First Galaxies: theory

Ken Nagamine
(Osaka / K-IPMU / UNLV)

JSPS postdoc fellowship

(≈ JP NSF) for foreigners

- **3-yrs** of funding at an institution of your choice + research fund ~10k USD.
- has to contact a host prof. in advance
- similar to NSF / Hubble fellowship
- https://www.jsps.go.jp/english/e-fellow/

Also MEXT fellowship for Ph.D. program.

Useful websites

arXiv.org

voxcharta.org

arxivsorter.org

astrobetter.com

Paper management:

Zotero, Mendeley,

Papers3 —> Readcube

Four Golden Lessons

2003 Nature

Four golden lessons

Scientist

Advice to students at the start of their scientific careers.

Steven Weinberg

When I received my undergraduate degree — about a hundred years ago — the physics literature seemed to me a vast, unexplored ocean, every part of which I had to chart before beginning any research of my own. How could I do anything without knowing everything that had already been done? Fortunately, in my first year of graduate school, I had the good luck to fall into the hands of senior physicists who insisted, over my anxious objections, that I must start doing research, and pick up what I needed to know as I went along. It was sink or swim. To my surprise, I found that this works. I managed to get a quick PhD — though when I got it I knew almost nothing about physics. But I did learn one big thing: that no one knows everything, and you don't have to.

Another lesson to be learned, to continue using my oceanographic metaphor, is that while you are swimming and not sinking you should aim for rough water. When I was teaching at the Massachusetts Institute of Technology in the late 1960s, a student told me that he wanted to go into general relativity rather than the area I was working on, elementary particle physics, because the principles of the former were well known, while the latter seemed like a mess to him. It struck me that he had just given a perfectly good reason for doing the opposite. Particle physics was an area where creative work could still be done. It really was a mess in the 1960s, but since that time the work of many theoretical and experimental physicists has been able to sort it out, and put everything (well, almost everything) together in a beautiful theory known as the standard model. My advice is to go for the messes — that's where the action is.

My third piece of advice is probably the hardest to take. It is to forgive yourself for wasting time. Students are only asked to solve problems that their professors (unless unusually cruel) know to be solvable. In addition, it doesn't matter if the problems are scientifically important — they have to be solved to pass the course. But in the real world, it's very hard to know which problems are important, and you never know whether at a given moment in history a problem is solvable. At the beginning of the twentieth century, several leading physicists, including Lorentz and Abraham, were trying to work out a theory of the electron. This was partly in order to understand why all attempts to detect effects of Earth's motion through the ether had failed. We now know that they were working on the wrong problem. At that time, no one could have developed a successful theory of the electron, because quantum mechanics had not yet been discovered. It took the genius of Albert Einstein in 1905 to realize that the right problem on which to work was the effect of motion on measurements of space and time. This led him to the special theory of relativity. As you will never be sure which are the right problems to work on, most of the time that you spend in the laboratory or at your desk will be wasted. If you want to be creative, then you will have to get used to spending most of your time not being creative, to being becalmed on the ocean of scientific knowledge.

Finally, learn something about the history of science, or at a minimum the history of your own branch of science. The least important reason for this is that the history may actually be of some use to you in your own scientific work. For instance, now and then scientists are hampered by believing one of the over-simplified models of science that have been proposed by philosophers from Francis Bacon to Thomas Kuhn and Karl Popper. The best antidote to the philosophy of science is a knowledge of the history of science.

More importantly, the history of science can make your work seem more worthwhile to you. As a scientist, you're probably not going to get rich. Your friends and relatives probably won't understand what you're doing. And if you work in a field like elementary particle physics, you won't even have the satisfaction of doing something that is immediately useful. But you can get great satisfaction by recognizing that your work in science is a part of history.

Look back 100 years, to 1903. How important is it now who was Prime Minister of Great Britain in 1903, or President of the United States? What stands out as really important is that at McGill University, Ernest Rutherford and Frederick Soddy were working out the nature of radioactivity. This work (of course!) had practical applications, but much more important were its cultural implications. The understanding of radioactivity allowed physicists to explain how the Sun and Earth's cores could still be hot after millions of years. In this way, it removed the last scientific objection to what many geologists and paleontologists thought was the great age of the Earth and the Sun. After this, Christians and Jews either had to give up belief in the literal truth of the Bible or resign themselves to intellectual irrelevance. This was just one step in a sequence of steps from Galileo through Newton and Darwin to the present that, time after time, has weakened the hold of religious dogmatism. Reading any newspaper nowadays is enough to show you that this work is not yet complete. But it is civilizing work, of which scientists are able to feel proud. ■

Steven Weinberg is in the Department of Physics, the University of Texas at Austin, Texas 78712, USA. This essay is based on a commencement talk given by the author at the Science Convocation at McGill University in June 2003.

USA/NETWORKS/KOBAL COLLECTION/R. FOREMAN

Dive right in: exploring the unclear, uncharted areas of science can lead to creative work.

by S. Weinberg
(1979 Nobel Prize, Physics)

1. **Learn to swim as you try not to drown.** — No one knows everything, and you don't have to.

2. **Aim for the rough water** (messes). — that's where the action is.

3. **Forgive yourself wasting time.**

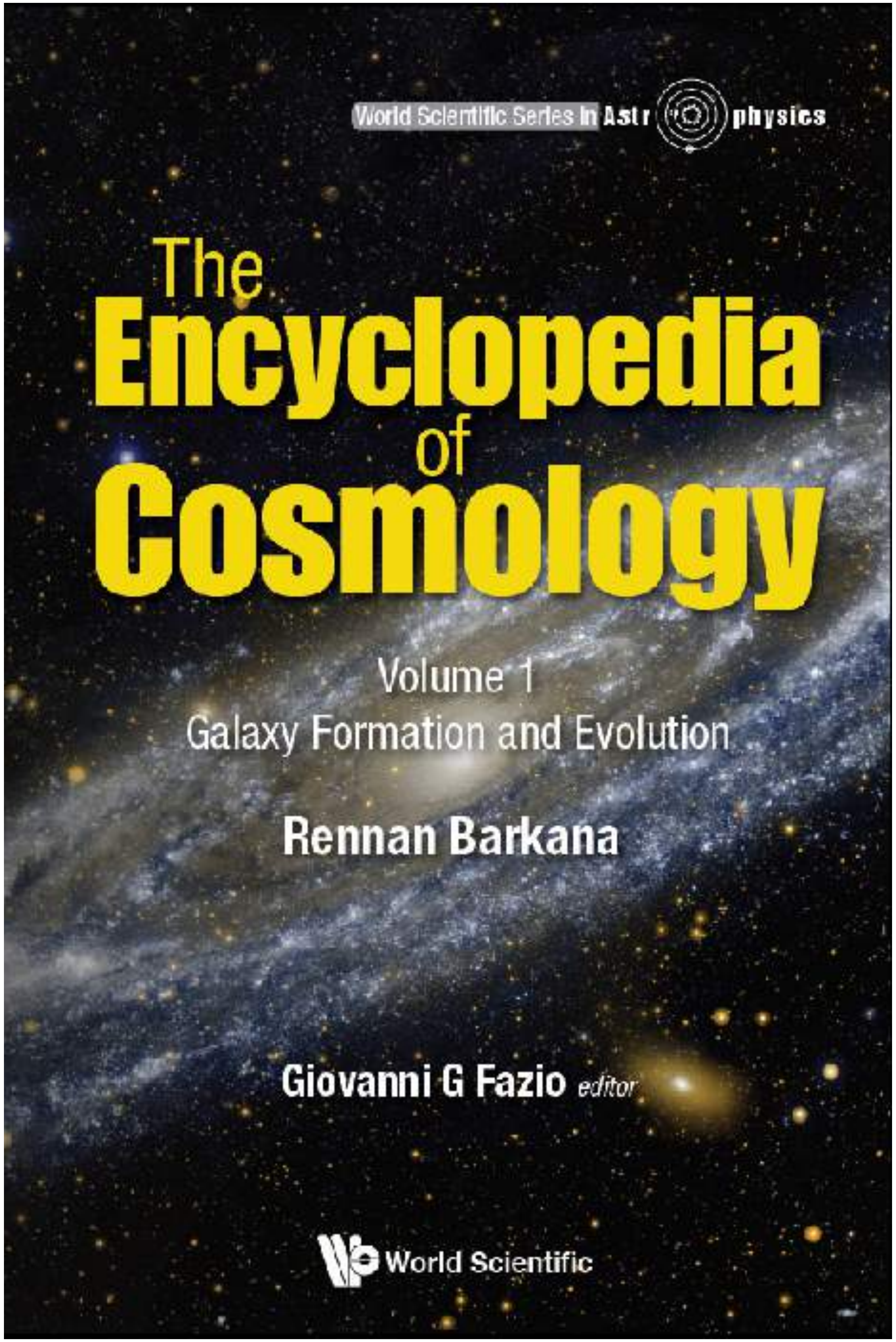
4. **Learn the history of science.** — at least of your own field.

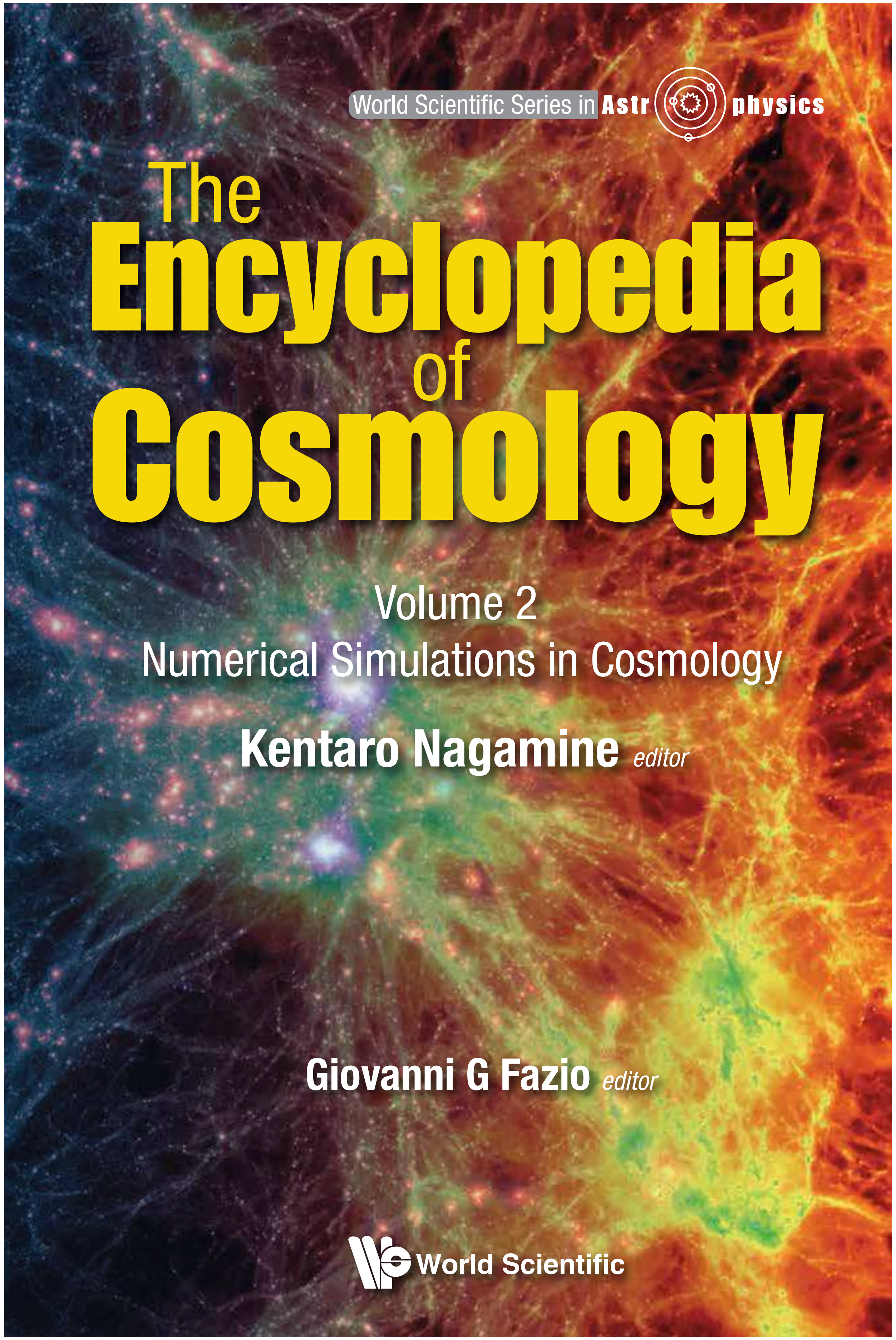
Recommended Textbooks

- "***Numerical Simulations in Cosmology***" Encyclopedia of Cosmology Vol. 2 (Nagamine+, World Scientific 2018)
- "***Galaxy Formation and Evolution***" (Mo et al. Cambridge 2010)
- "Cosmology" (2nd ed; Coles & Lucchin; Wiley '03)
- "Cosmological Physics" (Peacock; Cambridge '99)
- "Structure Formation in the Universe" (Padmanabhan; Cambridge '95)
- "Principles of Physical Cosmology" (Peebles; Princeton '93)
- "Early Universe" (Kolb & Turner; Addison-Wesley '90)
- "Gravitation & Cosmology" (Weinberg; Wiley '72)

World Scientific

Published in Mar 2018.





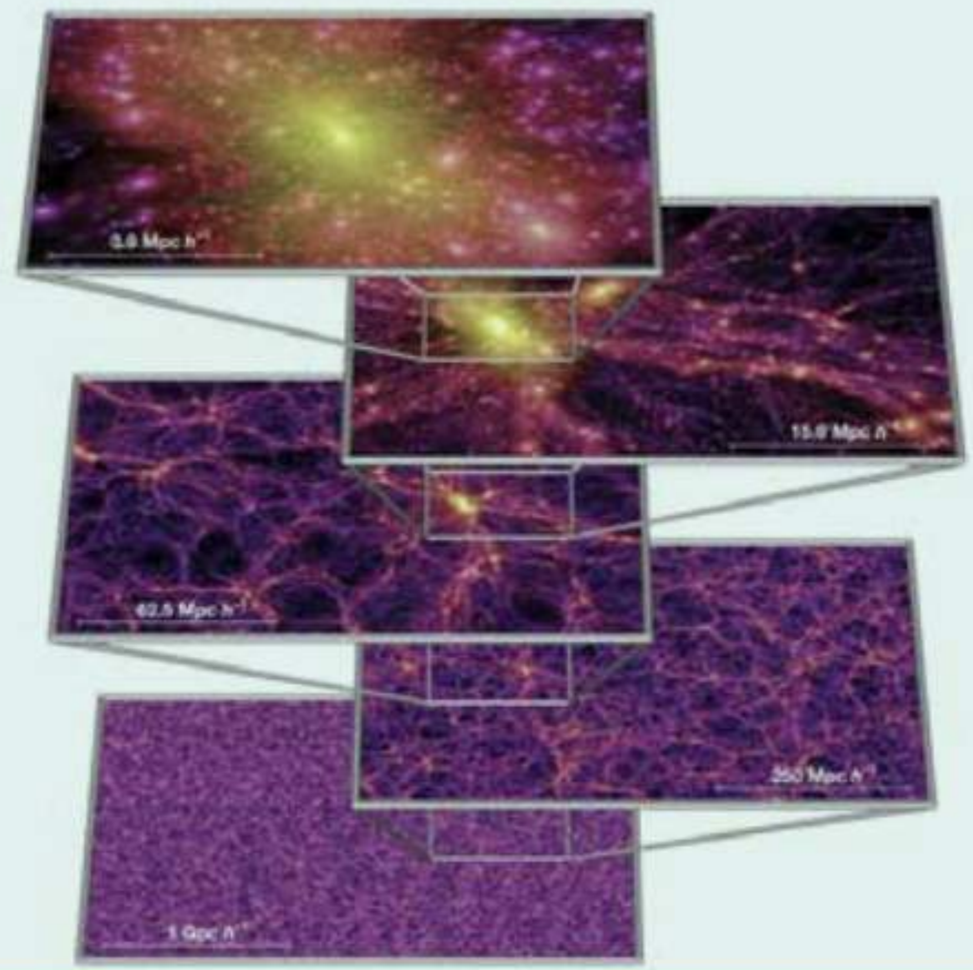
Amazon, or https://www.worldscientific.com/worldscibooks/10.1142/9496#t=toc

Volume 2

Numerical Simulations in Cosmology

edited by **Kentaro Nagamine** *(Osaka University / University of Nevada)*

1. Overview: Cosmological Framework and the History of Computational Cosmology
   Kentaro Nagamine *(Osaka University, Japan & University of Nevada, Las Vegas, USA)*
2. Cosmological N-body simulations
   Anatoly Klypin *(New Mexico State University)*
3. Hydrodynamic Methods for Cosmological Simulations
   Klaus Dolag *(Ludwig-Maximilian University of Munich & Max Planck Institute for Astrophysics; Germany)*
4. First Stars in Cosmos
   Hajime Susa *(Konan University, Japan)*
5. First Galaxies and Massive Black Hole Seeds
   Volker Bromm *(University of Texas at Austin, USA)*
6. Galaxy Formation and Evolution
   Kentaro Nagamine *(Osaka University, Japan & University of Nevada, Las Vegas, USA)*
7. Secular Evolution of Disk Galaxies
   Isaac Shlosman *(University of Kentucky, USA & Osaka University, Japan)*
8. Cosmic Gas and the Intergalactic Medium
   Greg L. Bryan *(Columbia University, USA)*
9. Computational Modeling of Galaxy Clusters
   Daisuke Nagai *(Yale University, USA)* &
   Klaus Dolag *(Ludwig-Maximilian University of Munich & Max Planck Institute for Astrophysics; Germany)*



My three lectures:

"Recipe" for Galaxy Formation

- Background Cosmology
- Gravitational Instability
- N-body dynamics (Dark Matter)
- Hydrodynamics
- Radiative Cooling of Gas, UVB
- Star Formation, Chemical Enrichment
- Feedback (SNe, AGNs)

Part I: Intro

(upper undergrad & 1st yr grad)

Quiz

Galaxy#1

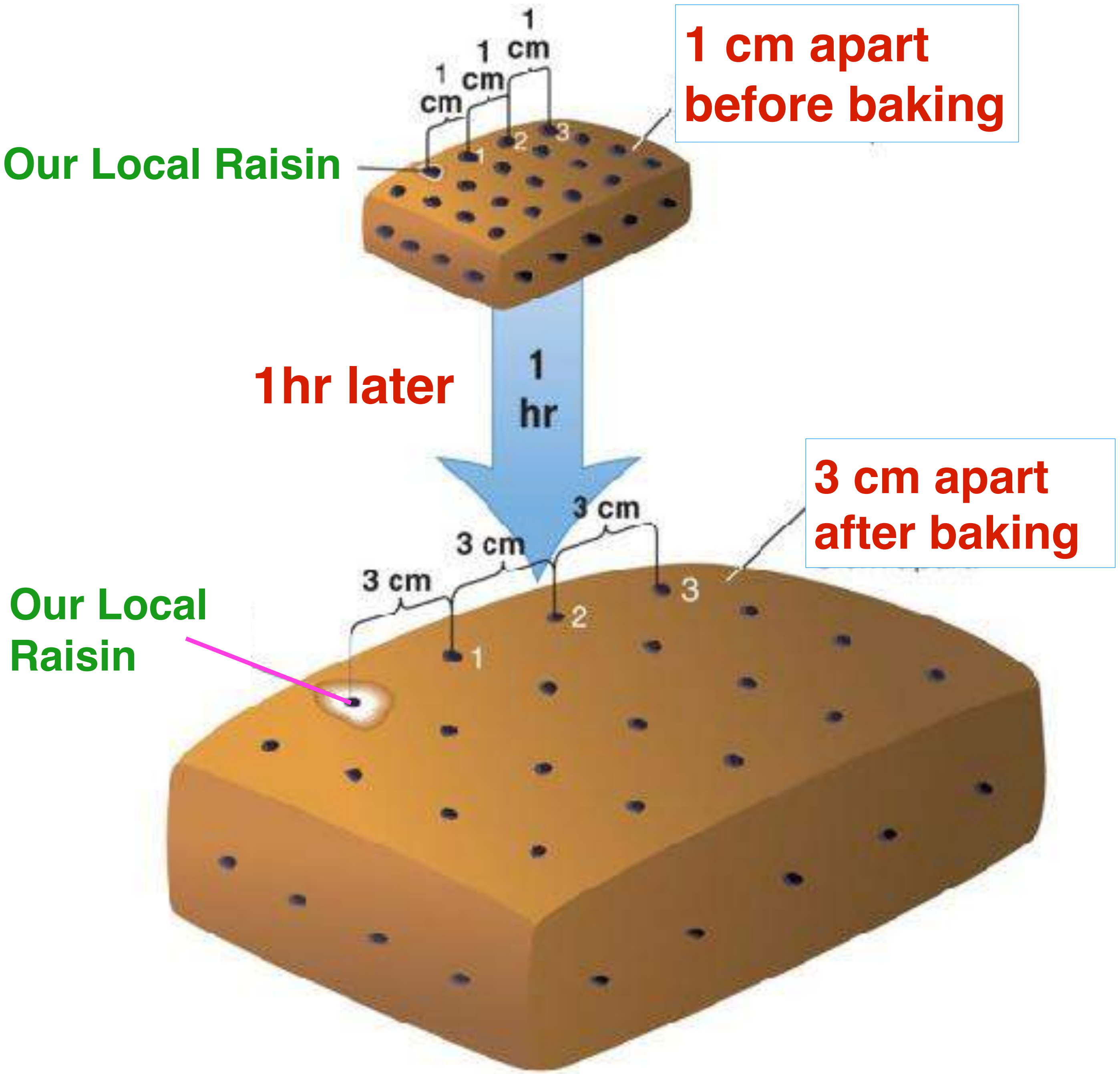
#2

#3

Consider 3 widely separated galaxies in an expanding universe. Imagine that you are located in **galaxy #1** and observe that both **galaxies #2** and **#3** are moving **away** from you. If you asked an observer in **galaxy #3** to describe how **galaxy #2** appears to move, what would he or she say?

a) “Galaxy 2 is not moving.”
b) “Galaxy 2 is moving toward galaxy 3.”
c) “Galaxy 2 is moving away from galaxy 3.”

Raisin bread = Expanding Universe



図：Pearson Addison-Wesley

Distances

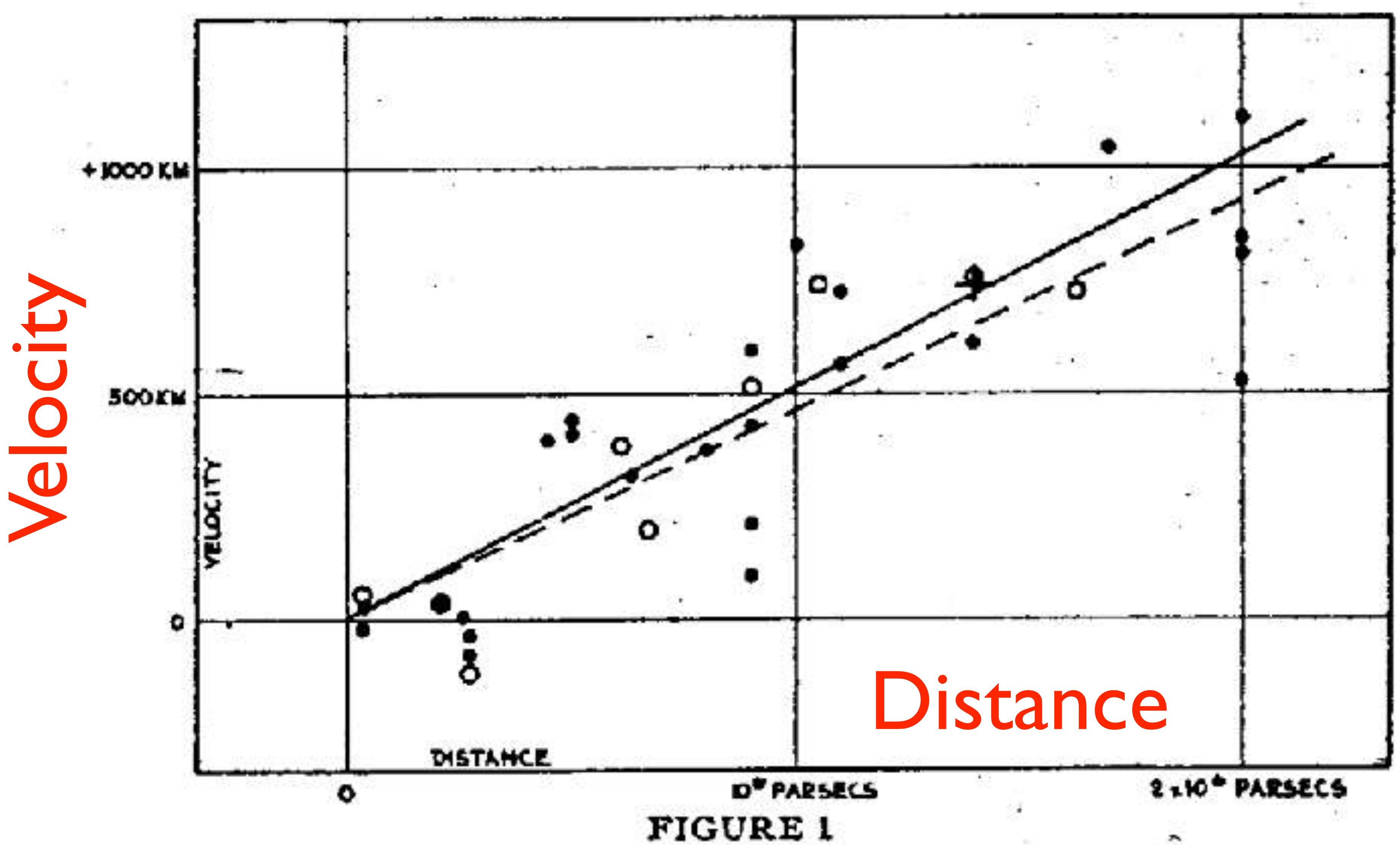
Raisin #	Before baking	After baking	Speed
1	1 cm	3 cm	2 cm/hr
2	2 cm	6 cm	4 cm/hr
3	3 cm	9 cm	6 cm/hr

Same for the galaxies!

Hubble's observation indicated an expanding universe.

Hubble measured the distances to whole bunch of other galaxies.

Hubble Diagram (1929)



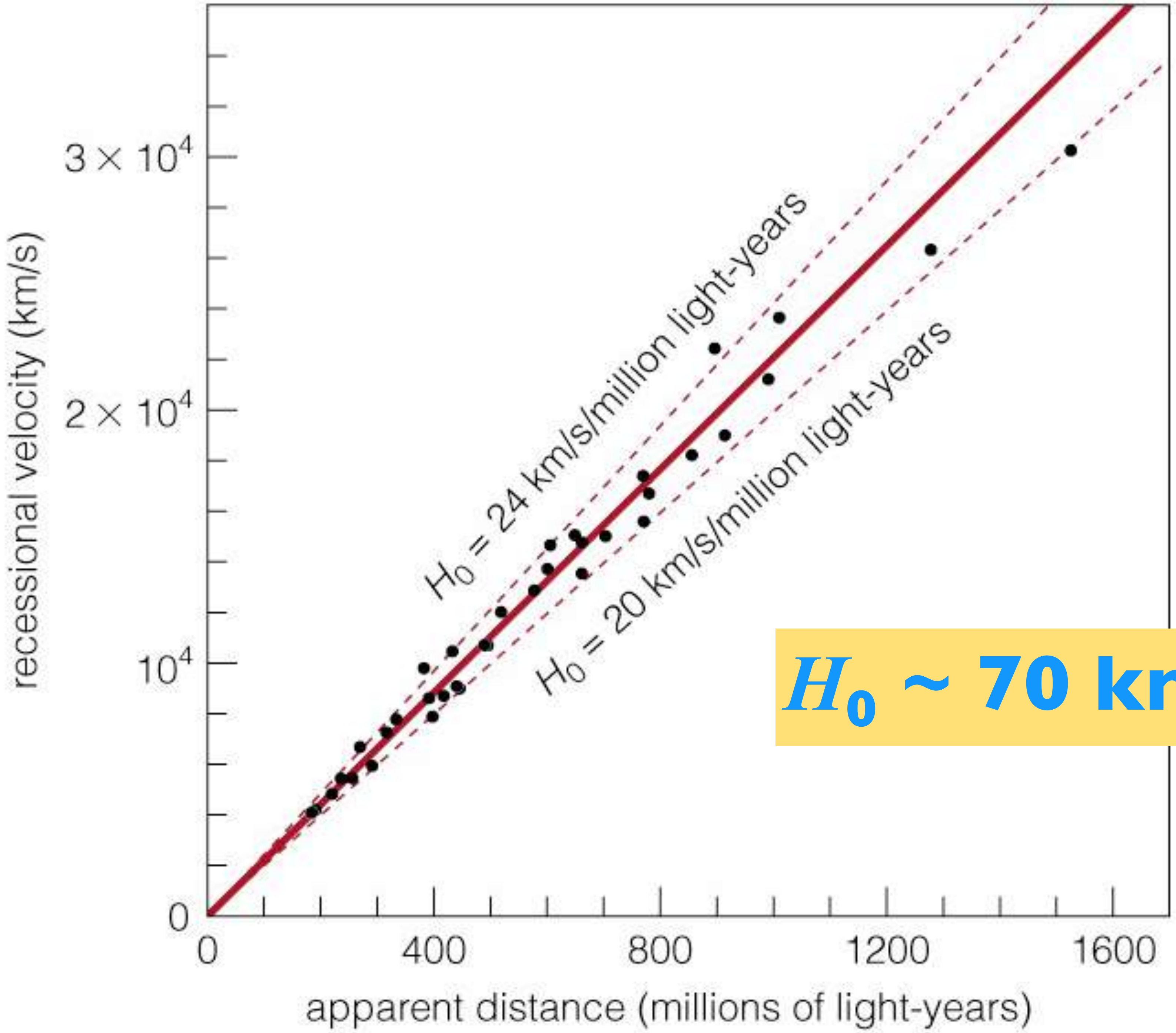
The more distant a galaxy is, the faster it is receding!!

Quiz

Your friend leaves your house. She later calls you on her cell phone, saying that she's been driving at 60 miles an hour directly away from you the entire time, and is now 60 miles away. How long has she been gone?

A. 1 minute
B. 30 minutes
C. 60 minutes
D. 120 minutes

Recession velocity is proportional to the distance



H_0 ~ 70 km/s/Mpc

Hubble's Law: velocity = H_0 x distance

H_0: Hubble parameter

$[1/H_0]$ = [time] ~ cosmic age

Quiz

According to modern ideas and observations, what can be said about the location of the center of our expanding universe?

a) Earth is at the center.
b) The Sun is at the center.
c) The Milky Way Galaxy is at the center.
d) The universe does not have a center.

History of Cosmology

- Copernican Revolution (16th century)

(1473 - 1543)

In 1543 Nicolaus Copernicus published his treatise *De revolutionibus orbium coelestium* (*On the Revolutions of the Heavenly Spheres*), which presented a **heliocentric model** view of the universe. It took about 200 years for a heliocentric model to replace the **Ptolemaic model** (Earth is center).

During my lecture, a bright student reminded me that it's actually "Aristarchus of Samos" who first promoted the heliocentric model.

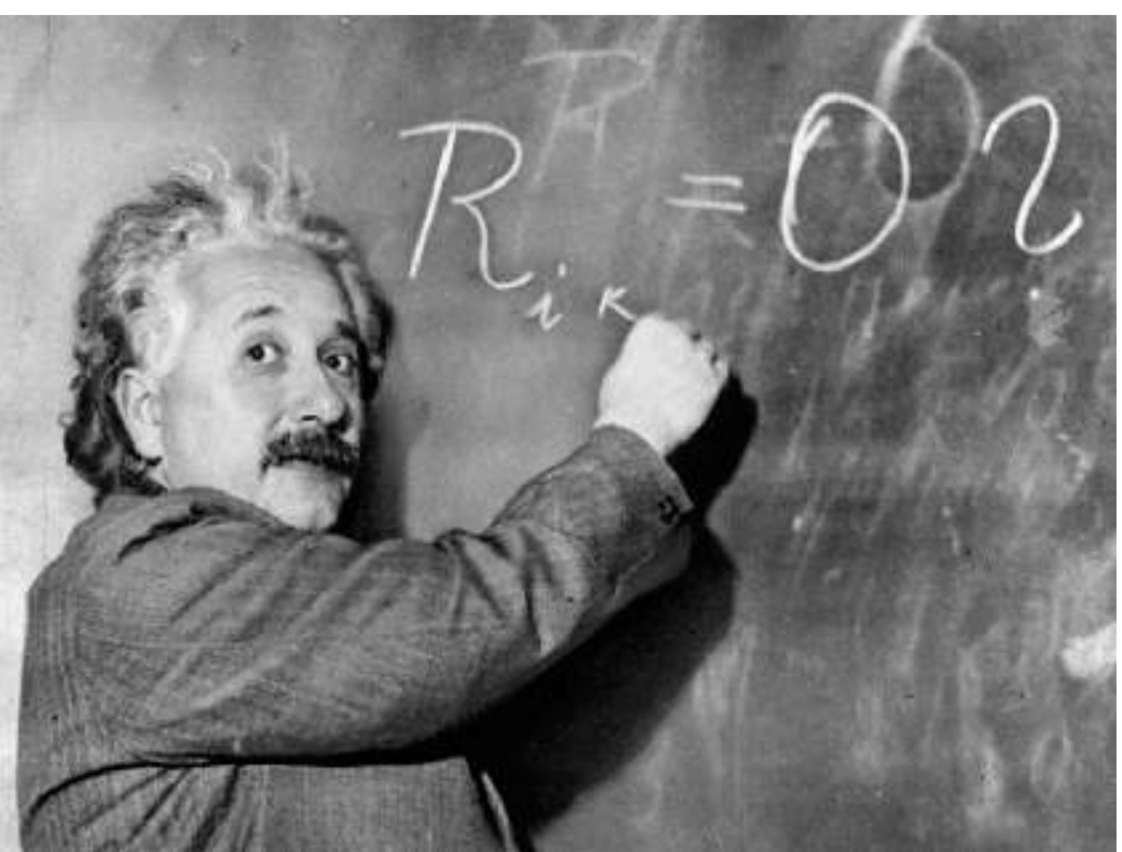
https://en.wikipedia.org/wiki/Aristarchus_of_Samos

History of Cosmology

(1473 - 1543)

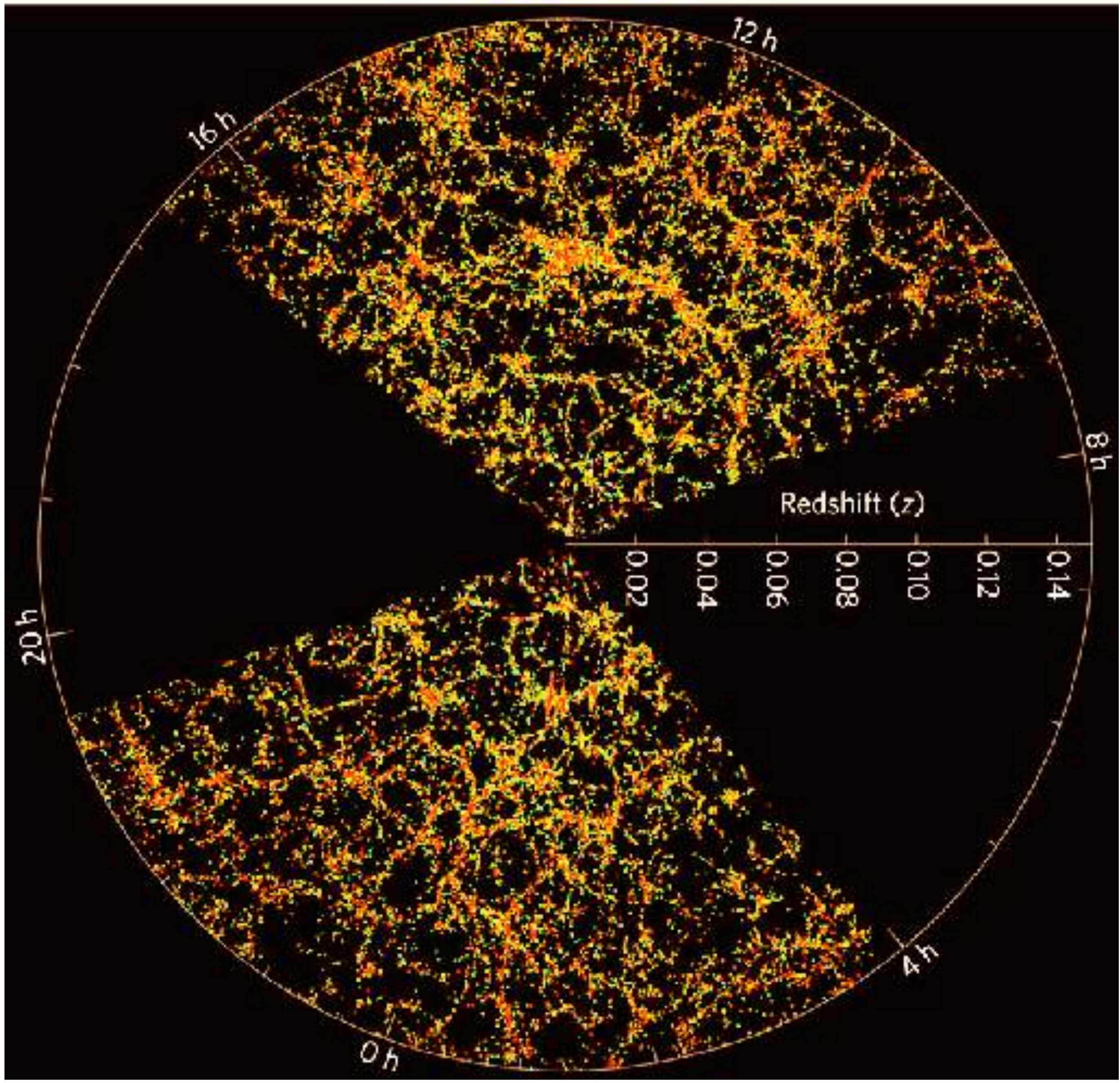
- Copernican Principle (16th-17th century)
- 1915-16 Einstein: theory of general relativity

The Cosmological Principle



The Universe is
homogeneous & isotropic

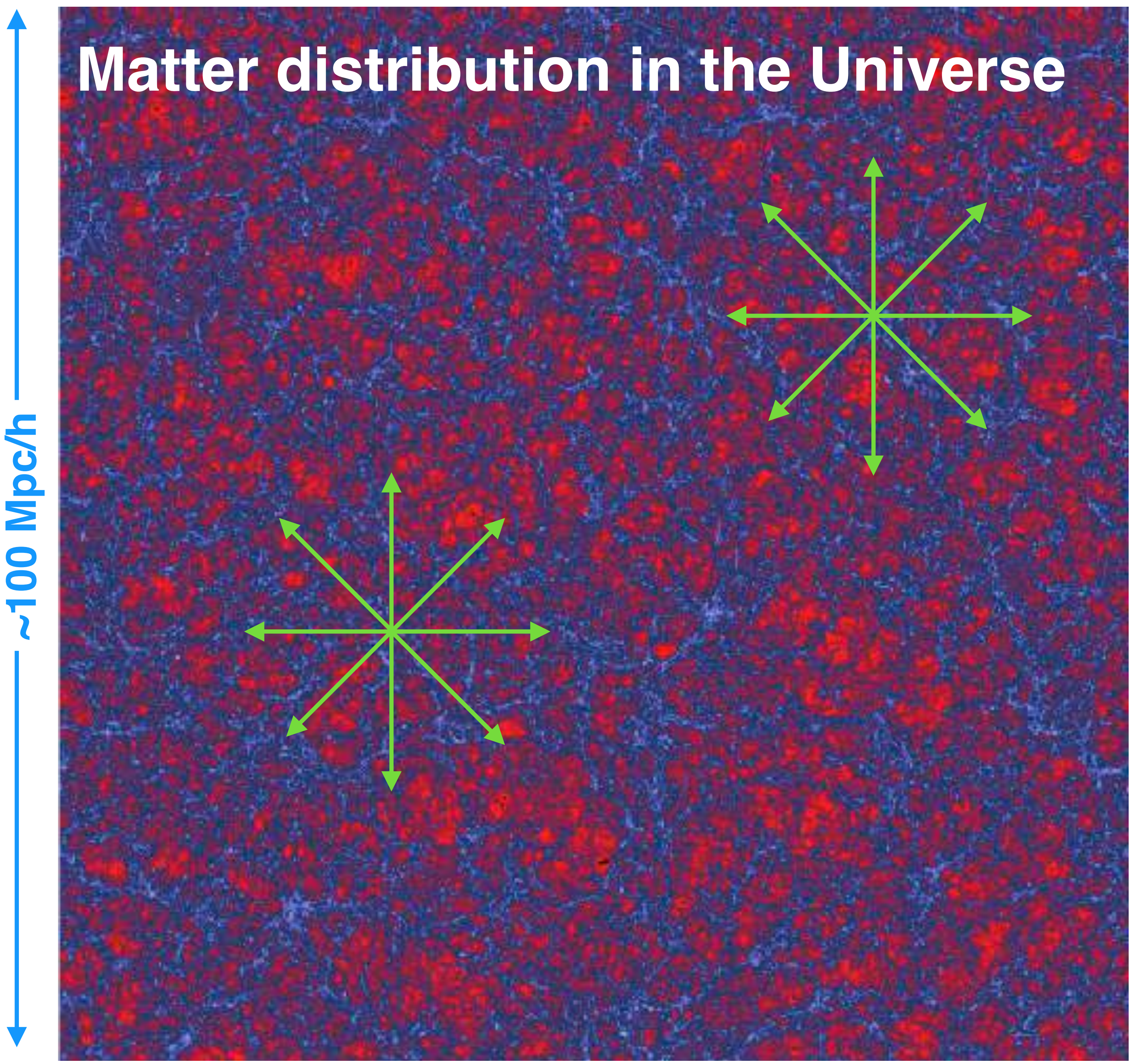
SDSS

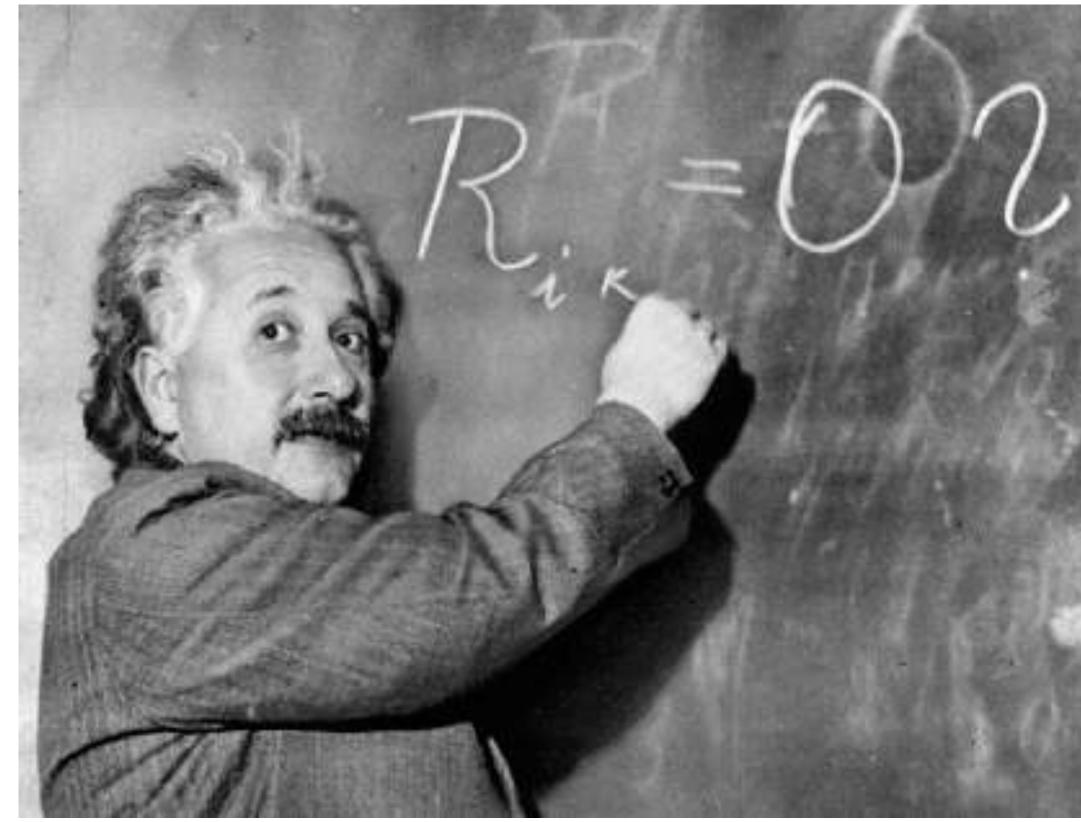


Isotropy does not necessarily imply **homogeneity** without the additional assumption of Cosmological Principle.

Cosmological Principle

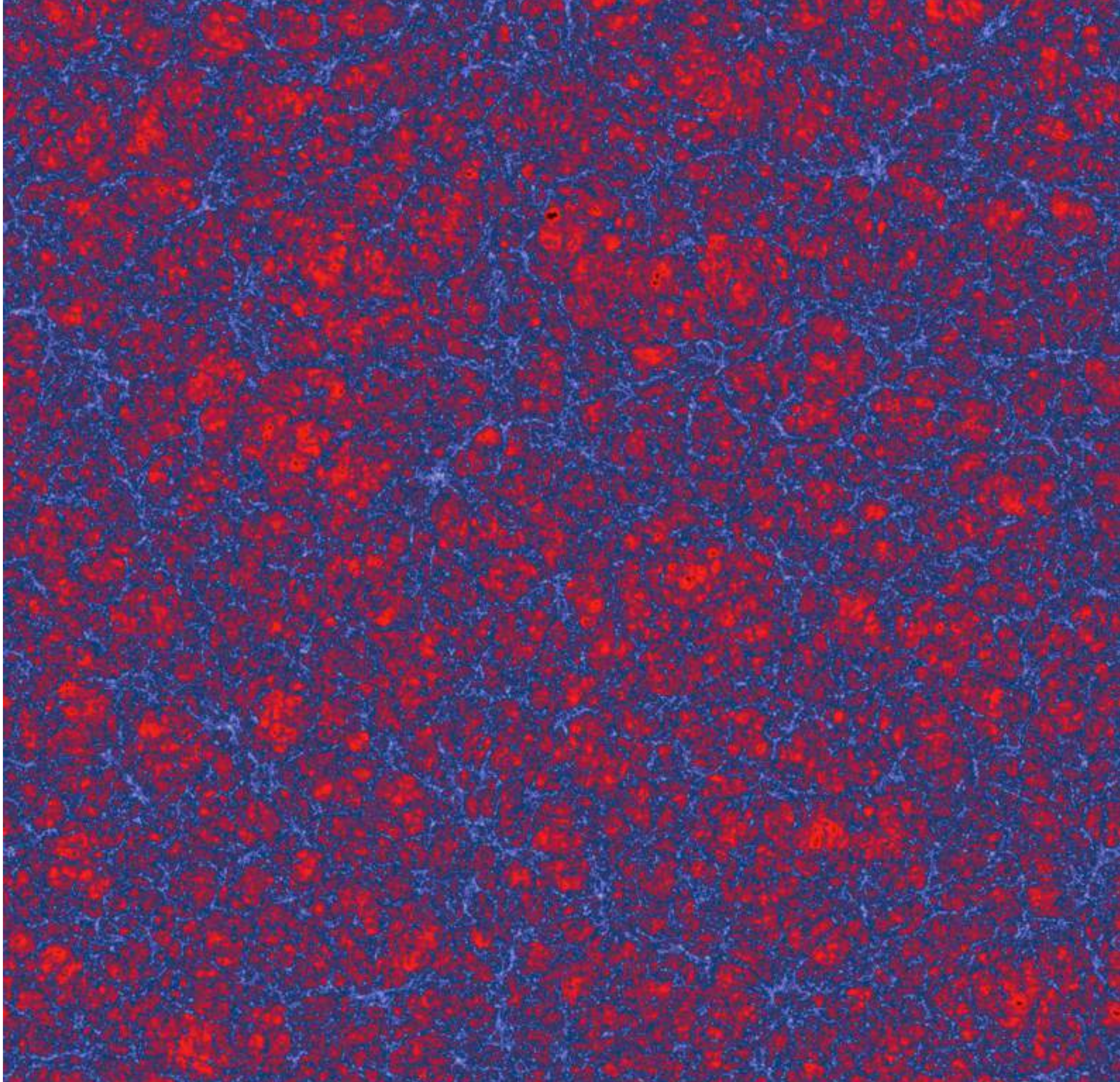
``**Isotropic & Homogeneous**”



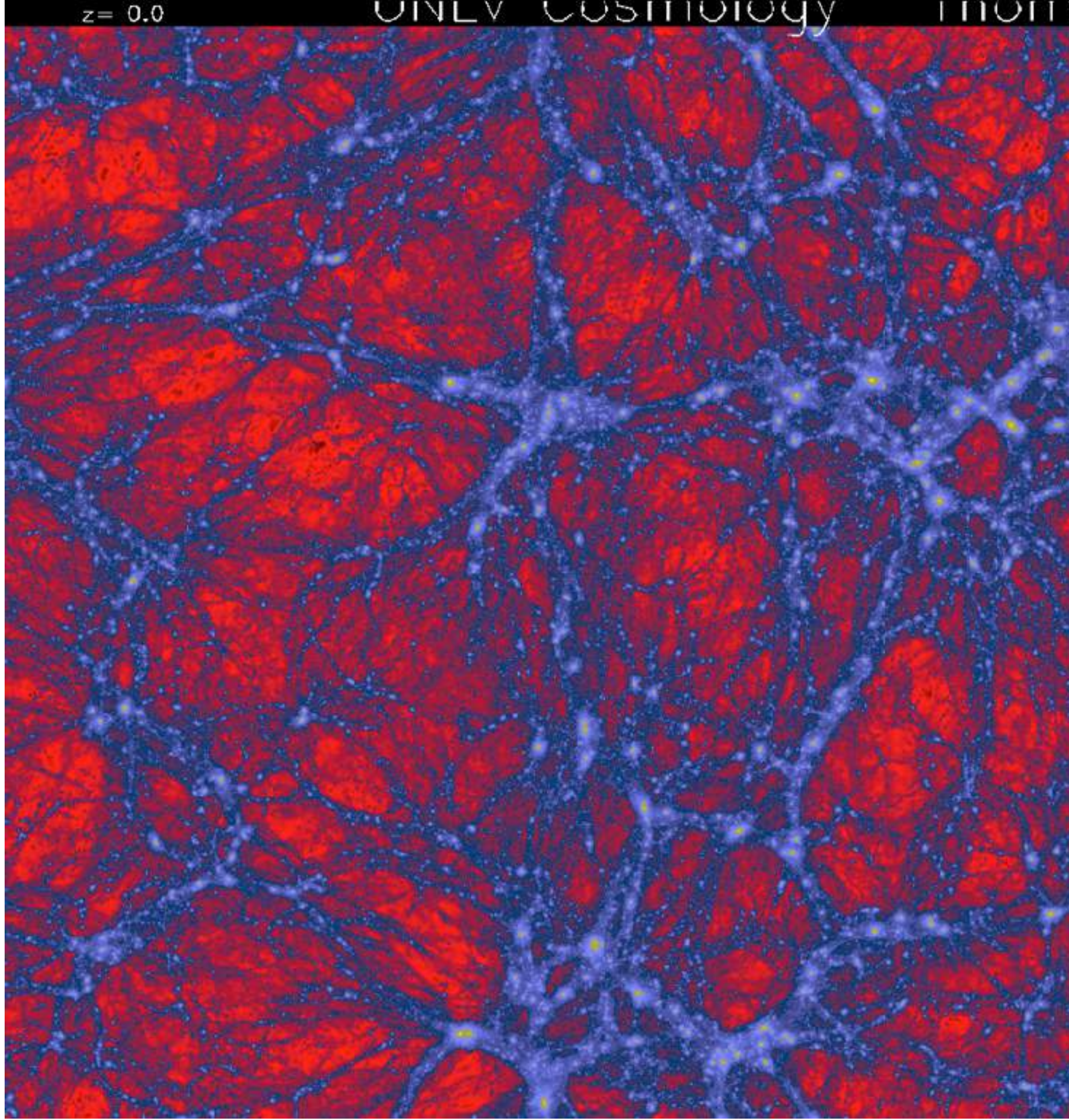


Albert Einstein, 1879-1955

1 Gpc/h
across



100 Mpc/h
across



Quiz

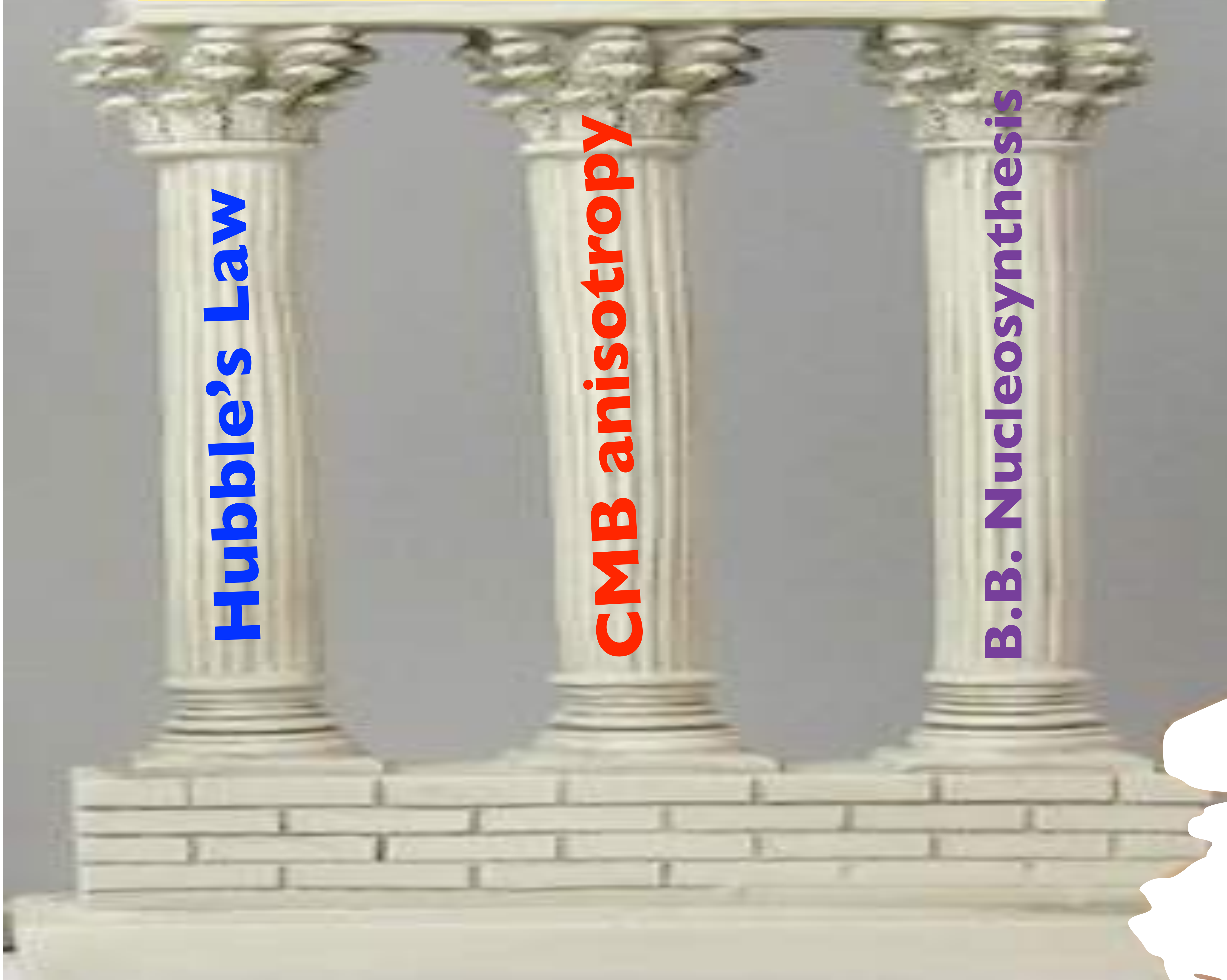
If our universe is expanding, what are the implications for the separation between two stars within our galaxy?

a) The two stars are moving farther apart.

b) The two stars are moving closer together.

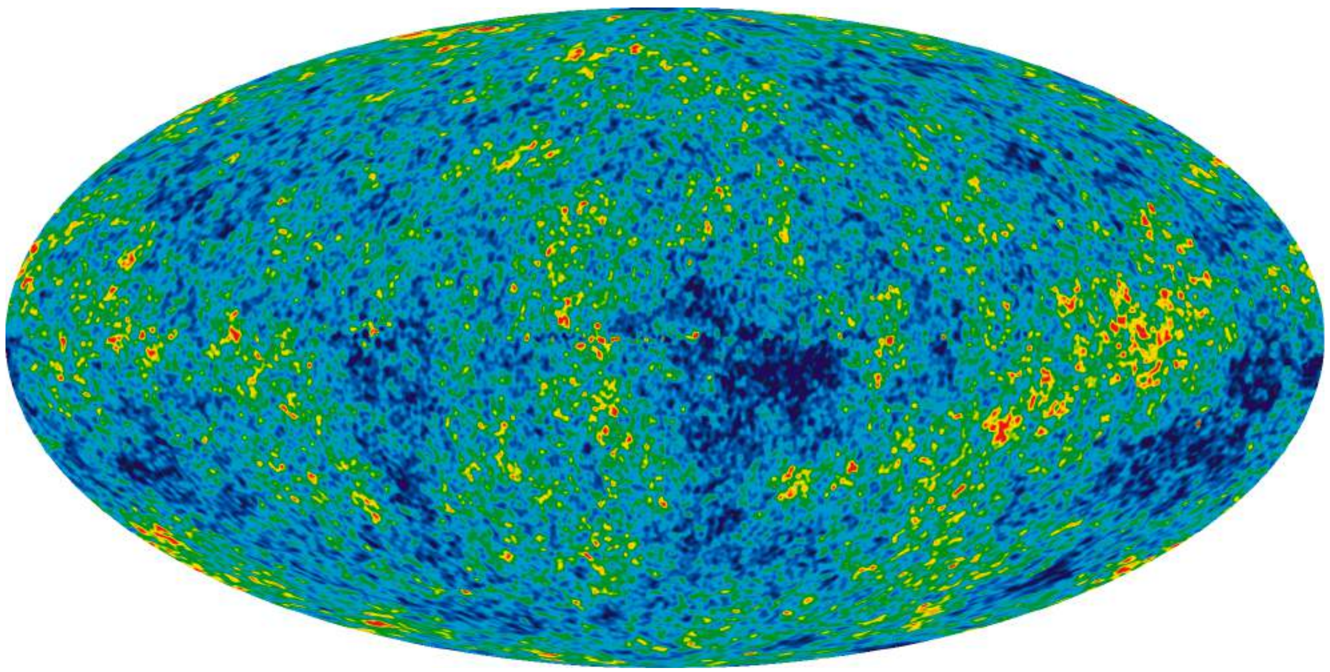
c) The distance between the two stars is unaffected.

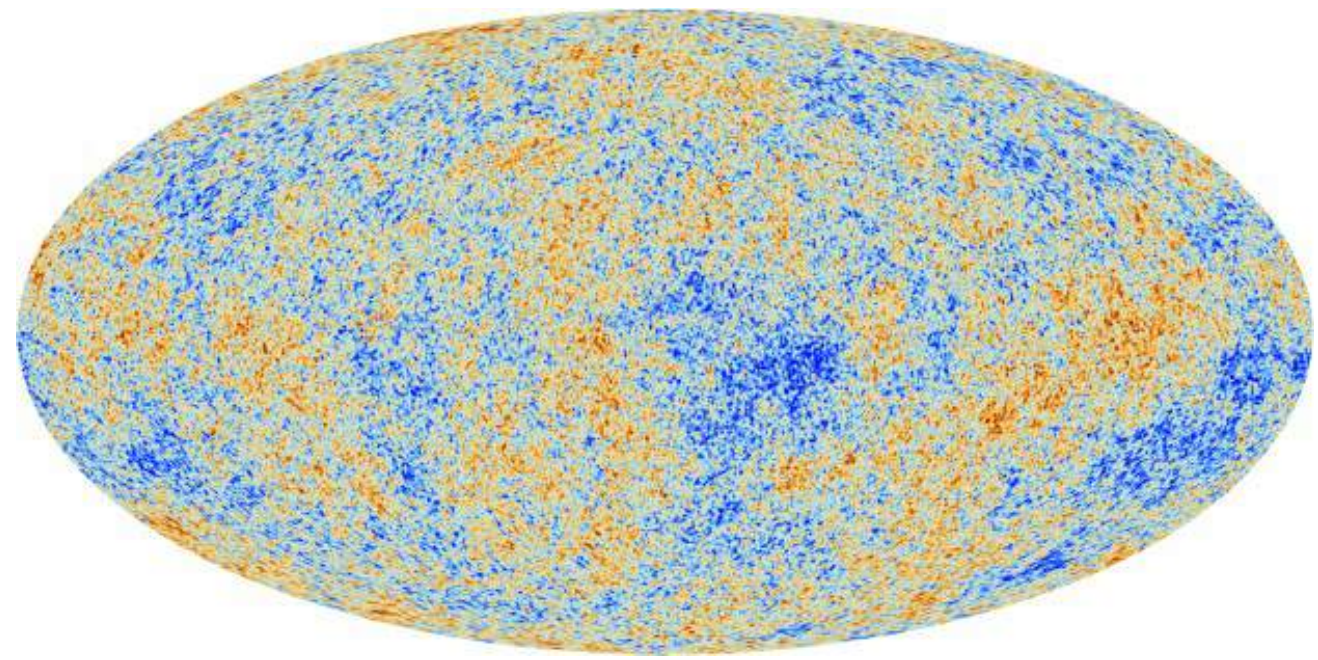
BIG BANG COSMOLOGY

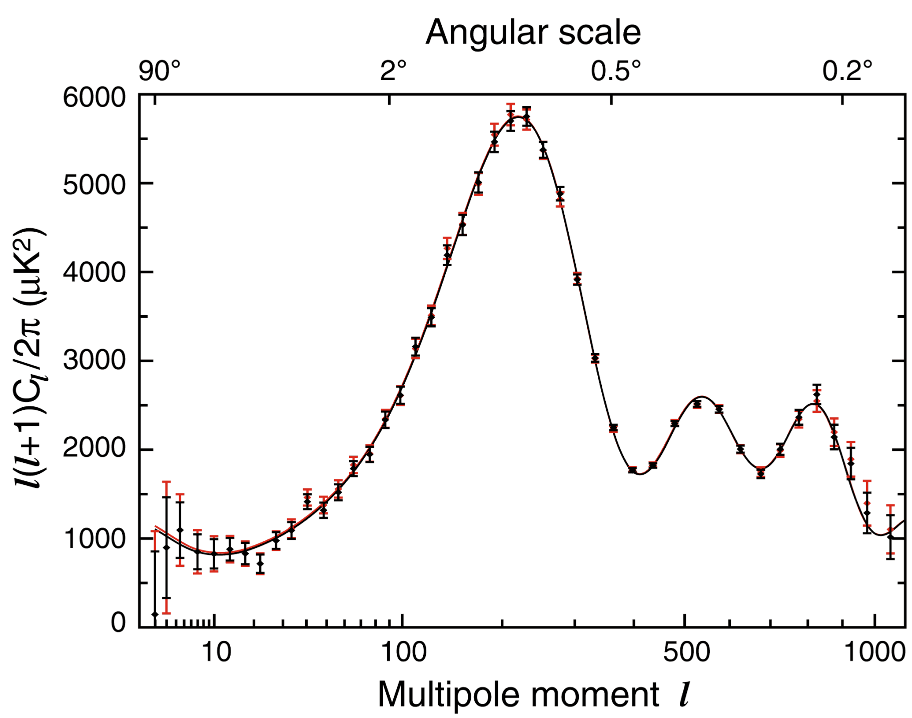


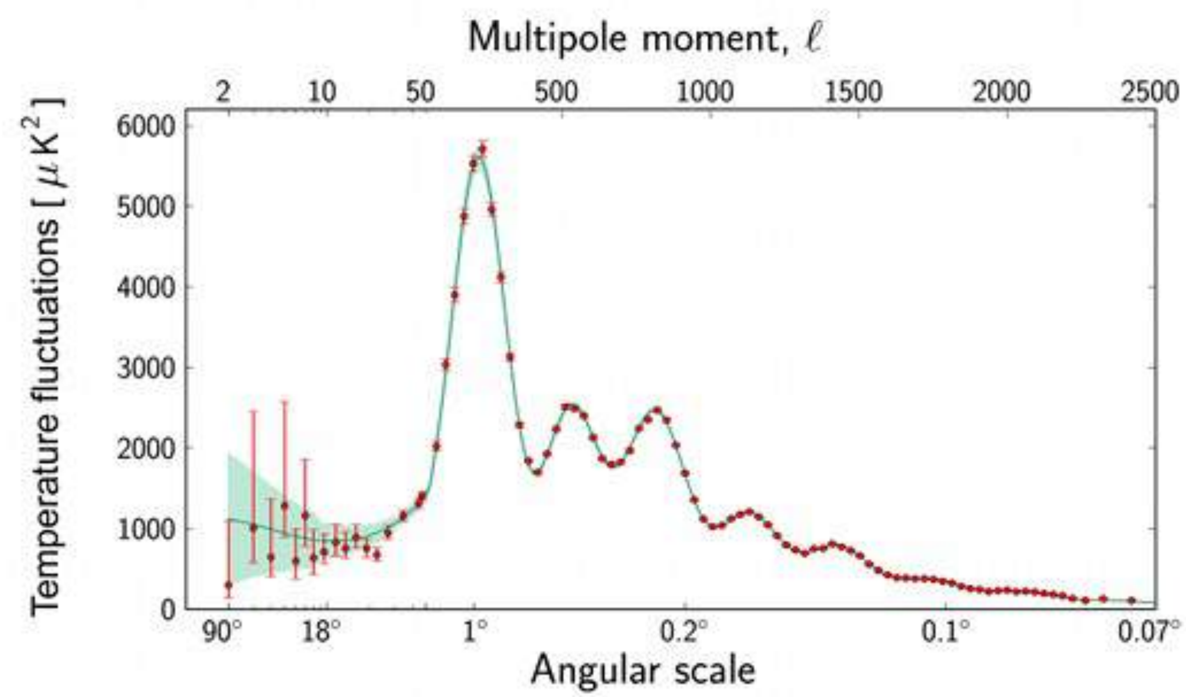
WMAP

Planck









WMAP9; Hinshaw+ '13

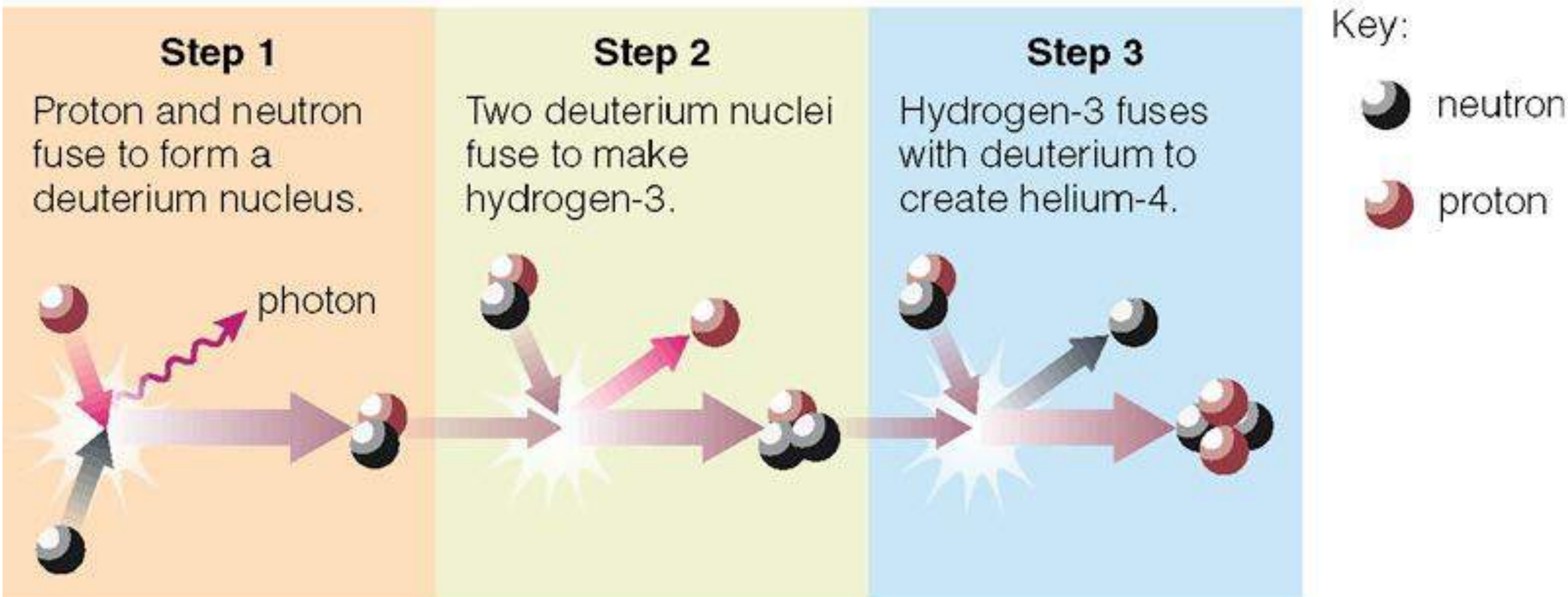
ESA March 2013 ('09-'13)

T ~ 2.73K black body with ~10^{-5} fluctuations

Movie — Geometry of the Universe

NASA

Hydrogen and **Helium** were made right after the Big Bang.



Protons and neutrons combined to make long-lasting helium **nuclei** when universe was ~ **3 minutes old**

Big Bang theory prediction: **75% H, 25% He** **(by mass)**

(+ a bit of Li)

Matches observations of nearly primordial gas

Quiz

Which of these abundance patterns is an unrealistic chemical composition for a star?

A.	25% H	75% He	less than 0.02% other
B.	50% H	48% He	2% other
C.	70% H	28% He	2% other
D.	95% H	5% He	less than 0.02% other

Cosmic Energy Budget

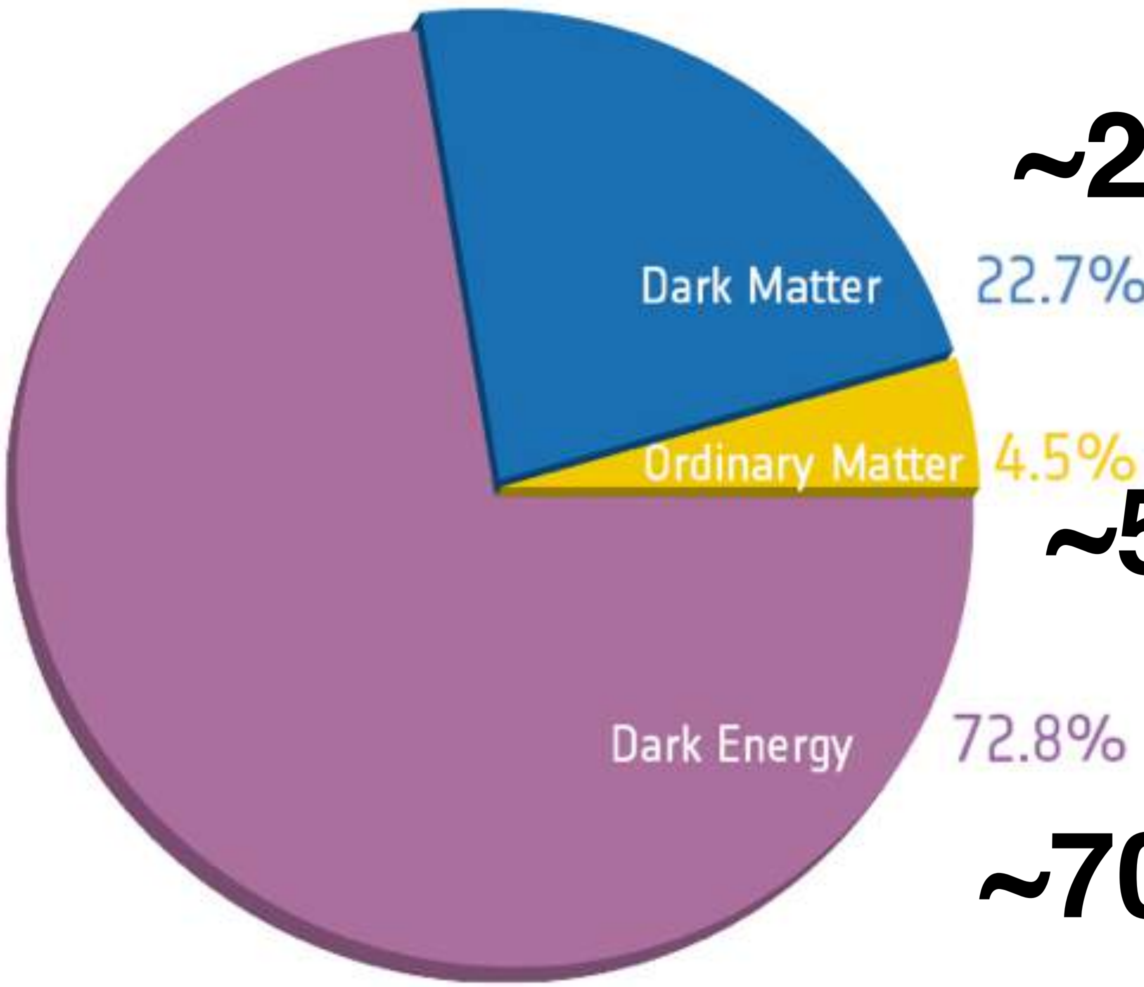
flat Λ universe

$$\frac{\Omega_{\rm DM}}{\Omega_b} \sim 5$$

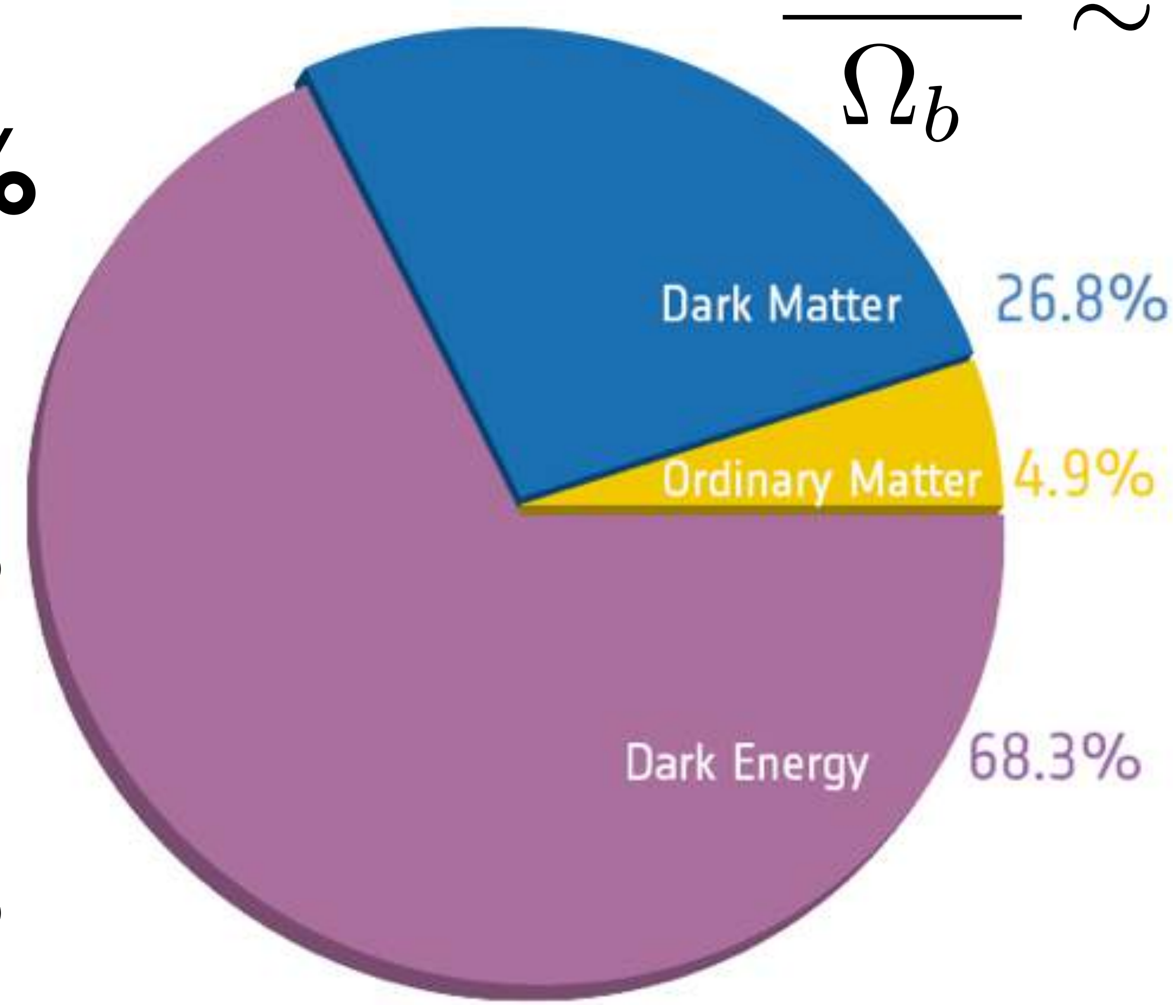
~25%

~5%

~70%



Before Planck

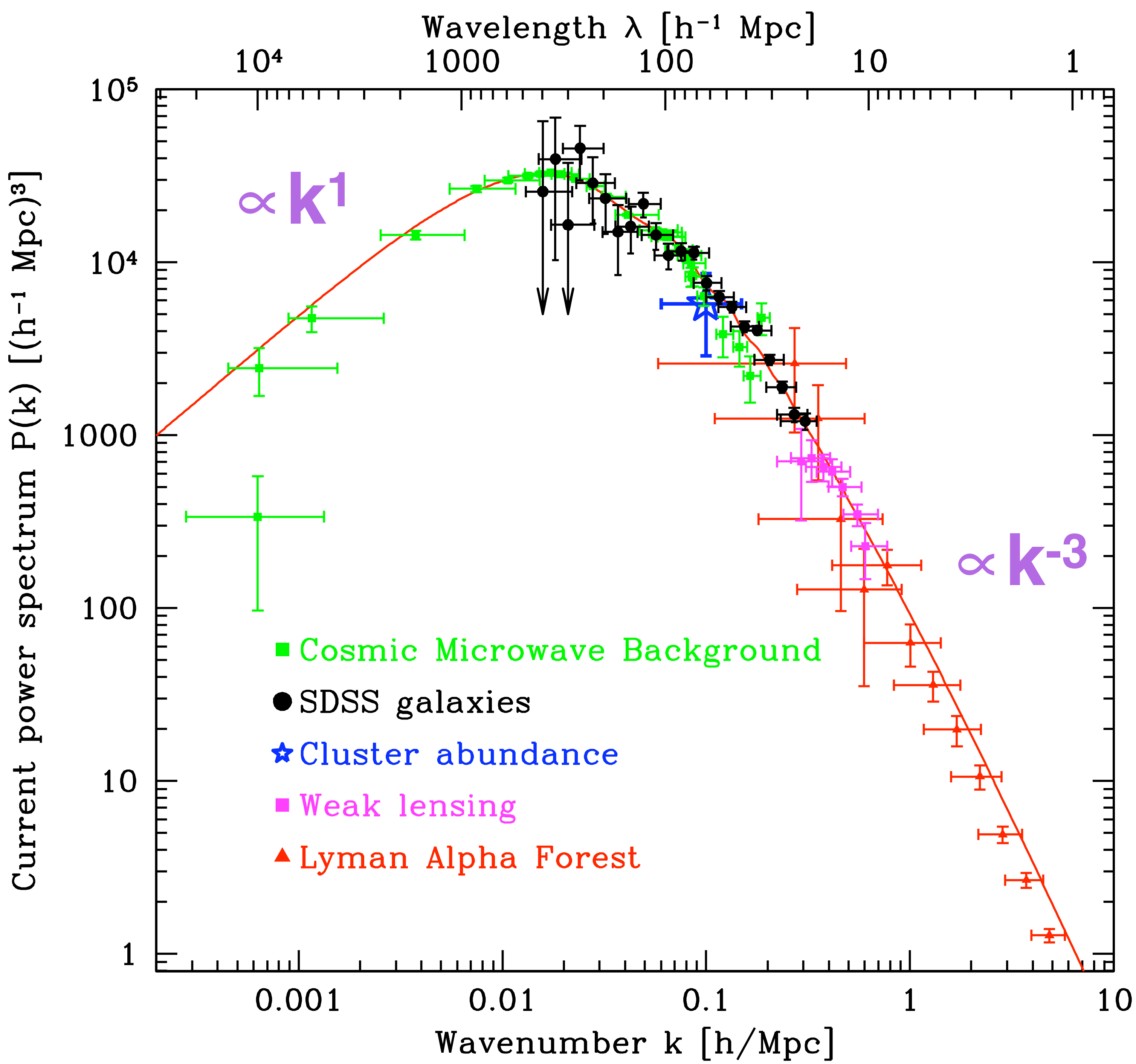


After Planck

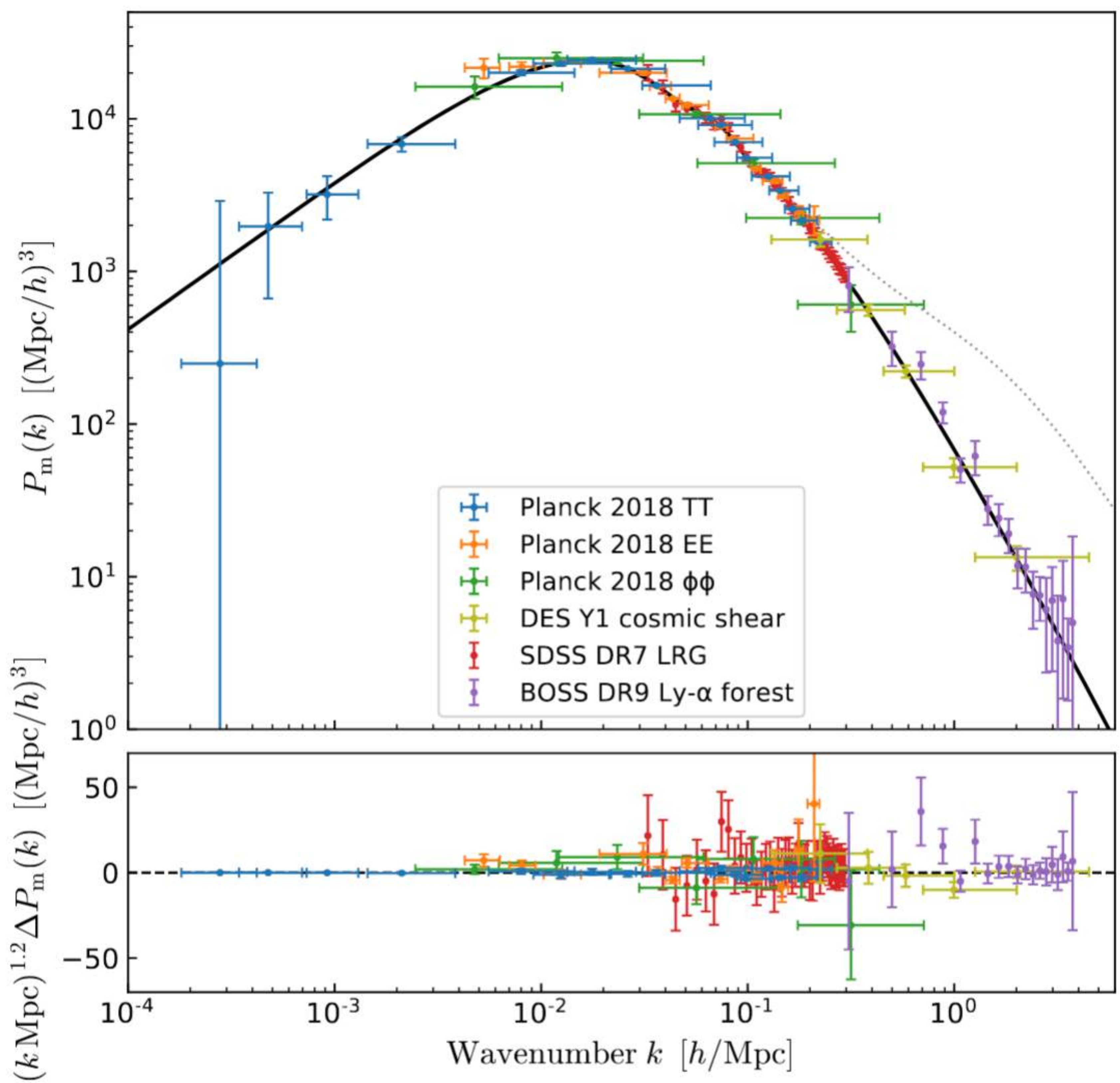
``Precision Cosmology"

ESA 2013

Matter Power Spectrum



Tegmark '04



Chabanier+'19

Big Issues in Modern Cosmology

Dark Matter

Dark Energy

Evidence of Dark Matter

and its success on large scales ($\gtrsim$10 kpc)

- stellar motions: Lord Kelvin (1884); Kapteyn '22; Oort '32
- **Galaxy clusters** — ~80% of mass is dark (Zwicky '33)
- **Galaxy rotation curves** (Rubin & Ford '70)
- **Galactic disk stability (stellar kinematics)** (Ostriker & Peebles '74)
- **Cosmic Microwave Background** (**CMB)** (angular power spec)
- **Structure formation** — P(k), galaxy clustering, Ly-α forest
- **Gravitational lensing** (strong & weak)
- **Bullet Cluster** (Markevich+'02; Clowe+'06)
- ……

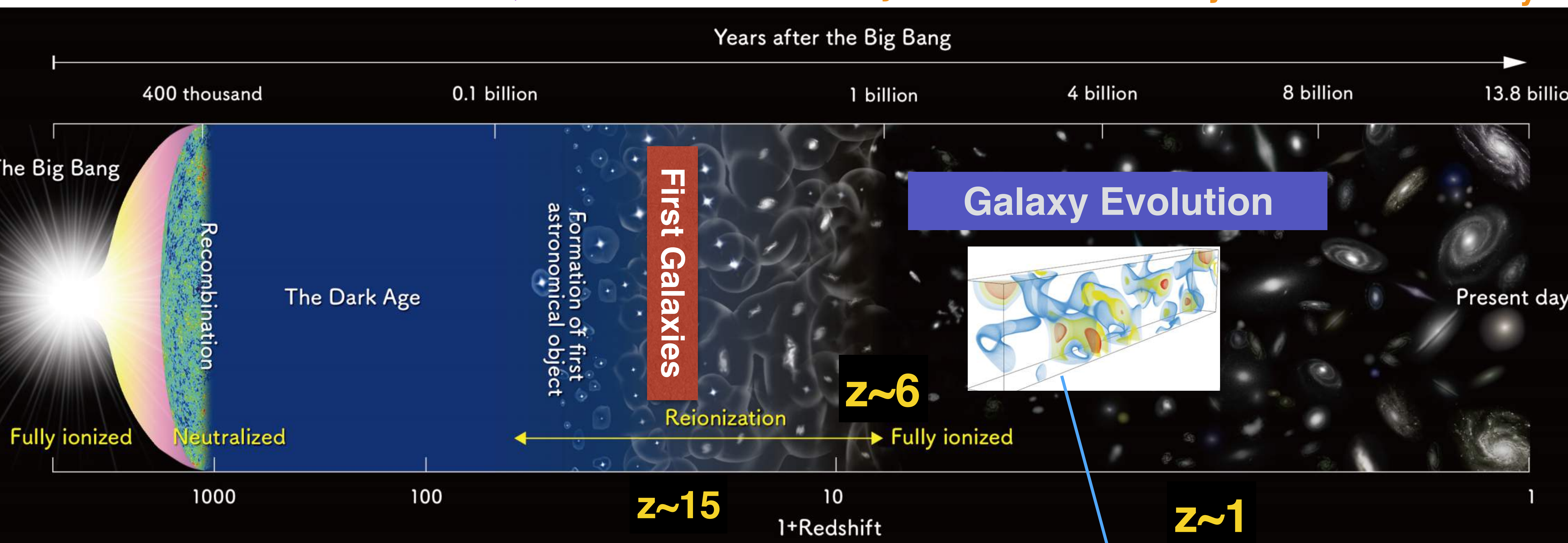
"Standard Model" of Cosmic Structure Formation (ΛCDM model)

Cosmic time

1 Gyr

6 Gyr

13.8 Gyr



JWST

HST

SKA

PFS

HSC

DES

MOONS

EUCLID…

SDSS, 2dF

Image: NAOJ

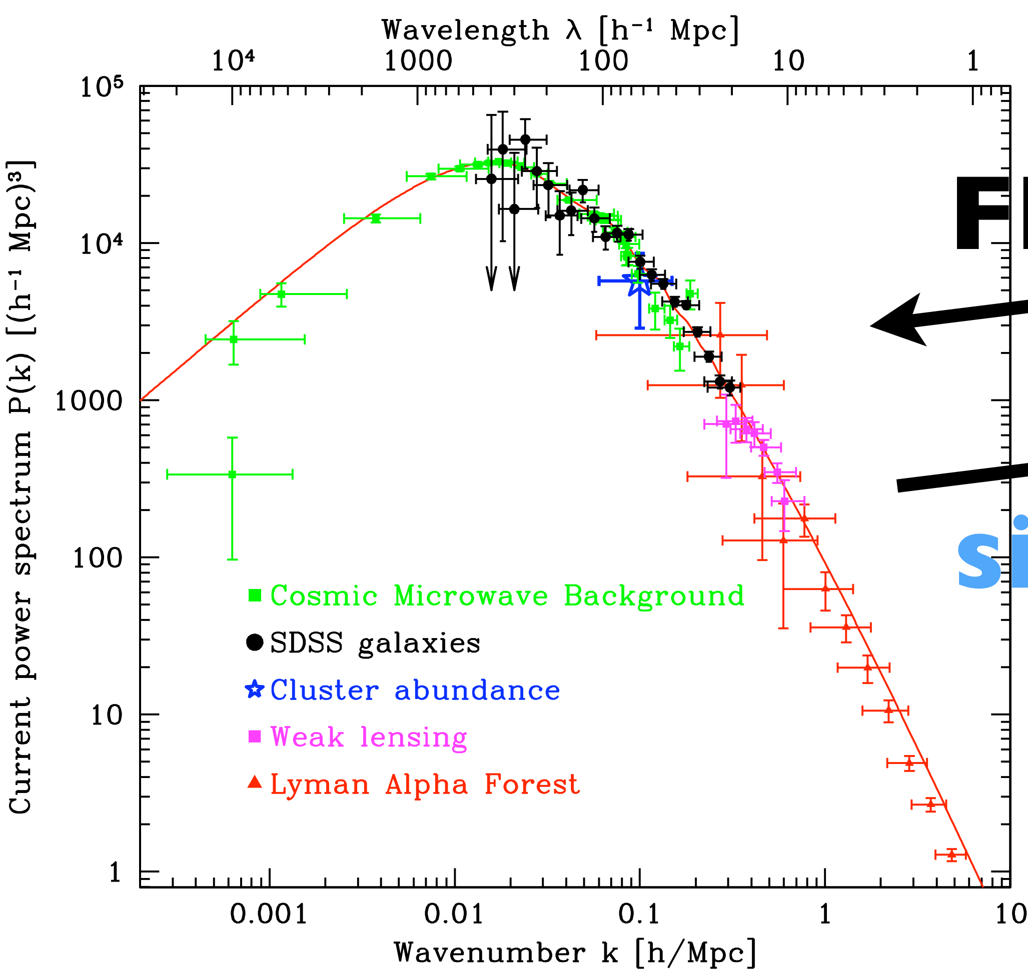
Concordance ΛCDM model

WMAP, Planck
SN Ia

$$(\Omega_M, \Omega_\Lambda, \Omega_b, h, \sigma_8, n_s) \approx (0.3, 0.7, 0.04, 0.7, 0.8, 0.96)$$

$$\Omega_{DM} \approx 0.26$$

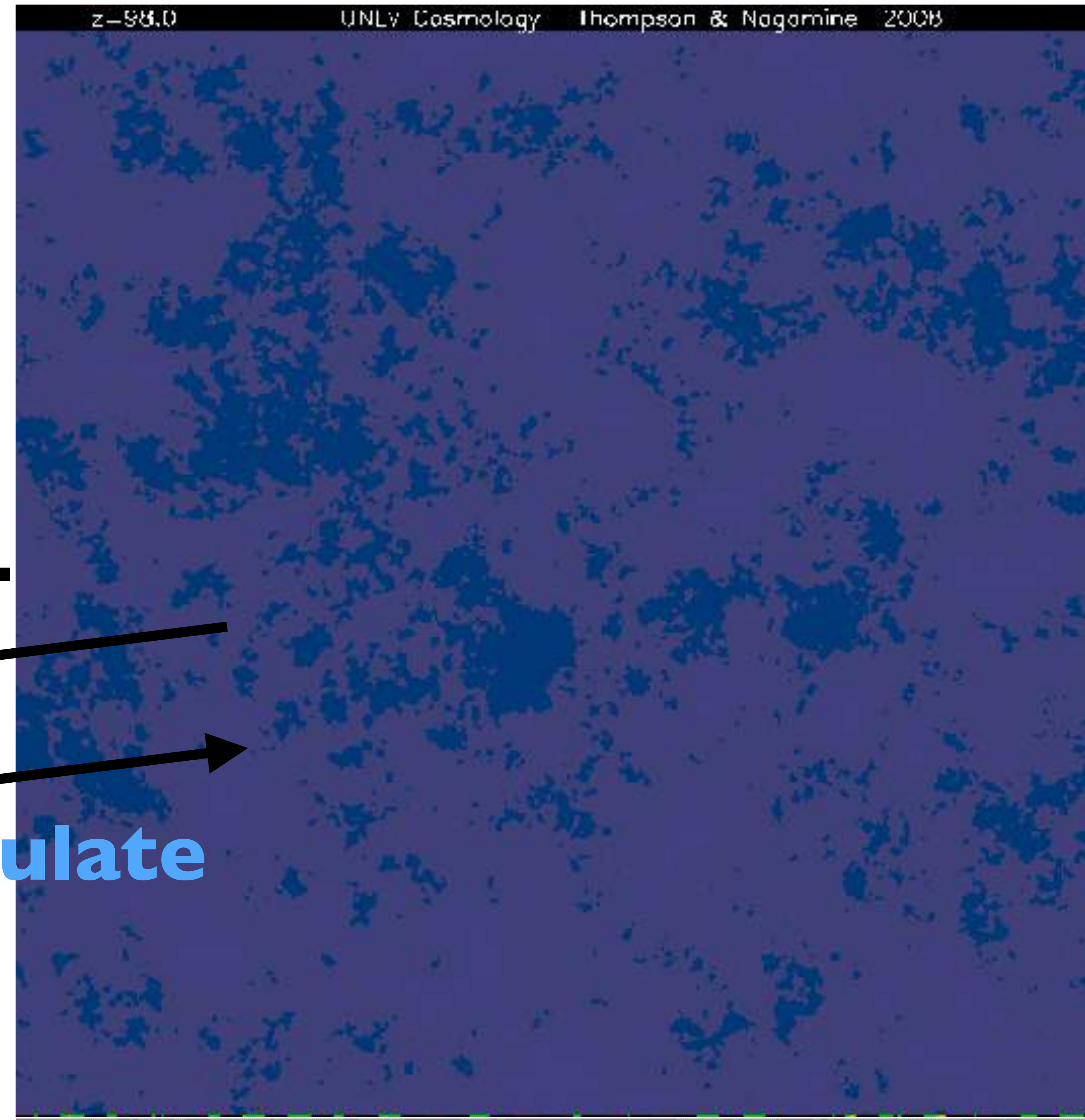
- Successful on large-scales (>1Mpc)
- Can we understand galaxy formation in this context?



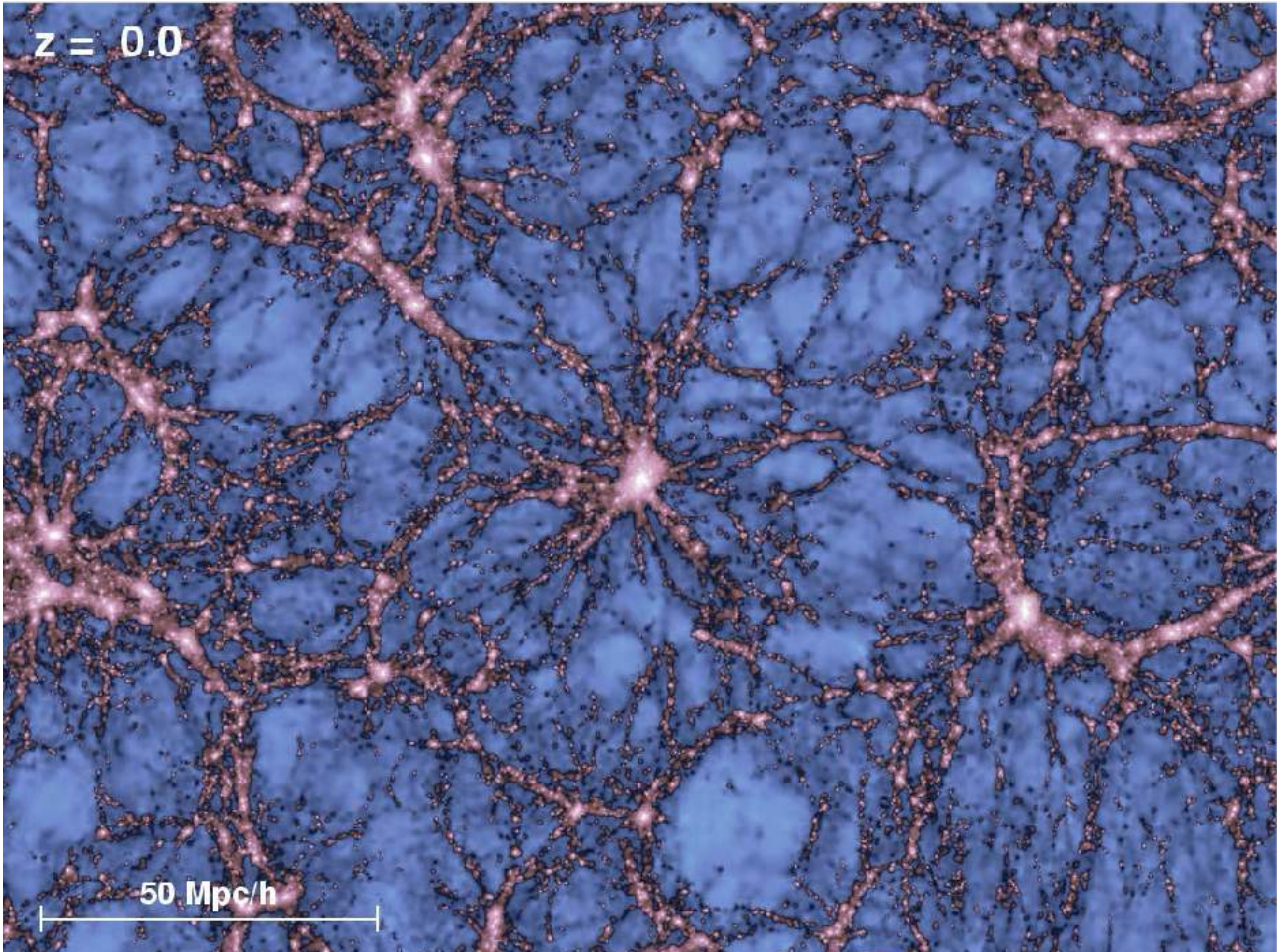
Tegmark+ (2004)

FFT

simulate



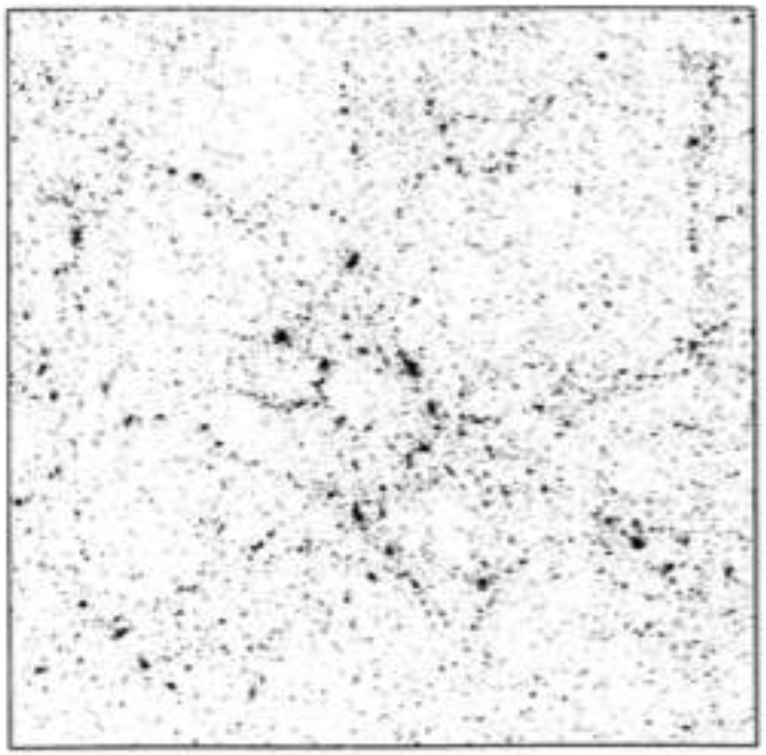
"Back-bone of structure"



Movie

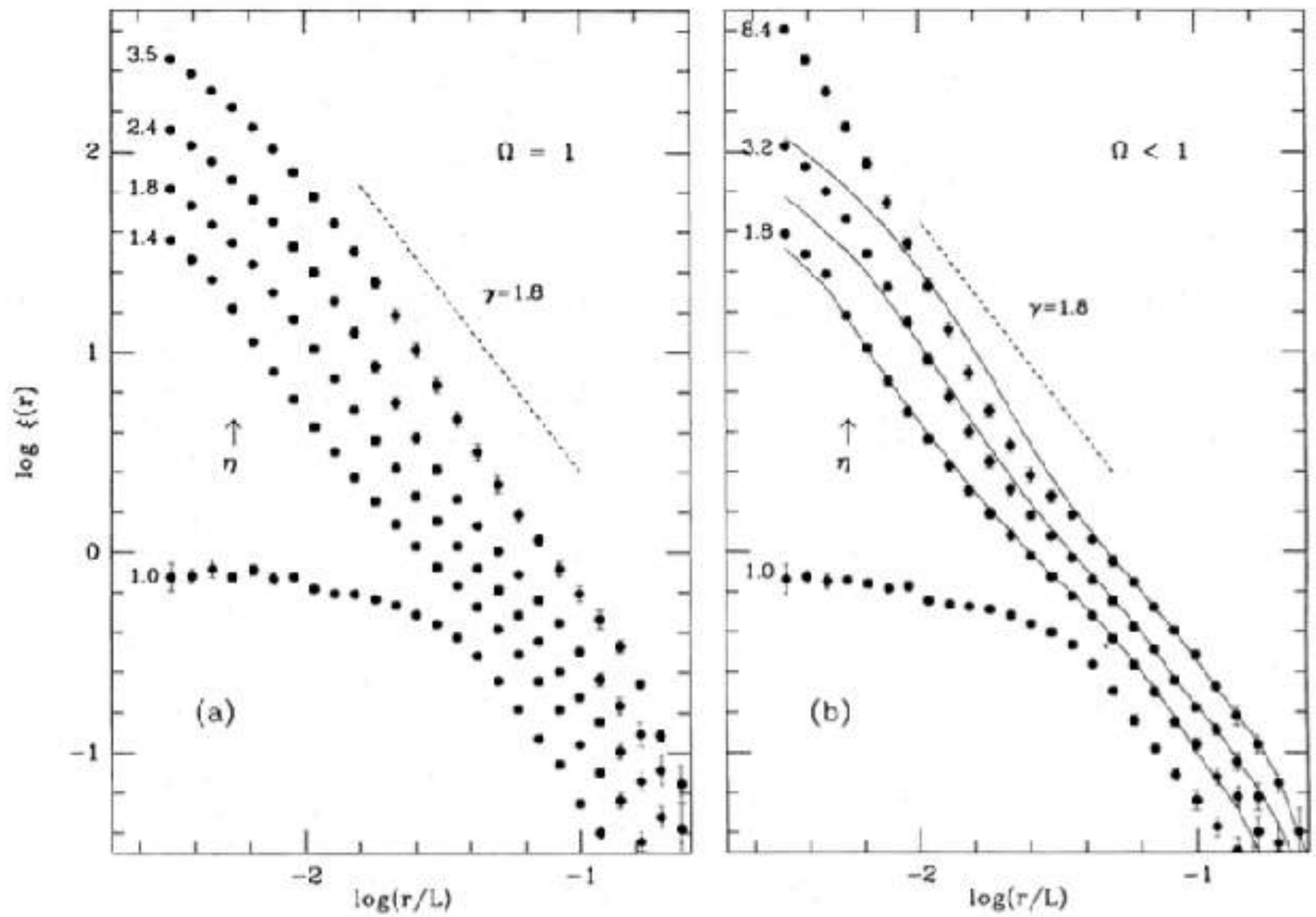
Millenium Simulation

Galaxy Correlation Function & Bias



Davis+'85

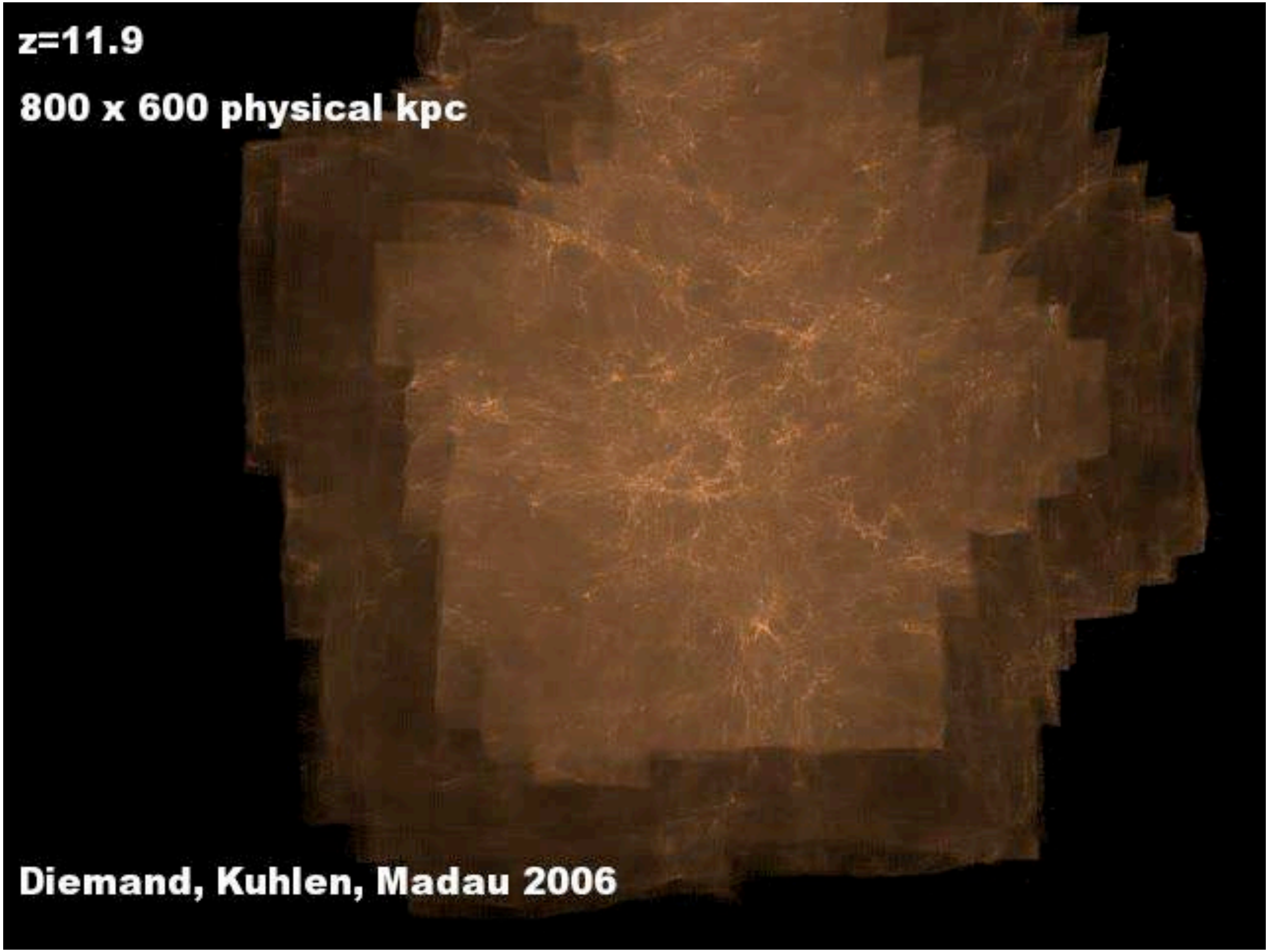
only 32^3 N-body!



CDM simulation can explain galaxy clustering w/ the idea of "bias"

$$\delta_{\rm gal} = b\,\delta_{\rm m}$$

Hierarchical Structure Formation



(showing only dark matter)

Einstein Equation

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

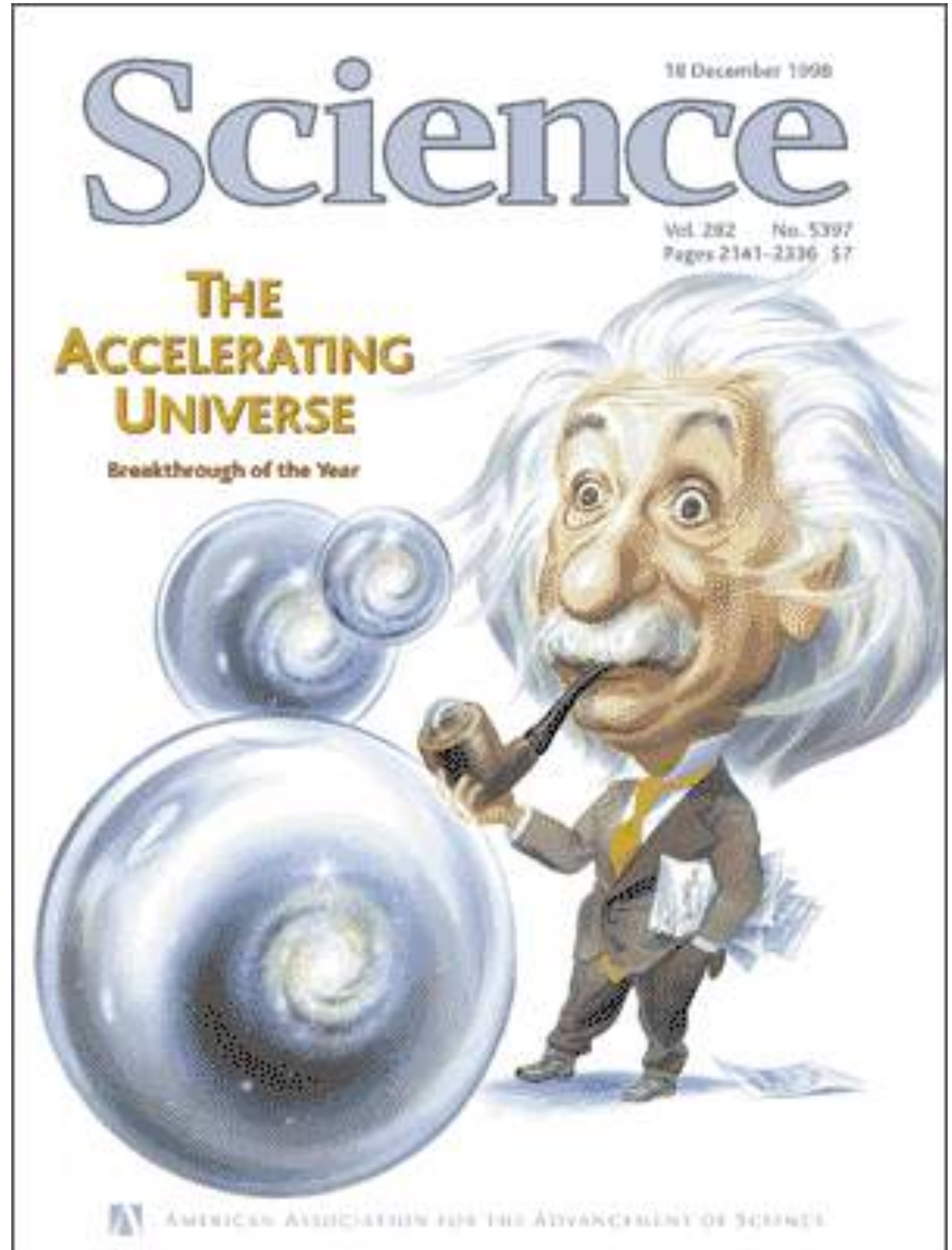
Space-time

Energy-momentum

Cosmological Constant

Non-zero Cosmological Constant !

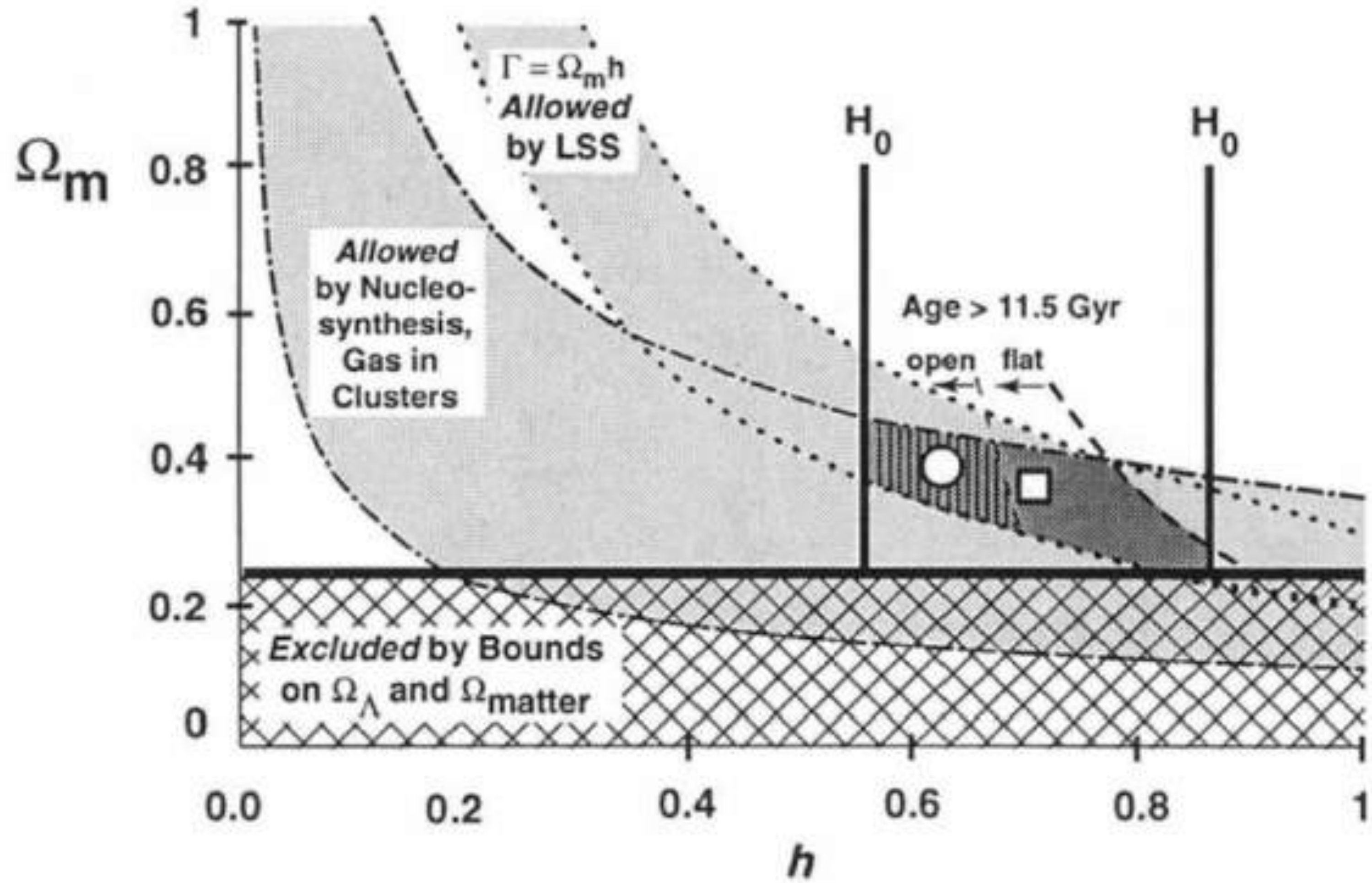
- In **1998**, two groups independently reported the non-zero cosmological constant
- They observed distant Type Ia supernovae to make a better Hubble diagram.
- "Λ" acts as a repulsive force
- Non-zero Λ suggests accelerating universe!



Dec 1998 issue

The observational case for a low-density Universe with a non-zero cosmological constant

J. P. Ostriker* & Paul J. Steinhardt†



The observations do not yet rule out the possibility that we live in an ever-expanding 'open' Universe, but a Universe having the critical energy density and a large cosmological constant appears to be favored.

1995, Nature, 377, 600

Friedmann Equation

✦ Plug in **R-W metric** to **Einstein Eq.** :

① **0-0 component:** $$\boxed{\left(\frac{\dot a}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}}$$ (NB: ρ = mass density)

if we use **energy density** $\varrho = \rho c^2$, then RHS $= \frac{8\pi G}{3c^2}\varrho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$

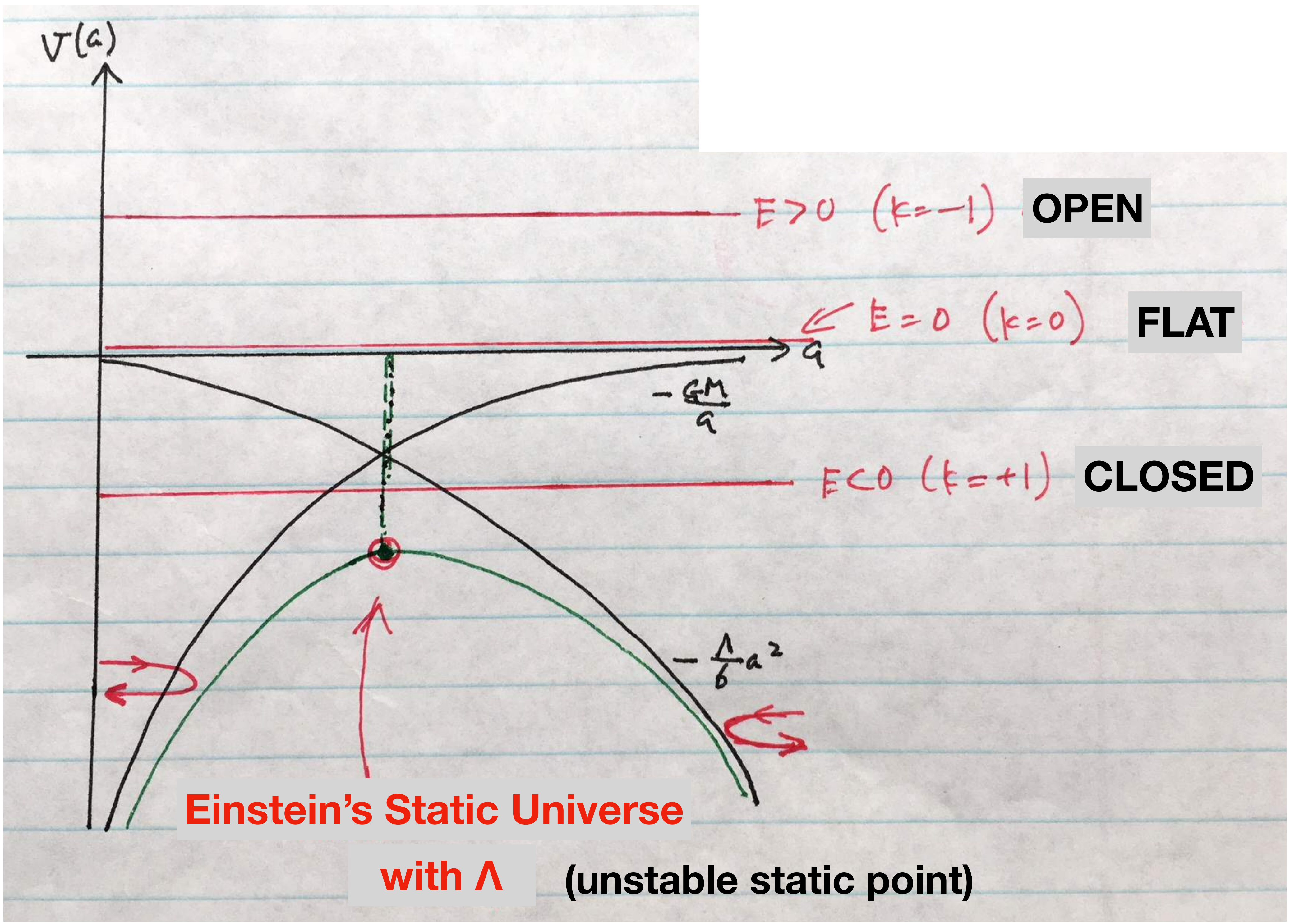
② **i-j component:** $$\boxed{\frac{\ddot a}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{p}{c^2}\right) + \frac{\Lambda c^2}{3}}$$

Eq. ① can be rewritten as $$\frac{1}{2}\dot a^2 - \frac{GM}{a} - \frac{\Lambda}{6}a^2 = E \quad \text{—③}$$

where $M = \frac{4\pi}{3}a^3\rho$, $\quad E = -\frac{kc^2}{2}$

$$\frac{1}{2}\dot{a}^2 - \underbrace{\frac{GM}{a} - \frac{\Lambda}{6}a^2}_{\text{potential } V(a)} = E$$

analogy with classical mechanics



✦ **So, in the Friedman Eq. set,**

3 unknowns: $\rho(t),\ p(t),\ a(t)$

$\Lambda,\ k$: constant

➡ **2 independent eqns + EOS** $\quad p = f(\rho)$

✦ **Examples of EOS:** **(e.g. perfect fluid in cosmology;** $p = w\rho$ **)**

(i) Relativistic matter: $p = \dfrac{1}{3}\varrho$

(photons, neutrino, …)

$$w = \frac{1}{3}$$

$$\varrho = \frac{N\langle h\nu\rangle}{V} \propto a^{-3}\,a^{-1} \propto a^{-4}$$

(ii) Non-relativistic (dust): $p = 0$

$$w = 0$$

$$\rho = \frac{N m_p}{V} \propto a^{-3}$$

Cosmological Parameters

✦ **Hubble Param.** $$H(t) = \frac{\dot{a}}{a}$$

Present value: $H_0 = H(t_0)$ **~ 70 km/s/Mpc**

Hubble Time: $t_H = H_0^{-1} = 9.78e9\, h^{-1}$ **yr**

Hubble distance: $d_H = cH_0^{-1} = 2998 h^{-1}$ **Mpc** **~ 3 Gpc**

✦ **Density Param.** $$\Omega(t) = \frac{\rho(t)}{\rho_{\rm crit}(t)}$$

Critical density: $$\rho_{\rm crit}(t) \equiv \frac{3H(t)^2}{8\pi G}$$

Current critical density: $$\rho_{\rm c,0} \equiv \frac{3H_0^2}{8\pi G} = 2.775e11\, h^2\, \mathrm{M}_\odot\, \mathrm{Mpc}^{-3}$$
$$= 1.88e{-29}\ h^2\, \mathrm{g\, cm}^{-3}$$

Friedmann Eq.① → $$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$1 = \frac{8\pi G}{3H^2}\rho - \frac{k}{a^2H^2} + \frac{\Lambda}{3H^2}$$

$$= \frac{\rho_m}{\rho_c} + \frac{\rho_k}{\rho_c} + \frac{\rho_\Lambda}{\rho_c}$$

I.e., $$\boxed{1 = \Omega_m + \Omega_k + \Omega_\Lambda}$$

$$\boxed{\Omega_k \equiv -\frac{kc^2}{a^2H^2} \qquad \Omega_\Lambda \equiv \frac{\Lambda c^2}{3H^2}}$$

$$\rho_k = -\frac{3kc^2}{8\pi G a^2} \qquad \rho_\Lambda = \frac{\Lambda c^2}{8\pi G}$$

✦ Deceleration Param.

$$q \equiv -\frac{\ddot{a}a}{\dot{a}^2}$$

Present value: $q_0 = q(t_0)$

✦ Redshift :

$$1 + z = \frac{a_0}{a} = \frac{1}{a}$$

✦ Other important constants to memorize:

$$G \sim 6.67\,e{-8} \quad \text{(cgs)}$$

$$c \sim 3\,e\,10 \text{ cm s}^{-1}$$

$$m_p \sim 1.6e{-24} \text{ g}$$

$$M_\odot \sim 2e33 \text{ g}$$

$$L_\odot \sim 3.83\,e\,33 \text{ erg s}^{-1}$$

$$\sigma_{\rm SB} \square\ 5.7e{-}5 \text{ cgs}$$

$$a_{\rm rad} = 4\frac{\sigma_{SB}}{c} \square\ 7.6e{-}15 \text{ cgs}$$

$$1\,\text{yr} \sim 3.15\,e\,7\,\text{sec}$$

$$1\,\text{AU} \sim 1.5\,e\,13\,\text{cm}$$

$$1\,\text{pc} \sim 3\,e\,18\,\text{cm}$$

$$1\,\text{km/s} \times 1\,\text{Myr} = 1\,\text{pc}$$

$$100\,\text{km/s} \times 1\,\text{Gyr} = 100\,\text{kpc}$$

$$1000\,\text{km/s} \times 10\,\text{Gyr} = 10\,\text{Mpc}$$

The Cosmic Triangle: Revealing the State of the Universe

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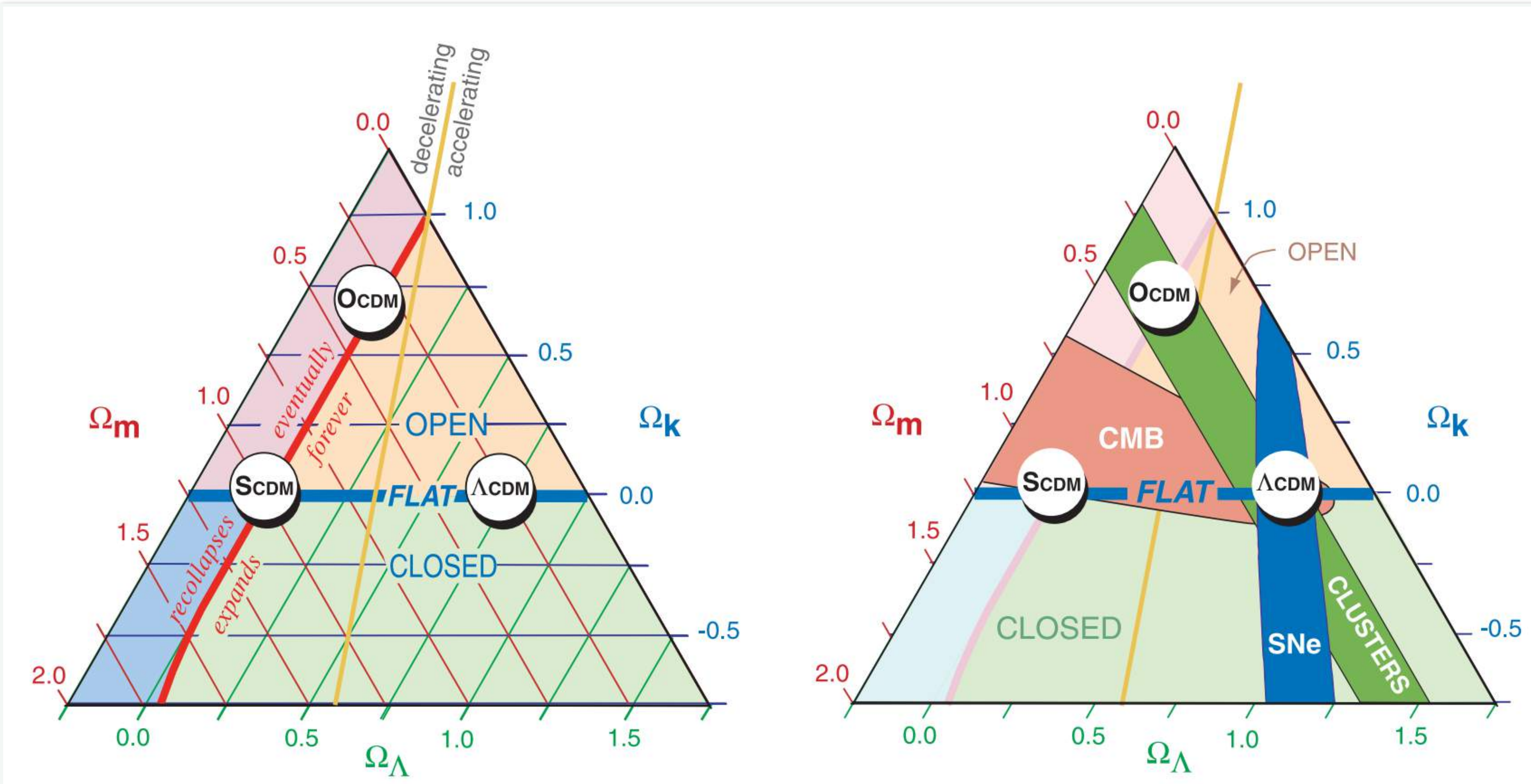
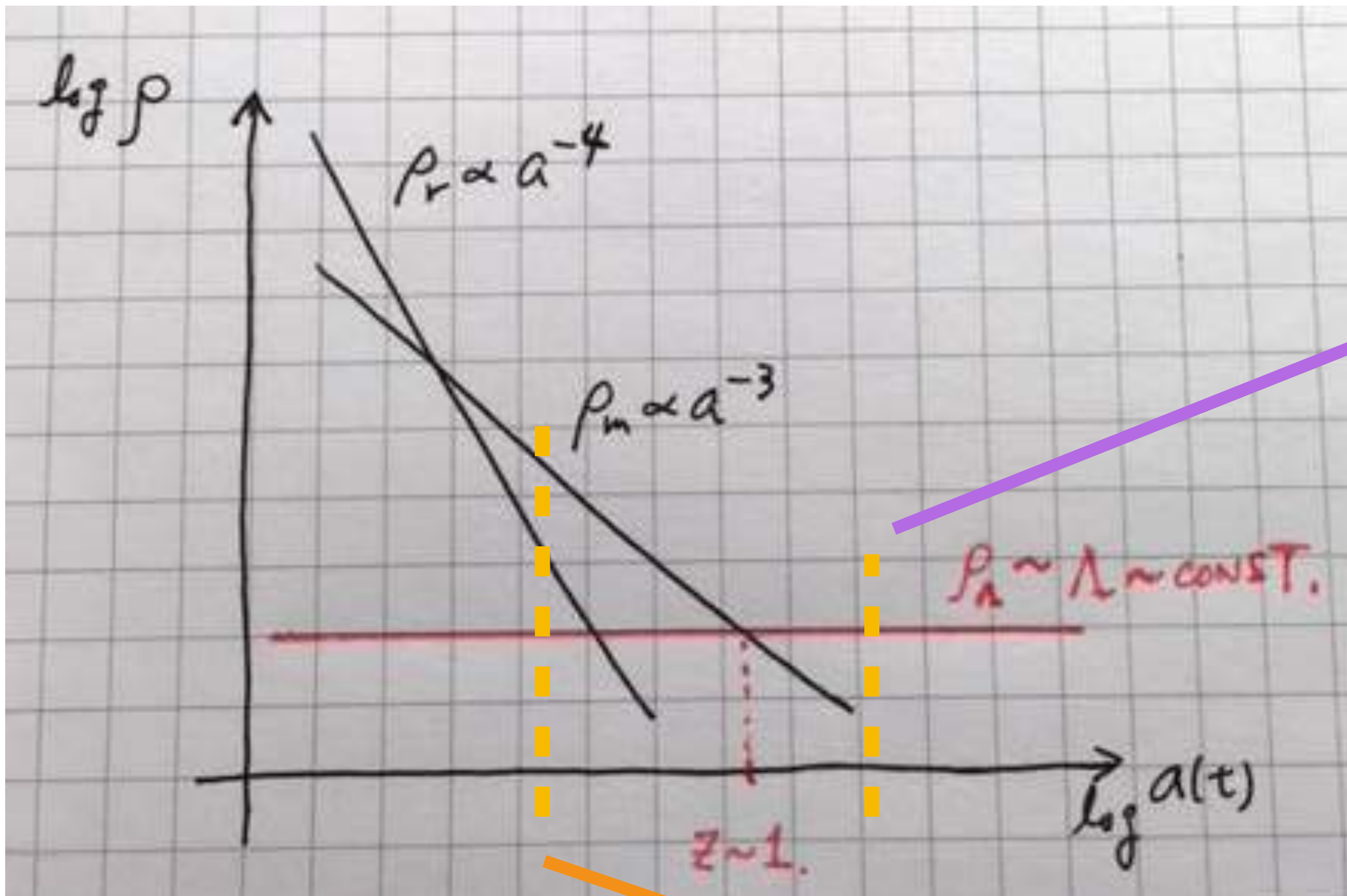
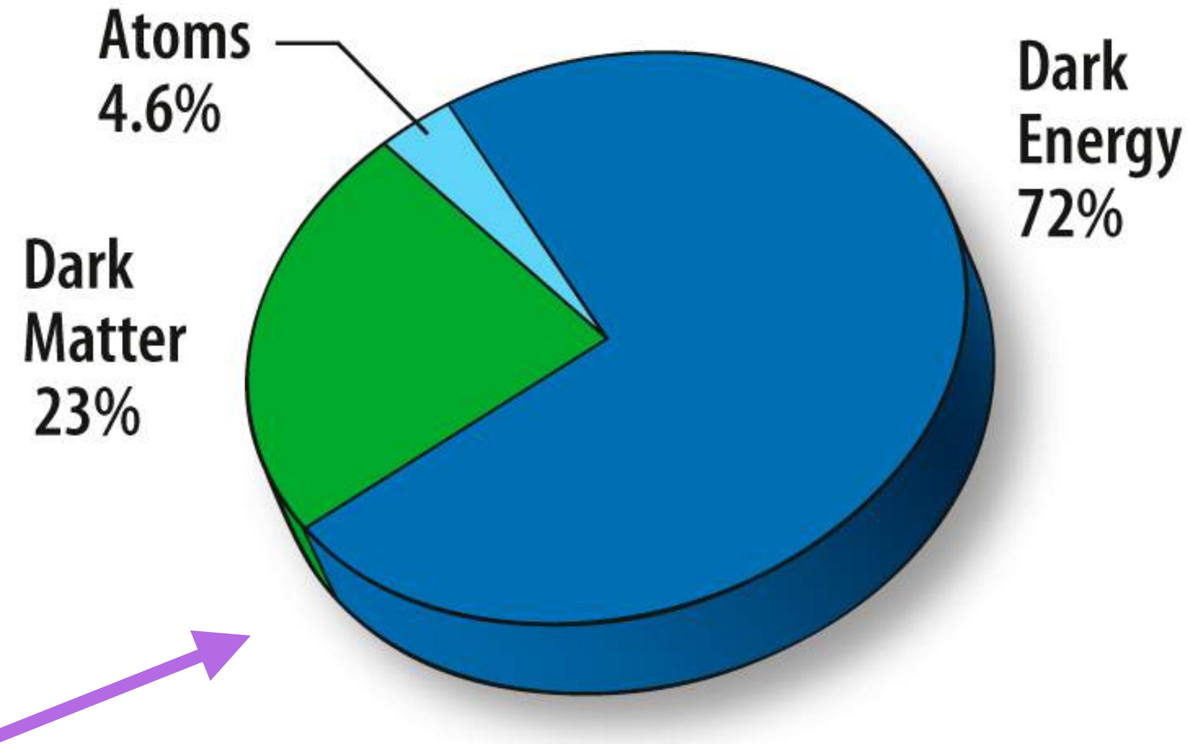


1999, Science, 284, 1481

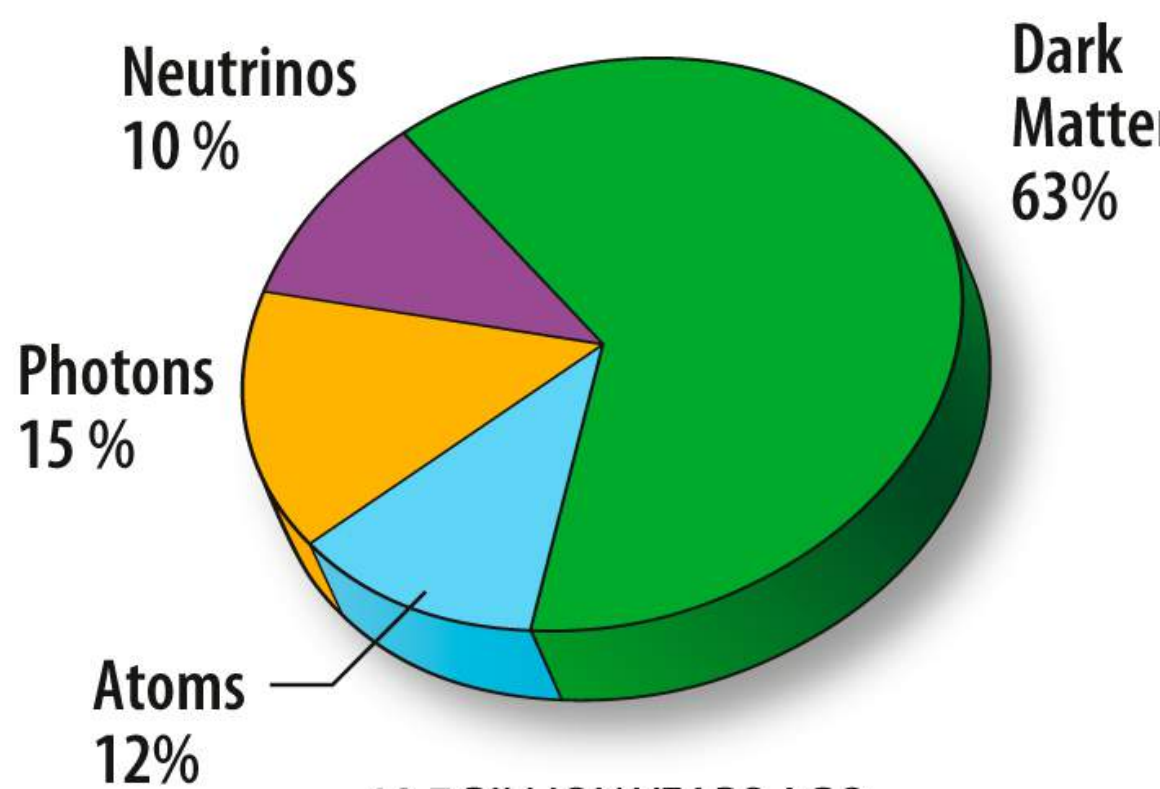
Evolution of Cosmic Energy Densities





TODAY

WMAP-5yr



13.7 BILLION YEARS AGO
(Universe 380,000 years old)

“Recipe” for Galaxy Formation

- [x] Background Cosmology
- [ ] Gravitational Instability
- [ ] N-body dynamics (Dark Matter)
- [ ] Hydrodynamics
- [ ] Radiative Cooling of Gas, UVB
- [ ] Star Formation, Chemical Enrichment
- [ ] Feedback (SNe, AGNs)