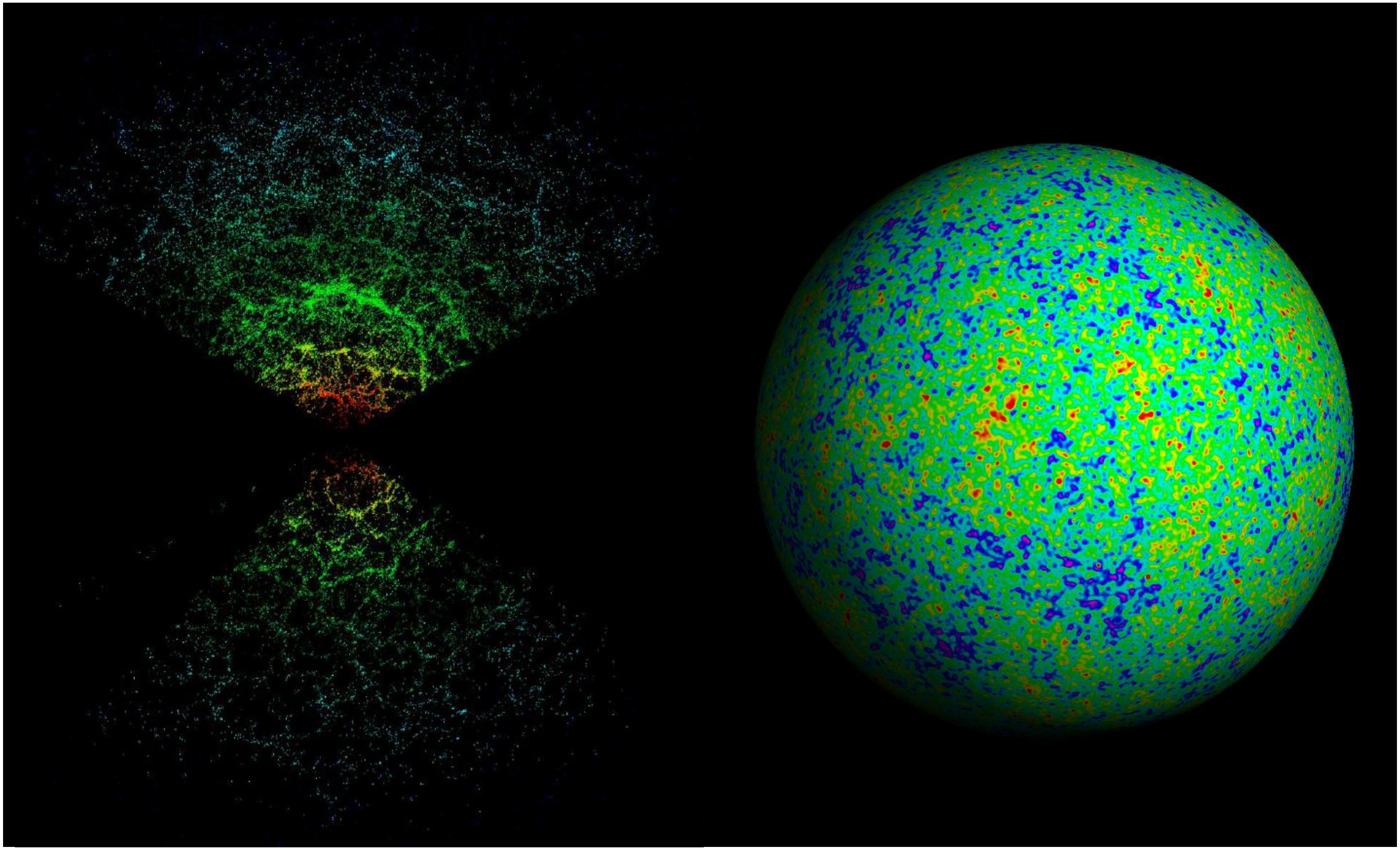
The beginning and end of our universe



Max Tegmark, MIT

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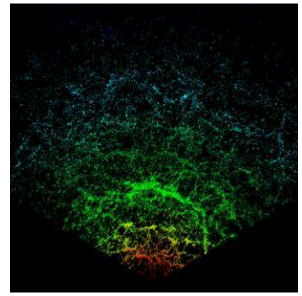
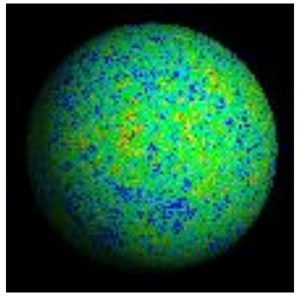
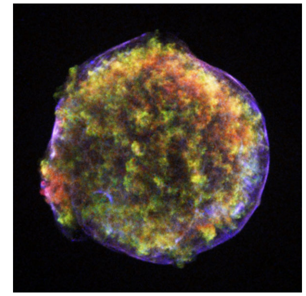
THE COSMIC SMÖRGÅSBORD



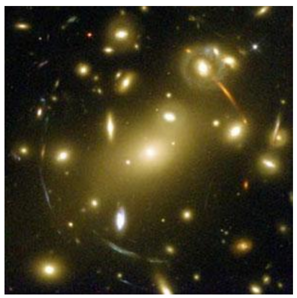
Galaxy surveys



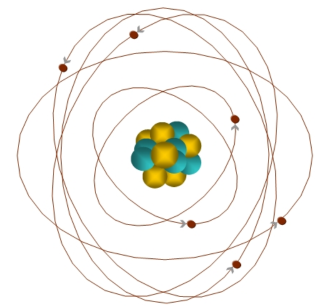
Microwave background



Supernovae Ia

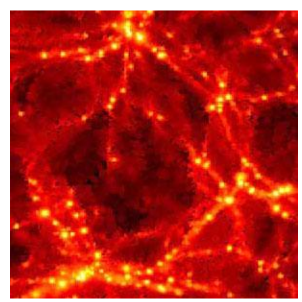


Gravitational lensing

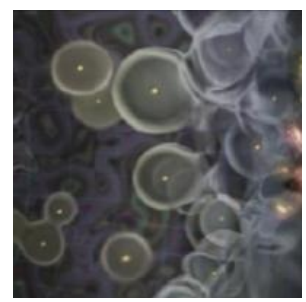


Big Bang nucleosynthesis

Galaxy clusters



Lyman α forest



Neutral hydrogen tomography

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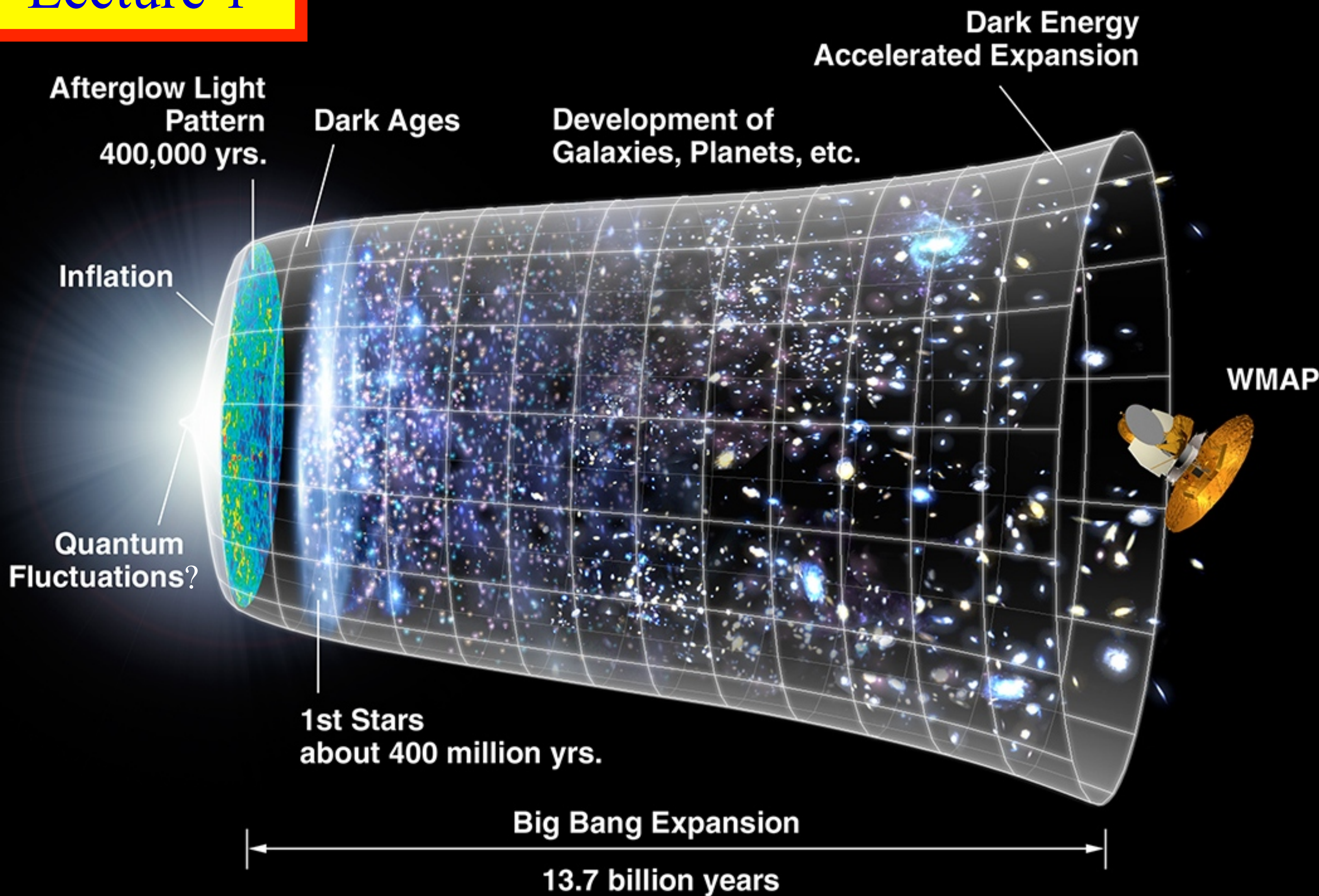
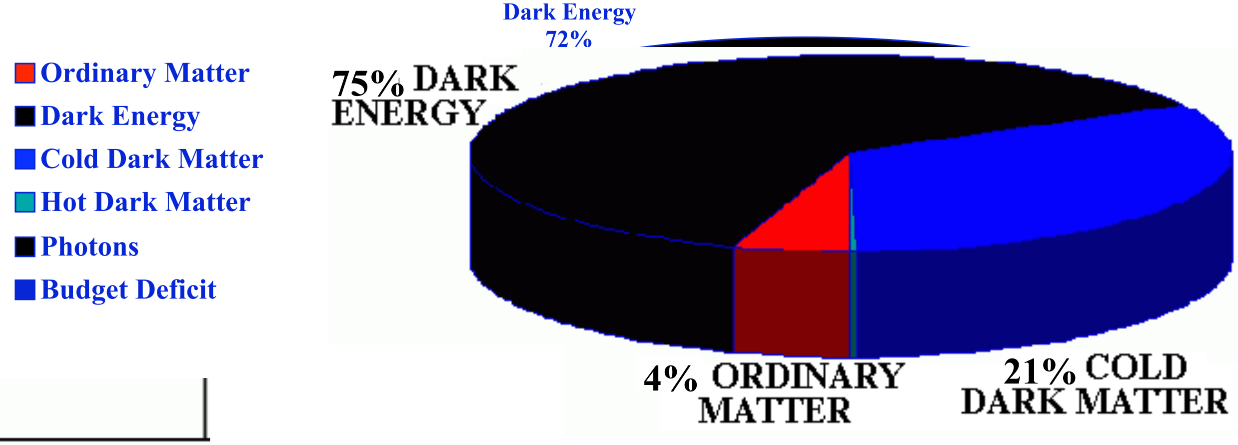
June 1, 2010

What have we learned?

Summary of Lecture 1



Summary of Lecture 2



Parameter	Value	
Matter budget parameters:		
Ω_{tot}	$1.003^{+0.010}_{-0.009}$	Total density/critical density
Ω_Λ	$0.761^{+0.017}_{-0.018}$	Dark energy density parameter
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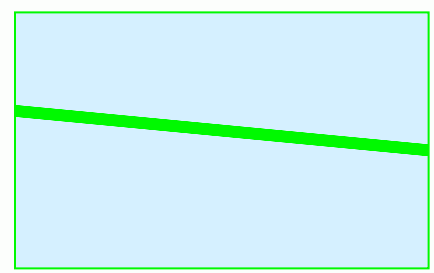
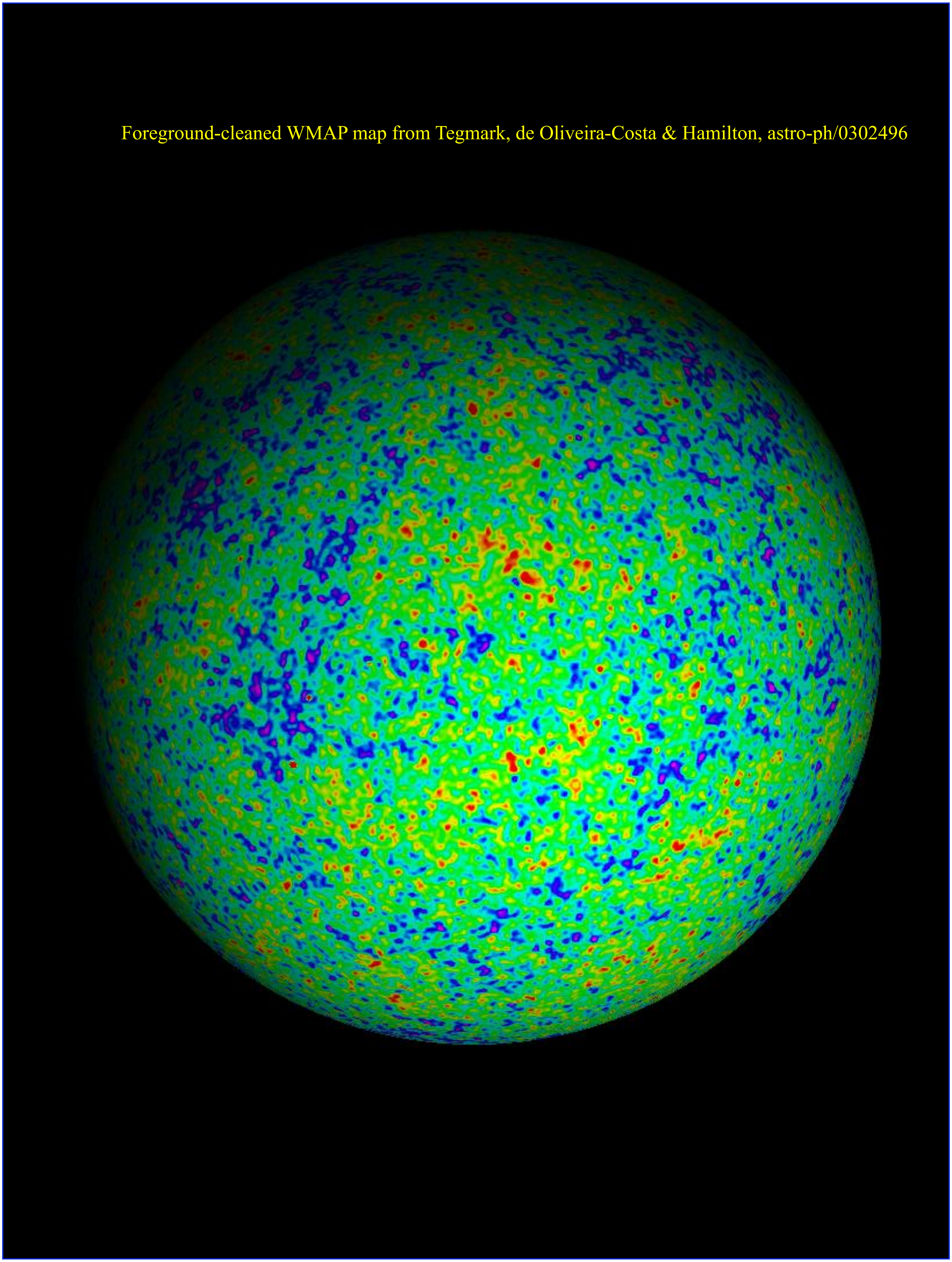
ω_c	$0.1050^{+0.0041}_{-0.0040}$	Cold dark matter density
ω_ν	< 0.010 (95%)	Massive neutrino density
w	$-0.941^{+0.087}_{-0.101}$	Dark energy equation of state
Seed fluctuation parameters:		
A_s	$0.690^{+0.045}_{-0.044}$	Scalar fluctuation amplitude
r	< 0.30 (95%)	Tensor-to-scalar ratio
n_s	$0.953^{+0.016}_{-0.016}$	Scalar spectral index
$n_t + 1$	$0.9861^{+0.0096}_{-0.0142}$	Tensor spectral index
α	$-0.040^{+0.027}_{-0.027}$	Running of spectral index



MORE EVIDENCE:

The fine details of cosmic clumpiness


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

$z = 1000$

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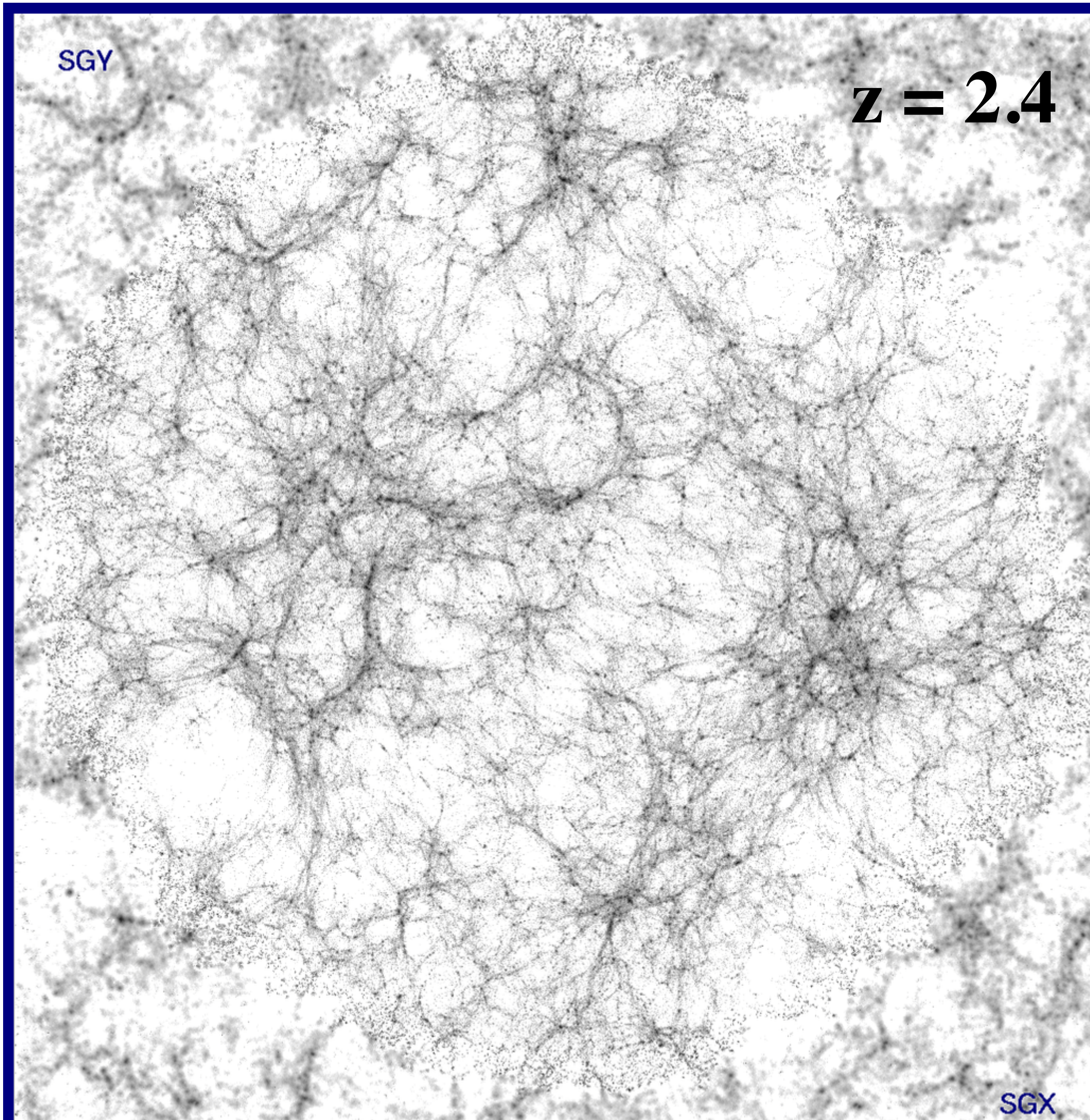
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



ΛCDM local universe at z=2.4 (Λ=0.7, Ω=0.3, h=0.7)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey

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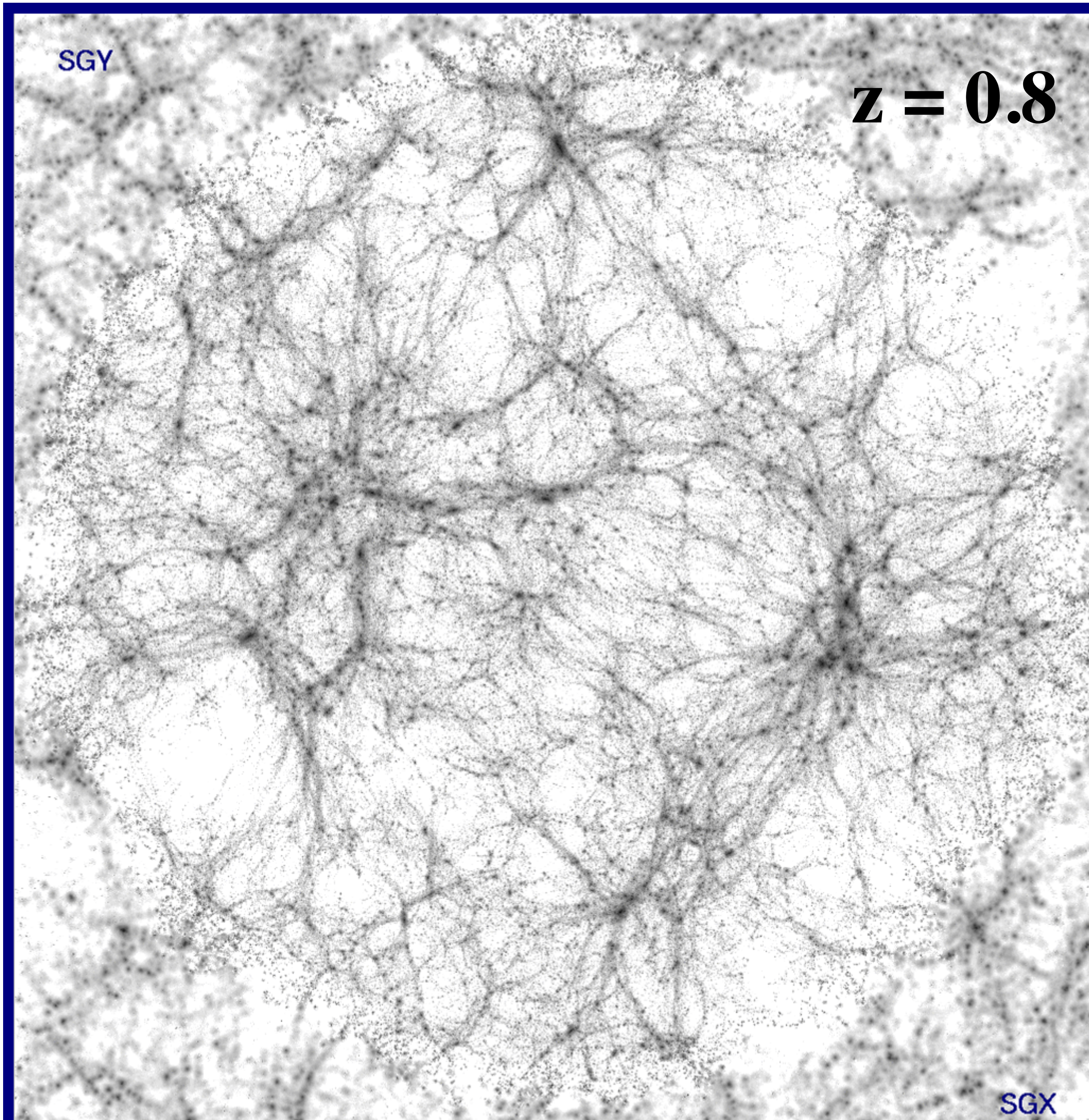
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



ΛCDM local universe at z=0.8 (Λ=0.7, Ω=0.3, h=0.7)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey

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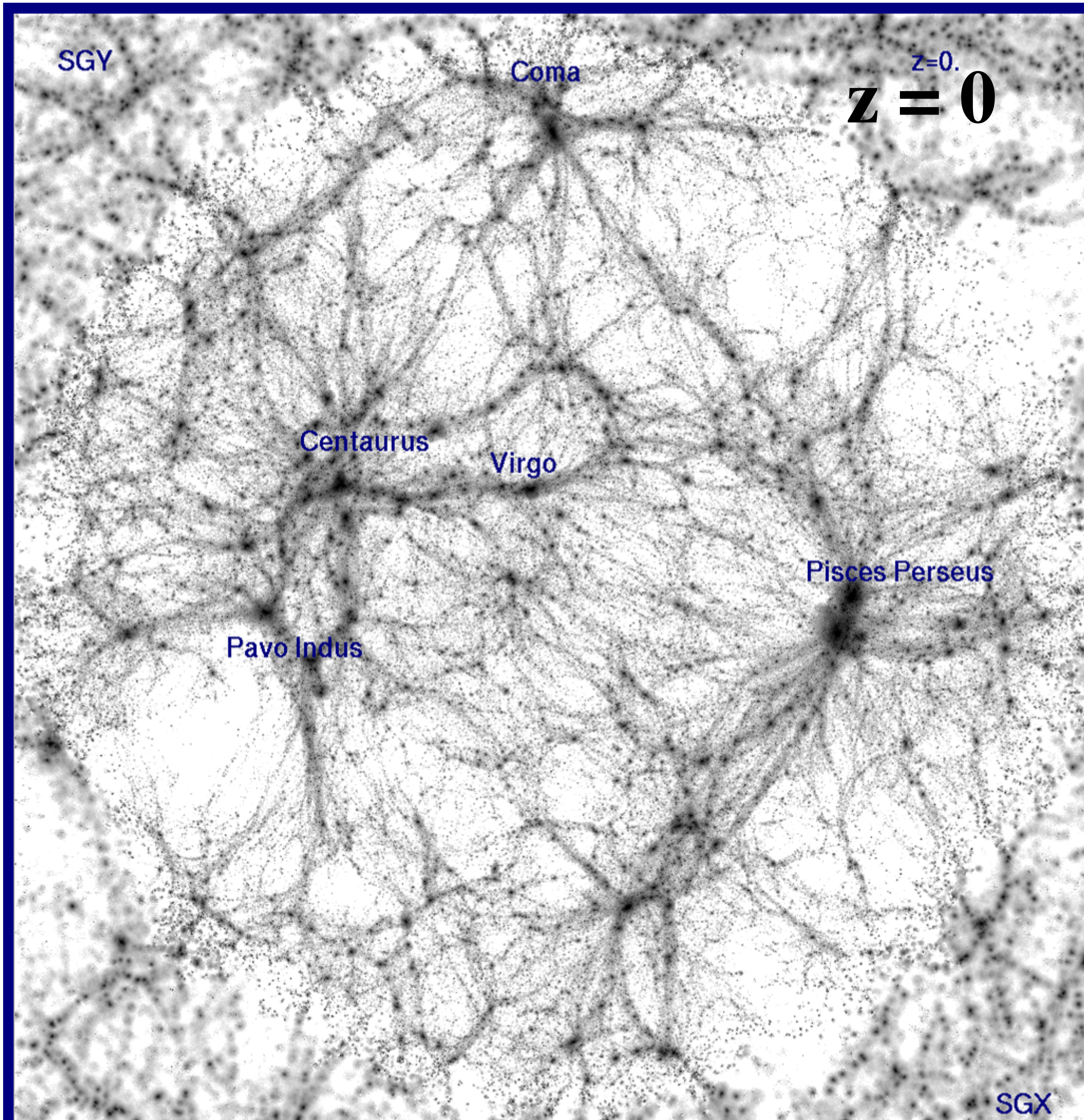
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



ΛCDM local universe (Λ=0.7, Ω=0.3, h=0.7)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey

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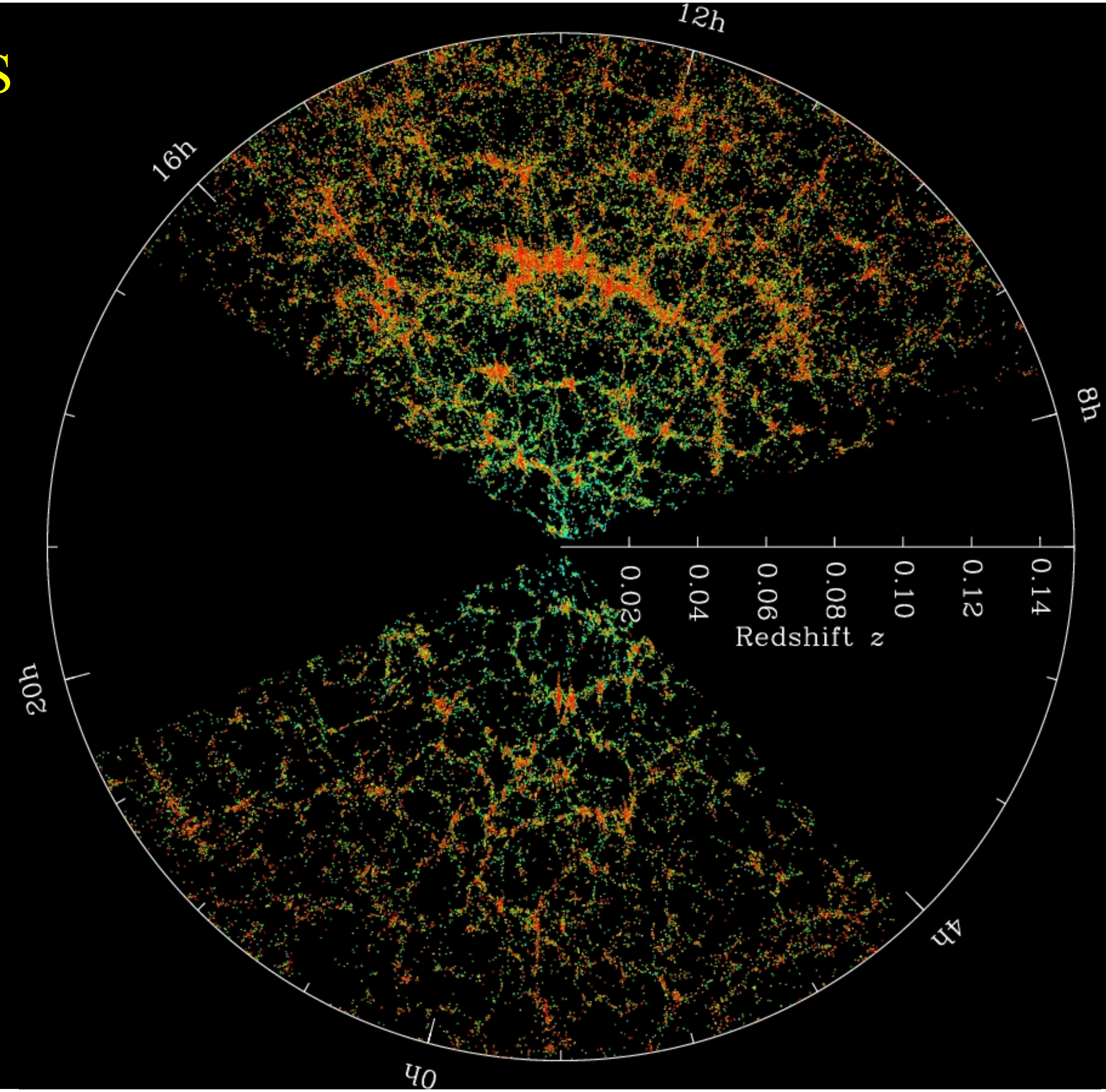
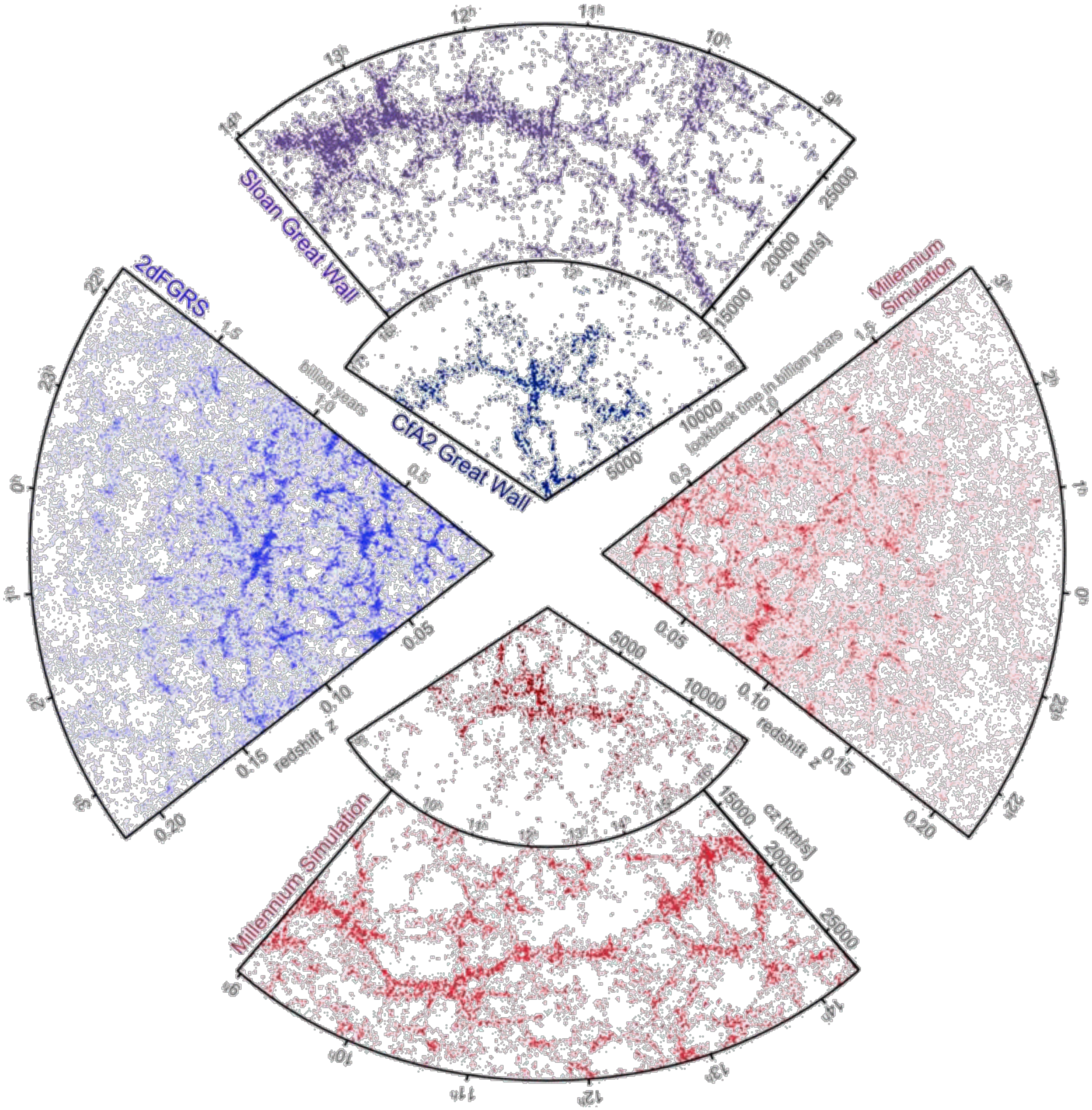
SDSS DR7



M Blanton/SDSS Team

Springel, Frenk & White 2006, Nature, 440, 11



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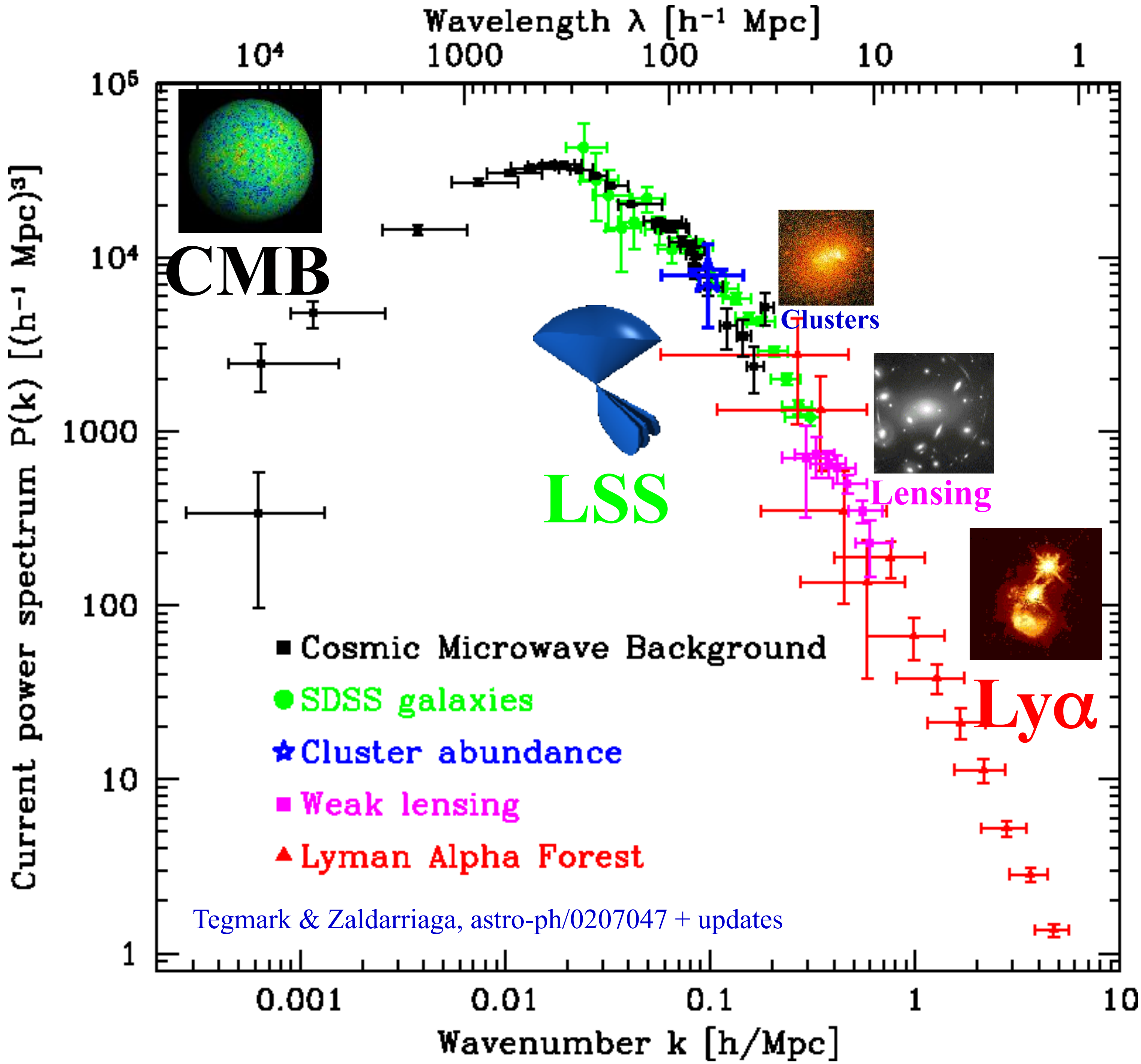

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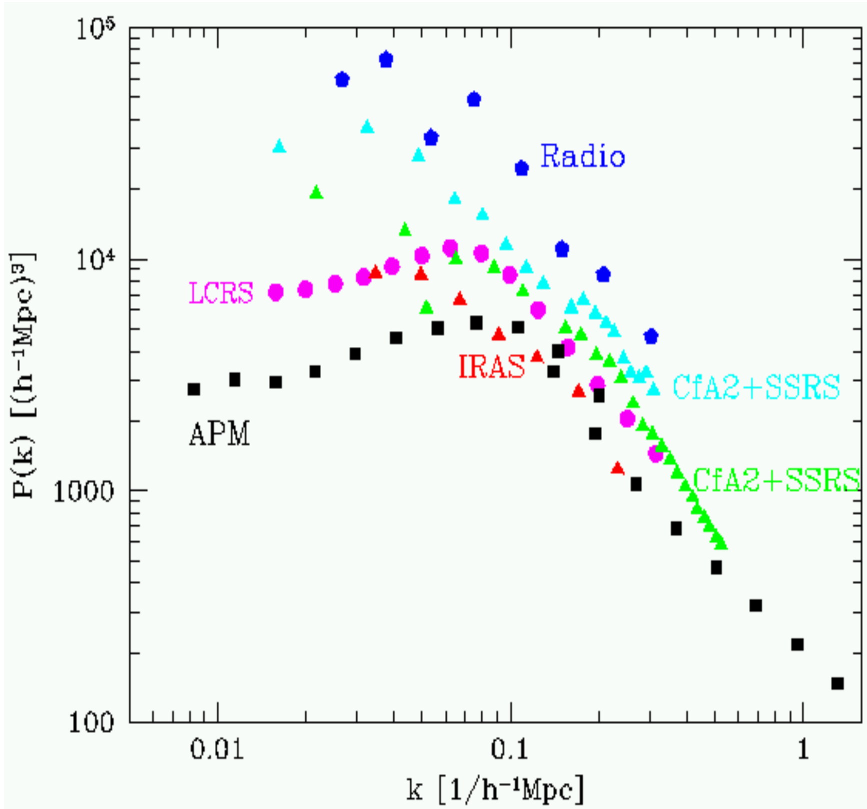

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

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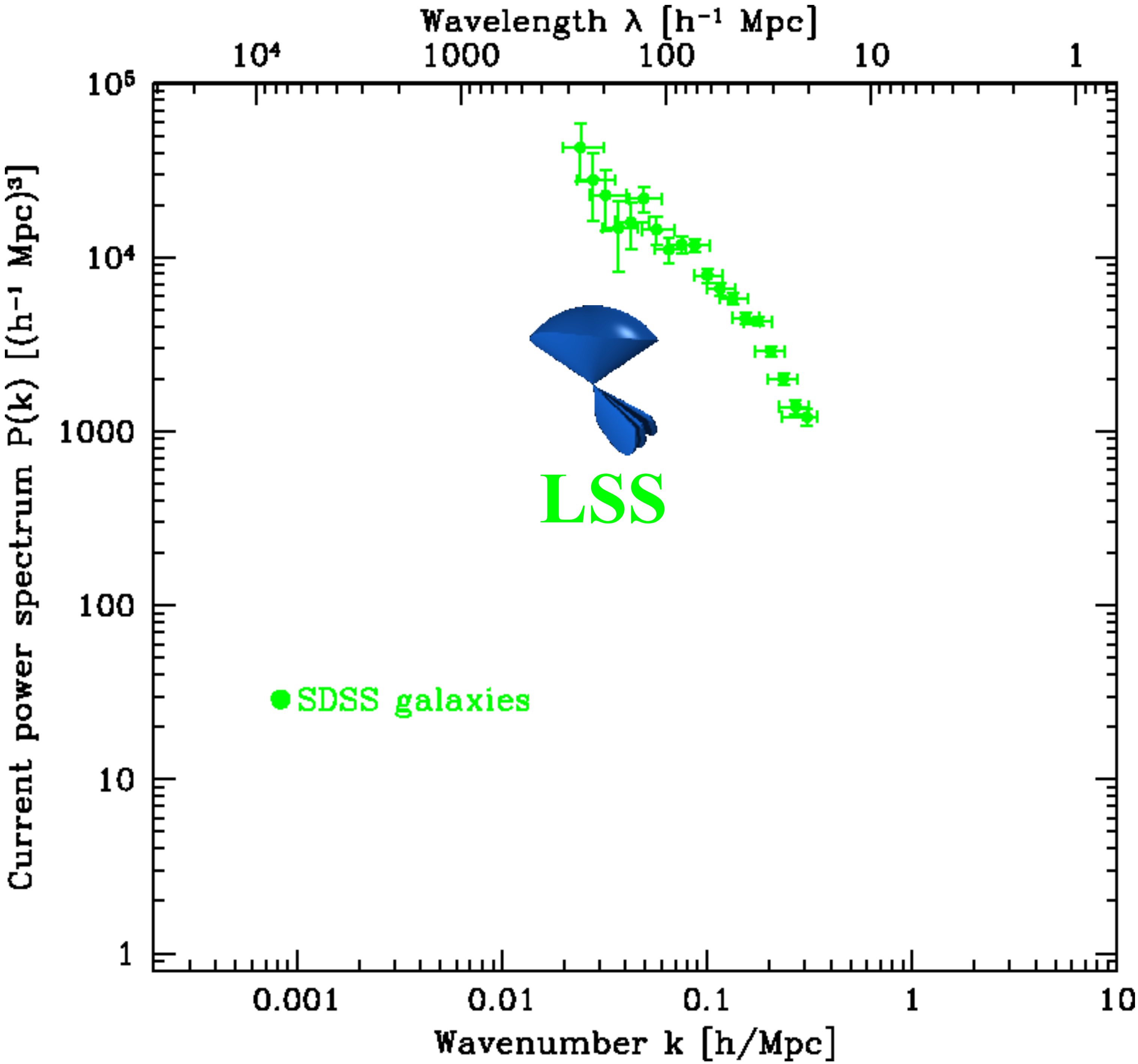
S



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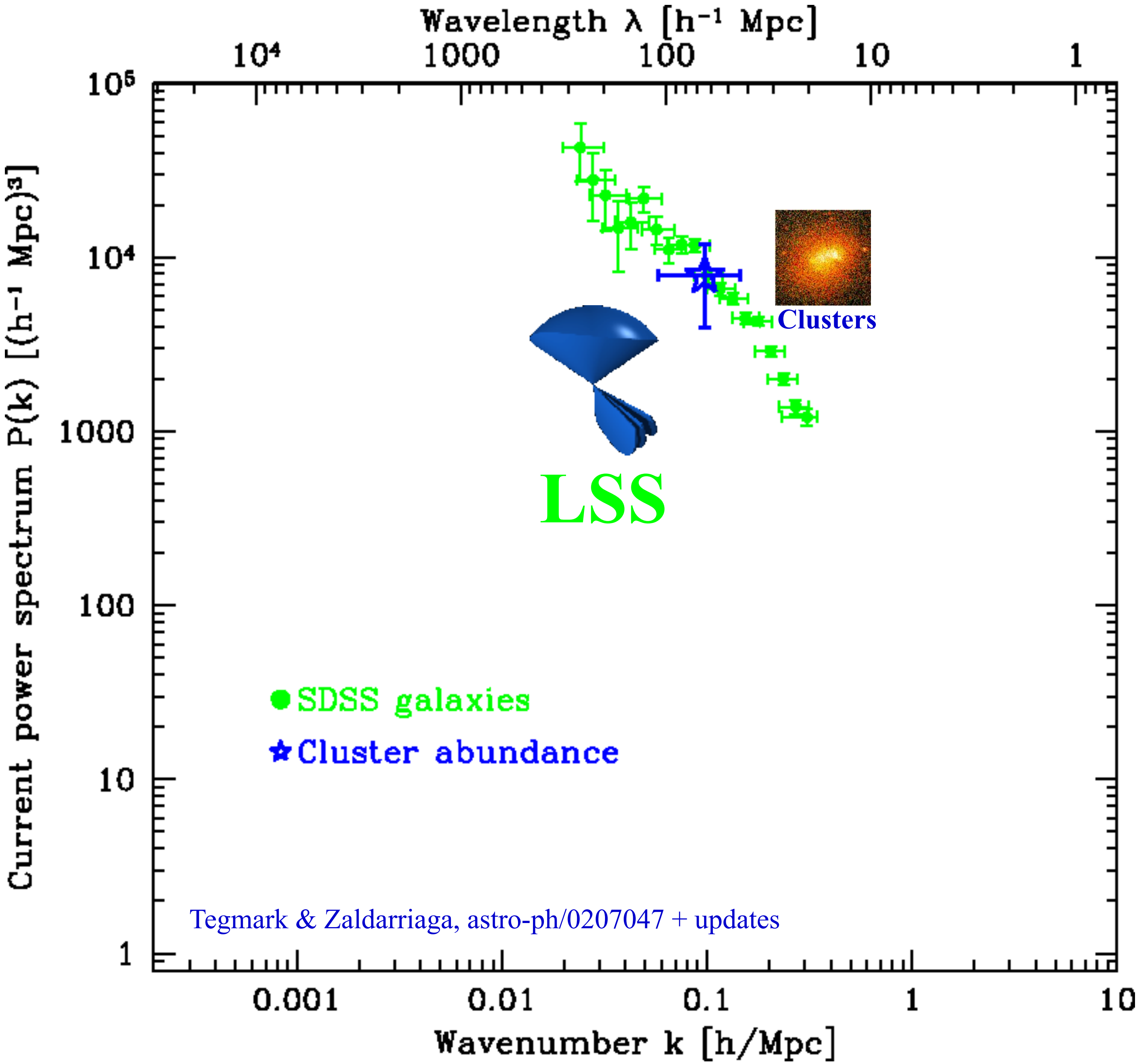

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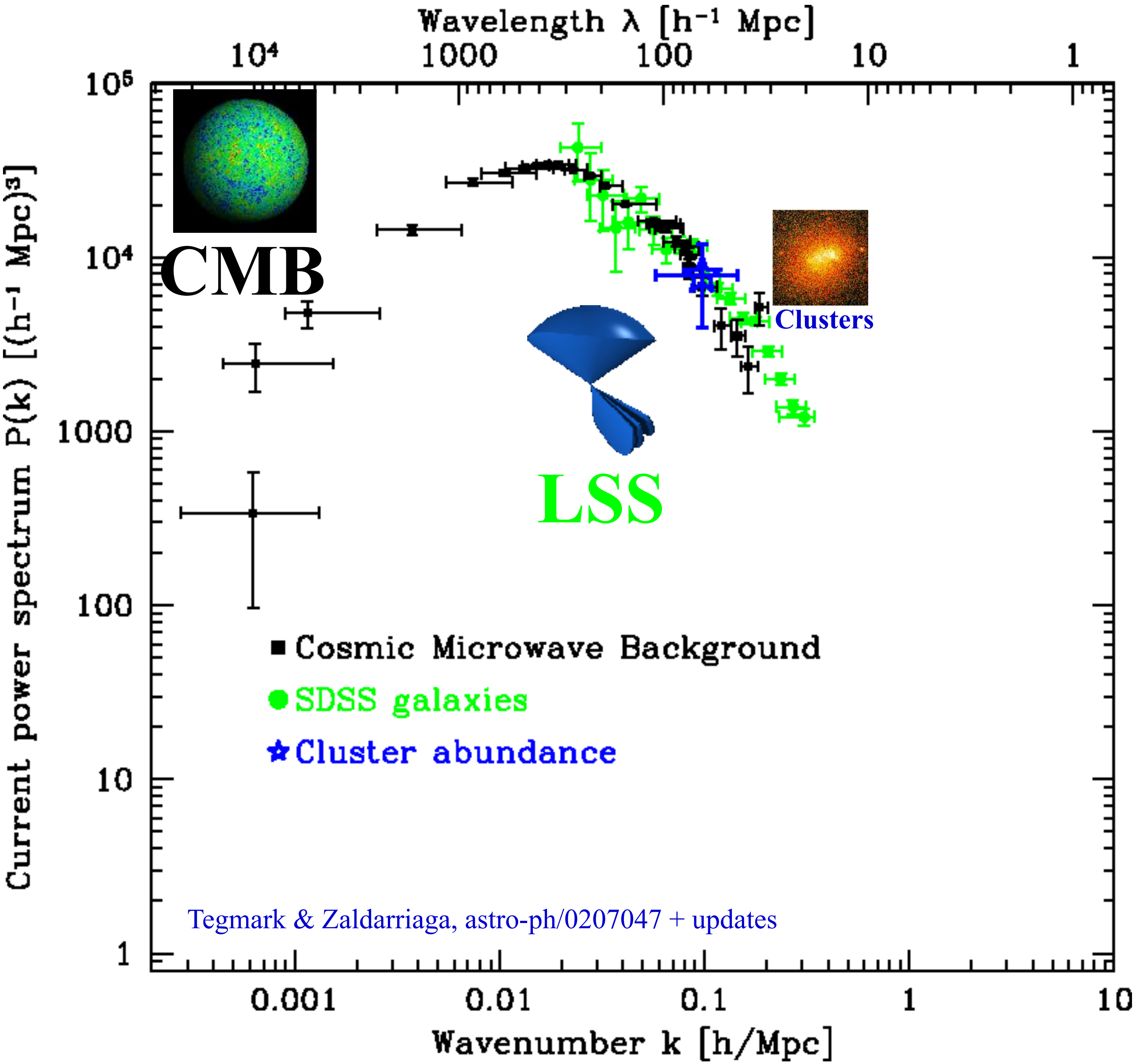

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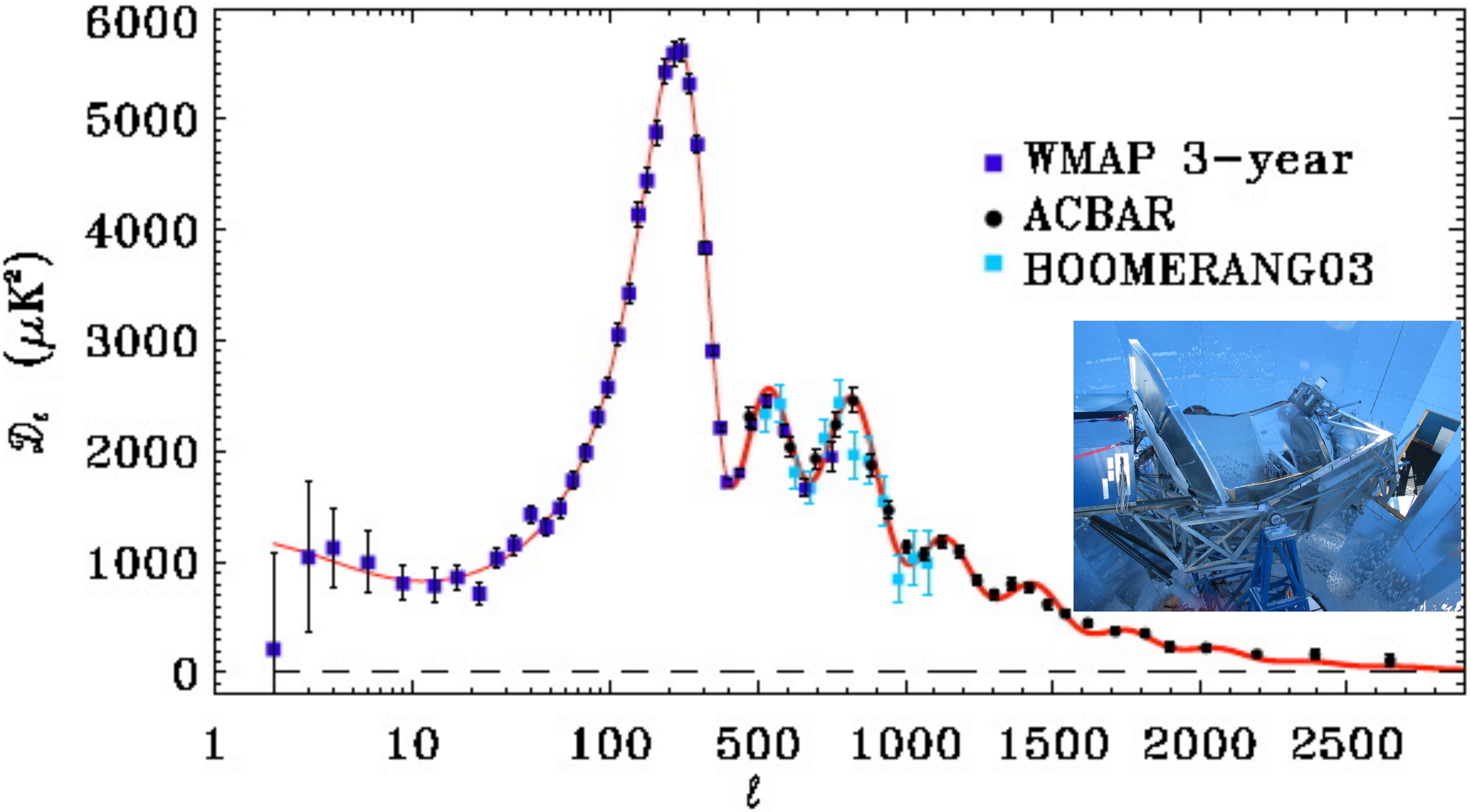
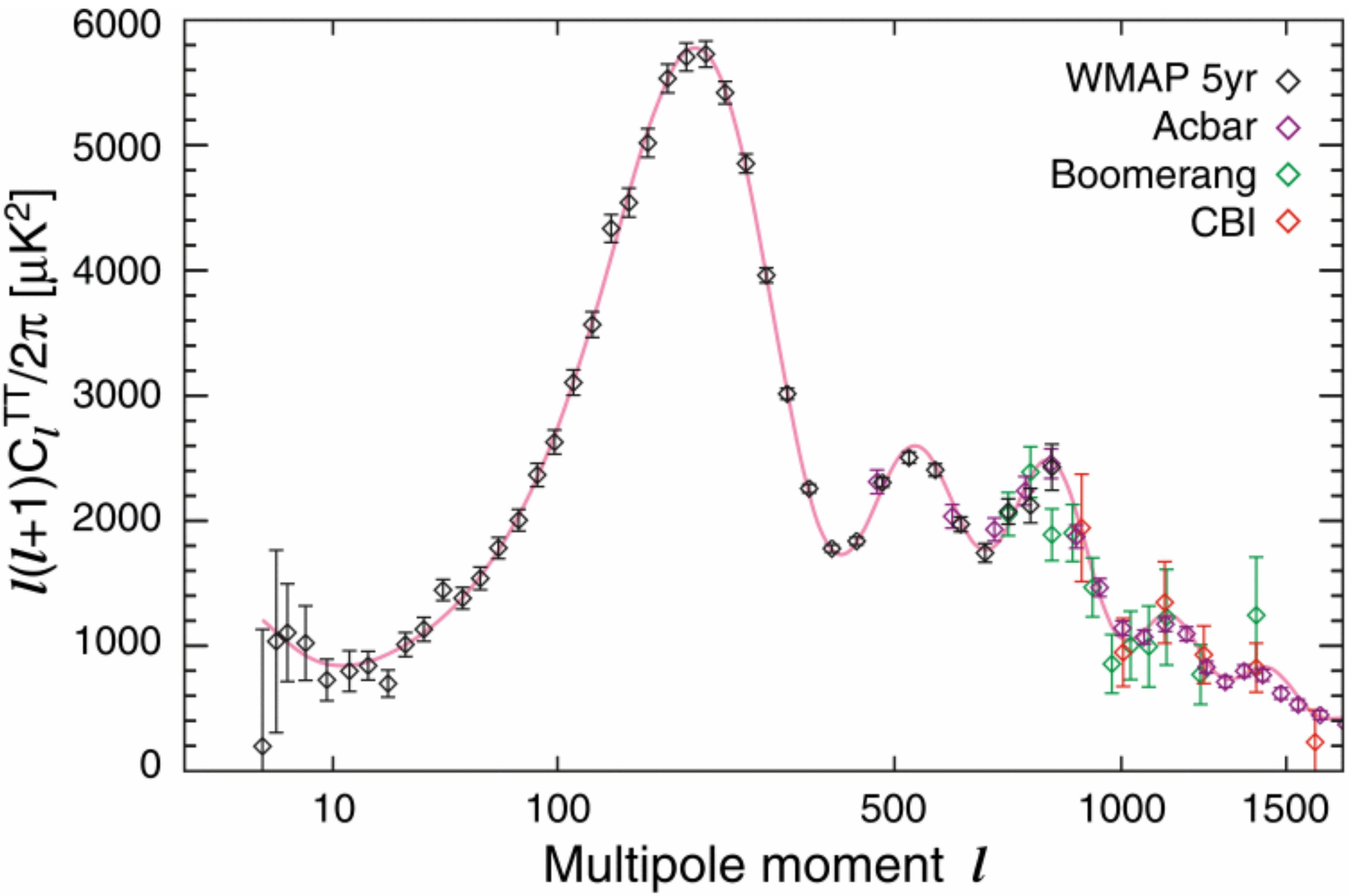
2008:



Reichardt et al 2008, arXiv:0801.1491

2008:



Nolta et al 2008, arXiv:0803.0593

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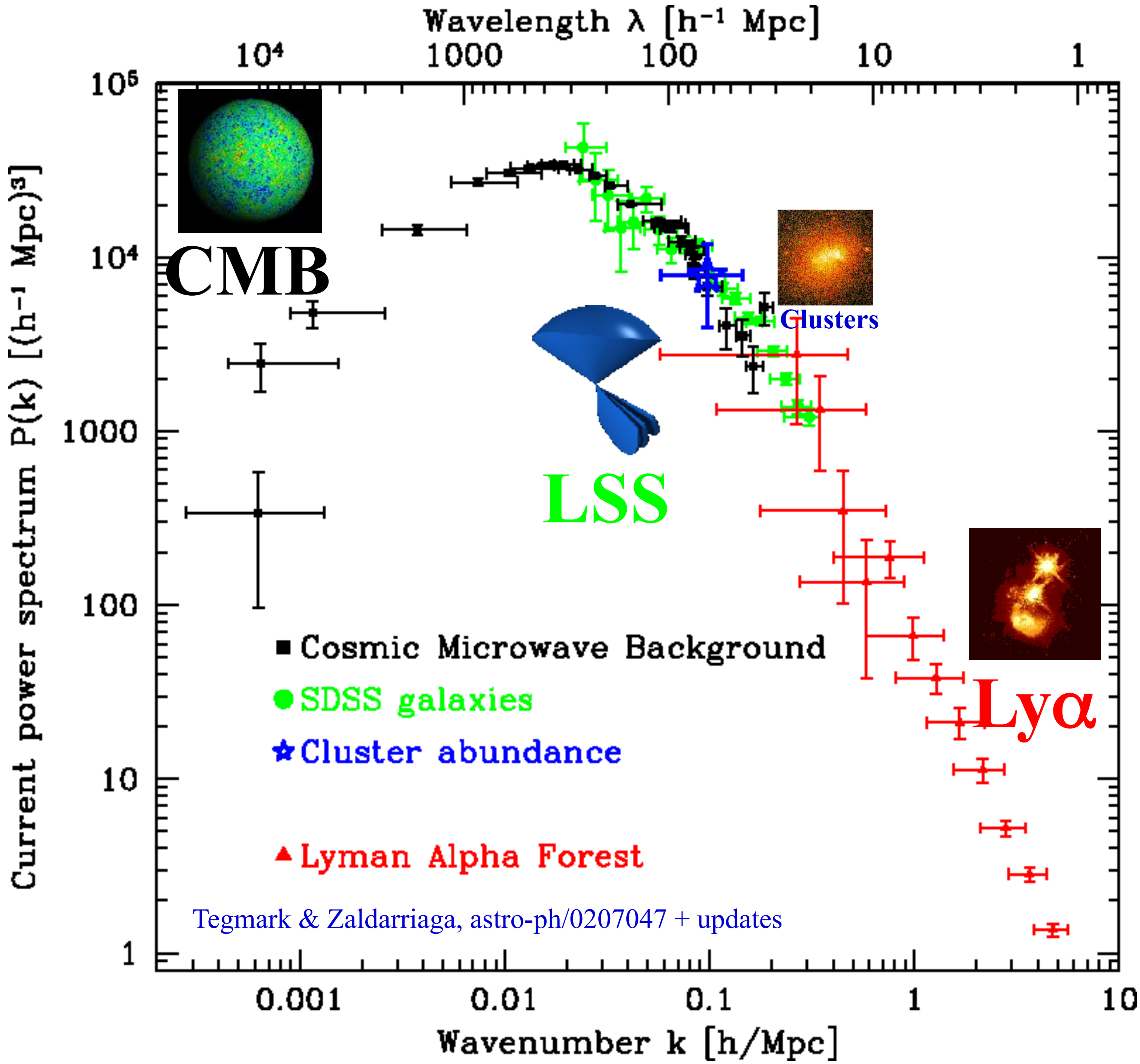

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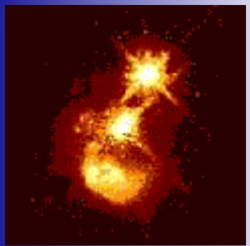
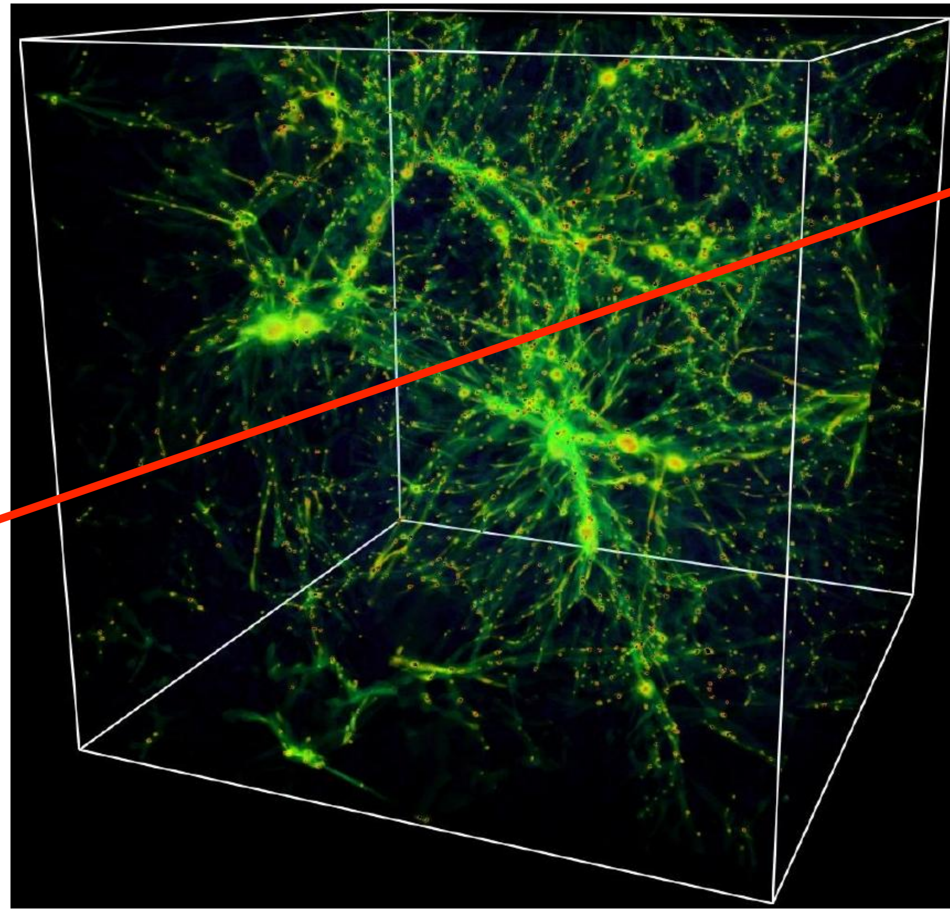
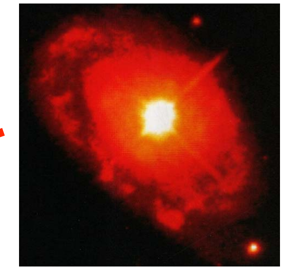
Lyman Alpha Forest Simulation: Cen et al 2001



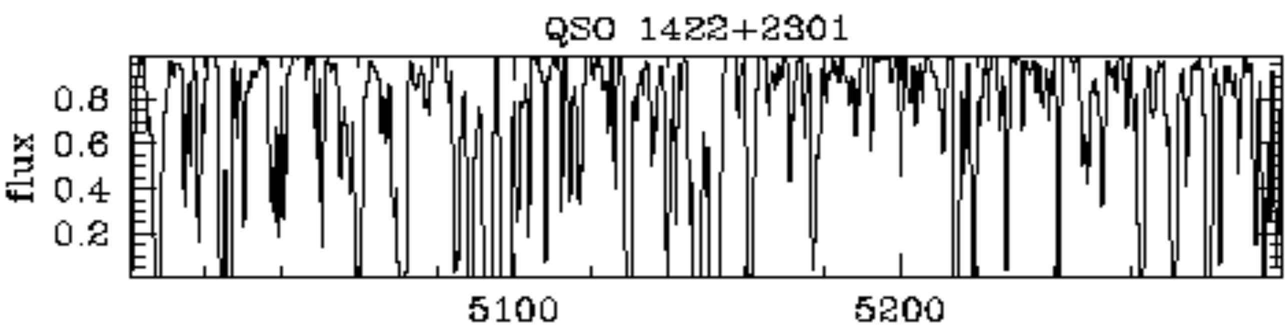
LyαF

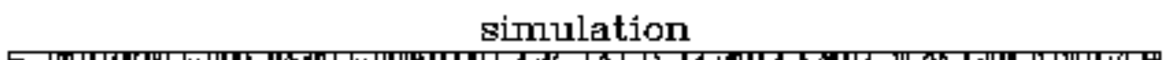




Quasar

You





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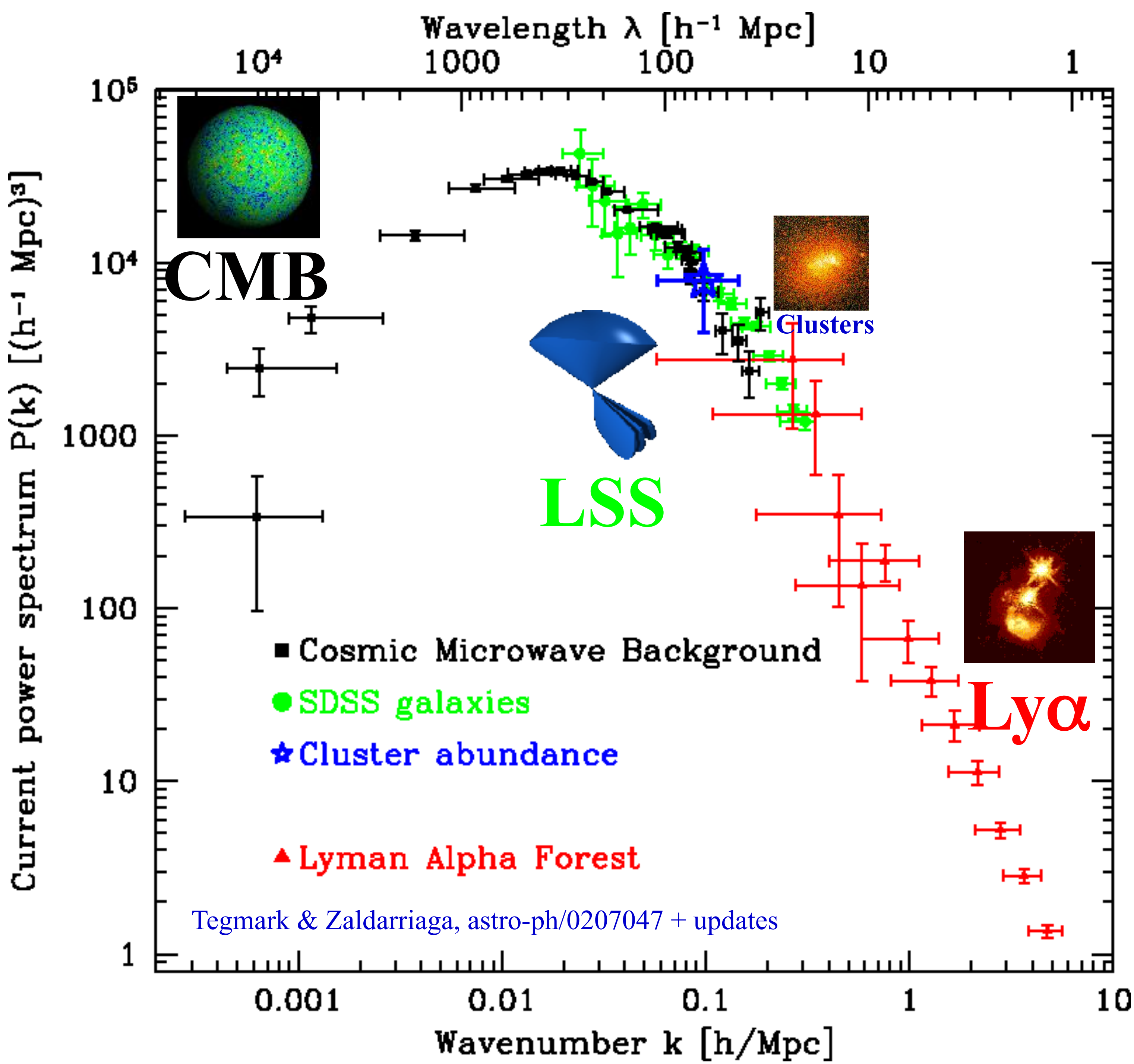

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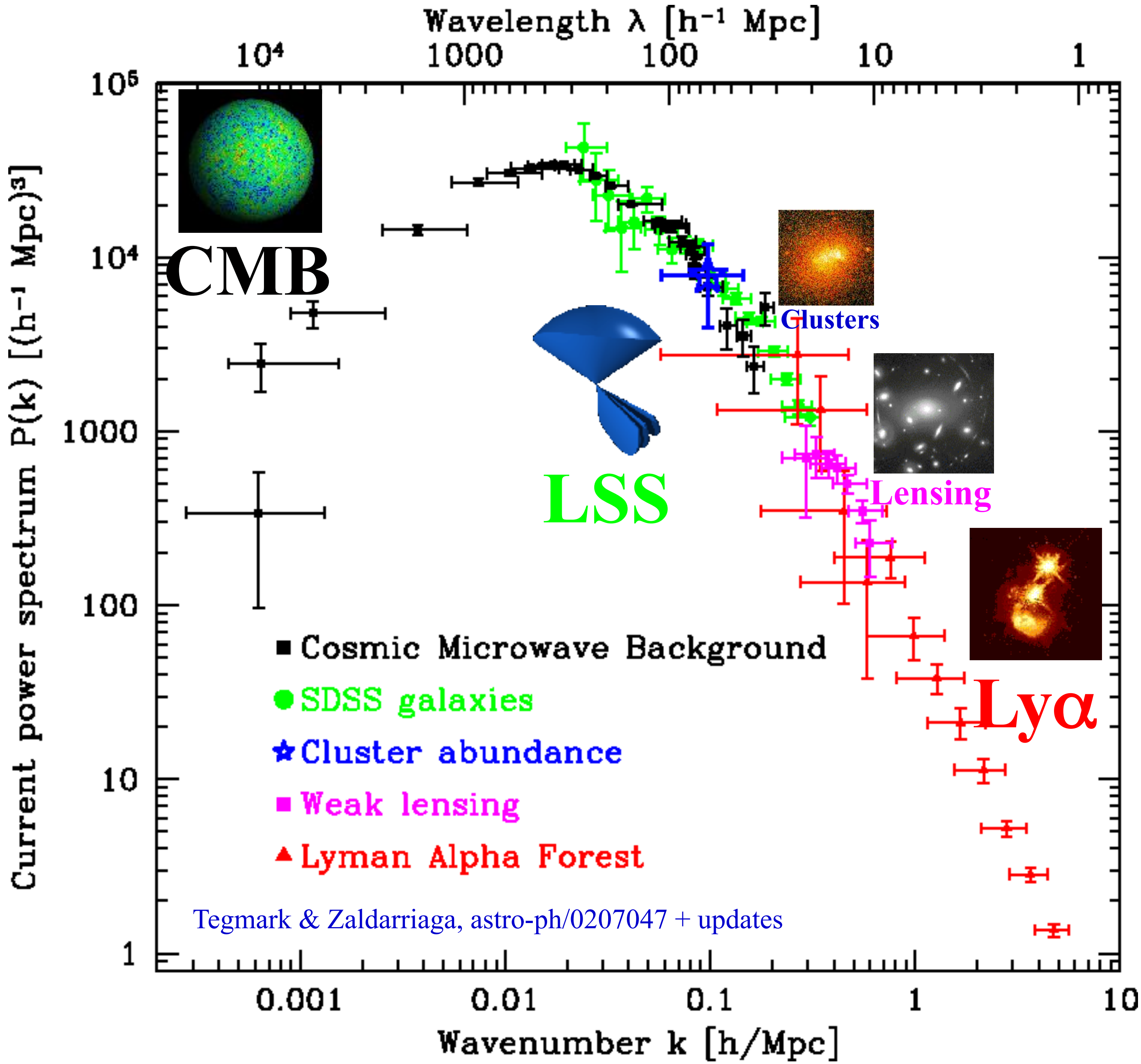

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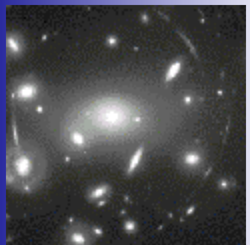
Chema movie

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



Lensing

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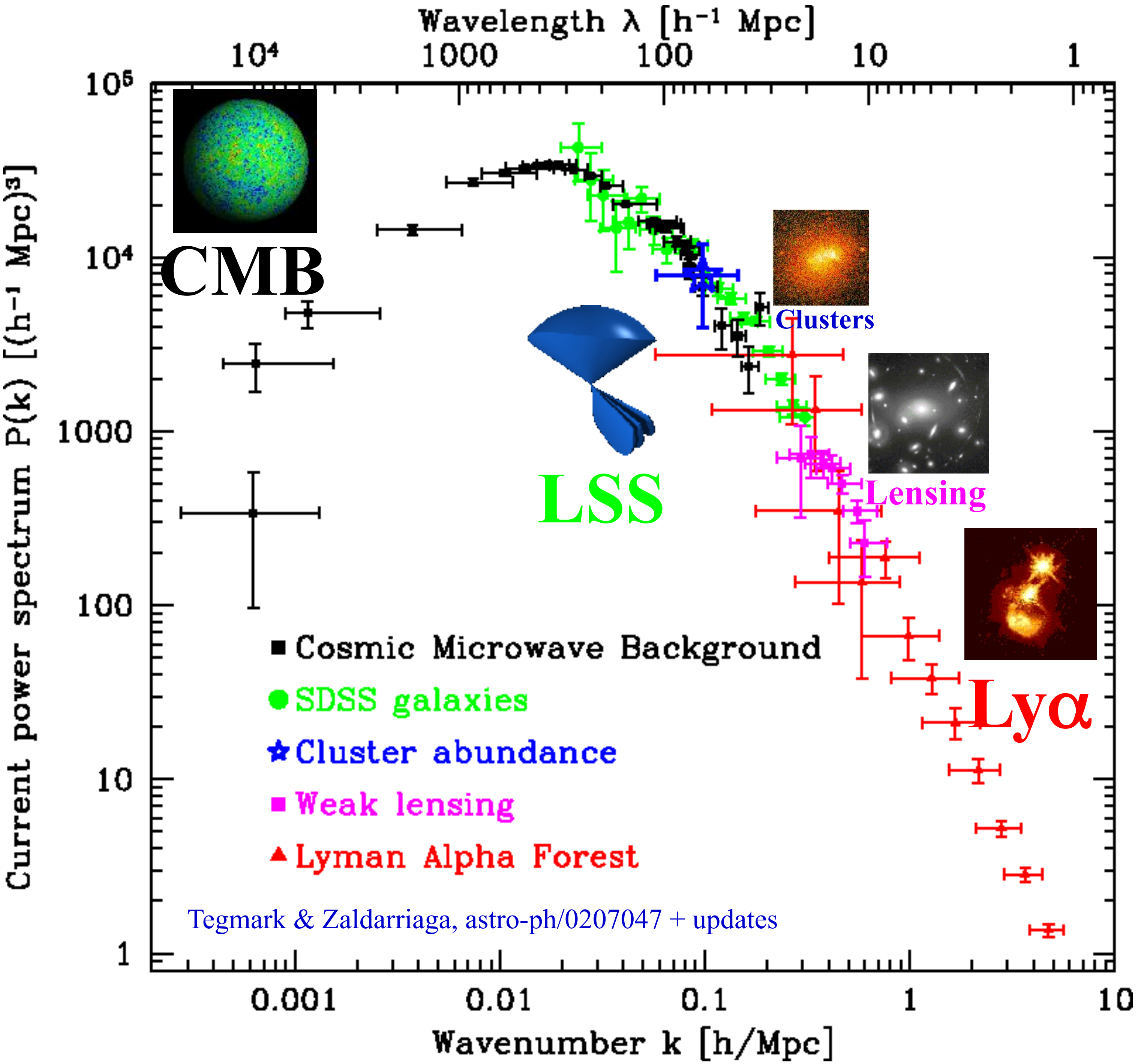

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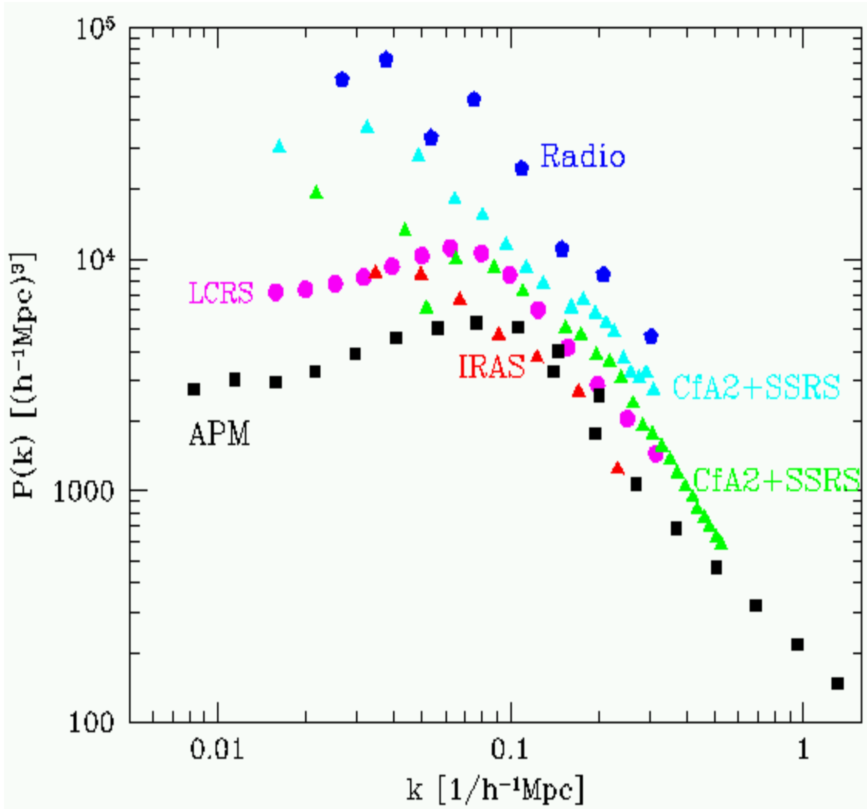

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

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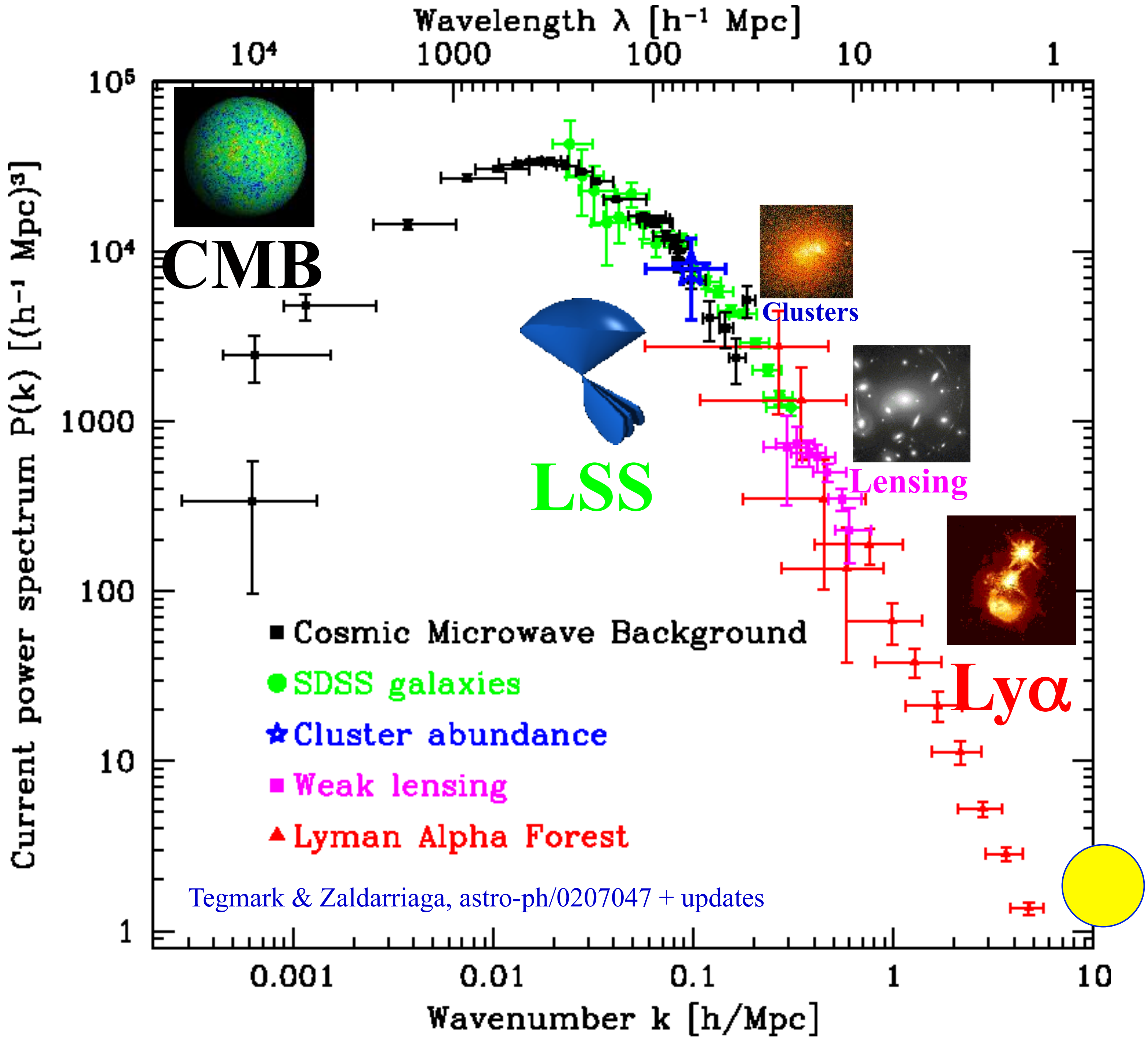

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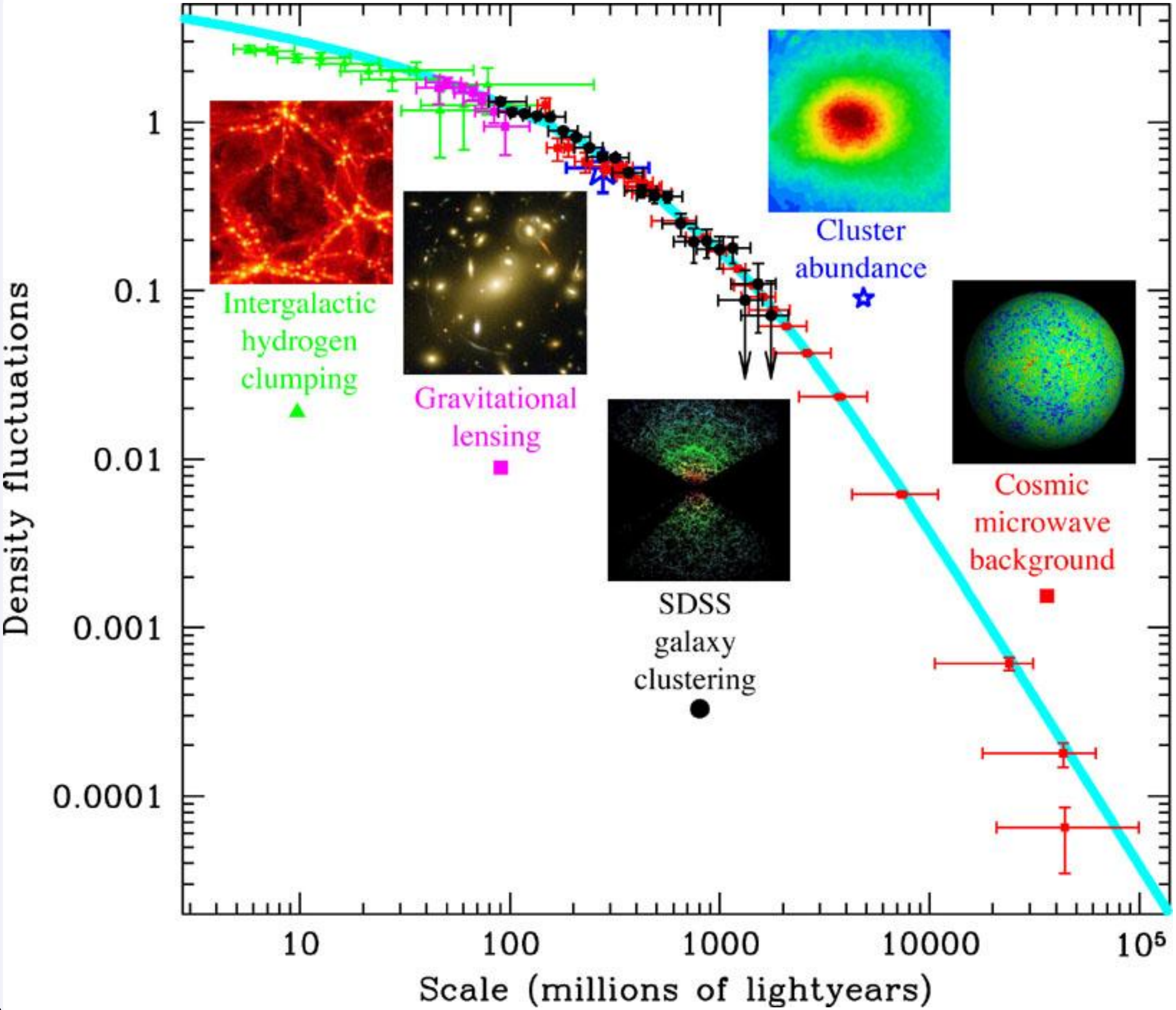
Measuring cosmological parameters



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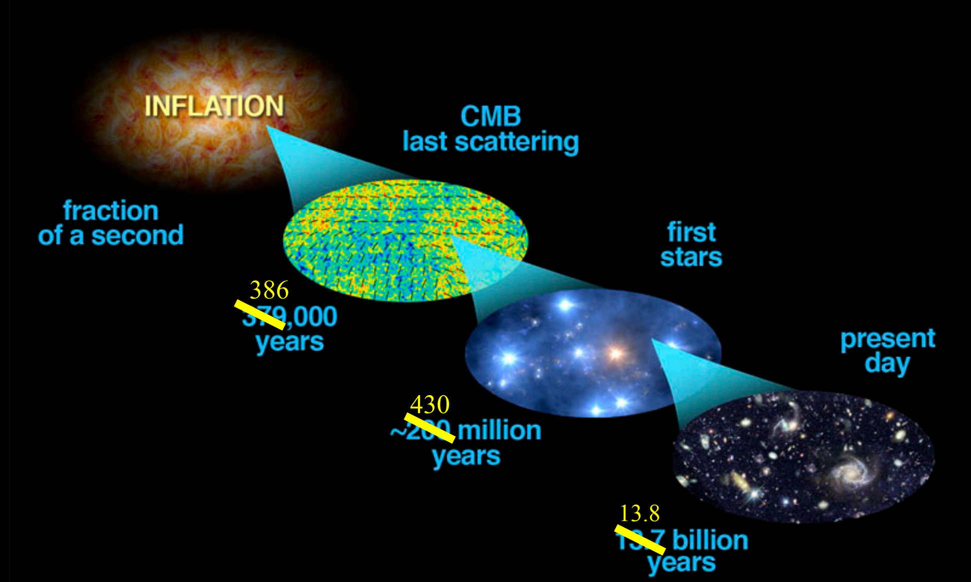
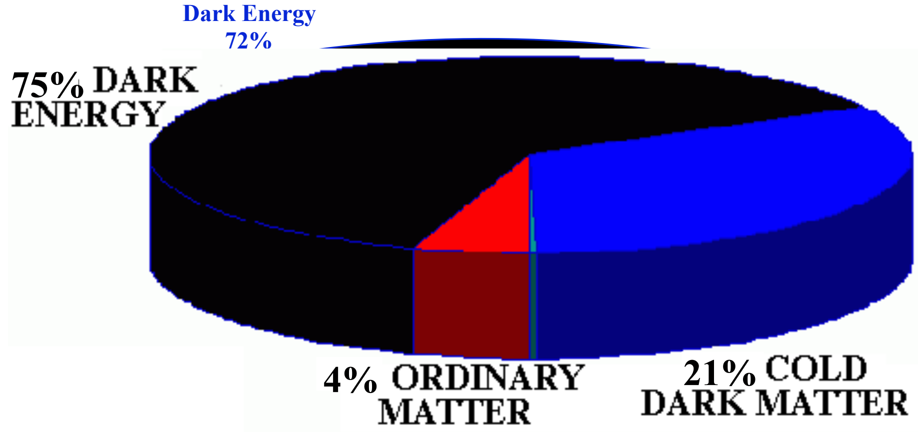
par movies



Cosmic history parameters:		
$z_{\rm eq}$	3057^{+105}_{-102}	Matter-radiation Equality redshift
$z_{\rm rec}$	$1090.25^{+0.93}_{-0.91}$	Recombination redshift
$z_{\rm ion}$	$11.1^{+2.2}_{-2.7}$	Reionization redshift (abrupt)
$z_{\rm acc}$	$0.855^{+0.059}_{-0.059}$	Acceleration redshift
$t_{\rm eq}$	$0.0634^{+0.0045}_{-0.0041}$ Myr	Matter-radiation Equality time
$t_{\rm rec}$	$0.3856^{+0.0040}_{-0.0040}$ Myr	Recombination time
$t_{\rm ion}$	$0.43^{+0.20}_{-0.10}$ Gyr	Reionization time
$t_{\rm acc}$	$6.74^{+0.25}_{-0.24}$ Gyr	Acceleration time
$t_{\rm now}$	$13.76^{+0.15}_{-0.15}$ Gyr	Age of Universe now

Using WMAP3 + SDSS LRGs:



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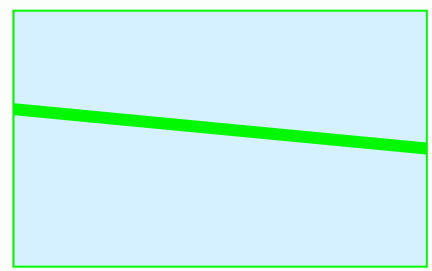

How will it all end?

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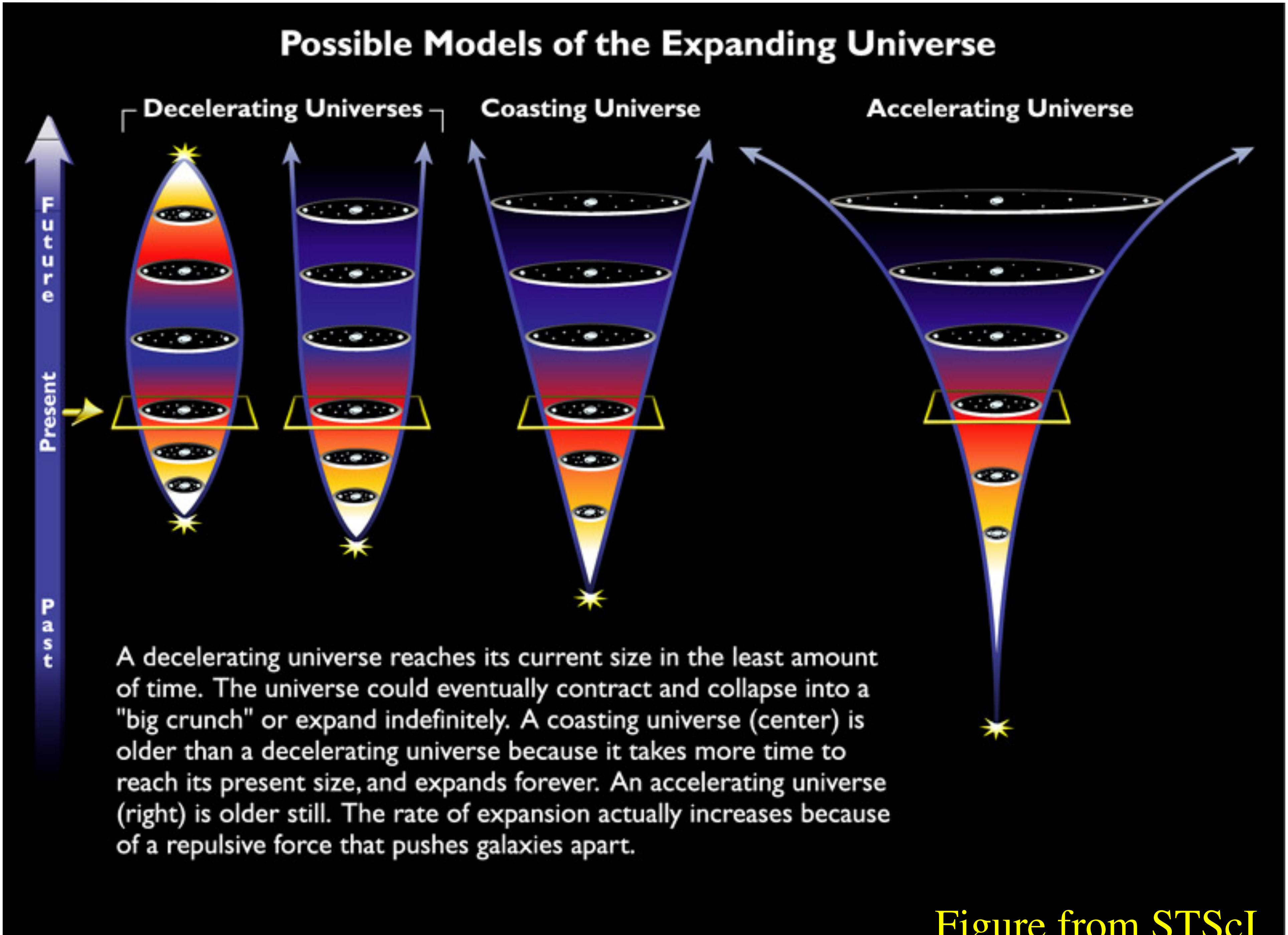
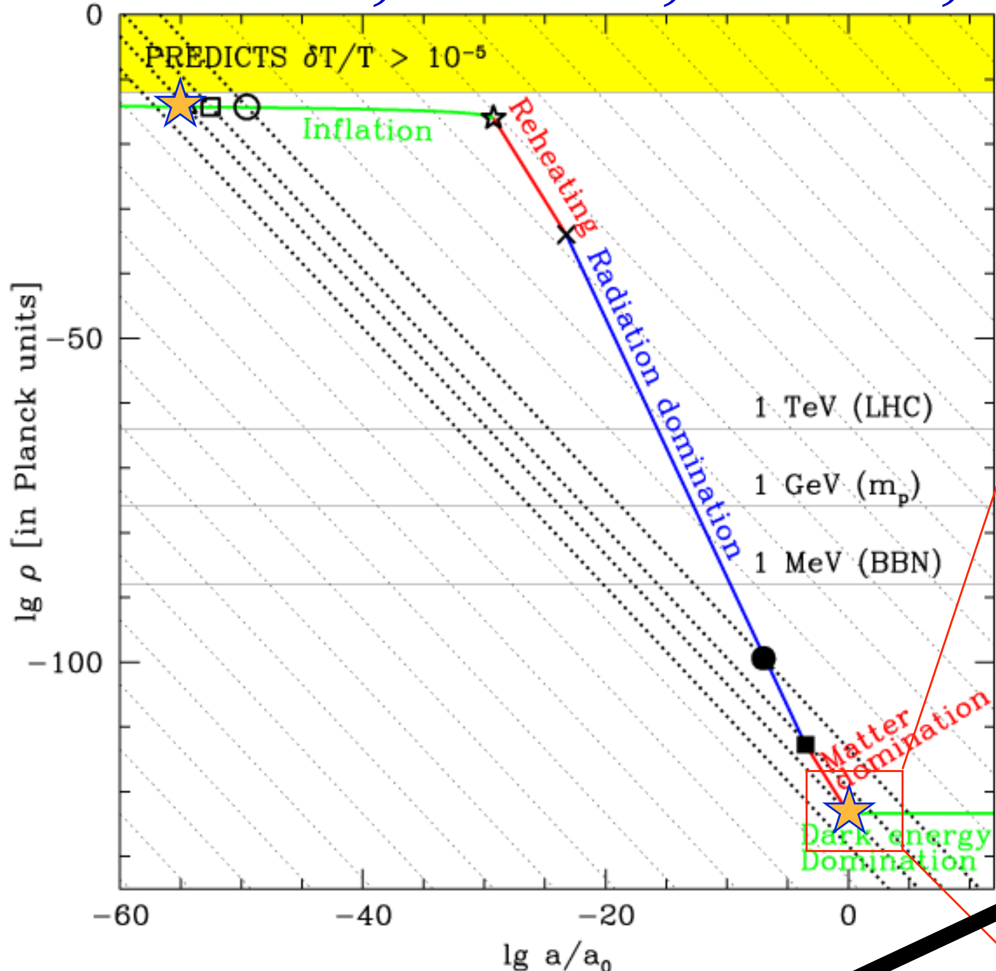
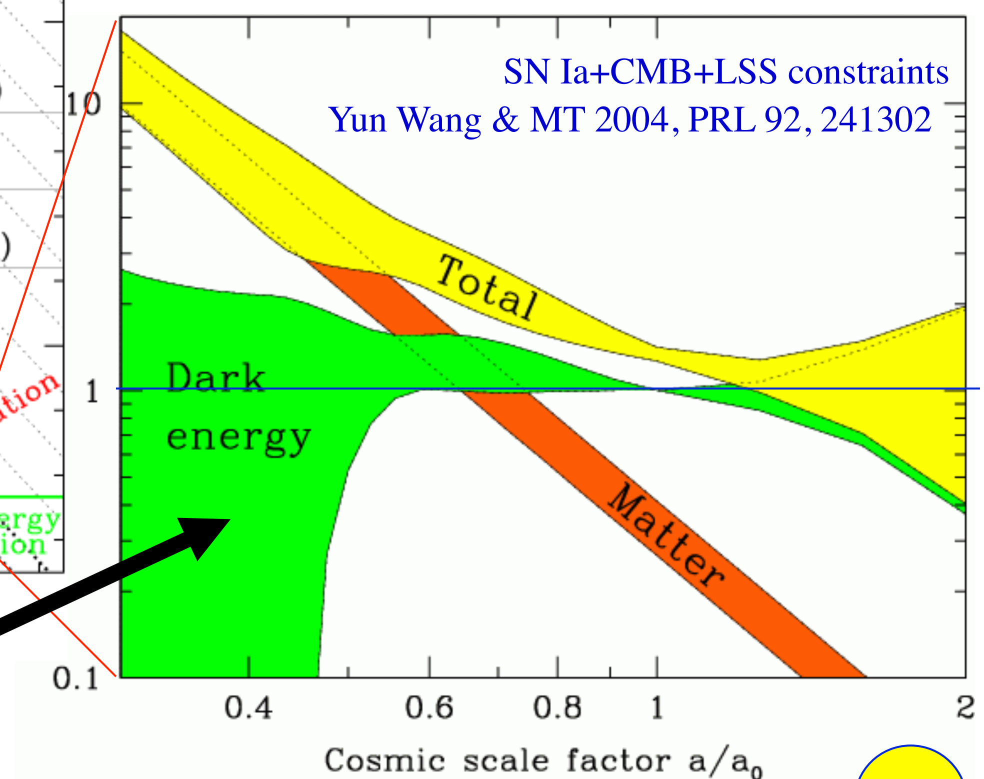


Figure from STScI

What we've learned about H(z) from SN Ia, CMB, BAO, BBN, etc:

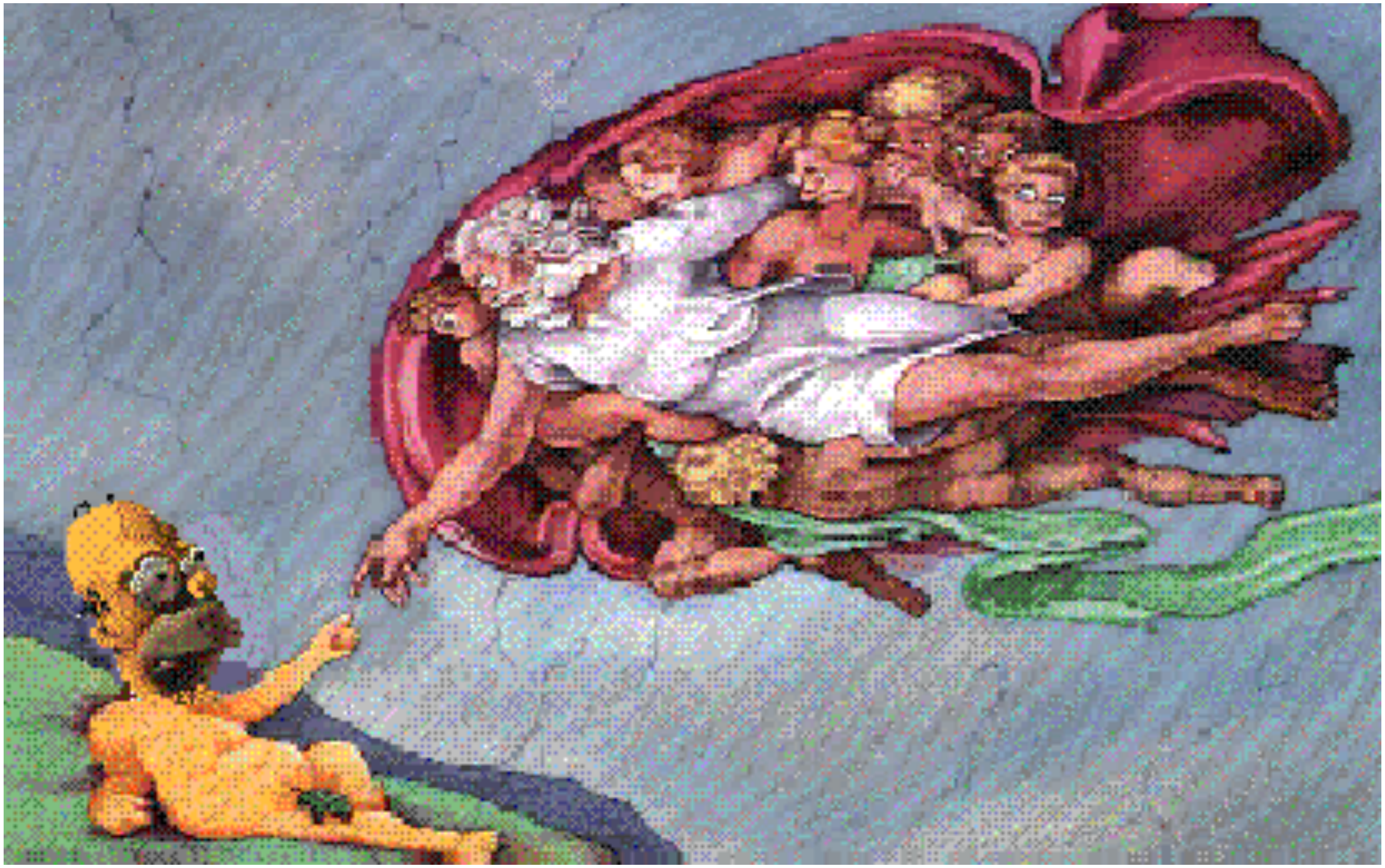


Assumes k=0



Vanilla rules OK!

How did it all begin?



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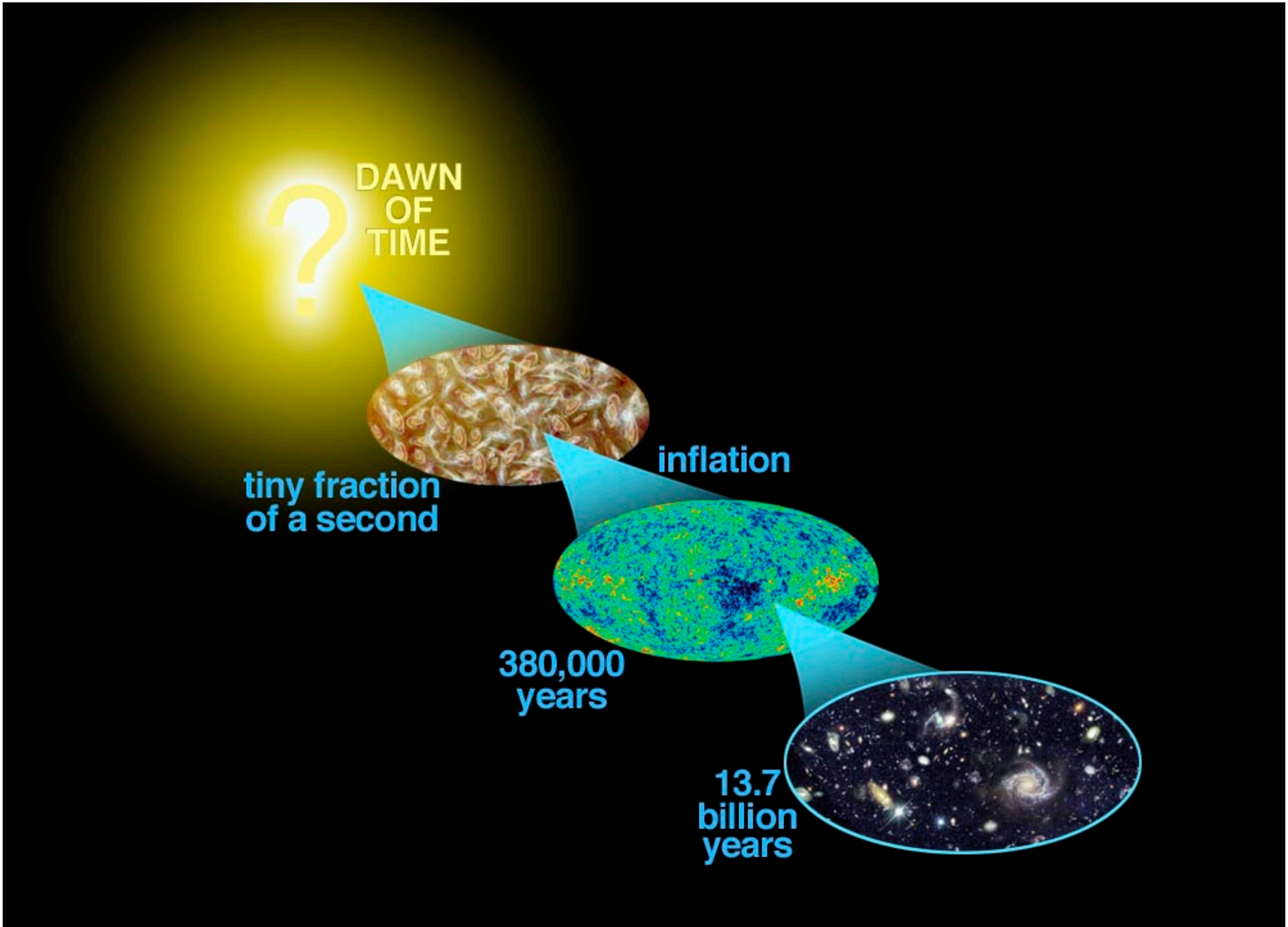
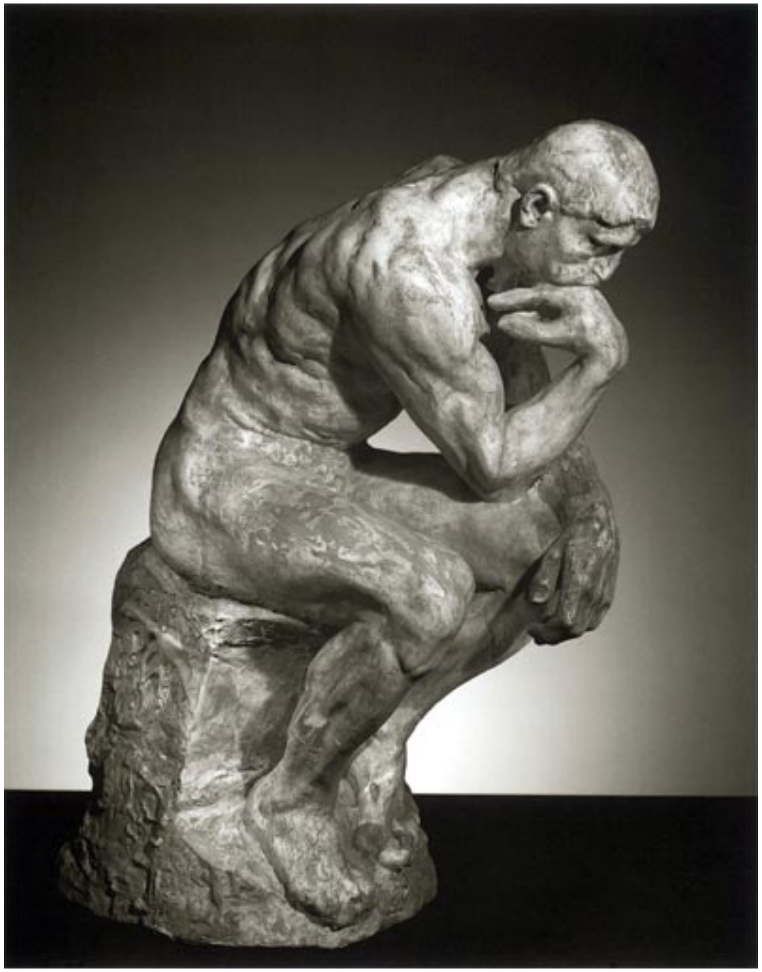


Graphics from WMAP team

Some things to ponder…



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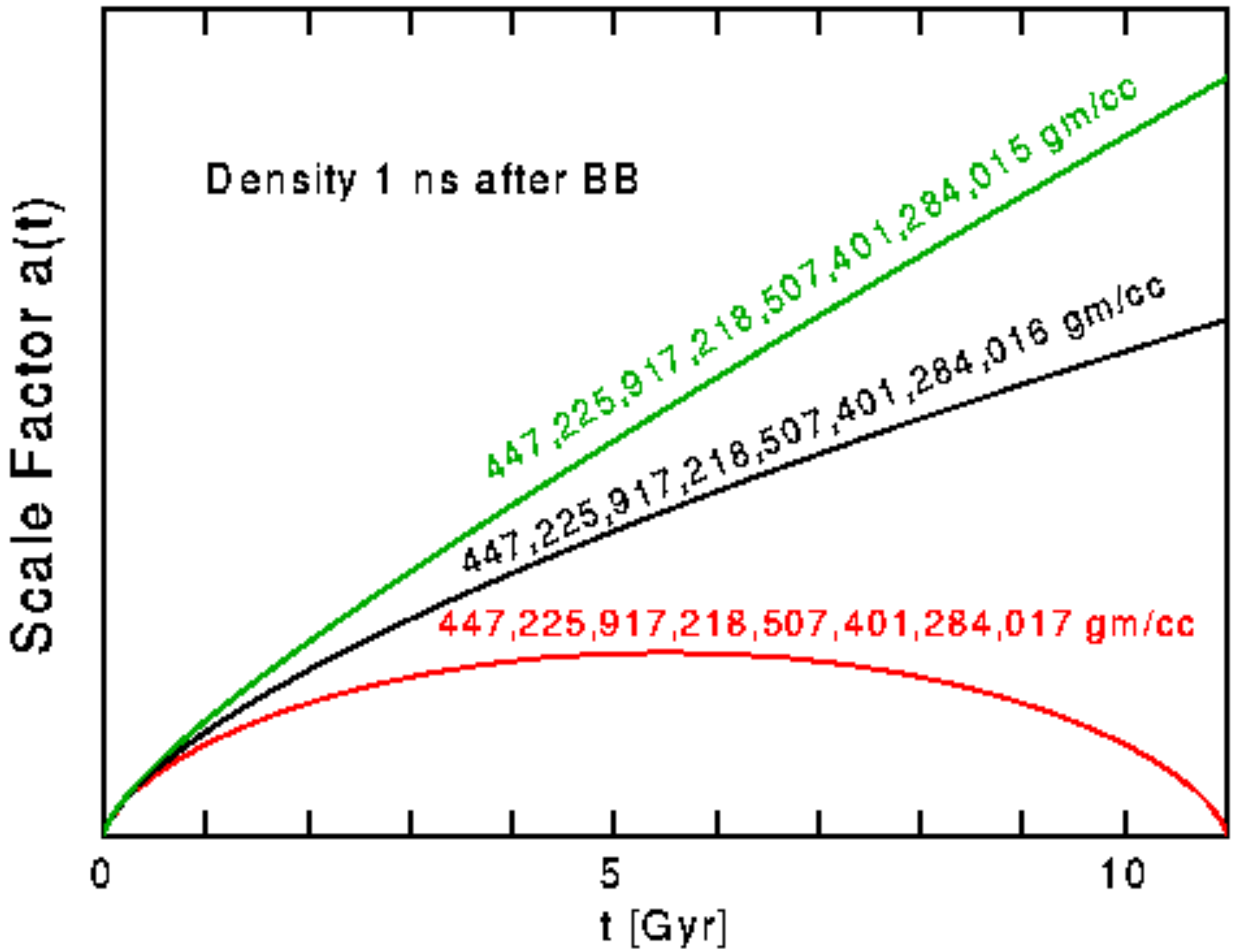

Ned Wright

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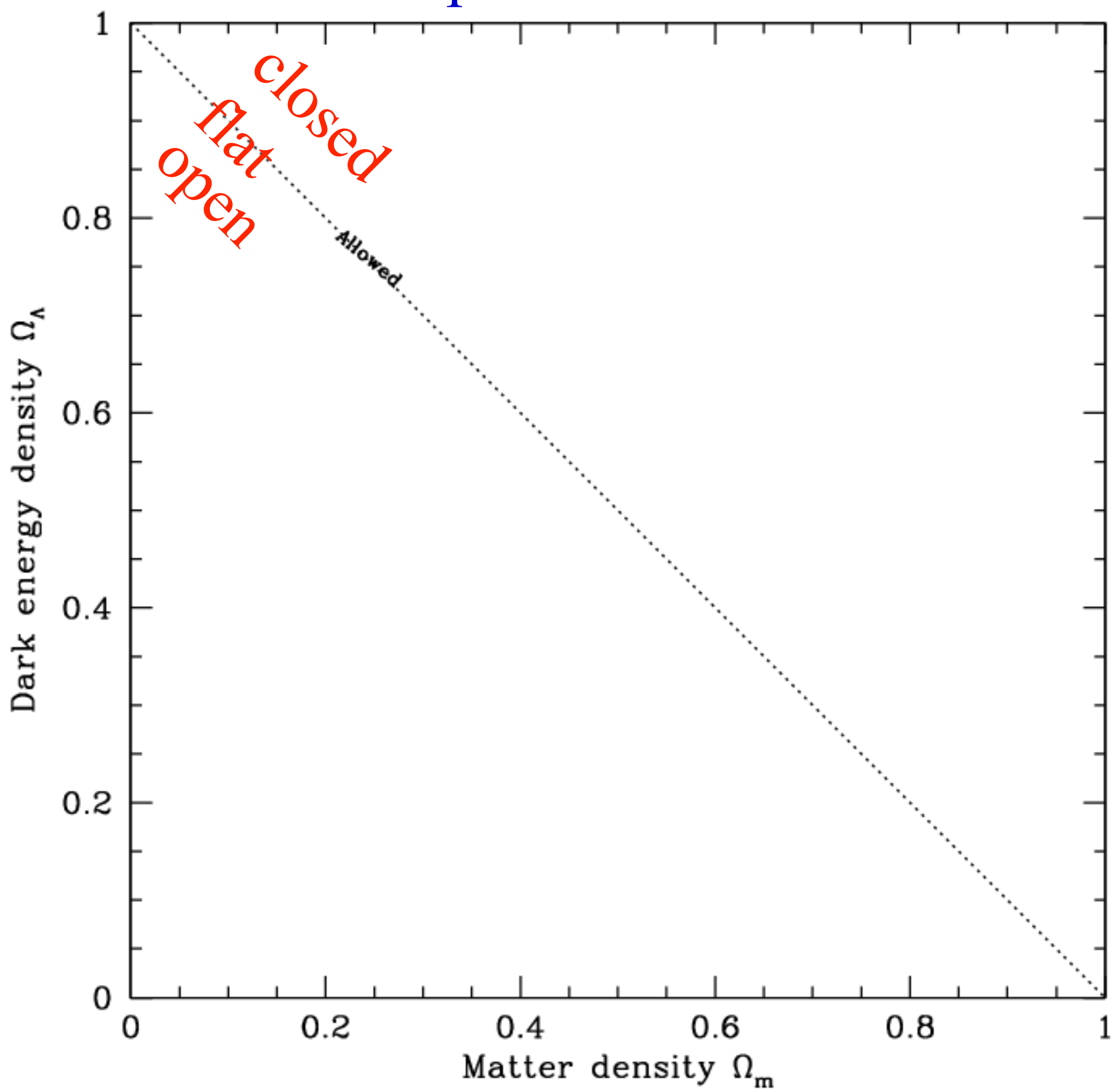
How flat is space?



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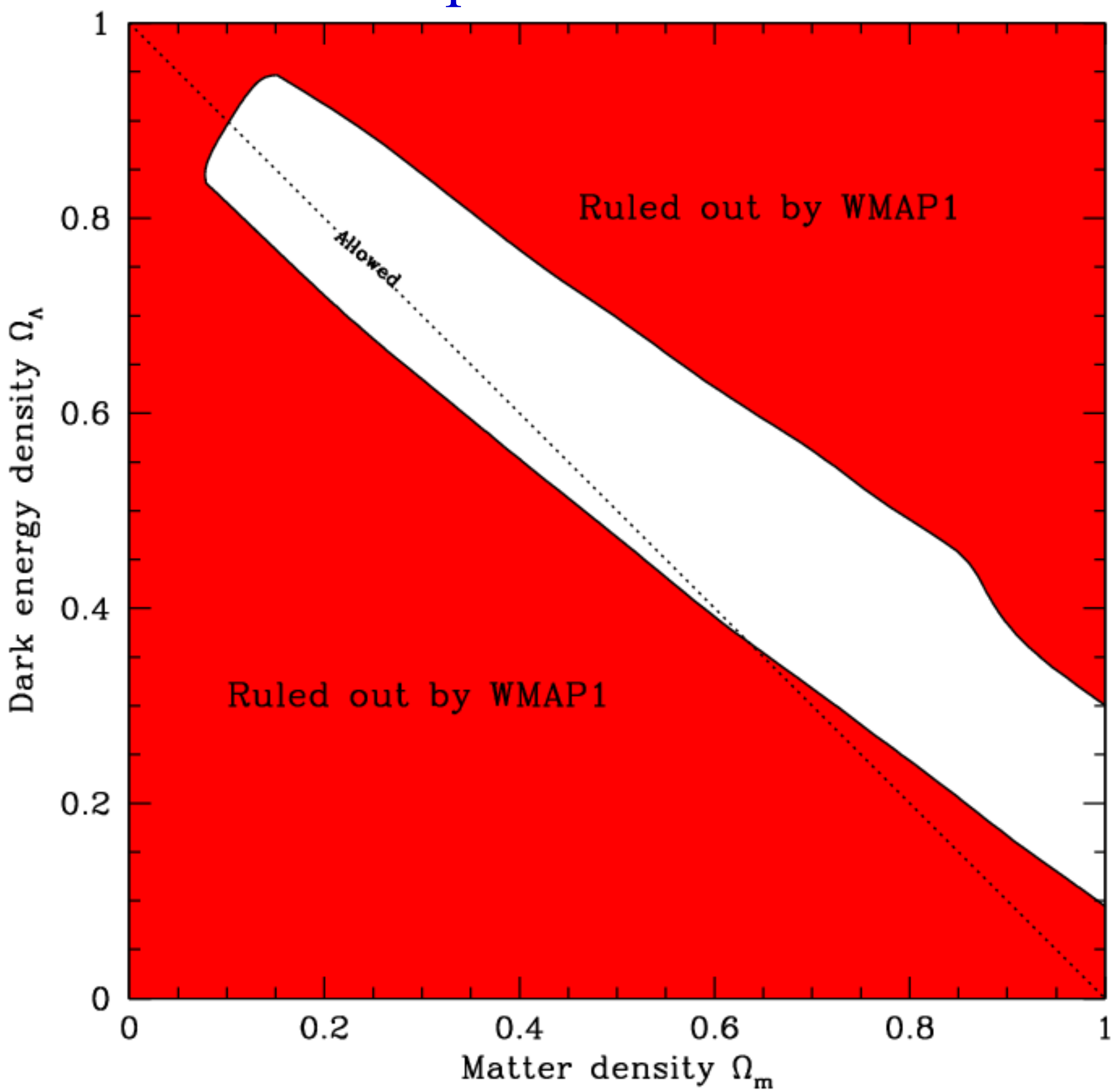
How flat is space?



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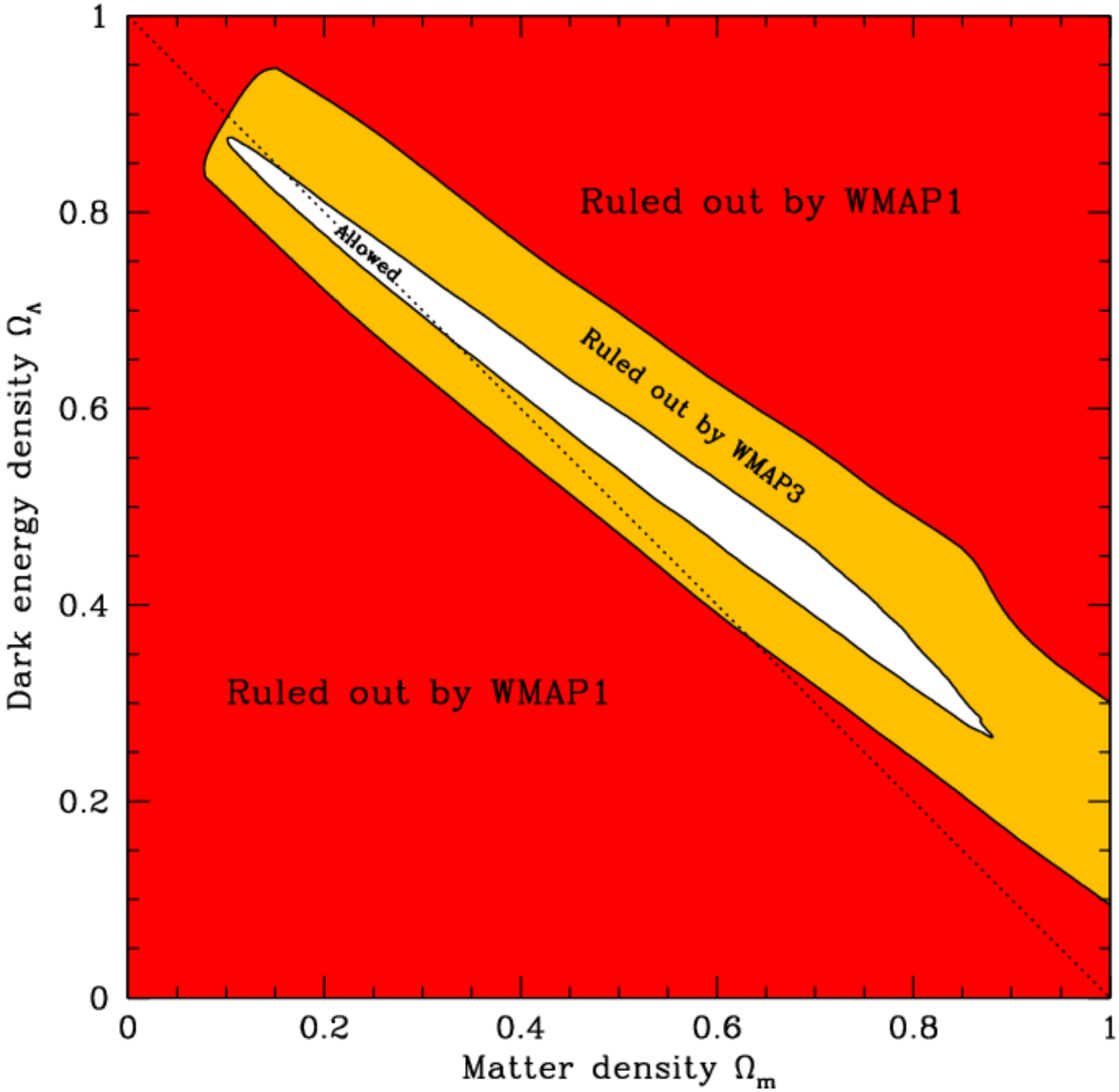
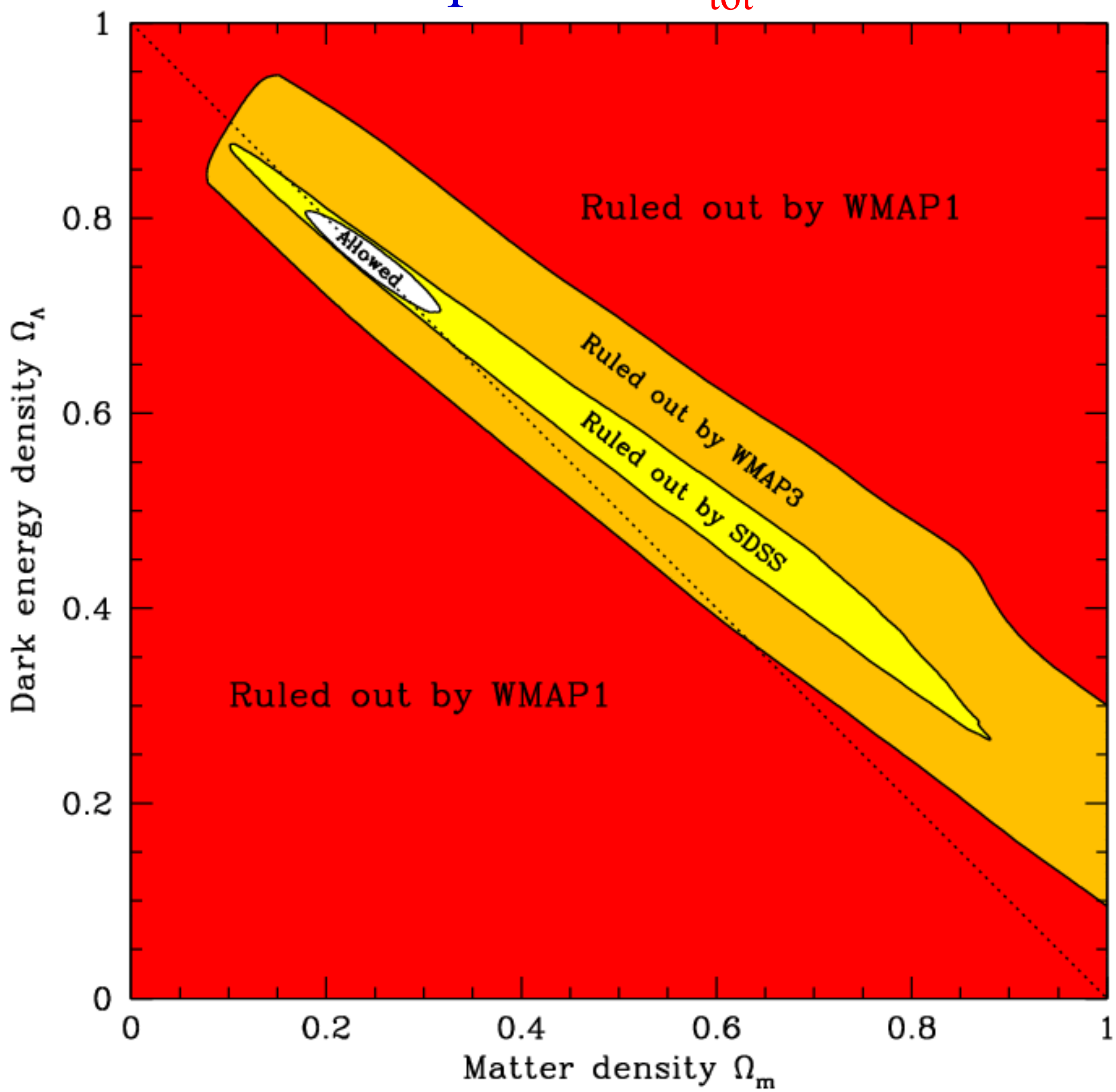
How flat is space? Somewhat.



How flat is space? $\Omega_{tot}=1.003\pm0.010$



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