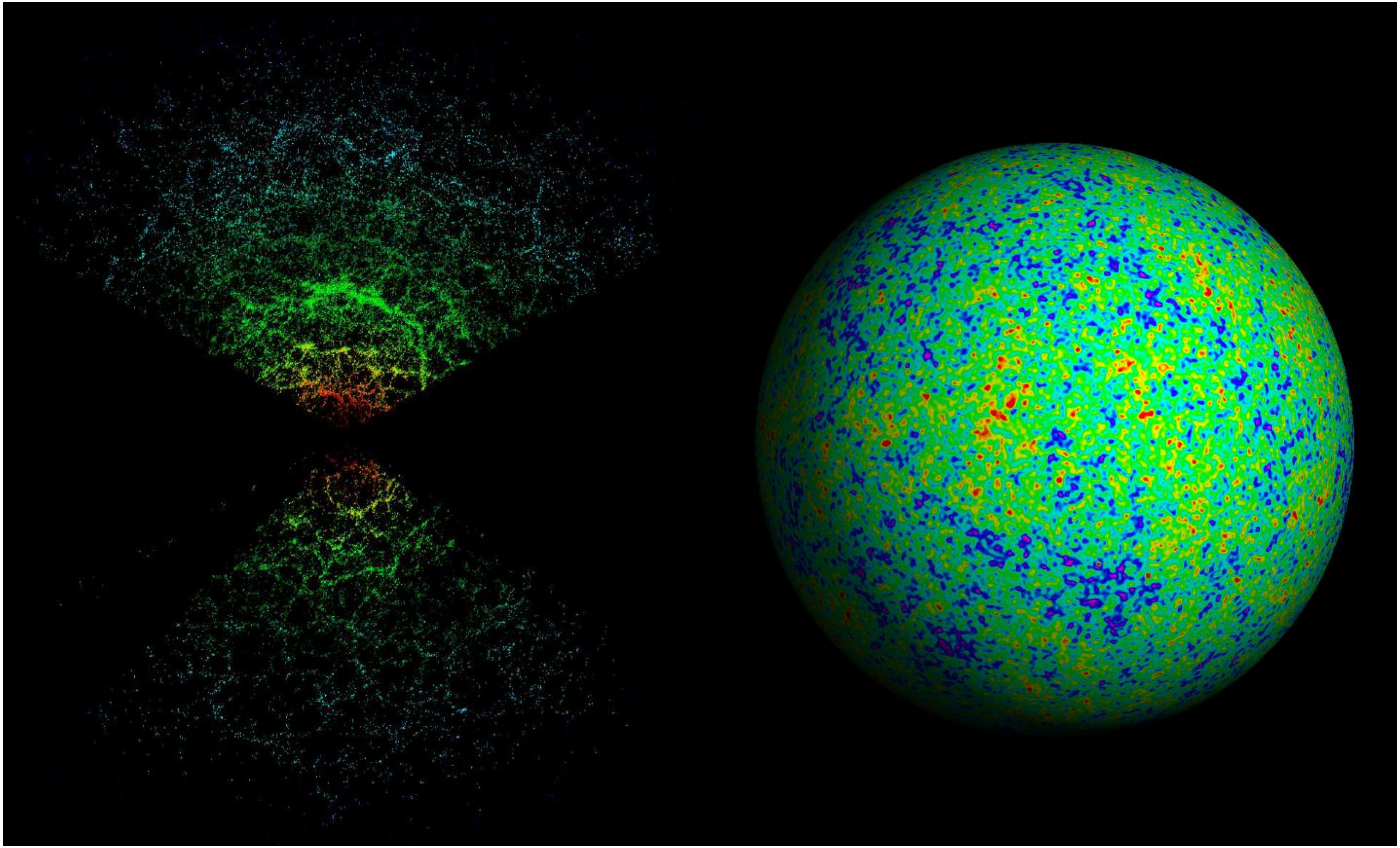
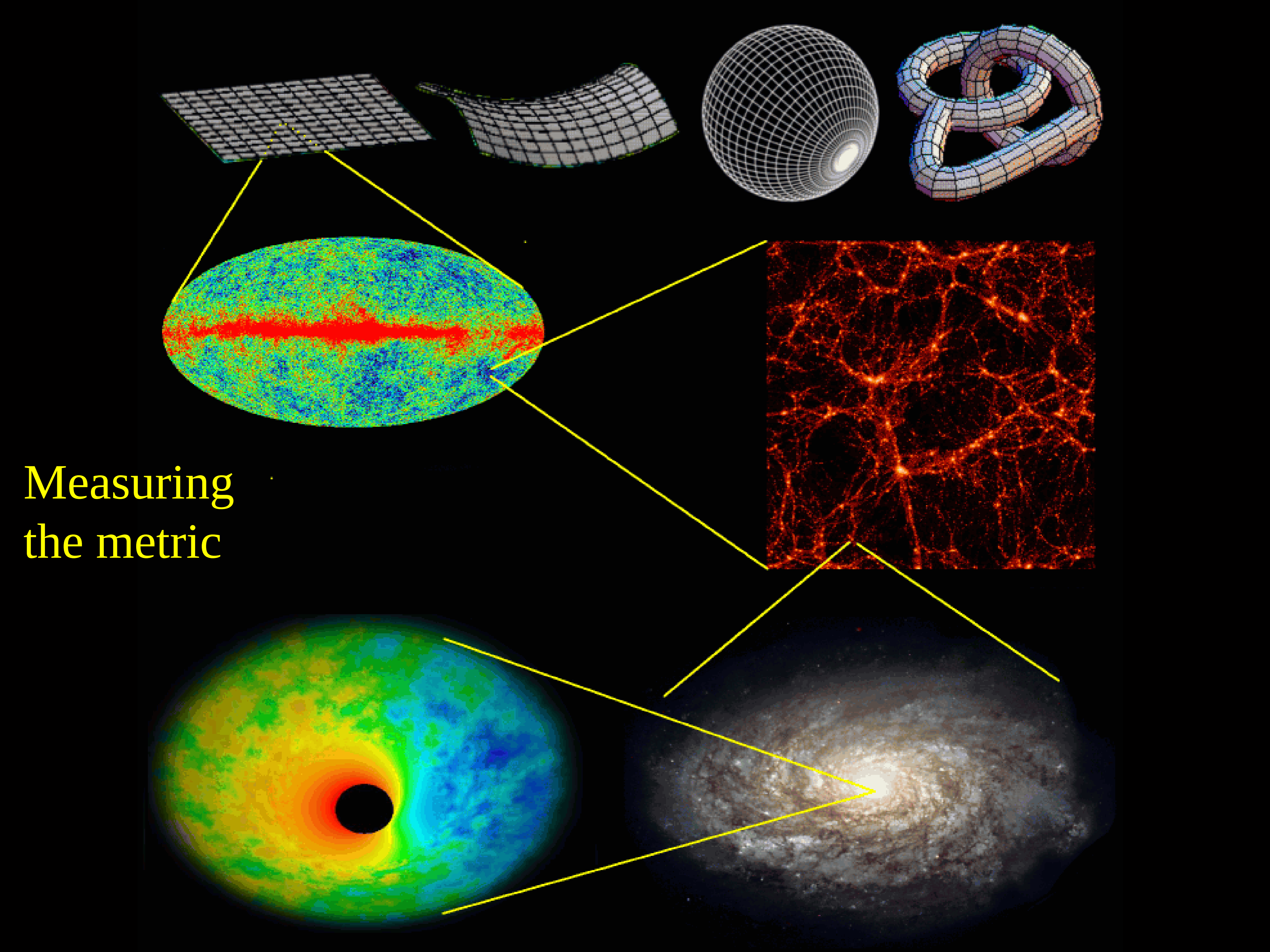
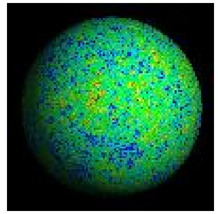
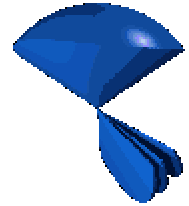
New Cosmic Maps & Measurements



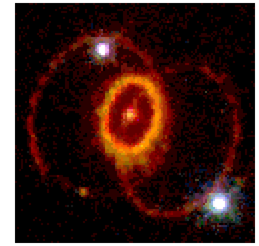

Measuring
the metric



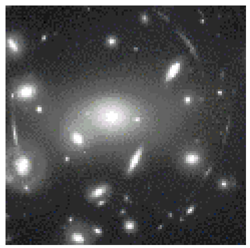
CMB



GALAXY
SURVEYS

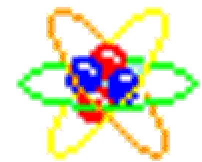


DISTANT
SUPERNOVAE

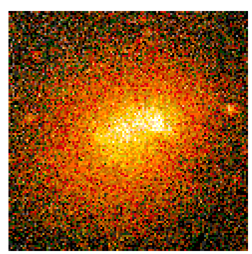


GRAVITATIONAL
LENSING

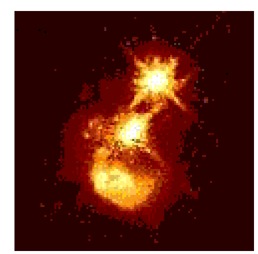
THE COSMIC SMÖRGÅSBORD



BIG BANG
NUCLEOSYNTHESIS



GALAXY
CLUSTERS



LYMAN ALPHA
FOREST

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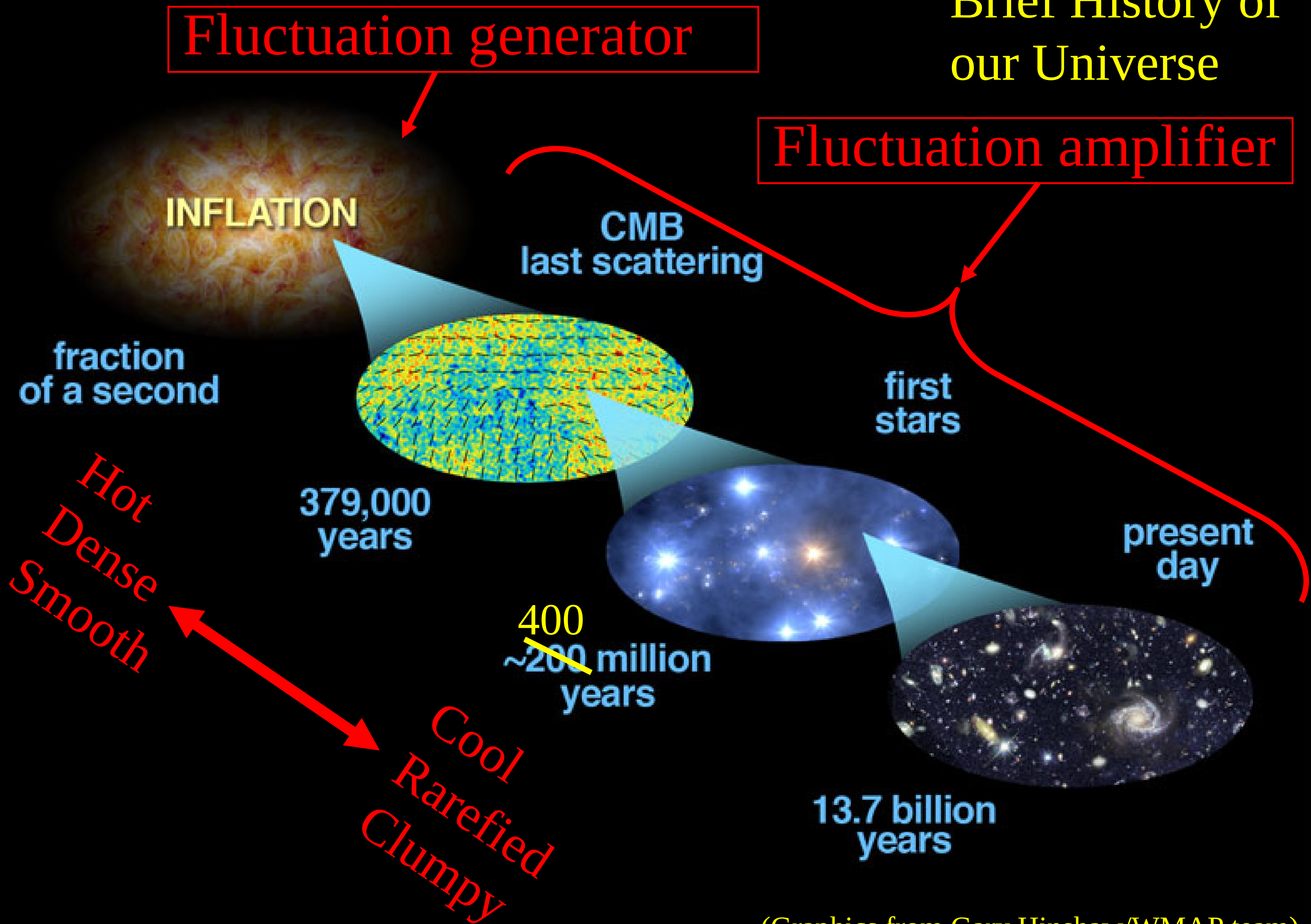
What have we learned?

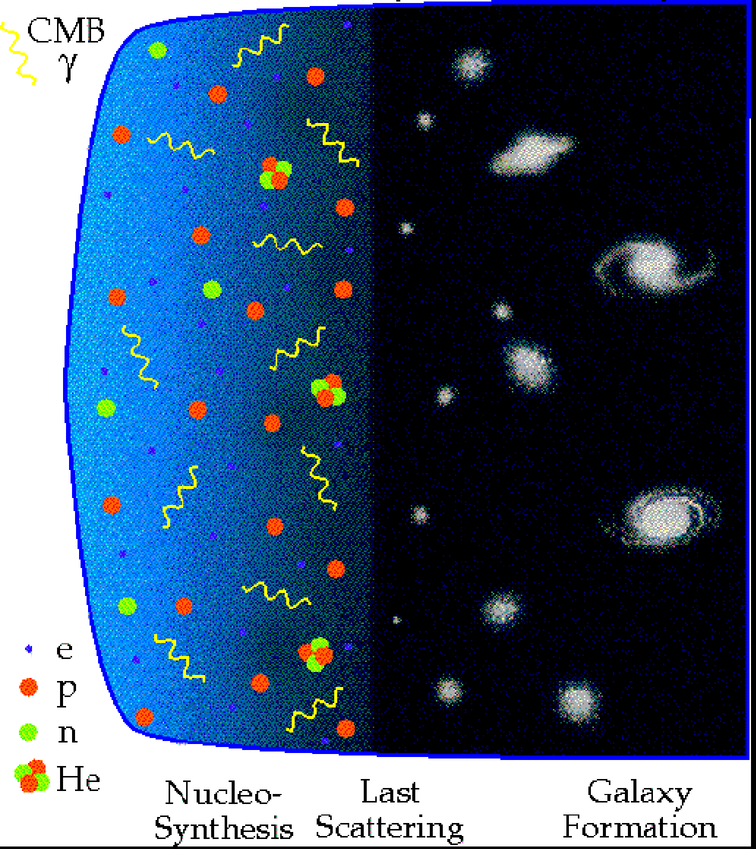
Brief History of our Universe



(Graphics from Gary Hinshaw/WMAP team)

Formation movies

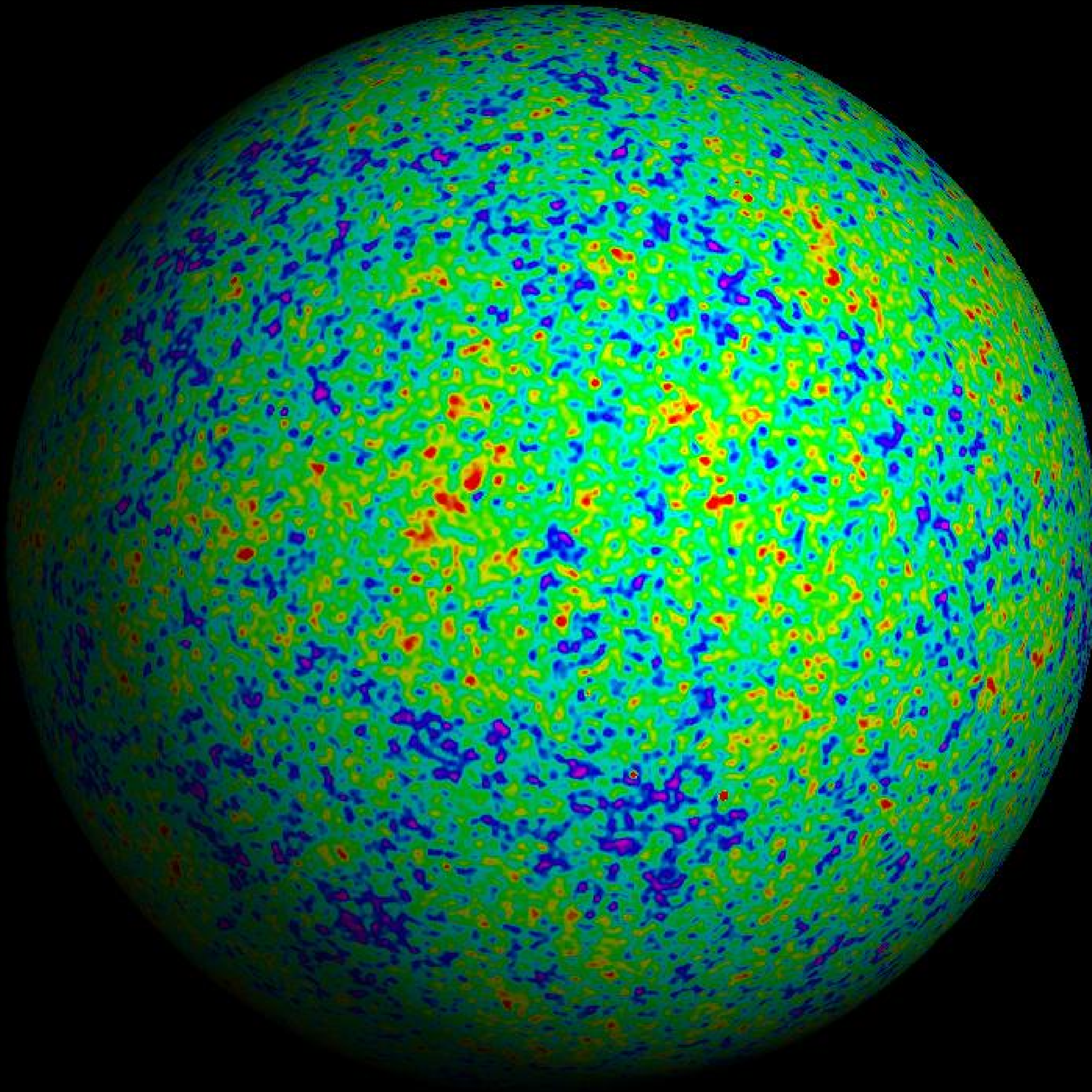
Cosmic clustering

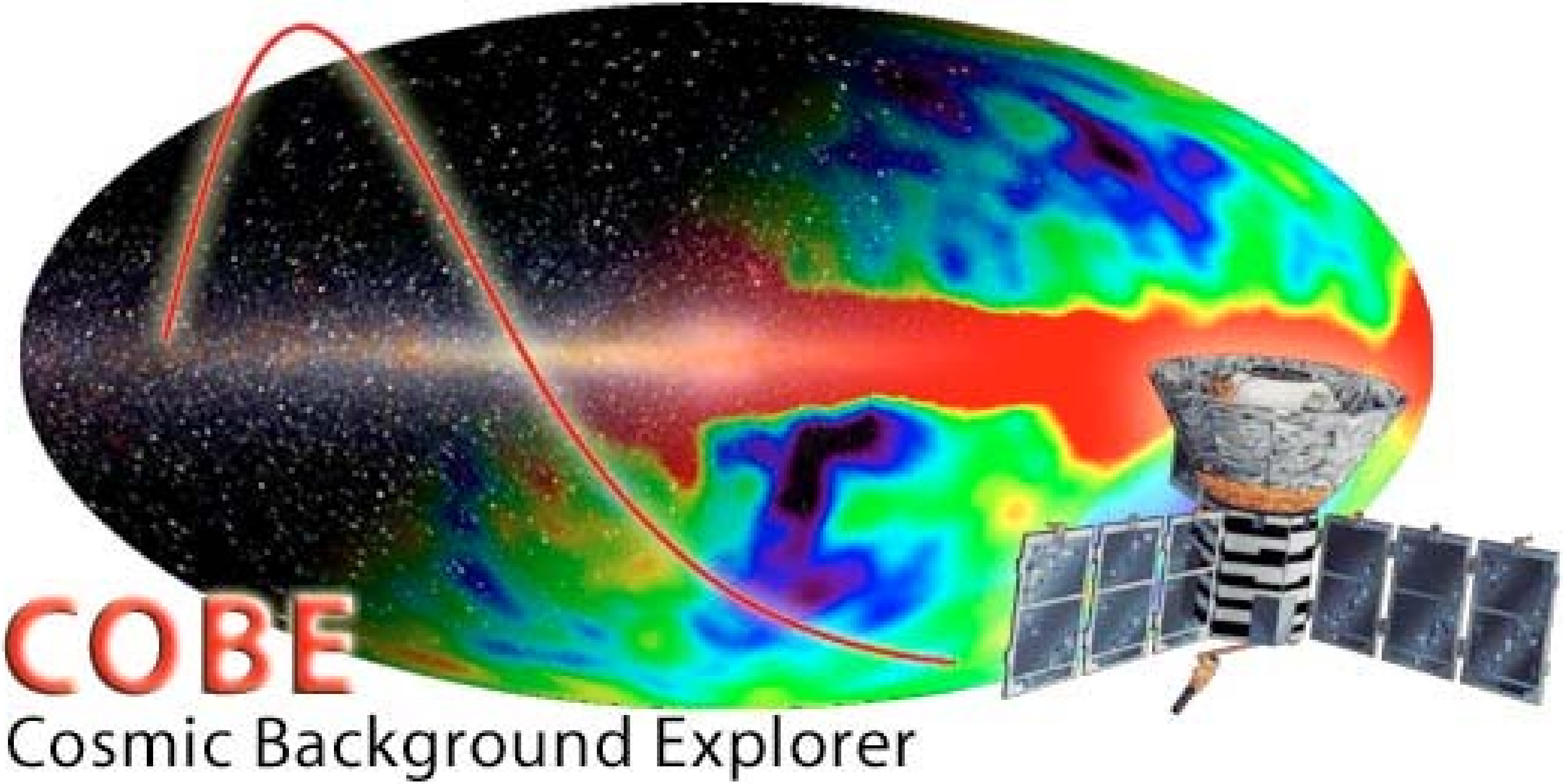


(Figure from Wayne Hu)

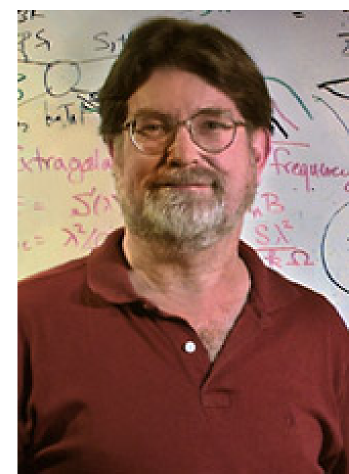
(Figure from WMAP team)

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



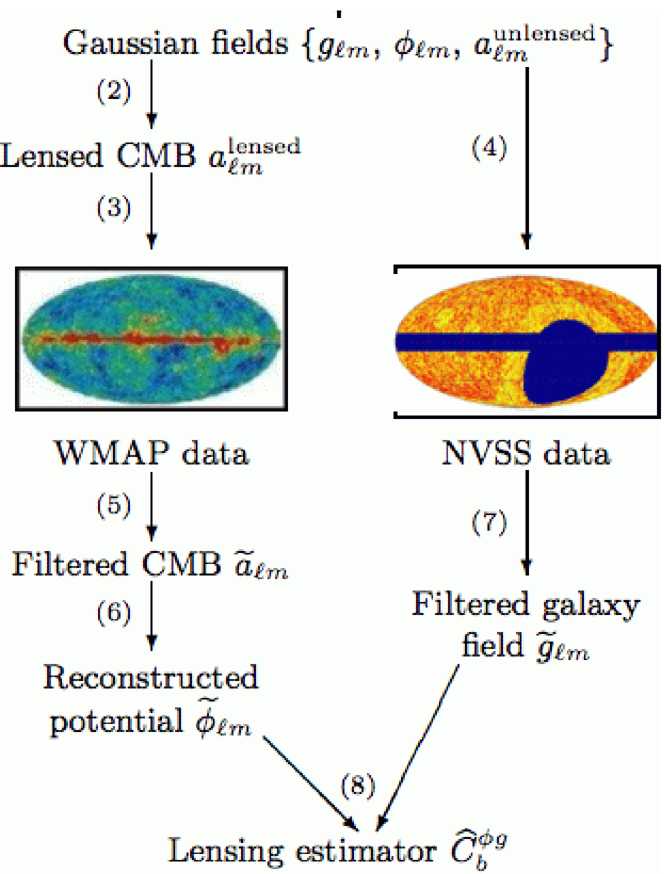


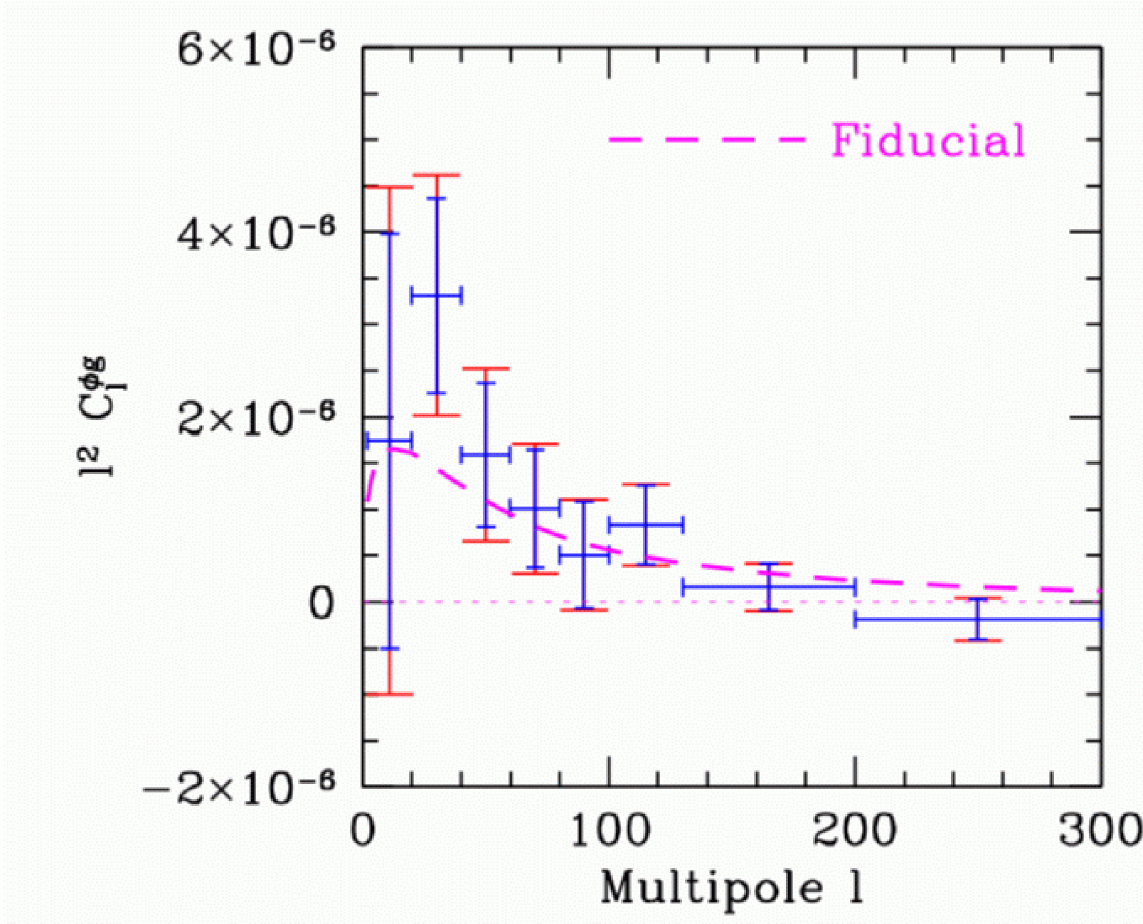
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

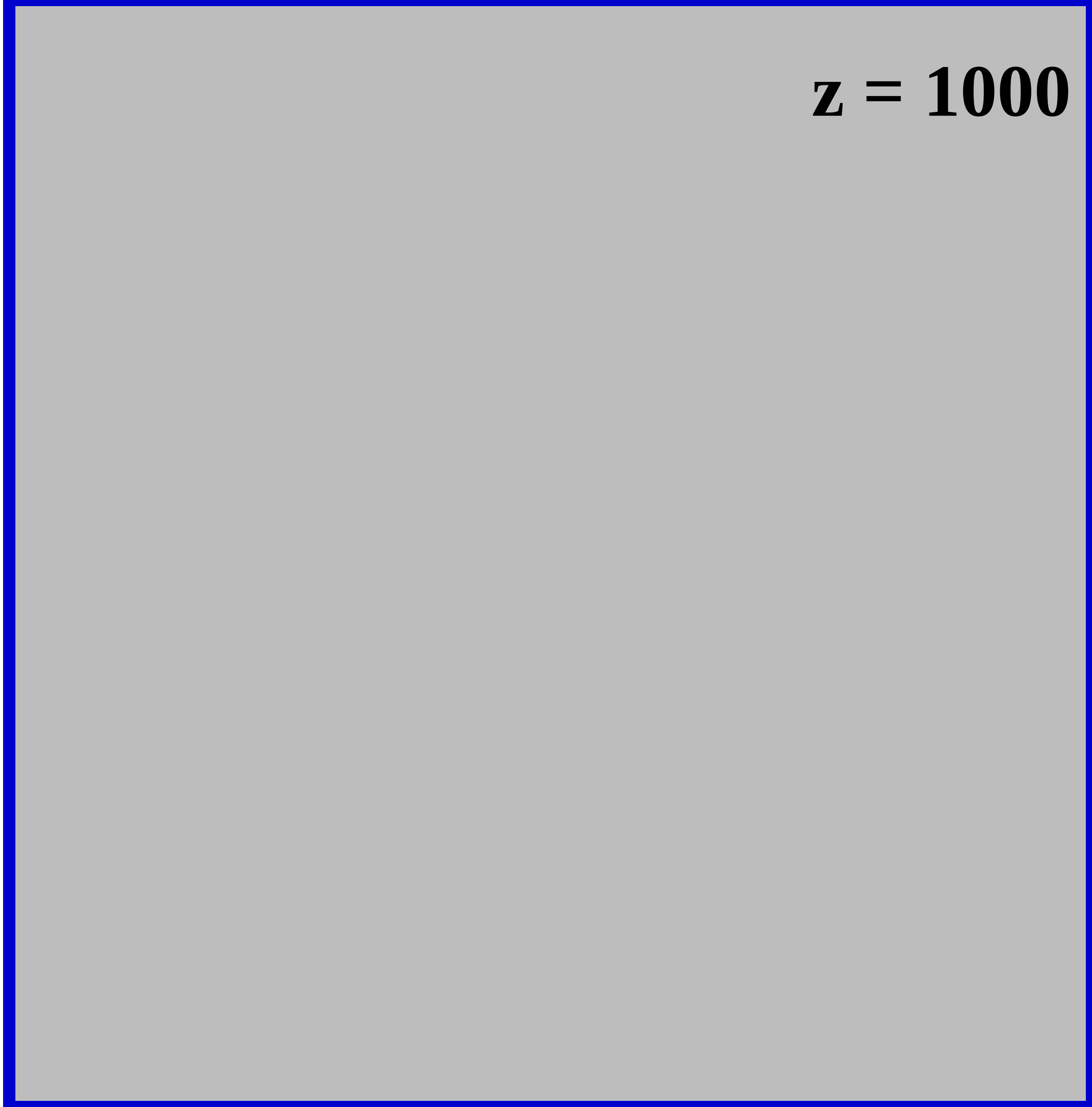


CMB lensing detected! (3.4σ)

Kendrick Smith, Oliver Zahn & Oliver Dore, arXiv 0705.3980 [astro-ph]







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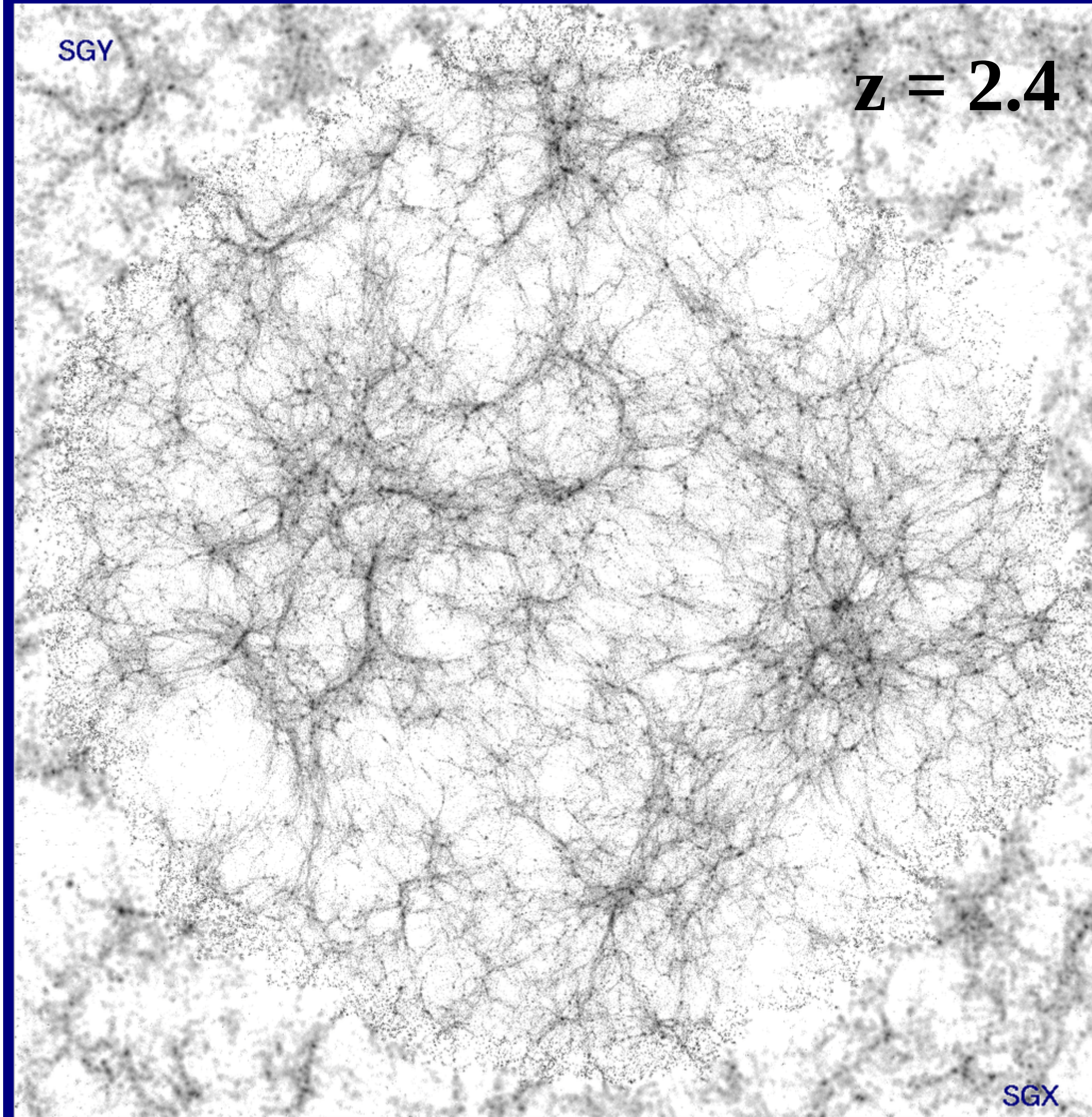

Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001

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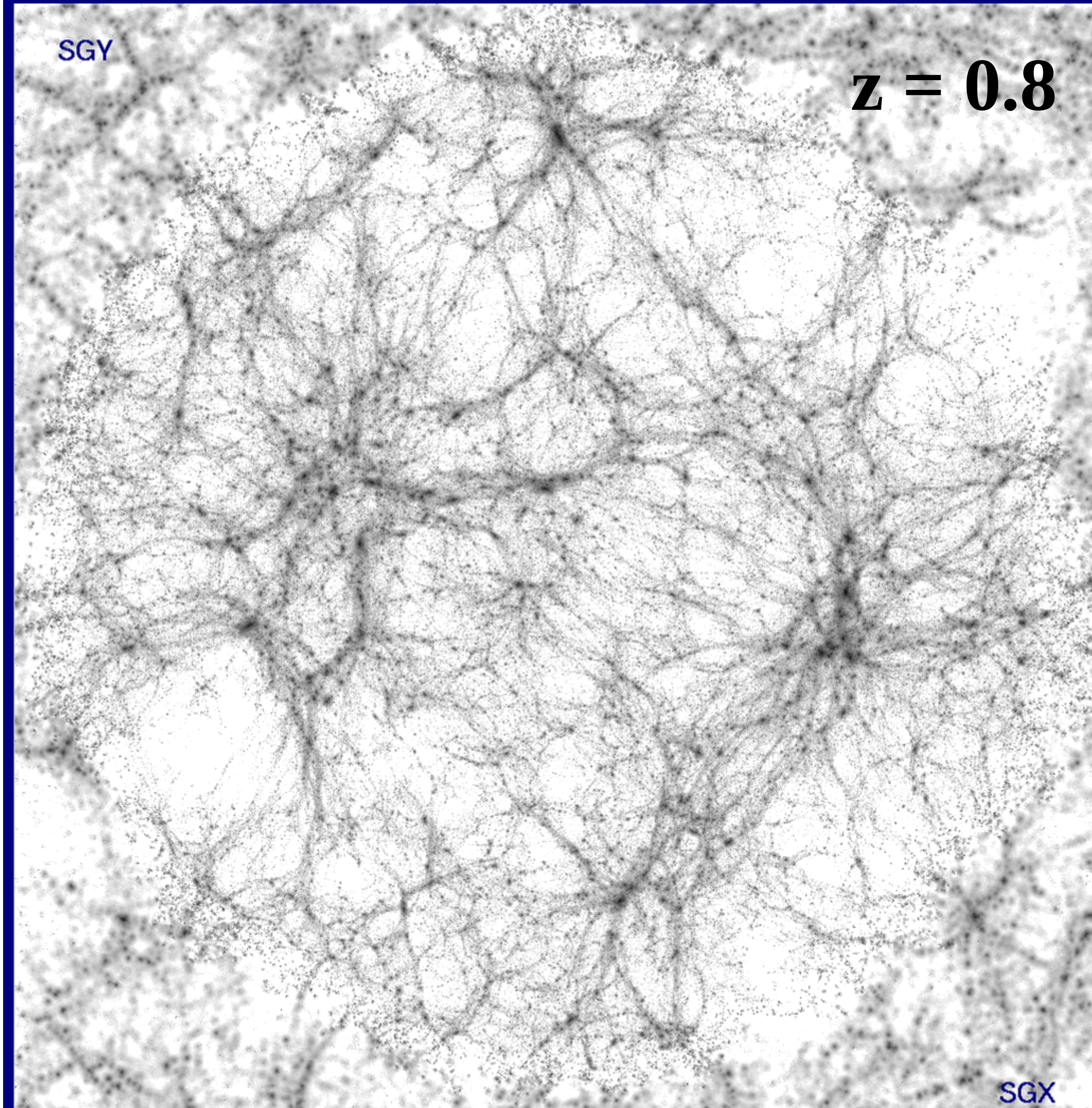
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



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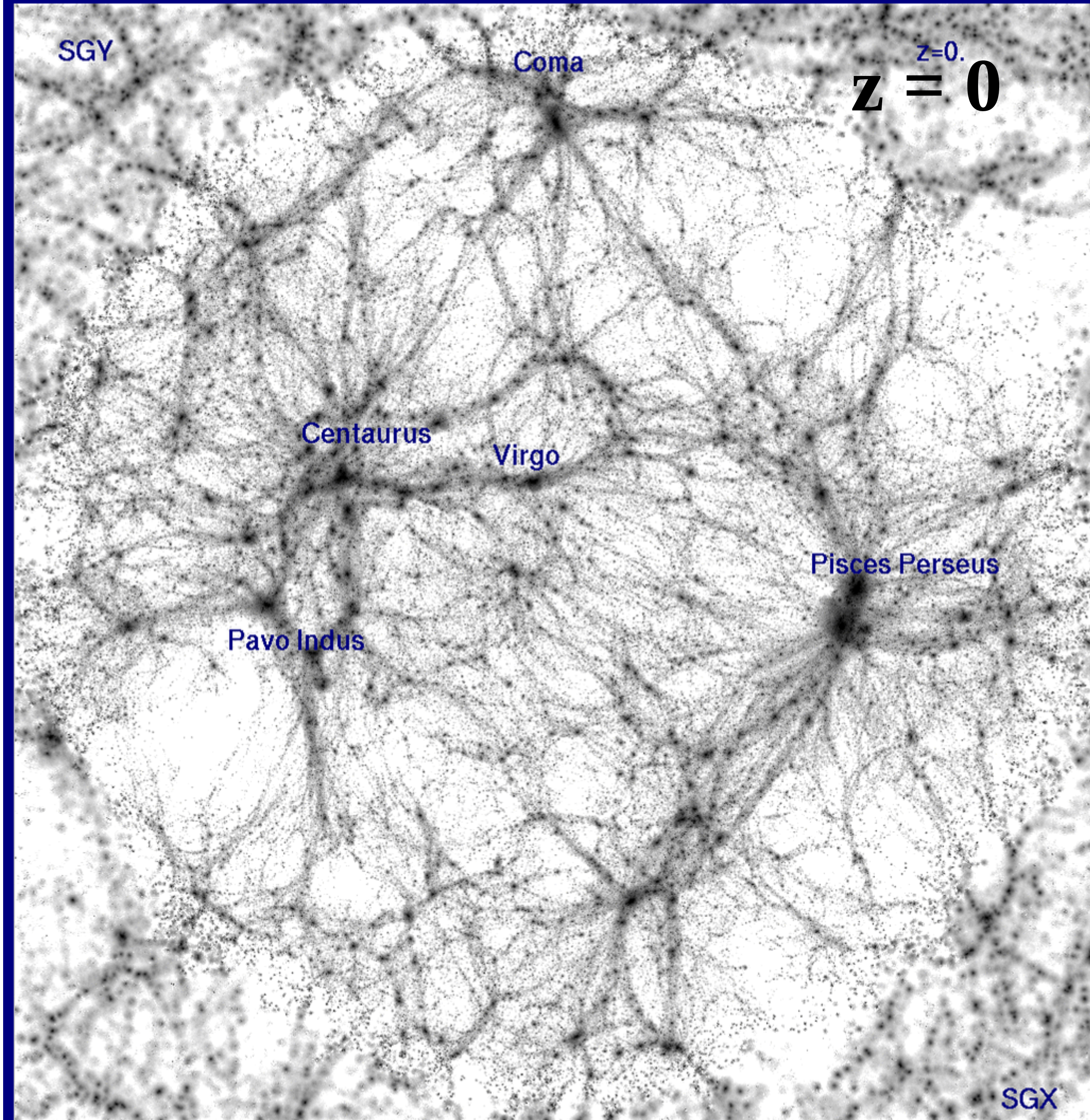
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



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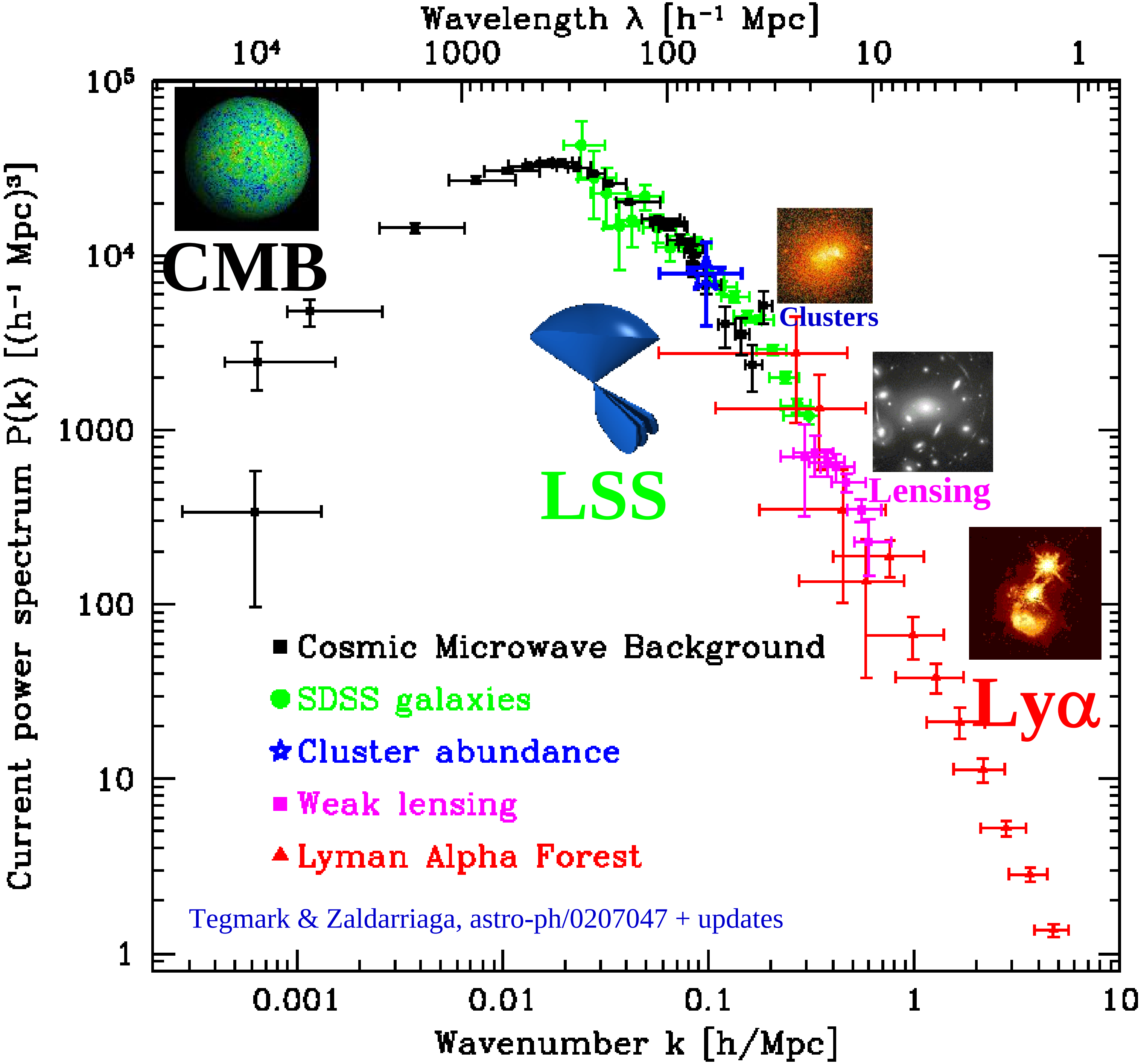

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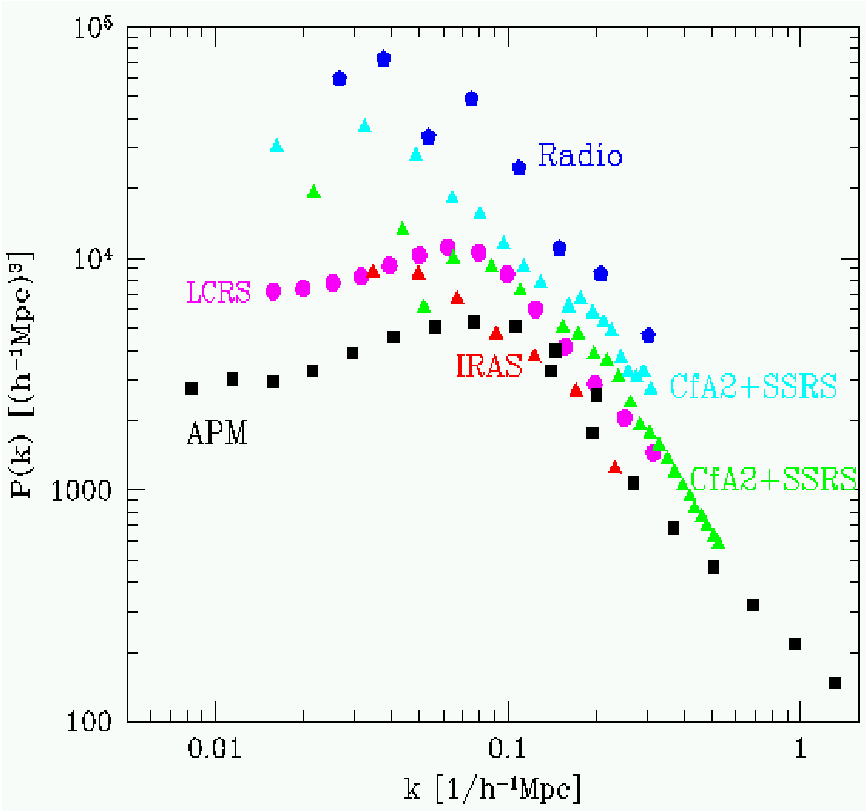

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

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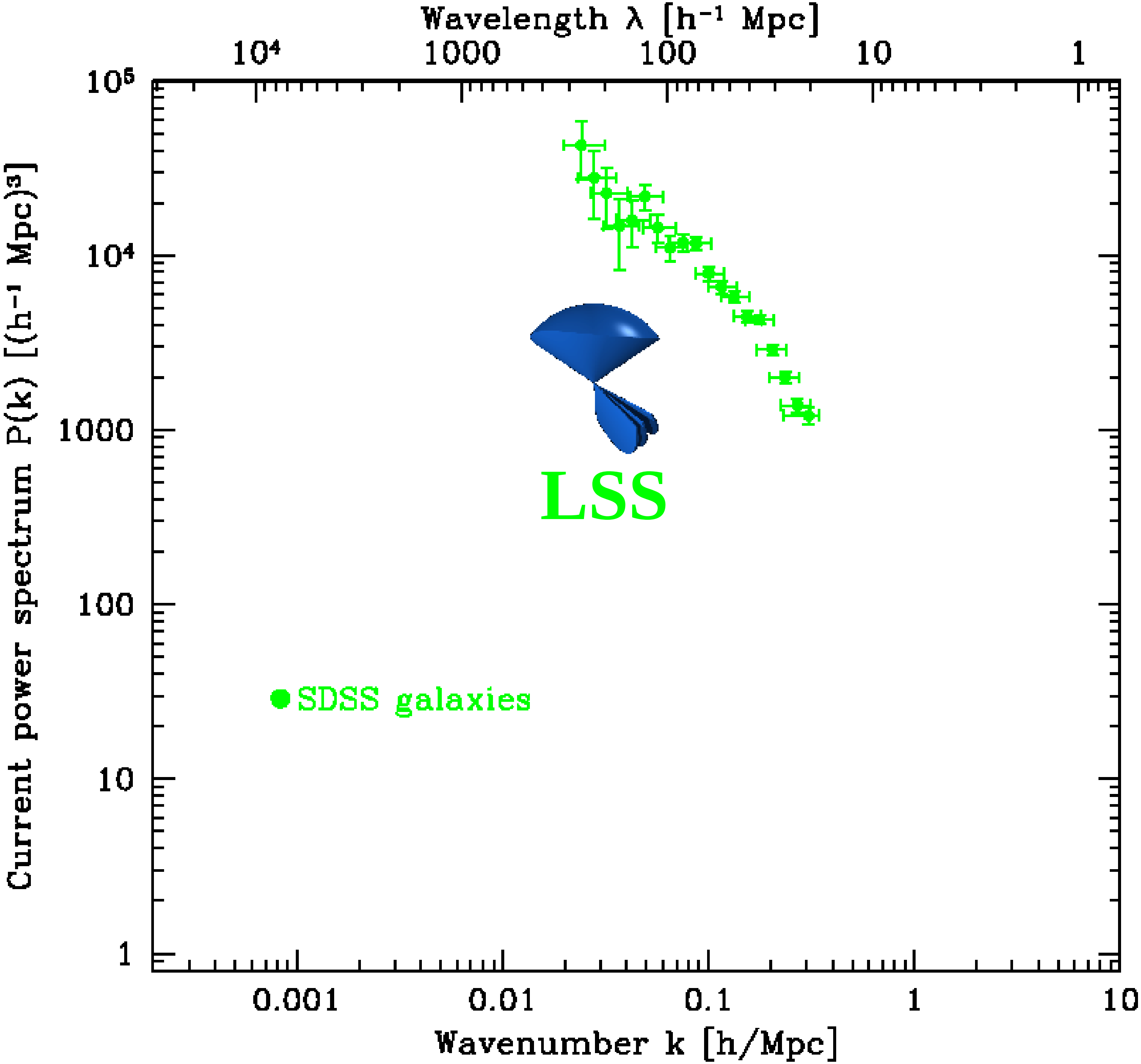

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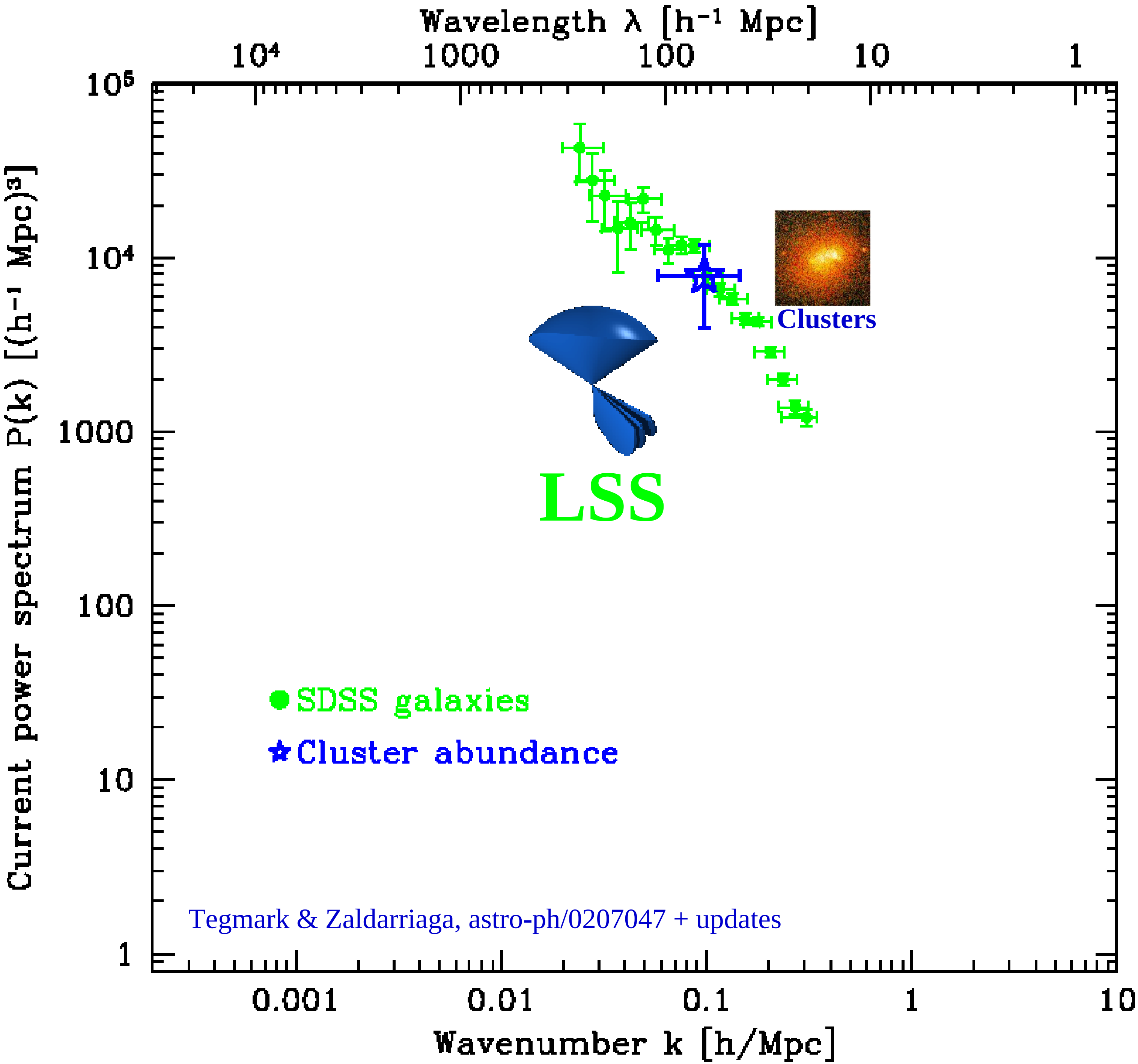

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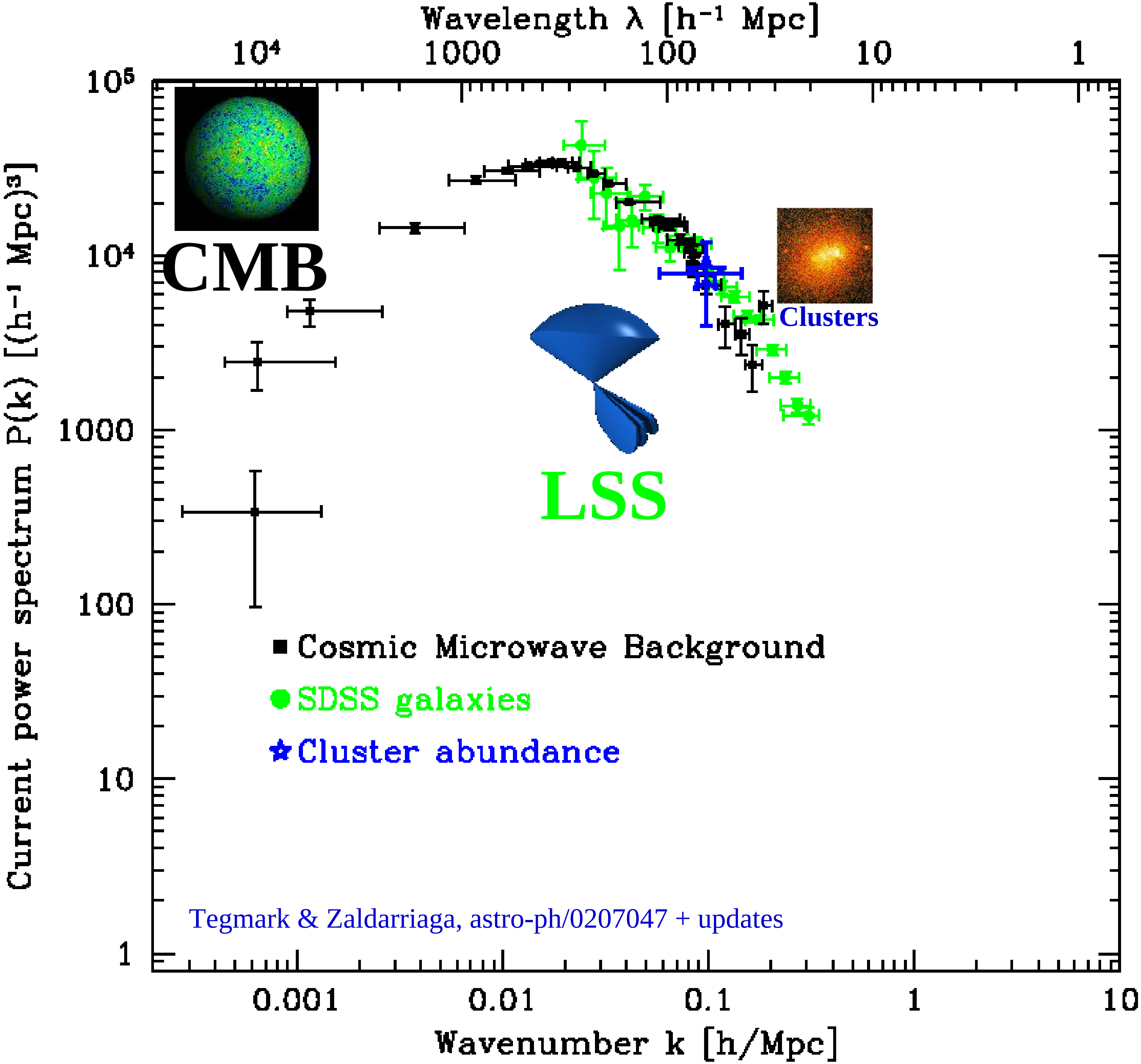

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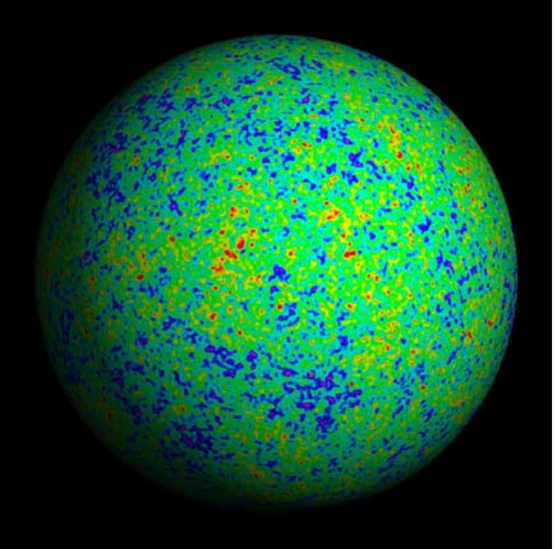

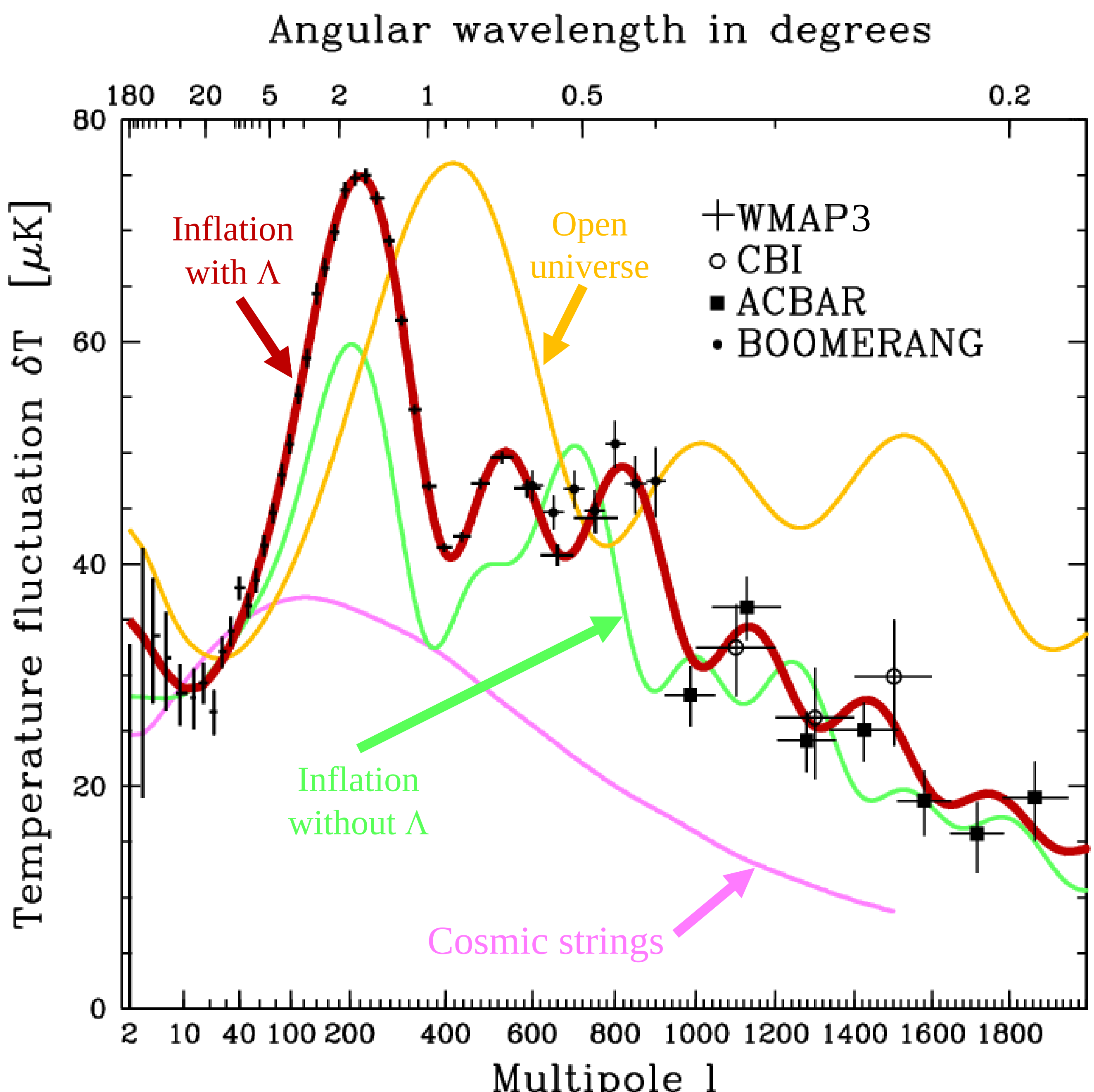

Guth & Kaiser 2005 (Science) + WMAP3

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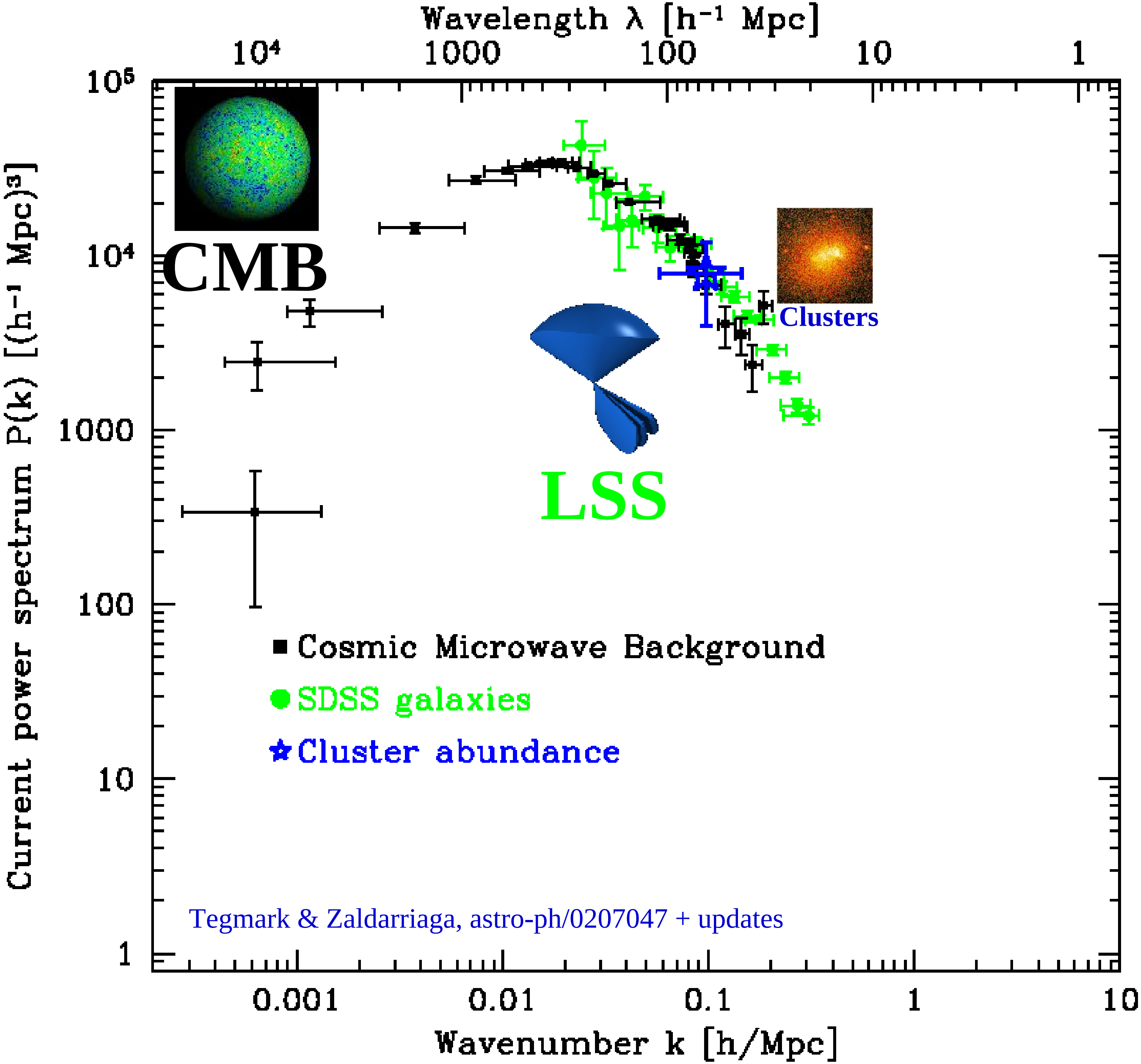

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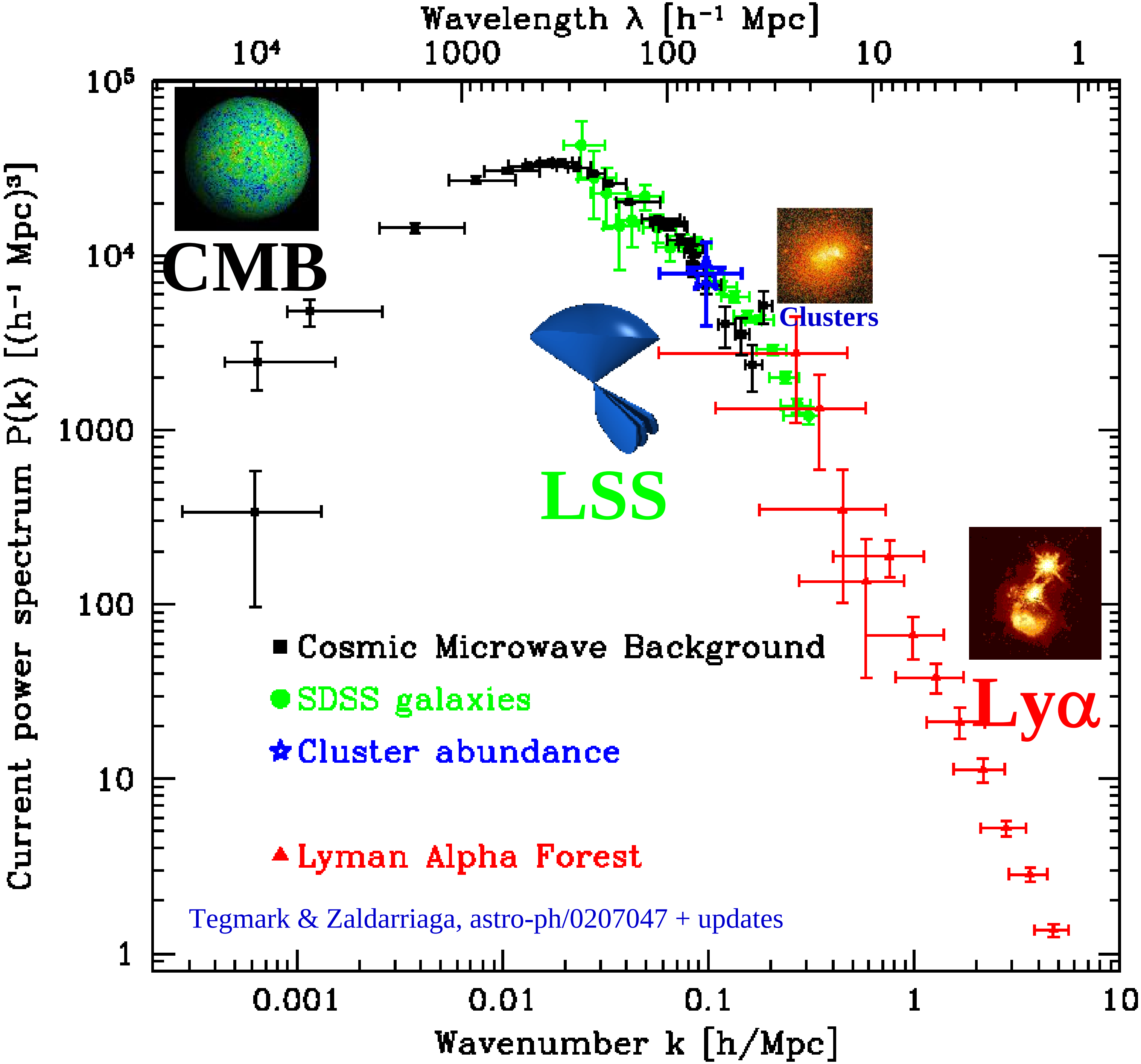

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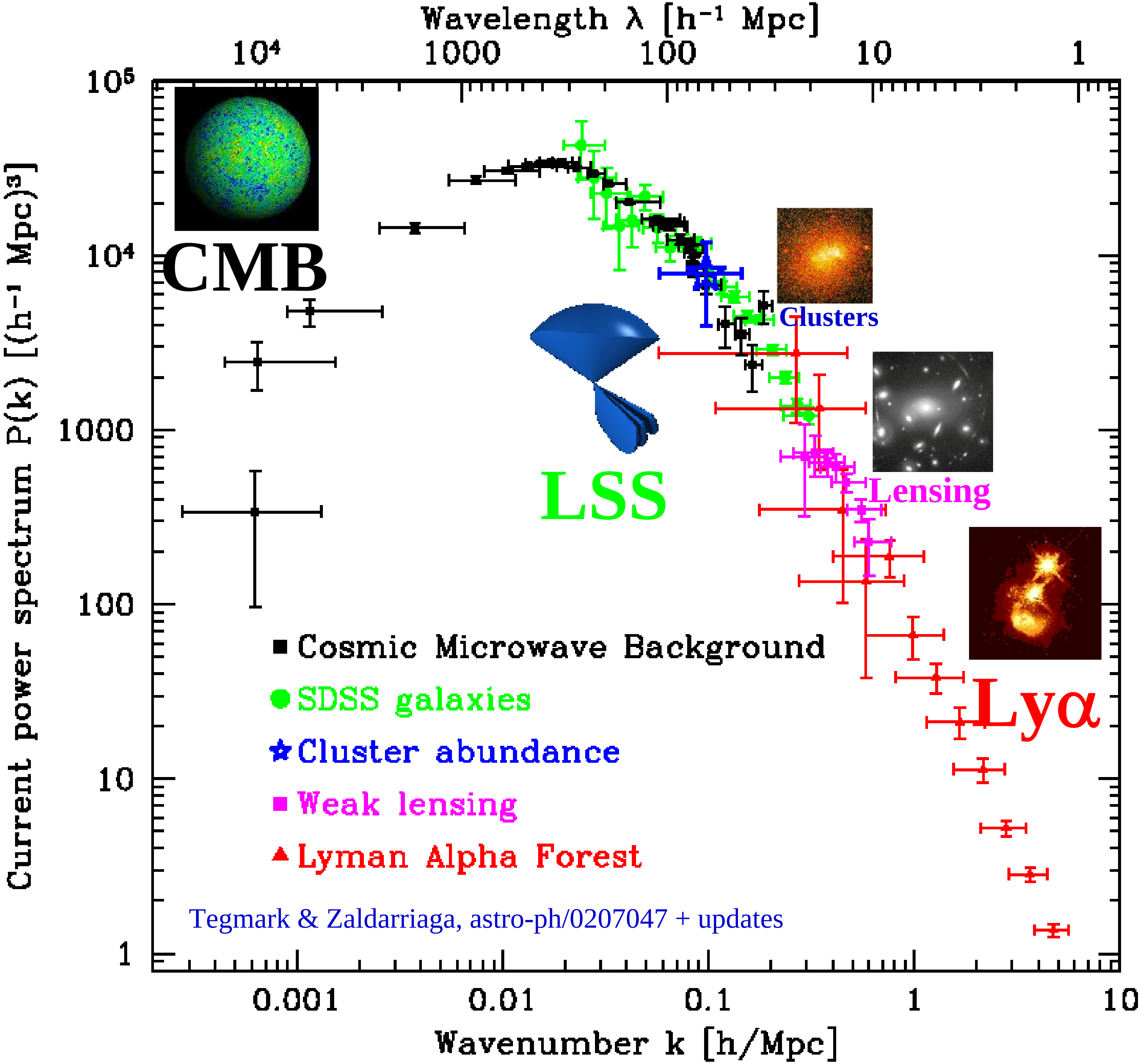

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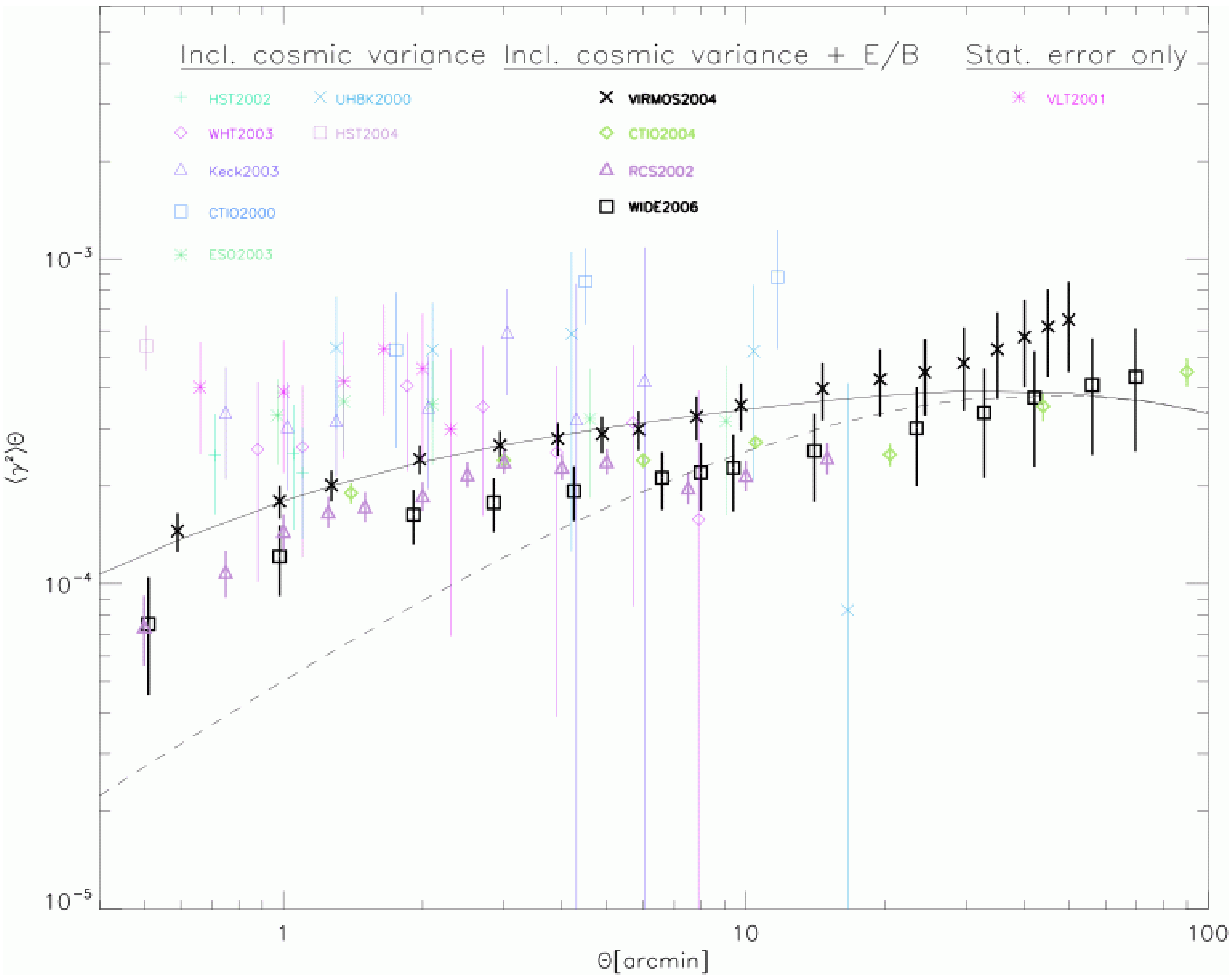
Current lensing measurements:



Compilation from Munshi, Valageas, van Waerbeke & Heavens, astro-ph/0612667

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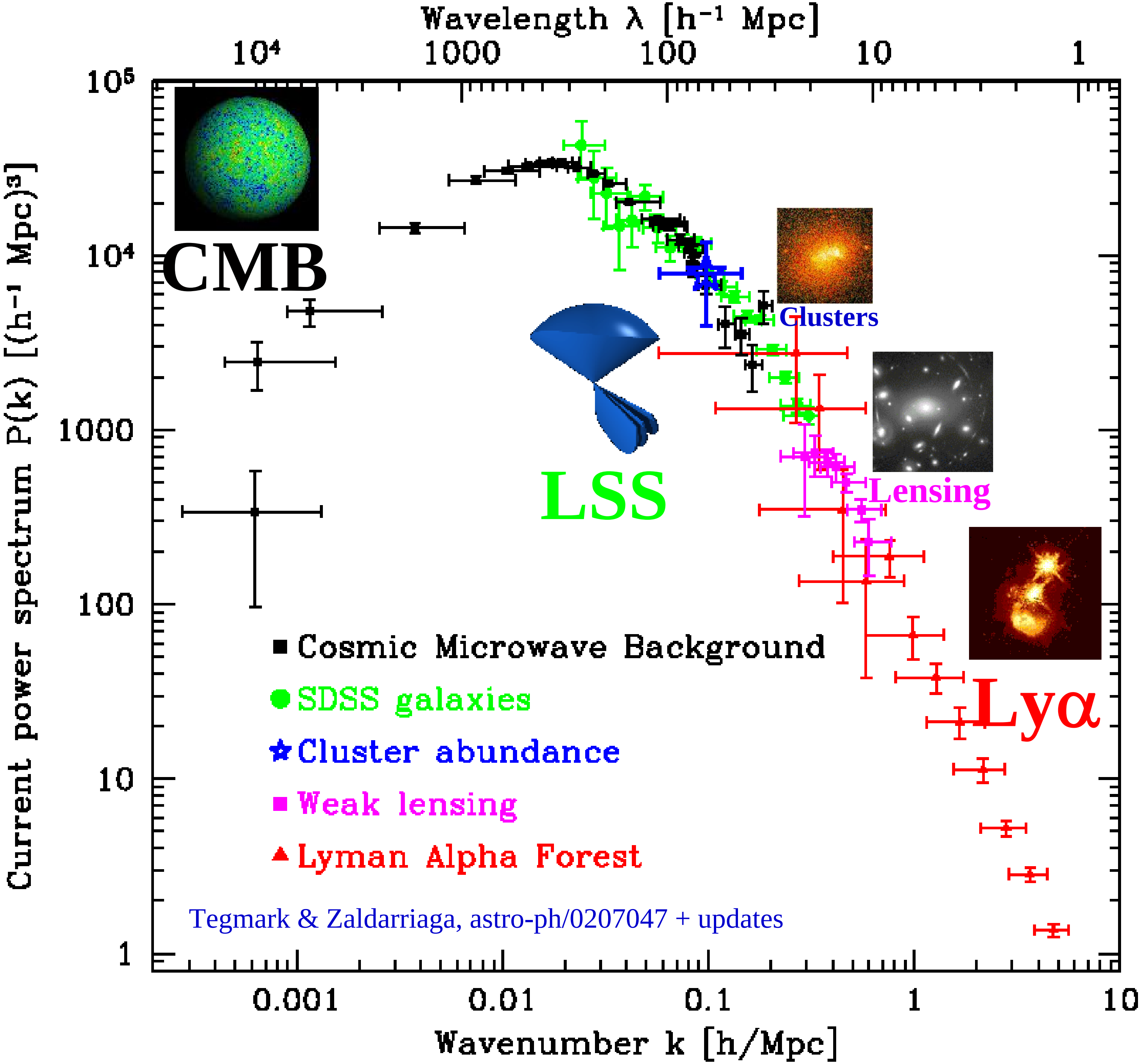

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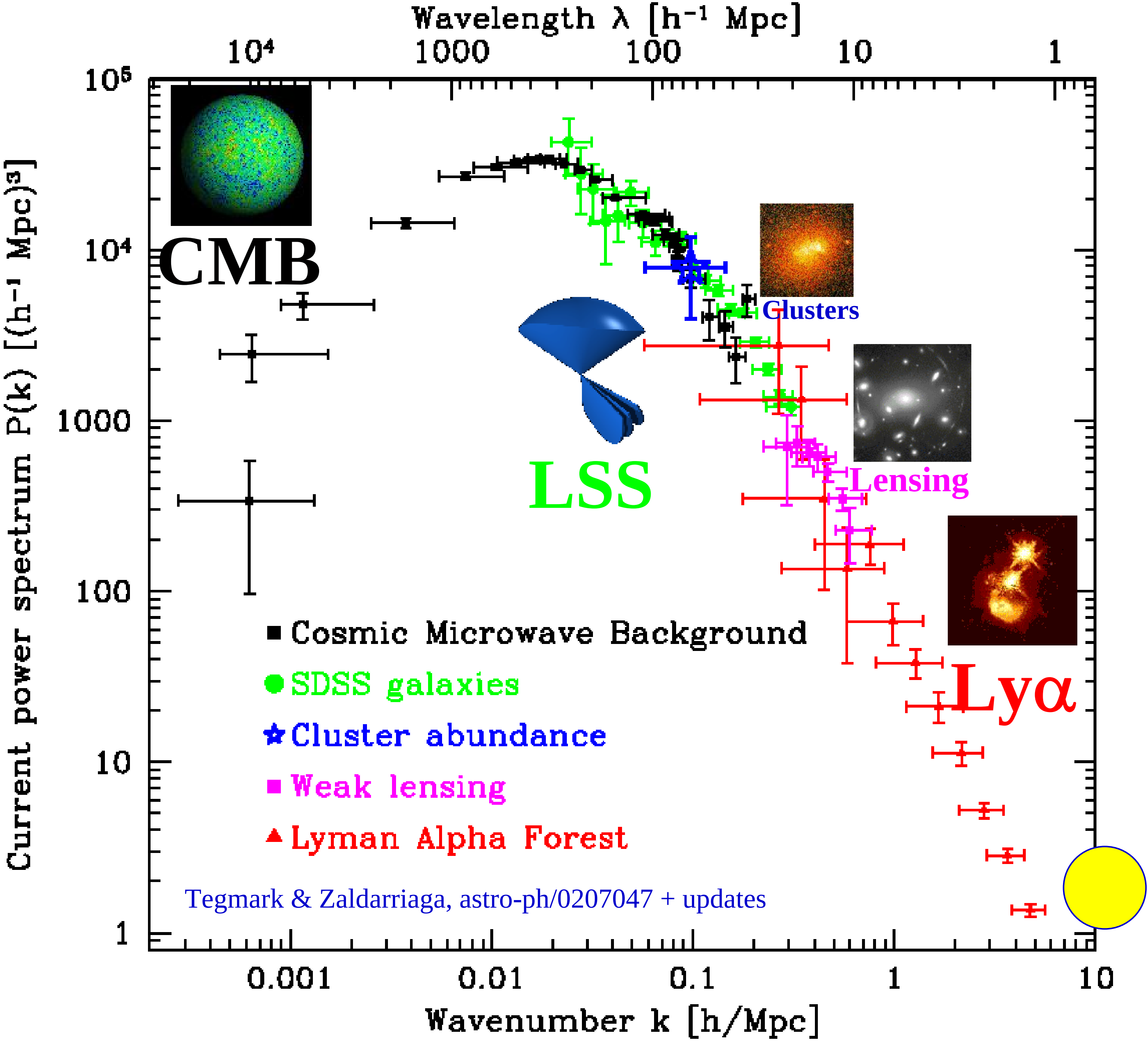

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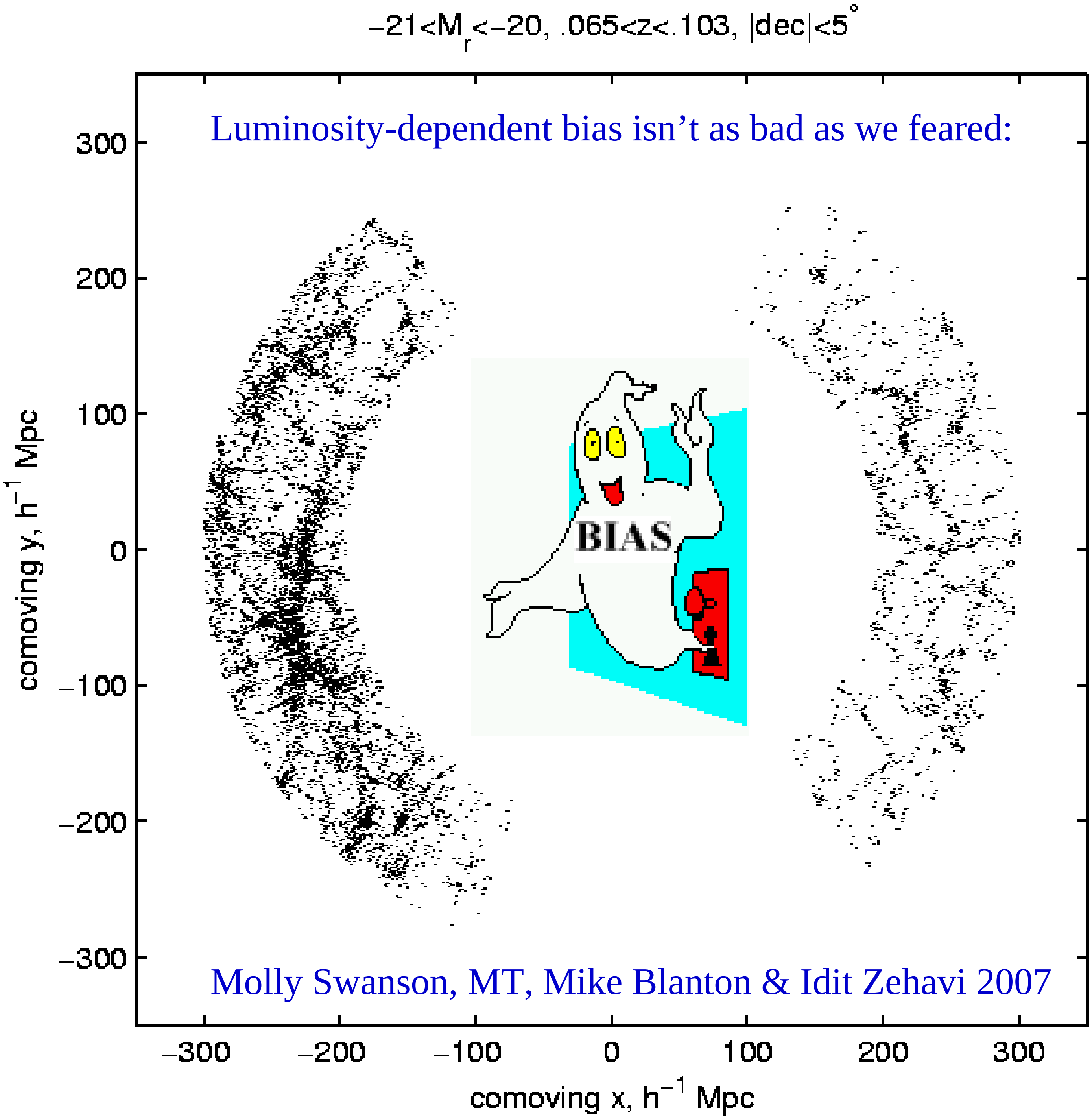
Galaxy clustering progress

Luminosity-dependent bias isn't as bad as we feared:



Molly Swanson, MT, Mike Blanton & Idit Zehavi 2007

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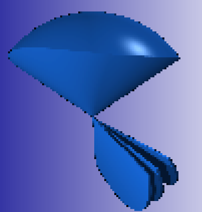
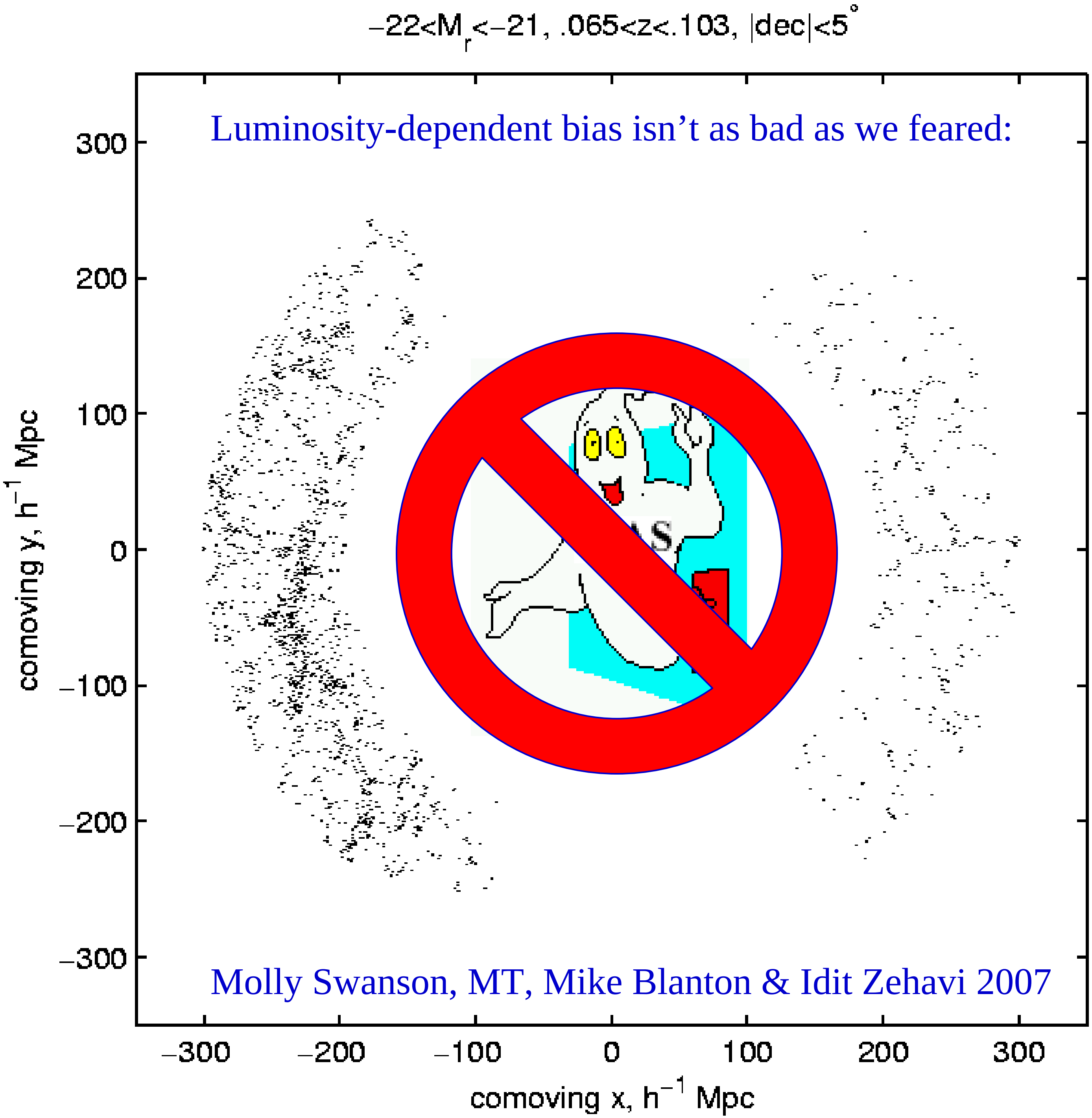


Luminosity-dependent bias isn't as bad as we feared:



Molly Swanson, MT, Mike Blanton & Idit Zehavi 2007

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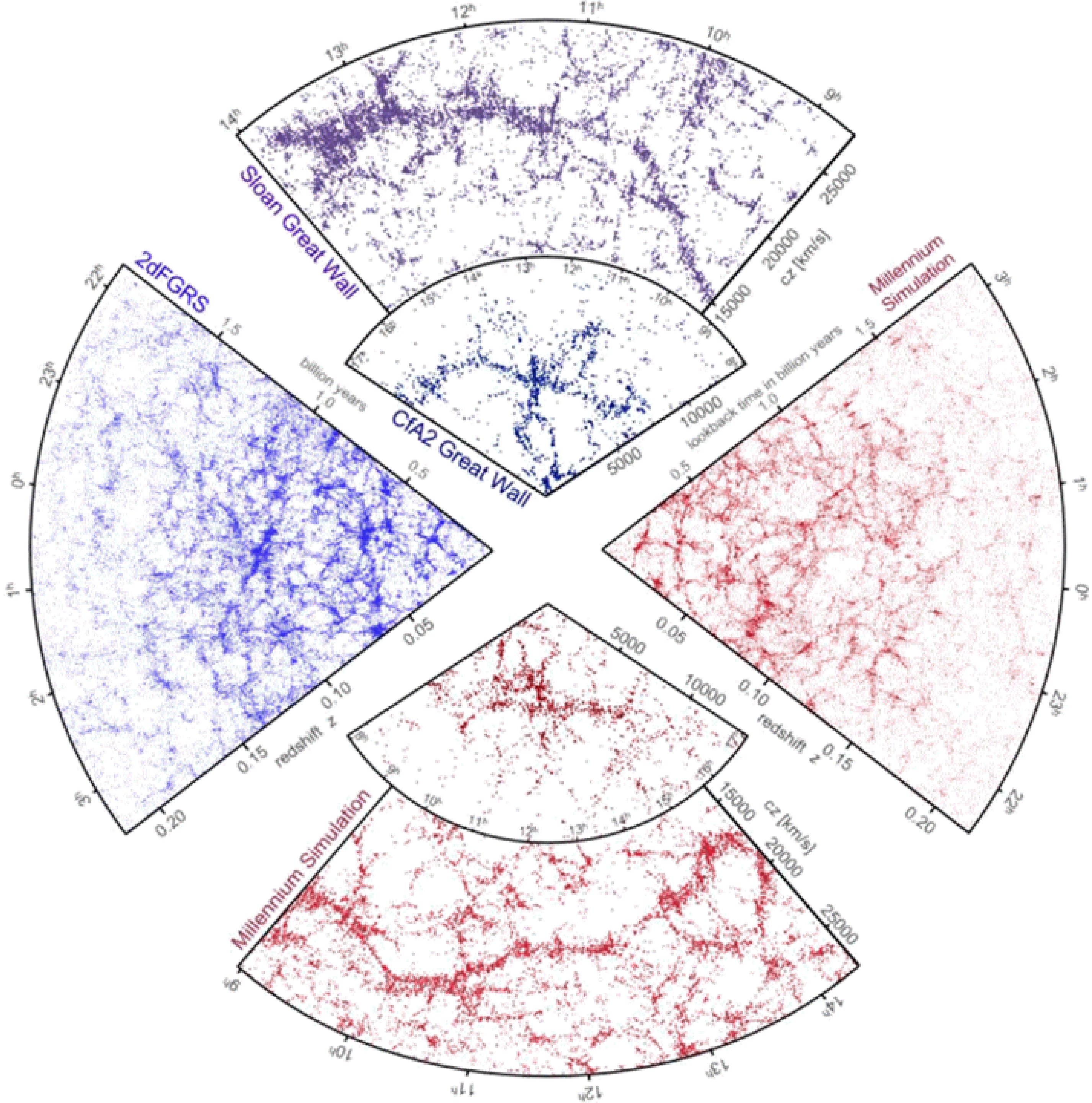
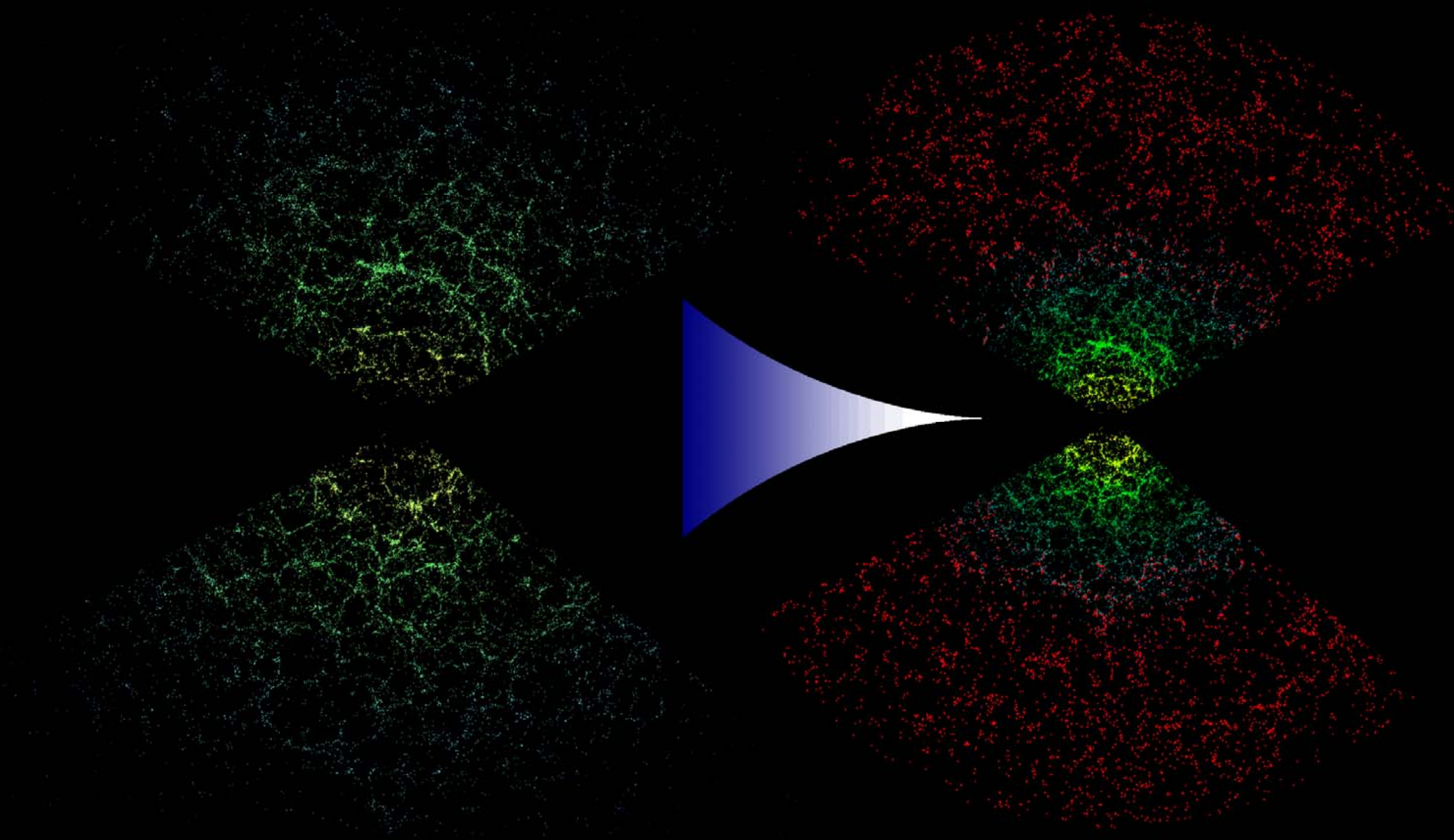
Cosmological Constraints from the SDSS Luminous Red Galaxies

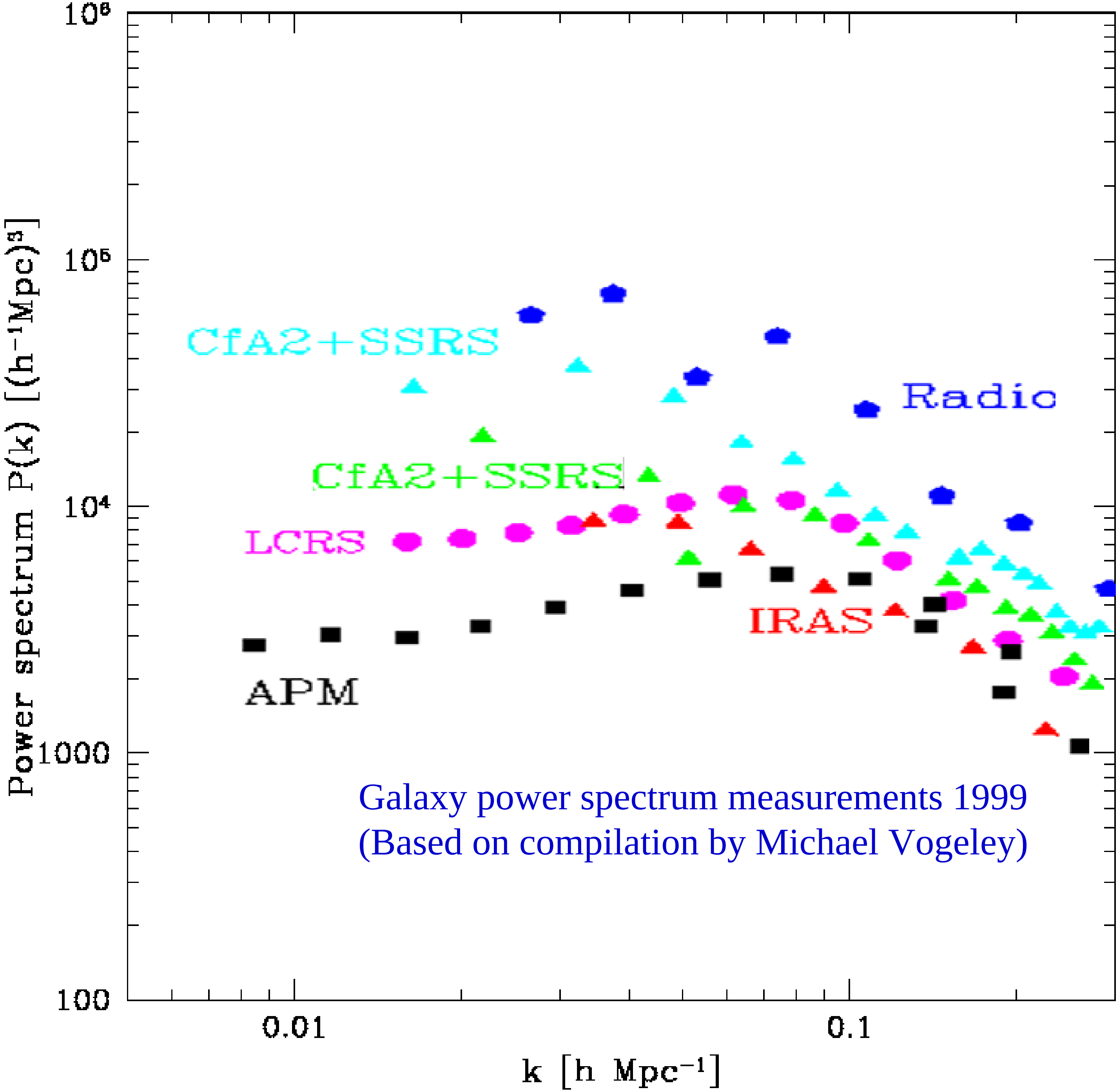
Max Tegmark[1], Daniel J. Eisenstein[2], Michael A. Strauss[3], David H. Weinberg[4], Michael R. Blanton[5], Joshua A. Frieman[6,7], Masataka Fukugita[8], James E. Gunn[3], Andrew J. S. Hamilton[9], Gillian R. Knapp[3], Robert C. Nichol[10], Jeremiah P. Ostriker[3], Nikhil Padmanabhan[11], Will J. Percival[10], David J. Schlegel[12], Donald P. Schneider[13], Roman Scoccimarro[5], Uroš Seljak[14,11], Hee-Jong Seo[2], Molly Swanson[1], Alexander S. Szalay[15], Michael S. Vogeley[16], Jaiyul Yoo[4], Idit Zehavi[17], Kevork Abazajian[18], Scott F. Anderson[19], James Annis[7], Neta A. Bahcall[3], Bruce Bassett[20,21], Andreas Berlind[5], Jon Brinkmann[22], Tamás Budavari[15], Francisco Castander[23], Andrew Connolly[24], Istvan Csabai[15], Mamoru Doi[25], Douglas P. Finkbeiner[3,26], Bruce Gillespie[22], Karl Glazebrook[15], Gregory S. Hennessy[27], David W. Hogg[5], Željko Ivezić[19,3], Bhuvnesh Jain[28], David Johnston[29,30], Stephen Kent[7], Donald Q. Lamb[6,31], Brian C. Lee[32,12], Huan Lin[7], Jon Loveday[33], Robert H. Lupton[3], Jeffrey A. Munn[27], Kaike Pan[22], Changbom Park[34], John Peoples[7], Jeffrey R. Pier[27], Adrian Pope[15], Michael Richmond[35], Constance Rockosi[6], Ryan Scranton[24], Ravi K. Sheth[28], Albert Stebbins[7], Christopher Stoughton[7], István Szapudi[36], Douglas L. Tucker[7], Daniel E. Vanden Berk[24], Brian Yanny[7], Donald G. York[6,31]

[1]Dept. of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA; [2]Department of Astronomy, University of Arizona, Tucson, AZ 85721, USA; [3]Princeton University Observatory, Princeton, NJ 08544, USA; [4]Dept. of Astronomy, Ohio State University, Columbus, OH 43210, USA; [5]Center for Cosmology and Particle Physics, Dept. of Physics, New York University, 4 Washington Pl., New York, NY 10003, USA; [6]Center for Cosmological Physics and Department of Astronomy & Astrophysics, Univ. of Chicago, Chicago, IL 60637, USA; [7]Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA; [8]Inst. for Cosmic Ray Research, Univ. of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, 277-8582, Japan; [9]JILA and Dept. of Astrophysical and Planetary Sciences, Univ. of Colorado, Boulder, CO 80309, USA; [10]Inst. of Cosmology & Gravitation, Univ. of Portsmouth, Portsmouth, P01 2EG, United Kingdom; [11]Dept. of Physics, Princeton University, Princeton, NJ 08544, USA; [12]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA; [13]Dept. of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA; [14]International Center for Theoretical Physics, Strada Costiera 11, 34014 Trieste, Italy; [15]Department of Physics and Astronomy, The Johns Hopkins University, 3701 San Martin Drive, Baltimore, MD 21218, USA; [16]Dept. of Physics, Drexel University, Philadelphia, PA 19104, USA; [17]Dept. of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106-7215; [18]Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA; [19]Dept. of Astronomy, Univ. of Washington, Box 351580, Seattle, WA 98195; [20]South African Astronomical Observatory, Cape Town, South Africa; [21]Applied Mathematics Dept., Univ. of Cape Town, Cape Town, South Africa; [22]Apache Point Observatory, 2001 Apache Point Rd, Sunspot, NM 88349-0059, USA; [23]Institut d'Estudis Espacials de Catalunya/CSIC, Campus UAB, 08034 Barcelona, Spain; [24]University of Pittsburgh, Department of Physics and Astronomy, 3941 O'Hara Street, Pittsburgh, PA 15260, USA; [25]Inst. of Astronomy, Univ. of Tokyo, Osawa 2-21-1, Mitaka, Tokyo, 181-0015, Japan; [26]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, MS46, Cambridge, MA 02138; [27]U.S. Naval Observatory, Flagstaff Station, 10391 W. Naval Obs. Rd., Flagstaff, AZ 86001-8521, USA; [28]Department of Physics, University of Pennsylvania, Philadelphia, PA 19104,

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







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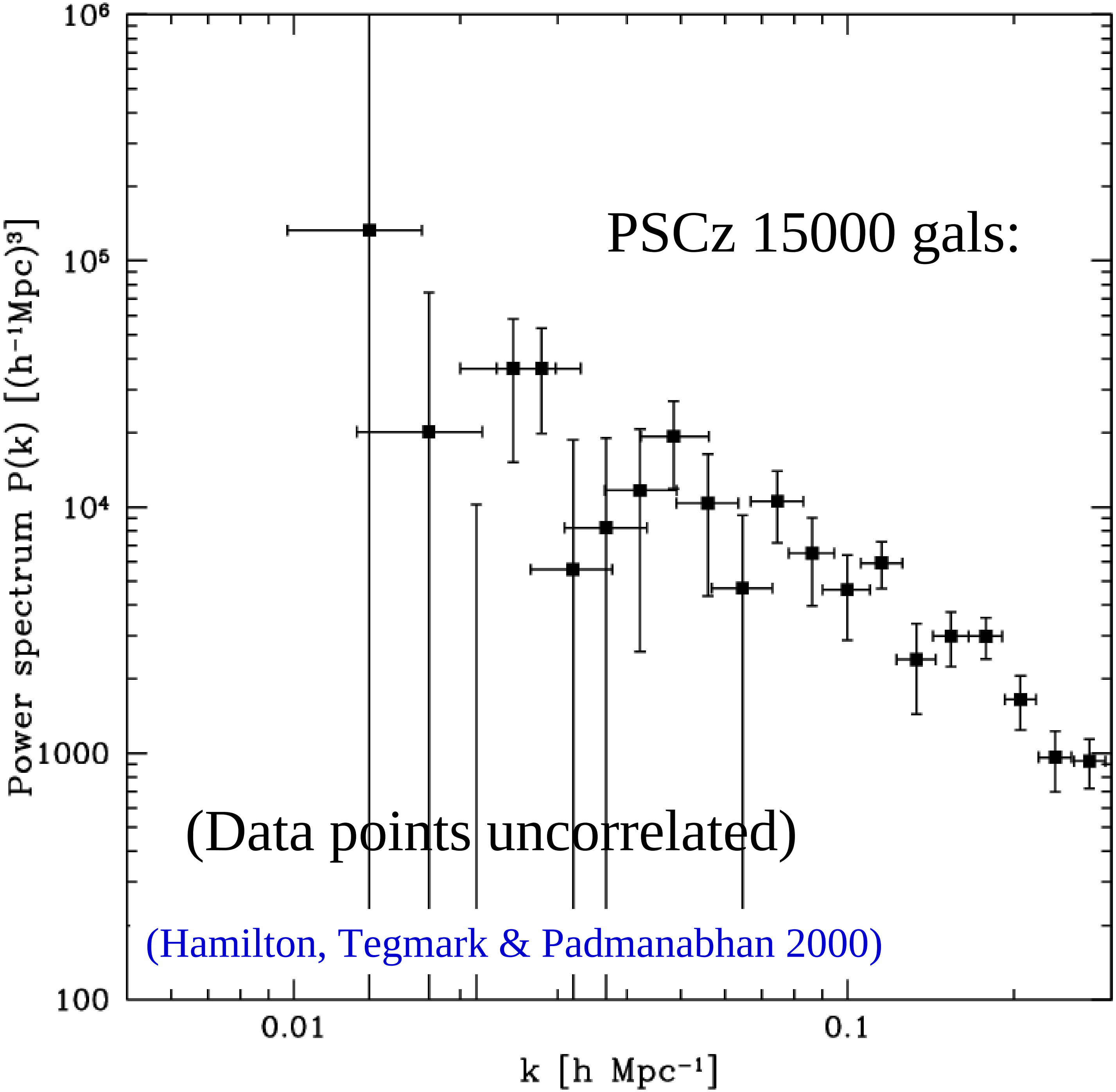

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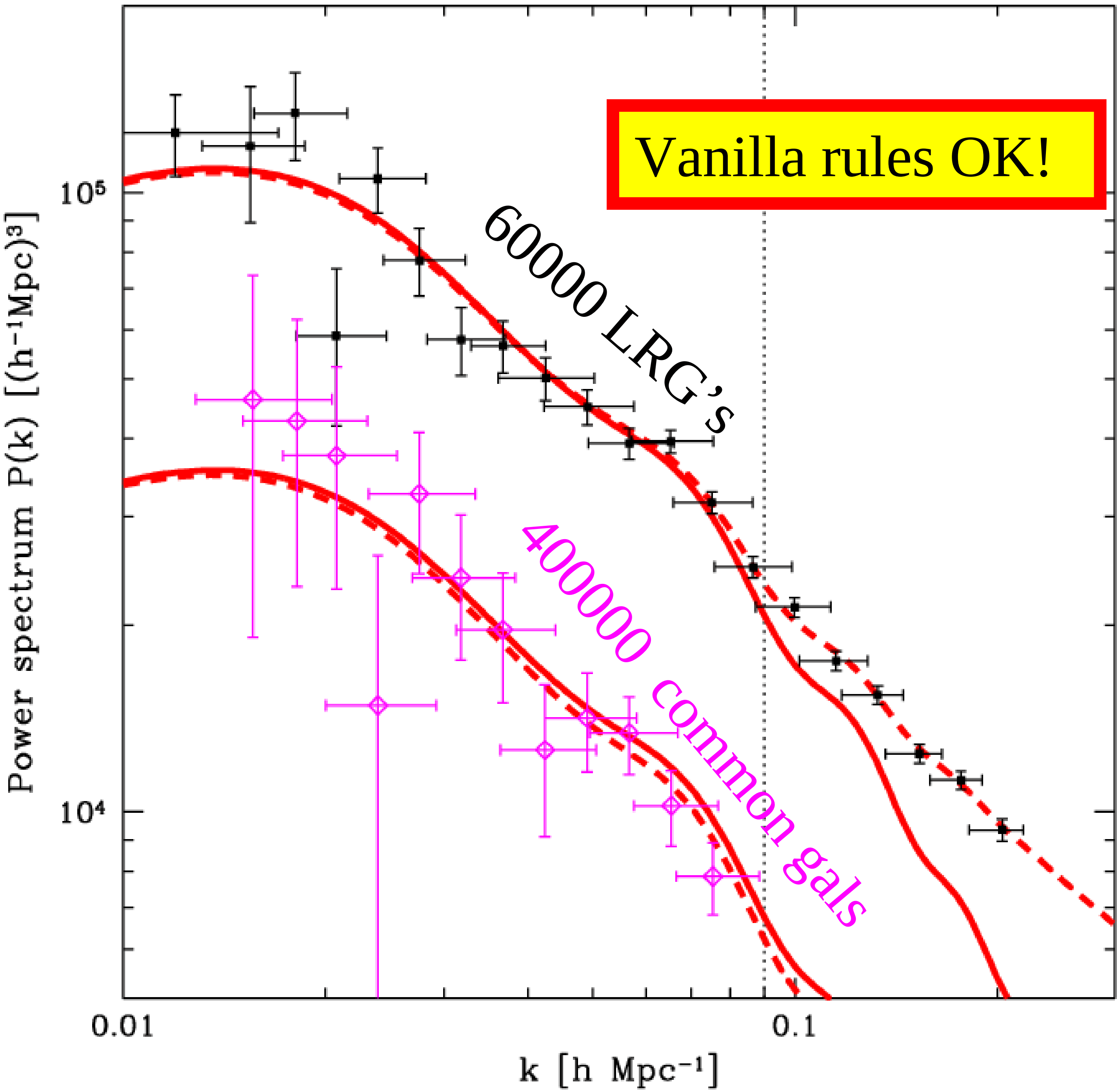

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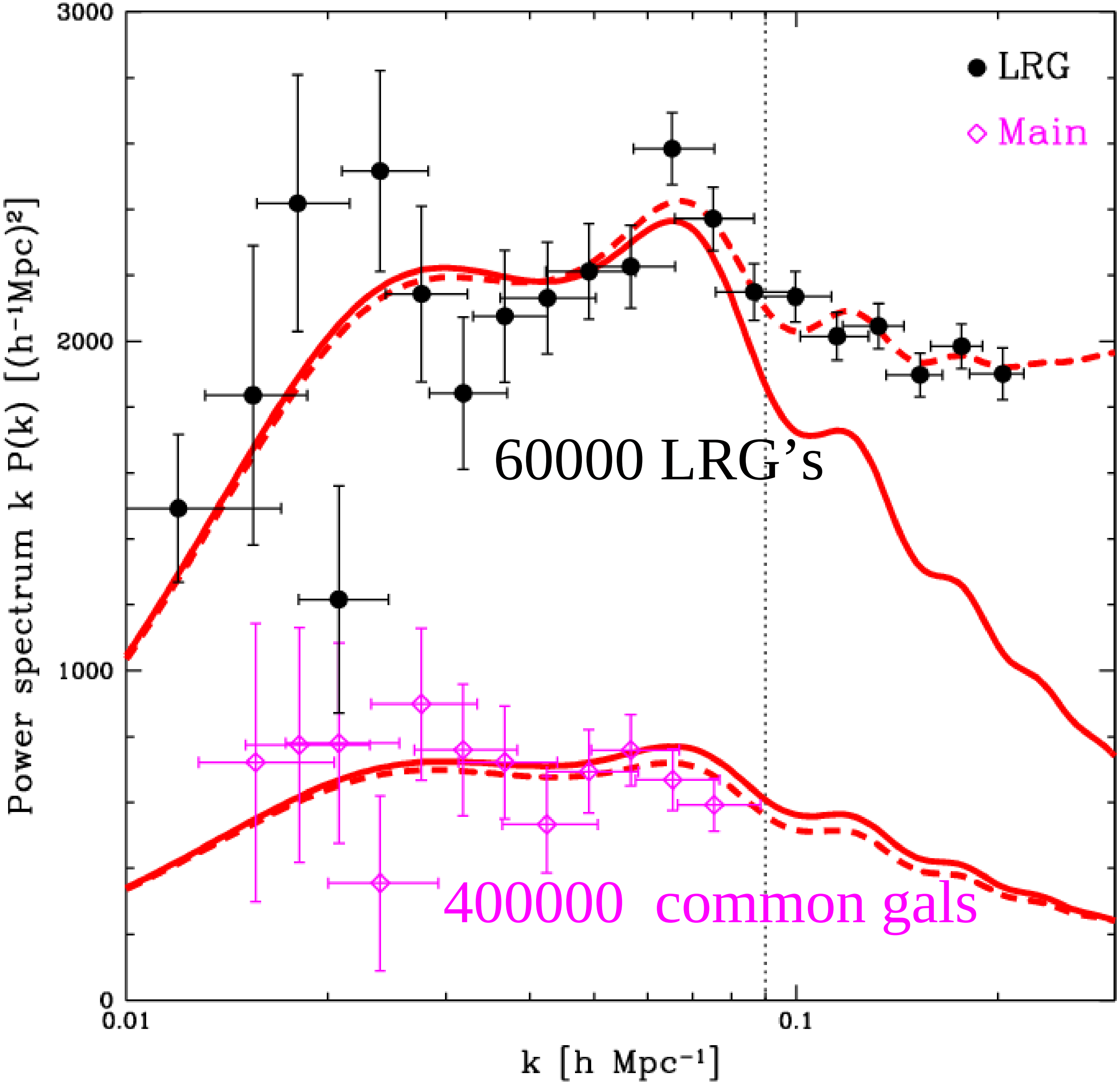

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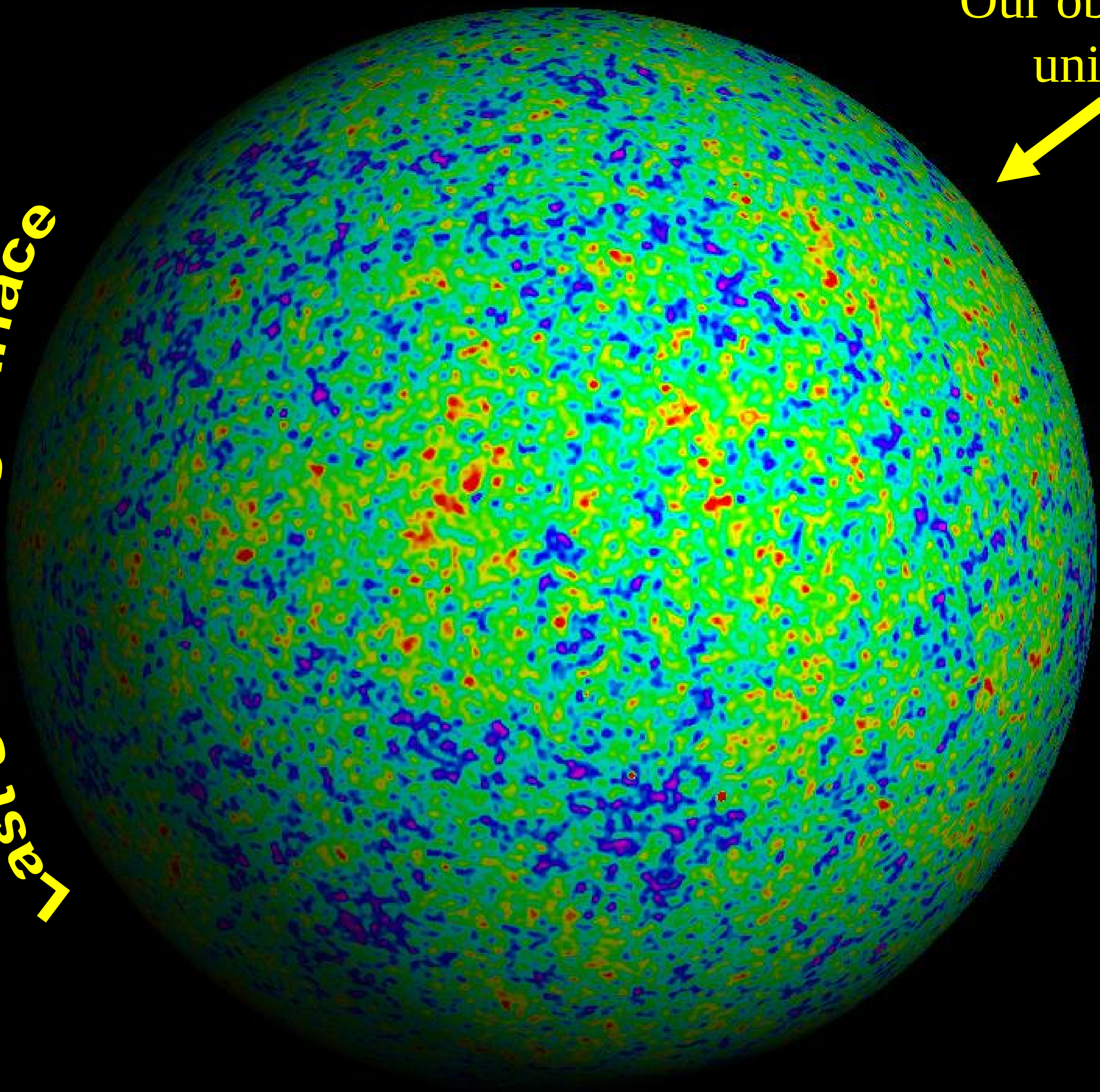
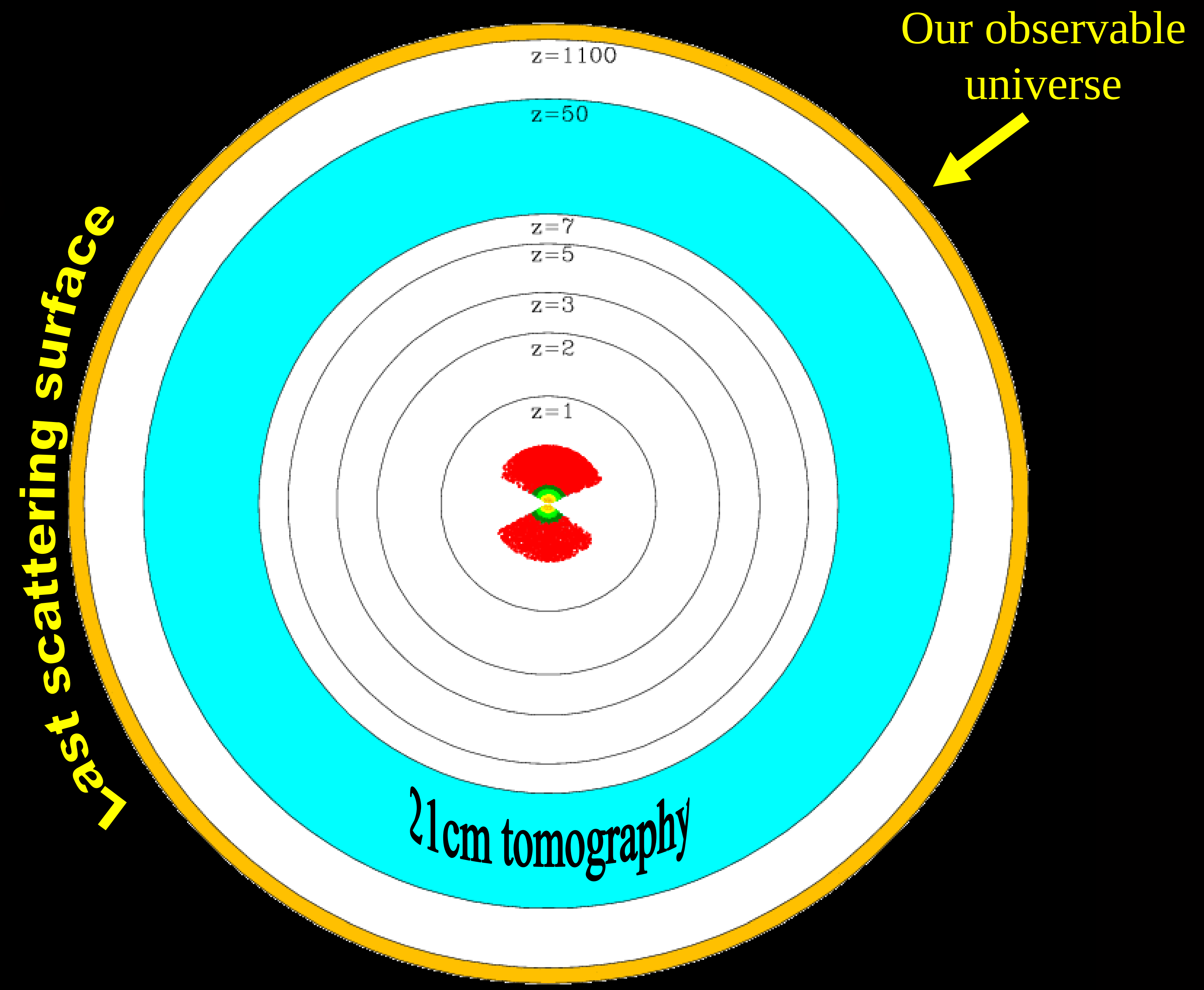
Why are LRGs so useful?

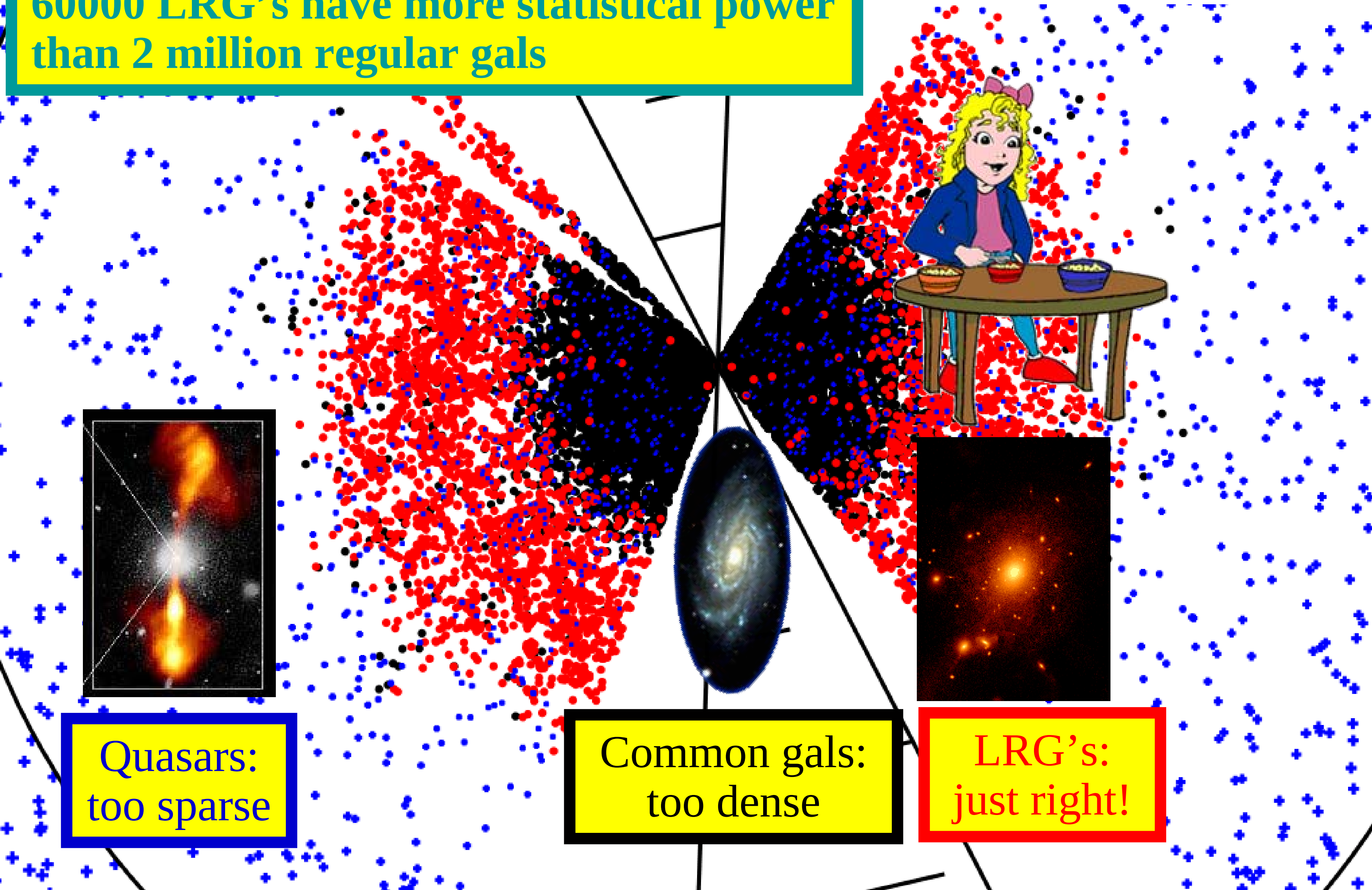


Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496


Our observable universe
Last scattering surface
z=1100
z=50
z=7
z=5
z=3
z=2
z=1
21cm tomography

Why LRG's are "Goldilocks galaxies":

60000 LRG's have more statistical power than 2 million regular gals



Quasars: too sparse

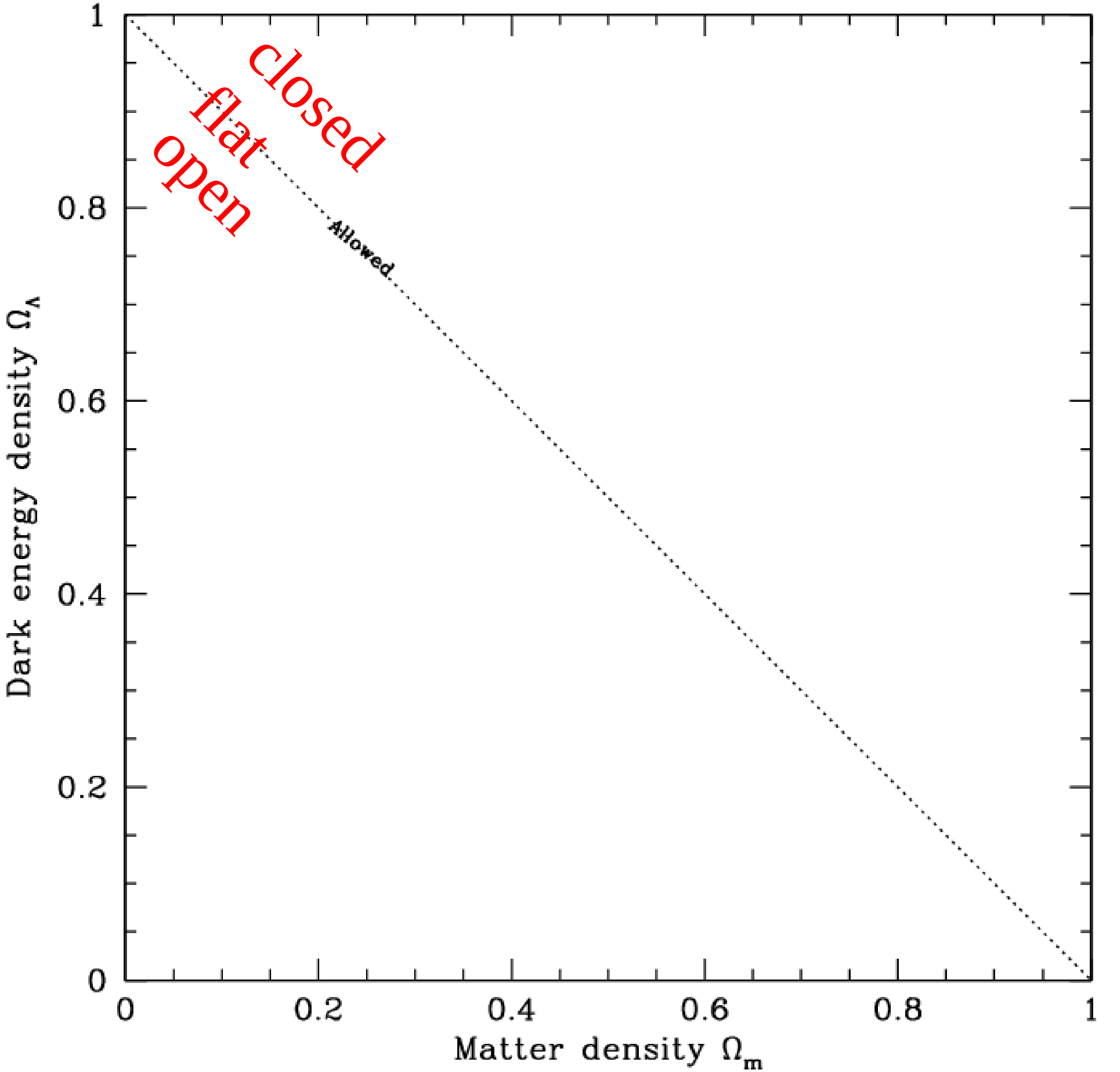
Common gals: too dense

LRG's: just right!

Cosmological parameters

Inflation

How flat is space?



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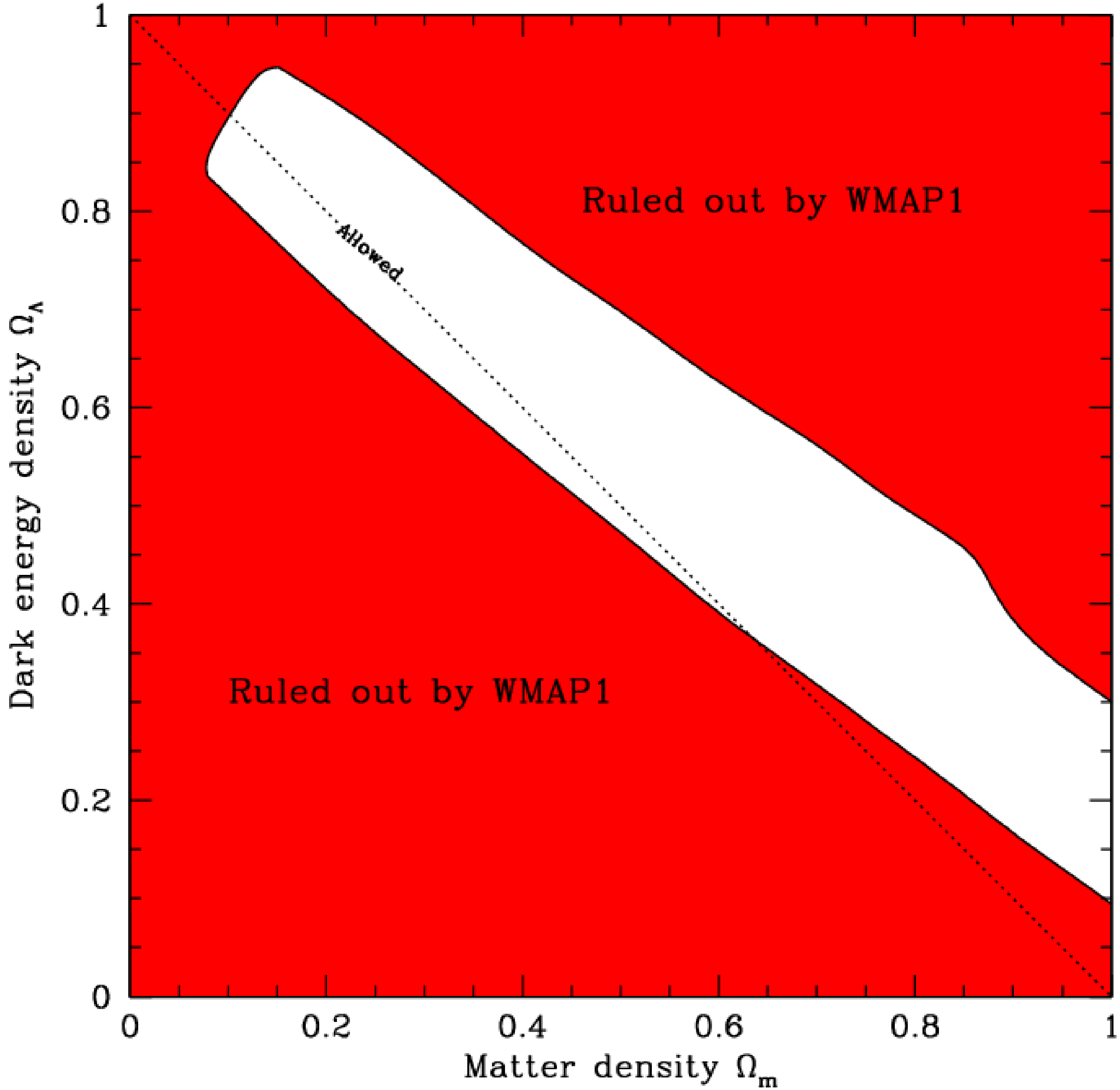
How flat is space?



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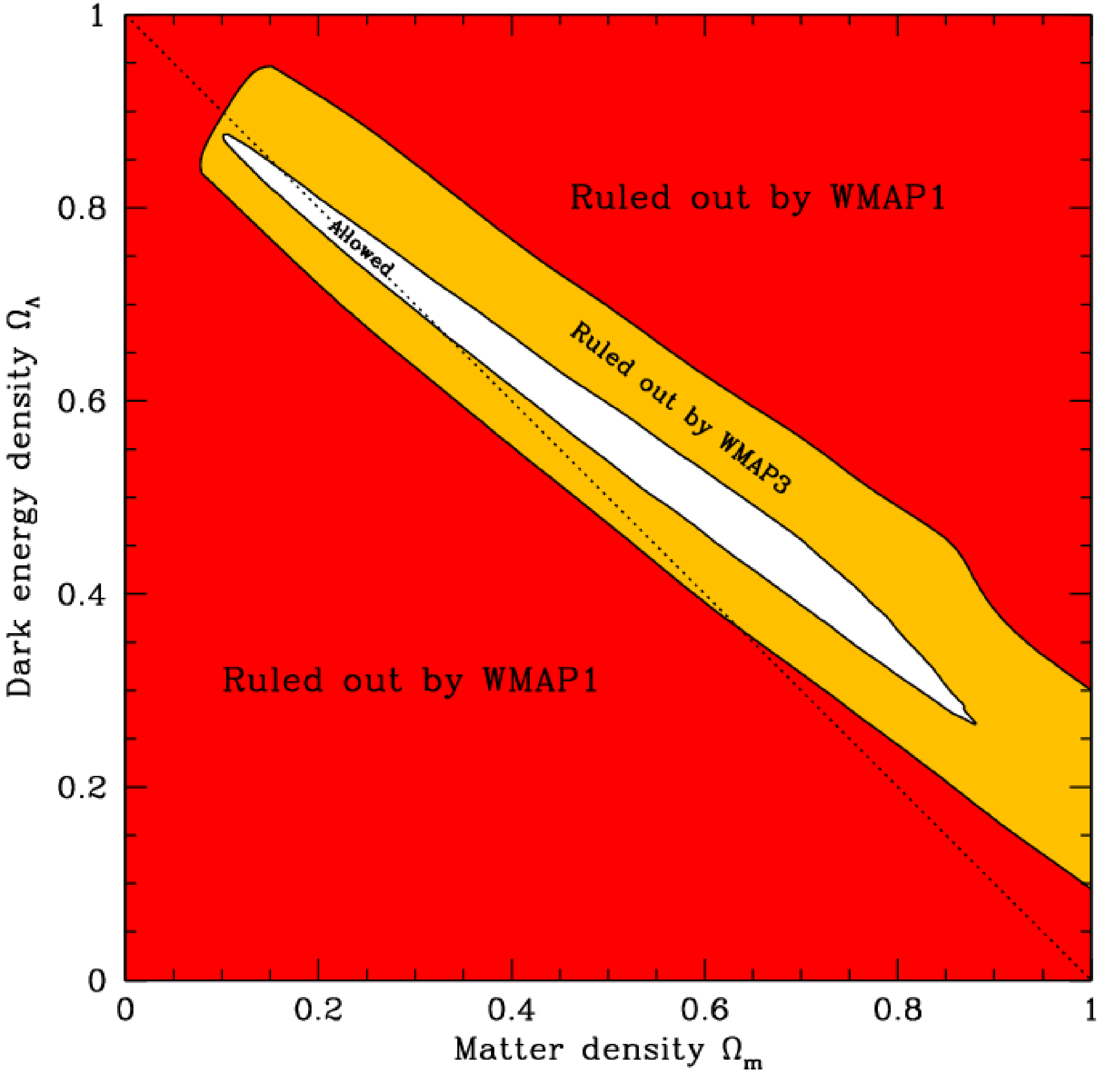
How flat is space? Somewhat.



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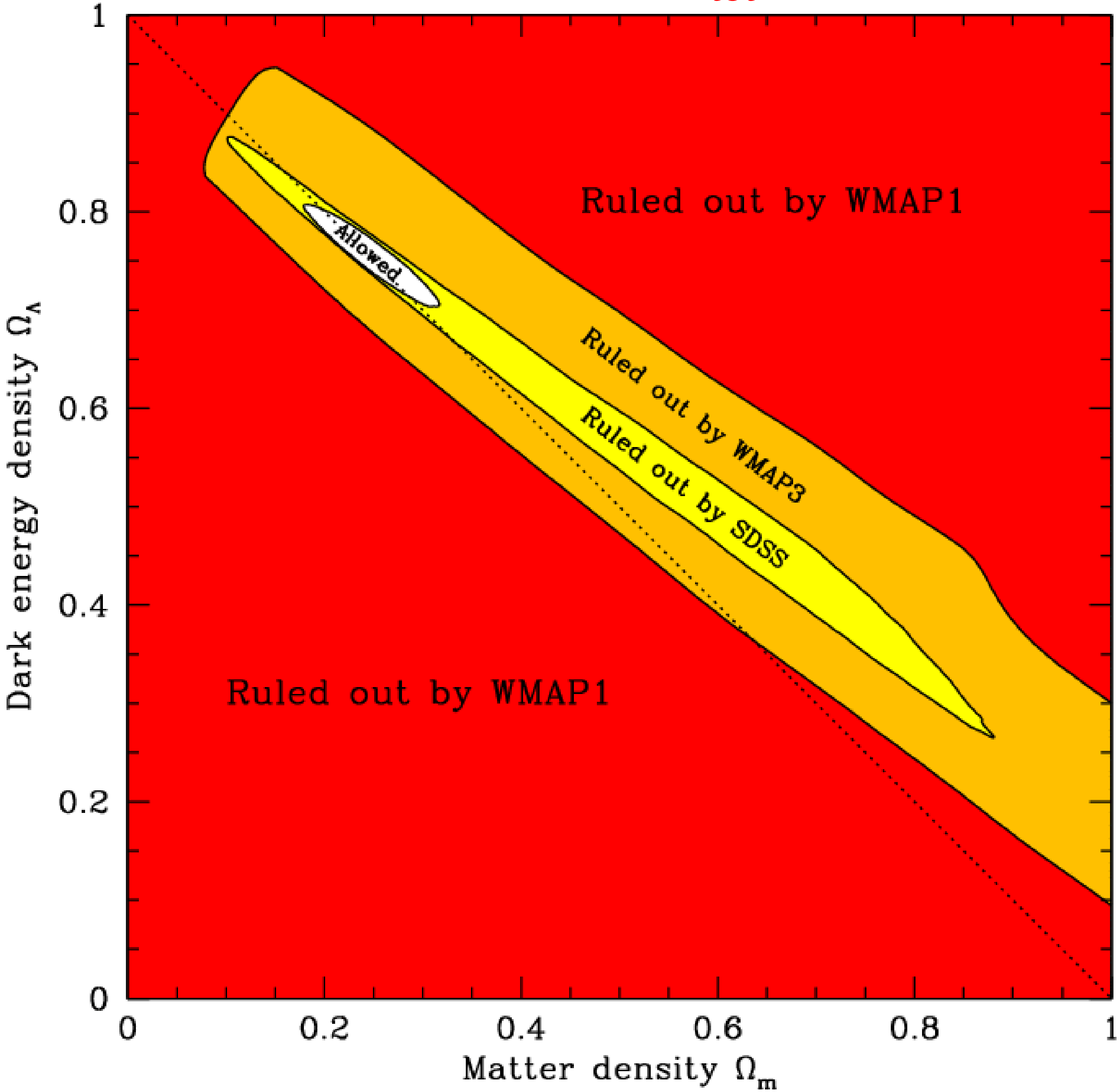
How flat is space? Ω_{tot}=1.003±0.010



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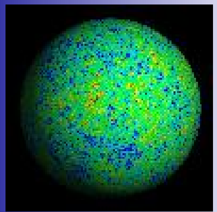
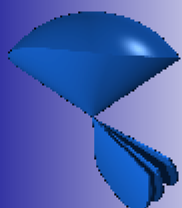


CMB

+



LSS

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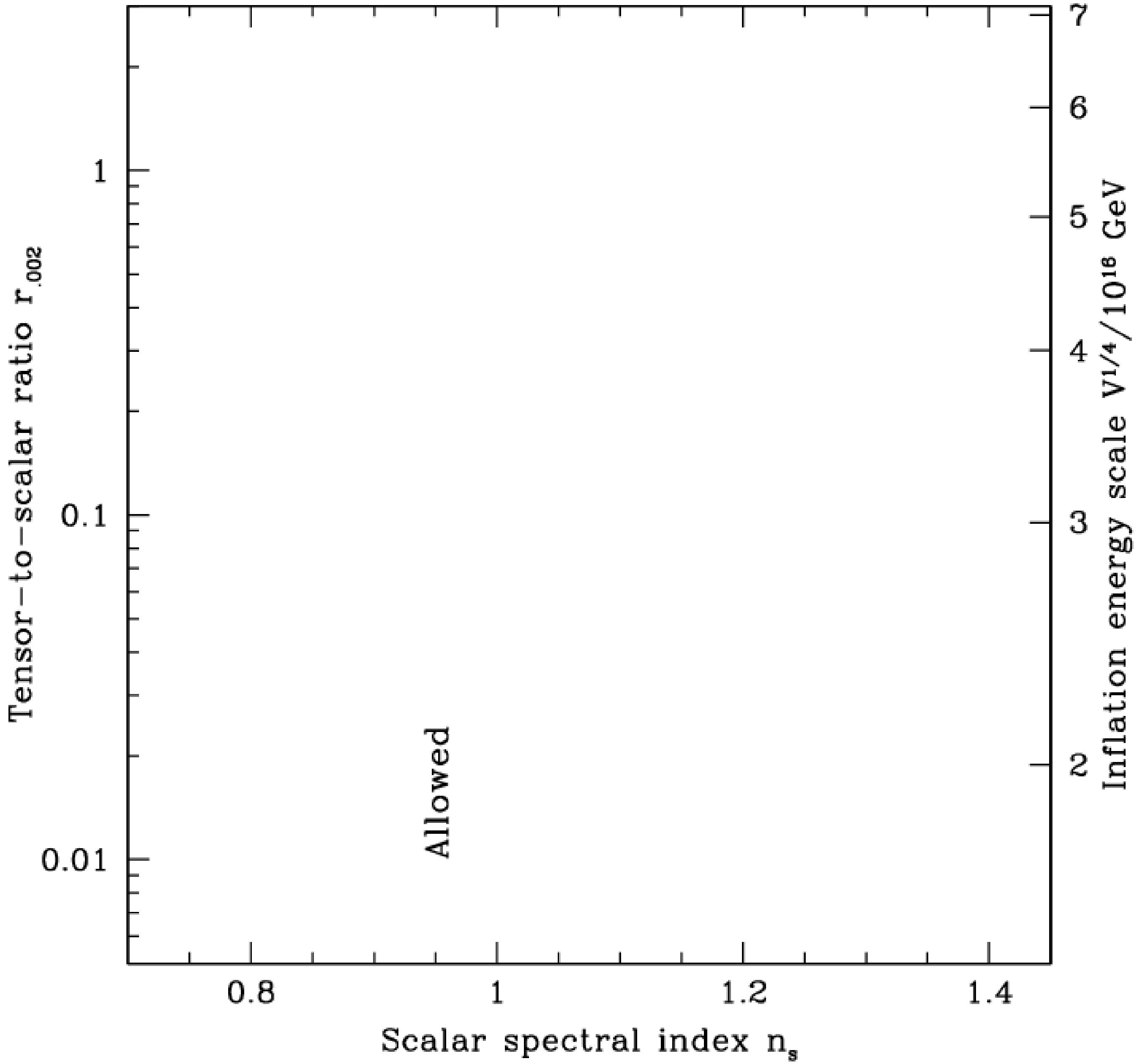
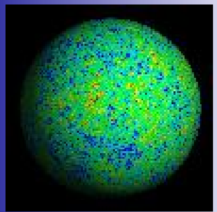
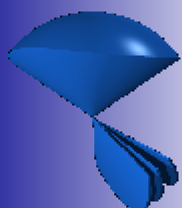


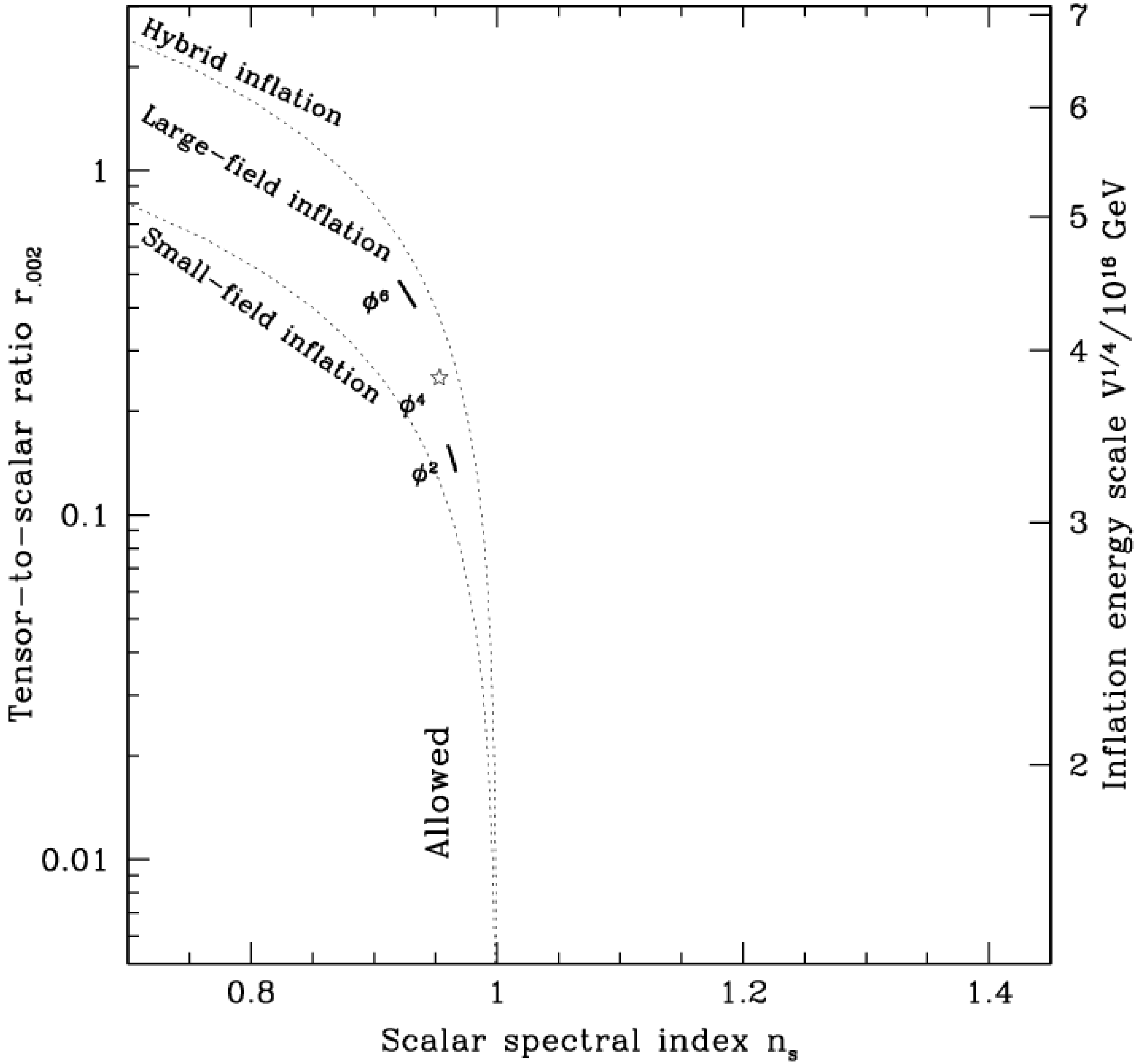


CMB

+



LSS



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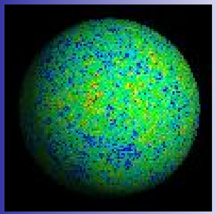
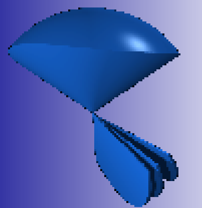
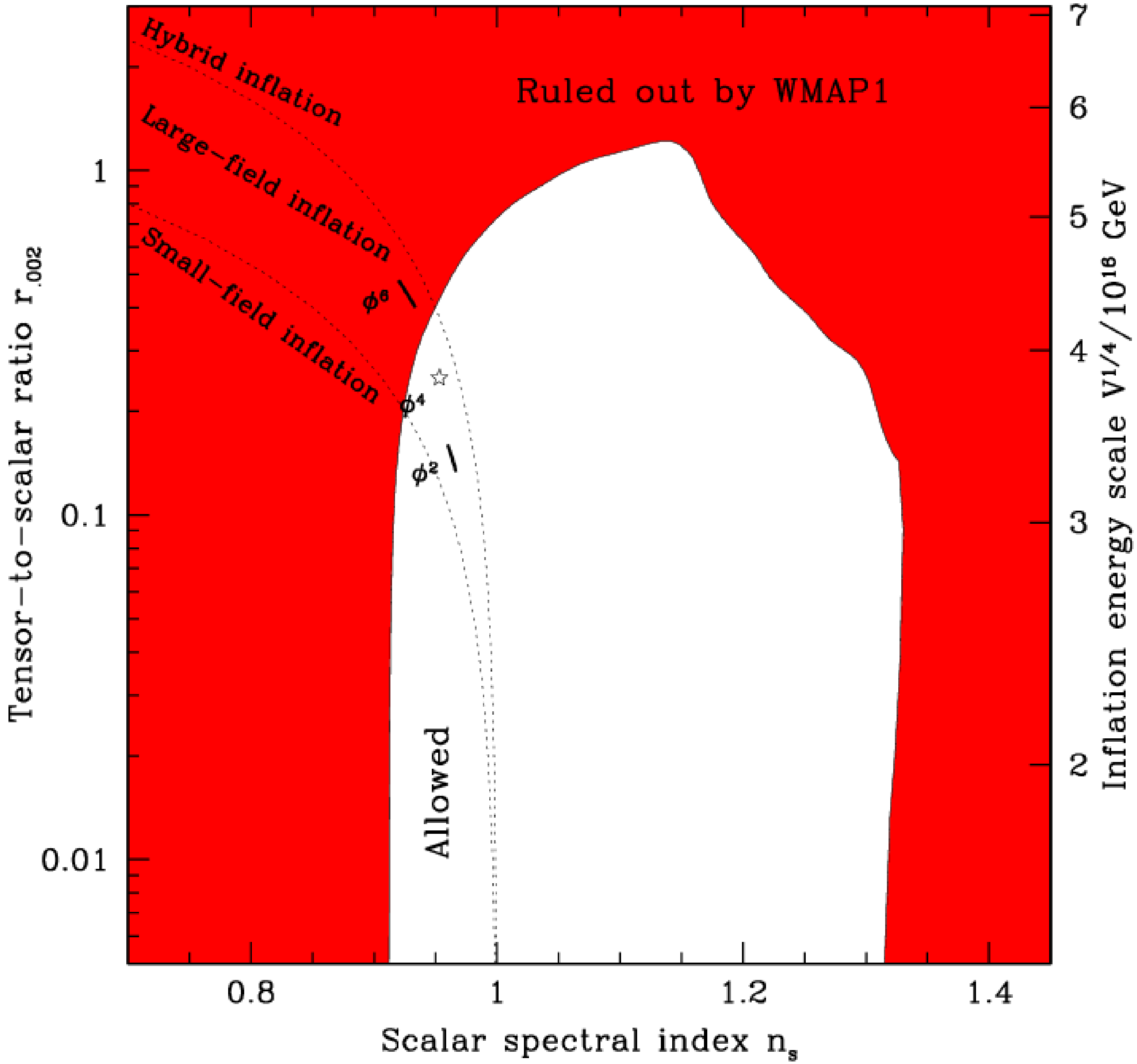


CMB
+



LSS



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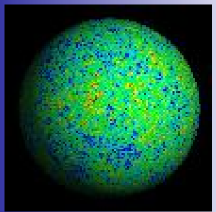
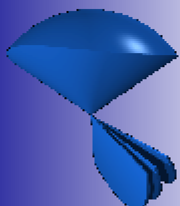
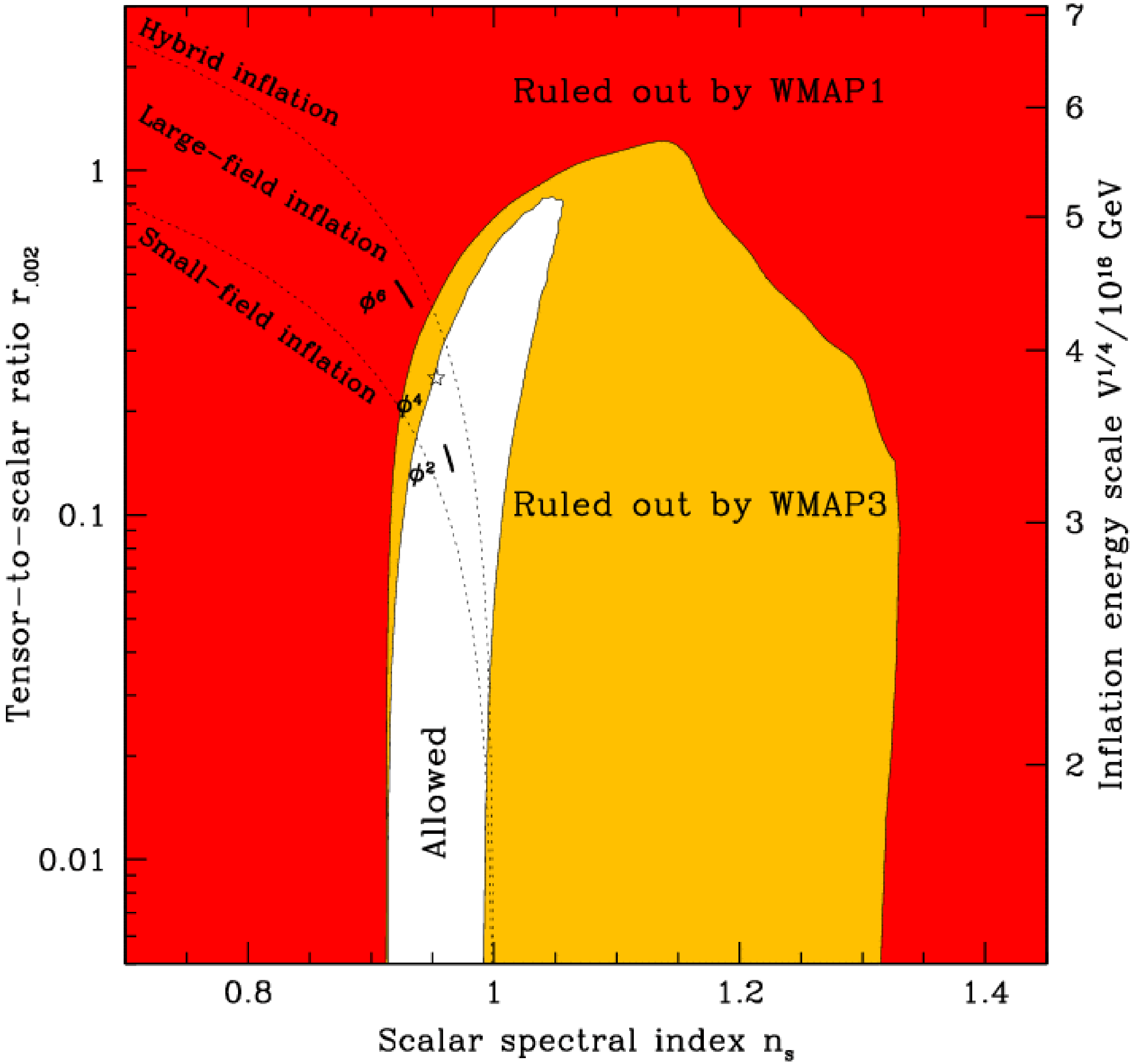


CMB +



LSS



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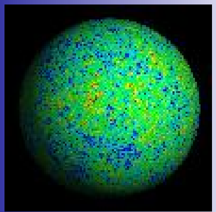
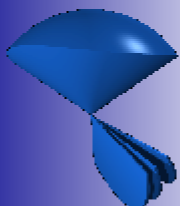
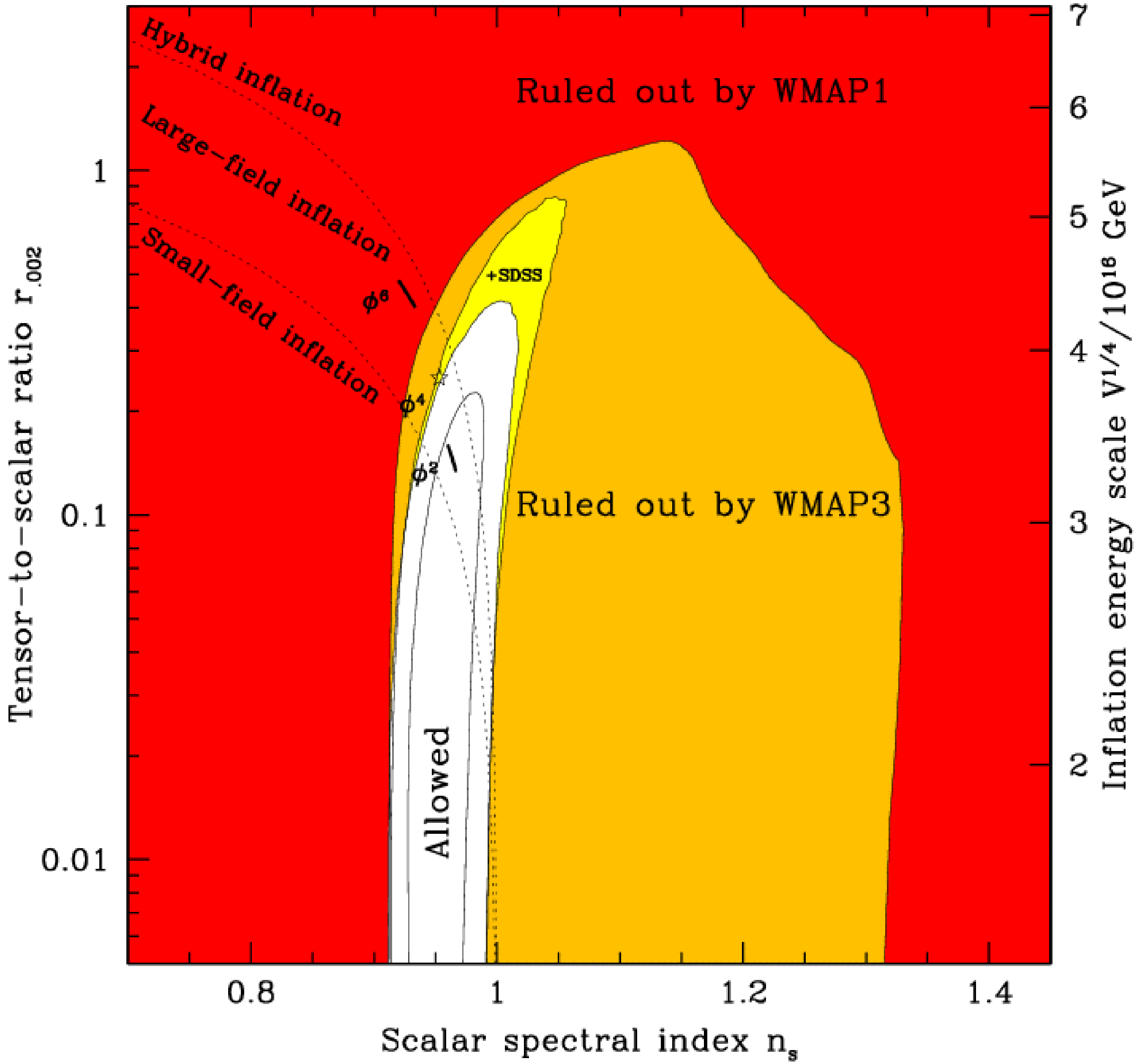


CMB
+



LSS



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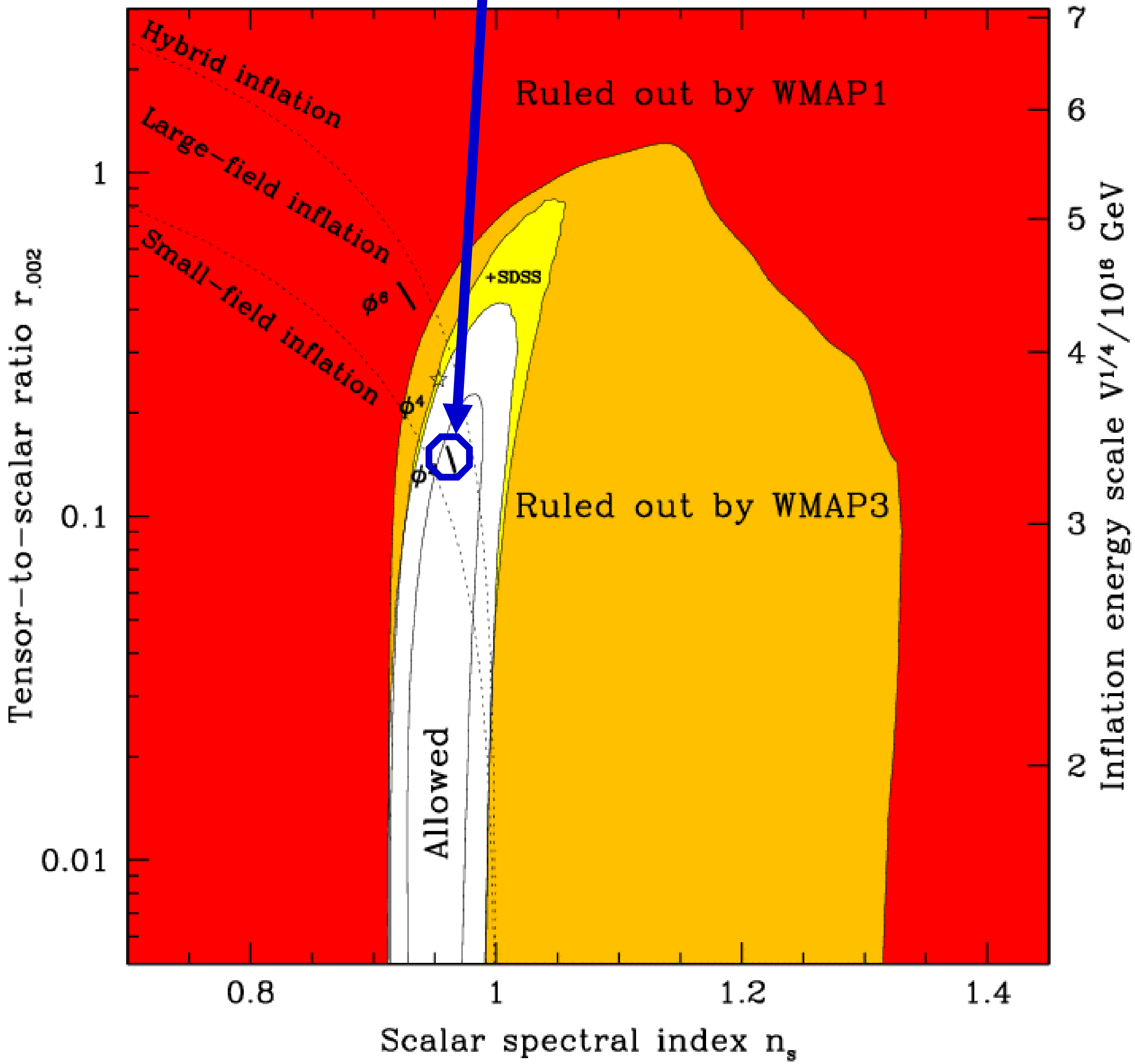
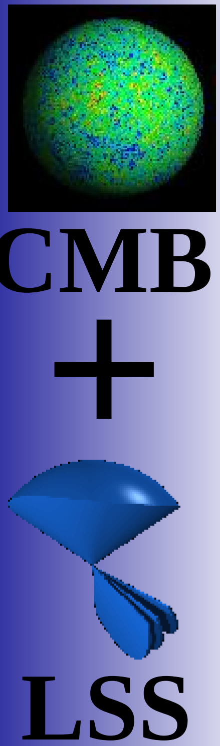
Planck + SDSS: Δn=0.008, Δr=0.012





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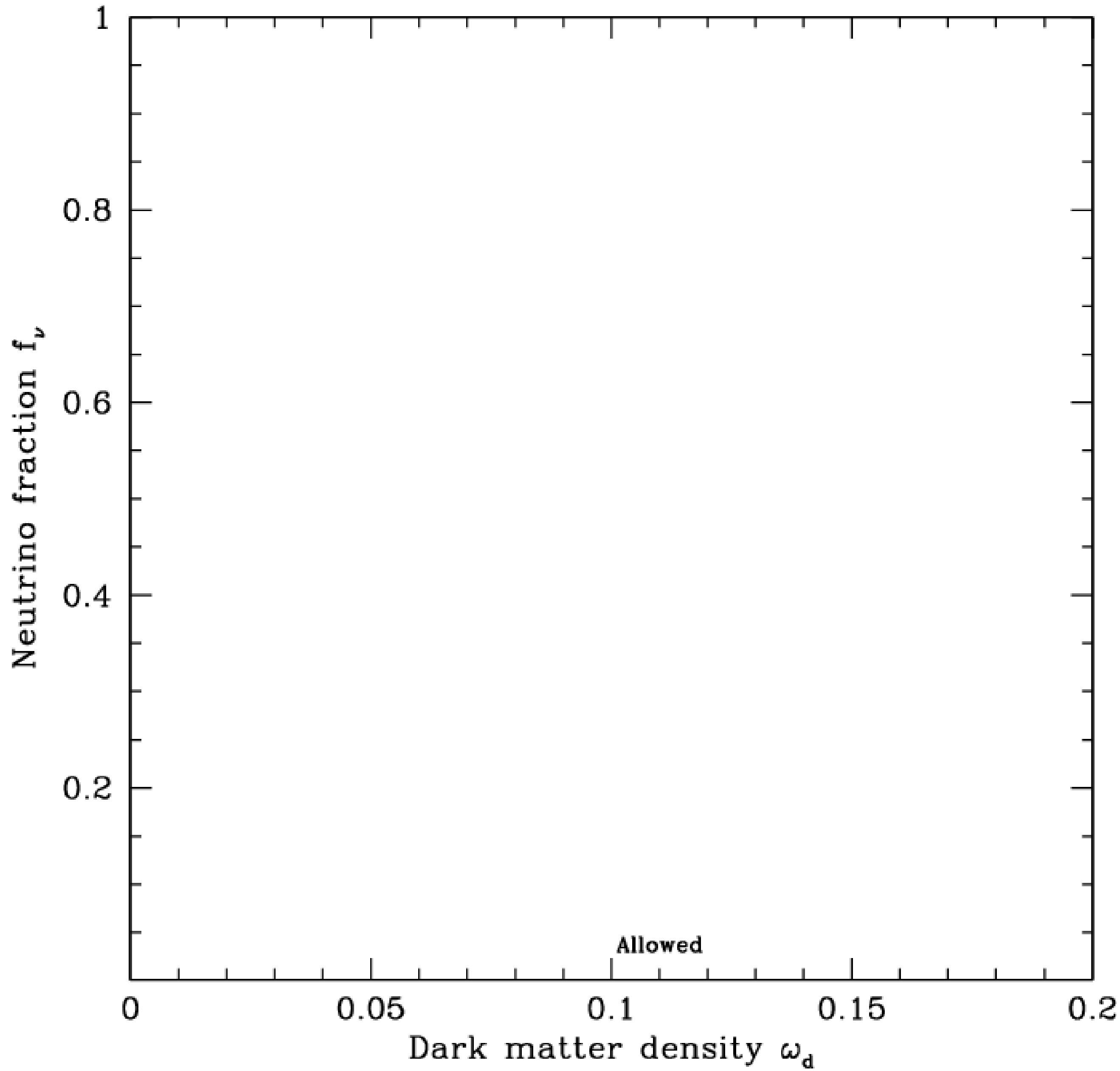
Neutrinos

Cosmological neutrino bounds



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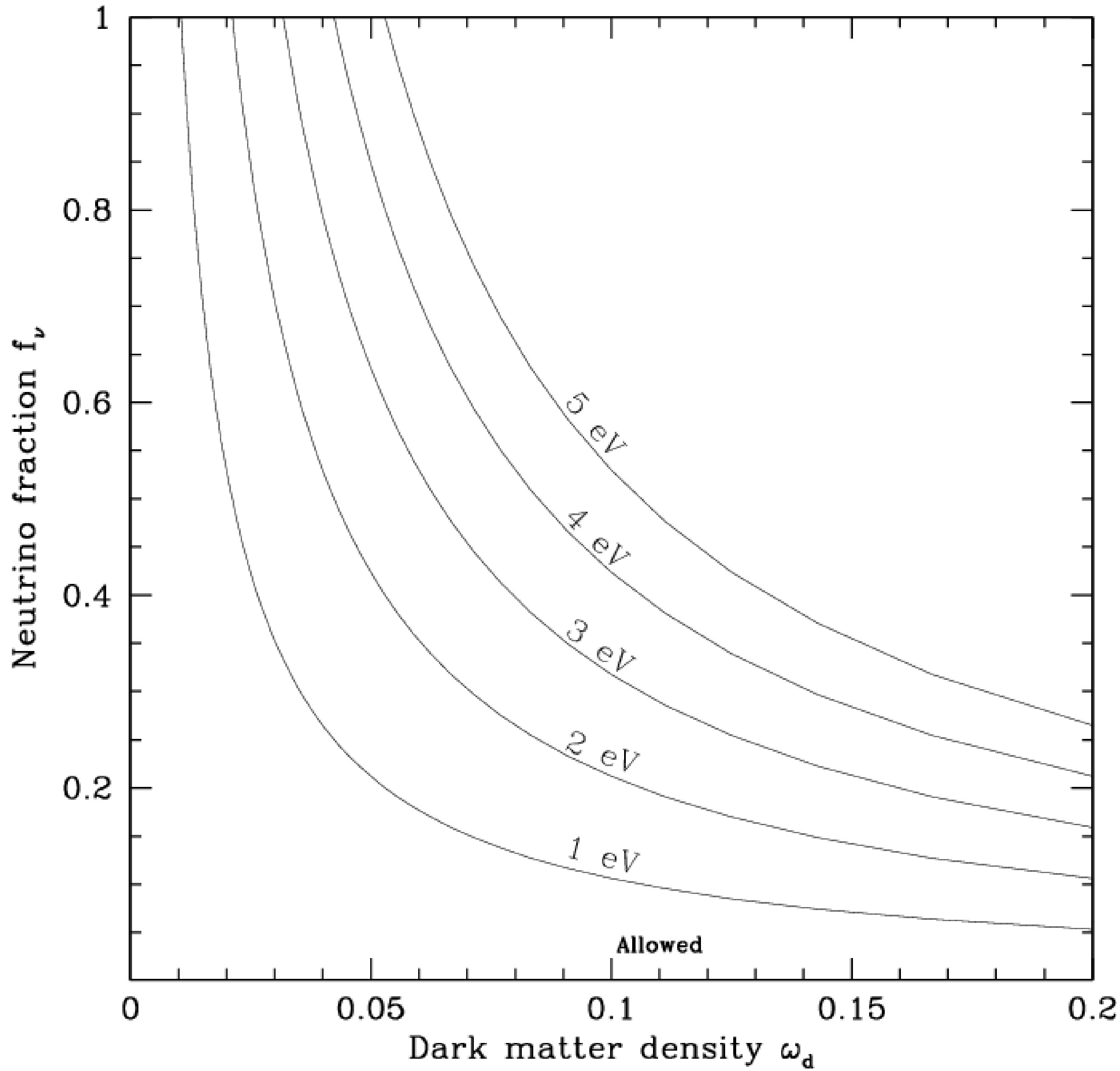
Cosmological neutrino bounds



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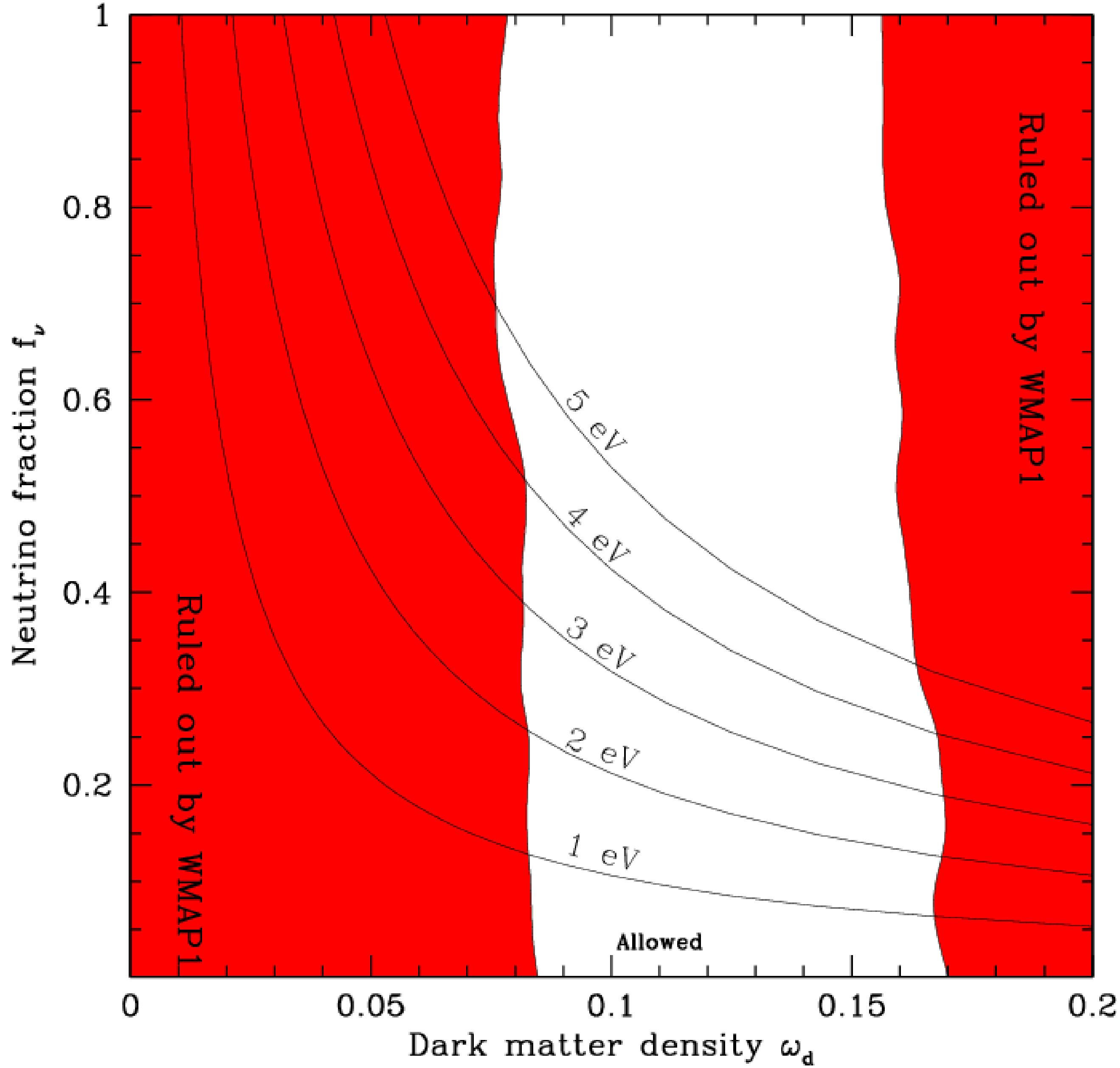
Cosmological neutrino bounds



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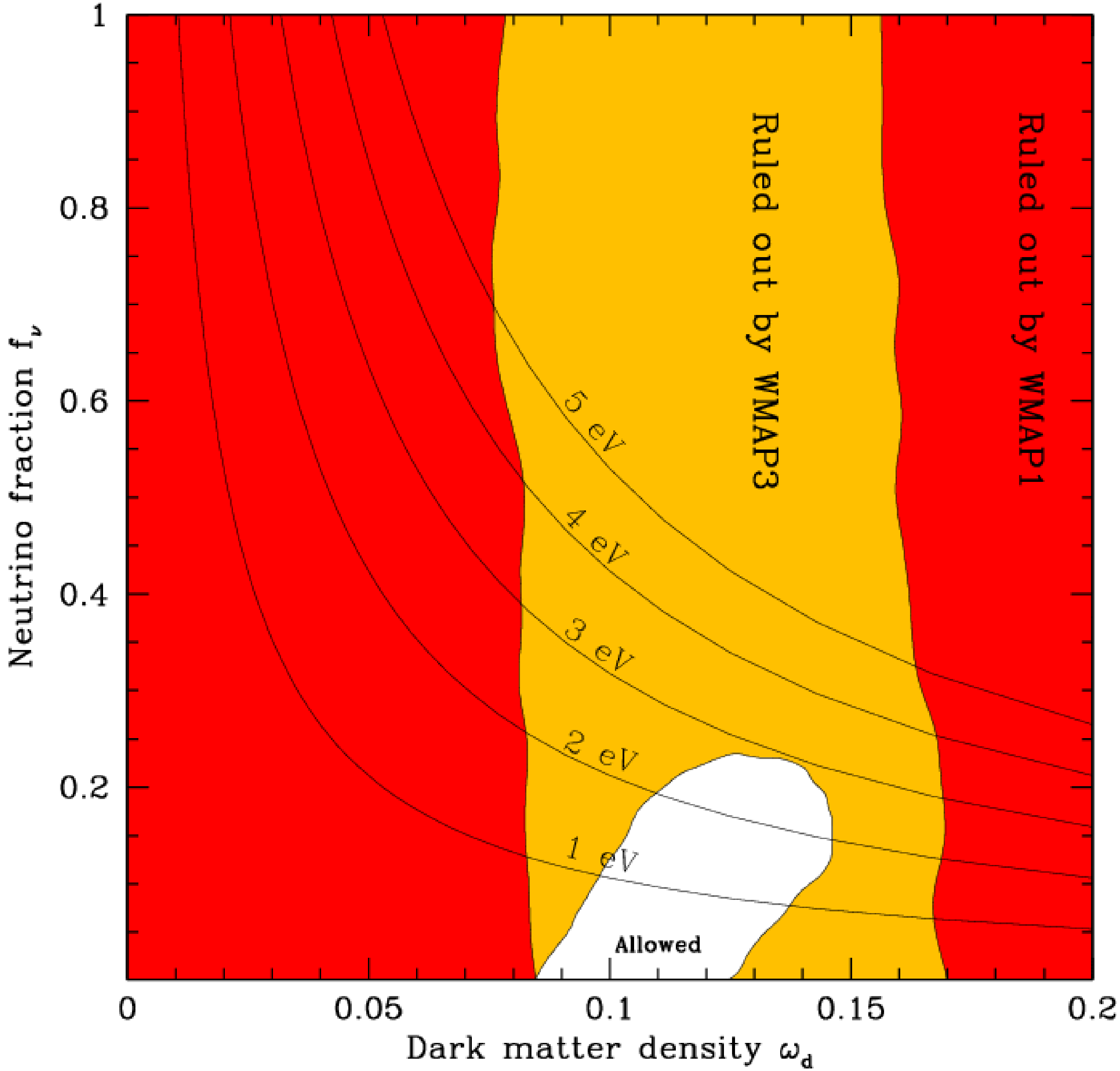
Cosmological neutrino bounds



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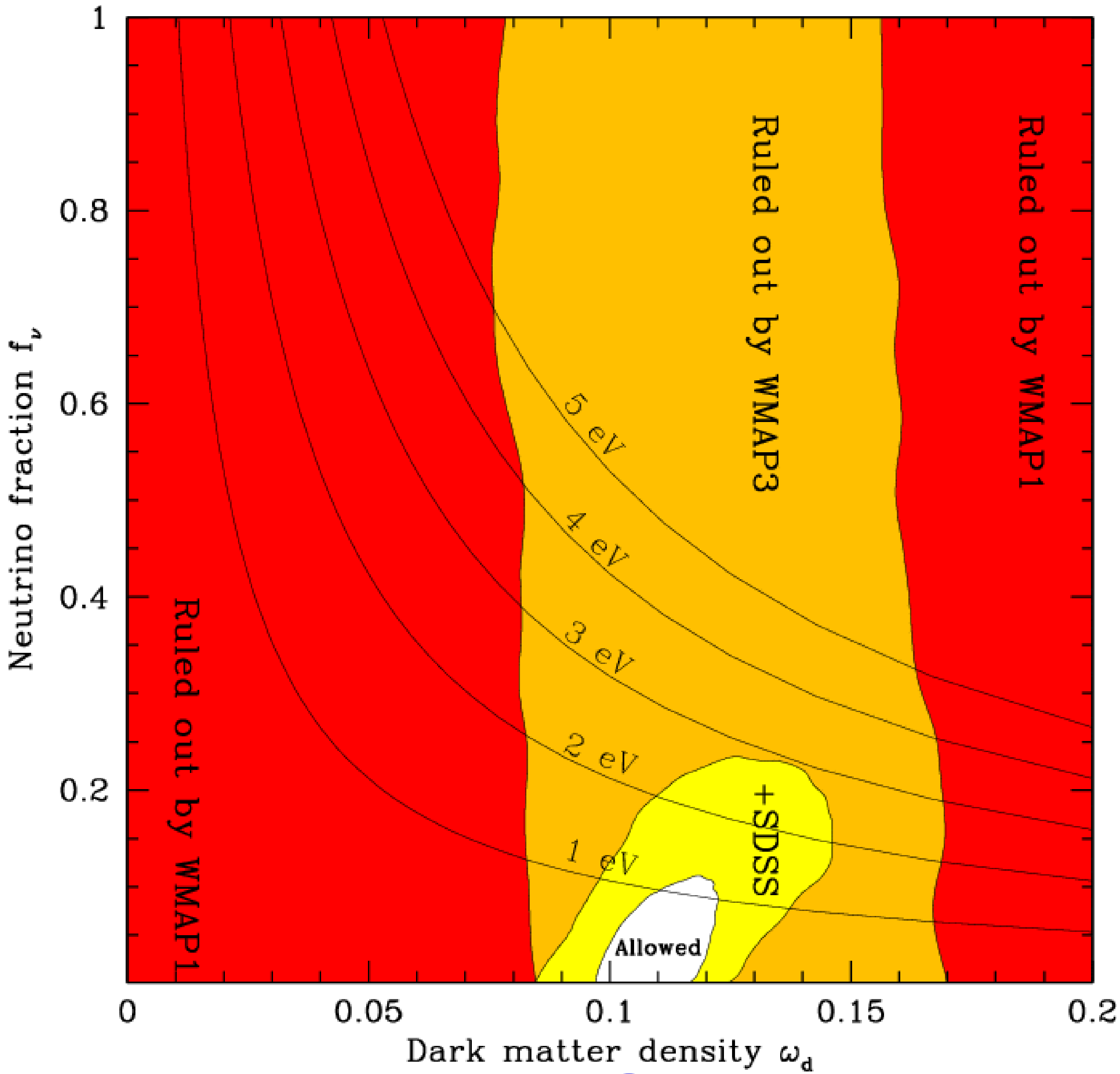
Cosmological neutrino bounds



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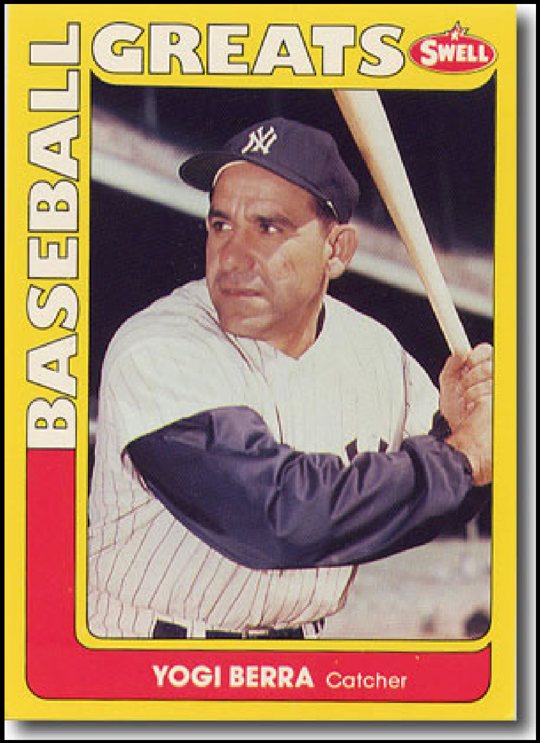
THE FUTURE

It's tough to make predictions, especially about the future.
Yogi Berra



Upcoming lensing measurements:

	Survey	Telescope	Sky coverage	Filters	depth
Ongoing	Deep Lens Survey	CTIO	7x4 deg^2	BVRz'	R=25
	CFHTLS-Wide	CFHT	170 deg^2	ugriz	i_{AB}=24.5
	RCS2	CFHT	1000 deg^2	grz	i_{AB}=22.5
Within a year	KIDS	VST	1500 deg^2	ugriz	i_{AB}=22.9
	Pan-STARRS	PS1	30000 deg^2	grizy	i_{AB}=24
	VIKING	VISTA	1500 deg^2	zYJHK	i_{AB}=22.9
	Dark Energy Survey	CTIO	5000 deg^2	griz	i_{AB}=24.5
Not yet guaranteed	DarkCam	VISTA	10000 deg^2	ugriz	i_{AB}=24
	HyperCam	SUBARU	3500 deg^2	TBD	TBD
	SNAP	Space	300/2000 deg^2	Narrow band (0.35-1.6)	TBD
	LSST	6m ground	20000 deg^2	Narrow band (0.35-1.2)	i_{AB}=27
	DUNE	Space	20000 deg^2	TBD	i_{AB}=25.5

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Compilation from Munshi, Valageas, van Waerbeke & Heavens, astro-ph/0612667

Upcoming massive galaxy redshift surveys:

- AAO wigglez
- AS2 BOSS
- LAMOST
- LOFAR/21cm/21CMA/SKA
- Subaru WFMOS?
- Adept?

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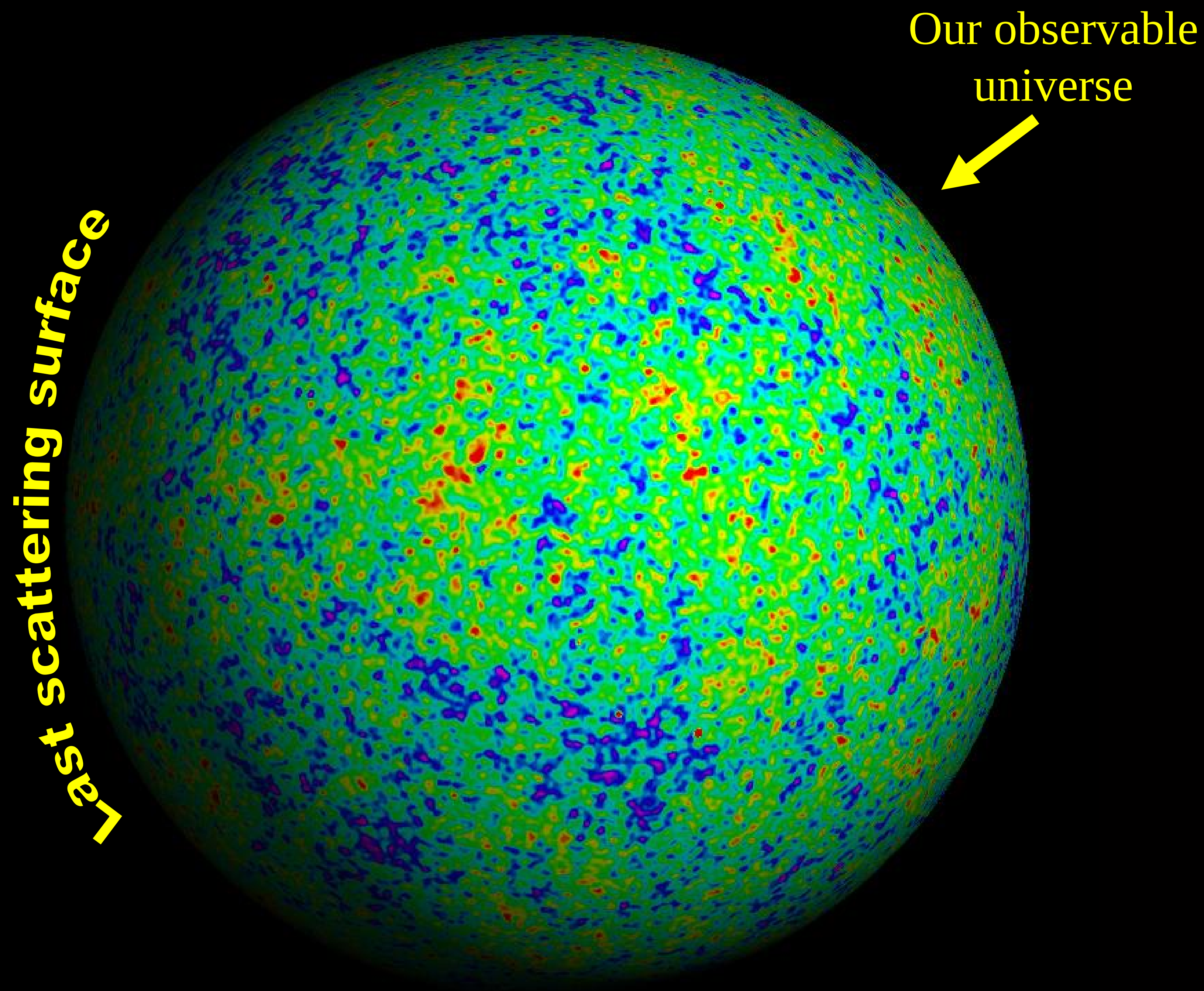
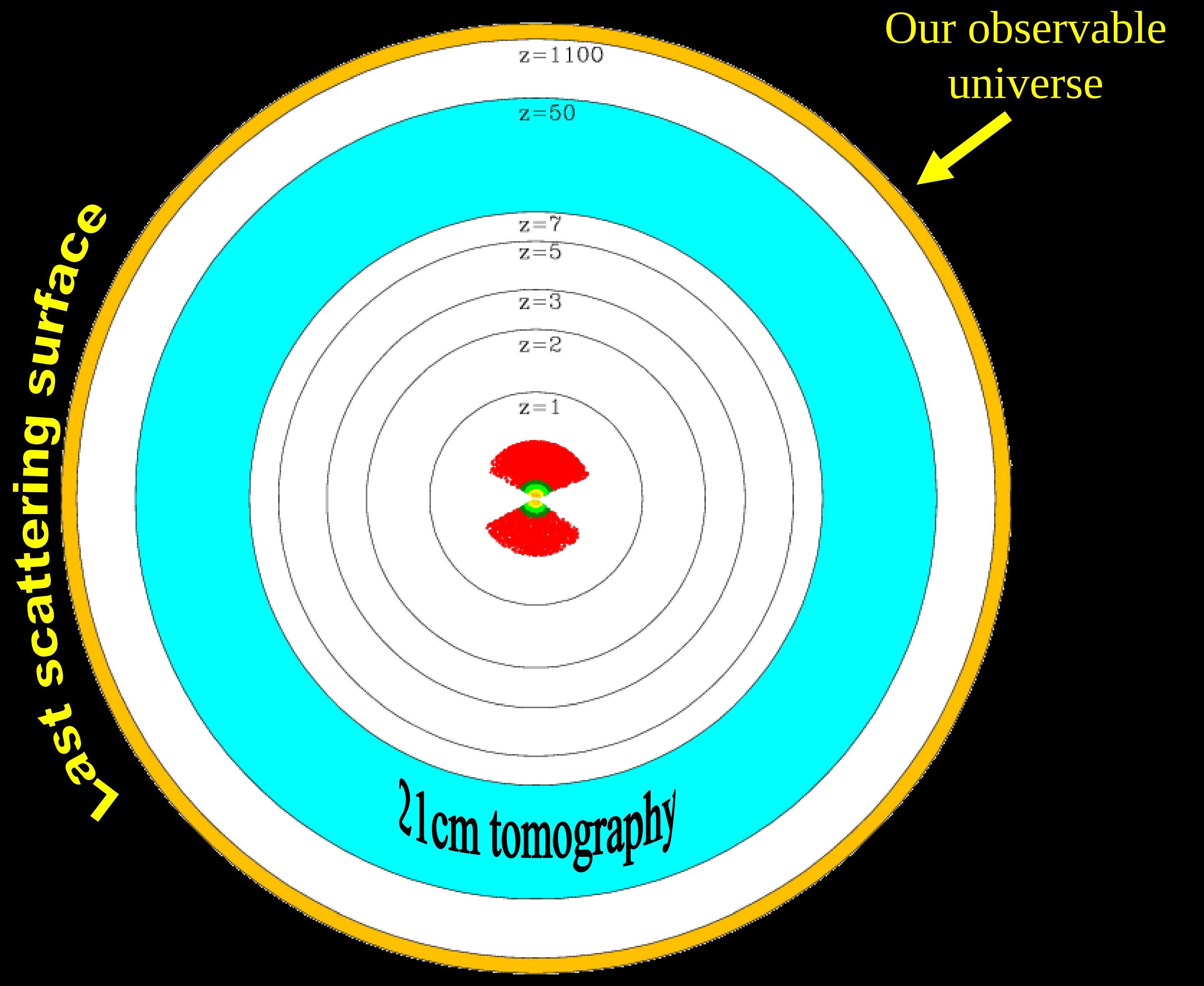
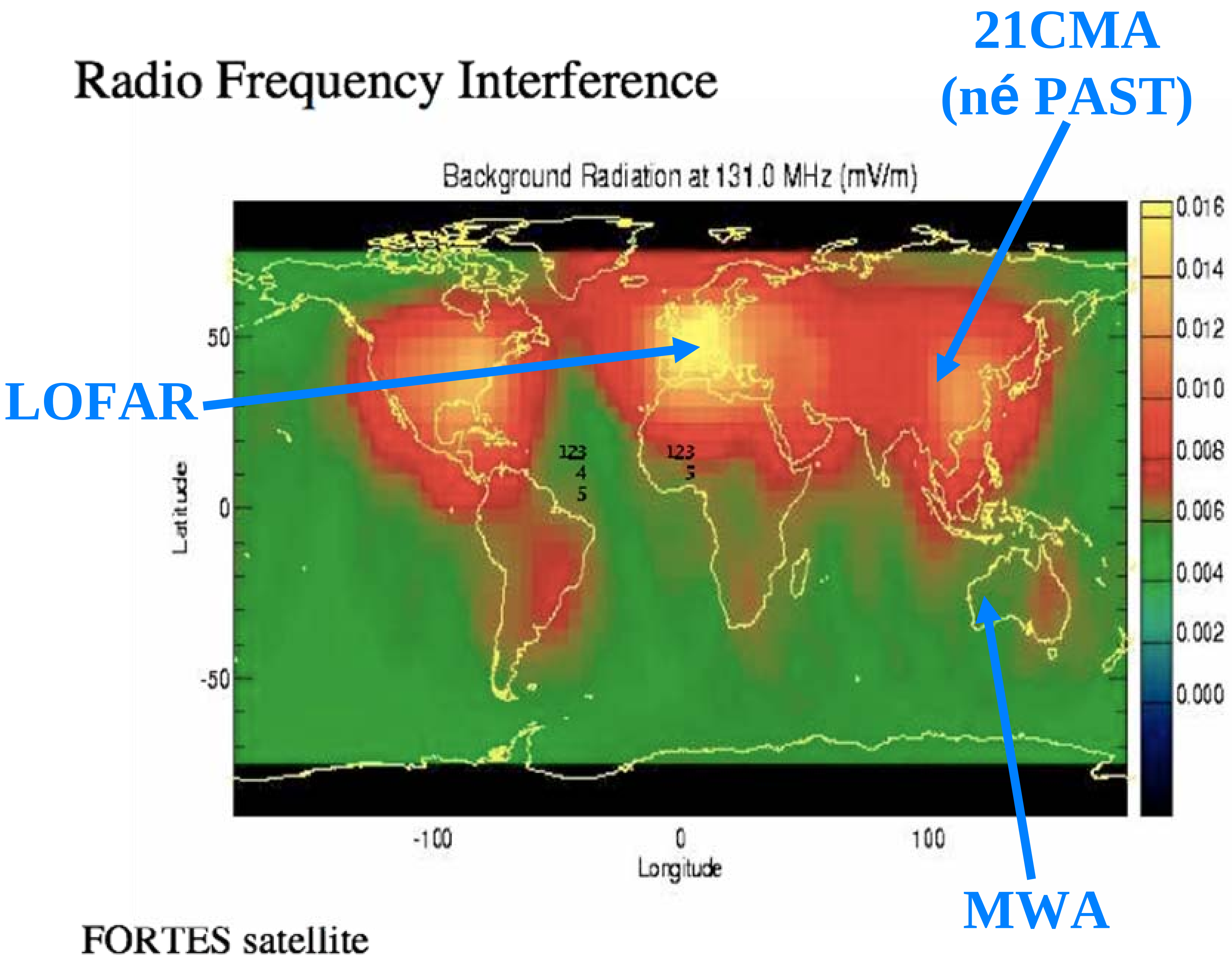


Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496



Our observable universe
Last scattering surface
z=1100
z=50
z=7
z=5
z=3
z=2
z=1
21cm tomography

Now 3 funded 21 cm tomography experiments:



Mileura Wide-Field Array (MWA):

MIT: Judd Bowman, B. Cappallo, Brian Corey, Angelica de Oliveira-Costa, Sheperd Doeleman, **Jaqueline Hewitt**, H. Hinteregger, Justin Kasper, Eric Kratzenberg, Colin Lonsdale, Miguel Morales, Divya Oberoi, Joseph Salah, Max Tegmark
CfA: **Lincoln Greenhill**, Lars Hernquist, Avi Loeb, Doug Mitchell, Randall Wayth, Matias Zaldarriaga
Melbourne: David Barnes, Chris Johnson, Bob Sault, James Stevens, Randall Wayth, Rachel Webster, Stuart Wyithe
Curtin University: David Herne, Mervyn Lynch, B. Stansby
Sydney University: Bryan Gaensler
ANU/Stromlo: Frank Briggs, J. Kocz
Yale: Steve Furlanetto
CSIRO/ATNF: J. Bunton, C. Jackson, M. Storey
Also U. Tasmania, W. Australian Gov't

- 500 16-dipole antennas
- Radio quiet Mileura site
- Full cross-correlation of all 500 antennas
- Very wide 20°– 40° field of view
- Designed to minimize & control systematics

Cosmological parameters from 21cm tomography:

		Ω_Λ	$\ln(\Omega_m h^2)$	$\ln(\Omega_b h^2)$	n_s	$\ln(A_s)$	τ	Ω_K	m_ν (eV)
WMAP		0.029	0.035	0.025	0.015	0.038	0.018	0.037	0.58
WMAP+MWA500	OPT	0.014	0.019	0.012	0.0075	0.025	0.013	0.0072	0.12
	MID II	0.013	0.020	0.022	0.012	0.038	0.017	0.0065	0.40
	MID I	0.029	0.034	0.025	0.015	0.038	0.018	0.025	0.56
	PESS	0.029	0.035	0.025	0.015	0.038	0.018	0.037	0.58
Planck		0.0070	0.0081	0.0059	0.0033	0.0088	0.0043	0.025	0.23
Planck+MWA5000	OPT	0.0040	0.0050	0.0036	0.0027	0.0060	0.0029	0.0017	0.015
	MID II	0.0014	0.0023	0.0043	0.0023	0.0086	0.0042	0.0012	0.052
	MID I	0.0066	0.0077	0.0057	0.0032	0.0087	0.0043	0.0041	0.077
	PESS	0.0069	0.0081	0.0058	0.0032	0.0087	0.0043	0.0095	0.11

Yi Mao, MT, Zaldarriaga, McQuinn, Zahn 2007

Improves Planck by factor up to 20

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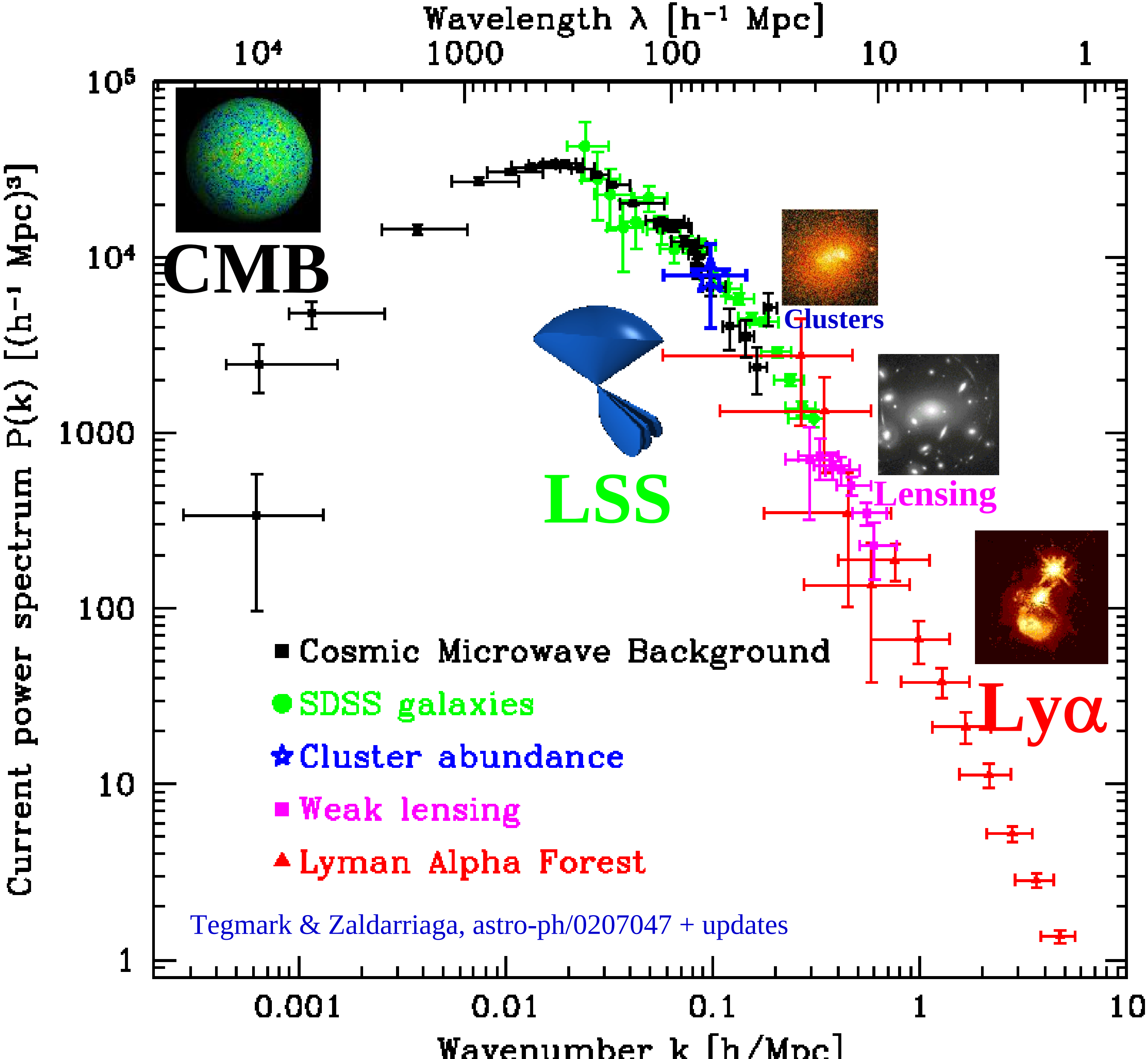

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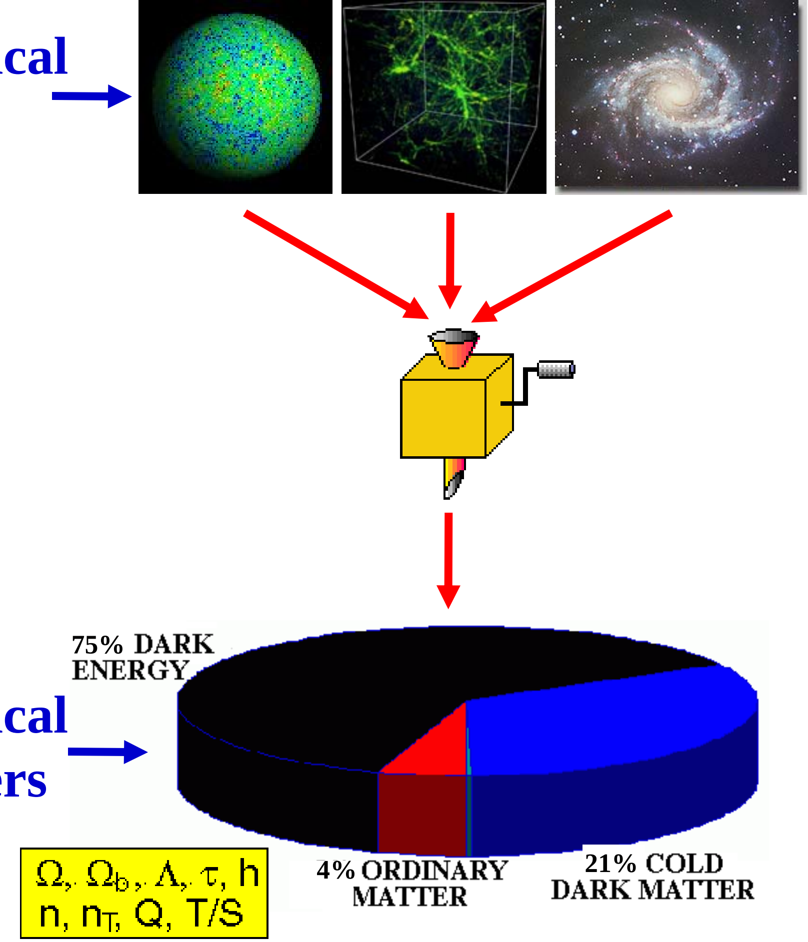
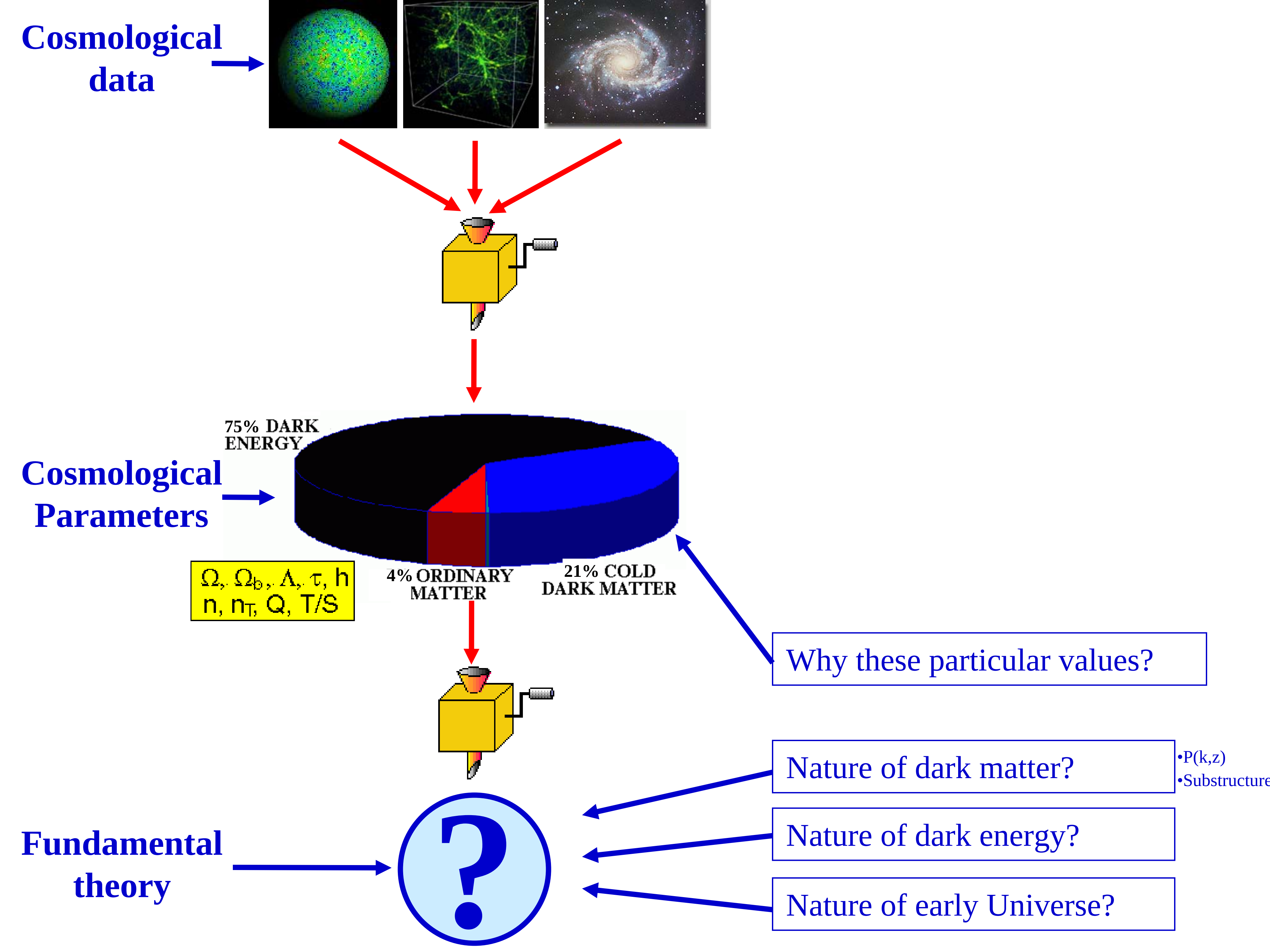
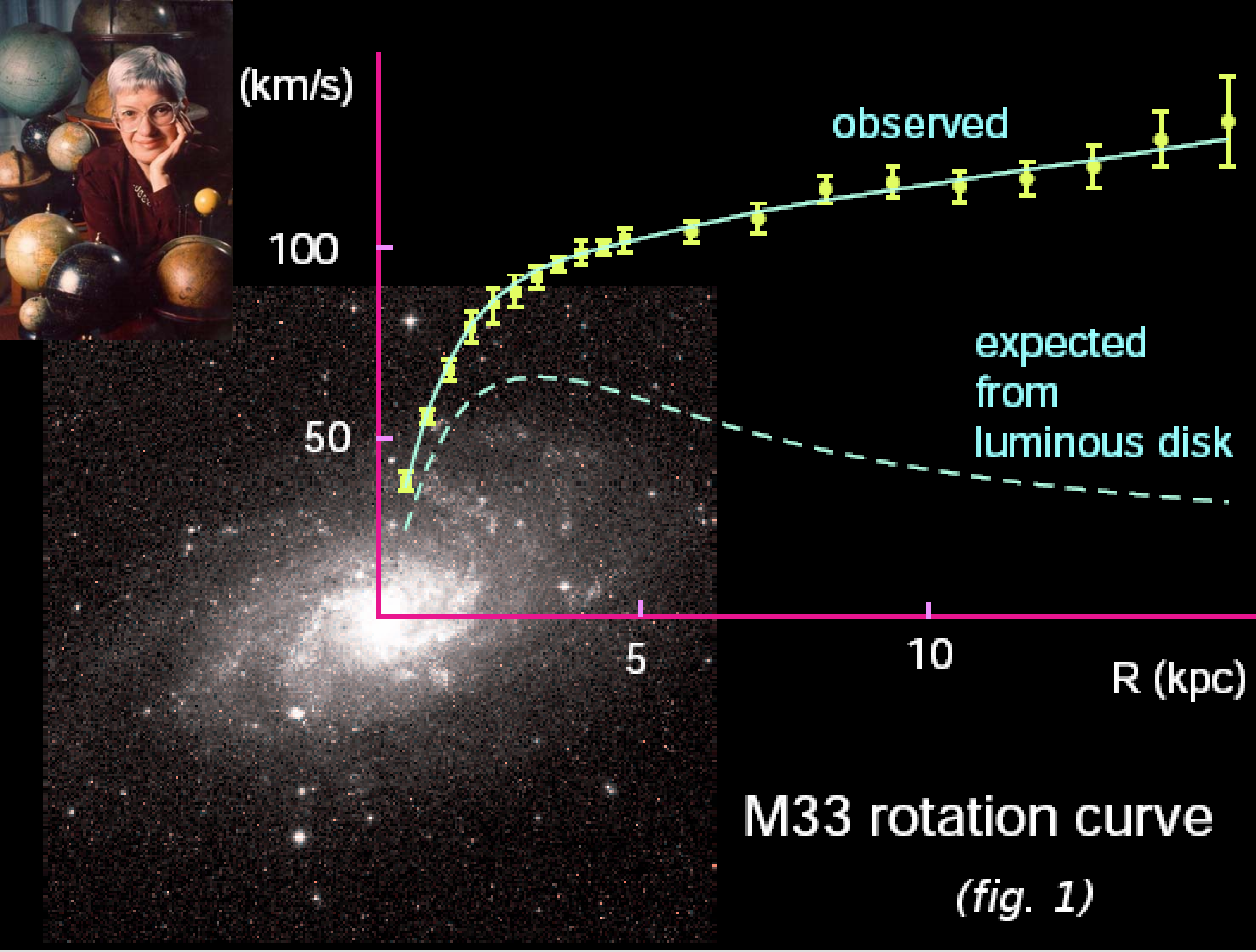
Cosmological data



Cosmological Parameters

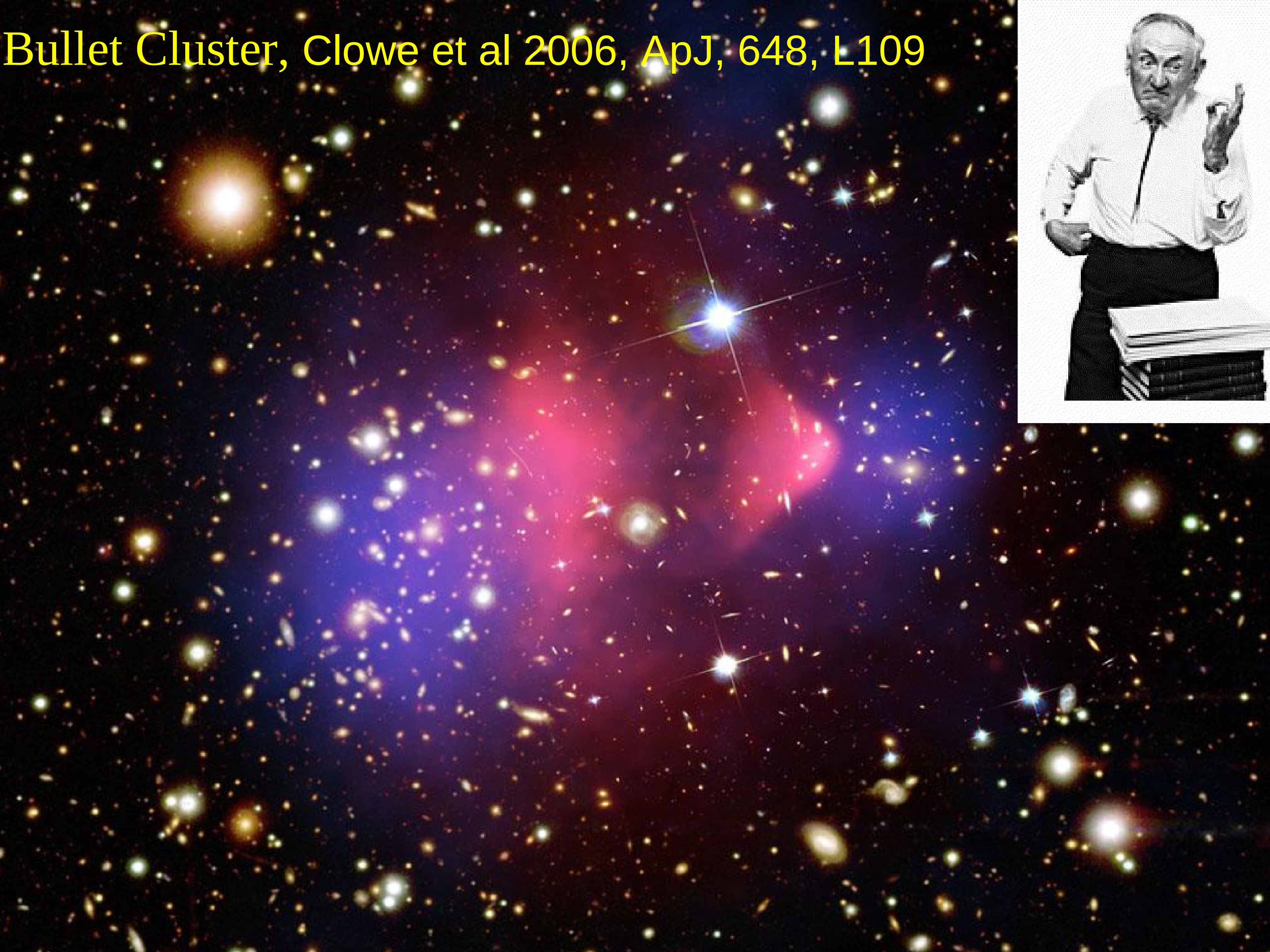

Cosmological data
Cosmological Parameters
75% DARK ENERGY
4% ORDINARY MATTER
21% COLD DARK MATTER
Ω, Ω_b, Λ, τ, h
n, n_T, Q, T/S
Why these particular values?
Fundamental theory
?
Nature of dark matter?
•P(k,z)
•Substructure
Nature of dark energy?
Nature of early Universe?



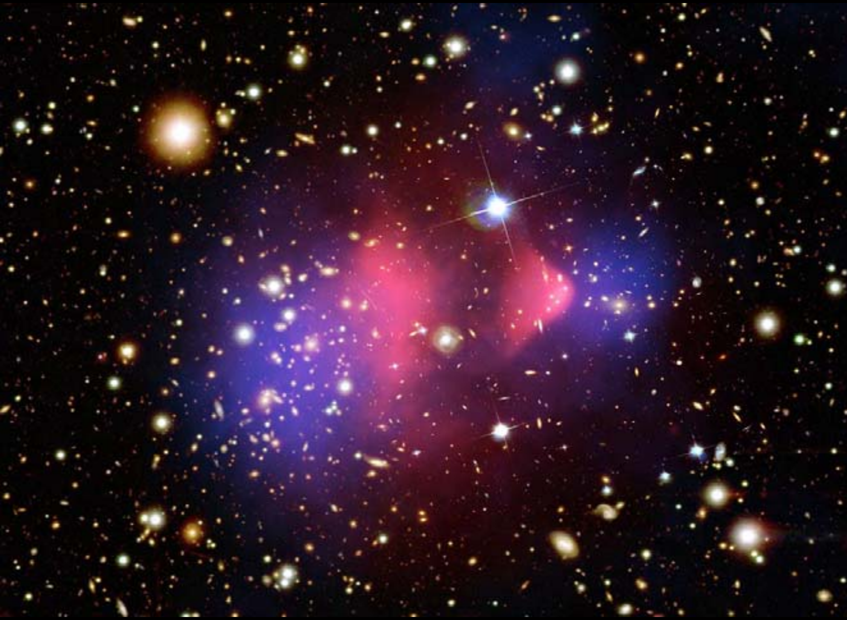
M33 rotation curve

(fig. 1)

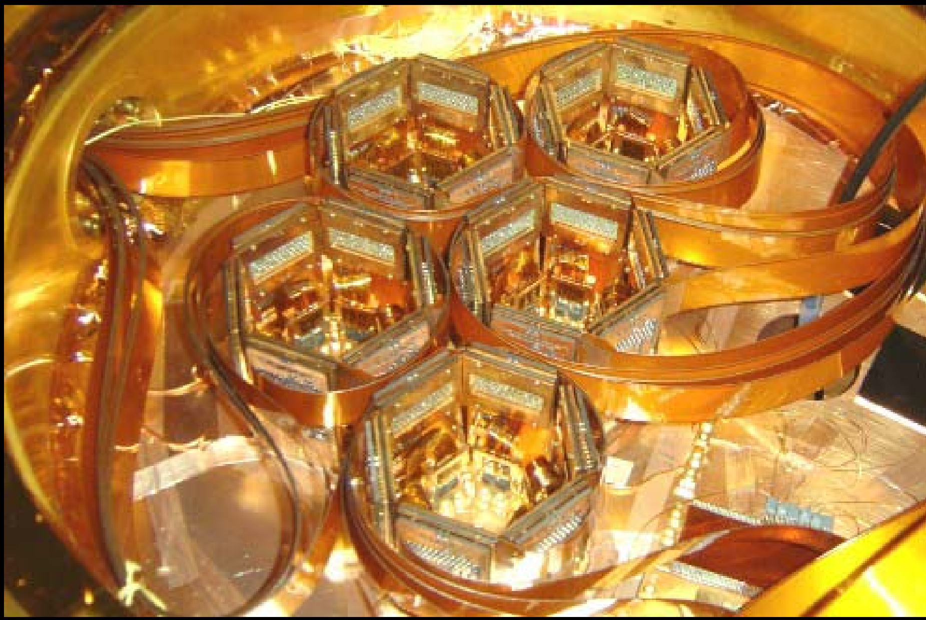
Bullet Cluster, Clowe et al 2006, ApJ, 648, L109



Four roads to dark matter:

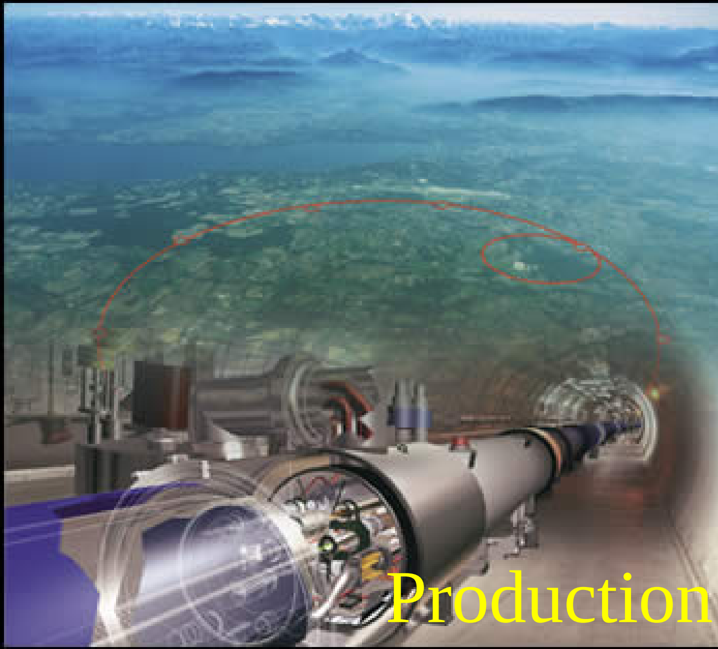


Gravitational



Direct

Indirect



Production