La question des premières étoiles de l'Univers

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Nuit étoilé sur le Rhone – Vincent Van Gogh (1888) – Musée d'Orsay

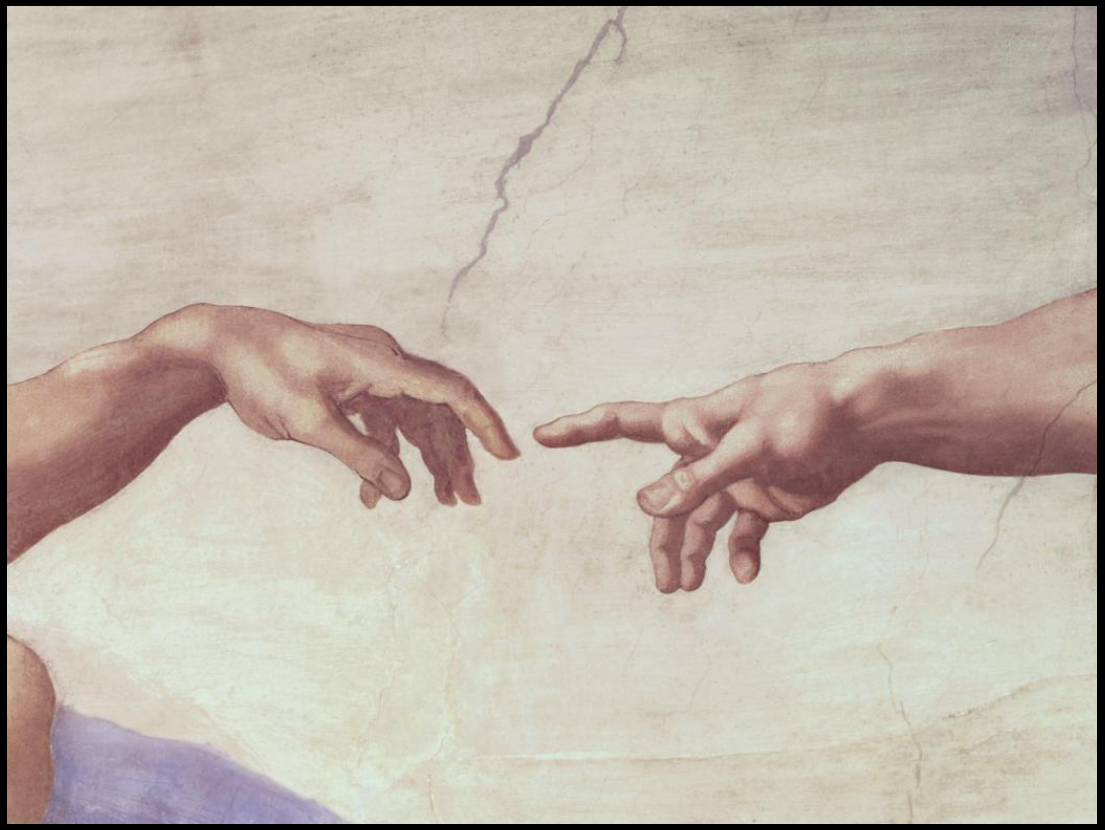
- Conférence publique CPPM –

Samedi 23 Novembre 2013

Centre de Physique des Particules de Marseille


WHERE THE HELL DID IT ALL COME FROM?

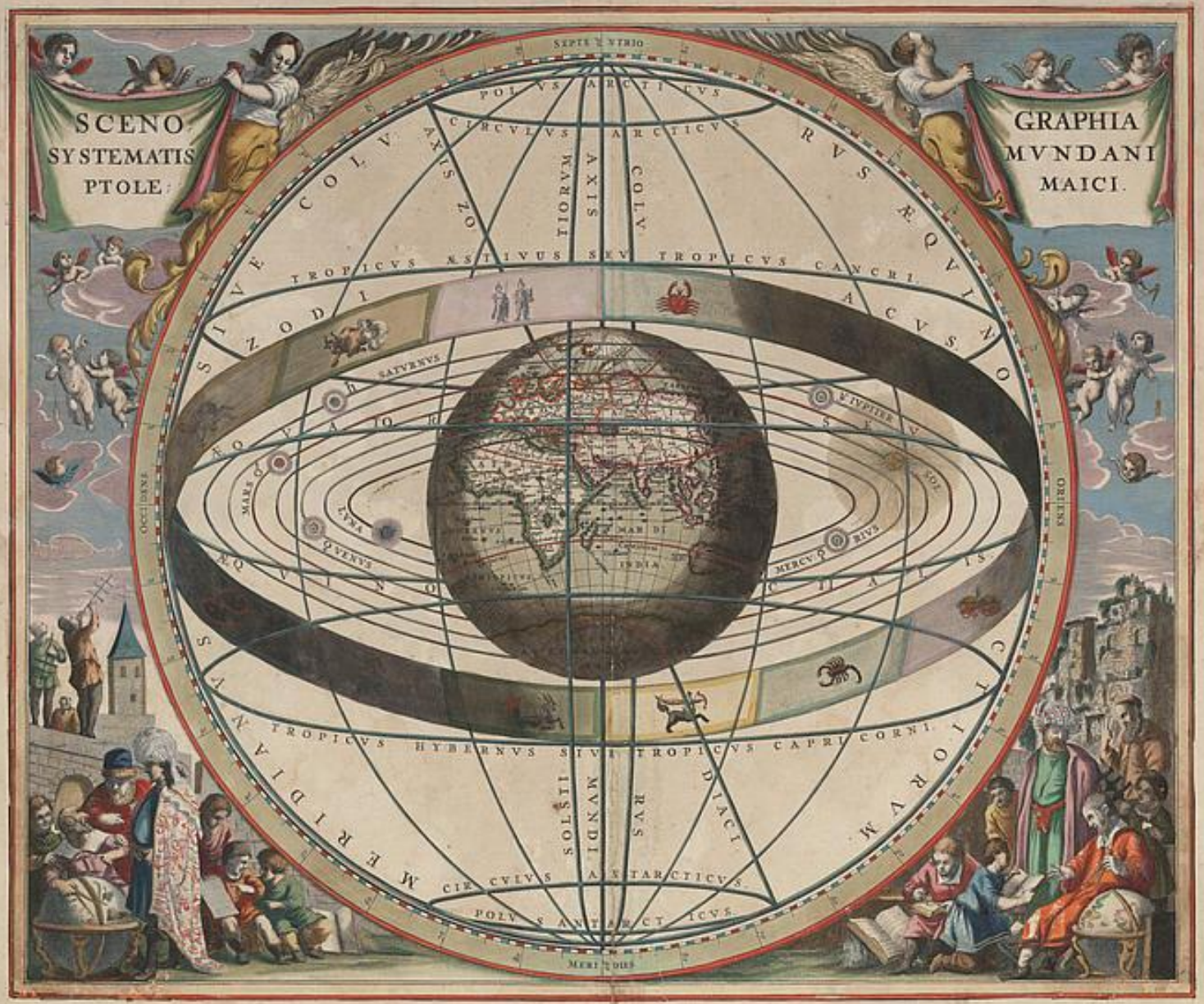
Premières ? … étoiles !



La création d'Adam (détail) – Michel Angelo (1541) – Chapelle Sixtine Rome

Existe t'il une histoire à l'Univers ?

Système de Ptolémée (1543)



Scenographia systematis mvndani Ptolemaici – Johannes Van Loon (1660) – Theological Institute – University of Utrecht

Système de Copernic (140)

NICOLAI COPERNICI TORINENSIS DE REVOLVTIONIbus orbium cœlestium, Libri VI.

IN QVIBVS STELLARVM ET FIXARVM ET ERRATICARVM MOTVS, EX VETEribus atq; recentibus obseruationibus, restituit hic autor. Præterea tabulas expeditas luculentasq; addidit, ex quibus eosdem motus ad quoduis tempus Mathematum studiosus facillime calculare poterit.

ITEM, DE LIBRIS REVOLVTIONVM NICOLAI Copernici Narratio prima, per M. Georgium Ioachimum Rheticum ad D. Ioan. Schonerum scripta.

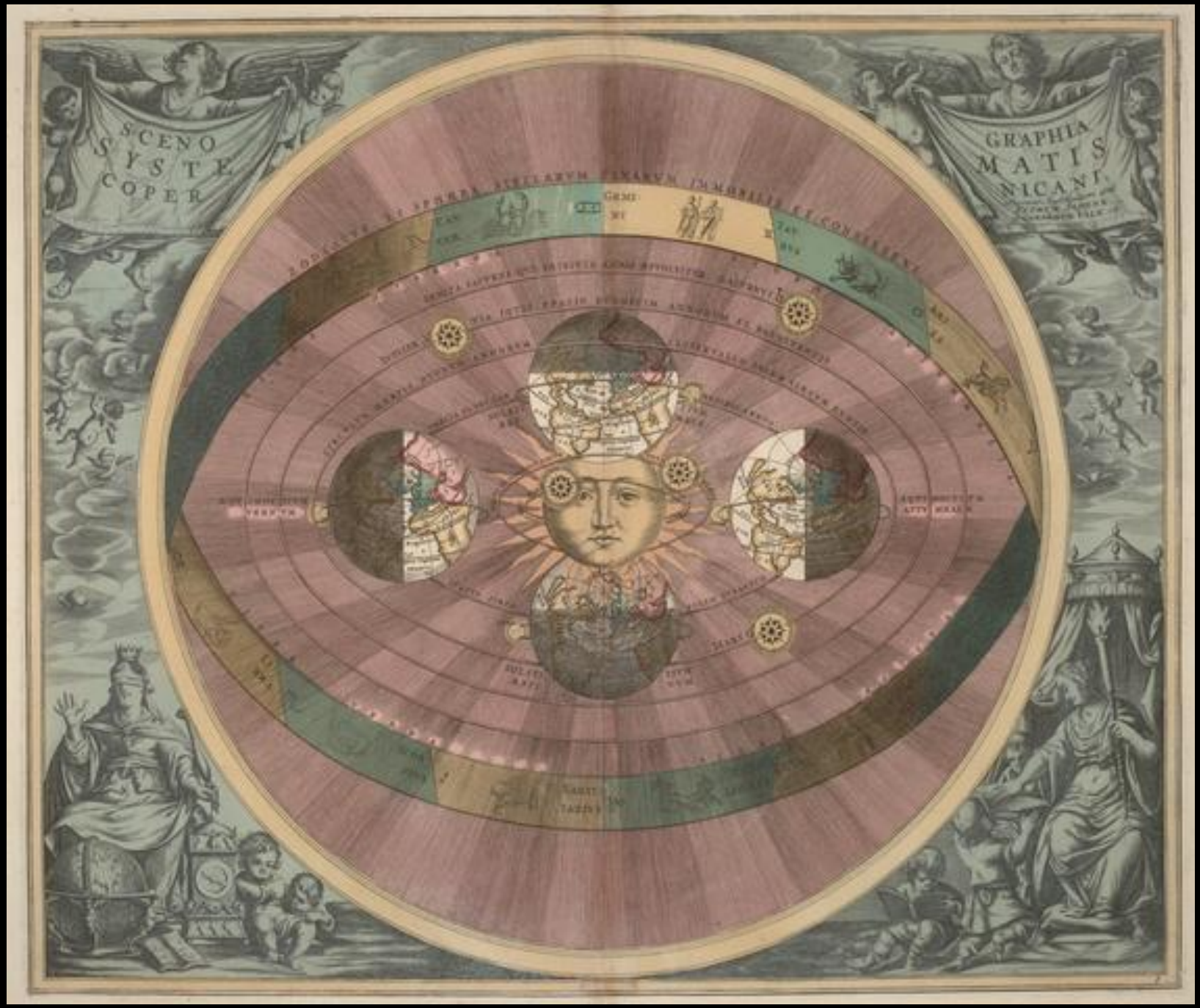
Cum Gratia & Priuilegio Cæs. Maiest.

BASILEAE, EX OFFICINA HENRICPETRINA.

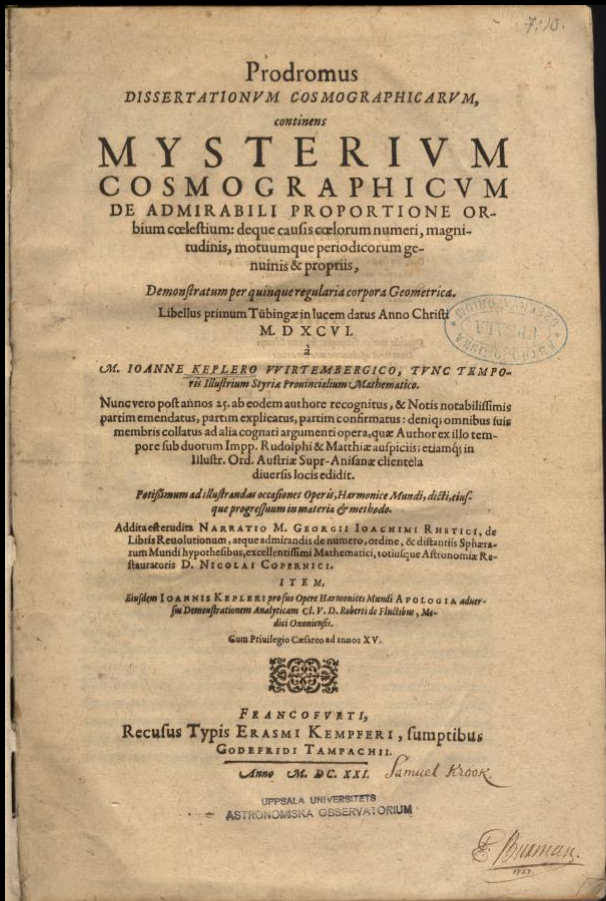
net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum spacio circũ currens. In medio uero omnium residet Sol. Quis enim in hoc

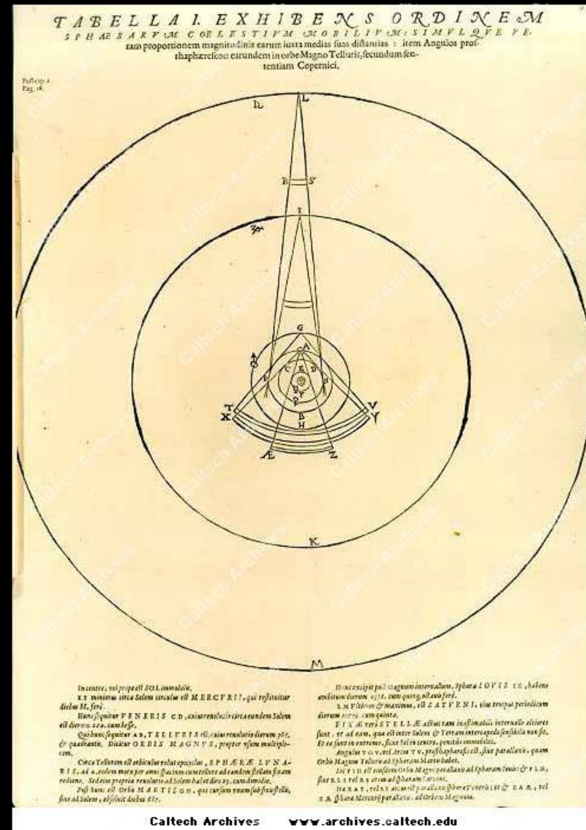
pulcherrimo templo lampadem hanc in alio uel meliori loco ponere, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentẽ omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoque minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximam Luna cum terra cognationẽ habet. Cõcipit interea à Sole terra, & impregnatur anno partu. Inuenimus igitur sub hac

Harmonia macrocosmica – Andreas Cellarius (1660) – Theological Institute – University of Utrecht

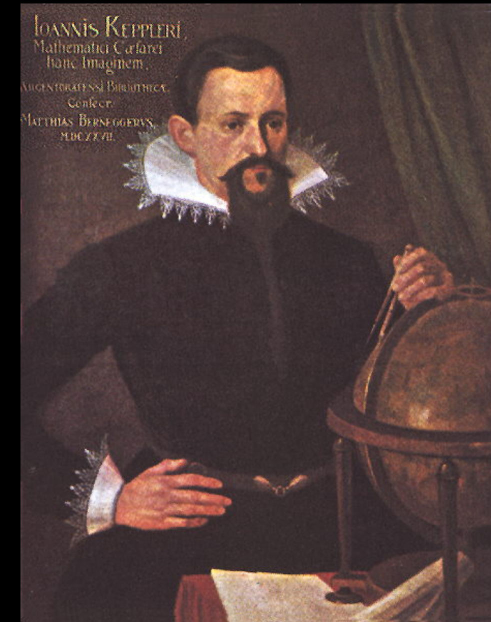


Harmonia macrocosmica – Andreas Cellarius (1660) – Theological Institute – University of Utrecht


Prodromus
DISSERTATIONVM COSMOGRAPHICARVM,
continens
MYSTERIVM
COSMOGRAPHICVM
DE ADMIRABILI PROPORTIONE ORbium cœlestium: deque causis cœlorum numeri, magnitudinis, motuumque periodicorum genuinis & propriis,
Demonstratum per quinque regularia corpora Geometrica.
Libellus primum Tübingæ in lucem datus Anno Christi M. D XCVI.
à
M. IOANNE KEPLERO VVIRTEMBERGICO, TVNC TEMPORIS Illustrium Styriæ Provincialium Mathematico.
Nunc vero post annos 25. ab eodem authore recognitus, & Notis notabilissimis partim emendatus, partim explicatus, partim confirmatus: deniq; omnibus suis membris collatus ad alia cognati argumenti opera, quæ Author ex illo tempore sub duorum Impp. Rudolphi & Matthiæ auspiciis; etiamq; in Illustr. Ord. Austriæ Supr-Anisanæ clientela diversis locis edidit.
Potissimum ad illustrandas occasiones Operis, Harmonice Mundi, dicti, eiusque progressum in materia & methodo.
Addita est erudita NARRATIO M. GEORGII IOACHIMI RHETICI, de Libris Revolutionum, atque admirandis de numero, ordine, & distantiis Sphærarum Mundi hypothesibus, excellentissimi Mathematici, totiusque Astronomiæ Restauratoris D. NICOLAI COPERNICI.
ITEM,
Eiusdem IOANNIS KEPLERI pro suo Opere Harmonices Mundi APOLOGIA adversus Demonstrationem Analyticam Cl. V. D. Roberti de Fluctibus, Medici Oxoniensis.
Cum Privilegio Cæsareo ad annos XV.
FRANCOFVRTI,
Recusus Typis ERASMI KEMPFERI, sumptibus GODEFRIDI TAMPACHII.
Anno M. DC. XXI.



Mysterium cosmographicum – Johannes Kepler (1660)



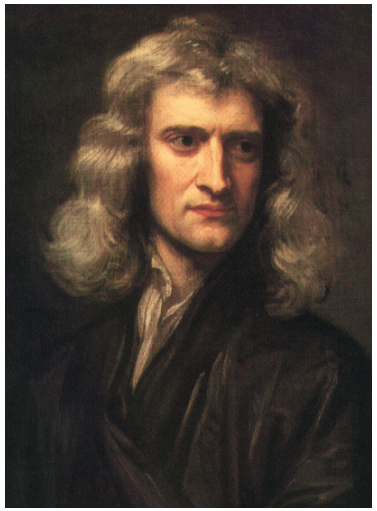
Johannes Kepler
(1571 - 1630)

Les planètes tournent autour du Soleil suivant **une trajectoire elliptique**

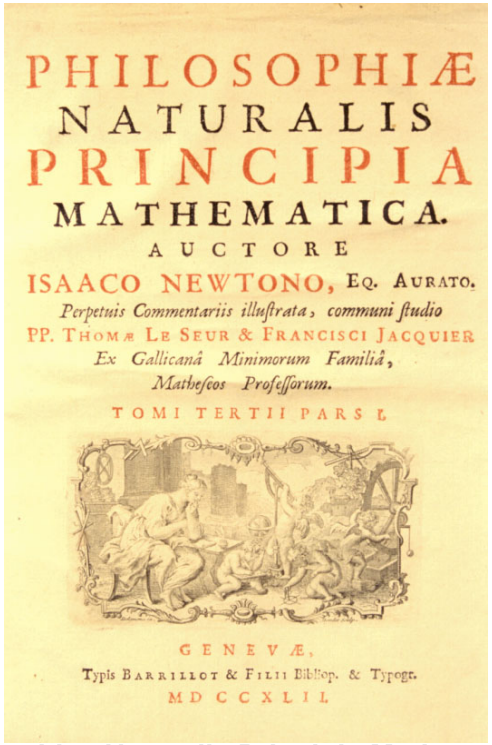
↓

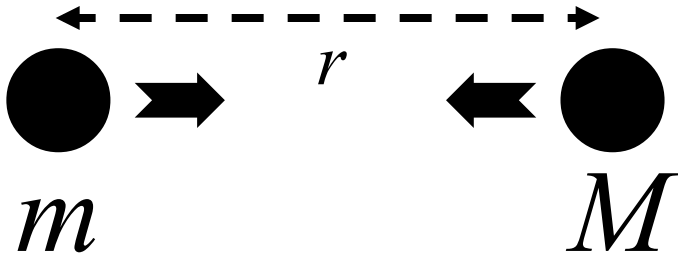
TRAJECTOIRE MATHEMATIQUE

L'EXPLICATION « THEORIQUE »



Isaac Newton
(1642-1727)

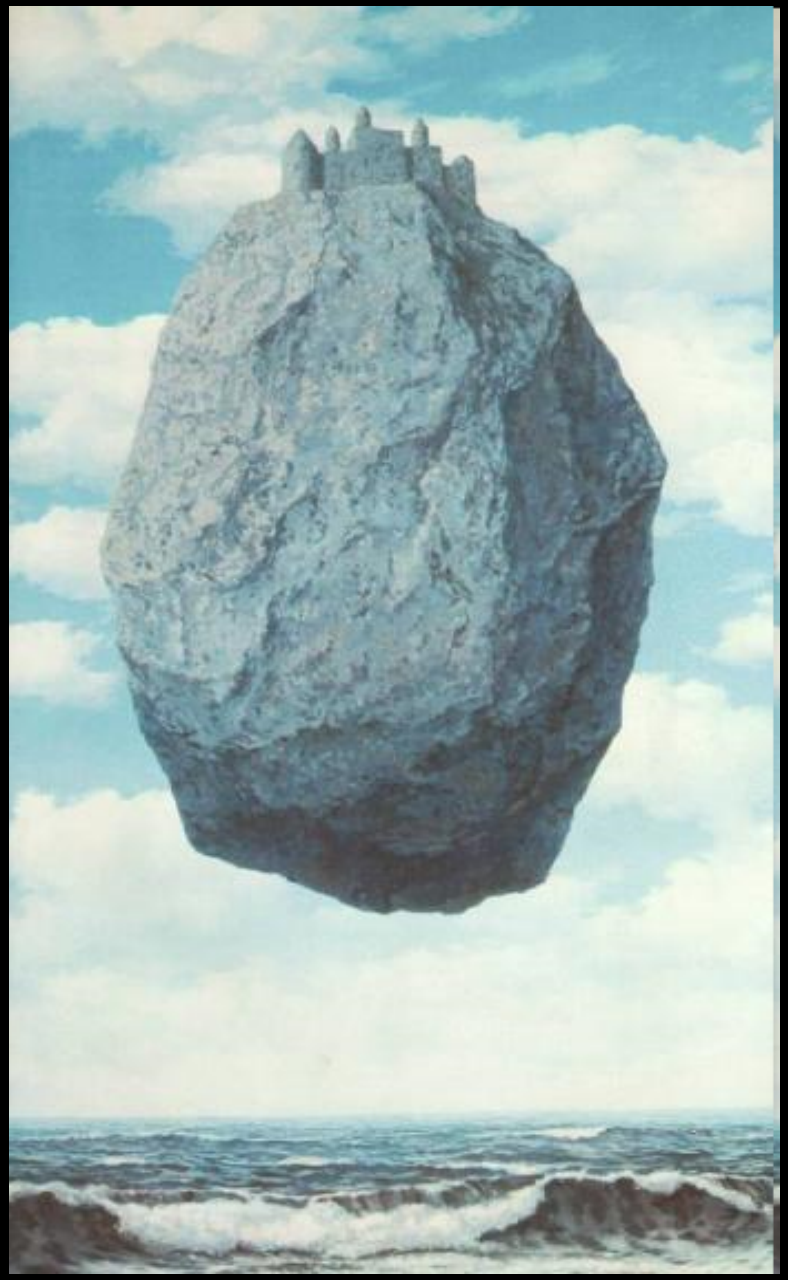




$$F = G\frac{mM}{r^2}$$

La force d'attraction F est inversement proportionnelle à la multiplication des distances

Philosophiae Naturalis Principia Mathematica– isaac Newton (1687)



Le château des Pyrénées – René Magritte (1959) – Israel Museum

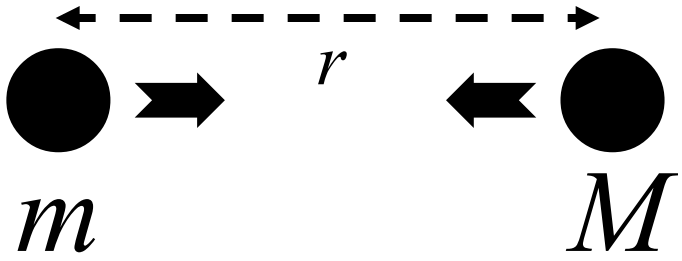
Origine de cette force ?

« *nega hypothesis* »

Newton introduit un « Monstre » !

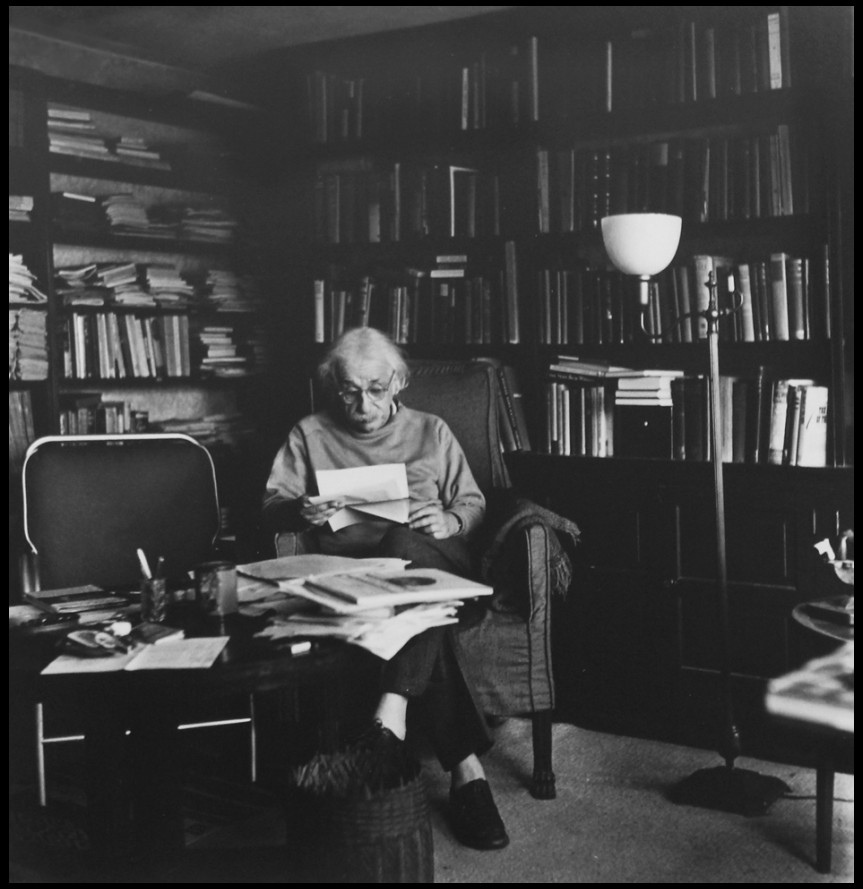
La force F est nulle

pour… r → ∞



$$F = G\frac{mM}{r^2}$$

La force gravitationnelle est partout présente dans l'Univers !



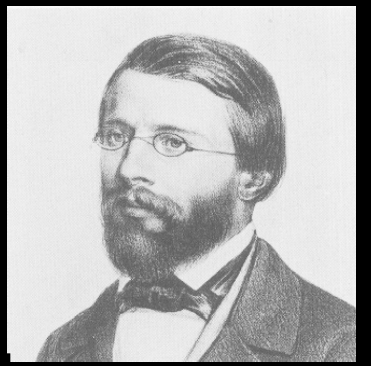
Albert Einstein
1879-1955

ALBERT EINSTEIN (1905) s'attaque à la définition de L'espace physique

Travaux sur les espaces courbes
Des mathématiciens:

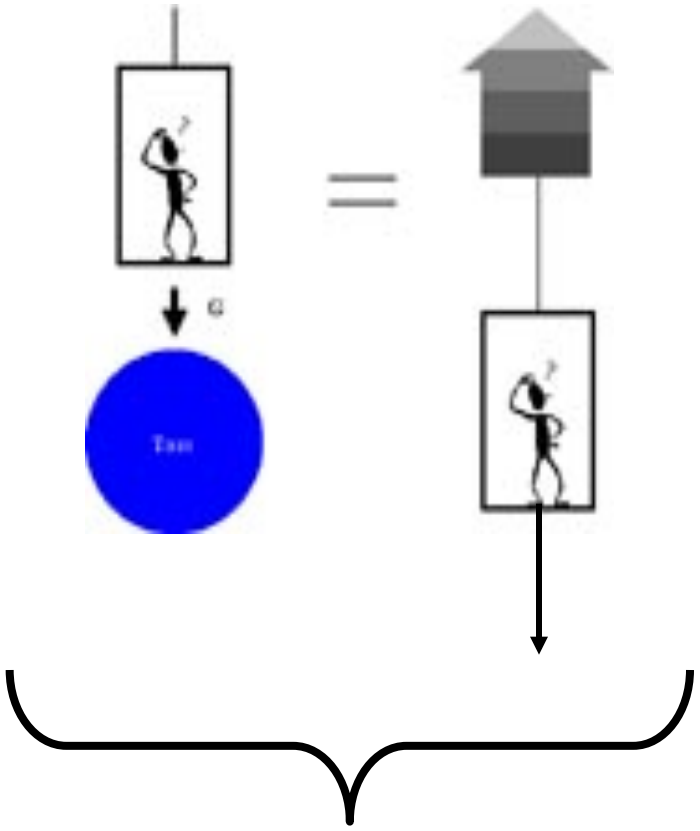
Carl Friedrich Gauss
1777-1855

Nicolaï Lobatchevski
1792-1856



Bernhard Riemann
1826-1866

PRINCIPE D'EQUIVALENCE



Même « poids »
dans les deux situations

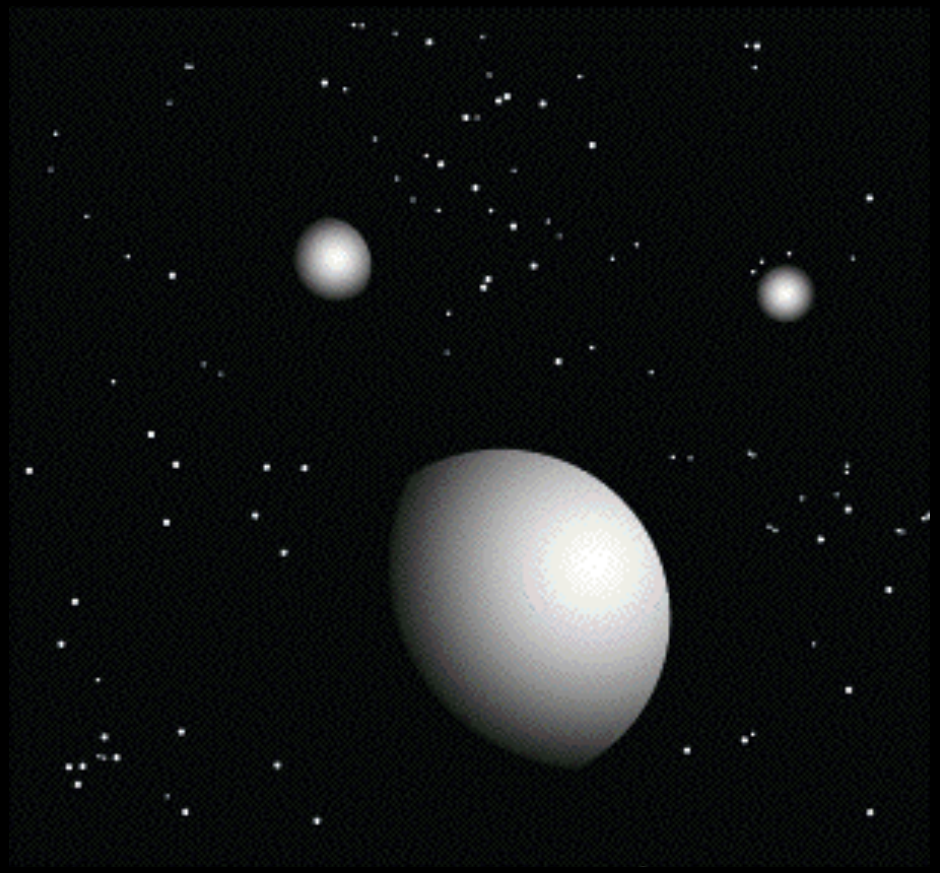
Aucun moyen de distinguer

la gravitation

d'une accélération

QUESTION

Qu'est ce que la gravité ?

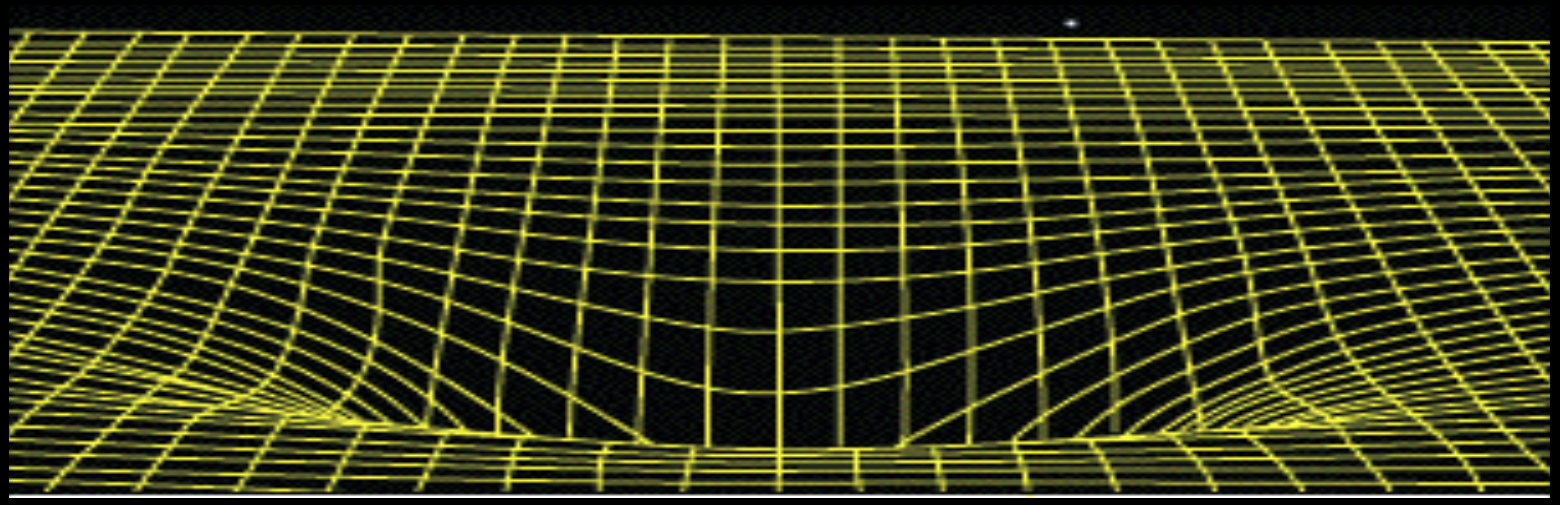


Dans la théorie Newtonienne

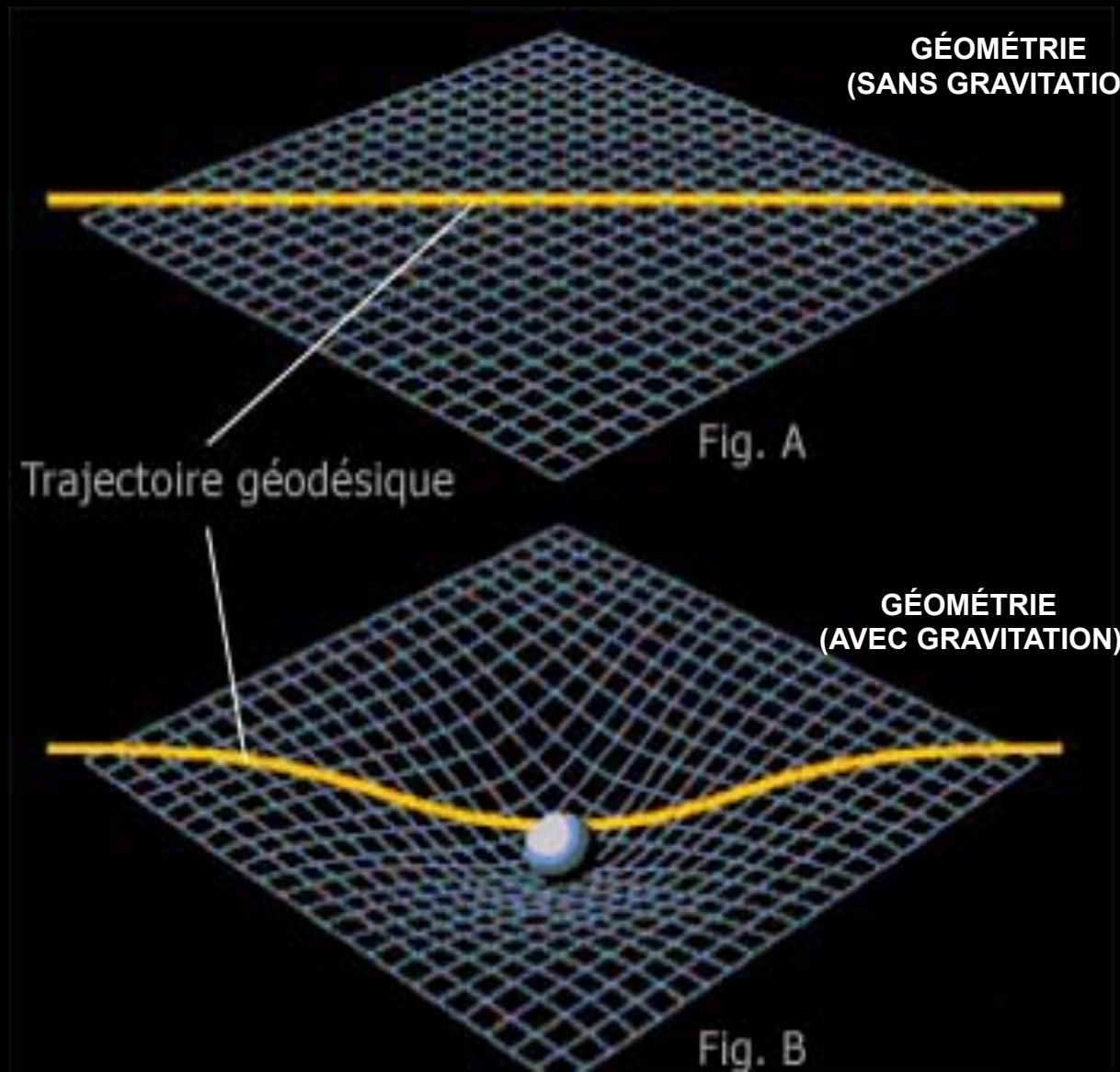
Les masses sont des objets ponctuels qui s’attirent en eux

Dans la théorie d'Einstein

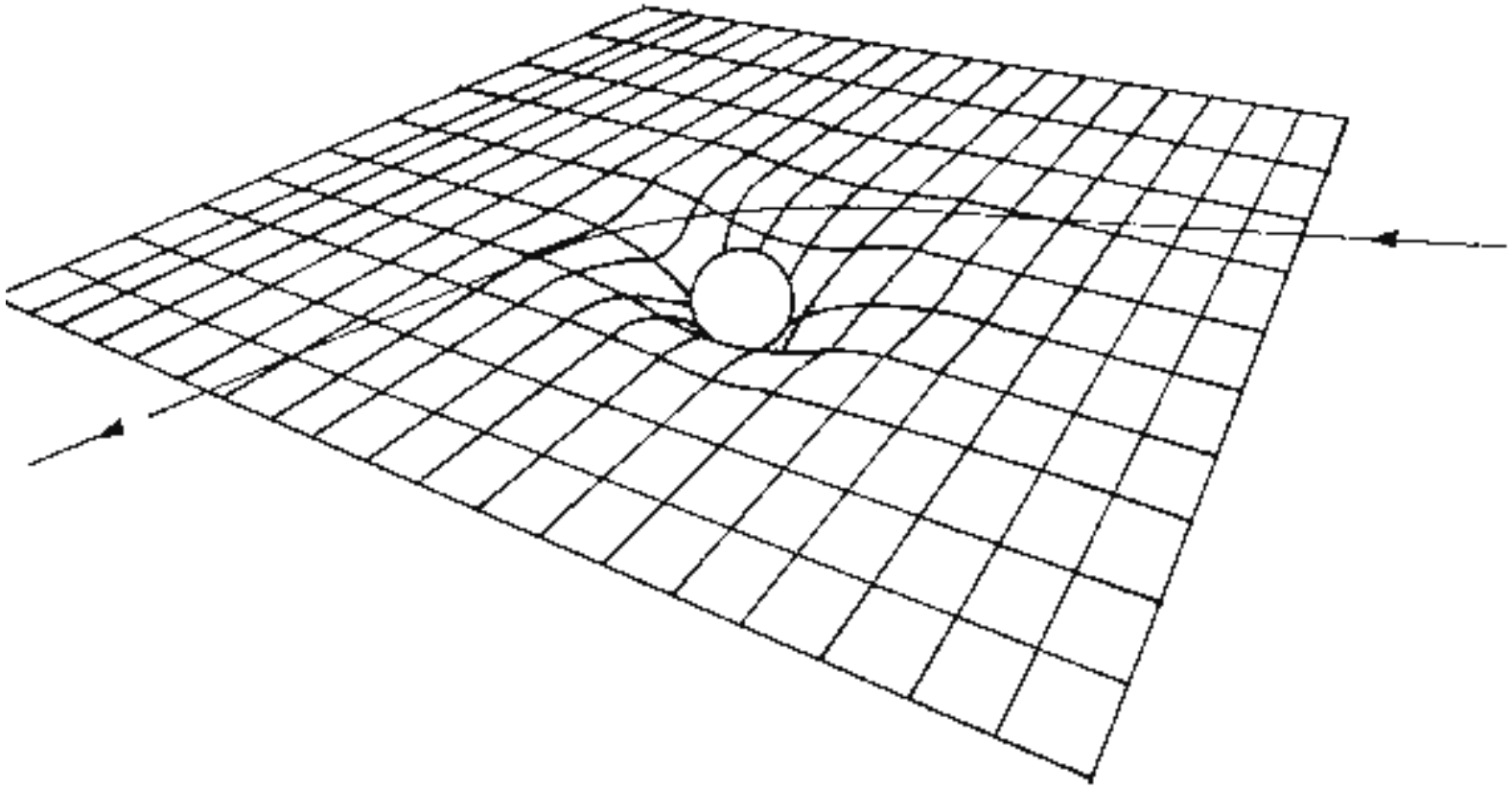
Les masses sont des courbures de l'espace



La gravitation est prise comme une déformation de l'espace physique (i.e. l'Univers)

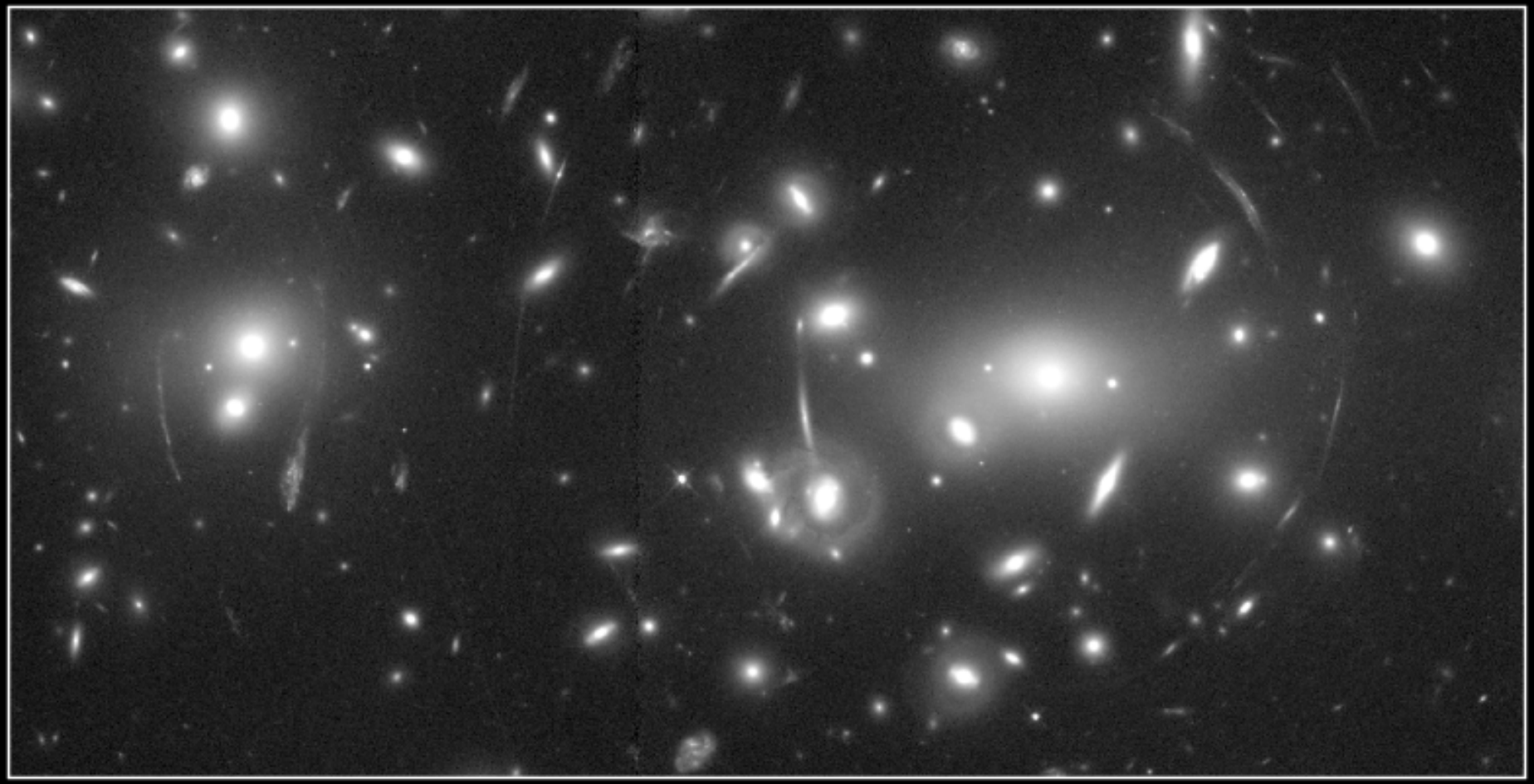


Conséquence: courbure de la lumière



Une masse courbe l'espace environnant

Courbure de la trajectoire d'un rayon lumineux

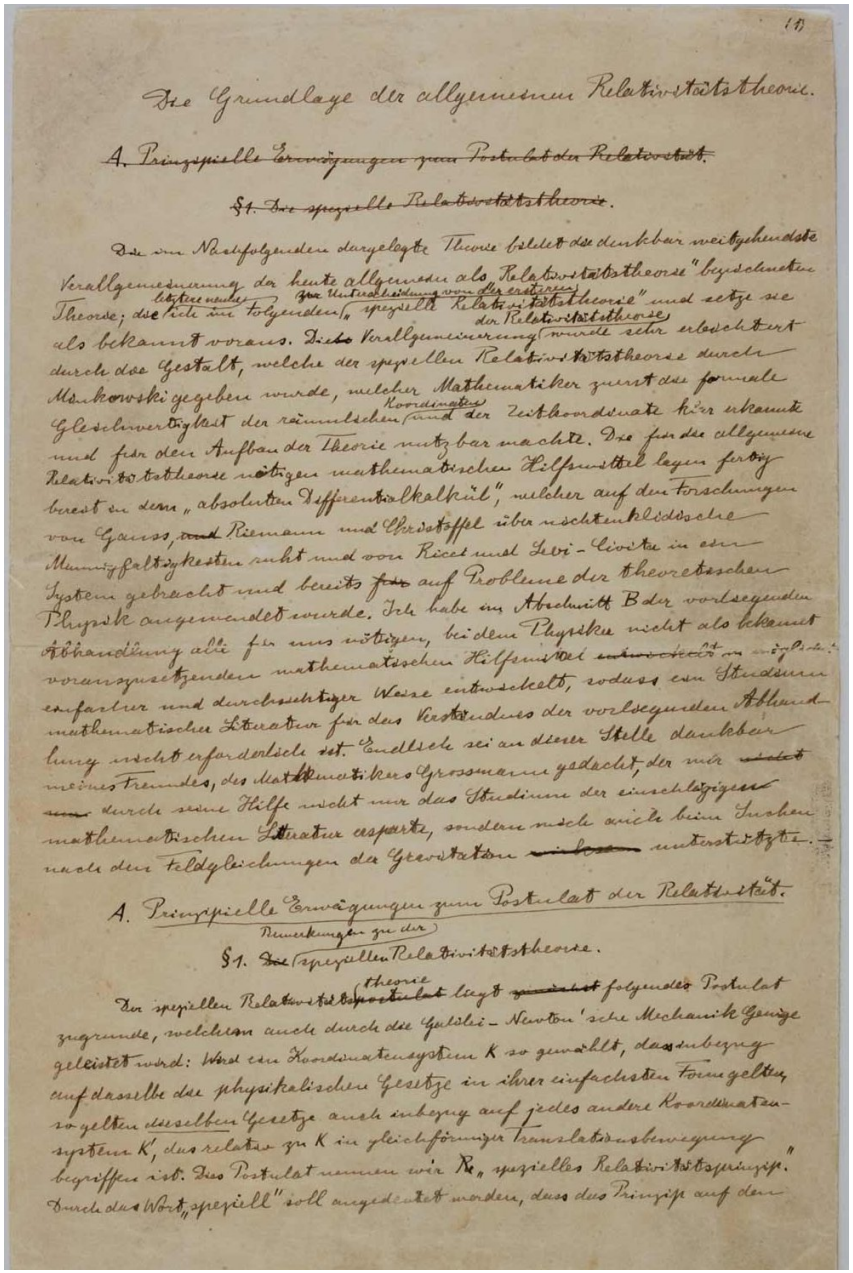


Gravitational Lens in Abell 2218

HST • WFPC2

PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA

Die Grundlage der allgemeinen Relativitätstheorie.
(Base de la relativité générale, 1916)



Die Grundlage der allgemeinen Relativitätstheorie.

A. Prinzipielle Erwägungen zum Postulat der Relativität.

§1. Die spezielle Relativitätstheorie.

Die im Nachfolgenden dargelegte Theorie bildet die denkbar weitgehendste Verallgemeinerung der heute allgemein als „Relativitätstheorie" bezeichneten Theorie; die letztere nenne ich zur Unterscheidung von der ersteren „spezielle Relativitätstheorie" und setze sie als bekannt voraus. Die Verallgemeinerung 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 entwickelt, in möglichst einfacher und durchsichtiger Weise entwickelt, sodass ein Studium mathematischen 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.

A. Prinzipielle Erwägungen zum Postulat der Relativität.

Bemerkungen zu der

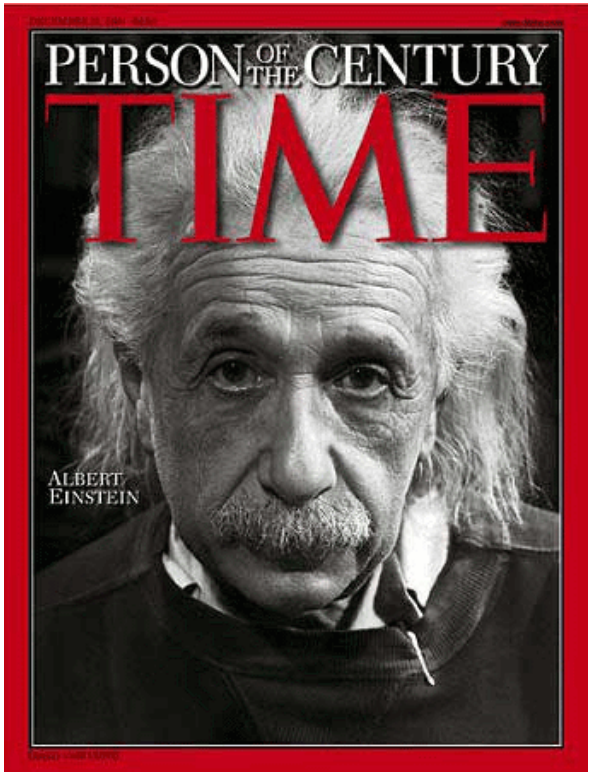
§1. Die speziellen Relativitätstheorie.

Der speziellen Relativitätstheorie liegt folgendes Postulat zugrunde, welchem auch durch die Galilei-Newton'sche Mechanik Genüge geleistet wird: Wird ein Koordinatensystem K so gewählt, dass bezogen auf dasselbe die physikalischen Gesetze in ihrer einfachsten Form gelten, so gelten dieselben Gesetze auch bezogen auf jedes andere Koordinatensystem K', das relativ zu K in gleichförmiger Translationsbewegung begriffen ist. Dies Postulat nennen wir „spezielles Relativitätsprinzip". Durch das Wort „speziell" soll angedeutet werden, dass das Prinzip auf den

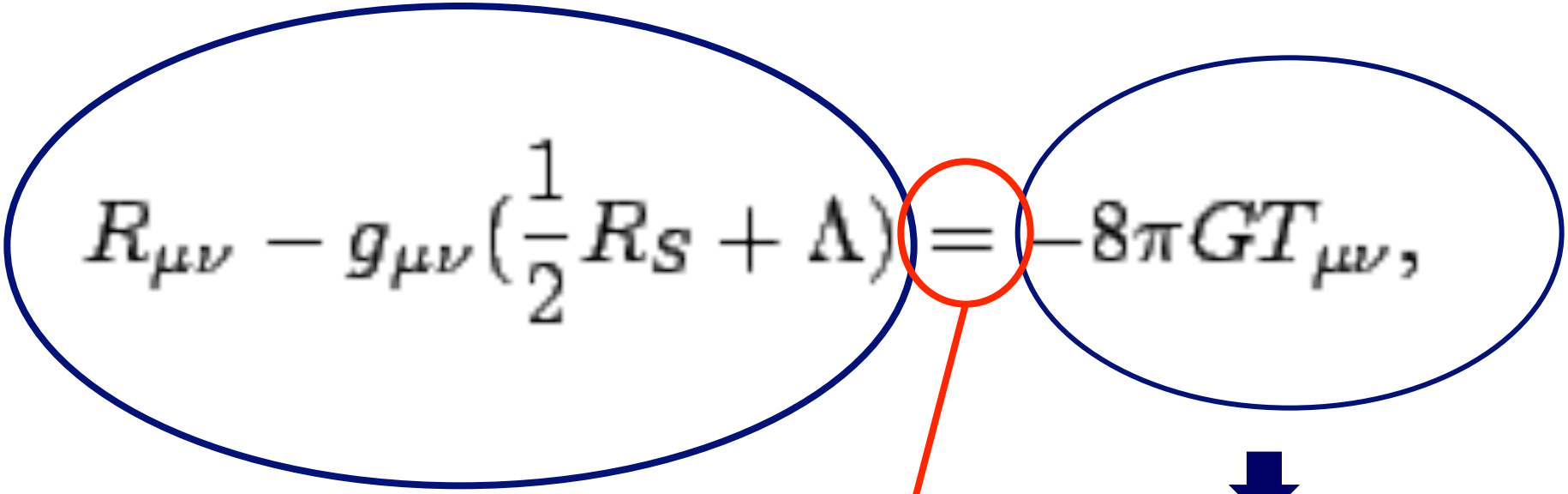
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Contenant géométrique

Contenu énergétique



A. Einstein



GÉOMÉTRIE DE L'UNIVERS

LE CONTENANT

L' ENERGIE DE L'UNIVERS

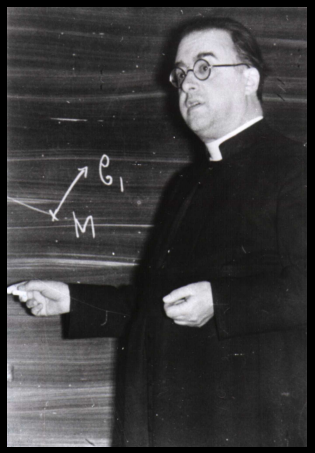
LE CONTENU

Théorie de la relativité générale

La gravité structure l'espace !

GÉNÉRALISATION DES ÉQUATIONS D'EINSTEIN

Alexander Friedmann
1888-1925

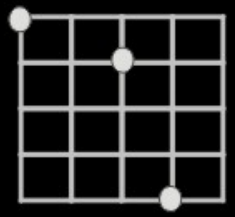


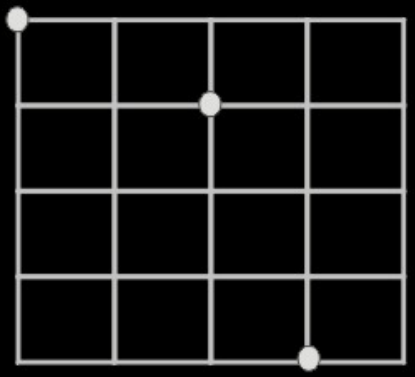
Georges Lemaître
1894-1966

Possibilité que l'Univers soit non statique !

⬇

Les distances entre objets varient au cours du temps





Expansion de l'Univers !

⬇

l'espace entre les objets croit au cours du temps

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho\leqq10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty}(10^6/t^2)dt\leqq5\times10^4, \qquad (2)$$

which gives us $t_0\leqq20$ sec. and $\rho_0\leqq2.5\times10^5$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^3 g sec./cm^3 which can possibly be understood if we

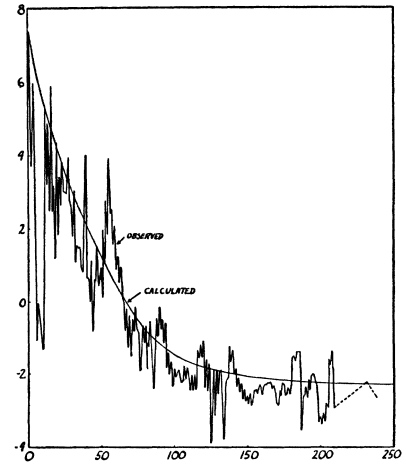


FIG. 1.
Log of relative abundance
Atomic weight

L'invention d'une histoire à l'Univers (1948)

L'article α β γ

A une époque antérieure

Georges Gamow
1904-1968

Si l'Univers se dilue au cours du temps
alors antérieurement

diamètre de l'Univers plus petit
température plus importante
densité plus importante

↓

Conditions physiques différentes

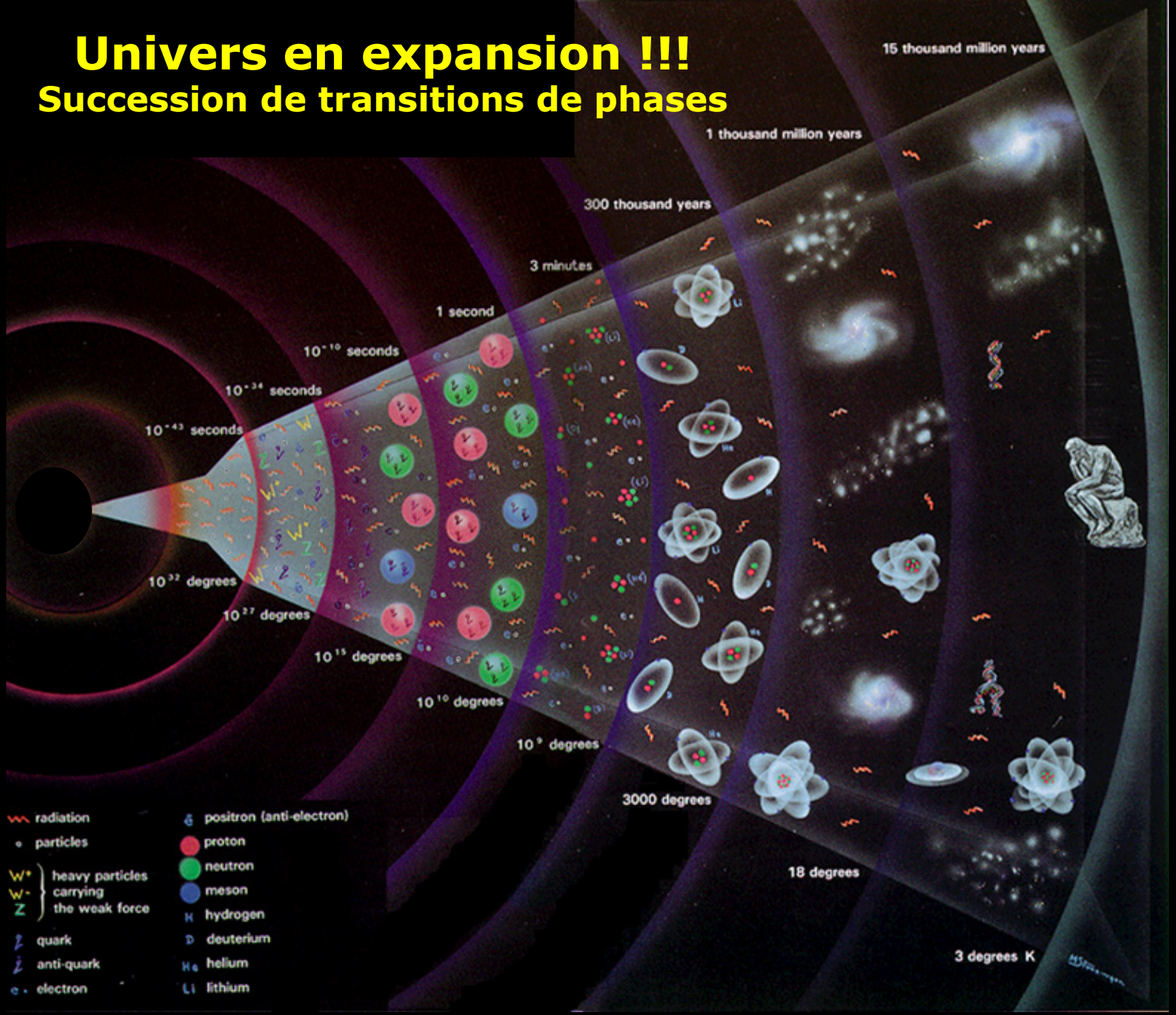
L'Univers évolue !

↓

L'idée de première chose

Univers en expansion !!!

Succession de transitions de phases



Formation des premiers noyaux

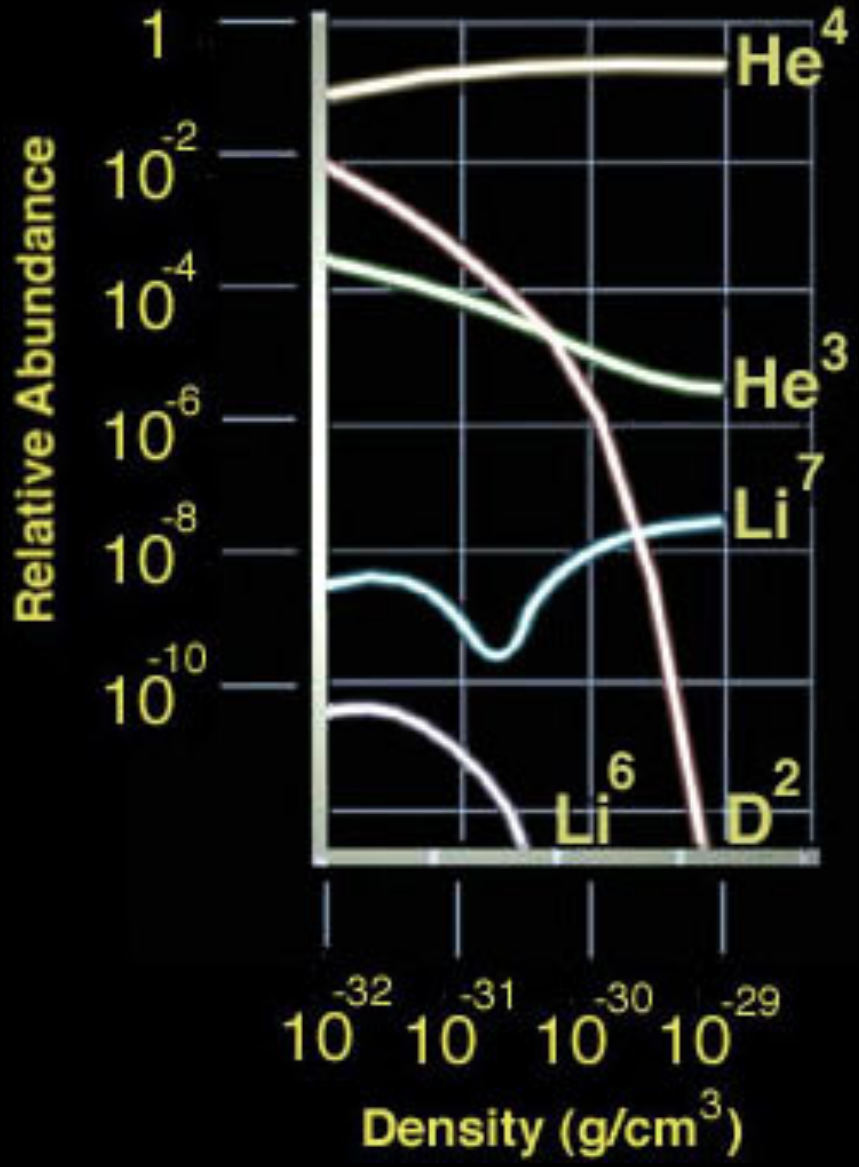
H~89 %

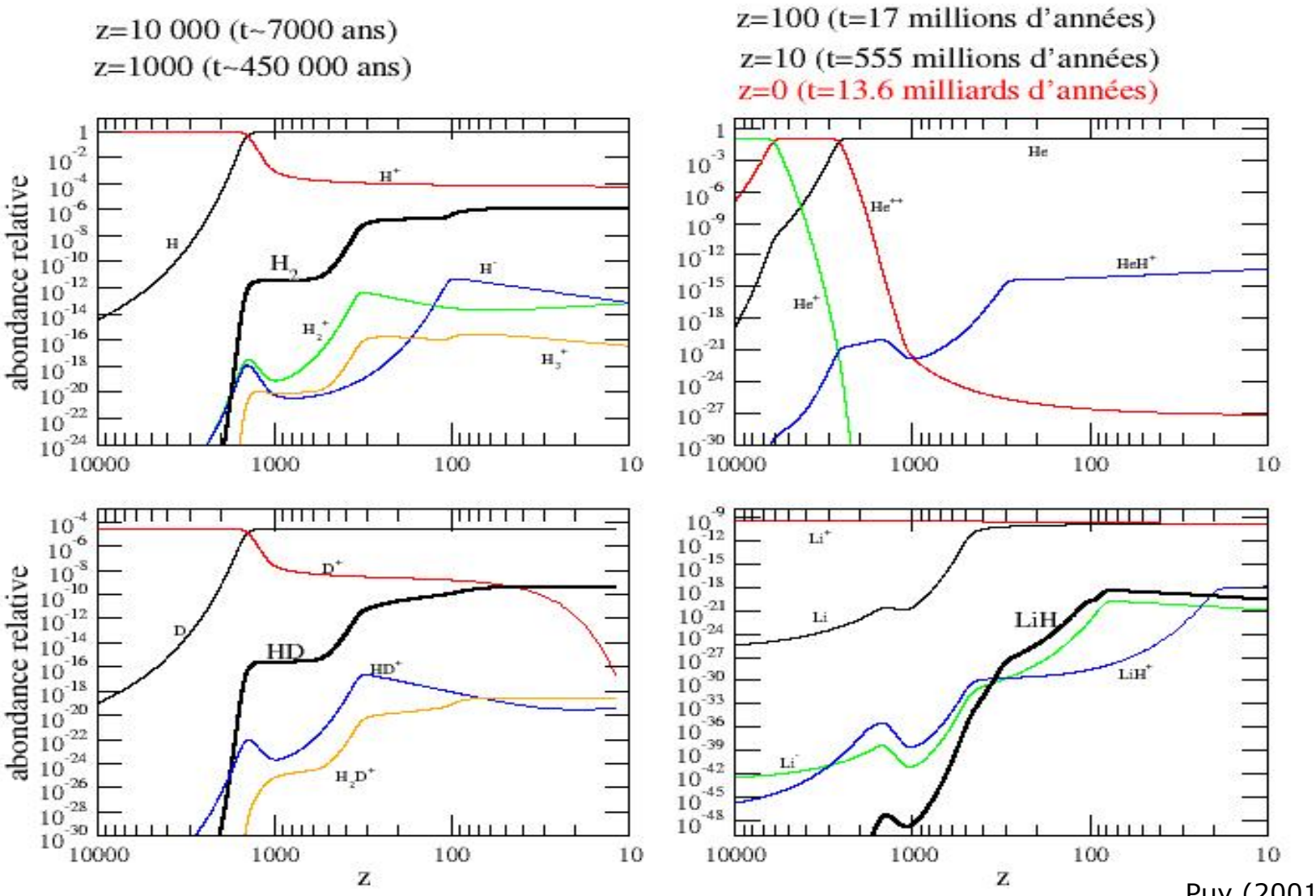
He ≈ 11 %

Li ≈ 3×10^{-5} %

D ≈ 3×10^{-10} %

À t ~ 5 minutes

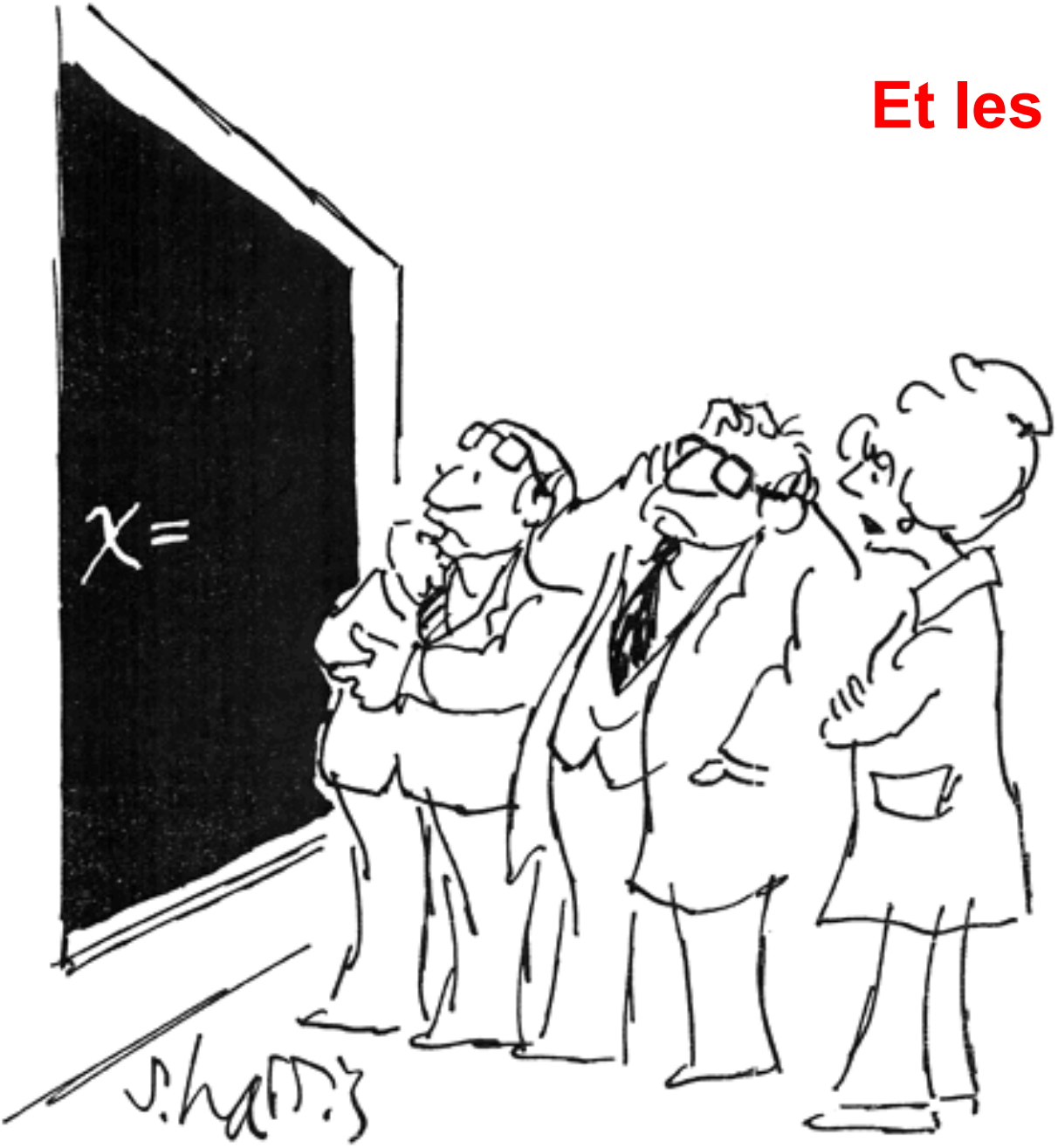




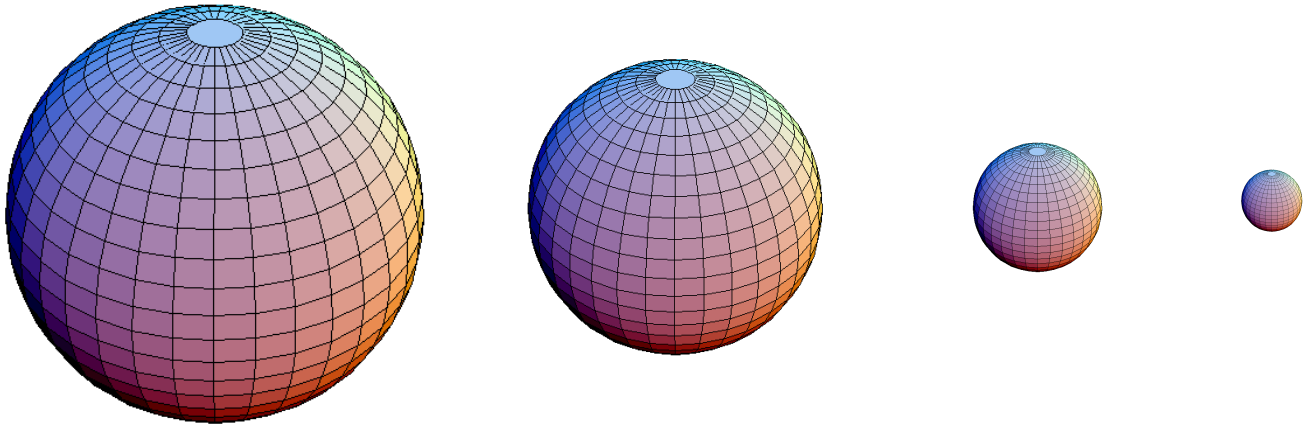
Puy (2001)

Les molécules H_2 , HD et LiH apparaissent à un age d'Univers de 450 000 ans (bien avant les premières structures)

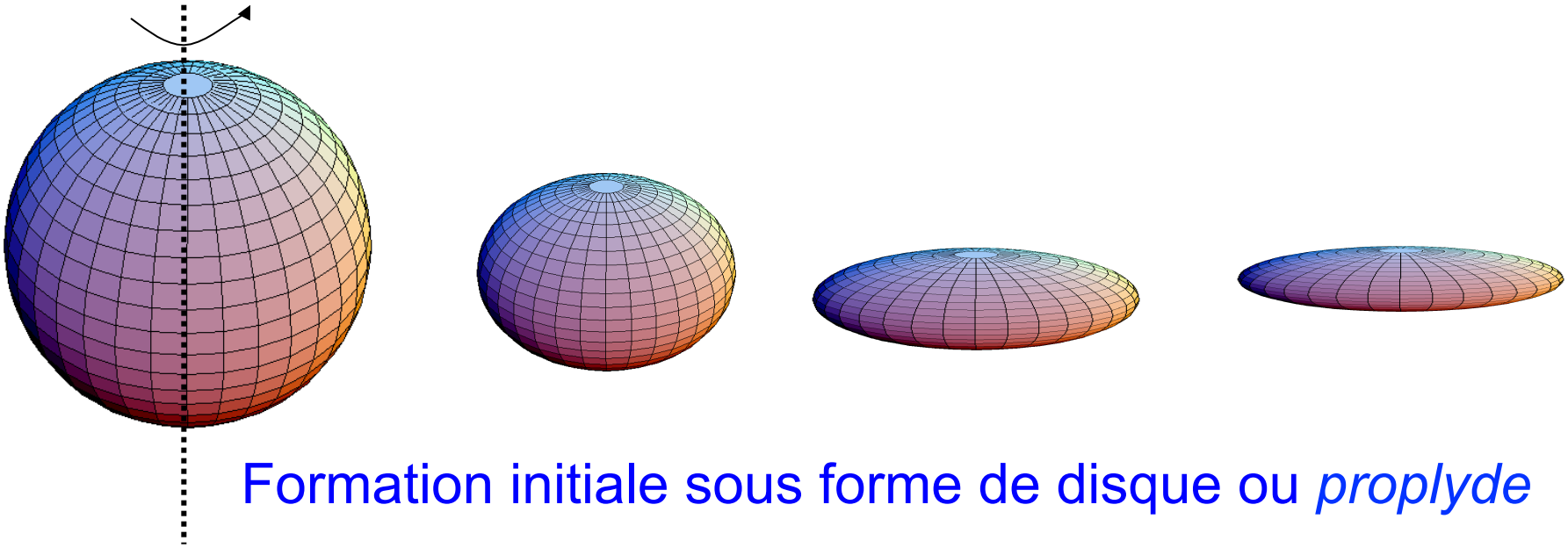
Et les étoiles ?



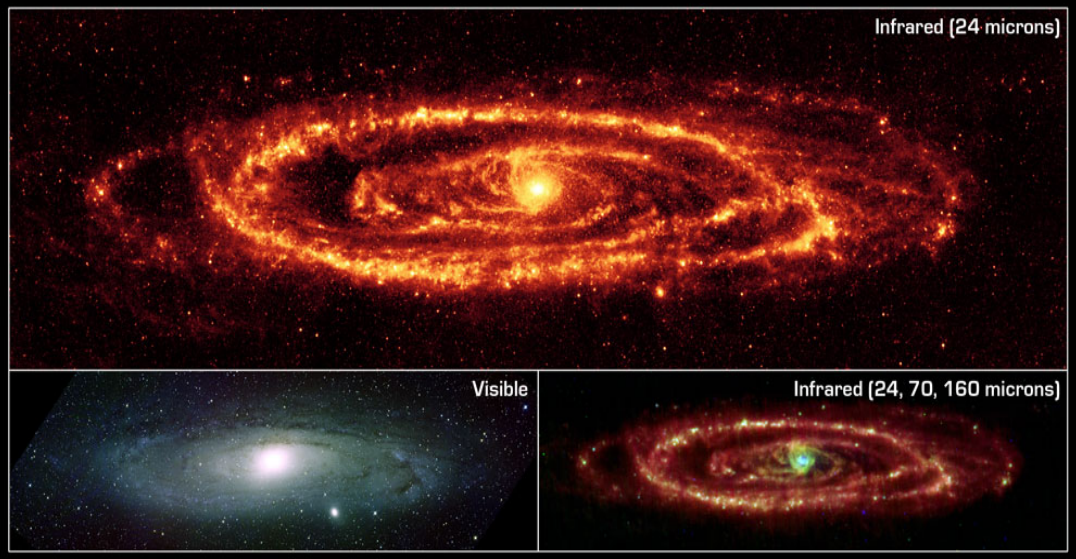
Effondrement sphérique



Peu réaliste… généralement constitution d'un axe de rotation (inhomogénéité)



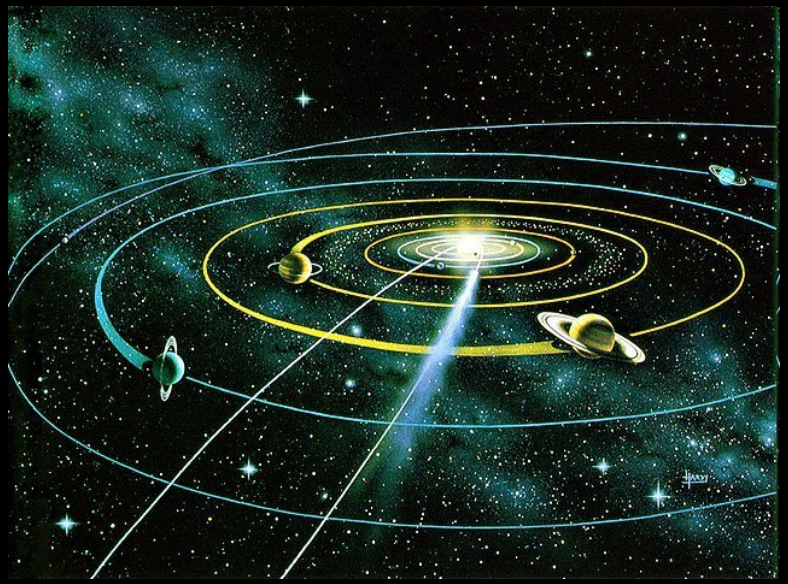
Formation initiale sous forme de disque ou *proplyde*



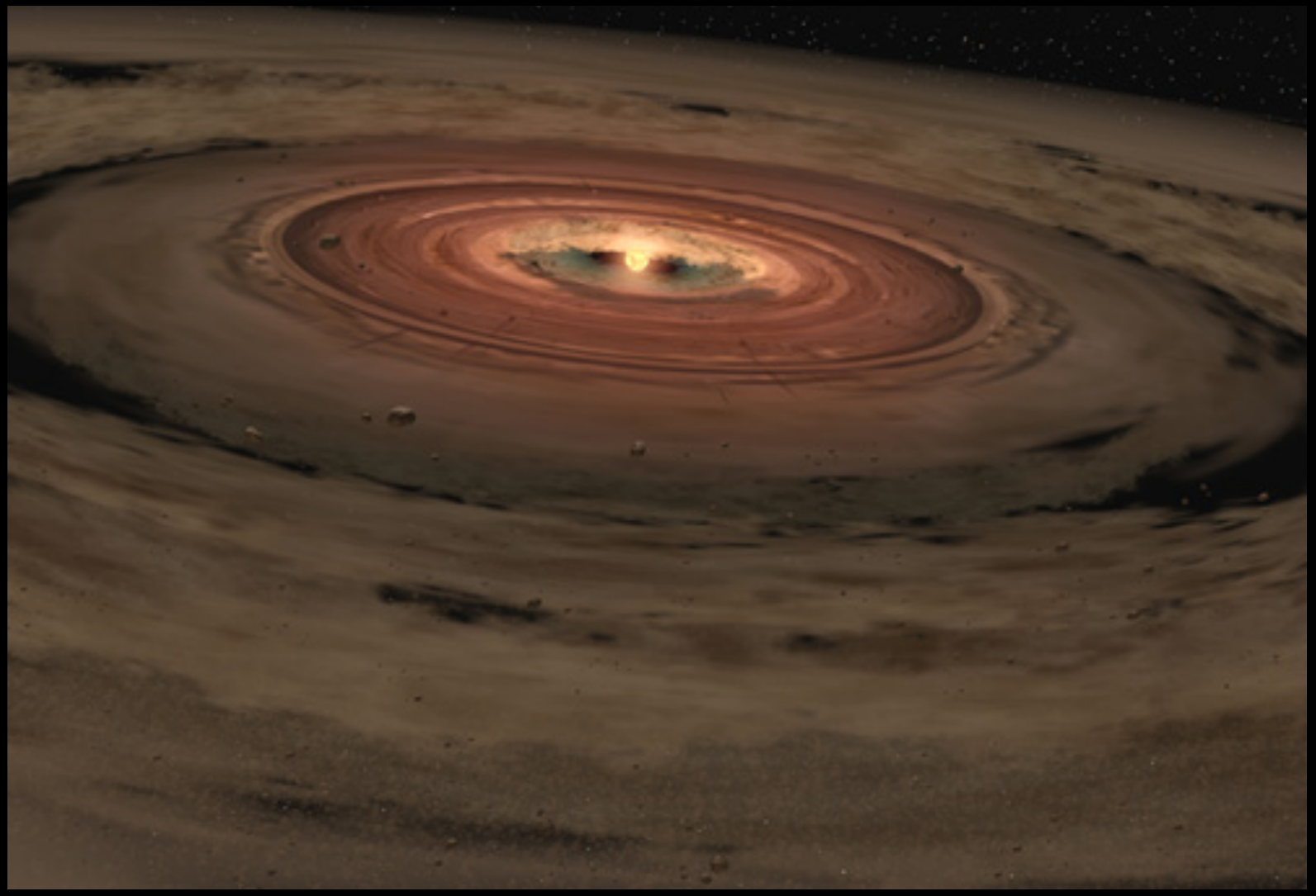
Dust in Andromeda Galaxy (M31)
NASA / JPL-Caltech / K. Gordon (University of Arizona)

Spitzer Space Telescope • MIPS
Visible: NOAO
ssc2005-20a

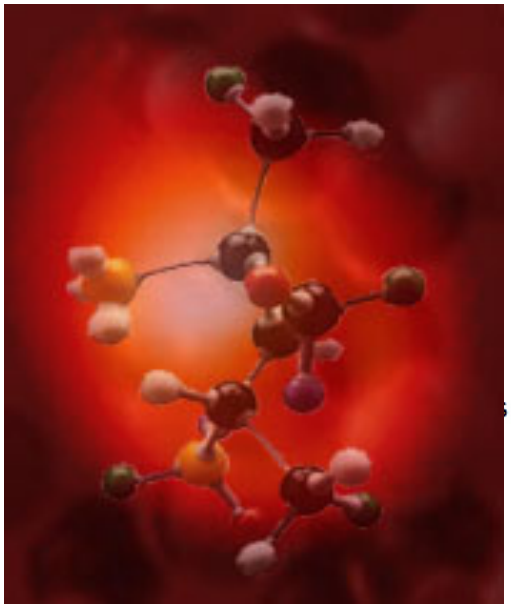
Les systèmes astrophysiques sont relativement plats

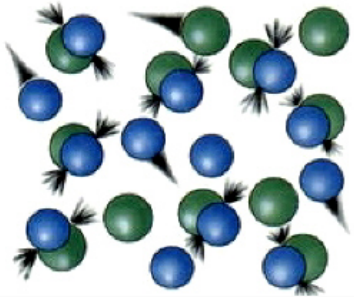


La gravité n’a pas d’échelles préférentielles



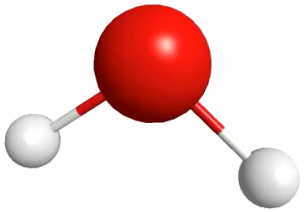
Les molécules peuvent jouer un rôle dans le processus d’effondrement gravitationnel

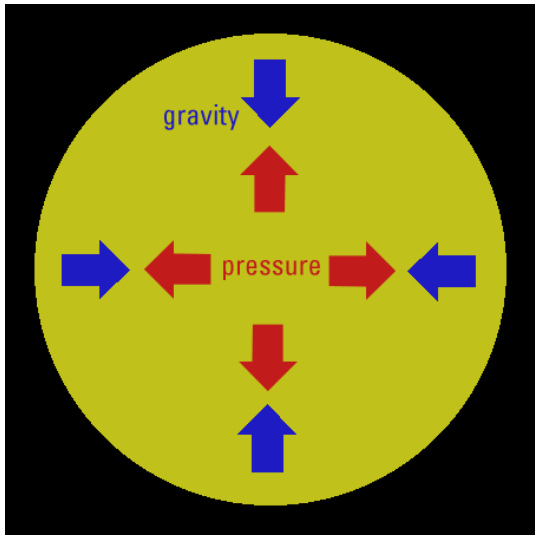




L'effondrement gravitationnel va provoquer des collisions

Une molécule peut vibrer après une collision





Les molécules peuvent refroidir localement

↓

Diminution de la pression locale

↓

La gravité a moins de résistance

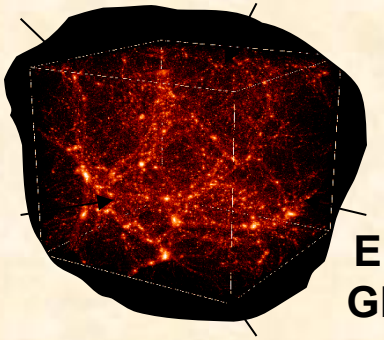
↓

FRAGMENTATION DE LA STRUCTURE EN EFFONDREMENT

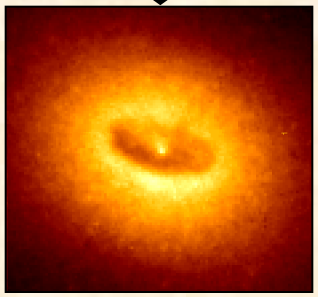
↓

FORMATION DE SOUS-STRUCTURES

SCENARIO SANS MOLECULES

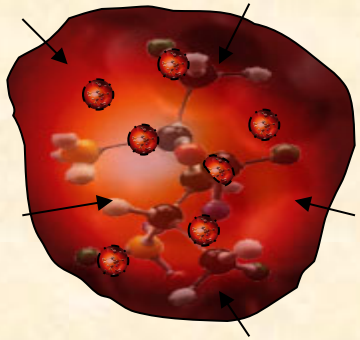


EFFONDREMENT GRAVITATIONNEL



FORMATION D'UN DISQUE DE GRANDE TAILLE

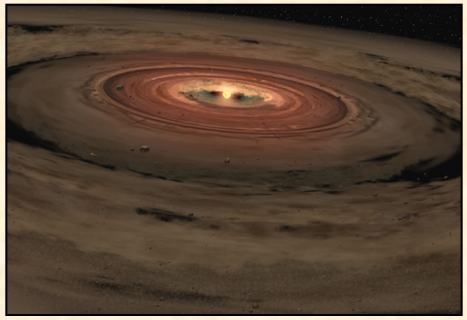
SCENARIO AVEC MOLECULES



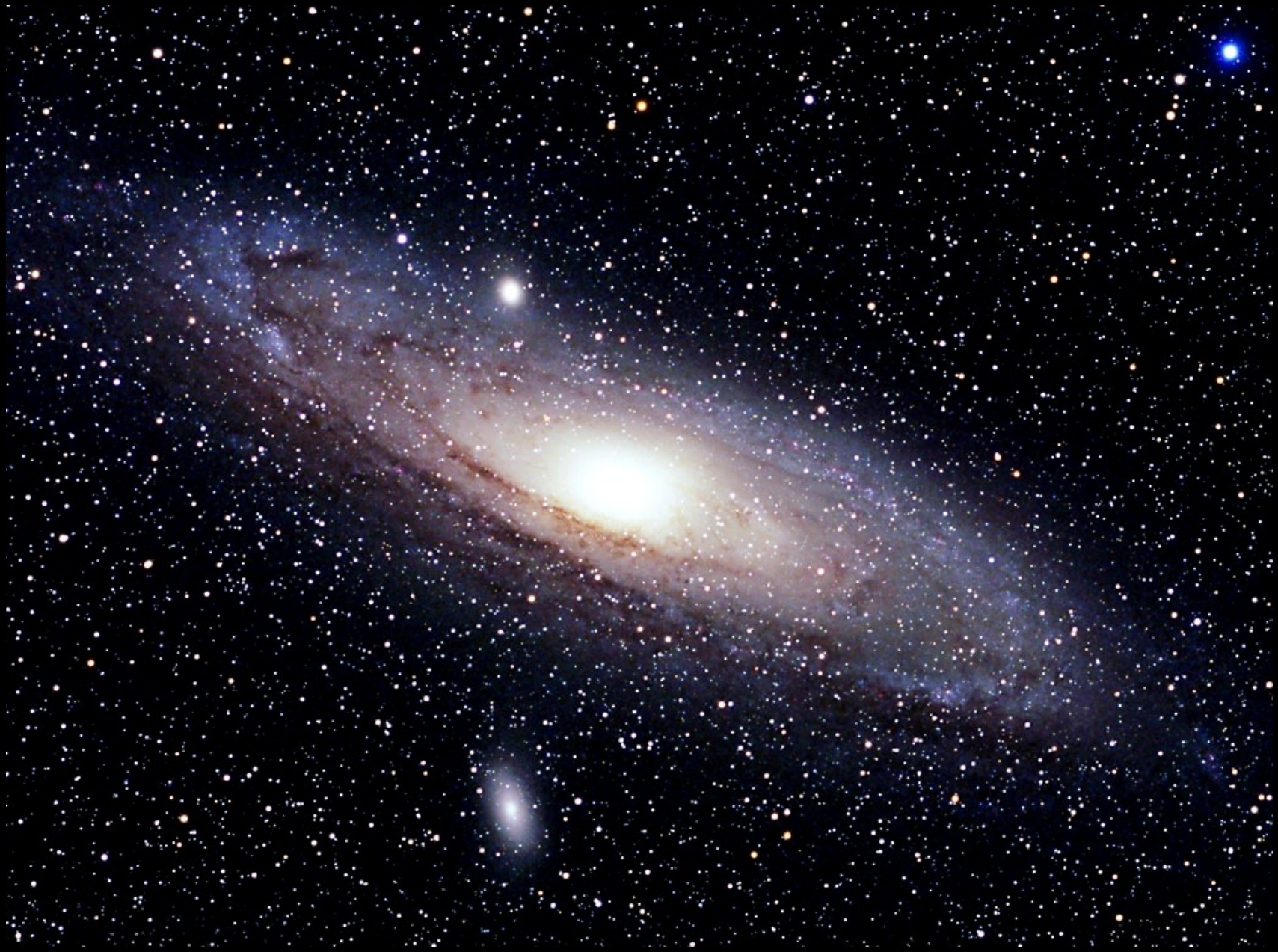
EFFONDREMENT GRAVITATIONNEL
EXTERIEUR FROID

PROCESSUS HYDRODYNAMIQUE D'EFFONDREMENT

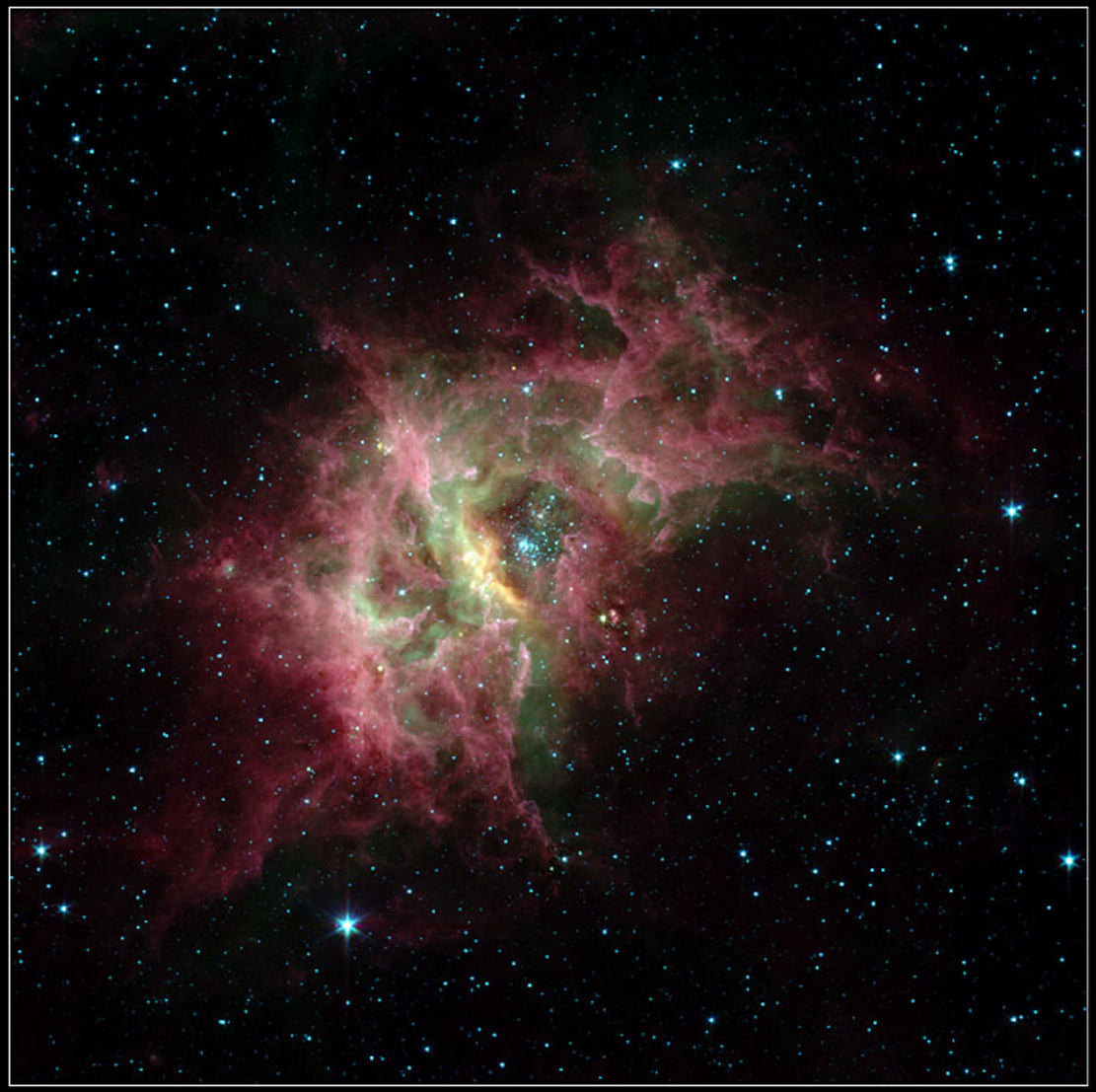
FRAGMENTATION



FORMATION D'UN DISQUE STELLAIRE

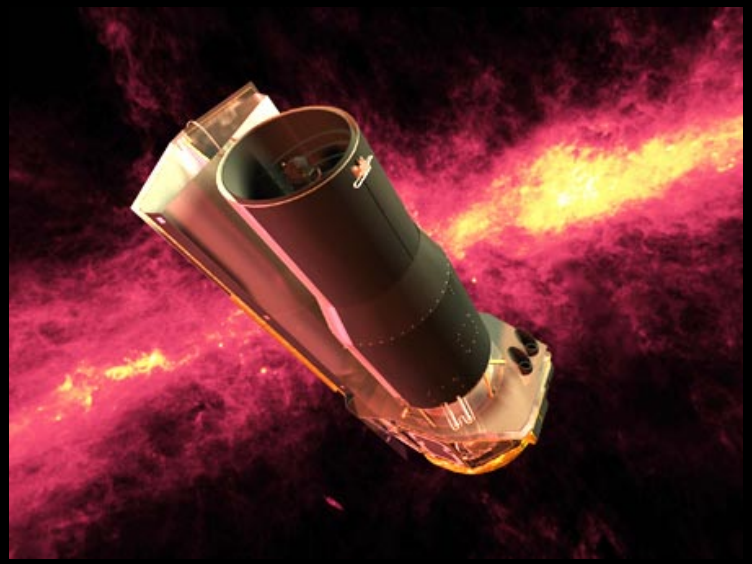



The Horsehead Nebula — Barnard 33
HUBBLESITE.org



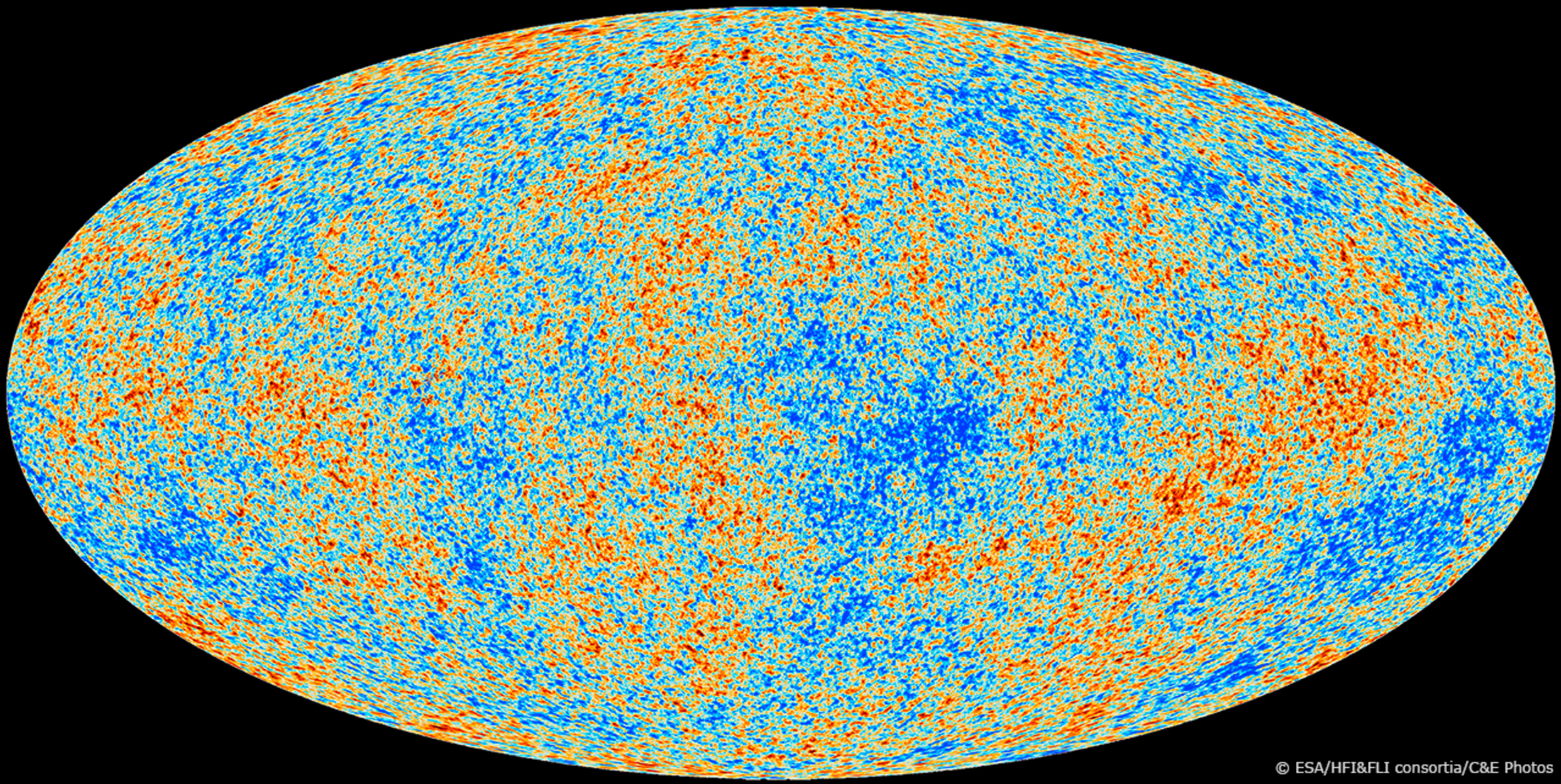
Star Formation in RCW49 Spitzer Space Telescope • IRAC

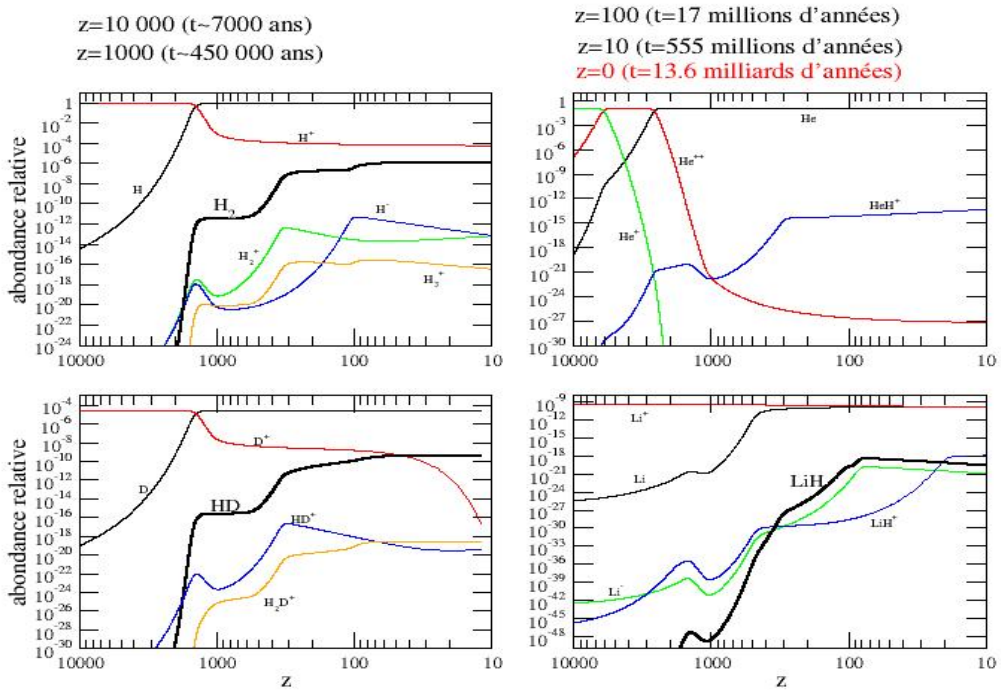
NASA / JPL-Caltech / E. Churchwell (Univ. of Wisconsin) ssc2004-08a



Télescope Infrarouge *Spitzer*

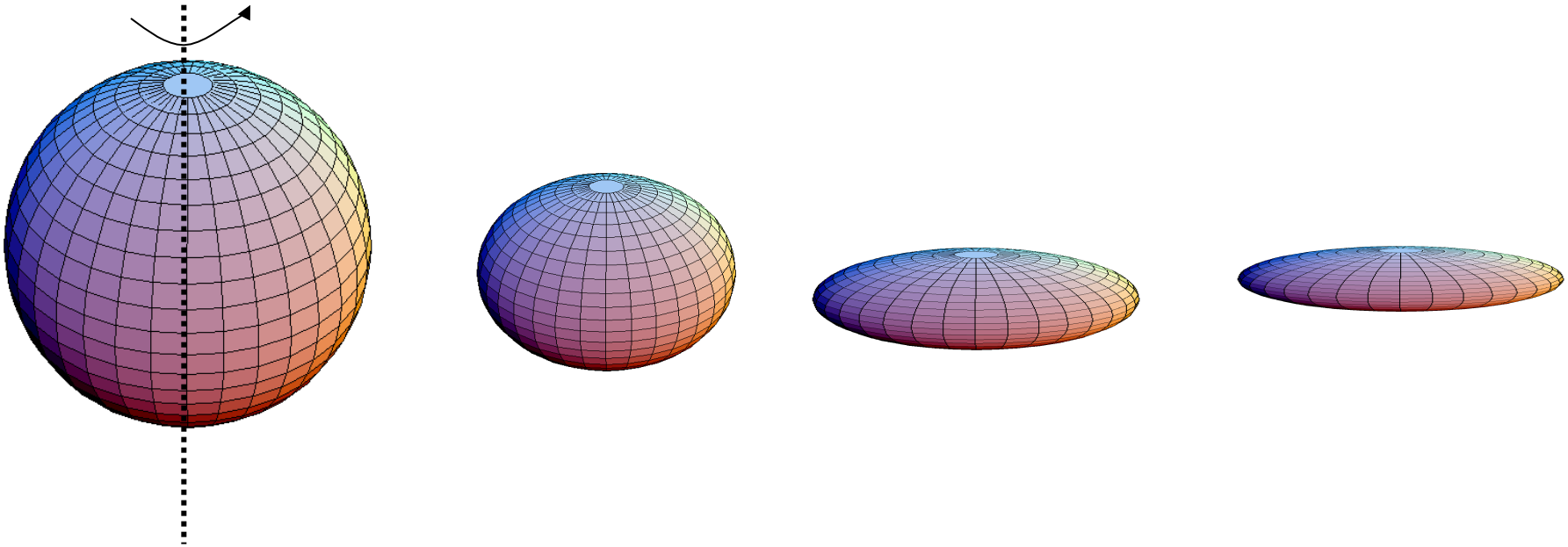
En 2005, Spitzer mis en évidence environ 300 protoétoiles accompagnés de disque d'accrétion (futur système solaire) dans la nébuleuse RCW49.

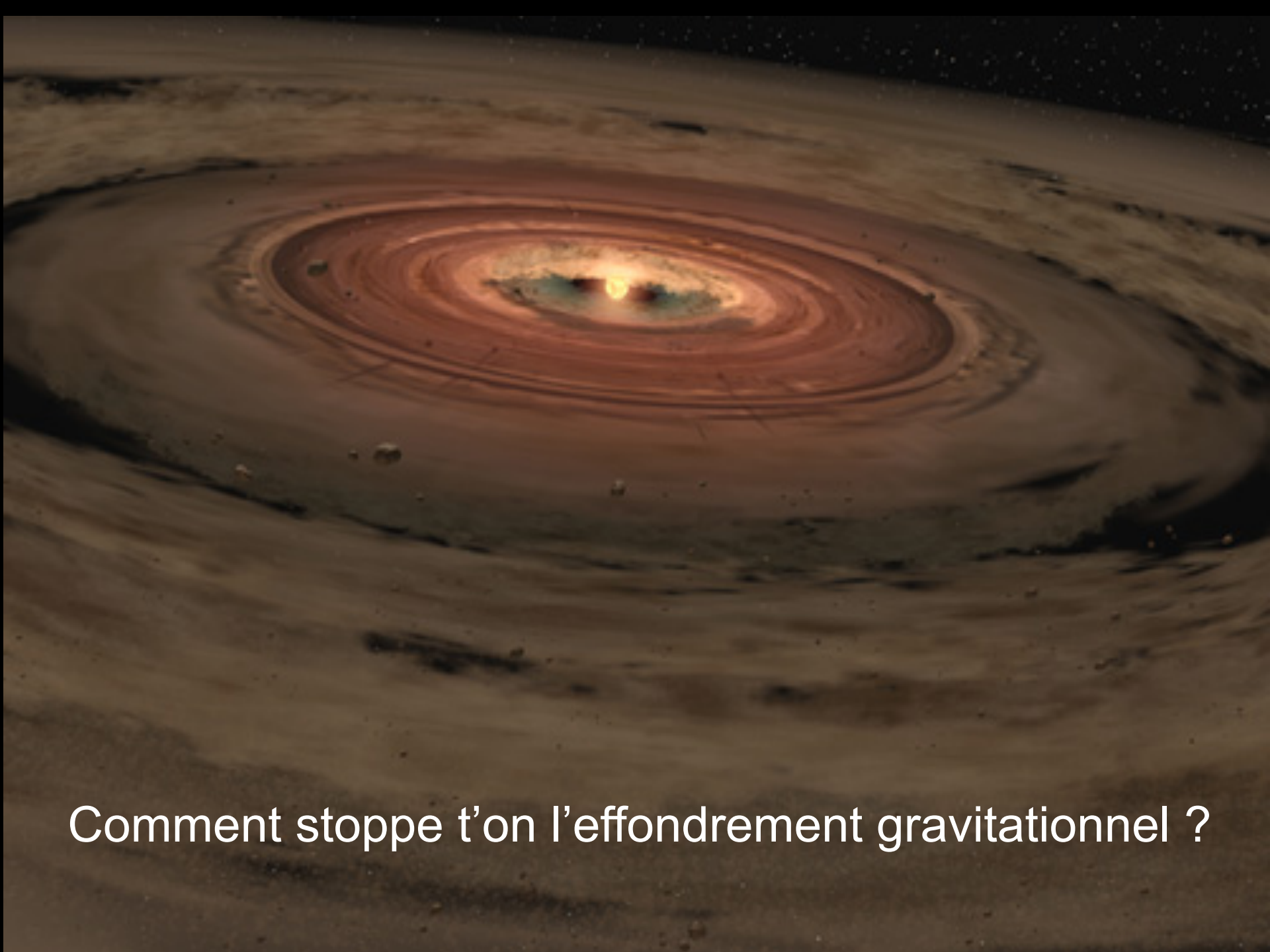

© ESA/HFI&FLI consortia/C&E Photos



L'existence
de molécules primordiales
peut engendrer des étoiles,
très tôt dans l'histoire de
l'Univers

?





Comment stoppe t’on l’effondrement gravitationnel ?

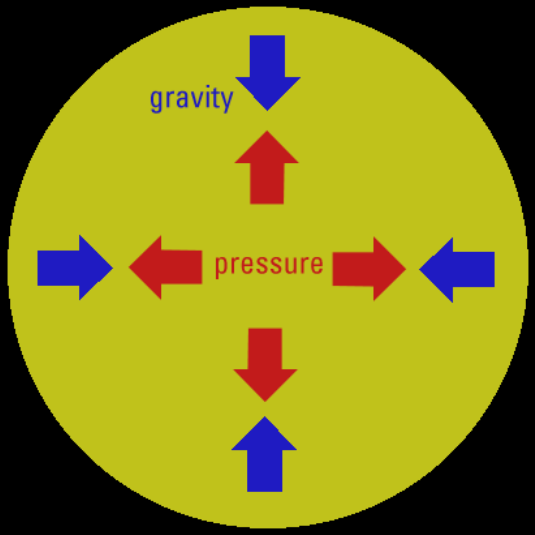
FORCES DE « PRESSION »
POUVANT « S’ OPPOSER » AUX FORCES GRAVITATIONNELLES

1- FORCE DE COHESION SOLIDE ET MOLECULAIRE
ROCHES

2- FORCE ATOMIQUE ET ELECTROMAGNETIQUE
PARTICULES CHARGÉES

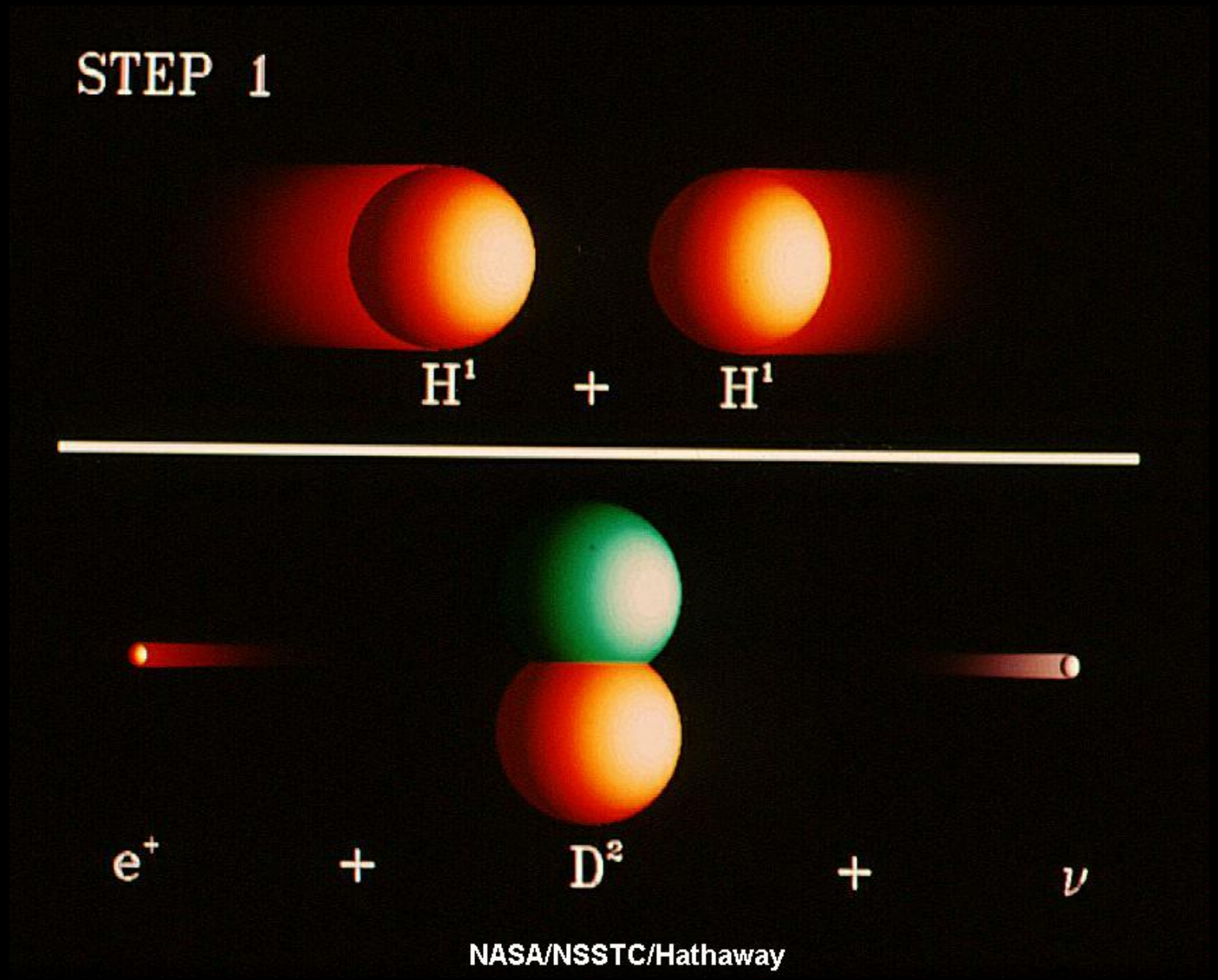
3- FORCE NUCLEAIRES
FUSION DE NOYAUX, RAYONNEMENT

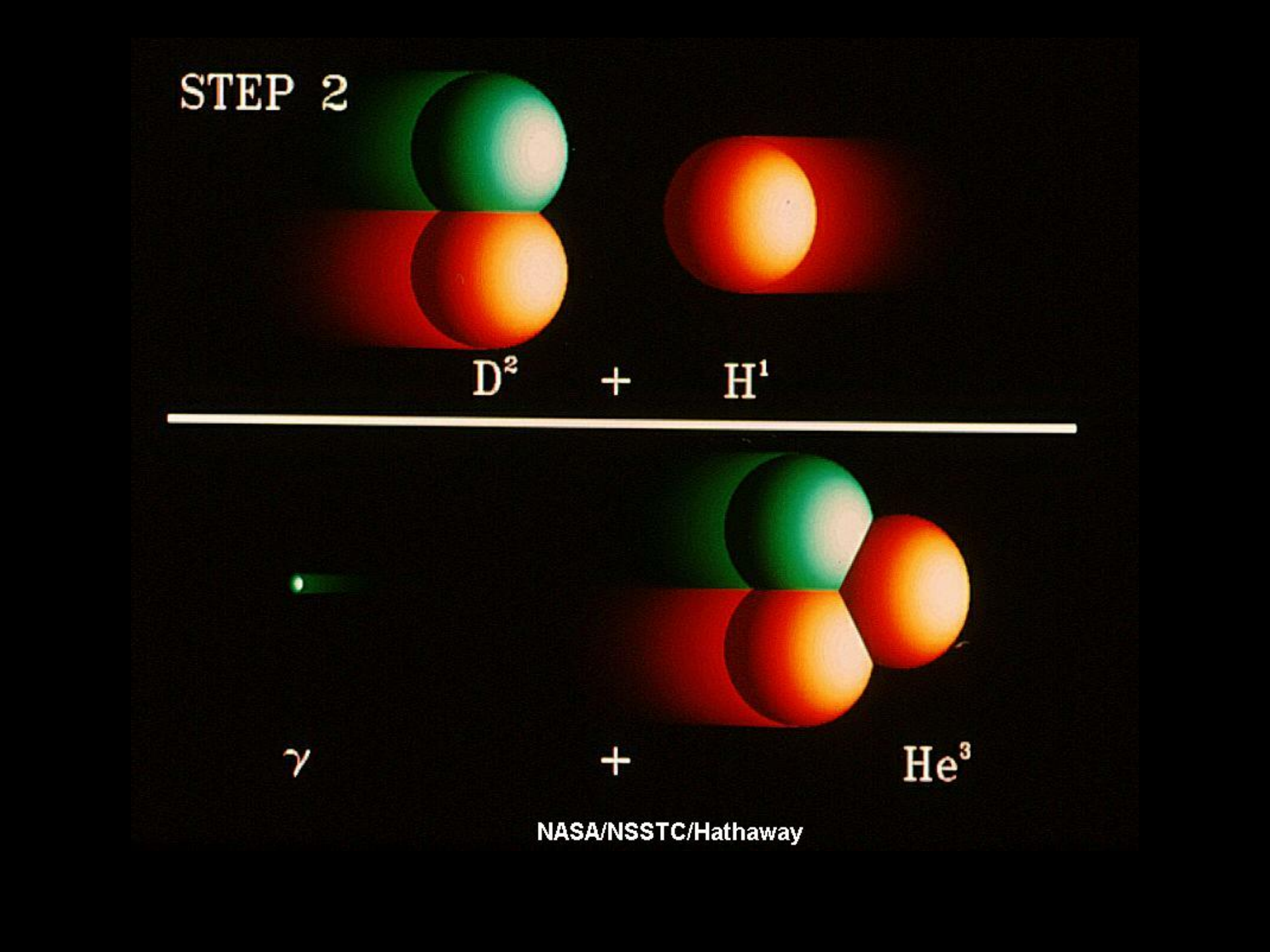
4- FORCES ELEMENTAIRES
FORCES FONDAMENTALES AU CONFINEMENT

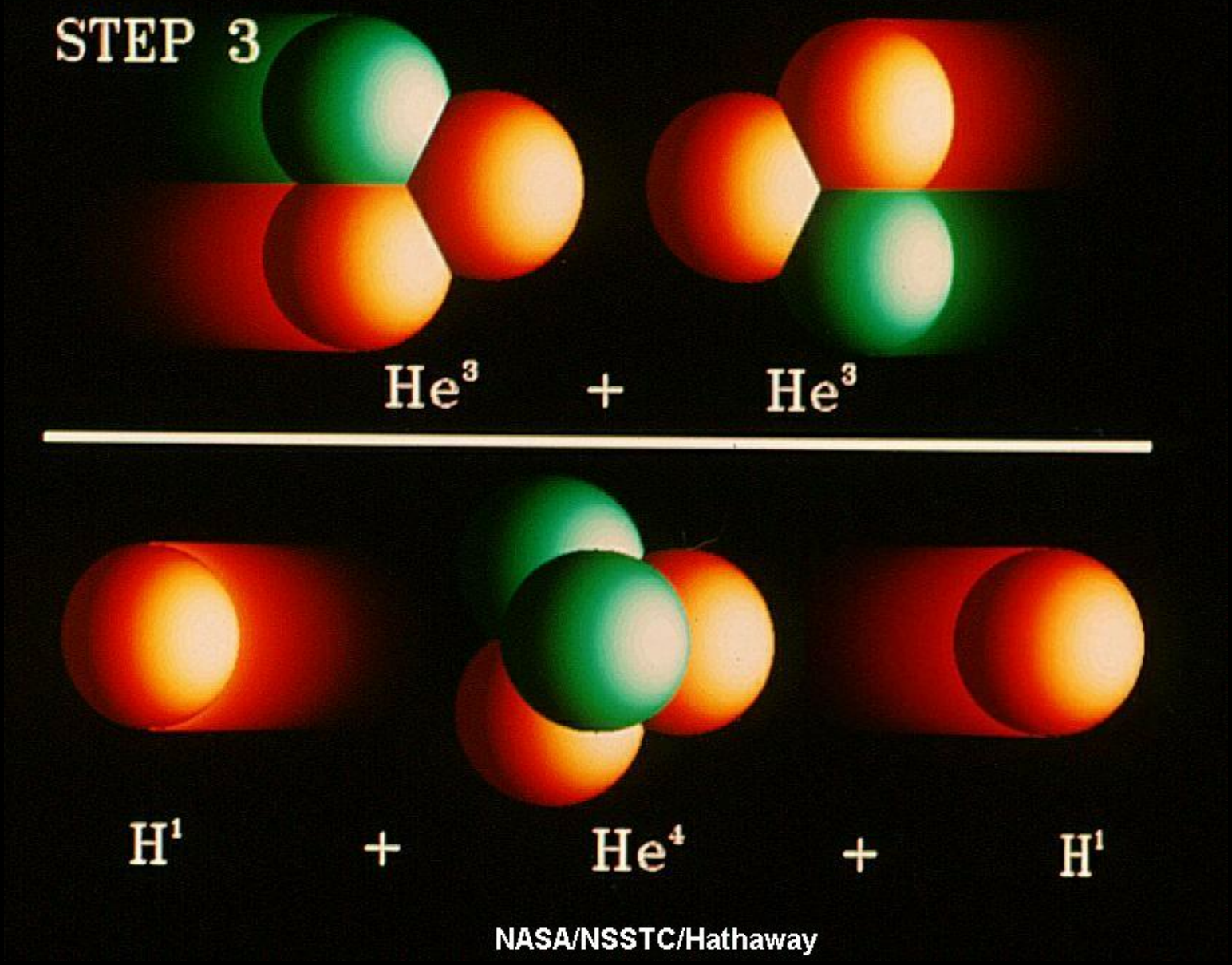


L’ opposition forces de pression et gravitation va dépendre de la masse en effondrement

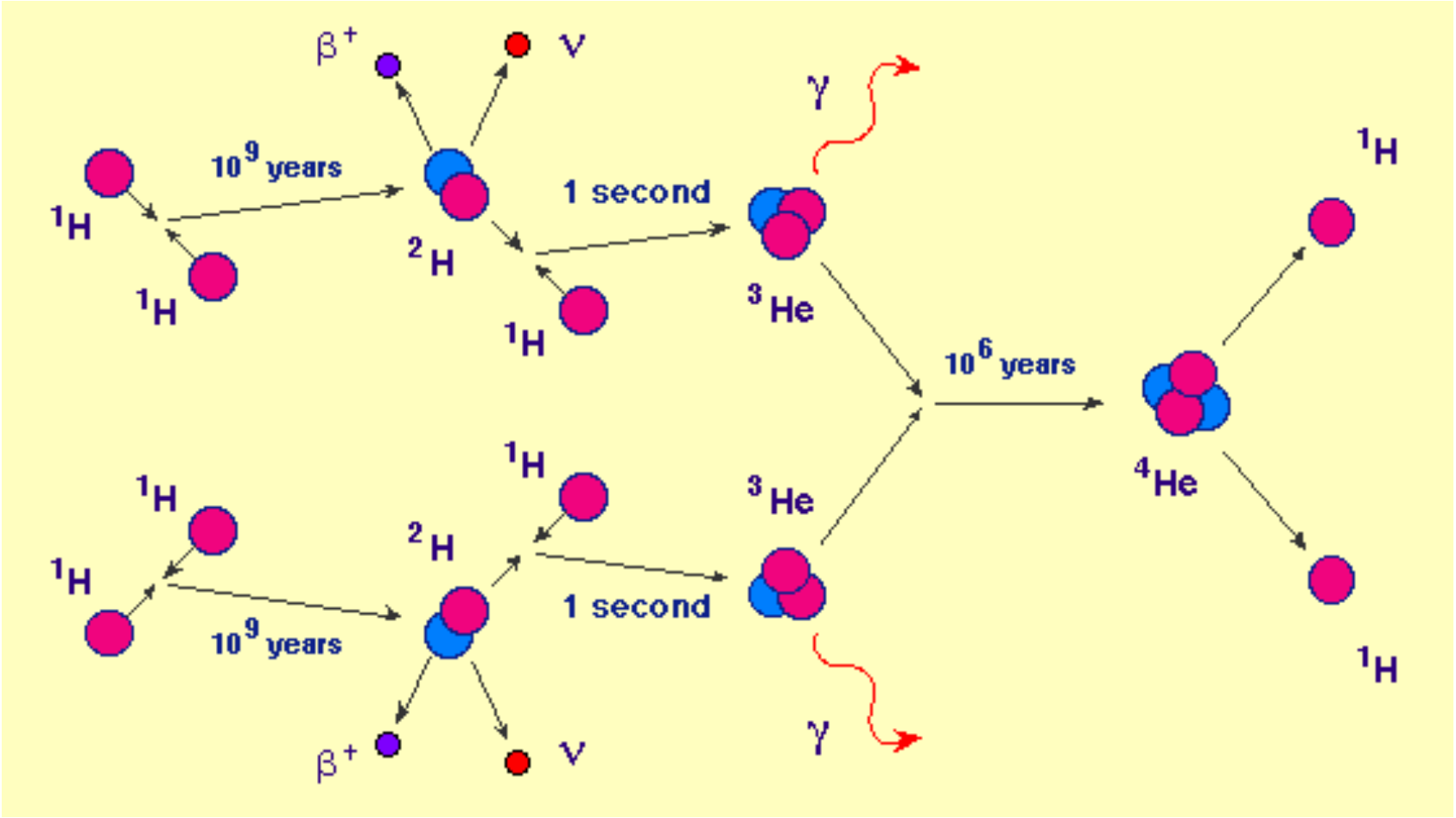
Pour une étoile, il s’agit de la force nucléaire


STEP 1
H¹ + H¹
e⁺ + D² + ν
NASA/NSSTC/Hathaway


STEP 2
D²
+
H¹
γ
+
He³
NASA/NSSTC/Hathaway

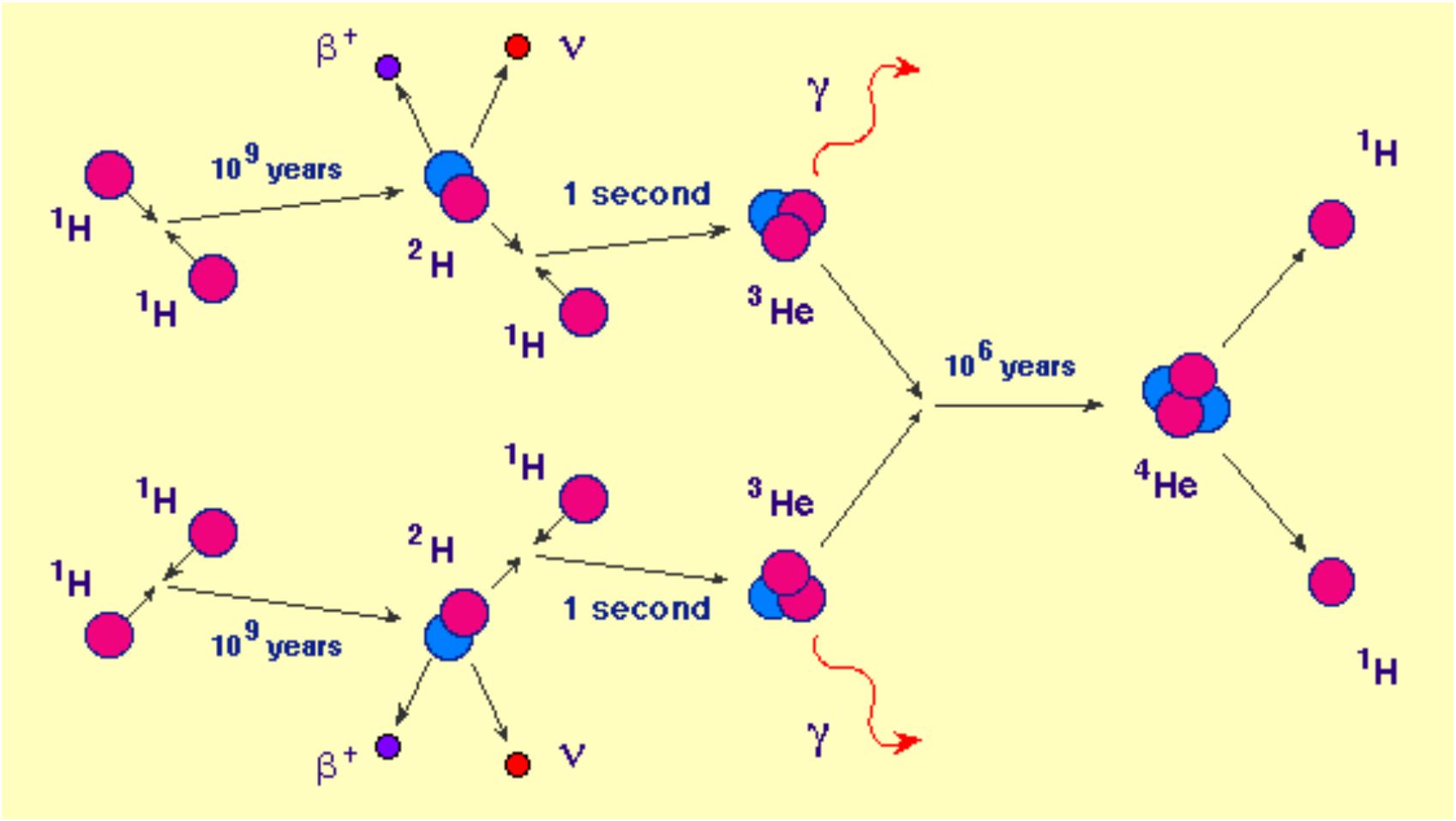

STEP 3
He^3 + He^3
H^1 + He^4 + H^1
NASA/NSSTC/Hathaway

Chaîne p-p : 1ere phase de l'étoile



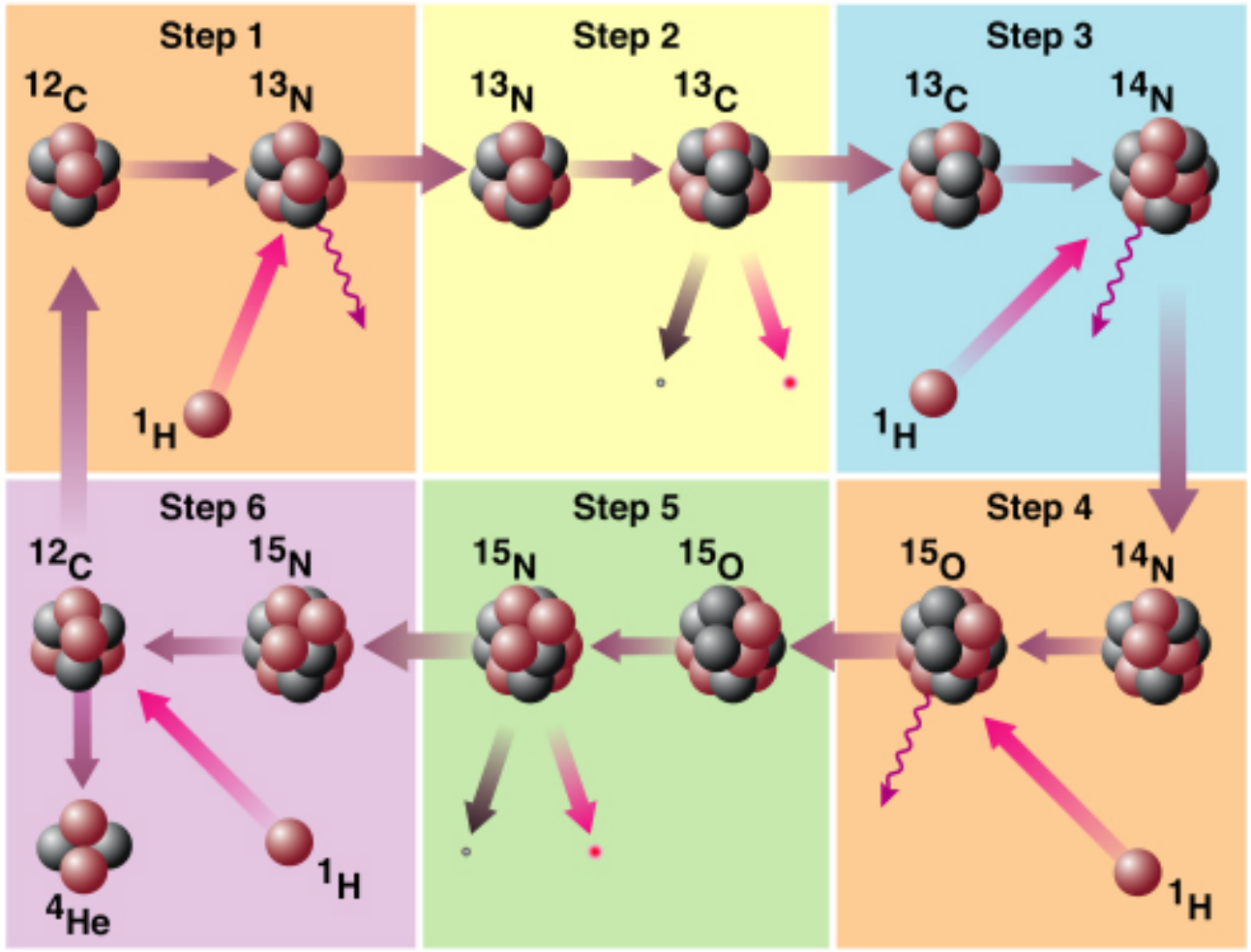
Durée: entre plusieurs milliards d'années et quelques dizaines de Millions d'années, dépend de la masse de l'étoile

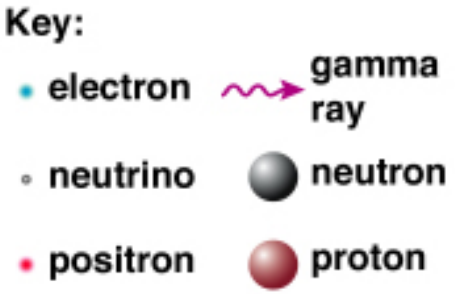
Lorsque la chaîne p-p est finie ?



Que se passe t-il ?

Cycle CNO





$$^{12}C + p \rightarrow {}^{13}N + \gamma$$

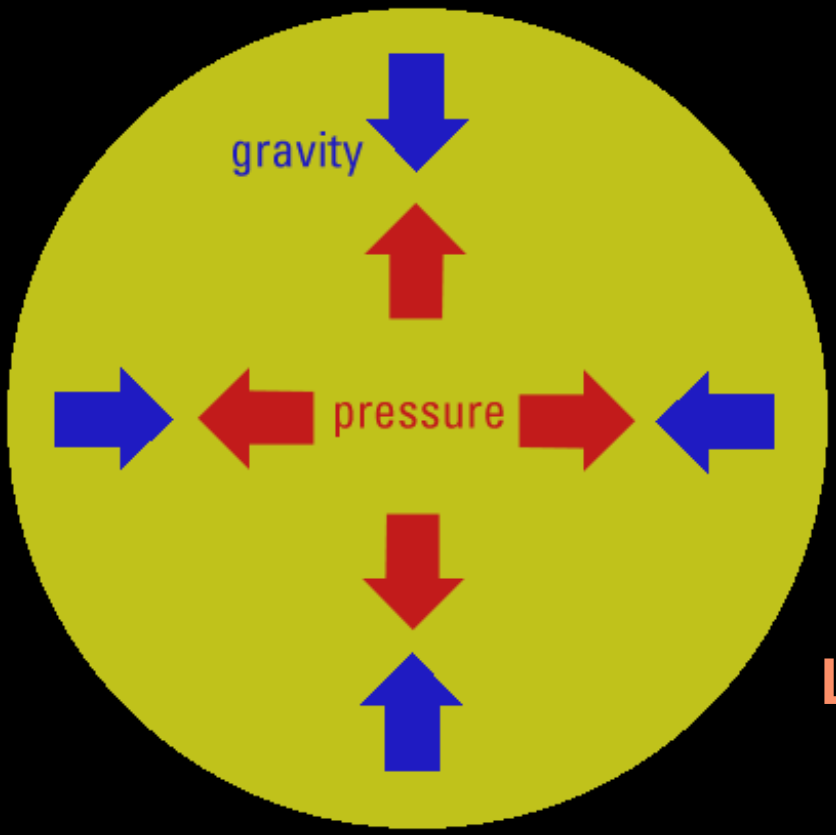
$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$$

$$^{13}C + p \rightarrow {}^{14}N + \gamma$$

$$^{14}N + p \rightarrow {}^{15}O + \gamma$$

$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$$

$$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$$



L’arrêt des réactions de chaîne pp

⬇

Les effets de pression diminuent
La gravité contracte le cœur

⬇

Le début des premières réactions du cycle CNO est violente

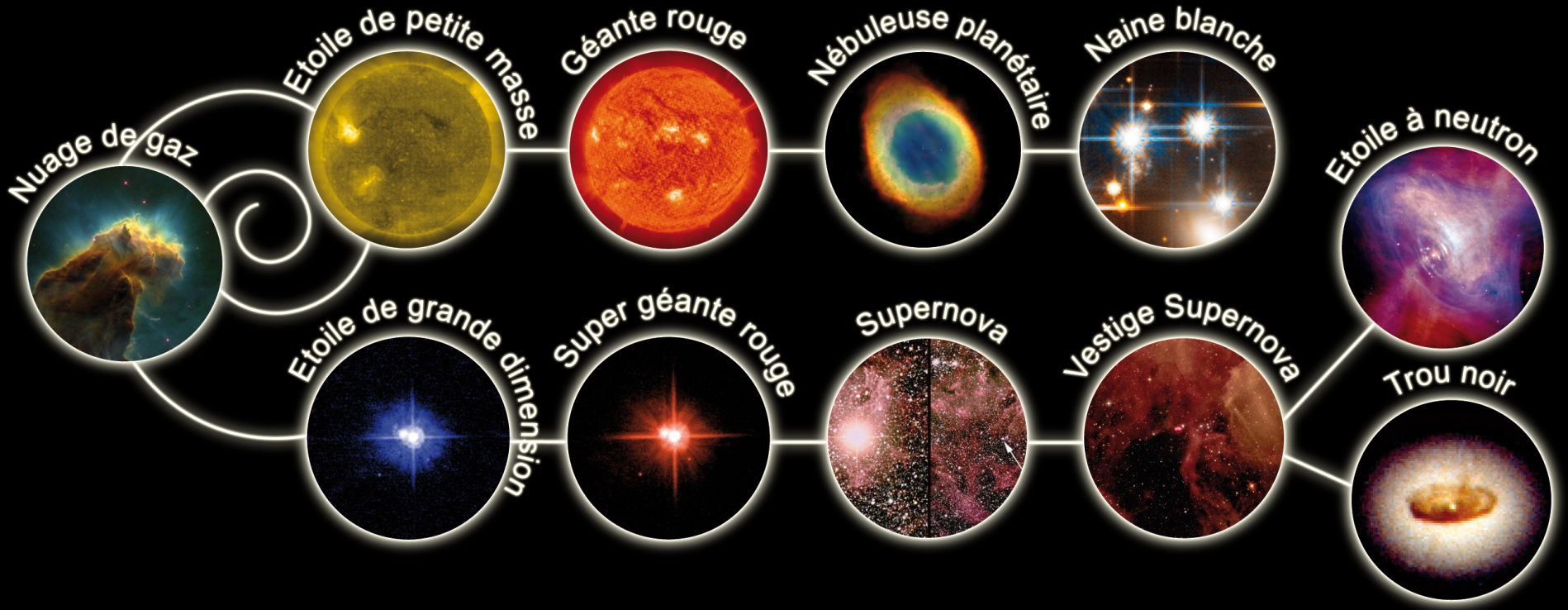
⬇

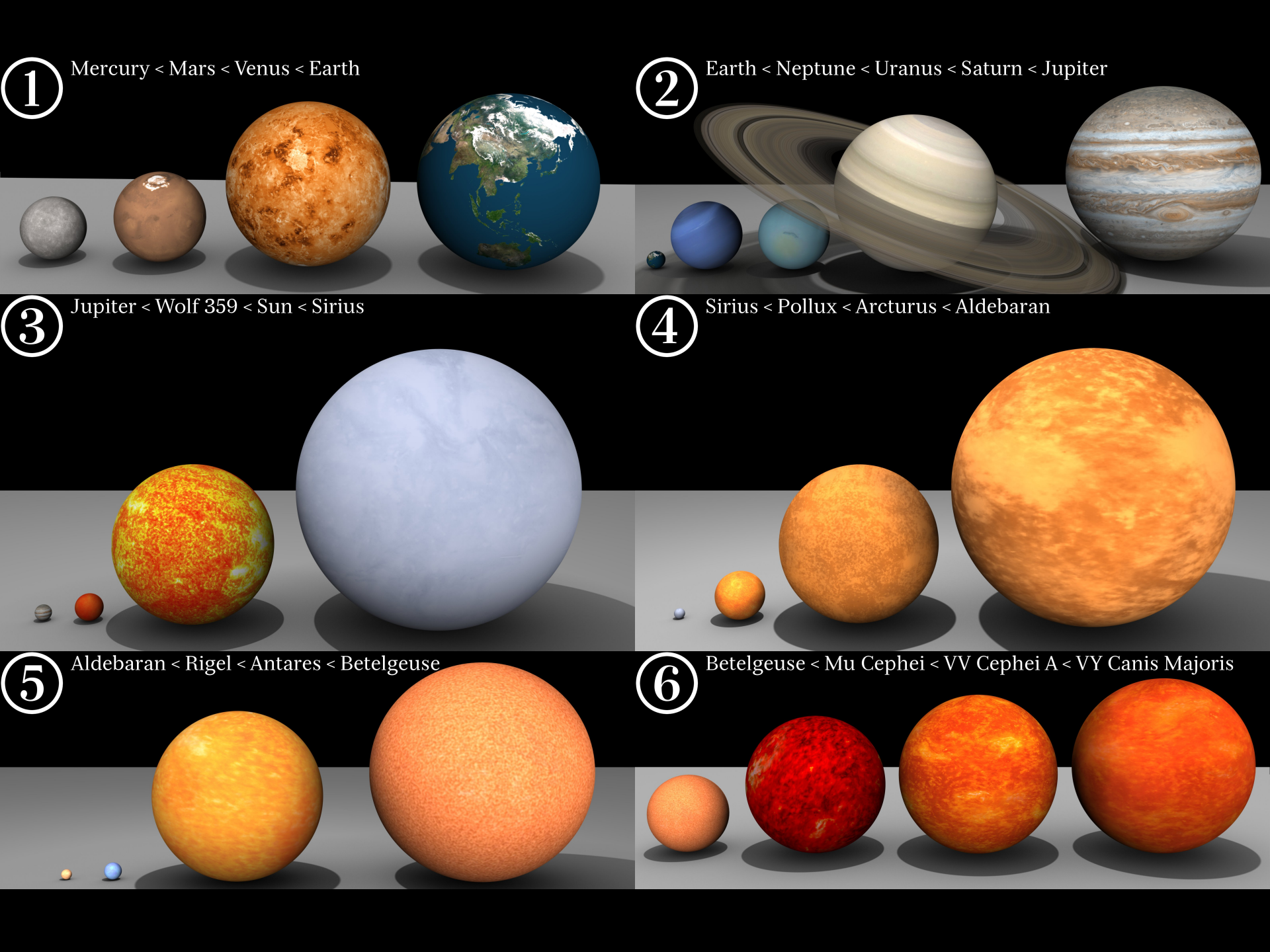
Effet de « souffle »
Le rayon de l’étoile croit fortement

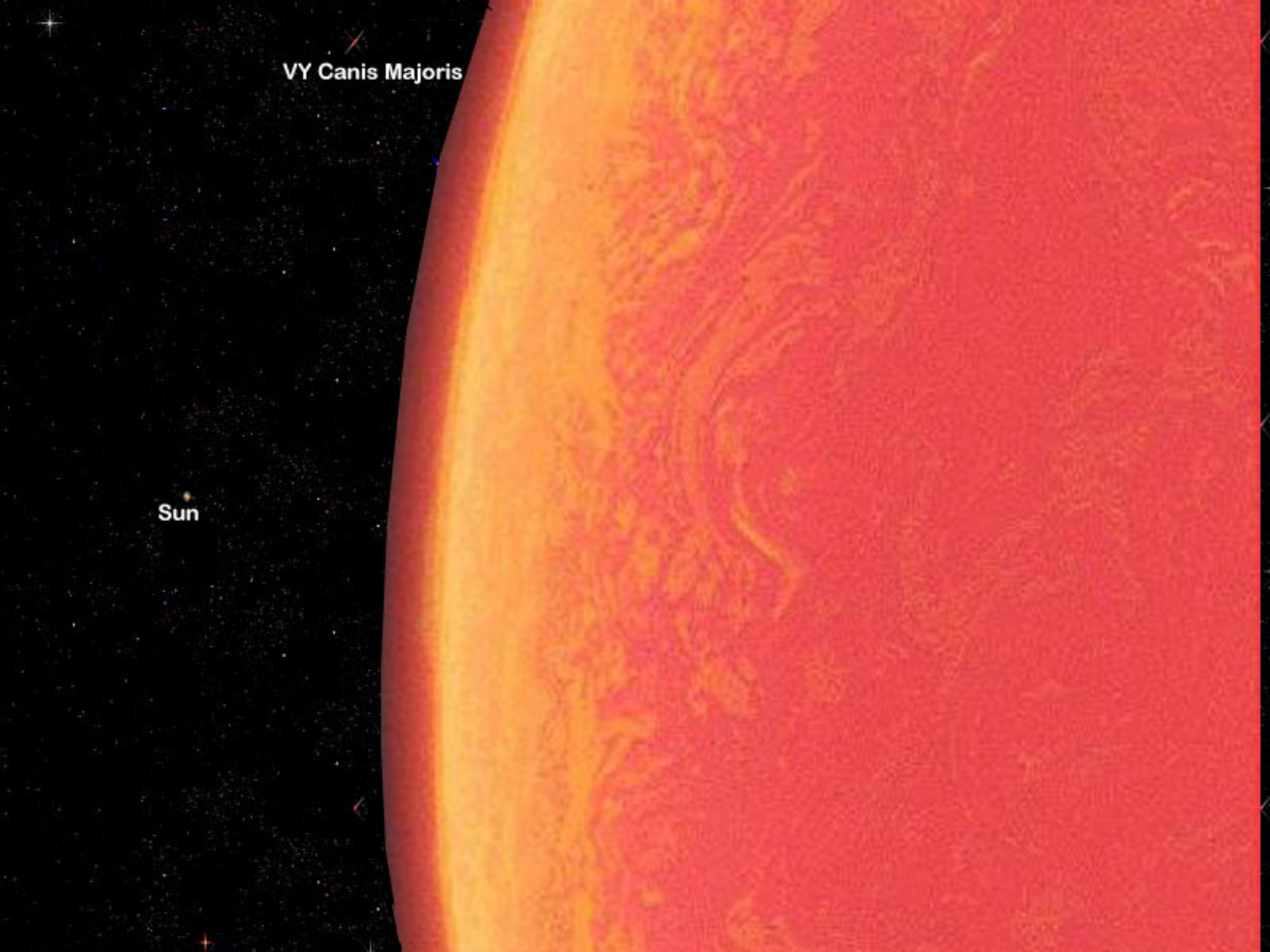
⬇

CONSTITUTION
D’UNE GÉANTE ROUGE

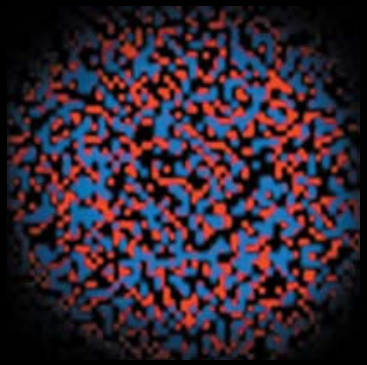
La vie d'une étoile



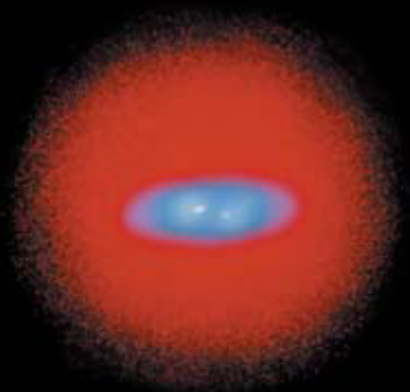

1
Mercury < Mars < Venus < Earth
2
Earth < Neptune < Uranus < Saturn < Jupiter
3
Jupiter < Wolf 359 < Sun < Sirius
4
Sirius < Pollux < Arcturus < Aldebaran
5
Aldebaran < Rigel < Antares < Betelgeuse
6
Betelgeuse < Mu Cephei < VV Cephei A < VY Canis Majoris


VY Canis Majoris
Sun

POSSIBLE HISTOIRE DE LA FORMATION DES PREMIÈRES ÉTOILES



Croissance des surdensités de matière

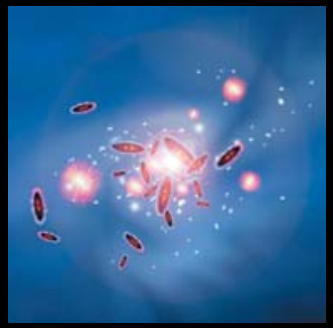


Formation de proto nuages moléculaires

Effondrement gravitationnel
Formation d'étoiles massives

Evolution « rapide » des étoiles massives
Explosion de Supernovae

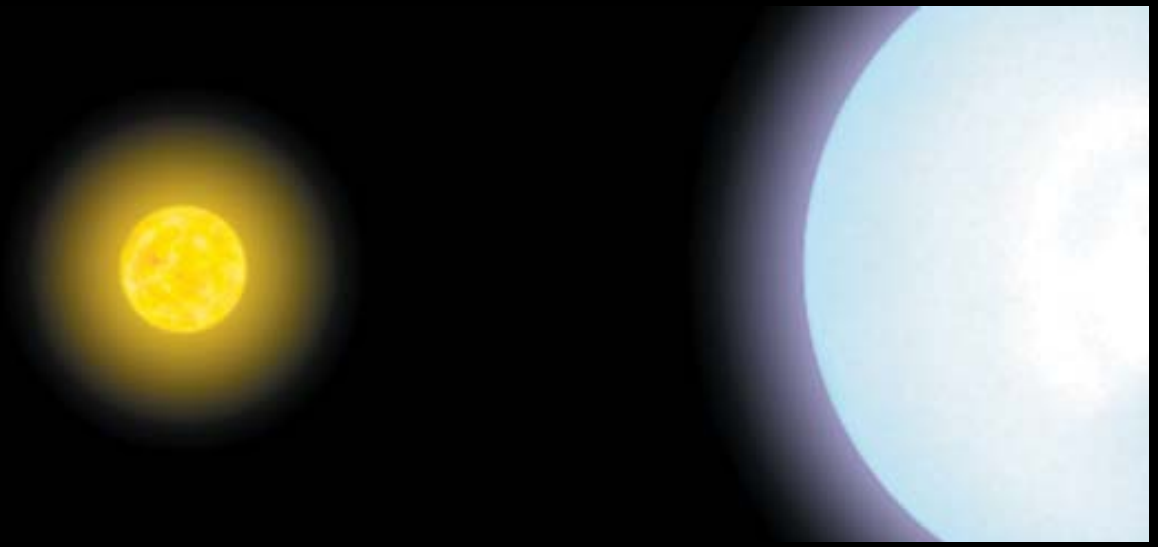
Ionisation du milieu



Regroupement gravitationnel

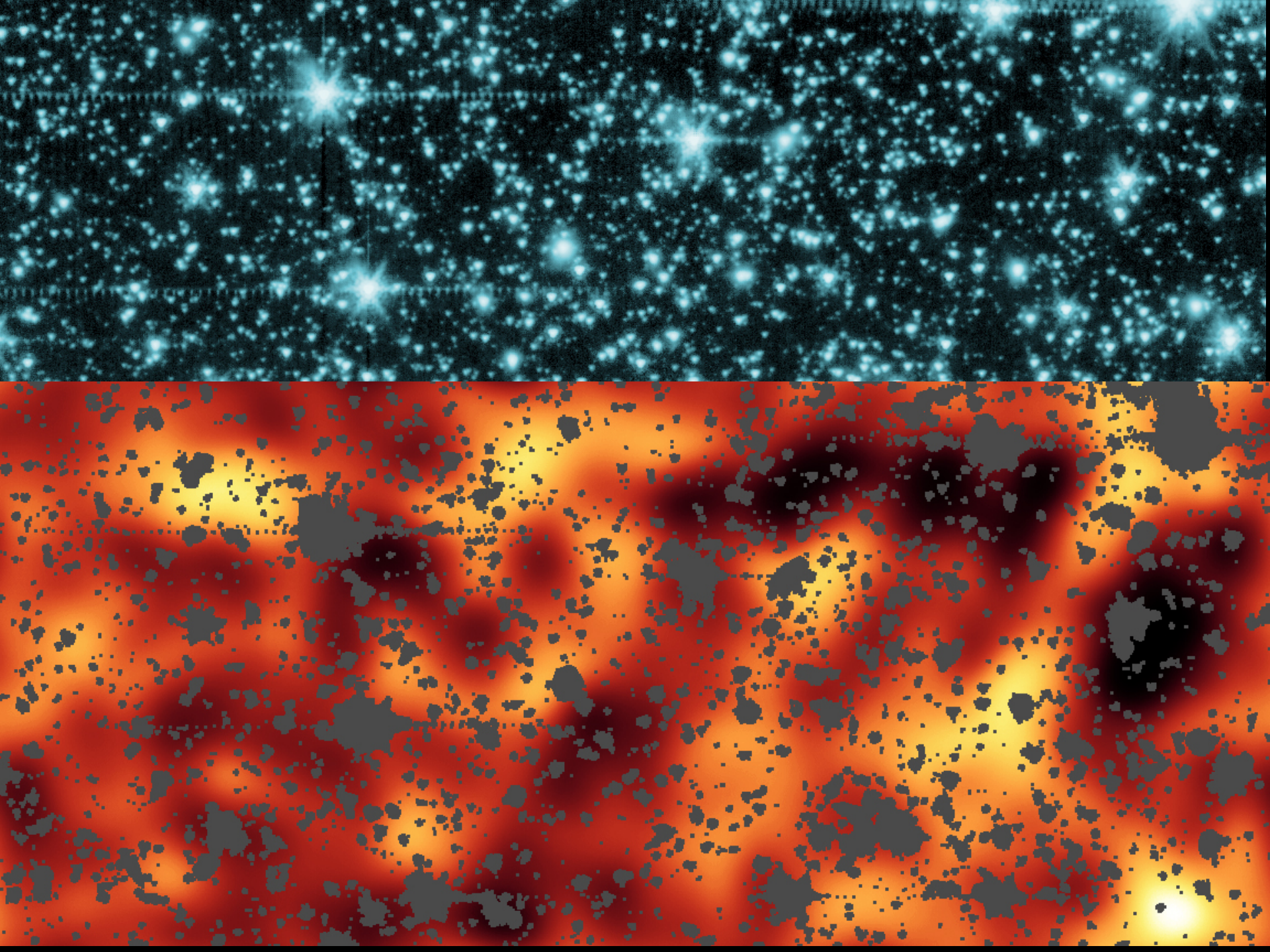
Formation de galaxies

ETOILES PRIMORDIALES



SOLEIL
Masse: **2 10^{30} kg**
Rayon: **696 000 km**
Temps de vie: **10 milliards d'années**

PREMIÈRES ÉTOILES
Masse: **50 à 100 fois la masse du soleil**
Rayon: **4 à 50 fois le rayon du soleil**
Luminosité: **1 million à 30 million de fois la luminosité solaire**
Temps de vie: **3 million d'années**

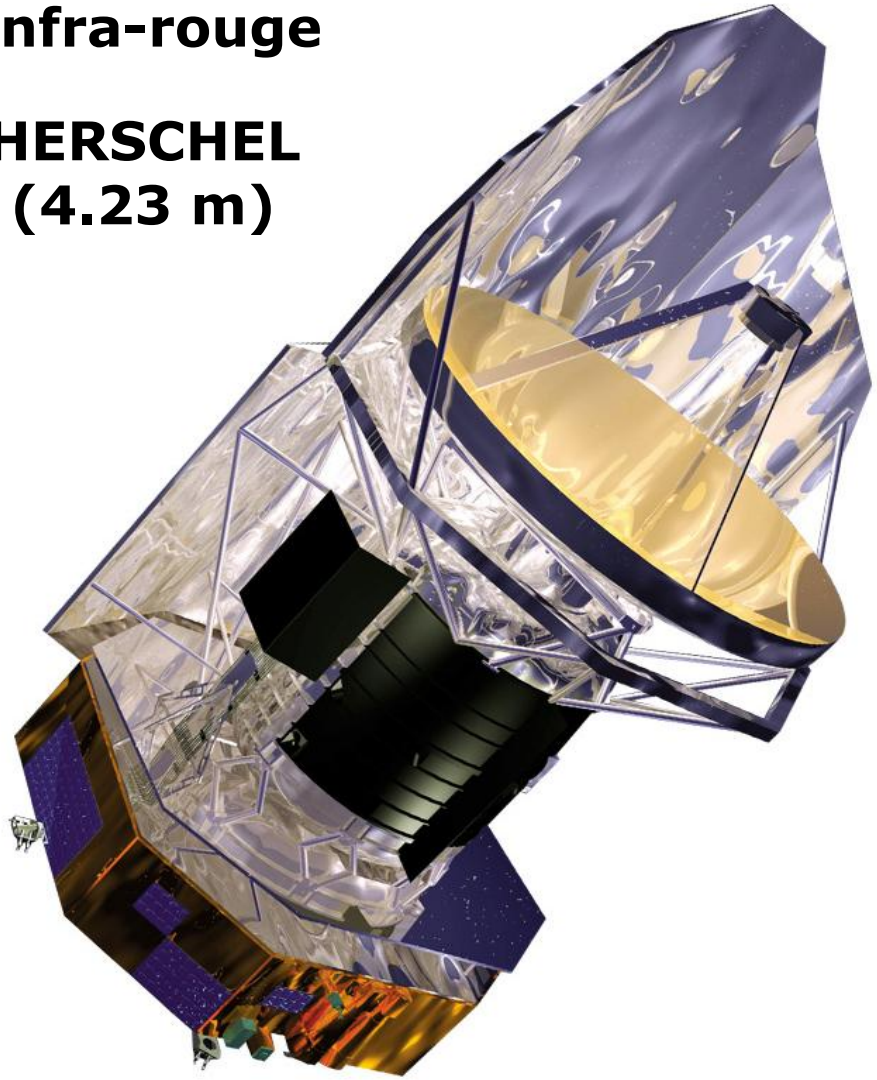


Herschel Space Telescope

(Miroir 3.5m , λ=55-672 μm)

Infra-rouge

HERSCHEL
(4.23 m)



Formation stellaire

Signature moléculaire

Objets froids

Atacama Large Millimeter Area

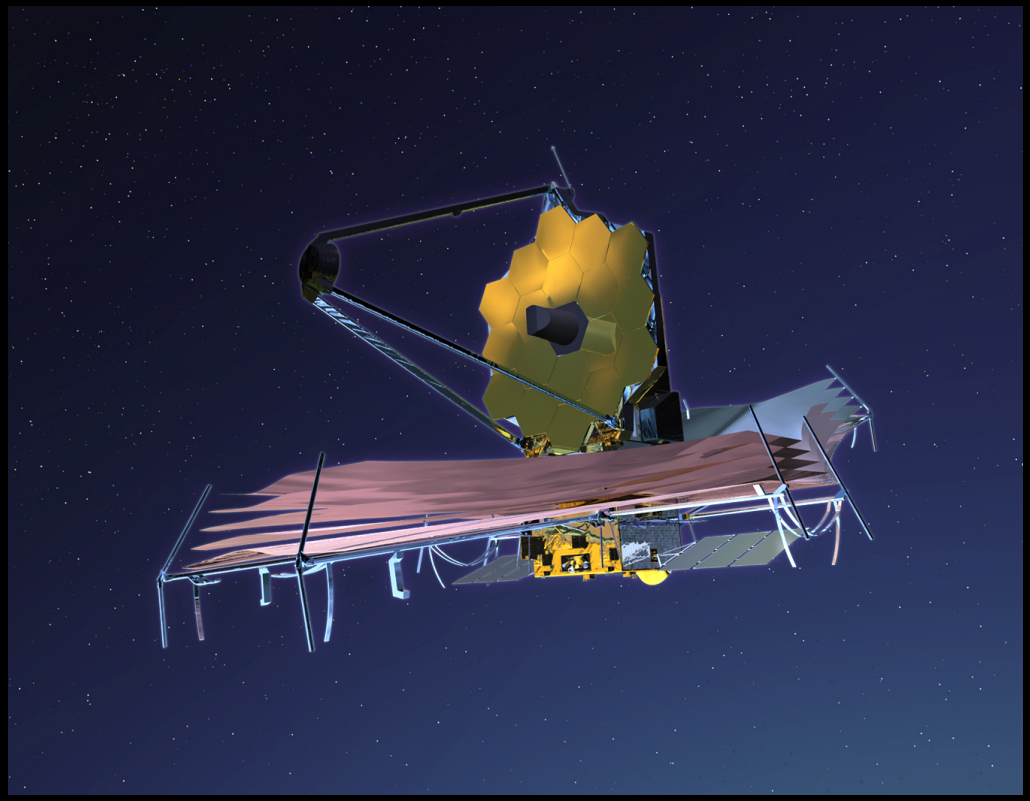
(66 high-precision antennas of 12 m, λ=0.3mm- 9mm)

Alma deep field

Signatures moléculaires

Proto nuages moléculaires

TELESCOPE SPATIAL NASA - 2015



Satellite *James Webb*
Evolution des galaxies
Signatures de premières galaxies

SATELLITE PLANCK

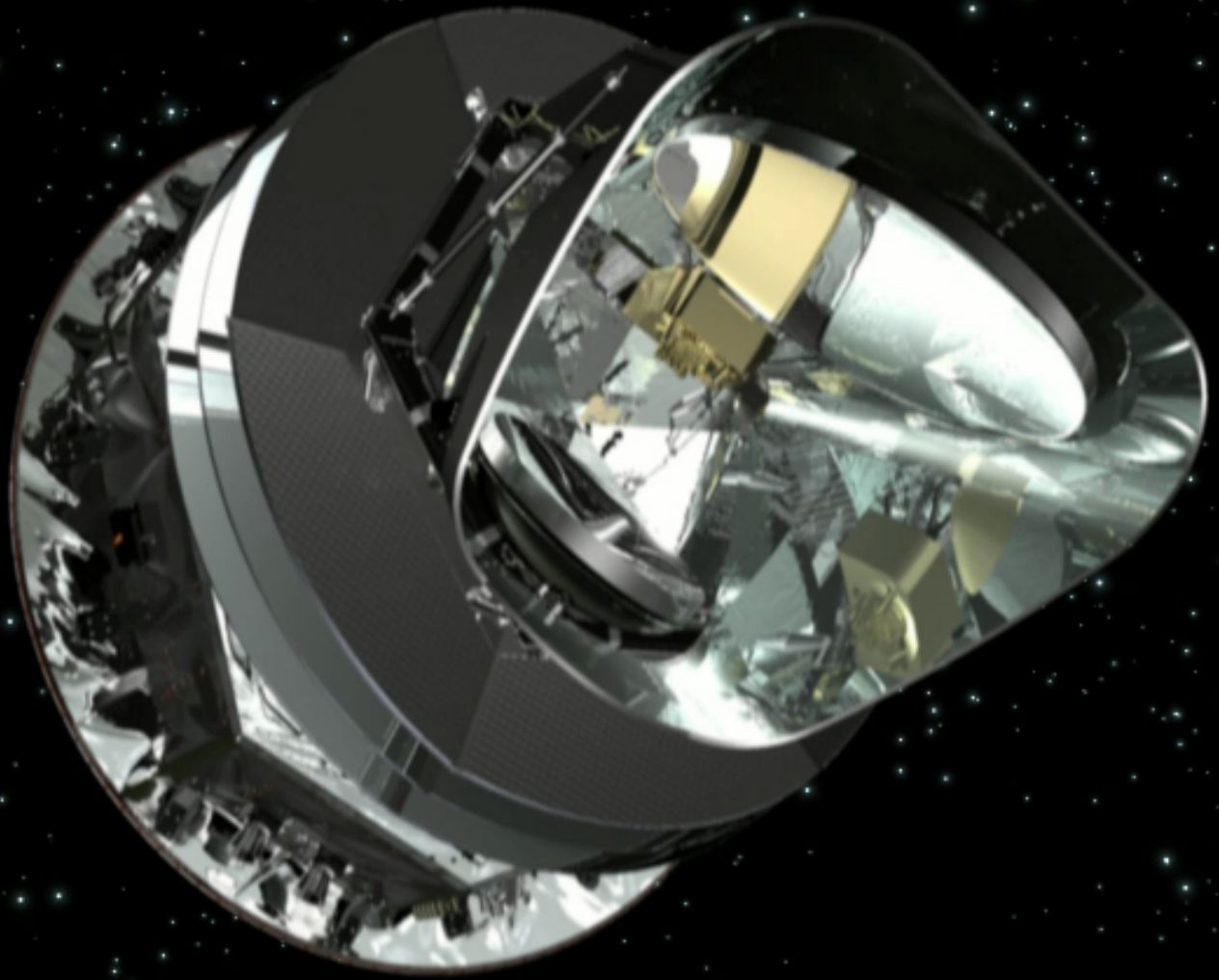
(2009-2013)

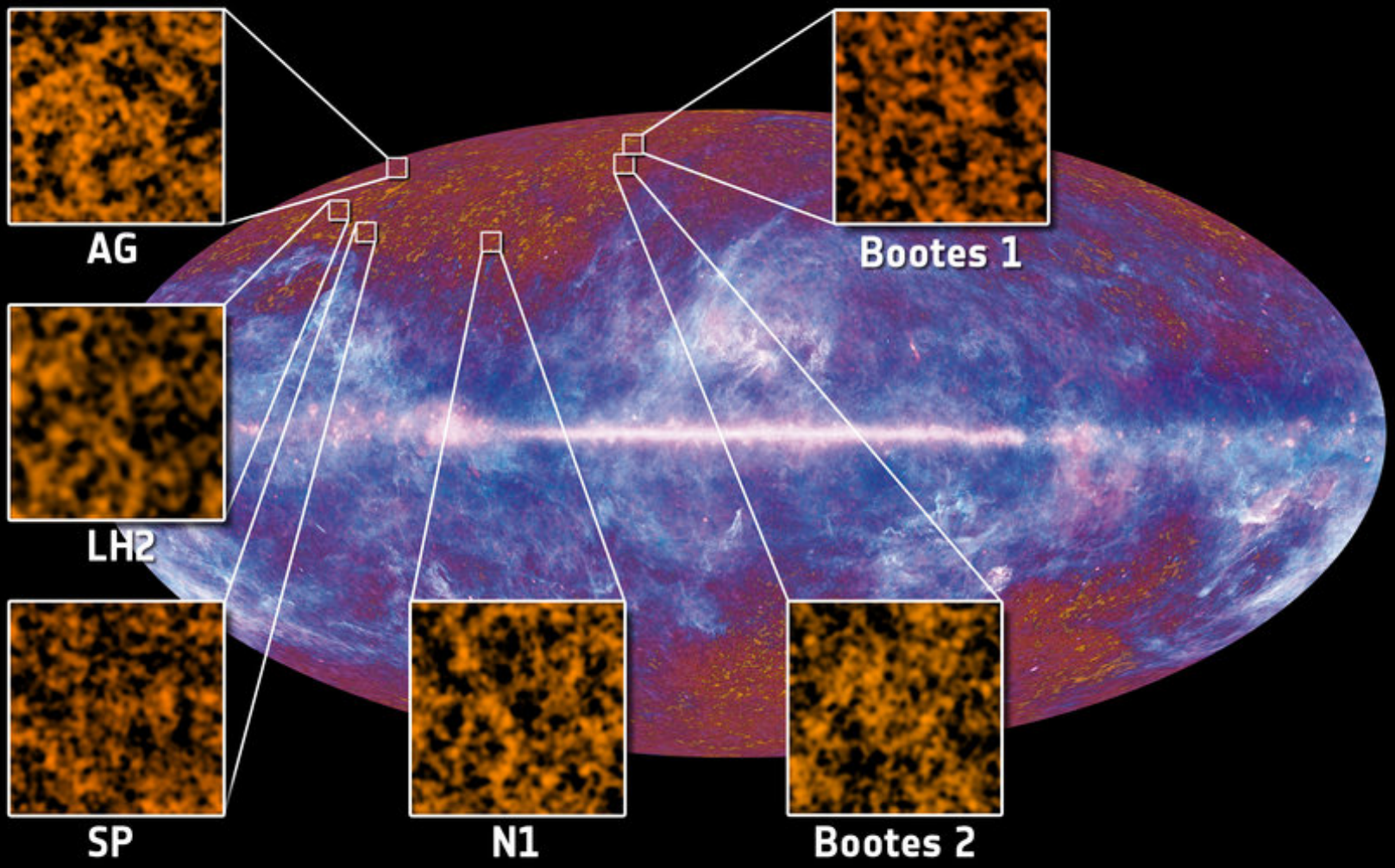
Miroir de 1m50 de diamètre

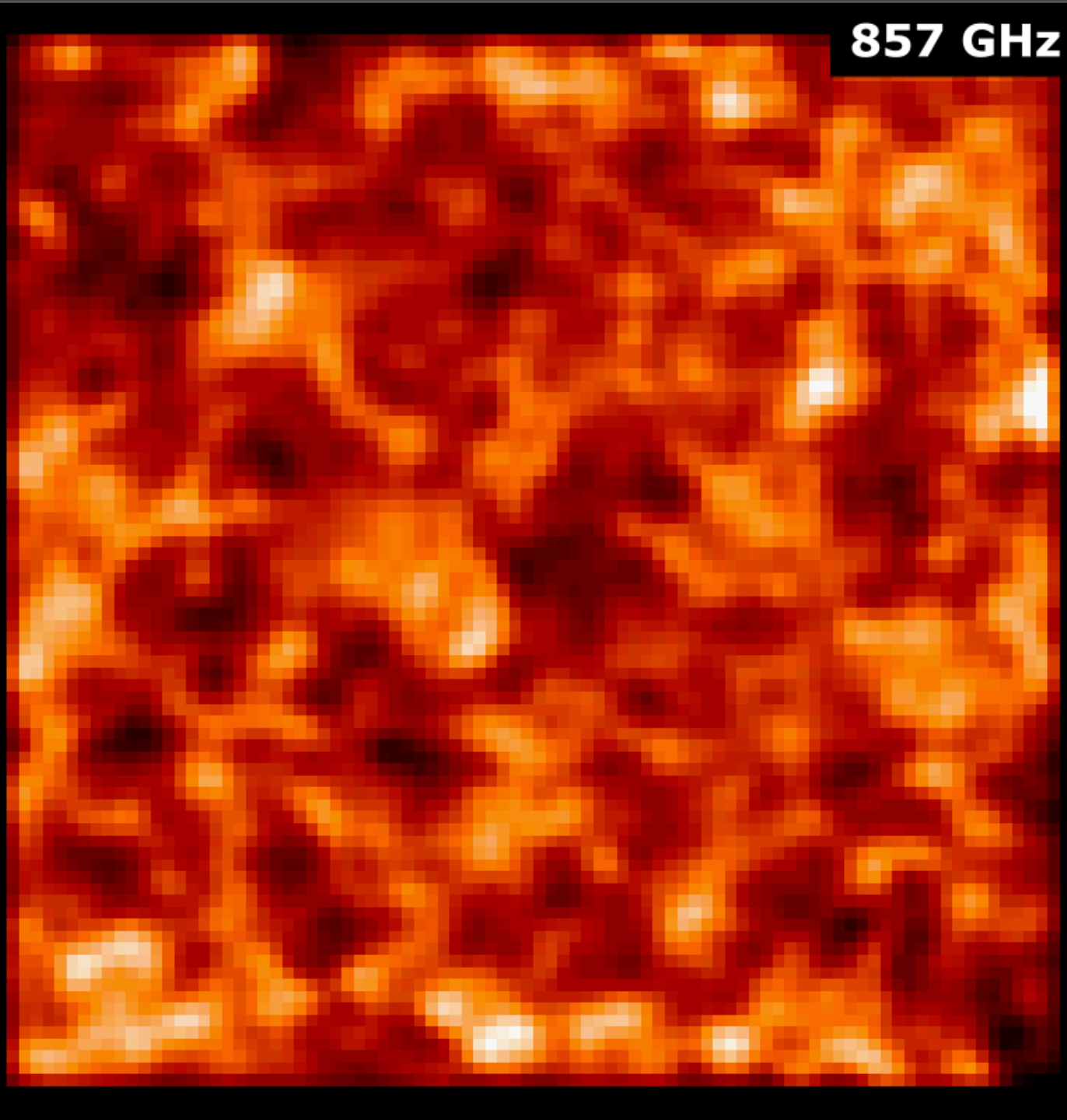
Bande de fréquences

100, 143, 217, 353, 545 et 857 GHz

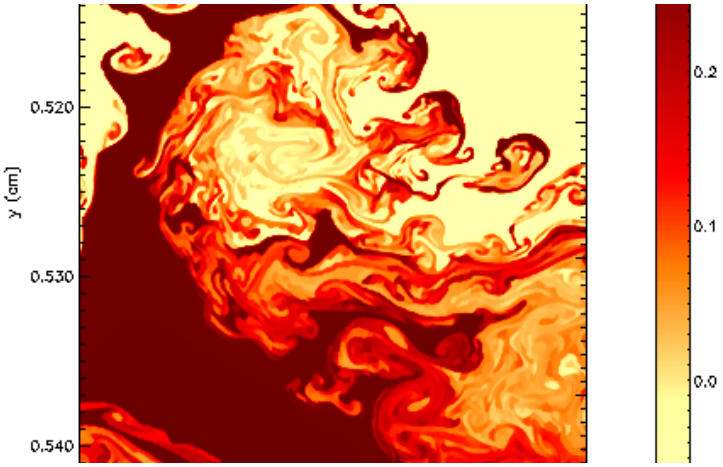
30 à 100 GHz

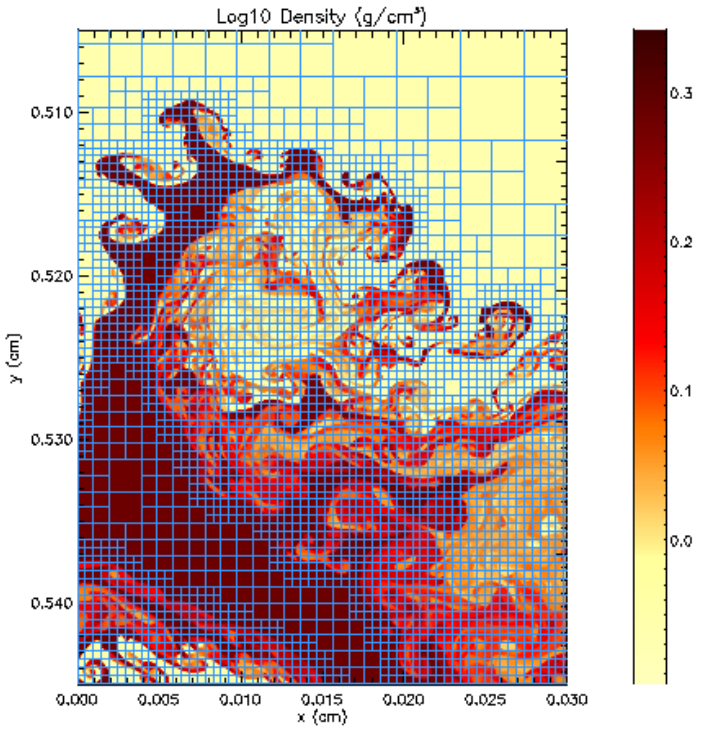



AG
LH2
SP
N1
Bootes 1
Bootes 2


857 GHz

Simulations numériques



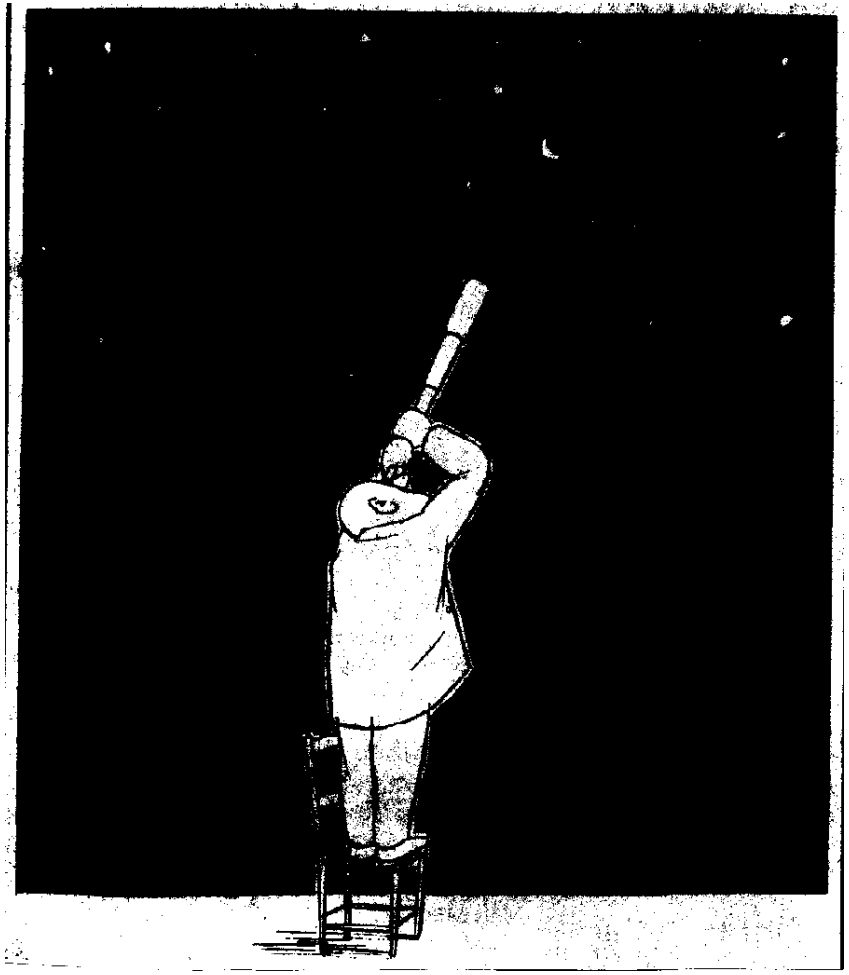


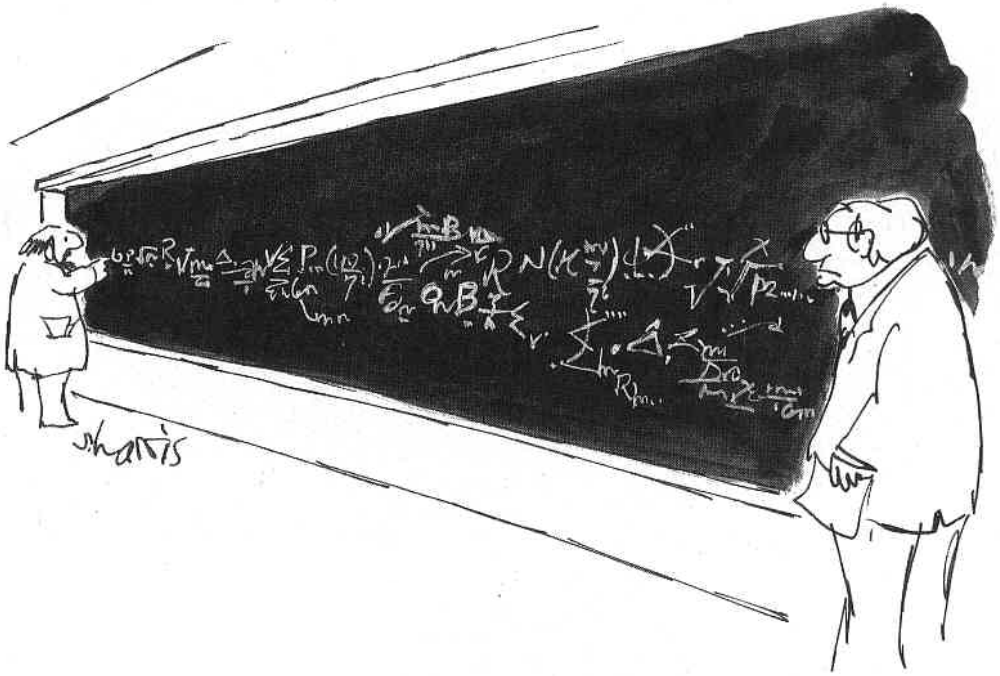
Jade superordinateur (CINES Montpellier)

Artist's View of Star Formation in the Early Universe

Painting by Adolf Schaller • STScI-PRC02-02

Encore beaucoup de travail
OBSERVATIONNEL et THEORIQUE… en perspective





COSMOLOGY MARCHES ON