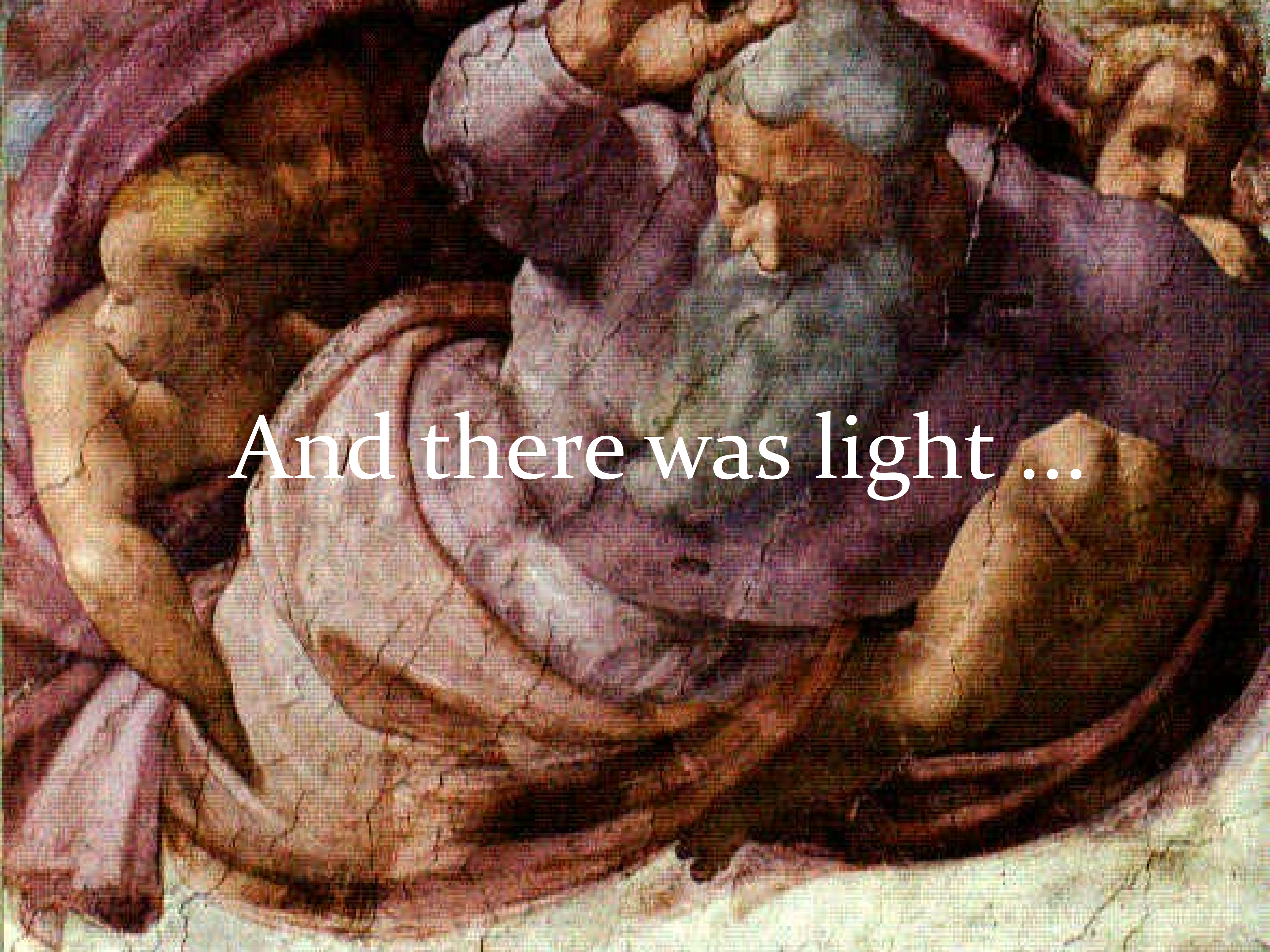
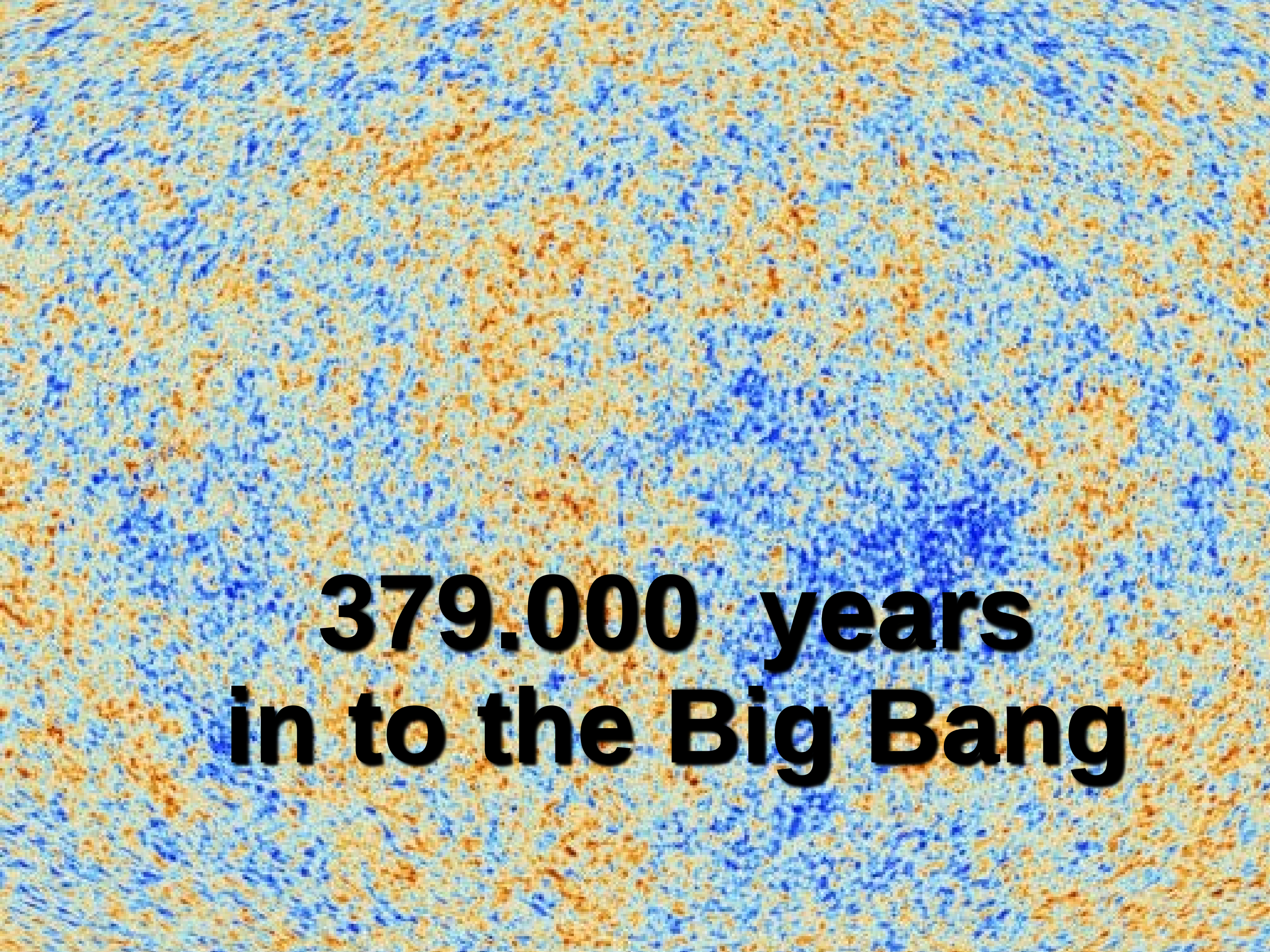
De Kosmische Dageraad:

structuurvorming in het jonge Heelal

Rien van de Weijgaert,
GVWS symposium, Groningen, 26 maart 2018


And there was light …


379.000 years
in to the Big Bang

then
the darkness fell upon us,

for 100 millions years
…

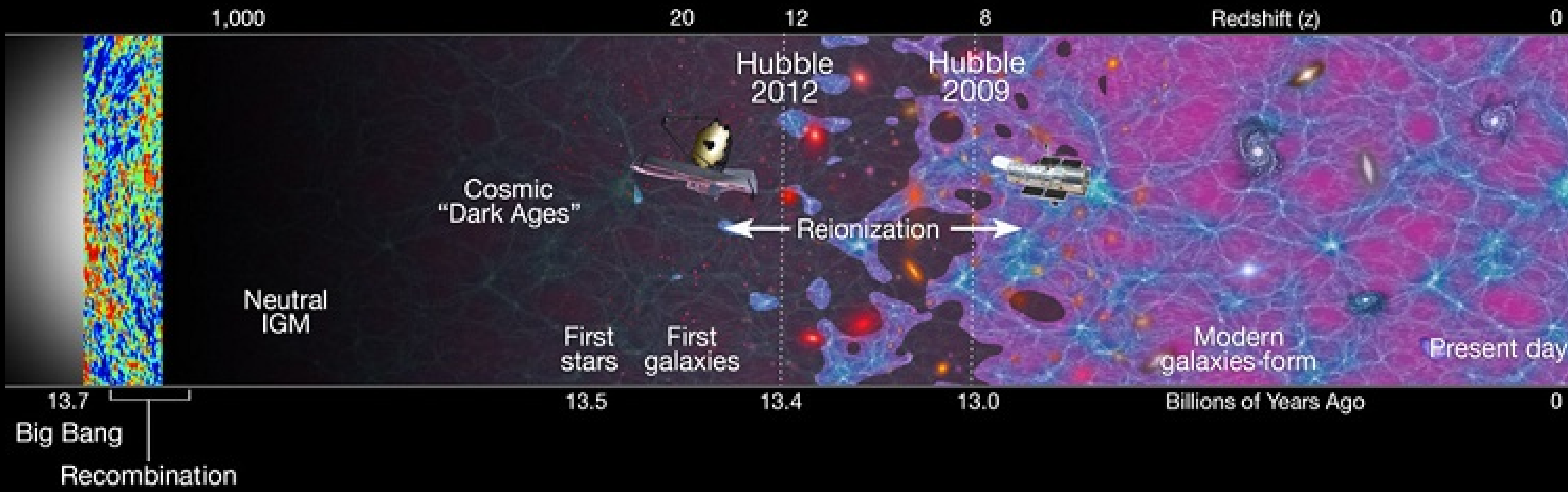
the Dark Ages

when
did the lights go on in the Universe ?

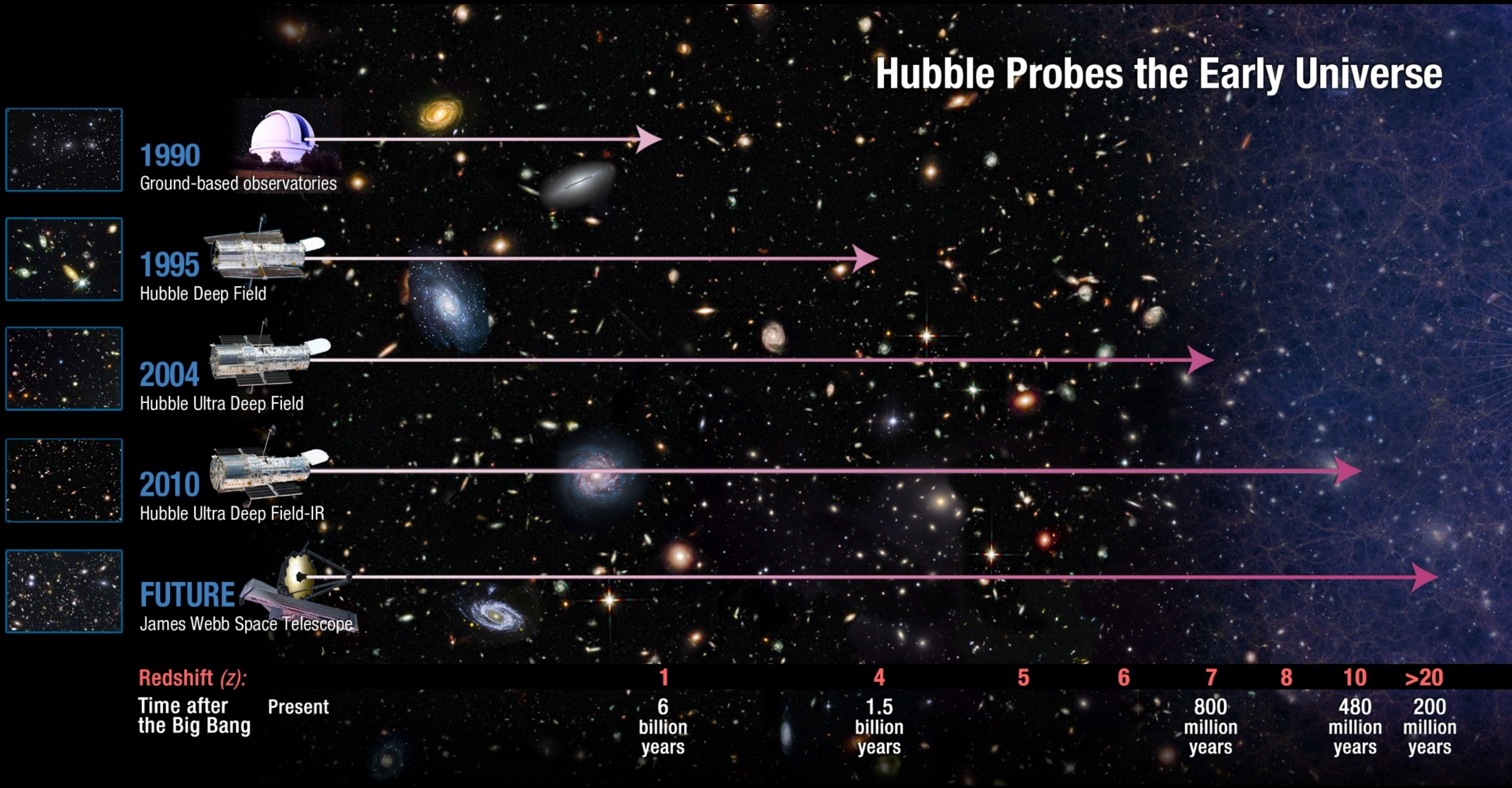
formation of the first stars,
and first galaxies…

Cosmic Dawn

Cosmic Timeline

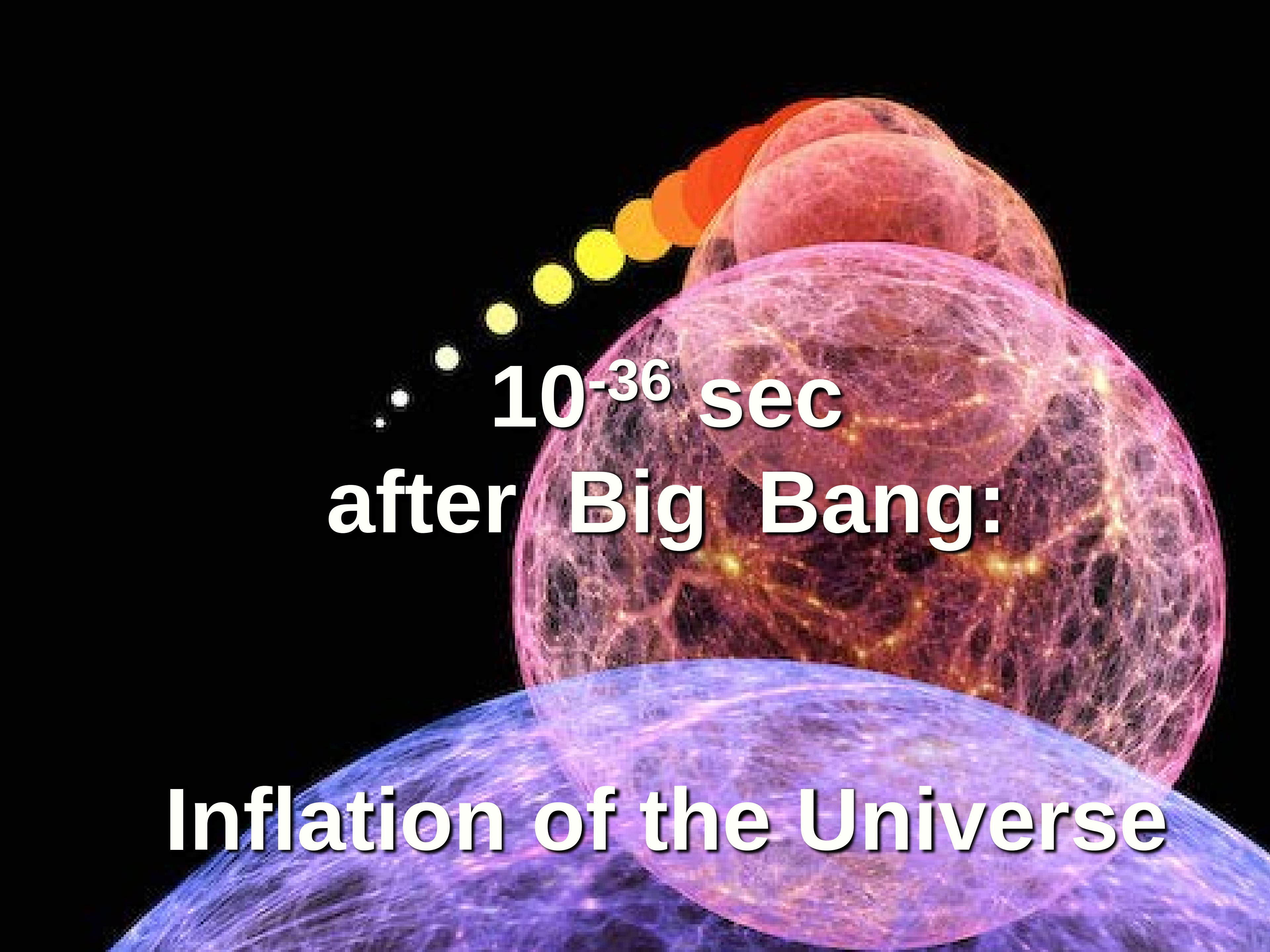


1,000
20
12
8
Redshift (z)
0
Hubble 2012
Hubble 2009
Cosmic "Dark Ages"
Reionization
Neutral IGM
First stars
First galaxies
Modern galaxies form
Present day
13.7
13.5
13.4
13.0
Billions of Years Ago
0
Big Bang
Recombination

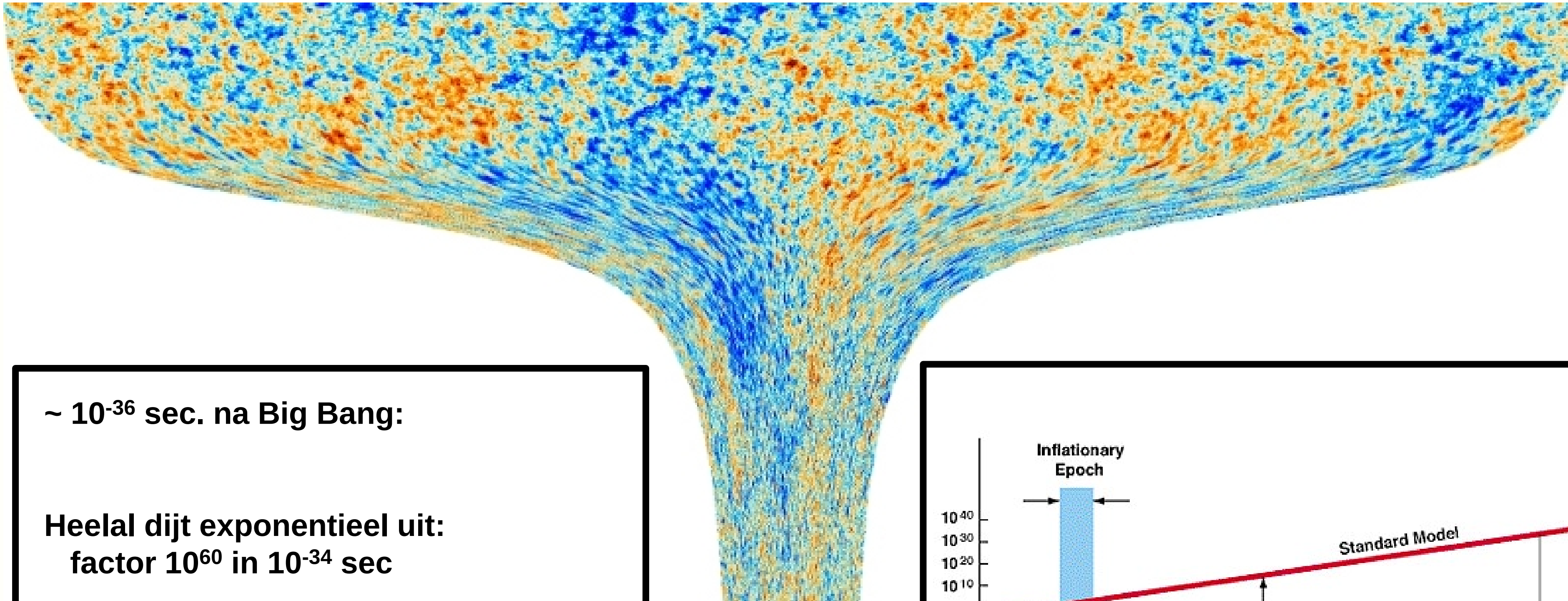

Hubble Probes the Early Universe
1990
Ground-based observatories
1995
Hubble Deep Field
2004
Hubble Ultra Deep Field
2010
Hubble Ultra Deep Field-IR
FUTURE
James Webb Space Telescope
Redshift (z):
1
4
5
6
7
8
10
>20
Time after the Big Bang
Present
6 billion years
1.5 billion years
800 million years
480 million years
200 million years

Cosmic Beginnings:

pre-recombination Ancient Universe


10^{-36} sec
after Big Bang:
Inflation of the Universe

Kosmische Inflatie

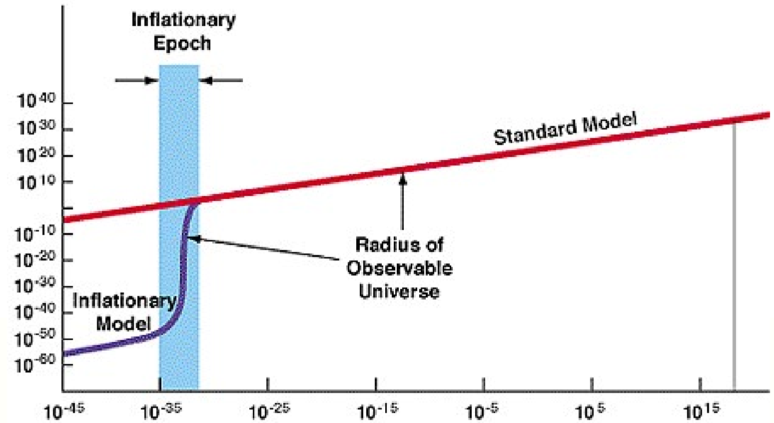


~ 10^{-36} sec. na Big Bang:

Heelal dijt exponentieel uit:
factor 10^{60} in 10^{-34} sec

Afmeting huidige zichtbare Heelal:

begin inflatie: 10^{-15} afmeting atoom
eind inflatie: diameter van stuiver



Adiabatic Cosmic Expansion

- The Universe of Einstein, Friedmann & Lemaitre expands *adiabatically*
- Energy of the expansion of the Universe corresponds to the decrease in the energy of its constituents
- *The Universe COOLS as a result of its expansion !*

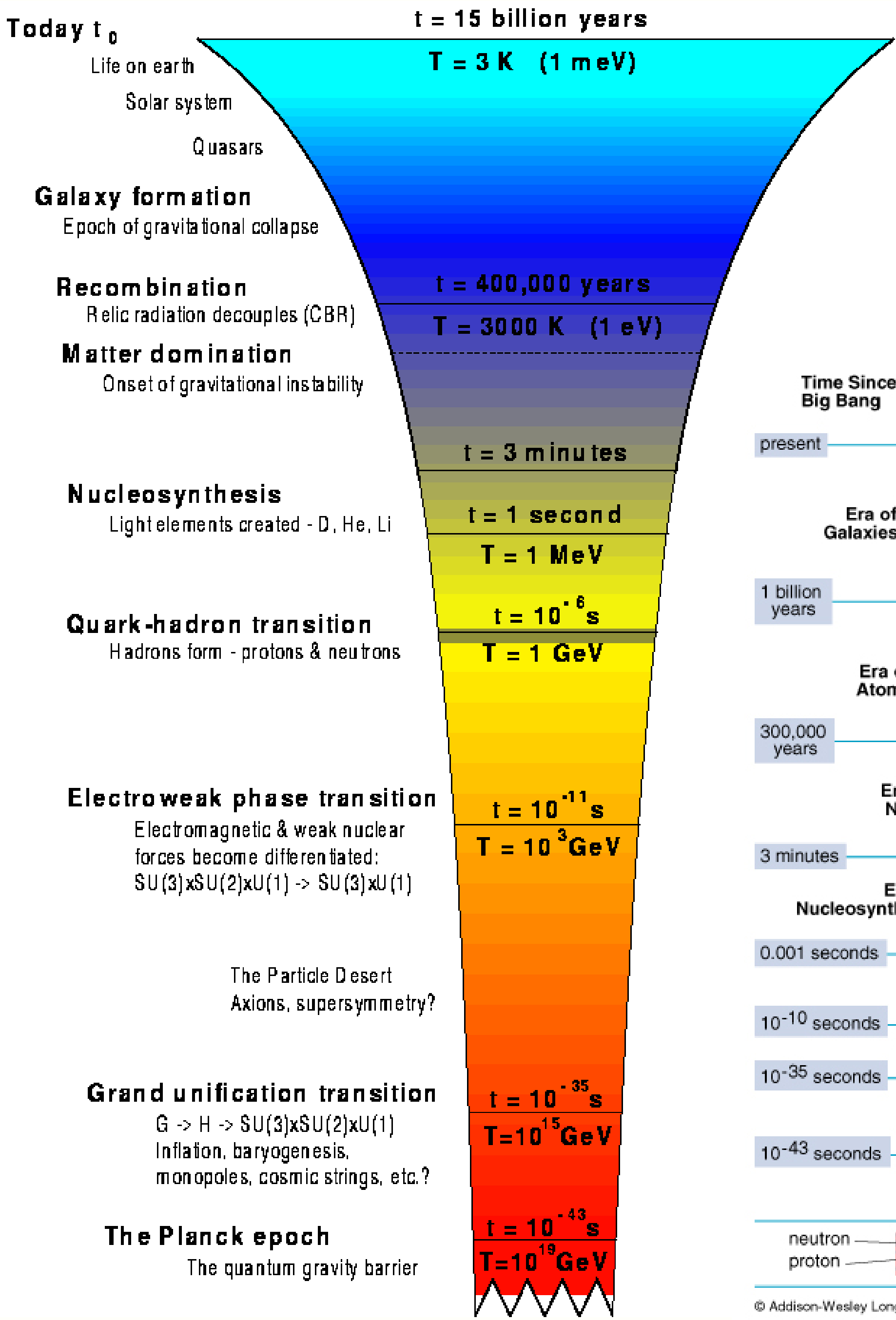
$$T_{rad}(t) \propto 1/a(t)$$

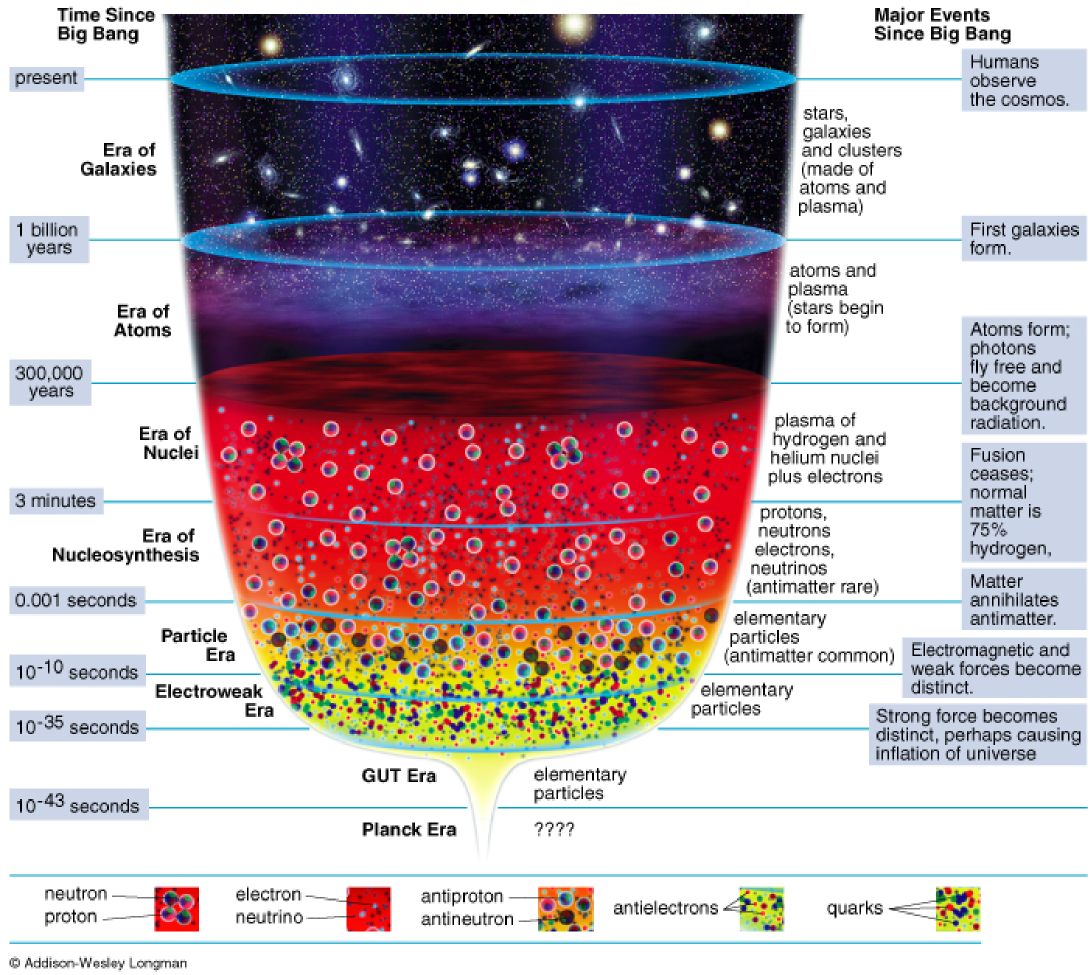
Cosmic Epochs

Epoch	Transitions	Time
Planck Epoch		$t < 10^{-43}$ sec
Phase Transition Era	GUT transition electroweak transition quark-hadron transition	10^{-43} sec $< t < 10^{5}$sec
Hadron Era		$t \sim 10^{-5}$ sec
Lepton Era	muon annihilation neutrino decoupling electron-positron annihilation primordial nucleosynthesis	10^{-5} sec $< t <$ 1 min
Radiation Era	radiation-matter equivalence recombination & decoupling	1 min $< t <$ 379,000 yrs
Post-Recombination Era	Structure & Galaxy formation Dark Ages Reionization Matter-Dark Energy transition	$t >$ 379,000 yrs

Adiabatic Expansion

reconstruction Thermal History of the Universe

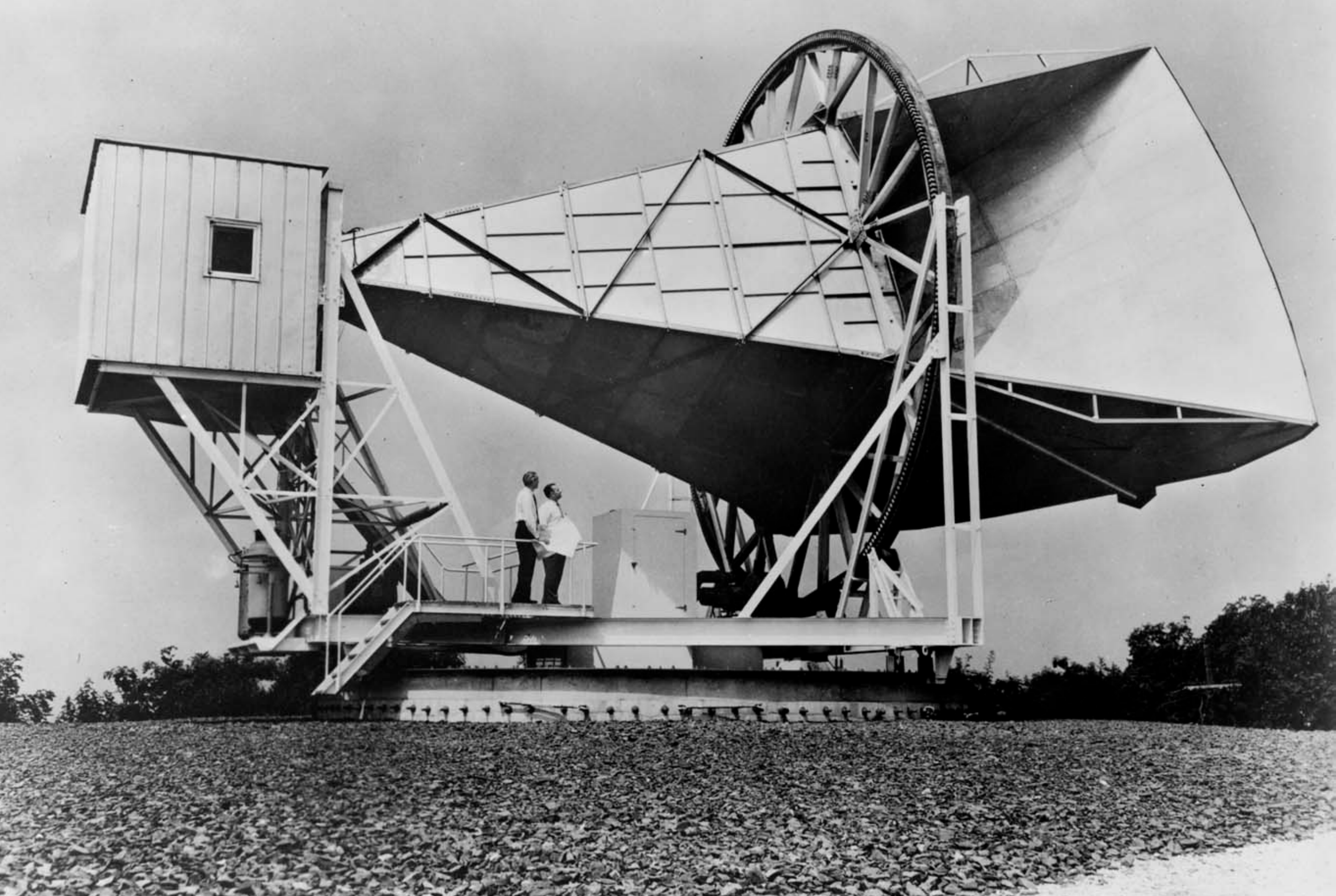




Echo of the Big Bang:

Recombination
&
Decoupling

Cosmic Microwave Background Radiation



the Cosmic TV Show

<u>Note:</u>

far from being an exotic faraway phenomenon, realize that the CMB nowadays is counting for approximately 1% of the noise on your (camping) tv set ...

!!!! Live broadcast from the Big Bang !!!!

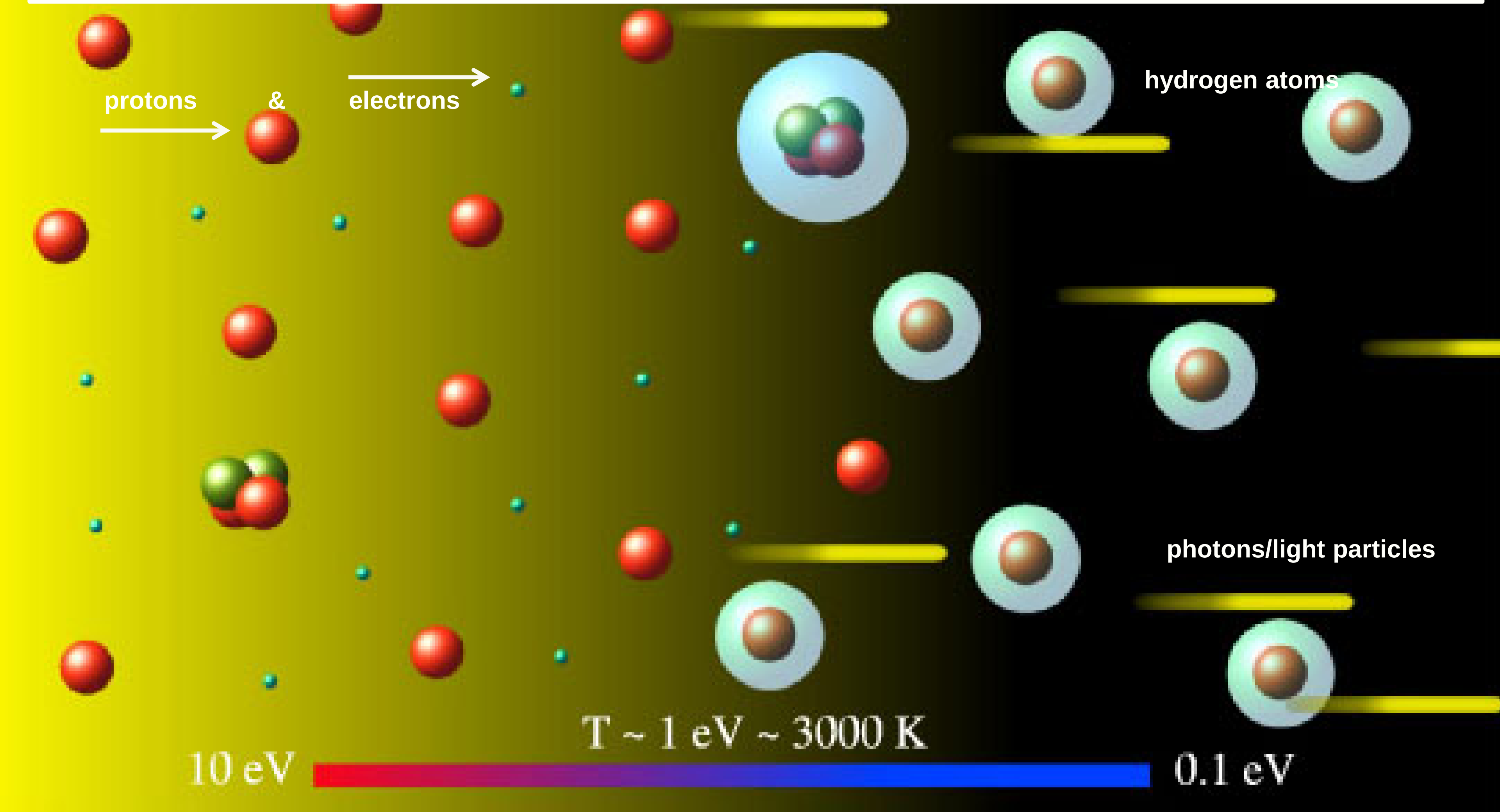
Courtesy: W. Hu

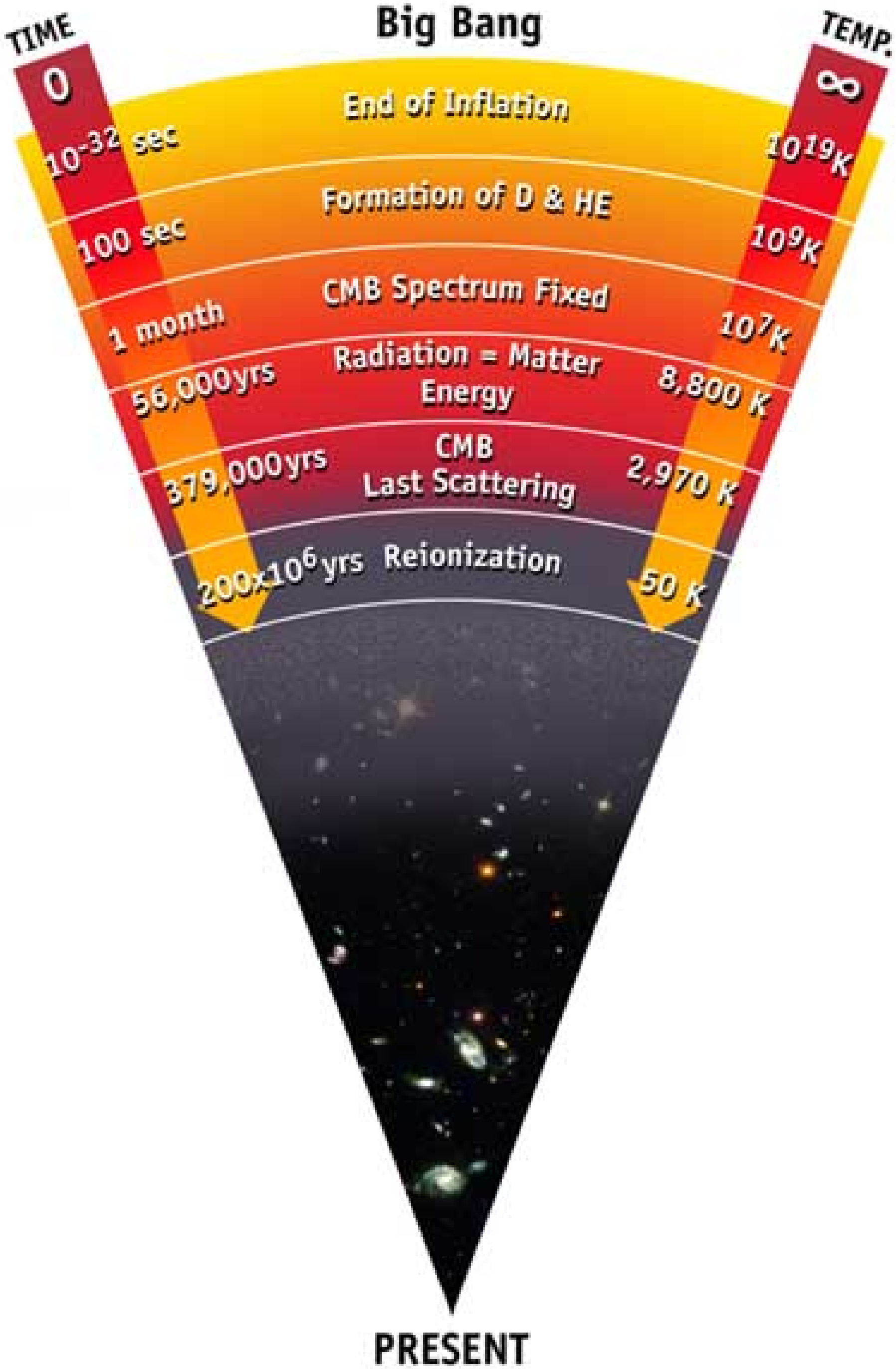
Cosmic Light (CMB): the facts

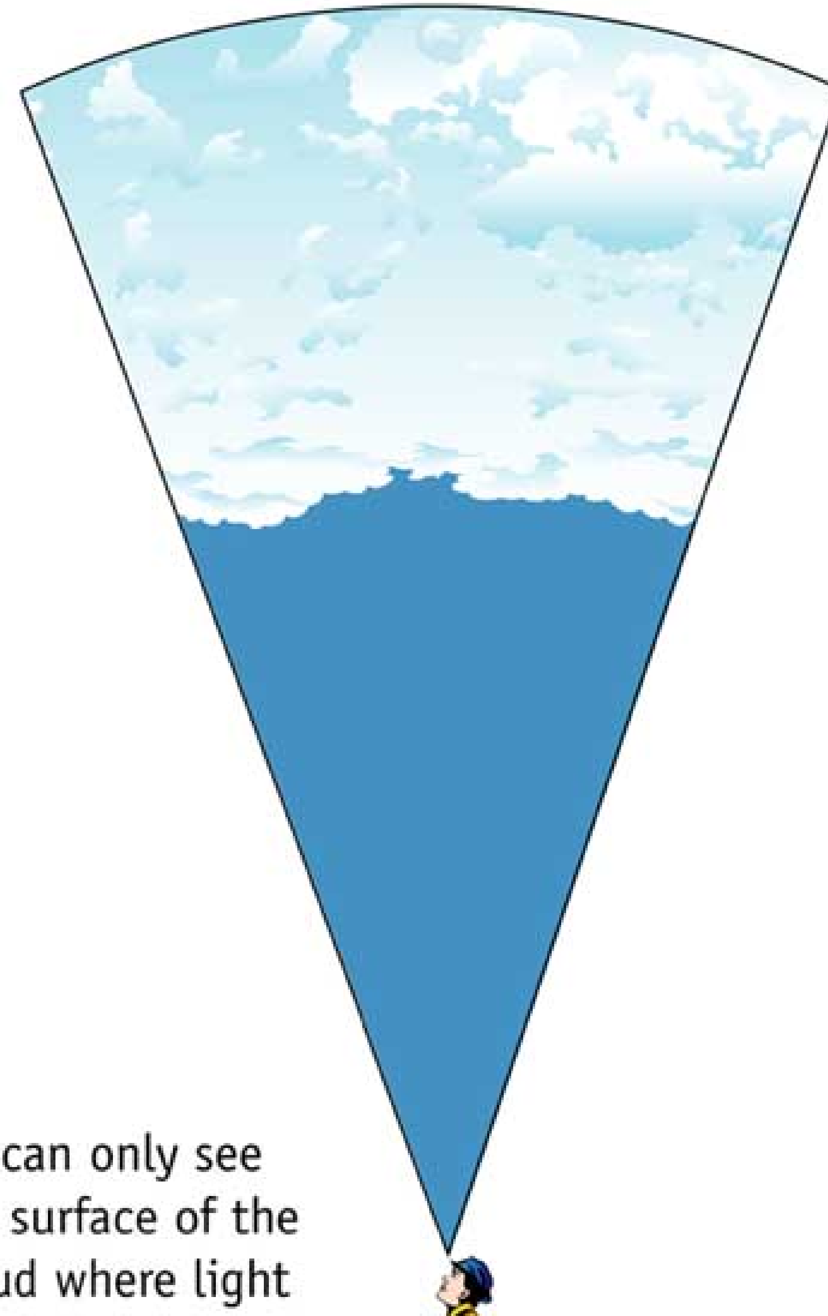
- Discovered serendipitously in 1965 — Penzias & Wilson, Nobelprize 1978 !!!!!
- Cosmic Licht that fills up the Universe uniformly
- Temperature: $T_\gamma = 2.725$ K
- (CMB) photons most abundant particle in the Universe: $n_\gamma \sim 415$ cm^{-3}
- Per atom in the Universe: $n_\gamma / n_B \sim 1.9 \times 10^9$
- Ultimate evidence of the Big Bang !!!!!!!!!!!!!!!!!!!!

Recombination & Decoupling:

379,000 years into the Big Bang

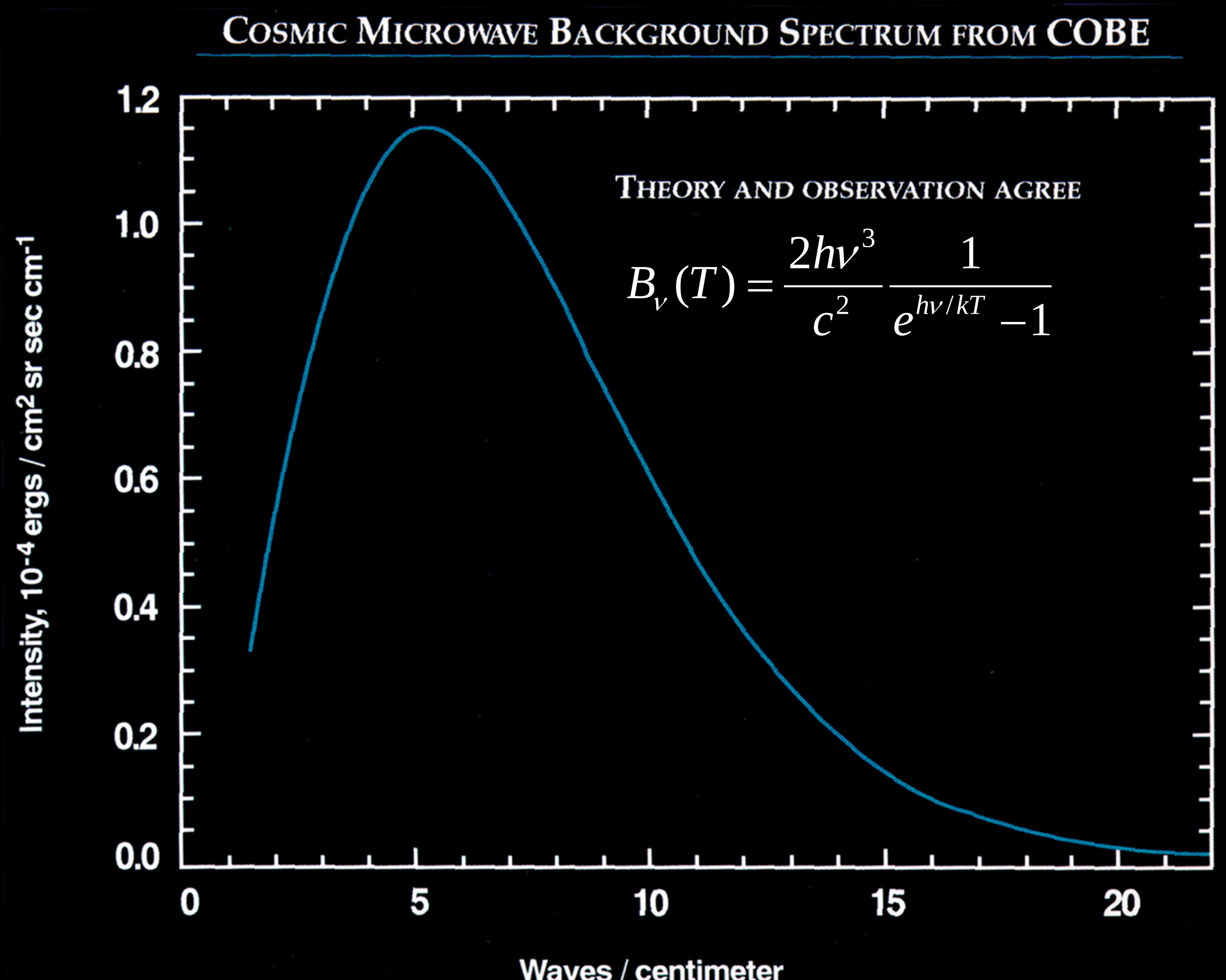






We can only see the surface of the cloud where light

Energy Spectrum
Cosmic Light



- **COBE-DIRBE:**
  temperatureT = 2.725 K
- **John Mather**
  Nobelprize physics
  2006
- **Most perfect**
  Black Body
  Spectrum ever seen !!!!

FRW Dynamics: Thermal Evolution

Adiabatic Expansion of the Universe:

- **Implication for Thermal History**
- **Temperature Evolution of cosmic components**

For a medium with adiabatic index γ:

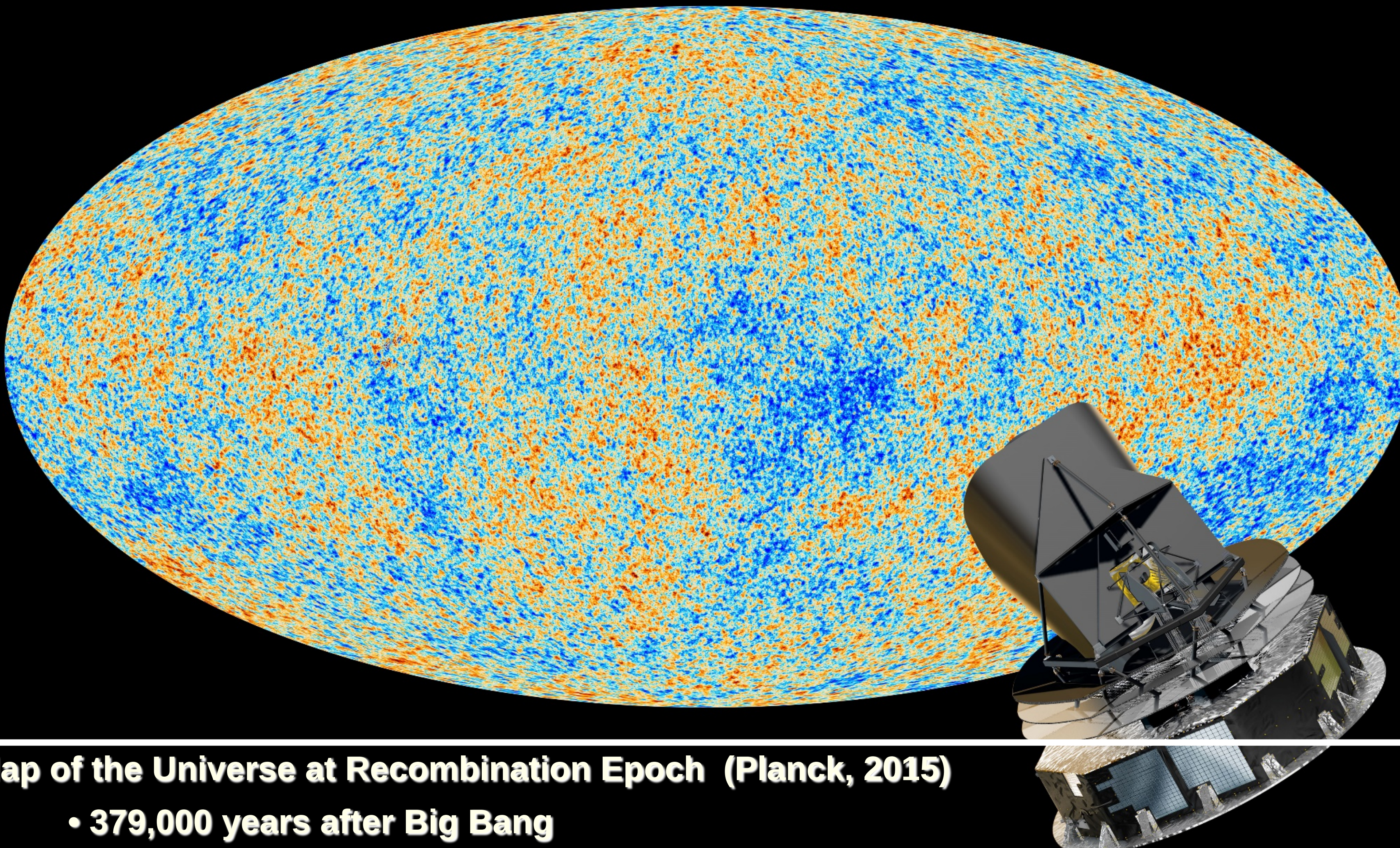
$$TV^{\gamma-1} = cst$$

Radiation (Photons)	$\gamma = \frac{4}{3}$	$T = \frac{T_0}{a}$
Monatomic Gas (hydrogen)	$\gamma = \frac{5}{3}$	$T = \frac{T_0}{a^2}$

Primordial Structure:

Gaussian Fields

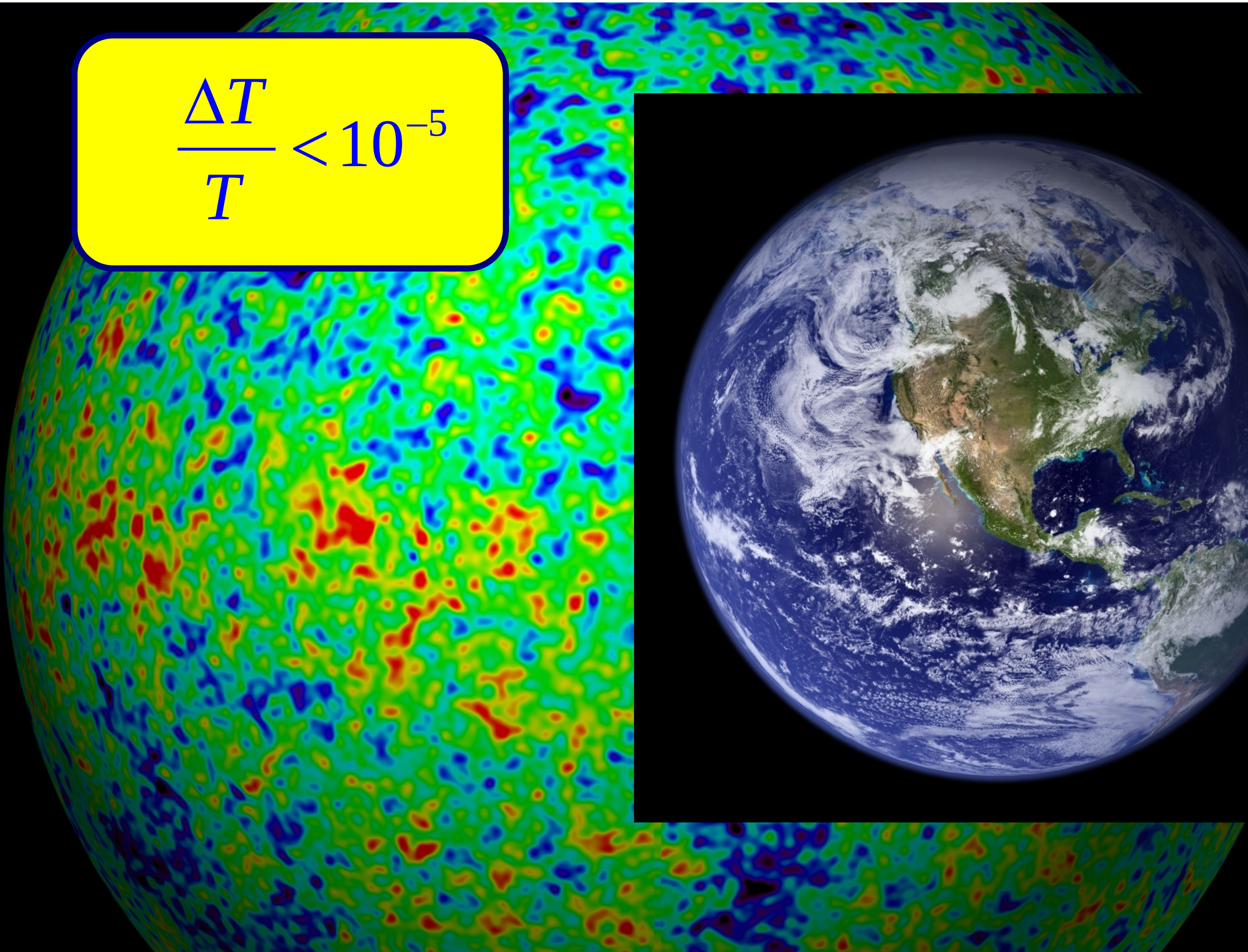
Cosmic Microwave Background



Map of the Universe at Recombination Epoch (Planck, 2015)

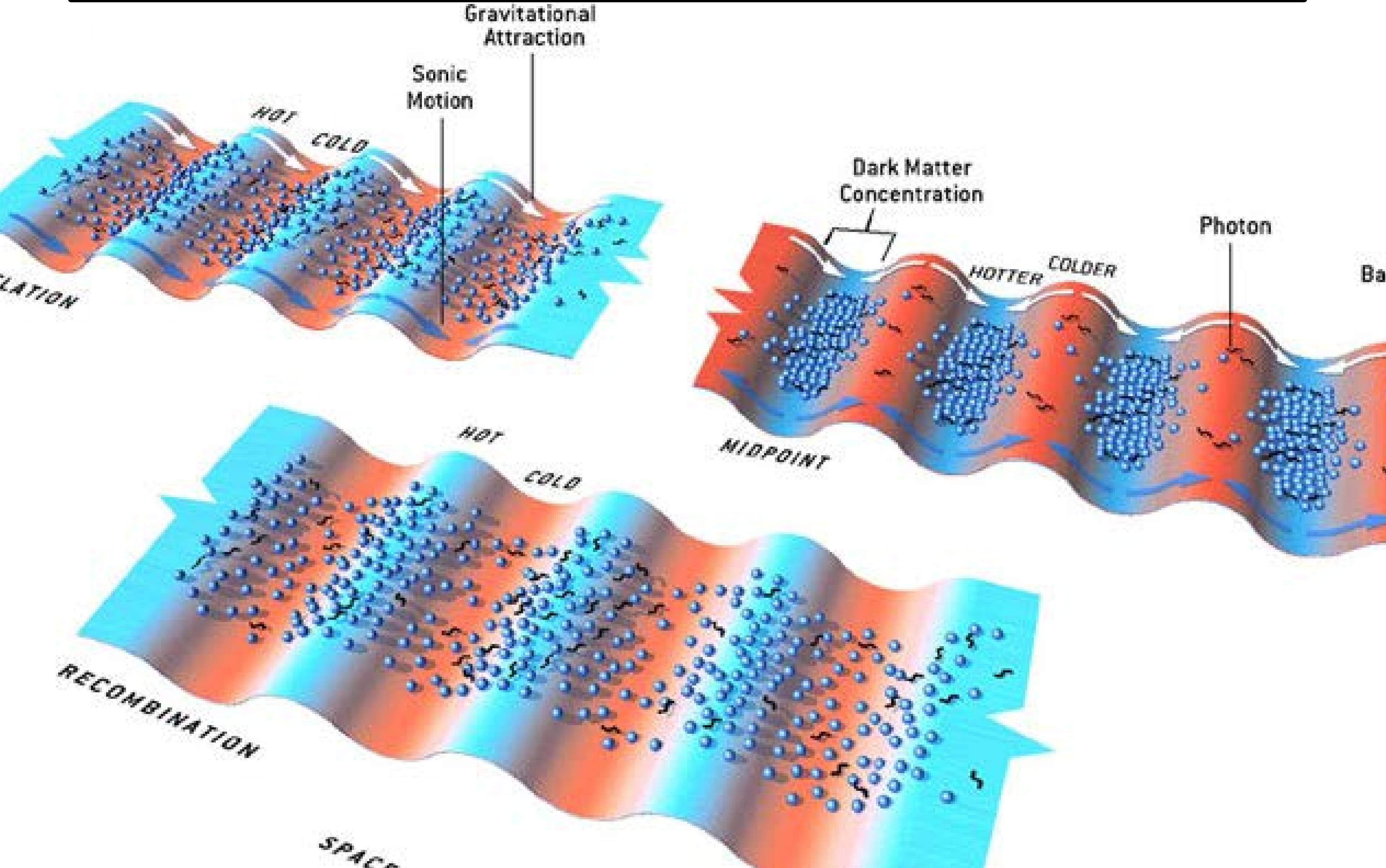
- 379,000 years after Big Bang
- Subhorizon perturbations: primordial sound waves
- $\Delta T/T$ < 10-5

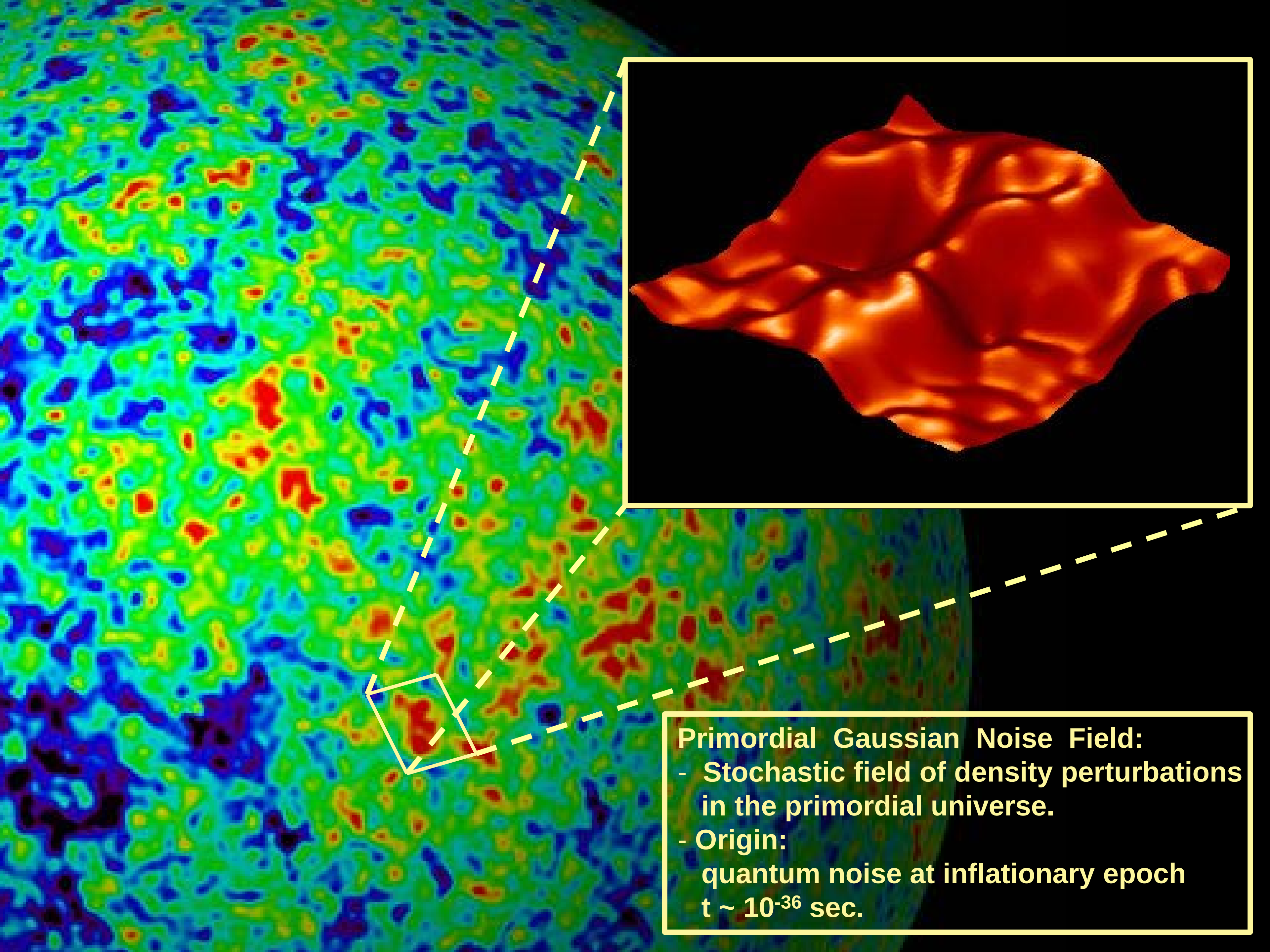
Extremely Smooth Radiation Field



$$\frac{\Delta T}{T} < 10^{-5}$$

Primordial Noise:
Matter & Radiation Fluctuations




Primordial Gaussian Noise Field:
- Stochastic field of density perturbations in the primordial universe.
- Origin:
quantum noise at inflationary epoch
t ~ 10^{-36} sec.

Cosmic Structure Formation

Gravitational Instability

Gravity Perturbations

$$\mathbf{g}(\mathbf{r},t) = -\frac{1}{a}\nabla\phi = \frac{3\Omega H^2}{8\pi}\int \mathrm{d}\mathbf{x}'\,\delta(\mathbf{x}',t)\,\frac{(\mathbf{x}'-\mathbf{x})}{|\mathbf{x}'-\mathbf{x}|^3}$$

Cosmic Structure Formation

(Energy) Density Perturbations

↓

Gravity Perturbations

↓

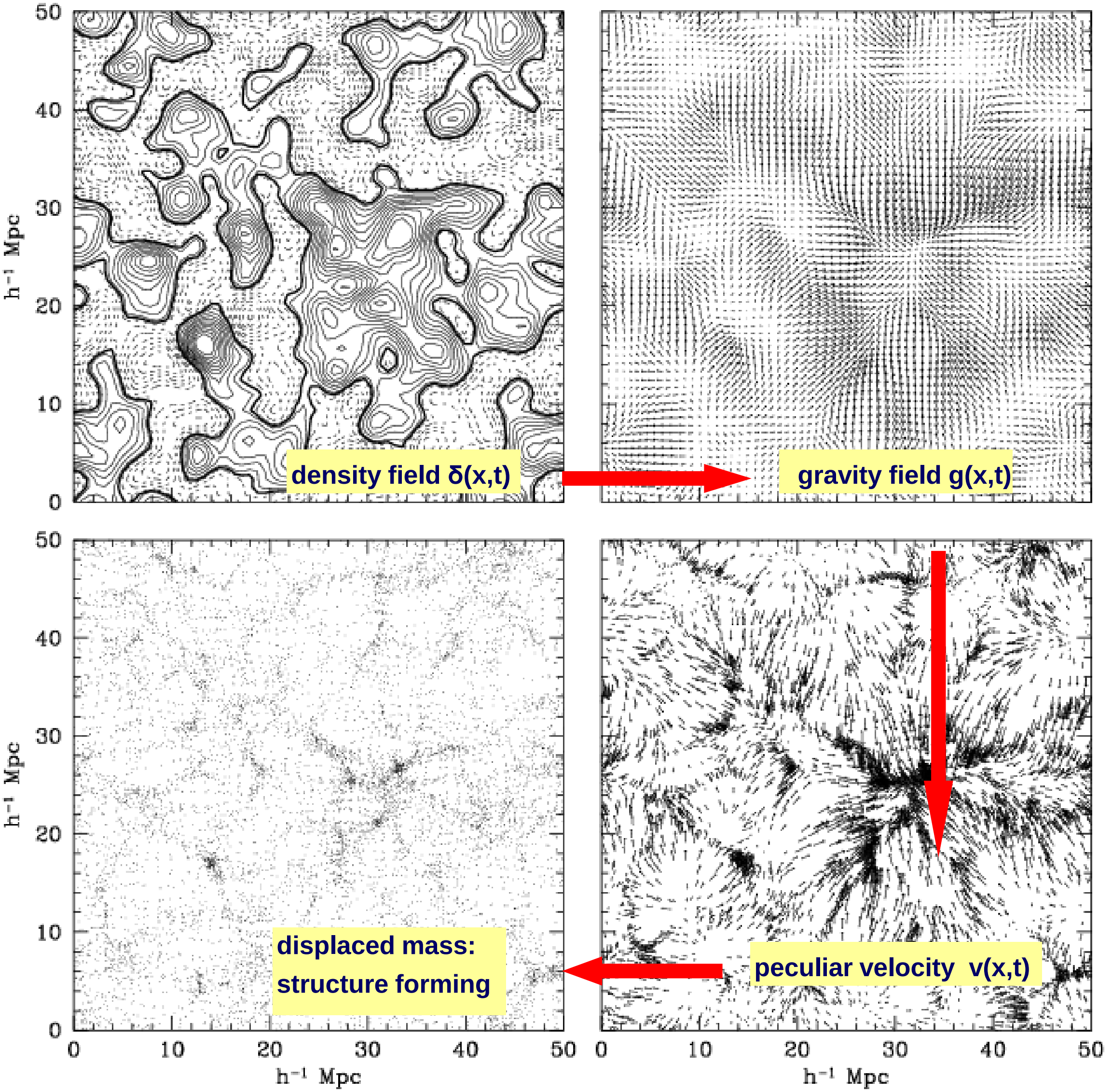
(Cosmic) Flows of (Energy) & Matter:

- towards high density regions:
  - assemble more and more matter
  - their expansion comes to a halt
  - turn around and collapse
- evacuating void regions
  - low-density regions expand
  - matter moves out of region
  - turn into prominent empty voids

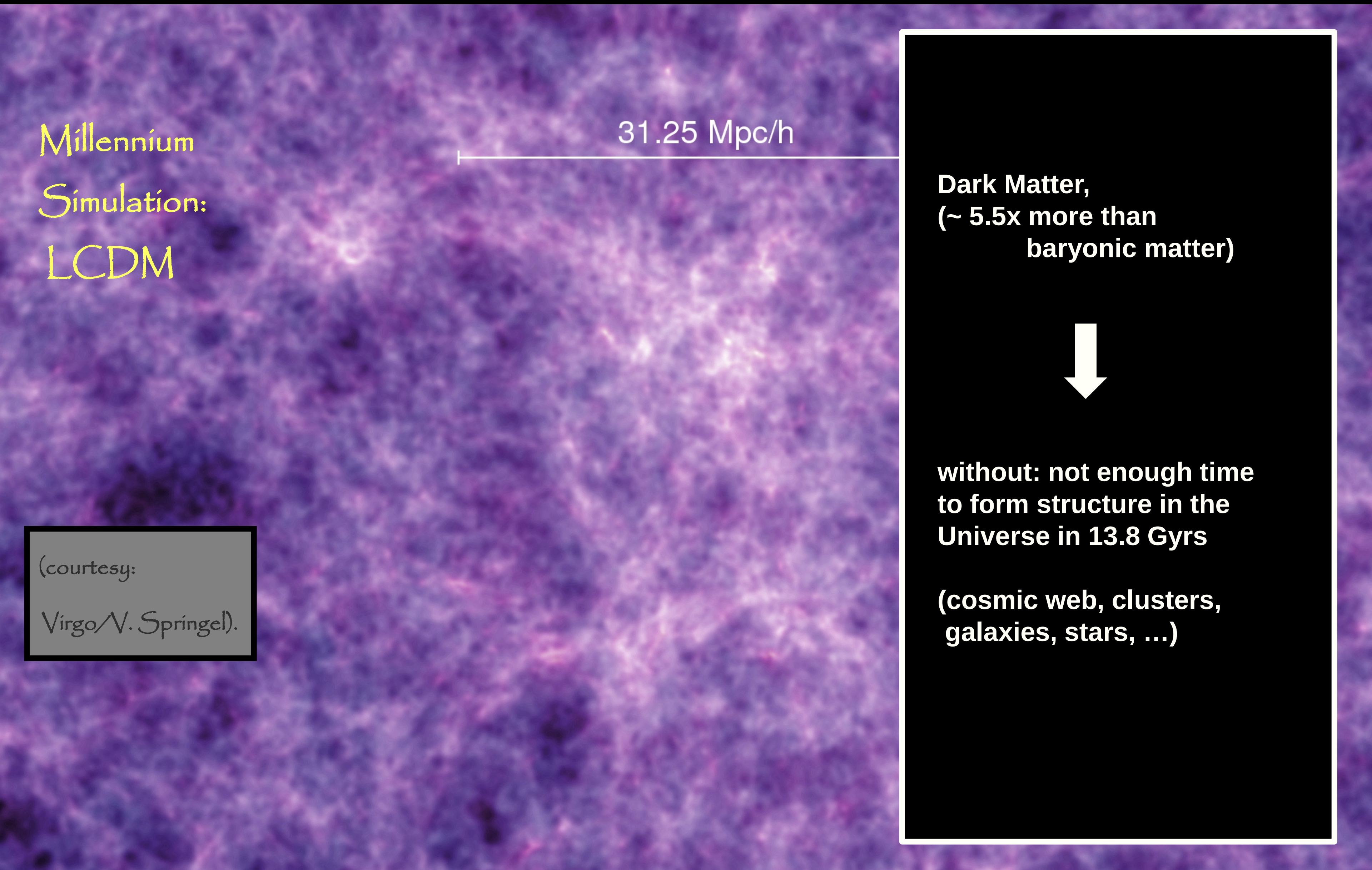
↓

Emergence of cosmic structures

- Computer Simulations
  - succesfull confrontation with observational reality



Cosmic Structure Formation



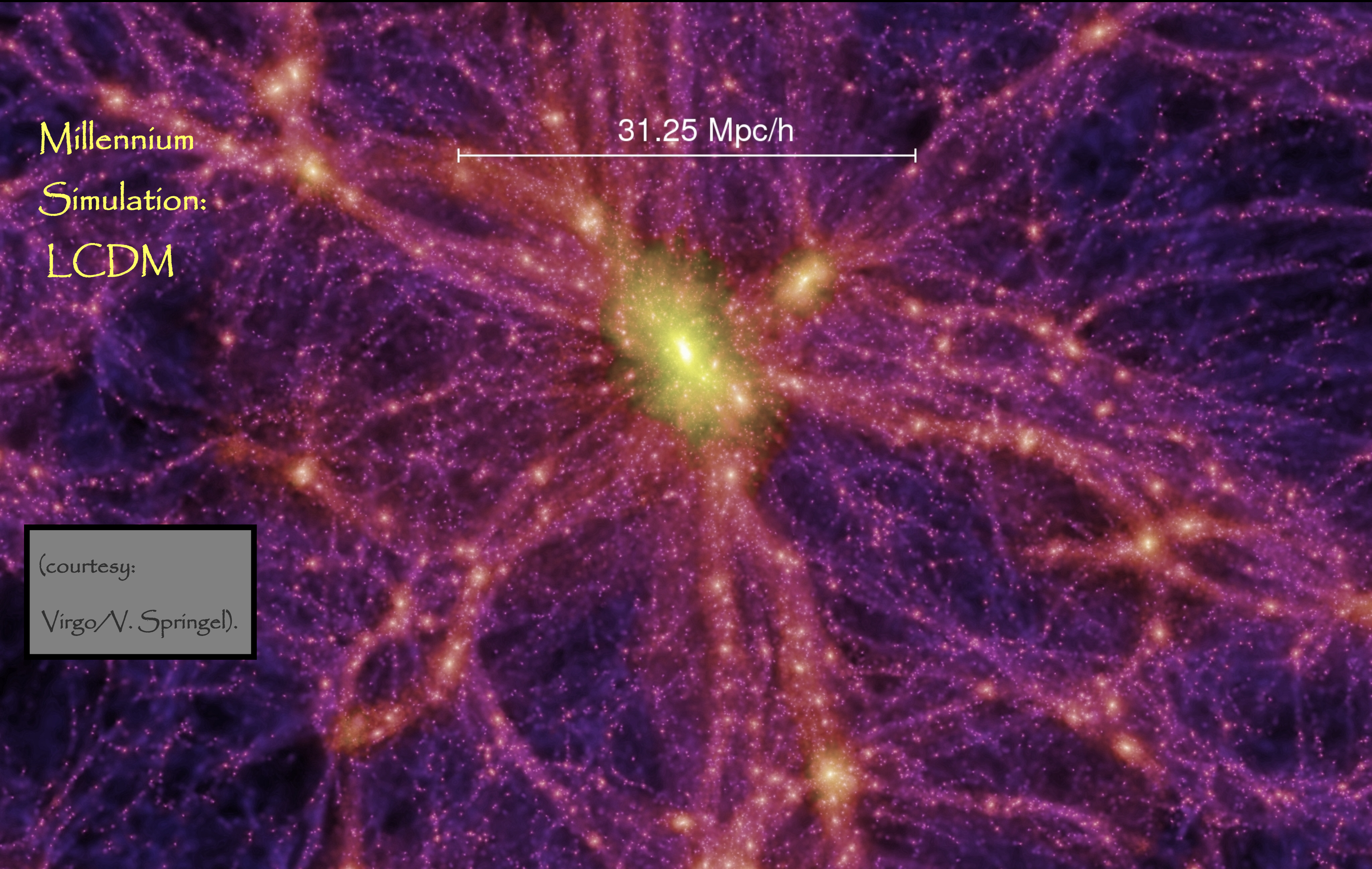
Dark Matter,
(~ 5.5x more than baryonic matter)

⬇

without: not enough time to form structure in the Universe in 13.8 Gyrs

(cosmic web, clusters, galaxies, stars, ...)

Cosmic Structure Formation



Cosmic Structure Formation

Formation
Cosmic Web:

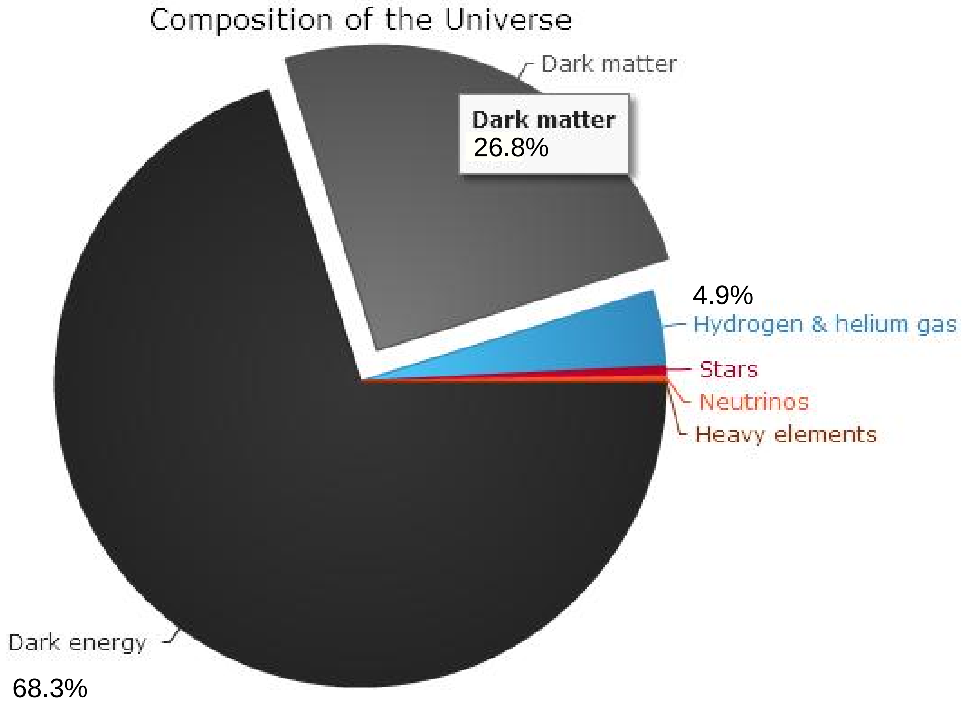
simulation
sequence

(cold)
dark matter

(courtesy:
Virgo/V. Springel).

Cosmic Composition

Cosmos: the Elements



Composition of the Universe

- **Normal matter** **~ 4.9%**
  - atoms of which we ourselves consist
  - stars represent only ~0.20% of cosmic energy budget!
- **Dark Matter** **~ 26.8%**
  - gravitationally dominant
  - invisible and unobservable
  - all structure in the Universe (galaxies, stars, planets, ...) only exists because of dark matter
  - unknown what it exists of/what it is
- **Dark Energy** **~ 68.3%**
  - gravitational repulsion
  - dominates expansion (& fate) of Universe
  - uniformly distributed over Universe,
  - does not clump: no major role in structure formation
  - discovered very recently, in 1998 !
- **Radiation** **~ 0.001%**
  - because of cooling Universe no longer energetically significant
  - by far most abundant particle in the Universe: 2×10^9 photons for each atom

Cosmic Energy Inventarisation

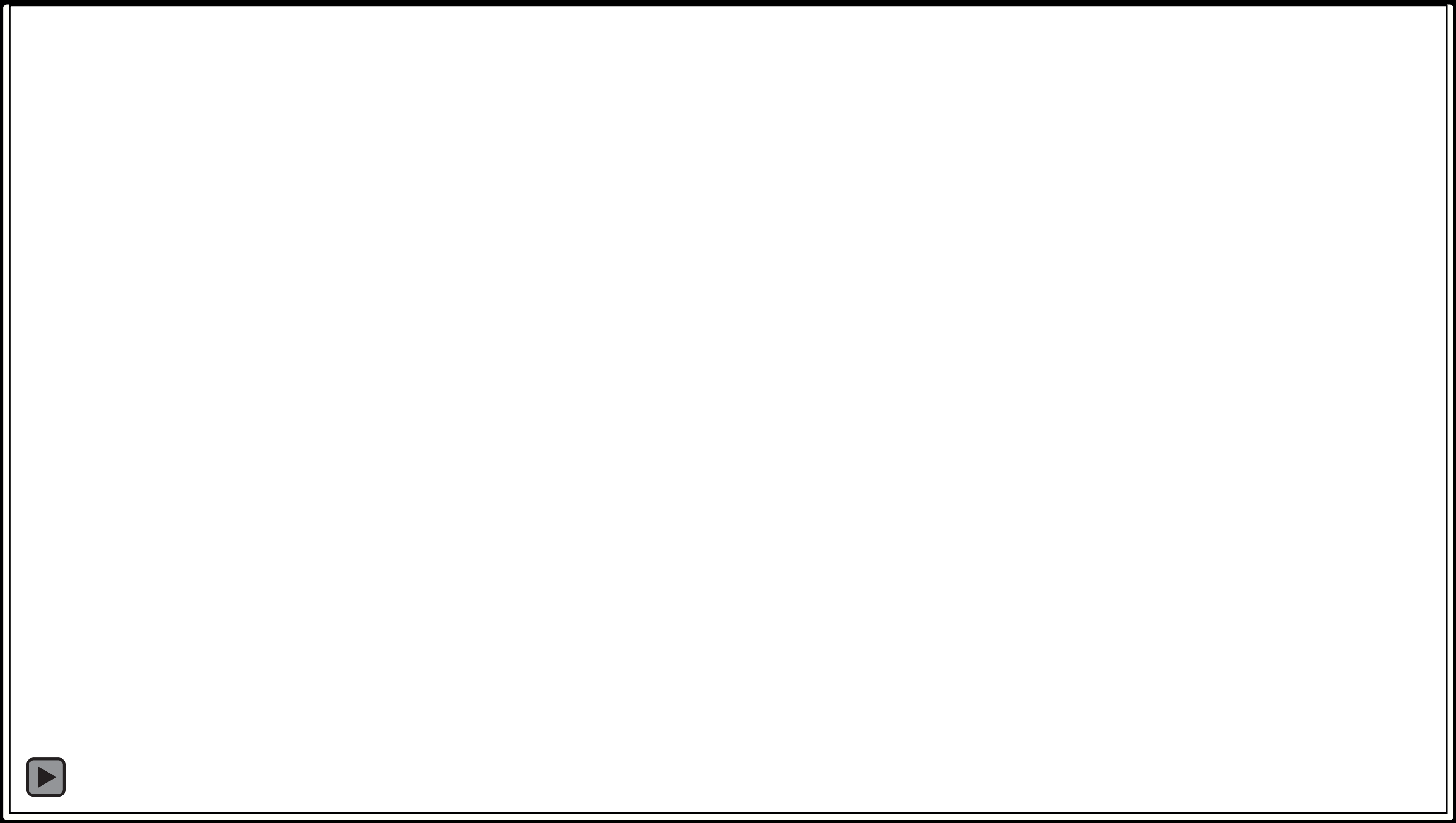
1	dark sector			0.954 ± 0.003
1.1	dark energy		0.72 ± 0.03	
1.2	dark matter		0.23 ± 0.03	
1.3	primeval gravitational waves		$\lesssim 10^{-10}$	
2	primeval thermal remnants			0.0010 ± 0.0005
2.1	electromagnetic radiation		$10^{-4.3\pm0.0}$	
2.2	neutrinos		$10^{-2.9\pm0.1}$	
2.3	prestellar nuclear binding energy		$-10^{-4.1\pm0.0}$	
3	baryon rest mass			0.045 ± 0.003
3.1	warm intergalactic plasma		0.040 ± 0.003	
3.1a	virialized regions of galaxies	0.024 ± 0.005		
3.1b	intergalactic	0.016 ± 0.005		
3.2	intracluster plasma		0.0018 ± 0.0007	
3.3	main sequence stars	spheroids and bulges	0.0015 ± 0.0004	
3.4		disks and irregulars	0.00055 ± 0.00014	
3.5	white dwarfs		0.00036 ± 0.00008	
3.6	neutron stars		0.00005 ± 0.00002	
3.7	black holes		0.00007 ± 0.00002	
3.8	substellar objects		0.00014 ± 0.00007	
3.9	HI + HeI		0.00062 ± 0.00010	
3.10	molecular gas		0.00016 ± 0.00006	
3.11	planets		10^{-6}	
3.12	condensed matter		$10^{-5.6\pm0.3}$	
3.13	sequestered in massive black holes		$10^{-5.4}(1+\epsilon_n)$	
4	primeval gravitational binding energy			$-10^{-6.1\pm0.1}$
4.1	virialized halos of galaxies		$-10^{-7.2}$	
4.2	clusters		$-10^{-6.9}$	
4.3	large-scale structure		$-10^{-6.2}$	

stars a mere ~0.1% energy in the Universe

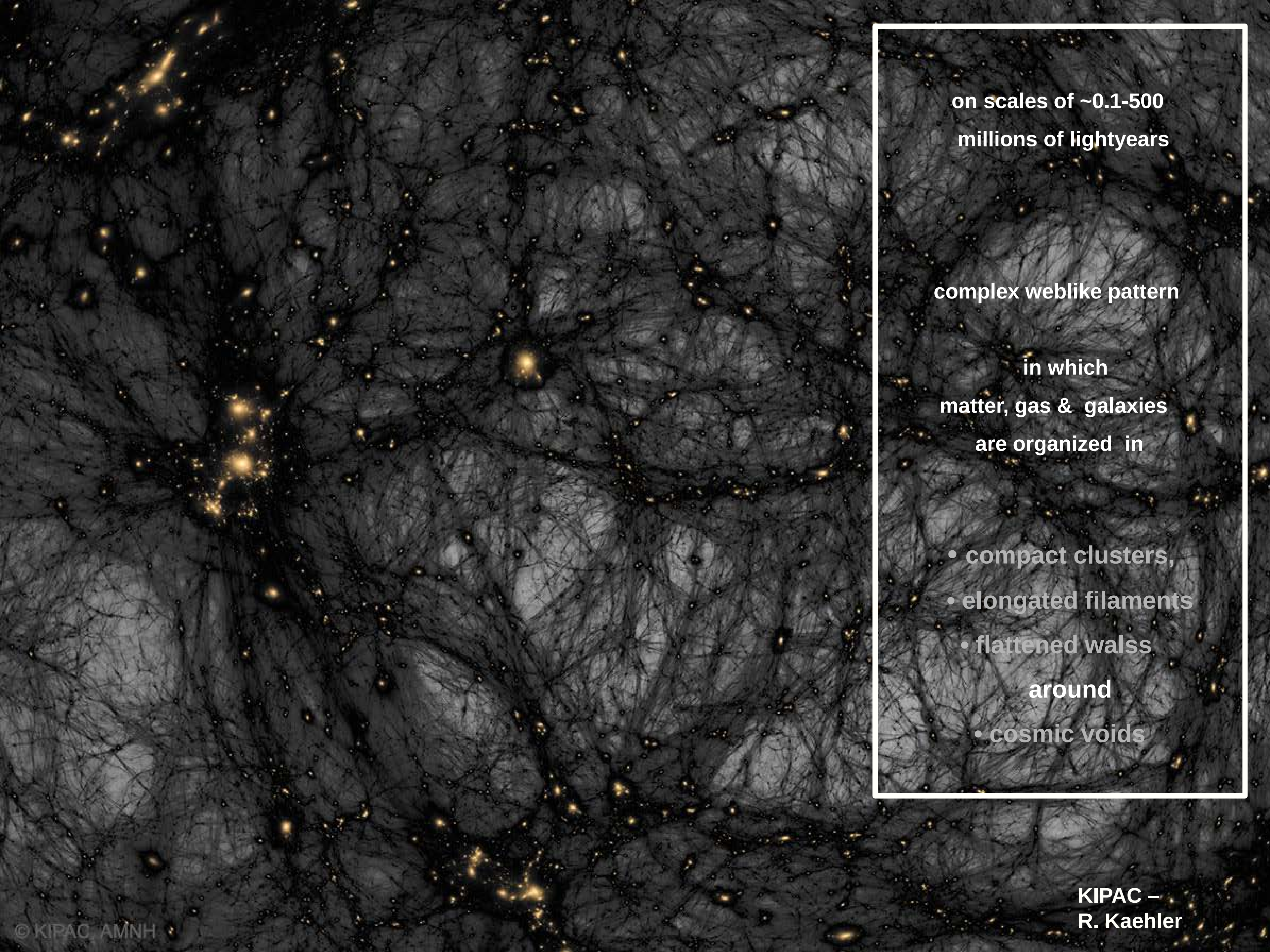
Fukugita & Peebles 2004

the Cosmic Web

Dark Matter weaving a Cosmic Tapestry



KIPAC –
R. Kaehler


on scales of ~0.1-500
millions of lightyears
complex weblike pattern
in which
matter, gas & galaxies
are organized in
• compact clusters,
• elongated filaments
• flattened walss
around
• cosmic voids
KIPAC –
R. Kaehler
© KIPAC, AMNH

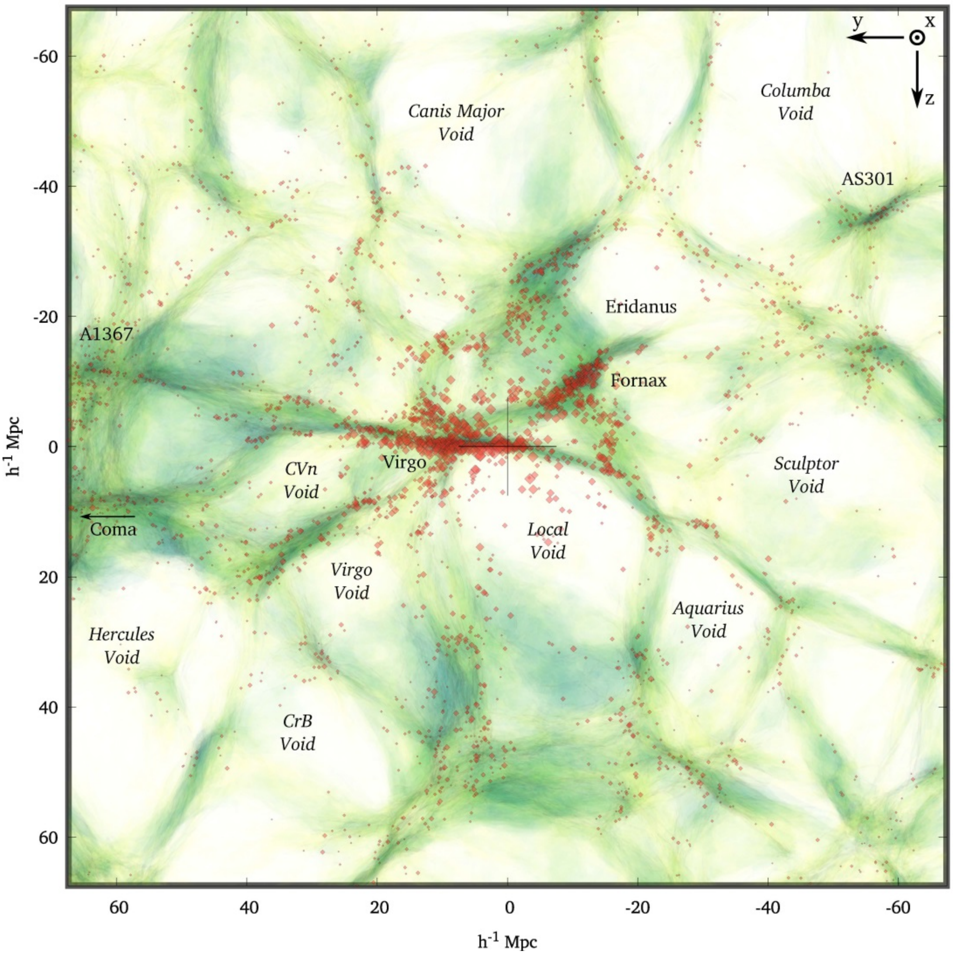
Cosmic Web Characteristics

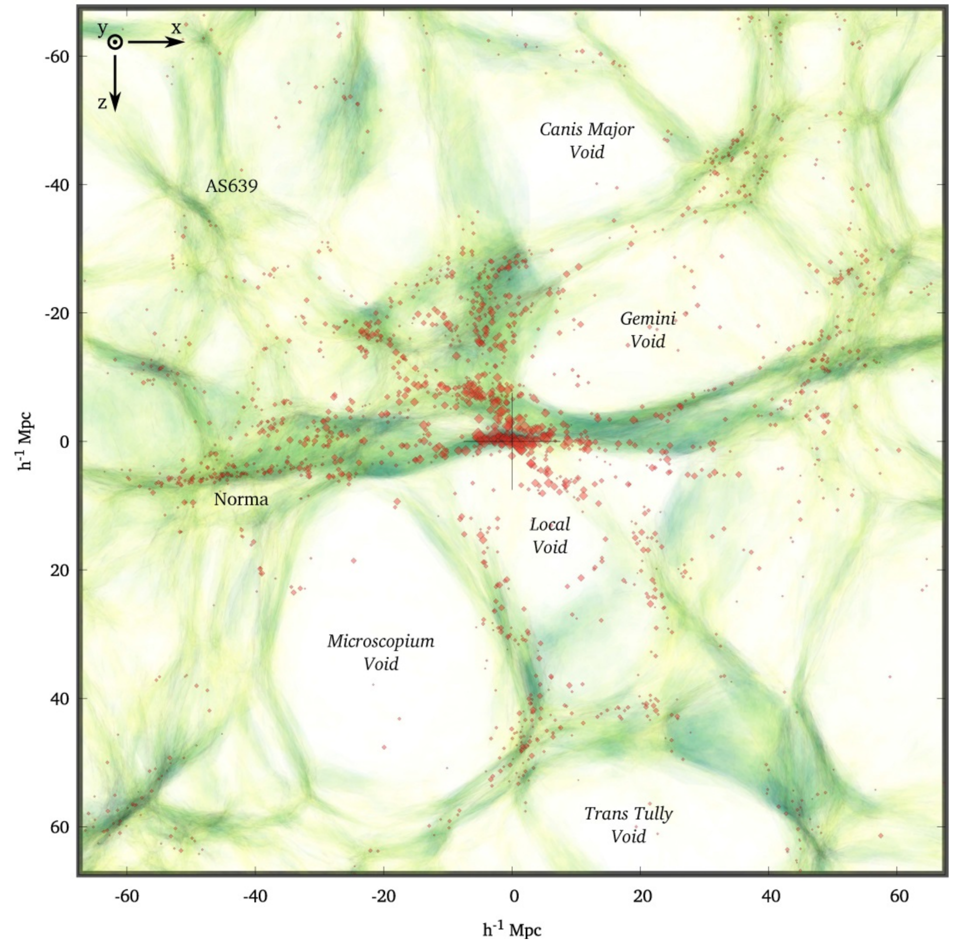
- **anisotropic structure:**
  - filaments dominant structural feature - elongated
  - sheets/walls - flattened
- **multiscale nature**
  - structure on wide range of scales
  - structures have wide range of densities
- **overdense-underdense asymmetry**
  - voids: underdense, large & roundish
  - filaments & walls: overdense, flattened/elongated
  - clusters: dense, massive & compact nodes
- **complex spatial connectivity**
  - all structural features connected in a complex, multiscale weblike network

Void Population Local Universe

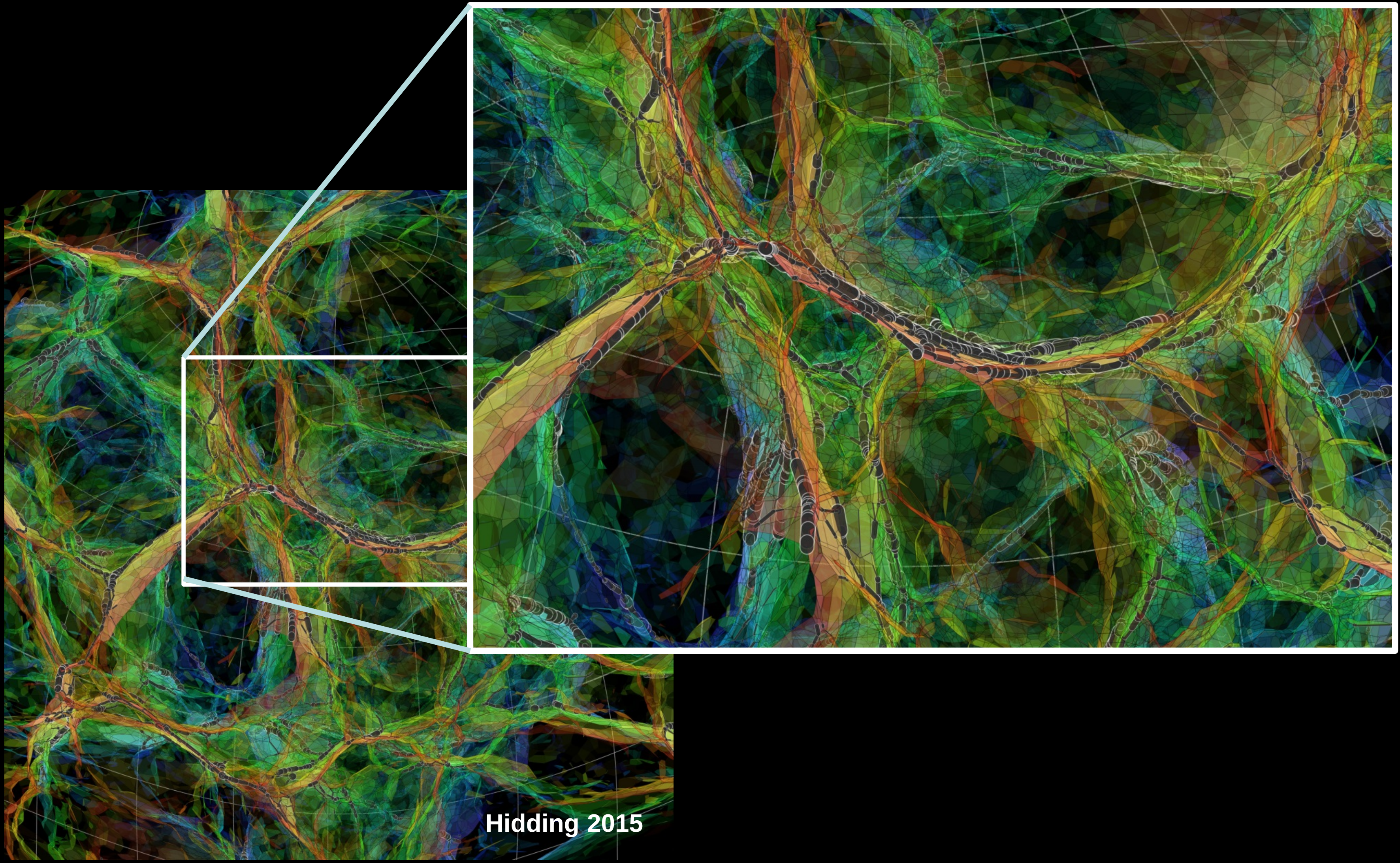
mean KIGEN-adhesion reconstruction (2MRS)

Hidding, Kitaura, vdW & Hess 2016/2017

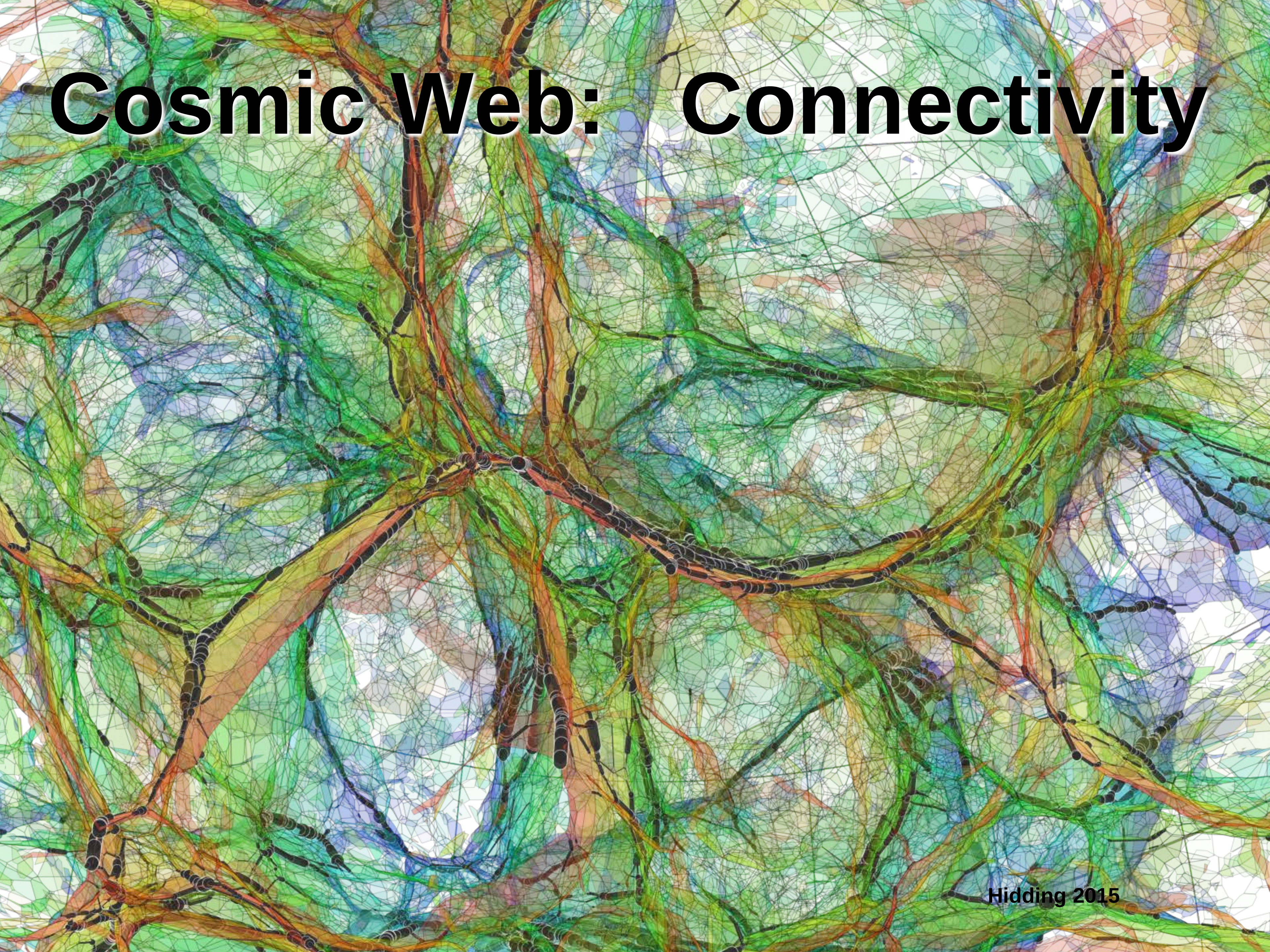




Pisces-Perseus Supercluster

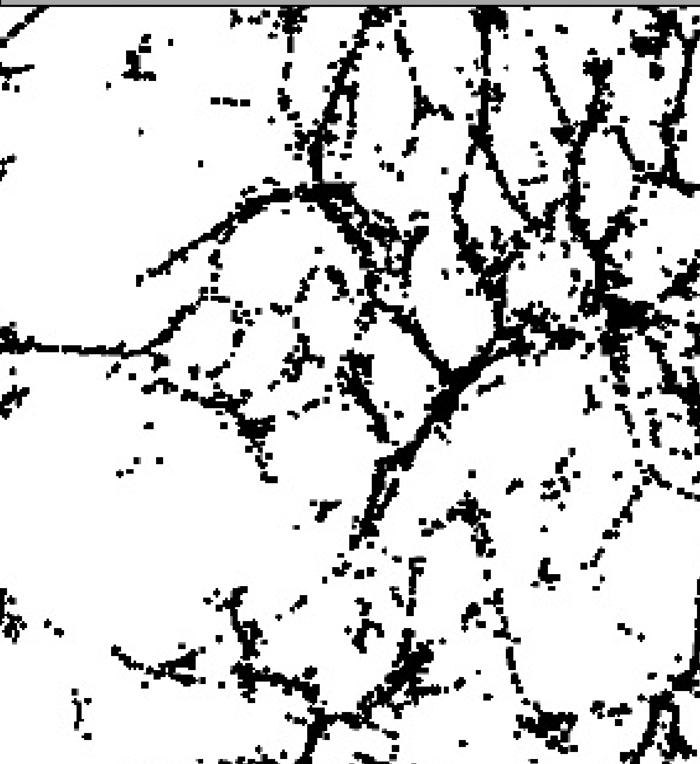


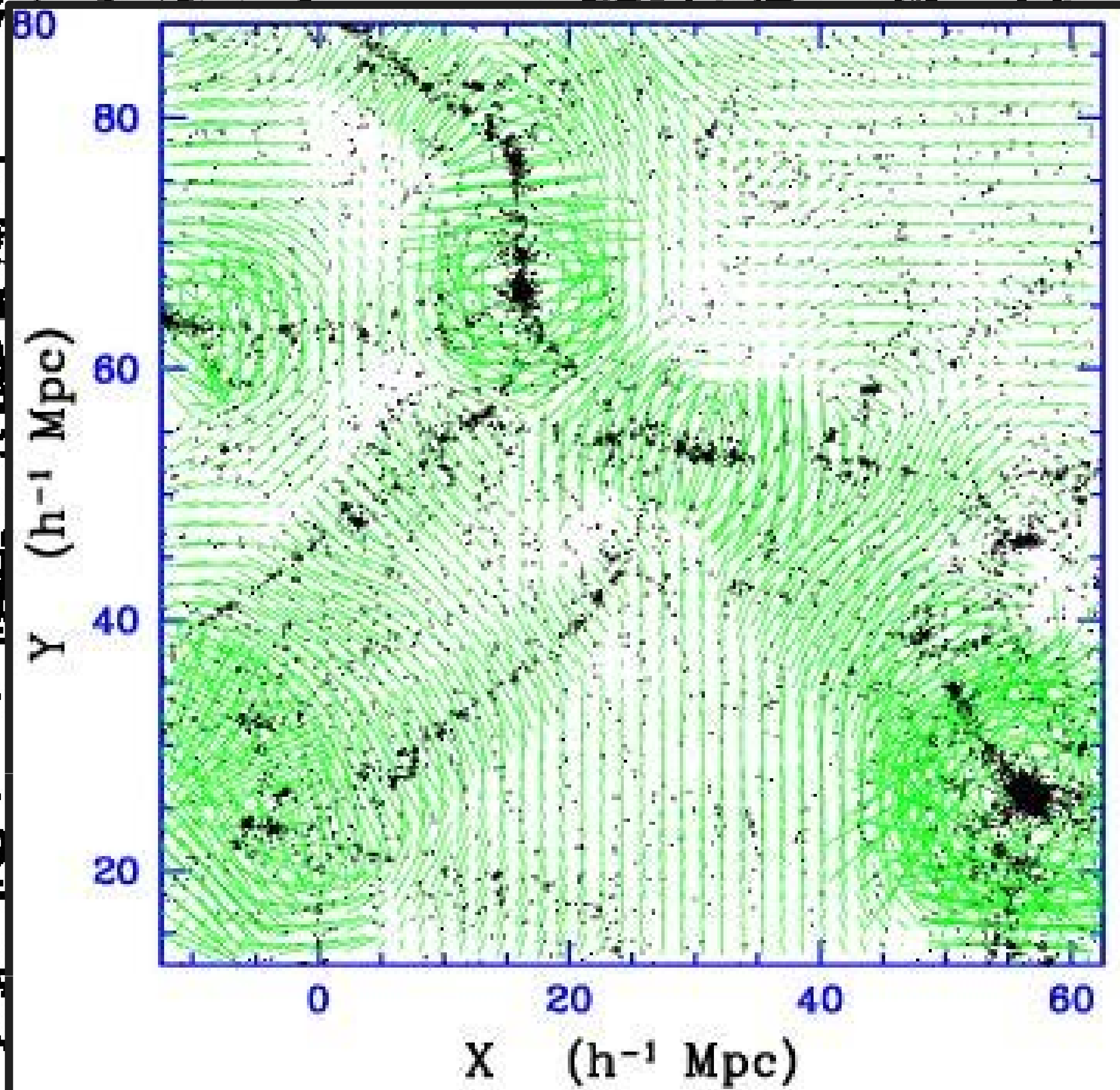
Cosmic Web: Connectivity



Hidding 2015

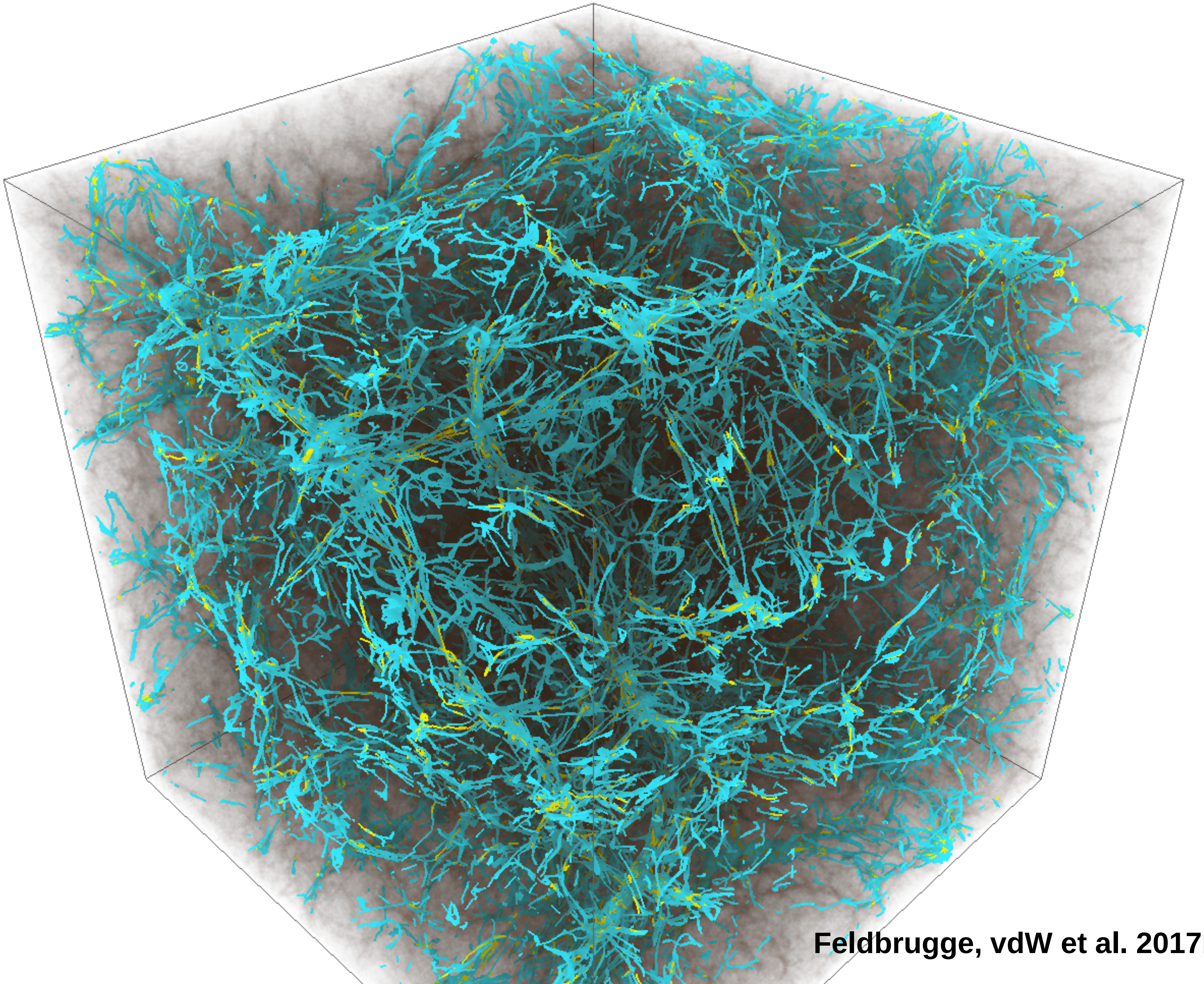
Tidal Shaping of the Cosmic Web



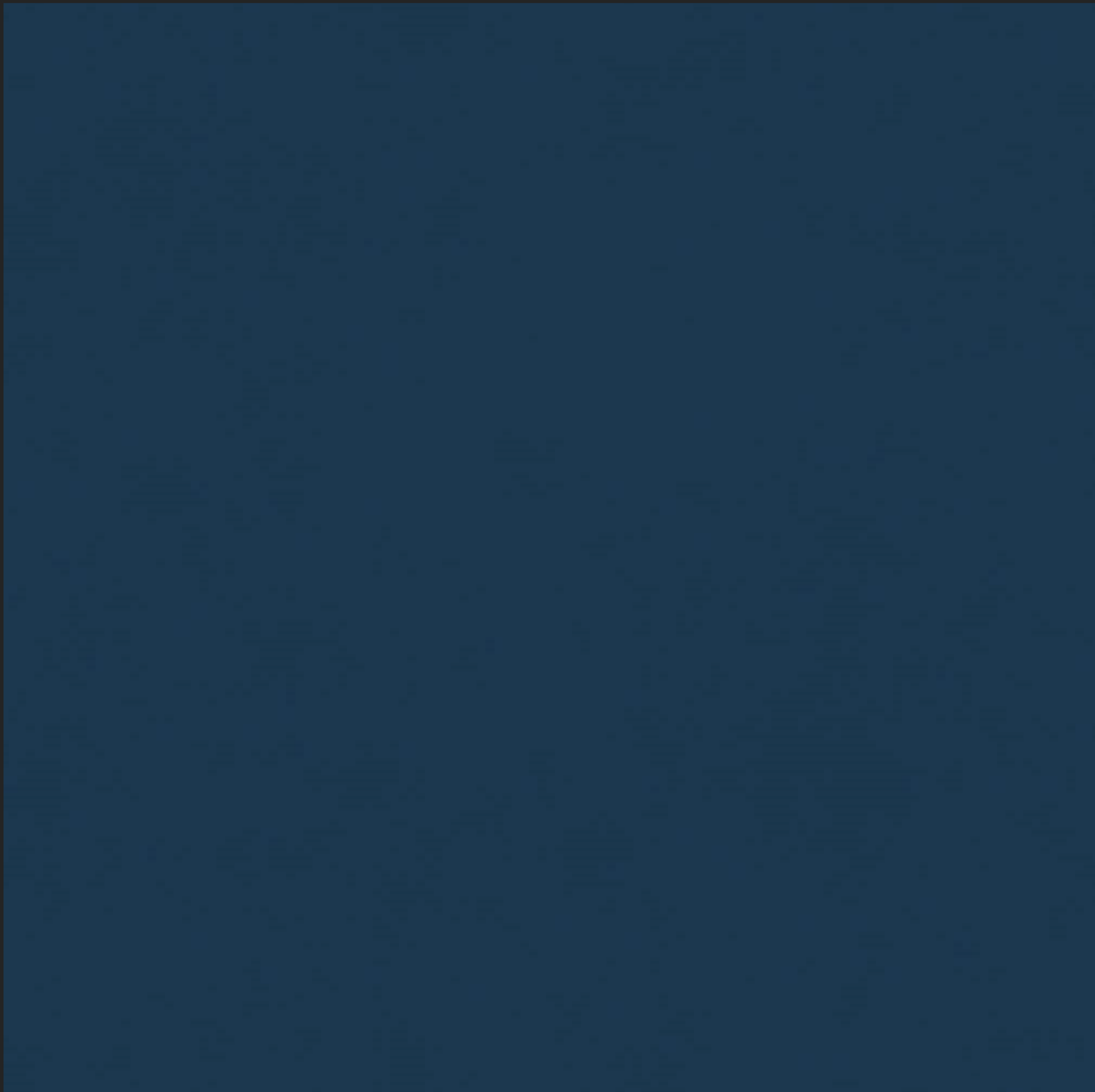


Tidal Forces shape the Cosmic Web

Skeleton of Cosmic Web



Feldbrugge, vdW et al. 2017b



Hierarchical Web Evolution:

Adhesion simulation buildup Cosmic Web

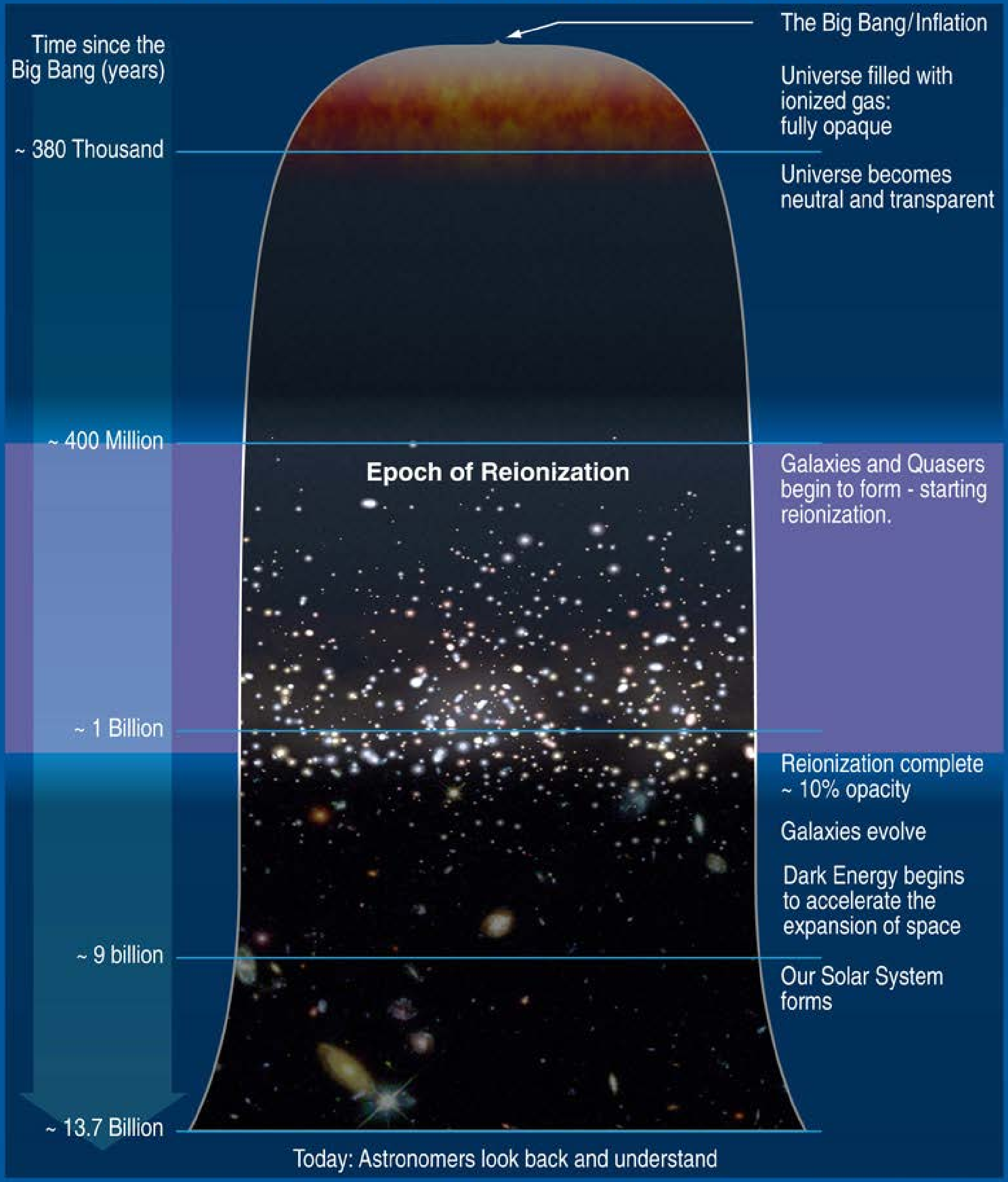
Johan Hidding
2012

Dark Ages

to

Cosmic Dawn

First Stars and Reionization Era



NASA/WMAP Science Team

100 seconds | **380 000 years** | **300–500 million years**

Light and matter are coupled

Dark matter evolves independently: it starts clumping and forming a web of structures

Light and matter separate

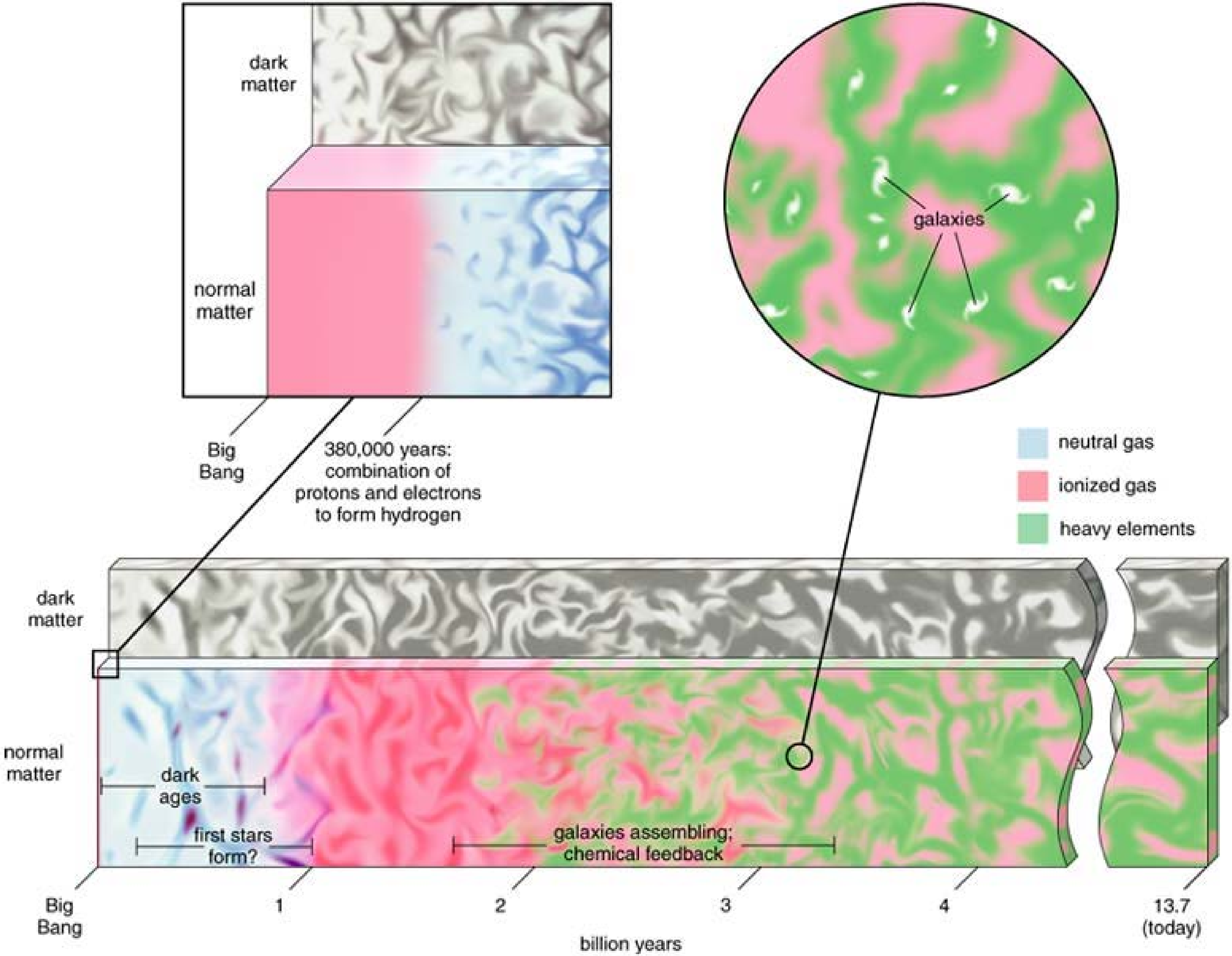
- Protons and electrons form atoms
- Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)

Dark ages

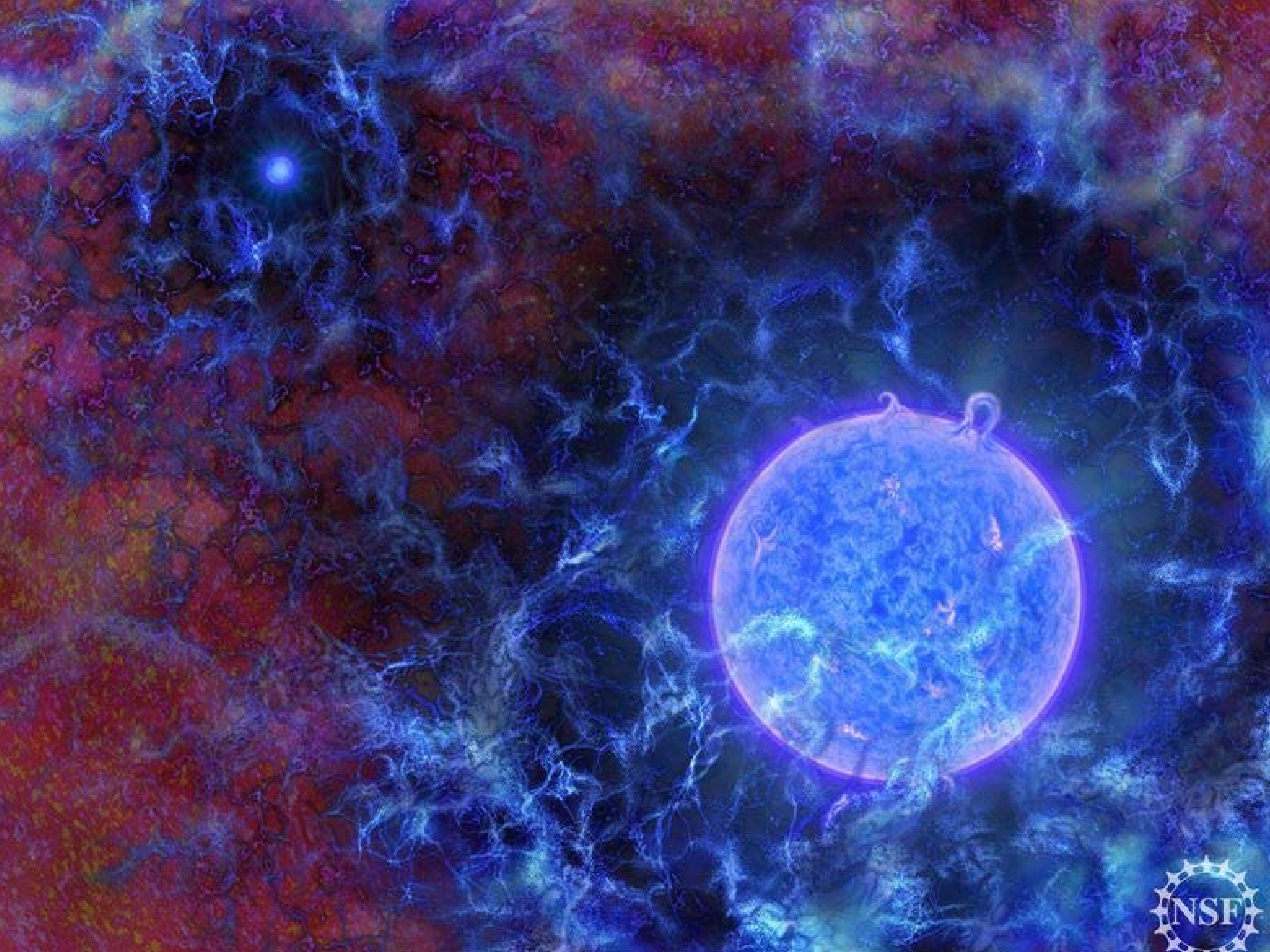
Atoms start feeling the gravity of the cosmic web of dark matter

First stars

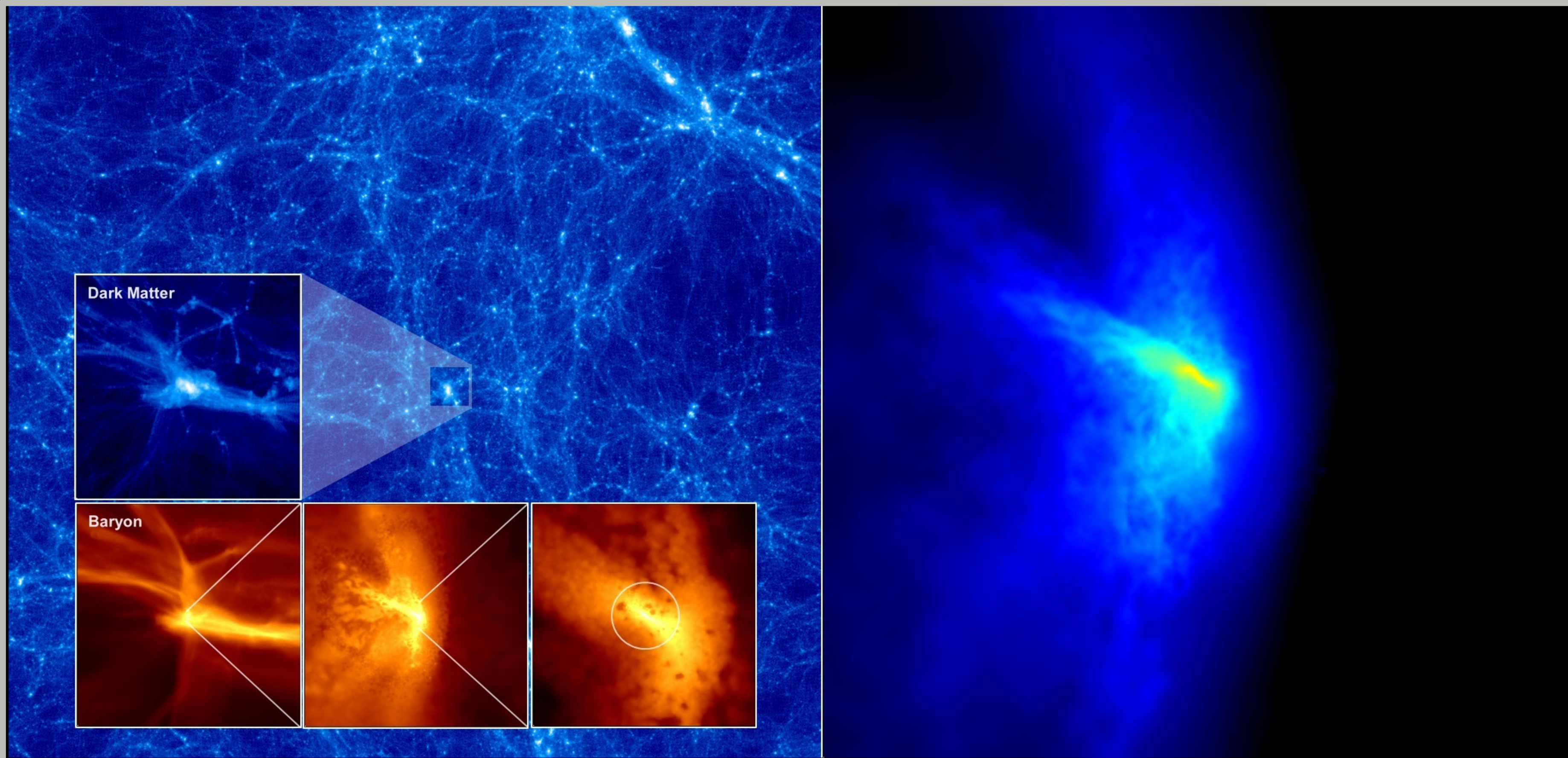
The first stars and galaxies form in the densest knots of the cosmic web


dark matter
normal matter
Big Bang
380,000 years: combination of protons and electrons to form hydrogen
galaxies
neutral gas
ionized gas
heavy elements
dark matter
normal matter
dark ages
first stars form?
galaxies assembling; chemical feedback
Big Bang
1
2
3
4
13.7 (today)
billion years

First Stars

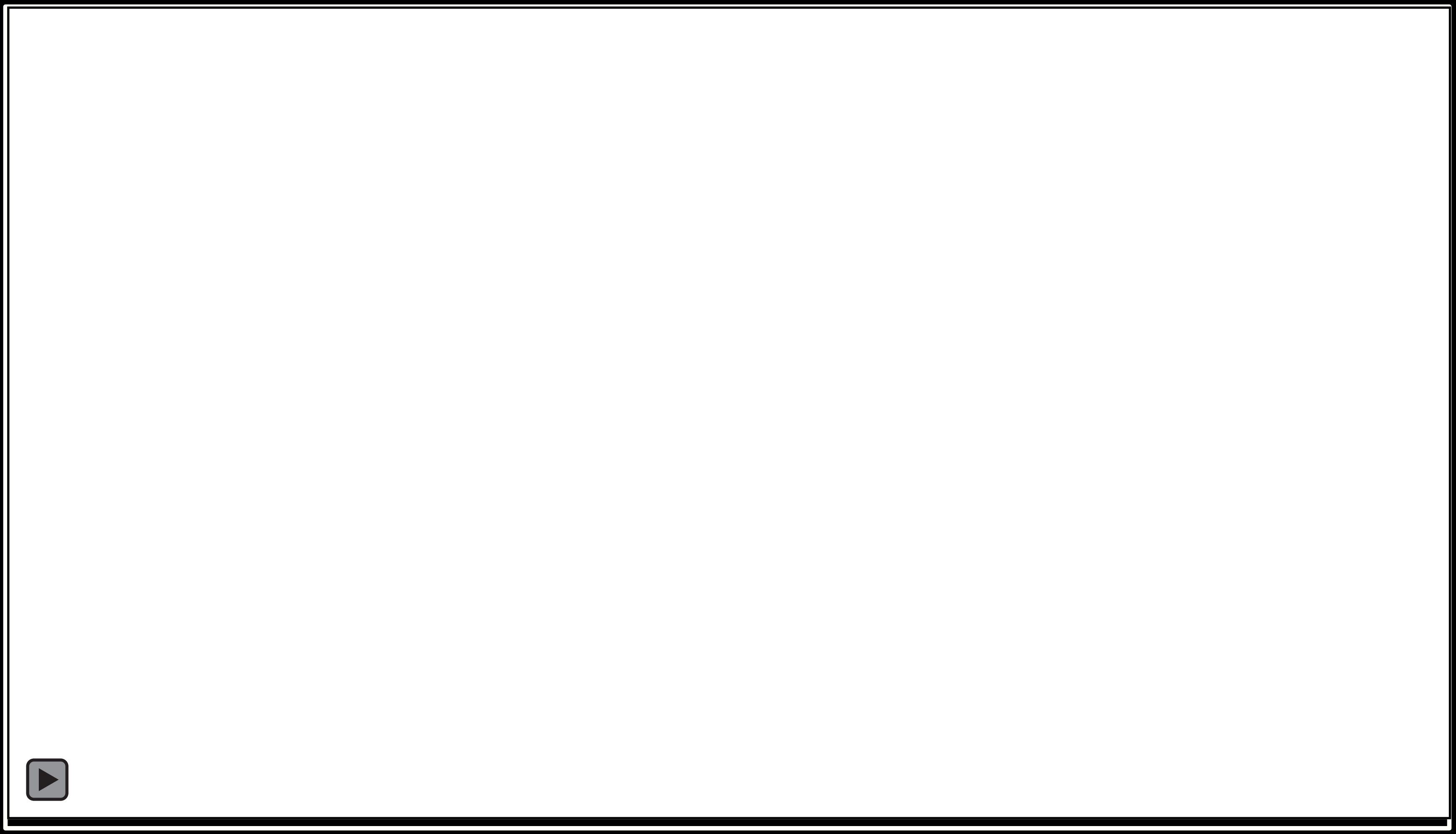


First Stars in the Universe:
at the nodes of Cosmic Web



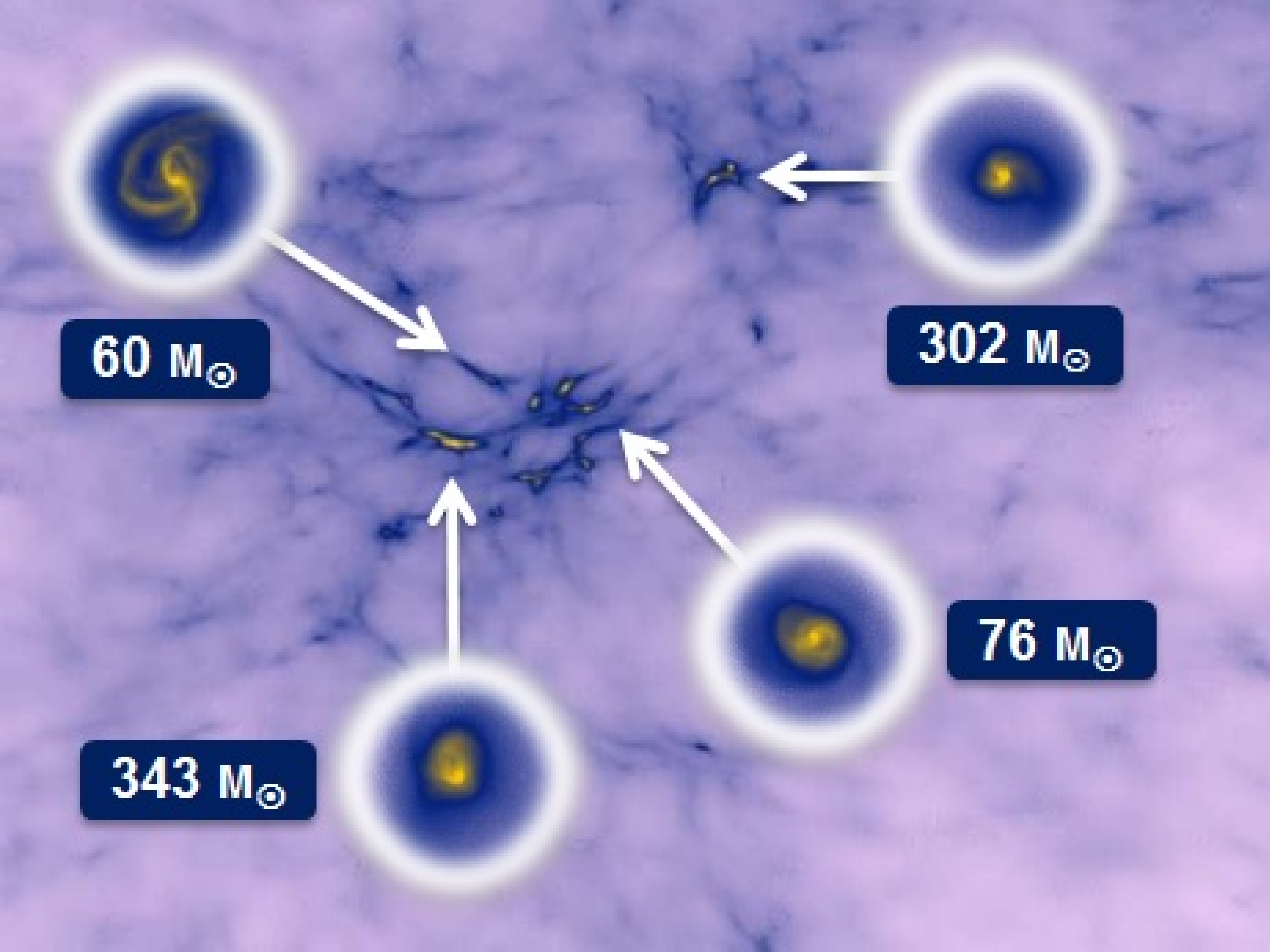
Gas (baryons) falls in into the nodes and filaments of the Cosmic Web:
- cannot contract further as long as pressure (temperature) too high
- as soon as gas so cold that molecular hydrogen H_2 forms:
- cooling by H_2 molecule transitions, via radiation losses
- formation of first baryonic cores - density increase by 24 orders magnitude: first stars

Early Star Formation

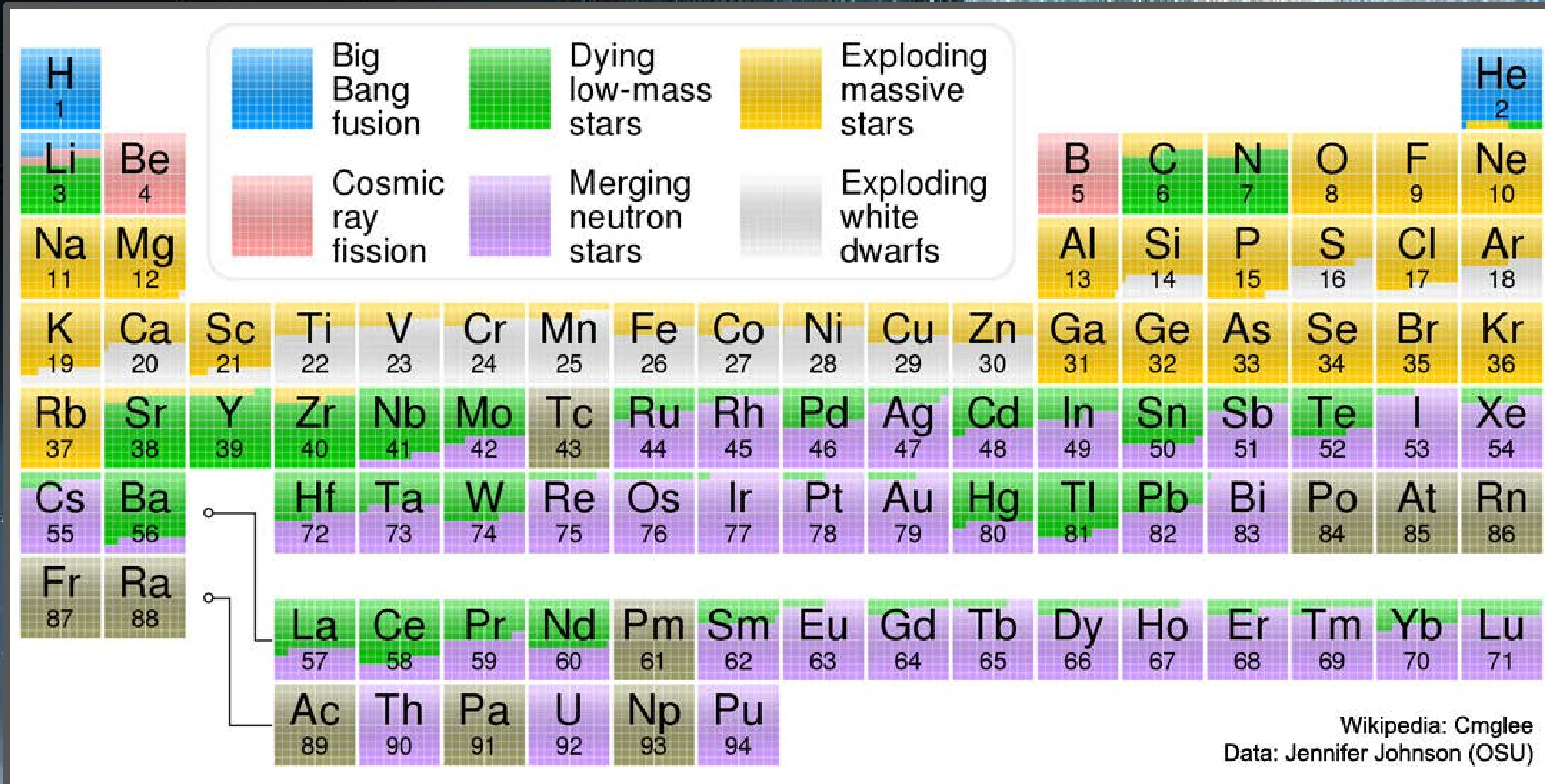


First Stars

- form in $10^5 - 10^6 M_\odot$ minihalos (of dark matter),
- located at the nodes of the cosmic web (at high z), or along its filaments
- form at z ~ 5-25
- primordial chemical abundance (only H, D, He and a bit of Li)
- gas cooling via H_2 and HD
- As a result of inefficient H2 cooling very massive: $M \sim 25 - 500 M_\odot$
- Shortlived: t_{life} ~ 2-3 Myr
- Extremely hot: T_{sur} ~ 100,000 K
- Extremly luminous: ionizing & Lyman photons $> 10^{50}$ s^{-1}
- Usually these primordial stars, consisting only of H and He, are called Pop III stars


60 $M_\odot$
302 $M_\odot$
76 $M_\odot$
343 $M_\odot$

Chemical Enrichment



Important result of the formation of the early population of PopIII stars:

- **rapid enrichment of the gaseous content of the Universe**
- **as a result of the short lives of the massive PopIII stars**

SMSS J031300.36-670839.3
oldest known star

SMSS J03100.36-670839.3

- distance: ~ 6,000 ly
- T ~ 5,125 K
- K dwarf

- age: ~ 13.6 Gyr
  (formed only
  100-200 Myr after Big Bang)

- Fe content: < 10^{-7} solar abundance
  (i.e. [Fe/H] = -7.1)

- contains C, Mg, Ca - no O, N

- one of first Pop II stars.
  formed out of gas cloud enriched
  by Pop III star

First Galaxies

Early Galaxy Formation in the Cosmic Web

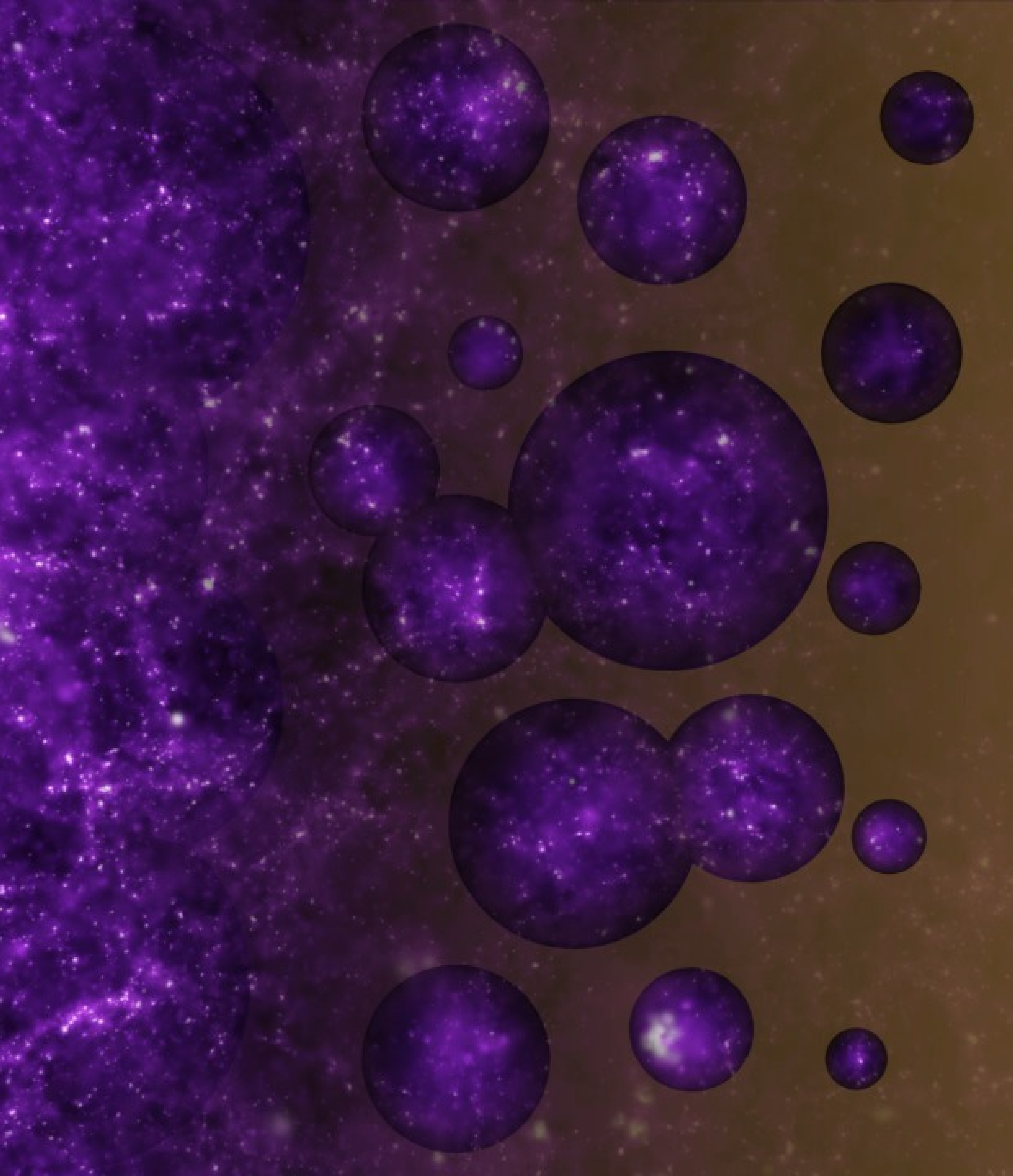
AMR simulation, 12 levels;
L=3.1 Mpc; finest scale: 1.5 pc;

z: 1080 - 11.8 (384 Myr)

M. Norman et al.

Ionizing the Universe:

Bubbles of Light



the intense UV radiation
of the first stars and galaxies

and possibly
the hard Xray radiation
of the first
Supermassive Black Holes

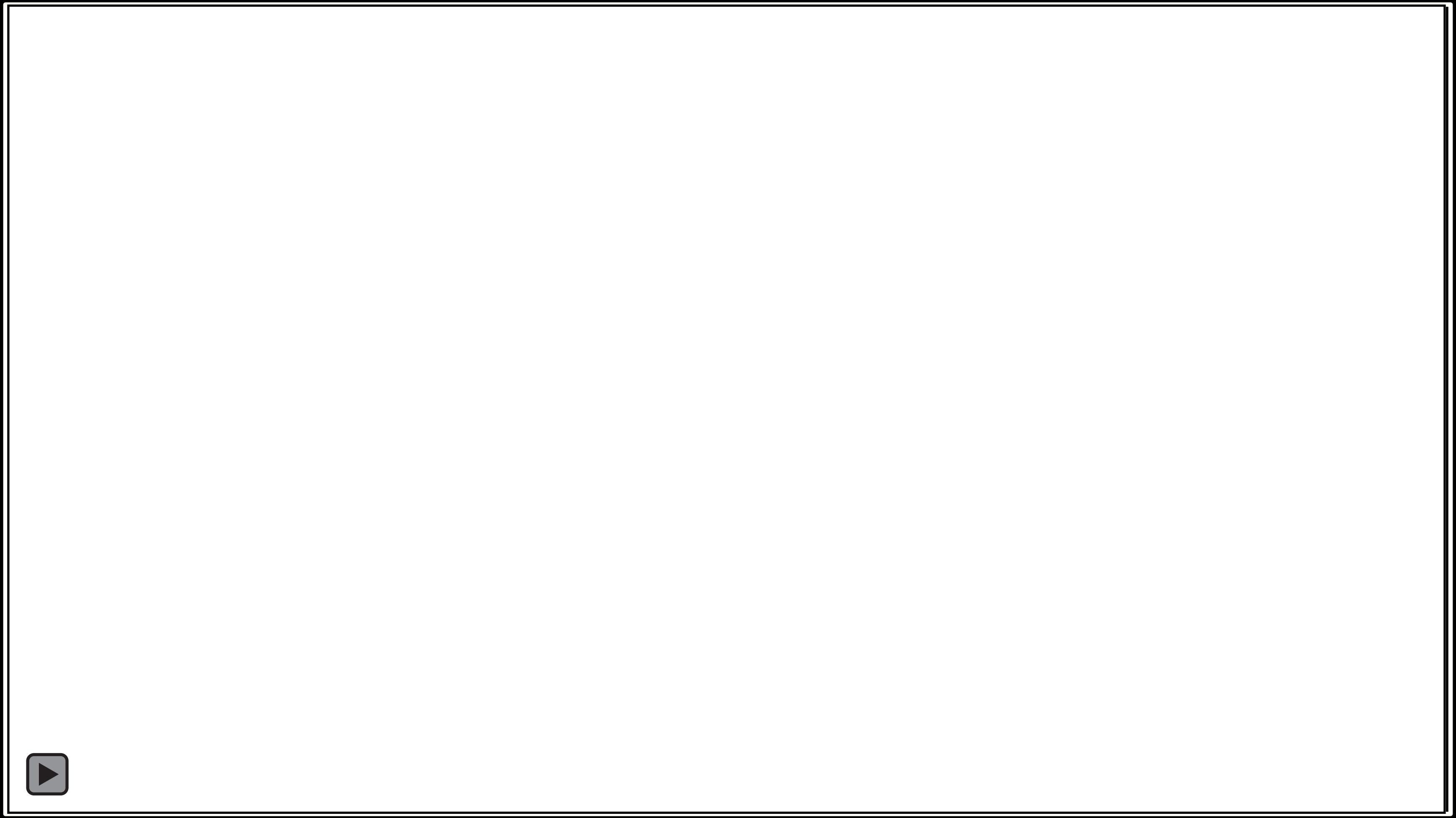
start to ionize the
neutral hydrogen in the
intergalactic medium

the IGM is mostly concentrated
in the filaments of the early Cosmic Web,
with still substantial amounts in the voids

the ionization bubbles around
these early objects expand and
gradually merge and occupy
major fractions of the Universe:

EPOCH OF REIONIZATION (EOR)

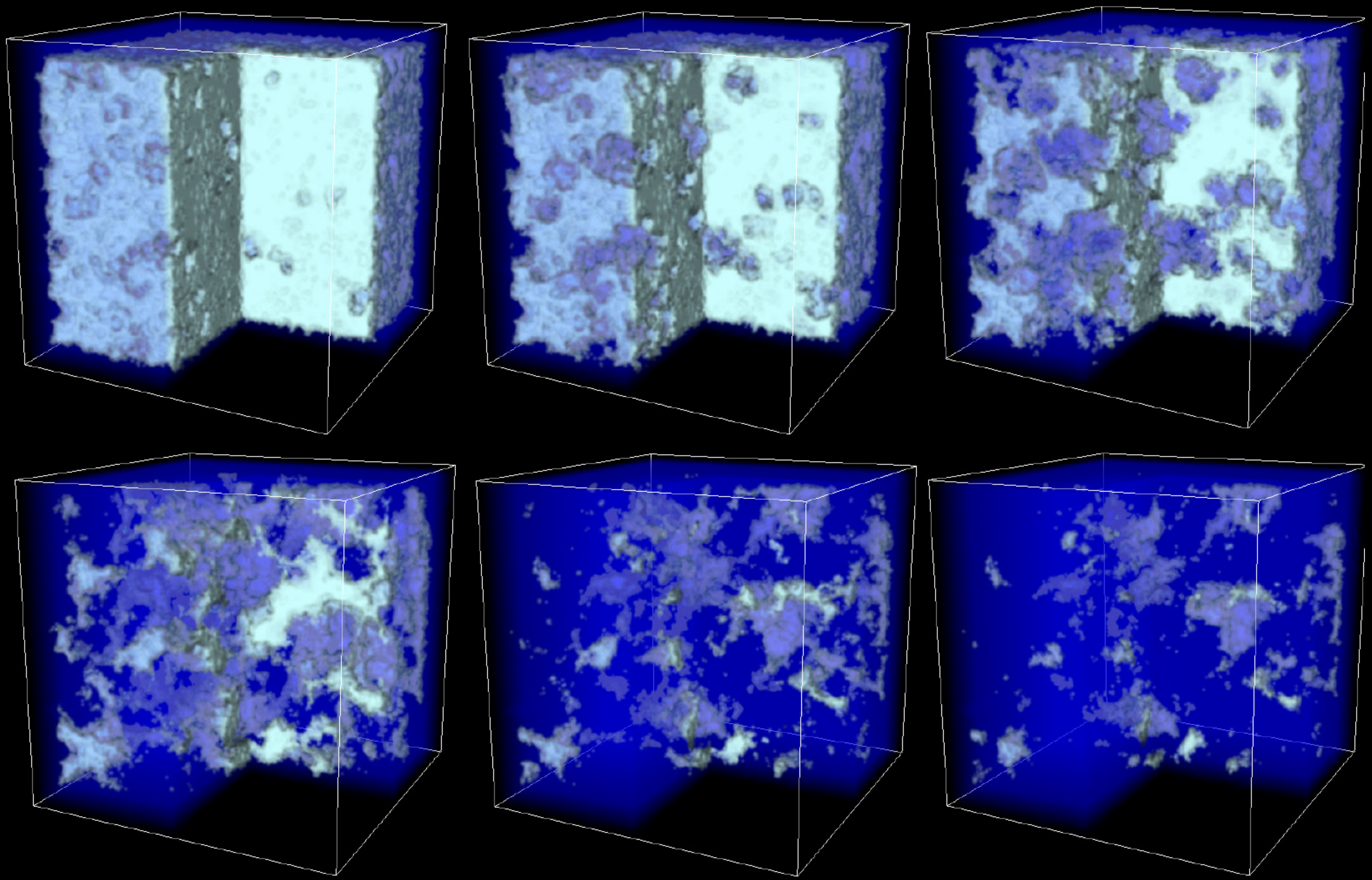
Cosmic Bubble Bath



AMR simulation;
L=15 Mpc;   z = 25-5,   t = 130 Myr - 1.2 Gyr

M. Norman et al.

Reionization Process



J. Ritzerveld, V. Icke

End of Dark Ages

&

Epoch of Reionization

EOR:
observational signatures

- Effect ionized gas on Cosmic Microwave Background:
  Thomson scattering photons on electrons: E polarization CMB

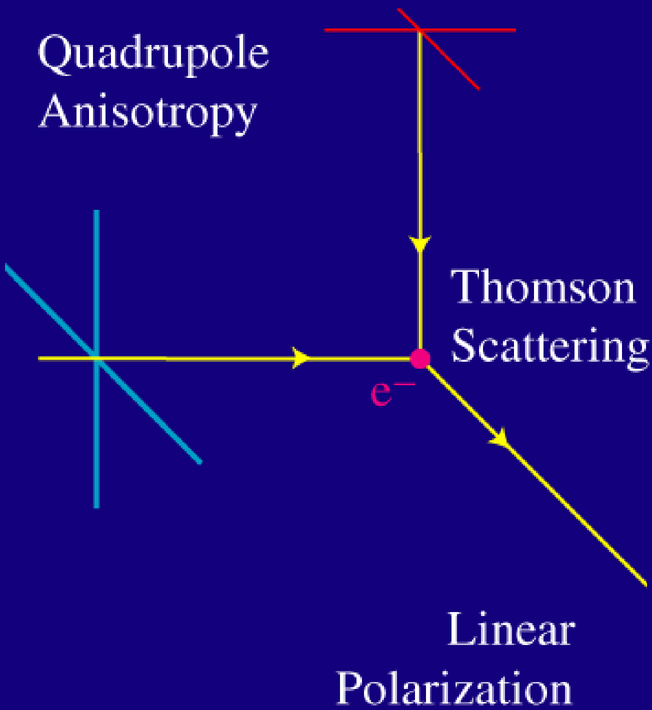
- Gunn-Peterson trough:
  absorption photons by (whiff) of neutral hydrogen (HI) gas –
  absorption troughs in spectra of high-z quasars

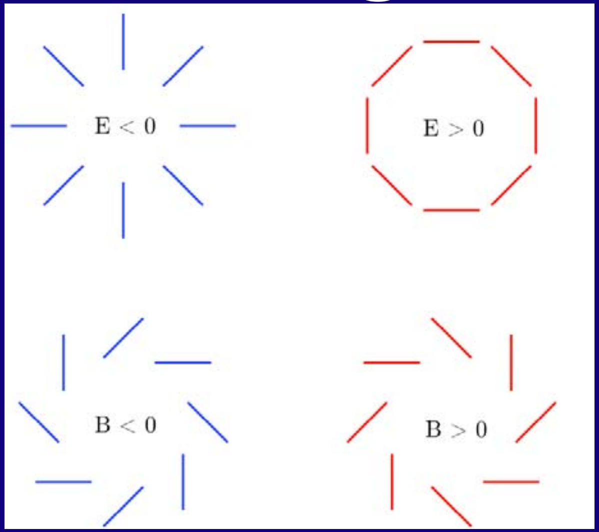
- HI 21cm line, absorption or emission,
  of remaining – not yet ionized - neutral HI gas

Polarization

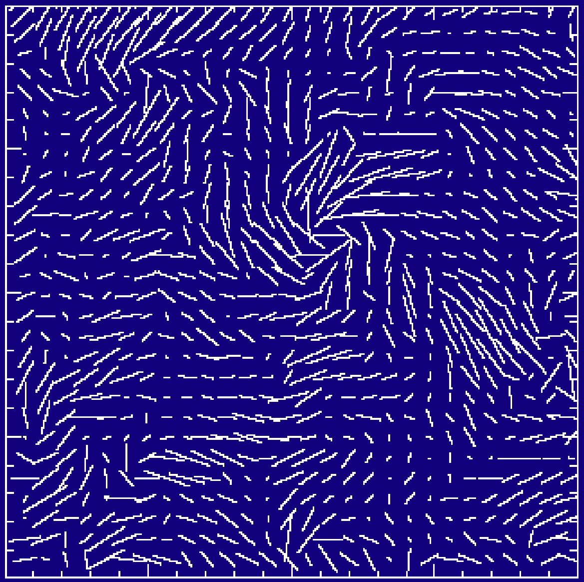
Cosmic Microwave Background

Reionization & CMB polarization: Thomson Scattering CMB photons

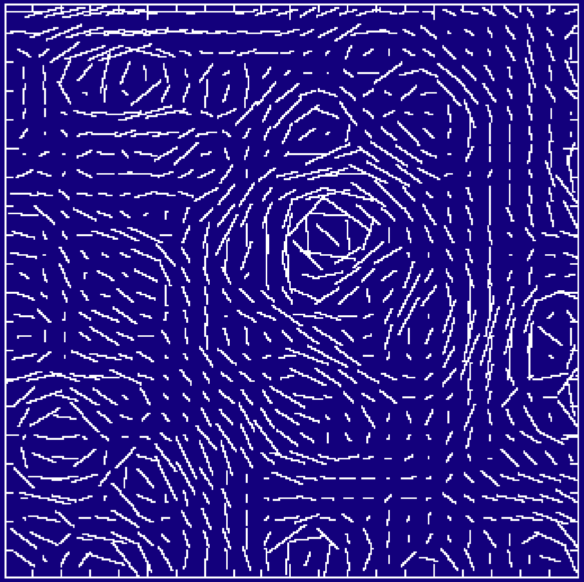




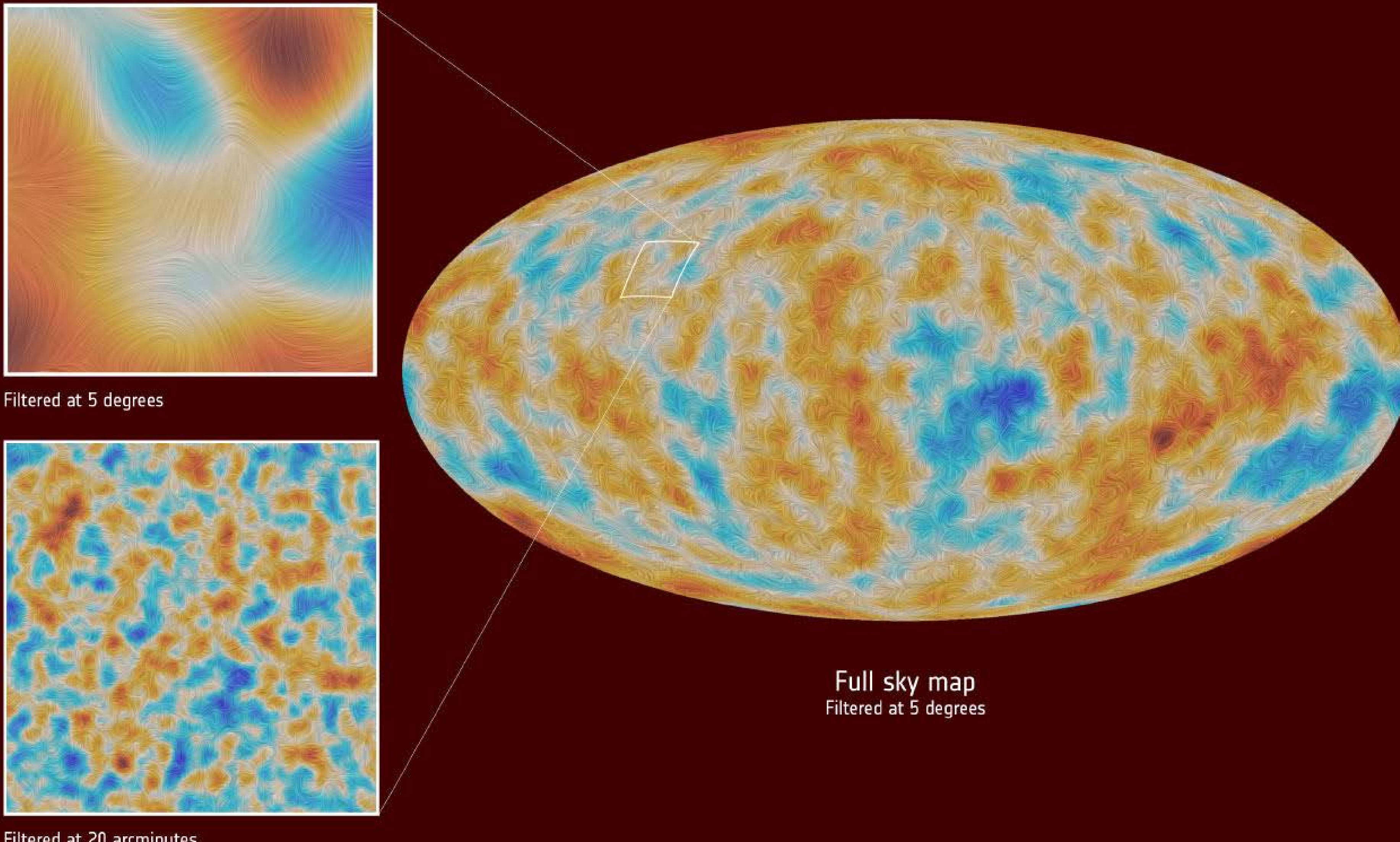
B-mode



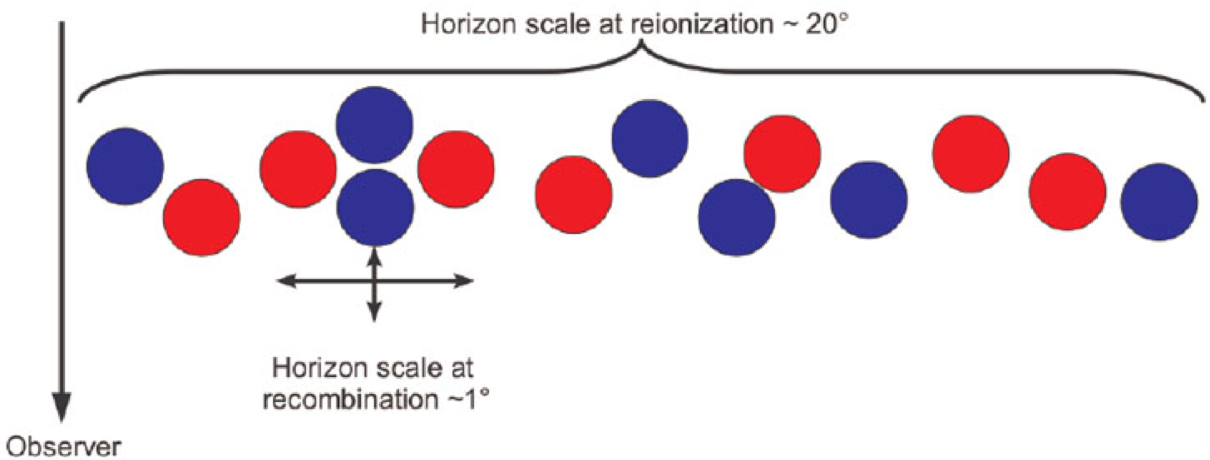
E-mode



Planck E-polarization



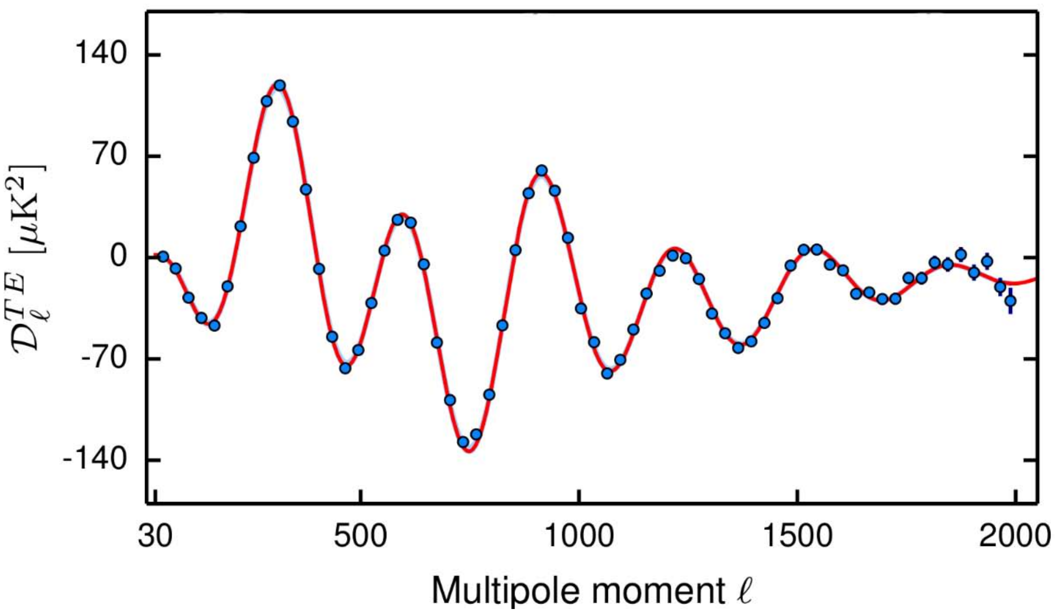
Planck E-polarizatтion Spectrum



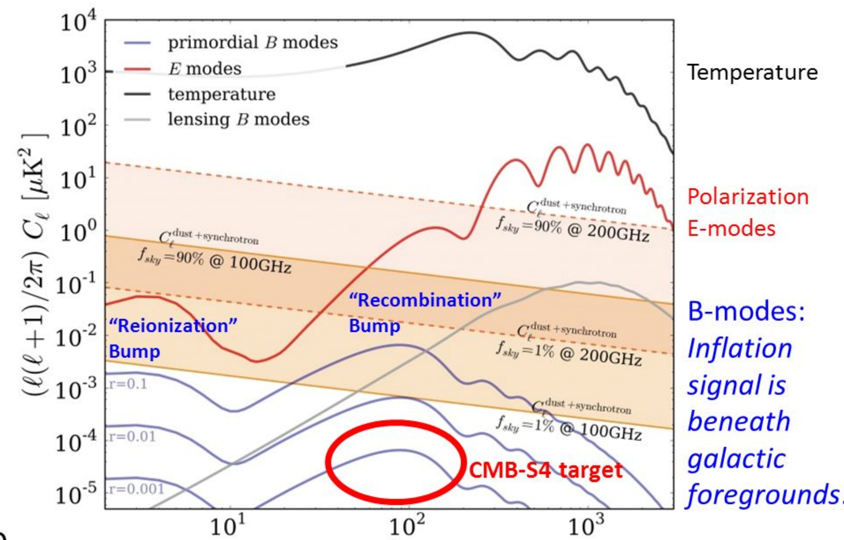
Planck (2015):
Thomson optical depth:

τ=0.058 +/- 0.012

z_{reion}=7.8-8.8



CMB Power Spectrum

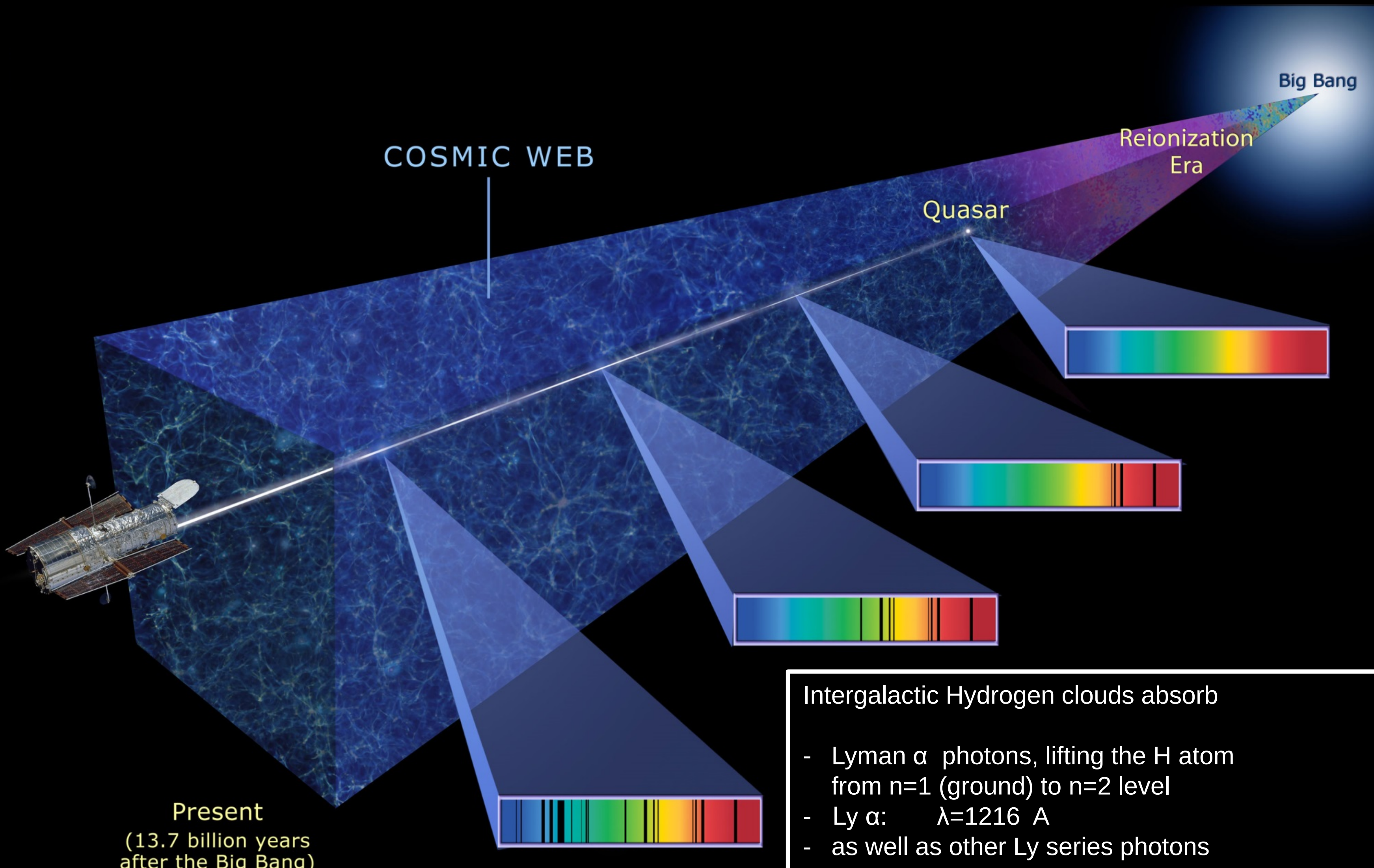


Errard, Feeny, Peiris, and Jaffe, arXiv:1509.06770

Gunn-Peterson:

looking through the Gaseous Cosmic Web

the Gaseous Cosmic Web

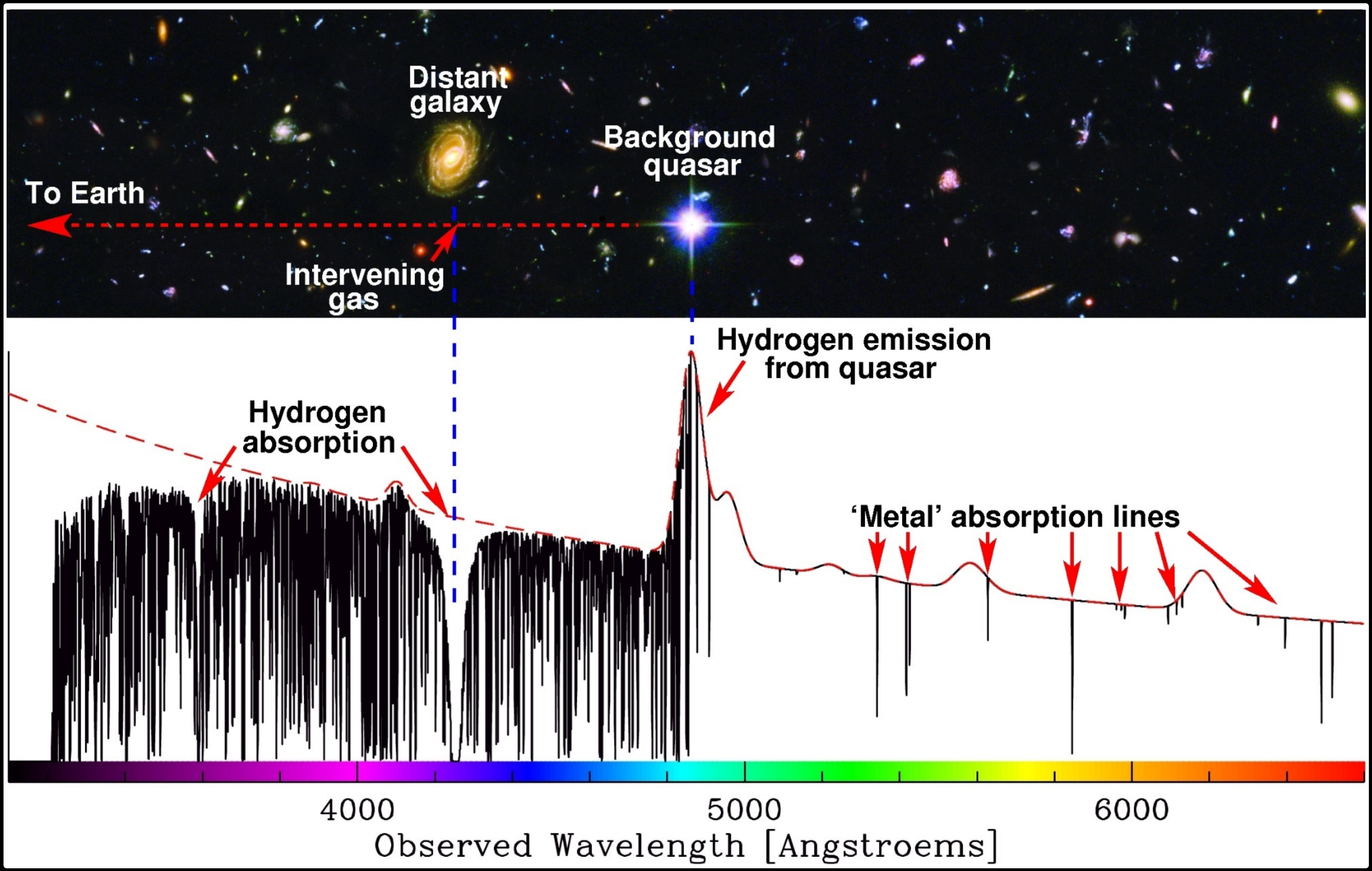


Intergalactic Hydrogen clouds absorb

- Lyman α photons, lifting the H atom from n=1 (ground) to n=2 level
- Ly α: λ=1216 A
- as well as other Ly series photons

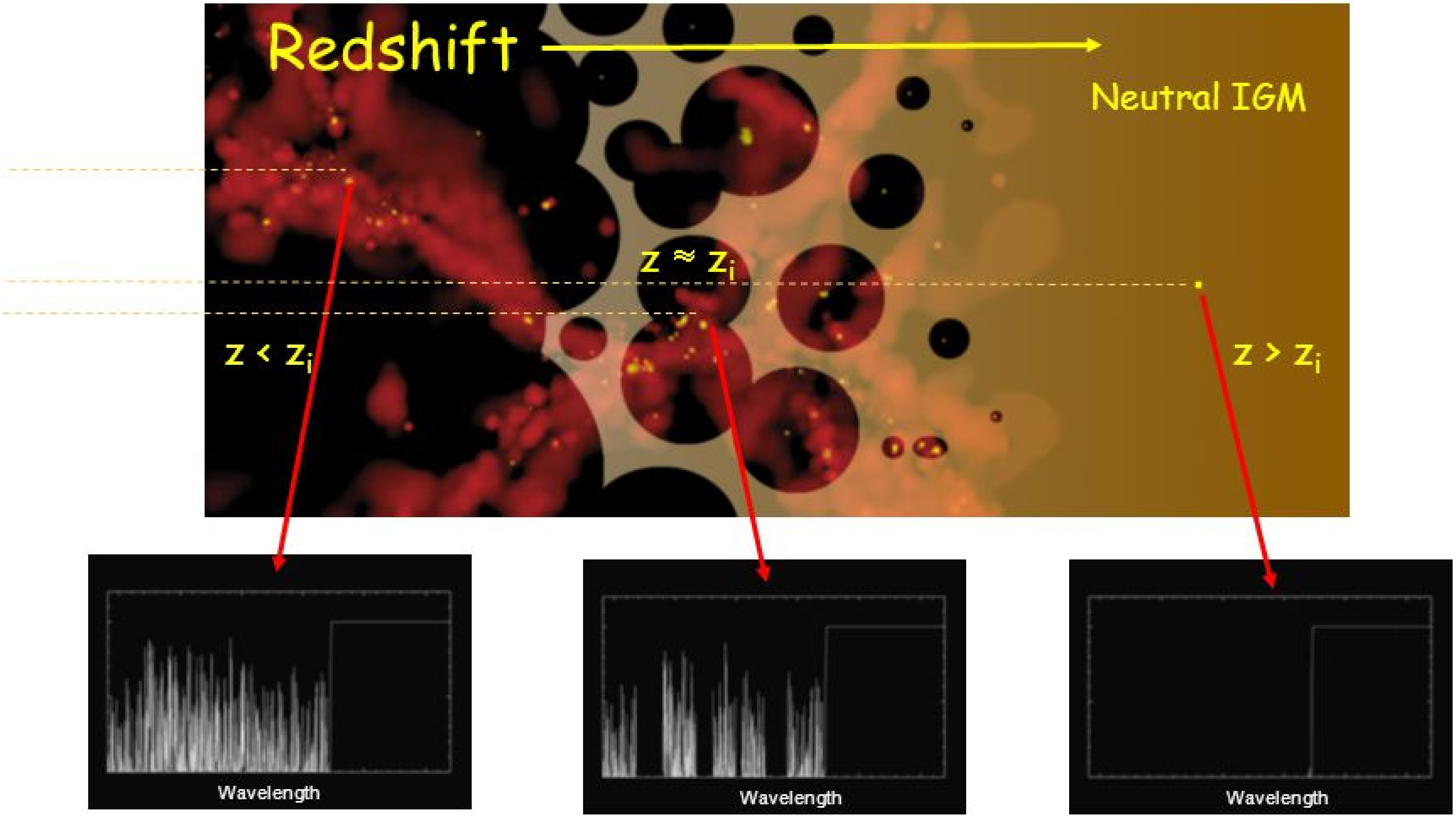
- due to redshifting of radiation as it travels the Universe, we see the Ly α absorption lines at different frequencies

Lyα forest:
piercing the Cosmic Web



Lyα forest:
piercing the Cosmic Web

Expected reionization history



Lyman Forest Absorption

Patchy Absorption

Black Gunn-Peterson trough

Courtesy of A. Ferrara

Gunn-Peterson troughs

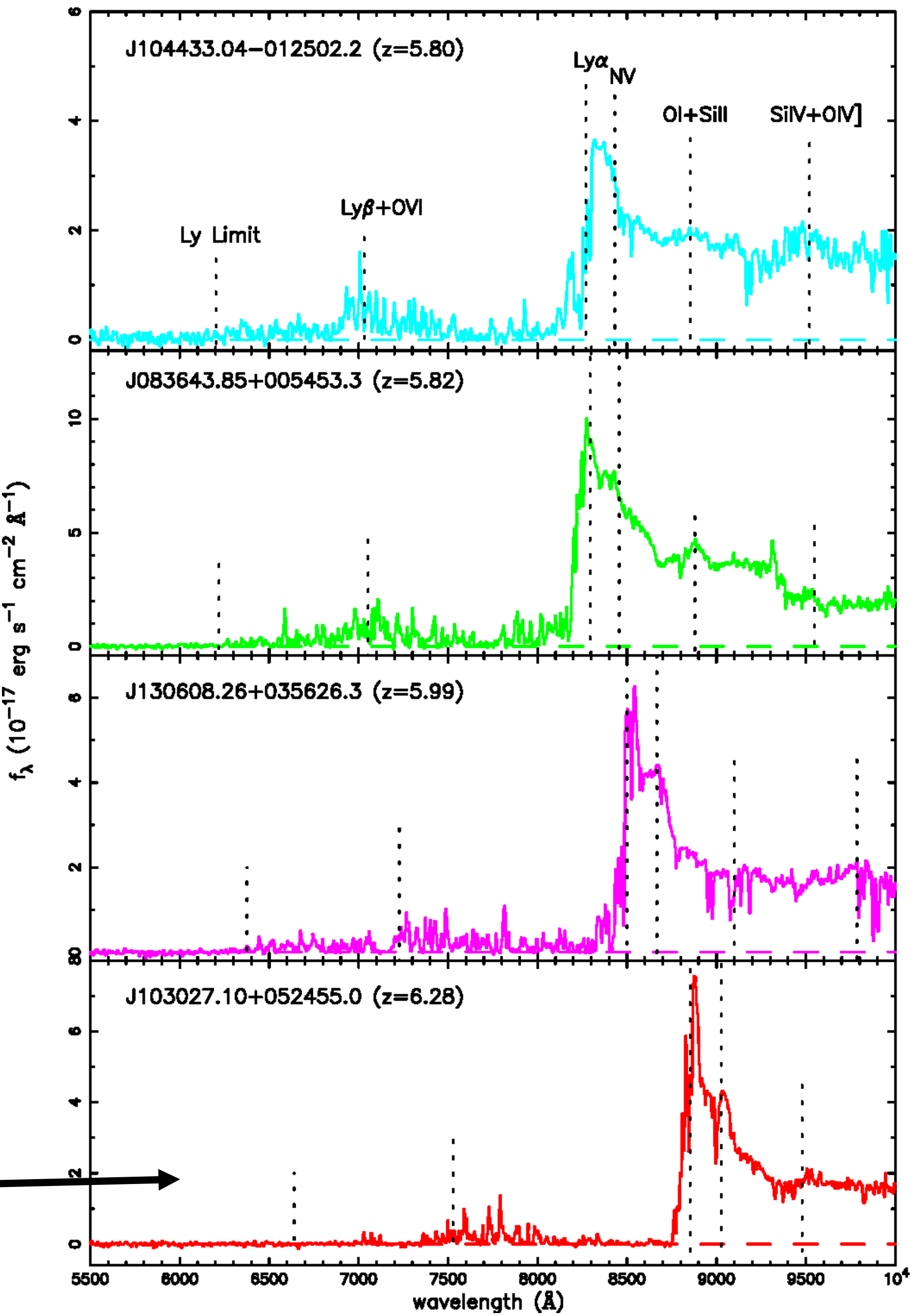
Neutral hydrogen:

- **Suppression emission quasar spectrum at wavelengths shorter than Lyα line at corresponding redshift.**
- **very low fraction x(HI) of neutral hydrogen sufficient to fully suppress radiation**

Gunn-Peterson optical depth:

$$\tau_{GP} = 2.6 \times 10^4 \ x(HI) \ (1+z)^{3/2}$$

- **even a fraction 10-4 is enough to nearly suppress any radiation**
- **no detectable flux shortward of Lyα and Lyβ**

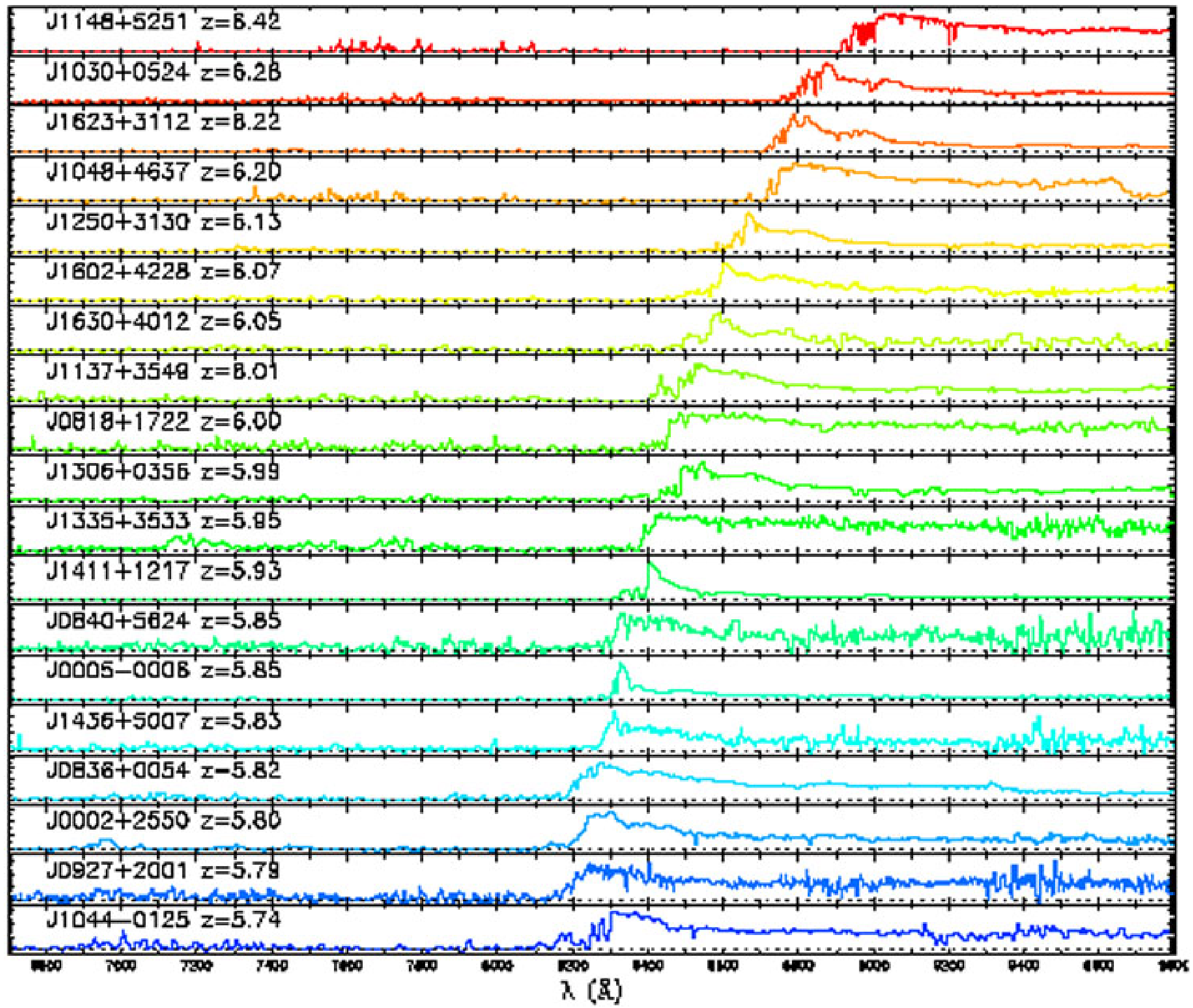


Becker et al. 2001 (SDSS)

Gunn-Peterson troughs

Growth of Gunn-Peterson trough towards z=6.42:

- **detailed and systematic assessment of quasar spectra reveals that τ_{GP} varies with direction**
- **implies variation in reionizing radiation**



21cm Cosmology

21cm Hyperfine transition

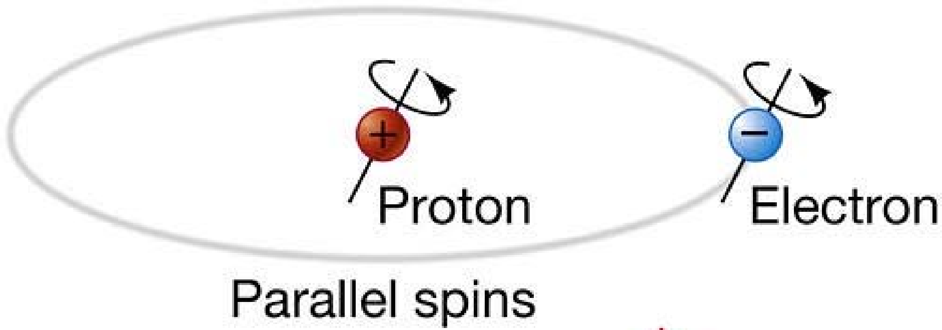
Hydrogen atom in the groundstate(1s):

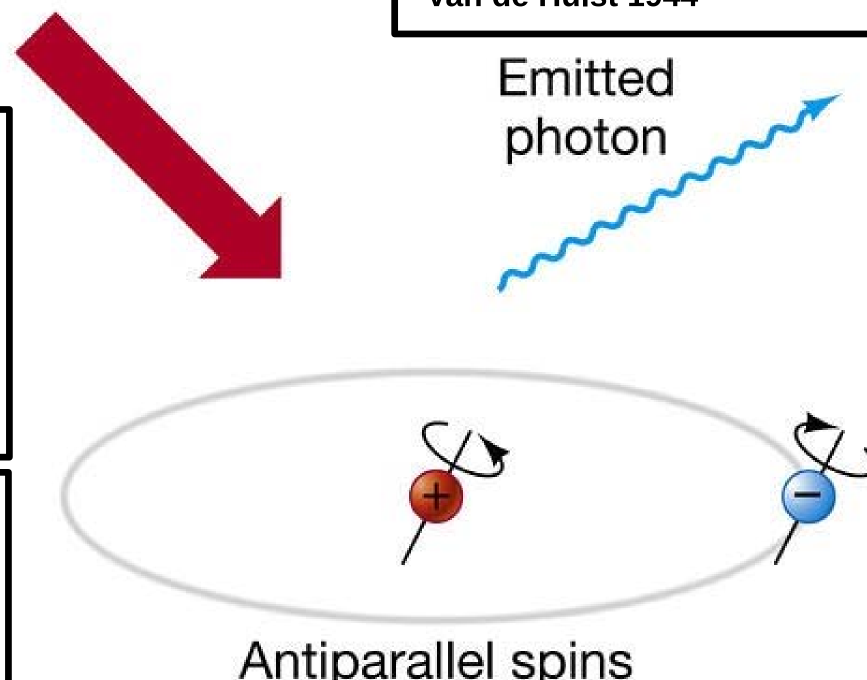
splits into 2 hyperfine levels:

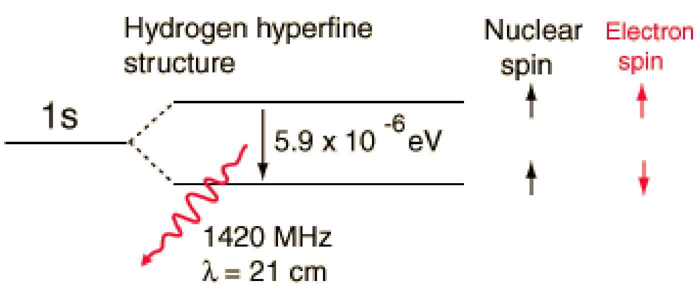
defined by
mutual spin direction of nucleus- electron

(tiny) energy difference corresponding:
ΔE = 5.9 x 10-6 eV
ν = 1420 MHz, λ=21cm

Van de Hulst 1944

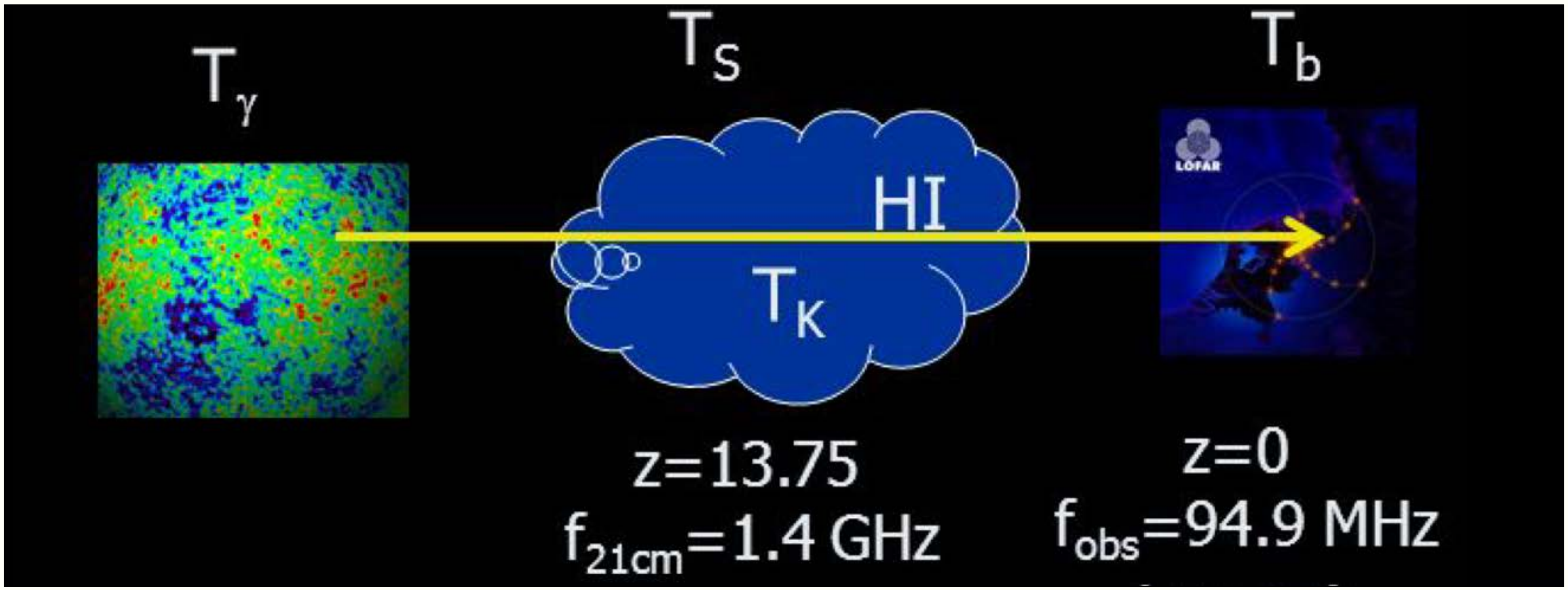






Spin temperature:

$$\frac{n_2}{n_1} = 3\exp\left\{-\frac{h\nu_{21cm}}{kT_S}\right\}$$



21cm Brightness Temperature

$$T_b = 27\, x_{HI}\, (1+\delta_b)\left(\frac{T_S - T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2} \quad mK$$

21cm Spin Temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

use backlight CMB:

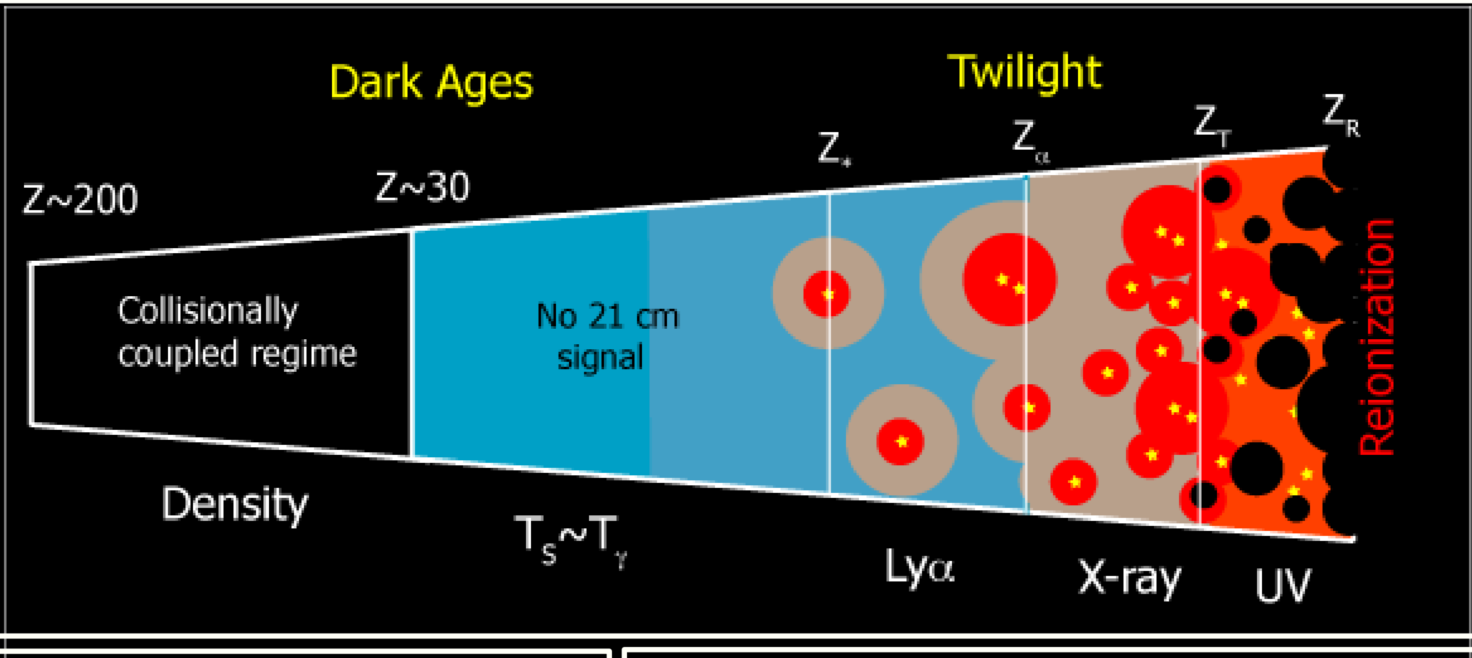
to probe 21cm transition along line of sight:
- from dark ages down to present day

Redshift 21cm line:

Z=6: 200 MHz
z=10: 129 MHz
z=18: 78 MHz

Low frequency radio astronomy

21cm Reionization Signal: Cosmic Phases



use backlight CMB:

21cm line visible when

- **spin temperature $T_S \neq$ CMB temperature T_γ**

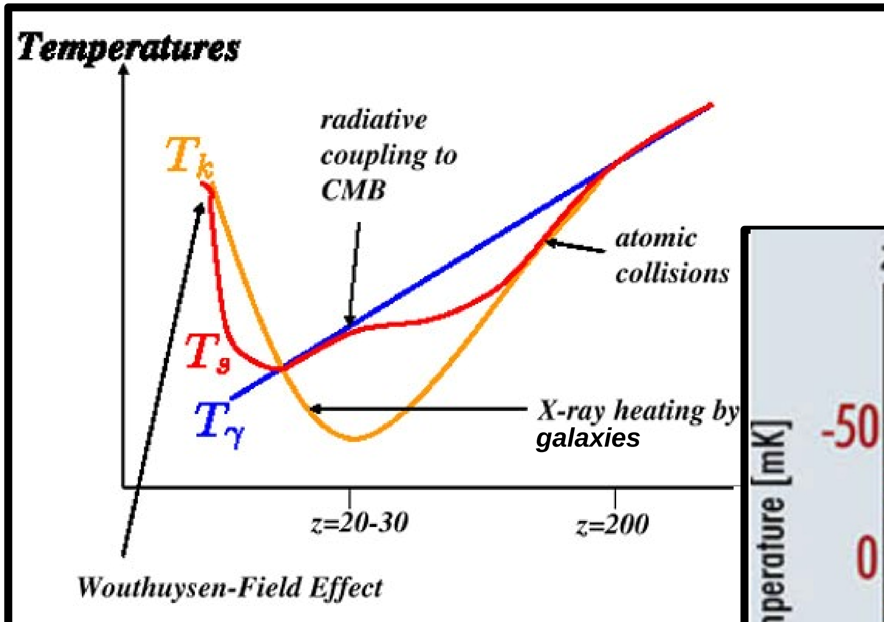
- **$T_S < T_\gamma$: absorption**
- **$T_S > T_\gamma$: emission**
- **$T_S = T_\gamma$: not visible**

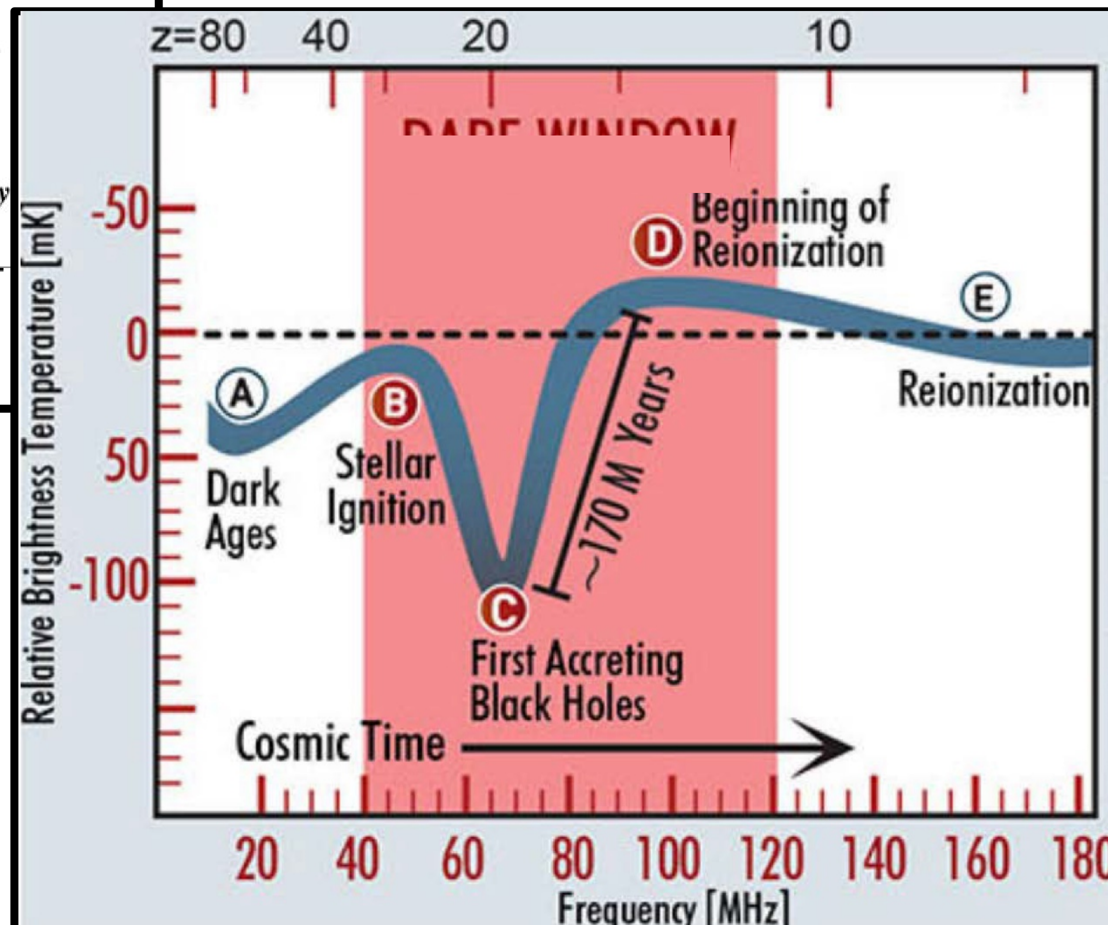
21cm line visibility dependent on:

- **Thermal history of gas**
- **Coupling between gas and spin excitation (collisions)**

- **Additional atomic and radiative processes:**
  - **Wouthuysen-Field pumping Lyα photons first stars & gals**
  - **radiative transitions due to CMB (after decoupling gas)**

Thermal History – from Dark Ages to EOR





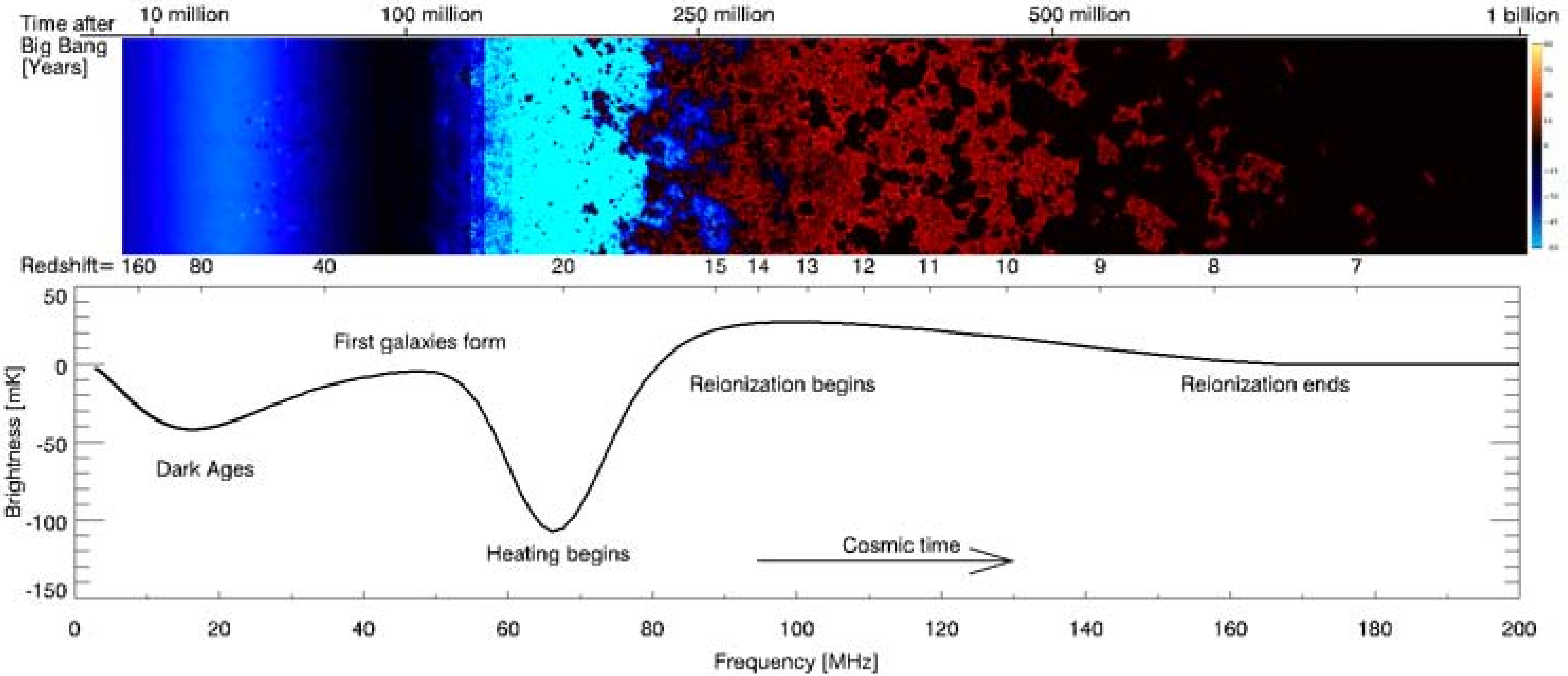
Temperature evolution:

- CMB temperature
- Gas temperature
- Spin temperature

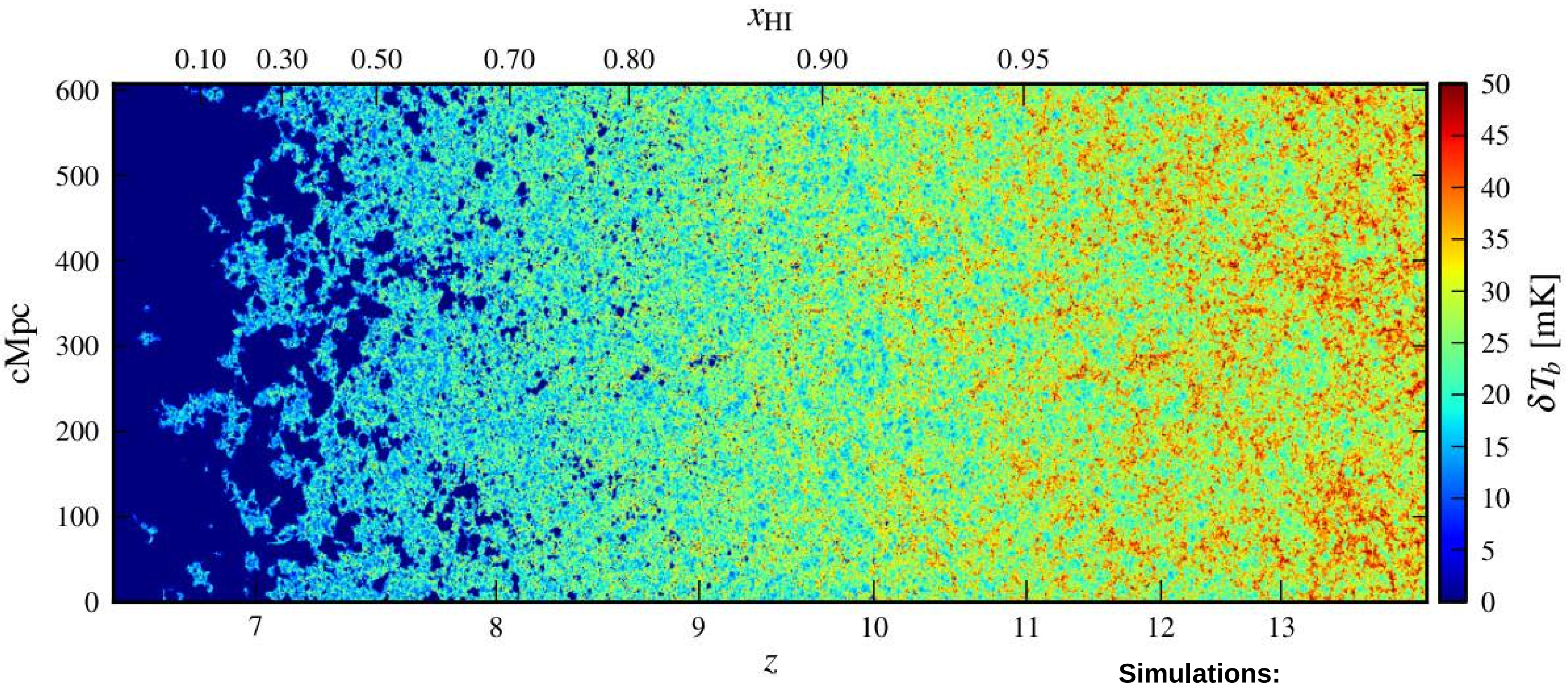
21cm Brightness Temperature evolution

- $T_B > 0$ mK: emission
- $T_B < 0$ mK: absorption

21cm Reionization Signal: Cosmic Phases

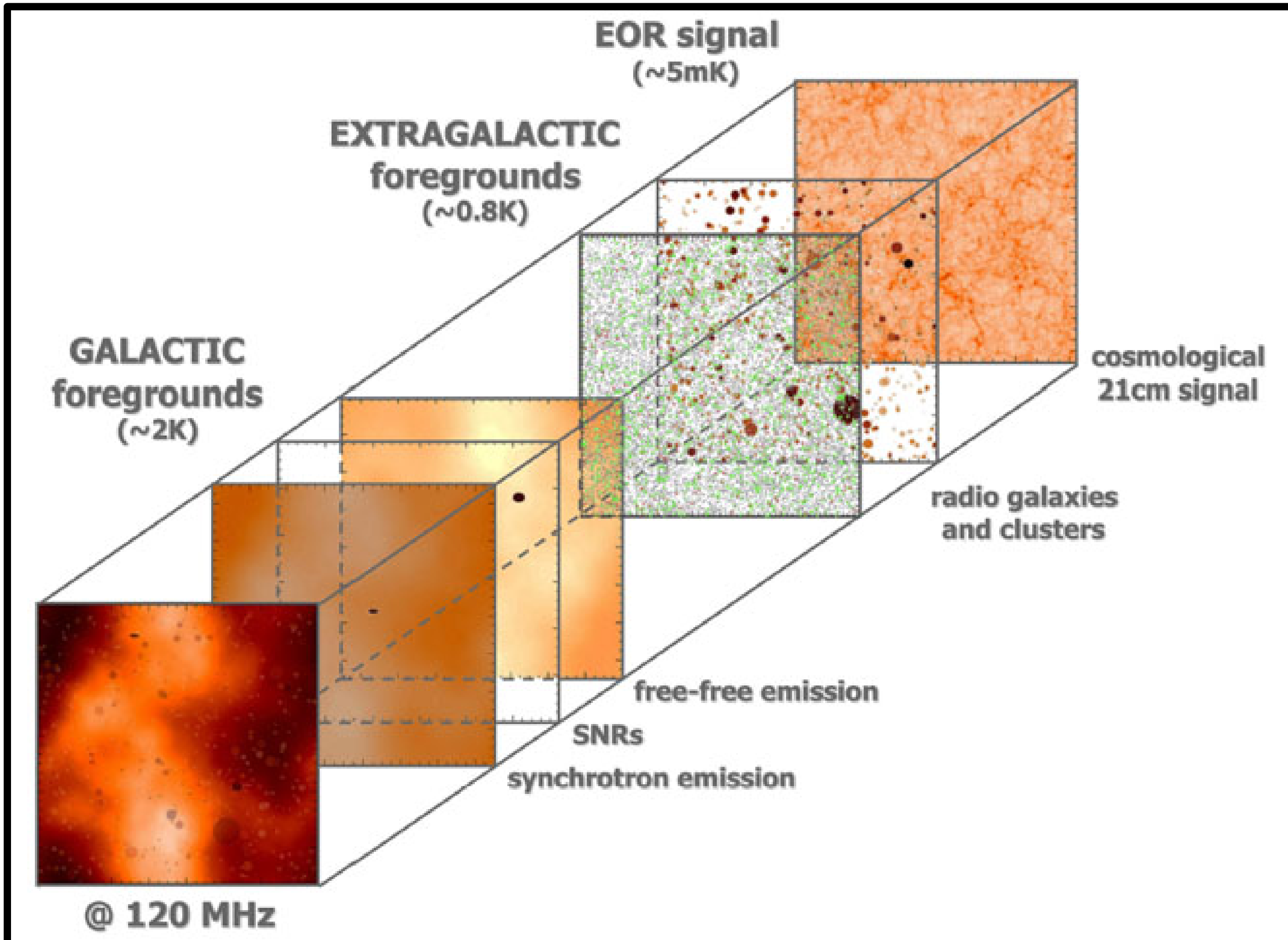


21cm Reionization Signal:
Redshift Ligthcone



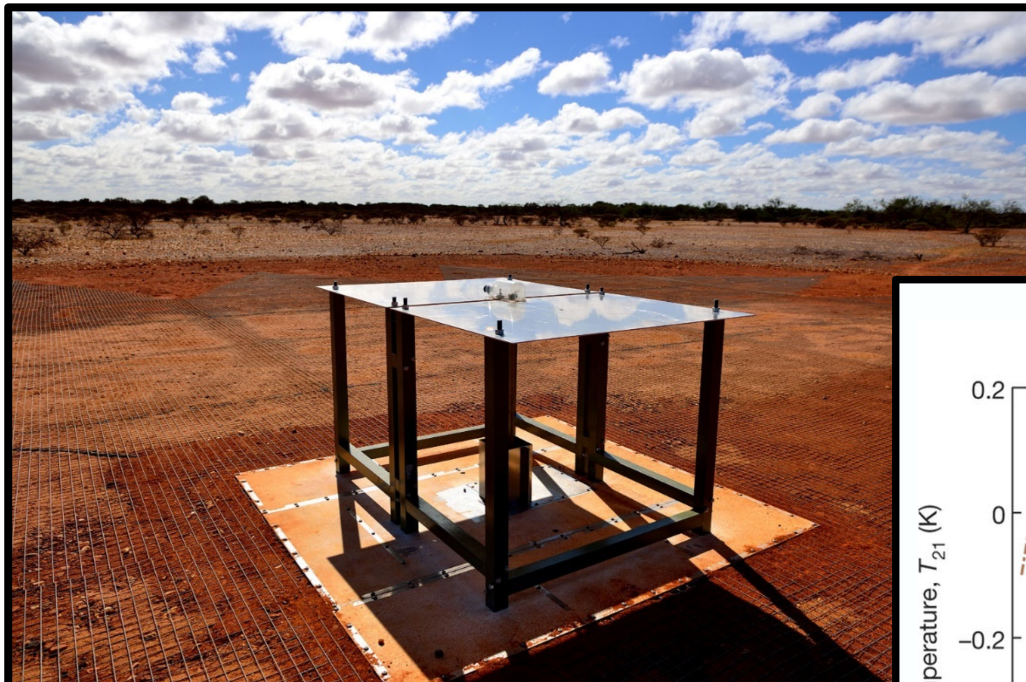
Simulations:
G. Mellema, I. Illiev et al.

21cm Reionization Signal: Foregrounds



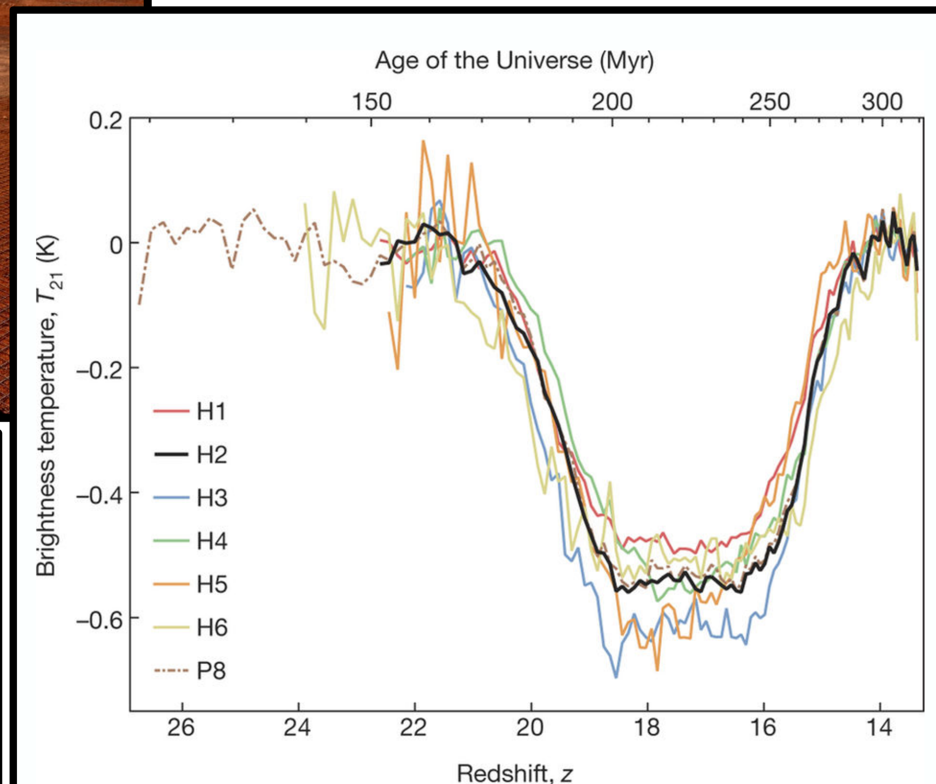
V. Jelic

EDGES: EOR detection ?



Bowman et al. (2018, Nature)

- report the first detection of a 21cm absorption line at 78 MHz (z ~ 18)
- EDGES detector in desert Western Australia(Perth)
- first detection onset reionization by first stars ?
- uncommonly deep absorption trough ?
- suggestion influence dark matter-baryon interaction



Cosmic Dawn Summary

- *Search for the signature of the first stars and galaxies one of the most outstanding challenges in present-day cosmology:*

  When do the Lights go on in the Universe ?

- *First stars finish the era of the Cosmic Dark Ages, and announce the Dawn of the Cosmos*

- *Dark Ages started after the Recombination Epoch, when due to the formation of hydrogen atoms, (cosmic) radiation and baryons decoupled*

- *During the dark ages, the structure in the dark matter distribution continues to grow as a consequence gravitational instability, and as it emerges from its primordial Gaussian nature evolves into a mildly nonlinear weblike distribution marked by filaments, sheets, nodes and voids.*

- *The weblike matter distribution evolves in a hierarchical fashion, merging and moulding into gradually larger and larger weblike patterns*

- *First stars and first galaxies formed at the nodes and along the filaments of the (small-scale) cosmic web at high redshifts,*

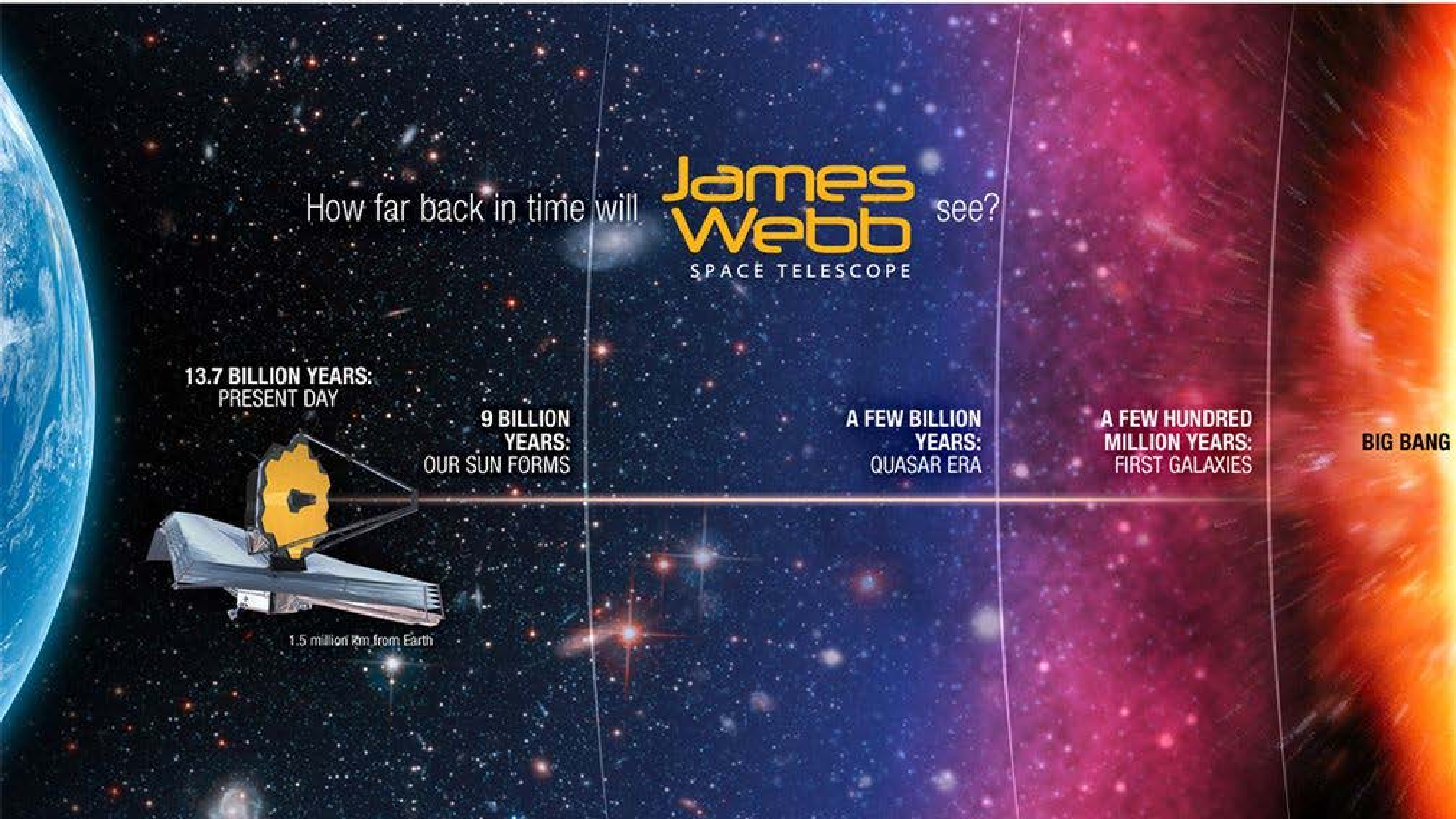
  once the gas had cooled to temperatures allowing the formation of molecular hydrogen (H_2), necessary to cool the gas and allow contraction to extremely high stellar densities

- *intense UV radiation of the first stars and galaxies start to reionize the gas in the Universe*

- *Ionization bubbles grow and start to overlap, gradually filling up the entire cosmic volume: the Reionization of the Universe*

- *Reionization signature can be picked up via a range of probes:*
  - *E-polarization CMB radiation*
  - *Gunn-Peterson quasar radiation absorption troughs*
  - *21cm cosmology – low frequency radio astronomy - direct detection, potential for mapping*

- *EDGES (Bowman et al. 2018): first detection epoch of reionization ?*



How far back in time will
James Webb
SPACE TELESCOPE
see?
13.7 BILLION YEARS:
PRESENT DAY
9 BILLION YEARS:
OUR SUN FORMS
A FEW BILLION YEARS:
QUASAR ERA
A FEW HUNDRED MILLION YEARS:
FIRST GALAXIES
BIG BANG
1.5 million km from Earth