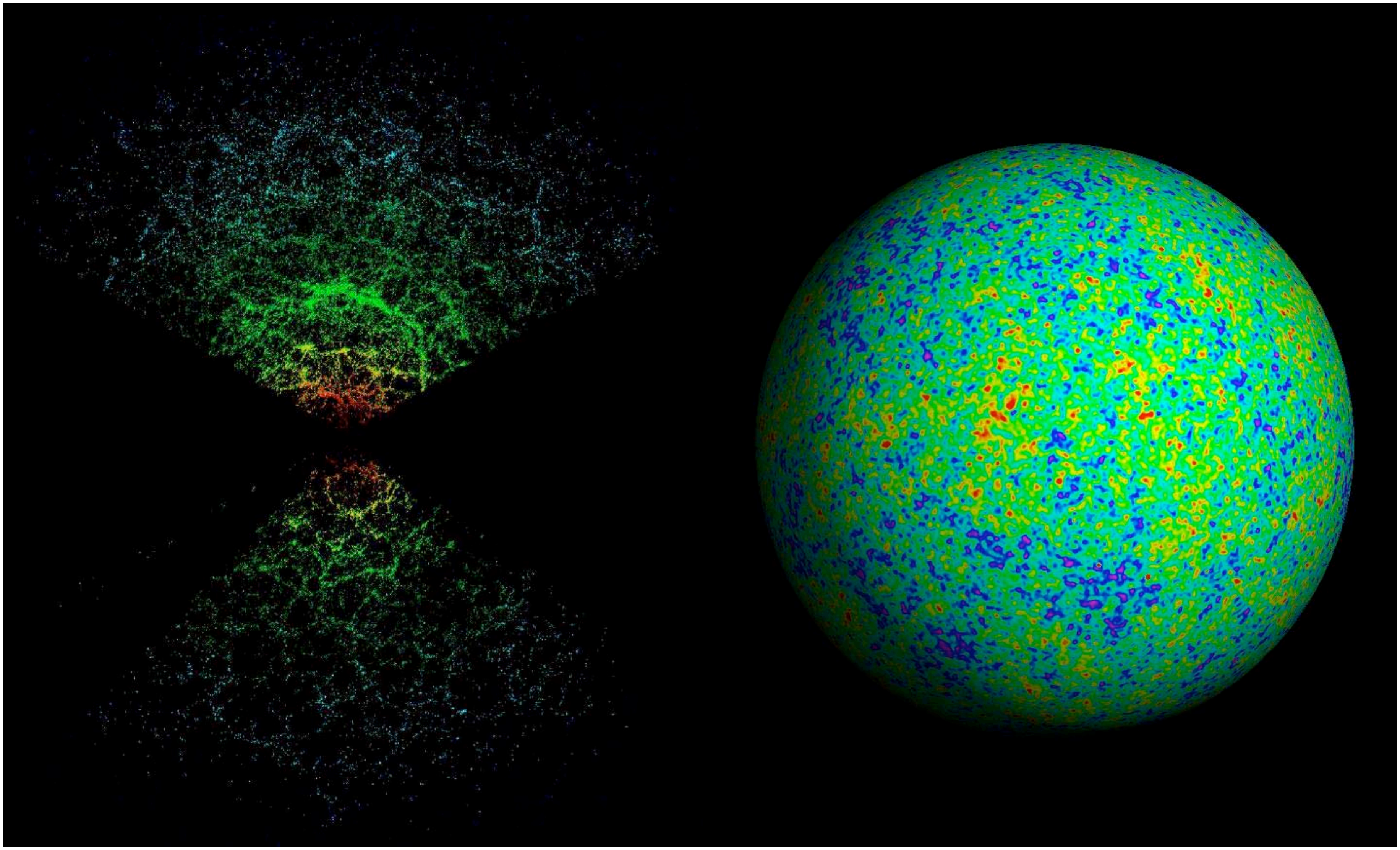
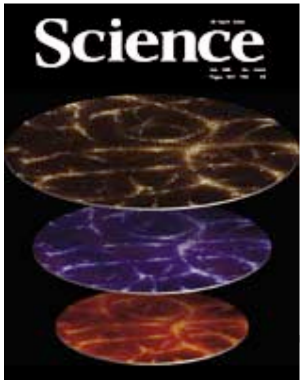
The History of the Universe in 60 Minutes



Max Tegmark, MIT



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

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.

—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.

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

Cosmology timeline:

500 BC

2000 AD

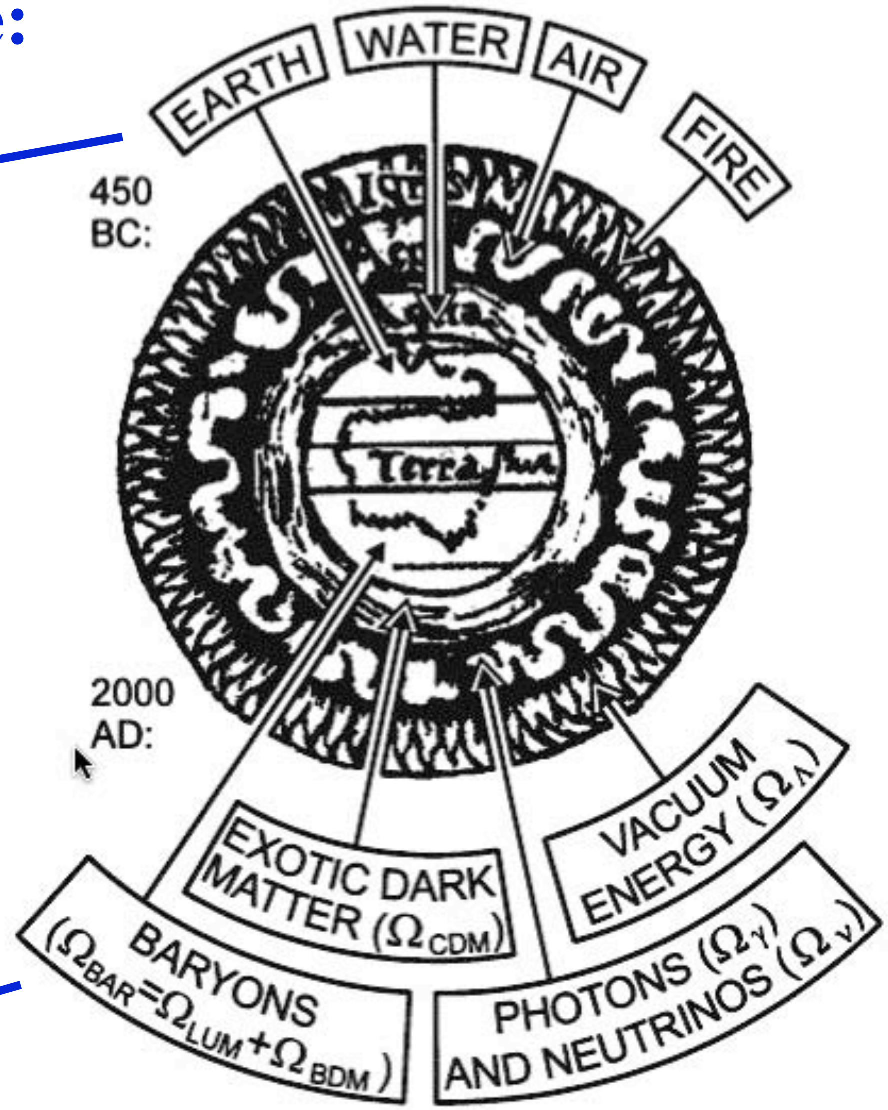
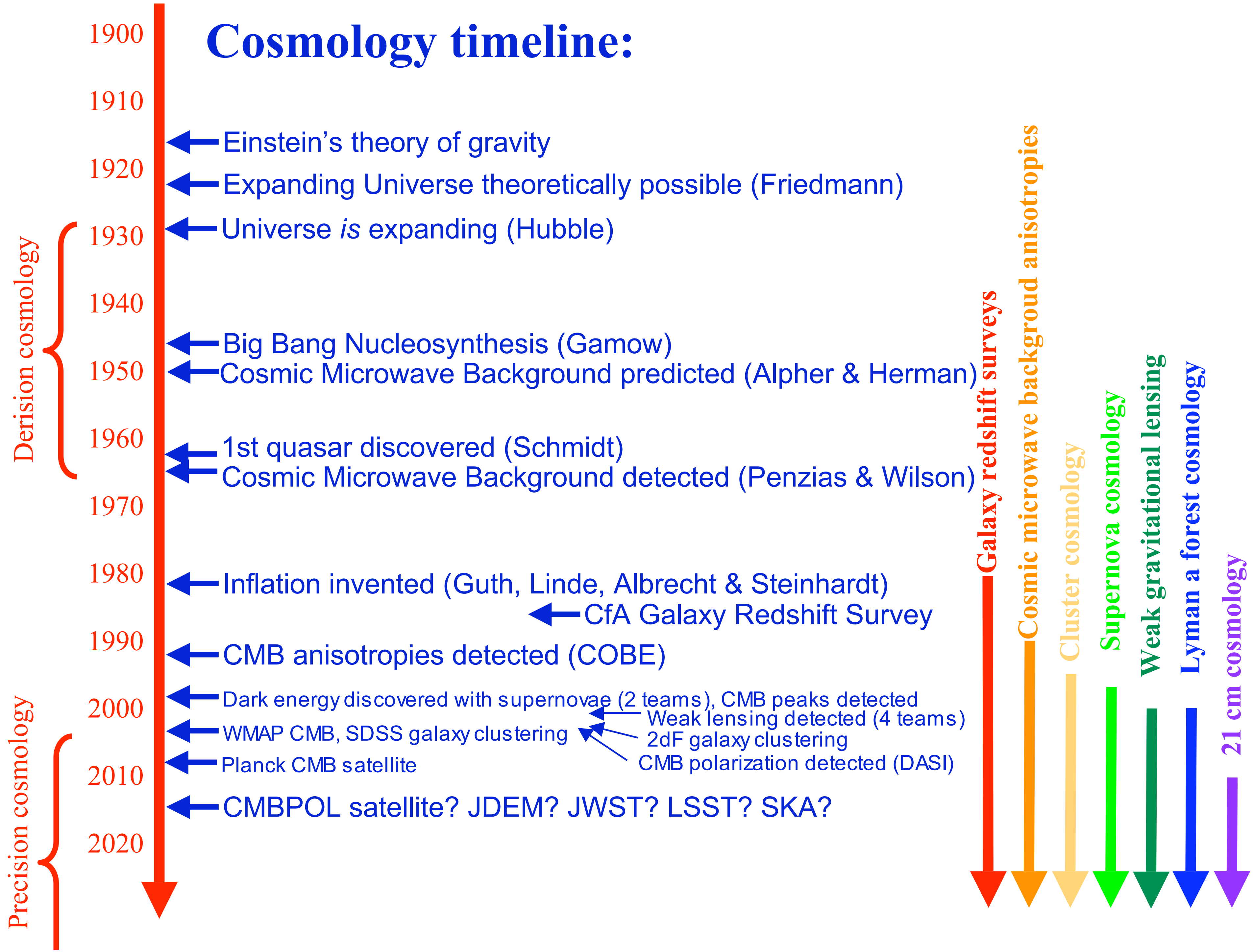


Fig. 1. The "four elements" of modern cosmology (adapted from a figure in a 1519 edition of Aristotle's *Libri de Caelo*)

Overduin & Priester 2001, astro-ph/0101484

Cosmology timeline:

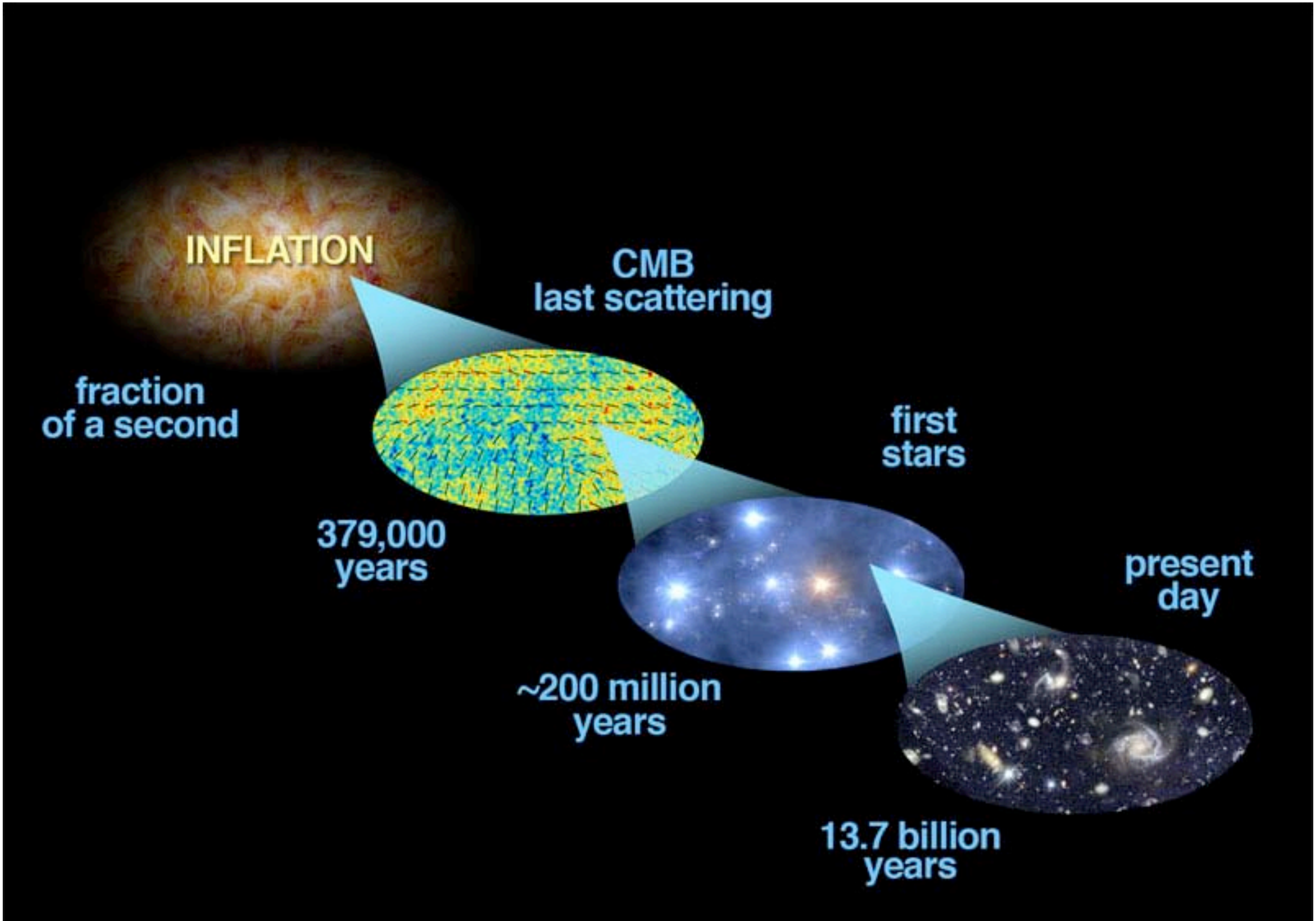


Flyabout

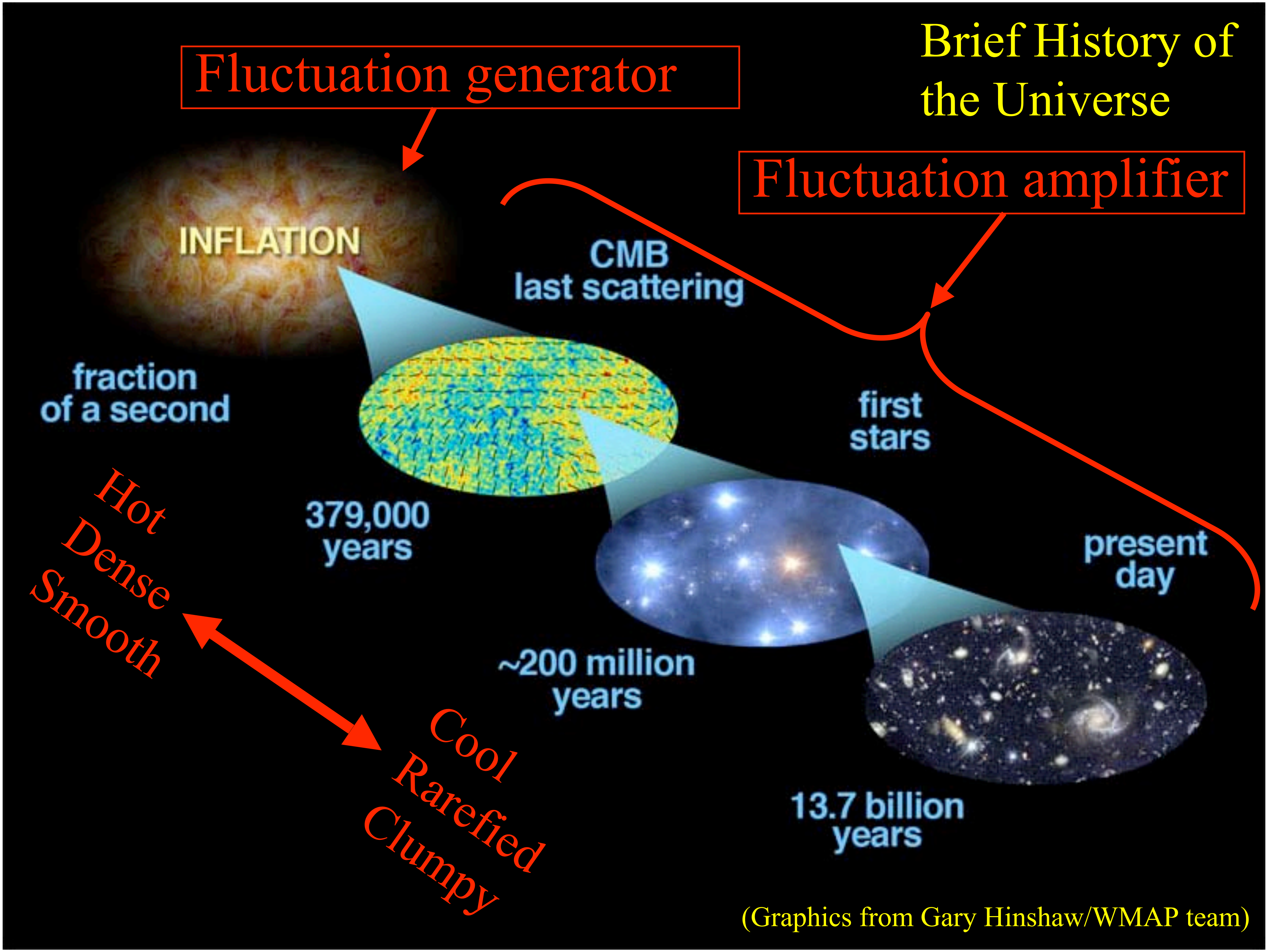
+

SDSS

movie



(Graphics from Gary Hinshaw/WMAP team)

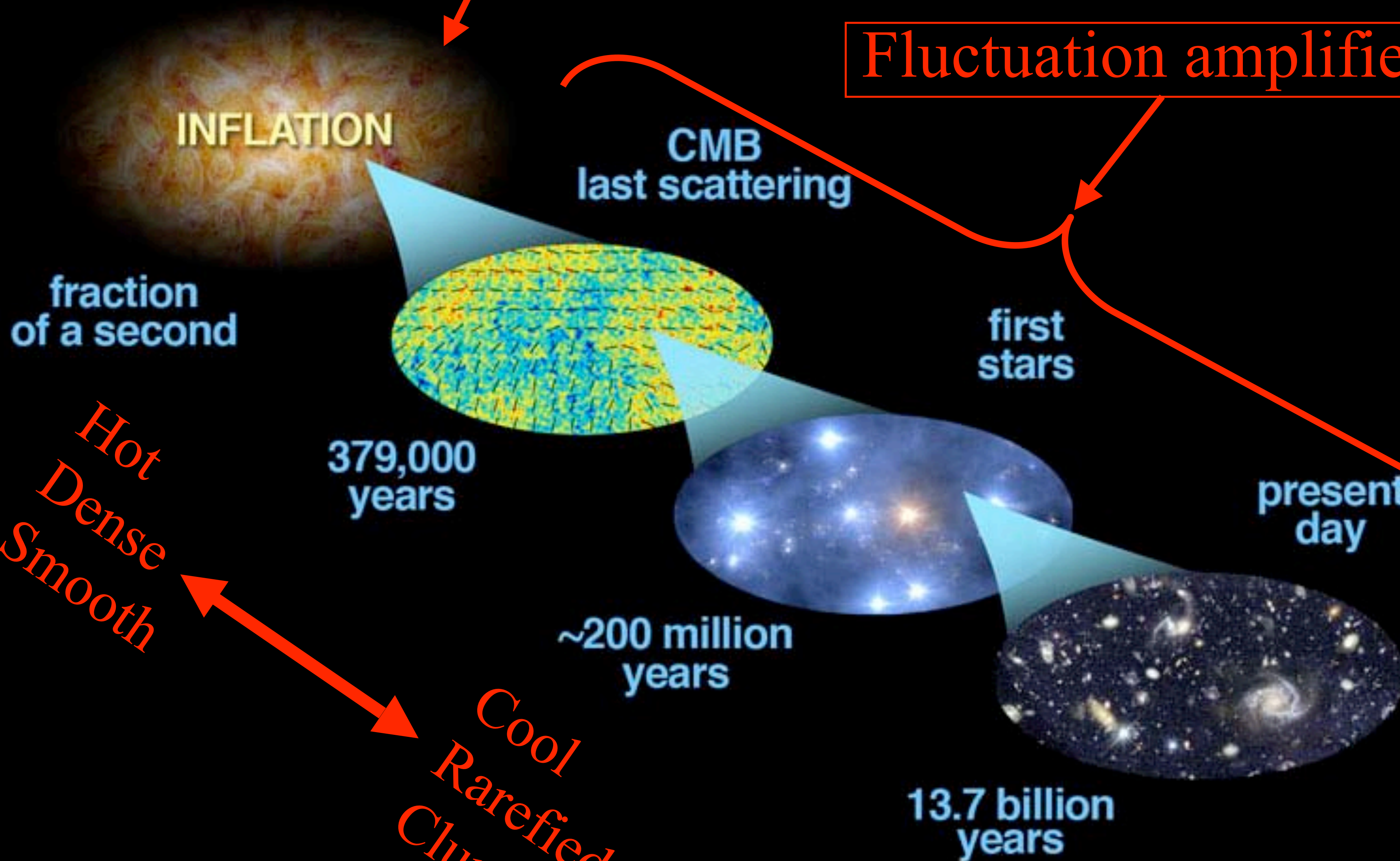


Brief History of the Universe
Fluctuation generator
Fluctuation amplifier
INFLATION
fraction of a second
CMB last scattering
379,000 years
first stars
~200 million years
present day
13.7 billion years
Hot Dense Smooth
Cool Rarefied Clumpy
(Graphics from Gary Hinshaw/WMAP team)

What do we want to measure?

Fluctuation generator

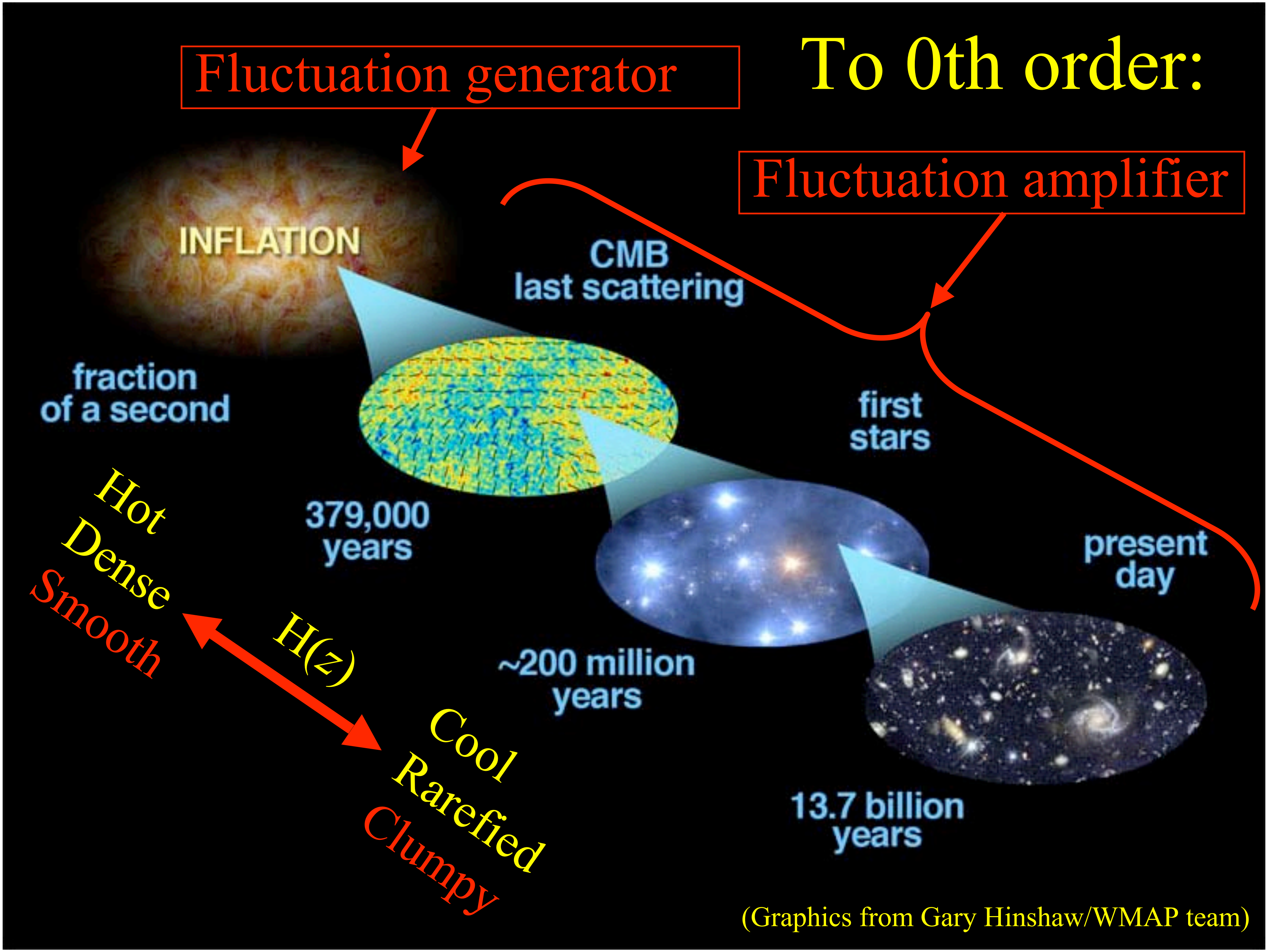
Fluctuation amplifier



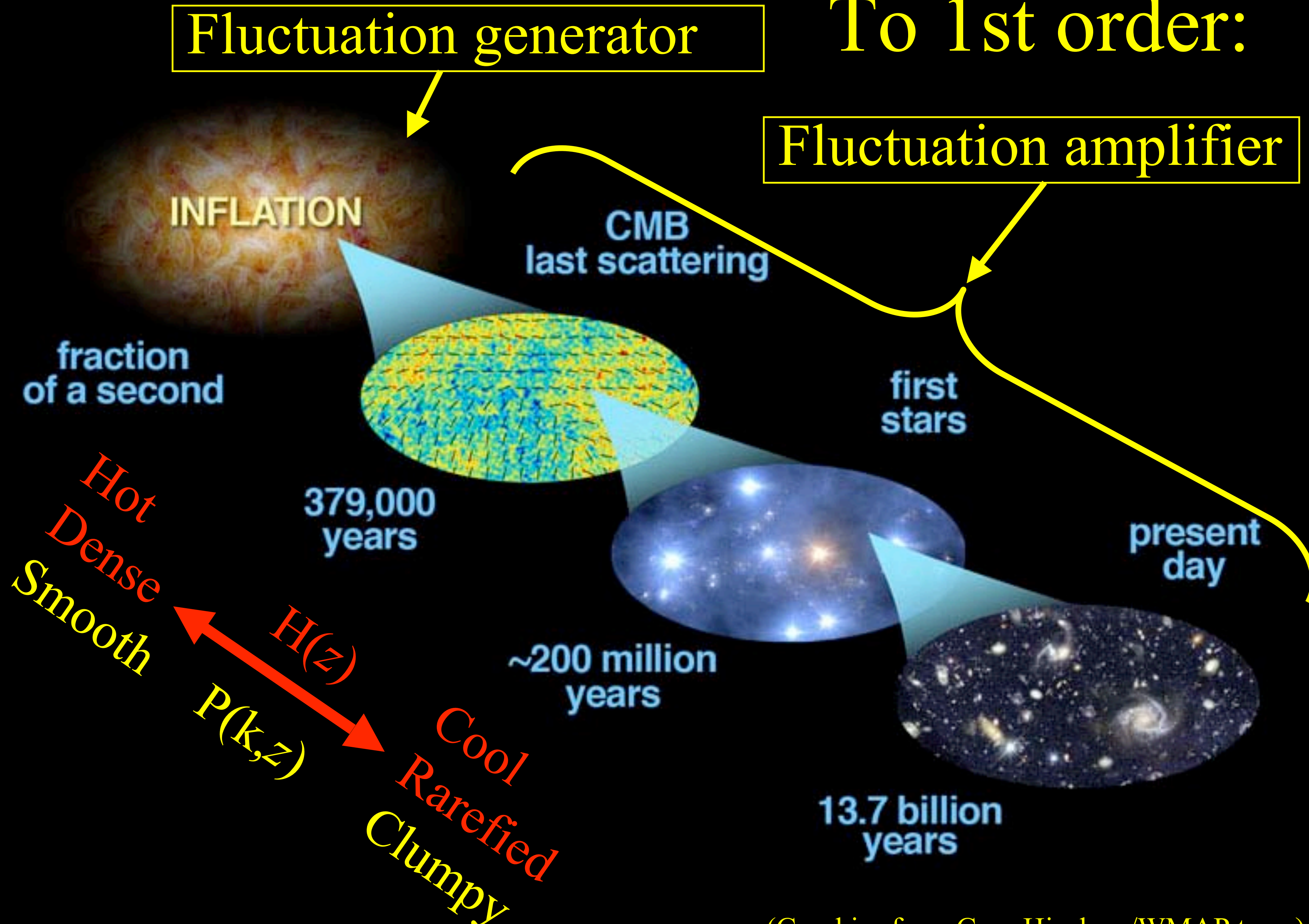
Hot
Dense
Smooth

Cool
Rarefied
Clumpy

(Graphics from Gary Hinshaw/WMAP team)

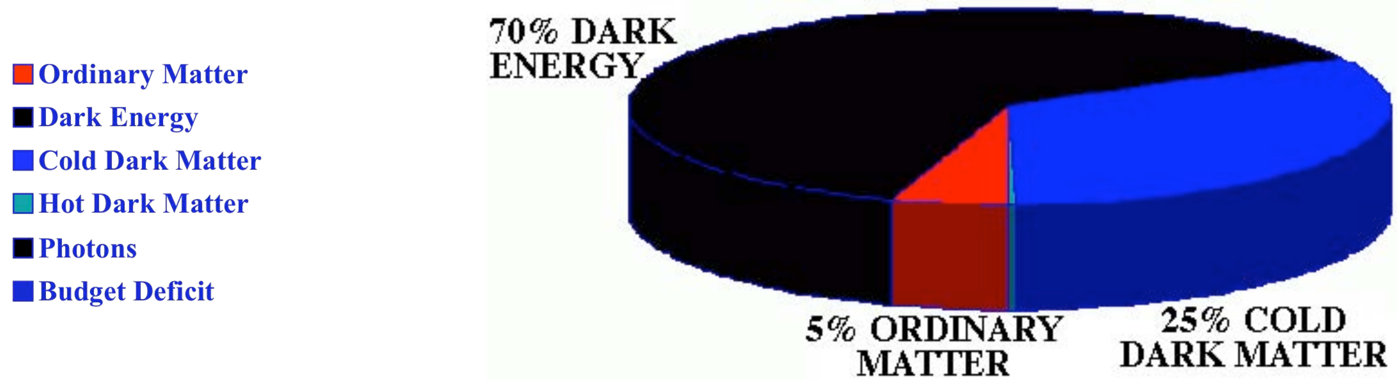

To 0th order:
Fluctuation generator
Fluctuation amplifier
INFLATION
fraction of a second
CMB last scattering
379,000 years
first stars
~200 million years
present day
13.7 billion years
Hot
Dense
Smooth
H(z)
Cool
Rarefied
Clumpy
(Graphics from Gary Hinshaw/WMAP team)

To 1st order:



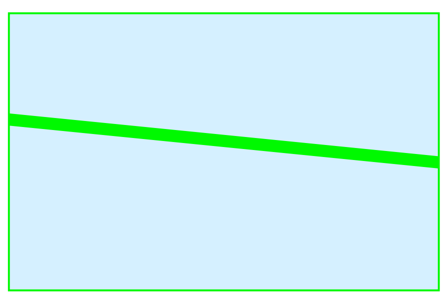
(Graphics from Gary Hinshaw/WMAP team)

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



OUR TOOLS

CMB

GALAXY SURVEYS

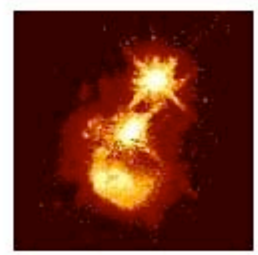
DISTANT SUPERNOVAE

GRAVITATIONAL LENSING

THE COSMIC SMÖRGÅSBORD

BIG BANG NUCLEOSYNTHESIS

GALAXY CLUSTERS



LYMAN ALPHA FOREST

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Measuring expansion

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

Alexander Friedmann

1888-1925

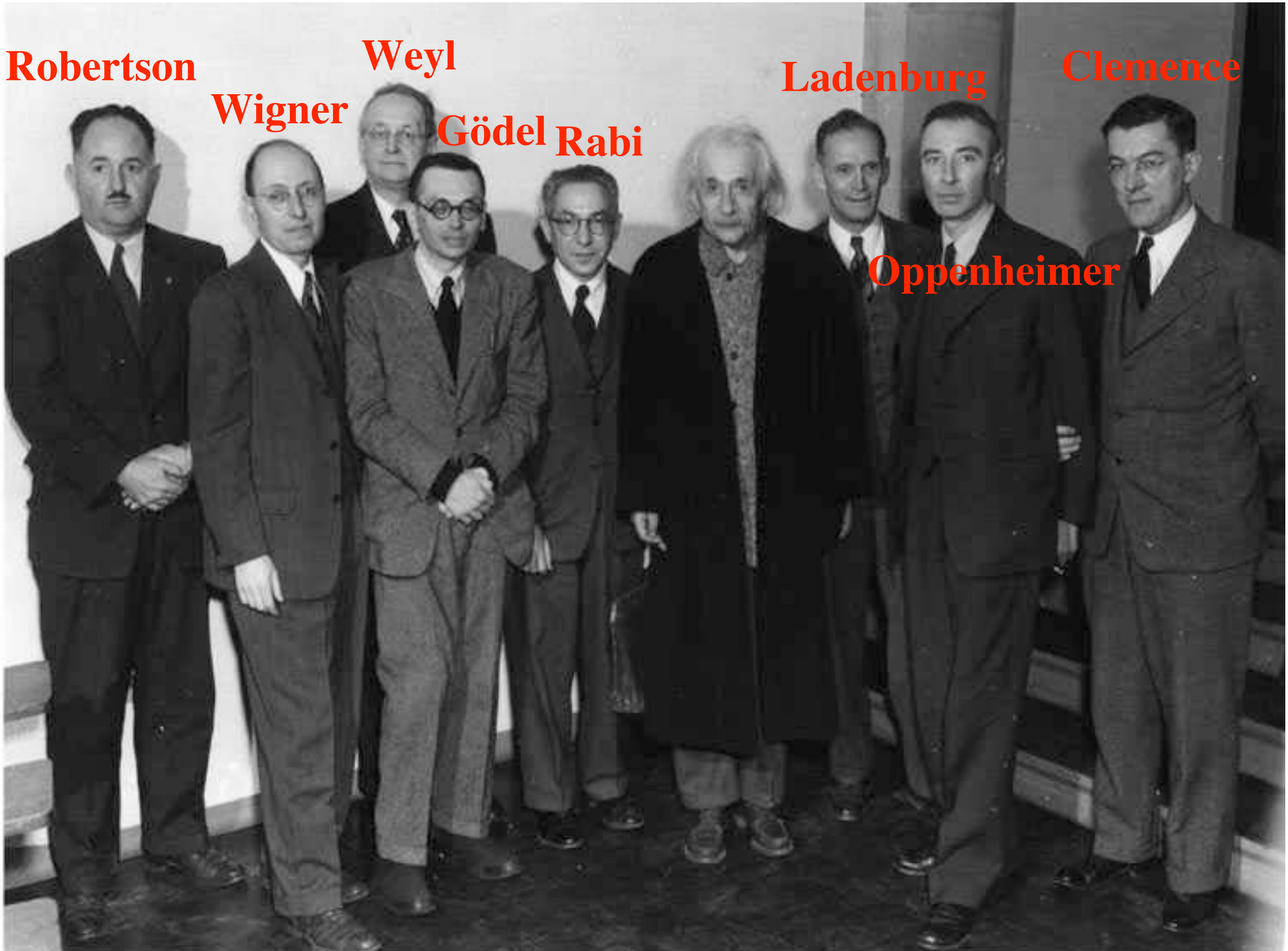
(Russian; 1922 paper)

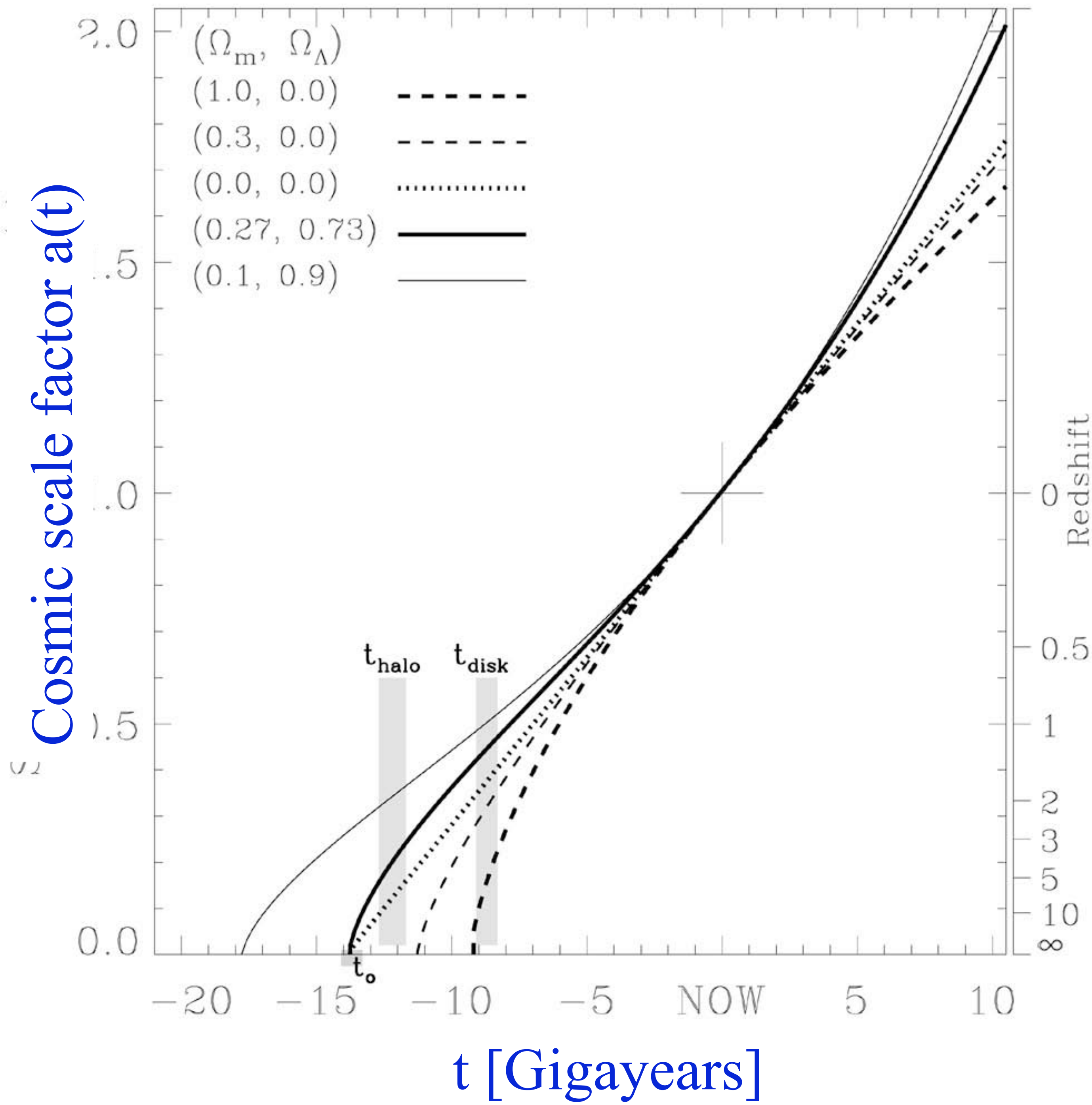
George Lemaître 1894-1936

(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



Cosmic scale factor a(t)
$(\Omega_m, \Omega_\Lambda)$
(1.0, 0.0)
(0.3, 0.0)
(0.0, 0.0)
(0.27, 0.73)
(0.1, 0.9)
t_{halo}
t_{disk}
t_o
0.0
1.0
1.5
2.0
Redshift
0
0.5
1
2
3
5
10
∞
−20
−15
−10
−5
NOW
5
10
t [Gigayears]

The Universe is expanding:

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

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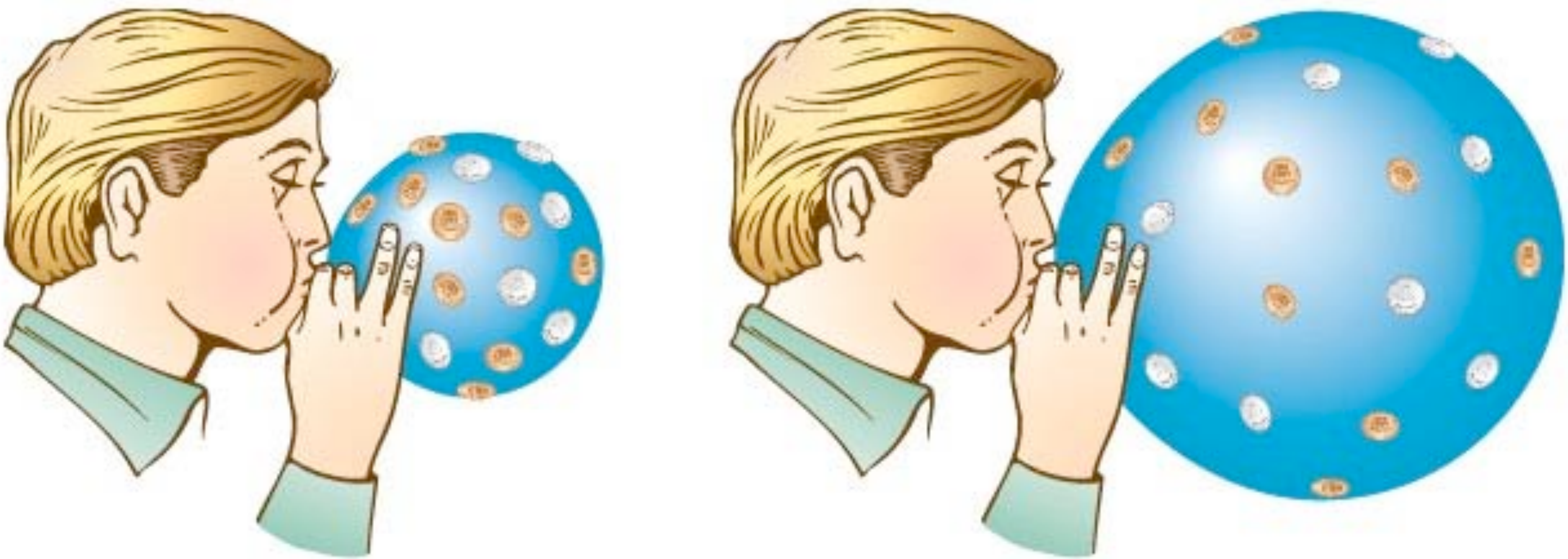


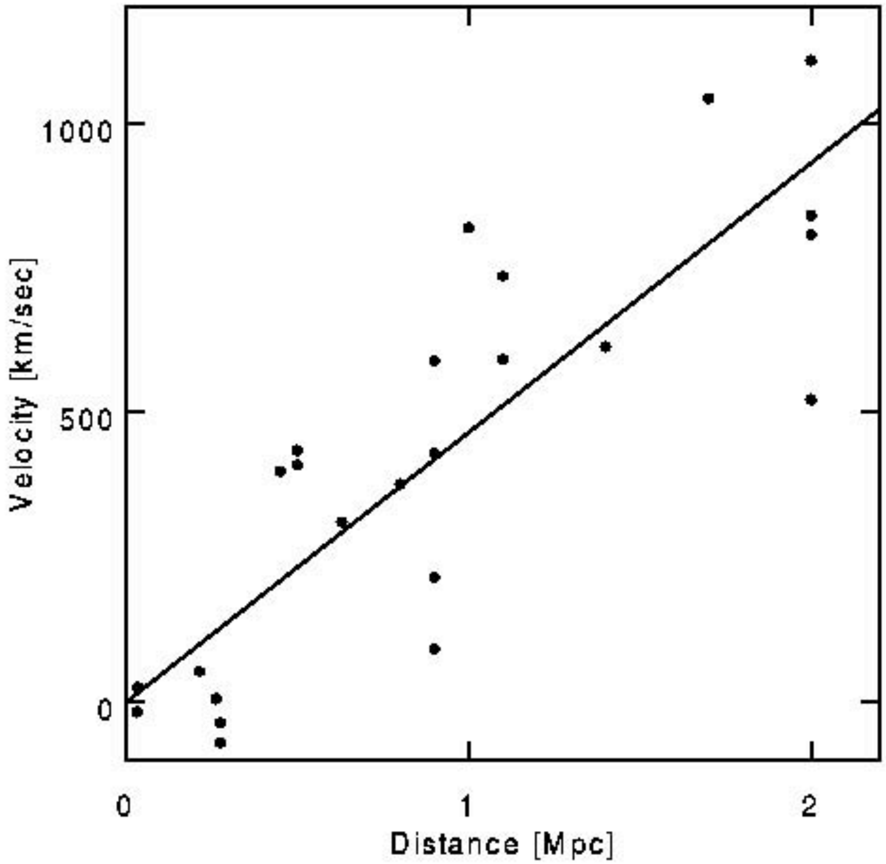
Edwin Hubble 1889-

(American; 1930 paper)

Mt. Wilson Observatory 1931

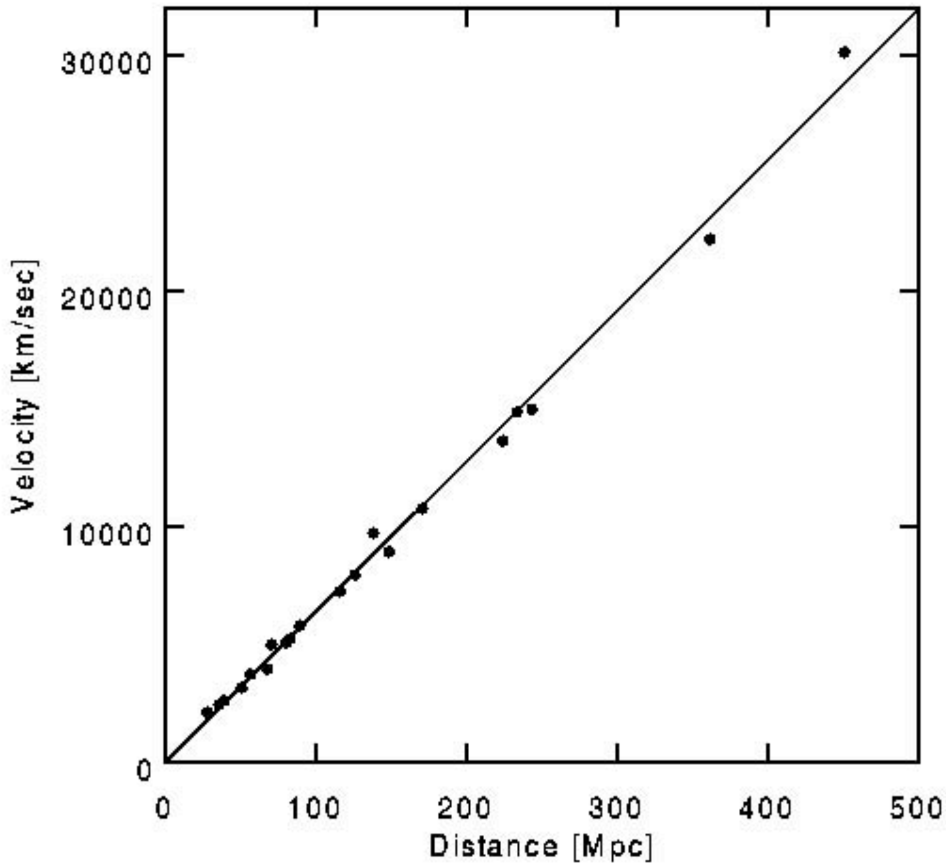
Hubble 1929:

H≈550 km/s/Mpc

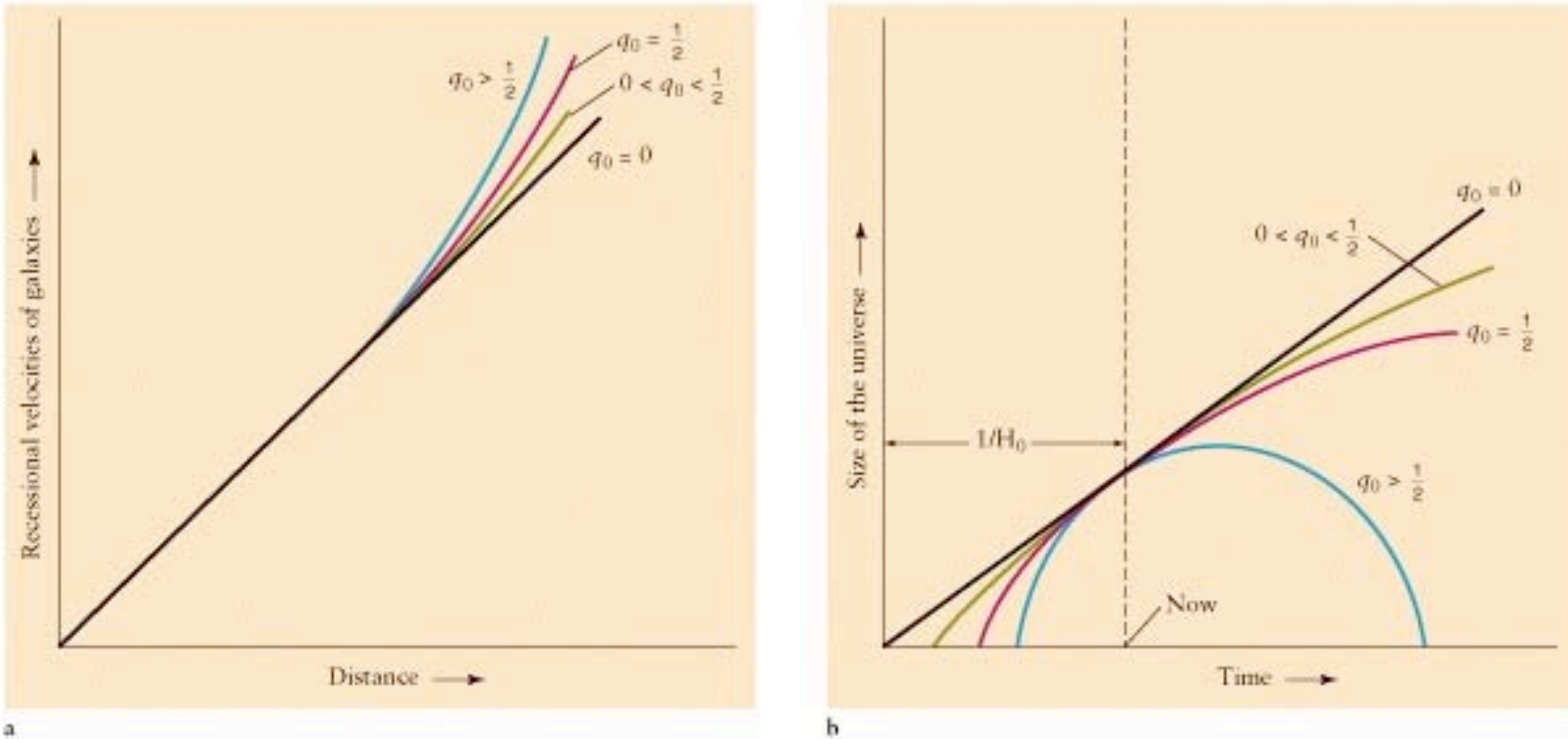


Riess et al 1996:

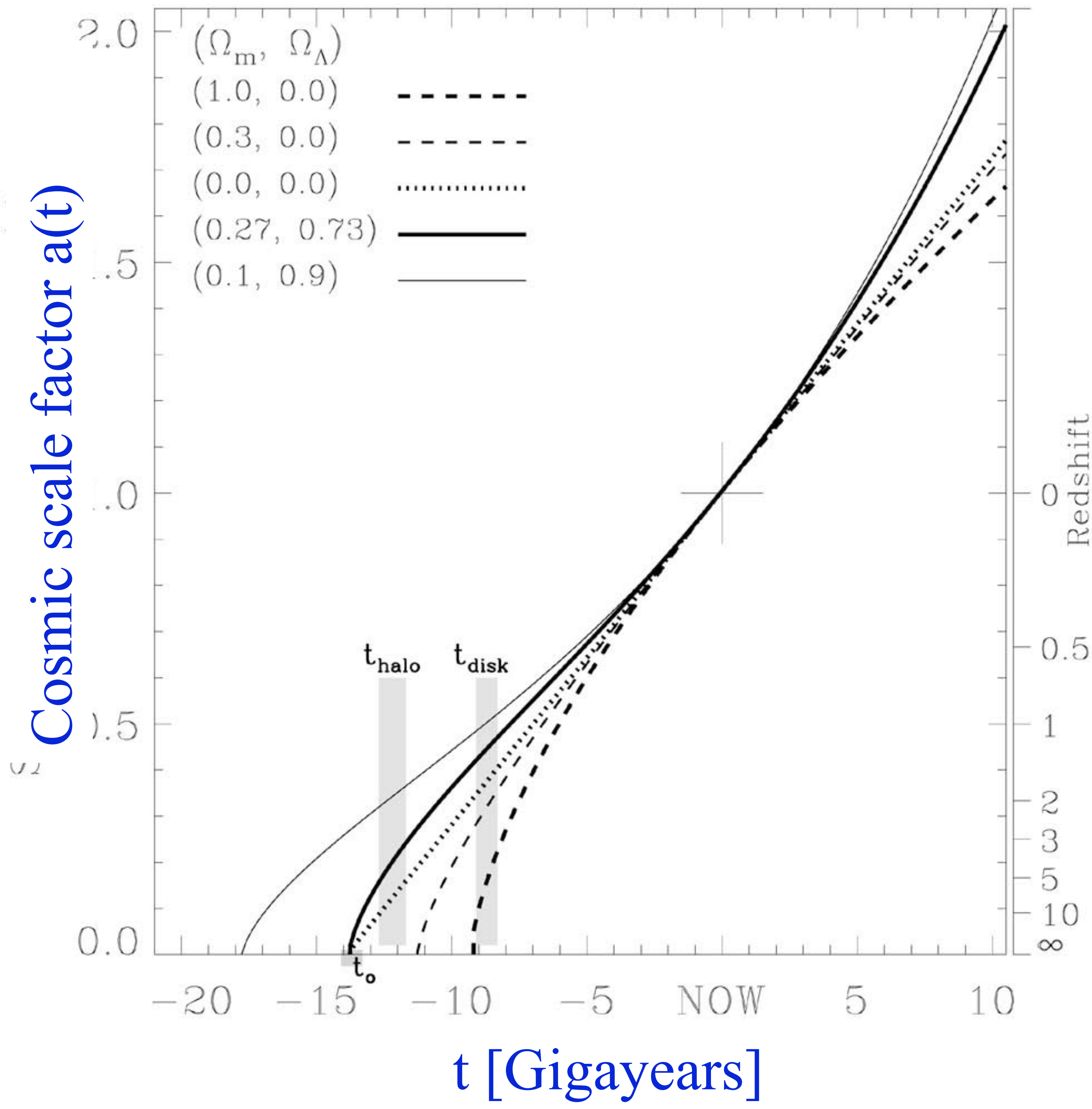
H≈70 km/s/Mpc



How measure distance & redshift?



$q_0 > \frac{1}{2}$
$q_0 = \frac{1}{2}$
$0 < q_0 < \frac{1}{2}$
$q_0 = 0$
Recessional velocities of galaxies
Distance
a
Size of the universe
$1/H_0$
Now
Time
b



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t [Gigayears]
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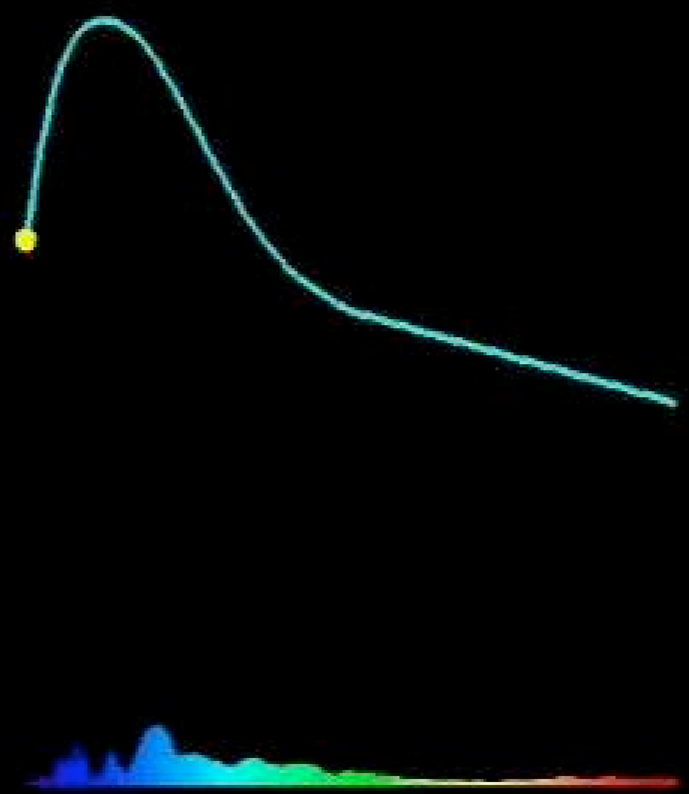
t_{halo}
t_{disk}
t_o
Redshift
0
0.5
1
2
3
5
10
∞
2.0
.5
.0
).5
0.0
−20
−15
−10
−5
NOW
5
10

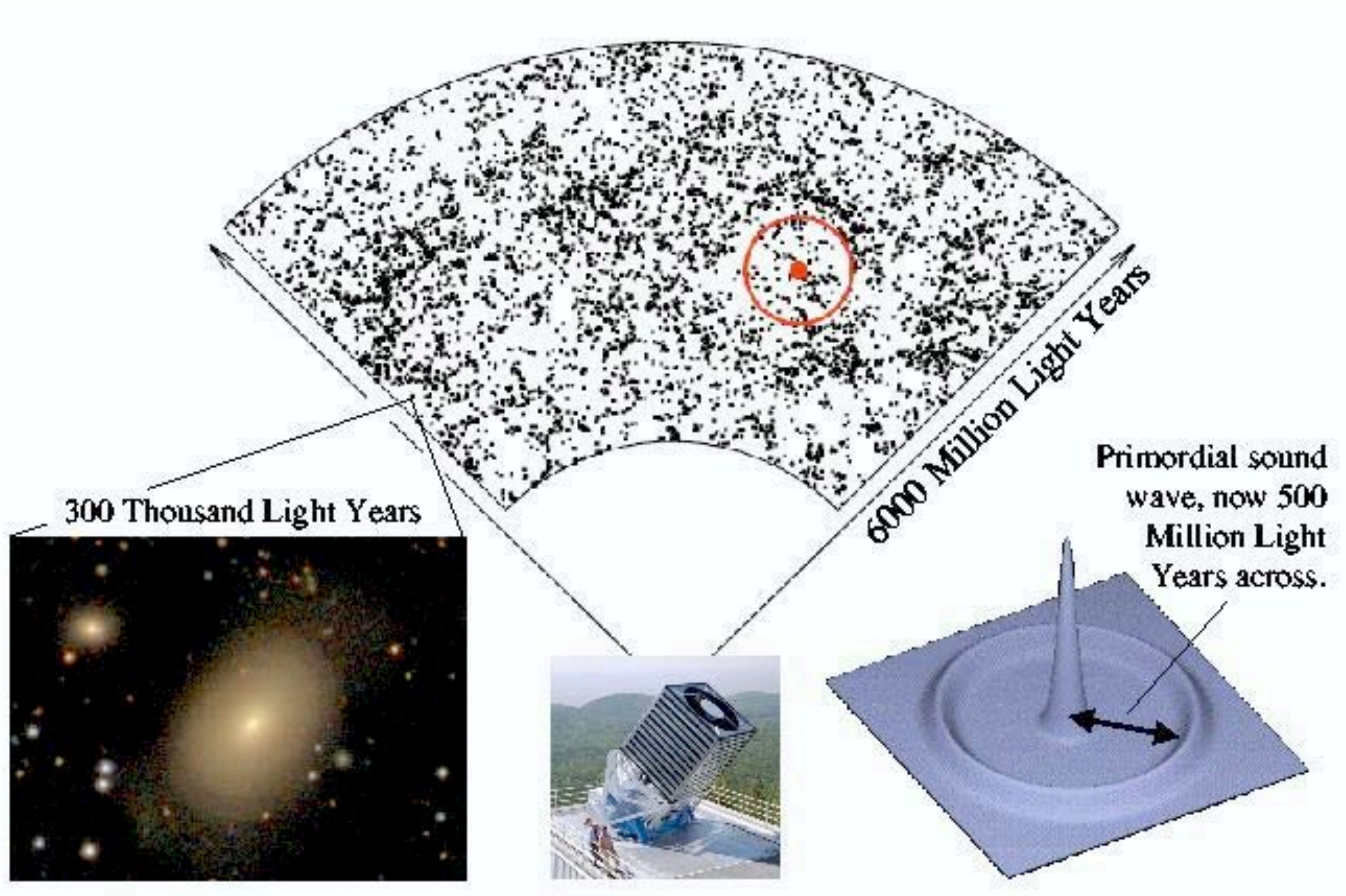
Standardizable candles

(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)



Easiest to understand in real space
(Bashinsky & Bertschinger, PRL, 87, 1301, 2001; PRD 123008, 2002)

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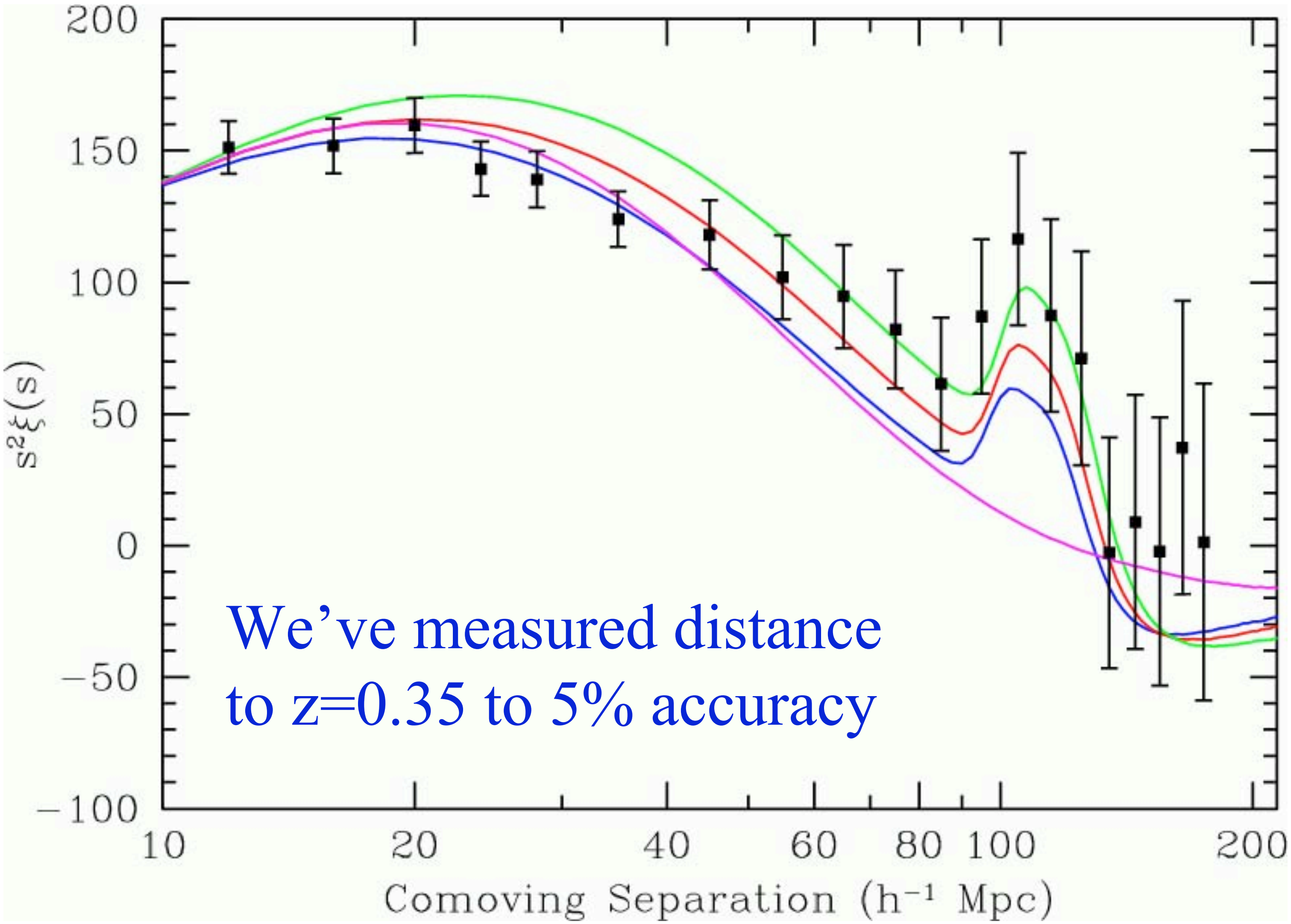
(Eisenstein et al 2005, for the SDSS collaboration astro-ph/050112)



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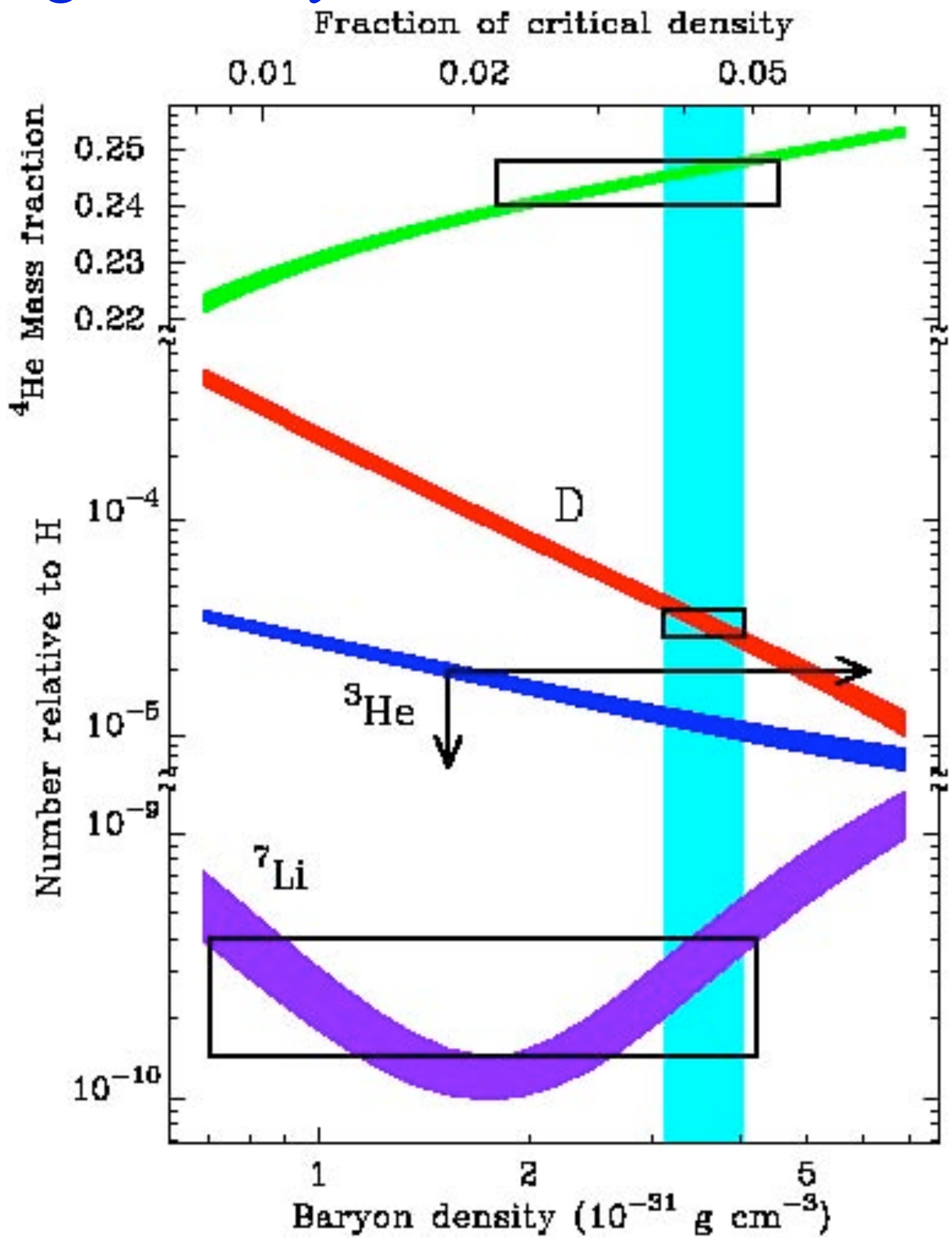
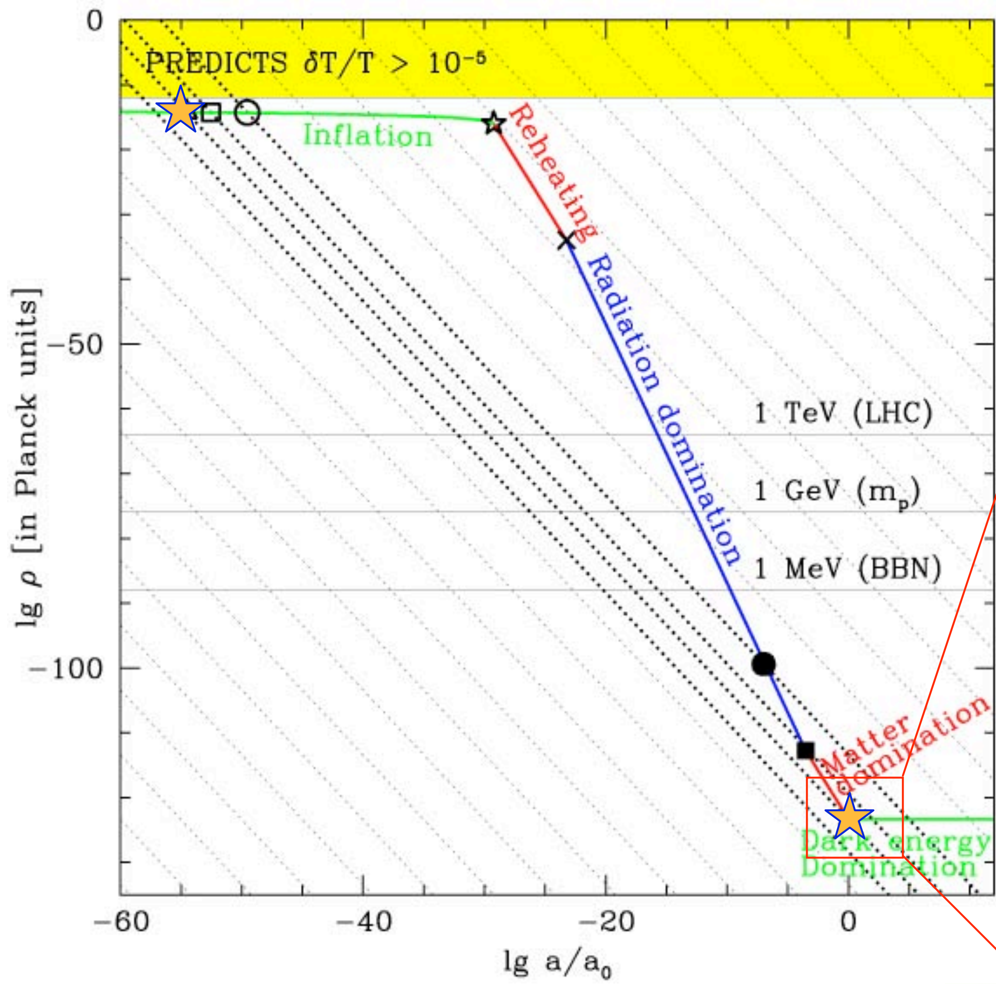
Big Bang nucleosynthesis as a standardizable clock:

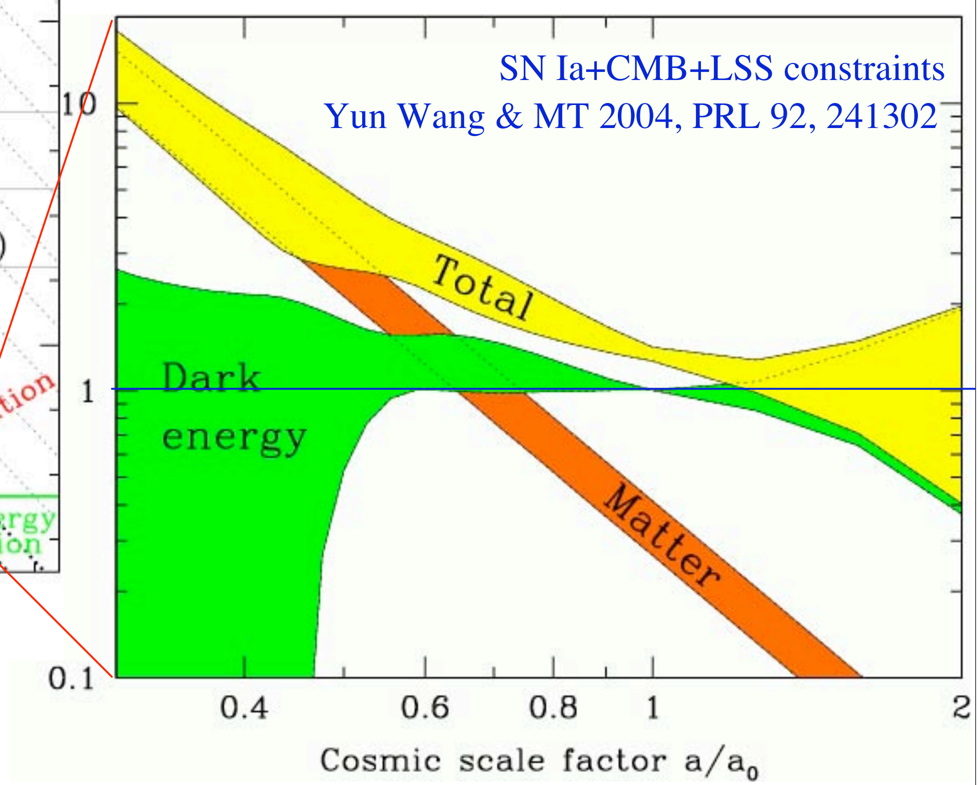


Tytler et al 2000, astro-ph/0001318

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

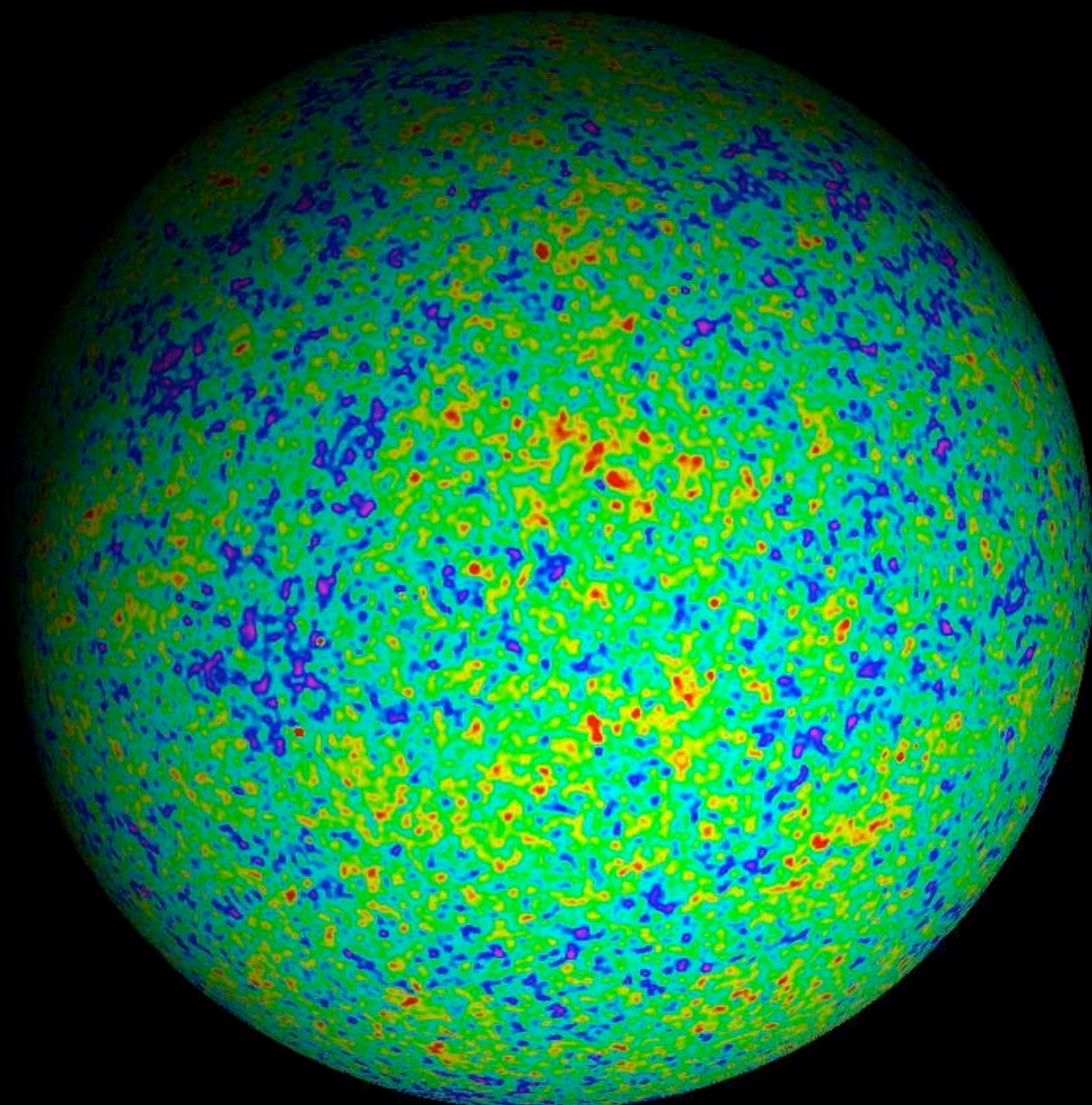
Assumes k=0





Measuring clustering

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



z = 1000

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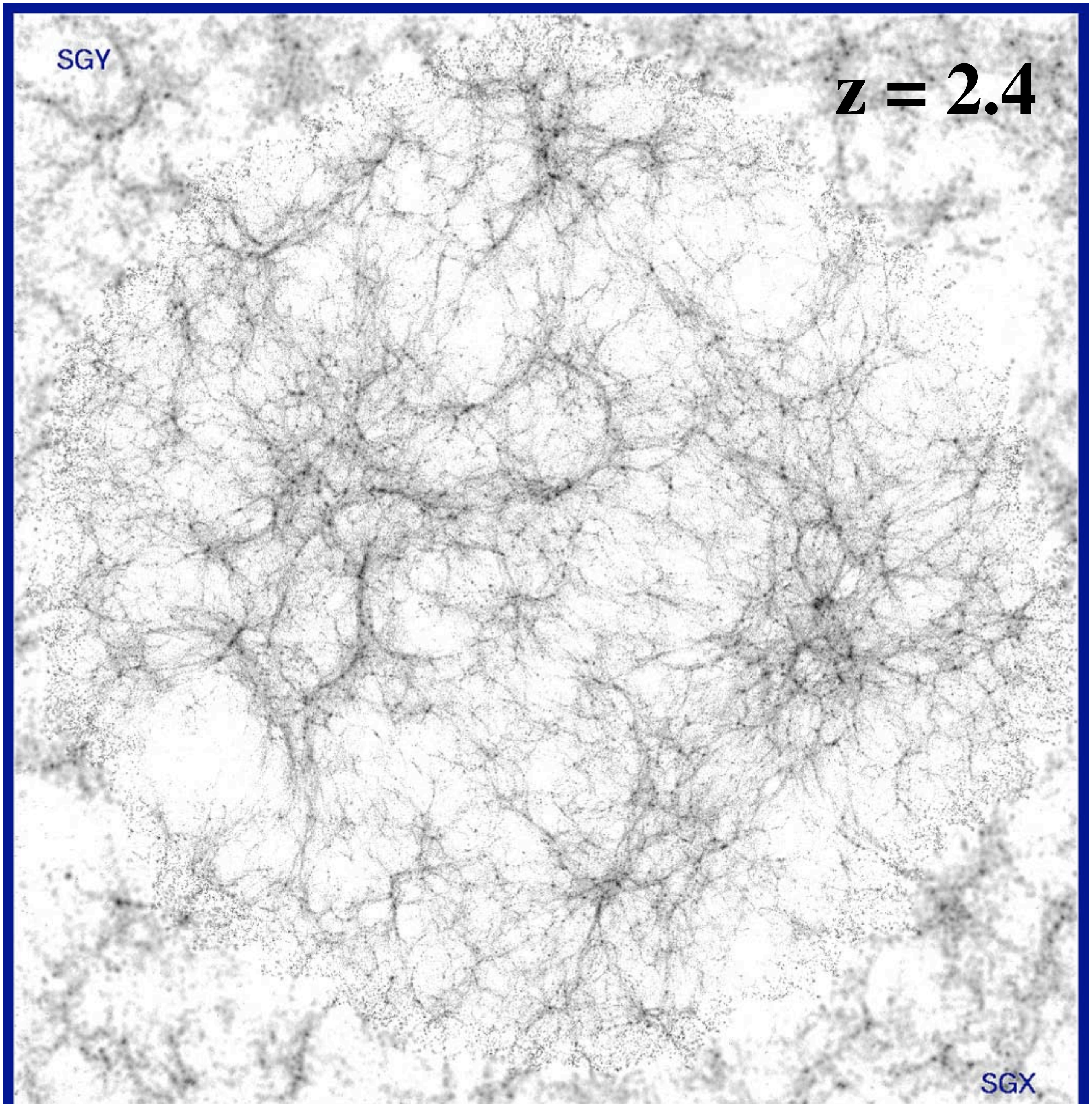
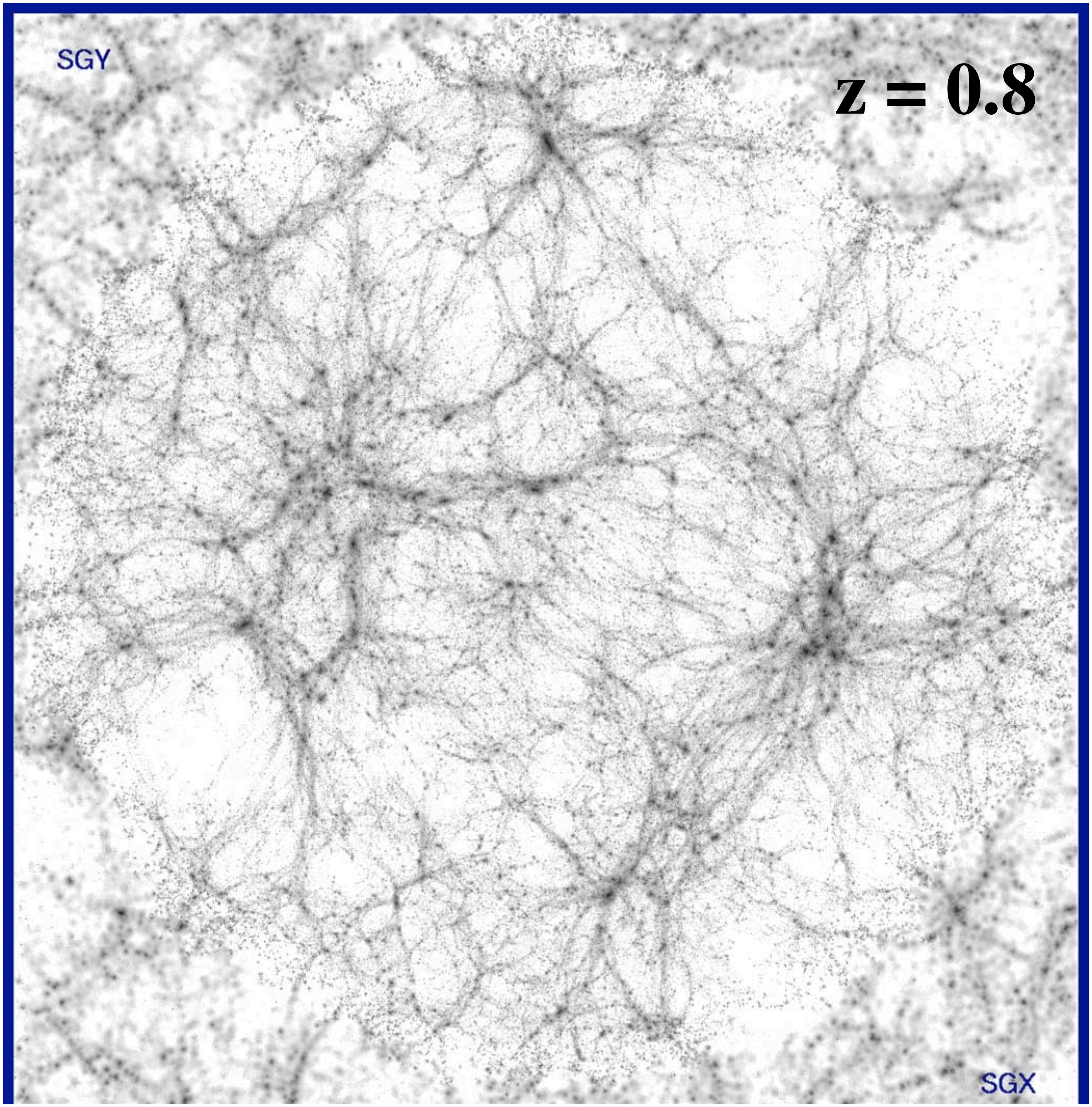
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001





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

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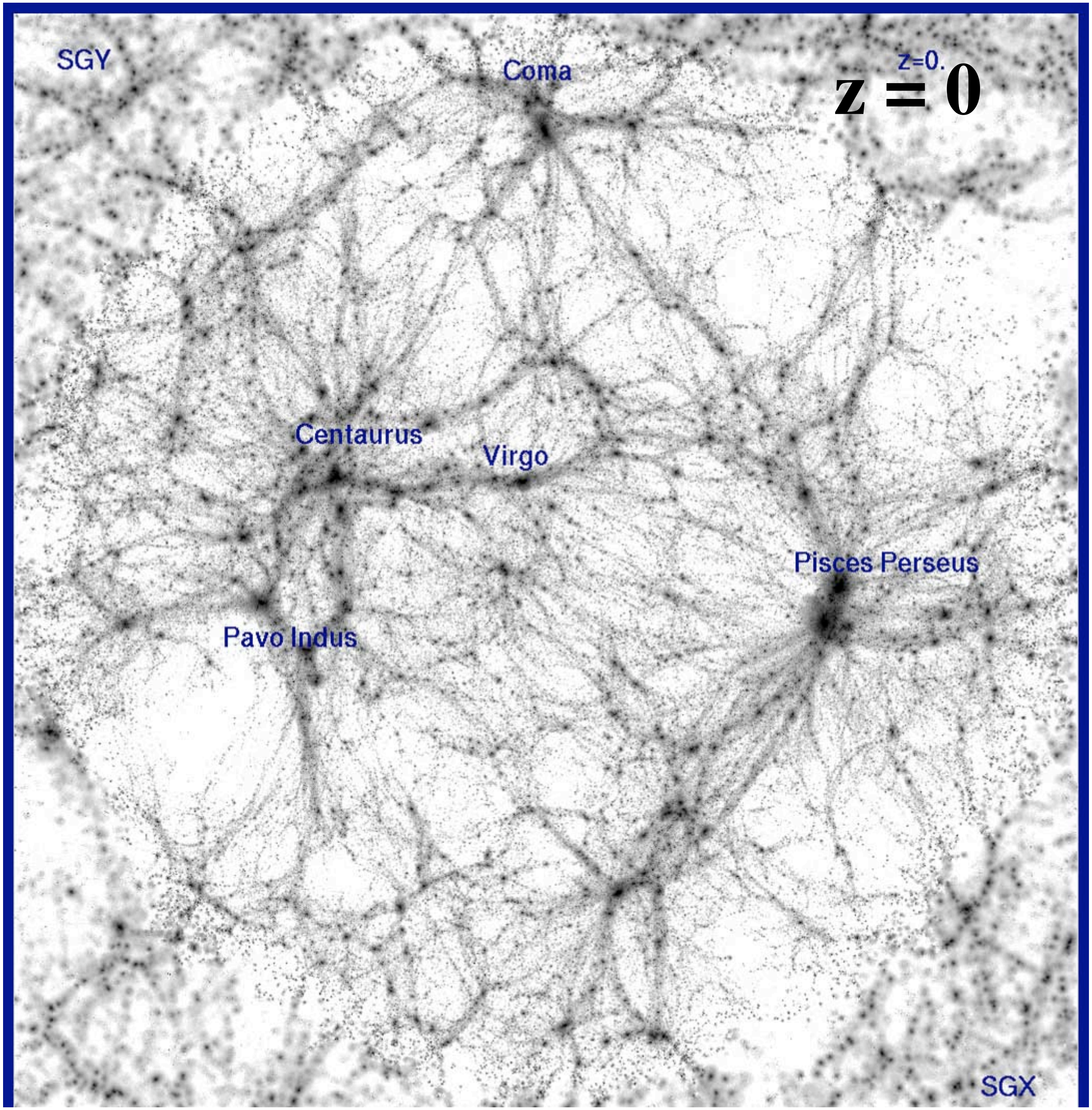
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



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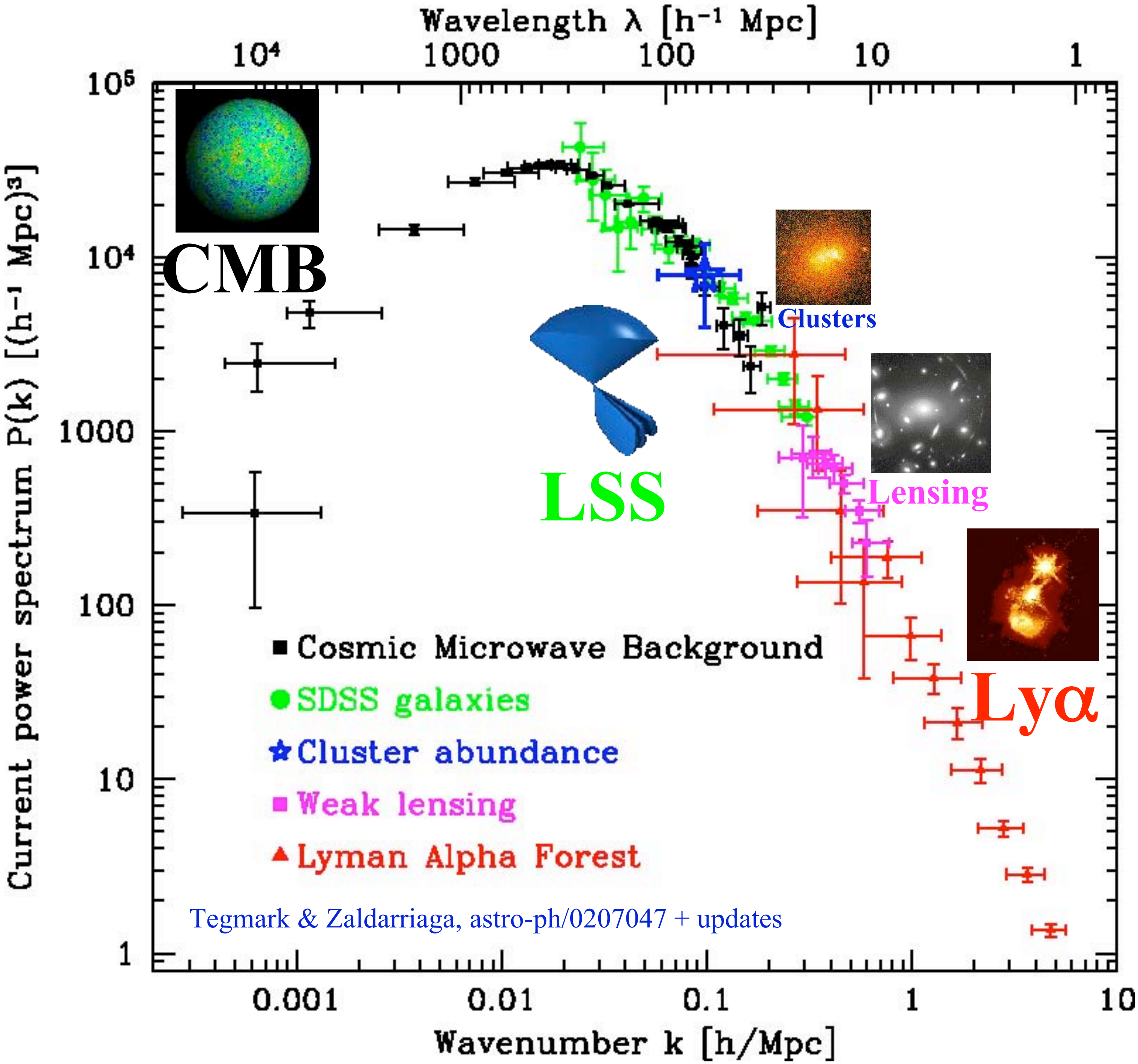

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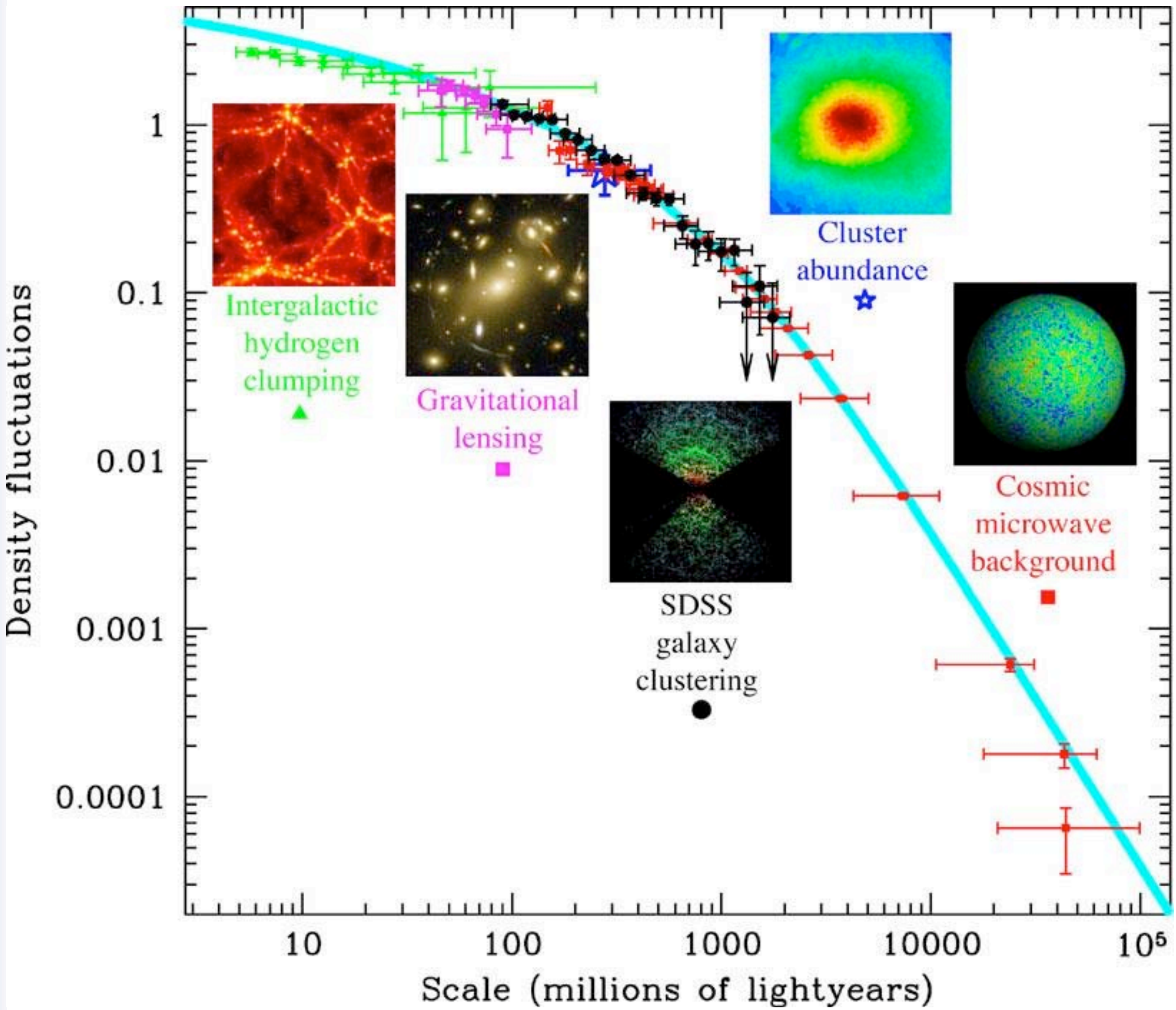

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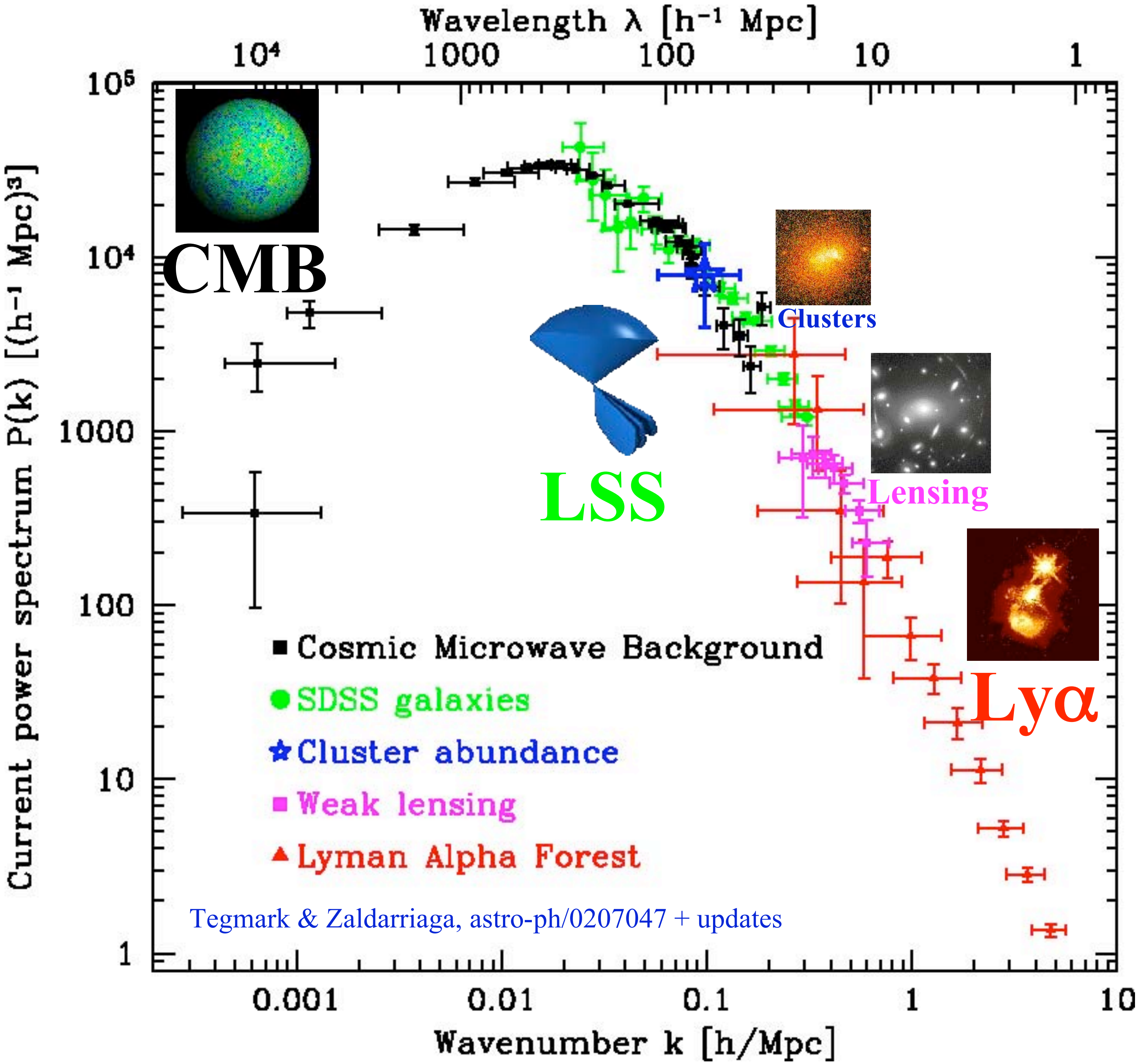

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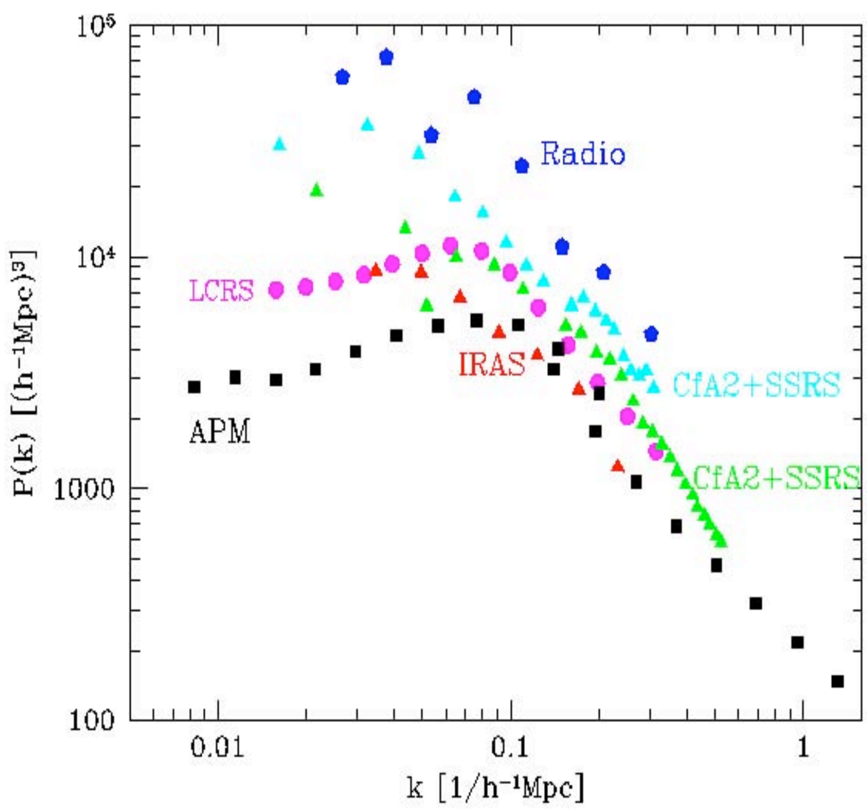

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

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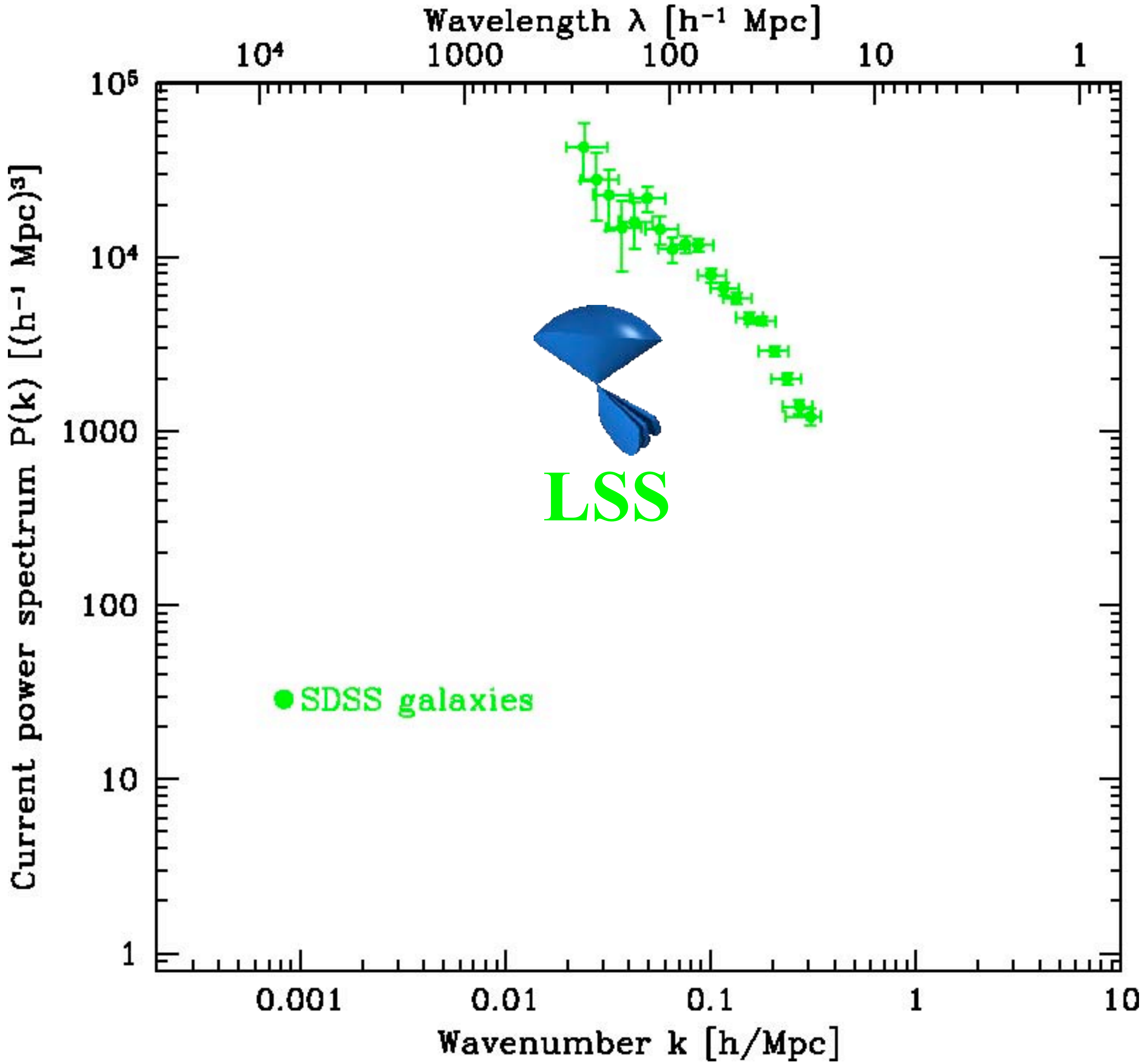

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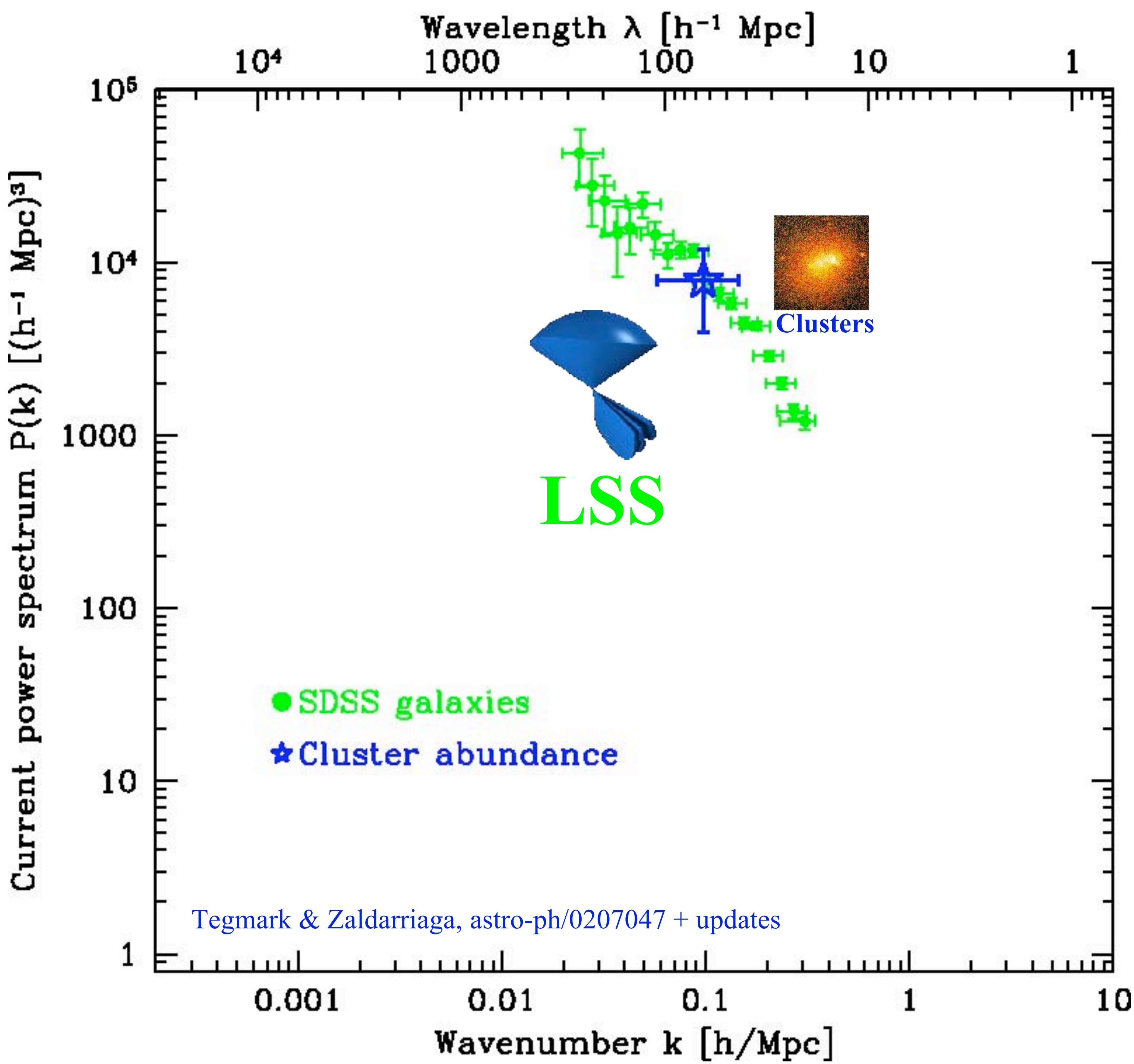

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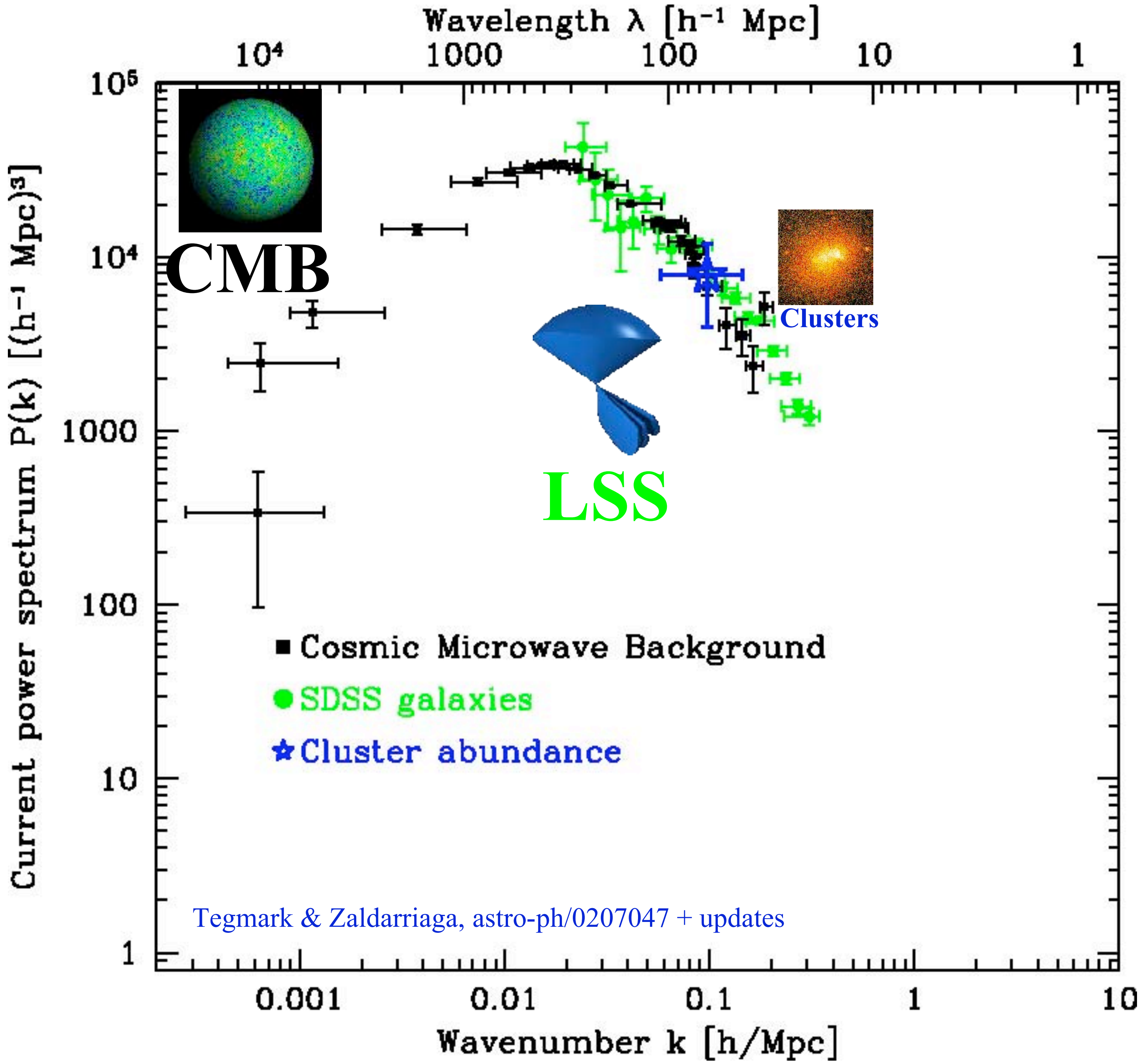

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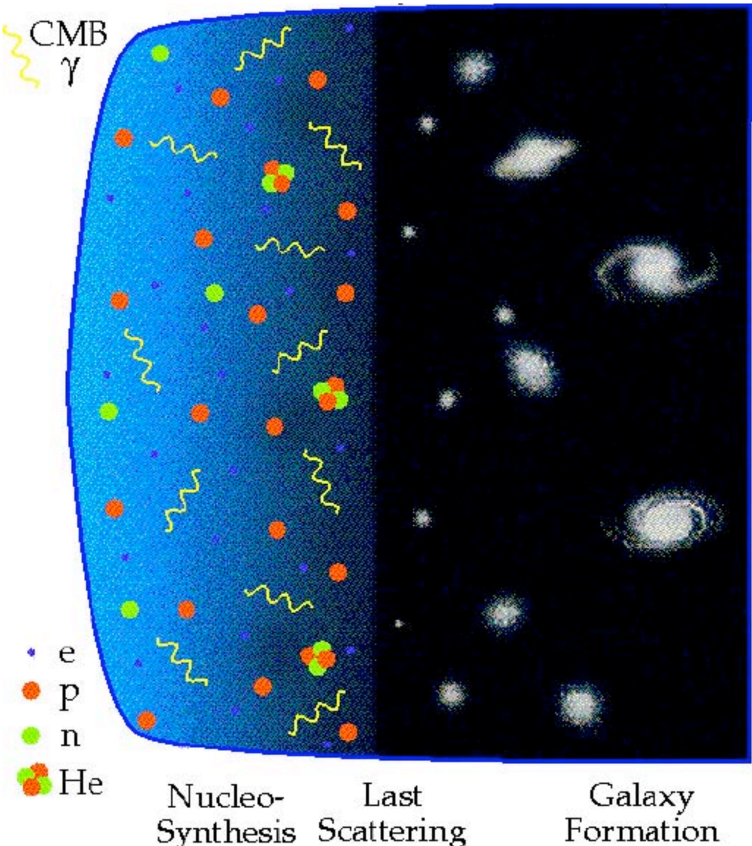
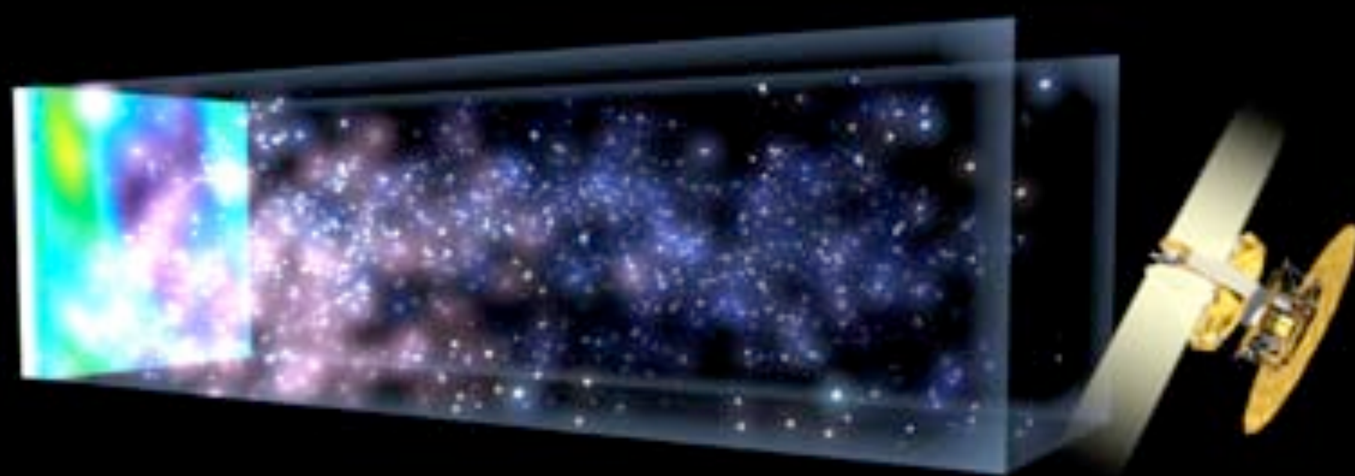
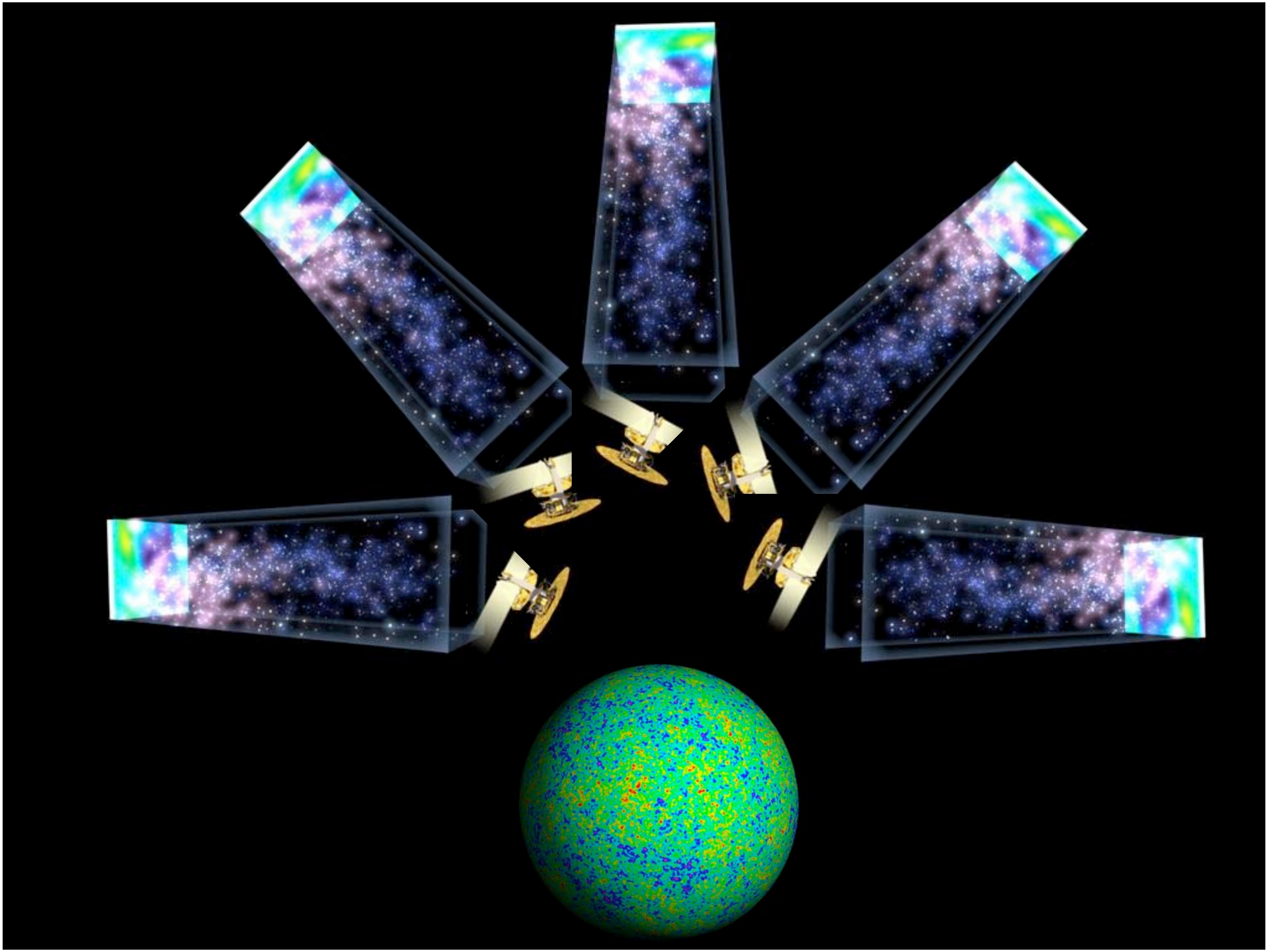


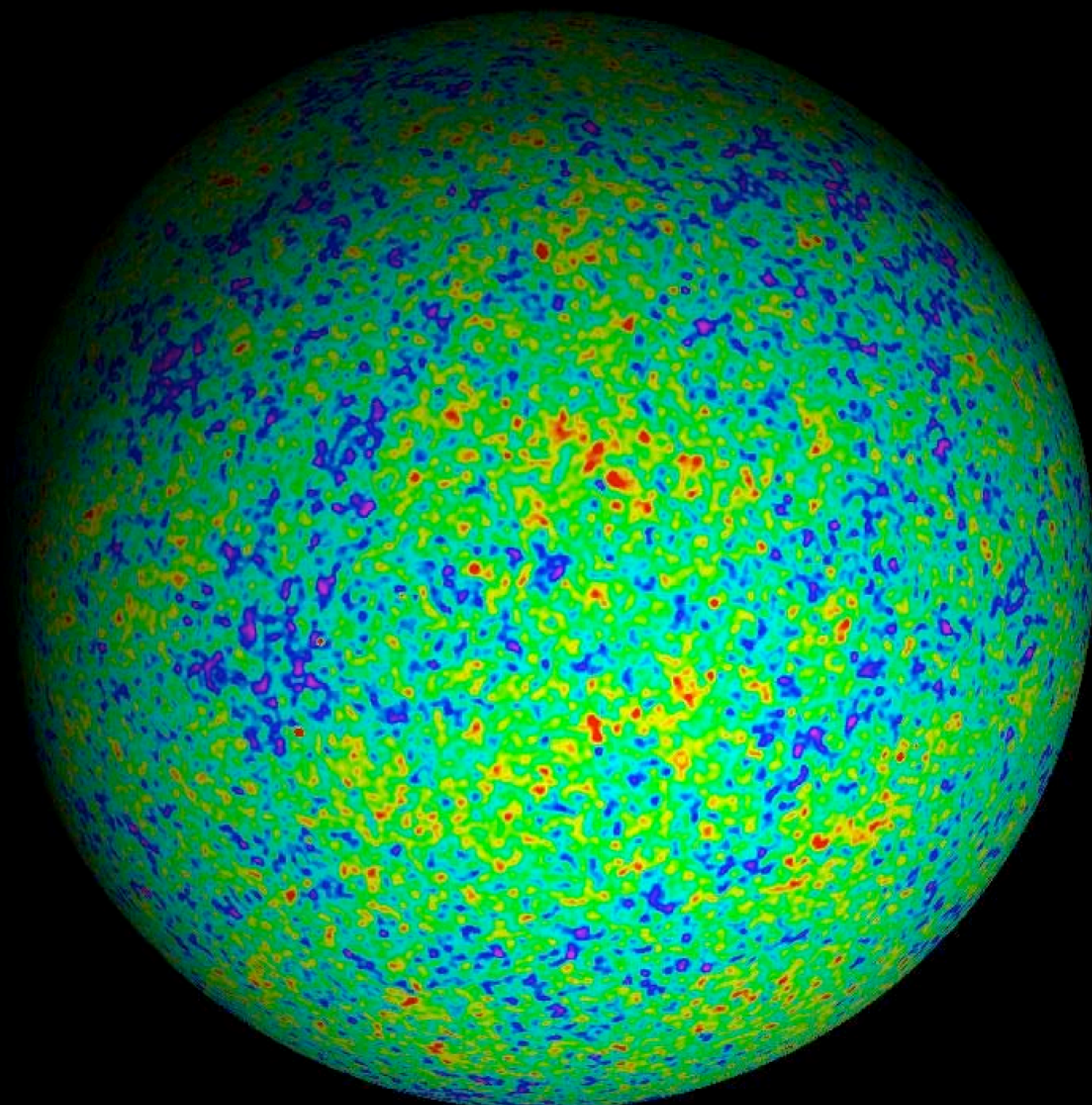
(Figure from Wayne Hu)

(Figure from WMAP team)

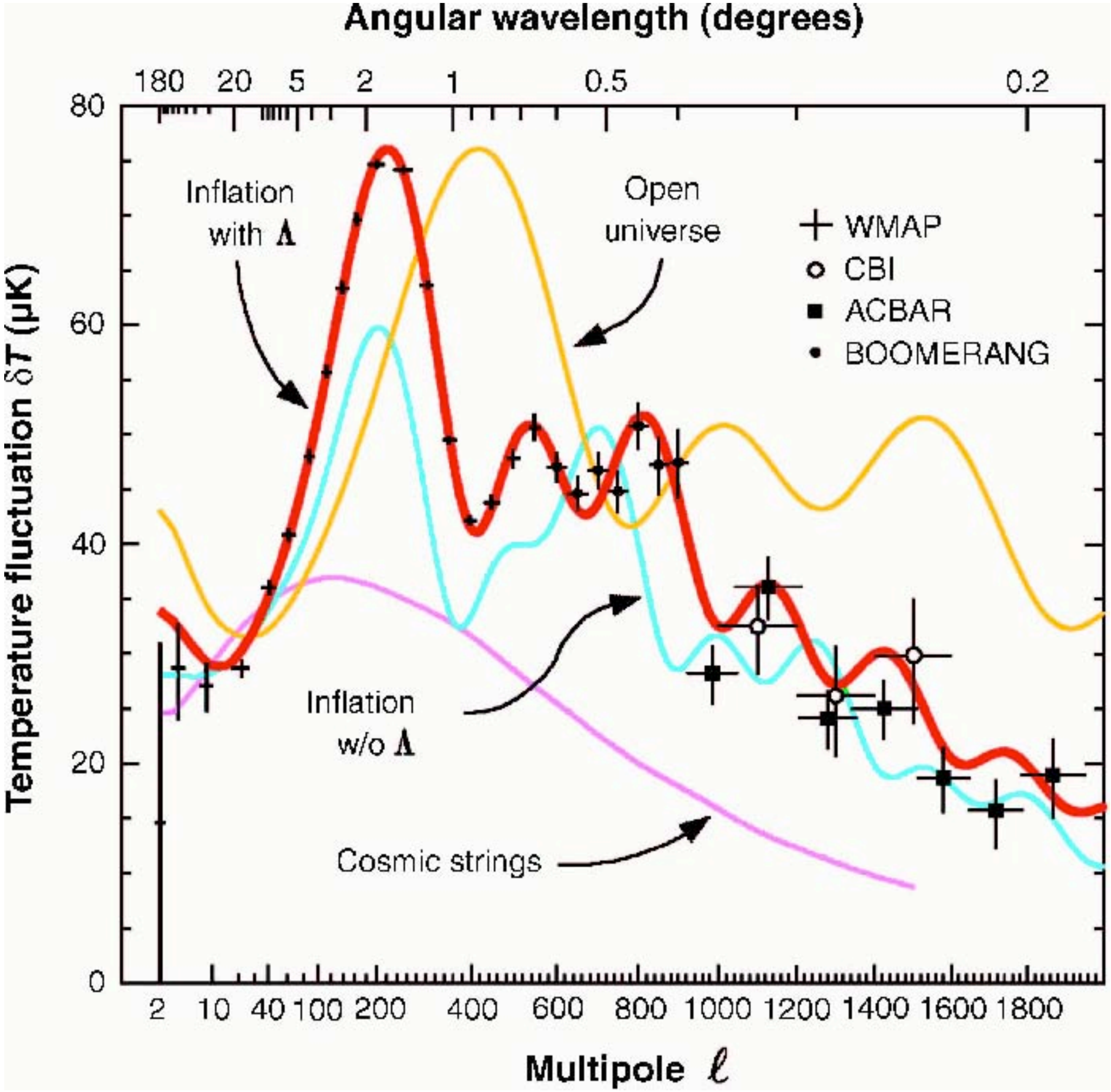




Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/030249



Guth & Kaiser 2005, Science



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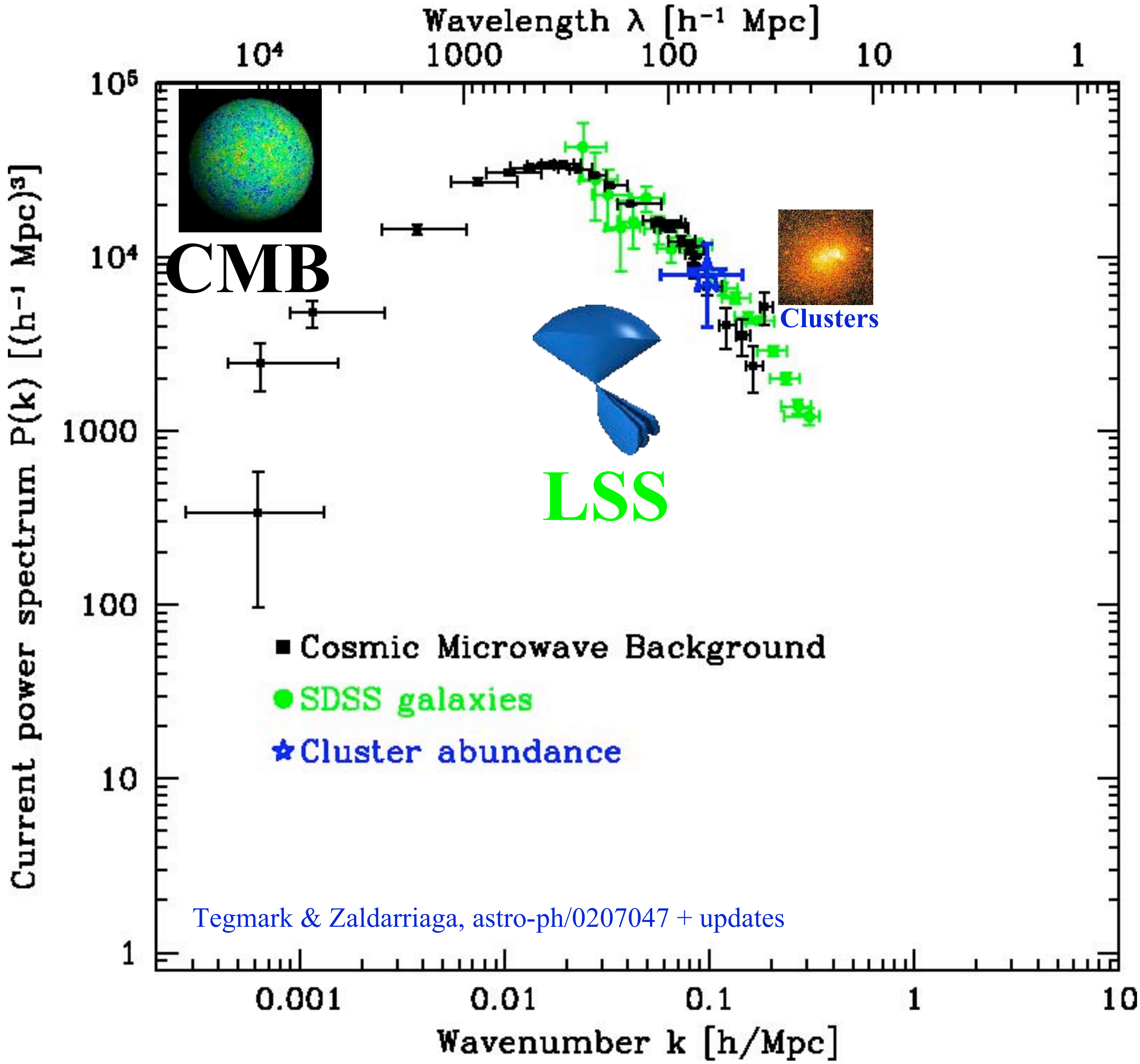

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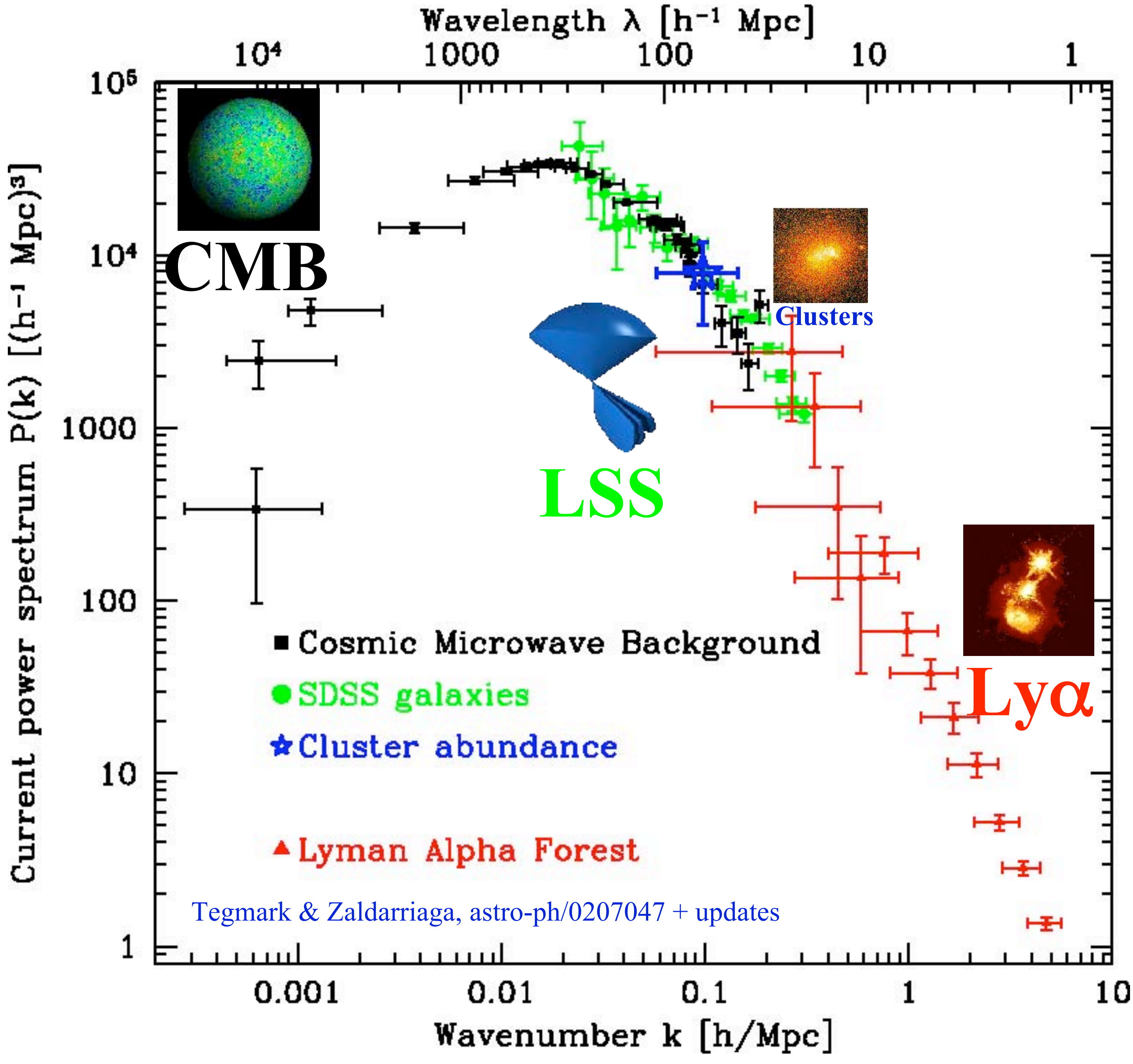

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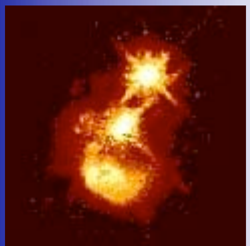
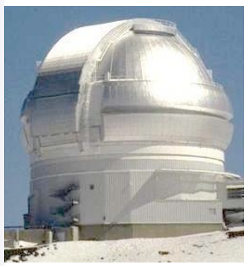
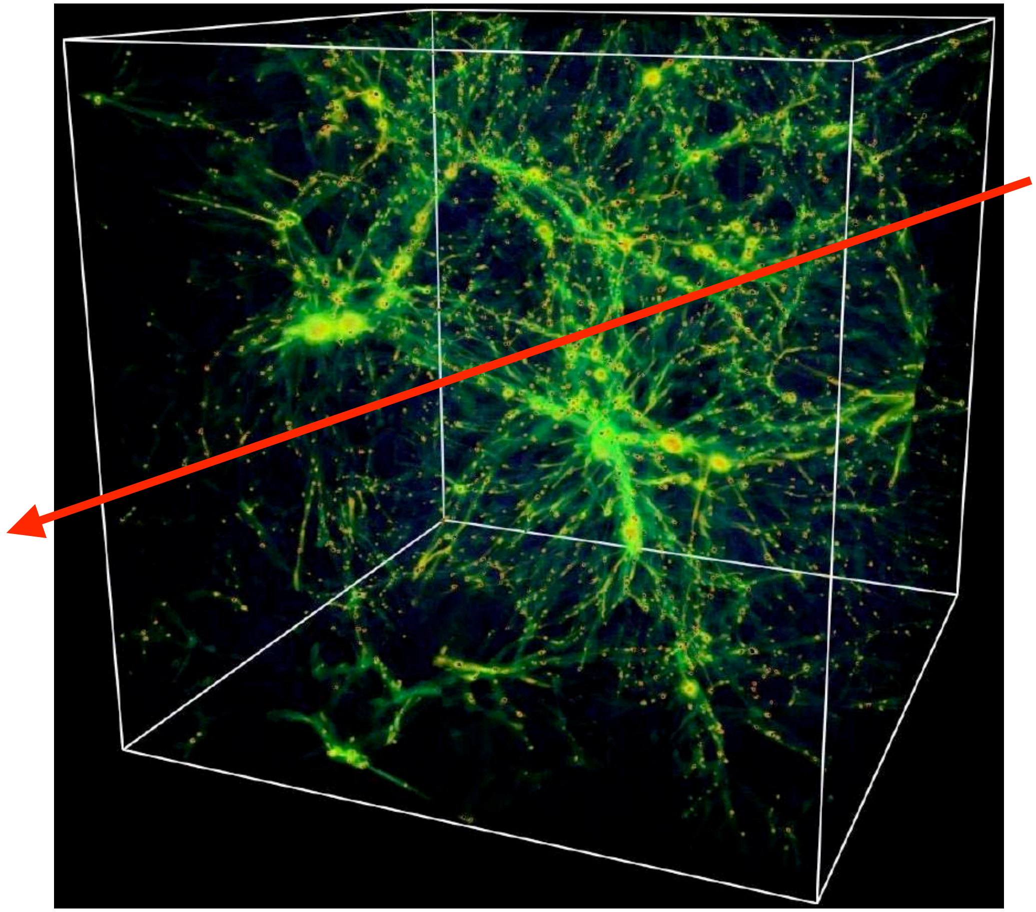


LyαF

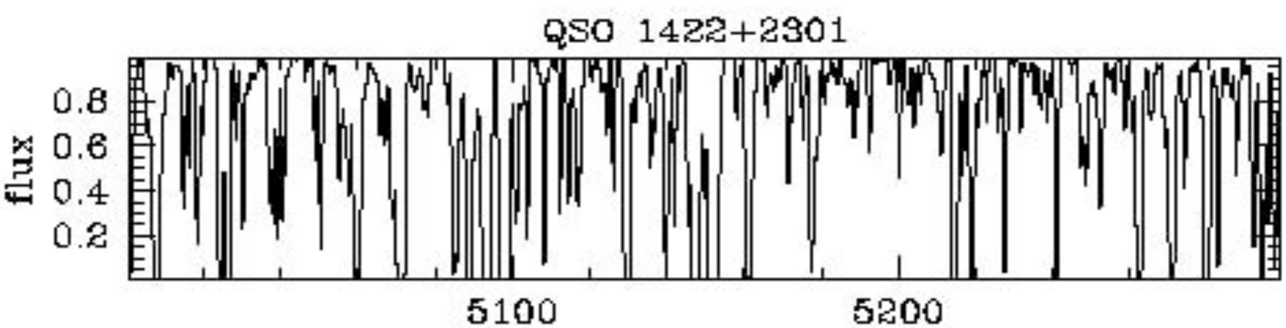
Lyman Alpha Forest Simulation: Cen et al 2001



You



Quasar



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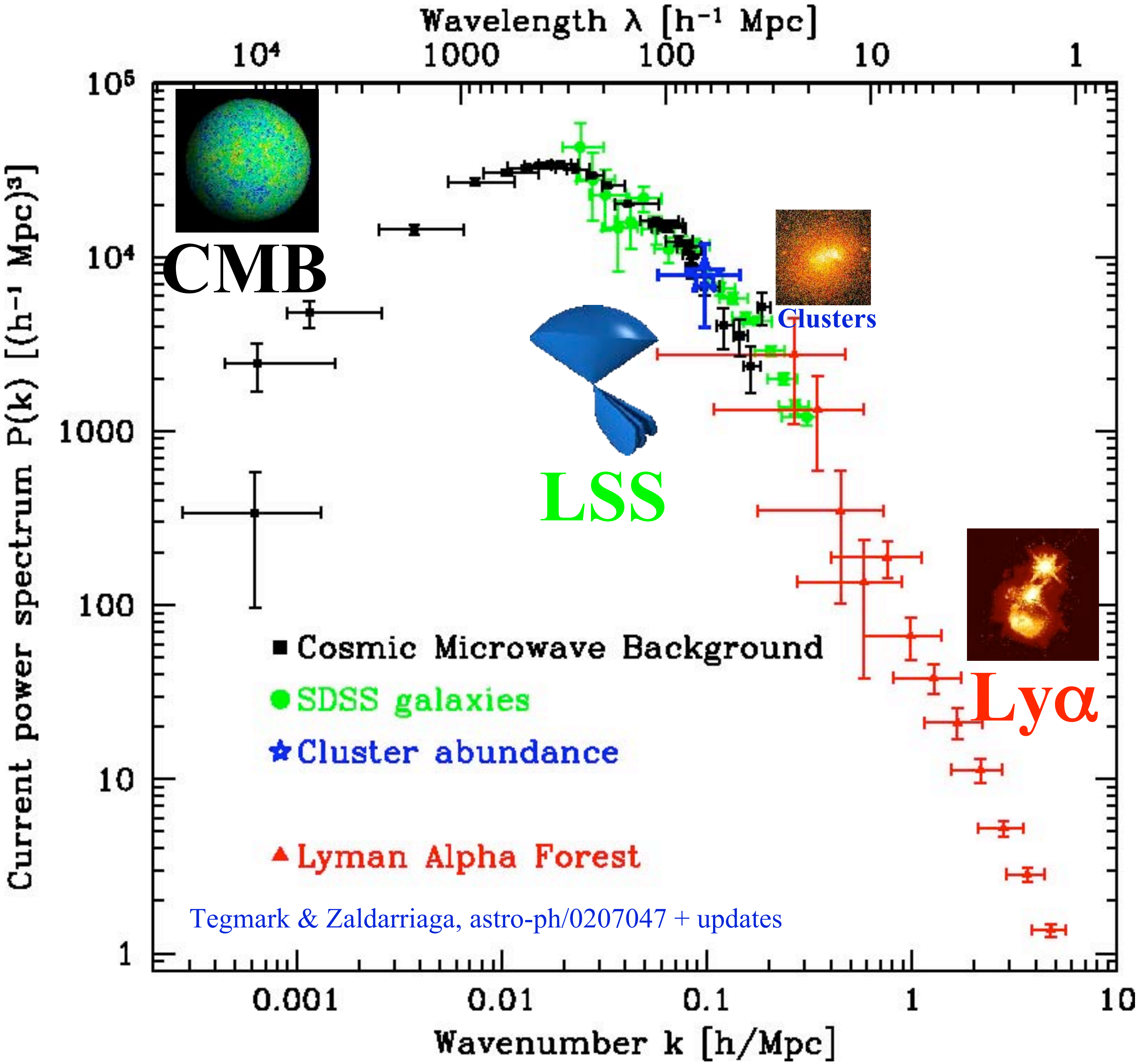

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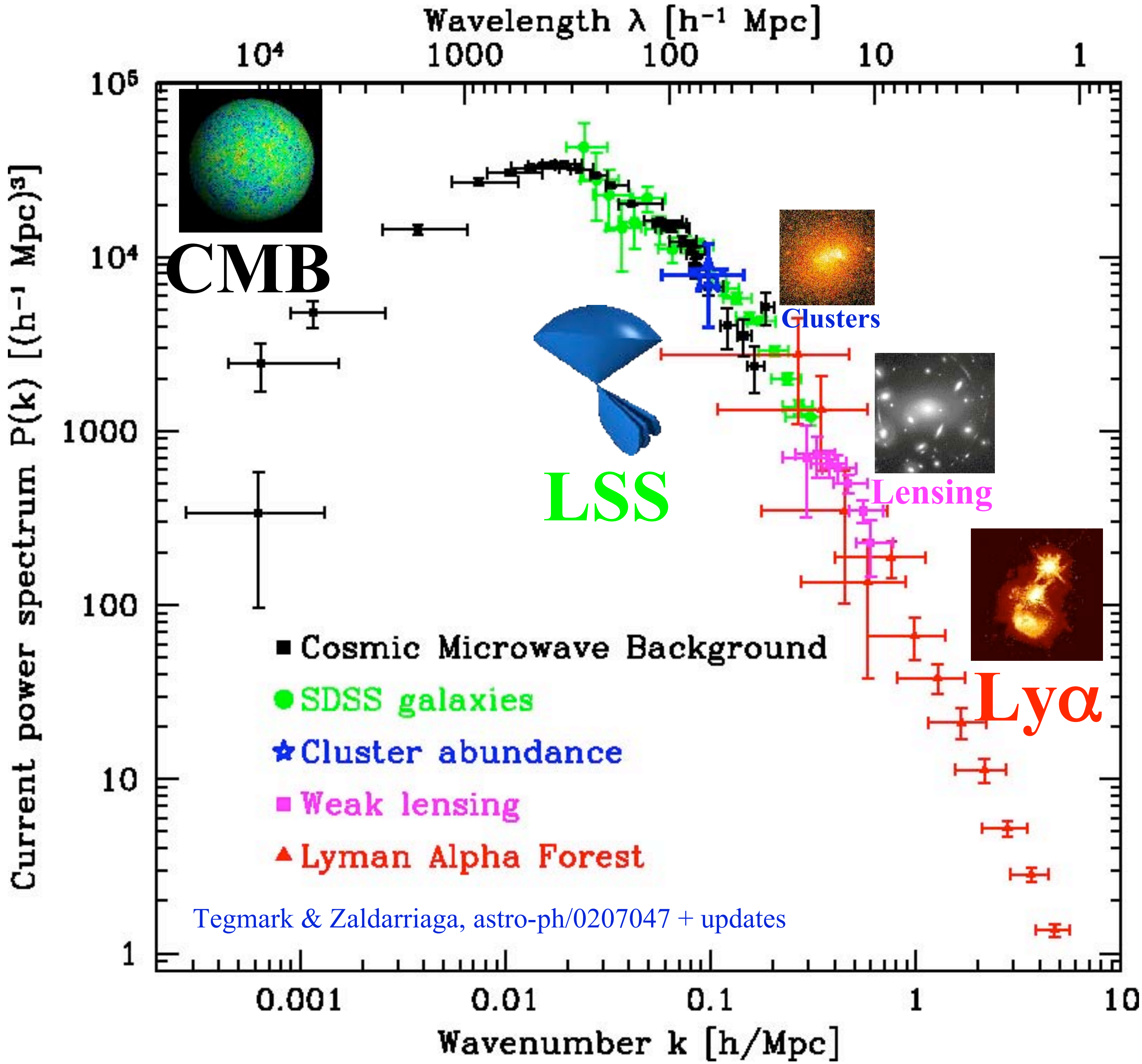

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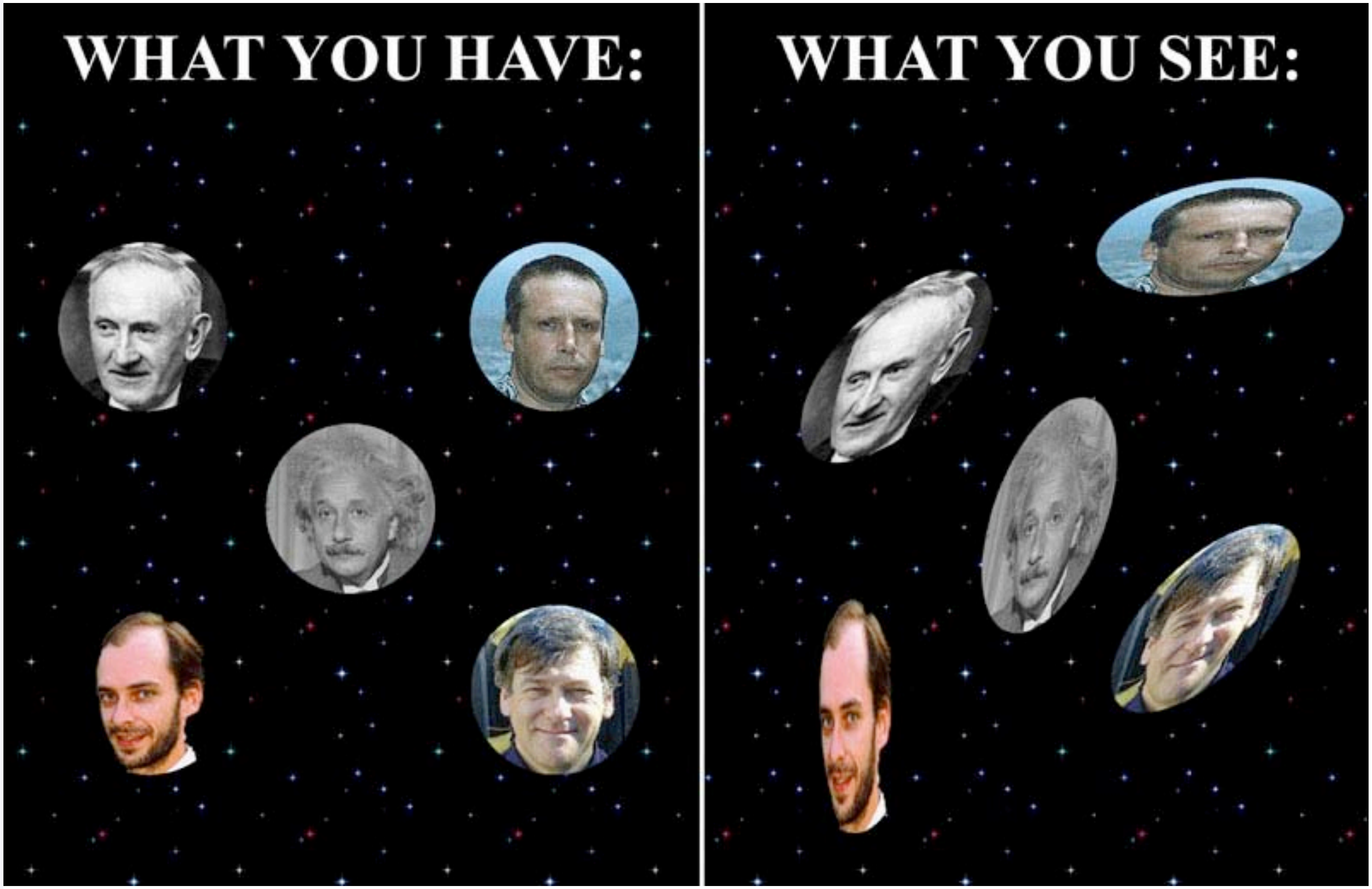
GRAVITATIONAL LENSING:
A1689 imaged by Hubble ACS, Broadhurst et al 2004

Lensing



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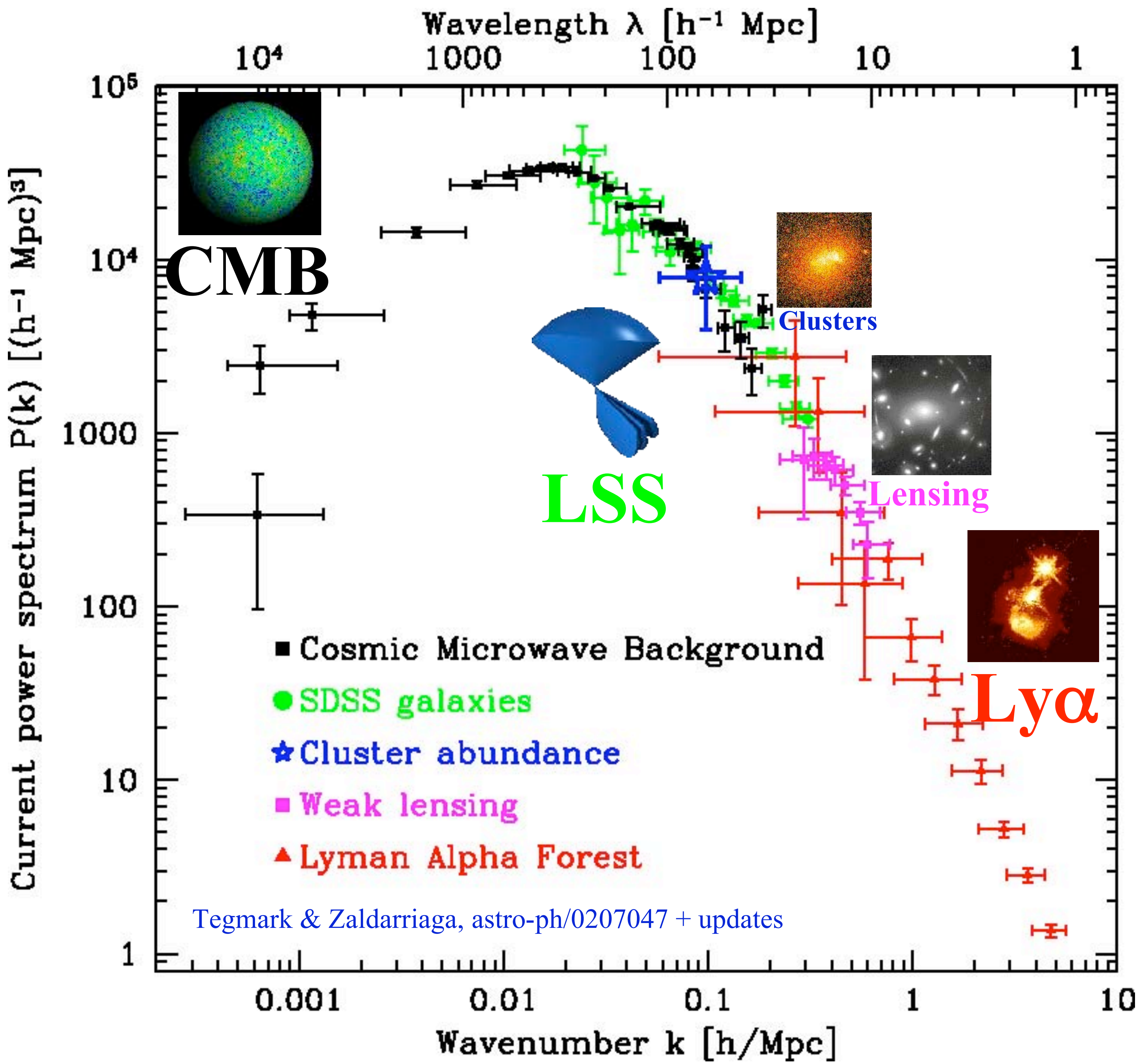

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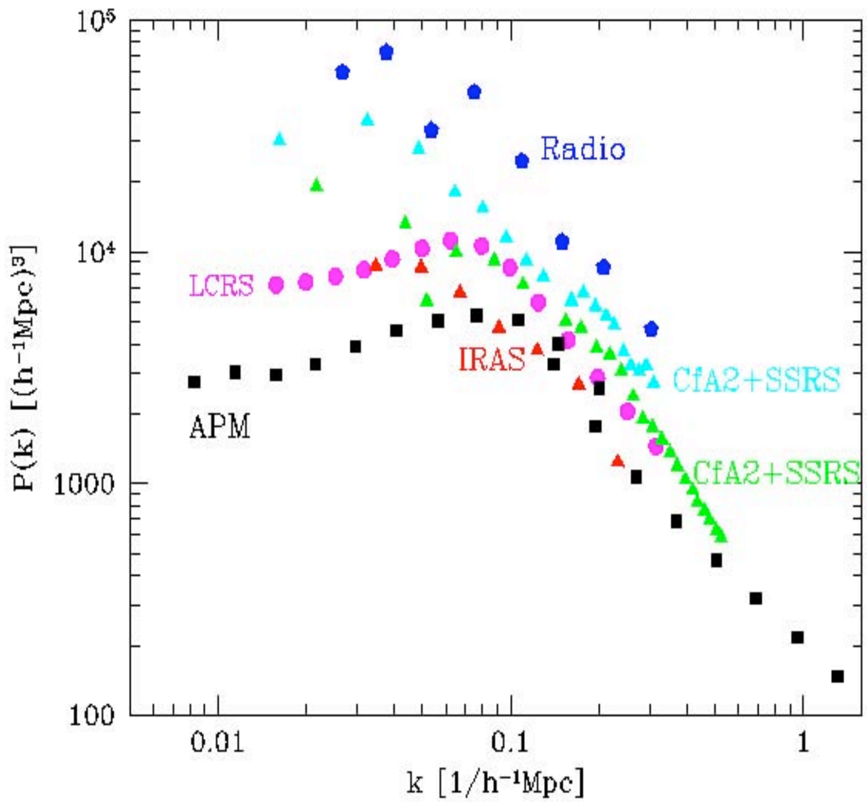

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

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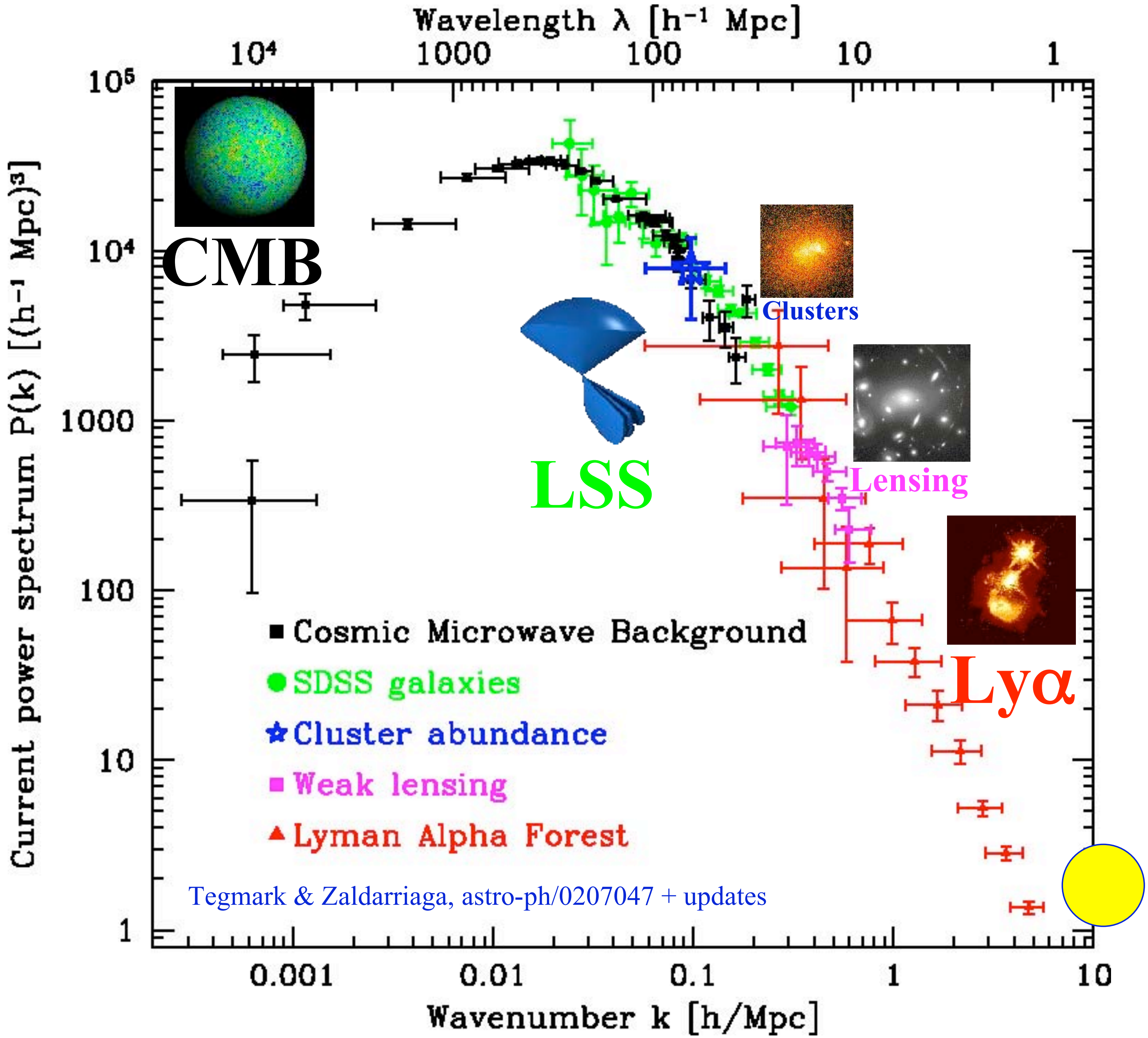

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But the best is yet to come…

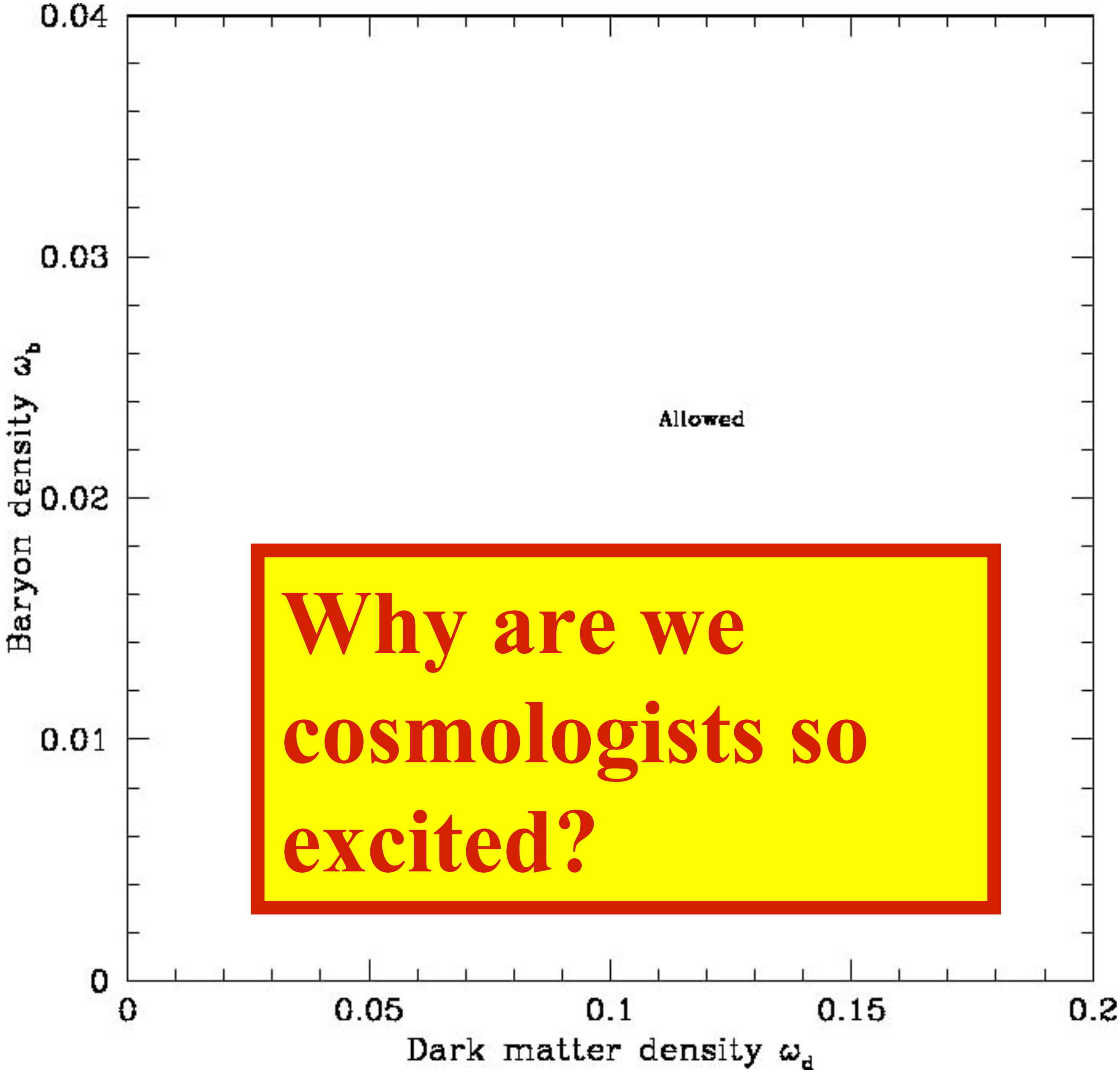
Measuring cosmological parameters

Cosmological parameter movies available at

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

How much dark matter is there?

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



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

Why are we cosmologists so excited?

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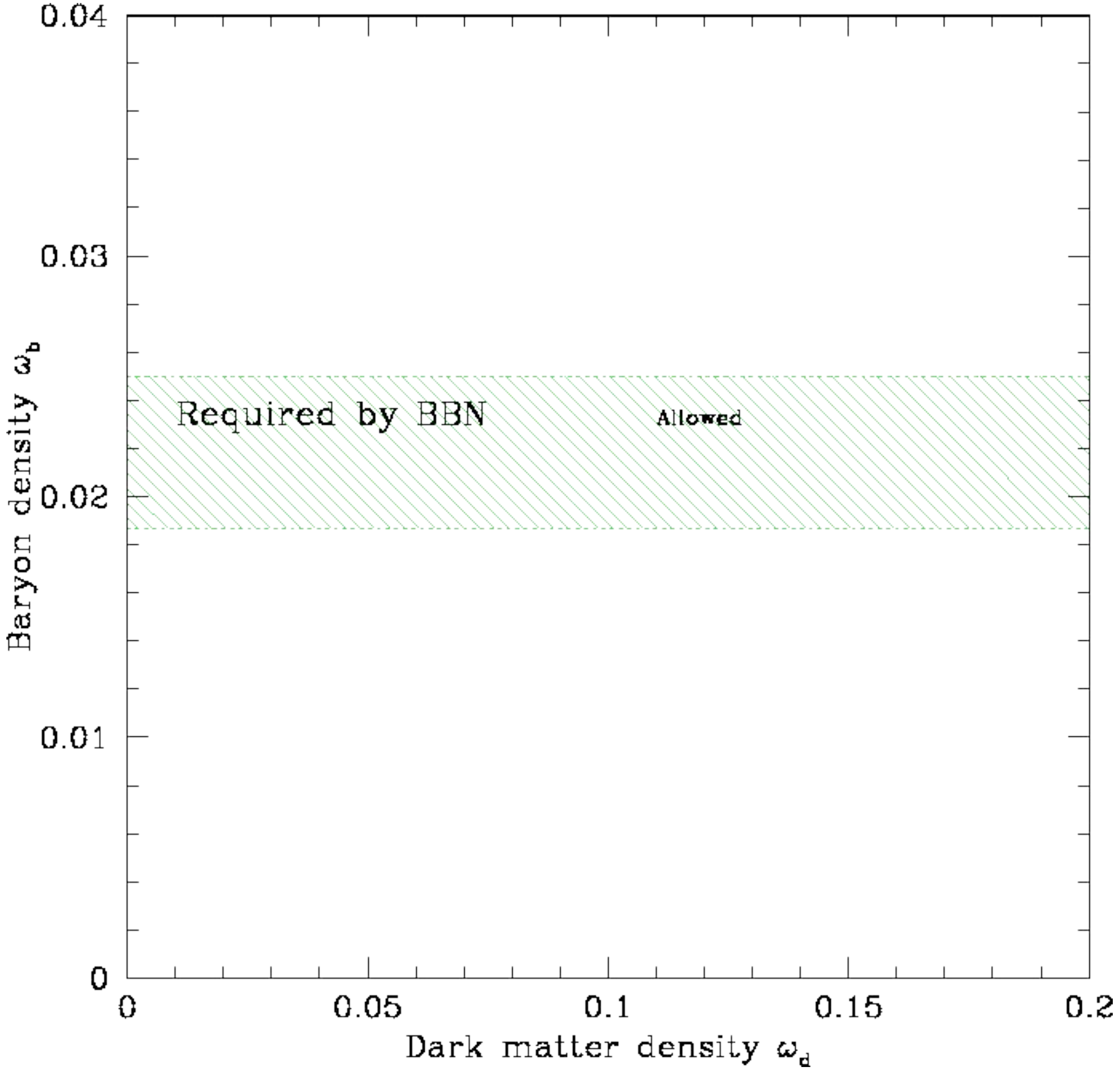

$\rho_b\,/(1.8788\times10^{-26}\ \mathrm{kg\ m^3})$

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

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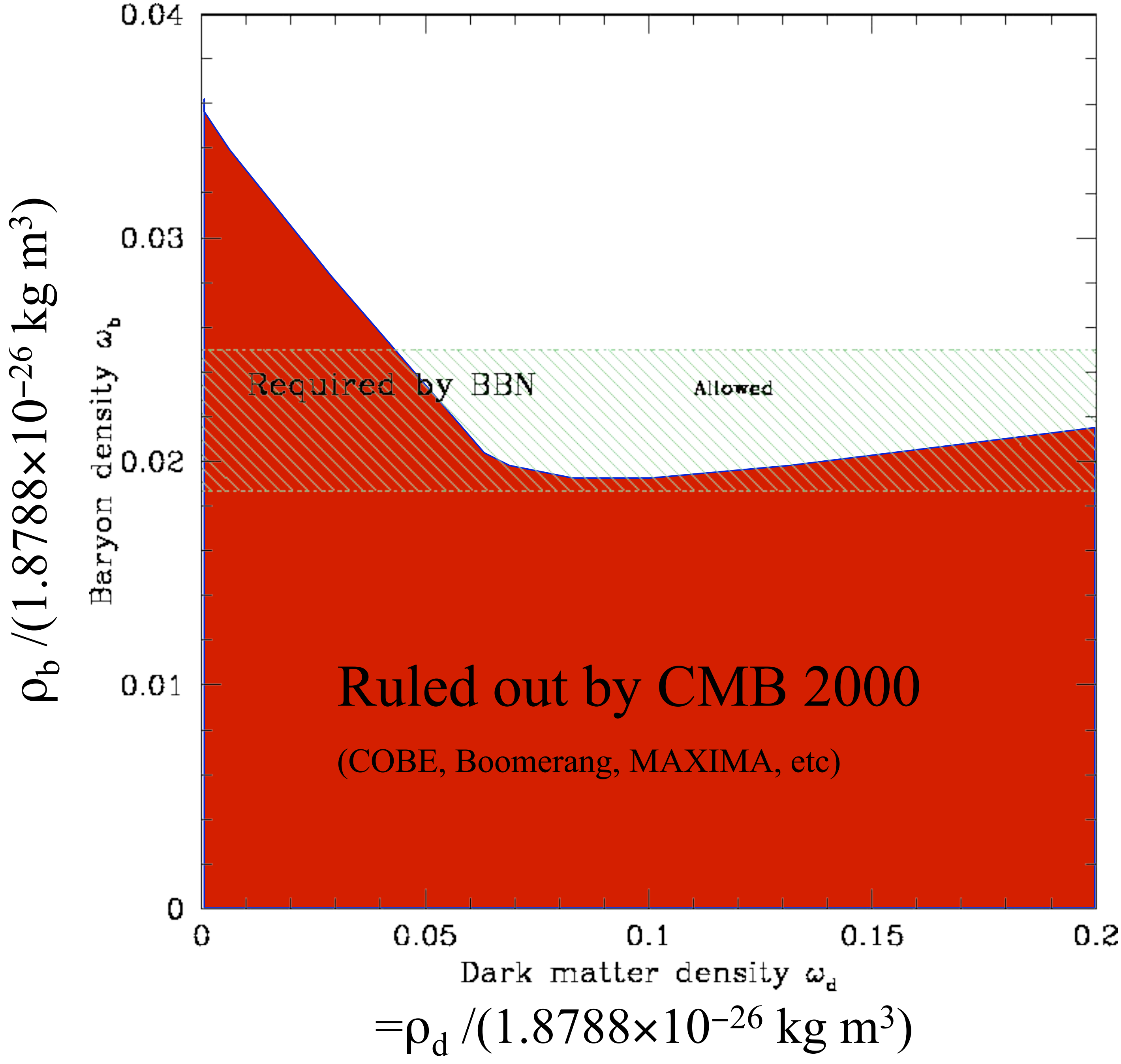

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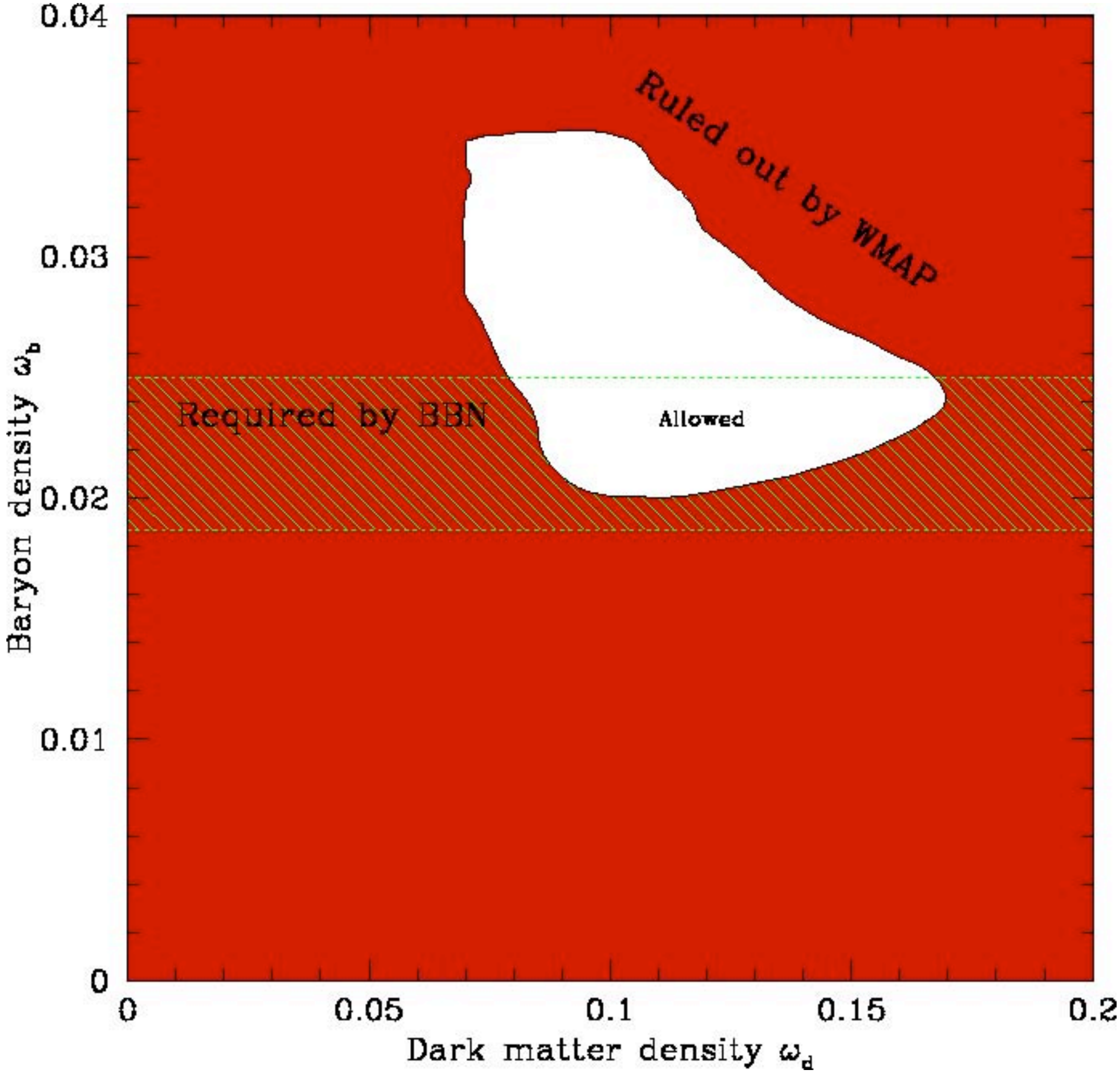

$\rho_b/(1.8788\times10^{-26}\ \mathrm{kg\ m^3})$

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

CMB

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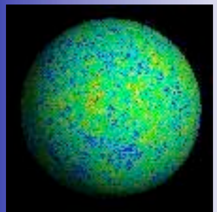
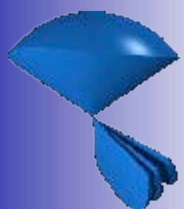
How much dark matter is there?



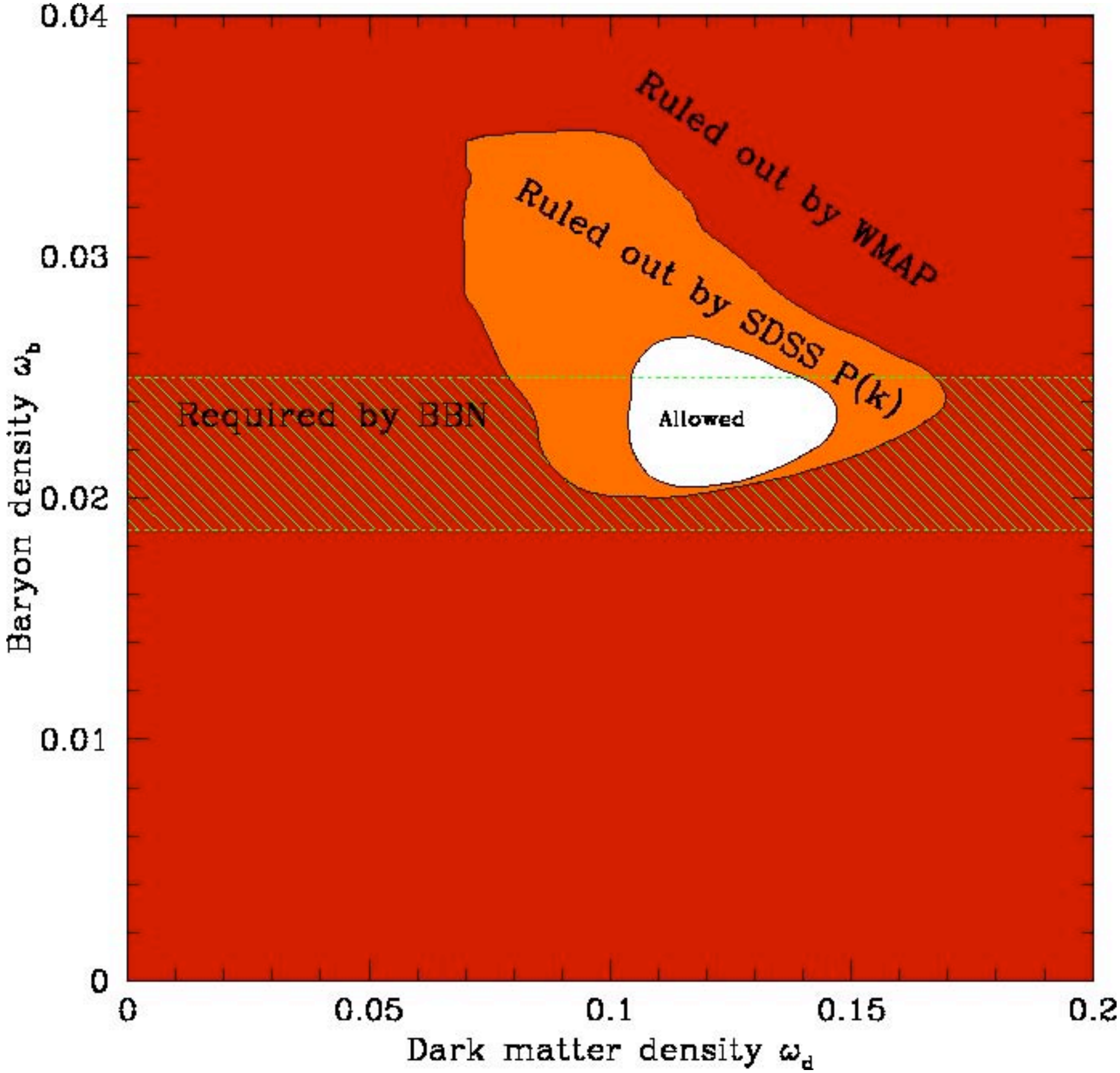
CMB

+



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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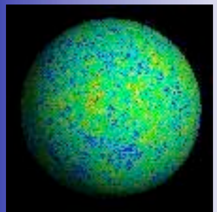
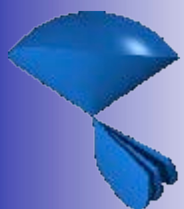
How much dark matter is there?



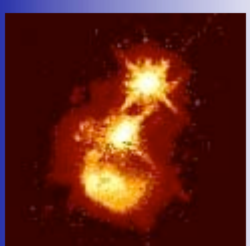
CMB

+



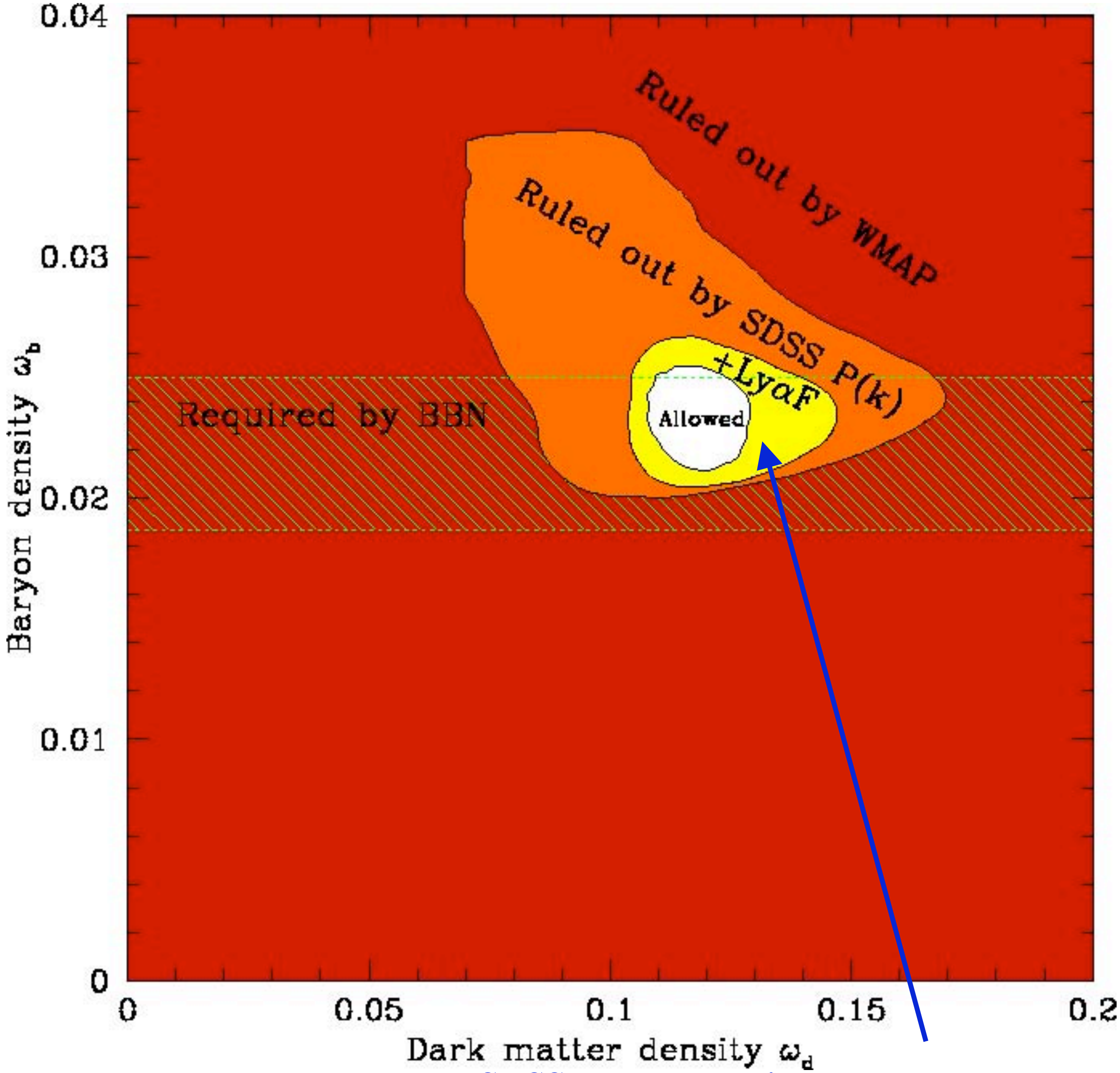
P(k)

+

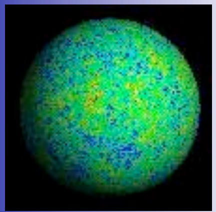


LyαF

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



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



CMB

	Using WMAP temperature and polarization information						No pol.
	6par+$\Omega_k+r+\alpha$	6par+Ω_k	6par+r	6par+f_ν	6par+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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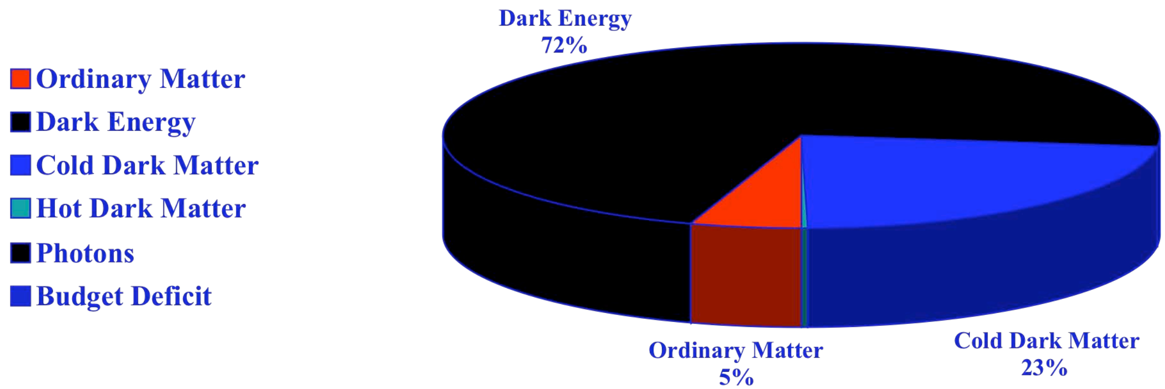
	Using SDSS + WMAP temperature and polarization information						No pol.	No WMAP
	6par+$\Omega_k+r+\alpha$	6par+Ω_k	6par+r	6par+f_ν	6par+w	6par	6par	6par
$e^{-2\tau}$	$0.53^{+0.22}_{-0.17}$	$0.69^{+0.15}_{-0.32}$	$0.776^{+0.098}_{-0.116}$	$0.776^{+0.095}_{-0.121}$	$0.80^{+0.10}_{-0.13}$	$0.780^{+0.094}_{-0.119}$	>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

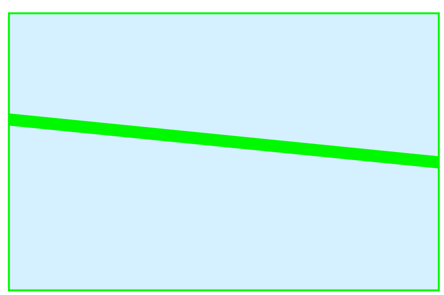
	Using SDSS + WMAP temperature and polarization information						No pol.	No WMAP
	$6\mathrm{par}+\Omega_k+r+\alpha$	$6\mathrm{par}+\Omega_k$	$6\mathrm{par}+r$	$6\mathrm{par}+f_\nu$	$6\mathrm{par}+w$	6par	6par	6par
$e^{-2\tau}$	$0.53^{+0.22}_{-0.17}$	$0.69^{+0.15}_{-0.32}$	$0.776^{+0.098}_{-0.116}$	$0.776^{+0.095}_{-0.121}$	$0.80^{+0.10}_{-0.13}$	$0.780^{+0.094}_{-0.119}$	>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*
$\Omega_{\rm tot}$	$1.056^{+0.045}_{-0.045}$	$1.058^{+0.039}_{-0.041}$	*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

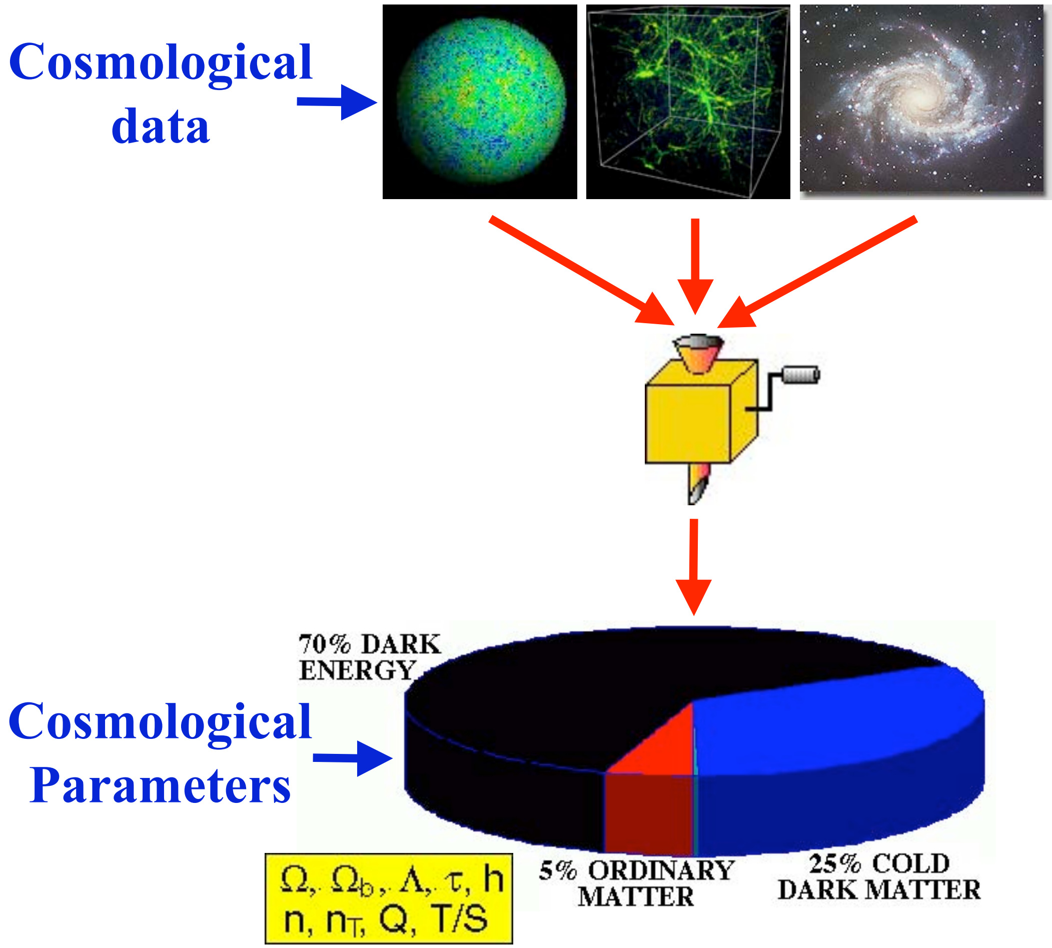
MATTER BUDGET

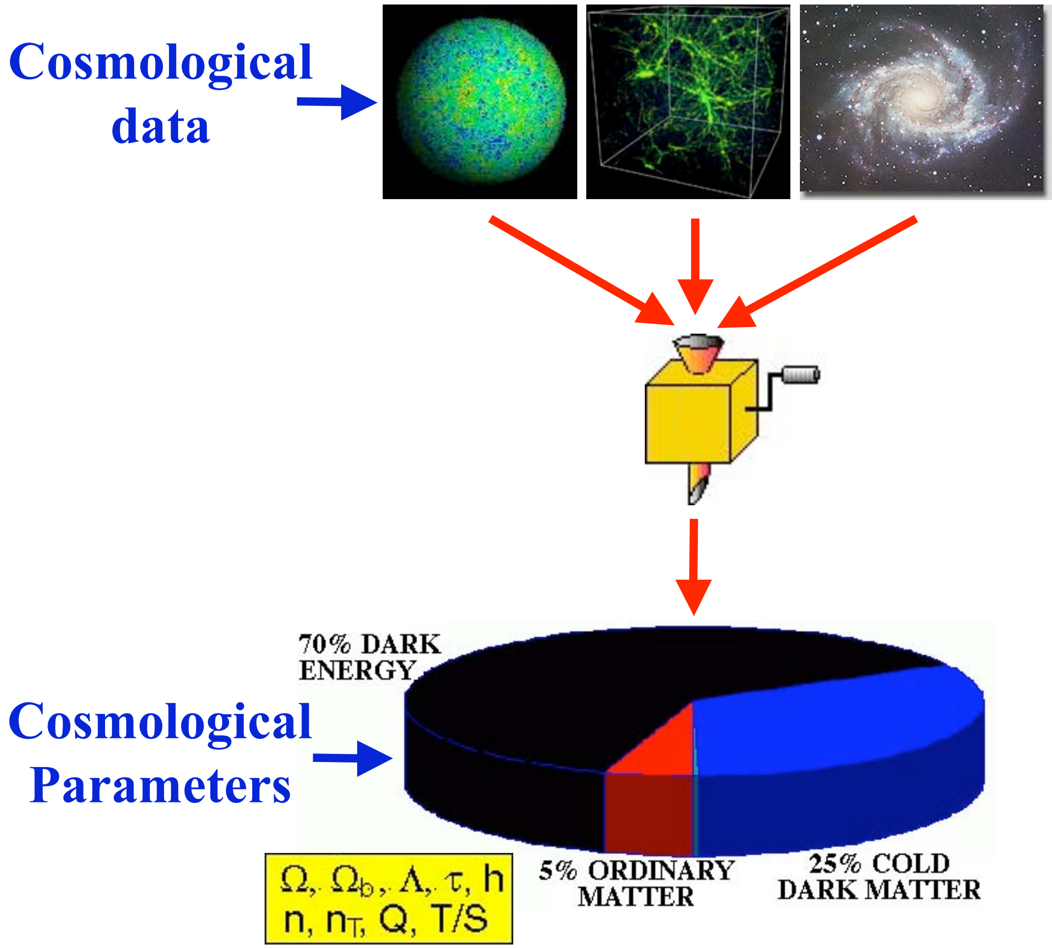


p	Meaning	Measured value
$\Omega_{\rm tot}$	Spatial curvature	1.01 ± 0.02
ρ_Λ	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124} m_{\rm Pl}^4$
w	Dark energy equation of state	-1 ± 0.1
δ_H	Scalar fluctuation amplitude (Q)	$(2.0 \pm 0.2) \times 10^{-5}$
n_s	Scalar spectral index	0.98 ± 0.02
α	Running 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

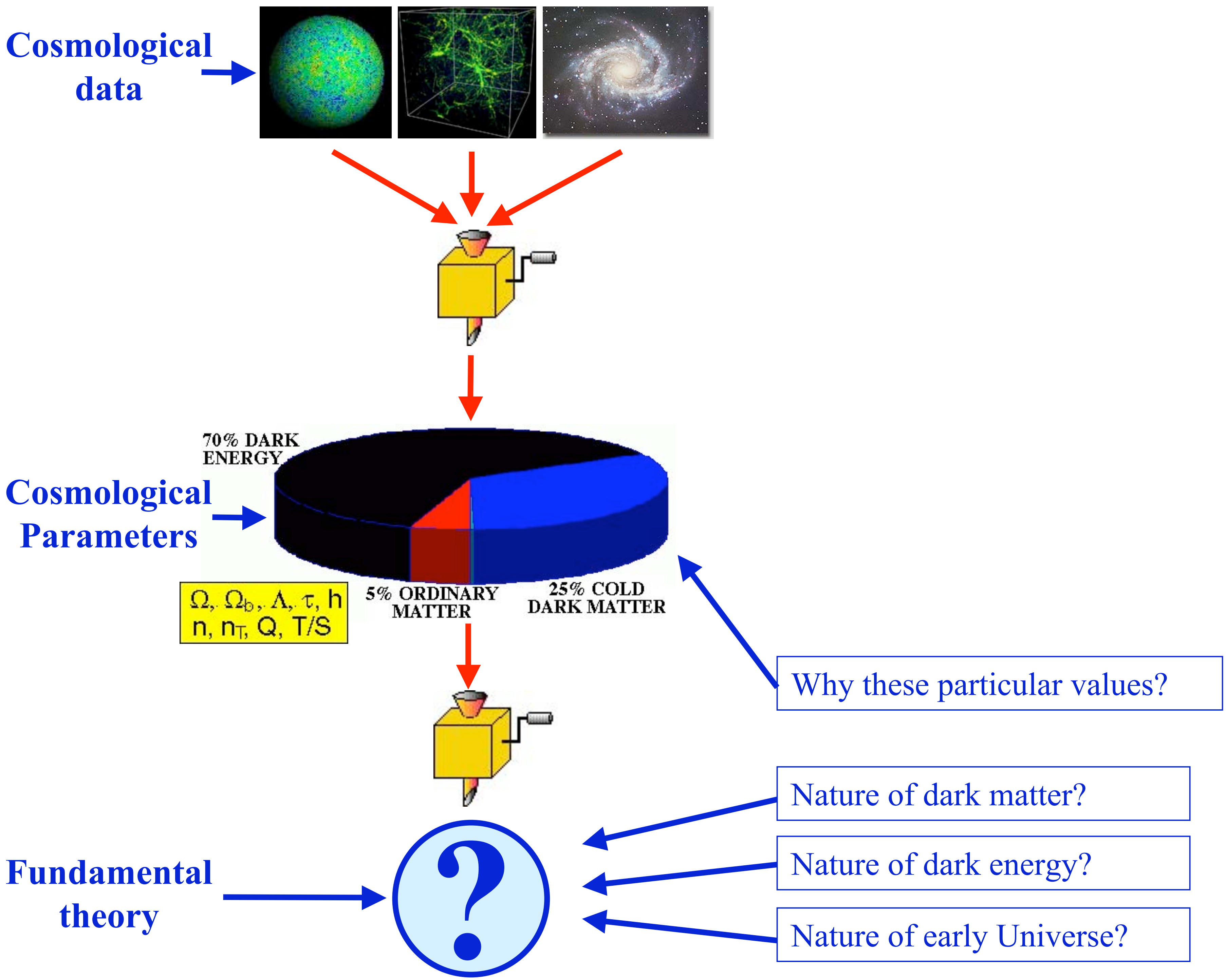
INITIAL CONDITIONS



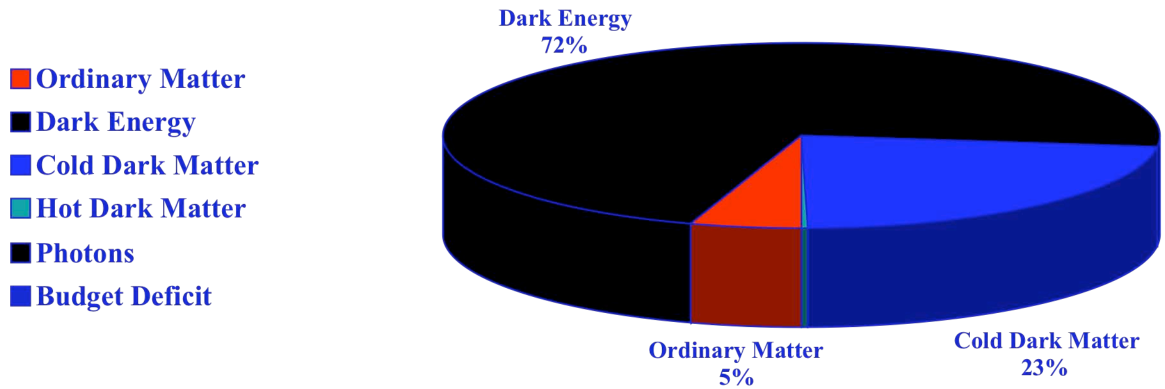

Cosmological data
Cosmological Parameters
70% DARK ENERGY
5% ORDINARY MATTER
25% COLD DARK MATTER
Ω, Ω_b, Λ, τ, h
n, n_T, Q, T/S


Cosmological data
70% DARK ENERGY
Cosmological Parameters
Ω, Ω_b, Λ, τ, h
n, n_T, Q, T/S
5% ORDINARY MATTER
25% COLD DARK MATTER

ARE WE DONE?

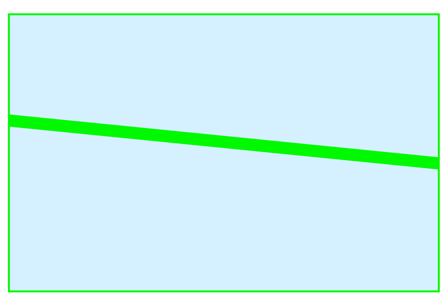

Cosmological data
Cosmological Parameters
70% DARK ENERGY
5% ORDINARY MATTER
25% COLD DARK MATTER
Ω, Ω_b, Λ, τ, h
n, n_T, Q, T/S
Why these particular values?
Nature of dark matter?
Nature of dark energy?
Nature of early Universe?
Fundamental theory
?

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 $dn_s/d\ln k$	$\|\alpha\| \lesssim 0.01$
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
	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
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	ξ_{b}	Baryon mass per photon $\rho_{\text{b}}/n_\gamma = m_{\text{p}}\eta$	(0.60 ± 0.03) eV
SUSY?	ξ_{c}	CDM mass per photon ρ_{c}/n_γ	(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

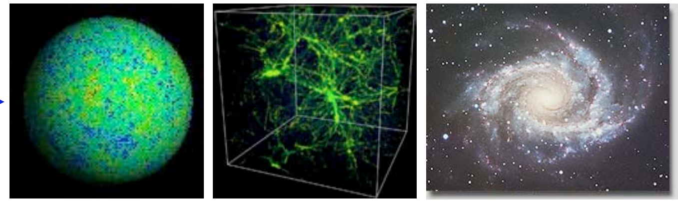
WHY?

Standard model parameters:

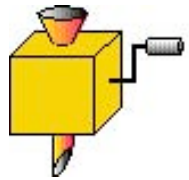
Why these values?

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		0.00003 ± 0.00002
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_{qcd}	CP-violating QCD vacuum phase		$< 10^{-9}$

Cosmological data



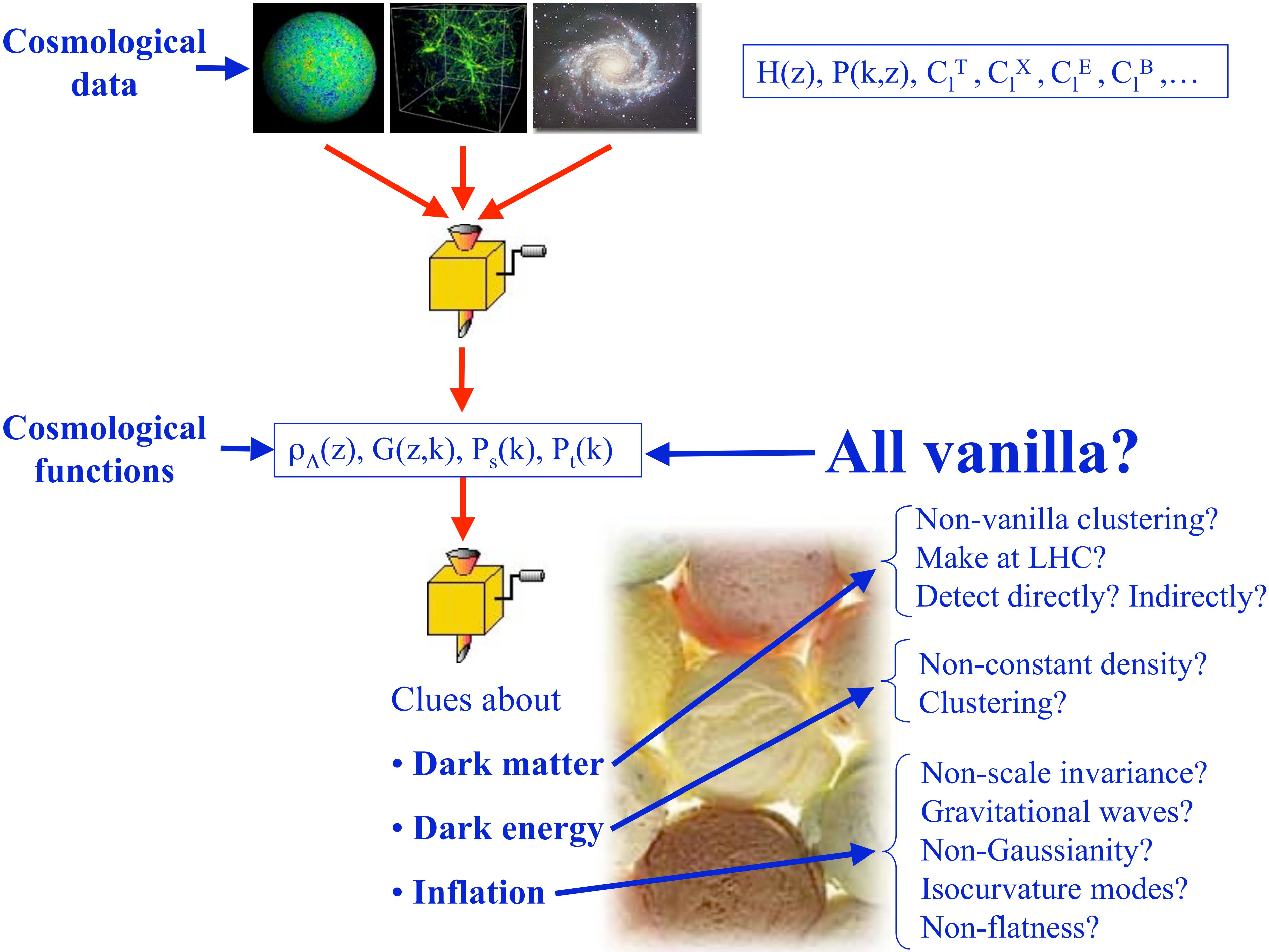
$H(z)$, $P(k,z)$, C_l^T, C_l^X, C_l^E, C_l^B, …

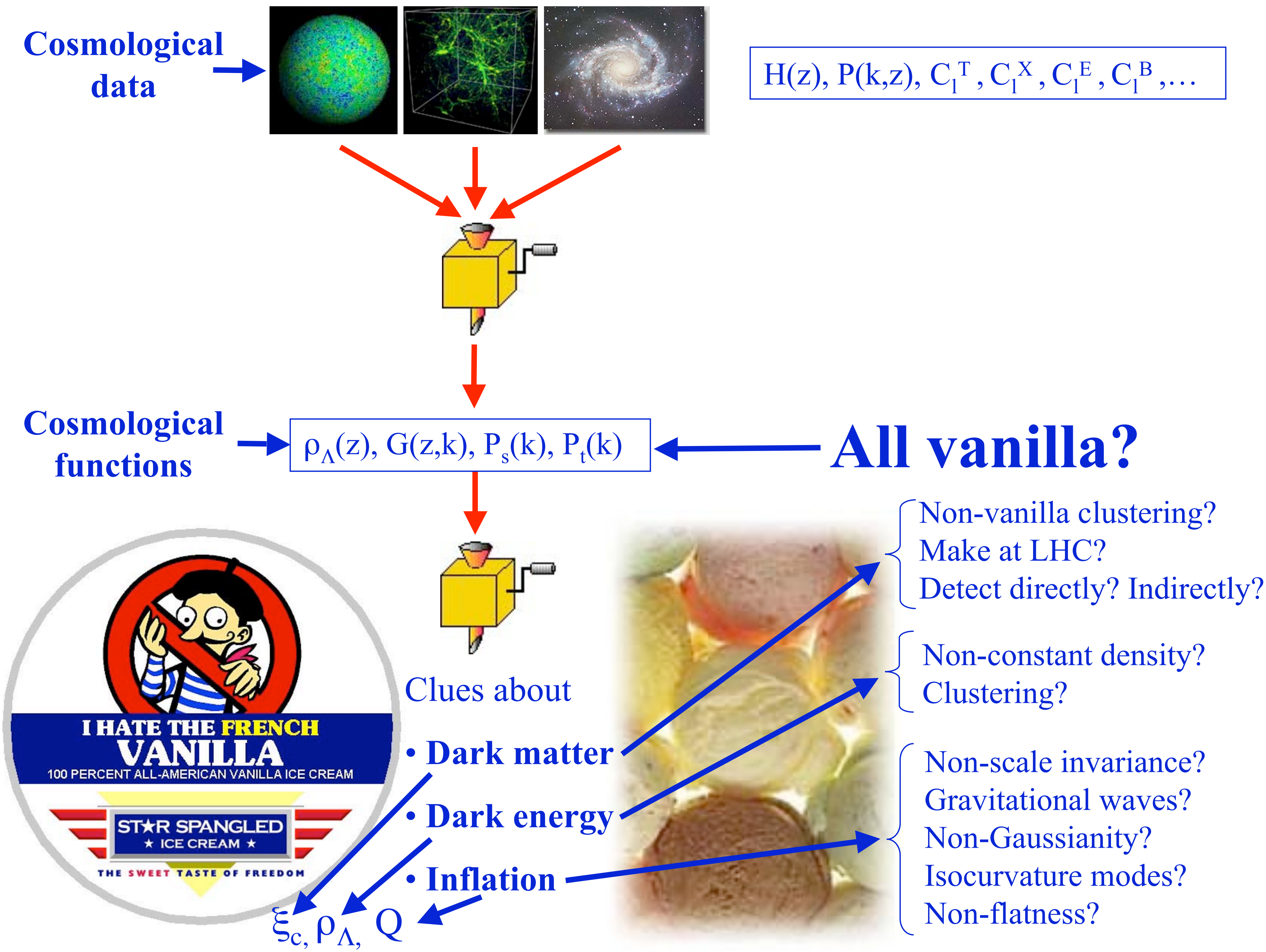


Cosmological functions

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

All vanilla?


Cosmological data
$H(z)$, $P(k,z)$, C_l^T, C_l^X, C_l^E, C_l^B, …
Cosmological functions
$\rho_\Lambda(z)$, $G(z,k)$, $P_s(k)$, $P_t(k)$
All vanilla?
Non-vanilla clustering?
Make at LHC?
Detect directly? Indirectly?
Non-constant density?
Clustering?
Non-scale invariance?
Gravitational waves?
Non-Gaussianity?
Isocurvature modes?
Non-flatness?
Clues about
• Dark matter
• Dark energy
• Inflation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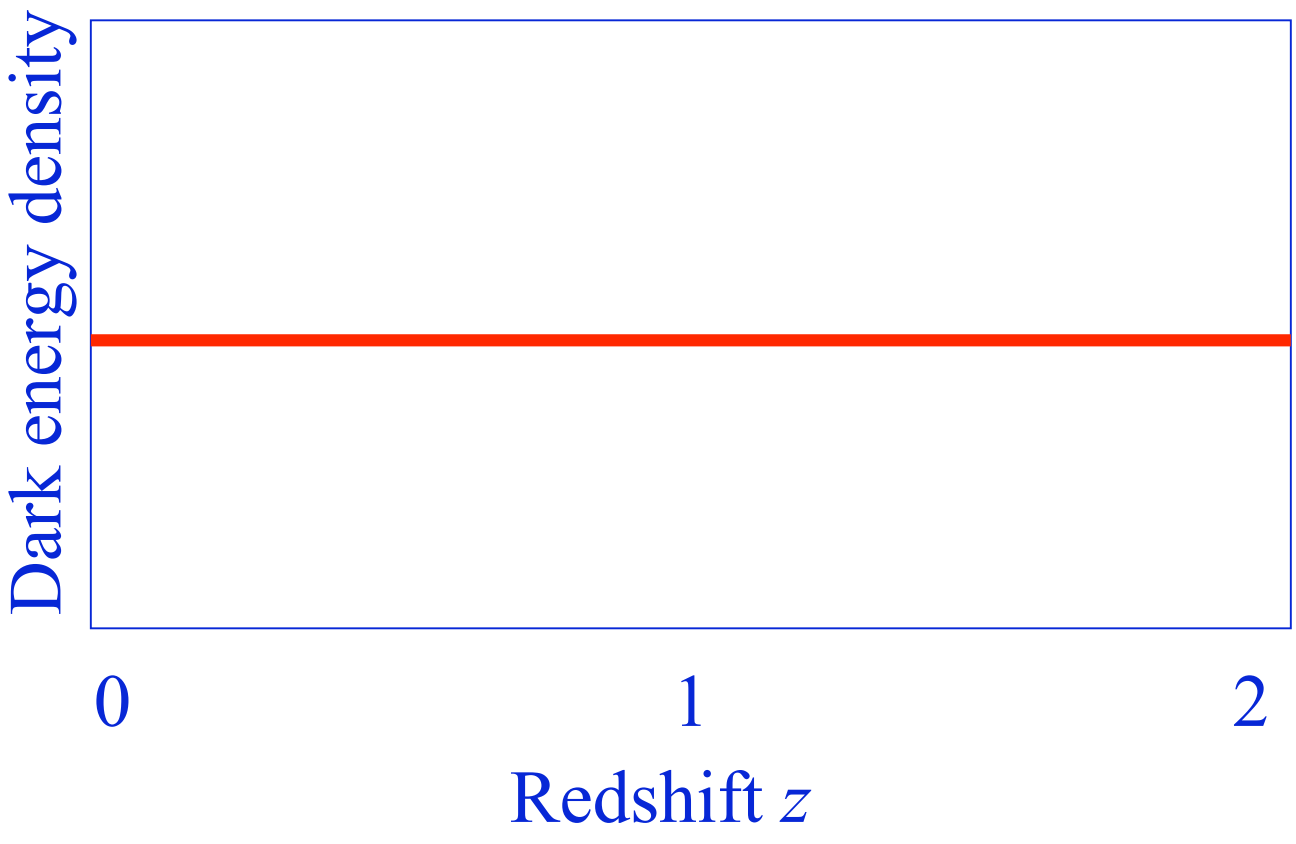
• Dark matter
• Dark energy
• Inflation
ξ_c, ρ_Λ, Q
I HATE THE FRENCH
VANILLA
100 PERCENT ALL-AMERICAN VANILLA ICE CREAM
ST★R SPANGLED
★ ICE CREAM ★
THE SWEET TASTE OF FREEDOM

DARK ENERGY:

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



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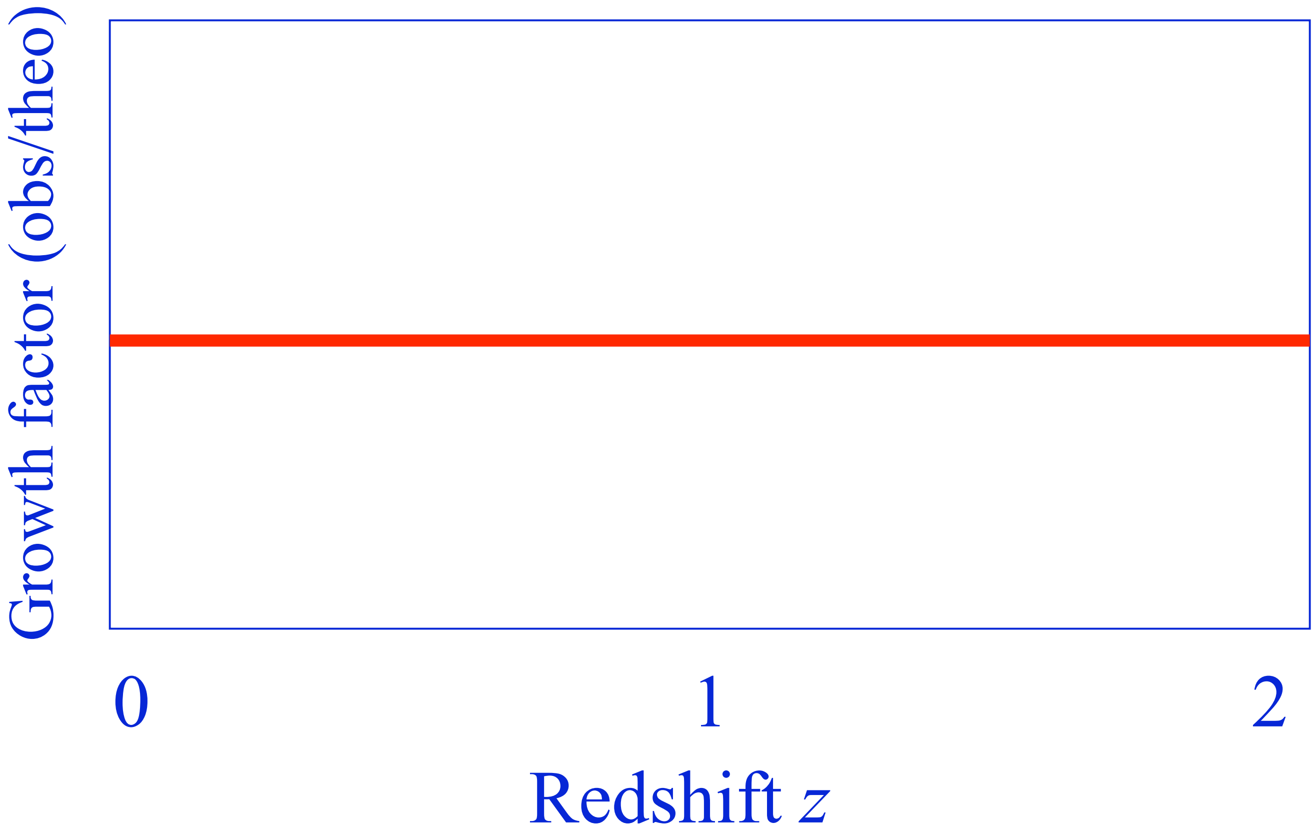
DARK MATTER:

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



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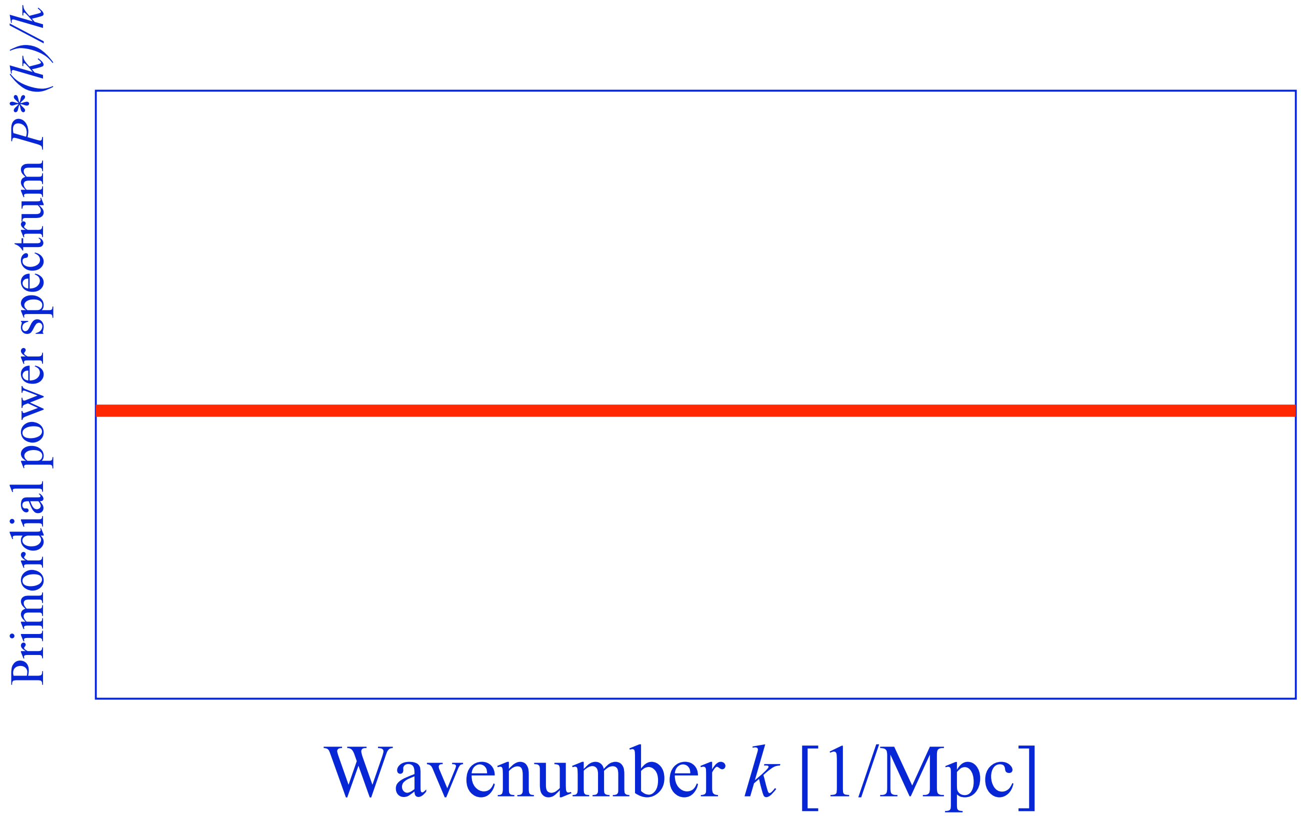
INFLATION:

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



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