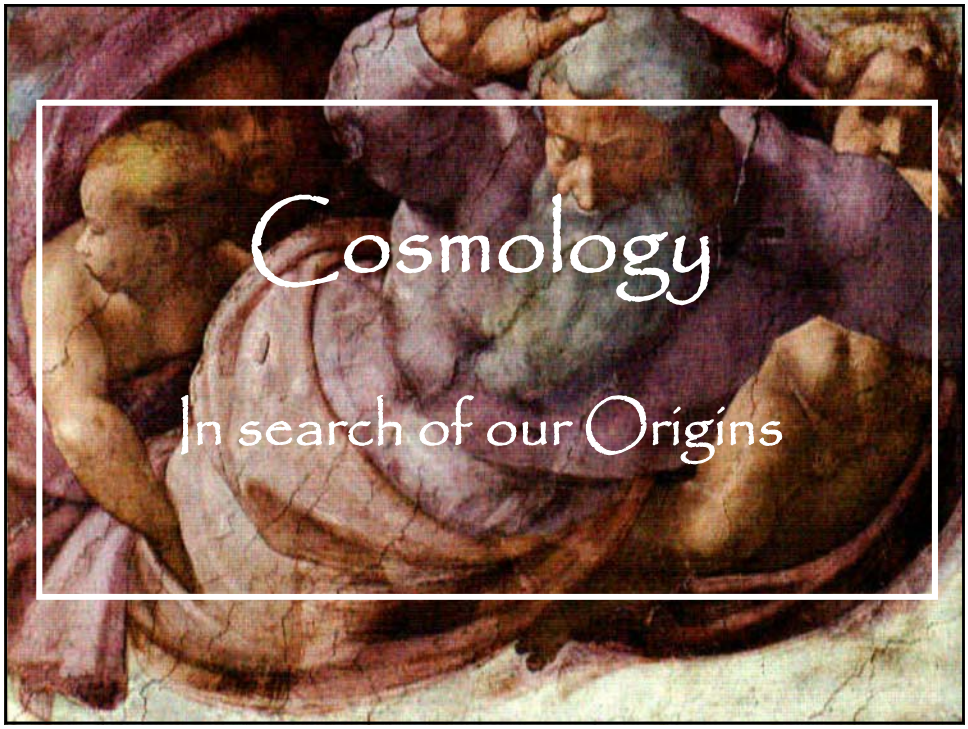
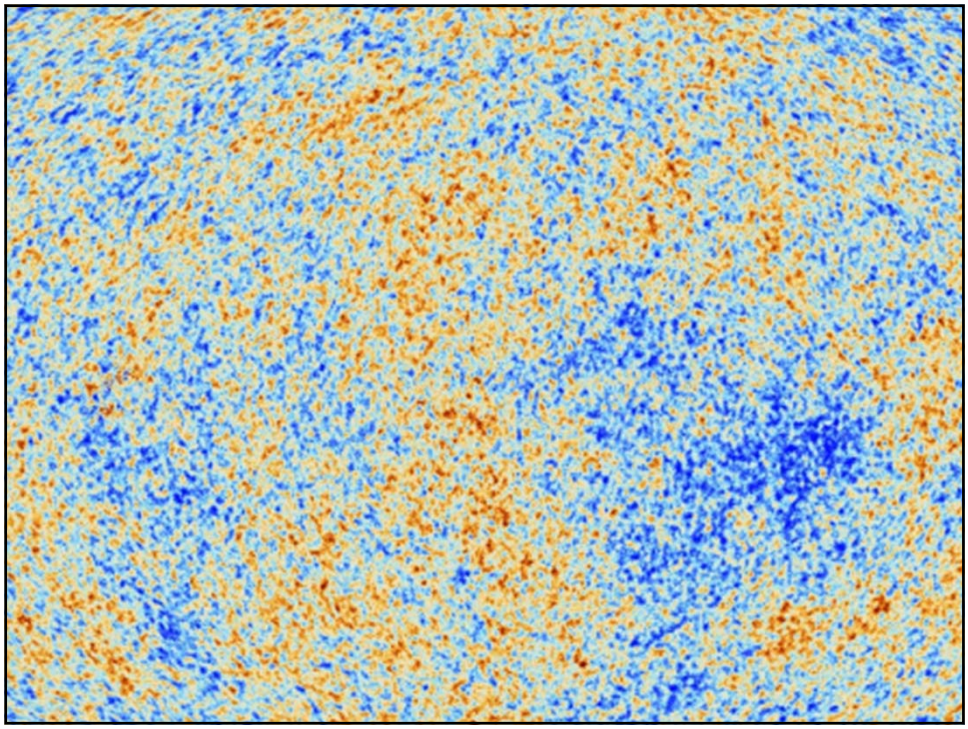
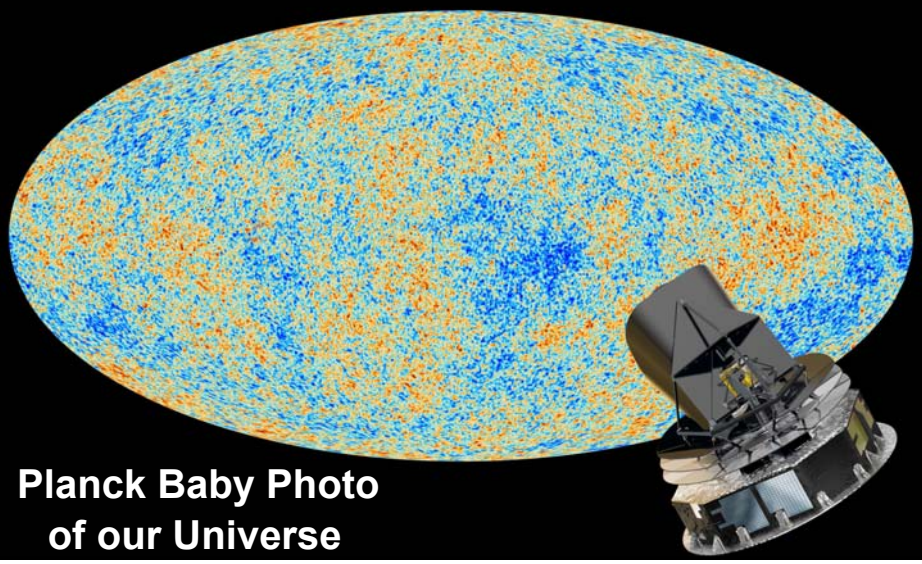

Cosmology
In search of our Origins



Cosmic Origins

- Universe 380.000 yrs after Big Bang
- 13.8 Gyrs ago (13.798±0.037 Gyrs)
- Temperature T = 2.72548±0.00057 K
- temperature/density fluctuations ($\Delta T/T<10^{-5}$)



Planck Baby Photo of our Universe

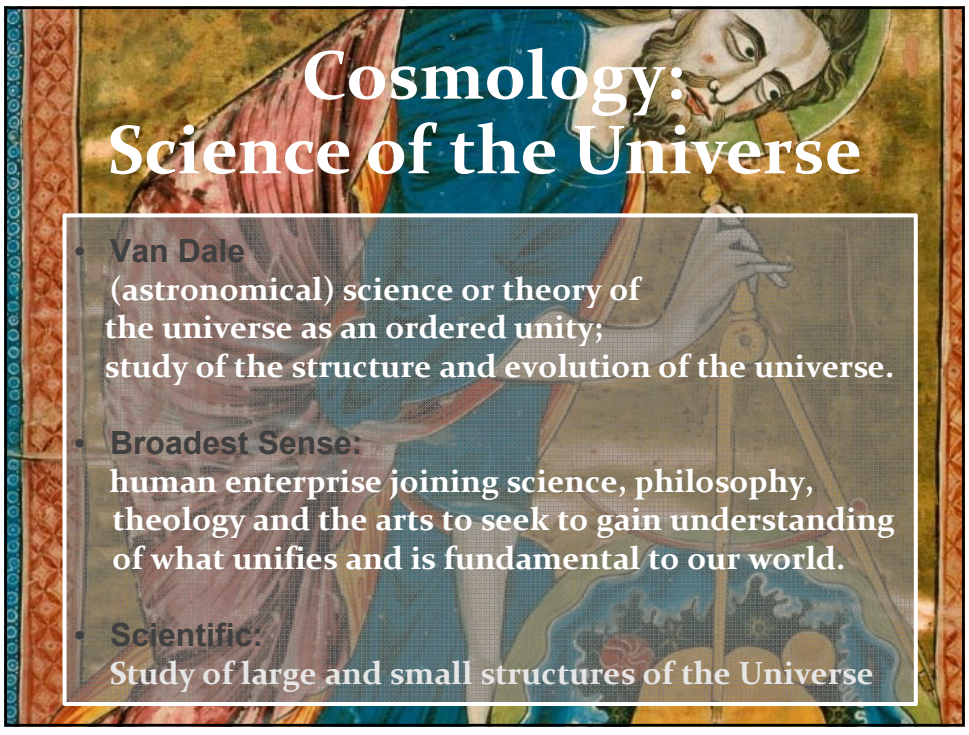
Age of Precision Cosmology

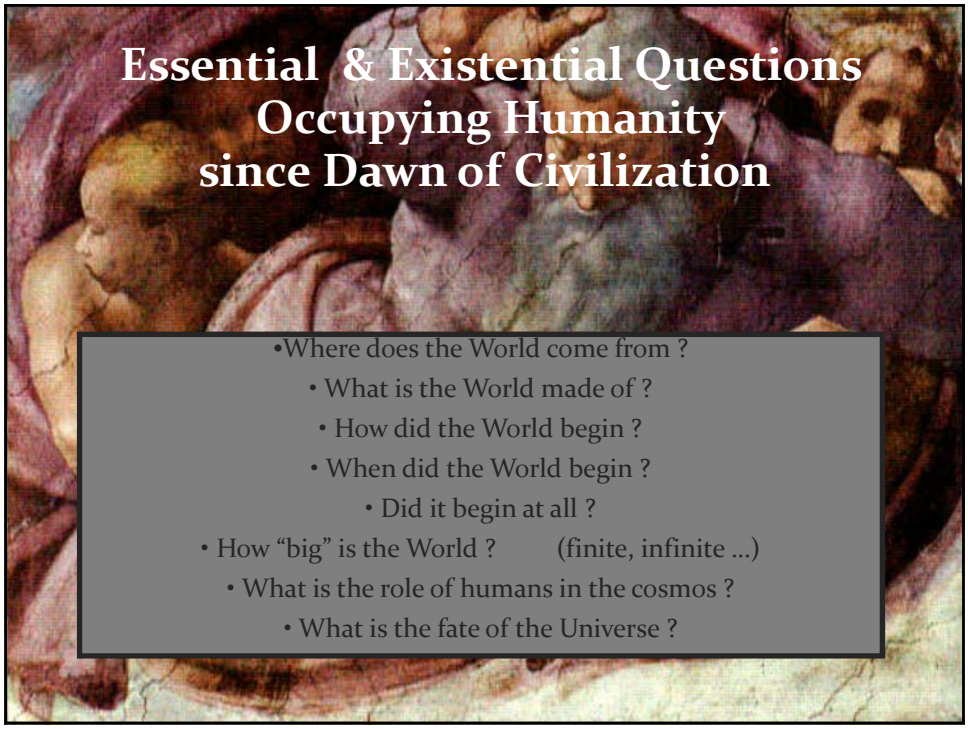
Over the past century - in particular the last 2 decades - we have established an amazingly accurate view of the Universe in which we live:

• It was formed in the Hot Big Bang:	T_0 = 13.798±0.037 Gigayears ago	
• Space (!!!) is expanding ever since:	H_0 = 67.74±0.46 km/s/Mpc	
expansion acceleraring since:	6.7 ± 0.4 Gigayears ago	
• It has an average energy density of:	$\rho_0 = 0.862 \times 10^{-29}$ g/cm^3	
• The outer edge/Horizon of the visible Universe:	d_H ~ 41 Giga lightyears	
within Horizon:	# galaxies ~ 100×10^9	
	# stars ~ 200×10^{18}	
• On every atom (proton/neutron):	$\eta \sim 1.9 \times 10^9$ photons	
• Space is almost perfectly flat:	$\Omega_k \sim 0.000 \pm 0.005$	
• Cosmic composition:	Baryons (protons/neutrons)	~ 4.9%
	Dark Matter	~ 26.8%
	Dark Energy	~ 68.3%

Cosmology,

Science of the Universe





Cosmic Time: Origin and Fate ?

- **Does the Universe have an origin ?**
  If so, how old is it ?
  Or, ... did it always exist, infinitely old ...
- **What is the fate of the Universe ?**
  ... will it always be there, or is there an end ?

Energy: Content of the Universe

- What are the components of the Universe ?
- How does each influence the evolution of the Universe ?

... and ...

- How is each influenced by the evolution of the Universe ?

Cosmological Riddles

- Is our Universe unique, or are there many other Universes (multiverse) ... ?
- What made the Universe originate ?

Cosmological Riddles

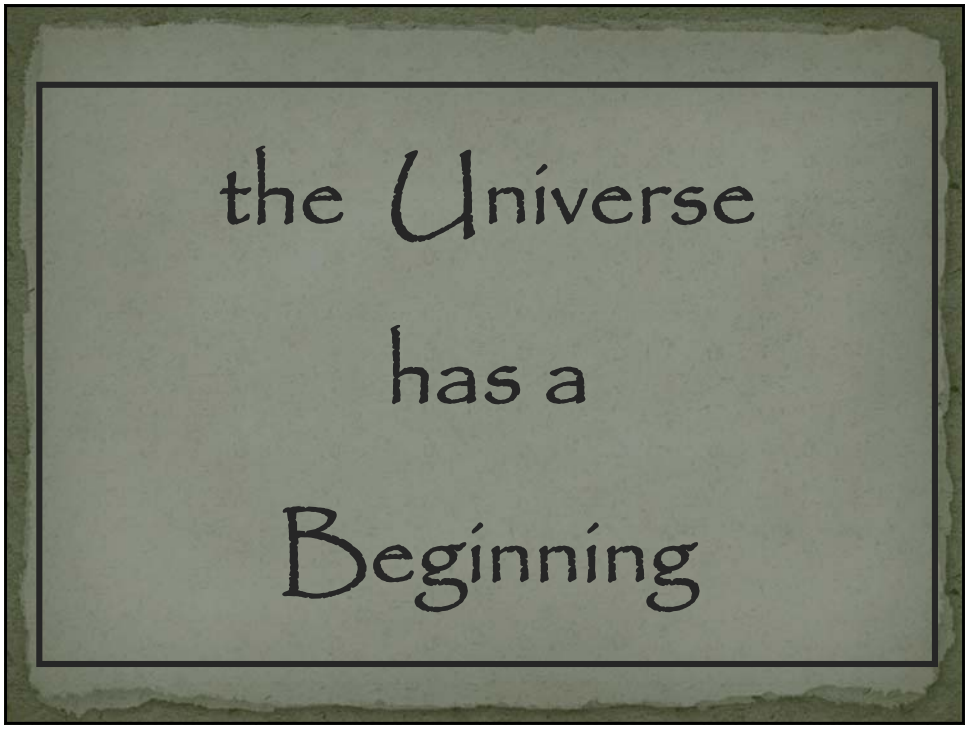
- Why are the physical laws as they are ?
  Do they need to be ?
- How many dimensions does the Universe have?
  More than 1timelike + 3 spacelike ?

Cosmological Riddles

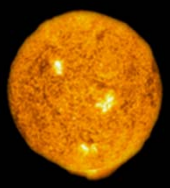
- … and …
- Are our brains sufficiently equipped to understand and answer the ultimate questions … ?

A unique time ...

- The past century, since 1915, marks a special epoch
- For the first time in human history, we are able to address the great questions of Cosmology ...
- scientifically ...



Night Sky is Dark



In an infinitely large, old and unchanging Universe each line of sight would hit a star:

⇒

Sky would be as bright as surface of star:

Night sky as bright as Solar Surface, yet the night sky is dark

⇒

finite age of Universe (13.8 Gyr)

Cosmology:

observing

the history of the Universe

Cosmology: exploring Space & Time

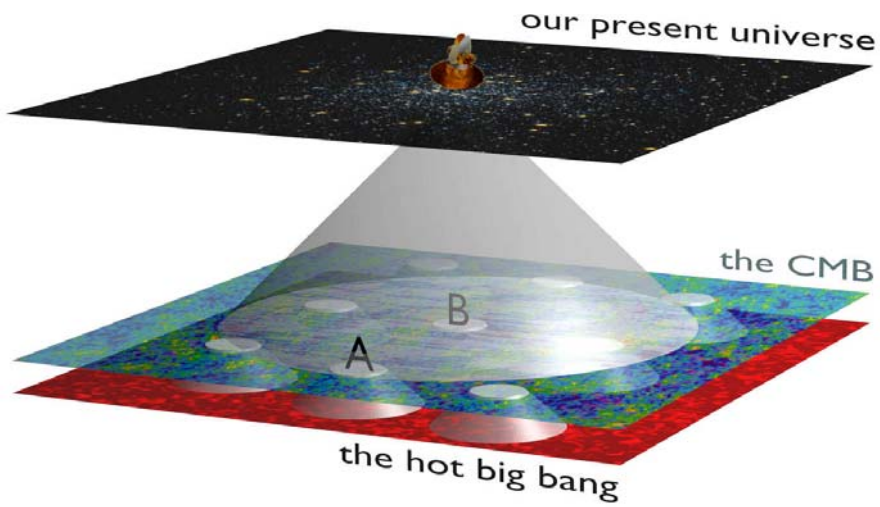
Cosmology is a unique science:

not only it looks out to the deepest realms and
largest scales of our Universe

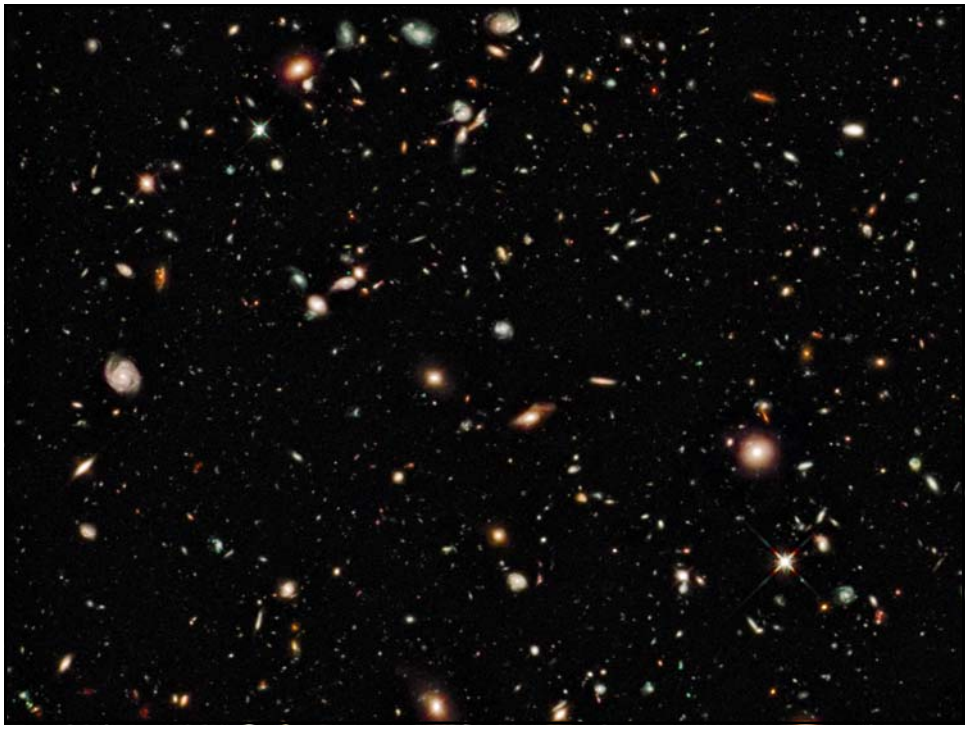
on cosmological scales,
the finite velocity of light becomes a critical factor ...

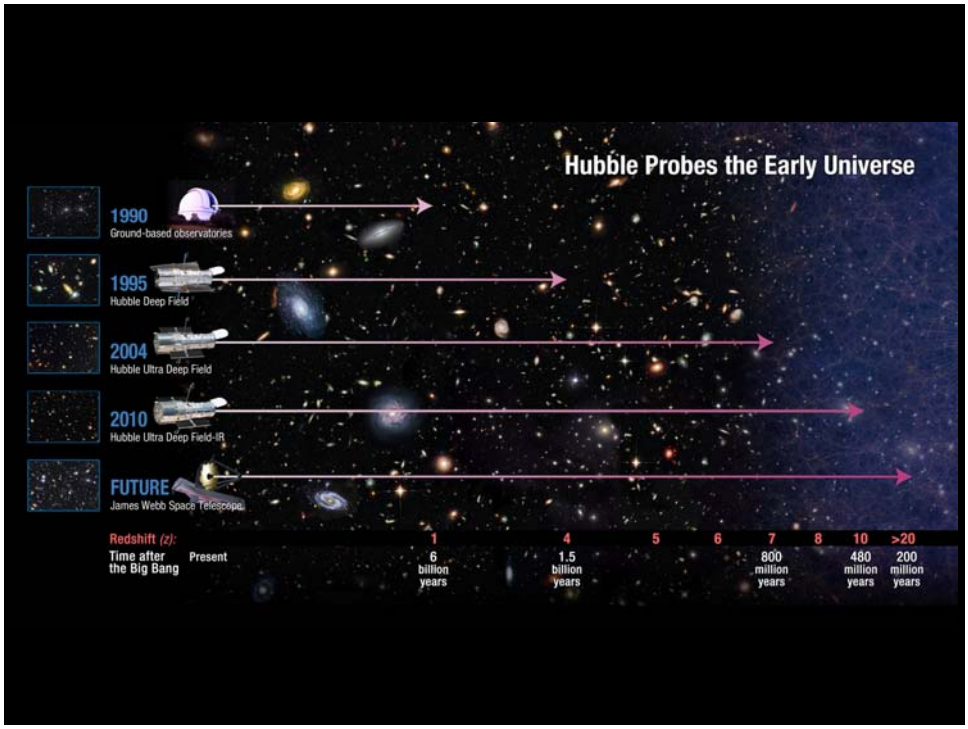
thus, it also looks back in time, to the earliest moments,
and thus is the ultimate archaeological science

Cosmic Depth = Cosmic Time

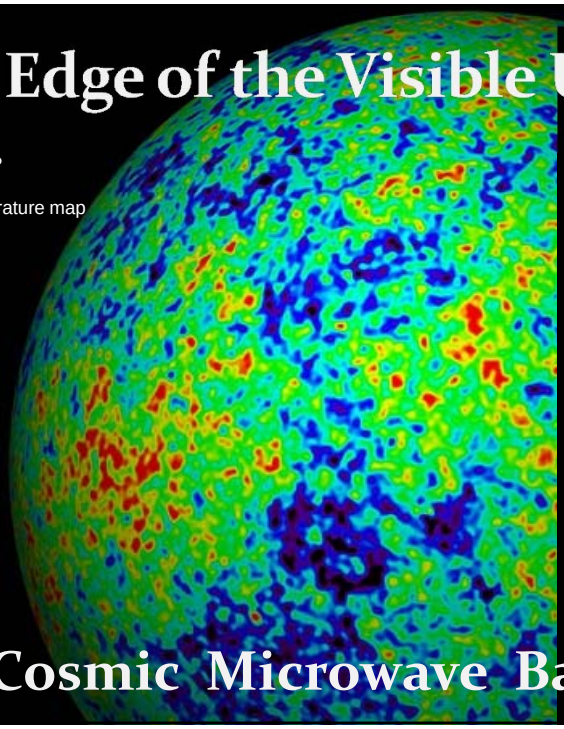


Light propagation through the Universe:
light has a finite velocity (c=300,000 km/s)
the further you look, the further you look in time !




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

Edge of the Visible Universe



WMAP
CMB
temperature map

Earliest View of our Cosmos:

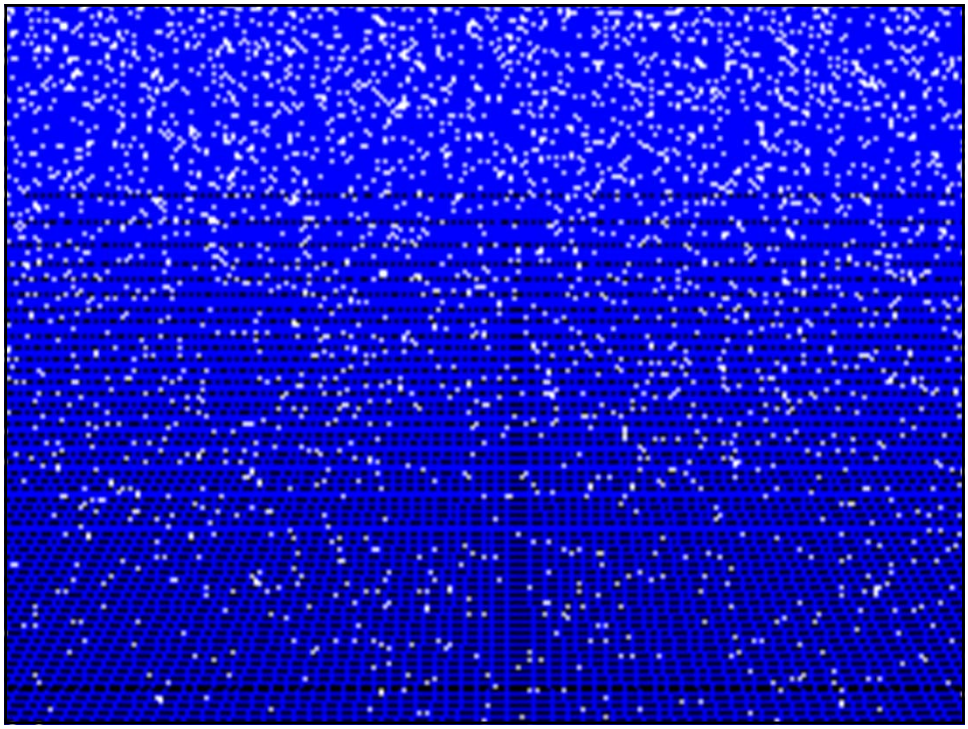
the Universe 379,000 years after the Big Bang

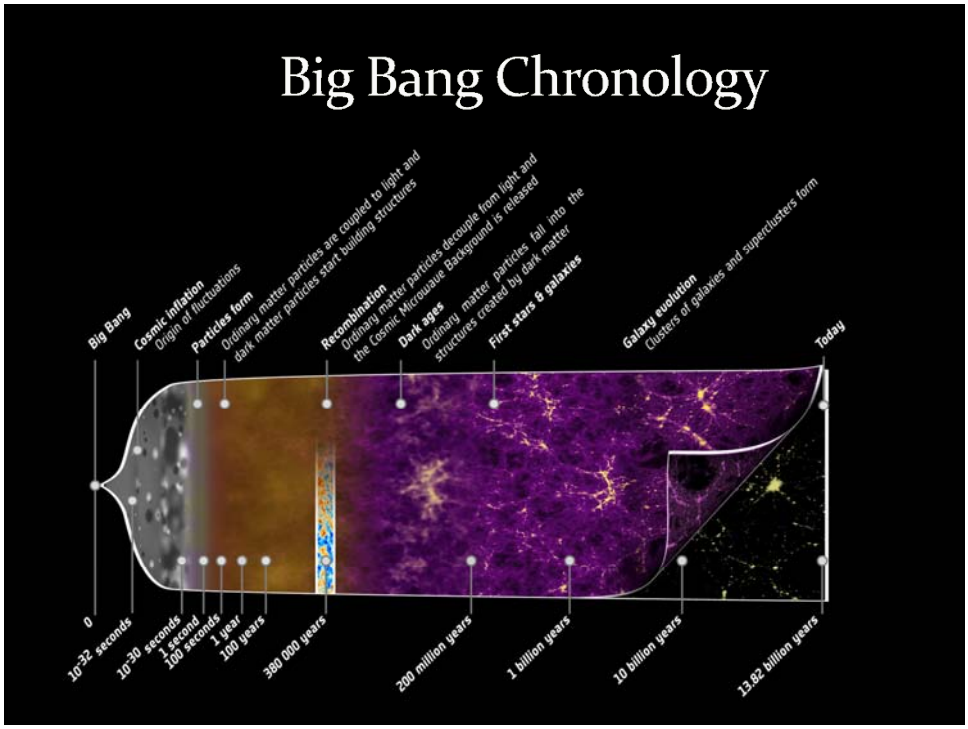
Cosmic Microwave Background

the Universe:
a Unique Astrophysical Object

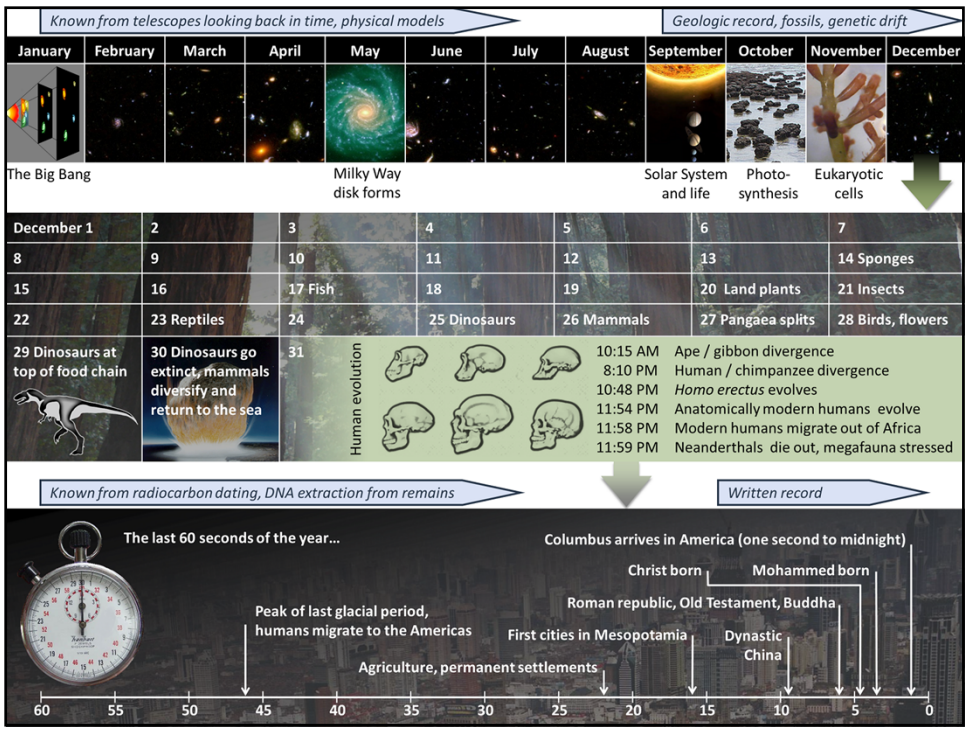
- **There is only one (visible) Universe …**
- **Finite velocity of light, c:**
  … a look in depth = a look back in time …
- **c & implications for space-time:**
  observational cosmology limited to only a minor thin "shell" of all of spacetime …

13.8 Gigayears
of
Cosmic History




Big Bang Chronology
Big Bang
0
Cosmic inflation
Origin of fluctuations
10^-32 seconds
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
10^-30 seconds
1 second
100 seconds
1 year
100 years
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
380 000 years
Dark ages
Ordinary matter particles fall into the structures created by dark matter
200 million years
First stars & galaxies
1 billion years
Galaxy evolution
Clusters of galaxies and superclusters form
10 billion years
Today
13.82 billion years

Cosmic Calendar



Cosmic Light: most abundant species

By far,

the most abundant particle species

in the Universe

to every proton/neutron

$n_\gamma/n_B \sim 1.9$ billion

the Cosmic TV Show

Note:

The cosmic microwave background is not an exotic phenomenon:

1% of the radiation (noise) on your (camping) tv is this CMB radiation:

!!!!! Live broadcast Big Bang !!!!!

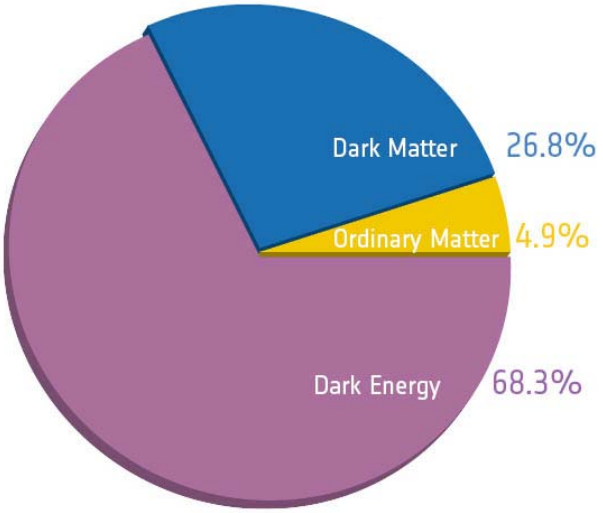
Courtesy: W. Hu

Cosmic Energy Inventory

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		$-10^{-6.2}$	

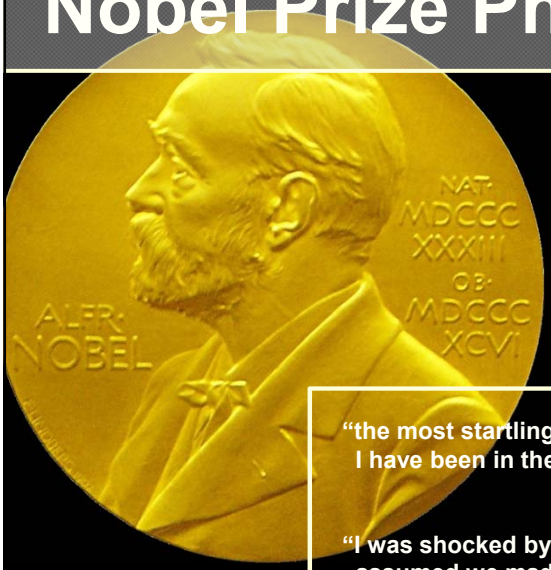
Fukugita & Peebles 2004

Cosmic Constituents



Fate of the Universe

Nobel Prize Physics 2011

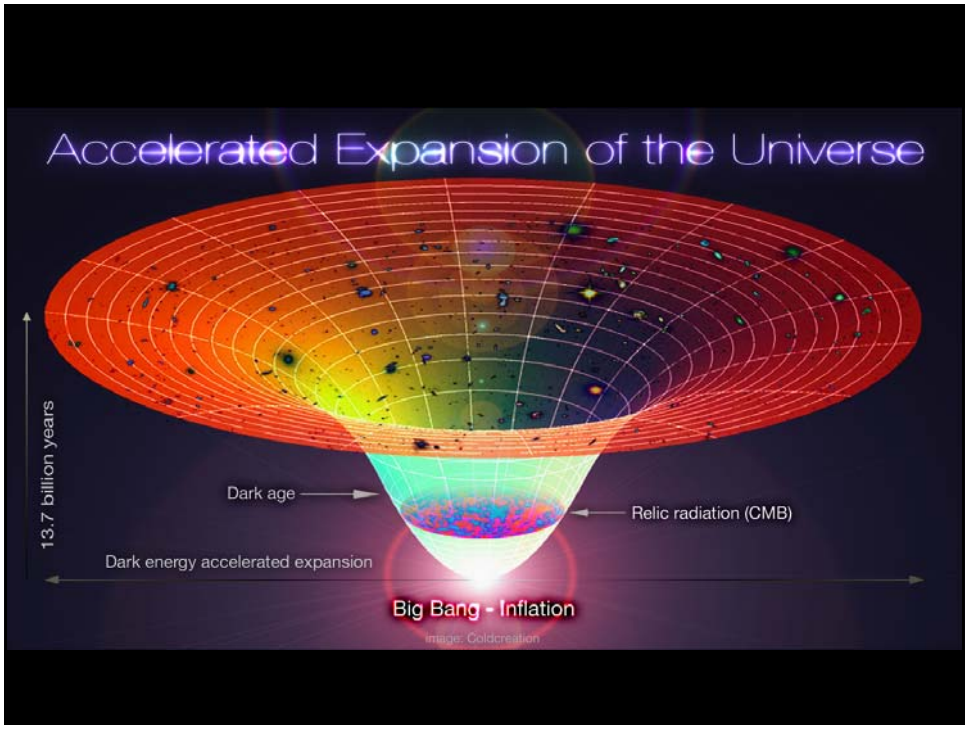


"the most startling discovery in physics since I have been in the field."

E. Witten

"I was shocked by my discovery, I just assumed we made a mistake"

Brian Schmidt



Cosmic Fate

100 Gigayears:
the end of Cosmology

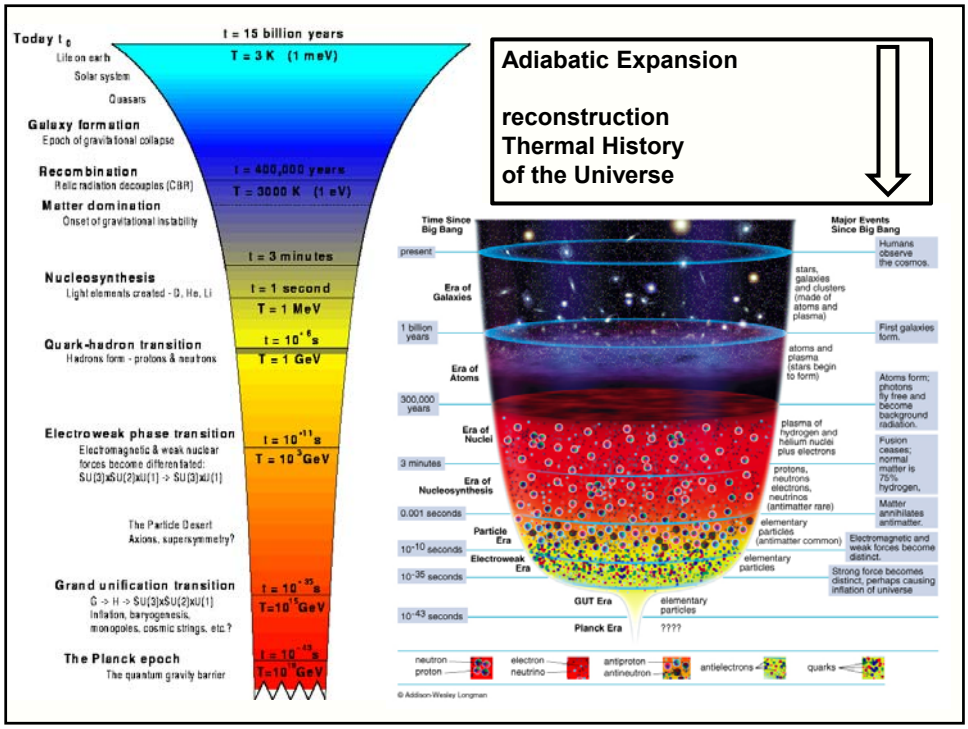
Age of Precision Cosmology

Parameter	Value	Description
	Basic parameters	
H_0	$70.9^{+2.4}_{-3.2}$ km s^{-1} Mpc^{-1}	Hubble parameter
Ω_b	$0.0444^{+0.0042}_{-0.0035}$	Baryon density
Ω_m	$0.266^{+0.025}_{-0.040}$	Total matter density (baryons + dark matter)
τ	$0.079^{+0.029}_{-0.032}$	Optical depth to reionization
A_s	$0.813^{+0.042}_{-0.052}$	Scalar fluctuation amplitude
n_s	$0.948^{+0.015}_{-0.018}$	Scalar spectral index
	Derived parameters	
ρ_0	$0.94^{+0.06}_{-0.09} \times 10^{-26}$ kg/m^3	Critical density
Ω_Λ	$0.732^{+0.040}_{-0.025}$	Dark energy density
z_{ion}	$10.5^{+2.6}_{-2.9}$	Reionization red-shift
σ_8	$0.772^{+0.036}_{-0.048}$	Galaxy fluctuation amplitude
t_0	$13.73^{+0.13}_{-0.17} \times 10^9$ years	Age of the universe

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023
f_{2000}^{143}	29.9 ± 2.9	30.4 ± 2.9	30.3 ± 2.8	29.5 ± 2.7	30.2 ± 2.7	30.0 ± 2.7
$f_{2000}^{143\times217}$	32.4 ± 2.1	32.8 ± 2.1	32.7 ± 2.0	32.2 ± 1.9	32.8 ± 1.9	32.6 ± 1.9
f_{2000}^{217}	106.0 ± 2.0	106.3 ± 2.0	106.2 ± 2.0	105.8 ± 1.9	106.2 ± 1.9	106.1 ± 1.8

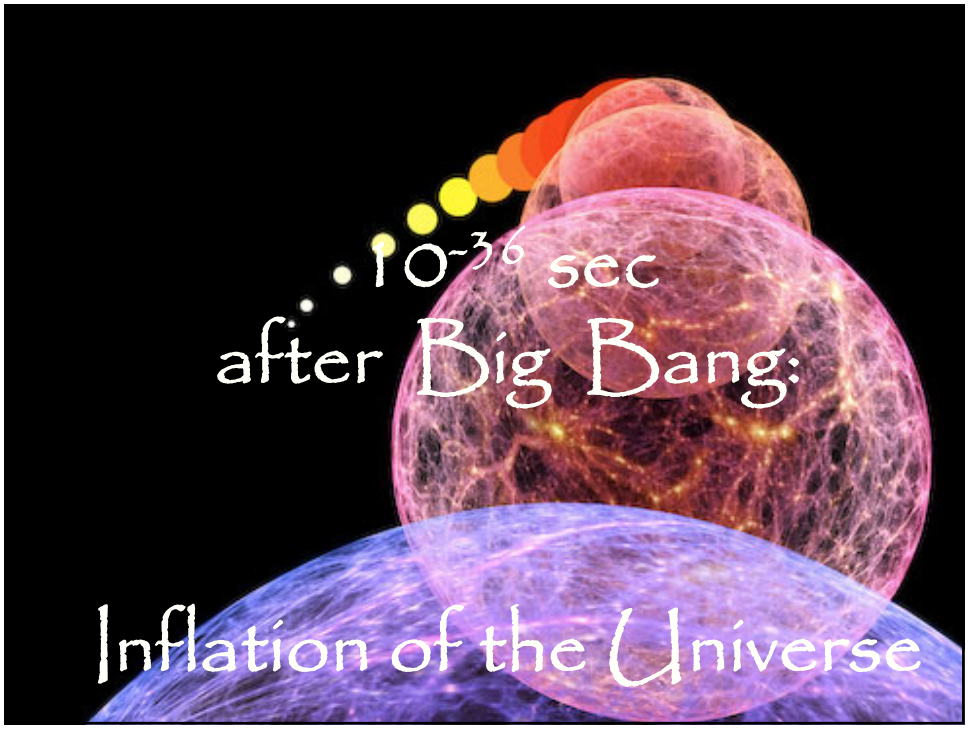
the

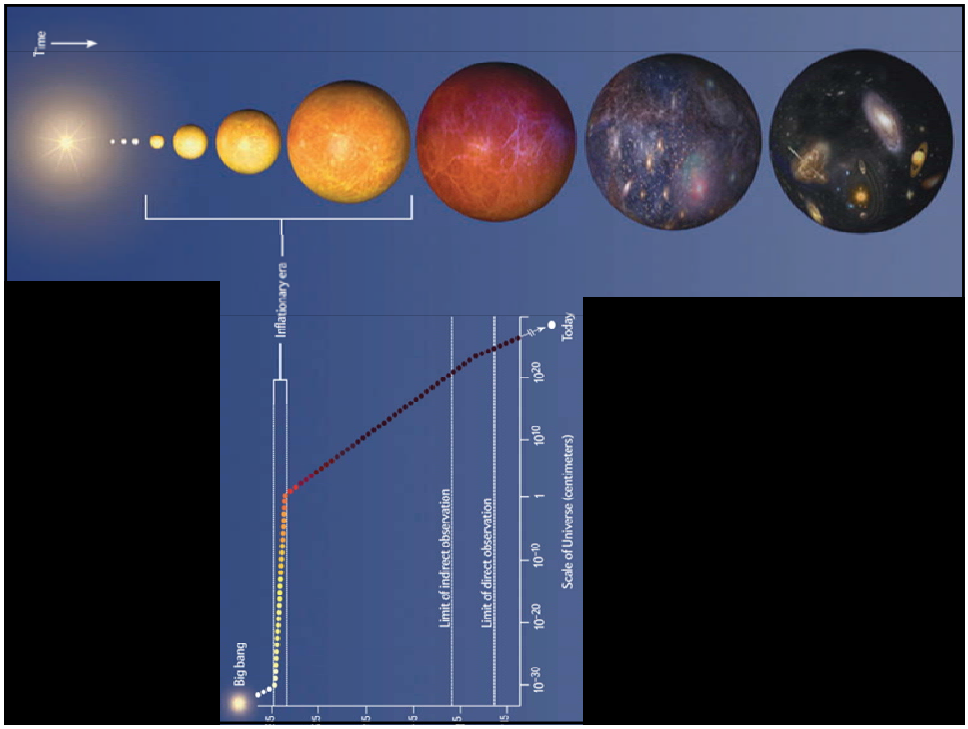
first moments



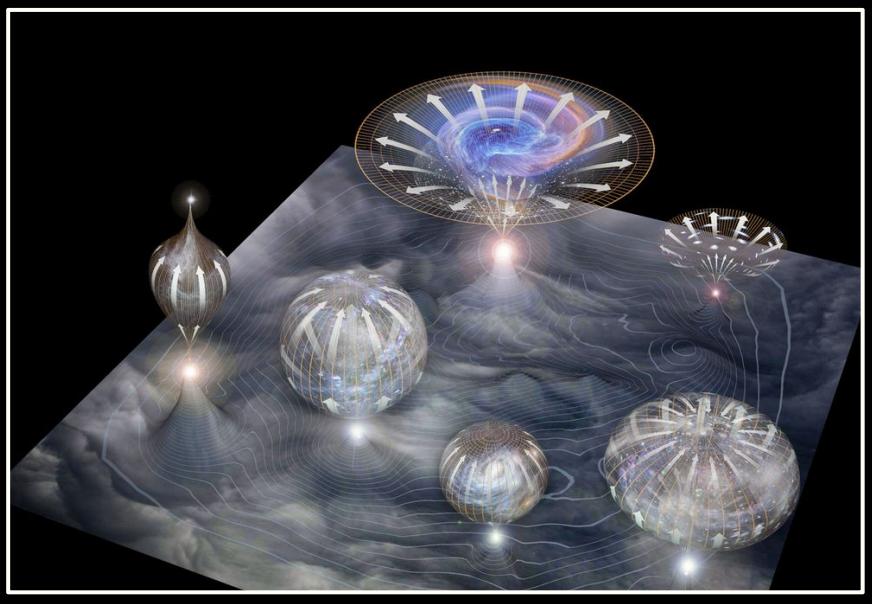
Episodes Thermal History

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





Inflation & Multiverse



Milky Way:

our Galaxy

"Over the Top" by Luc Perrot (www.lucperrot.fr). The central bulge of the Milky Way rises over a volcano in Réunion Island of France (southern Indian Ocean). The first winner in Beauty of the Night Sky category. The 2014 International Earth & Sky Photo Contest. twanight.org/contest

Kyklos Galaktikos

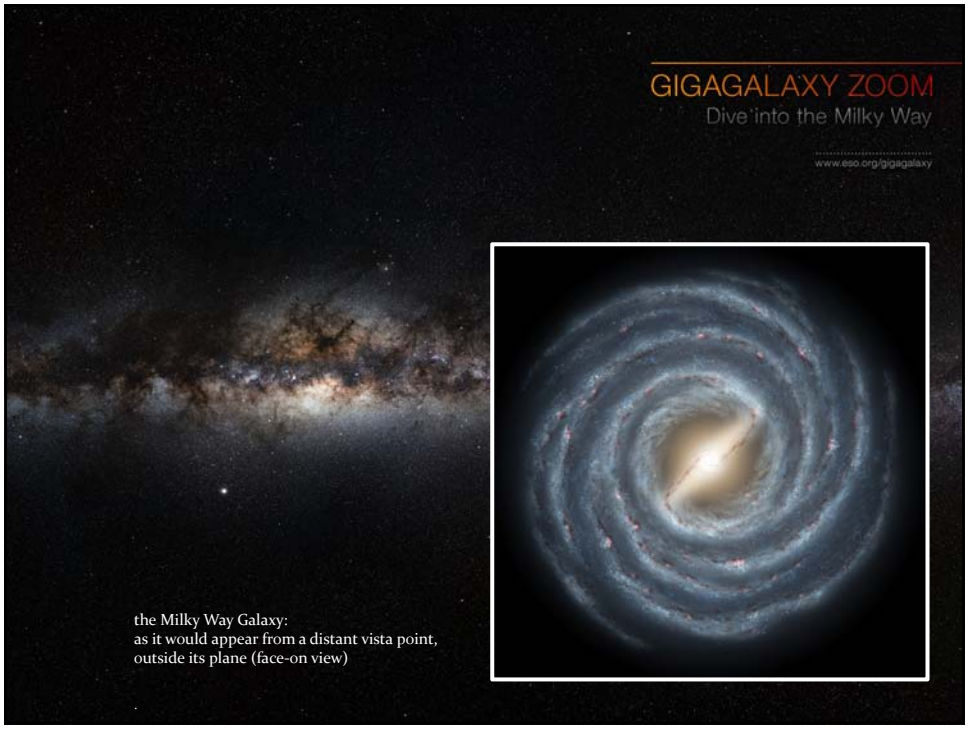
- Als de oude Grieken op een heldere zomeravond naar de hemel keken, zagen ze daar een zwakke band van licht die zich uitstrekte van horizon tot horizon. Het deed hen denken aan een stroom melk ...
- ze voorzagen dit ontzagwekkende fenomeen van de naam ``Kyklos Galaktikos'' ofwel melkachtige cirkel.

- Mythe 1:

  Melkweg gecreeerd door Heracles toen hij een baby was. Zijn vader was Zeus, zijn menselijke moeder Alcmene. Zeus besloot om het kindje Heracles te laten zogen bij zijn goddelijke vrouw Hera terwijl ze sliep, zodat de baby goddelijke eigenschappen zou krijgen. Toen Hera wakker werd en realiseerde dat ze een onbekend kind zoogde, duwde ze hem weg, en de gemorste melk werd de Melkweg.
- Mythe 2:

  De melk is afkomstig van de godin Rhea, de vrouw van Cronus. Cronus at zijn eigen kinderen om zijn positie als oppergod van het Pantheon en als hemelgod te verzekeren. Rhea vatte het plan om haar nieuw geboren zoon Zeus te redden. Ze wikkelde een steen in babykleren en gaf het aan Cronus om het te verslinden. Cronus vroeg haar het kind nog eenmaal te zogen voor het te verzwelgen, en de melk die ze gaf toen ze de rots pretendeerde te zogen werd de Melkweg.

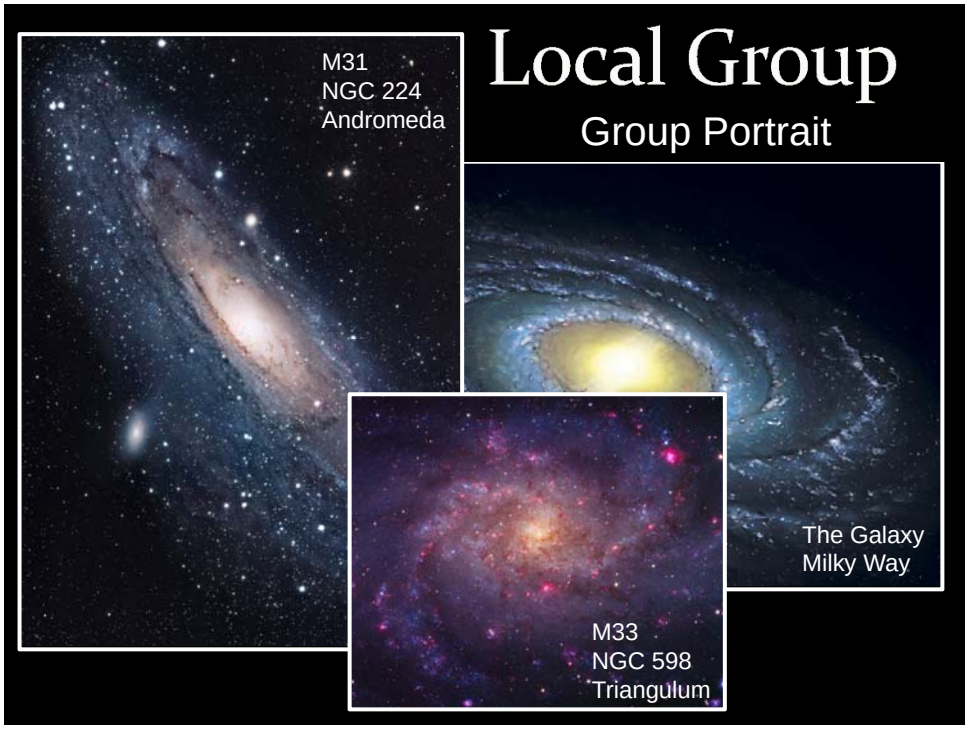

GIGAGALAXY ZOOM
Dive into the Milky Way
www.eso.org/gigagalaxy



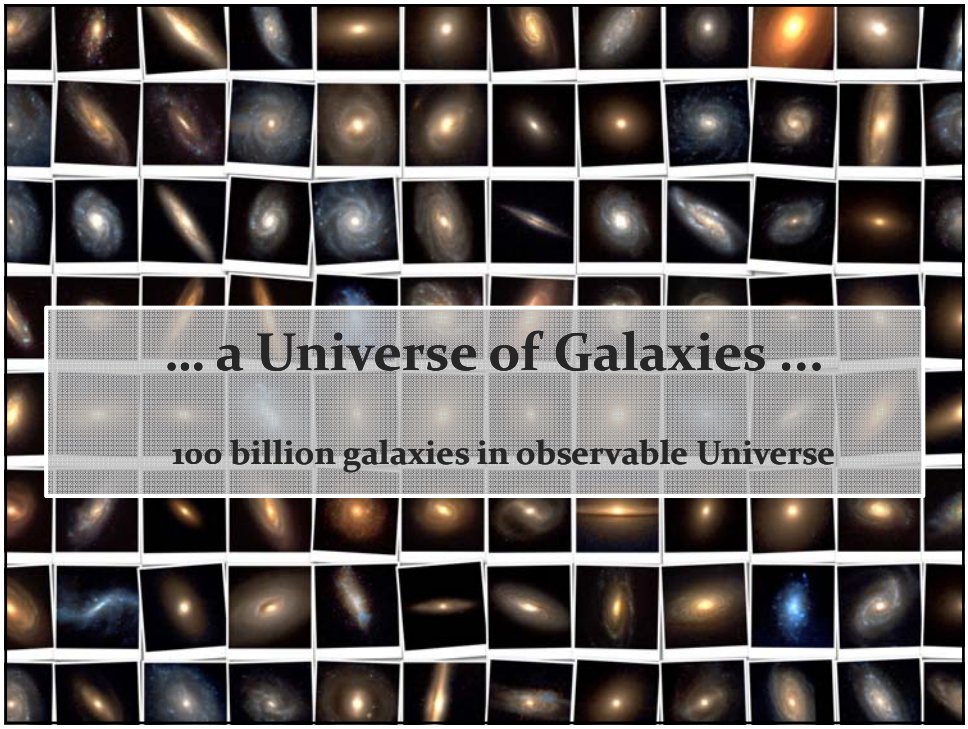
the Milky Way Galaxy:
as it would appear from a distant vista point,
outside its plane (face-on view)

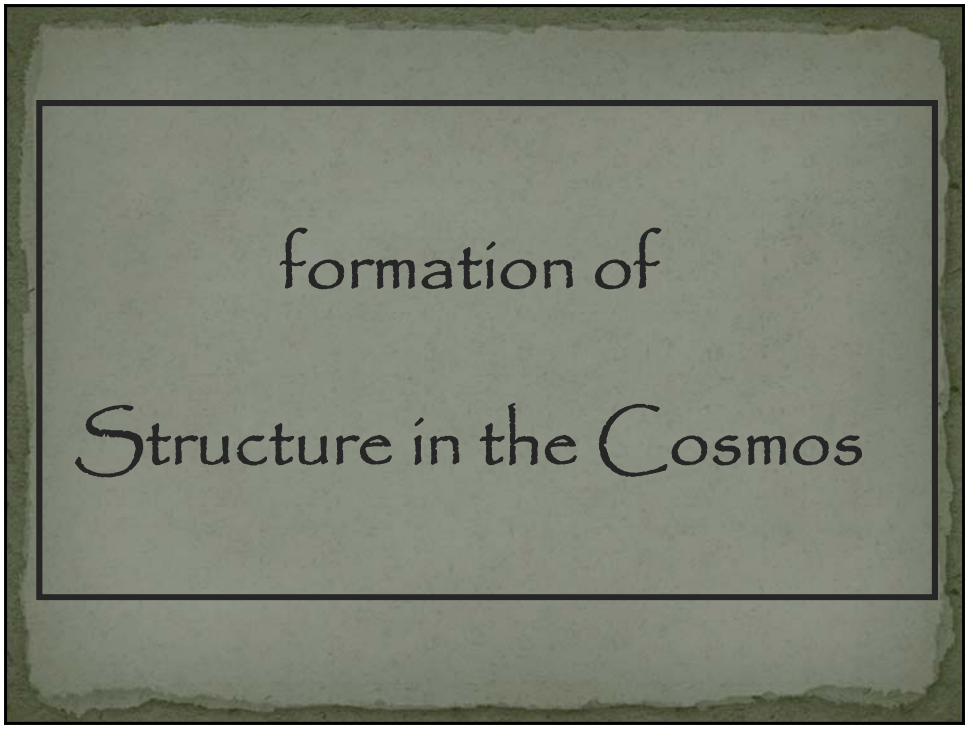
Galaxies:

Island Universes

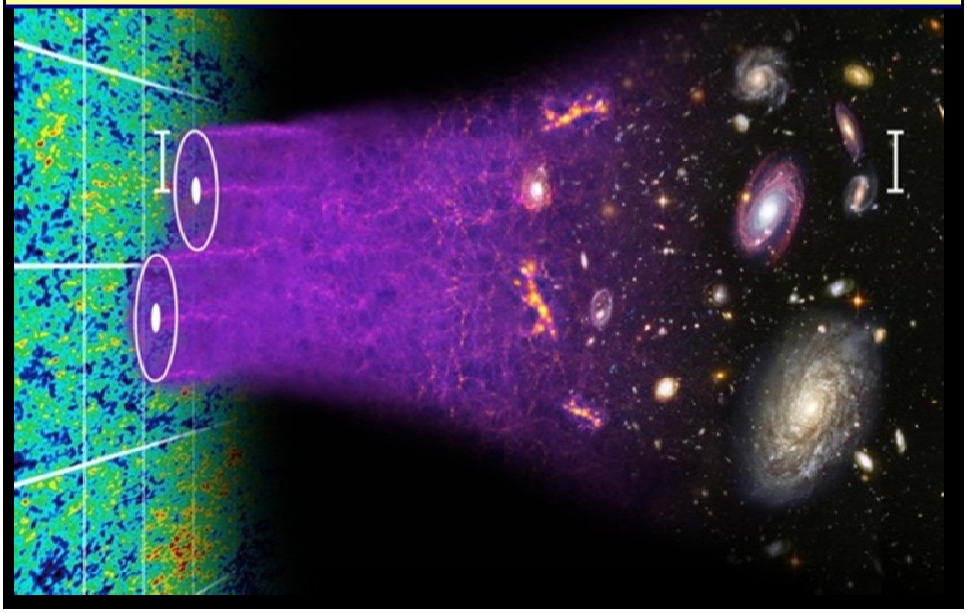

Local Group
Group Portrait
M31
NGC 224
Andromeda
The Galaxy
Milky Way
M33
NGC 598
Triangulum

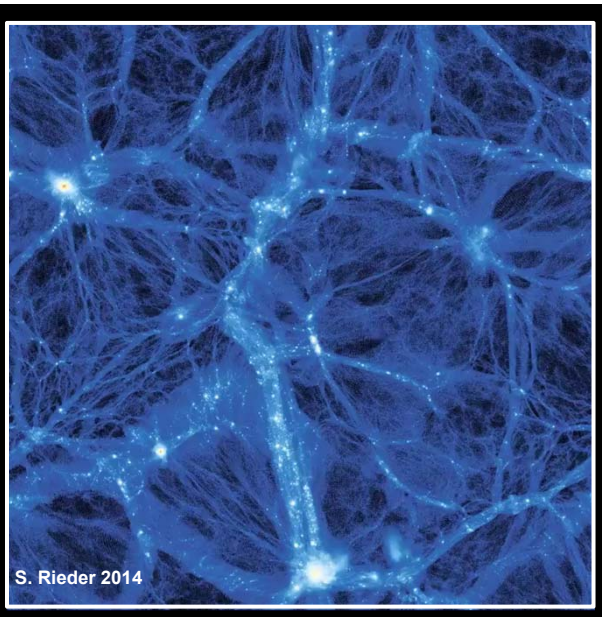

... Galaxies ...


... a Universe of Galaxies ...
100 billion galaxies in observable Universe


formation of
Structure in the Cosmos

Formation Cosmic Structures





on scales of ~0.1 -100s Mpc

complex weblike pattern

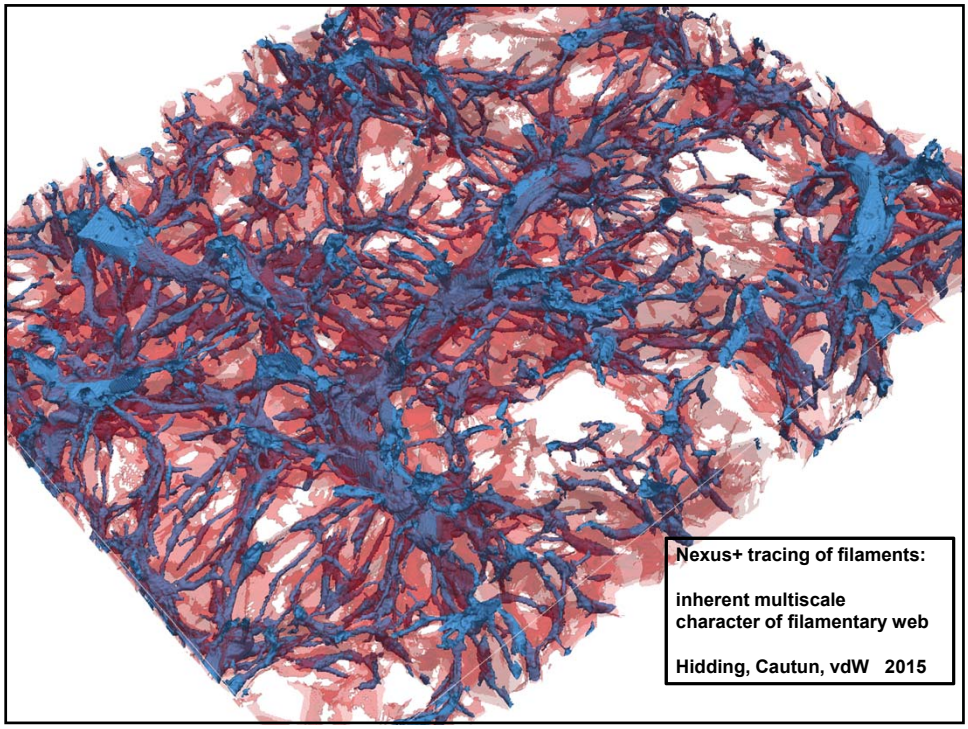
in which
matter, gas & galaxies
aggregate in

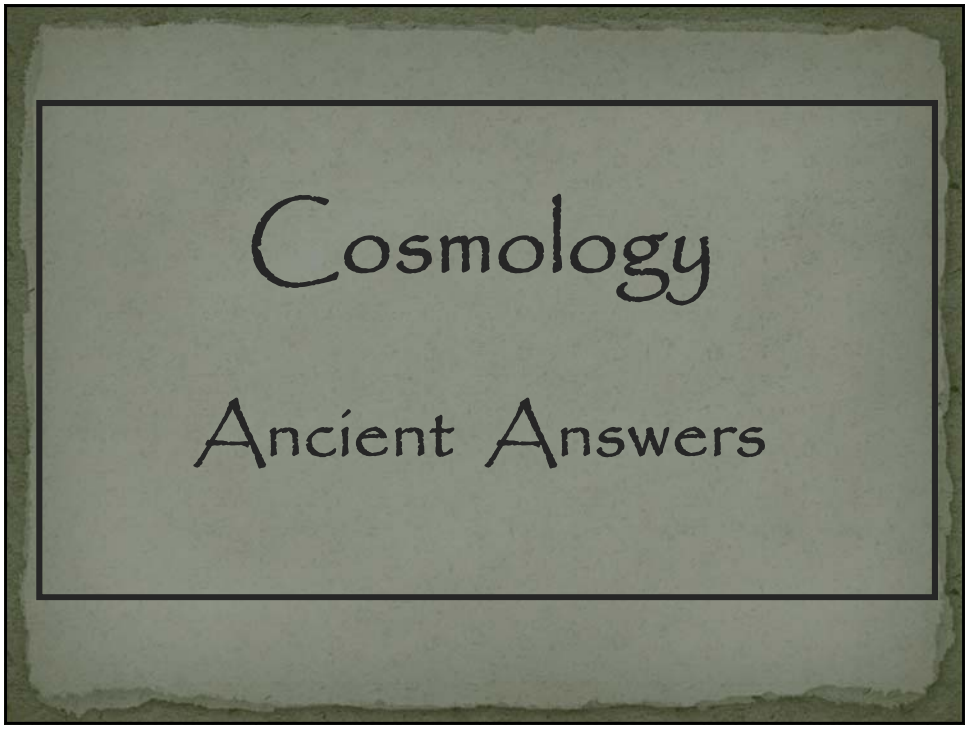
- compact clusters,
- elongated filaments
- flattened sheets

around

- cosmic voids

Cosmic Web


Nexus+ tracing of filaments:
inherent multiscale
character of filamentary web
Hidding, Cautun, vdW 2015


Cosmology
Ancient Answers

14 And God said, Let there be lights in the firmament of the heaven
to divide the day from the night; and let them be for signs, and for seasons,
and for days, and years:
15 And let them be for lights in the firmament of the heaven to give light upon the earth:
and it was so.
16 And God made two great lights;
the greater light to rule the day, and the lesser light to rule the night:
[he made] the stars also.
17 And God set them in the firmament of the heaven to give light upon the earth,
18 And to rule over the day and over the night,
and to divide the light from the darkness:
and God saw that *[it was]* good.
19 And the evening and the morning were the fourth day.

Genesis 1:14-1:19

Enuma Elis

Enuma Elis is
the Babylonian creation mythos.

Striking similarity to Genesis

Important source for understanding
Babylonian worldview, centered on the
supremacy of Marduk
and the creation of humankind for the
service of the gods.

Marduk and the Dragon
Marduk, chief god of Babylon, destroys – with his thunderbolt – Tiamat the dragon of primeval chaos

When the sky above was not named
And the earth beneath did not yet bear a name
And the primeval Apsu, who begat them,
And chaos, Tiamat, the mother of them both,
Their waters were mingled together,
And no field was formed, no marsh was to be seen;
When the gods none had been called into being.

Hindu Cosmology

- The **Nasadiya Sukta**
  (after the incipit *ná ásat* "not the non-existent"), also known as the
- **Hymn of Creation**,
  is the 129th hymn of the 10th Mandala of the
- **Rigveda (10:129).**
  It is concerned with cosmology and the origin of the universe

Nasadiya Sukta – Hymn of Creation

There was neither non-existence nor existence then;
Neither the realm of space, nor the sky which is beyond;
What stirred? Where? In whose protection?

There was neither death nor immortality then;
No distinguishing sign of night nor of day;
That One breathed, windless, by its own impulse;
Other than that there was nothing beyond.

Darkness there was at first, by darkness hidden;
Without distinctive marks, this all was water;
That which, becoming, by the void was covered;
That One by force of heat came into being;

Who really knows? Who will here proclaim it?
Whence was it produced? Whence is this creation?
Gods came afterwards, with the creation of this universe.
Who then knows whence it has arisen?

Whether God's will created it, or whether He was mute;
Perhaps it formed itself, or perhaps it did not;
Only He who is its overseer in highest heaven knows,
Only He knows, or perhaps He does not know.

The Rig Veda, 10.129.1–7

Jain Cosmology

According to Jain doctrine,
- the universe and its constituents always existed
- the universe was not created, and there is no creator