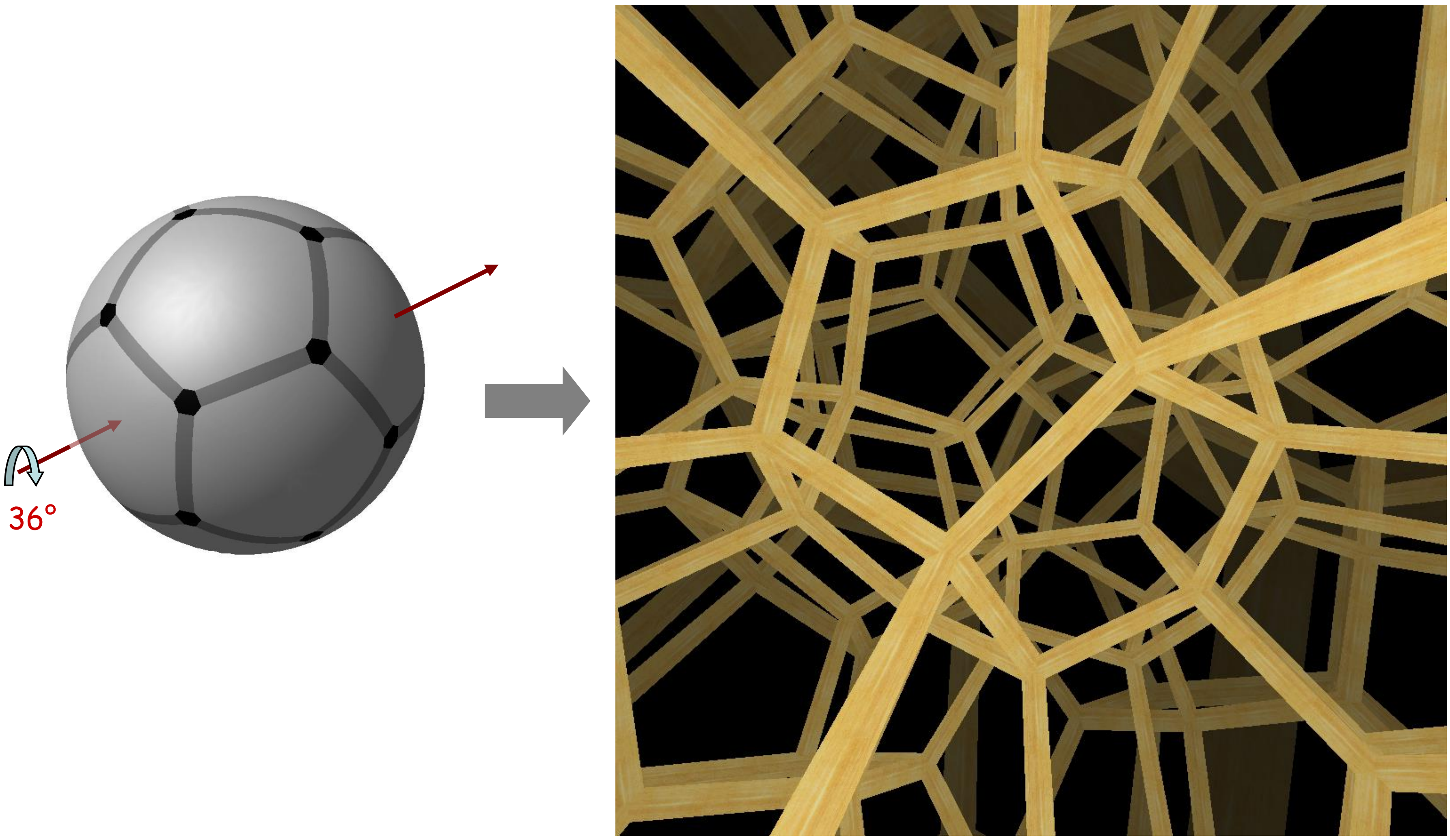
Poincaré Dodecahedral Spherical space (PDS)

Luminet et al., Nature ***425****, 593 (2003)*

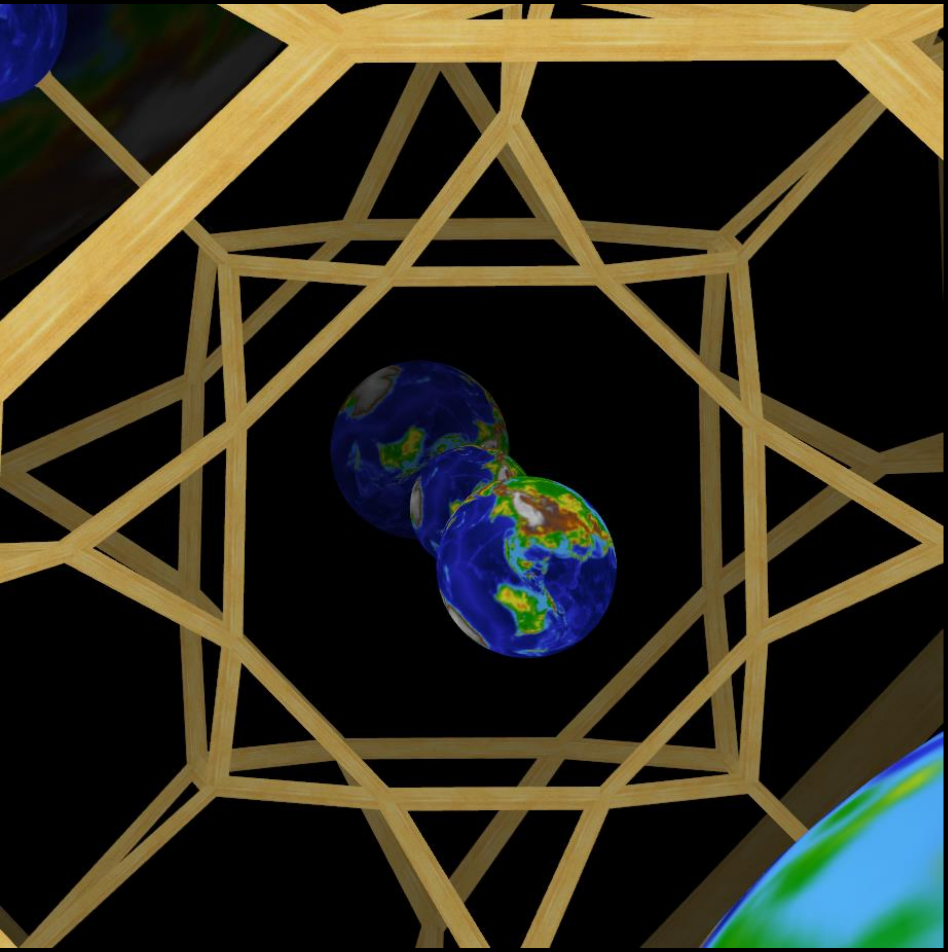
- fit low quadrupole
- fit low octopole
- [illegible] < Ω_{tot} < 1.02

Planck Surveyor (2007)

The « football Universe »

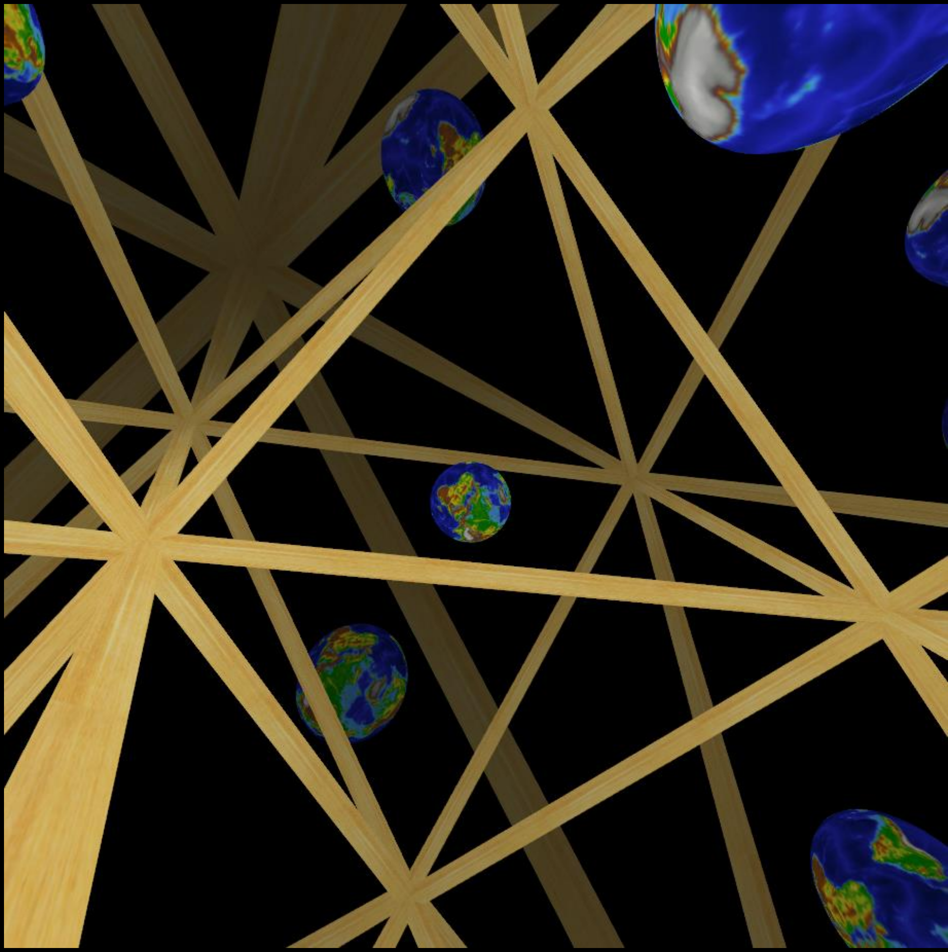


Also compatible …



Octahedral space

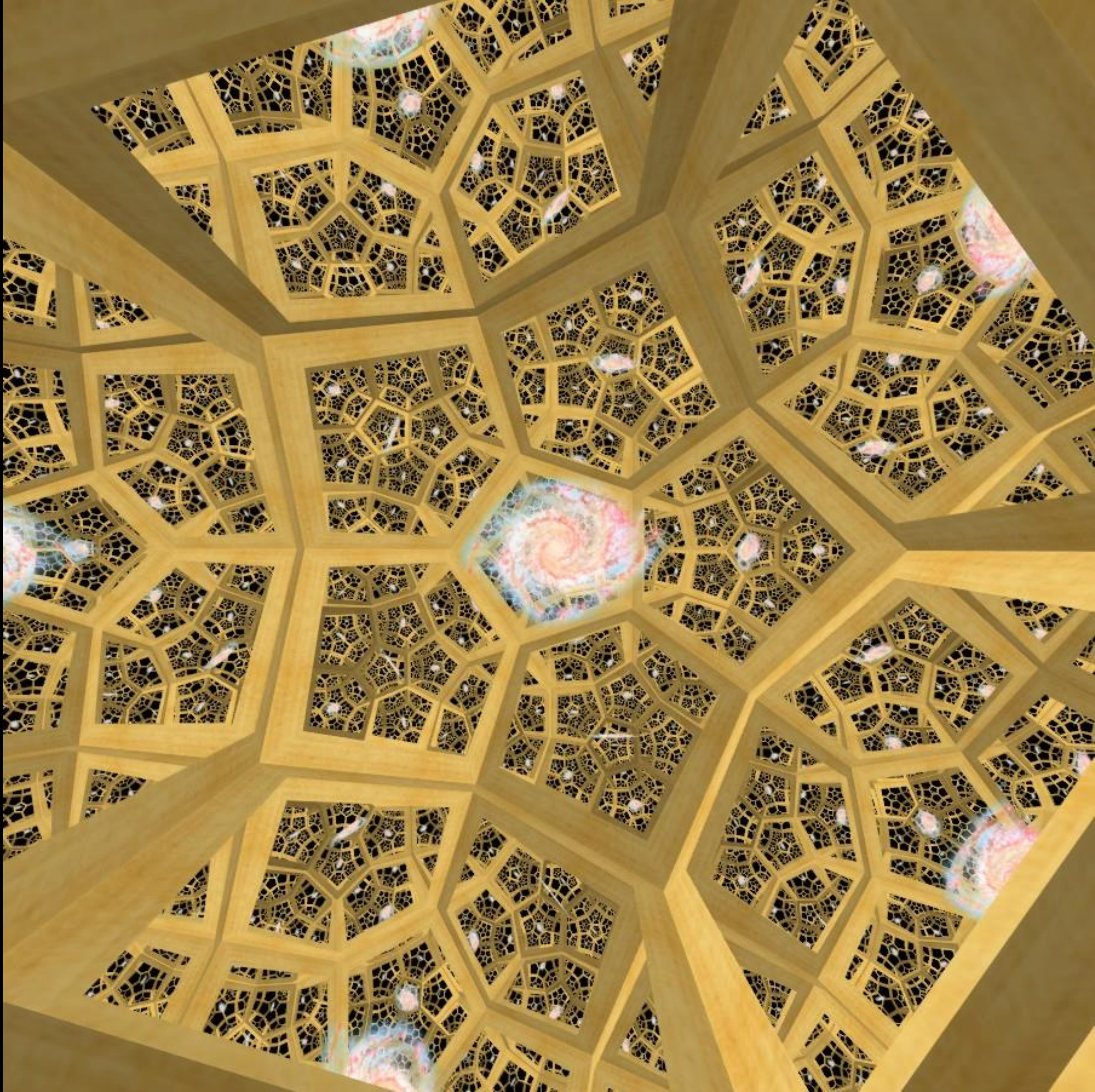
$(\Omega_{tot} > 1.015)$



Tetrahedral space

$(\Omega_{tot} > 1.025)$

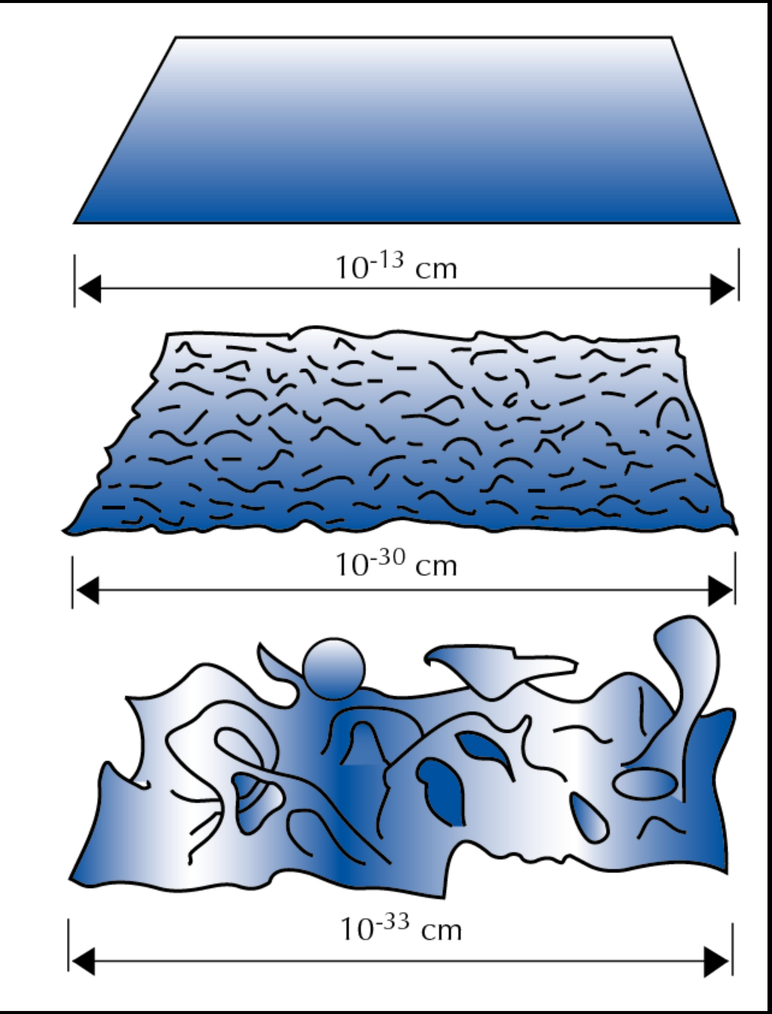
J. Weeks, 2006



Imaging Quantum Gravity

Quantum foam

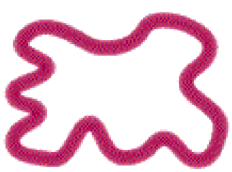
(J. Wheeler)



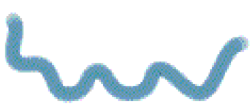
Solution 1 : string theory

Veneziano, Green,
Schwarz, Witten, etc.

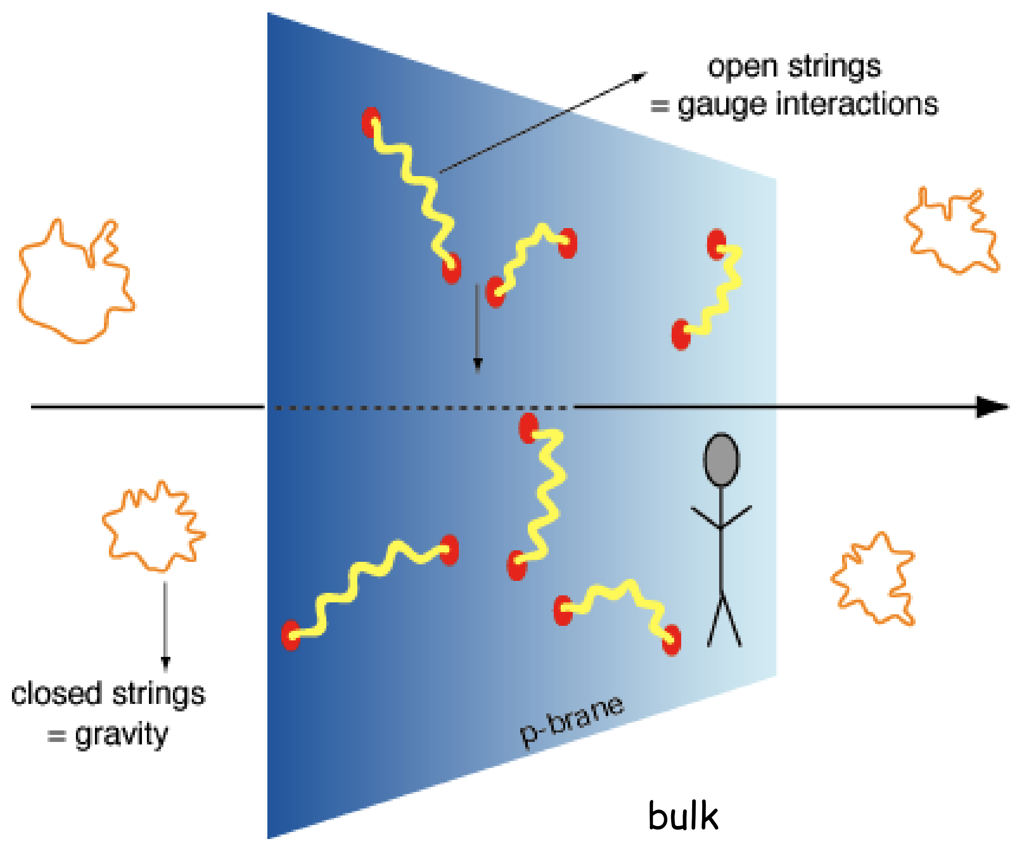
Price to pay :
extra-dimensions



Closed string



Open string



Solution 2 : loop quantum gravity

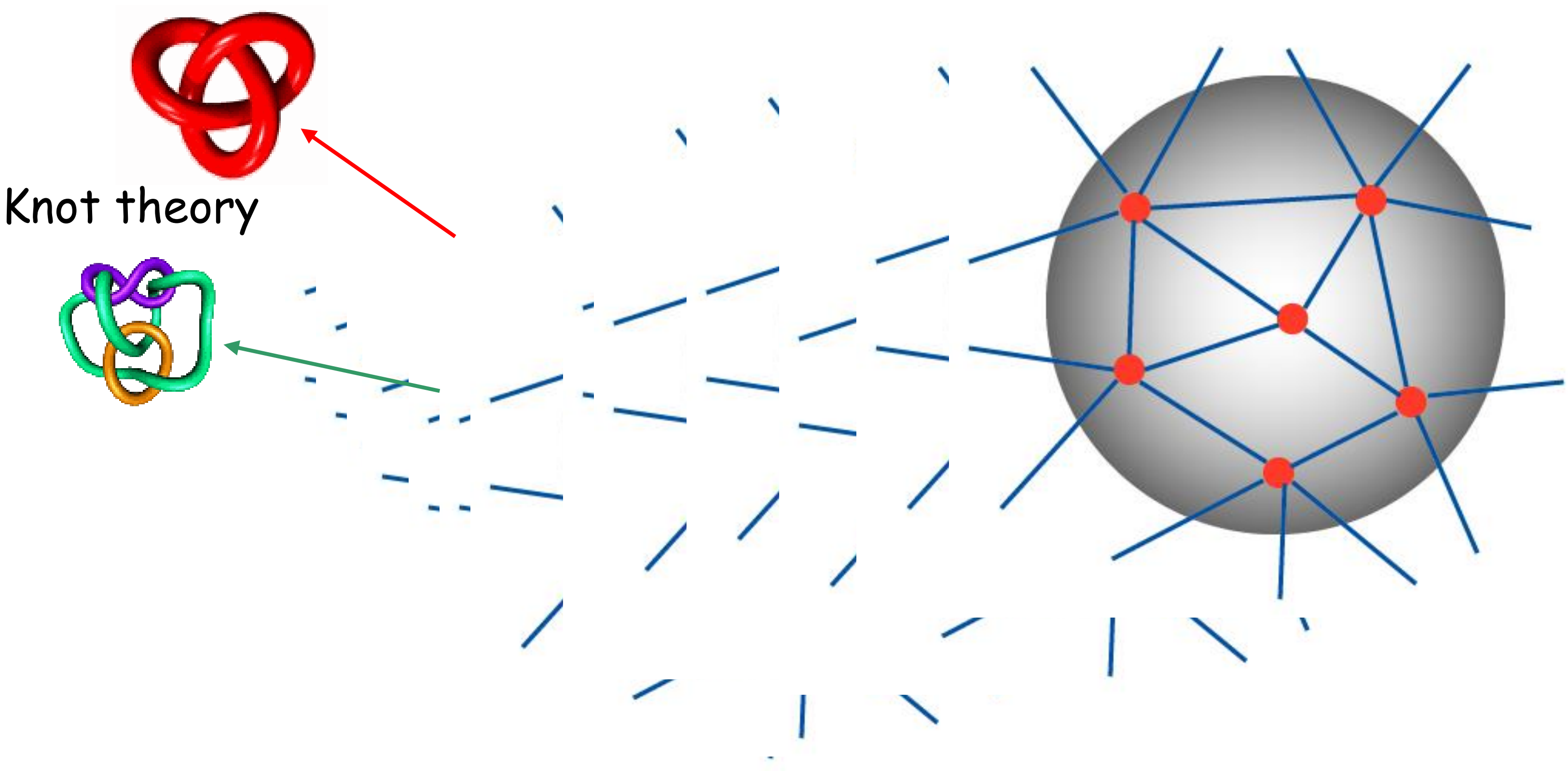
Ashtekhar, Smolin, Rovelli, Bojowald

Atoms of space: 10^{-99} cm^3

Spin network

Atoms of time : 10^{-43} sec

Spin foam



If God had consulted me before embarking upon Creation, I should have recommended something simpler.

Alfonso X, King of Castile