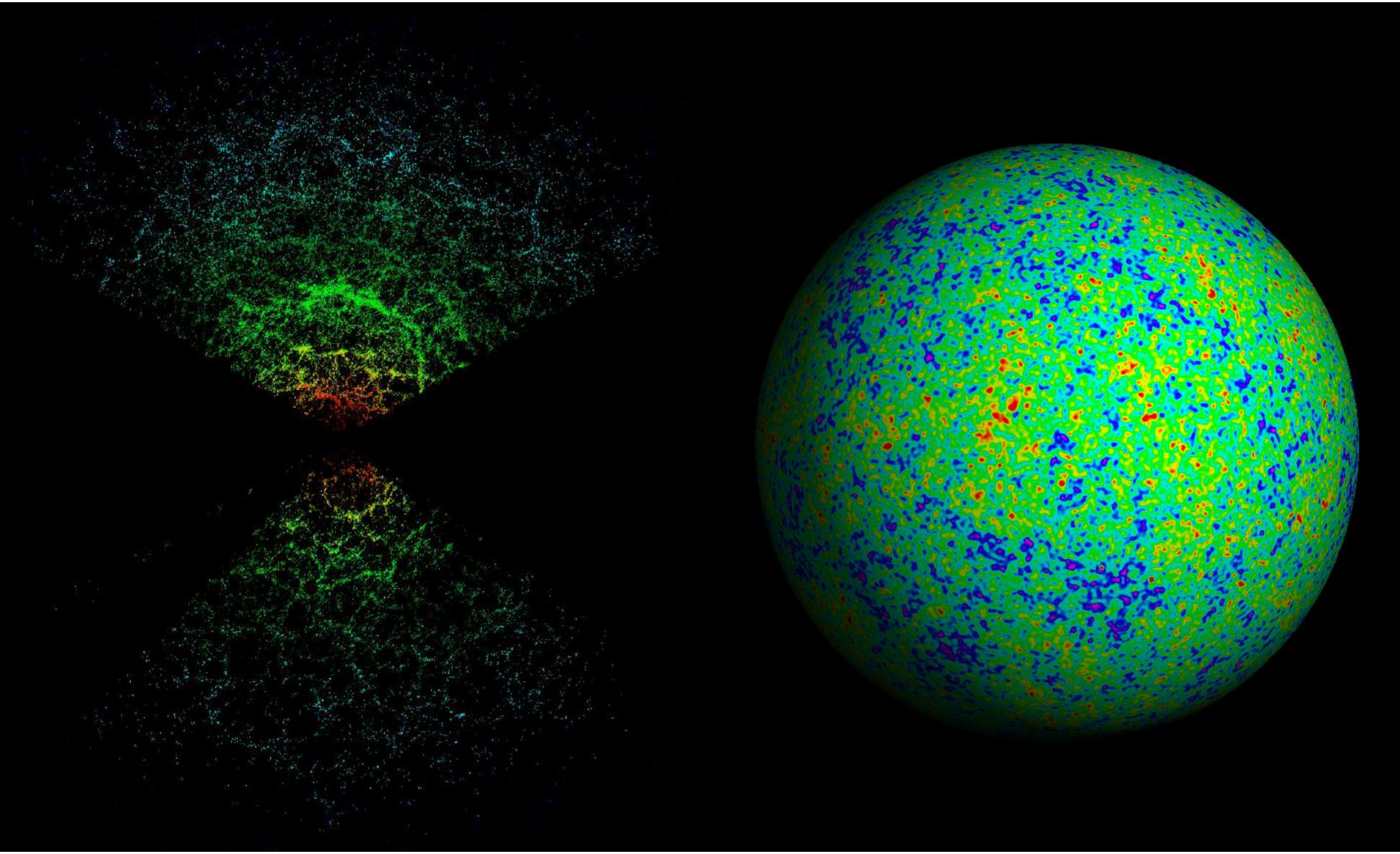
Data

Cosmo pars

Connection to early universe

SDSS, WMAP & the Early Universe



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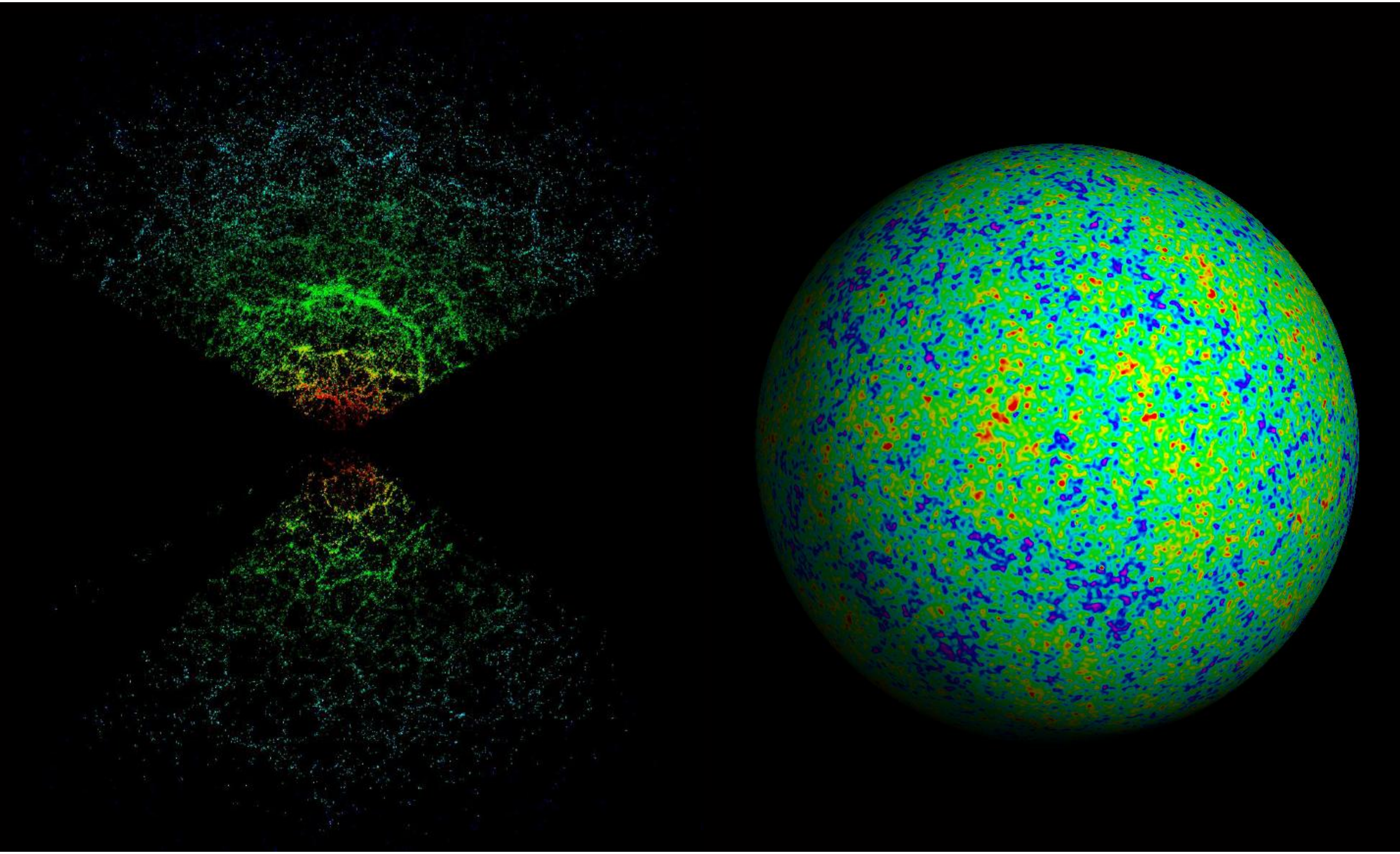
SDSS, WMAP & the Early Universe



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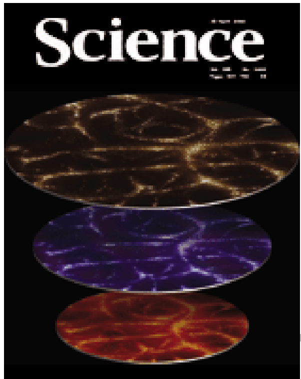


WMAP release, February

tational 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

Breakthrough Online
For an expanded version of this section, with references and links, see www.sciencemag.org/content/vol302/issue5653/#special

Breakthrough of the Year

#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 sported 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 rattles 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 existence of this irresistible 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 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 roiled under the competing influences of gravity and light. The big bang had set the entire cosmos ringing like a bell, 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 shape and the material it's made of, so does the "sound" 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, and 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": slate 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 the distribution of those galaxies, the way they clump and spread out, scientists can figure out the forces that caused 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 crushing—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.

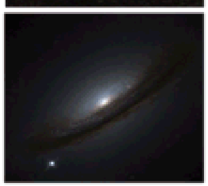
Some of the work of cosmology can now turn to understanding the forces that shaped the universe when it was a fraction of a millisecond old. After the universe burst forth from a cosmic singularity, the fabric of the newborn universe expanded faster than the speed of light. This was the era of inflation, and that burst of growth—and its abrupt end after less than 10^{-30} seconds—shaped our present-day universe.

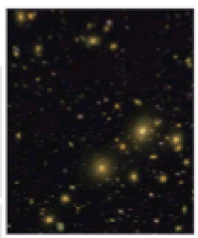
For decades, inflation provided few testable hypotheses. Now the exquisite precision of the WMAP data is finally allowing scientists to test inflation directly. Each current version of inflation proposes a slightly different scenario about the precise nature of the inflating force, and each makes a concrete 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





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.

THE RUNNERS-UP

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

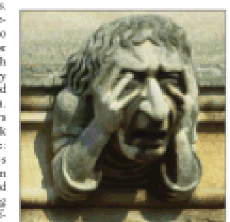
#2 Decoding mental illness. Schizophrenia, depression, and bipolar disorder often run in families, but only recently have researchers identified particular genes that reliably increase one's risk of disease. Now they're unraveling how these genes can distort the brain's information processing and nudge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

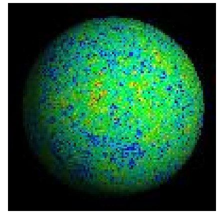
People with the high-risk allele have unusually heightened activity in a fear-focused brain region called the amygdala when viewing scary pictures. Together, these studies suggest that the gene variant biases people to perceive the world as highly menacing, which amplifies life stresses to the point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

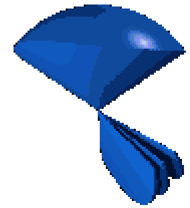
Late in 2002, an allele of a gene for brain-derived neurotrophic factor (BDNF) was implicated in bipolar disorder, once known as manic depression. This year the allele was found to curb activity in the hippocampus, a structure necessary for memory that is shrunken in people with mood disorders. BDNF 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.



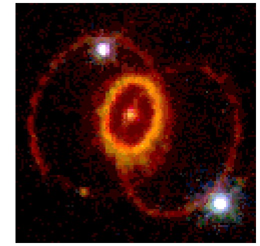
Agony antecedents. New work links genes, brain activity biases, and mental illness.



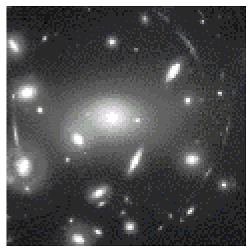
CMB



GALAXY SURVEYS

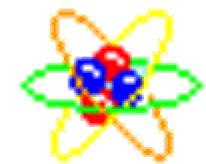


DISTANT SUPERNOVAE

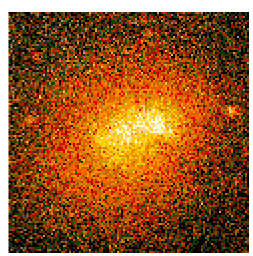


GRAVITATIONAL LENSING

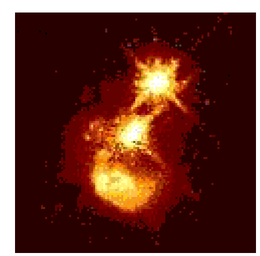
THE COSMIC SMÖRGÅSBORD



BIG BANG NUCLEOSYNTHESIS



GALAXY CLUSTERS



LYMAN ALPHA FOREST

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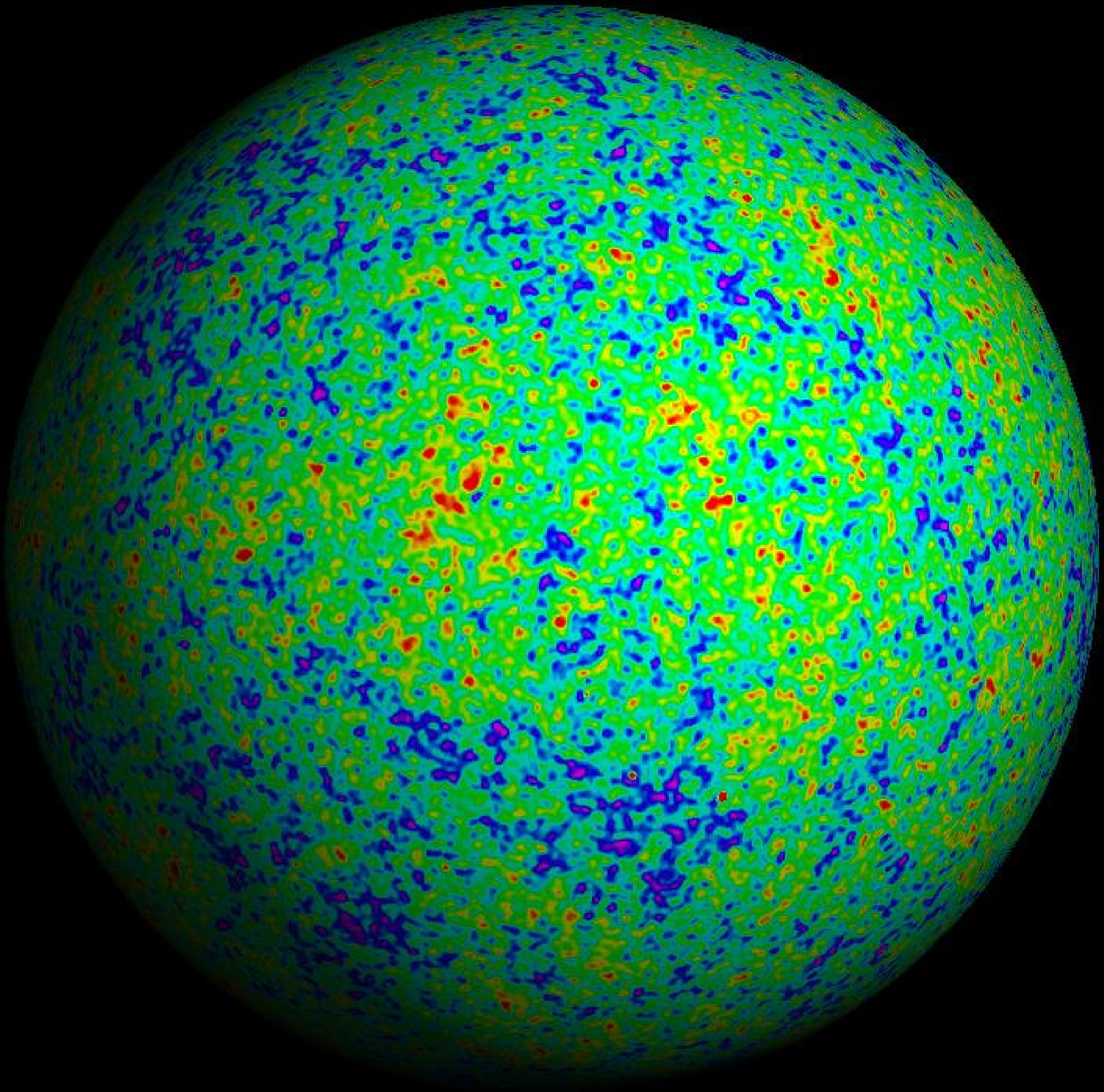

Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/030249

$z = 1000$

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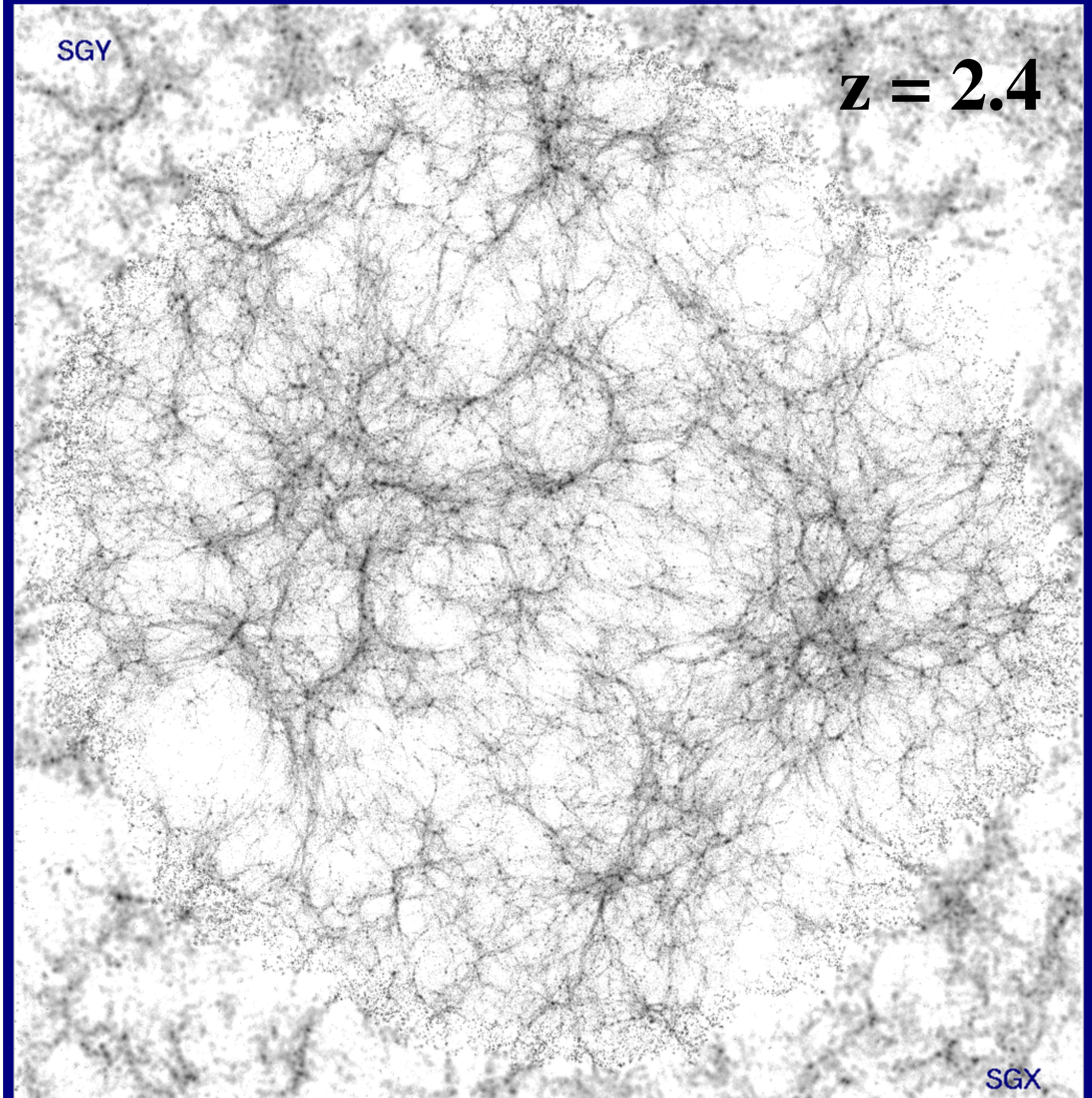
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2



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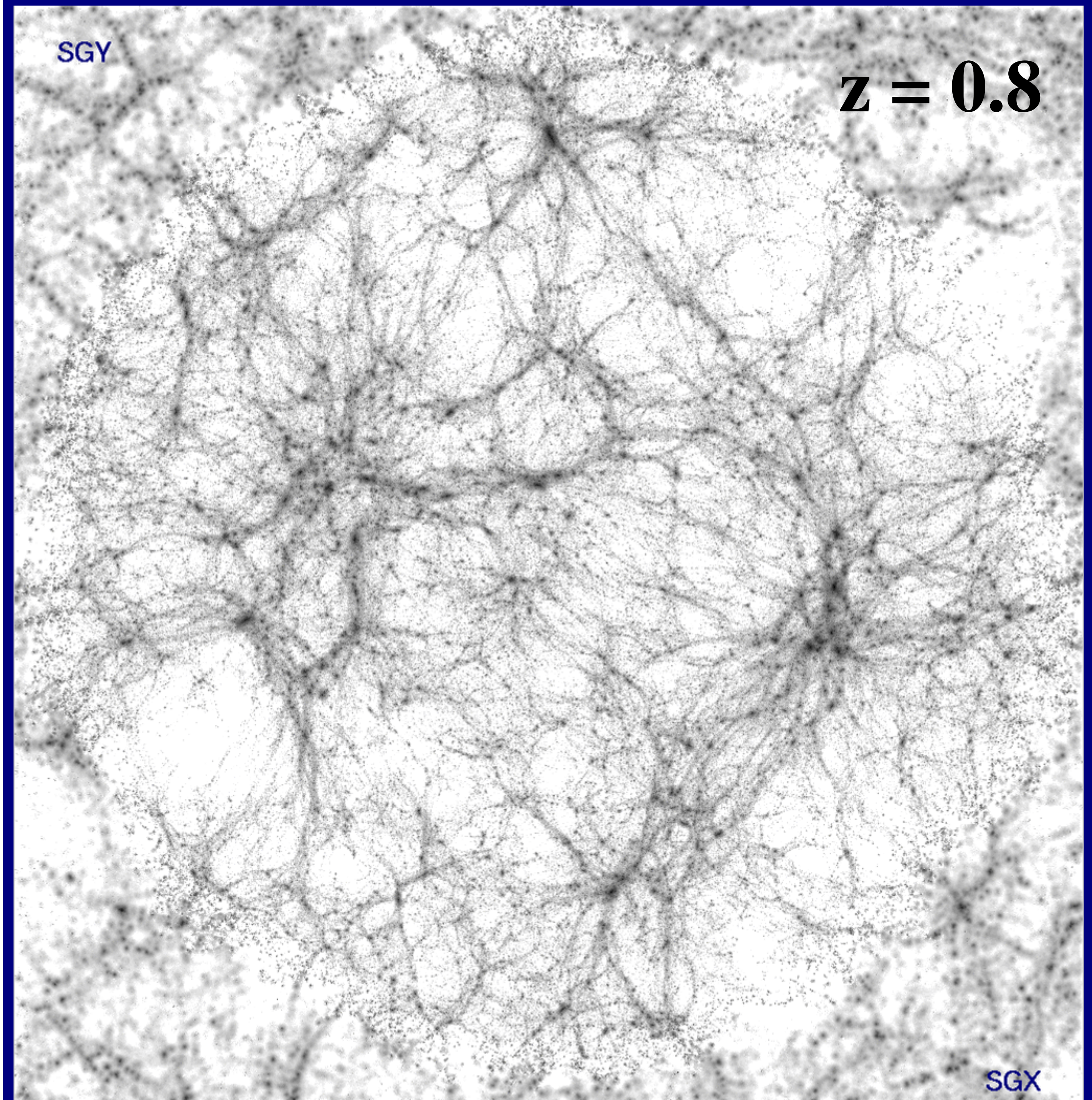

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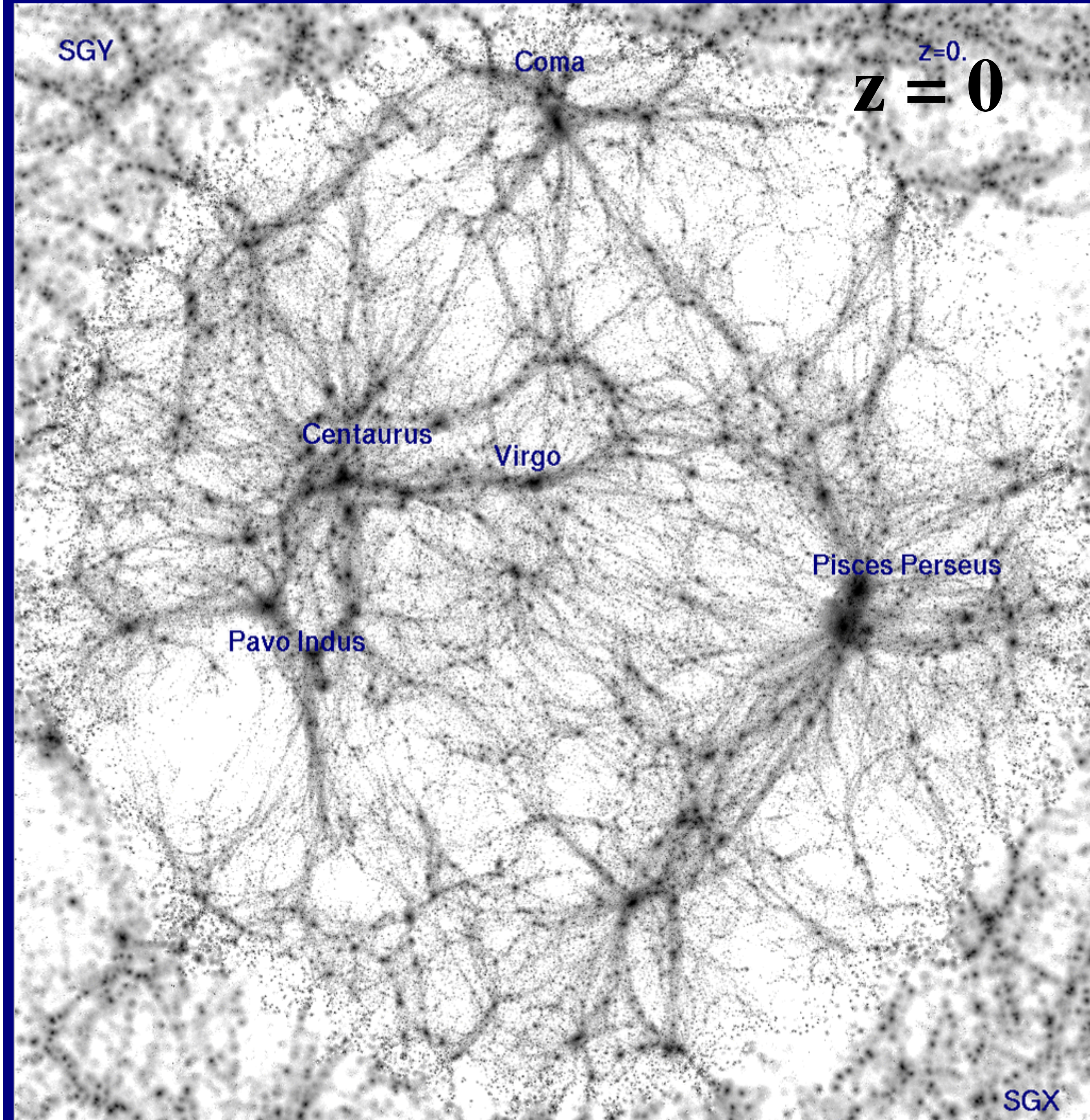

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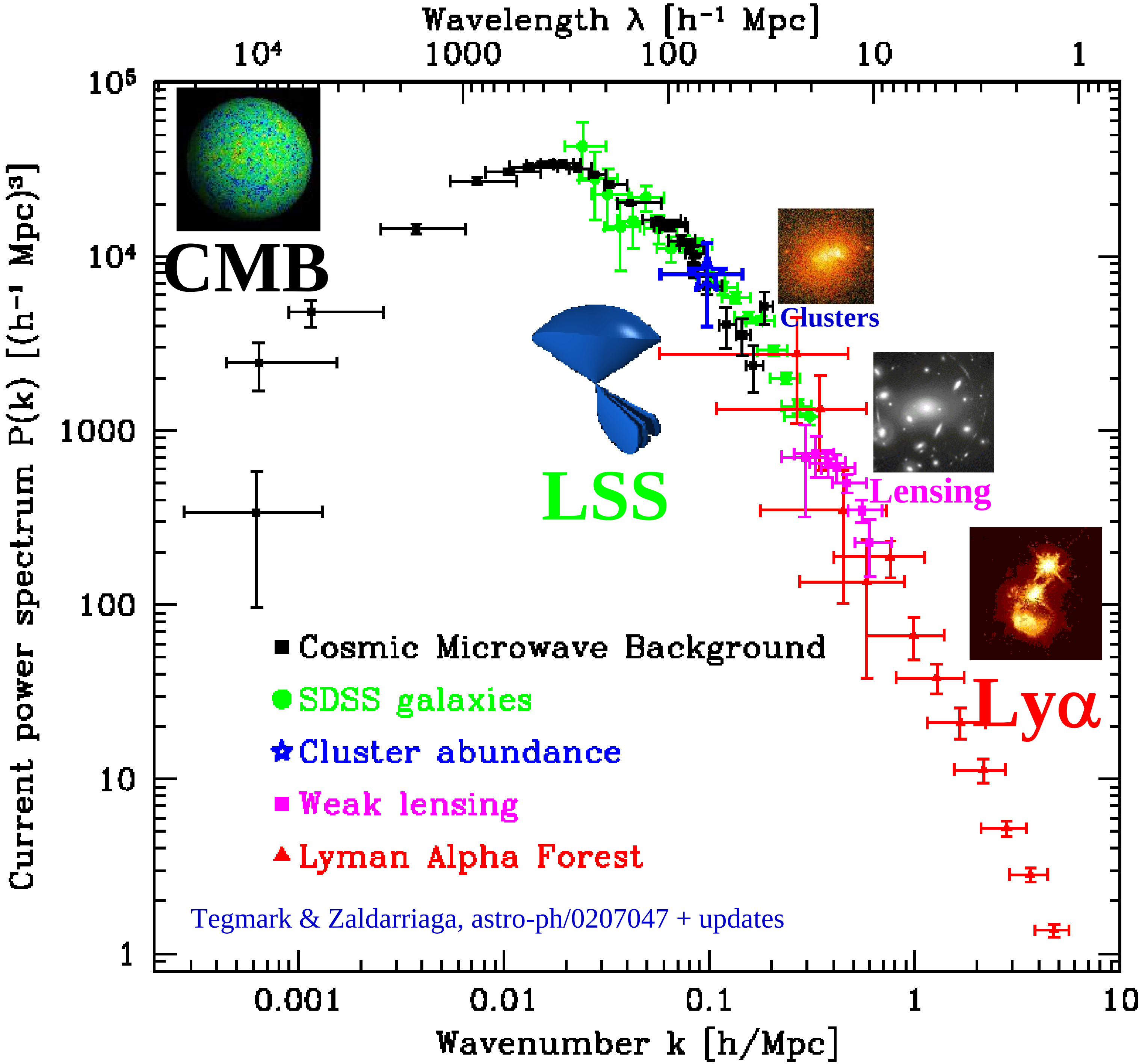

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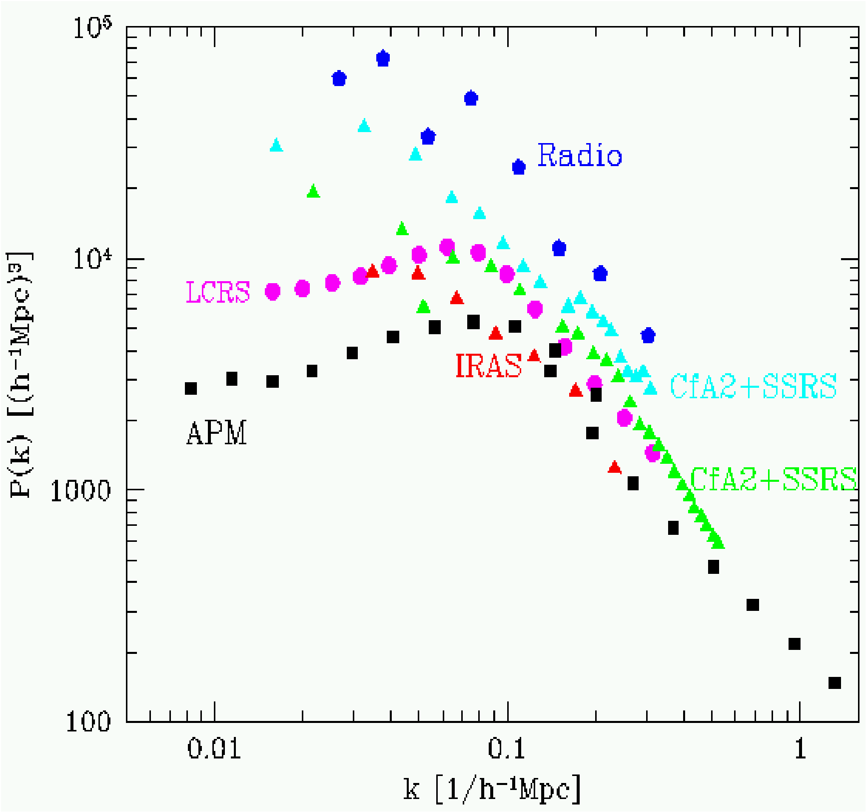

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

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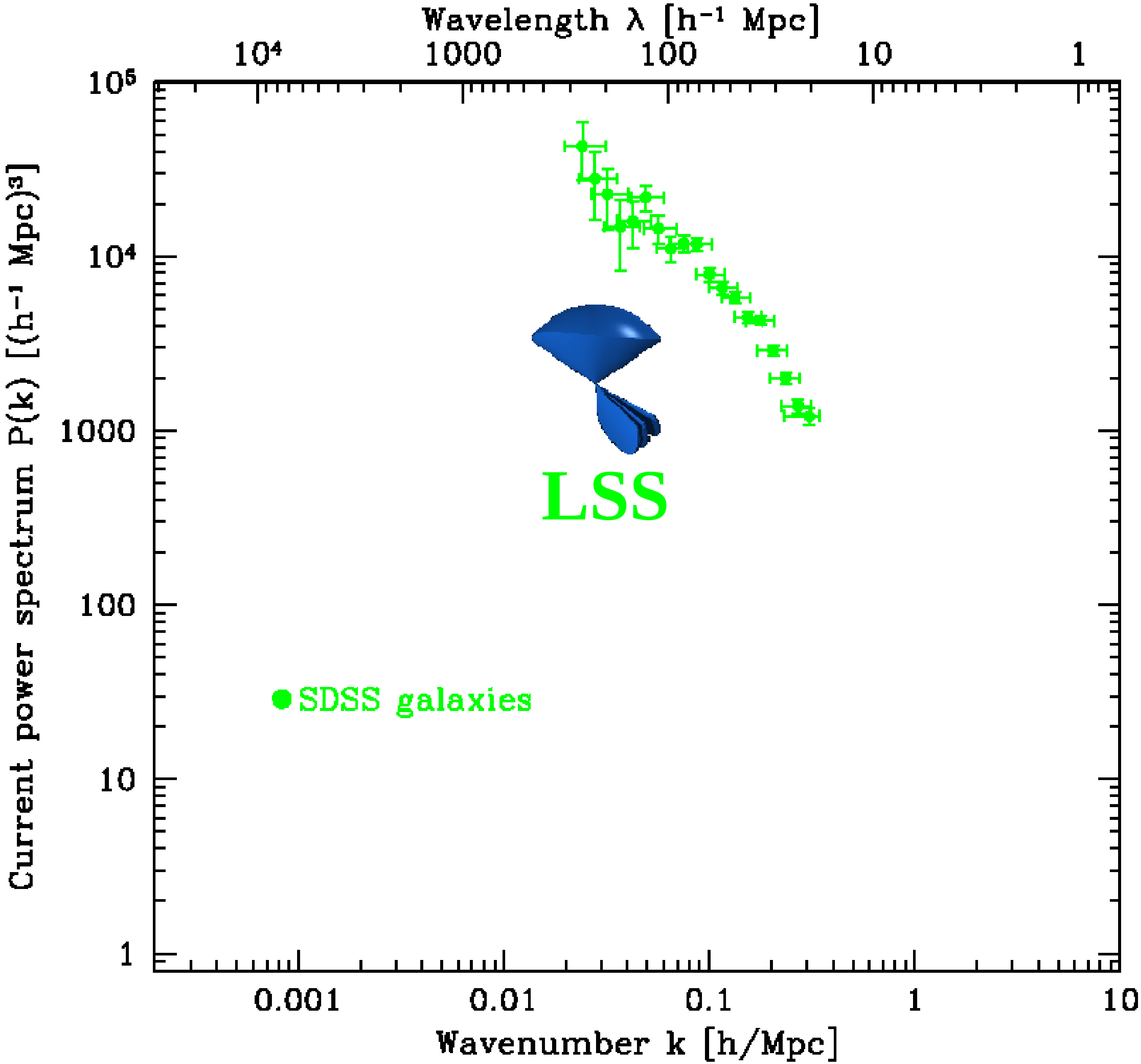

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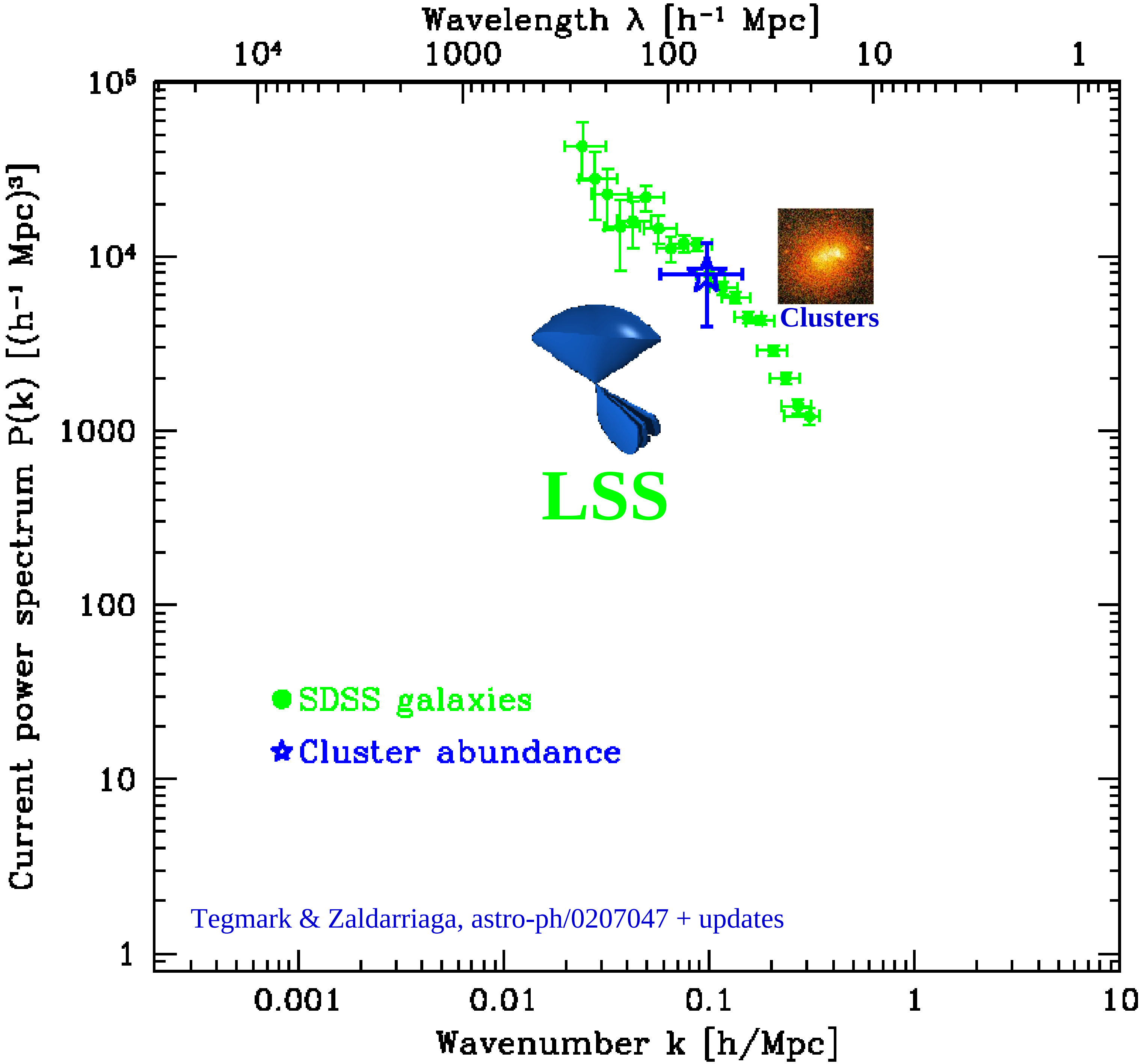

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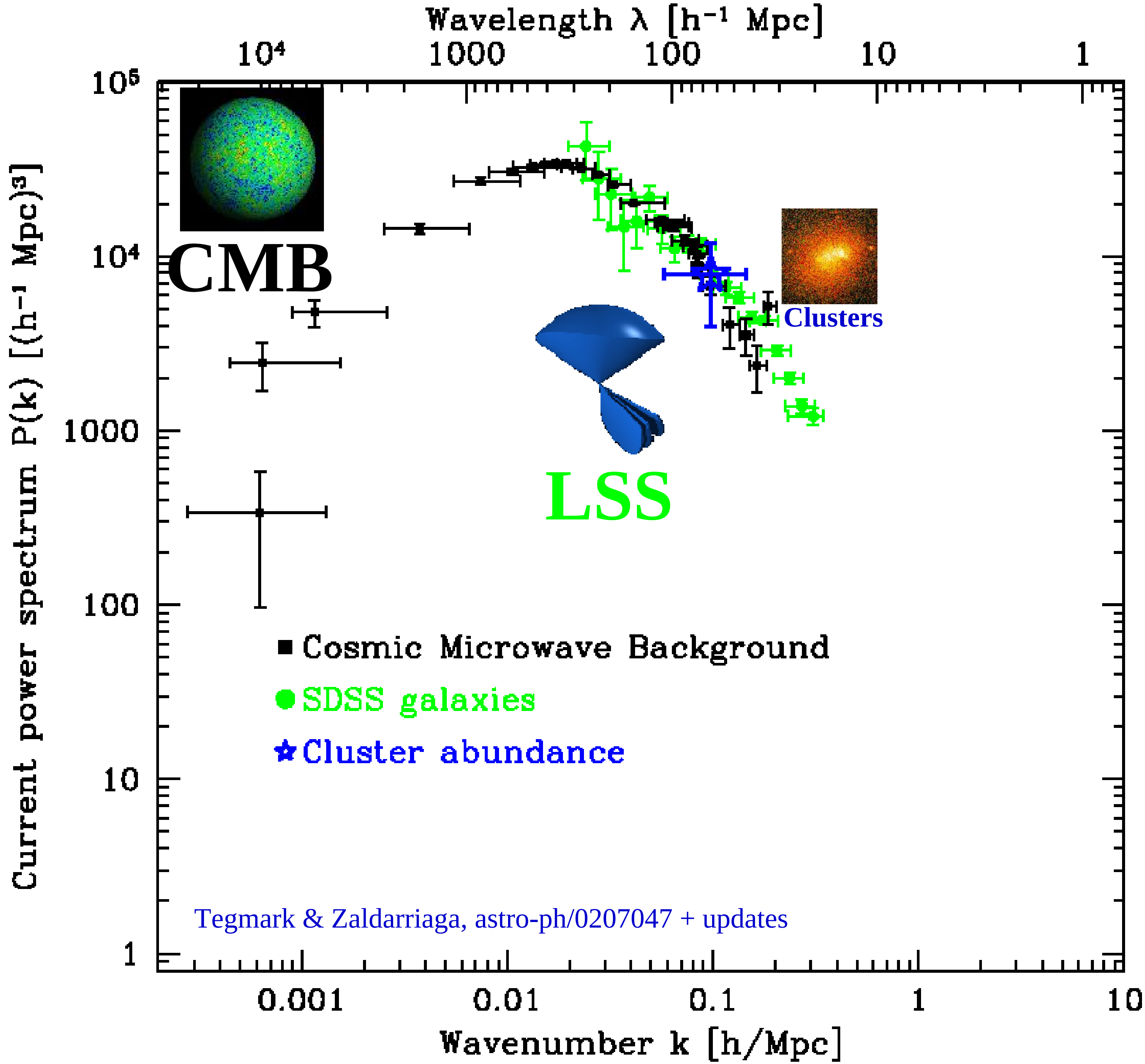

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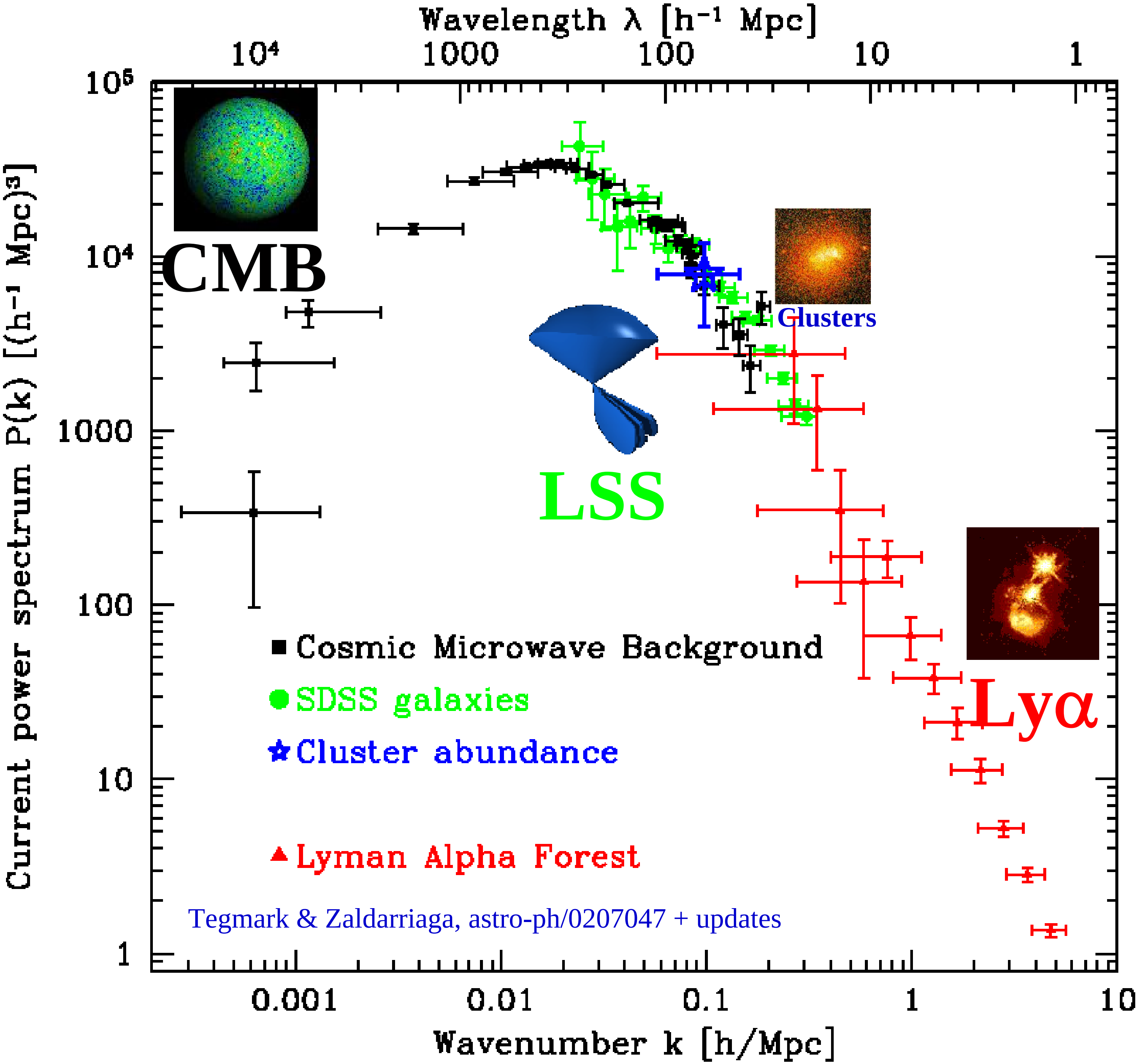

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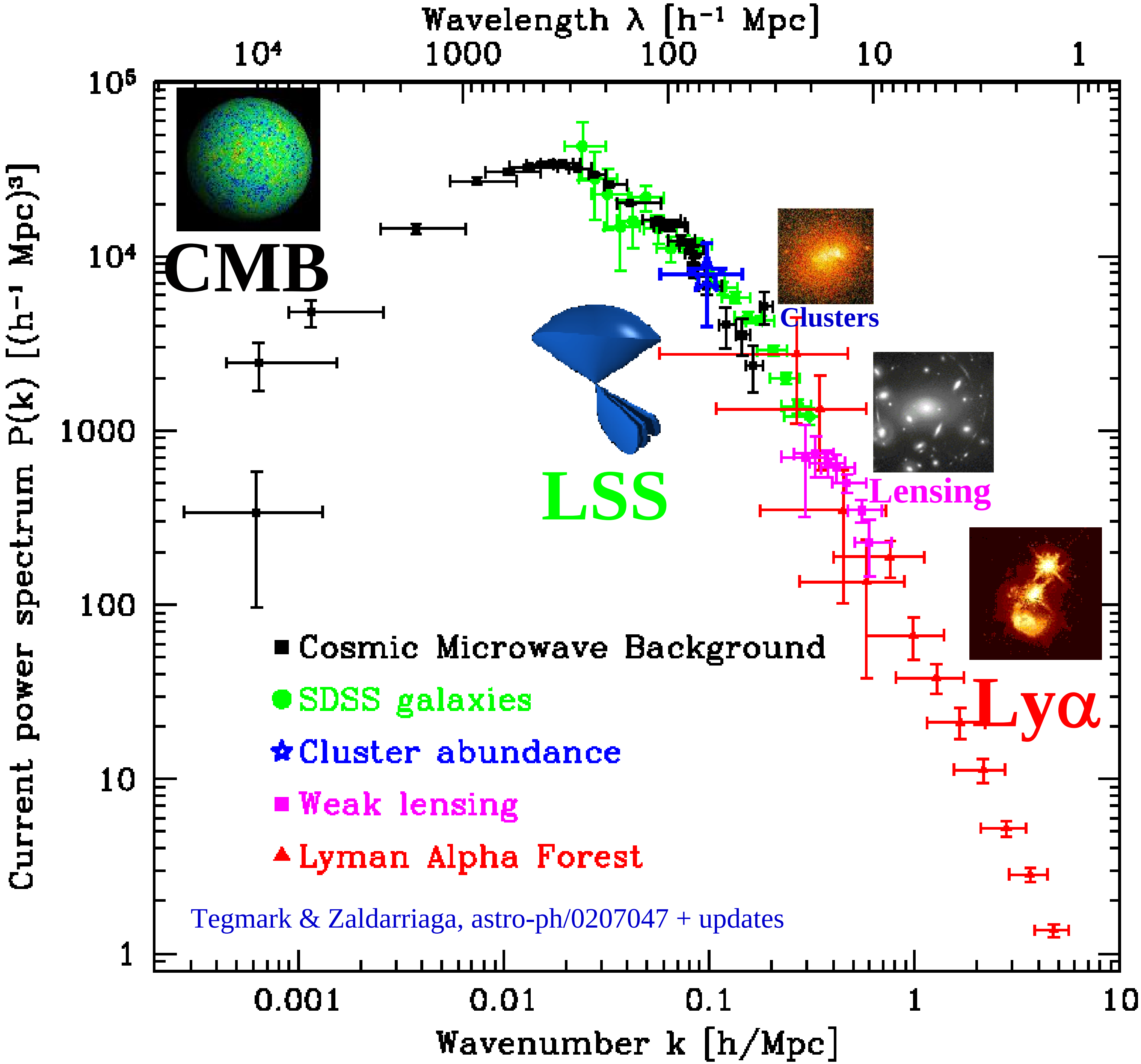

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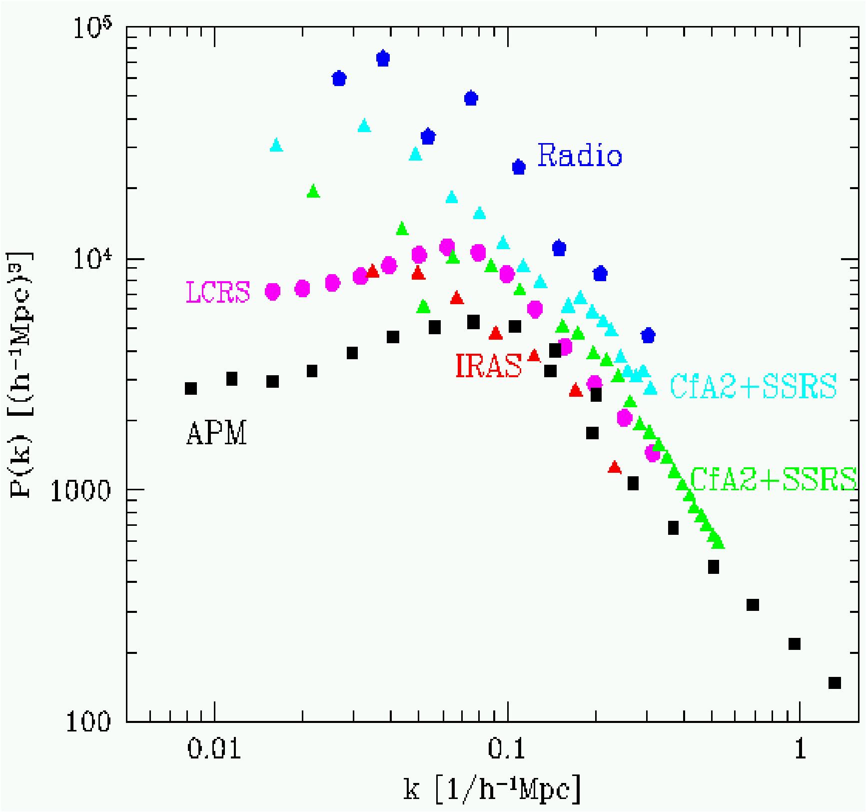

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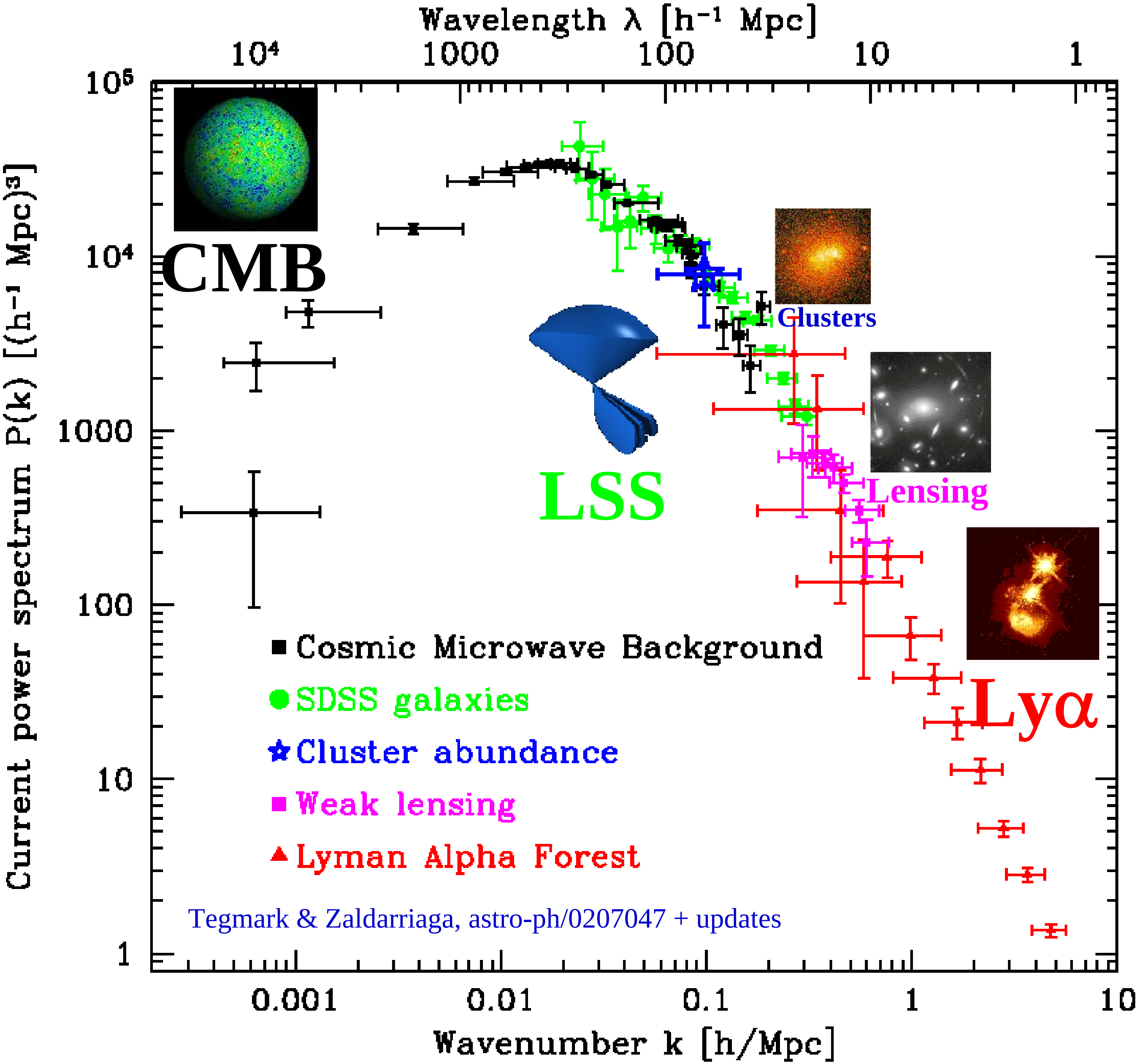

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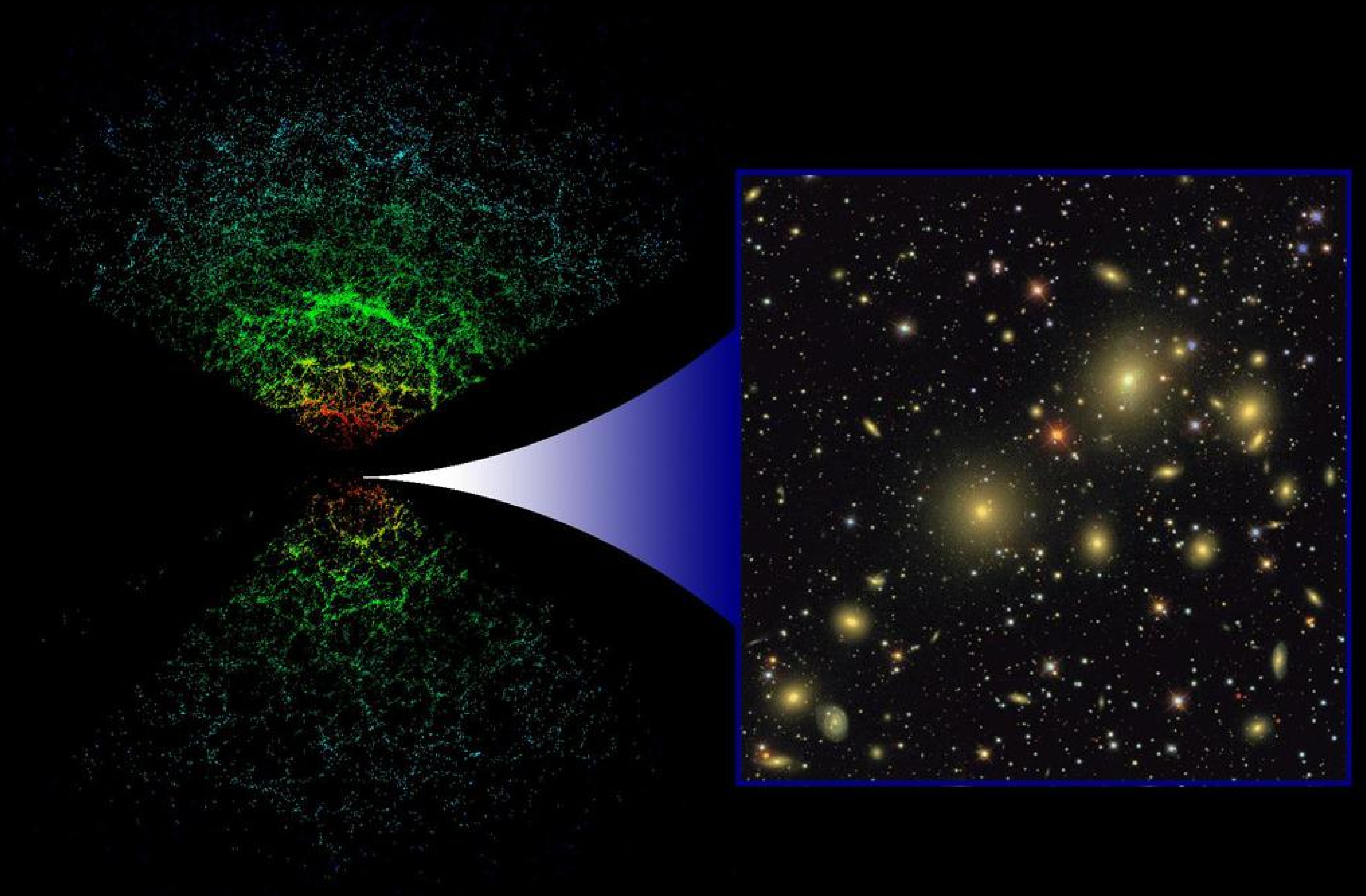
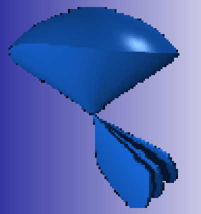
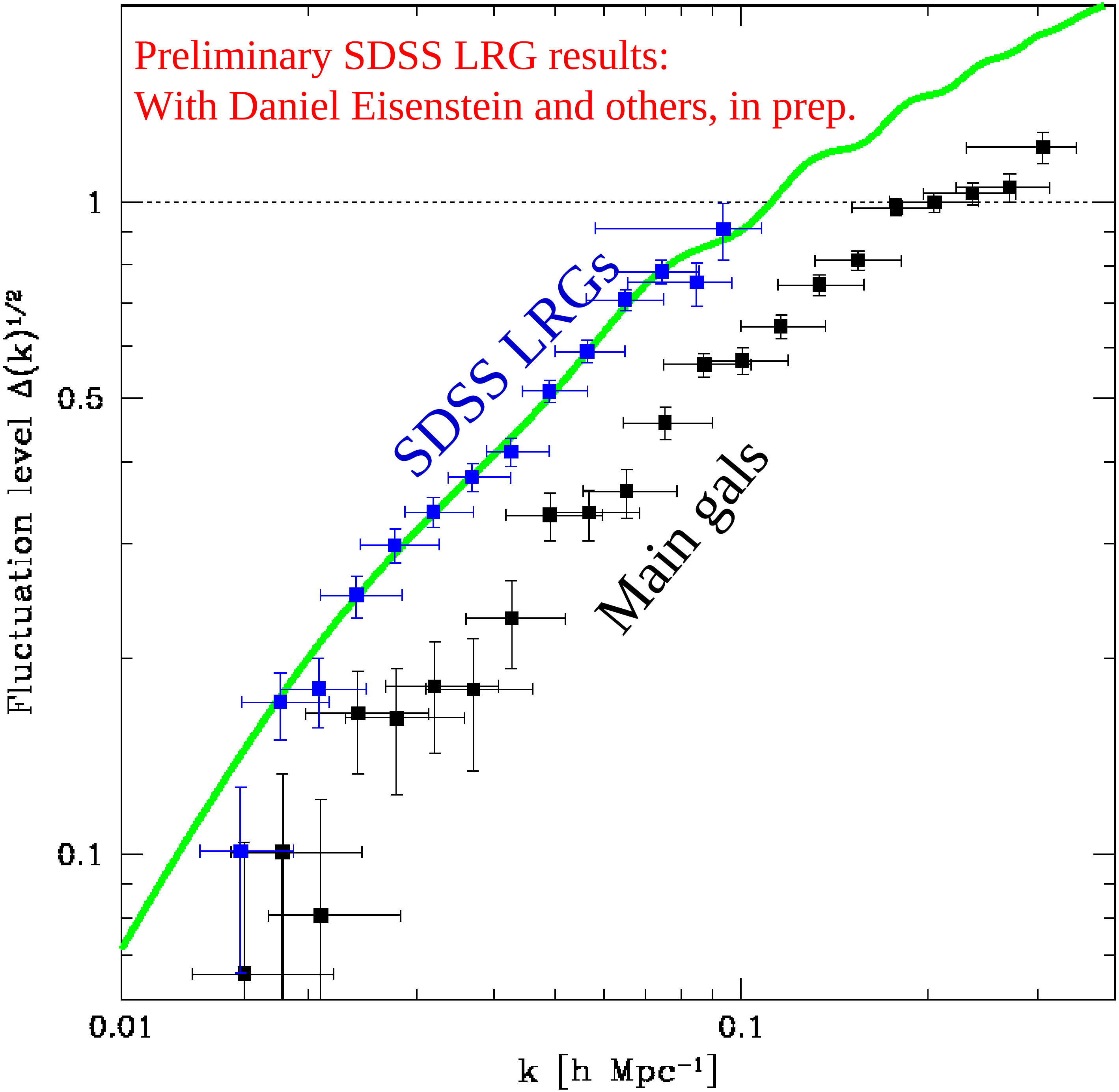
It’s just going to get better





LSS



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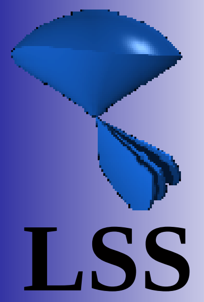

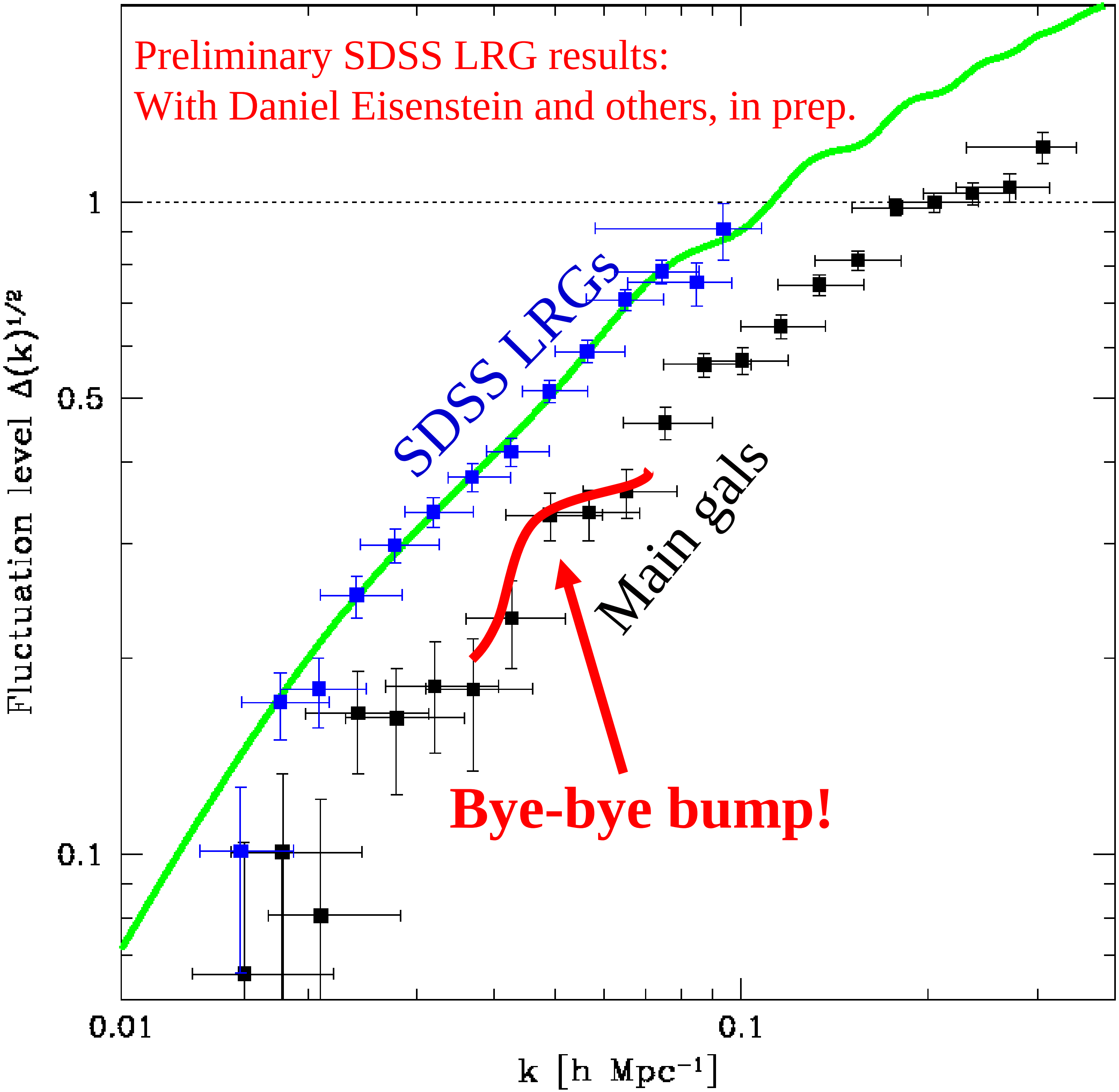

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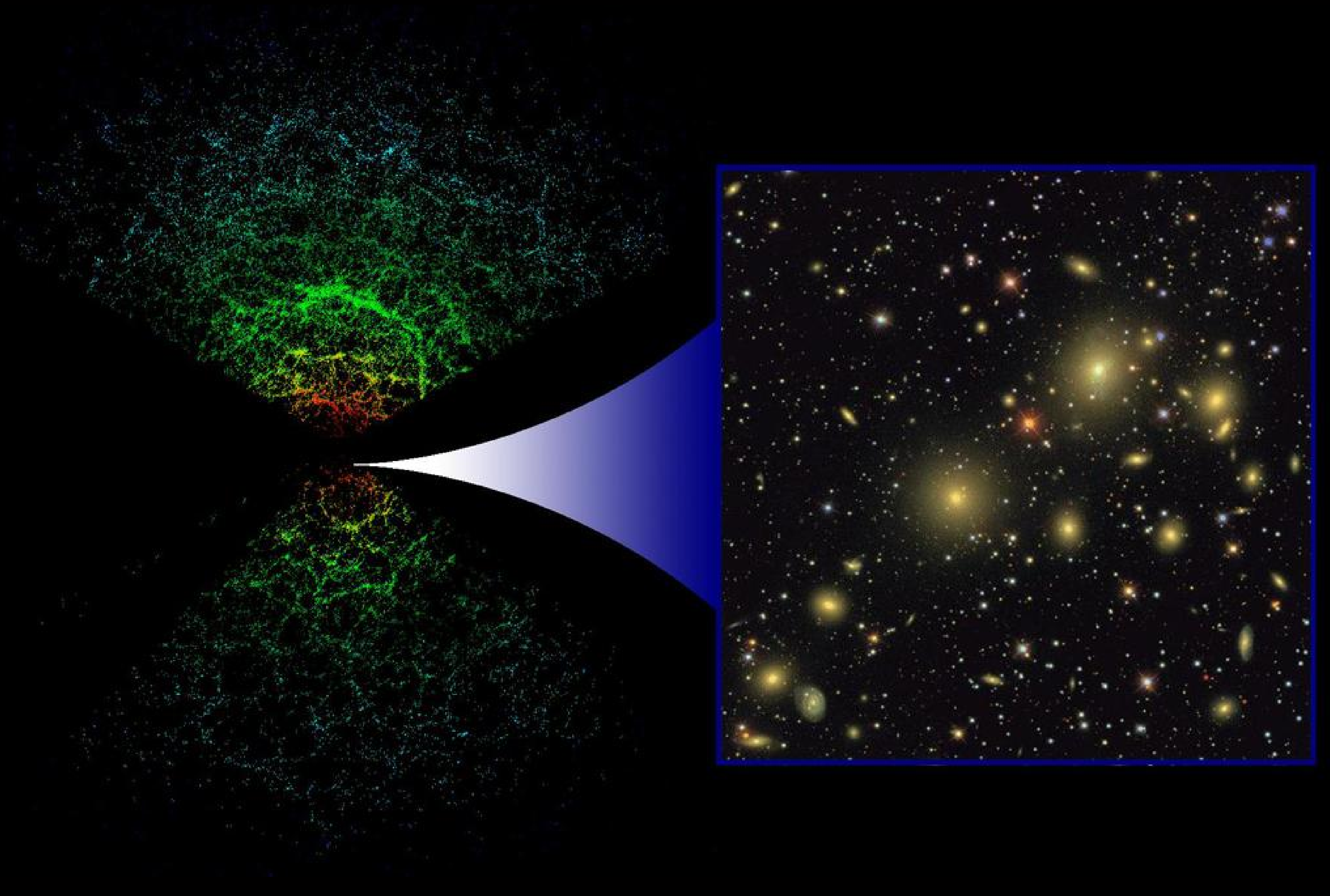
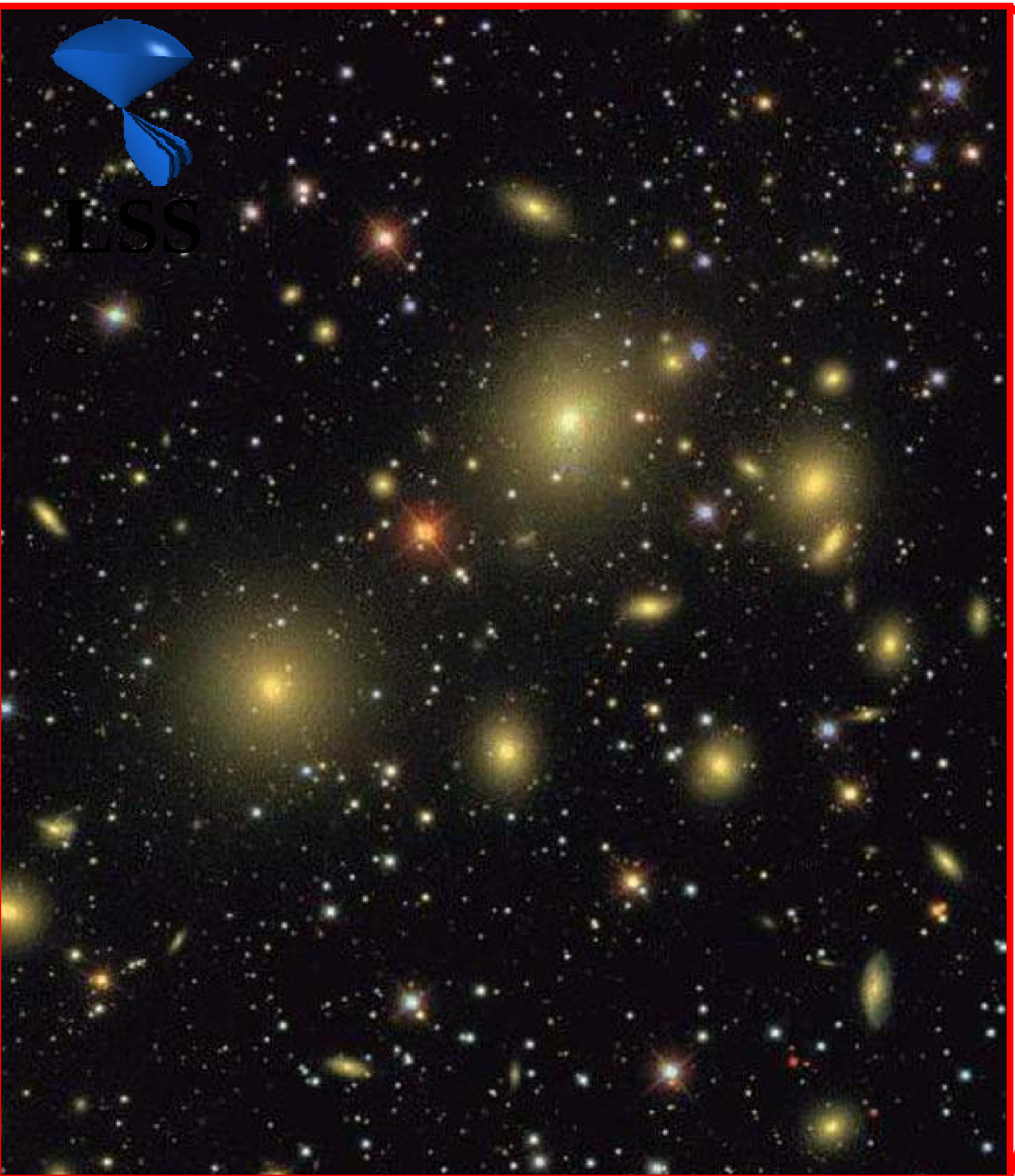
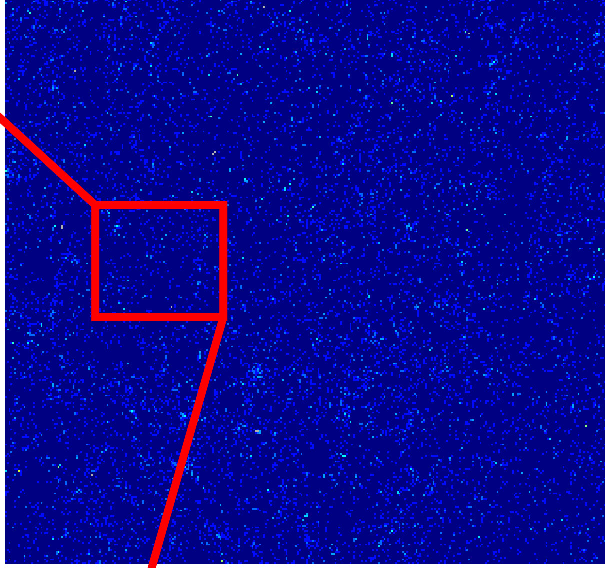
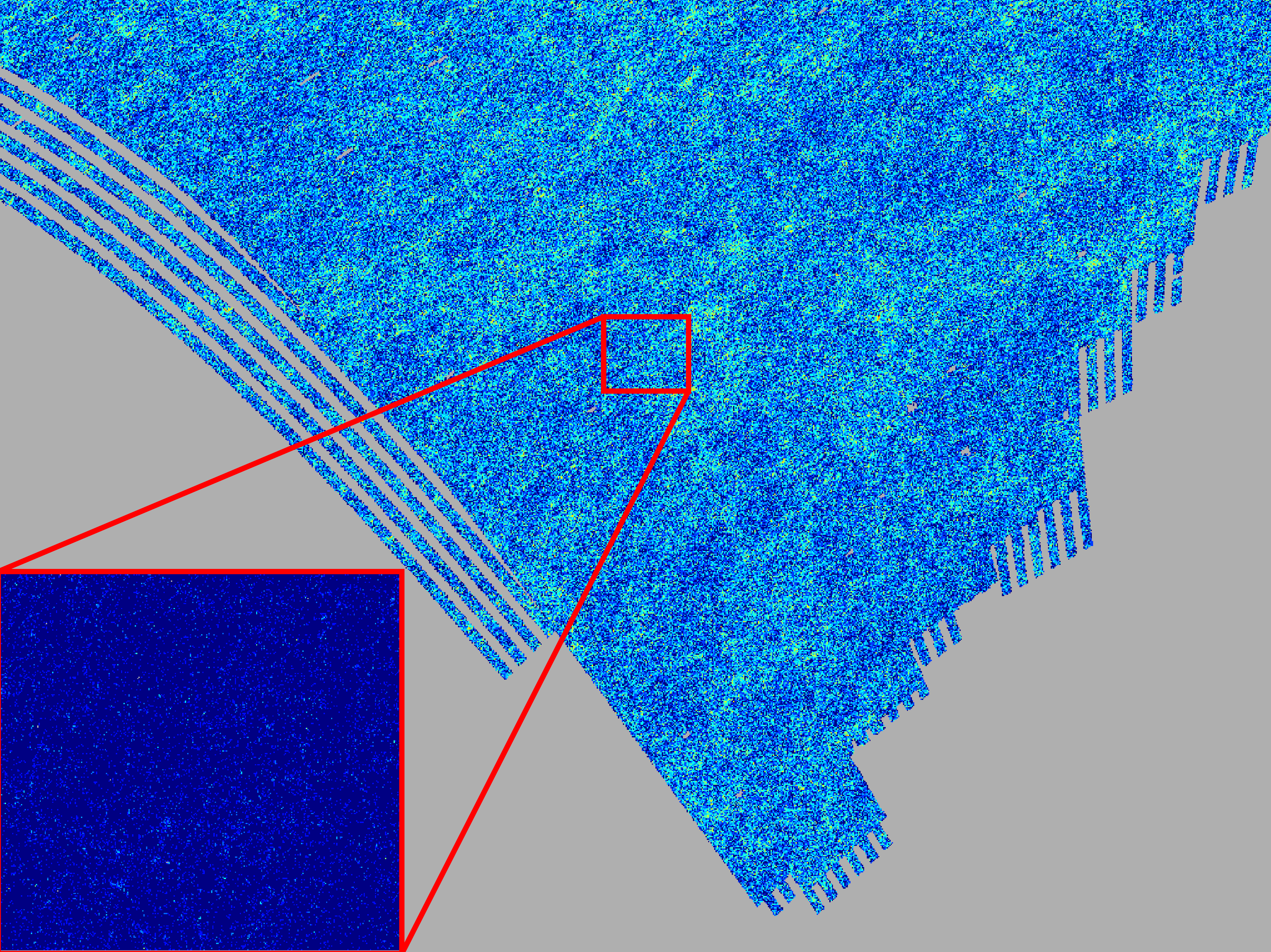
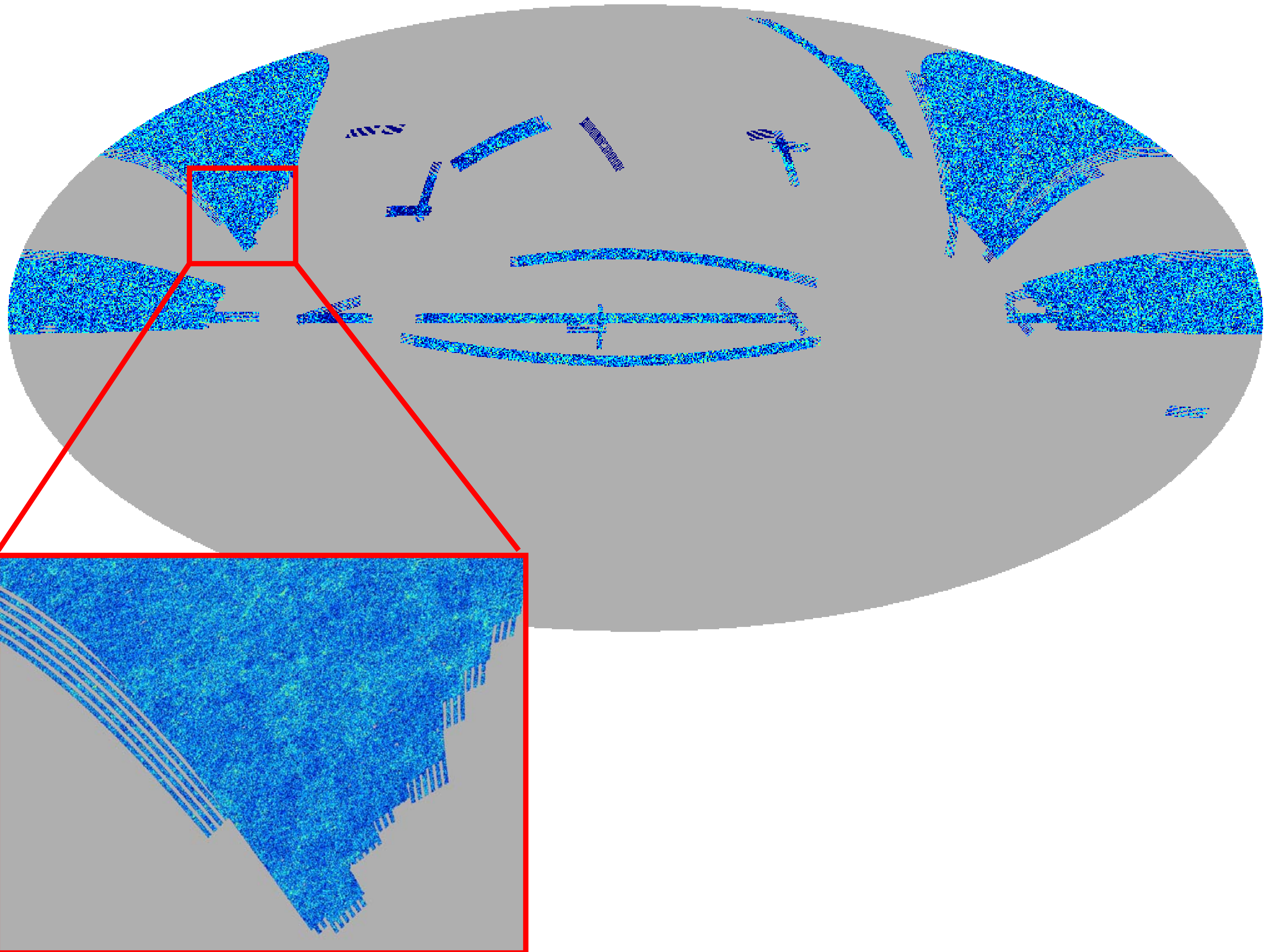






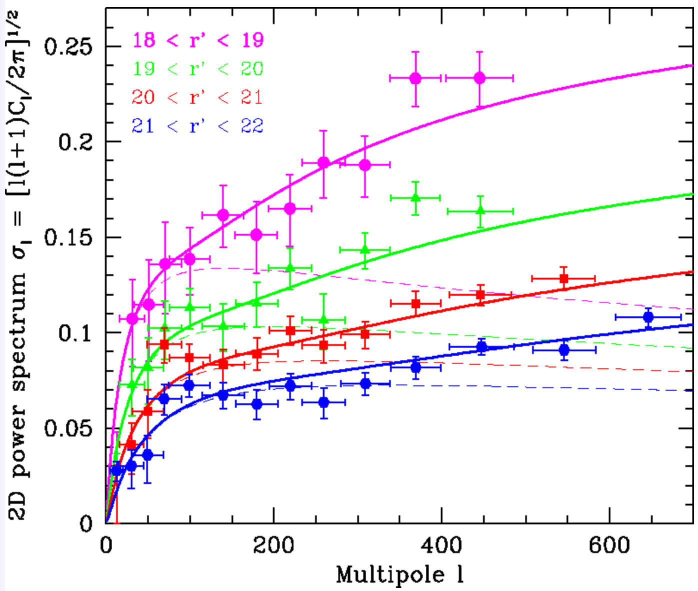
Data & image processing by Robert Lupton & David Schlegel



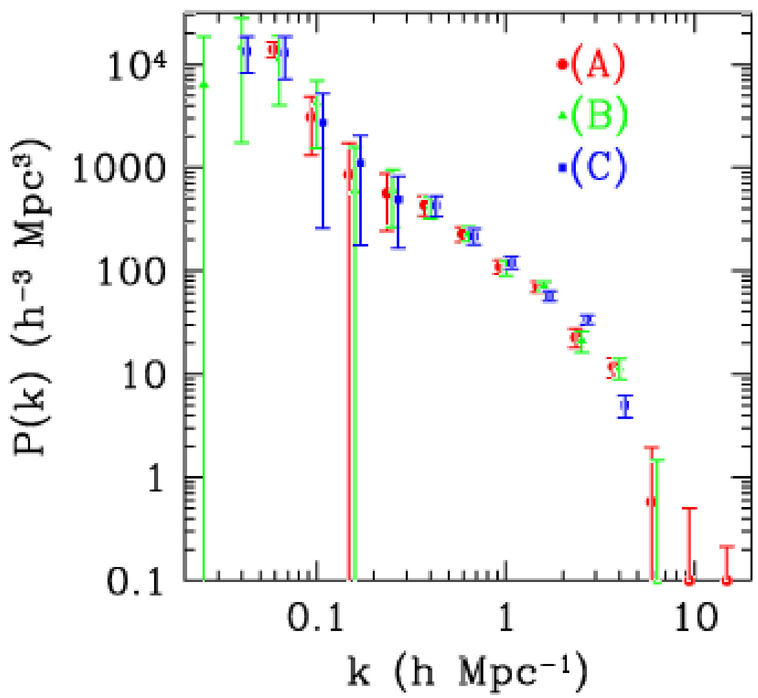


This was from just 400 square degrees:

Tegmark et al 2002, for SDSS collab.



Dodelson et al 2002, for SDSS collab.



Now we have an order of magnitude more, and photometric redshifts.

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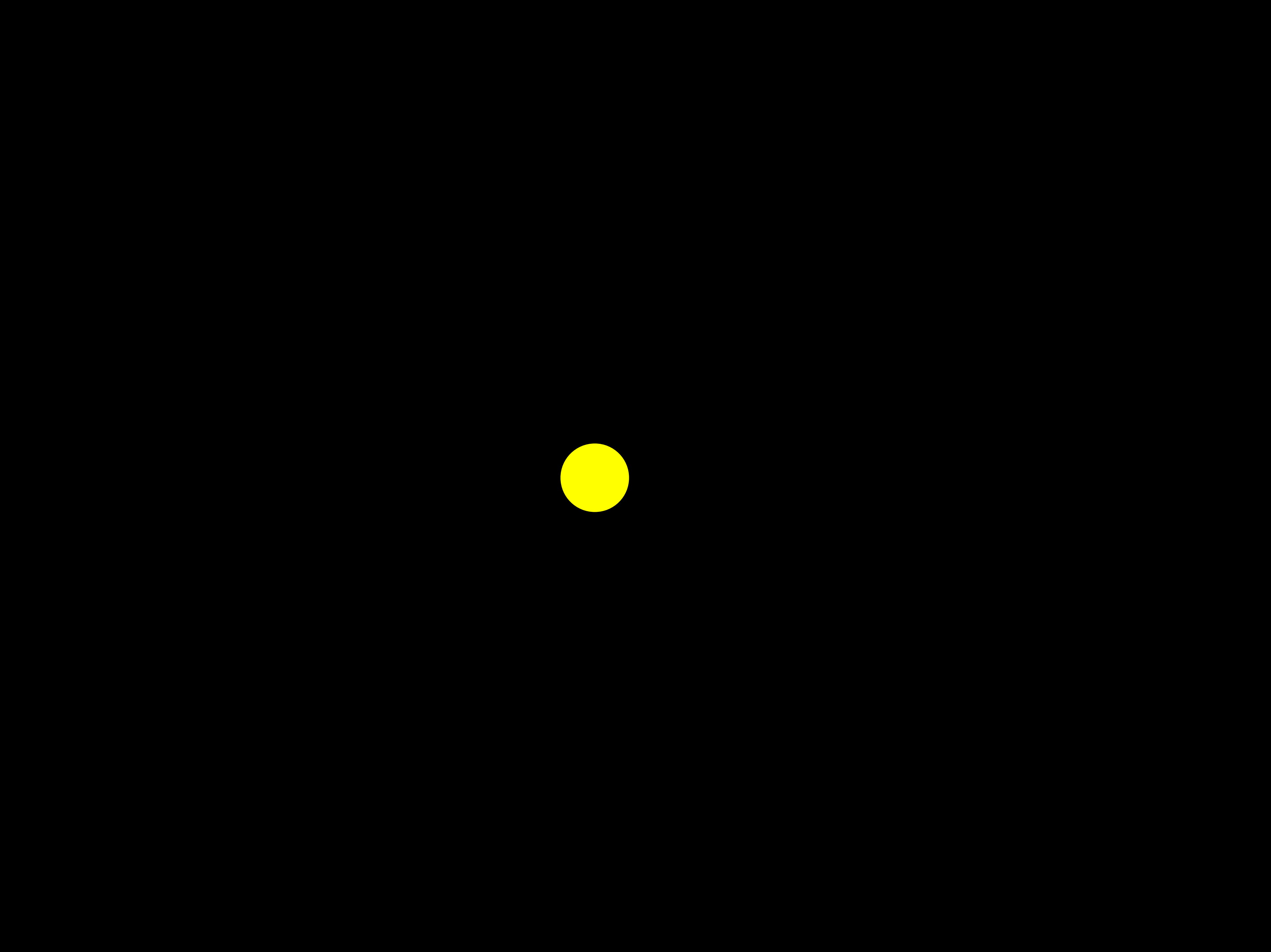
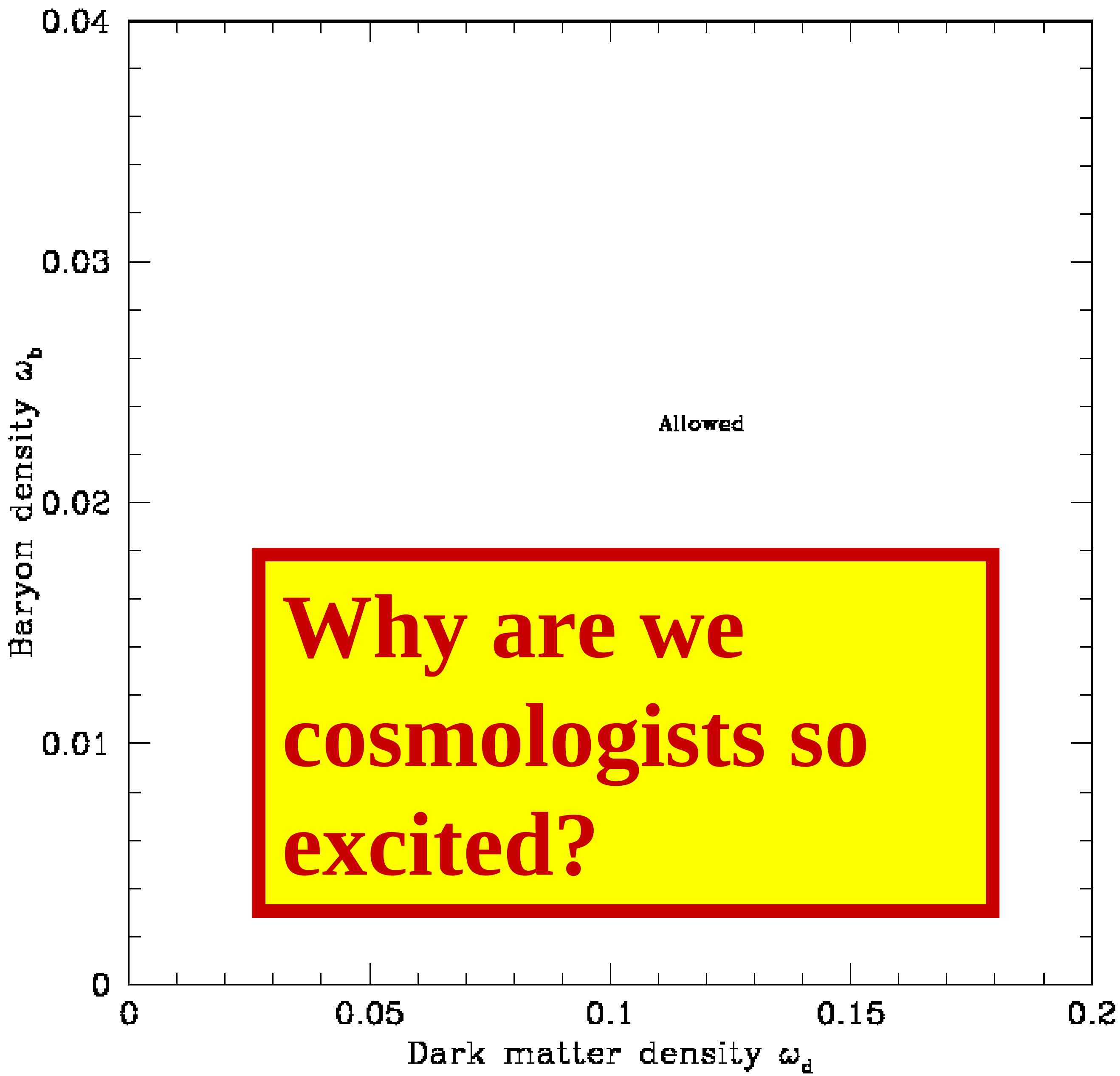
Measuring cosmological parameters



How much dark matter is there?

ρ_b /(1.8788×10^{-26} kg m^3)



Why are we cosmologists so excited?

=ρ_d /(1.8788×10^{-26} kg m^3)

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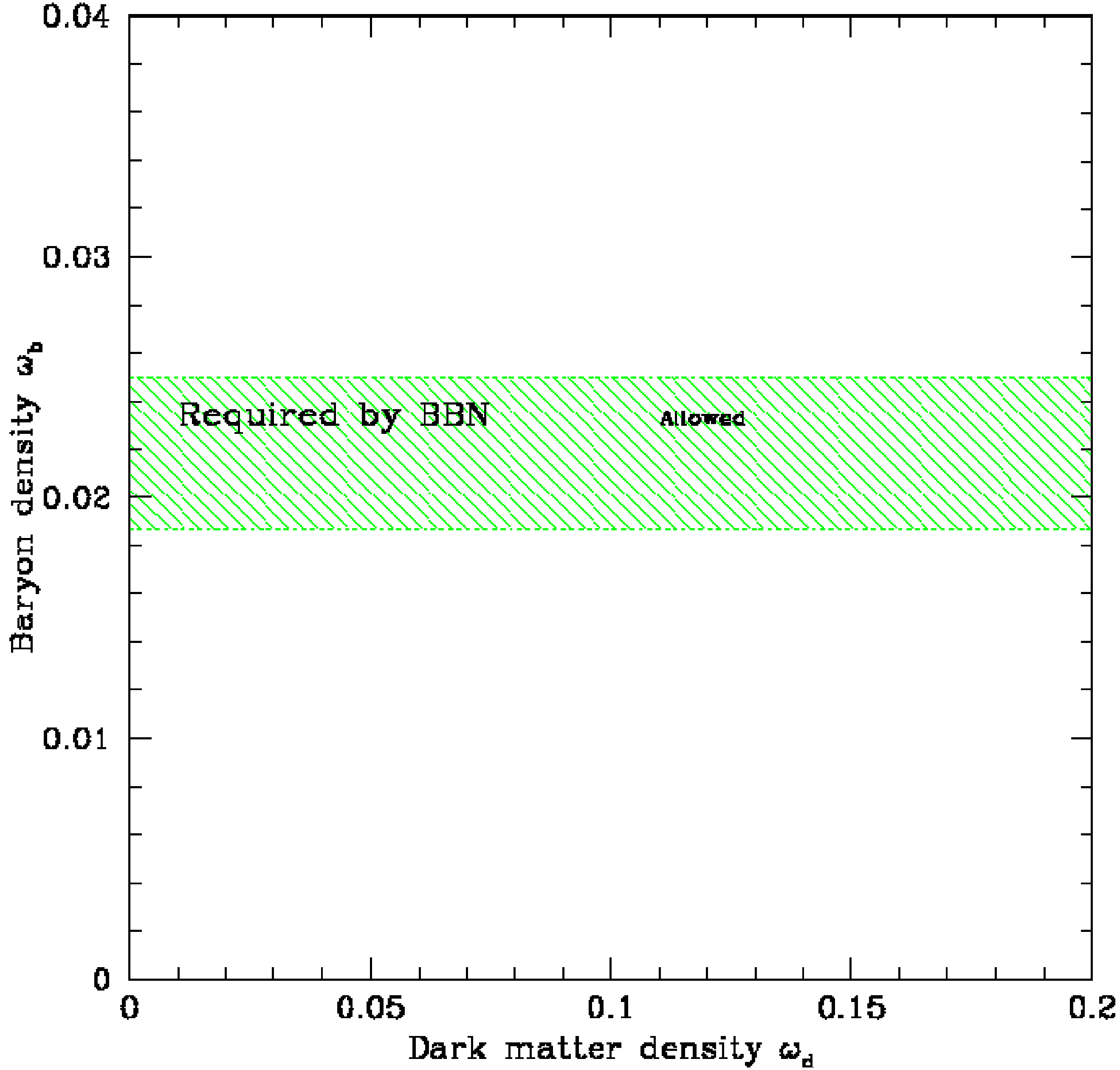

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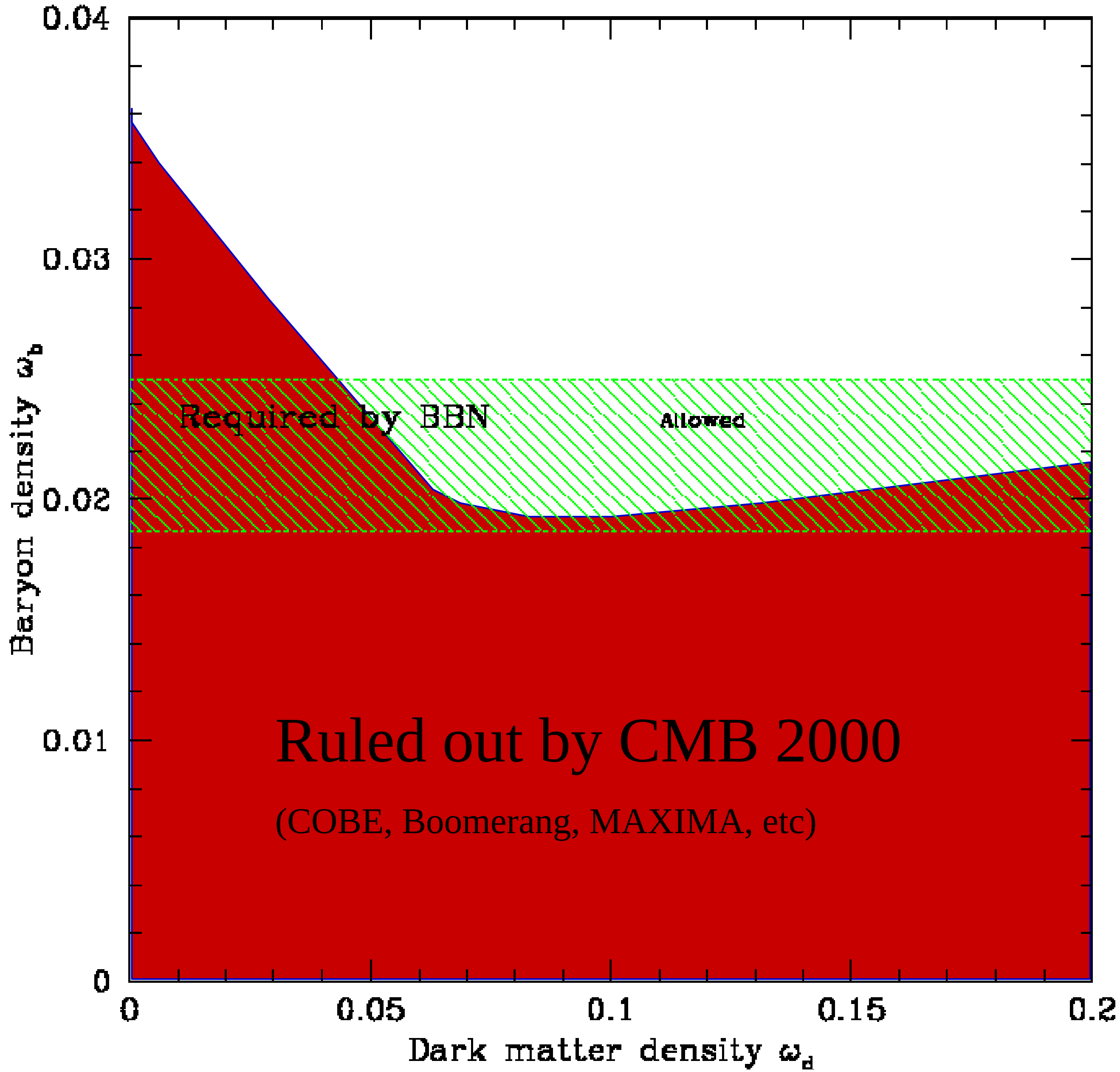

$\rho_b /(1.8788\times10^{-26}$ kg m$^3)$

$=\rho_d /(1.8788\times10^{-26}$ kg m$^3)$

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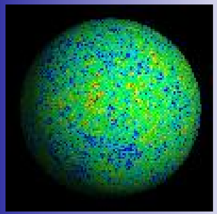
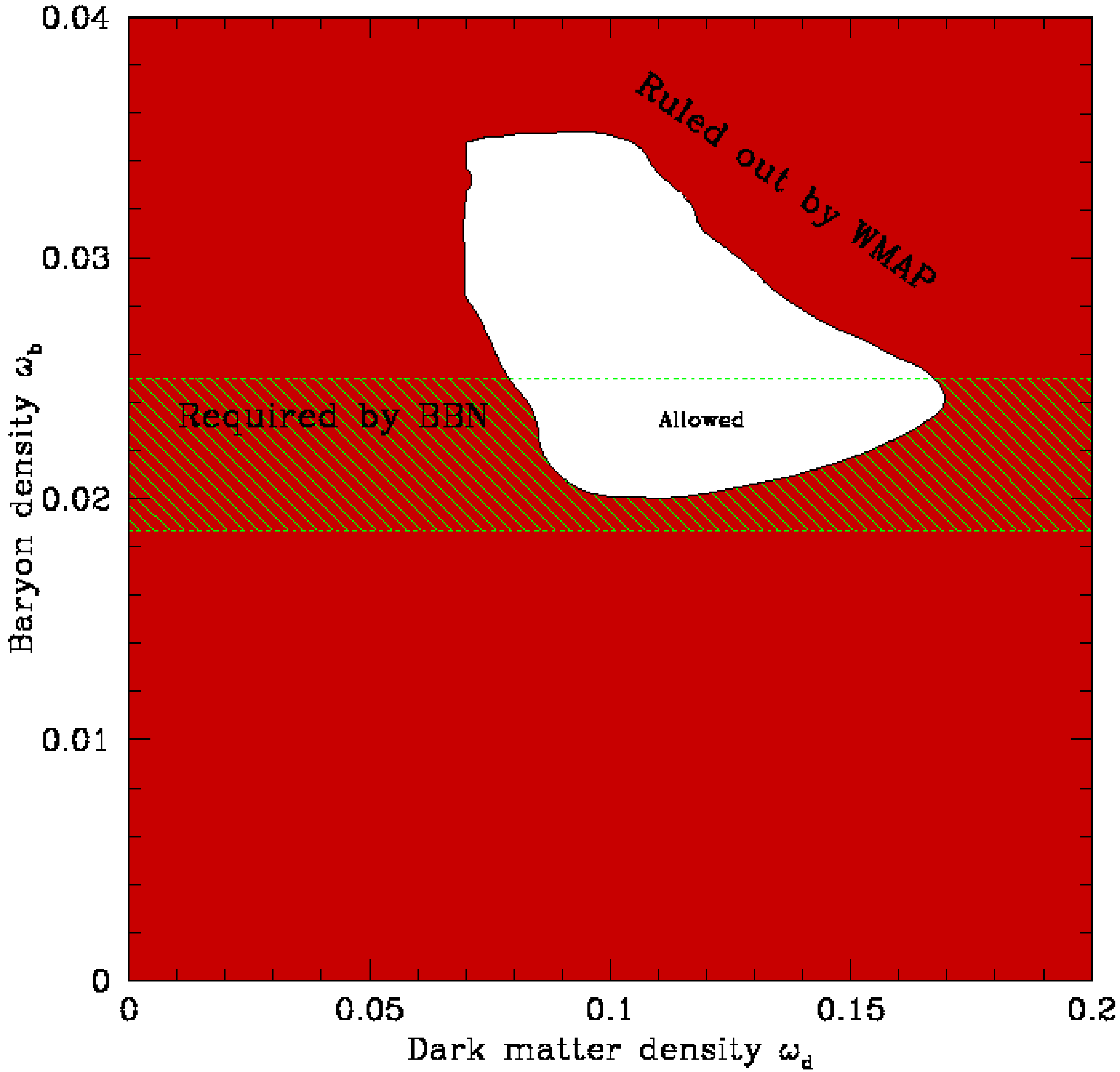
How much dark matter is there?



CMB



ρ_b /(1.8788×10^{-26} kg m^3)

=ρ_d /(1.8788×10^{-26} kg m^3)

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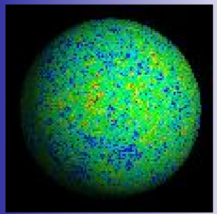
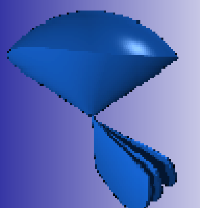


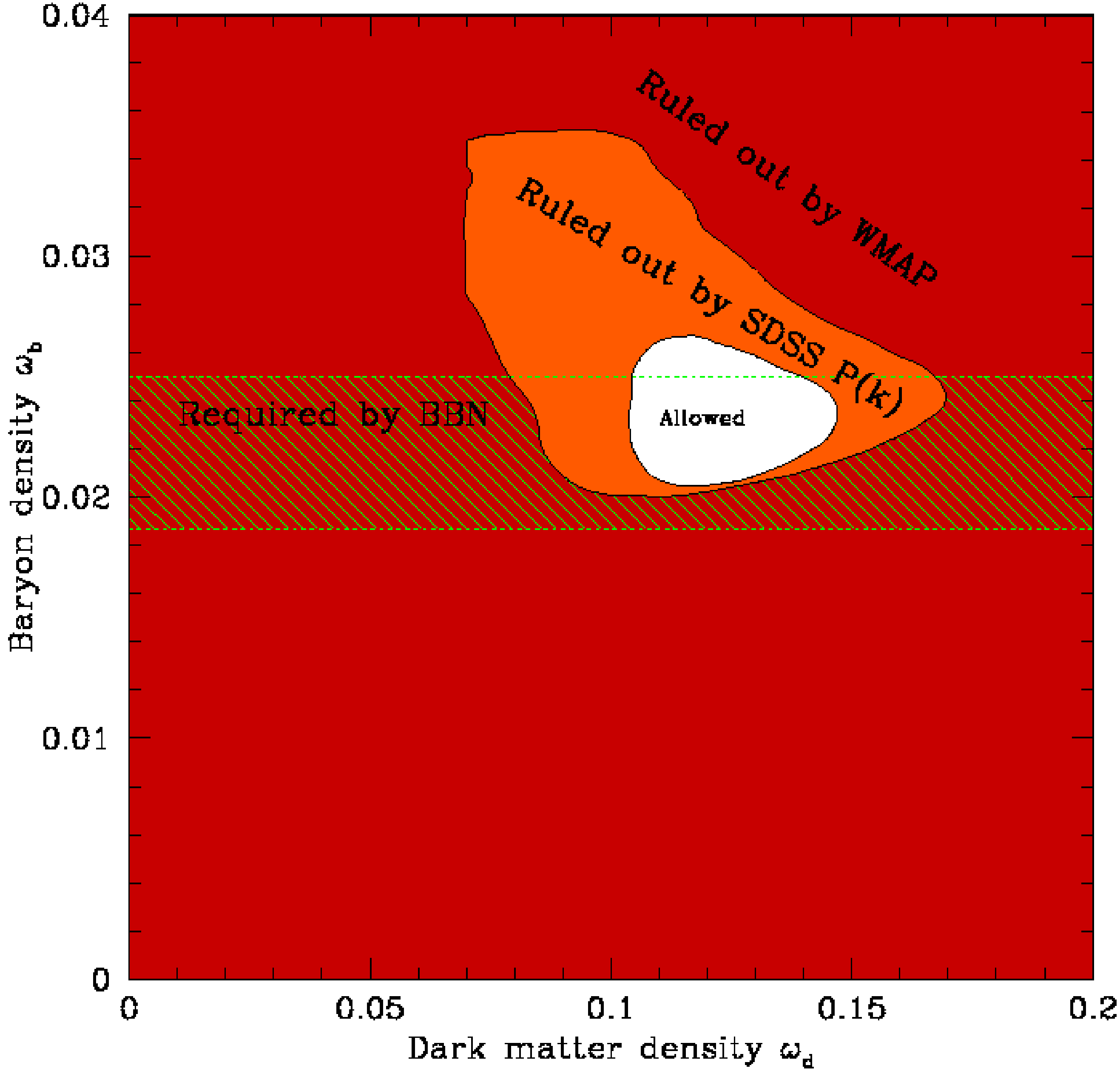
CMB

+



P(k)

$\rho_b \,/(1.8788\times10^{-26}\ \mathrm{kg\ m^3})$



$=\rho_d \,/(1.8788\times10^{-26}\ \mathrm{kg\ m^3})$

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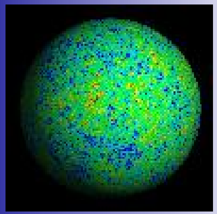
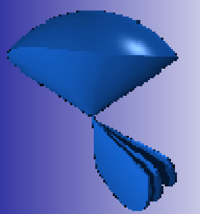


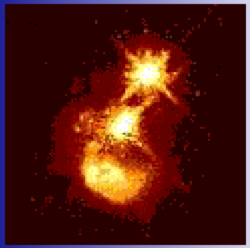
CMB

+

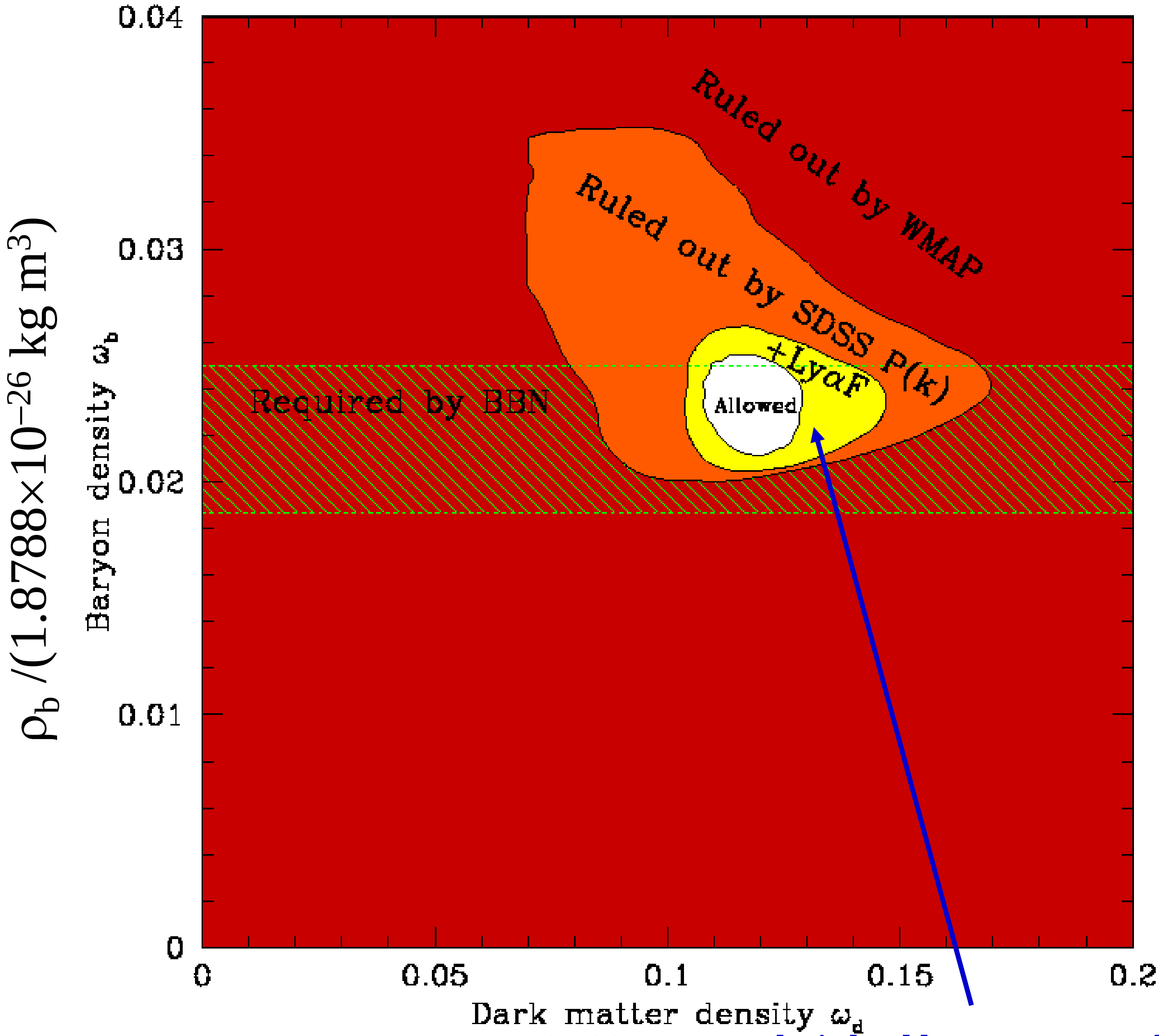


P(k)

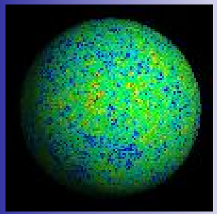
+



LyαF



SDSS LyaF analysis lead by Pat McDonald, Uros Seljak & co



CMB

	Using WMAP temperature and polarization information						No pol.
	$6\text{par}+\Omega_k+r+\alpha$	$6\text{par}+\Omega_k$	$6\text{par}+r$	$6\text{par}+f_\nu$	$6\text{par}+w$	6par	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 [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_ν [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

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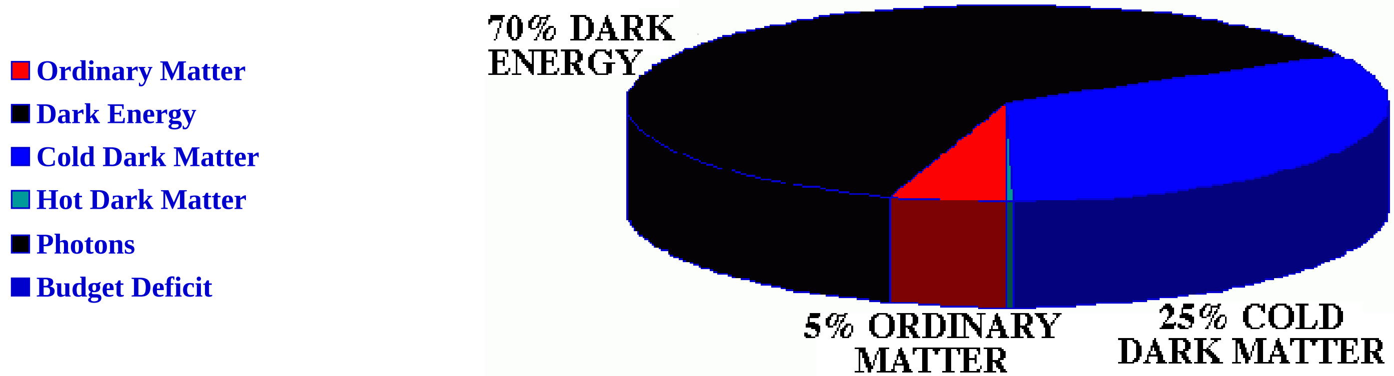
	Using SDSS + WMAP temperature and polarization information						No pol.	No WMAP
	6par+$\Omega_k+r+\alpha$	6par+Ω_k	6par+r	6par+f_ν	6par+w	6par	6par	6par
$e^{-2\tau}$	$0.53^{+0.22}_{-0.17}$	$0.69^{+0.15}_{-0.32}$	$0.776^{+0.098}_{-0.116}$	$0.776^{+0.095}_{-0.121}$	$0.80^{+0.10}_{-0.13}$	$0.780^{+0.094}_{-0.119}$	> 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]	$15.8^{+1.5}_{-1.8}$	$15.9^{+1.3}_{-1.5}$	$13.32^{+0.27}_{-0.33}$	$13.65^{+0.25}_{-0.28}$	$13.47^{+0.26}_{-0.27}$	$13.54^{+0.23}_{-0.27}$	$13.55^{+0.21}_{-0.23}$	$13.51^{+0.32}_{-0.31}$
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*
$\Omega_{\rm tot}$	$1.095^{+0.094}_{-0.144}$	$1.086^{+0.057}_{-0.128}$	$1.058^{+0.039}_{-0.041}$	$1.054^{+0.048}_{-0.041}$	$1.012^{+0.018}_{-0.022}$	*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[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_ν[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

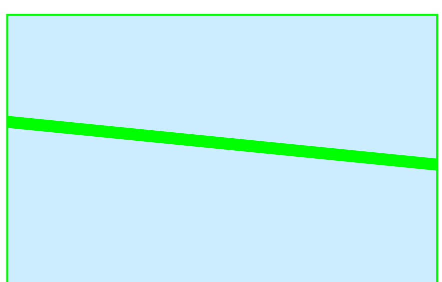
	Using SDSS + WMAP temperature and polarization information						No pol.	No WMAP
	6par+$\Omega_k+r+\alpha$	6par+Ω_k	6par+r	6par+f_ν	6par+w	6par	6par	6par
$e^{-2\tau}$	$0.53^{+0.22}_{-0.17}$	$0.69^{+0.15}_{-0.32}$	$0.776^{+0.098}_{-0.116}$	$0.776^{+0.095}_{-0.121}$	$0.80^{+0.10}_{-0.13}$	$0.780^{+0.094}_{-0.119}$	> 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]	$15.8^{+1.5}_{-1.8}$	$15.9^{+1.3}_{-1.5}$	$13.32^{+0.27}_{-0.33}$	$13.65^{+0.25}_{-0.28}$	$13.47^{+0.26}_{-0.27}$	$13.54^{+0.23}_{-0.27}$	$13.55^{+0.21}_{-0.23}$	$13.51^{+0.32}_{-0.31}$
σ_8	$0.91^{+0.11}_{-0.10}$	$0.86^{+0.13}_{-0.11}$	$0.919^{+0.086}_{-0.073}$	$0.823^{+0.098}_{-0.077}$	$0.928^{+0.084}_{-0.076}$	$0.917^{+0.090}_{-0.072}$	$0.879^{+0.088}_{-0.082}$	$0.842^{+0.069}_{-0.053}$
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



p	Meaning	Measured value
$\Omega_{\rm tot}$	Spatial curvature	1.01 ± 0.02
ρ_Λ	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124} m_{\rm Pl}^4$
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 $dn_s/d\ln k$	$\lvert\alpha\rvert \lesssim 0.01$
r	Tensor-to-scalar ratio $(\delta_H^T/\delta_H)^2$	$\lesssim 0.36$
n_t	Tensor spectral index	Unconstrained
$\xi_{\rm b}$	Baryon mass per photon $\rho_{\rm b}/n_\gamma = m_{\rm p}\eta$	(0.60 ± 0.03) eV
$\xi_{\rm c}$	CDM mass per photon $\rho_{\rm c}/n_\gamma$	(3.3 ± 0.2) eV
ξ_ν	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11}\sum m_{\nu_i}$	< 0.11 eV

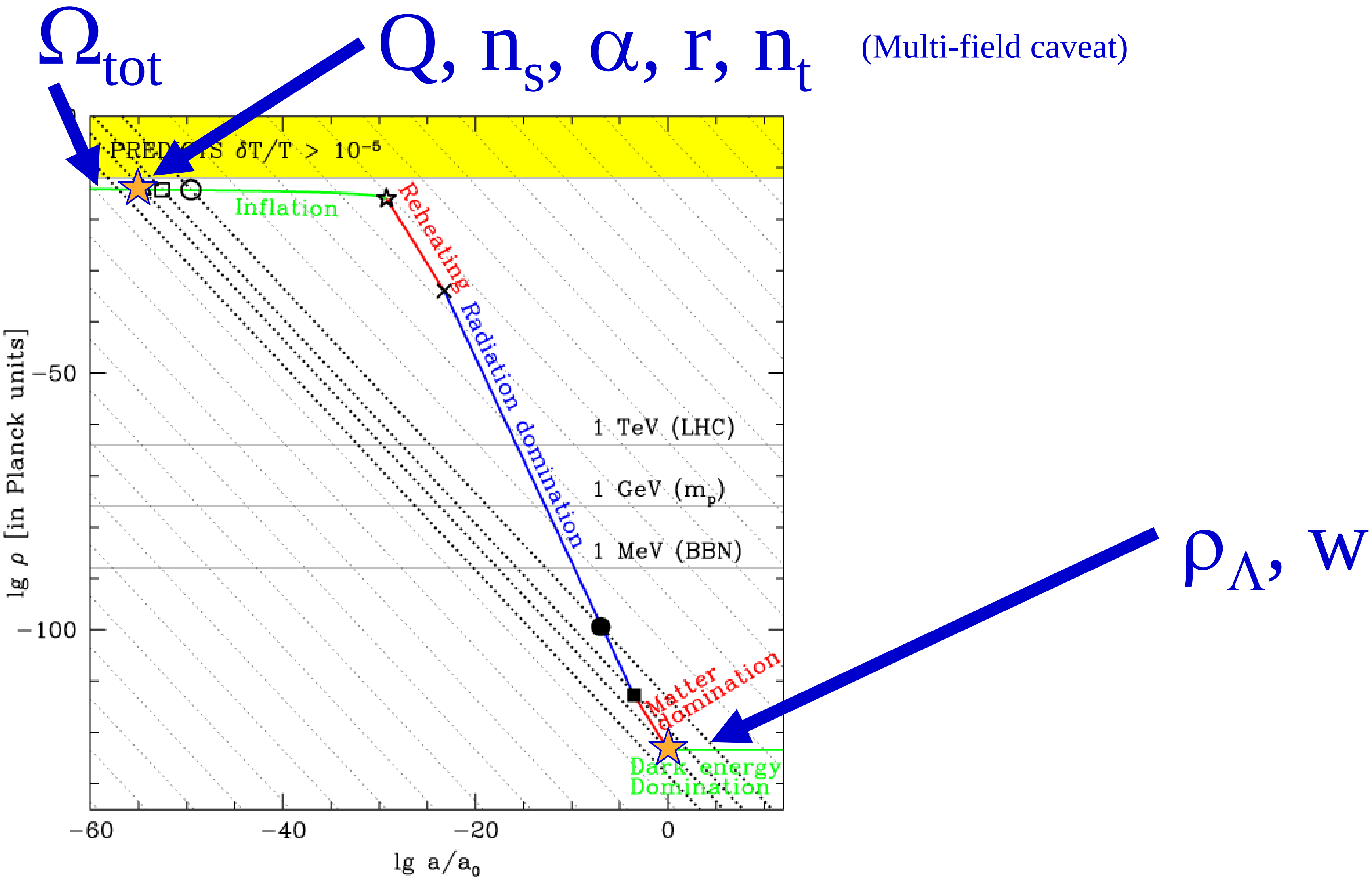
INITIAL CONDITIONS



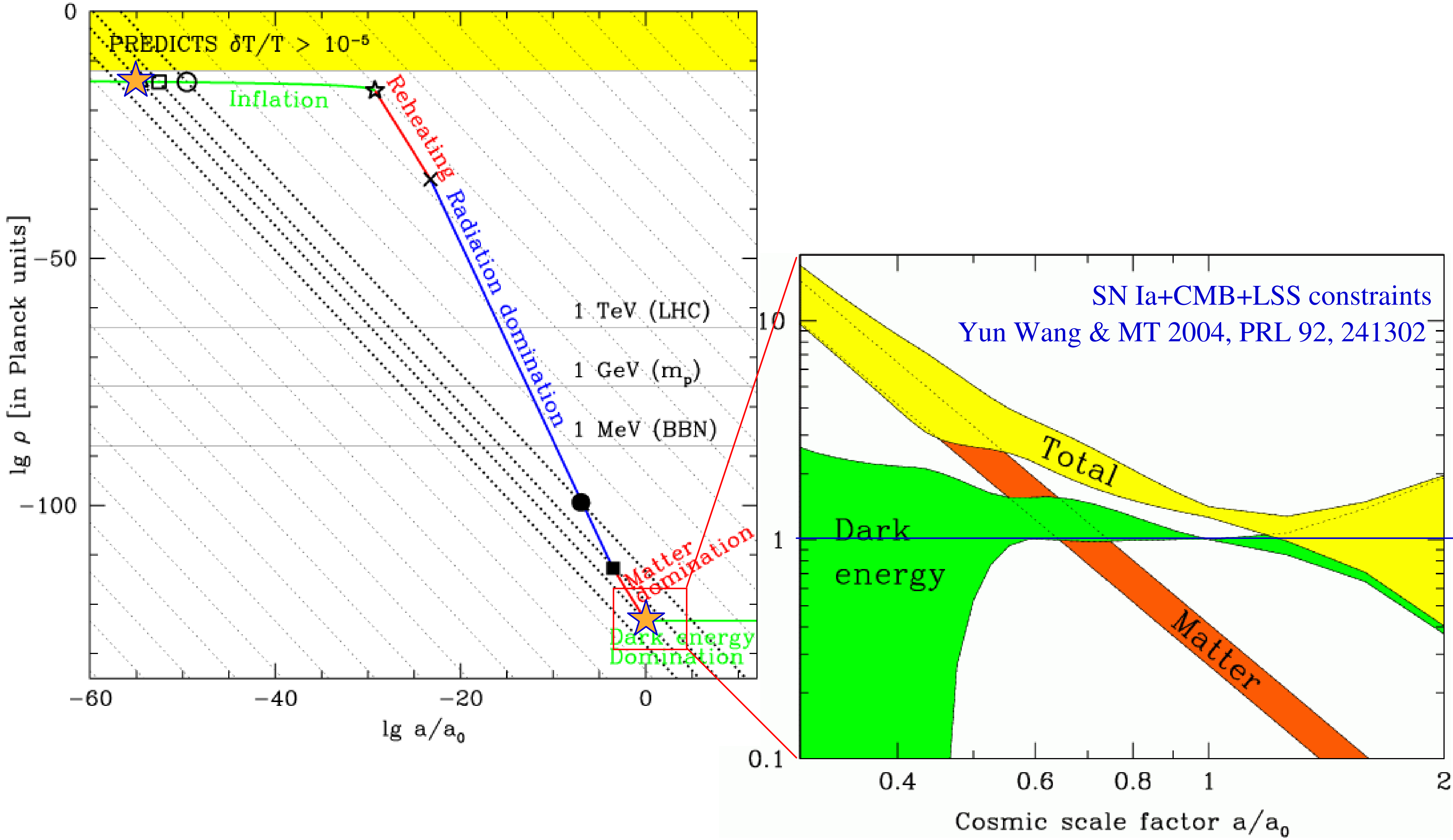
	p	Meaning	Measured value
	$\Omega_{\rm tot}$	Spatial curvature	1.01 ± 0.02
	ρ_Λ	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124} m_{\rm Pl}^4$
	w	Dark energy equation of state	-1 ± 0.1
Inflation!	δ_H	Scalar fluctuation amplitude (Q)	$(2.0 \pm 0.2) \times 10^{-5}$
	n_s	Scalar spectral index	0.98 ± 0.02
	α	Running of spectral index $dn_s/d\ln k$	$\lvert\alpha\rvert \lesssim 0.01$
	r	Tensor-to-scalar ratio $(\delta_H^T/\delta_H)^2$	$\lesssim 0.36$
	n_t	Tensor spectral index	Unconstrained
Baryogenesis	$\xi_{\rm b}$	Baryon mass per photon $\rho_{\rm b}/n_\gamma = m_{\rm p}\eta$	(0.60 ± 0.03) eV
SUSY?	$\xi_{\rm c}$	CDM mass per photon $\rho_{\rm c}/n_\gamma$	(3.3 ± 0.2) eV
ν-physics	ξ_ν	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11}\sum m_{\nu_i}$	< 0.11 eV

WHY?

How inflation predicts these parameters



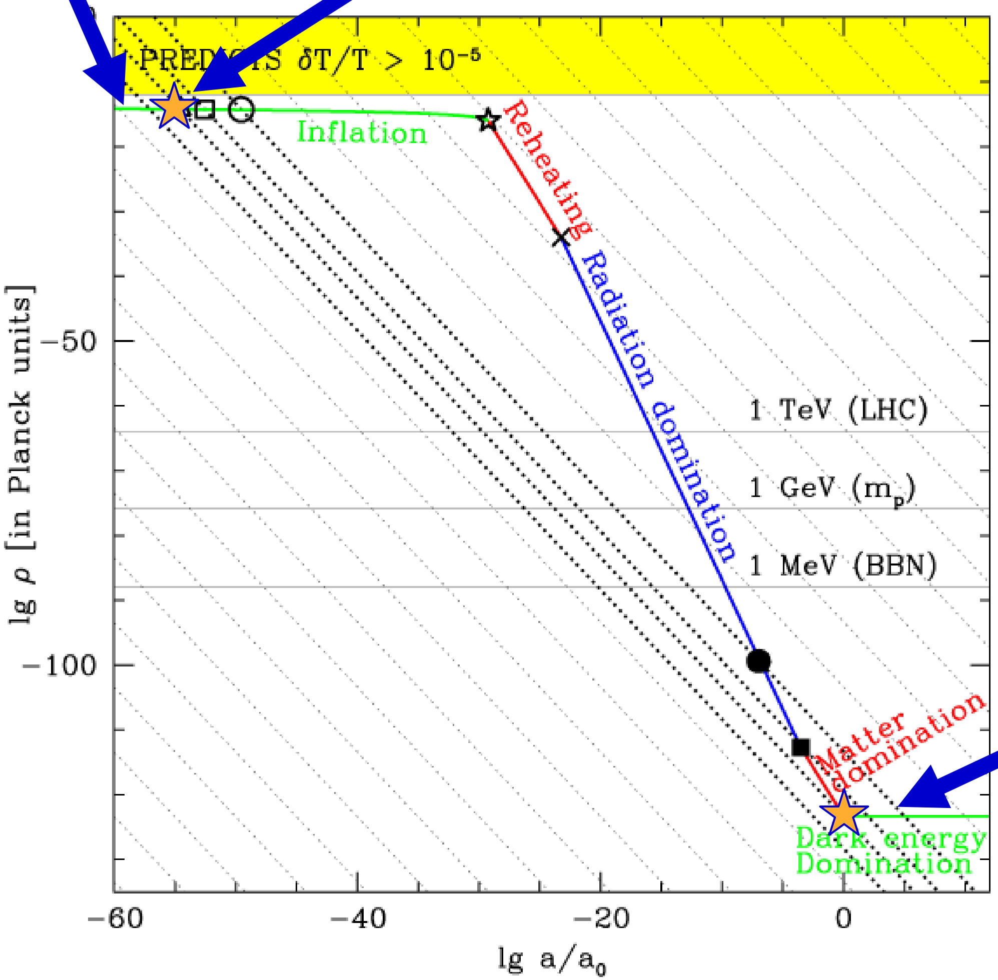
Ω_{tot}
Q, n_s, α, r, n_t
(Multi-field caveat)
ρ_Λ, w
PREDICTS $\delta T/T > 10^{-5}$
Inflation
Reheating
Radiation domination
Matter domination
Dark energy Domination
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
lg ρ [in Planck units]
lg a/a_0
−50
−100
−60
−40
−20
0



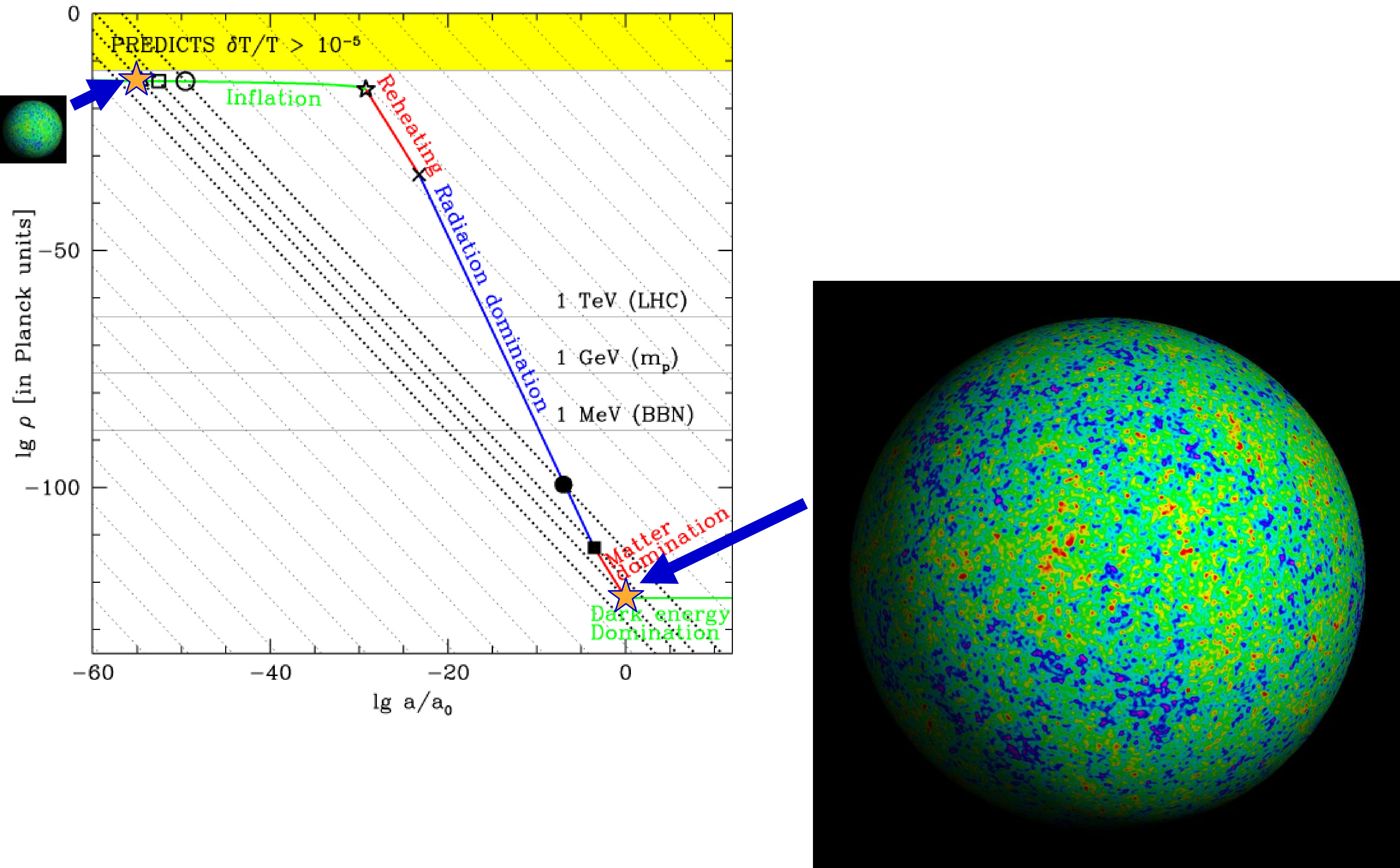
PREDICTS δT/T > 10⁻⁵
Inflation
Reheating
Radiation domination
1 TeV (LHC)
1 GeV (mp)
1 MeV (BBN)
Matter domination
Dark energy Domination
lg ρ [in Planck units]
lg a/a0
0
−50
−100
−60
−40
−20
0
SN Ia+CMB+LSS constraints
Yun Wang & MT 2004, PRL 92, 241302
Total
Dark energy
Matter
10
1
0.1
0.4
0.6
0.8
1
2
Cosmic scale factor a/a0

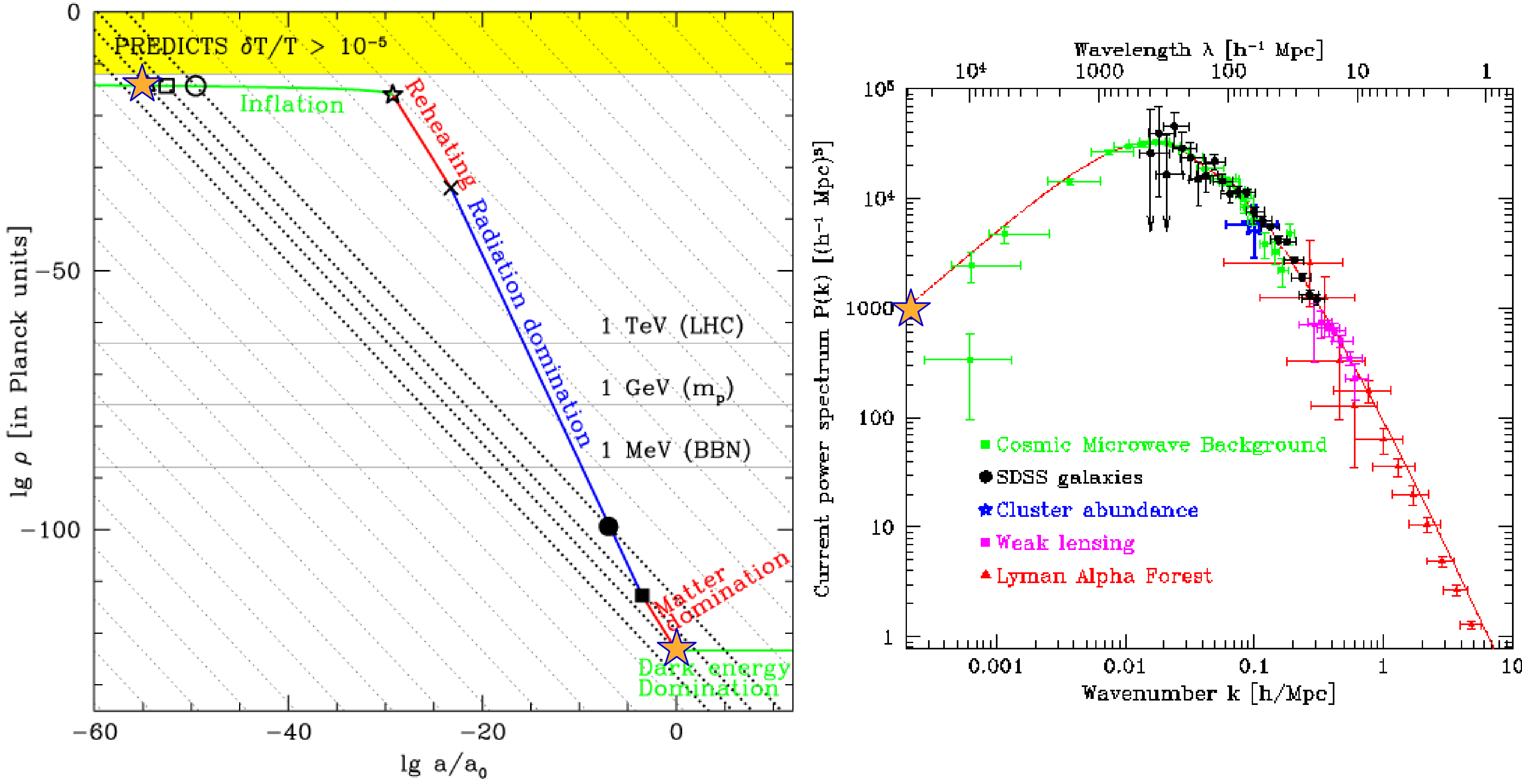
Ω_{tot}

Q, n_s, α, r, n_t (Multi-field caveat)

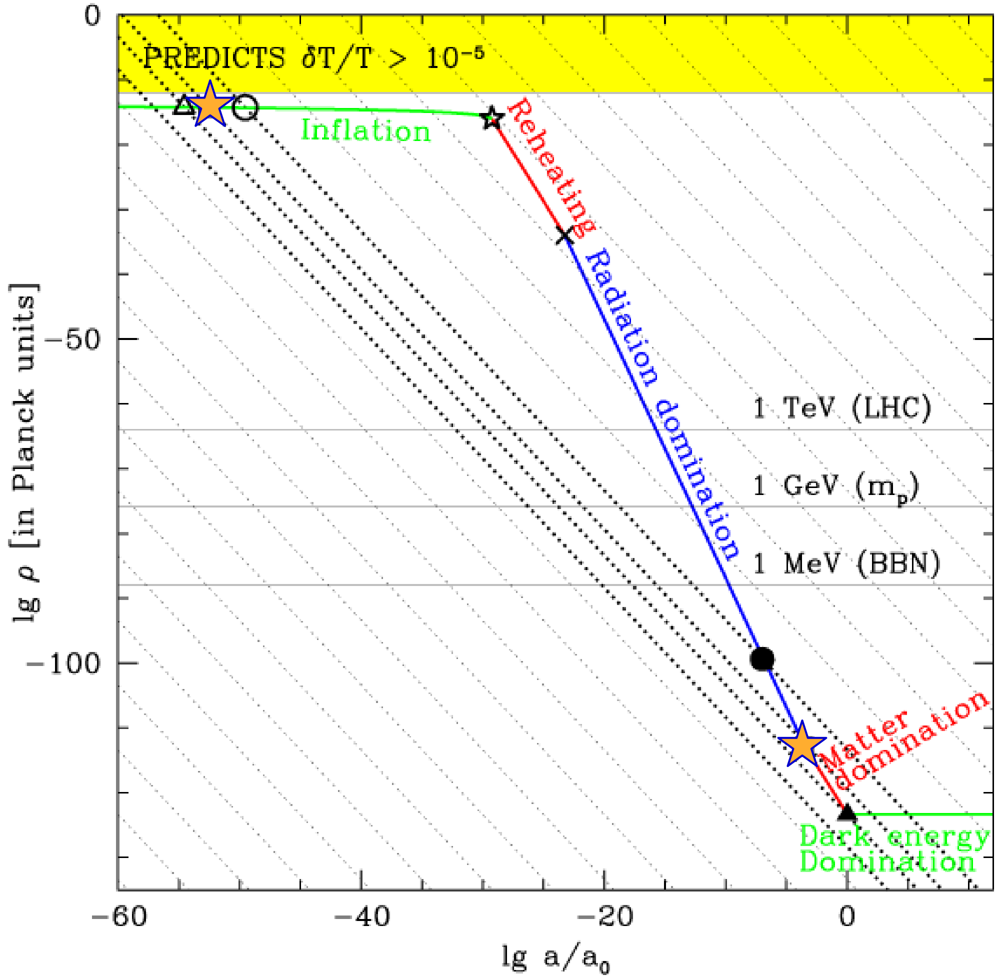


ρ_Λ, w

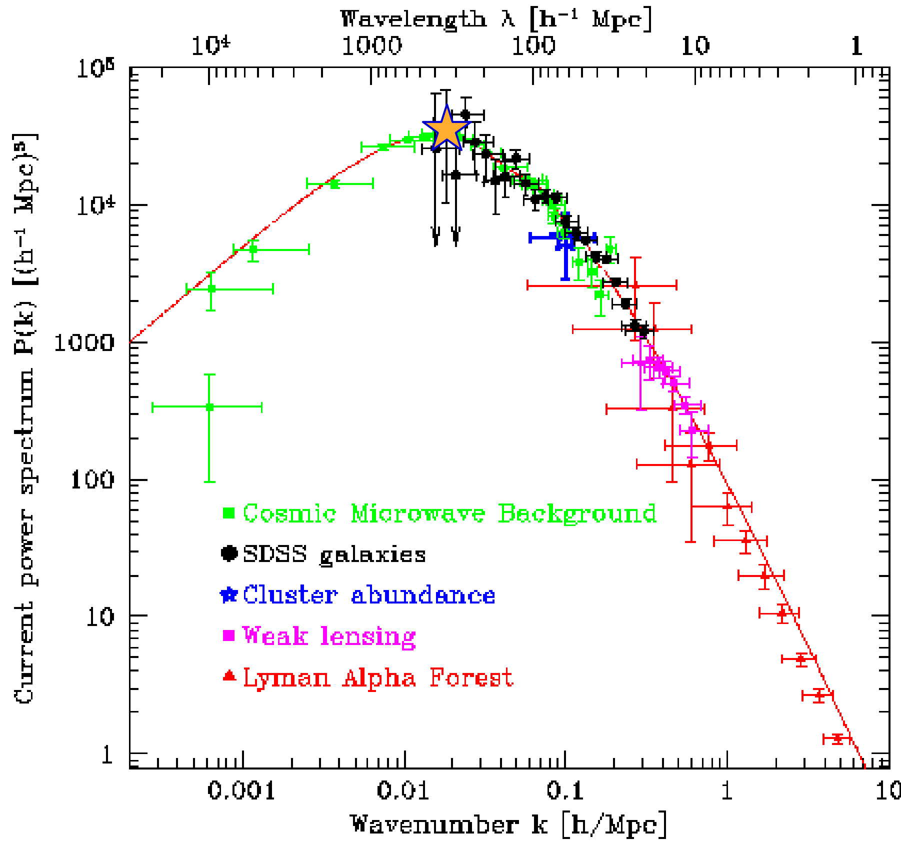

PREDICTS δT/T > 10⁻⁵
Inflation
Reheating
Radiation domination
Matter domination
Dark energy Domination
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
lg ρ [in Planck units]
lg a/a₀
0
−50
−100
−60
−40
−20
0



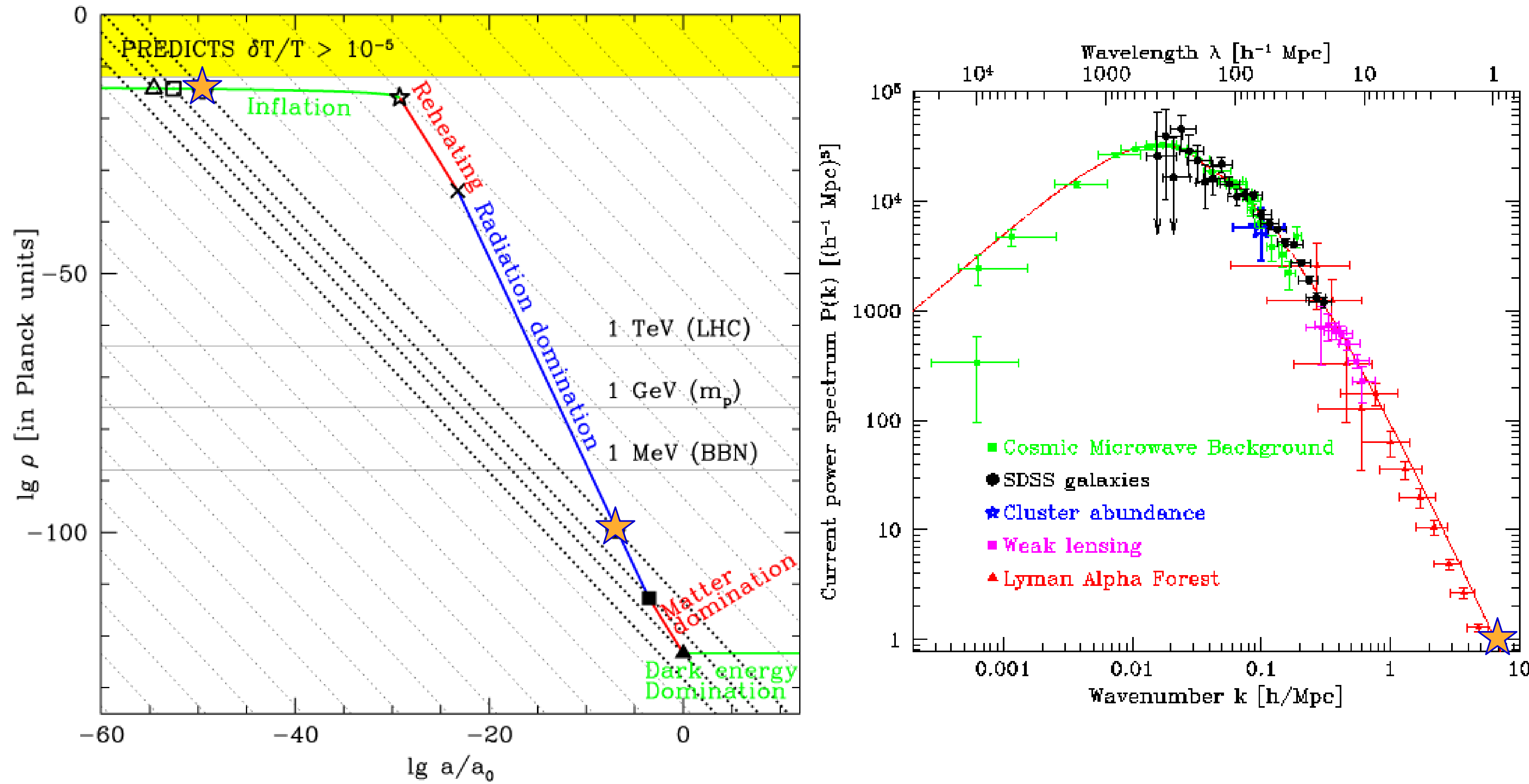
PREDICTS δT/T > 10⁻⁵
Inflation
Reheating
Radiation domination
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
Matter domination
Dark energy Domination
lg ρ [in Planck units]
lg a/a₀
Wavelength λ [h⁻¹ Mpc]
Current power spectrum P(k) [(h⁻¹ Mpc)³]
Wavenumber k [h/Mpc]
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest



PREDICTS δT/T > 10⁻⁵
Inflation
Reheating
Radiation domination
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
Matter domination
Dark energy Domination
lg ρ [in Planck units]
lg a/a₀

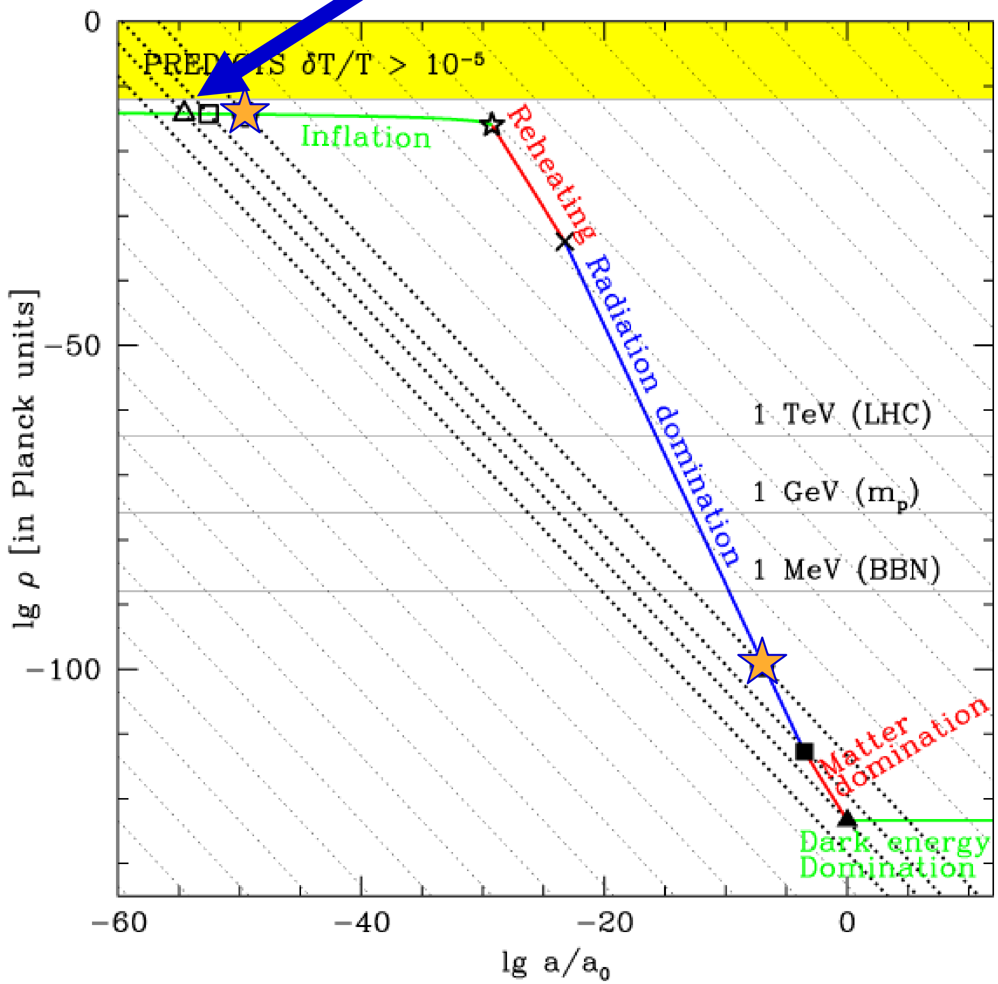


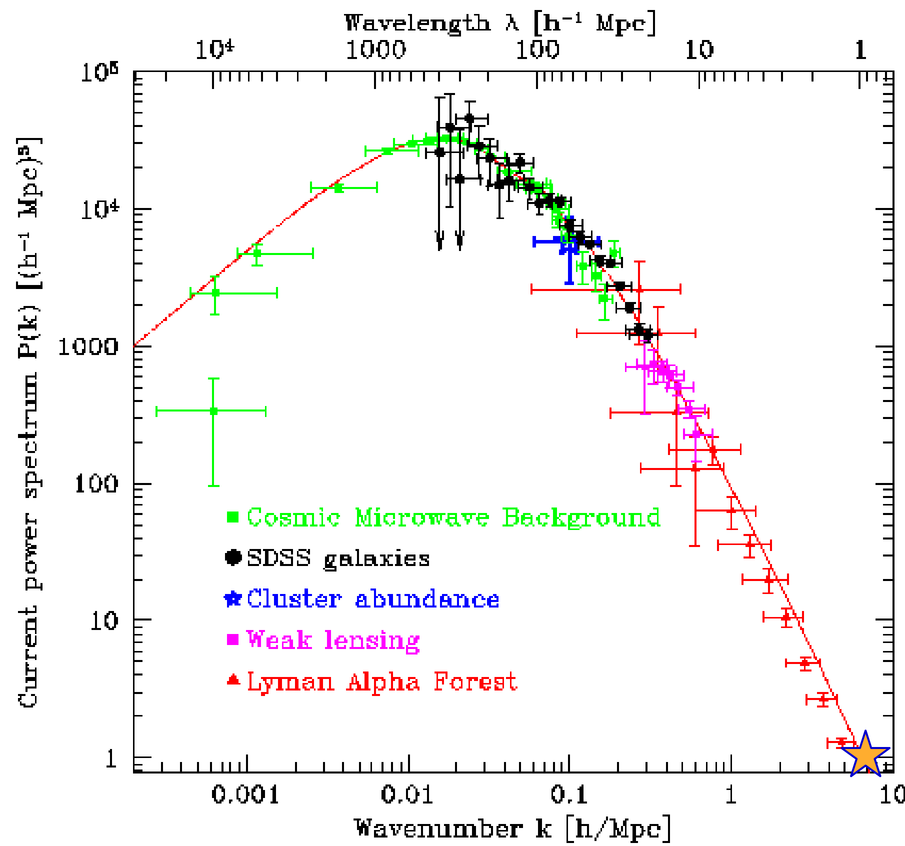
Wavelength λ [h⁻¹ Mpc]
Current power spectrum P(k) [(h⁻¹ Mpc)³]
Wavenumber k [h/Mpc]
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest

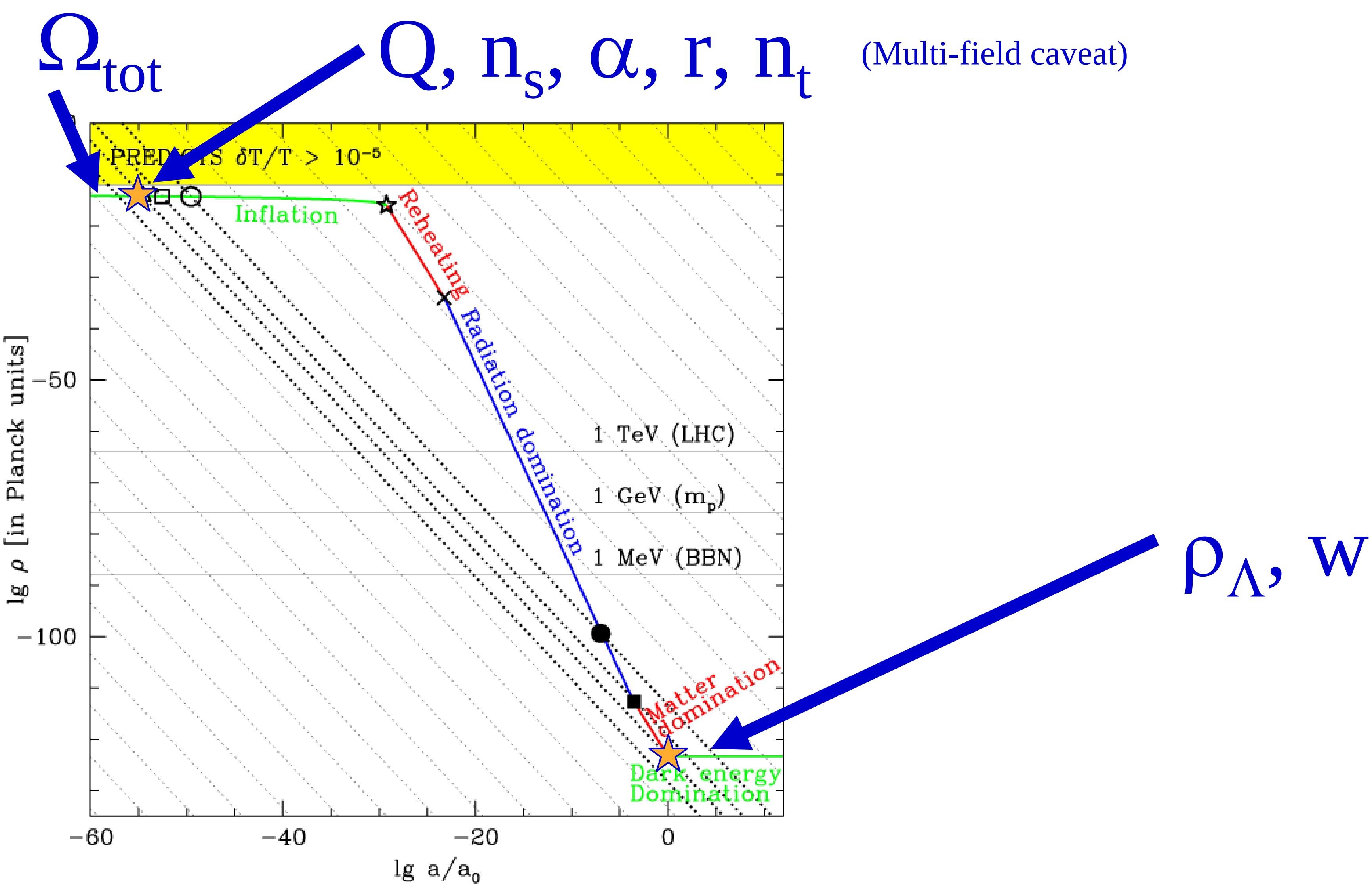


PREDICTS δT/T > 10⁻⁵
Inflation
Reheating
Radiation domination
Matter domination
Dark energy Domination
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
lg ρ [in Planck units]
lg a/a₀
Wavelength λ [h⁻¹ Mpc]
Current power spectrum P(k) [(h⁻¹ Mpc)³]
Wavenumber k [h/Mpc]
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest

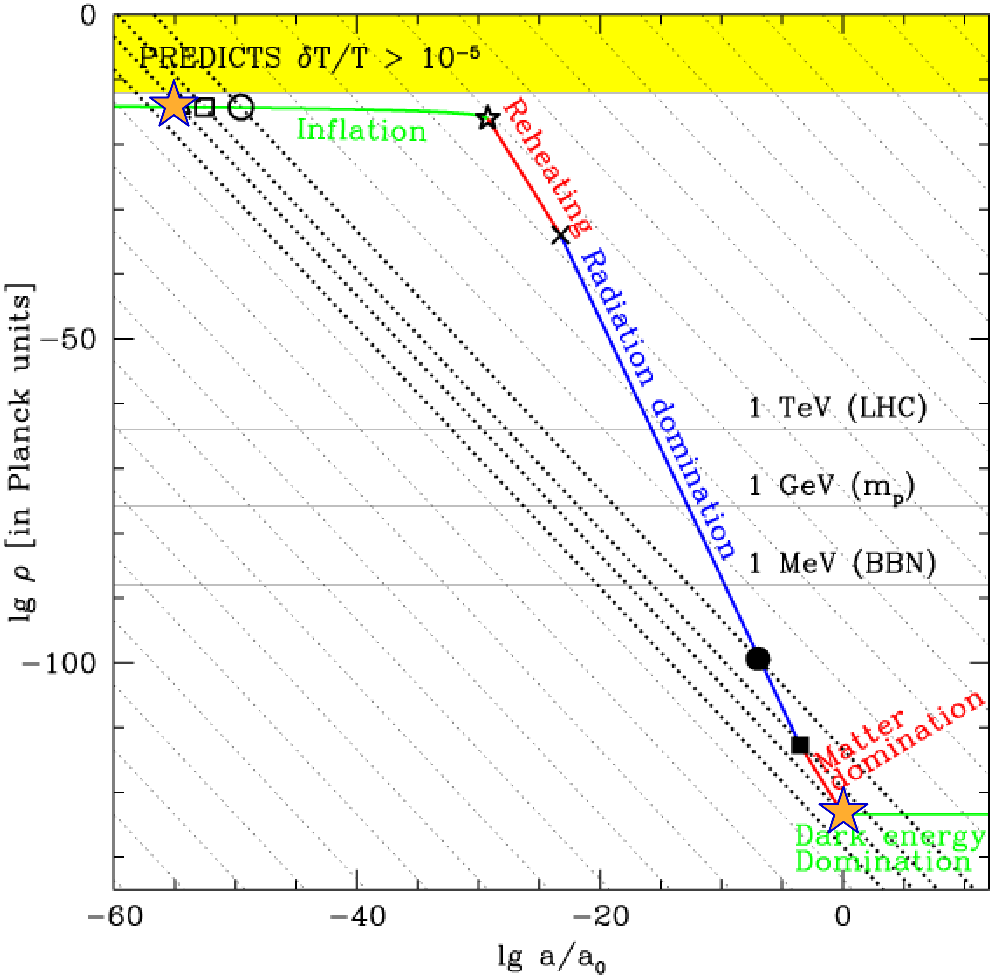
Q, n_s, α, r, n_t







Ω_{tot}
$Q,\ n_s,\ \alpha,\ r,\ n_t$
(Multi-field caveat)
$\rho_\Lambda,\ w$
PRED TS $\delta T/T > 10^{-5}$
Inflation
Reheating
Radiation domination
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
Matter domination
Dark energy Domination
−50
−100
−60
−40
−20
0
lg ρ [in Planck units]
lg a/a_0



PREDICTS $\delta T/T > 10^{-5}$
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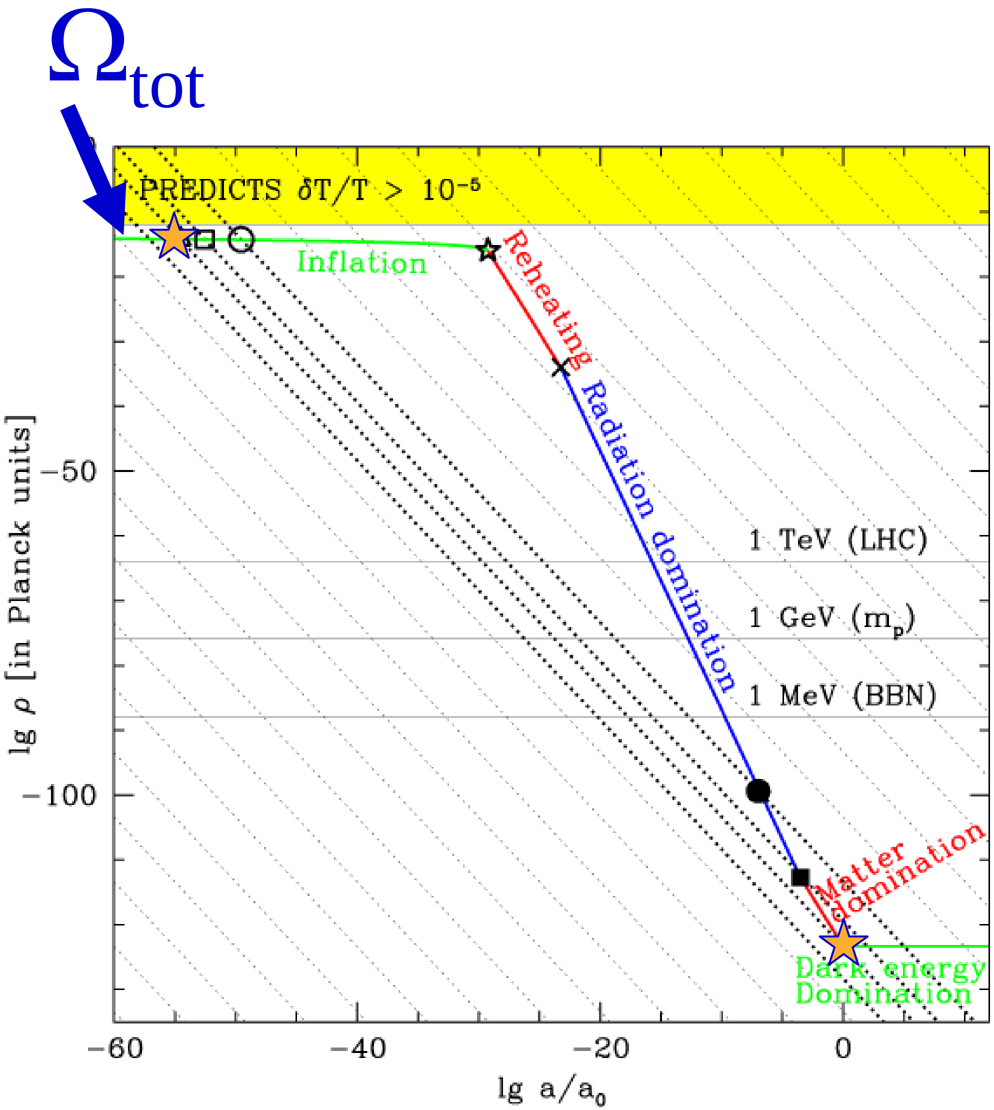

Ω_tot
PREDICTS δT/T > 10^-5
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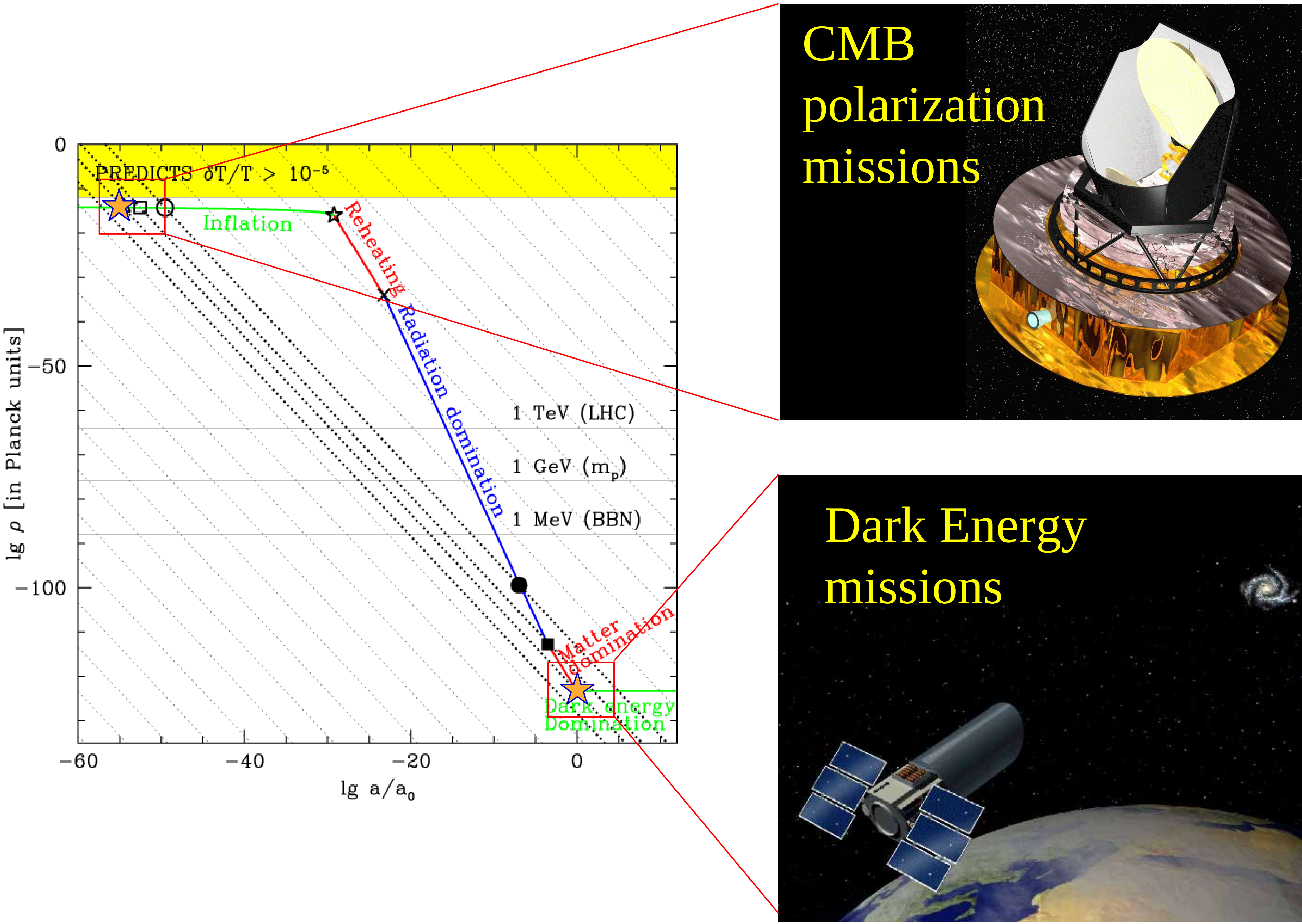

CMB
polarization
missions
Dark Energy
missions
PREDICTS δT/T > 10^-5
Inflation
Reheating
Radiation domination
Matter domination
Dark energy
Domination
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
lg ρ [in Planck units]
lg a/a_0
0
−50
−100
−60
−40
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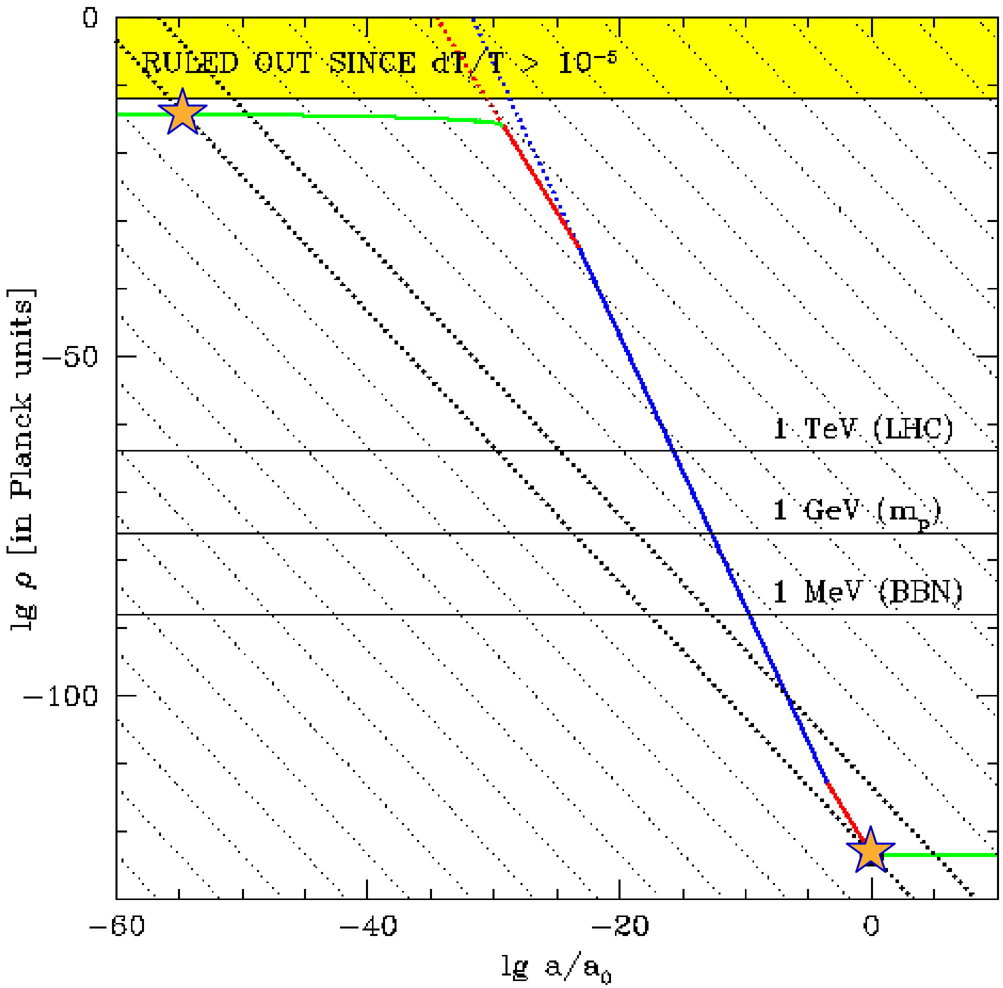
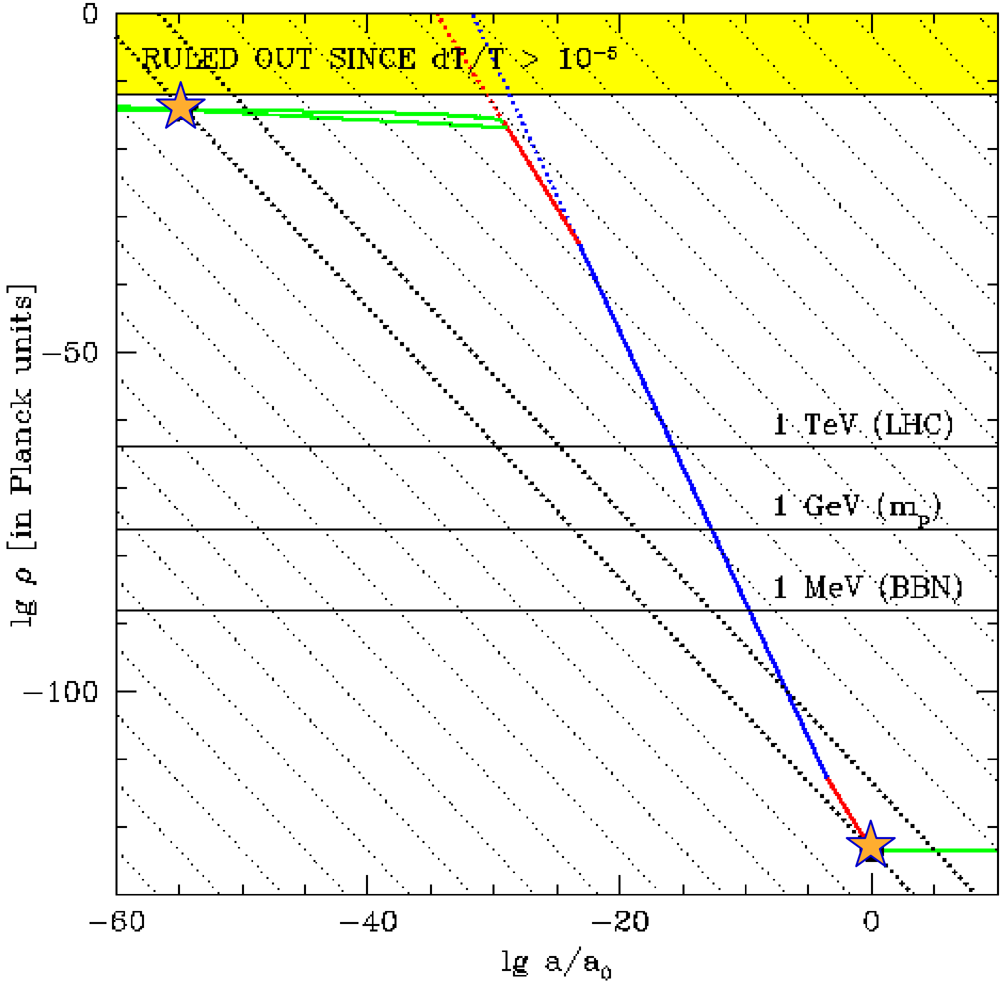
0

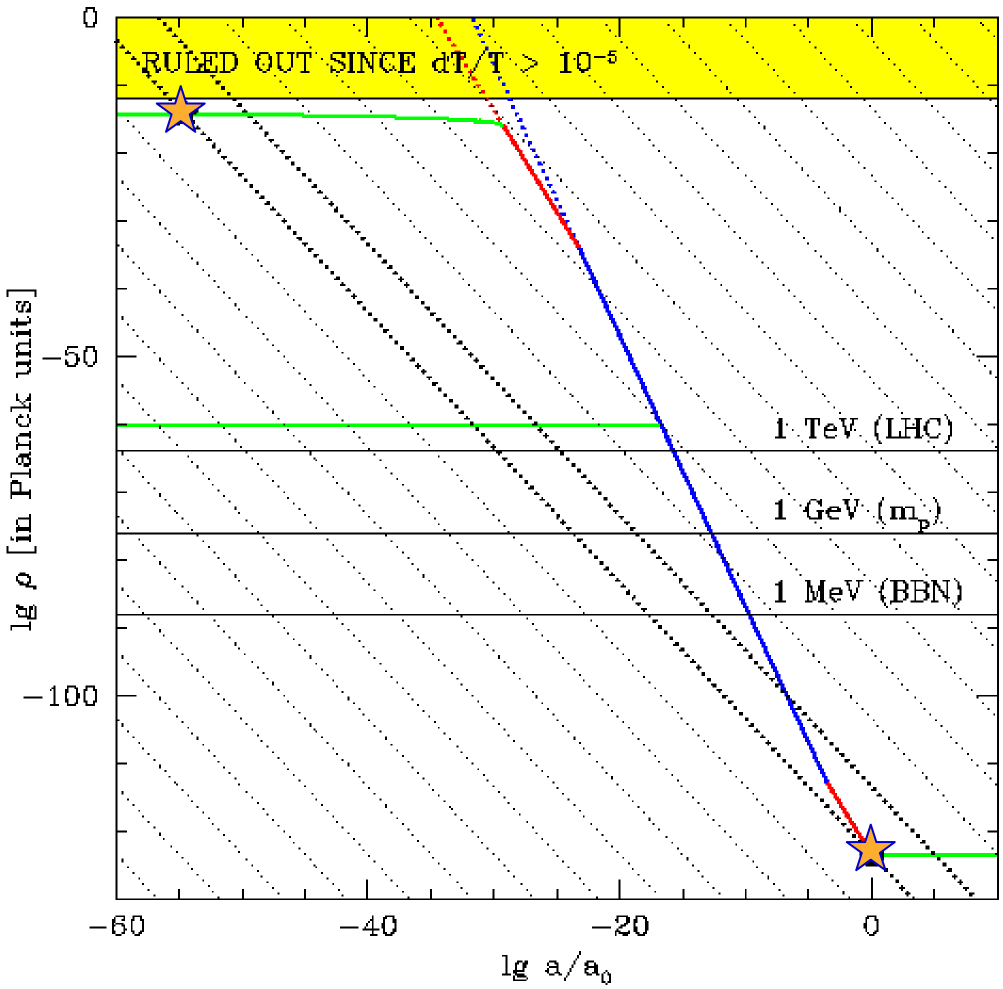
What does inflation really predict?



RULED OUT SINCE dT/T > 10^-5
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
lg ρ [in Planck units]
lg a/a_0
0
−50
−100
−60
−40
−20
0

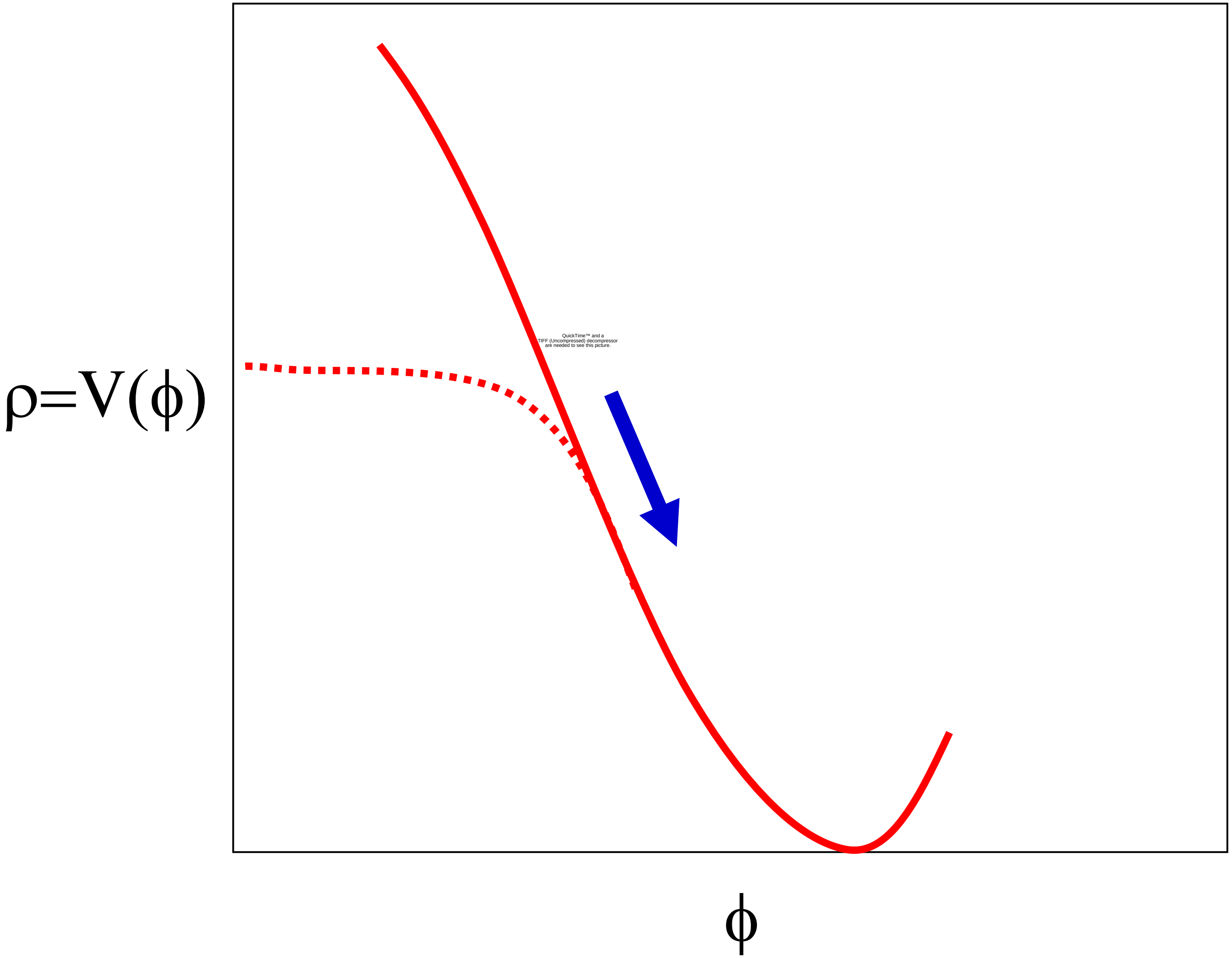


RULED OUT SINCE dT/T > 10⁻⁵
1 TeV (LHC)
1 GeV (m_p)
1 MeV (BBN)
lg ρ [in Planck units]
lg a/a₀
0
−50
−100
−60
−40
−20
0



What’s the physics?

Traditional view: *the* inflaton potential



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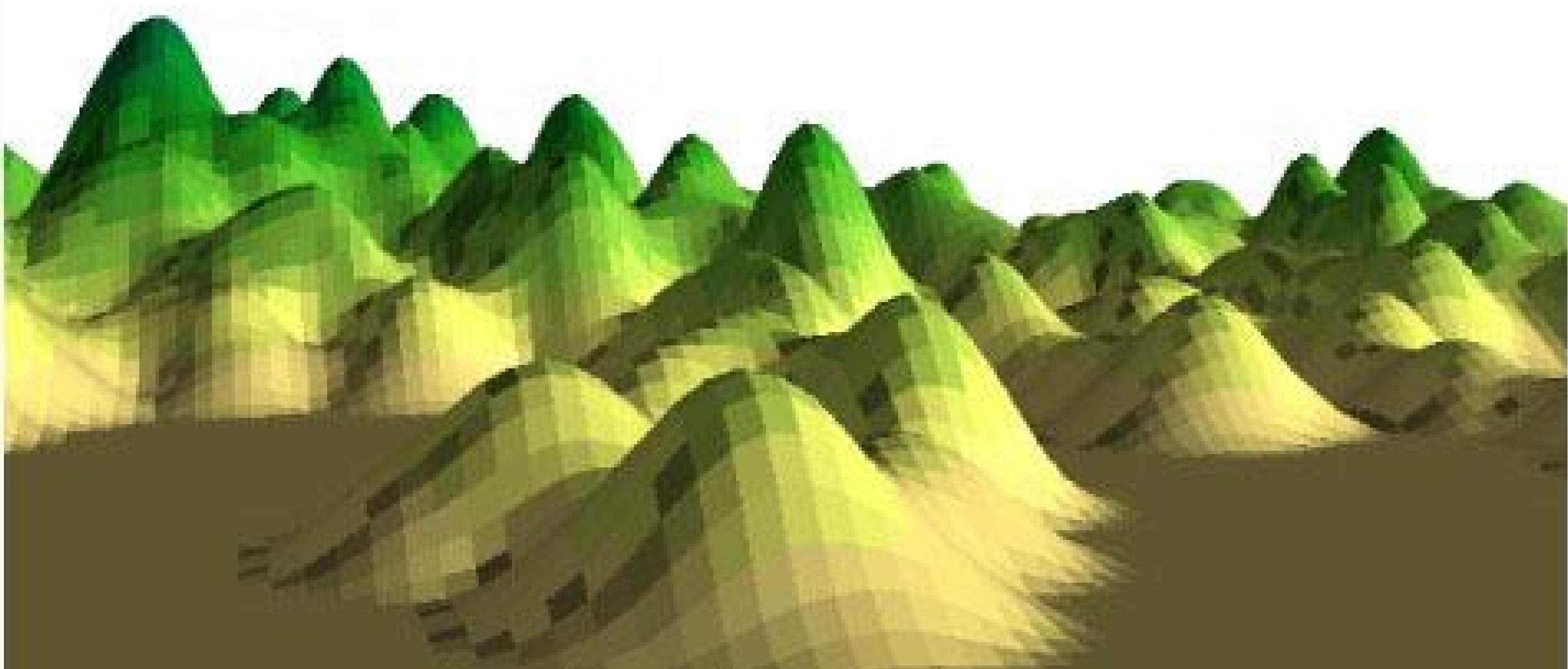
Landscape view: many non-equivalent minima



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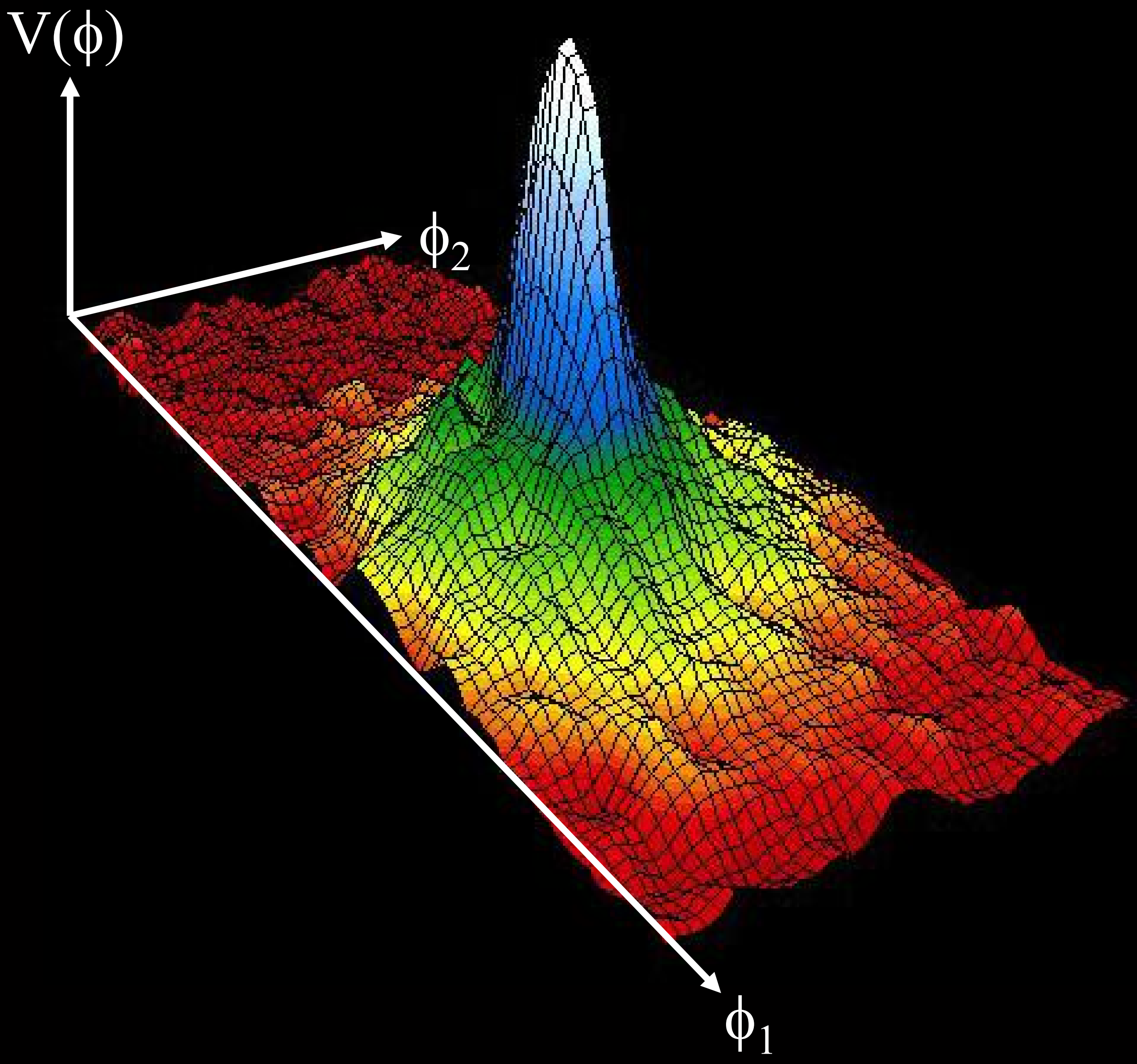

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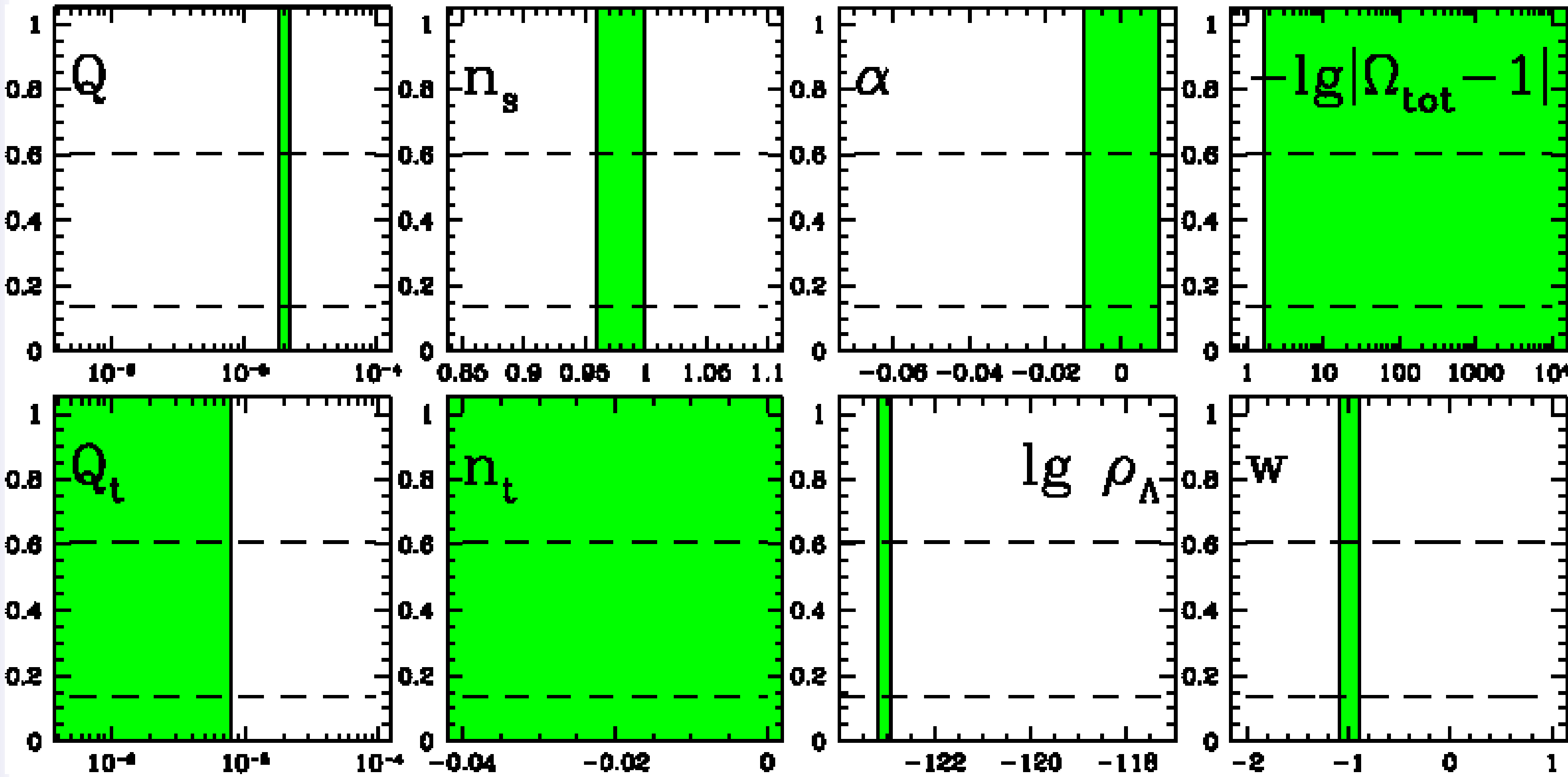

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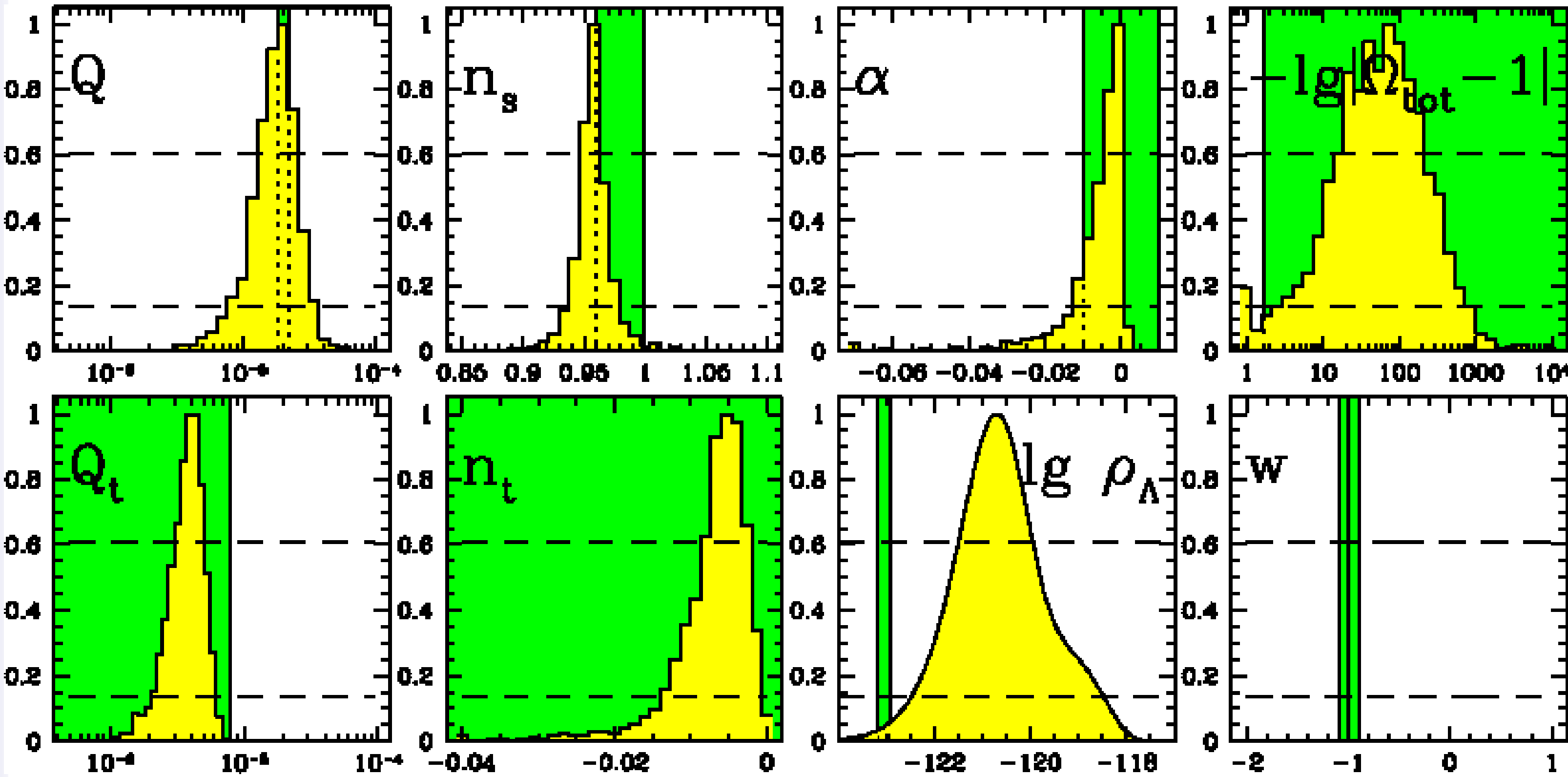
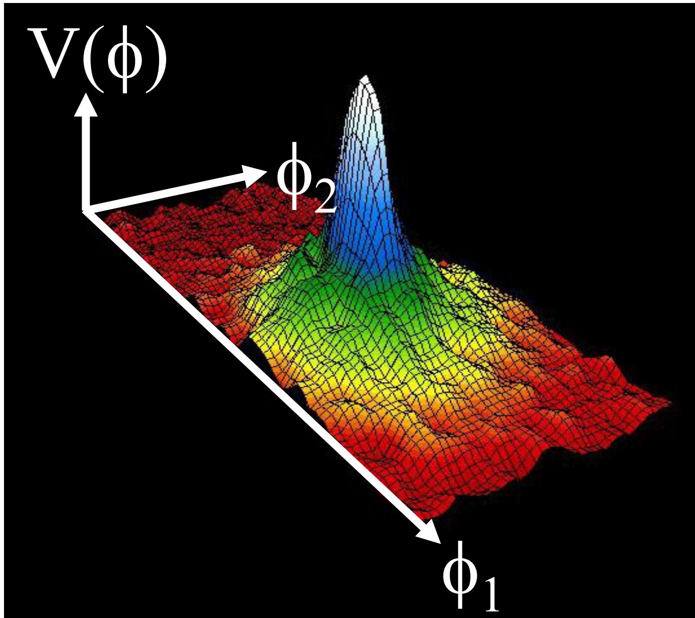


Testable?

(Compare QM)



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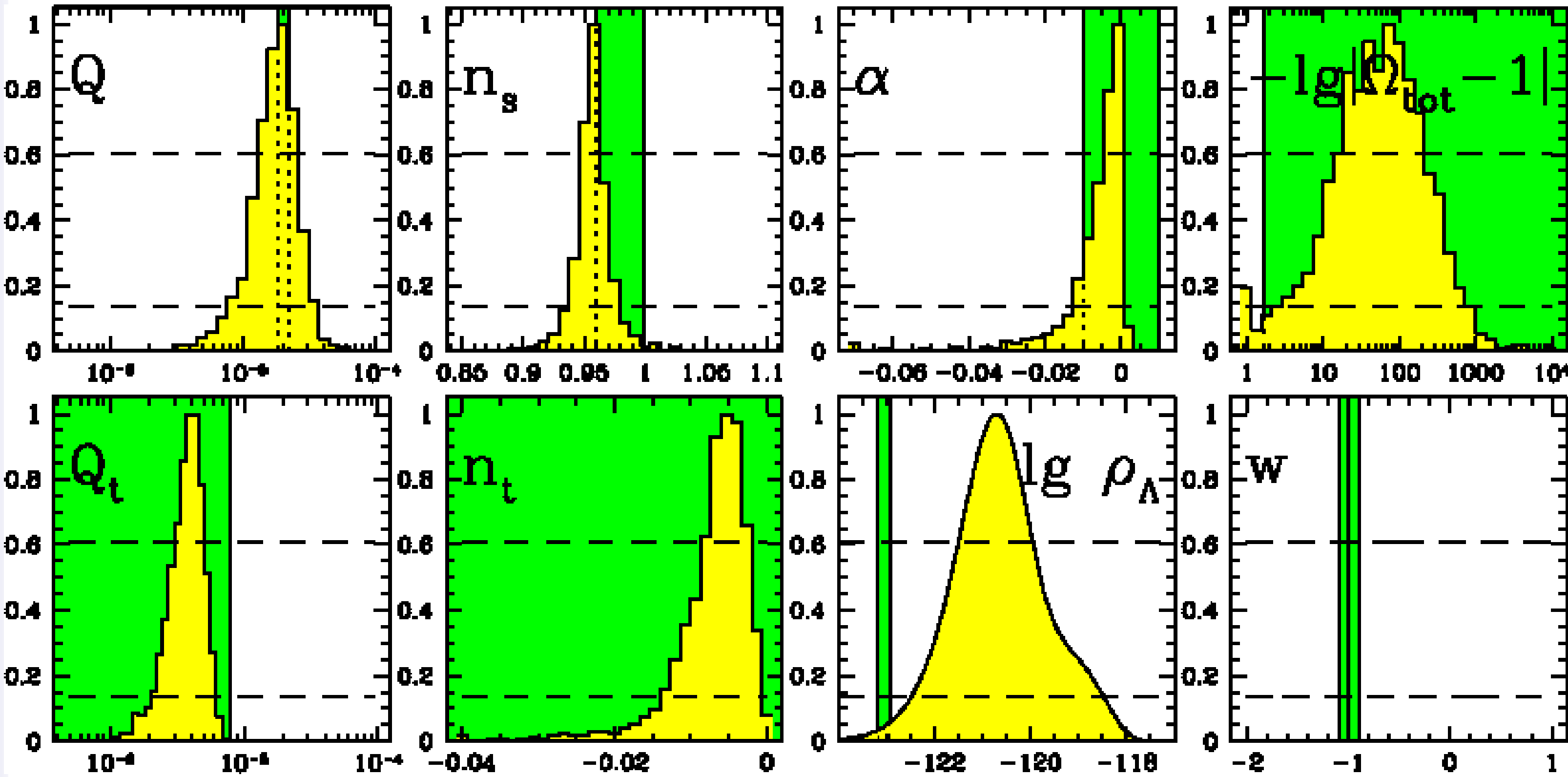
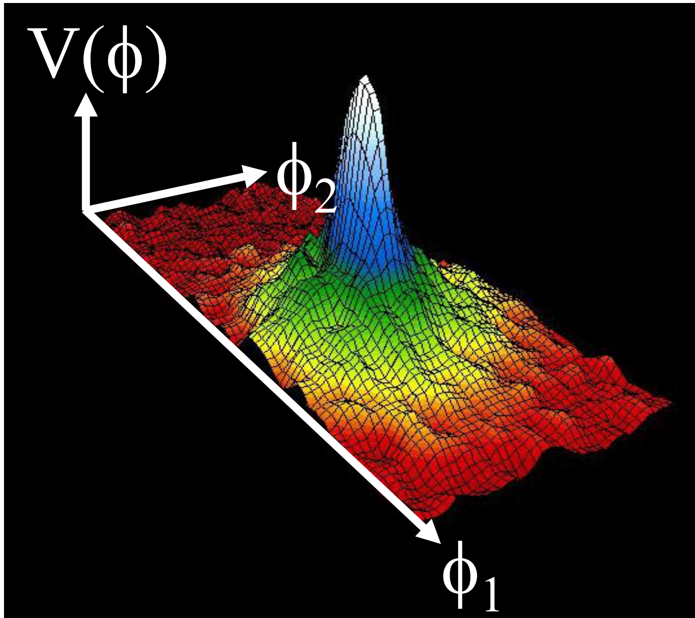


What features of V(ϕ) determine these predictions?



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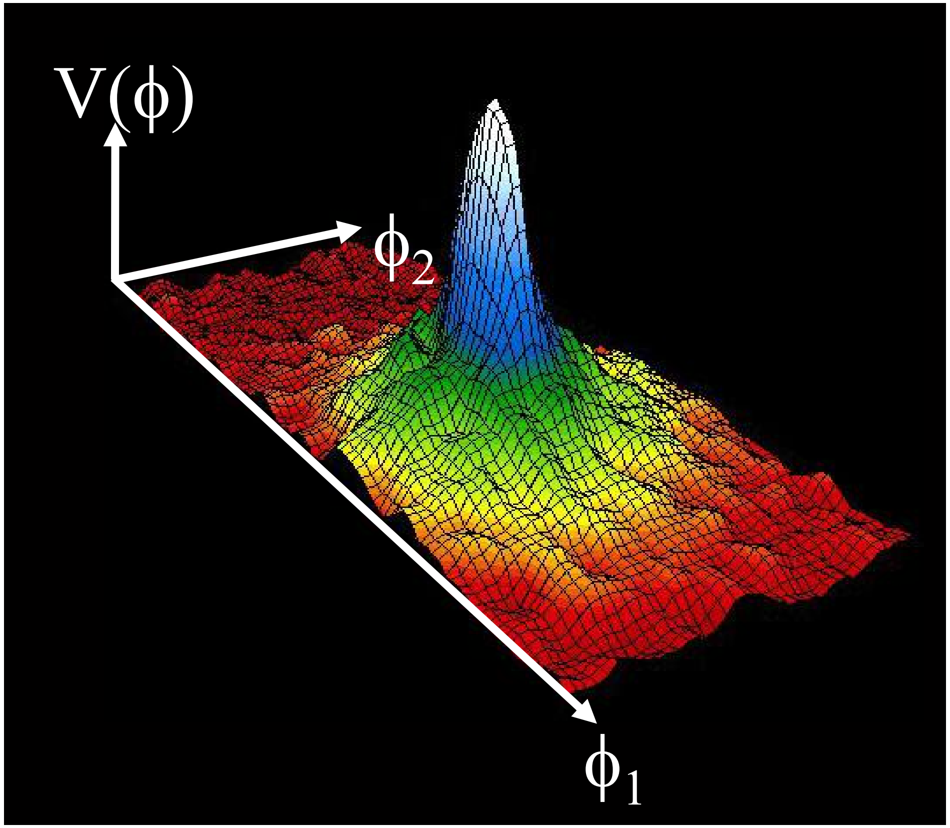
NUMERICAL EXPERIMENT:

* $V(\phi) = m_v^4 f(\phi/m_h)$
* m_h and m_v set horizontal and vertical scale of potential
* f is a dimensionless random function of one variable
* Make 10^{10} random potentials
* Weigh by matter fraction gravitationally bound in stable halos (requires expansion factor $>e^{55}$, rewards high Q, low $|\rho_\Lambda|$)



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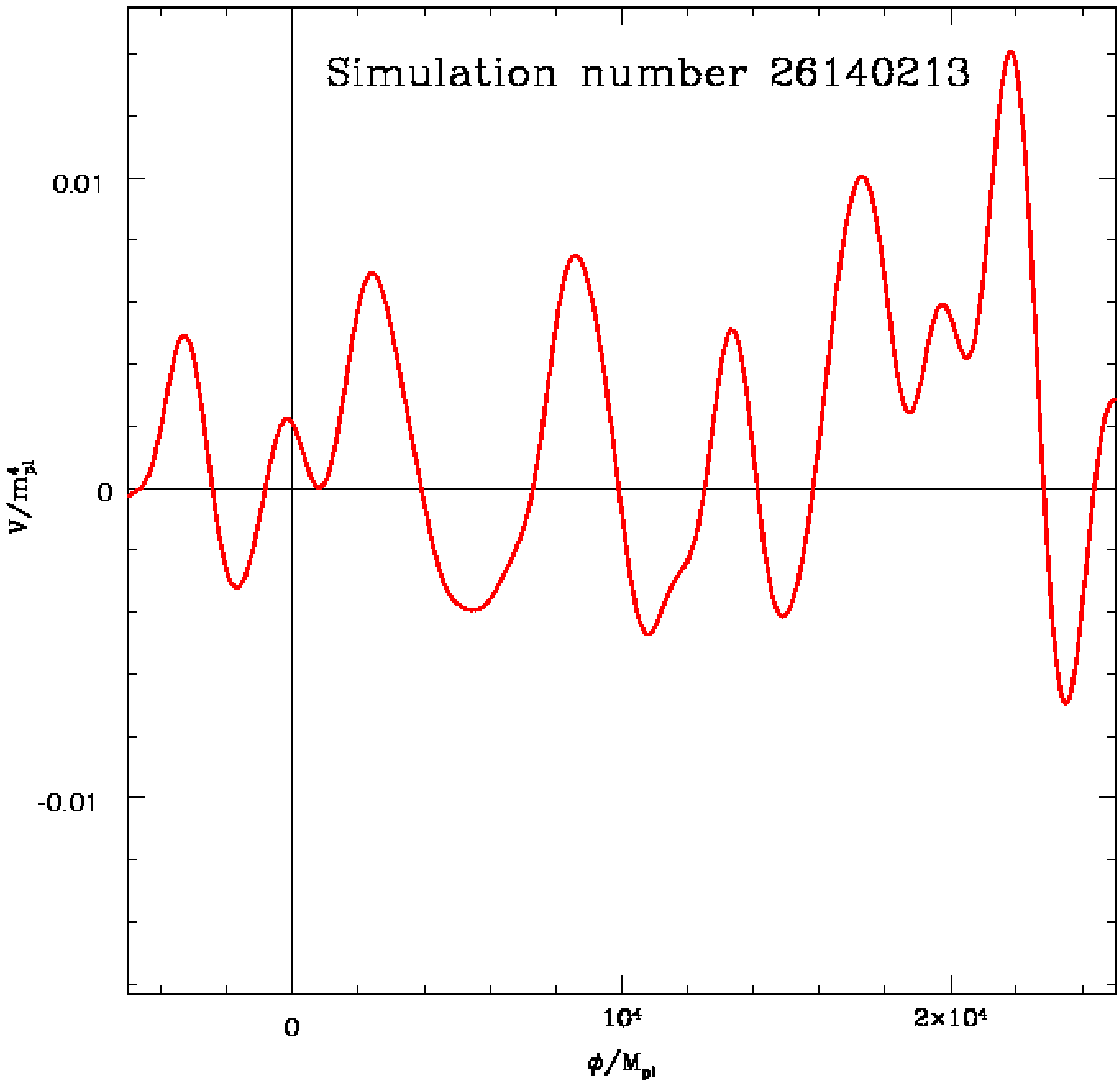

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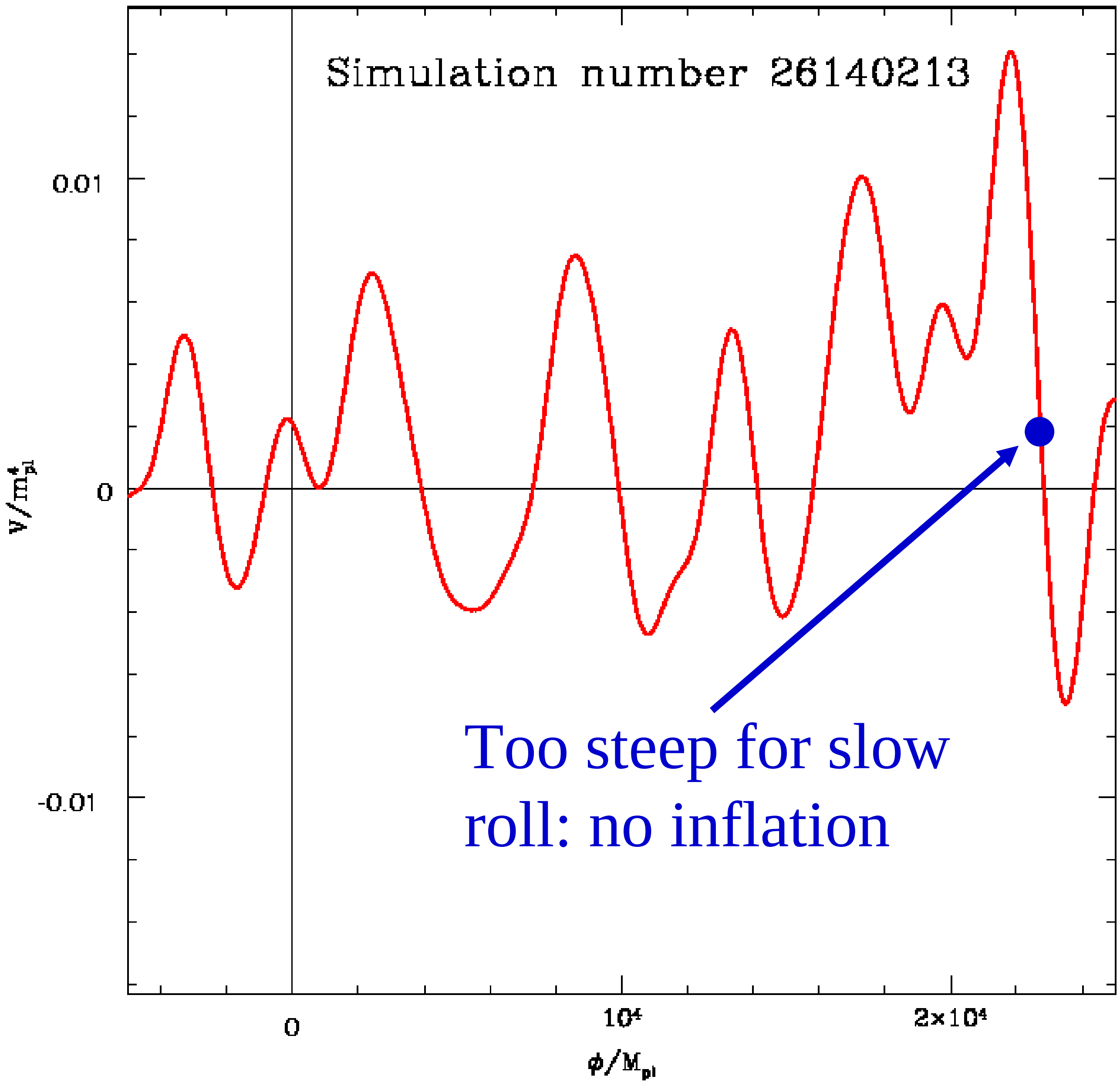

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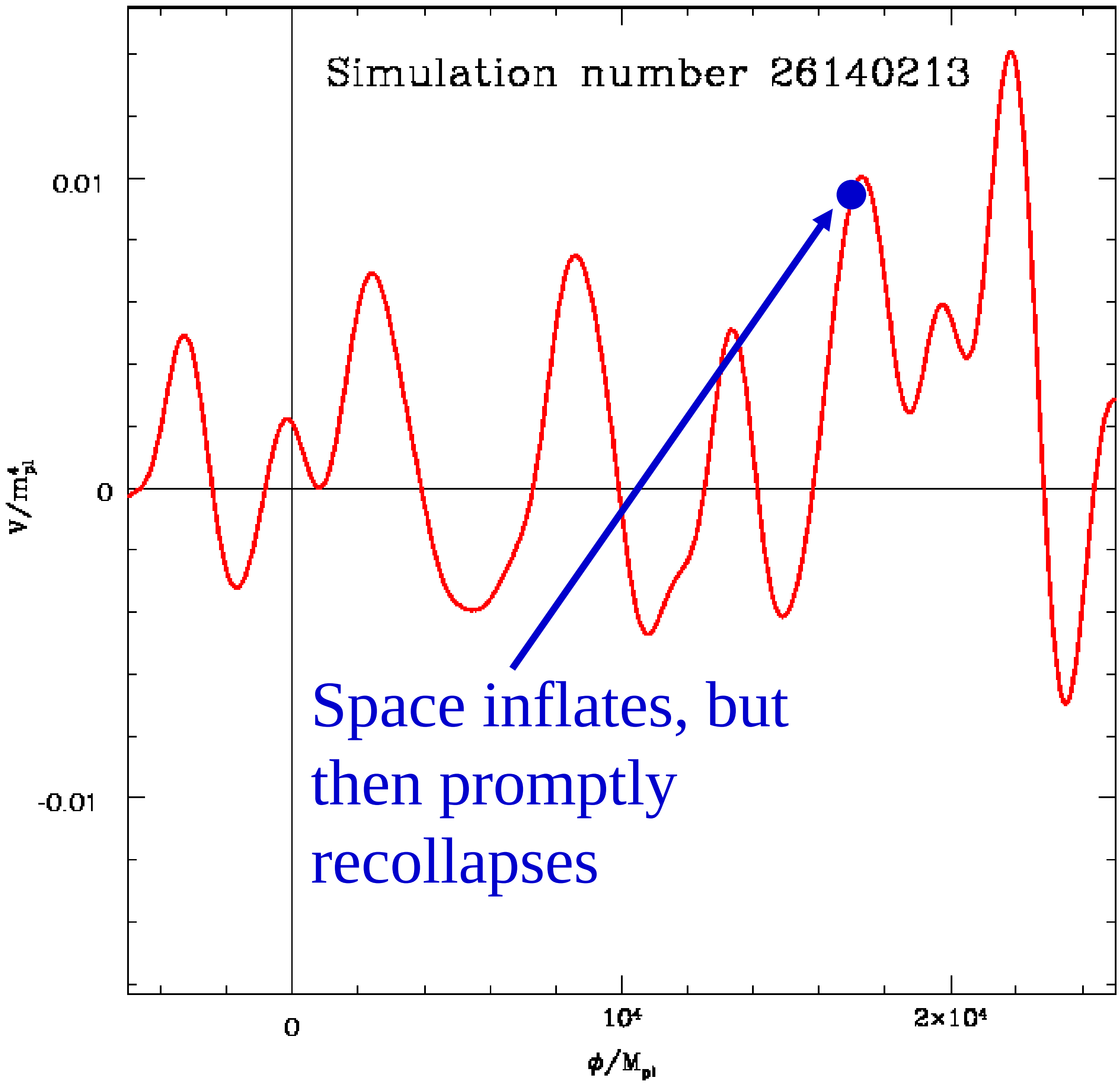

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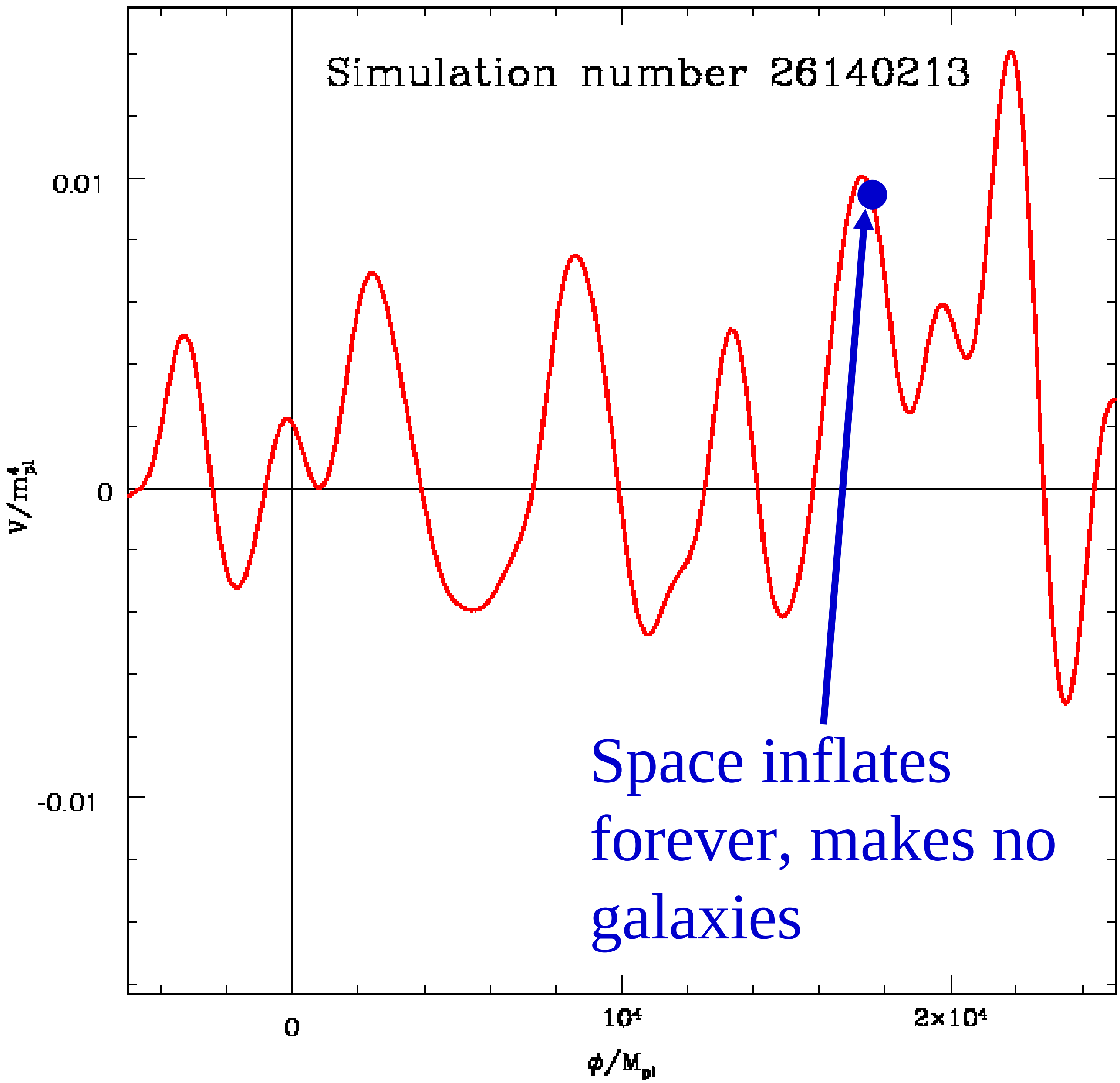

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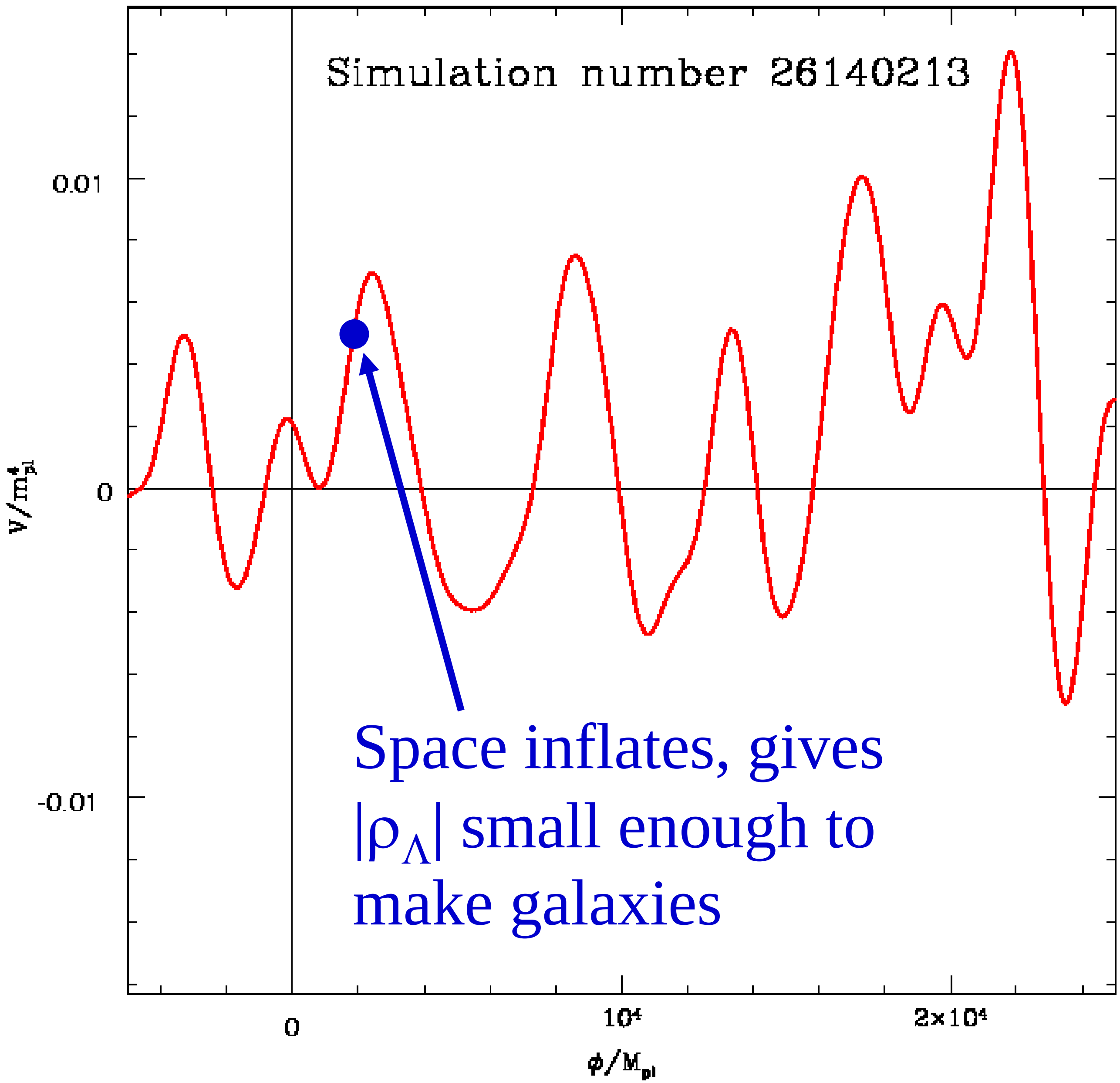

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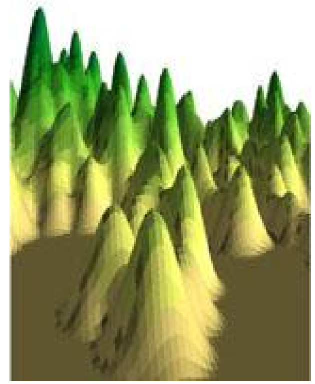
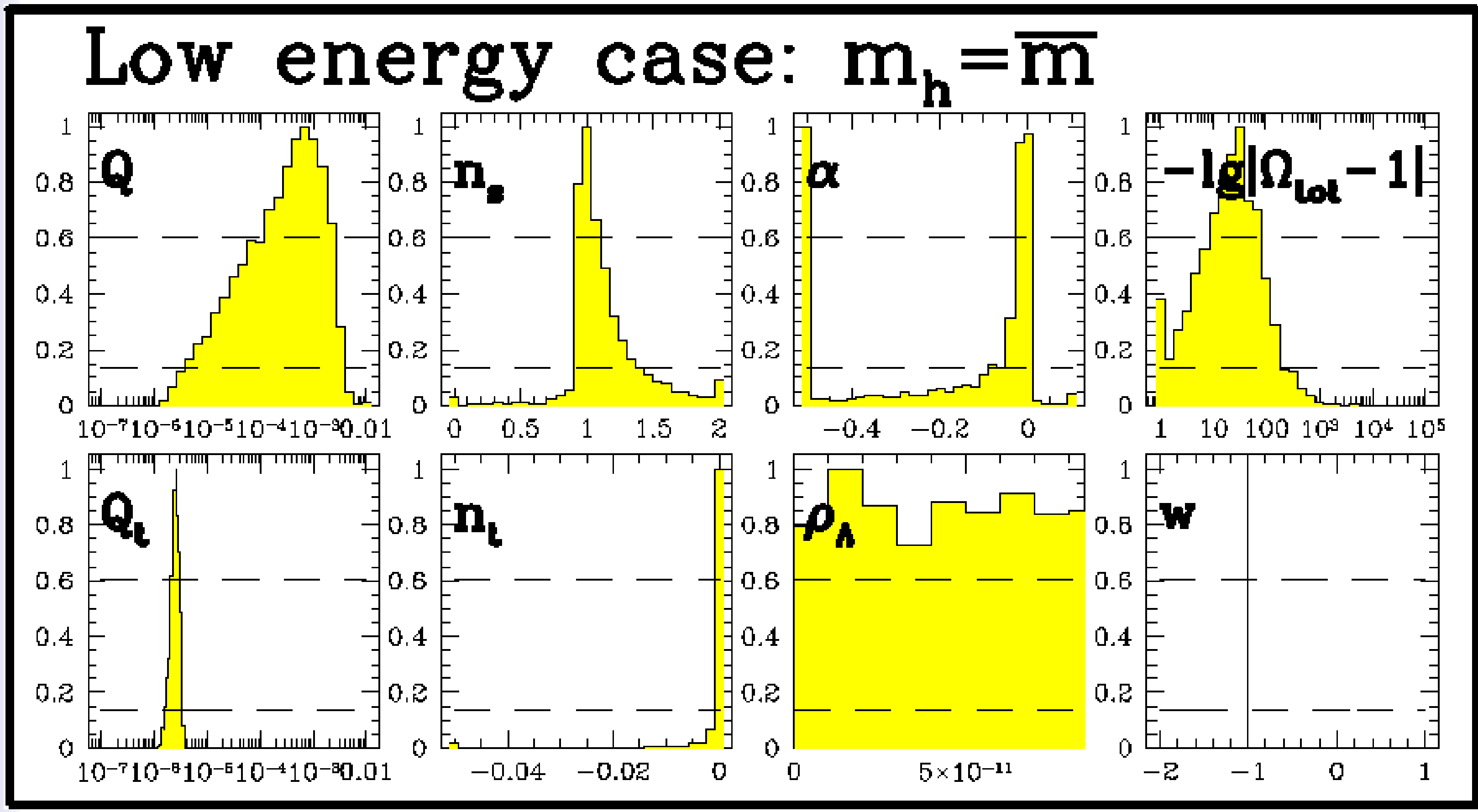
$m_h = 0.2\ m_{Pl}$:





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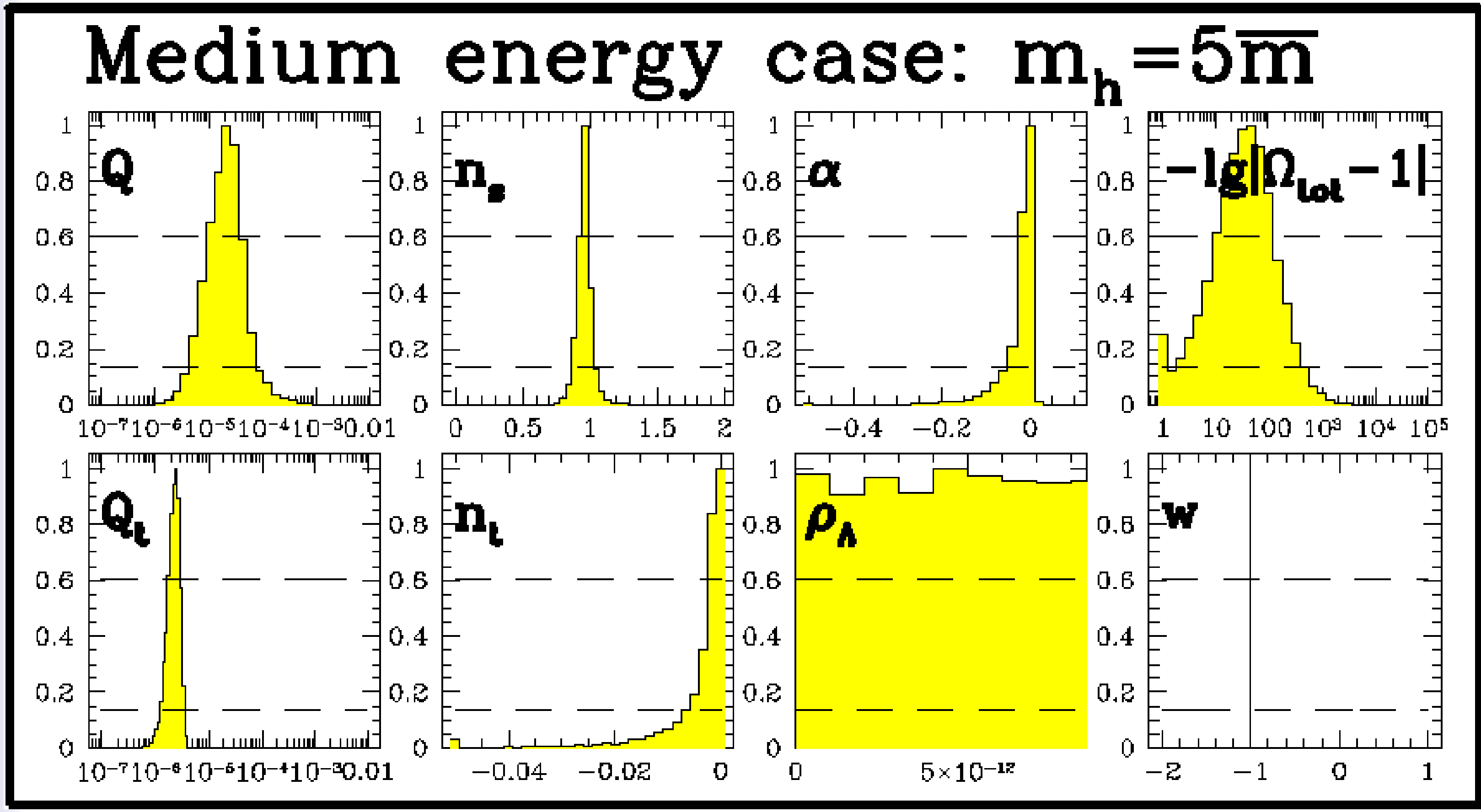
$m_h = 1\ m_{Pl}$:



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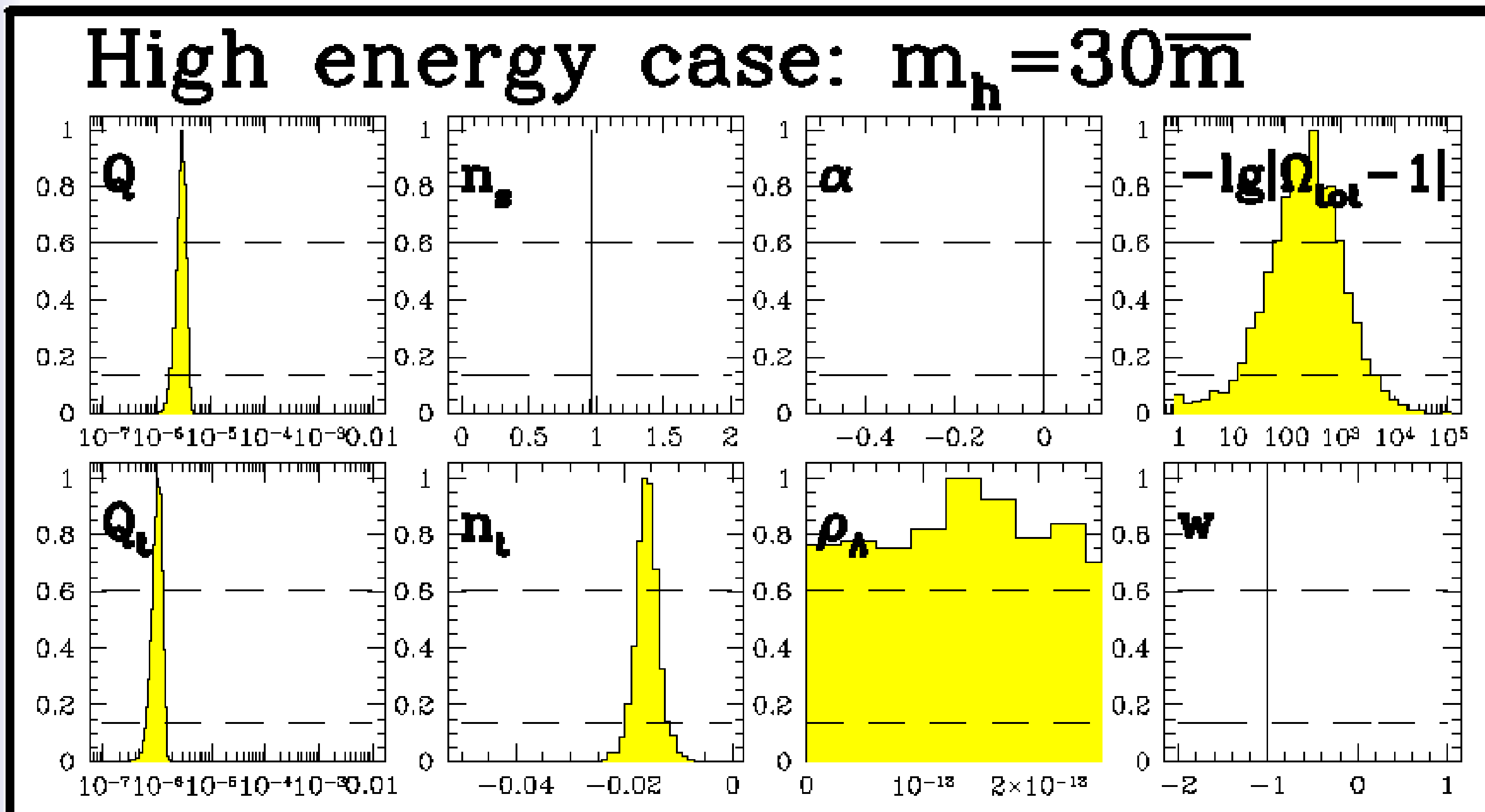
m_h=6 m_{Pl} :



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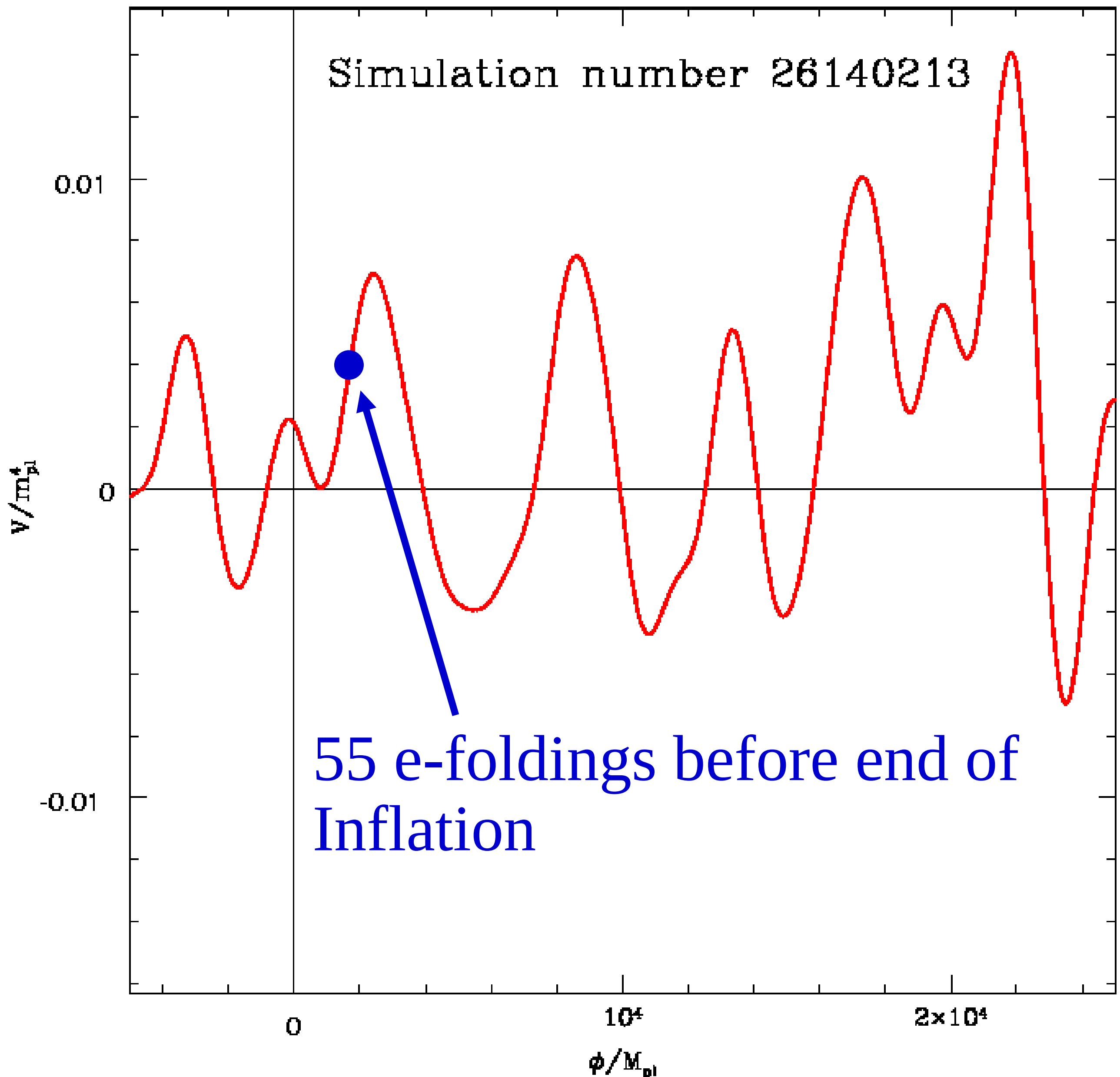

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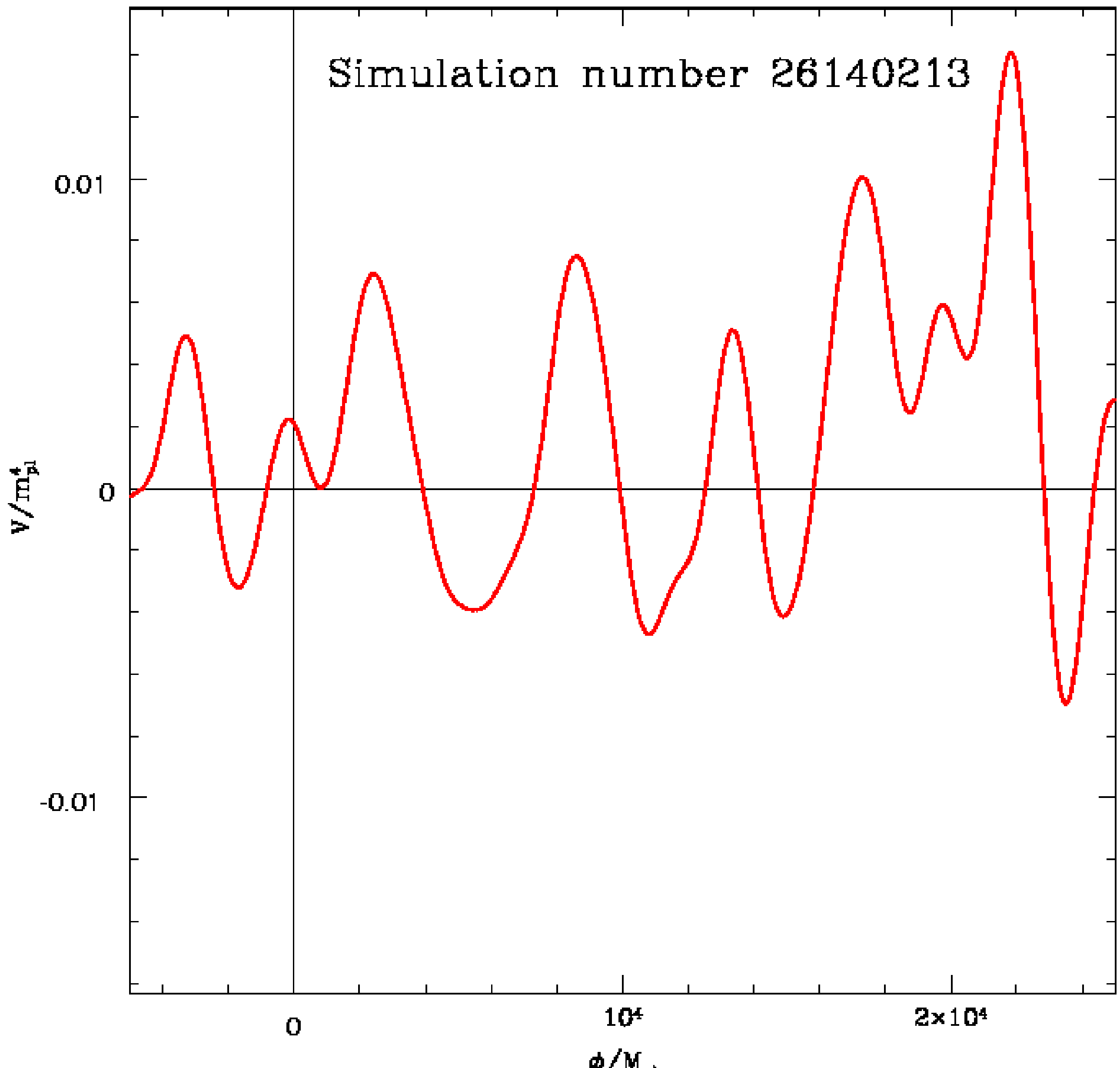

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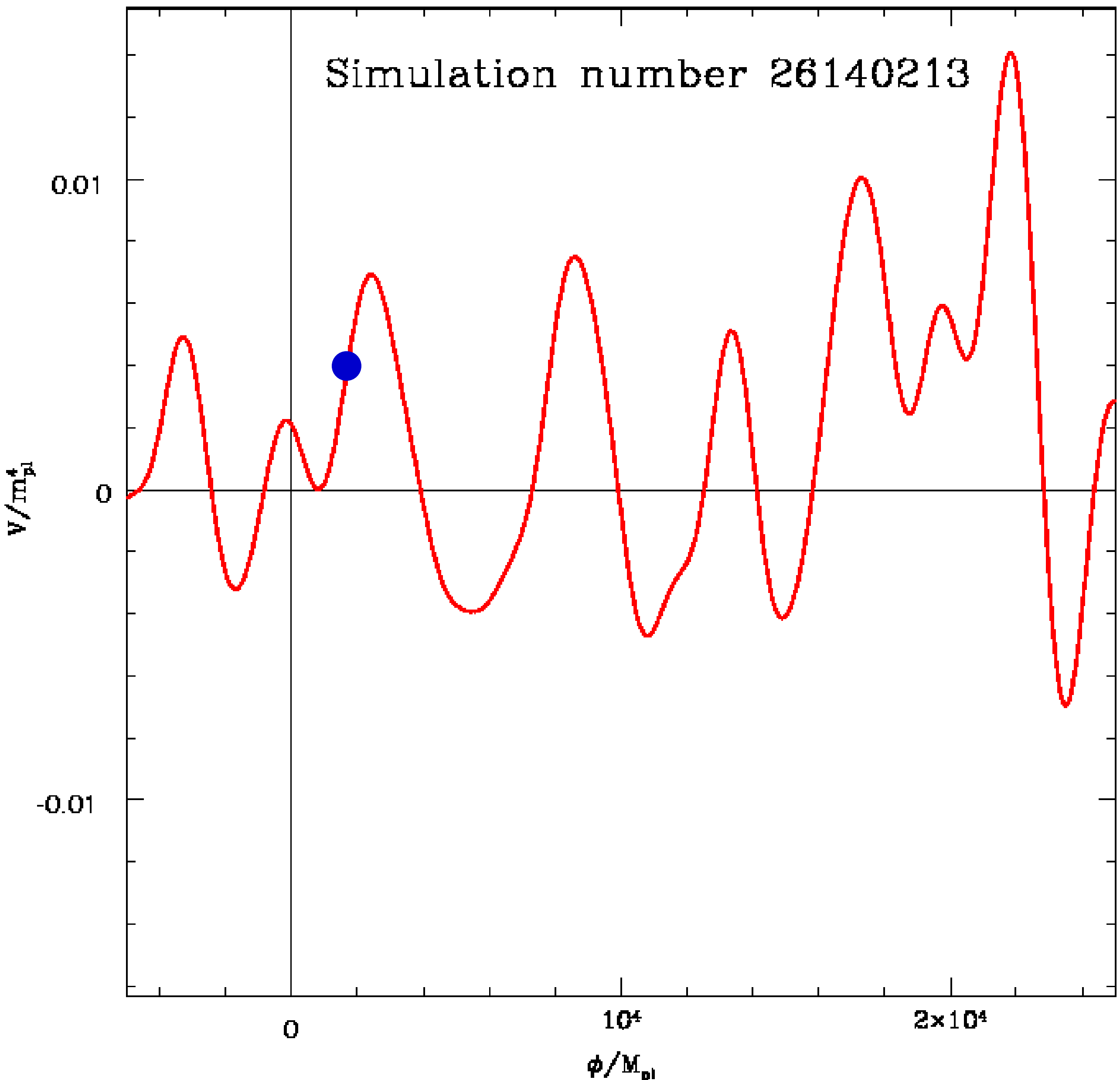

Simulation number 26140213
0.01
0
-0.01
V/m_{pl}^4
0
10^4
2×10^4
ϕ/M_{pl}

Unsolved problems

The measure problem:

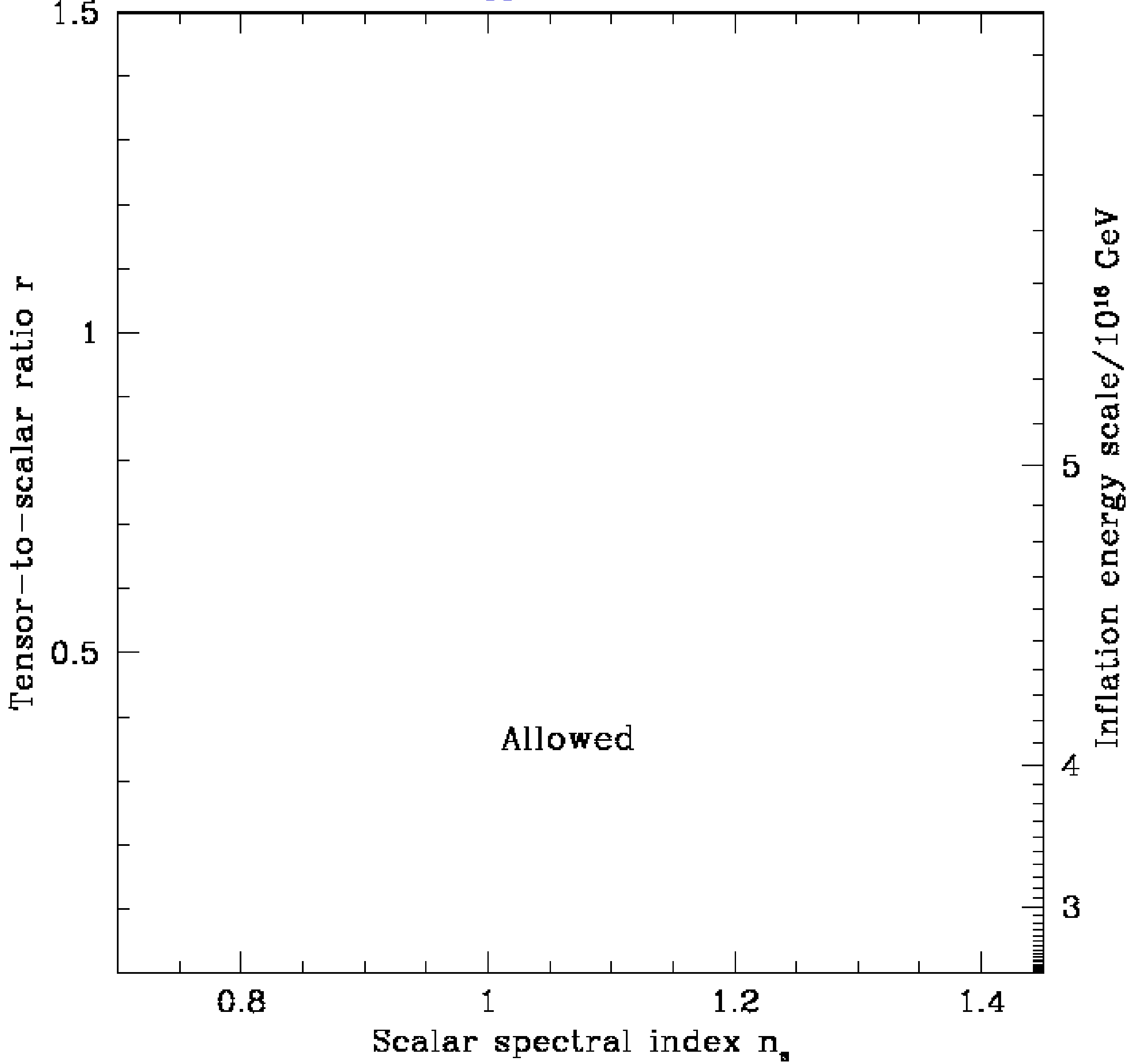
Aguirre,
Guth,
Hogan,
Linde,
Rees,
Vilenkin,
…

- Ordering

- Initial conditions

- Selection effects

Testing inflation II:



SDSS collaboration, astro-ph/0310723, PRD 68, 193591

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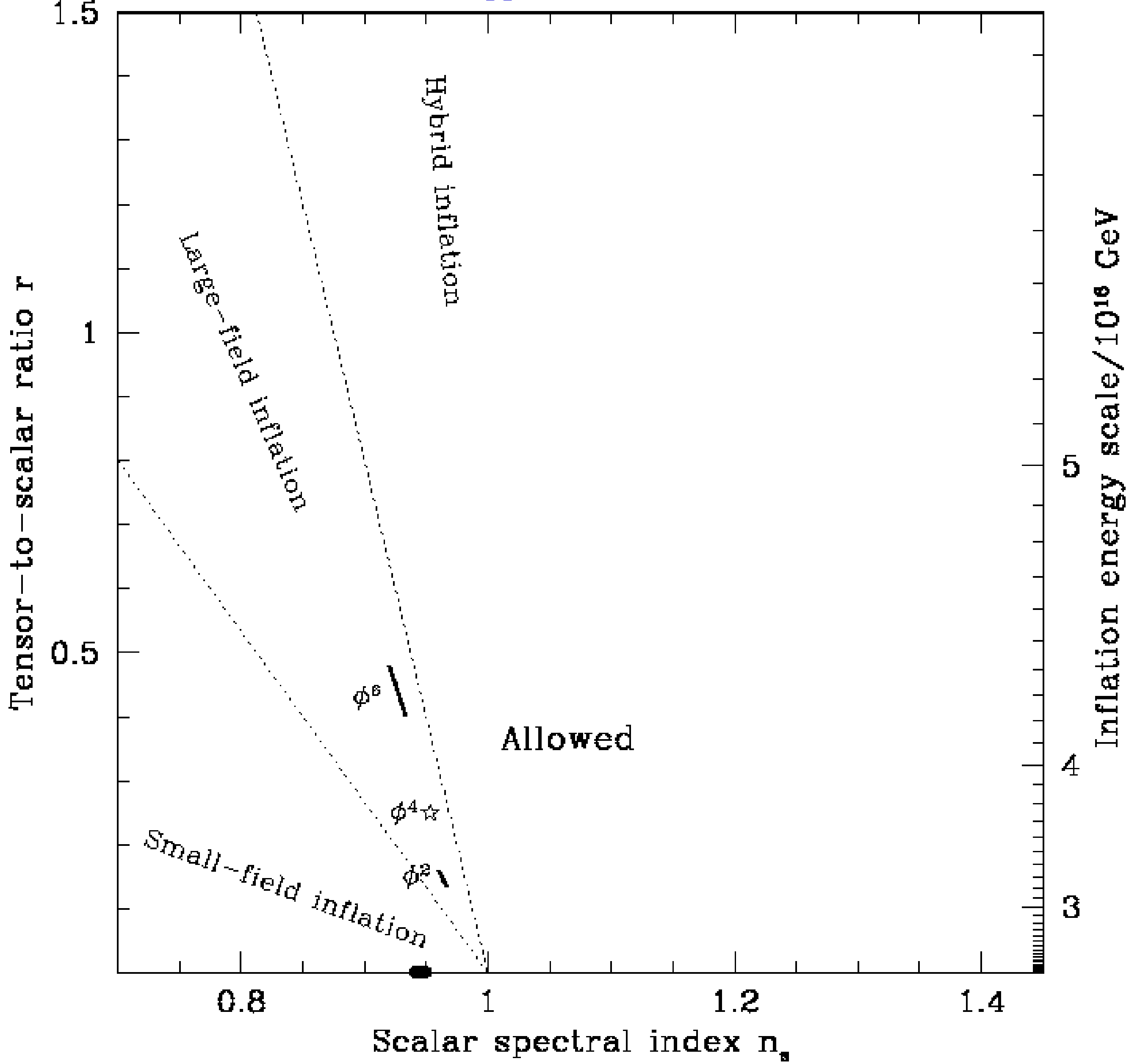
Testing inflation II:



SDSS collaboration, astro-ph/0310723, PRD 68, 193591

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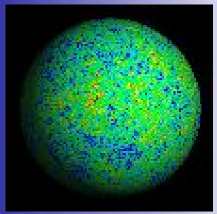
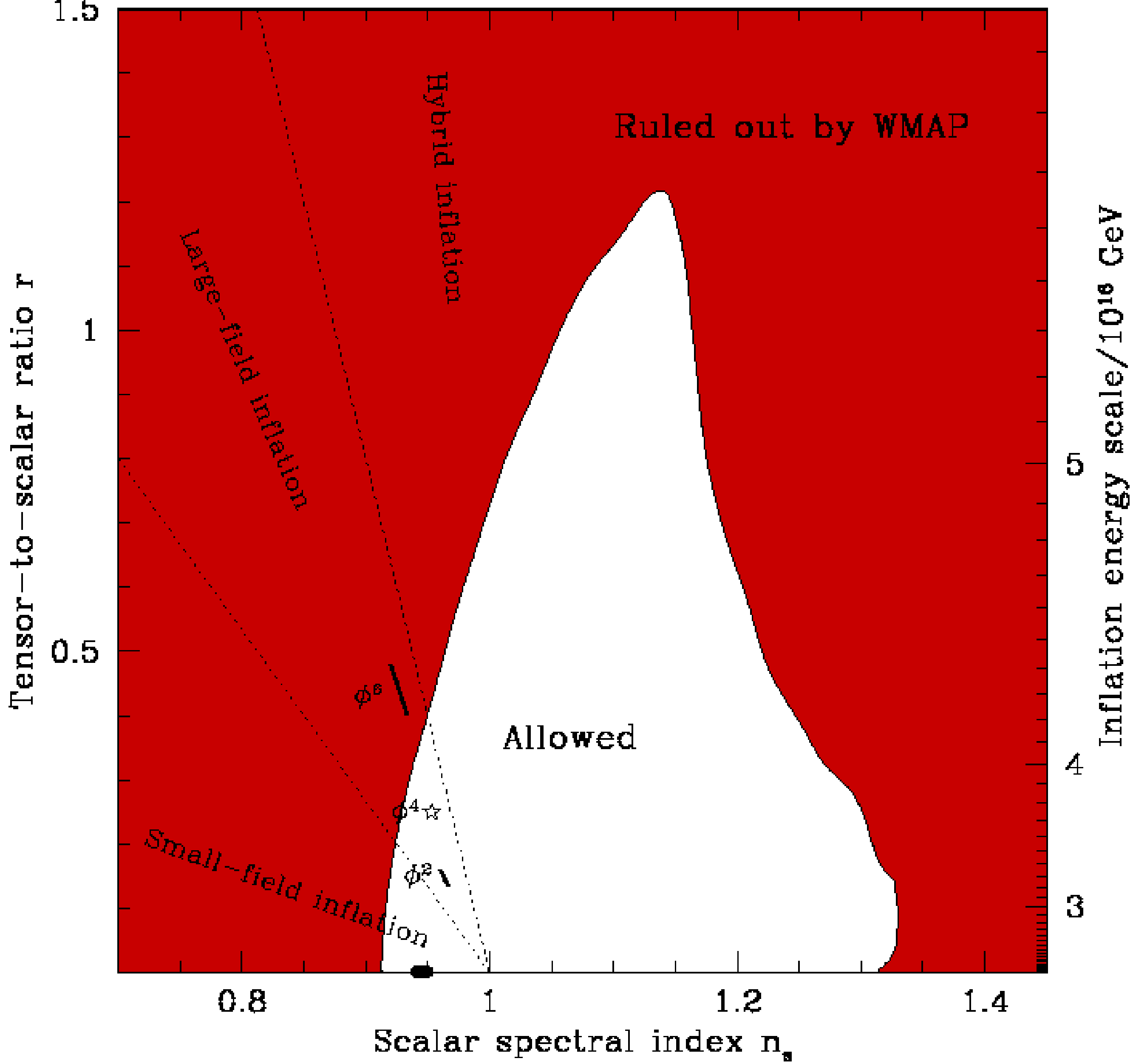


CMB

Testing inflation II:



SDSS collaboration, astro-ph/0310723, PRD 68, 193591

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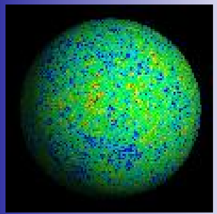
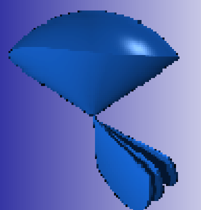
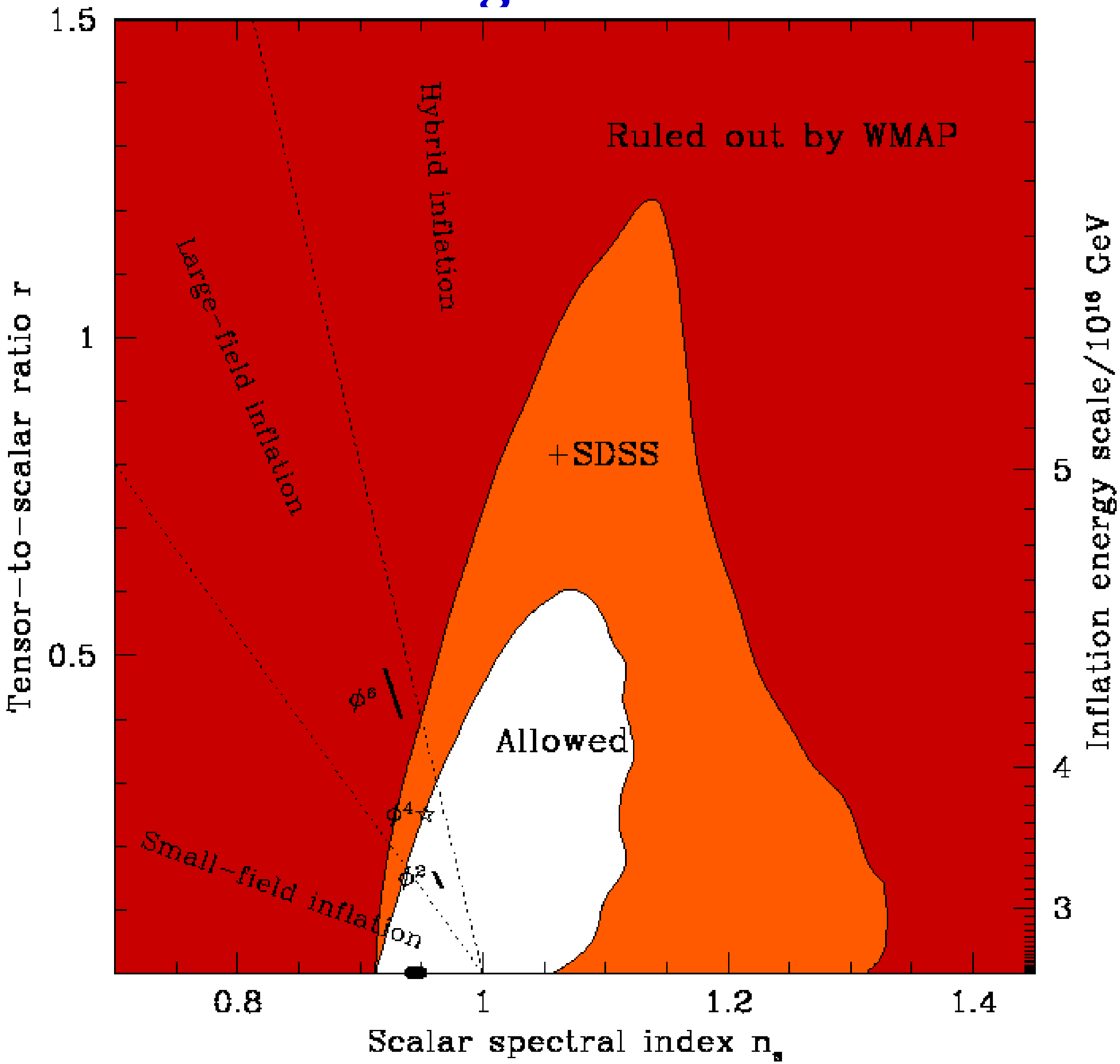


CMB

+



LSS



SDSS collaboration, astro-ph/0310723, PRD 68, 193591

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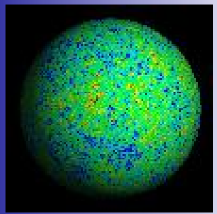
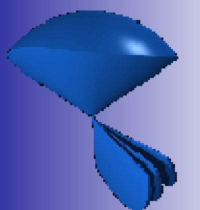
Testing inflation II:

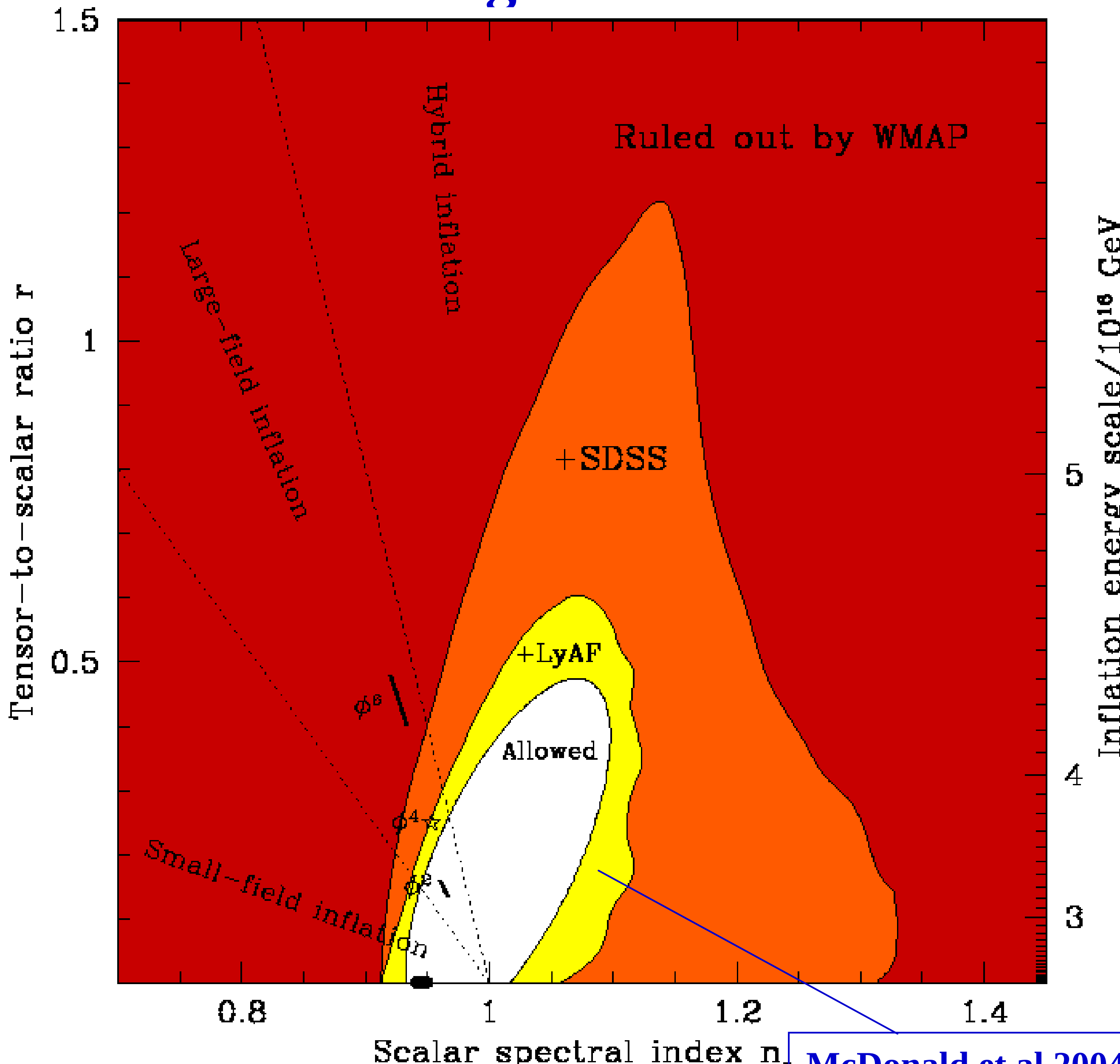


CMB

+



LSS



McDonald et al 2004
Seljak et al 2004

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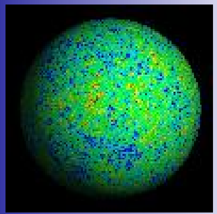
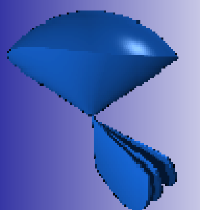
Testing inflation II:

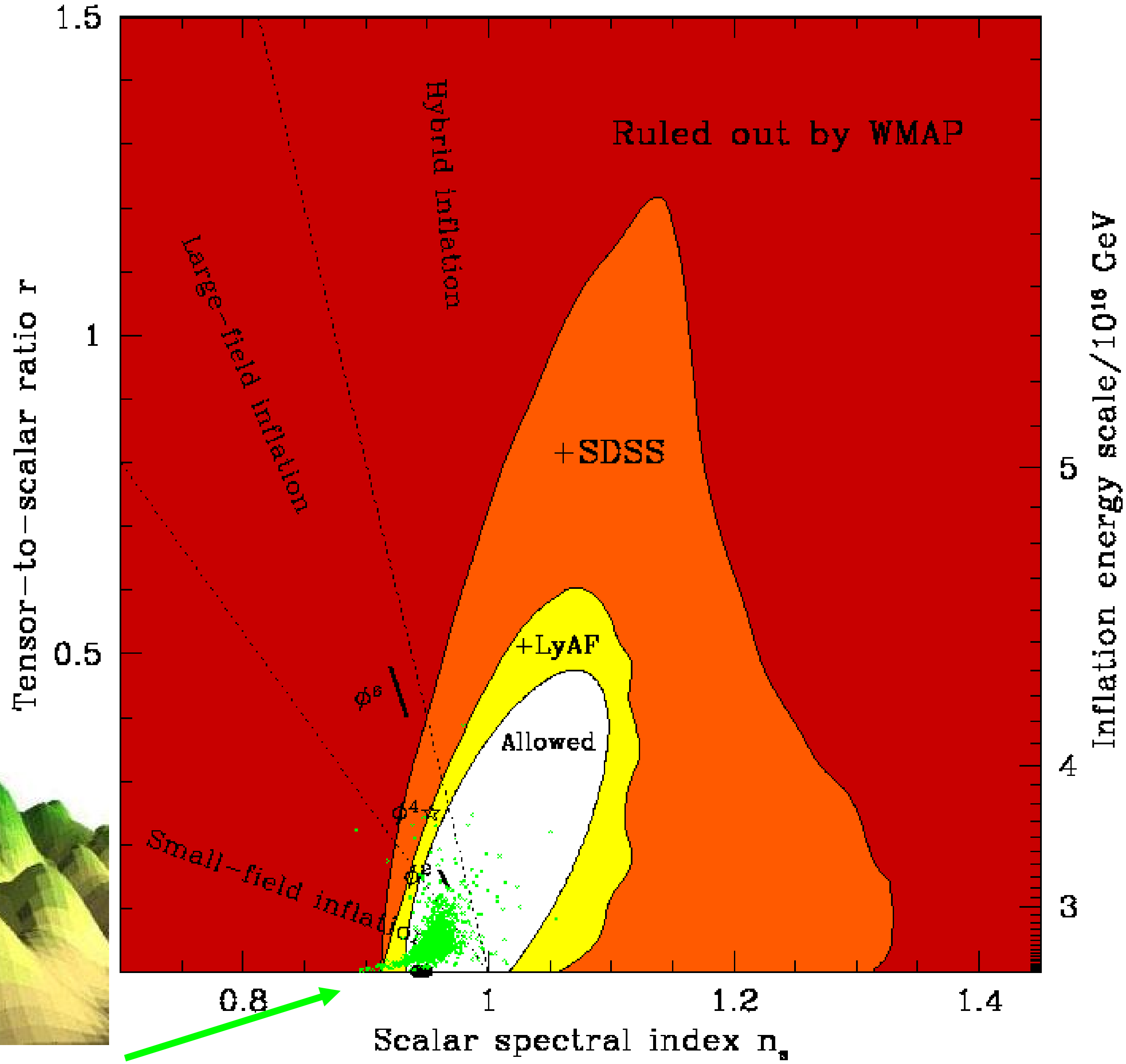


CMB

+



LSS



m_h=1 m_{Pl} :

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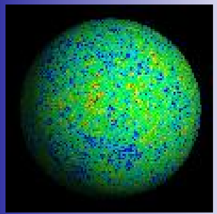
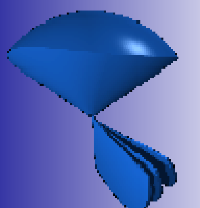


CMB

+



LSS

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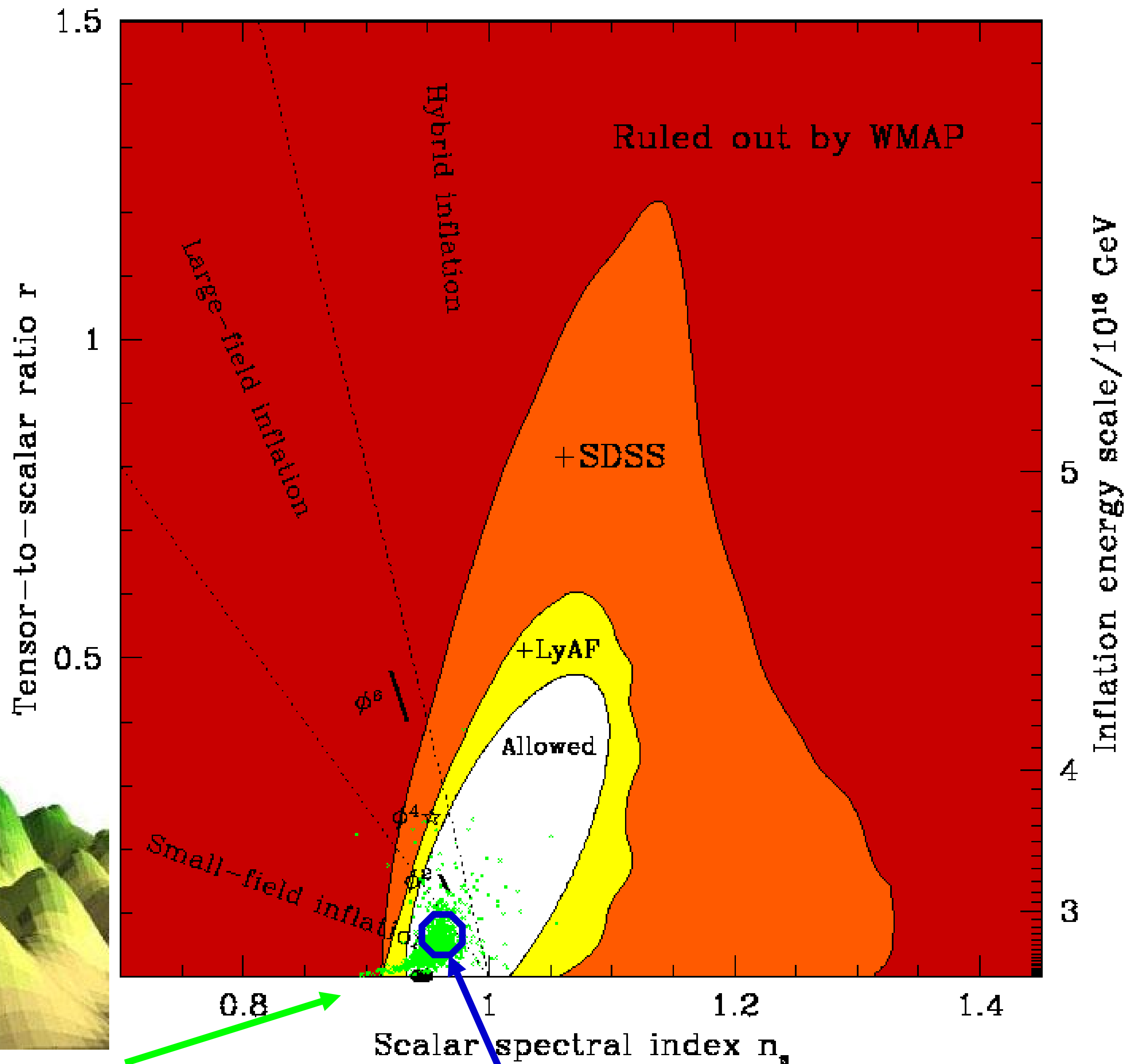

m_h=1 m_{Pl} :

Planck + SDSS: Δn=0.008, Δr=0.012