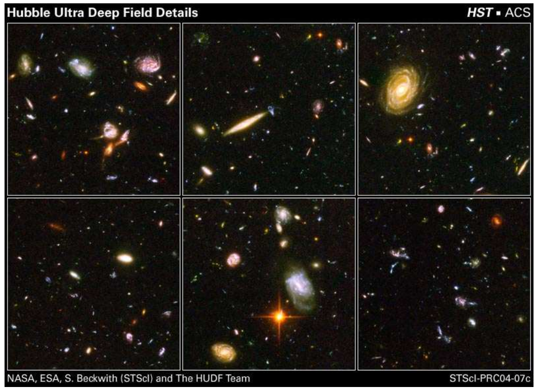
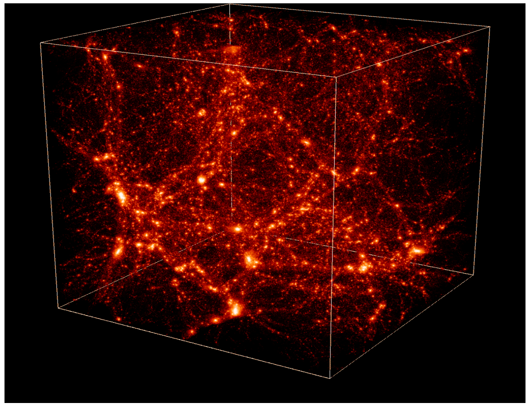




Starbursting infancy of galaxies

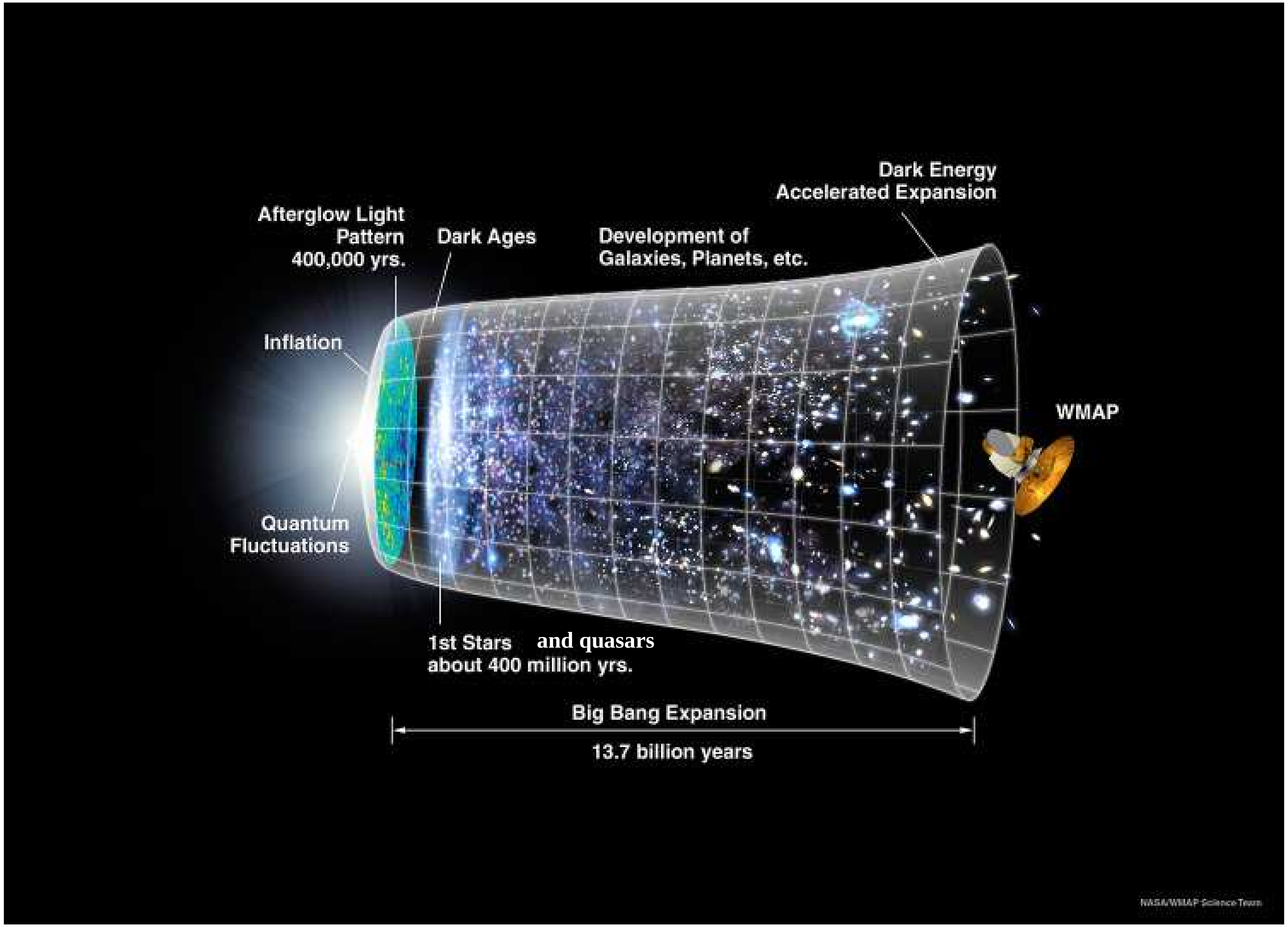
their massive black-holes

and the history of star formation in the Universe

Alain Omont, Institut d'Astrophysique de Paris

CNRS & Université Paris 6

Understanding the history of the Universe
and even that the Universe has an history
is probably the major achievement of astronomy in XXth Century



Starbursting infancy of galaxies
their massive black-holes
History of star formation in the Universe

This talk
bridging the gap between

Popular talk on

Astronomical revolutions in XXth Century

and

my personal research on

Hyper-luminous starbursts and AGN at high redshift

With emphasis on physics

Astronomical revolutions in XXth Century

Five major breakthroughs :

- **Emergence of the notion de galaxies** **1920**

- **Expansion of the Universe → Big Bang model** **1930 – 1960 ..**

- ***Understanding how stars work and make chemical elements*** ***1940 - 1950***

- ***Unveiling the world of high energies and most extreme objects: supernovae ; quasars-black holes, etc.*** ***1915 - 1960***

- Exploration of Solar System 1960 ….
  Discovery of exo-planets. 1995

→ → Questions for the XXIth Century

Back to a century ago, ~1900

➢ After three centuries of consolidation of the scientific revolution

- **End of geocentrism :**

  *** The Earth moves around the Sun and is not the center of the World; it is just a planet among others**

  *** The Sun is just a star among millions of others**

  *** There could be other inhabited worlds ?**

- **Findings and triumphs of classical physics,**

  *** from the laws of mechanics (Galileo,-Newton : 17th Century)**

  *** to those of electricity, optics, thermodynamics (→ 19th Century)**

➢ Motors of astronomical discoveries in the XXth Century

- Fantastic technology bonds en avant

- Quantum (microphysics) et relativity revolutions in physics

→ → five major breakthroughs

Astronomical revolutions in XXth Century : initial state

GLIMPSE AT ASTRONOMY IN 1900

- **Exquisite refinements of the mechanics of Solar System → Neptun discovery**
- **Major achievements in the exploration of the world of stars and their physics**
- **Well formulated questions about planets, comets, plurality of the Worlds …**

→ → ***but unavoidable shortsight, deadends, and amazing limitations …***

GLIMPSE AT ASTRONOMY IN 1900

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→ →but unavoidable shortsight, deadends, and amazing limitations …

• **<u>Limited physics</u> → impossible of :**

- **understanding the source energy of stars, the Earth age and thus the Sun age**
- **a fortiori imagining the most extreme objects of modern astronomy**
- **→ No idea about actual scales of time and energy**

• **<u>Notion of galaxy not yet established</u>**

→ apparent dimension of the Univers a <u>million times smaller than in reality</u>

→ Terribly poor vision of the Universe compared to ours

Prodigious technology progress

Telescopes and optics

From photographic plates to enormous arrays of electronic detectors

ESO/VLT Paranal Chile

4 x 8m telescopes

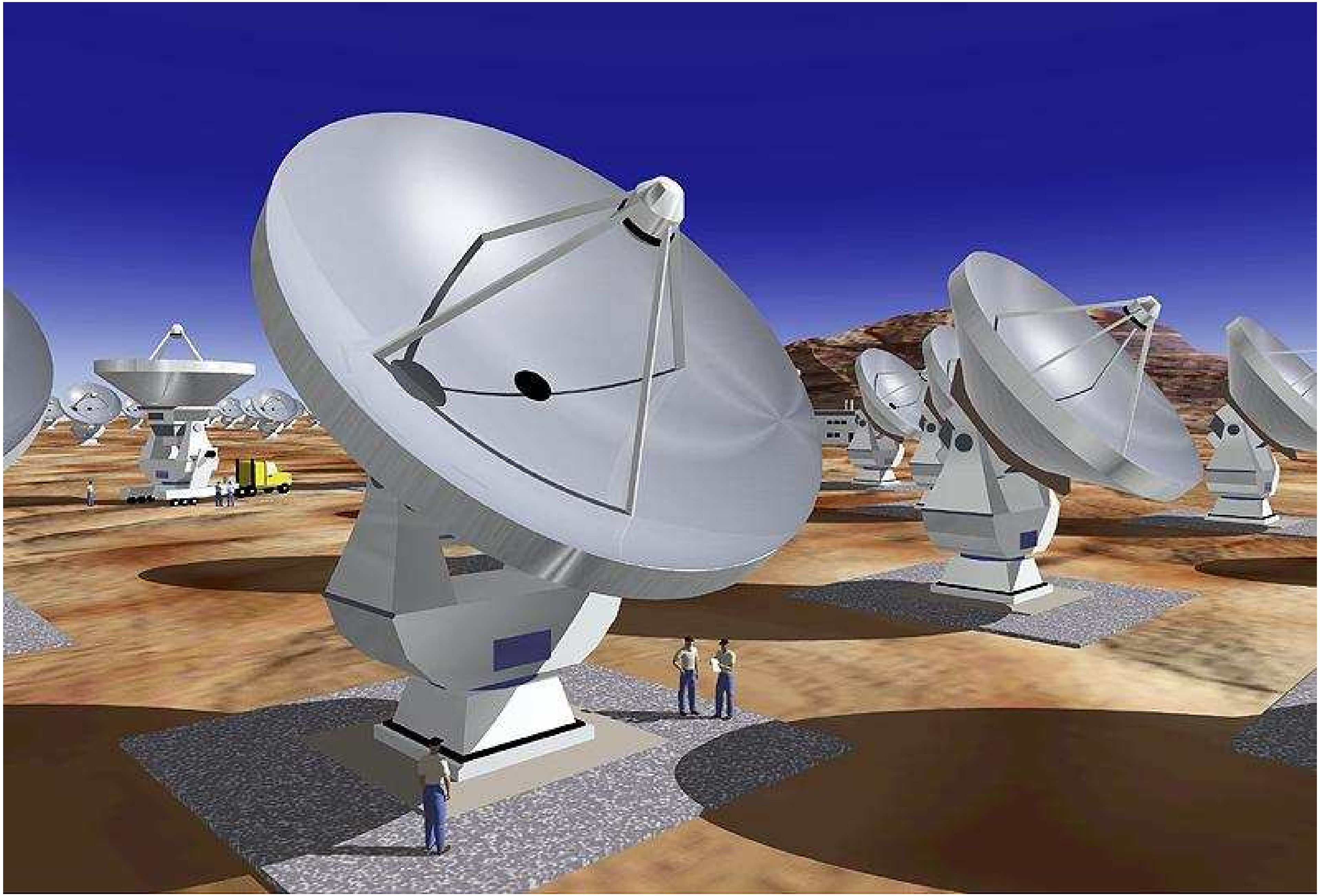
Major astronomical sites of early XXIth Century: Mauna Kea Hawaï

Prodigious technology progress

Telescopes and optics
From photographic plates to enormous arrays of electronic detectors

Opening of new spectral domains :
- Radioastronomy

Submillimeter array ALMA, Chajnantor Chili about 2012



Prodigious technology progress

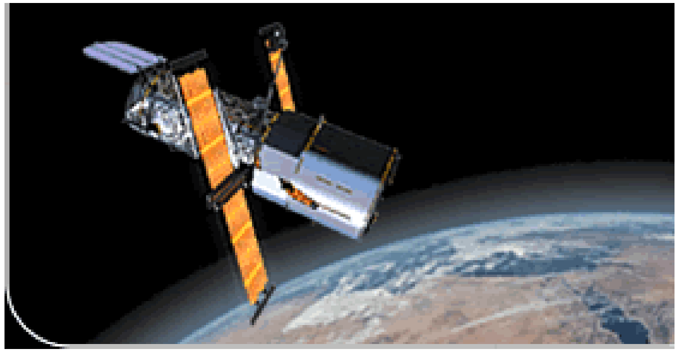
Telescopes and optics
From photographic plates to enormous arrays of electronic detectors

Opening of new spectral domains :

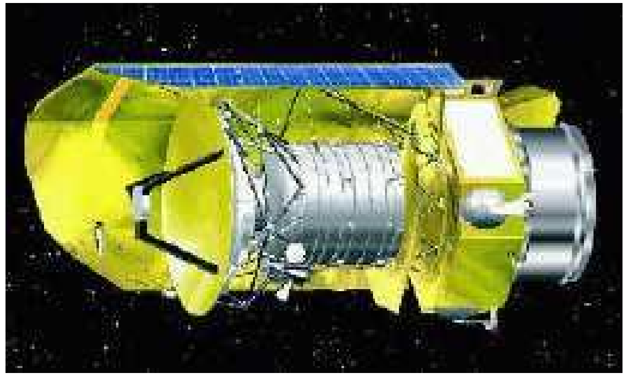
- **Radioastronomy**
- **Space :**
  - *** Telescopes rid of Earth atmosphere absorption and perturbations**
    - **→ infrared, UV, X-rays, gamma-rays**

Space telescopes and probes

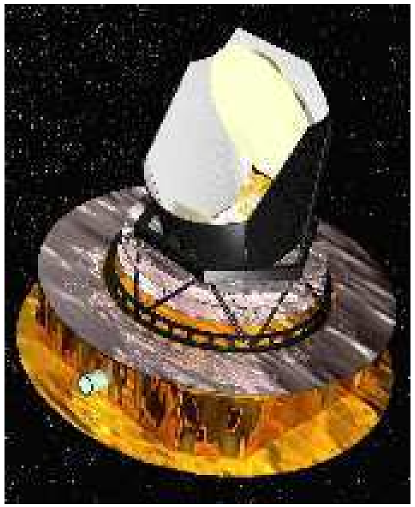
Hubble



Herschel 2008

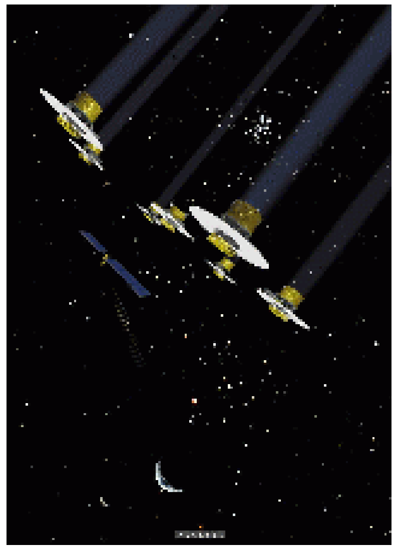


Planck 2008



Rosetta 2004-

Darwin about 2020



Prodigious technology progress

<u>Telescopes</u> and optics
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Opening of new spectral domains :

- **<u>Radioastronomy</u>**
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  * **In situ exploration of Solar System**

Motors of astronomical révolutions in XXth Century

Prodigious technology progress

Telescopes and optics
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- **Radioastronomy**
- **Space :**
  - **Telescopes rid of Earth atmosphere absorption and perturbations**
    → infrared, UV, X-rays, gamma-rays

  - **In situ exploration of Solar System**

Exponential growth of computing power
→ Handling and processing huge amounts of data. Sophisticated data analysis

Motors of astronomical révolutions in XXth Century

Consequences of Physics revolutions in early XXth Century

Quantum physics :

- **Has allowed a very complete understanding of stars, their physics and evolution *(1940-1950)***
- **Underlies ALL modern astrophysics**

Relativity: physics of high energies and gravitation

- **Cosmology: Big Bang, inflation, dark matter, dark energy, etc.**
- **Gravitational lensing**
- **Black Holes; neutron stars; gravitational waves**
- **High energy astrophysics:**

- Cosmic rays

- Radio jets; quasars

- Supernovae; gamma-ray bursts

- X-rays, gamma-rays, neutrinos

Five major breakthroughs:

Stars:

Most familiar astronomical objects: night sky, Sun
Most of visible light in the Universe
Most of nucleosynthesis

1. Physics and evolution of stars *(1940-1950)*

→ synthesis of atoms of chemical elements

Comprehensive theory of stars and the origin of atoms: a monument of XXth Century:

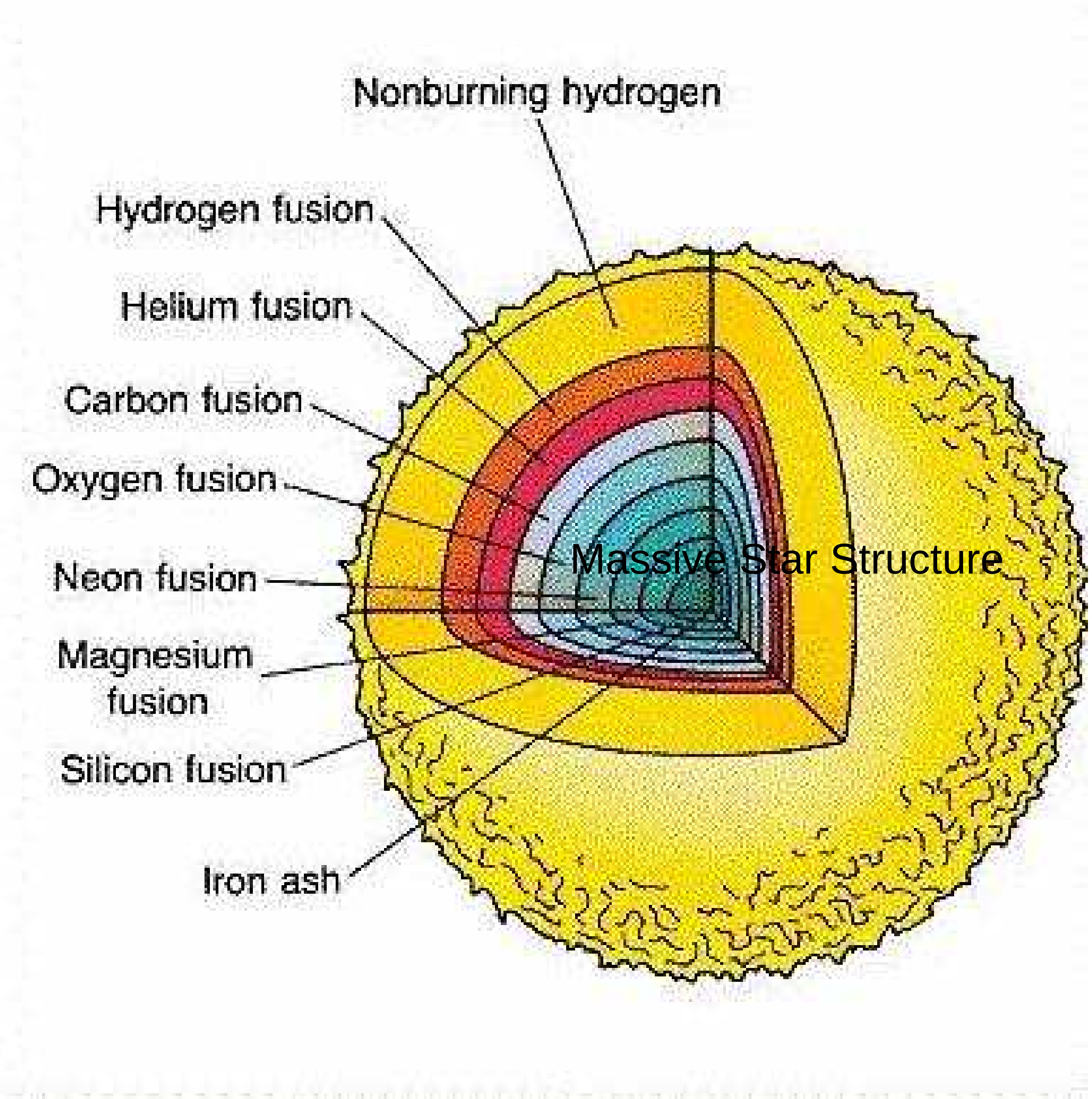
- **Relatively simple thermal machines (spheres of very hot gas)**

- **Nuclear fournaises in their core (10 million K)**
  Regulated nuclear reactions (4 ^{1}H → ^{4}He) *(neutrino emission)*
  Synthesis of chemical elements (3 ^{4}He → ^{12}C, etc.)

- **Sophisticated comprehensive models**
(difficulties with convection, rotation, MHD, mass-loss, oscillations, etc.)

- **→ Detailed understanding of evolution and age of stars** *(billions of years)*

Sketch of a very massive star close to explose as a supernova



LIFE and DEATH OF STARS

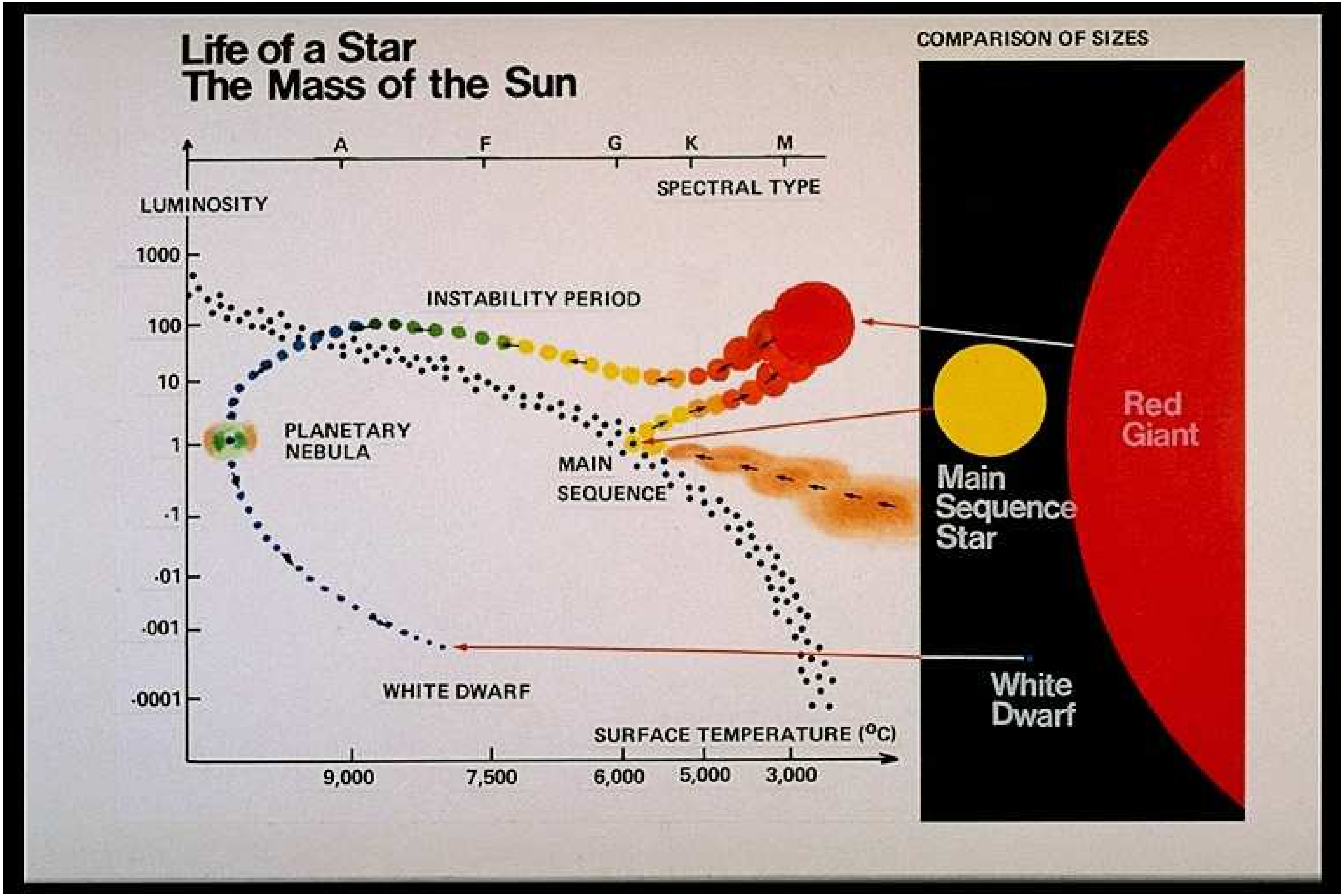
- **<u>Quick formation</u> from gravitational collapse of a condensation of Interstellar gas**

- **Long stable, well regulated stage of hydrogen combustion (~9 billion years for the Sun)**

- **Enflure in <u>red giant</u>**

- **Final « explosion » either mild (planetary nebulae)**
  or very violent (supernovae, γ-ray burst) (*very difficult physics*)
- **« Remnant» either compact (white dwarf)**
  or very compact (neutron star *(pulsars)* → *strange star*, *black-hole*)

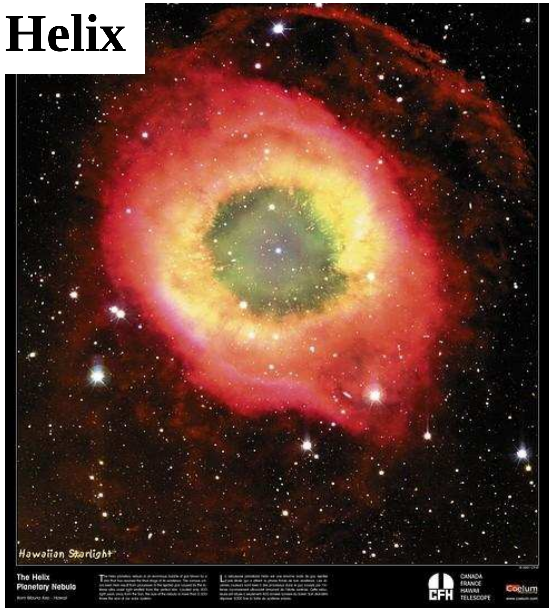
Massive stars are hyperluminous and have a very short lifetime
Small stars live very long
→ <u>Brown dwarfs:</u> aborted stars, too small to initiate Hydrogen burning



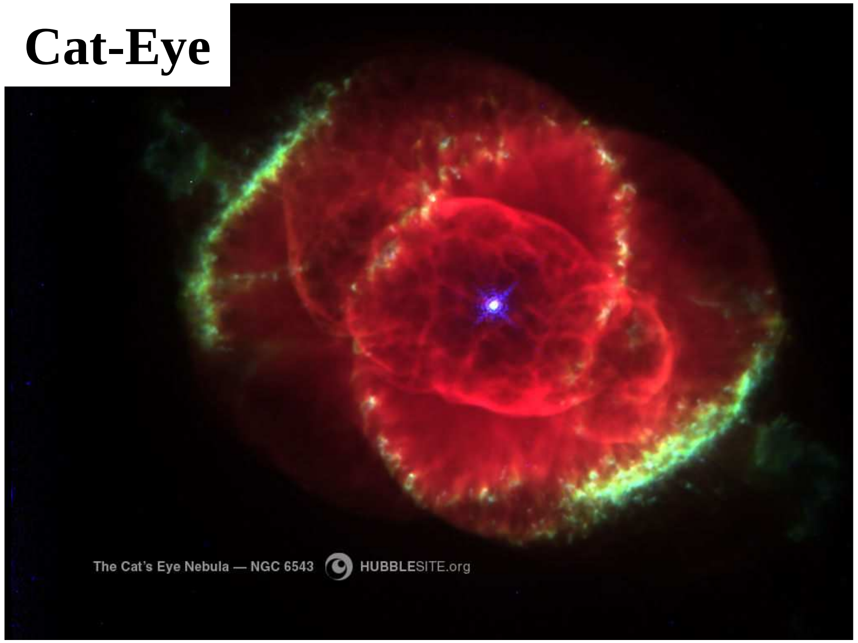
Life of a Star
The Mass of the Sun
COMPARISON OF SIZES
A
F
G
K
M
SPECTRAL TYPE
LUMINOSITY
1000
100
10
1
·1
·01
·001
·0001
INSTABILITY PERIOD
PLANETARY
NEBULA
MAIN
SEQUENCE
WHITE DWARF
SURFACE TEMPERATURE (°C)
9,000
7,500
6,000
5,000
3,000
Red
Giant
Main
Sequence
Star
White
Dwarf

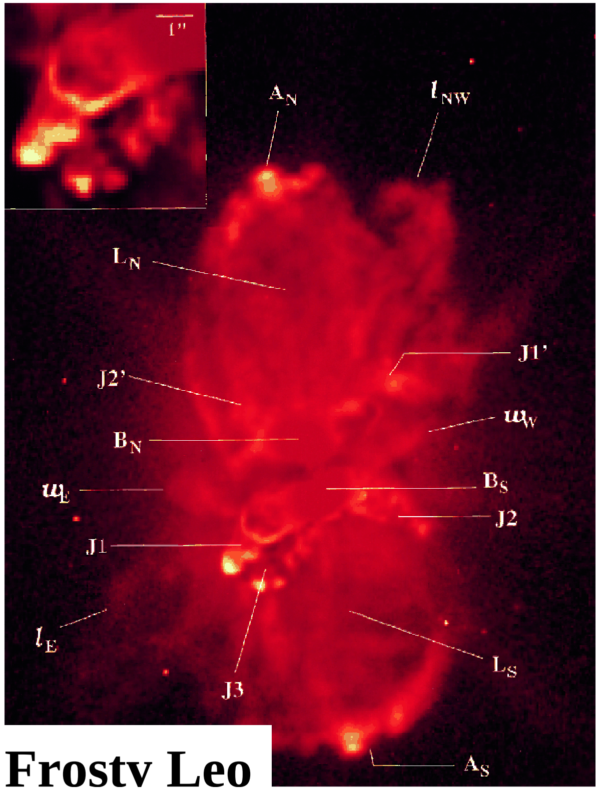
« Planetary » Nebulae

Helix

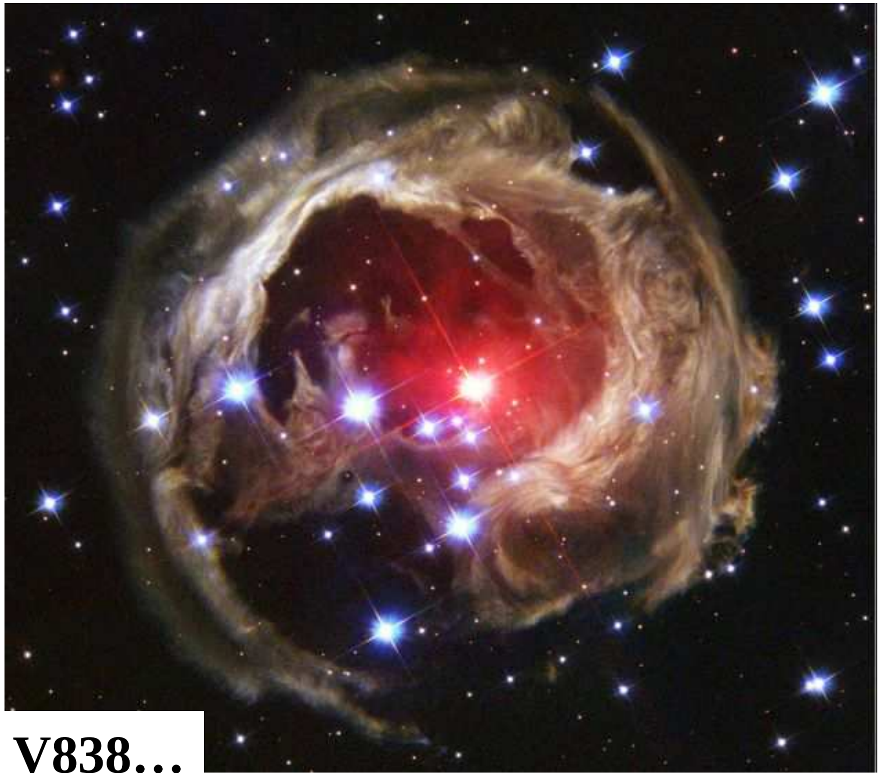


Cat-Eye



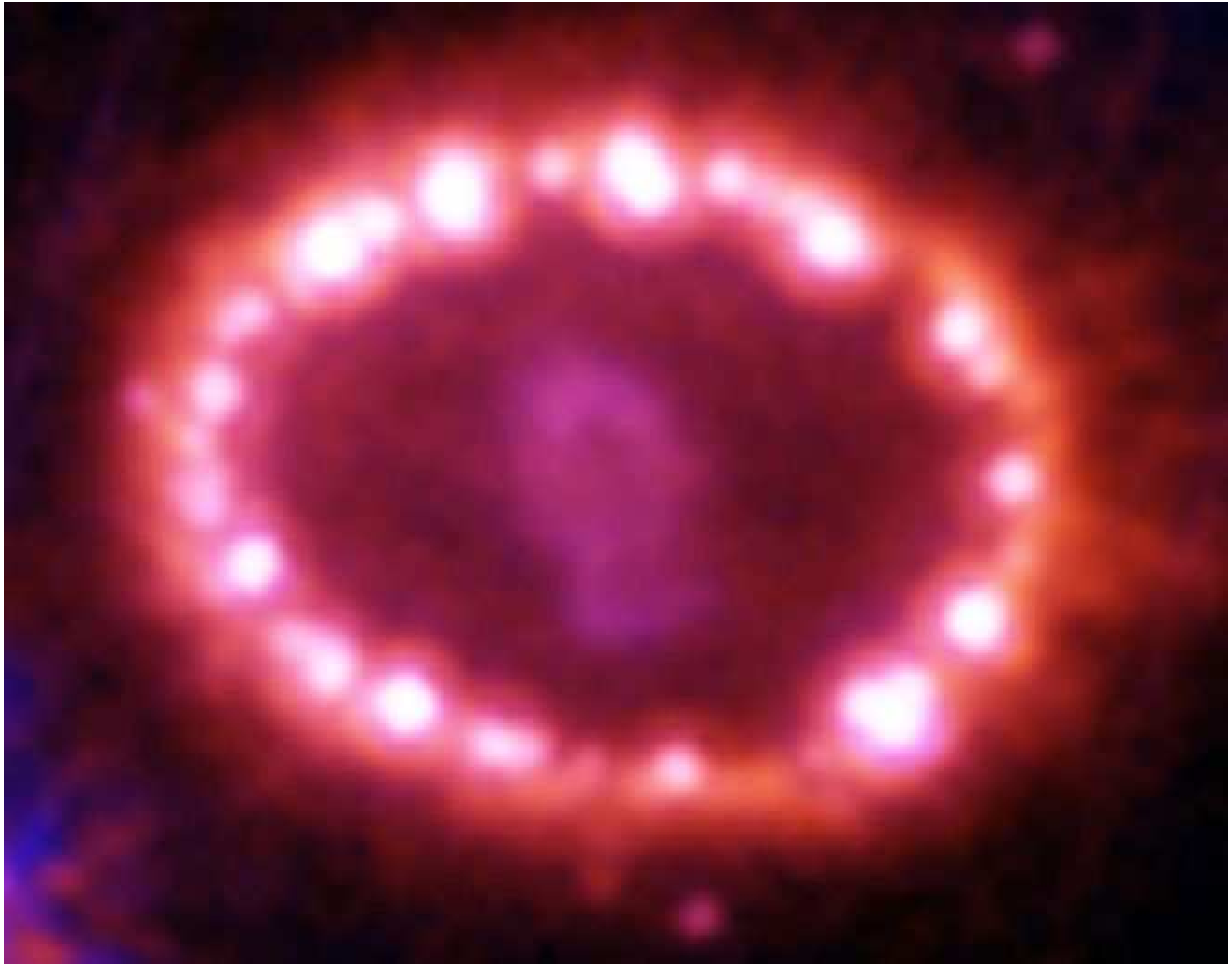


Frosty Leo



V838…

Recent view of the shell around the 1987 supernova



Crab Nebula

Filailamentary
in expansion
around a pulsar
(neutron star)

Created by the
bright supernova
observed in 1064

Five major breakthroughs:

2. Emergence of the notion of galaxies, their interstellar medium and their world

- **Accepted very late, only about 1920**

Up to this epoch, the universe of astronomers was limited to what is presently known as our galaxy, the Milky Way

- **Elementary bricks of the Universe**

- **The Milky Way**

- **Evolving systems, different classes**

Our Galaxy, the Milky Way
Archetype of spiral galaxies

The Milky Way in a glimpse:

- **100-200 billion stars**
  bound by forces of gravitational attraction
  practically point objects at galactic scales

•~10% of gas (mostly hydrogen: H, H_2, H^+)
(+ ~0.1% of dust (which completely screen the inner regions of the Galactic disk)

- **Mysterious dark matter, significantly more massive than the total mass of stars**

- **Overall rotation (~100 km/s → period a few 100 million years)**
  Very flat Disk, especially for the gas
  Luminous spiral arms (young stars); bar
  'Spherical' Halo of dark matter and a few old stars, plus central bulge of stars

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Archetype of spiral galaxies

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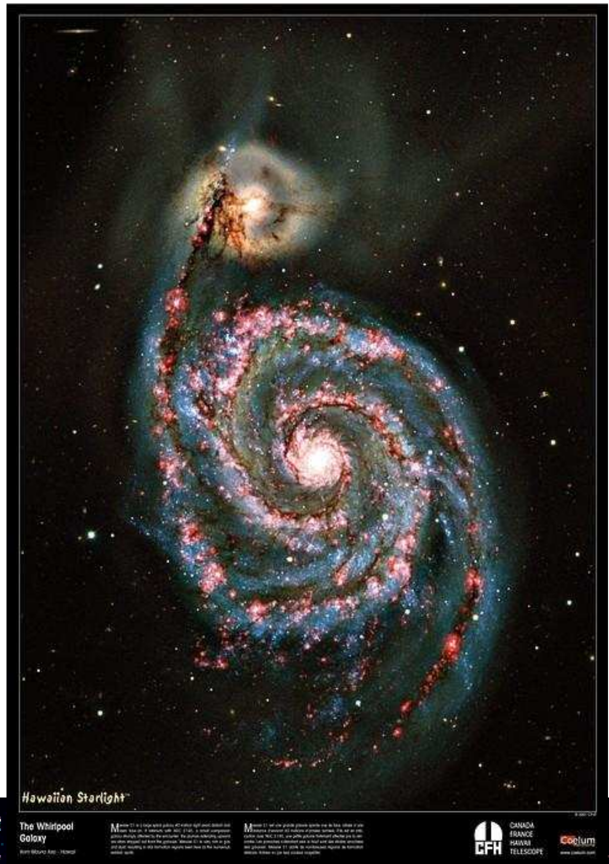
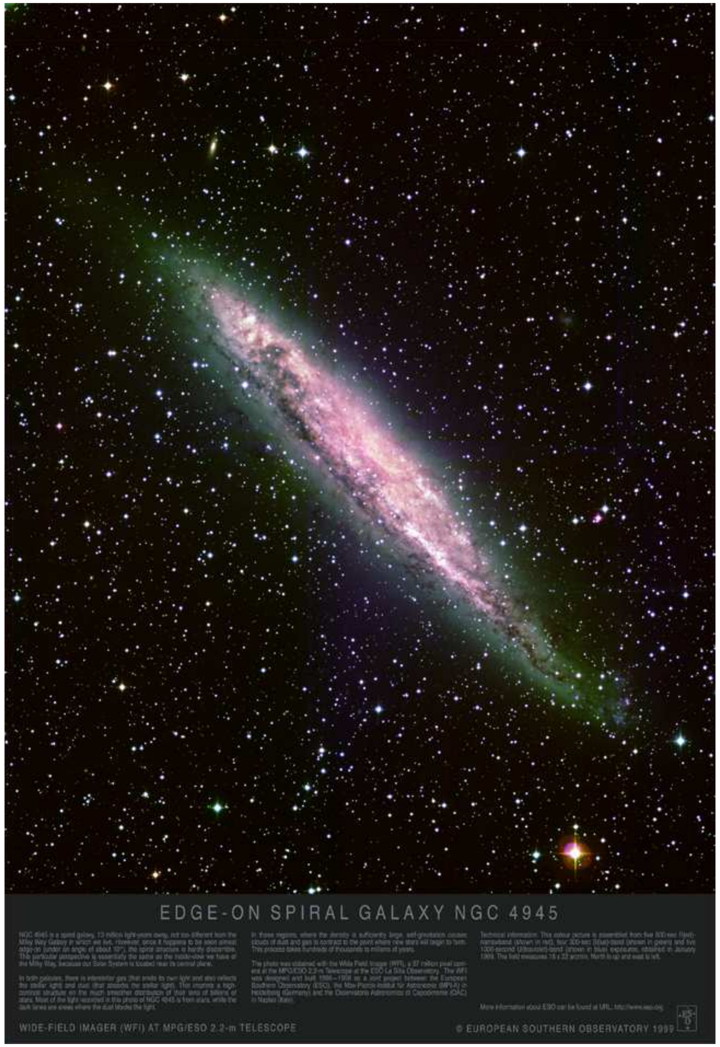
- **Much is expected from GAIA, space astrometry European mission (2012-2017):**
Distance & velocity of >10^9 stars → stellar populations, MW history, dark matter

Spiral galaxies

M51



Andromeda



The Milky Way seen in infrared

e

Infrared radiation is little absorbed by dust and gives a faithful image of the distribution of infrared luminous concentrated in the disk and in the Galactic bulge around the Galactic Center

The evolving world of galaxies

✓ Complex interplay between stars and the interstellar medium:

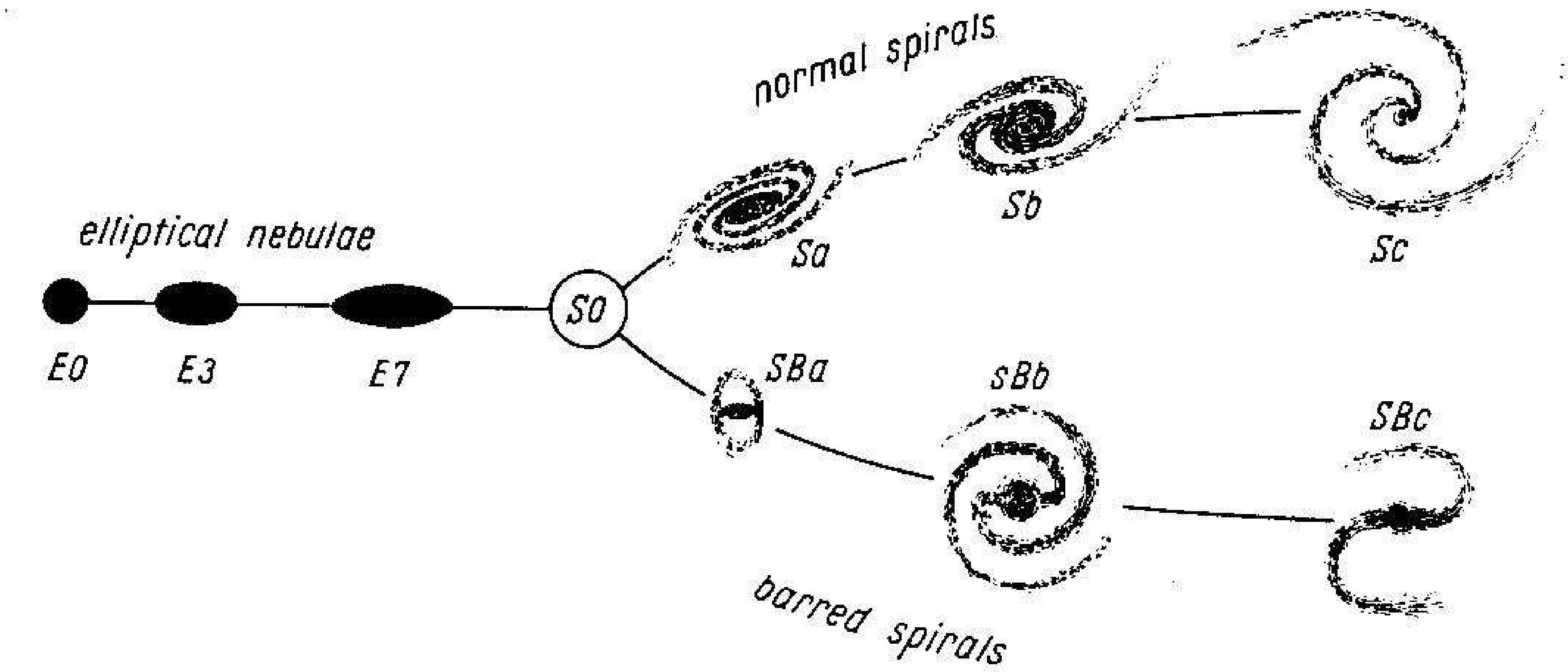
- Star formation from the gas as long as available:
  ~1 MSun per year presently in the Milky Way
- Return of gas enriched in heavy elements (mostly towards the end of star lifes)
- Evolution in: proportion of gas, galactic structure,abondance of chemical elements

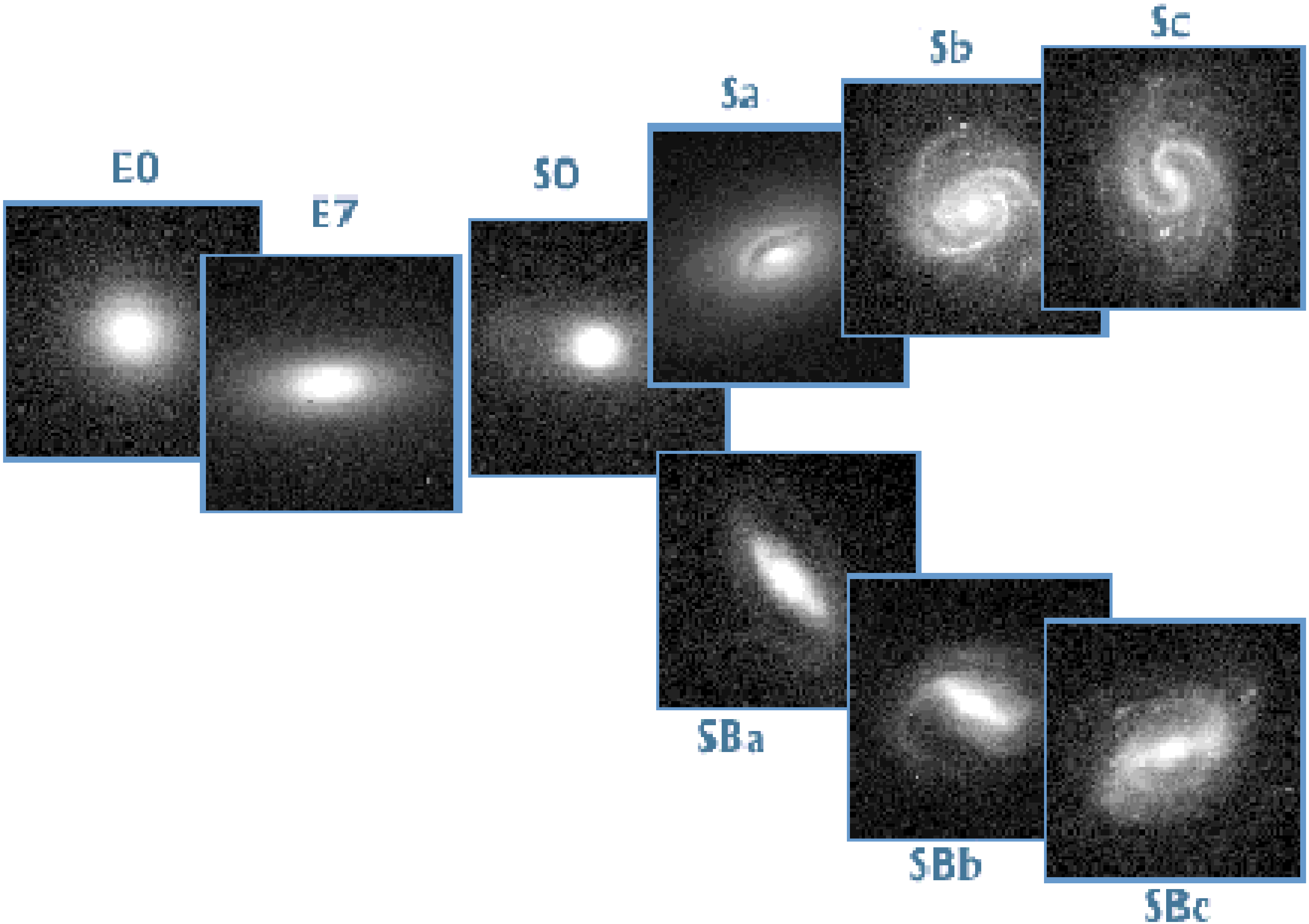
✓ Complex formation of galaxies:

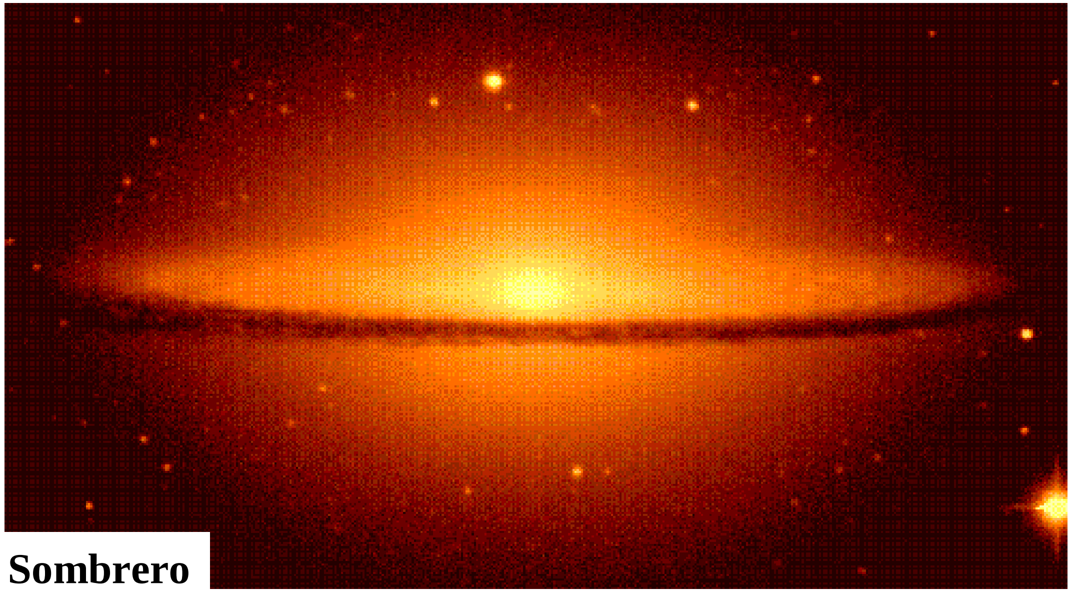
- Initial formation of dark matter spherical halos by gravitational collapse
- Further condensation of the gas in the center of the halos, possibly flattened in disk if fast rotation
- Then star formation, with initial strong starbursts
- But also collisions/mergings of galaxies (frequent in the young Universe)

→ Strong perturbations ; new starbursts
(e.g. merging Milky Way-Andromeda in a few billion years)

Classification sketch of galaxies

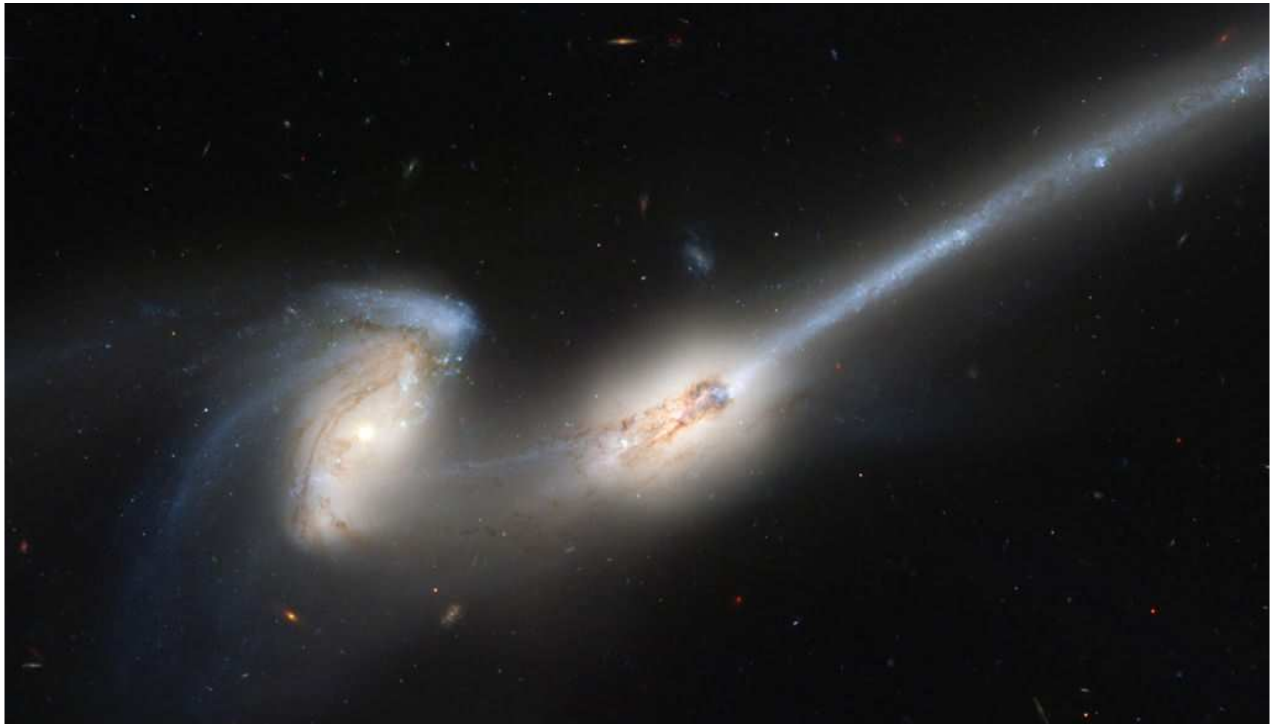



E0
E7
S0
Sa
Sb
Sc
SBa
SBb
SBc



Sombrero

Elliptical galaxy



Centaurus A

Five major breakthroughs:

3. Emergence of a global model (cosmological) of Universe

3.1 The Universe at large, uniformity

One now knows that the visible part of the Universe contains hundreds billion of galaxies

At very large scale (much larger than galaxy clusters), galaxies are distributed in a remarkably uniform way in average, perfectly identical in all directions
→ The Universe is uniform, it has no centre, no edge and is probably infinite

→ Great simplicity: the global state of the Univers and its history, i.e. the objects of Cosmology, depend only on a few parameters. They are rather well known today

Five major breakthroughs:

3. Emergence of a global model (cosmological) of Universe

3.2 Expansion of the Universe → Big Bang model

The discovery by Hubble in the 1920's of the recession (flight) of the galaxies, with v=Hd, is among the most important ones of the century

It implies an initial state extremely dense and hot, in expansion
→ Big Bang model

Initial homogeneous mixture of elementary particles (quarks, etc.)
Cooling:
→ protons, electrons, photons, neutrinos, neutrons
→ gas of hydrogen and helium
→stars and galaxies ***(more or less distributed in groups, clusters and large structures)***

Sketch of the current « standard » cosmological model

Very precise ; results from the combination and crosschecks of a number of data of various origin, derived from immense efforts in the recent years

Broad agreement (e.g. WMAP 2006):
Age of theUniverse ~13.7 billion years
The Universe is pratically « flat » : light propagates in straight line
It is apparently made of three « components » :

Ordinary matter (atoms) « baryons » :	**~4% (only~1% in stars/galaxies)**
Dark matter	**~22%**
« Dark energy »	**~74%**

The precise nature, and even concept, of dark matter and especially dark energy remains unknown

It seems well established that there was an initial phase of « inflation » when the dimensions of the Universe breathtakingly increased

There is a very close ralationship between particle physics and Big Bang cosmology, especially in the inflation phase, with possible questioning about space extra-dimensions, topology, etc.

Science Case

Primary science case:

- Measurement of the dark energy equation of state parameter (w_0) and its evolution (w_a) from z=0 to 1, with a joint precision better than 5% and 20%, respectively.

  → Is it a cosmological constant (w=-1)? Is it dynamical vacuum energy ($w_a \neq 0$)?

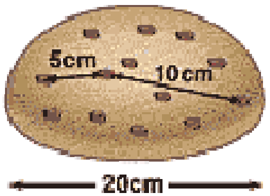
- Measurement of statistics of the dark matter distribution and its evolution from z = 0 to 1 from linear to non-linear scales (power spectrum, high order correlation functions)

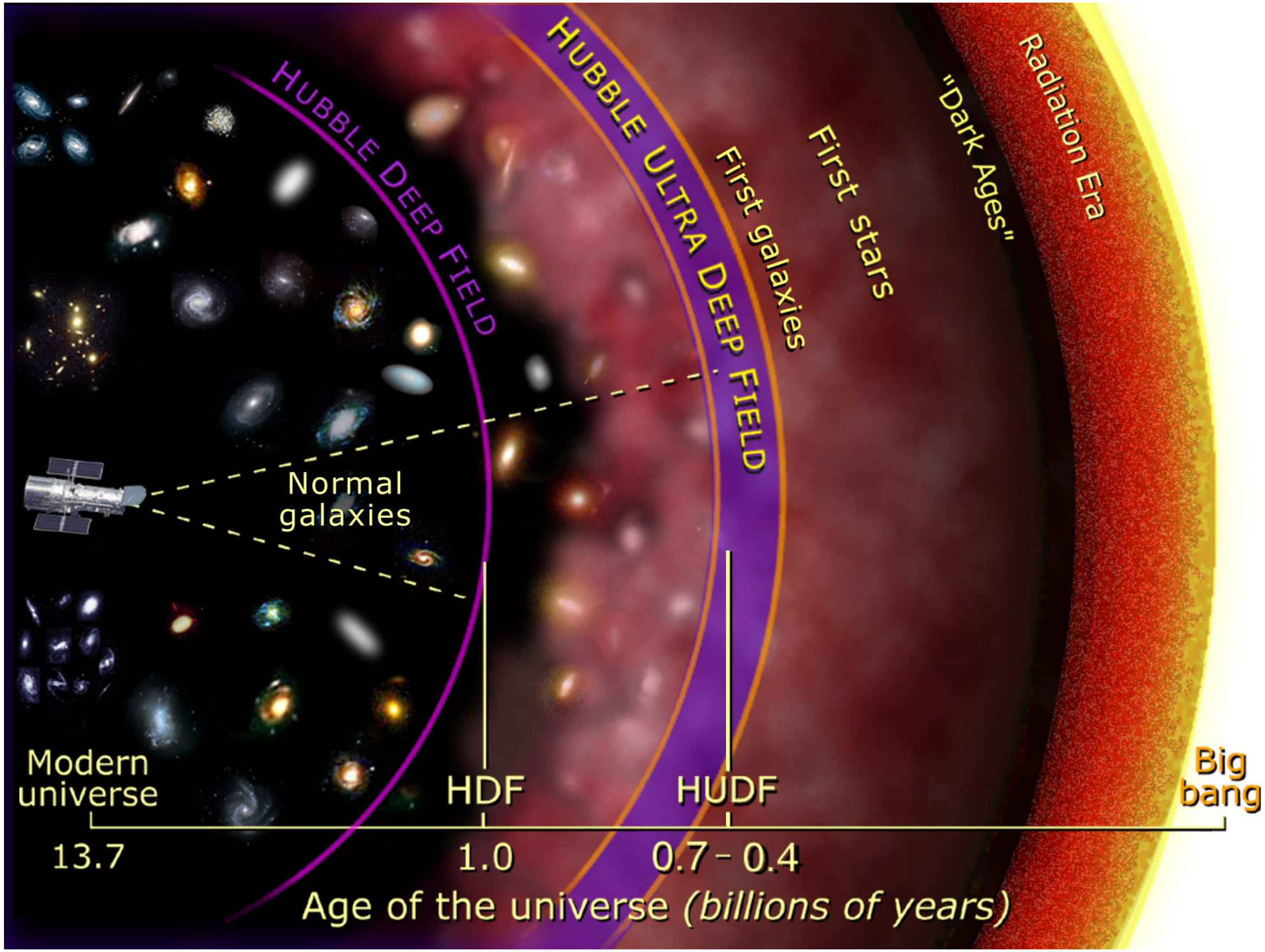
  → Is Dark Matter cold? Does it interact via gravity only?

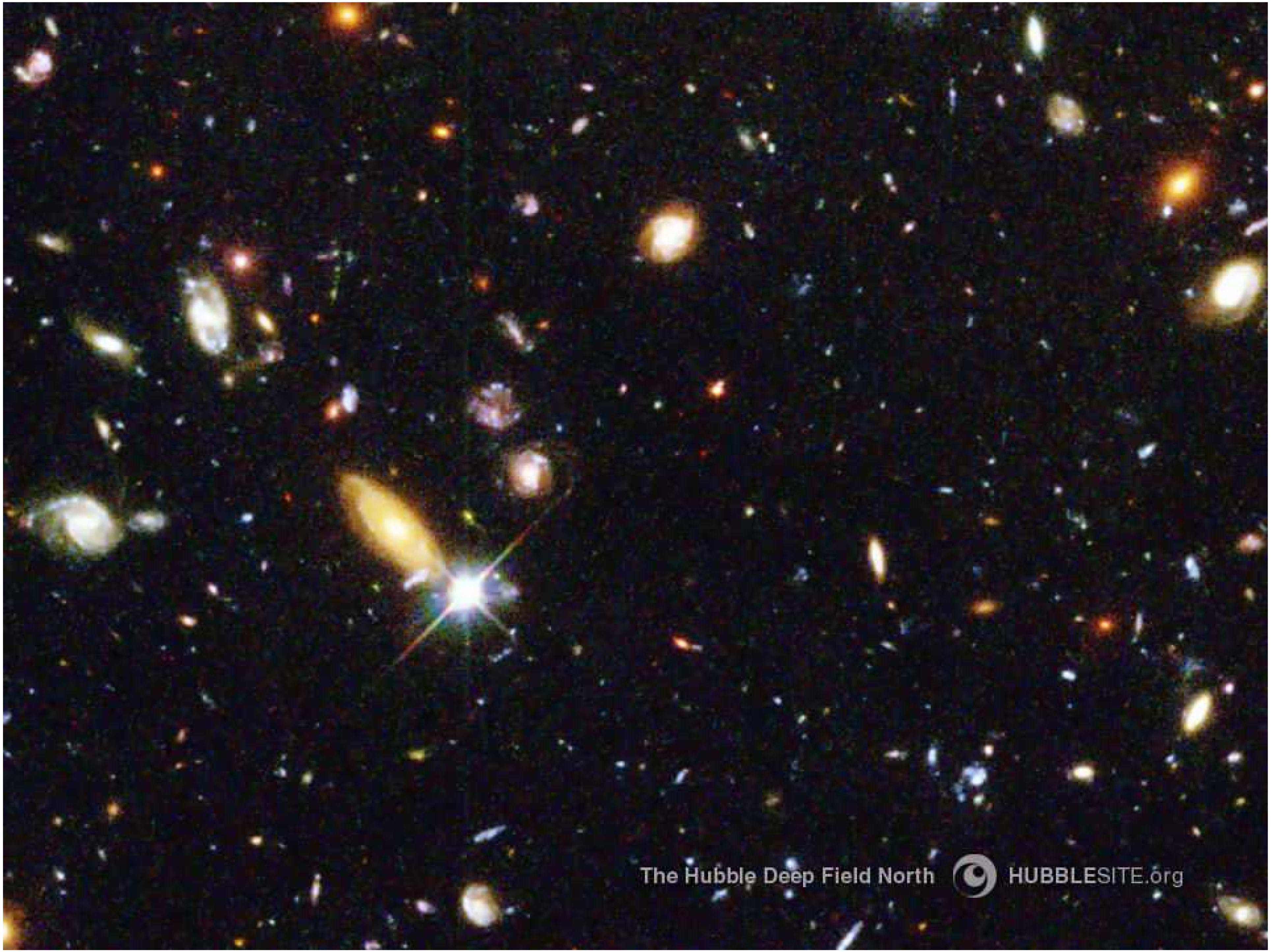
- Constraints on initial conditions via the reconstruction of the primordial power spectrum

  → Is there a special scale in the early universe? Is inflation correct

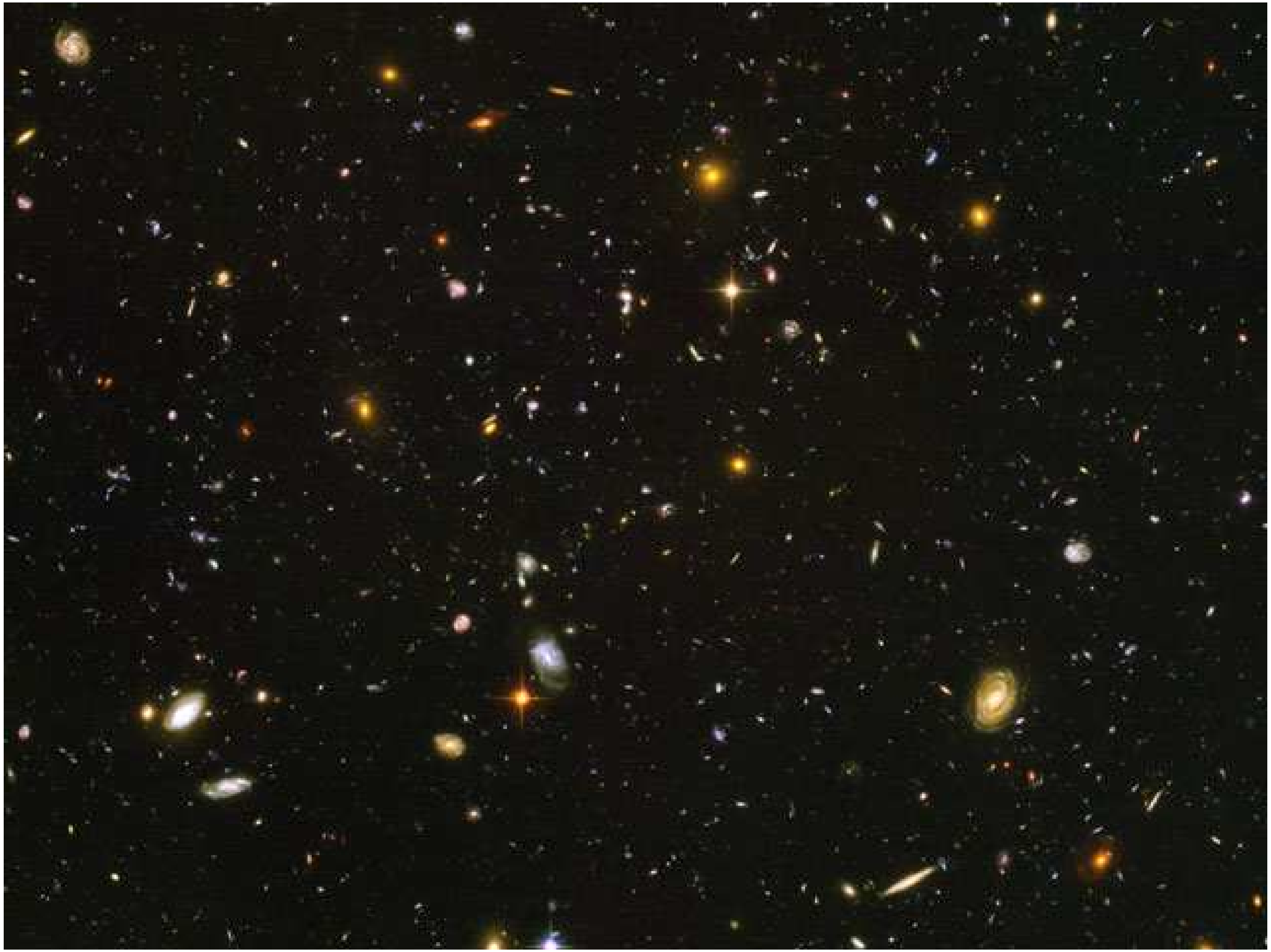
Sketch of Universe History



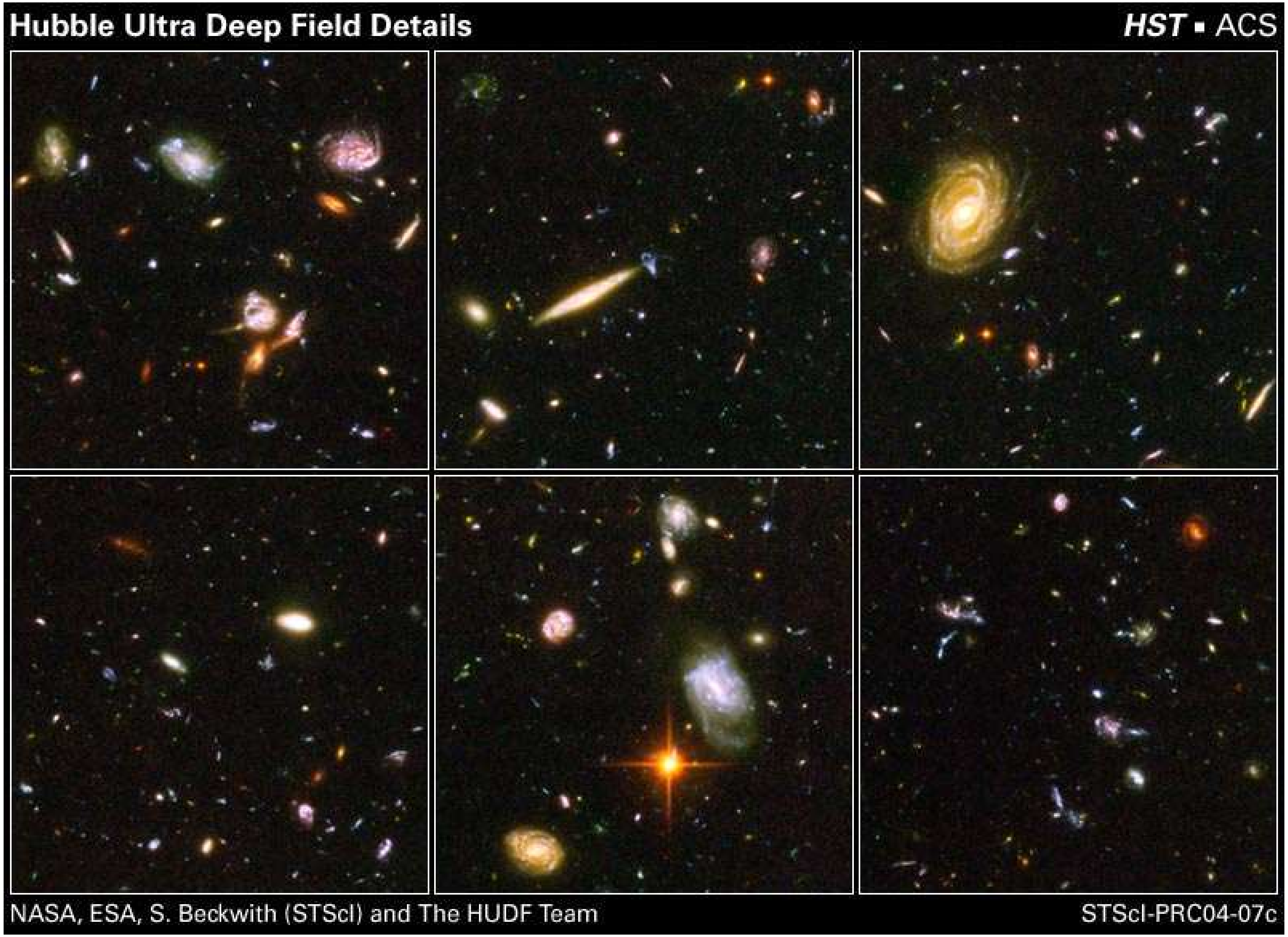



The Hubble Deep Field North
HUBBLESITE.org

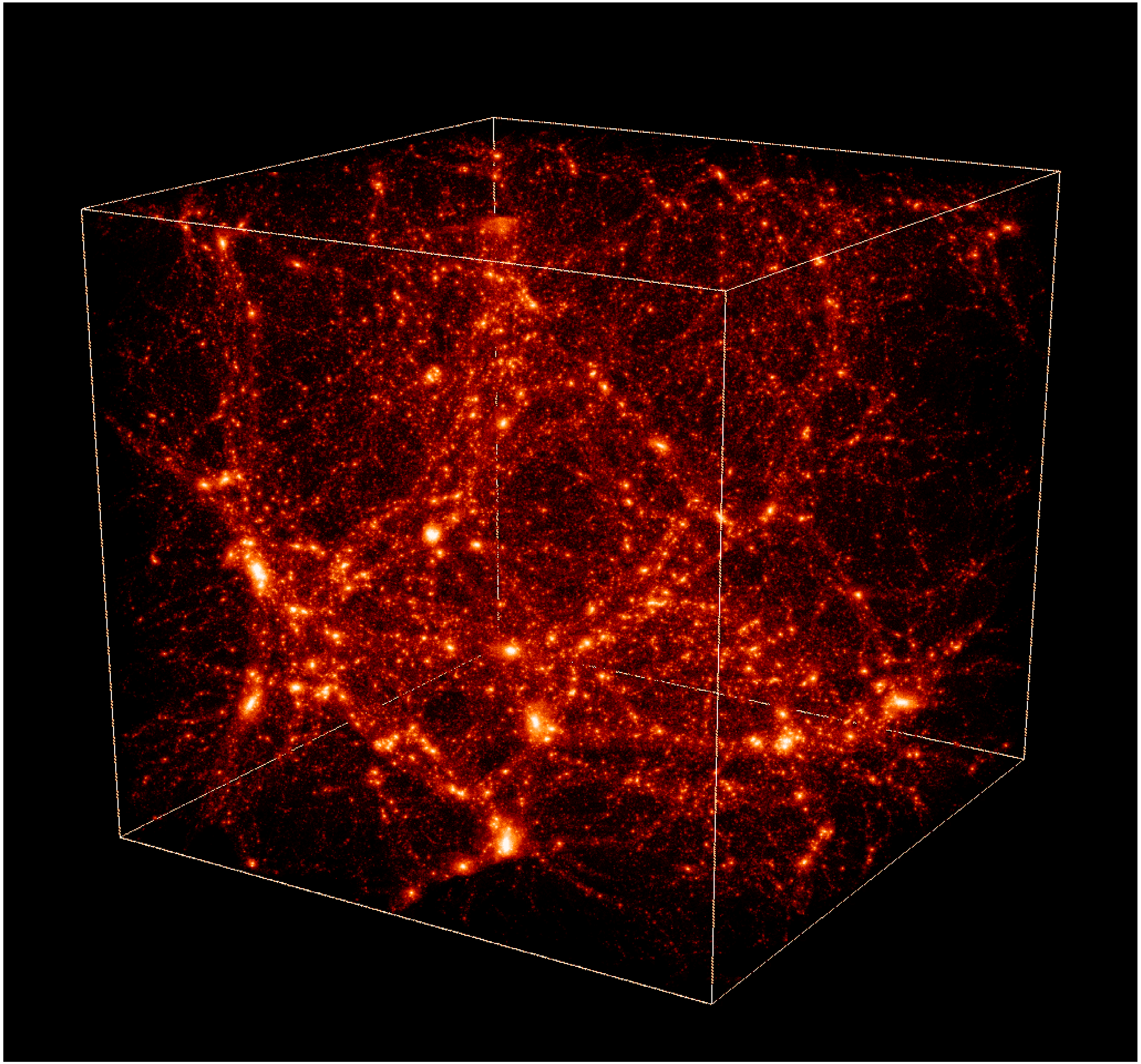
Since a few years, we are able to currently detect galaxies extremely distant in space and time (more than ten billion years) and thus directly observe the main phases of star formation in galaxies similar to the Milky Way, in particular the violent initial starbursts



Hubble Ultra Deep Field


Hubble Ultra Deep Field Details
HST ▪ ACS
NASA, ESA, S. Beckwith (STScI) and The HUDF Team
STScI-PRC04-07c

Model of the filament structure of the distribution of galaxies in the Universe at scale of 300 million light-year



Five major breakthroughs:

4. The violent Univers , at physics frontiers

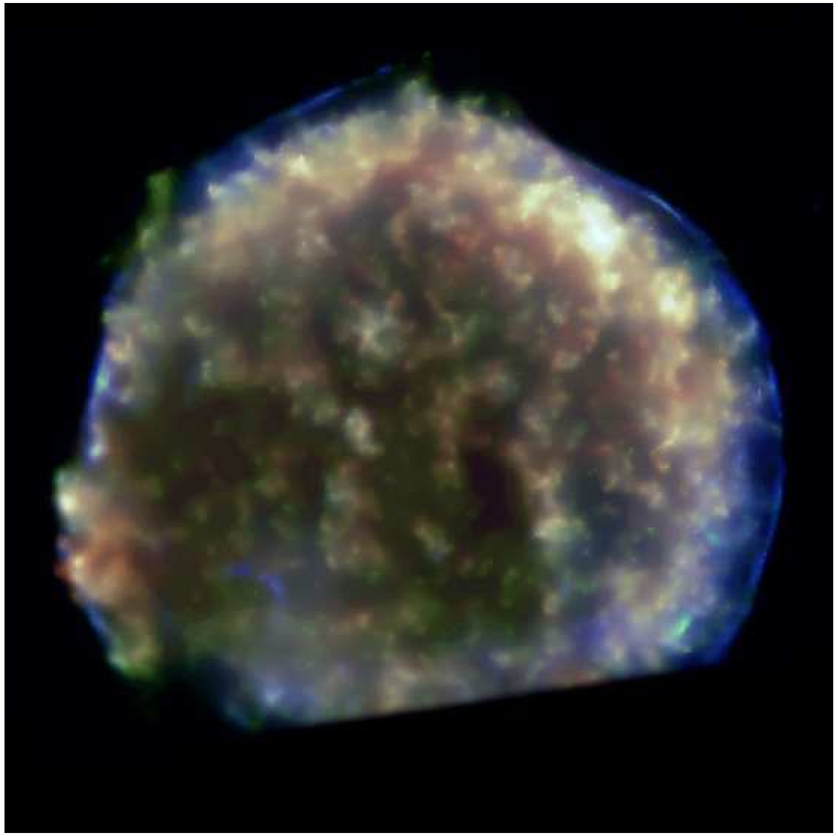
Revelation of energy sources infinitely more powerful than stars:

- **Supernova explosions → hypernovae/γ-ray bursts : billions of suns**
- **Quasars : up to million of billions of suns!**

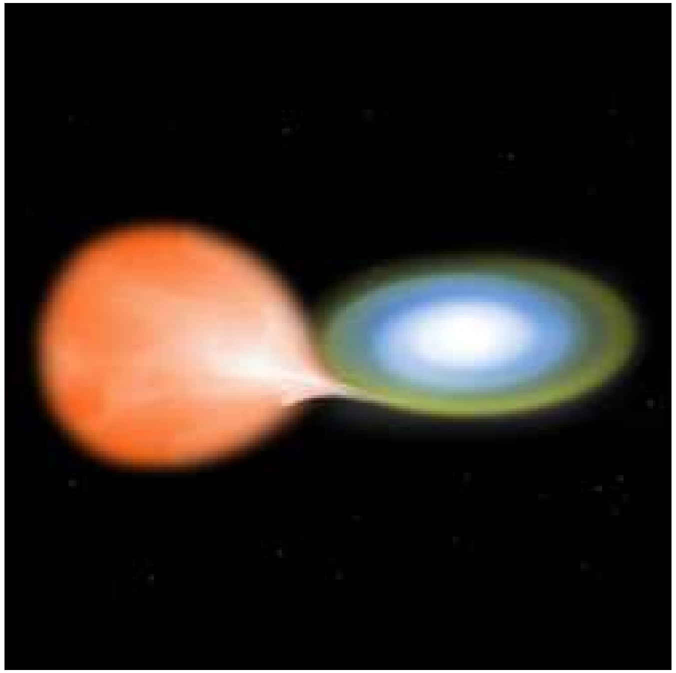
Supernova remnants attesting the violence of explosions

Crab 1064

Tycho 16th Century



Sketch model of a binary star X



The gas of the big star is suck and violently falls onto the compact object

Five major breakthroughs:

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Energy mainly gravitational

Related to hyper-compact objects *(physics not yet perfectly understood):*

- **Neutron stars (density ~1 billion tons per cm^3 !)**
- **Black holes**

Emission of high energy radiation:

- **X-rays and gamma-rays, neutrinos, cosmic rays**
- **routinely detectables with telescopes on satellites, or from the ground for the highest energies (and neutrinos)**

Black Holes

Energy of gravitational forces close to mc^2 → ultra-relativistic

Singularity/divergence of space, strongly bent

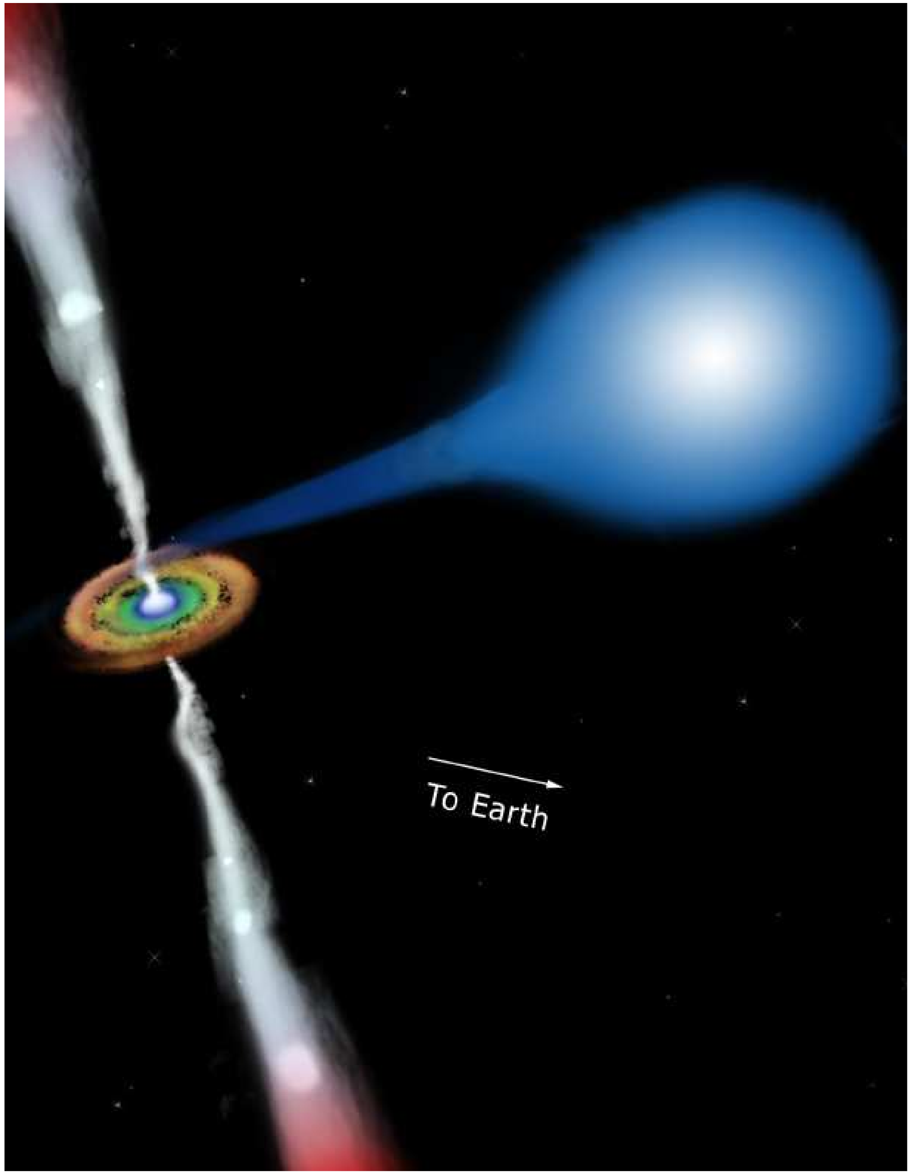
Gravitational forces are so strong that « nothing can get out », not even light

Enormous energy injected into the matter which is accreted (‘falling’) onto the black hole; part is radiated before engulfment → quasar

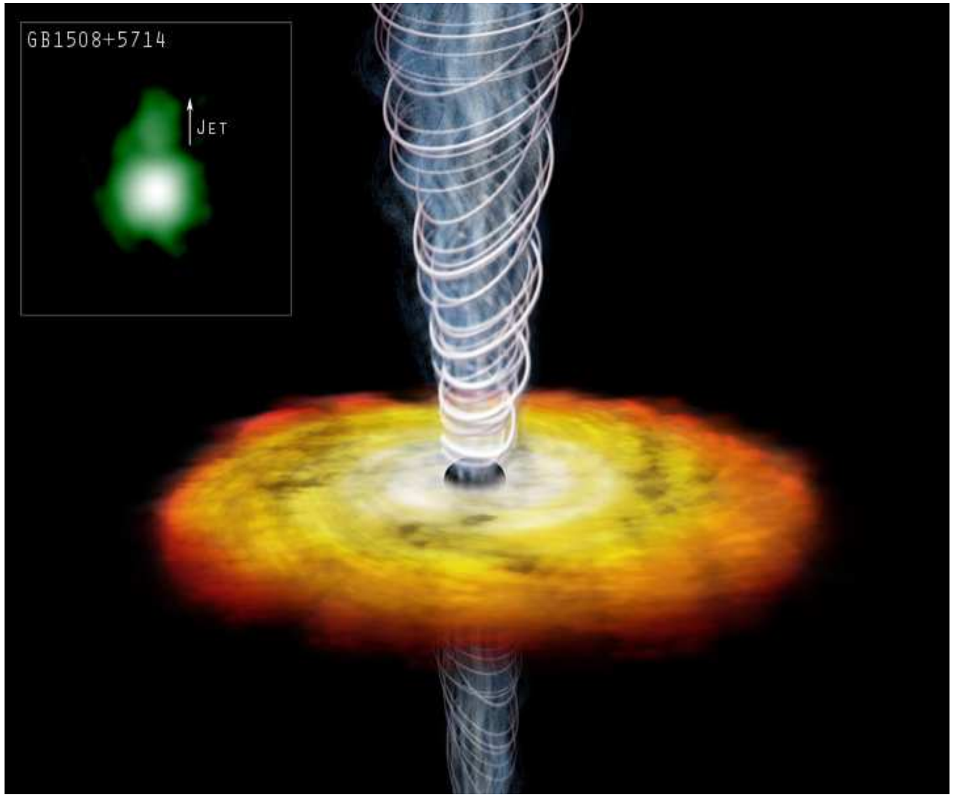
In some cases, huge jets of relativistic matter are ejected
→ radio sources, radio loud quasars, mini-quasars

Sketch models of jets :

binary X / mini-quasar



quasar



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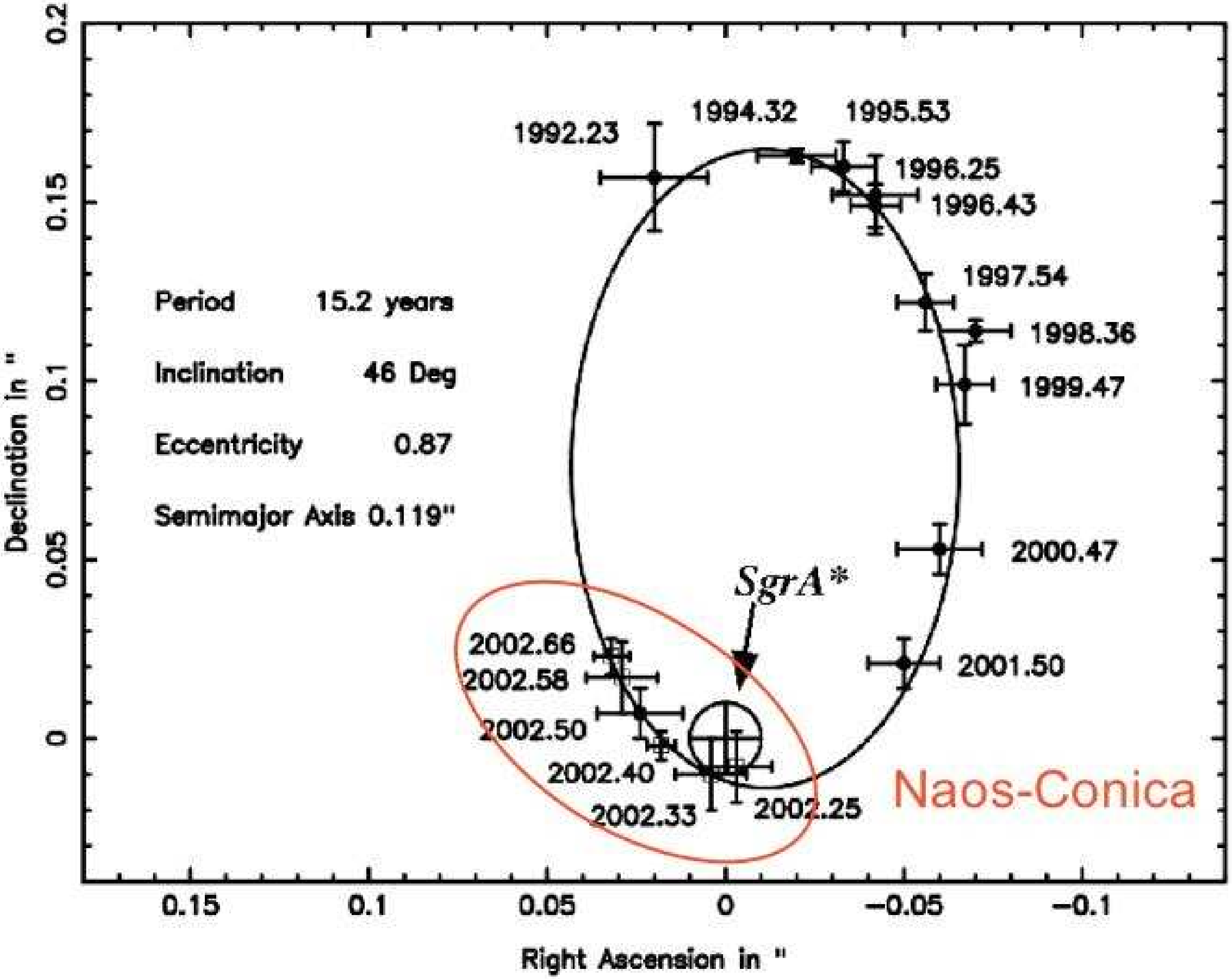
Super-massive : 1 million/1 billion solar mass

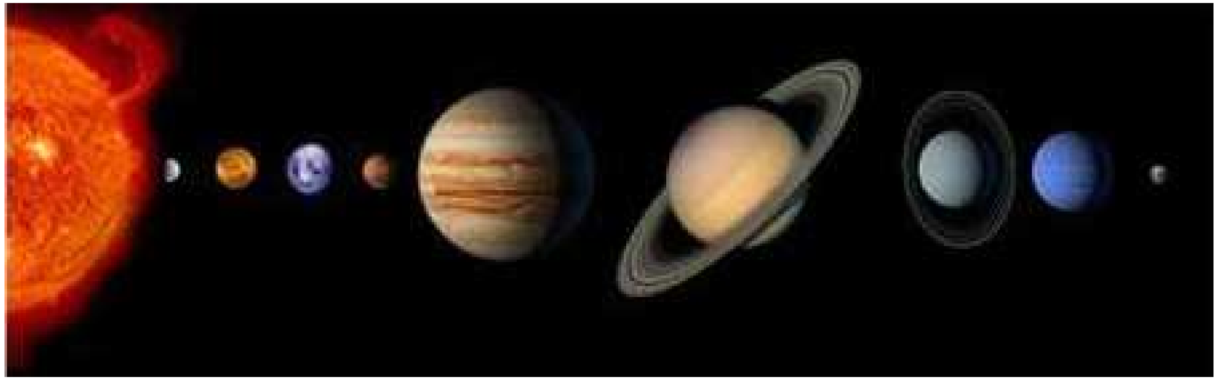
- prominent at the centre of galaxies with active nucleus (AGN) : quasars, radio galaxies, etc.
- present without much activity in all massive galaxies, especially elliptical ones
- well identified at the Centre of the Milky Way : a few millions of solar mass : orbits of close stars

Sketch model of disruption and engulfment of a star by a massive black hole

Well identified black hole at the Centre of the Milky Way :
a few millions of solar mass : orbits of close stars

Observed orbits of stars around the central black hole of theMilky Way





Cinq Percées majeures :

5. Exploration du Système Solaire et Exo-planètes

Exploration directe de tout le Système Solaire par sondes spatiales

Découverte de plus de 100 exo-planètes

→ Exo-biologie

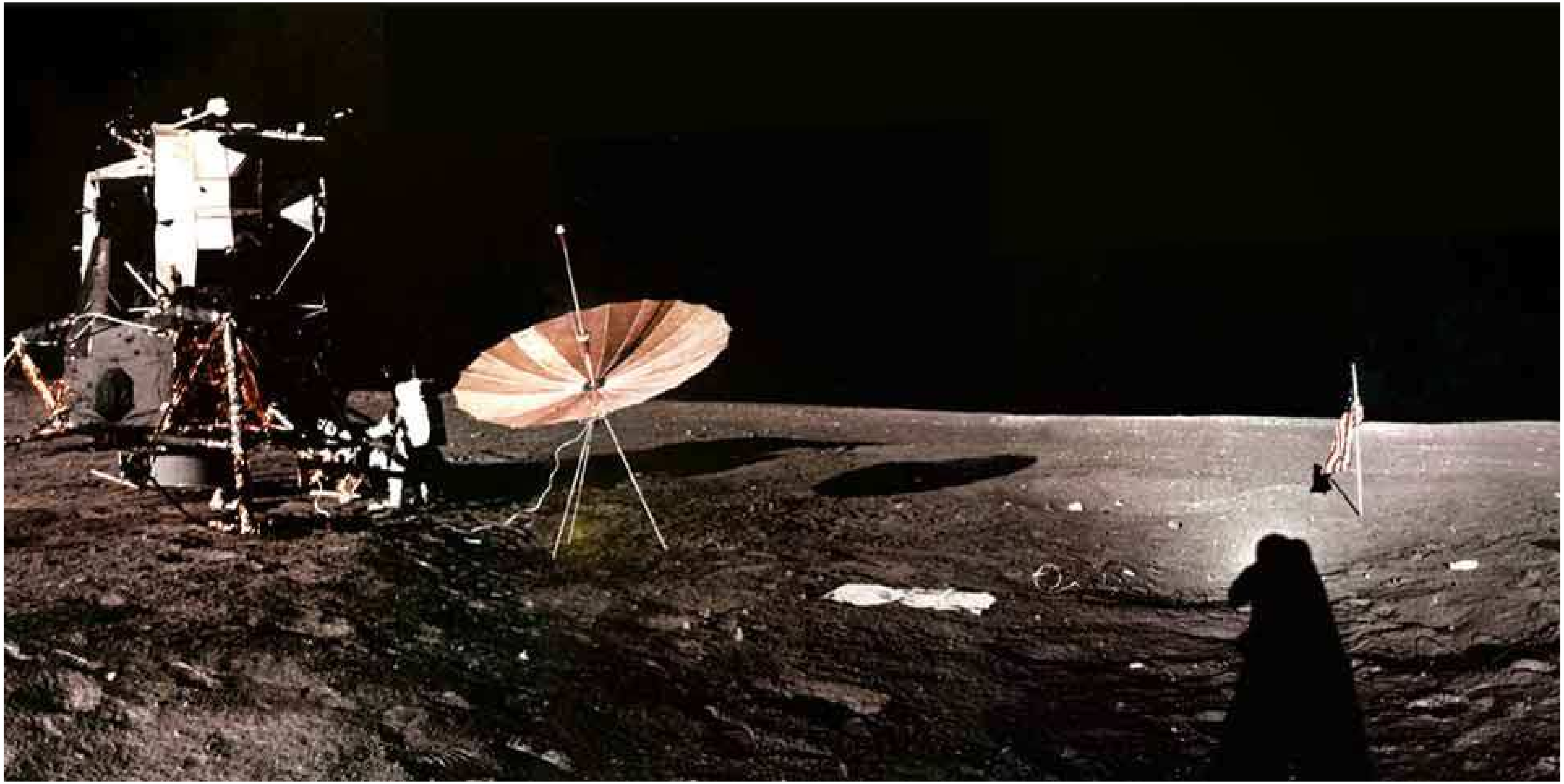
Axe majeur de recherche pour le XXIème Siècle

Exploration directe de tout le Système Solaire par sondes spatiales

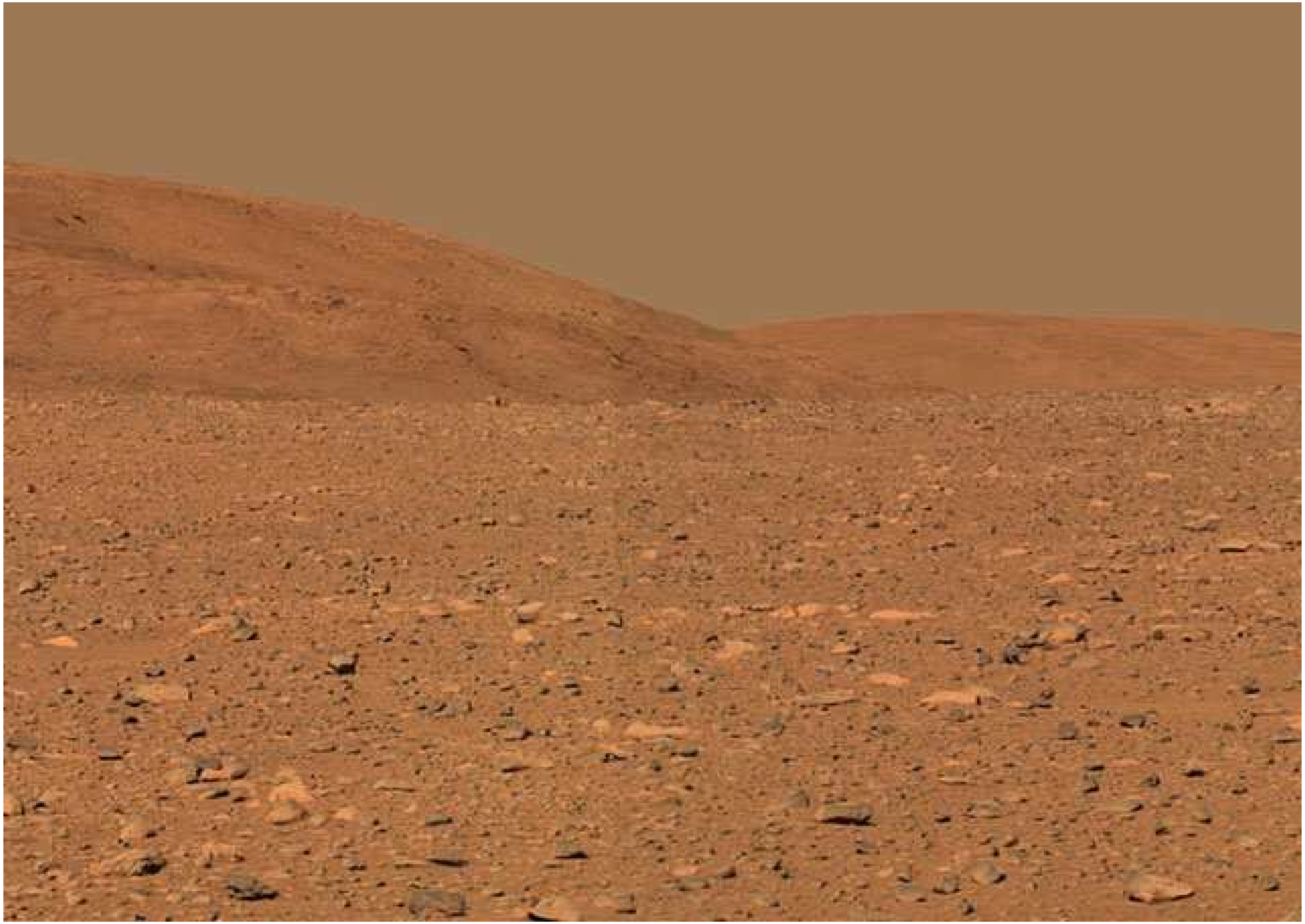
Lune : Apollo ***(1969)***

Mars : multiples missions : ***fabuleuses images***

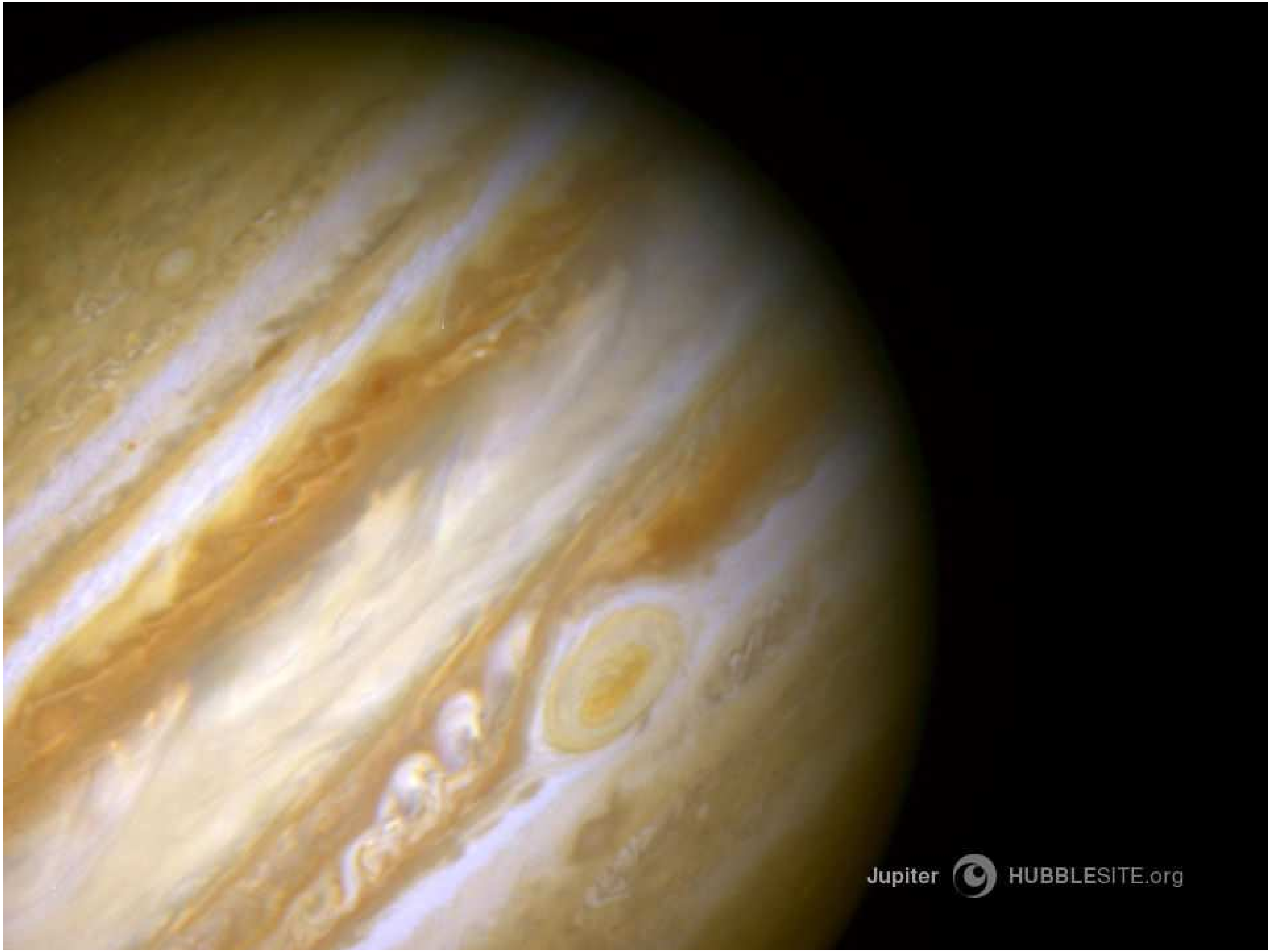
Autres planètes et satellites ***→ Saturne/Titan (2005)***



Paysage Martien

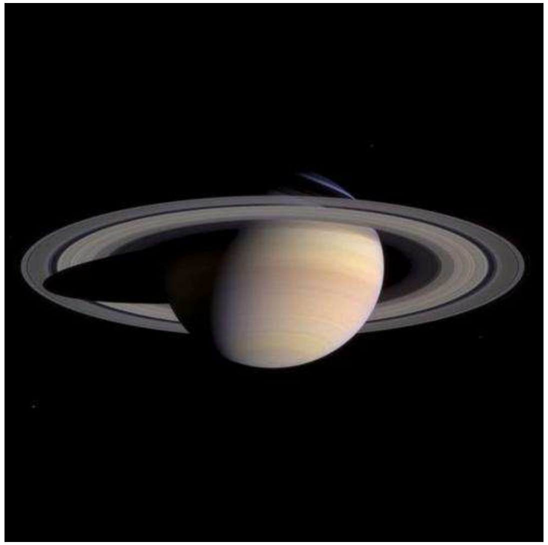


Canyon géant sur Mars


Jupiter
HUBBLESITE.org

Sonde Cassini

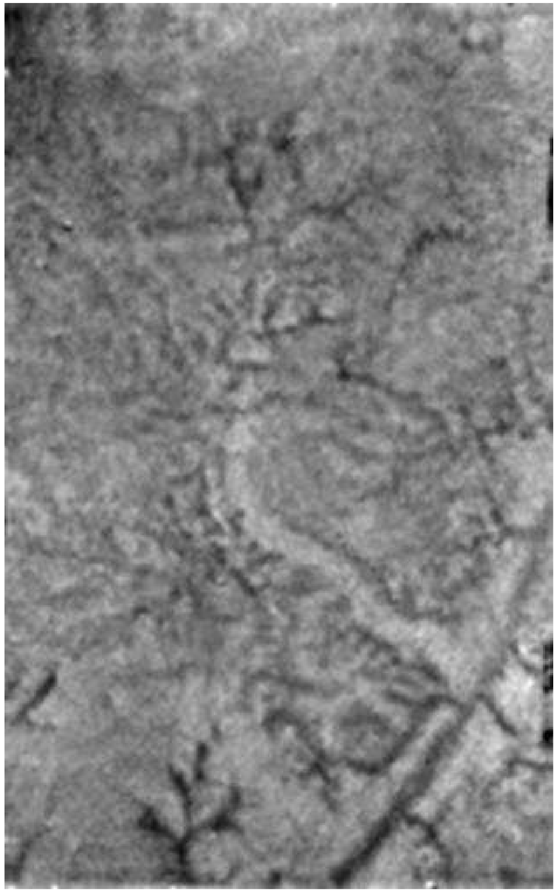
Saturne



Titan

Anneaux en couleurs réelles

Titan
Sources de méthane dans un sol de glace ?



Exploration directe de tout le Système Solaire par sondes spatiales

Lune : Apollo *(1969)*

Mars : multiples missions : *fabuleuses images*

Autres planètes et satellites → *Saturne/Titan (2005)*

Etudes comparées de l'évolution des planètes : atmosphère, intérieurs compréhension de leur formation et de l'histoire du Système Solaire

Recherche de vie : Mars → Europa, etc.

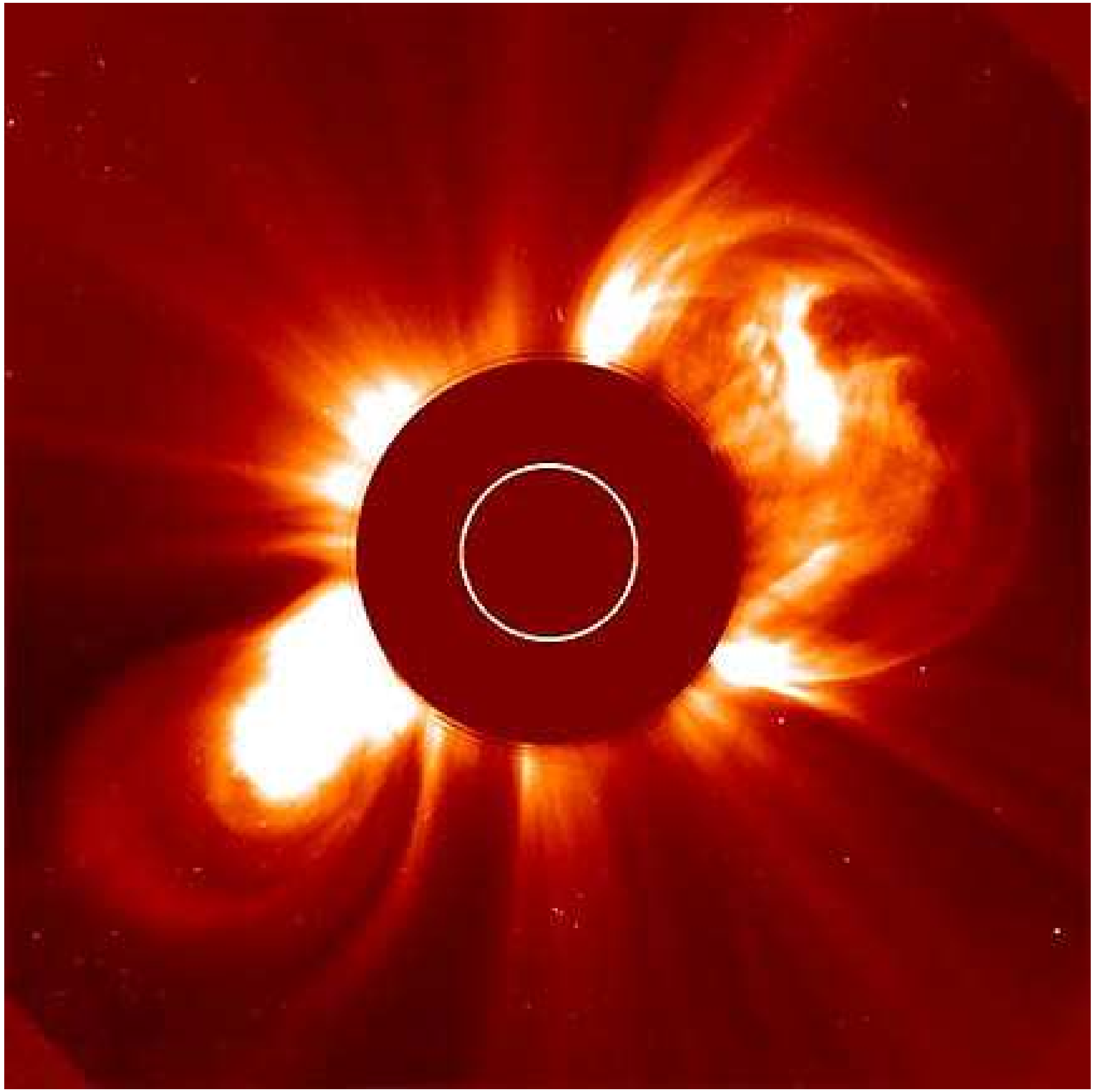
Comètes (et astéroïdes) → matière primitive interstellaire

+ Riche information de l'analyse chimique de météorites primitives → Acides aminés

Comète Hayakutate

Survol du noyau d’une comète

Gigantesque éruption-tempête solaire
(satellite SOHO)



Exo-Planètes

La généralité des systèmes planétaires autour des étoiles était suspectée depuis longtemps

Détection difficile : Terre qq millionèmes de la masse du Soleil ; Jupiter qq millièmes

En fait détection tardive, mais plus facile que prévu : surprise de trouver des planètes massives tout près de certaines étoiles → petit mouvement de l'étoile autour du centre de gravité étoile+planète

Plus de cent exo-planètes connues

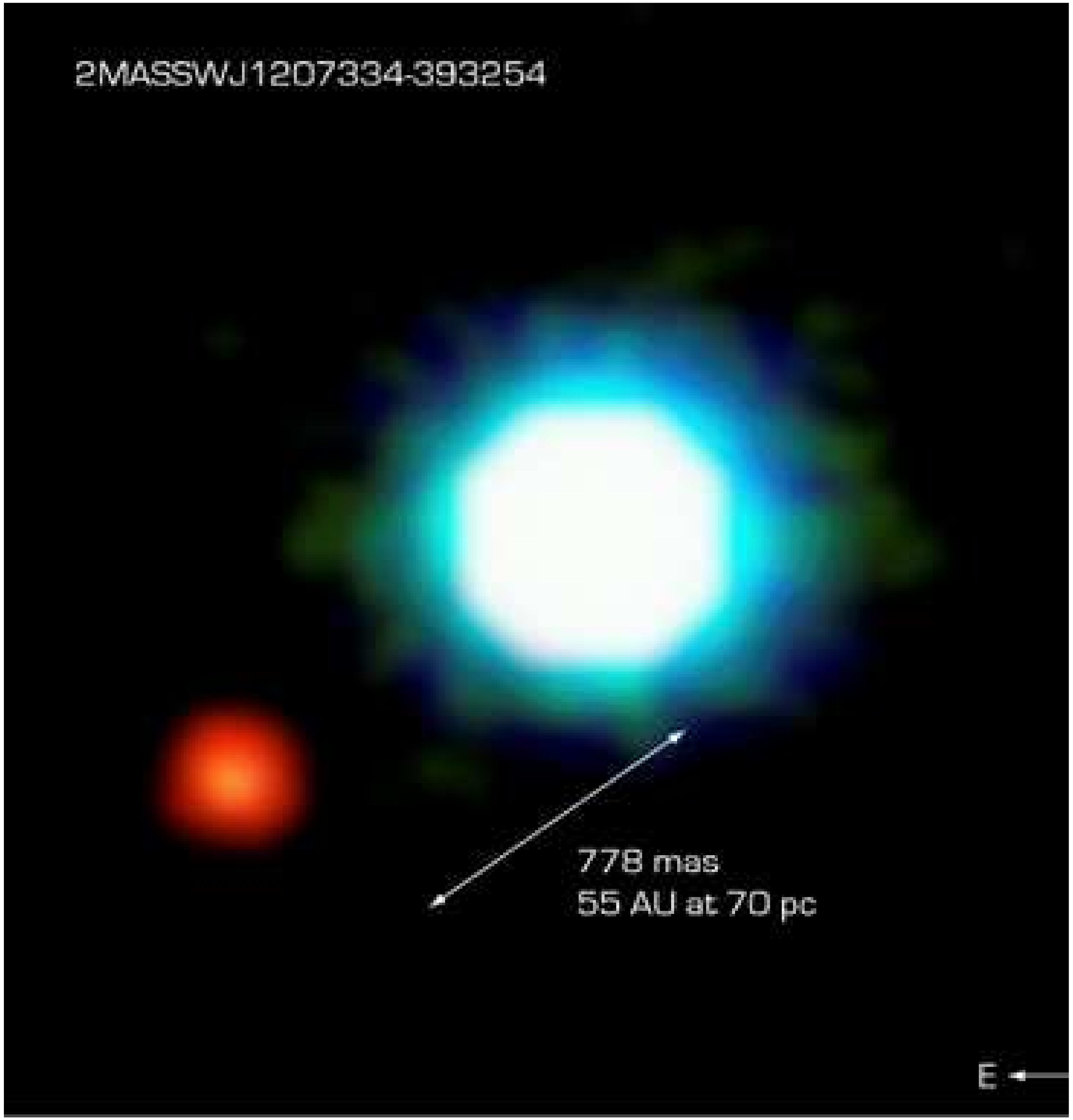
Intense activité → projets très pointus au sol et dans l'espace pour détecter des planètes de masse terrestre et caractériser leur atmosphère : Oxygène = vie

→ Un des grands objectifs qui dominera tout le XXIe Siècle

Première image directe d’une exo-planète

(à coté de son étoile naine brune)

(ESO-VLT avril 2005)



The Brown Dwarf 2M1207 and its Planetary Companion (VLT/NACO)

Exobiology

Central question in our exploration of the Universe

Continual speculations for centuries about the existence of extra-terrestrial beings
→ 2 levels :

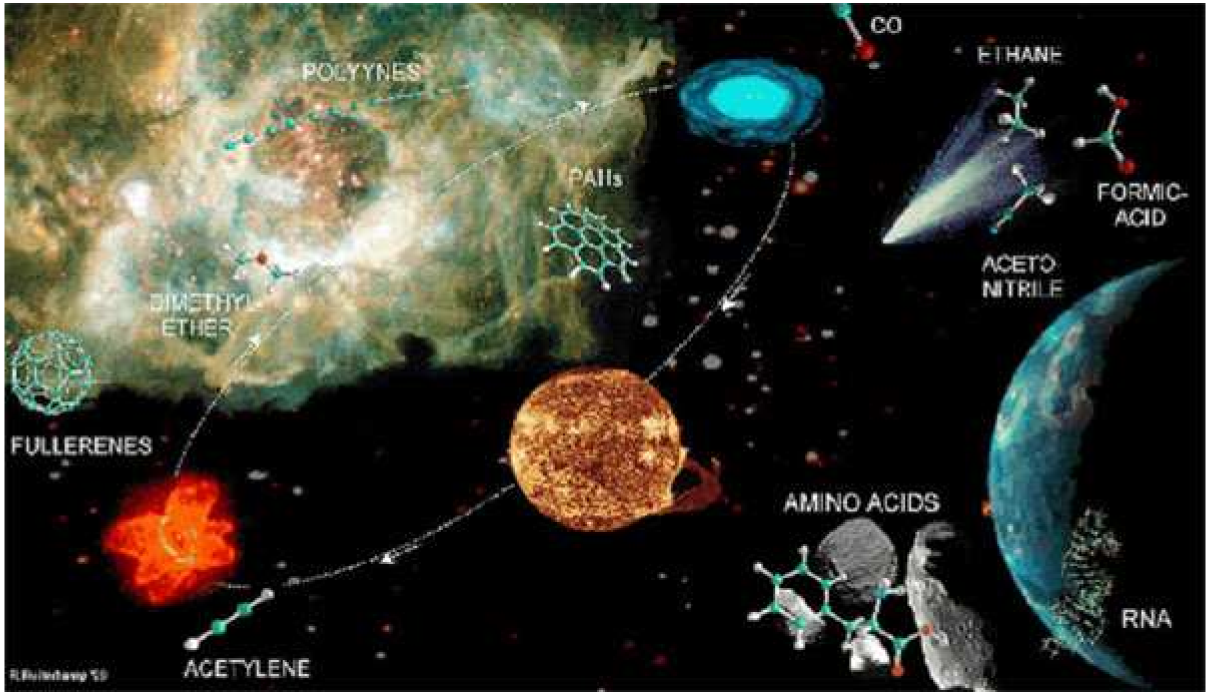
1. **Origin of life**

Question to biologists first
→ astronomers : nothing or little (existence of the Moon?) special in astronomical conditions of the Earth and Solar System when life appeared
→ thousands of billions of similar systems in the Universe
Is the appearance of life usual or unique?
A first answer should come from the Solar System: Mars, etc. If life is found there, is it related to terrestrial life ?

2. **Appearance/becoming//survival of advanced civilisations ???**

A relatively fast colonisation of a galaxy seems possible. No sign

→Possibility of an infinity of parallel Universes allowing the existence, in one of them, of very exceptional conditions favorable to life: anthropic principle ?????


CO
ETHANE
POLYYNES
PAHs
FORMIC-
ACID
ACETO
NITRILE
DIMETHYL
ETHER
FULLERENES
AMINO ACIDS
RNA
ACETYLENE

Open tracks and questions for the XXIth Century

- 1. Under way → results within 20 years or so :

- **Better cosmic parameters**
- **Detection of the first generations of galaxies et stars in the Universe**
- **Detection of gravitational waves ; merging of massive black holes, etc.**
- **Detailed surveying of the Milky Way (GAIA)**
- **First Earth-like exo-planets**
- **Comet sample return→ prebiotic matter**
- **Mars sample return → Life or not on Mars**

Open tracks and questions for the XXIth Century

- 2. In the century :

- Man on Mars
- Life or not in Solar System.
- Analysis of earth-like exo-planets → Life or not
- Analysis of pre-biotic matter: comets, etc.
- Very detailed knowledge of the Milky Way and its history
- Advanced radio search of technological civilisations in the Milky Way

- But one may bet that most of other major findings will answer the most difficult Following questions, or other questions not yet expressed

Open tracks and questions for the XXIth Century

- 3. Questions difficiles

(connected to particle physics, whose answers may be as well soon as very late)

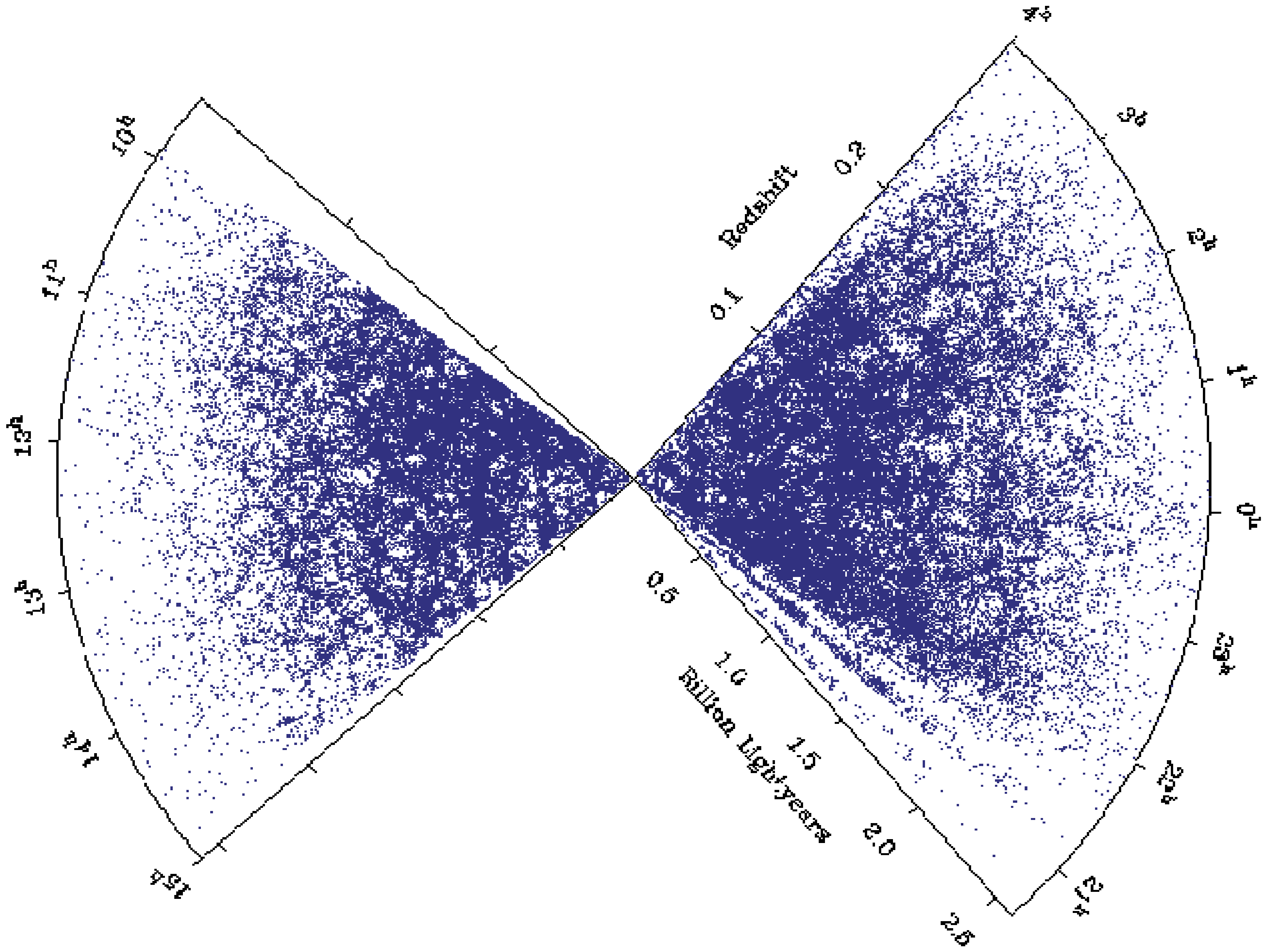
- **Nature of dark matter**
- **Origin of reacceleration (dark energy)**
- **Physics of inflation and before**
- **Possibility/need of additional dimensions for the Universe (branes, etc.) and non trivial topology?**

Plus :

- Extra-terrestrial Life/Intelligence (origin of life)

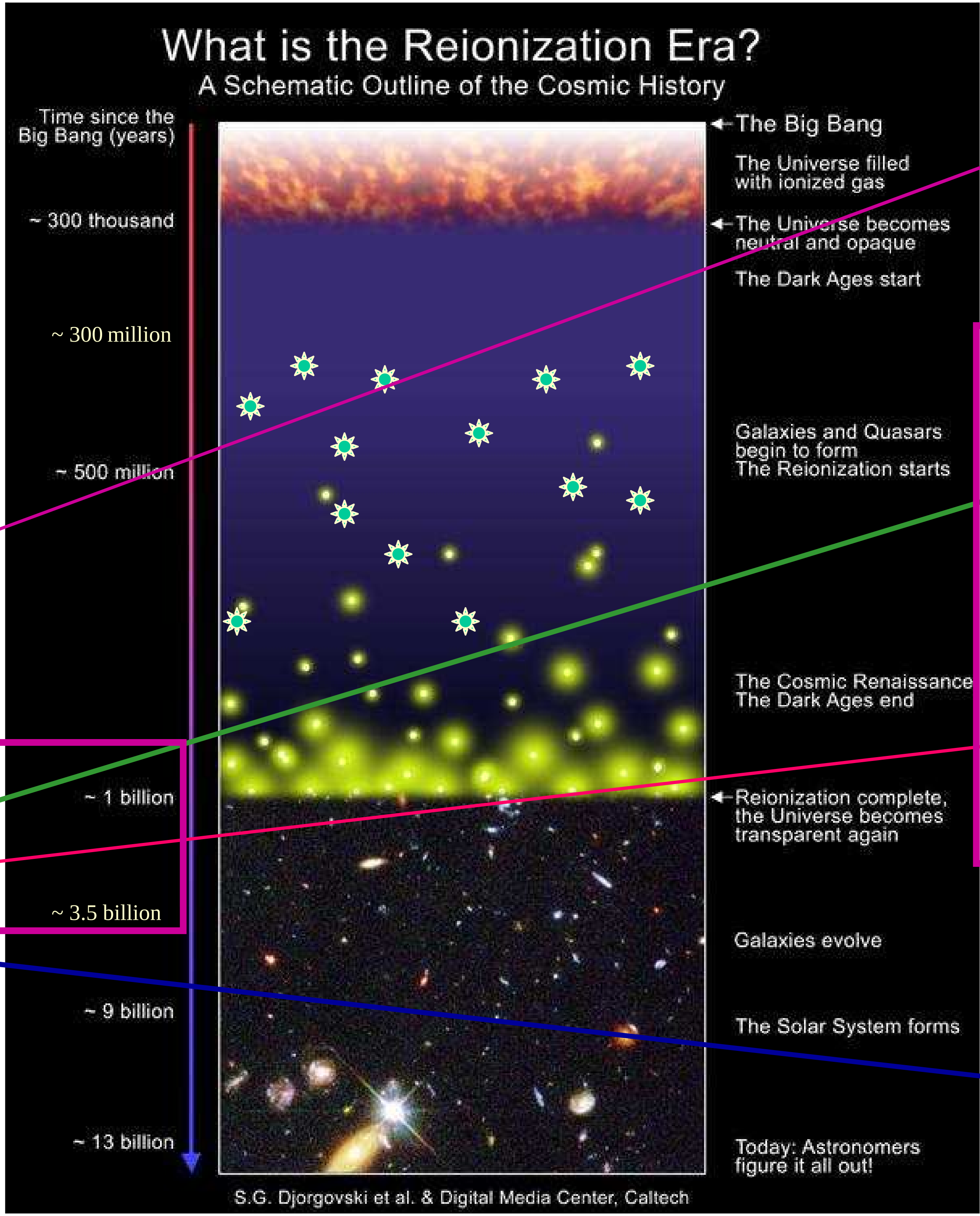
- (Anthropic principle)


Gravitational Lens in Galaxy Cluster Abell 1689
HUBBLESITE.org



10h
11h
12h
13h
14h
15h
4h
3h
2h
1h
0h
23h
22h
21h
Redshift
0.1
0.2
0.5
1.0
1.5
2.0
2.5
Billion Light-years

z	D_{phot} (Gpc)
1000	
20	230
12	130
z= 6	60
z=2	16
0.5	3
0	

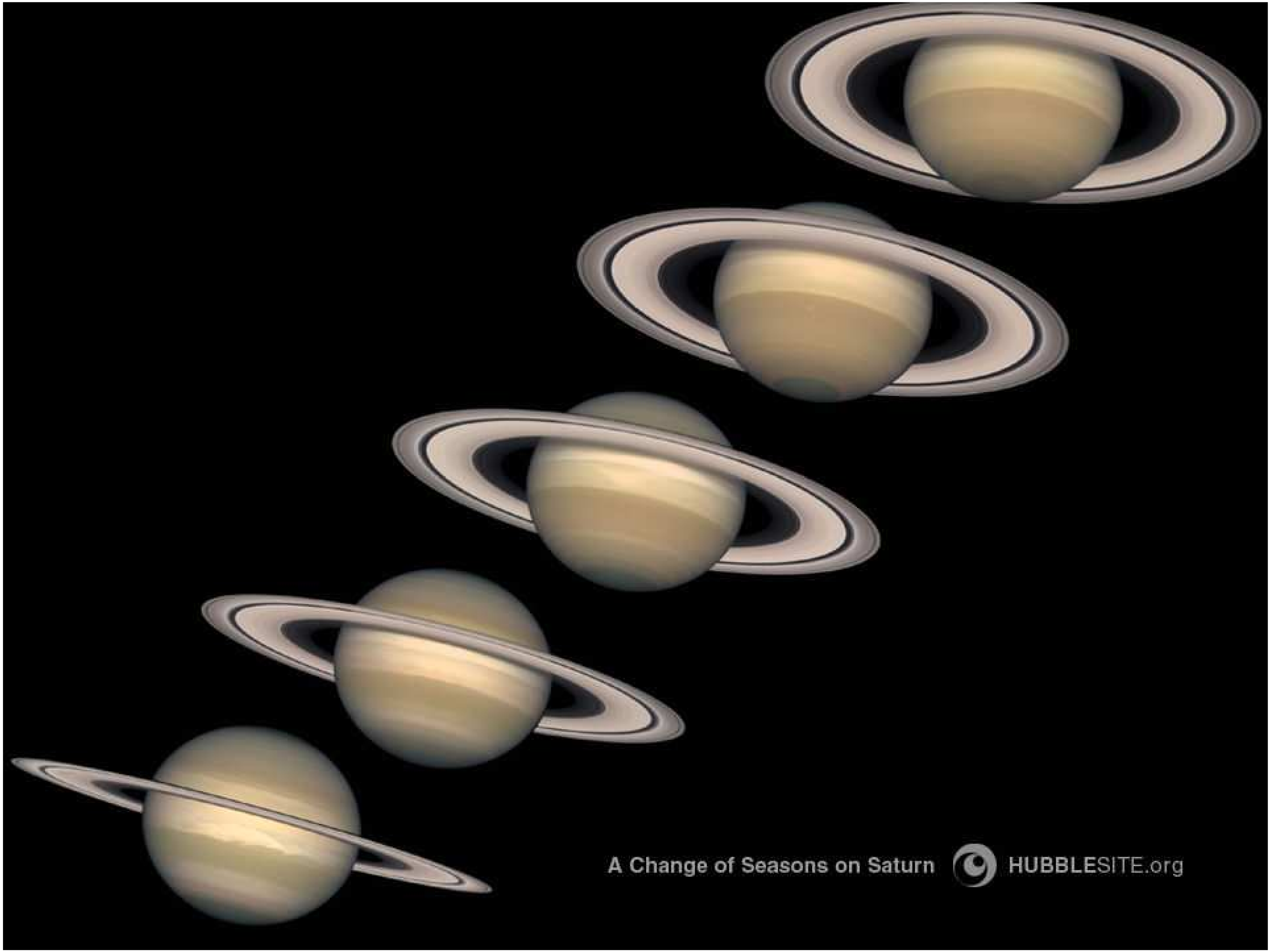


z ~ 7 – 20 ?
- Reionization
PopIII stars +1st galaxies
- Formation of 1st galaxies
Pop. II stars
- First AGN

z ~ 4 – 7 :
Current frontier
- Galaxies and QSOs detection
- End of reionization

z ~ 1.5 -4:
- Peak of star formation
submm sources + LBGs
- Peak of QSO activity
Proto-cluster formation

z ~ 0.5-1.5 :
Final phase of active star formation
- ISOCAM sources
- Weak X-ray AGN
- Cluster formation


A Change of Seasons on Saturn
HUBBLESITE.org