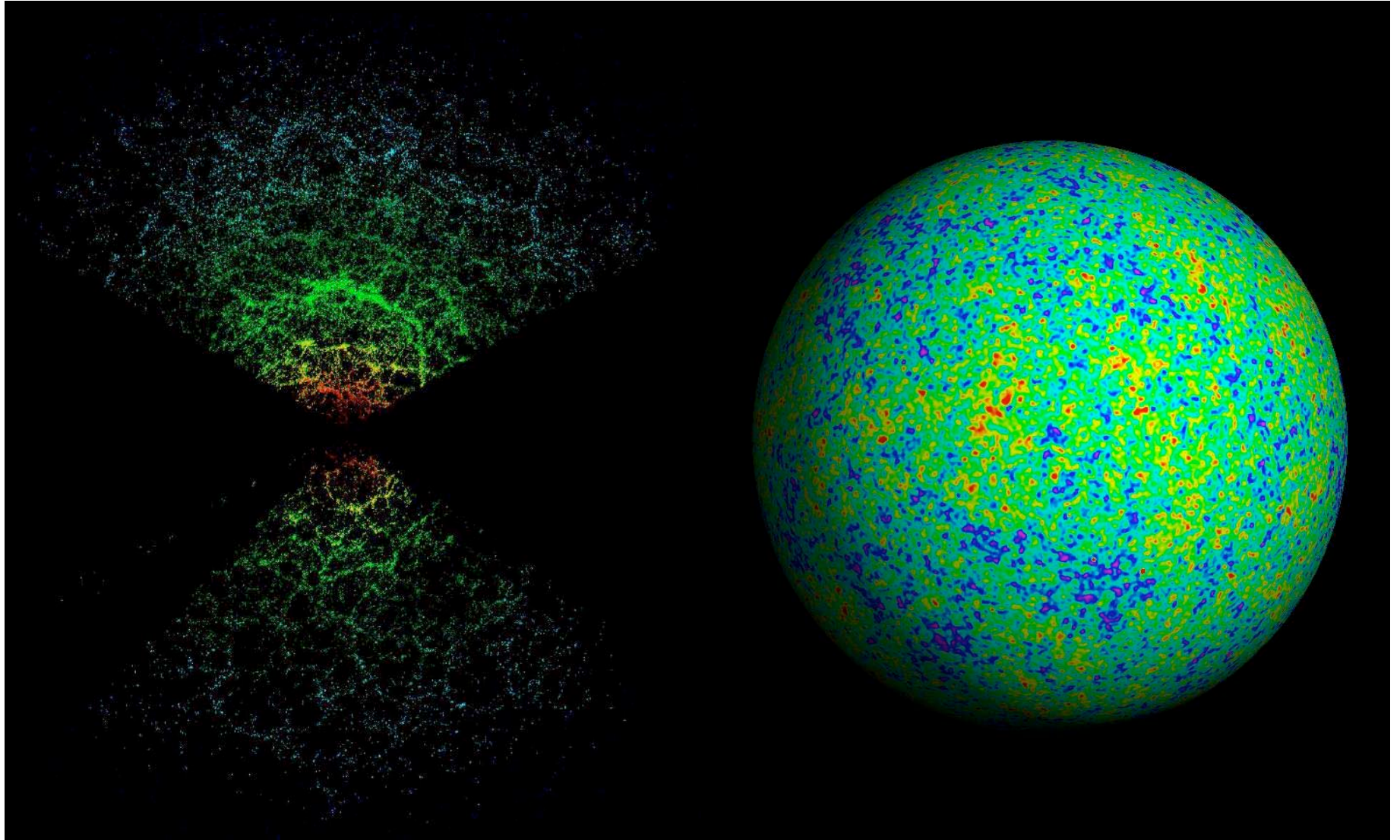
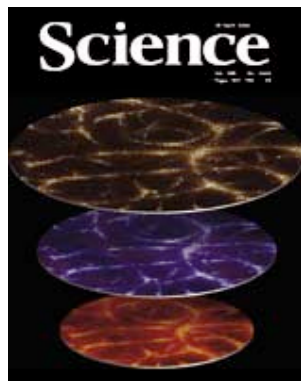


The History of the Universe in 60 Minutes



Max Tegmark, MIT



Breakthrough Online
For an expanded version
of this section, with refer-
enced links, see www.
sciencemag.org/content/
vol332/issue5653/special

Breakthrough

#1

The Winner

Portraits of the earliest universe and the lacy pattern of galaxies in today's sky confirm that the universe is made up largely of mysterious dark energy and dark matter. They also give the universe a firm age and a precise speed of expansion.

Illuminating the Dark Universe

A lonely satellite spinning slowly through the void has captured the very essence of the universe. In February, the Wilkinson Microwave Anisotropy Probe (WMAP) produced an image of the infant cosmos, of all of creation when it was less than 400,000 years old. The brightly colored picture marks a turning point in the field of cosmology. Along with a handful of other observations revealed this year, it ends a decades-long argument about the nature of the universe and confirms that our cosmos is much, much stranger than we ever imagined.

Five years ago, *Science's* cover spotted the visage of Albert Einstein looking shocked by 1998's Breakthrough of the Year: the accelerating universe. Two teams of astronomers had seen the faint imprint of a ghostly force in the death rattle of dying stars. The apparent brightness of a certain type of supernova gave cosmologists a way to measure the expansion of the universe at different times in its history. The scientists were surprised to find that the universe was expanding ever faster, rather than decelerating, as general relativity—and common sense—had led astrophysicists to believe. This was the first sign of the mysterious "dark energy," an unknown force that counteracts the effects of gravity and flings galaxies away from each other.

Although the supernova data were compelling, many cosmologists hesitated to embrace the bizarre idea of dark energy. Teams of astronomers across the world rushed to test the evidence of this invisible force in independent ways. That quest ended this year. No longer are scientists trying to confirm the existence of dark energy; now they are trying to find out what it's made of, and what it tells us about the birth and evolution of the universe.

Lingering doubts about the existence of

dark energy and the composition of the universe dissolved when the WMAP satellite took the most detailed picture ever of the cosmic microwave background (CMB). The CMB is the most ancient light in the universe: the radiation that streamed from the newborn universe when it was still a glowing ball of plasma. This faint microwave glow surrounds us like a distant wall of

shape and the material it's made of, so does the "noise" of the early universe—the relative abundances and sizes of the hot and cold spots in the microwave background—depend on the composition of the universe and its shape. WMAP is the instrument that finally allowed scientists to hear the celestial music and figure out what sort of instrument our cosmos is.

The answer was disturbing and comforting at the same time. The WMAP data confirmed the incredibly strange picture of the universe that other observations had been painting. The universe is only 4% ordinary matter, the stuff of stars and trees and people. Twenty-three percent is exotic matter: dark mass that astrophysicists believe is made up of an as-yet-undetected particle. And the remainder, 73%, is dark energy.

The tone of the cosmic bell also reveals the age of the cosmos and the rate at which it is expanding.

WMAP has nearly perfect pitch. A year ago, a cosmologist would likely have said that the universe is between 12 billion and 15 billion years old. Now the estimate is 13.7 billion years, plus or minus a few hundred thousand. Similar calculations based on WMAP data have also pinned down the rate of the universe's expansion—71 kilometers per second per megaparsec, plus or minus a few hundredths—and the universe's "shape," also flat. All the arguments of the last few decades about the basic properties of the universe—its age, its expansion rate, its composition, its density—have been settled in one fell swoop.

As important as WMAP is, it is not this year's only contribution to cosmologists' understanding of the history of the universe. The Sloan Digital Sky Survey (SDSS) is mapping out a million galaxies. By analyzing



Through a glass, darkly. Microwave data observed by the WMAP satellite (upper left), supernovae (lower left), and galaxy clusters (above) all reveal a universe dominated by dark energy.



fire. The writing on the wall—tiny fluctuations in the temperature (and other properties)

of the ancient light—reveals what the universe is made of.

Long before there were stars and galaxies, the universe was made of a hot, glowing plasma that cooled under the competing influences of gravity and light. The big bang had set the entire cosmos reeling like a ball, and pressure waves rattled through the plasma, compressing and expanding and compressing clouds of matter. Hot spots in the background radiation are the images of compressed, dense plasma in the cooling universe, and cold spots are the signature of rarefied regions of gas.

Just as the tone of a bell depends on its

of the Year

ing the distribution of these galaxies, the way they clump and spread out, scientists can figure out the forces that cause that clumping and spreading—be they the gravitational attraction of dark matter or the anti-gravity push of dark energy. In October, the SDSS team revealed its analysis of the first quarter-million galaxies it had collected. It came to the same conclusion that the WMAP researchers had reached: The universe is dominated by dark energy.

This year scientists got their most direct view of dark energy in action. In July, physicists superimposed the galaxy-clustering data of SDSS on the microwave data of WMAP and proved—beyond a reasonable doubt—that dark energy must exist. The proof relies on a phenomenon known as the integrated Sachs-Wolfe effect. The remnant microwave radiation acted as a backlight, shining through the gravitational dimples caused by the galaxy clusters that the SDSS spotted. Scientists saw a gentle crinkling—apparent as a slight shift toward shorter wavelengths—of the microwaves shining near those gravitational pits. In an uncurved universe such as our own, this can happen only if there is some antigravitational force—a dark energy—stretching out the fabric of spacetime and flattening the dimples that galaxy clusters sit in.

Some of the work of cosmology can now turn to understanding the forces that shaped the universe when it was a fraction of a millisecond old. After the universe burst forth from a cosmic singularity, the fabric of the newborn universe expanded faster than the speed of light. This was the era of inflation, and that burst of growth—and its abrupt end after less than 10^{-32} seconds—shaped our present-day universe.

For decades, inflation provided few testable hypotheses. Now the exquisite precision of the WMAP data is finally allowing scientists to test inflation directly. Each current version of inflation proposes a slightly different scenario about the precise nature of the inflation force, and each makes a concrete prediction about the CMB, the distribution of galaxies, and even the clustering of gas clouds in the later universe. Scientists are just beginning to winnow out a handful of theories and test some make-or-break hypotheses. And as the SDSS data set grows—yielding information on distant quasars and gas clouds as well as the distribution of galaxies—scientists will challenge inflation theories with more boldness.

The properties of dark energy are also

now coming under scrutiny. WMAP, SDSS, and a new set of supernova observations released this year are beginning to give scientists a handle on the way dark energy reacts to being stretched or squished. Physicists have already had to discard some of their assumptions about dark energy. Now they have to consider a form of dark energy that might cause all the matter in the universe to die a violent and sudden death. If the dark energy

is stronger than a critical value, then it will eventually tear apart galaxies, solar systems, planets, and even atoms themselves in a "big rip." (Not to worry, cosmologists aren't losing sleep about the prospect.)

For the past 5 years, cosmologists have tested whether the baffling, counterintuitive model of a universe made of dark matter and blown apart by dark energy could be correct. This year, thanks to WMAP, the SDSS data, and new supernova observations, they know the answer is yes—and they're starting to ask new questions. It is, perhaps, a sign that scientists will finally begin to understand the beginning.

—CHARLES SEIFE

THE RUNNERS-UP

This year's discoveries illuminated realms as small as a single molecule and as large as a gamma ray burst.

#2

Decoding mental illness. Schizophrenia, depression, and bipolar disorder often run in families, but only recently have researchers identified particular genes that reliably increase one's risk of disease. Now they're unraveling how these genes can distort the brain's information processing and nudge someone into mental illness.

The chemical messenger serotonin relays its signal through a receptor that's a target of antidepressant drugs.

The gene for this receptor comes in two common flavors, or alleles, one of which had been tentatively linked to an increased risk of depression. This year, researchers revealed why the link had been so elusive: The allele increases the risk of depression only when combined with stress. Among people who had suffered bereavement, romantic rejection, or job loss in their early 20s, those who carried the vulnerability gene were more likely to be depressed than those with the other gene variant.

People with the high-risk allele have unusually heightened activity in a fear-focused brain region called the amygdala when viewing scary pictures. Together, these studies suggest that the gene variant biases people to perceive the world as highly menacing, which amplifies life stresses to the point of inducing depression.

A different brain area, the prefrontal cortex, is regulated in part by a gene called COMT, one of the handful associated with risk of schizophrenia. It encodes an enzyme that breaks down neurotransmitters such as dopamine. Two years ago, one version of this gene was shown to muddle the prefrontal cortex, which is necessary for planning and problem-solving skills that are impaired by schizophrenia. Even healthy people who carry the schizophrenia risk allele

have extra activity in the prefrontal cortex even when doing relatively simple tasks. The nonschizophrenia allele, which allows more efficient activity in the prefrontal cortex, appears to increase the risk of anxiety, suggesting that the two disorders lie at opposite ends of a spectrum.

Late in 2002, an allele of a gene for brain-derived neurotrophic factor (BDNF) was implicated in bipolar disorder, once known as manic depression. This



Agony antecedents. New work links genes, brain activity biases, and mental illness.

year the allele was found to curb activity in the hippocampus, a structure necessary for memory that is shrunken in people with mood disorders. BDNF encourages the birth of new neurons in the hippocampus; other work this year showed that antidepressants require this neurogenesis to be effective. Through these and similar insights, researchers hope to understand brain biases underlying mental illnesses well enough to correct them.

Cosmology timeline:

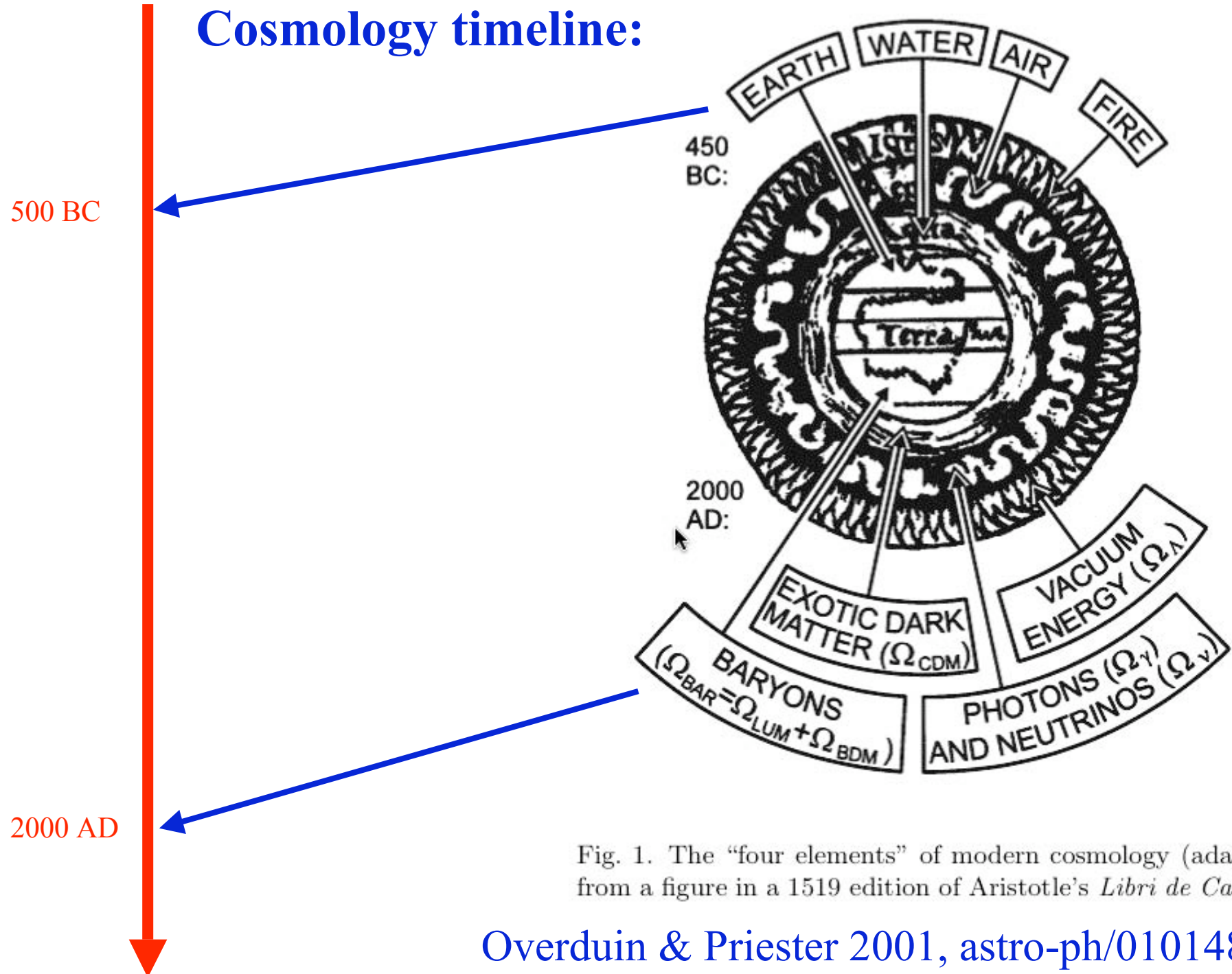
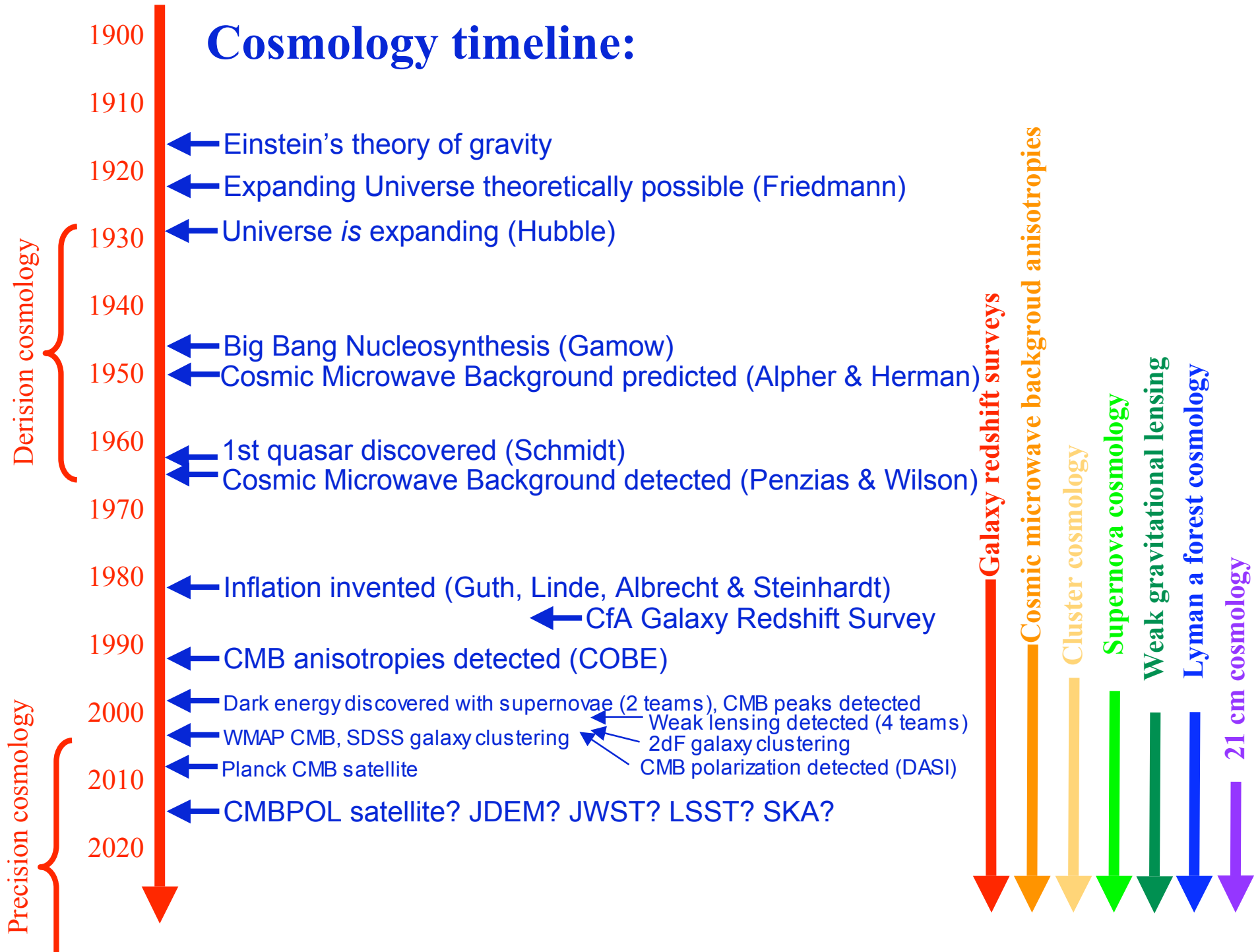


Fig. 1. The “four elements” of modern cosmology (adapted from a figure in a 1519 edition of Aristotle’s *Libri de Caelo*)

Overduin & Priester 2001, astro-ph/0101484

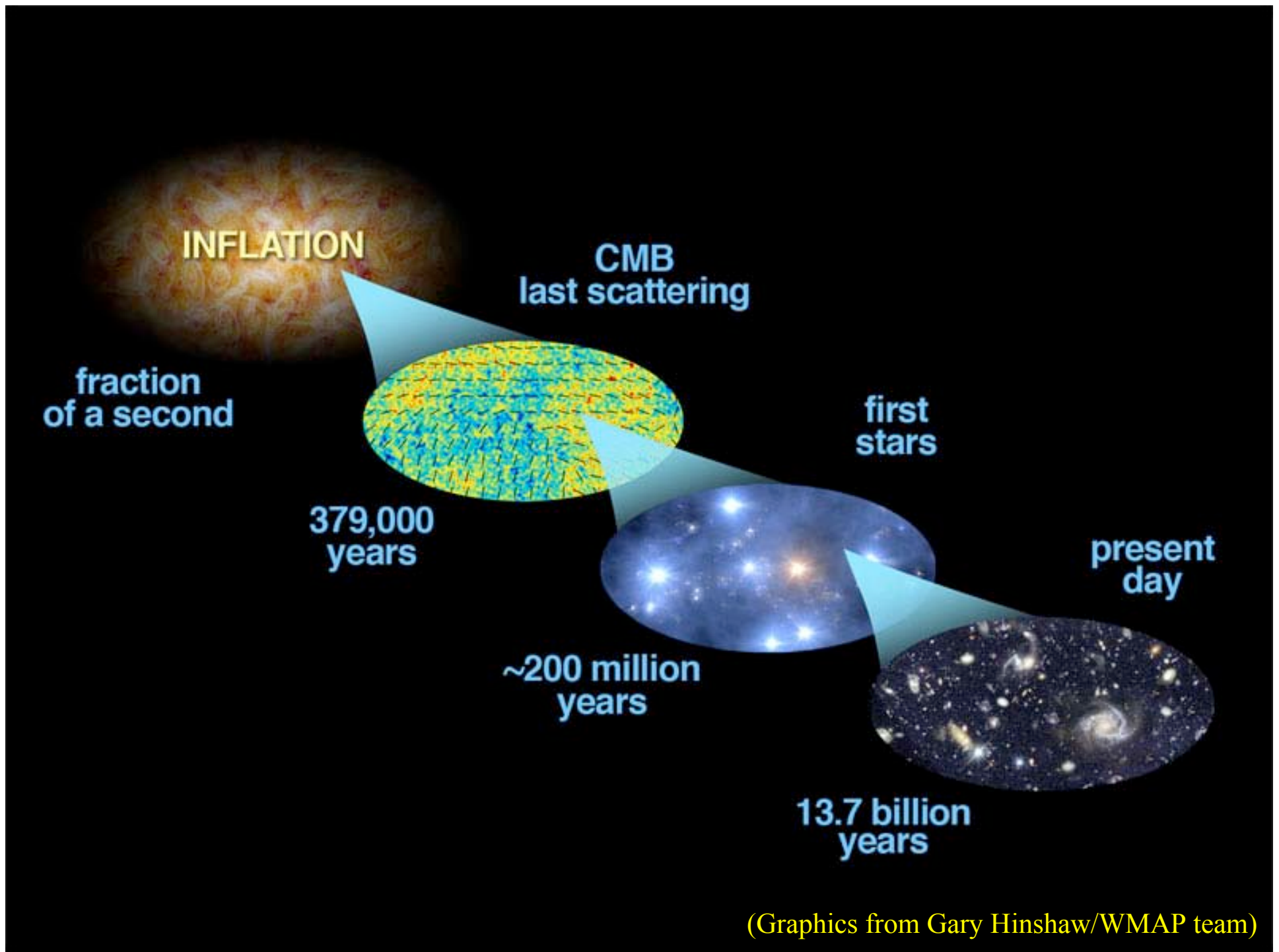
Cosmology timeline:



Flyabout

+

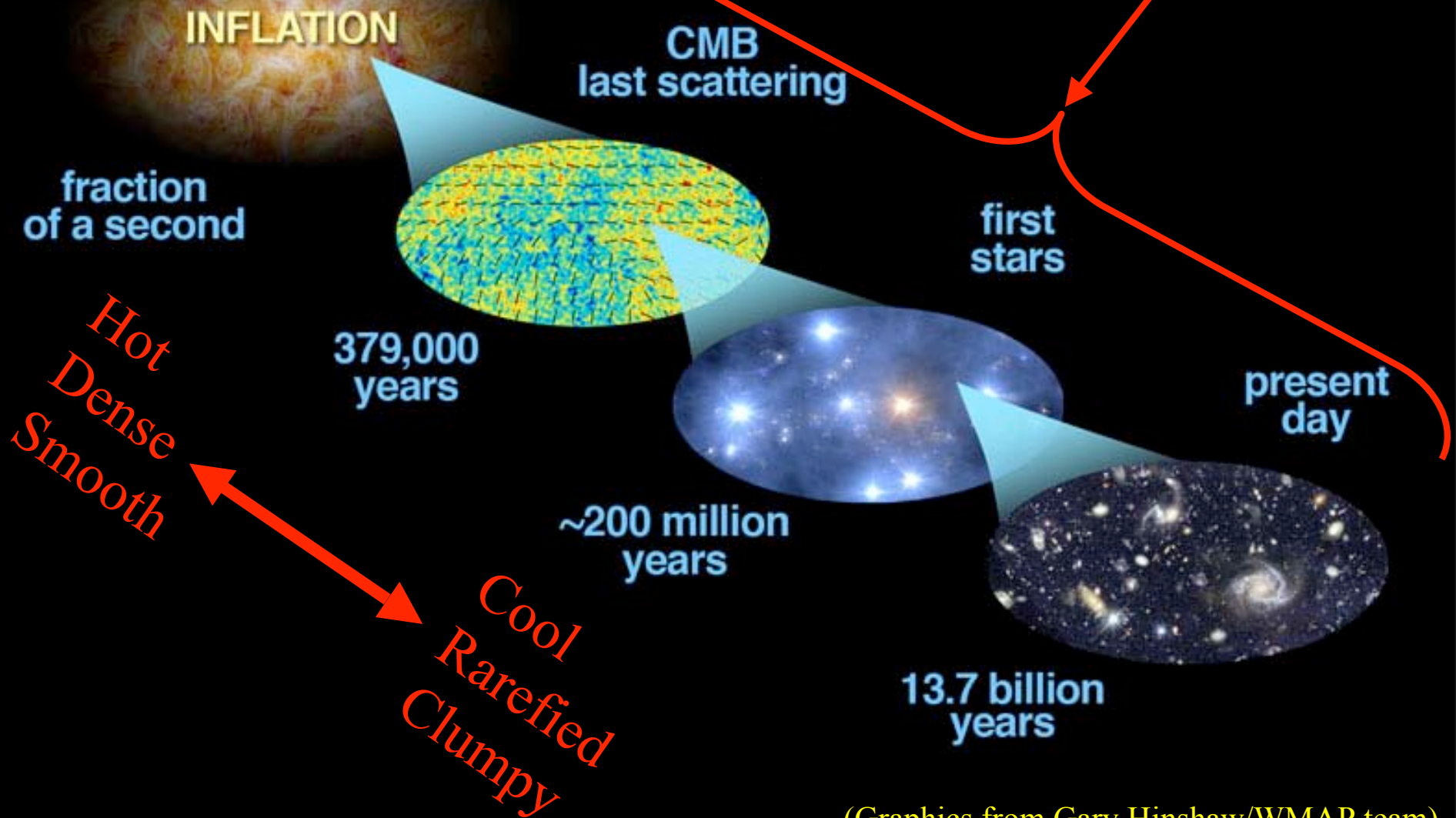
SDSS
movie



Brief History of the Universe

Fluctuation generator

Fluctuation amplifier

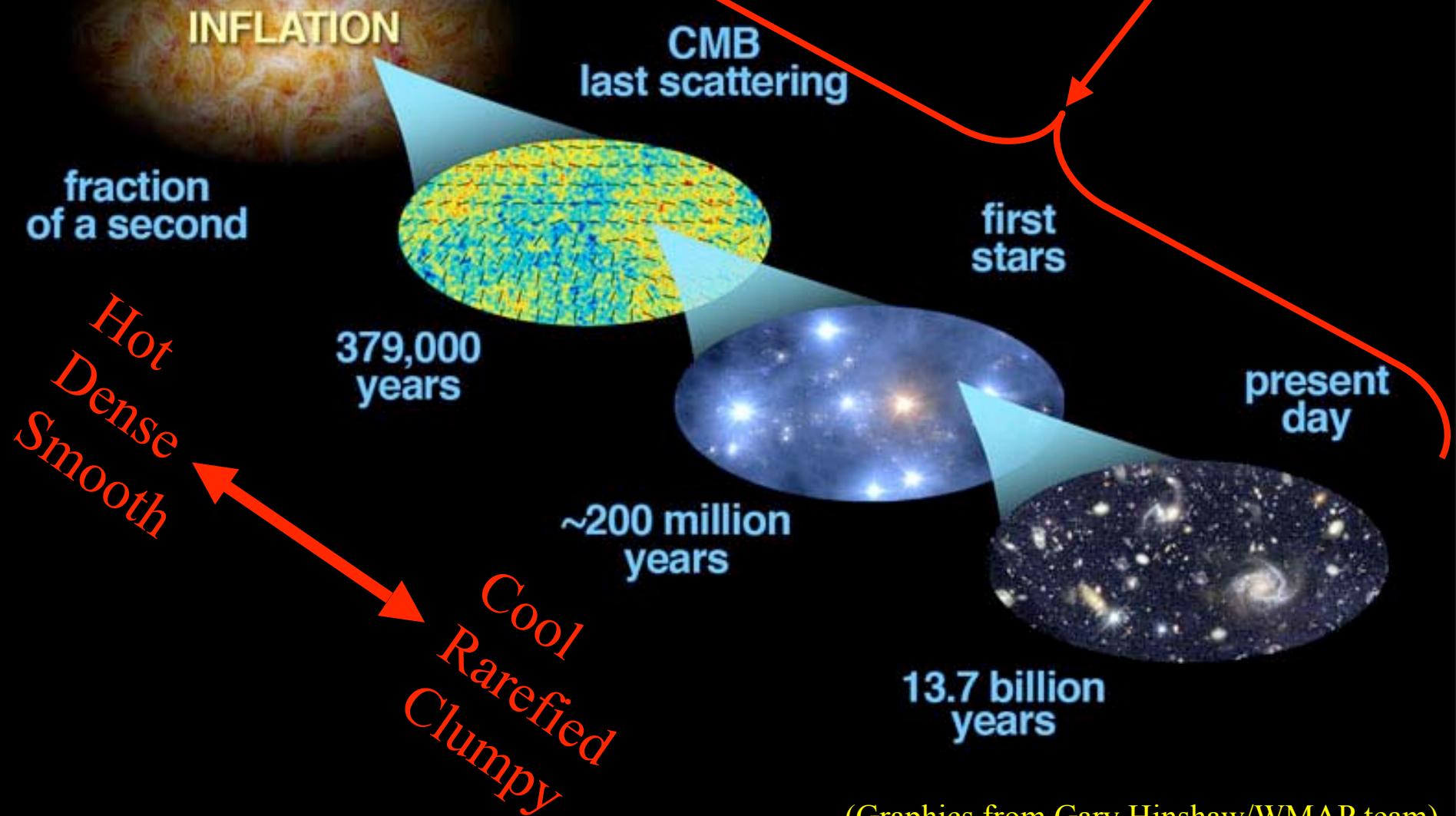


(Graphics from Gary Hinshaw/WMAP team)

Fluctuation generator

What do we want
to measure?

Fluctuation amplifier

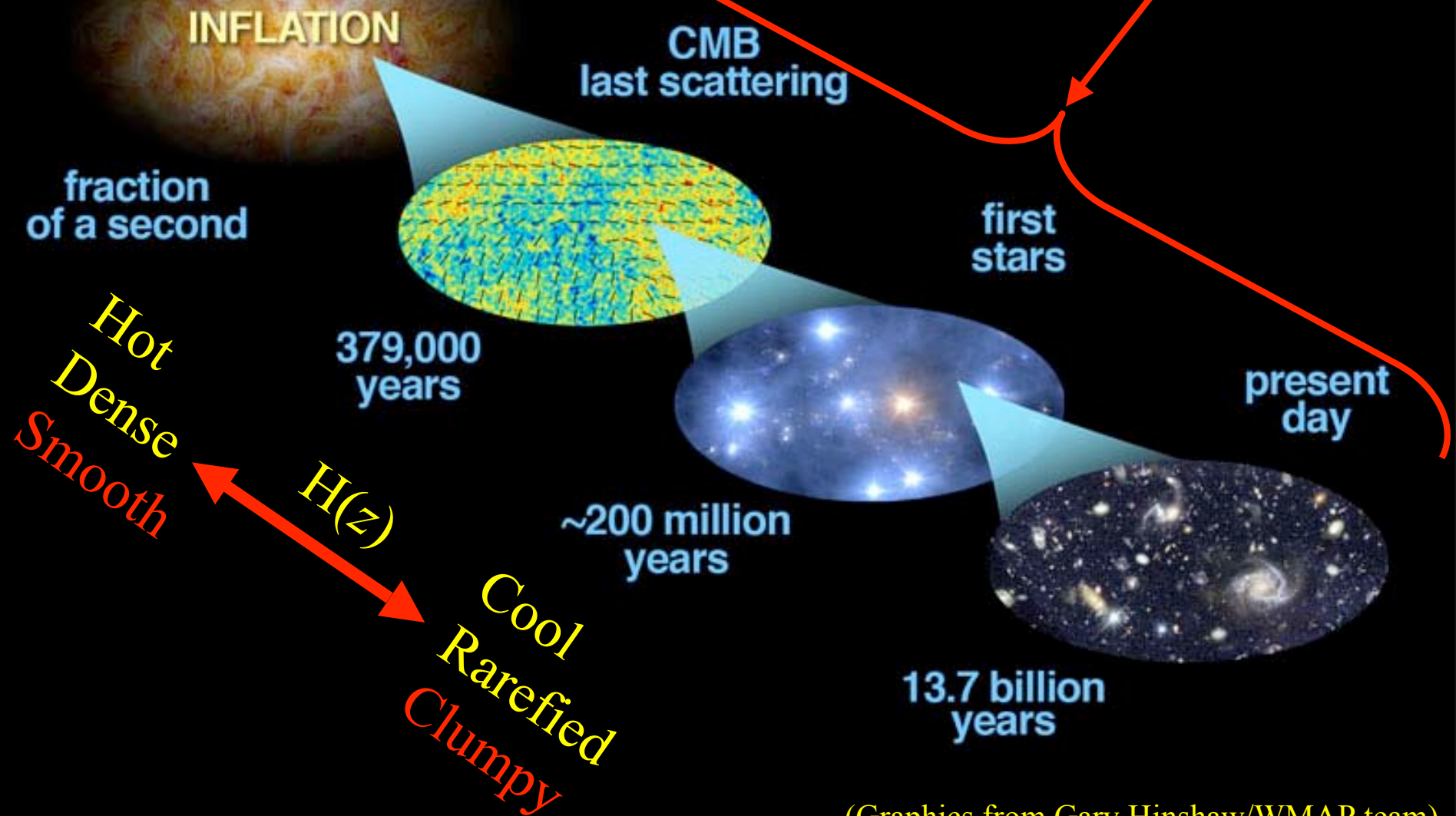


(Graphics from Gary Hinshaw/WMAP team)

Fluctuation generator

To 0th order:

Fluctuation amplifier

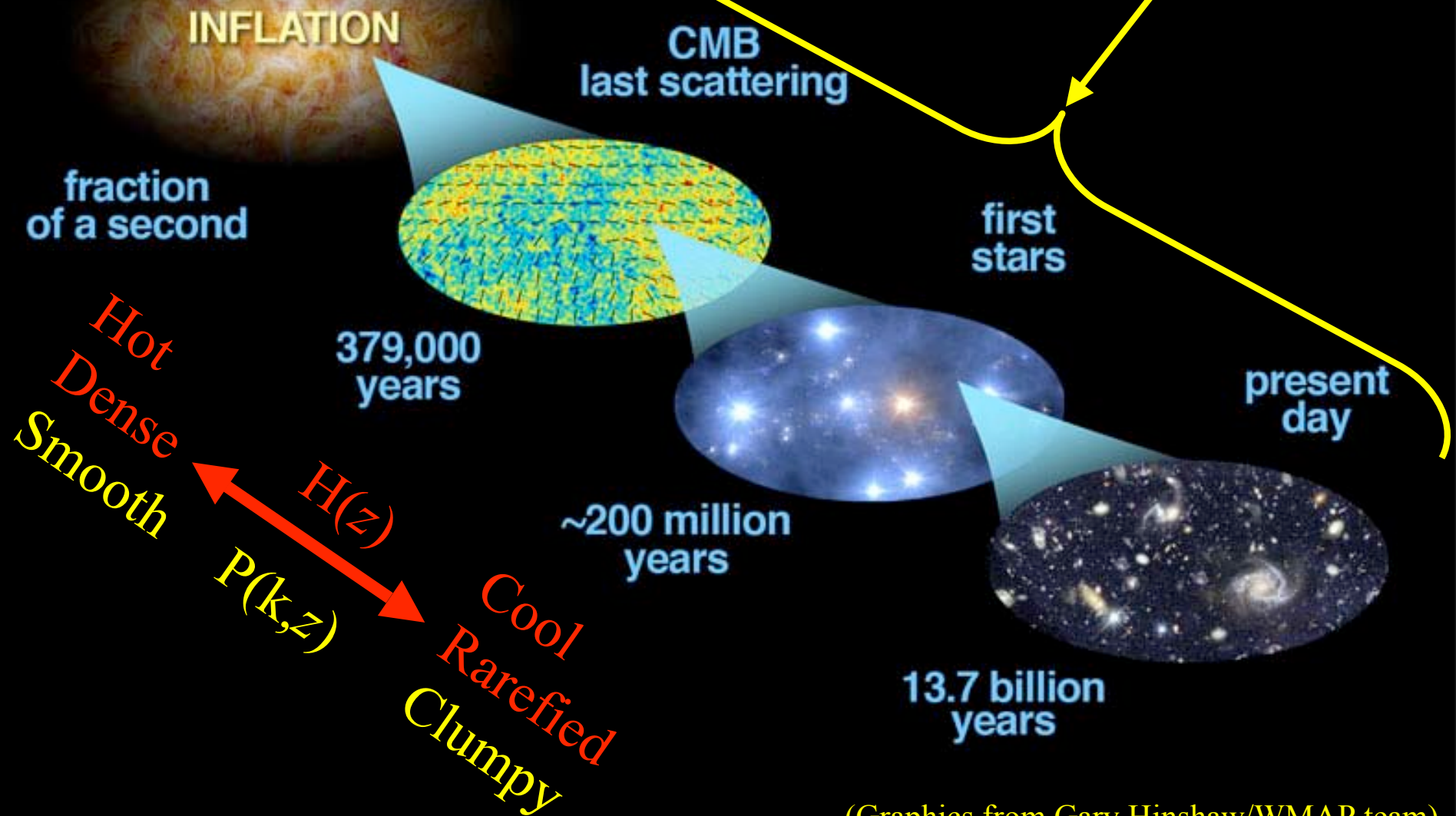


(Graphics from Gary Hinshaw/WMAP team)

Fluctuation generator

To 1st order:

Fluctuation amplifier

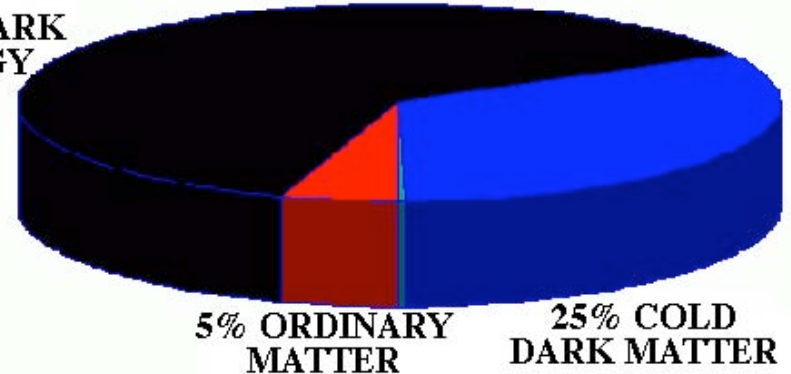


(Graphics from Gary Hinshaw/WMAP team)

MATTER BUDGET

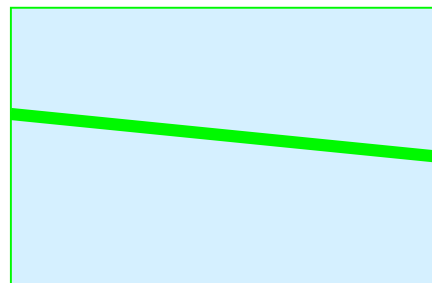
- Ordinary Matter
- Dark Energy
- Cold Dark Matter
- Hot Dark Matter
- Photons
- Budget Deficit

70% DARK ENERGY

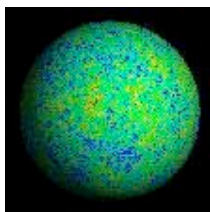


p	Meaning	Measured value
Ω_{tot}	Spatial curvature	1.01 ± 0.02
ρ_{Λ}	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124} m_{\text{Pl}}^4$
w	Dark energy equation of state	-1 ± 0.1
δ_H	Scalar fluctuation amplitude (Q)	$(2.0 \pm 0.2) \times 10^{-5}$
n_s	Scalar spectral index	0.98 ± 0.02
α	Running of spectral index $dn_s/d \ln k$	$ \alpha \lesssim 0.01$
r	Tensor-to-scalar ratio $(\delta_H^T / \delta_H)^2$	$\lesssim 0.36$
n_t	Tensor spectral index	Unconstrained
ξ_b	Baryon mass per photon $\rho_b / n_\gamma = m_p \eta$	$(0.60 \pm 0.03) \text{ eV}$
ξ_c	CDM mass per photon ρ_c / n_γ	$(3.3 \pm 0.2) \text{ eV}$
ξ_ν	Neutrino mass per photon $\rho_\nu / n_\gamma = \frac{3}{11} \sum m_{\nu_i}$	$< 0.11 \text{ eV}$

INITIAL CONDITIONS



OUR TOOLS



CMB



GALAXY
SURVEYS



DISTANT
SUPERNOVAE

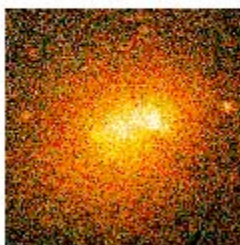


GRAVITATIONAL
LENSING

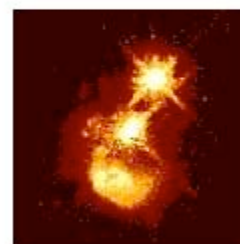
THE COSMIC SMÖRGÅSBORD



BIG BANG
NUCLEOSYNTHESIS



GALAXY
CLUSTERS



LYMAN ALPHA
FOREST



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Measuring expansion

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2}$$



Alexander
Friedmann

1888-1925

(Russian; 1922
paper)



George Lemaître 1894-1936

(Belgian; indep. 1927 paper)



Arthur Geoffrey
Walker 1909-?

(British; 1935 paper
with H P Robertson
showed that **F(L)RW**
metric is *only*
homogeneous &
isotropic metric)



Robertson

Wigner

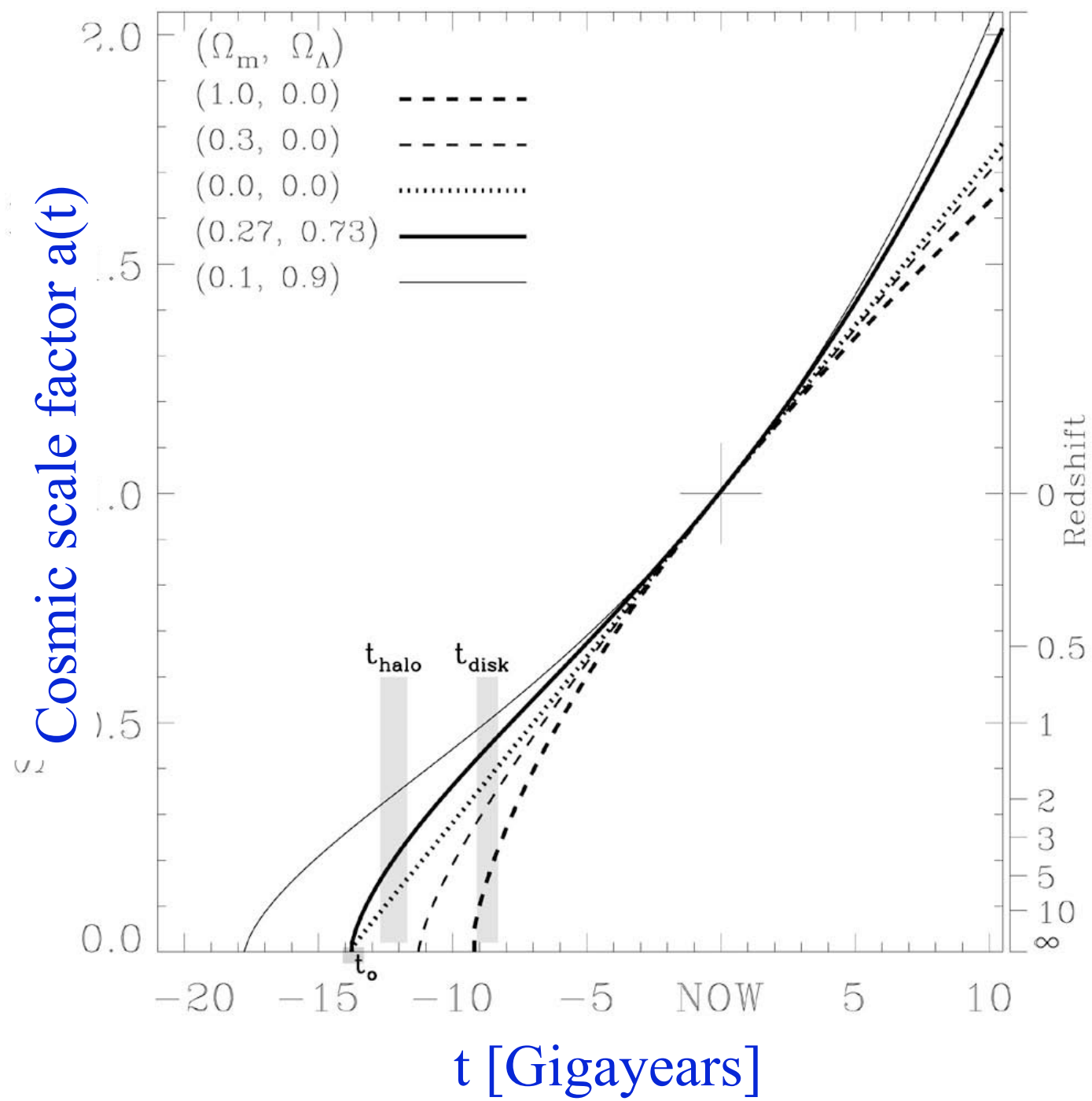
Weyl

Gödel Rabi

Ladenburg

Clemence

Oppenheimer



The Universe is expanding:

- $H > 0$ today
- $v \approx Hr$ for $v \ll c$







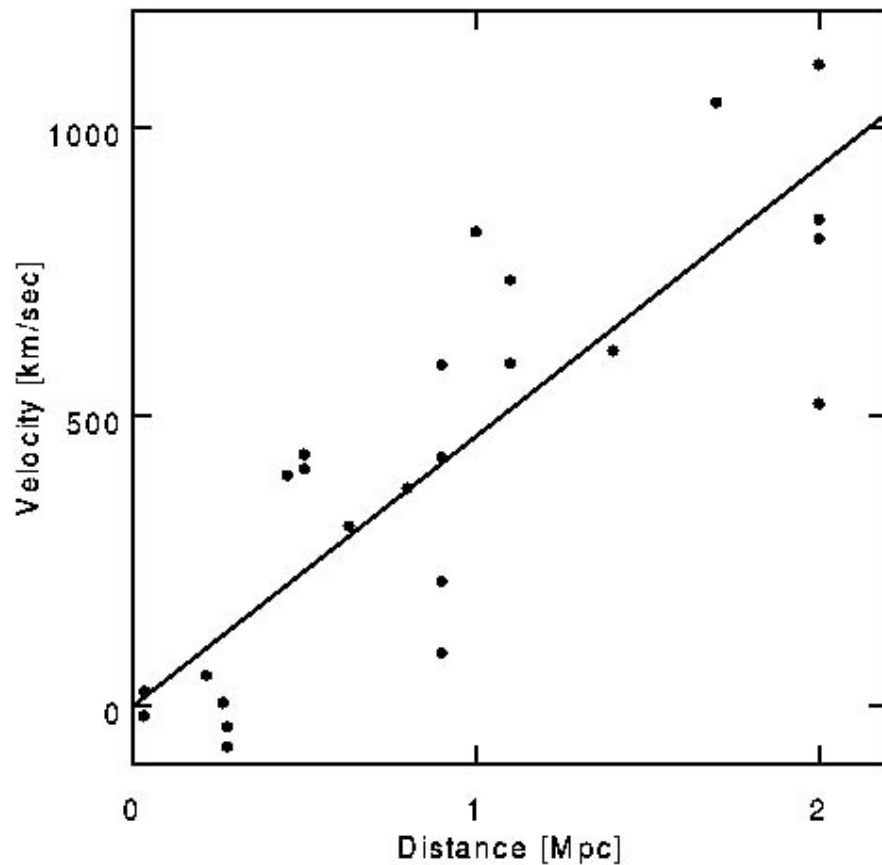
Edwin Hubble 1889-
(American; 1930 paper)



Mt. Wilson Observatory 1931

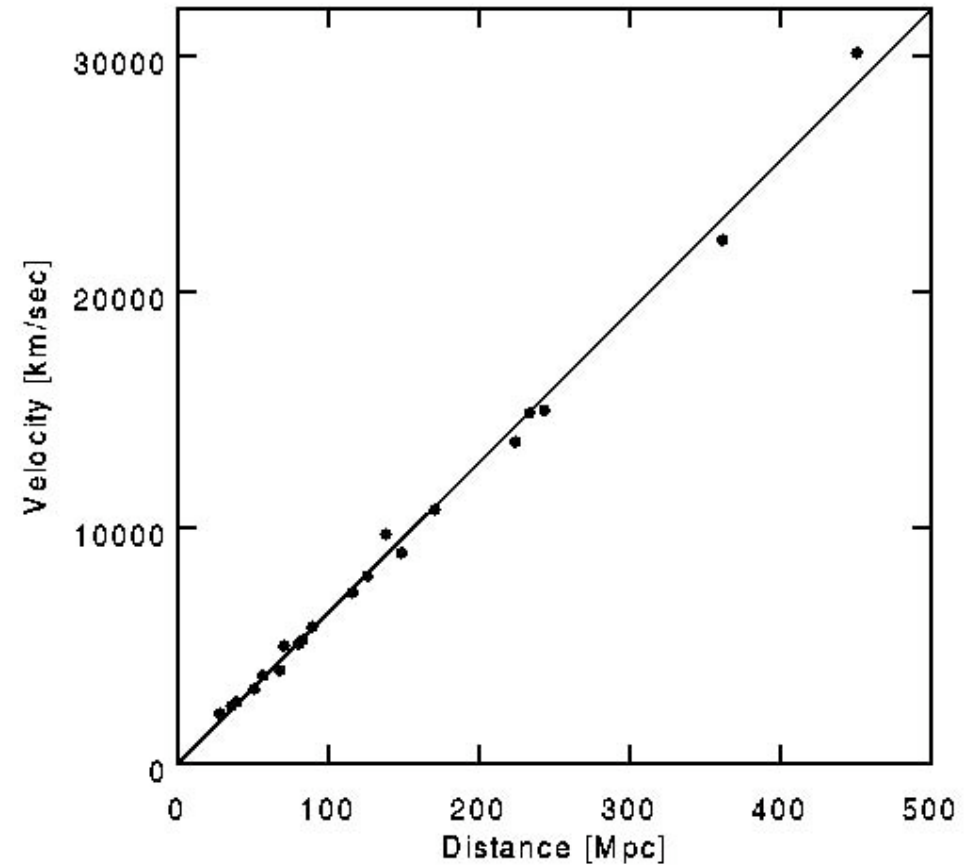
Hubble 1929:

$H \approx 550 \text{ km/s/Mpc}$

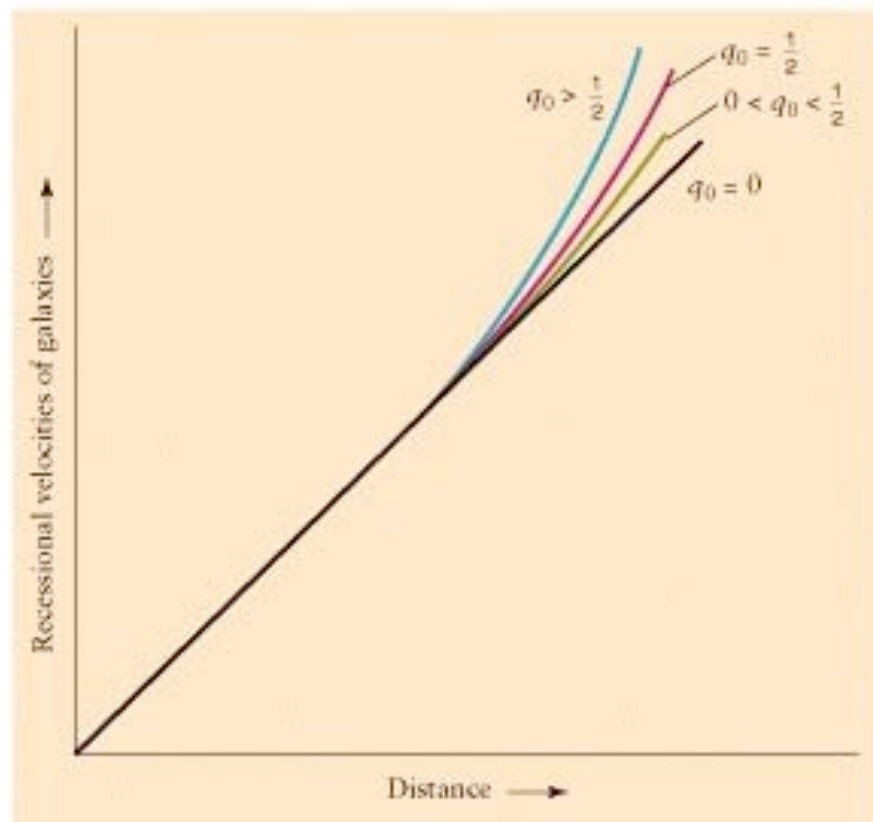


Riess et al 1996:

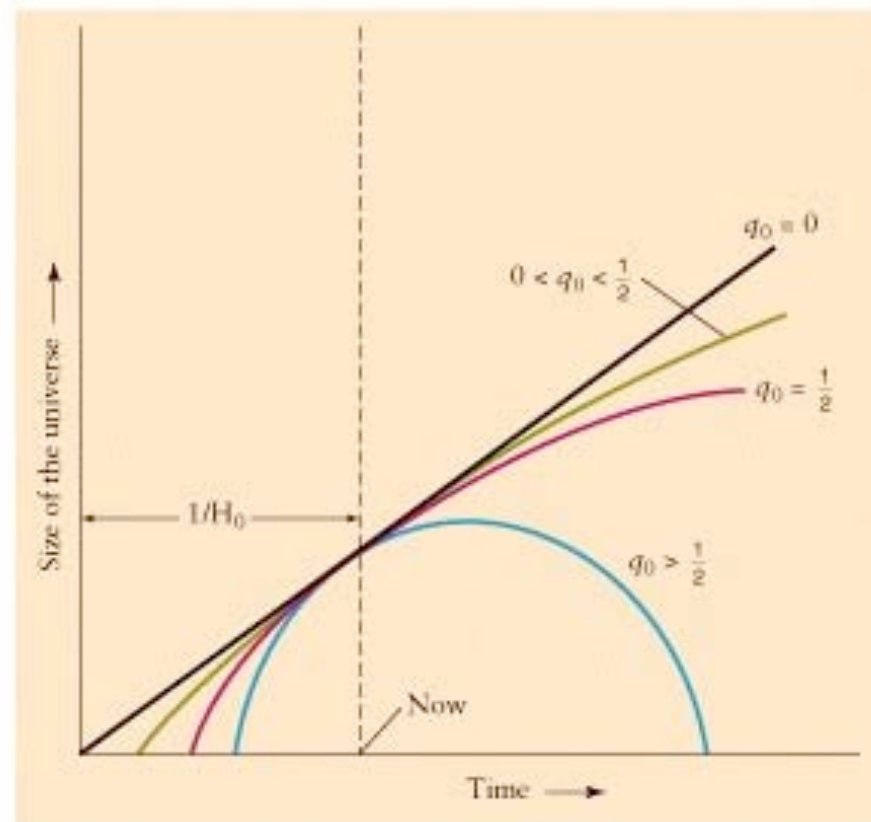
$H \approx 70 \text{ km/s/Mpc}$



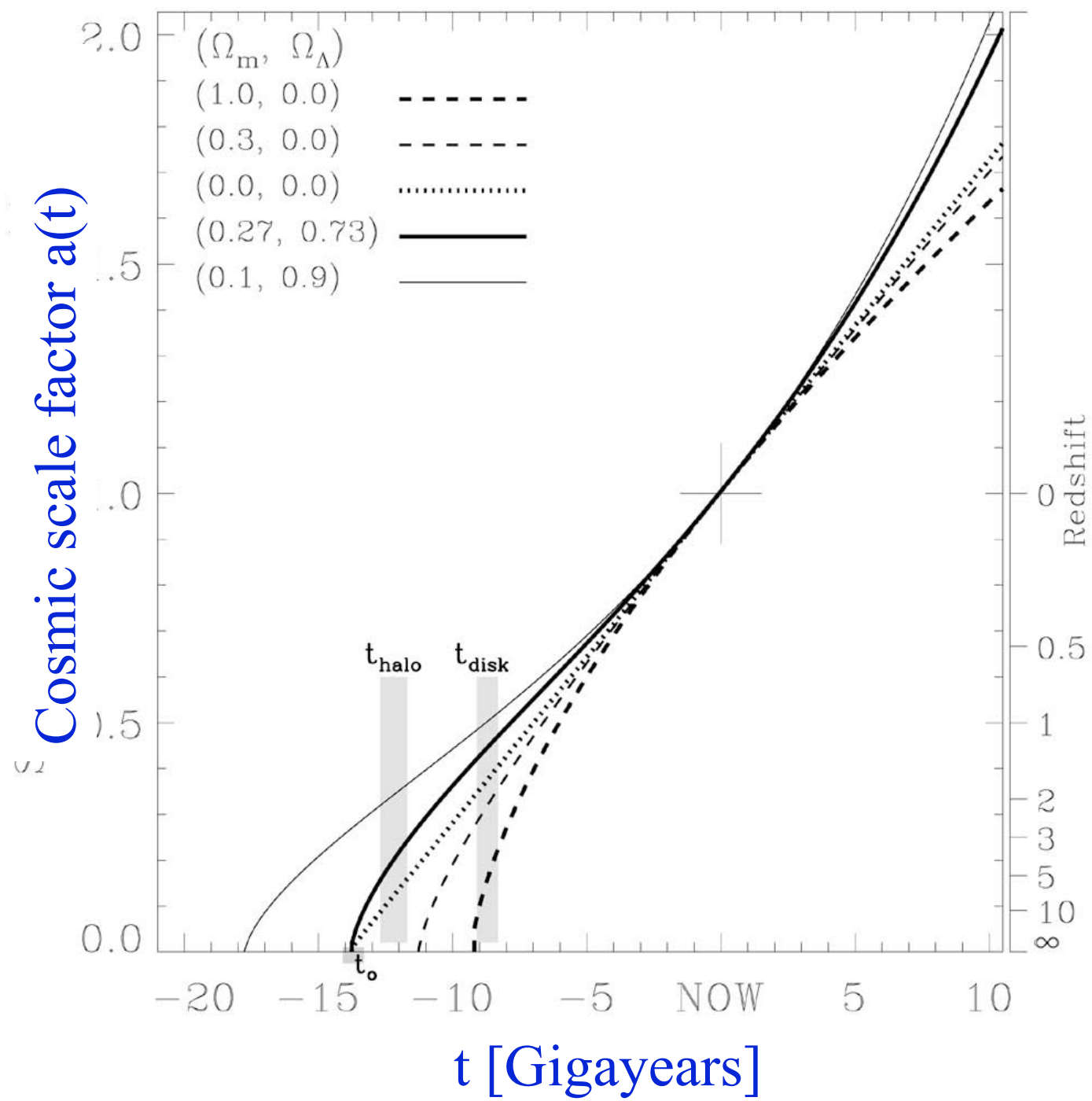
How measure distance & redshift?



a

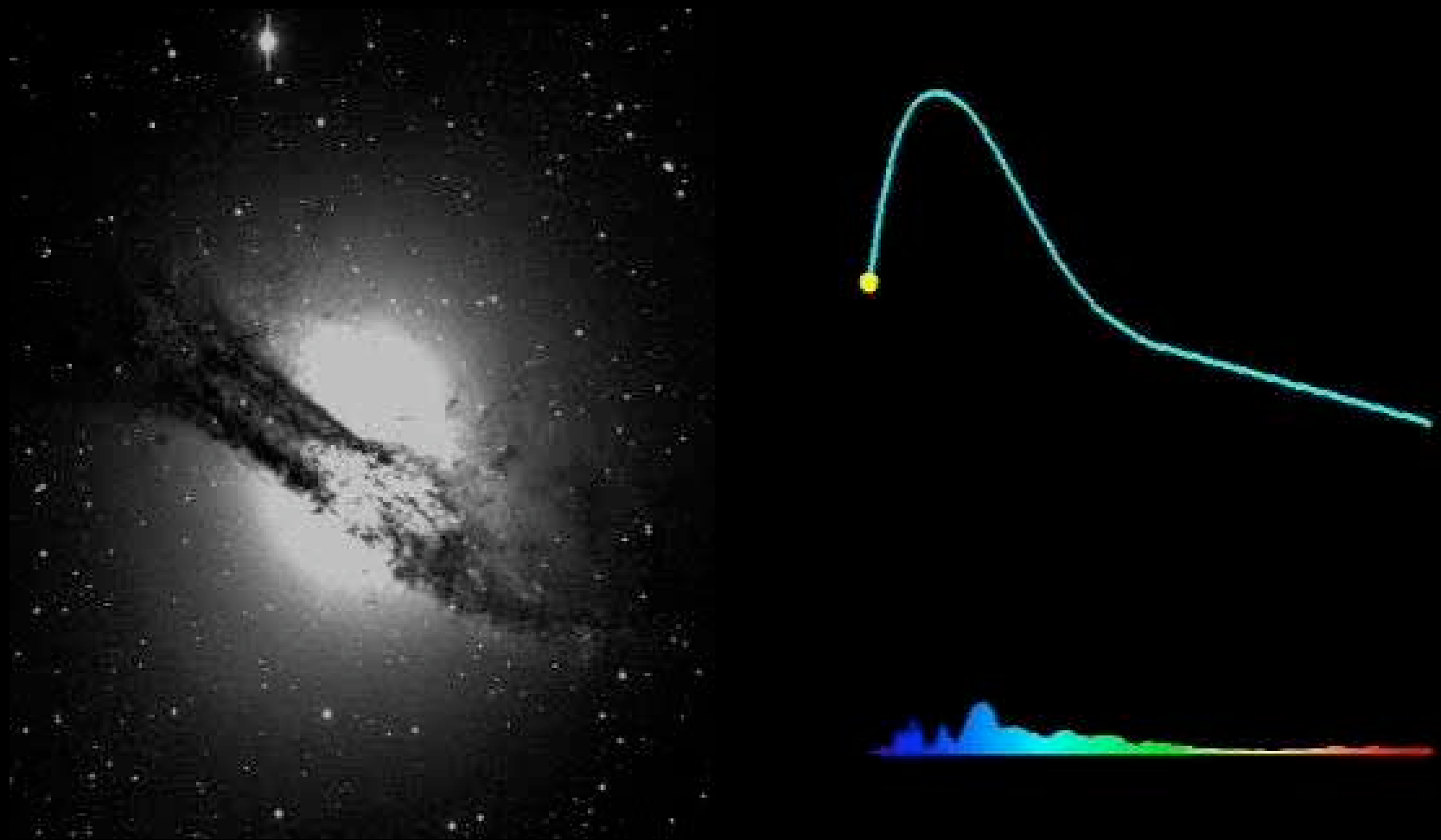


b



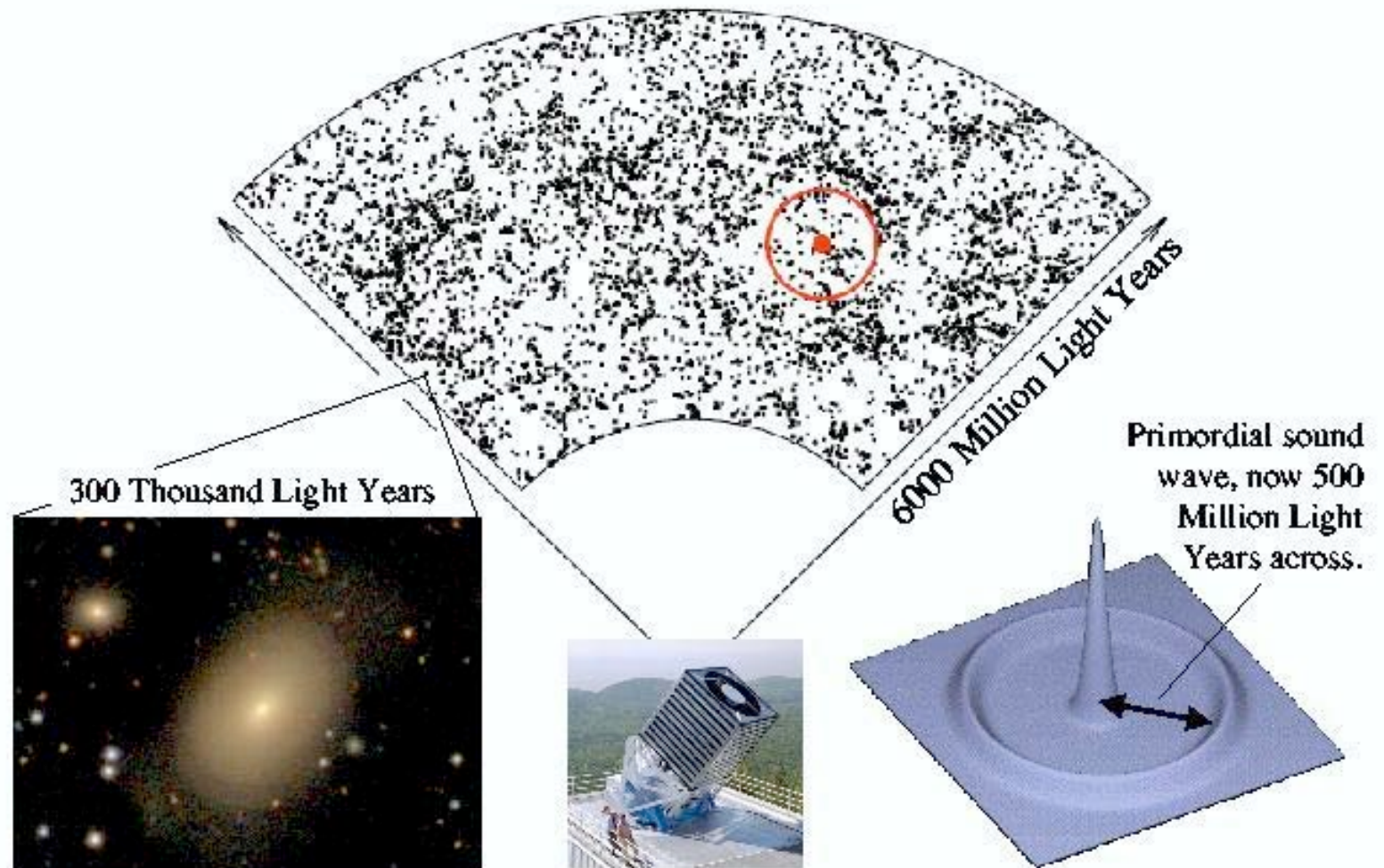
Standardizable candles

(From Saul Perlmutter's web site)



Using galaxy correlations as a standardizable ruler:

(Eisenstein, Hu & MT 1998; Eisenstein et al 2005; Cole et al 2005)

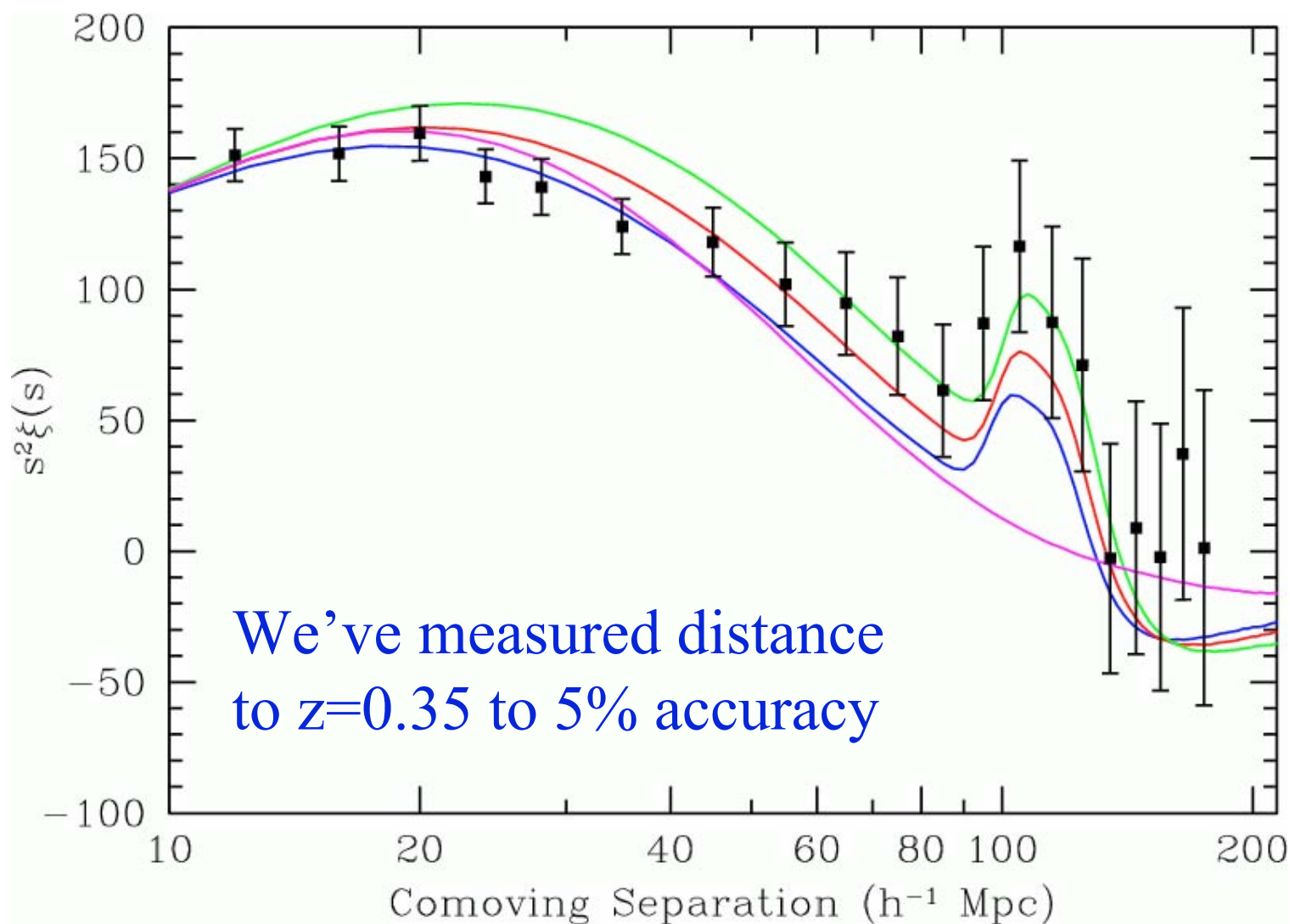


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Easiest to understand in real space

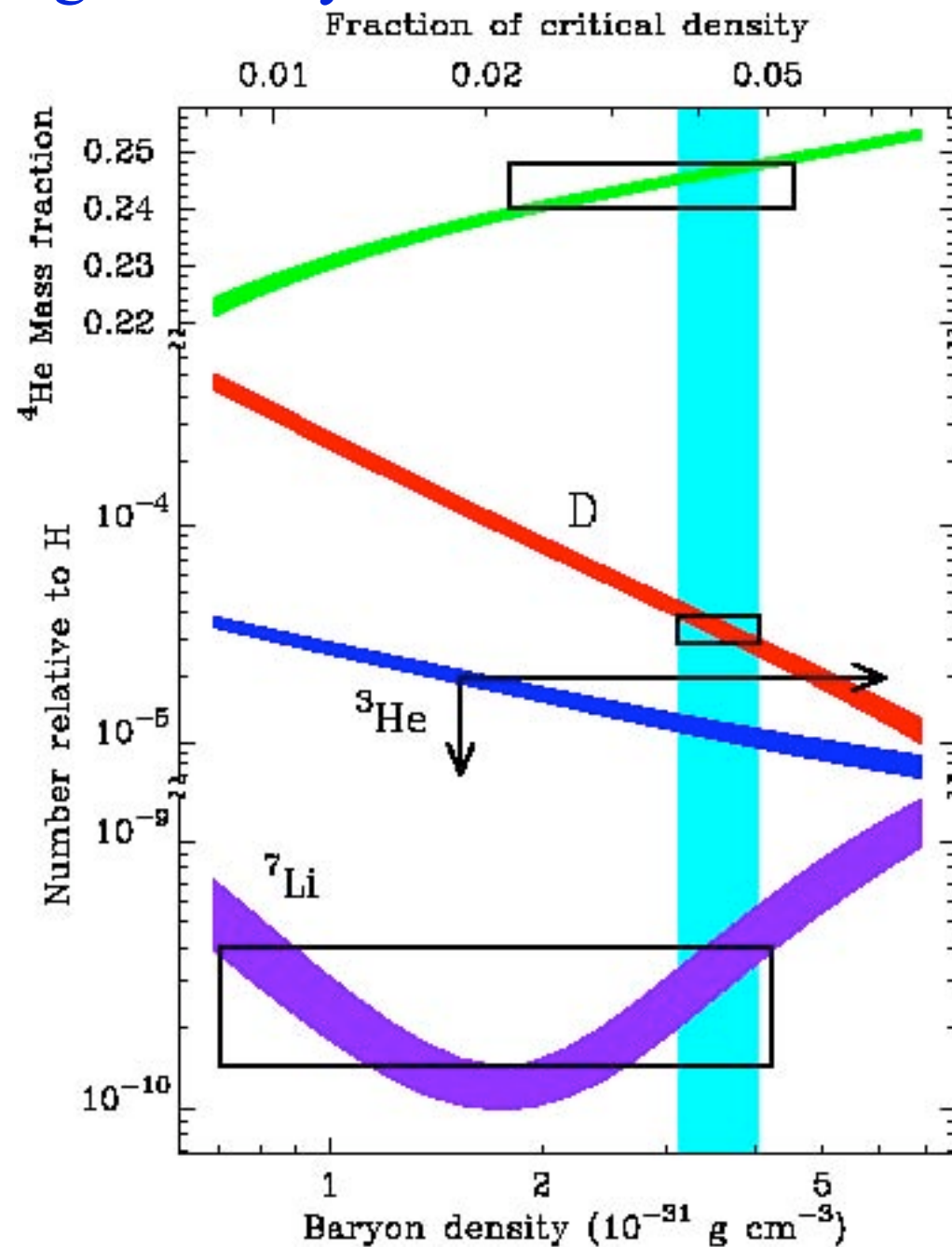
(Bashinsky & Bertschinger, PRL, 87, 1301, 2001; PRD 123008, 2002)

(Eisenstein et al 2005, for the SDSS collaboration astro-ph/050112)



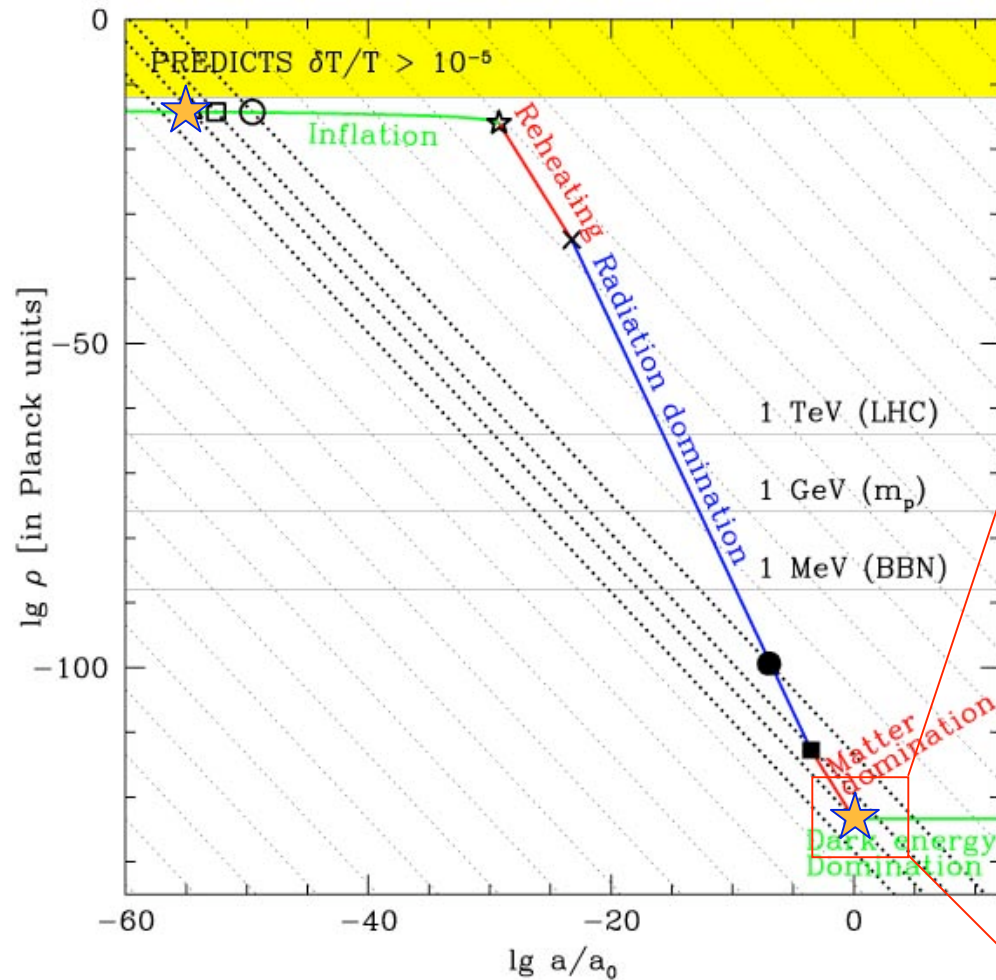
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Big Bang nucleosynthesis as a standardizable clock:

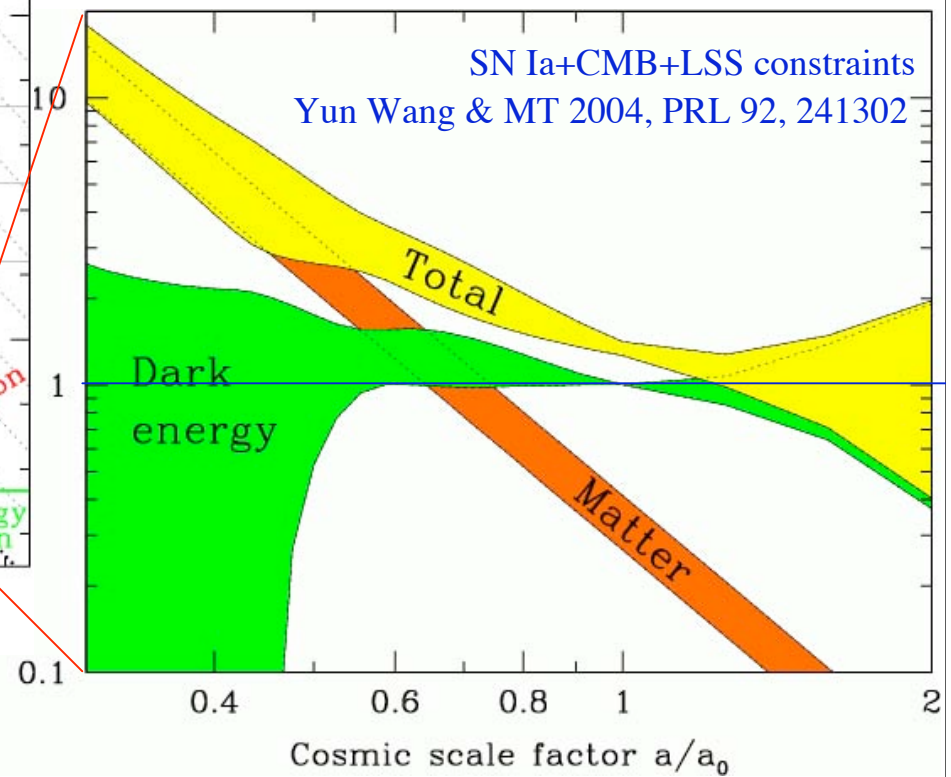


Tytler et al 2000, astro-ph/0001318

$$H = d \ln a / dt, \quad H^2 \propto \rho, \quad r(z) = \int_0^z \frac{dz'}{H(z')}$$

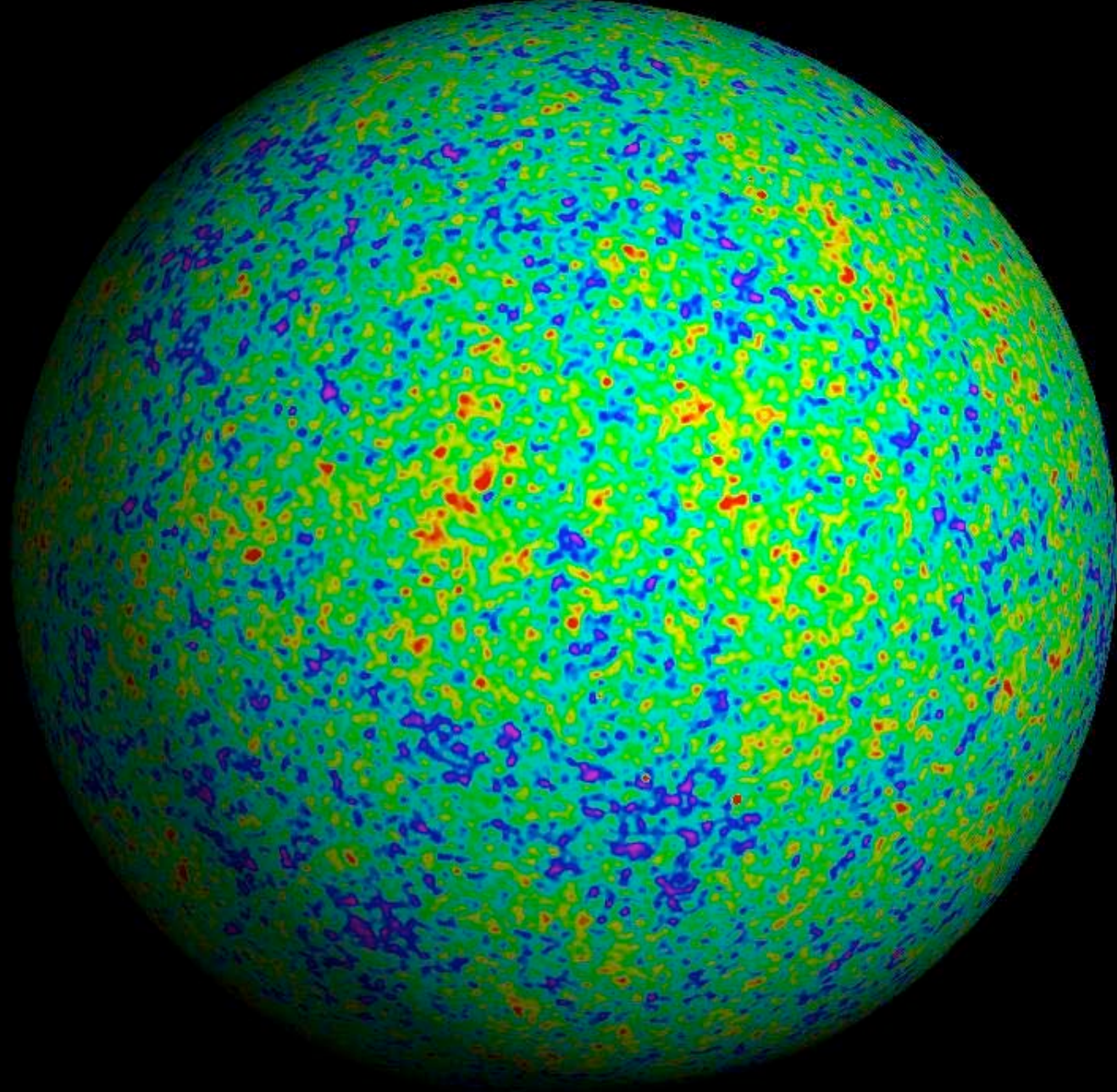


Assumes $k=0$



Measuring clustering

Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496



$z = 1000$

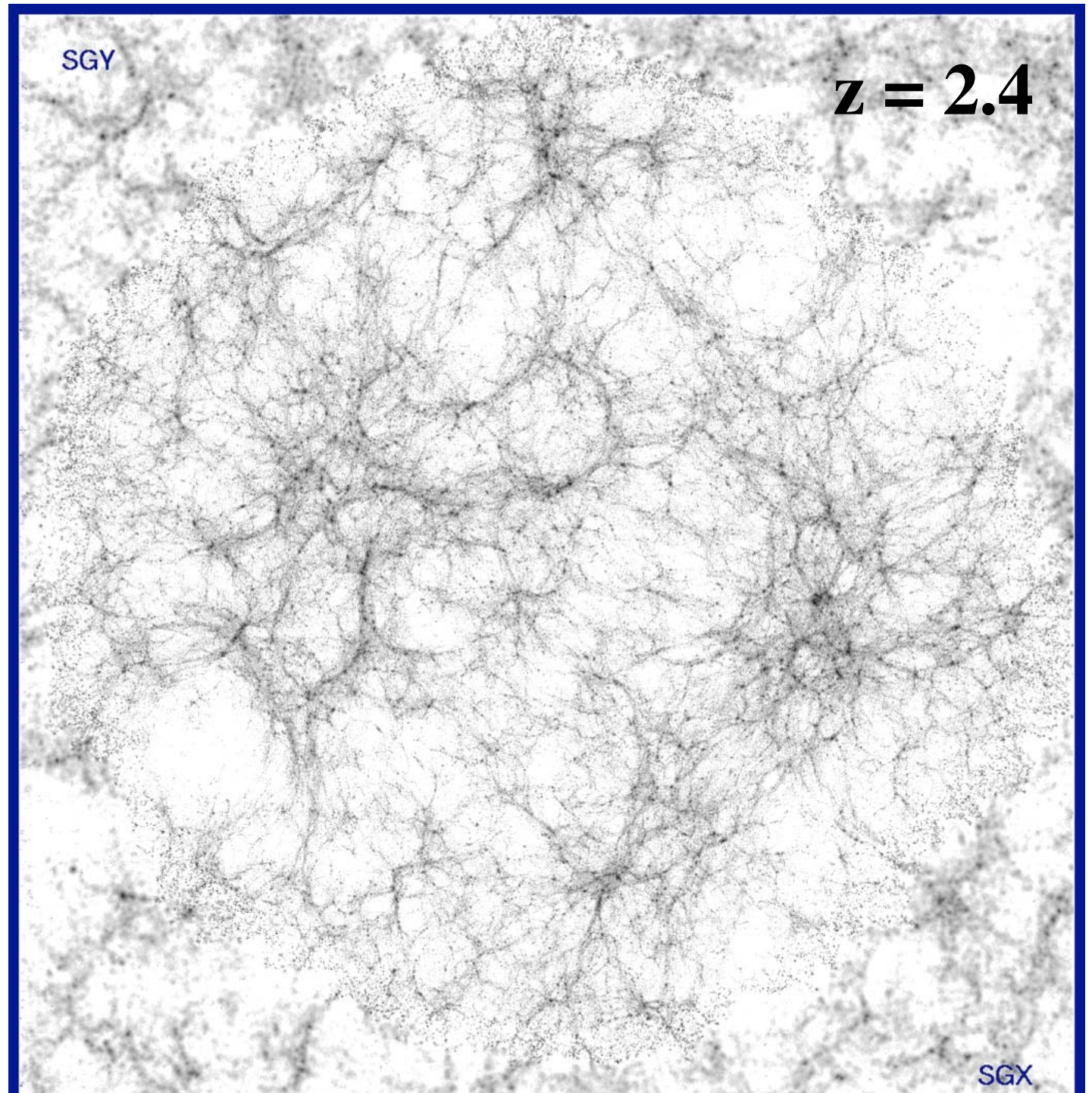


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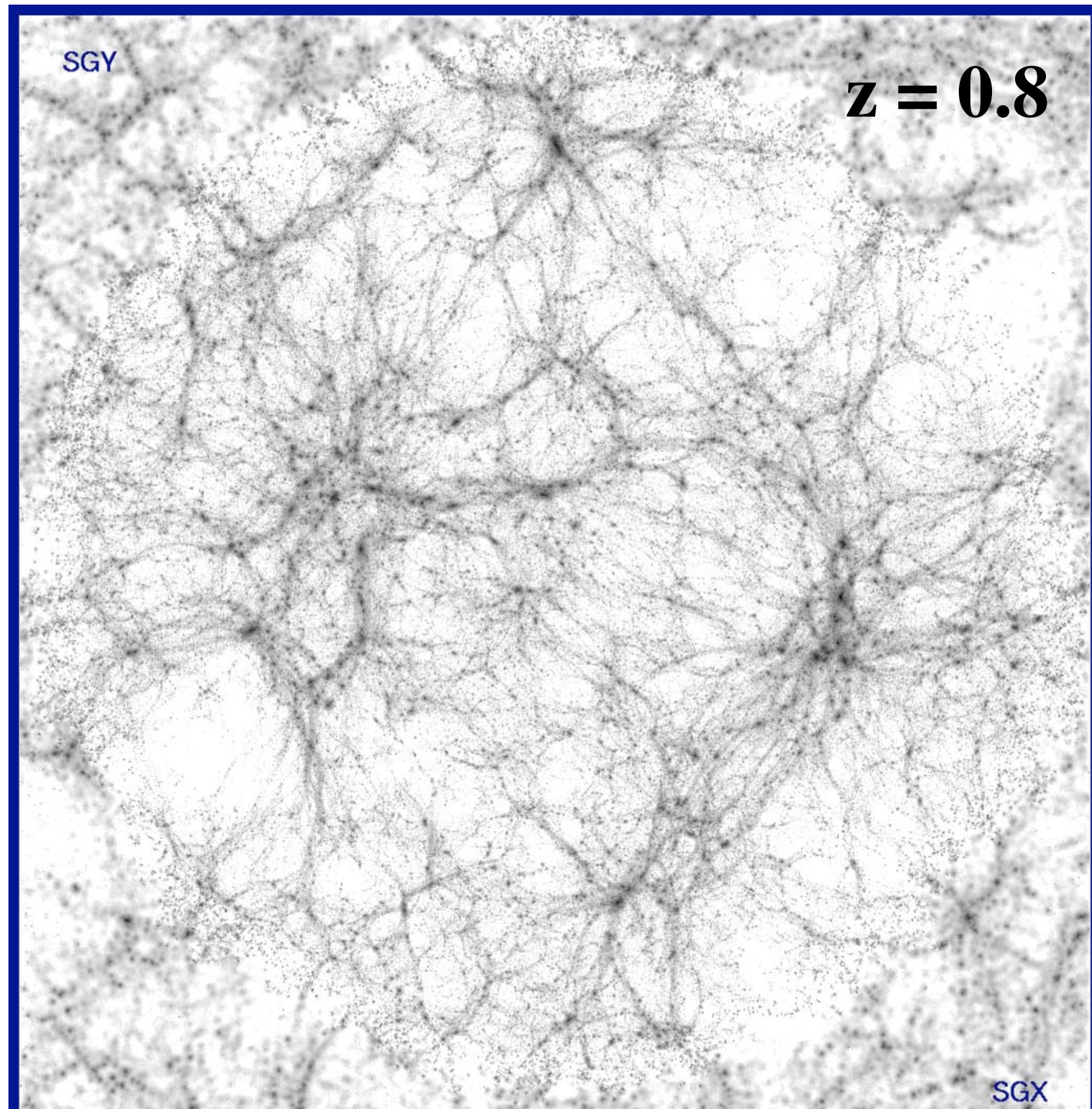
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001





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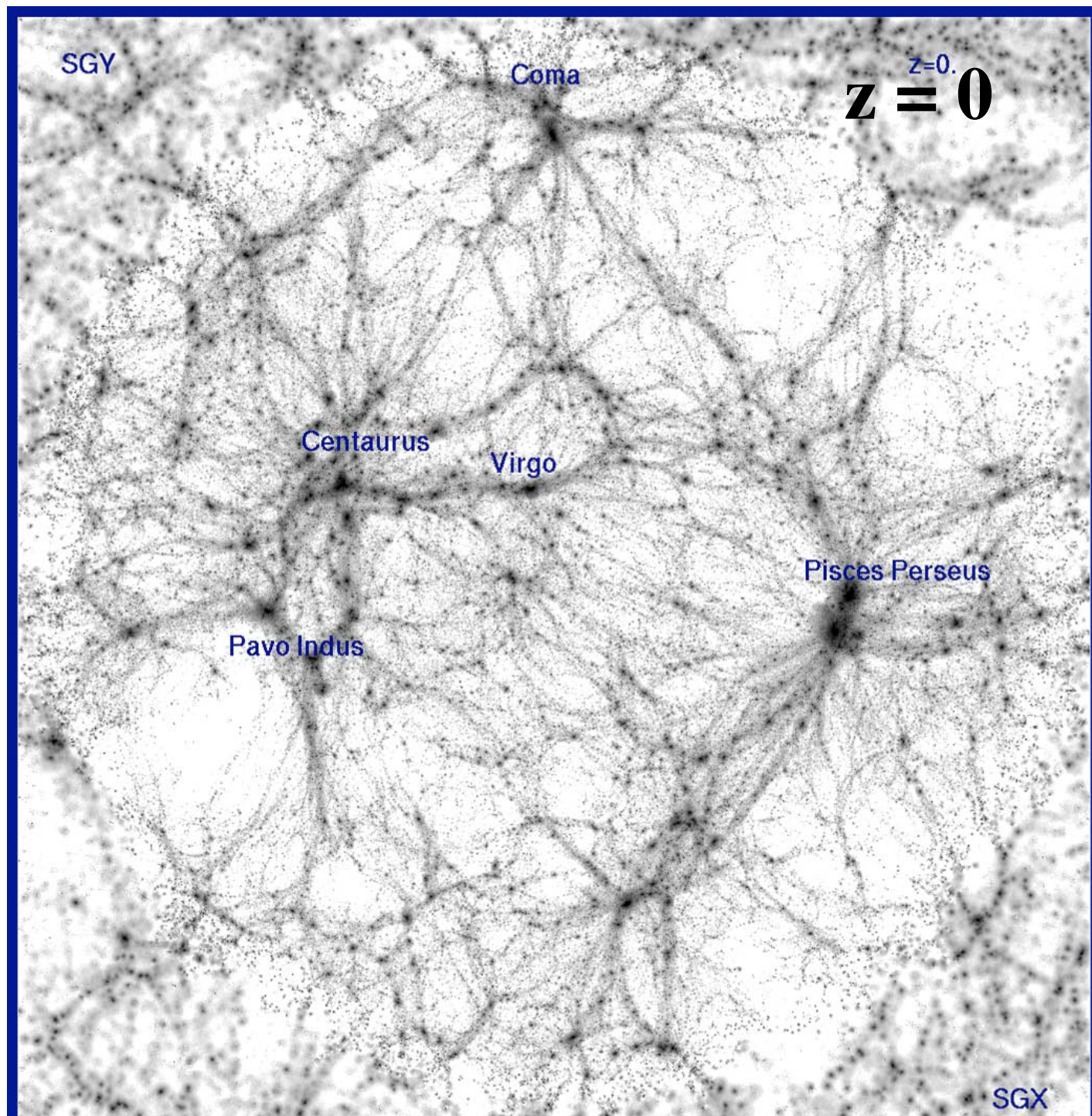
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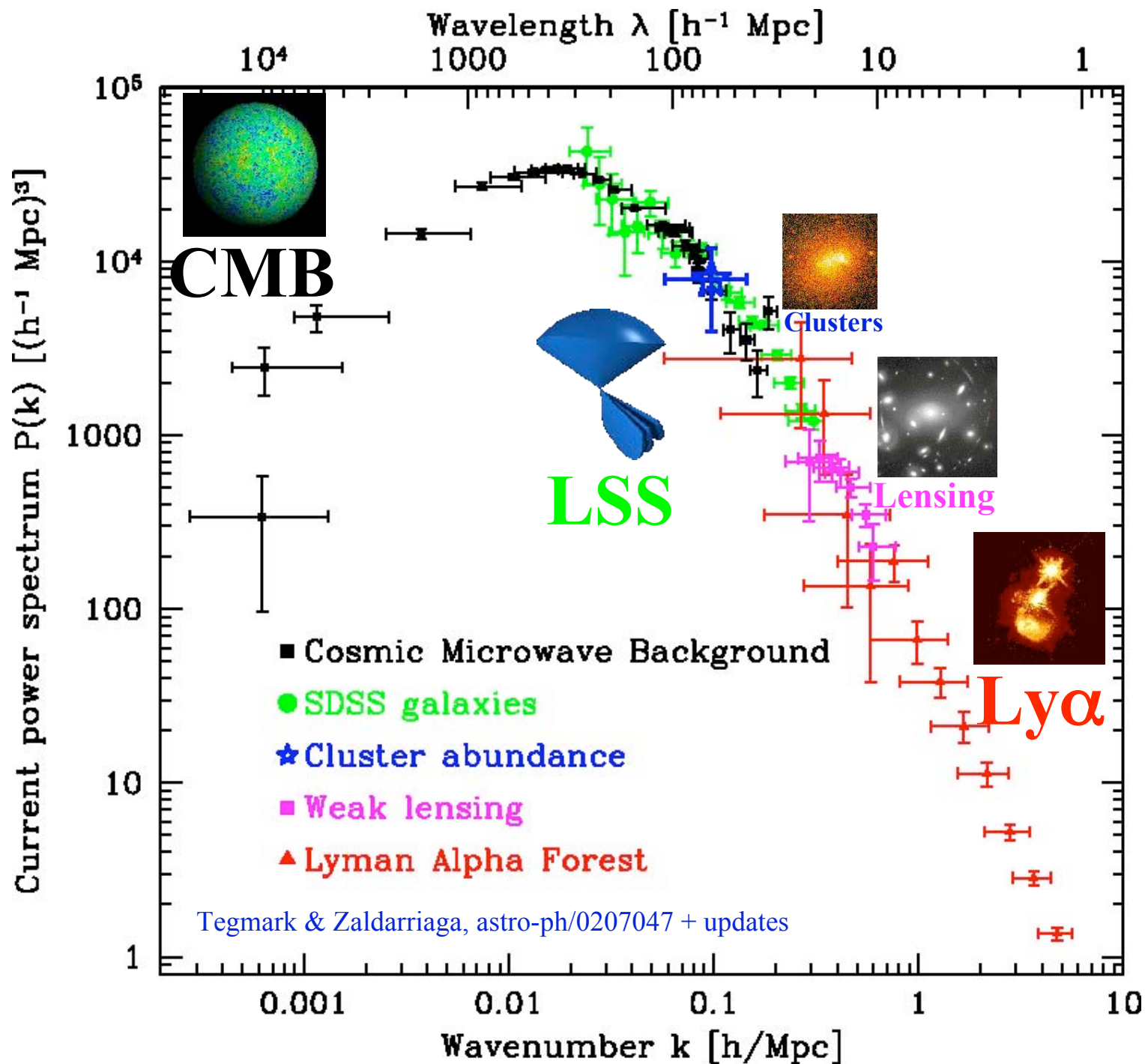
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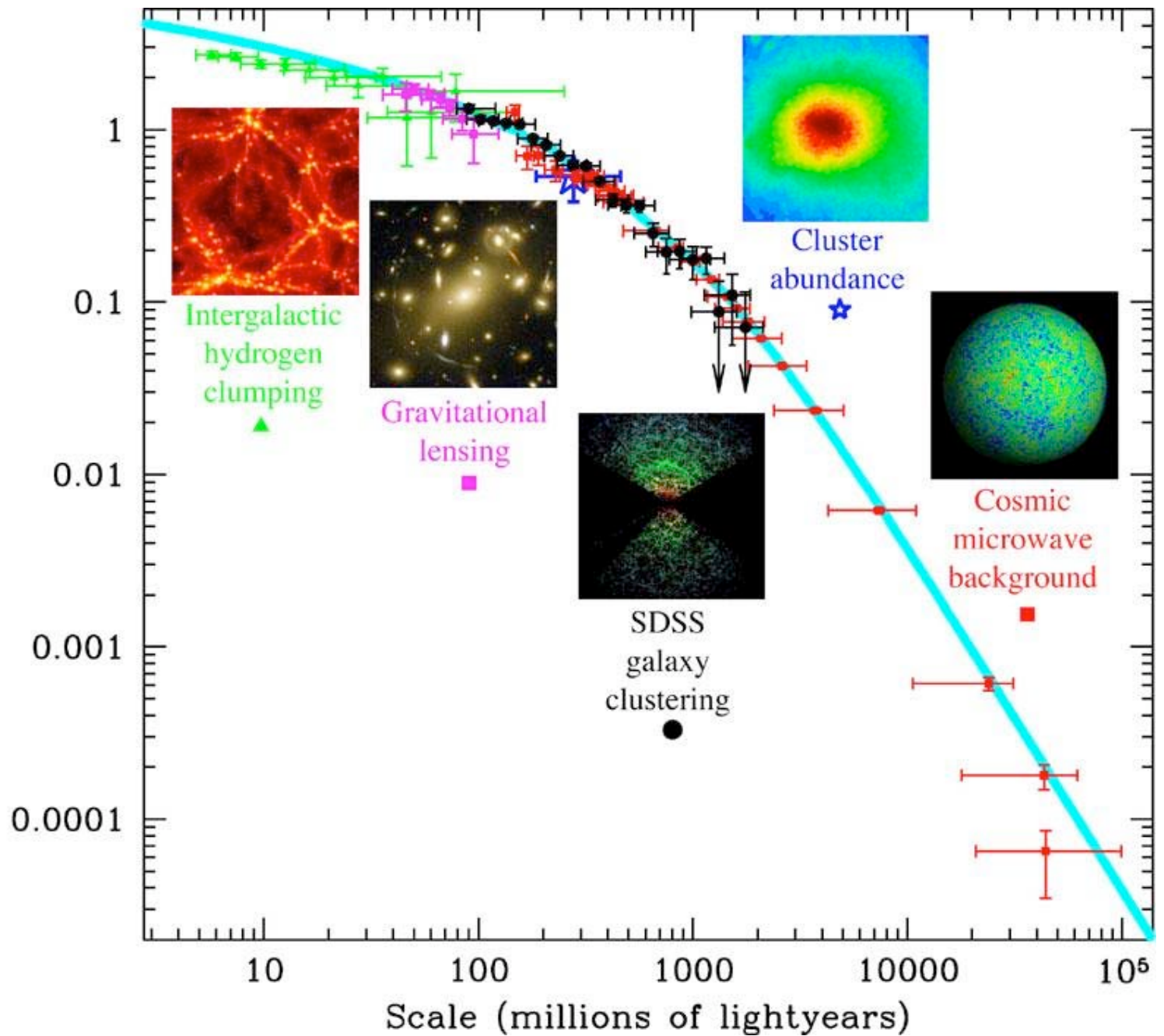




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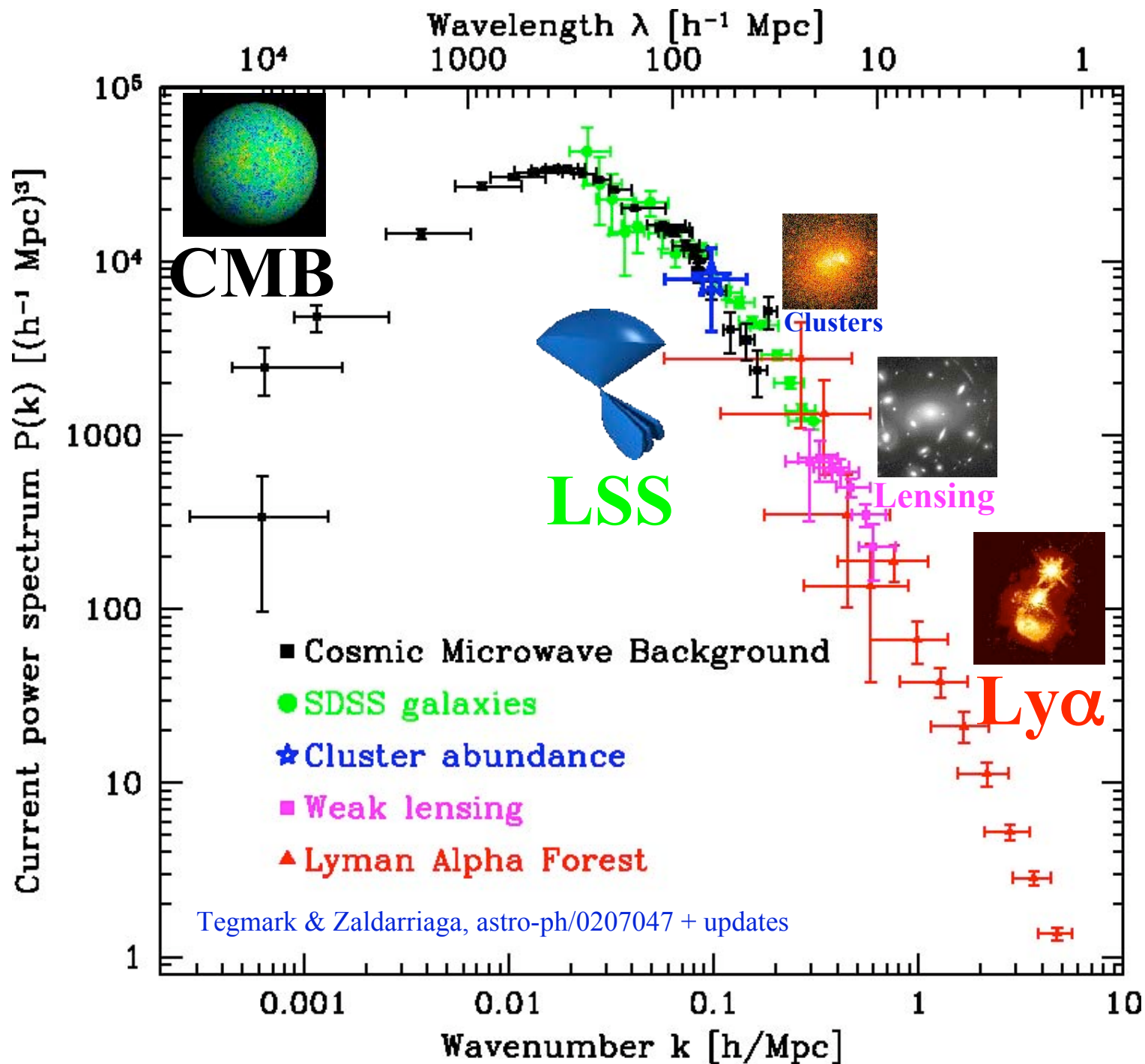
Density fluctuations

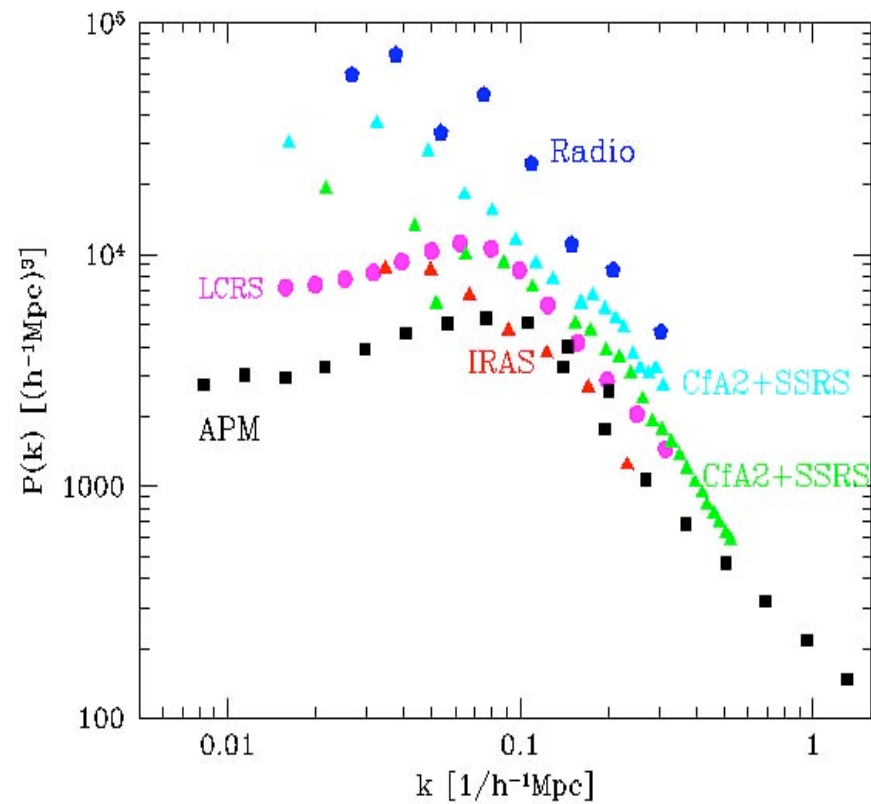


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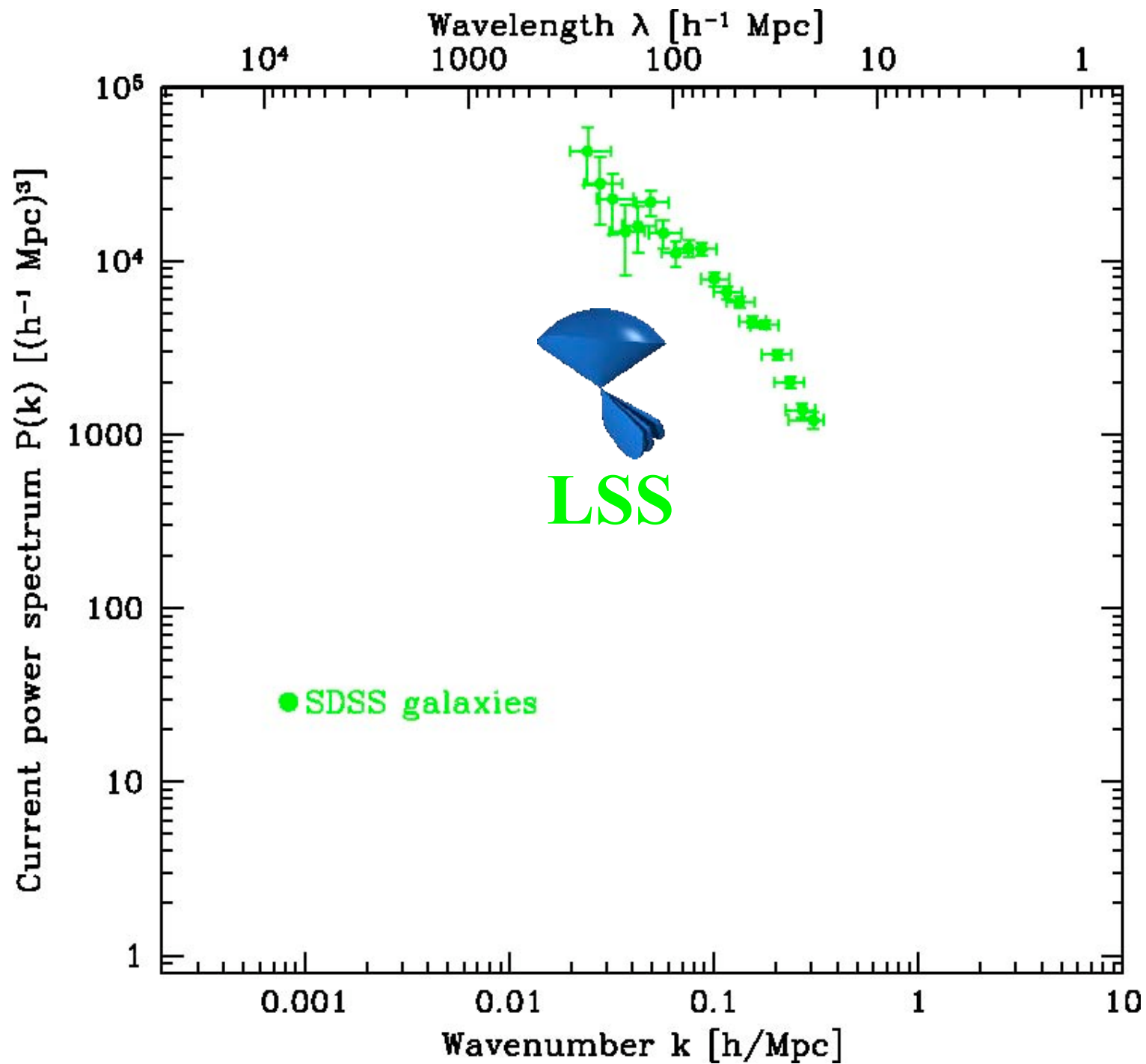


Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)



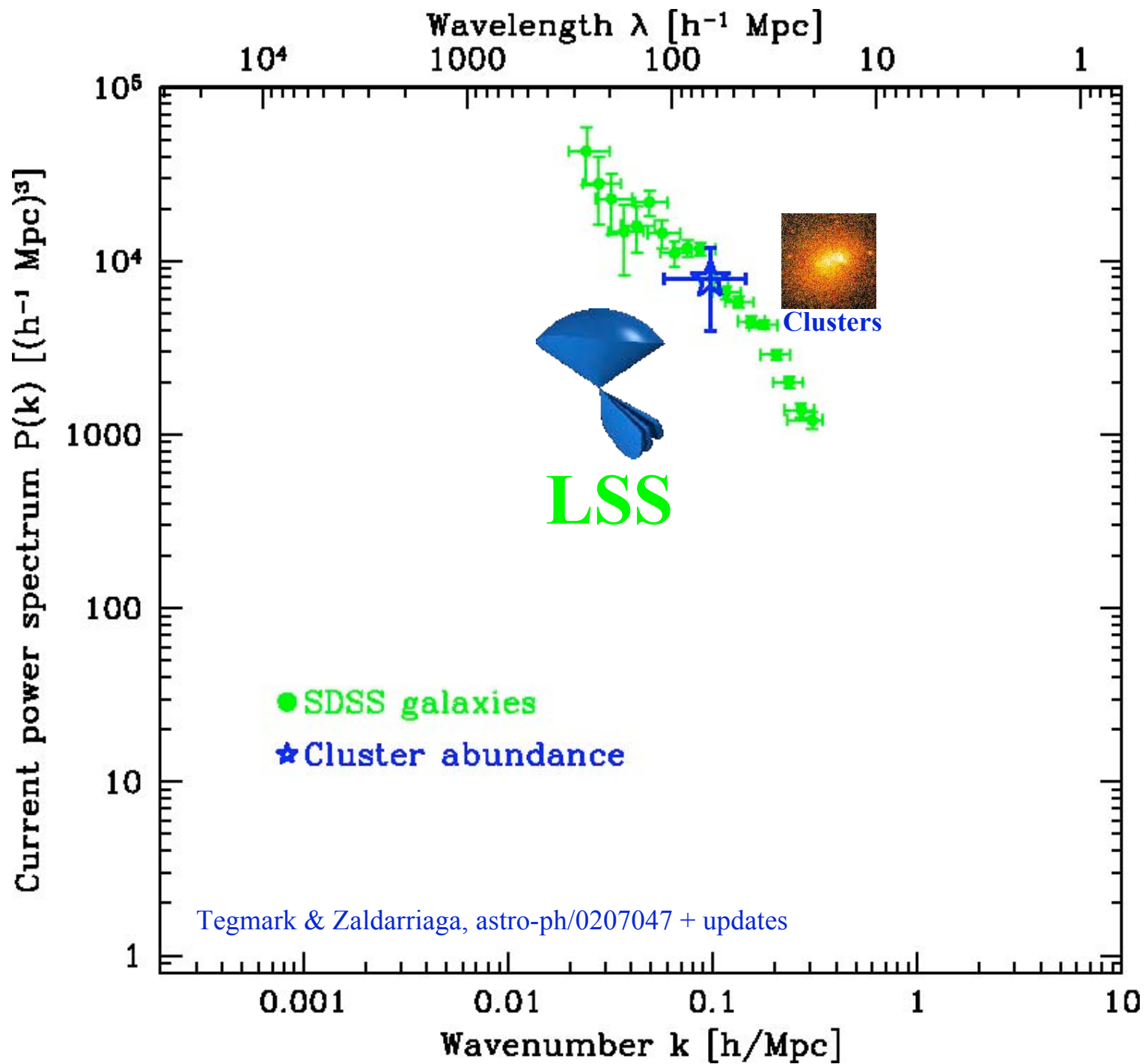


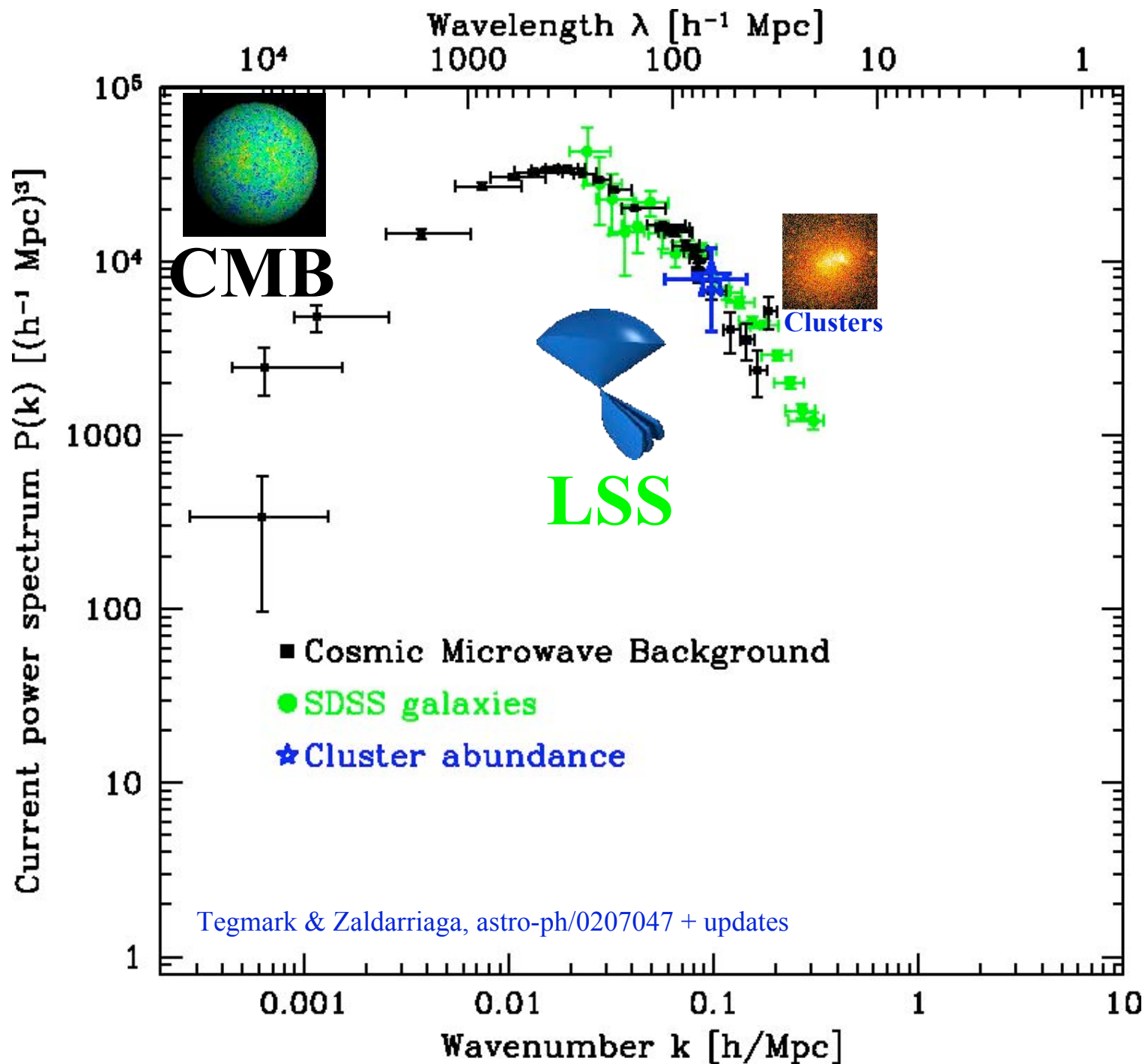
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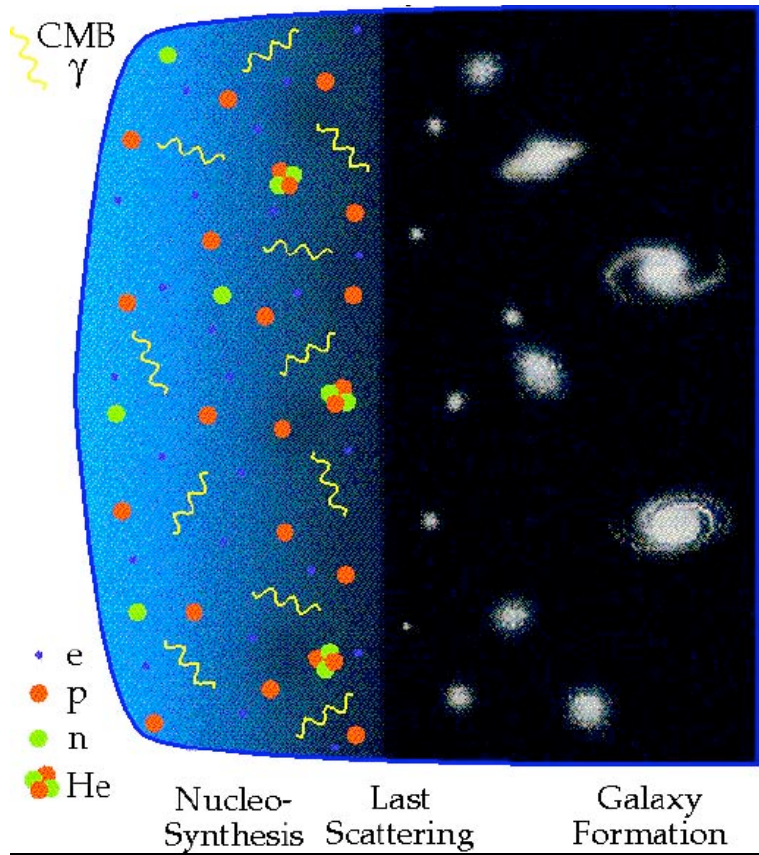




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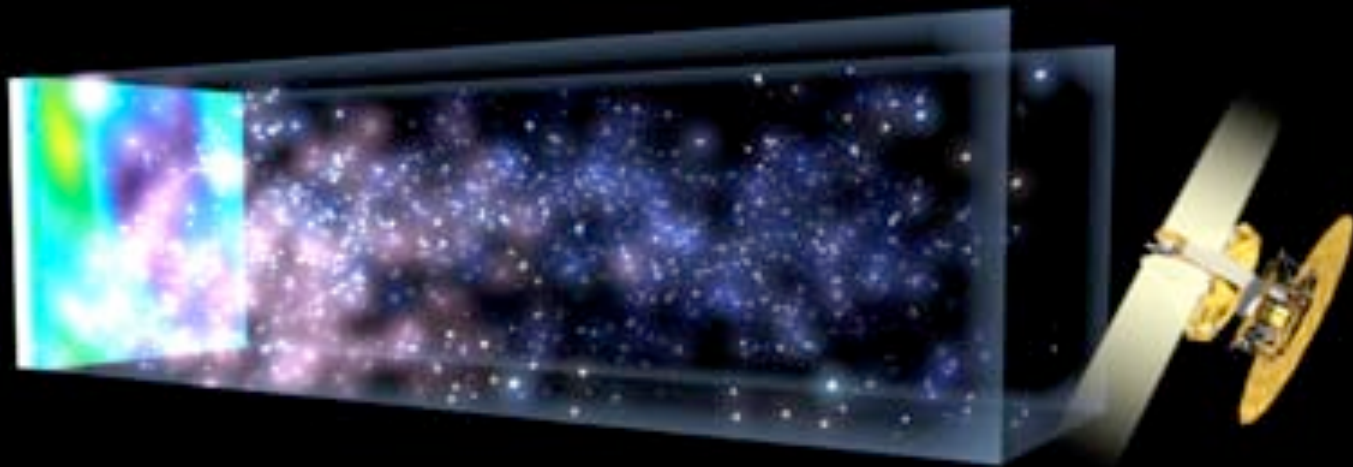


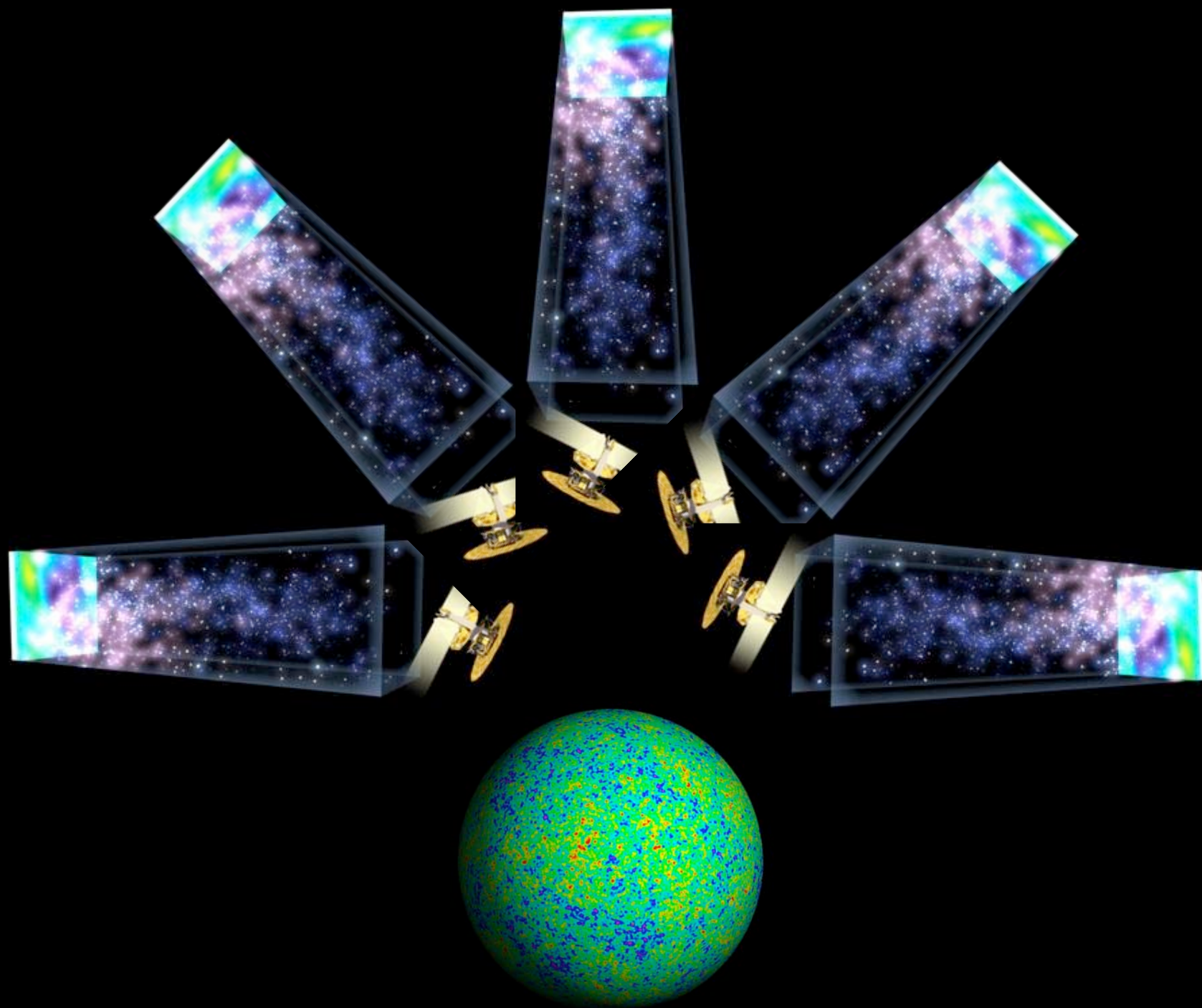




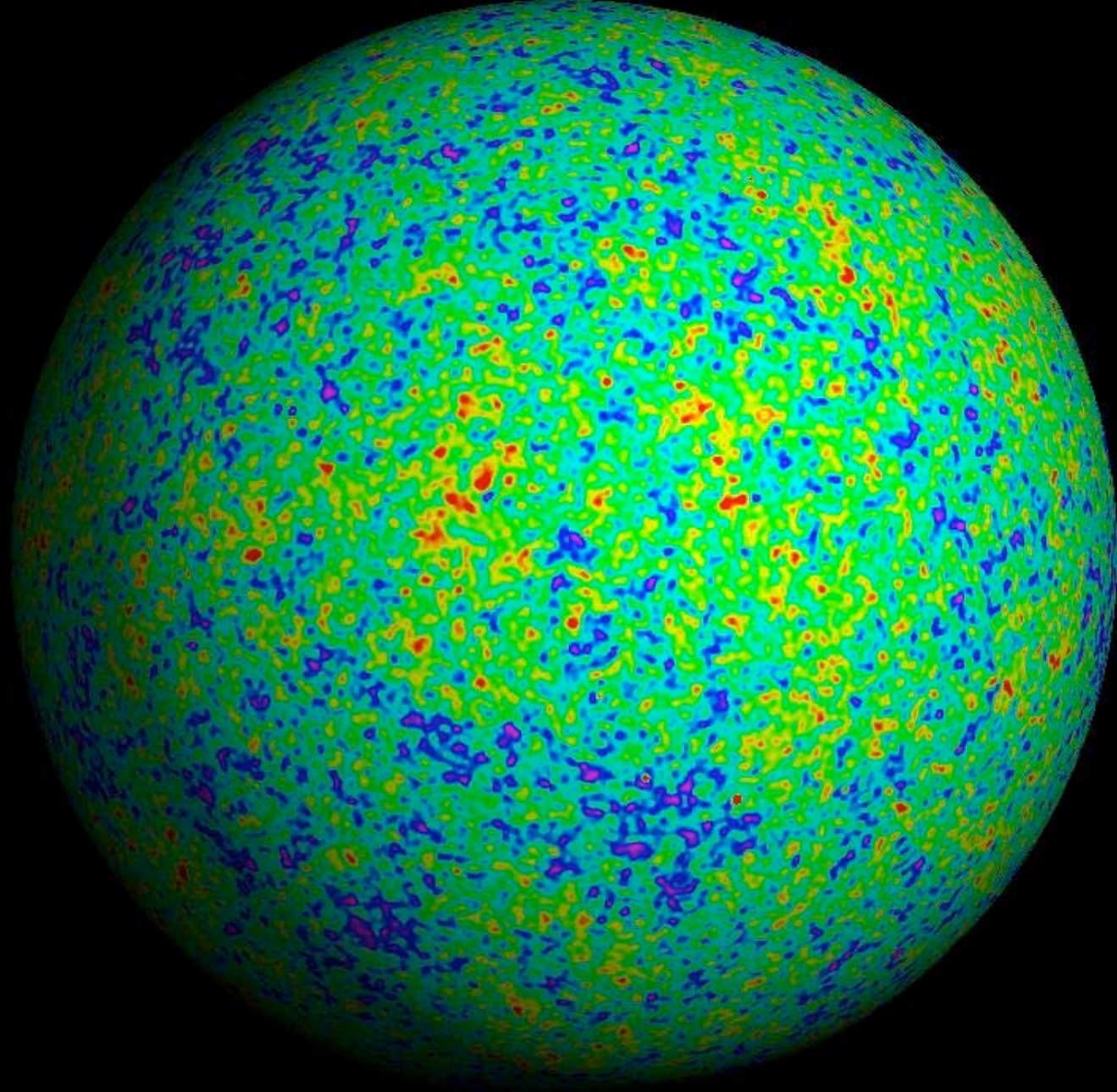
(Figure from Wayne Hu)

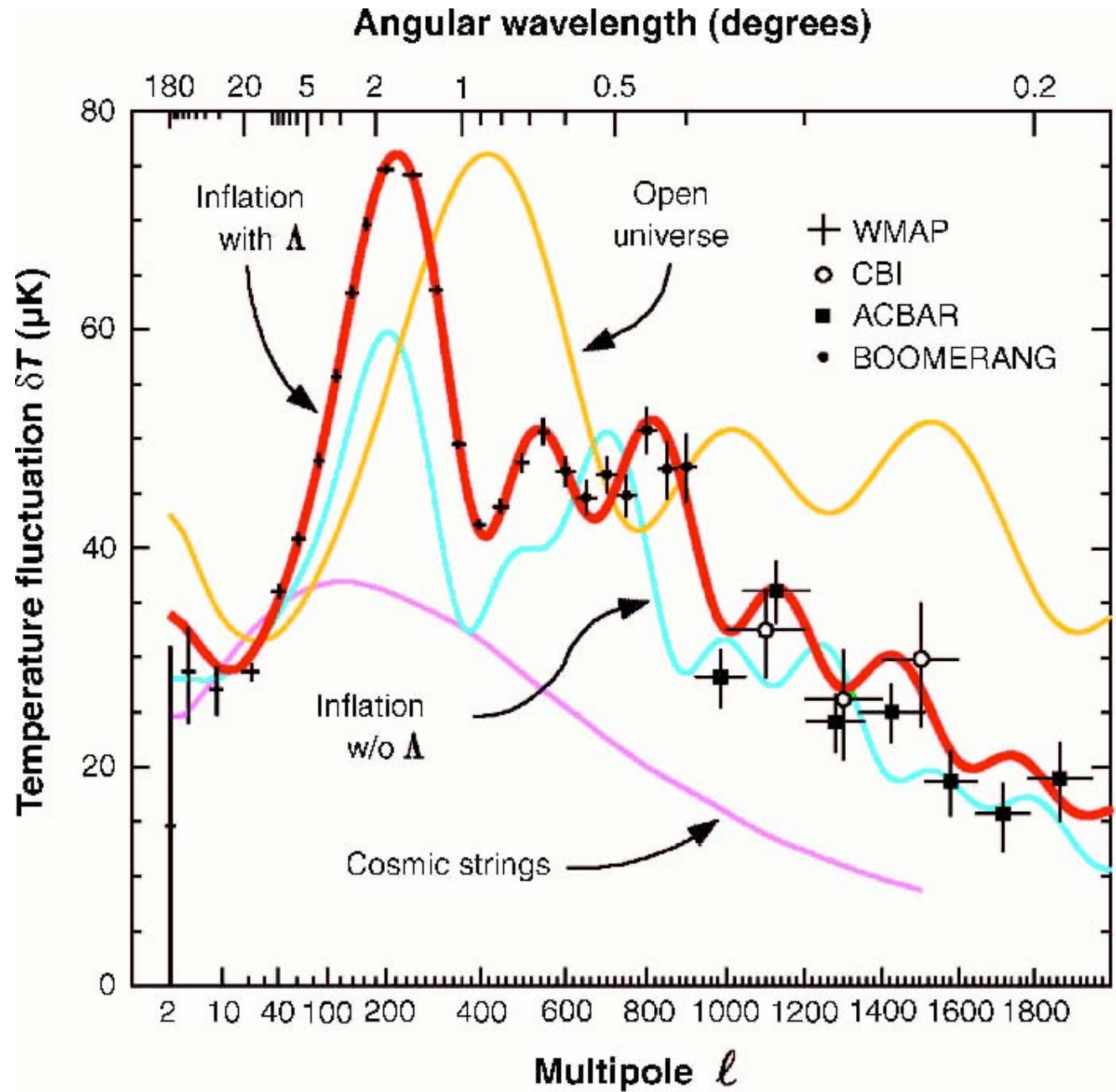
(Figure from WMAP team)

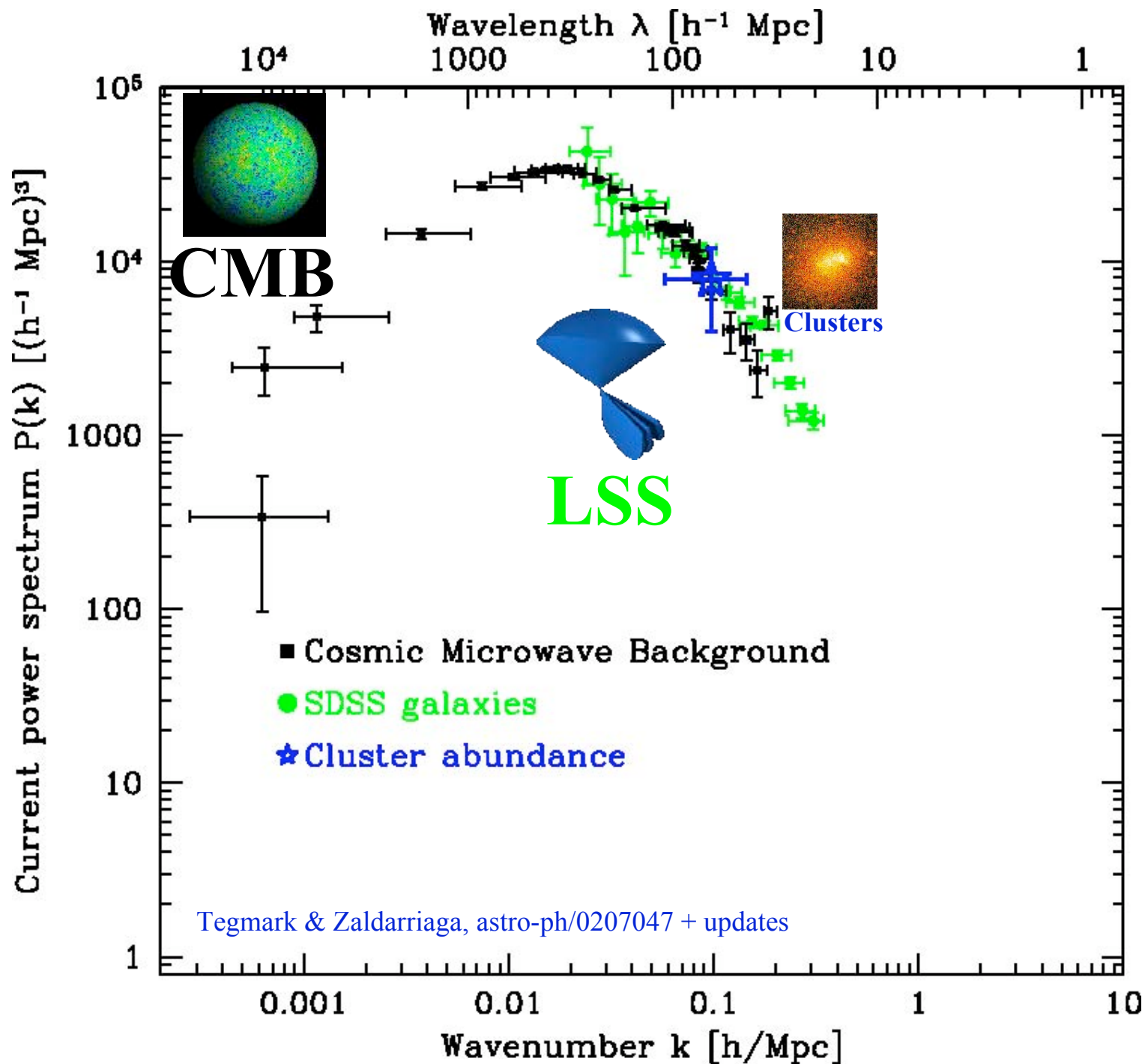




Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/030249

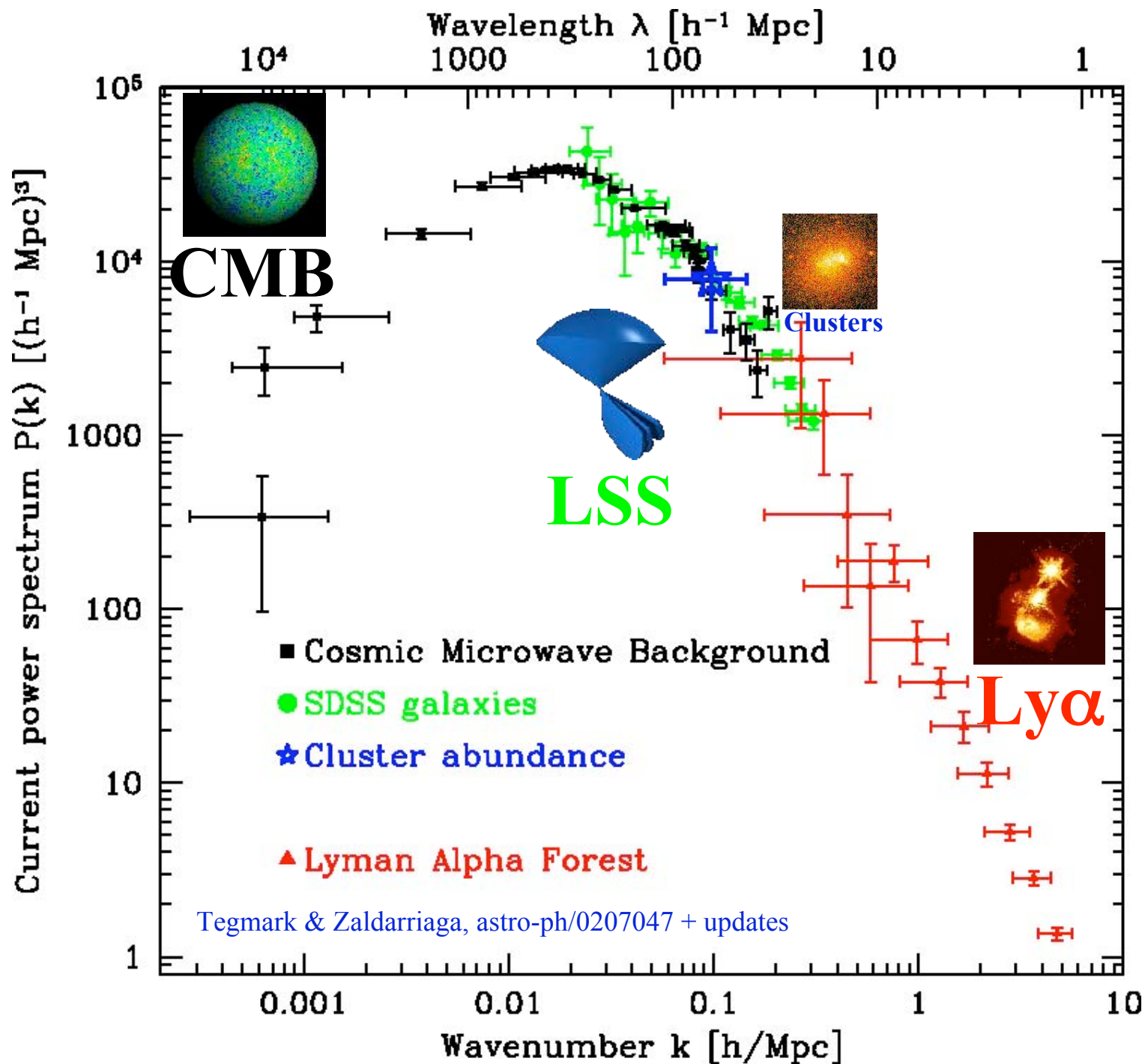




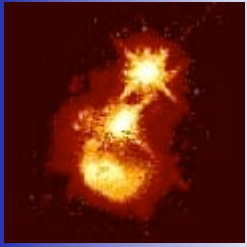




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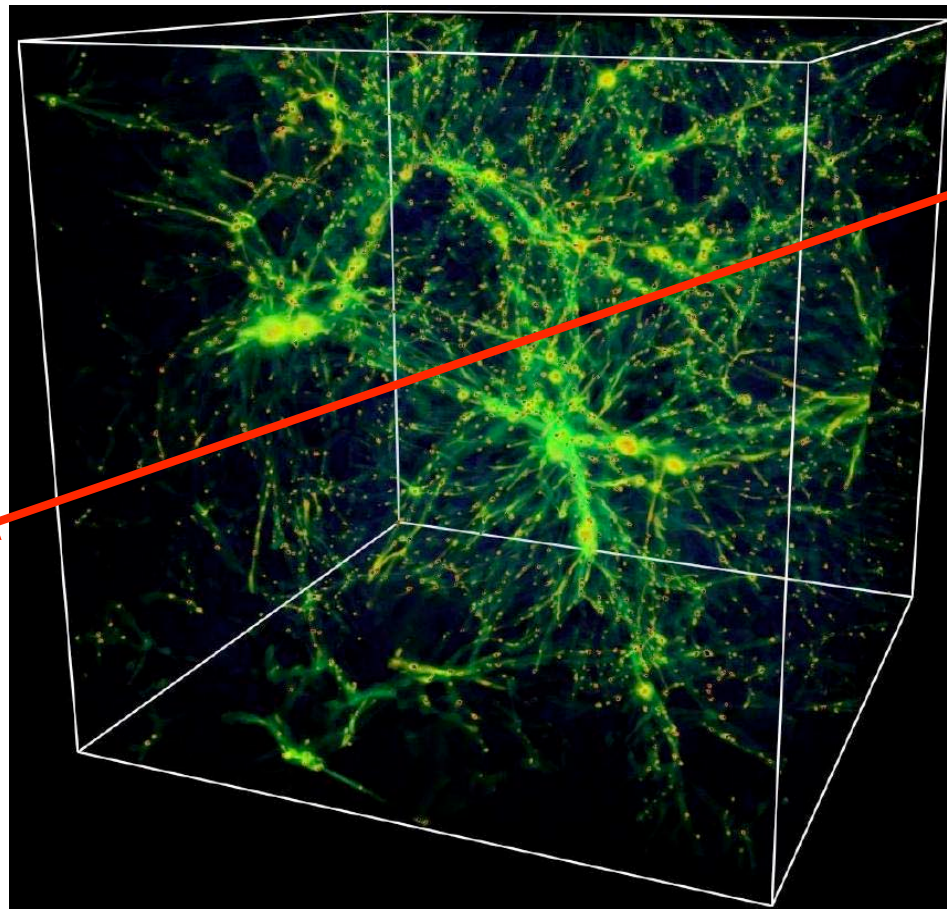
Lyman Alpha Forest Simulation: Cen et al 2001



Ly α F

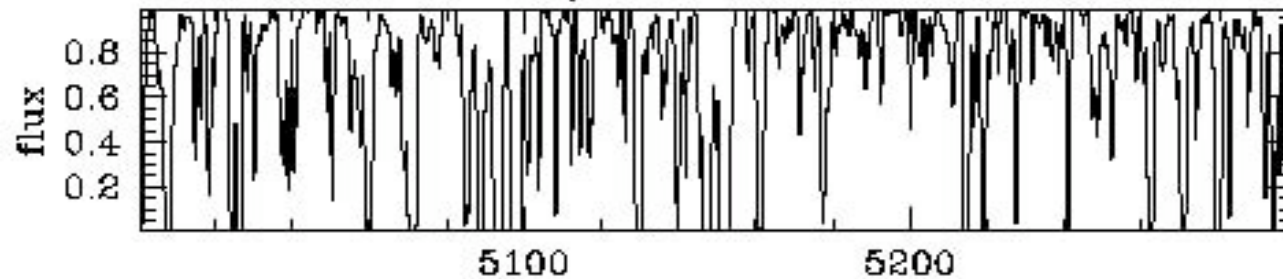


You



Quasar

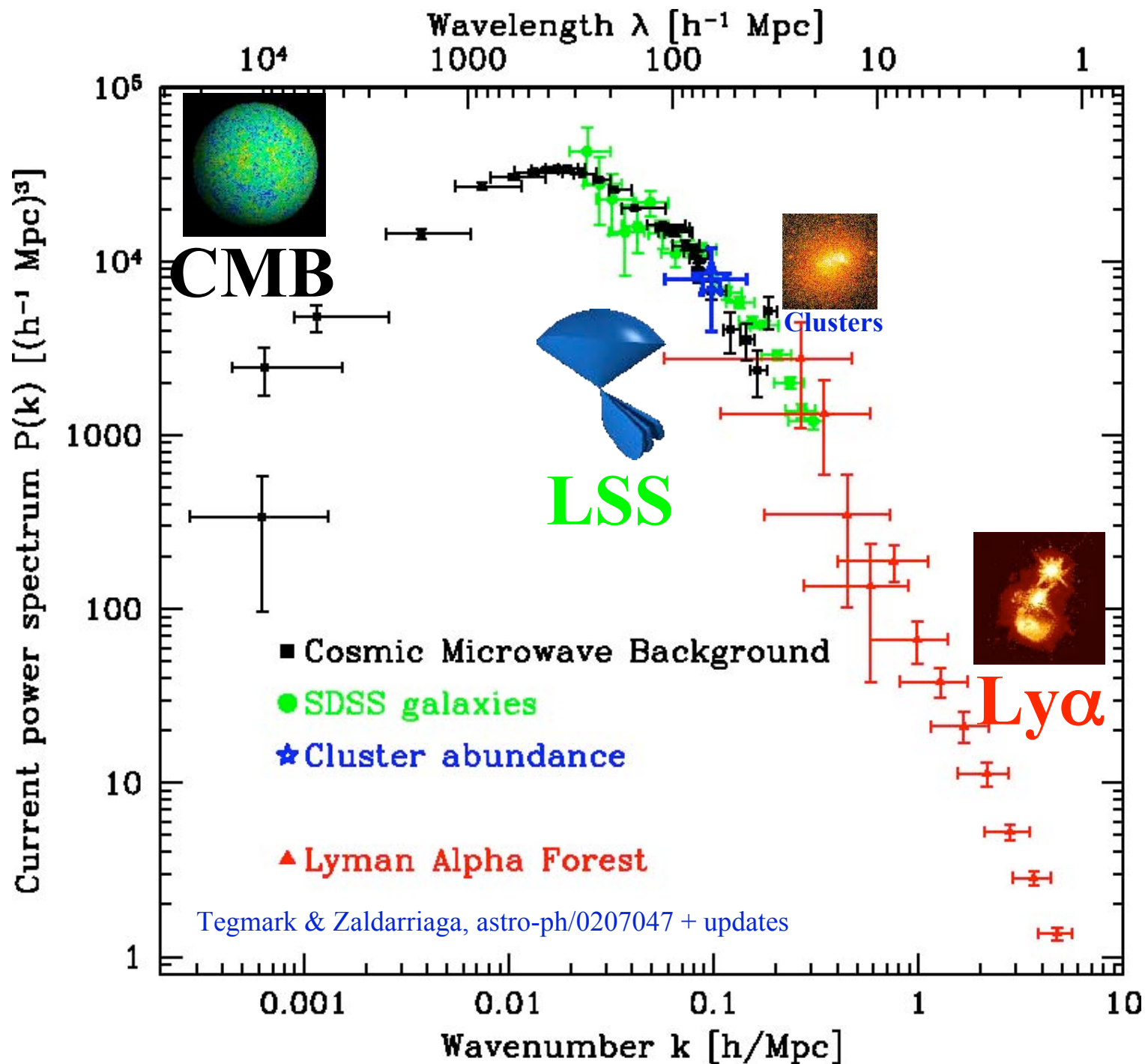
QSO 1422+2301



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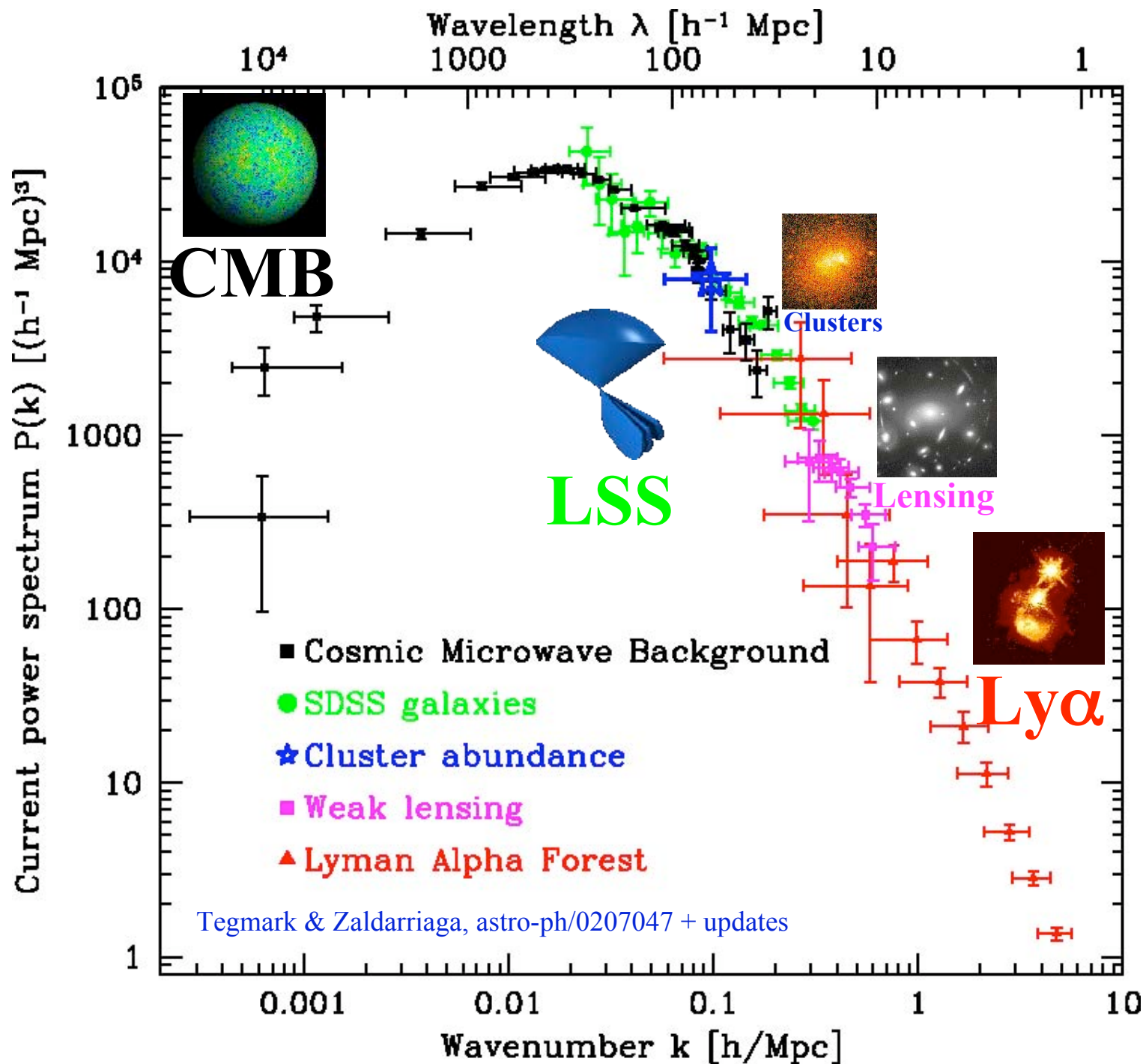


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**GRAVITATIONAL LENSING:
A1689 imaged by Hubble ACS, Broadhurst et al 2004**





Lensing

WHAT YOU HAVE:



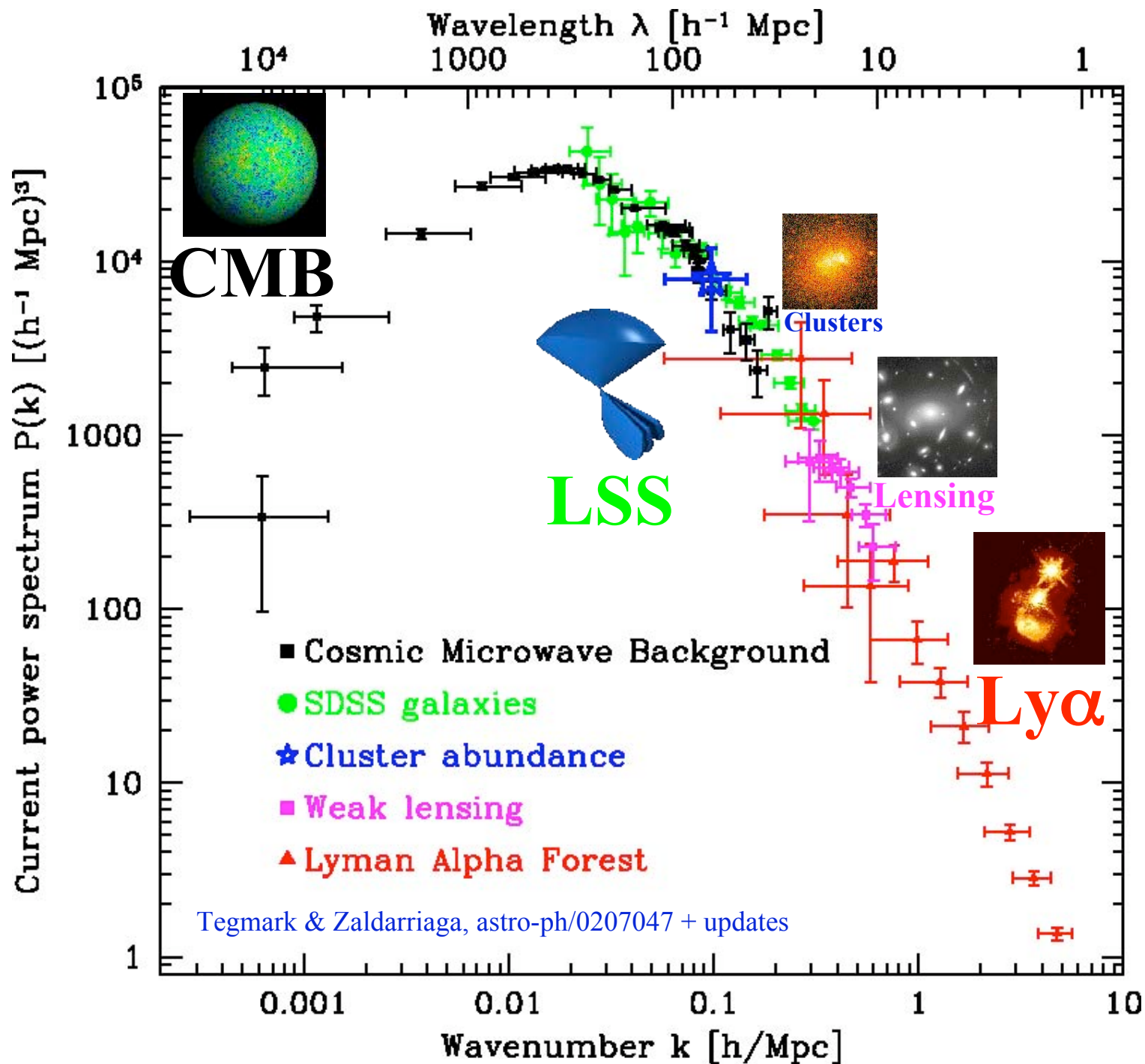
WHAT YOU SEE:

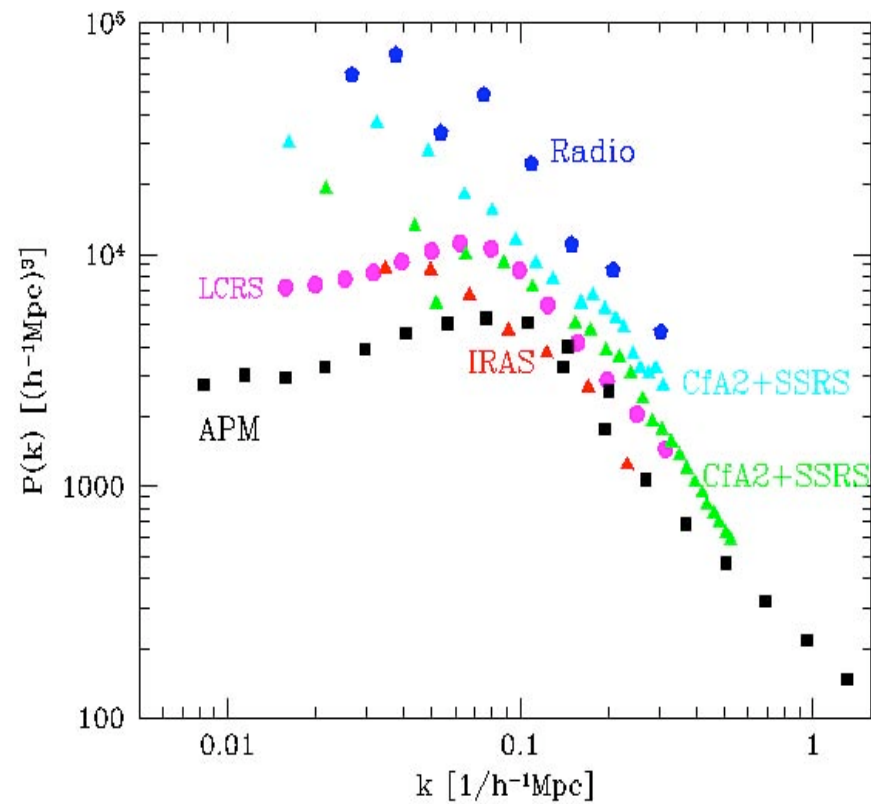


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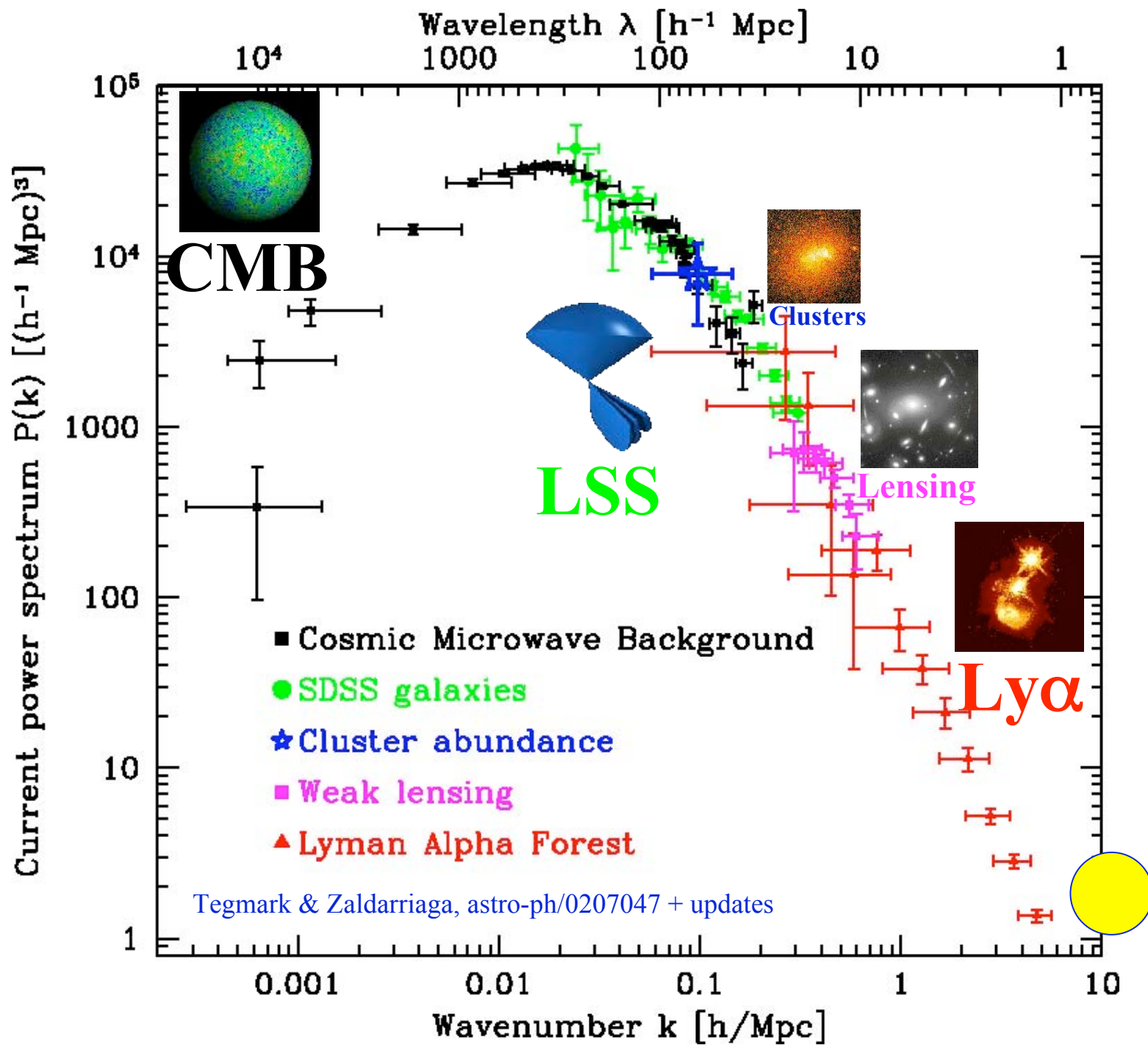


Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)



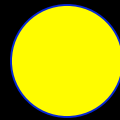


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But the best
is yet to
come...

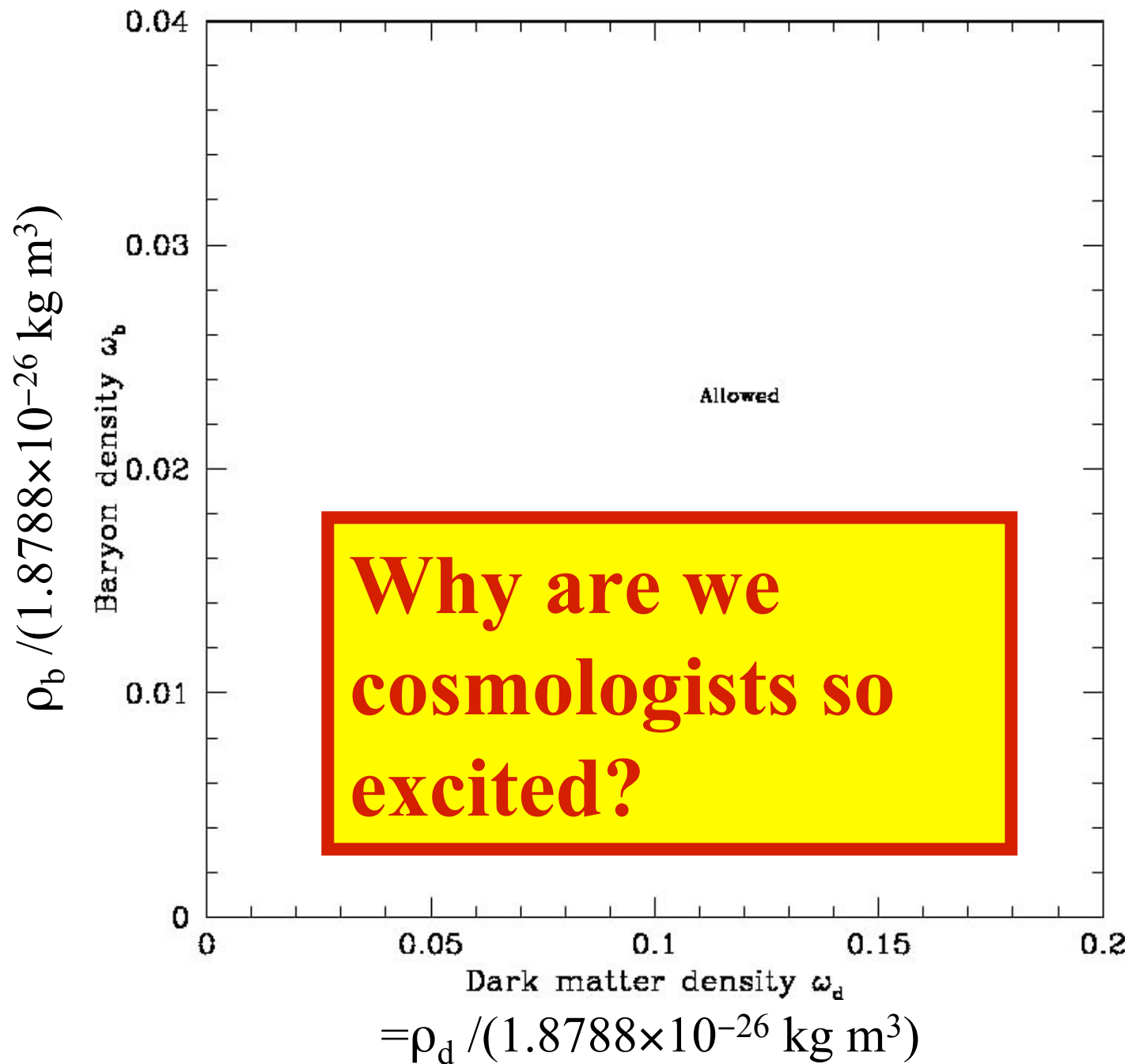
Measuring cosmological parameters



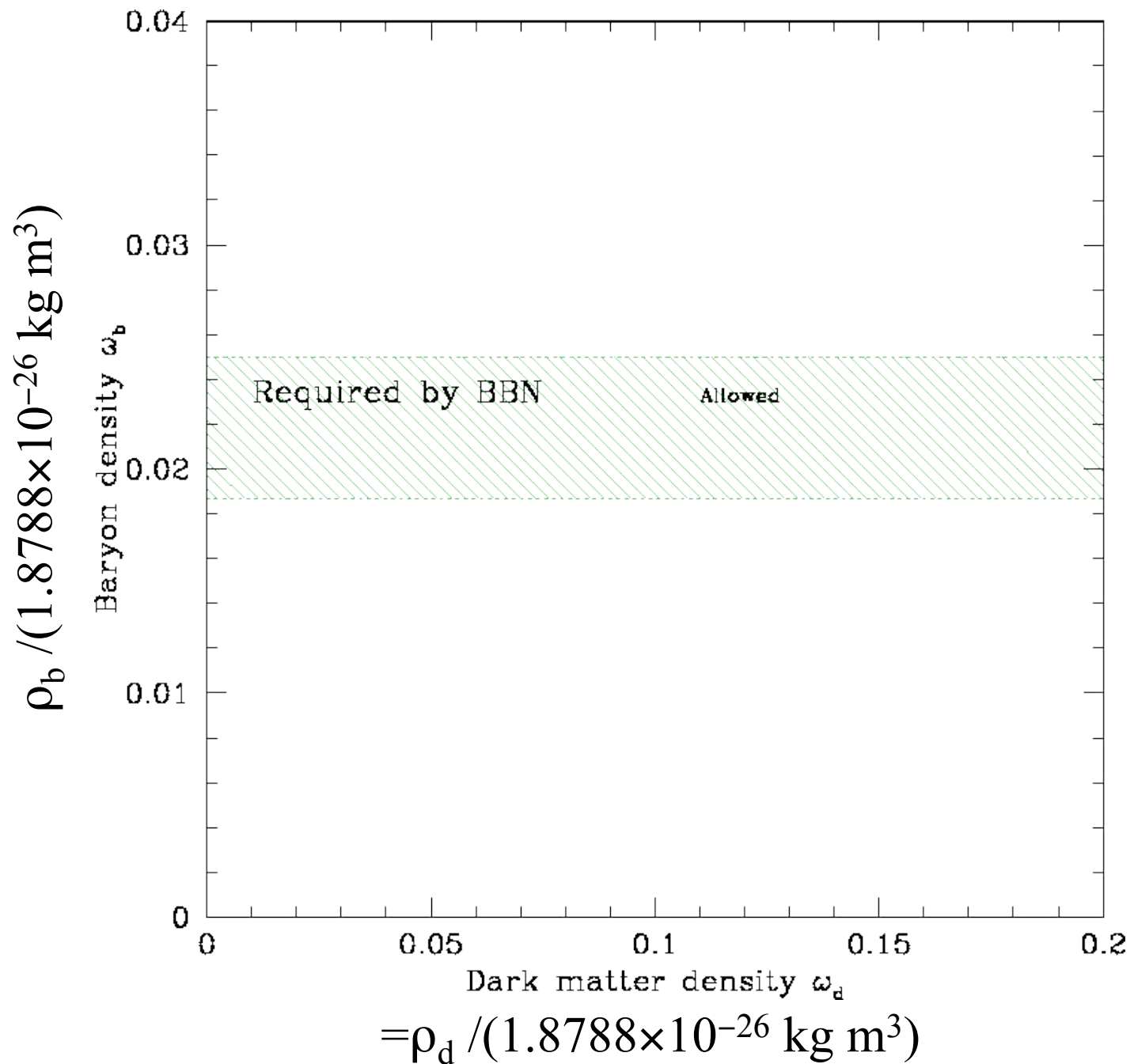
Cosmological parameter movies available at

<http://space.mit.edu/home/tegmark/movies.html>

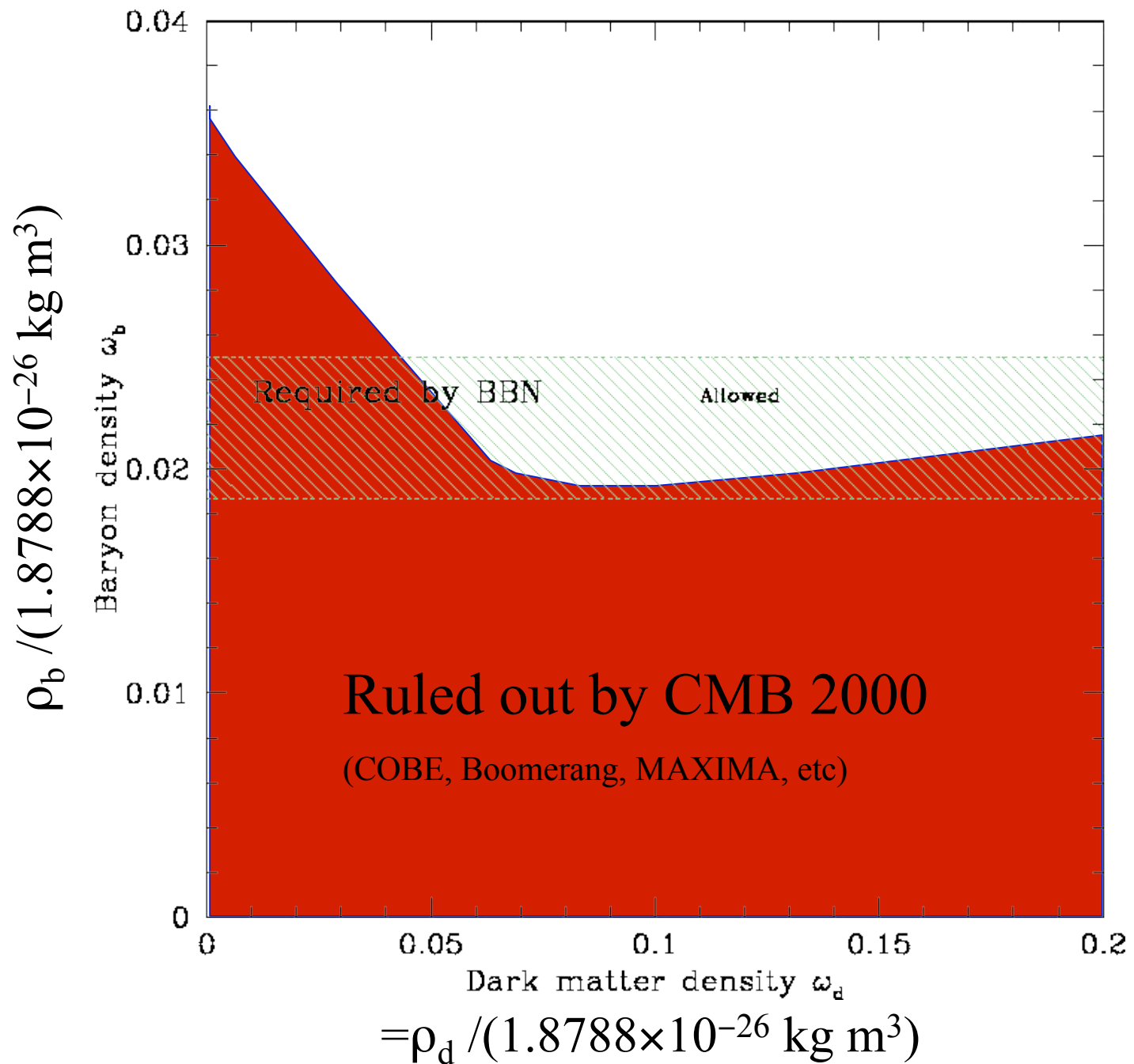
How much dark matter is there?

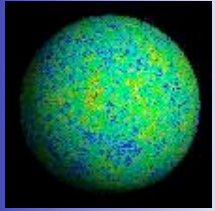


How much dark matter is there?



How much dark matter is there?



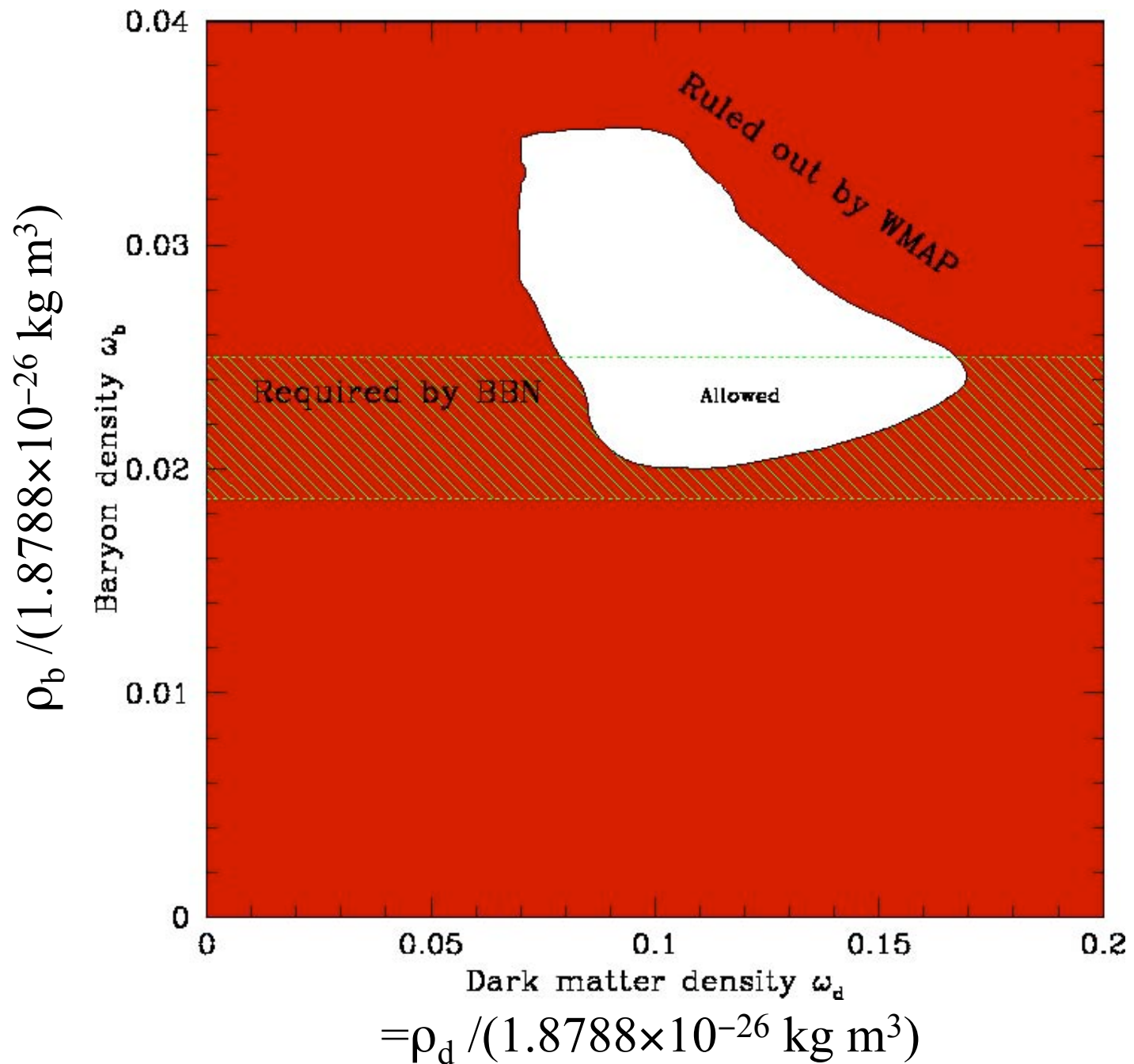


CMB

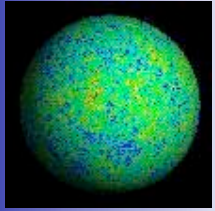


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How much dark matter is there?

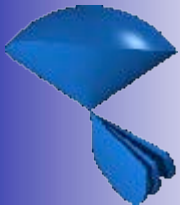


How much dark matter is there?



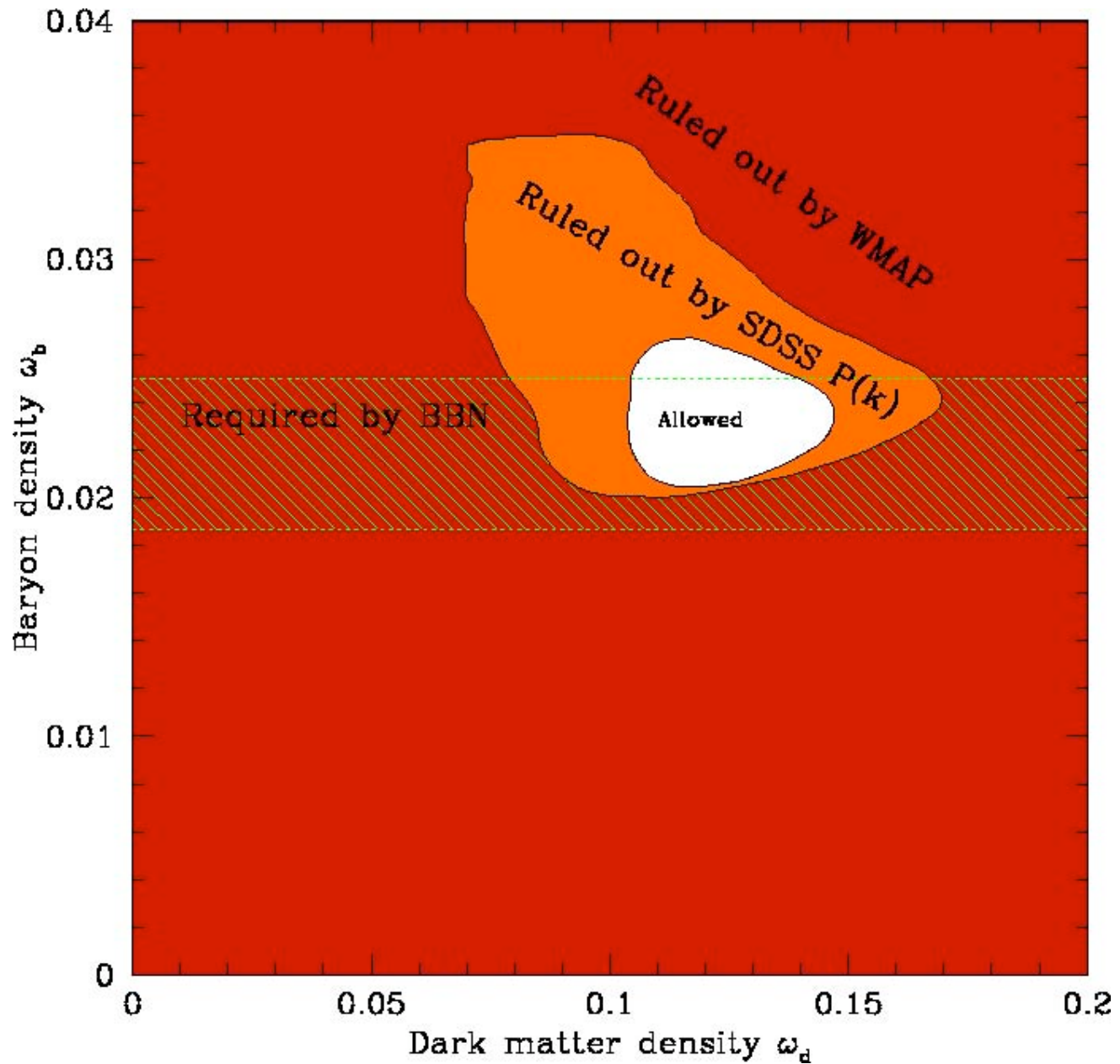
CMB

+



P(k)

$$\rho_b / (1.8788 \times 10^{-26} \text{ kg m}^3)$$

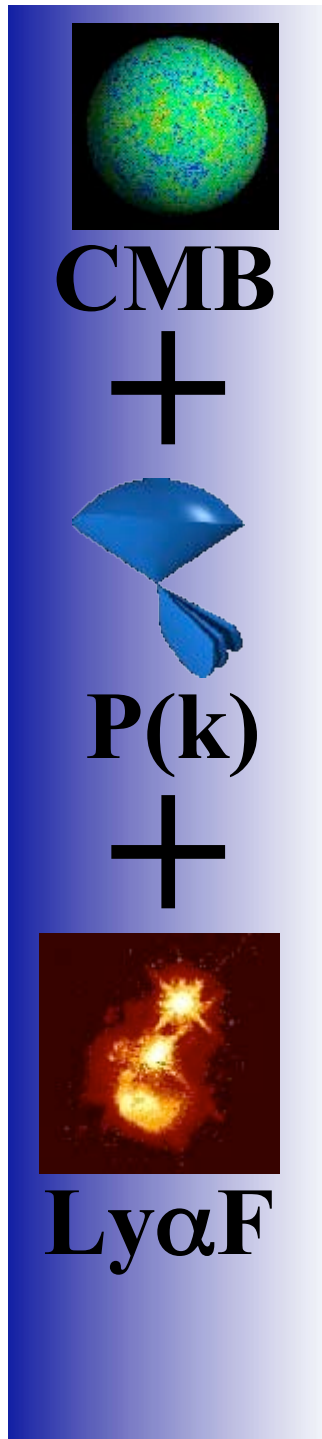


$$= \rho_d / (1.8788 \times 10^{-26} \text{ kg m}^3)$$

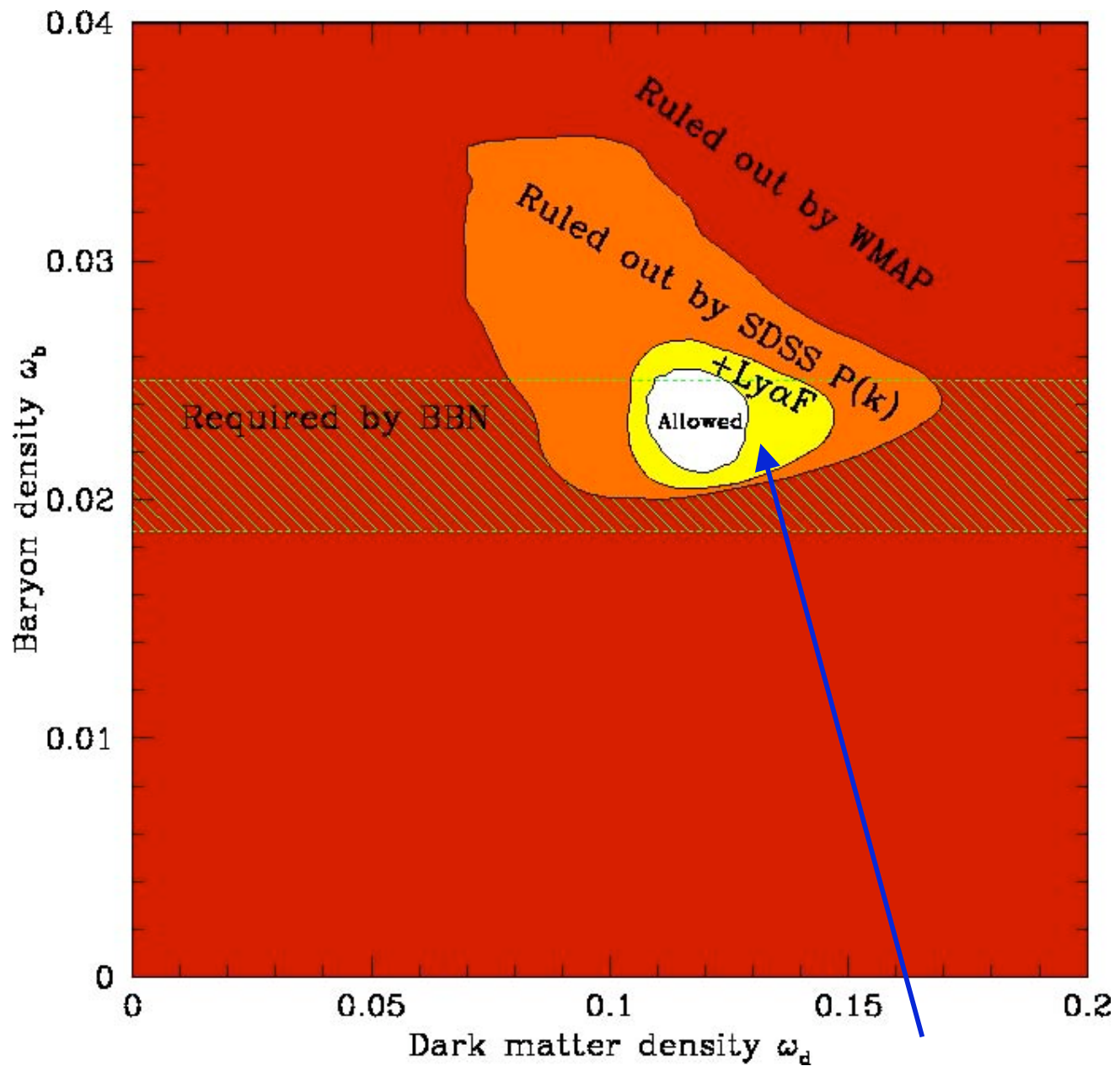


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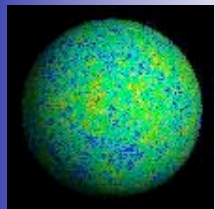
How much dark matter is there?



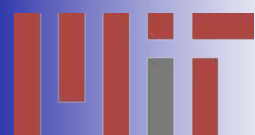
$$\rho_b / (1.8788 \times 10^{-26} \text{ kg m}^3)$$



SDSS Ly α F analysis lead by Pat McDonald, Uros Seljak, Scott Burles & co



CMB



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	Using WMAP temperature and polarization information						No pol. 6par
	6par+ $\Omega_k + r + \alpha$	6par+ Ω_k	6par+ r	6par+ f_ν	6par+ w	6par	
$e^{-2\tau}$	$0.52^{+0.21}_{-0.15}$	$0.65^{+0.19}_{-0.32}$	$0.68^{+0.13}_{-0.16}$	$0.75^{+0.12}_{-0.23}$	$0.68^{+0.15}_{-0.21}$	$0.66^{+0.17}_{-0.25}$	> 0.50 (95%)
Θ_s	$0.602^{+0.010}_{-0.006}$	$0.603^{+0.015}_{-0.005}$	$0.5968^{+0.0048}_{-0.0056}$	$0.5893^{+0.0062}_{-0.0056}$	$0.5966^{+0.0066}_{-0.0105}$	$0.5987^{+0.0052}_{-0.0048}$	$0.5984^{+0.0041}_{-0.0042}$
Ω_Λ	$0.54^{+0.24}_{-0.33}$	$0.53^{+0.24}_{-0.32}$	$0.823^{+0.058}_{-0.082}$	$0.687^{+0.087}_{-0.097}$	$0.64^{+0.14}_{-0.17}$	$0.75^{+0.10}_{-0.10}$	$0.674^{+0.086}_{-0.093}$
$h^2\Omega_d$	$0.105^{+0.023}_{-0.023}$	$0.108^{+0.022}_{-0.034}$	$0.097^{+0.021}_{-0.018}$	$0.119^{+0.018}_{-0.016}$	$0.118^{+0.020}_{-0.020}$	$0.115^{+0.020}_{-0.021}$	$0.129^{+0.019}_{-0.018}$
$h^2\Omega_b$	$0.0238^{+0.0035}_{-0.0027}$	$0.0241^{+0.0055}_{-0.0020}$	$0.0256^{+0.0025}_{-0.0019}$	$0.0247^{+0.0029}_{-0.0016}$	$0.0246^{+0.0038}_{-0.0017}$	$0.0245^{+0.0050}_{-0.0019}$	$0.0237^{+0.0018}_{-0.0013}$
f_ν	0	0	0	No constraint	0	0	0
n_s	$0.97^{+0.13}_{-0.10}$	$1.01^{+0.18}_{-0.06}$	$1.064^{+0.066}_{-0.059}$	$0.962^{+0.098}_{-0.041}$	$1.03^{+0.12}_{-0.05}$	$1.02^{+0.16}_{-0.06}$	$0.989^{+0.061}_{-0.031}$
$n_t + 1$	$0.9847^{+0.0097}_{-0.0141}$	1	$0.959^{+0.026}_{-0.037}$	1	1	1	1
A_p	$0.593^{+0.053}_{-0.044}$	$0.602^{+0.053}_{-0.051}$	$0.592^{+0.049}_{-0.046}$	$0.602^{+0.045}_{-0.050}$	$0.637^{+0.045}_{-0.046}$	$0.633^{+0.044}_{-0.041}$	$0.652^{+0.049}_{-0.046}$
r	< 0.90 (95%)	0	< 0.84 (95%)	0	0	0	0
b	No constraint	No constraint	No constraint	No constraint	No constraint	No constraint	No constraint
w	-1	-1	-1	-1	$-0.72^{+0.34}_{-0.27}$	-1	-1
α	$-0.075^{+0.047}_{-0.055}$	0	0	0	0	0	0
Ω_{tot}	$1.095^{+0.094}_{-0.144}$	$1.086^{+0.057}_{-0.128}$	0	0	0	0	0
Ω_m	$0.57^{+0.45}_{-0.33}$	$0.55^{+0.47}_{-0.29}$	$0.177^{+0.082}_{-0.058}$	$0.313^{+0.097}_{-0.087}$	$0.36^{+0.17}_{-0.14}$	$0.25^{+0.10}_{-0.10}$	$0.326^{+0.093}_{-0.086}$
$h^2\Omega_m$	$0.128^{+0.022}_{-0.021}$	$0.132^{+0.021}_{-0.028}$	$0.123^{+0.020}_{-0.018}$	$0.144^{+0.018}_{-0.016}$	$0.143^{+0.020}_{-0.019}$	$0.140^{+0.020}_{-0.018}$	$0.153^{+0.020}_{-0.018}$
h	$0.48^{+0.27}_{-0.12}$	$0.50^{+0.16}_{-0.13}$	$0.84^{+0.12}_{-0.10}$	$0.674^{+0.087}_{-0.049}$	$0.63^{+0.14}_{-0.10}$	$0.74^{+0.18}_{-0.07}$	$0.684^{+0.070}_{-0.045}$
τ	$0.33^{+0.17}_{-0.17}$	$0.22^{+0.34}_{-0.13}$	$0.19^{+0.13}_{-0.09}$	$0.15^{+0.18}_{-0.07}$	$0.19^{+0.18}_{-0.10}$	$0.21^{+0.24}_{-0.11}$	< 0.35 (95%)
z_{ion}	$25.9^{+4.4}_{-8.8}$	$20.1^{+9.2}_{-8.3}$	$17.1^{+5.8}_{-5.8}$	$15.5^{+8.6}_{-5.6}$	$18.5^{+7.1}_{-6.6}$	$19.6^{+7.8}_{-7.4}$	< 25 (95%)
A_s	$1.14^{+0.42}_{-0.31}$	$0.97^{+0.73}_{-0.23}$	$0.87^{+0.28}_{-0.16}$	$0.81^{+0.35}_{-0.13}$	$0.94^{+0.40}_{-0.18}$	$0.98^{+0.56}_{-0.21}$	$0.80^{+0.26}_{-0.12}$
A_t	$0.14^{+0.13}_{-0.10}$	0	$0.30^{+0.22}_{-0.17}$	0	0	0	0
β	No constraint	No constraint	No constraint	No constraint	No constraint	No constraint	No constraint
$t_0[\text{Gyr}]$	$16.5^{+2.6}_{-3.1}$	$16.3^{+2.3}_{-1.8}$	$13.00^{+0.41}_{-0.47}$	$13.75^{+0.36}_{-0.59}$	$13.53^{+0.52}_{-0.65}$	$13.24^{+0.41}_{-0.89}$	$13.41^{+0.29}_{-0.37}$
σ_8	$0.90^{+0.13}_{-0.13}$	$0.87^{+0.15}_{-0.13}$	$0.84^{+0.17}_{-0.17}$	$0.32^{+0.36}_{-0.32}$	$0.95^{+0.16}_{-0.14}$	$0.99^{+0.19}_{-0.14}$	$0.94^{+0.15}_{-0.12}$
H_1	$4.8^{+3.8}_{-1.9}$	$7.0^{+4.7}_{-1.6}$	$6.5^{+1.5}_{-1.0}$	$4.77^{+0.87}_{-0.59}$	$7.0^{+3.4}_{-1.7}$	$5.5^{+1.7}_{-0.7}$	$5.64^{+0.75}_{-0.60}$
H_2	$0.441^{+0.013}_{-0.014}$	$0.4581^{+0.0090}_{-0.0083}$	$0.4541^{+0.0067}_{-0.0081}$	$0.426^{+0.018}_{-0.010}$	$0.4541^{+0.0084}_{-0.0085}$	$0.4543^{+0.0083}_{-0.0085}$	$0.4541^{+0.0085}_{-0.0086}$
H_3	$0.424^{+0.043}_{-0.040}$	$0.455^{+0.033}_{-0.029}$	$0.452^{+0.034}_{-0.033}$	$0.441^{+0.039}_{-0.033}$	$0.477^{+0.036}_{-0.034}$	$0.474^{+0.037}_{-0.033}$	$0.475^{+0.032}_{-0.030}$
A_{pivot}	$0.595^{+0.056}_{-0.048}$	$0.599^{+0.055}_{-0.064}$	$0.584^{+0.050}_{-0.046}$	$0.602^{+0.045}_{-0.046}$	$0.631^{+0.047}_{-0.045}$	$0.624^{+0.048}_{-0.042}$	$0.652^{+0.048}_{-0.046}$
$M_\nu[\text{eV}]$	0	0	0	< 10.6 (95%)	0	0	0
χ^2/dof	1426.1/1339	1428.4/1341	1430.9/1341	1431.8/1341	1431.8/1341	1431.5/1342	972.4/893

	Using SDSS + WMAP temperature and polarization information						No pol.	No WMAP
	6par+ $\Omega_k + r + \alpha$	6par+ Ω_k	6par+r	6par+ f_ν	6par+w	6par	6par	6par
$e^{-2\tau}$	$0.53^{+0.22}_{-0.17}$	$0.69^{+0.15}_{-0.32}$	$0.776^{+0.098}_{-0.116}$	$0.776^{+0.095}_{-0.121}$	$0.80^{+0.10}_{-0.13}$	$0.780^{+0.094}_{-0.119}$	> 0.63 (95%)	> 0.71 (95%)
Θ_s	$0.601^{+0.010}_{-0.006}$	$0.600^{+0.013}_{-0.004}$	$0.5982^{+0.0034}_{-0.0032}$	$0.5948^{+0.0033}_{-0.0030}$	$0.5954^{+0.0037}_{-0.0038}$	$0.5965^{+0.0031}_{-0.0030}$	$0.5968^{+0.0030}_{-0.0030}$	$0.5977^{+0.0048}_{-0.0045}$
Ω_Λ	$0.660^{+0.080}_{-0.097}$	$0.653^{+0.082}_{-0.084}$	$0.727^{+0.041}_{-0.042}$	$0.620^{+0.074}_{-0.087}$	$0.706^{+0.032}_{-0.033}$	$0.699^{+0.042}_{-0.045}$	$0.684^{+0.041}_{-0.046}$	$0.691^{+0.039}_{-0.053}$
$h^2\Omega_d$	$0.103^{+0.020}_{-0.022}$	$0.103^{+0.016}_{-0.024}$	$0.1195^{+0.0084}_{-0.0082}$	$0.135^{+0.014}_{-0.012}$	$0.124^{+0.012}_{-0.011}$	$0.1222^{+0.0090}_{-0.0082}$	$0.1254^{+0.0093}_{-0.0083}$	$0.1252^{+0.0088}_{-0.0076}$
$h^2\Omega_b$	$0.0238^{+0.0036}_{-0.0026}$	$0.0232^{+0.0051}_{-0.0017}$	$0.0242^{+0.0017}_{-0.0013}$	$0.0234^{+0.0014}_{-0.0011}$	$0.0232^{+0.0013}_{-0.0010}$	$0.0232^{+0.0013}_{-0.0010}$	$0.0231^{+0.0011}_{-0.0009}$	$0.0229^{+0.0016}_{-0.0015}$
f_ν	0	0	0	< 0.12 (95%)	0	0	0	0
n_s	$0.97^{+0.12}_{-0.10}$	$0.98^{+0.18}_{-0.04}$	$1.012^{+0.049}_{-0.036}$	$0.972^{+0.041}_{-0.027}$	$0.976^{+0.040}_{-0.024}$	$0.977^{+0.039}_{-0.025}$	$0.973^{+0.030}_{-0.021}$	$1.015^{+0.036}_{-0.033}$
$n_t + 1$	$0.9852^{+0.0093}_{-0.0154}$	1	$0.976^{+0.016}_{-0.021}$	1	1	1	1	1
A_p	$0.584^{+0.045}_{-0.033}$	$0.584^{+0.038}_{-0.028}$	$0.635^{+0.023}_{-0.021}$	$0.645^{+0.029}_{-0.026}$	$0.637^{+0.027}_{-0.027}$	$0.633^{+0.024}_{-0.022}$	$0.637^{+0.025}_{-0.023}$	$0.588^{+0.025}_{-0.025}$
r	< 0.50 (95%)	0	< 0.47 (95%)	0	0	0	0	0
b	$0.94^{+0.12}_{-0.10}$	$1.03^{+0.15}_{-0.13}$	$0.963^{+0.075}_{-0.081}$	$1.061^{+0.096}_{-0.105}$	$0.956^{+0.075}_{-0.076}$	$0.962^{+0.073}_{-0.083}$	$1.009^{+0.068}_{-0.091}$	$1.068^{+0.066}_{-0.079}$
w	-1	-1	-1	-1	$-1.05^{+0.13}_{-0.14}$	-1	-1	-1
α	$-0.071^{+0.042}_{-0.047}$	0	0	0	0	0	0	0
Ω_{tot}	$1.056^{+0.045}_{-0.045}$	$1.058^{+0.039}_{-0.041}$	0	0	0	0	0	0
Ω_m	$0.40^{+0.10}_{-0.09}$	$0.406^{+0.093}_{-0.091}$	$0.273^{+0.042}_{-0.041}$	$0.380^{+0.087}_{-0.074}$	$0.294^{+0.033}_{-0.032}$	$0.301^{+0.045}_{-0.042}$	$0.316^{+0.046}_{-0.041}$	$0.309^{+0.053}_{-0.039}$
$h^2\Omega_m$	$0.126^{+0.019}_{-0.019}$	$0.126^{+0.016}_{-0.019}$	$0.1438^{+0.0084}_{-0.0080}$	$0.158^{+0.015}_{-0.012}$	$0.147^{+0.012}_{-0.011}$	$0.1454^{+0.0091}_{-0.0082}$	$0.1486^{+0.0095}_{-0.0084}$	$0.1481^{+0.0091}_{-0.0077}$
h	$0.55^{+0.11}_{-0.06}$	$0.550^{+0.092}_{-0.055}$	$0.725^{+0.049}_{-0.036}$	$0.645^{+0.048}_{-0.040}$	$0.708^{+0.033}_{-0.030}$	$0.695^{+0.039}_{-0.031}$	$0.685^{+0.033}_{-0.028}$	$0.693^{+0.038}_{-0.040}$
τ	$0.32^{+0.19}_{-0.17}$	$0.18^{+0.31}_{-0.10}$	$0.127^{+0.081}_{-0.059}$	$0.127^{+0.085}_{-0.058}$	$0.113^{+0.090}_{-0.059}$	$0.124^{+0.083}_{-0.057}$	< 0.23 (95%)	< 0.17 (95%)
z_{ion}	$25.3^{+4.8}_{-8.8}$	18^{+10}_{-7}	$14.1^{+4.8}_{-4.7}$	$14.9^{+5.4}_{-4.8}$	$13.6^{+5.7}_{-5.2}$	$14.4^{+5.2}_{-4.7}$	< 20 (95%)	< 18 (95%)
A_s	$1.12^{+0.43}_{-0.31}$	$0.86^{+0.68}_{-0.16}$	$0.82^{+0.15}_{-0.10}$	$0.83^{+0.16}_{-0.09}$	$0.80^{+0.15}_{-0.09}$	$0.81^{+0.15}_{-0.09}$	$0.72^{+0.15}_{-0.07}$	$0.64^{+0.10}_{-0.04}$
A_t	$0.14^{+0.12}_{-0.09}$	0	$0.16^{+0.15}_{-0.11}$	0	0	0	0	0
β	$0.633^{+0.081}_{-0.076}$	$0.587^{+0.066}_{-0.062}$	$0.506^{+0.056}_{-0.053}$	$0.554^{+0.059}_{-0.054}$	$0.533^{+0.051}_{-0.048}$	$0.537^{+0.056}_{-0.052}$	$0.529^{+0.059}_{-0.052}$	$0.493^{+0.060}_{-0.051}$
t_0 [Gyr]	$15.8^{+1.3}_{-1.8}$	$15.9^{+1.3}_{-1.5}$	$13.32^{+0.27}_{-0.33}$	$13.65^{+0.25}_{-0.28}$	$13.47^{+0.26}_{-0.27}$	$13.54^{+0.23}_{-0.27}$	$13.55^{+0.21}_{-0.23}$	$13.51^{+0.32}_{-0.31}$
σ_8	$0.91^{+0.11}_{-0.10}$	$0.86^{+0.13}_{-0.11}$	$0.919^{+0.086}_{-0.073}$	$0.823^{+0.098}_{-0.077}$	$0.928^{+0.084}_{-0.076}$	$0.917^{+0.090}_{-0.072}$	$0.879^{+0.088}_{-0.062}$	$0.842^{+0.069}_{-0.053}$
H_1	$3.9^{+1.6}_{-1.2}$	$5.5^{+1.7}_{-0.6}$	$5.8^{+1.0}_{-0.7}$	$5.04^{+0.51}_{-0.41}$	$4.99^{+0.56}_{-0.45}$	$5.06^{+0.46}_{-0.40}$	$5.46^{+0.54}_{-0.49}$	$6.8^{+1.2}_{-0.9}$
H_2	$0.441^{+0.013}_{-0.012}$	$0.4577^{+0.0086}_{-0.0082}$	$0.4535^{+0.0081}_{-0.0084}$	$0.4521^{+0.0091}_{-0.0100}$	$0.4545^{+0.0087}_{-0.0090}$	$0.4550^{+0.0083}_{-0.0082}$	$0.4549^{+0.0082}_{-0.0083}$	$0.475^{+0.018}_{-0.020}$
H_3	$0.422^{+0.027}_{-0.031}$	$0.444^{+0.026}_{-0.025}$	$0.468^{+0.019}_{-0.017}$	$0.472^{+0.022}_{-0.019}$	$0.461^{+0.018}_{-0.017}$	$0.459^{+0.018}_{-0.016}$	$0.460^{+0.017}_{-0.015}$	$0.485^{+0.020}_{-0.018}$
A_{pivot}	$0.587^{+0.049}_{-0.041}$	$0.582^{+0.041}_{-0.036}$	$0.632^{+0.022}_{-0.021}$	$0.648^{+0.028}_{-0.025}$	$0.639^{+0.027}_{-0.028}$	$0.635^{+0.024}_{-0.022}$	$0.639^{+0.024}_{-0.022}$	$0.586^{+0.024}_{-0.025}$
M_ν [eV]	0	0	0	< 1.74 (95%)	0	0	0	0
χ^2/dof	1444.4/1356	1445.4/1359	1446.9/1359	1447.3/1359	1622.0/1530	1447.2/1359	987.8/911	134.6/163

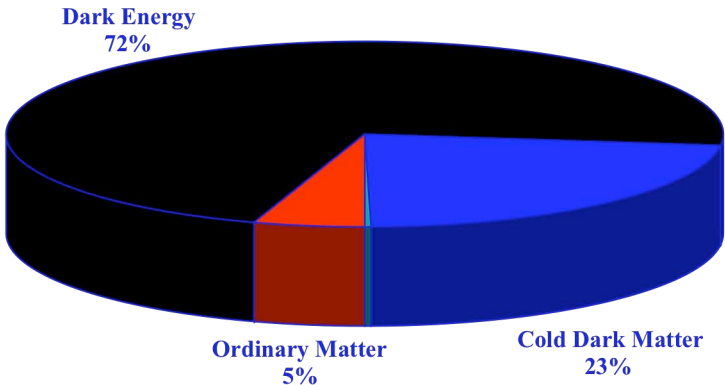
	9 parameters ($\tau, \Omega_k, \Omega_\Lambda, \omega_d, \omega_b, A_s, n_s, \alpha, r$) free					WMAP+SDSS, 6 vanilla parameters free			
	WMAP	+ $r = \alpha = 0$	+SDSS	+SN Ia	+ $\tau < 0.3$	+other CMB	+ $n_s = 1$	+ $V(\phi) \propto \phi^2$	
$e^{-2\tau}$	$0.52^{+0.21}_{-0.15}$	$0.65^{+0.19}_{-0.32}$	$0.69^{+0.15}_{-0.32}$	$0.44^{+0.34}_{-0.13}$	$0.75^{+0.11}_{-0.12}$	$0.780^{+0.094}_{-0.119}$	$0.813^{+0.081}_{-0.092}$	$0.720^{+0.057}_{-0.049}$	$0.833^{+0.063}_{-0.059}$
Θ_s	$0.602^{+0.010}_{-0.006}$	$0.603^{+0.015}_{-0.005}$	$0.600^{+0.013}_{-0.004}$	$0.606^{+0.011}_{-0.010}$	$0.5971^{+0.0034}_{-0.0034}$	$0.5965^{+0.0031}_{-0.0030}$	$0.5956^{+0.0025}_{-0.0026}$	$0.5979^{+0.0024}_{-0.0024}$	$0.5953^{+0.0021}_{-0.0022}$
Ω_Λ	$0.54^{+0.24}_{-0.33}$	$0.53^{+0.24}_{-0.32}$	$0.653^{+0.082}_{-0.084}$	$0.725^{+0.039}_{-0.044}$	$0.695^{+0.034}_{-0.037}$	$0.699^{+0.042}_{-0.045}$	$0.691^{+0.032}_{-0.040}$	$0.707^{+0.031}_{-0.039}$	$0.685^{+0.032}_{-0.041}$
$h^2\Omega_d$	$0.105^{+0.023}_{-0.023}$	$0.108^{+0.022}_{-0.034}$	$0.103^{+0.016}_{-0.024}$	$0.090^{+0.028}_{-0.016}$	$0.115^{+0.012}_{-0.012}$	$0.1222^{+0.0090}_{-0.0082}$	$0.1231^{+0.0075}_{-0.0068}$	$0.1233^{+0.0089}_{-0.0079}$	$0.1233^{+0.0082}_{-0.0071}$
$h^2\Omega_b$	$0.0238^{+0.0035}_{-0.0027}$	$0.0241^{+0.0055}_{-0.0020}$	$0.0232^{+0.0051}_{-0.0017}$	$0.0263^{+0.0042}_{-0.0036}$	$0.0230^{+0.0013}_{-0.0011}$	$0.0232^{+0.0013}_{-0.0010}$	$0.0228^{+0.0010}_{-0.0008}$	$0.0238^{+0.0006}_{-0.0006}$	$0.0226^{+0.0006}_{-0.0006}$
f_ν	0	0	0	0	0	0	0	0	0
n_s	$0.97^{+0.13}_{-0.10}$	$1.01^{+0.18}_{-0.06}$	$0.98^{+0.18}_{-0.04}$	$1.10^{+0.11}_{-0.13}$	$0.979^{+0.036}_{-0.029}$	$0.977^{+0.039}_{-0.025}$	$0.966^{+0.025}_{-0.020}$	1	0.96
$n_t + 1$	$0.9847^{+0.0097}_{-0.0141}$	1	1	1	1	1	1	1	0.993
A_p	$0.593^{+0.053}_{-0.044}$	$0.602^{+0.053}_{-0.051}$	$0.584^{+0.038}_{-0.028}$	$0.582^{+0.043}_{-0.025}$	$0.613^{+0.034}_{-0.033}$	$0.633^{+0.024}_{-0.022}$	$0.631^{+0.020}_{-0.019}$	$0.642^{+0.023}_{-0.022}$	$0.629^{+0.021}_{-0.019}$
r	< 0.50 (95%)	0	0	0	0	0	0	0	0.15
b	1	1	$1.03^{+0.15}_{-0.13}$	$0.93^{+0.10}_{-0.08}$	$0.998^{+0.098}_{-0.088}$	$0.962^{+0.073}_{-0.083}$	$0.990^{+0.060}_{-0.062}$	$0.918^{+0.036}_{-0.033}$	$1.006^{+0.043}_{-0.039}$
w	-1	-1	-1	-1	-1	-1	-1	-1	-1
α	$-0.075^{+0.047}_{-0.055}$	0	0	0	0	0	0	0	0
Ω_{tot}	$1.095^{+0.094}_{-0.144}$	$1.086^{+0.057}_{-0.128}$	$1.058^{+0.039}_{-0.041}$	$1.054^{+0.048}_{-0.041}$	$1.012^{+0.018}_{-0.022}$	0	0	0	0
Ω_m	$0.57^{+0.45}_{-0.33}$	$0.55^{+0.47}_{-0.29}$	$0.406^{+0.093}_{-0.091}$	$0.328^{+0.050}_{-0.049}$	$0.317^{+0.053}_{-0.045}$	$0.301^{+0.045}_{-0.042}$	$0.309^{+0.040}_{-0.032}$	$0.293^{+0.039}_{-0.031}$	$0.315^{+0.041}_{-0.032}$
$h^2\Omega_m$	$0.128^{+0.022}_{-0.021}$	$0.132^{+0.021}_{-0.028}$	$0.126^{+0.016}_{-0.019}$	$0.117^{+0.024}_{-0.013}$	$0.138^{+0.012}_{-0.012}$	$0.1454^{+0.0091}_{-0.0082}$	$0.1459^{+0.0077}_{-0.0071}$	$0.1471^{+0.0090}_{-0.0080}$	$0.1459^{+0.0084}_{-0.0073}$
h	$0.48^{+0.27}_{-0.12}$	$0.50^{+0.16}_{-0.13}$	$0.550^{+0.092}_{-0.055}$	$0.599^{+0.090}_{-0.062}$	$0.660^{+0.067}_{-0.064}$	$0.695^{+0.039}_{-0.031}$	$0.685^{+0.027}_{-0.026}$	$0.708^{+0.023}_{-0.024}$	$0.680^{+0.022}_{-0.024}$
τ	$0.33^{+0.17}_{-0.17}$	$0.22^{+0.34}_{-0.13}$	$0.18^{+0.31}_{-0.10}$	$0.41^{+0.17}_{-0.28}$	$0.143^{+0.089}_{-0.066}$	$0.124^{+0.083}_{-0.057}$	$0.103^{+0.060}_{-0.047}$	$0.165^{+0.035}_{-0.038}$	$0.092^{+0.036}_{-0.036}$
z_{ion}	$25.9^{+4.4}_{-8.8}$	$20.1^{+9.2}_{-8.3}$	18^{+10}_{-7}	$26.7^{+3.2}_{-12.4}$	$15.6^{+5.1}_{-5.0}$	$14.4^{+5.2}_{-4.7}$	$12.8^{+4.3}_{-4.2}$	$17.0^{+2.2}_{-2.6}$	$11.9^{+2.9}_{-3.4}$
A_s	$1.14^{+0.42}_{-0.31}$	$0.97^{+0.73}_{-0.23}$	$0.86^{+0.68}_{-0.16}$	$1.30^{+0.50}_{-0.51}$	$0.82^{+0.14}_{-0.11}$	$0.81^{+0.15}_{-0.09}$	$0.777^{+0.100}_{-0.072}$	$0.893^{+0.051}_{-0.053}$	$0.758^{+0.050}_{-0.050}$
A_t	$0.14^{+0.13}_{-0.10}$	0	0	0	0	0	0	0	$0.1137^{+0.0075}_{-0.0074}$
β	$0.73^{+0.28}_{-0.29}$	$0.72^{+0.29}_{-0.24}$	$0.587^{+0.066}_{-0.062}$	$0.577^{+0.062}_{-0.063}$	$0.530^{+0.050}_{-0.045}$	$0.537^{+0.056}_{-0.052}$	$0.534^{+0.044}_{-0.046}$	$0.553^{+0.054}_{-0.047}$	$0.525^{+0.052}_{-0.045}$
$t_0[\text{Gyr}]$	$16.5^{+2.6}_{-3.1}$	$16.3^{+2.3}_{-1.8}$	$15.9^{+1.3}_{-1.5}$	$15.6^{+1.4}_{-1.8}$	$14.1^{+1.0}_{-0.9}$	$13.54^{+0.23}_{-0.27}$	$13.62^{+0.20}_{-0.20}$	$13.40^{+0.13}_{-0.12}$	$13.67^{+0.12}_{-0.12}$
σ_8	$0.90^{+0.13}_{-0.13}$	$0.87^{+0.15}_{-0.13}$	$0.86^{+0.13}_{-0.11}$	$0.948^{+0.089}_{-0.101}$	$0.882^{+0.094}_{-0.084}$	$0.917^{+0.090}_{-0.072}$	$0.894^{+0.060}_{-0.055}$	$0.966^{+0.046}_{-0.050}$	$0.879^{+0.041}_{-0.046}$
H_1	$4.8^{+3.8}_{-1.9}$	$7.0^{+4.7}_{-1.6}$	$5.5^{+1.7}_{-0.6}$	$6.1^{+2.1}_{-1.2}$	$5.04^{+0.42}_{-0.39}$	$5.06^{+0.46}_{-0.40}$	$4.98^{+0.39}_{-0.39}$	$5.14^{+0.40}_{-0.34}$	$4.84^{+0.37}_{-0.35}$
H_2	$0.441^{+0.013}_{-0.014}$	$0.4581^{+0.0090}_{-0.0083}$	$0.4577^{+0.0086}_{-0.0082}$	$0.4585^{+0.0086}_{-0.0093}$	$0.4558^{+0.0082}_{-0.0083}$	$0.4550^{+0.0083}_{-0.0082}$	$0.4552^{+0.0087}_{-0.0079}$	$0.4543^{+0.0081}_{-0.0081}$	$0.4556^{+0.0081}_{-0.0081}$
H_3	$0.424^{+0.043}_{-0.040}$	$0.455^{+0.033}_{-0.029}$	$0.444^{+0.026}_{-0.025}$	$0.457^{+0.020}_{-0.021}$	$0.449^{+0.021}_{-0.021}$	$0.459^{+0.018}_{-0.016}$	$0.454^{+0.013}_{-0.012}$	$0.467^{+0.012}_{-0.011}$	$0.451^{+0.011}_{-0.010}$
A_{pivot}	$0.595^{+0.056}_{-0.048}$	$0.599^{+0.055}_{-0.064}$	$0.582^{+0.041}_{-0.036}$	$0.567^{+0.058}_{-0.028}$	$0.616^{+0.033}_{-0.032}$	$0.635^{+0.024}_{-0.022}$	$0.634^{+0.020}_{-0.018}$	$0.642^{+0.023}_{-0.022}$	$0.634^{+0.021}_{-0.019}$
$M_\nu[\text{eV}]$	0	0	0	0	0	0	0	0	0
χ^2/dof	1426.1/1339	1428.4/1341	1445.4/1359	1619.6/1530	1621.8/1530	1447.2/1360	1475.6/1395	1447.9/1359	1447.1/1395

	Using SDSS + WMAP temperature and polarization information						No pol.	No WMAP
	6par+ $\Omega_k + r + \alpha$	6par+ Ω_k	6par+ r	6par+ f_ν	6par+ w	6par	6par	6par
$e^{-2\tau}$	$0.53^{+0.22}_{-0.17}$	$0.69^{+0.15}_{-0.32}$	$0.776^{+0.098}_{-0.116}$	$0.776^{+0.095}_{-0.121}$	$0.80^{+0.10}_{-0.13}$	$0.780^{+0.094}_{-0.119}$	> 0.63 (95%)	> 0.71 (95%)
Θ_s	$0.601^{+0.010}_{-0.006}$	$0.600^{+0.013}_{-0.004}$	$0.5982^{+0.0034}_{-0.0032}$	$0.5948^{+0.0033}_{-0.0030}$	$0.5954^{+0.0037}_{-0.0038}$	$0.5965^{+0.0031}_{-0.0030}$	$0.5968^{+0.0030}_{-0.0030}$	$0.5977^{+0.0048}_{-0.0045}$
Ω_Λ	$0.660^{+0.080}_{-0.097}$	$0.653^{+0.082}_{-0.084}$	$0.727^{+0.041}_{-0.042}$	$0.620^{+0.074}_{-0.087}$	$0.706^{+0.032}_{-0.033}$	$0.699^{+0.042}_{-0.045}$	$0.684^{+0.041}_{-0.046}$	$0.691^{+0.039}_{-0.053}$
$h^2\Omega_d$	$0.103^{+0.020}_{-0.022}$	$0.103^{+0.016}_{-0.024}$	$0.1195^{+0.0084}_{-0.0082}$	$0.135^{+0.014}_{-0.012}$	$0.124^{+0.012}_{-0.011}$	$0.1222^{+0.0090}_{-0.0082}$	$0.1254^{+0.0093}_{-0.0083}$	$0.1252^{+0.0088}_{-0.0076}$
$h^2\Omega_b$	$0.0238^{+0.0036}_{-0.0026}$	$0.0232^{+0.0051}_{-0.0017}$	$0.0242^{+0.0017}_{-0.0013}$	$0.0234^{+0.0014}_{-0.0011}$	$0.0232^{+0.0013}_{-0.0010}$	$0.0232^{+0.0013}_{-0.0010}$	$0.0231^{+0.0011}_{-0.0009}$	$0.0229^{+0.0016}_{-0.0015}$
f_ν	0	0	0	< 0.12 (95%)	0	0	0	0
n_s	$0.97^{+0.12}_{-0.10}$	$0.98^{+0.18}_{-0.04}$	$1.012^{+0.049}_{-0.036}$	$0.972^{+0.041}_{-0.027}$	$0.976^{+0.040}_{-0.024}$	$0.977^{+0.039}_{-0.025}$	$0.973^{+0.030}_{-0.021}$	$1.015^{+0.036}_{-0.033}$
$n_t + 1$	$0.9852^{+0.0093}_{-0.0154}$	1	$0.976^{+0.016}_{-0.021}$	1	1	1	1	1
A_p	$0.584^{+0.045}_{-0.033}$	$0.584^{+0.038}_{-0.028}$	$0.635^{+0.023}_{-0.021}$	$0.645^{+0.029}_{-0.026}$	$0.637^{+0.027}_{-0.027}$	$0.633^{+0.024}_{-0.022}$	$0.637^{+0.025}_{-0.023}$	$0.588^{+0.025}_{-0.025}$
r	< 0.50 (95%)	0	< 0.47 (95%)	0	0	0	0	0
b	$0.94^{+0.12}_{-0.10}$	$1.03^{+0.15}_{-0.13}$	$0.963^{+0.075}_{-0.081}$	$1.061^{+0.096}_{-0.105}$	$0.956^{+0.075}_{-0.076}$	$0.962^{+0.073}_{-0.083}$	$1.009^{+0.068}_{-0.091}$	$1.068^{+0.066}_{-0.079}$
w	-1	-1	-1	-1	$-1.05^{+0.13}_{-0.14}$	-1	-1	-1
α	$-0.071^{+0.042}_{-0.047}$	0	0	0	0	0	0	0
Ω_{tot}	$1.056^{+0.045}_{-0.045}$	$1.058^{+0.039}_{-0.041}$	0	0	0	0	0	0
Ω_m	$0.40^{+0.10}_{-0.09}$	$0.406^{+0.093}_{-0.091}$	$0.273^{+0.042}_{-0.041}$	$0.380^{+0.087}_{-0.074}$	$0.294^{+0.033}_{-0.032}$	$0.301^{+0.045}_{-0.042}$	$0.316^{+0.046}_{-0.041}$	$0.309^{+0.053}_{-0.039}$
$h^2\Omega_m$	$0.126^{+0.019}_{-0.019}$	$0.126^{+0.016}_{-0.019}$	$0.1438^{+0.0084}_{-0.0080}$	$0.158^{+0.015}_{-0.012}$	$0.147^{+0.012}_{-0.011}$	$0.1454^{+0.0091}_{-0.0082}$	$0.1486^{+0.0095}_{-0.0084}$	$0.1481^{+0.0091}_{-0.0077}$
h	$0.55^{+0.11}_{-0.06}$	$0.550^{+0.092}_{-0.055}$	$0.725^{+0.049}_{-0.036}$	$0.645^{+0.048}_{-0.040}$	$0.708^{+0.033}_{-0.030}$	$0.695^{+0.039}_{-0.031}$	$0.685^{+0.033}_{-0.028}$	$0.693^{+0.038}_{-0.040}$
τ	$0.32^{+0.19}_{-0.17}$	$0.18^{+0.31}_{-0.10}$	$0.127^{+0.081}_{-0.059}$	$0.127^{+0.085}_{-0.058}$	$0.113^{+0.090}_{-0.059}$	$0.124^{+0.083}_{-0.057}$	< 0.23 (95%)	< 0.17 (95%)
z_{ion}	$25.3^{+4.8}_{-8.8}$	18^{+10}_{-7}	$14.1^{+4.8}_{-4.7}$	$14.9^{+5.4}_{-4.8}$	$13.6^{+5.7}_{-5.2}$	$14.4^{+5.2}_{-4.7}$	< 20 (95%)	< 18 (95%)
A_s	$1.12^{+0.43}_{-0.31}$	$0.86^{+0.68}_{-0.16}$	$0.82^{+0.15}_{-0.10}$	$0.83^{+0.16}_{-0.09}$	$0.80^{+0.15}_{-0.09}$	$0.81^{+0.15}_{-0.09}$	$0.72^{+0.15}_{-0.07}$	$0.64^{+0.10}_{-0.04}$
A_t	$0.14^{+0.12}_{-0.09}$	0	$0.16^{+0.15}_{-0.11}$	0	0	0	0	0
β	$0.633^{+0.081}_{-0.076}$	$0.587^{+0.066}_{-0.062}$	$0.506^{+0.056}_{-0.053}$	$0.554^{+0.059}_{-0.054}$	$0.533^{+0.051}_{-0.048}$	$0.537^{+0.056}_{-0.052}$	$0.529^{+0.059}_{-0.052}$	$0.493^{+0.060}_{-0.051}$
t_0 [Gyr]	$15.8^{+1.3}_{-1.8}$	$15.9^{+1.3}_{-1.5}$	$13.32^{+0.27}_{-0.33}$	$13.65^{+0.25}_{-0.28}$	$13.47^{+0.26}_{-0.27}$	$13.54^{+0.23}_{-0.27}$	$13.55^{+0.21}_{-0.23}$	$13.51^{+0.32}_{-0.31}$
σ_8	$0.91^{+0.11}_{-0.10}$	$0.86^{+0.13}_{-0.11}$	$0.919^{+0.086}_{-0.073}$	$0.823^{+0.098}_{-0.077}$	$0.928^{+0.084}_{-0.076}$	$0.917^{+0.090}_{-0.072}$	$0.879^{+0.088}_{-0.062}$	$0.842^{+0.069}_{-0.053}$
H_1	$3.9^{+1.6}_{-1.2}$	$5.5^{+1.7}_{-0.6}$	$5.8^{+1.0}_{-0.7}$	$5.04^{+0.51}_{-0.41}$	$4.99^{+0.56}_{-0.45}$	$5.06^{+0.46}_{-0.40}$	$5.46^{+0.54}_{-0.49}$	$6.8^{+1.2}_{-0.9}$
H_2	$0.441^{+0.013}_{-0.012}$	$0.4577^{+0.0086}_{-0.0082}$	$0.4535^{+0.0081}_{-0.0084}$	$0.4521^{+0.0091}_{-0.0100}$	$0.4545^{+0.0087}_{-0.0090}$	$0.4550^{+0.0083}_{-0.0082}$	$0.4549^{+0.0082}_{-0.0083}$	$0.475^{+0.018}_{-0.020}$
H_3	$0.422^{+0.027}_{-0.031}$	$0.444^{+0.026}_{-0.025}$	$0.468^{+0.019}_{-0.017}$	$0.472^{+0.022}_{-0.019}$	$0.461^{+0.018}_{-0.017}$	$0.459^{+0.018}_{-0.016}$	$0.460^{+0.017}_{-0.015}$	$0.485^{+0.020}_{-0.018}$
A_{pivot}	$0.587^{+0.049}_{-0.041}$	$0.582^{+0.041}_{-0.036}$	$0.632^{+0.022}_{-0.021}$	$0.648^{+0.028}_{-0.025}$	$0.639^{+0.027}_{-0.028}$	$0.635^{+0.024}_{-0.022}$	$0.639^{+0.024}_{-0.022}$	$0.586^{+0.024}_{-0.025}$
M_ν [eV]	0	0	0	< 1.74 (95%)	0	0	0	0
χ^2/dof	1444.4/1356	1445.4/1359	1446.9/1359	1447.3/1359	1622.0/1530	1447.2/1359	987.8/911	134.6/163



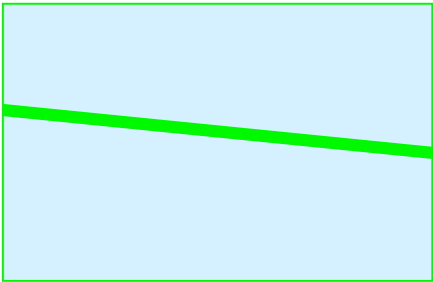
MATTER
BUDGET

- Ordinary Matter
- Dark Energy
- Cold Dark Matter
- Hot Dark Matter
- Photons
- Budget Deficit

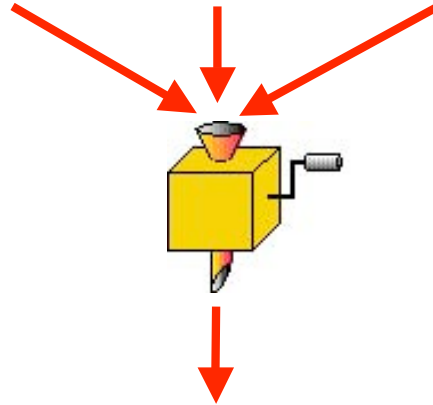
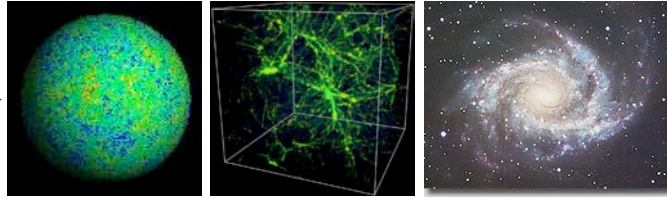


p	Meaning	Measured value
Ω_{tot}	Spatial curvature	1.01 ± 0.02
ρ_{Λ}	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124} m_{\text{Pl}}^4$
w	Dark energy equation of state	-1 ± 0.1
δ_H	Scalar fluctuation amplitude (Q)	$(2.0 \pm 0.2) \times 10^{-5}$
n_s	Scalar spectral index	0.98 ± 0.02
α	Running of spectral index $dn_s/d \ln k$	$ \alpha \lesssim 0.01$
r	Tensor-to-scalar ratio $(\delta_H^T/\delta_H)^2$	$\lesssim 0.36$
n_t	Tensor spectral index	Unconstrained
ξ_b	Baryon mass per photon $\rho_b/n_\gamma = m_p \eta$	$(0.60 \pm 0.03) \text{ eV}$
ξ_c	CDM mass per photon ρ_c/n_γ	$(3.3 \pm 0.2) \text{ eV}$
ξ_ν	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11} \sum m_{\nu_i}$	$< 0.11 \text{ eV}$

INITIAL
CONDITIONS



**Cosmological
data**



**Cosmological
Parameters**

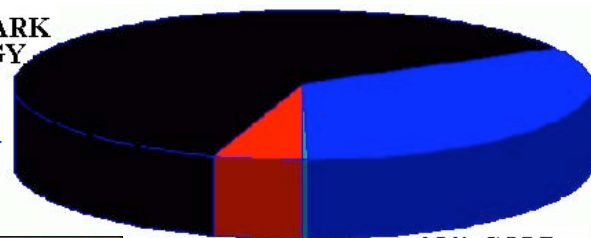


$\Omega, \Omega_b, \Lambda, \tau, h$
 $n, n_T, Q, T/S$

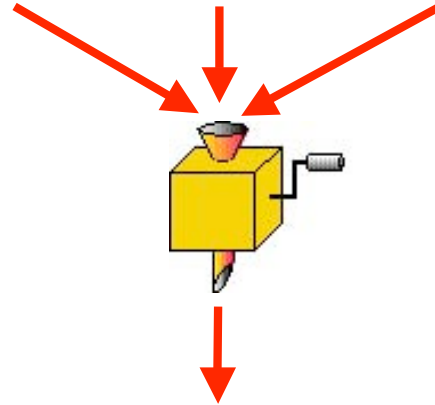
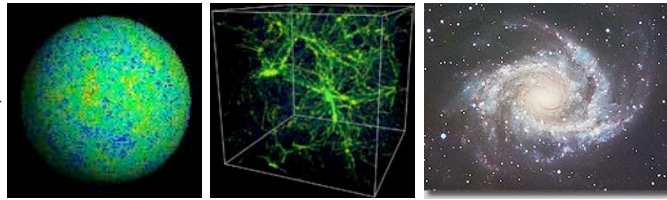
70% DARK
ENERGY

5% ORDINARY
MATTER

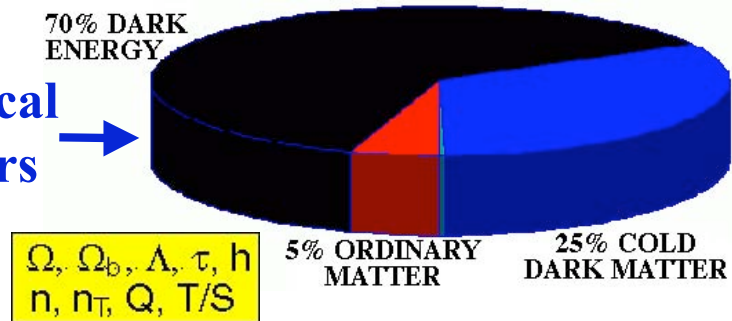
25% COLD
DARK MATTER



Cosmological
data

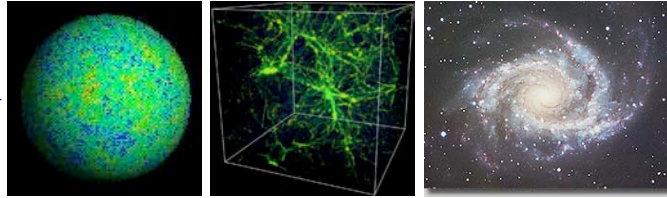


Cosmological
Parameters

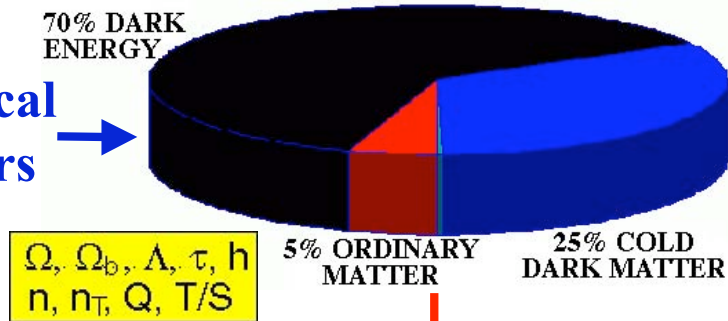


*ARE WE
DONE?*

Cosmological
data



Cosmological
Parameters



Fundamental
theory



Why these particular values?

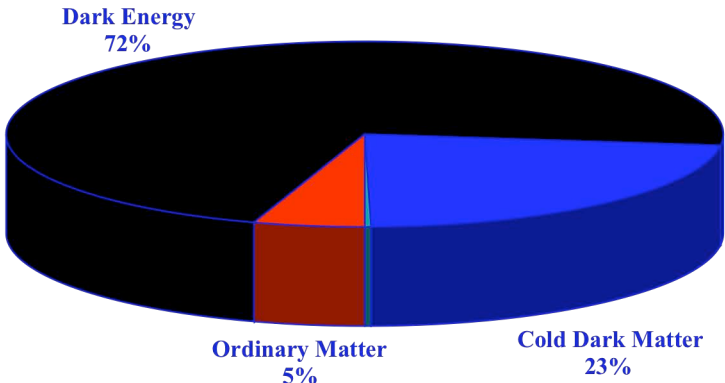
Nature of dark matter?

Nature of dark energy?

Nature of early Universe?

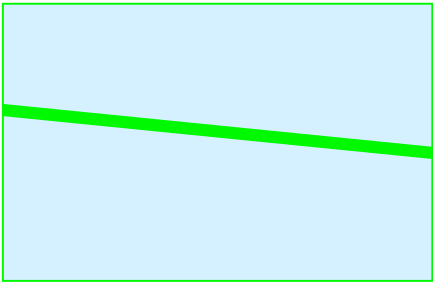
MATTER
BUDGET

- Ordinary Matter
- Dark Energy
- Cold Dark Matter
- Hot Dark Matter
- Photons
- Budget Deficit



p	Meaning	Measured value
Ω_{tot}	Spatial curvature	1.01 ± 0.02
ρ_{Λ}	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124} m_{\text{Pl}}^4$
w	Dark energy equation of state	-1 ± 0.1
δ_H	Scalar fluctuation amplitude (Q)	$(2.0 \pm 0.2) \times 10^{-5}$
n_s	Scalar spectral index	0.98 ± 0.02
α	Running of spectral index $dn_s/d \ln k$	$ \alpha \lesssim 0.01$
r	Tensor-to-scalar ratio $(\delta_H^T/\delta_H)^2$	$\lesssim 0.36$
n_t	Tensor spectral index	Unconstrained
ξ_b	Baryon mass per photon $\rho_b/n_\gamma = m_p \eta$	$(0.60 \pm 0.03) \text{ eV}$
ξ_c	CDM mass per photon ρ_c/n_γ	$(3.3 \pm 0.2) \text{ eV}$
ξ_ν	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11} \sum m_{\nu_i}$	$< 0.11 \text{ eV}$

INITIAL
CONDITIONS



p	Meaning	Measured value
Ω_{tot}	Spatial curvature	1.01 ± 0.02
ρ_{Λ}	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124} m_{\text{Pl}}^4$
w	Dark energy equation of state	-1 ± 0.1
δ_H	Scalar fluctuation amplitude (Q)	$(2.0 \pm 0.2) \times 10^{-5}$
n_s	Scalar spectral index	0.98 ± 0.02
α	Running of spectral index $dn_s/d \ln k$	$ \alpha \lesssim 0.01$
r	Tensor-to-scalar ratio $(\delta_H^T/\delta_H)^2$	$\lesssim 0.36$
n_t	Tensor spectral index	Unconstrained
ξ_b	Baryon mass per photon $\rho_b/n_\gamma = m_p \eta$	$(0.60 \pm 0.03) \text{ eV}$
ξ_c	CDM mass per photon ρ_c/n_γ	$(3.3 \pm 0.2) \text{ eV}$
ξ_ν	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11} \sum m_{\nu_i}$	$< 0.11 \text{ eV}$

Inflation! →

Baryogenesis →

SUSY? →

ν -physics →

WHY? ●

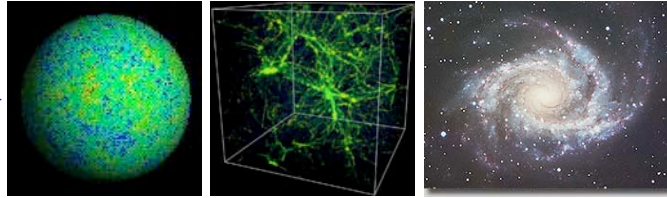
Standard model parameters:

Why these values?

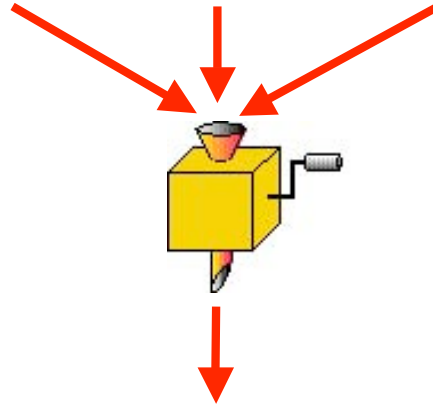


Parameter	Meaning	Definition	Measured value
g	Weak coupling constant		0.6425
θ_W	Weinberg angle		0.4908
g_s	Strong coupling constant		≈ 1.2
μ^2	Quadratic Higgs coefficient	$V(\Phi) = \mu^2 \Phi ^2 + \lambda \Phi ^4$	$\sim -10^{-33}$
λ	Quartic Higgs coefficient		$\sim 1?$
G_e	Electron Yukawa coupling		2.94×10^{-6}
G_μ	Muon Yukawa coupling		0.000607
G_τ	Tauon Yukawa coupling		0.0102156233
m_u	Up quark Yukawa coupling		0.000016 ± 0.000007
m_d	Down quark Yukawa coupling		0.000003 ± 0.000002
m_c	Charm quark Yukawa coupling		0.0072 ± 0.0006
m_s	Strange quark Yukawa coupling		0.0006 ± 0.0002
m_t	Top quark Yukawa coupling		1.002 ± 0.029
m_b	Bottom quark Yukawa coupling		0.026 ± 0.003
$\sin\theta_{12}$	Quark CKM matrix angle		0.2243 ± 0.0016
$\sin\theta_{23}$	Quark CKM matrix angle		0.0413 ± 0.0015
$\sin\theta_{13}$	Quark CKM matrix angle		0.0037 ± 0.0005
δ_{13}	Quark CKM matrix phase		1.05 ± 0.24
θ_{qed}	CP-violating QCD vacuum phase		$< 10^{-9}$

**Cosmological
data**



$$H(z), P(k,z), C_1^T, C_1^X, C_1^E, C_1^B, \dots$$



**Cosmological
functions**

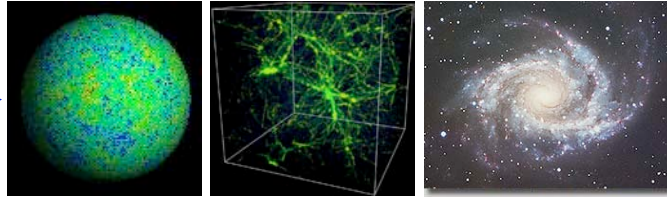


$$\rho_\Lambda(z), G(z,k), P_s(k), P_t(k)$$



All vanilla?

Cosmological
data

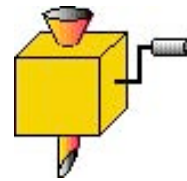


$$H(z), P(k,z), C_1^T, C_1^X, C_1^E, C_1^B, \dots$$

Cosmological
functions

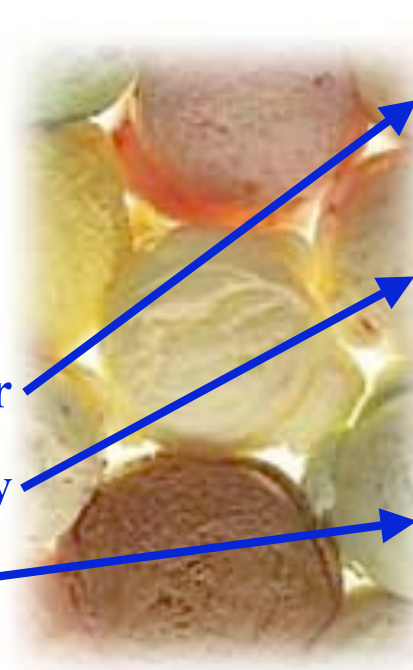
$$\rho_\Lambda(z), G(z,k), P_s(k), P_t(k)$$

All vanilla?



Clues about

- **Dark matter**
- **Dark energy**
- **Inflation**

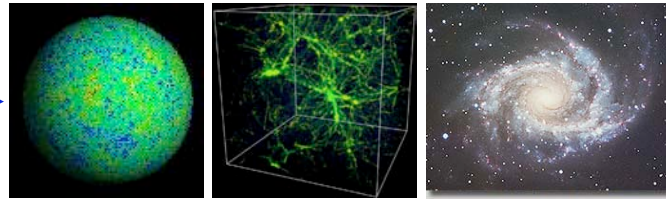


Non-vanilla clustering?
Make at LHC?
Detect directly? Indirectly?

Non-constant density?
Clustering?

Non-scale invariance?
Gravitational waves?
Non-Gaussianity?
Isocurvature modes?
Non-flatness?

Cosmological
data



$$H(z), P(k,z), C_l^T, C_l^X, C_l^E, C_l^B, \dots$$

Cosmological
functions

$$\rho_\Lambda(z), G(z,k), P_s(k), P_t(k)$$

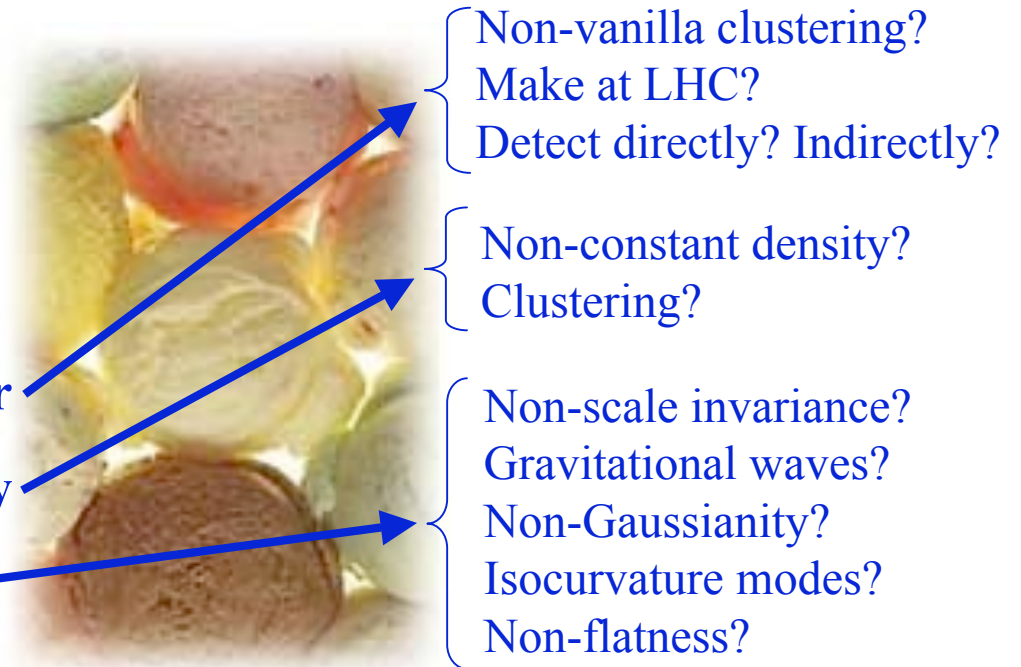
All vanilla?



Clues about

- Dark matter
- Dark energy
- Inflation

$$\xi_c, \rho_\Lambda, Q$$



Non-vanilla clustering?
Make at LHC?
Detect directly? Indirectly?

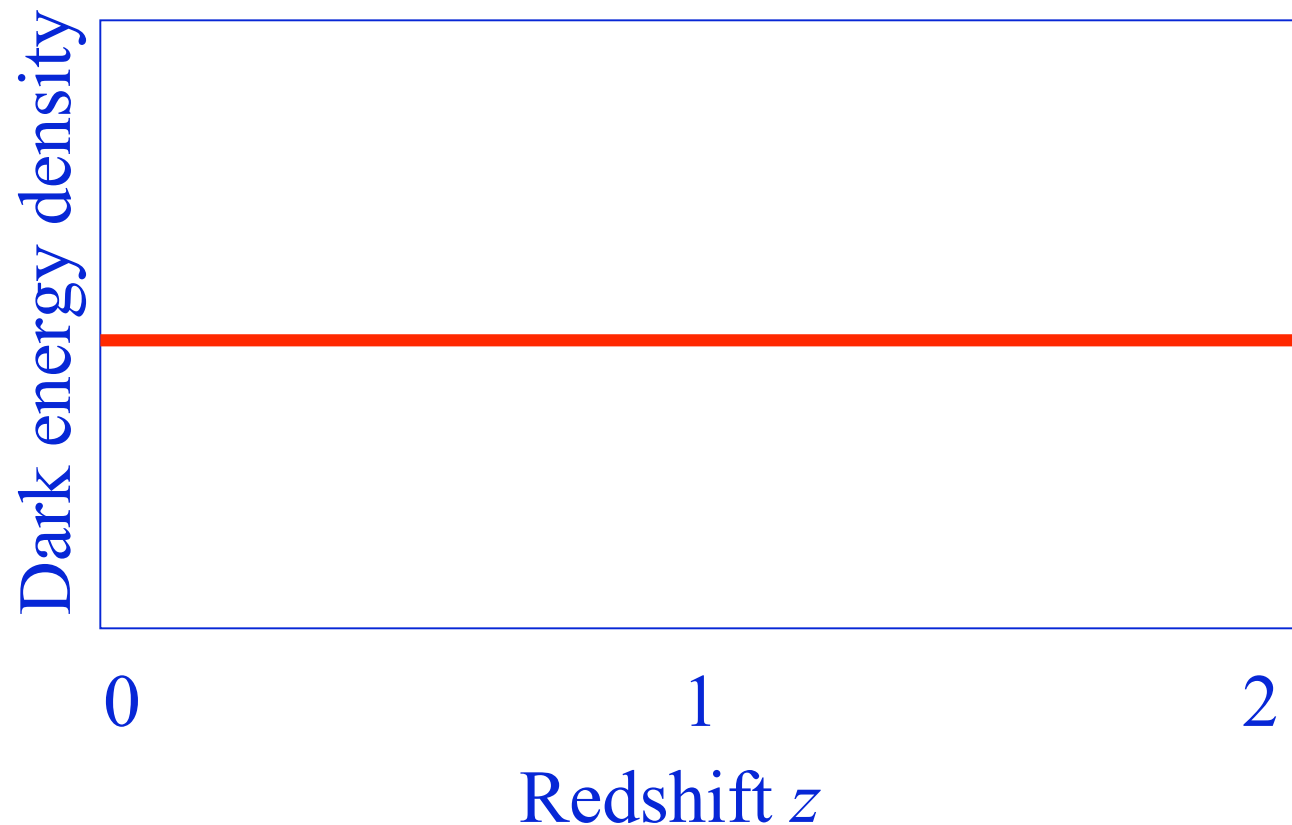
Non-constant density?
Clustering?

Non-scale invariance?
Gravitational waves?
Non-Gaussianity?
Isocurvature modes?
Non-flatness?



DARK ENERGY:

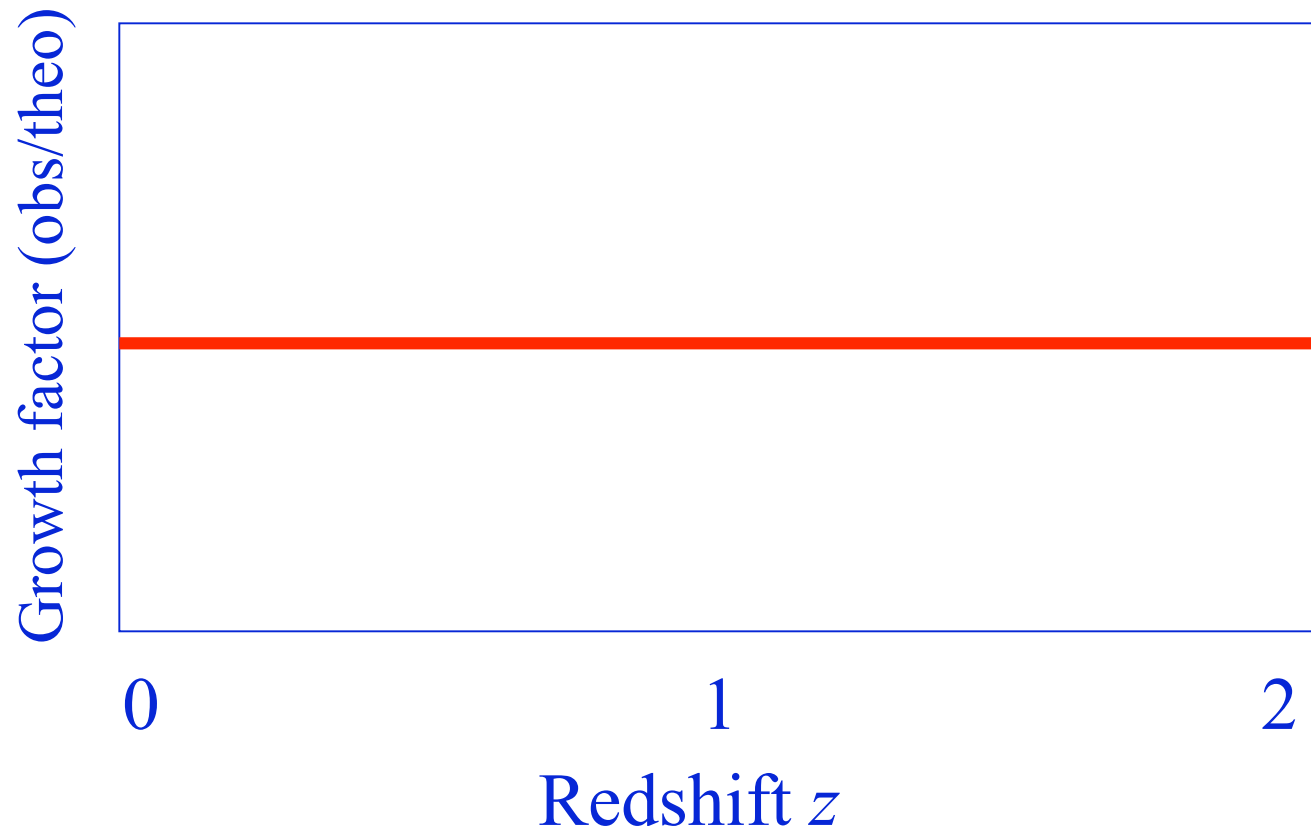
- $w(z) = -1$, $w' = w'' = \dots = 0$
- No dark energy clustering





DARK MATTER:

- No direct detection
- No indirect detection
- No accelerator detection
- No astrophysically observed departures from vanilla CDM



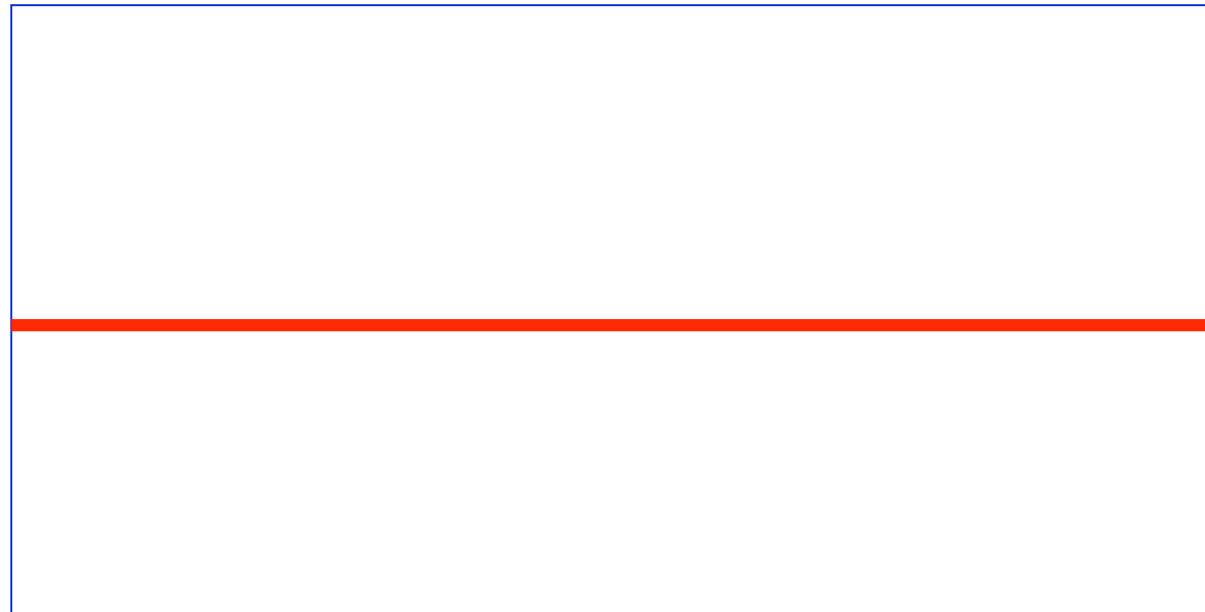
Max Tegmark
Dept. of Physics, MIT
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NEPPSR
August 15, 2005



INFLATION:

- No departures from scale invariance detected ($n=1$, $dn/d\ln k=0$, etc)
- No gravity waves detected
- No non-Gaussianity detected
- No isocurvature detected

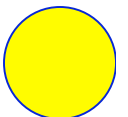
Primordial power spectrum $P^*(k)/k$



Wavenumber k [1/Mpc]



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NEPPSR
August 15, 2005





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