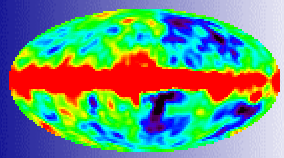
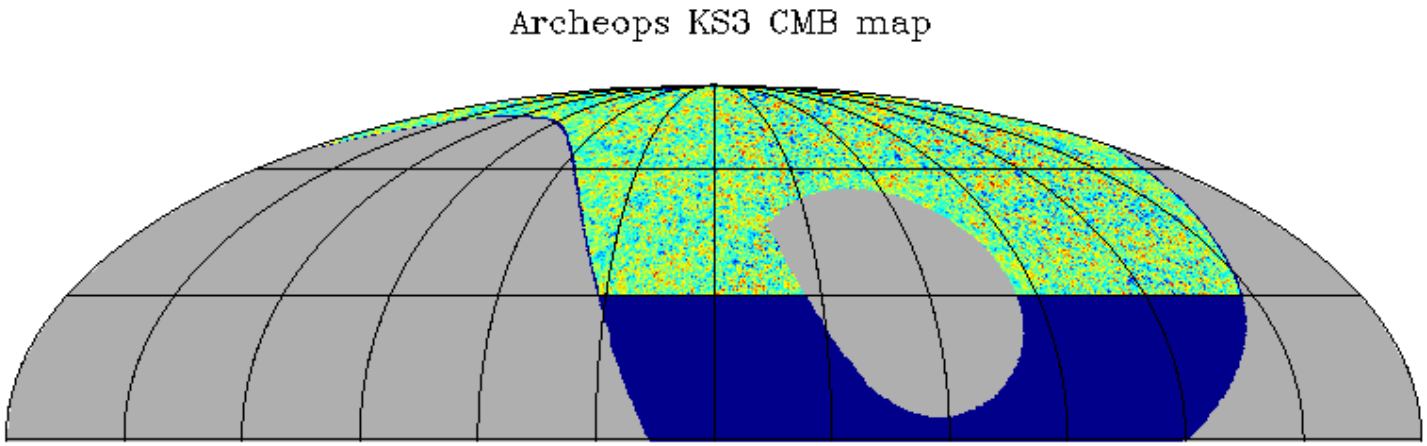
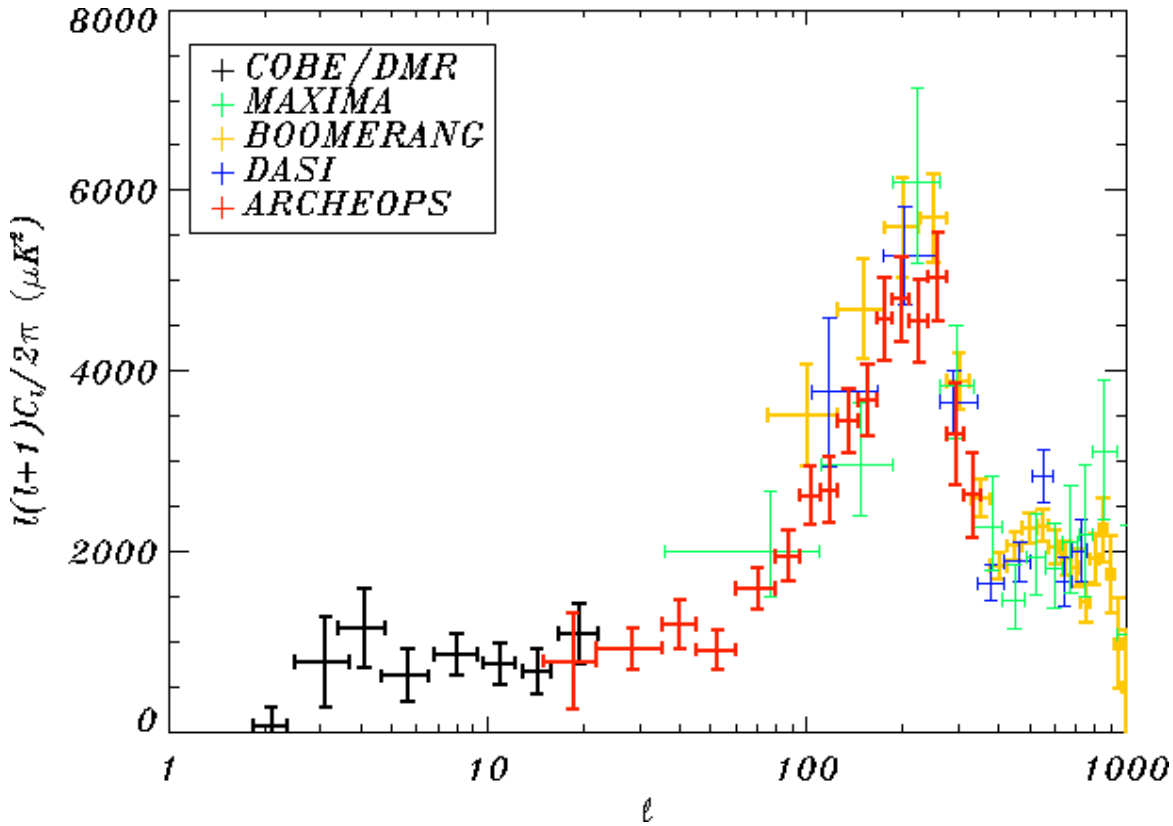


CMB

ARCHEOPS RESULTS: Benoit et al, October 14 2002ž





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Beyond cosmological parameters

Max Tegmark, University of Pennsylvania

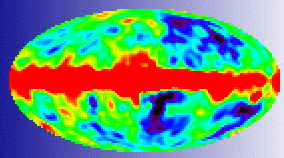
Xiaomin Wang, Penn

Yongzhong Xu, Penn

Matias Zaldarriaga, NYU

Andrew Hamilton, Boulder

SDSS team



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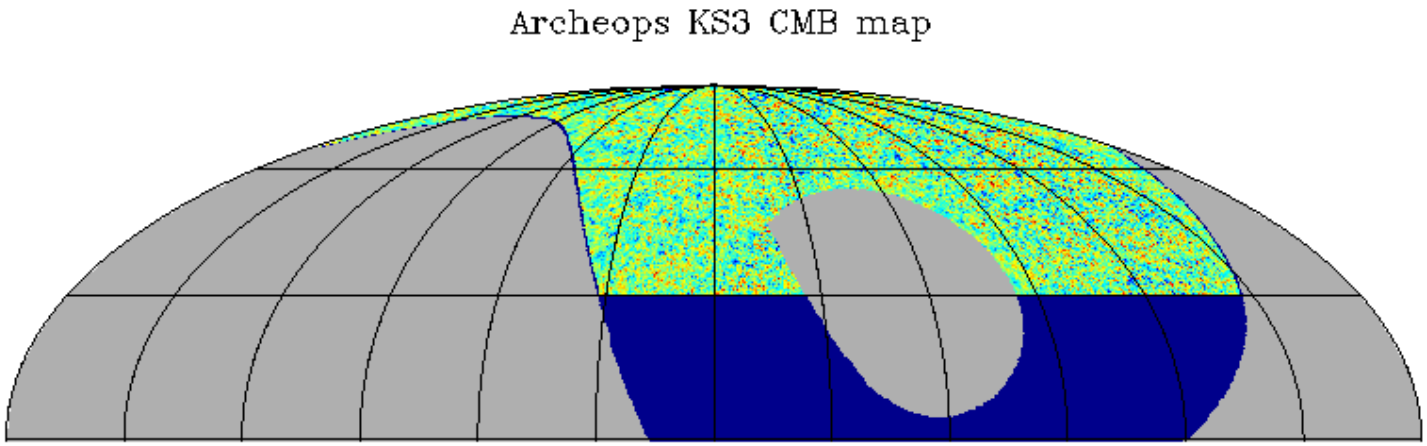

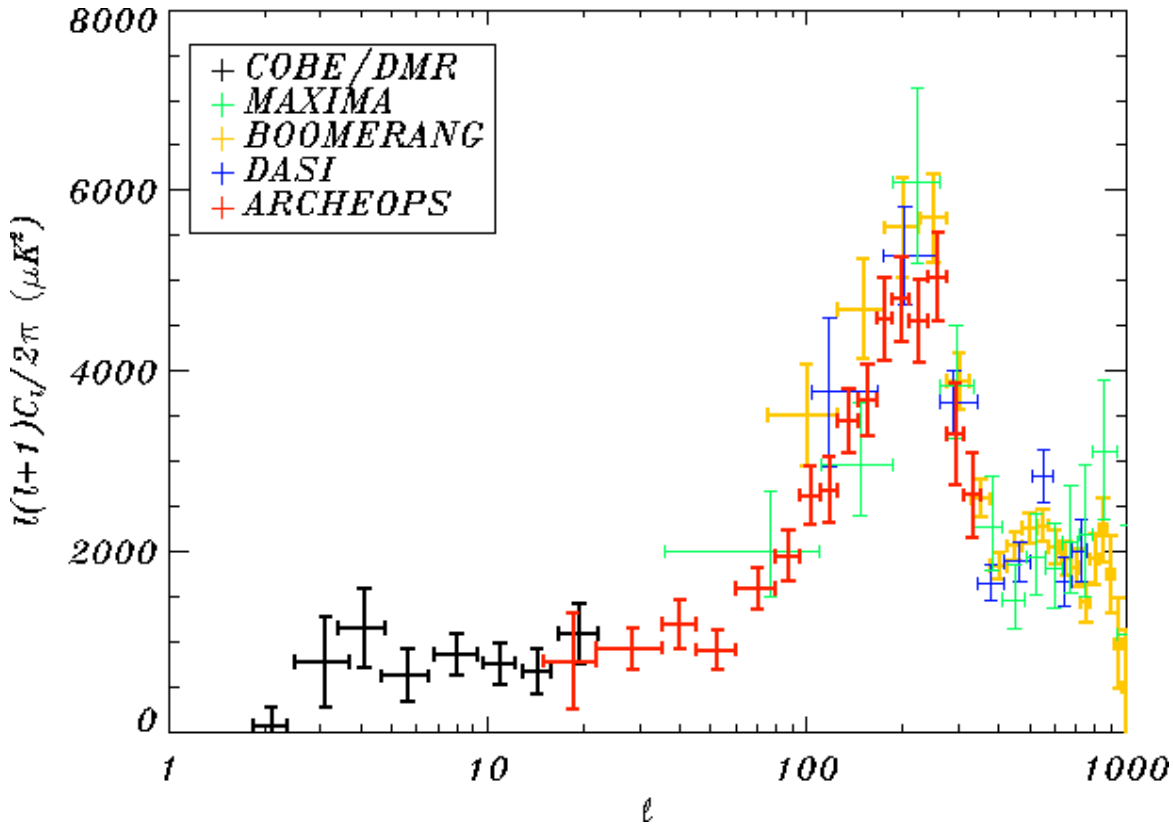

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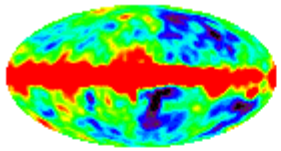

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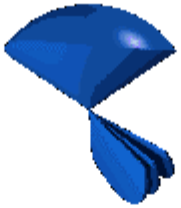
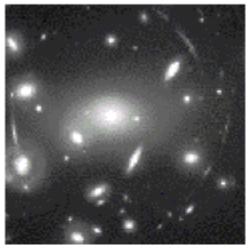


GALAXY SURVEYS

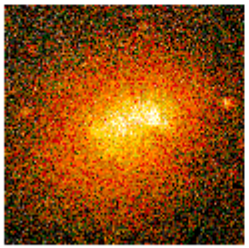
DISTANT SUPERNOVAE



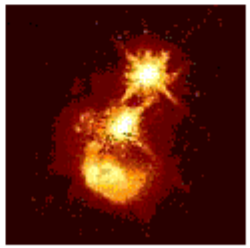
GRAVITATIONAL LENSING

THE COSMIC SMÖRGÅSBORD

BIG BANG NUCLEOSYNTHESIS



GALAXY CLUSTERS



LYMAN ALPHA FOREST

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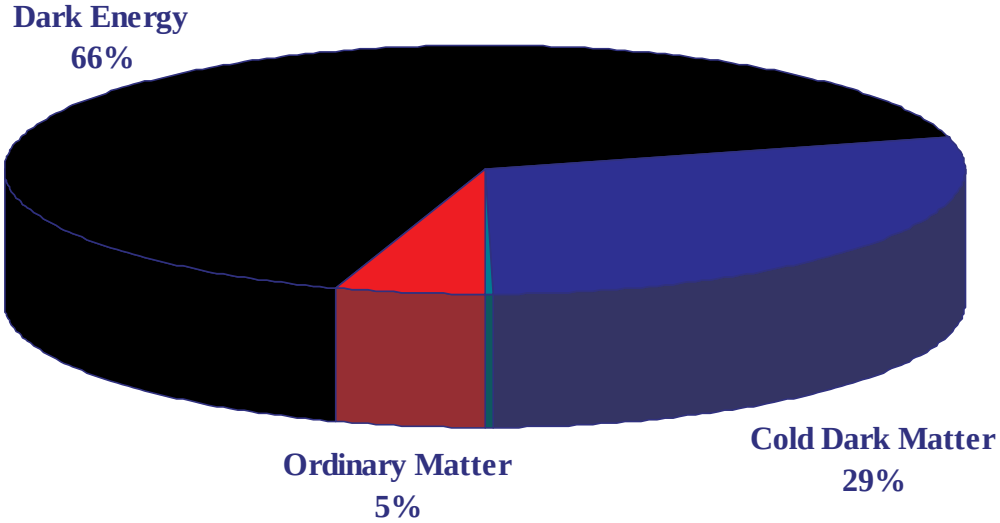
THOSE PESKY PARAMETERS: WE'RE ZEROING IN!
(August 2002)

•Matter Budget

- Ordinary Matter $h^2\Omega_b = .021^{+.006}_{-.006}$
- Dark Energy $\Omega_\Lambda = 0.66^{+.10}_{-.13}$
- Cold Dark Matter $h^2\Omega_c = 0.12^{+.05}_{-.03}$
- Hot Dark Matter $h^2\Omega_\nu = .001^{+.04}$
- Photons $h^2\Omega_\gamma = 0.0001$
- Budget Deficit $\Omega_k = 0.00^{+.06}_{-.06}$

(95% limits)



•Early Universe

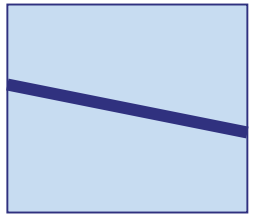
Scalar normalization $Q \sim 10^{-5}$

Scalar tilt $n = 0.93^{+.12}_{-.10}$

Running of tilt $\alpha = ?$

Tensor normalization $R < 0.2$

Tensor tilt $n_T = ?$



(Post-CBI parameters from Xiaomin Wang)

•Gastrophysics

Reionization optical depth $\tau = 0.07^{+.16}_{-.07}$

Galaxy bias $b \sim 1$ (for 2dF L*)

Hubble parameter $h = 0.65^{+.11}_{-.11}$

Is cosmology solved? We still have no clue what 95% of all stuff is made of!

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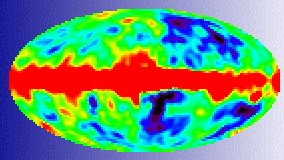
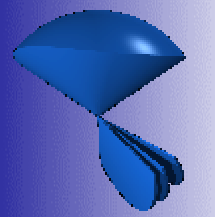
Measuring parameters

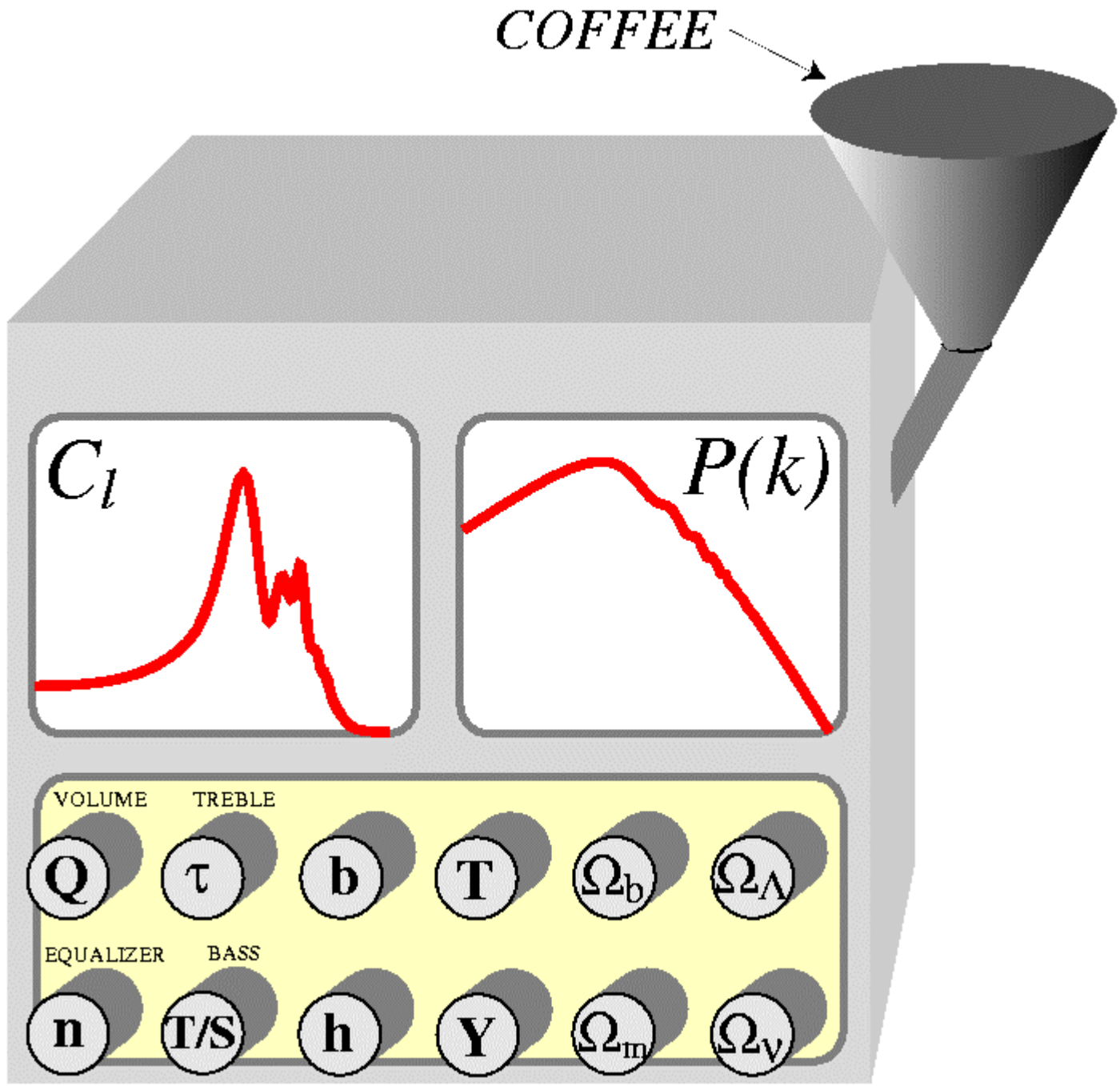


CMB

+



LSS



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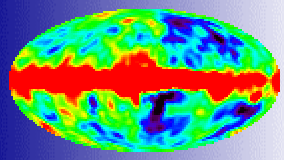
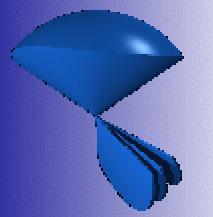
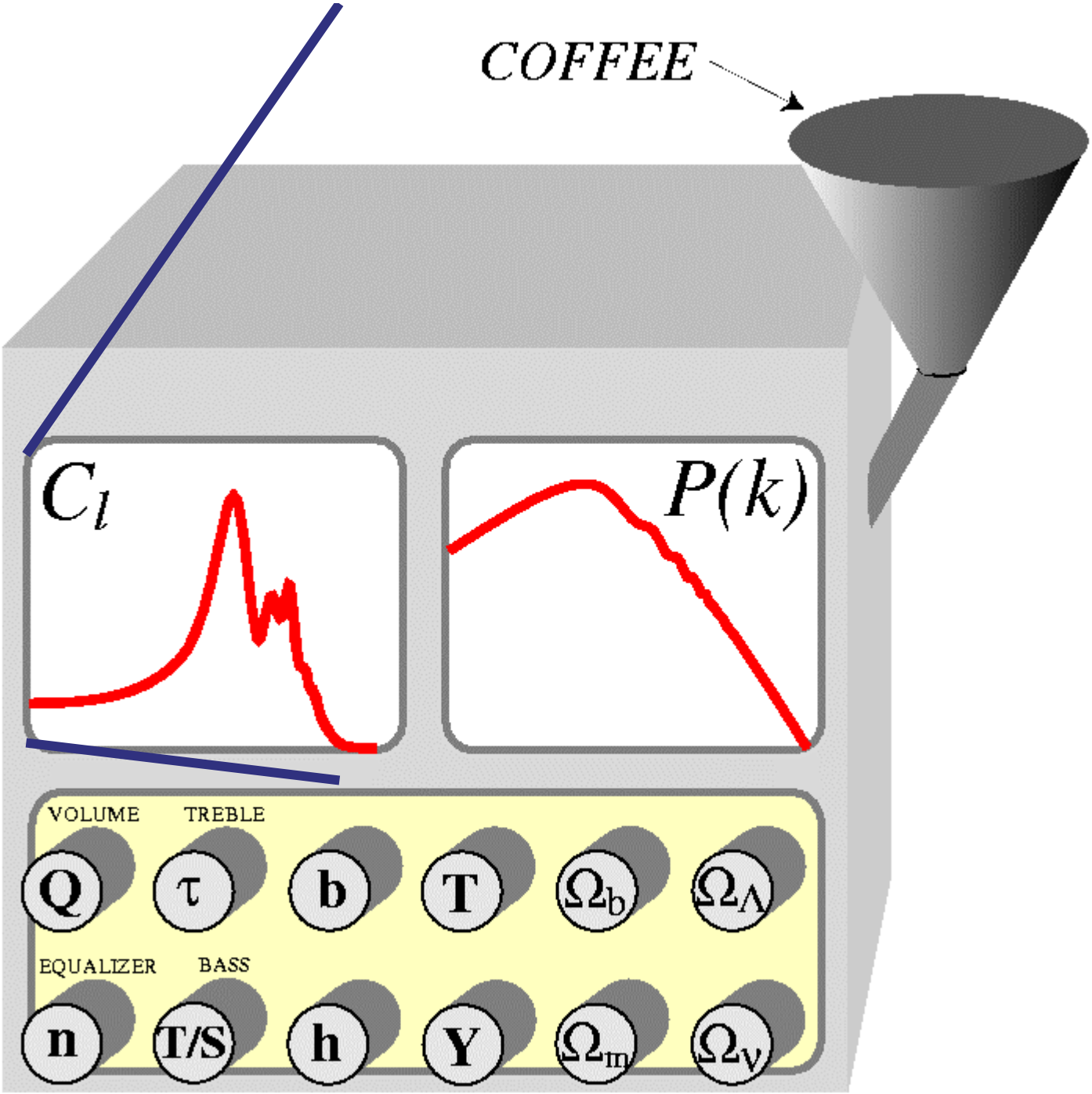


CMB + LSS





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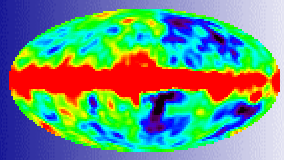

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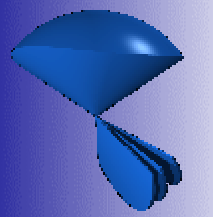

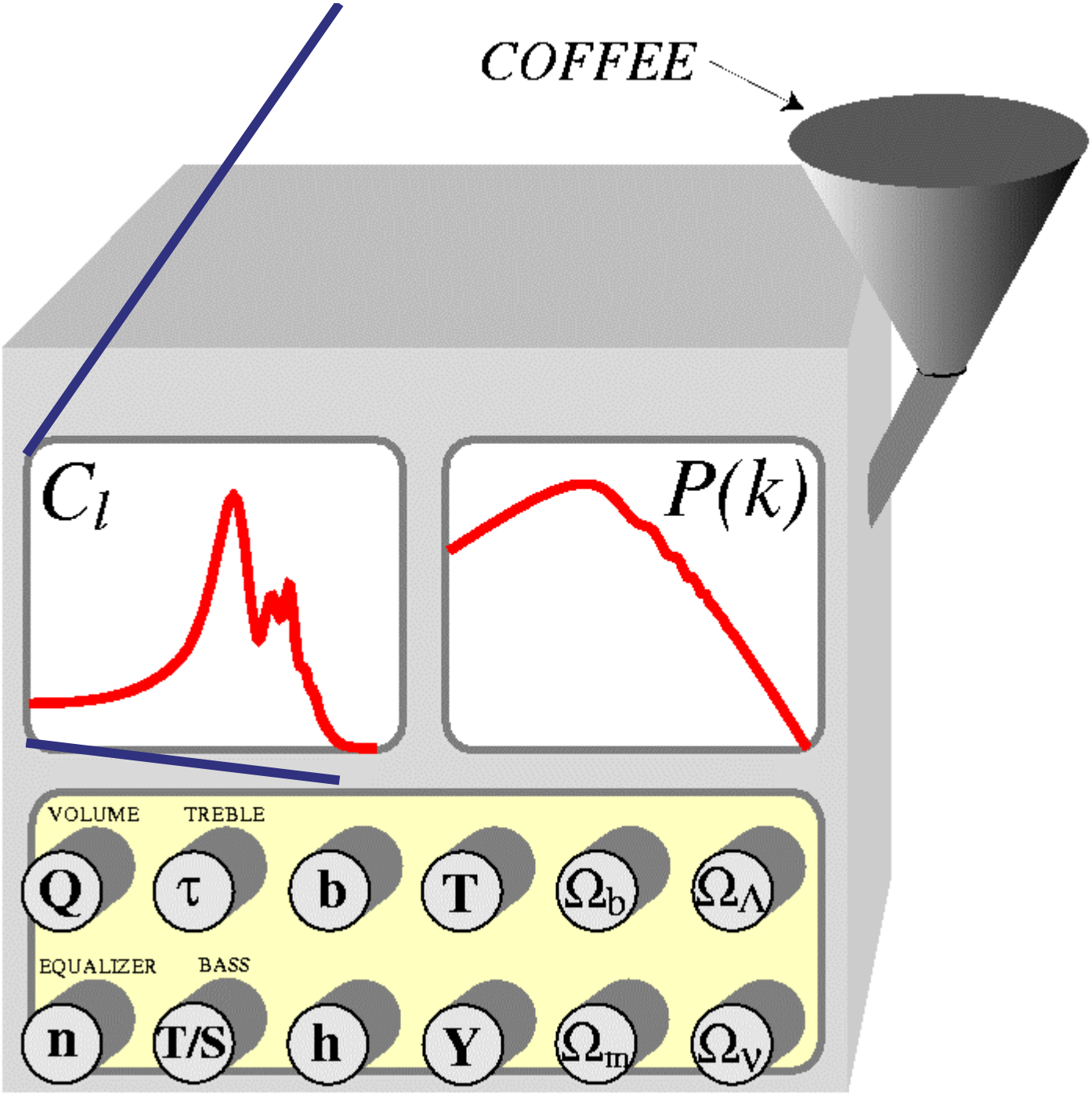

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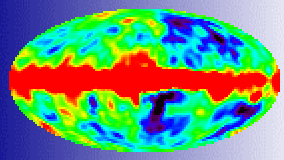

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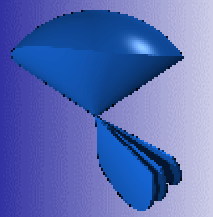

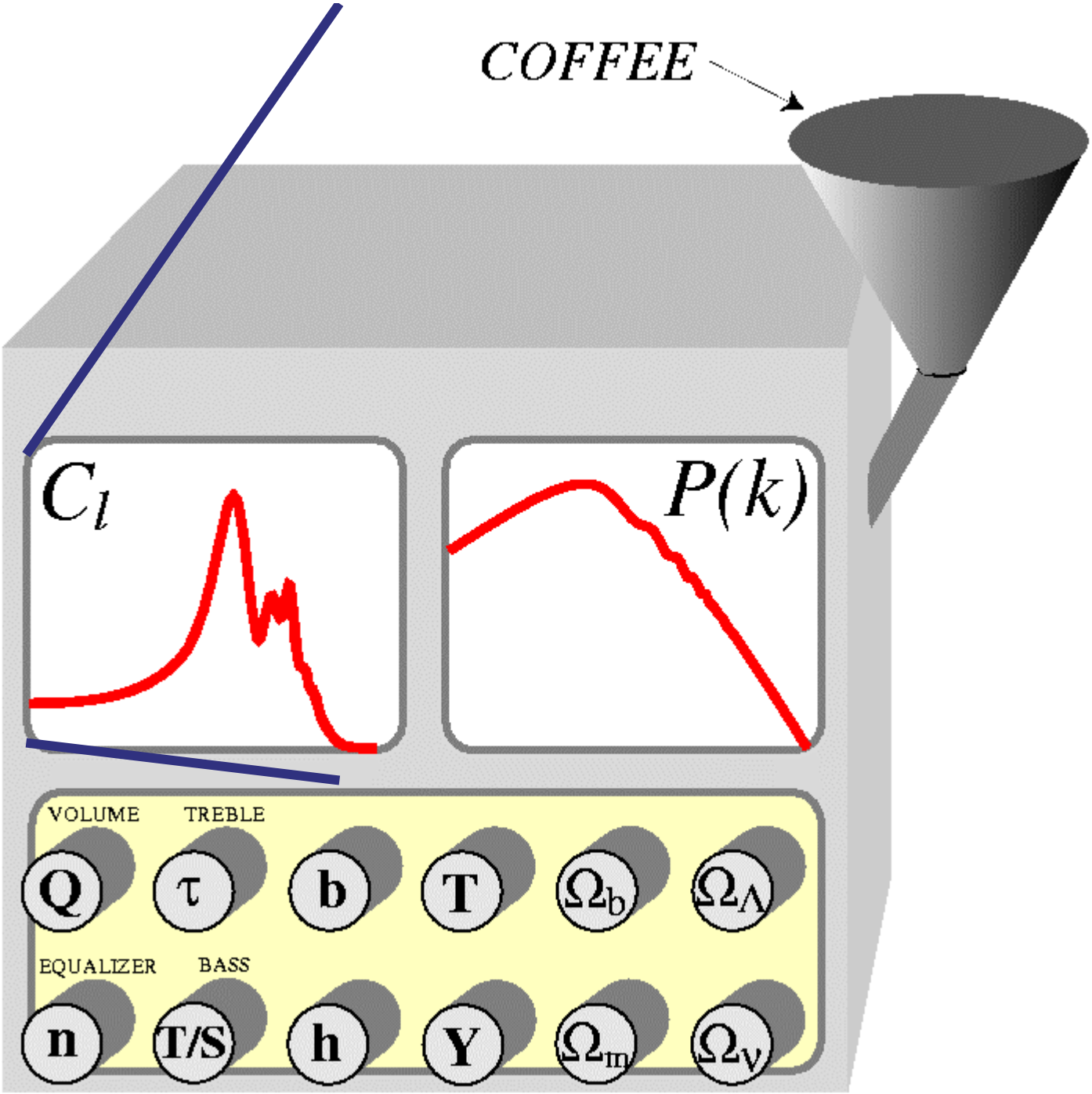

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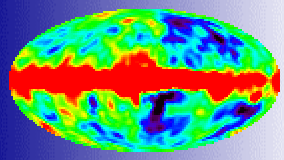

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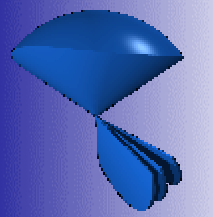

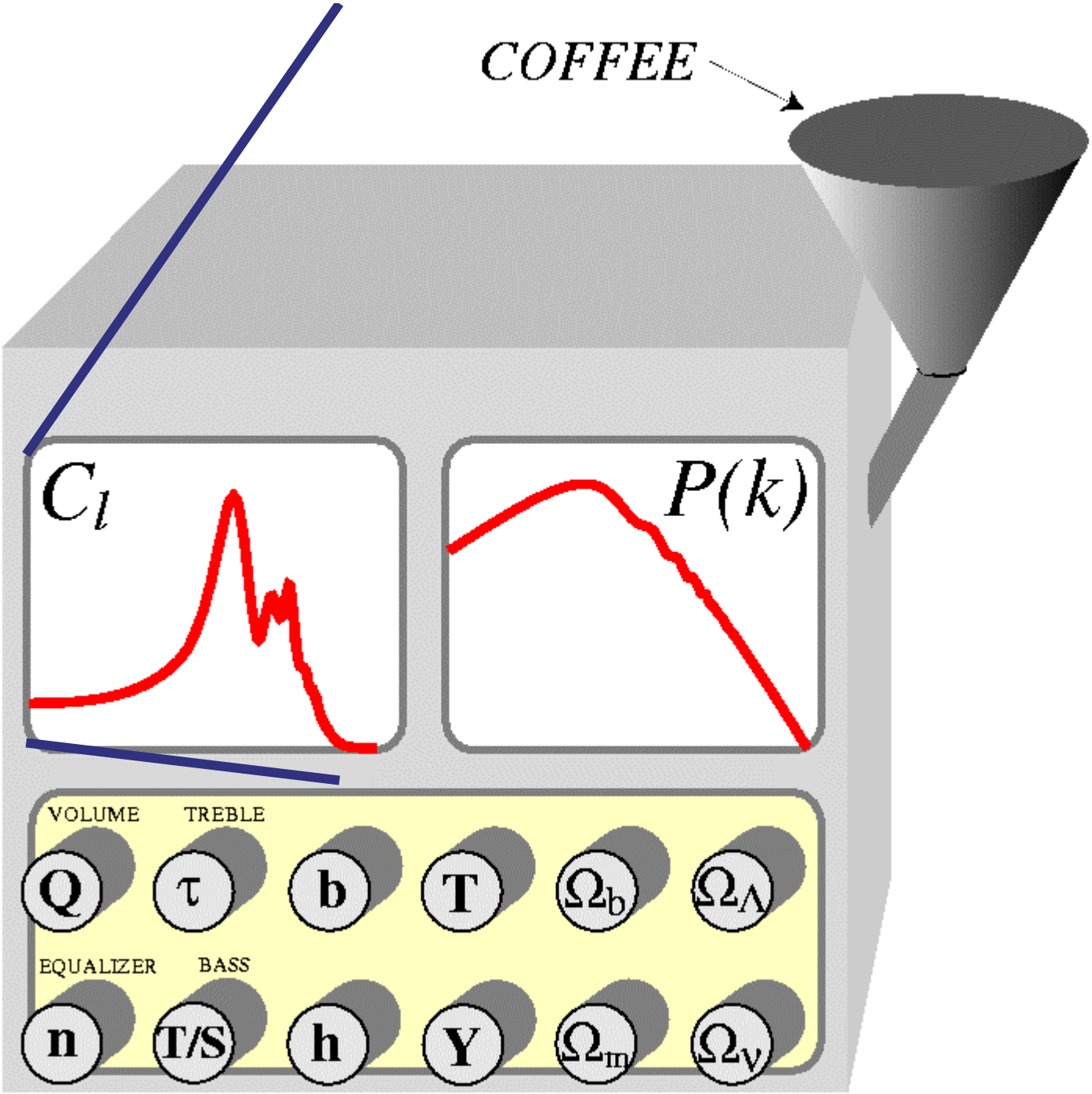

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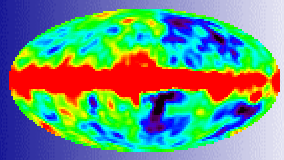

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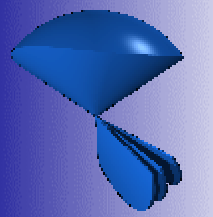

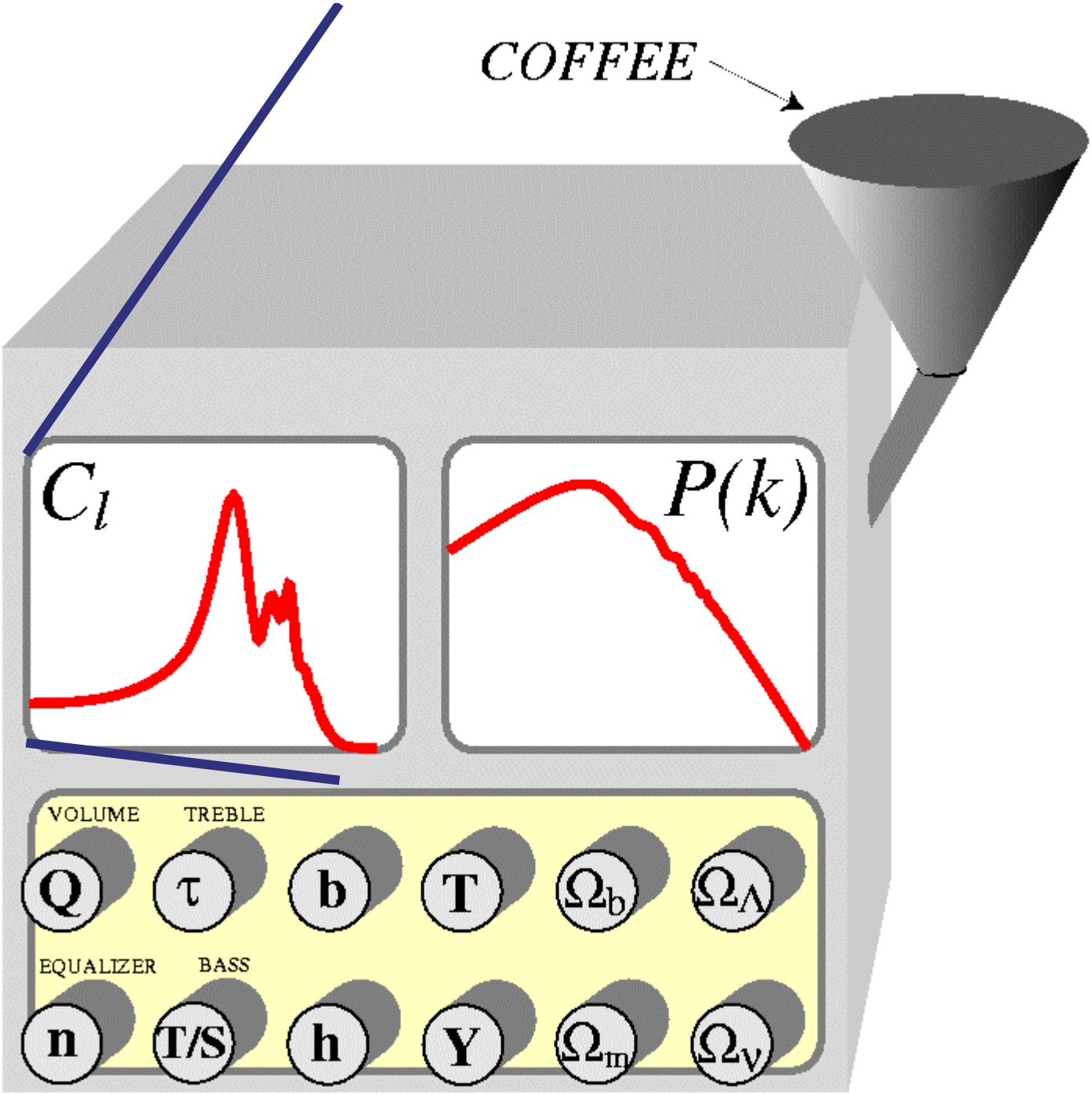

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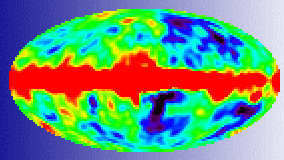

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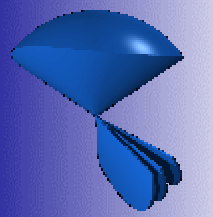

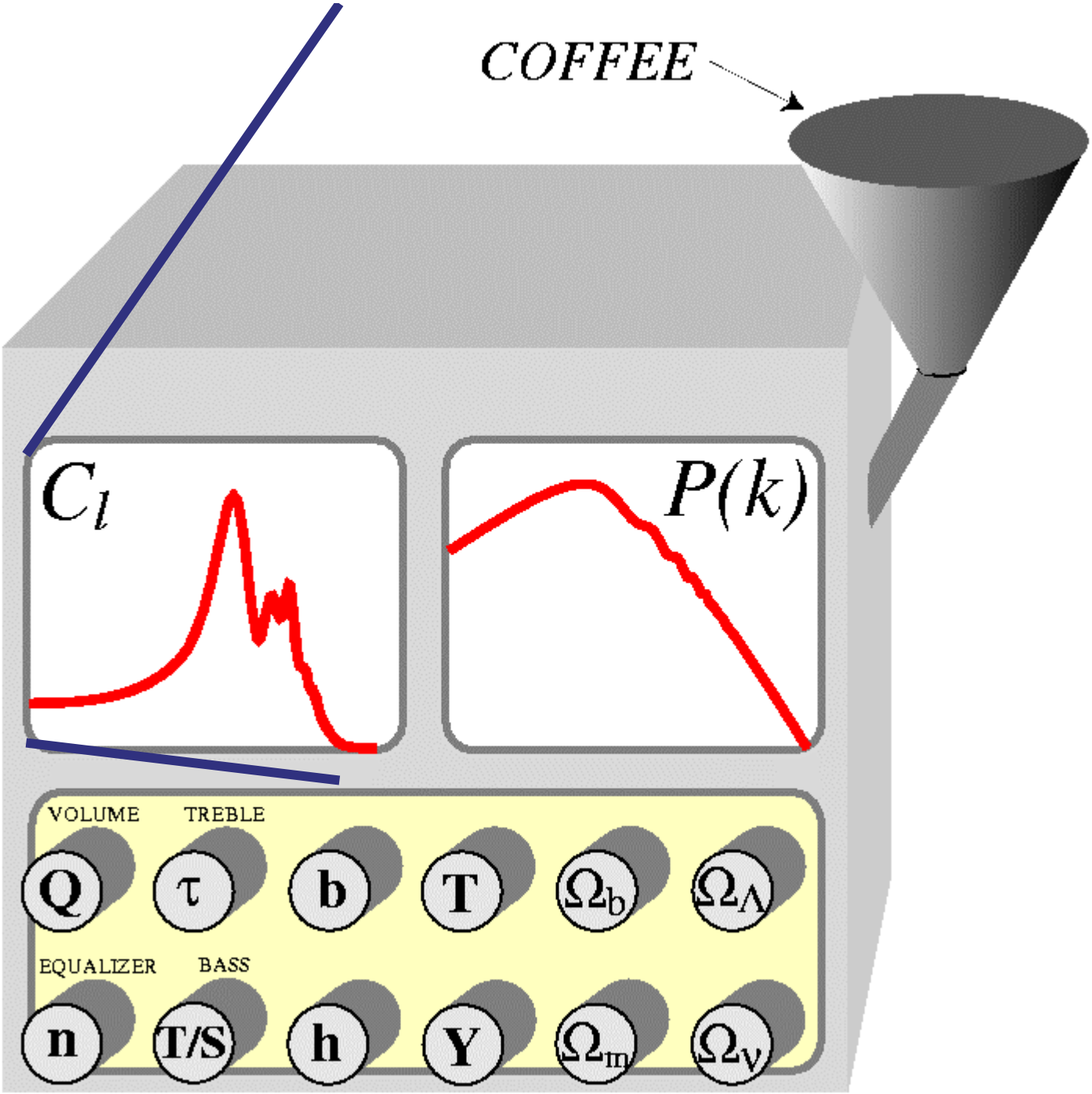

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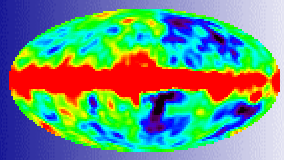

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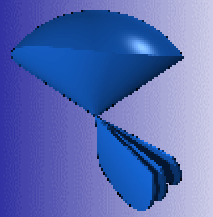

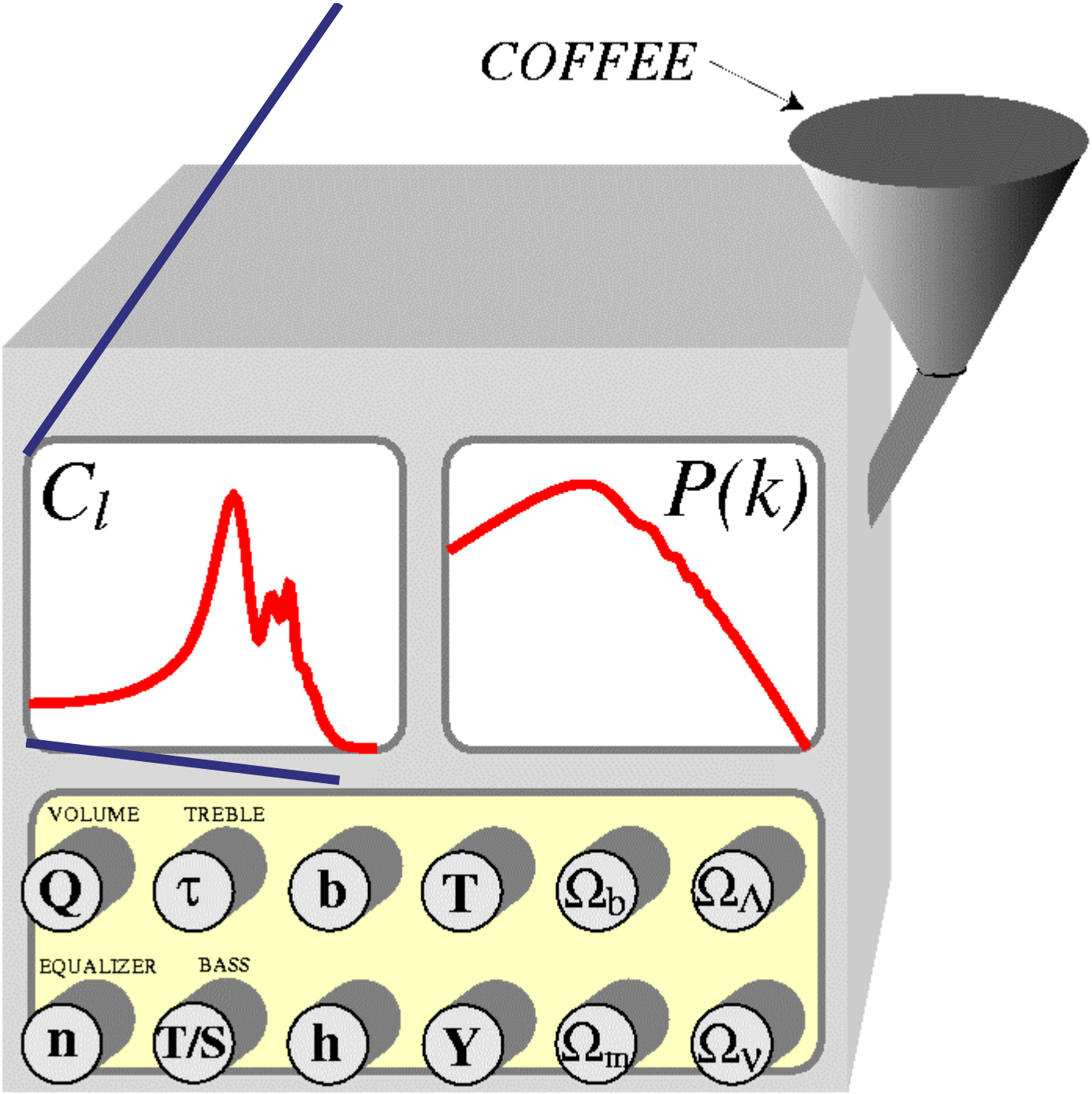

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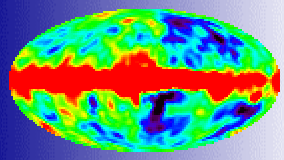

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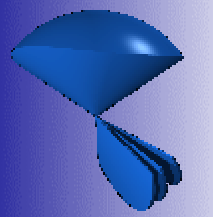

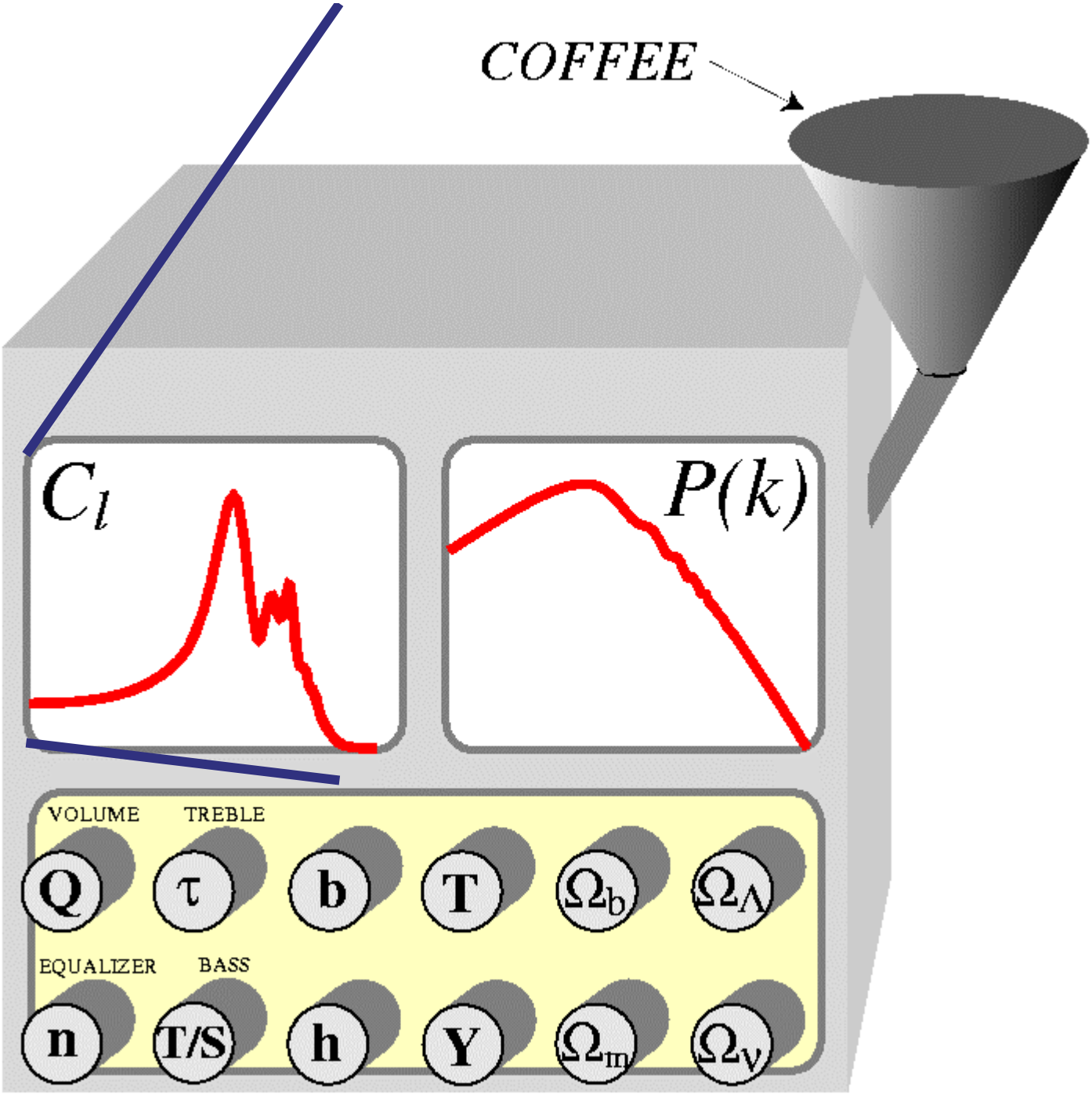

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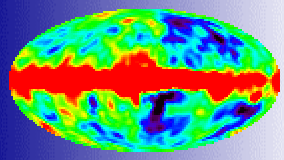

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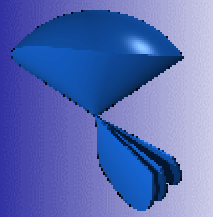

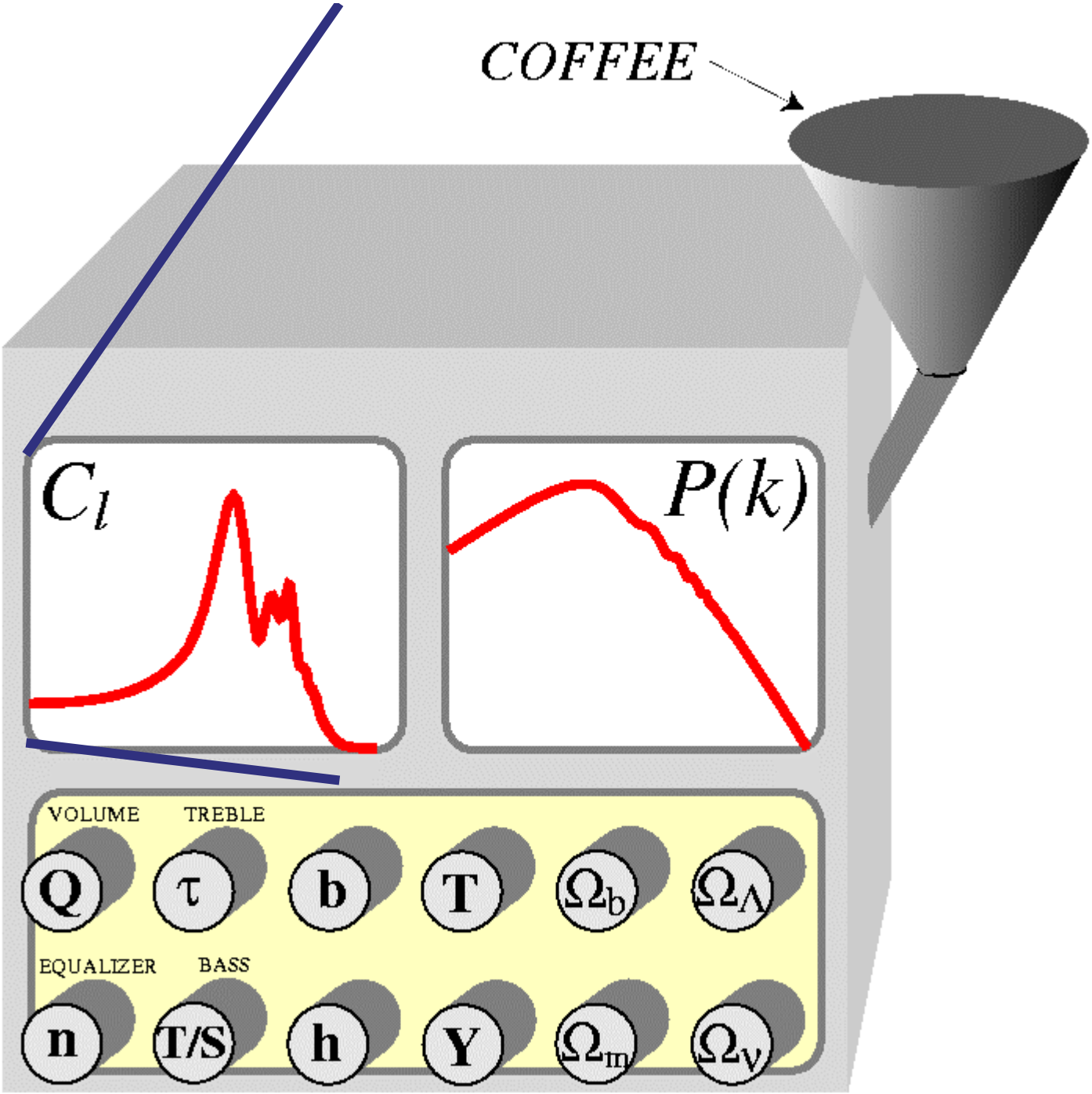

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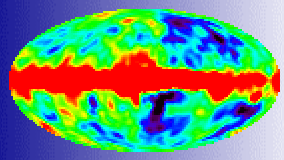

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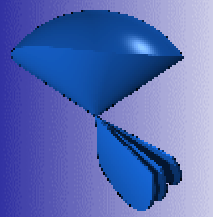

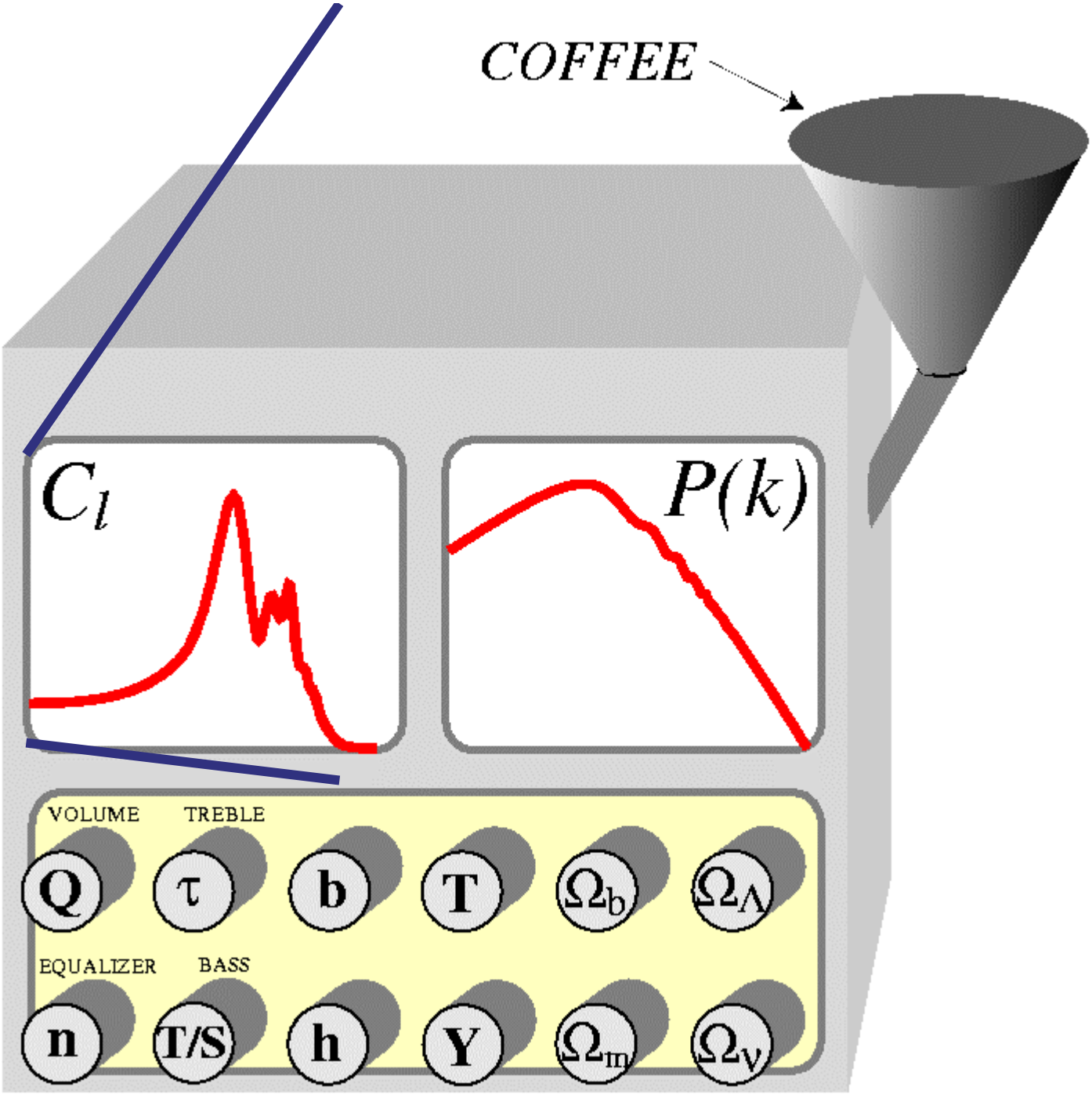

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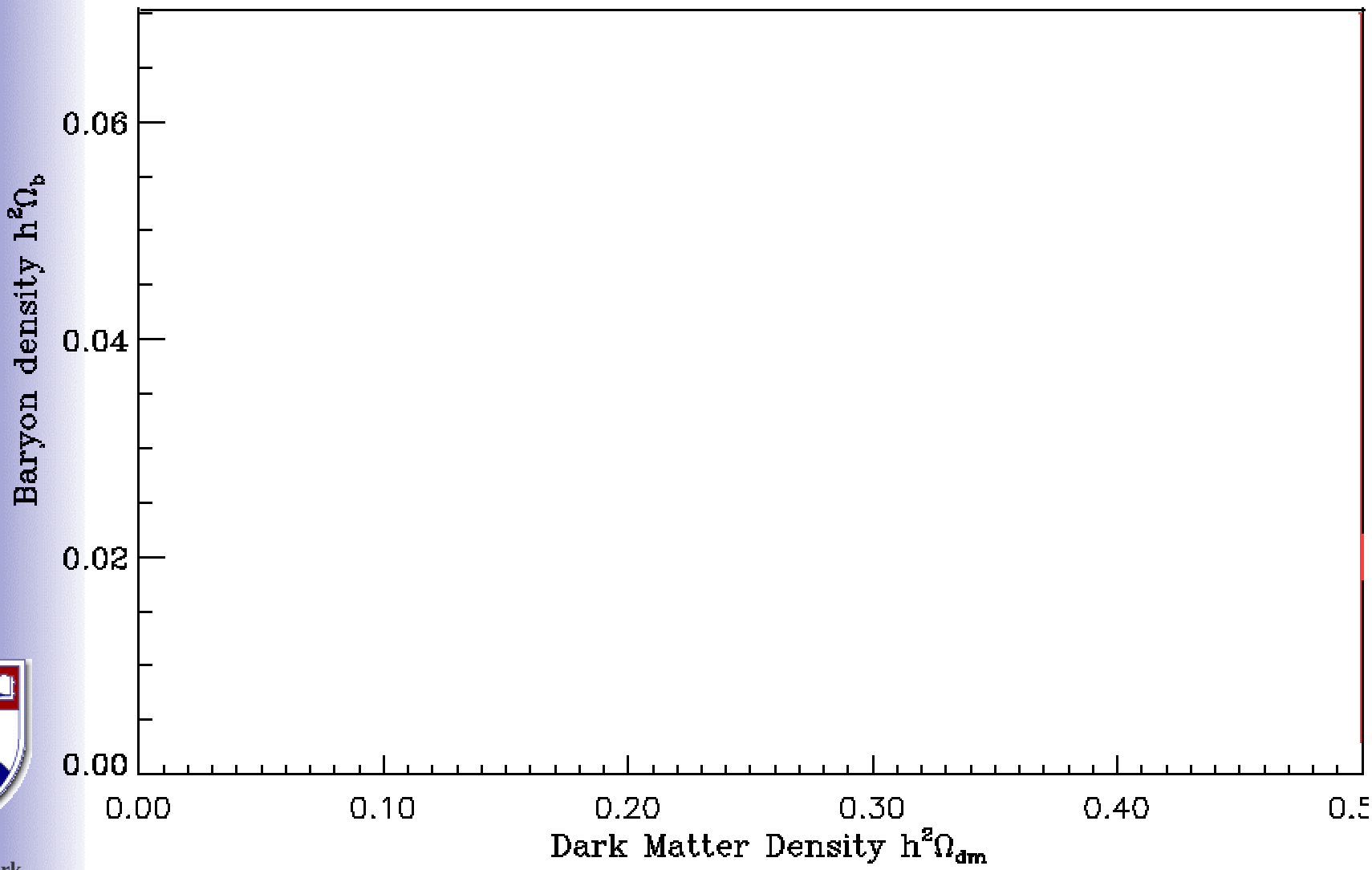
Constraints on dark matter

Wang, Tegmark & Zaldarriaga 2001



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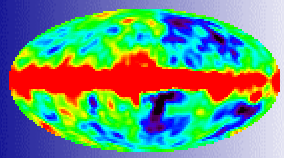
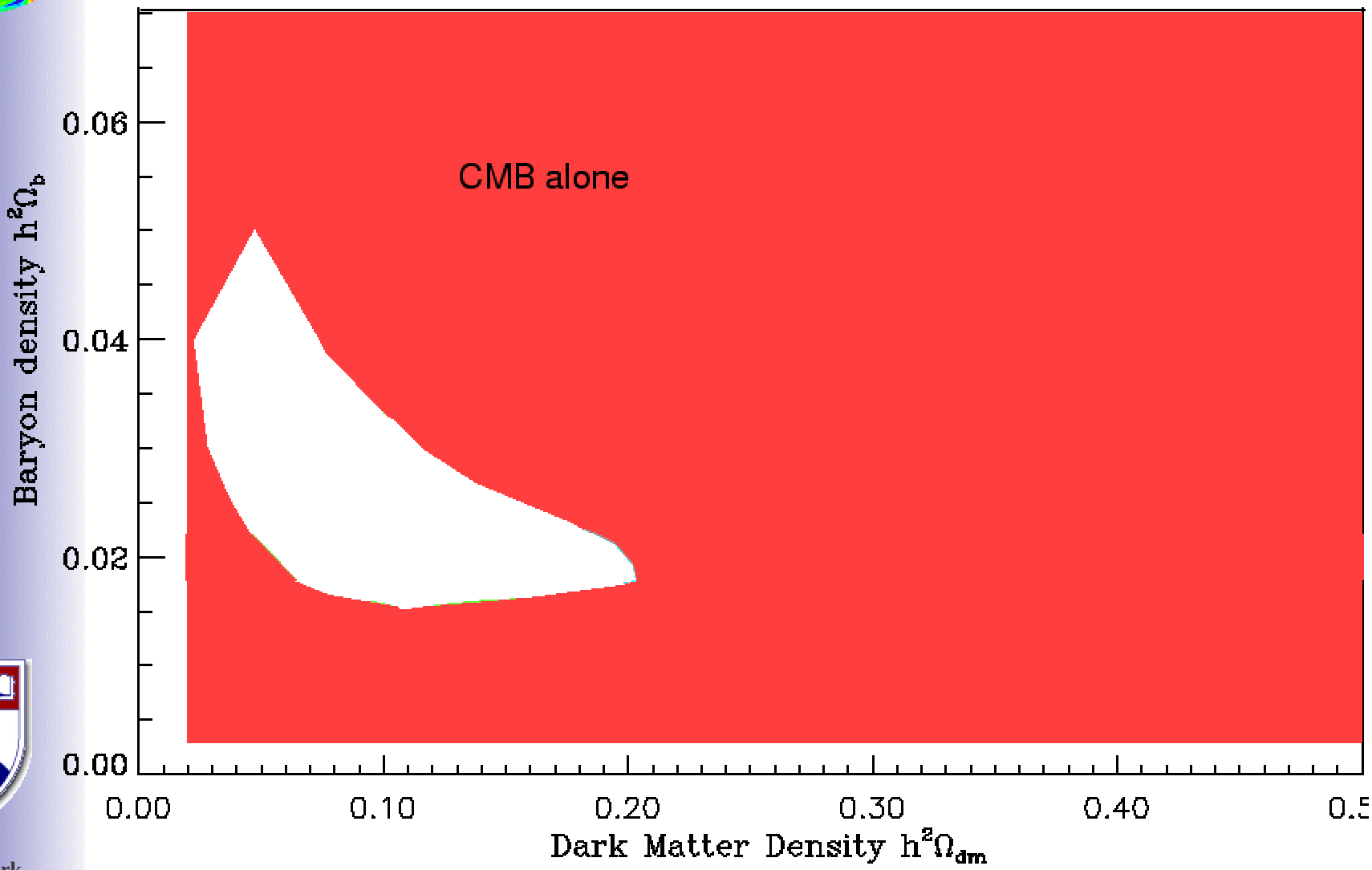


Wang, Tegmark & Zaldarriaga 2001



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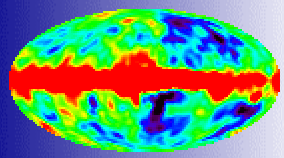
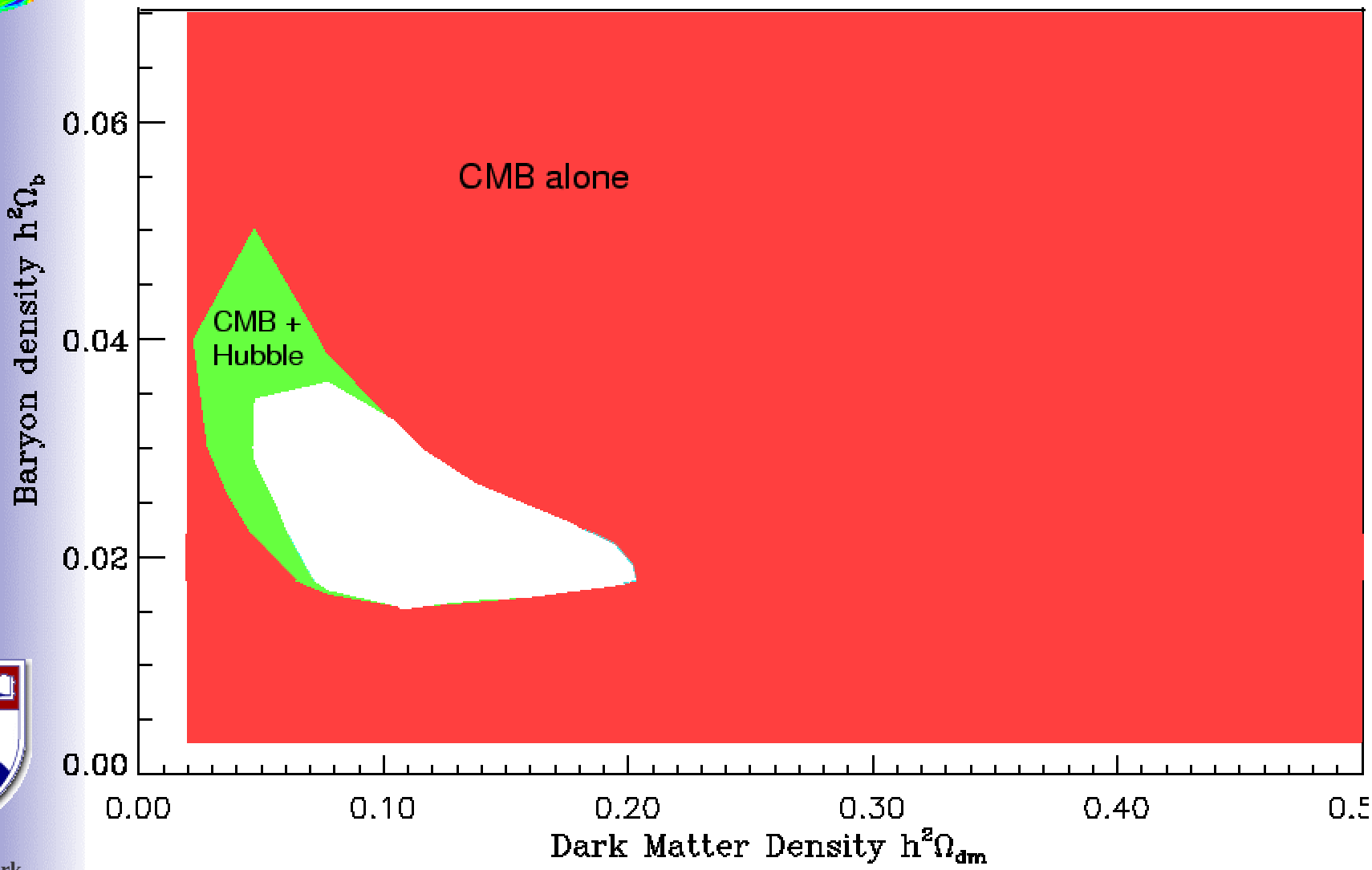


Wang, Tegmark & Zaldarriaga 2001



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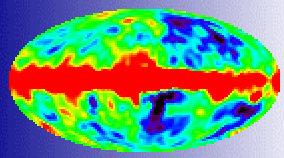
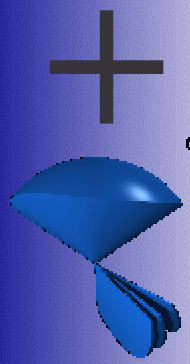
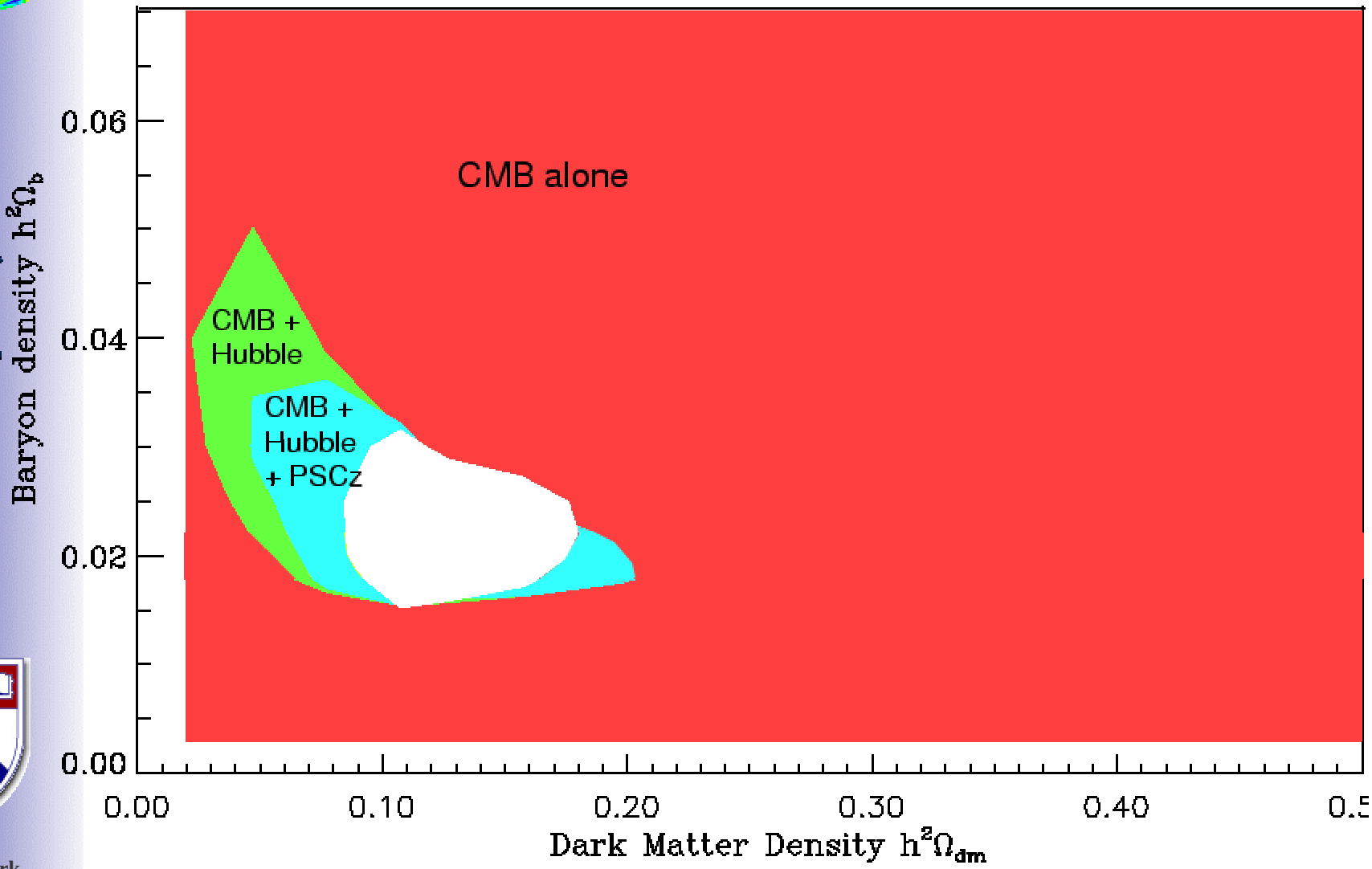




Wang, Tegmark & Zaldarriaga 2001



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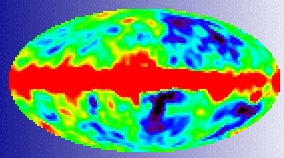

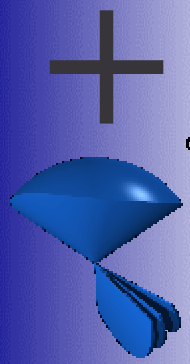

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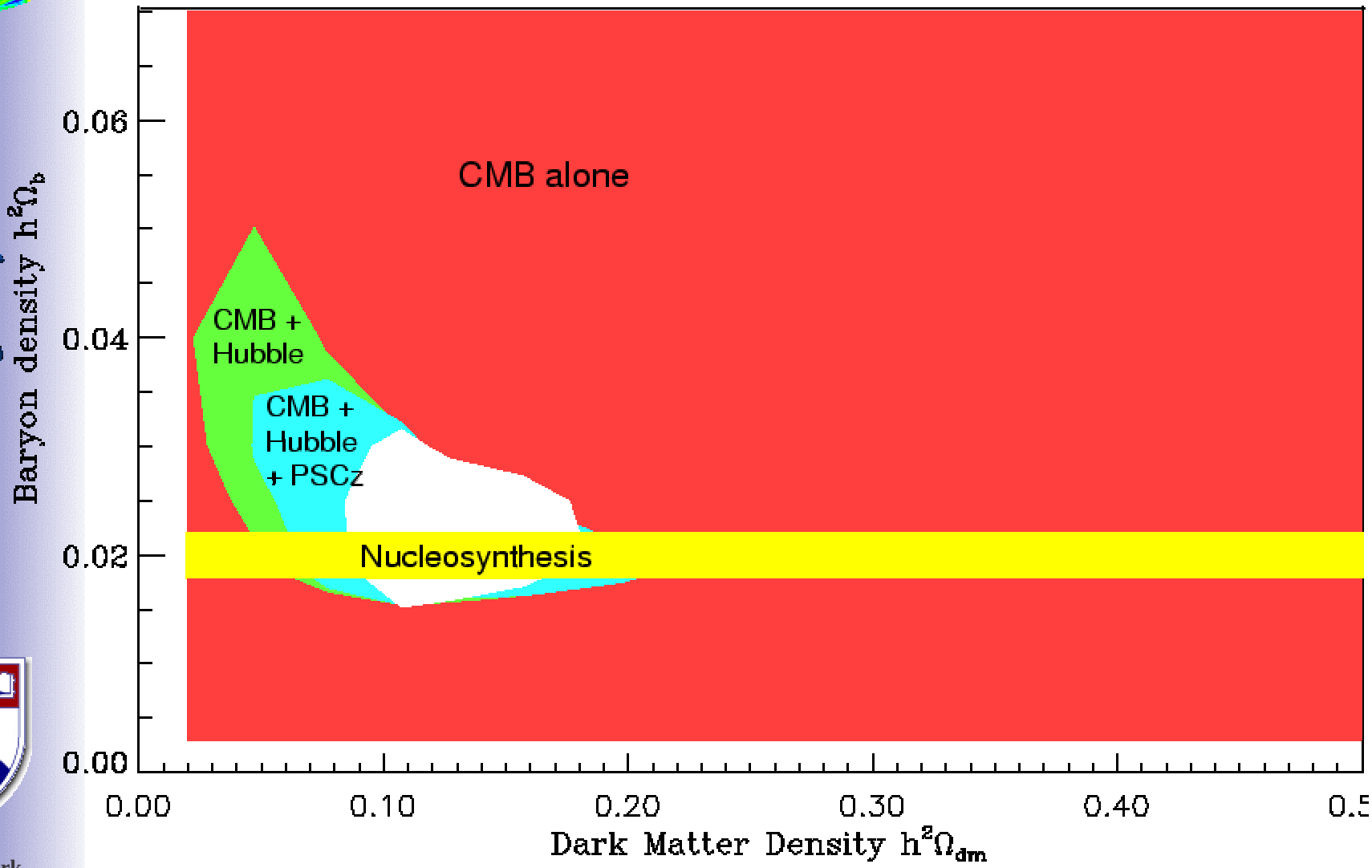

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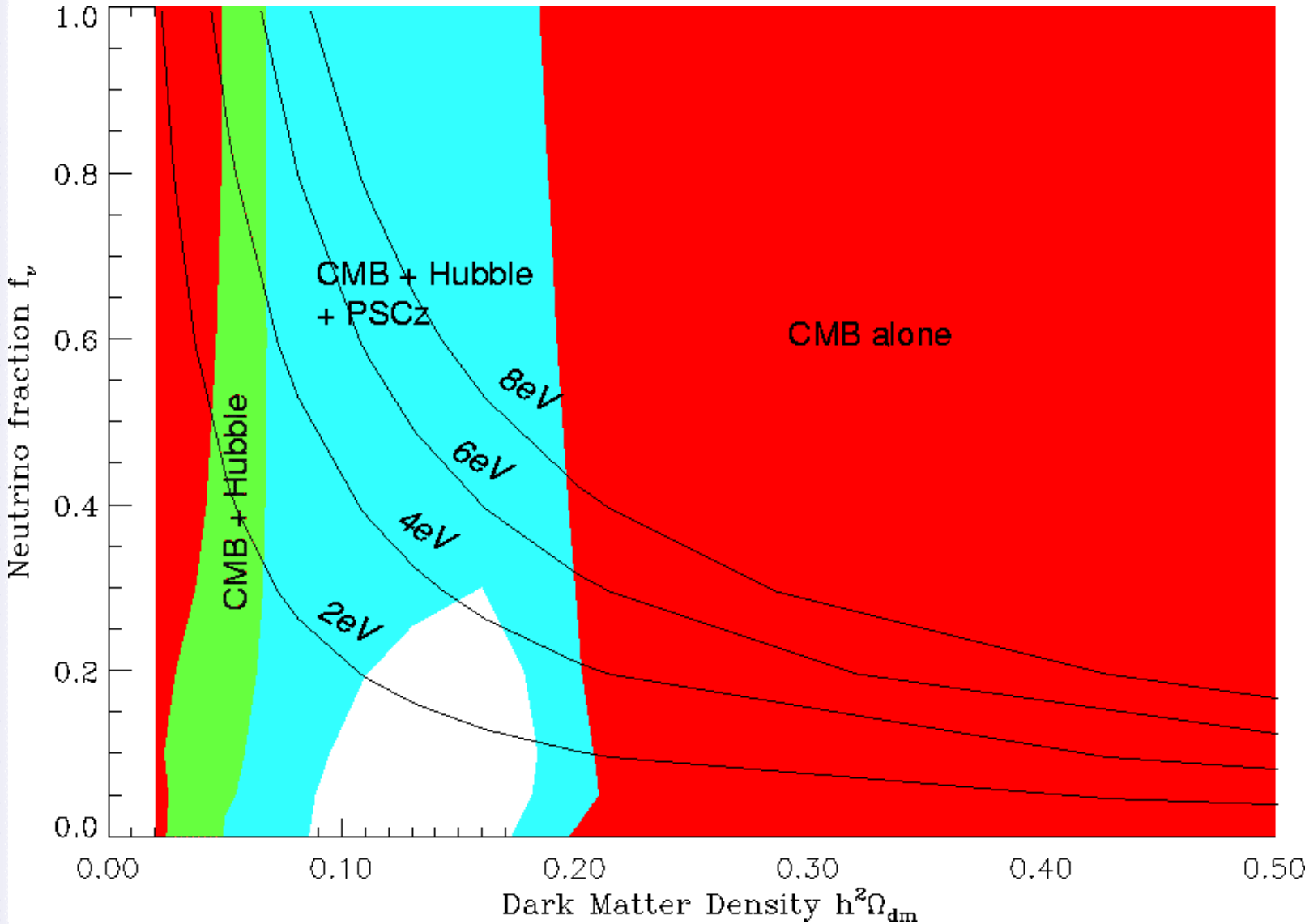
Constraints on neutrinos



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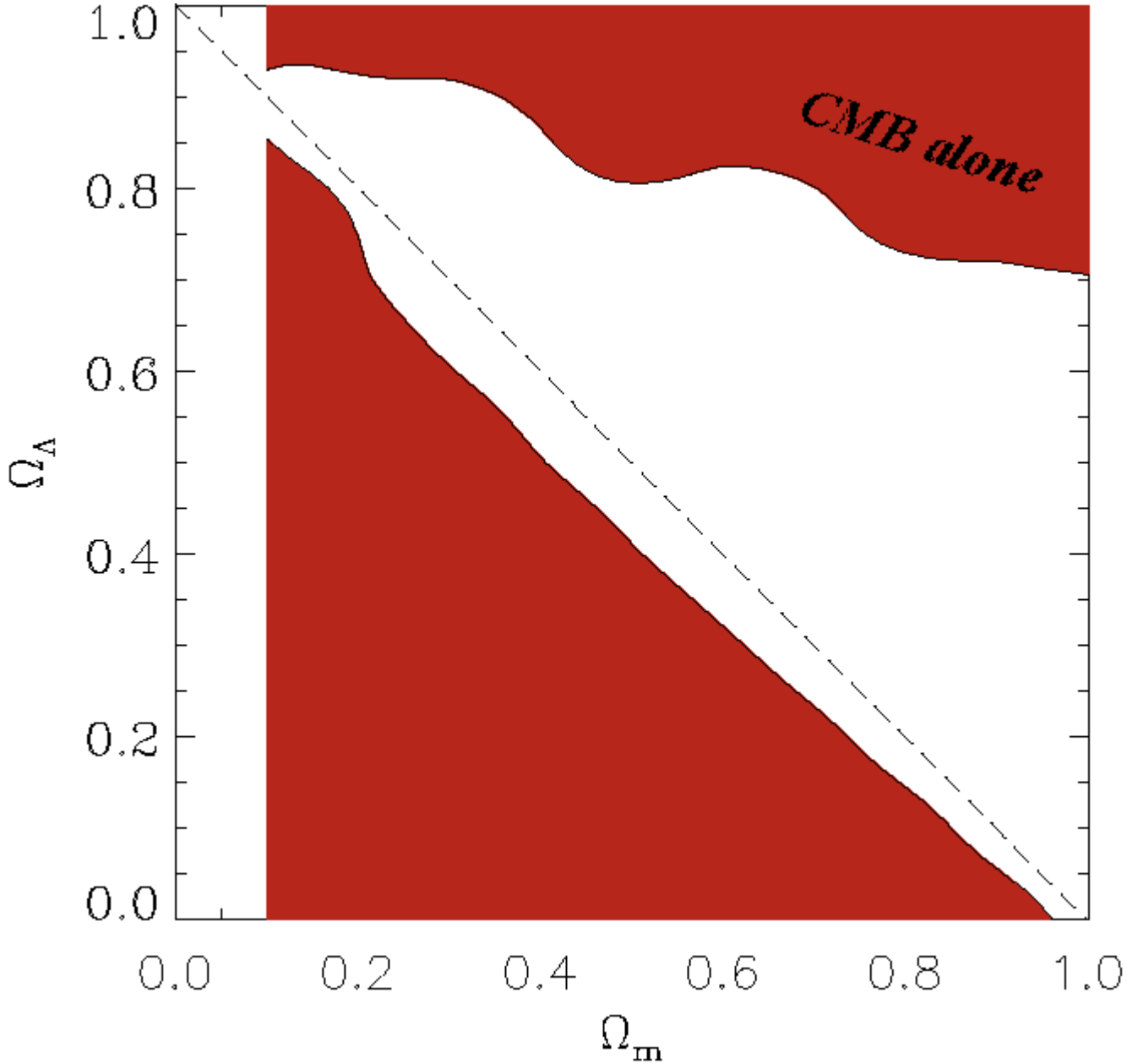
Constraints on dark energy

CMB

Tegmark, Zaldarriaga & Hamilton 2000



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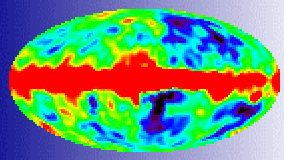

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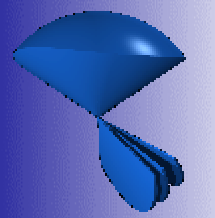

LSS

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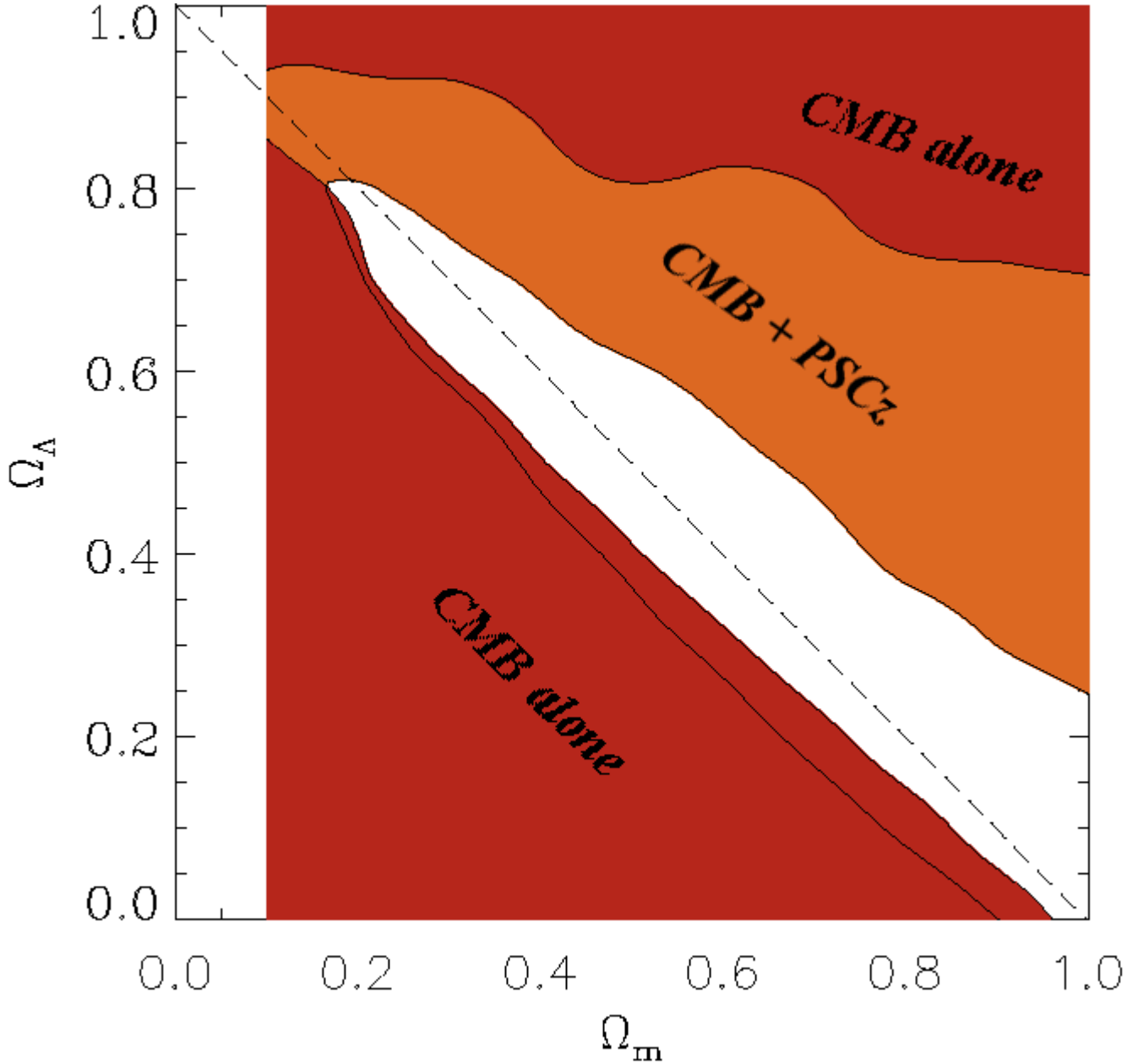
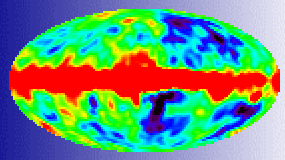
Tegmark, Zaldarriaga & Hamilton 2000





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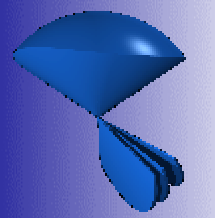

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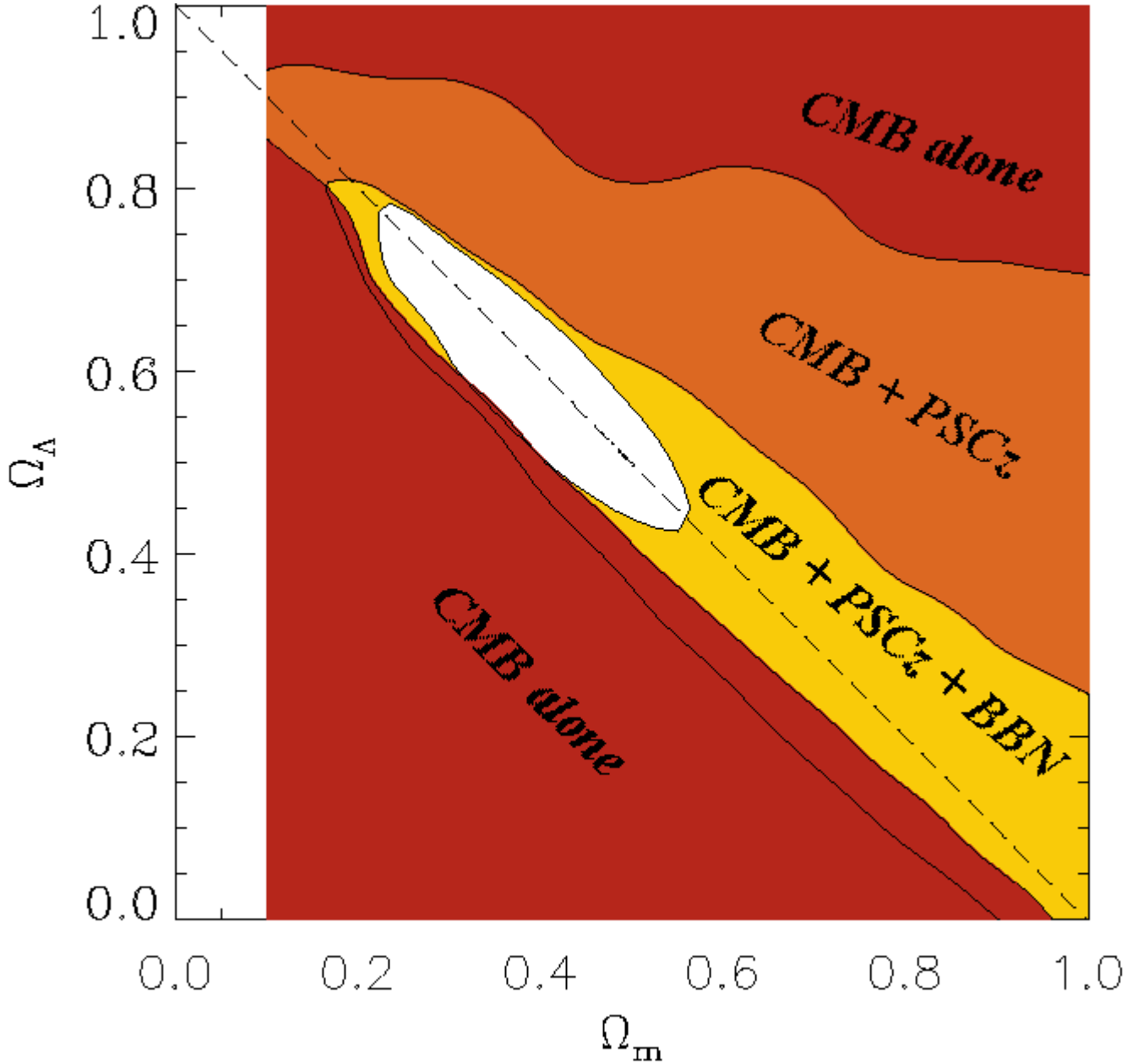

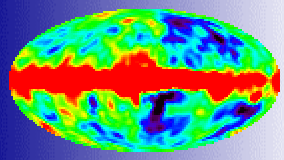

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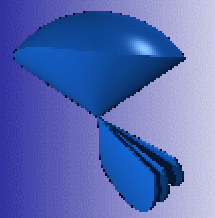

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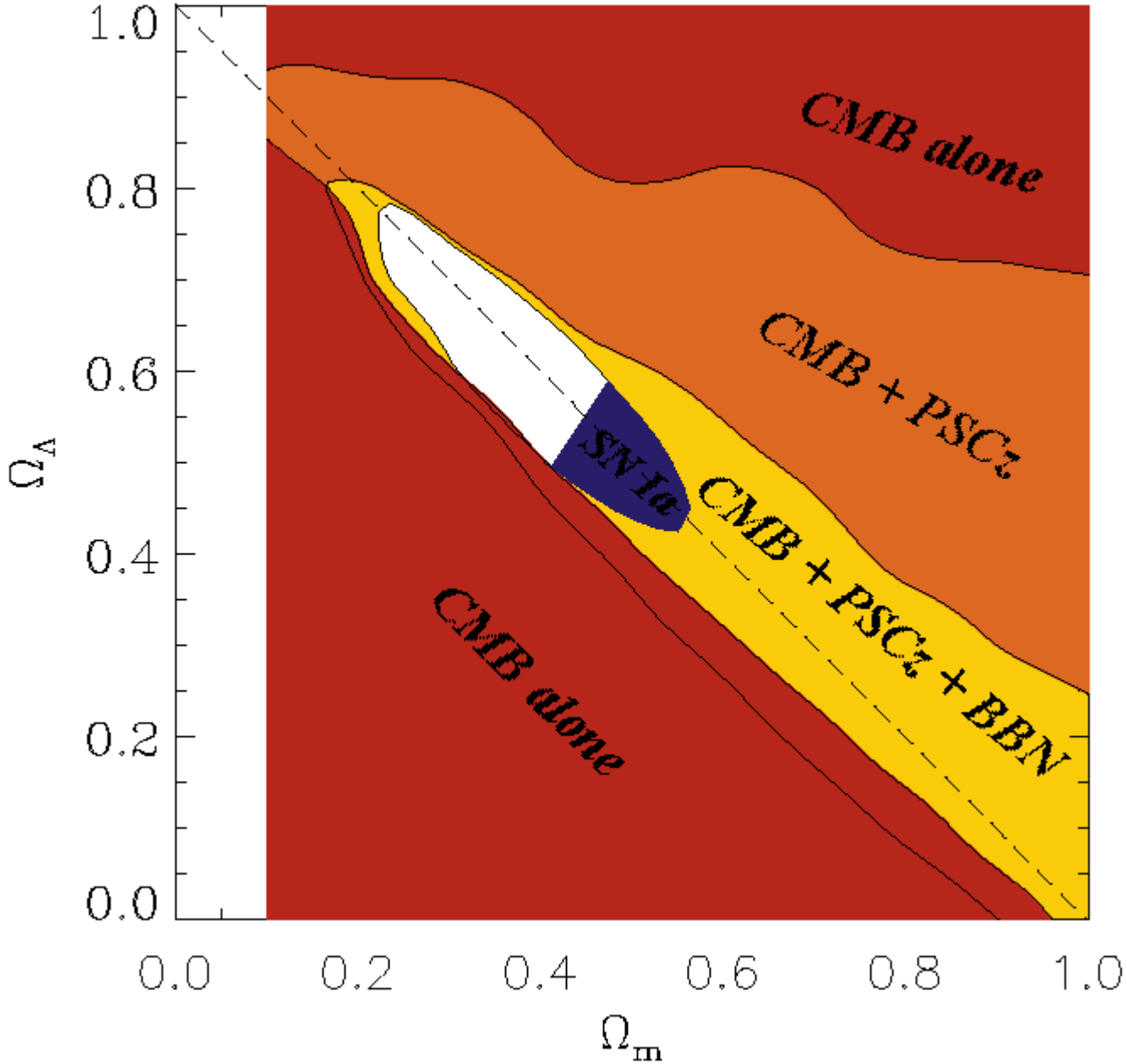
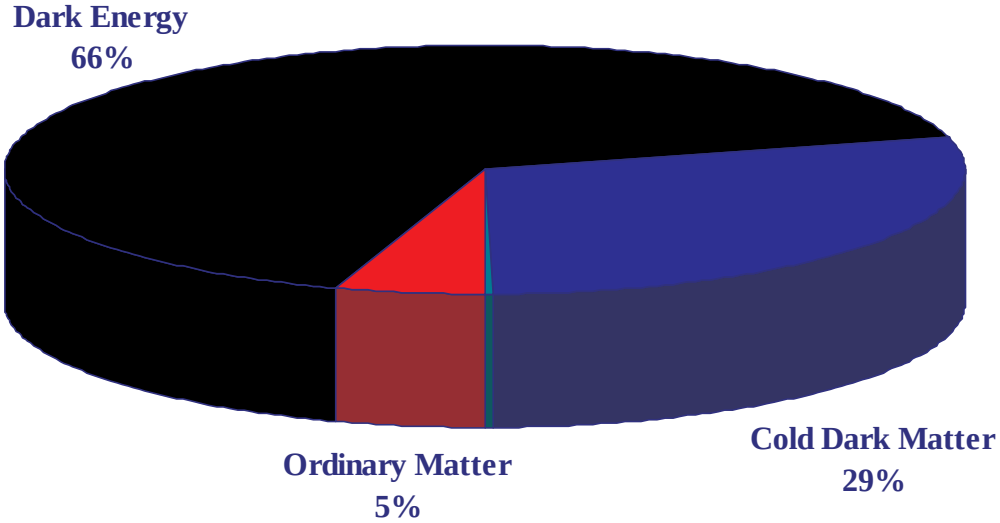


THOSE PESKY PARAMETERS: WE'RE ZEROING IN!
(December 2001)

•Matter Budget

- Ordinary Matter $h^2\Omega_b = .021^{+.006}_{-.006}$
- Dark Energy $\Omega_\Lambda = 0.66^{+.10}_{-.13}$
- Cold Dark Matter $h^2\Omega_c = 0.12^{+.05}_{-.03}$
- Hot Dark Matter $h^2\Omega_\nu = .001^{+.04}$
- Photons $h^2\Omega_\gamma = 0.0001$
- Budget Deficit $\Omega_k = 0.00^{+.06}_{-.06}$

(95% limits)



•Early Universe

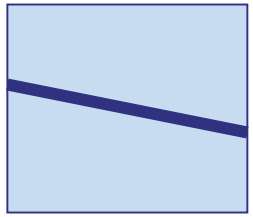
Scalar normalization $Q \sim 10^{-5}$

Scalar tilt $n = 0.93^{+.12}_{-.10}$

Running of tilt $\alpha = ?$

Tensor normalization $R < 0.2$

Tensor tilt $n_T = ?$



•Gastrophysics

Reionization optical depth $\tau = 0.07^{+.16}_{-.07}$

Galaxy bias $b \sim 1$ (for 2dF L*)

Hubble parameter $h = 0.65^{+.11}_{-.11}$

Is cosmology solved? We still have no clue what 95% of all stuff is made of!

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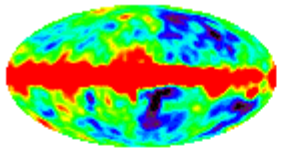

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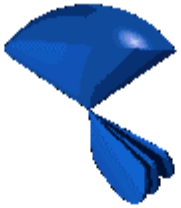
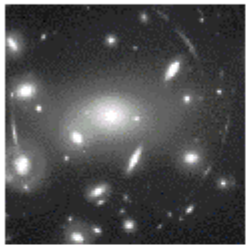


GALAXY SURVEYS

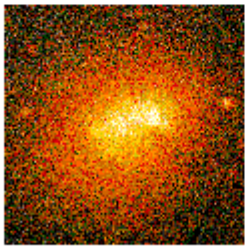
DISTANT SUPERNOVAE



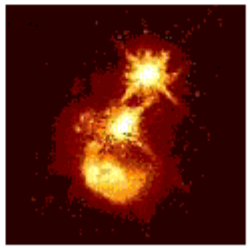
GRAVITATIONAL LENSING

THE COSMIC SMÖRGÅSBORD

BIG BANG NUCLEOSYNTHESIS



GALAXY CLUSTERS



LYMAN ALPHA FOREST

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Beyond cosmological parameters, summary:

- *Test the underlying physics rather than assuming it*
- *Understand the nature of dark matter, dark energy, bias and gravity*
- *Cosmological functions rather than cosmological parameters*
- *Measure the free functions rather than parametrizing them in a way involving untested physical assumptions - a form of data compression*

Do observations disagree with each other or with theory?

Data => Cosmological functions <= Theory

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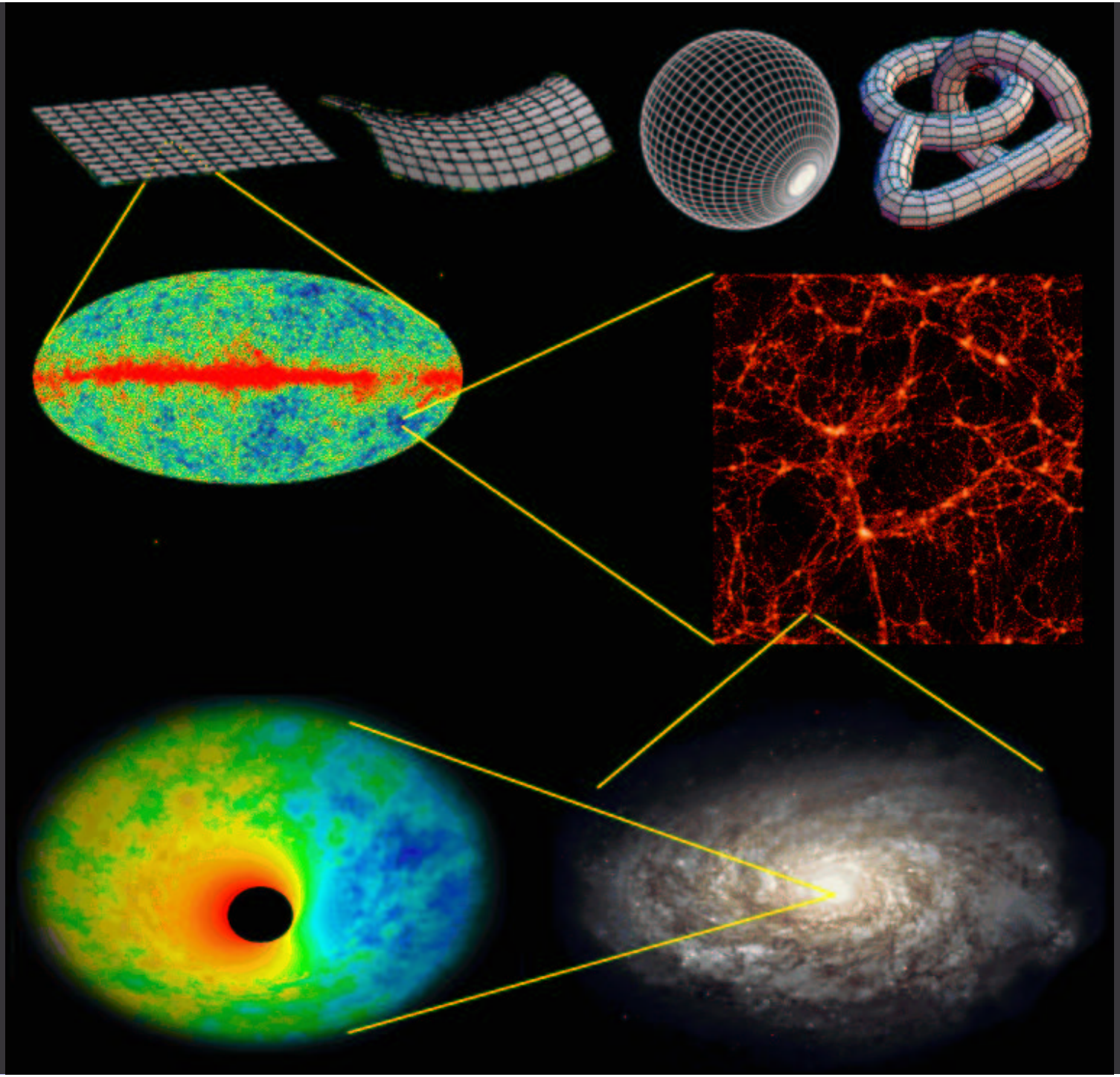
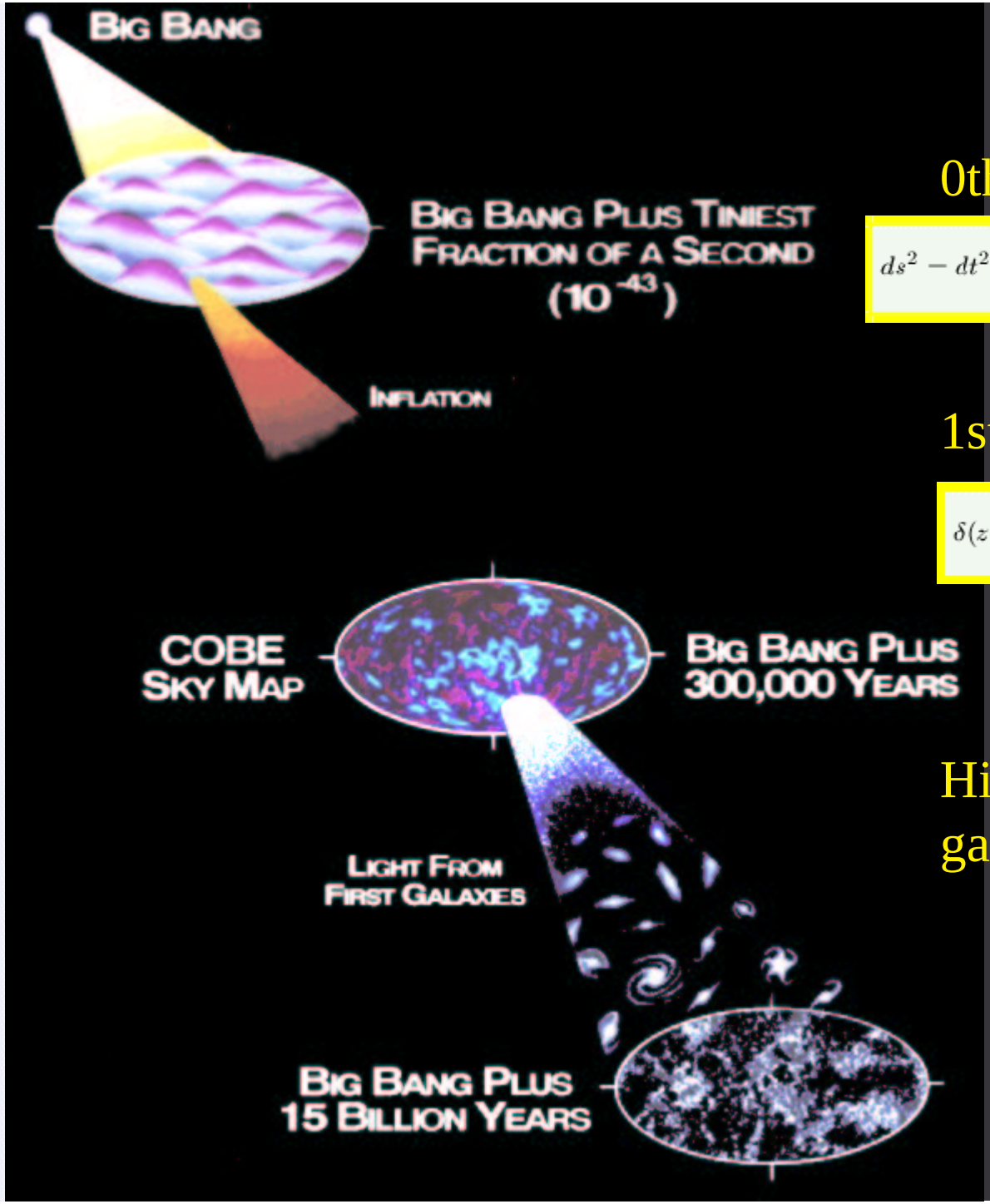
HOPELESS?



Tegmark 2002, Science, 296, 1427-3



0th order: a(t)

$$ds^2 - dt^2 - a(t)^2 \left[\frac{dr^2}{1 - kr^2} - r^2 d\Omega^2 \right]$$

1st order: g(z,k)

$$\delta(z, \mathbf{k}) = \frac{g(z,k)}{(1+z)} \delta(0; k)$$

Higher order: gastrophysics

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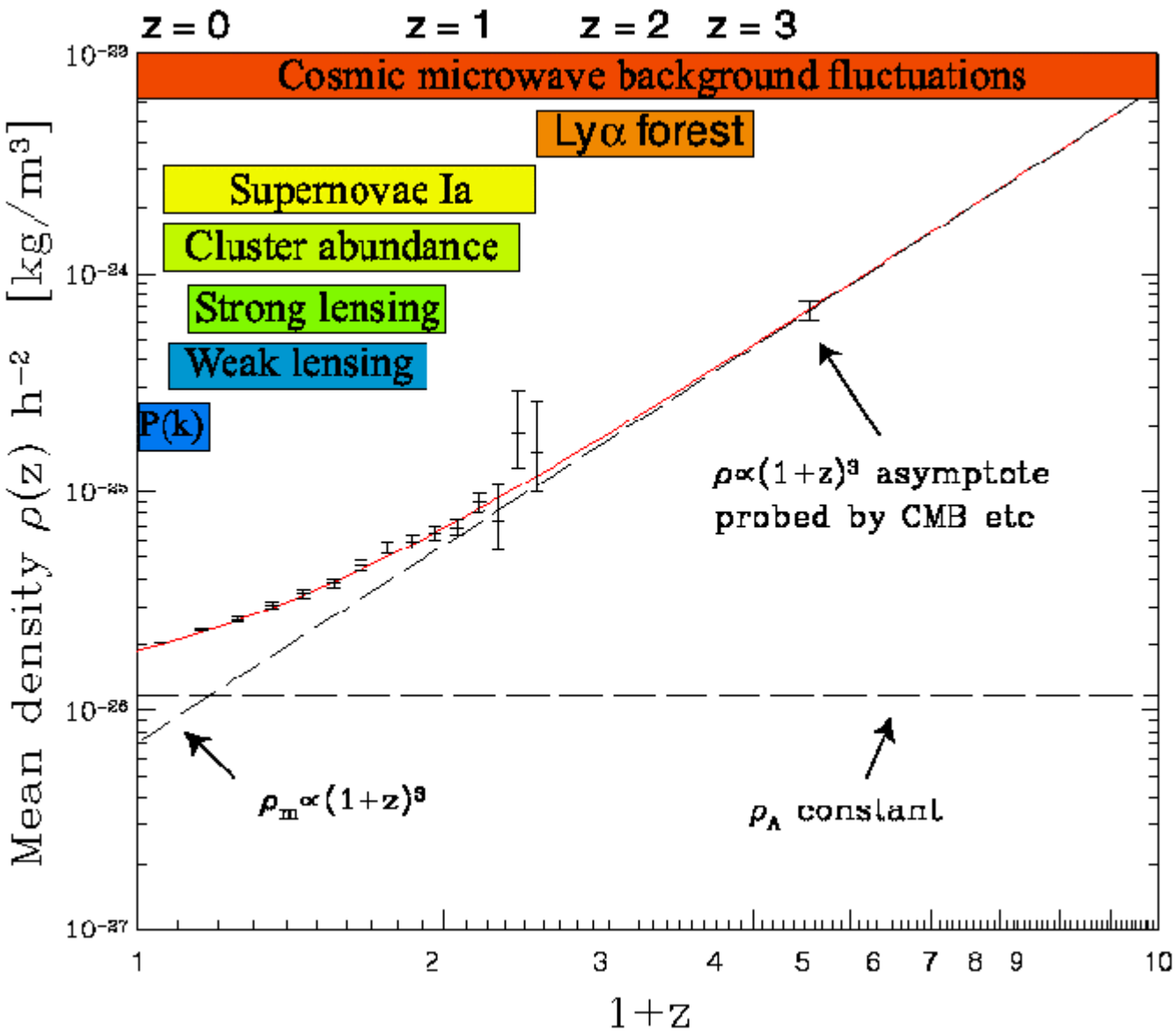
Measuring a(t)

Tegmark 2001



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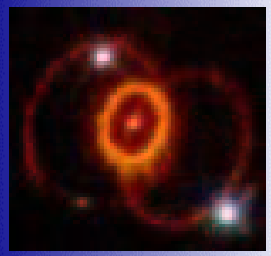
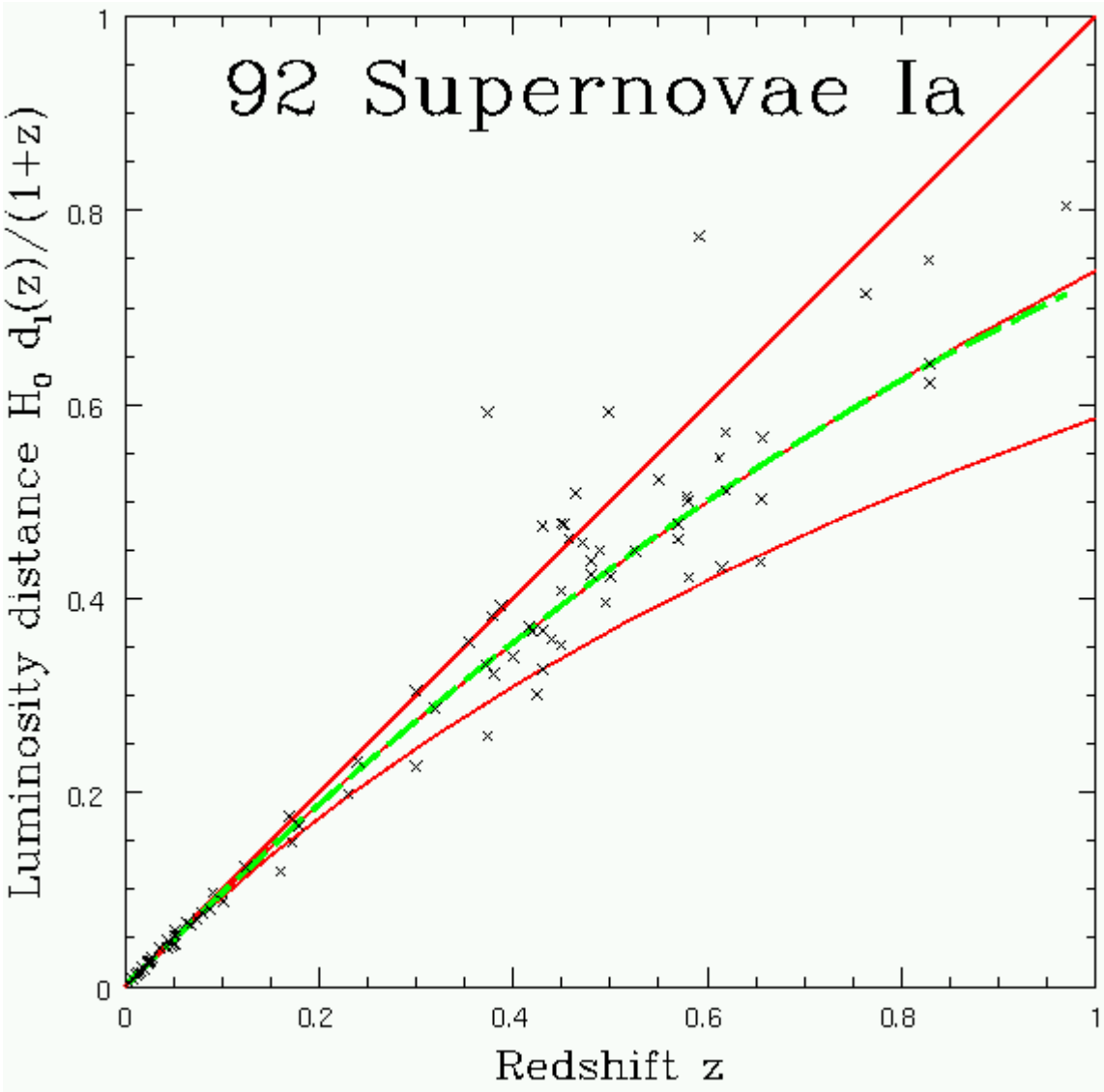


SN Ia

Tegmark 2001



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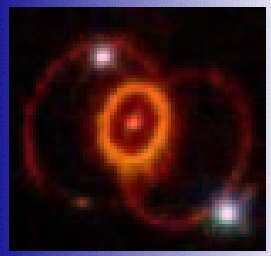
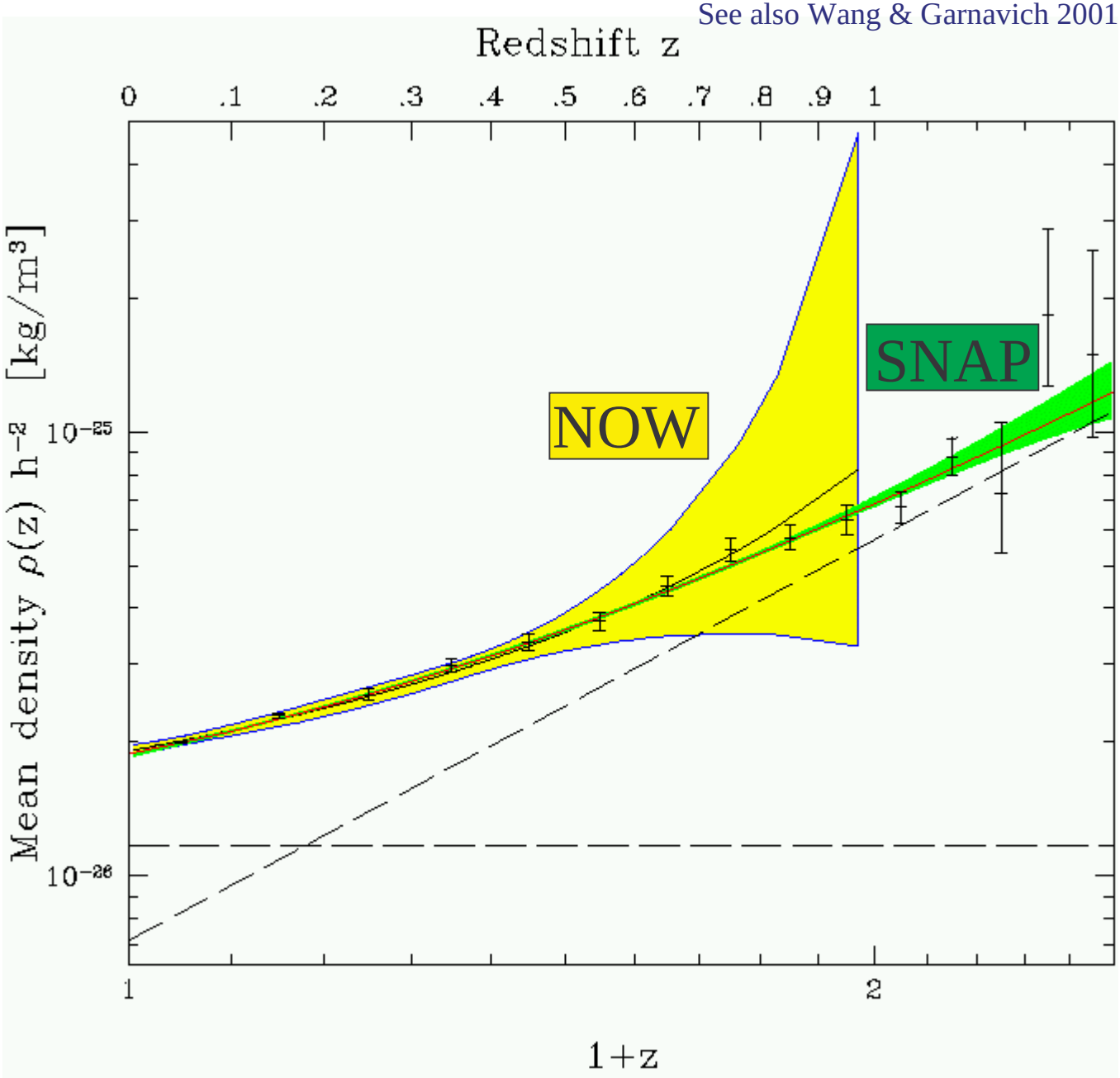


SN Ia

Tegmark 2001

See also Wang & Garnavich 2001



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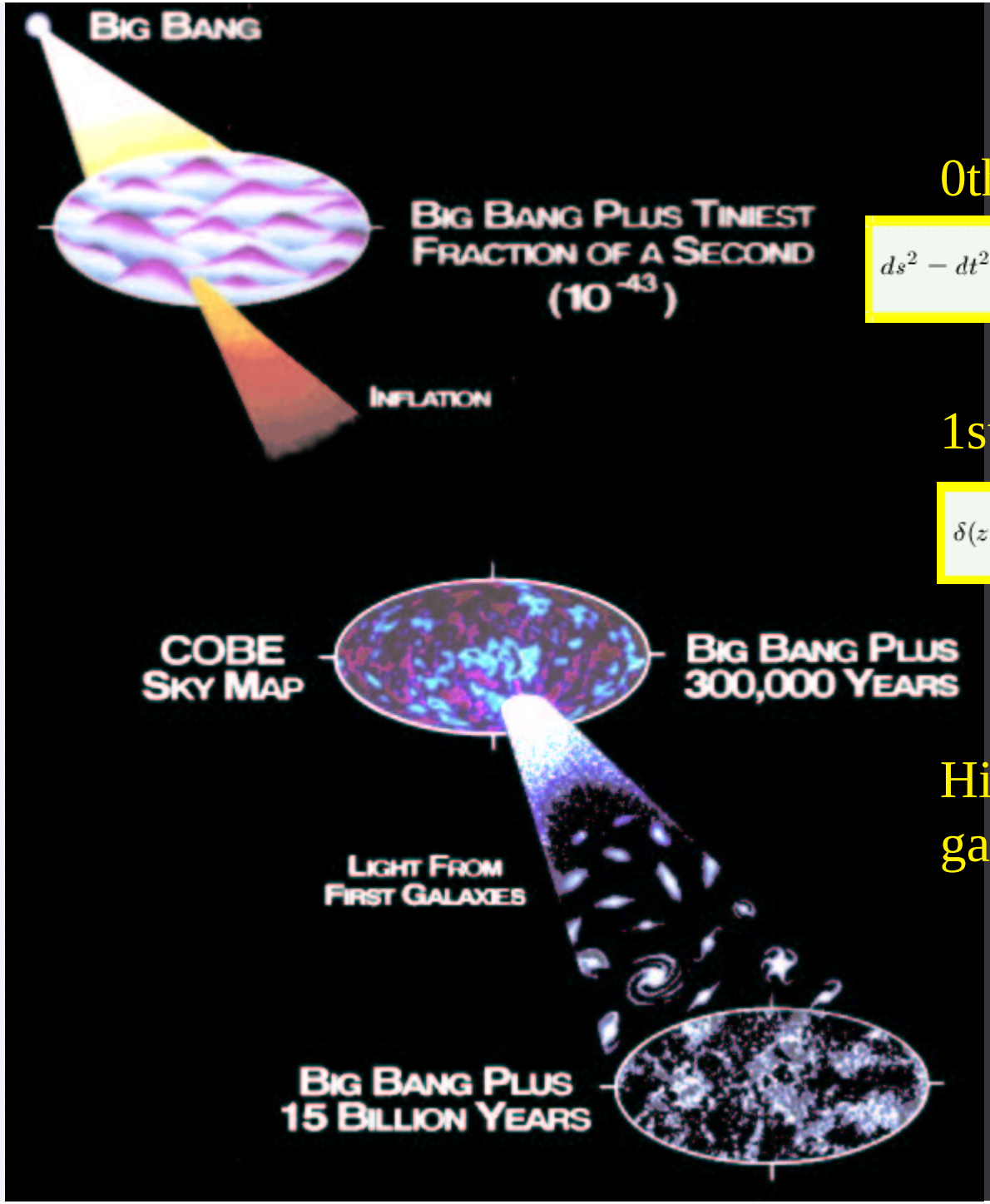

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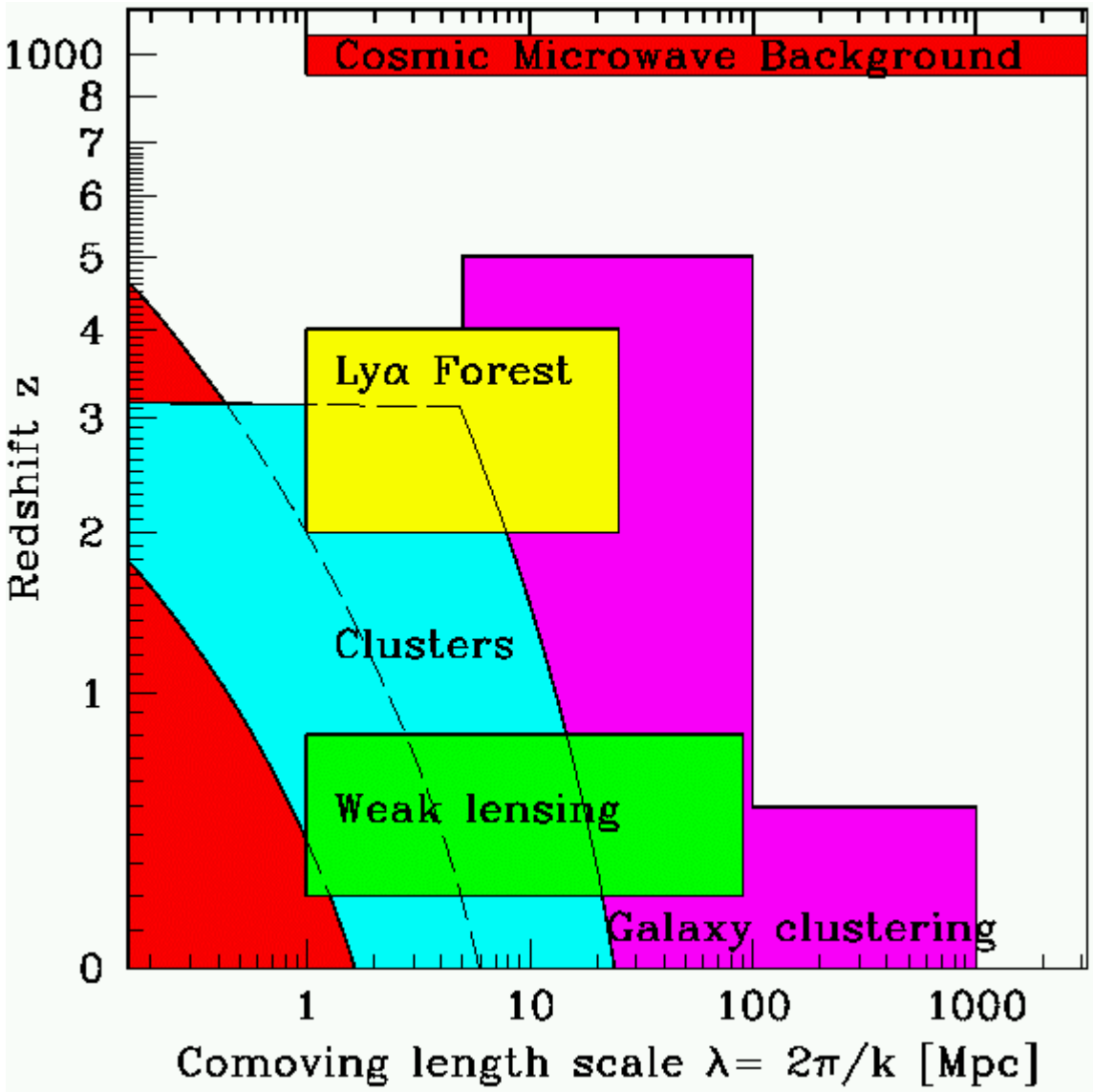

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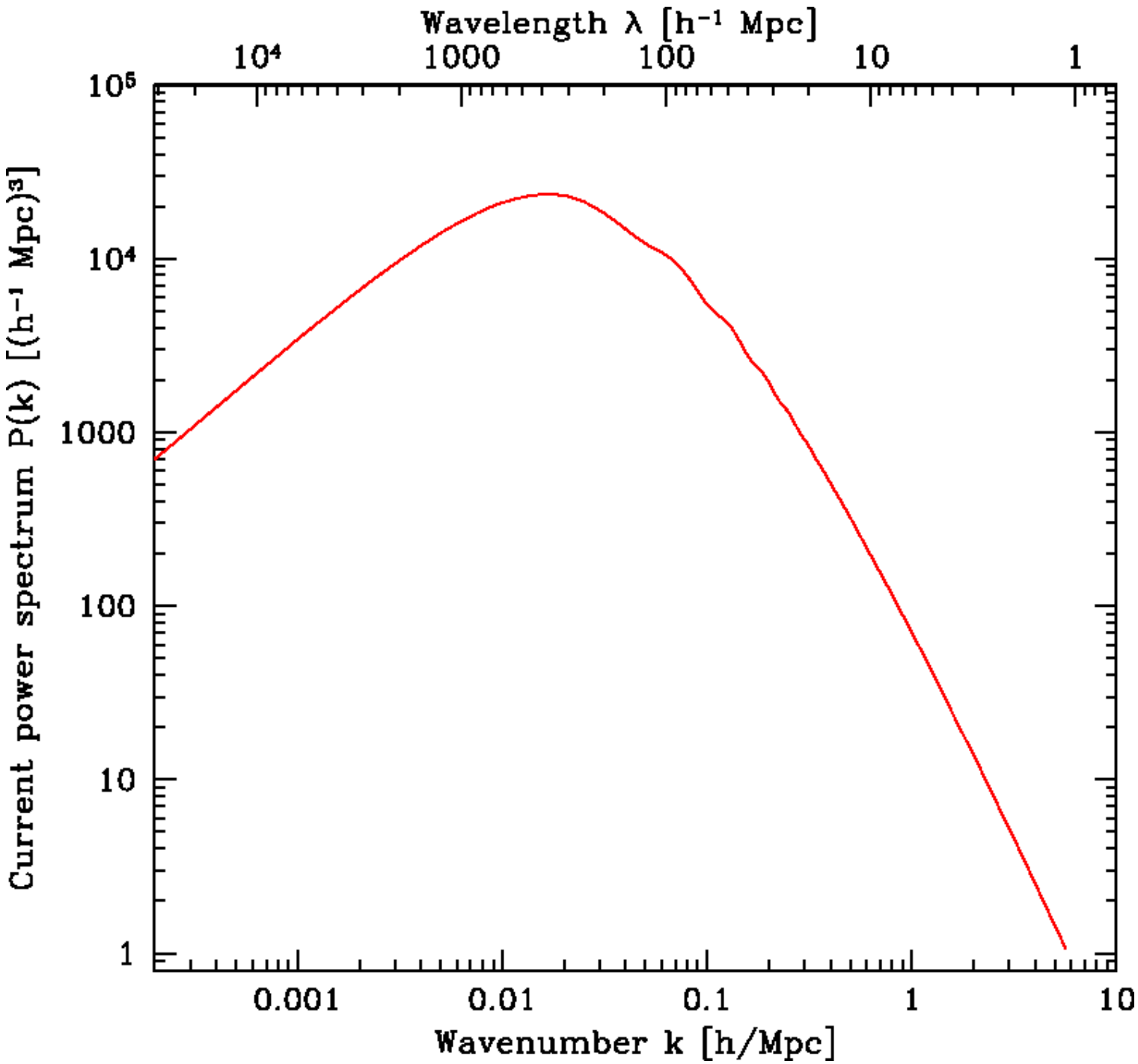

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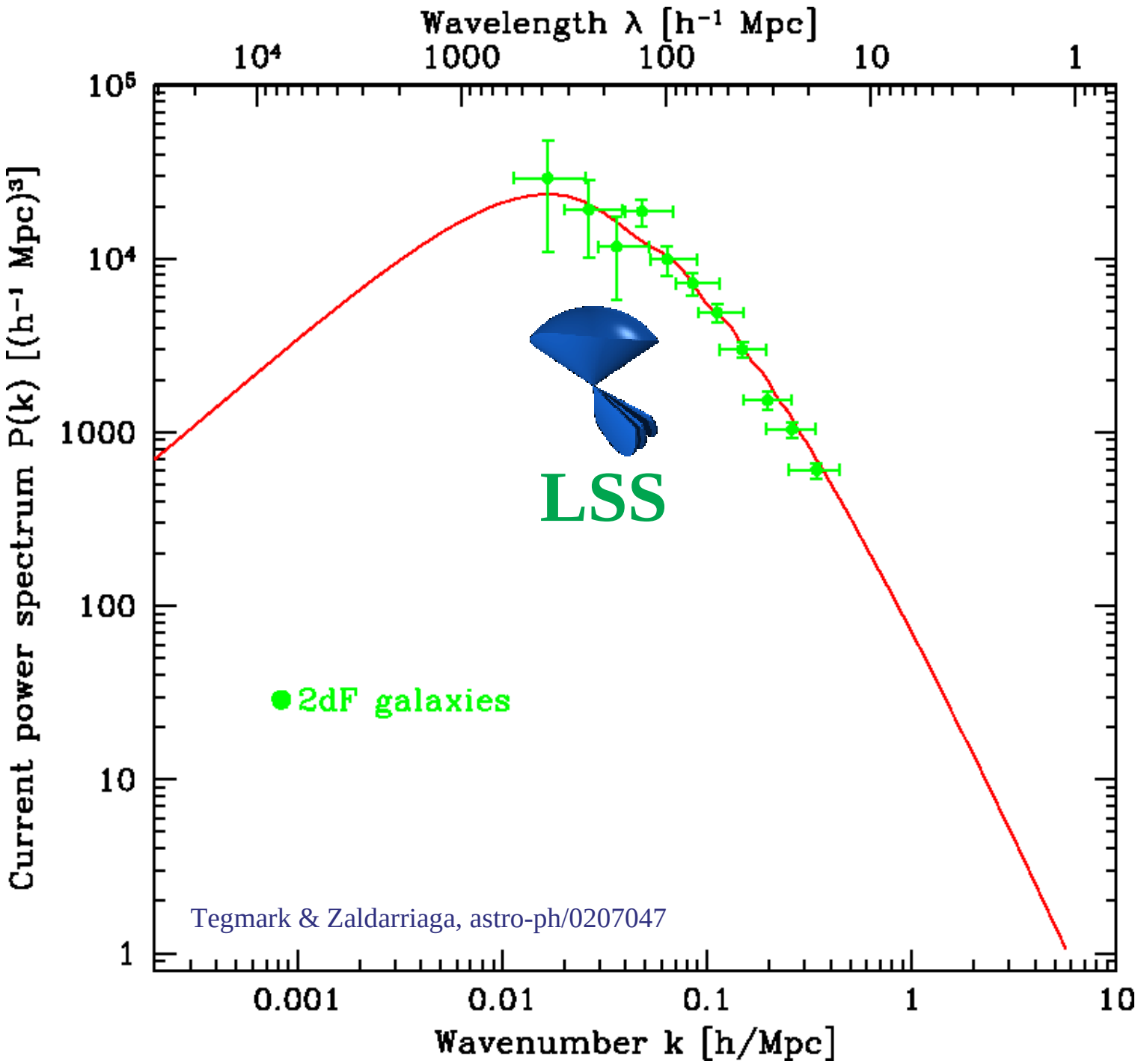

Tegmark & Zaldarriaga, astro-ph/0207047

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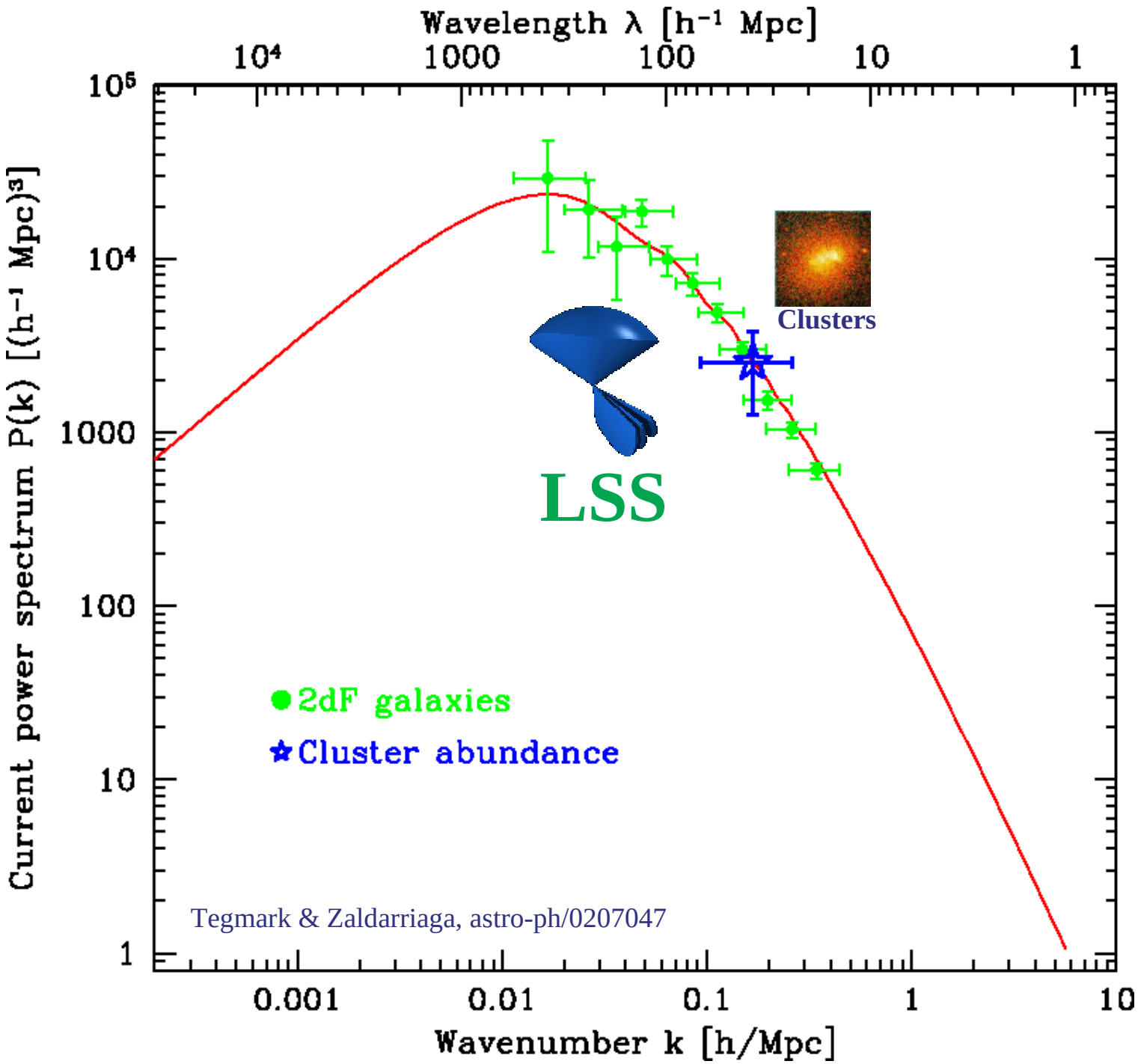

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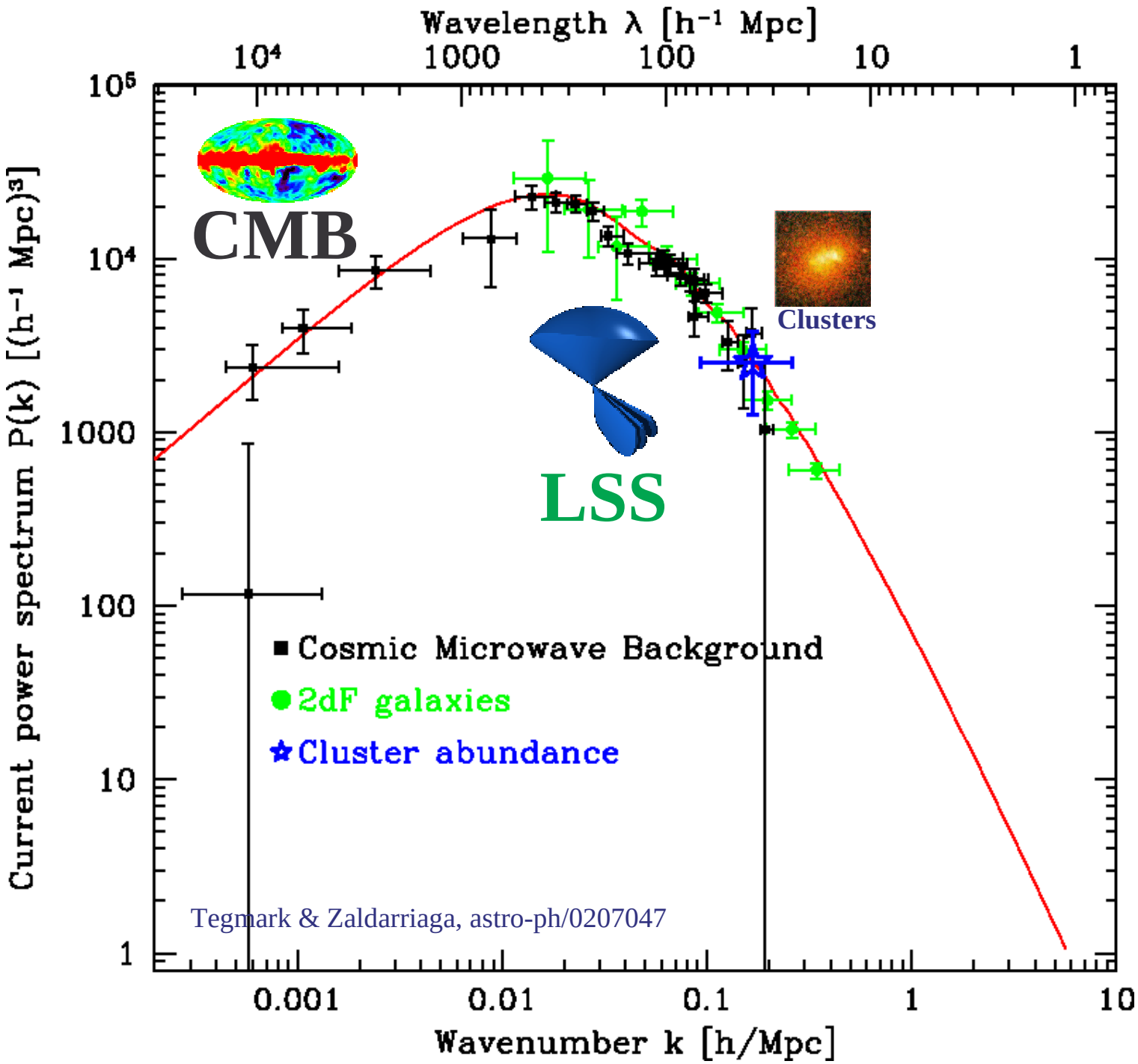

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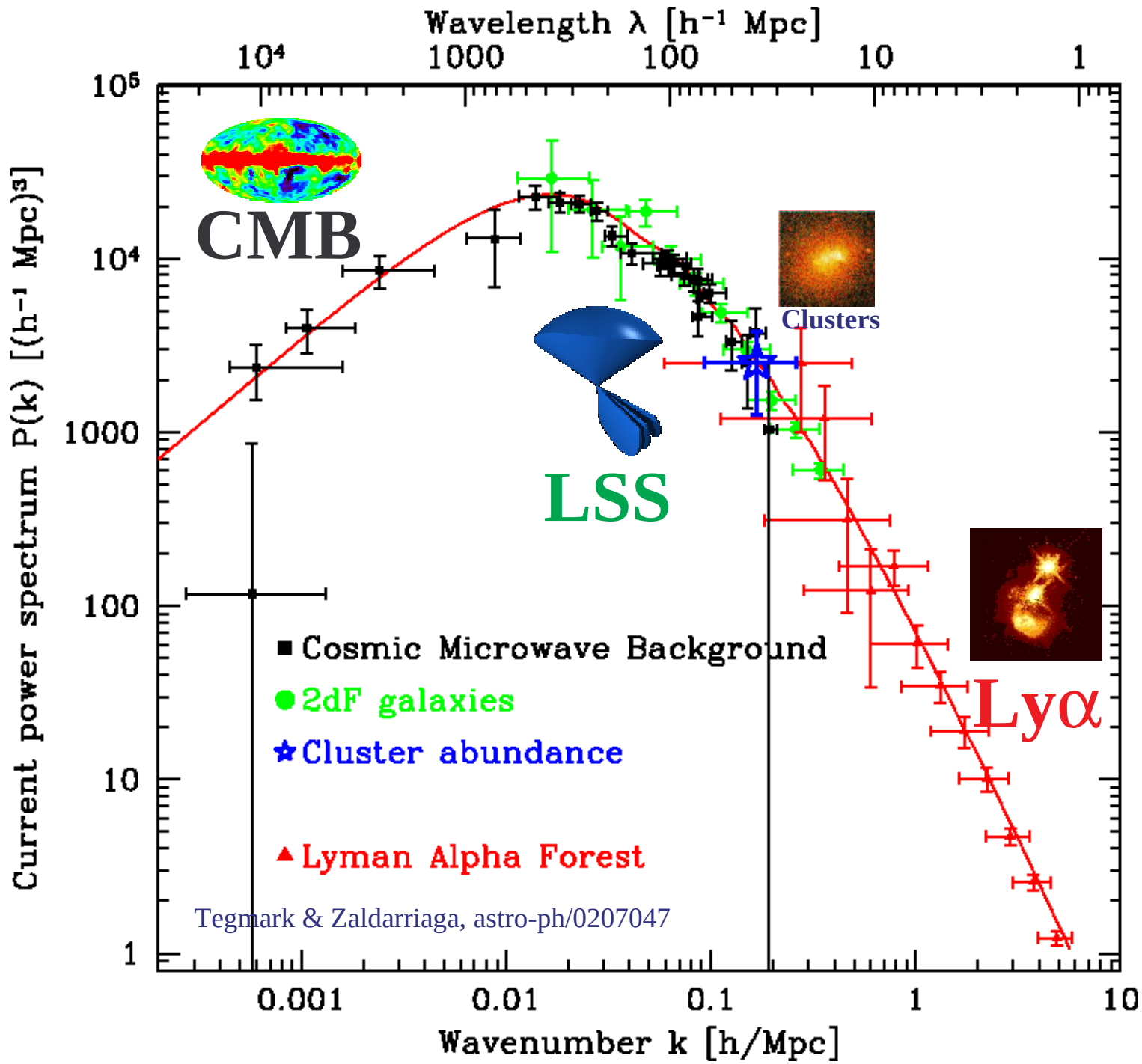

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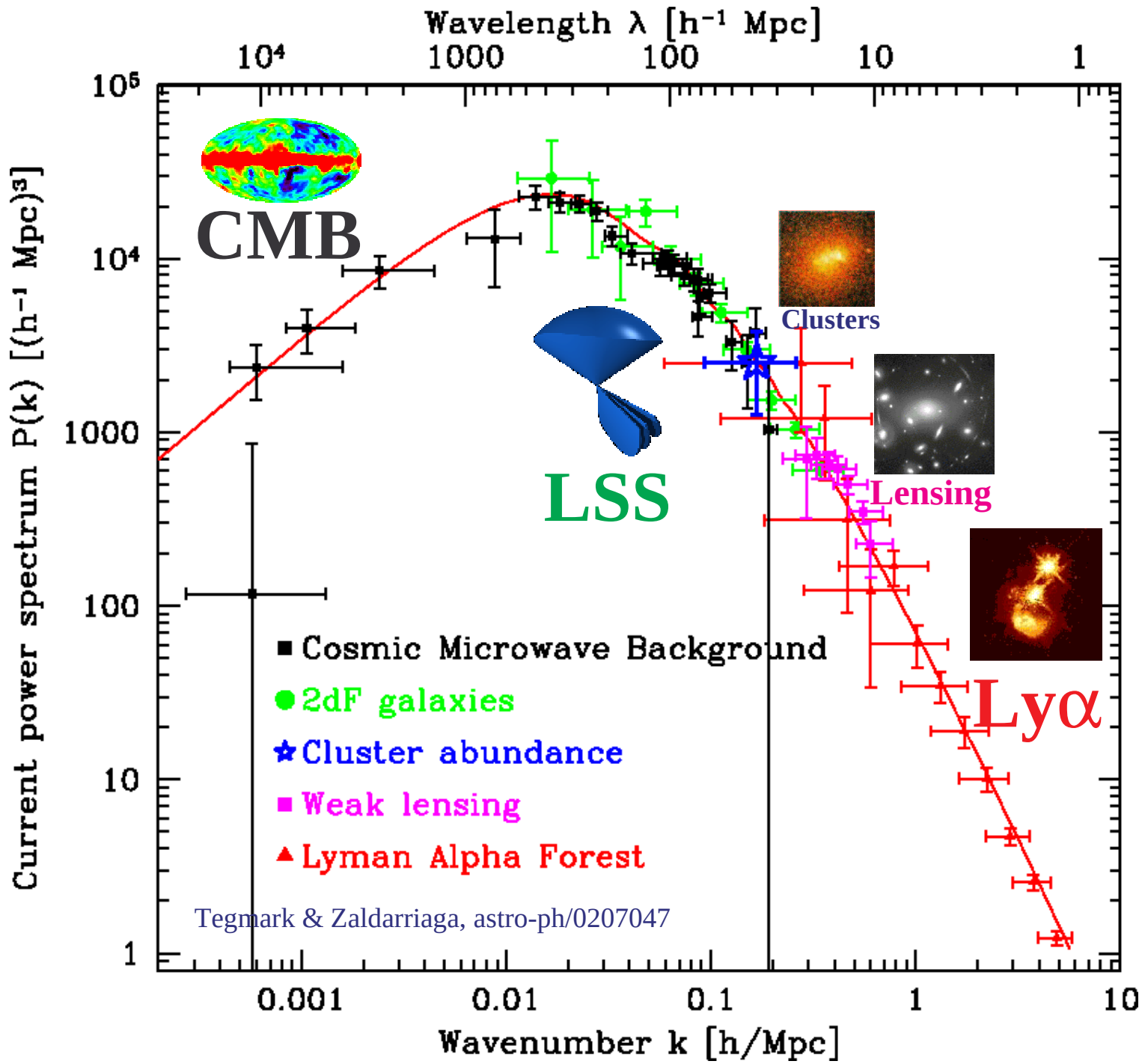

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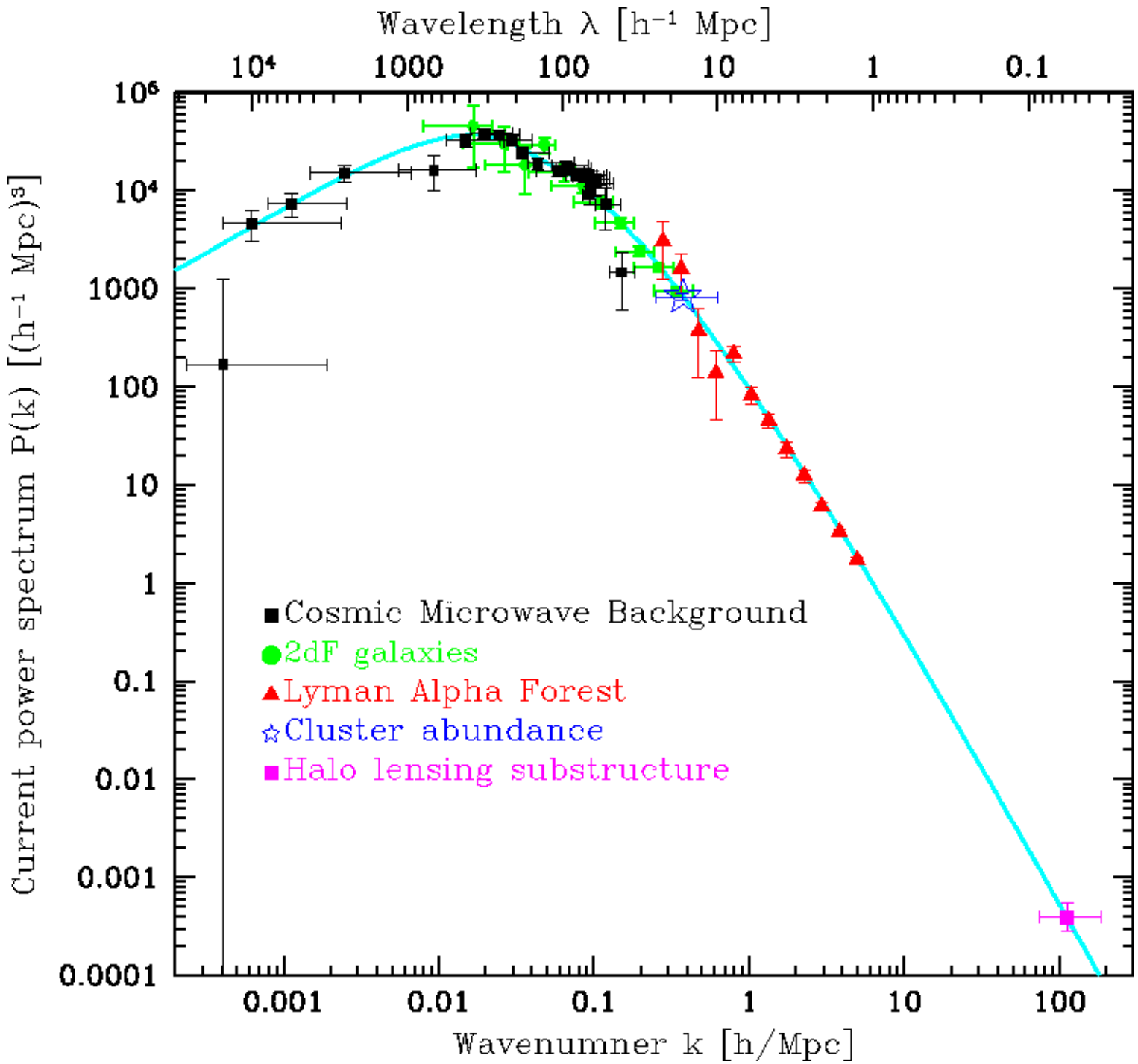

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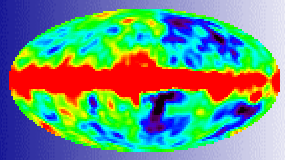
Measuring P(k) with CMB



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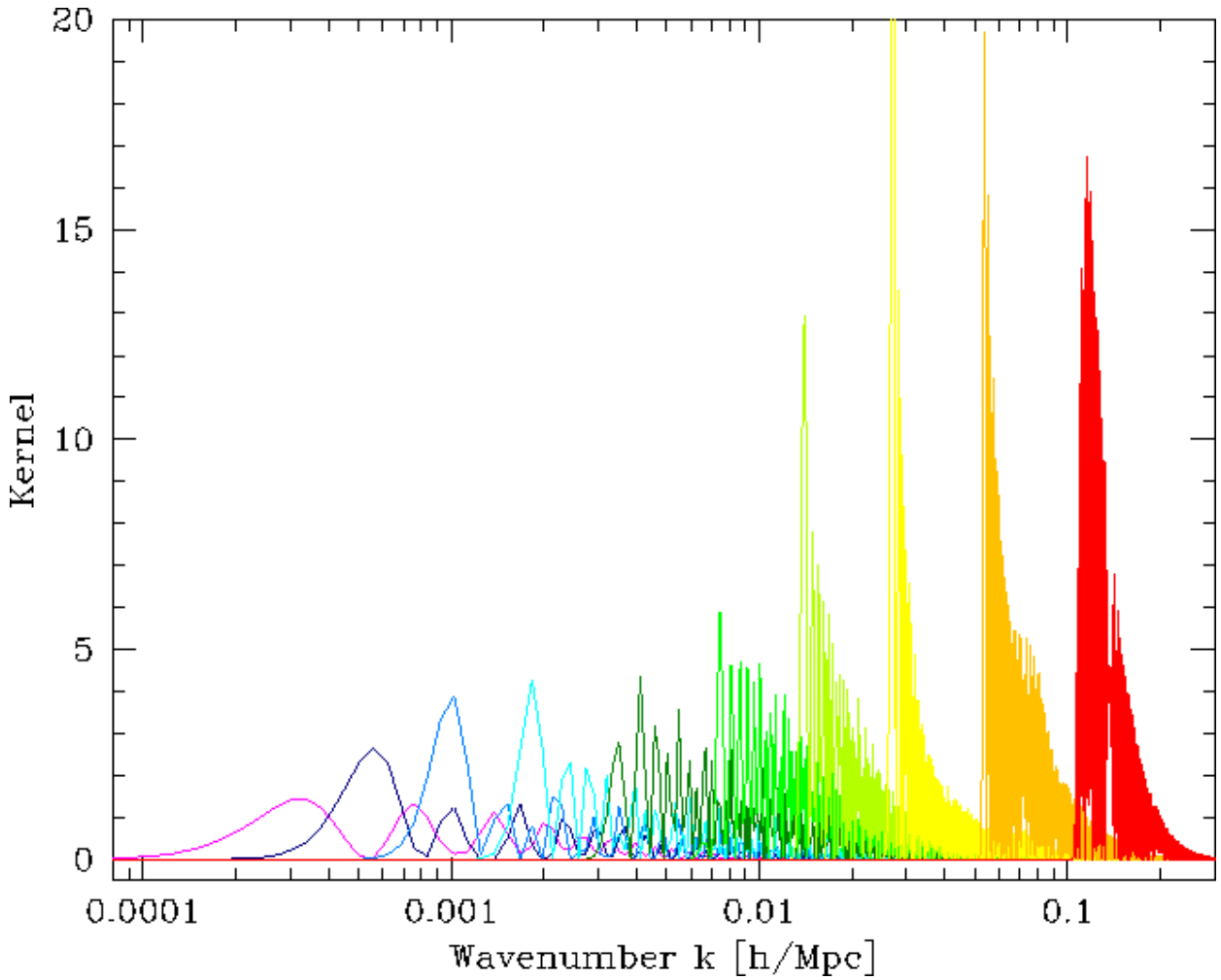

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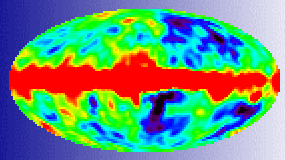

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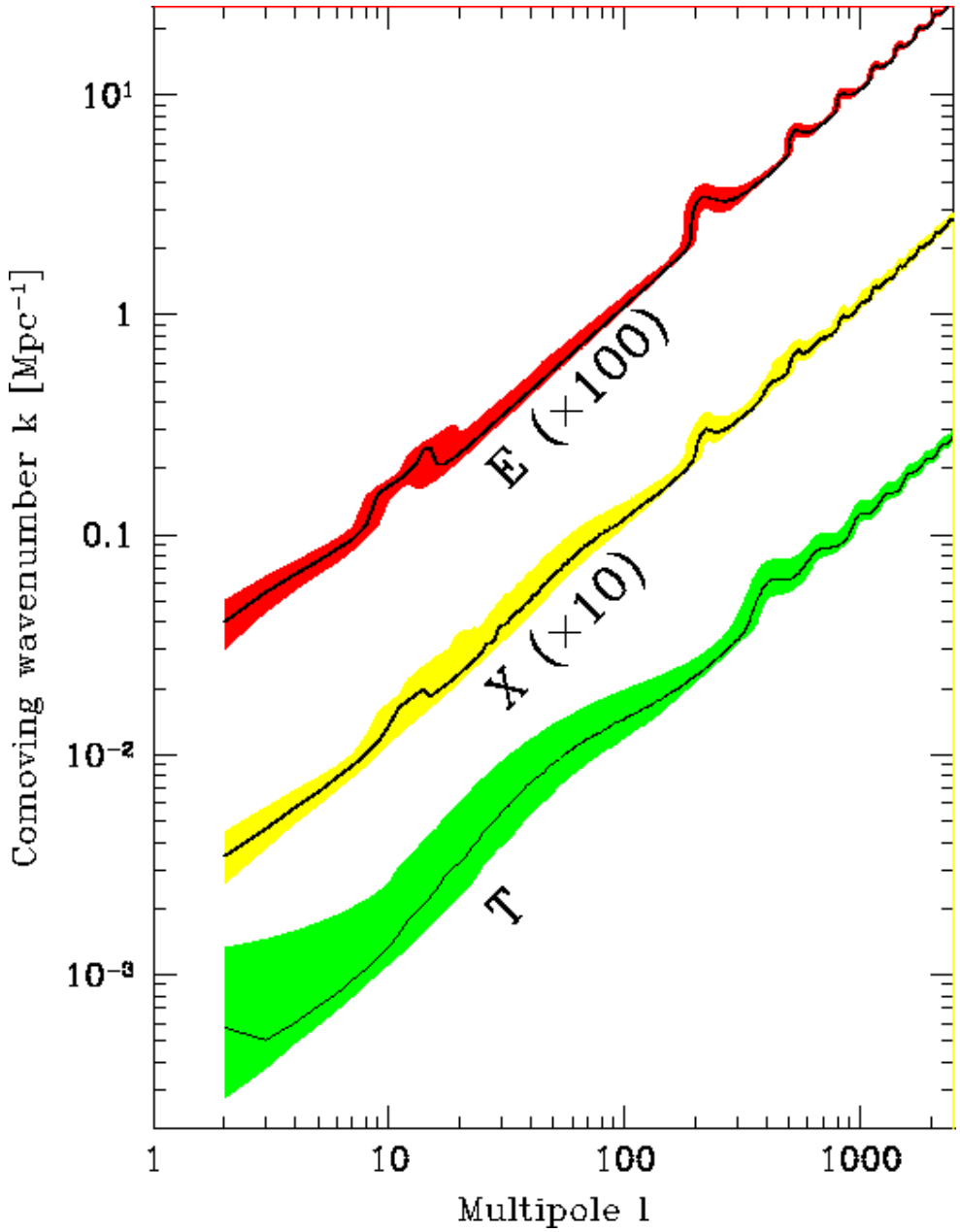

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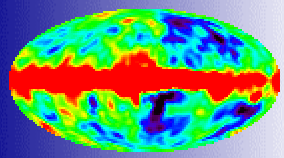
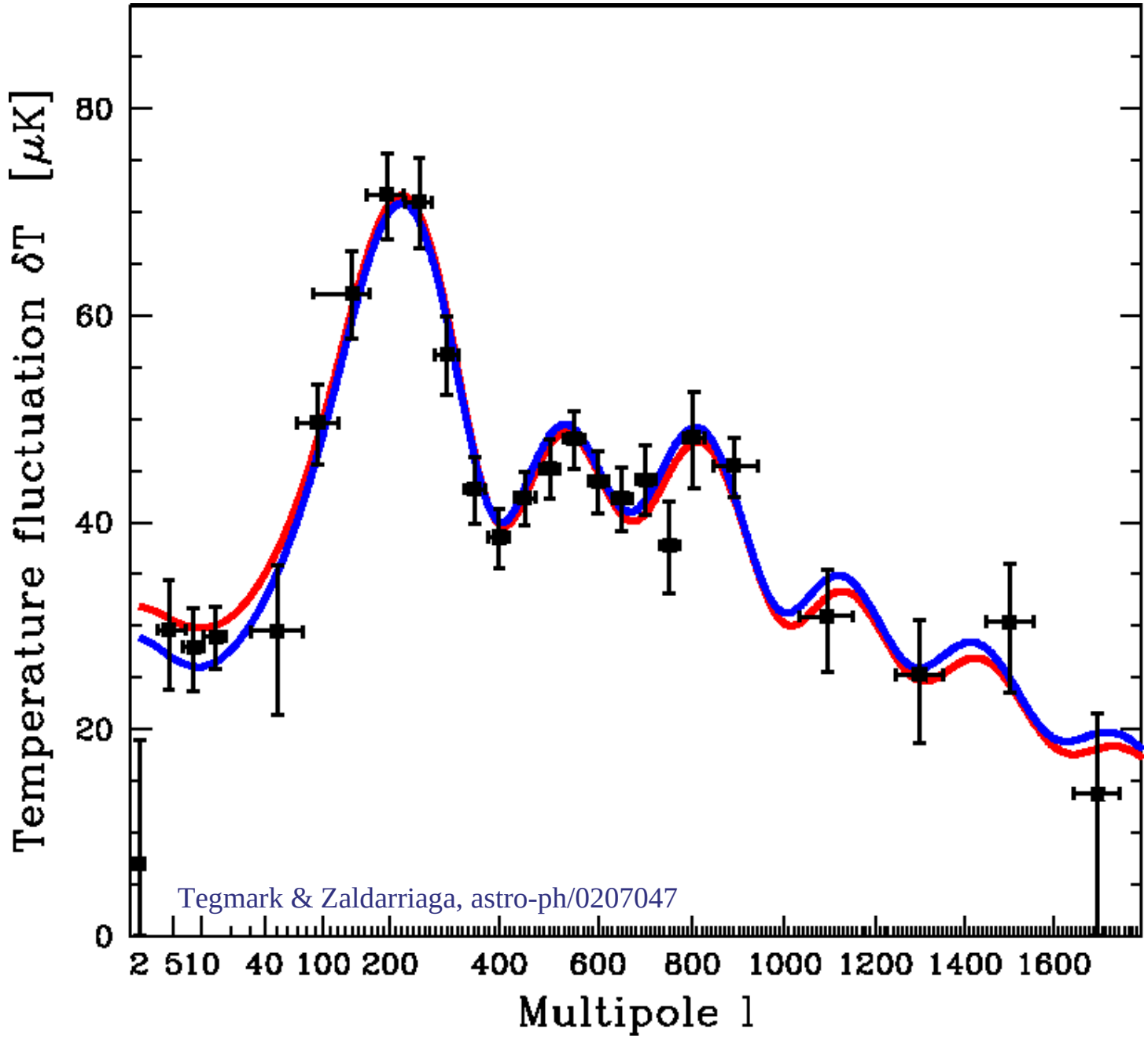


CMB

May 23, 2002: New CBI & VSA results



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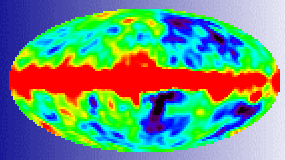

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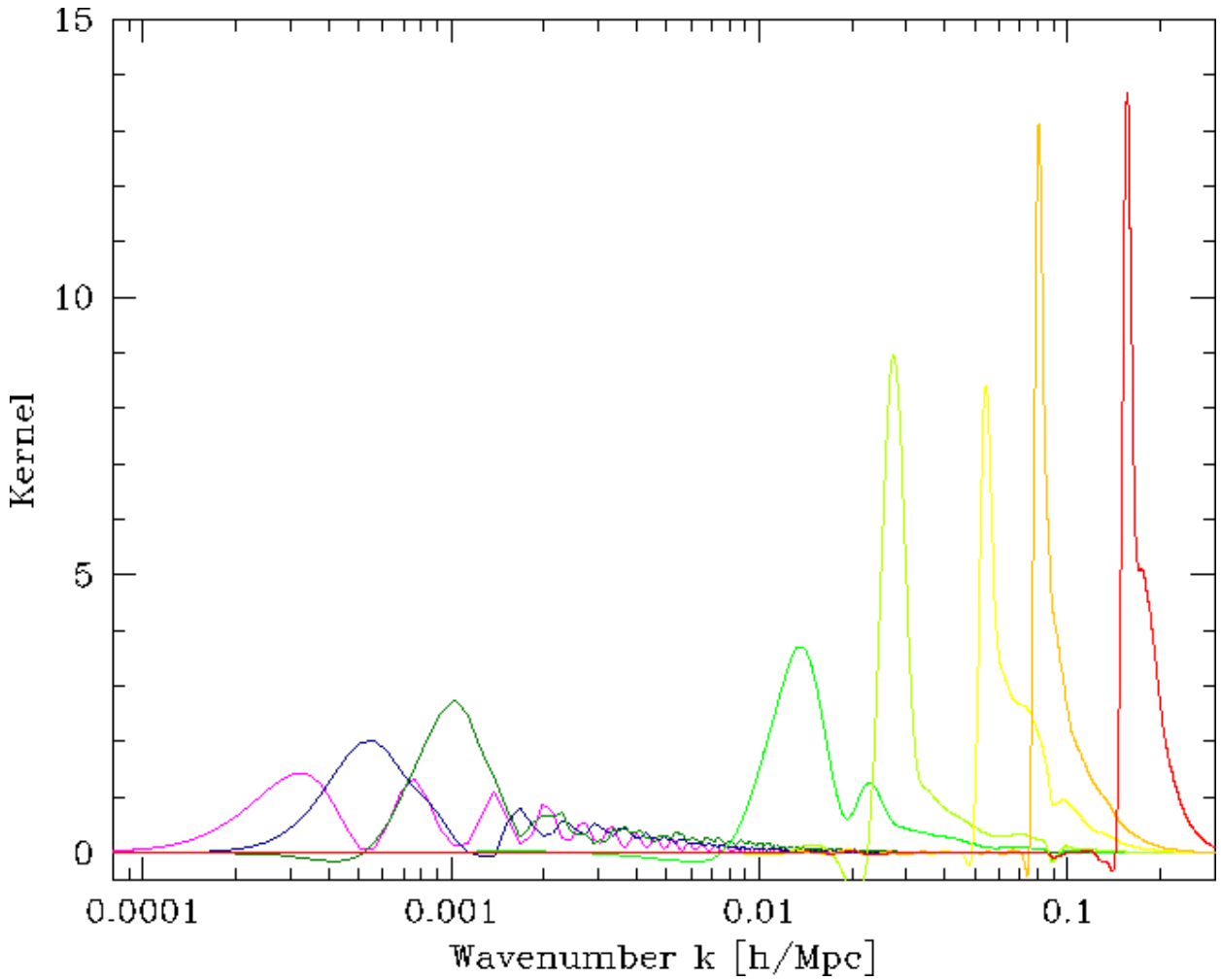

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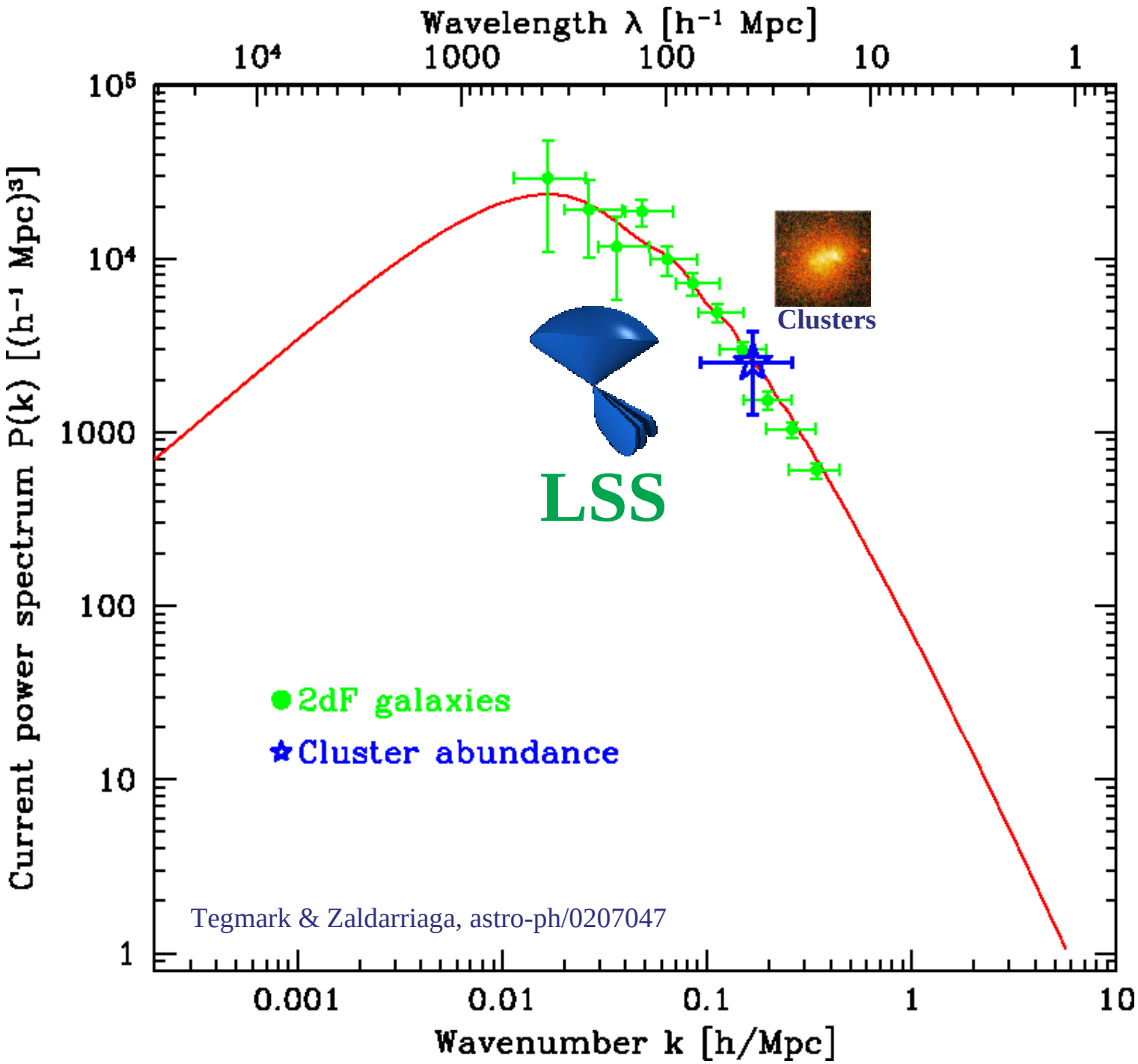

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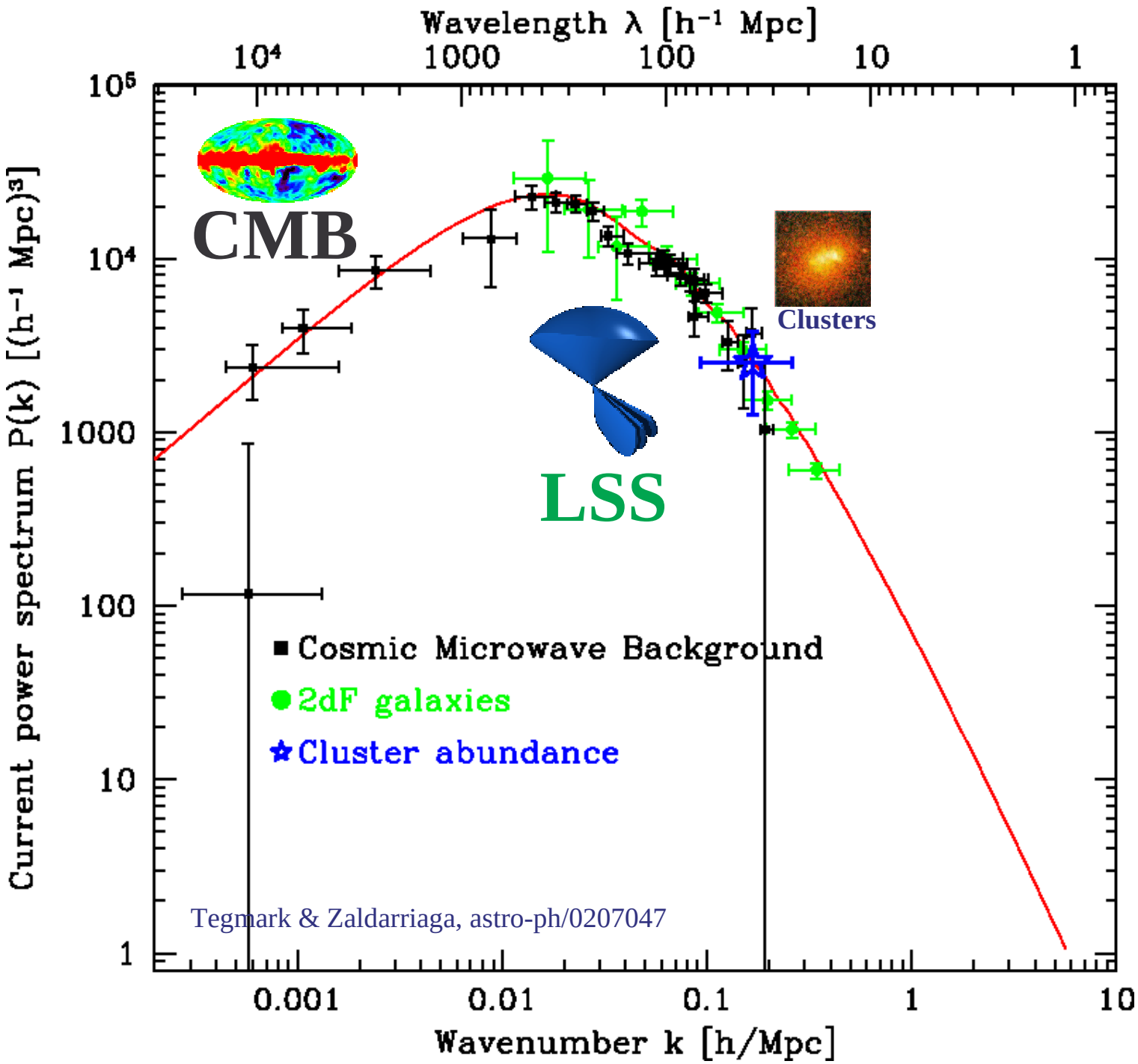

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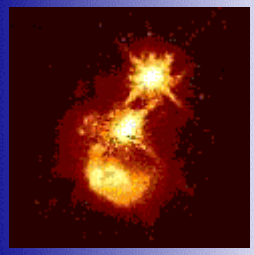
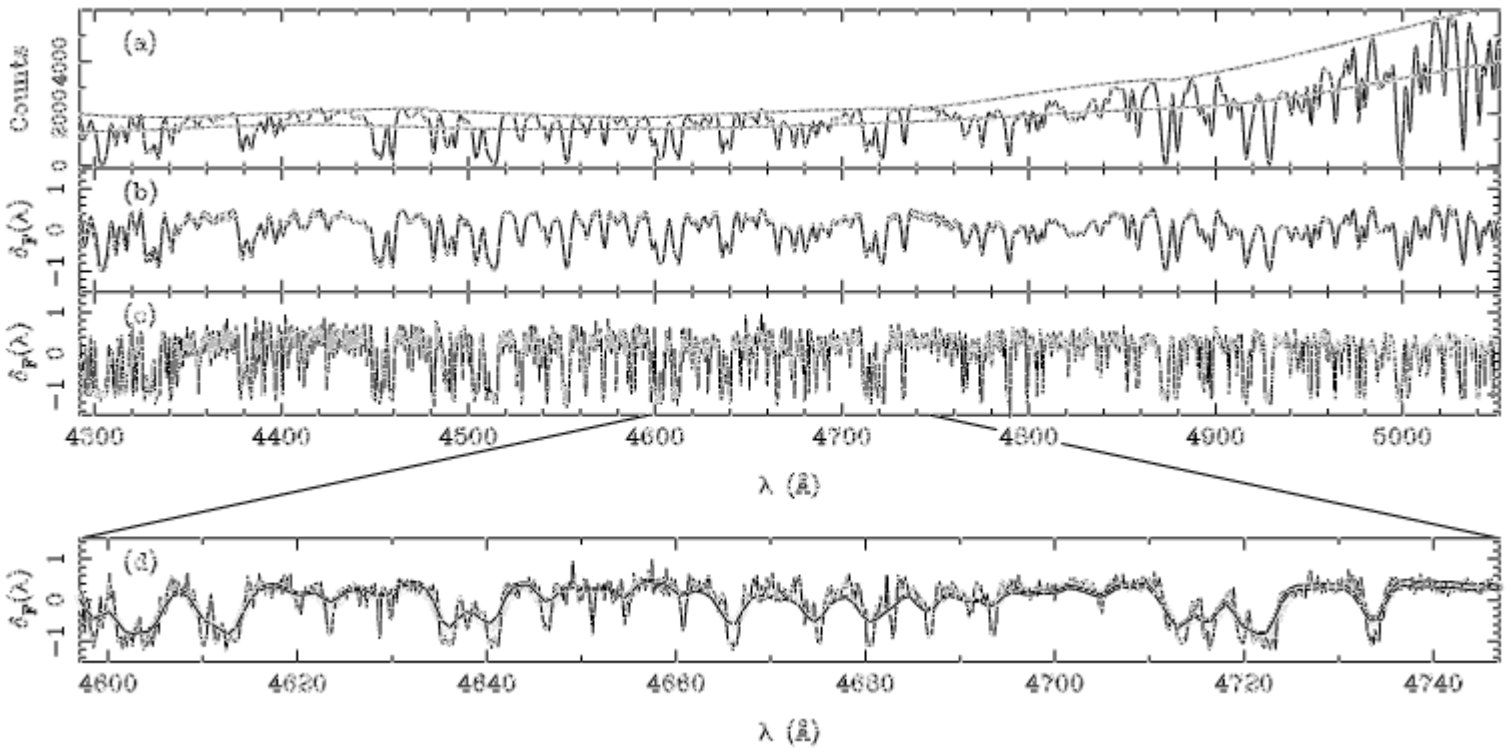
Measuring P(k) with the LyαF



Lyα

Croft et al 2000



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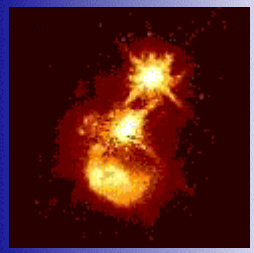
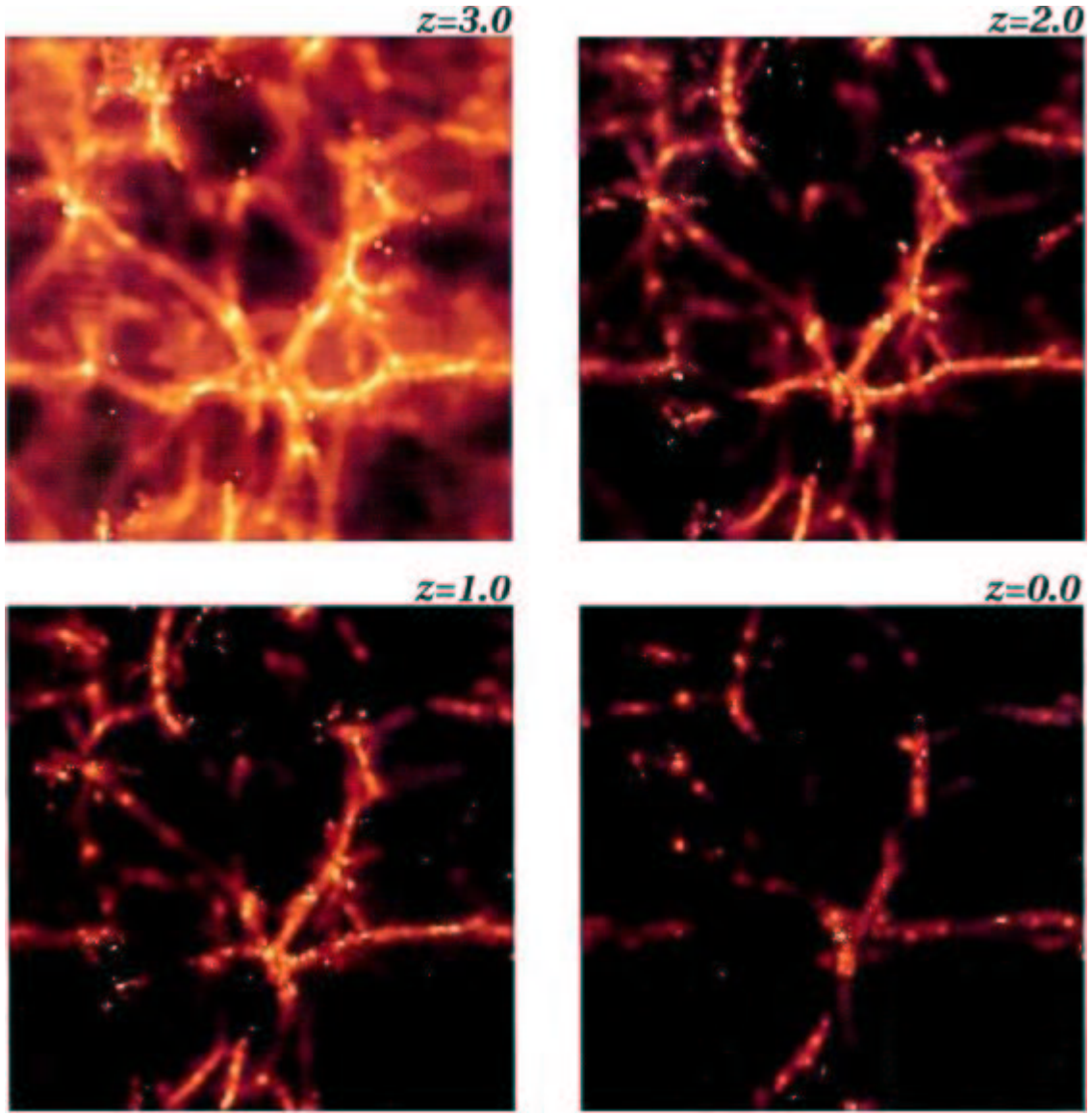


Lyα

Lyman Alpha Forest Simulations: Dave, Hernquist, Katz & Weinberg 1999



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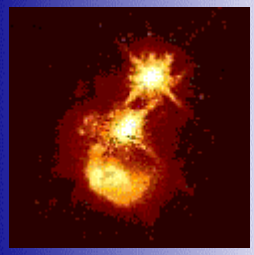

Lyα

Reanalysis of Croft et al (astro-ph/0012324) by Hamilton & Gredin (astro-ph/0111194)

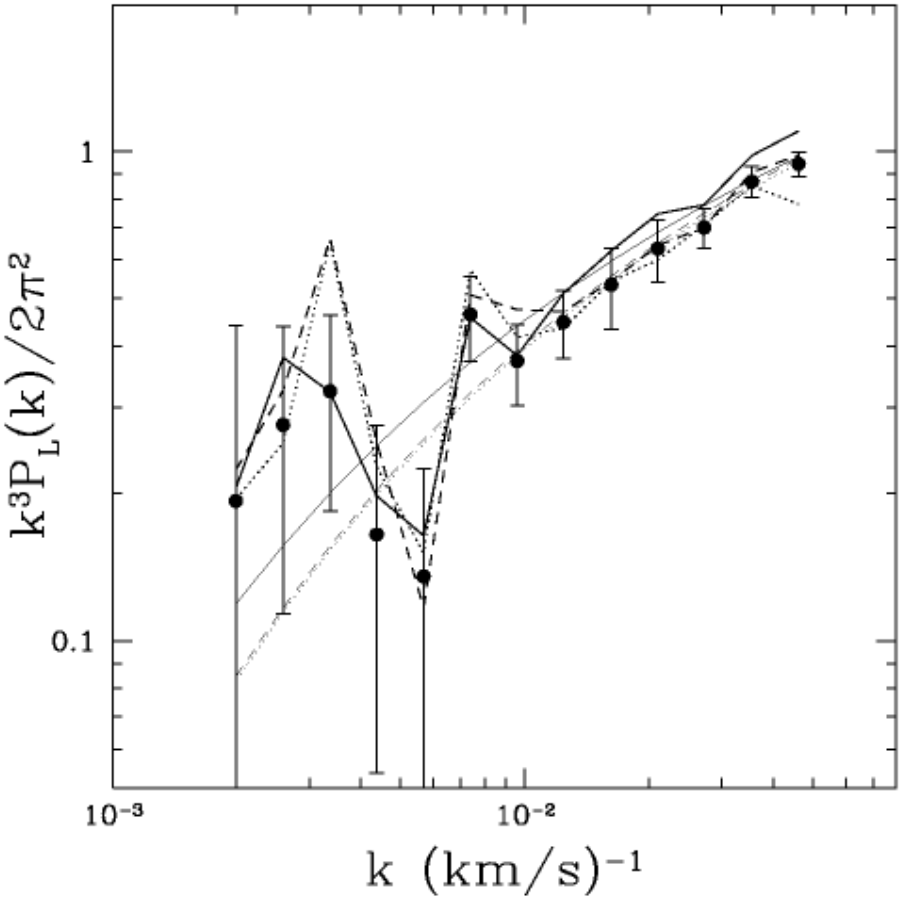

Figure 3. The flux power spectrum

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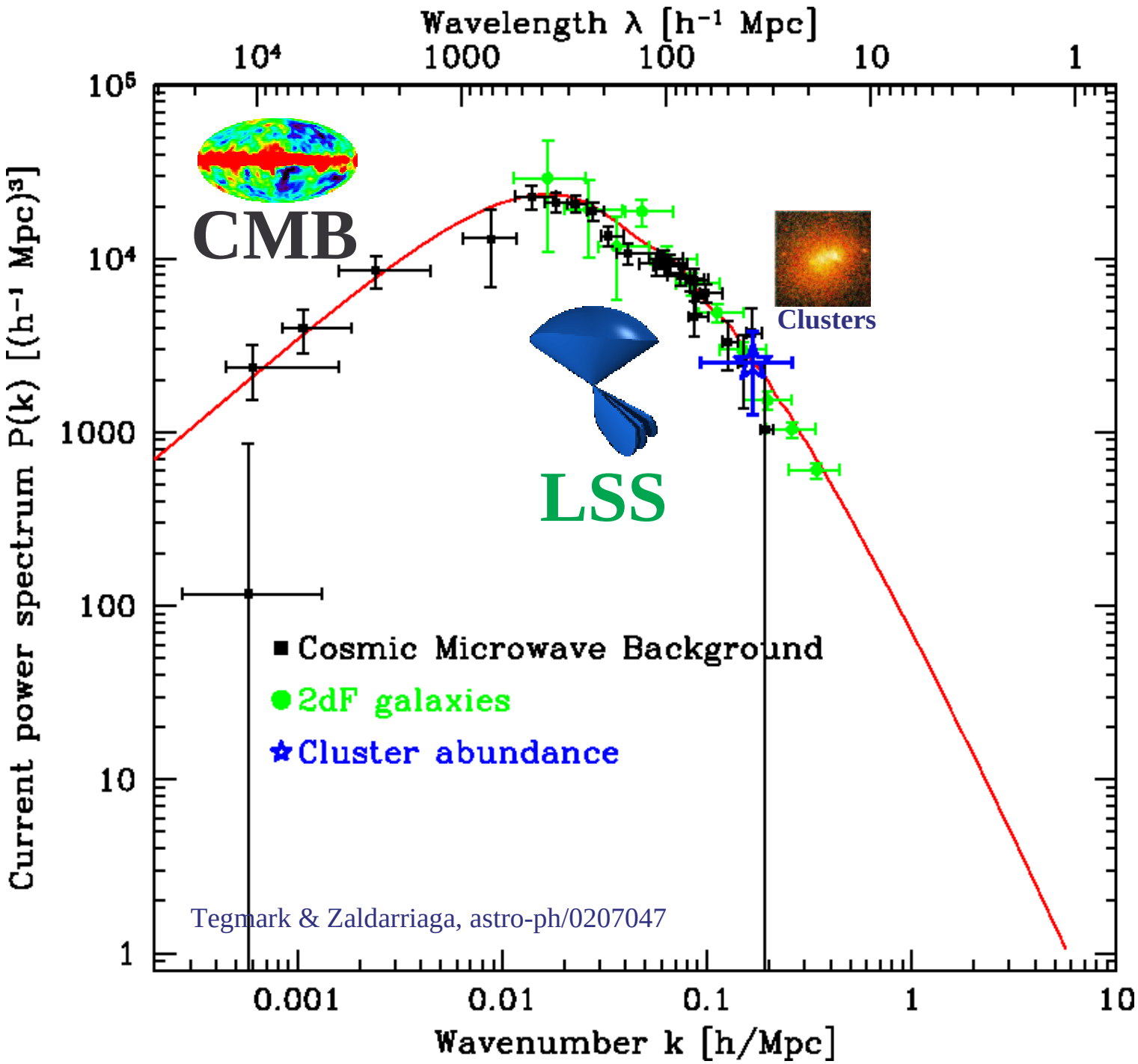

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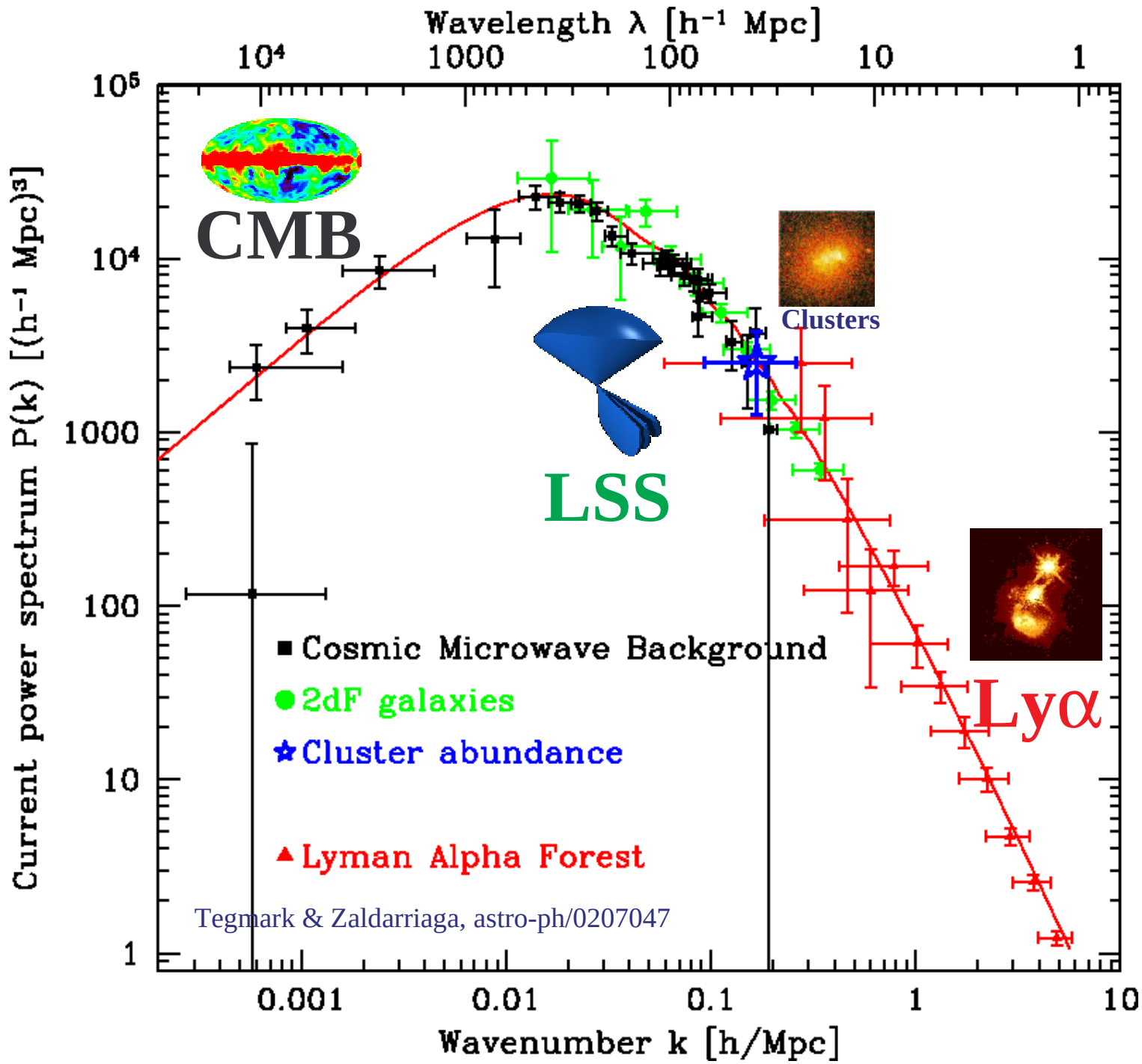

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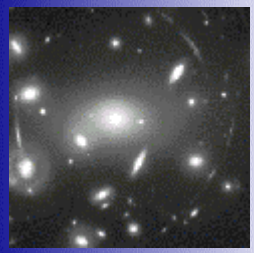
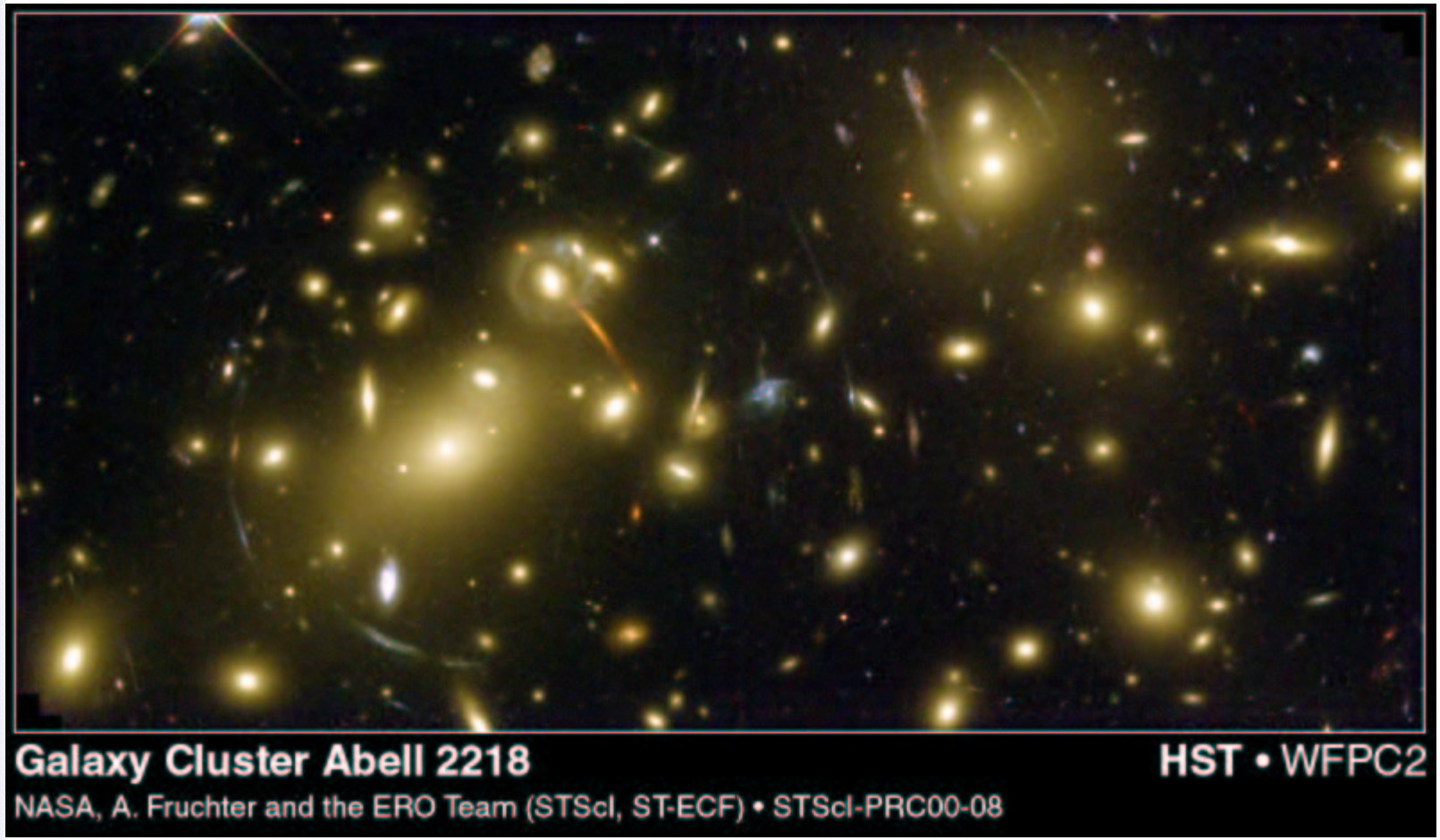
Measuring P(k) with weak lensing



Lensing

Gravitational lensing



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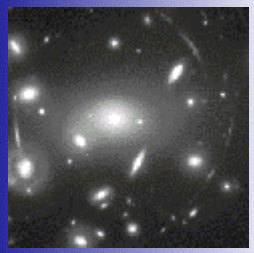

Lensing

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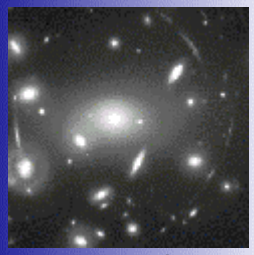
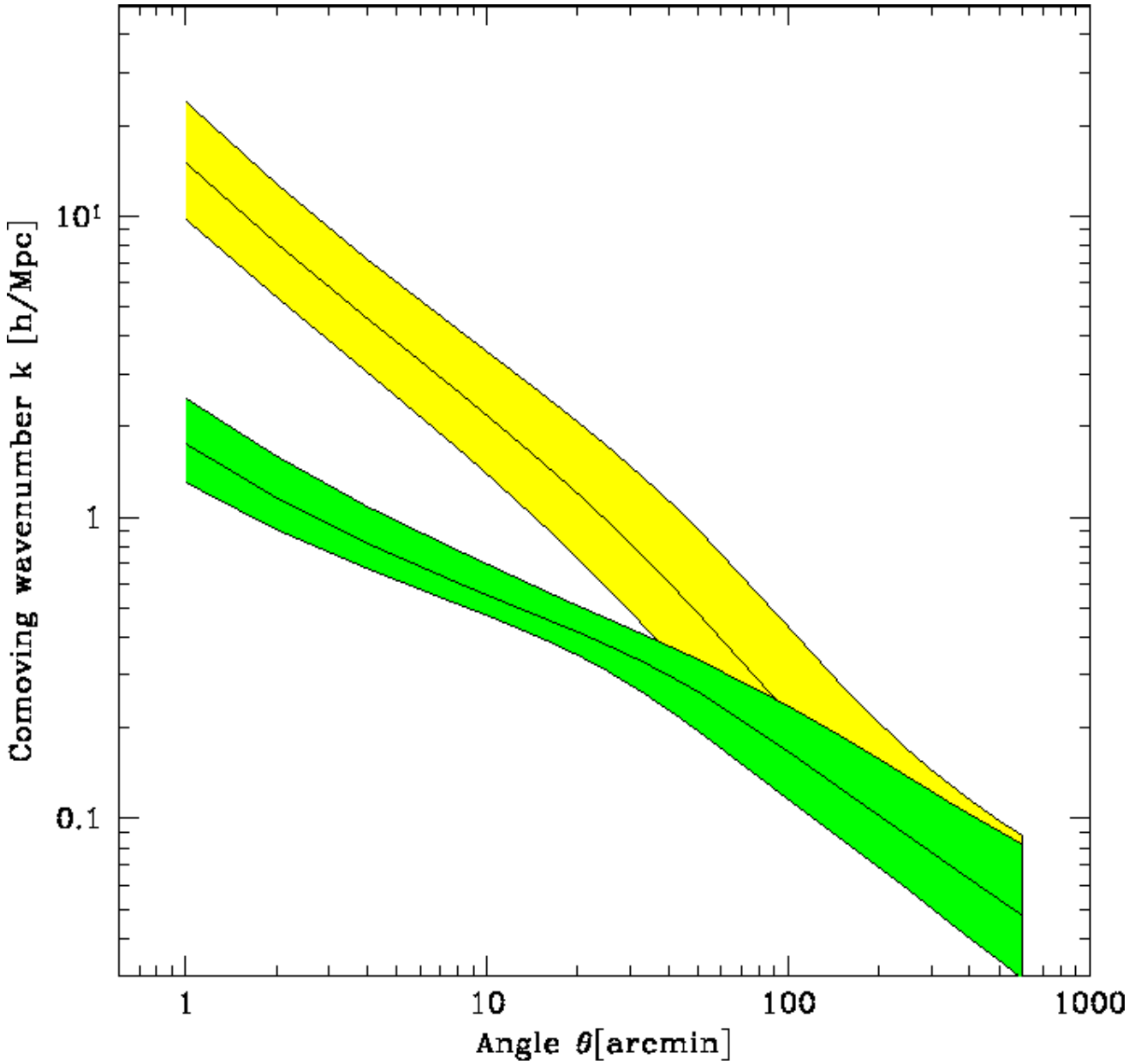


Lensing



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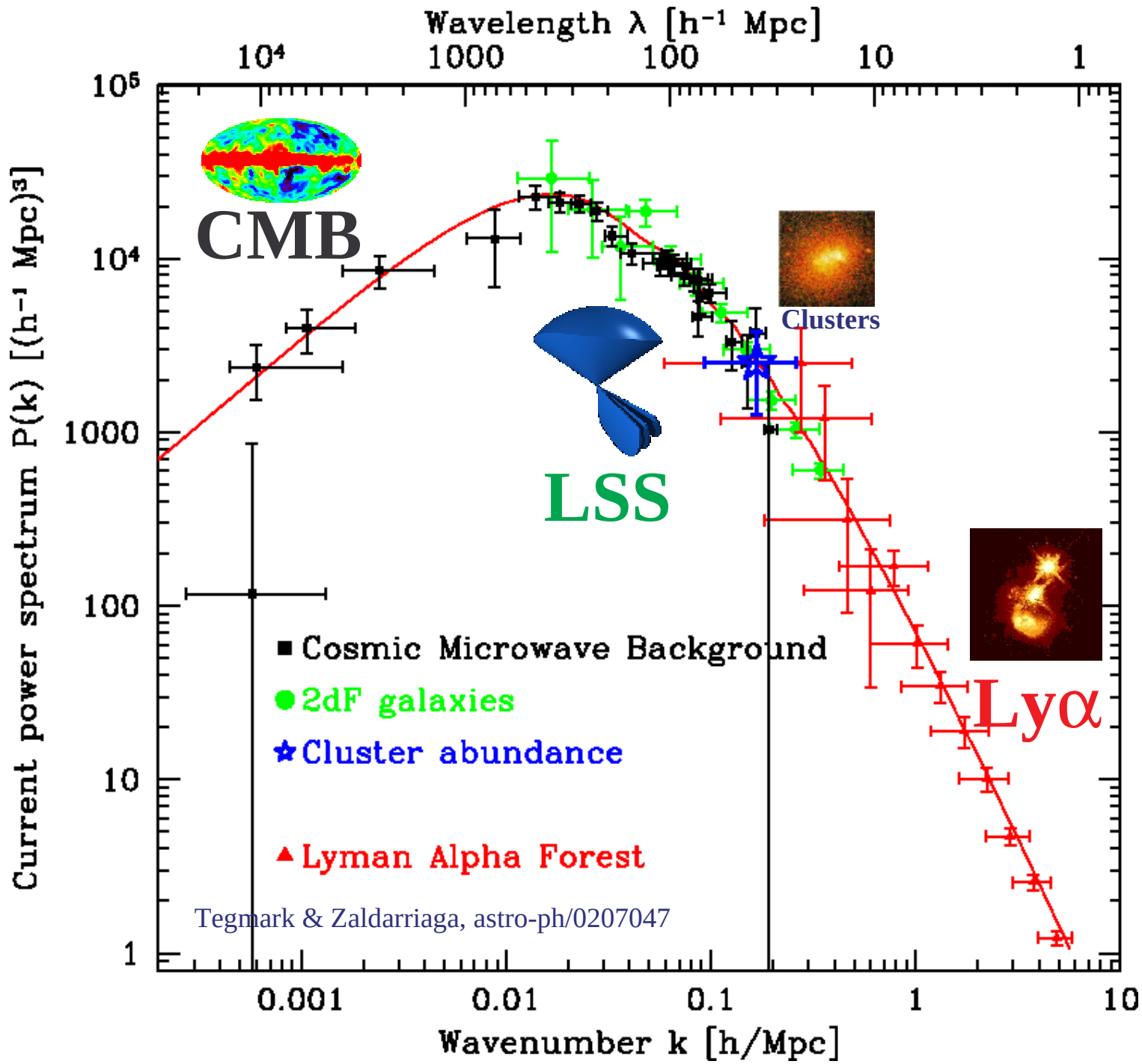

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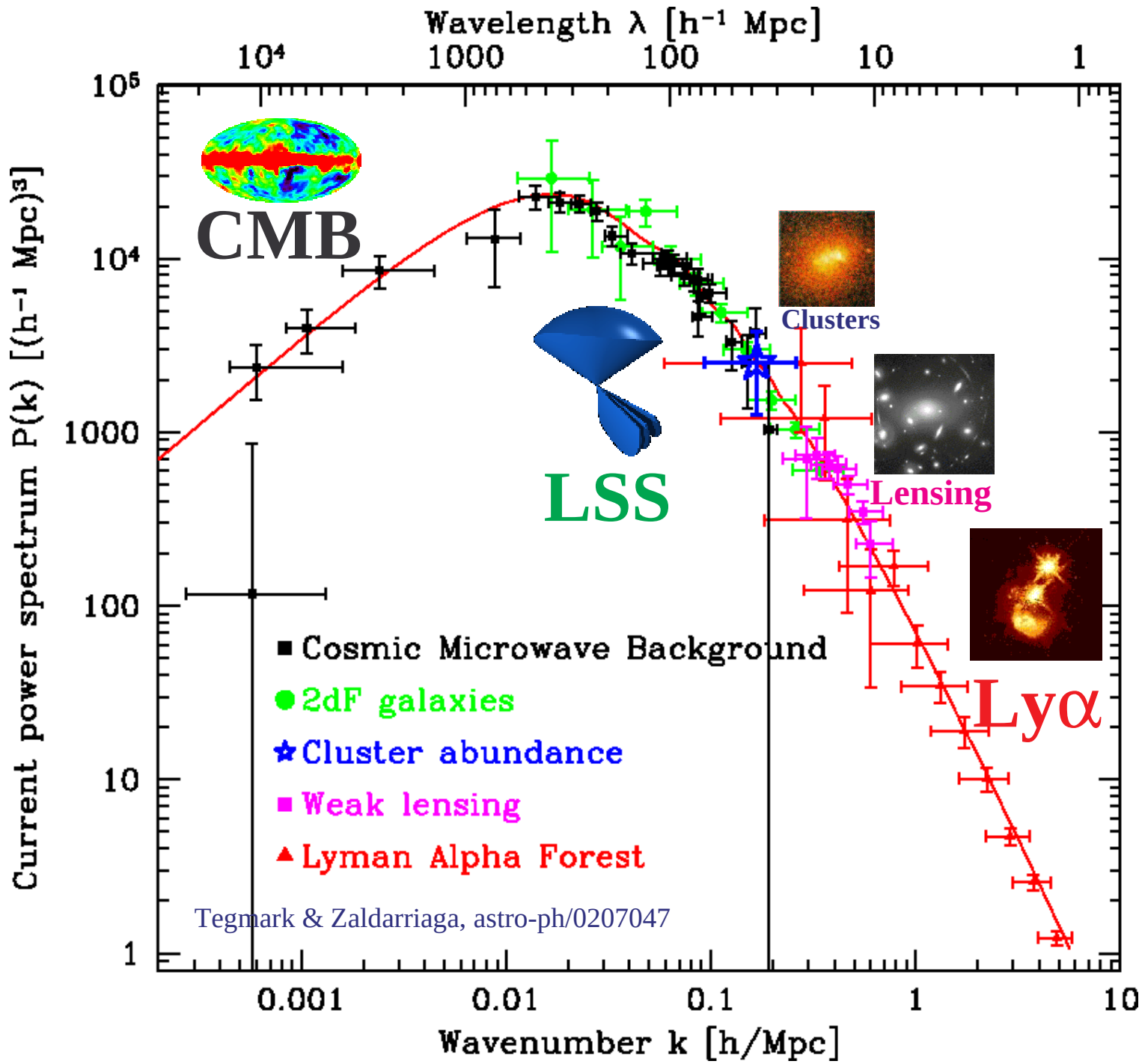

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Measuring P(k) with SDSS

Early SDSS P(k) results

For the SDSS collaboration

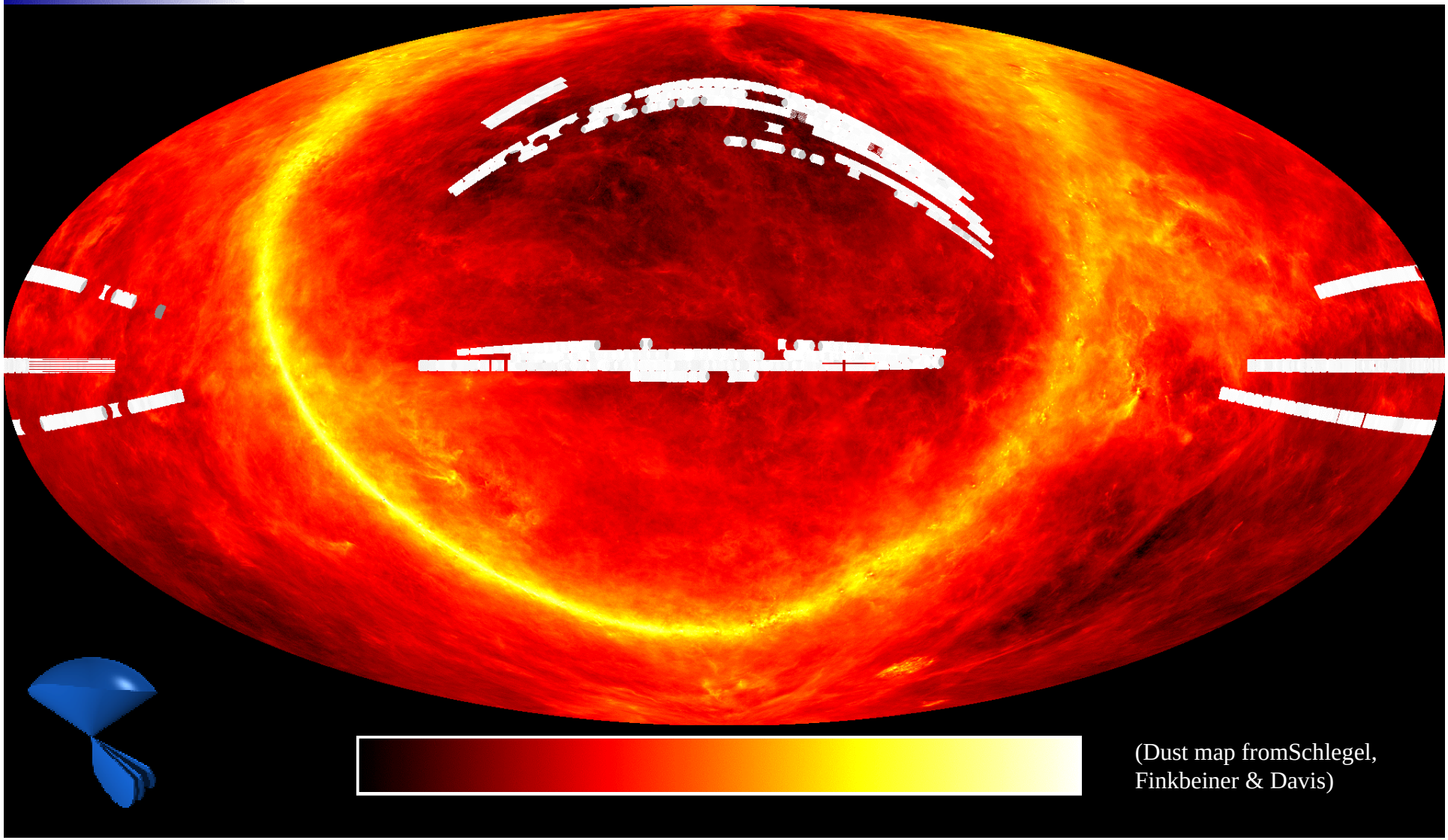
A real team effort. Particularly important contributions by Michael Blanton, Fiona Hoyle, Michael Strauss, Michael Vogeley, David Weinberg, Idit Zehavi, Adrian Pope, Josh Frieman & Alex Szalay.

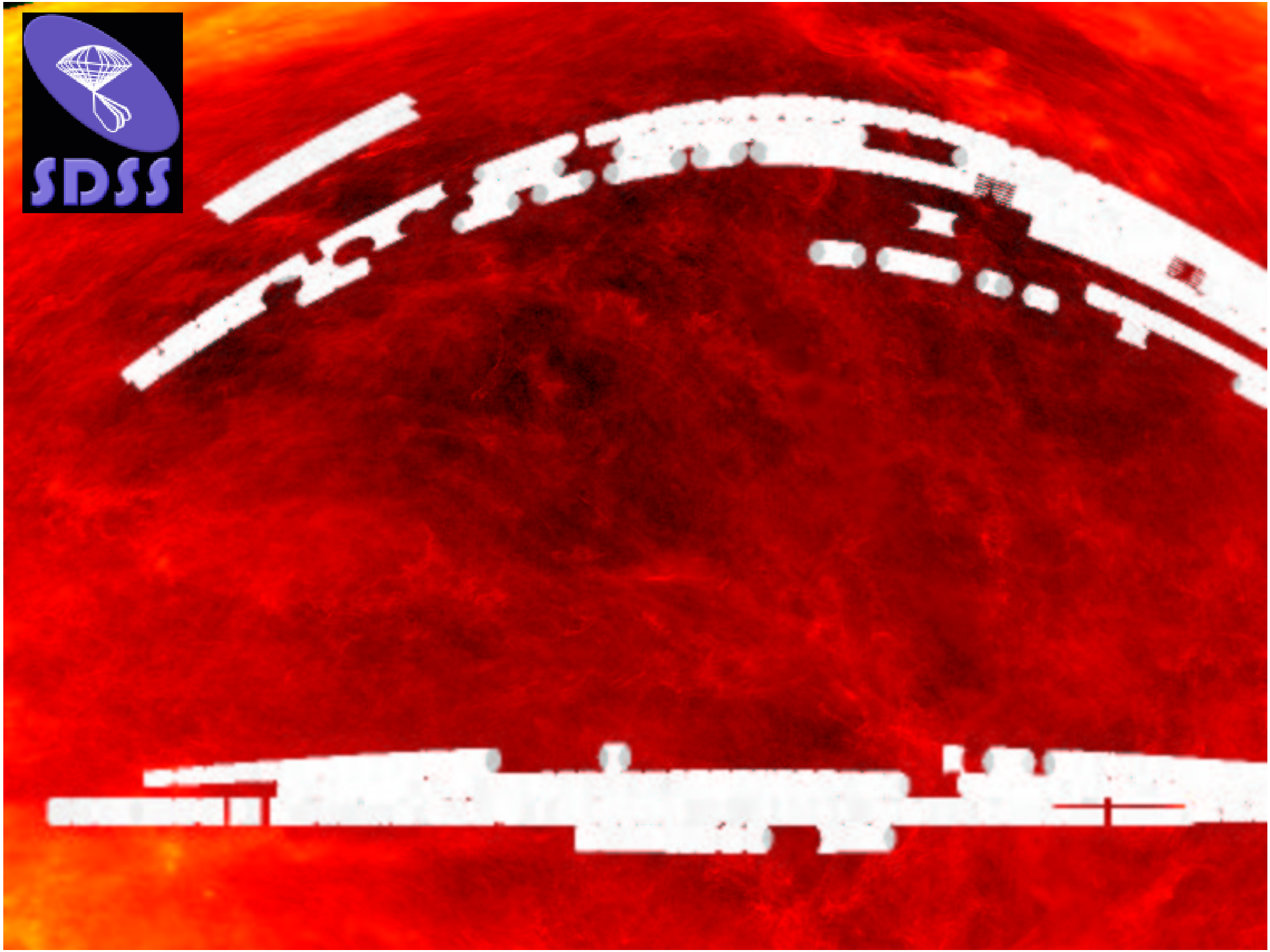
Special thanks to Andrew Hamilton for sharing mask & mode code.

Data

Sky coverage of SDSS redshift survey

(Aitoff projection, equatorial coordinates)

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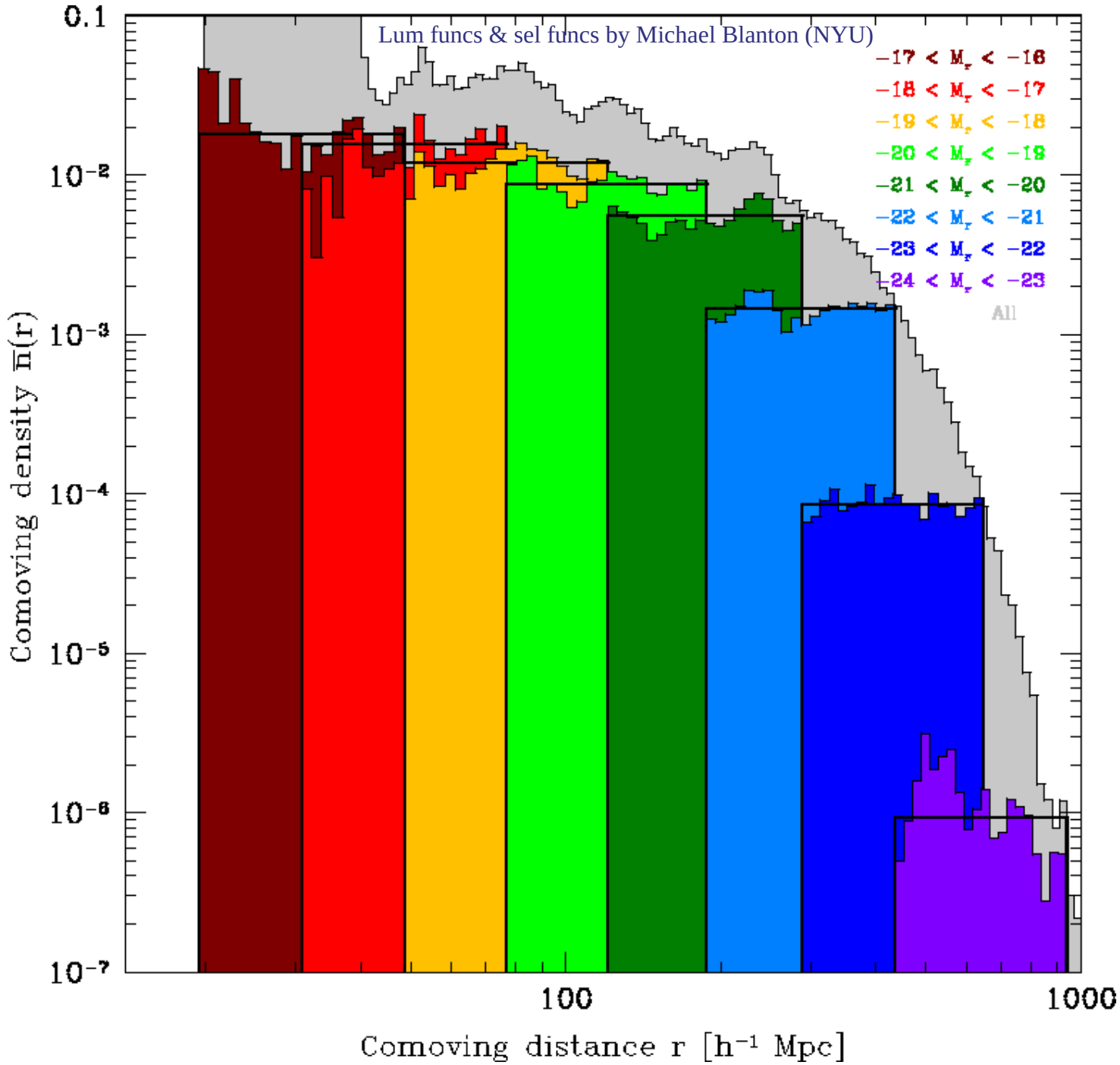

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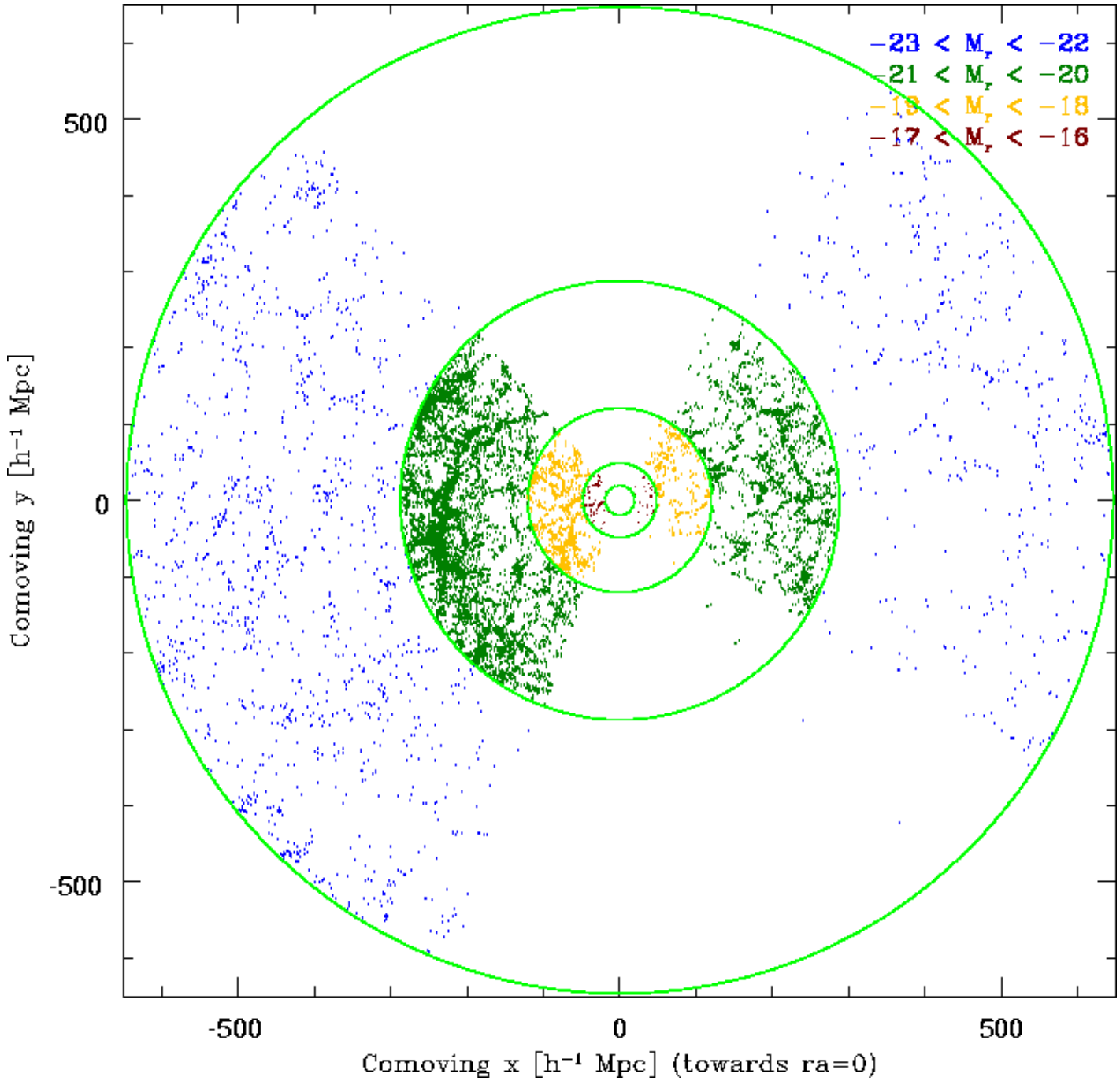

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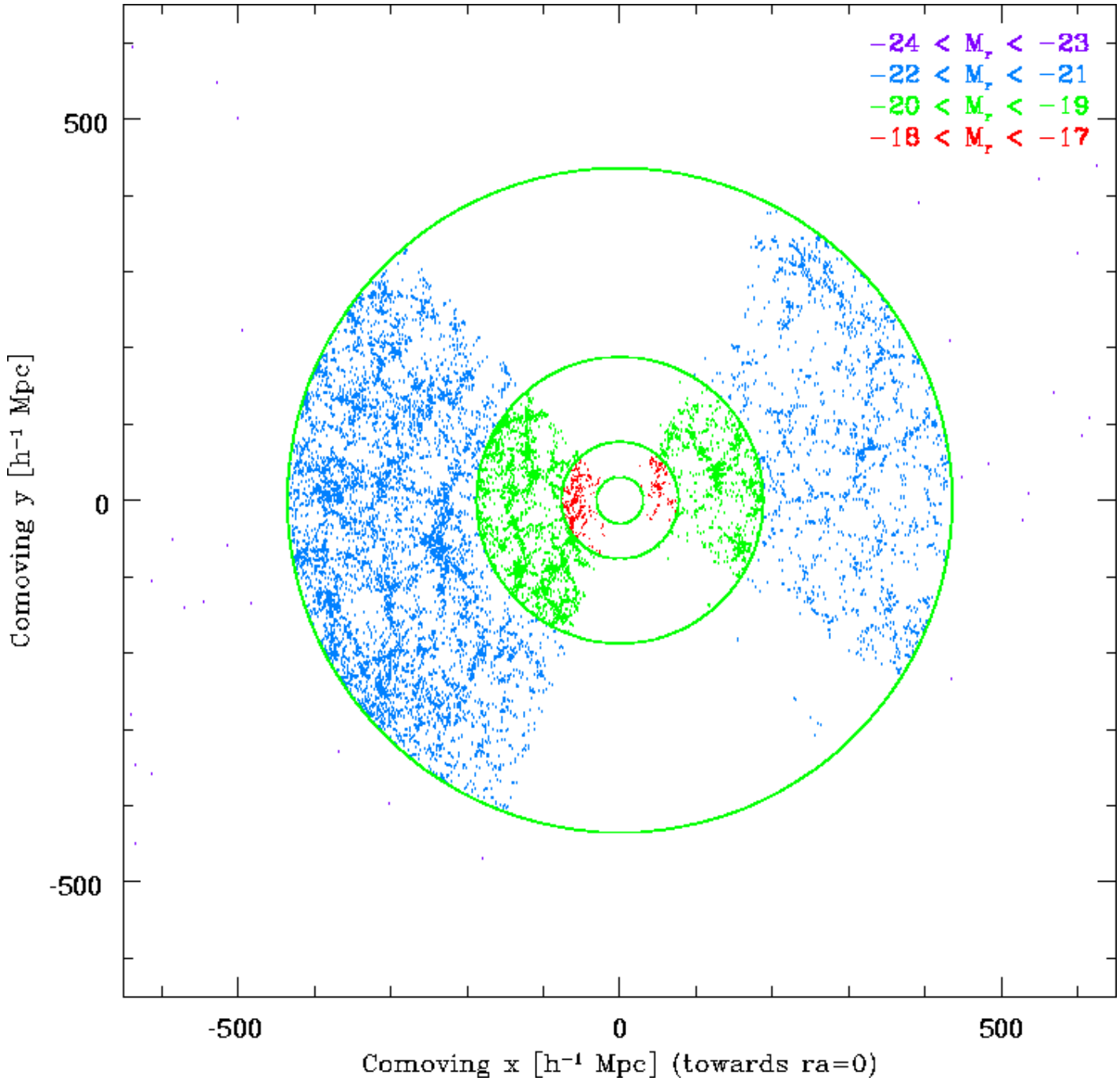

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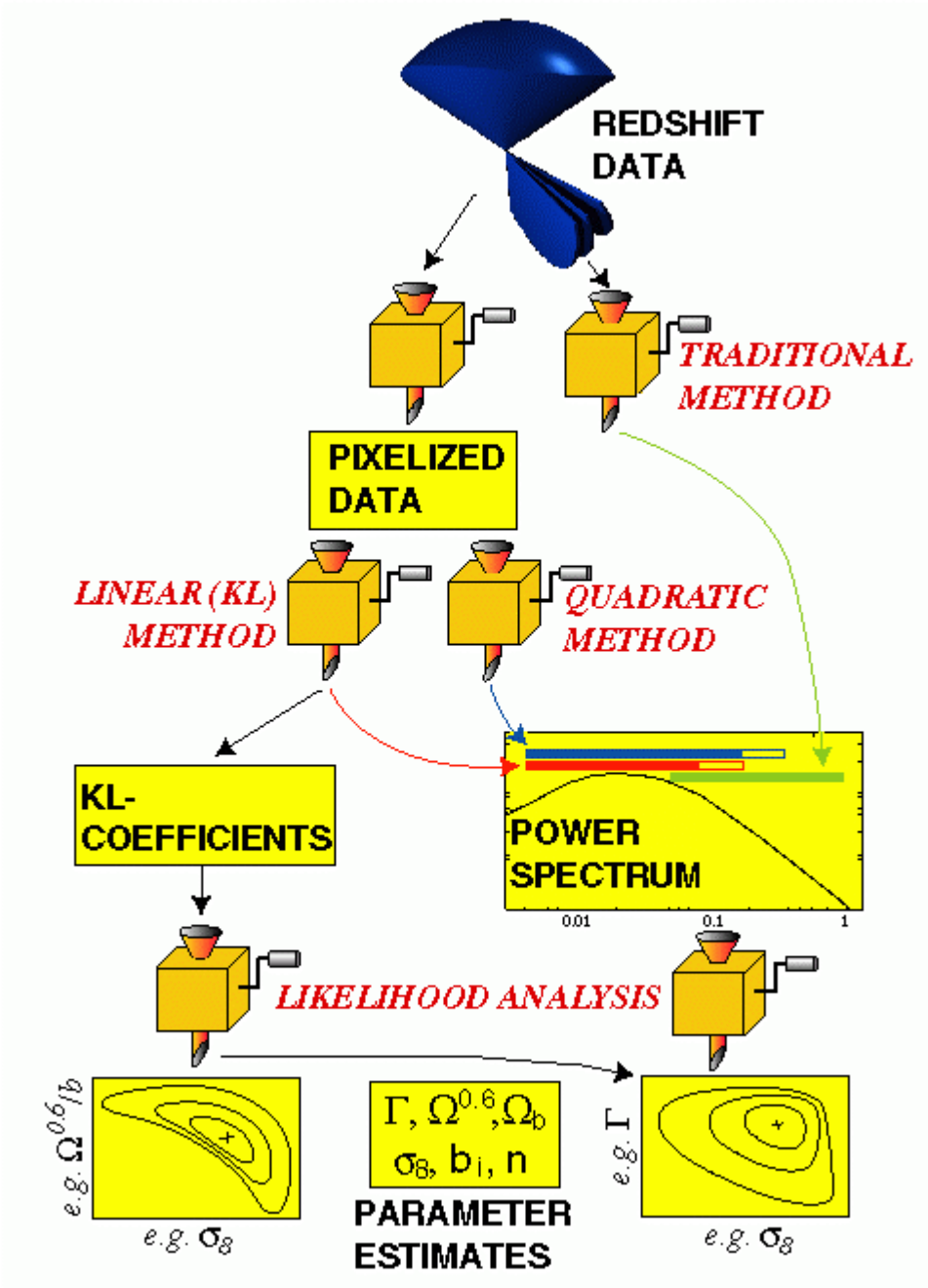
Analysis

Tegmark, Hamilton, Strauss, Vogeley & Szalay 1998



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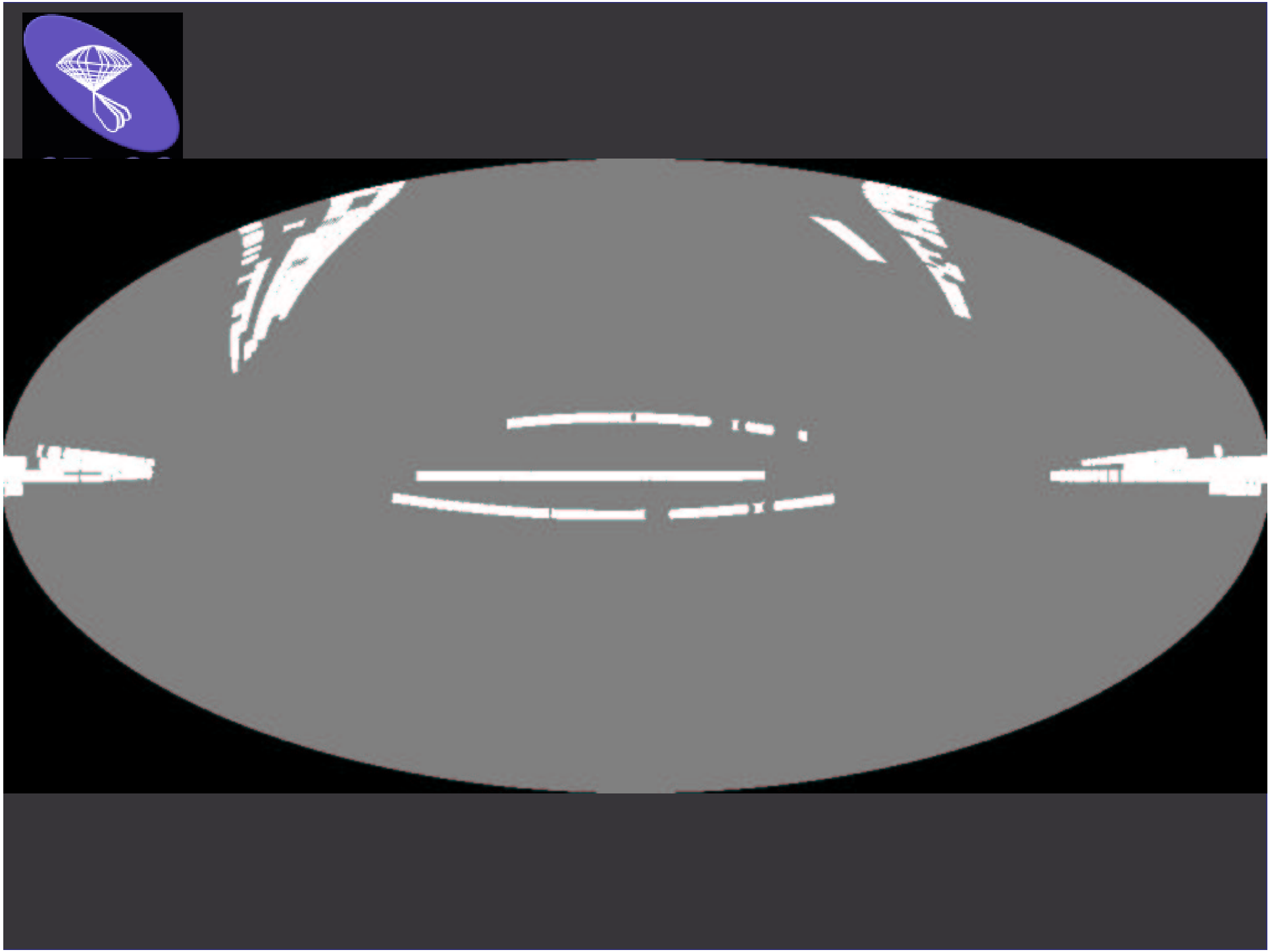

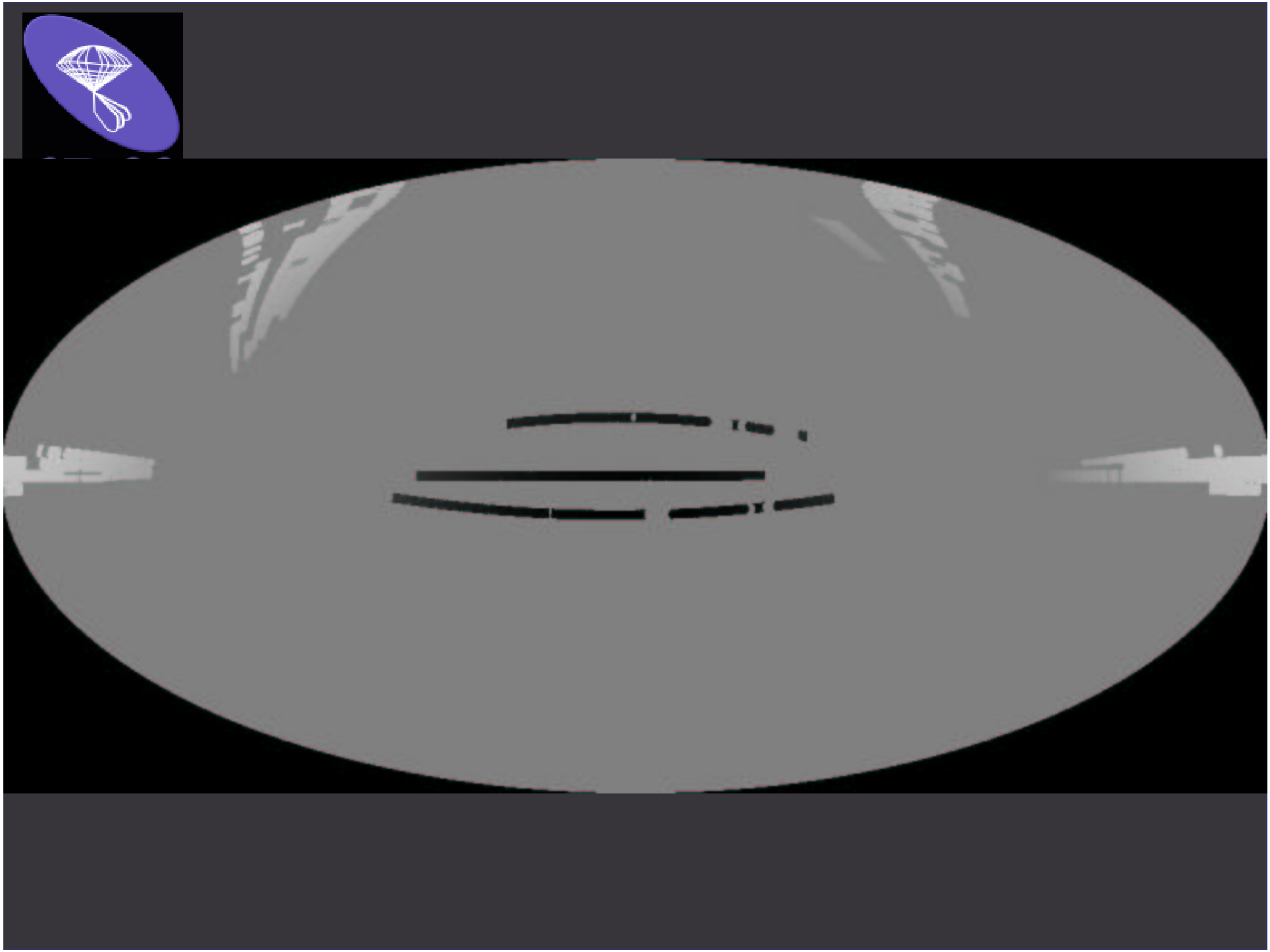

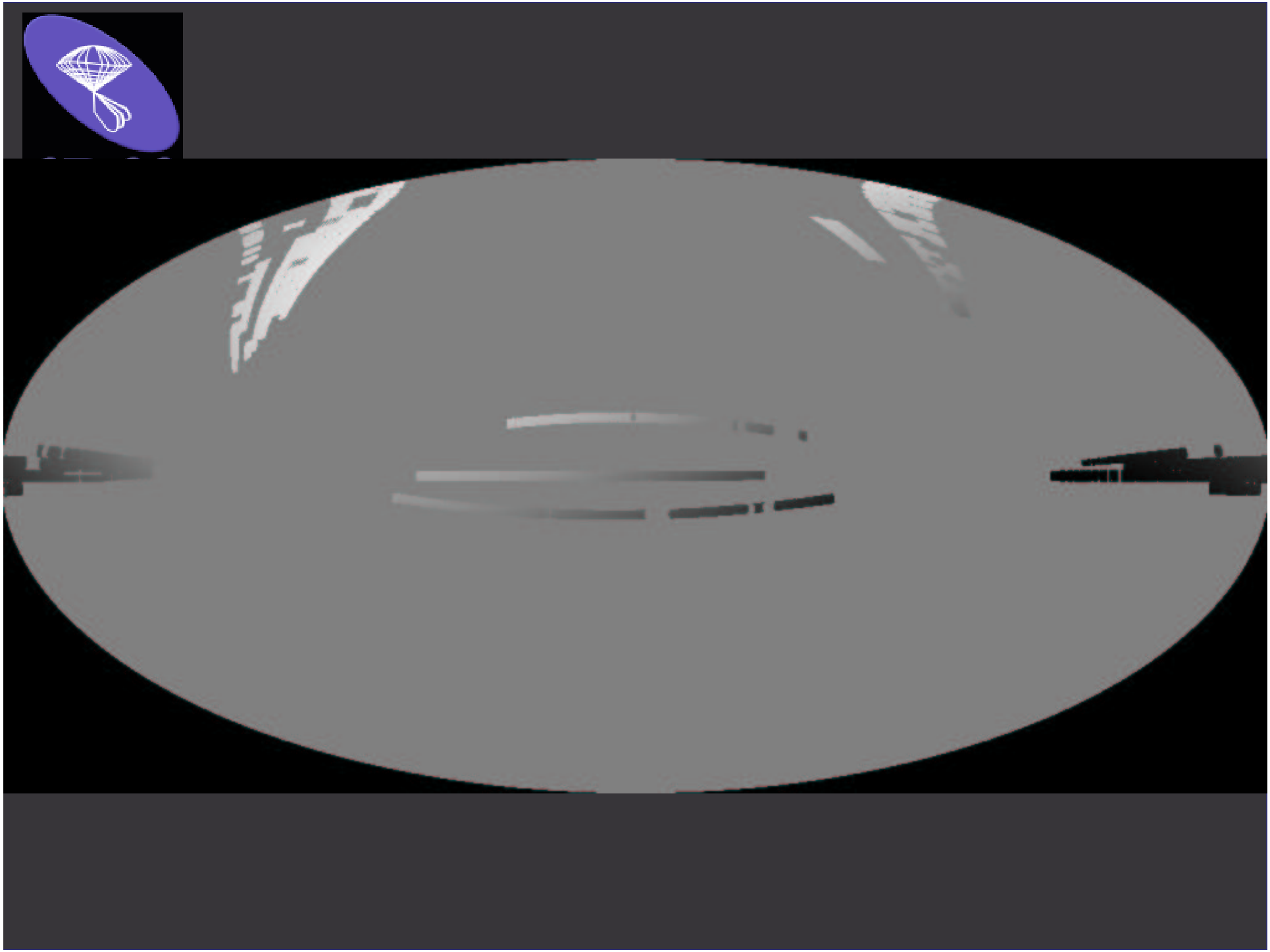

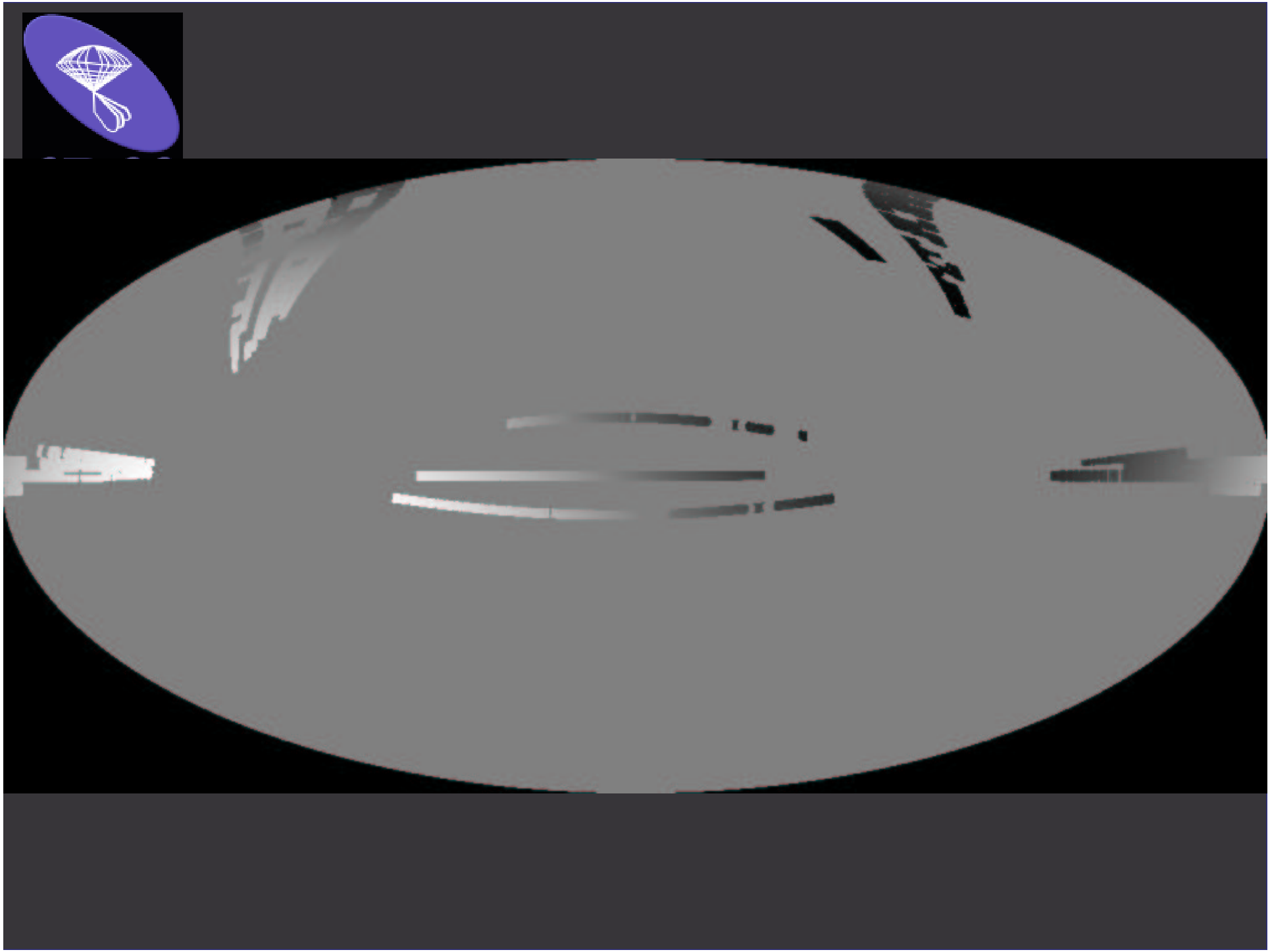

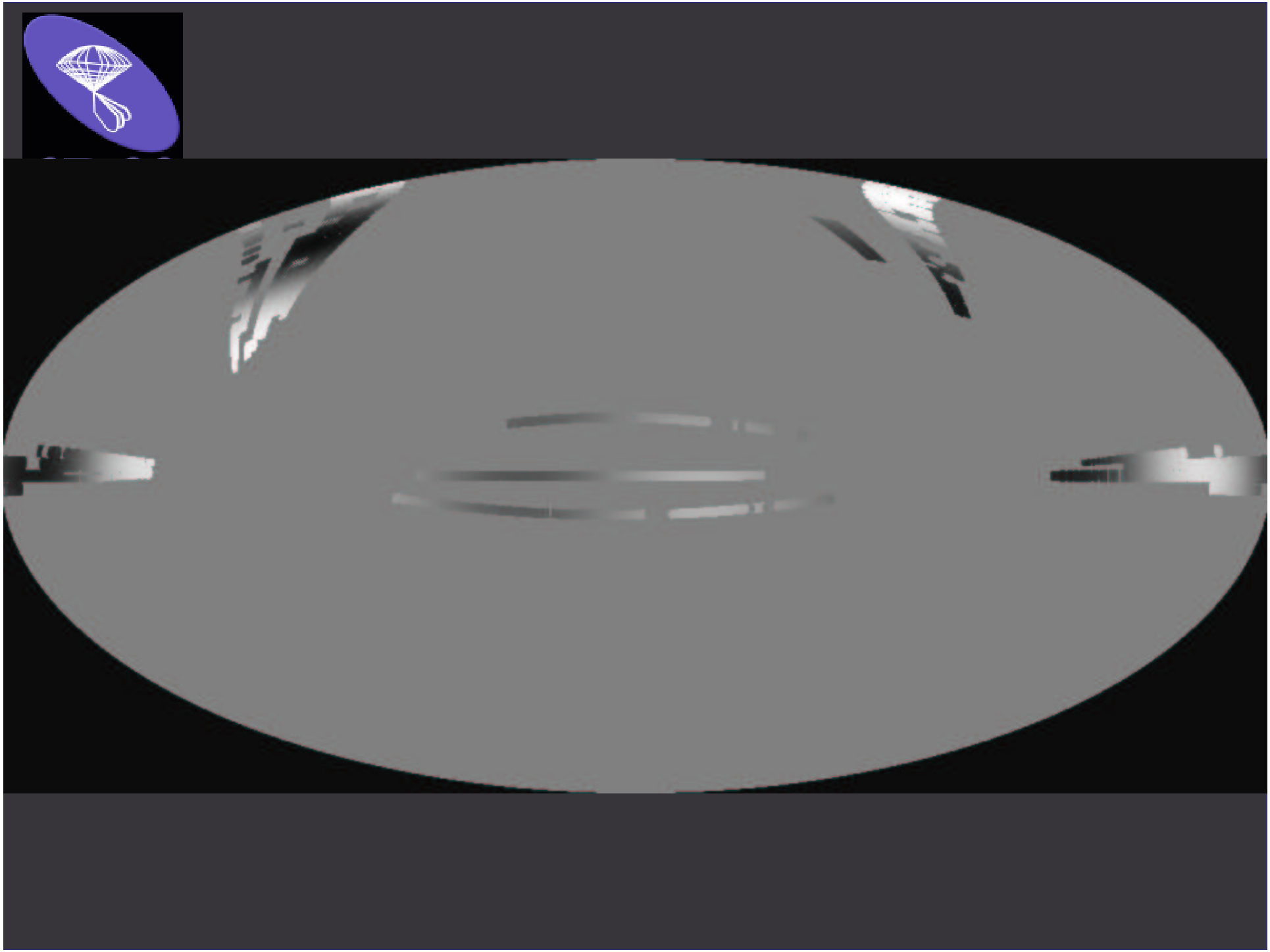

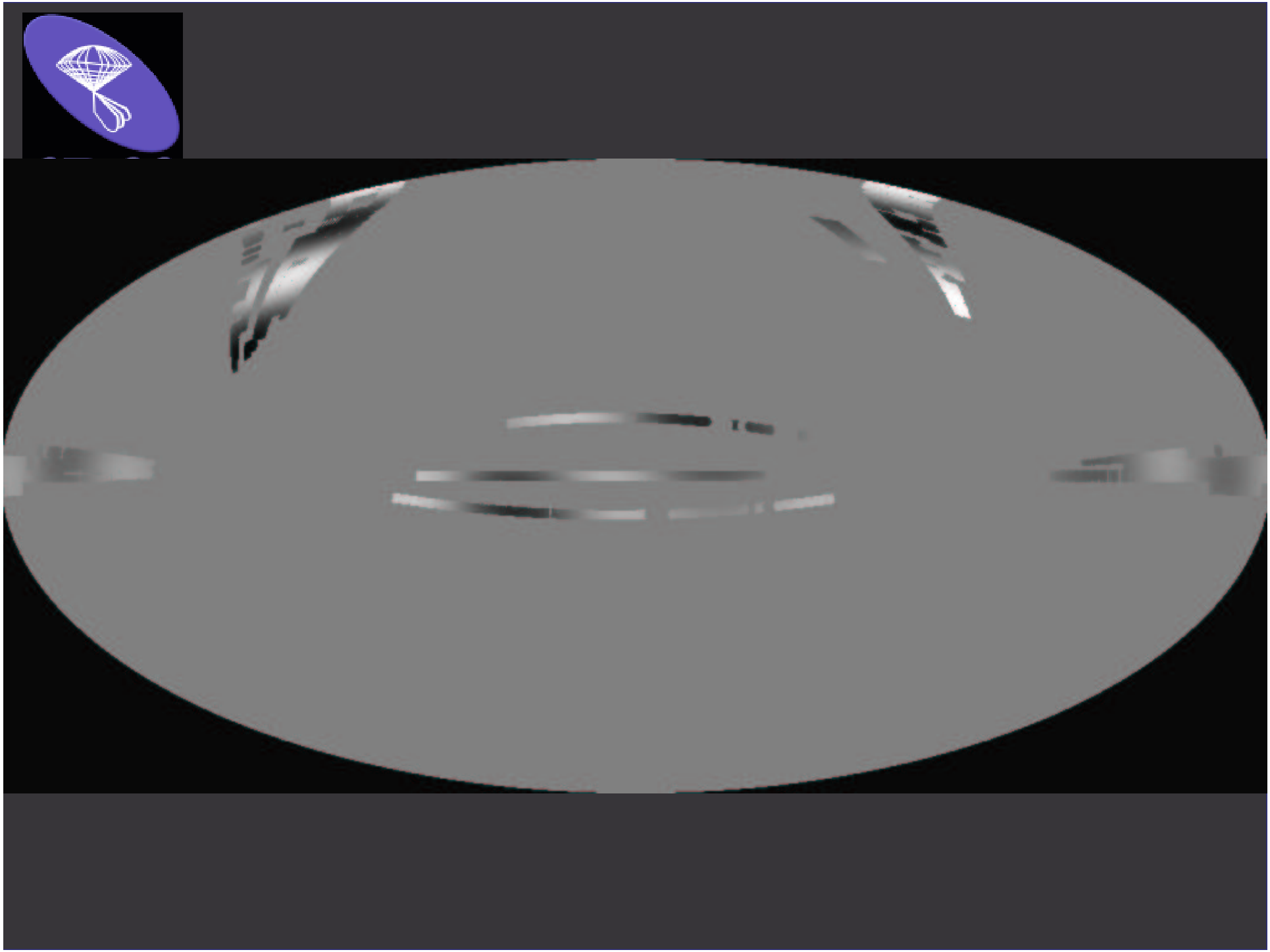

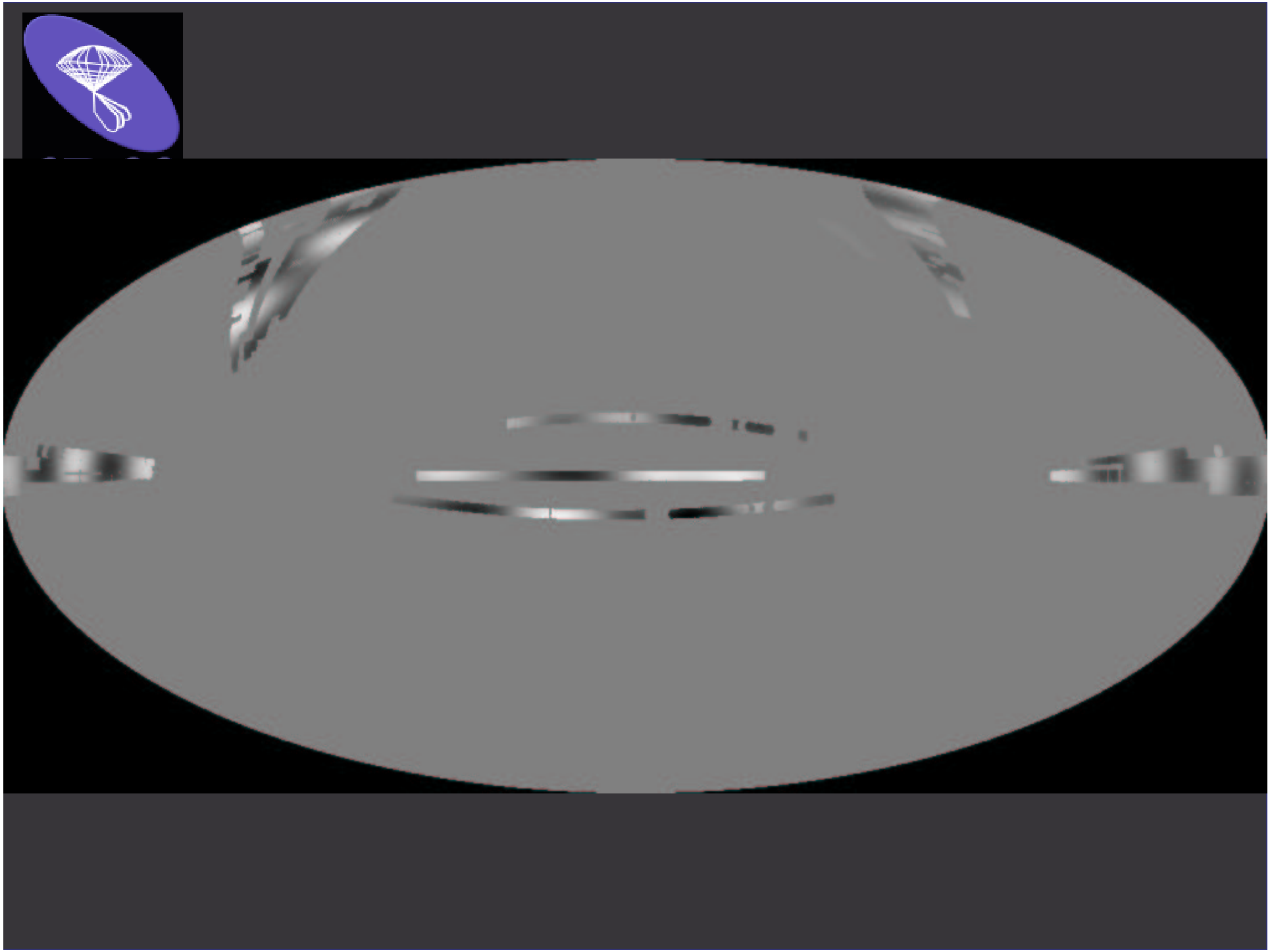

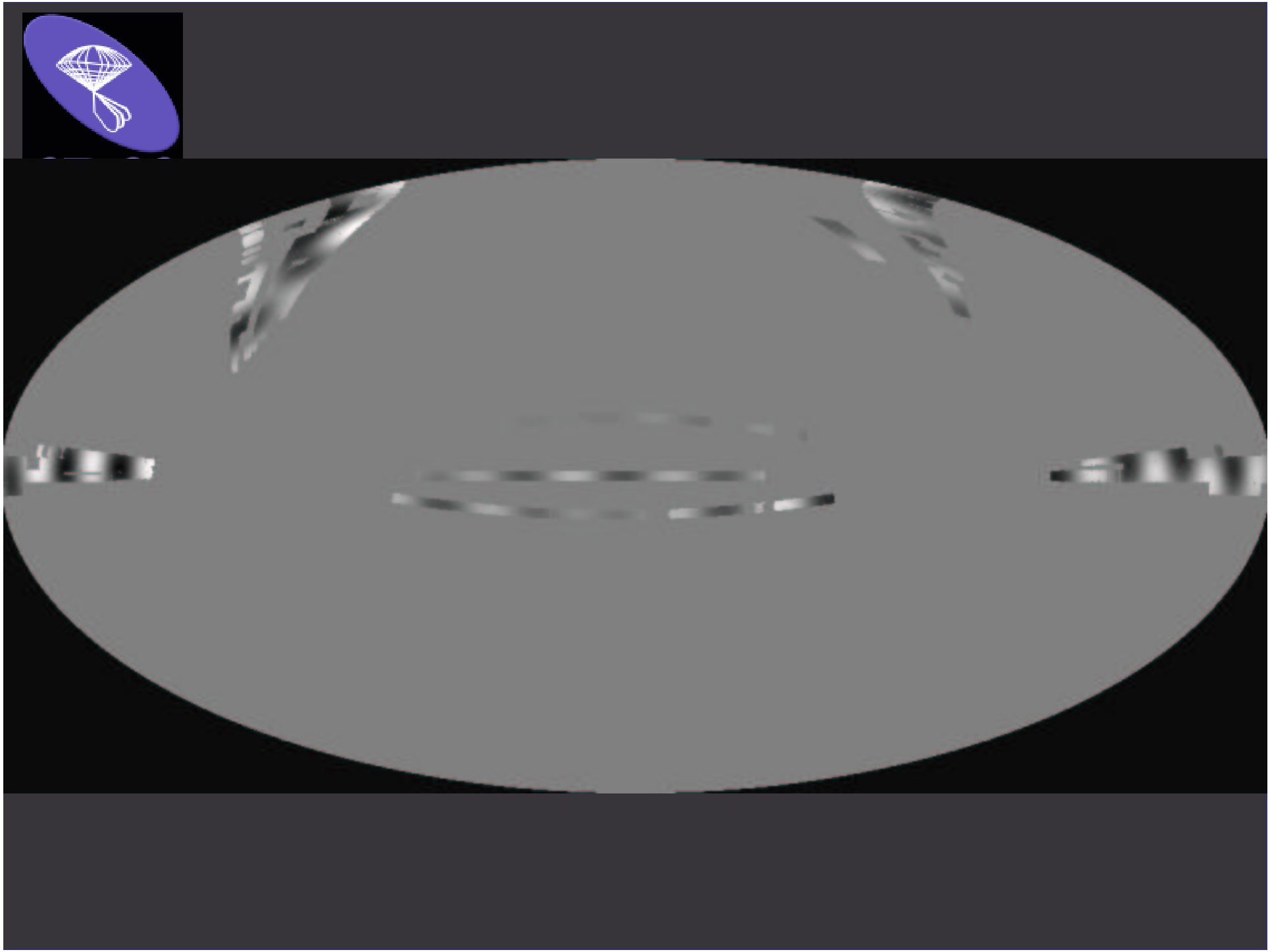

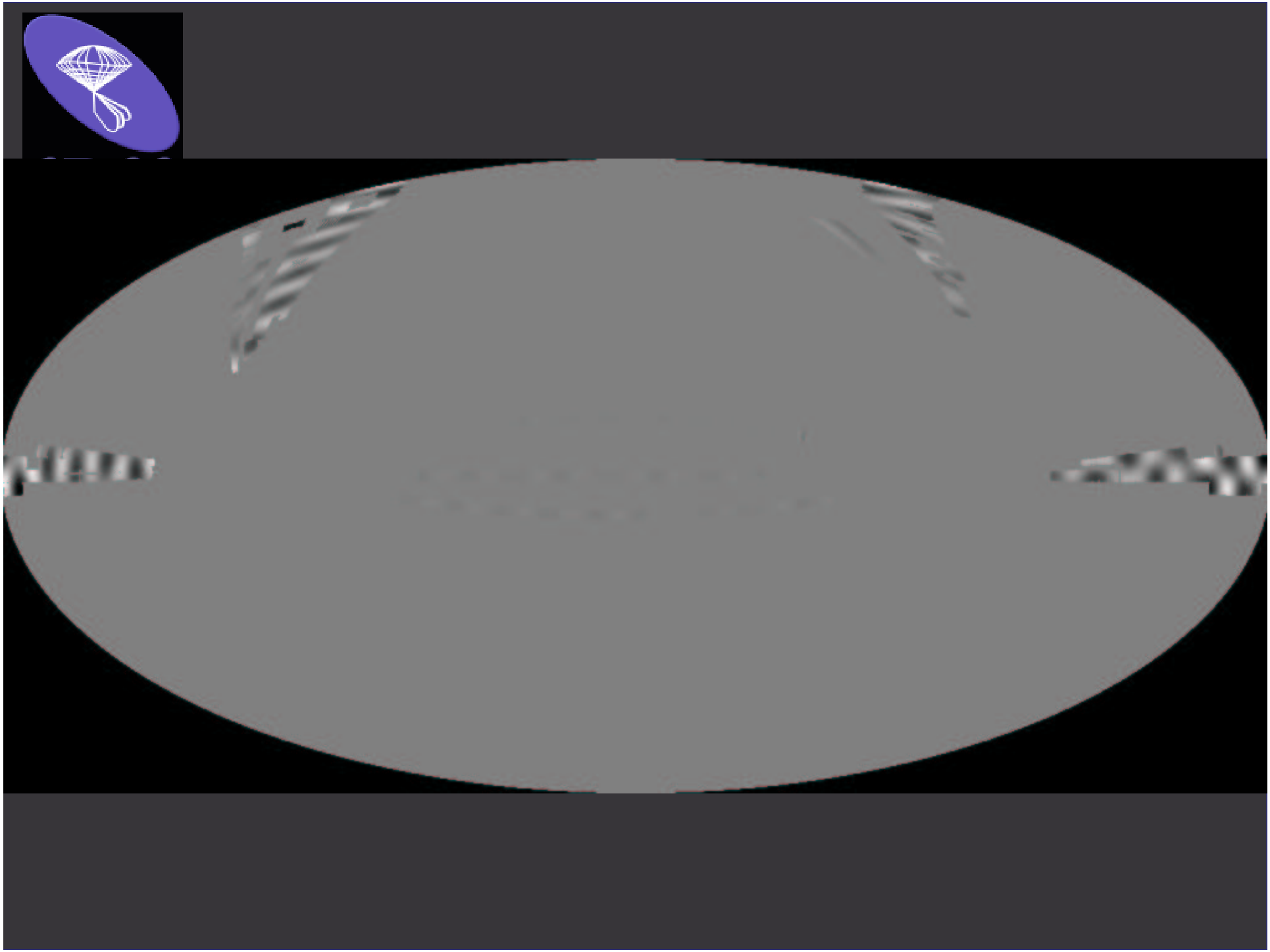

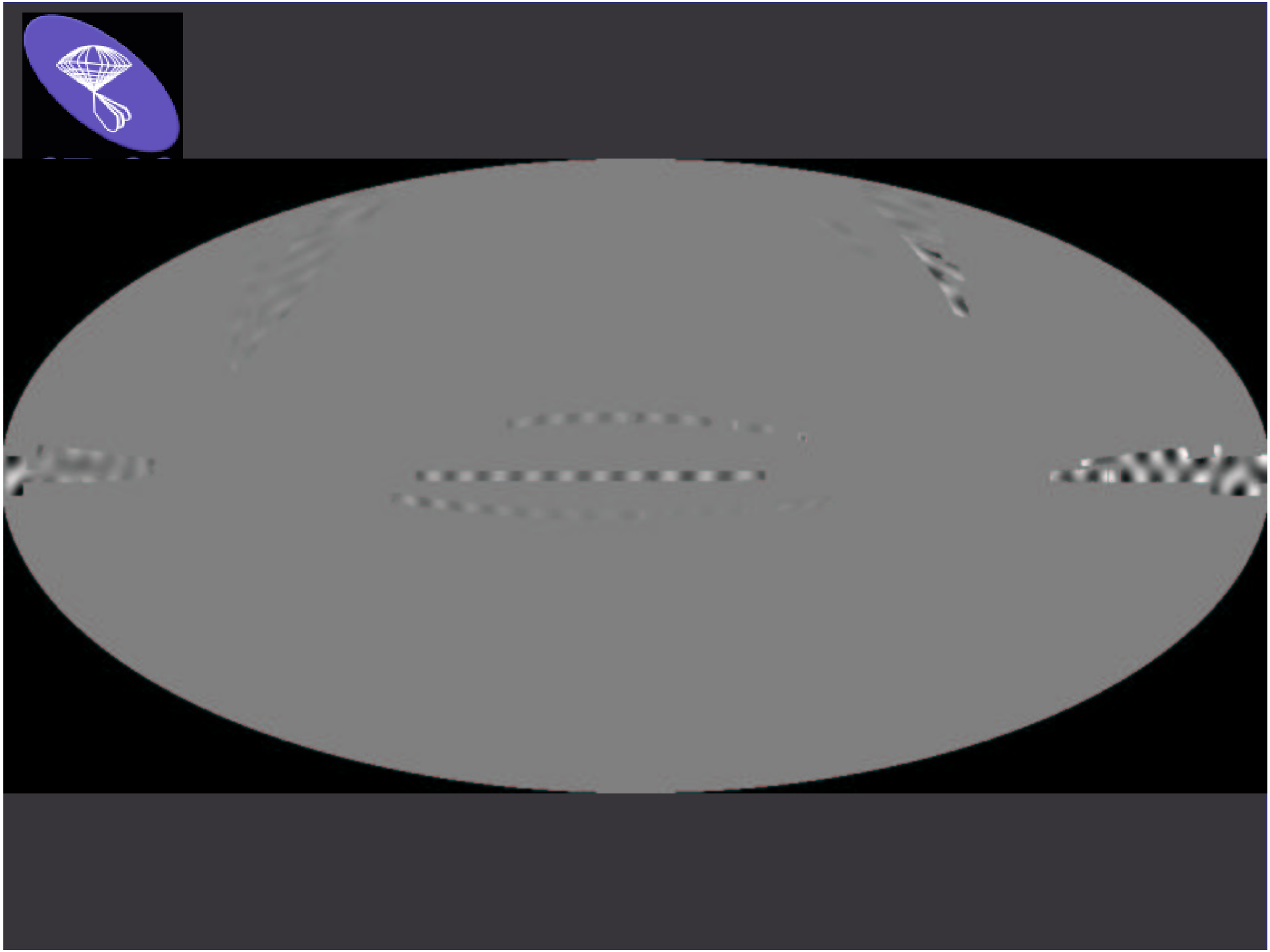

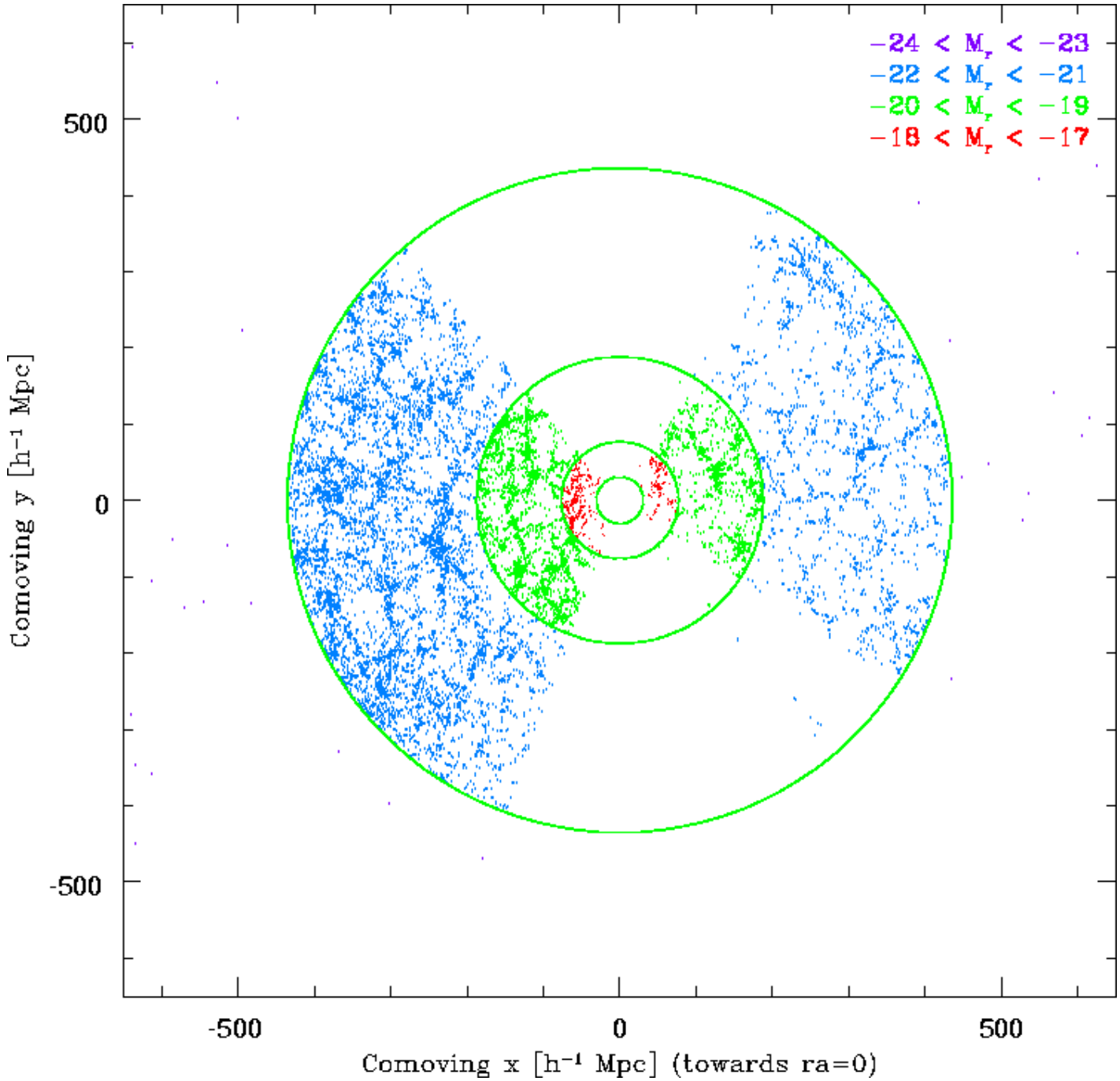

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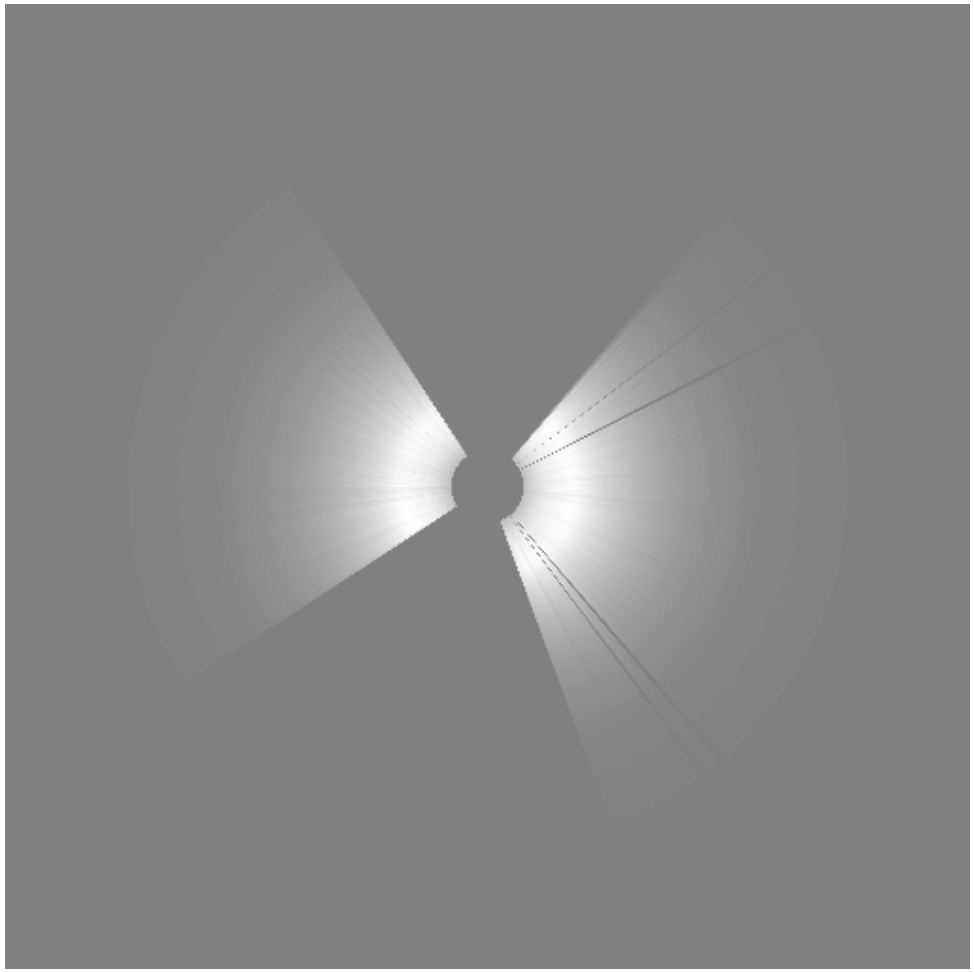

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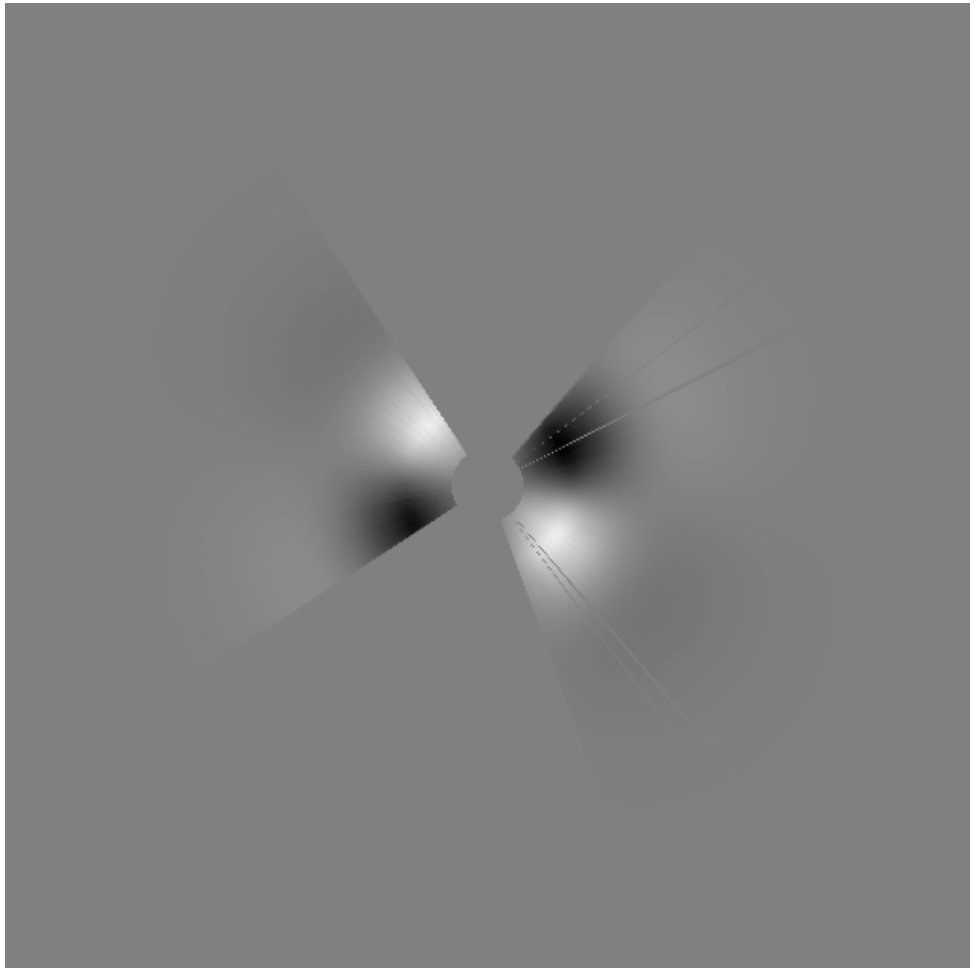

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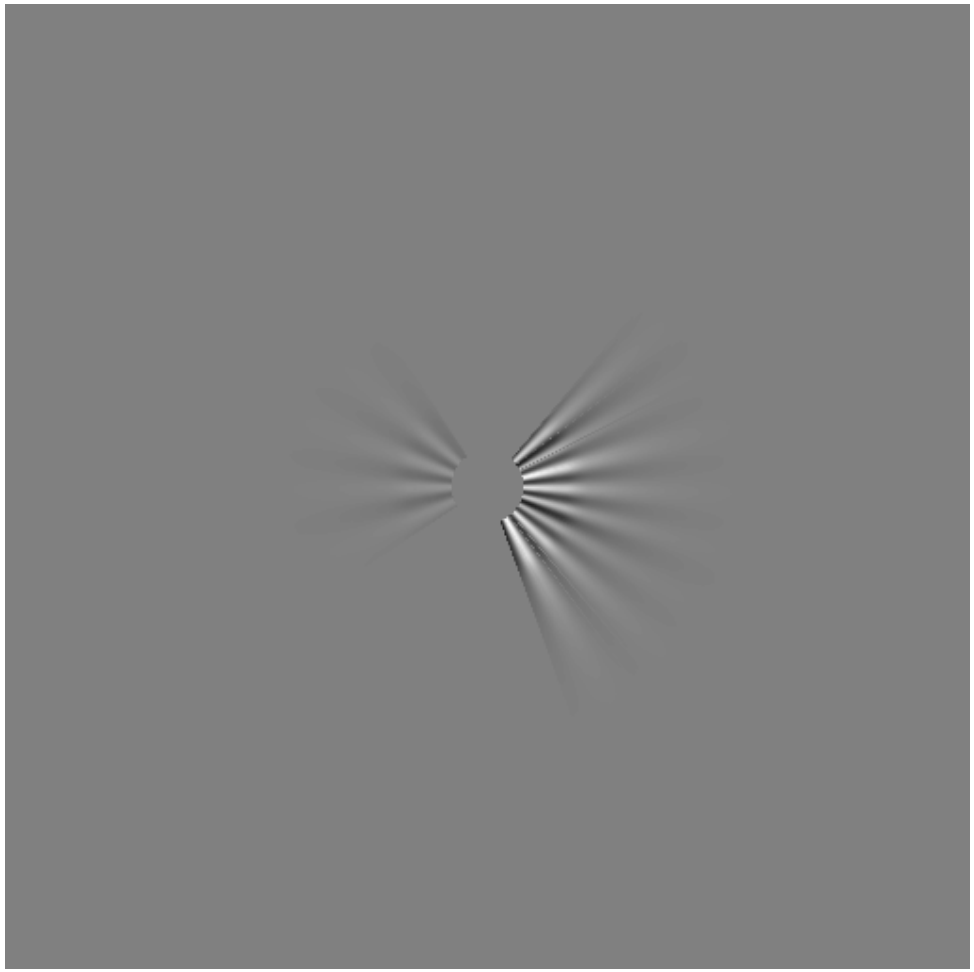

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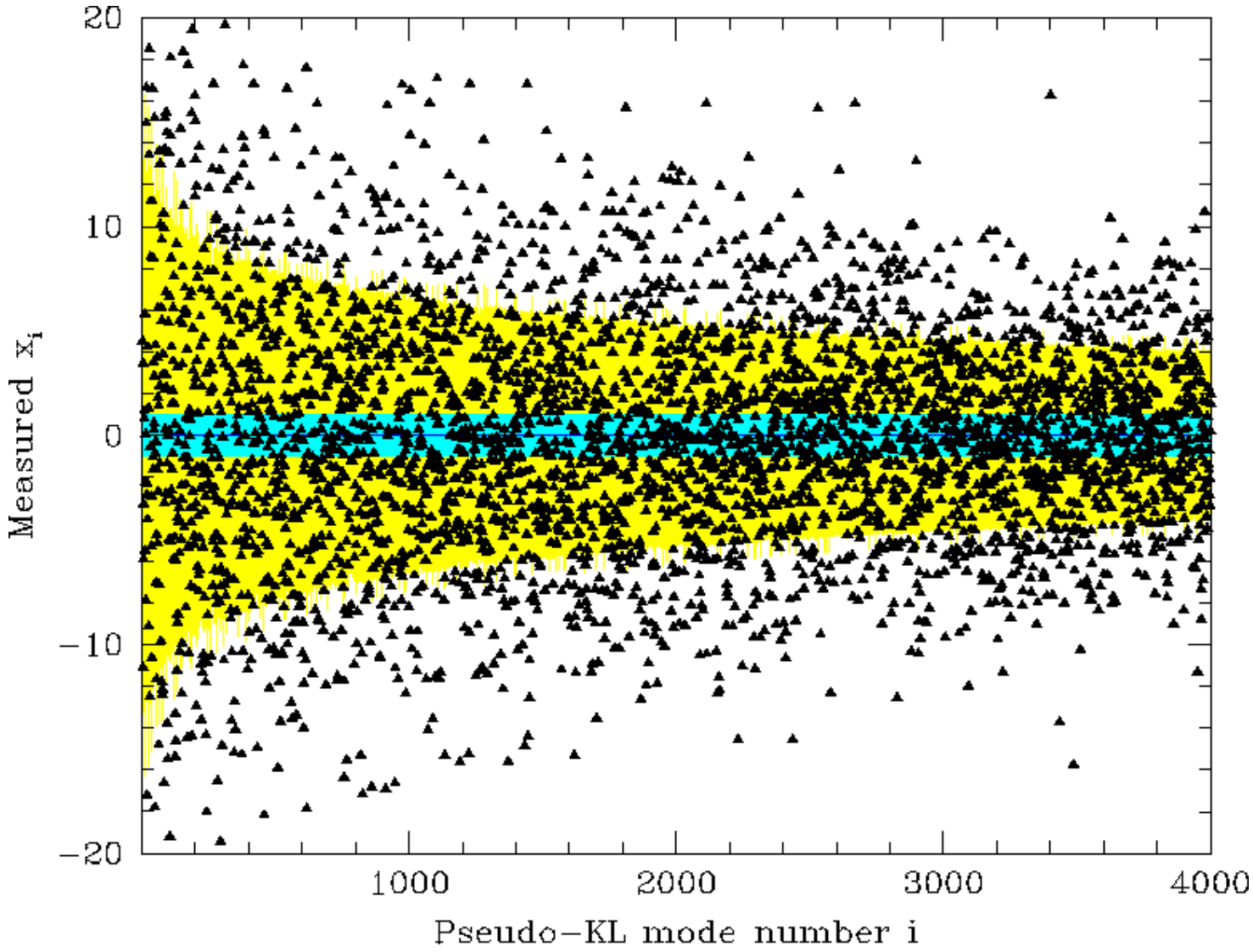

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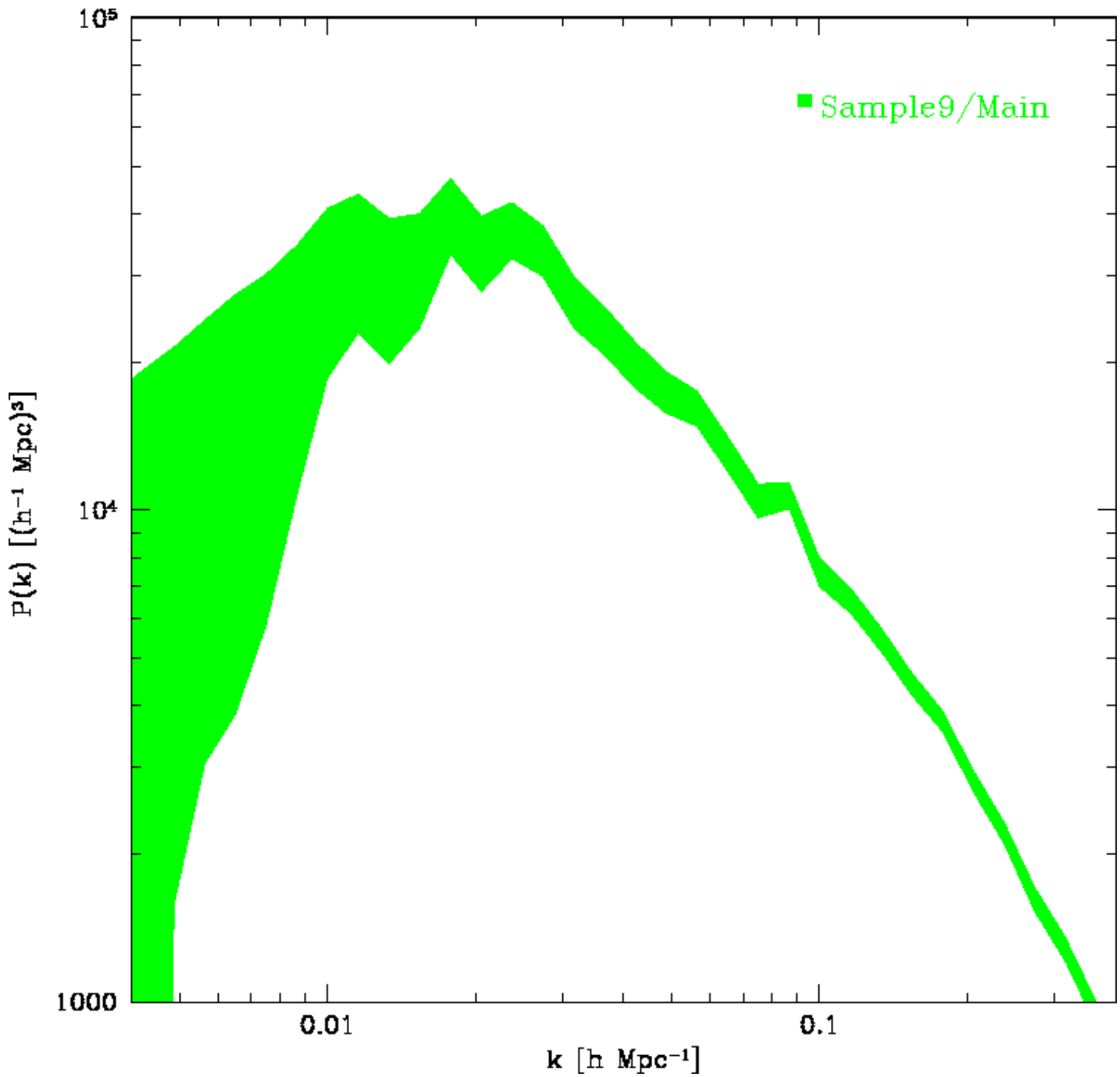
Results



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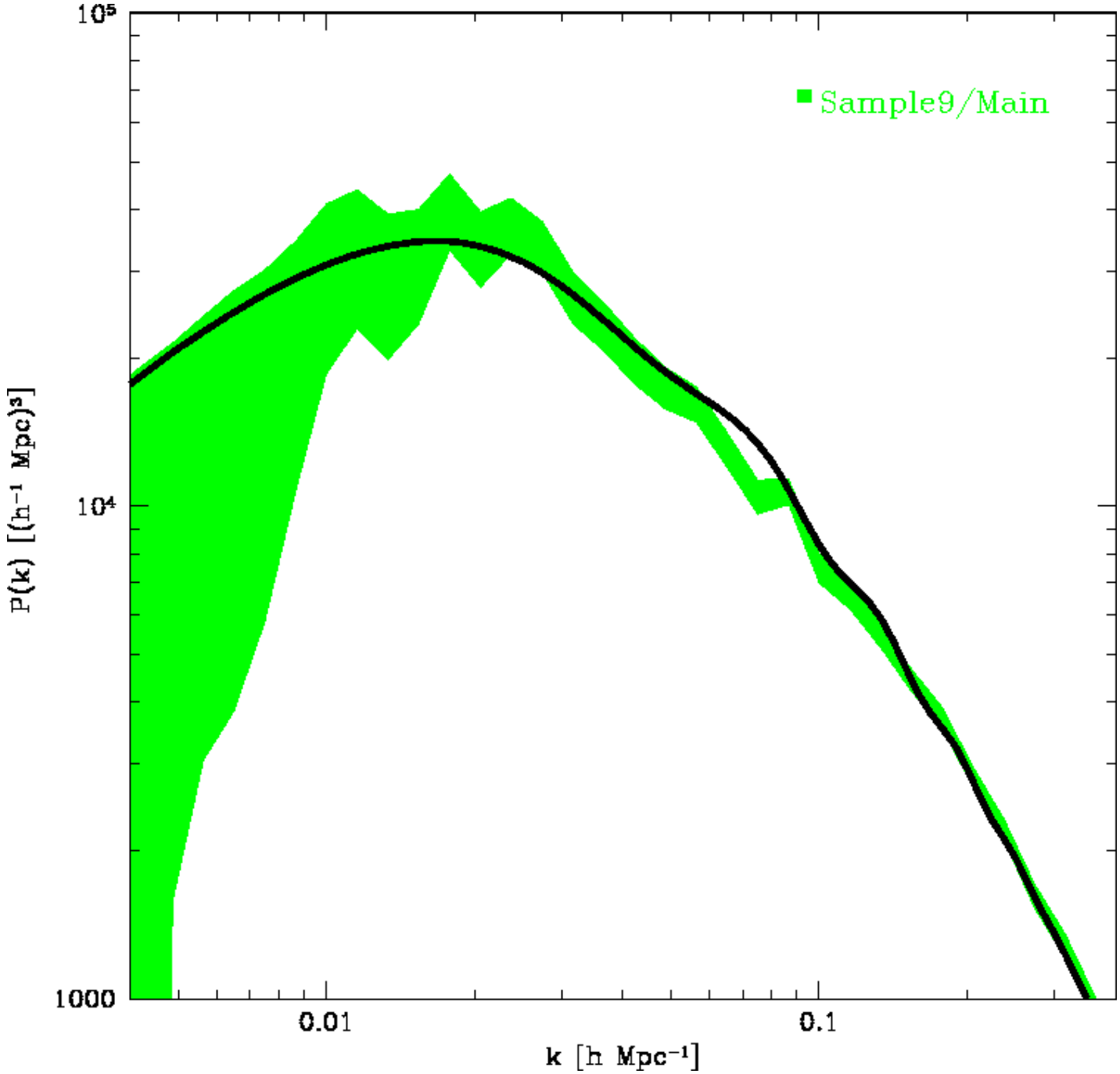

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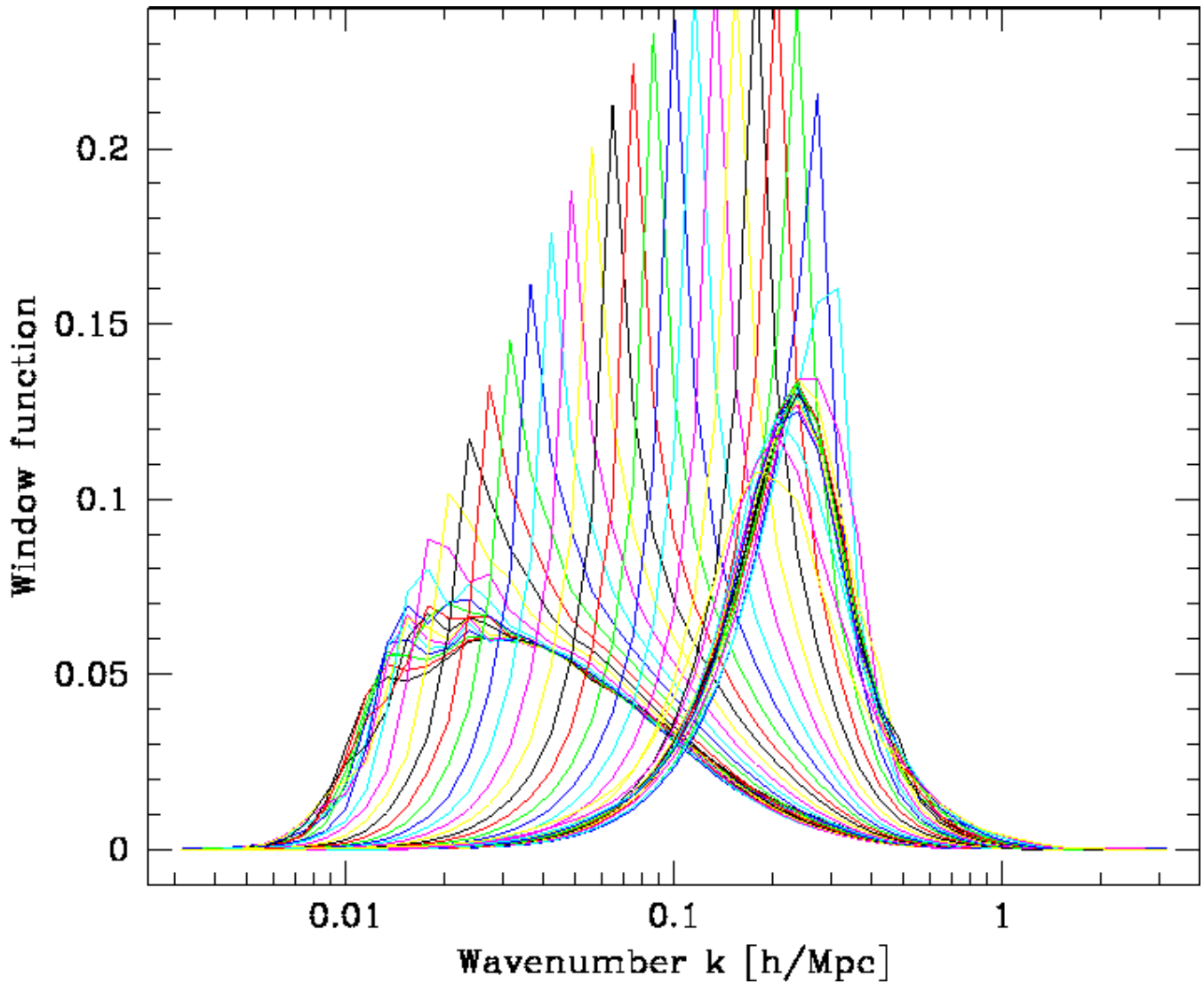

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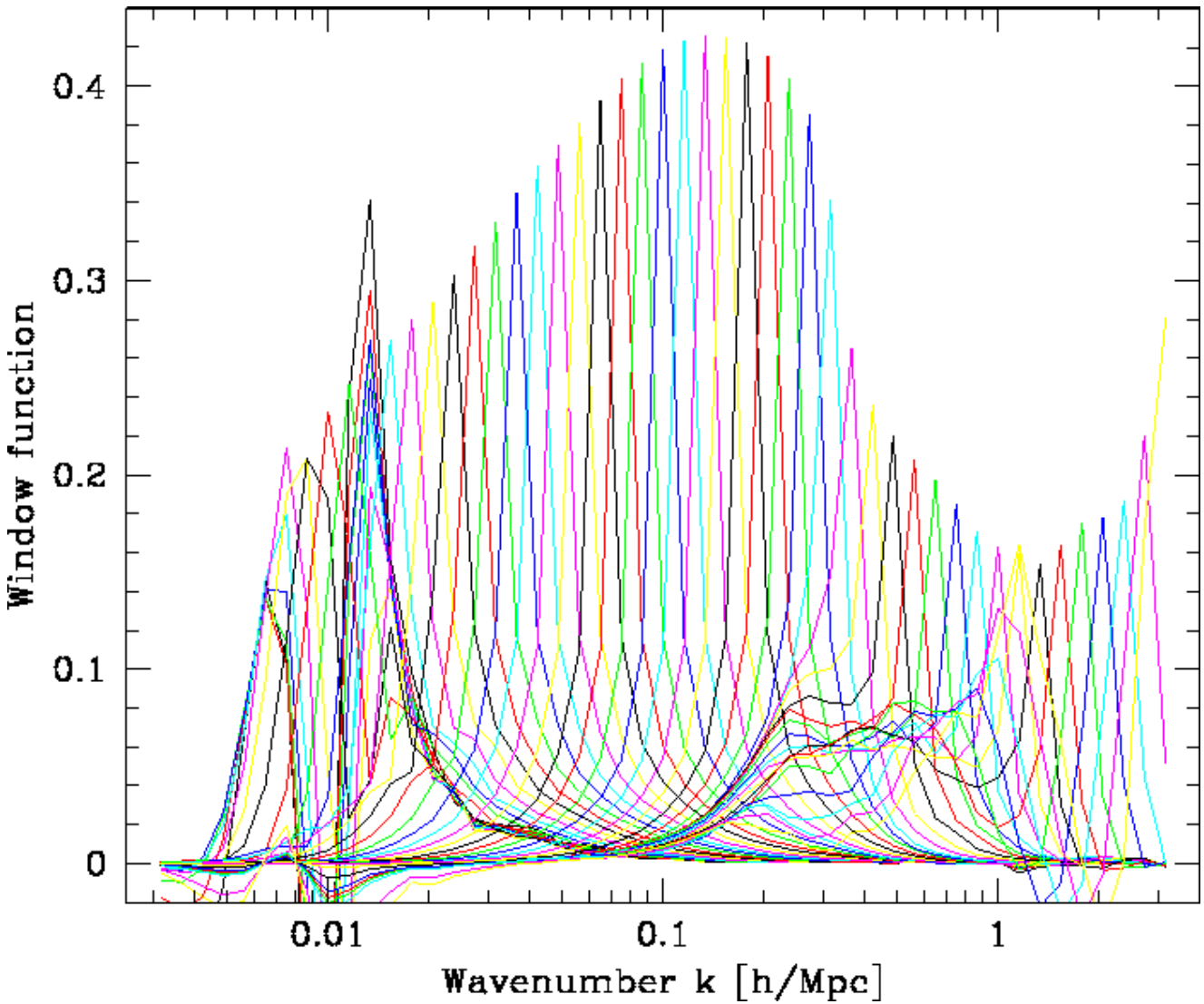

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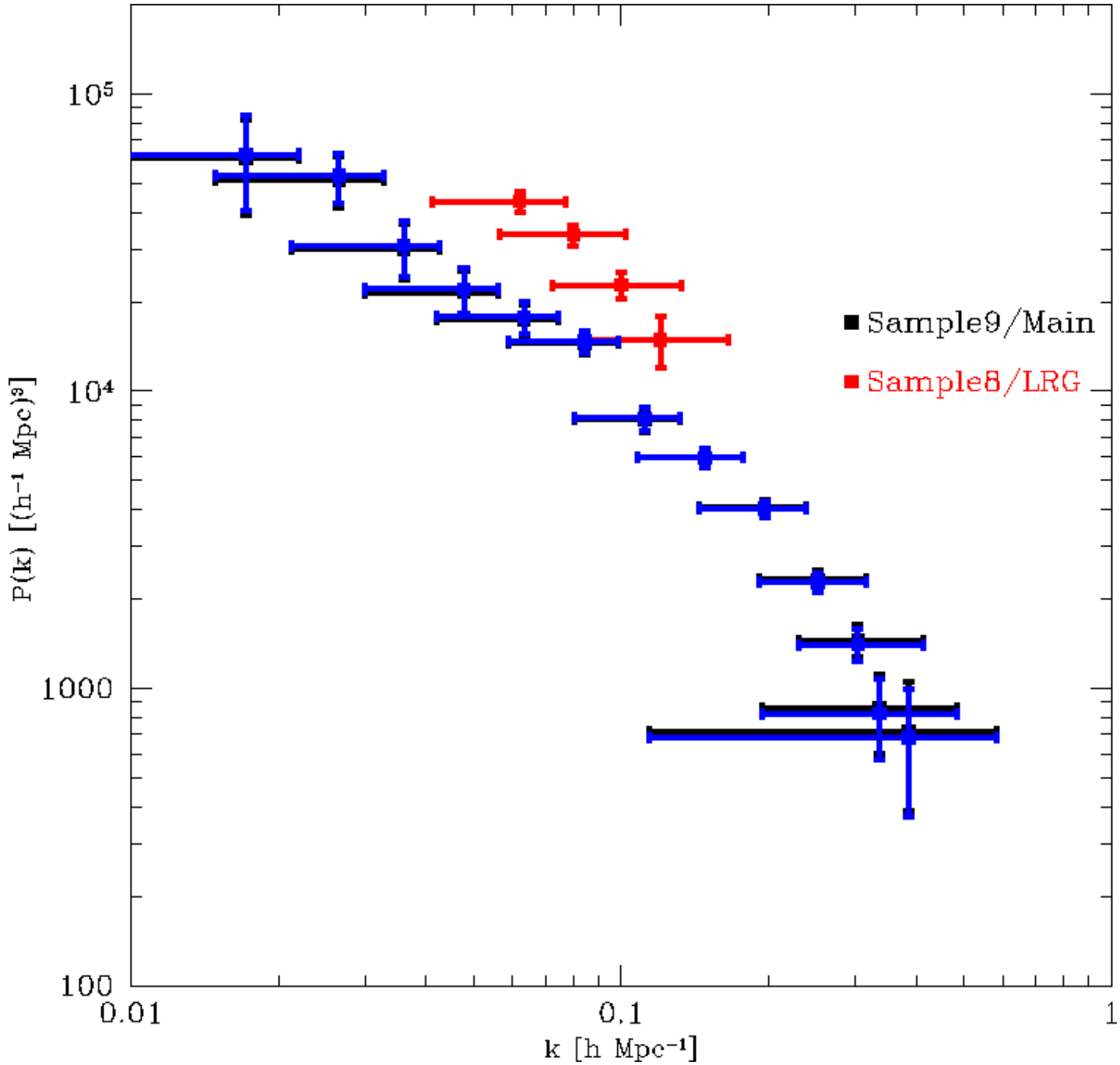

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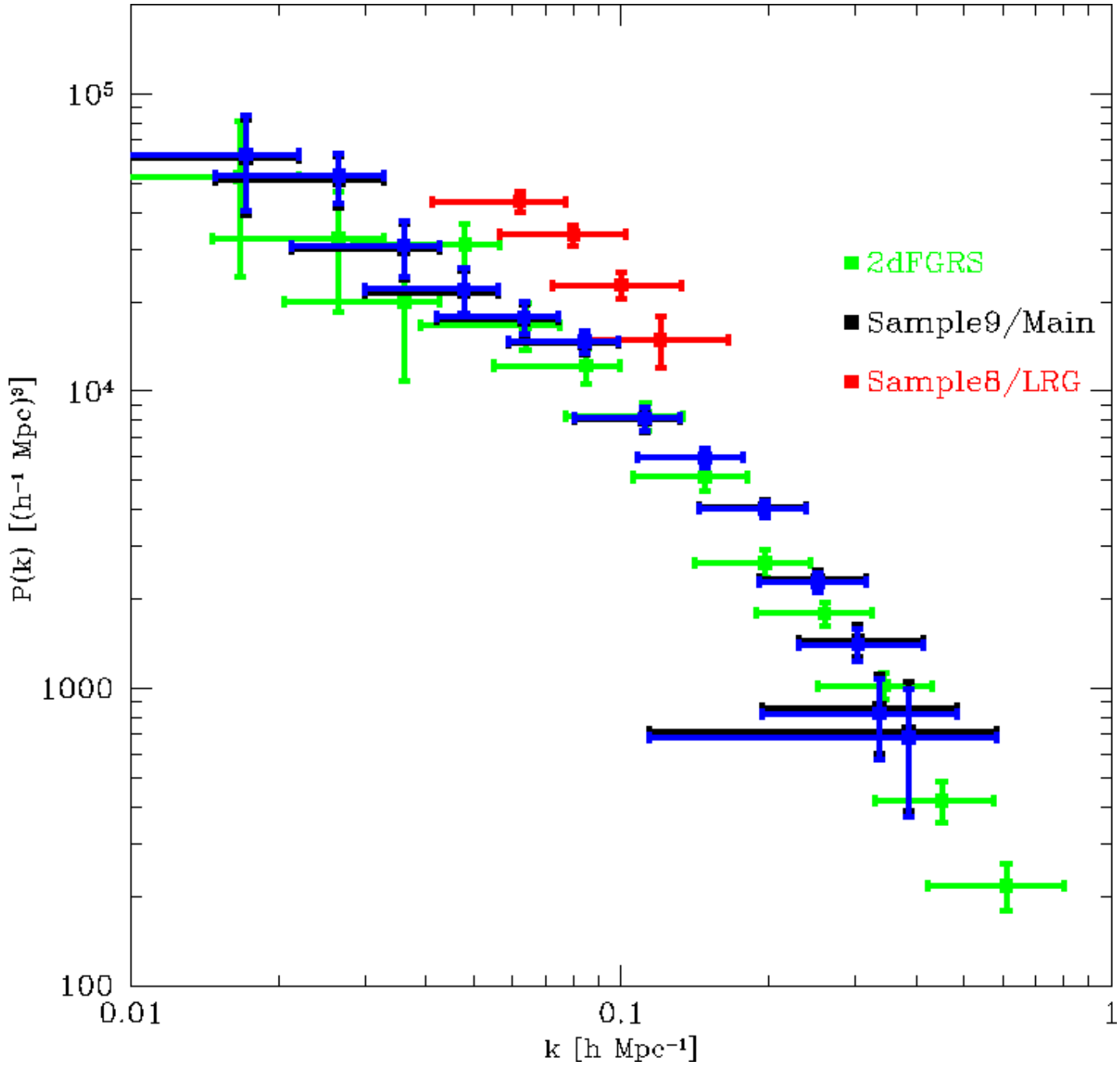

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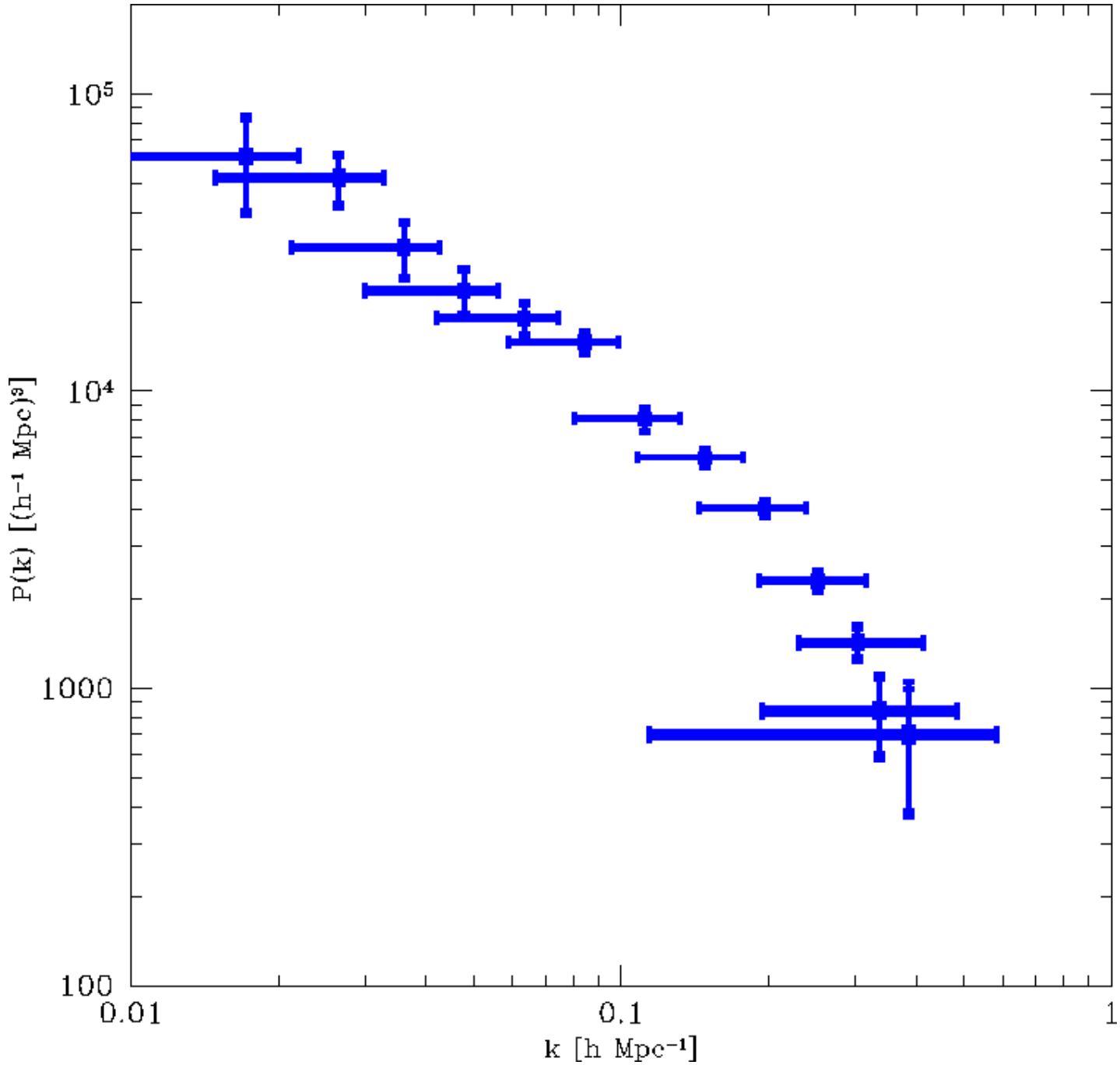

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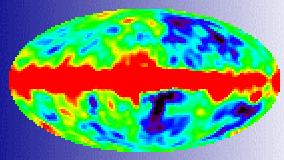
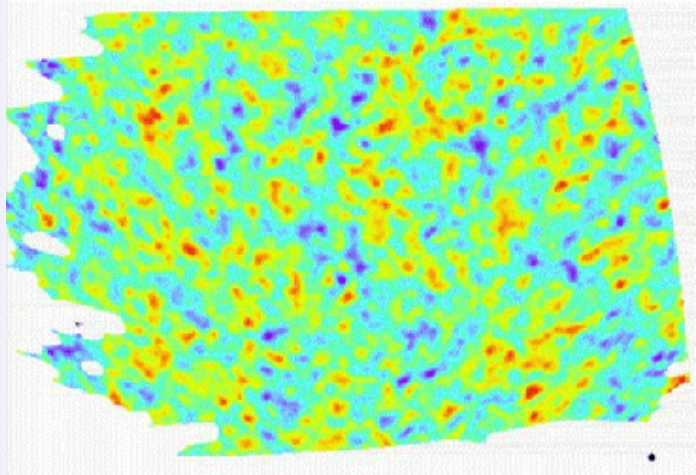
Bias

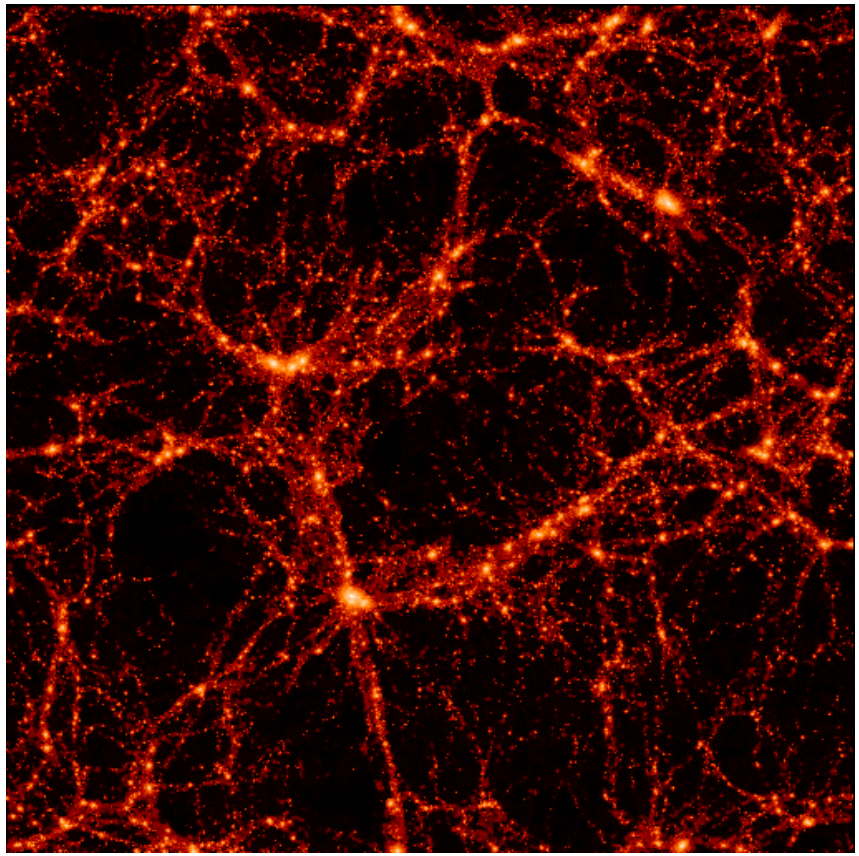


CMB

Boomerang



Virgo LCDM simulation



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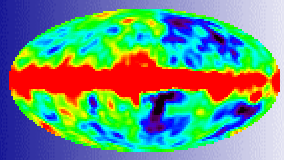

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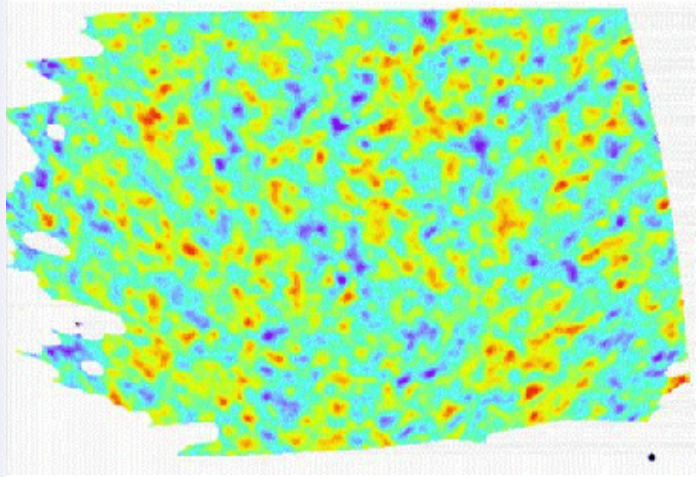
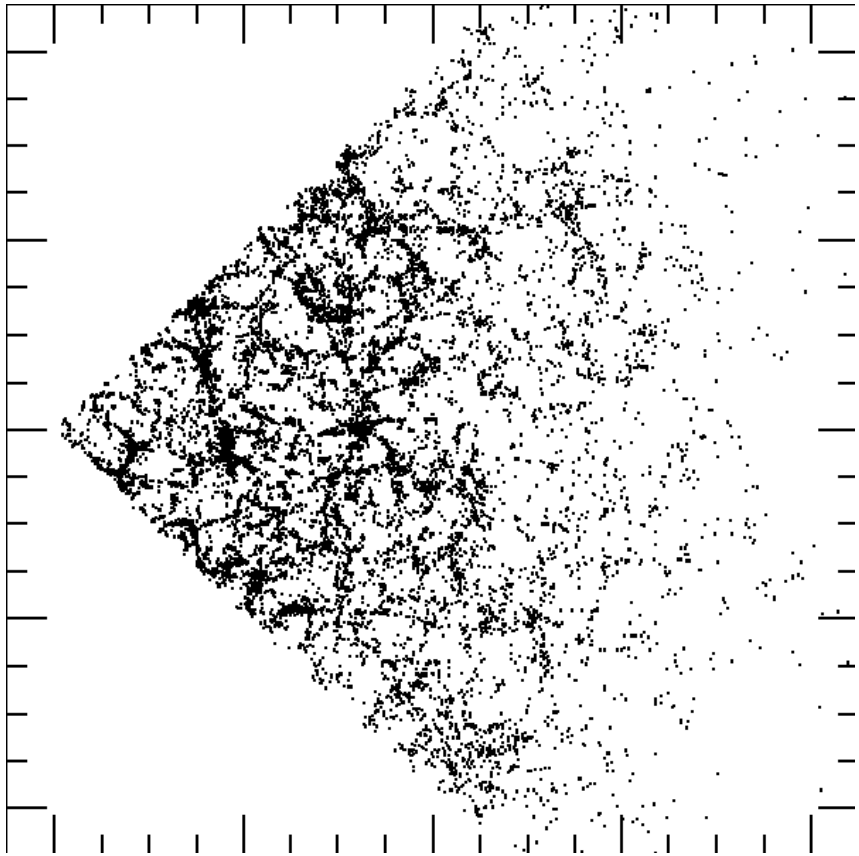


2dF galaxies



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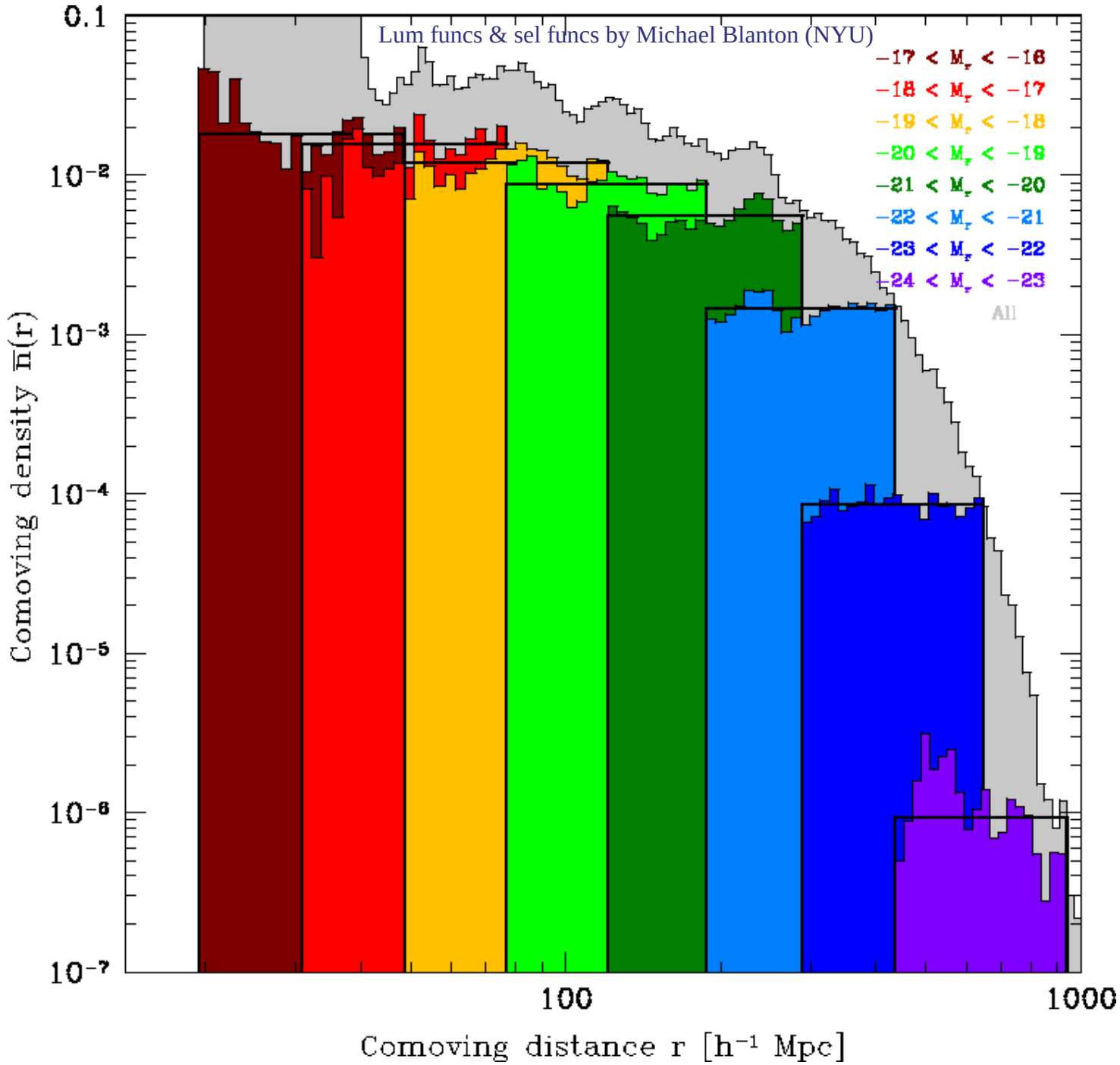

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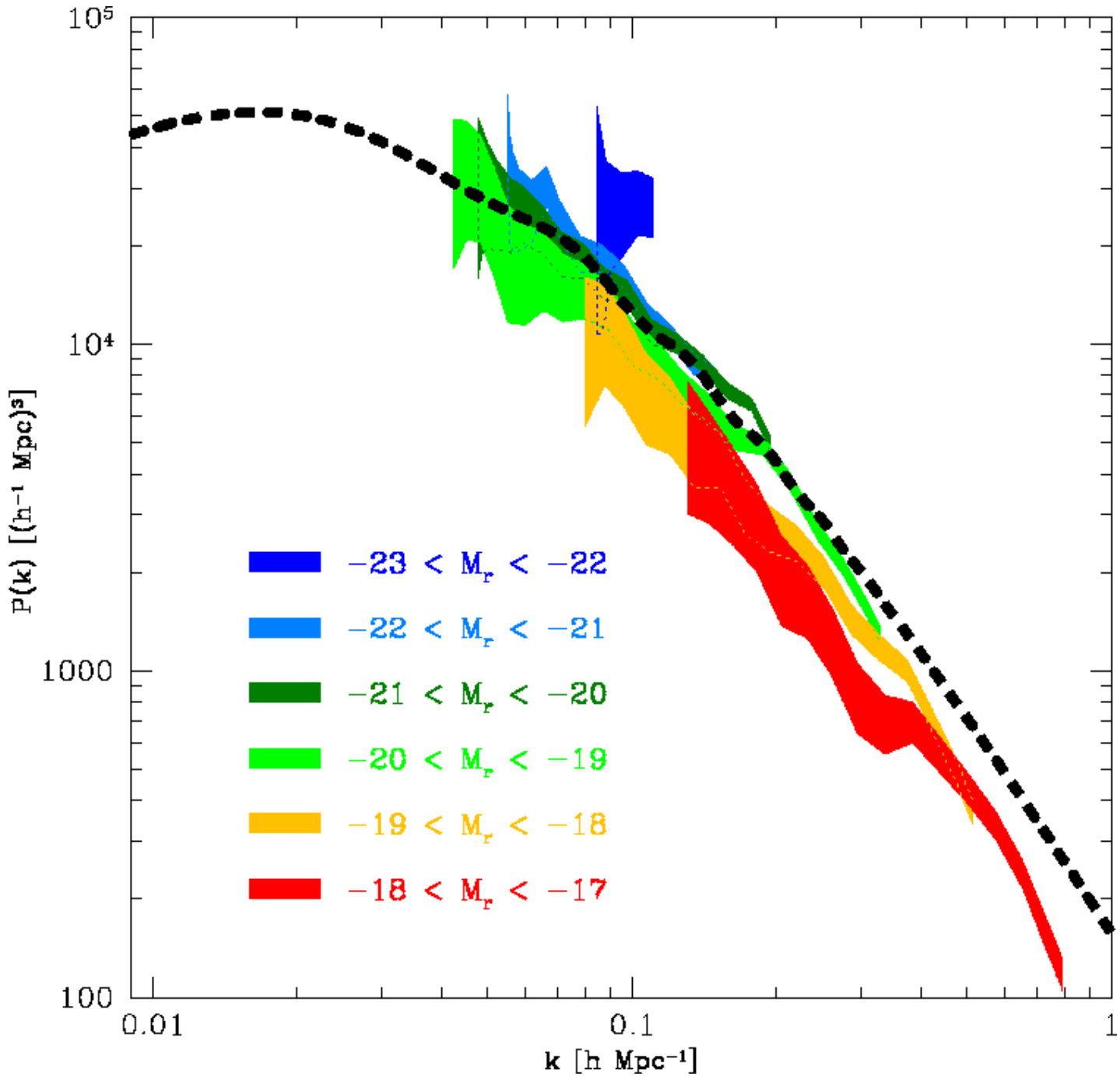

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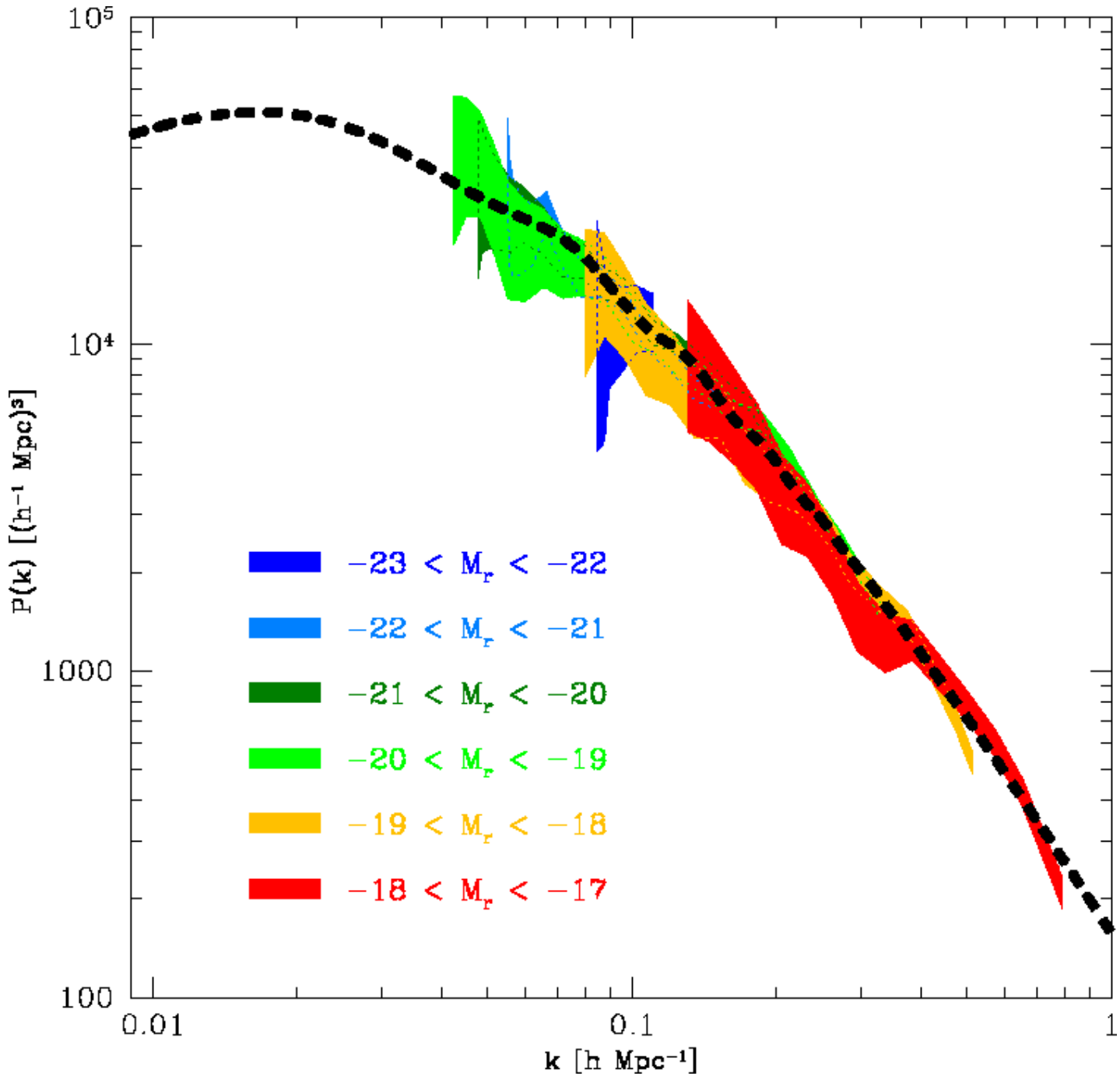

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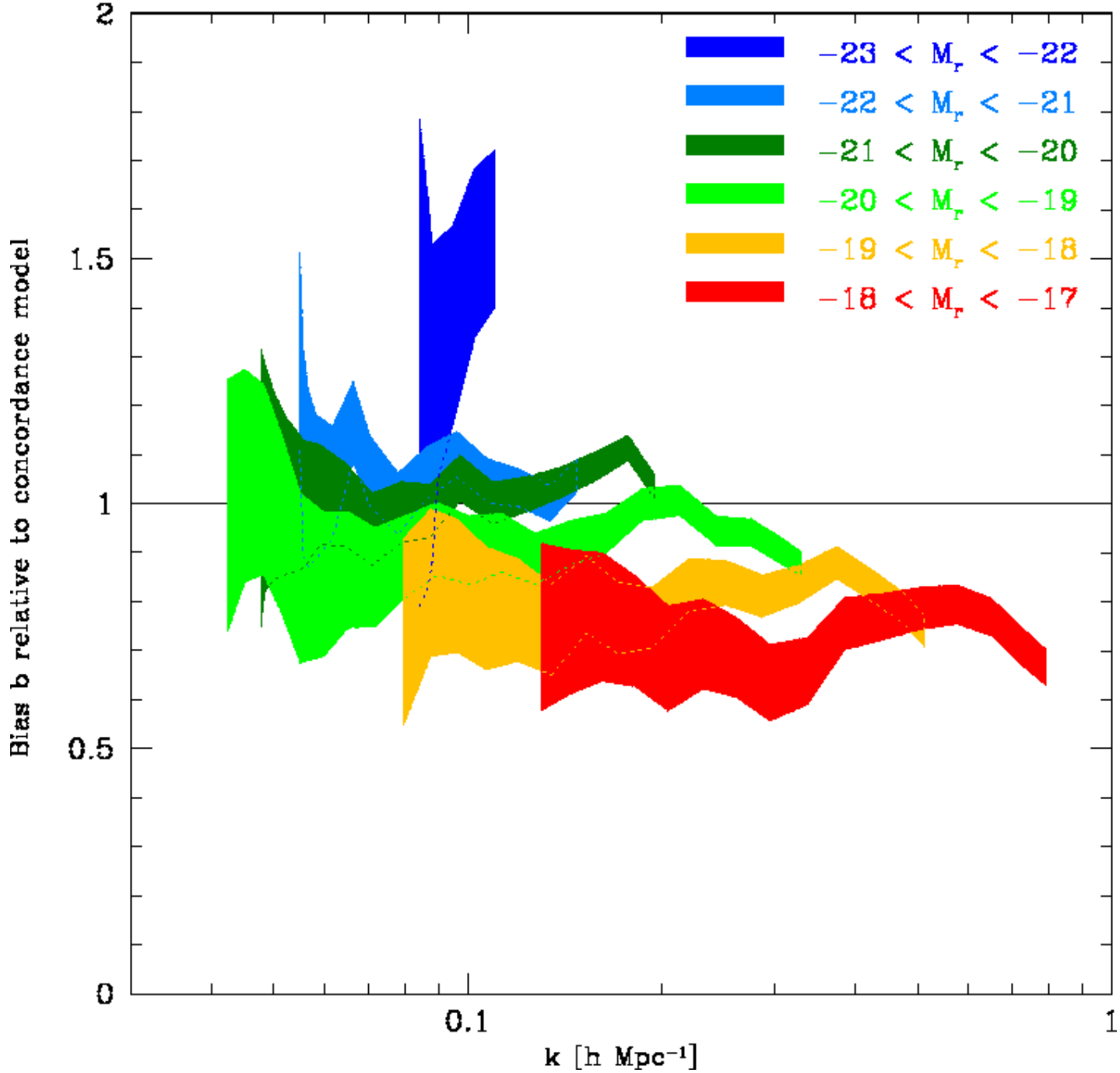

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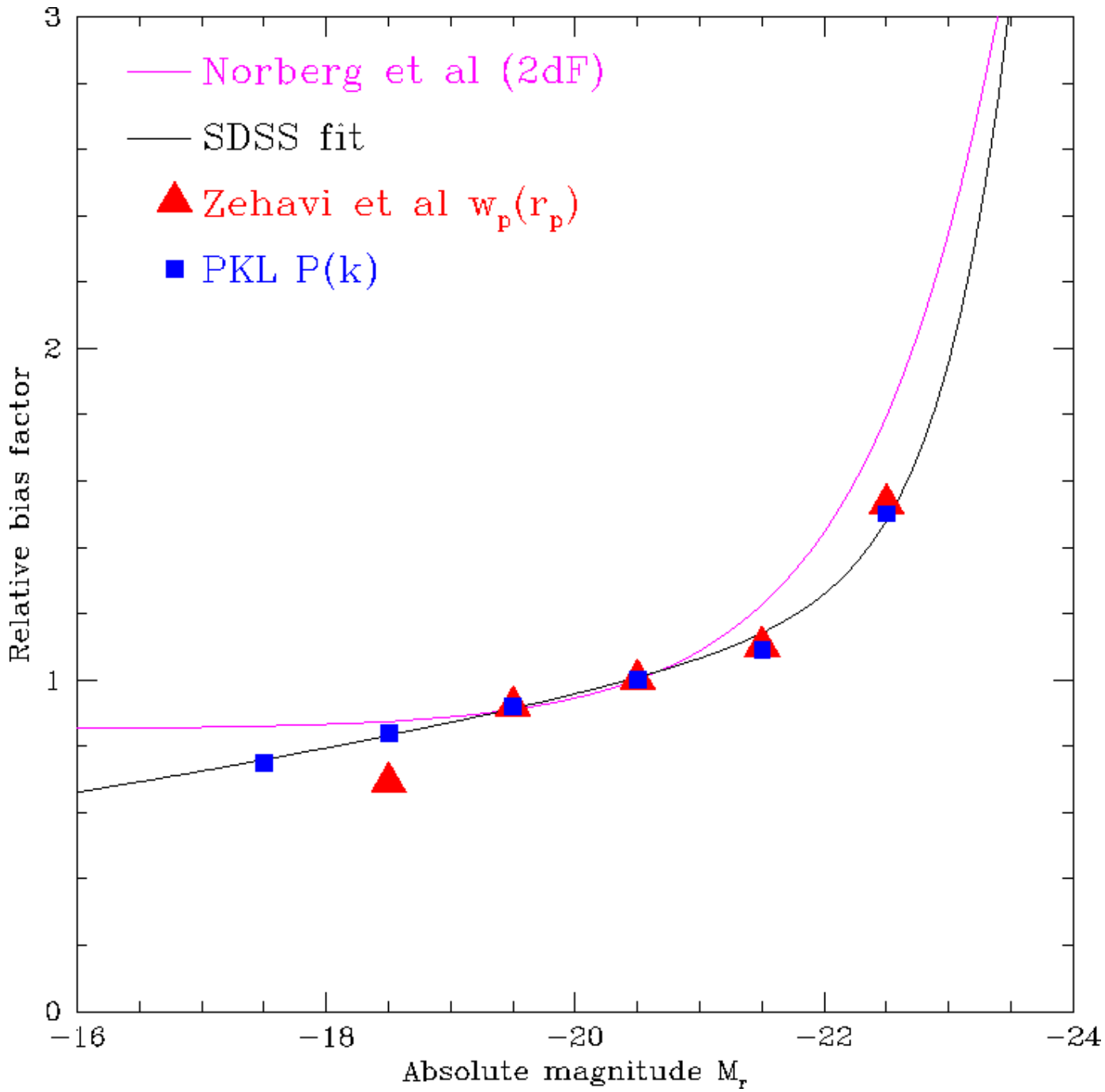

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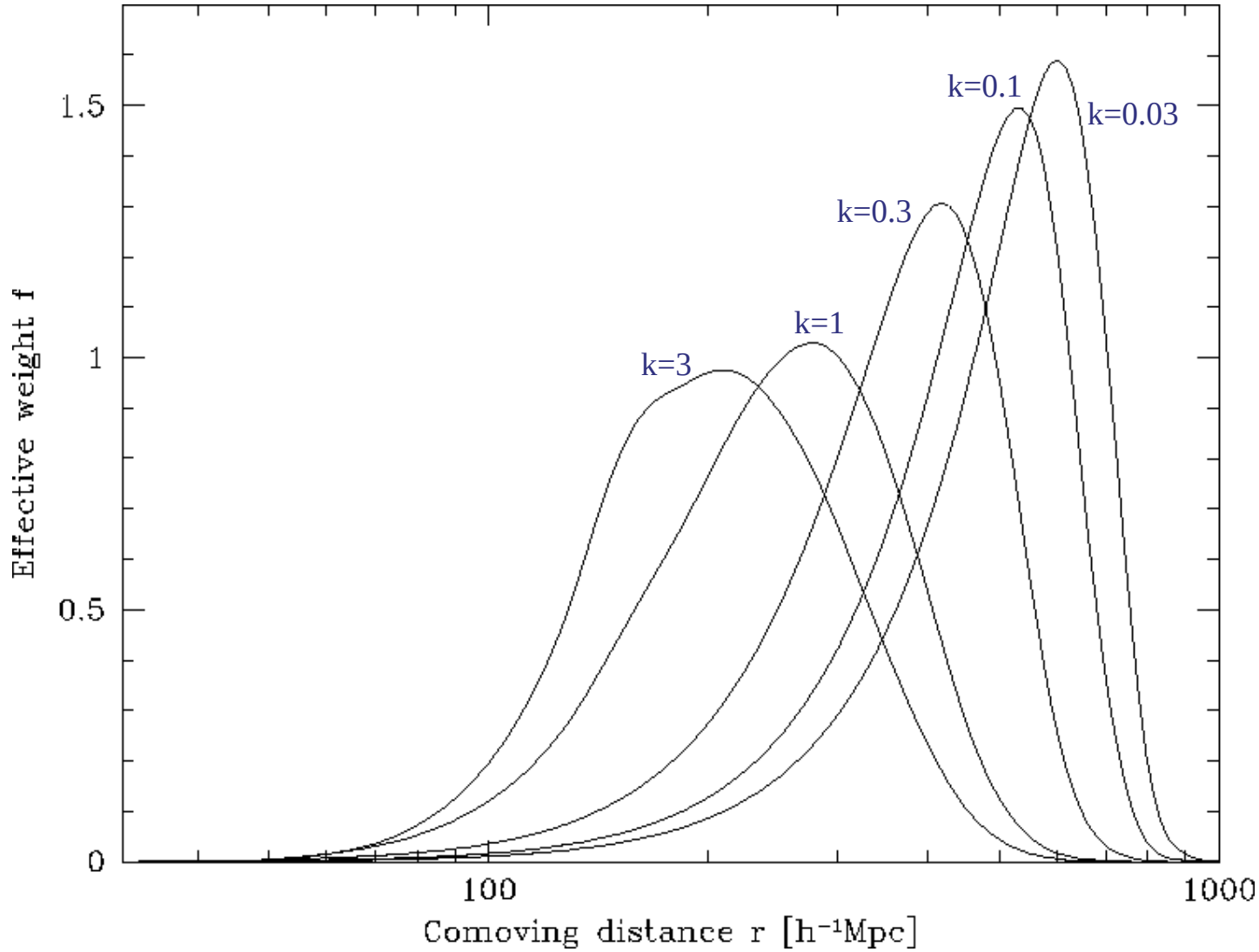

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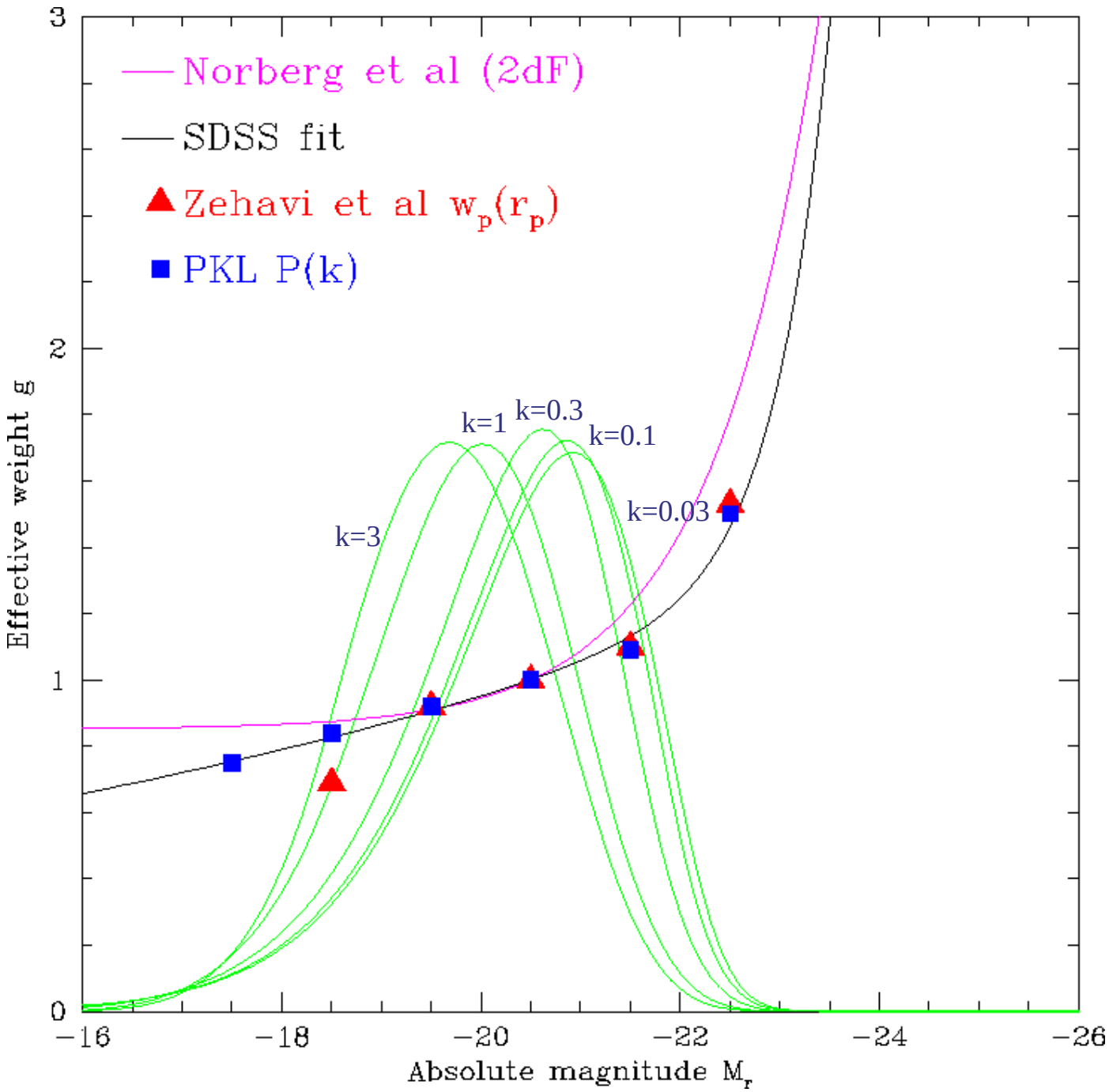

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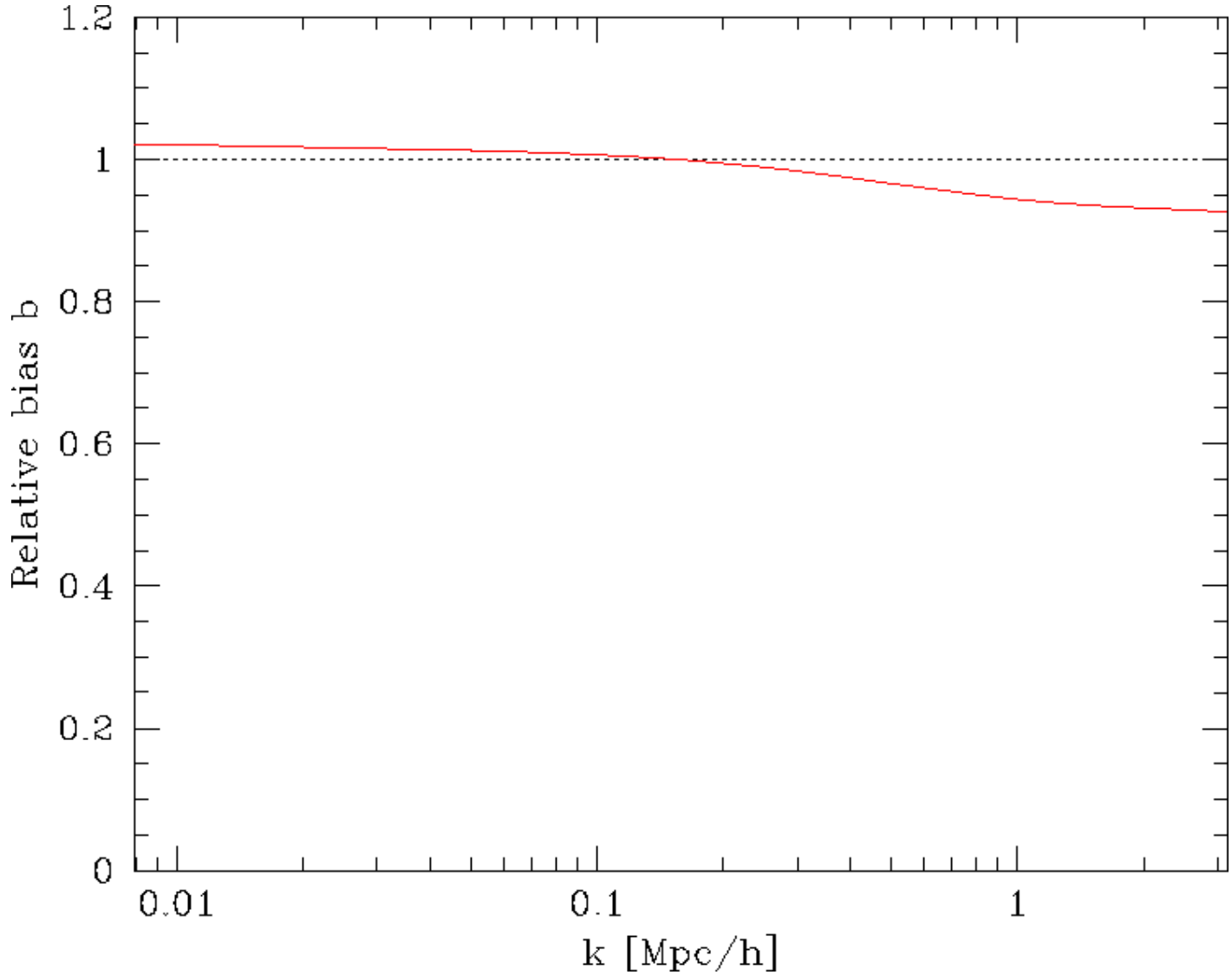

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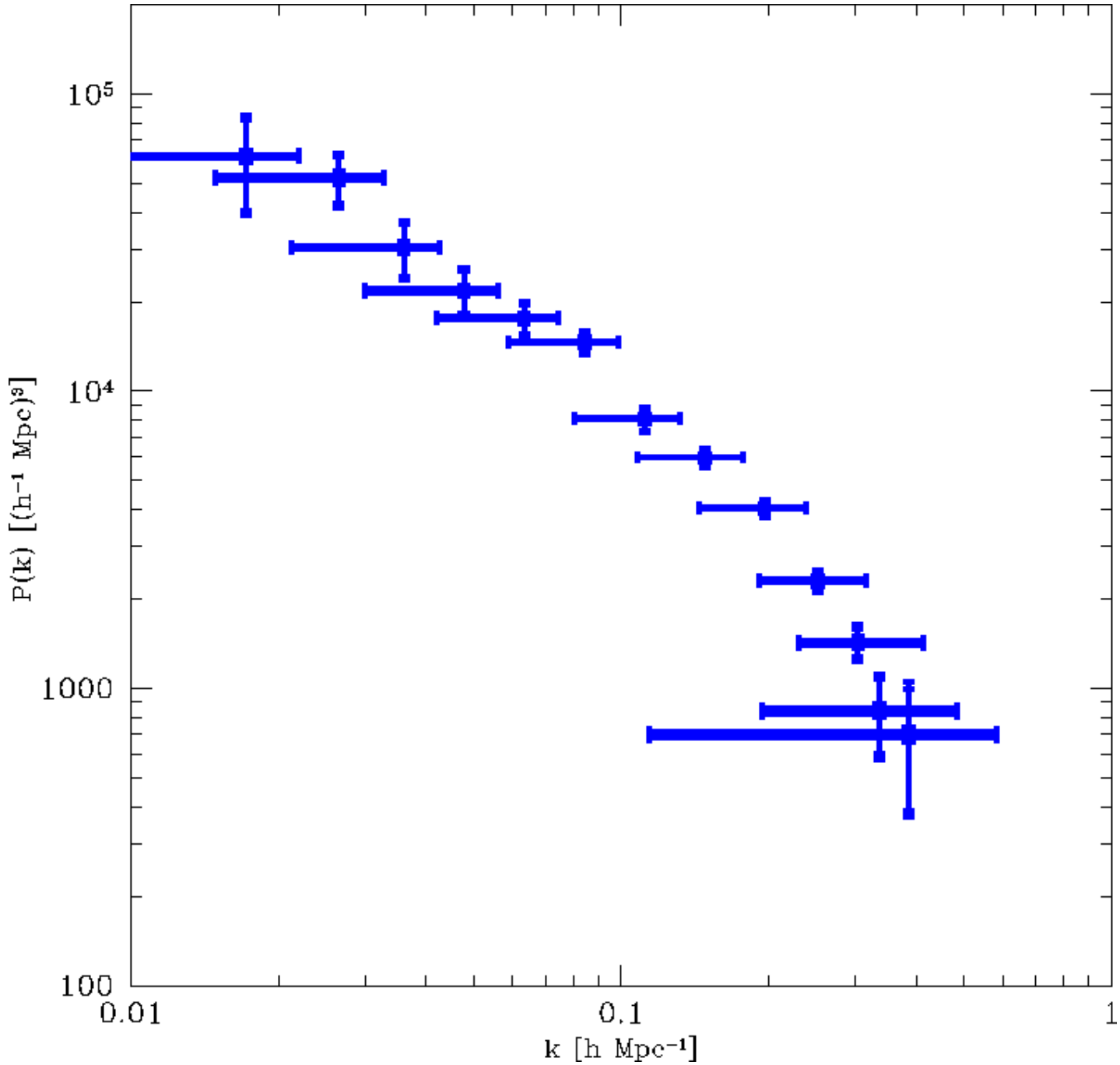

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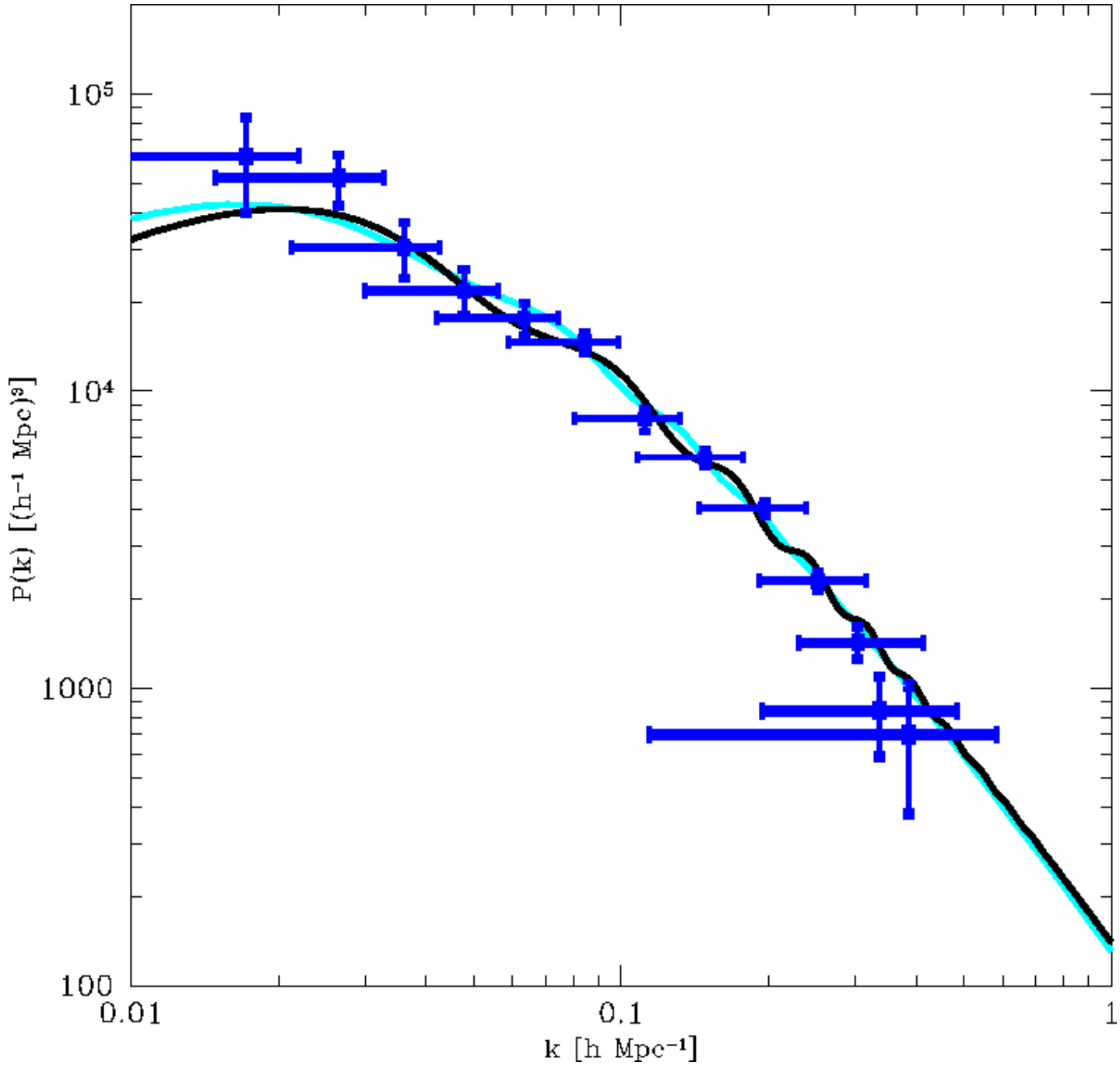
Here there be wiggles?



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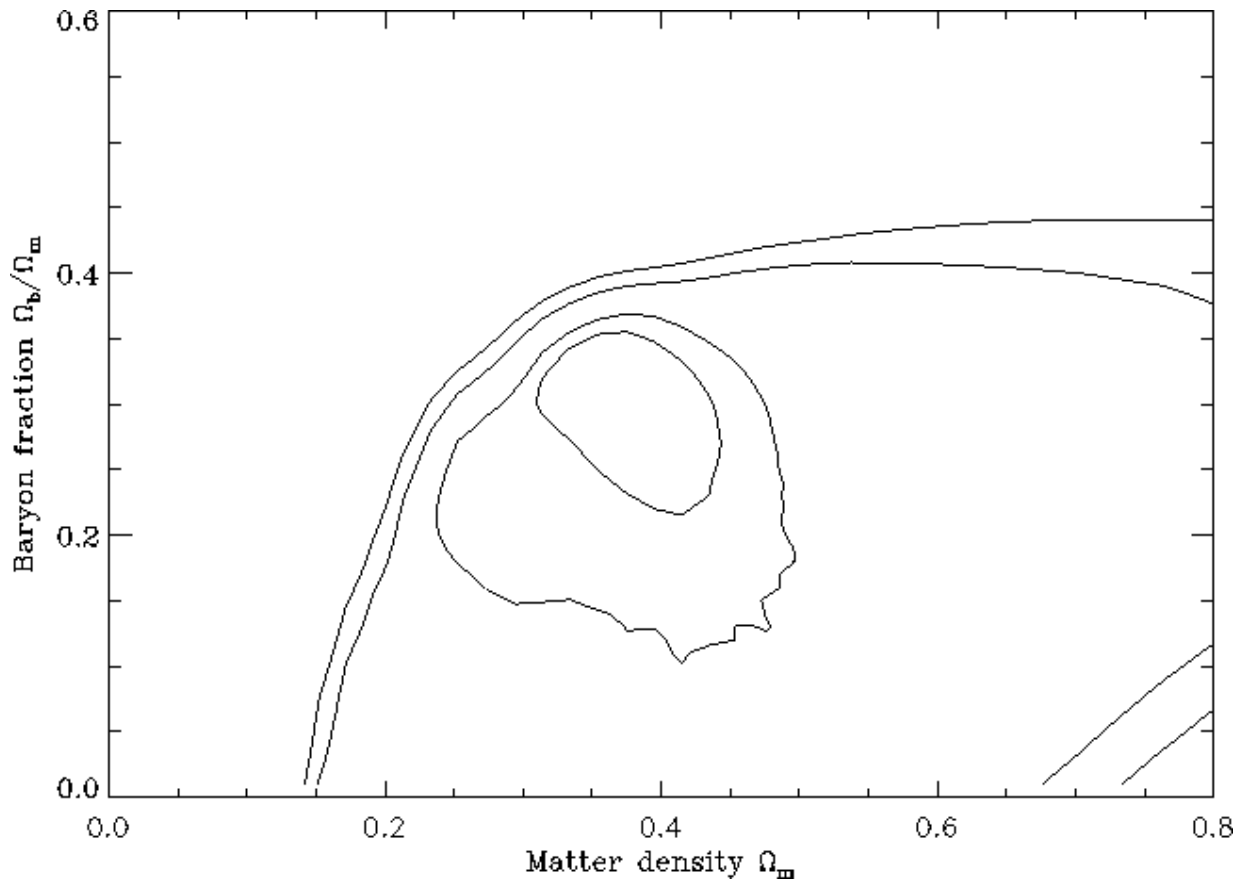
Prior: n=1



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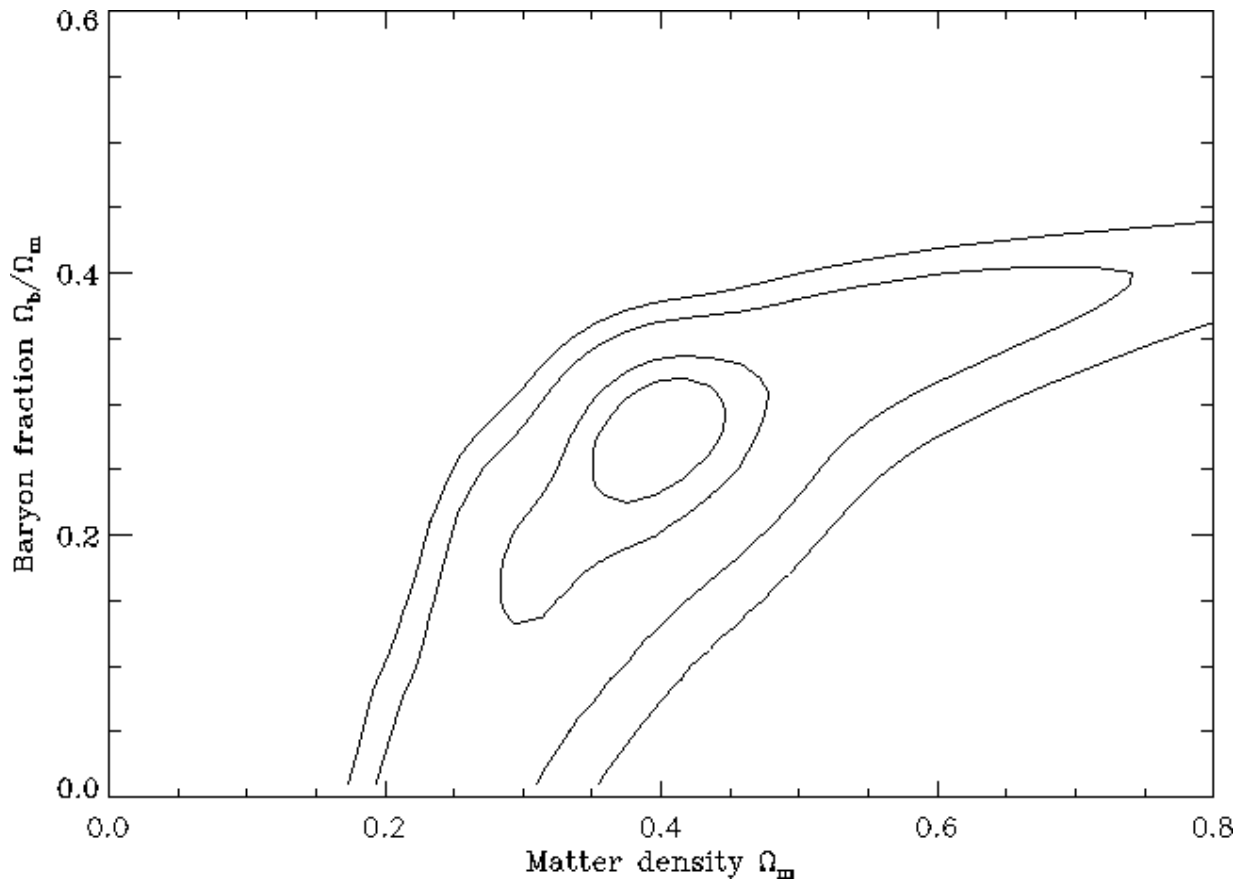
Prior: n=1, h=0.72 ± 0.08



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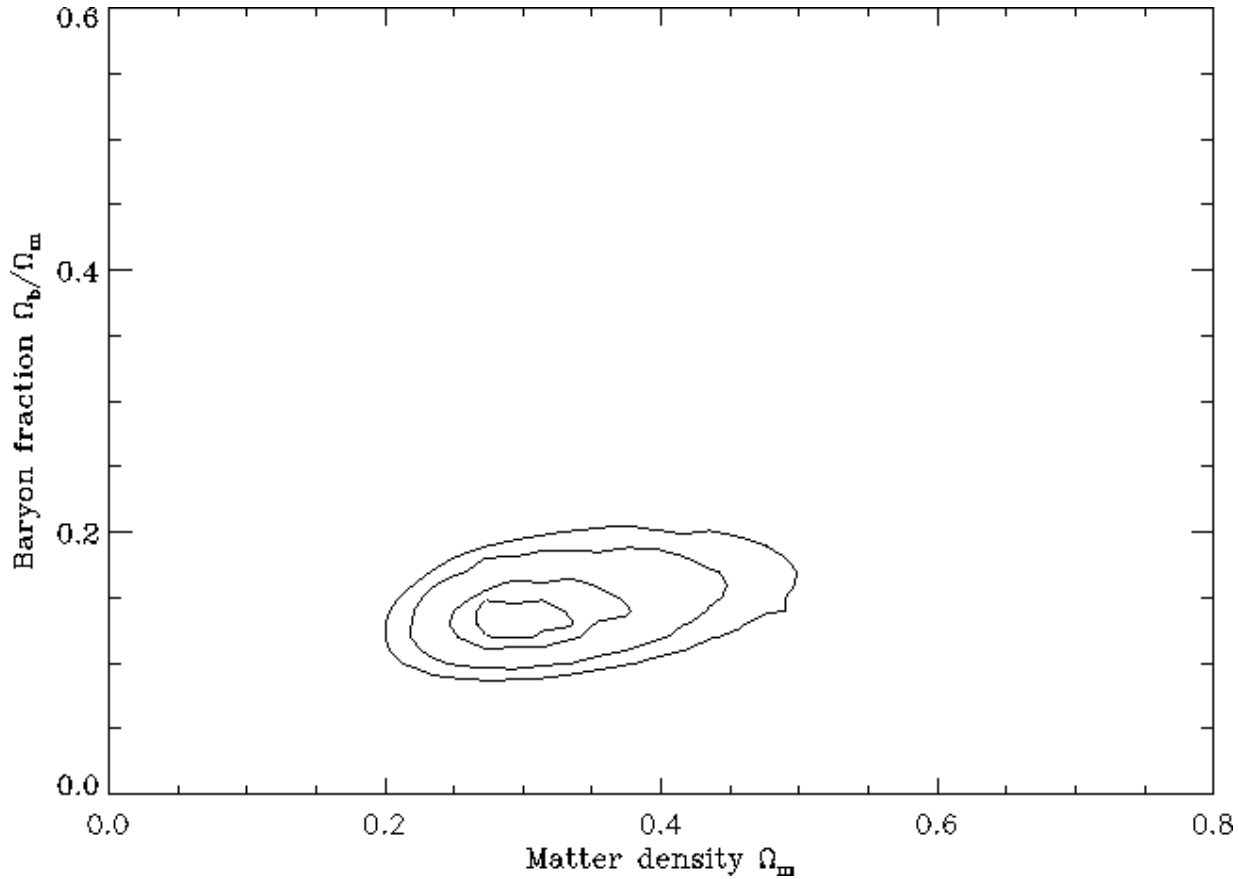
Prior: n=1, h=0.72 ± 0.08, ω_b=0.02±0.002



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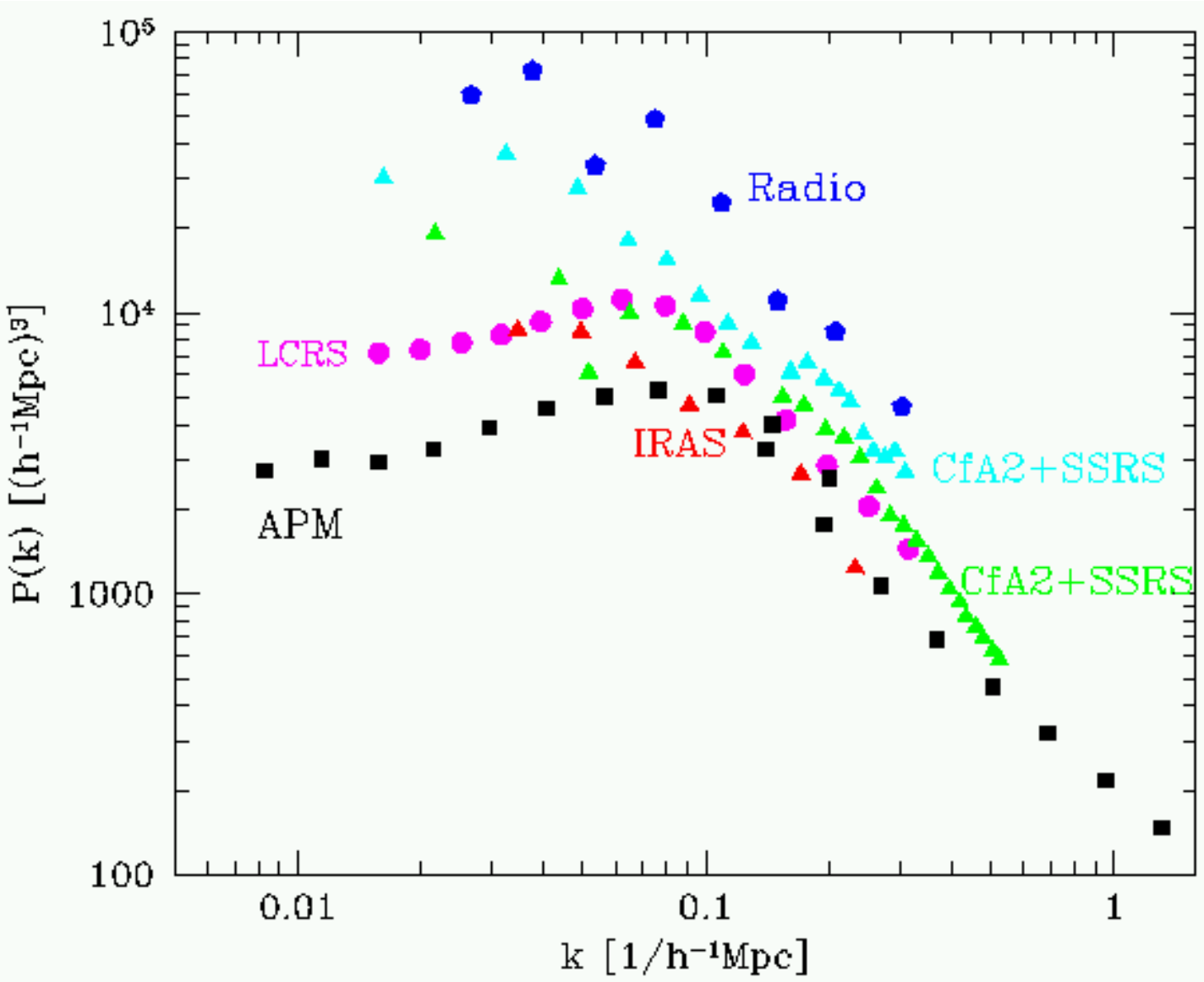
LSS

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



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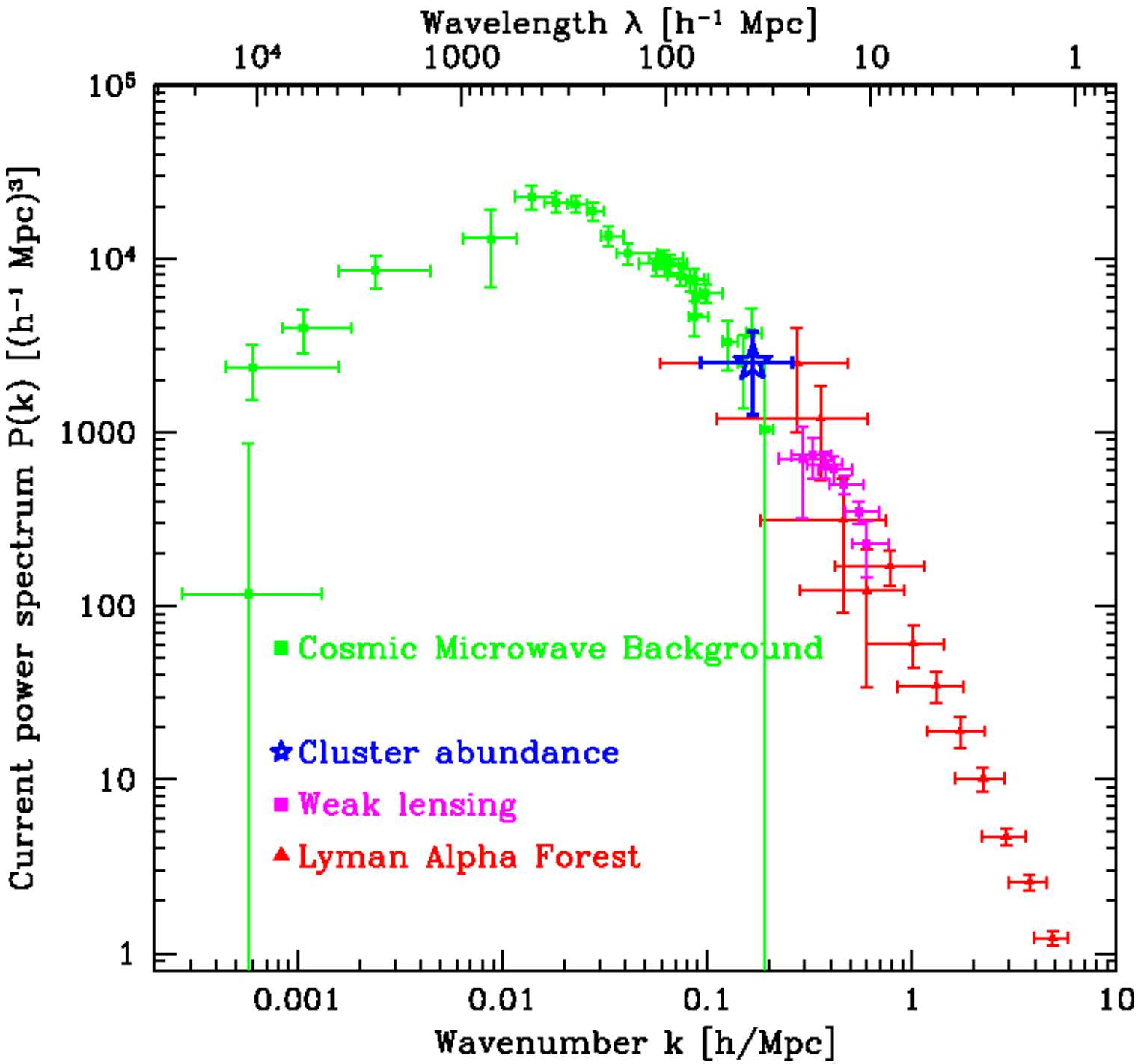

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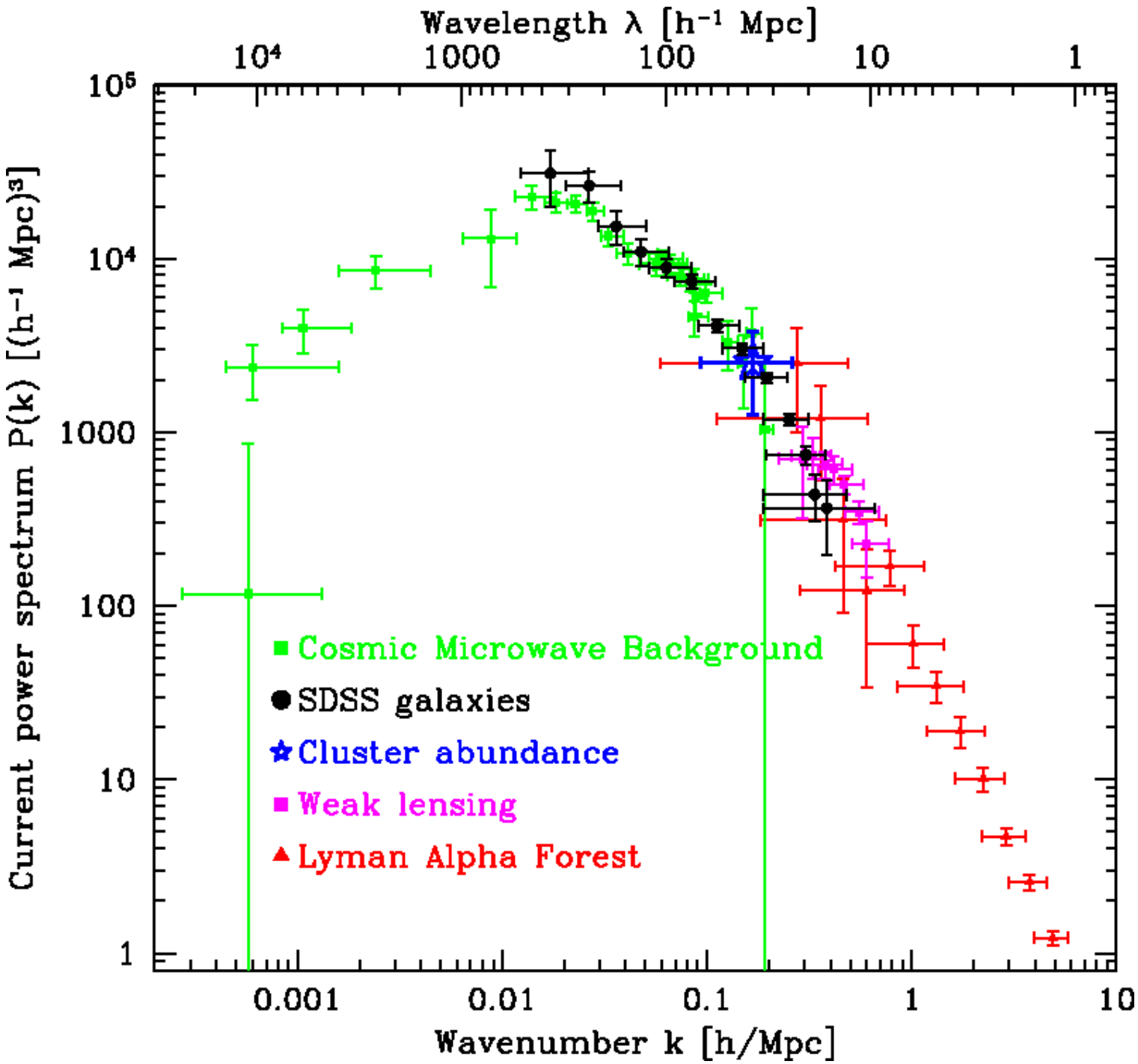

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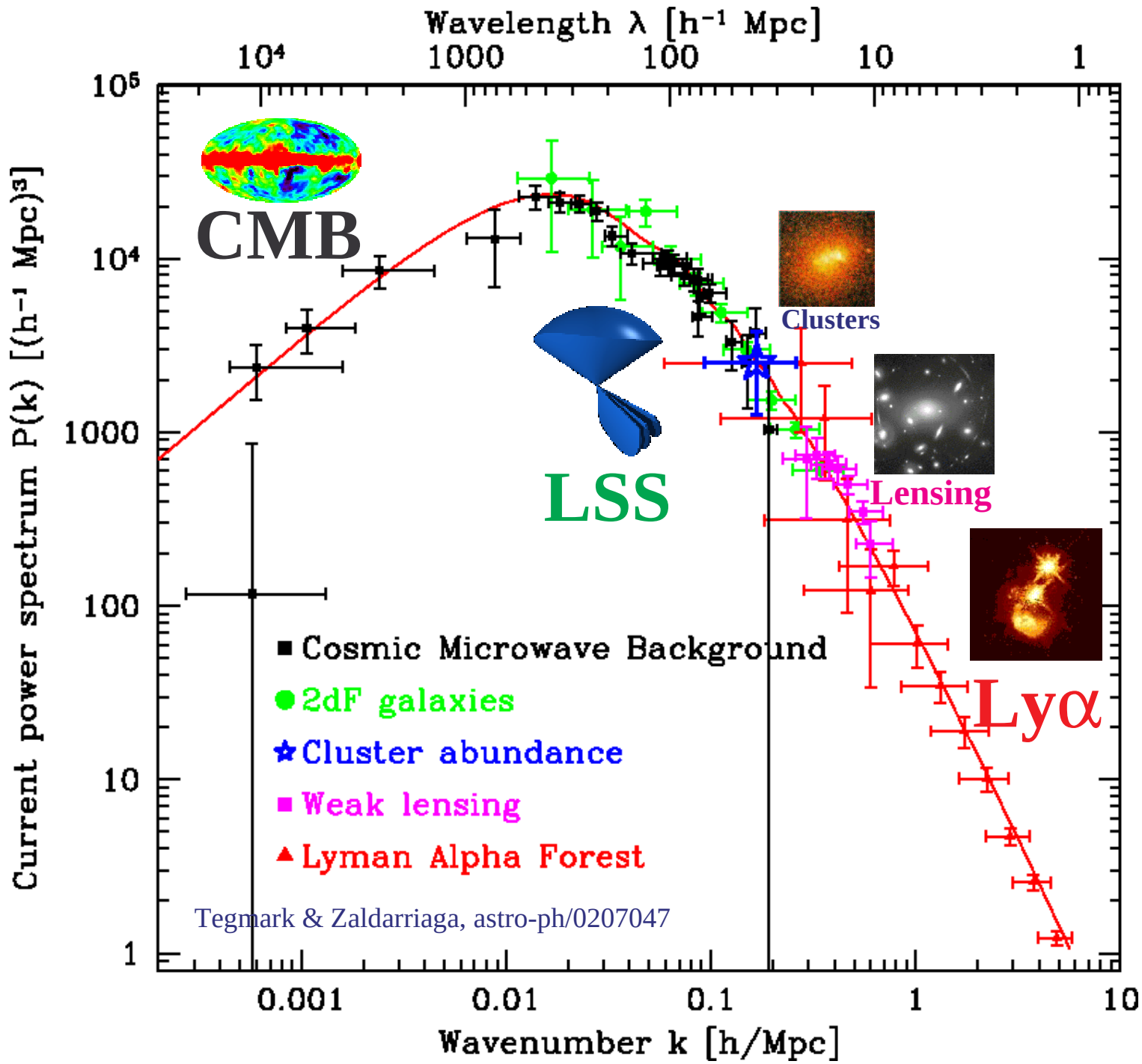
Measuring the primordial power spectrum $P_*(k)$



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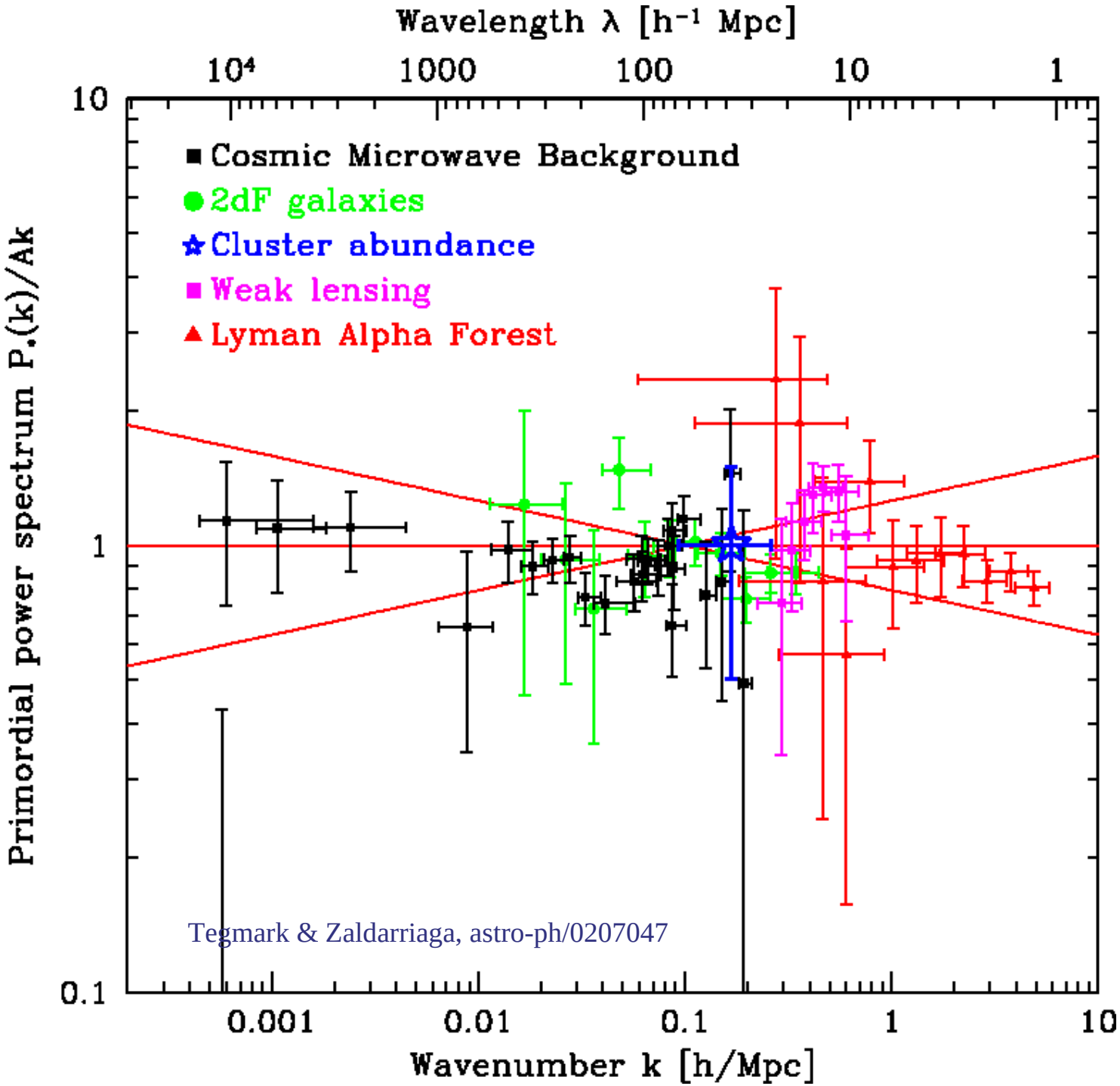

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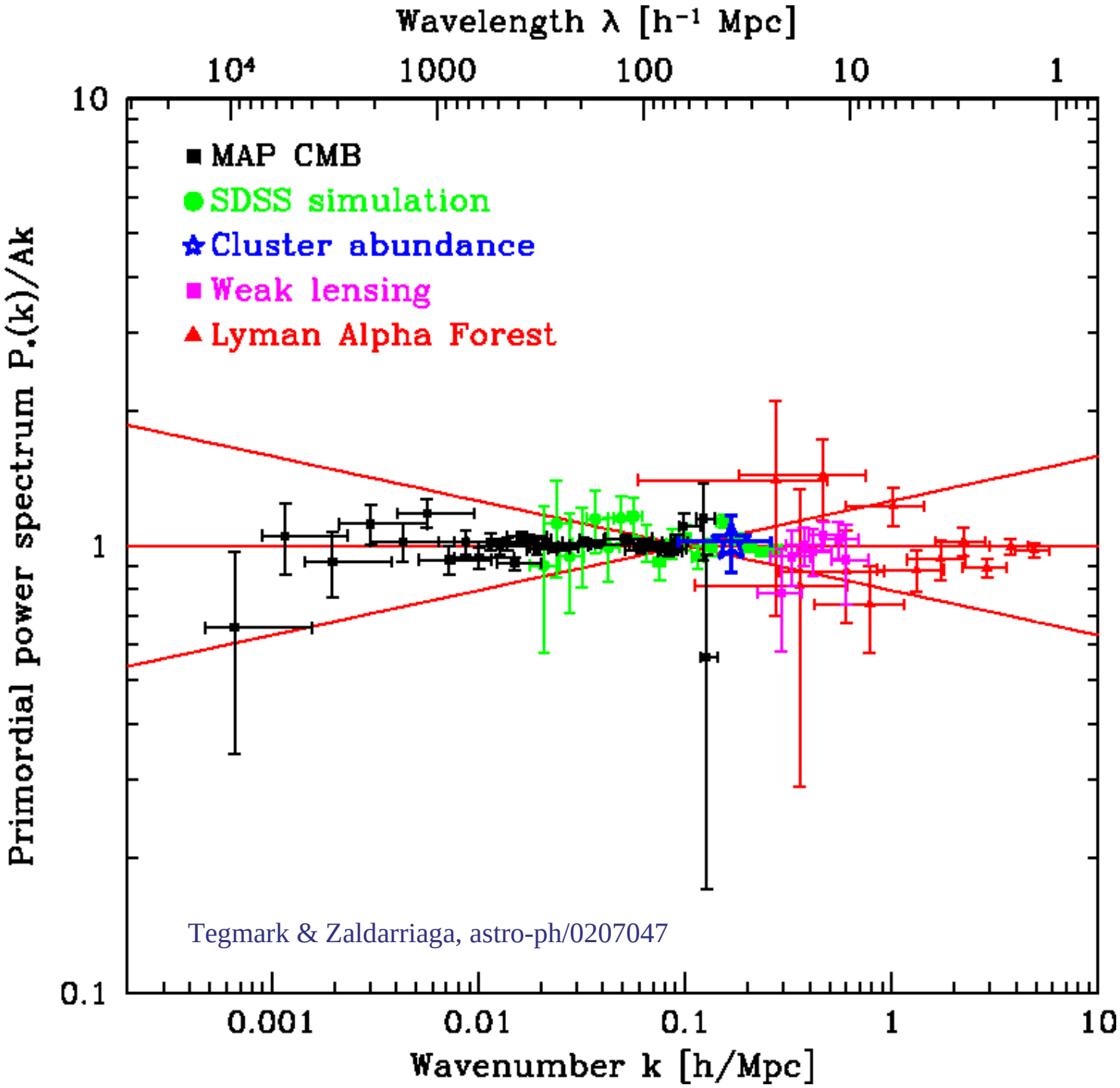

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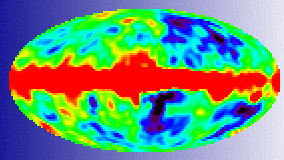
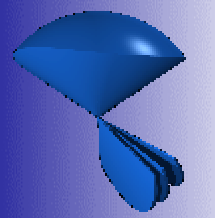


CMB + LSS



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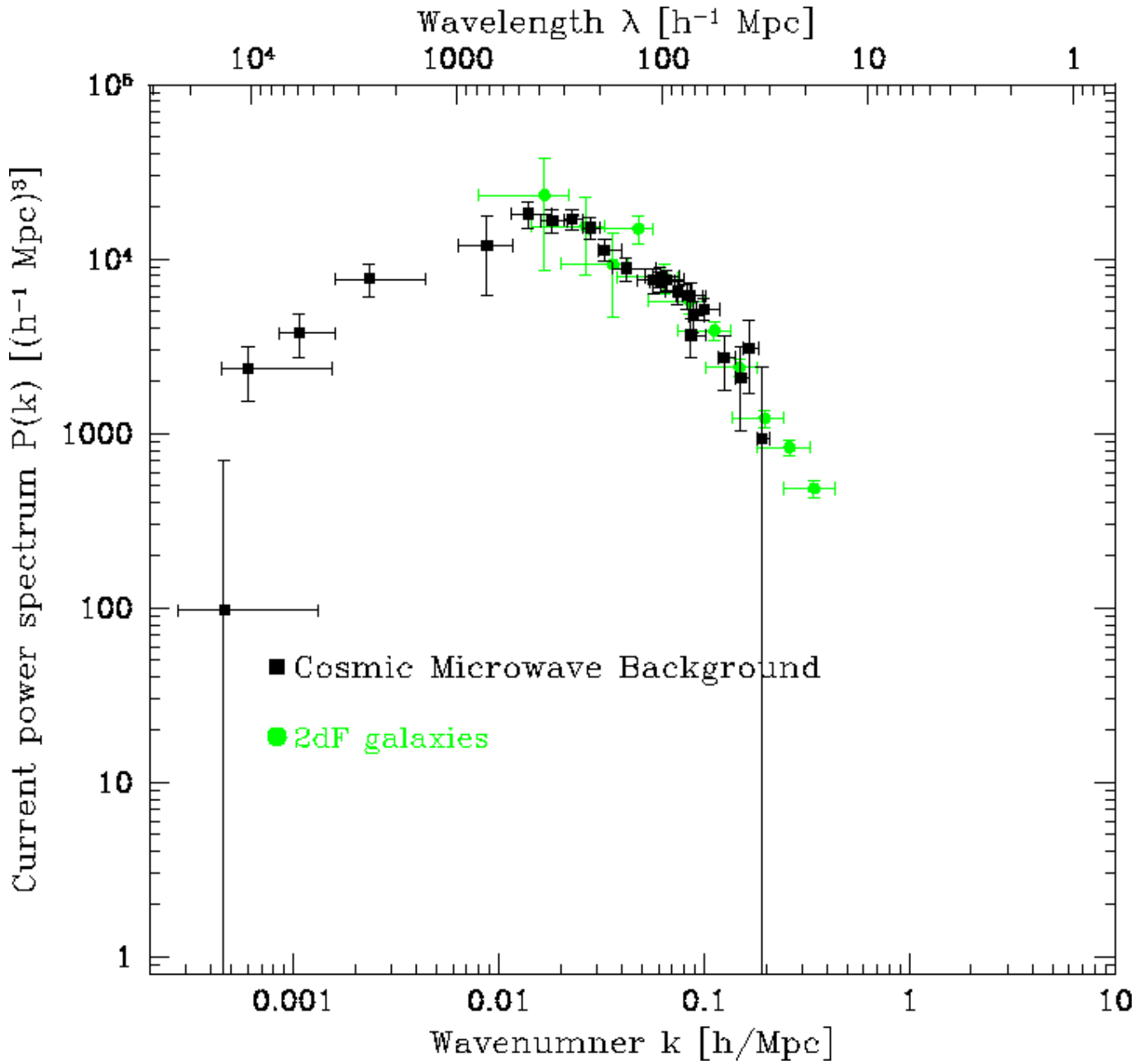

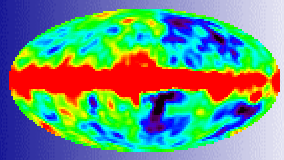

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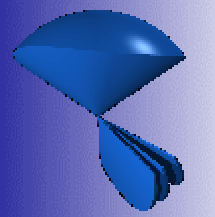

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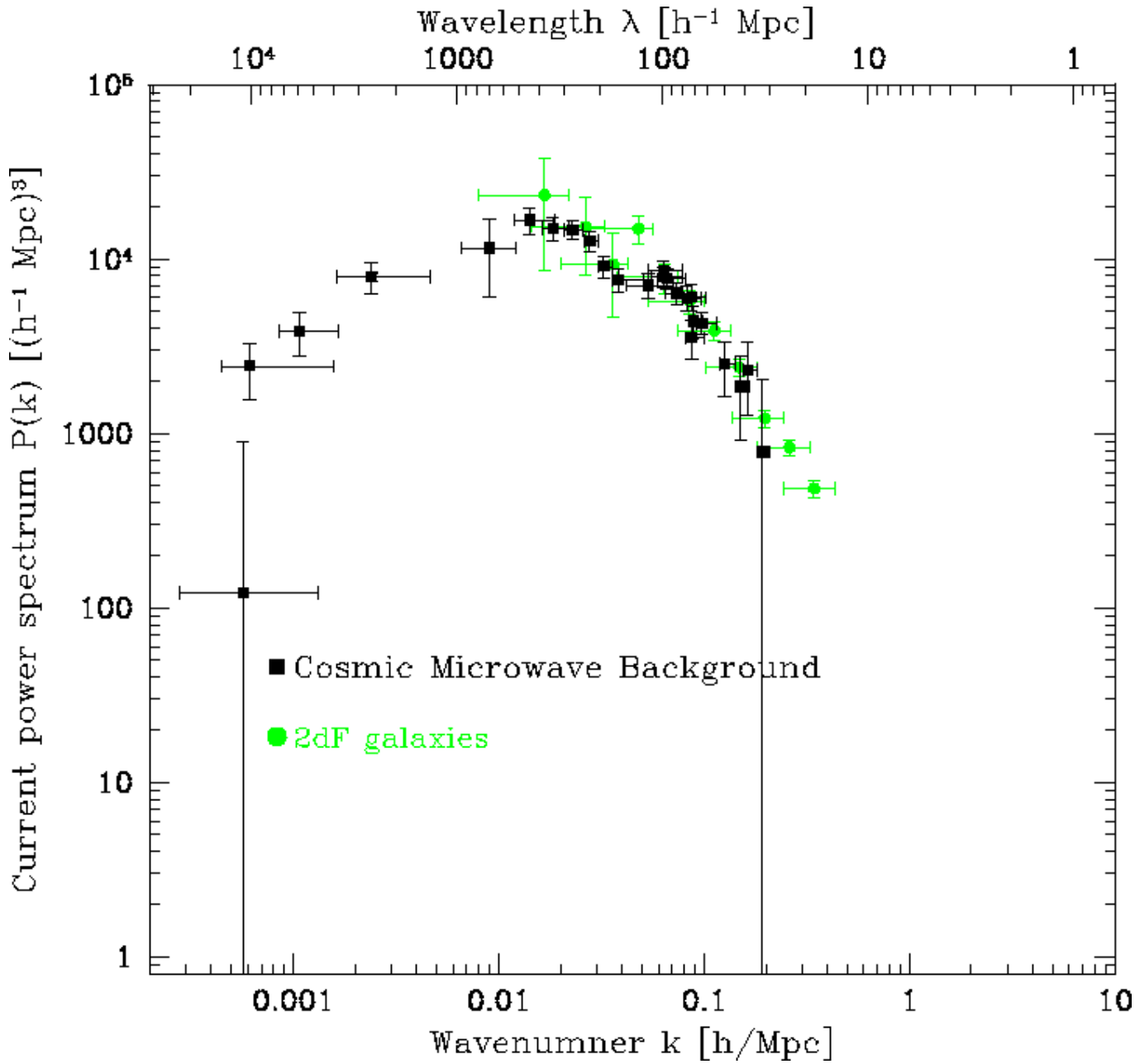

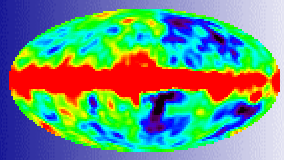

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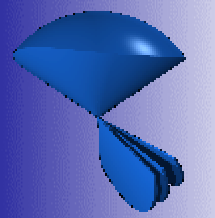

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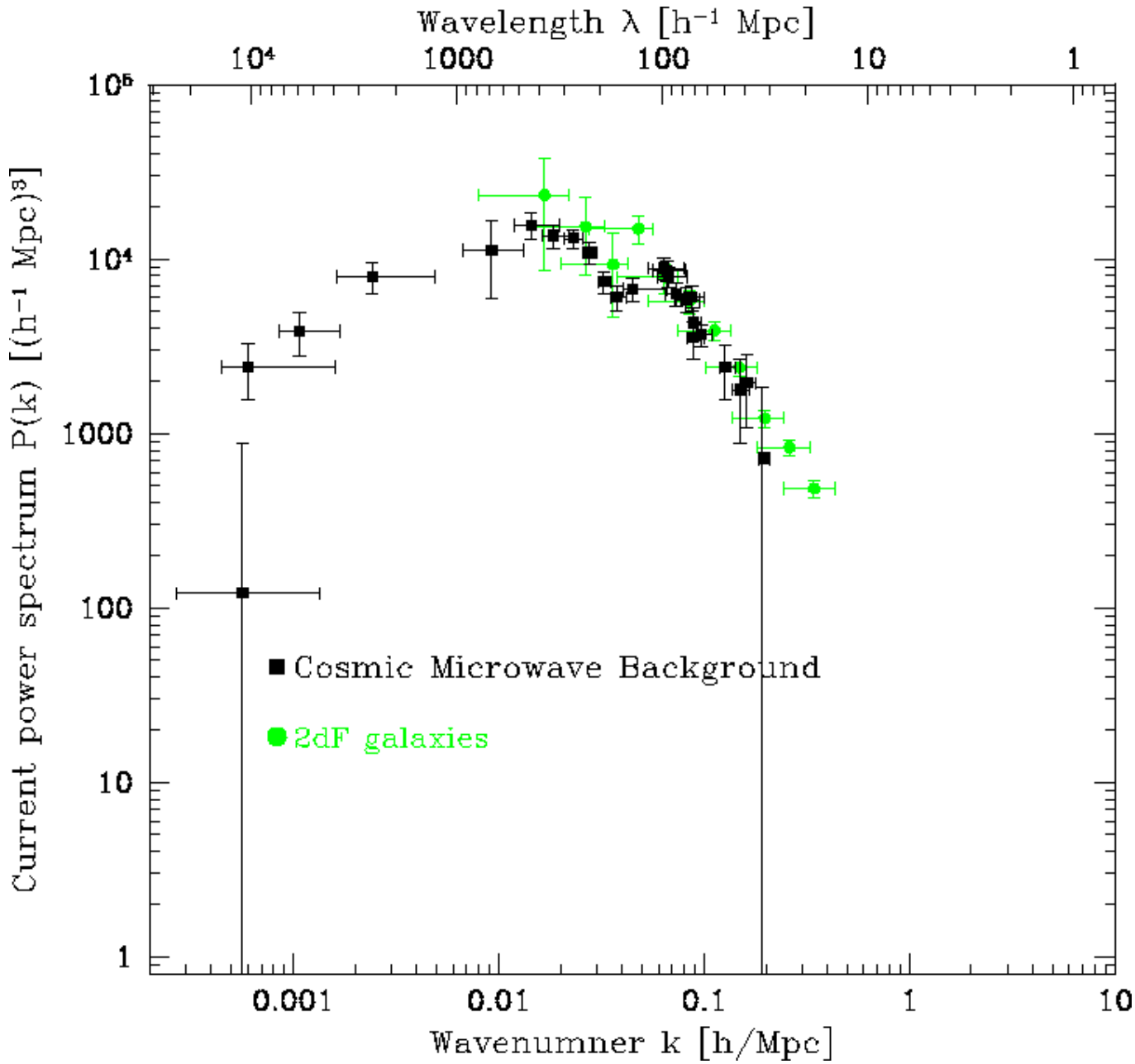

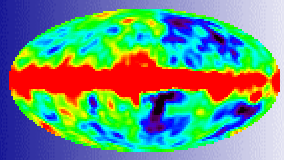

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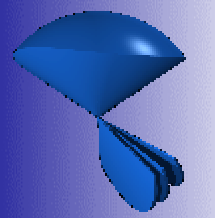

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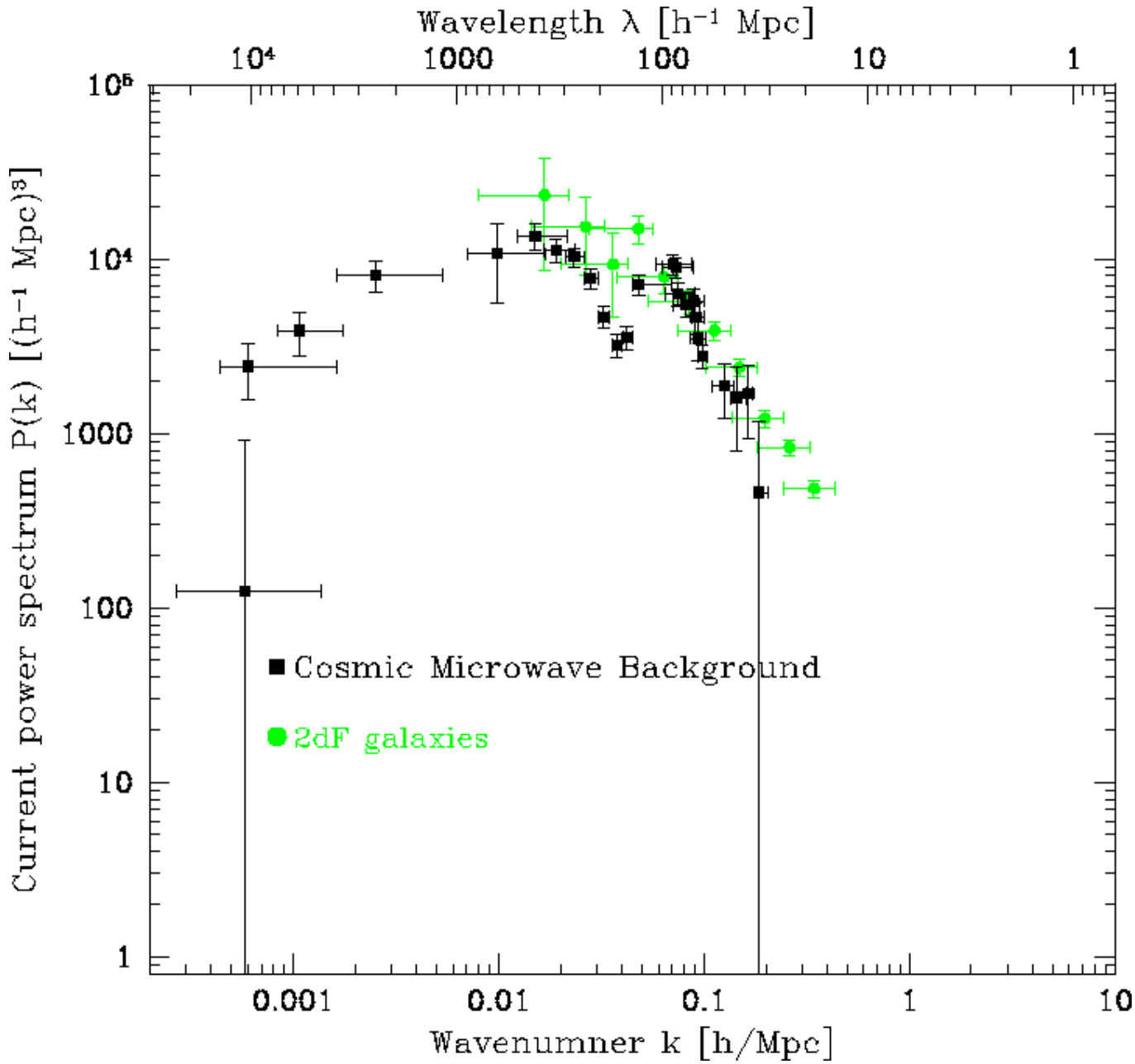

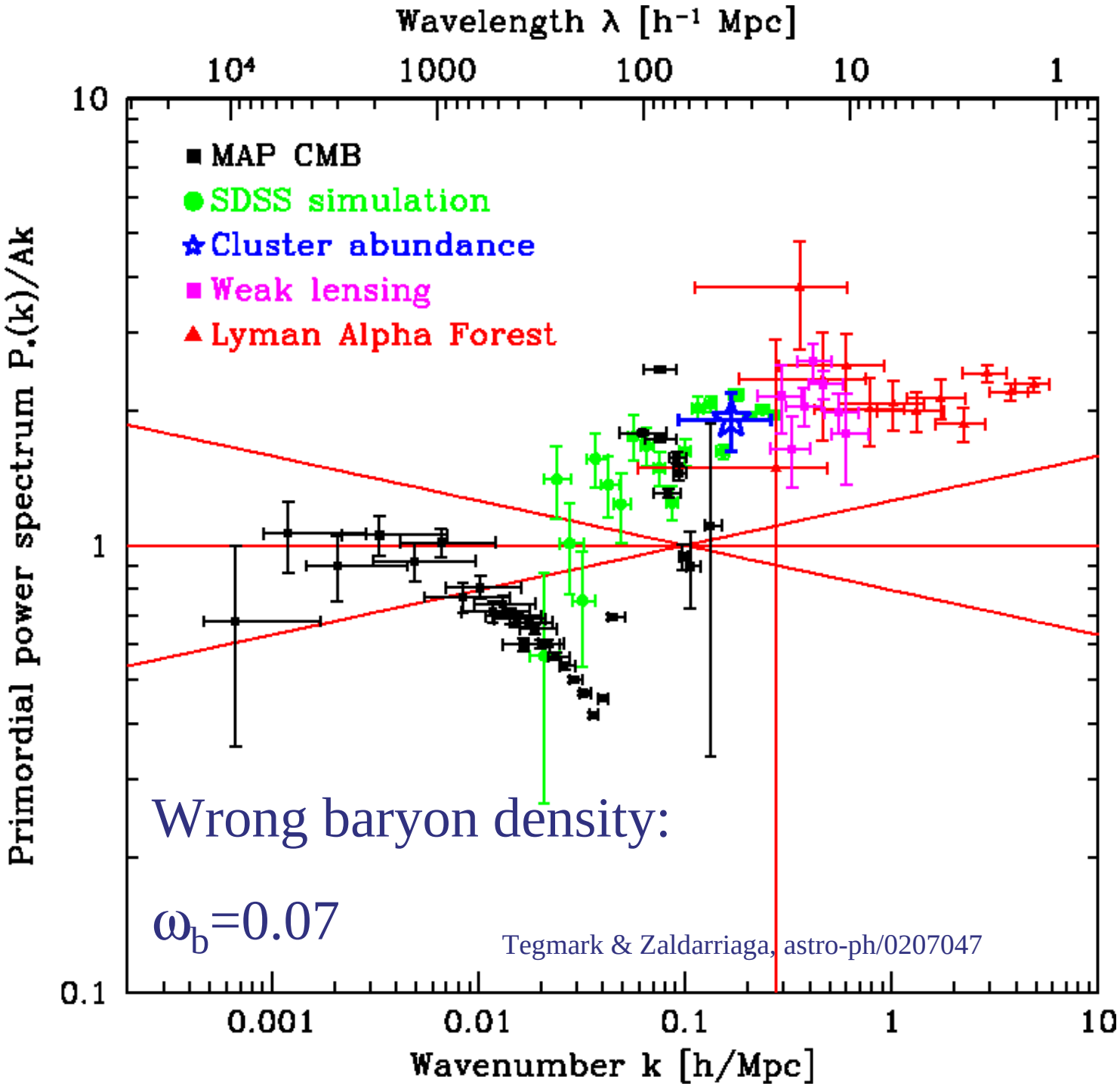

Wrong baryon density:

ω_b=0.07

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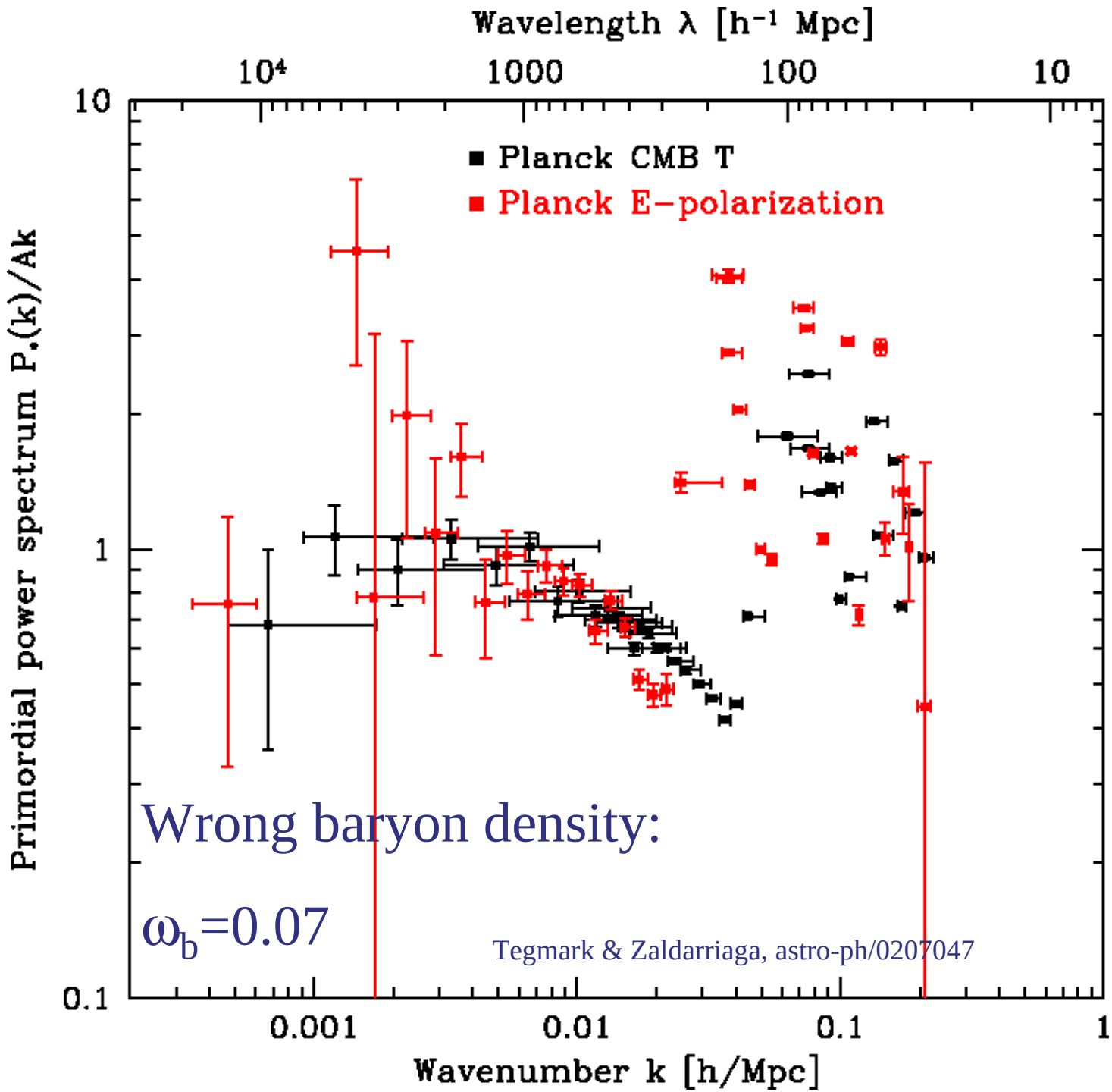

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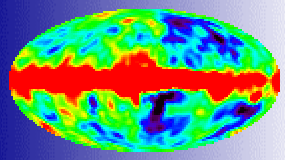

CMB

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Beyond cosmological parameters, summary:

- *Test the underlying physics rather than assuming it*
- *Understand the nature of dark matter, dark energy, bias and gravity*
- *Cosmological functions rather than cosmological parameters*
- *Measure the free functions rather than parametrizing them in a way involving untested physical assumptions - a form of data compression*

	$a(t)$	$g_i(z,k)$	$P_*(k)$	Ω_k	$x(z)$	Gastro
Physics						
Early Universe			$\oplus$	$\oplus$		
Dark energy	$\oplus$	$\oplus$				
Dark matter	$+$	$\oplus$				
Neutrinos	$+$	$\oplus$				
First light					$\oplus$	
CMB observable						
Primary CMB	$\oplus$	$\oplus$	$\oplus$	$\oplus$	$\oplus$	
OV, KSZ	$+$	$\oplus$	$\oplus$	$+$	$\oplus$	$+$
Thermal SZ	$+$	$\oplus$	$\oplus$	$+$		$\oplus$
CMB lensing	$+$	$\oplus$	$\oplus$	$+$		
Rees-Sciama		$\oplus$	$\oplus$			
Other observable						
SN 1a	$\oplus$					
LSS	$+$	$\oplus$	$\oplus$	$+$		$+$
Lyα forest	$+$	$\oplus$	$\oplus$	$+$	$+$	$+$
Lensing	$+$	$\oplus$	$\oplus$	$+$		

Do observations disagree with each other or with theory?

Data => Cosmological functions <= Theory

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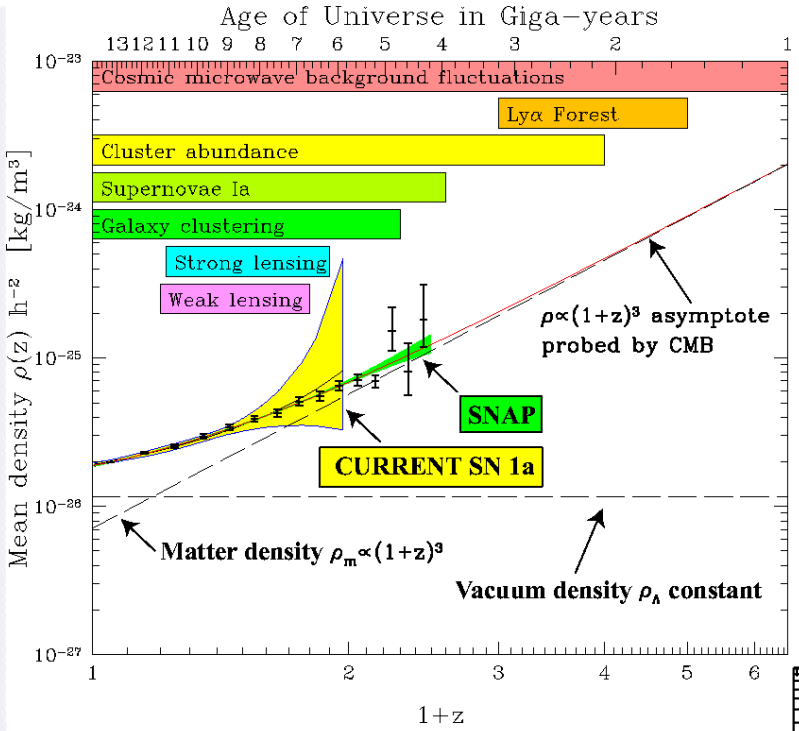
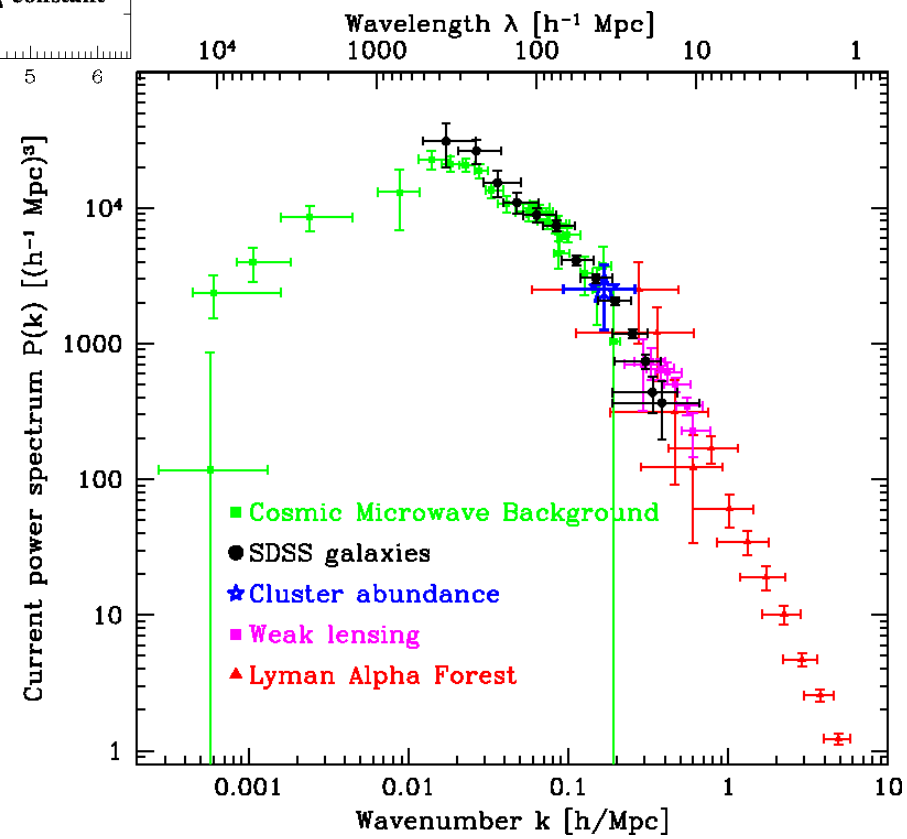


0th order

1st order



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