Cosmology

Alexander Knebe *(Universidad Autonoma de Madrid)*

Cosmology

- *explain this!*
- *principles*
- *cosmology – science or science fiction?*
- *cosmological structure formation*

Cosmology

- *explain this!*
- *principles*
- *cosmology – science or science fiction?*
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Cosmology

explain this!

Cosmology

explain this!

Cosmology

explain this!

"my god, it's full of stars!"

only stars?

Cosmology

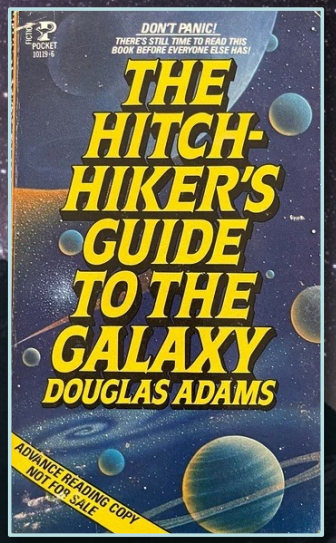
explain this!

Cosmology

explain this!

Cosmology

explain this!

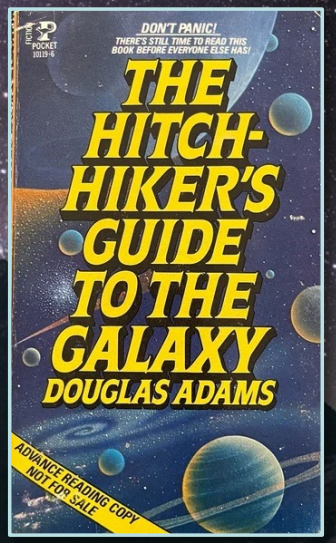


Cosmology

explain this!

"the infinite improbability drive,
a wonderful new method of crossing interstellar
distances in a mere nothingth of a second"

*"a small blue-green planet
in the uncharted backwaters of the unfashionable end
of the western spiral arm of the Milky Way Galaxy"*

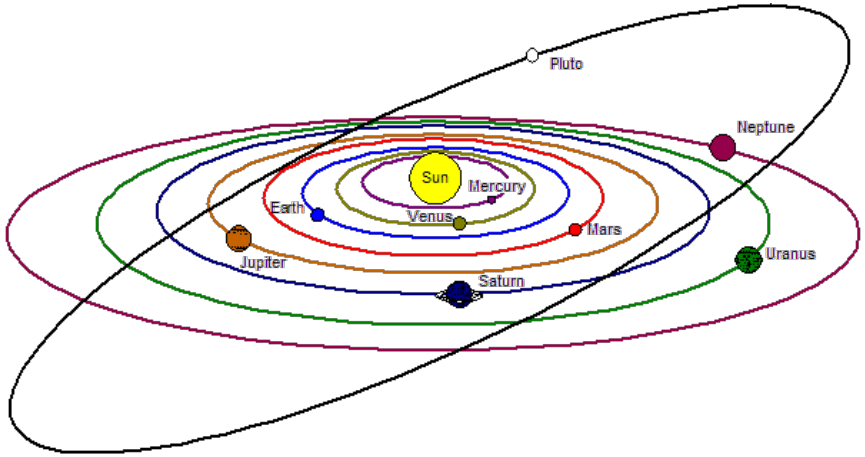


Cosmology

explain this!

Space, the final frontier?

our solar system



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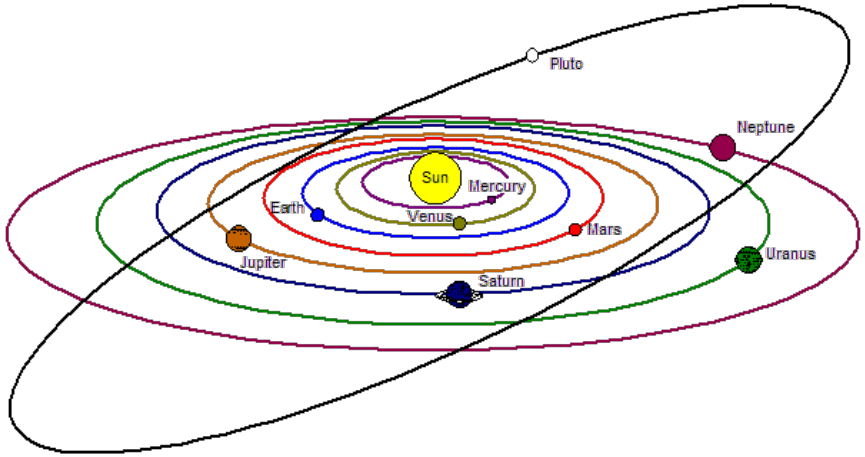

- *Proxima Centauri*

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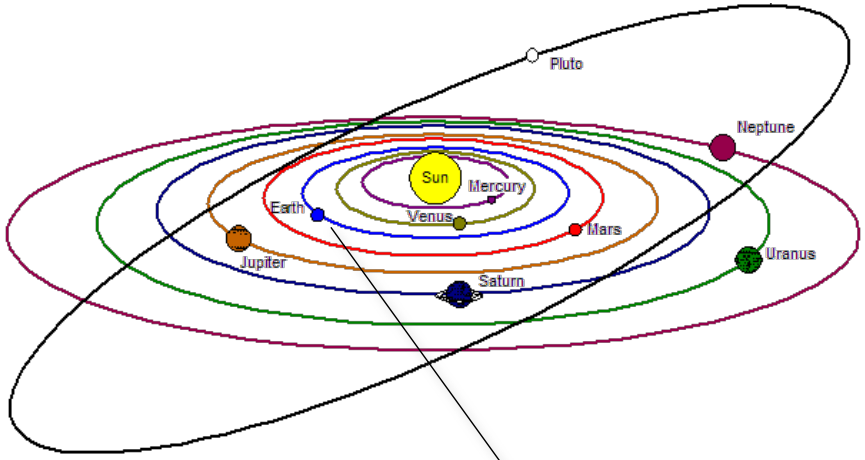

4 lighyears (ca. 40.000.000.000.000 km)

Proxima Centauri

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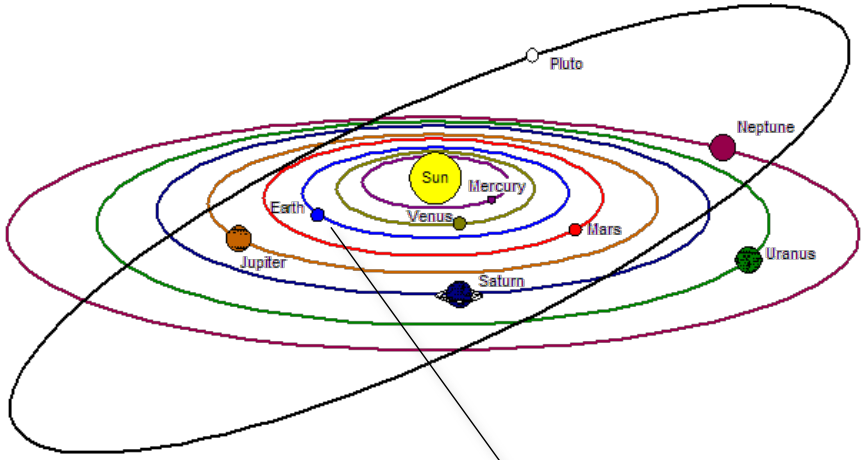

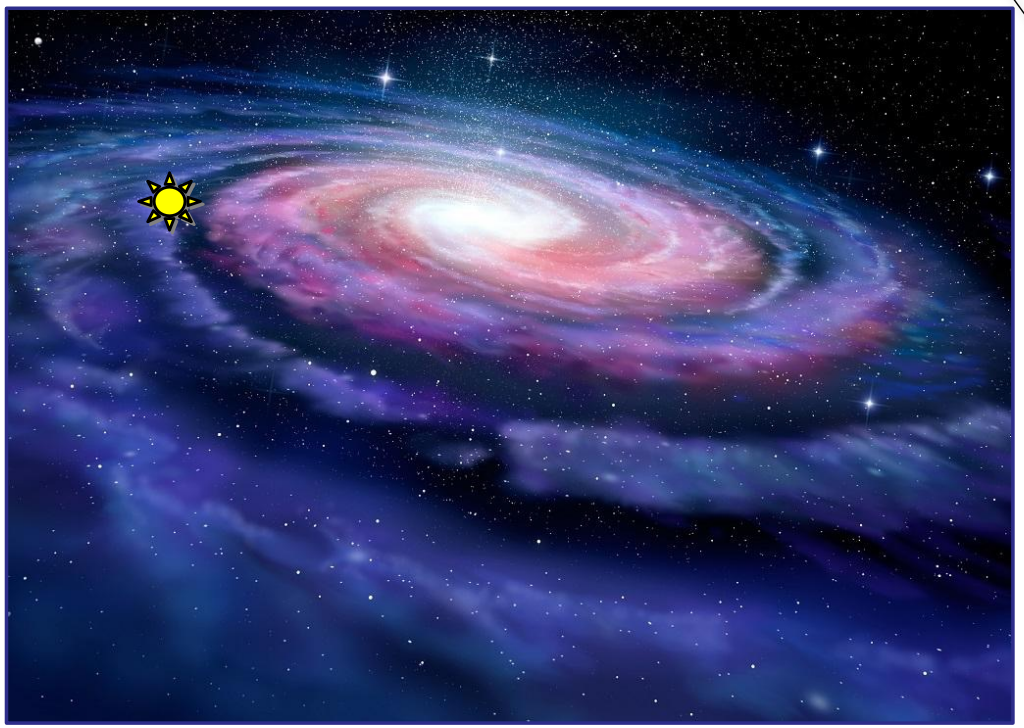

4 lighyears (ca. 40.000.000.000.000 km)

?

Proxima Centauri

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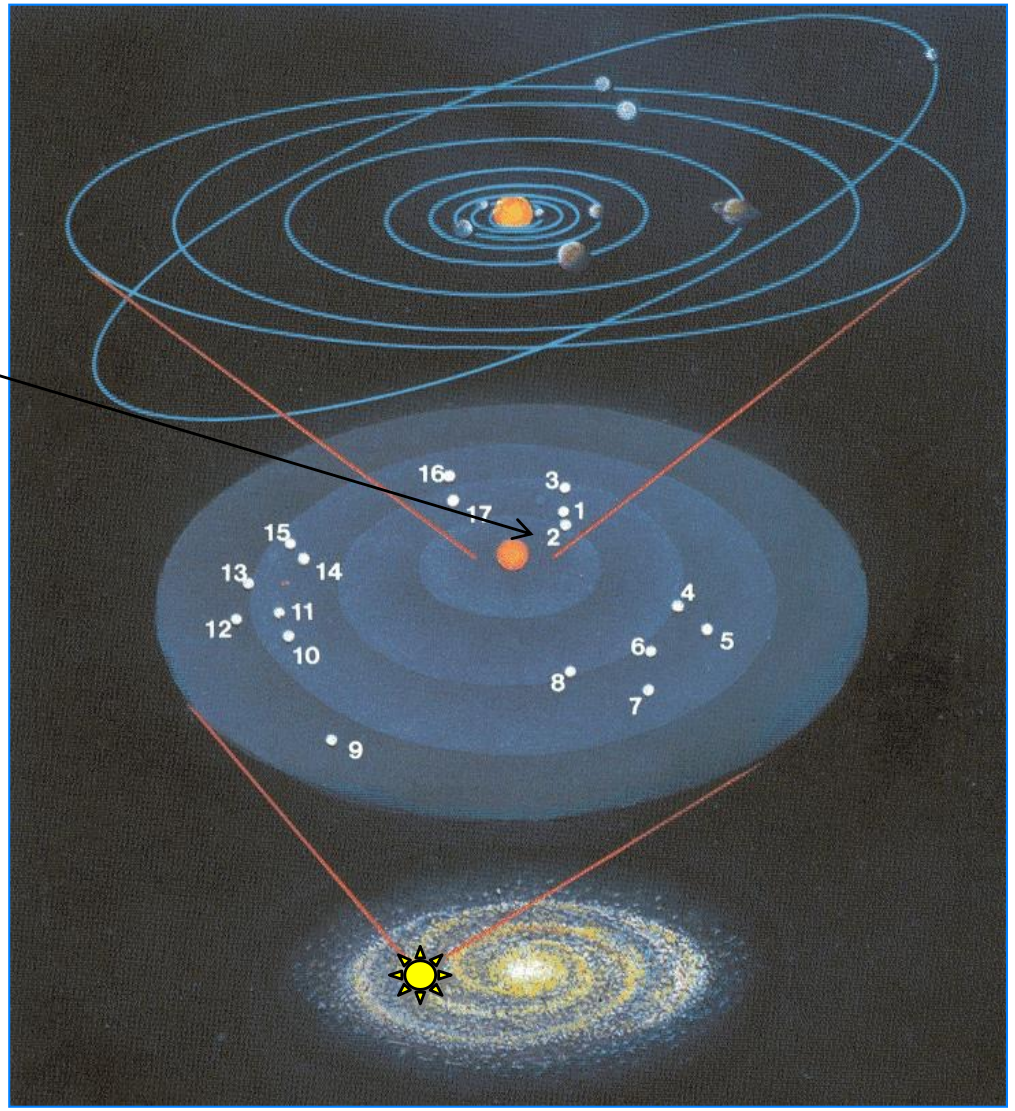
Space, the final frontier!

2=Proxima Centauri



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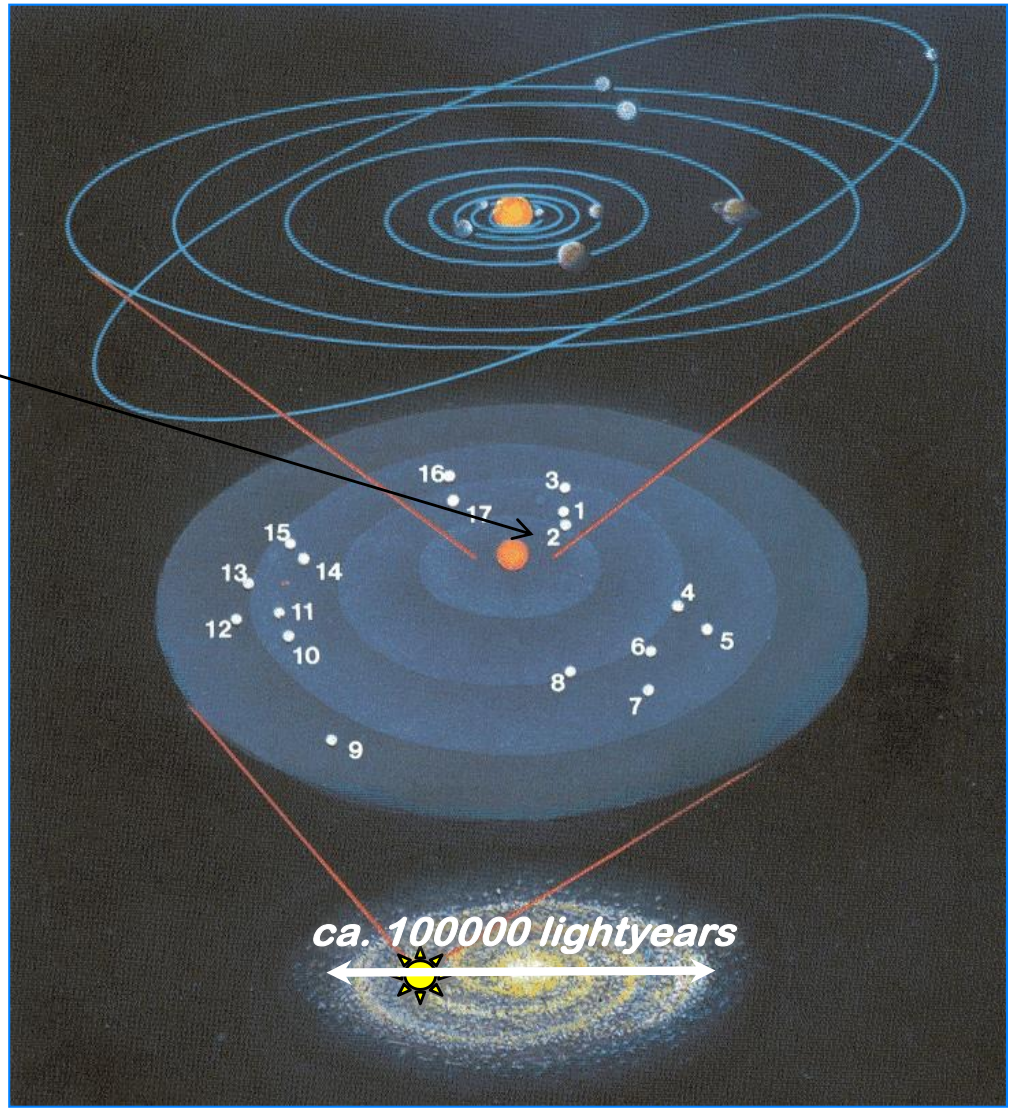

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Space, the final frontier!

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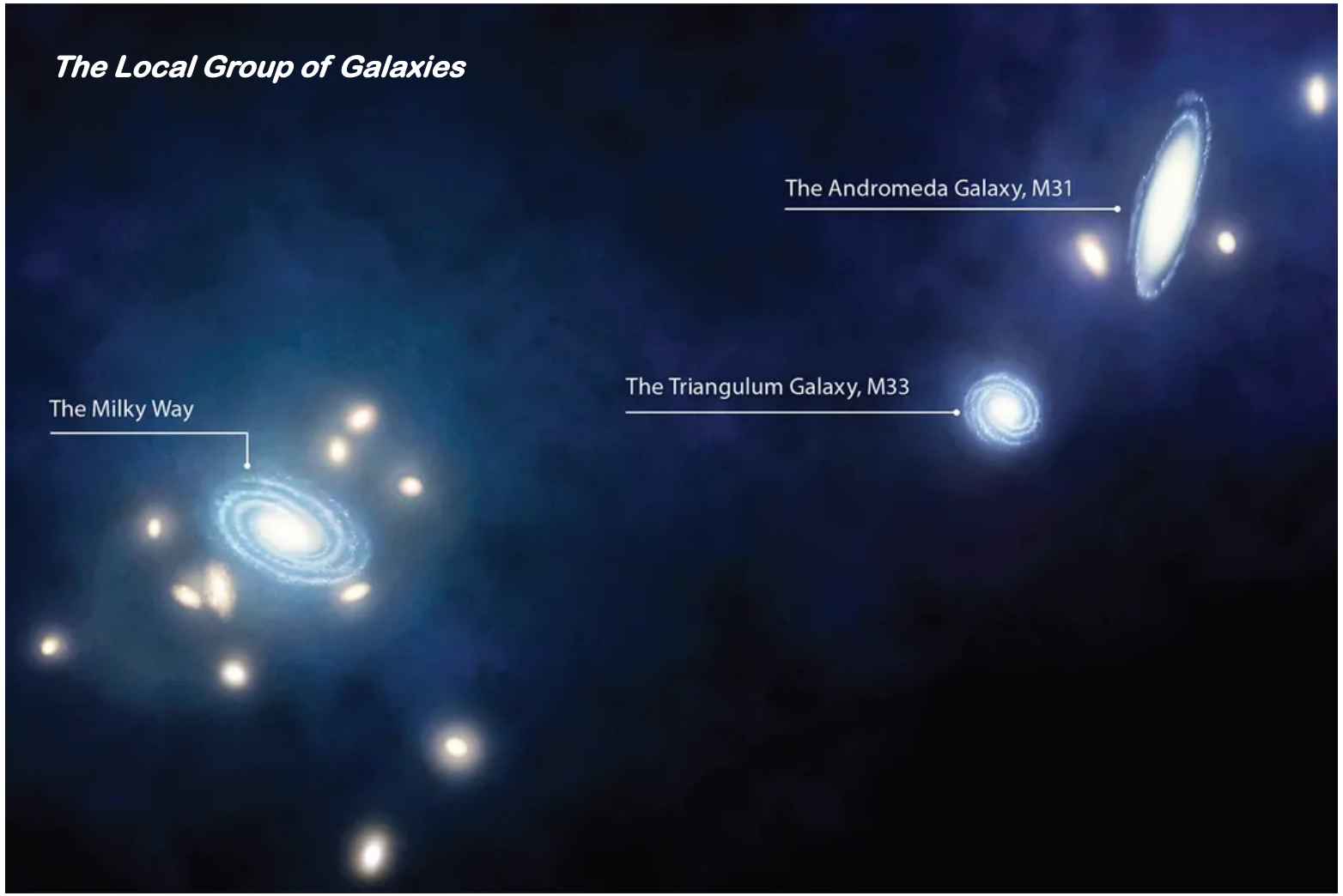

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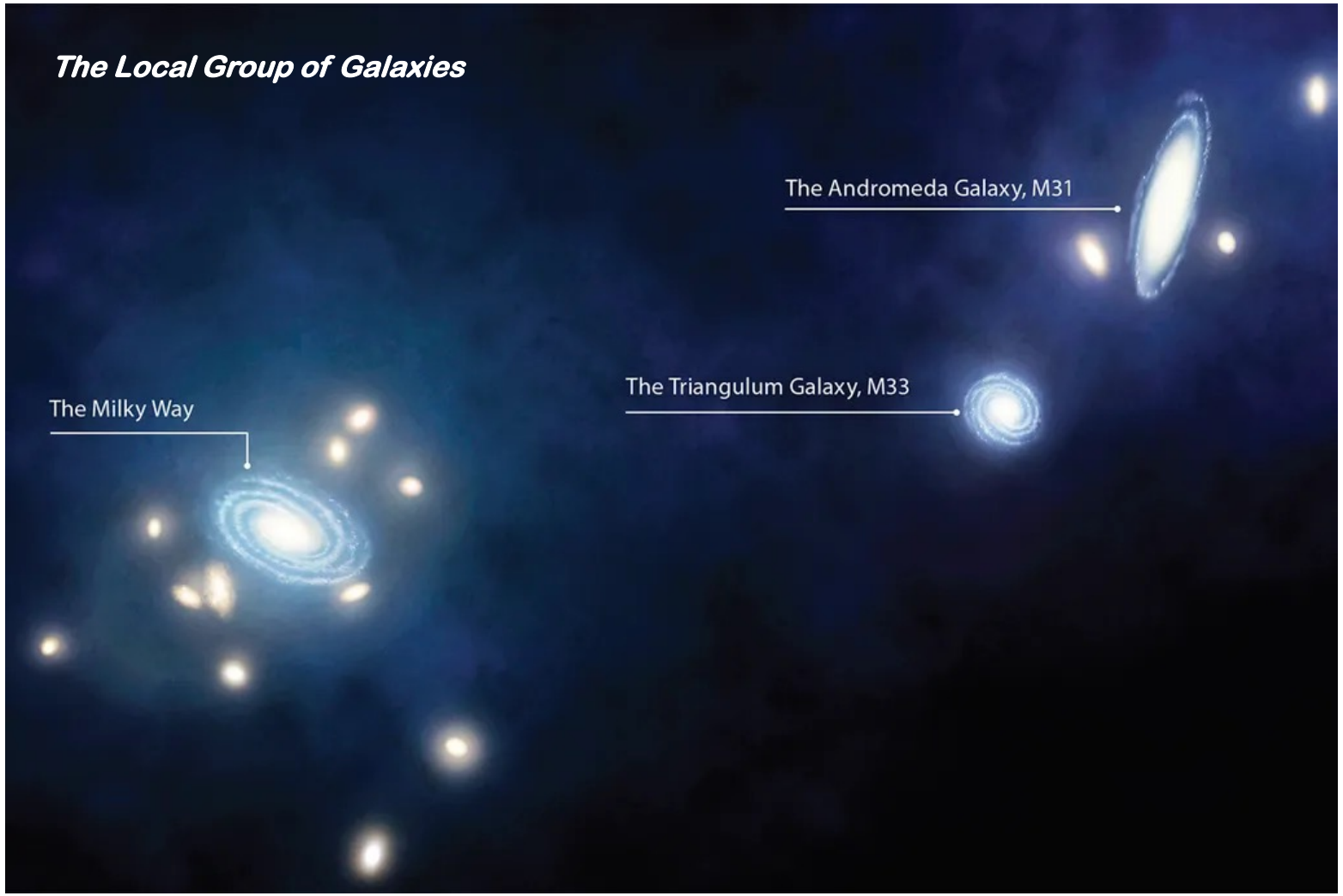


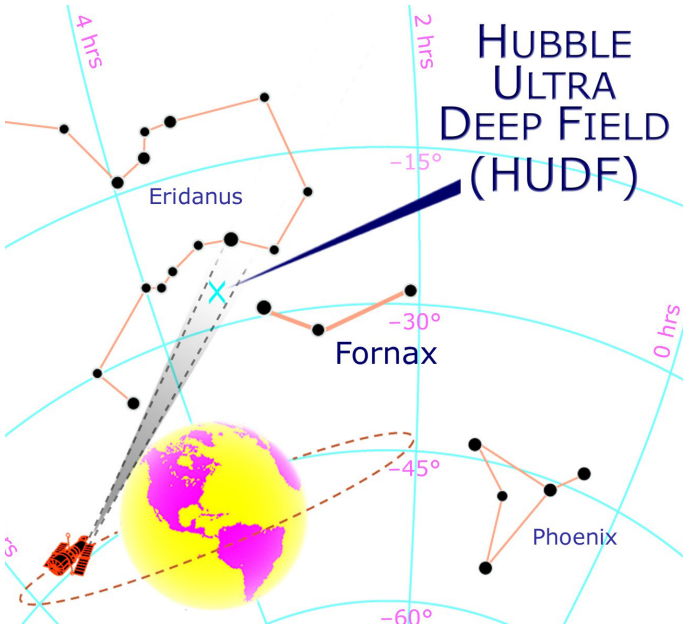
how many galaxies are there in the Universe?

Cosmology

explain this!

Space, the final frontier!

Sept. 2003 - Jan. 2004:



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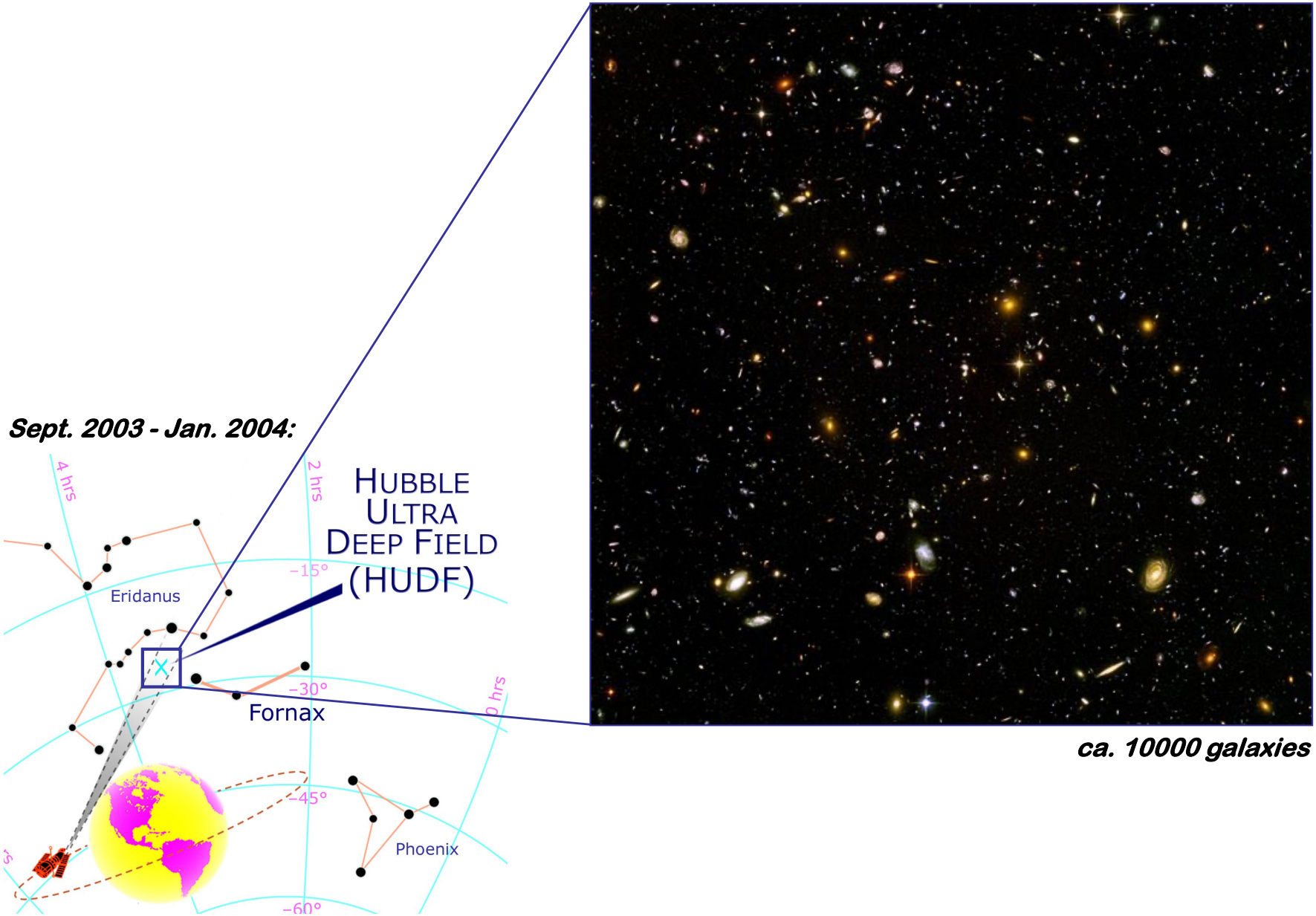

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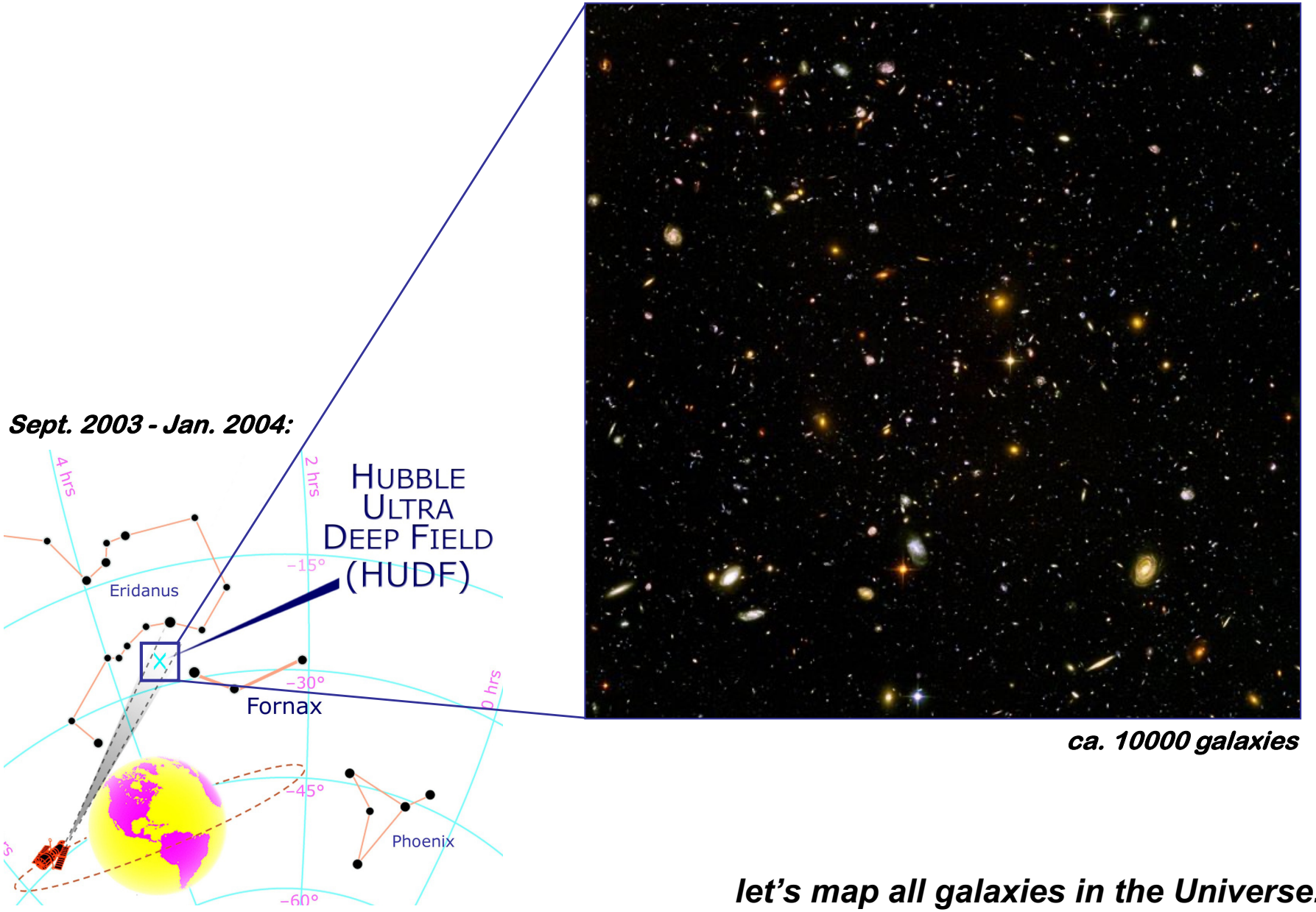

ca. 10000 galaxies

let's map all galaxies in the Universe...

Cosmology

explain this!

Space, the final frontier!

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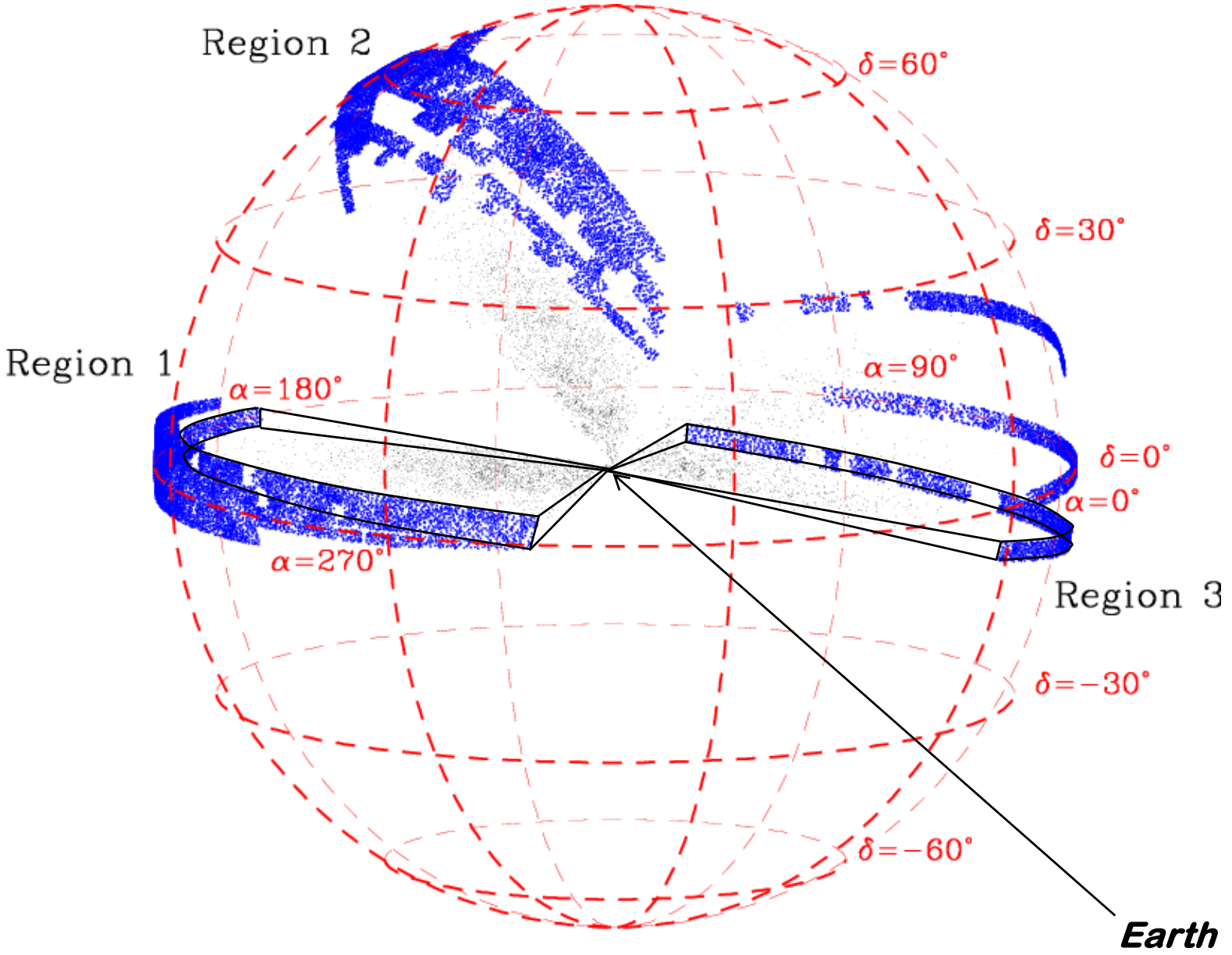

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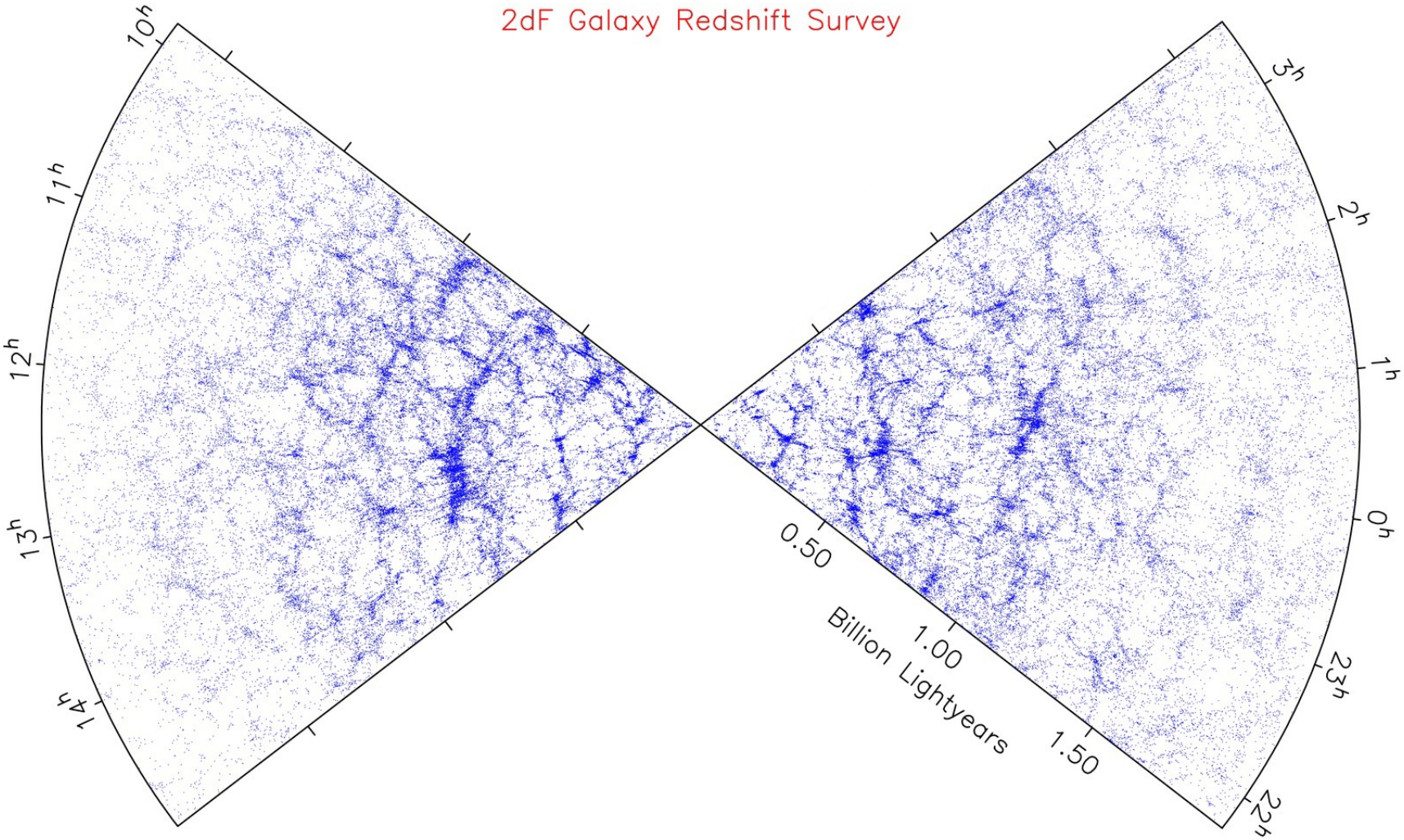

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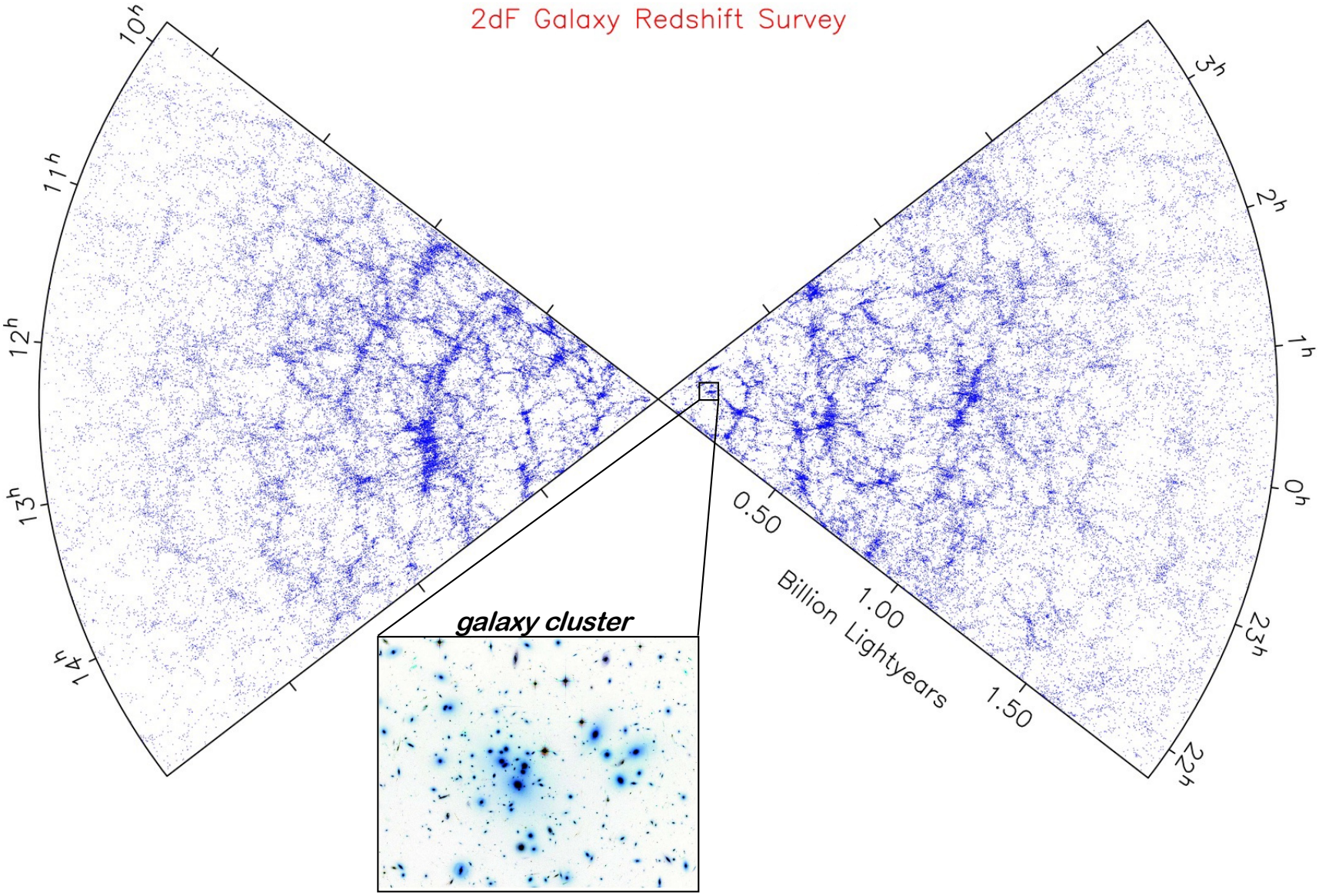

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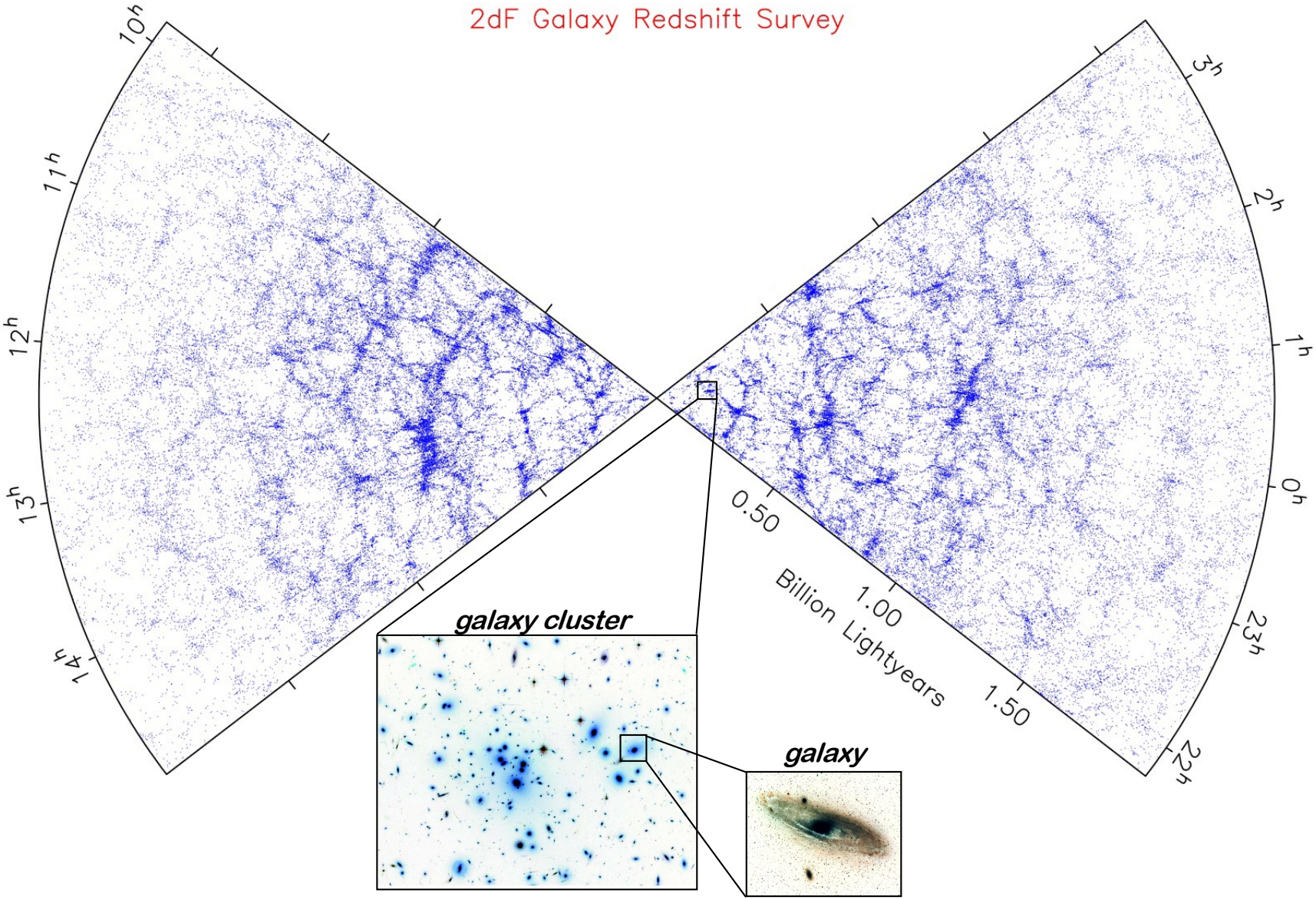

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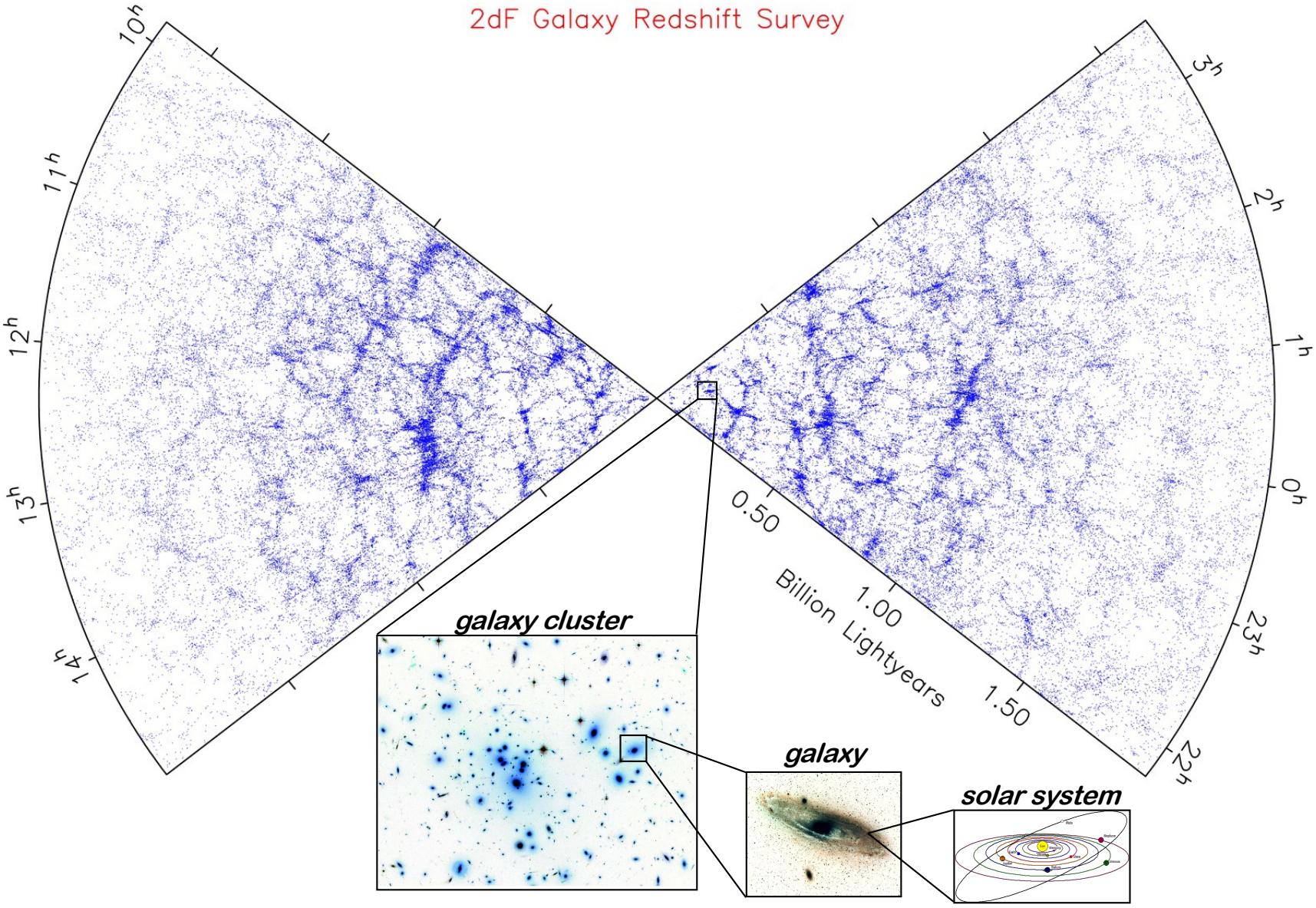

Cosmology

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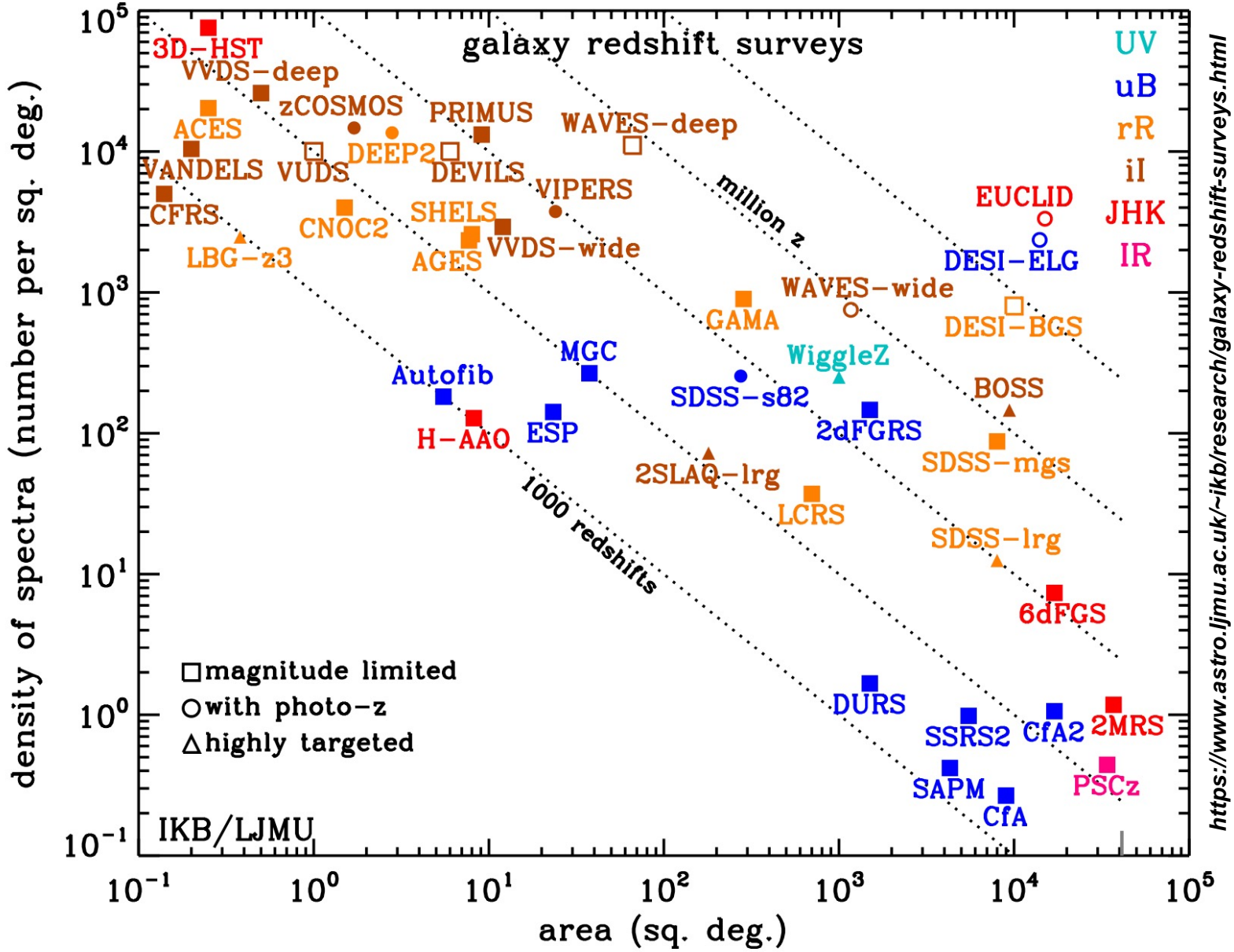
Space, the final frontier!

History & Principles

Space, the final frontier!



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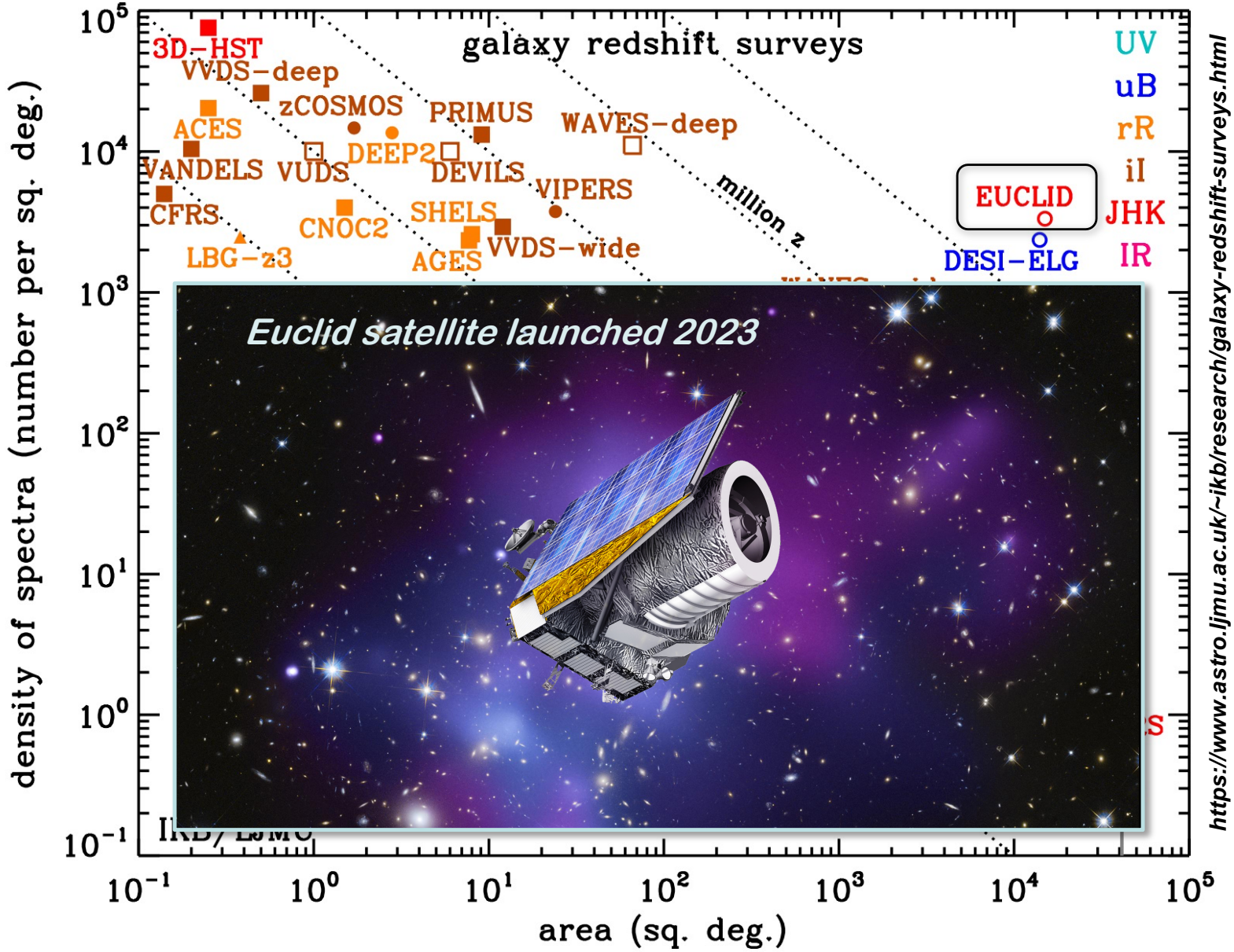

History & Principles

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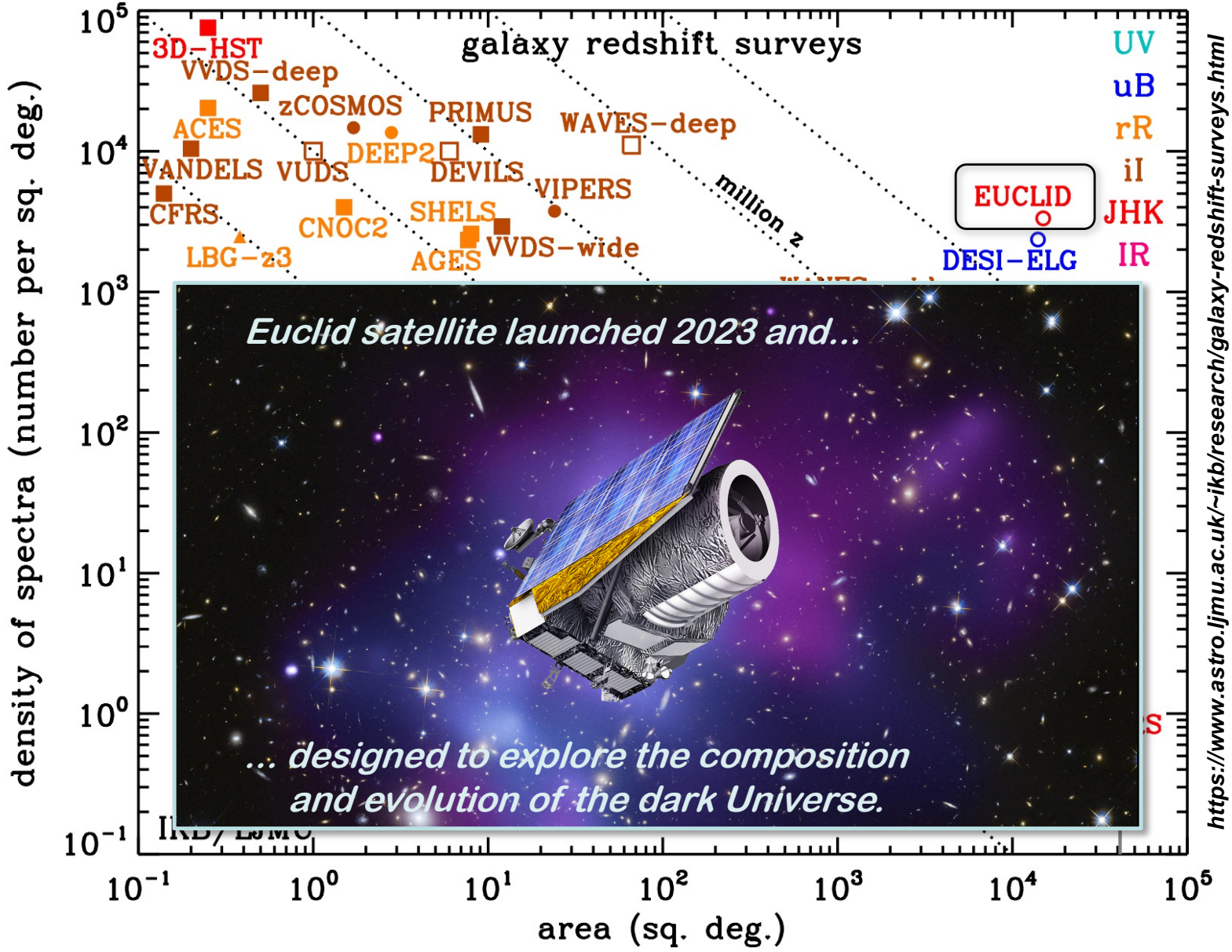

History & Principles

Cosmology

explain this!

Cosmology is…

…the Science of

the Origin and Evolution

of the Universe

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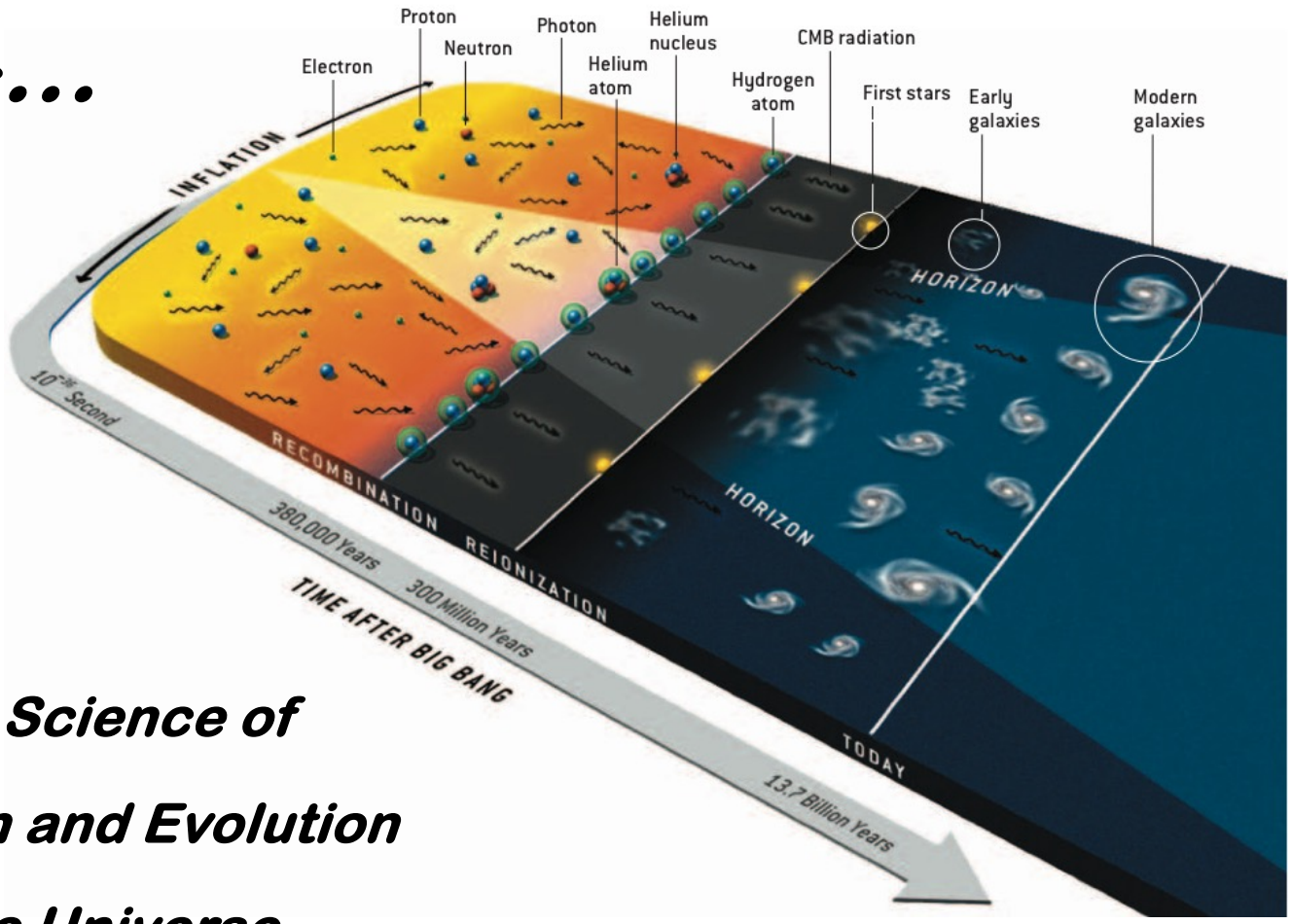

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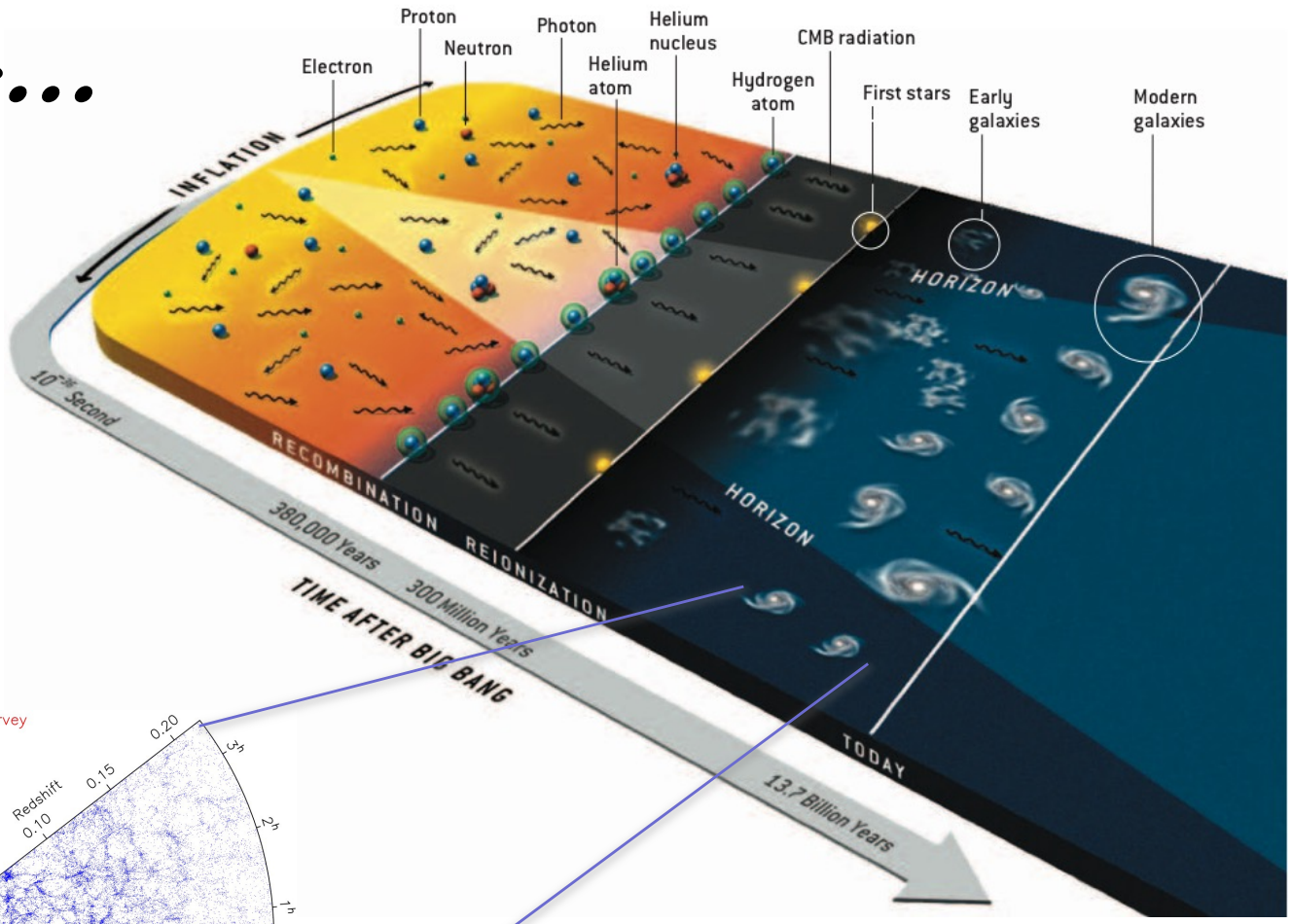

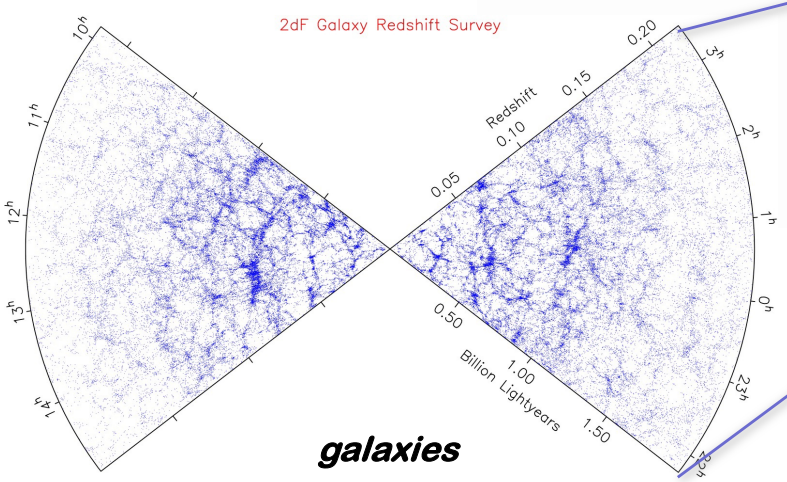

galaxies

and

their large-scale structure distribution

Origin and Evolution of the Universe

Cosmology

explain this!

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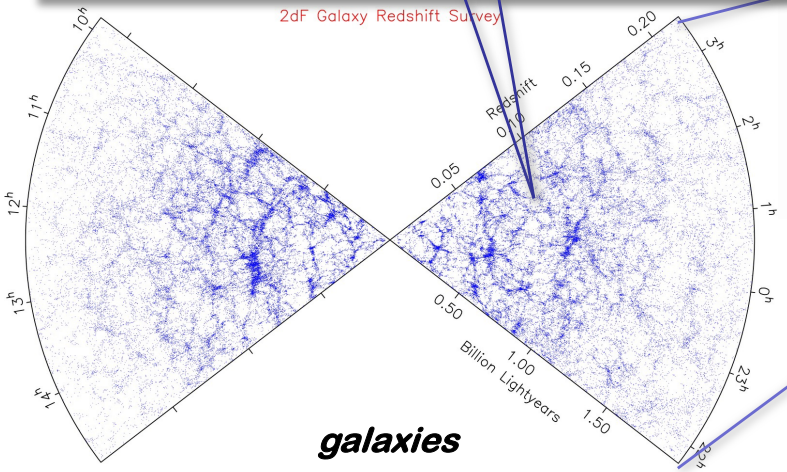

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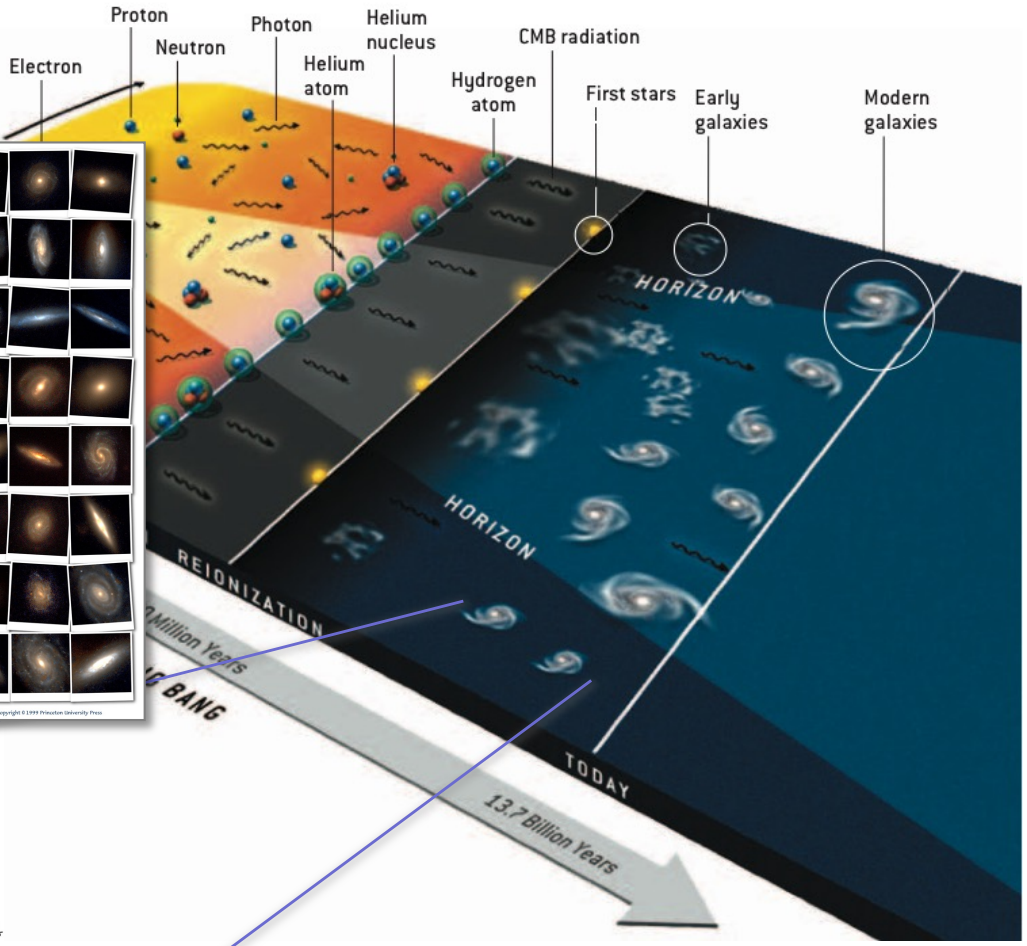

Origin and Evolution of the Universe

Cosmology

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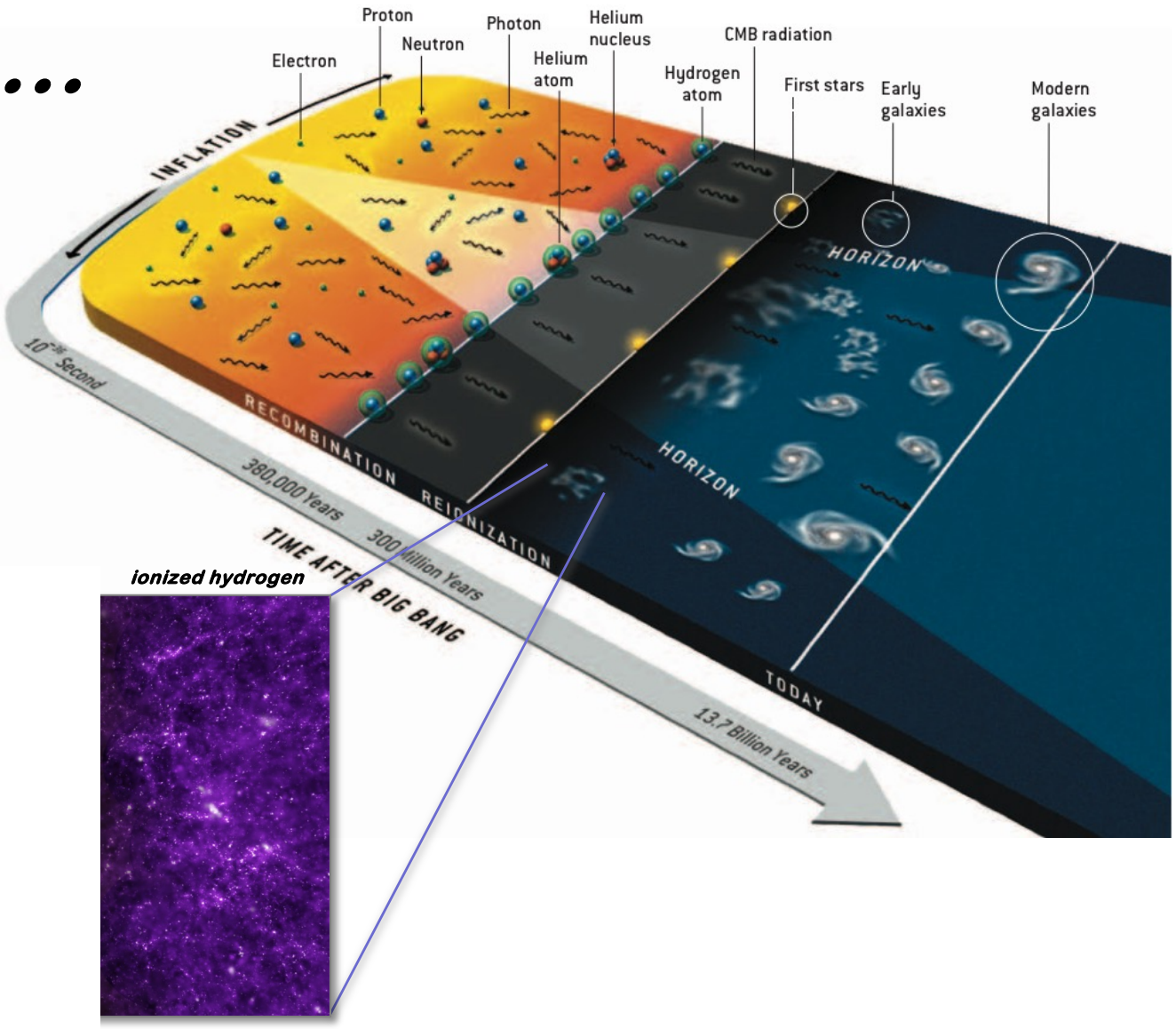

Origin and Evolution of the Universe

History & Principles

Cosmology

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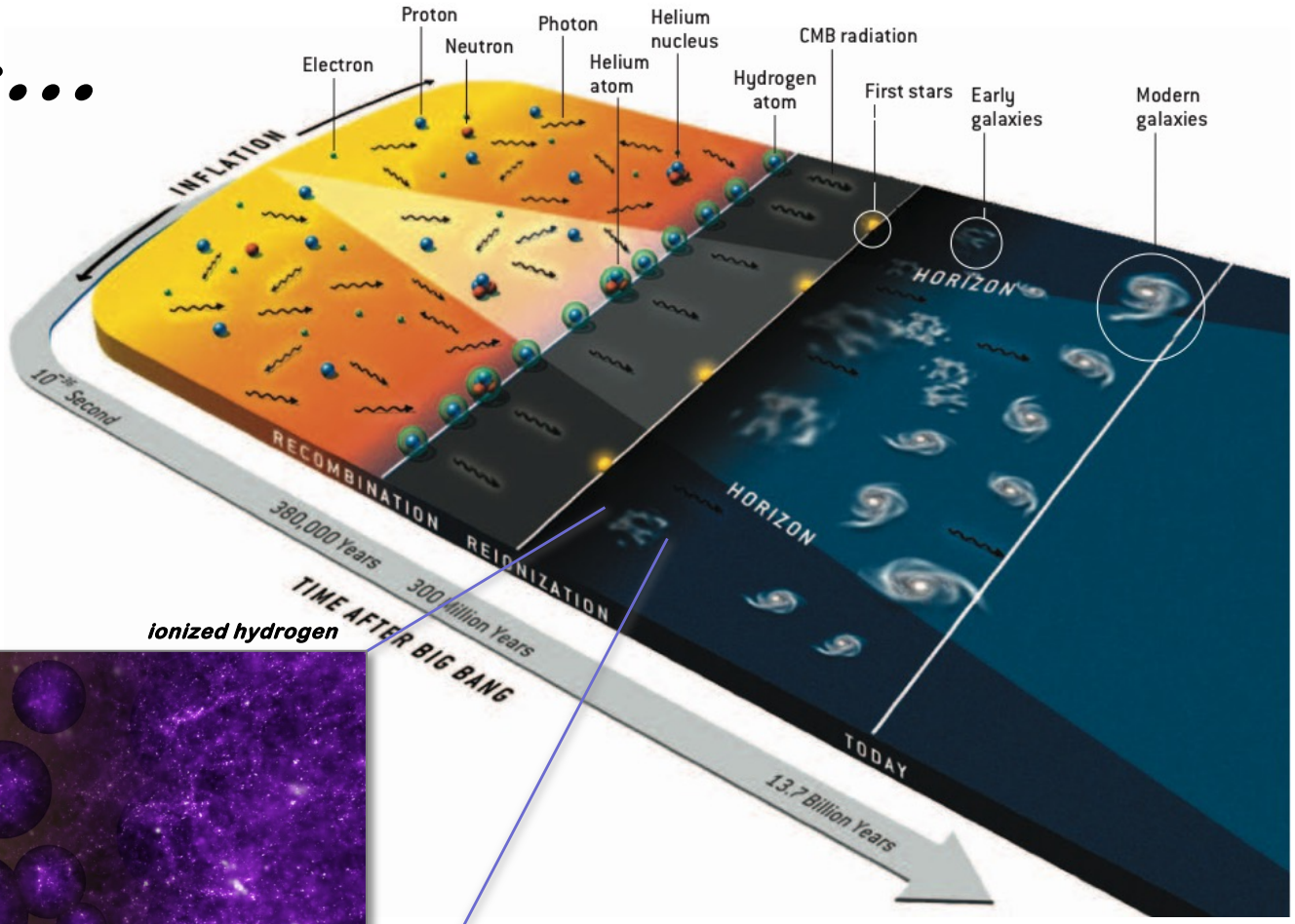

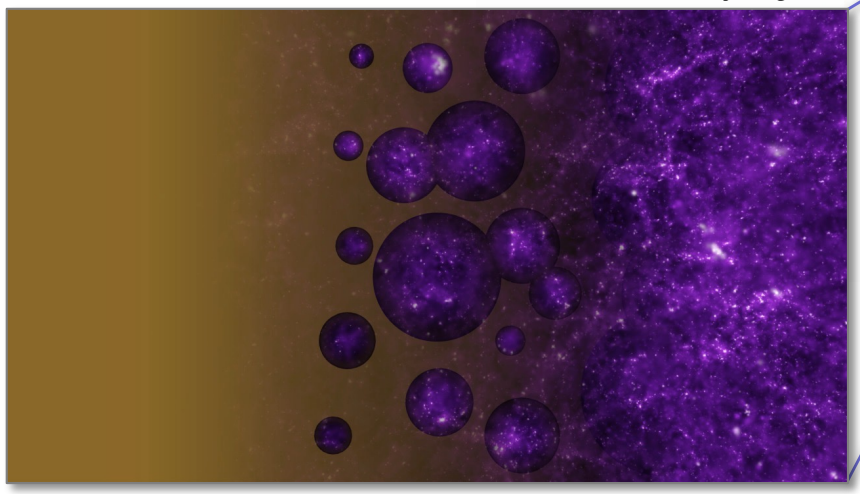

cosmic reionisation

Origin and Evolution of the Universe

History & Principles

Cosmology

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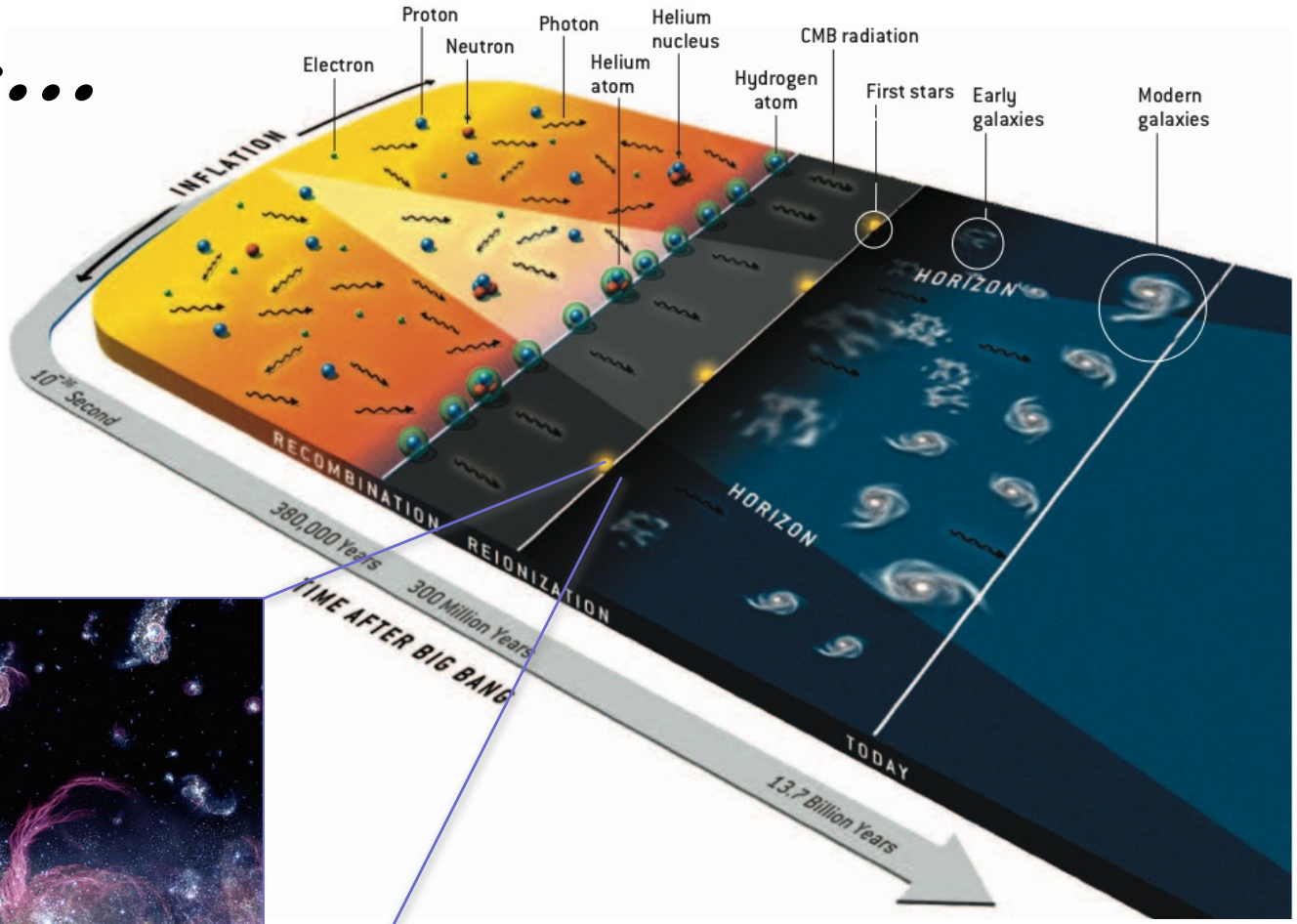
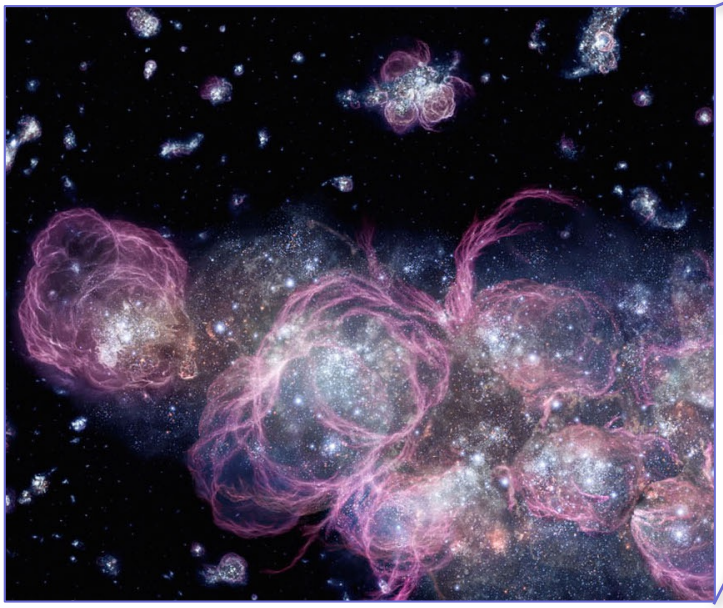




the first stars and galaxies

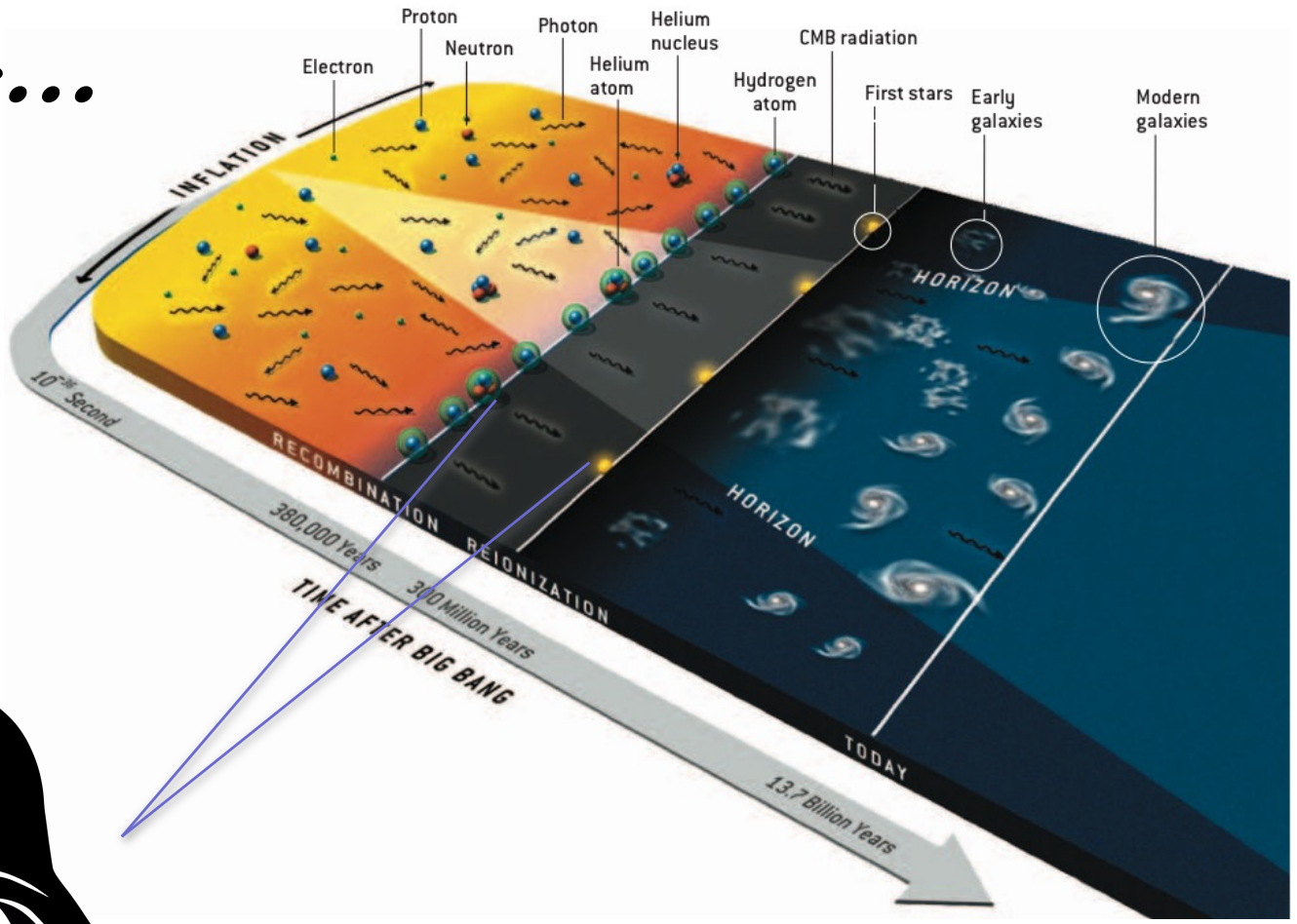
Origin and Evolution of the Universe

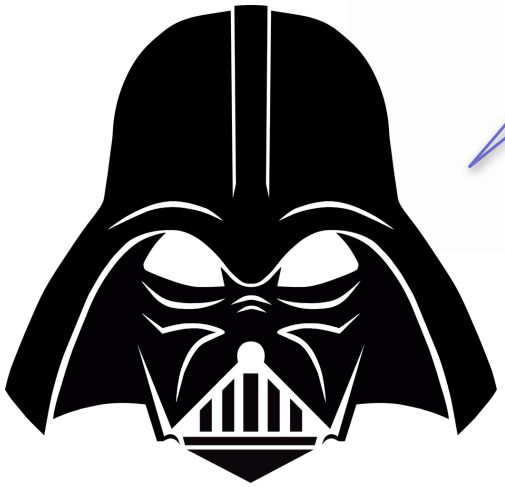
History & Principles

Cosmology

explain this!

Cosmology is…





the dark ages

Origin and Evolution of the Universe

History & Principles

Cosmology

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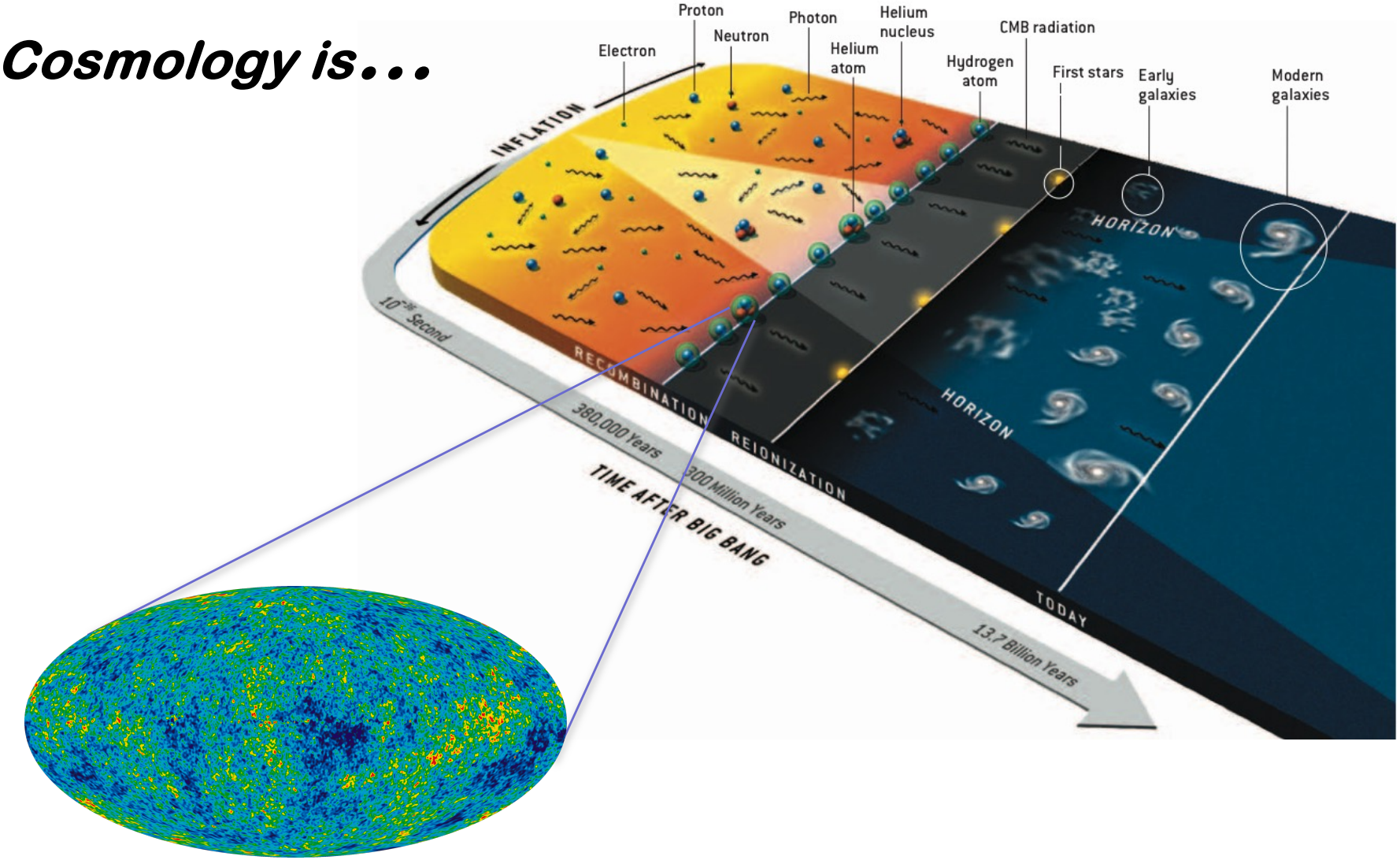

cosmic microwave background radiation

Origin and Evolution of the Universe

Cosmology

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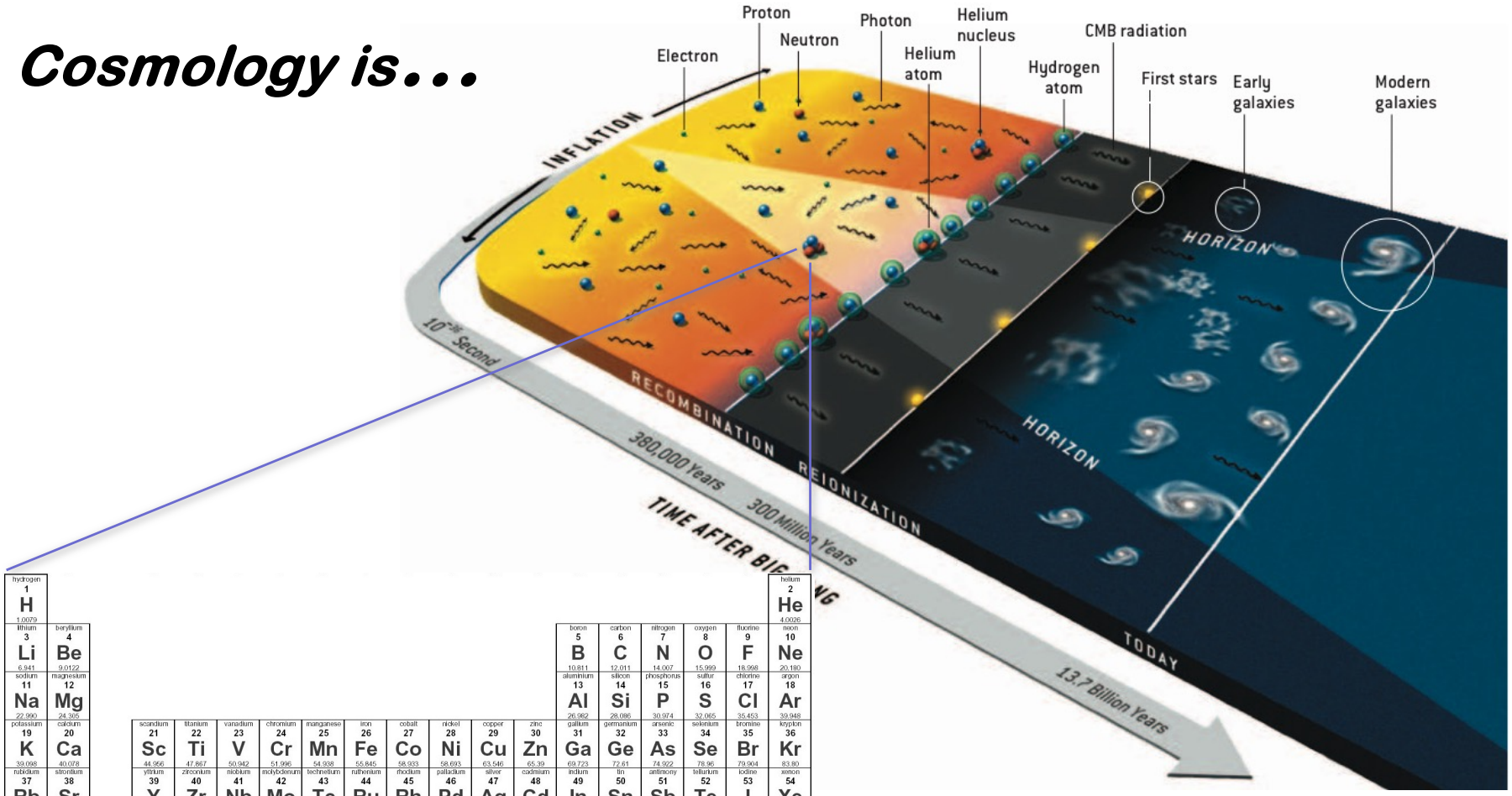

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57-70 *	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89-102 **	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub		114 Uuq				

*Lanthanide series	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb
**Actinide series	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No

big bang nucleosynthesis

Origin and Evolution of the Universe

History & Principles

Cosmology

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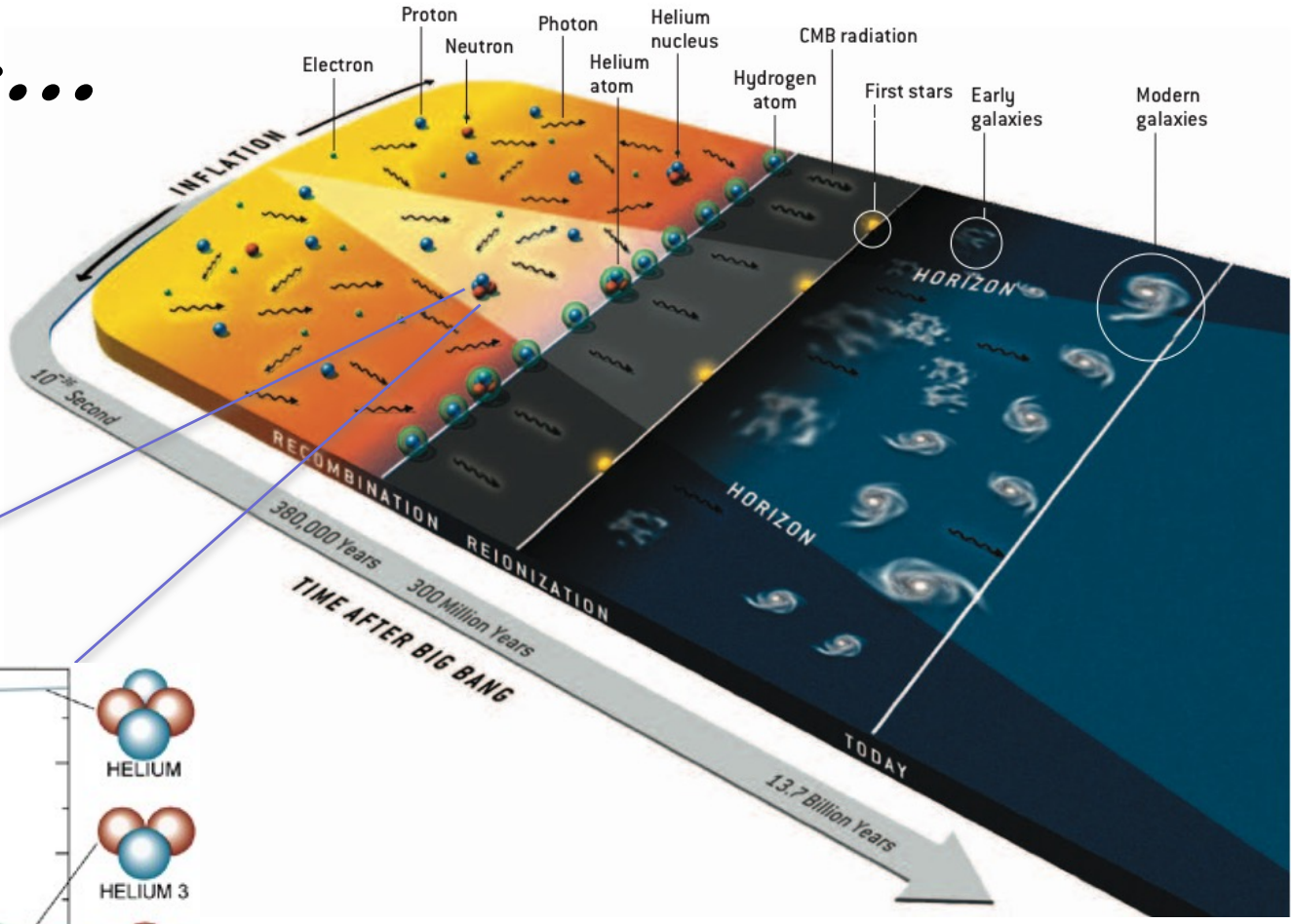

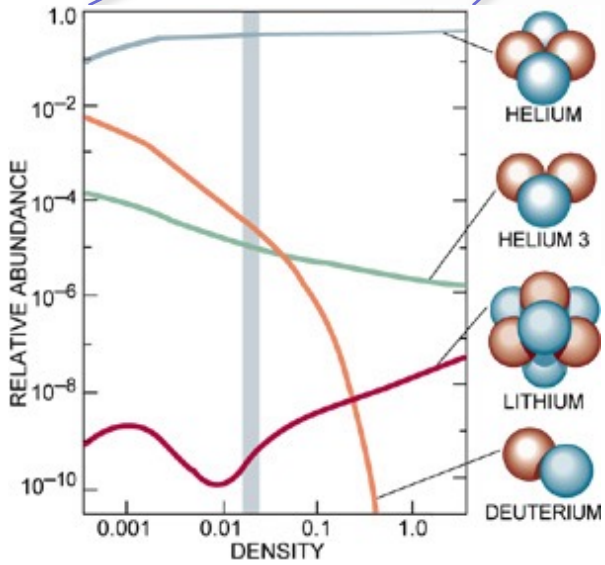

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Origin and Evolution of the Universe

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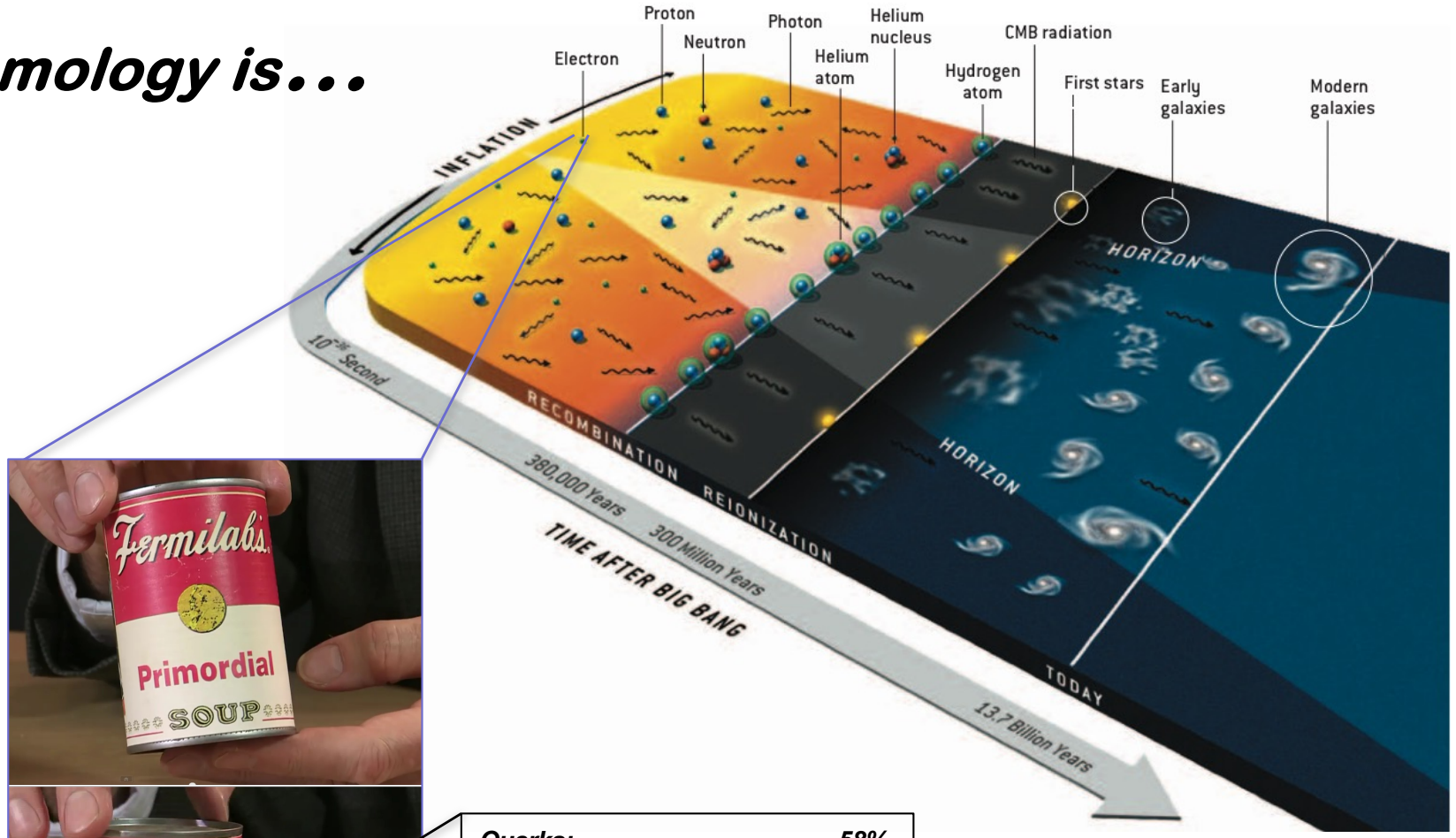
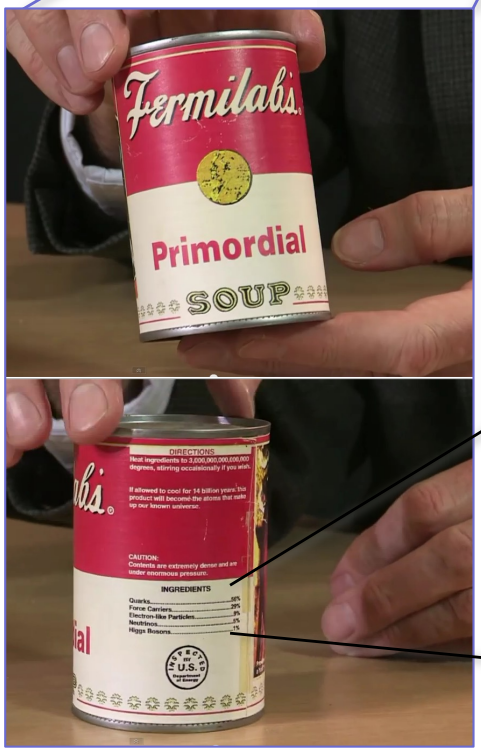




baryogenesis

Quarks:	*58%*
Force Carriers:	*29%*
Electron-like Particles:	*9%*
Neutrinos:	*5%*
Higgs-Bosons:	*1%*

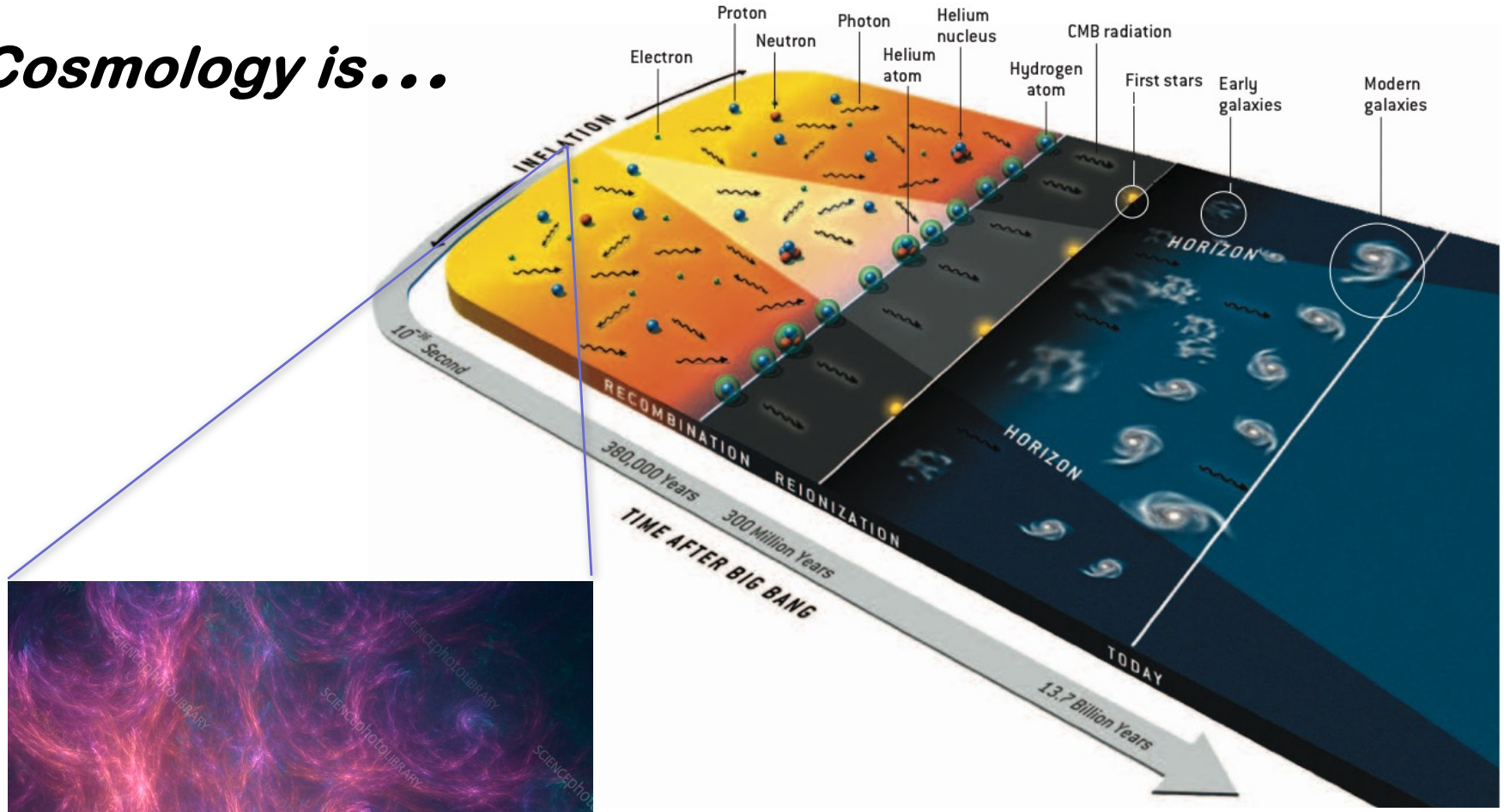
Origin and Evolution of the Universe

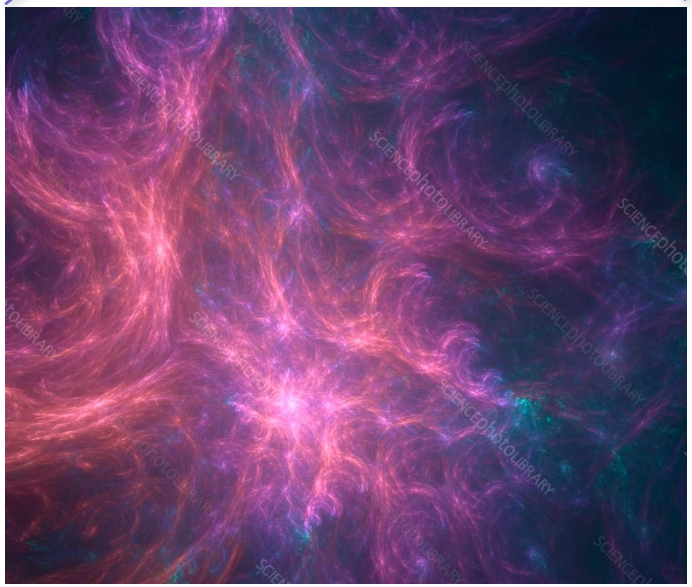
History & Principles

Cosmology

explain this!

Cosmology is…





cosmic inflation

Origin and Evolution of the Universe

History & Principles

Cosmology

explain this!

Event	time t
Inflation	10^{-34} s (?)
Baryogenesis	?
EW phase transition	20 ps
QCD phase transition	20 μs
Dark matter freeze-out	?
Neutrino decoupling	1 s
Electron-positron annihilation	6 s
Big Bang nucleosynthesis	3 min
Matter-radiation equality	60 kyr
Recombination	260–380 kyr
Photon decoupling	380 kyr
Reionization	100–400 Myr
Dark energy-matter equality	9 Gyr
Present	13.8 Gyr

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COSMO Lecture

Inflation

Baryogenesis

Thermal History

Big Bang Nucleosynthesis

Cosmic Microwave Background Radiation

Cosmic Dawn

Large-Scale Structure

Observational Cosmology

Gravitational Waves

Open Problems

Cosmology

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Dark energy-matter equality	9 Gyr
Present	13.8 Gyr

orders of magnitude in space and time

Cosmology

explain this!

Event	time t
Inflation	10^{-34} s (?)
Baryogenesis	?
EW phase transition	20 ps
QCD phase transition	20 μs
Dark matter freeze-out	?
Neutrino decoupling	1 s
Electron-positron annihilation	6 s
Big Bang nucleosynthesis	3 min
Matter-radiation equality	60 kyr
Recombination	260–380 kyr
Photon decoupling	380 kyr
Reionization	100–400 Myr
Dark energy-matter equality	9 Gyr
Present	13.8 Gyr

orders of magnitude in space and time...

...covering all fields of physics!

Cosmology

explain this!

Cosmology...

...explains the origin and evolution of the Universe

...is based upon certain principles

...is a respectable field of science (and not science-fiction...)

Cosmology

explain this!

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Cosmology

- *explain this!*
- *principles*
- *cosmology – science or science fiction?*
- *cosmological structure formation*

Cosmology

- ***weak equivalence principle***
- ***strong equivalence principle***
- ***cosmological principle***
- ***strong cosmological principle***
- ***principle of relativity***

Cosmology

- ***weak equivalence principle***
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Cosmology

- *weak equivalence principle*
- *strong equivalence principle*
- *cosmological principle*
- *strong cosmological principle*
- *principle of relativity*

- ***weak equivalence principle***

$$m \frac{d^2 r}{dt^2} = -m \frac{GM}{r^2}$$

Newton's 2nd law of motion:

m = **"resistance to force"**

Newton's law of gravity:

m = **"gravitating mass"**

- *weak equivalence principle*
- *strong equivalence principle*
- *cosmological principle*
- *strong cosmological principle*
- *principle of relativity*

- ***weak equivalence principle***

"gravitational and inertial masses are equal"

$$m_{\mathcal{I}} \frac{d^2 r}{dt^2} = -m_{\mathcal{G}} \frac{GM}{r^2}$$

Newton's 2nd law of motion:

$m_{\mathcal{I}}$ = **"resistance to force"**

Newton's law of gravity:

$m_{\mathcal{G}}$ = **"gravitating mass"**

weak principle of equivalence:

$$m_{\mathcal{I}} = m_{\mathcal{G}}$$

Cosmology

- ***weak equivalence principle***
- ***strong equivalence principle***
- ***cosmological principle***
- ***strong cosmological principle***
- ***principle of relativity***

- *weak equivalence principle*
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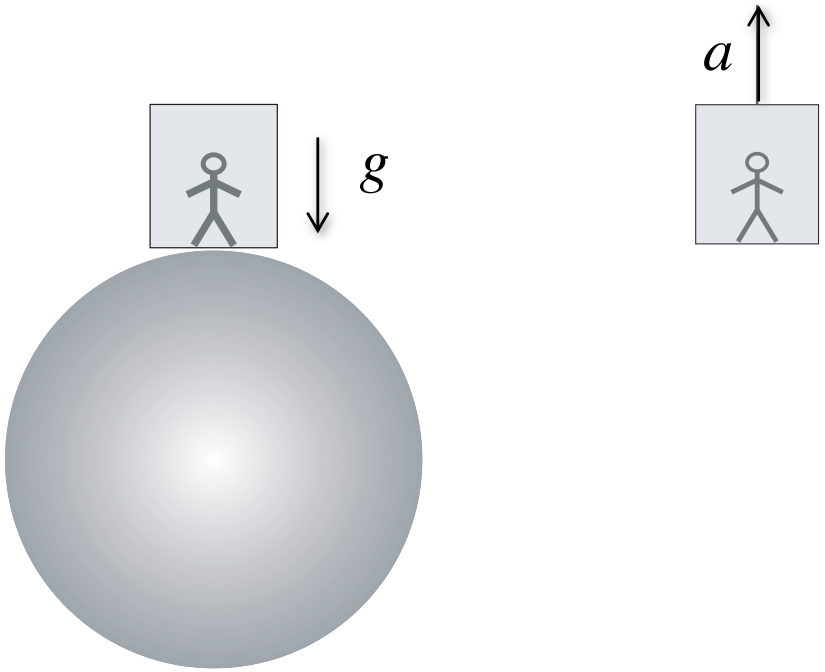
- *principle of relativity*

- ***strong equivalence principle***

"there is no observable distinction between the local effects of gravity and acceleration"



Cosmology

- *weak equivalence principle*
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• *strong equivalence principle*

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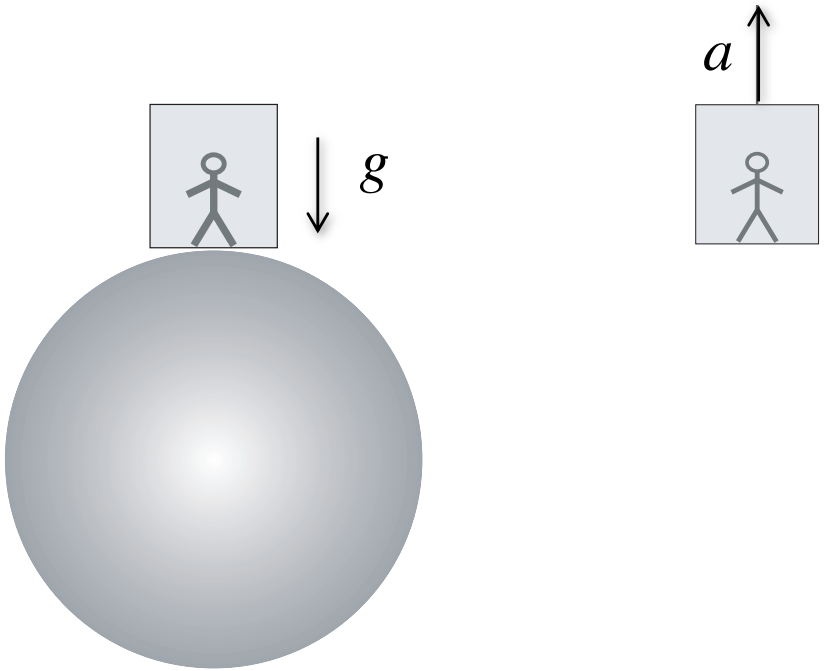

consequences:

✓ time dilation

✓ light deflection

✓ gravitational red- & blueshift

Cosmology

- *weak equivalence principle*
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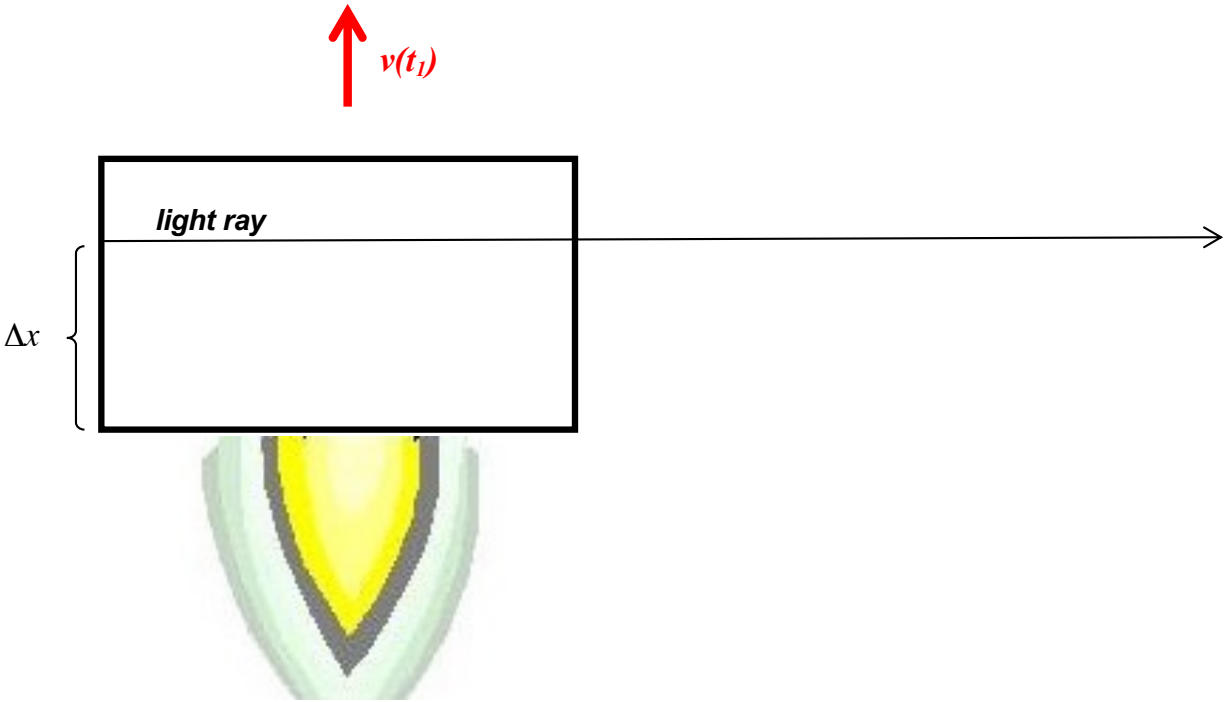

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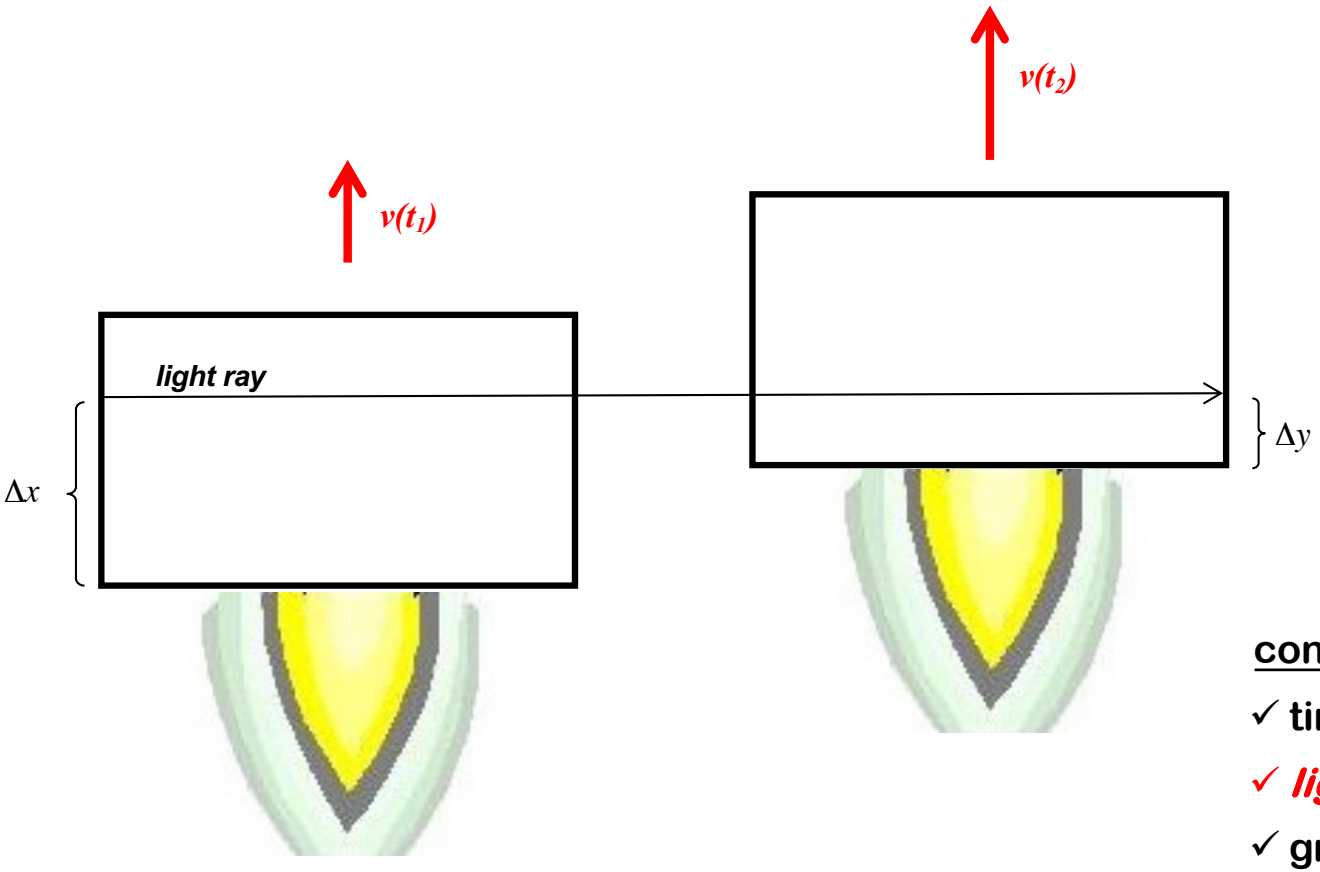

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Cosmology

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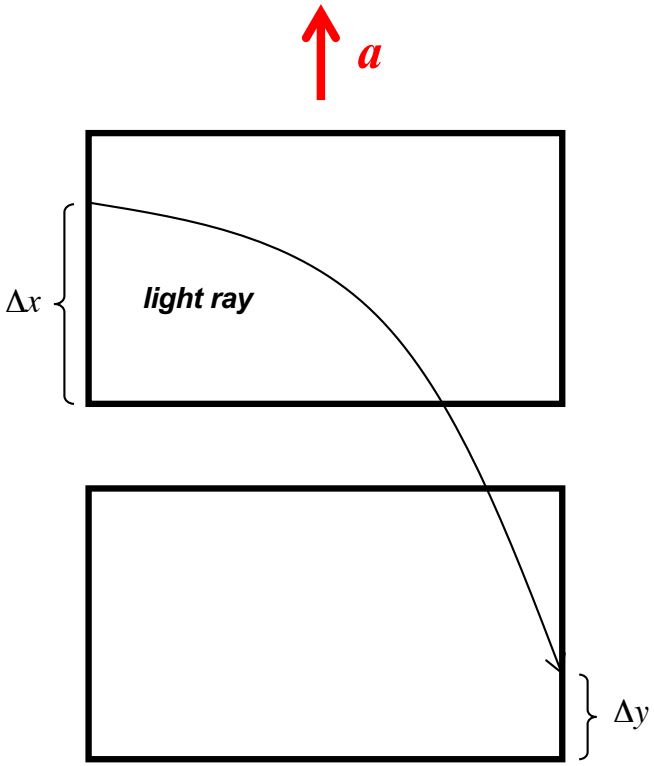

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Cosmology

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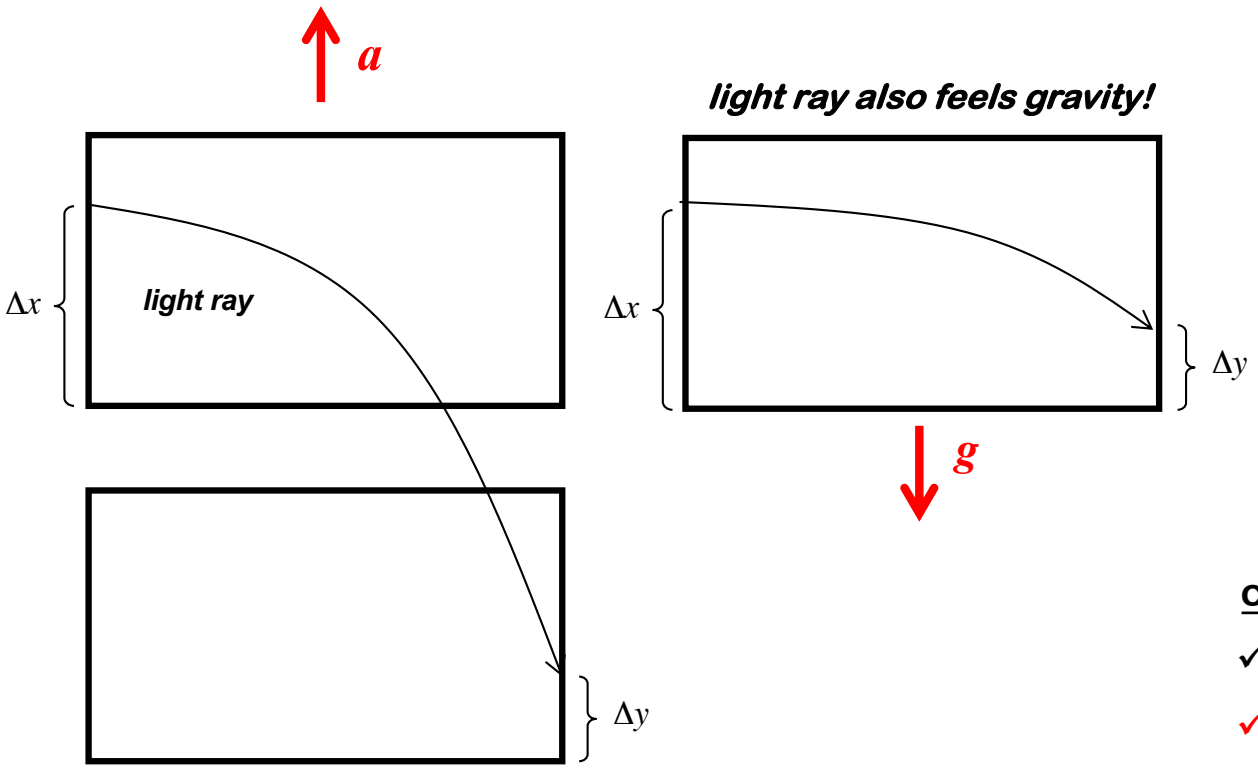

consequences:

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Cosmology

principles

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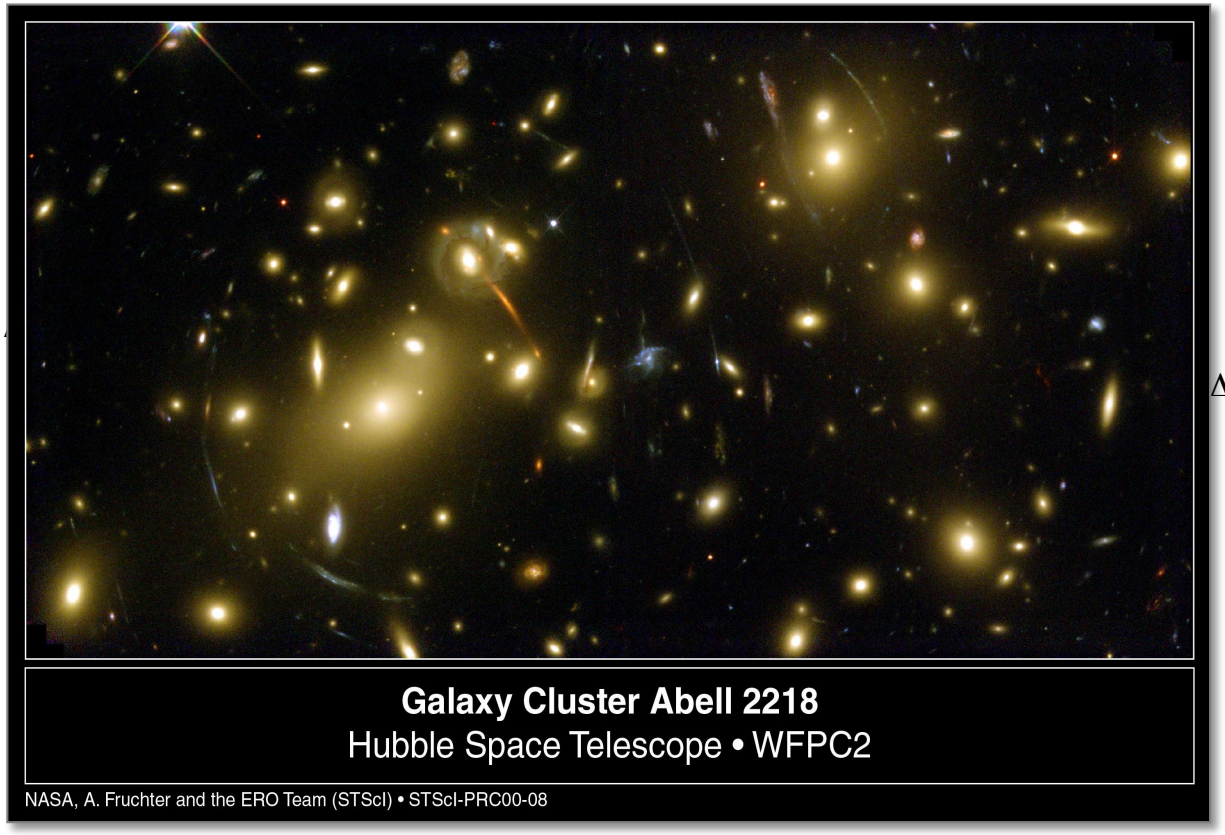

Galaxy Cluster Abell 2218
Hubble Space Telescope • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Δy

consequences:

- ✓ time dilation
- ✓ ***light deflection***
- ✓ gravitational red- & blueshift

Cosmology

- ***weak equivalence principle***
- ***strong equivalence principle***
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Cosmology

- *weak equivalence principle*
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- ***cosmological principle***

"the Universe is homogeneous & isotropic in space"

Cosmology

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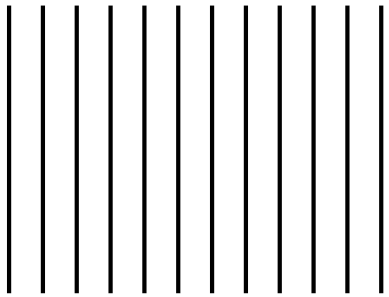
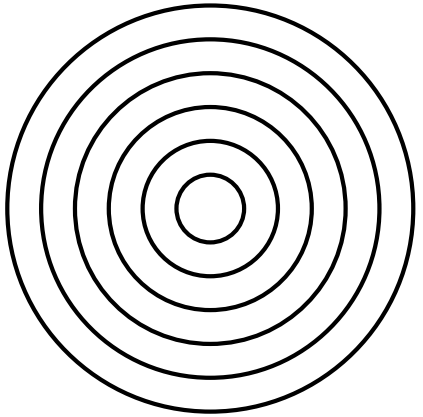


homogeneous
(translational invariance)



isotropic
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Cosmology

- *weak equivalence principle*
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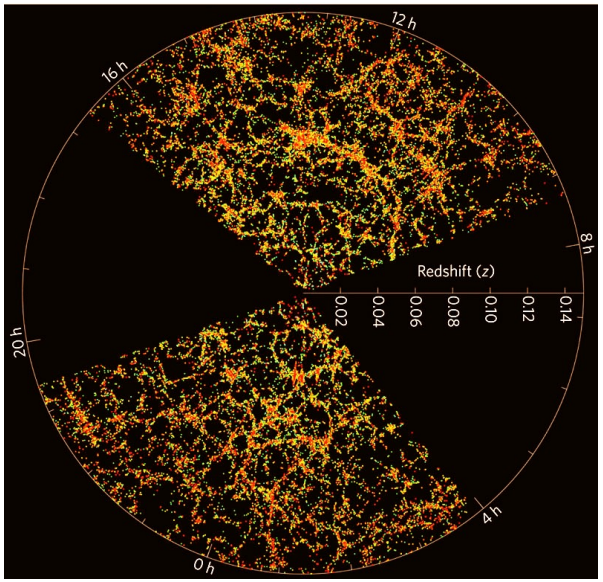
"the Universe is homogeneous & isotropic in space"

SDSS galaxies



homogeneous
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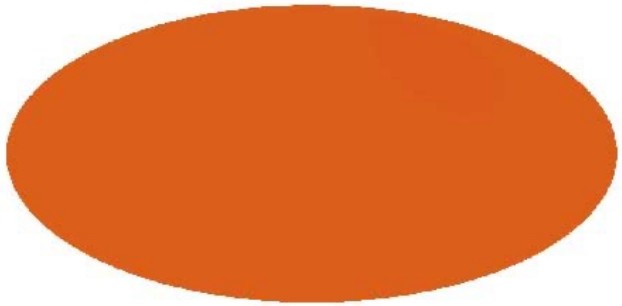
CMB monopole



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Cosmology

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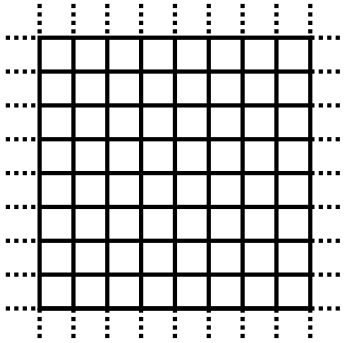

homogeneous & isotropic

Cosmology

- ***weak equivalence principle***
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Cosmology

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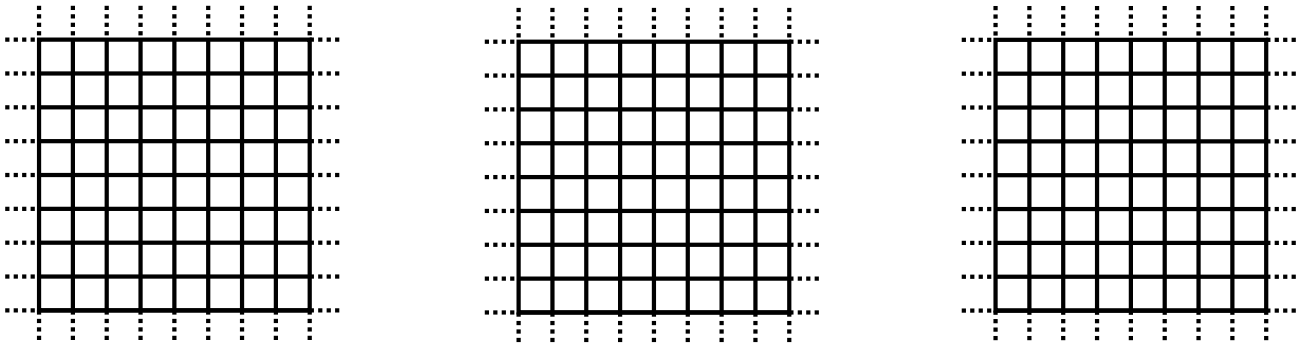
- ***strong cosmological principle****

"the Universe is homogeneous & isotropic in space and time"



time

***sometimes also referred to as the 'perfect cosmological principle'**

Cosmology

- *weak equivalence principle*
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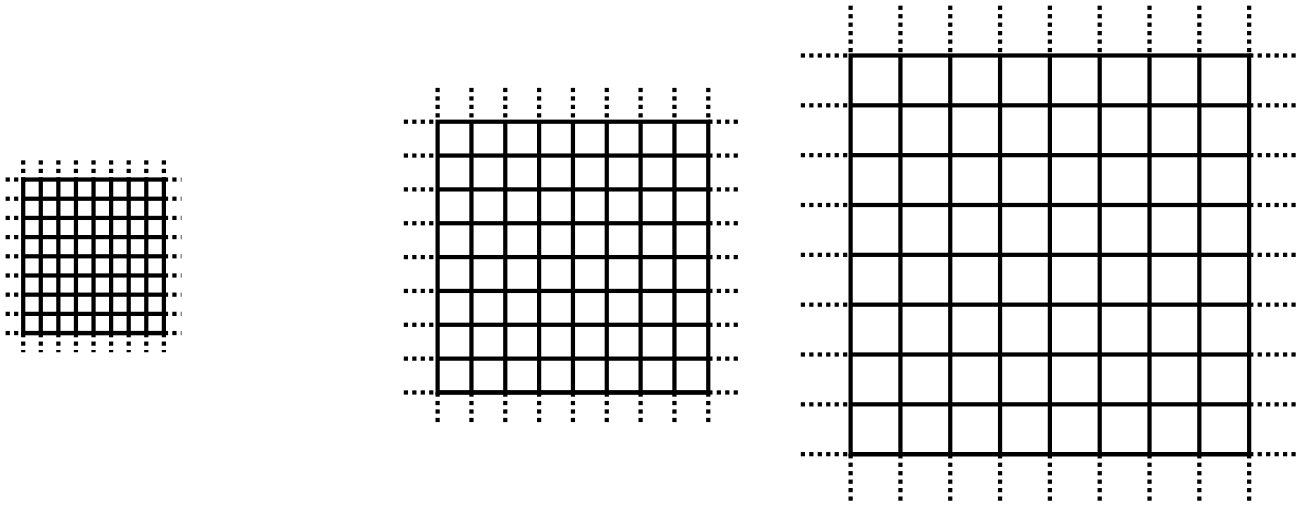
"the Universe is homogeneous & isotropic in space ~~and time~~"



the Universe expands! (more later…)

time

Cosmology

- ***weak equivalence principle***
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Cosmology

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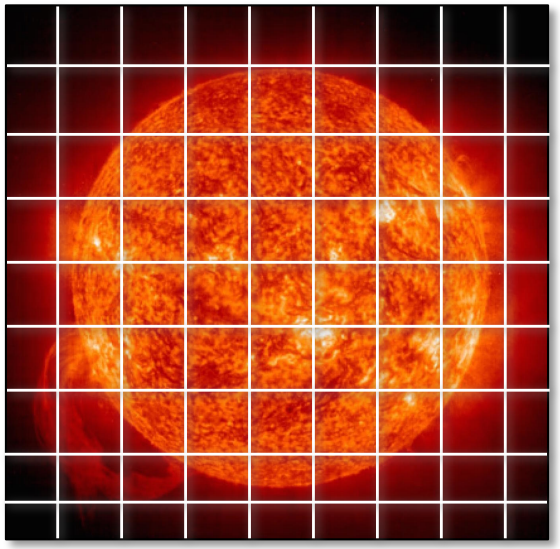
- ***principle of relativity***

"the equations describing the laws of physics have the same form irrespective of the coordinate system"



Cosmology

- *explain this!*
- *principles*
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Cosmology

science or science-fiction?

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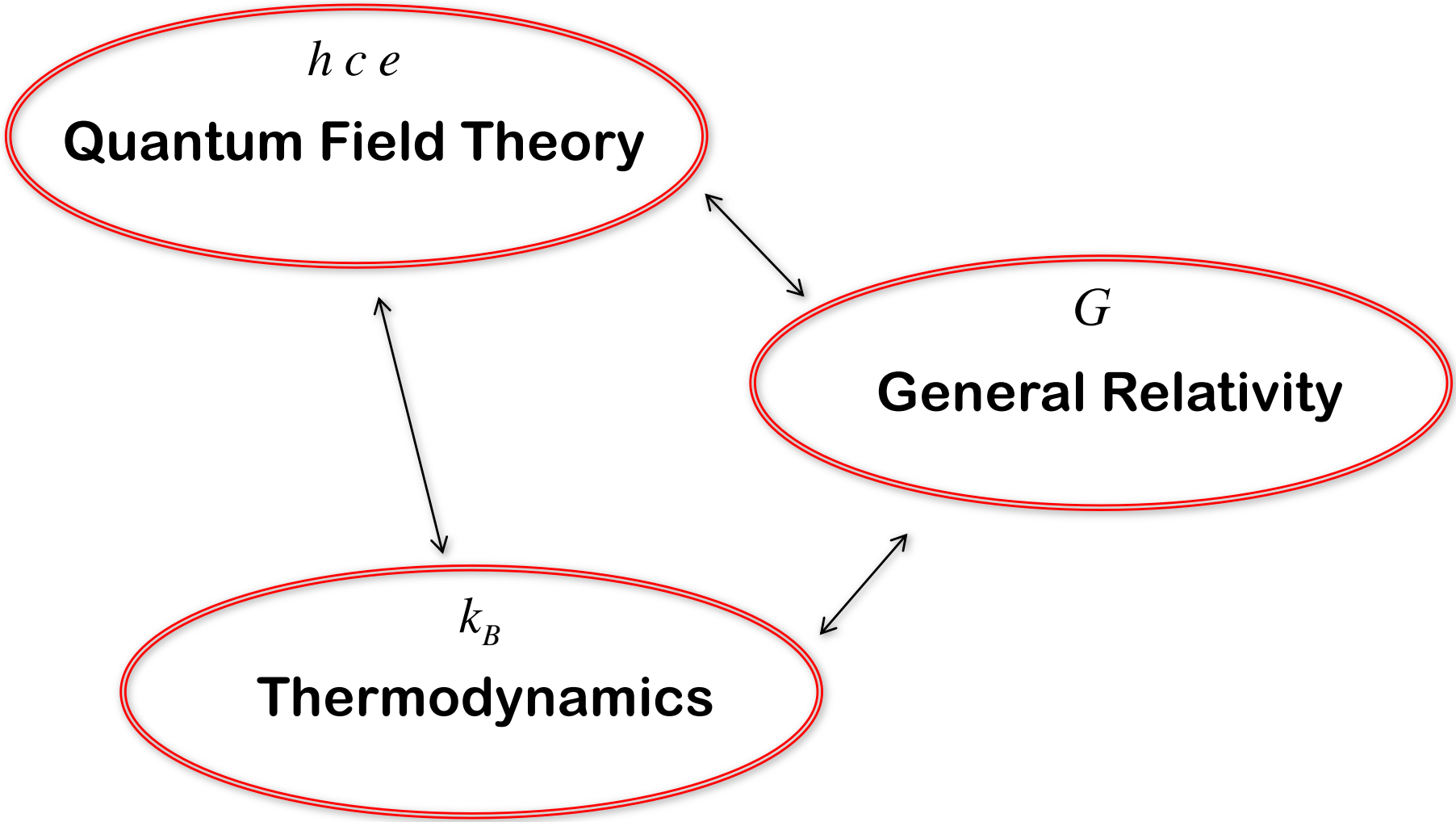
orders of magnitude in space and time...

...covering all fields of physics!

Cosmology

…is a combination of all fields in physics:



...is a combination of all fields in physics:

fundamental constants in Nature:

Quantum Mechanics	h	***Planck constant***
Special Relativity	c	***speed of light***
General Relativity	G	***gravitational constant***
Thermodynamics	k_B	***Boltzmann constant***

$$k_B^{\delta} h^{\alpha} c^{\beta} G^{\gamma}$$

Cosmology

science or science-fiction?

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$\sqrt{\frac{Gh}{c^3}} \approx 1.7 \times 10^{-33}\, cm$	***scale***
$\sqrt{\frac{Gh}{c^5}} \approx 10^{-43}\, \mathrm{sec}$	***time***
$\sqrt{\frac{hc}{G}} \approx 2.5 \times 10^{-5}\, g$	***mass***
$\sqrt{\frac{hc^5}{G}} \approx 1.2 \times 10^{19}\, GeV$	***energy***
$k_B^{-1}\sqrt{\frac{hc^5}{G}} \approx 1.4 \times 10^{32}\, K$	***temperature***

Cosmology

science or science-fiction?

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Planck units

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History & Principles

...started with General Relativity:

fundamental constants in Nature:

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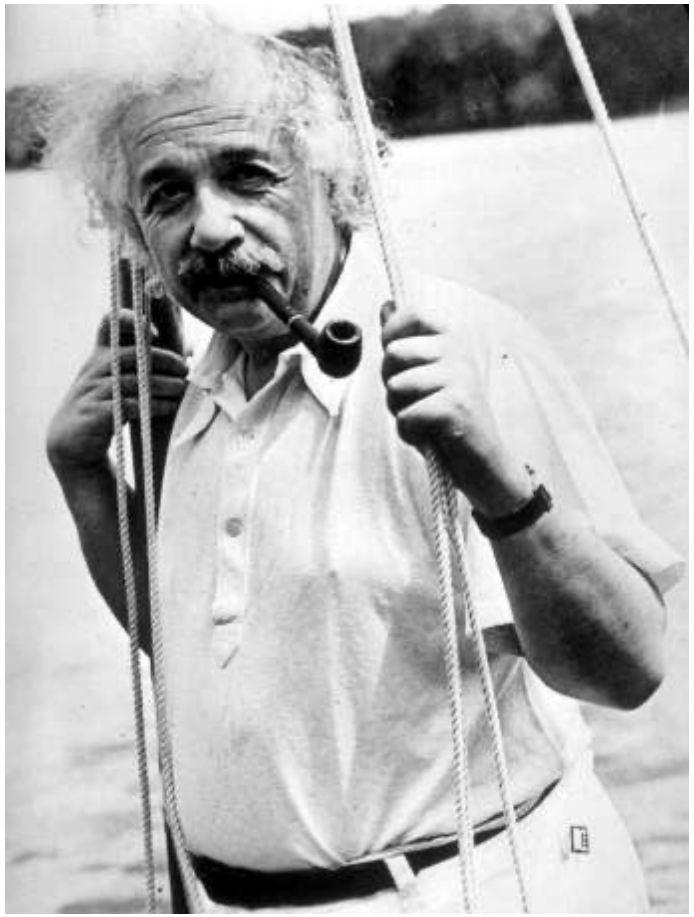
Cosmology

science or science-fiction?

Albert Einstein:

1905 special relativity

1915 general relativity



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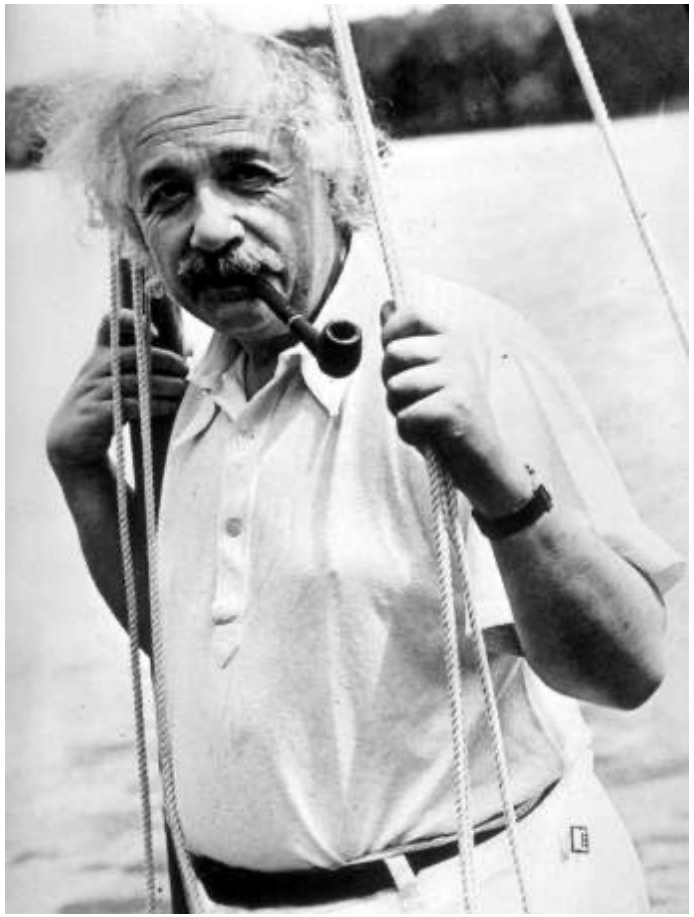

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Cosmology

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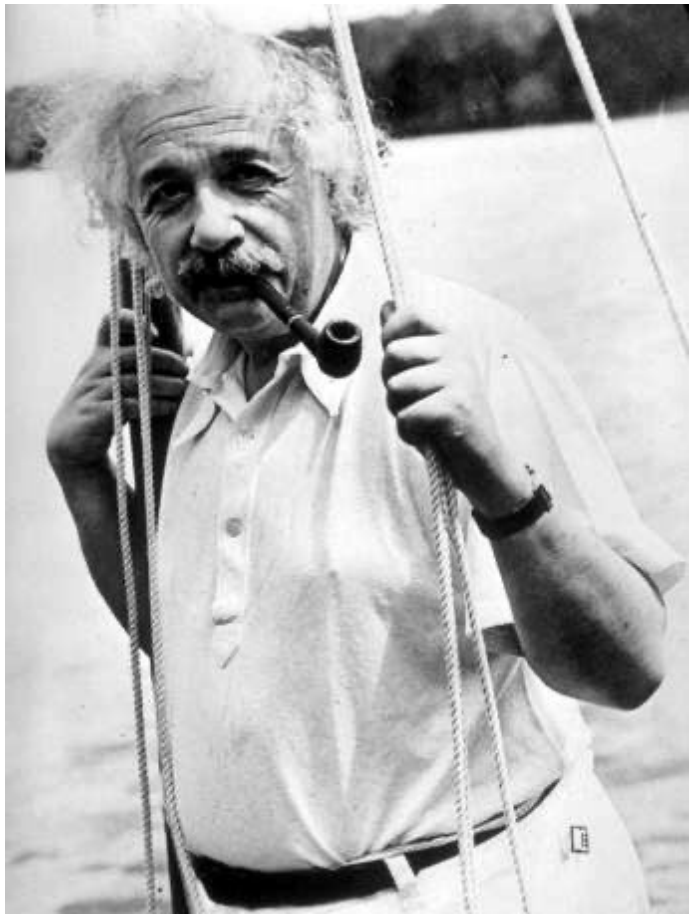

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matter tells space how to curve...

Cosmology

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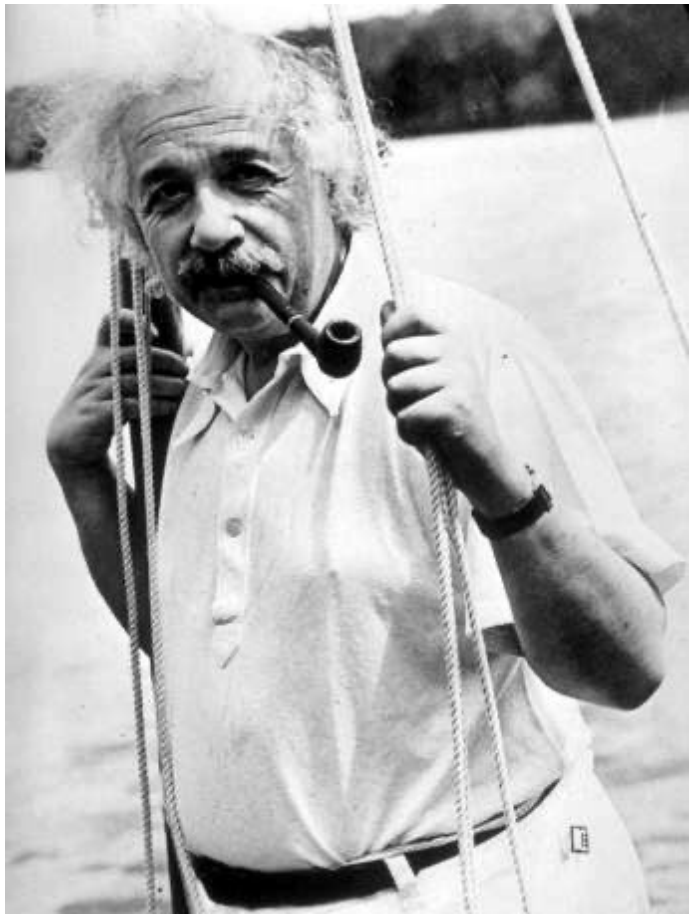

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

space tells matter how to move...

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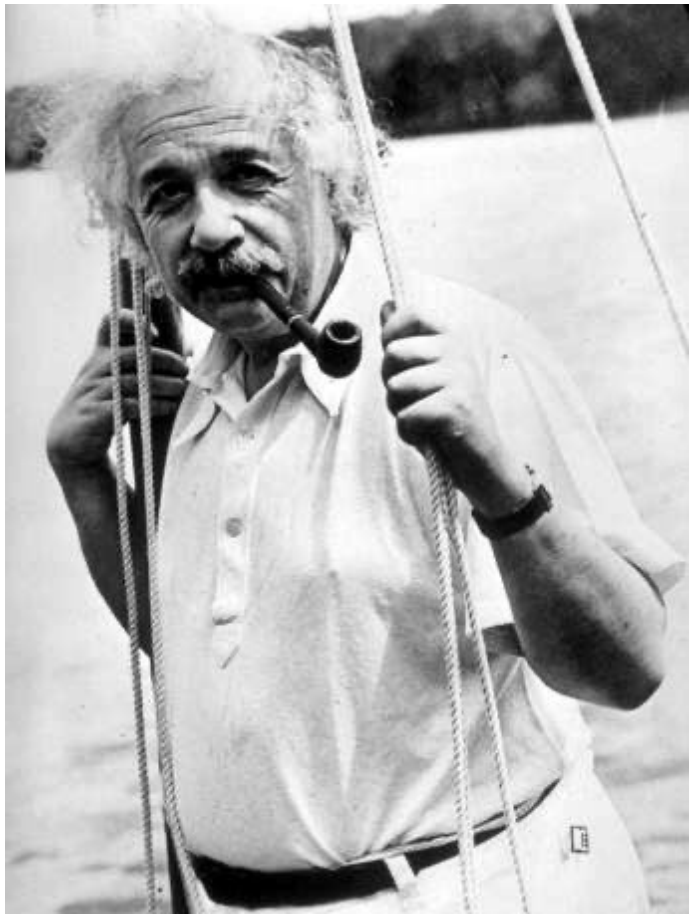

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

permits a static solution...

(more in a few slides)

Cosmology

science or science-fiction?

Albert Einstein:

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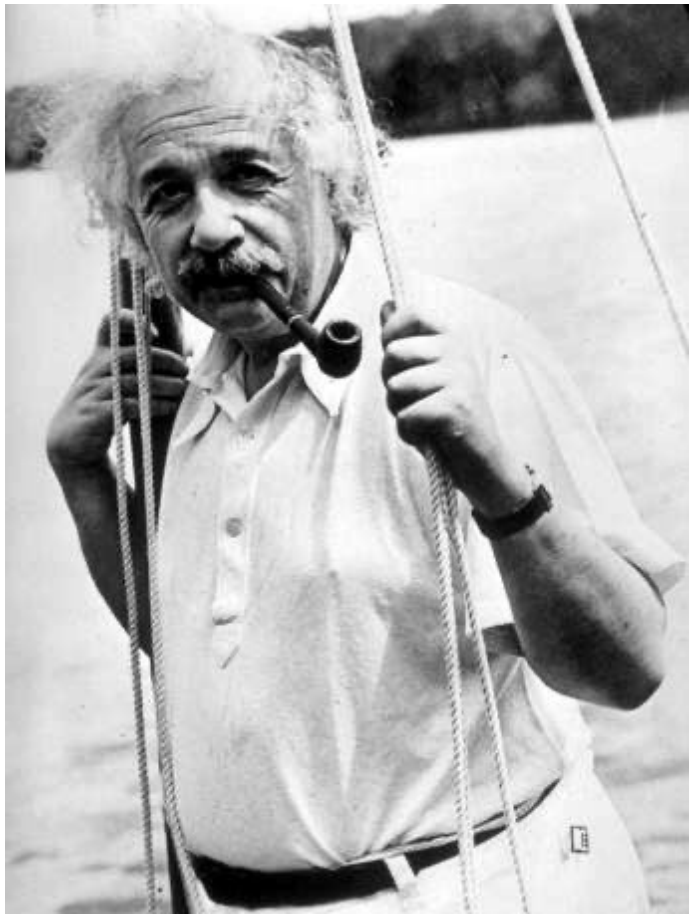
1915 general relativity:

permits singularities in space-time



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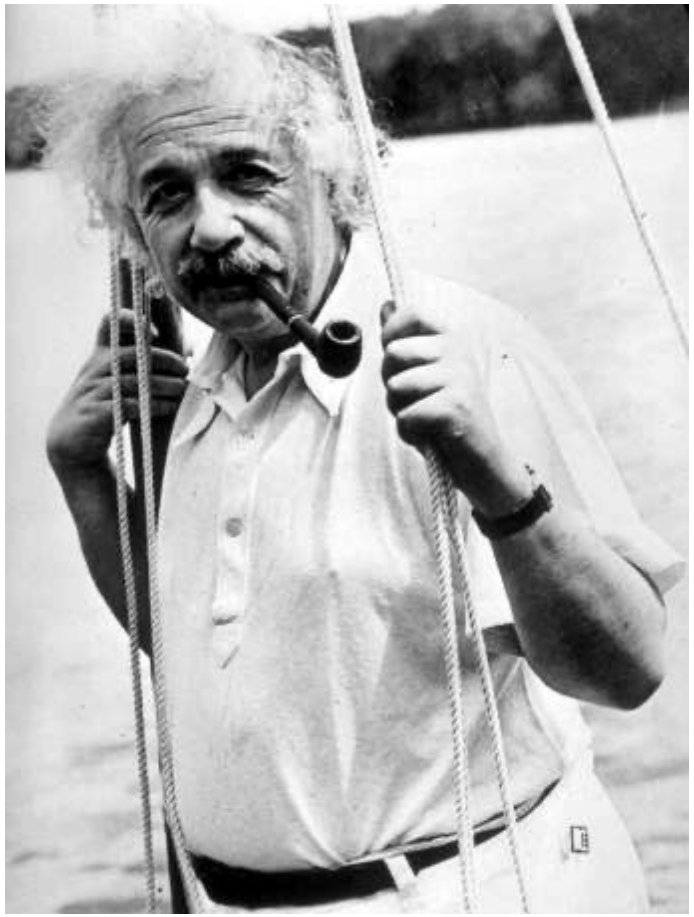

and what about solutions in general?

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

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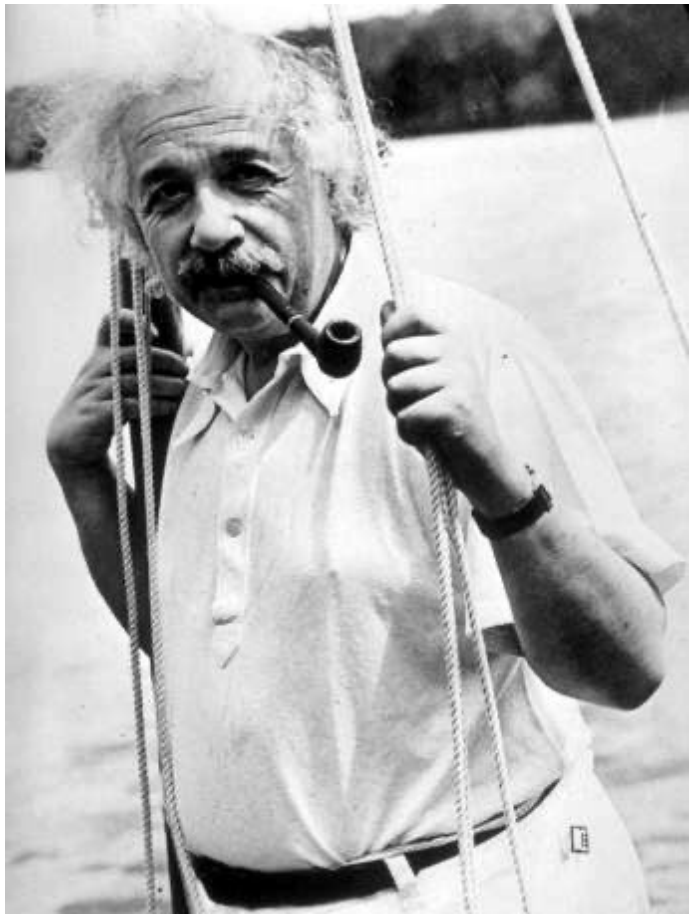

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$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu} \Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

homogeneous and isotropic 3D space →

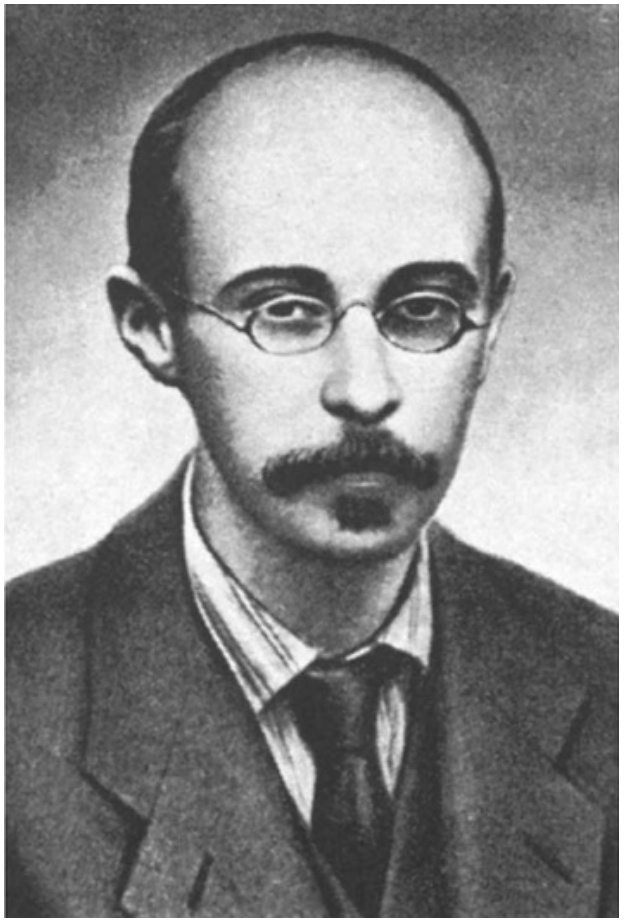
Cosmology

science or science-fiction?

Alexander Friedmann:

1922 Friedmann equation*

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 - kc^2$$



****derived under the assumption of the Cosmological Principle and without a cosmological constant (cf. FRW lecture)***

Cosmology

science or science-fiction?

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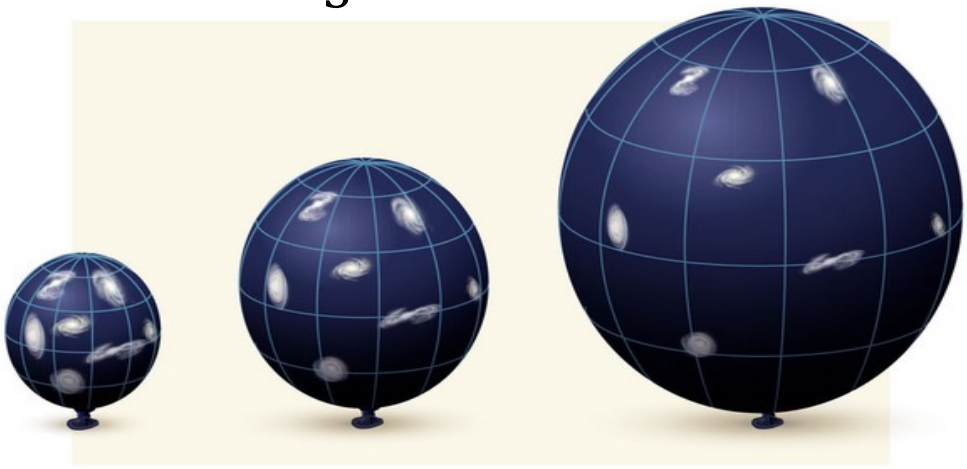

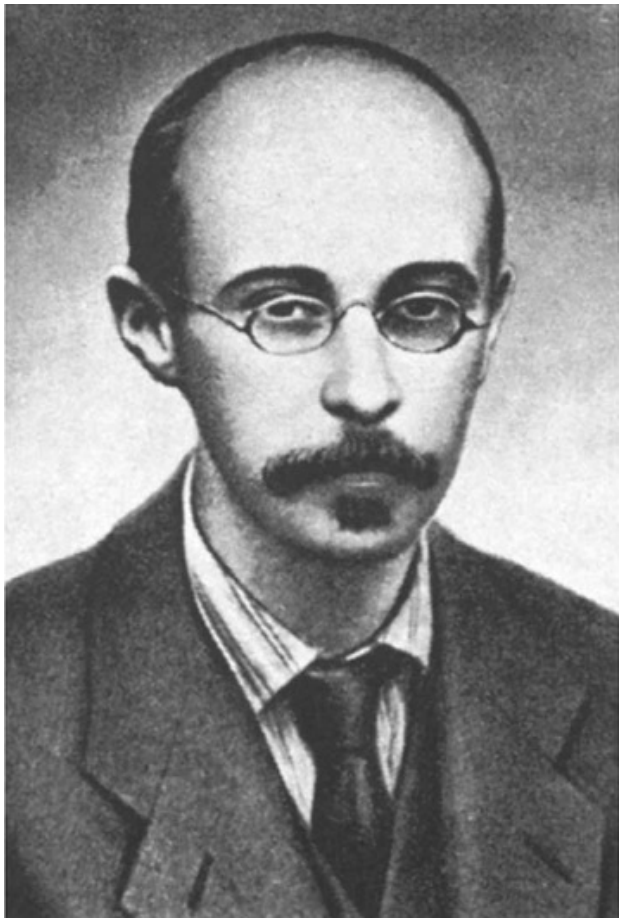

$a(t)$ ***measures change of distance scale in Universe***

Cosmology

science or science-fiction?

Alexander Friedmann:

1922 Friedmann equation

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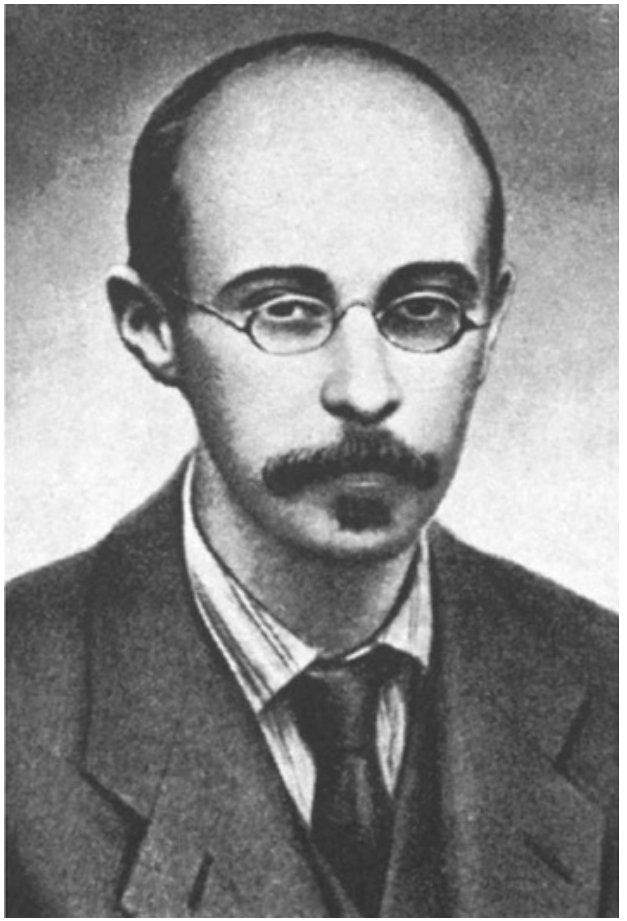
the Universe cannot be static!

$$\dot{a} \neq 0$$



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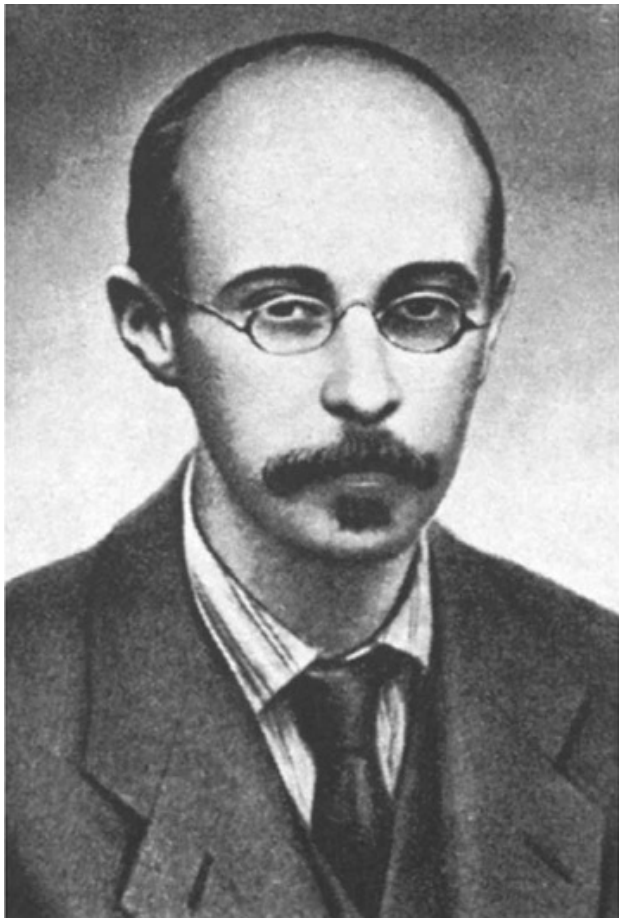

the Universe cannot be static!

the Universe itself began in a singularity!?

Cosmology

science or science-fiction?

Alexander Friedmann:

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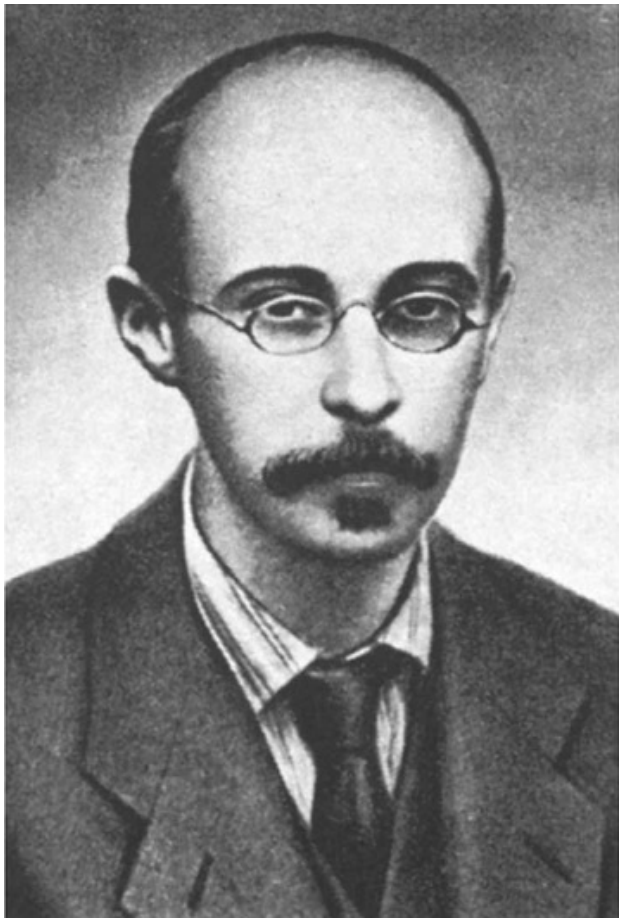

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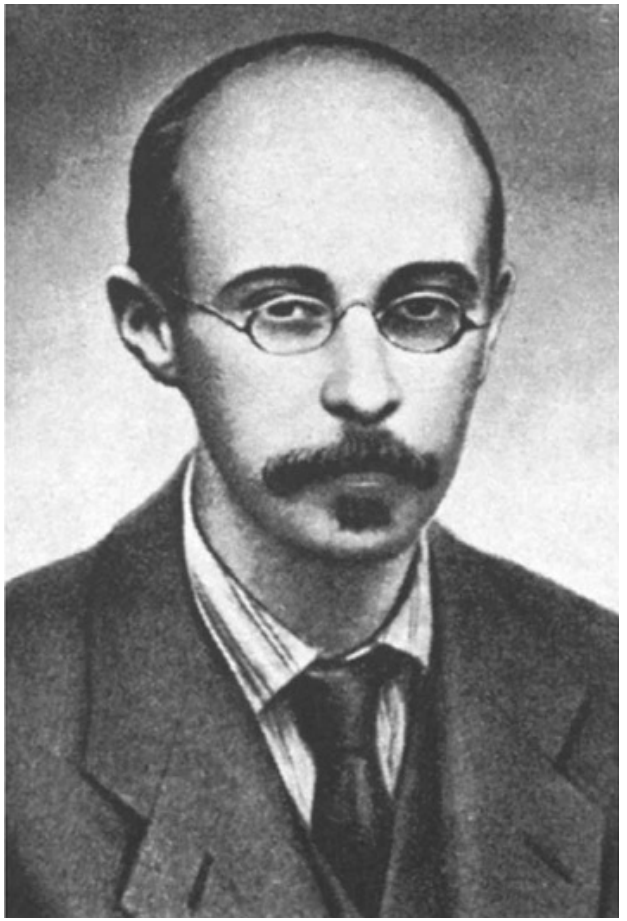

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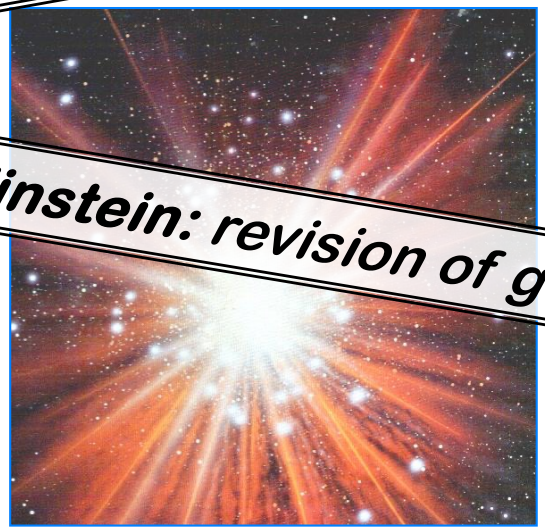

Albert Einstein: revision of general relativity (Λ-term, 1917)

the Universe itself began in a singularity!?

Cosmology

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Alexander Friedmann:

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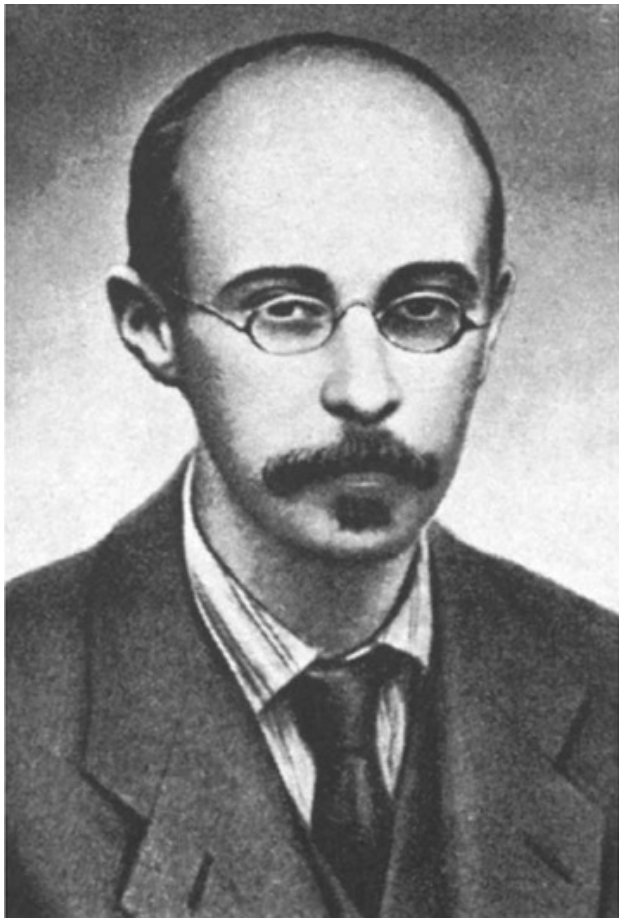
$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 + \frac{1}{3}\Lambda c^2 a^2 - kc^2$$

with Λ it could be static, but…



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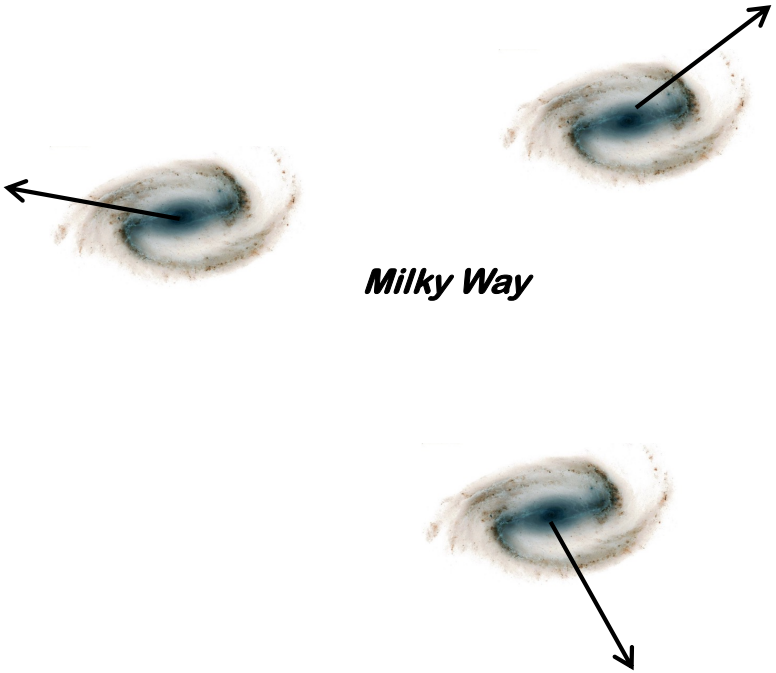
science or science-fiction?

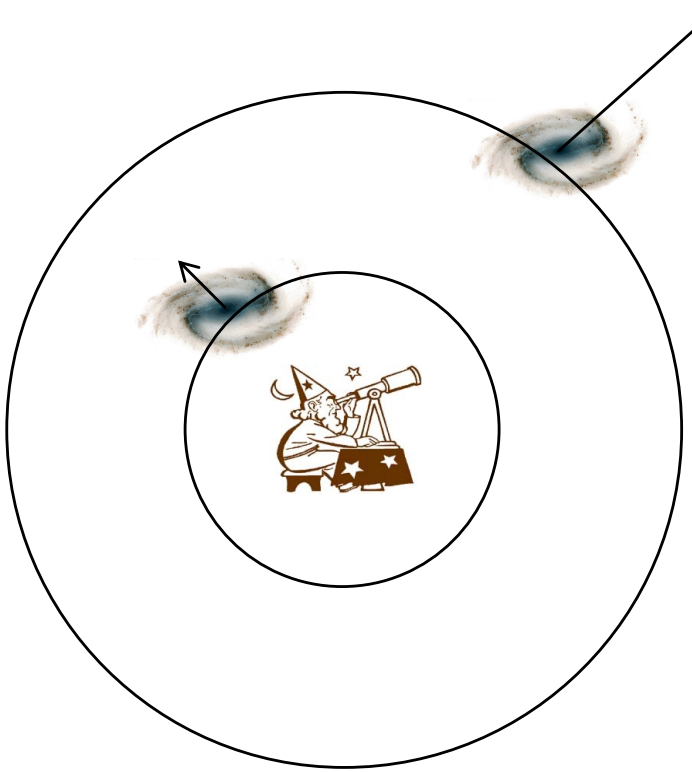
Vesto Slipher:

1916 galaxies in our vicinity are receding from us



George Lemaitre:

1927 galaxies further away recede faster



$$v = L_0 r$$

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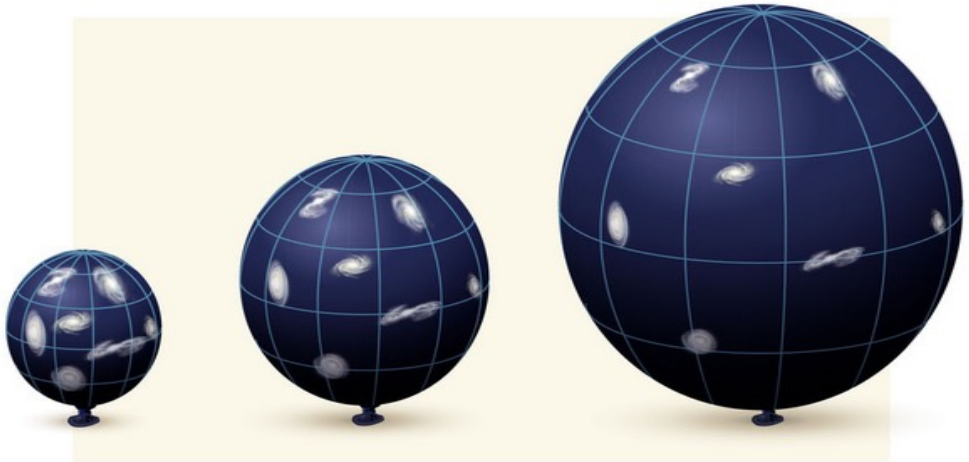
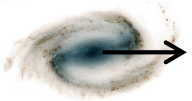
expansion of the Universe!?

$$L_0 = 625 \frac{km}{s} / Mpc$$





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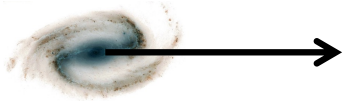

apparent velocity v

distance r

History & Principles

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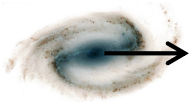
first only published in French*,
later translated by Arthur Eddington to English
and published in MNRAS in 1931



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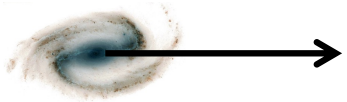

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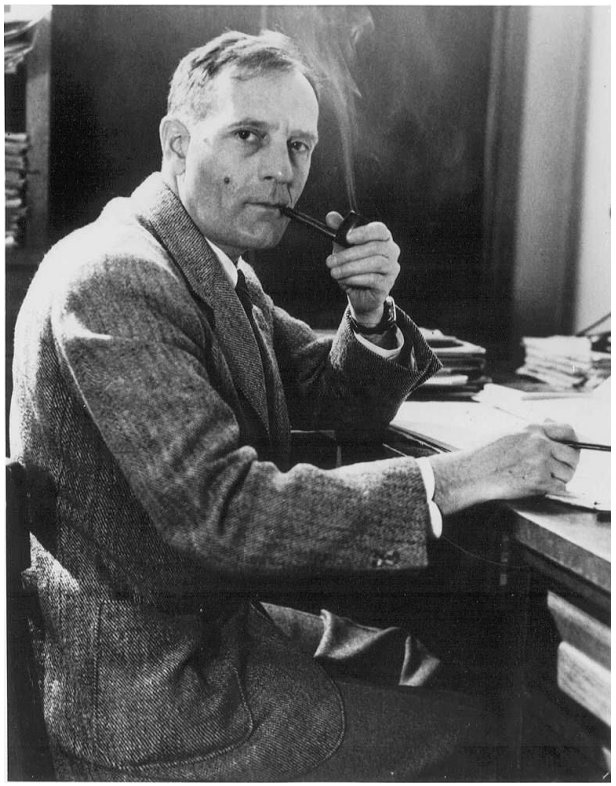
distance r

**Annales de la Societe Scientifique de Bruxelles*

Edwin Hubble:



1929 expansion of the Universe

$$H_0 = 500\ km/s/Mpc$$

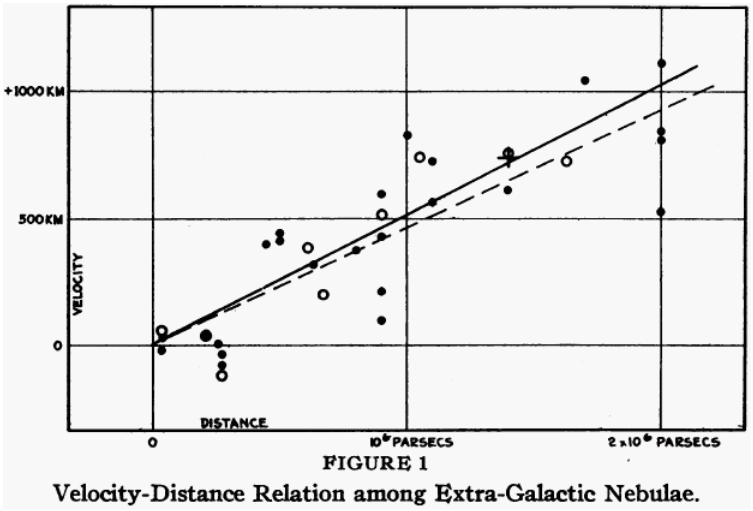
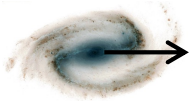


FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.



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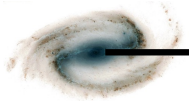

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distance r

(published in the Proceedings of the National Academy of Sciences of the USA)

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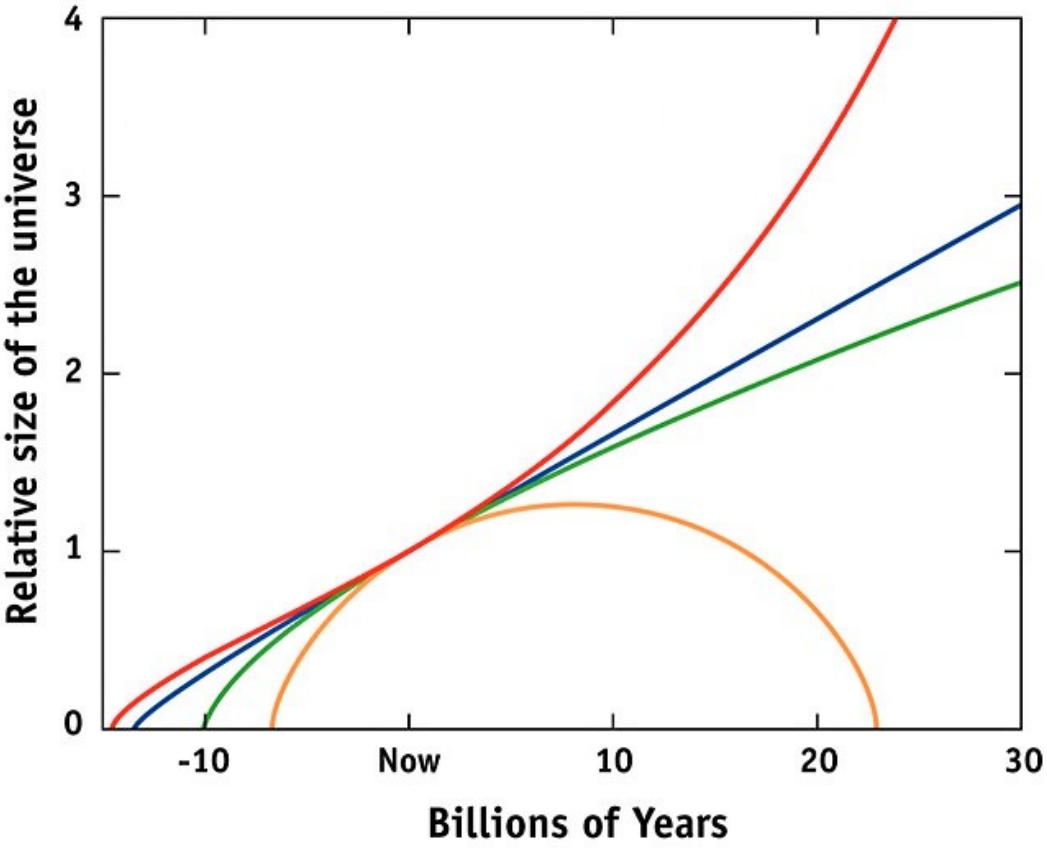
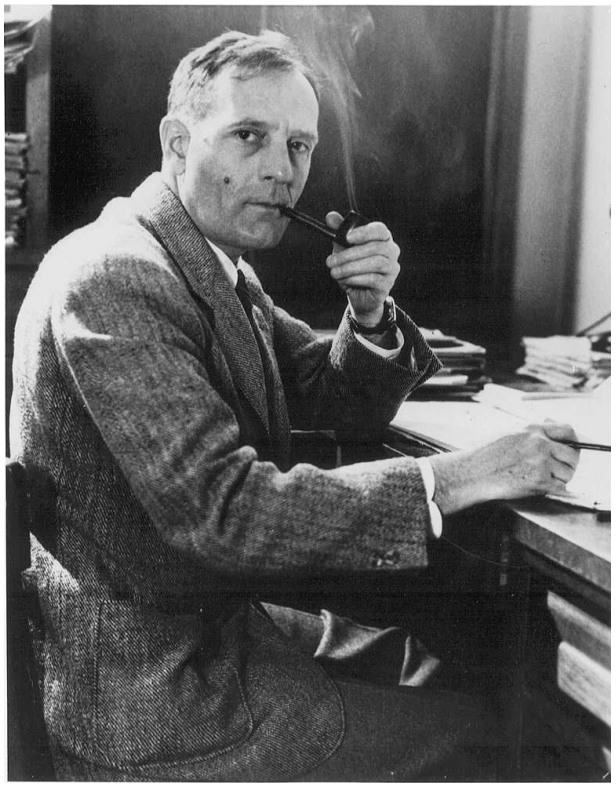
H_0 *: present-day expansion rate*





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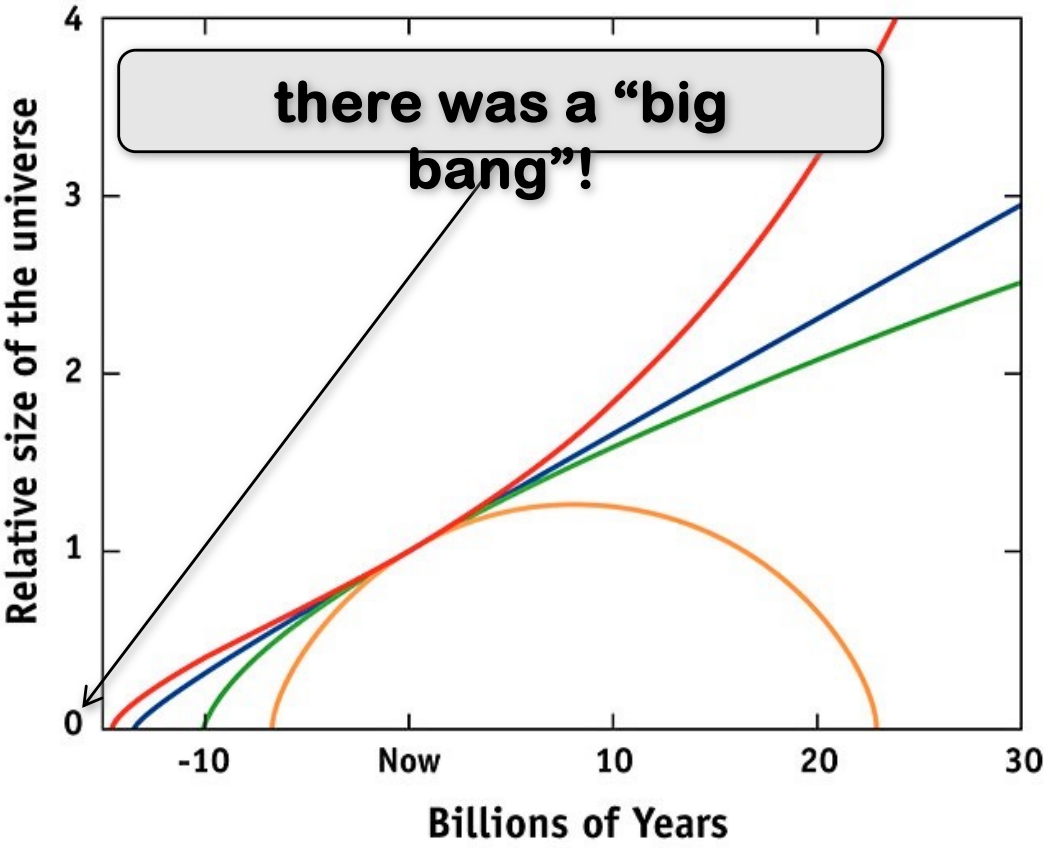

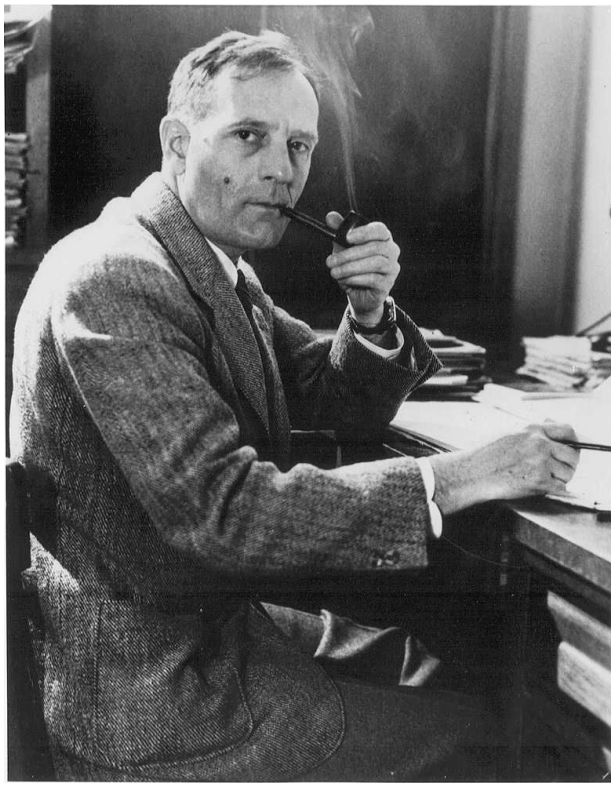

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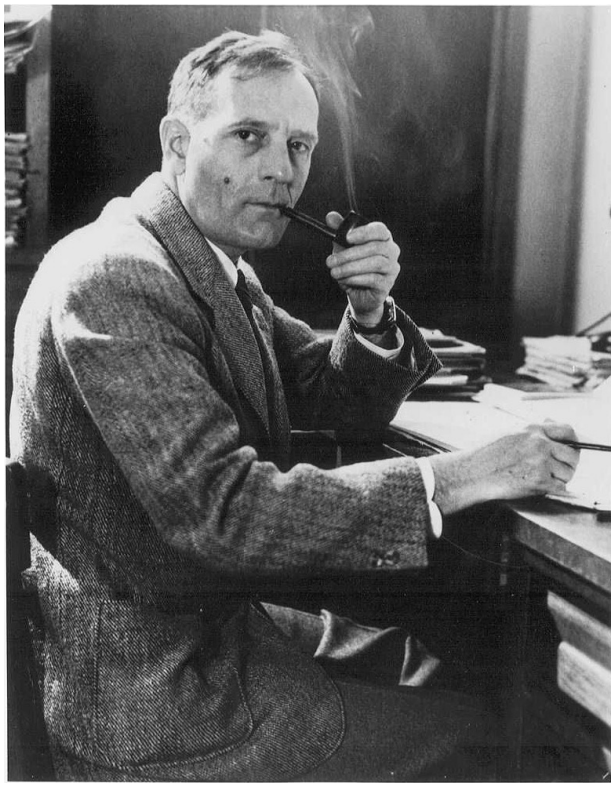

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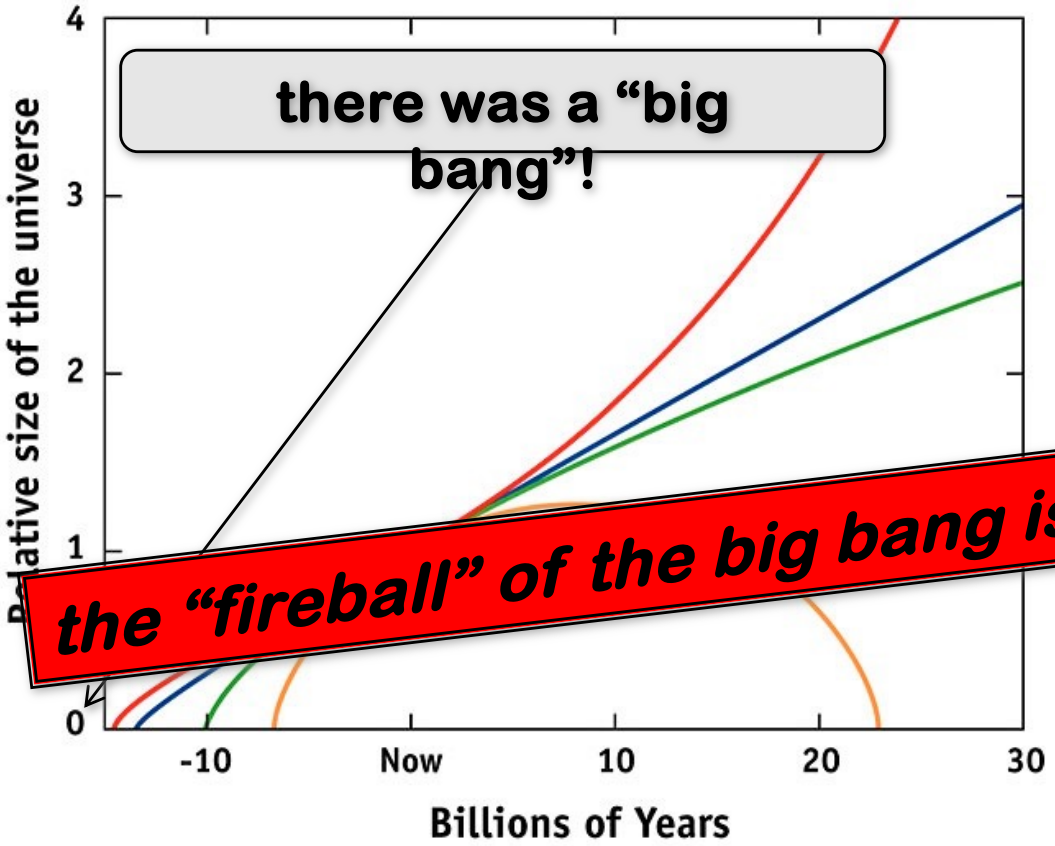

the "fireball" of the big bang is still visible today!

History & Principles

The Fireball of the Big Bang

Penzias und Wilson 1965

Penzias & Wilson worked 1965 for Bell-Labs and

…investigating radio emission from the Milky Way

…discovering “strange noise”

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discovery of the “cosmic microwave background radiation”

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D. T. Wilkinson

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spectacular announcement?!

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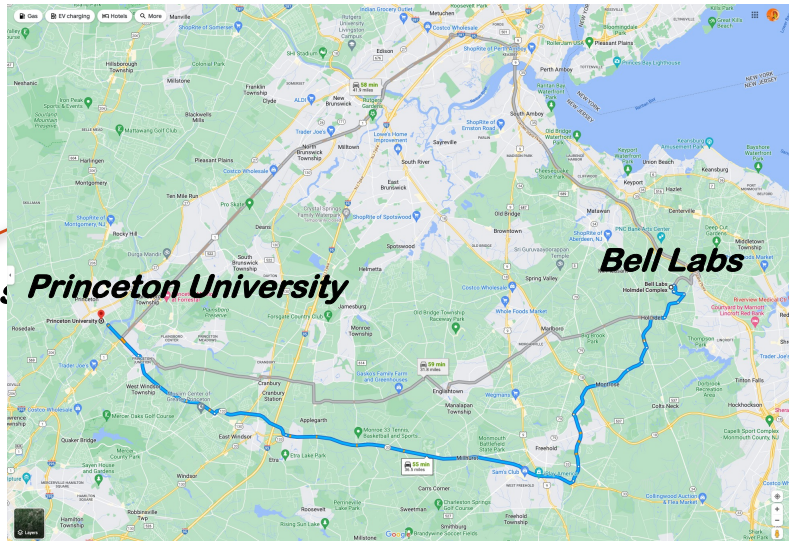

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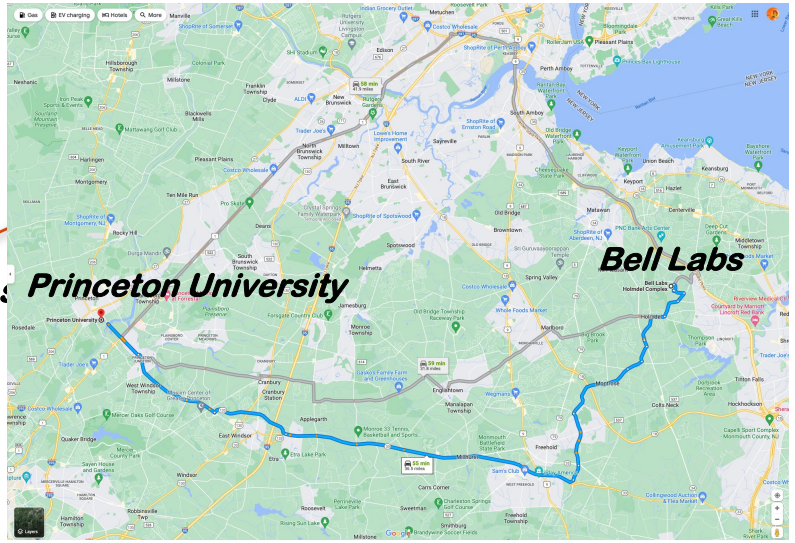

History & Principles

The Fireball of the Big Bang

No. 1, 1965 LETTERS TO THE EDITOR 419

high pressure, such as the zero-mass scalar, capable of speeding the universe through the period of helium formation. To have a closed space, an energy density of 2×10^{-29} gm/cm^3 is needed. Without a zero-mass scalar, or some other "hard" interaction, the energy could not be in the form of ordinary matter and may be presumed to be gravitational radiation (Wheeler 1958).

One other possibility for closing the universe, with matter providing the energy content of the universe, is the assumption that the universe contains a net electron-type neutrino abundance (in excess of antineutrinos) greatly larger than the nucleon abundance. In this case, if the neutrino abundance were so great that these neutrinos are degenerate, the degeneracy would have forced a negligible equilibrium neutron abundance in the early, highly contracted universe, thus removing the possibility of nuclear reactions leading to helium formation. However, the required ratio of lepton to baryon number must be $> 10^9$.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

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Wheeler, J. A , 1958, *La Structure et l'évolution de l'univers* (11th Solvay Conf. [Brussels: Éditions Stoops]), p. 112.
——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

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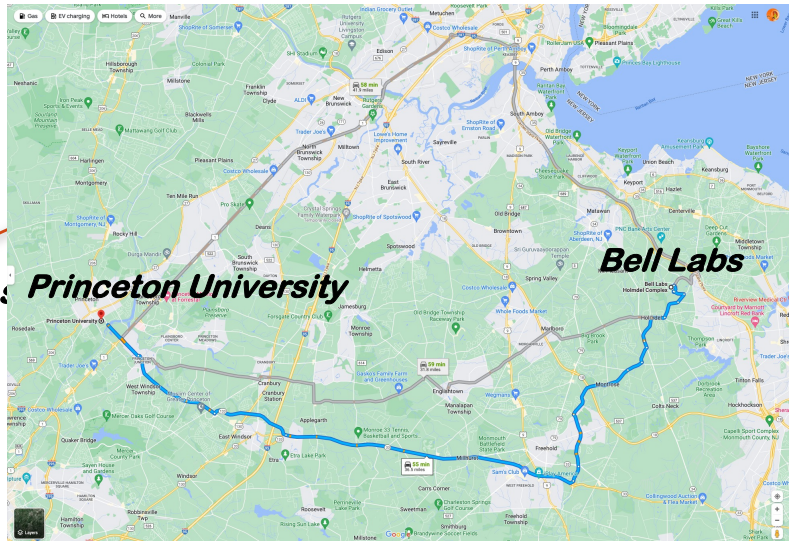
Penzias und Wilson 1965

theoretical explanation in same volume…

"Fireball" with T~3.5K!?

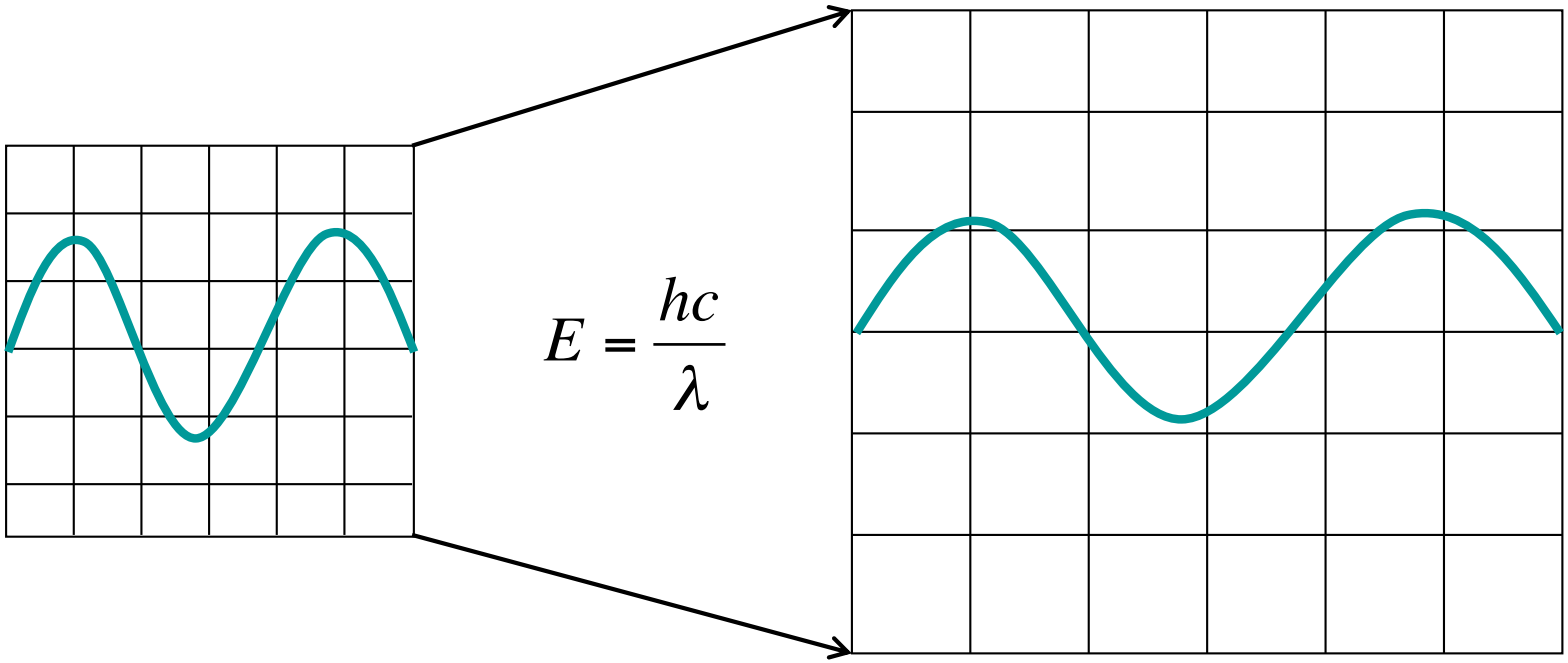


History & Principles

The Fireball of the Big Bang

Penzias und Wilson 1965

expanding space - the principle of "redshift":



History & Principles

The Fireball of the Big Bang

Penzias und Wilson 1965

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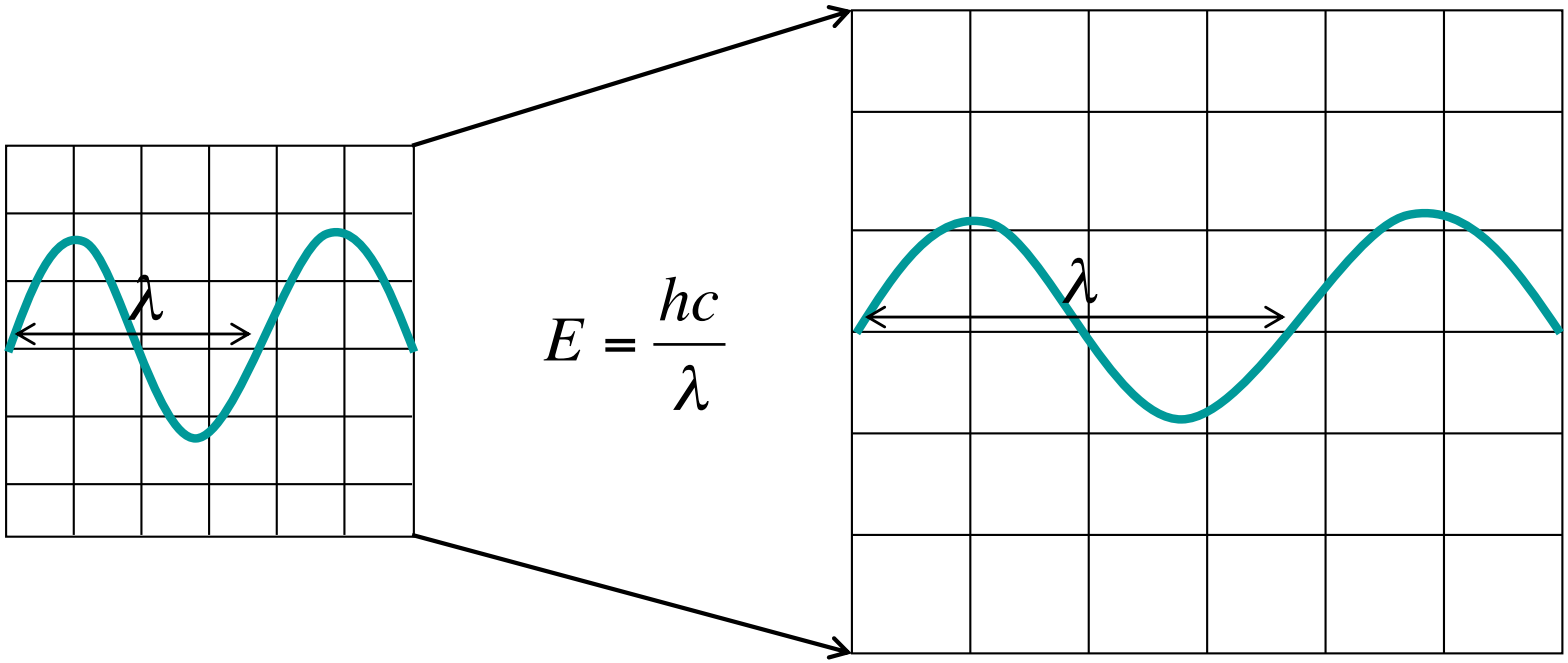

History & Principles

The Fireball of the Big Bang

Penzias und Wilson 1965

expanding space - the principle of "redshift":

$$T = k_B^{-1}\sqrt{\frac{hc^5}{G}} \approx 1.4\times10^{32}K$$

$$T \approx 2.76K$$

History & Principles

The Fireball of the Big Bang

Penzias und Wilson 1965

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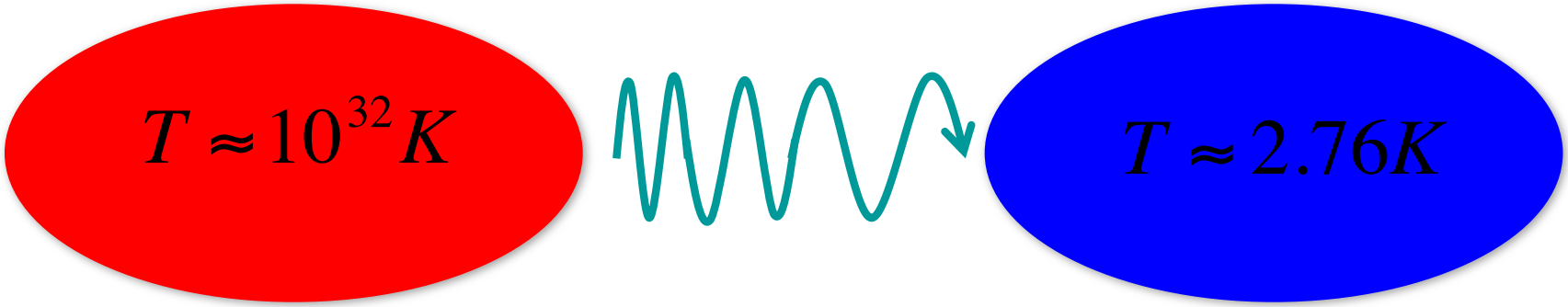


do we really see the

fireball of the Big Bang?

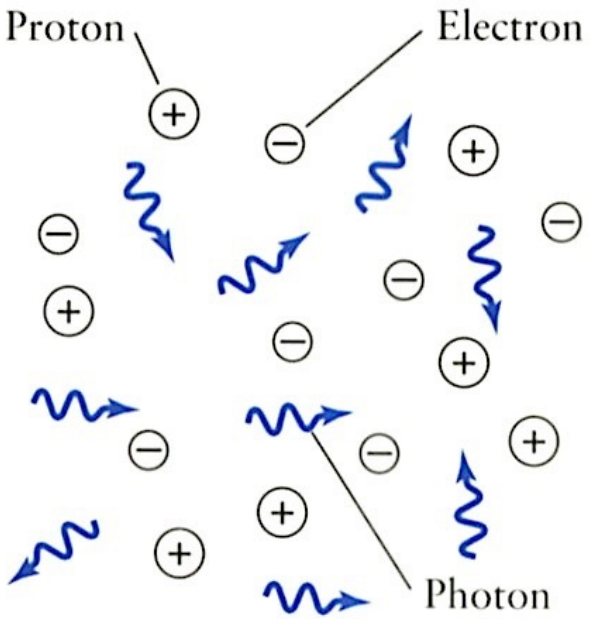
The Fireball of the Big Bang

photons cannot travel freely

in early Universe!

Penzias und Wilson 1965

← big bang



primordial plasma

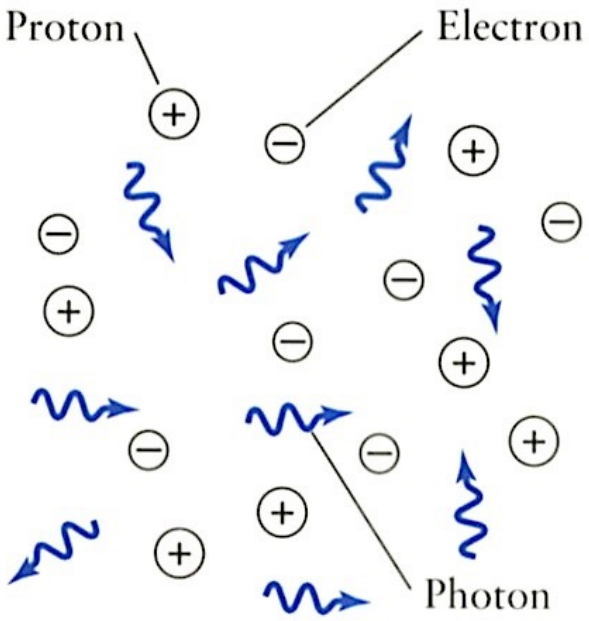
The Fireball of the Big Bang

release of CMB photons

after "recombination"

Penzias und Wilson 1965

← big bang



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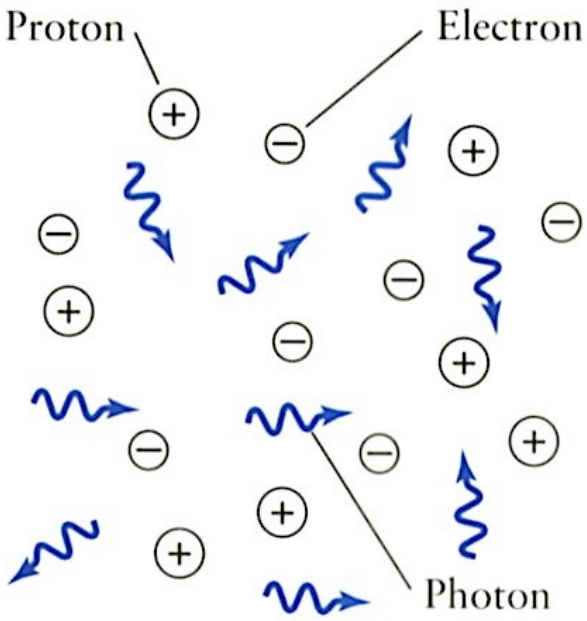

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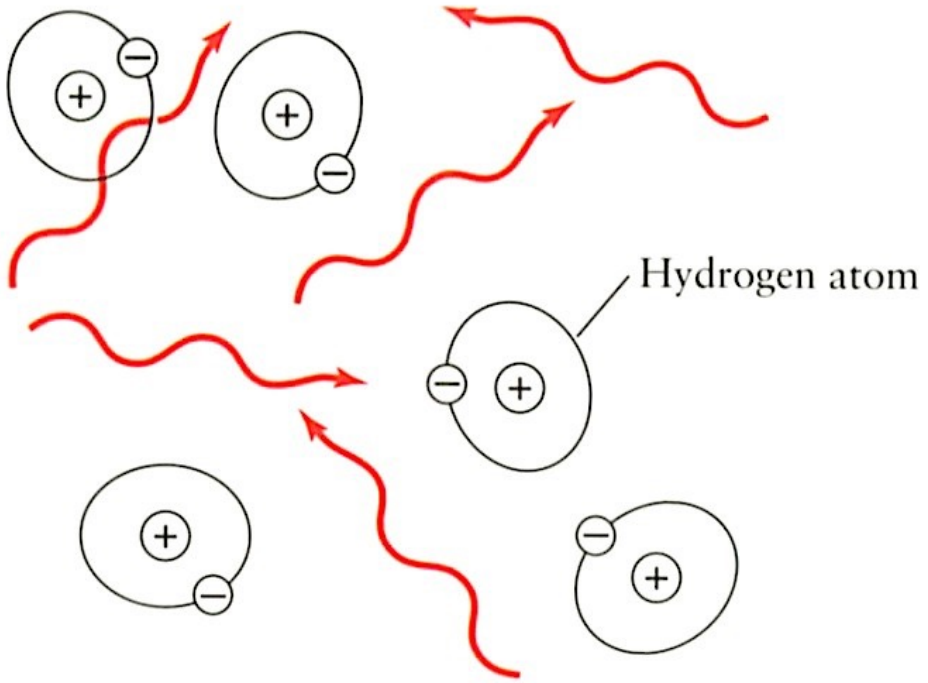

neutral Hydrogen

History & Principles

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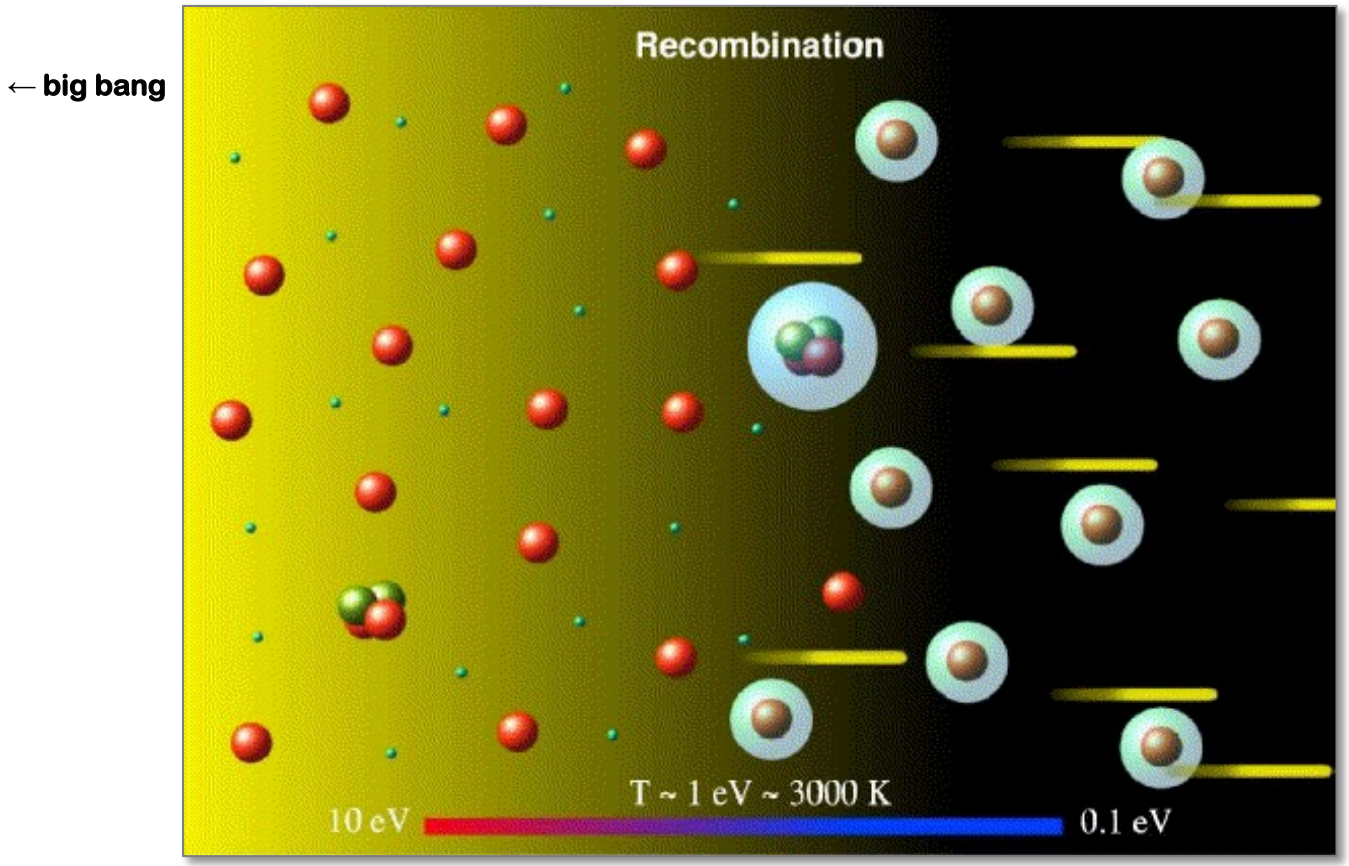

History & Principles

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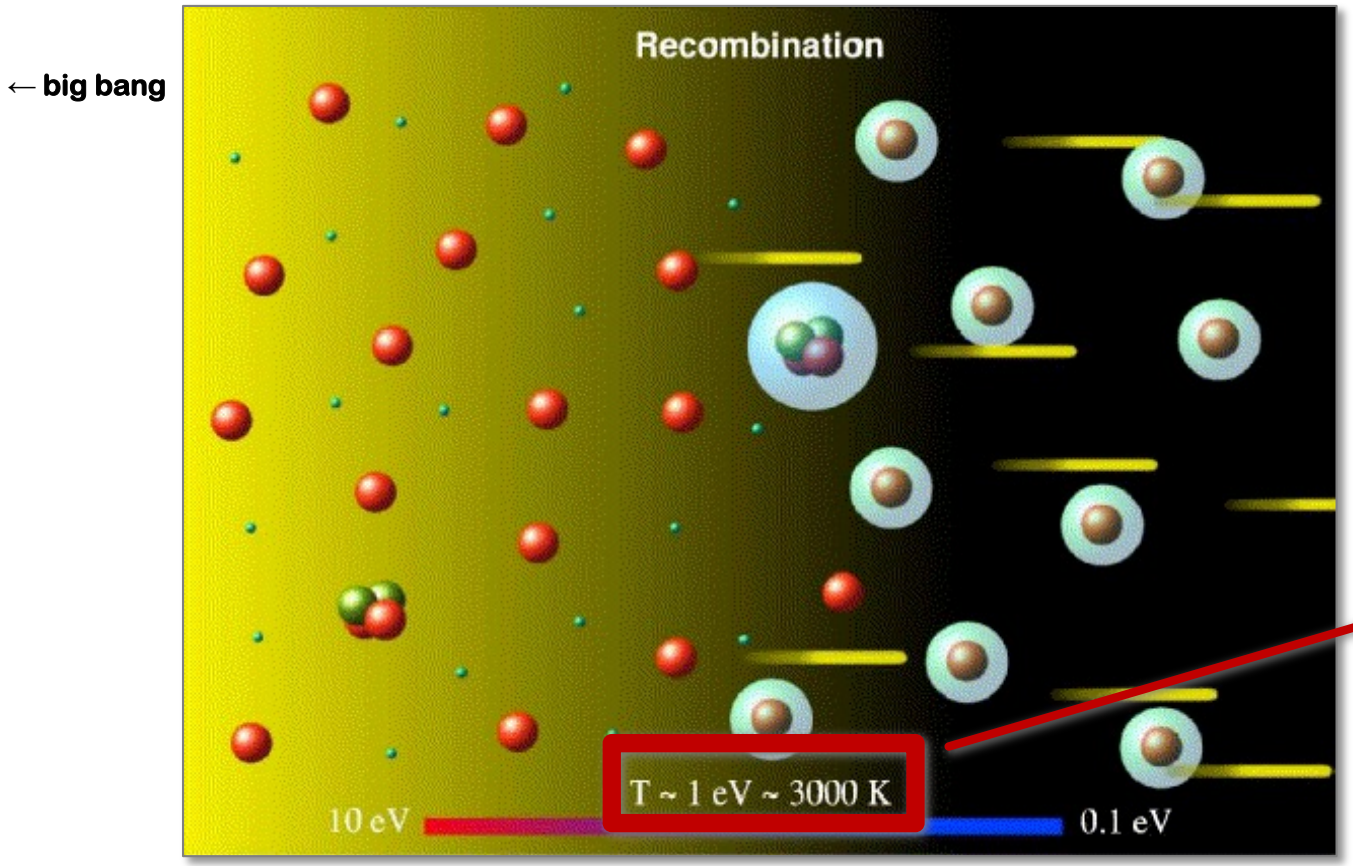

$$!= 10^{32} K$$

History & Principles

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Penzias und Wilson 1965

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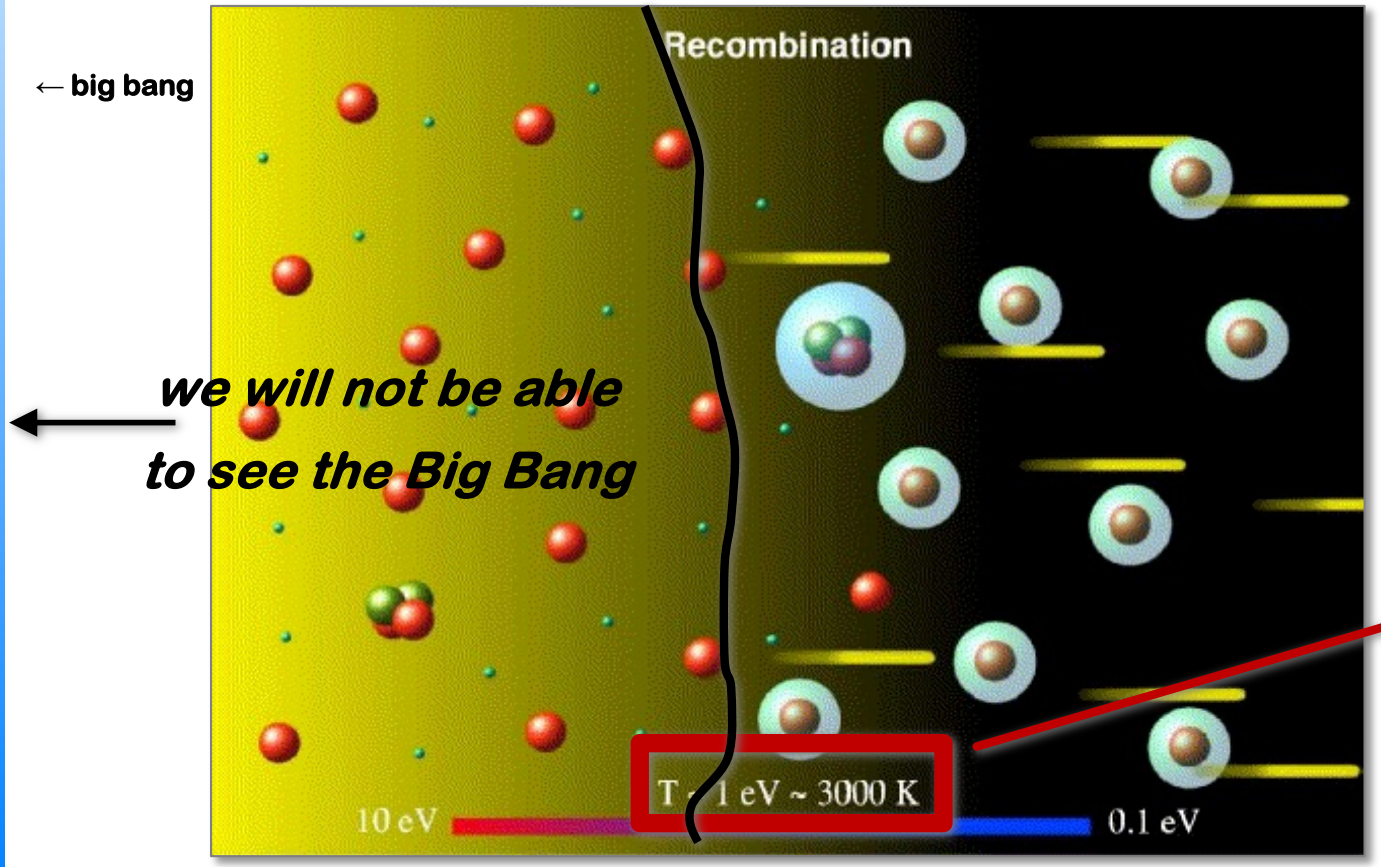

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The Fireball of the Big Bang

Penzias und Wilson 1965

Penzias & Wilson worked 1965 for Bell-Labs and

…investigating radio emission from the Milky Way

…discovering [illegible]

1978 noble prize in physics

discovery of the “cosmic microwave background radiation”

History & Principles

The Fireball of the Big Bang

Penzias und Wilson 1965

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…investigating radio emission from the Milky Way

…discovering [illegible]

1978 noble prize in physics

discovery of the "cosmic microwave background radiation"

followed by numerous Nobel prizes in Cosmology/Astrophysics →

nobel prizes related to cosmology...

2XXX: => *explanation for dark energy*
20XX: => *discovery of dark matter*

2020: **Penrose and Genzel & Ghez**
=> relativity and black holes

2019: **Peebles and Mayor & Queloz**
=> *physical cosmology and exoplanets*

2017: **Weiss, Barish & Thorne**
=> *discovery of gravitational waves*

2011: **Perlmutter, Schmidt & Riess**
=> *discovery of accelerated expansion of the Universe*

2006: **Smoot & Mather**
=> *discovery of anisotropies in the CMB*

2002: **Giacconi**
=> *discovery of cosmic X-ray sources*

1978: **Penzias & Wilson**
=> *discovery of CMB*

Cosmology

science or science-fiction?

nobel prizes related to cosmology...

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twice for CMB!?

Cosmology

science or science-fiction?

nobel prizes related to cosmology...

2XXX: => *explanati*

20XX: => *dis*

2020:

2019:

$$T \approx 2.76K$$

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nobel prizes related to cosmology...

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20XX
2020
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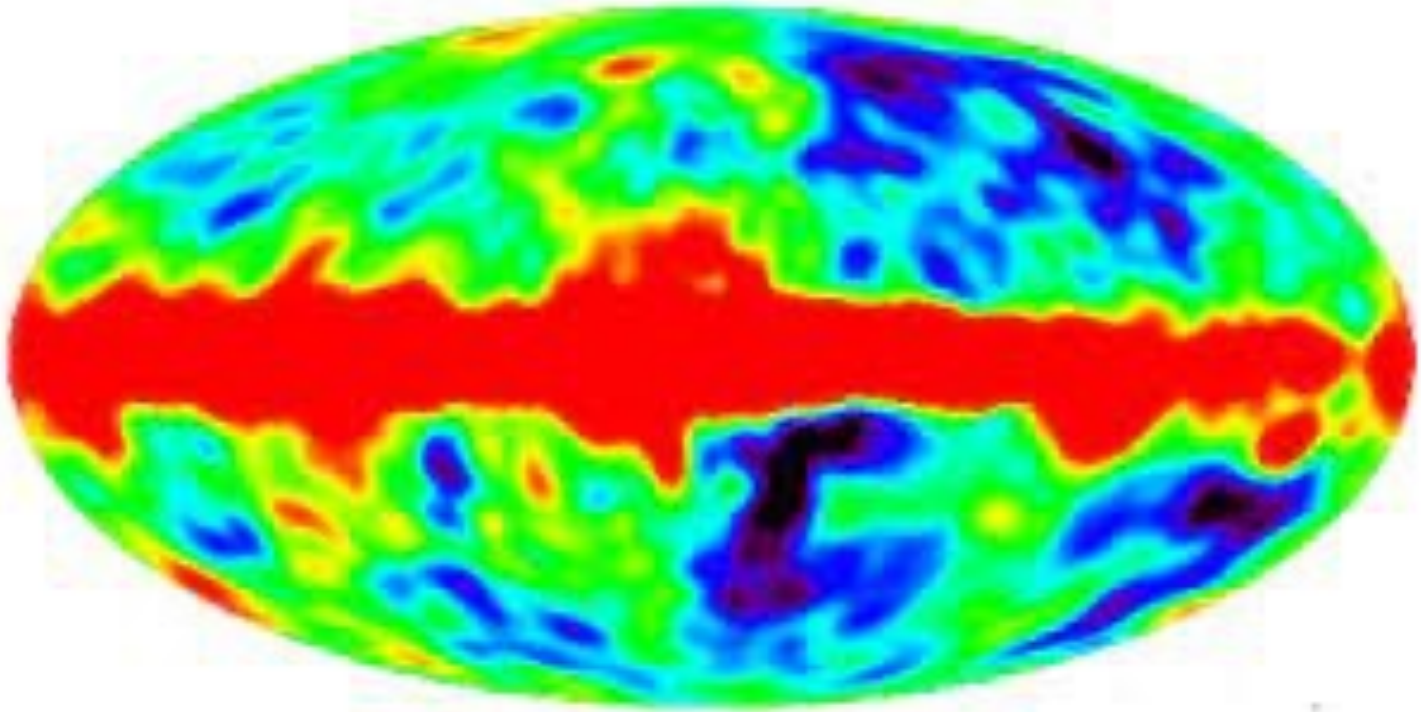
2011



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science or science-fiction?

nobel prizes related to cosmology...

2XXX: => *explanation for dark energy*

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202[illegible]

20[illegible]

20[illegible]

Cosmology is science (and not science-fiction)

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=> *discovery of accelerated expansion of the Universe*

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twice for CMB!

Cosmology

science or science-fiction?

History & Principles

*General Relativity**

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

**Einstein did not receive the Nobel prize for GR!*

History & Principles

Friedmann equation

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 + \frac{1}{3}\Lambda c^2 a^2 - kc^2$$

cosmological principle (cf. FRW lecture)

General Relativity

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

History & Principles

Friedmann equation

$$a(t)$$

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General Relativity

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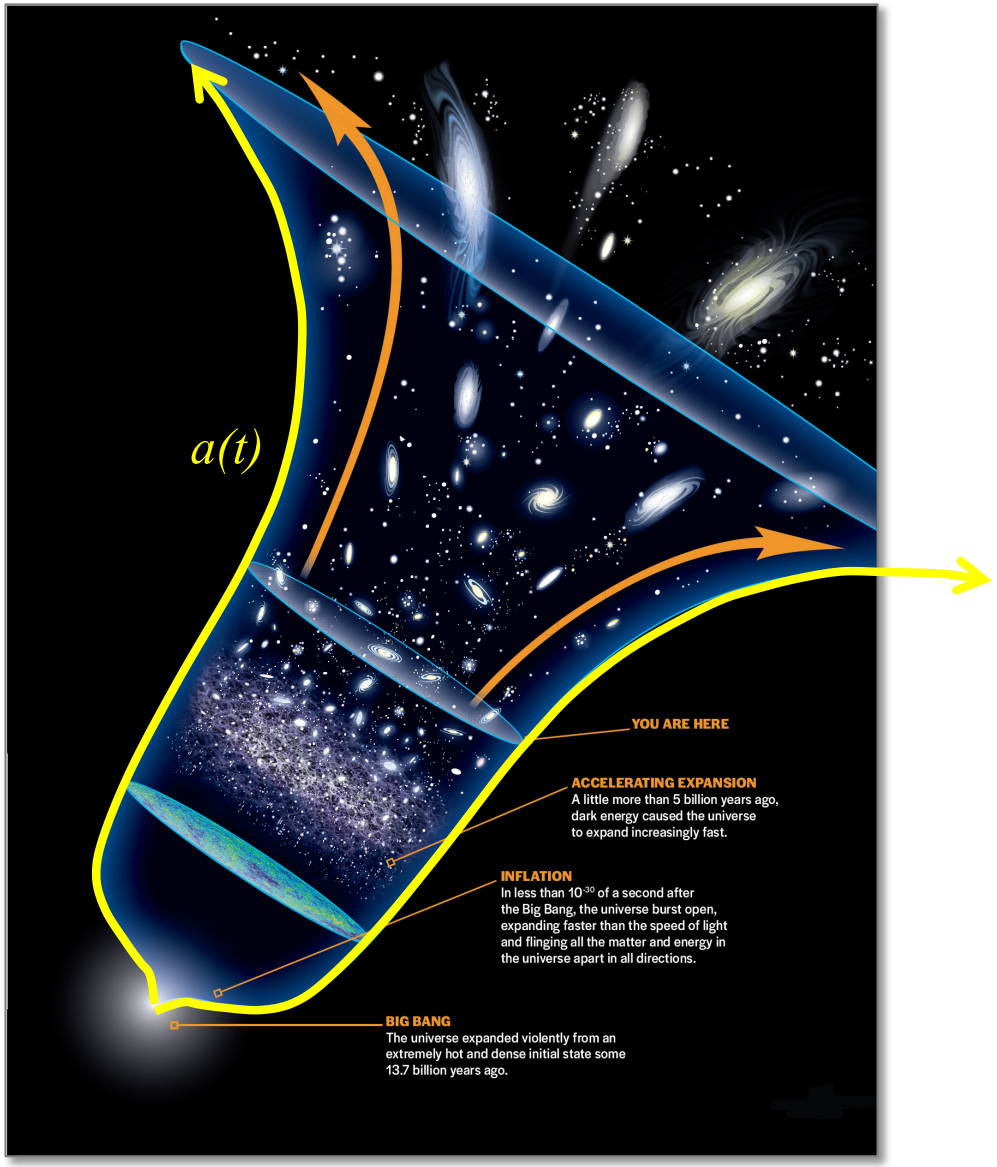
History & Principles

Friedmann equation*...describes the evolution of the Universe as a whole:*



Friedmann equation

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History & Principles

Friedmann equation

$$\dot{a}^2 = \frac{8\pi G}{3}\rho a^2 + \frac{1}{3}\Lambda c^2 a^2 - kc^2$$

depending on various things...

*Friedmann equation**

$$\frac{\dot{a}^2}{a^2} = H_0^2 \left(\frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{k,0}}{a^2} + \Omega_{\Lambda,0} \right)$$

**in its most memorable form (derivation in FRW lecture)*

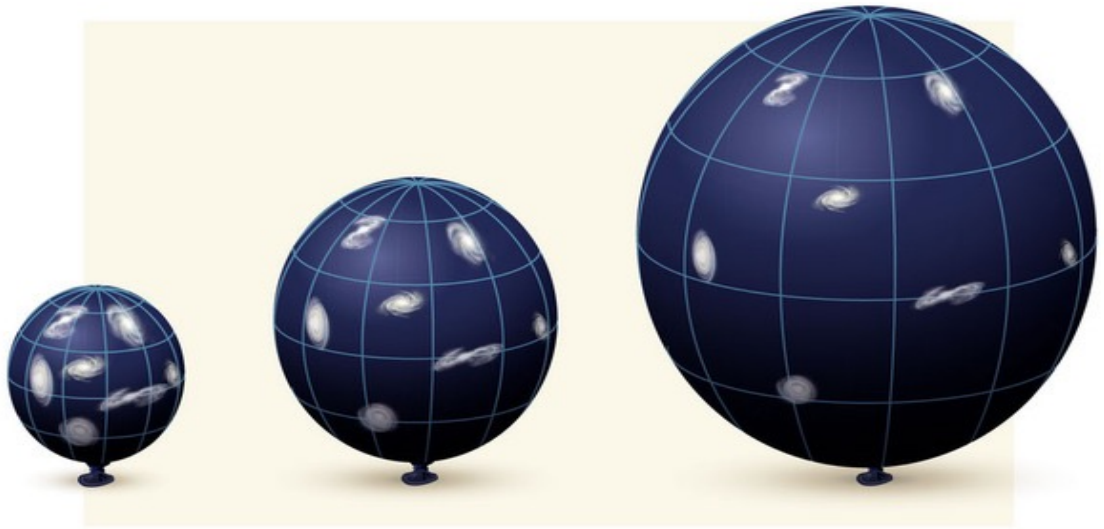
History & Principles

Friedmann equation

a = measure for radius of Universe

$\dot{a}$ = measure for expansion rate

$$\frac{\dot{a}^2}{a^2} = H_0^2 \left(\frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{k,0}}{a^2} + \Omega_{\Lambda,0} \right)$$



History & Principles

Friedmann equation

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present expansion rate $H_0^2 = \frac{\dot{a}_0^2}{a_0^2}$

Friedmann equation

present radiation content

$$\frac{\dot{a}^2}{a^2} = H_0^2 \left(\frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{k,0}}{a^2} + \Omega_{\Lambda,0} \right)$$

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History & Principles

Friedmann equation

present matter content

present radiation content

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present cosmological constant ("dark energy")

present expansion rate $H_0^2 = \frac{\dot{a}_0^2}{a_0^2}$

Friedmann equation

present matter content

present radiation content

present curvature

$$\frac{\dot{a}^2}{a^2} = H_0^2 \left(\frac{\Omega_{r,0}}{a^4} + \frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{k,0}}{a^2} + \Omega_{\Lambda,0} \right)$$

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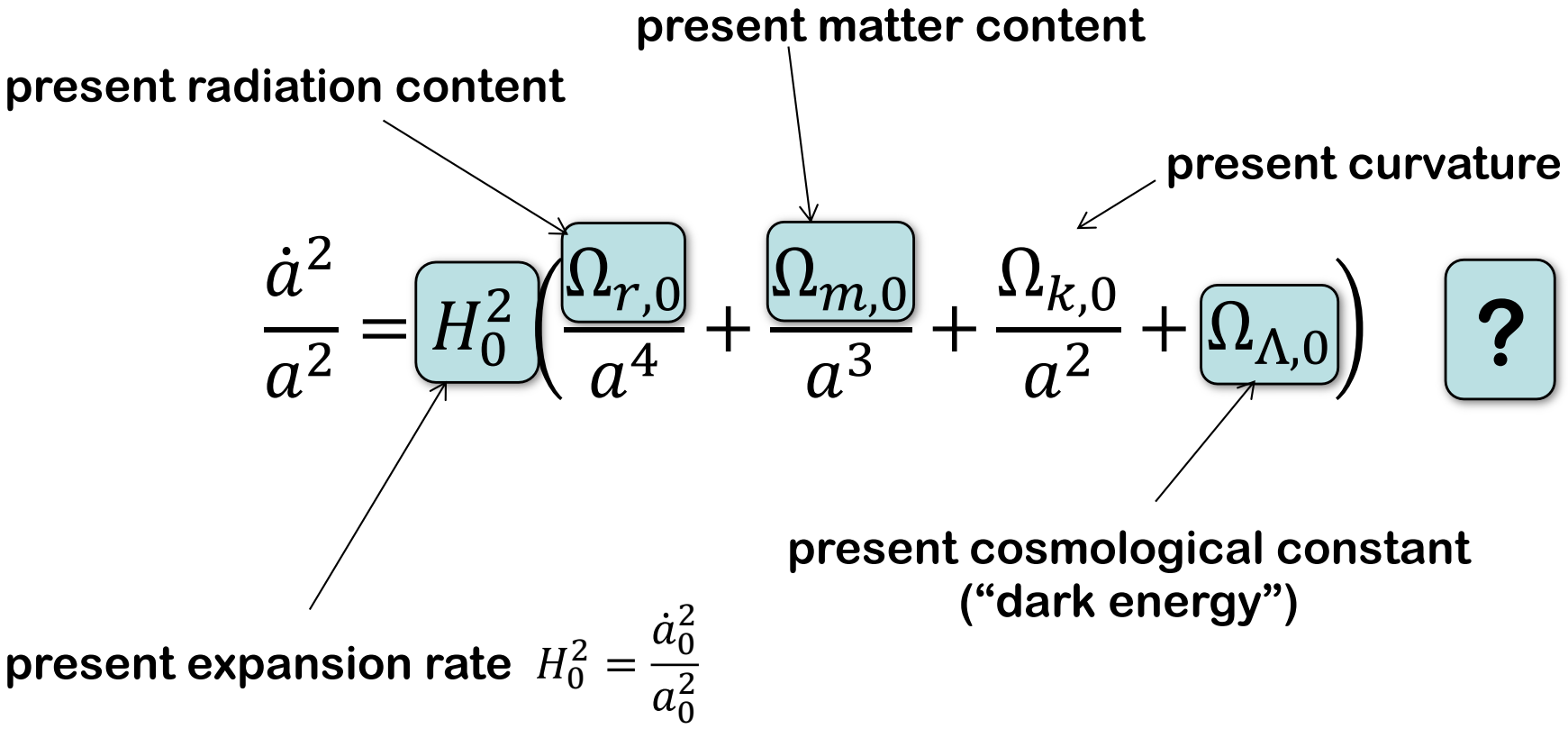
present cosmological constant ("dark energy")

present expansion rate $H_0^2 = \frac{\dot{a}_0^2}{a_0^2}$

only 3 of the 4 density parameters are independent as $1 = \Omega_r + \Omega_m + \Omega_k + \Omega_\Lambda$

History & Principles

Friedmann equation



only 3 of the 4 density parameters are independent as $1 = \Omega_r + \Omega_m + \Omega_k + \Omega_\Lambda$

History & Principles

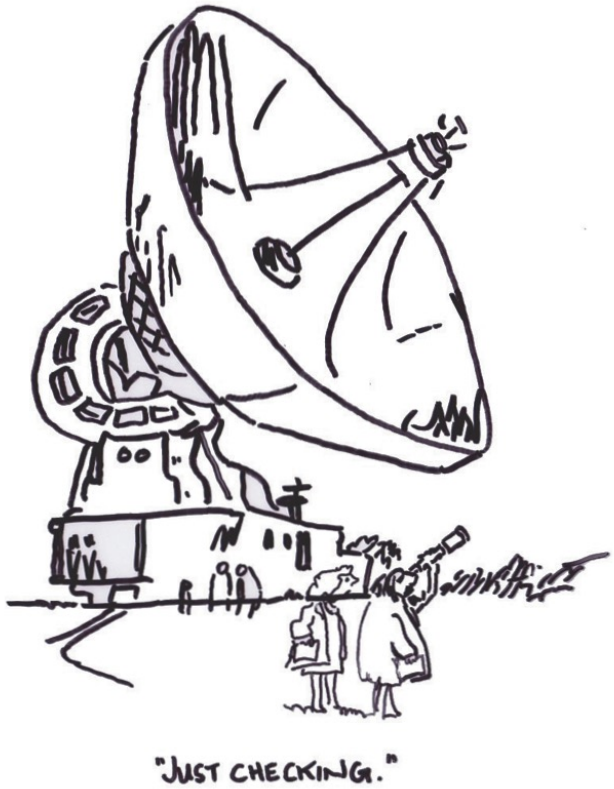
cosmological parameters

$$H_0, \quad \Omega_{r,0}, \quad \Omega_{m,0}, \quad \Omega_{\Lambda,0}$$

cosmological parameters

$$H_0, \quad \Omega_{r,0}, \quad \Omega_{m,0}, \quad \Omega_{\Lambda,0}$$

determination
via
observations!



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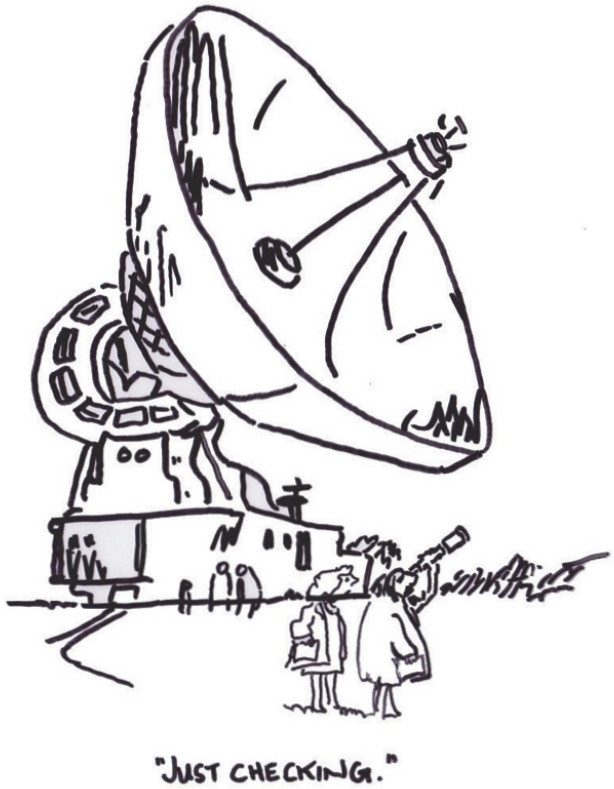
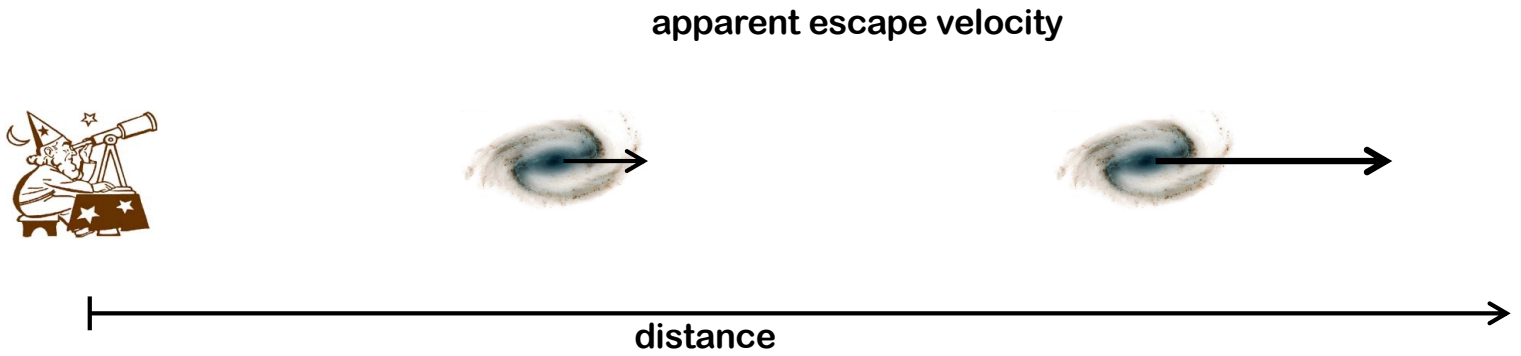


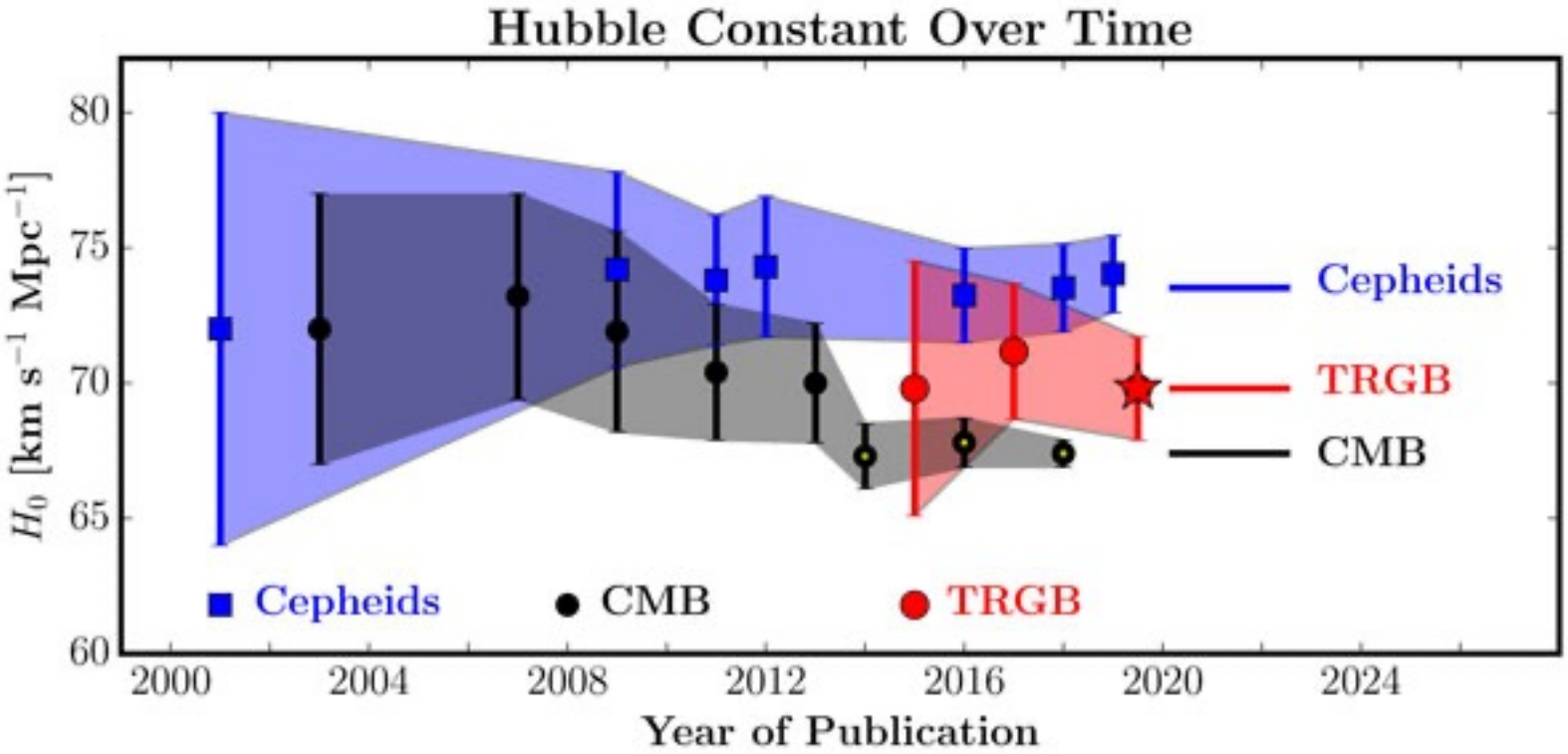
Cosmology

H_0 : *Hubble-Lemaitre Parameter*



$$H_0 = 70 \frac{km/\sec}{Mpc}$$

H_0 : *Hubble-Lemaitre Parameter*



$$H_0 = 70 \frac{km/\sec}{Mpc} \quad ?$$

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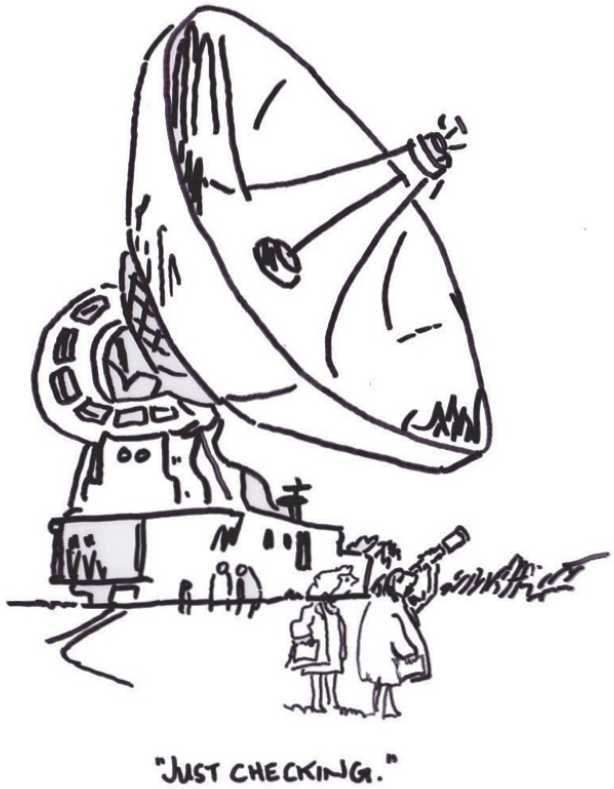

History & Principles

$\Omega_{r,0}$: *radiation content*

Penzias und Wilson 1965

No. 1, 1965 LETTERS TO THE EDITOR 419

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——— 1964, in *Relativity, Groups and Topology*, ed C. DeWitt and B. DeWitt (New York: Gordon & Breach).
Zel'dovich, Ya. B. 1962, *Soviet Phys.—J.E.T.P.*, **14**, 1143.

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

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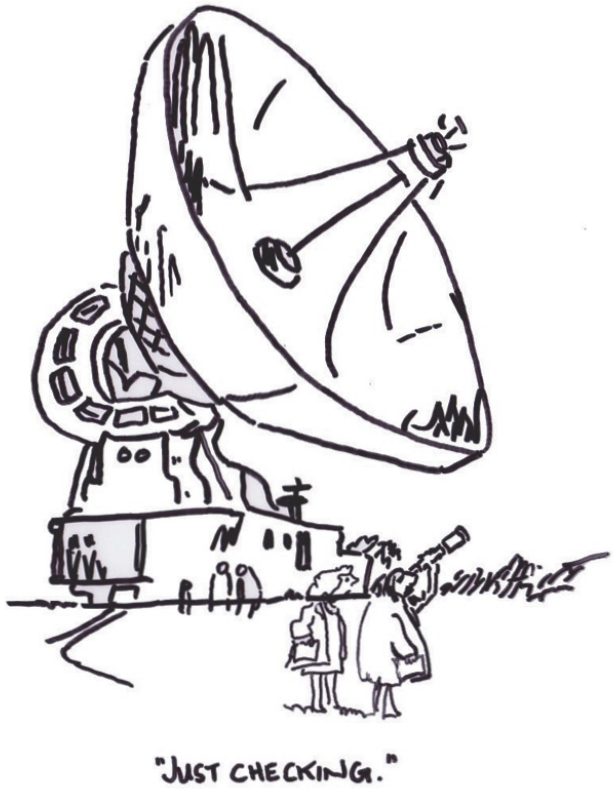
$$\Omega_{r,0} \approx 10^{-6}$$

(this is why we mostly ignore Ω_r when dealing with present-day structures)

cosmological parameters

$$H_0, \quad \Omega_{r,0}, \quad \Omega_{m,0}, \quad \Omega_{\Lambda,0}$$

determination
via
observations!

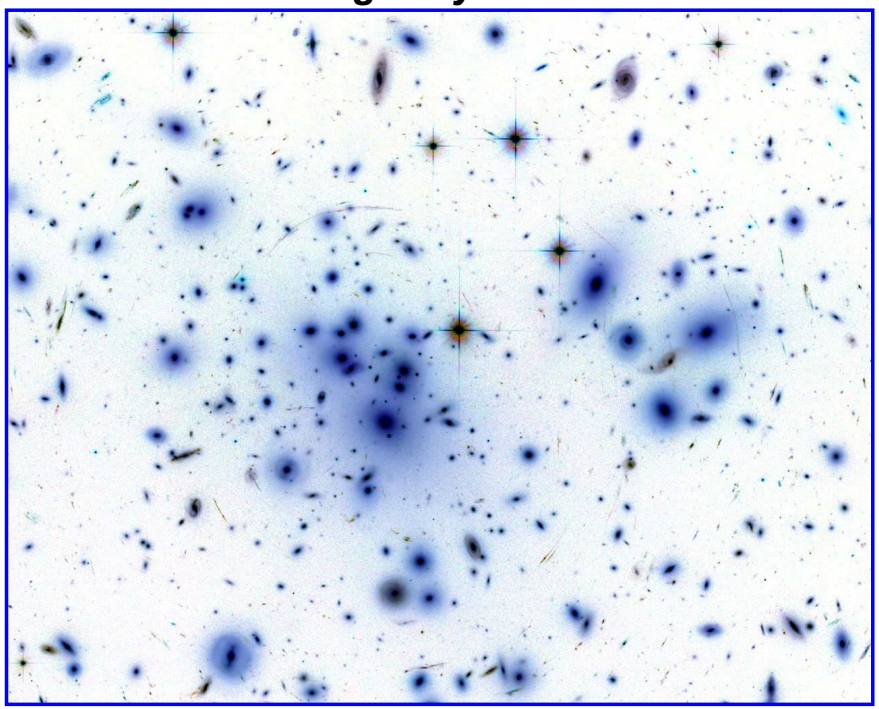


Cosmology

$\Omega_{m,0}$: *matter content*

"Dark Matter" already proposed by Fritz Zwicky in 1933:

galaxy cluster



Cosmology

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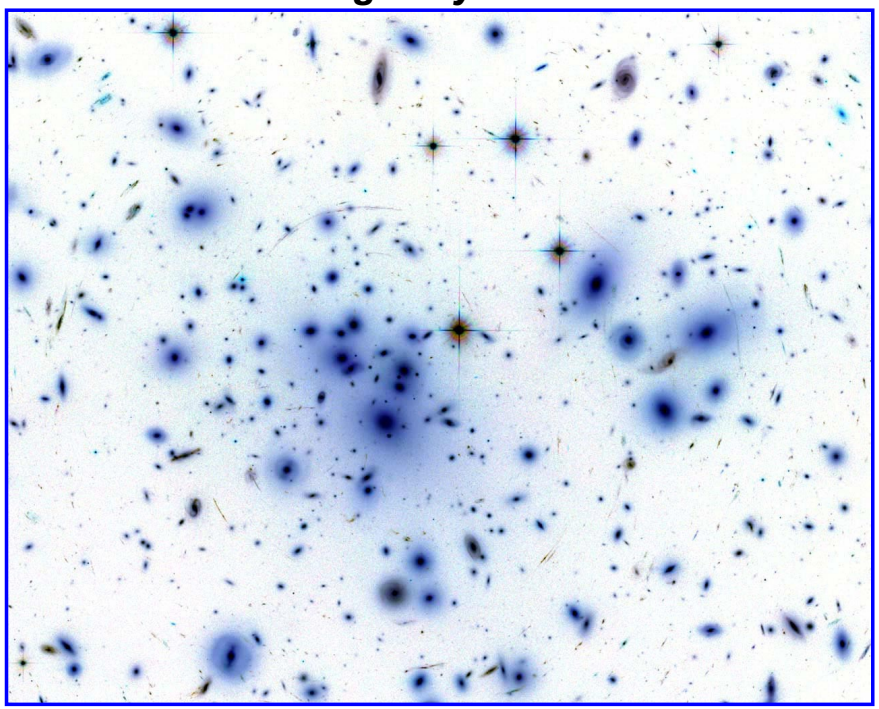
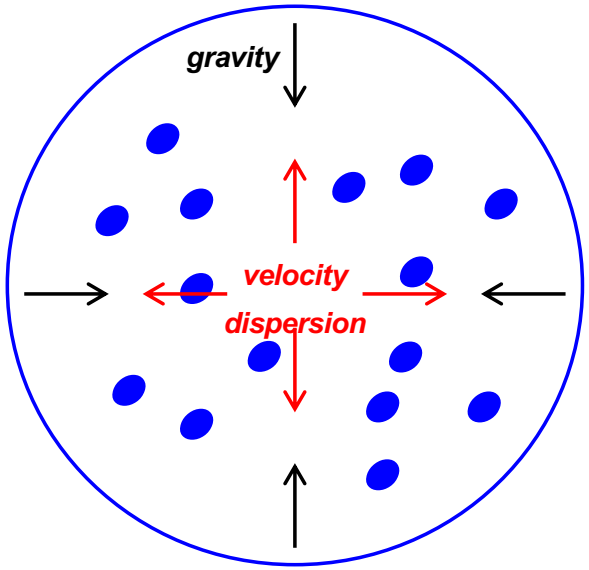


=>



Cosmology

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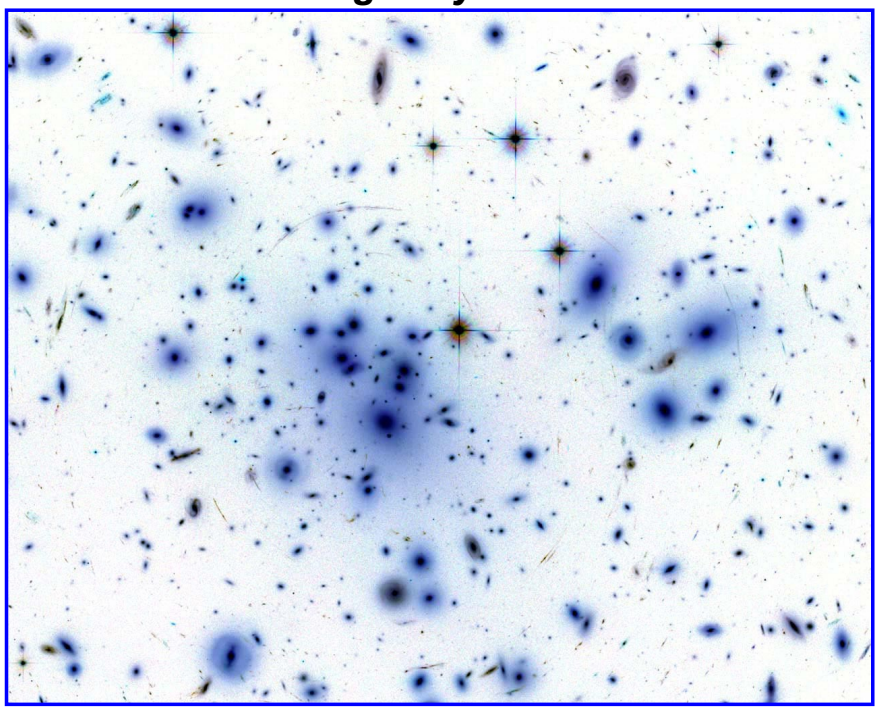
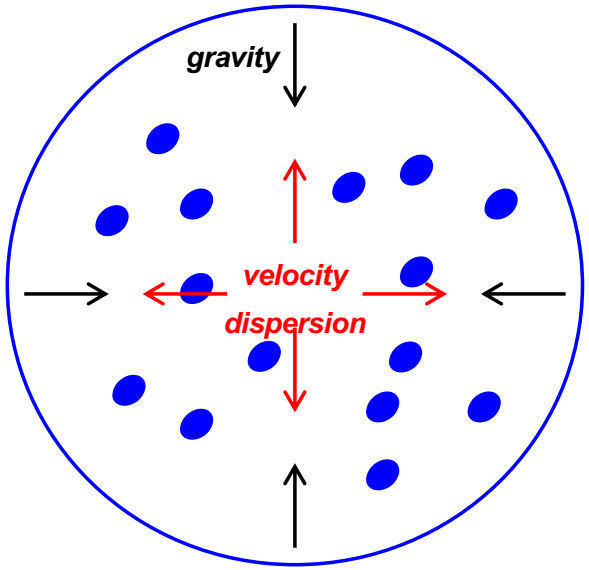


=>

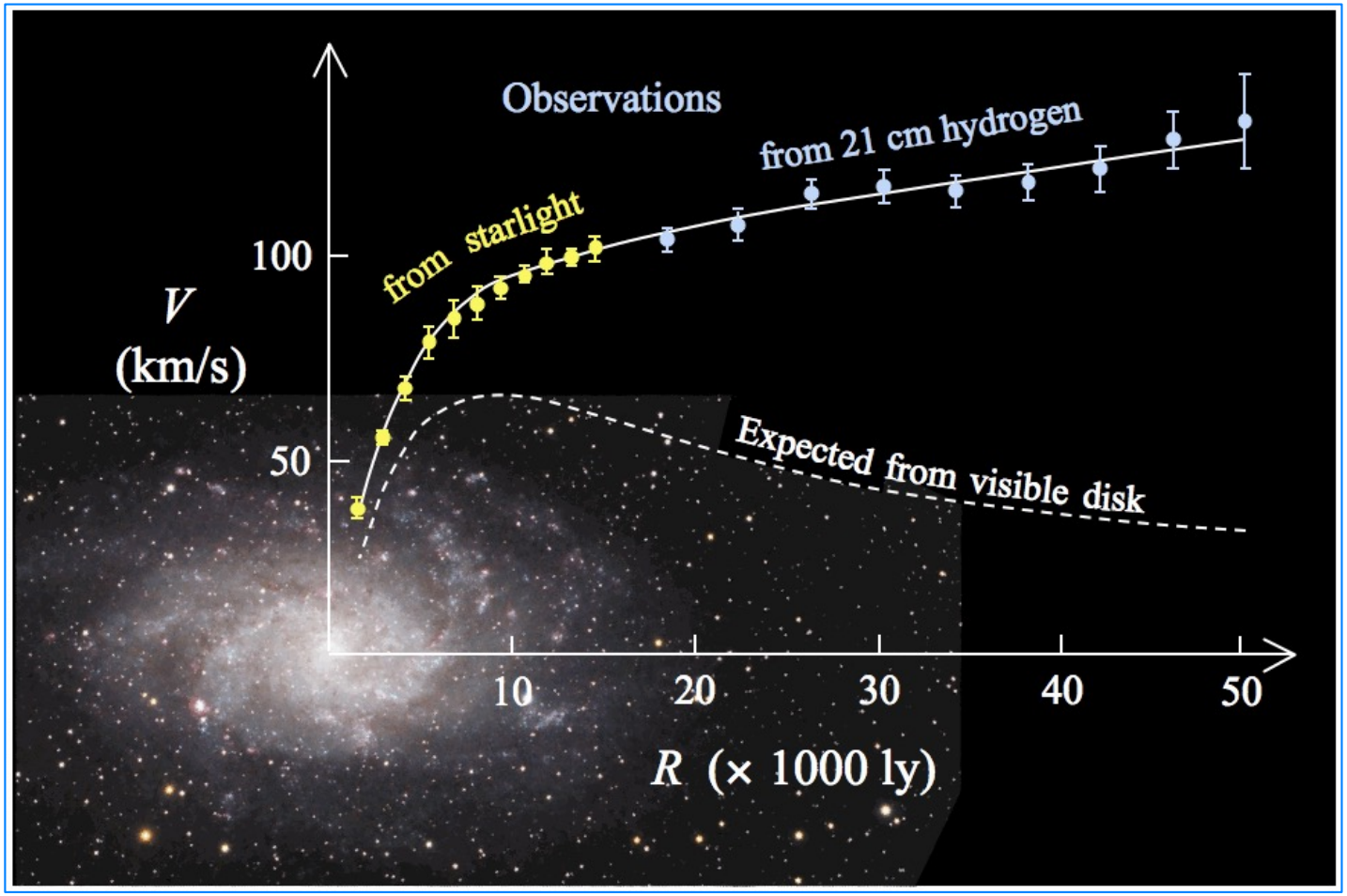


equilibrium requires more matter than is seen

Cosmology

$\Omega_{m,0}$: *matter content*

"Dark Matter" needed to explain Vera Rubin's galactic rotation curves in 1975/80:



Cosmology

$\Omega_{m,0}$: ***matter content***

30% of the Universe consists of matter…

…but only 17% of this matter is visible!

$$\Omega_m = 30\%$$

$\Omega_{m,0}$: ***matter content***

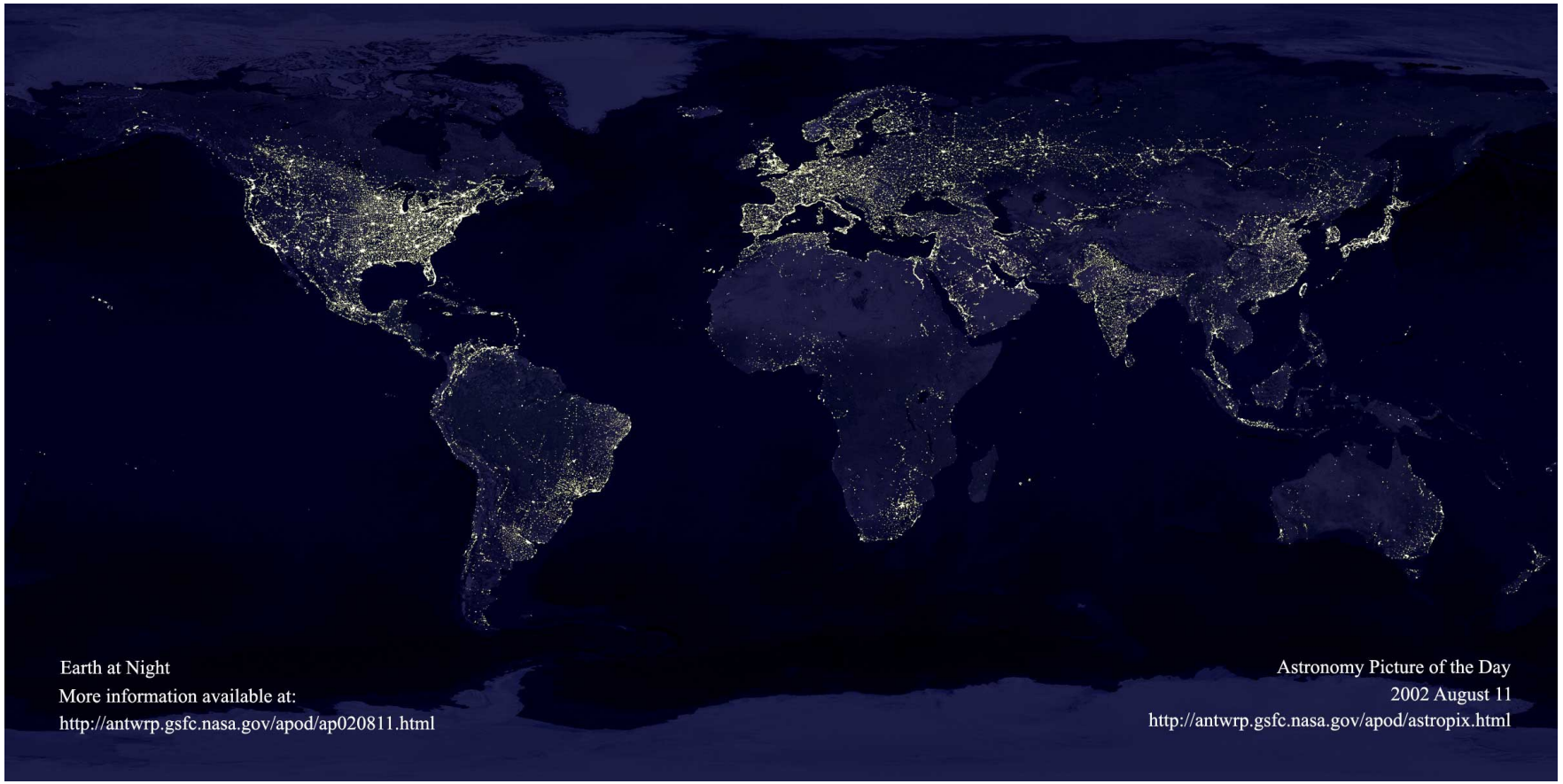
30% of the Universe

the majority of the matter in the Universe is "dark matter"

matter is visible!

$$\Omega_m = 30\%$$

$\Omega_{m,0}$: *dark vs. luminous matter*

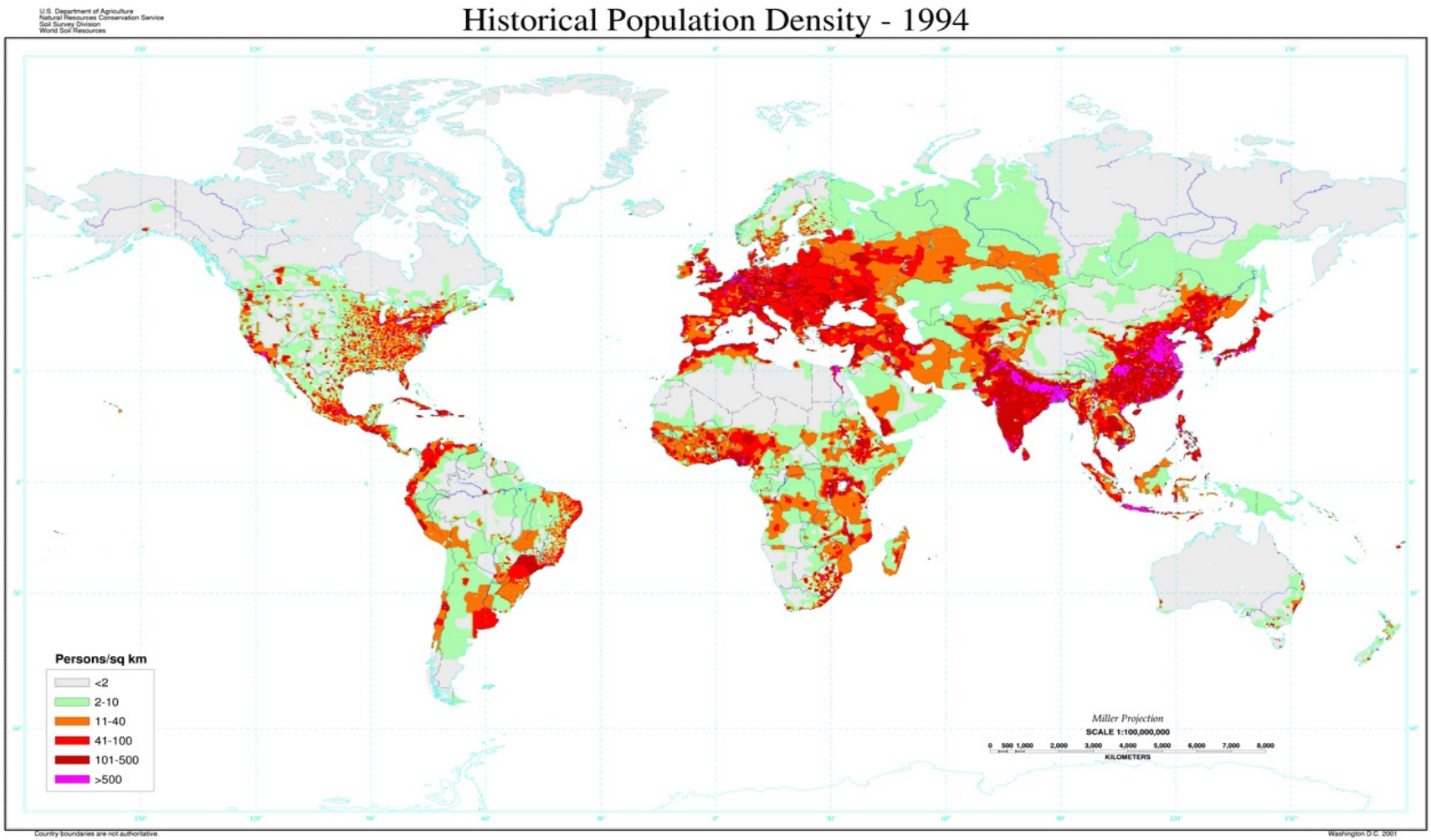


What You See Is What You Get?

Cosmology

science

$\Omega_{m,0}$: *dark vs. luminous matter*



What You See Is What You Get?

Cosmology

$\Omega_{m,0}$: *dark vs. luminous matter*

30% of the Universe consists of matter...

$$\Omega_m = 30\%$$

$\Omega_{m,0}$: ***dark vs. luminous matter***

30% of the Universe consists of matter...

what about the remaining 70%?

$$\Omega_m = 30\%$$

$\Omega_{m,0}$: ***dark vs. luminous matter***

30% of the Universe consists of matter...

what about the remaining 70%*?

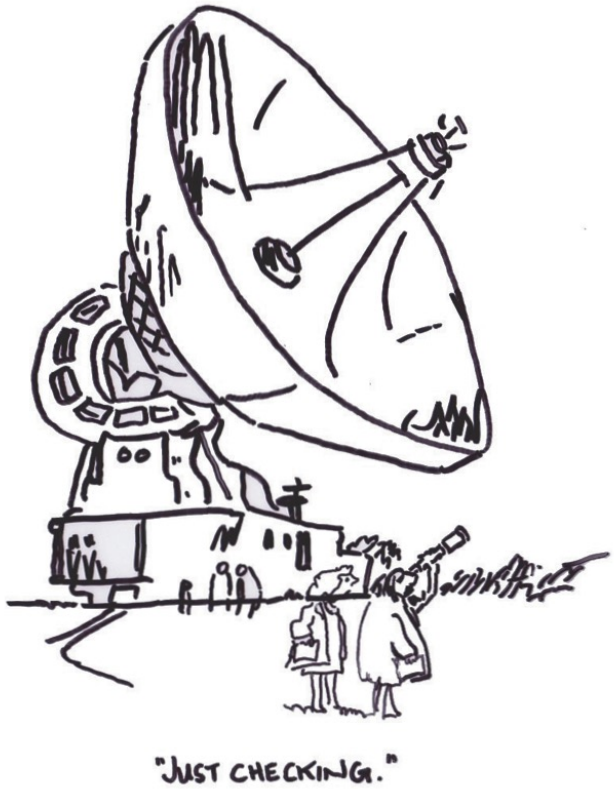
$$\Omega_m = 30\%$$

* $1 = \Omega_m + \Omega_k + \Omega_\Lambda$: *the remaining 70% could be either curvature, dark energy, or a mix of both*

cosmological parameters

$$H_0, \quad \Omega_{r,0}, \quad \Omega_{m,0}, \quad \Omega_{\Lambda,0}$$

determination
via
observations!



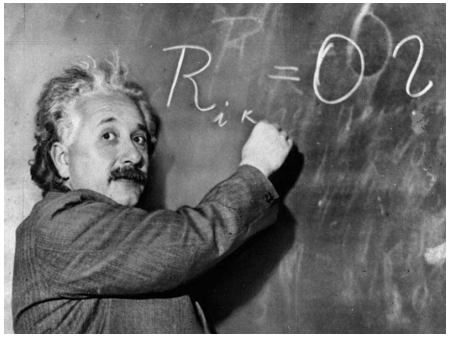
Cosmology

$\Omega_{\Lambda,0}$: ***dark energy***

$$\Omega_{\Lambda} = 70\%$$

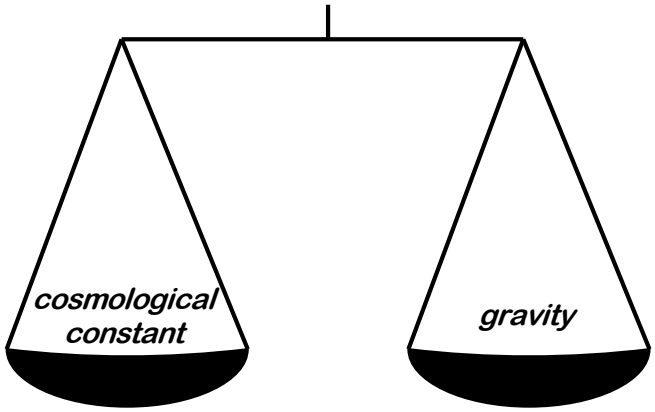
Cosmology

$\Omega_{\Lambda,0}$: ***dark energy***



Einstein's "biggest blunder":

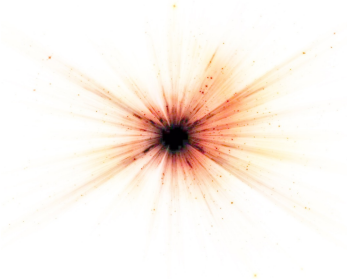
introduction of cosmological constant to counter-balance gravity...



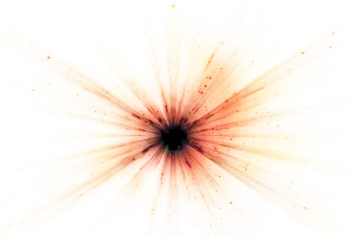
$$\Omega_{\Lambda} = 70\%$$

Cosmology

$\Omega_{\Lambda,0}$: *dark energy*



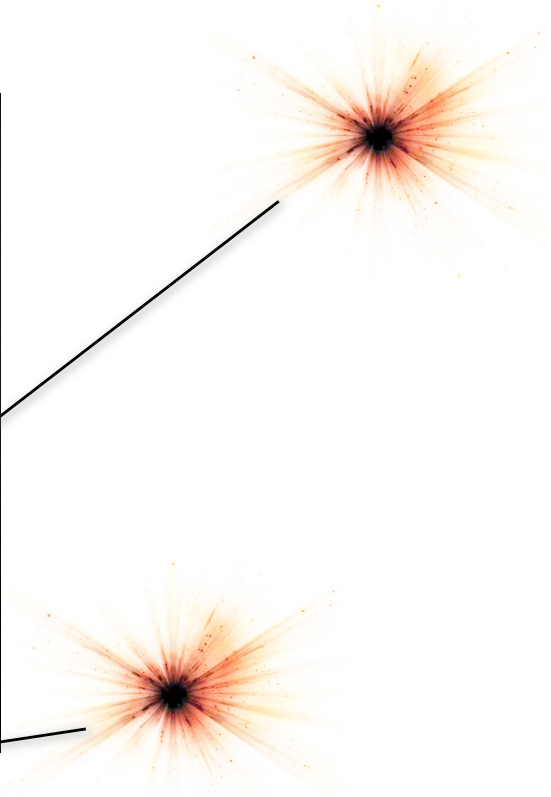
observer on Earth



light-emitting object

Cosmology

$\Omega_{\Lambda,0}$: *dark energy*



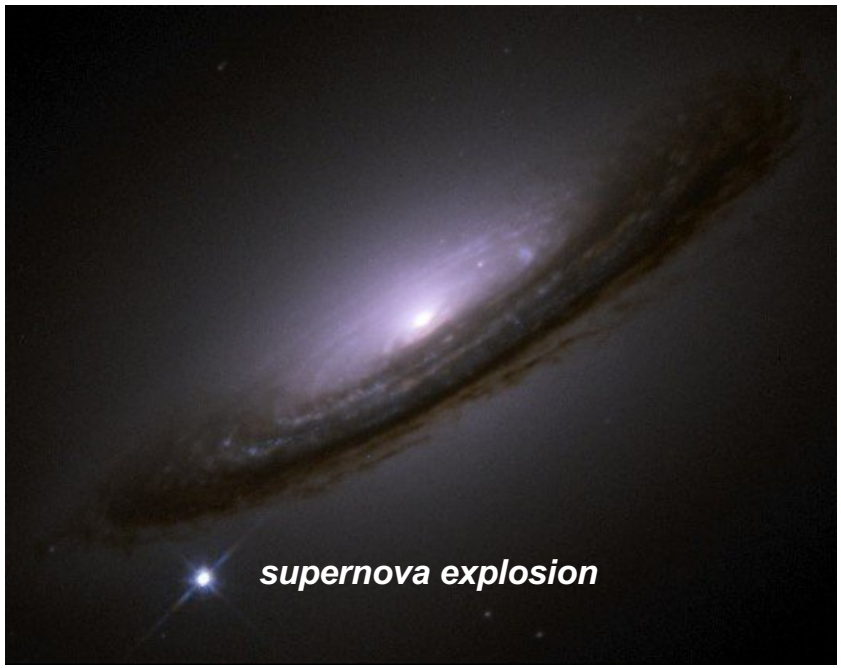
observer on Earth

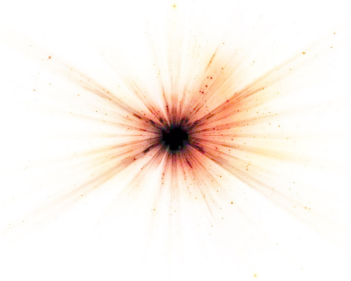
supernovae as standard candles

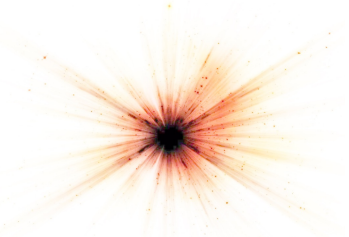
light-emitting object

Cosmology

$\Omega_{\Lambda,0}$: *dark energy*







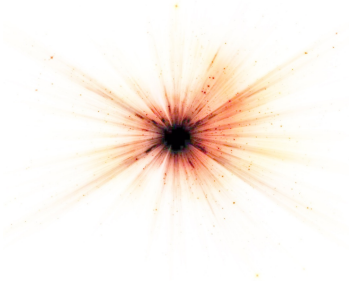
observer on Earth

supernovae as standard candles

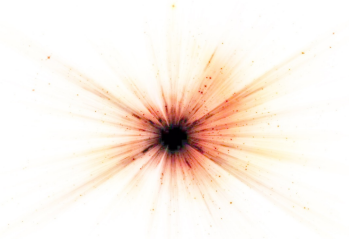
light-emitting object

Cosmology

$\Omega_{\Lambda,0}$: *dark energy*

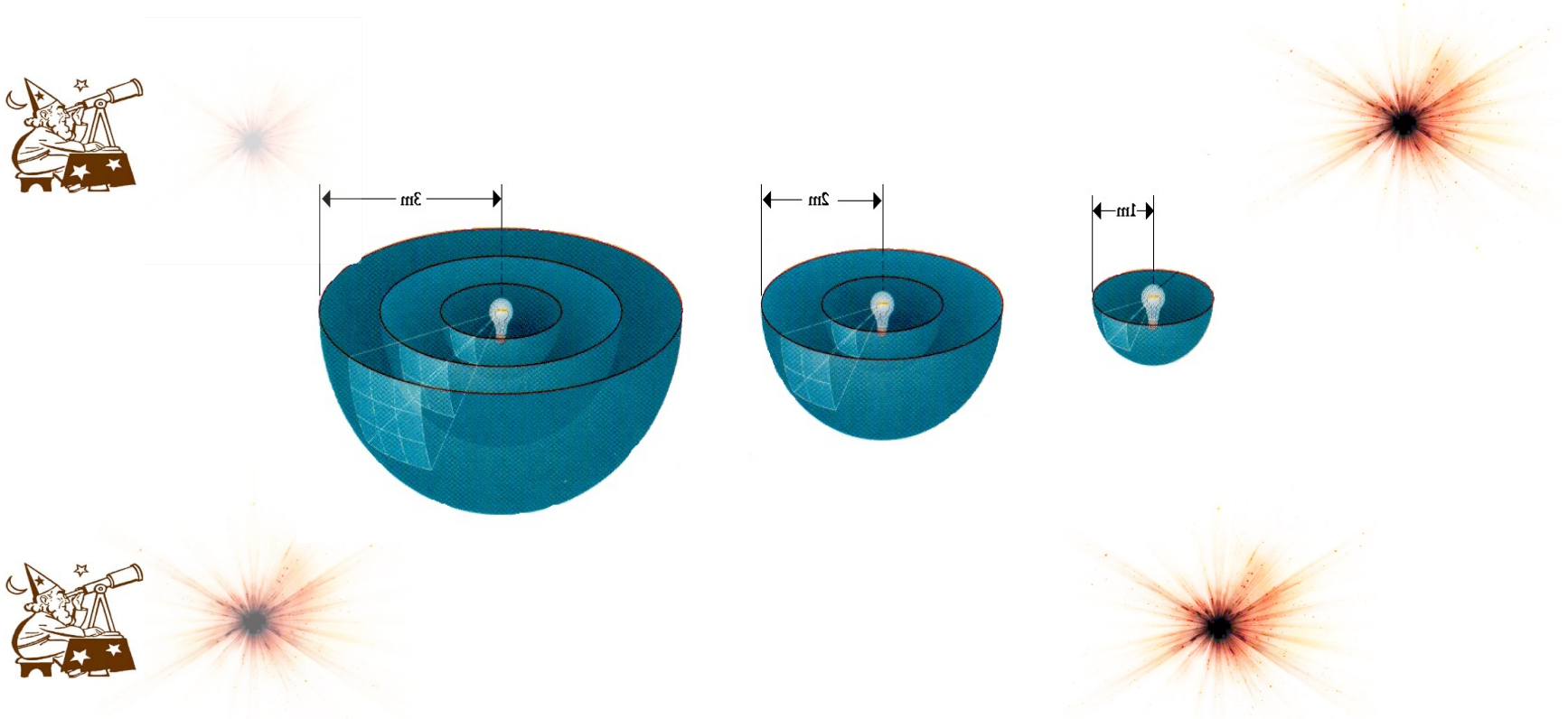


observer on Earth



light-emitting object

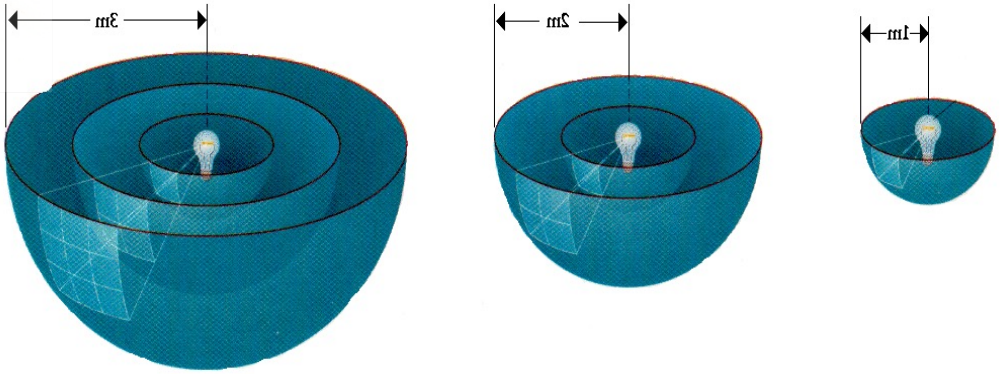
$\Omega_{\Lambda,0}$: *dark energy*



Cosmology

$\Omega_{\Lambda,0}$: *dark energy*

only that simple, if space is not curved!

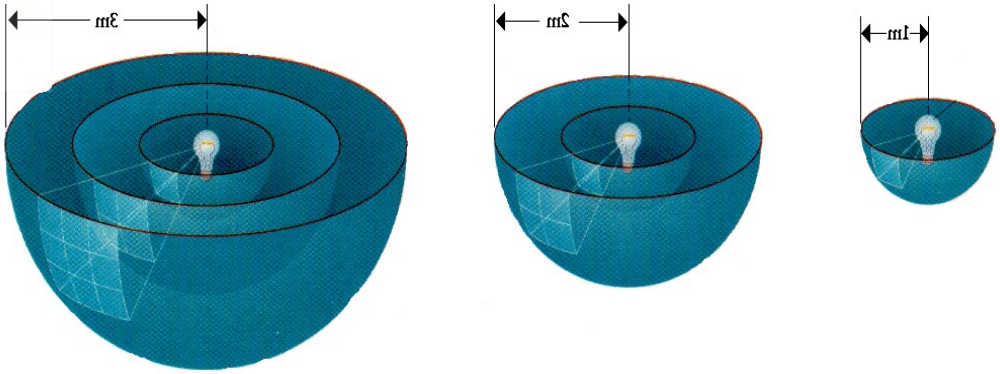


observer on Earth

light-emitting object

$\Omega_{\Lambda,0}$: *dark energy*

only that simple, if space is not curved!



observer on Earth

light-emitting object

...but matter and *dark energy(!)* bend space!

Cosmology

$\Omega_{\Lambda,0}$: *dark energy*

distance (measured via redshift z)

distance (measured via redshift z)

observer on Earth

light-emitting object

...but matter and dark energy bend space!

Cosmology

$\Omega_{\Lambda,0}$: *dark energy*

luminosity
(measured via m)

distance (measured via redshift z)

observer on Earth

distance (measured via redshift z)

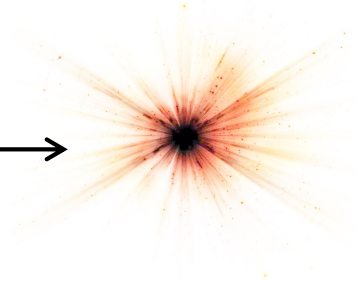
light-emitting object

...but matter and dark energy bend space!

$\Omega_{\Lambda,0}$: *dark energy*

luminosity
(measured via m)

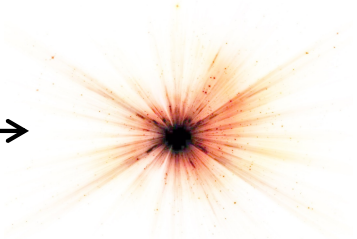
distance (measured via redshift z)



$$m(z) = M + 5\log_{10}\left(\frac{c(1+z)}{\sqrt{|k|}}\ \gamma\left(\sqrt{|k|}\int_0^z\left[(1+z')^2(1+\Omega_m z') - z'(2+z')\Omega_\Lambda\right]^{-1/2}dz'\right)\right)$$

observer on Earth

distance (measured via redshift z)



light-emitting object

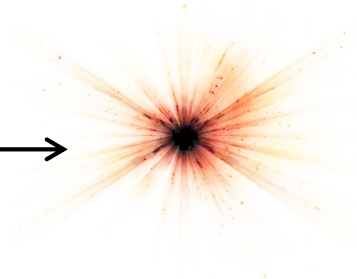
...but matter and dark energy bend space!

(derivation of $m(z)$ in lecture Observations I: 'cosmological distances')

$\Omega_{\Lambda,0}$: *dark energy*

luminosity
(measured via m)

distance (measured via redshift z)



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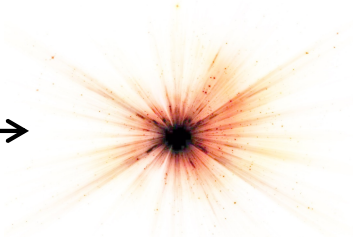
observer on Earth

distance (measured via redshift z)



light-emitting object

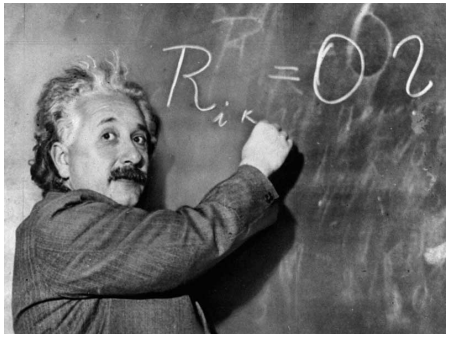
...but matter and dark energy bend space!

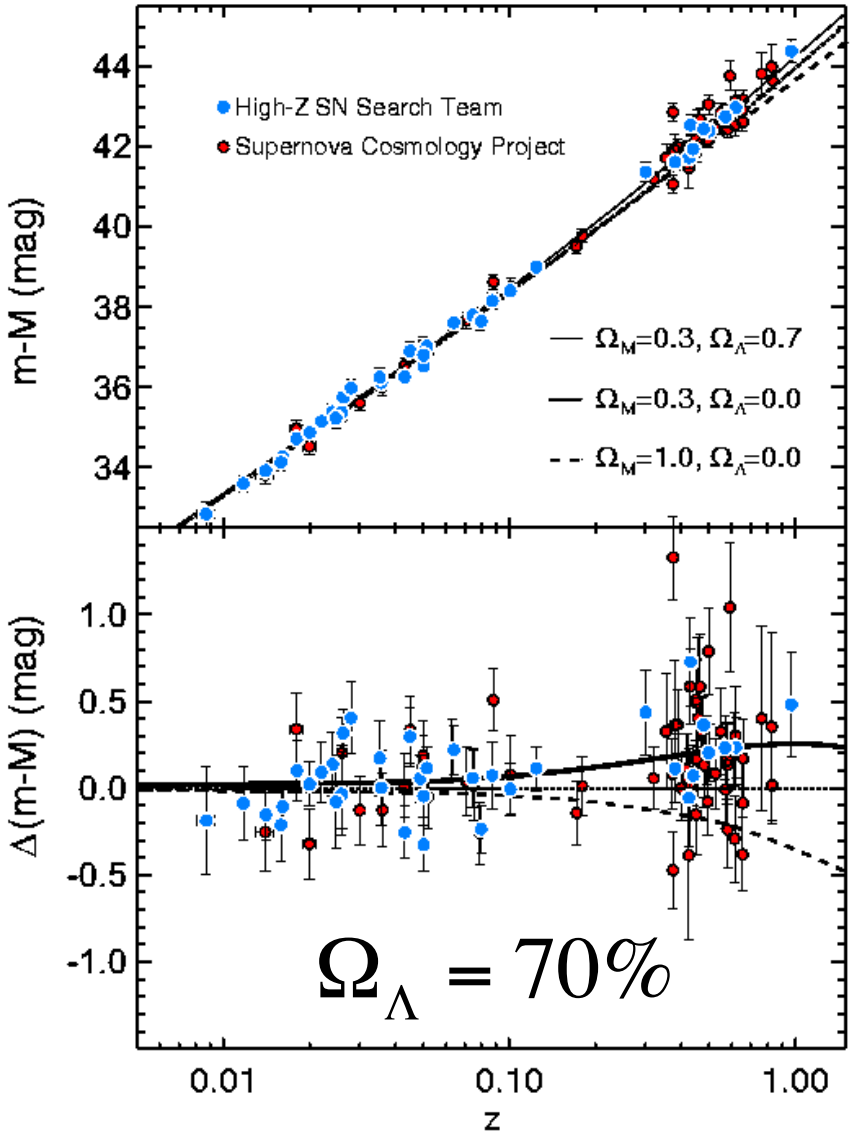
(derivation of $m(z)$ in lecture Observations I: 'cosmological distances')

History & Principles

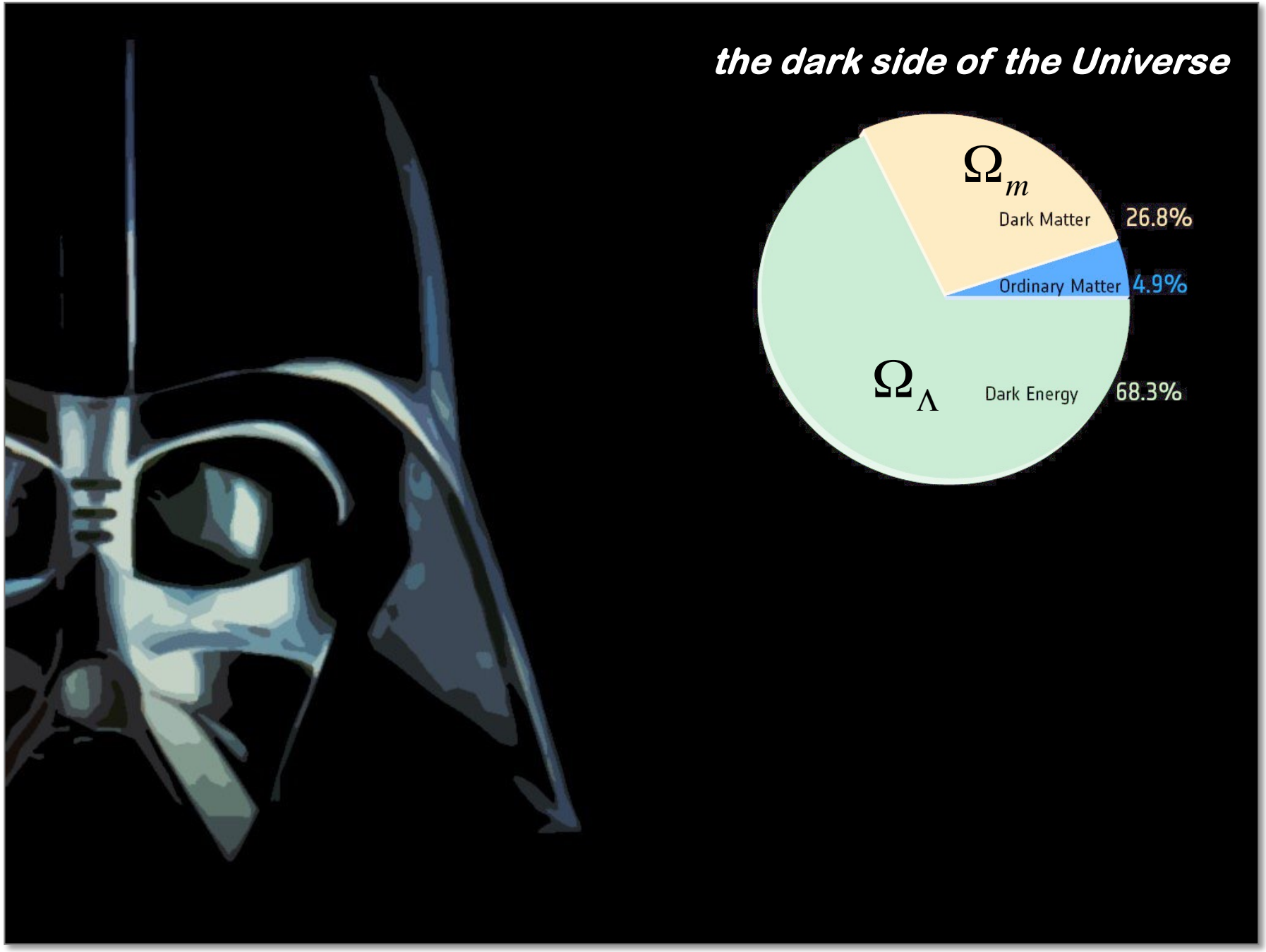
Cosmology

$\Omega_{\Lambda,0}$: *dark energy*





Cosmology


the dark side of the Universe
Ω_m
Dark Matter
26.8%
Ordinary Matter
4.9%
Ω_Λ
Dark Energy
68.3%

Cosmology

science

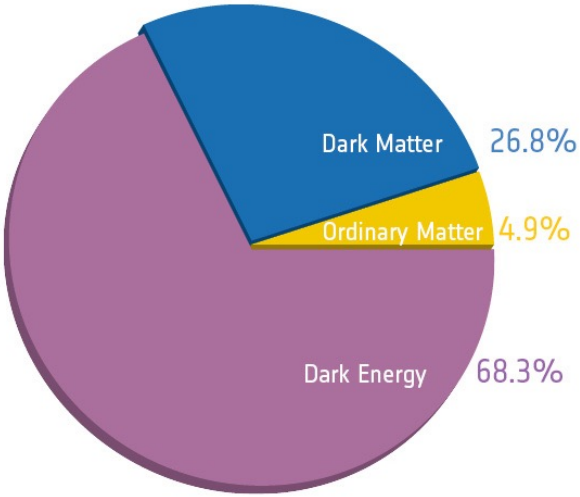
the Universe as a whole...

theory **&** **observations**

Cosmology

the Universe as a whole...

$$\dot{a}^2 = H_0^2 \left(\frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{k,0}}{a^2} + \Omega_{\Lambda,0} \right) \&$$



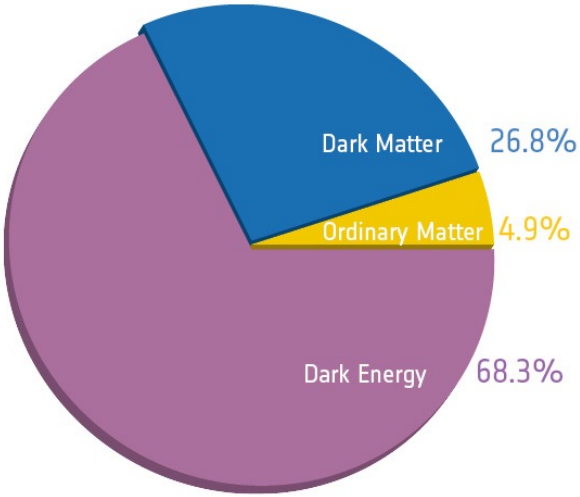
(neglecting radiation as today $T_{CMB} \sim 3K$)

Cosmology

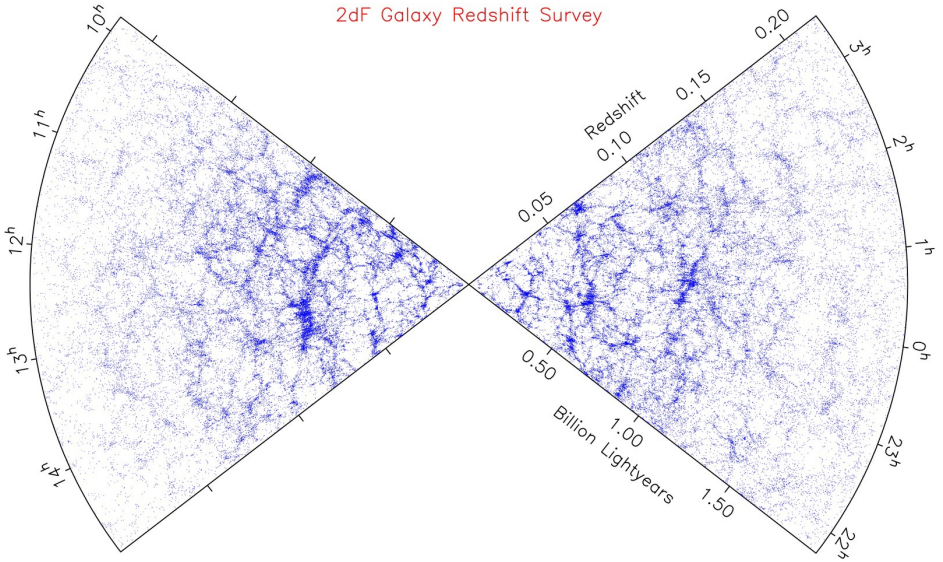
science

the Universe as a whole...

$$\dot{a}^2 = H_0^2 \left(\frac{\Omega_{m,0}}{a^3} + \frac{\Omega_{k,0}}{a^2} + \Omega_{\Lambda,0} \right) \&$$



...but how do stars, galaxies, clusters, and the cosmic web form?



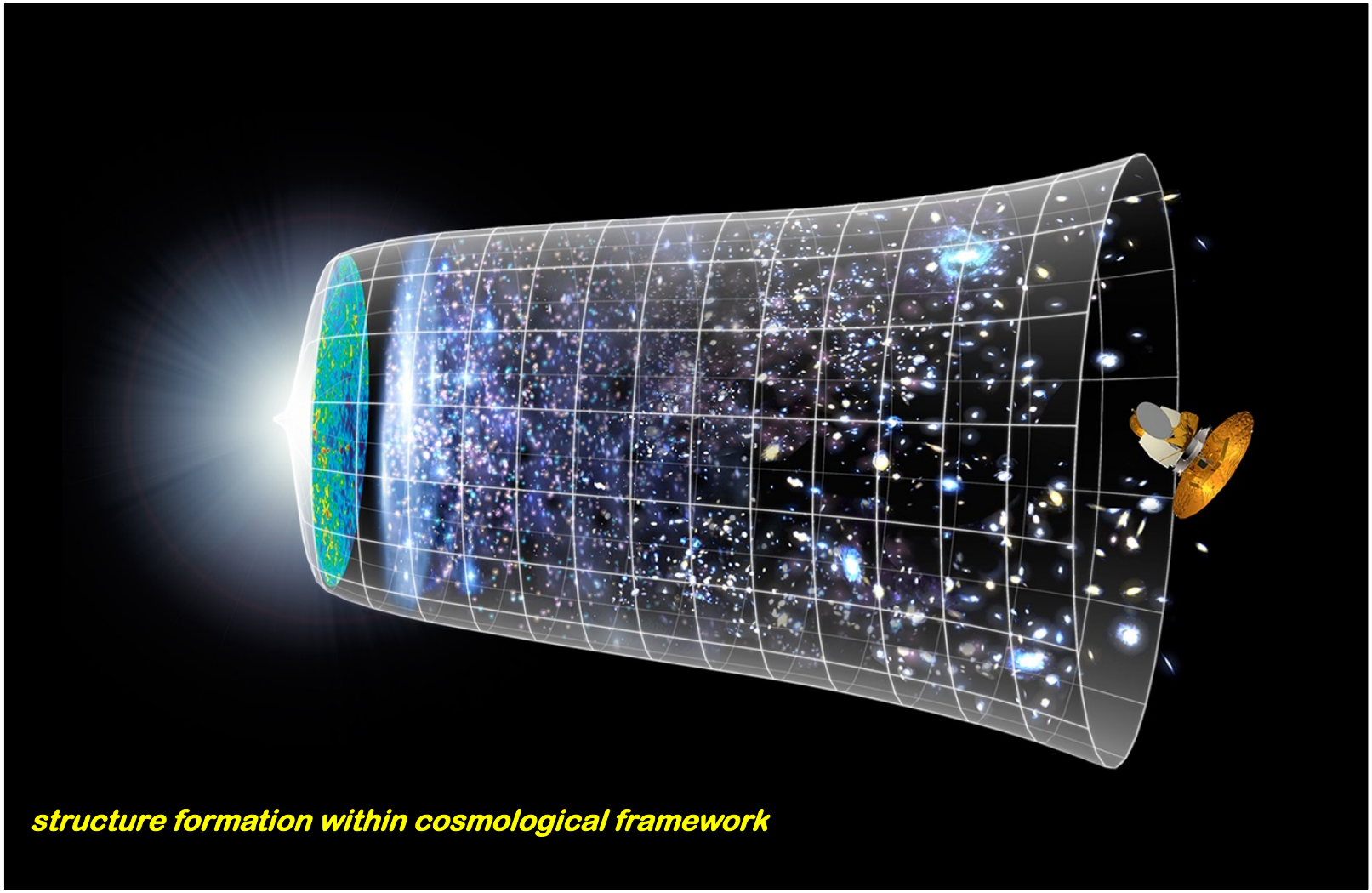
History & Principles

Cosmology

- *explain this!*
- *principles*
- *cosmology – science or science fiction?*
- *cosmological structure formation*

Cosmology

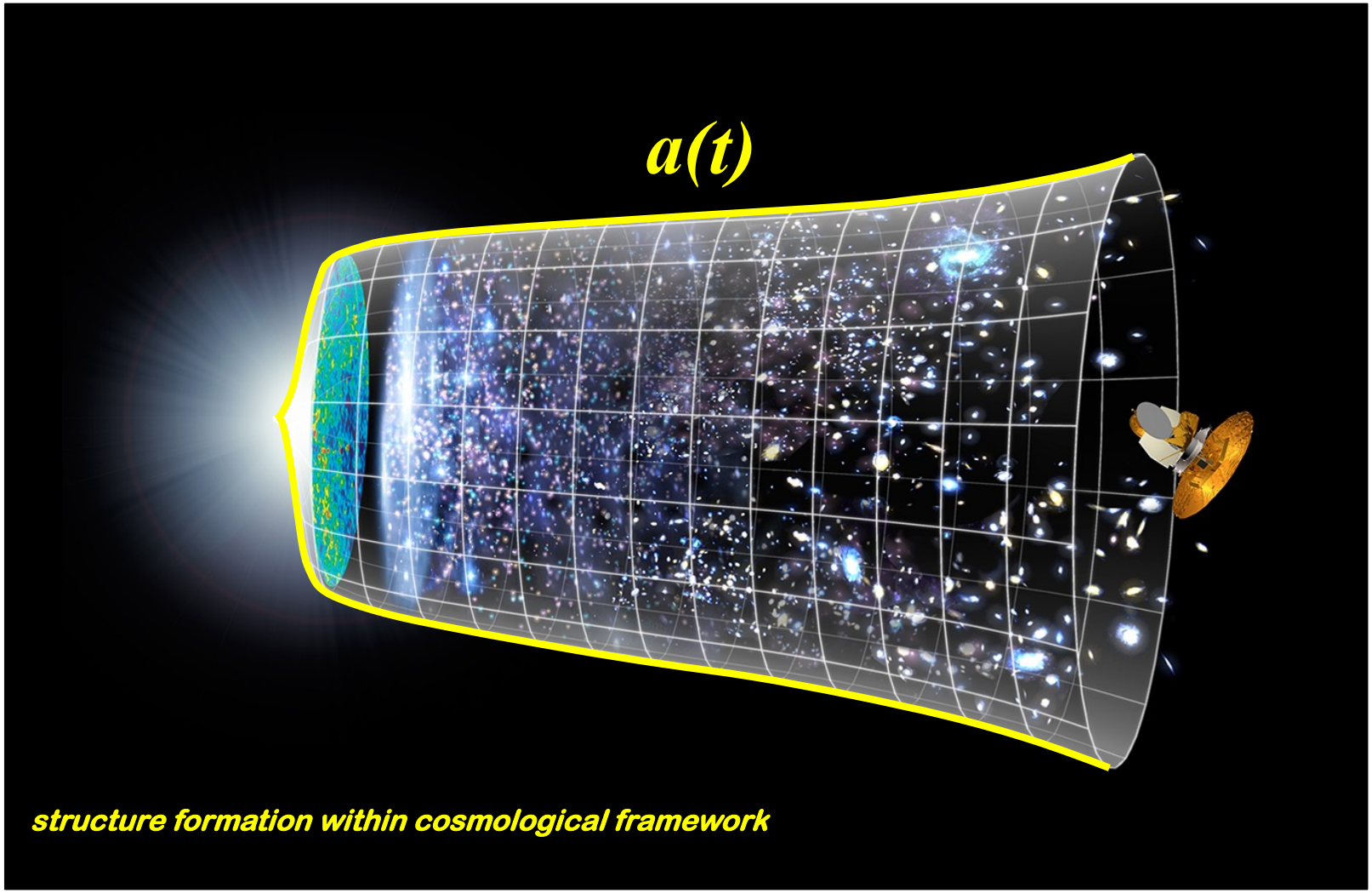
structure formation



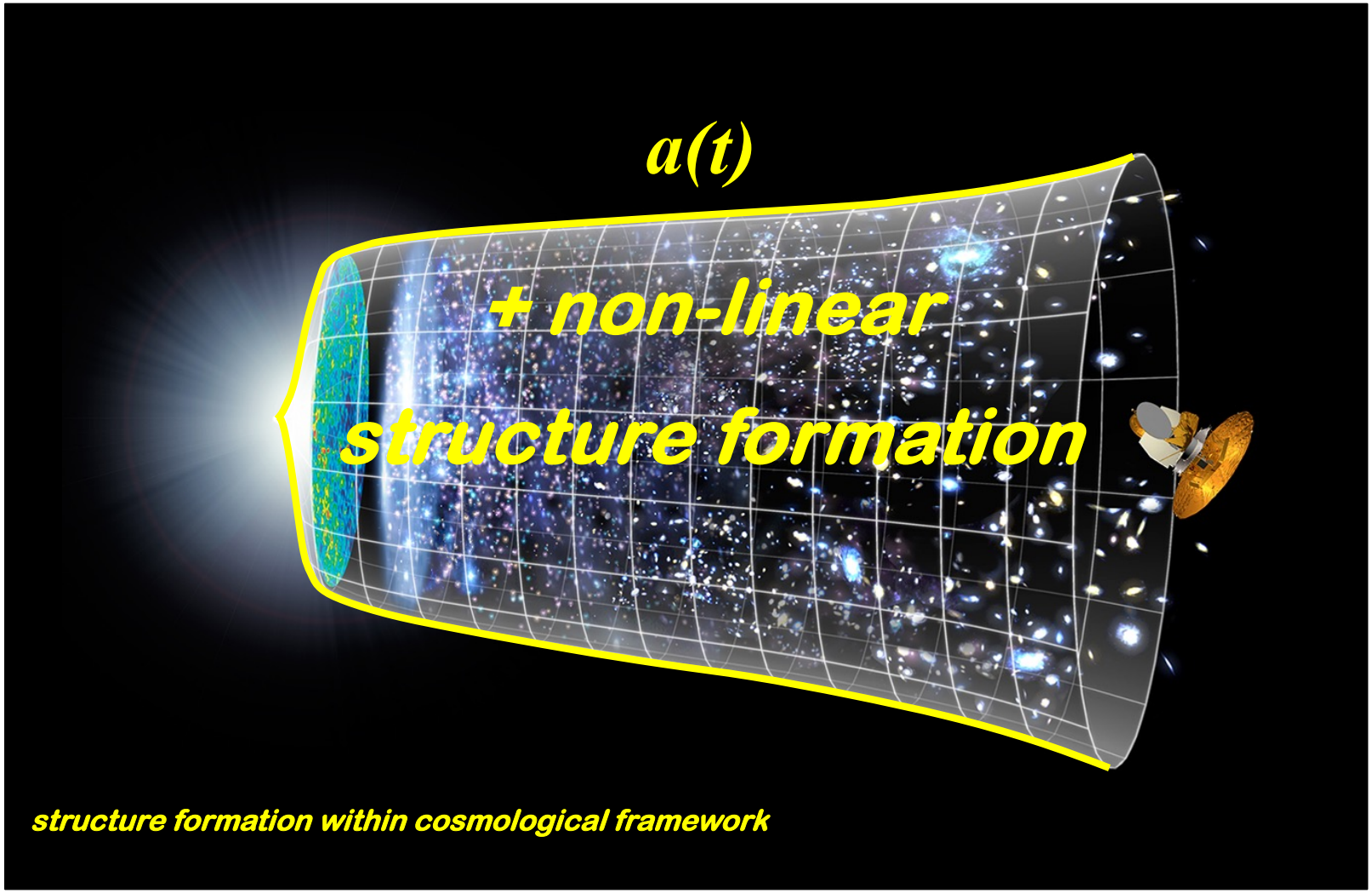
structure formation within cosmological framework

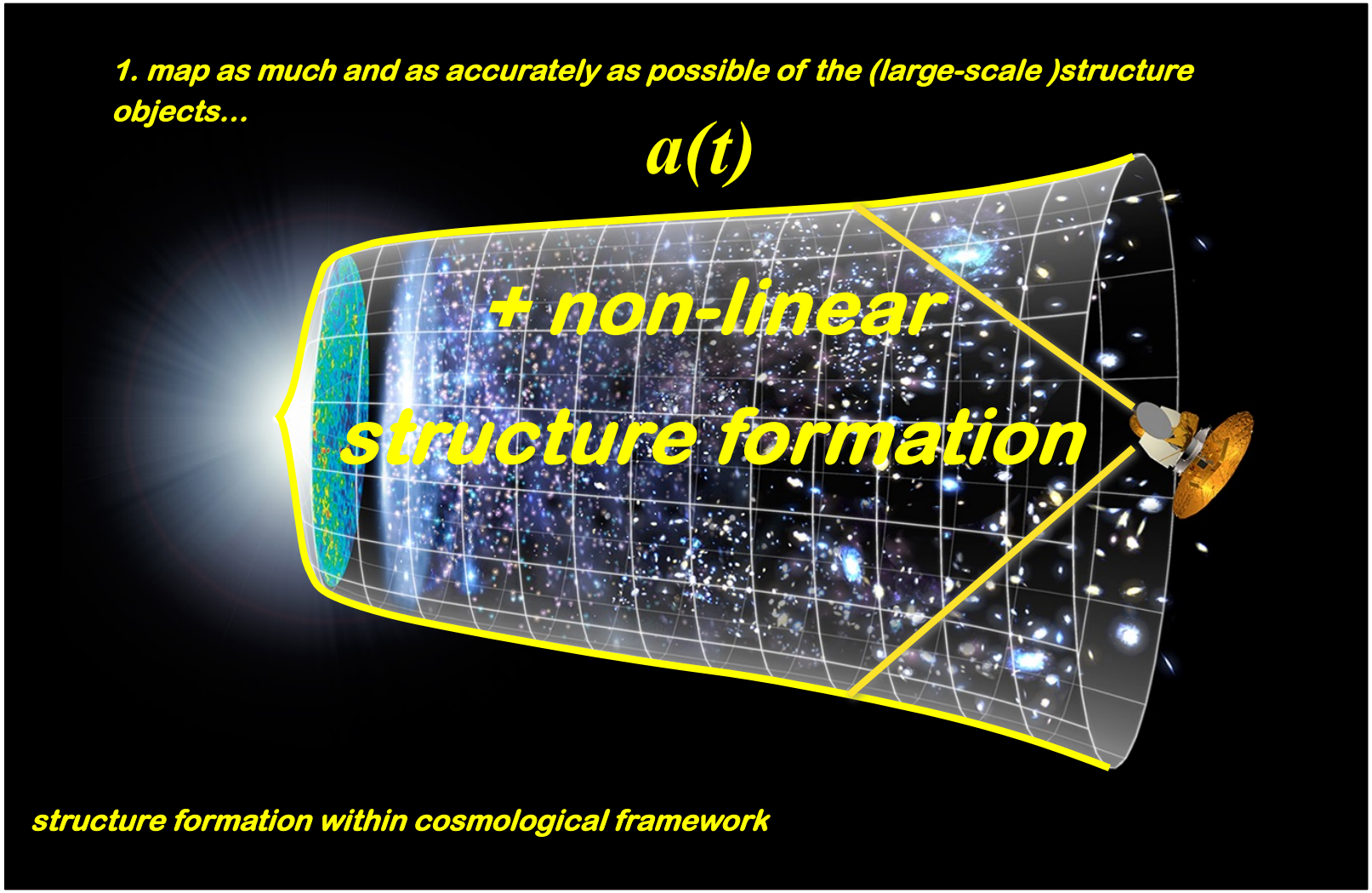
Cosmology

structure formation

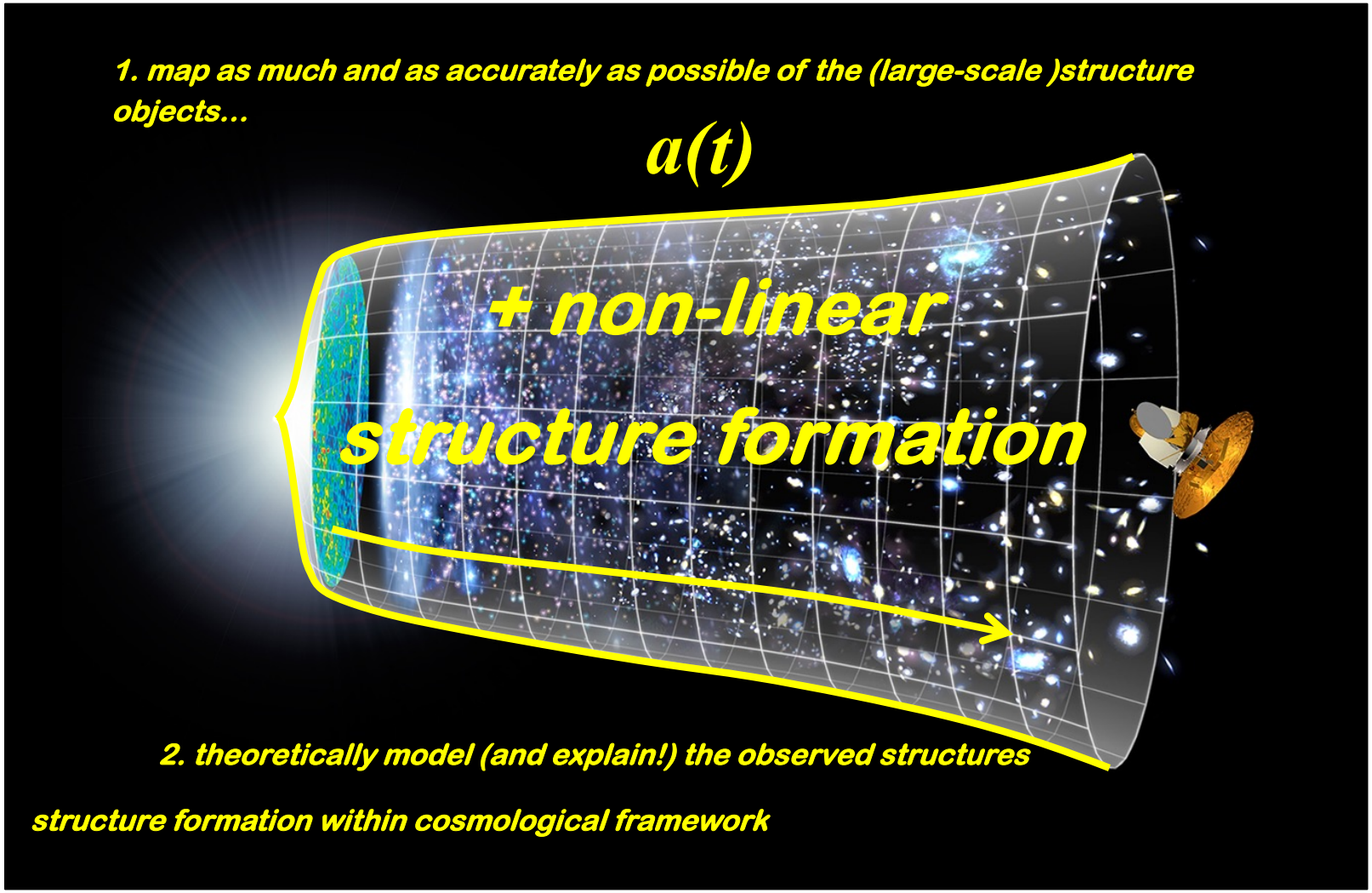


Cosmology

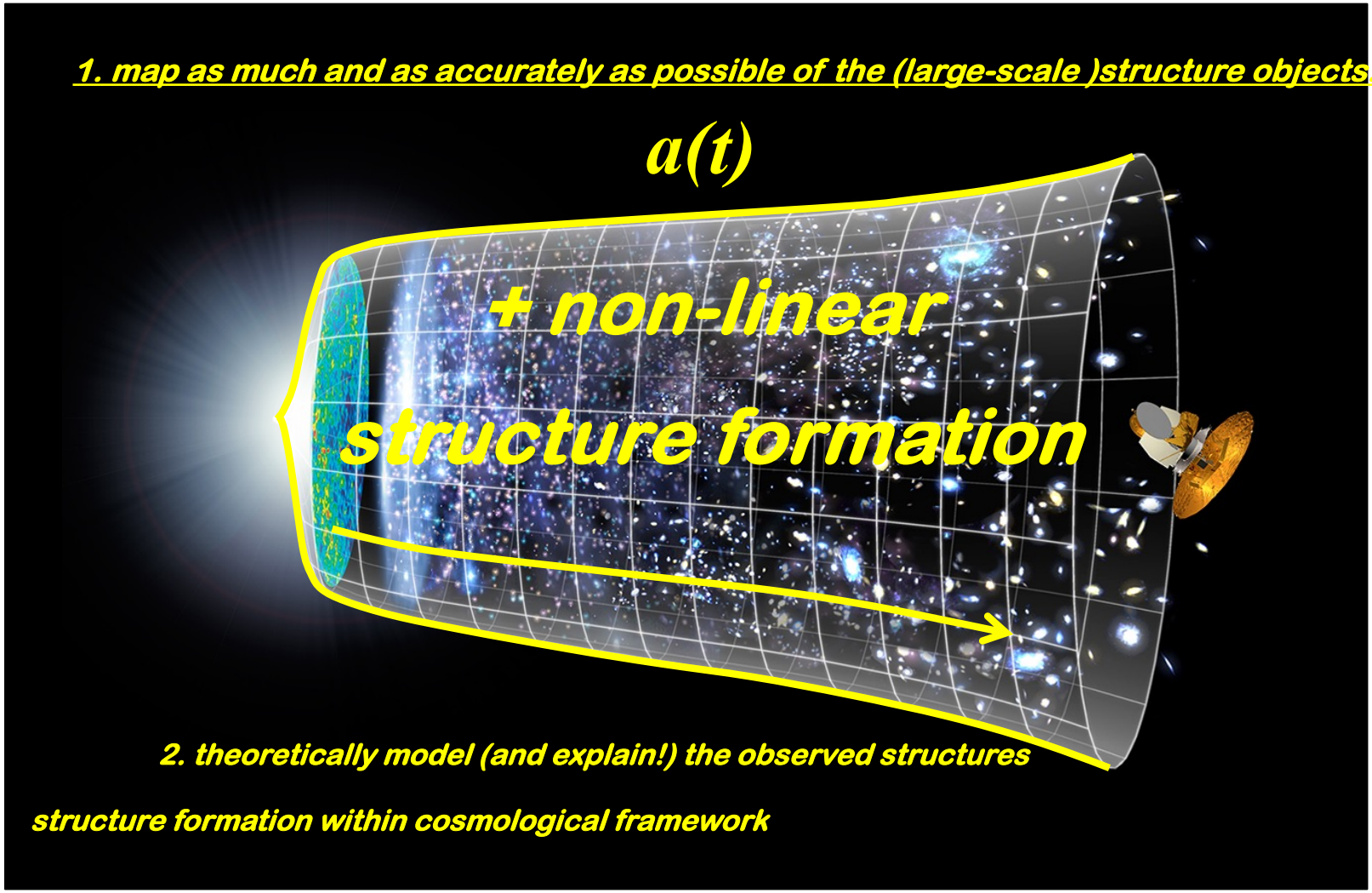

a(t)
+ non-linear
structure formation
structure formation within cosmological framework


1. map as much and as accurately as possible of the (large-scale)structure objects…
a(t)
+ non-linear
structure formation
structure formation within cosmological framework

Cosmology

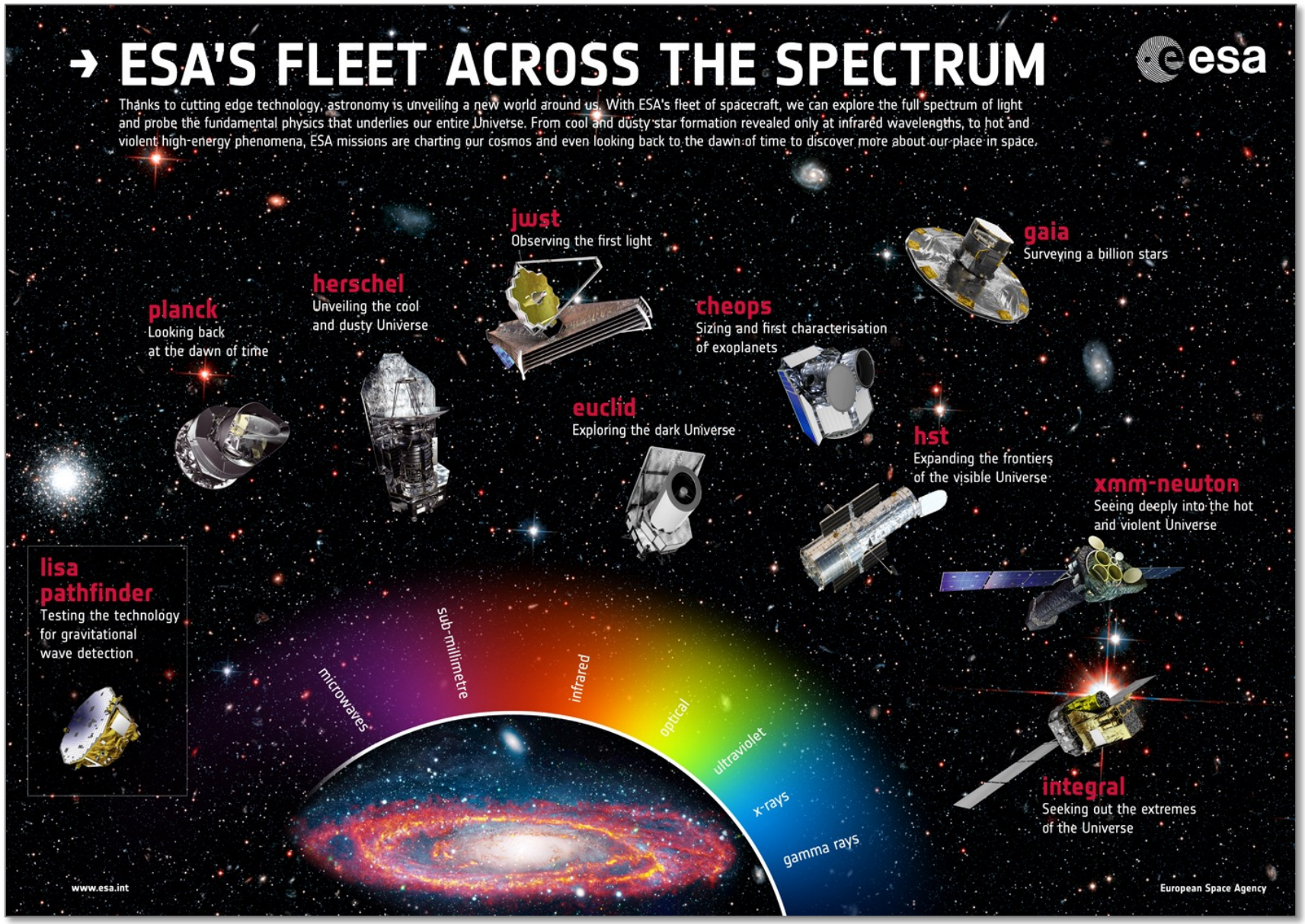

1. map as much and as accurately as possible of the (large-scale)structure objects…
a(t)
+ non-linear
structure formation
2. theoretically model (and explain!) the observed structures
structure formation within cosmological framework

Cosmology


1. map as much and as accurately as possible of the (large-scale)structure objects…
a(t)
+ non-linear
structure formation
2. theoretically model (and explain!) the observed structures
structure formation within cosmological framework

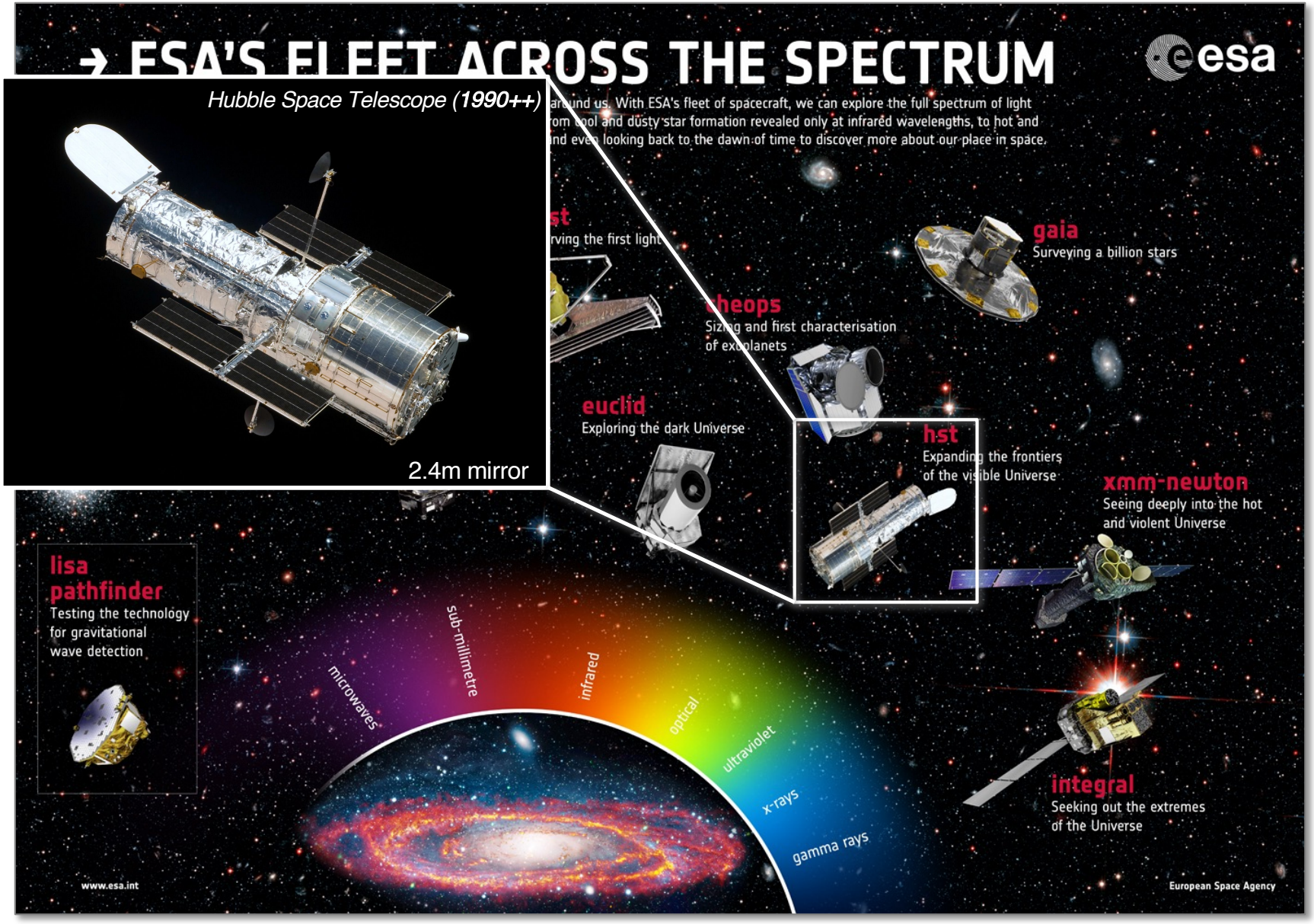
Cosmology

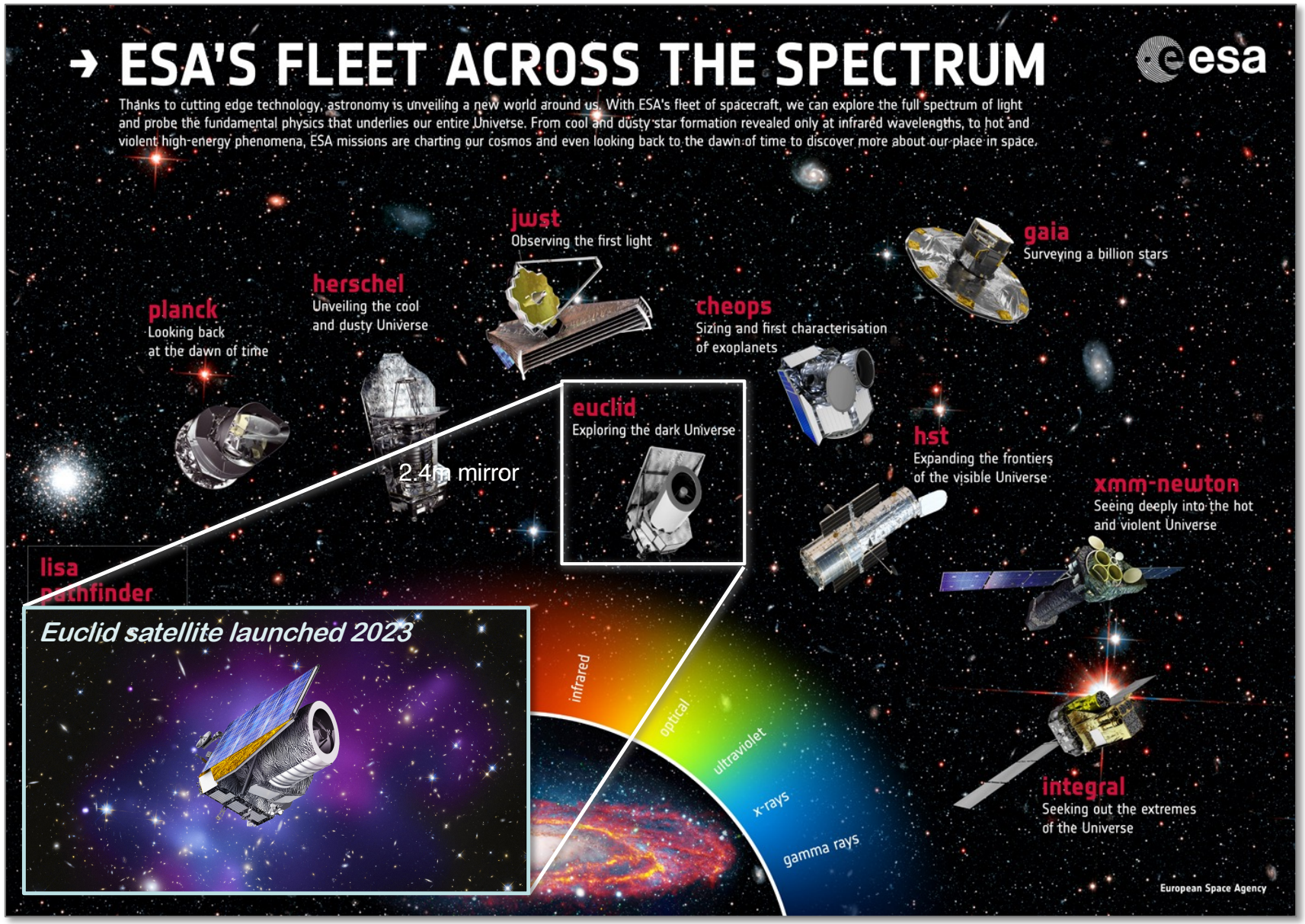
structure formation - observed


ESA'S FLEET ACROSS THE SPECTRUM
esa
Thanks to cutting edge technology, astronomy is unveiling a new world around us. With ESA's fleet of spacecraft, we can explore the full spectrum of light and probe the fundamental physics that underlies our entire Universe. From cool and dusty star formation revealed only at infrared wavelengths, to hot and violent high-energy phenomena, ESA missions are charting our cosmos and even looking back to the dawn of time to discover more about our place in space.
jwst
Observing the first light
gaia
Surveying a billion stars
herschel
Unveiling the cool and dusty Universe
planck
Looking back at the dawn of time
cheops
Sizing and first characterisation of exoplanets
euclid
Exploring the dark Universe
hst
Expanding the frontiers of the visible Universe
xmm-newton
Seeing deeply into the hot and violent Universe
lisa pathfinder
Testing the technology for gravitational wave detection
microwaves
sub-millimetre
infrared
optical
ultraviolet
x-rays
gamma rays
integral
Seeking out the extremes of the Universe
www.esa.int
European Space Agency

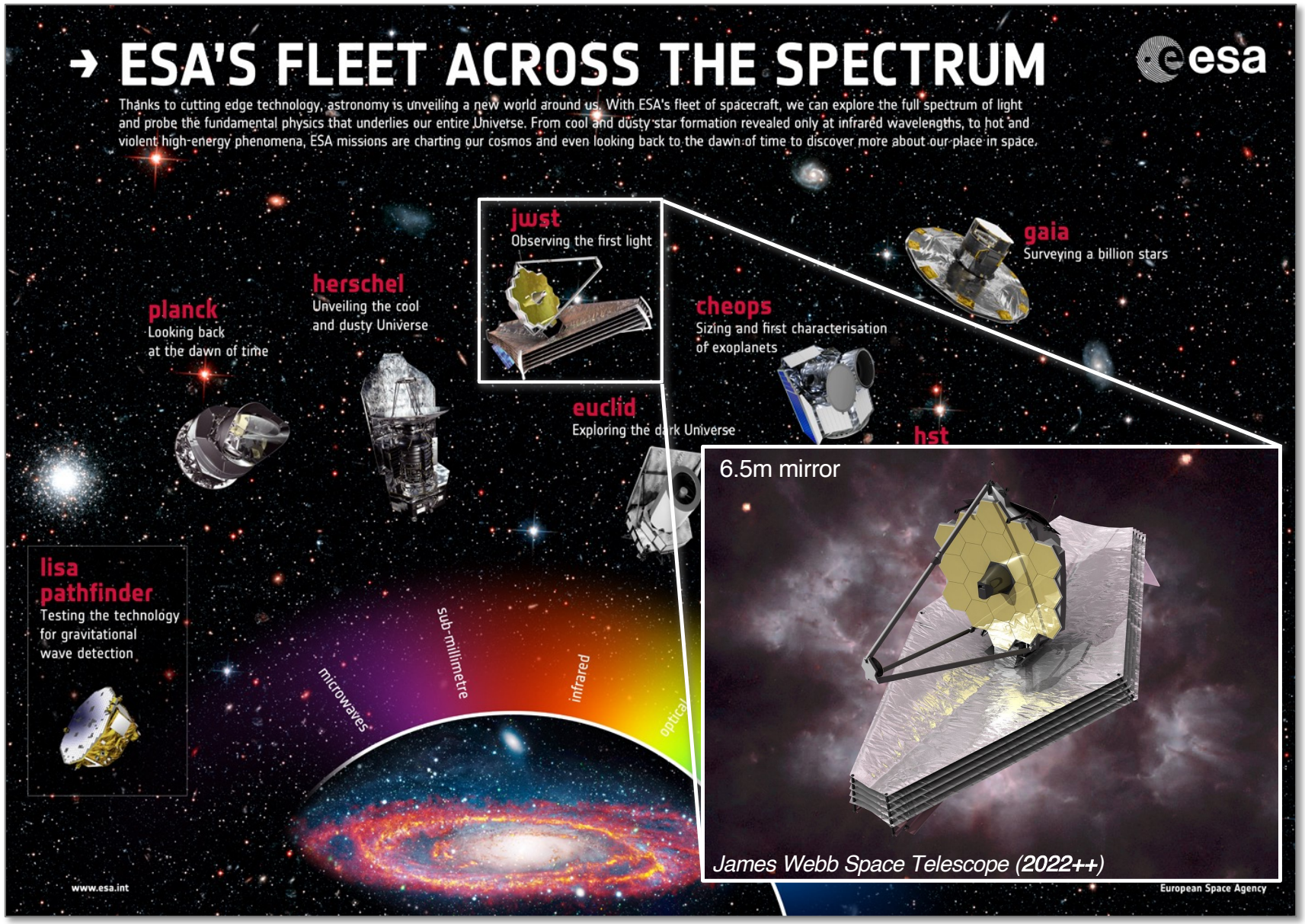
Cosmology

structure formation - observed





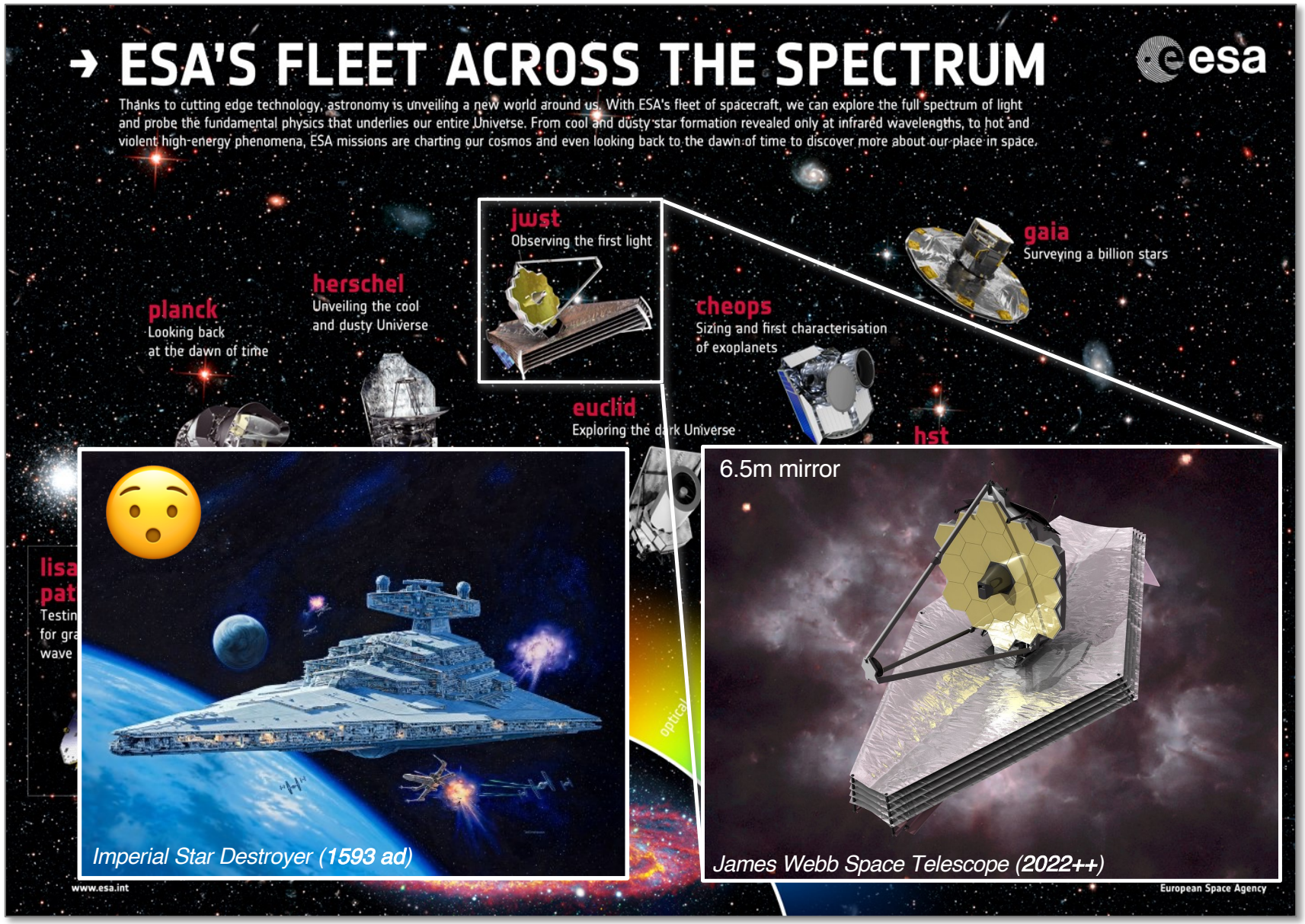
History & Principles



History & Principles

Cosmology

structure formation - observed



Cosmology

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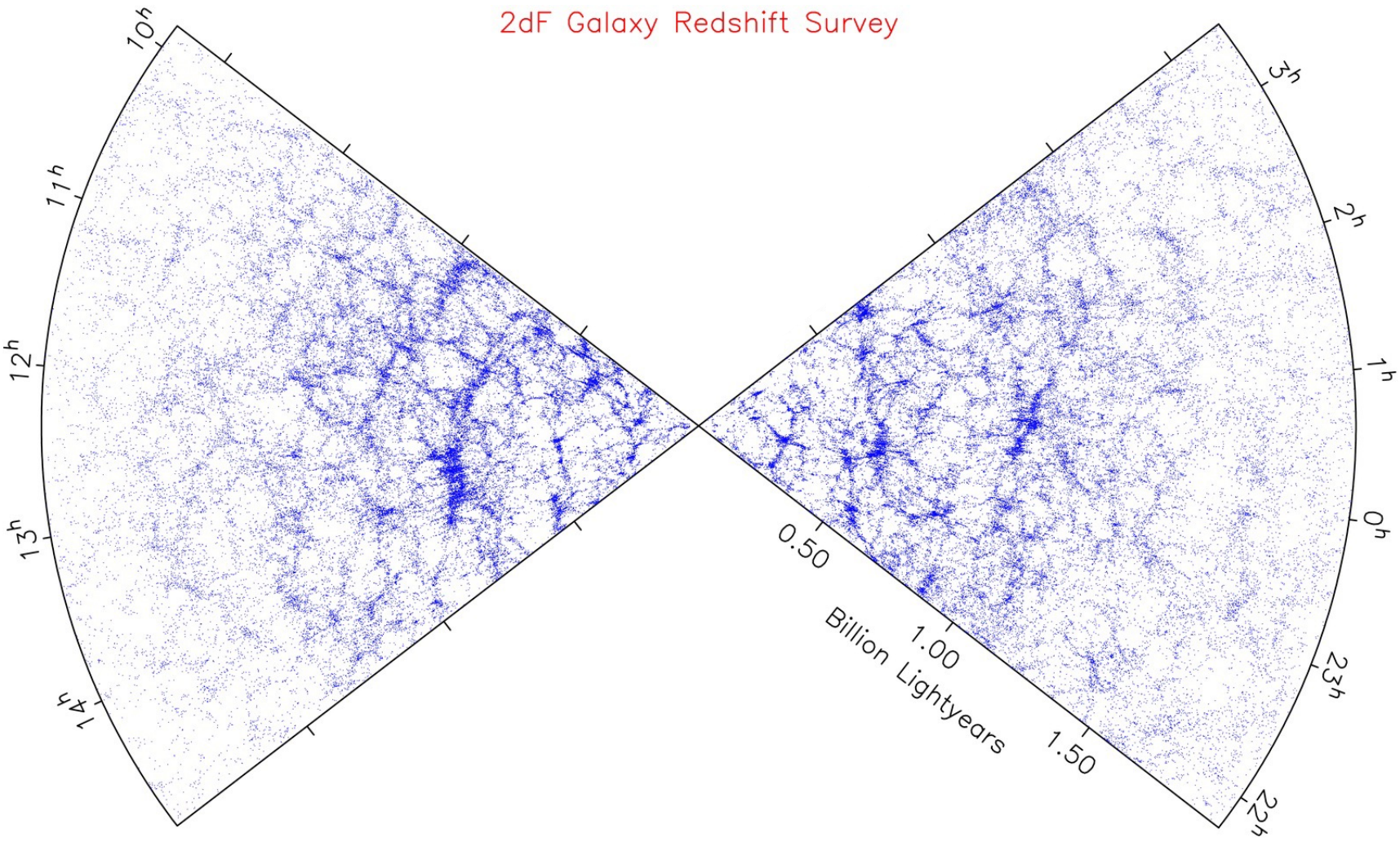
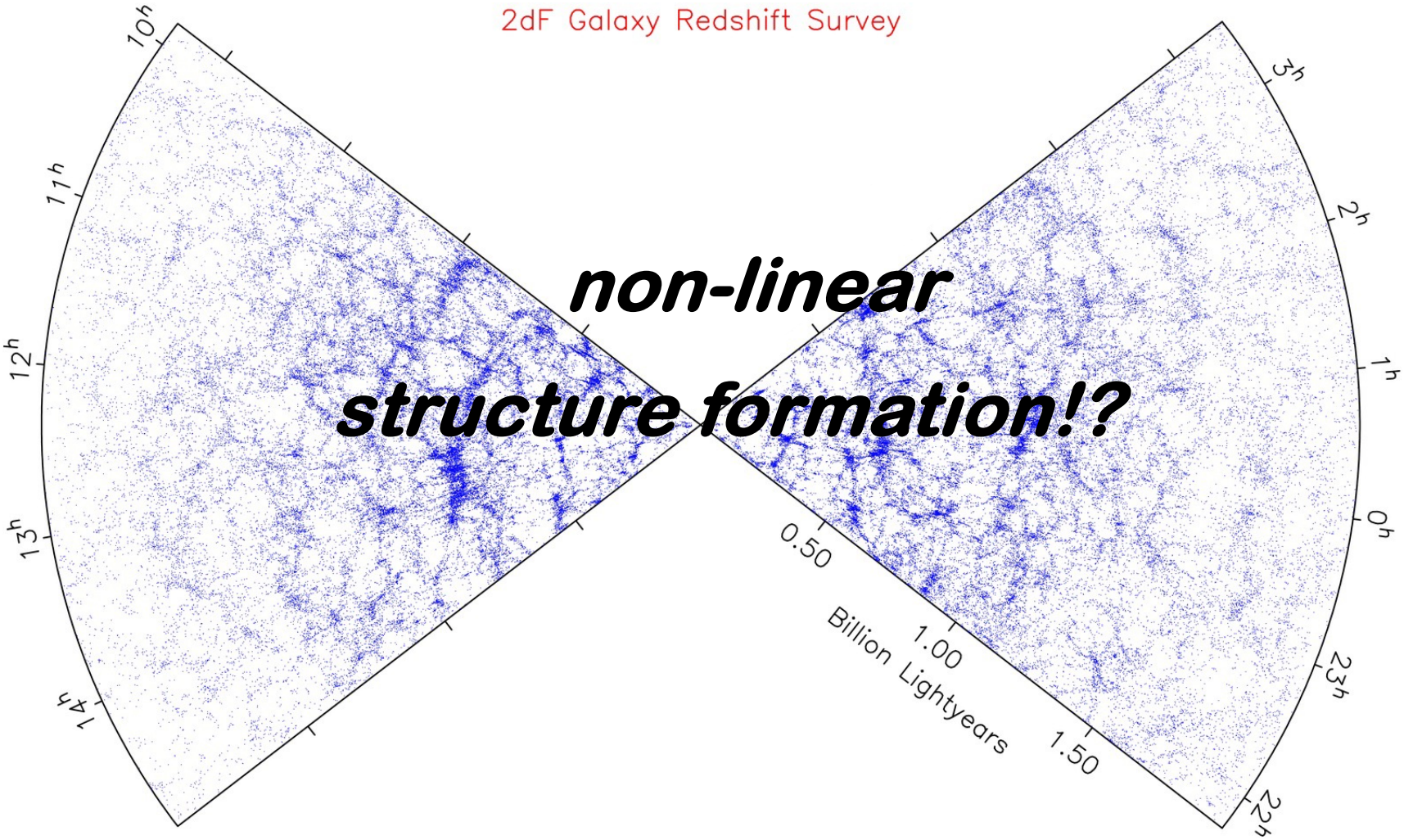




non-linear

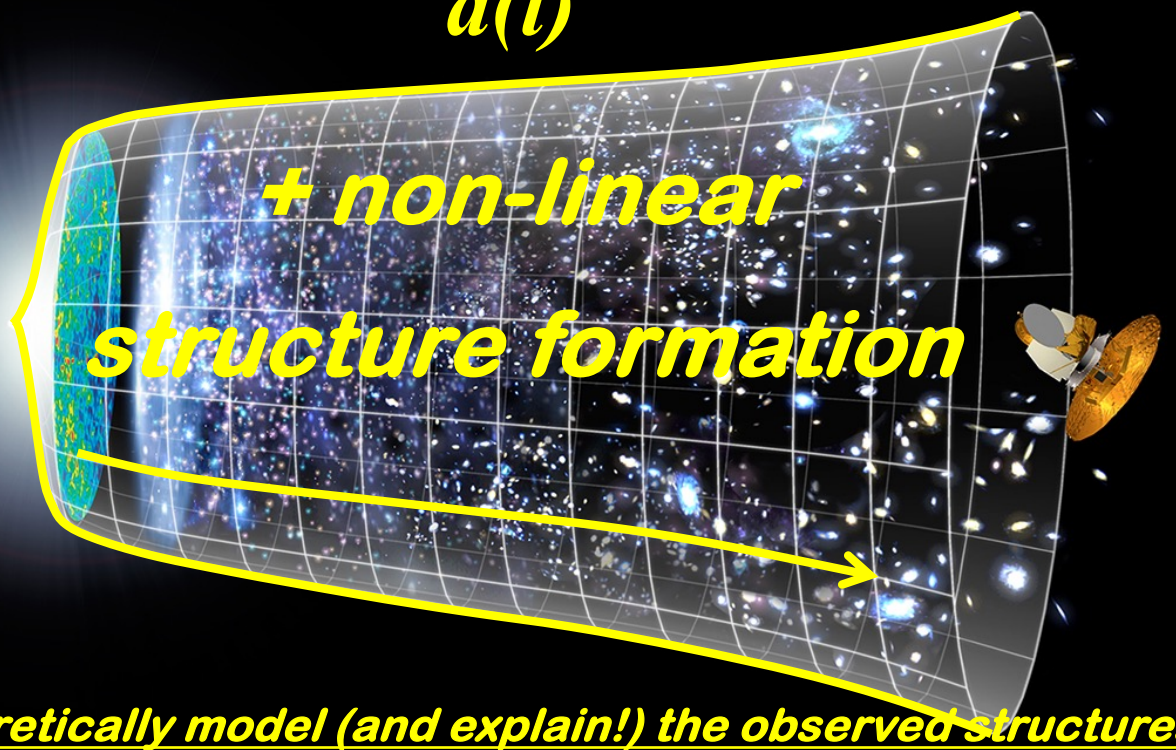
structure formation!?

Cosmology

1. map as much and as accurately as possible of the (large-scale)structure objects…

$a(t)$

+ non-linear structure formation



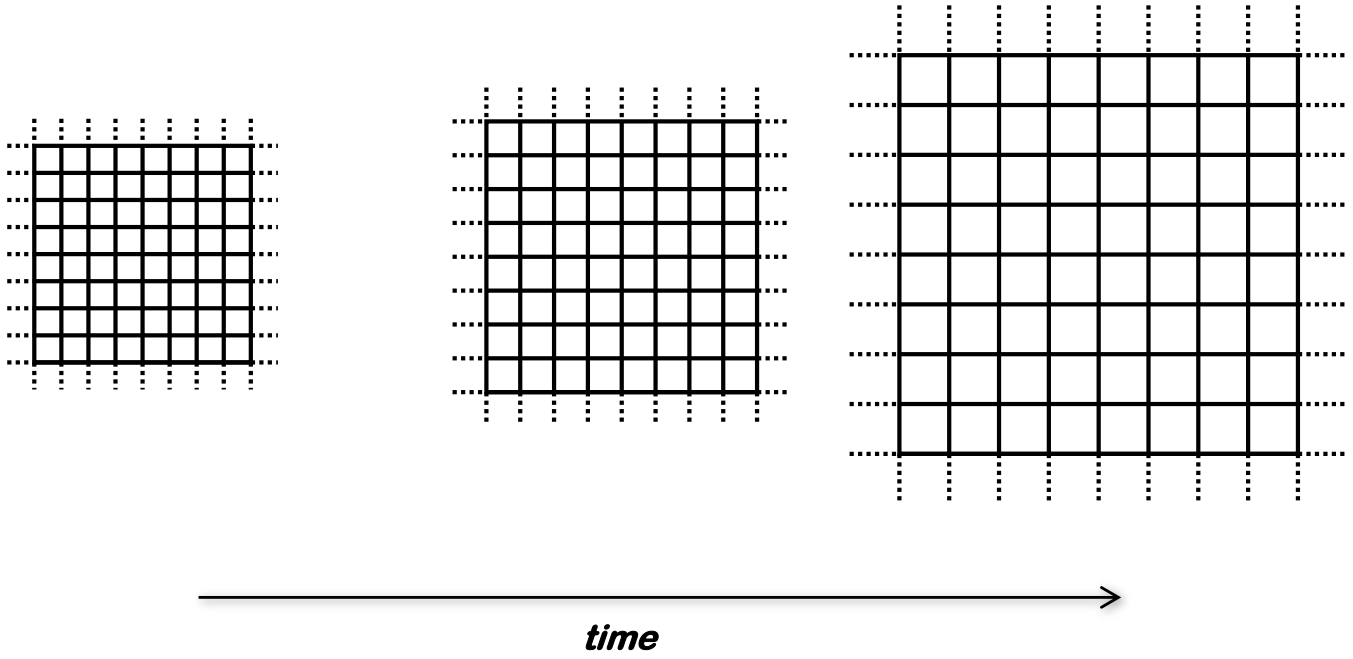
2. theoretically model (and explain!) the observed structures

structure formation within cosmological framework

Cosmology

structure formation - modeled

- ***expansion of homogeneous & isotropic Universe…***

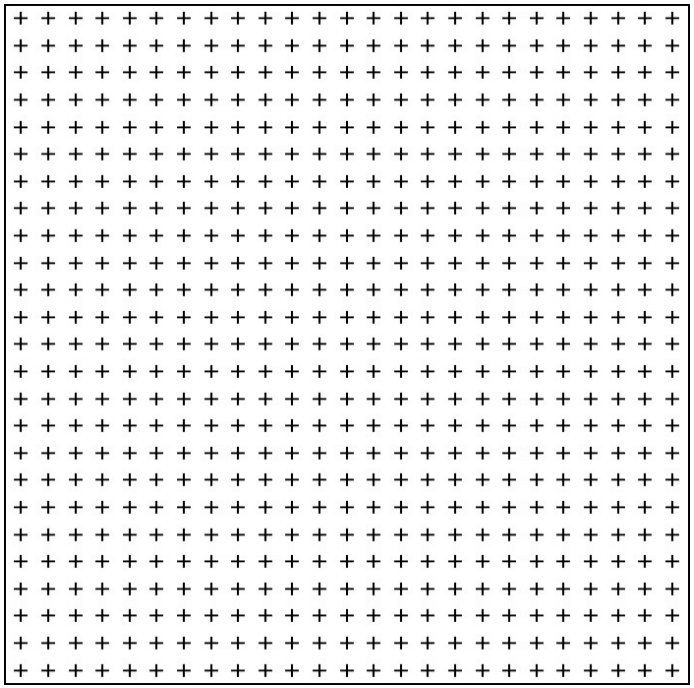


…does not give rise to any structures!

Cosmology

structure formation - modeled

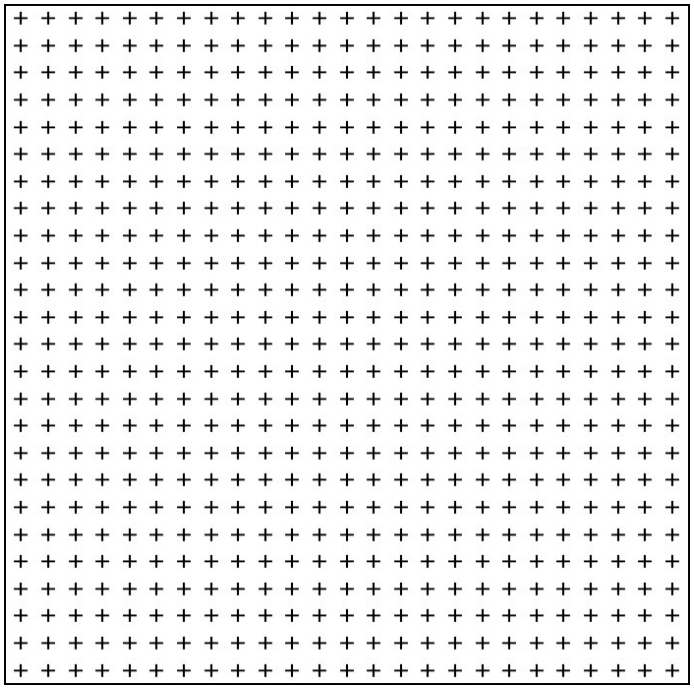
homogeneous & isotropic



Cosmology

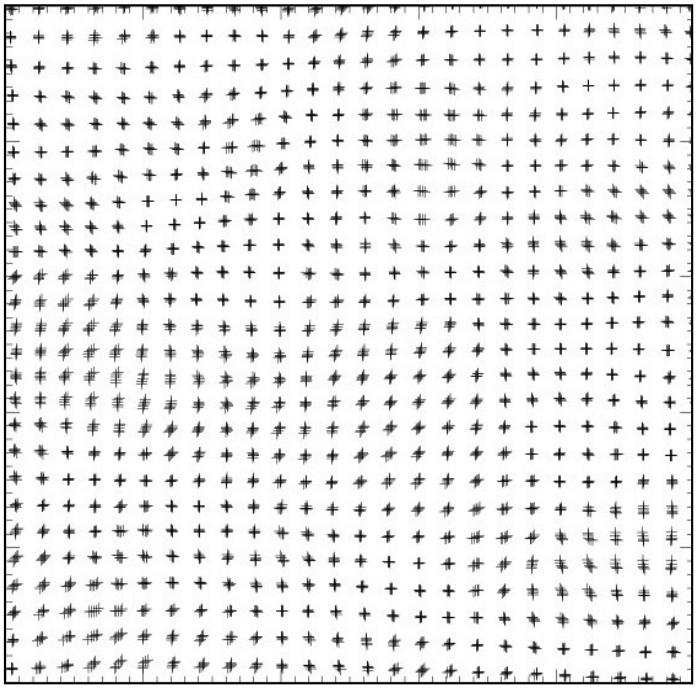
structure formation - modeled

homogeneous & isotropic



?

homogeneous & isotropic

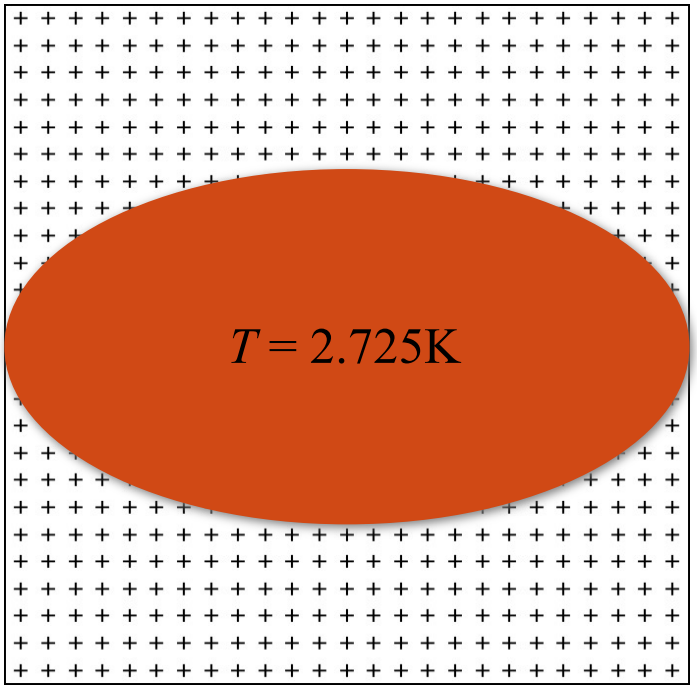


w/ small perturbations

Cosmology

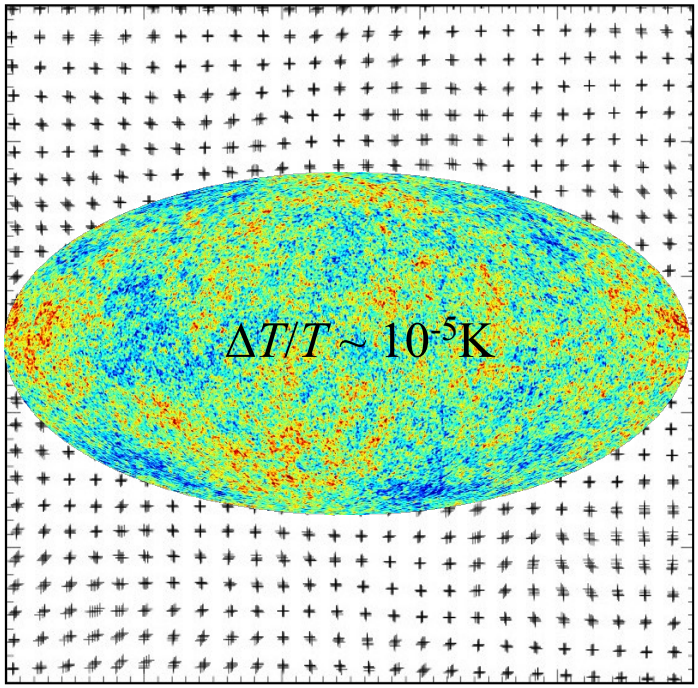
structure formation - modeled

homogeneous & isotropic



?

homogeneous & isotropic



w/ small perturbations:

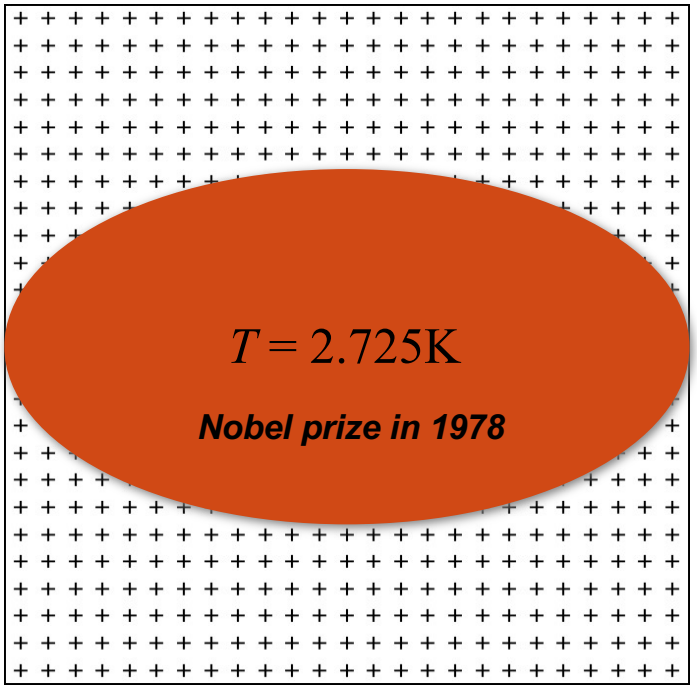
temperature fluctuations are reflecting underlying matter fluctuations

(more in CMB Lectures)

Cosmology

structure formation - modeled

homogeneous & isotropic



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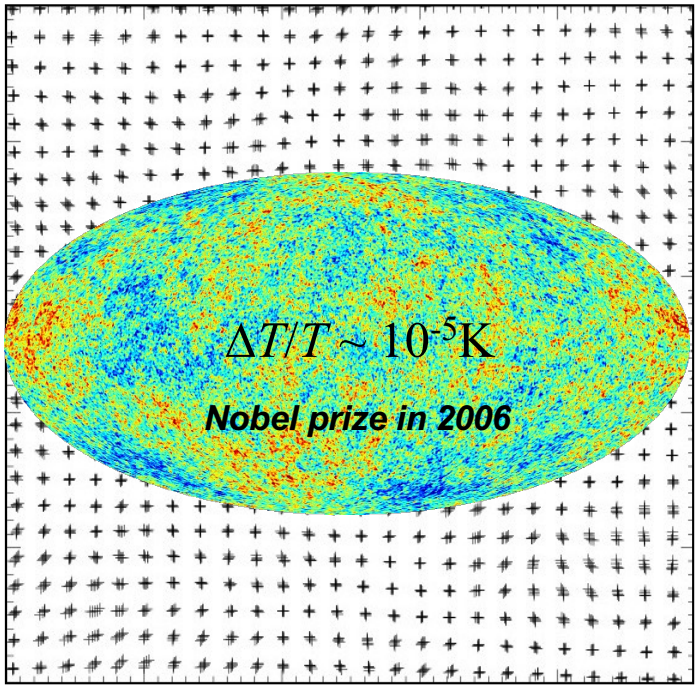
homogeneous & isotropic



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Cosmology

structure formation - modeled

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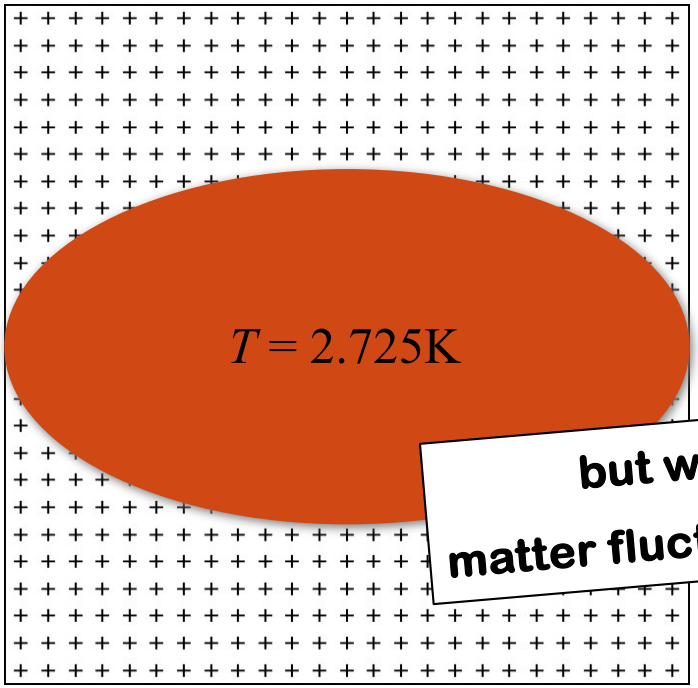
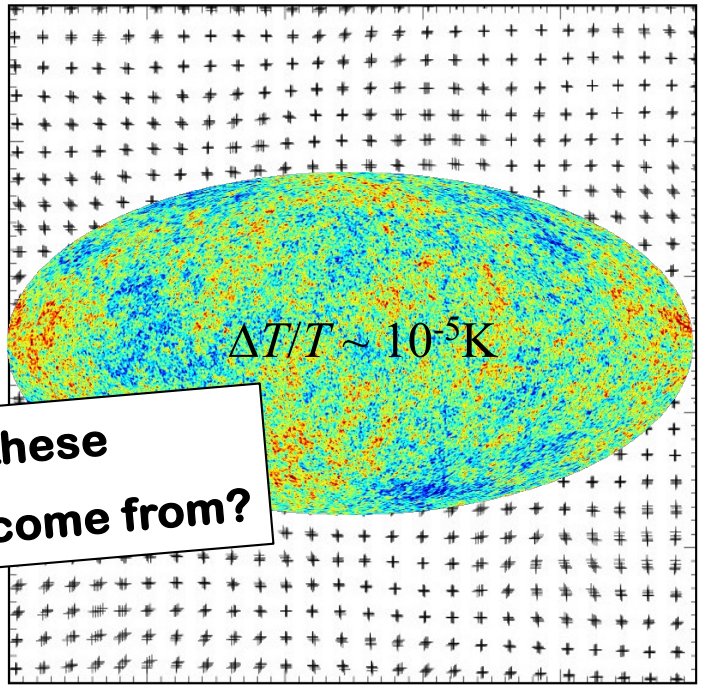


?

but where do these matter fluctuations come from?

homogeneous & isotropic



w/ small perturbations:

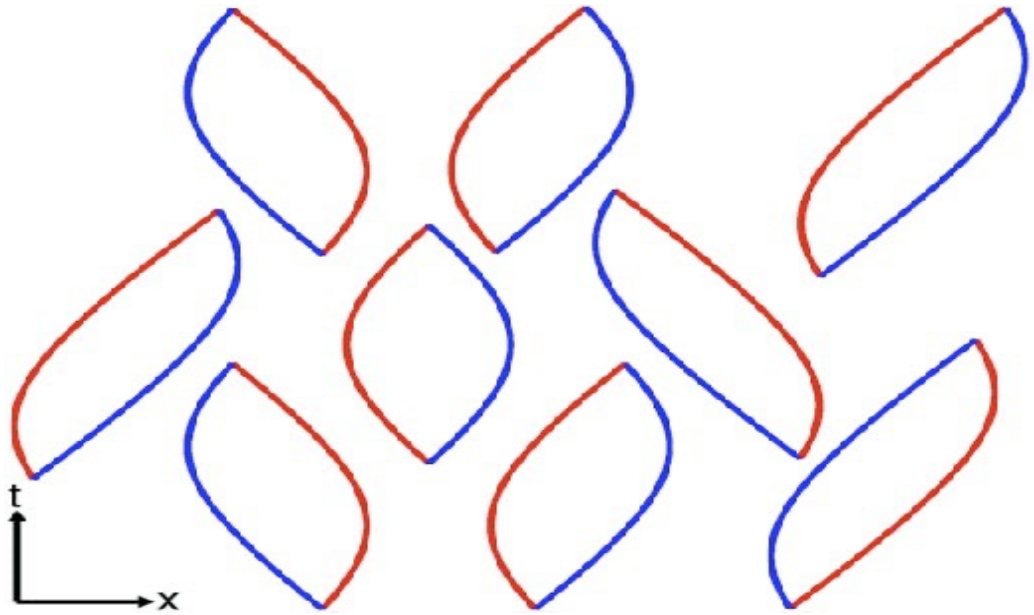
temperature fluctuations are reflecting underlying matter fluctuations

(more in CMB Lectures)

- **origin of matter perturbations**

  - **quantum fluctuations:**

    “empty space” is a sea of virtual particles winking in and out of existence



Cosmology

structure formation - modeled

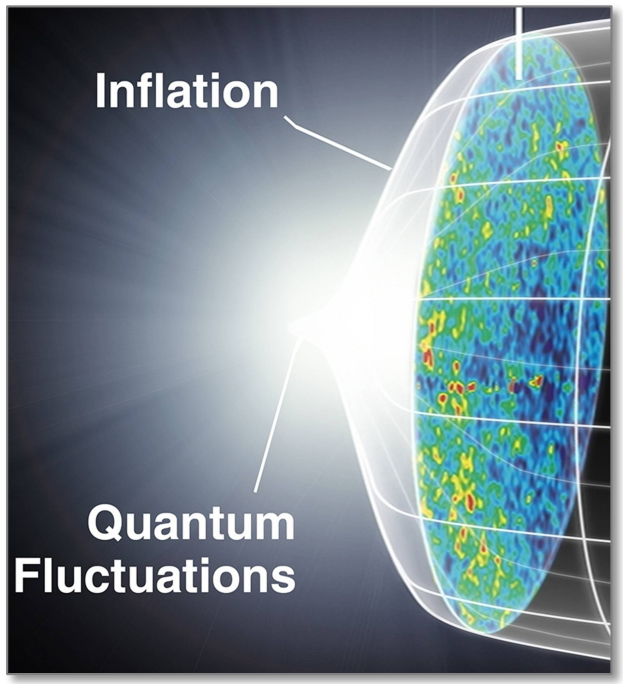
- **origin of matter perturbations**

  - **quantum fluctuations:**

    "empty space" is a sea of virtual particles winking in and out of existence

  - **inflation:**

    the early Universe underwent a phase of rapid expansion



(more details in Inflation lecture…)

- **origin of matter perturbations**

  - **quantum fluctuations:**

    "empty space" is a sea of virtual particles winking in and out of existence

  - **inflation:**

    the early Universe underwent a phase of rapid expansion

quantum fluctuations,

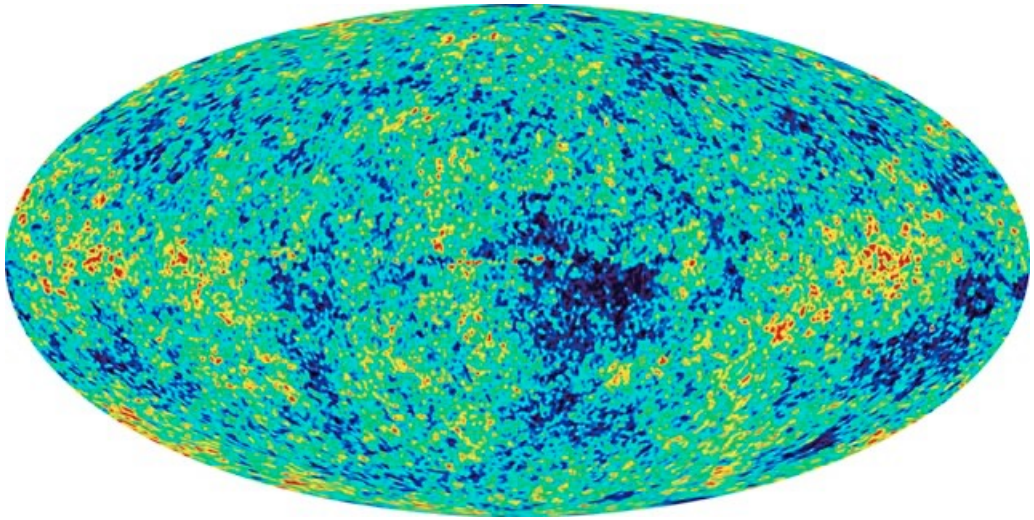
magnified to cosmic size during "inflation",

become the seeds for structures in the Universe

Cosmology

structure formation - modeled

- **growth of matter perturbations**



temperature fluctuations

Cosmology

structure formation - modeled

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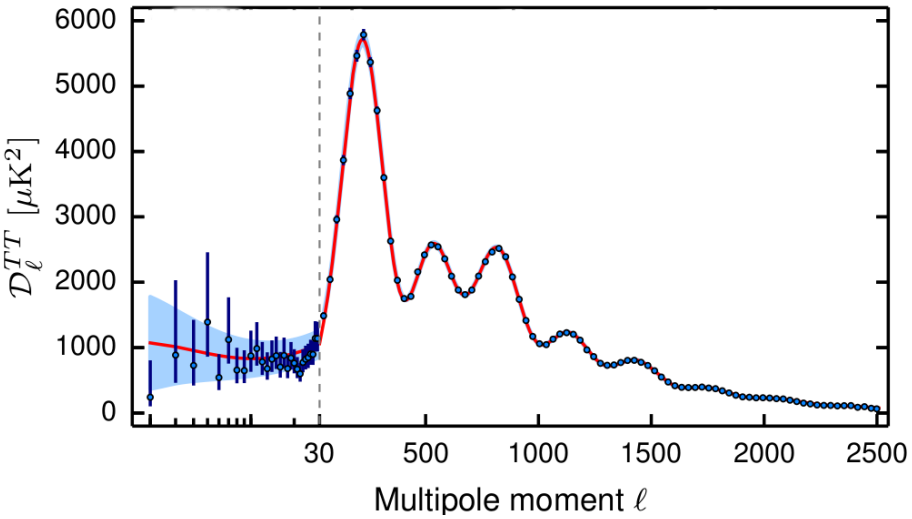

temperature fluctuations

Cosmology

structure formation - modeled

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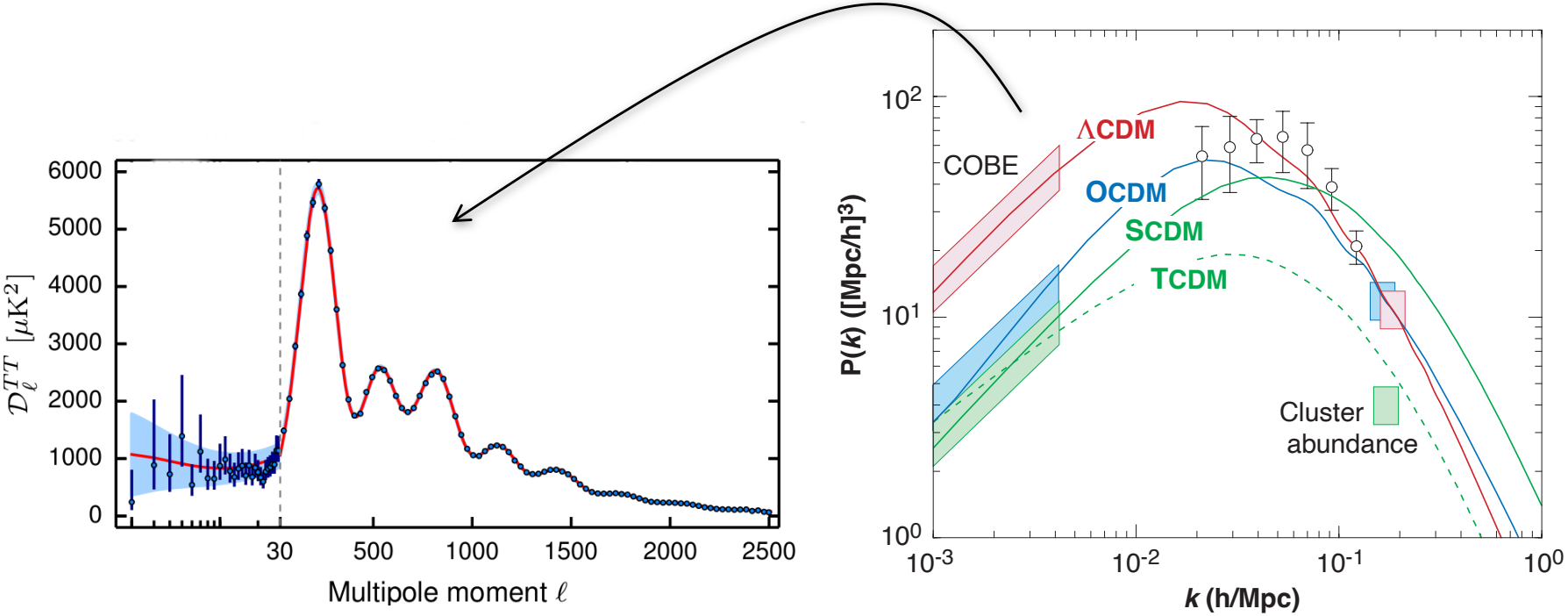

temperature fluctuations …are reflecting underlying matter fluctuations

Cosmology

structure formation - modeled

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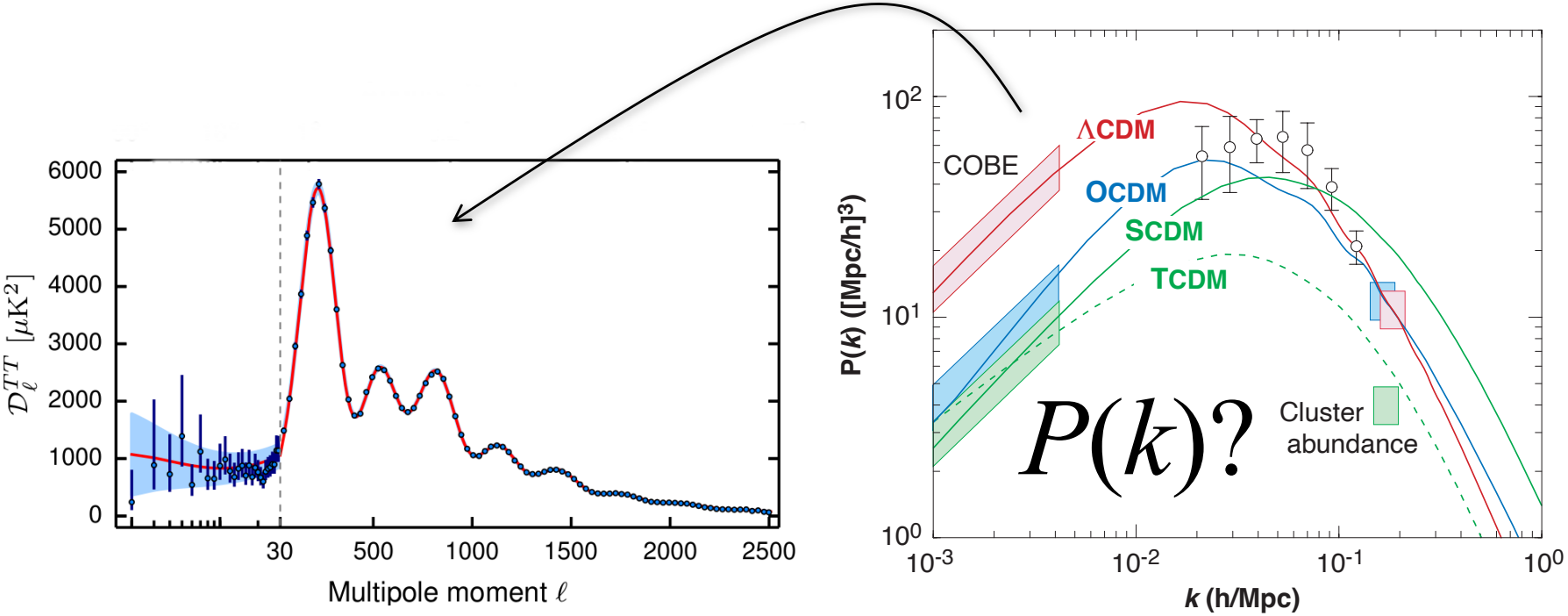
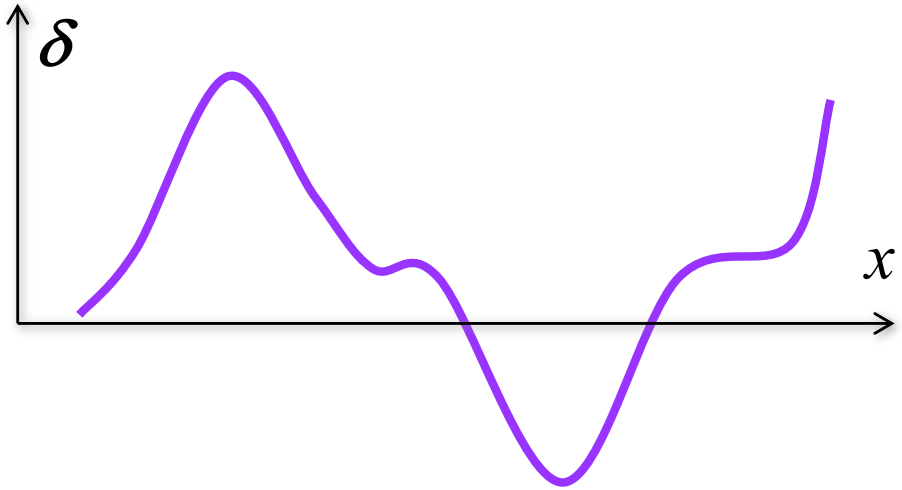
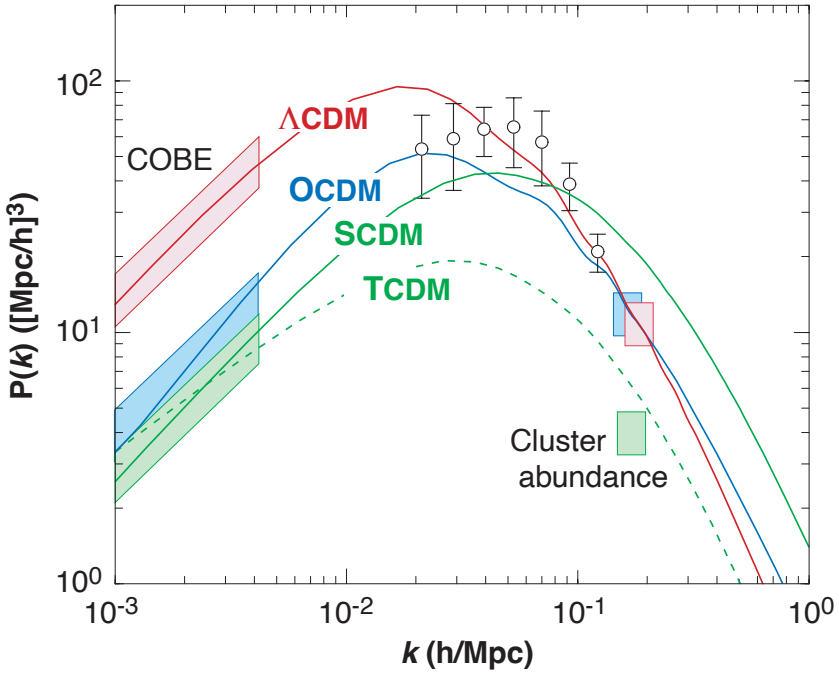


temperature fluctuations…are reflecting underlying matter fluctuations

History & Principles

- **growth of matter perturbations**



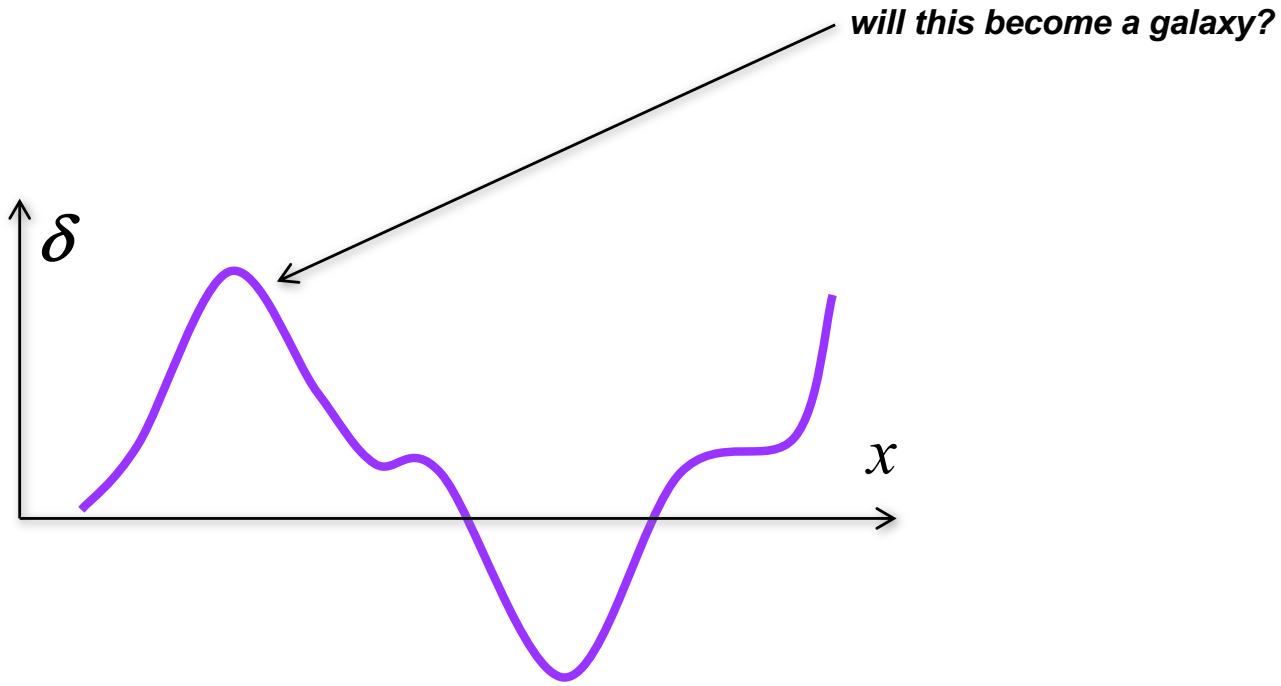


$$\delta(\vec{x},t) = \frac{\rho(\vec{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$ **density contrast**

matter fluctuations

$$P(k) = \left\langle \left| \hat{\delta}(\vec{k}) \right|^2 \right\rangle_{|\vec{k}|=k}$$ **power spectrum of density perturbations**

- **growth of matter perturbations**



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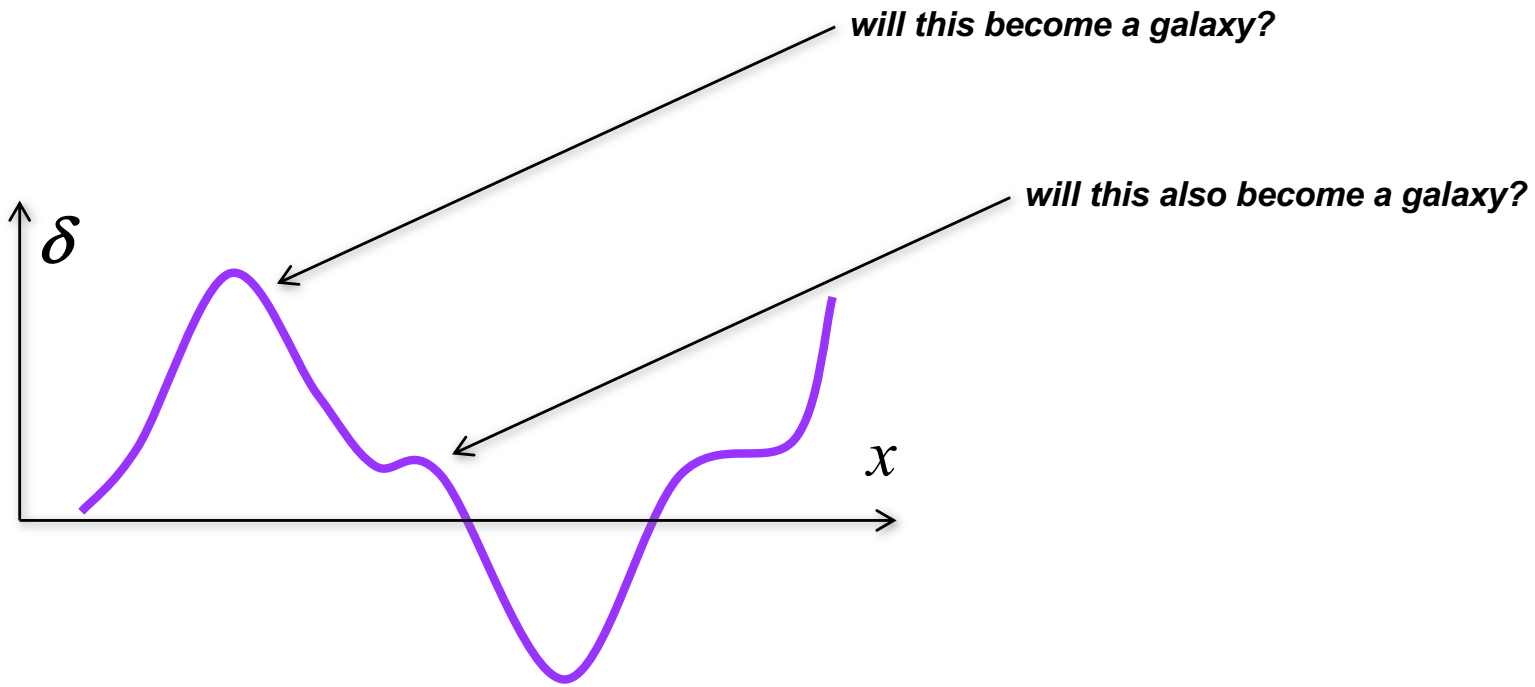

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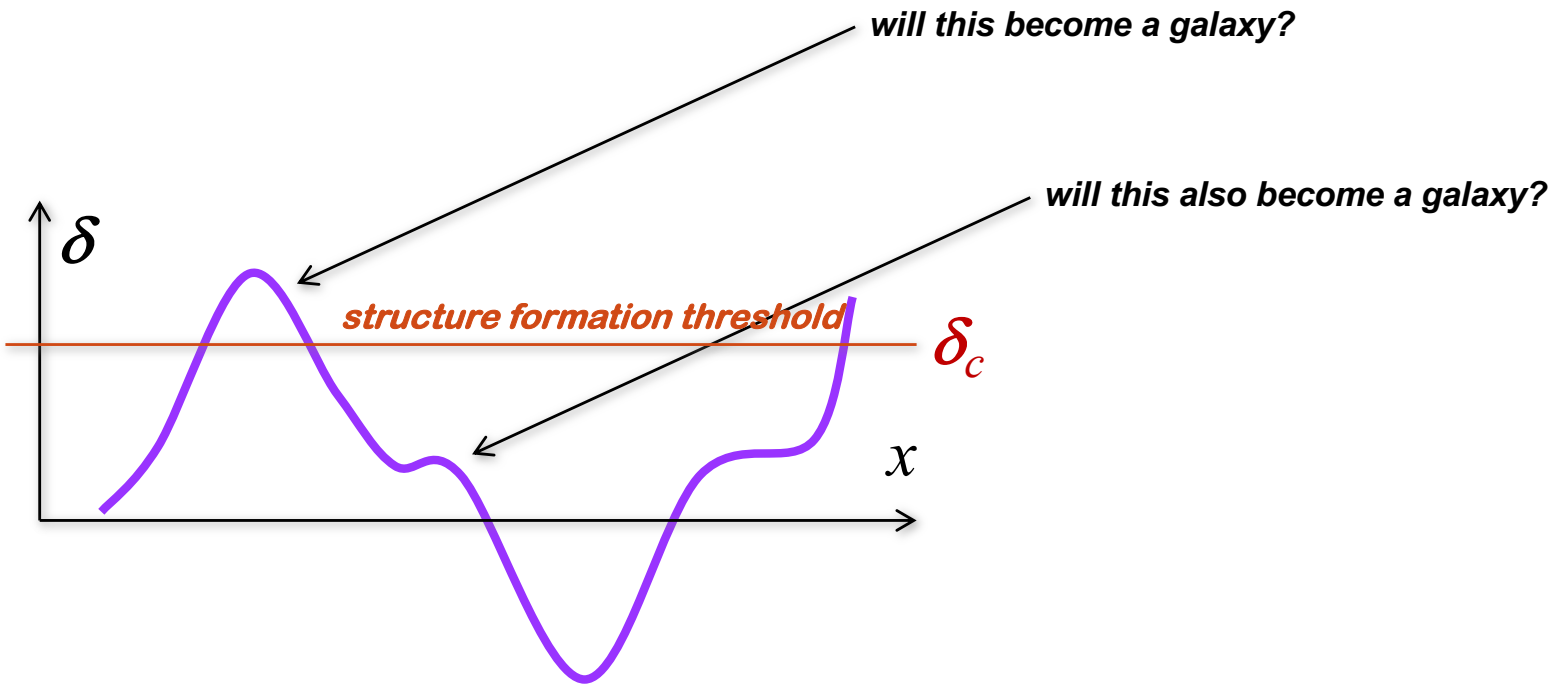

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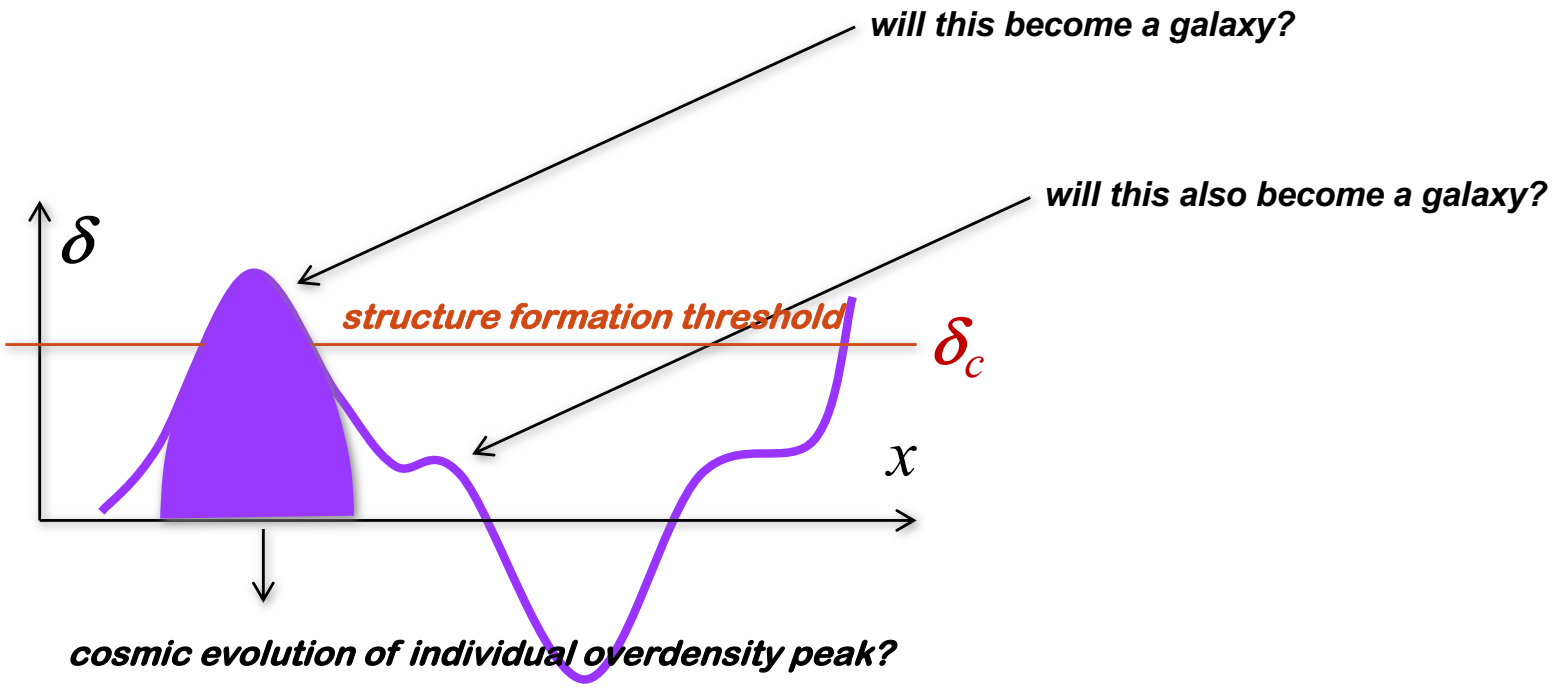

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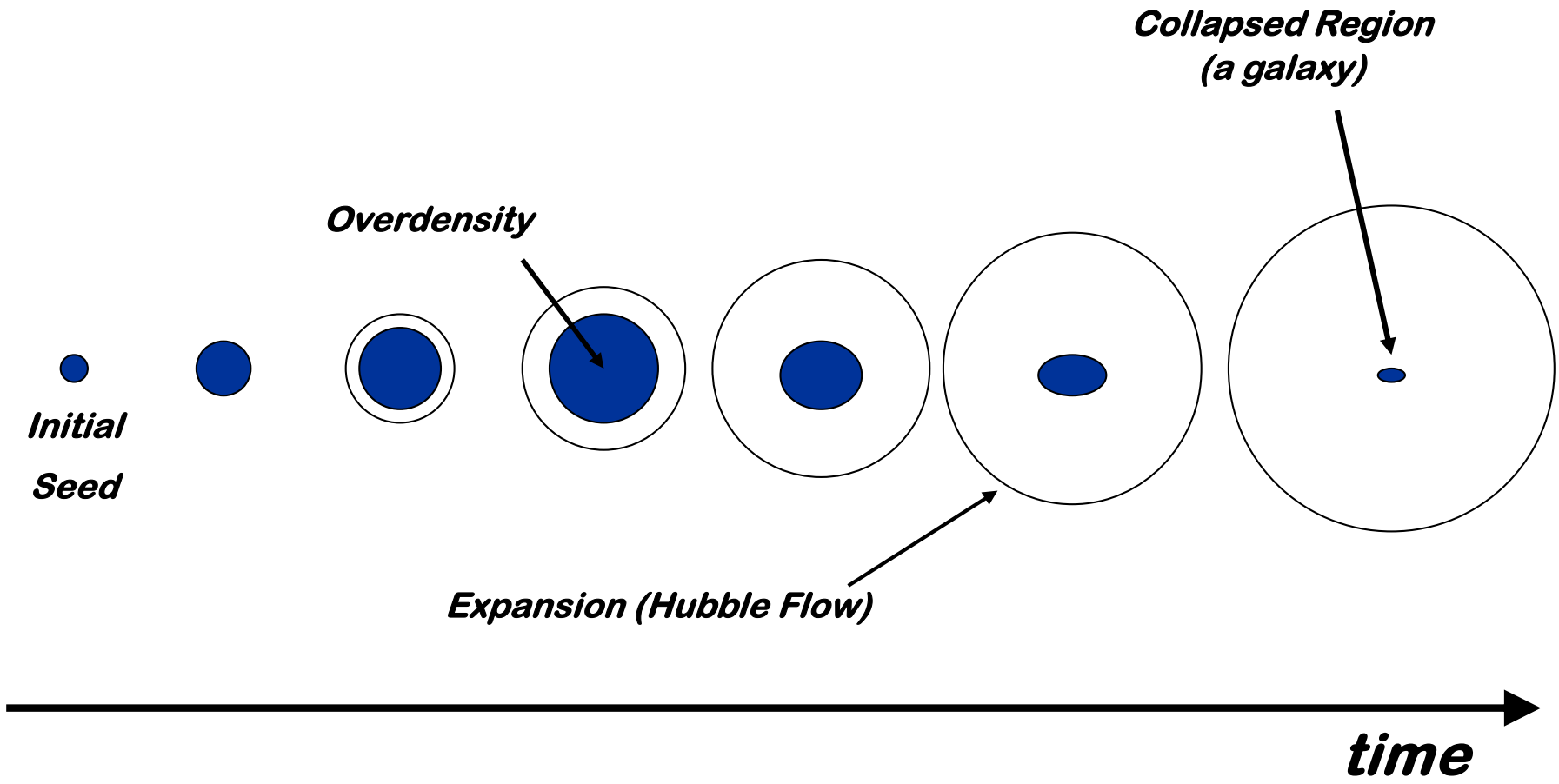

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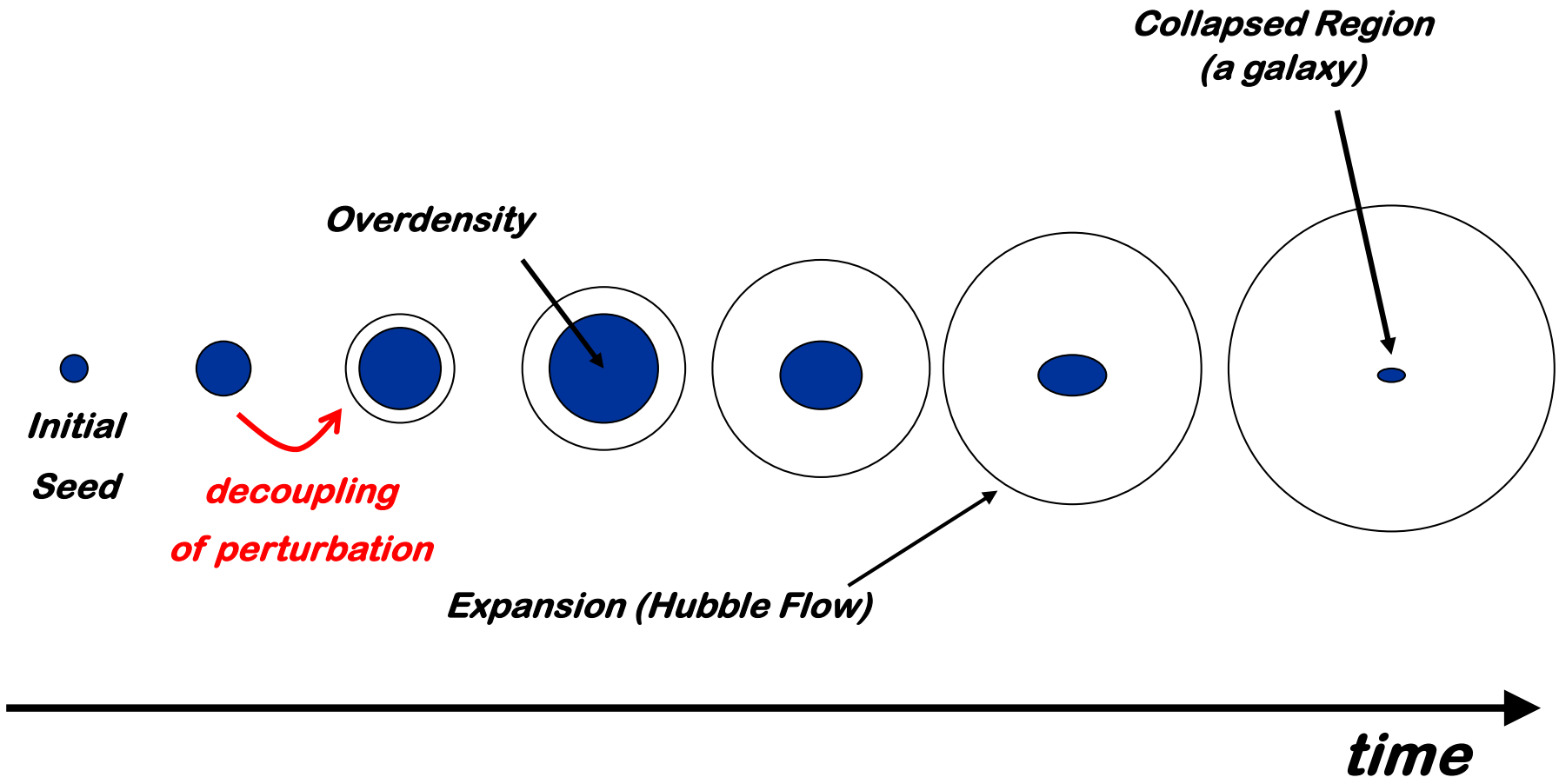

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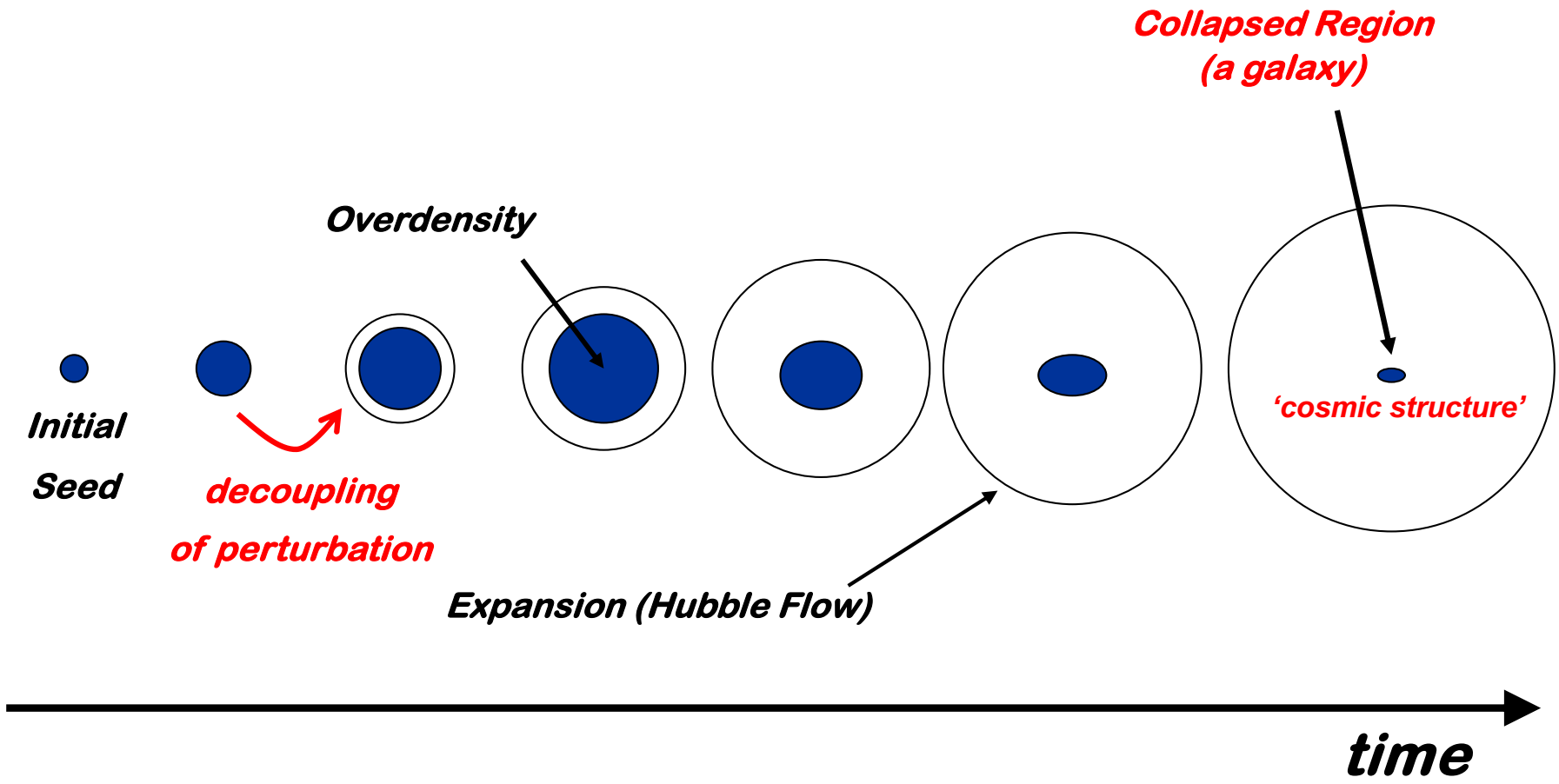


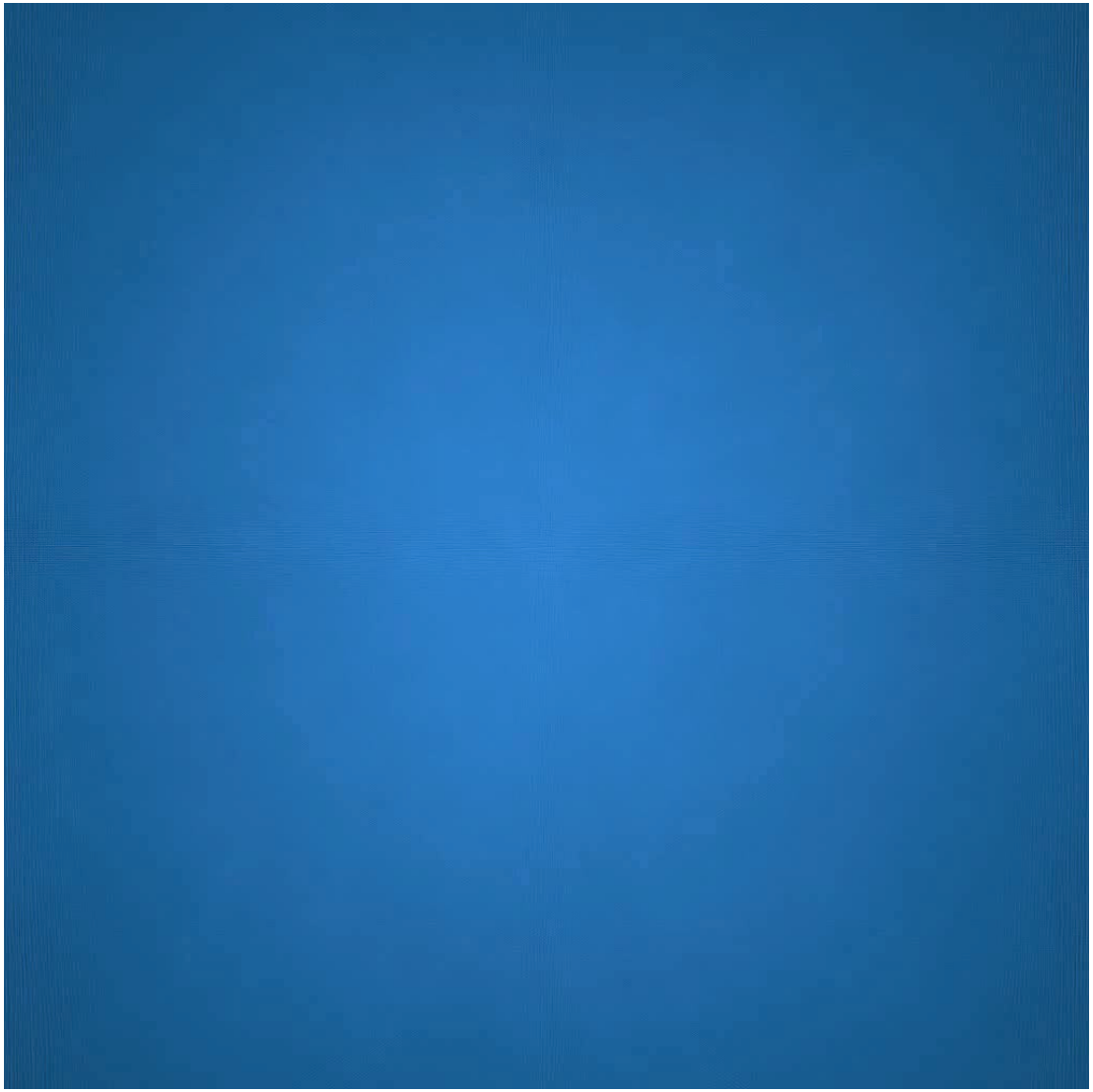
Cosmology

- **growth of matter perturbations**
  - **analytically: LSS lecture**
  - **numerically: Computational Cosmology lecture**

Cosmology

structure formation - modeled

- **growth of matter perturbations – simulations…**

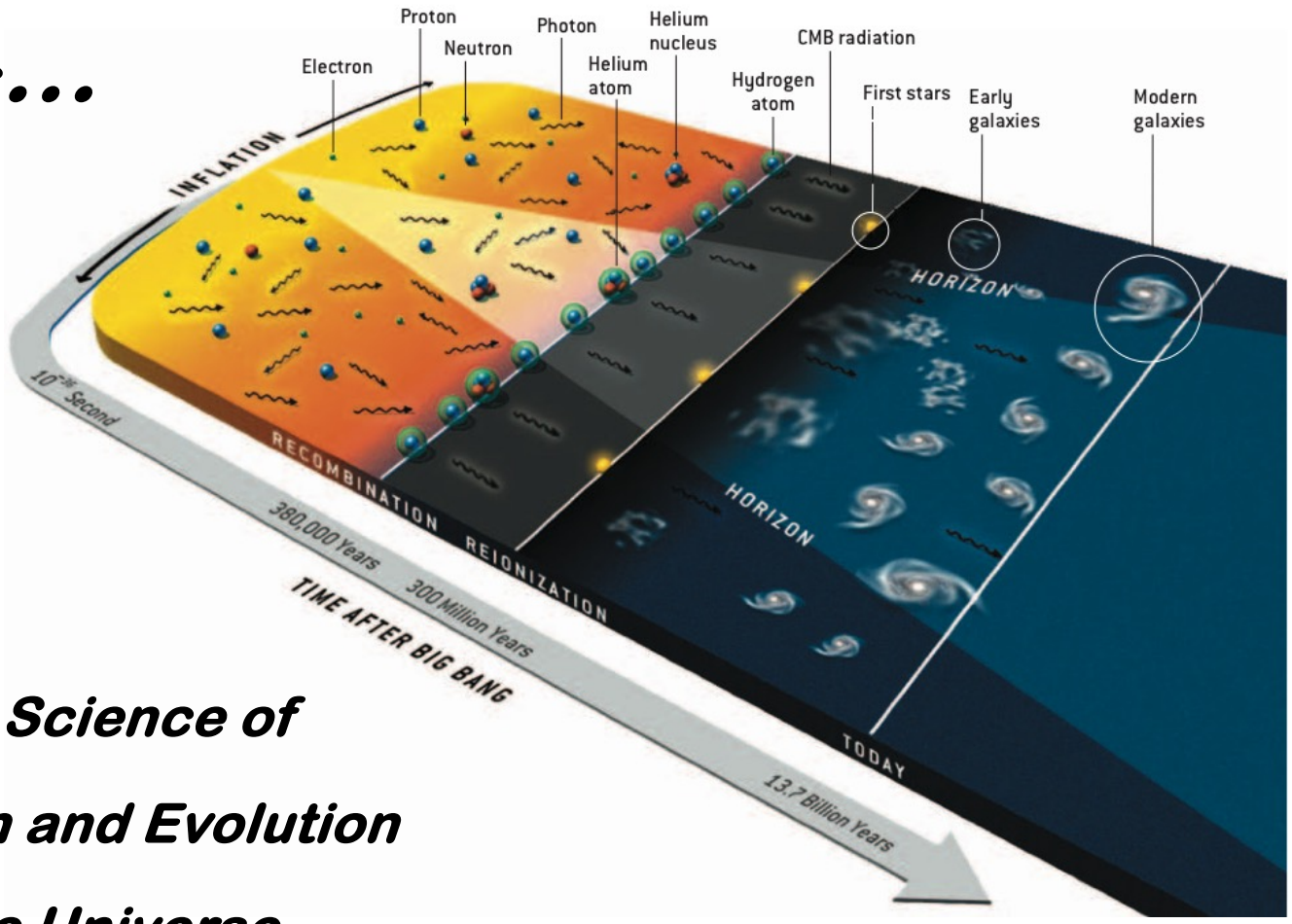


Cosmology

- *explain this!*
- *principles*
- *cosmology – science or science fiction?*
- *cosmological structure formation*

Cosmology

Cosmology is…



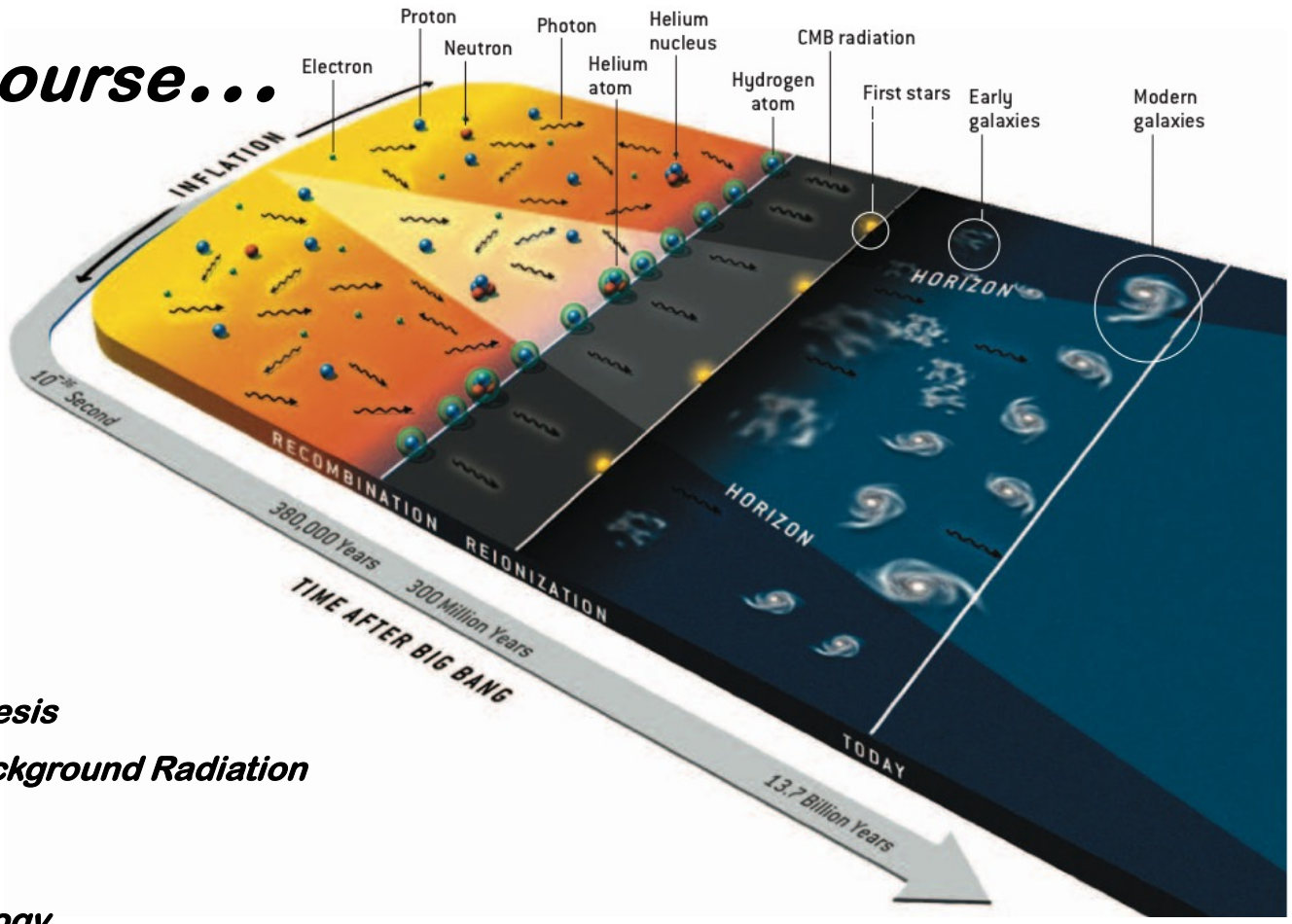
…the Science of

the Origin and Evolution

of the Universe

Cosmology

Cosmology Course…



- *Inflation*
- *Baryogenesis*
- *Thermal History*
- *Big Bang Nucleosynthesis*
- *Cosmic Microwave Background Radiation*
- *Cosmic Dawn*
- *Large-Scale Structure*
- *Observational Cosmology*
- *Gravitational Waves*
- *Open Problems*