From Black Holes to Cosmology :

The Universe in the Computer

J.-P.Luminet

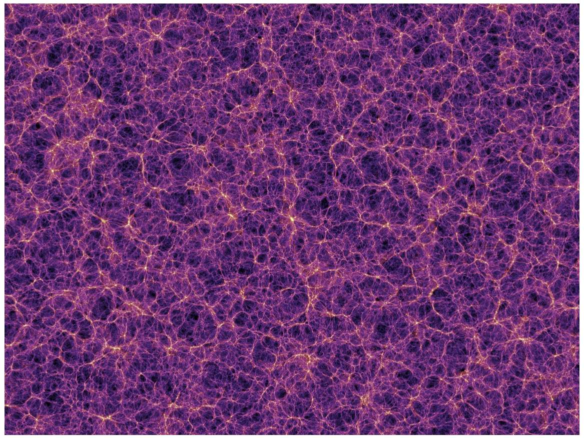
Observatoire de Paris (LUTH)

XVth ACAT Workshop, Beijing 2013

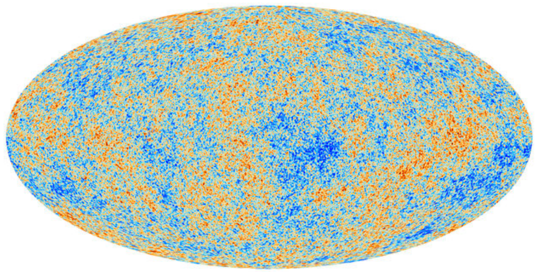
- **Numerical Relativity**
- **Numerical Astrophysics**
- **Numerical Cosmology**

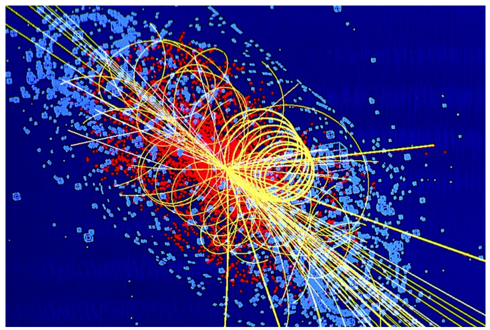
Important to distinguish between :

• Numerical modelisation
(Simulations)



• Data Treatment & Data Analysis





Facilities

Laboratory → France → Europe

Laboratory
LUTH

Laboratory **U**niverse & **TH**eories

- Sequential machines
- Small clusters *(10-100 nodes)*
- Mesocenters *(200 nodes)*
- Supercomputers *(10 000 nodes)*
- Grids

Numerical Tools:
- Codes
- Libraries

France
GENCI

Grand **E**quipement **N**ational de **C**alcul **I**ntensif

coordinates the principal French equipments in high performance computing

5 partners:
- Ministery of Research
- CEA
- CNRS
- Universities
- INRIA

Europe
PRACE

Partnership fo**R** **A**dvanced **C**omputing in **E**urope

creates a pan-European supercomputing infrastructure for large scale scientific and engineering applications

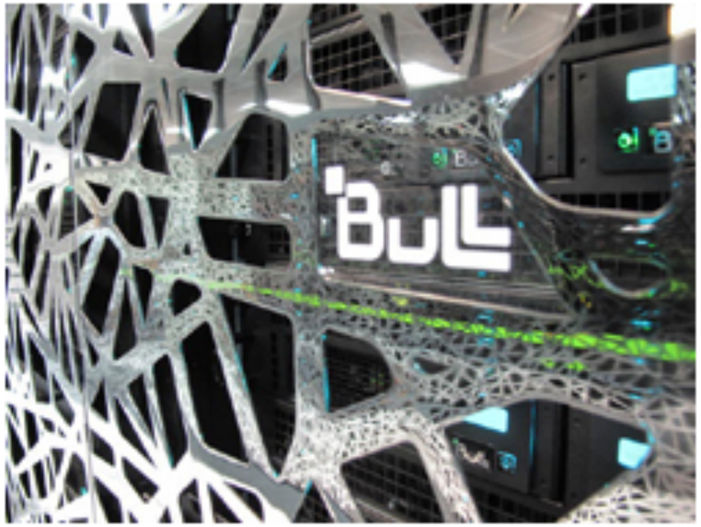
25 member countries
- BSC (Spain)
- CINECA (Italy)
- GCS (Germany)
- GENCI (France)

GENCI

TGCC

The Curie supercomputer, owned by GENCI and operated into the TGCC by CEA, is the first French Tier0 system open to scientists through the French participation into the PRACE research infrastructure.

Curie is offering 3 different fractions of x86-64 computing resources for addressing a wide range of scientific challenges and offering an aggregate peak performance of 2 PetaFlops.



Tianhe-1A

天河一号

(Milky Way n°1)

National Supercomputing Center of Tianjin

2.6 PetaFlops

Titan-Cray (U.S.A.)

17 PetaFlops

K-computer (Japan)

10 PetaFlops

Juqueen (Germany)

4 PetaFlops

Numerical Grand Challenges

« A grand challenge is a fundamental problem in science or engineering, with broad applications, whose solution would be enabled by the application of high performance computing resources that could become available in the near future. »

→ Simulations on Supercomputers

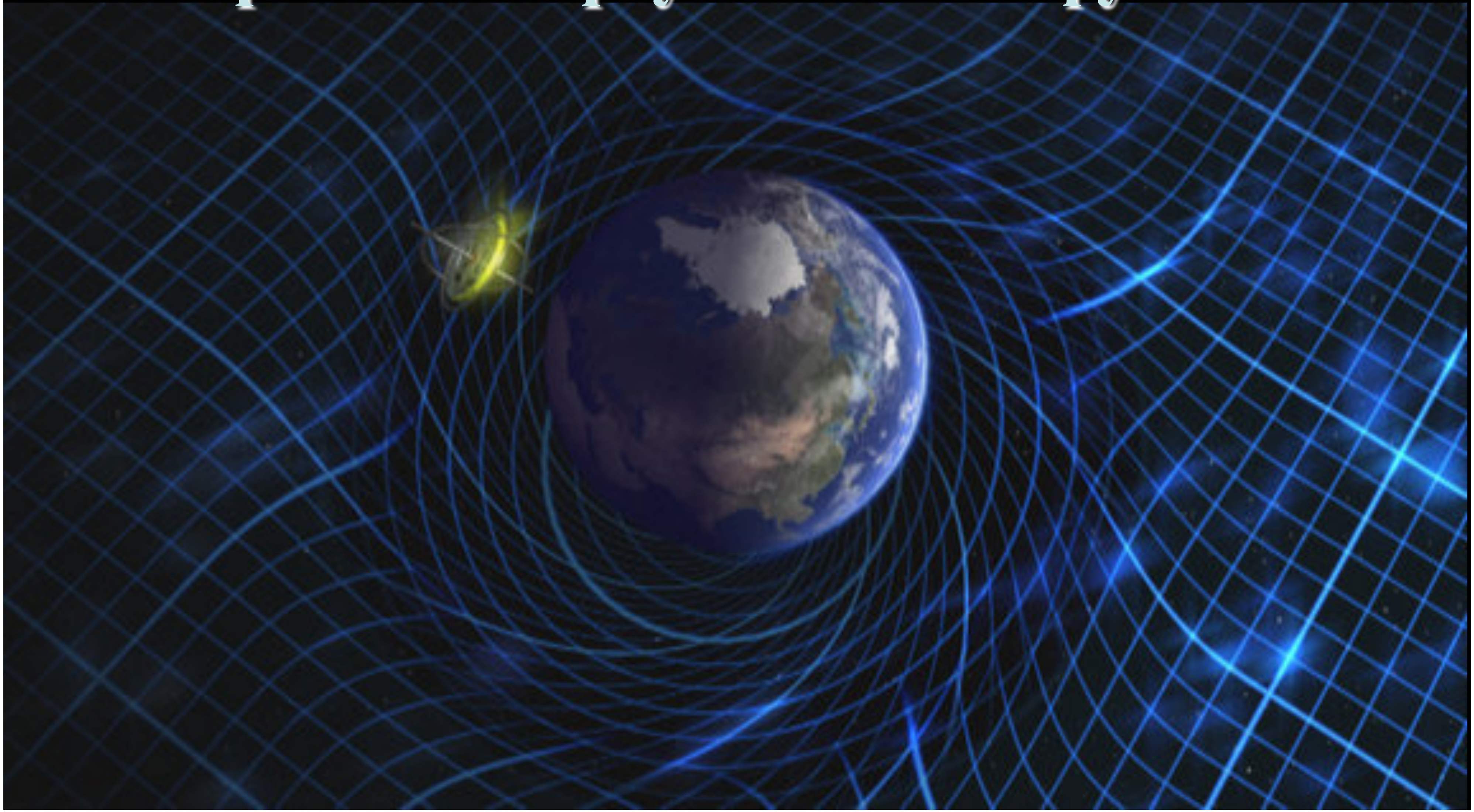
(> 10 000 nodes)

Specificities

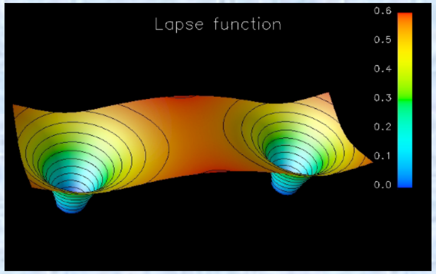
- Massive parallelization
- Very large flux of I/O data
- Requires teams of researchers + engineers +technicians

Numerical Relativity :

A powerful tool to explore fundamental problems in physics and astropysics

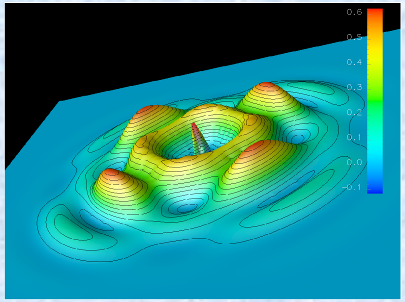


Numerical Relativity

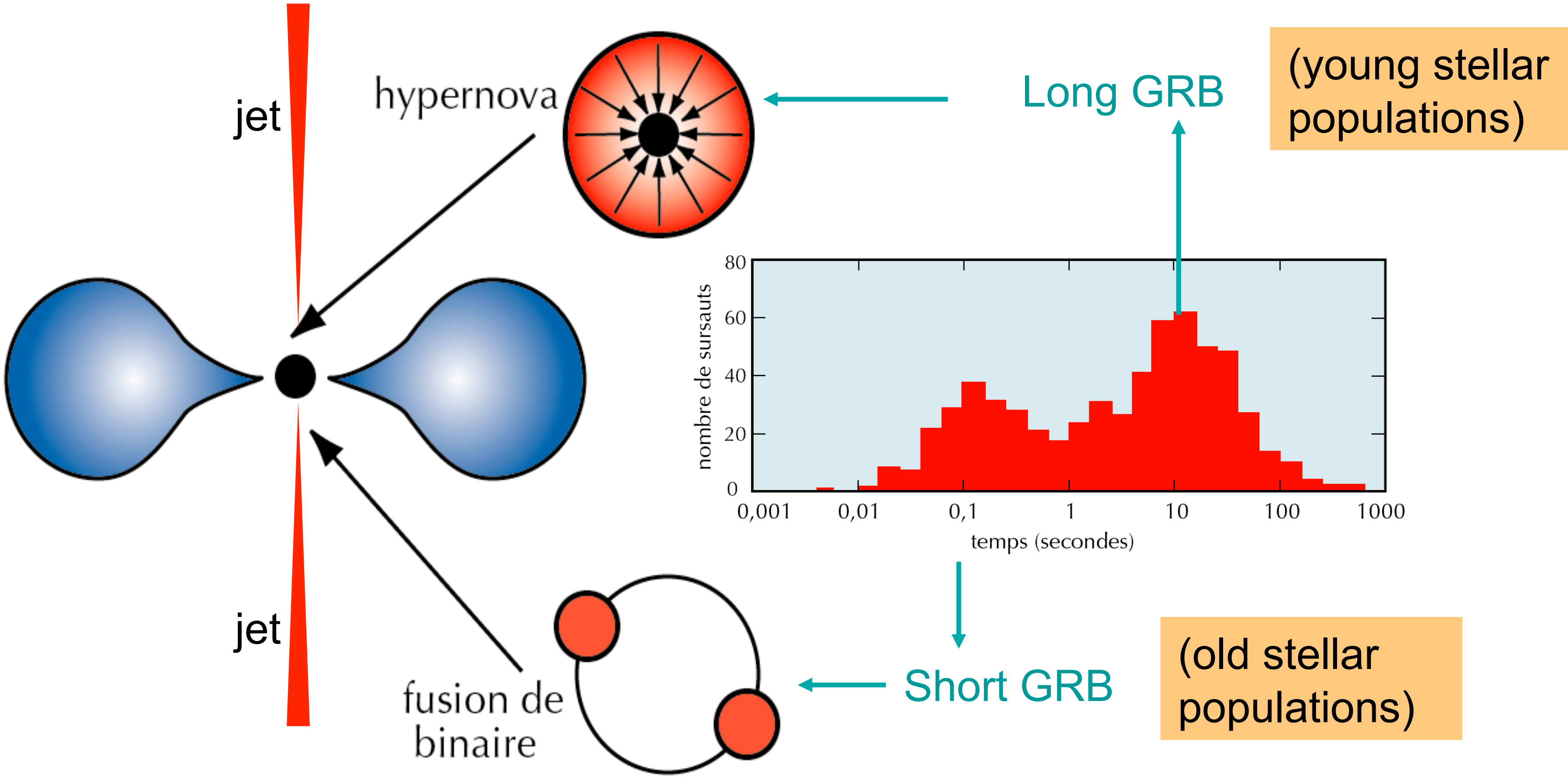


Spectacular progress in the last decade

- Larger computational facilities
- More advanced & accurate numerical techniques
- New formulation of Einstein's and MHD equations well-suited for numerical evolution



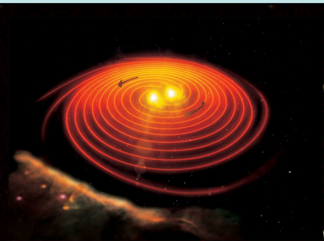
Example 1 : From gravitational collapse to Gamma-Ray Bursts



well-supported by full GR simulations

How crashing neutron stars can make gamma-ray bursts jets

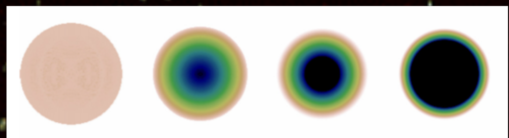
Binary Neutron Stars



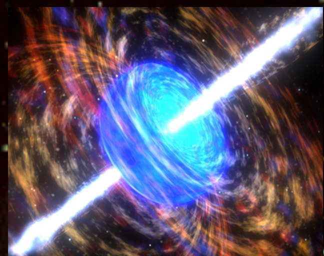
Inspiral phase (gravitational waves)

Coalescence

Merger (HMNS)



BH formation + accretion torus (ringing the modes)



Relativistic outflow

Short GRB

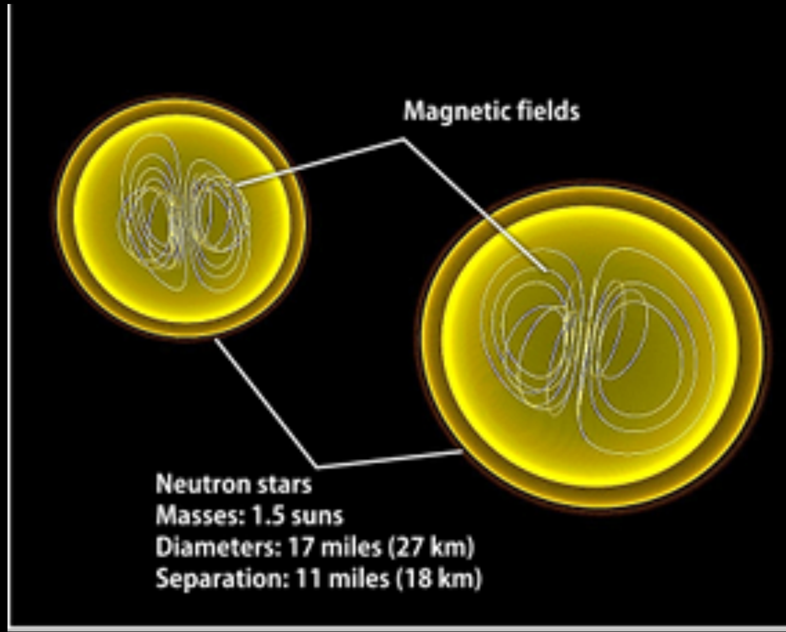
10^{48}-10^{50} ergs in 0.1-1 sec

Evolution of density and Magnetic Field

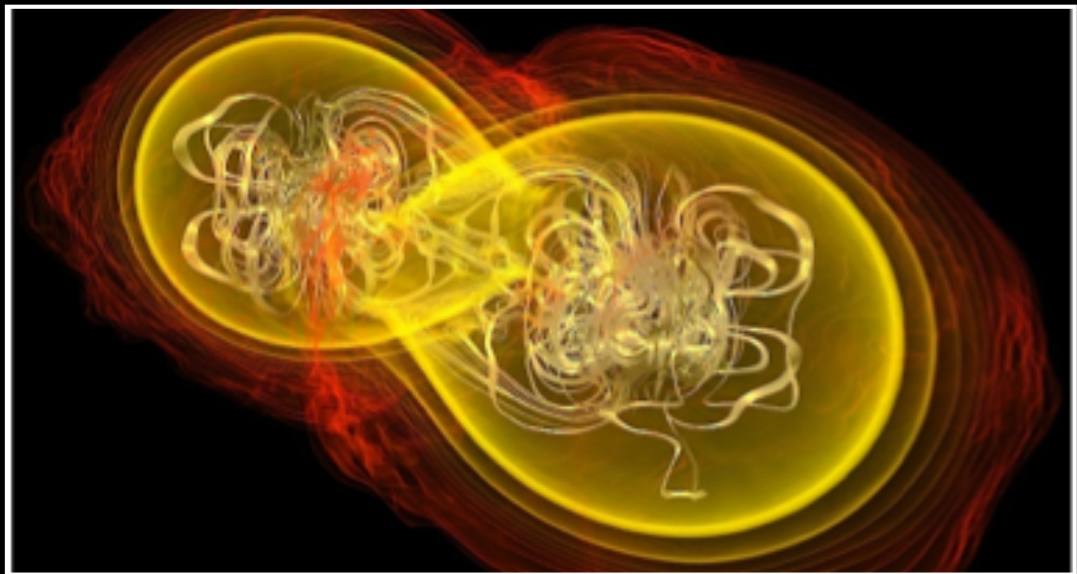
Rezzolla 2013

(MPI Potsdam, Germany)

t = 0 : simulation begins

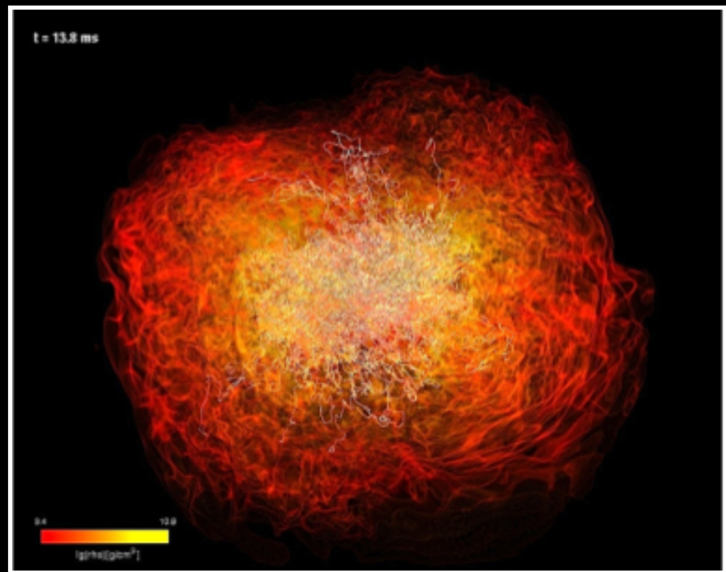


t=7.4 ms



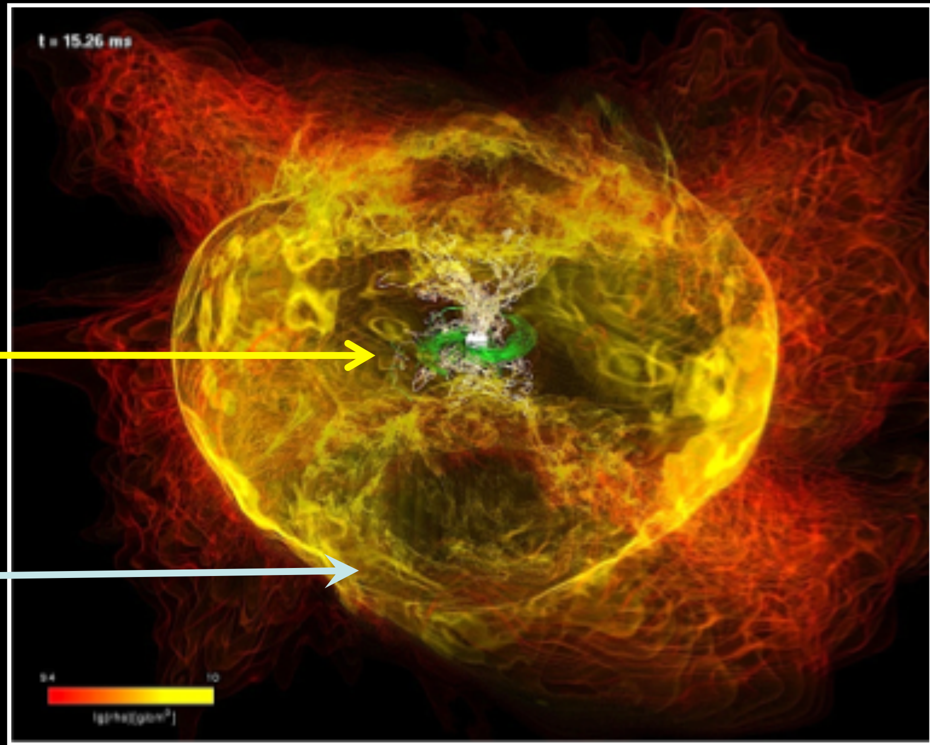
Merger after 3 orbits

t=13.8 ms



HMNS

t=15.3 ms

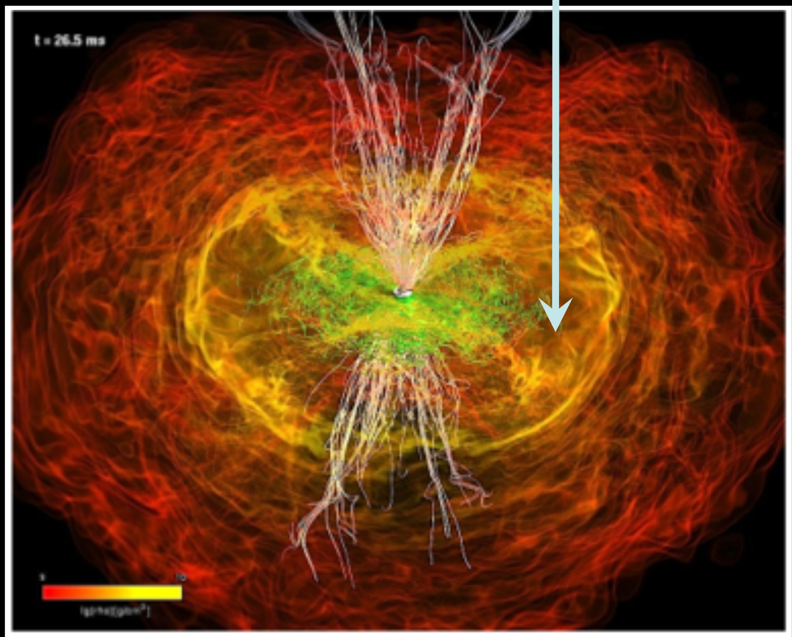


BH forms

2.9 M_S

accretion torus

t=26.5 ms



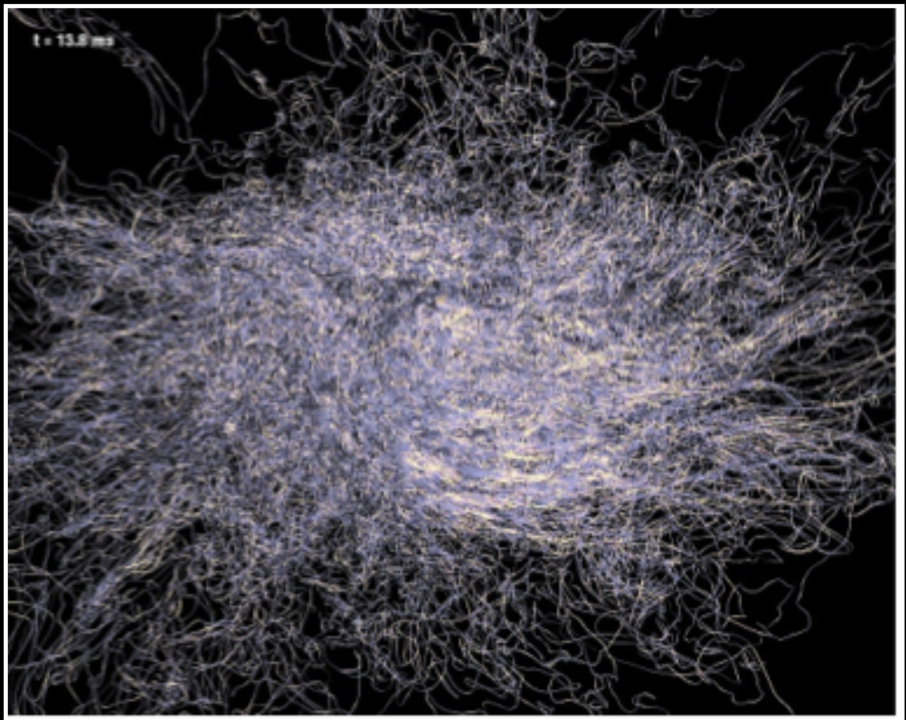
MF lines along BH spin axis

MF lines in the torus

MF Structure before & after Collapse

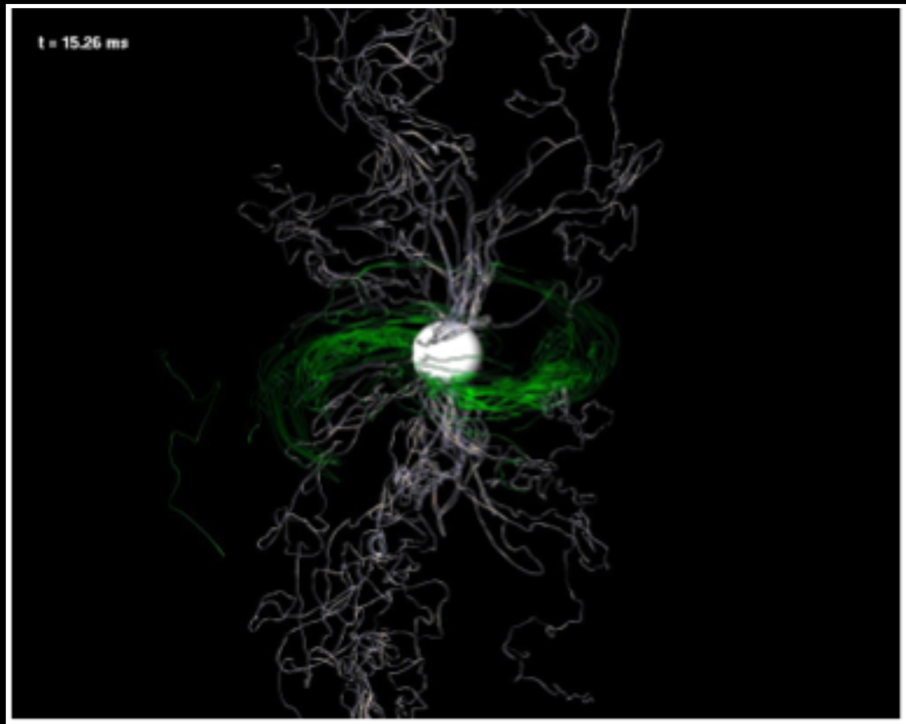
Rezzolla 2013 (MPI Potsdam, Germany)

t=13.8 ms



1: In the HMNS
turbulent poloidal MF

t=15.2 ms

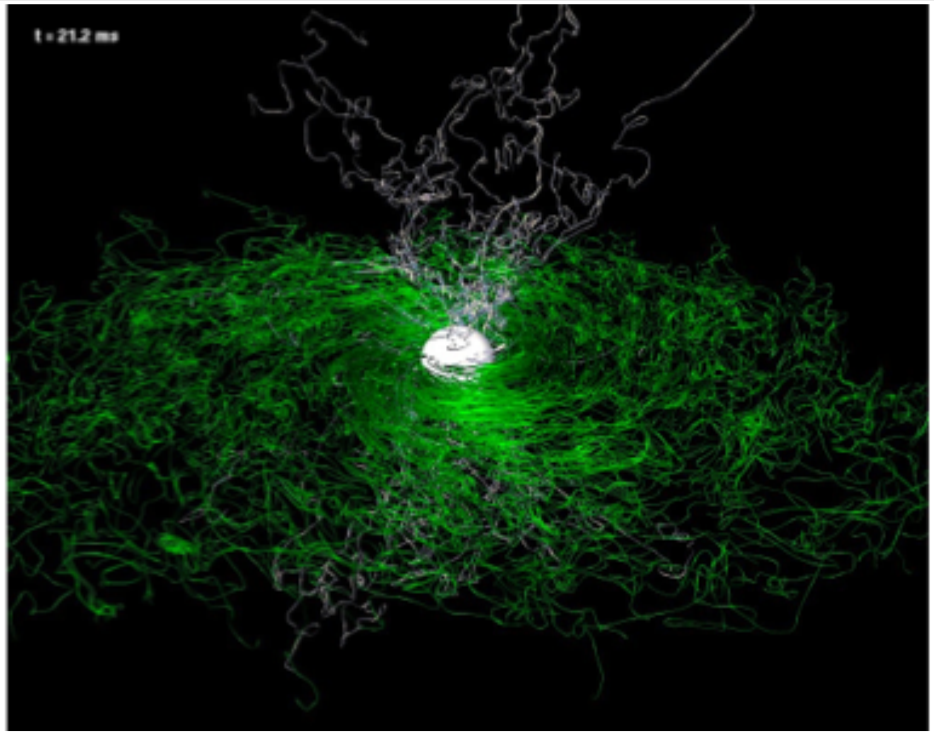


2: BH formation
MF ordering

MF Structure before & after Collapse

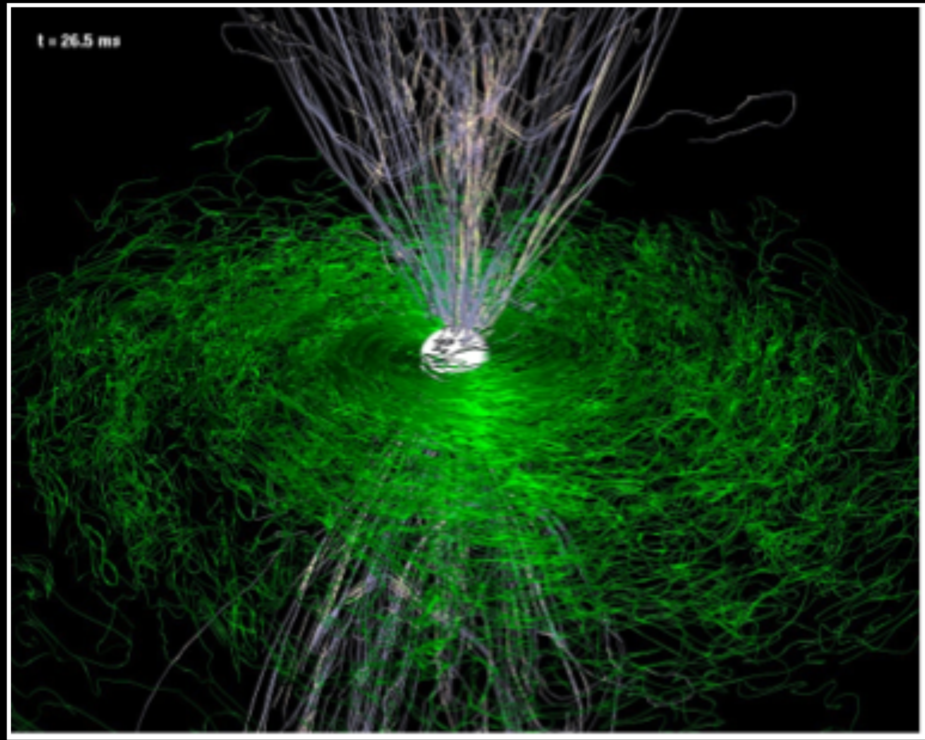
Rezzolla 2013 (MPI Potsdam, Germany)

t=21.2 ms



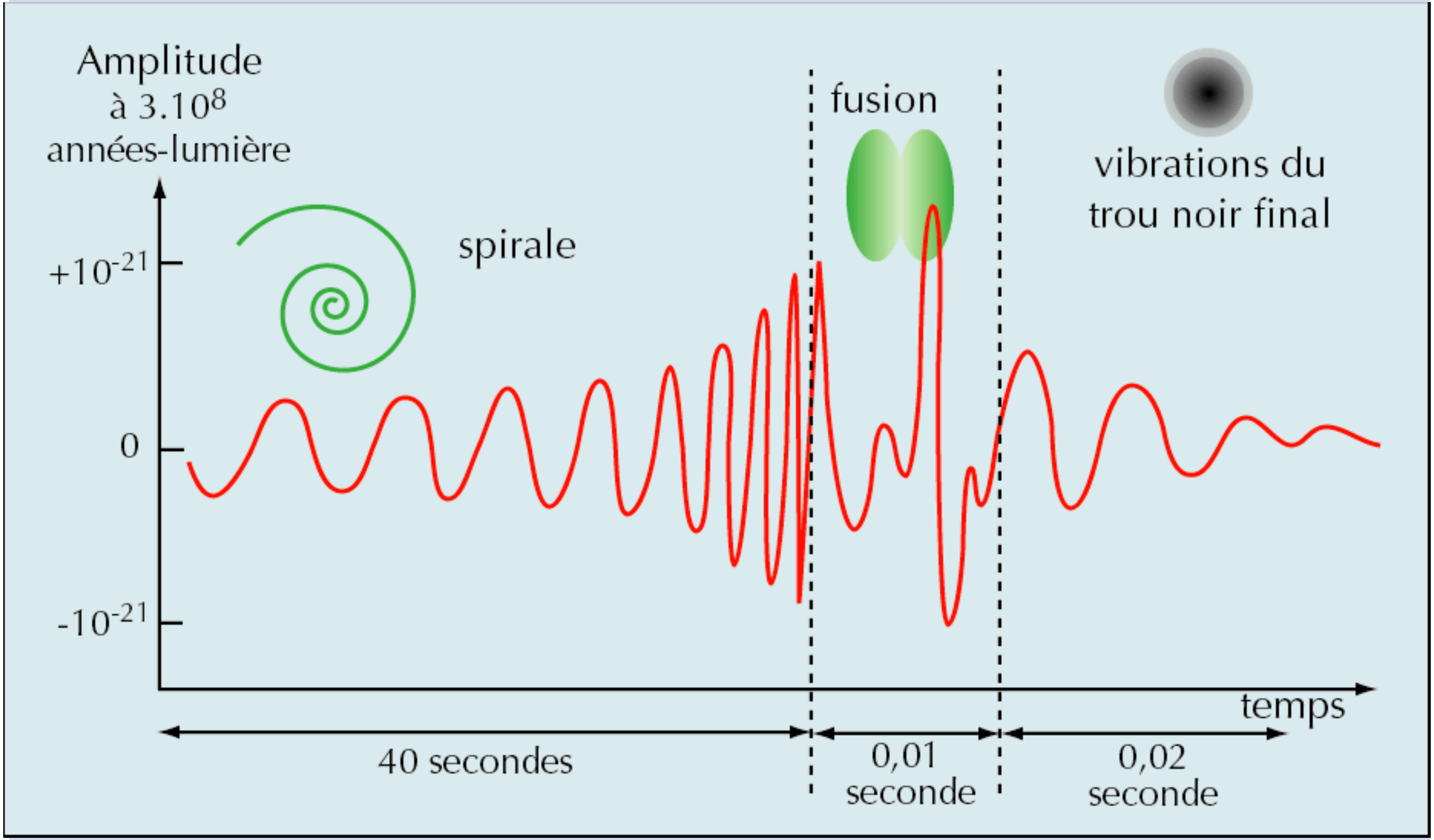
3: BH + accretion torus
toroidal MF

t=26.5 ms



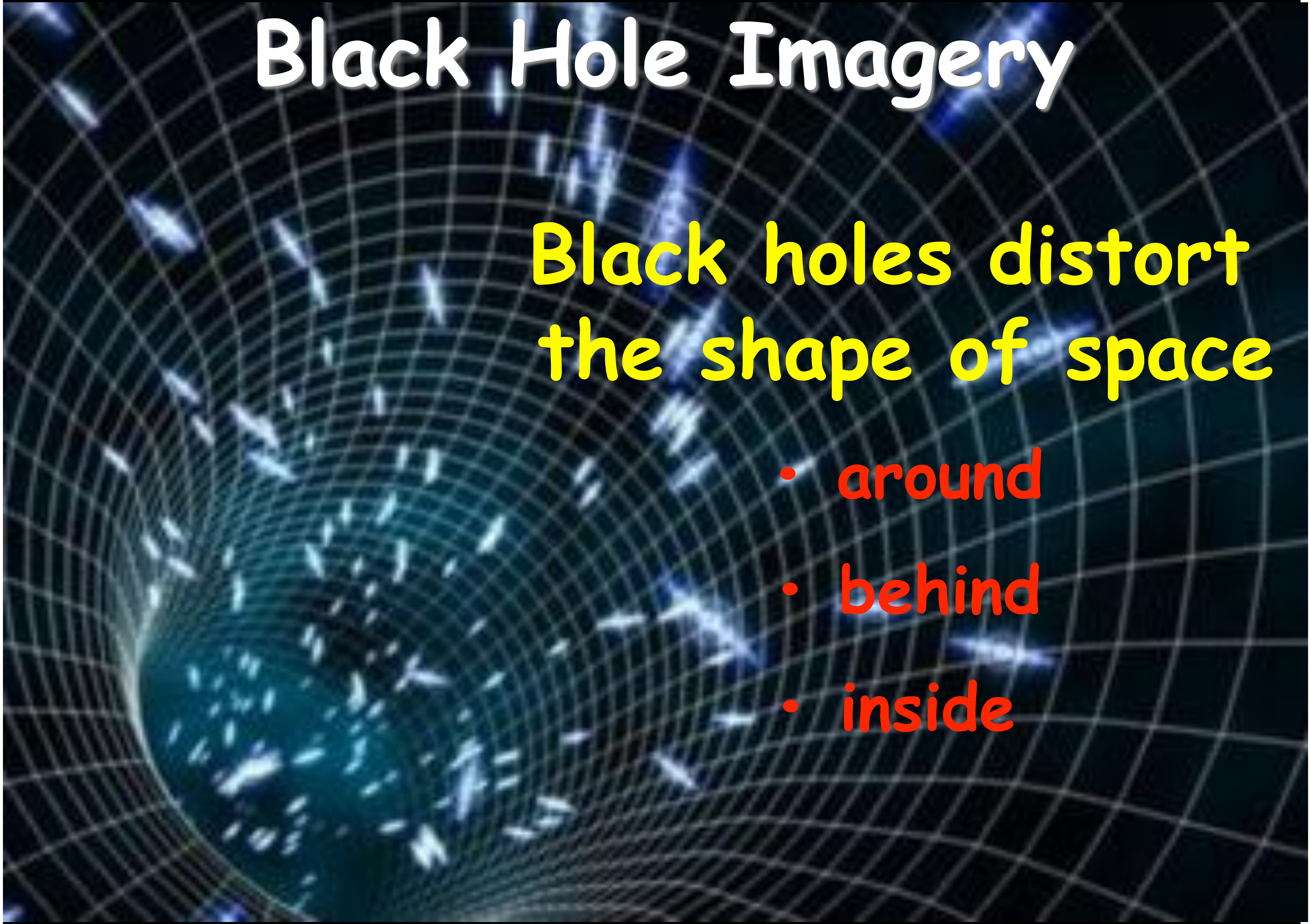
4: ordered MF

Gravitational Waveform



provides mock catalogues for Virgo-Ligo & e-LISA future data

Black Hole Imagery

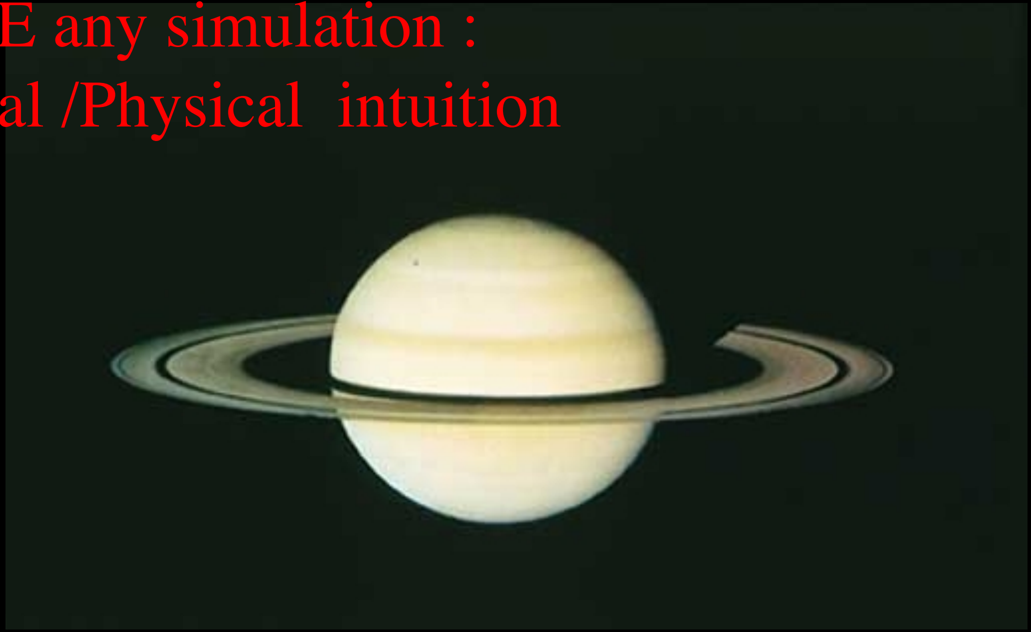


Black holes distort the shape of space

- around
- behind
- inside

BEFORE any simulation :
Geometrical /Physical intuition

Newtonian Spacetime



Curved Spacetime

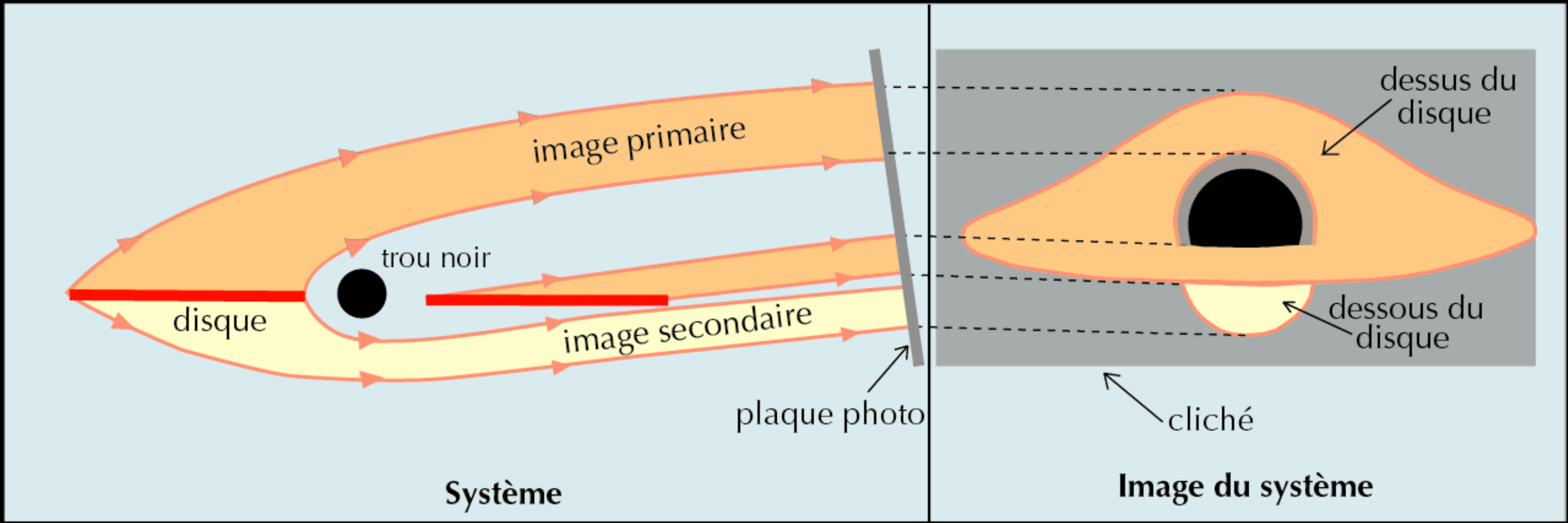
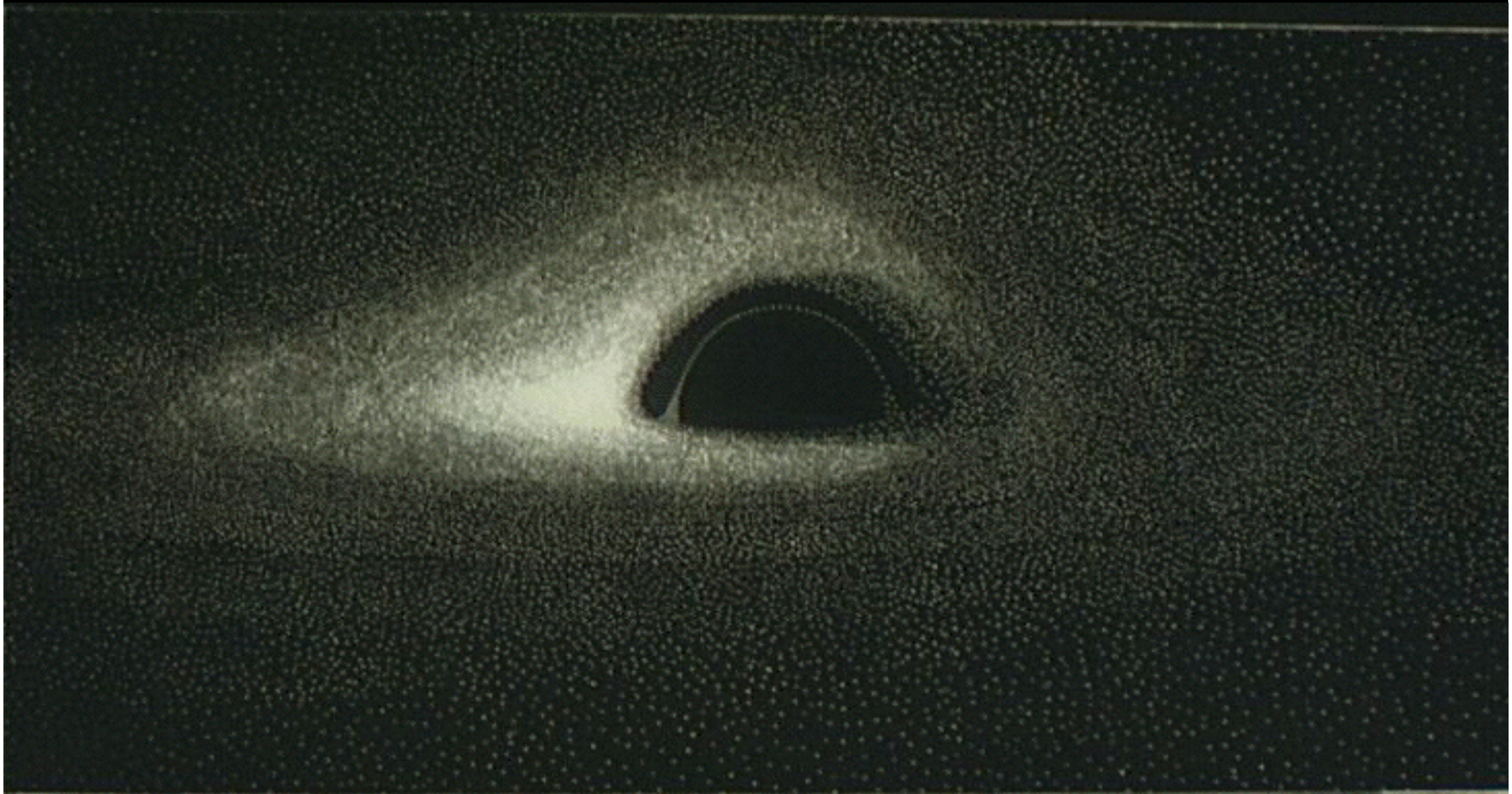


Image of a spherical black hole with thin accretion disk

(J.-P. Luminet, 1979)



IBM 7040 (with punched cards, no visualization device)

Short-cut method of solution of geodesic equations for Schwarzchild black hole

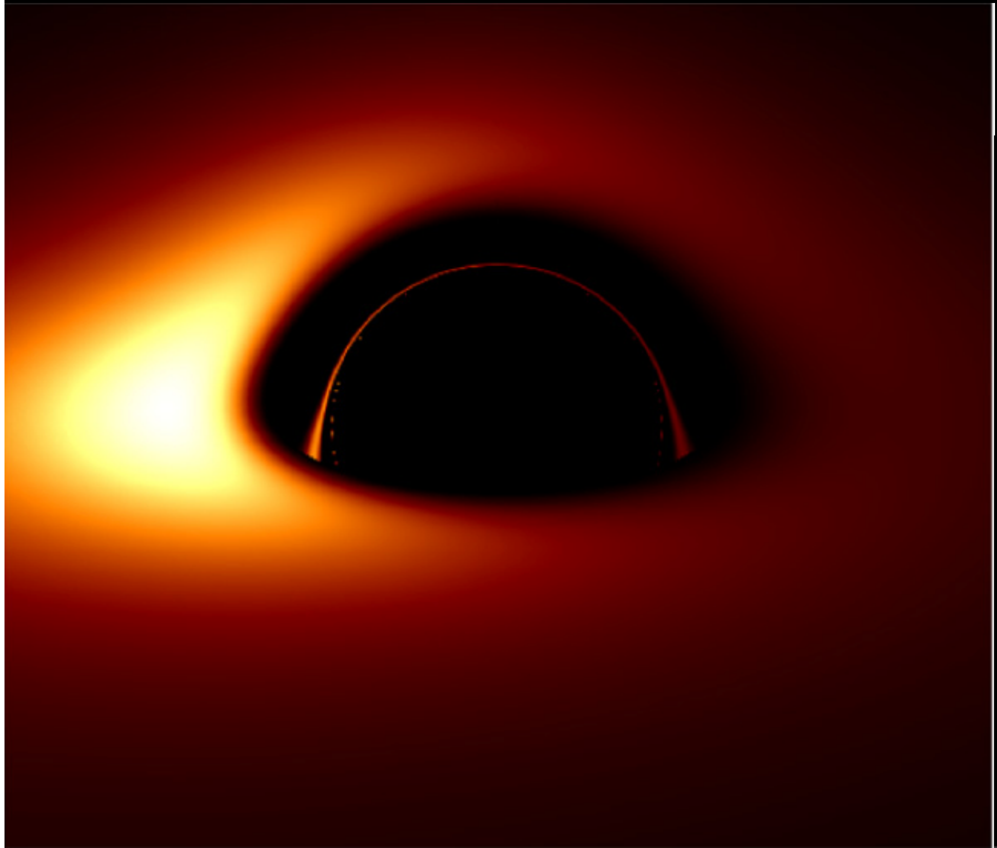
(J.-A. Marck, 1996)

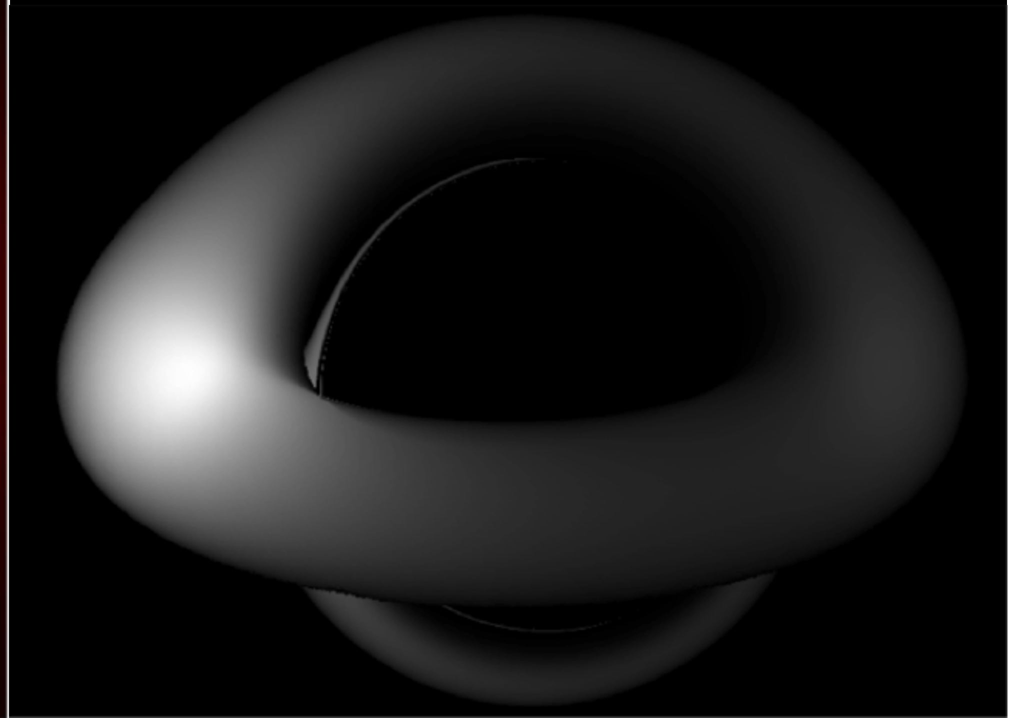
Spherical black hole with thin accretion disk

(Vincent et al., 2011)

Kerr (rotating) black hole with accretion torus

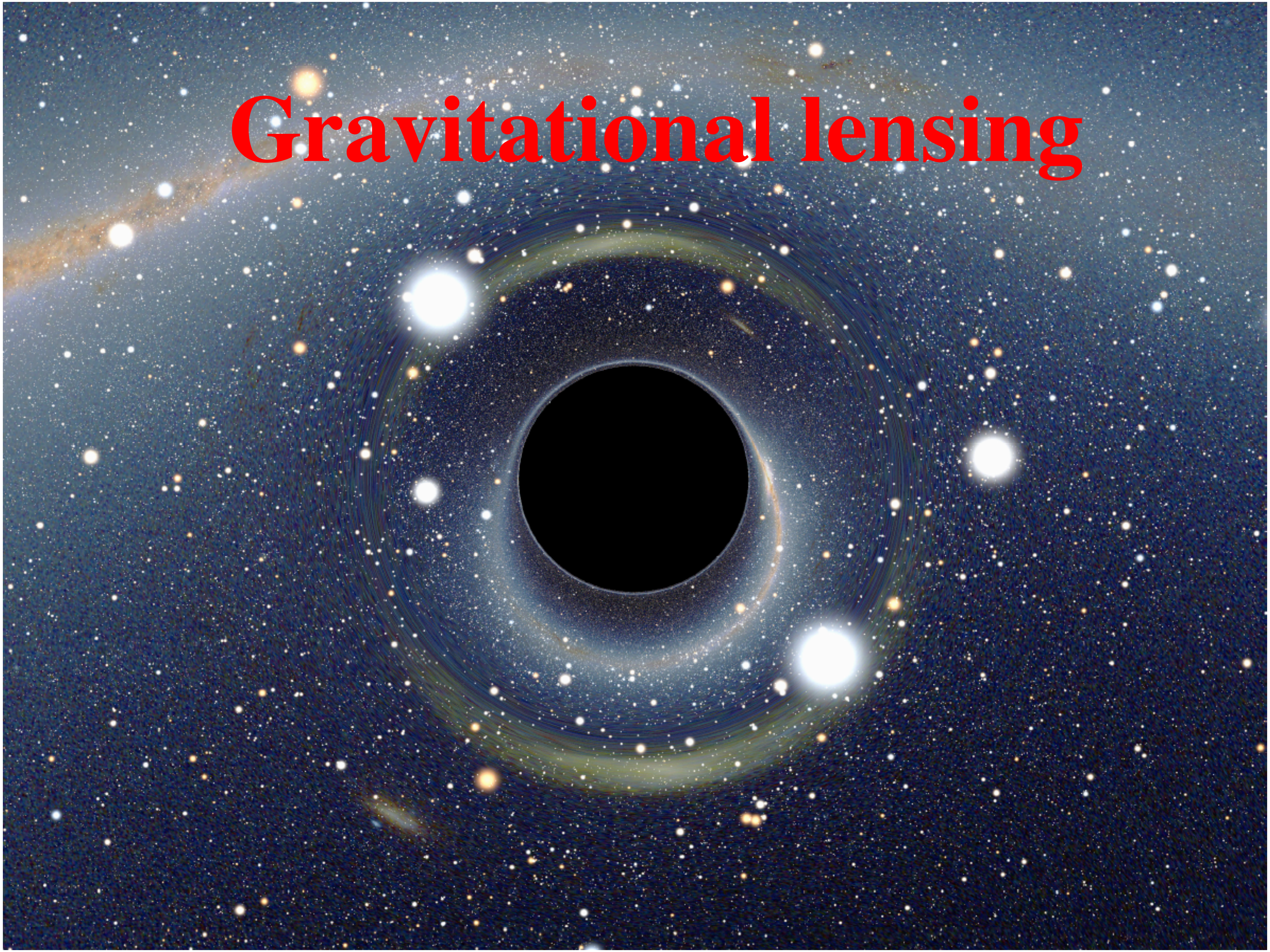
(Vincent et al., 2011)

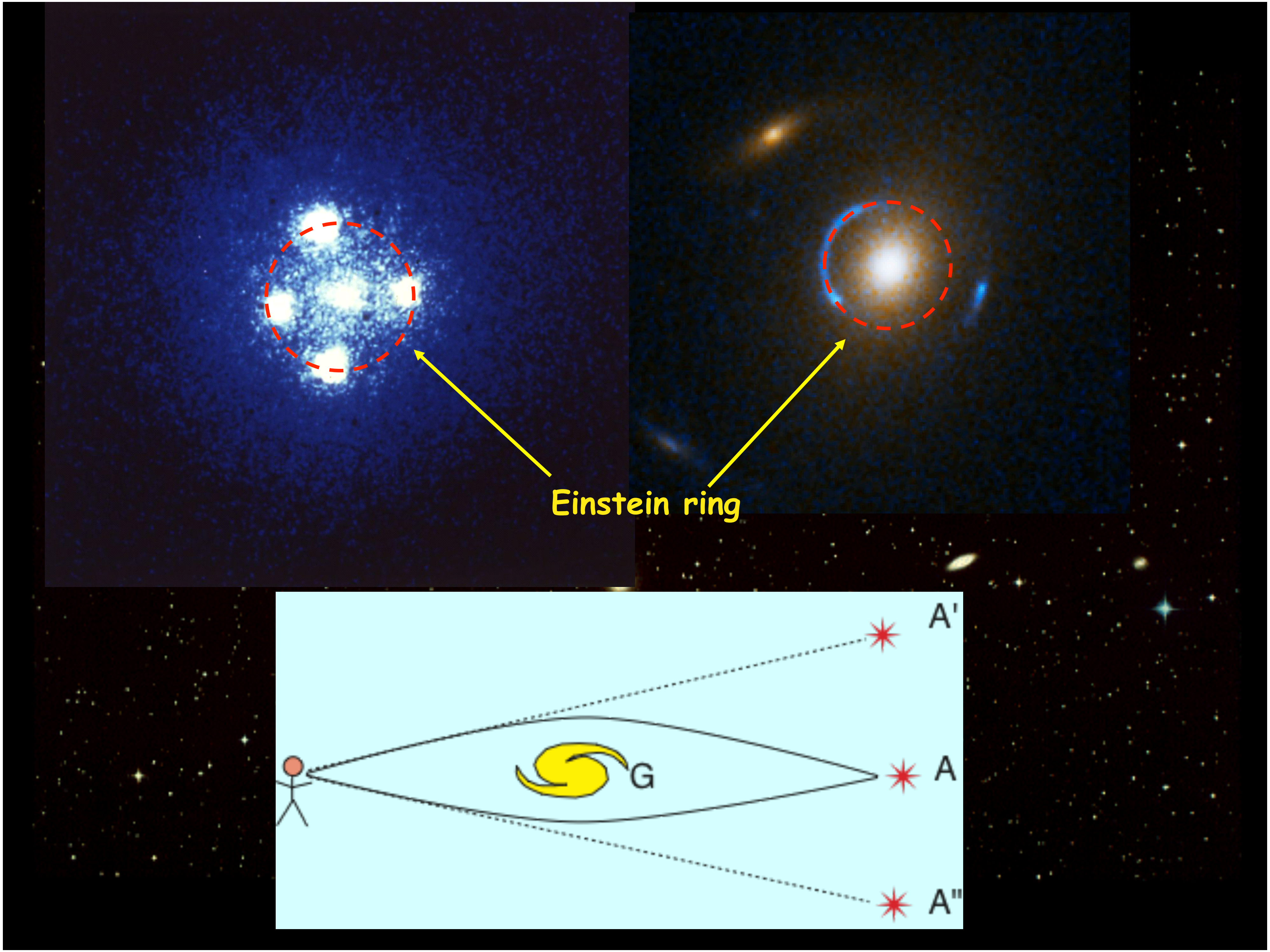




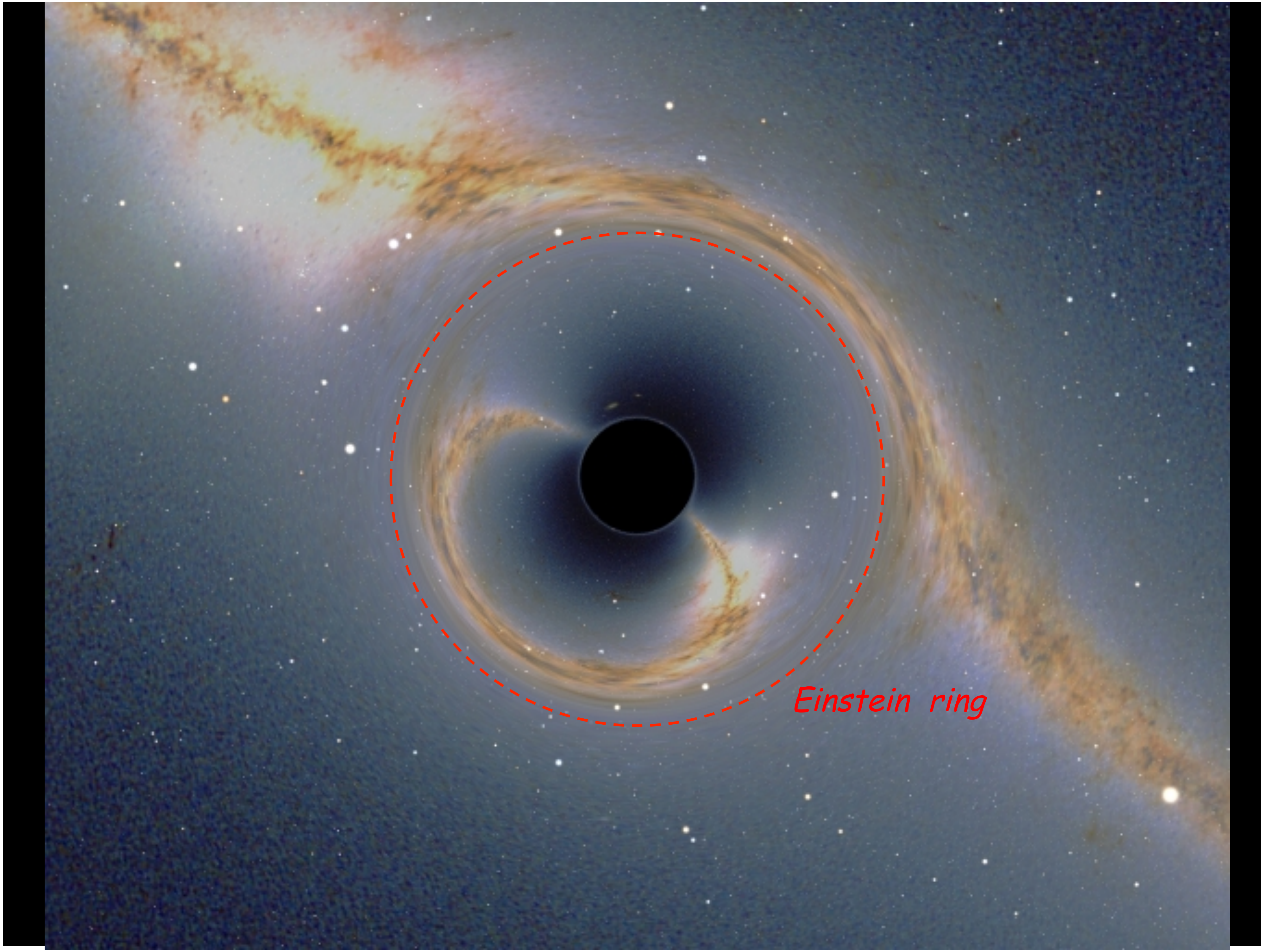
General relativit**Y** **O**rbit **T**racer of Paris **O**bservatory (**GYOTO**)

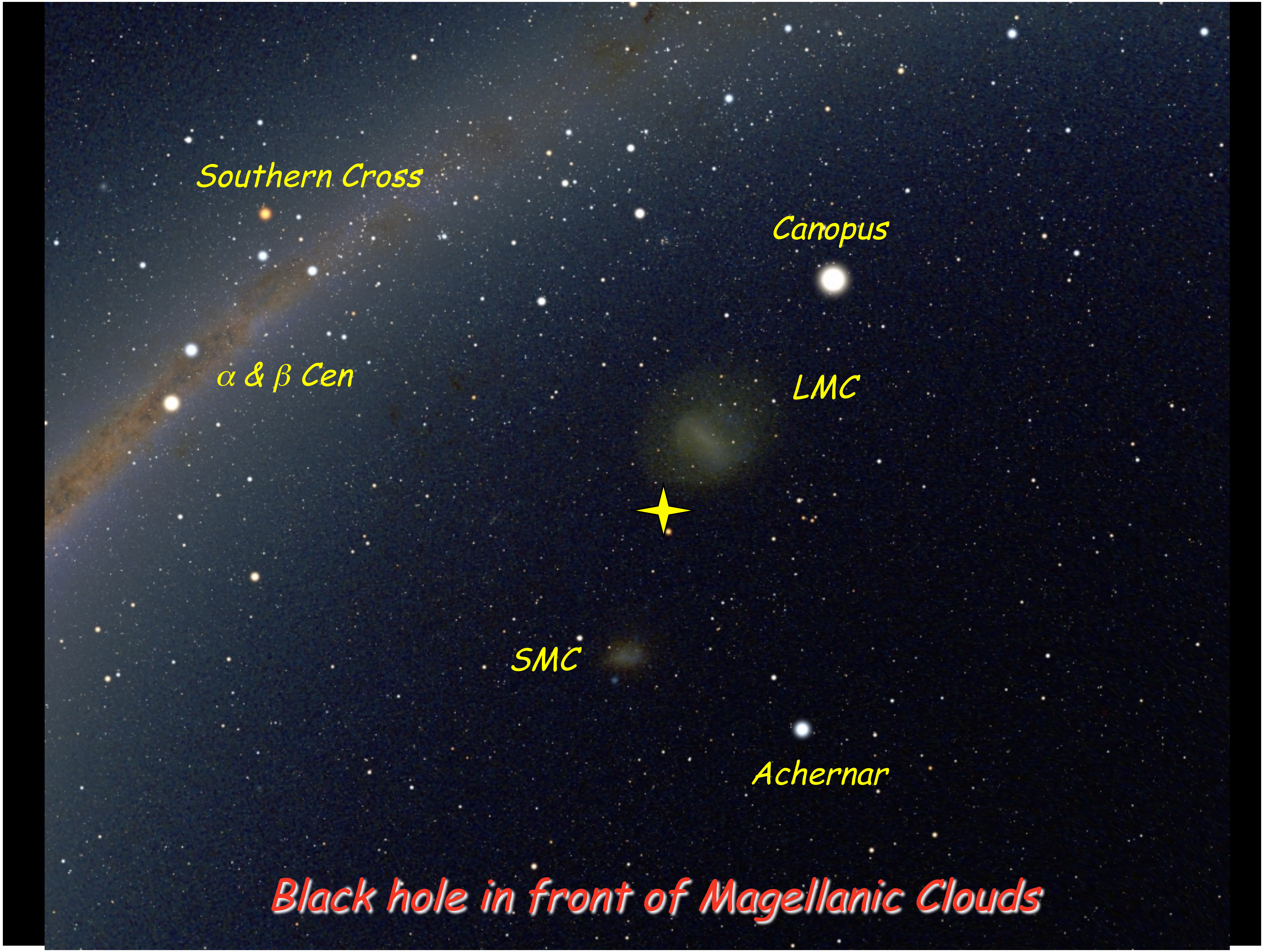
Gravitational lensing

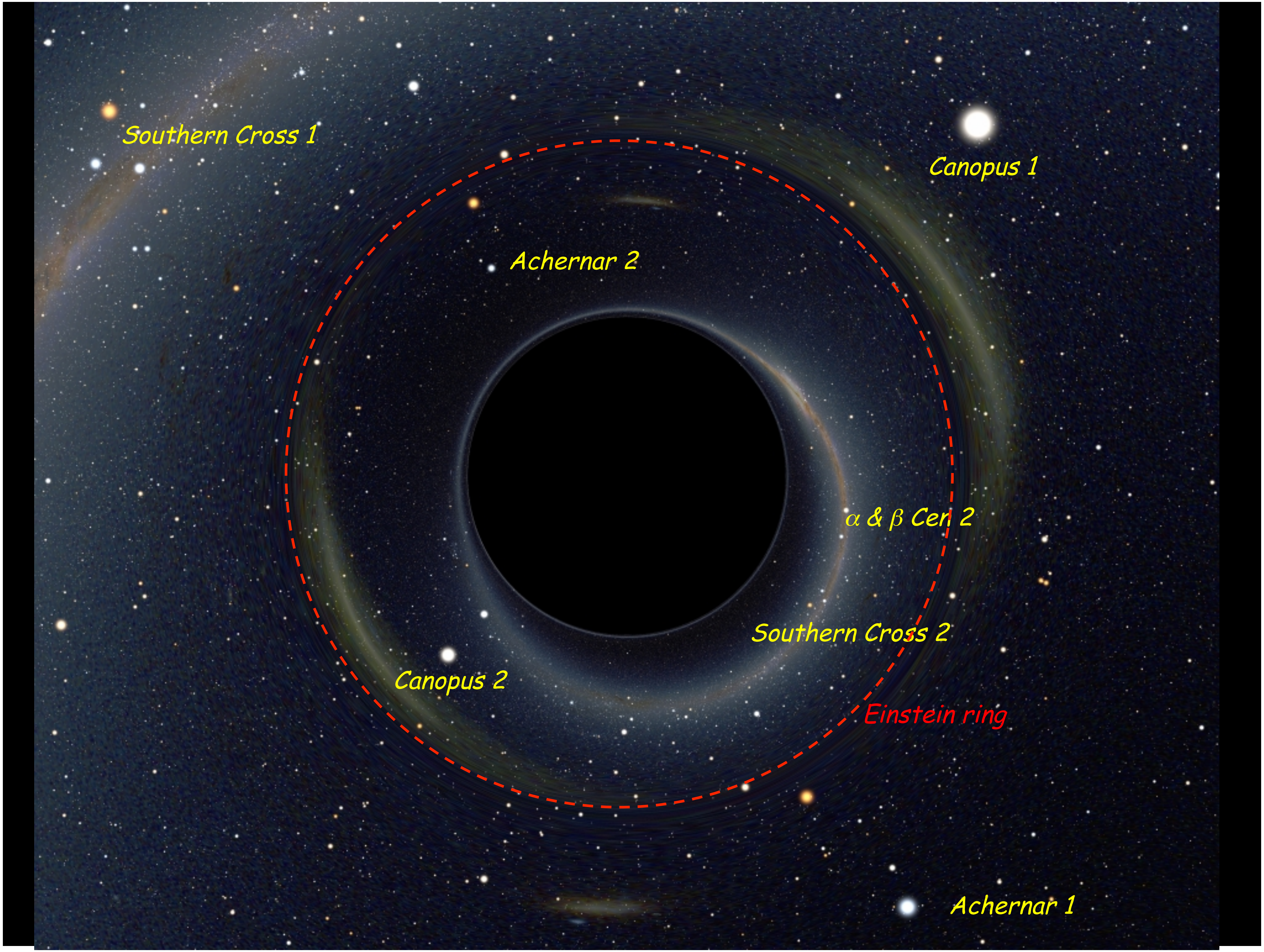


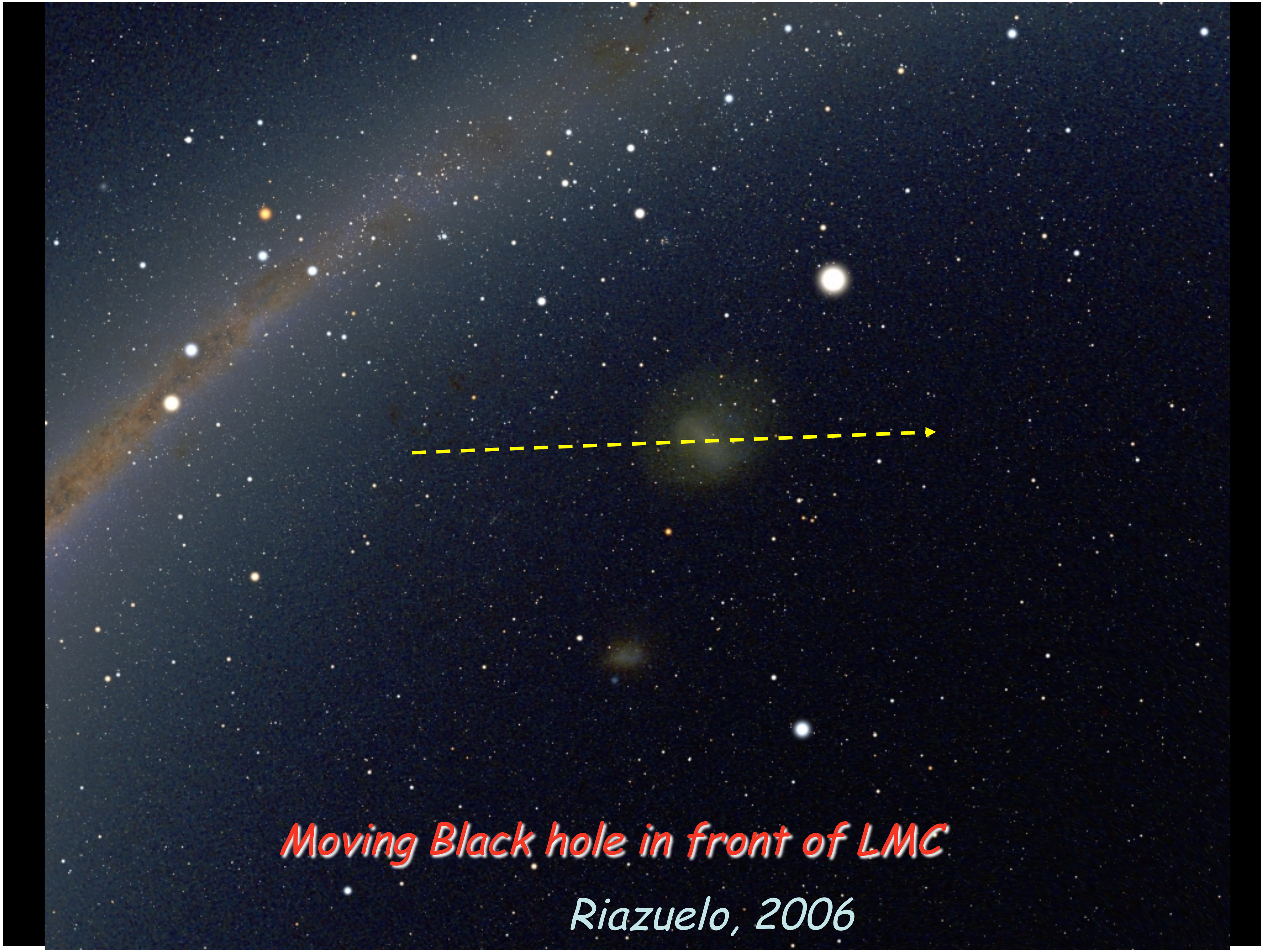

Einstein ring
A'
G
A
A"

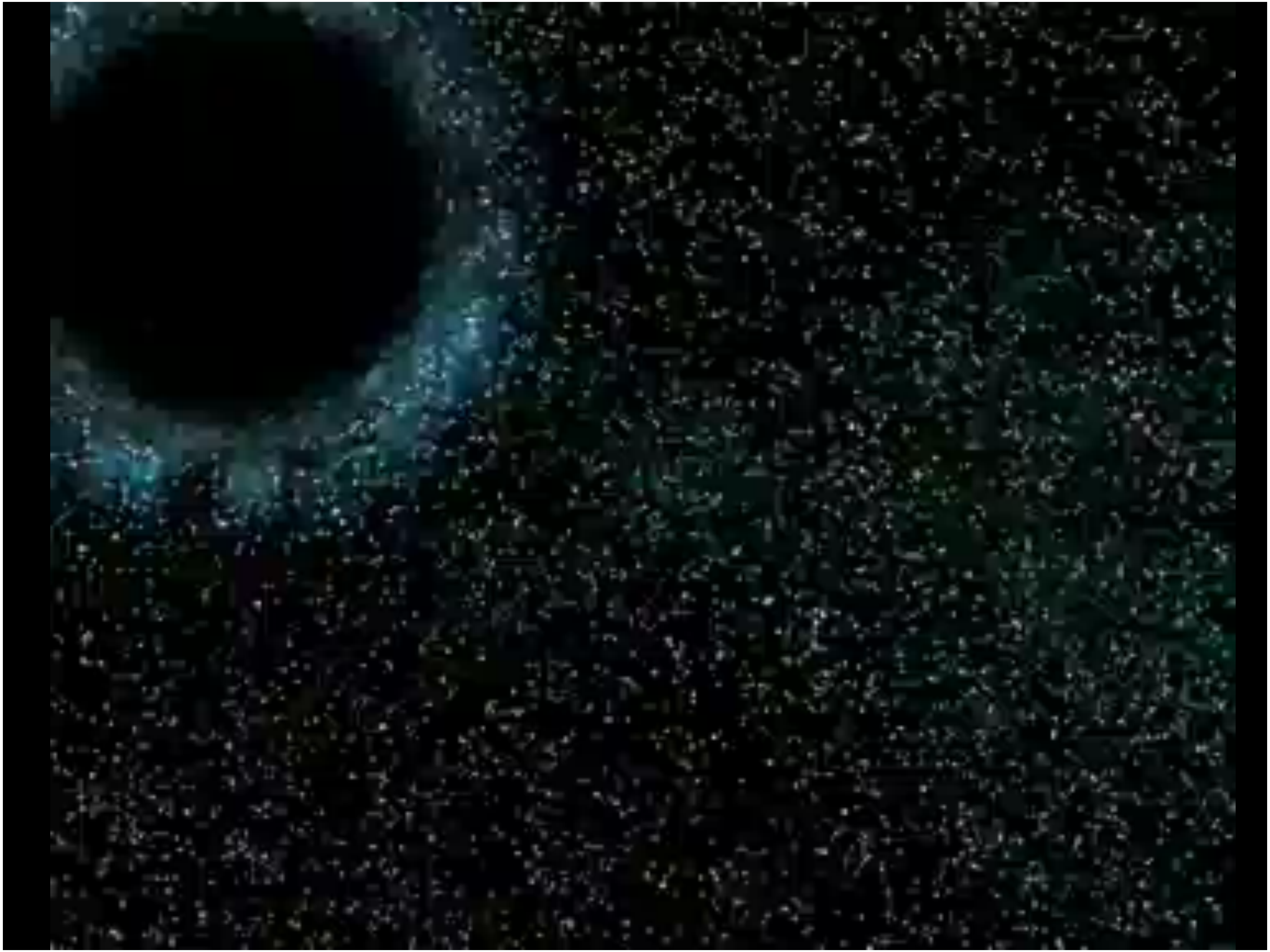

Black hole in front of Milky Way
Riazuelo, 2006

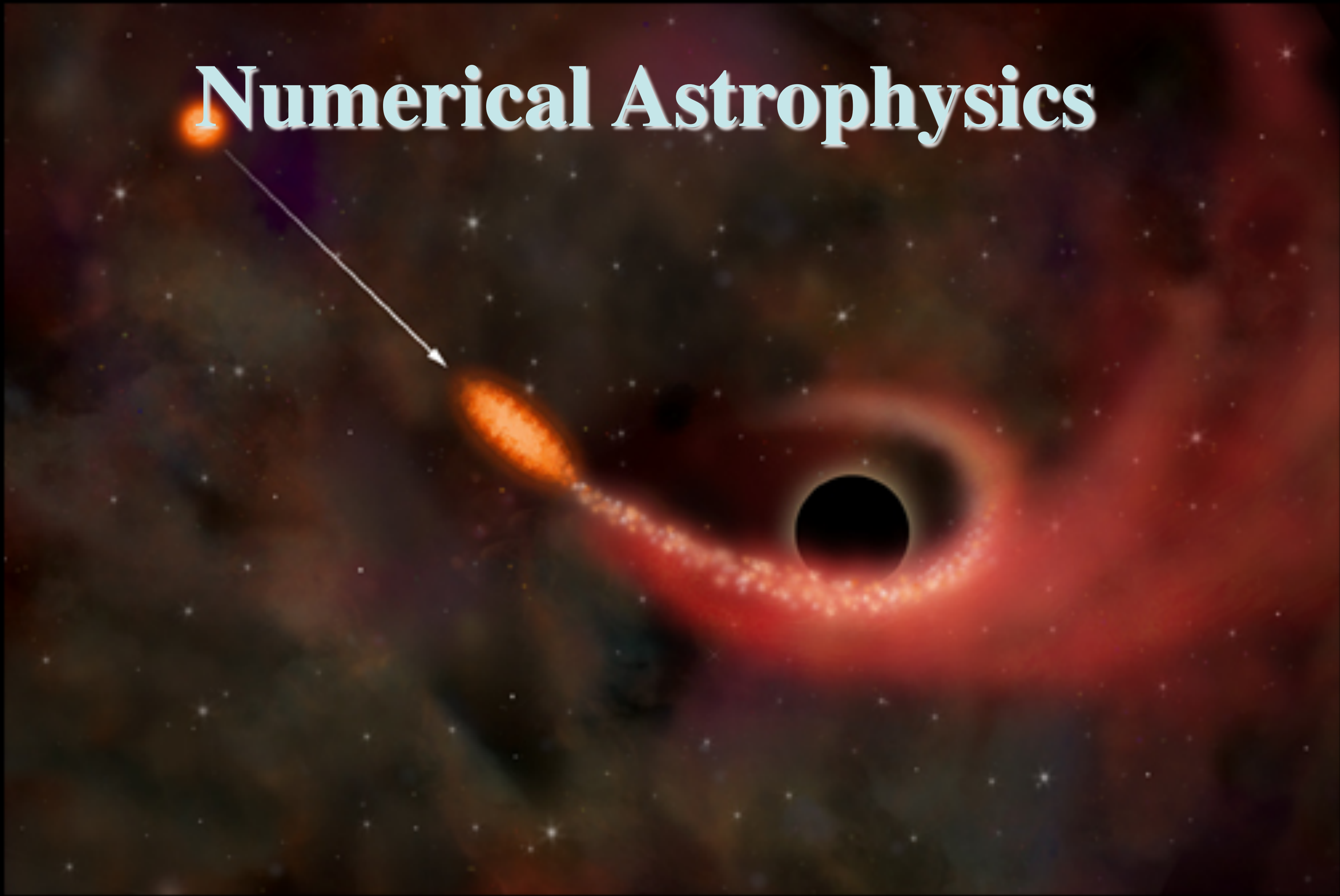

Einstein ring


Southern Cross
Canopus
α & β Cen
LMC
SMC
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

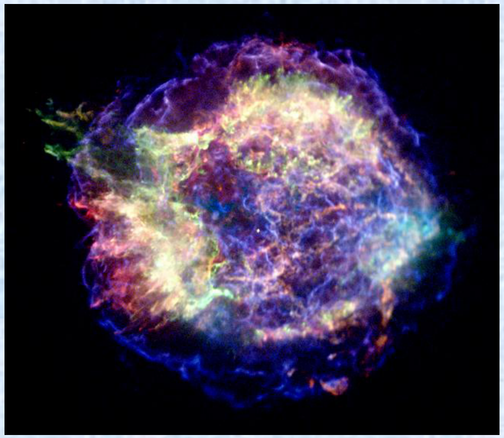

Moving Black hole in front of LMC
Riazuelo, 2006




Numerical Astrophysics

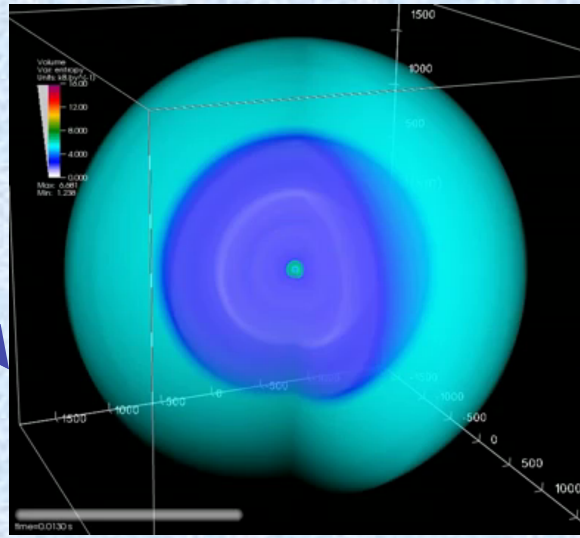
Numerical Astrophysics (1)

Simulations of type II supernova explosions



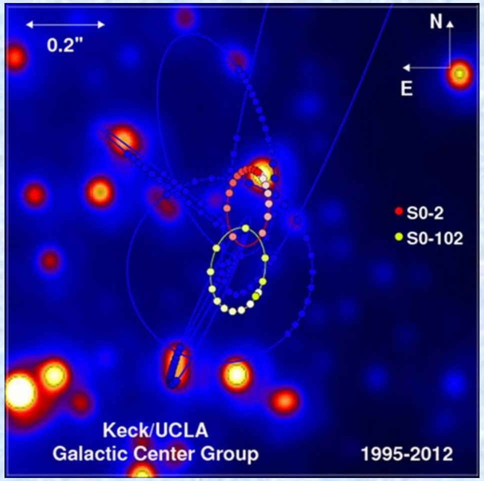
• Supernova equations don't explode!

• Supercomputers + 3D neutrino physics + shock waves + magnetic fields + …

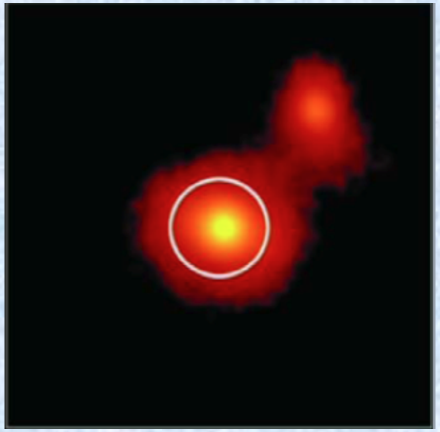


Marek & Janka 2009

Numerical Astrophysics (2)



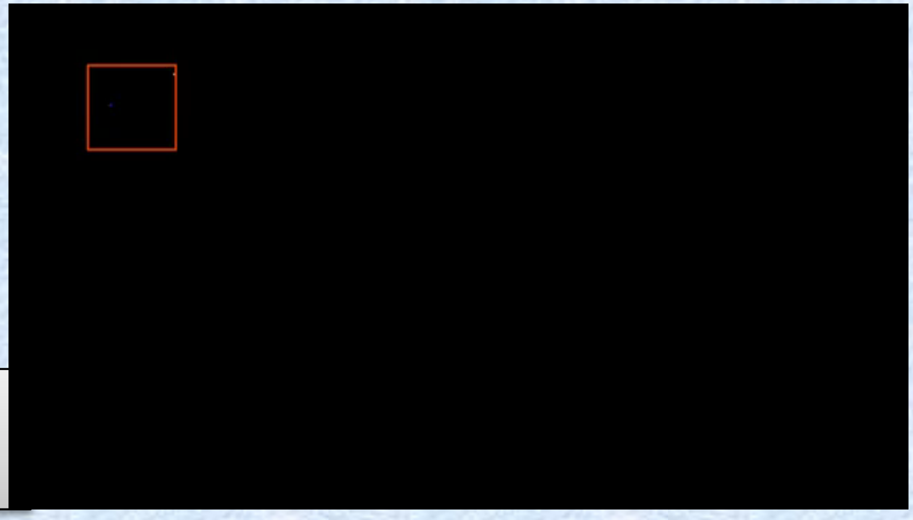
Tidal destruction of stars by giant black holes



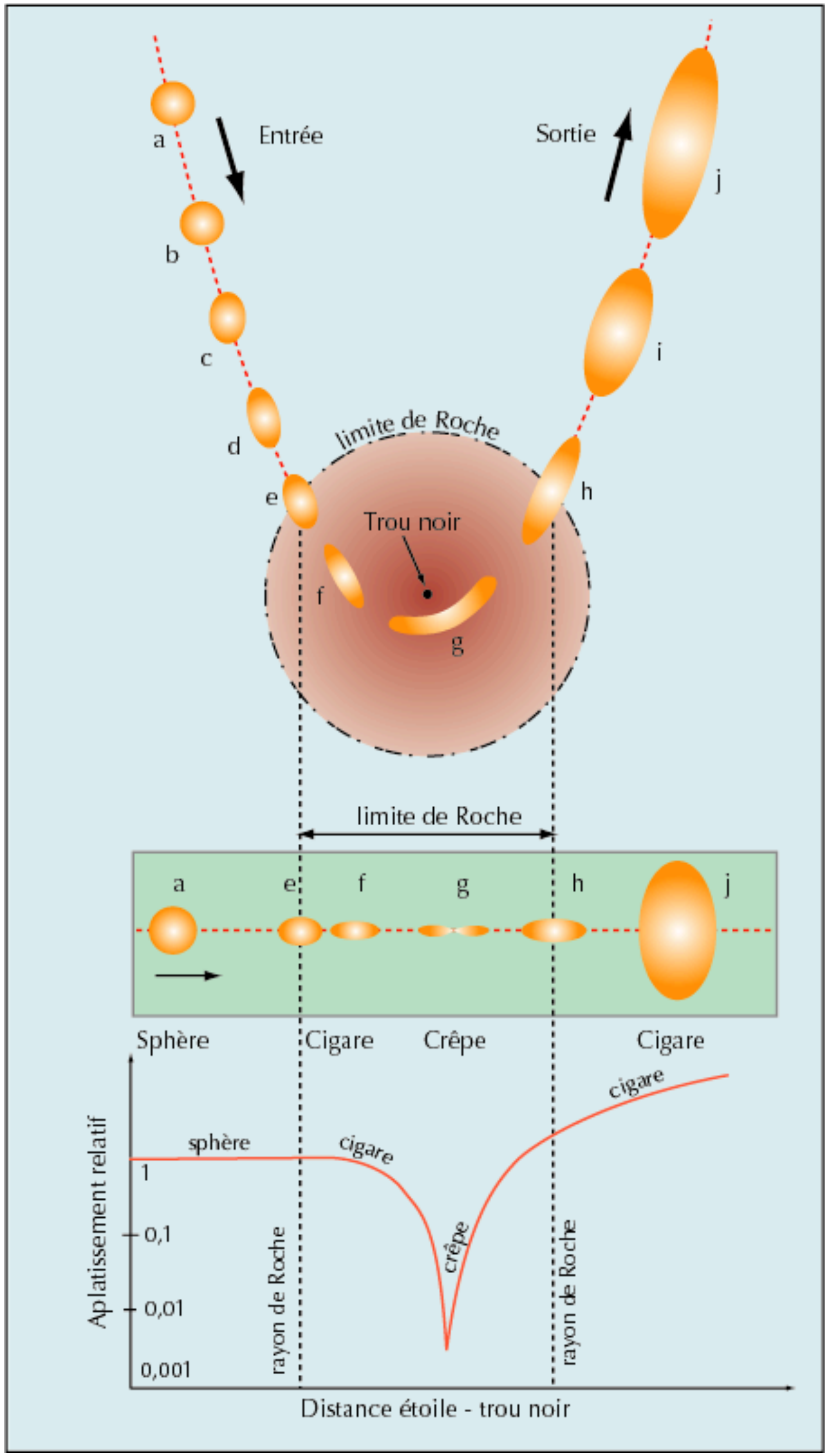
Luminet *et al.*

- 1982-1990 : First simulations and predictions

- 1995- today: Detection of X-UV flares from galactic nuclei …



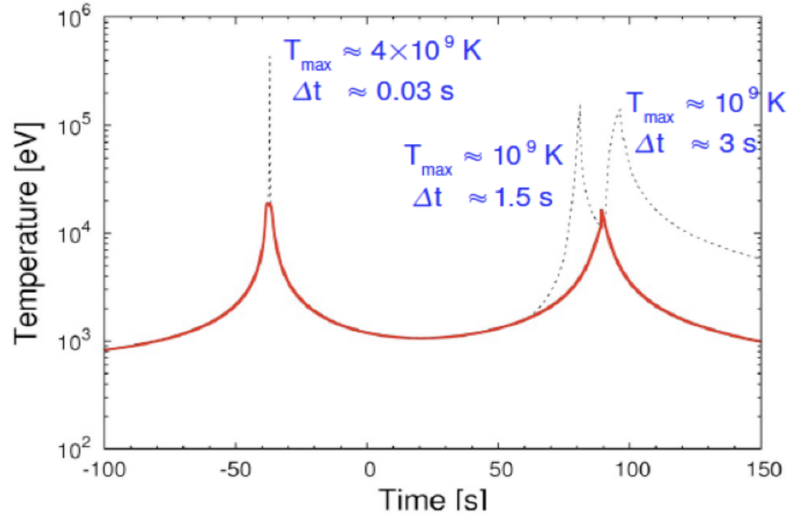
Guillochon 2012



Flambeed stellar pancakes

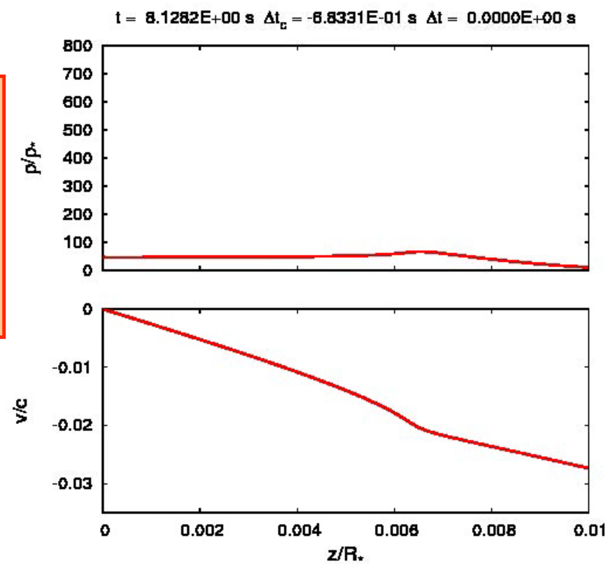
(Carter & Luminet, *Nature* 1982)

(Brassart & Luminet, 2010)

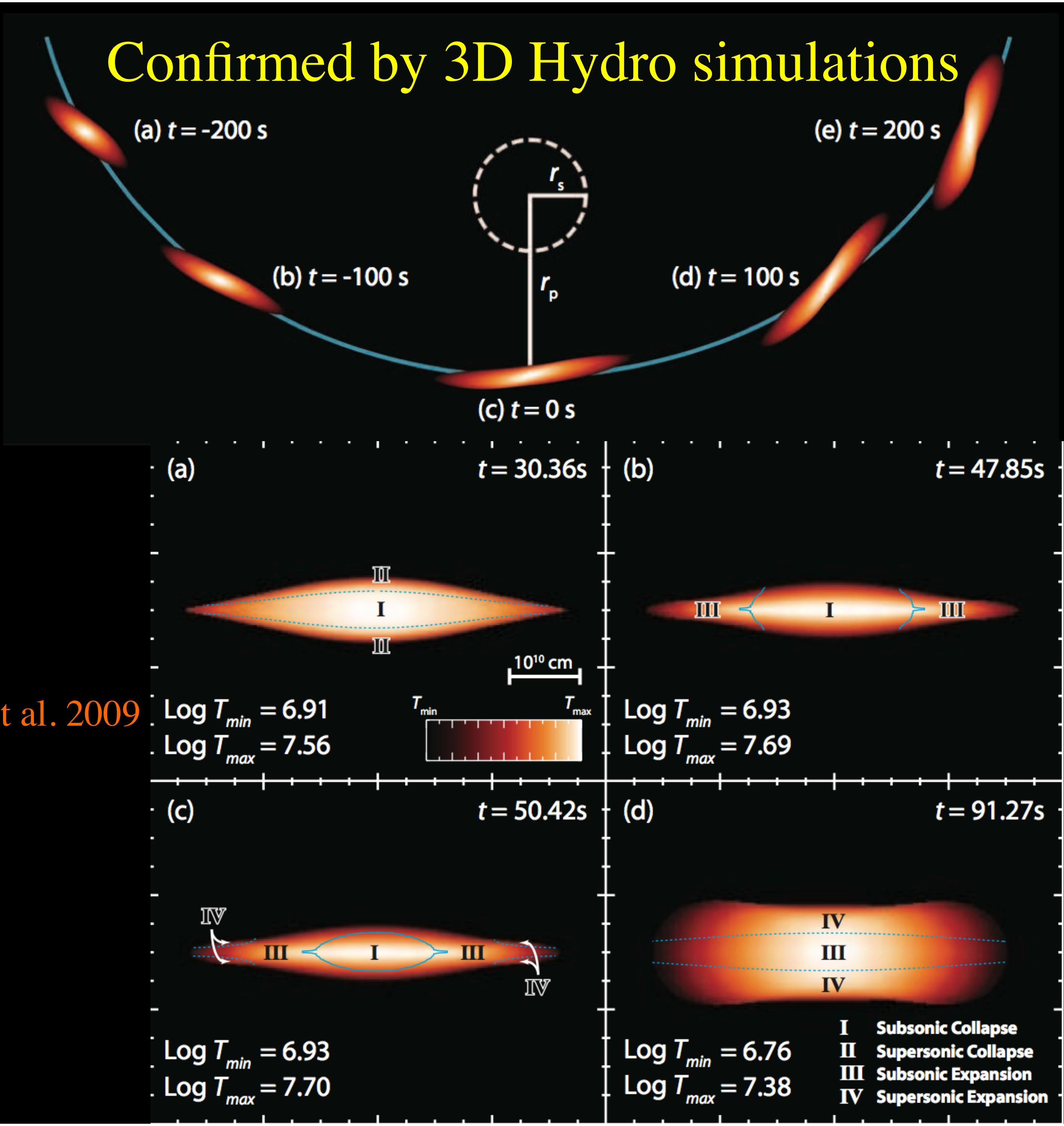


Hydro + shock waves + Nuclear network +eq. of state

Tidally induced supernovae?



Confirmed by 3D Hydro simulations



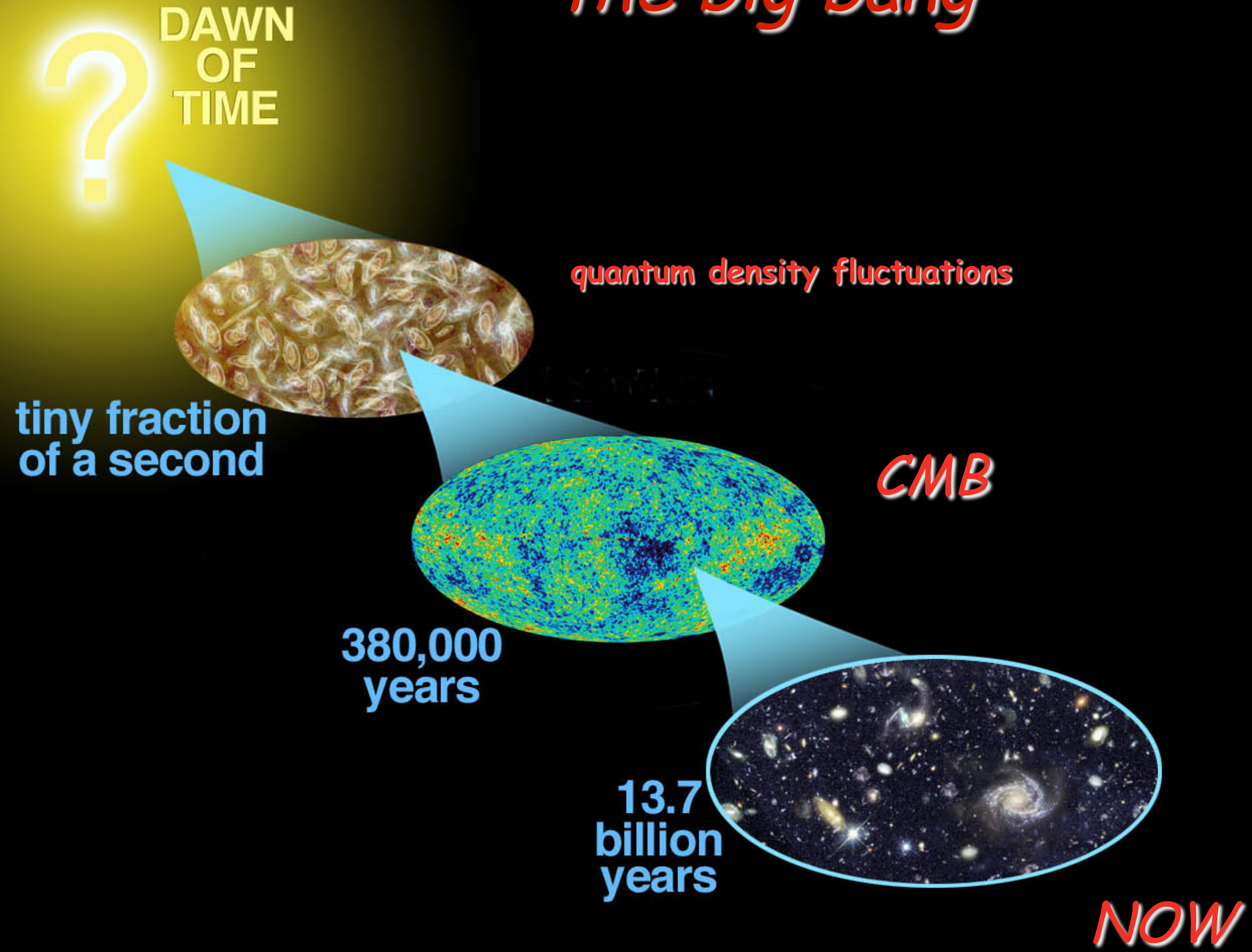
Guillochon et al. 2009

Numerical Cosmology

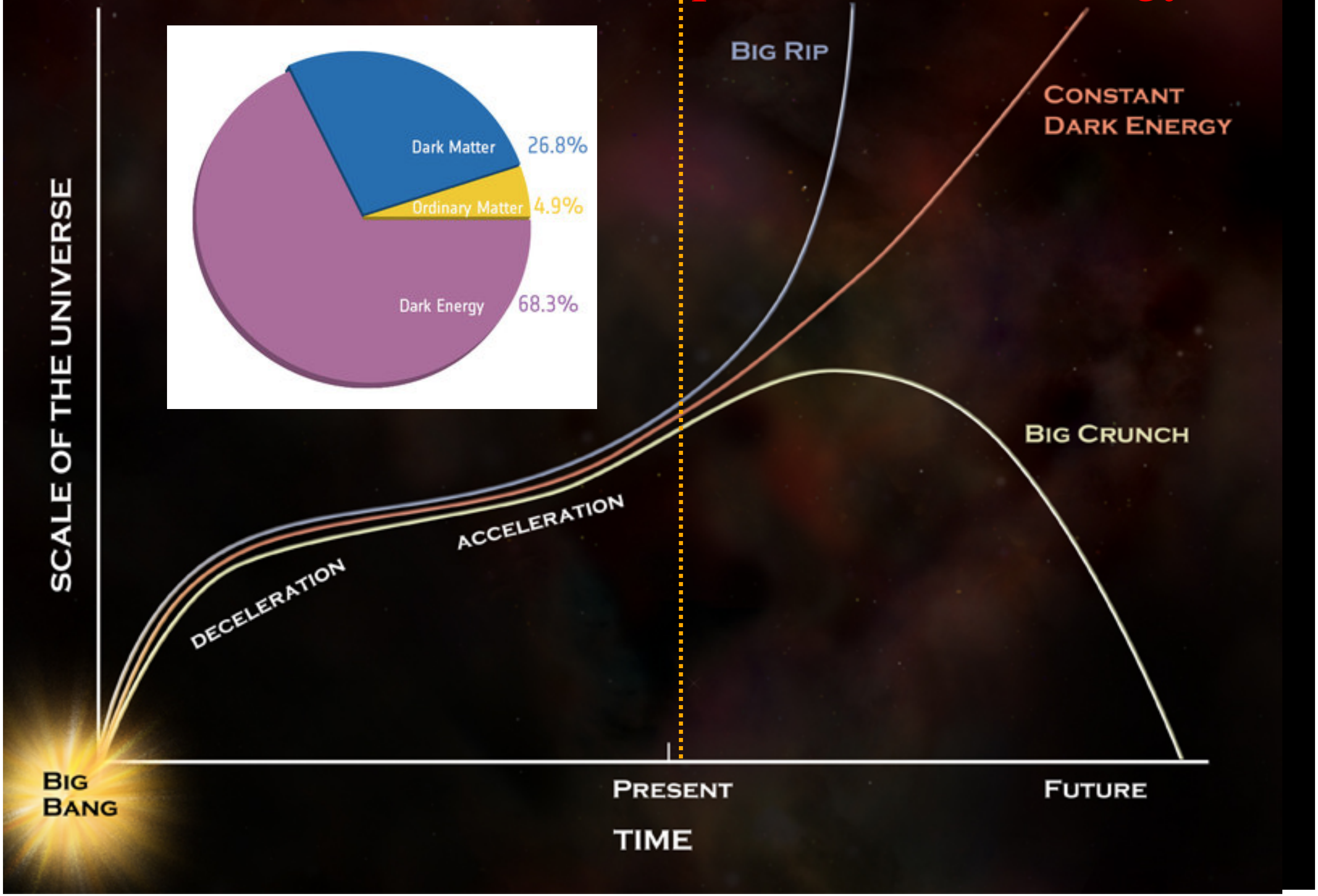
- Dark Energy and Formation of Structures

- Cosmic Topology

Standard model of the big bang



Fate of the universe ? Depends on dark energy !



How to discriminate the many models of Dark Energy ?

ΛCDM	WCDM	RPCDM	Etc.
Cosmological Constant	Phantom Model	Quintessence Model	

PROBLEM : The corresponding cosmological models cannot be distinguished with present data (SN, CMB, etc.)…

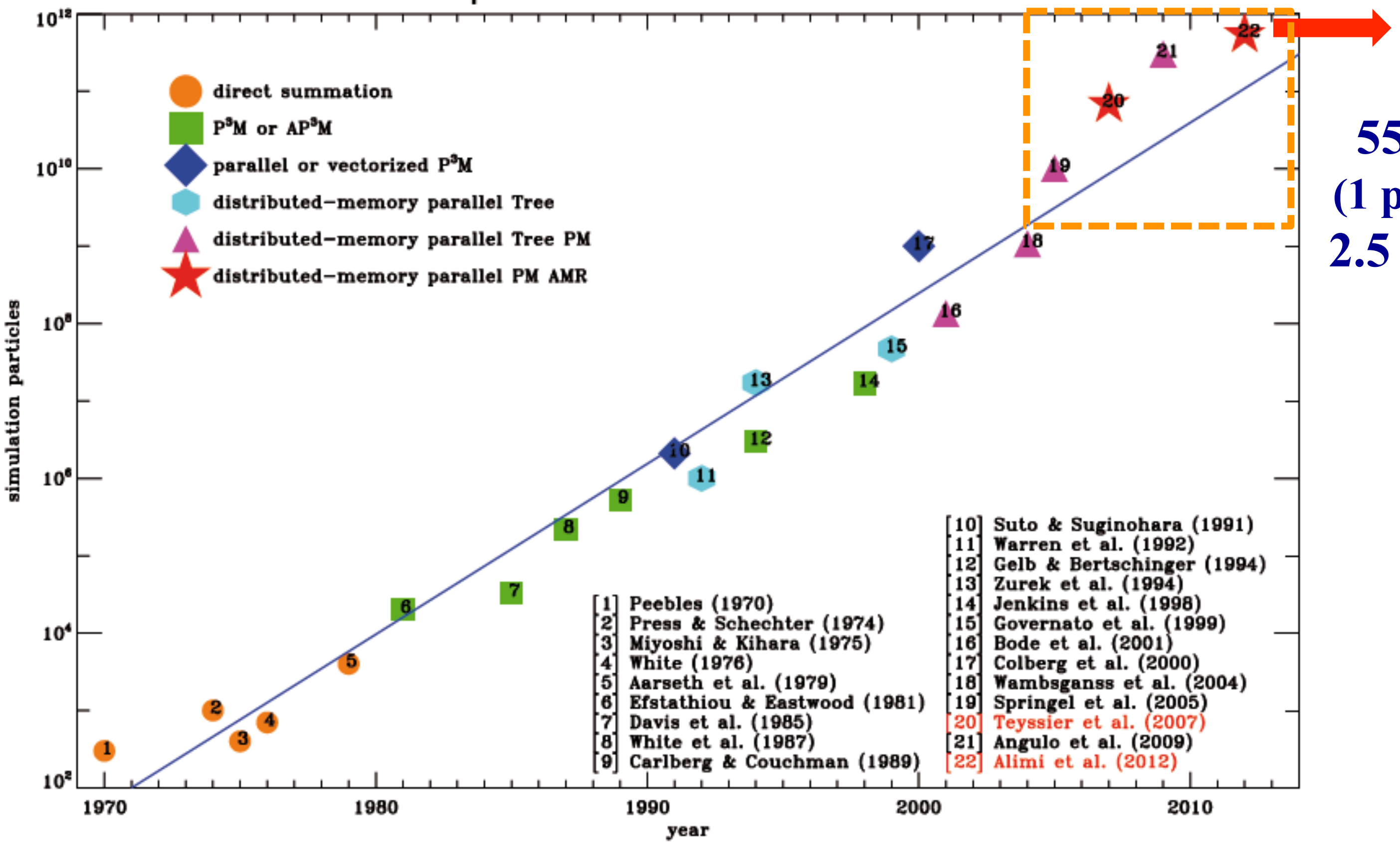
BUT : Dark Energy has an influence on the formation of large scale structures

Dark Energy Universe Simulation

DEUS Consortium

Cosmological N body simulations

Euclid resolution: particle mass = 0.1 billion solar masses



DEUS Consortium

550 billion particles (1 particle = Milky Way) 2.5 trillion computing points

The average evolution of the size of cosmological N-body simulations, starting from 2005, is FASTER than a « Moore law » : size increases by a factor 10 every 4.55 years (instead of a factor 2 every 18 months) !

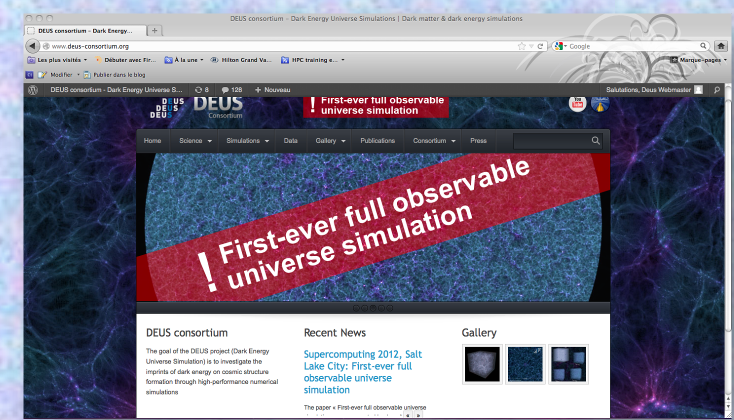
The world-greatest set of cosmological N-body simulations (N = 550 billion)

- able to follow the formation of structures from the CMB to today
- masses from 10^{11} M_0 to 10^{16} M_0
- across 6 orders of magnitude length scales - from the size of the Milky Way (1 particle) to the volume of the WHOLE observable Universe (95 billion light-years box).
- Simulations for 4 realistic models of dark energy : LCDM, RPCDM, SUCDM, WCDM
- The challenge is to reproduce with unprecedented precision the process of formation of cosmic structures.

> • Uses 80 000 cores on Curie Supercomputer (Prace)
>
> • Each run uses 300 TB of memory for 5 million hours CPU (3 days on Curie) distributed as 1/3 I/O time + 2/3 computation time
>
> • generates 50 PB of data

Consortium DEUS (website: www.deus-consortium.org)

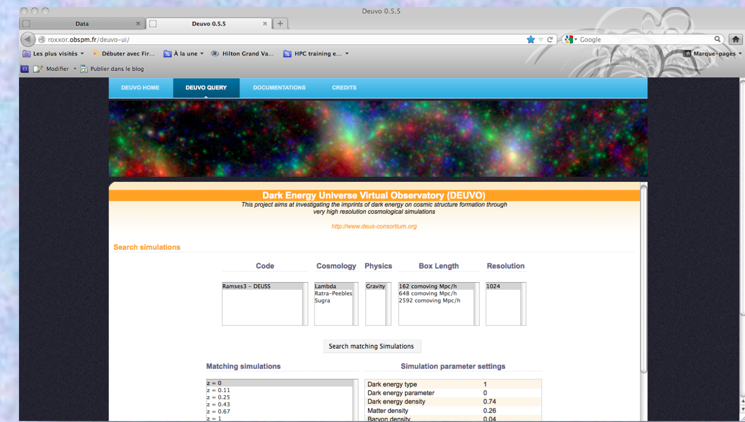
DEUS Consortium



France – Italy – UK – USA – Brazil - Korea

Data base: **DEUVO**

(website: roxxor.obspm.fr/deuvo-ui)

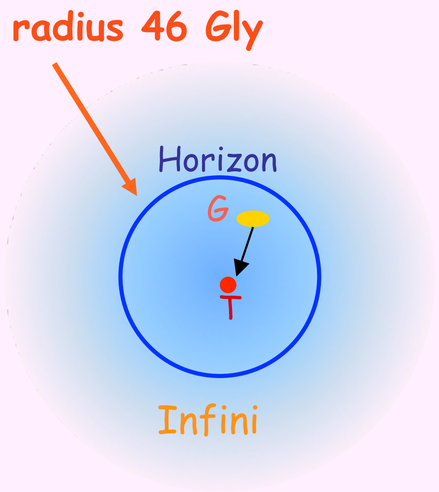


• preparation to data analysis of future large-scale maps of the Universe such as EUCLID (2020), a space mission to map the Dark Universe up to z~ 2 (10 billion years)

• Challenge of the next decade : 100 times more particles (15 days per run on a pre-exascale supercomputer)

Cosmic Topology :

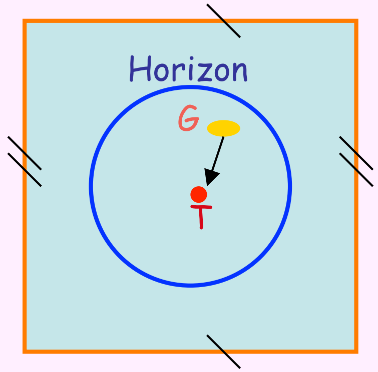
What is the size and shape of space ?



Assumption 1

Not testable

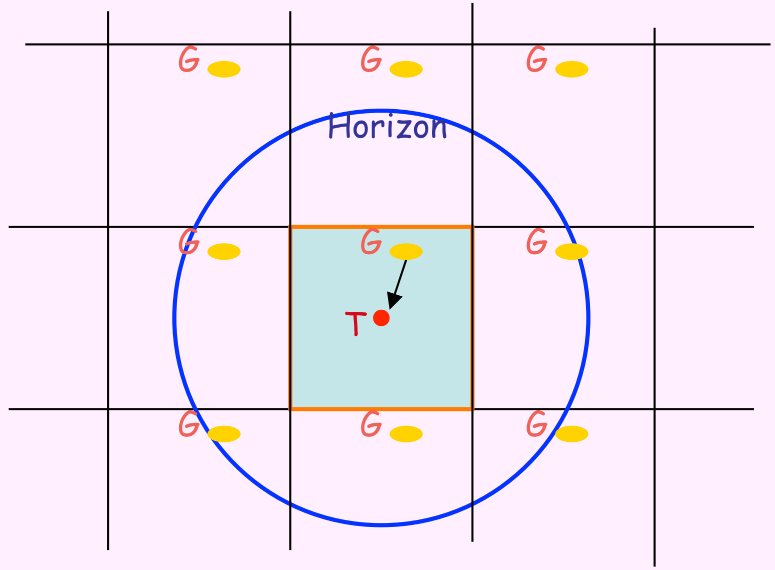
(only $L >> R_h$)



Assumption 2

May be testable

- if $L >\sim R_h$
- if special position

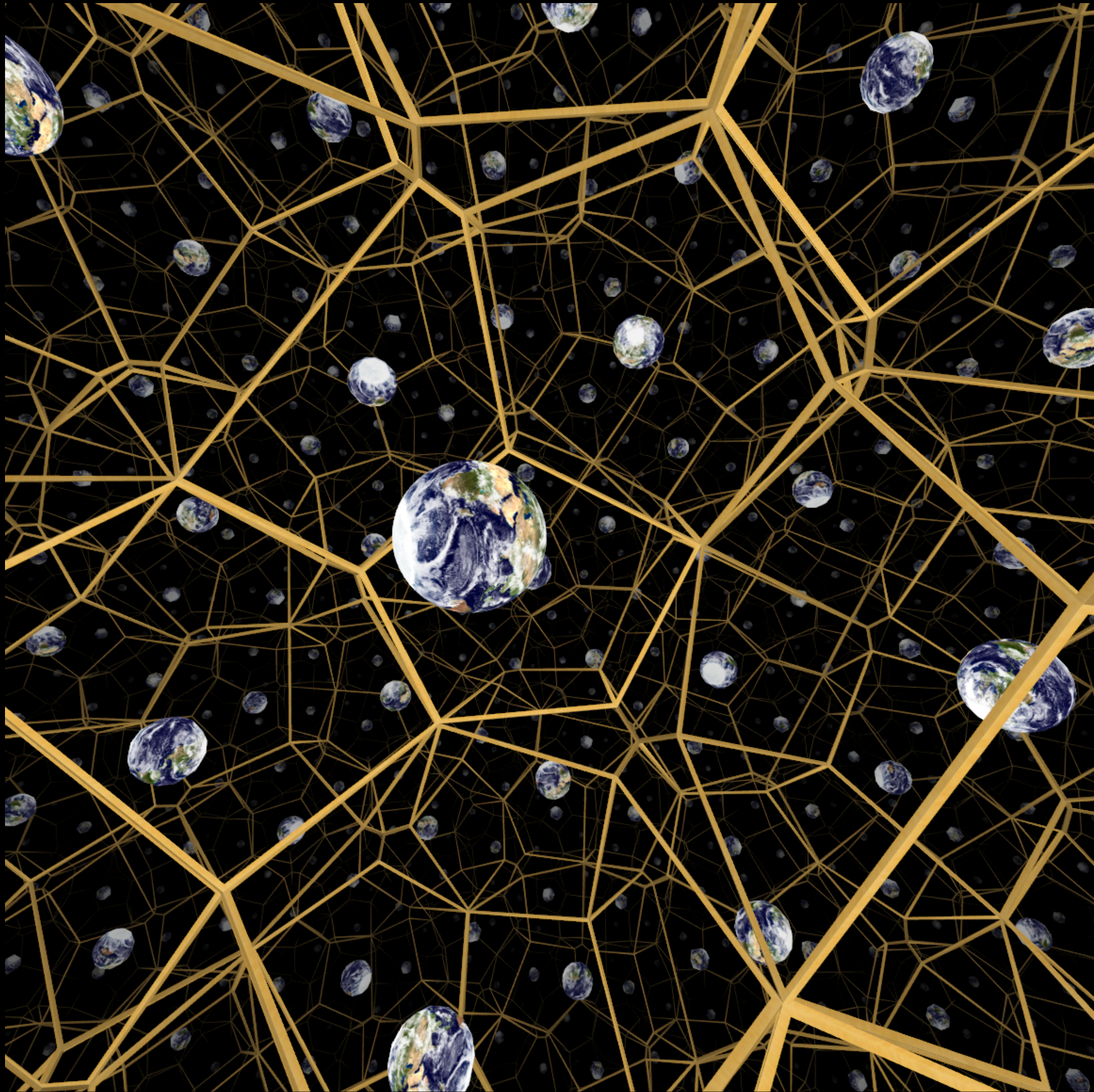


Assumption 3

Testable

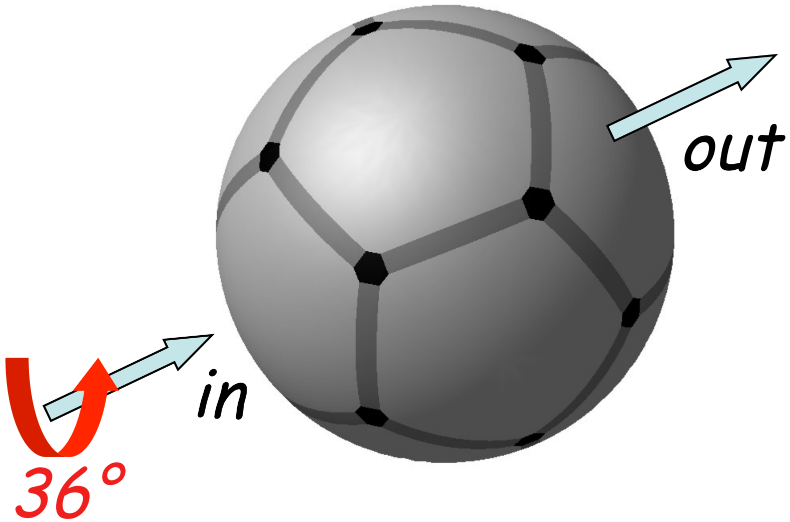
- topological lensing

Curved Spaces Program



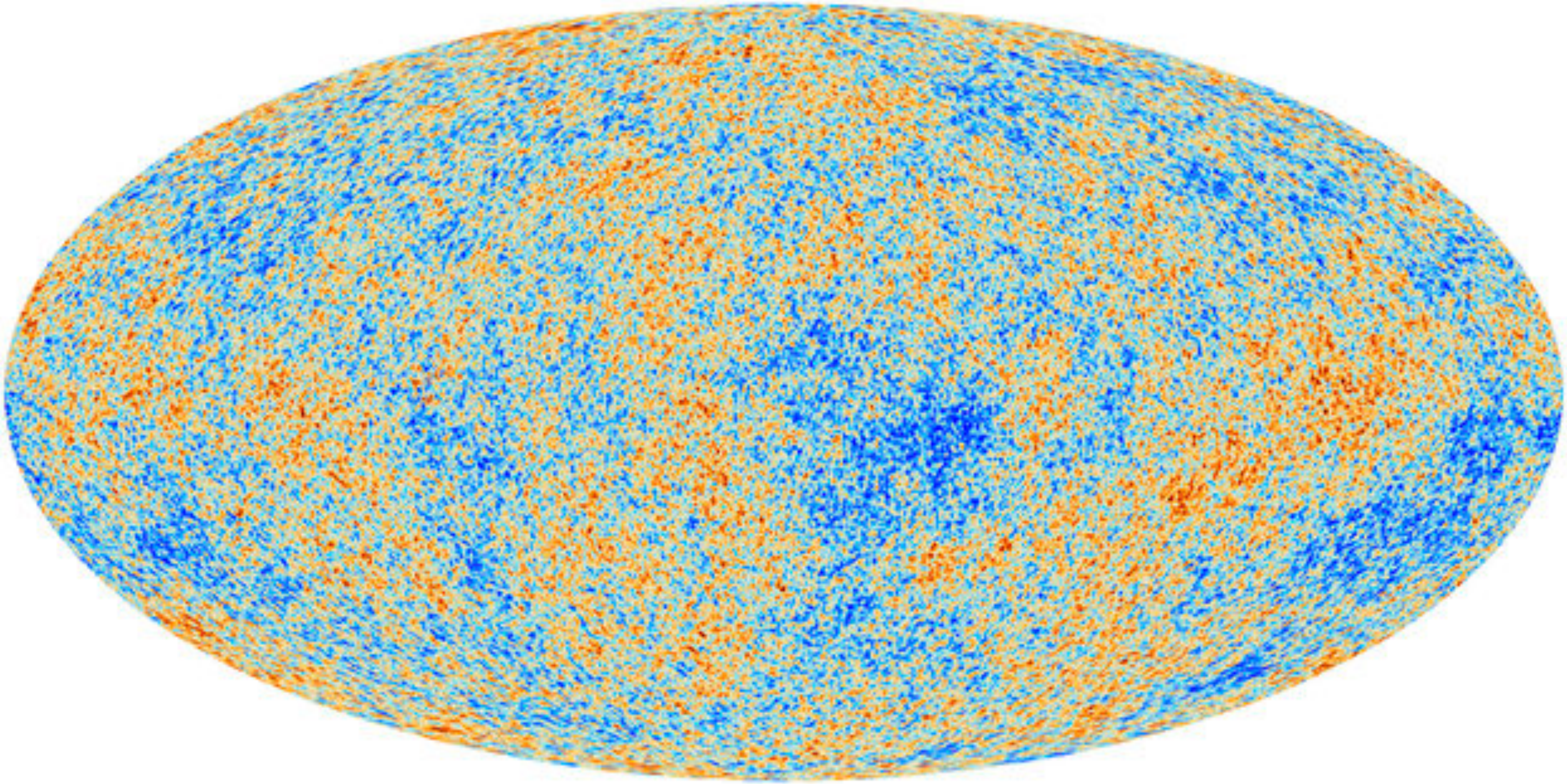
geometrygames.org

Poincaré Dodecahedral Space



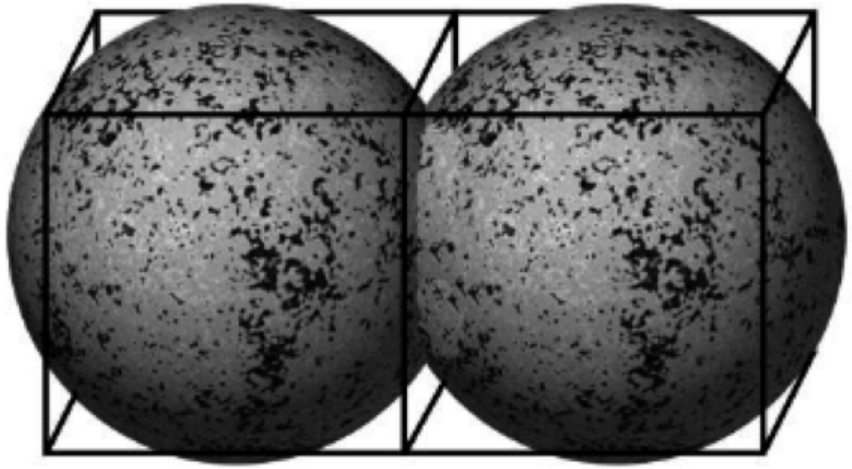
Luminet et al., Nature ***425****, 593 (2003)*

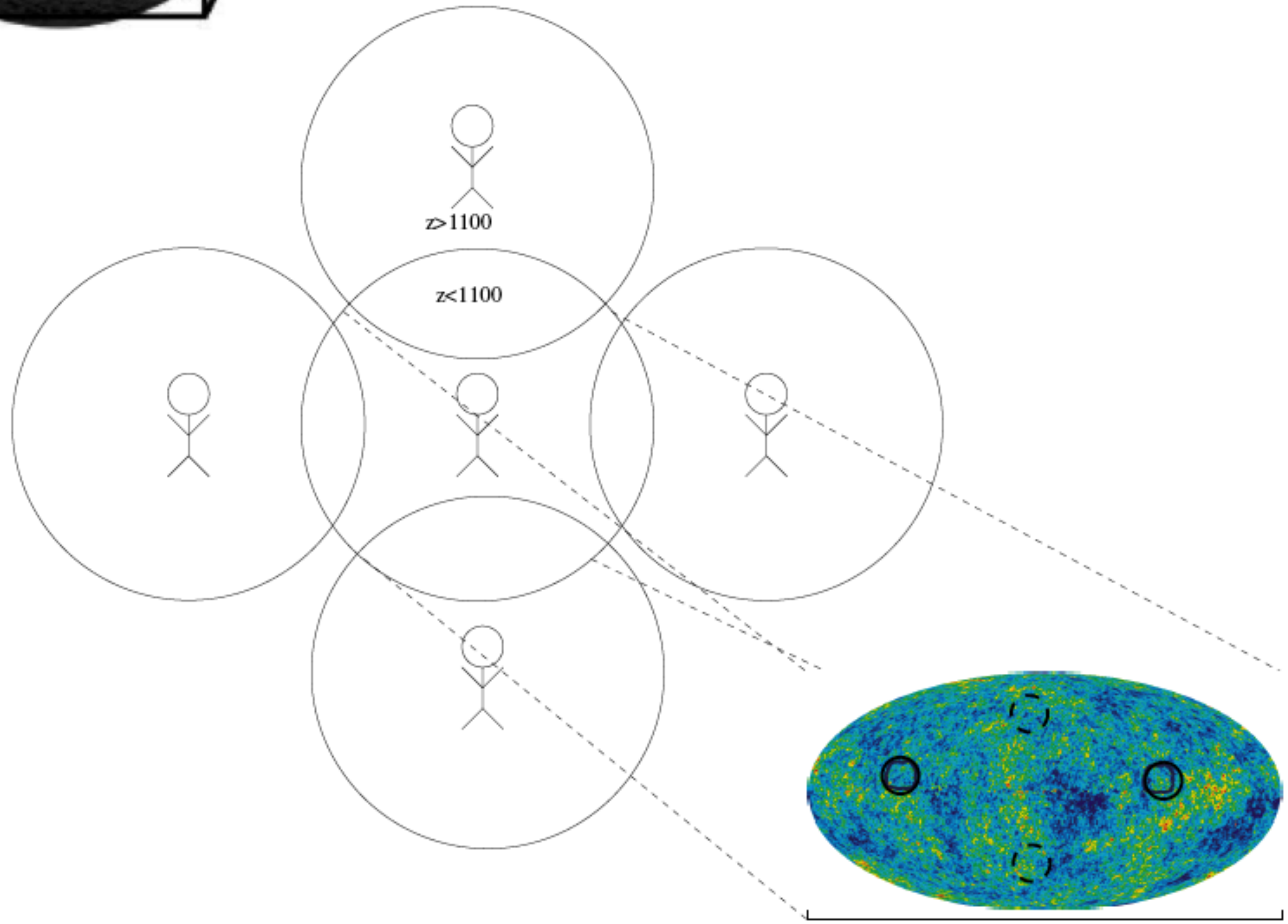
Cosmic Microwave Background

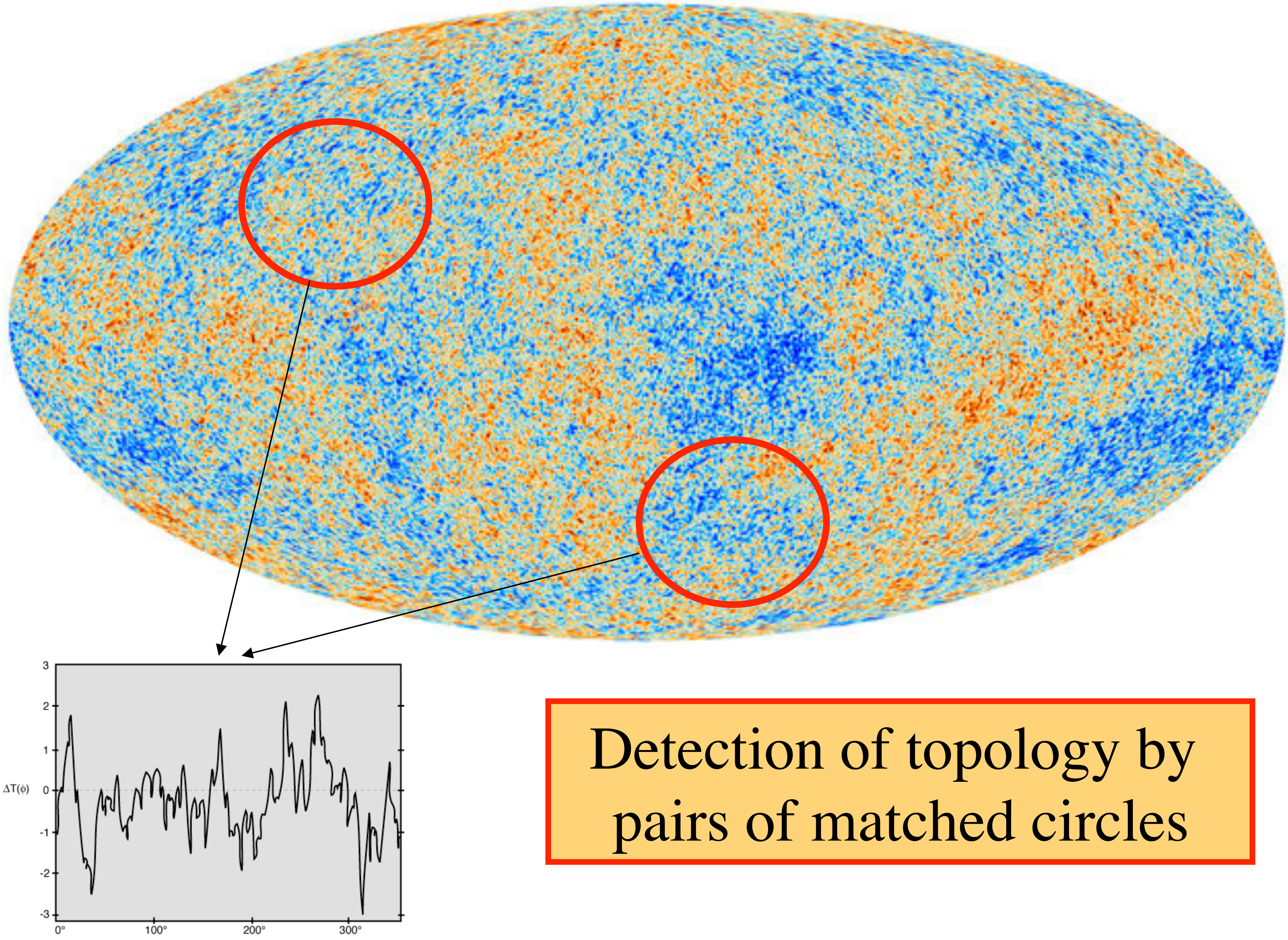


Planck Telescope (2013)

The method of matched circles







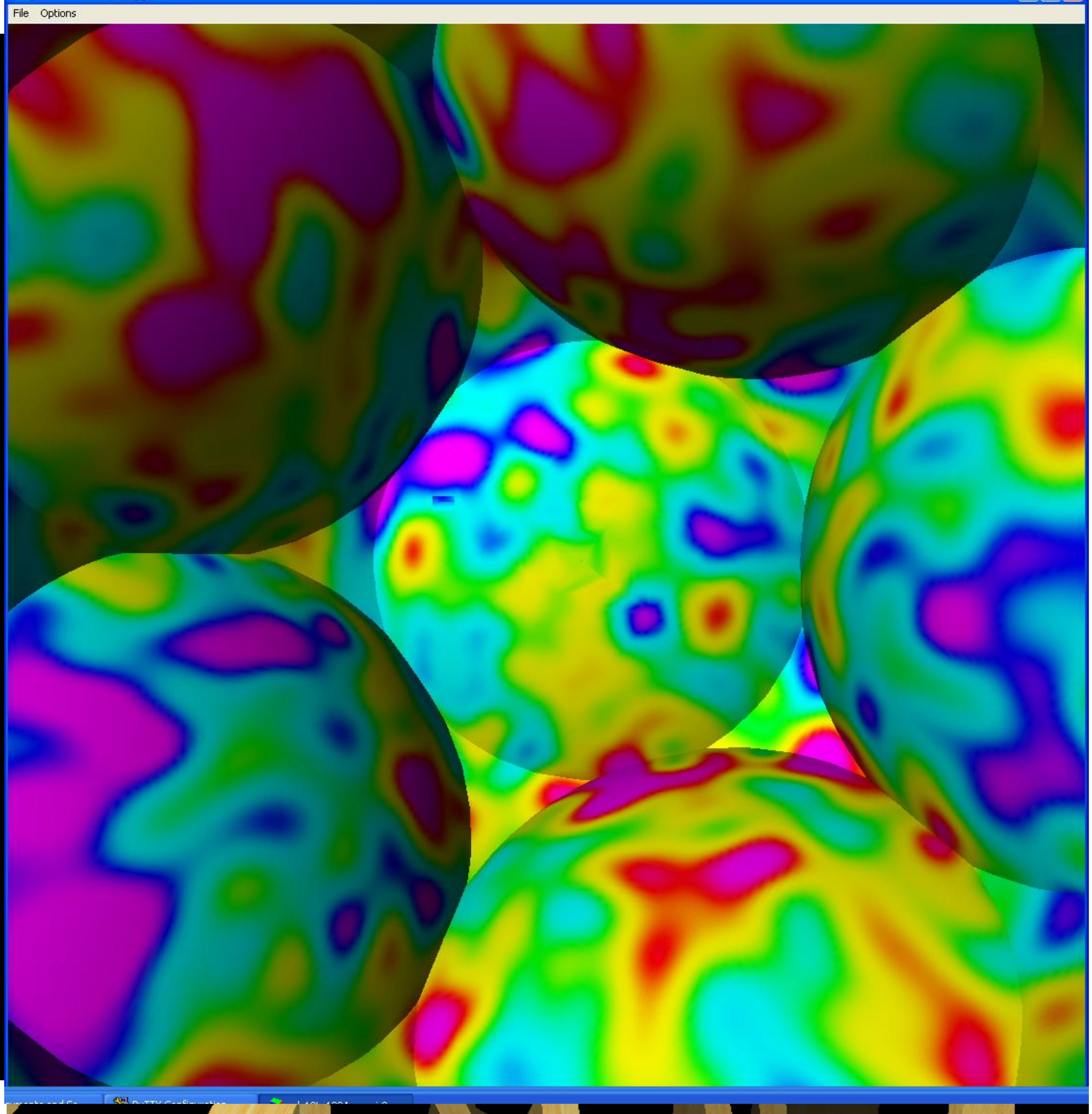
Detection of topology by pairs of matched circles

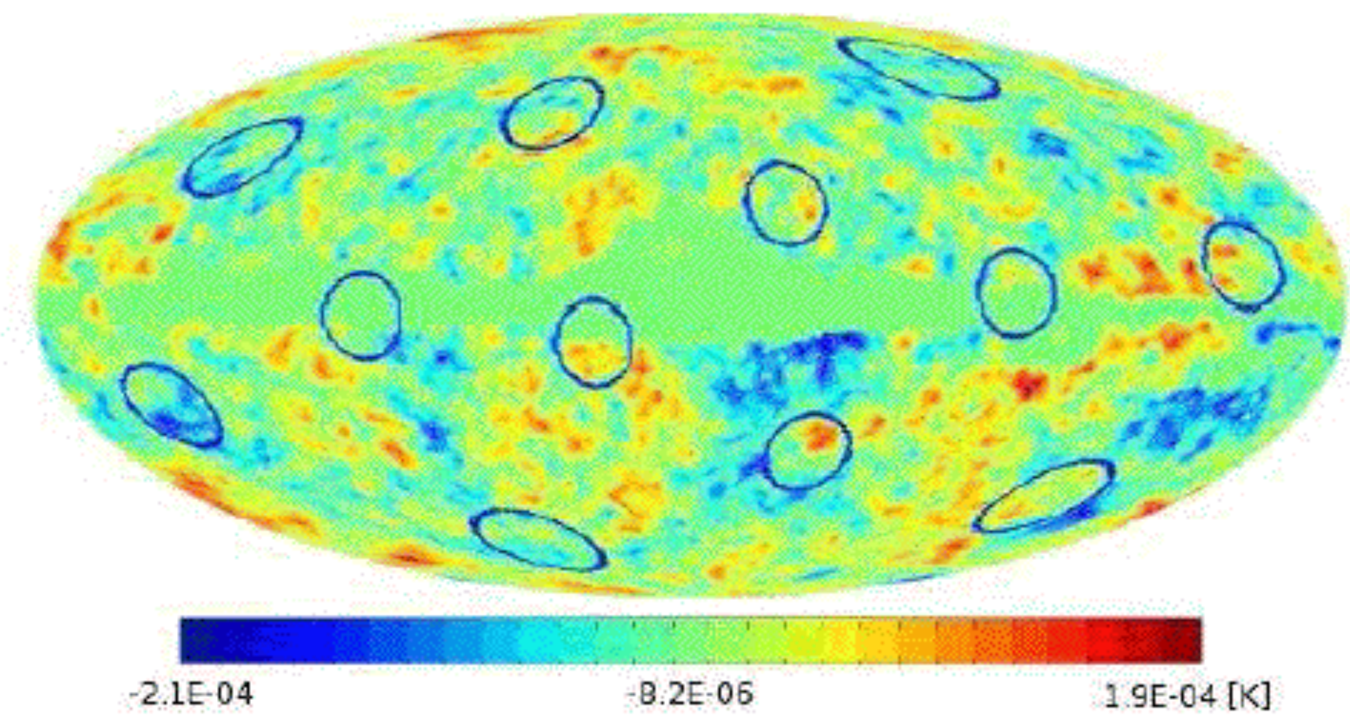
Pairs of circles in computed PDS map

for

$\Omega = 1.018$

(Caillerie, Luminet et al. 2005)





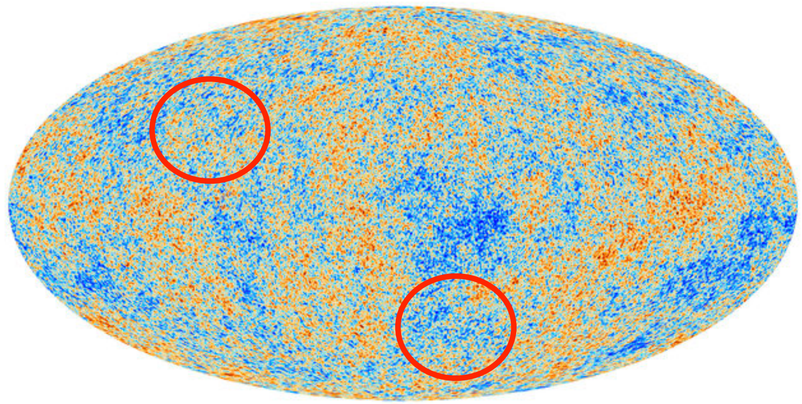
PDS : Six pairs of antipodal matched circles twisted by 36°

WMAP, Planck data ?

Search for matched circles

General 6 parameters search

- Location of first circle center (2)
- Location of second circle center (2)
- Radius of the circle (1)
- Relative phase of the two circles (1)



Search cost

Planck map: N = 50.10^6 pixels

➔ full search takes $N^{5/2} \sim 10^{27}$ operations

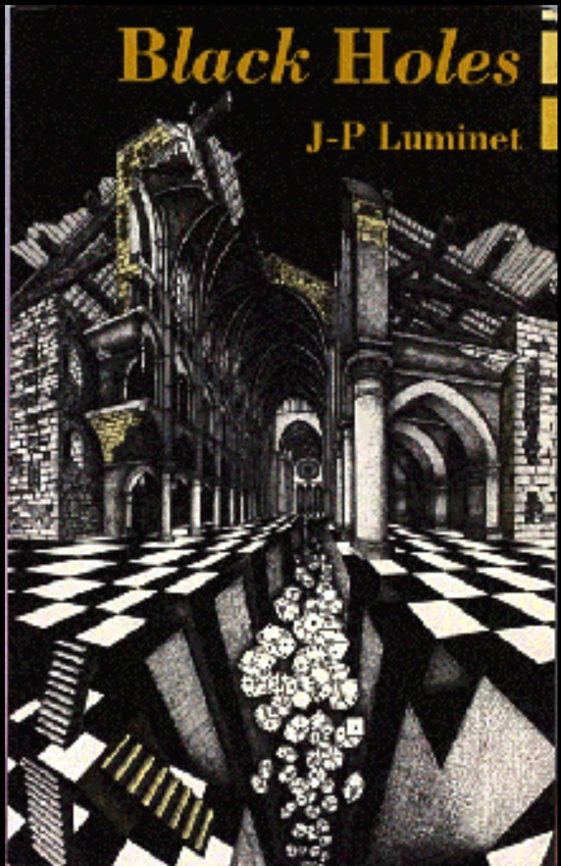
➔ ~ 3000 full years on petaflop supercomputers

Reduced parameters search (coarser grid, given topology with antipodal circles)

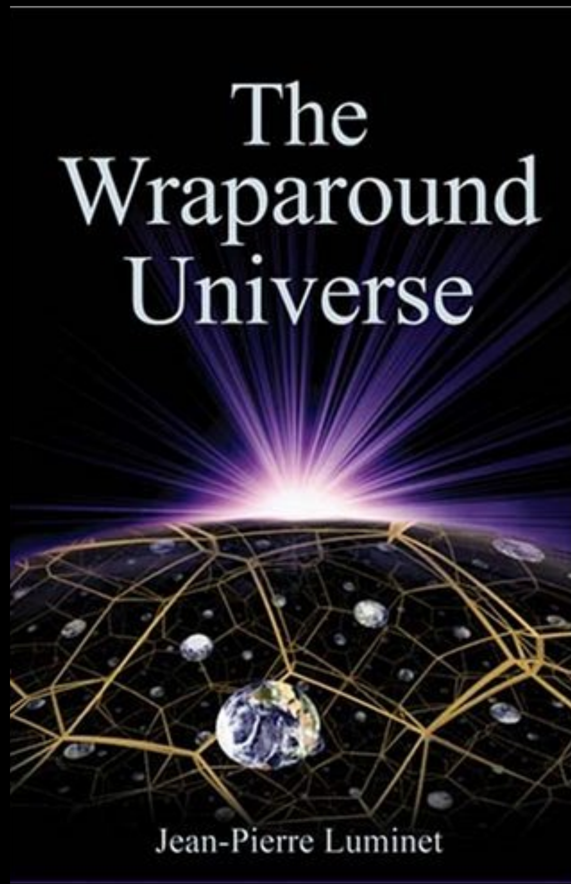
- Location of first circle center (2)
- Radius of the circle (1)
- Relative phase of the two circles (1)

Planck 2013 results, paper XXVI

Thank you !　谢谢


Black Holes
J-P Luminet


黑洞


The Wraparound Universe
Jean-Pierre Luminet