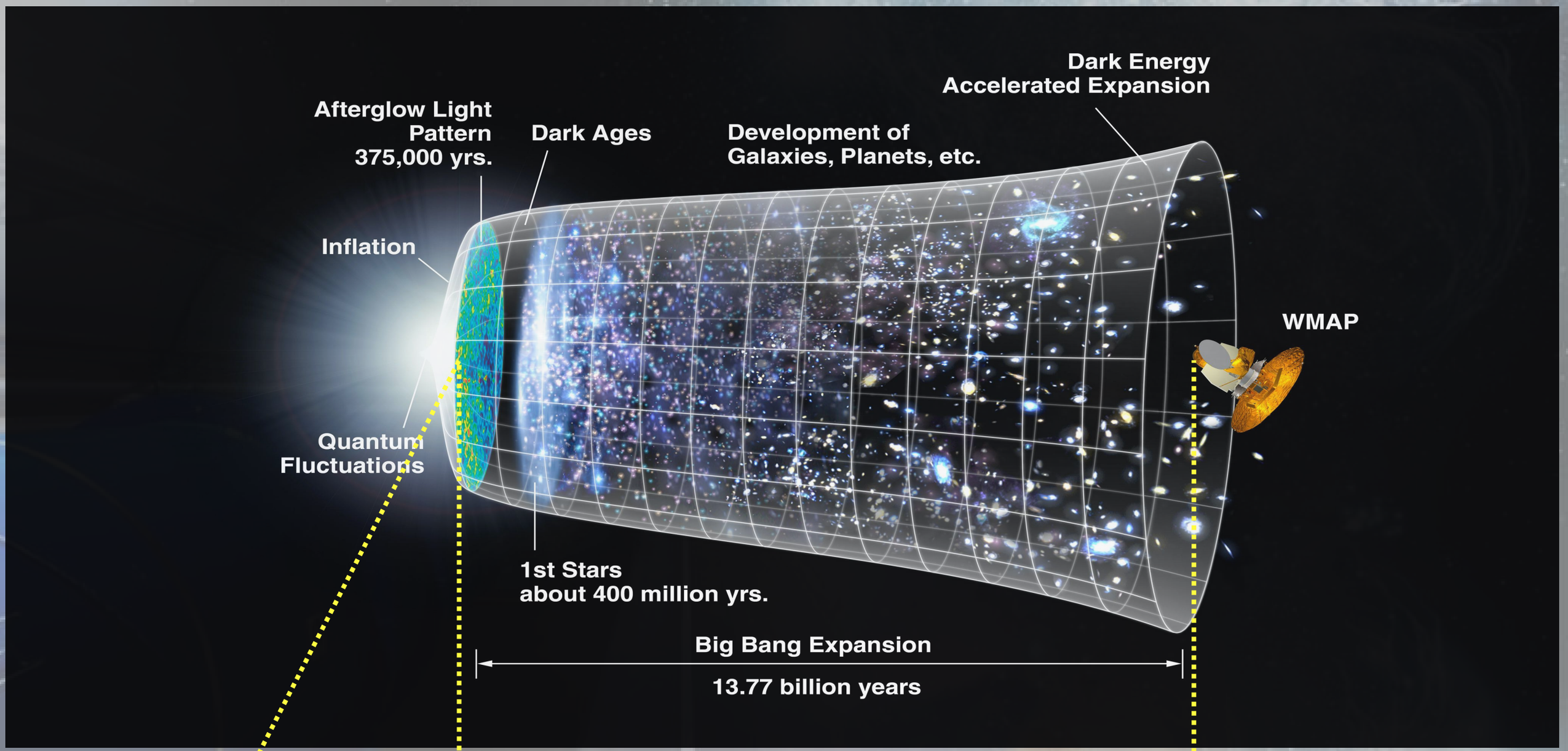
Evolution of the universe:

Latest ~13.8 billions of years...

P. Milenovic, November 2020

Evolution of the universe



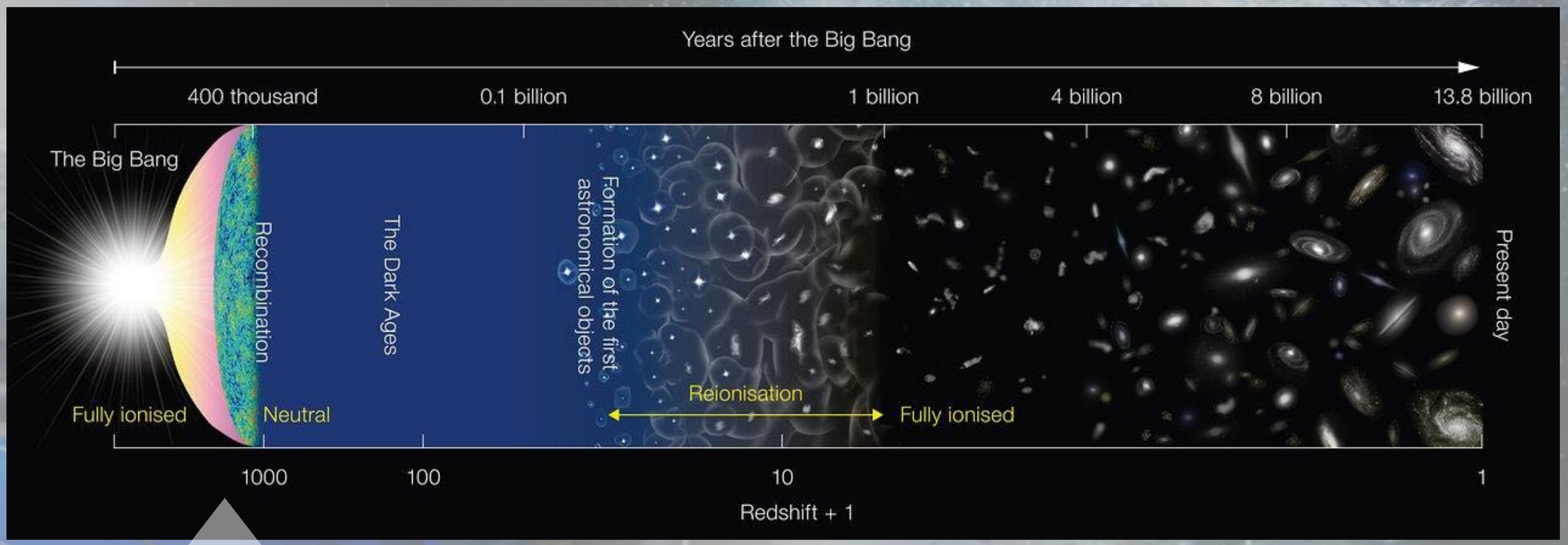
~3 min.

~13.8 billion years

talk by A.Greljo

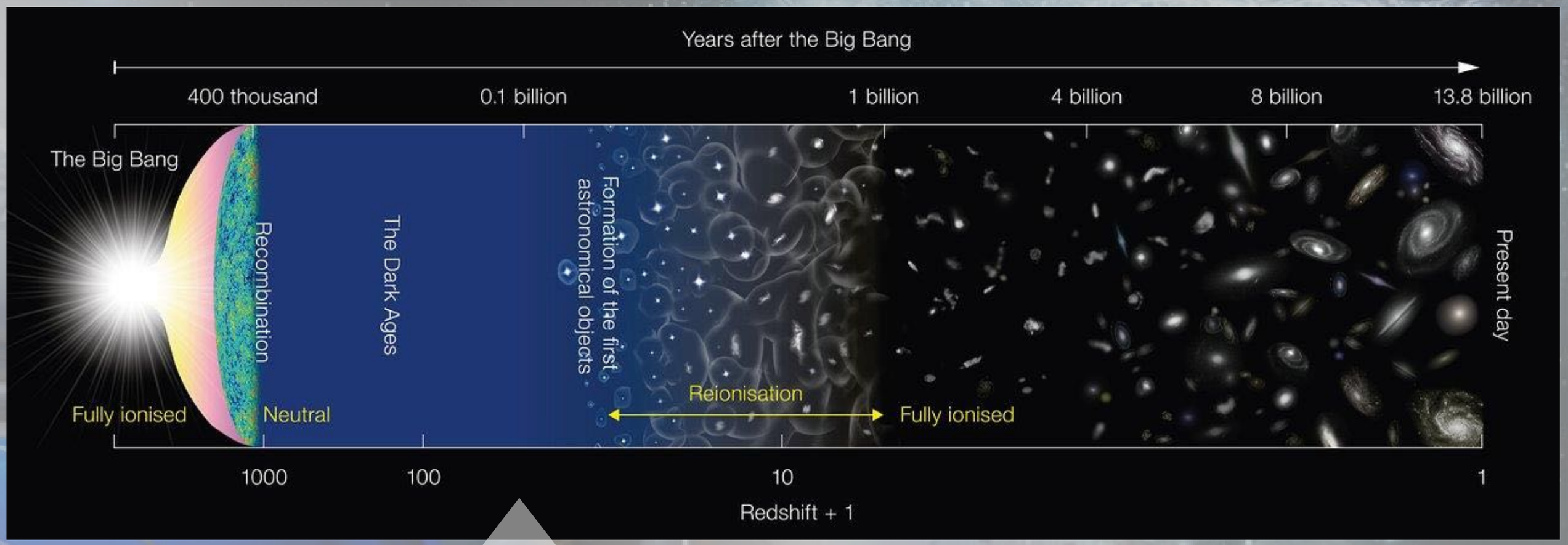
this talk...

Epochs of the universe



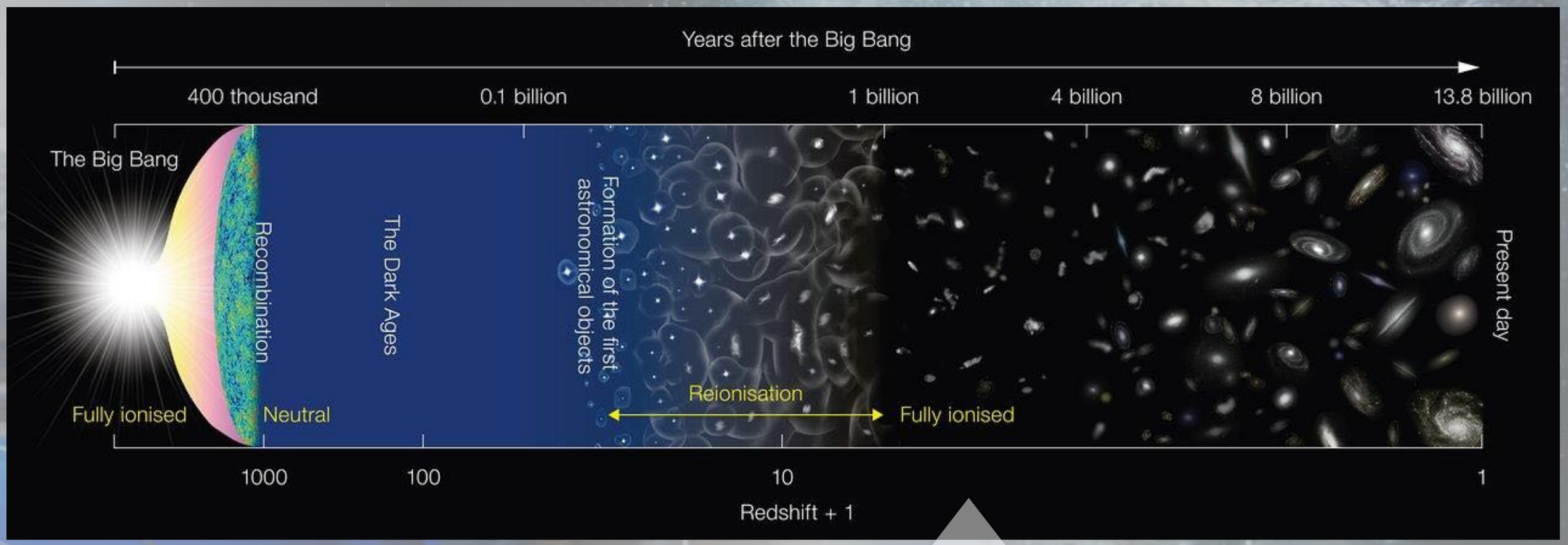
Epoch featuring transition from radiation dominance to matter dominance era, and neutral atom formation

Epochs of the universe



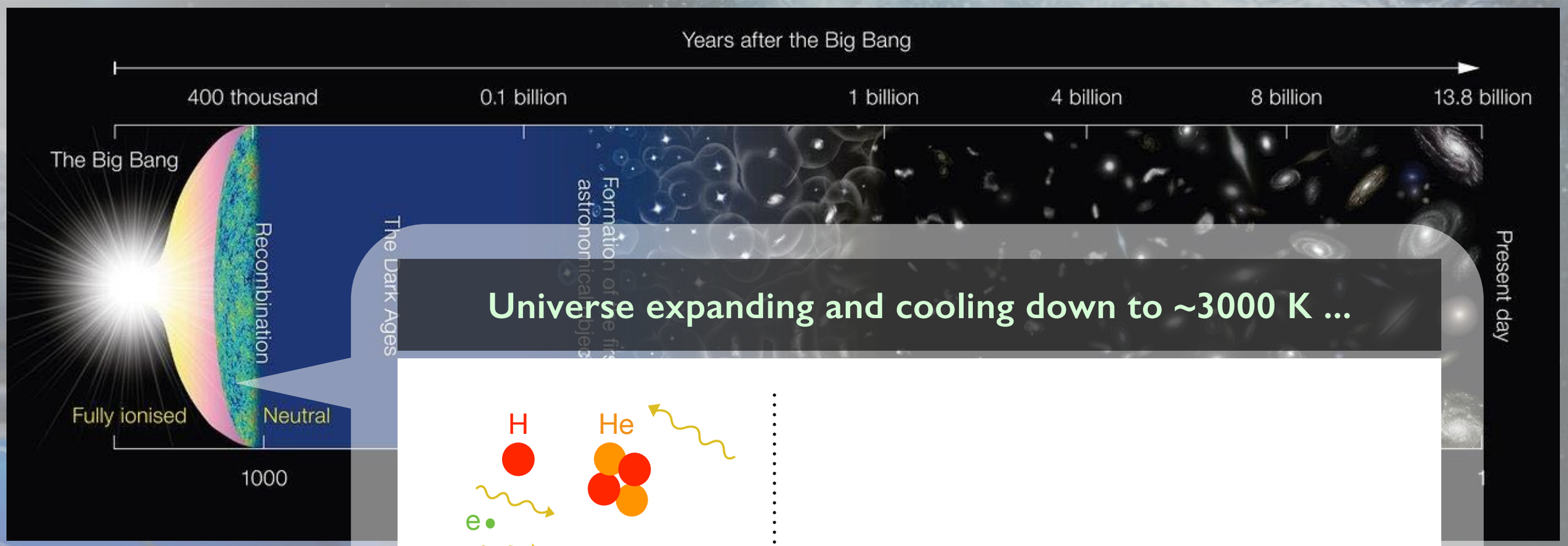
Epoch featuring matter dominance era, and formation of first astronomical objects

Epochs of the universe

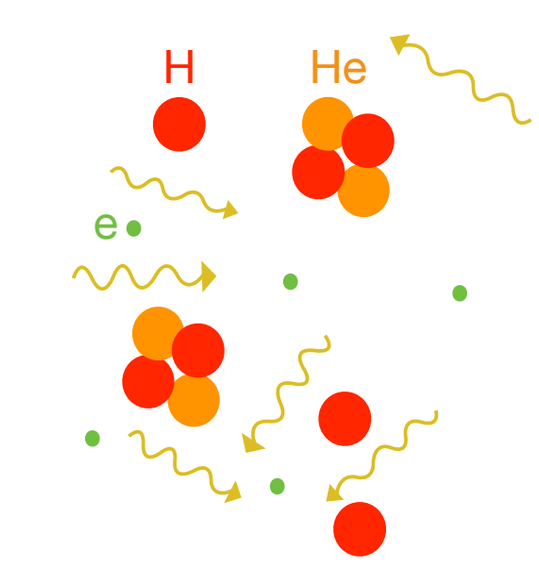


Epoch featuring formation and evolution of astronomical objects, and transition from matter dominance to dark energy dominance era

From radiation-dominated era to recombination



Universe expanding and cooling down to ~3000 K ...

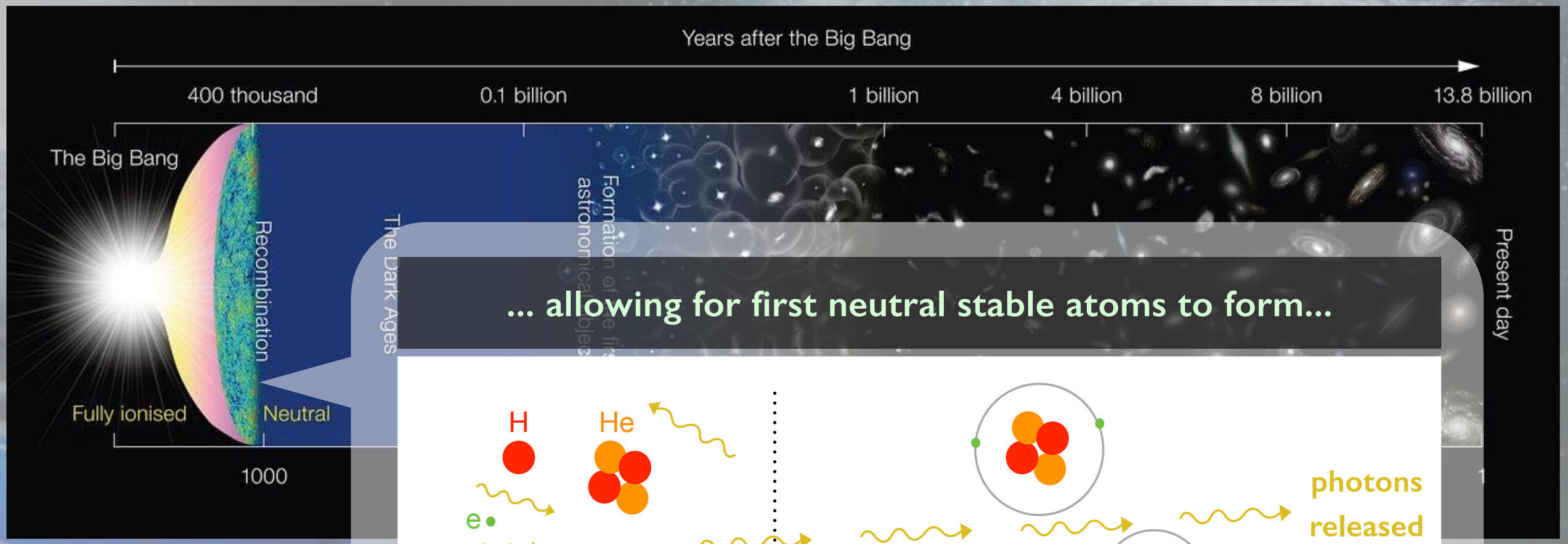


earlier — later — *time*

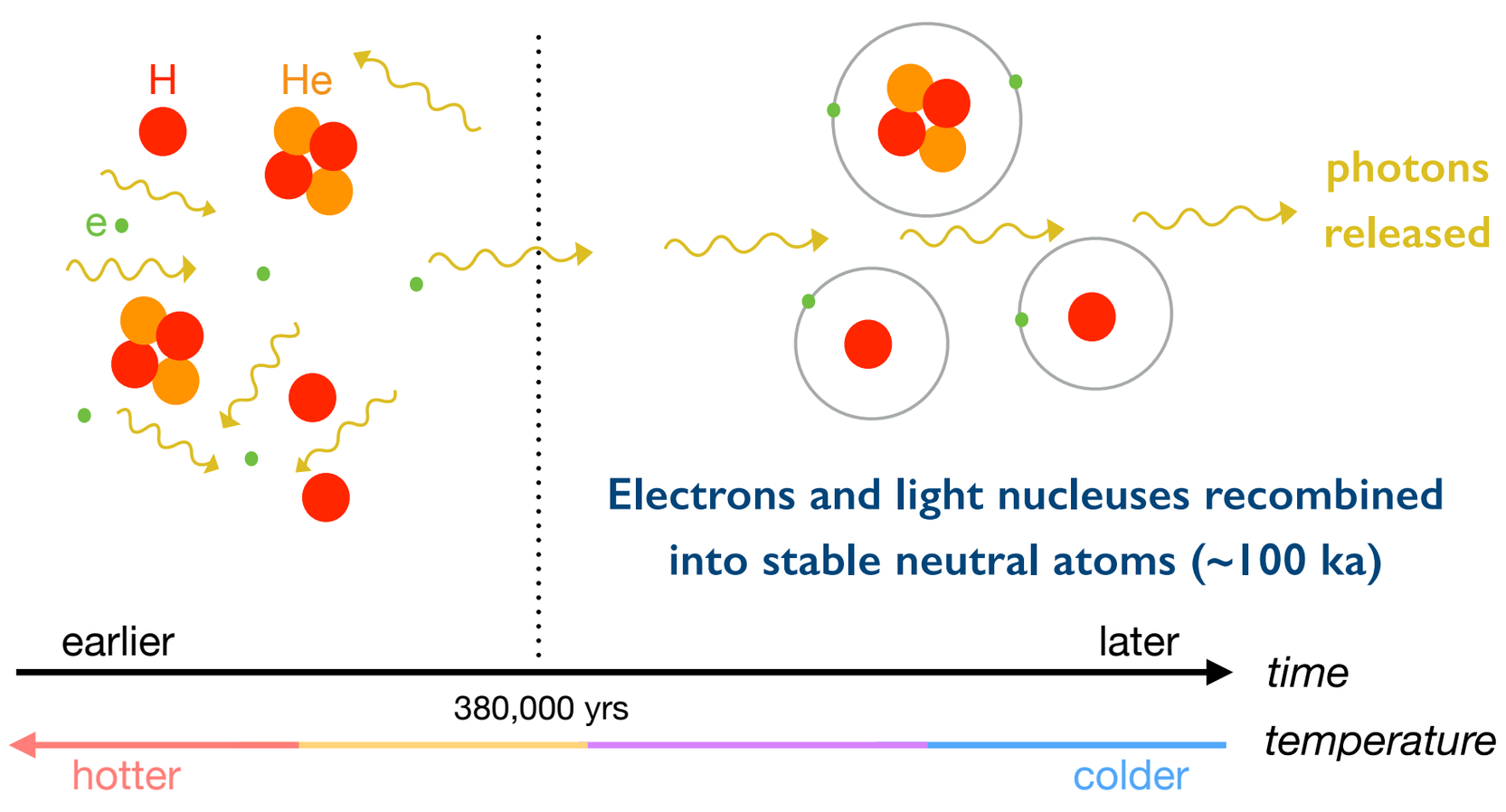
380,000 yrs

hotter — colder — *temperature*

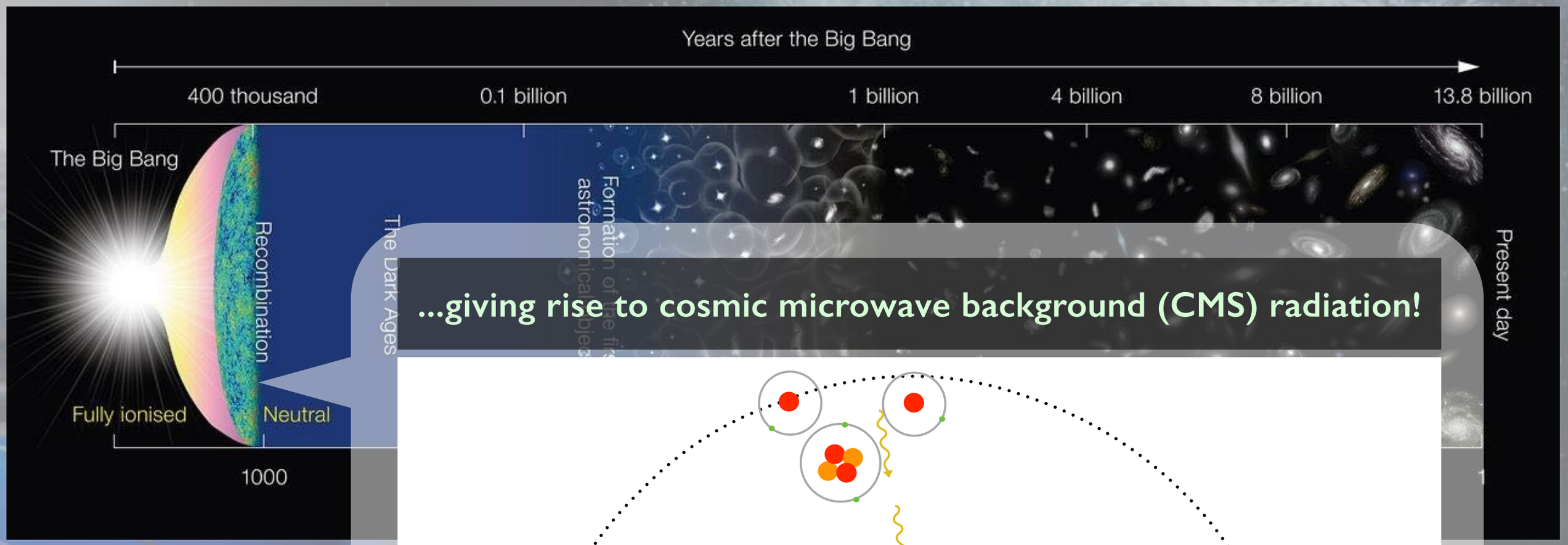
From radiation-dominated era to recombination



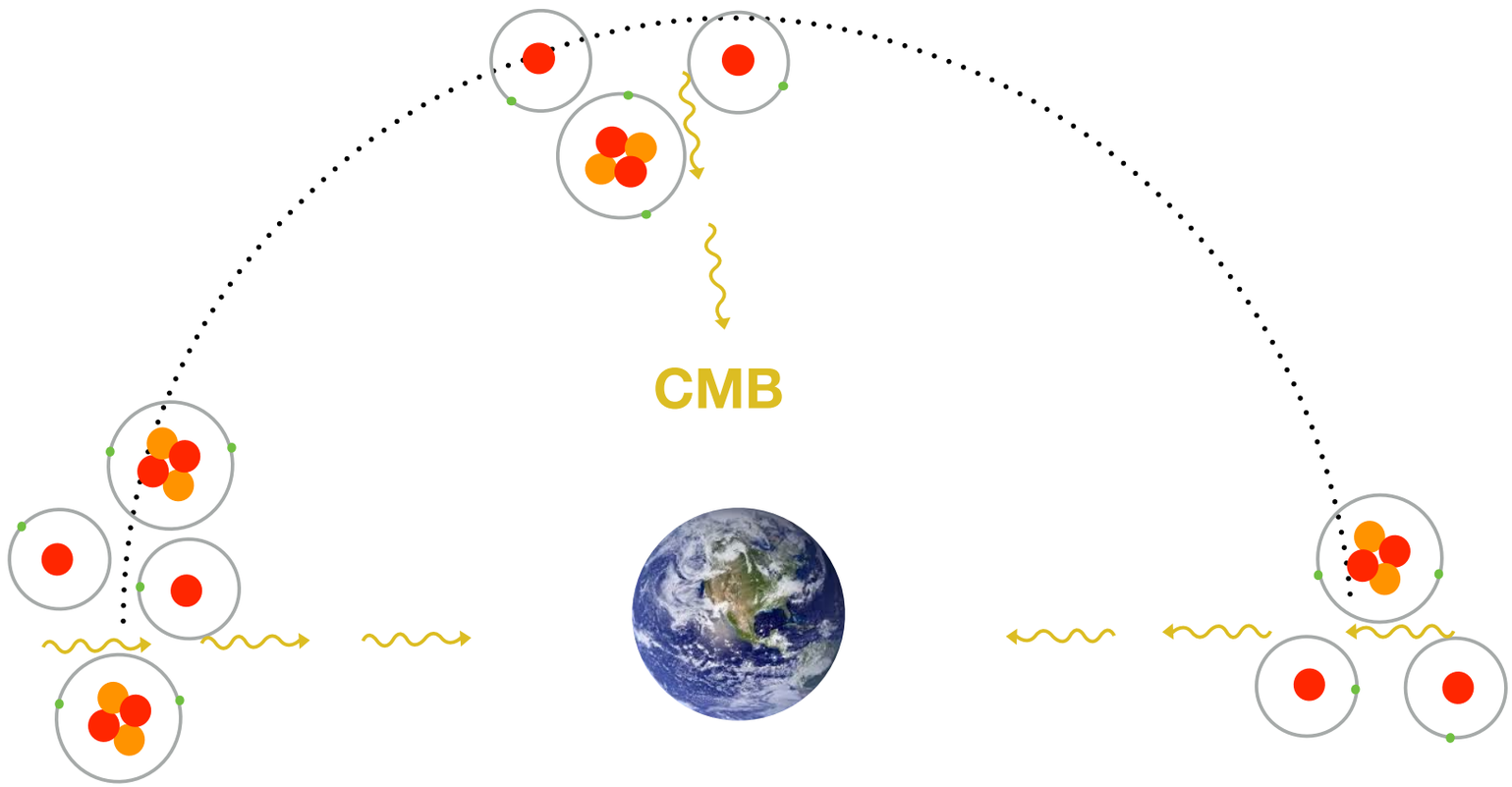
... allowing for first neutral stable atoms to form...



From radiation-dominated era to recombination

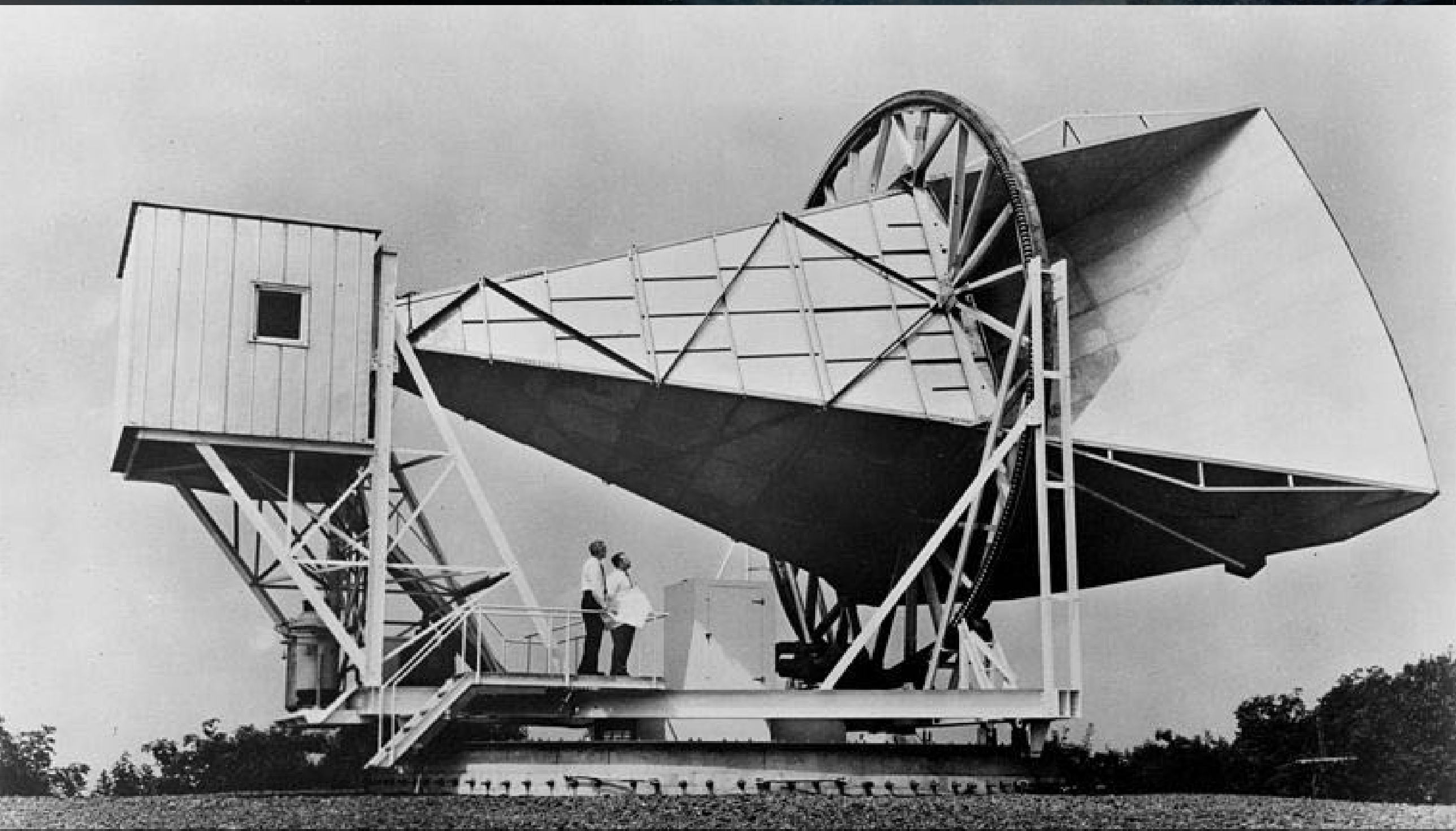


...giving rise to cosmic microwave background (CMS) radiation!



- *410 photons per cubic centimeter*
- *cooled by the expansion: 2.7 K*

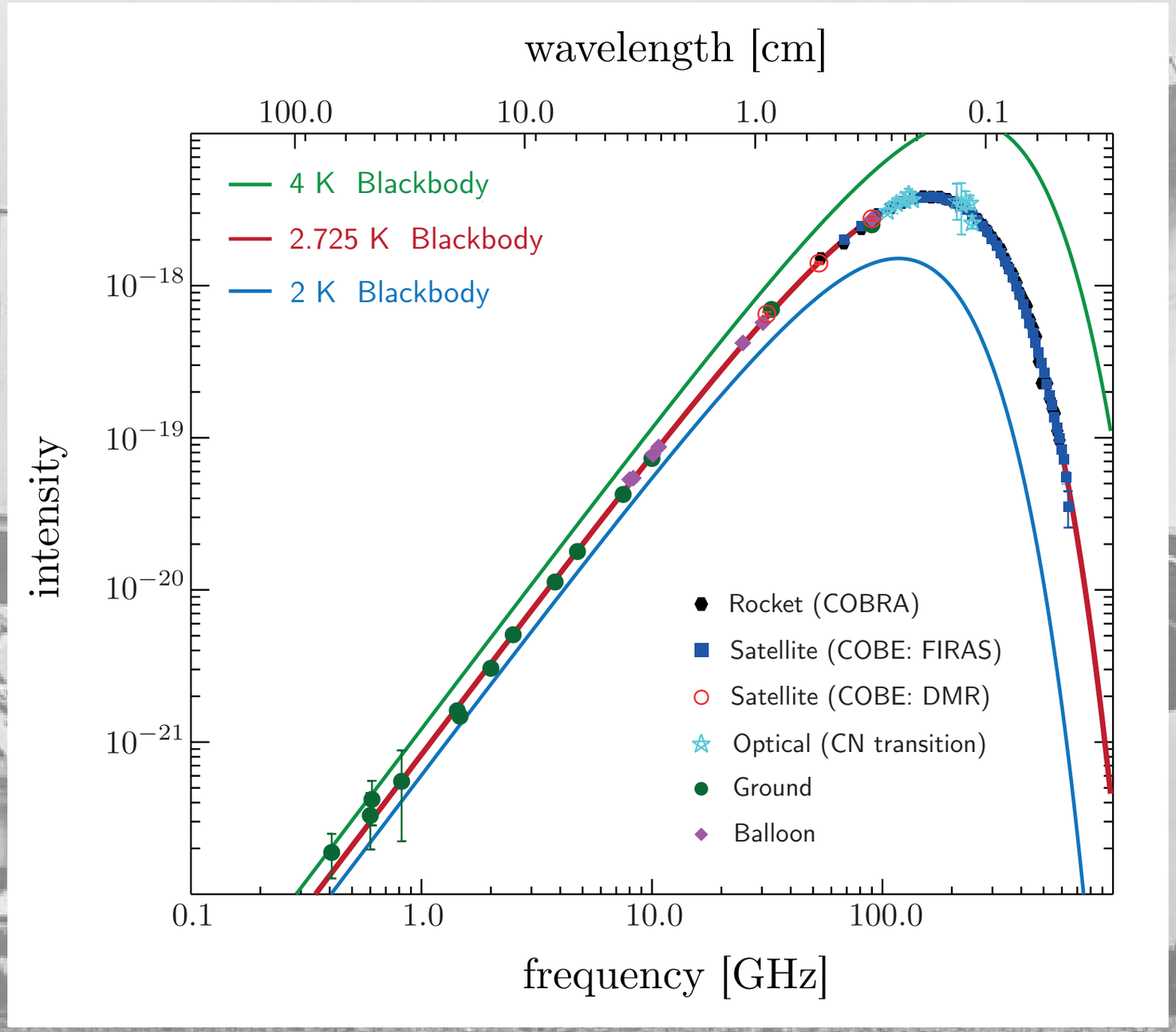
Afterglow of the Big Bang



Penzias & Wilson discovered the Cosmic Microwave Background (CMB) in 1965

Afterglow of the Big Bang

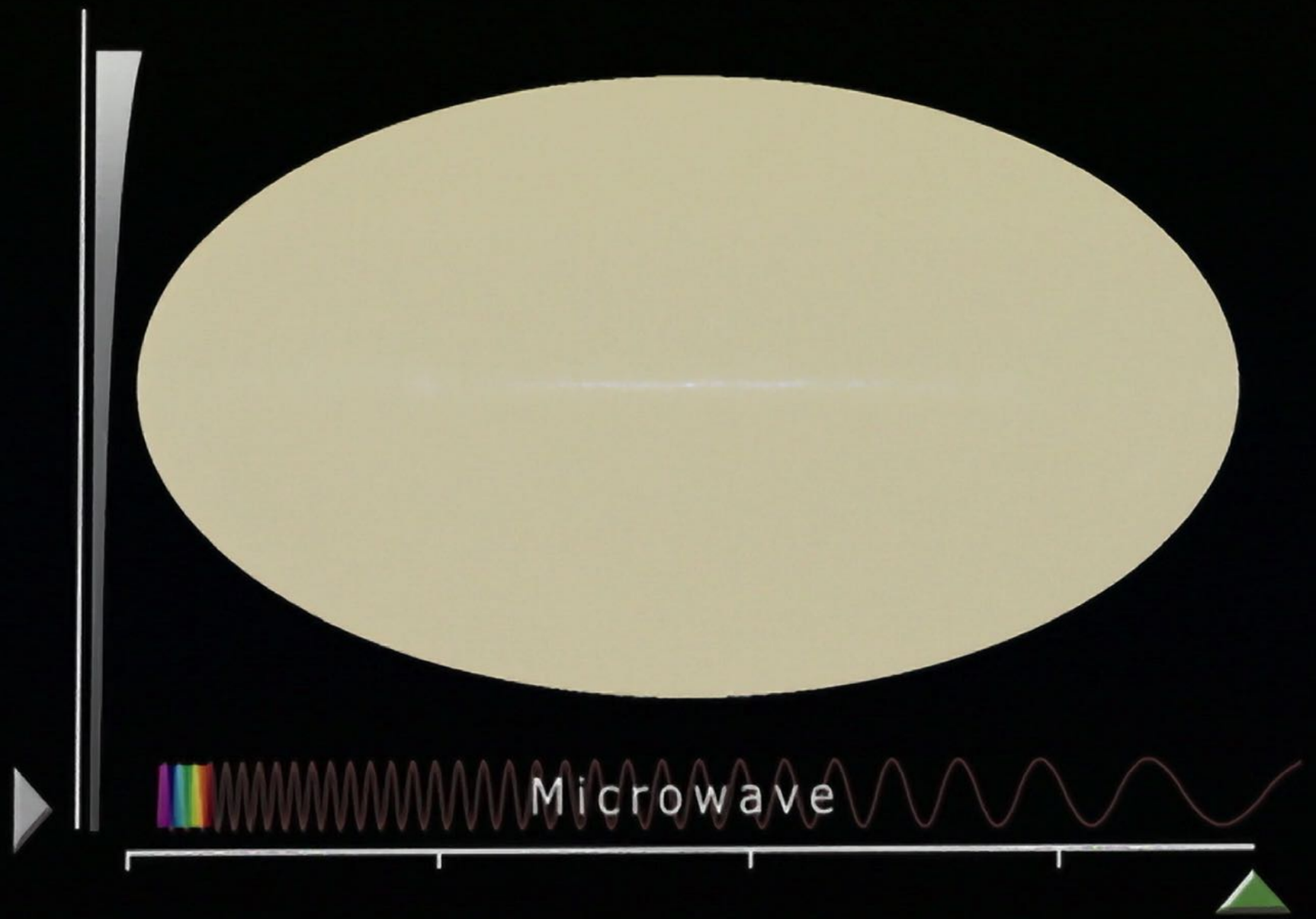
They found is the most perfect blackbody spectrum in Nature...



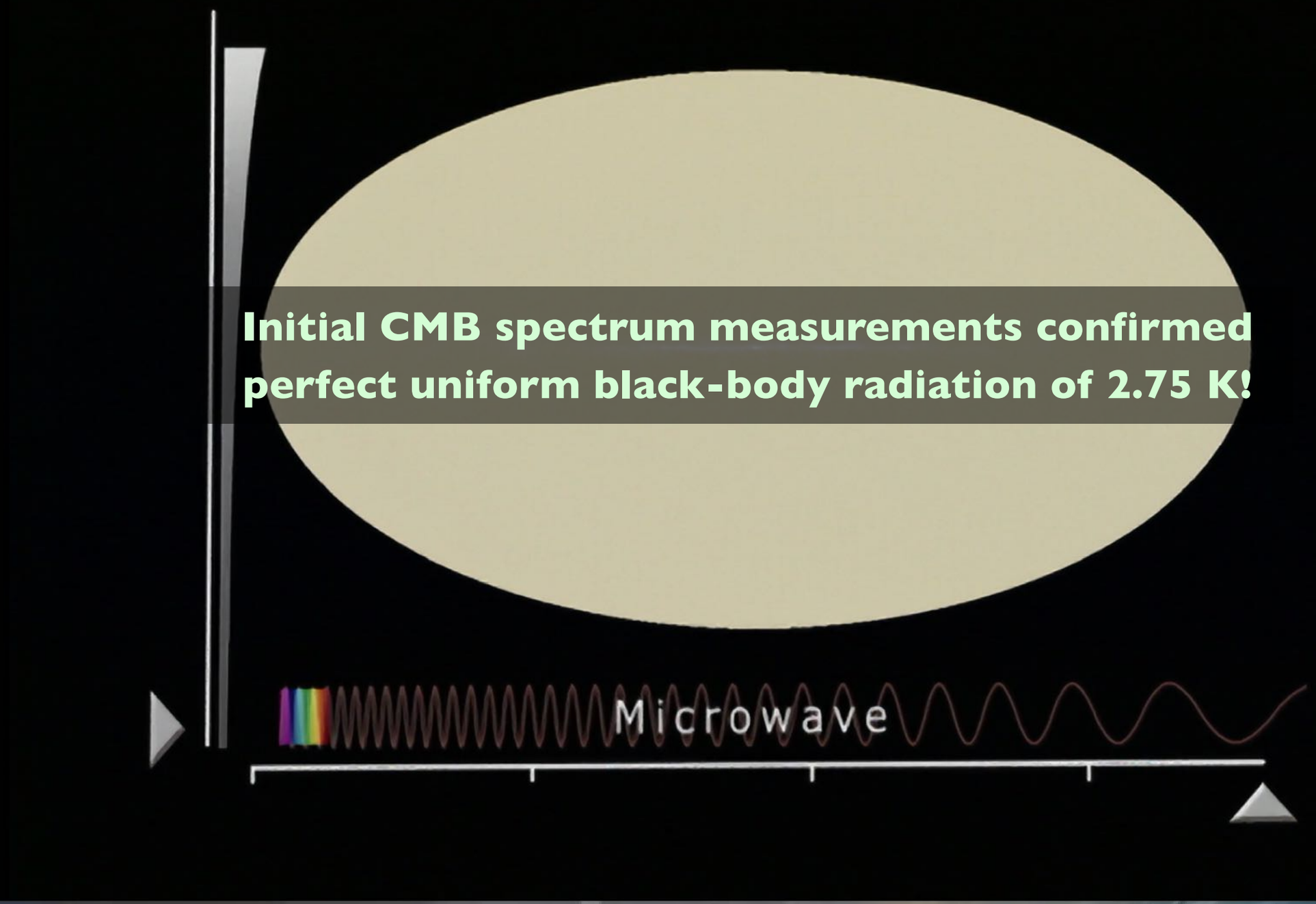
Penzias & Wilson discovered the Cosmic Microwave Background (CMB) in 1965

Observed in every direction and has no single origin point...

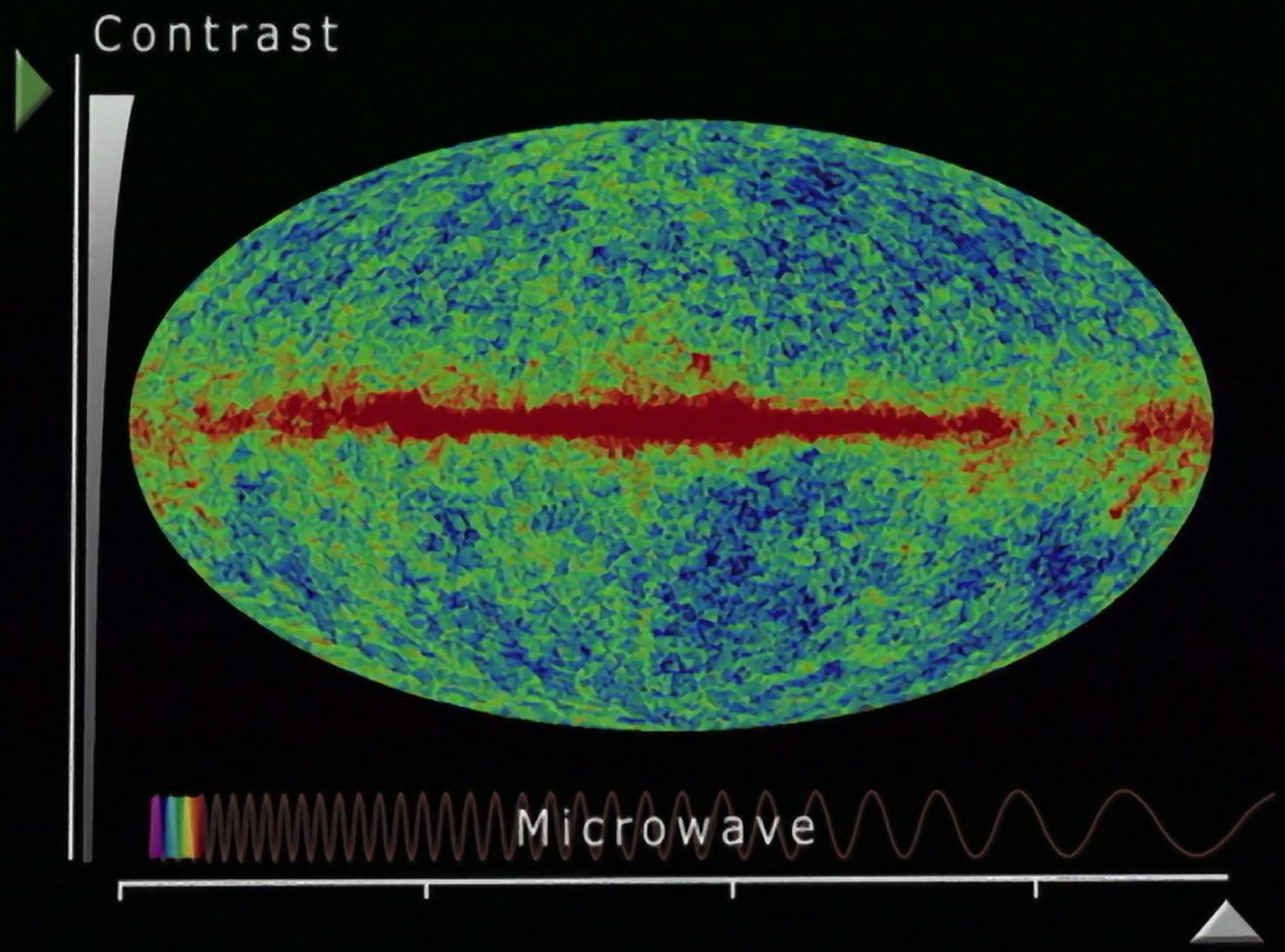
Observing the CMB radiation



Observing the CMB radiation

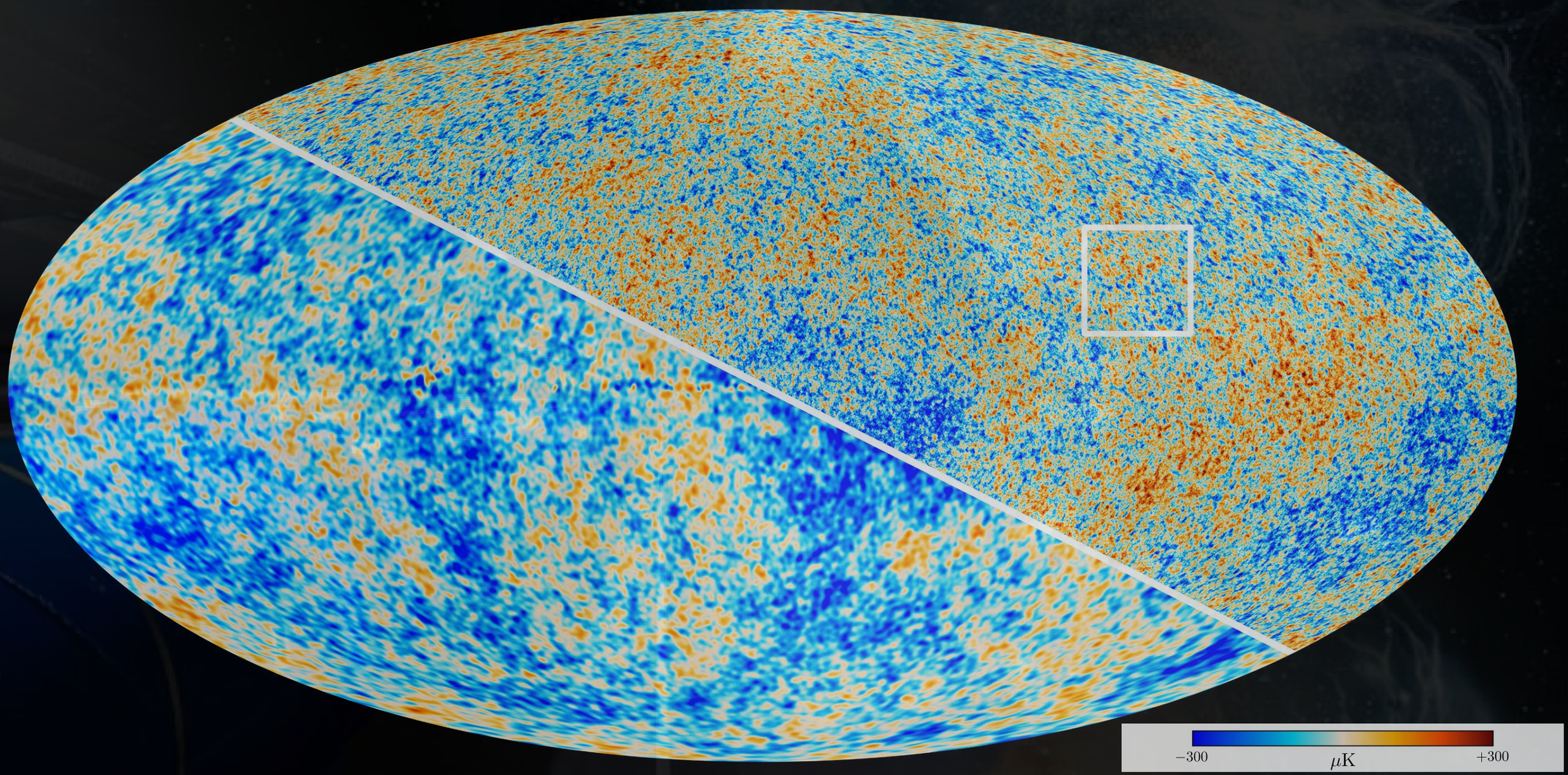


Observing the CMB radiation



With ever-more precise space-based experiments (COBE, WMAP, Planck)
CMB spectrum measured at extraordinary details!

Observing the CMB radiation

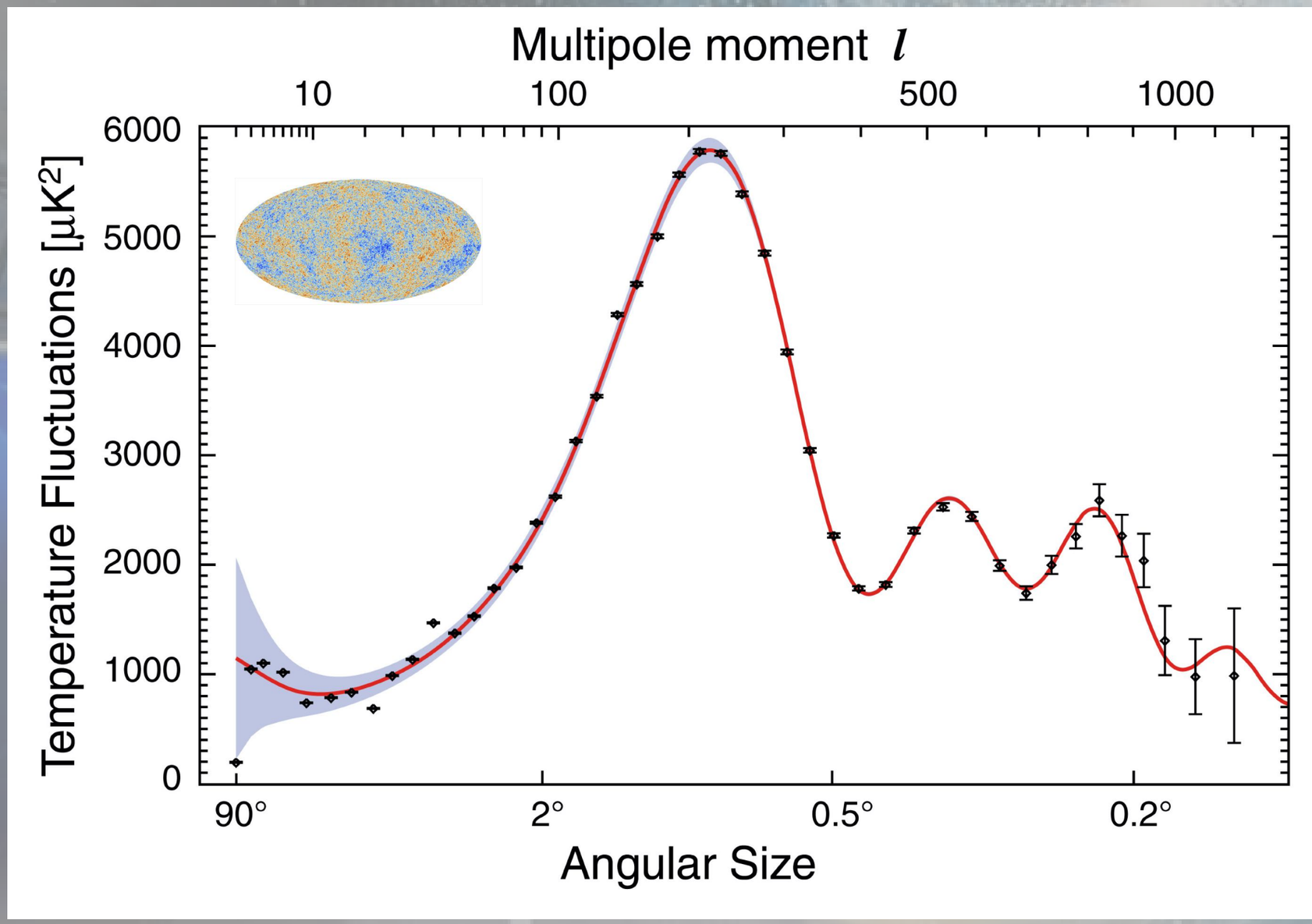


Temperature of the CMB found to vary with direction...

...with tiny variations, just 1 part in 10,000!

CMB : Fingerprinting the universe

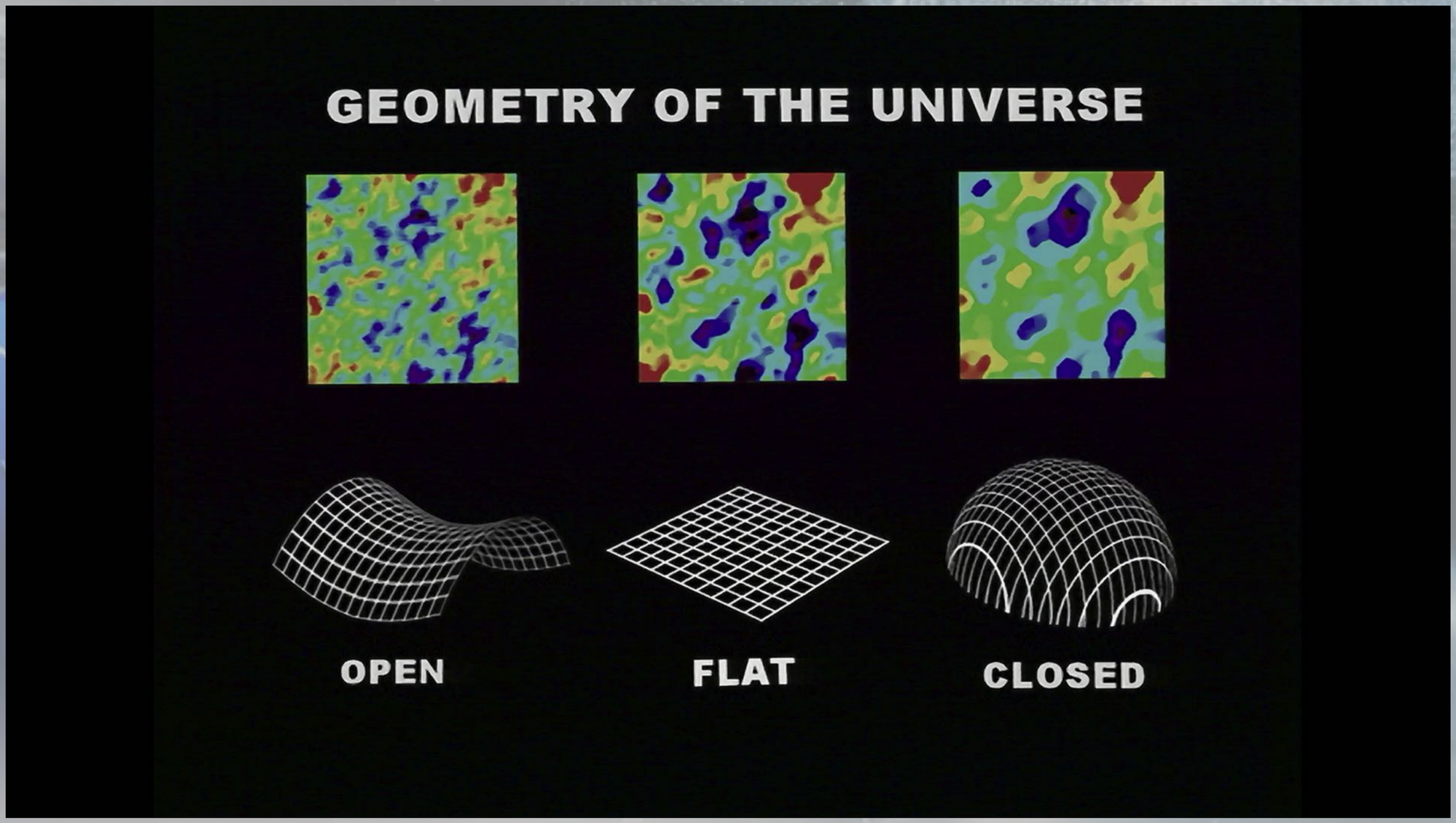
Matter/density variations in an early universe imprinted in tiny CMB "ripples".
Initial CMB cooled down gradually with the expansion of the universe.



CMB pattern today allows to infer: age, shape, and composition of our universe!

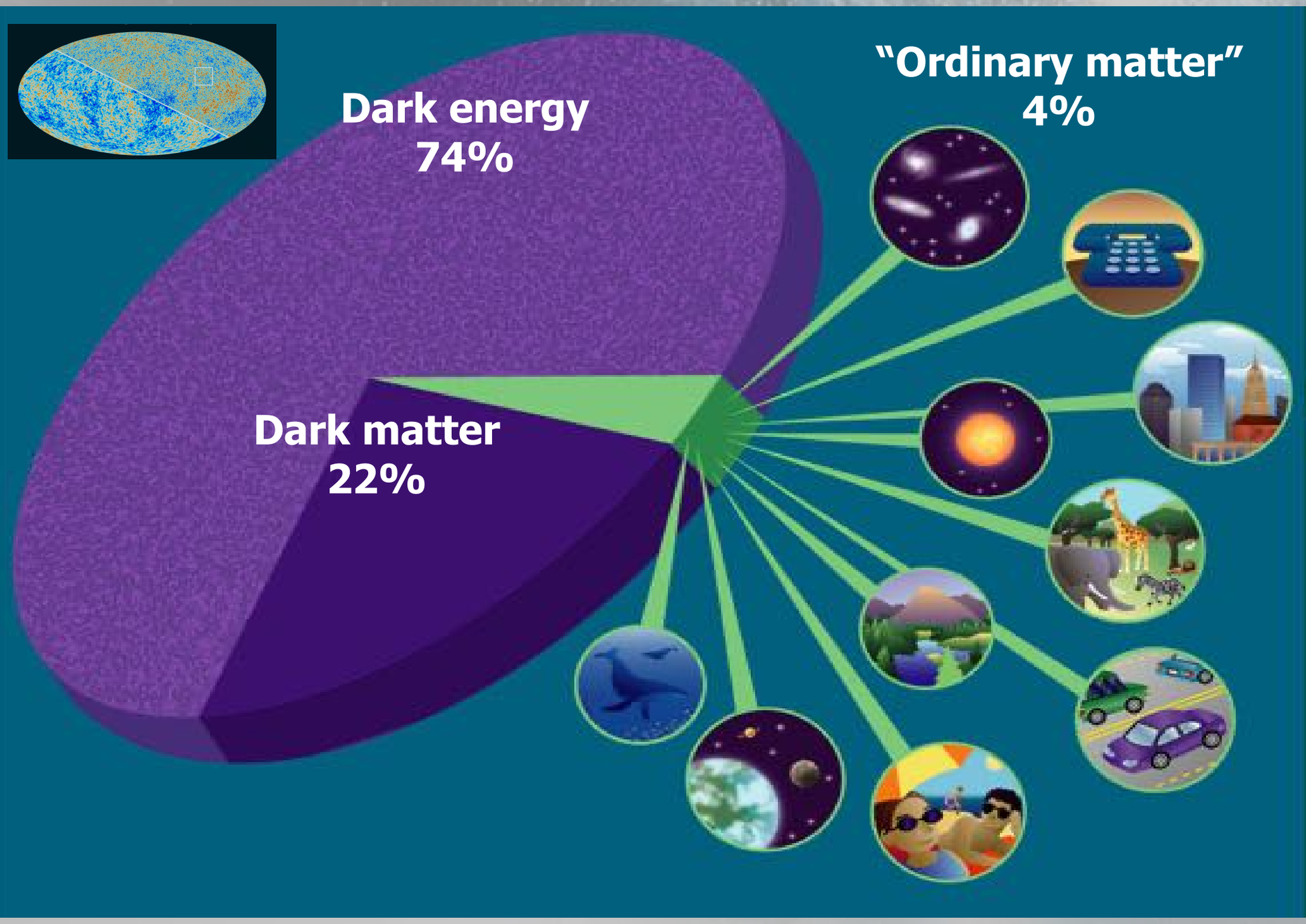
CMB : Fingerprinting the universe

Shape: **Universe predominantly has flat geometry!**

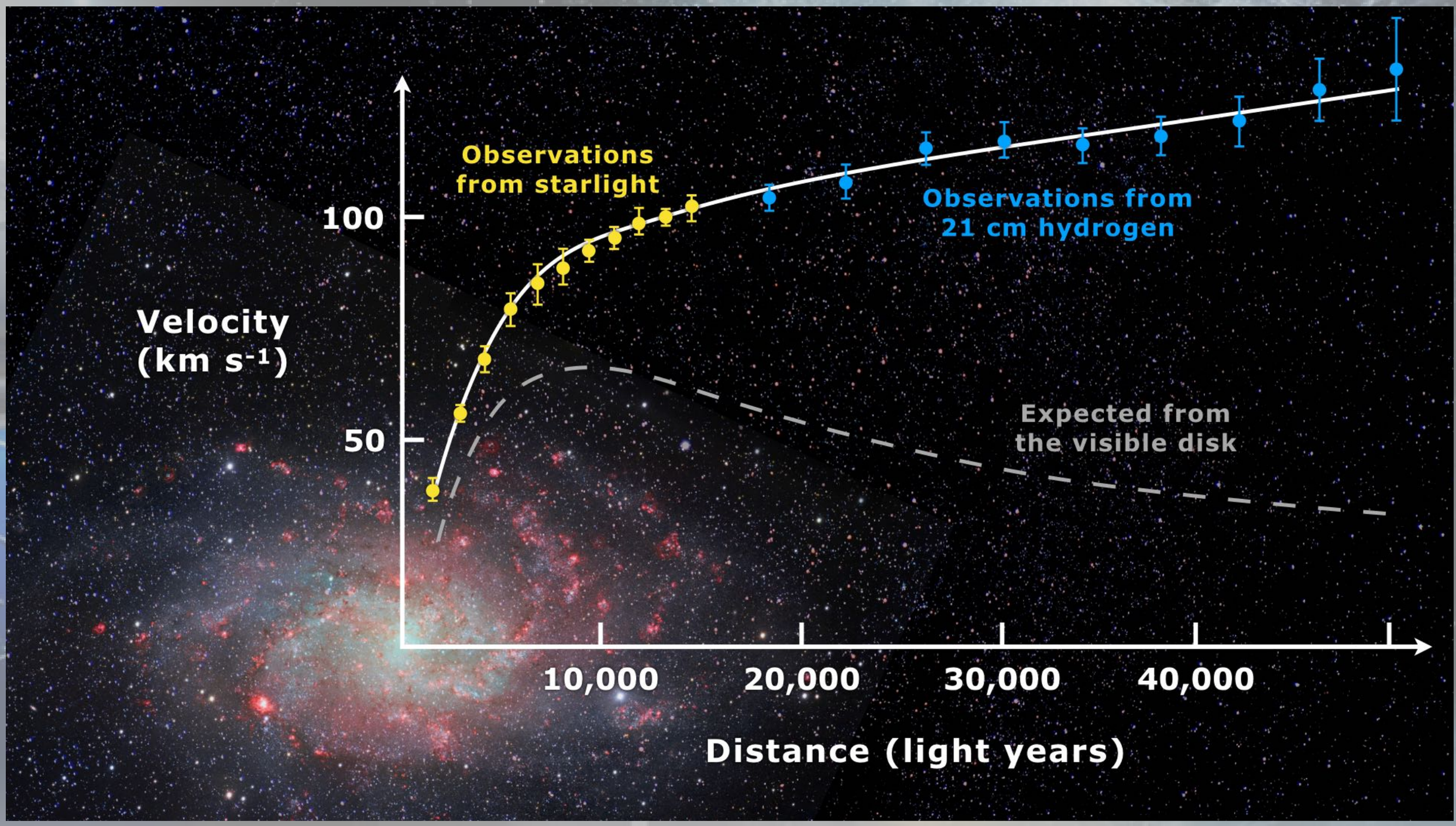


CMB : Fingerprinting the universe

Composition: Universe seems to be dominated by non-ordinary forms of matter!

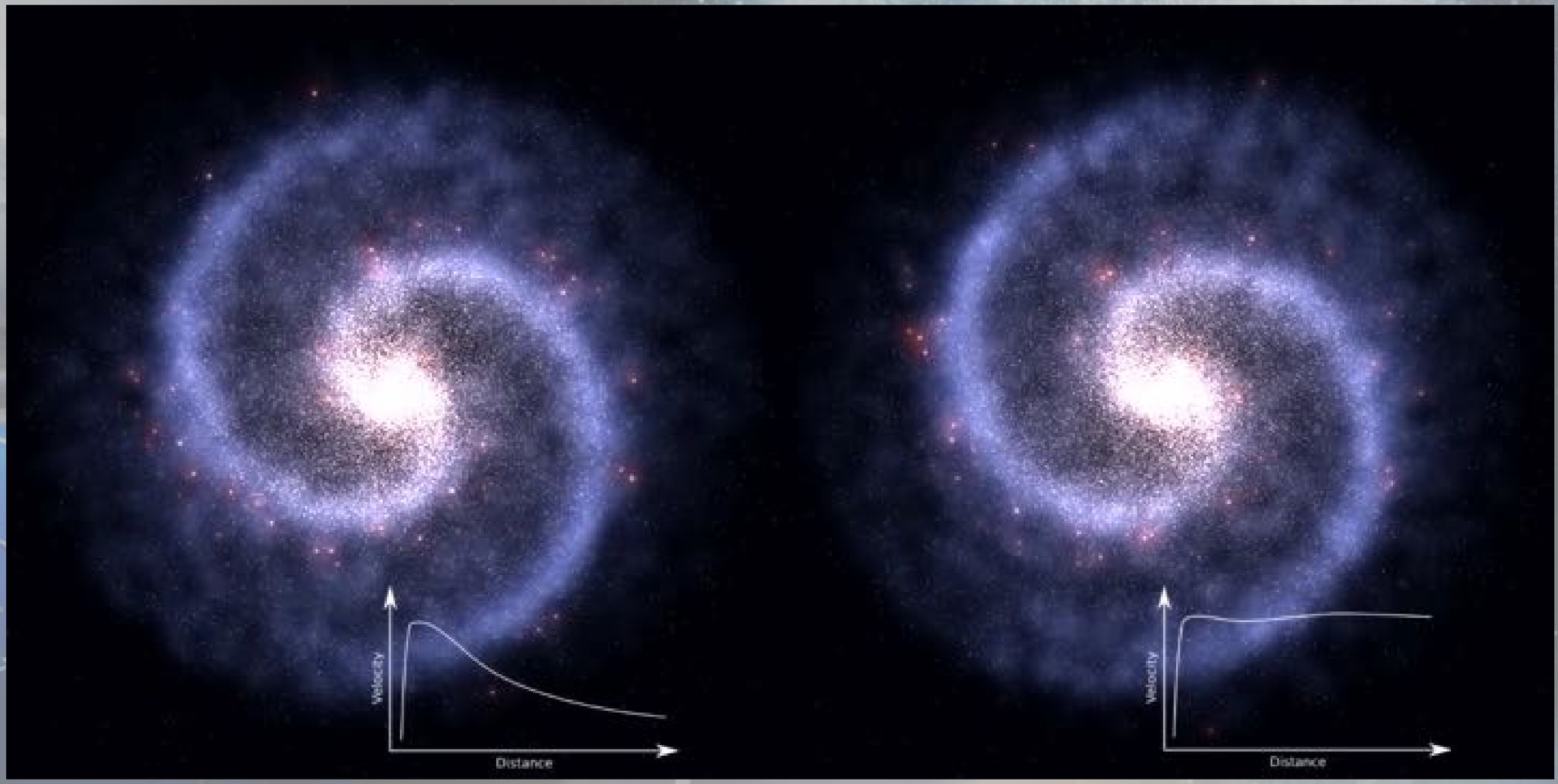


Dark matter: indirect evidences



Galaxy rotation curves and stars velocity dispersions consistent with presence of dark matter!

Dark matter: indirect evidences



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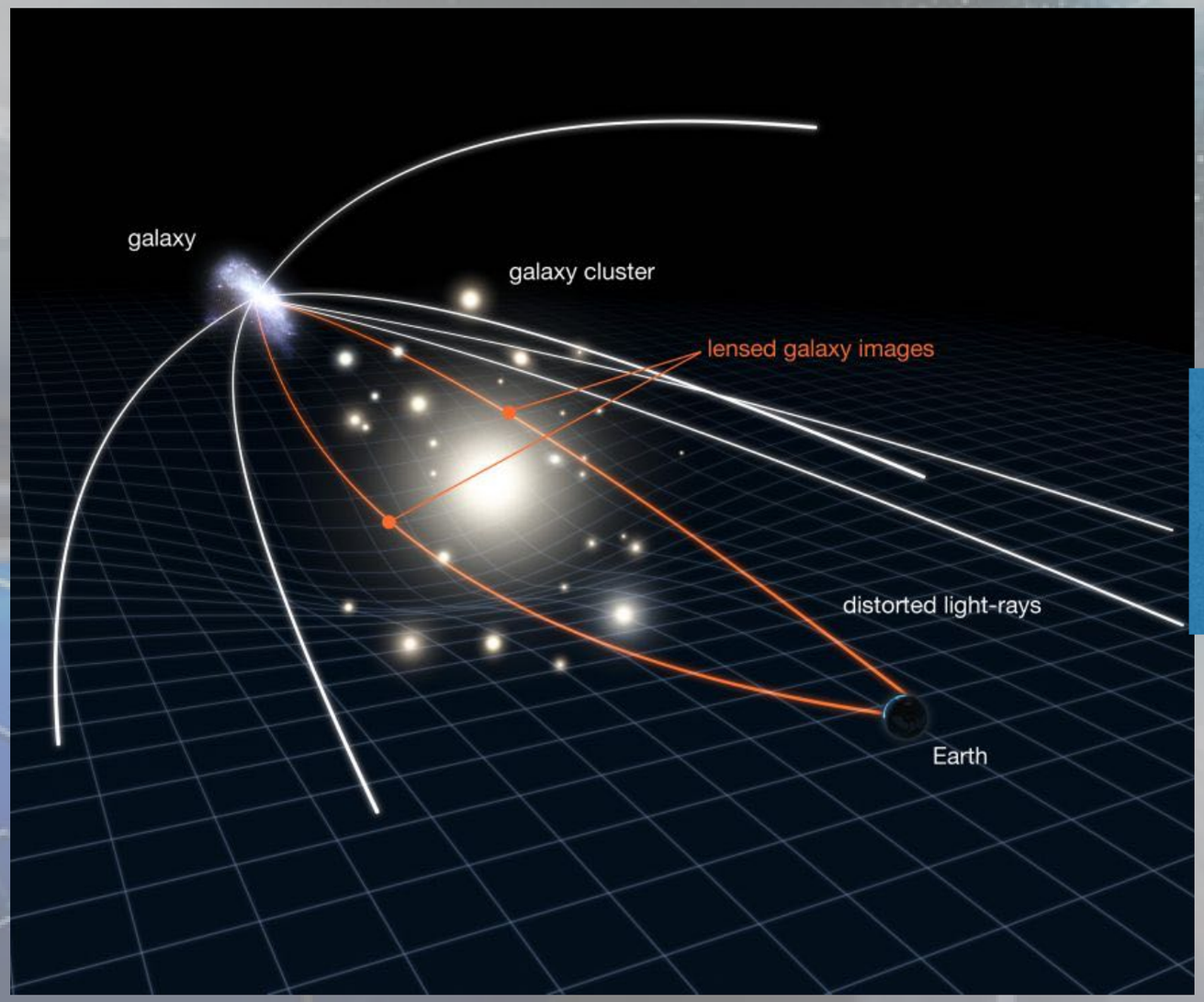
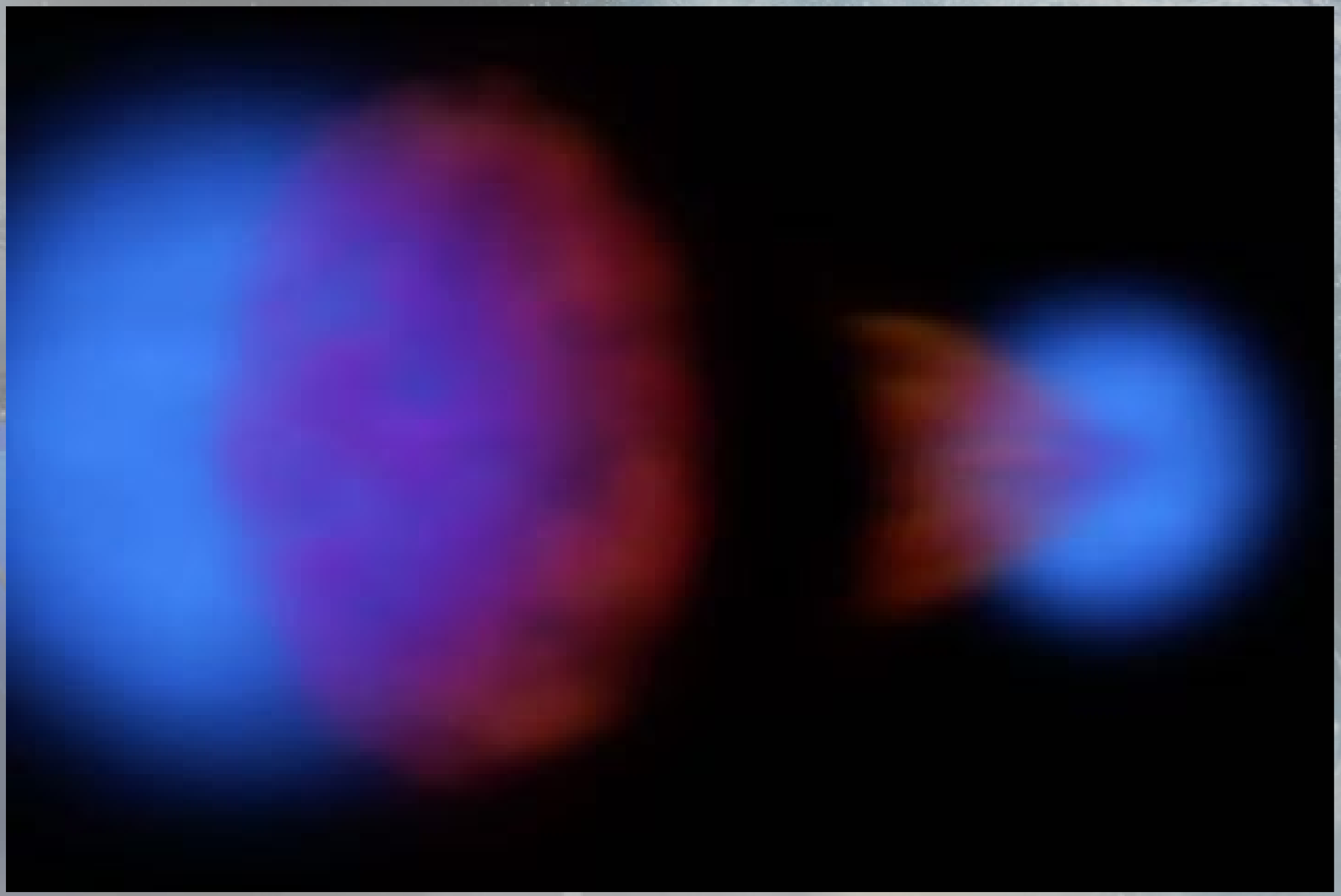


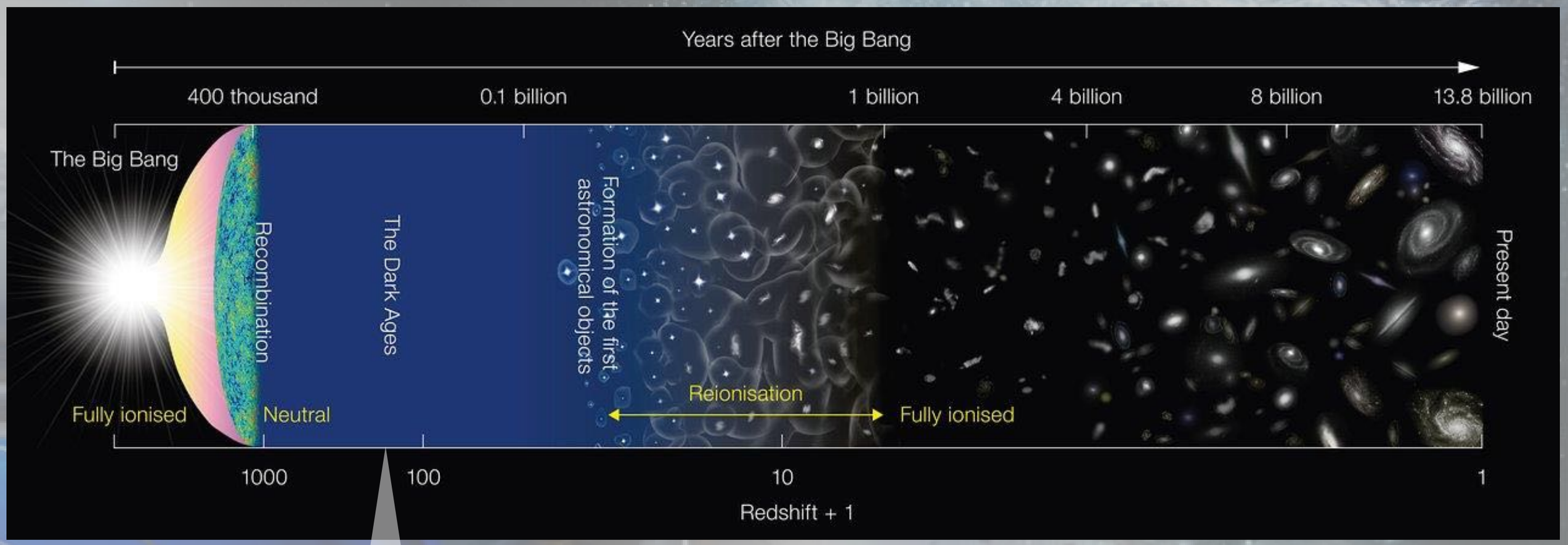
Dark matter bends space-time resulting in lensing effect:
observations consistent with presence of dark matter!

Dark matter: (almost) direct evidences



Distribution of matter during the collisions of two clusters of galaxies:
most of the mass exhibits interaction consistent with dark matter!

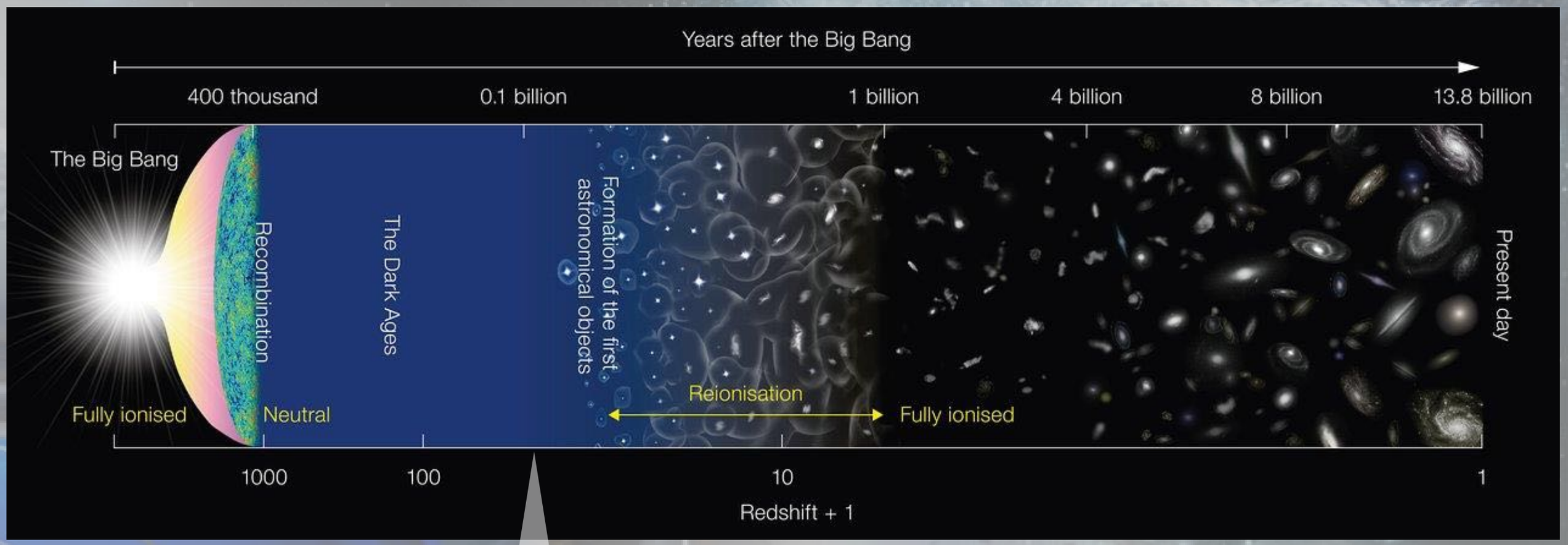
Emerging from the Dark Ages



Epoch of dark ages:
CMB temperature cooled down from ~3000 K to ~60 K,
no visible light photons, hydrogen/helium density stable.

~15 ma: CMB had a temperature of a "warm summer day on Earth"

Emerging from the Dark Ages



Gravitational collapse:
ordinary matter falls into the structures created by dark matter, first smaller and larger non-linear structures begin to take shape.

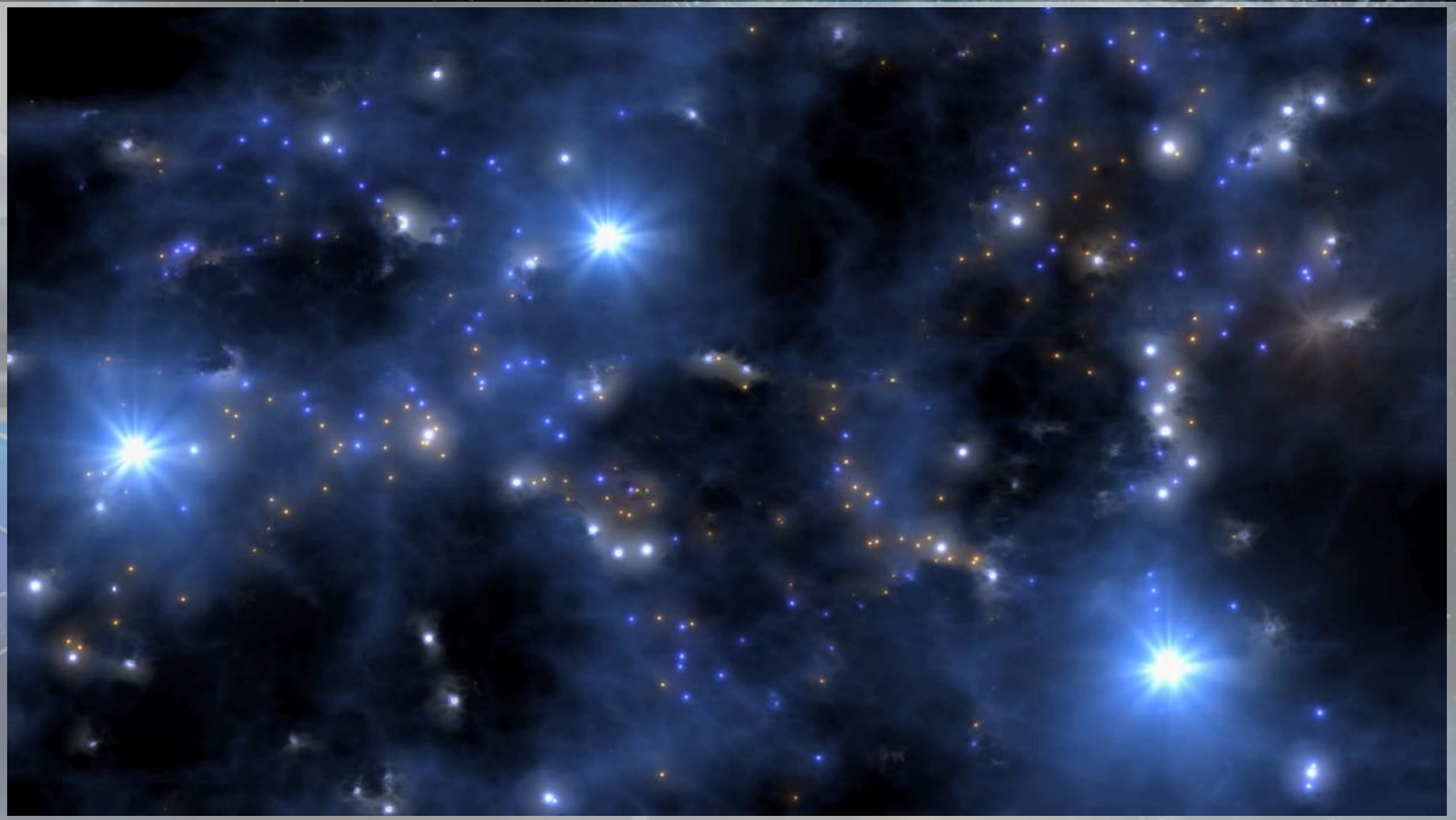
UV light starts to ionize neutral gas

From quantum fluctuations to large-scale structures

Quantum fluctuation in space-time induced variations in matter density

ordinary matter falls into the structures created by dark matter!

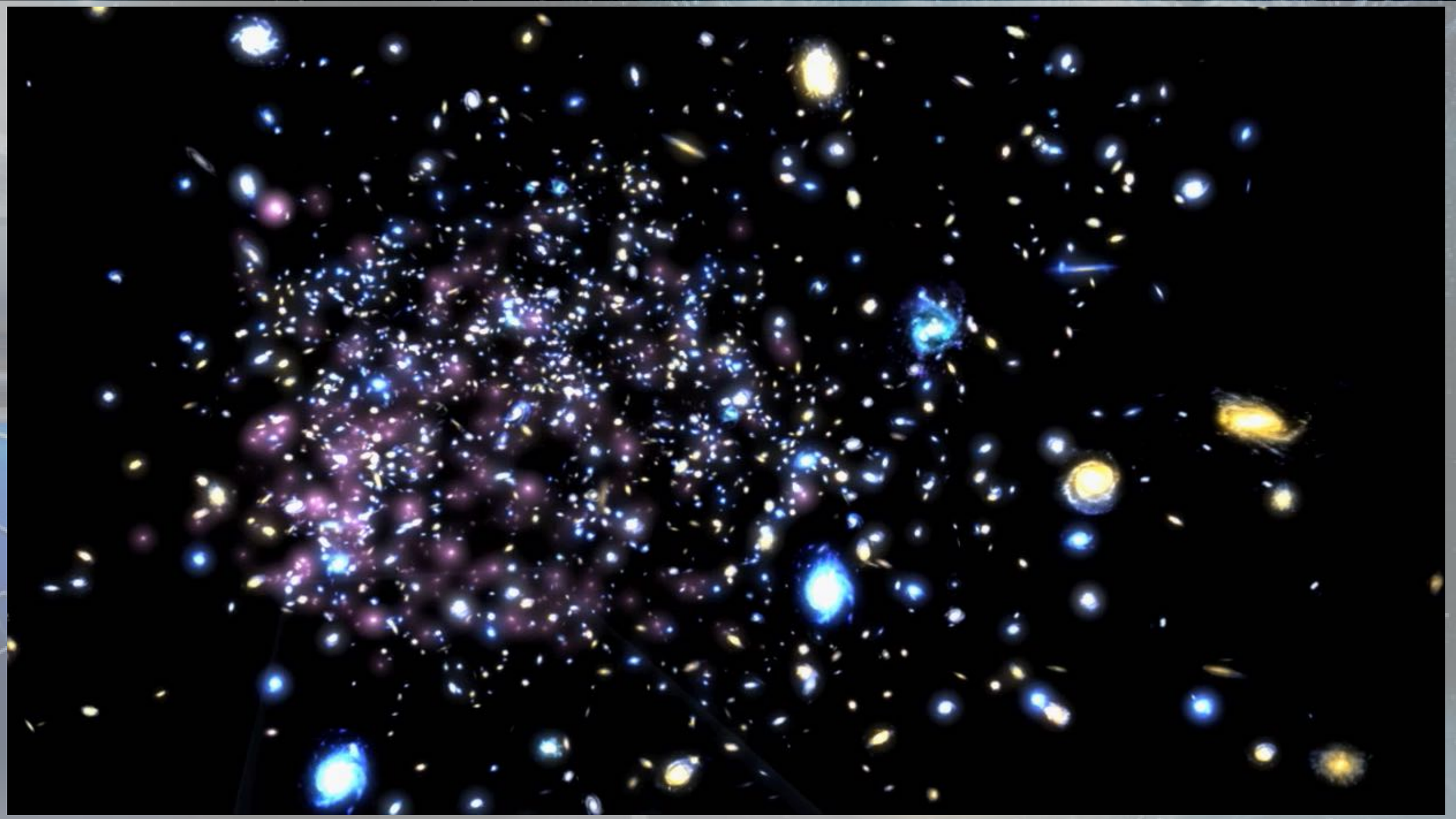
From quantum fluctuations to large-scale structures



First smaller and larger non-linear structures begin to take shape (100 ma)

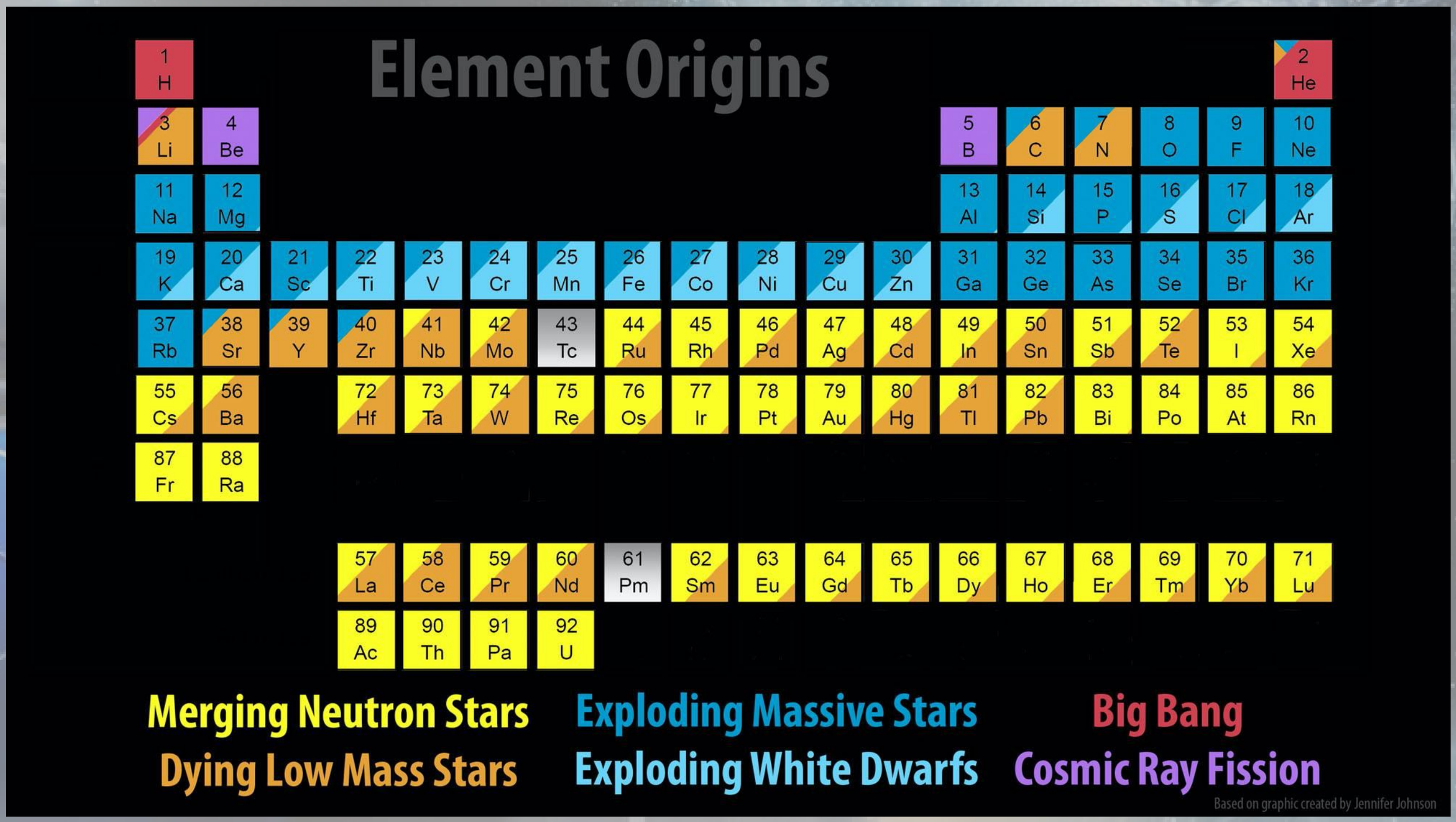
first proto-stars made of hydrogen and helium begin to shine (200-300 ma)!

From quantum fluctuations to large-scale structures



Large-scale astronomical objects (protogalaxies, quasars) begun forming porto-stars producing heavy elements allowing for "metallic" stars (>300 ma) !

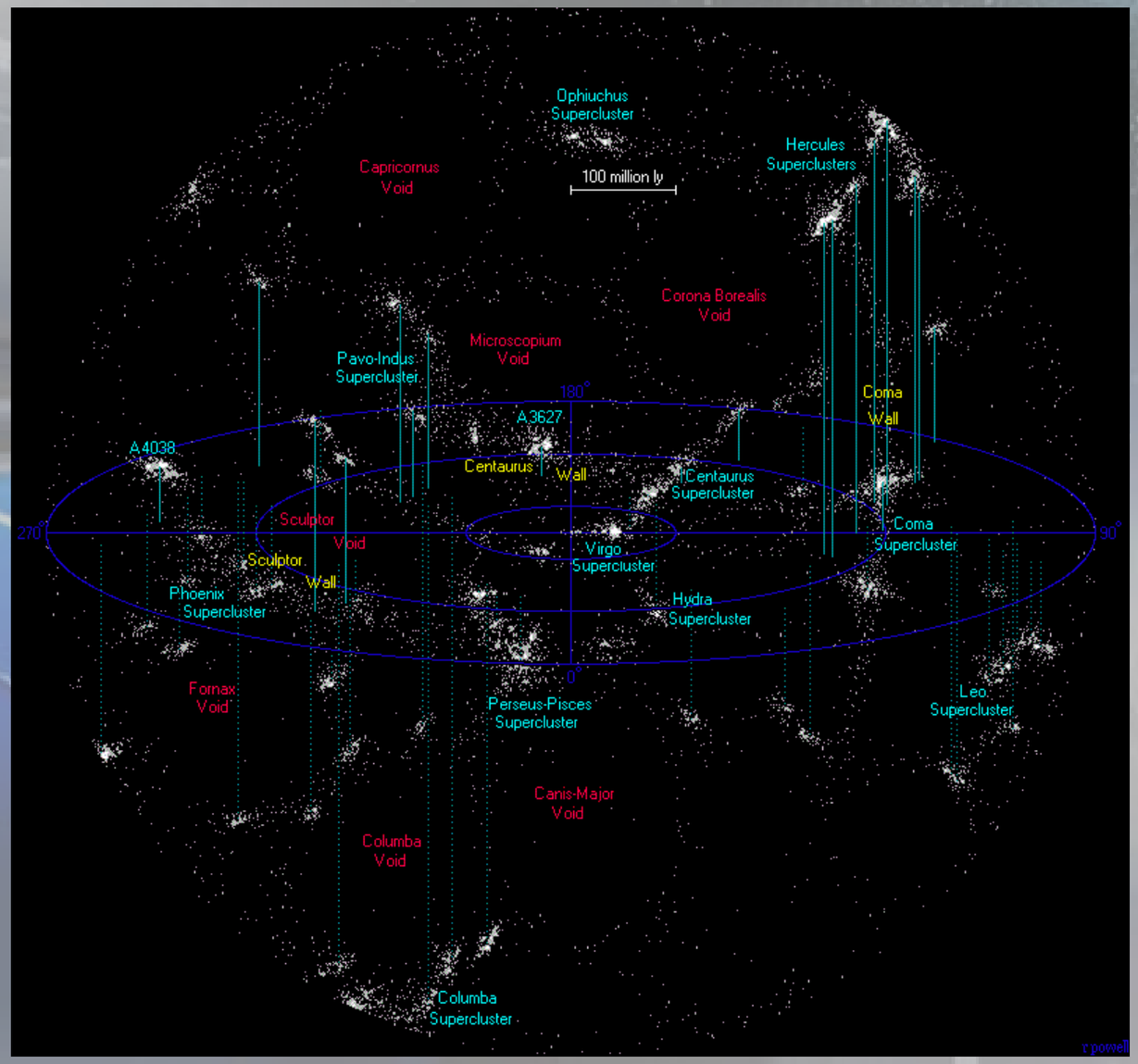
Origin of elements

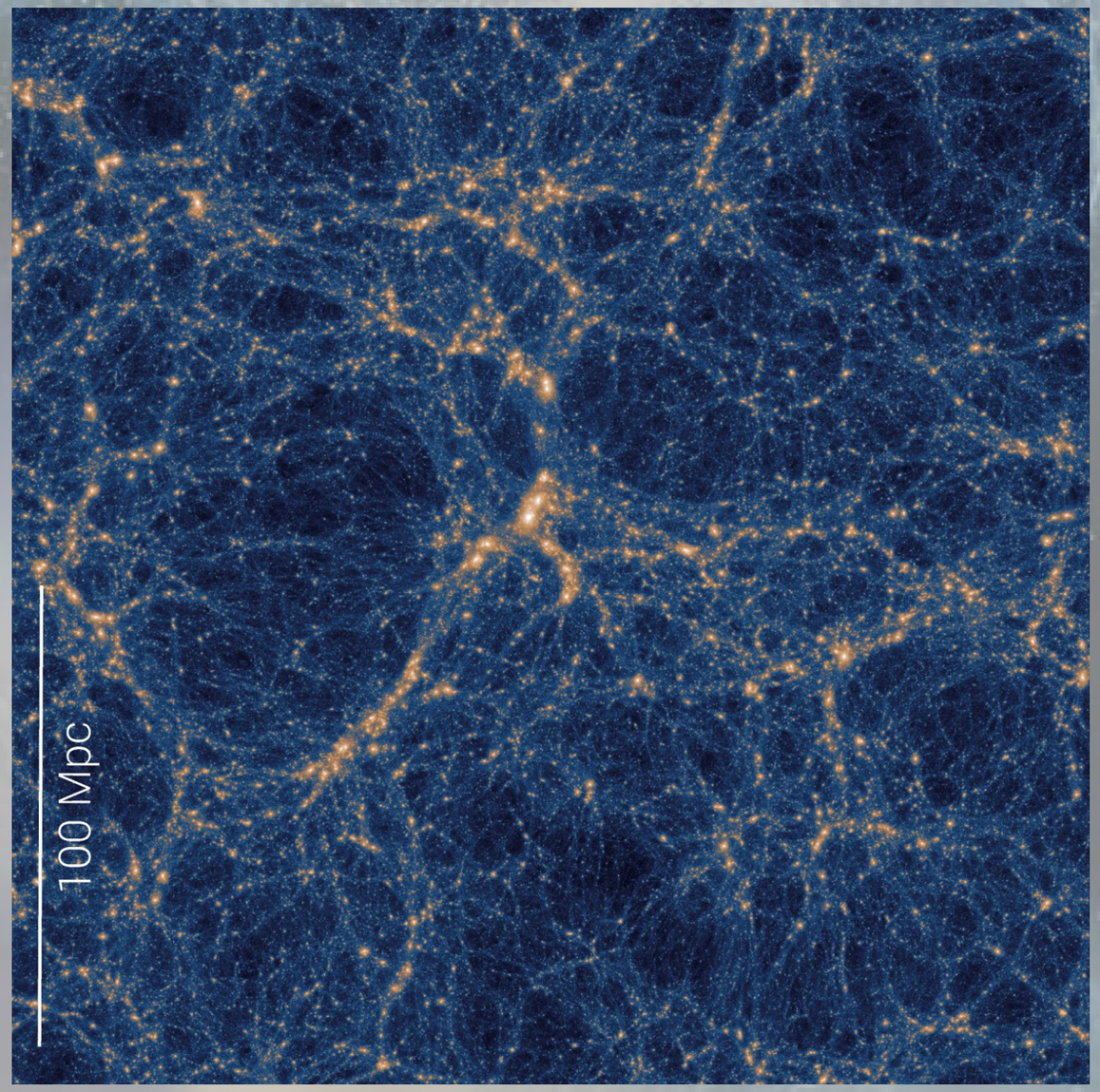


All heavy chemical elements have stellar origin:
from stellar merging/dying/exploding events !

Large-scale structures of the universe

From Sky surveys and mappings: Cosmic structures follow a hierarchical model with organization up to the scale of superclusters and filaments (not beyond).

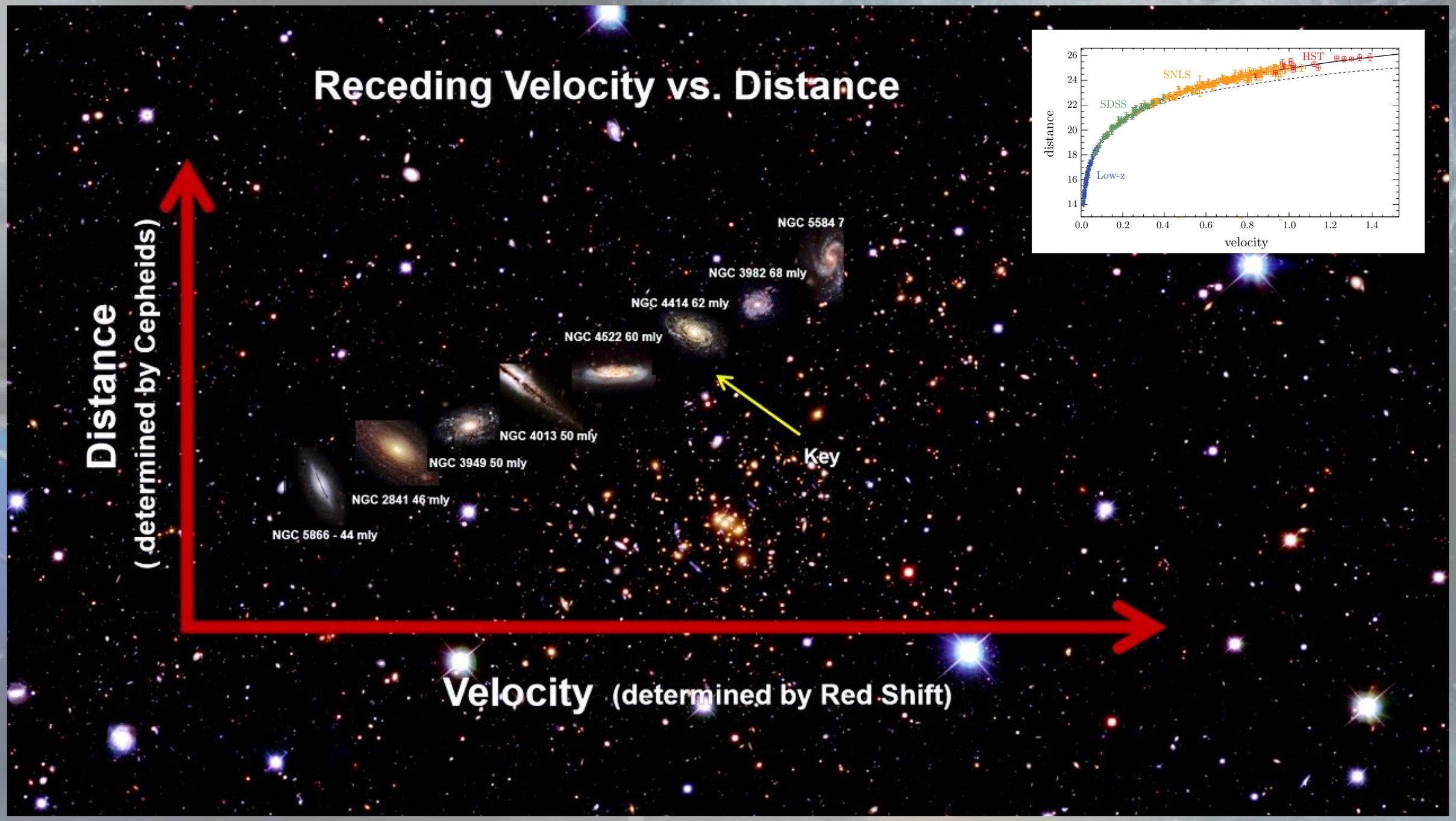




Simulations of the Universe reproduce its key structural features

still the largest structures observed are larger than expected (~10 billion ly) !

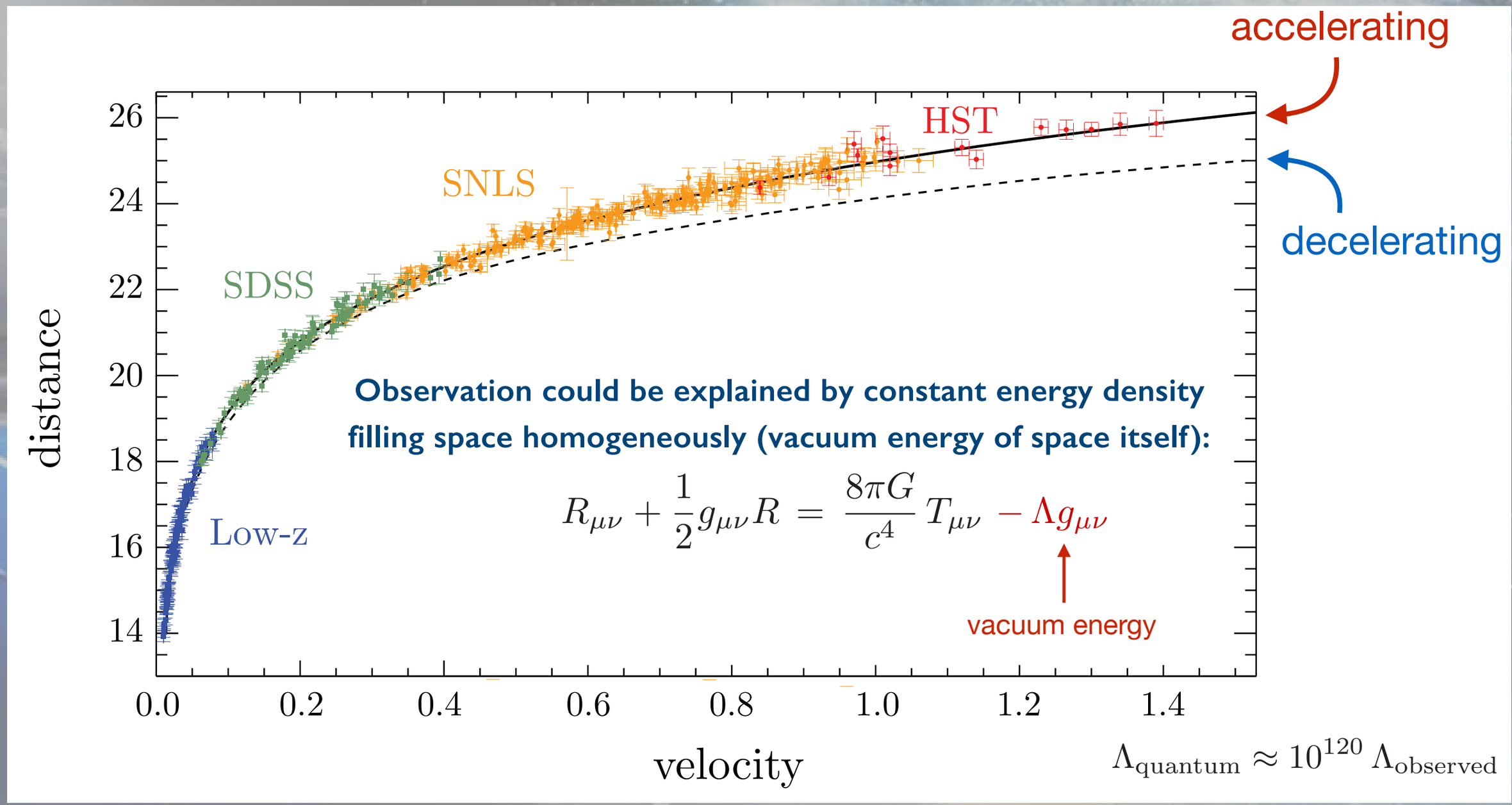
Expansion of the universe: Hubble's law



Galaxies are moving away from Earth at speeds proportional to their distance

giving observational basis for the expansion of the universe !

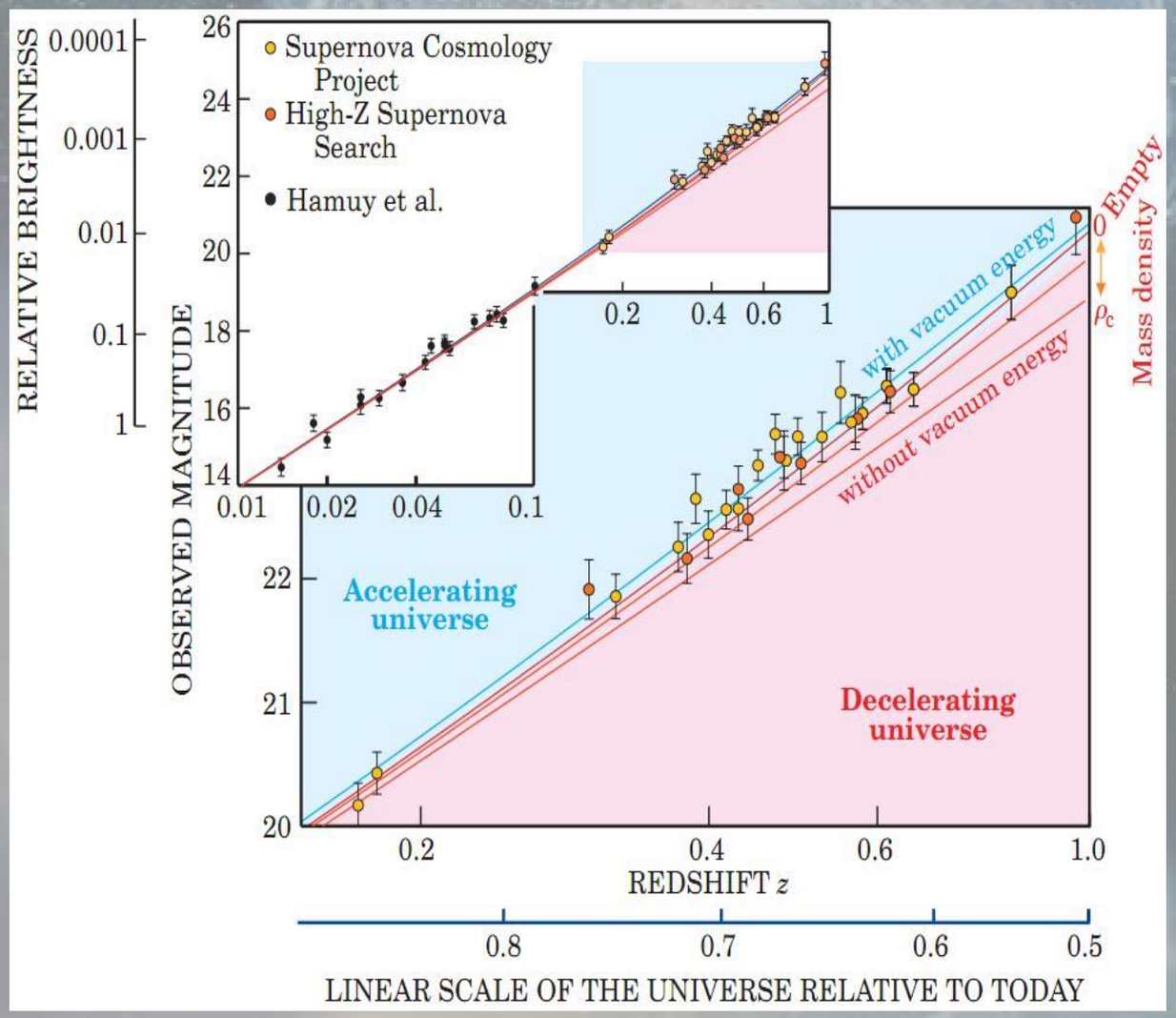
Accelerated expansion of the universe



Observed accelerated expansion of the universe can be explained by the dark energy (e.g. vacuum energy or scalar field) !

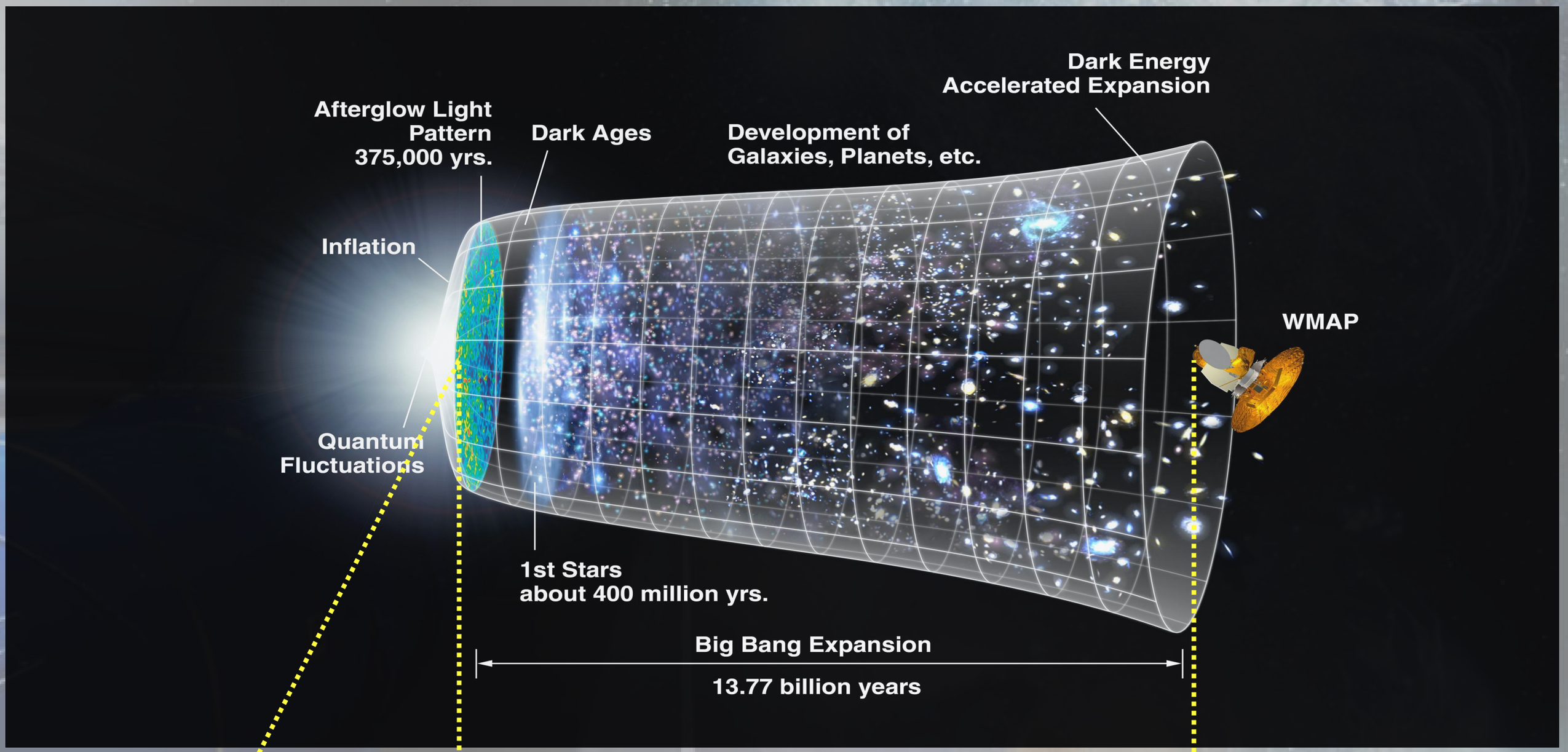
Dark energy & accelerated expansion

Confirmed by studying distribution/distance/velocity of Supernovae Type Ia (Nobel Prize in Physics 2011).



Dark energy also consistent with need for the observationally flat universe, and observed large-scale wave-patterns of mass density in the universe!

Evolution of the universe



~3 min.

~13.8 billion years

...until the end.

talk by A.Greljo

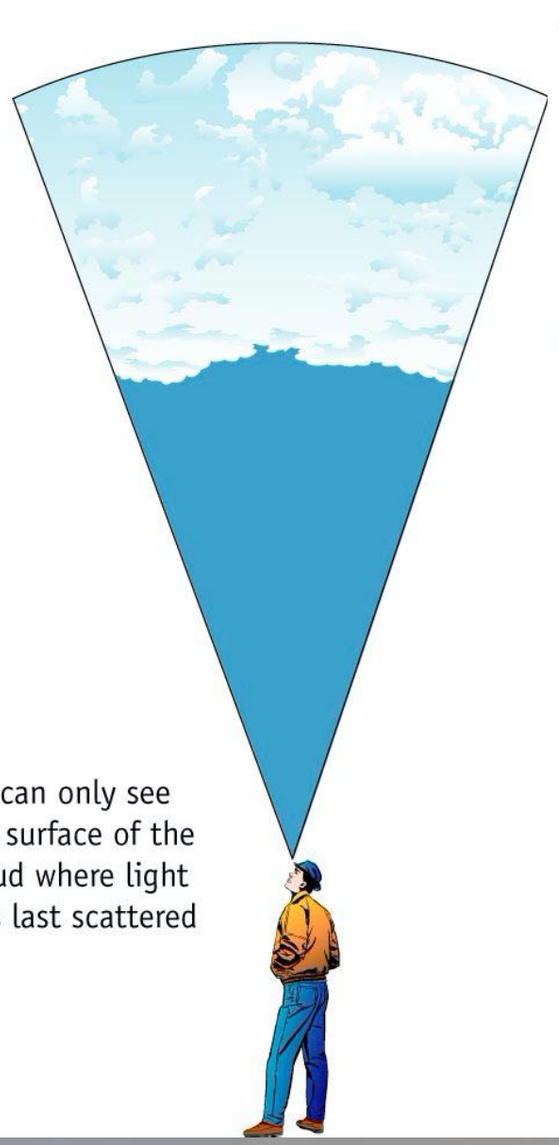
this talk...

talk by I. Puljak

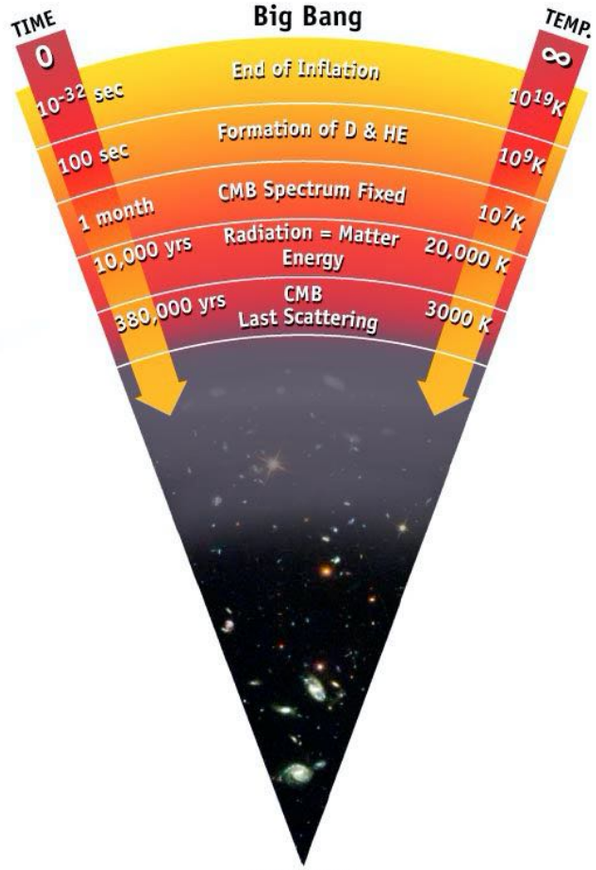
Additional material

CMB : Fingerprinting the universe

Matter/density variations in an early universe imprinted in tiny CMB "ripples".
Initial CMB cooled down gradually with the expansion of the universe.

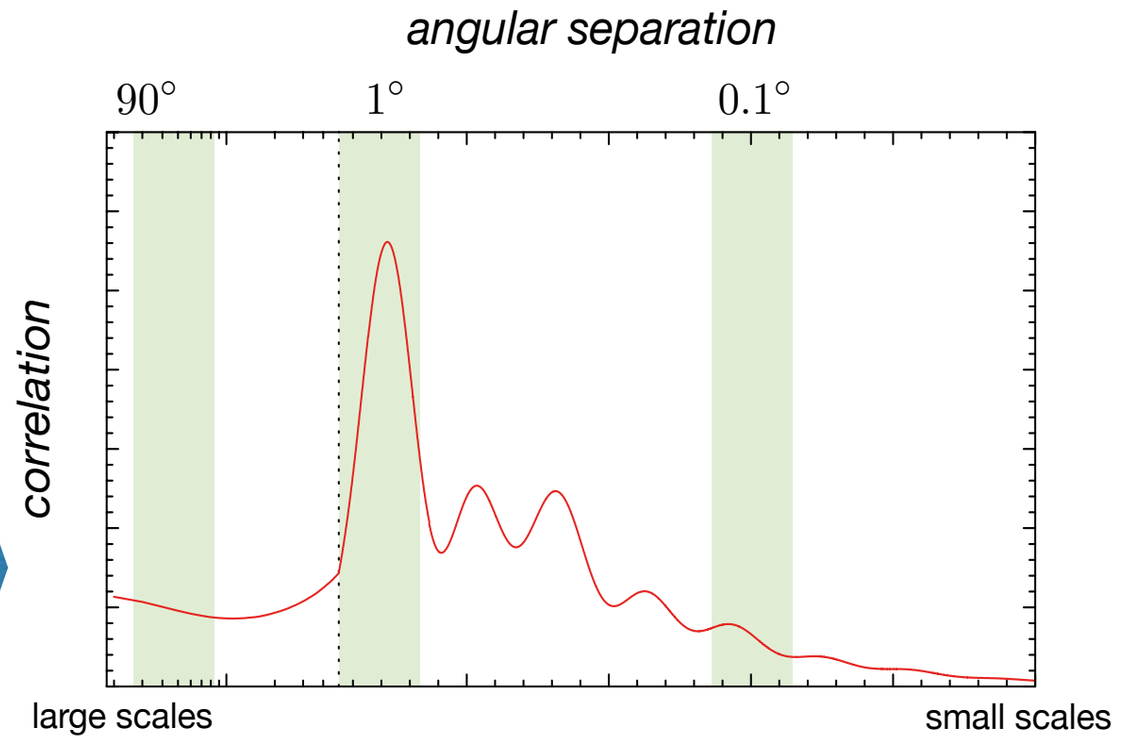


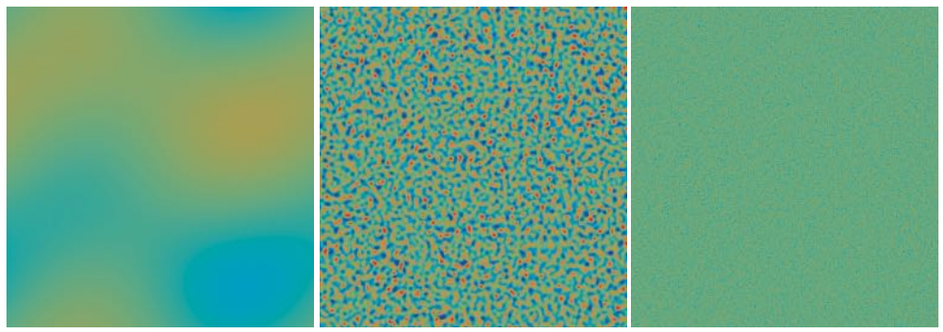
We can only see the surface of the cloud where light was last scattered



PRESENT
13.7 Billion Years after the Big Bang

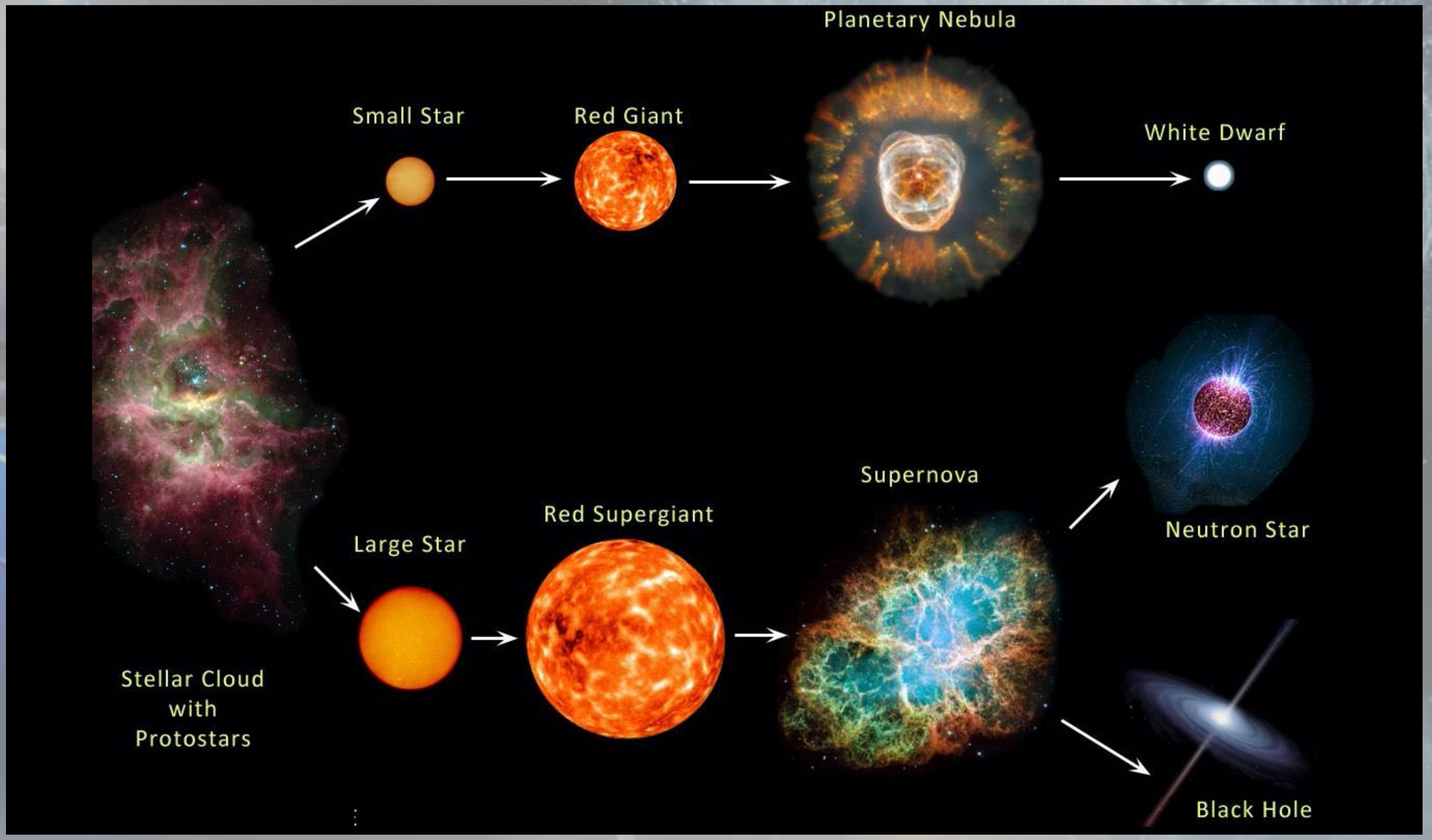
The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.





CMB pattern today allows to infer: age, shape, and composition of our universe!

Evolution of stars



Stellar evolution is complex/cyclic process, often with compact final objects: white/brown dwarfs, neutron stars, and black holes !

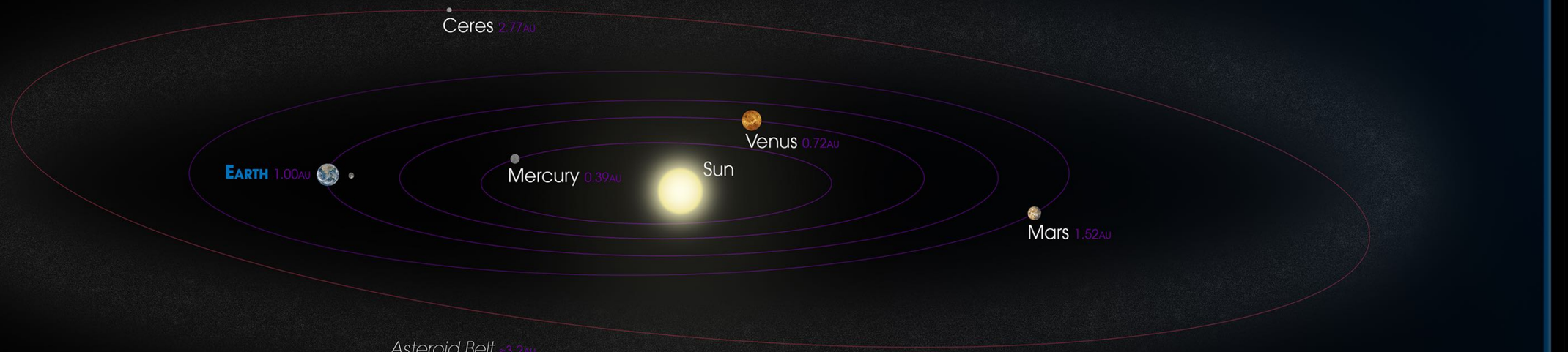
Our location at the Universe

Moon 384402KM

EARTH

Our location at the Universe

INNER SOLAR SYSTEM



Our location at the Universe

OUTER SOLAR SYSTEM

Makemake 45.8AU

Kuiper Belt ≈40AU

Neptune 30.05AU

Uranus 19.2AU

Jupiter 5.20AU

SUN

Pluto 39.5AU

Saturn 9.58AU

Haumea 43.1AU

Eris 96.4AU

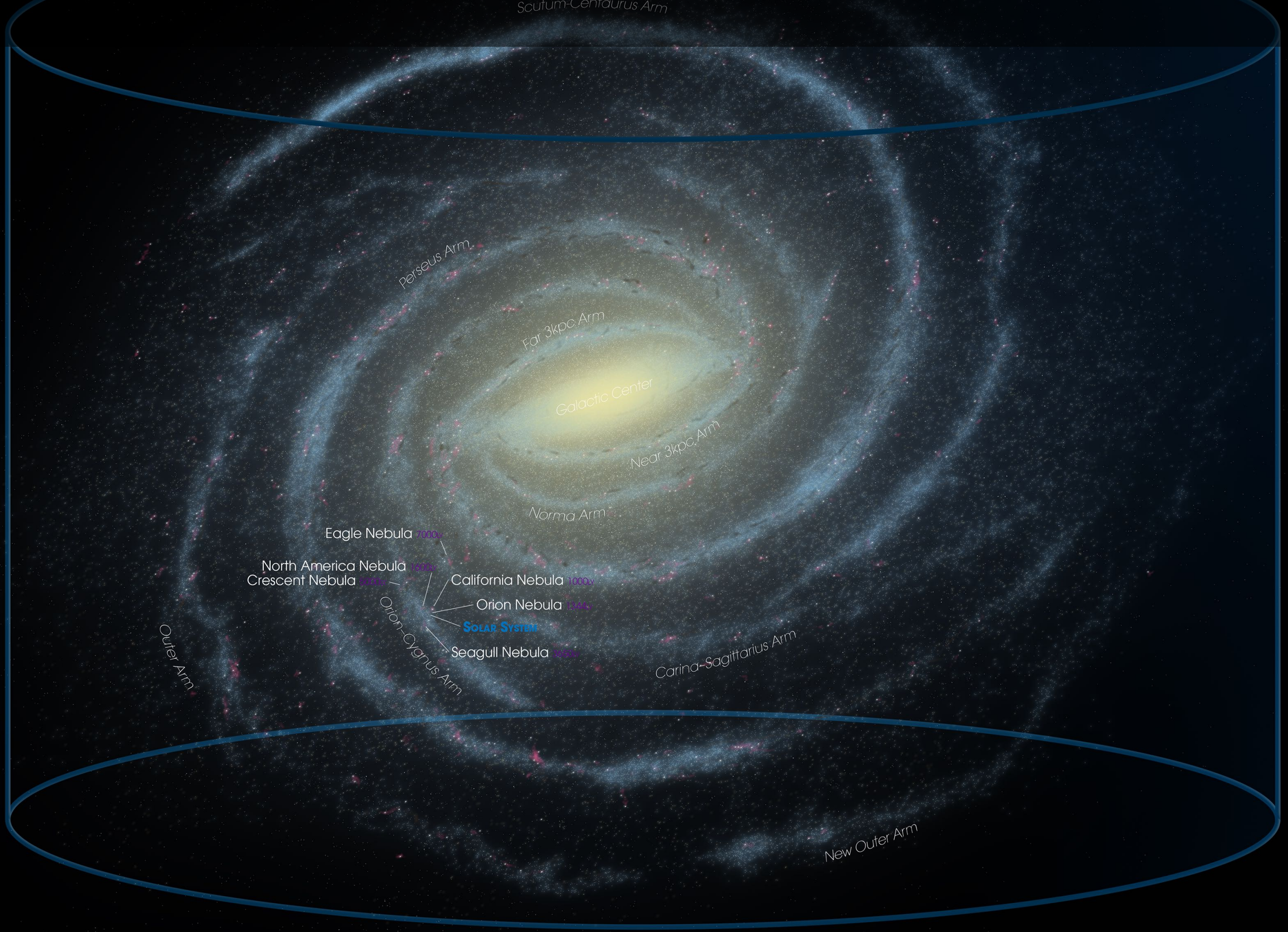
Our location at the Universe

CLOSEST STARS

Kruger 60 B 13.07LY
Kruger 60 A 13.07LY
Groombridge 34 A 11.61LY
Groombridge 34 B 11.61LY
Struve A 11.48LY
Struve B 11.48LY
Ross 248 10.29LY
61 Cygni B 11.4LY
61 Cygni A 11.4LY
Teegarden's Star 12.49LY
DX Cancri 11.67LY
Lalande 21185 8.3LY
Luyten's Star 12.19LY
WISE 0855-0714 7.26LY
Procyon A 11.4LY
Procyon B 11.4LY
Ross 614 A 13.42LY
Ross 614 B 13.42LY
Epsilon Eridani 10.44LY
SOL
Wolf 359 7.85LY
Tau Ceti 11.75LY
Luyten 726-8 B 8.71LY
YZ Ceti 12.1LY
Luyten 726-8 A 8.71LY
Barnard's Star 5.95LY
EZ Aquarii C 11.1LY
EZ Aquarii A 11.1LY
Sirius A 8.65LY
Sirius B 8.65LY
Ross 128 11LY
Luhman 16 A 6.5LY
Luhman 16 B 6.5LY
EZ Aquarii B 11.1LY
Alpha Centauri A 4.36LY
Proxima Centauri 4.24LY
Lacaille 9352 10.72LY
Alpha Centauri B 4.36LY
Ross 154 9.7LY
Gliese 1061 11.98LY
Wolf 1061 14.04LY
Kapteyn's Star 12.82LY
Lacaille 8760 12.95LY
Epsilon Indi A 11.86LY
Epsilon Indi Ba 11.86LY
DEN 1048-3956 13.19LY
Epsilon Indi Bb 11.86LY
SCR 1845-6357 A 12.57LY
SCR 1845-6357 B 12.57LY

Our location at the Universe

MILKY WAY GALAXY



Our location at the Universe

LOCAL GROUP

And XXIV
And XVII 4.42MLY
And V 2.52MLY
M110 2.69MLY
Cassiopeia Dwarf 2.58MLY
Andromeda Galaxy 2.54MLY
And X 2.9MLY
And XXI 2.8MLY
SagDIG 3.39MLY
And IX 2.5MLY
PegDIG 3.0MLY
M32 2.49MLY
And XV
NGC 147 2.53MLY
And XVI
And XI 2.6MLY
And XXVIII
Aquarius Dwarf 3.2MLY
Triangulum Galaxy 2.73MLY
And XXIII
NGC 185 2.05MLY
And XIII
And XIX
And XX
And XXVI
And II 2.22MLY
Pegasus 2.7MLY
And XVII
Canes Venatici II 506KLY
Barnard's Galaxy 1.63MLY
And XXII 3.07MLY
And XIV
Canes Venatici I 698KLY
And XXV
And I 2.4MLY
Pisces Dwarf 2.51MLY
And III 2.44MLY
Ursa Major I 330KLY
Hercules 455KLY
Boötes I 197KLY
Boötes III 150KLY
Draco 260KLY
Coma Berenices 140KLY
Pisces II 585KLY
Ursa Minor 200KLY
Leo I 820KLY
Leo A 2.6MLY
Ursa Major II 98KLY
Sextans 290KLY
SagDEG 65KLY
Leo V 578KLY
Triangulum II 98KLY
Leo IV 520KLY
IC 1613 2.38MLY
MILKY WAY GALAXY
Leo II 690KLY
Leo T 1365KLY
Reticulum II 98KLY
Carina 330KLY
Wolf–Lundmark–Melotte 3.04MLY
Sculptor 290KLY
Grus 290KLY
Small Magellanic Cloud 200KLY
Large Magellanic Cloud 163KLY
Crater II 383KLY
Horologium I 326KLY
Tucana II 228KLY
Fornax Dwarf 460KLY
Phoenix Dwarf 1.44MLY

Our location at the Universe

LANIAKEA

PAVO-INDUS SUPERCLUSTER

NGC 6769 Group 185MLY

Teloscopium Group 125MLY

Delphinus Void

CENTAURUS SUPERCLUSTER

NGC 5419/5488 Group 190MLY

NGC 6753 Group 150MLY

Pegasus Cluster 180MLY

Pavo Cluster 180MLY

Local Void

VIRGO SUPERCLUSTER

Virgo III Groups 68-85MLY

A3565 Group 165MLY

Centaurus A/M83 Group 11.9MLY

Sculptor Group 12.7MLY

M94 Group 15MLY

NGC 7172 Group 125MLY

NGC 7329 Group 150MLY

LOCAL GROUP

Canes II Group 25.1MLY

M101 Group 21MLY

Virgo Cluster 55MLY

Centaurus Cluster 170MLY

M81 Group 12MLY

IC 341/Maffei Group 10.7MLY

Coma I Group 47.3MLY

Leo I Group 37MLY

Ursa Major Cluster 60MLY

NCG 2997 Group 24.8MLY

SOUTHERN SUPERCLUSTER

NGC 1023 Group 20.6MLY

Eridanus Void

Leo II Groups 65-90MLY

Corvus Void

Dorado Group 60MLY

Fornax Cluster 62MLY

Leo Void

Hydra Cluster 190.1MLY

Eridanus Cluster 75MLY

Antlia Cluster 132.7MLY

Puppis Cluster 95MLY

HYDRA SUPERCLUSTER

Taurus Void

Gemini Void

NGC 1417 Group 189MLY

Cancer Cluster 200MLY

Our location at the Universe

LOCAL SUPERCLUSTERS

Corona-Borealis Supercluster ≈989MLY

Ophiuchus Superclusters

Capricornus Supercluster

Hercules Supercluster B ≈554MLY

Hercules Supercluster A ≈413MLY

Corona Borealis Void

Capricornus Void

Boötes Superclusters ≈839MLY

Shapley Supercluster A ≈507MLY

Pavo-Indus Supercluster ≈235MLY

Boötes Void

Shapley Supercluster B ≈654MLY

Macroscopium Void

Pices-Cetus Supercluster B ≈878MLY

CfA2 Great Wall

Sculptor Void

Centaurus Supercluster ≈194MLY

Phoenix Supercluster ≈372MLY

VIRGO SUPERCLUSTER

Fornax Void

Sculptor Wall

Hydra Supercluster ≈132MLY

Coma Supercluster ≈300MLY

Ursa Major Supercluster ≈787MLY

Pices-Cetus Supercluster A ≈813MLY

Perseus-Pisces Supercluster ≈222MLY

Leo Supercluster ≈440MLY

Canis-Major Void

Columba Void

Sextans Supercluster ≈380MLY

Horologium Supercluster ≈937MLY

Columba Supercluster ≈458MLY

Our location at the Universe

OBSERVABLE UNIVERSE

Local Superclusters