LEE KUAN YEW

Distinguished Visitors PROGRAMME

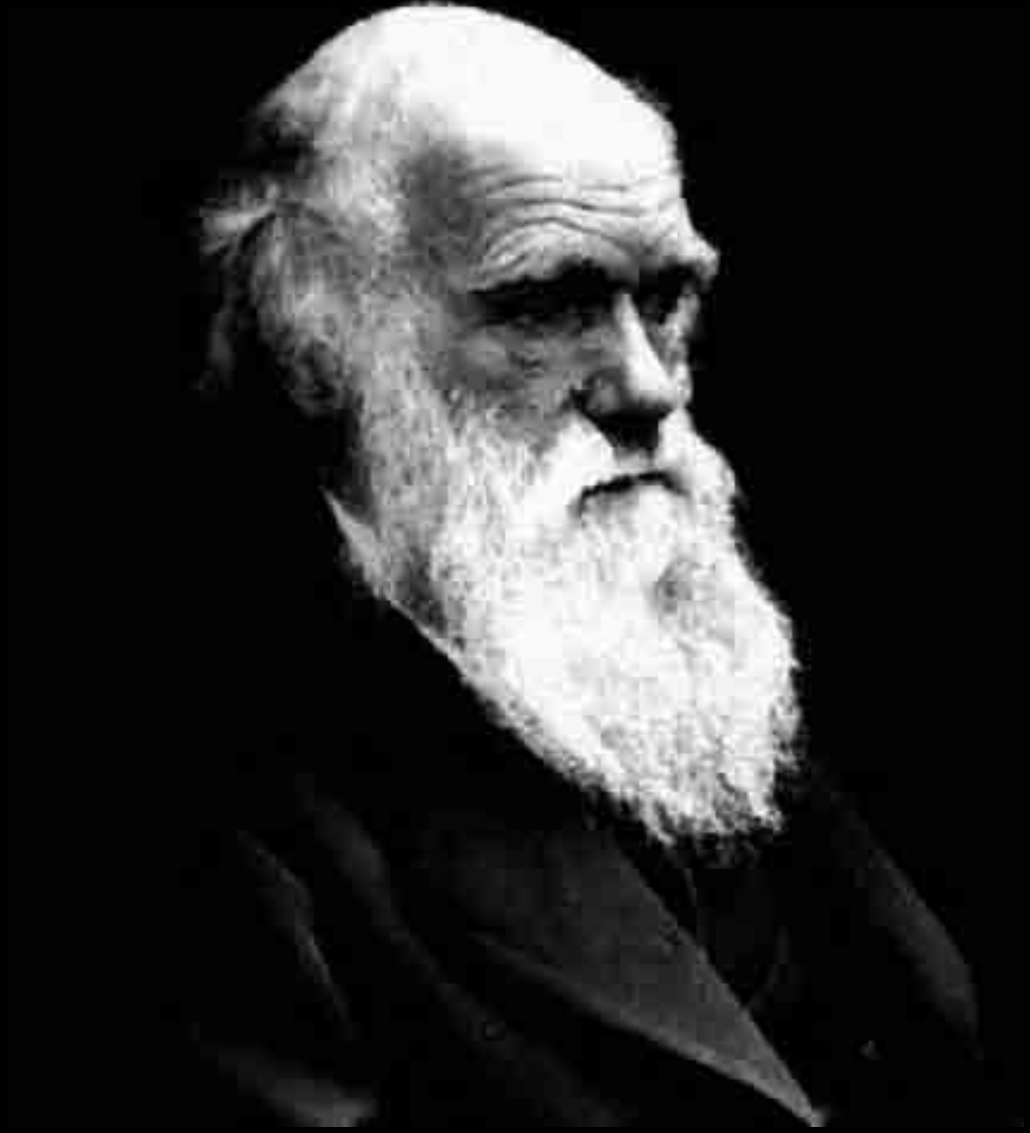
PUBLIC LECTURE SERIES

Lord Martin Rees

Professor of Cosmology and Astrophysics
Master of Trinity College, University of Cambridge

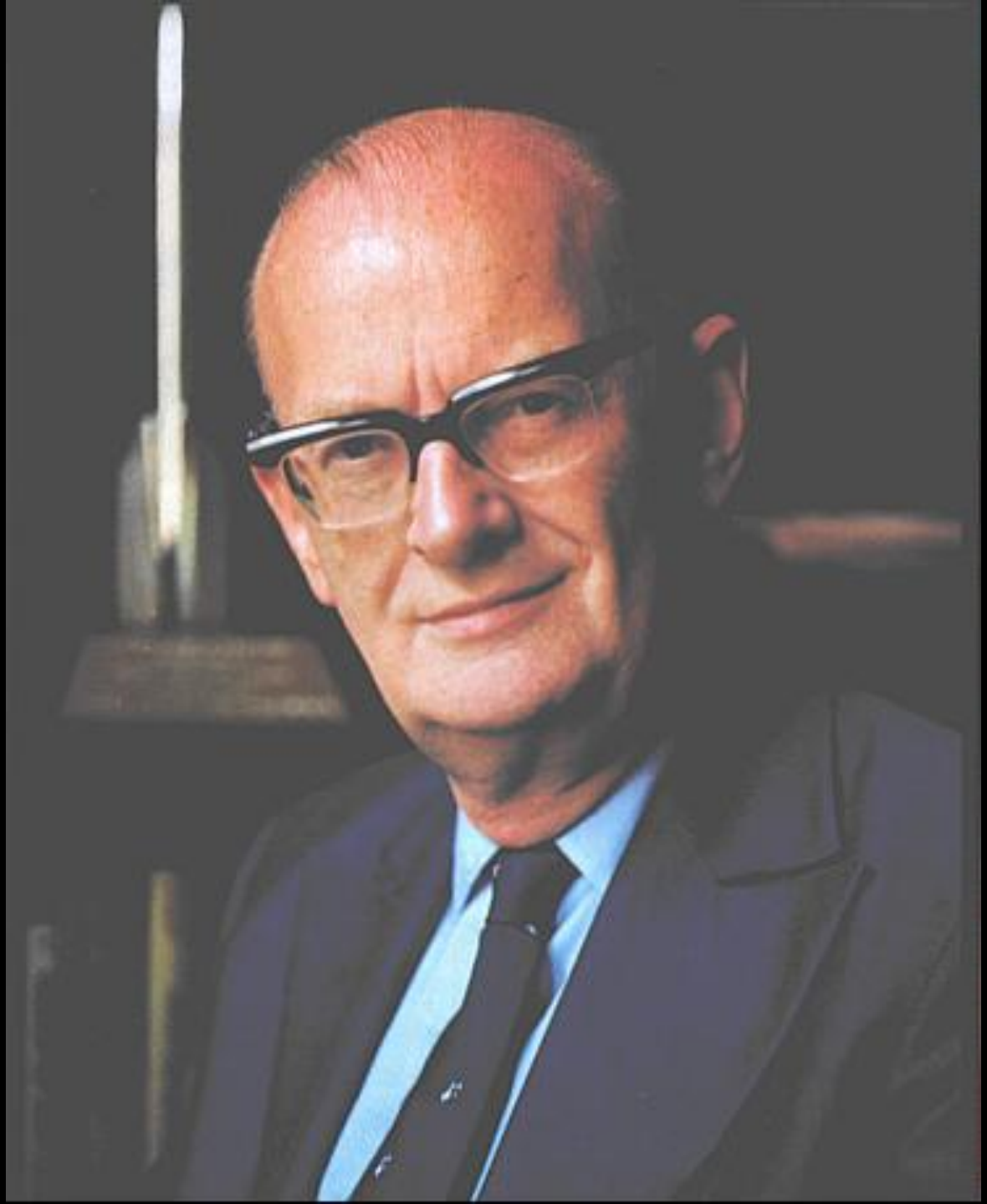
OUR UNIVERSE, AND THE ROLE OF LIFE IN IT

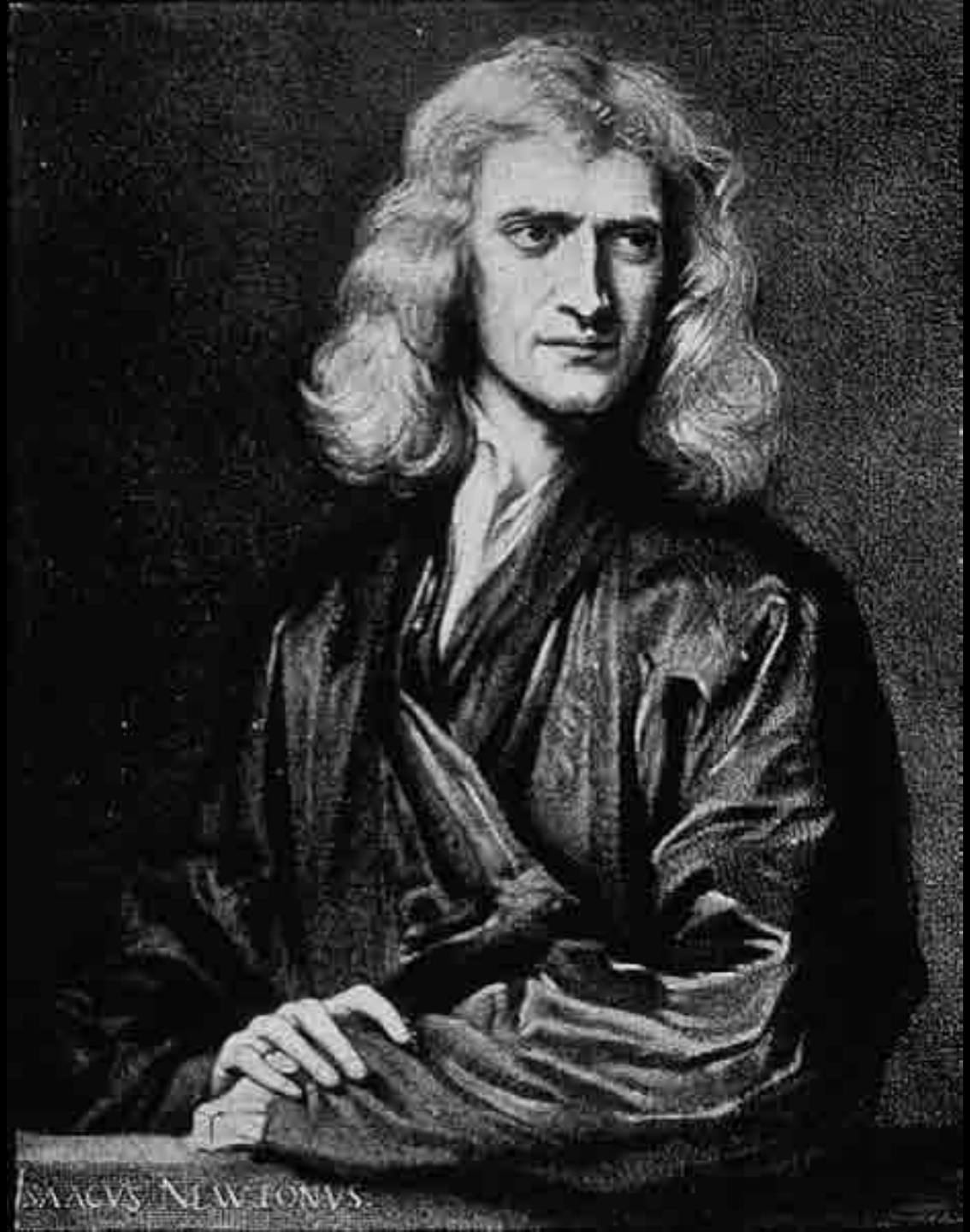
NUS National University of Singapore

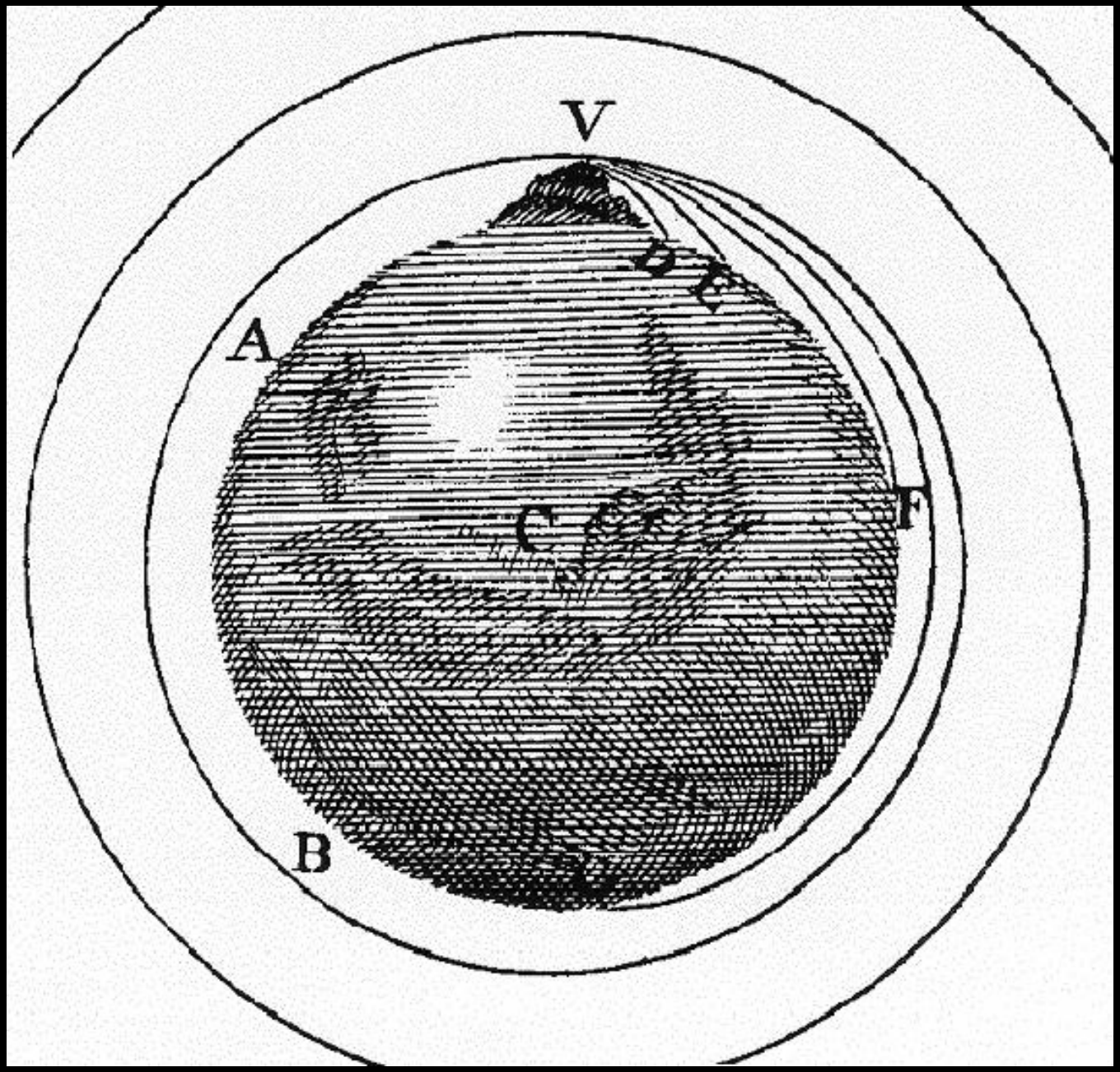


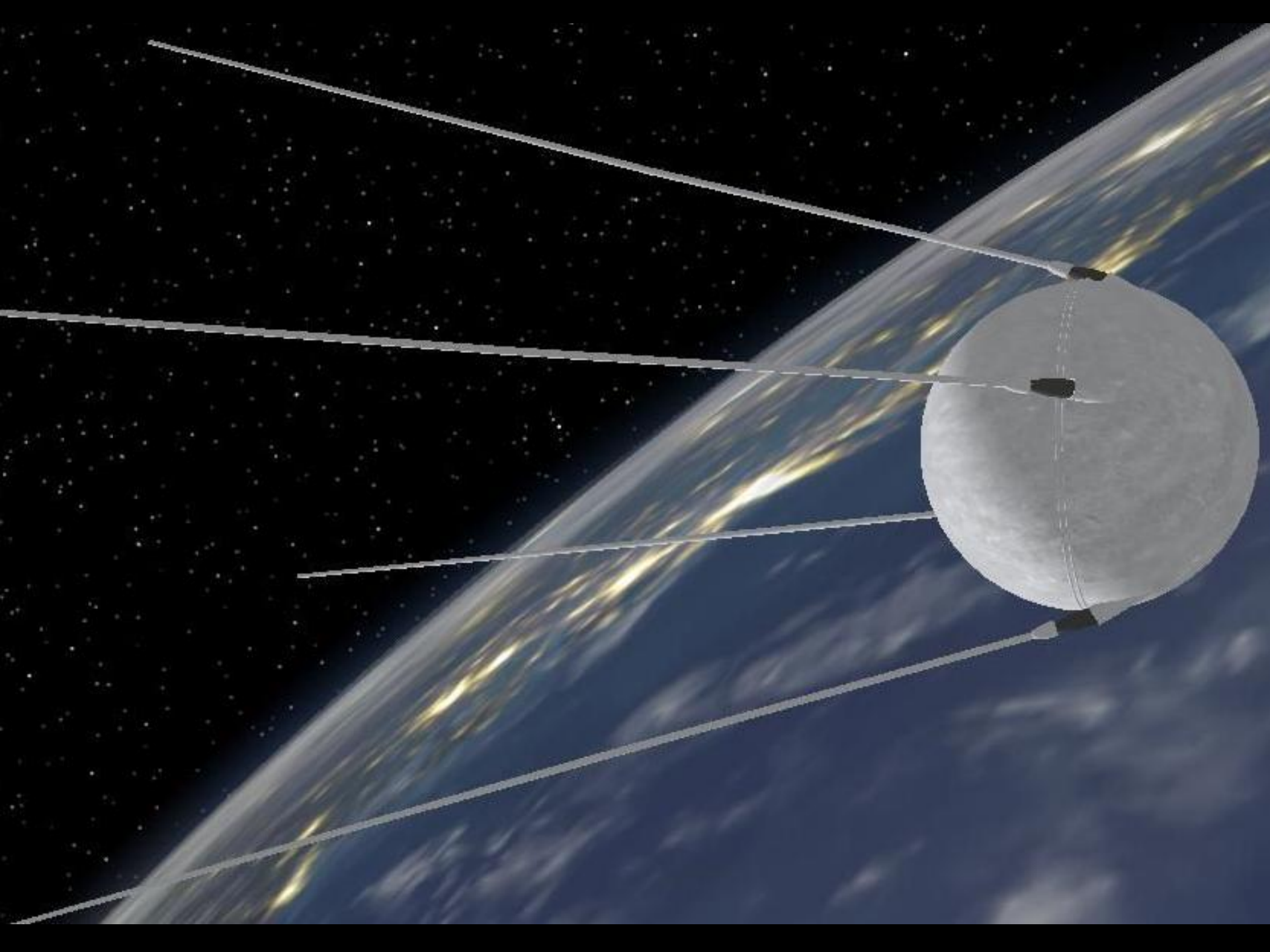
”whilst this planet has been cycling on according to the fixed law of gravity, from so simple a beginning…. forms most wonderful have been and are being evolved"

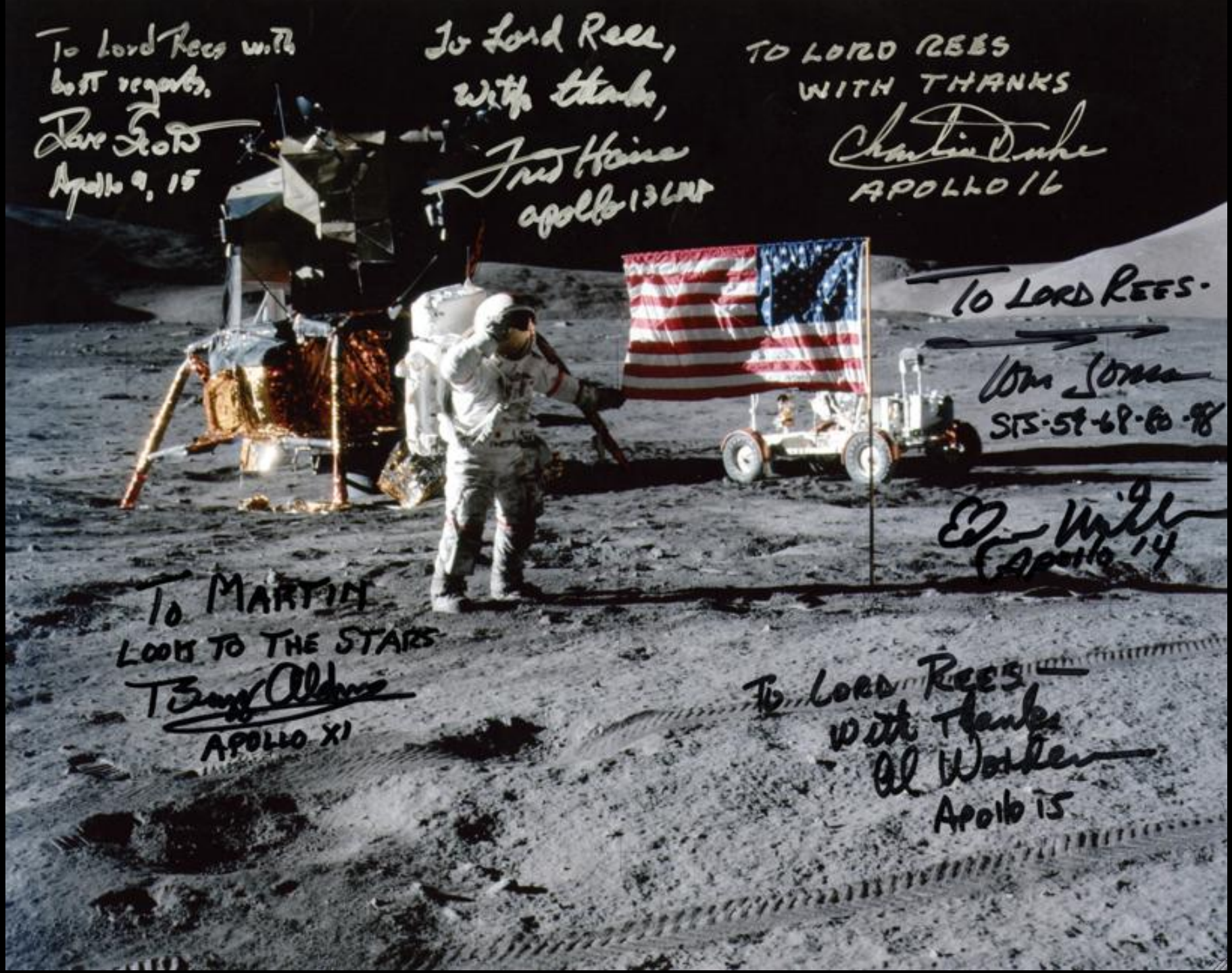
Charles Darwin

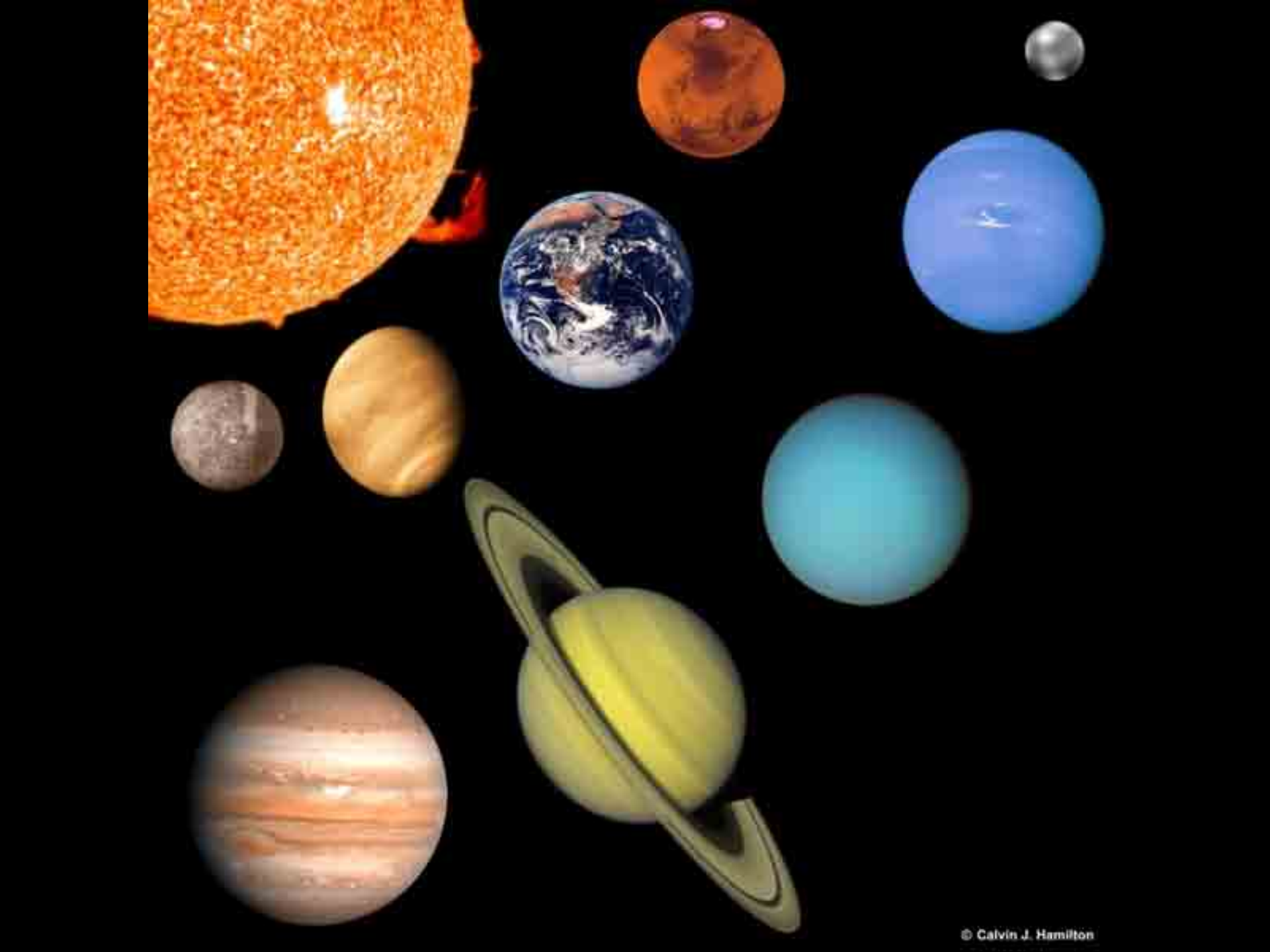


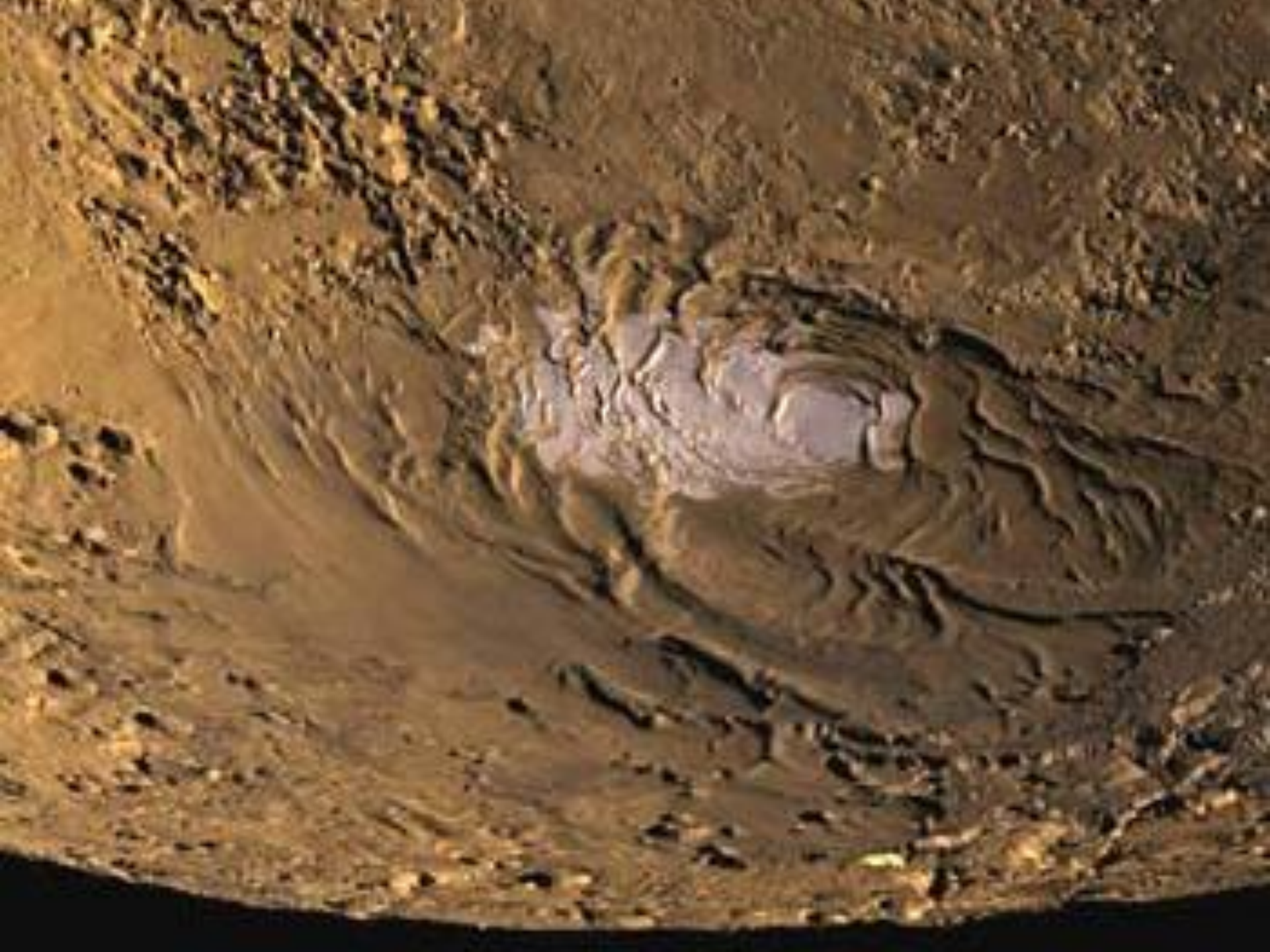

ISAACVS NEWTONVS.

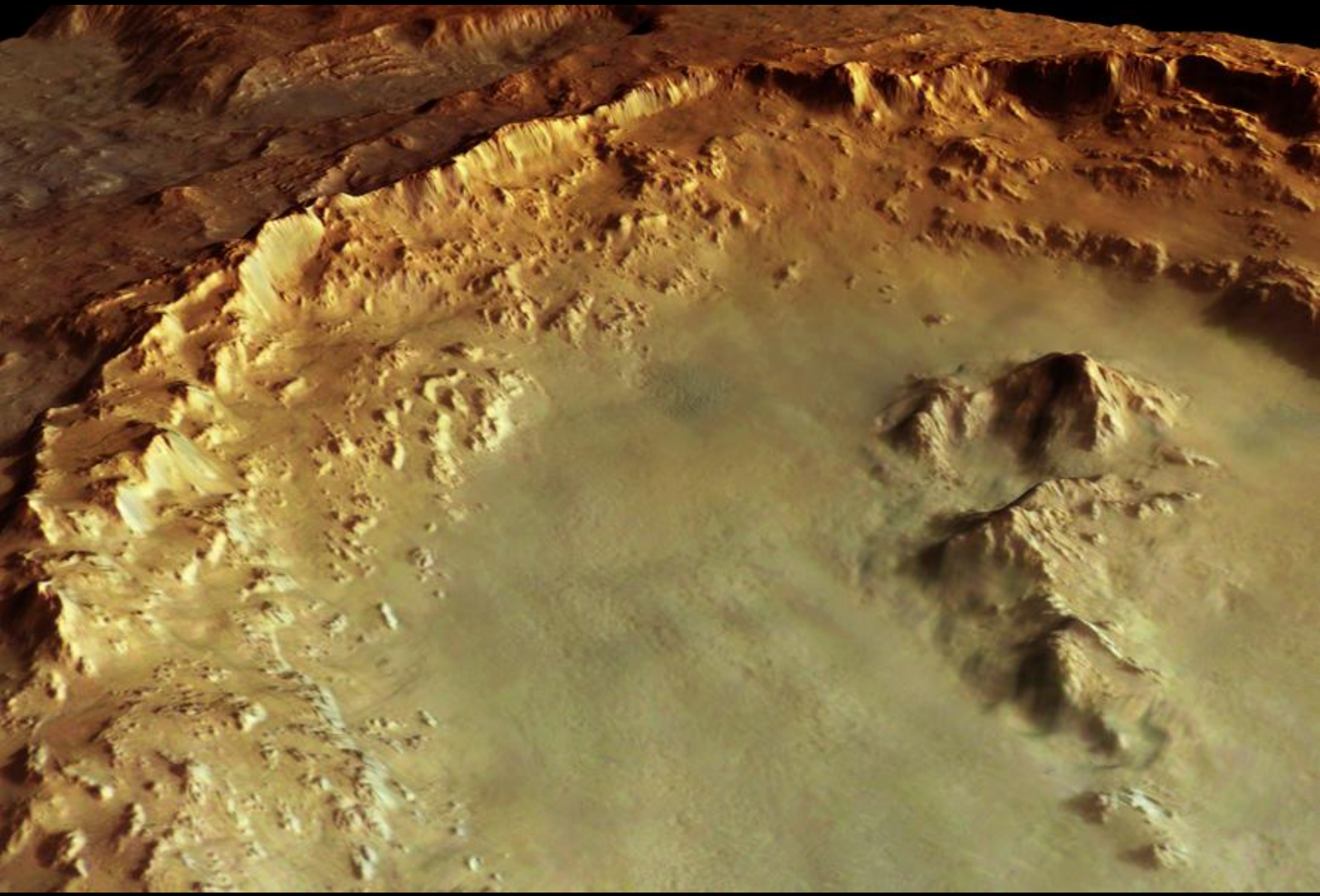

V
A
F
B




To Lord Rees with best regards.
Dave Scott
Apollo 9, 15
To Lord Rees, With thanks,
Fred Haise
Apollo 13 LMP
TO LORD REES WITH THANKS
Charlie Duke
APOLLO 16
To Lord Rees.
Tom Jones
STS-51-G-61-C-88
Ed Mitchell
Apollo 14
To Martin
Looks to the Stars
Buzz Aldrin
Apollo XI
To Lord Rees
With Thanks
Al Worden
Apollo 15


© Calvin J. Hamilton





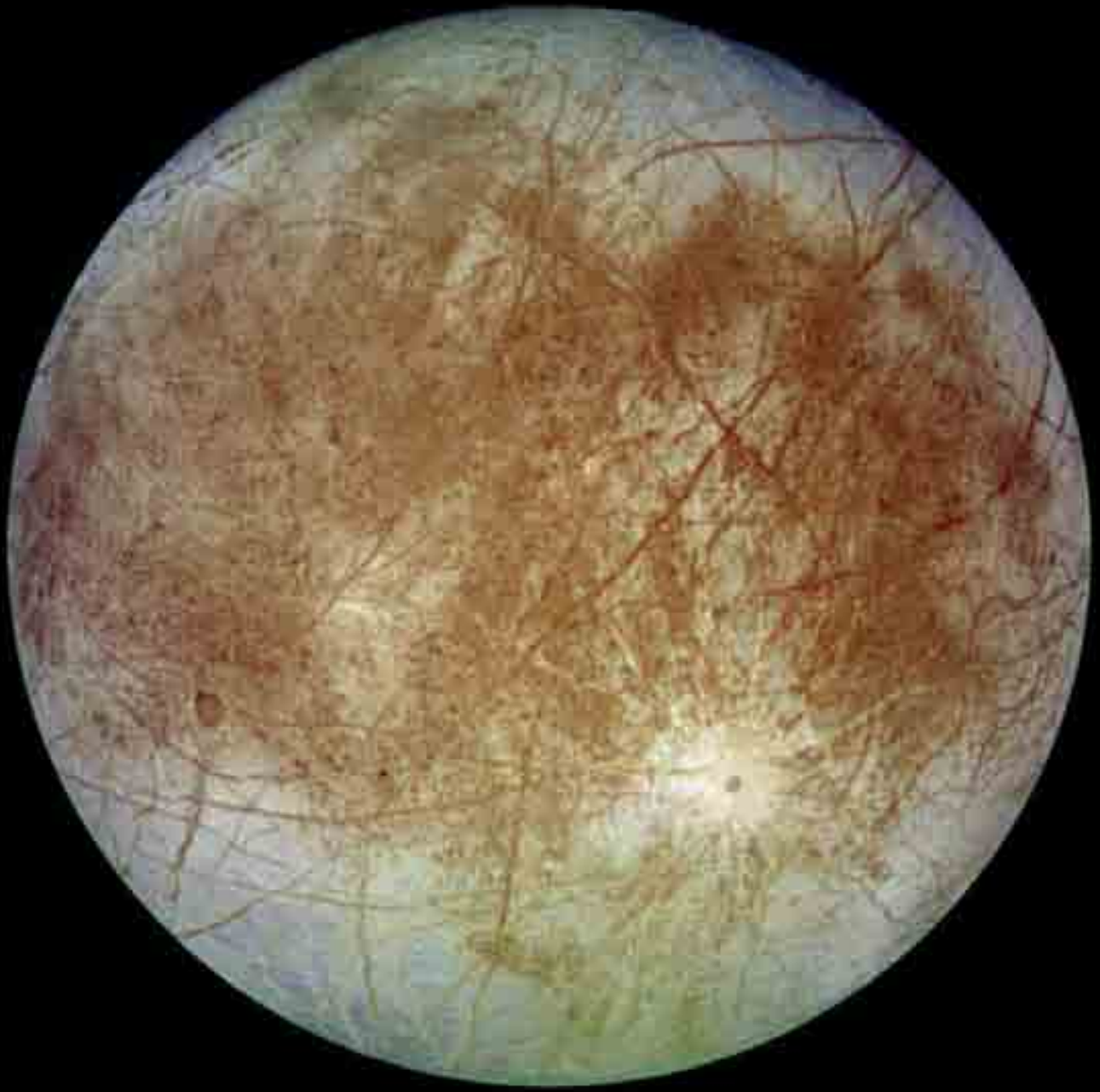
The Satellites of Jupiter

Io

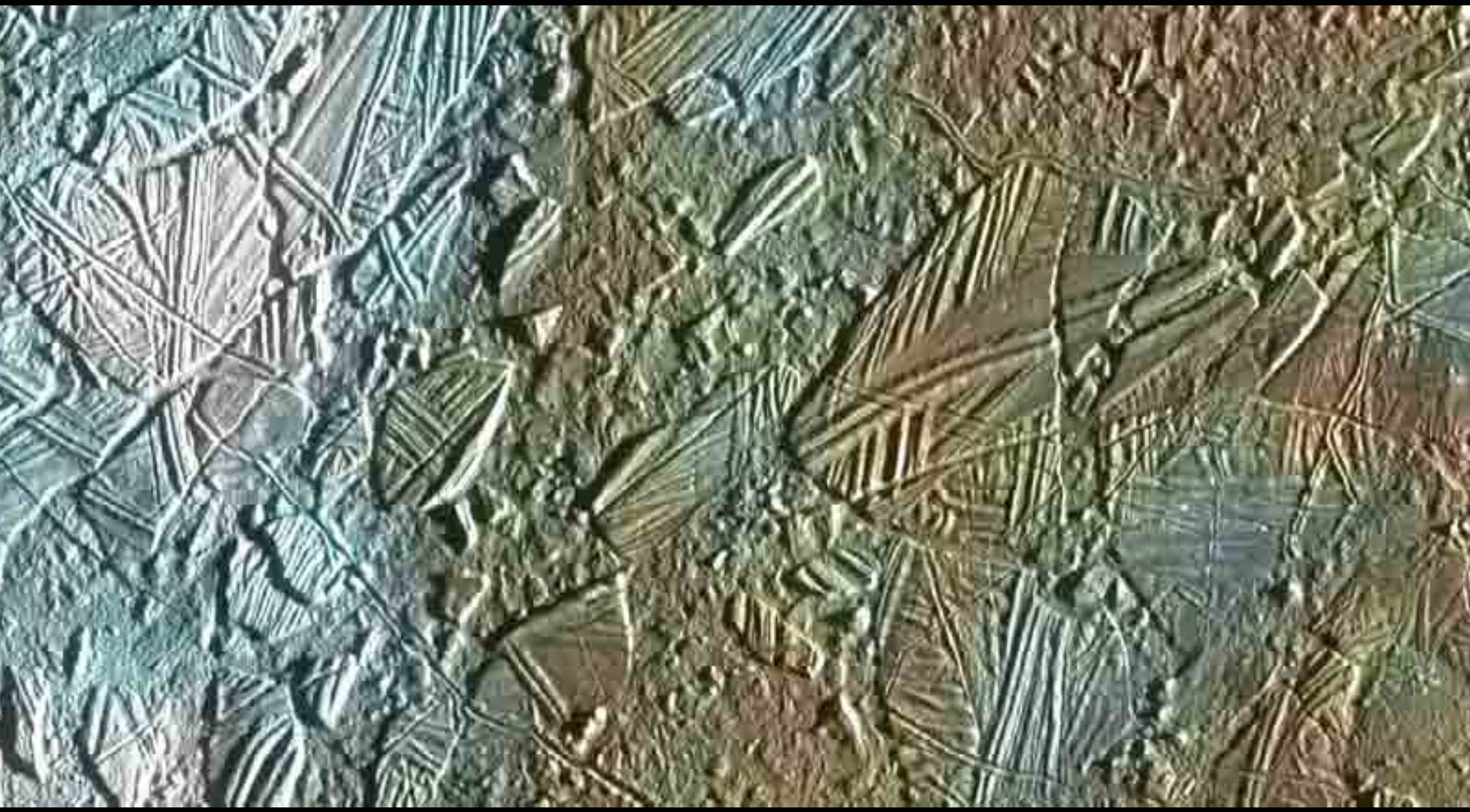
Europa

Ganymede

Callisto



Europa



Region 30km by 65km

Exploring the Solar System

Saturn - Cassini-Huygens

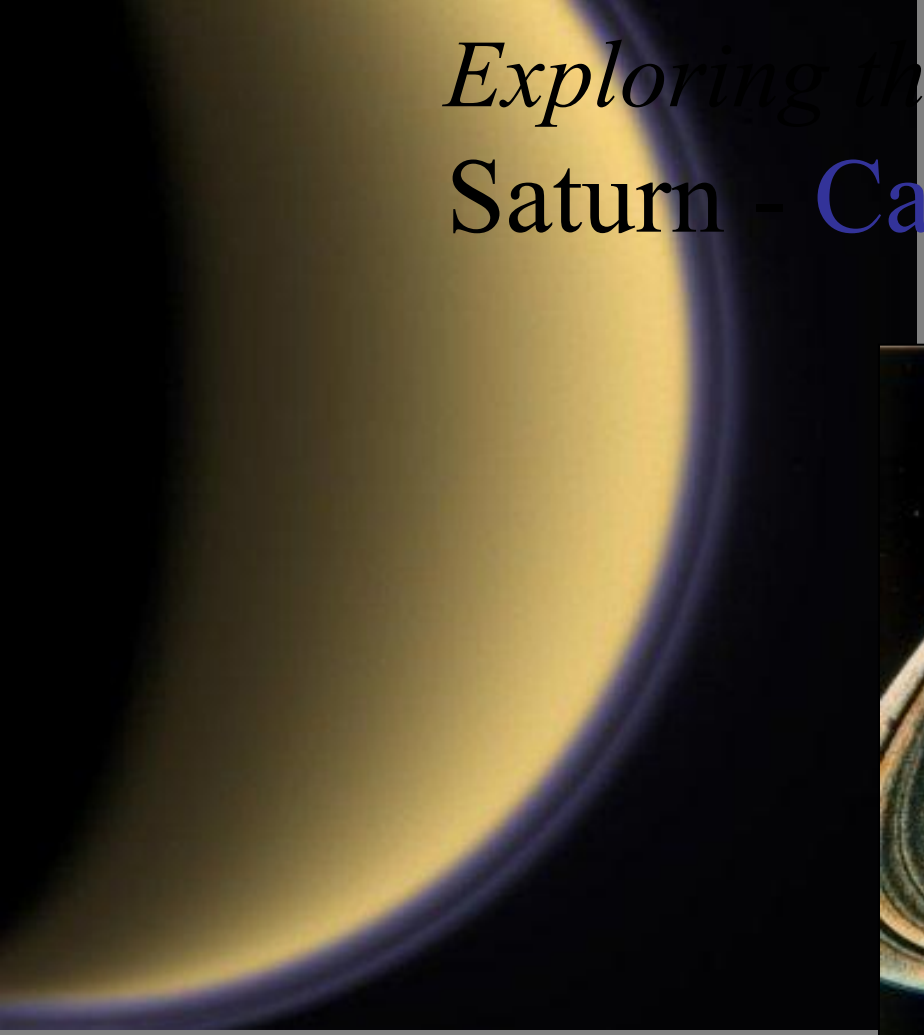
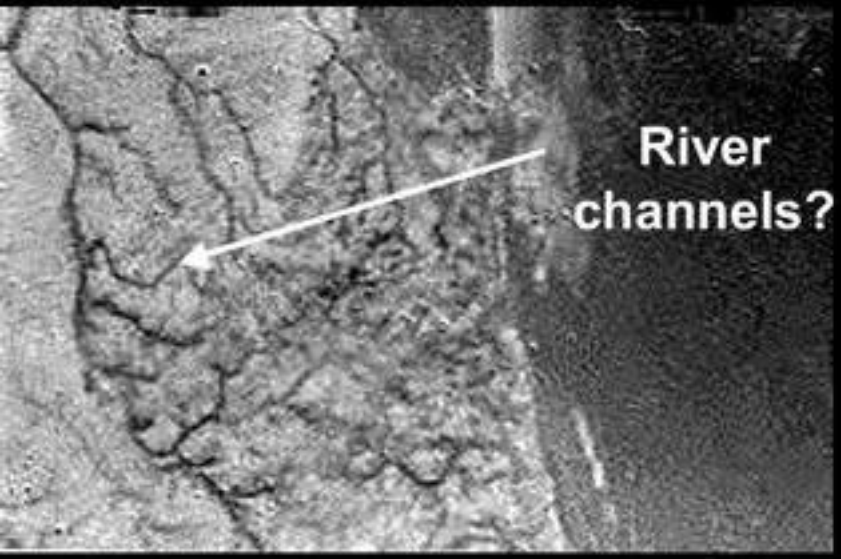


Image of Titan by Cassini spacecraft

Enhanced colour image of the rings of Saturn by Cassini spacecraft

Huygens Entry, Descent and Landing

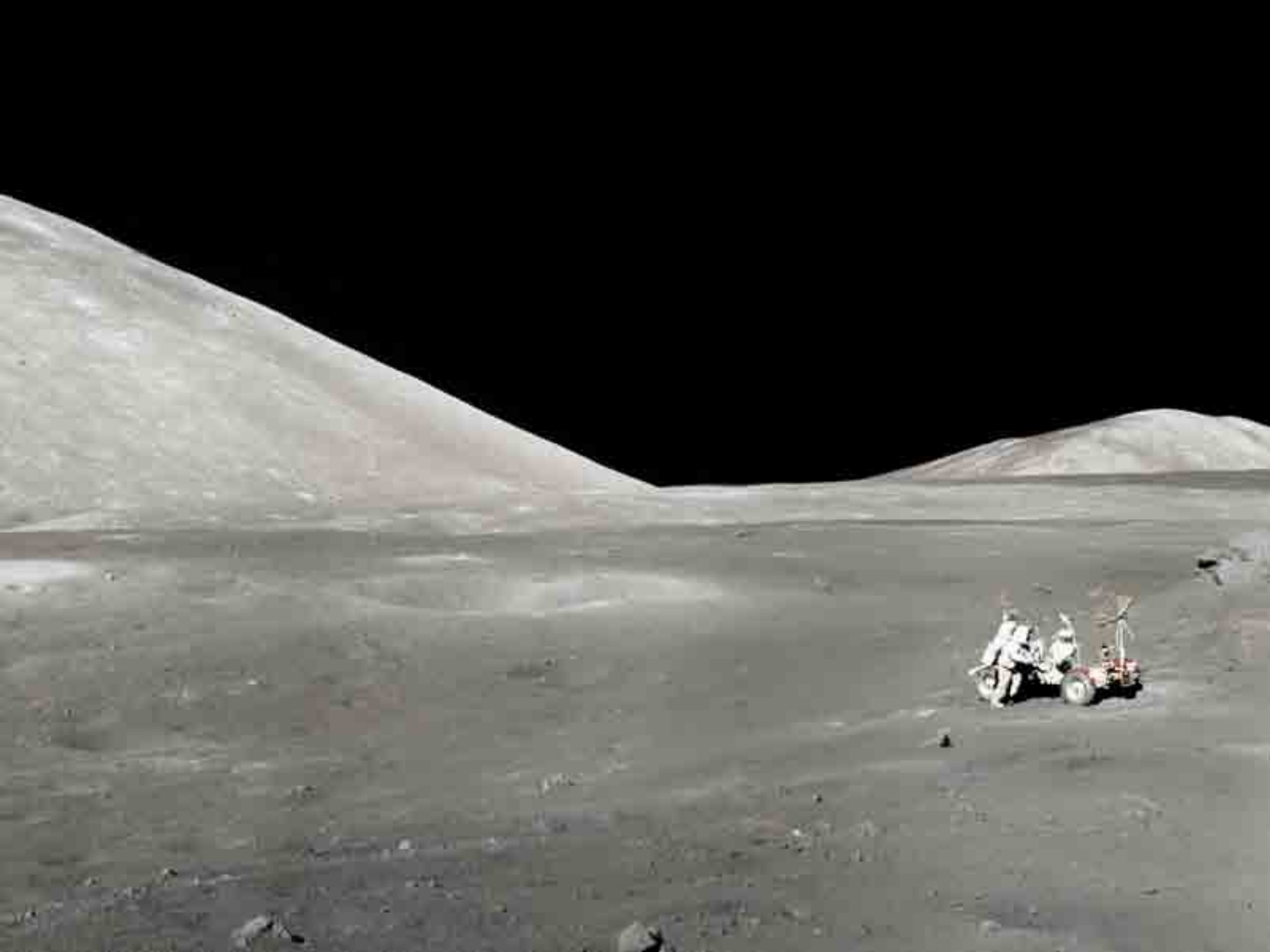
Huygens Probe Lands on Titan

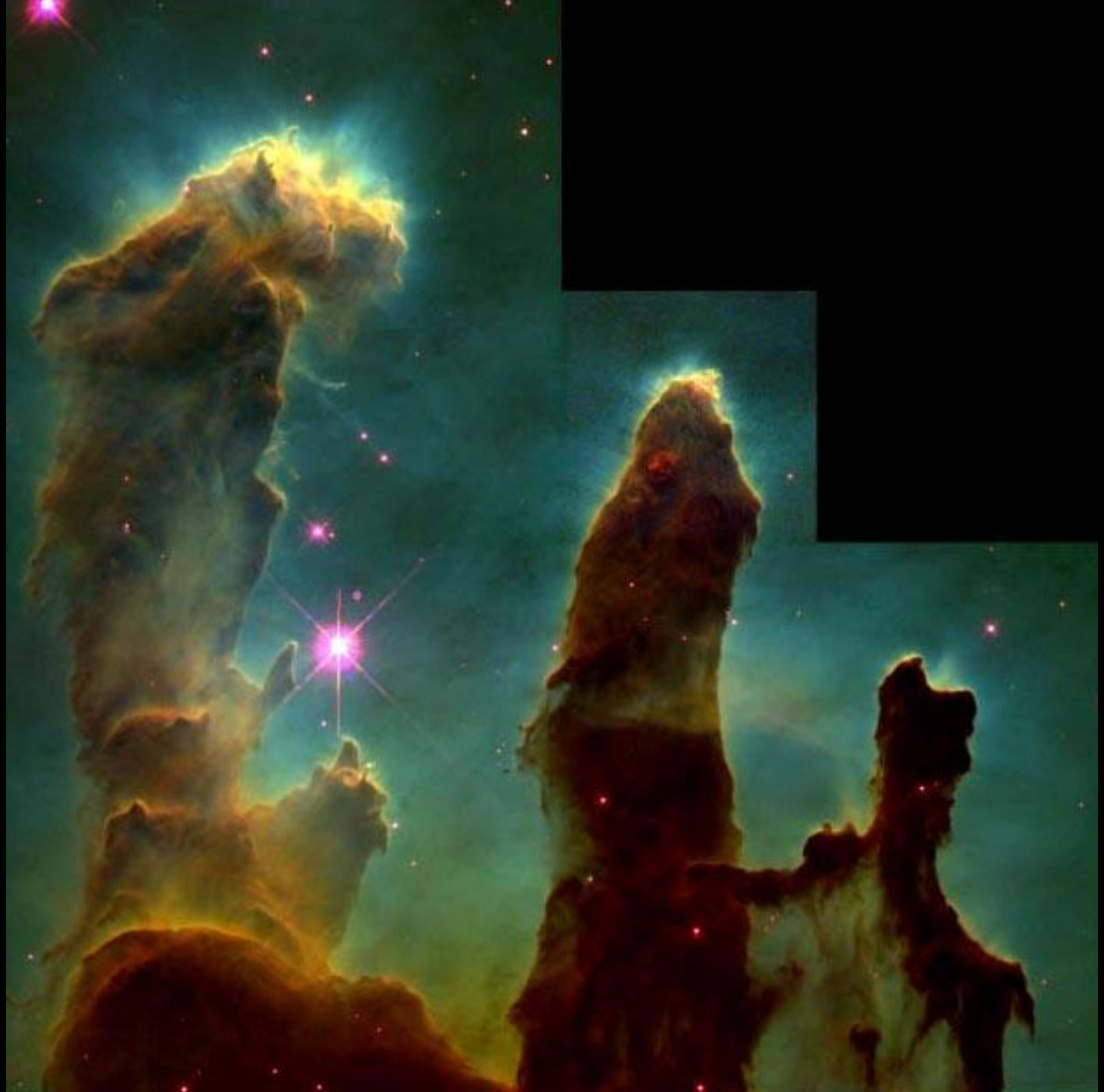


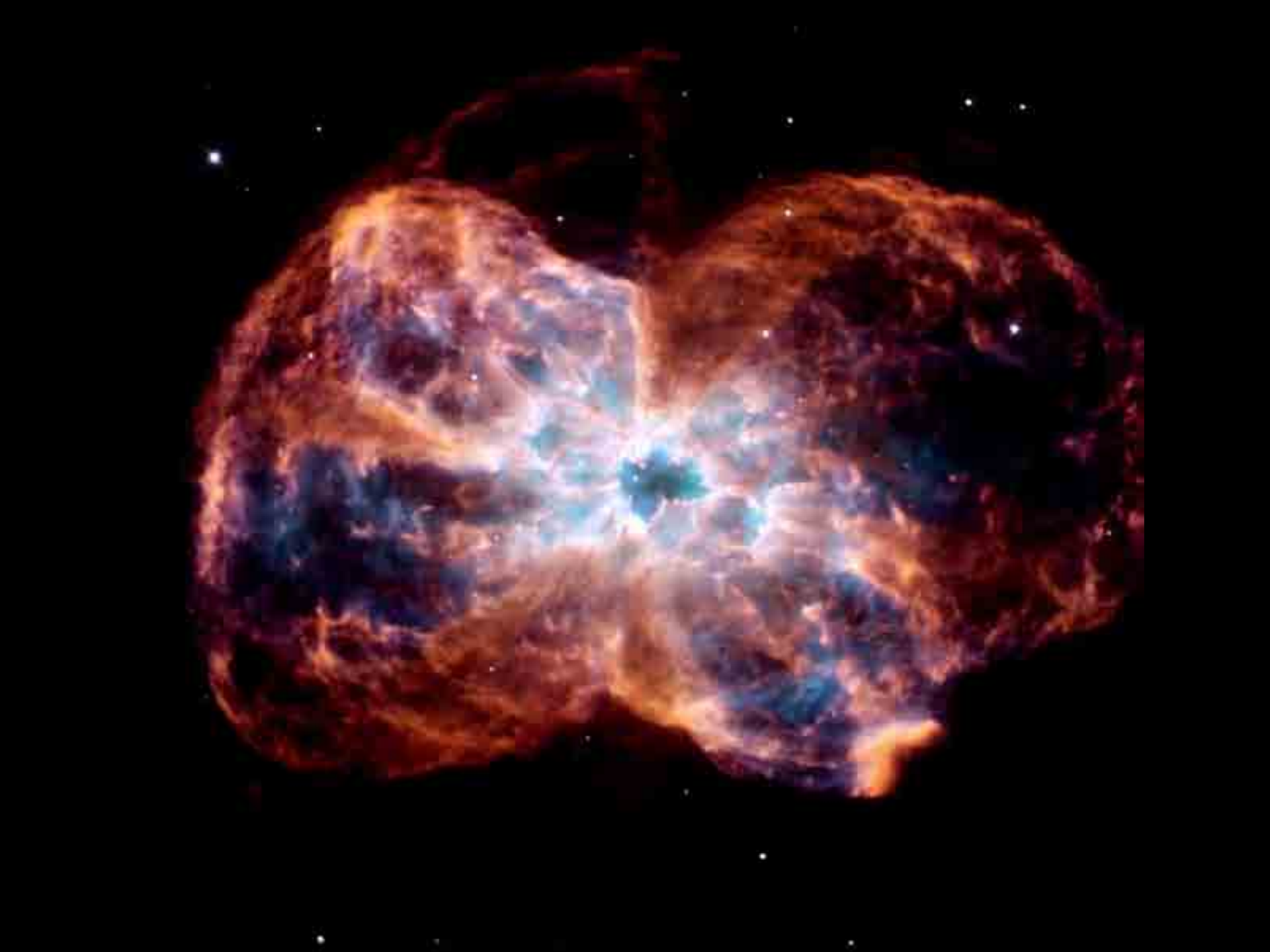
Surface seen from
Descending Probe

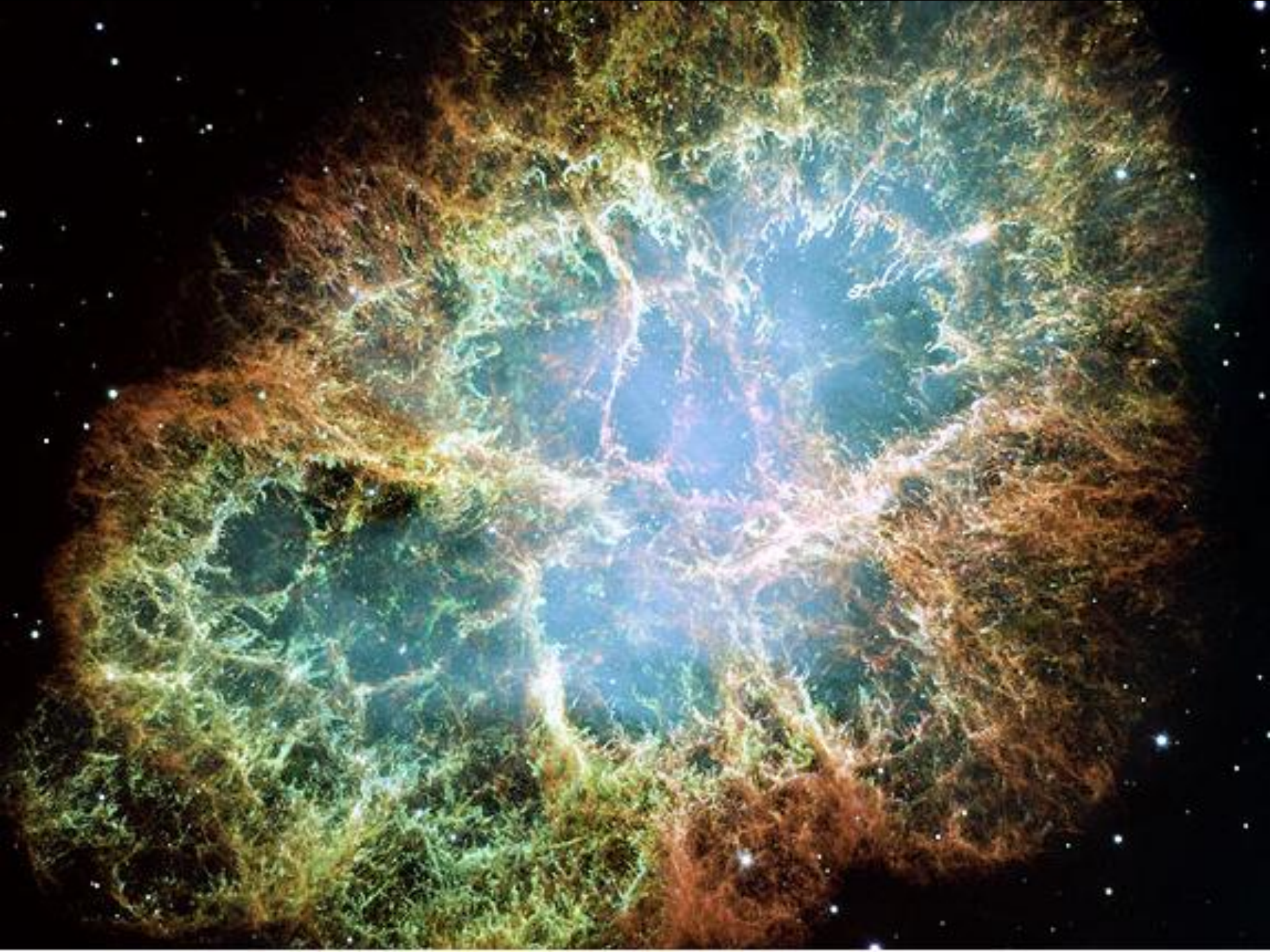
Probe Survives
Landing

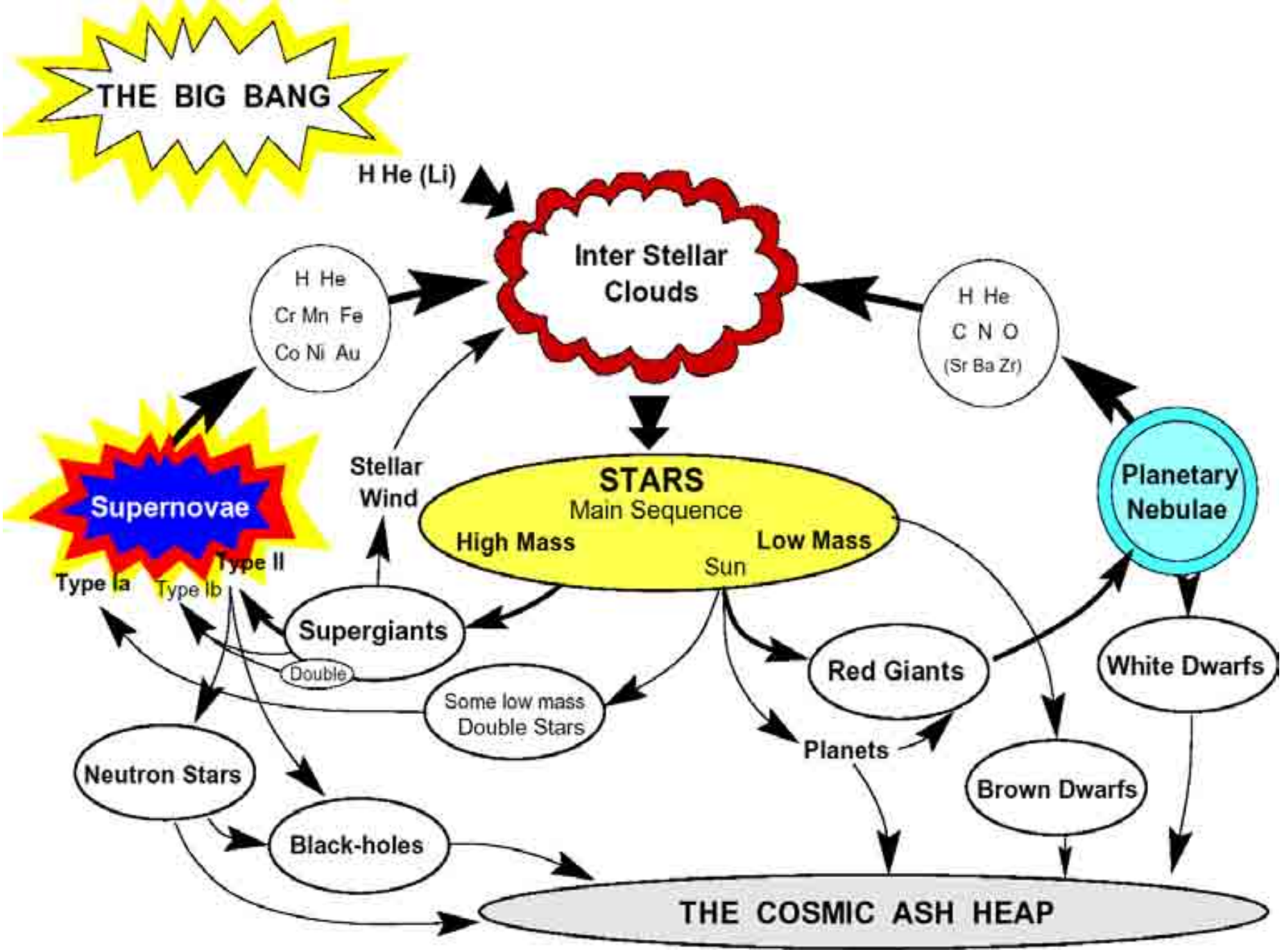
Methane Lake?

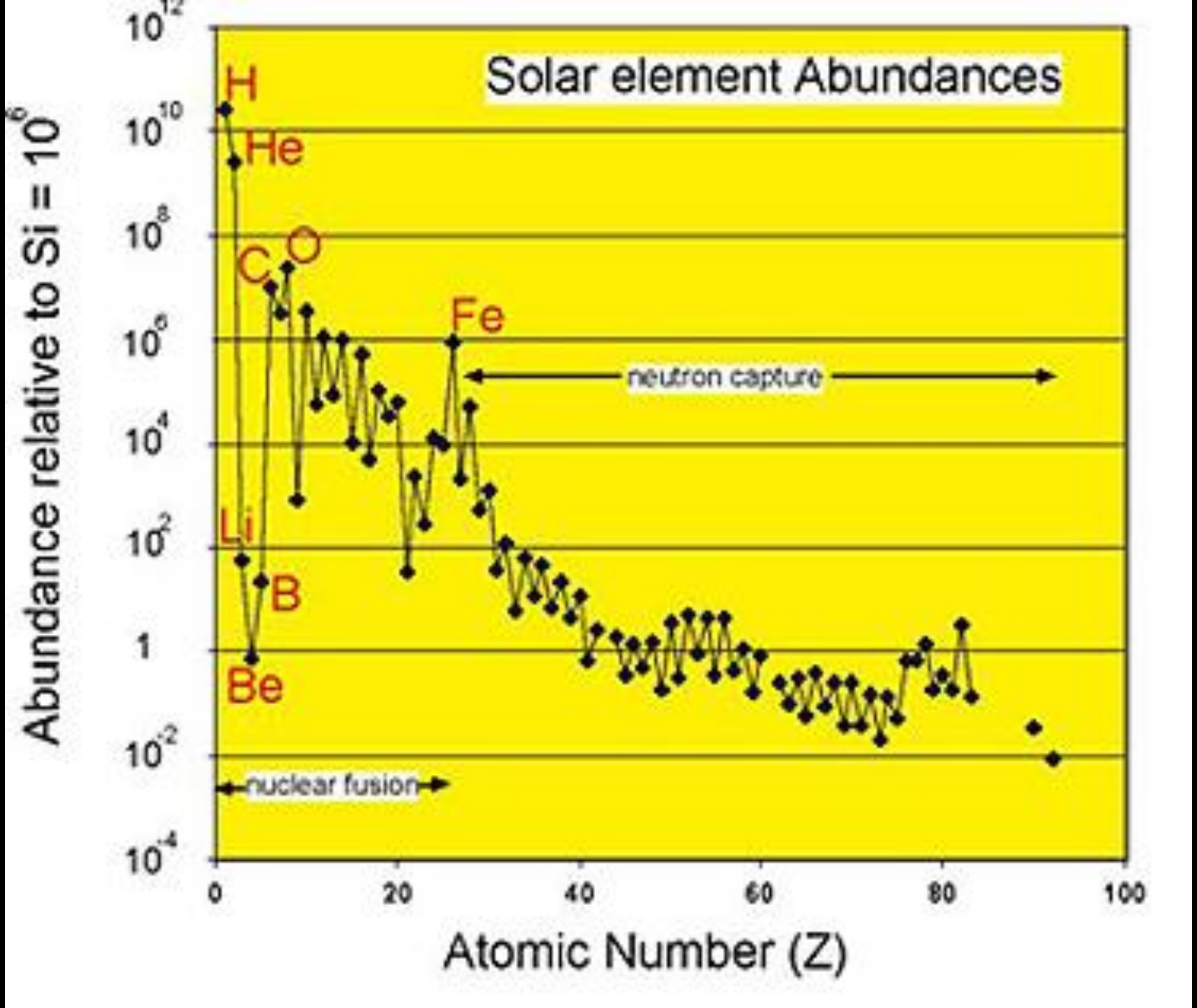


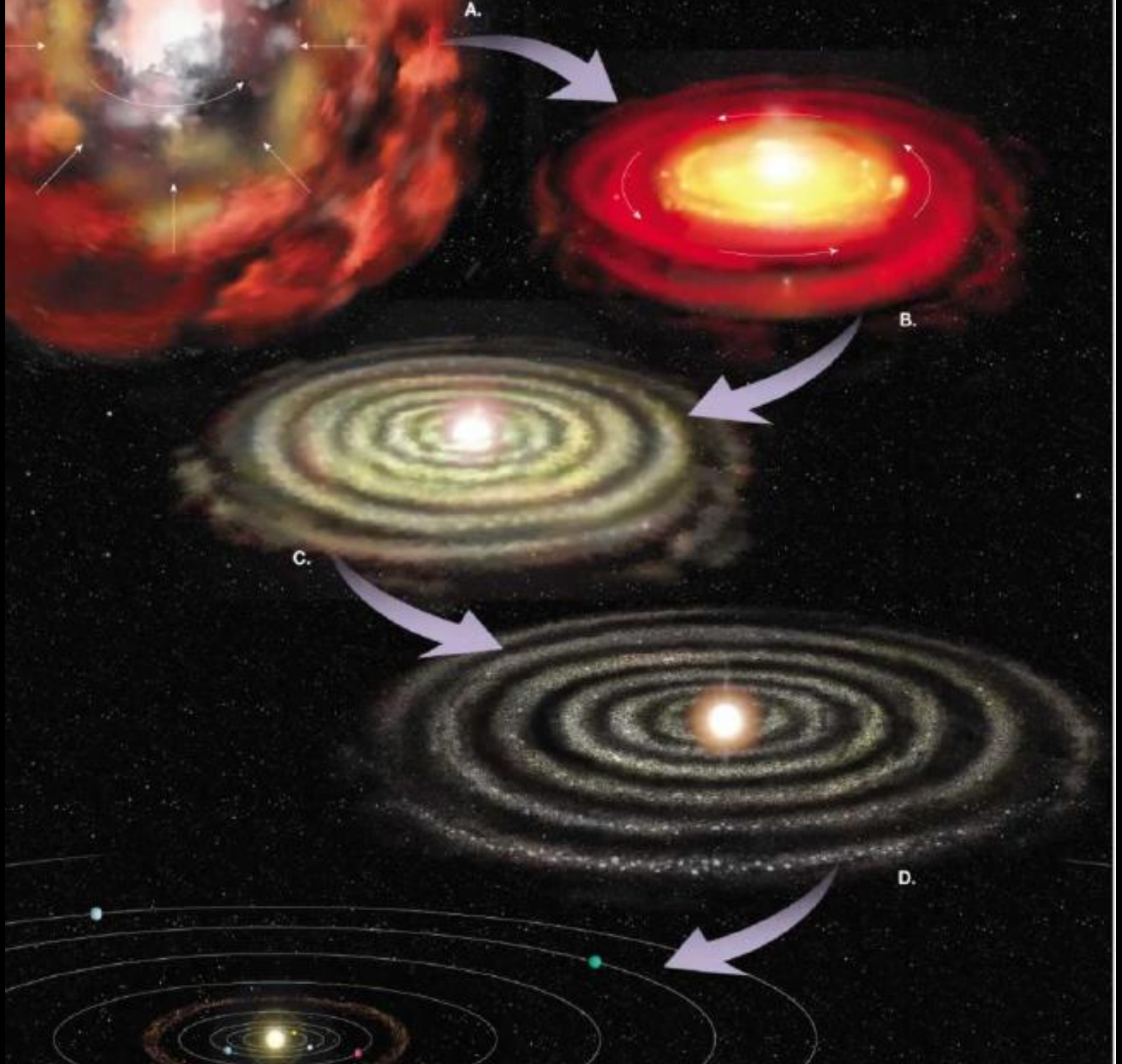




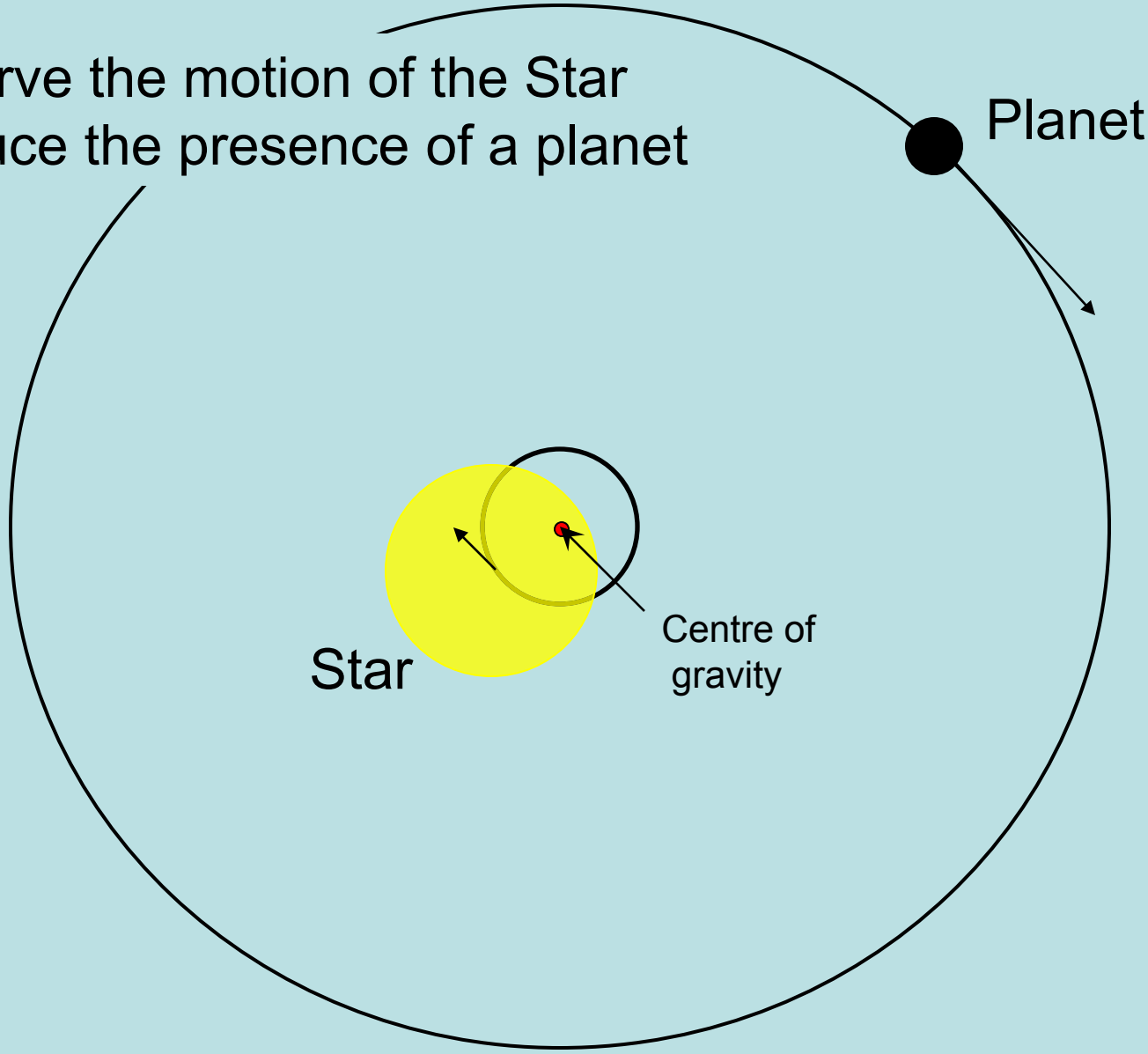


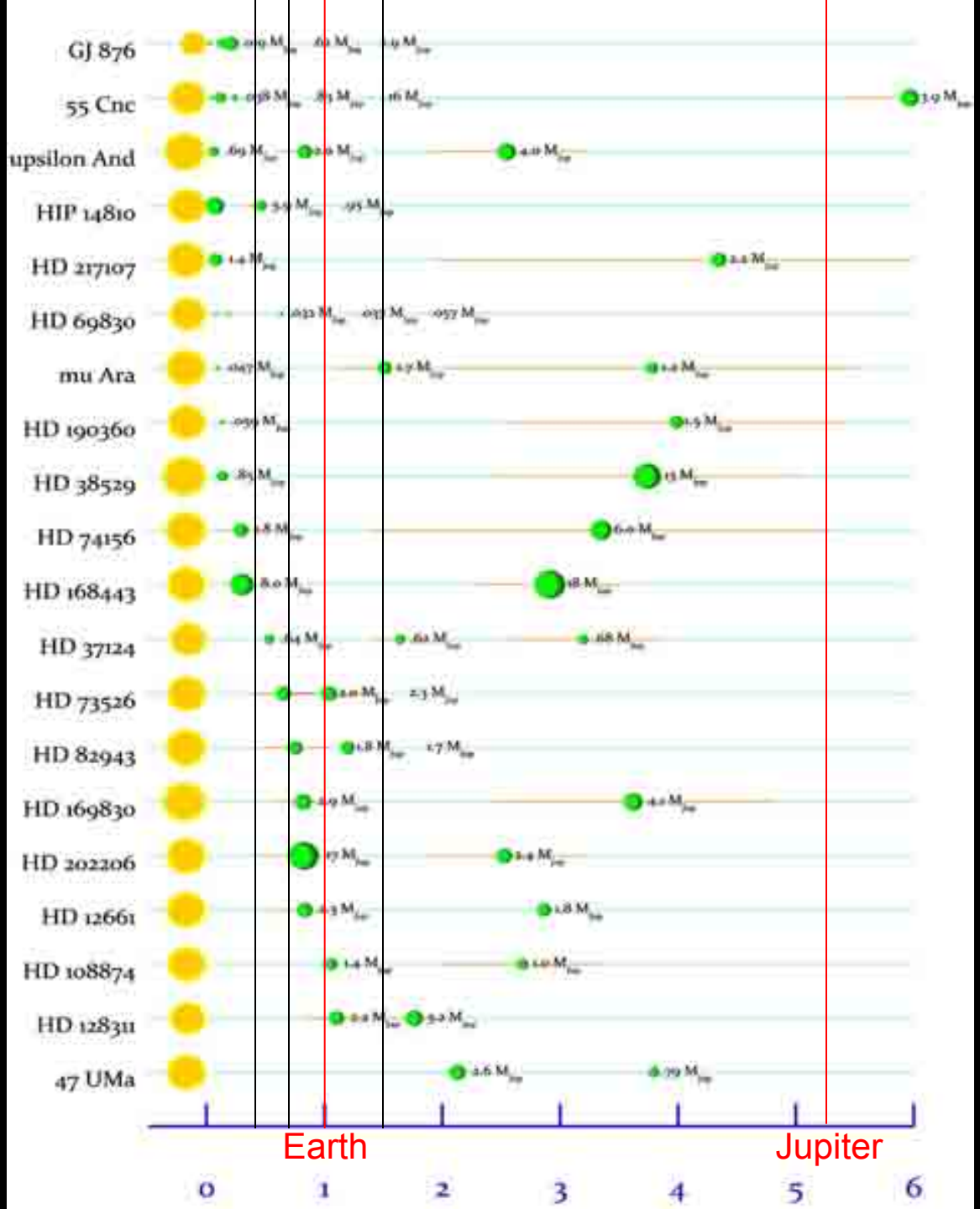

THE BIG BANG
H He (Li)
Inter Stellar Clouds
H He
Cr Mn Fe
Co Ni Au
H He
C N O
(Sr Ba Zr)
Supernovae
Stellar Wind
STARS
Main Sequence
High Mass
Low Mass
Sun
Planetary Nebulae
Type Ia
Type Ib
Type II
Supergiants
Double
Red Giants
White Dwarfs
Some low mass Double Stars
Planets
Neutron Stars
Brown Dwarfs
Black-holes
THE COSMIC ASH HEAP


Solar element Abundances
H
He
C
O
Fe
Li
B
Be
neutron capture
nuclear fusion
Abundance relative to Si = 10^6
Atomic Number (Z)
0
20
40
60
80
100

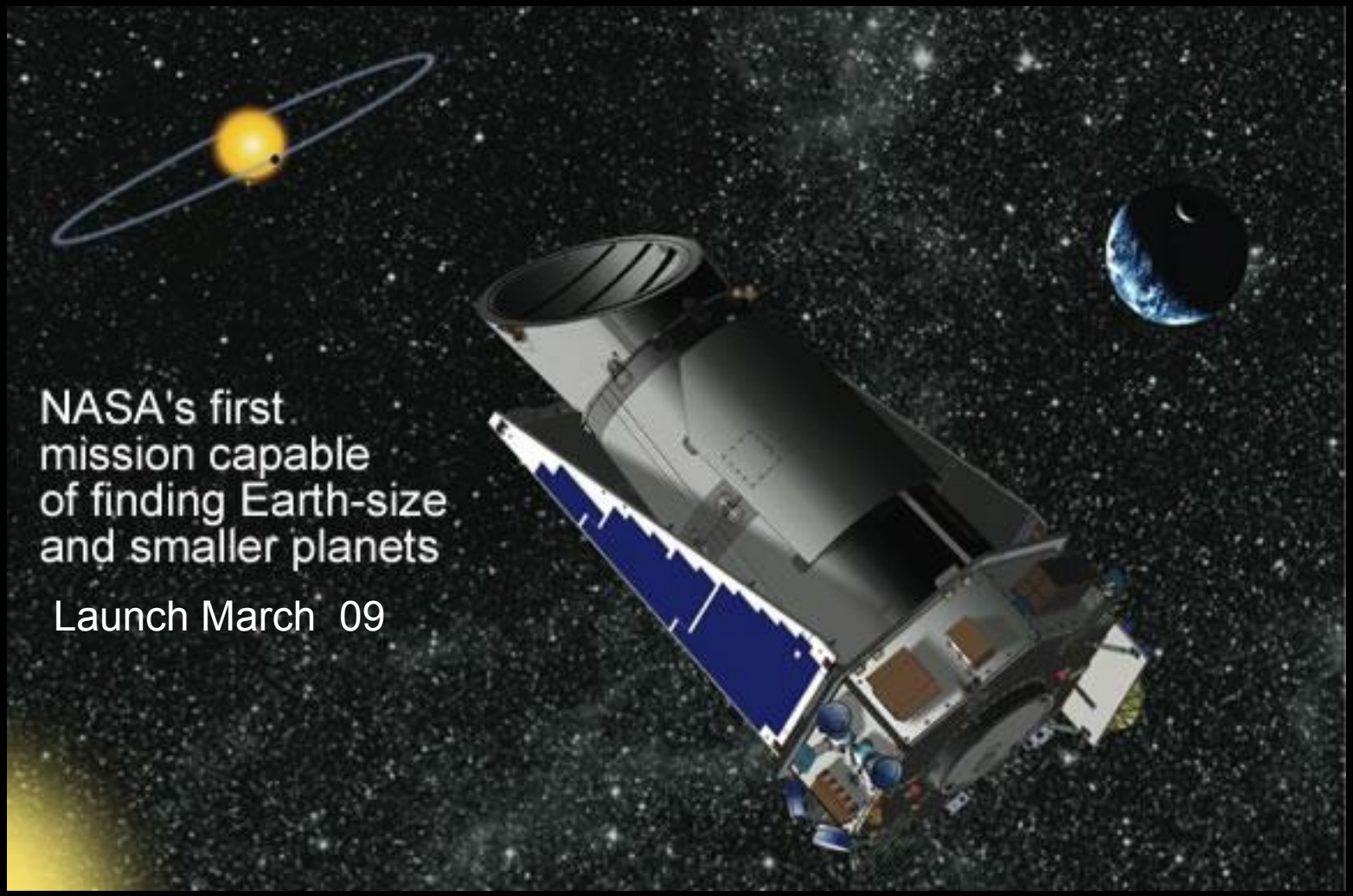

A.
B.
C.
D.

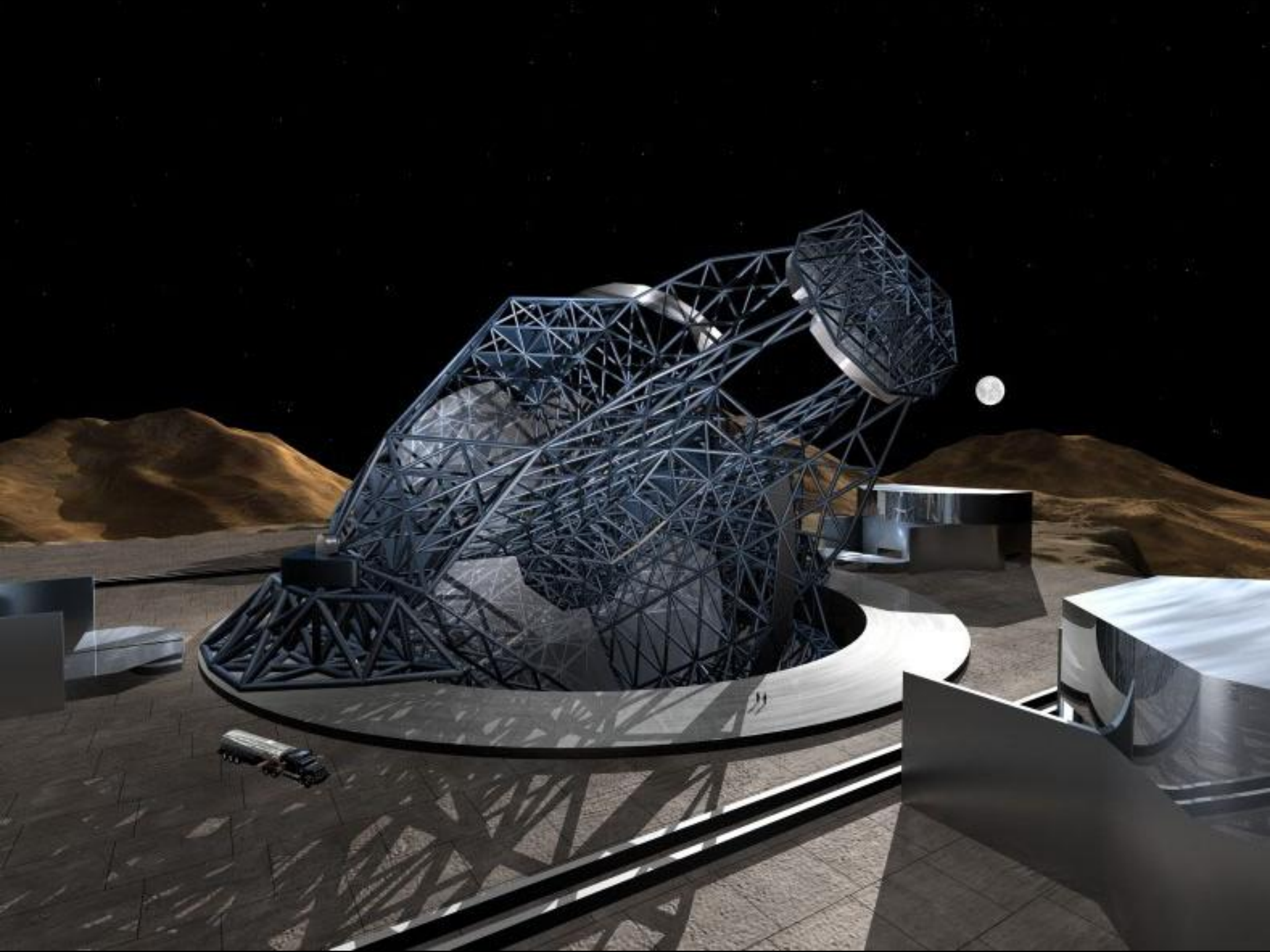
We observe the motion of the Star
and deduce the presence of a planet




GJ 876
55 Cnc
upsilon And
HIP 14810
HD 217107
HD 69830
mu Ara
HD 190360
HD 38529
HD 74156
HD 168443
HD 37124
HD 73526
HD 82943
HD 169830
HD 202206
HD 12661
HD 108874
HD 128311
47 UMa
Earth
Jupiter
0
1
2
3
4
5
6

NASA Kepler Mission



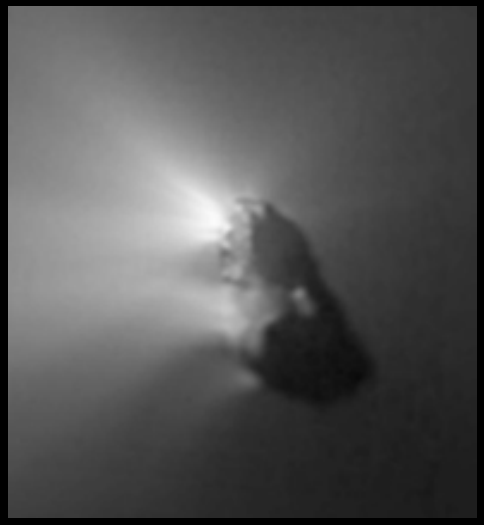


Other possible places for life in our Solar System

Mars

ALH84001 a meteorite from Mars

Titan

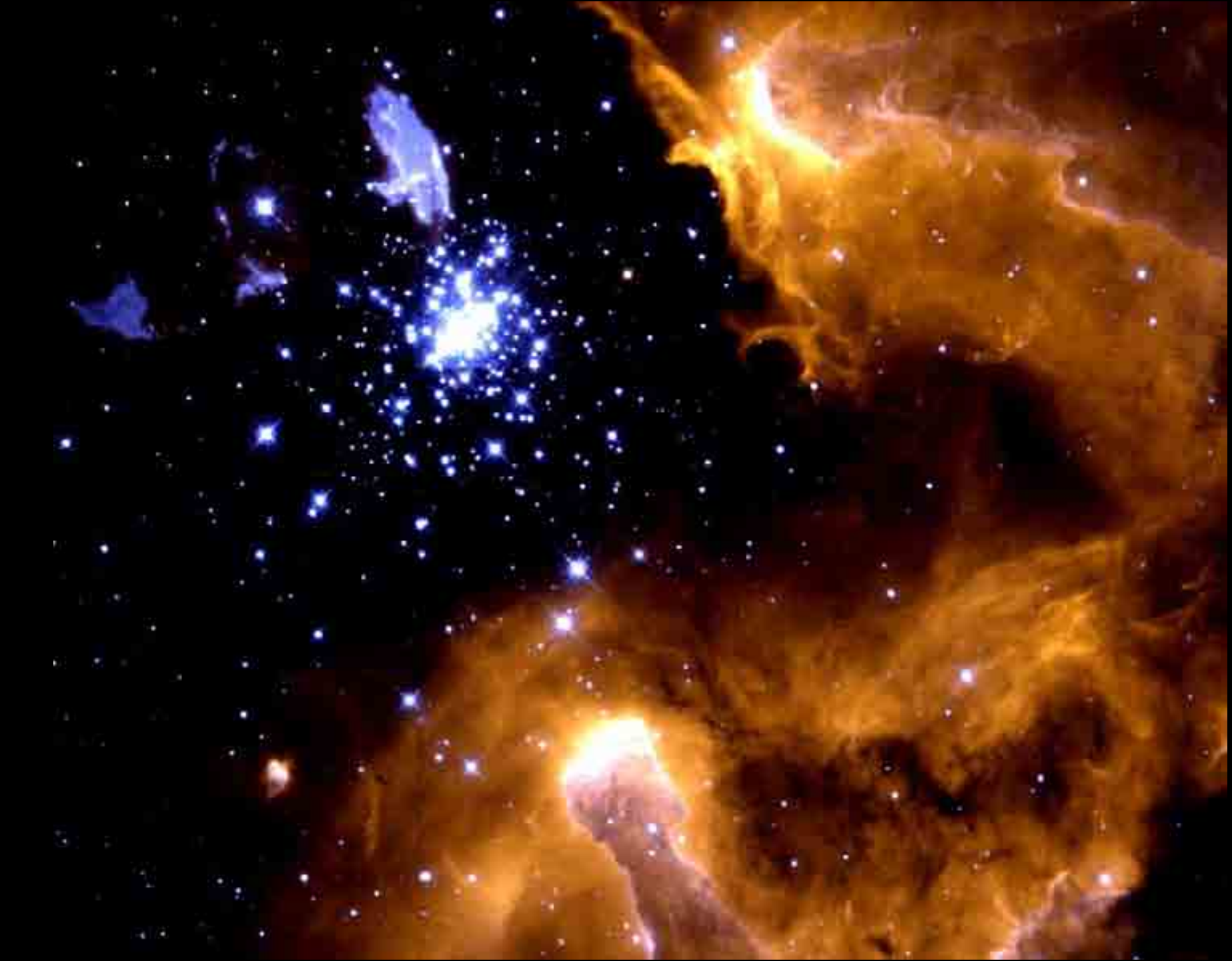


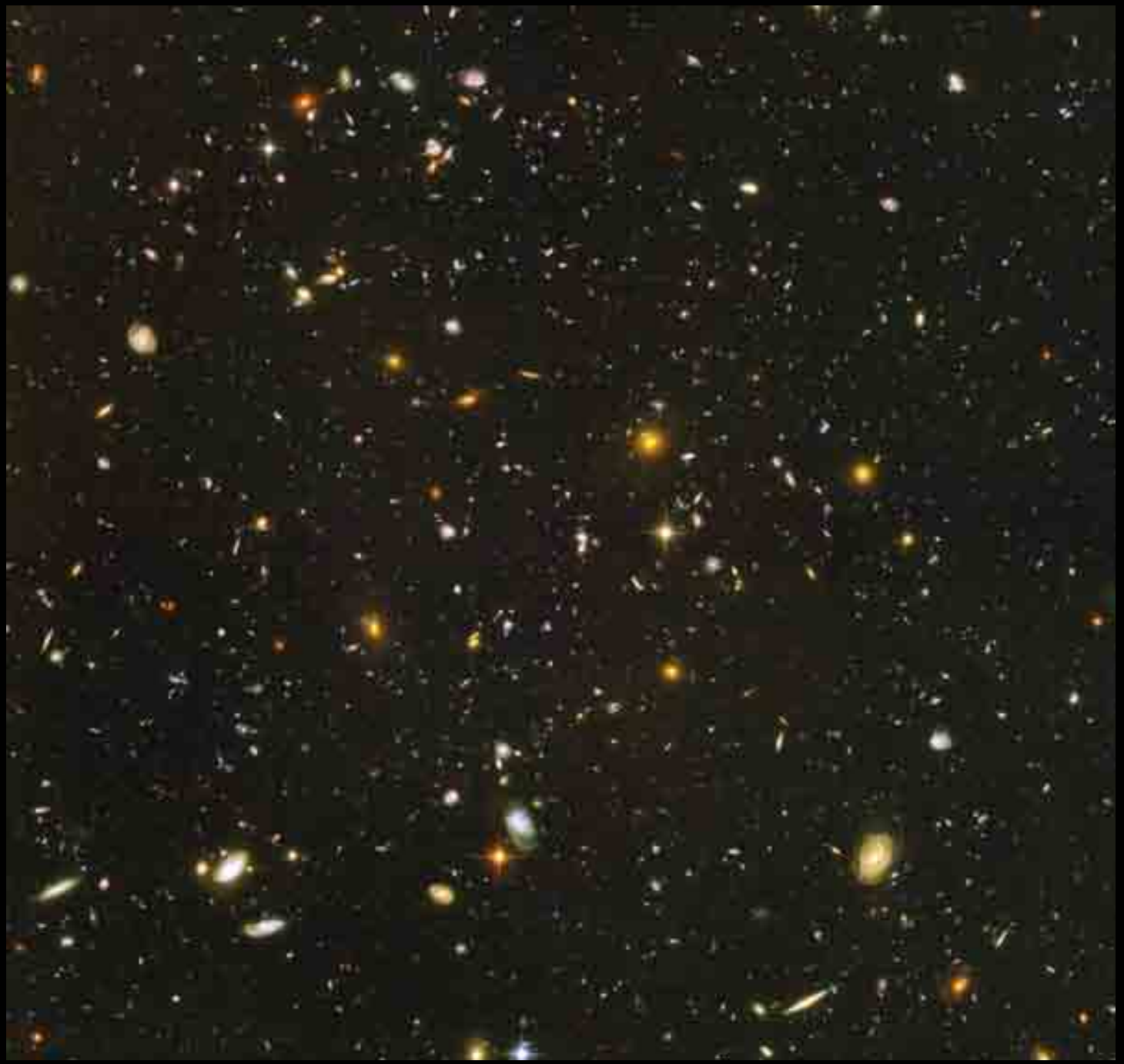
Halley's Comet

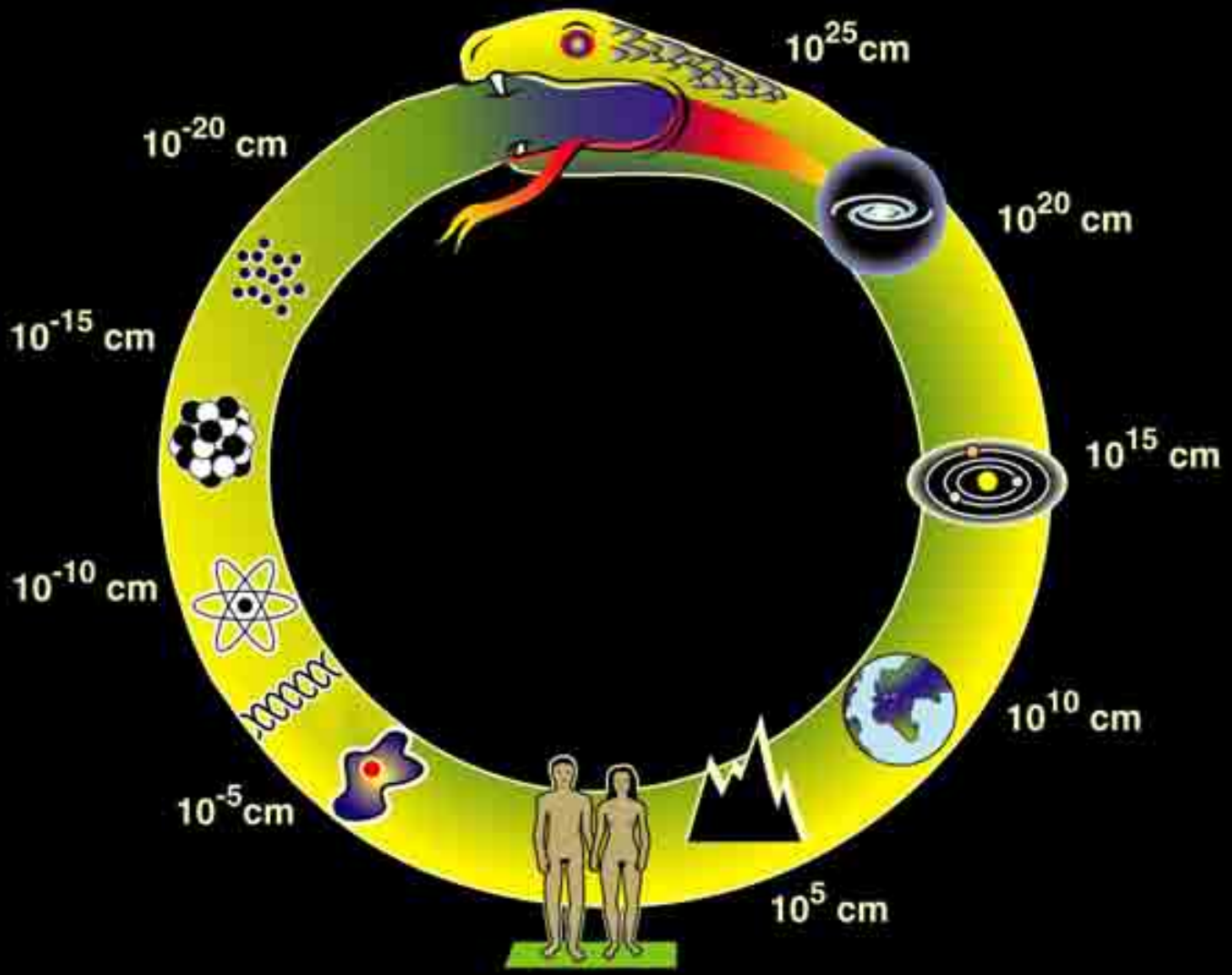
Europa

Things that make our Earth special

- Stability of the Sun
- Size and location of the Earth
- Size of our Moon
- Size and position of Jupiter
- Time of formation of Sun
- Location in Galaxy






10^{25}cm
10^{20} cm
10^{15} cm
10^{10} cm
10^{5} cm
10^{-5}cm
10^{-10} cm
10^{-15} cm
10^{-20} cm

HOW MUCH LIES BEYOND OUR HORIZON (10^{10} 1.y distant)?

Cannot be sure of anything beyond present causal horizon.

Moreover, topology could be complex or 'kaleidoscopic'.

But lack of discernible gradients across Hubble scale suggest that our universe extends for $> 10^{15}$ l.y

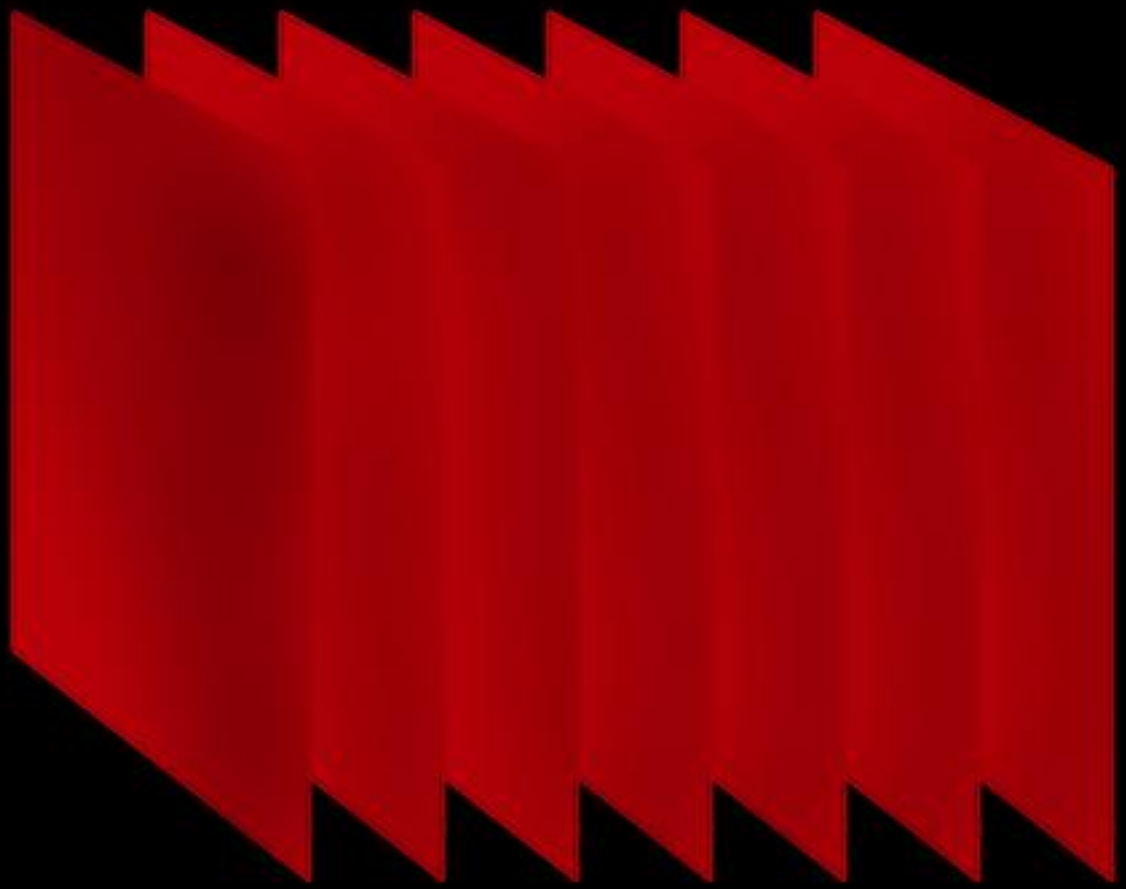
and space could extend $> 10^{100}$ l.y

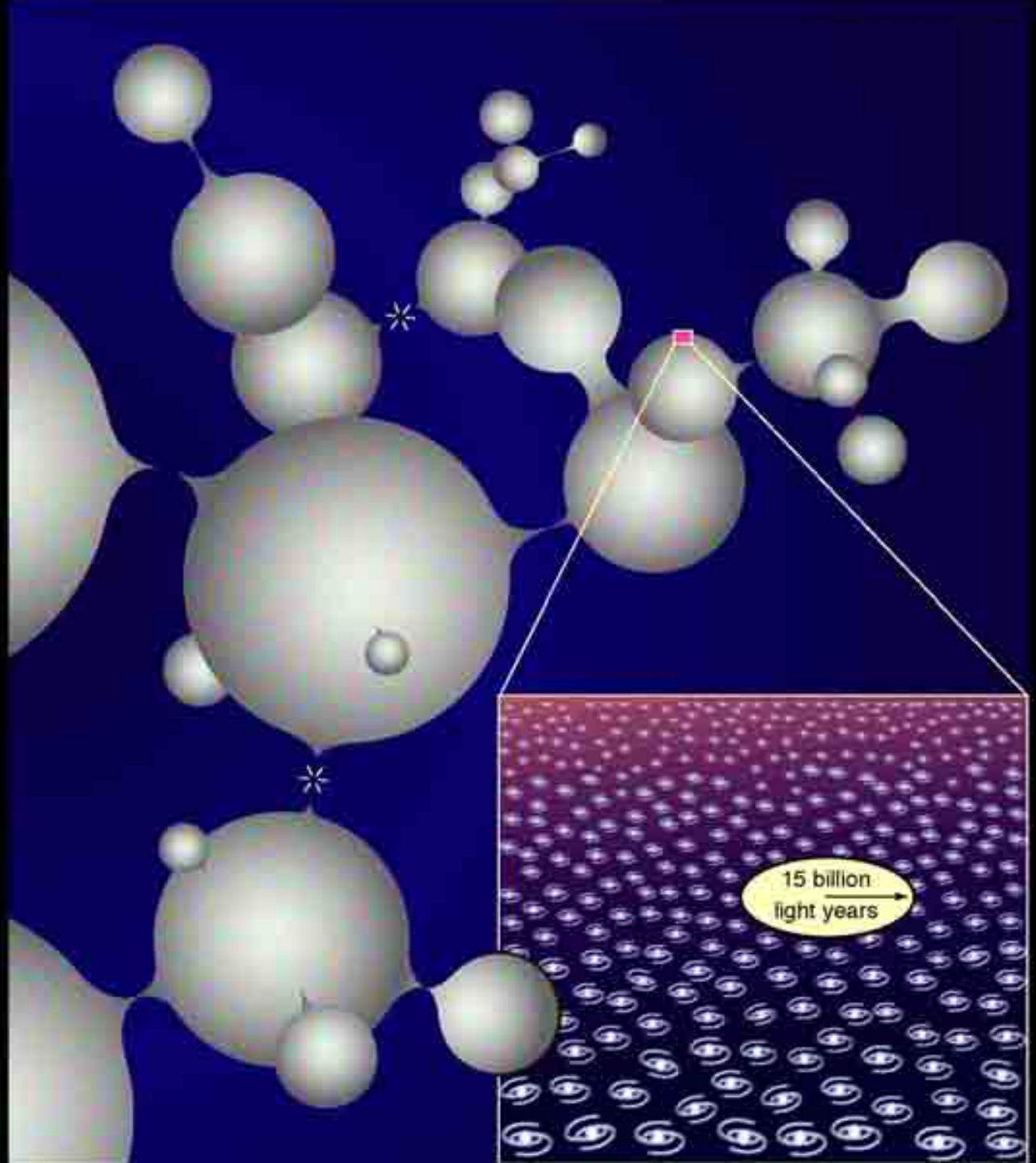
or even >>>>>>

(replicas!)

Moreover, this immense could be the aftermath of just
one big bang out of many (eternal inflation, braneworlds, etc)

Braneworlds É




15 billion
light years

History of Life on Earth

Sun and planets form

Late Heavy Bombardment

Continent cores formed

Oxygen present in atmosphere

4000M

3000M

2000M

1000M

Today

Simple cells prokaryotes

Structured cells eukaryotes

Multicelled life

Production of oxygen

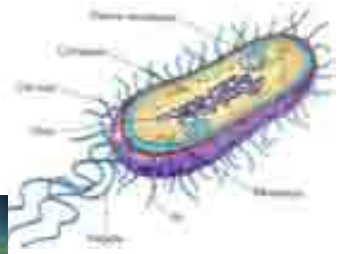
Plants

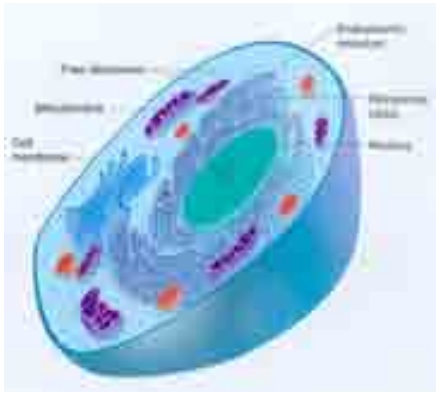
Oldest known rocks

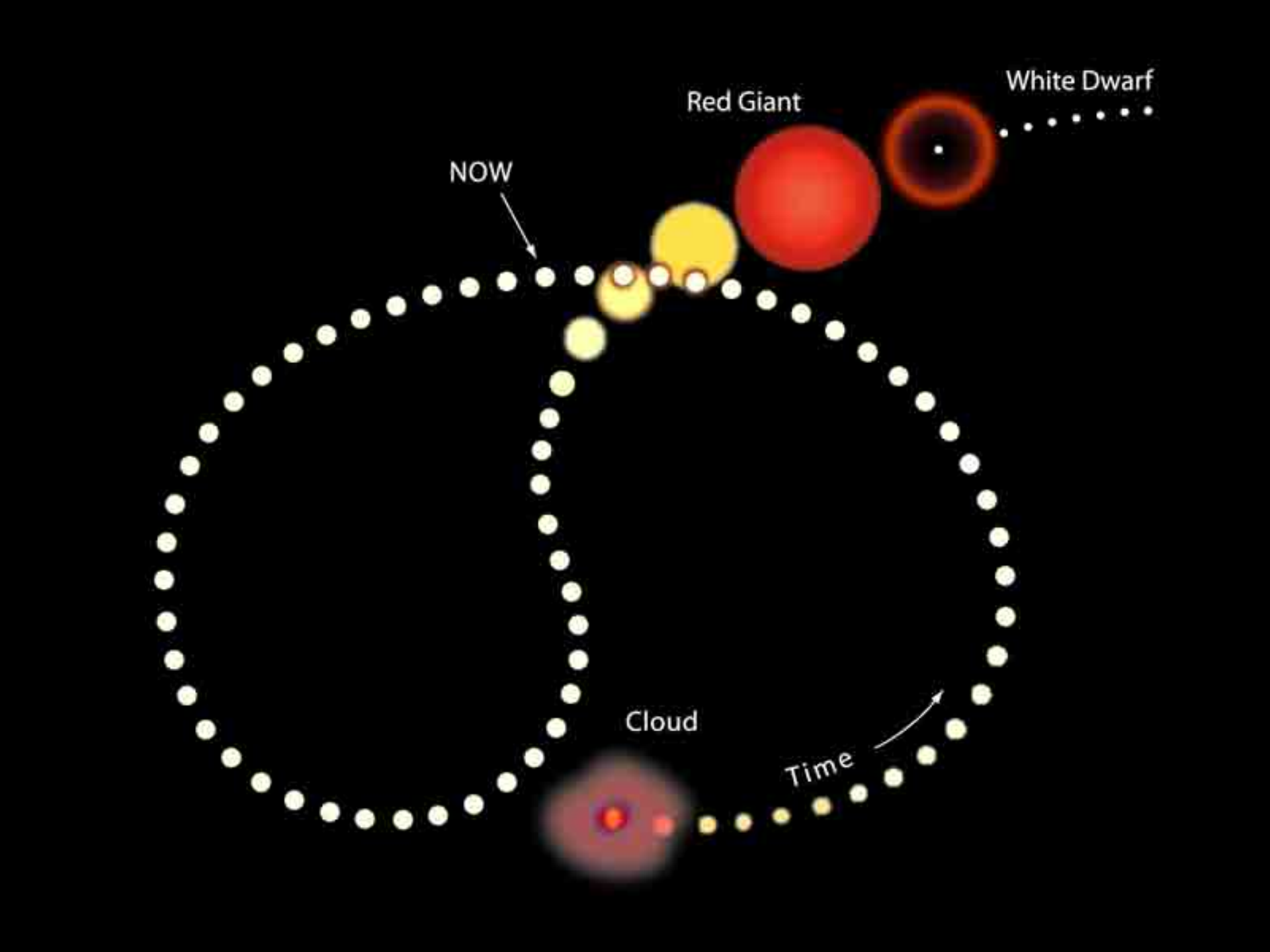
Land animals

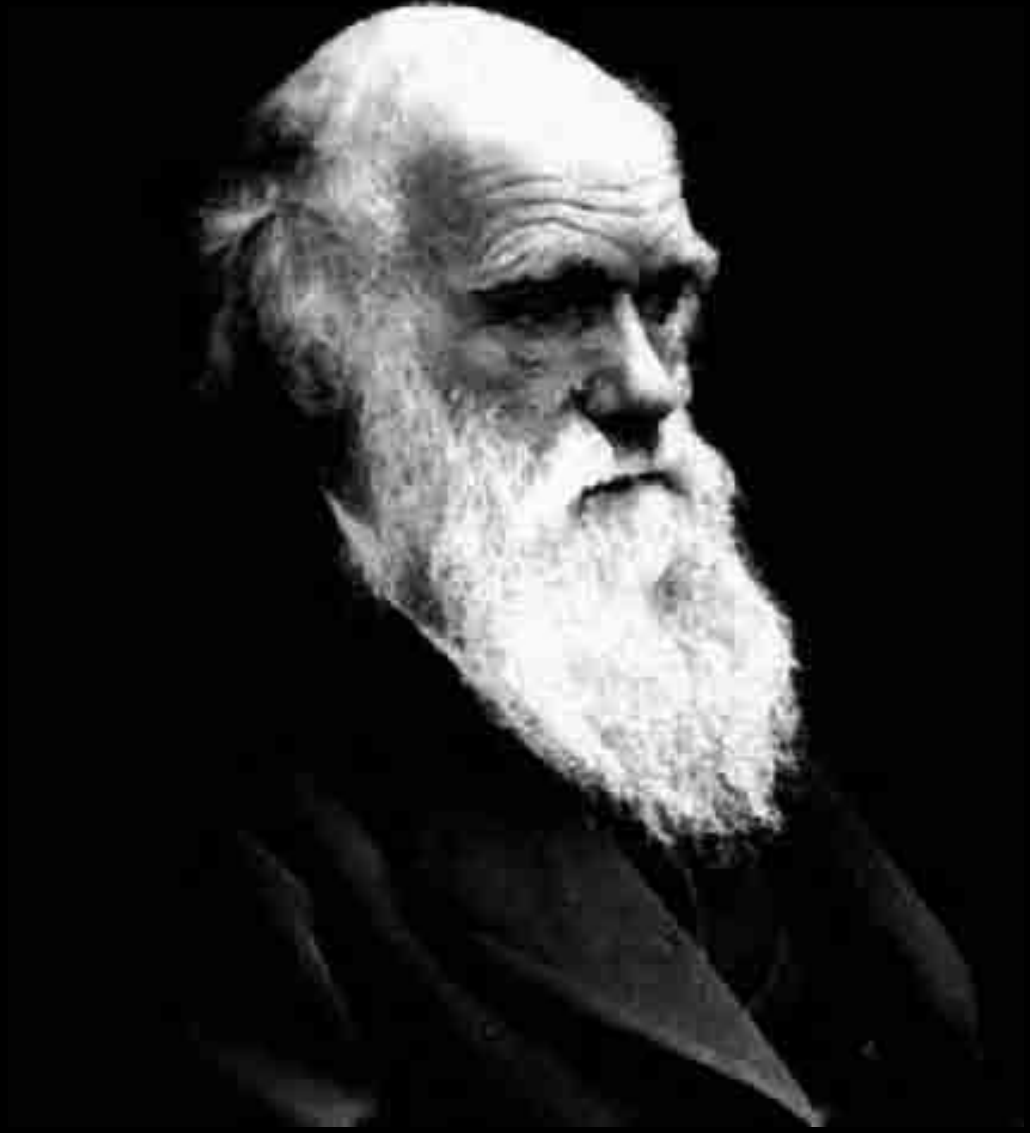
Oldest trace of life

Mammals





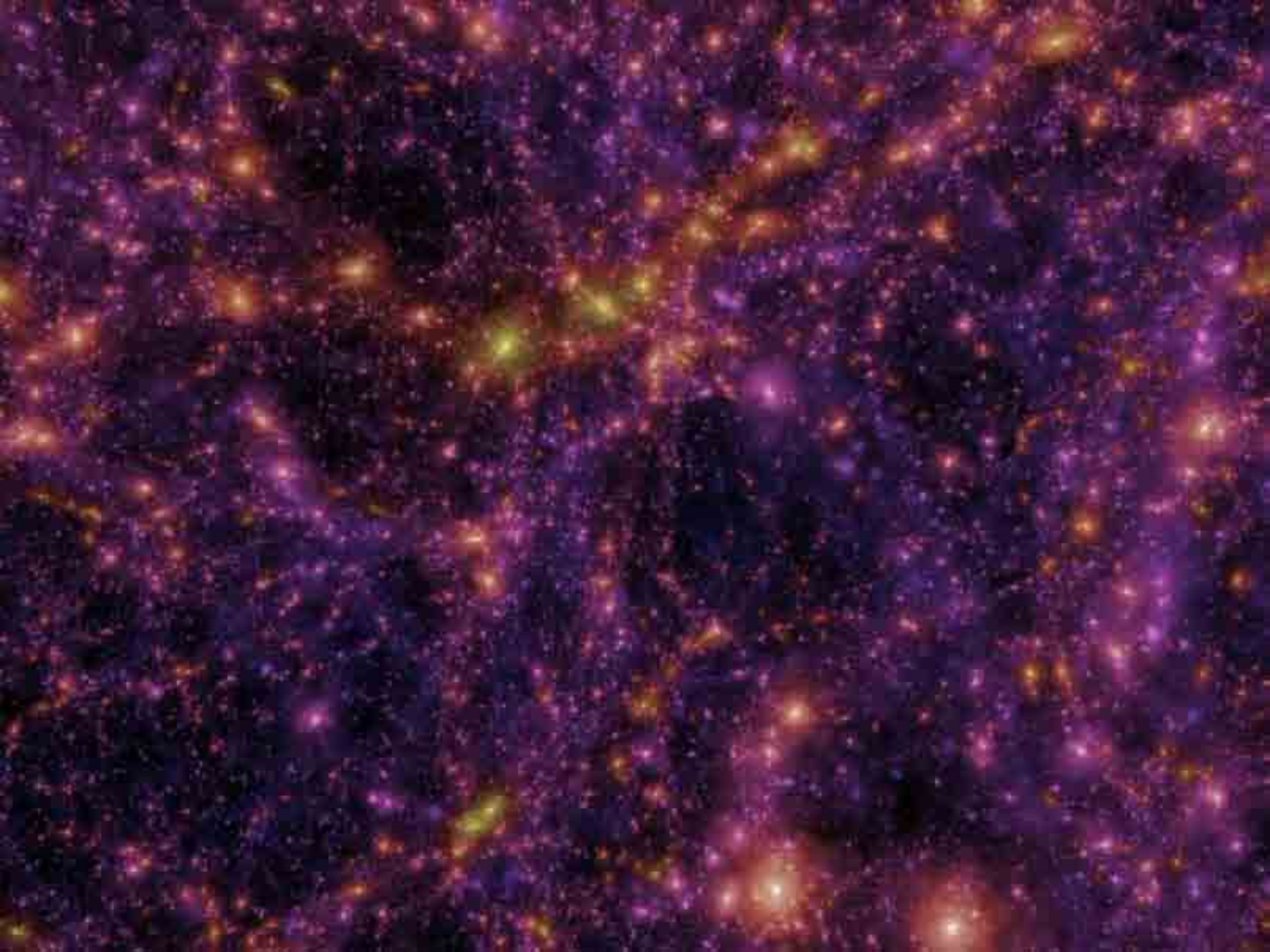

White Dwarf
Red Giant
NOW
Cloud
Time



”not one living species will transmit its unaltered likeness to a distant futurity…. "

Charles Darwin

Postcard from planet Earth



Things that make our Earth special

- Stability of the Sun
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- Size of our Moon
- Size and position of Jupiter
- Time of formation of Sun
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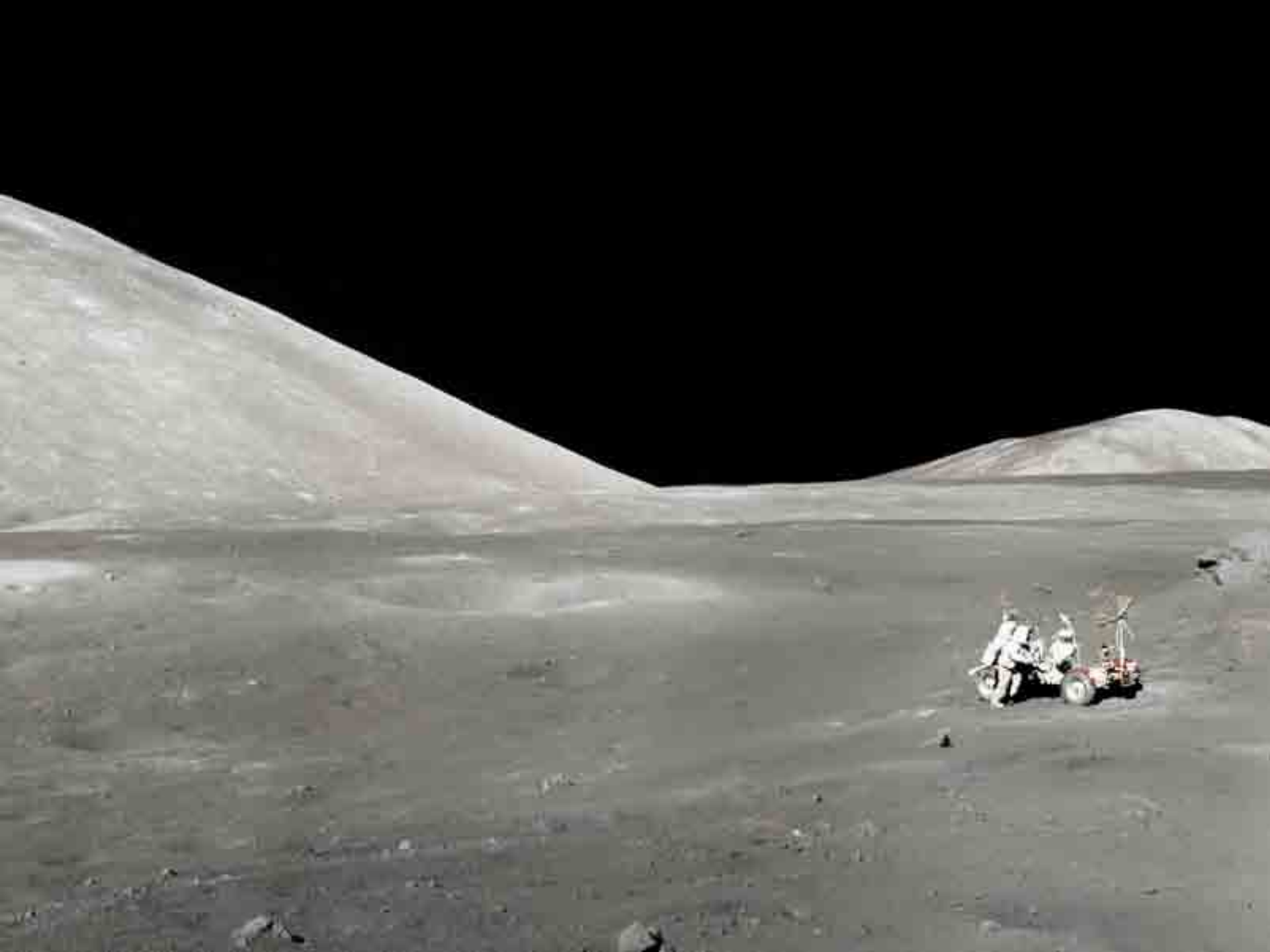
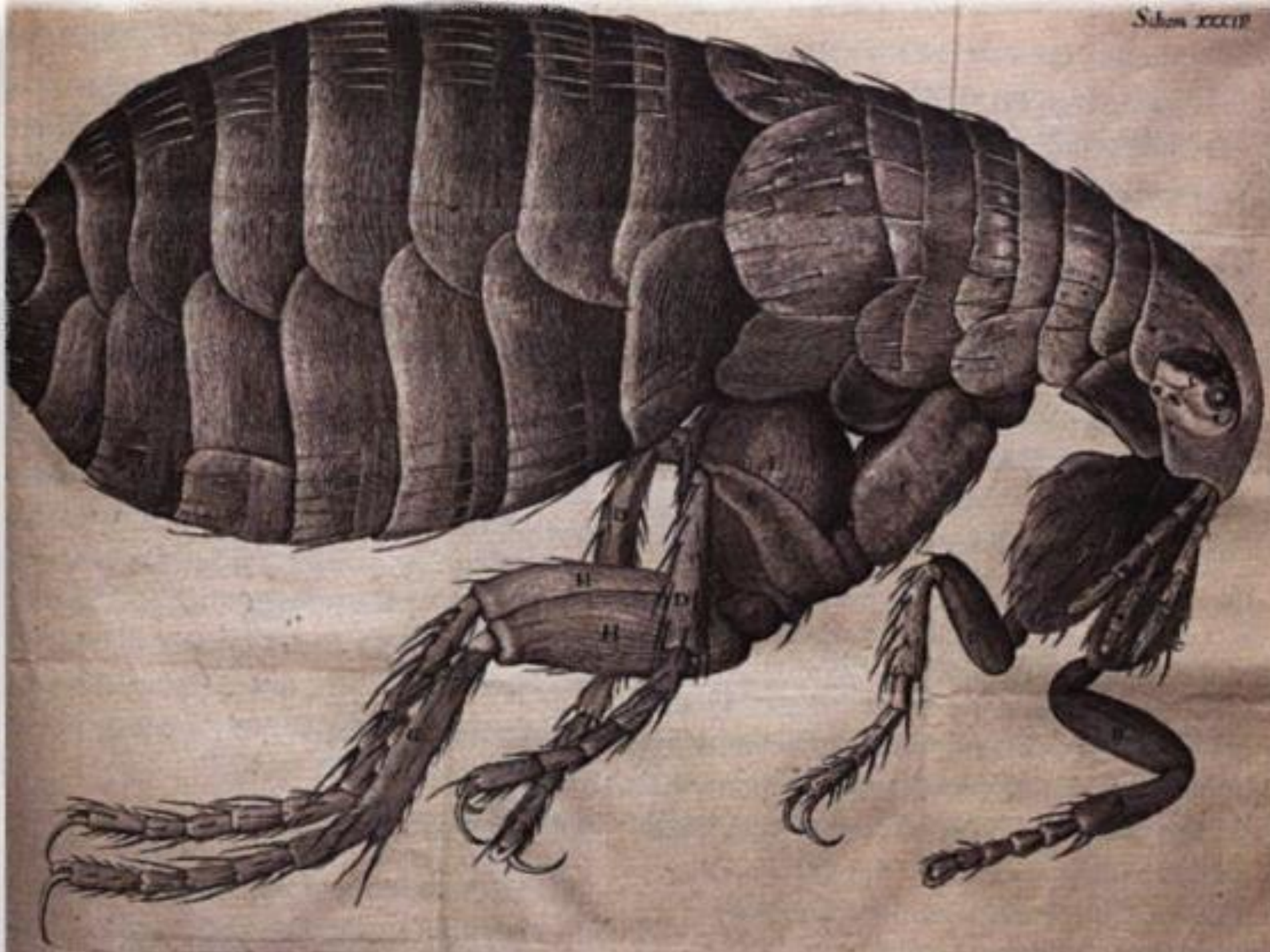
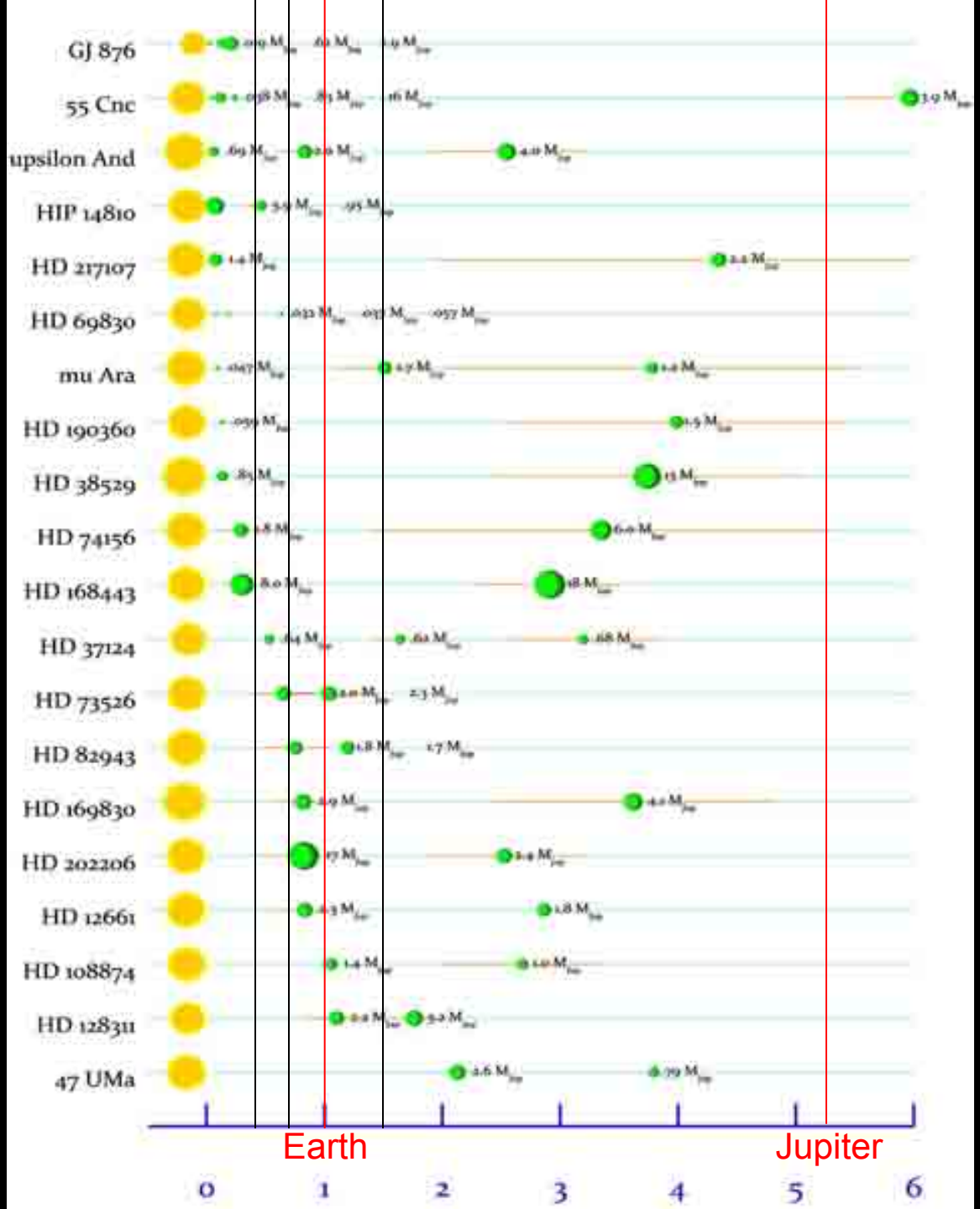




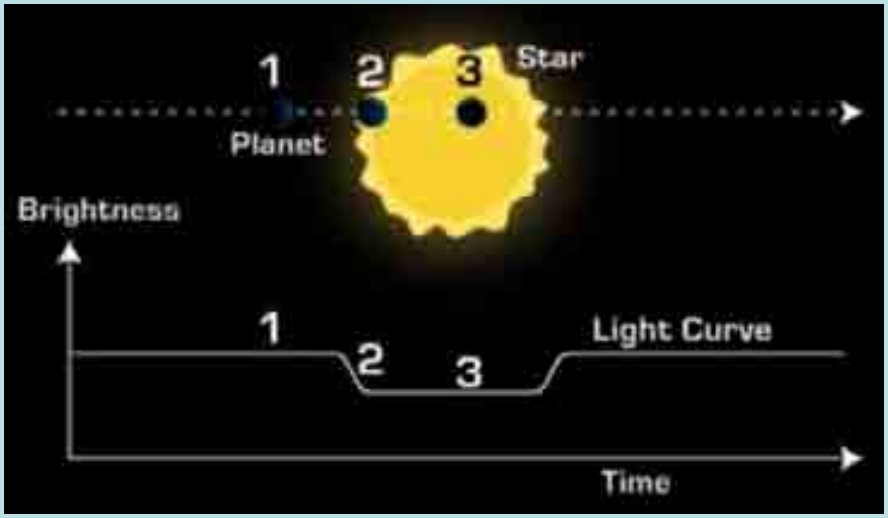

GJ 876
55 Cnc
upsilon And
HIP 14810
HD 217107
HD 69830
mu Ara
HD 190360
HD 38529
HD 74156
HD 168443
HD 37124
HD 73526
HD 82943
HD 169830
HD 202206
HD 12661
HD 108874
HD 128311
47 UMa
Earth
Jupiter
0
1
2
3
4
5
6

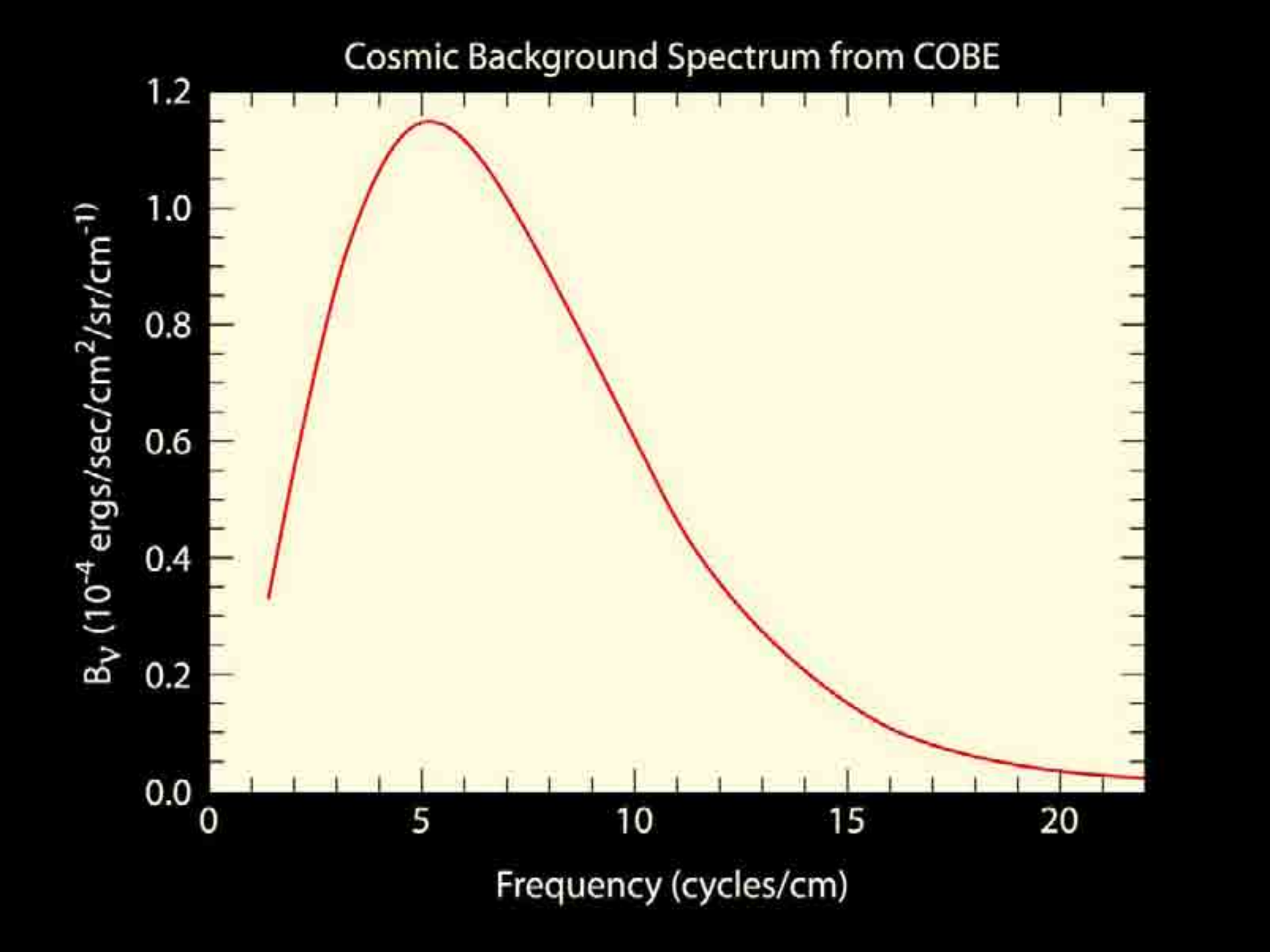
Kepler Mission

- Find the frequency of terrestrial planets in the Galaxy
- Characterize the properties of inner planetary systems.
- Determine the properties of stars (single & multiple) hosting planets.
- Discover terrestrial planets in habitable zones (or show that they are rare).
- Detect true Earth analogs
- A NULL result would also be very significant (frequency of stars with terrestrial planets is less than 5%)

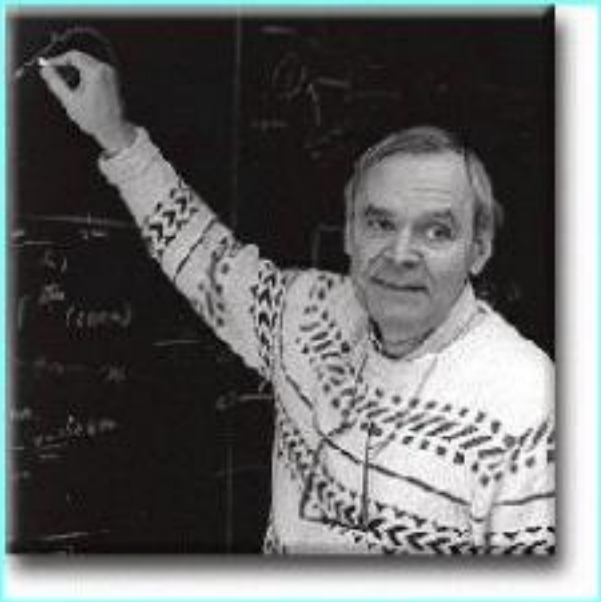
Kepler is uniquely qualified to detect Earth-sized *extrasolar planets!*

Kepler Mission
Transit Method of Detection
March 2009 launch



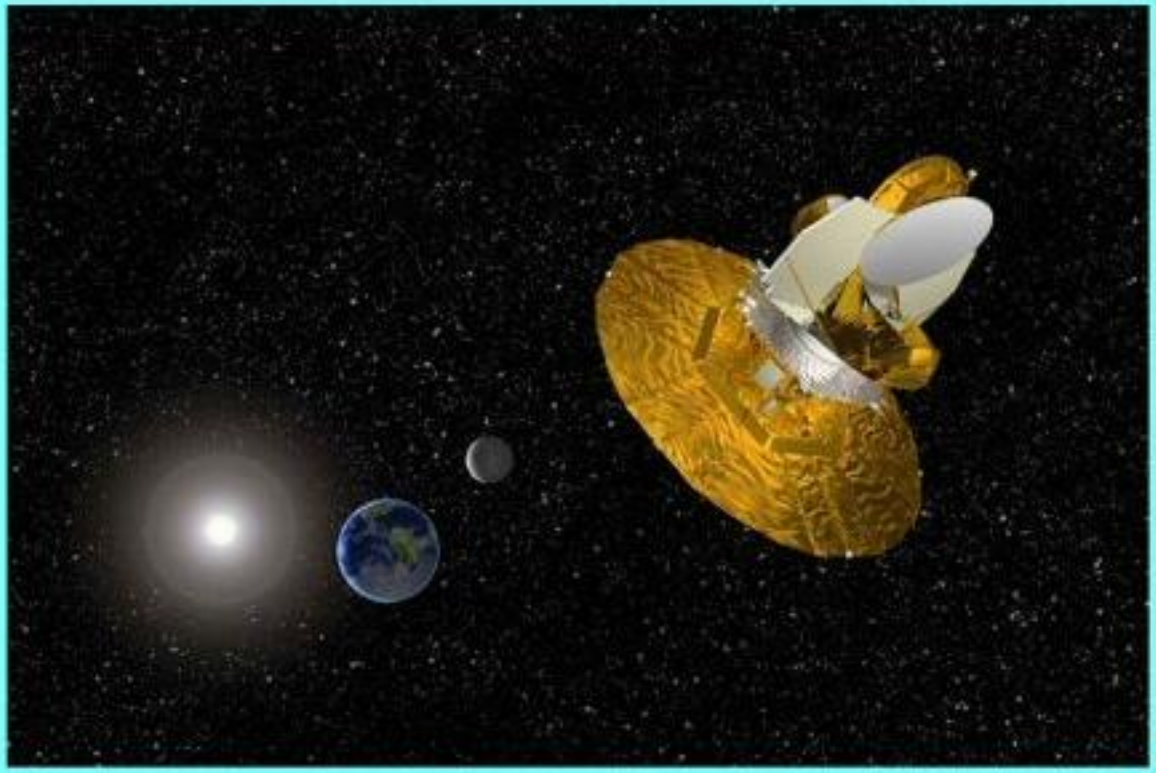

Cosmic Background Spectrum from COBE
1.2
1.0
0.8
0.6
0.4
0.2
0.0
B_ν (10^{-4} ergs/sec/cm^2/sr/cm^{-1})
0
5
10
15
20
Frequency (cycles/cm)

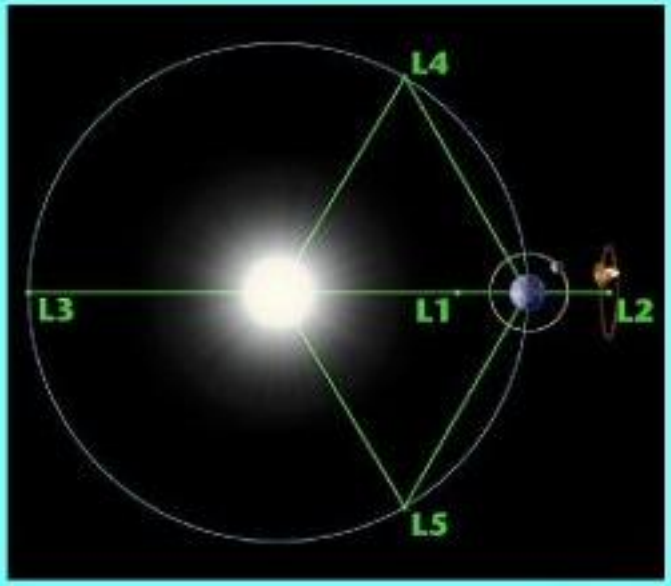
WMAP: Wilkinson Microwave Anisotropy Probe



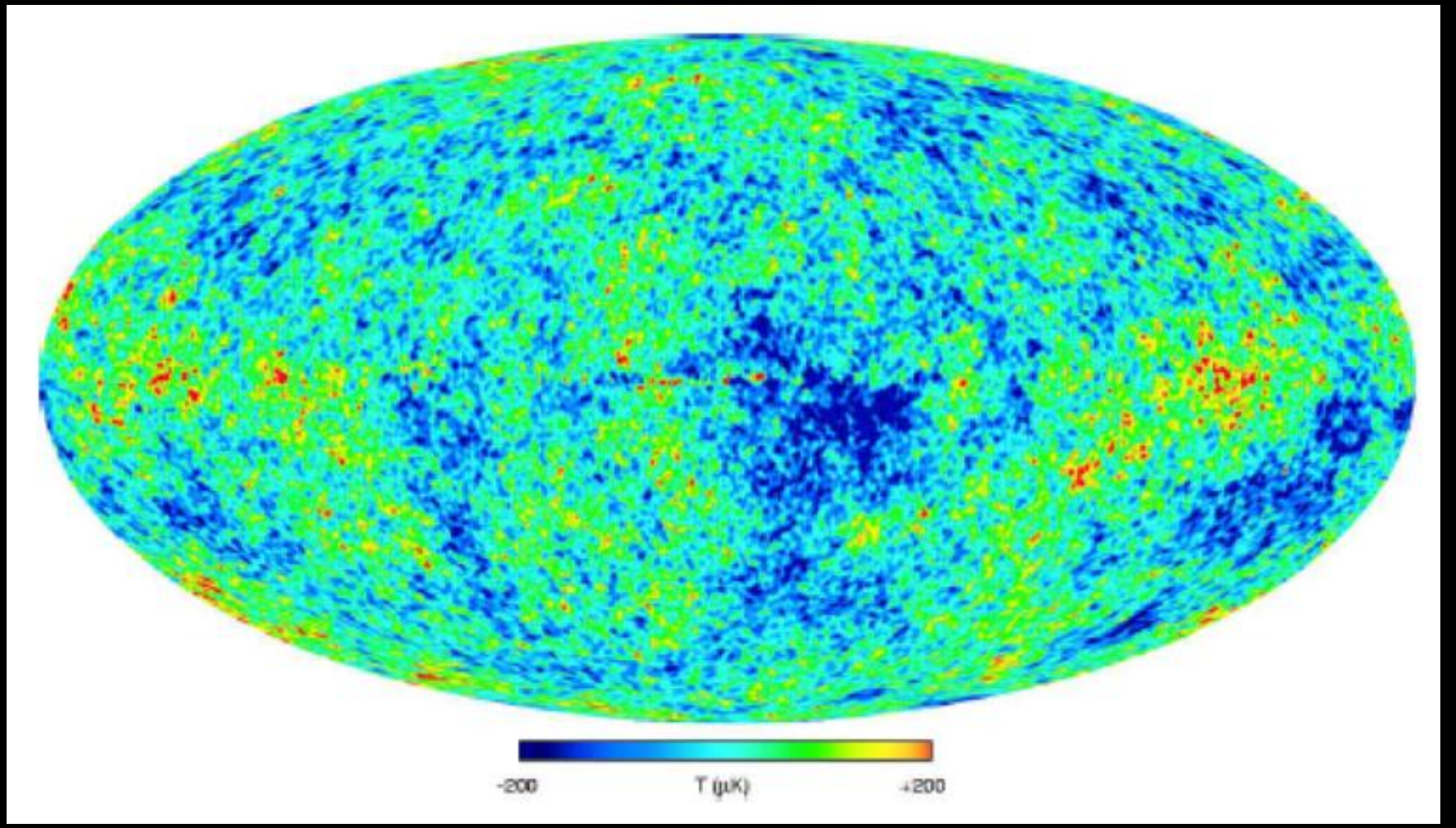
David T. Wilkinson

Images courtesy of NASA/WMAP Science Team



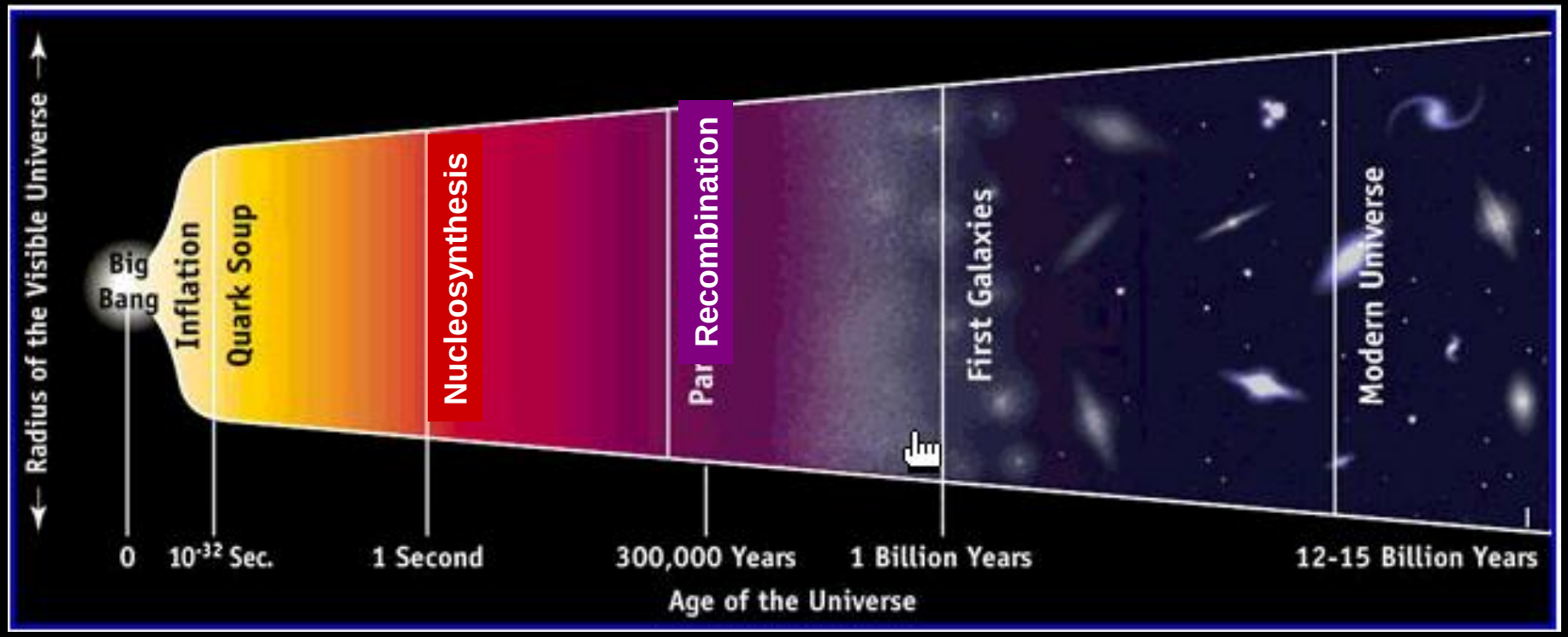


WMAP CBR SKY



Page et al; 2003

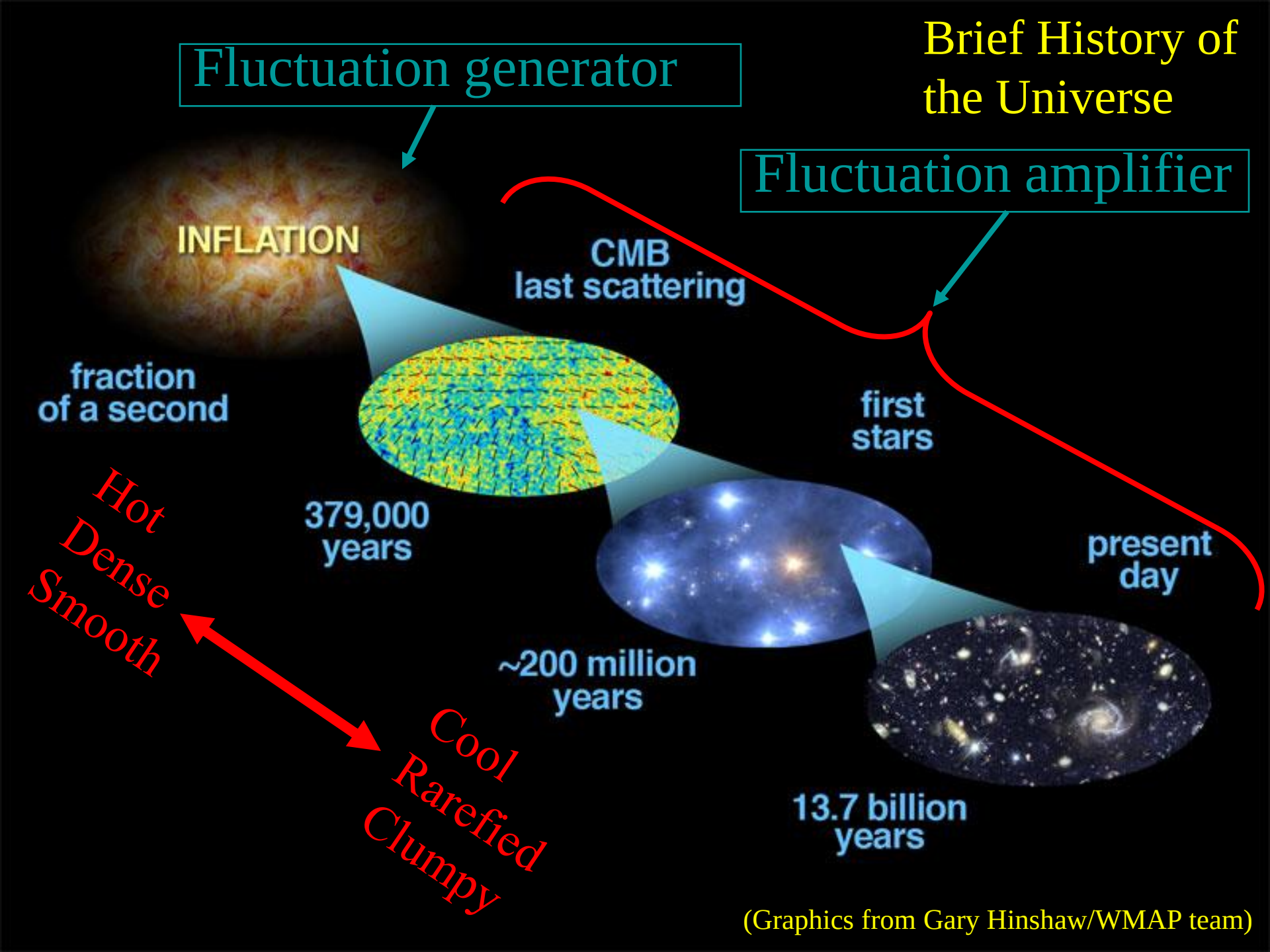
Cosmic Evolution -Cartoon



Well-understood

nonlinear simulations

Brief History of the Universe



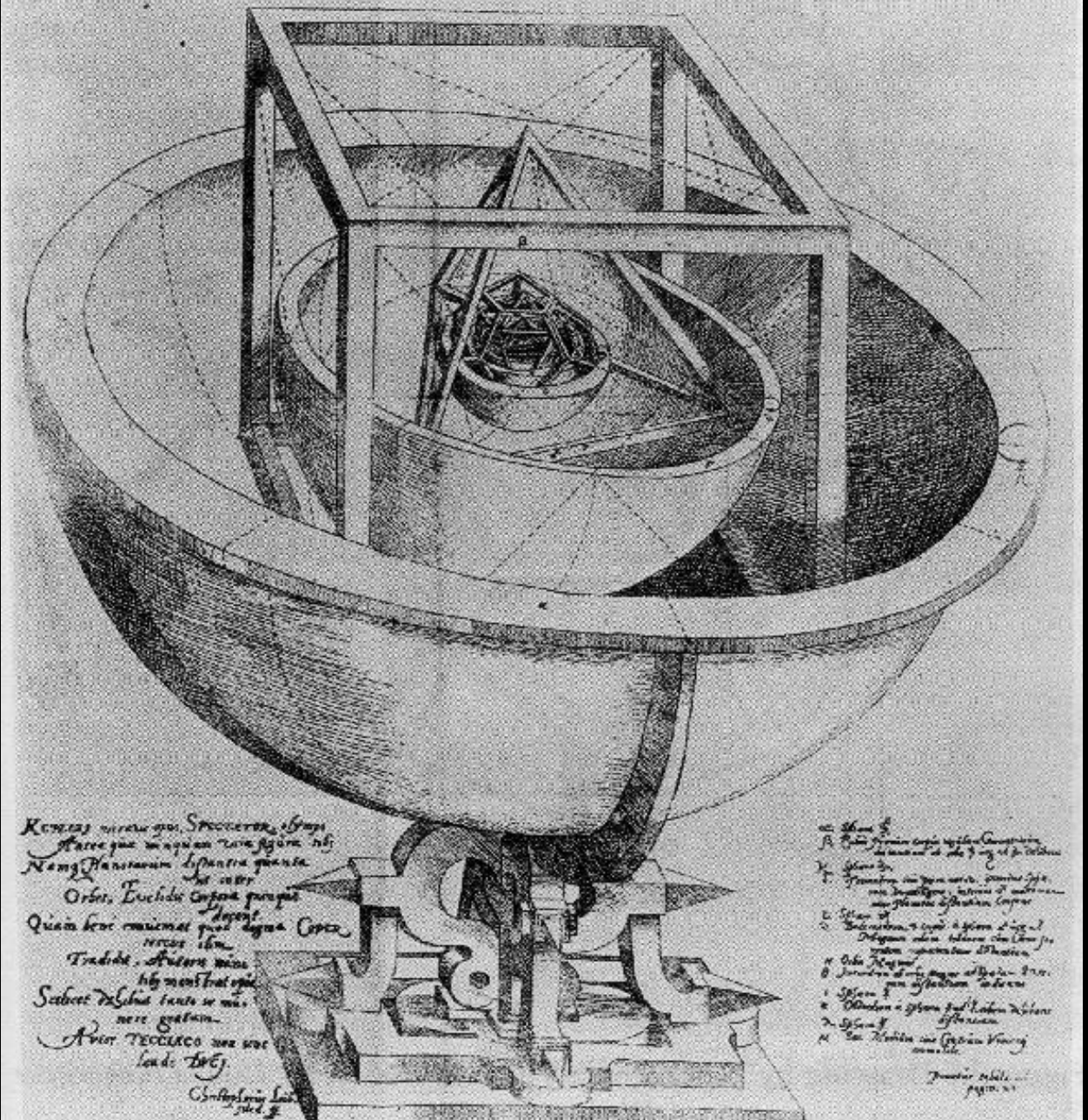
(Graphics from Gary Hinshaw/WMAP team)

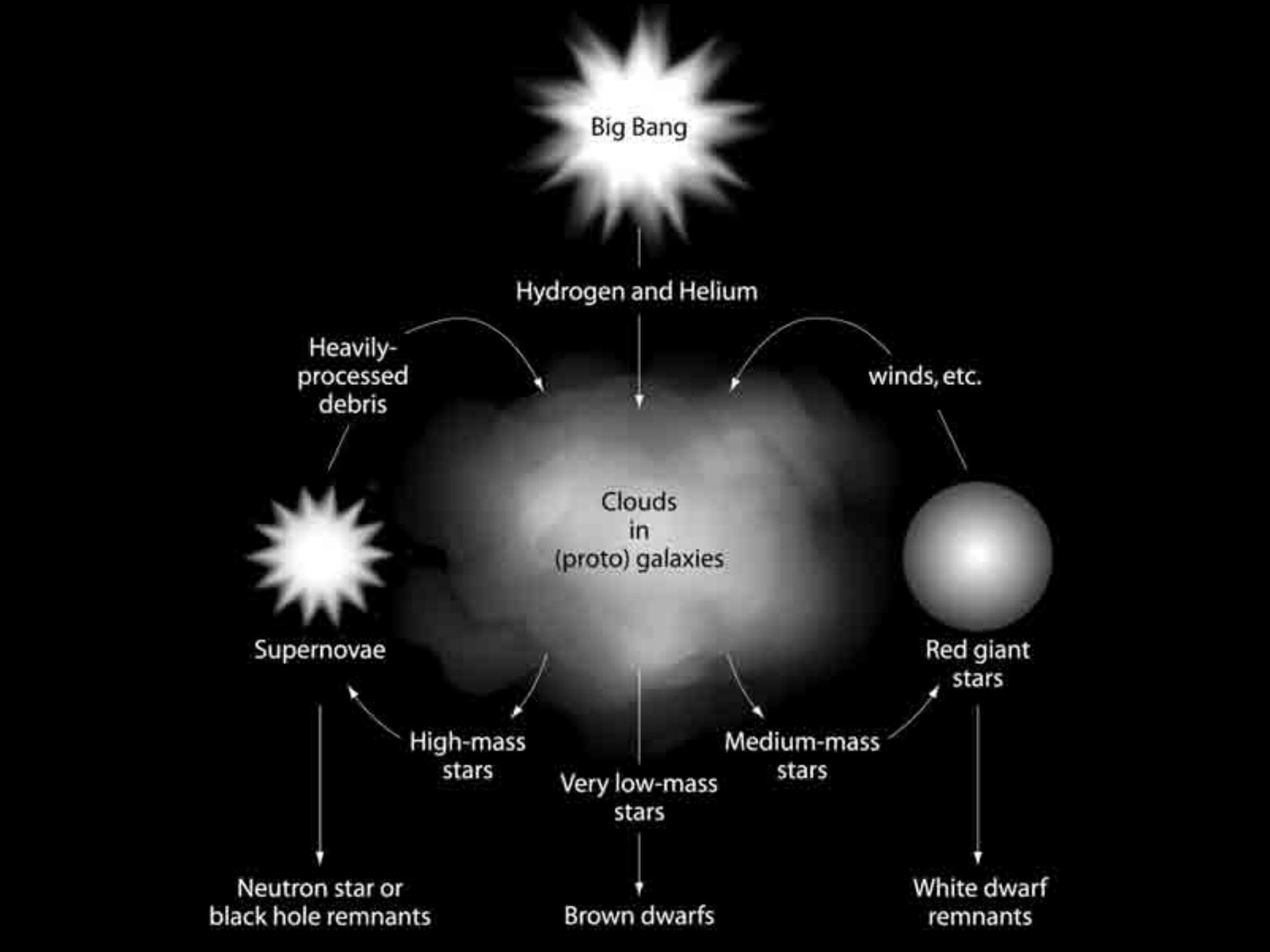
Prerequisites for complex cosmos

- *Gravity -- but weaker the better (at least one very large number in physics)*
- *Non-trivial chemistry ('tuning' between nuclear and e-m forces)*
- *Matter/antimatter asymmetry*
- *'Tuned' cosmic expansion rate*
- *Non-zero fluctuations in early universe*

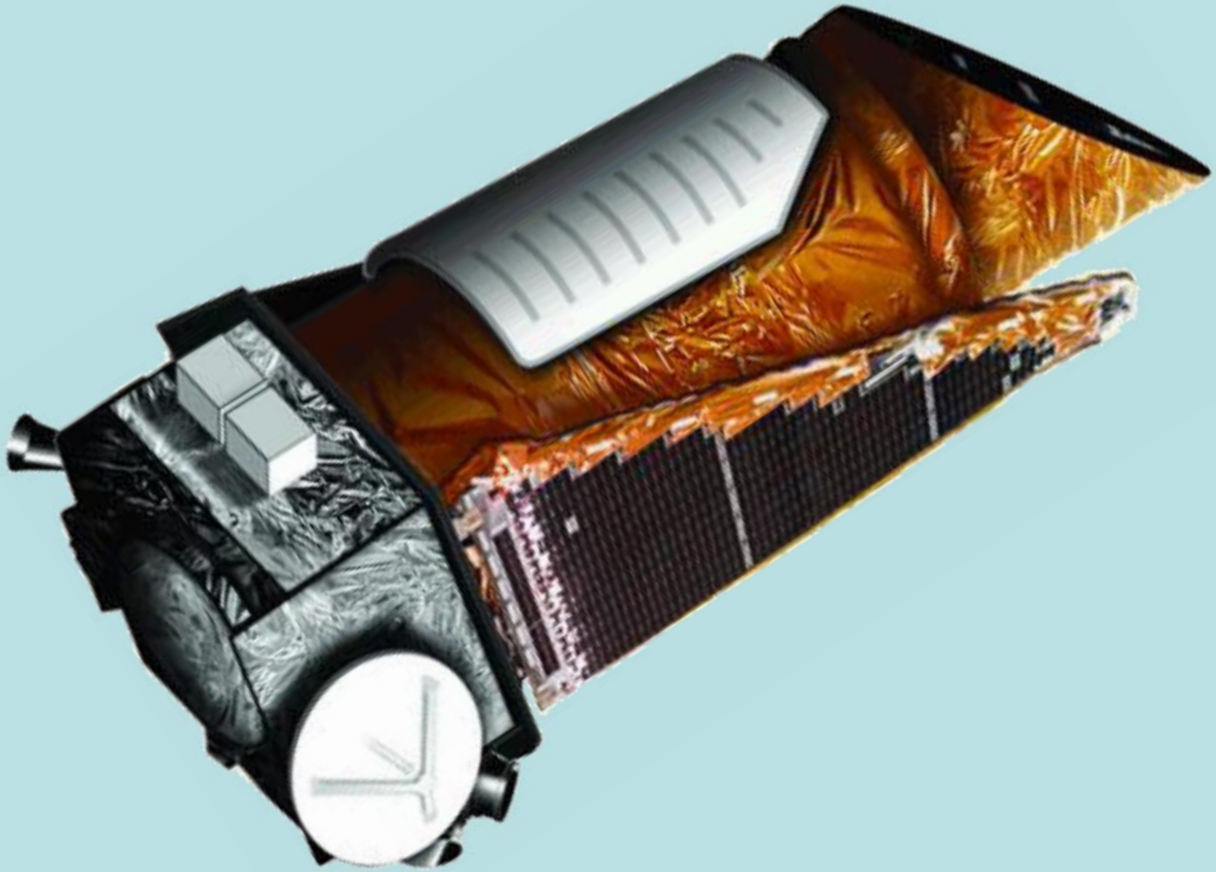
TABVLA III. ORBIVM PLANETARVM DIMENSIONES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA GEOMETRICA EXHIBENS.

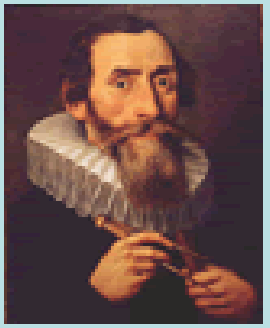
ILLVSTRISS. PRINCIPI, AC DNO. DNO. FRIDERICO, DVCI WIRTENBERGICO, ET TECCIO, COMITI MONTIS BELGARVM, ETC. CONSECRATA.

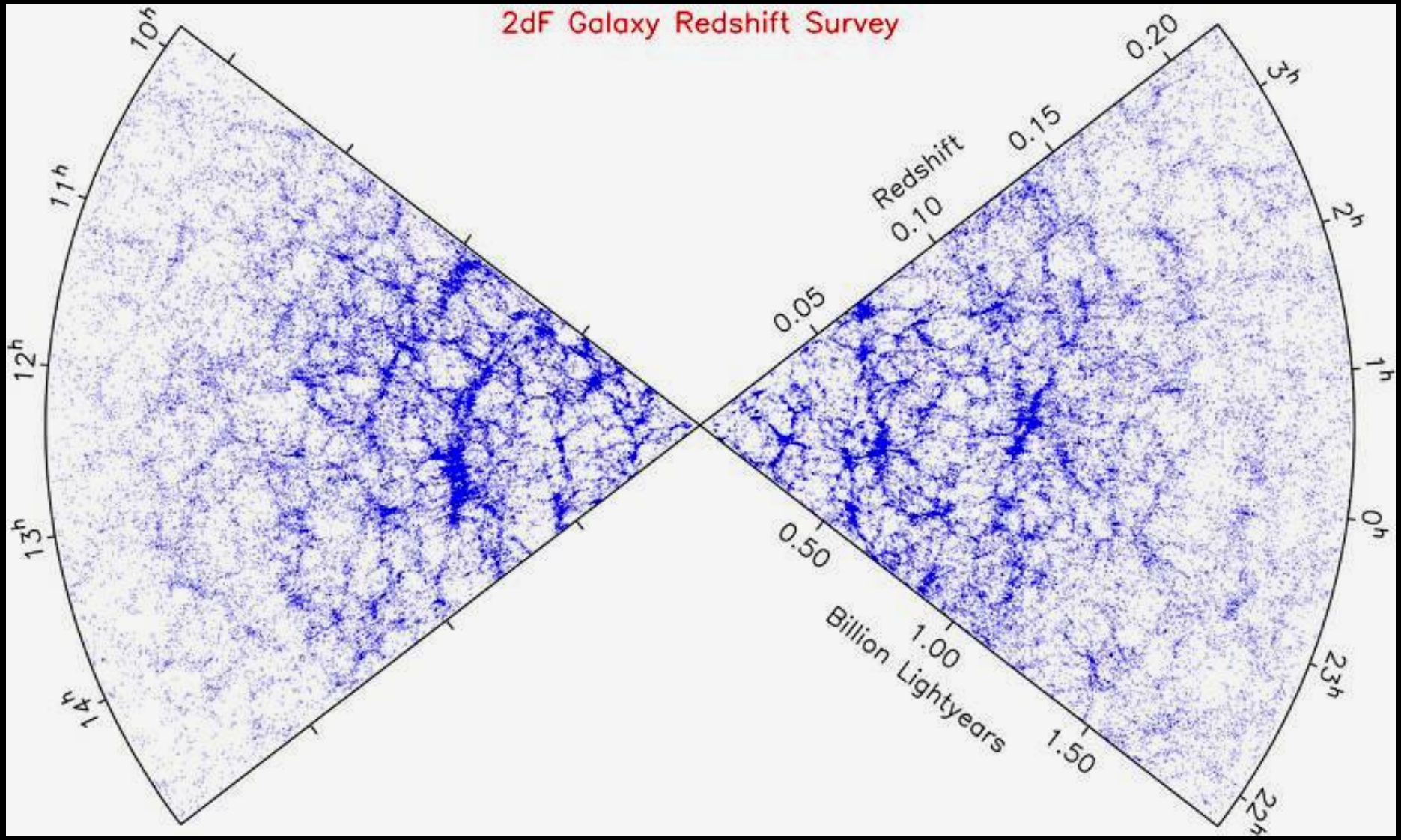



Big Bang
Hydrogen and Helium
Heavily-processed debris
winds, etc.
Clouds in (proto) galaxies
Supernovae
Red giant stars
High-mass stars
Medium-mass stars
Very low-mass stars
Neutron star or black hole remnants
Brown dwarfs
White dwarf remnants

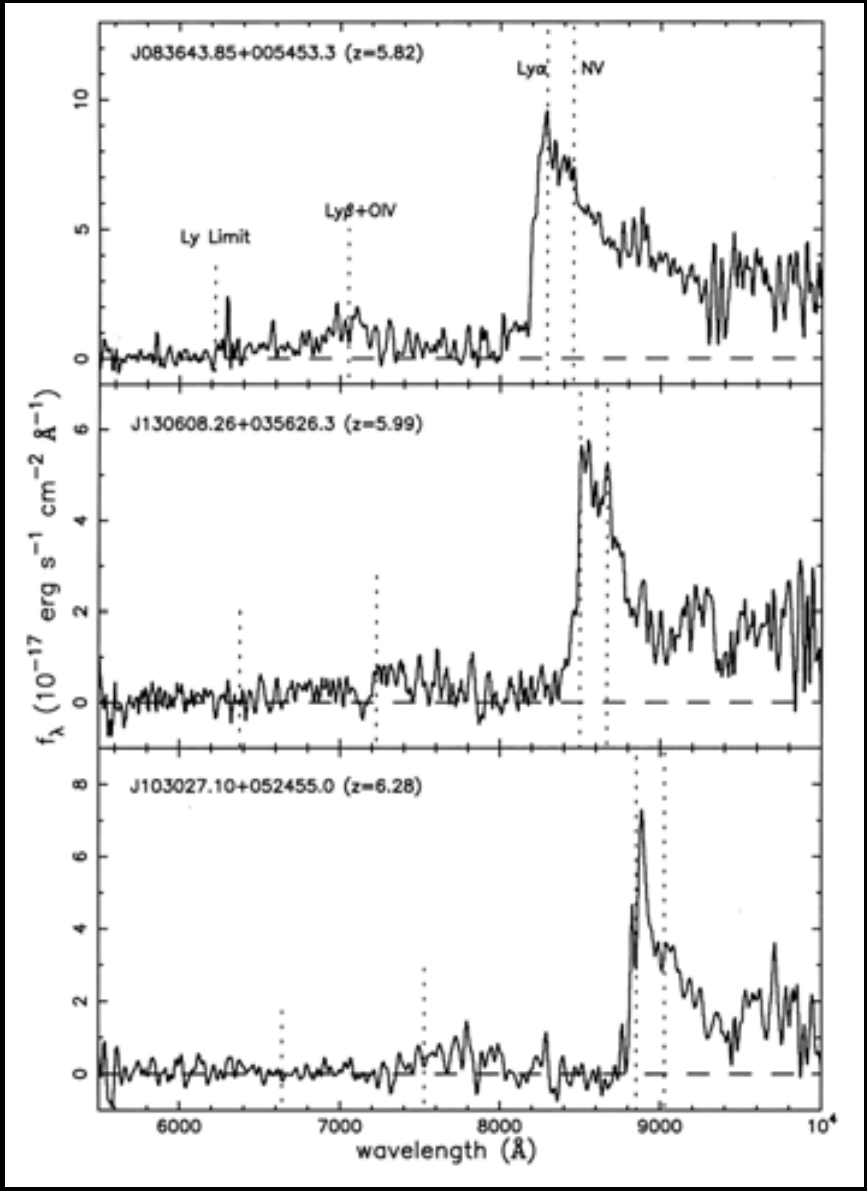
Kepler Mission

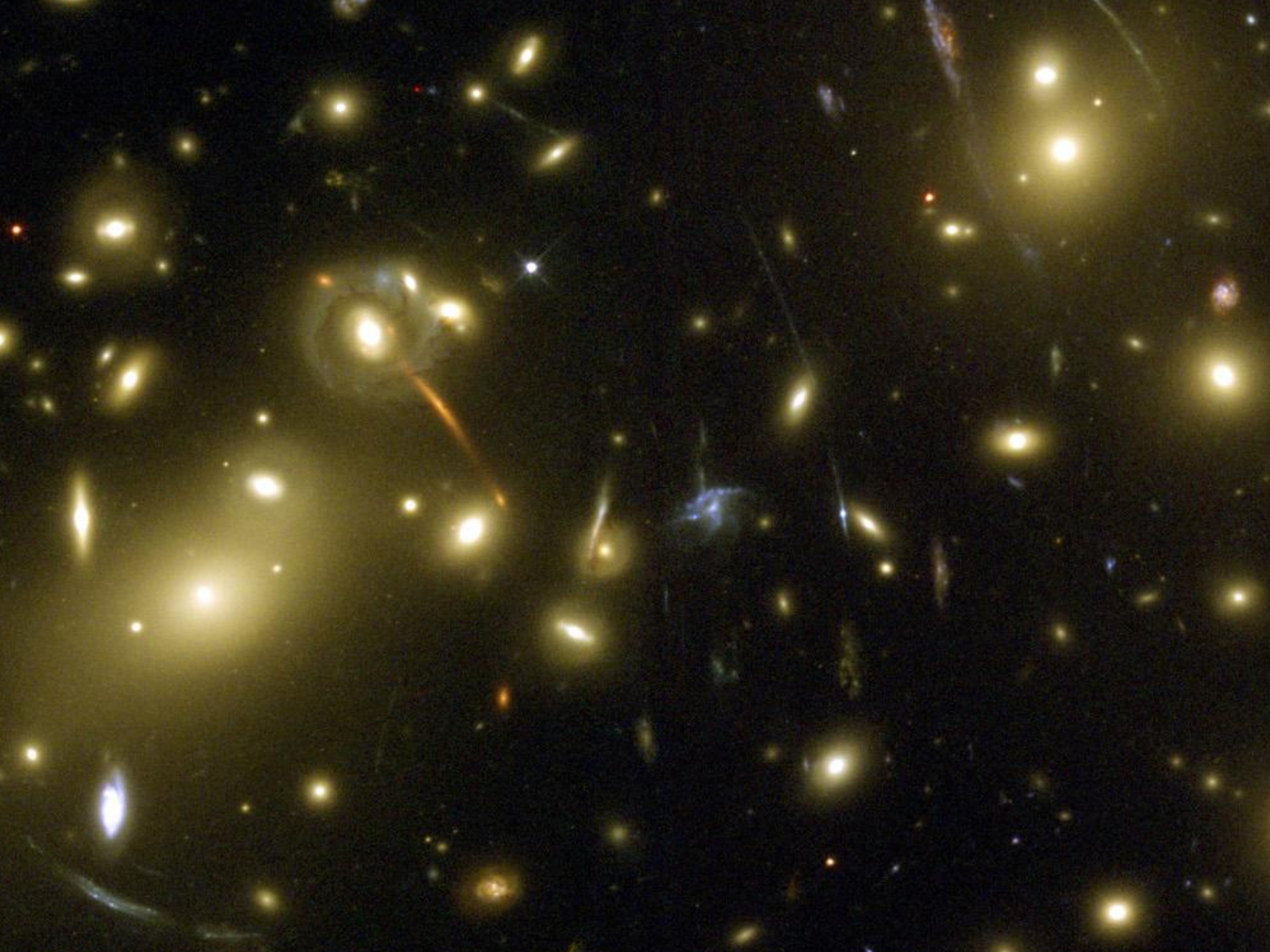




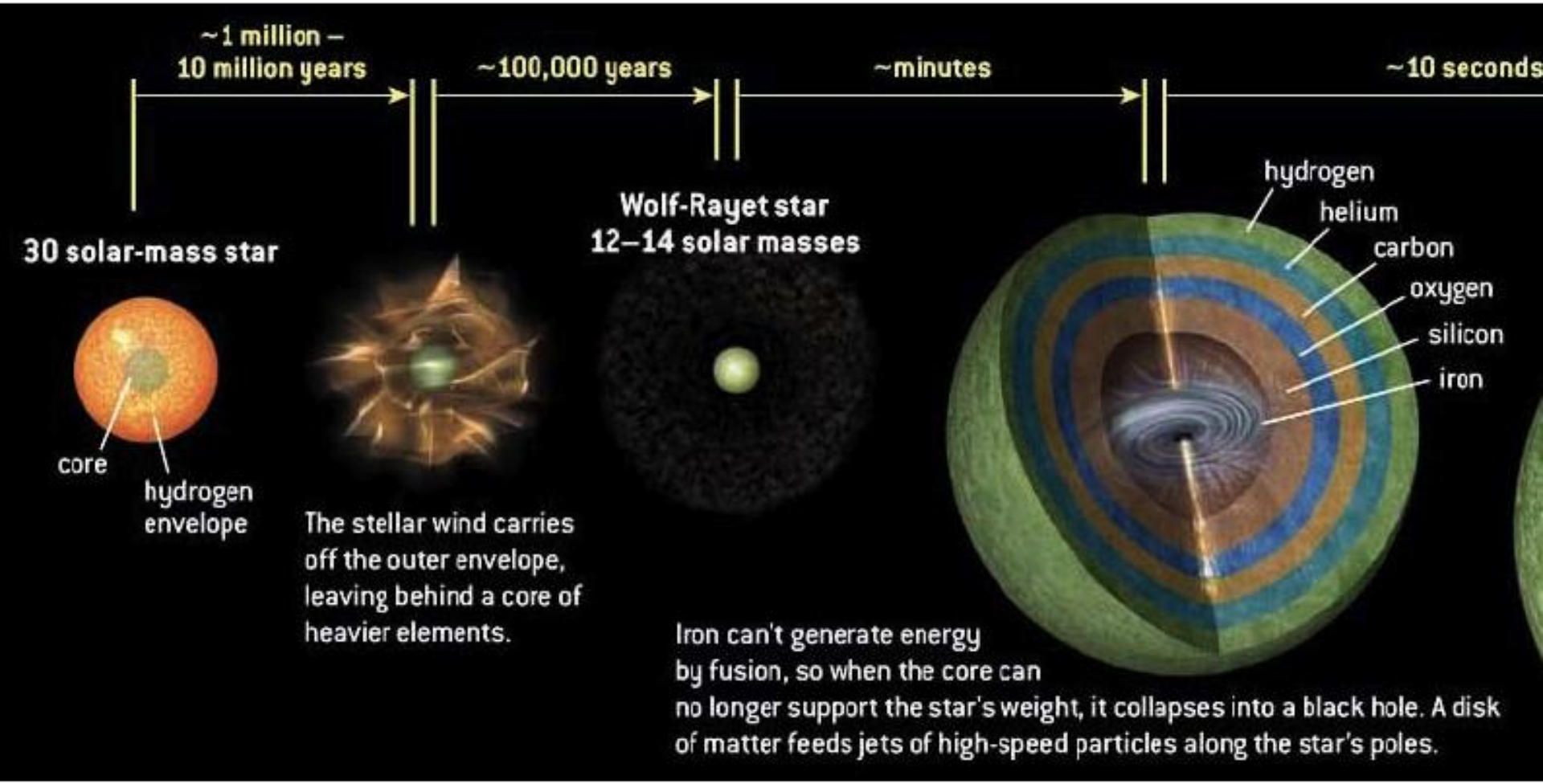

2dF Galaxy Redshift Survey
10h
11h
12h
13h
14h
Redshift
0.05
0.10
0.15
0.20
0.50
1.00
1.50
Billion Lightyears
3h
2h
1h
0h
23h
22h

THE HIGHEST-REDSHIFT QUASARS

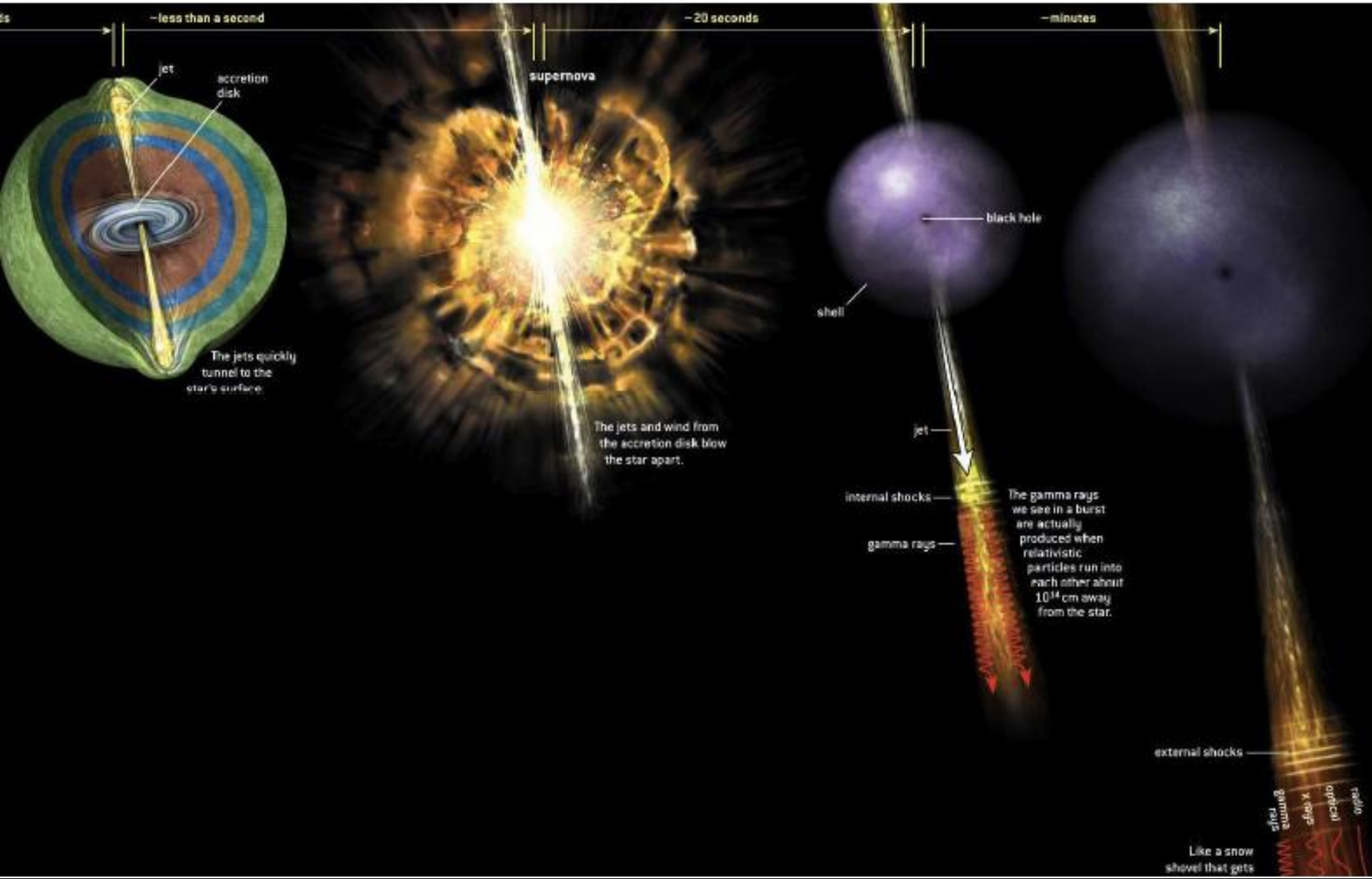




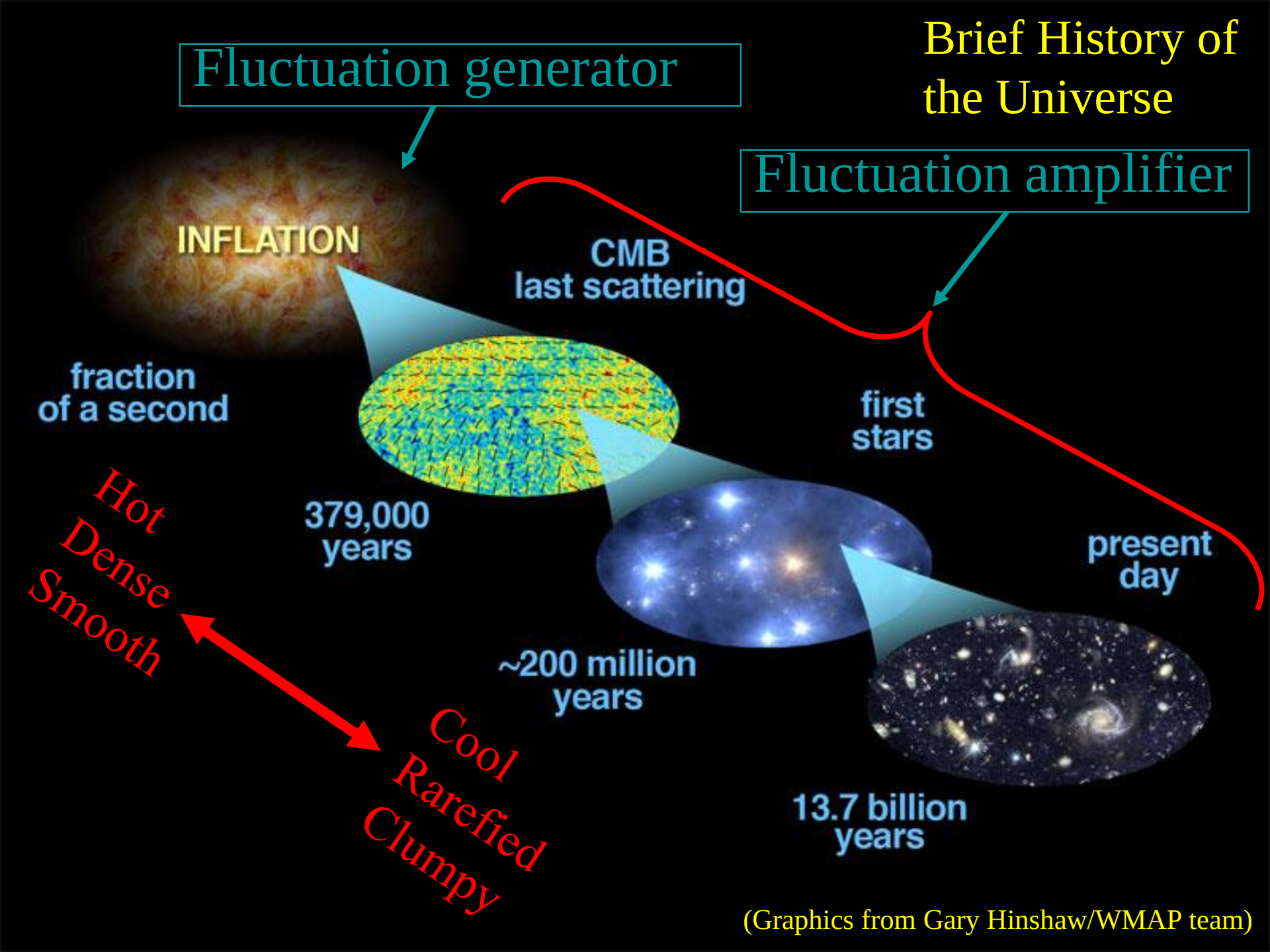
"long" GRB from "collapsars"



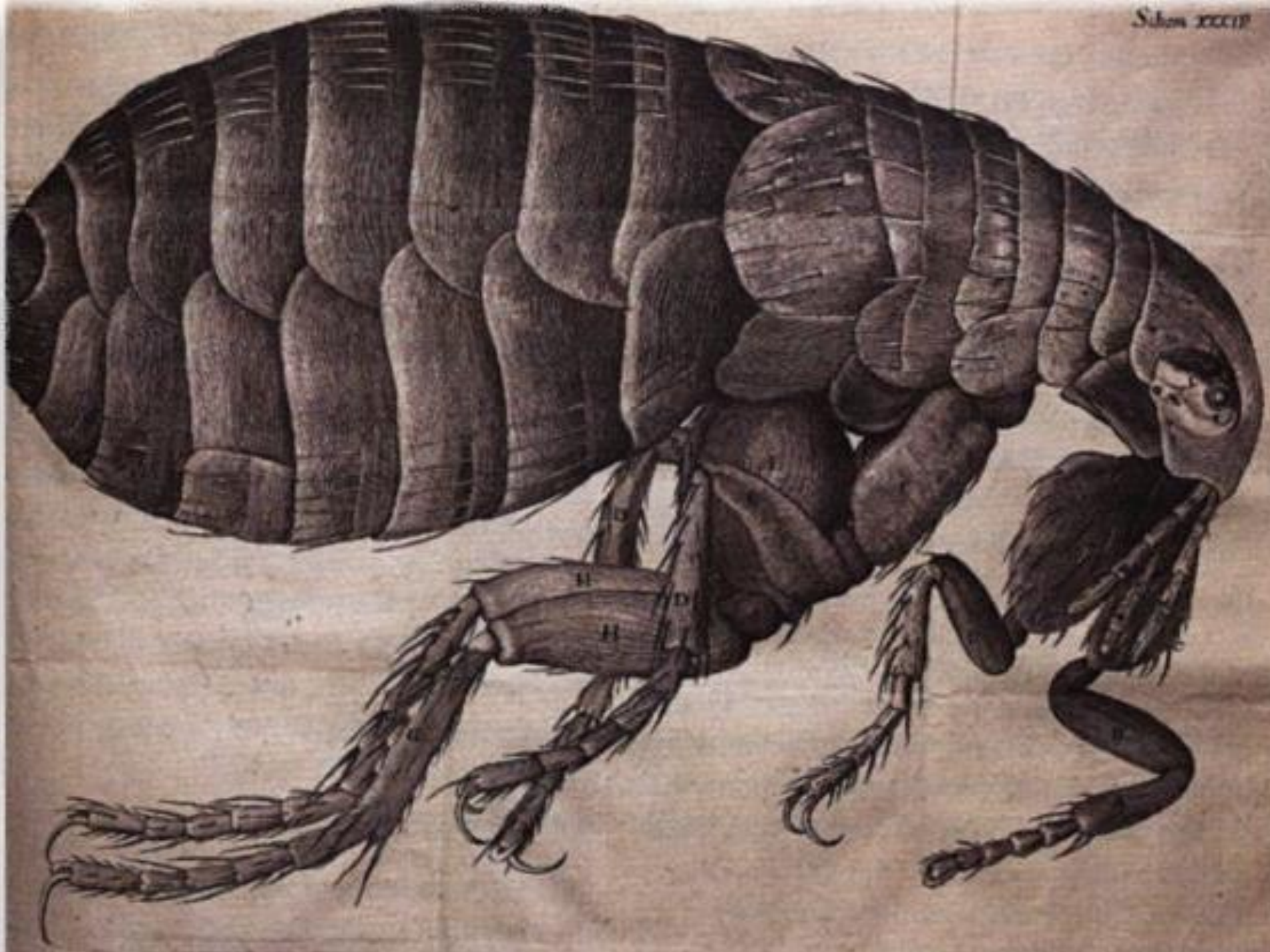
Collapsar GRB (cont.)



Brief History of the Universe

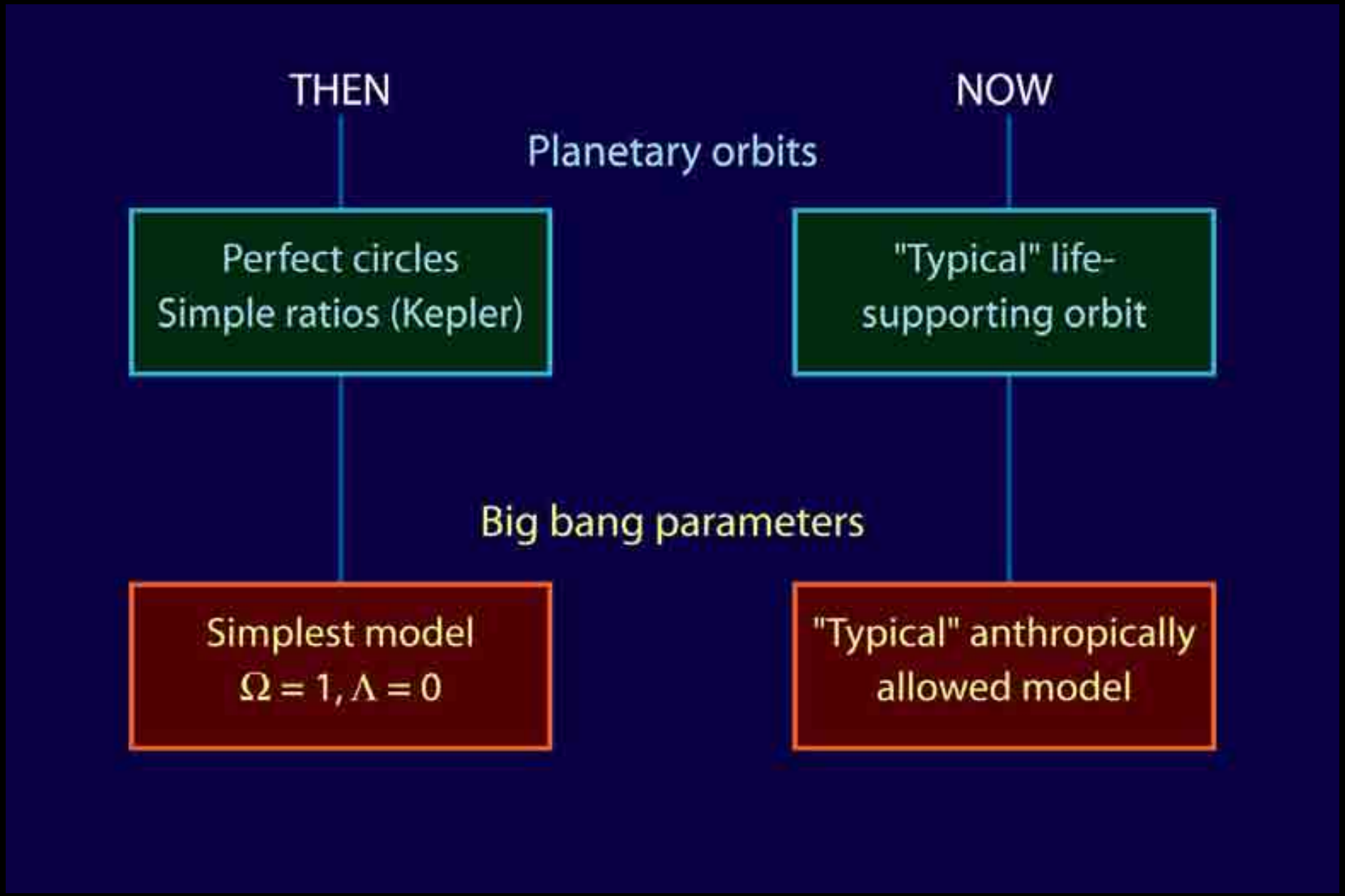


(Graphics from Gary Hinshaw/WMAP team)



the challenges

- What is out there? Cosmic exploration.
- Interpreting phenomena in terms of known (and perhaps ‘new’) physics.
- How, from a ‘simple beginning’, did our Universe evolve into its present complexity (stars, planets, people)?
- Can we understand, at a deeper level, why our Universe is the way it is?


THEN
NOW
Planetary orbits
Perfect circles
Simple ratios (Kepler)
"Typical" life-supporting orbit
Big bang parameters
Simplest model
$\Omega = 1, \Lambda = 0$
"Typical" anthropically allowed model

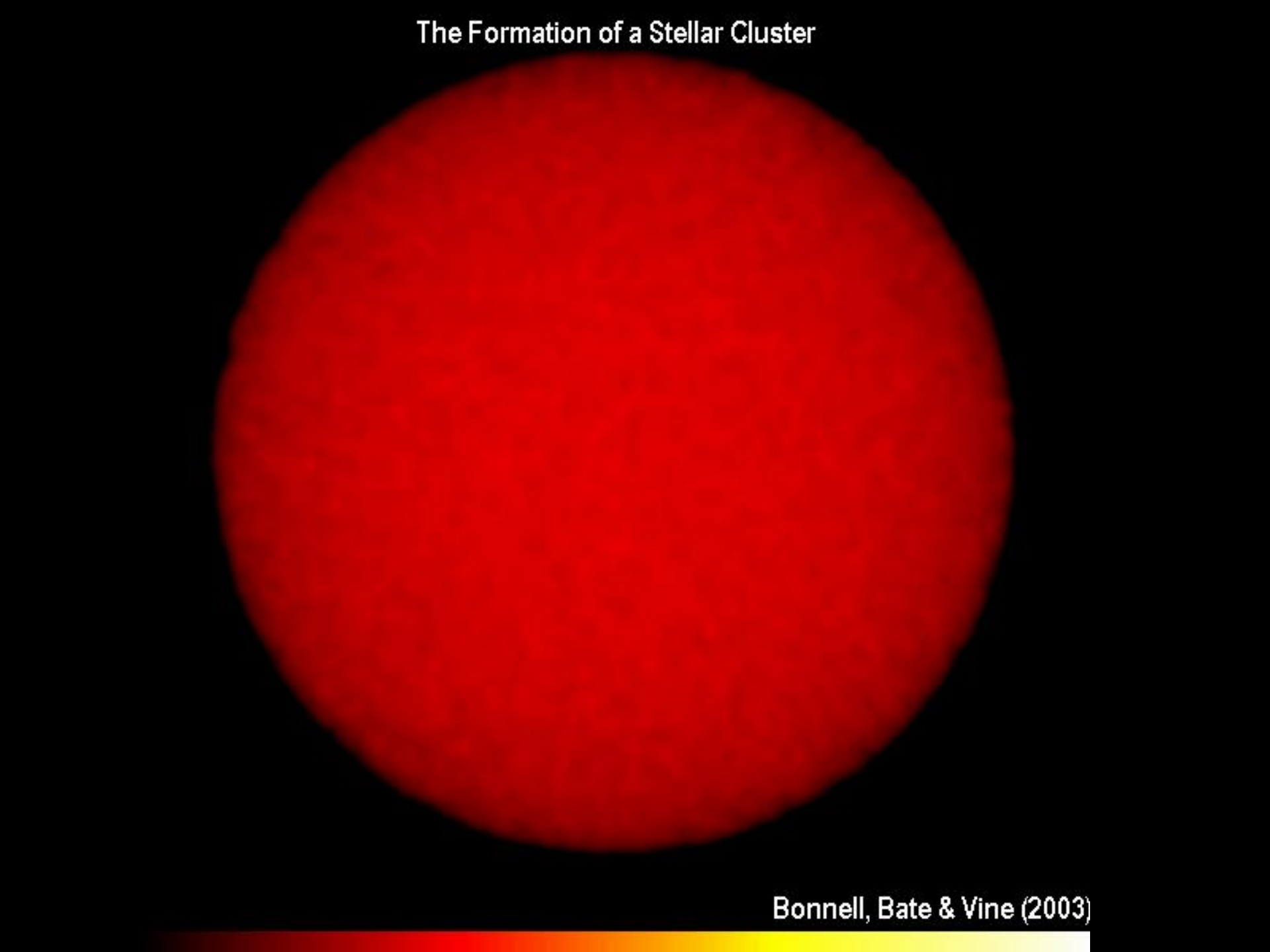
Just six numbers

Six constants of nature whose values must lie in an ‘anthropic’ range for life to emerge

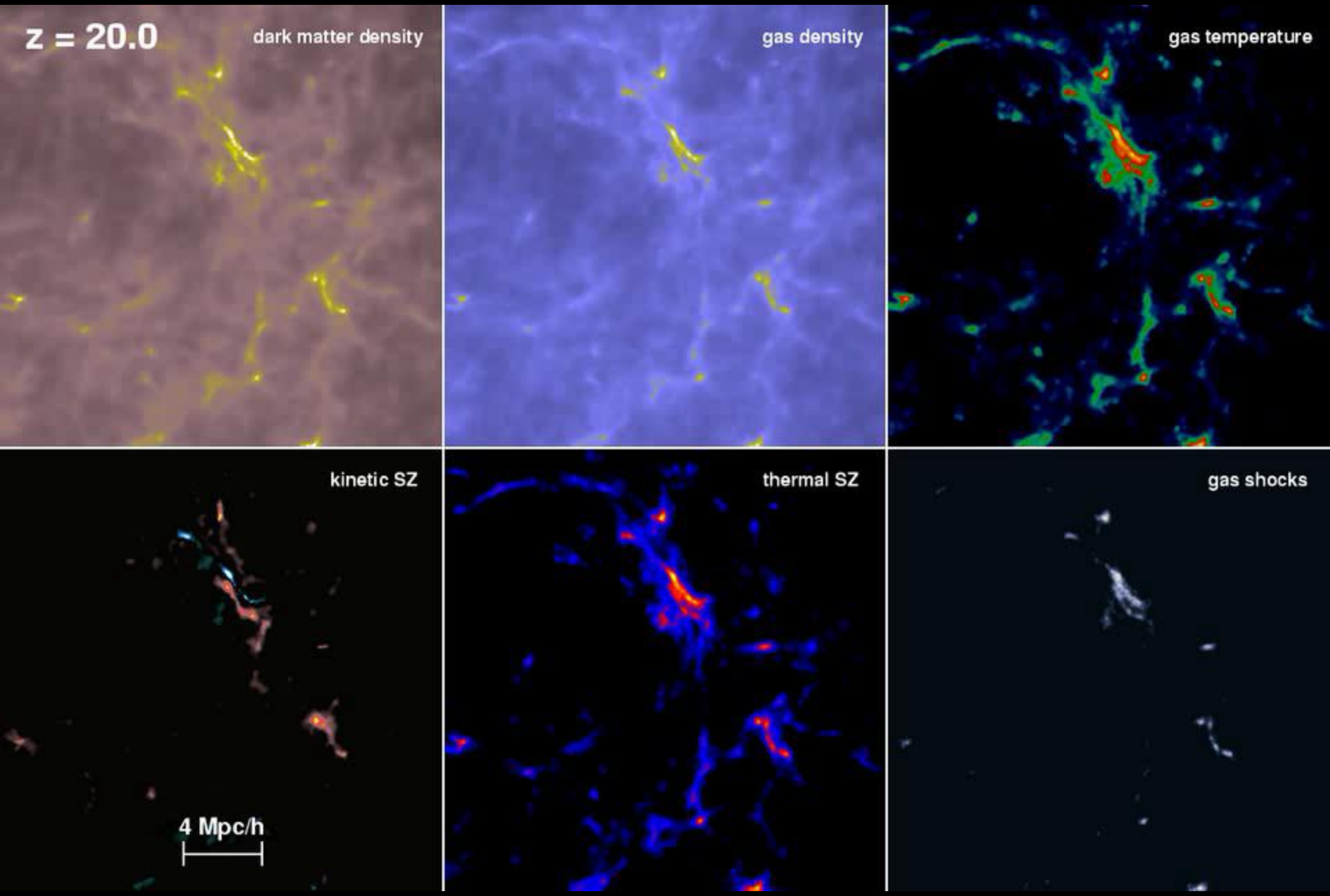
1. D = 3 The number of spatial dimensions
2. G/E = 10^{-36} The ratio of gravitational to electrostatic force
3. S = 0.007 A measure of the strong force that binds nuclei
4. $\Omega_{Total} = 1$ The density of matter/energy in space
5. Q= 0.00001 The scale of fluctuations in the microwave background
6. $\Omega_{\Lambda} = 0.7$ Omega lambda, a measure of the vacuum energy of the universe

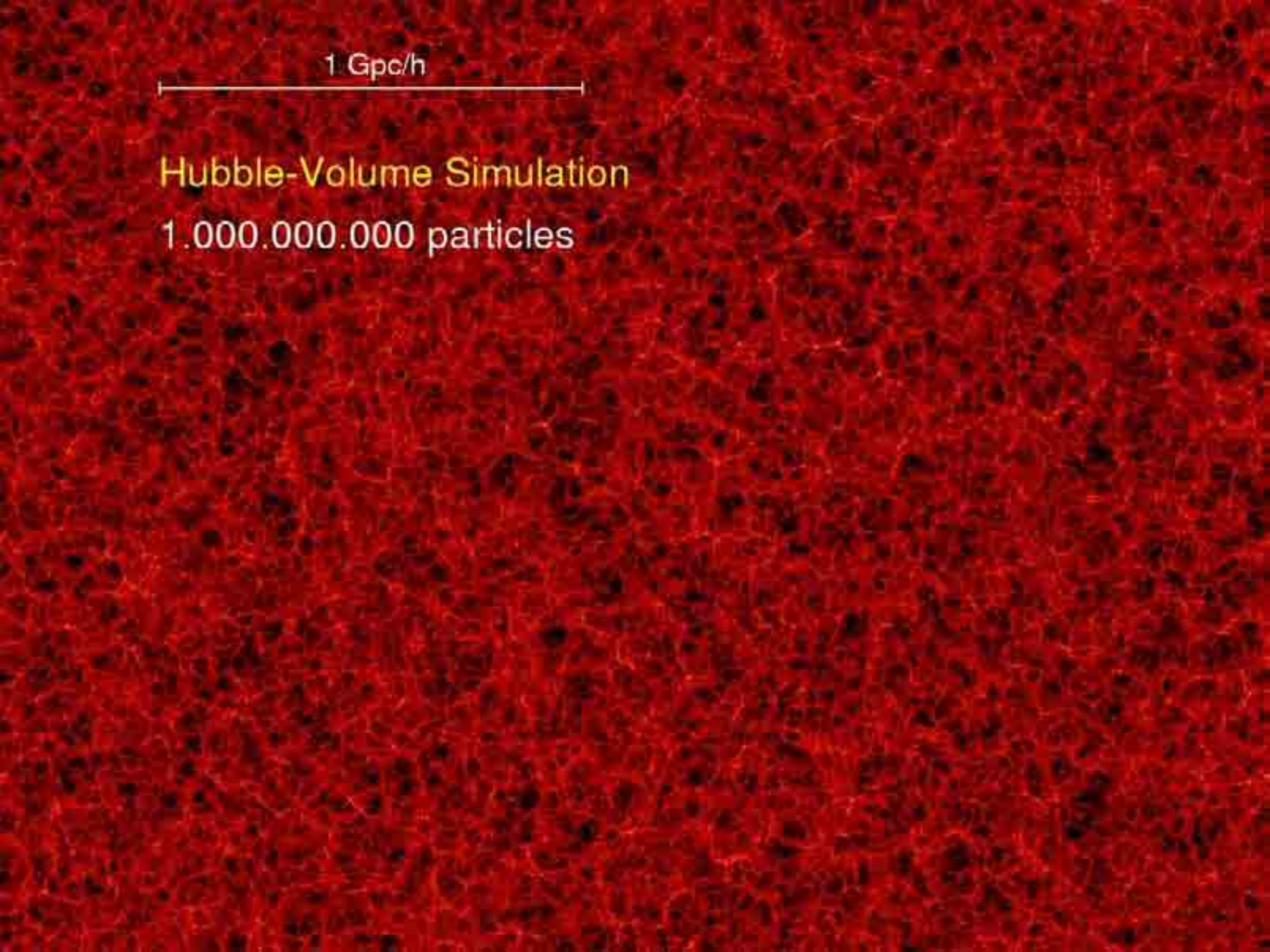
- Coincidence?
- Consequence?
- Multiverse?

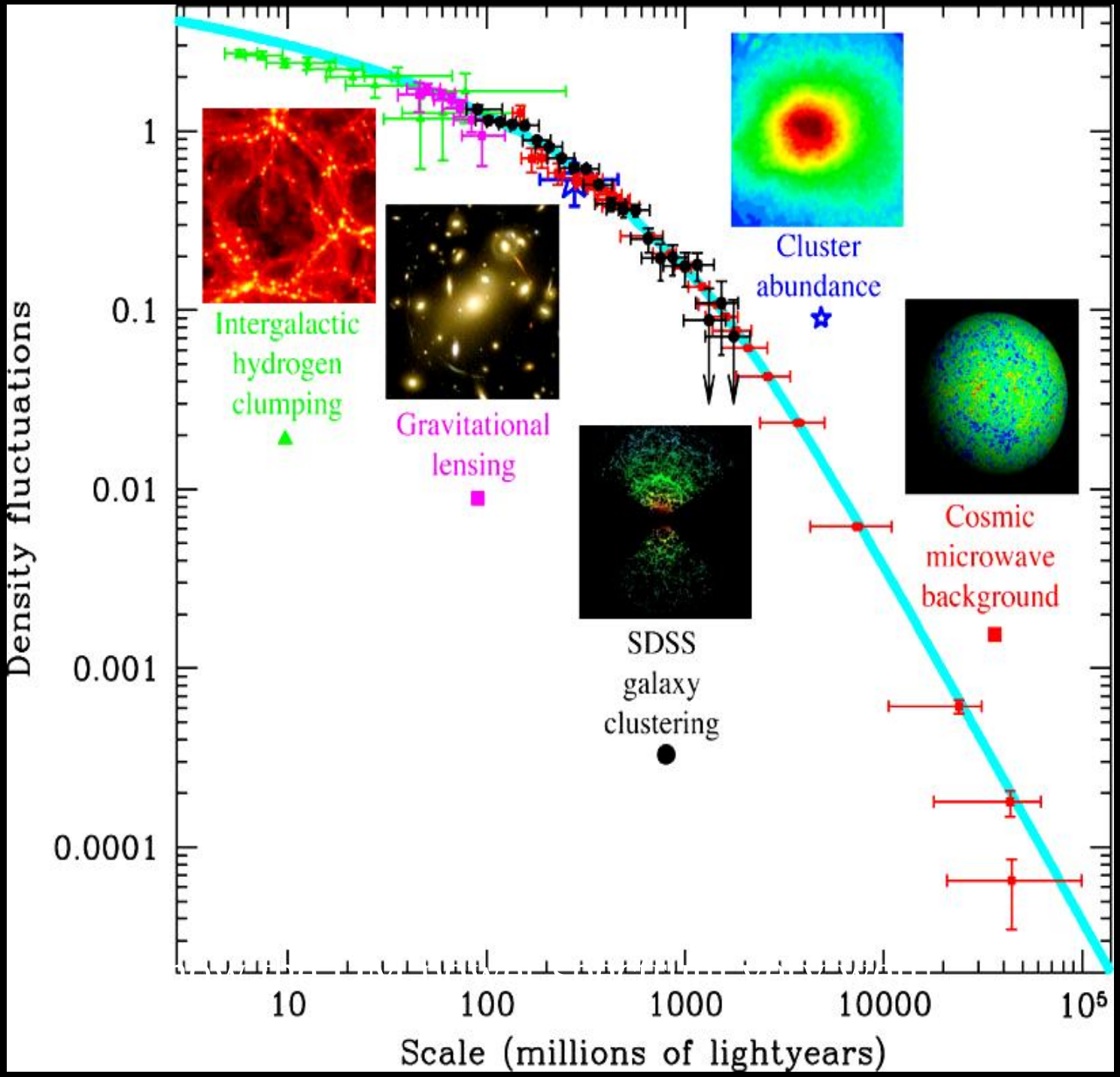
The Formation of a Stellar Cluster

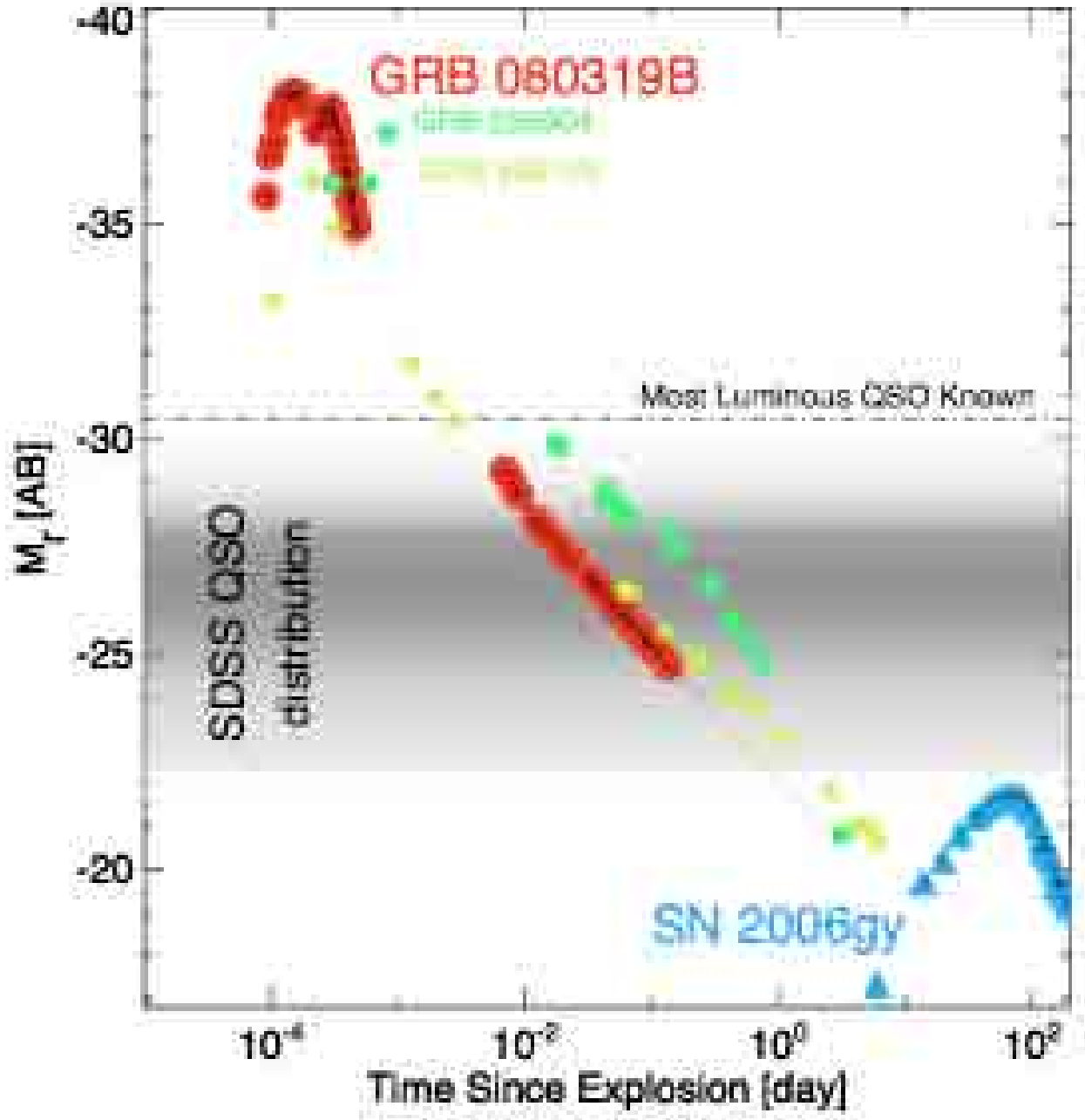


Bonnell, Bate & Vine (2003)


z = 20.0
dark matter density
gas density
gas temperature
kinetic SZ
thermal SZ
gas shocks
4 Mpc/h


1 Gpc/h
Hubble-Volume Simulation
1.000.000.000 particles


Density fluctuations
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10⁵
Scale (millions of lightyears)
Intergalactic hydrogen clumping
Gravitational lensing
SDSS galaxy clustering
Cluster abundance
Cosmic microwave background


GRB 080319B
Most Luminous QSO Known
SDSS QSO
distribution
SN 2006gy
-40
-35
-30
-25
-20
M_r [AB]
10^{-4}
10^{-2}
10^{0}
10^{2}
Time Since Explosion [day]

5 WAYS TO REFUTE "HOT BIG BANG"

Object with $\ll$23% helium

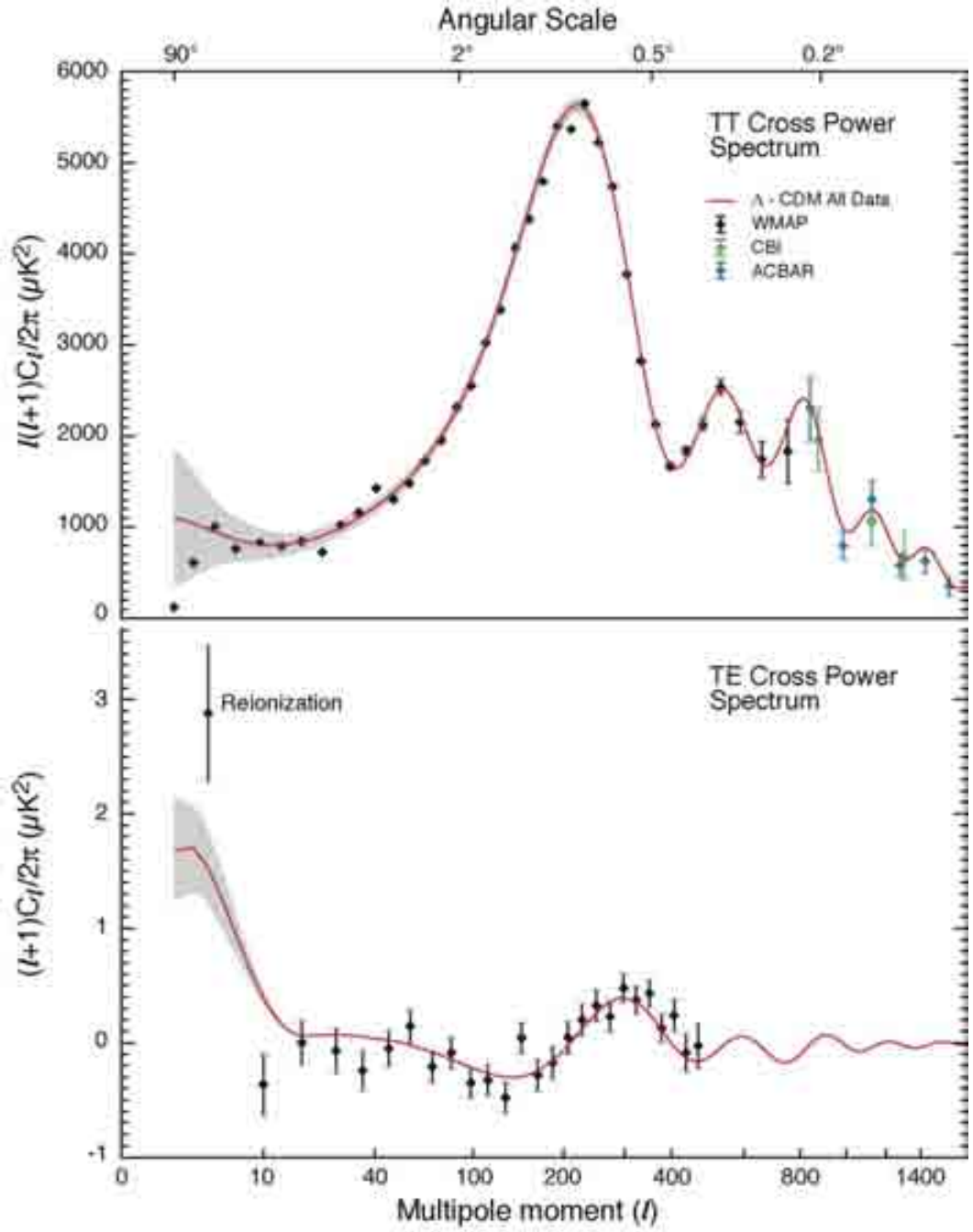
Millimetre-wave background below prediction

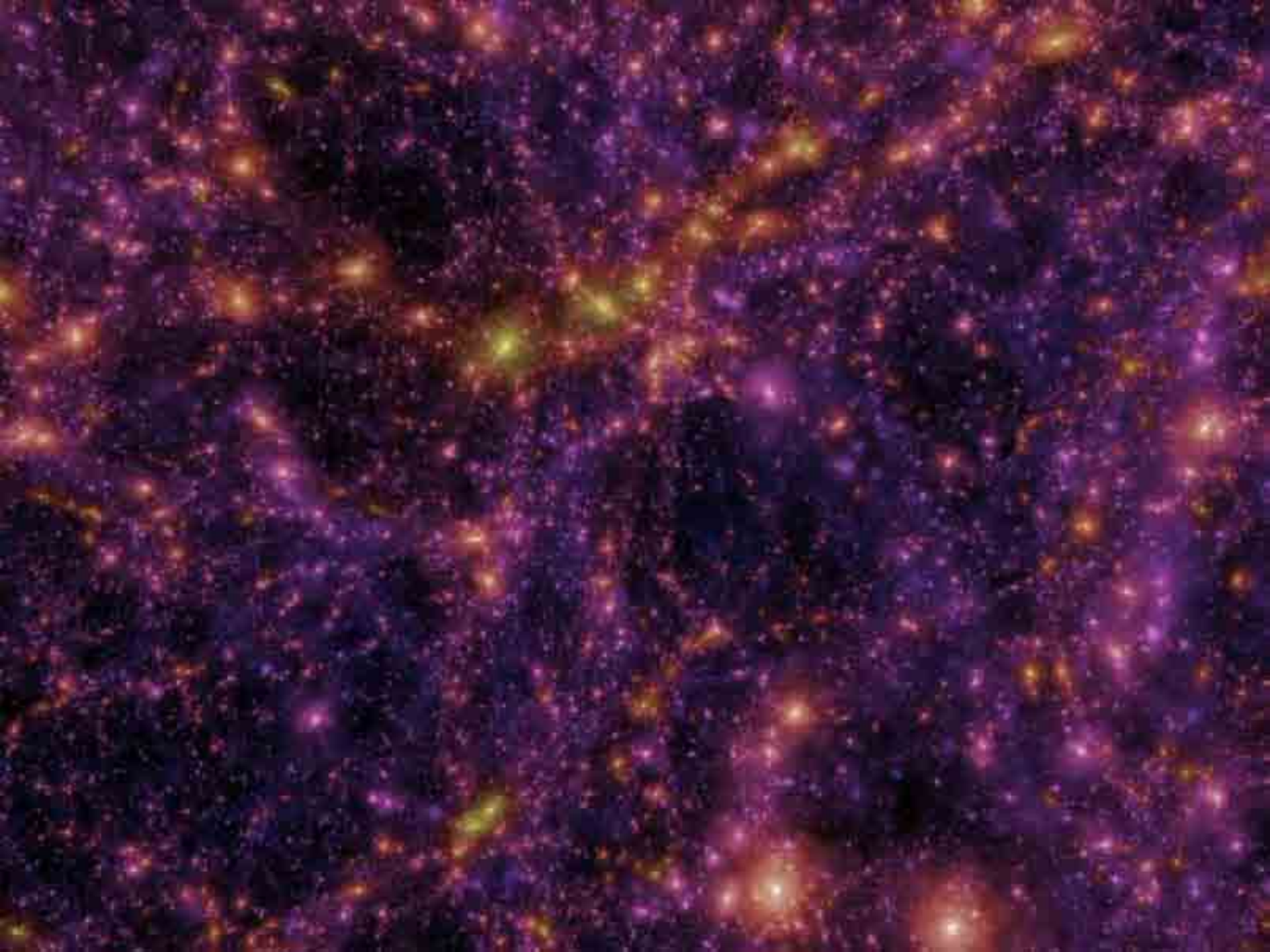
Stable neutrino with mass $100 - 10^6$ eV

Too much deuterium to match baryon density

$\Delta T/T$ too small to account for present structure

WMAP


Angular Scale
90°
2°
0.5°
0.2°
TT Cross Power Spectrum
Λ - CDM All Data
WMAP
CBI
ACBAR
l(l+1)C_l/2π (μK²)
6000
5000
4000
3000
2000
1000
0
TE Cross Power Spectrum
Reionization
(l+1)C_l/2π (μK²)
3
2
1
0
-1
0
10
40
100
200
400
800
1400
Multipole moment (l)



Calculations of the primal "cooking" of the chemical elements predict

Hydrogen

Helium

Lithium

etc, correctly!

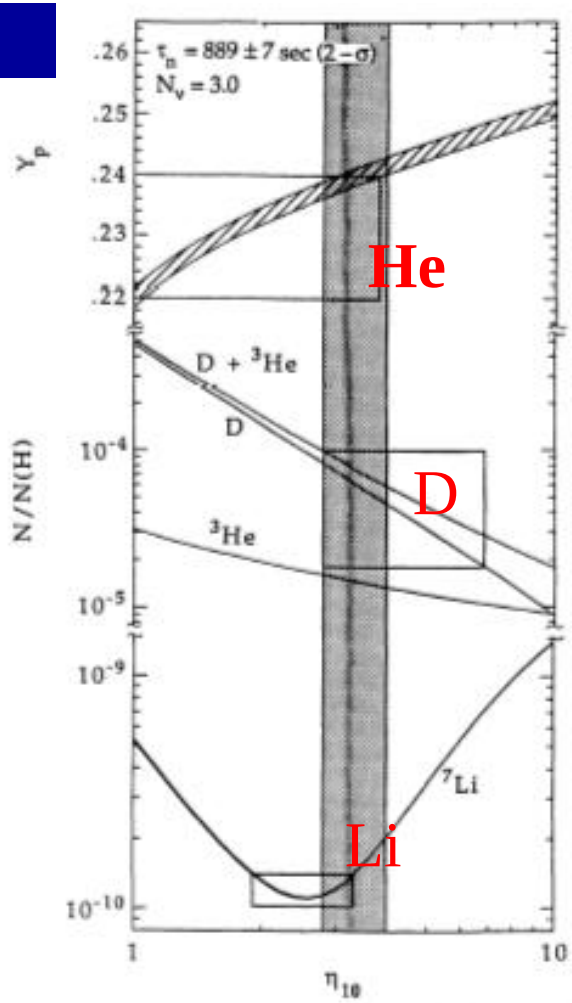
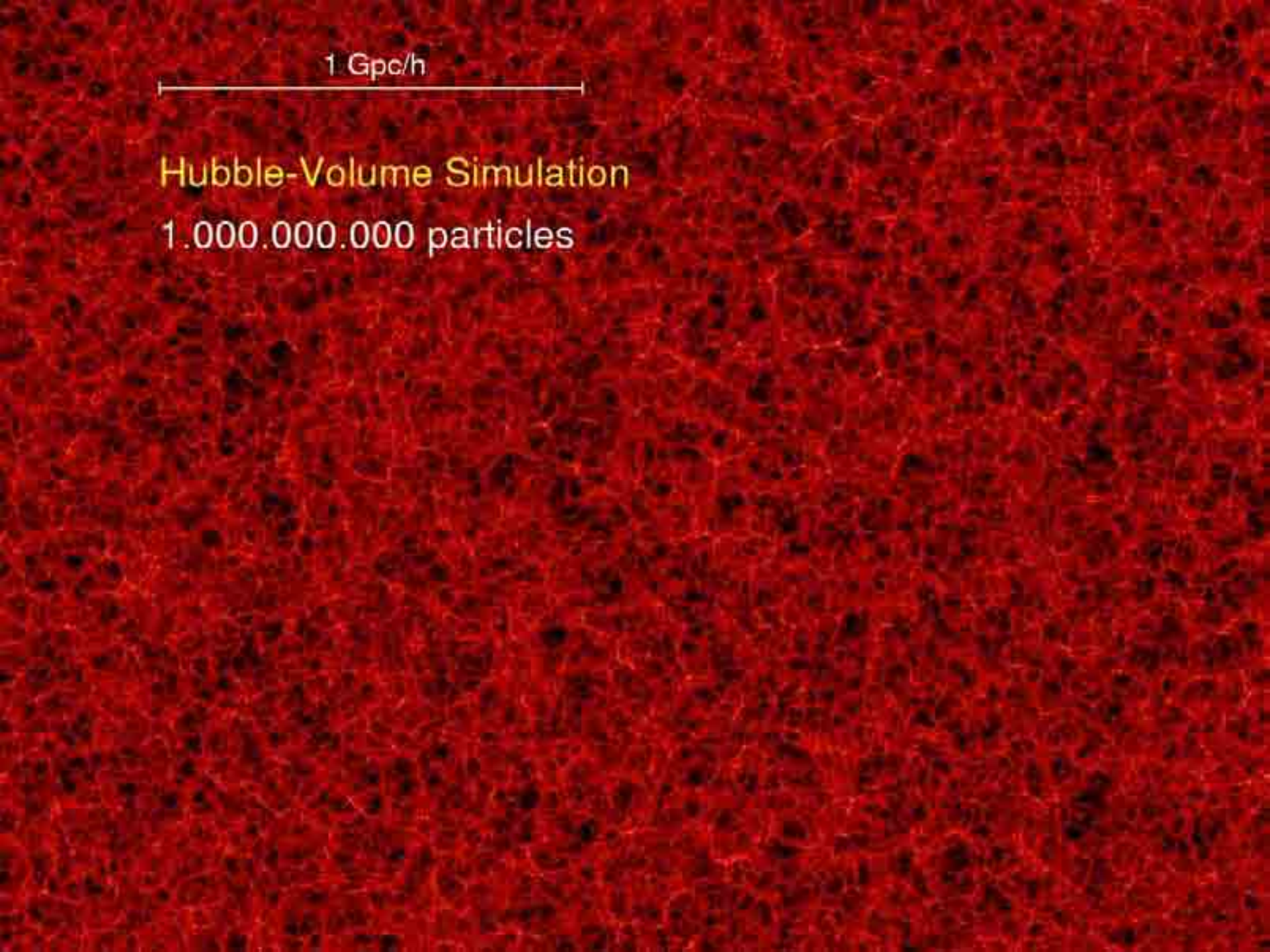


FIG. 13.—Predicted abundances (by number) of D, ^{3}He, D + ^{3}He, and ^{7}Li, and the ^{4}He mass fraction as a function of η for $N_\nu = 3$ and $882 \leq \tau_n \leq 896$ s. The 95% CL bounds on the abundances (see text) are shown. The vertical band delimits the range of η consistent with the observations.


1 Gpc/h
Hubble-Volume Simulation
1.000.000.000 particles

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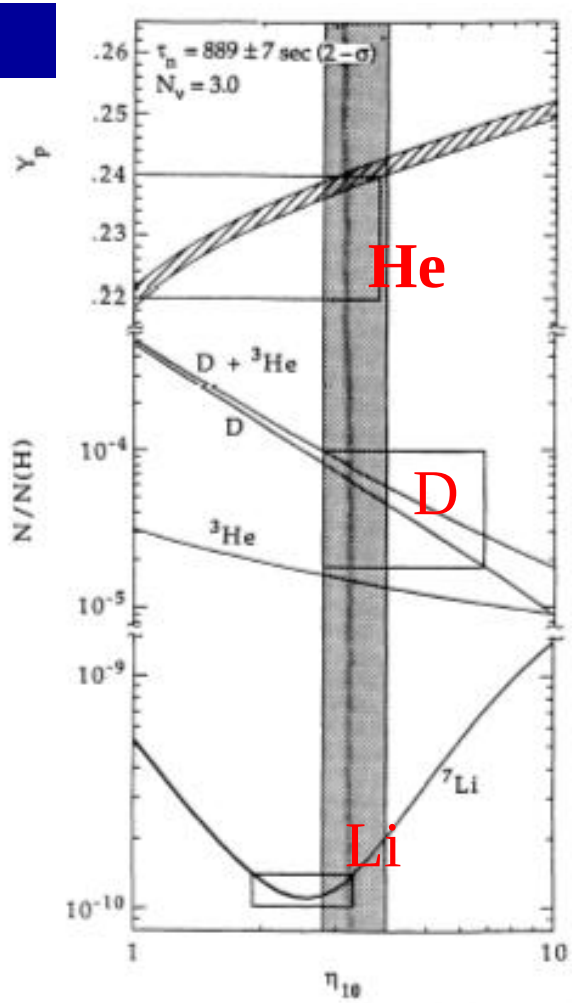

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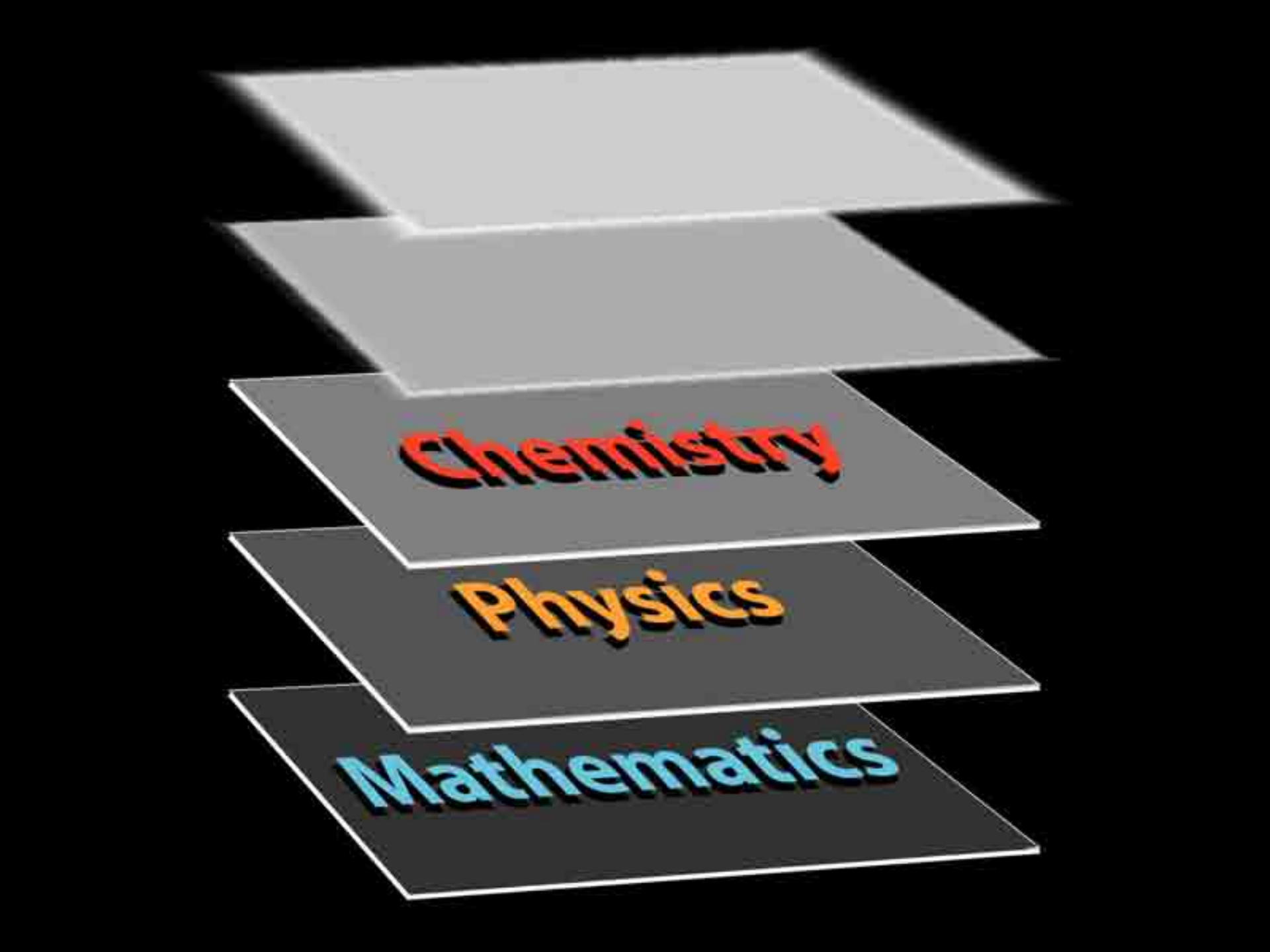
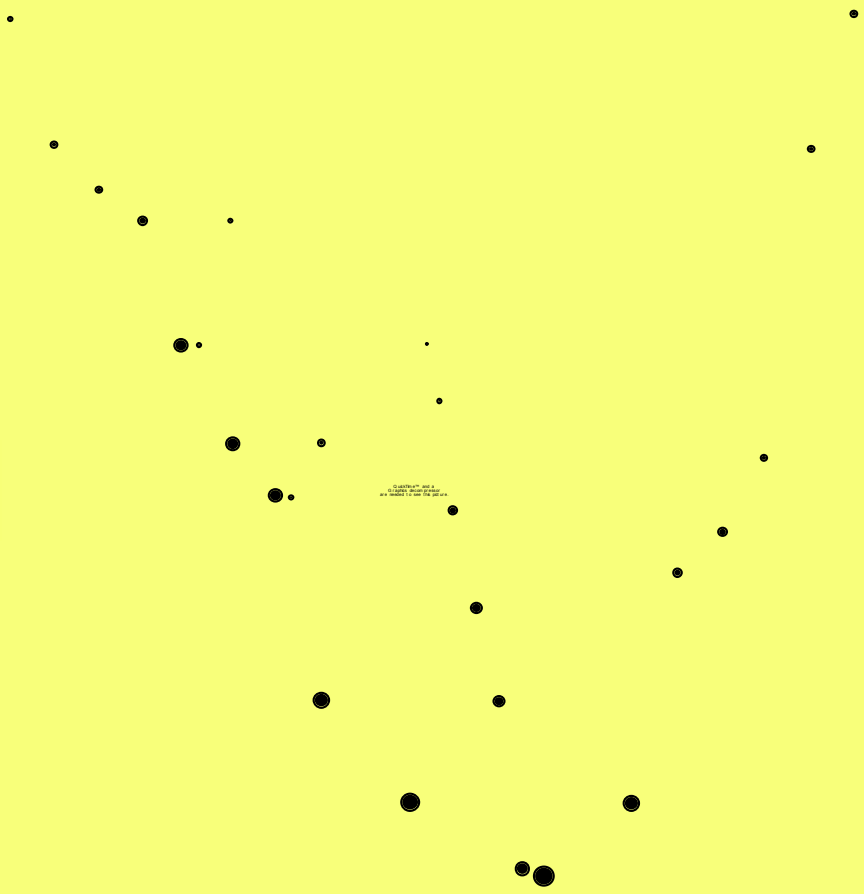

Chemistry
Physics
Mathematics

Supermassive holes grow from seed pregalactic BHs. These seeds are incorporated in larger and larger halos, accreting gas and dynamically interacting after mergers.

All models for first BHs predict a biased formation: in the HIGHEST PEAKS OF DENSITY FLUCTUATIONS at z~20-30



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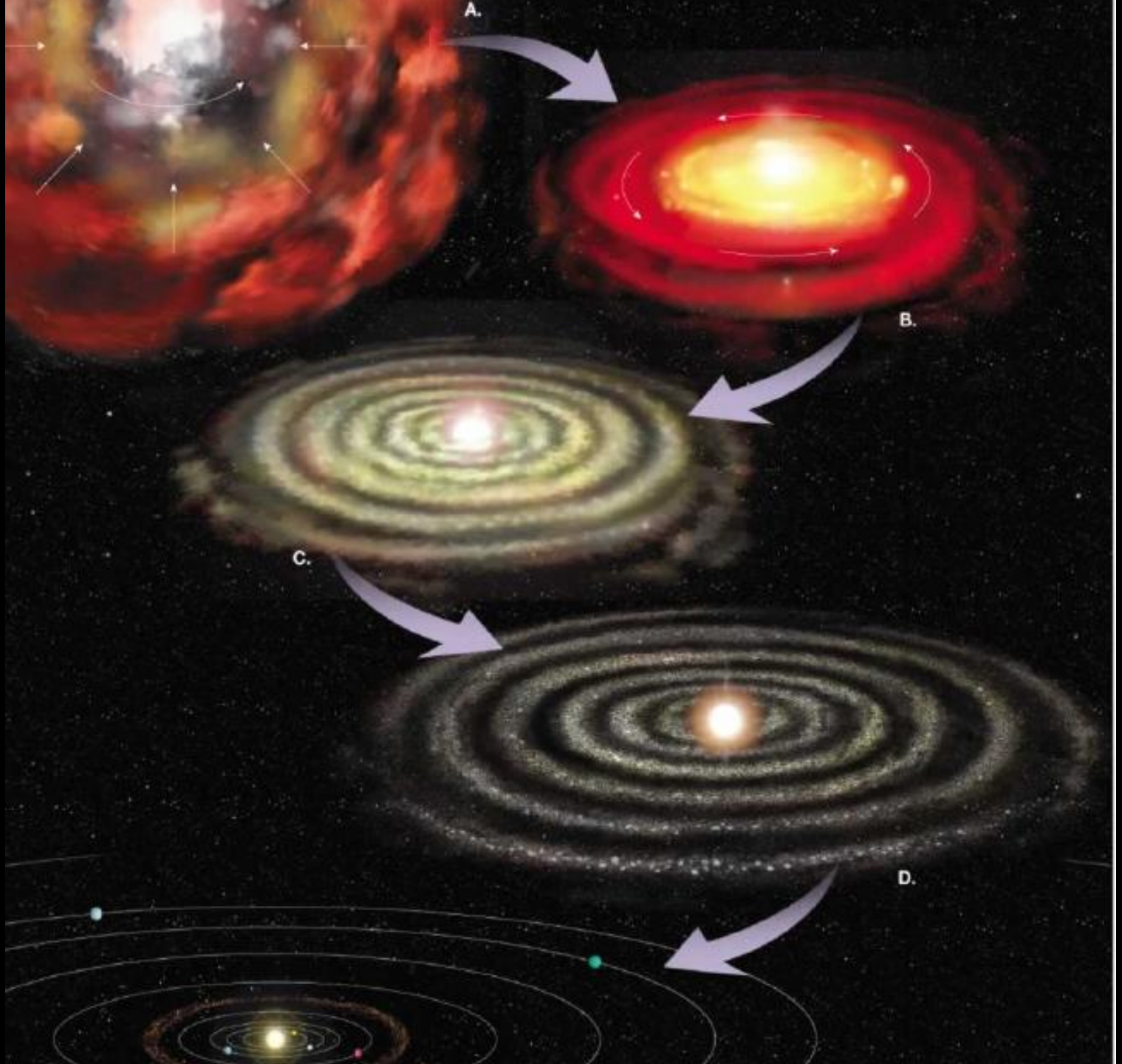
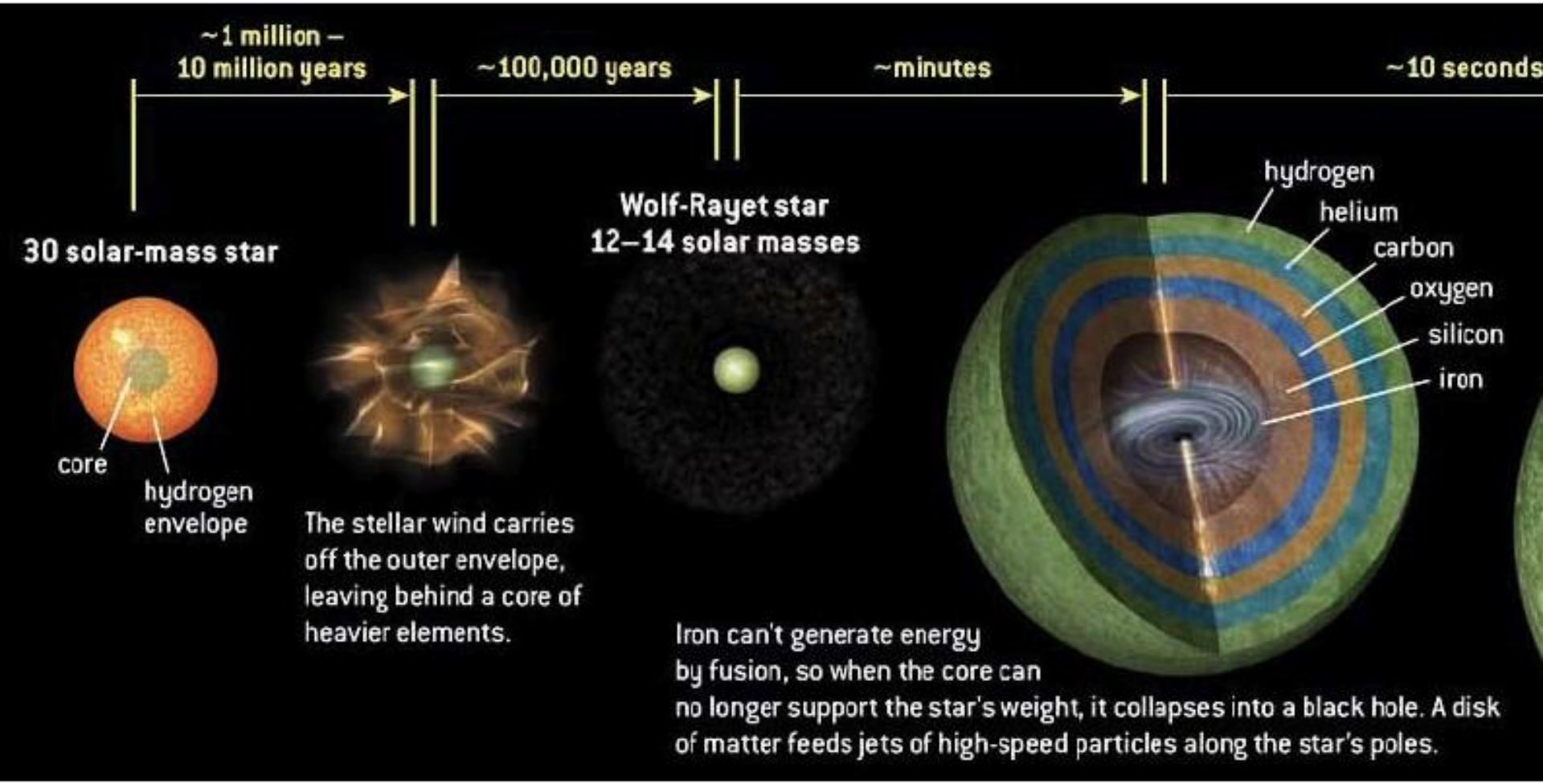
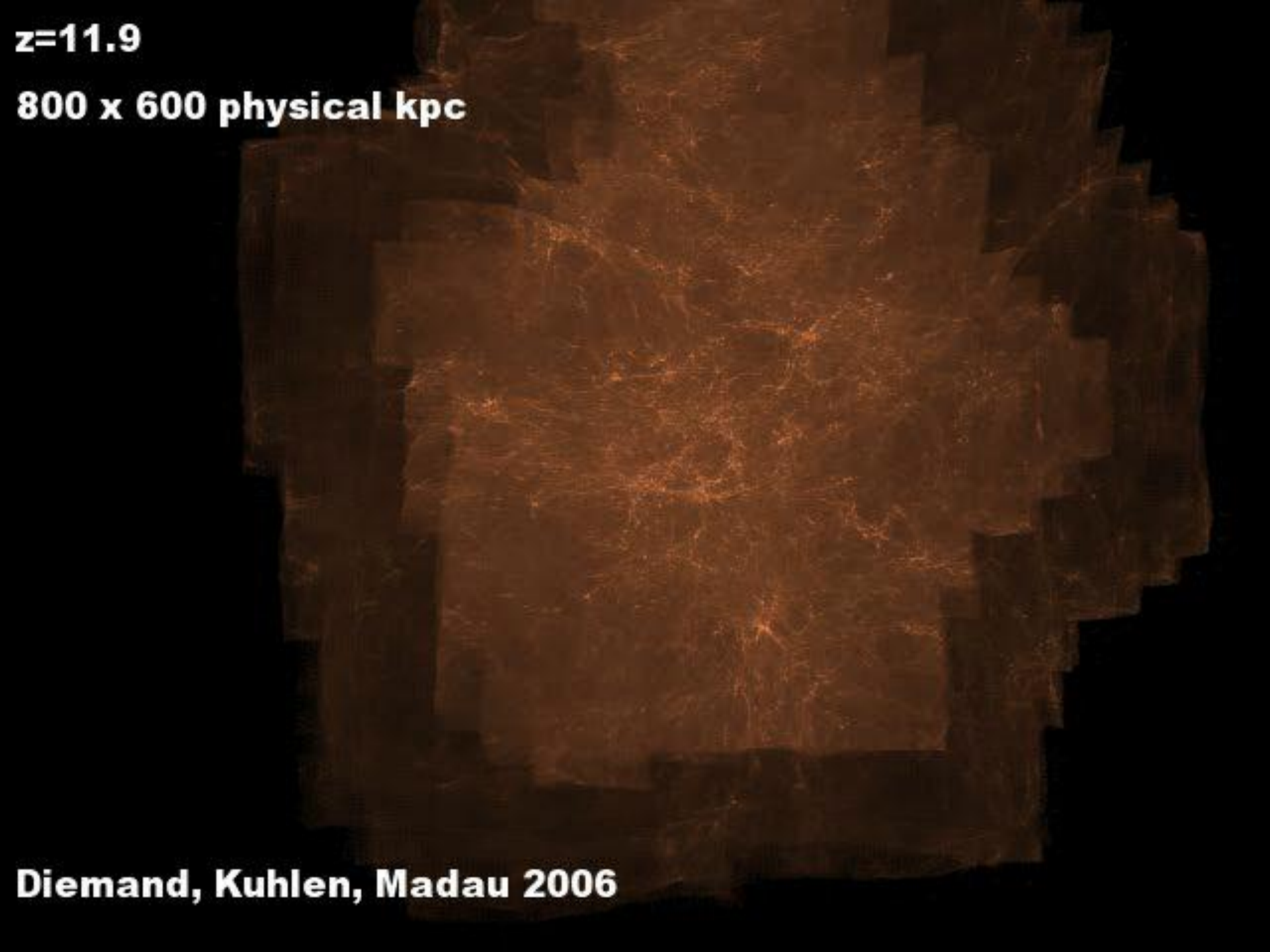
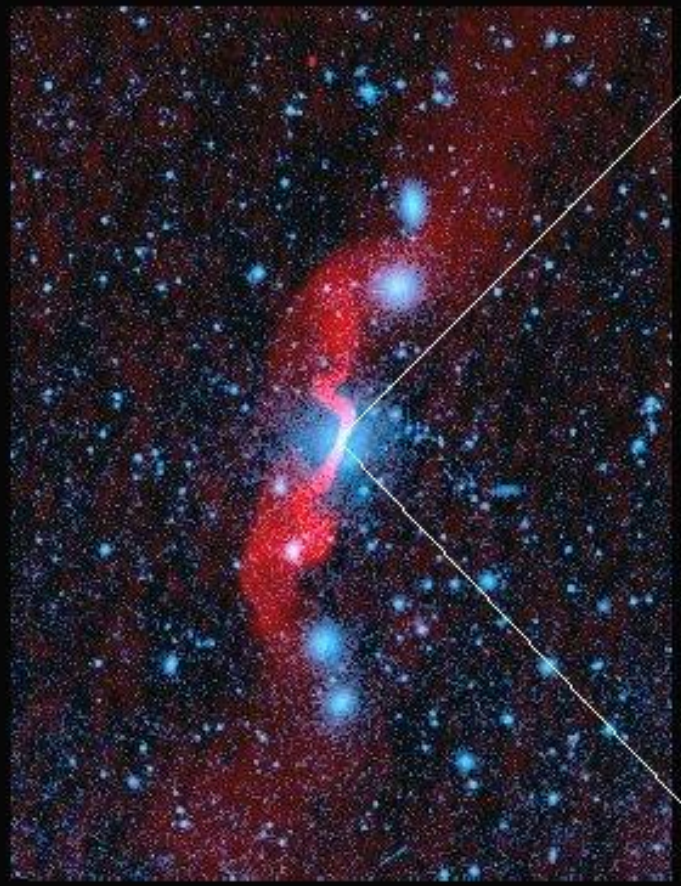
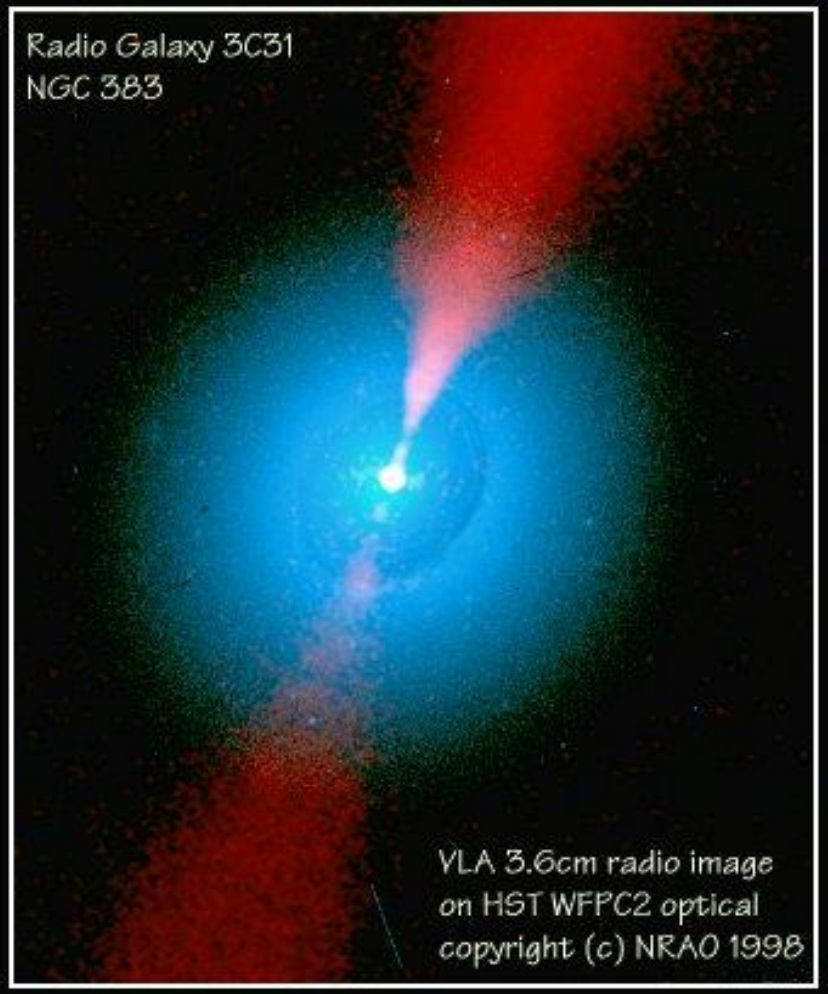

A.
B.
C.
D.

"long" GRB from "collapsars"

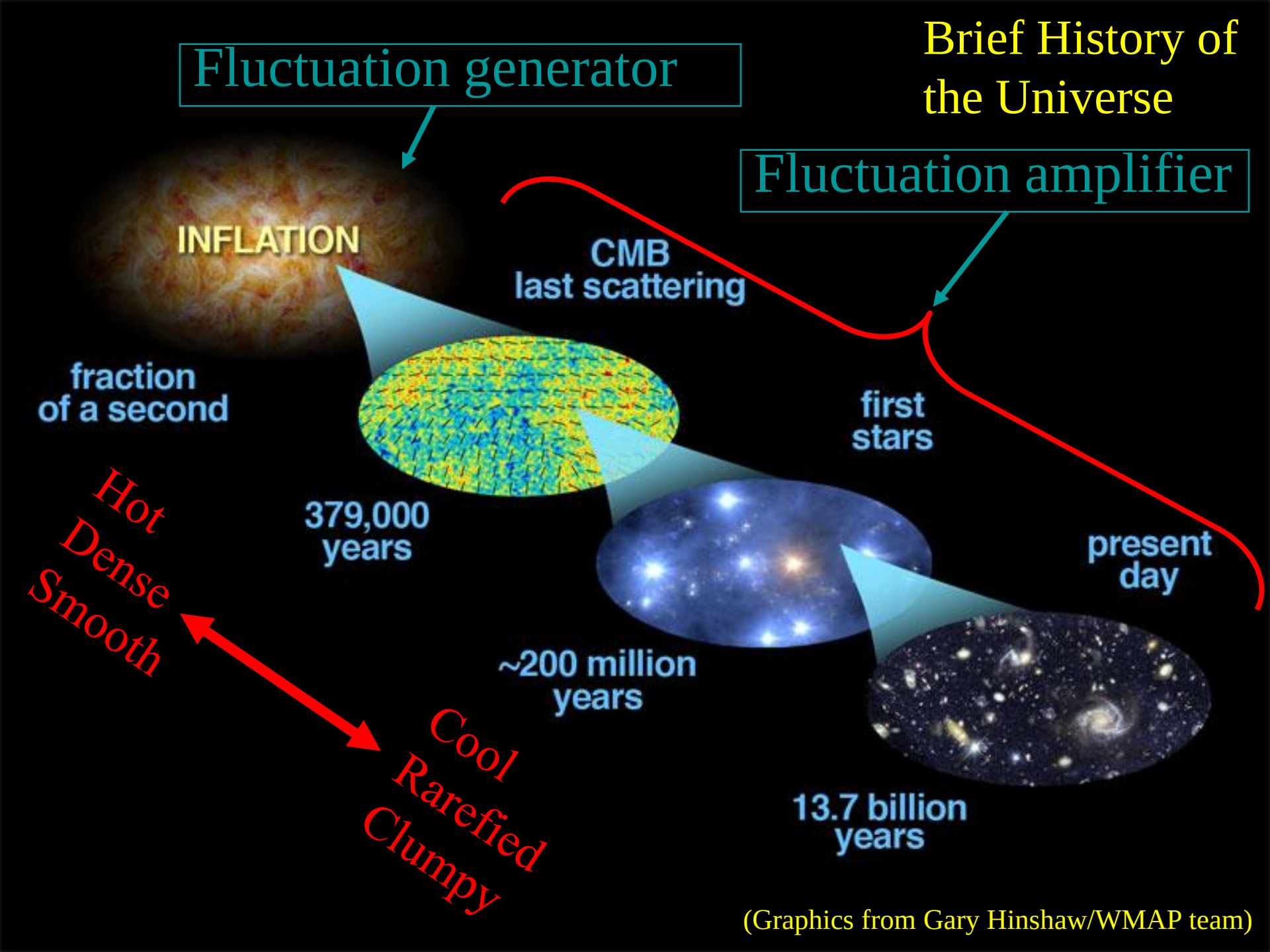



z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006



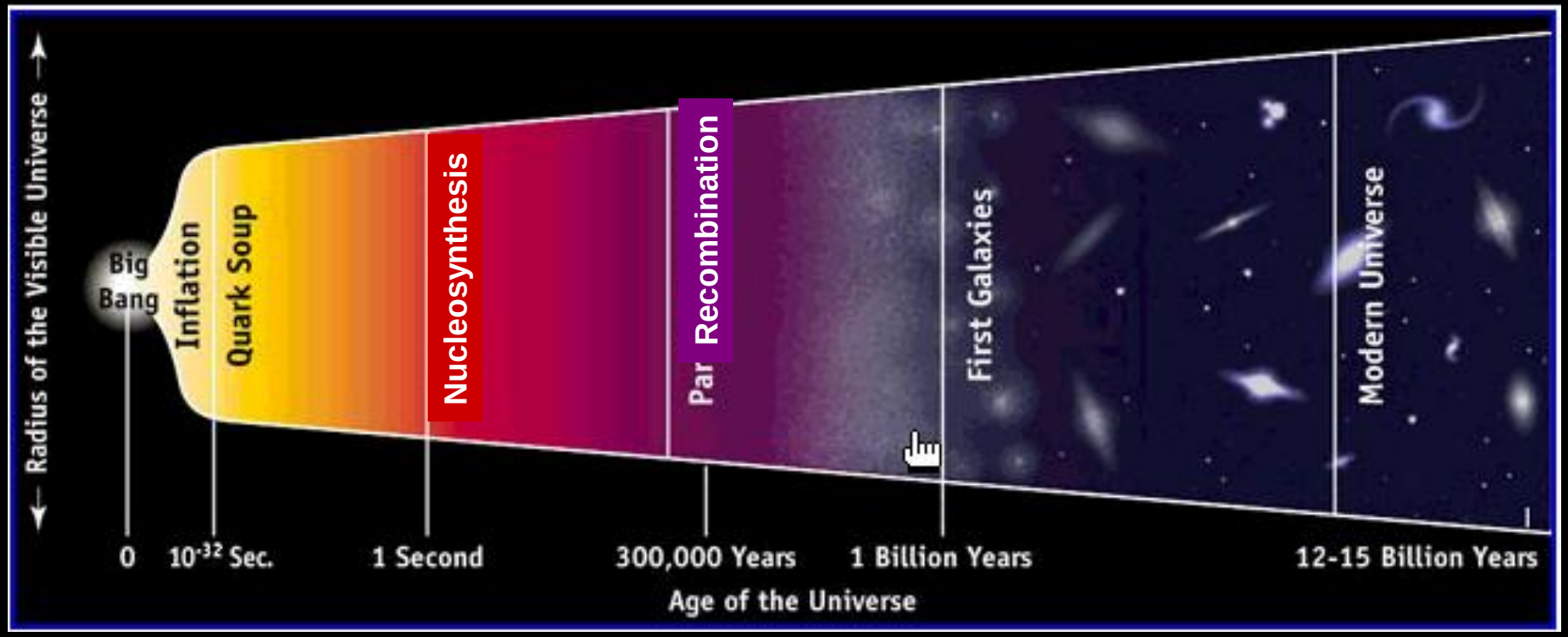

Radio Galaxy 3C31
NGC 383
VLA 3.6cm radio image
on HST WFPC2 optical
copyright (c) NRAO 1998

Brief History of the Universe



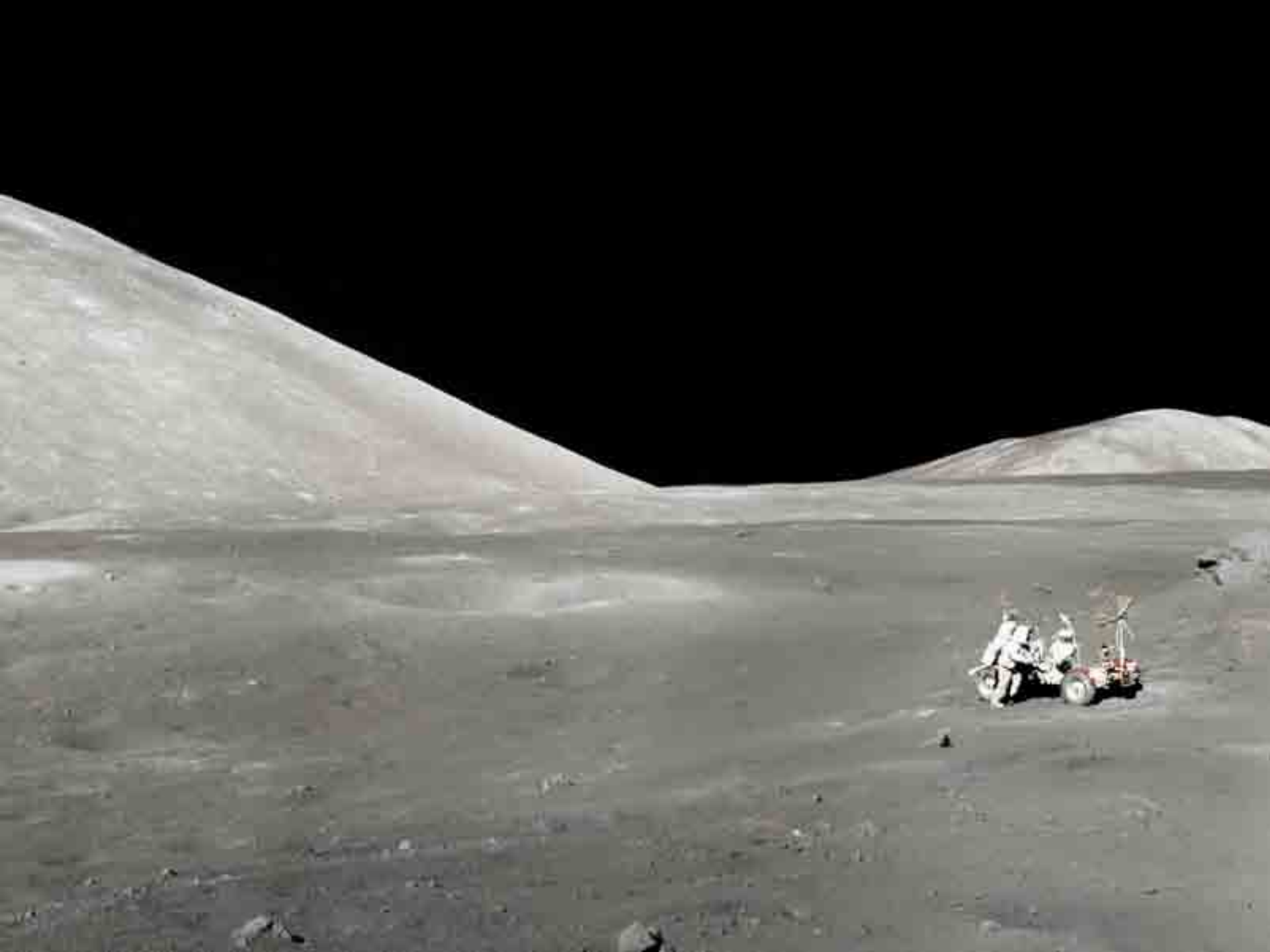
(Graphics from Gary Hinshaw/WMAP team)

Cosmic Evolution -Cartoon

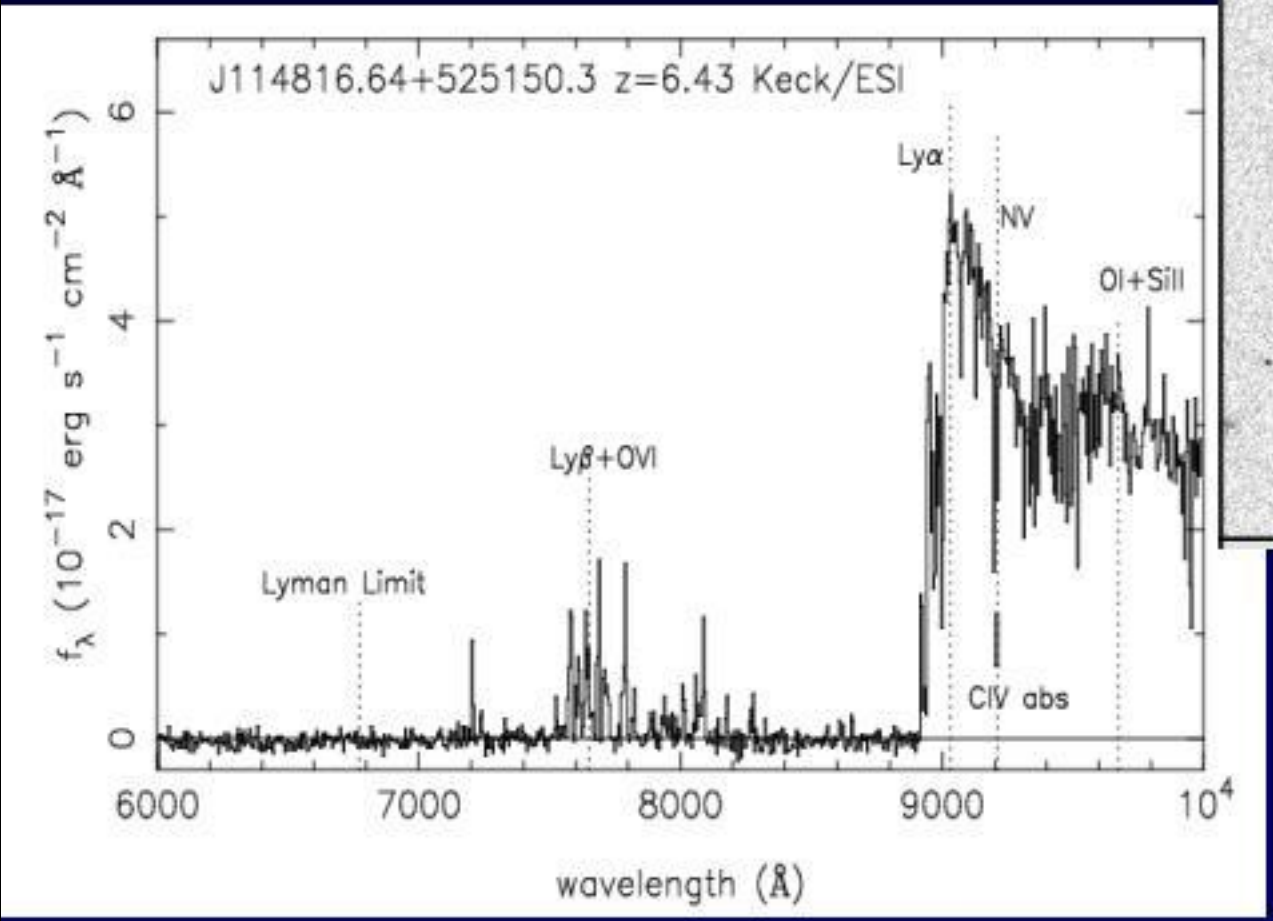


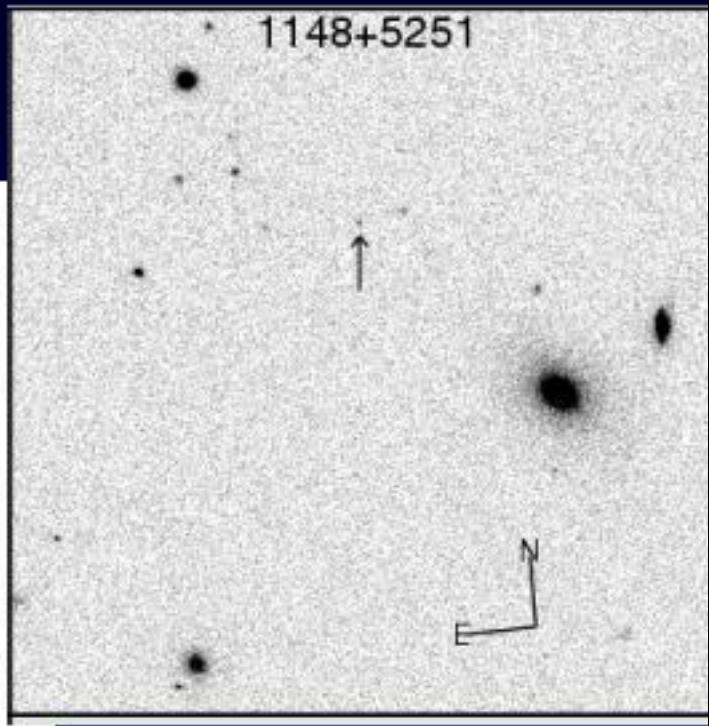
Well-understood

nonlinear simulations



The Earliest Quasar Detected: z=6.4

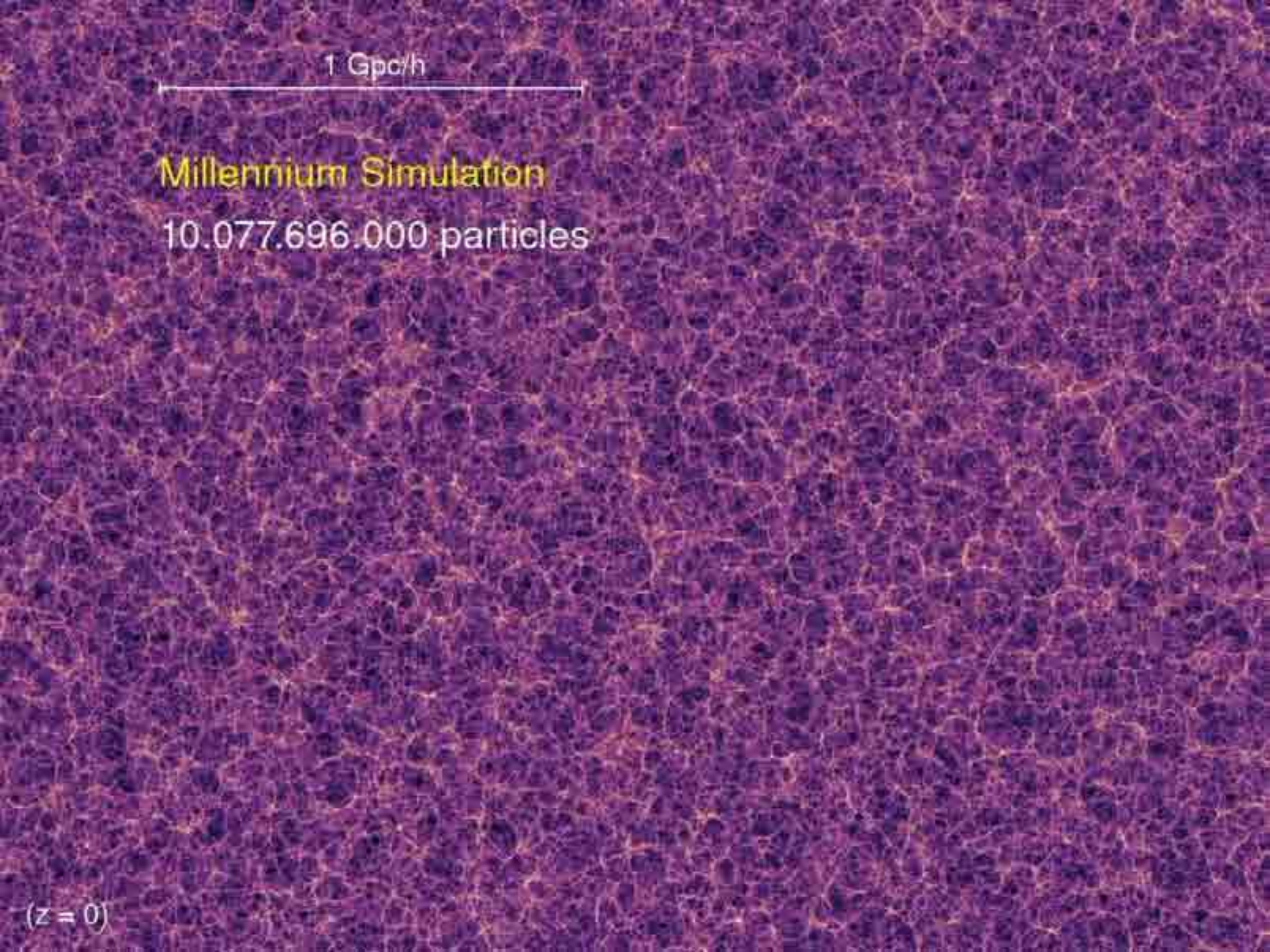


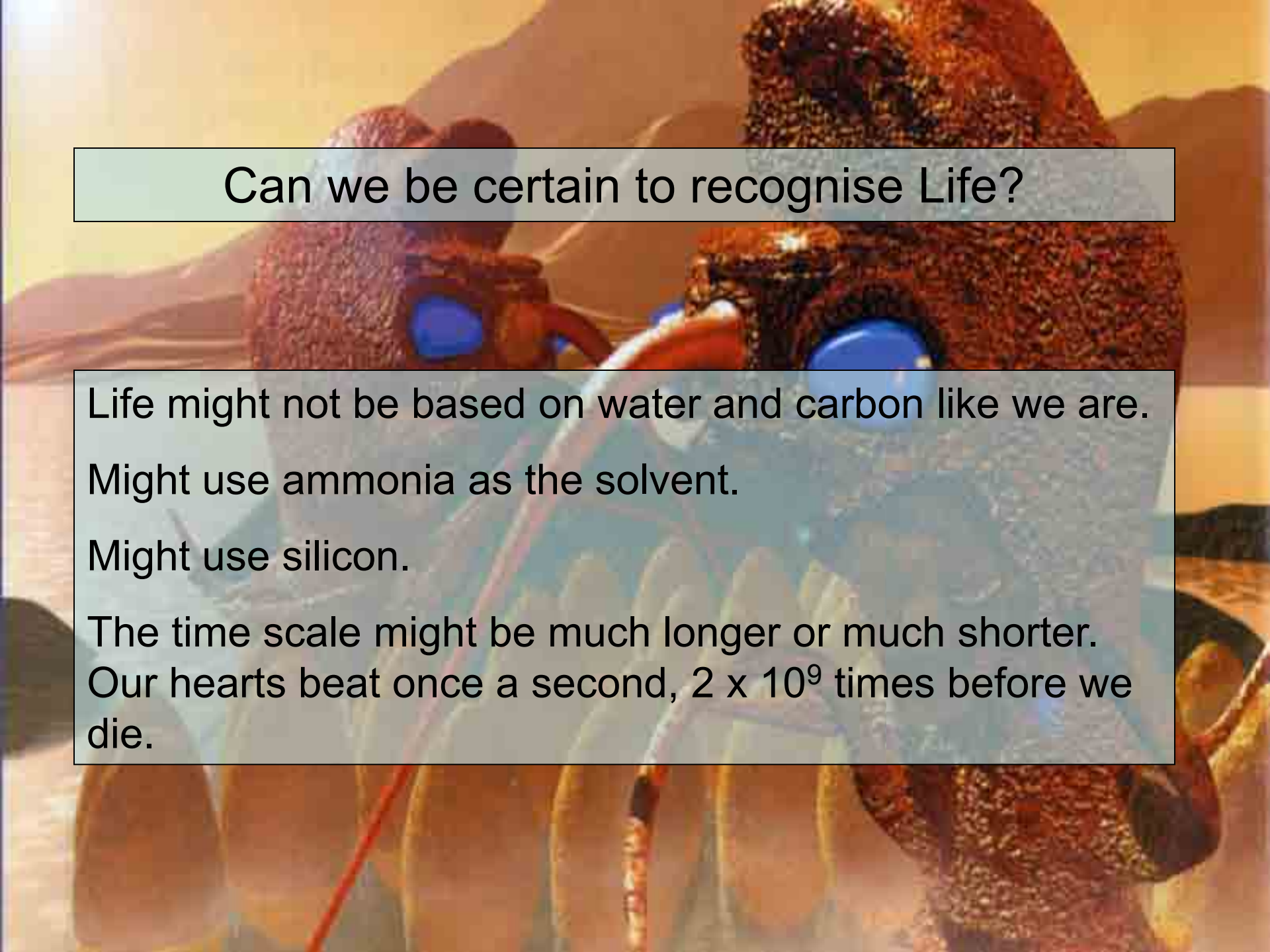


Fan et al. 2002

the challenge

- How, from a ‘beginning’ described by a few parameters, did our Universe evolve into its present complexity?
- Can we understand, at a deeper level, why our Universe is the way it is?


1 Gpc/h
Millennium Simulation
10.077.696.000 particles
(z = 0)



Can we be certain to recognise Life?

Life might not be based on water and carbon like we are.

Might use ammonia as the solvent.

Might use silicon.

The time scale might be much longer or much shorter. Our hearts beat once a second, 2×10^9 times before we die.

FLUCTUATION AMPLITUDE

$$Q \cong 10^{-5}\left(\sim \frac{\Delta T}{T}\right)$$

→ Bound Systems* with Gravitational Binding Energy QMc^2
(Virial Velocity $Q^{1/2}c$)

Max Non-:Linear Scale

→ $Q^{1/2}$ x (Hubble Radius).

*Formation of Bound System Requires Expansion Factor of >~ Q^{-1} After System Enters Horizon.

AN ANAEMIC UNIVERSE ($Q = 10^{-6}$)

Small loosely-bound galaxies form later than in our universe; star formation is still possible, but processed material is likely to be expelled from shallow potential wells. There may be no second-generation stars containing heavy elements, and so no planetary systems at all.

If Q were significantly lower than 10^{-6}, then gas would be unable to cool with a Hubble time.*

In a Λ-dominated universe, isolated clumps could survive for an infinite time without merging into a larger scale of hierarchy. So eventually, for any $Q > 10^{-8}$, a 'star' could form – but by that time there would be merely one minihalo within the entire event horizon!

UNIVERSE WITH $Q > 10^{-3}$

Monster overdensities (up to 10^{18} $M_{\odot}$) condense out early enough that they trap the CMB radiation, and collapse as radiation-pressure-dominated hypermassive objects unable to fragment*. This leads to universe of vast holes, clustered on scales up to several percent of Hubble radius (and probably pervaded by intense ‘hard’ radiation).

It isn’t obvious that much baryonic material would ever go into stars. (If so they would be in very compact highly bound systems.)

**This does not require pre-combination collapse. Collapse at (say) 10^7 years would lead to sufficient partial reionization (via strong shocks) to recouple the baryons and CMB.*

POSSIBLE UNIVERSE WITH $Q = 10^{-4}$

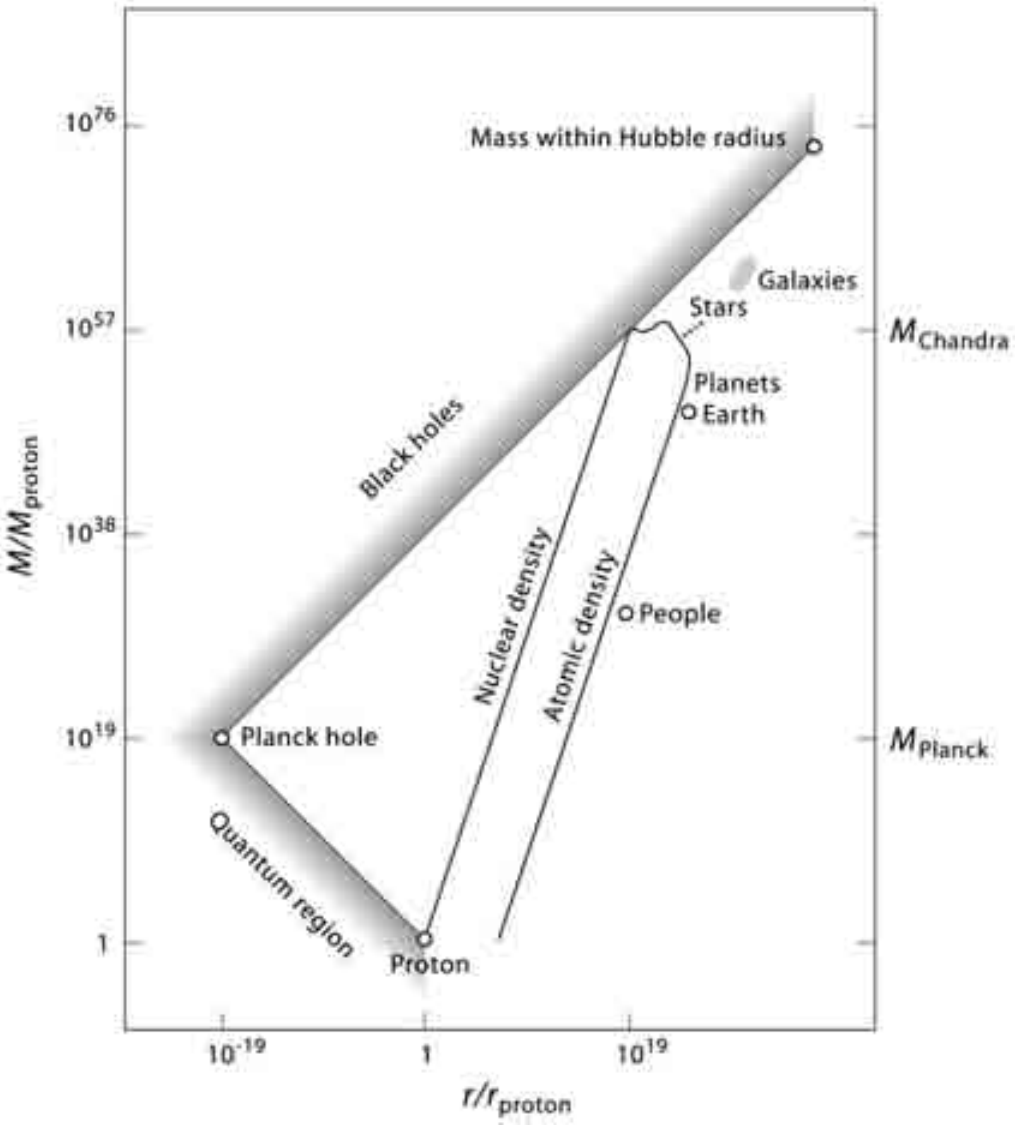
**perhaps more interesting than ours!*

Masses $>\sim 10^{14}\ M_{\odot}$ condense at 3.10^{8} yrs into huge disc galaxies with orbital velocity ~2000 km/sec (gas would cool efficiently via Compton cooling, leading probably to efficient star formation).

These would, after 10^{10} yrs, be in clusters of

$$>\sim 10^{16}\ M_{\odot}.$$

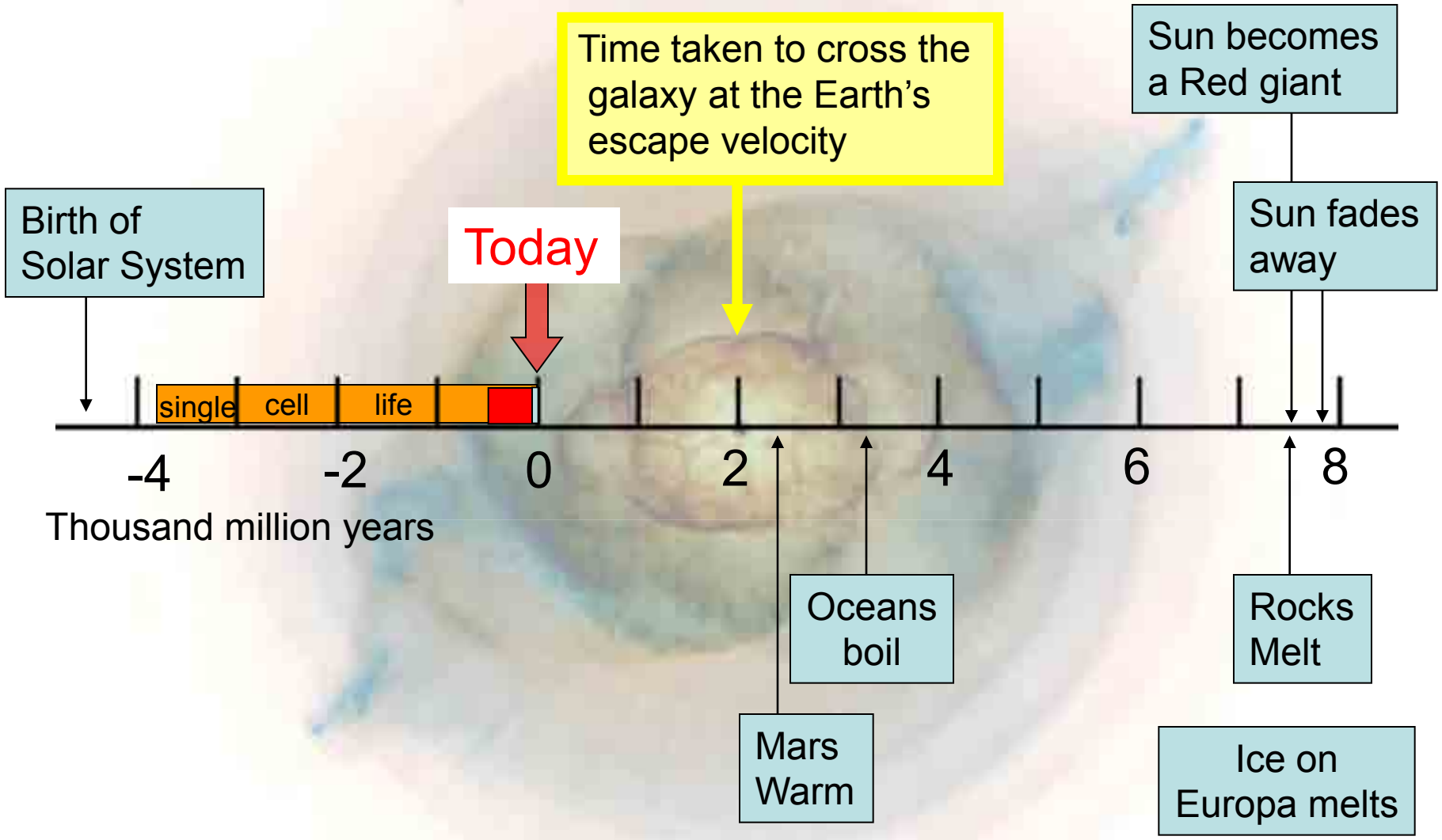
There would be a larger range of non-linear scales than in our actual universe. Only possible 'disfavouring' feature is that stellar systems may be too packed together to permit unperturbed planetary orbits.

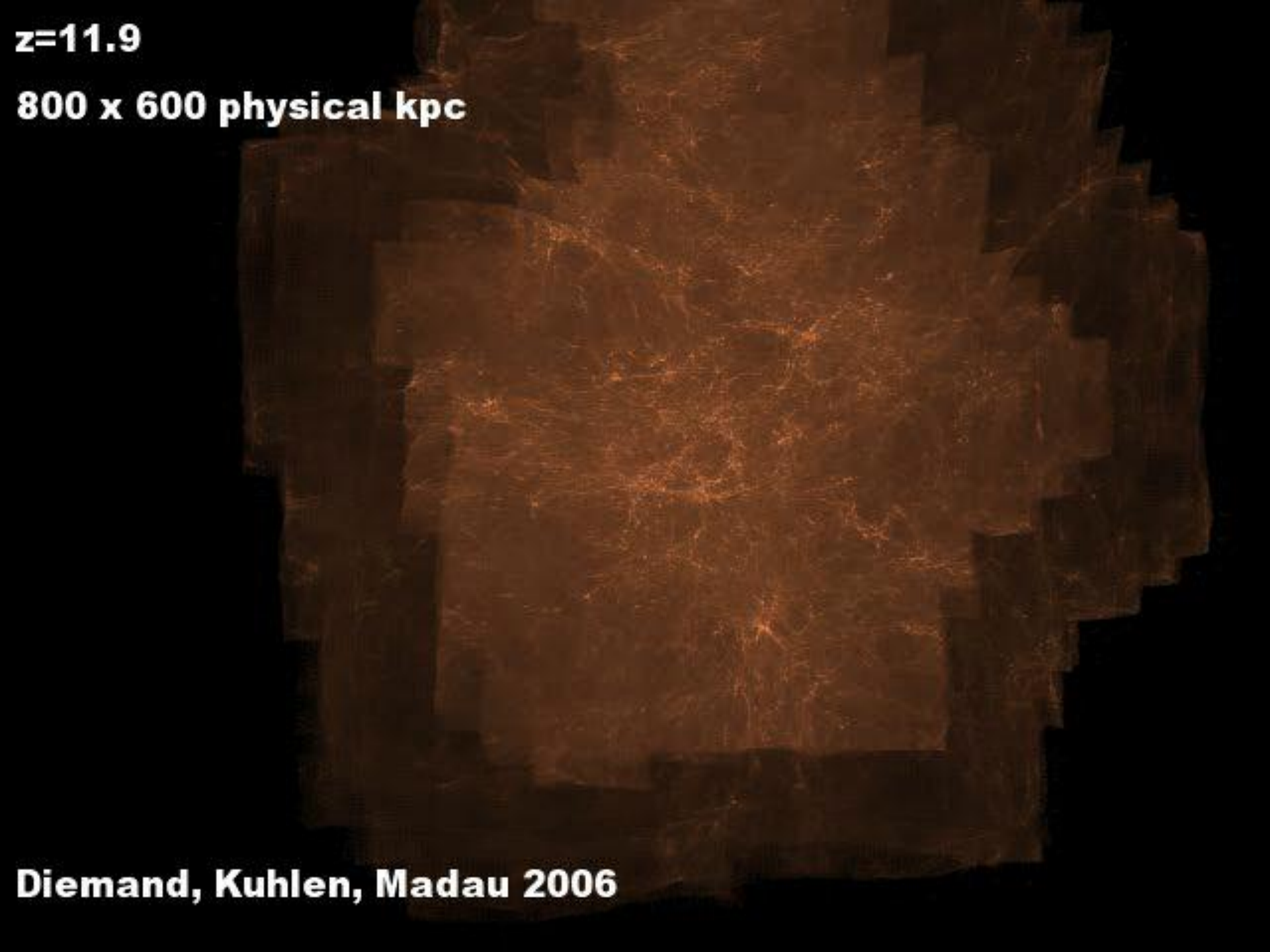

10^{76}
10^{57}
10^{38}
10^{19}
1
M/M_{proton}
Mass within Hubble radius
Galaxies
Stars
$M_{Chandra}$
Planets
Earth
Black holes
Nuclear density
Atomic density
People
Planck hole
M_{Planck}
Quantum region
Proton
10^{-19}
1
10^{19}
r/r_{proton}

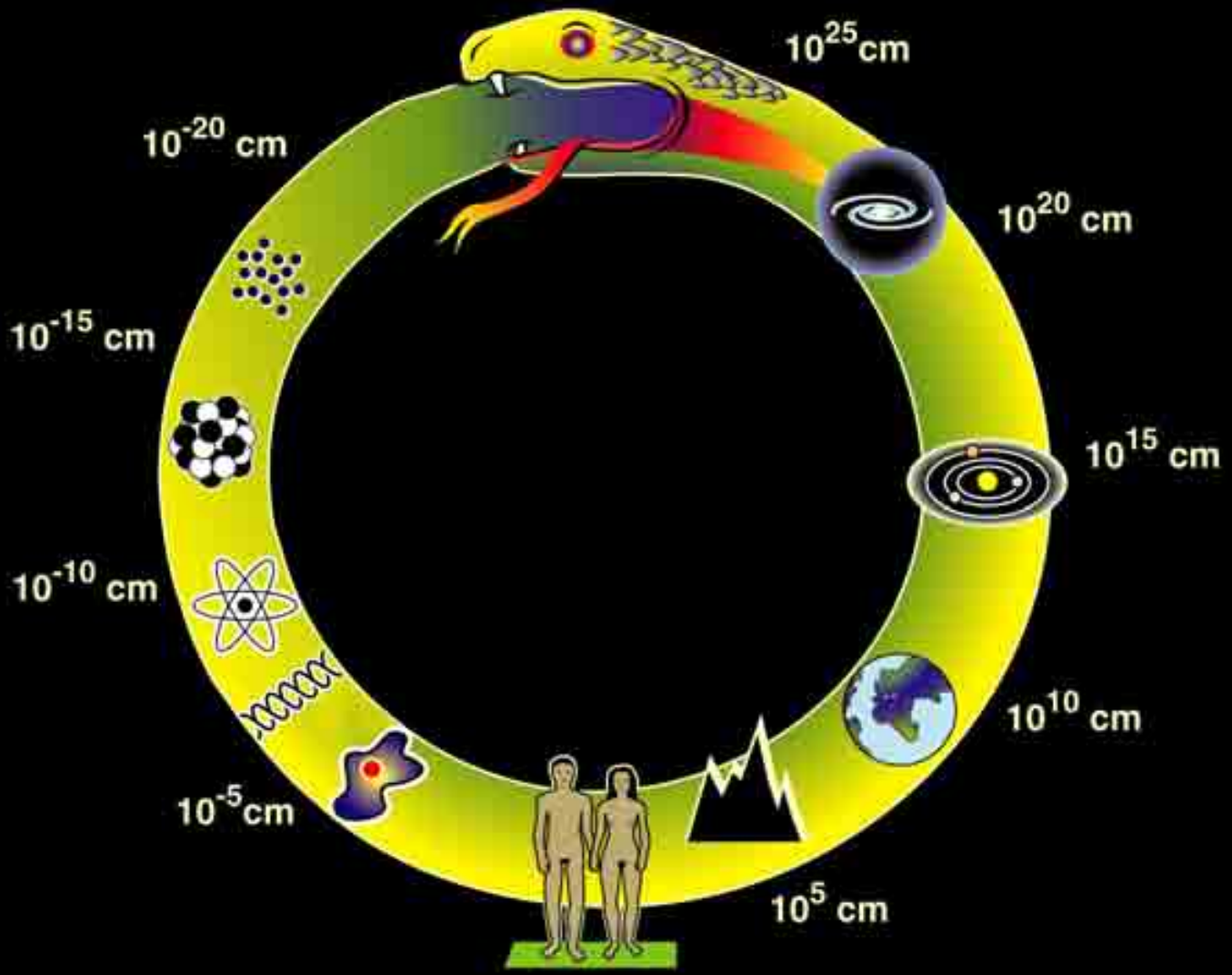
the challenges

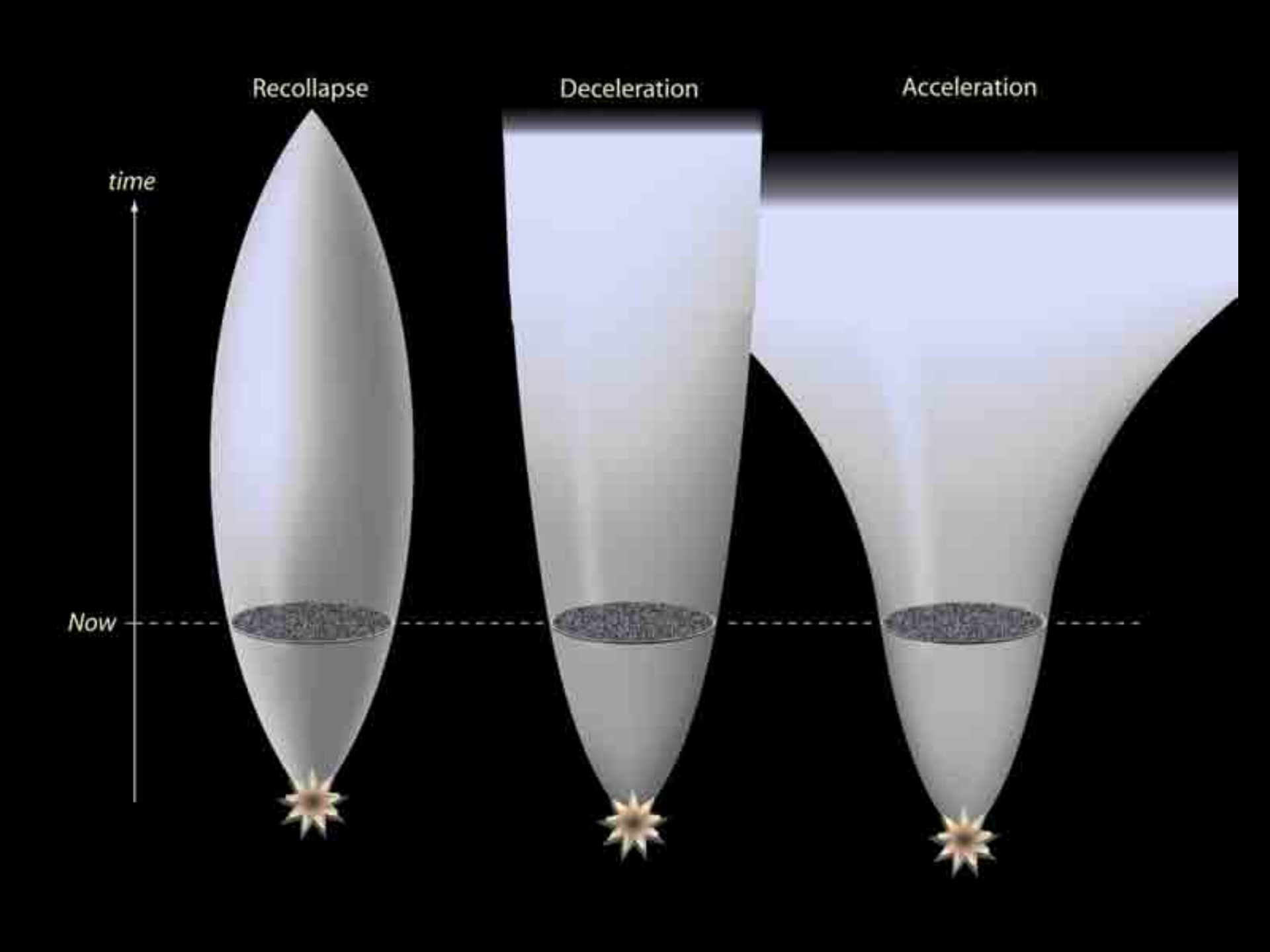
- What is out there? Cosmic exploration.
- Interpreting phenomena in terms of known (and perhaps ‘new’) physics.
- How, from a ‘simple beginning’, did our Universe evolve into its present complexity (stars, planets, people)?
- Can we understand, at a deeper level, why our Universe is the way it is?

The Past and Future of Life on Earth




z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

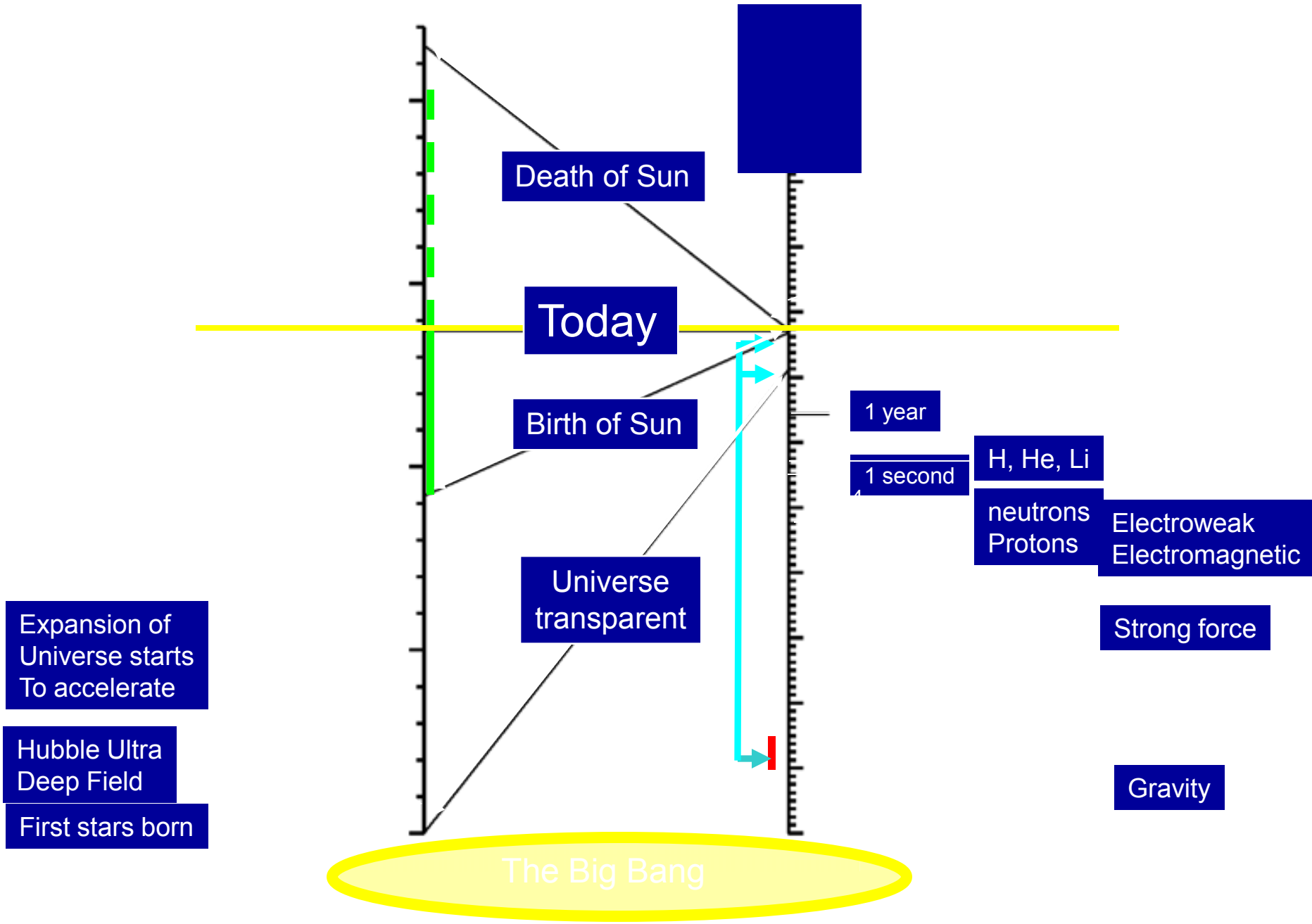

10^{25}cm
10^{20} cm
10^{15} cm
10^{10} cm
10^{5} cm
10^{-5}cm
10^{-10} cm
10^{-15} cm
10^{-20} cm

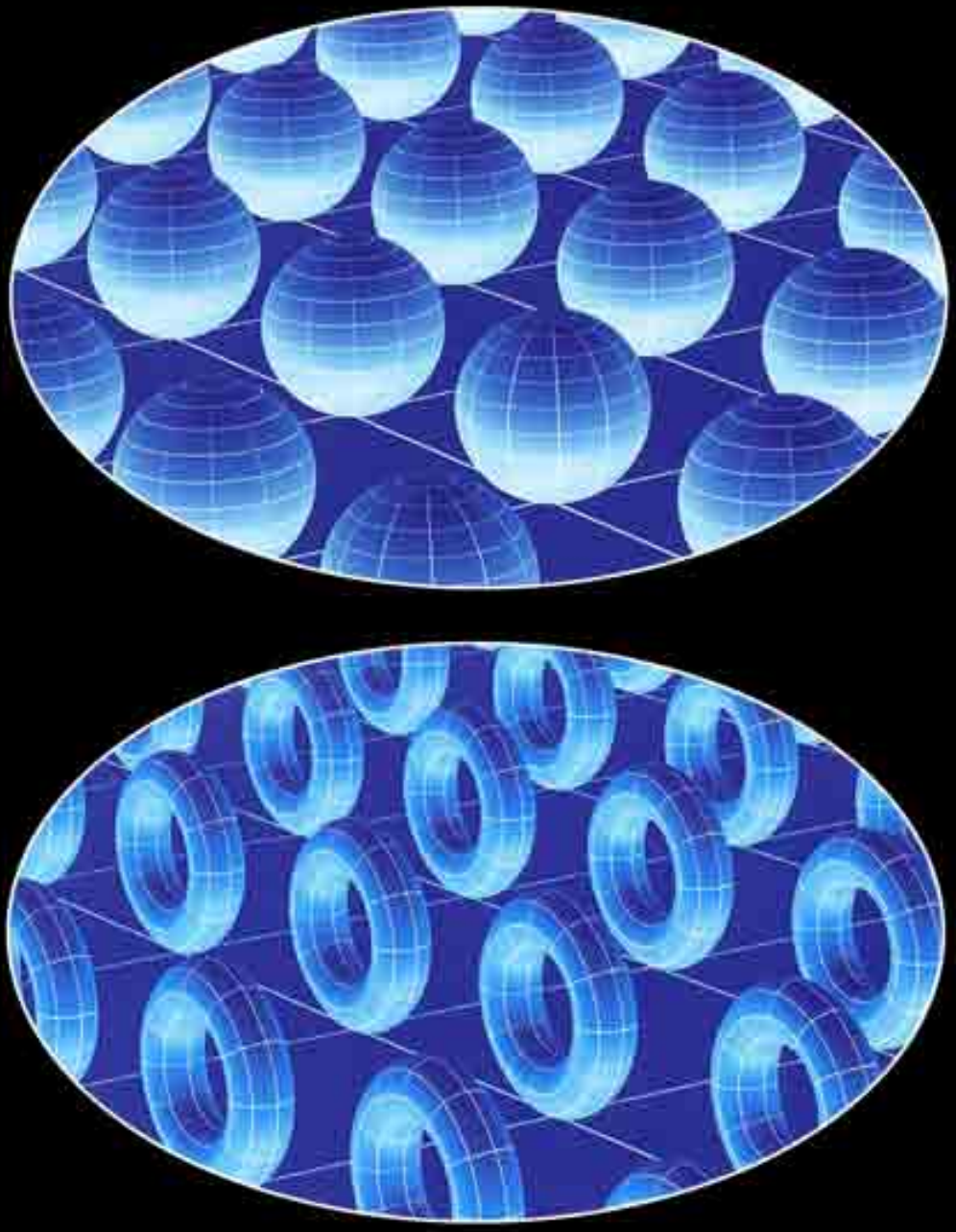

Recollapse
Deceleration
Acceleration
time
Now

Obviously, at the present time we have more than enough to do in order to understand how the world works the way we find it. But I think ***one must have at least a modicum of curiosity about the strange dimensionless numbers that appear in physics.***

There seem to be ***two lines of attack*** on questions such as these, the ***first*** to demonstrate that the precise numerical values of the dimensionless ***numbers are all entirely necessary to the logical consistency of physics***. The ***second*** point of view is that some, if not all, of the numbers in question are fluctuations; that in ***other places of the universe their values would be different. My inclination is to favour this second point of view. On this second basis the curious placing of the levels in C^{12} and O^{16} need no longer have the appearance of astonishing accidents***. It could simply be that since creatures like ourselves depend on a balance between carbon and oxygen, we can exist only in the portions of the universe where these levels happen to be correctly placed. In other places the level in O^{16} might be a little higher, so that the addition of α-particles to C^{12} was highly resonant. In such a place oxygen would be overwhelmingly more abundant than carbon, and creatures like ourselves could not exist.

Hoyle "Galaxies, Nuclei & Quasars" 1968


Death of Sun
Today
Birth of Sun
Universe transparent
1 year
1 second
H, He, Li
neutrons
Protons
Electroweak
Electromagnetic
Strong force
Gravity
Expansion of Universe starts To accelerate
Hubble Ultra Deep Field
First stars born
The Big Bang



Gliese 581, distance 20 Ly

European Southern Observatory
Powerful ground-based instruments can spot Earth-like planets around distant stars

European Space Agency's Gorot probe
Already in orbit and expected to discover hundreds of new planets

Earth to aliens: we know where you live

Last week a planet with all the properties for sustaining life was found, and more are on the way, says **Jonathan Leake**

Just a few years ago the search for alien life was the stuff of science fiction – the domain of writers, film makers and conspiracy theorists.

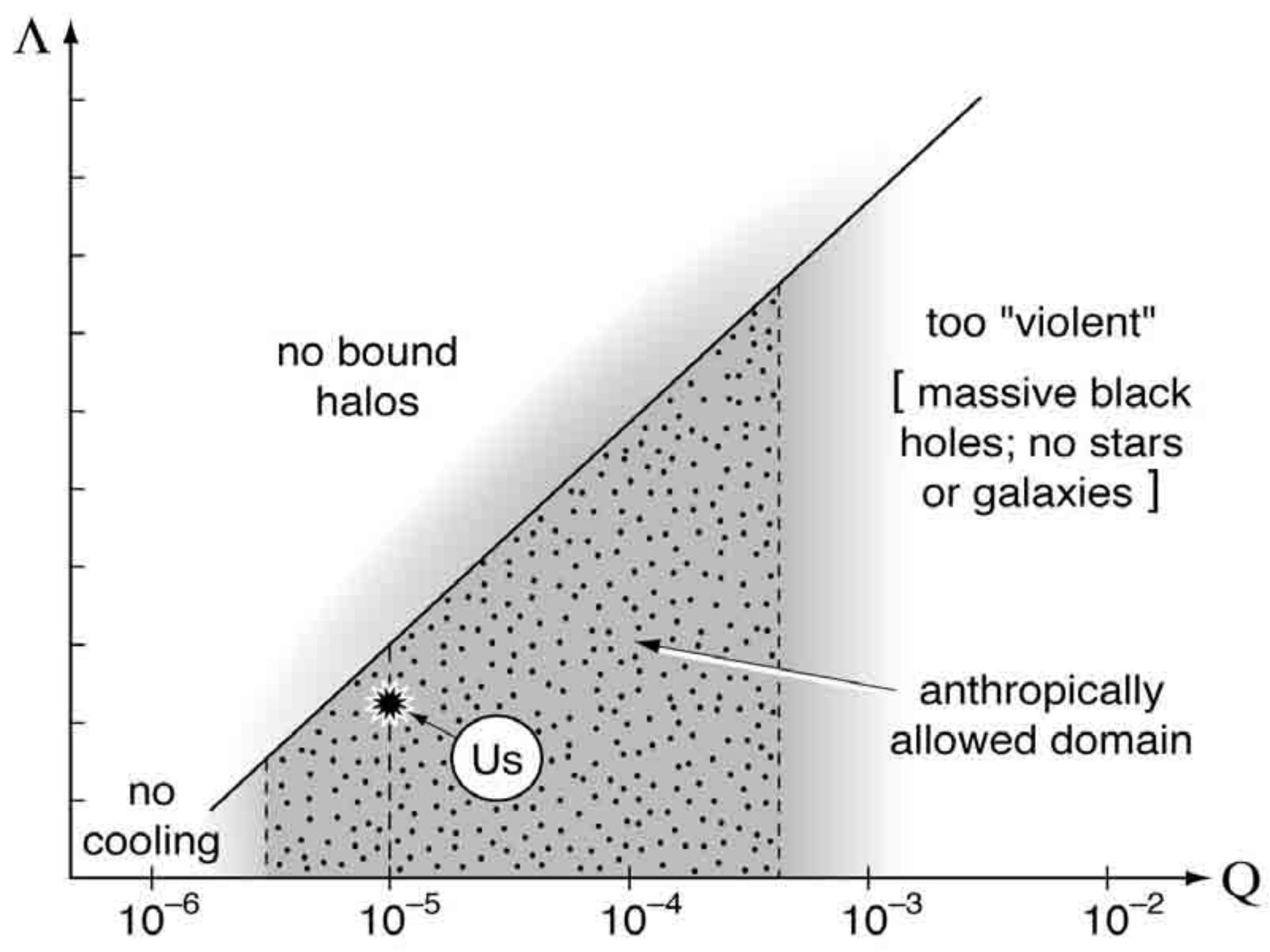
This weekend, however, in a house in Berkhamsted, Hertfordshire, two of Europe's leading astronomers are finalising plans to turn that search into reality.

Glenn White and Malcolm Fridlund are the lead scientists for the Darwin mission, a space telescope so powerful that it would be able to spot distant planets, take photographs of them and even analyse their atmospheres for the telltale gases that indicate life.

For the past 10 years they and a team of astronomers around Europe have been perfecting the designs for Darwin. They are now collating that work into a formal proposal for the European Space Agency (ESA), which has already indicated it wants to adopt it as the centrepiece of Europe's space research programme for the next decade.

"What we will be looking for is no less than life itself," said White, professor of astronomy at the Open University. "The Darwin mission will be able to look at stars up to 100 light years away and see if the planets orbiting around them have evolved life."

ESA's plans by Darwin come at one of the most exciting times for planet hunters. In the past 12 years this specialised group of astronomers has found more than 220 planets orbiting other suns in it and its ability


Λ
no bound halos
too "violent"
[massive black holes; no stars or galaxies]
anthropically allowed domain
Us
no cooling
Q
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}

What do we mean by life?

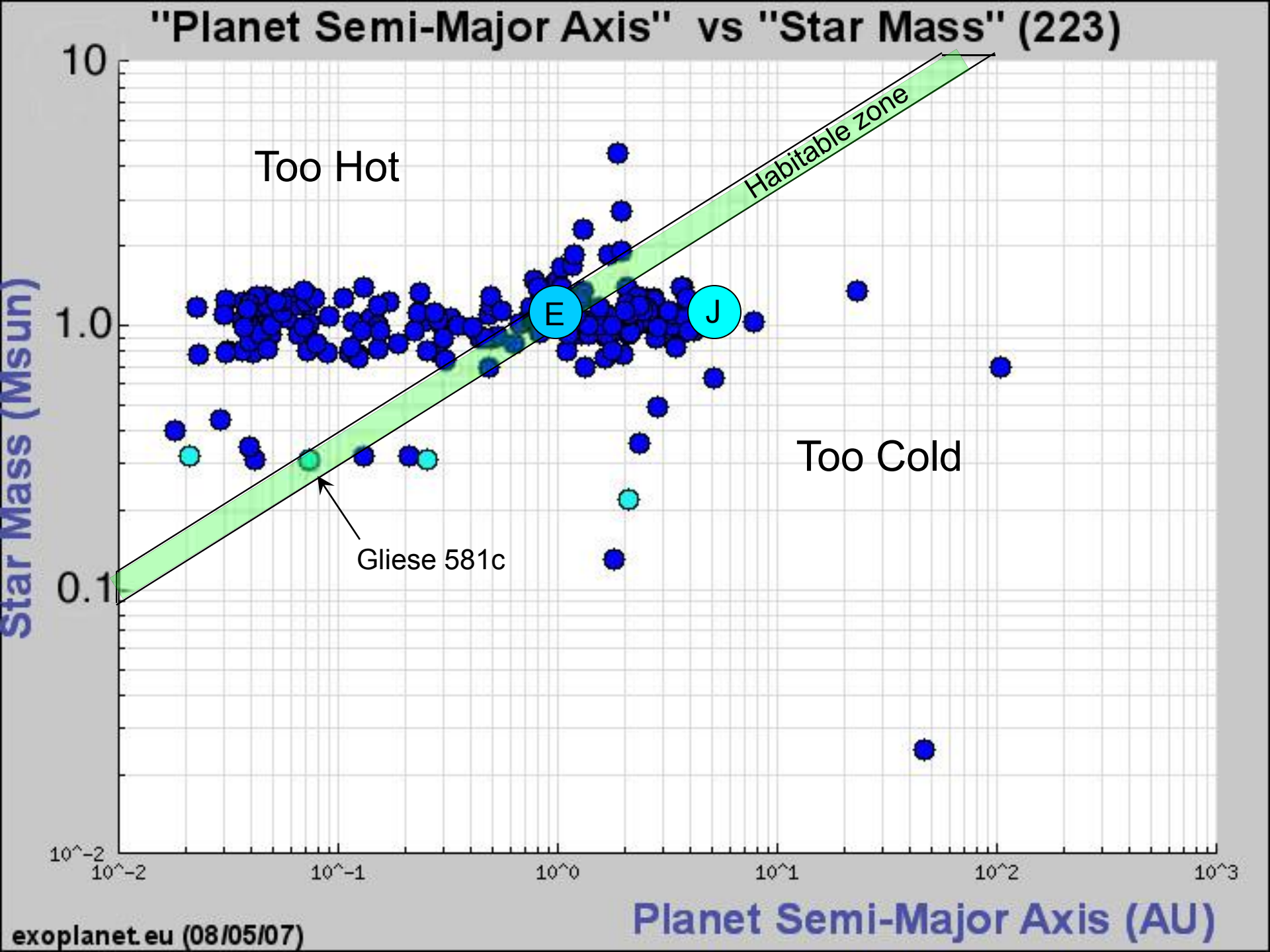
Single-celled

Multi-celled

Conscious

Communicating

Technologically advanced


"Planet Semi-Major Axis" vs "Star Mass" (223)
Too Hot
Habitable zone
E
J
Too Cold
Gliese 581c
10
1.0
0.1
10^-2
Star Mass (Msun)
10^-2
10^-1
10^0
10^1
10^2
10^3
Planet Semi-Major Axis (AU)
exoplanet.eu (08/05/07)