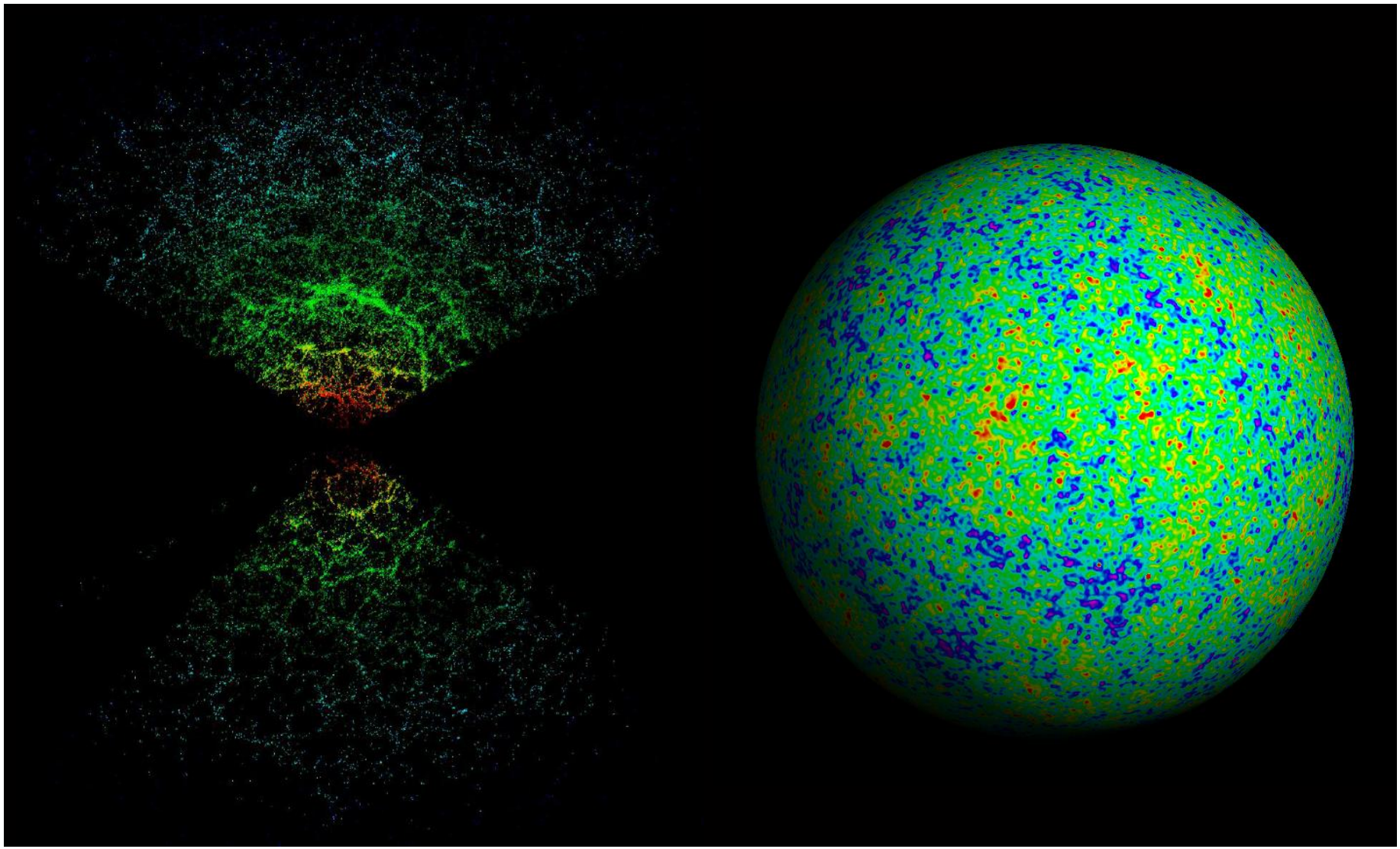
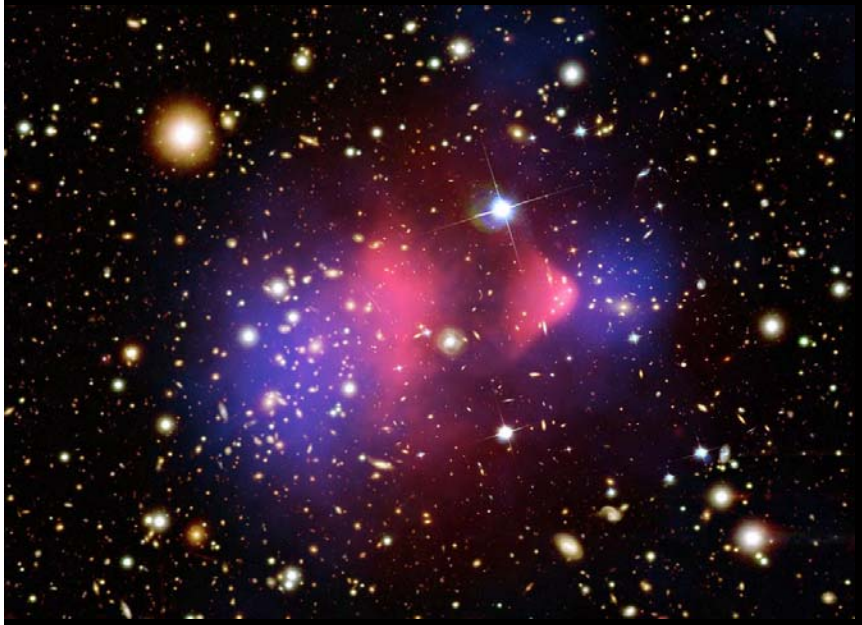
Dark Matter & Cosmology

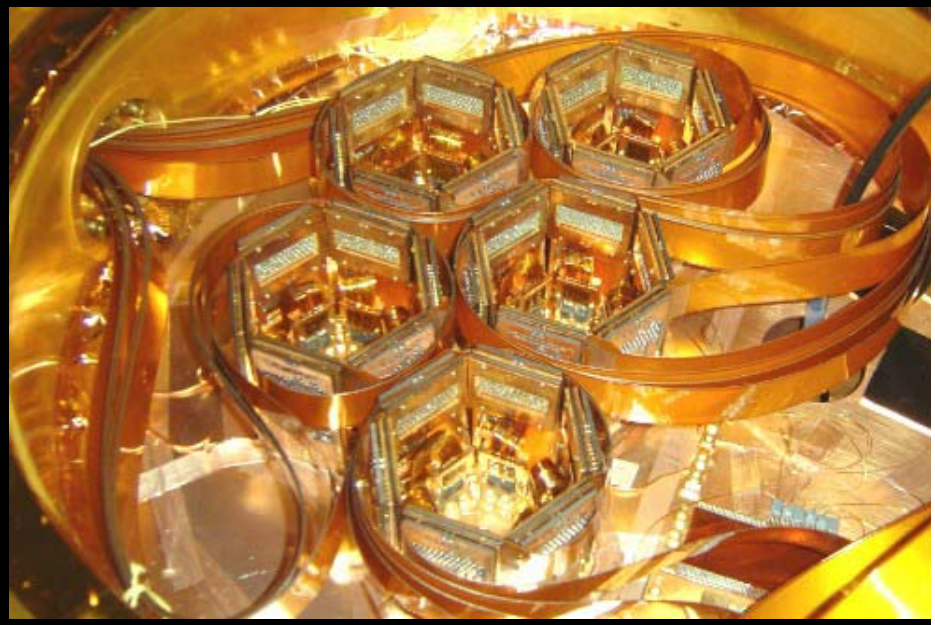


Max Tegmark, MIT

Four roads to dark matter:

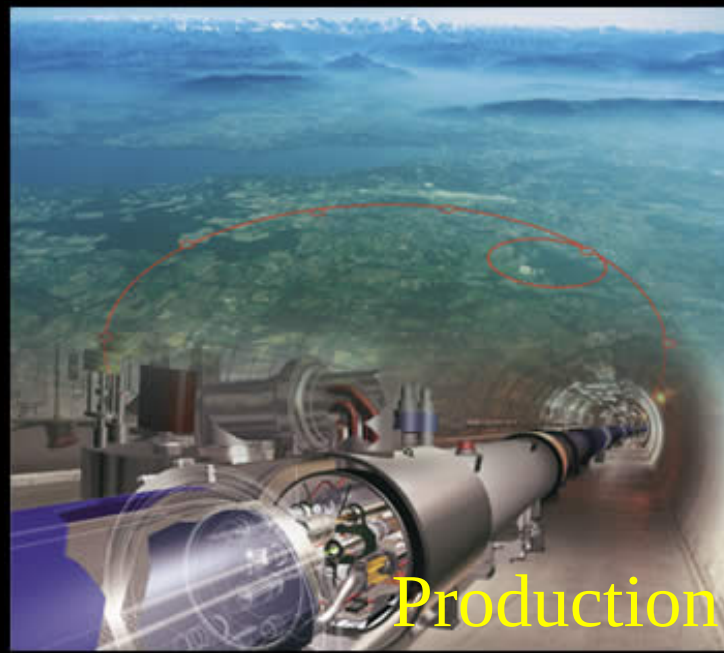


Gravitational



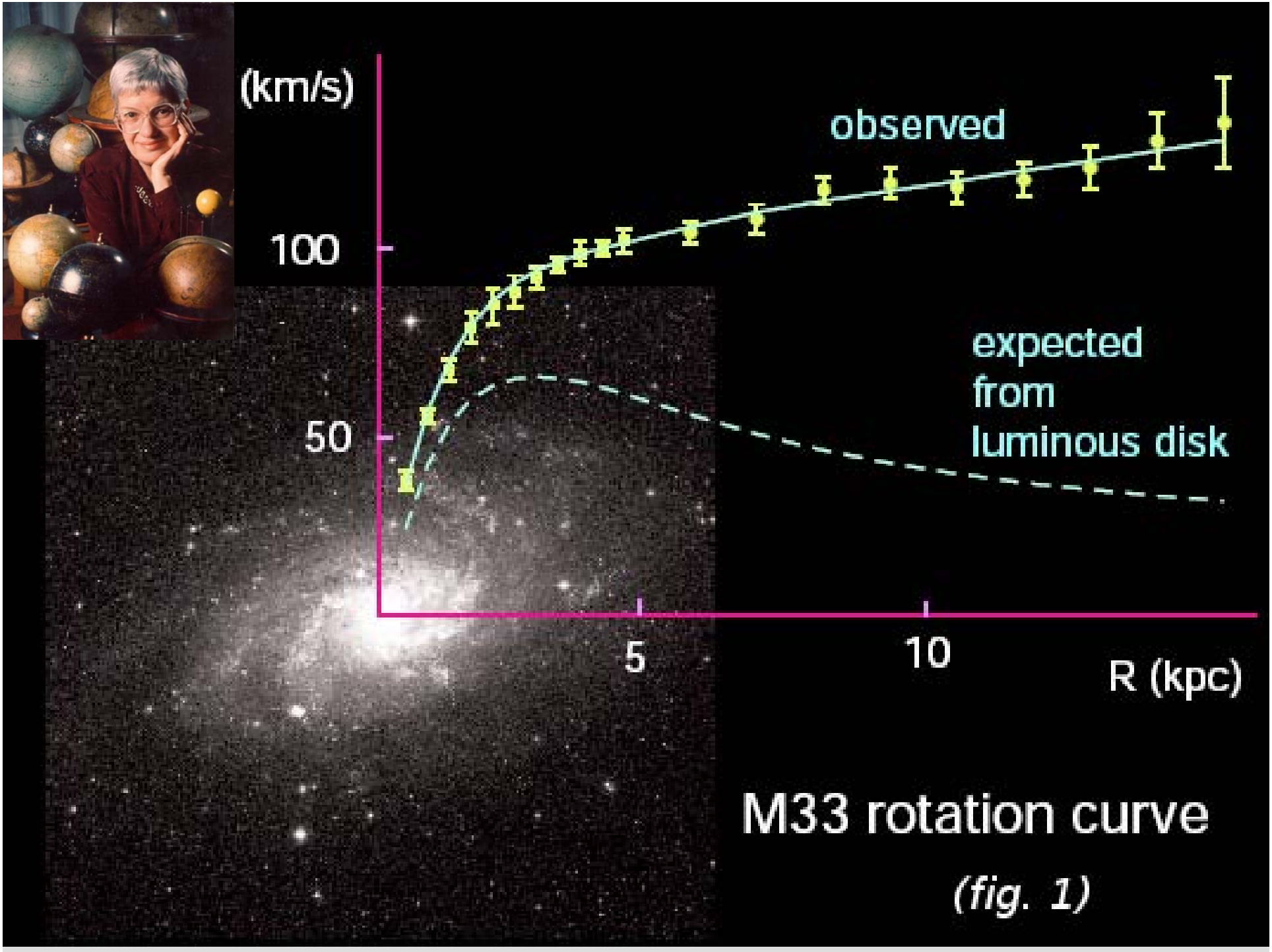
Direct

Indirect

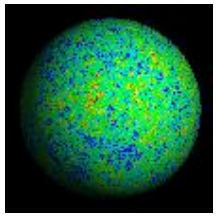


Production

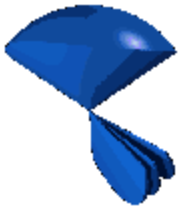
Bullet Cluster, Clowe et al 2006, ApJ, 648, L109


(km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve
(fig. 1)

THE COSMIC SMÖRGÅSBORD

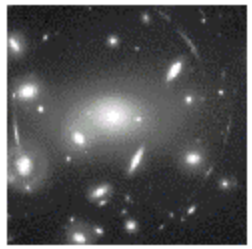


CMB



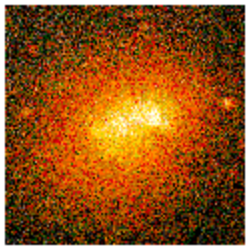
GALAXY SURVEYS

DISTANT SUPERNOVAE

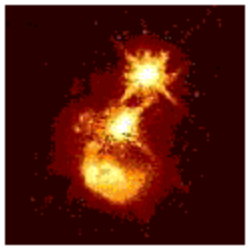


GRAVITATIONAL LENSING

BIG BANG NUCLEOSYNTHESIS



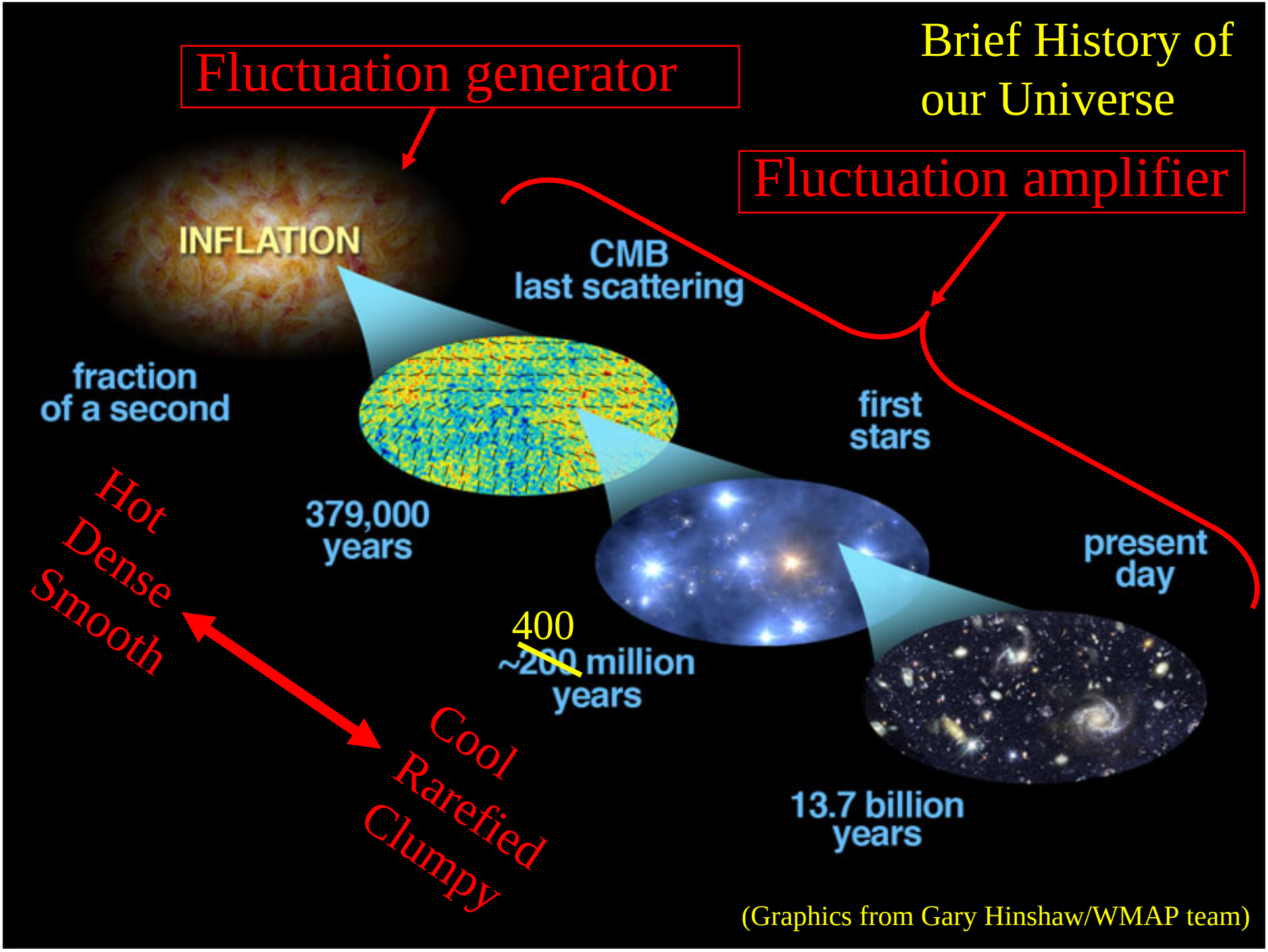
GALAXY CLUSTERS

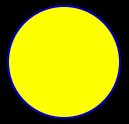


LYMAN ALPHA FOREST

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

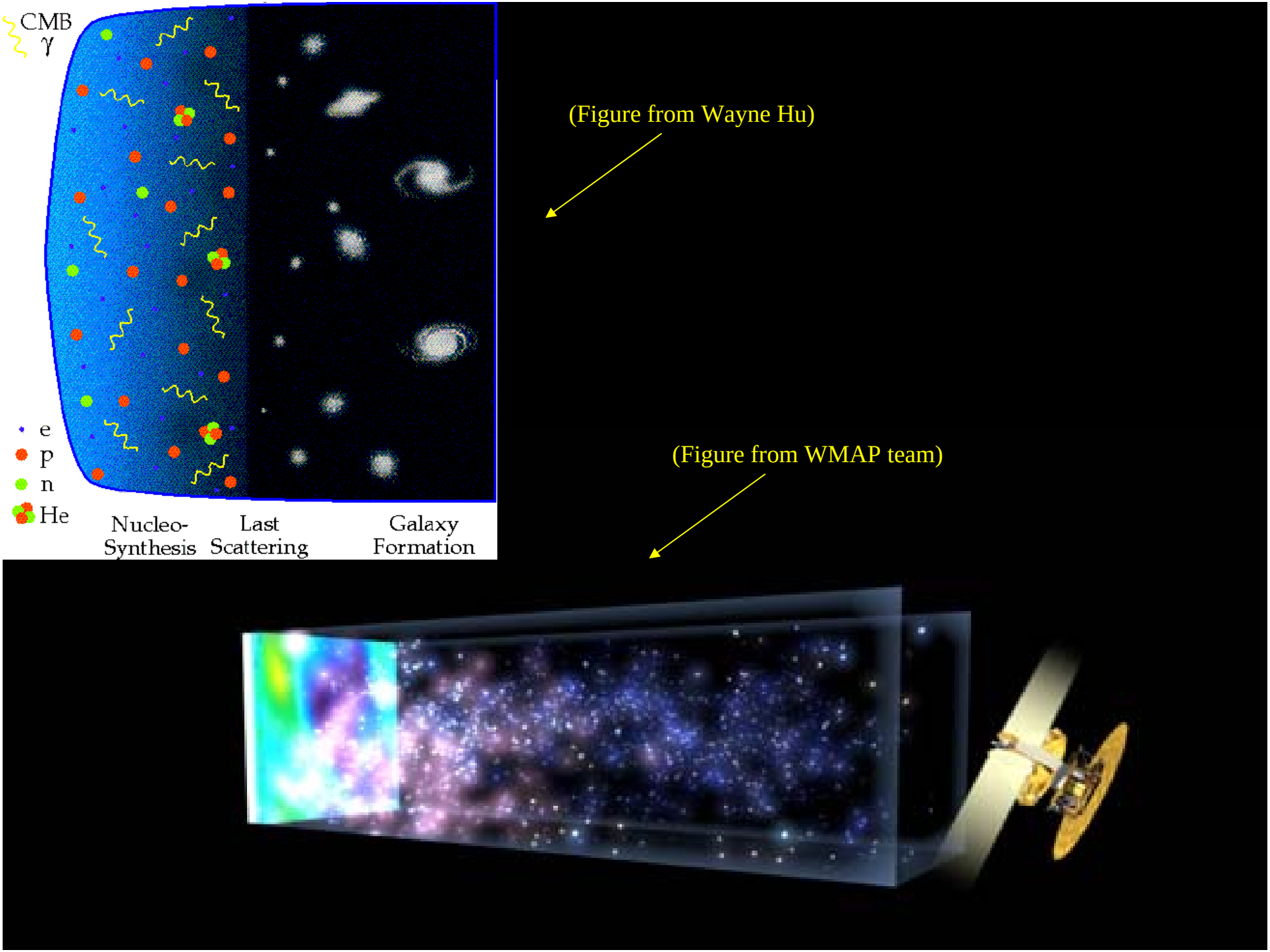
What have we learned?

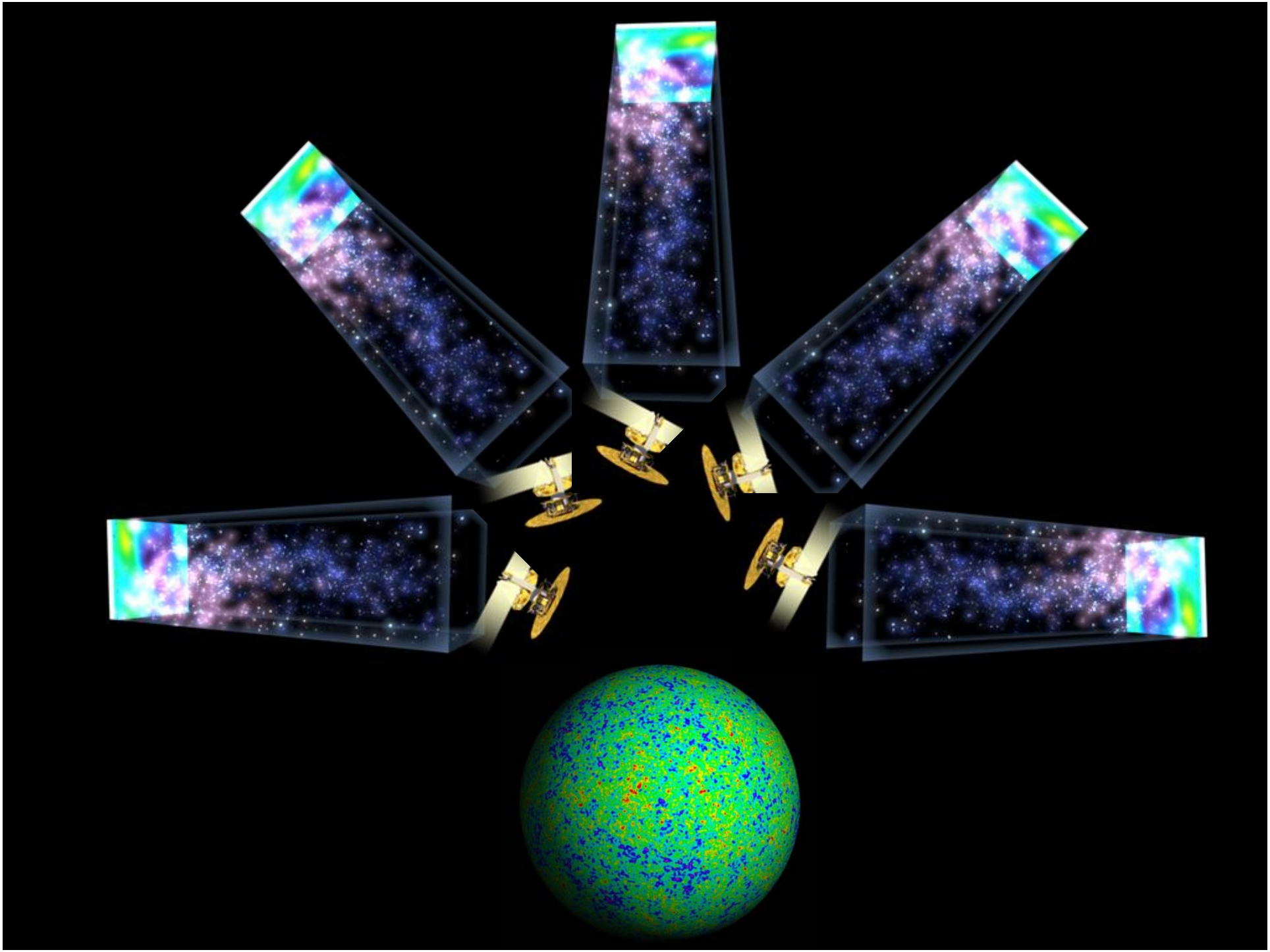

Brief History of our Universe
Fluctuation generator
Fluctuation amplifier
INFLATION
CMB last scattering
fraction of a second
379,000 years
first stars
present day
Hot Dense Smooth
400 million years
Cool Rarefied Clumpy
13.7 billion years
(Graphics from Gary Hinshaw/WMAP team)



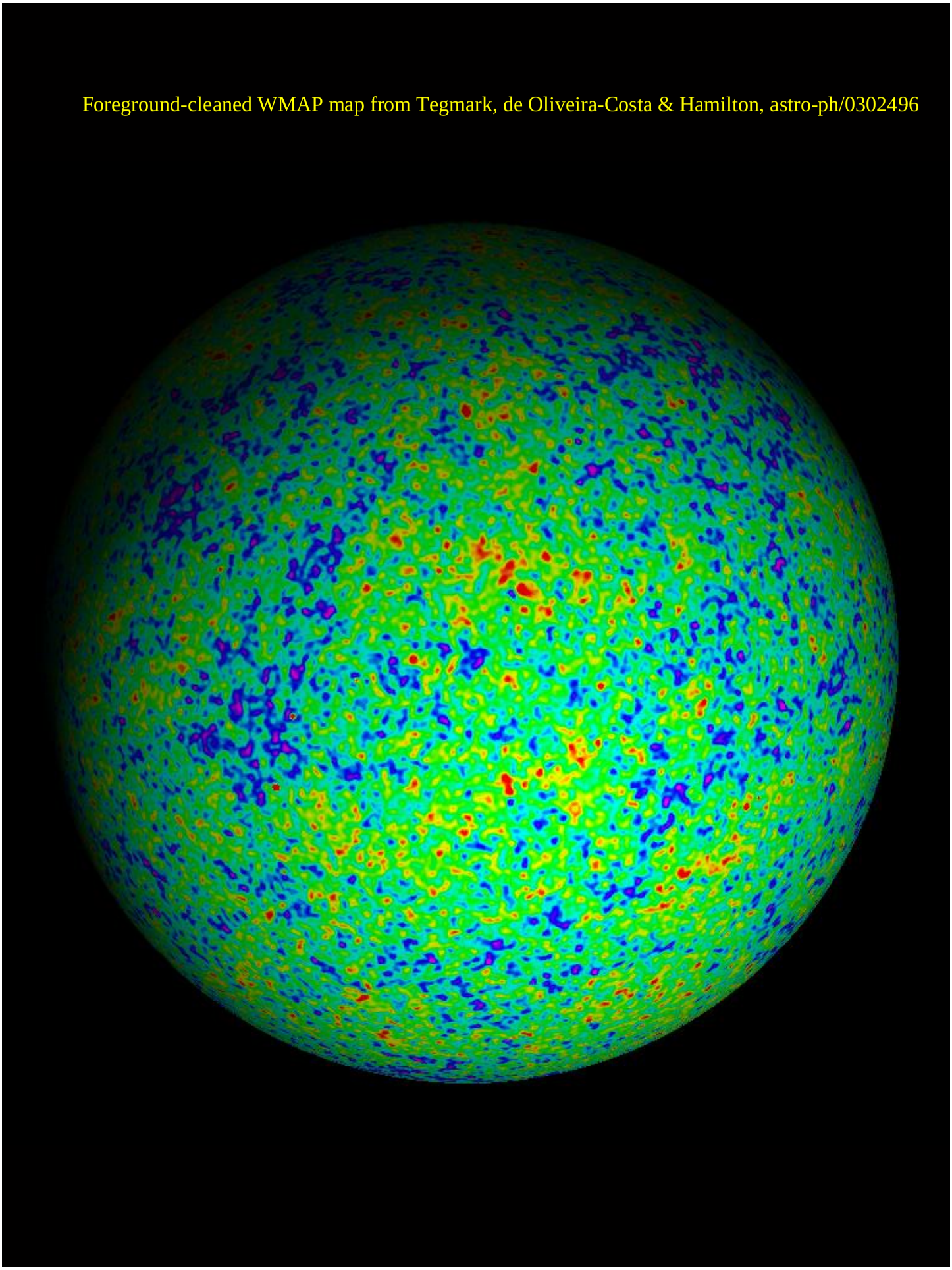
Formation movies

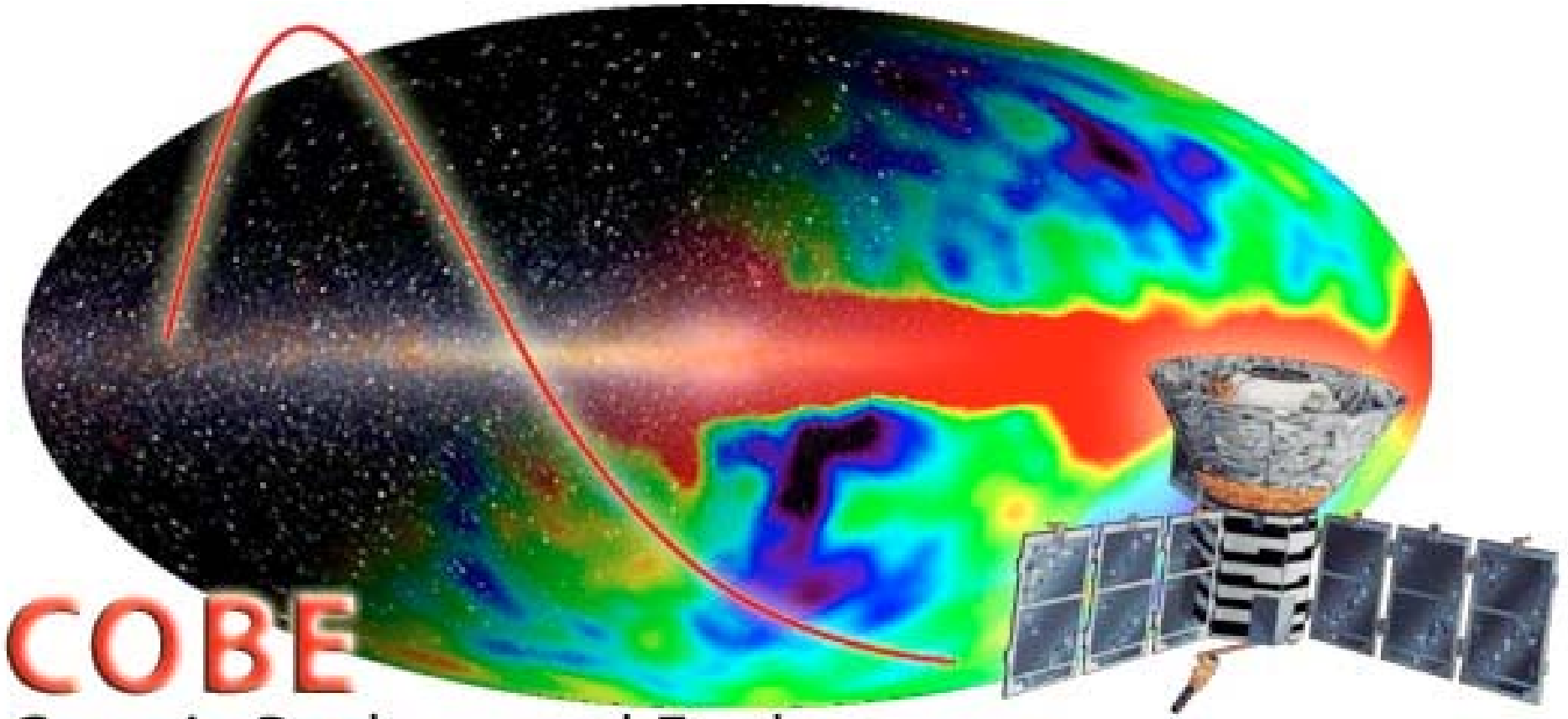
Cosmic clustering


CMB
γ
e
p
n
He
Nucleo-
Synthesis
Last
Scattering
Galaxy
Formation
(Figure from Wayne Hu)
(Figure from WMAP team)



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

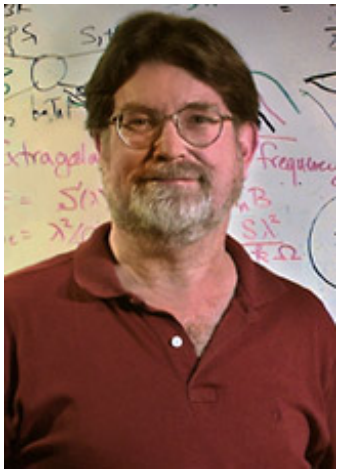




COBE

Cosmic Background Explorer

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

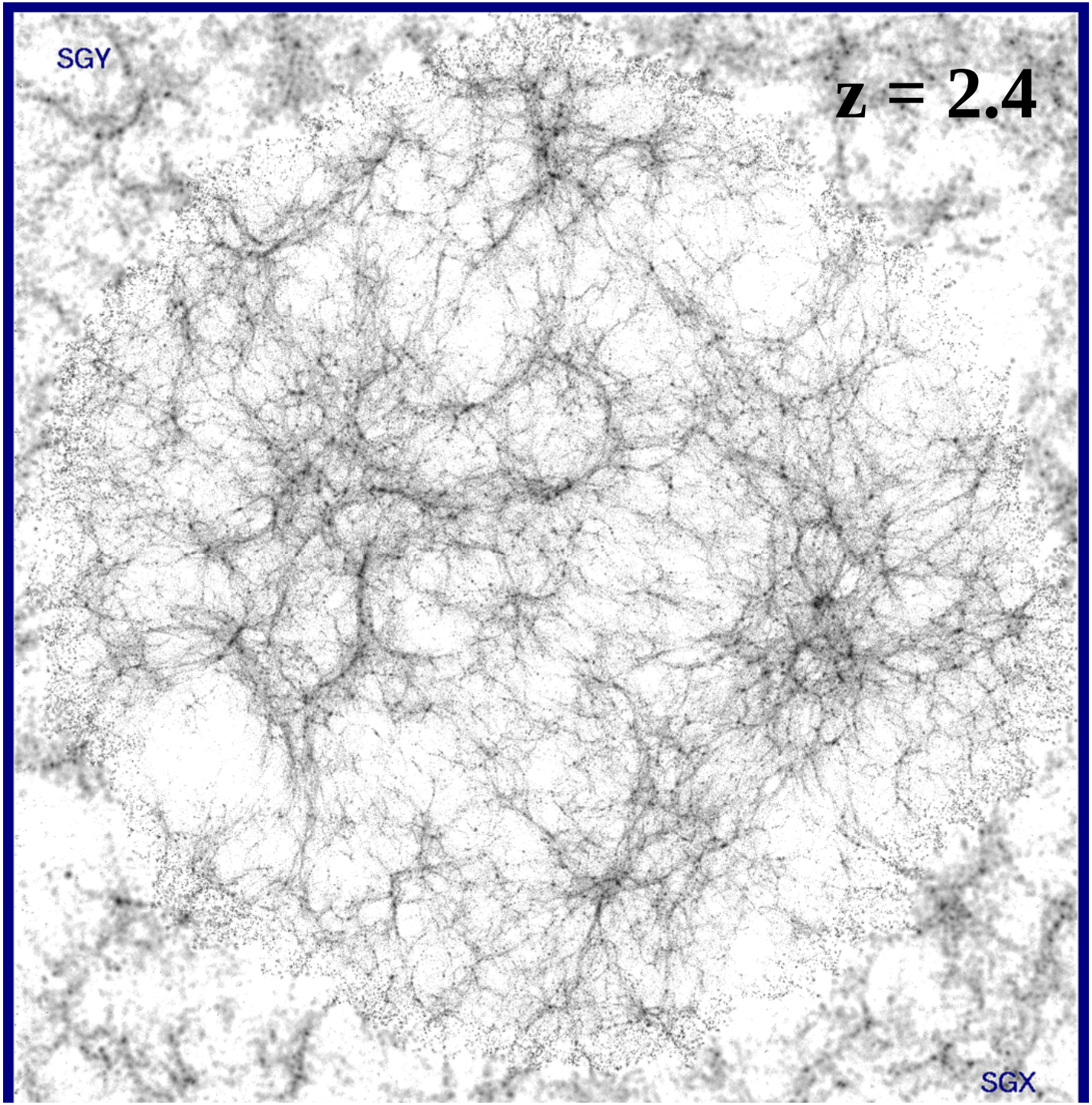


z = 1000

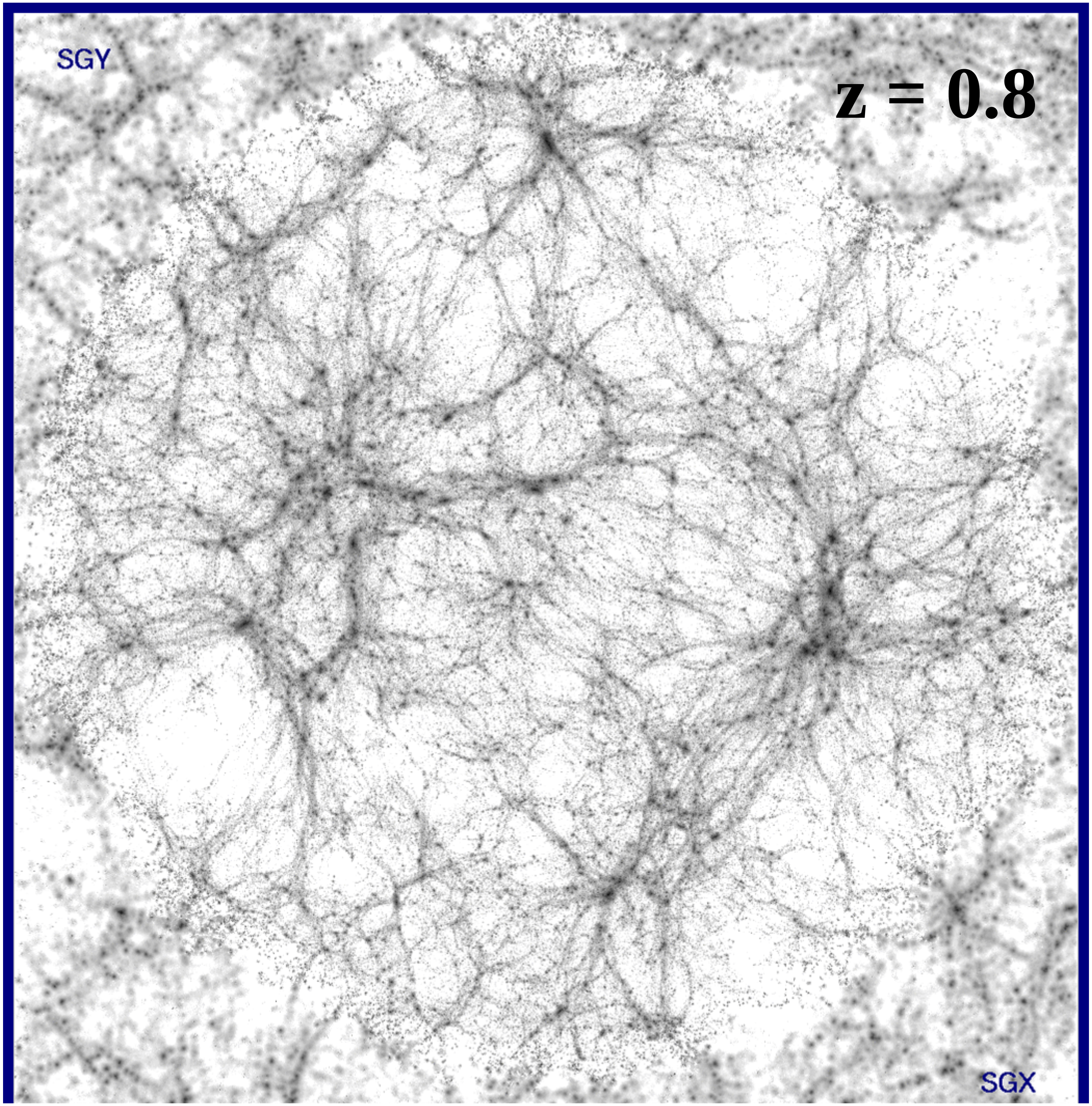
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

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



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



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

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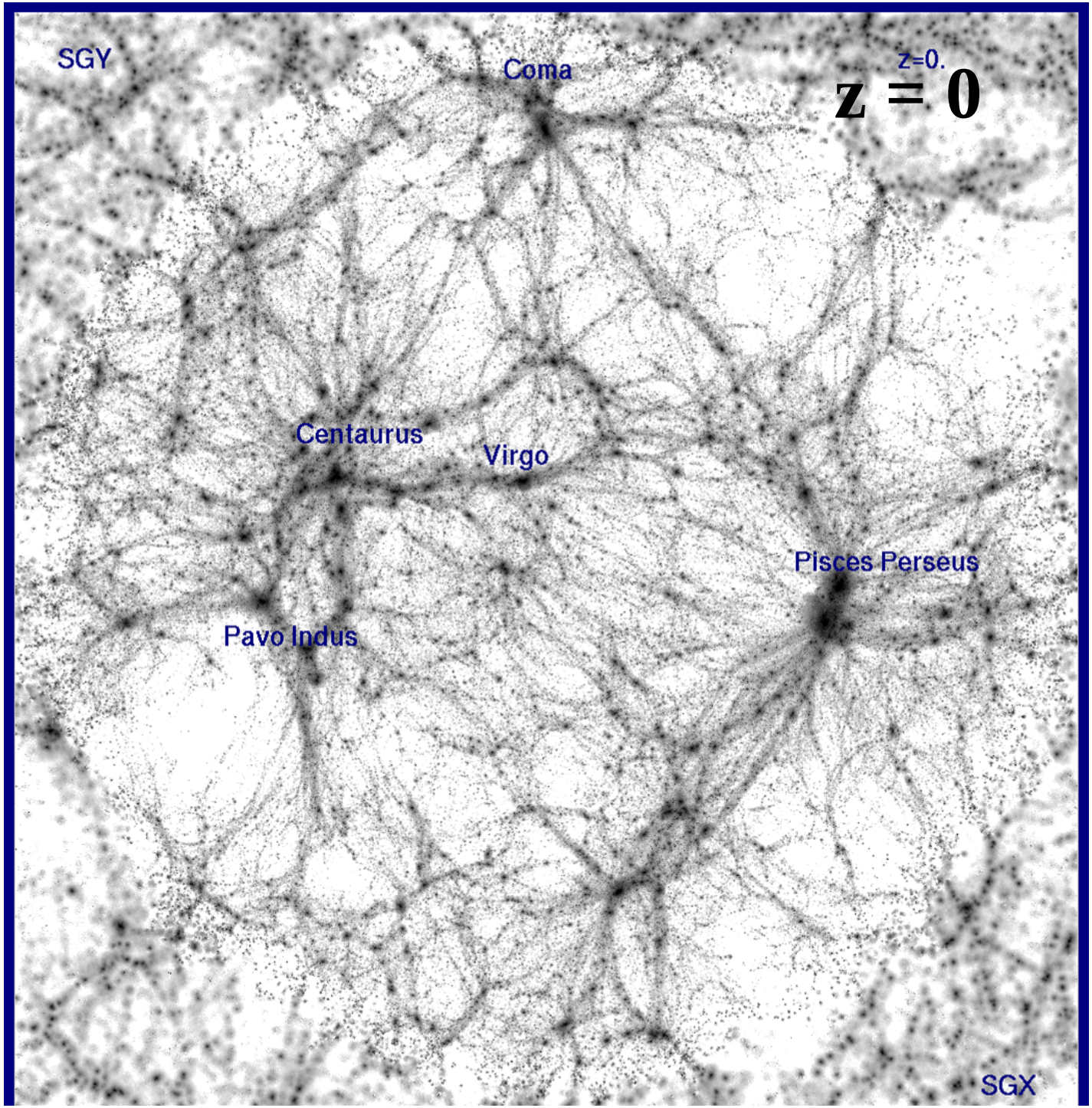

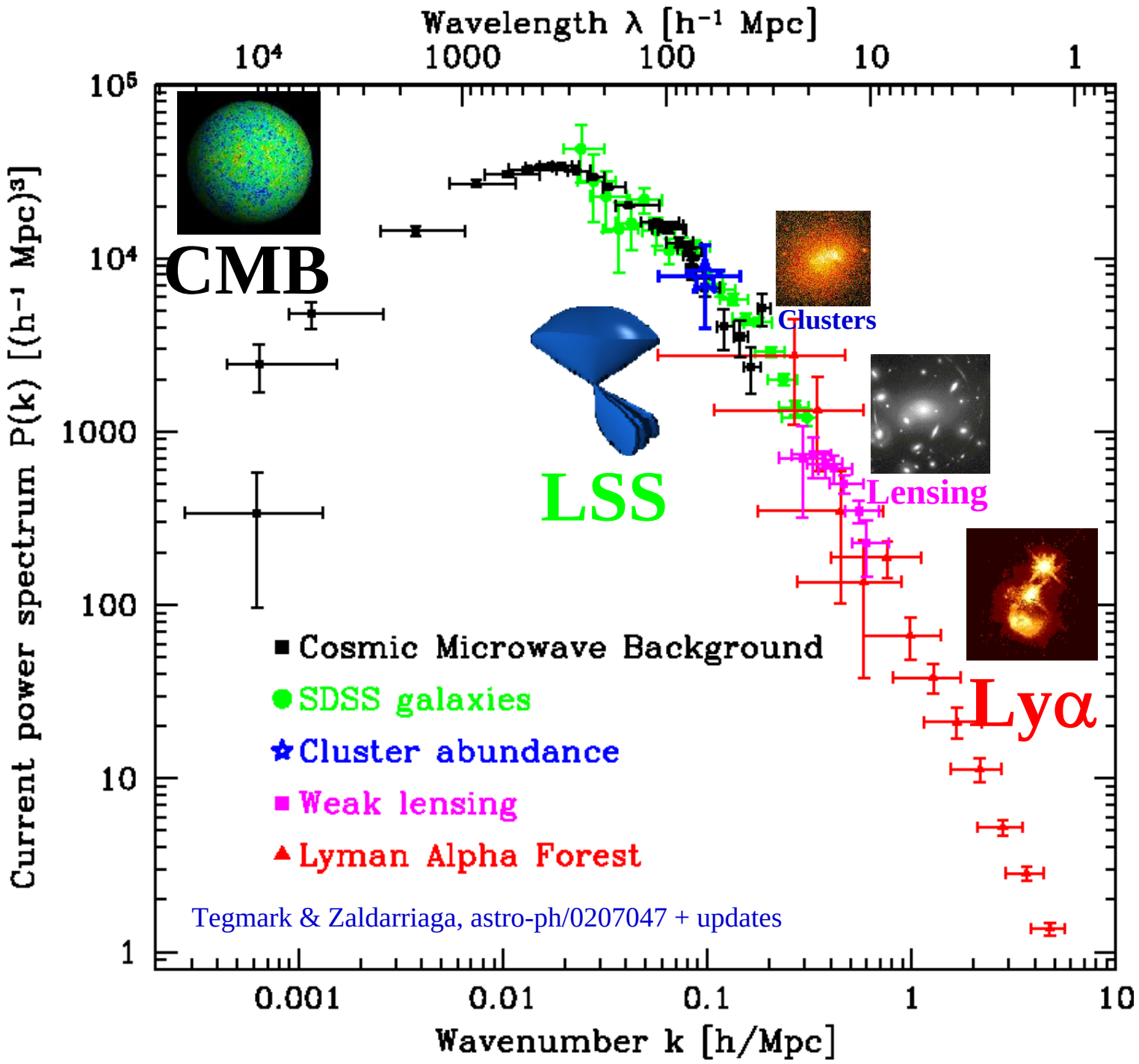

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu

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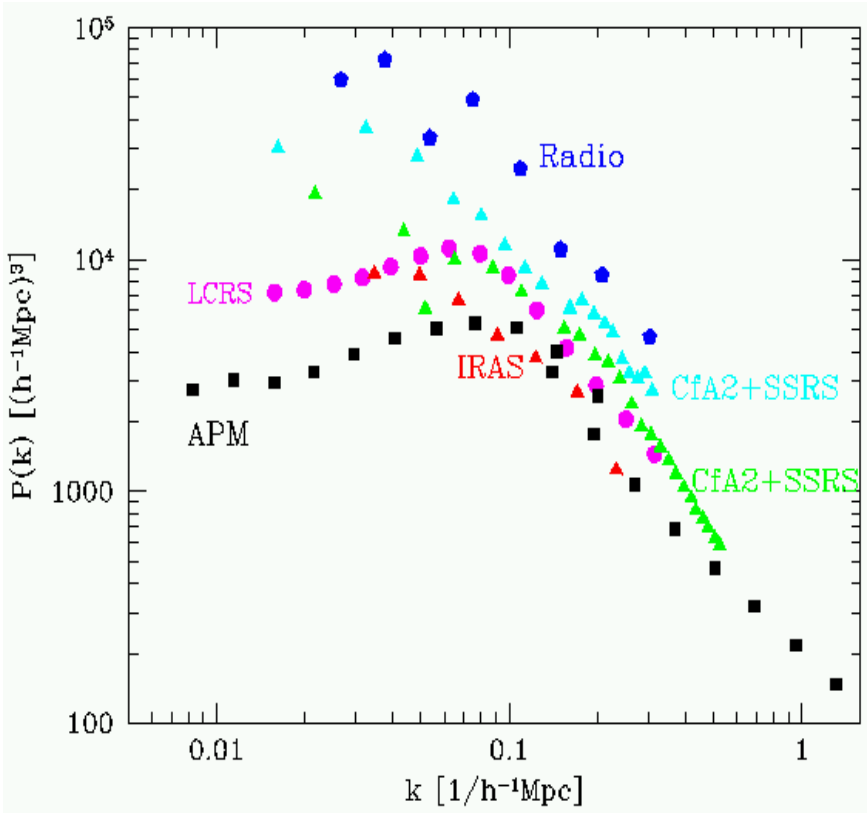
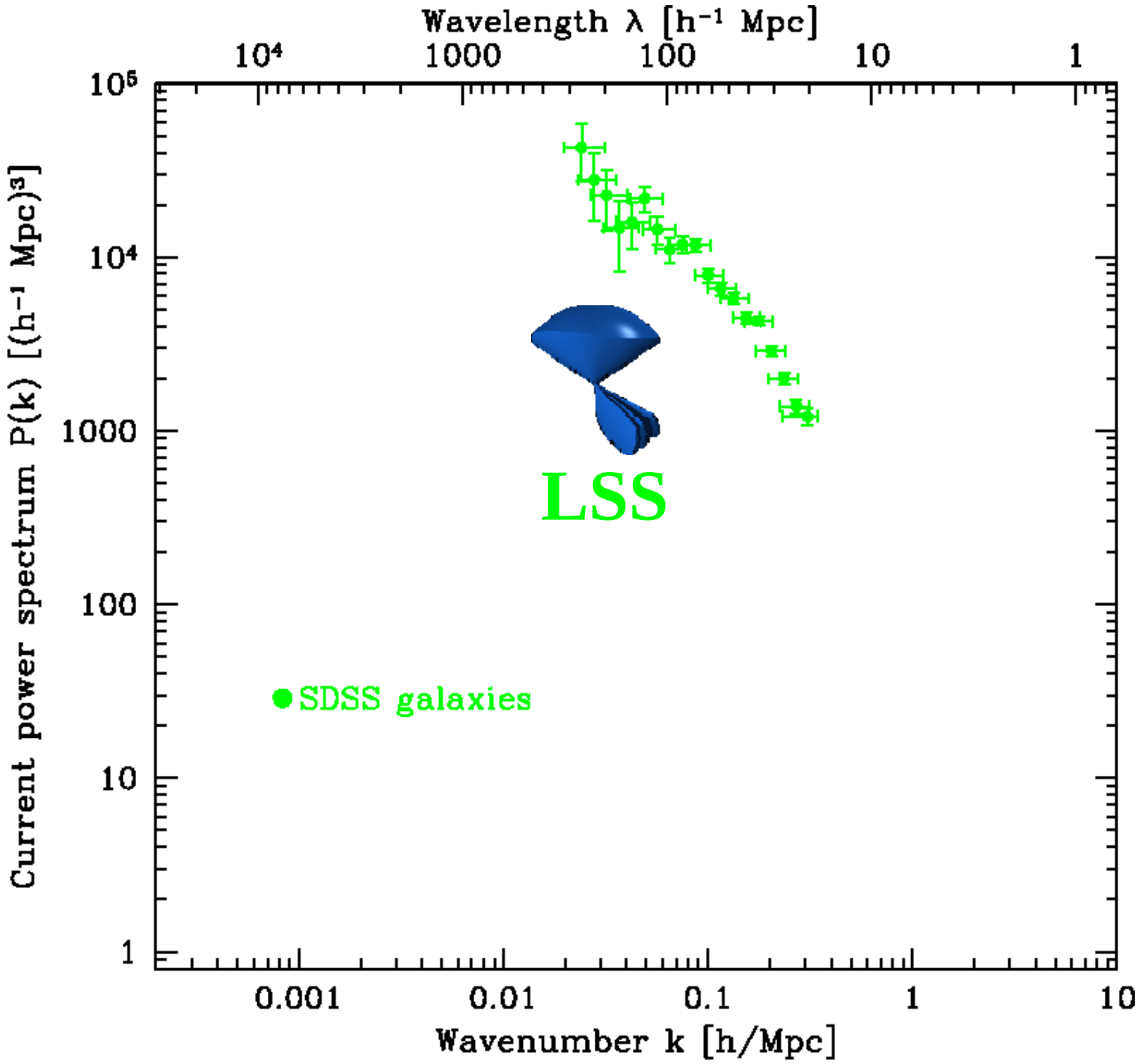
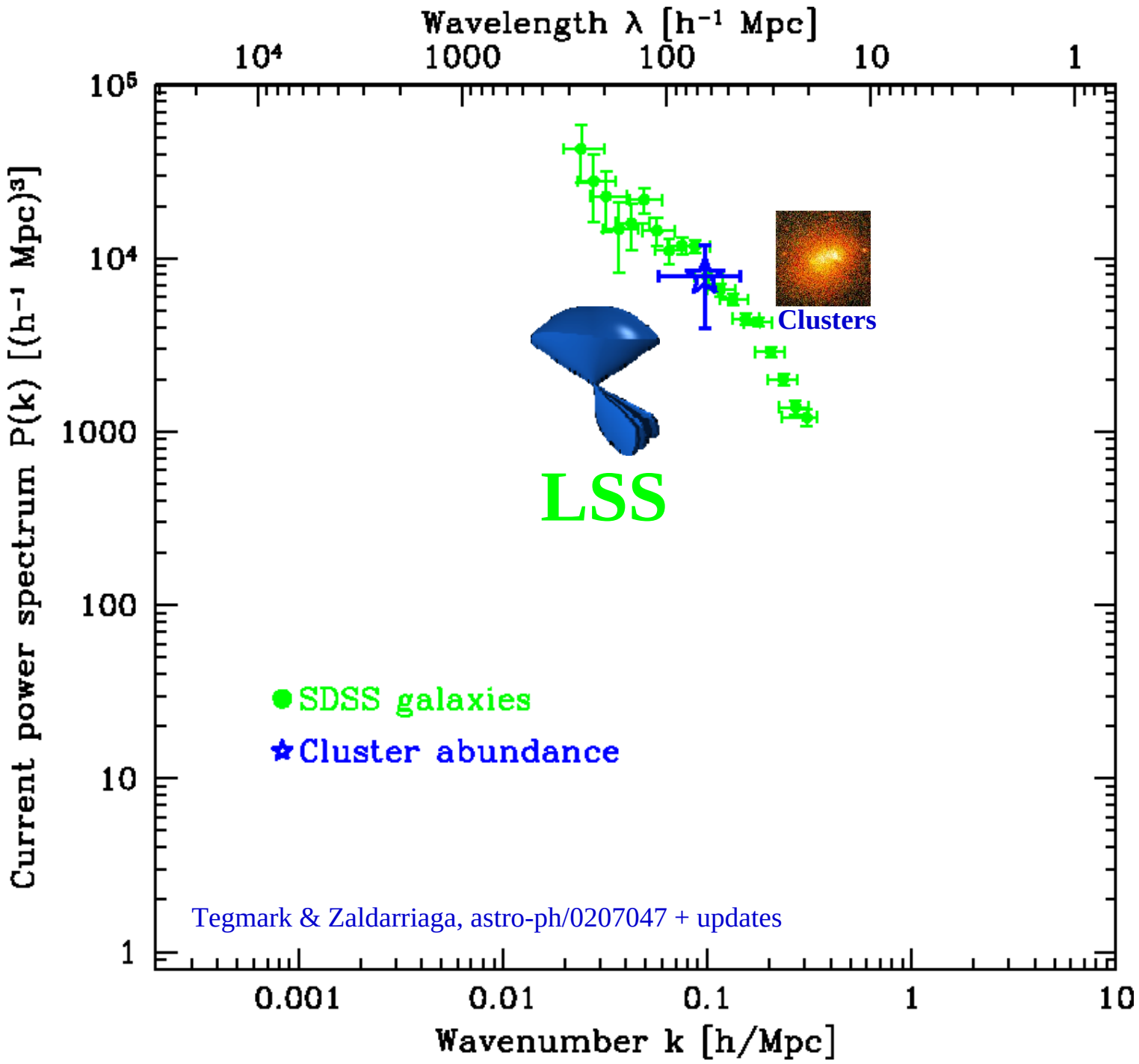


Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

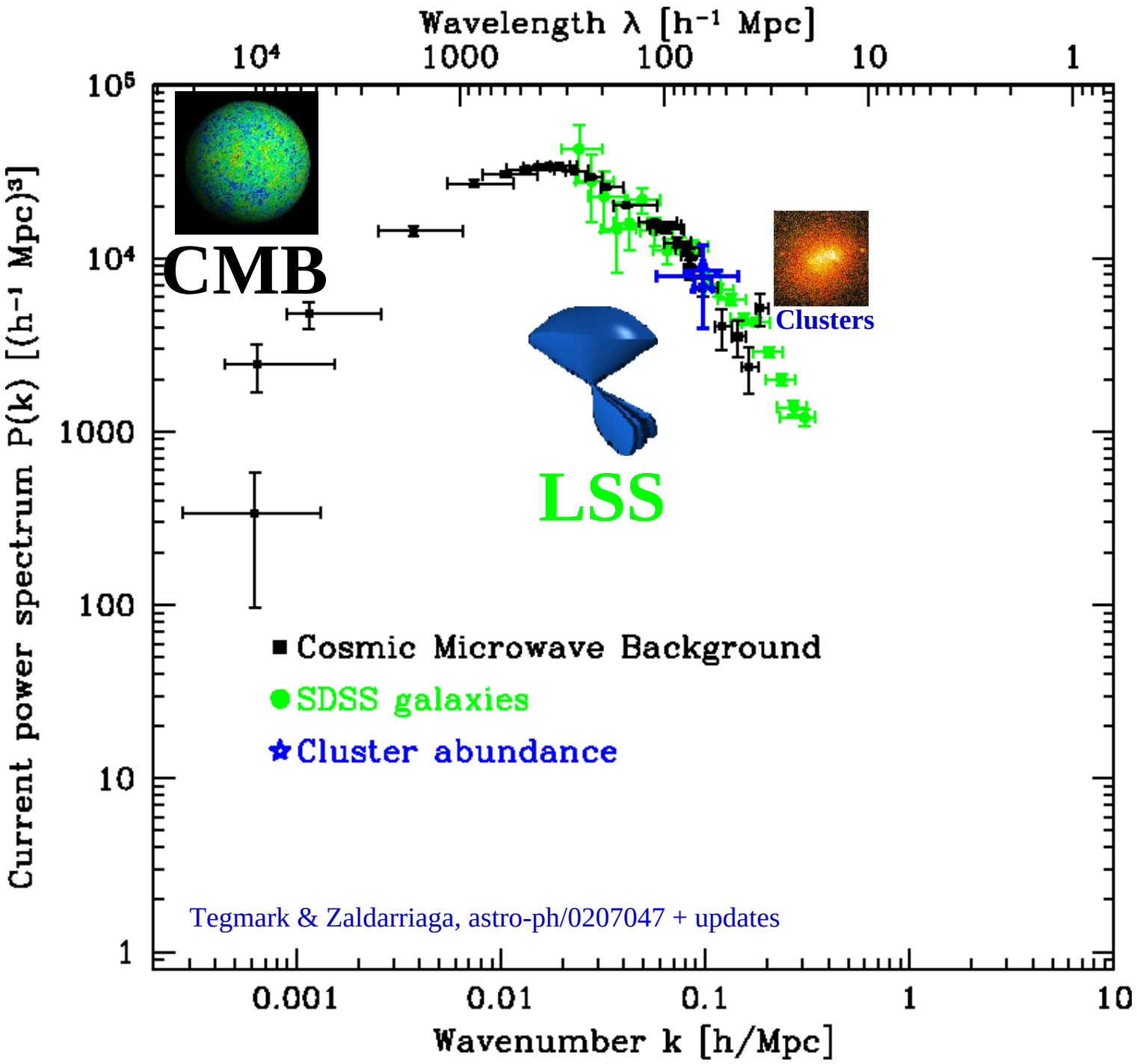
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007



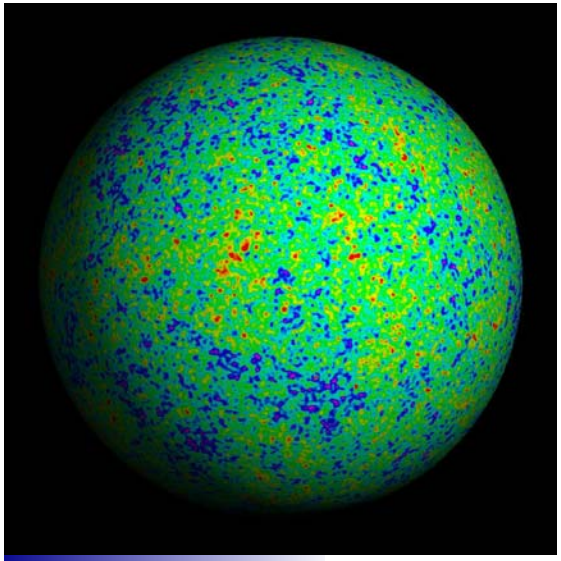
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

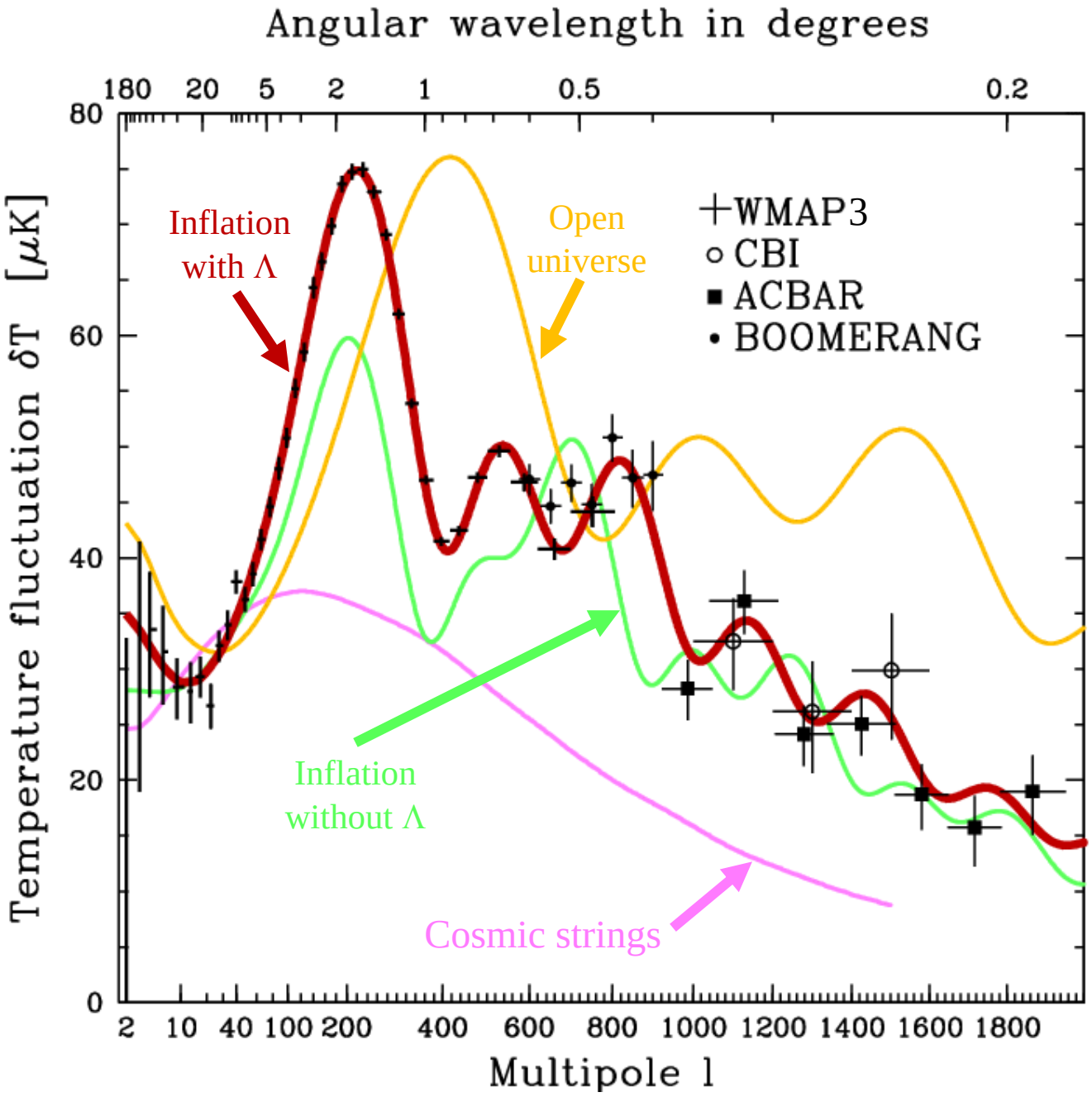


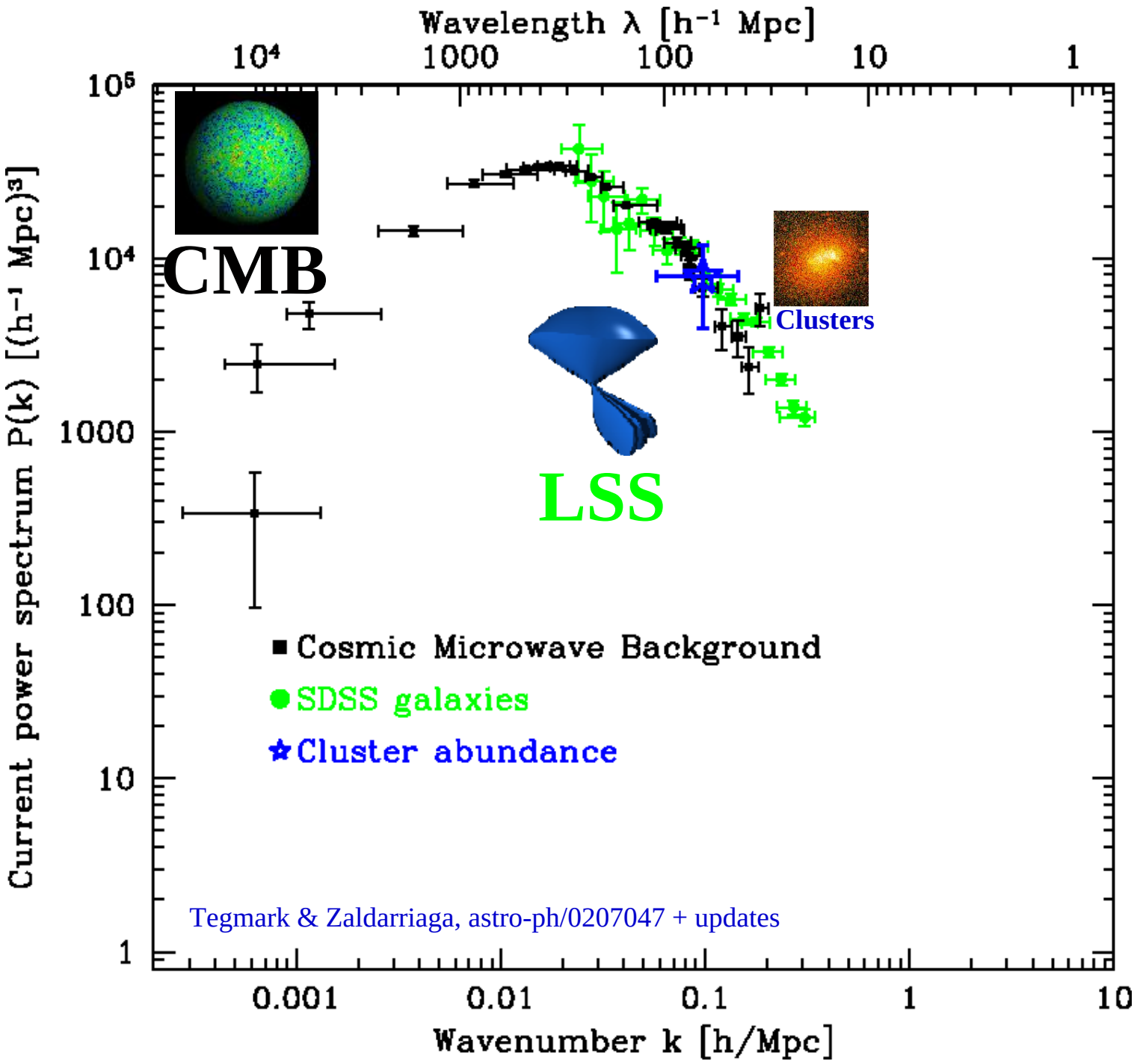
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007



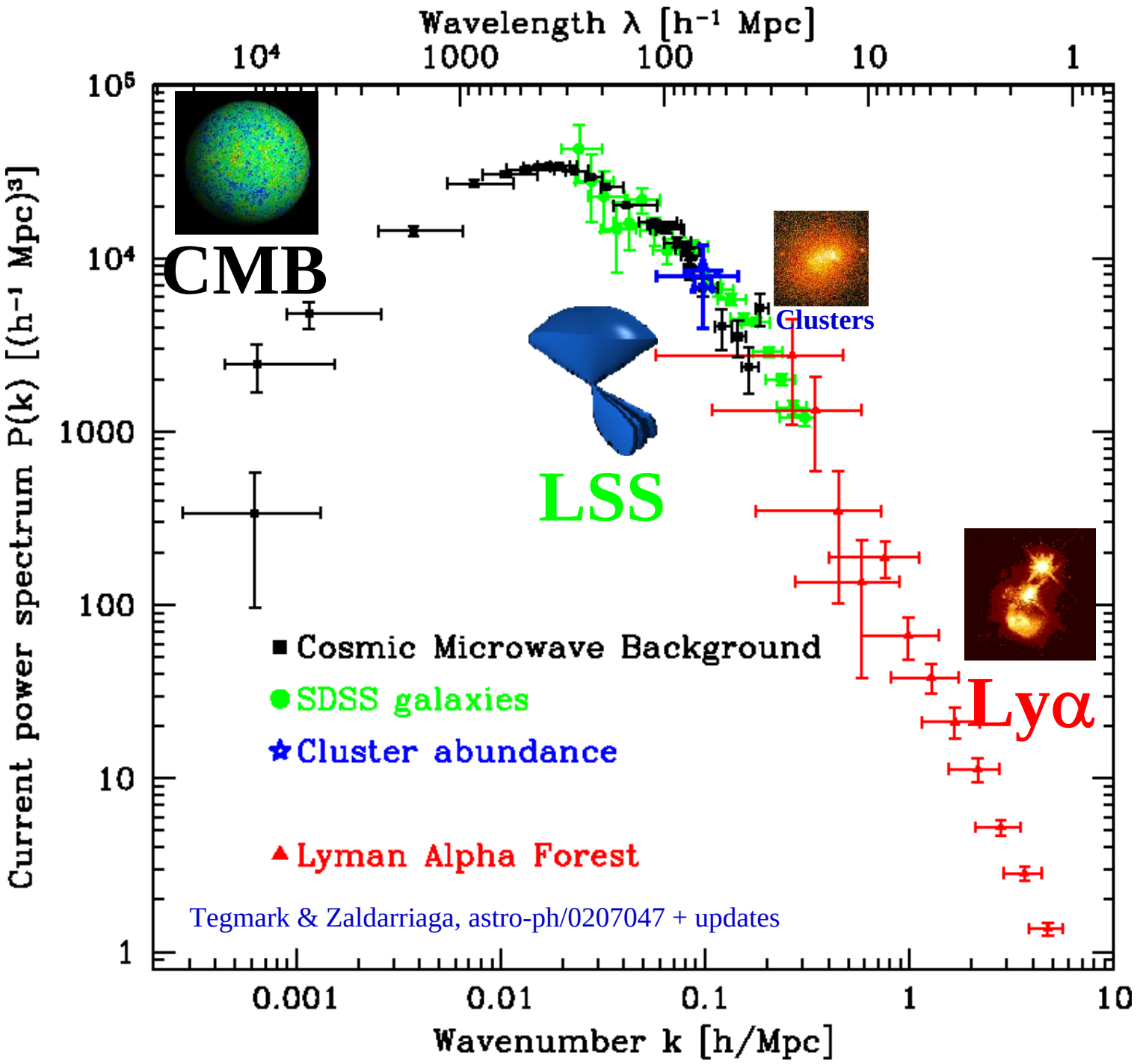
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

Guth & Kaiser 2005 (Science) + WMAP3

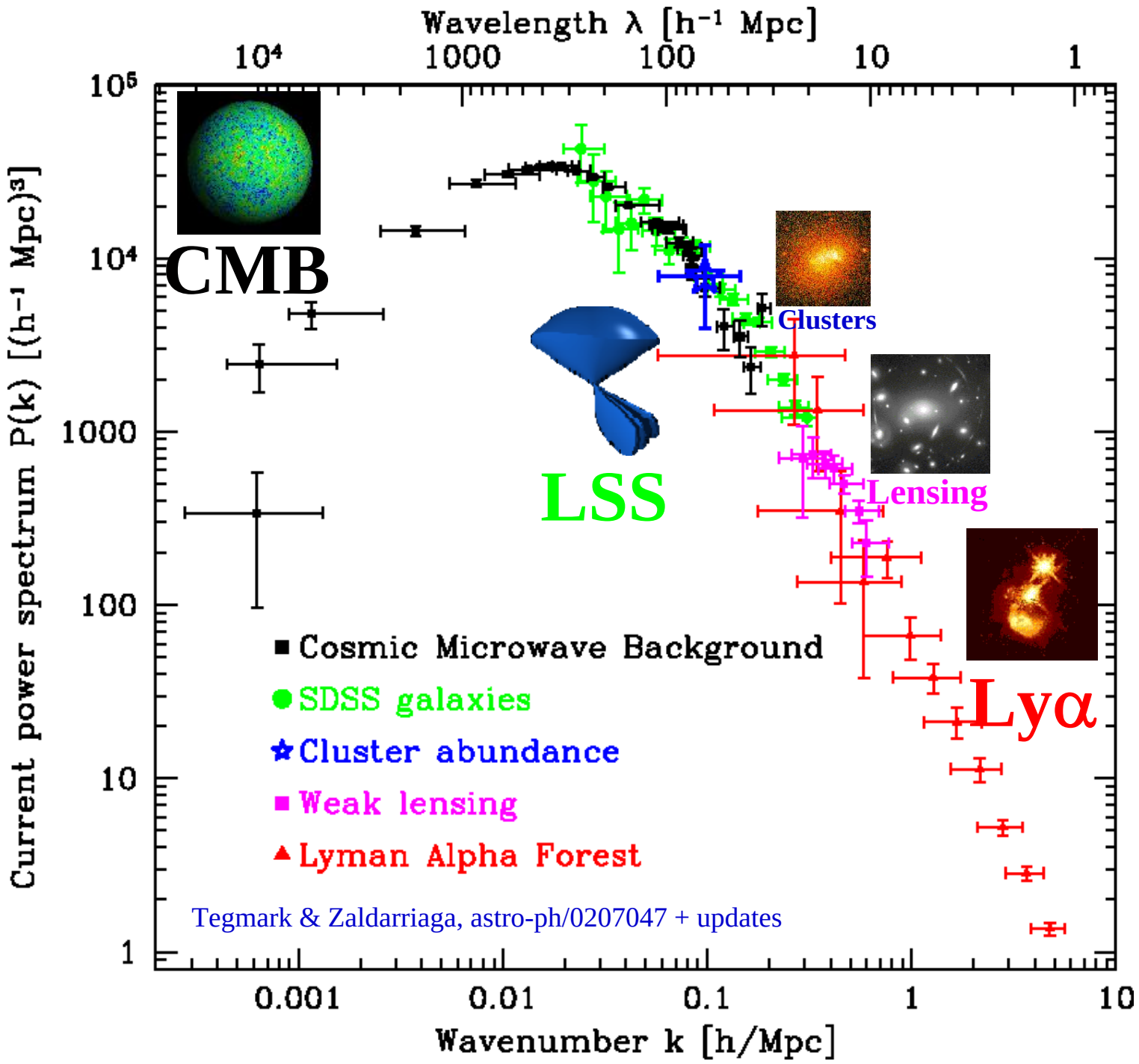




Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu

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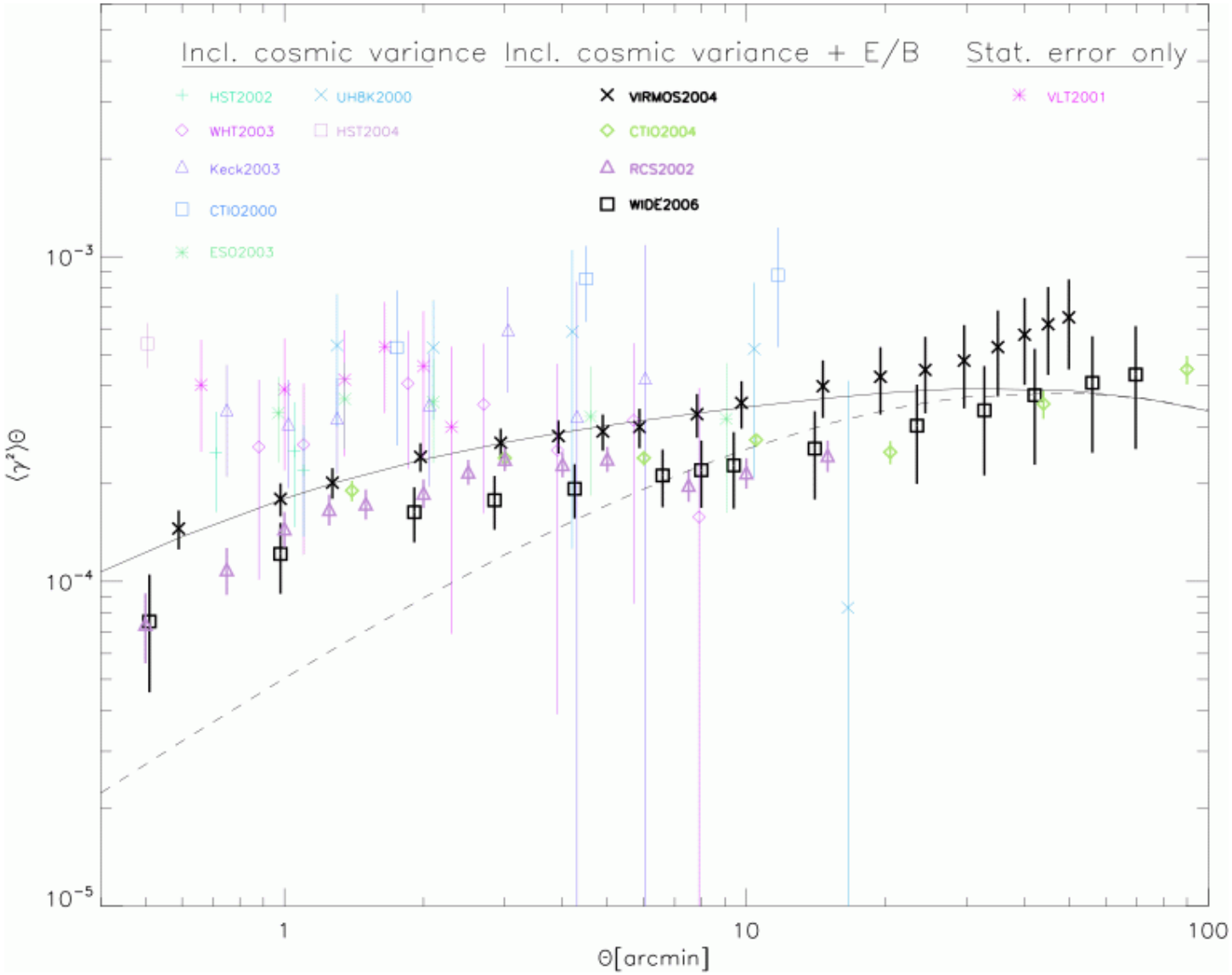
Current lensing measurements:



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu

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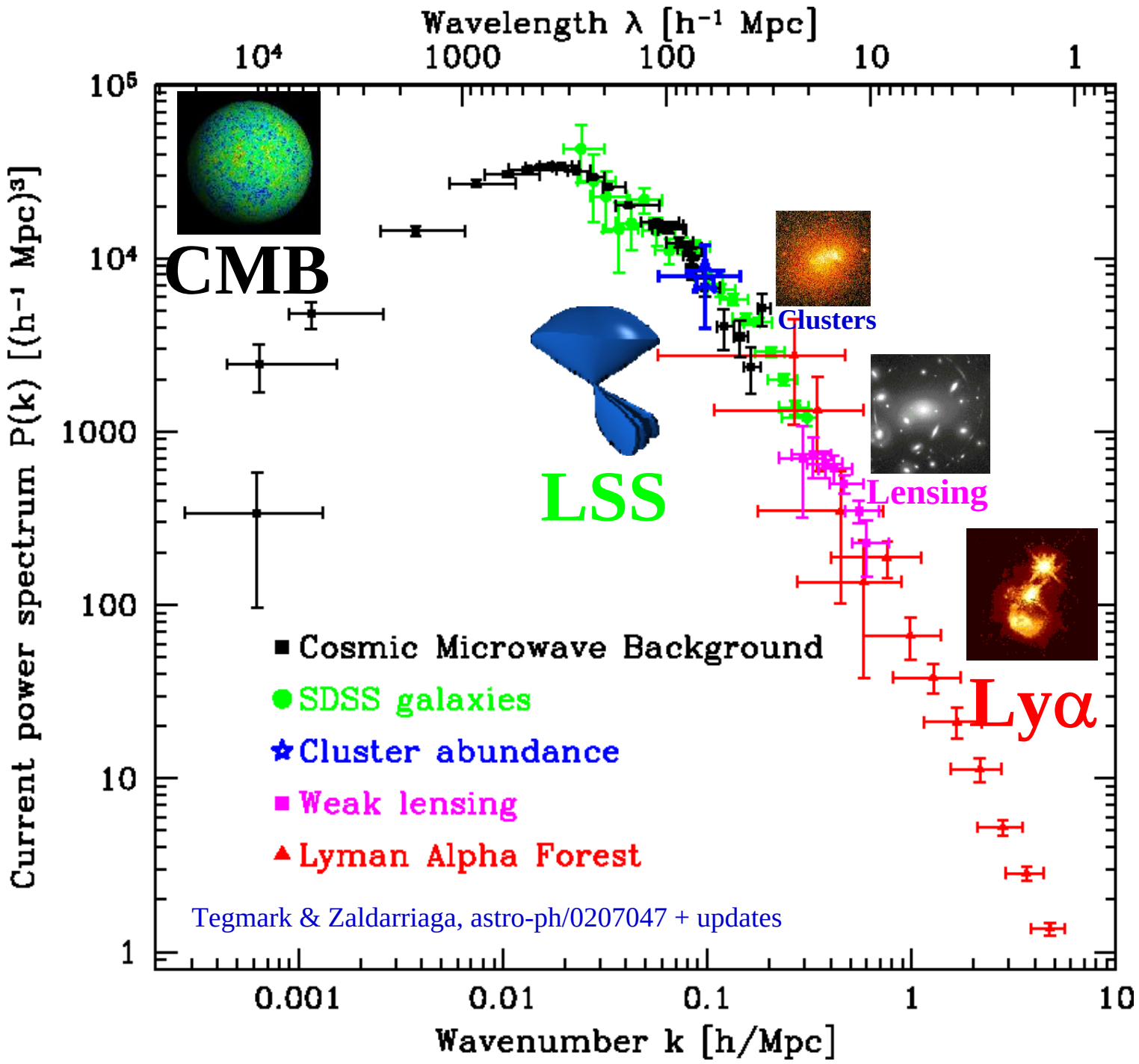
Compilation from Munshi, Valageas, van Waerbeke & Heavens, astro-ph/0612667



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu

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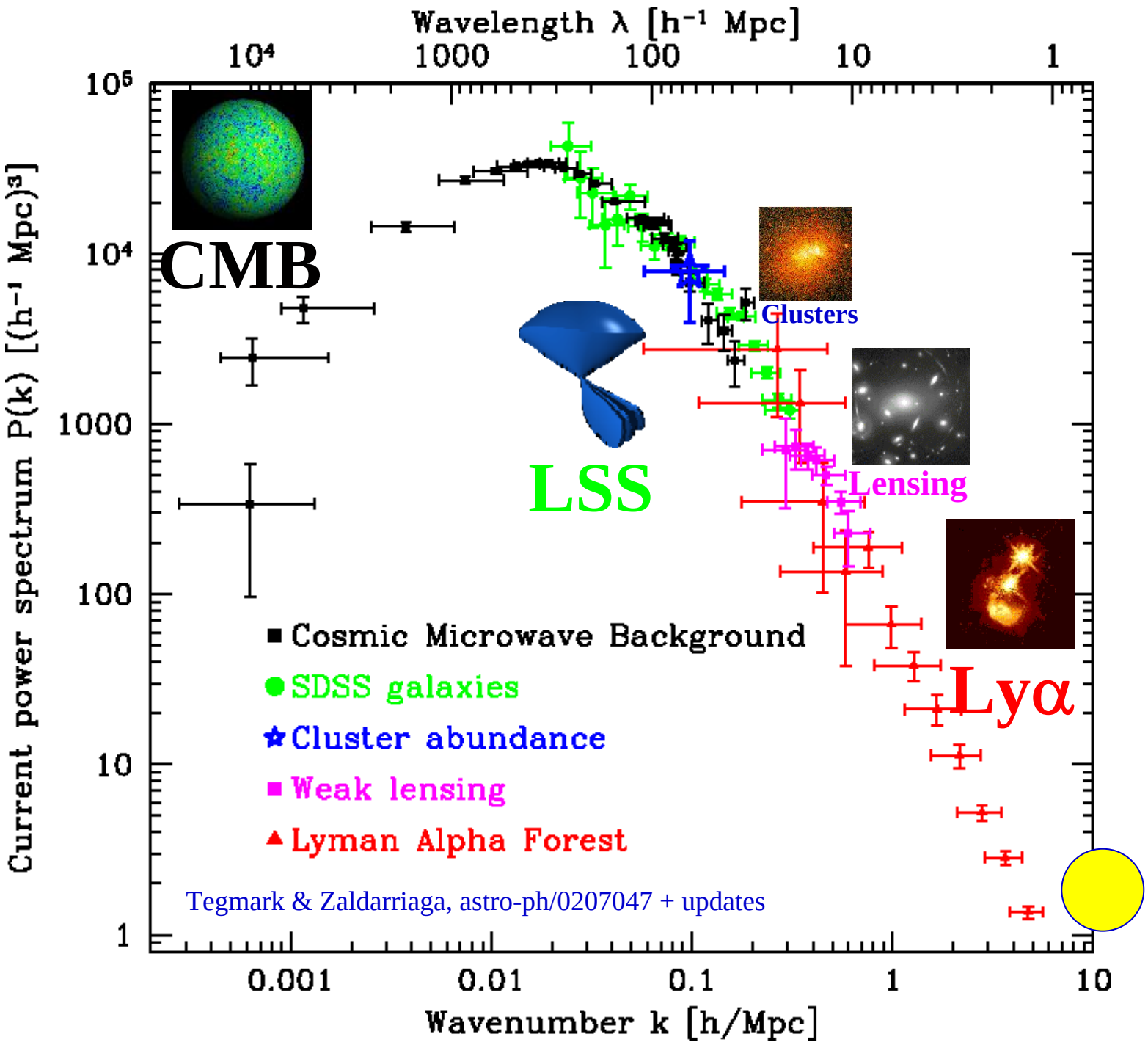


Tegmark & Zaldarriaga, astro-ph/0207047 + updates

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

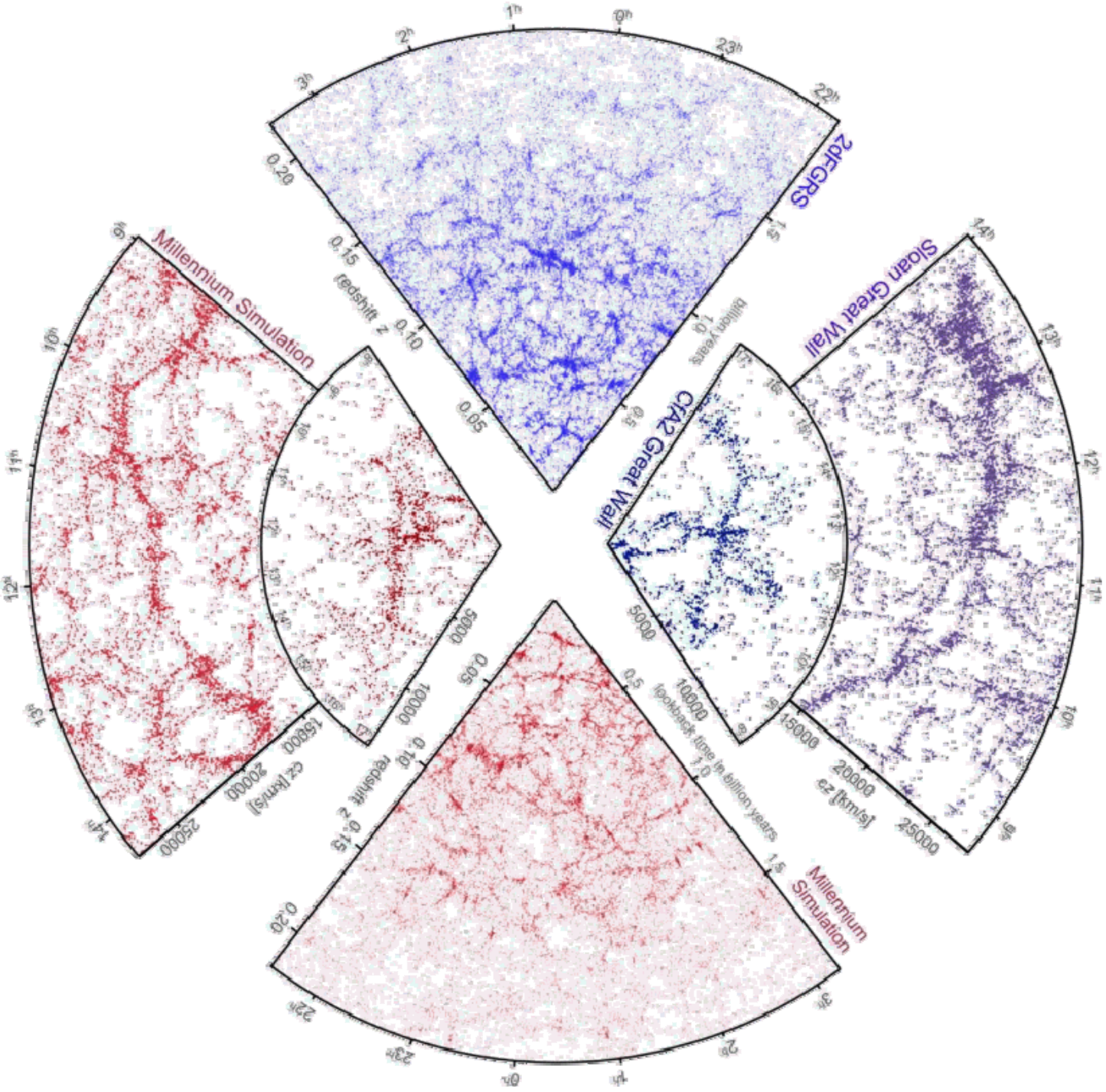
Galaxy clustering progress

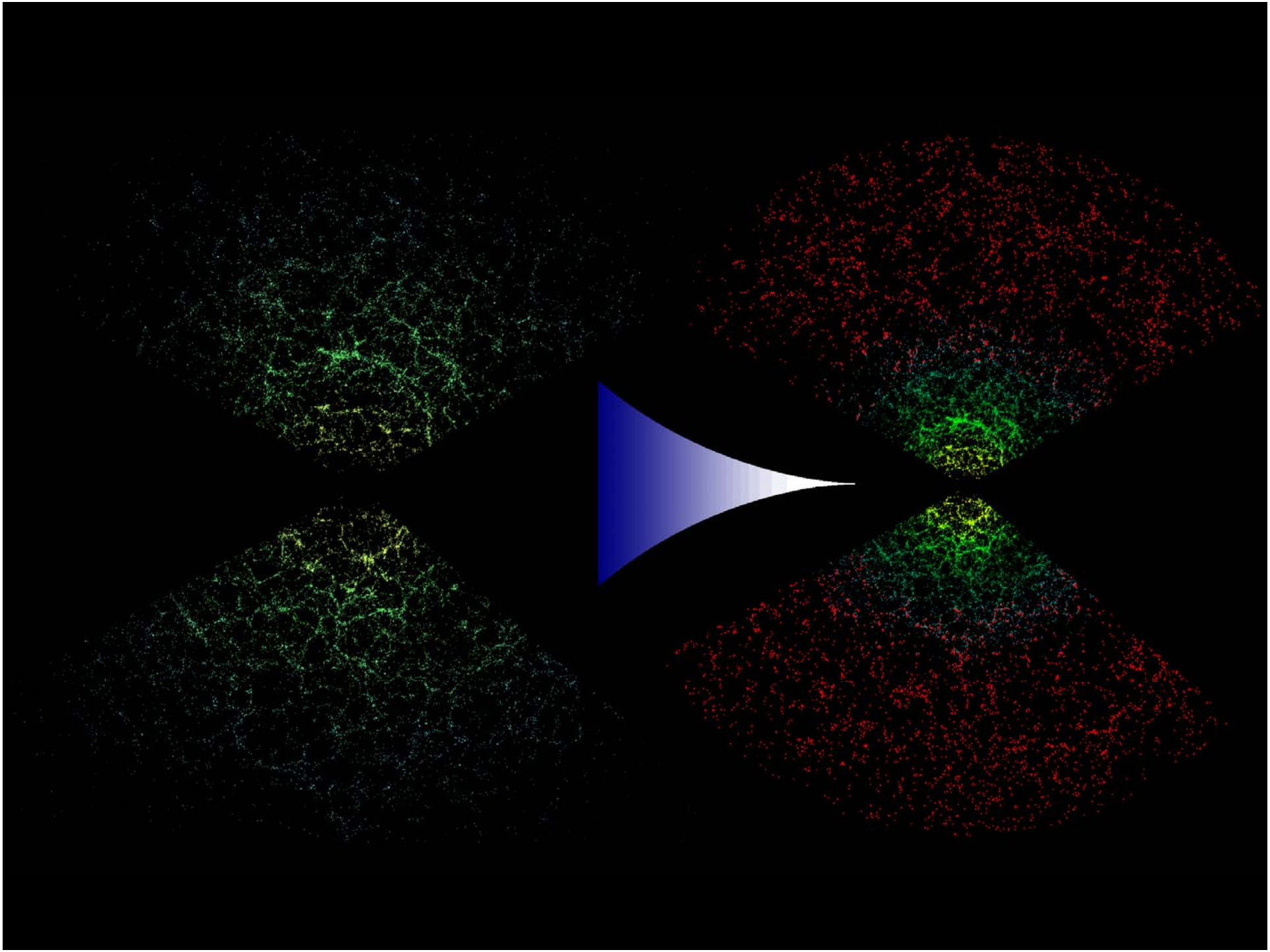
Cosmological Constraints from the SDSS Luminous Red Galaxies

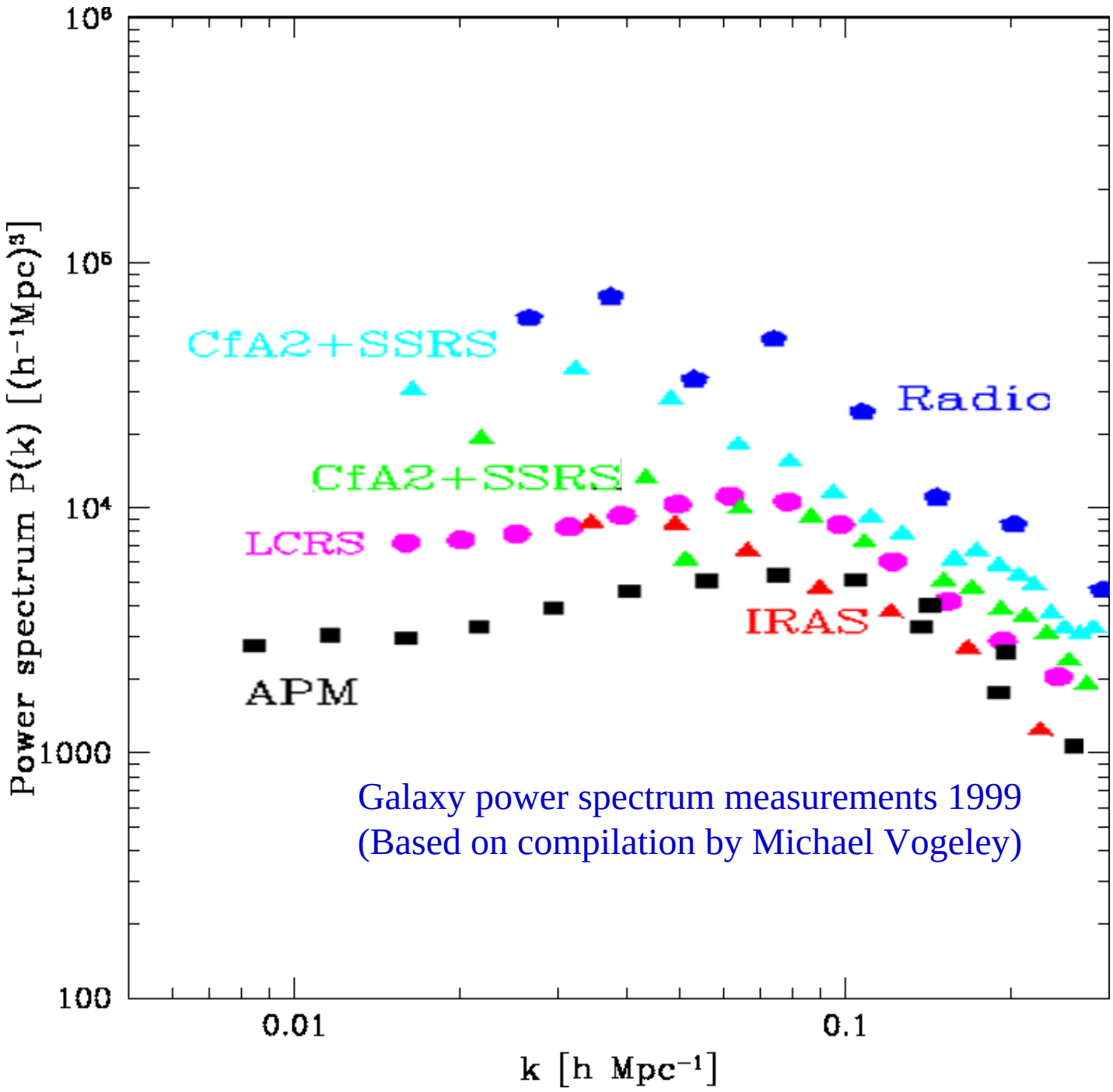
Max Tegmark[1], Daniel J. Eisenstein[2], Michael A. Strauss[3], David H. Weinberg[4], Michael R. Blanton[5], Joshua A. Frieman[6,7], Masataka Fukugita[8], James E. Gunn[3], Andrew J. S. Hamilton[9], Gillian R. Knapp[3], Robert C. Nichol[10], Jeremiah P. Ostriker[3], Nikhil Padmanabhan[11], Will J. Percival[10], 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

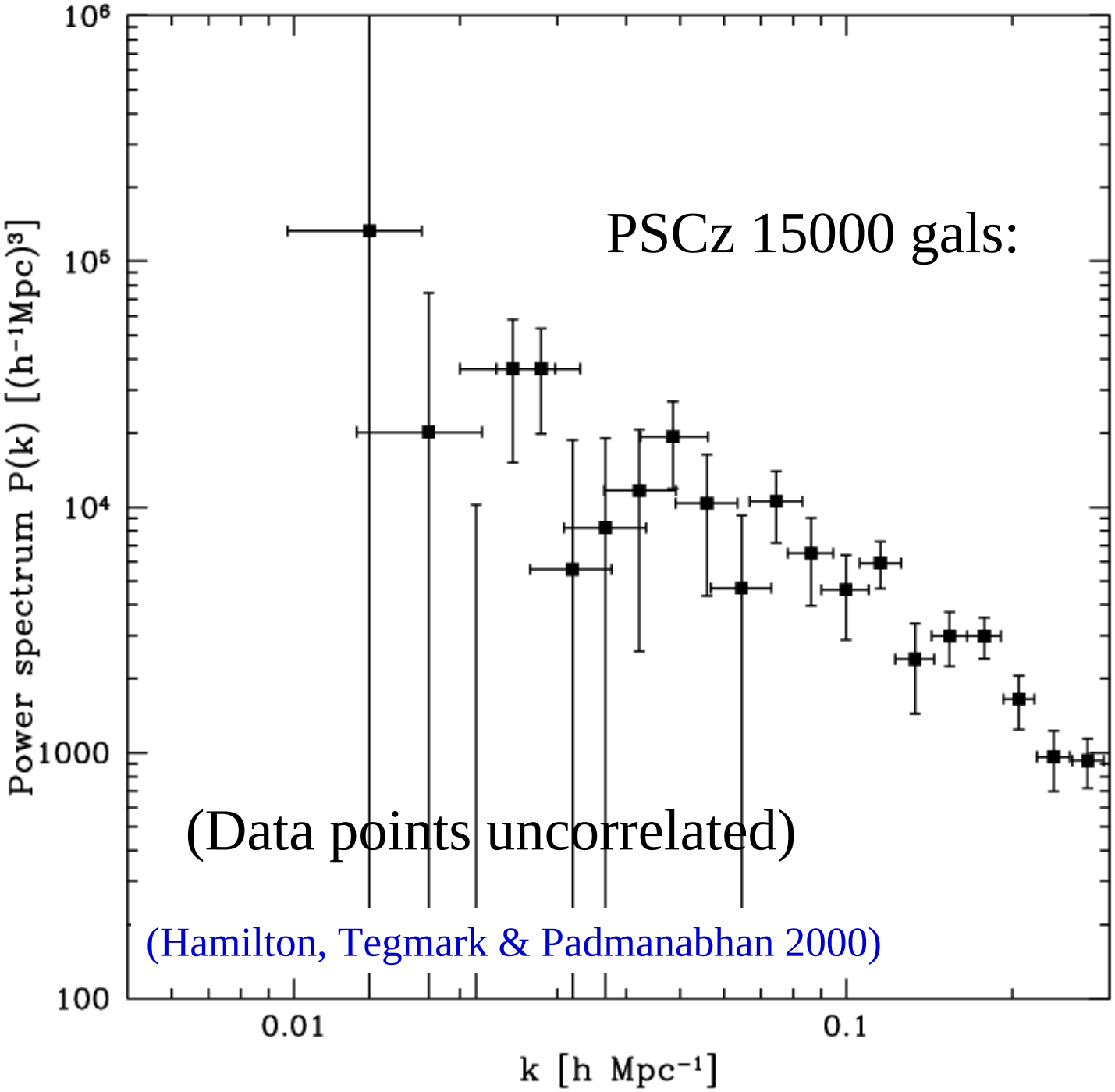




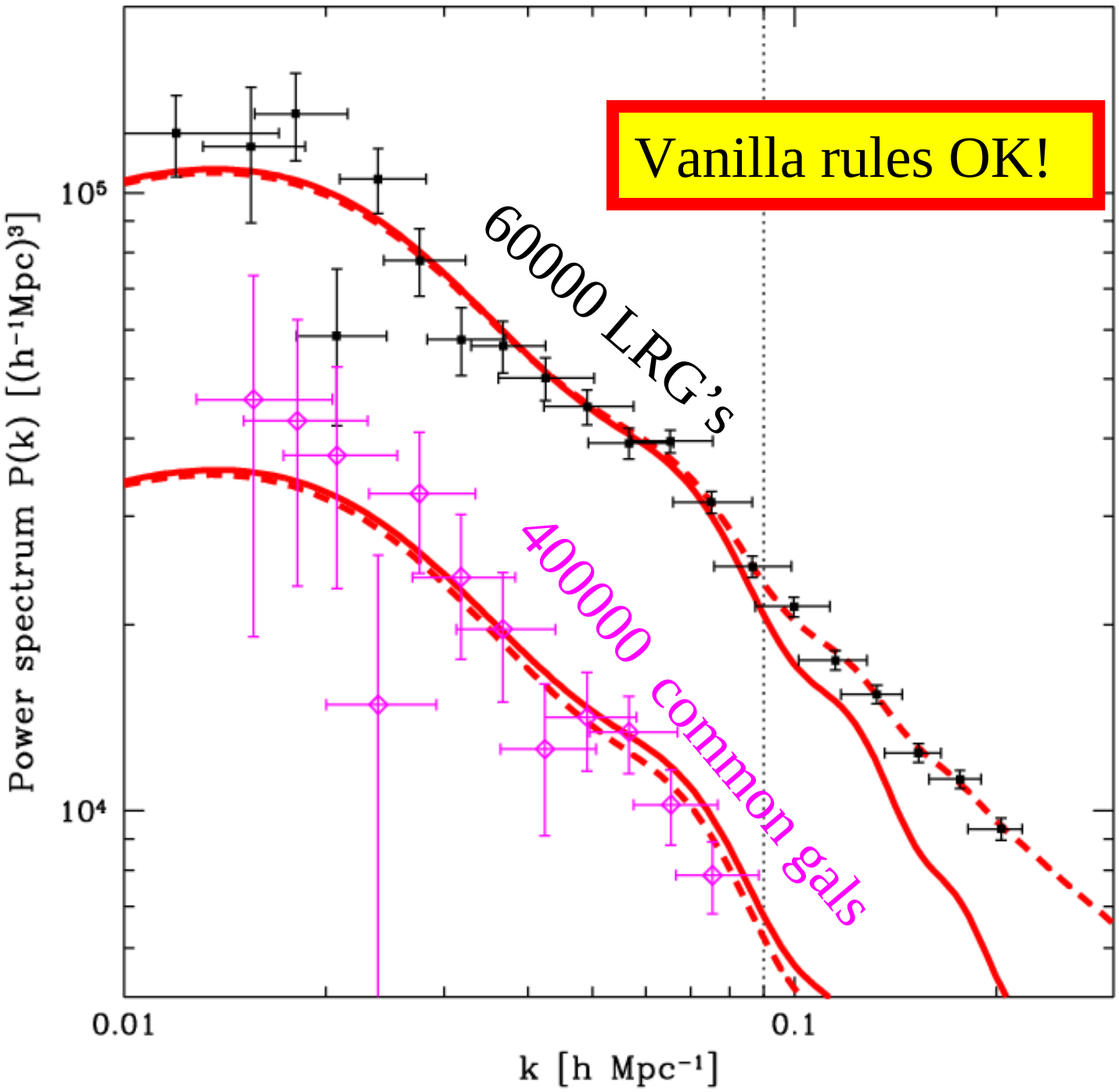


Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

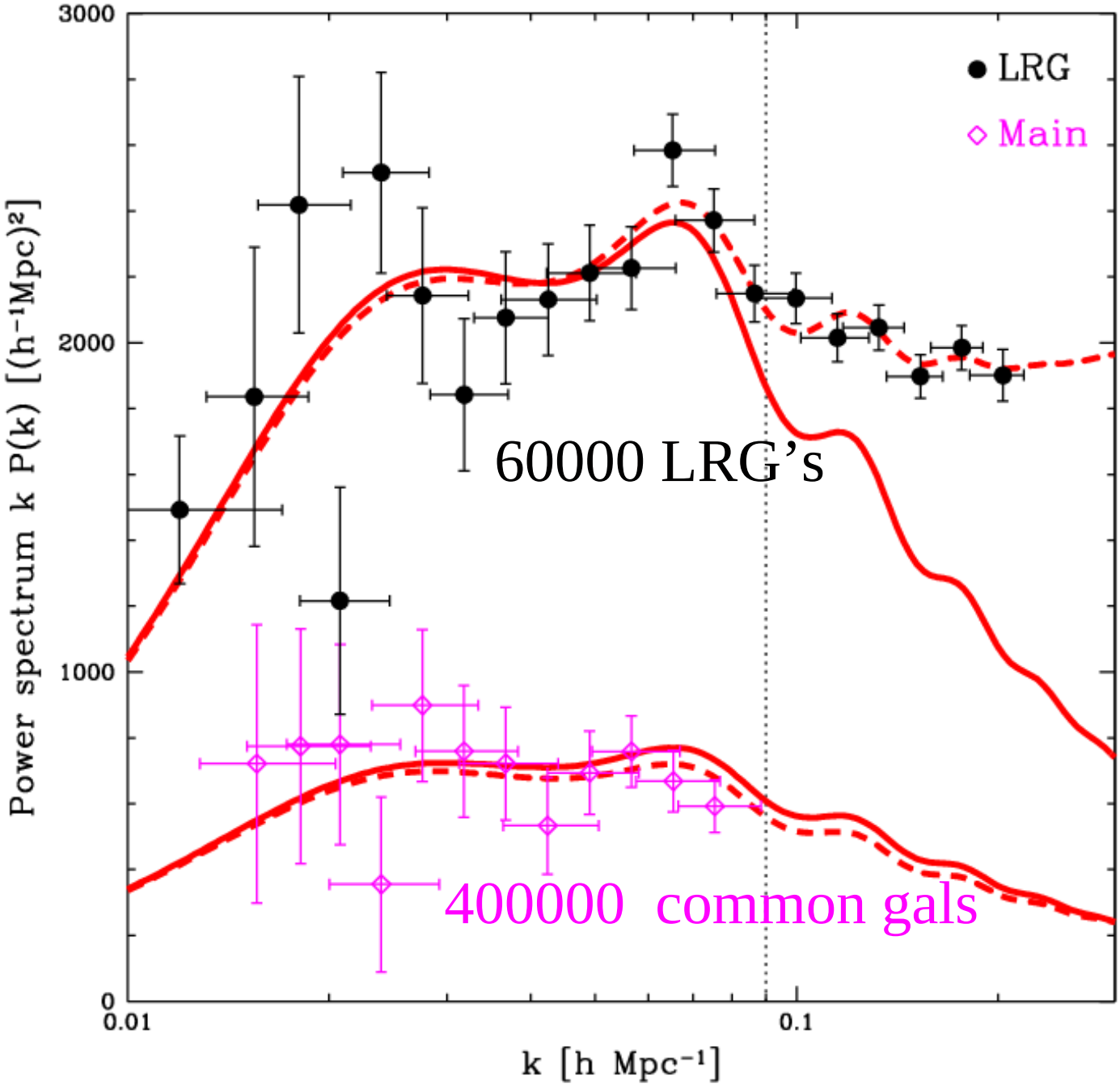
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

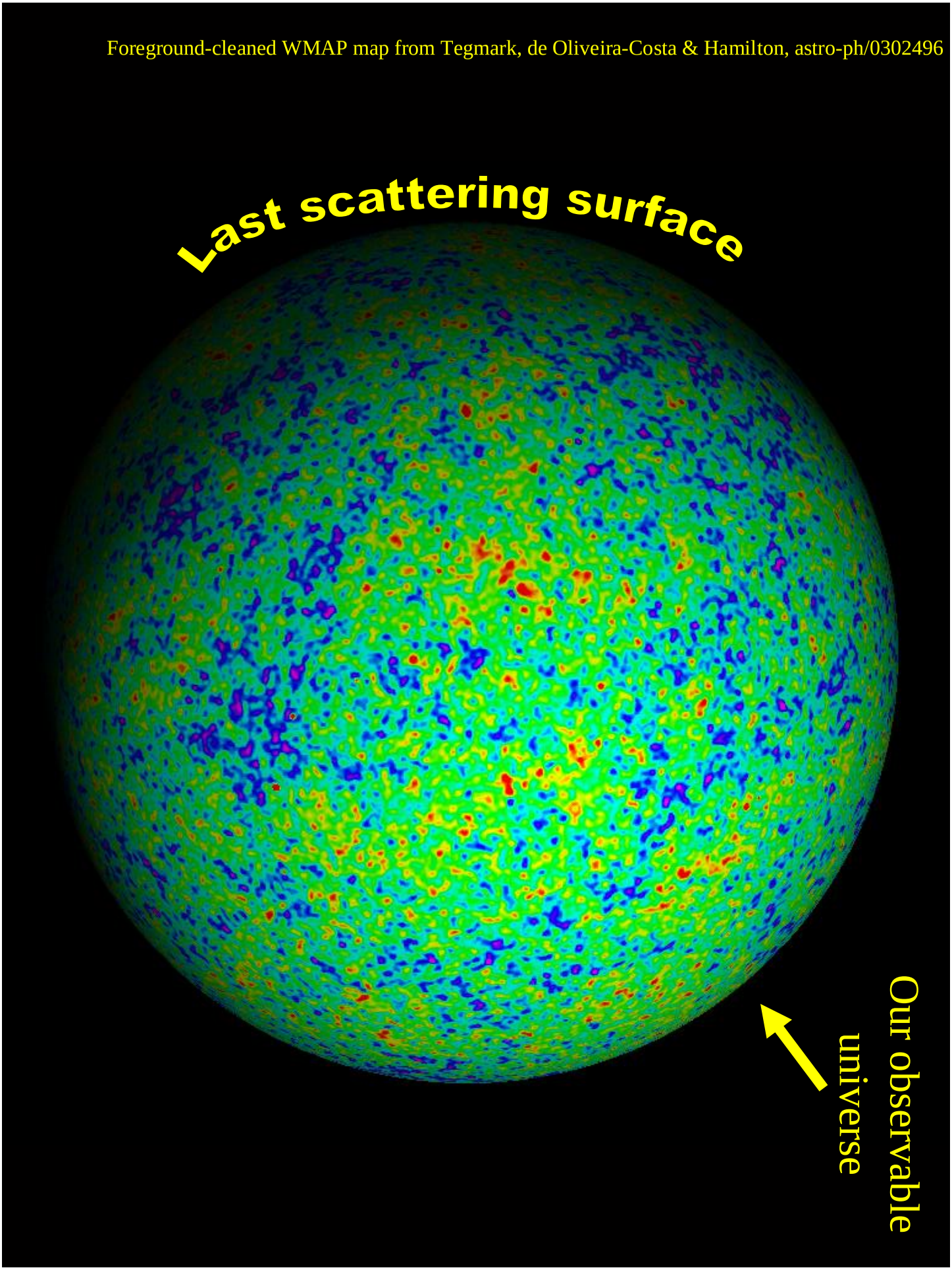


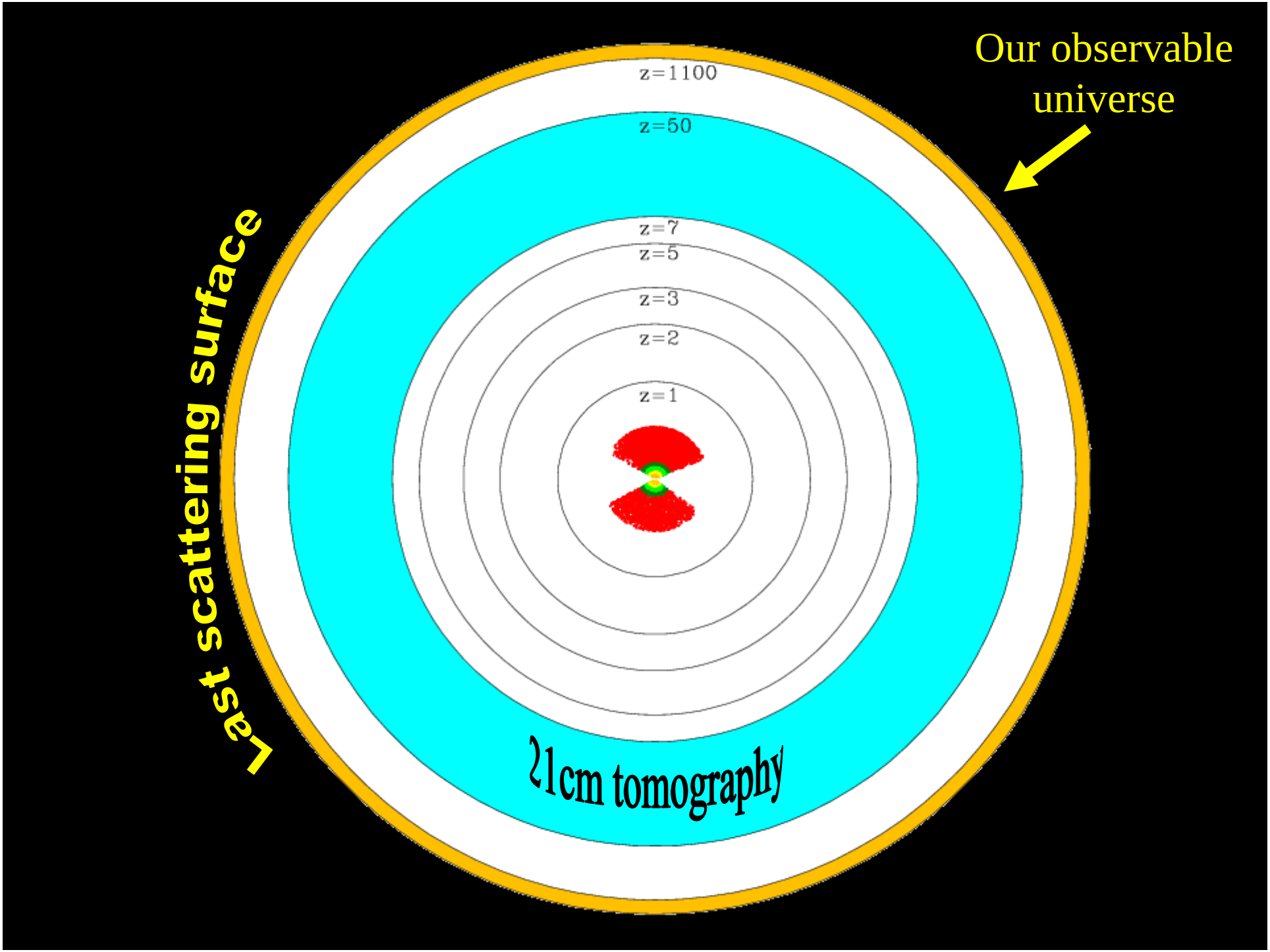
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

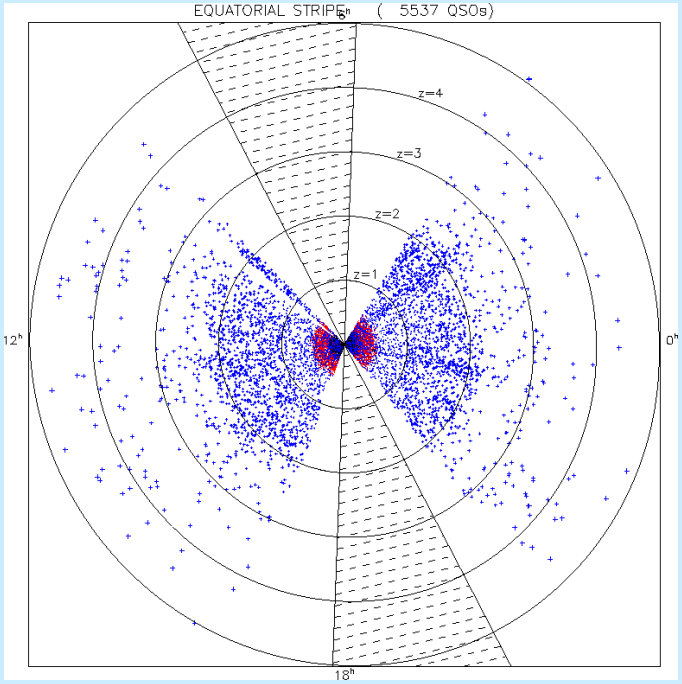
Why are LRGs so useful?


Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496
Last scattering surface
Our observable universe


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

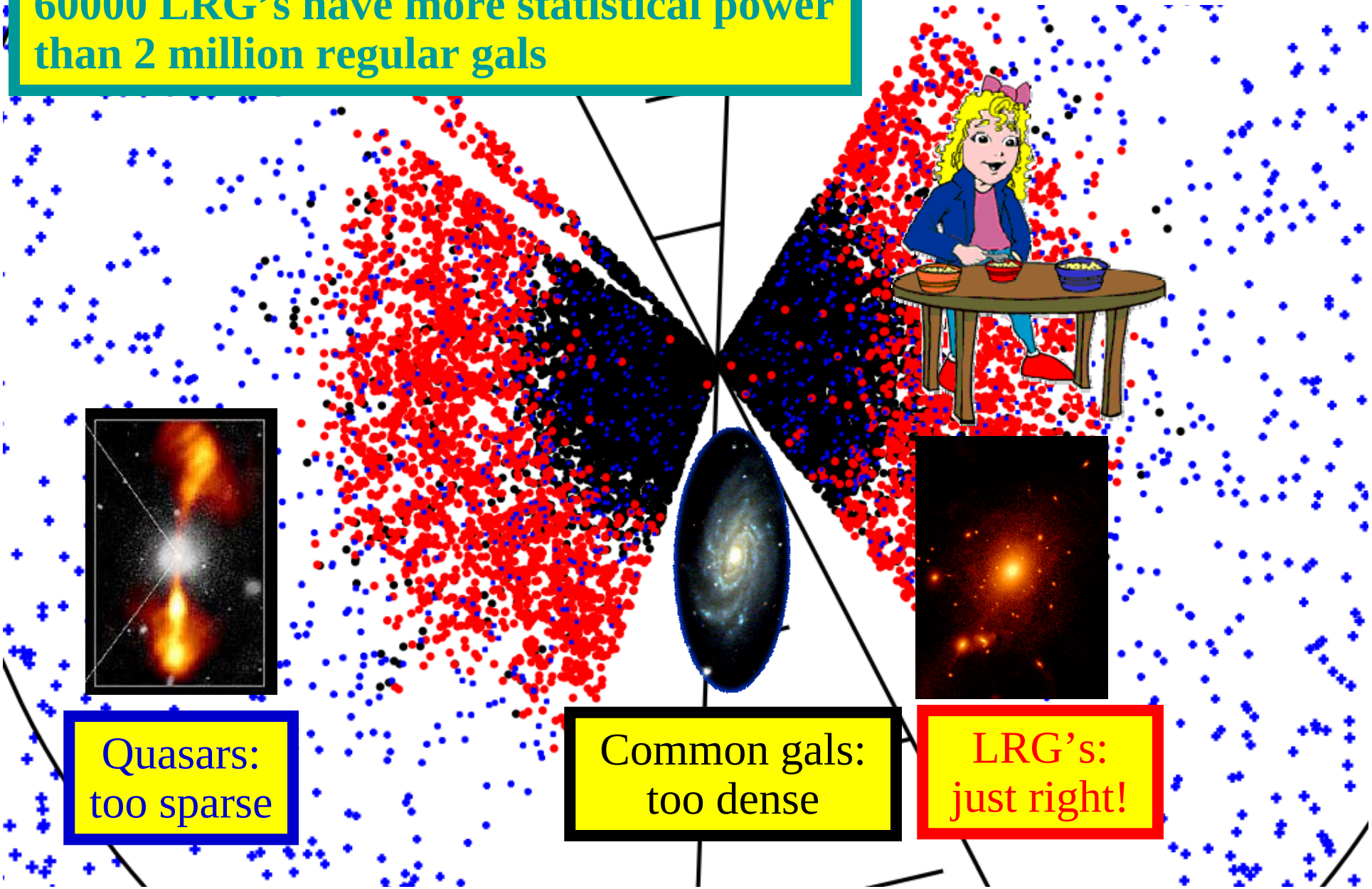
Our observable universe

Last scattering surface



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

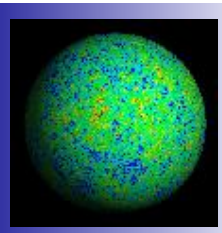
LRG's: just right!

Cosmological parameters

Effects of dark matter

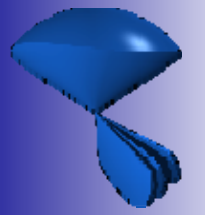
par movies

How much dark matter is there?

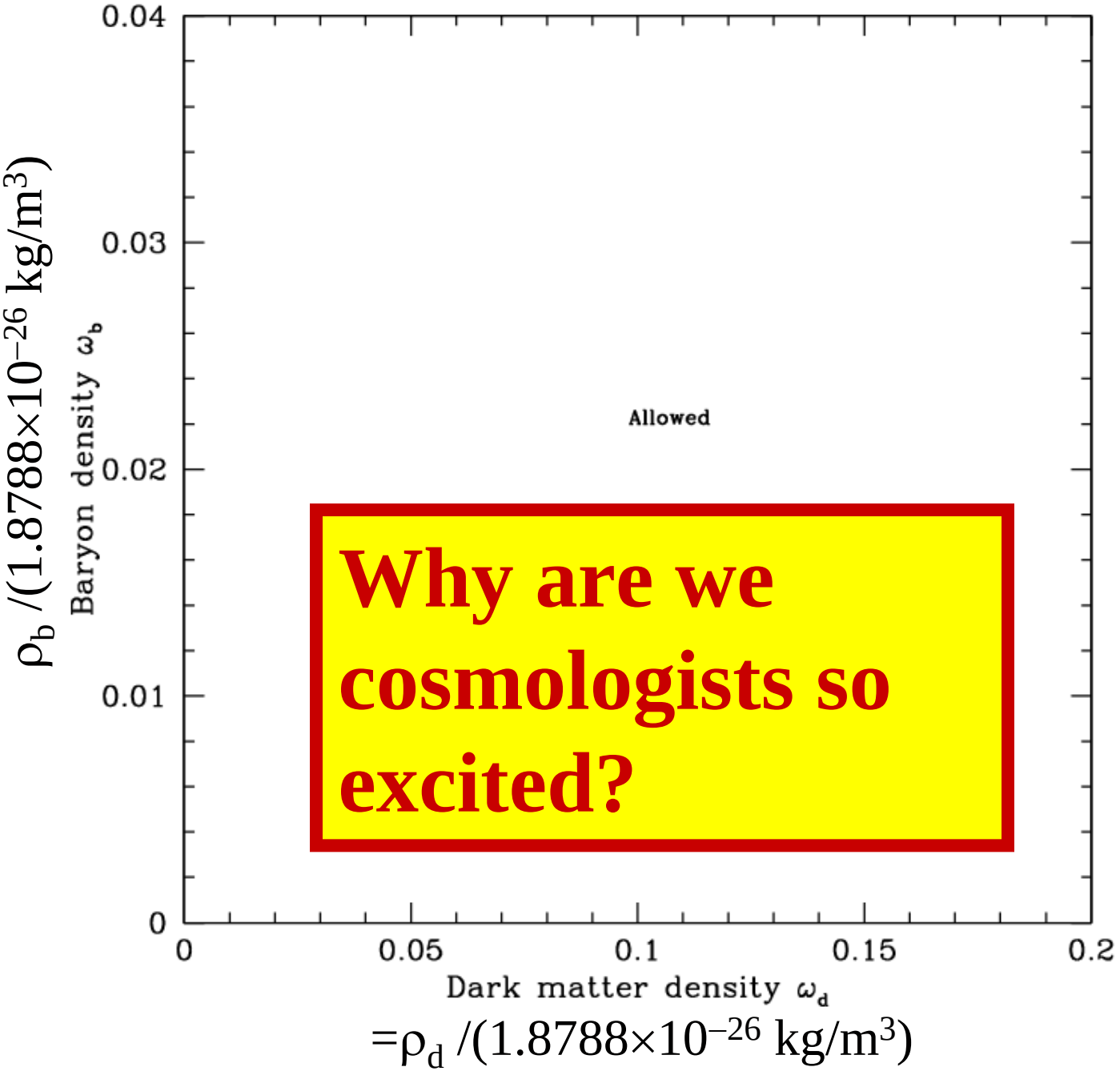


CMB

+



P(k)

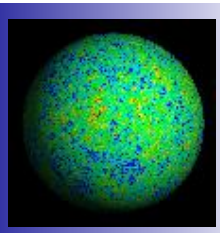


Why are we cosmologists so excited?

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu

Hunt for Dark Matter
May 11, 2007

How much dark matter is there?



CMB

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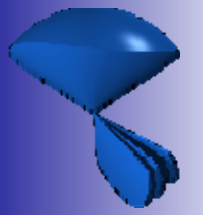
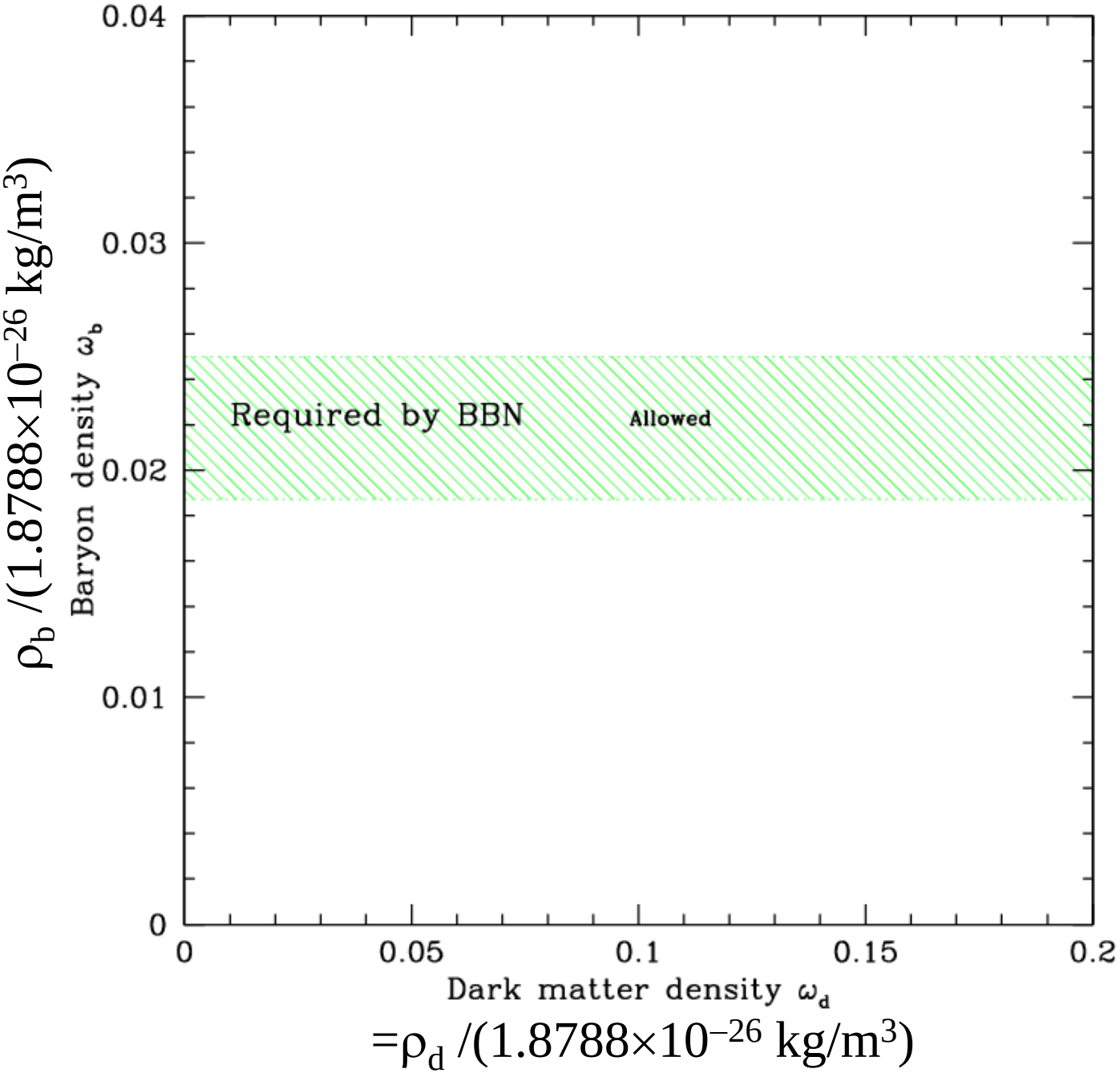


P(k)



Max Tegmark
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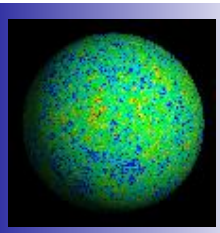

CMB

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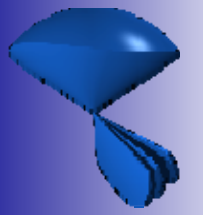

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tegmark@mit.edu

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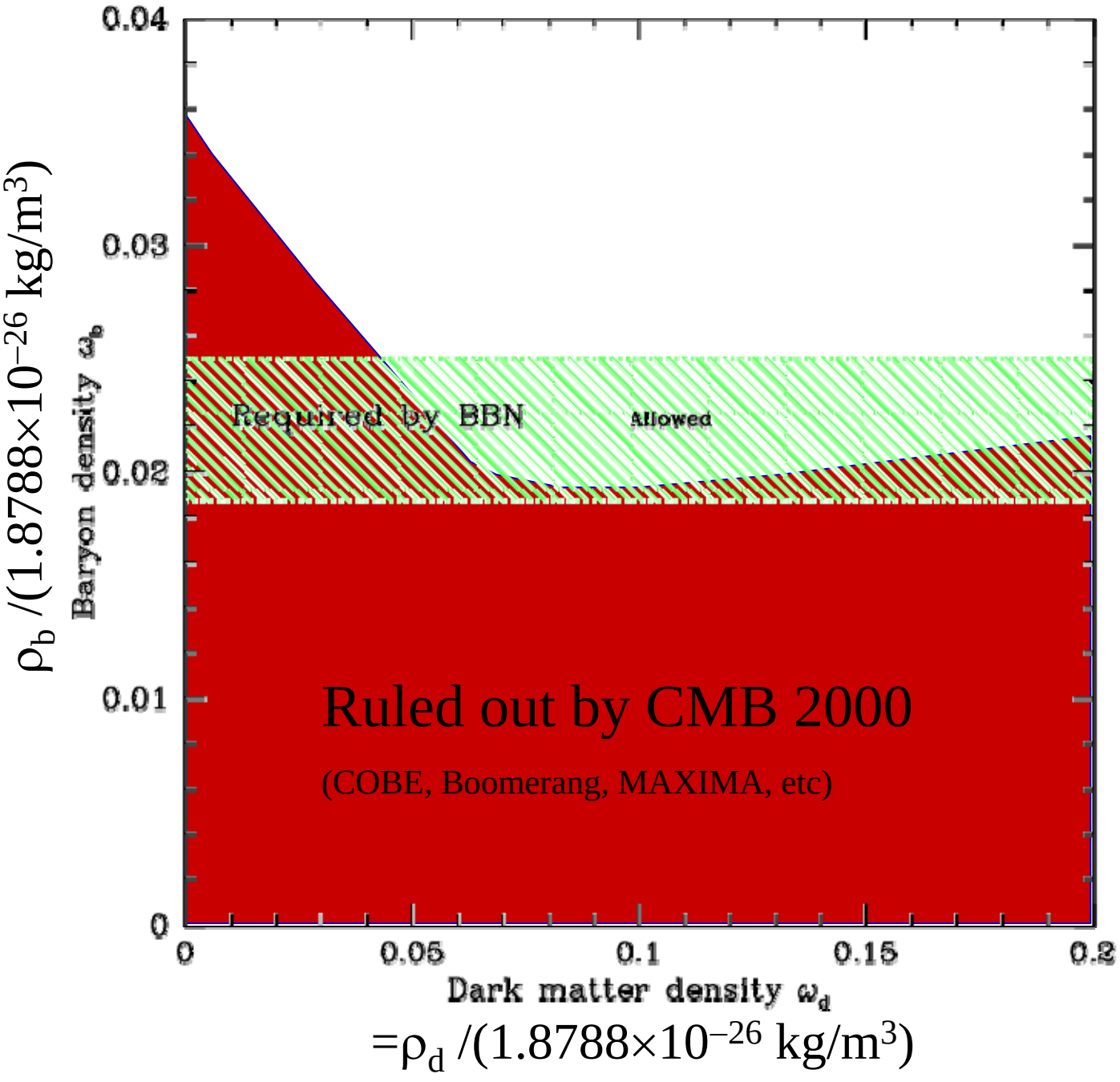

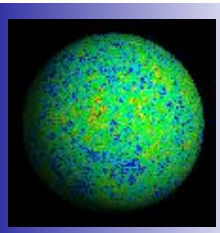

CMB

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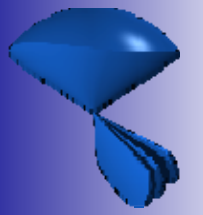

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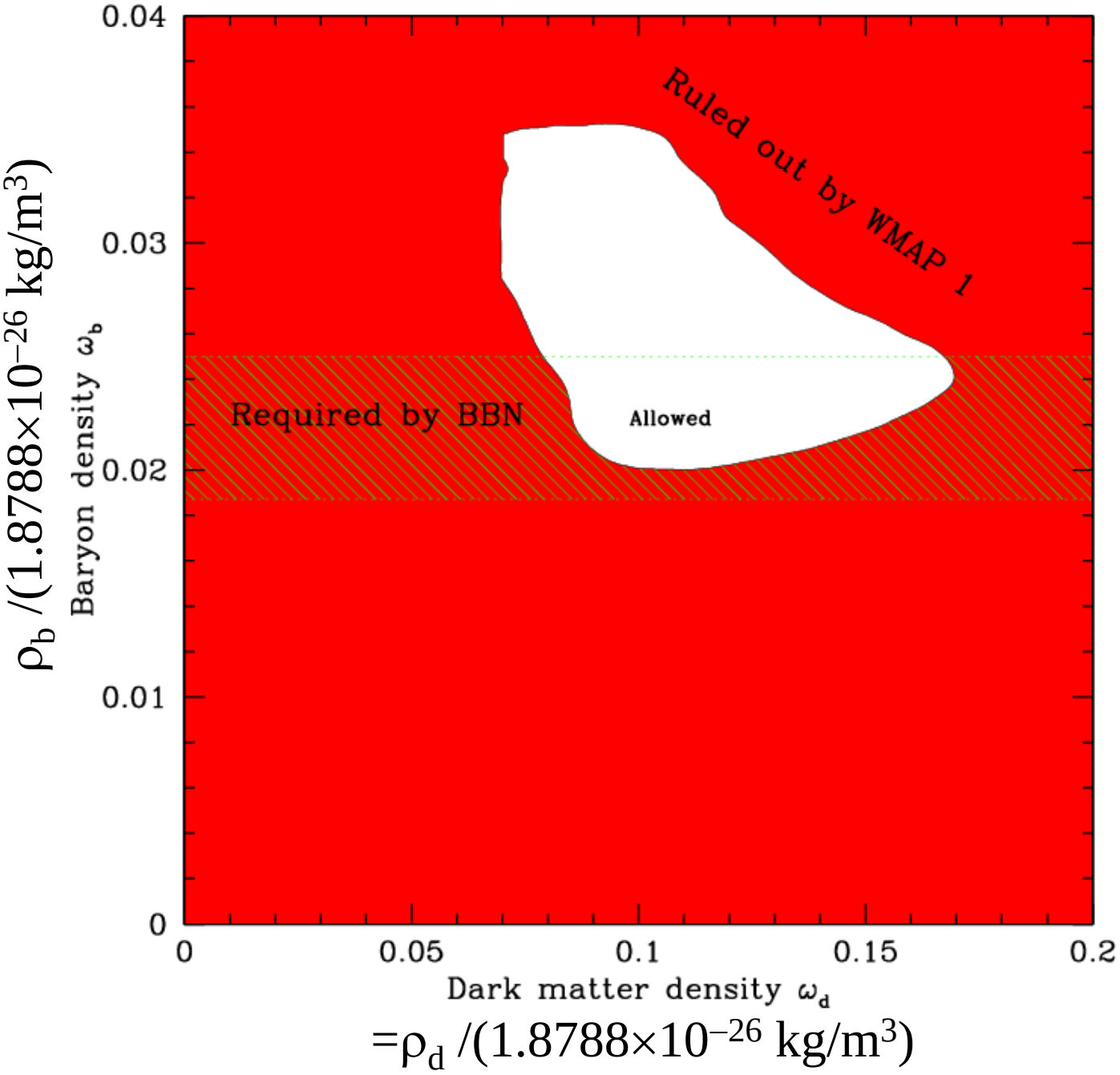

Max Tegmark
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tegmark@mit.edu

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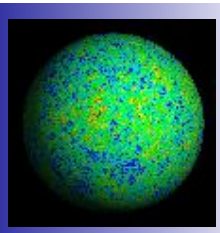

CMB

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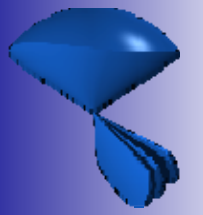

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Dept. of Physics, MIT
tegmark@mit.edu

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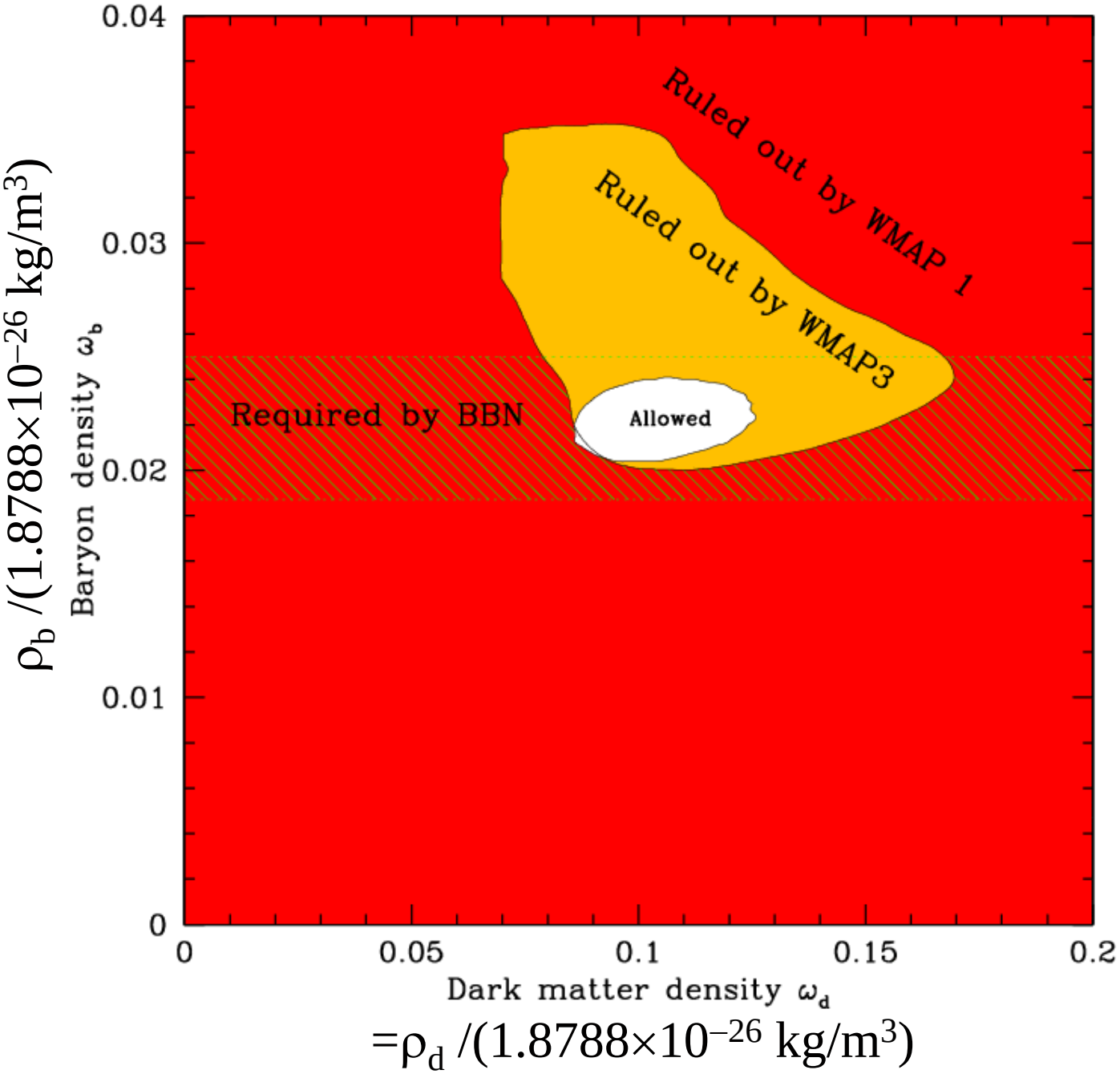

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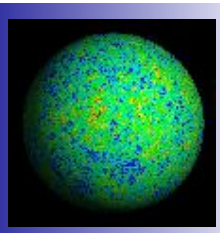

CMB

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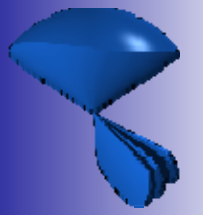
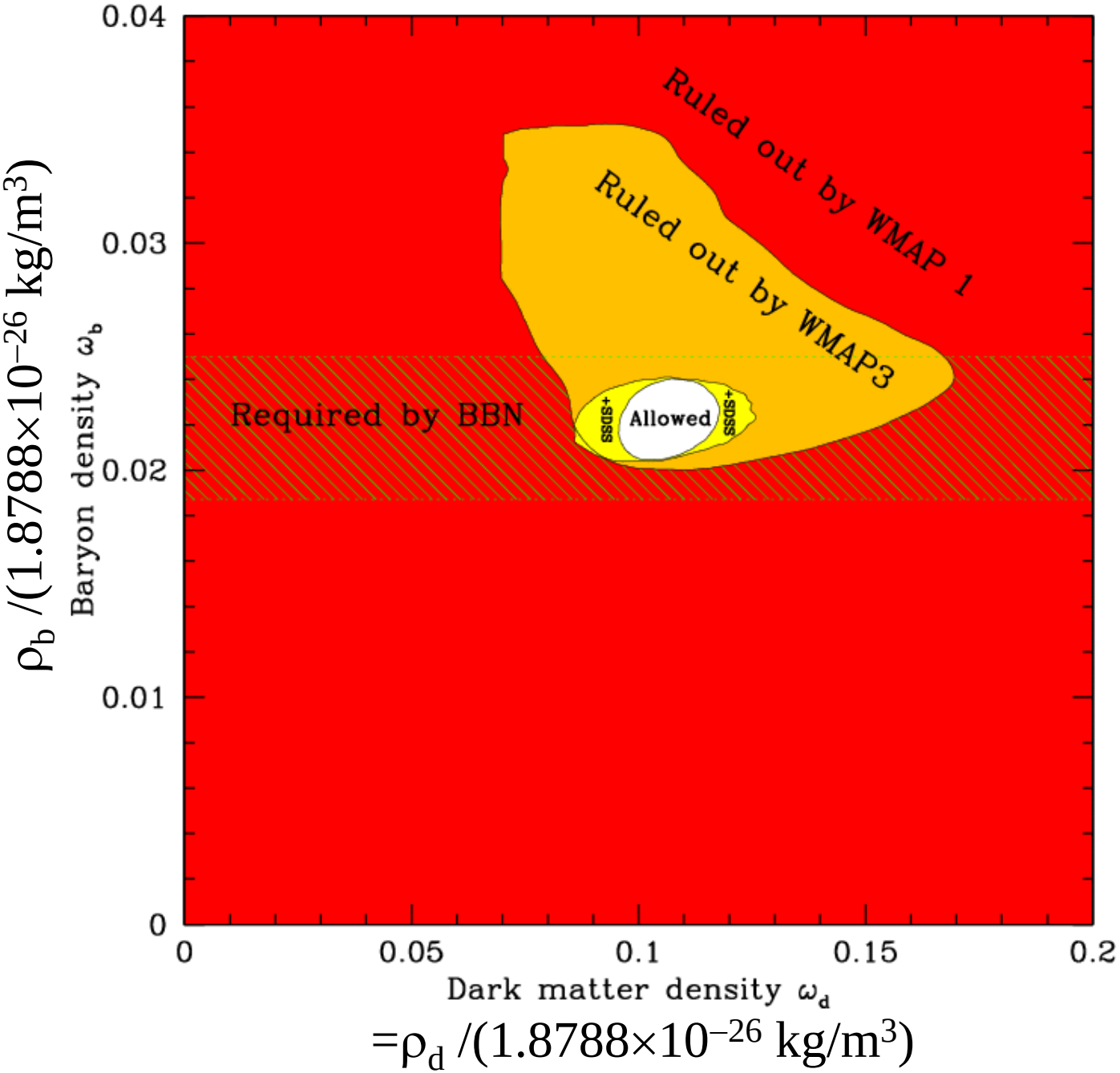


P(k)



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu

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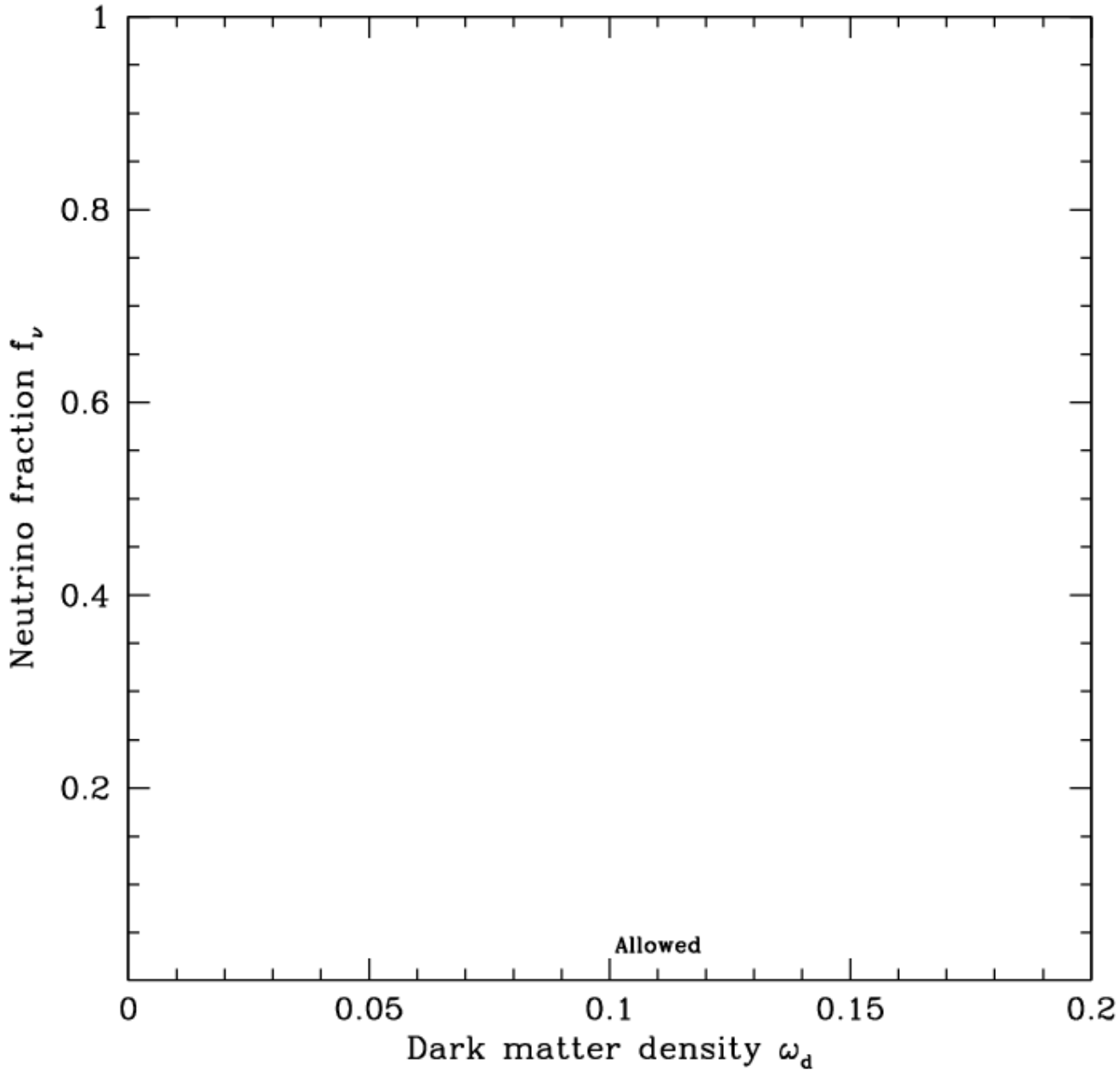
Neutrinos

Cosmological neutrino bounds



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
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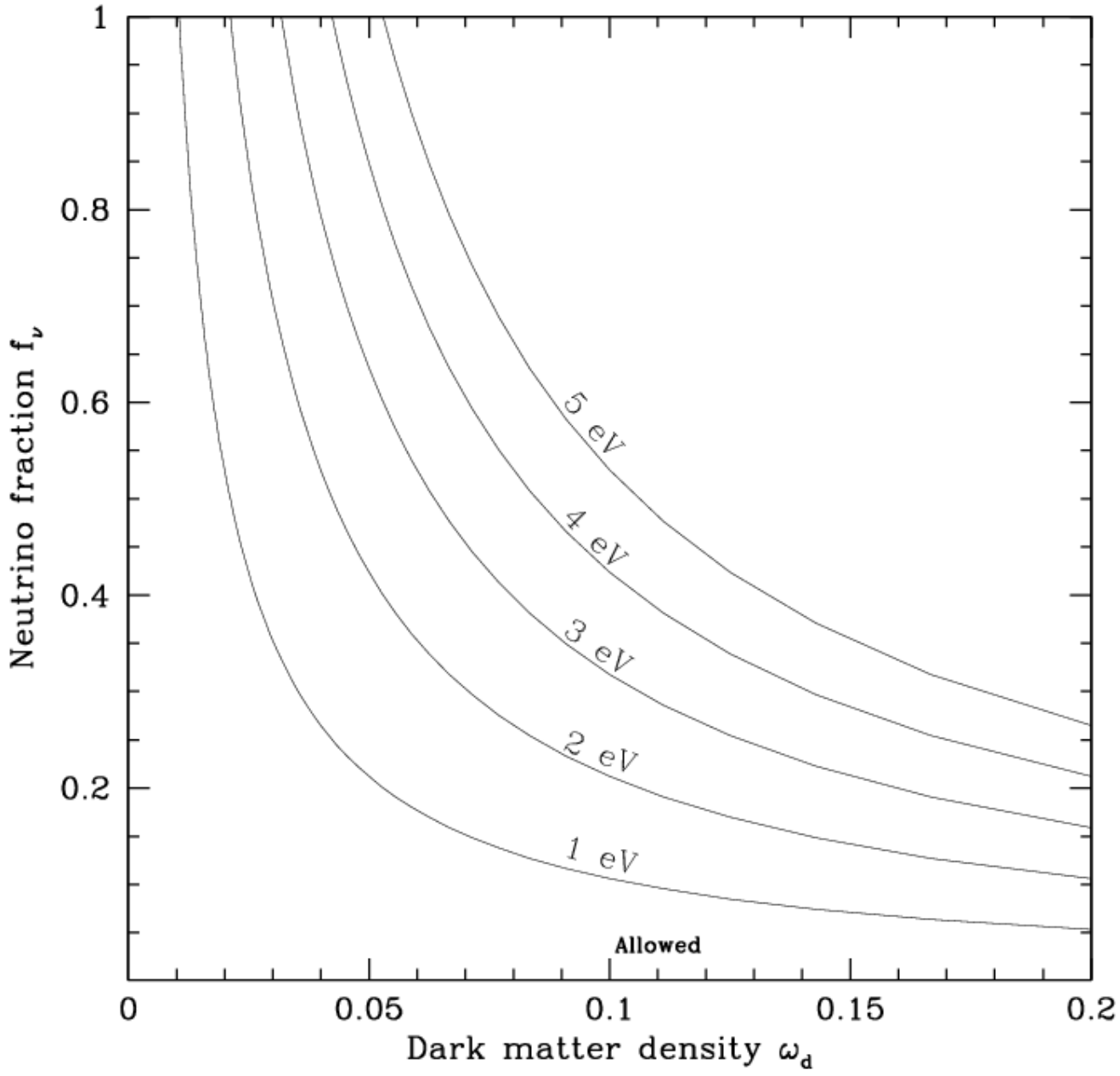
Cosmological neutrino bounds



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tegmark@mit.edu

Hunt for Dark Matter
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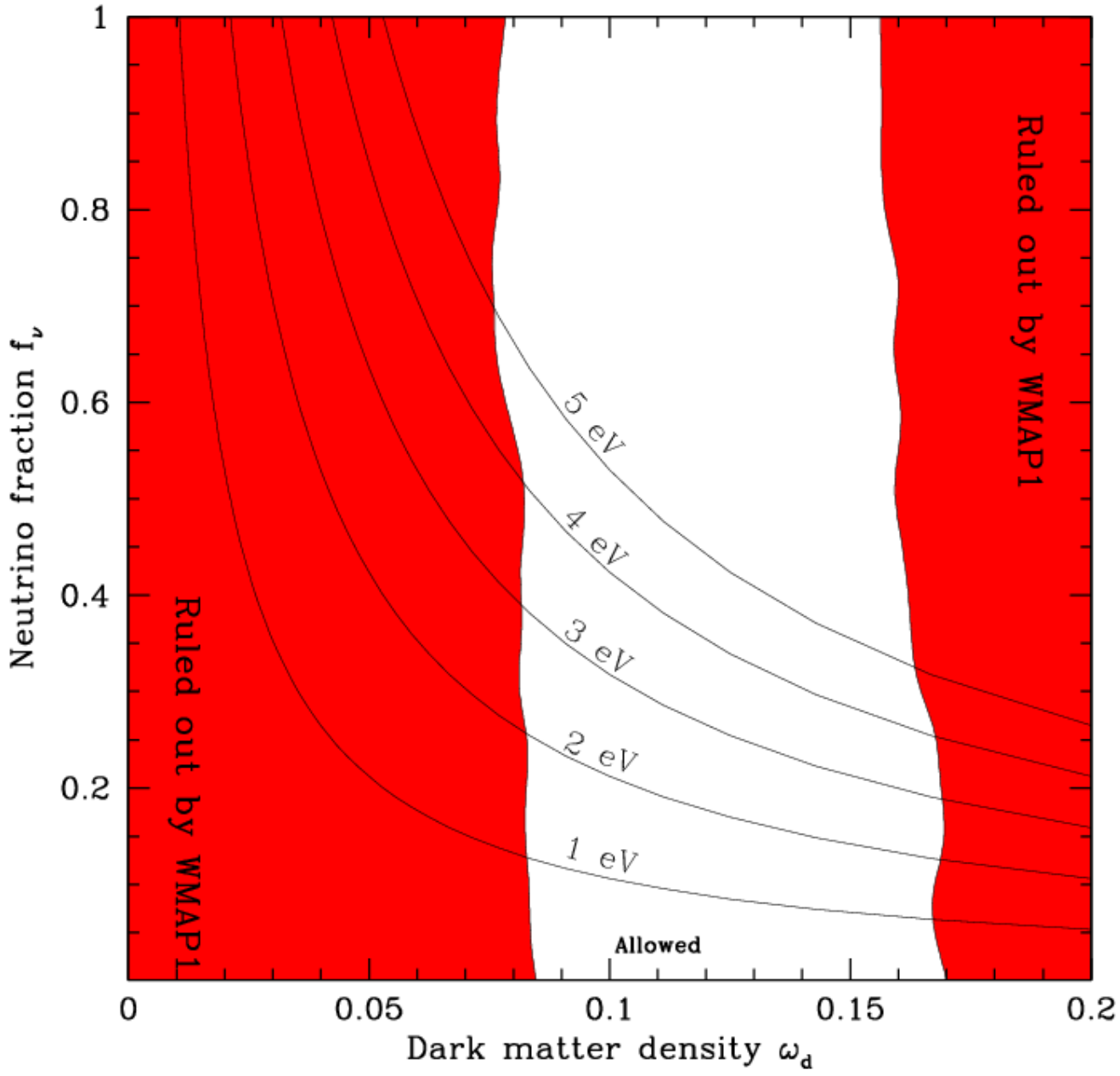
Cosmological neutrino bounds



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tegmark@mit.edu

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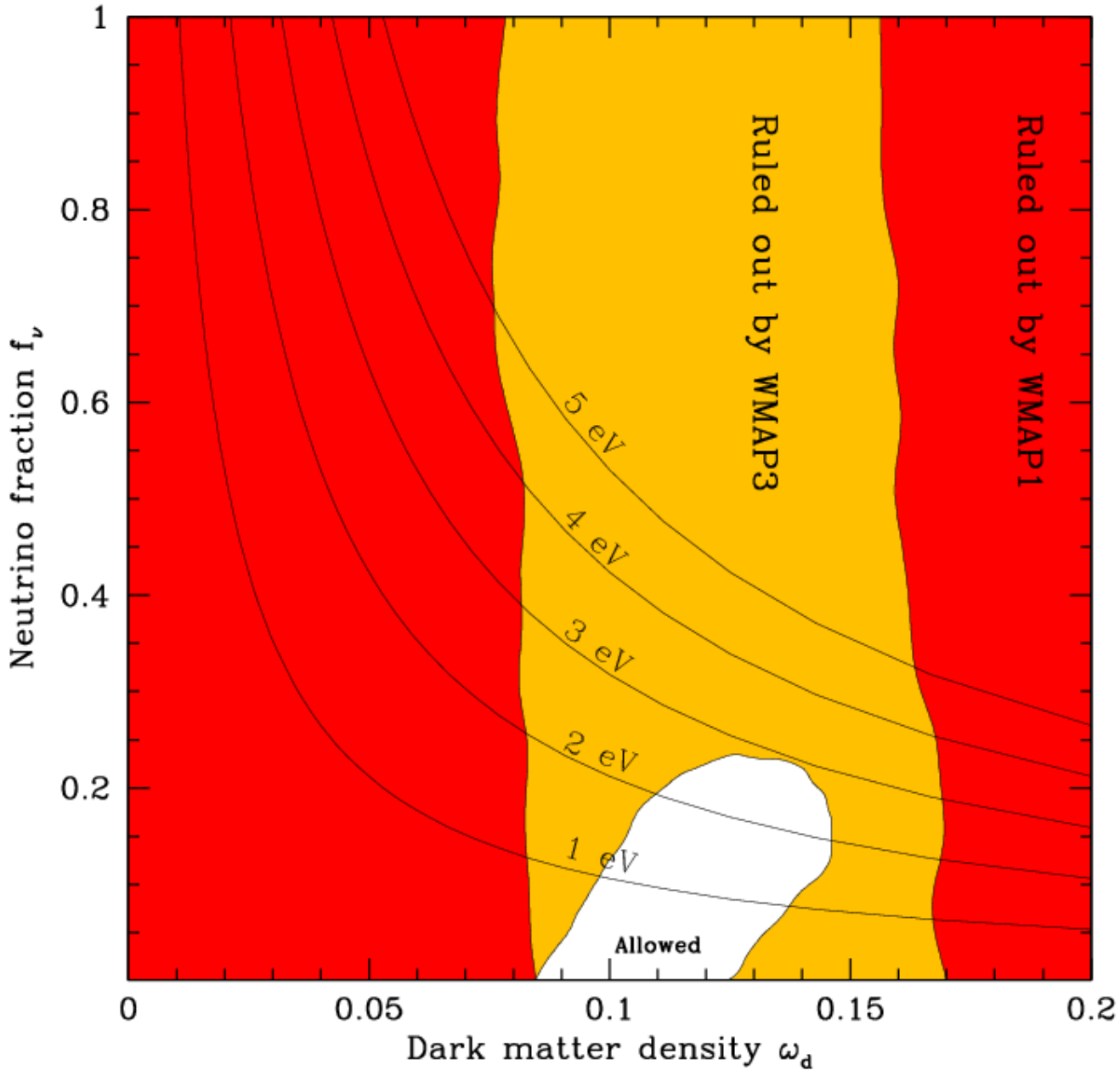
Cosmological neutrino bounds



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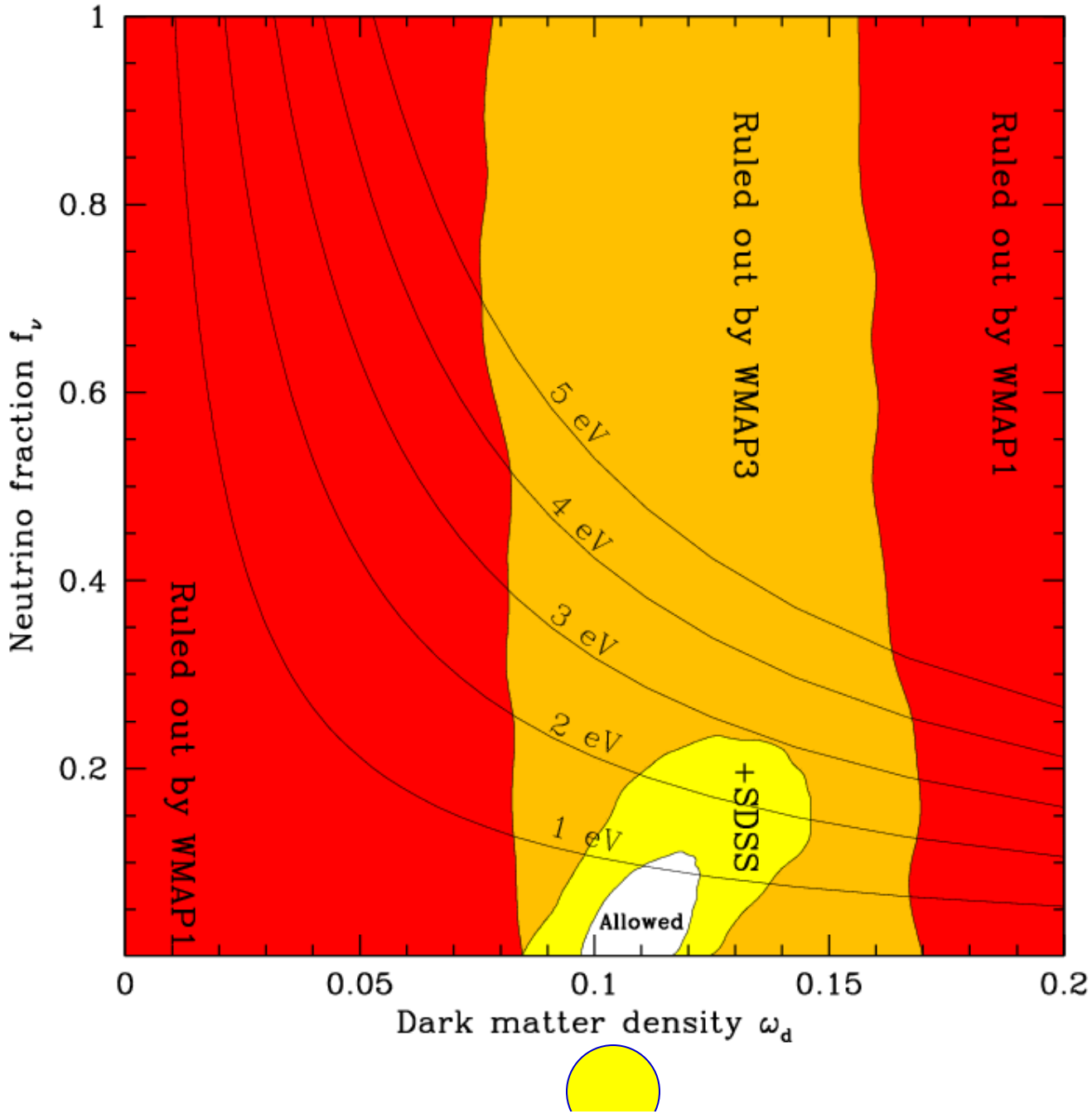

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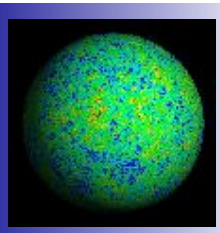

CMB

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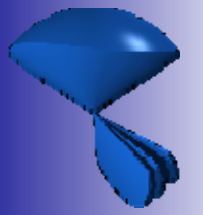
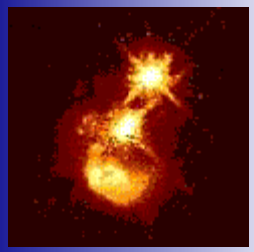
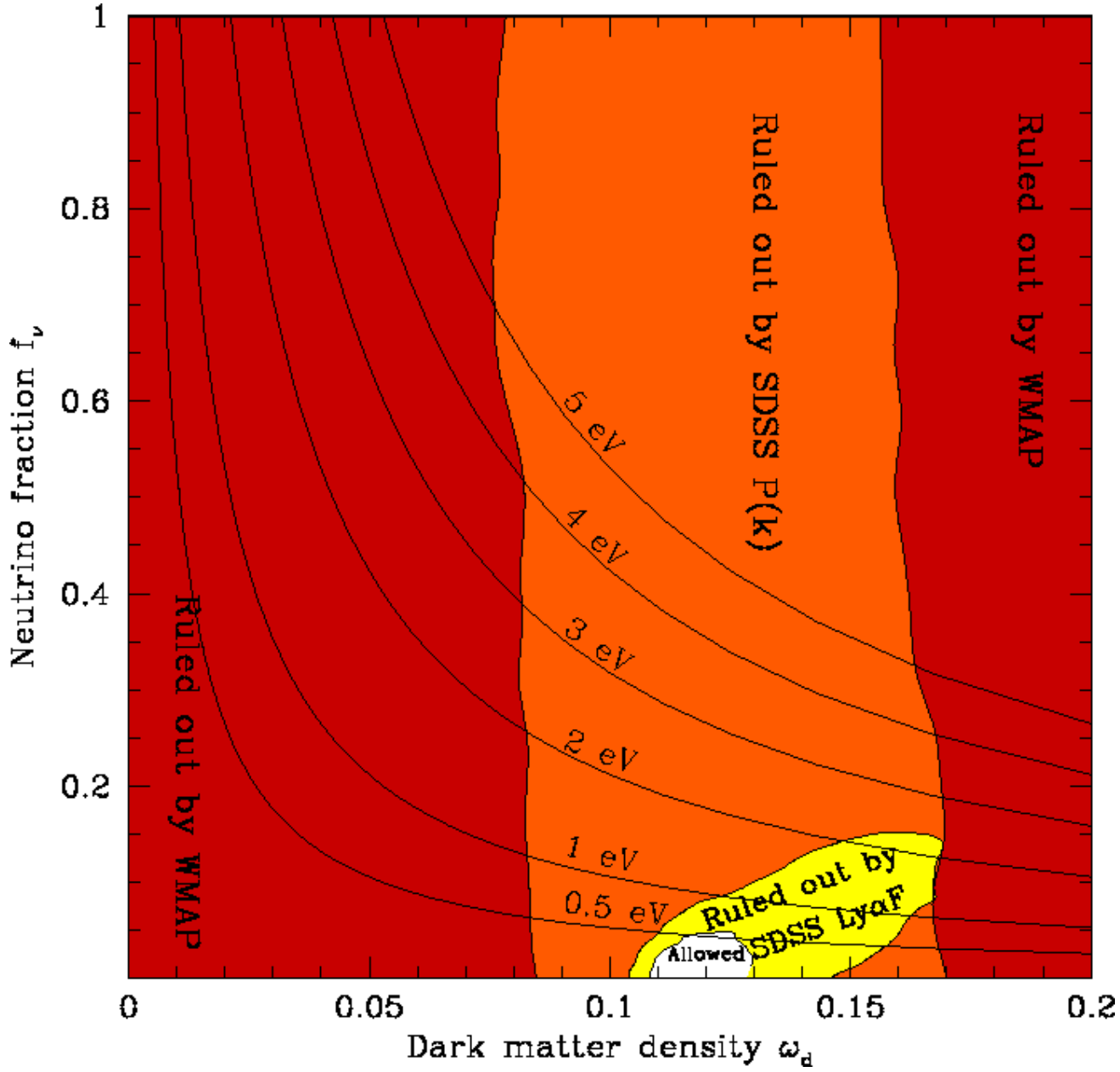


P(k)

+

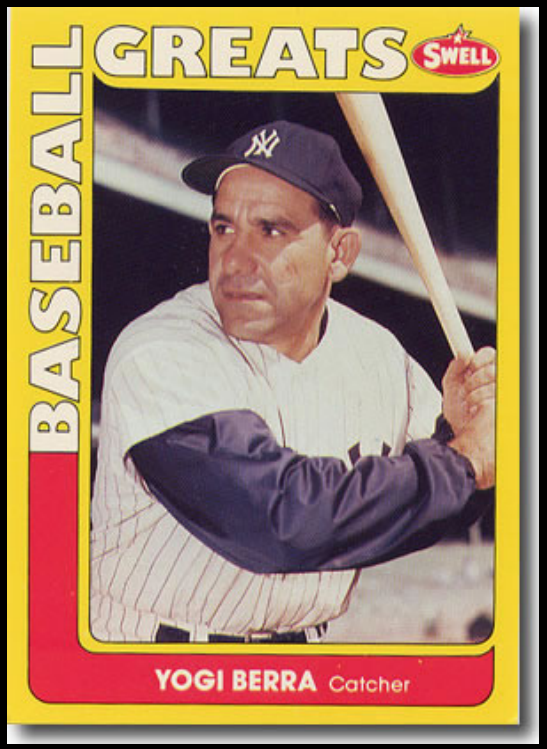


LyαF


Neutrino fraction f_ν
1
0.8
0.6
0.4
0.2
0
0.05
0.1
0.15
0.2
Dark matter density ω_d
Ruled out by WMAP
Ruled out by SDSS P(k)
Ruled out by WMAP
5 eV
4 eV
3 eV
2 eV
1 eV
0.5 eV
Ruled out by SDSS LyαF
Allowed

THE FUTURE

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



Upcoming lensing measurements:

Ongoing

Within a year

Not yet guaranteed

Survey	Telescope	Sky coverage	Filters	depth
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
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
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

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
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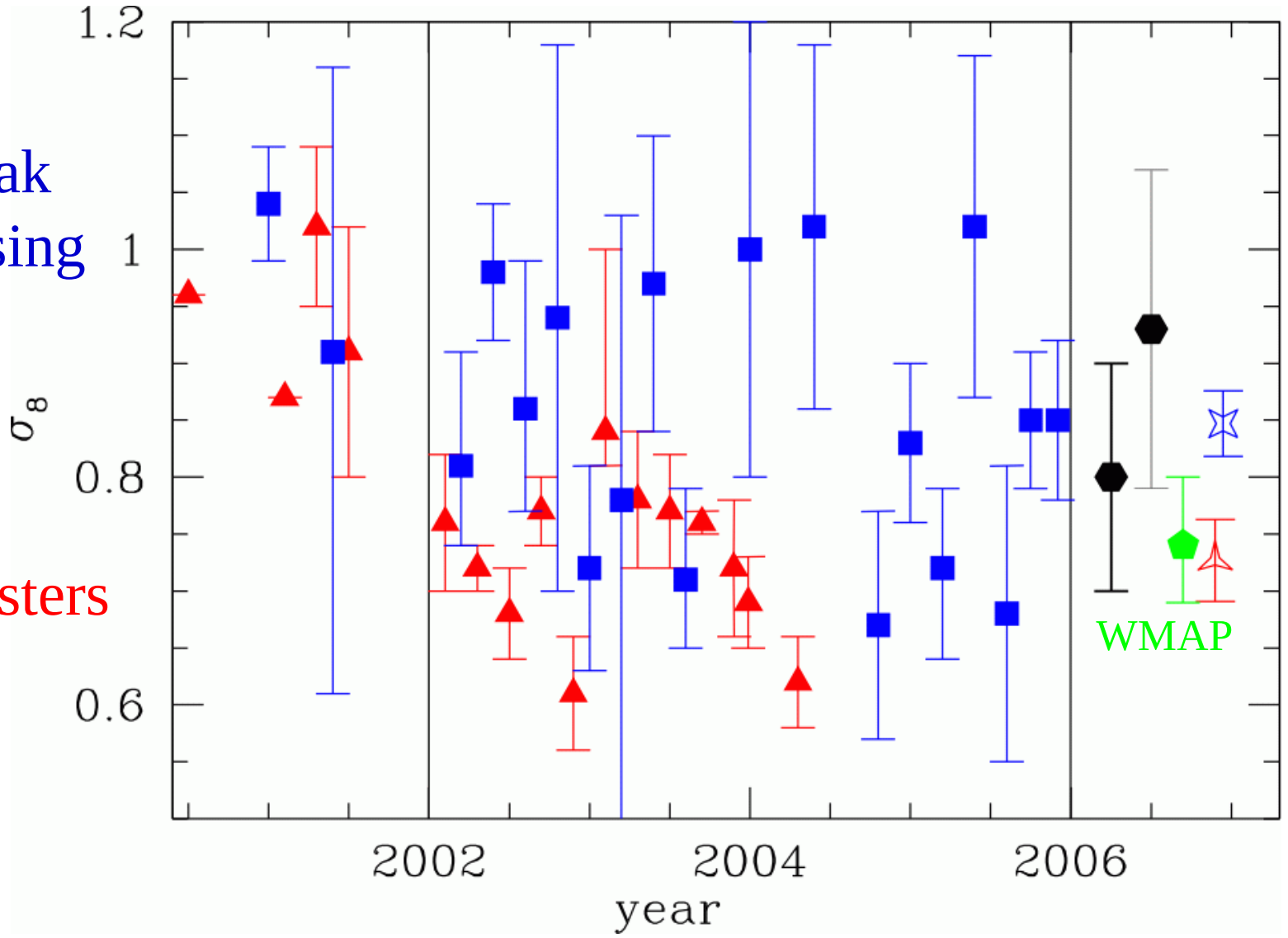
Compilation from Munshi, Valageas, van Waerbeke & Heavens, astro-ph/0612667

Nailing normalization is nontrivial:

Weak lensing

Clusters



Compilation from Hetterscheidt et al, astro-ph/0606571

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
May 11, 2007

Upcoming massive galaxy redshift surveys:

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

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Hunt for Dark Matter
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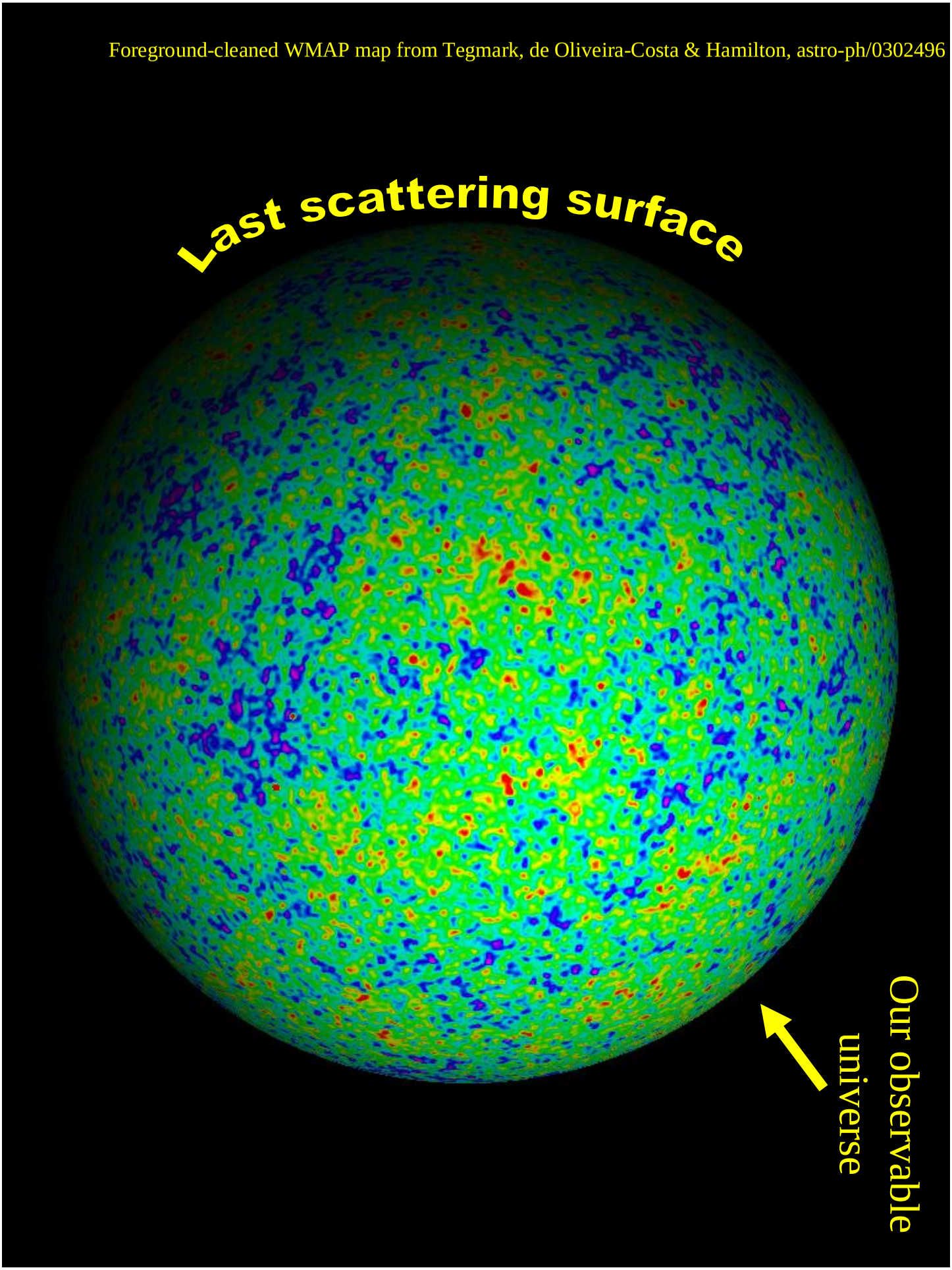
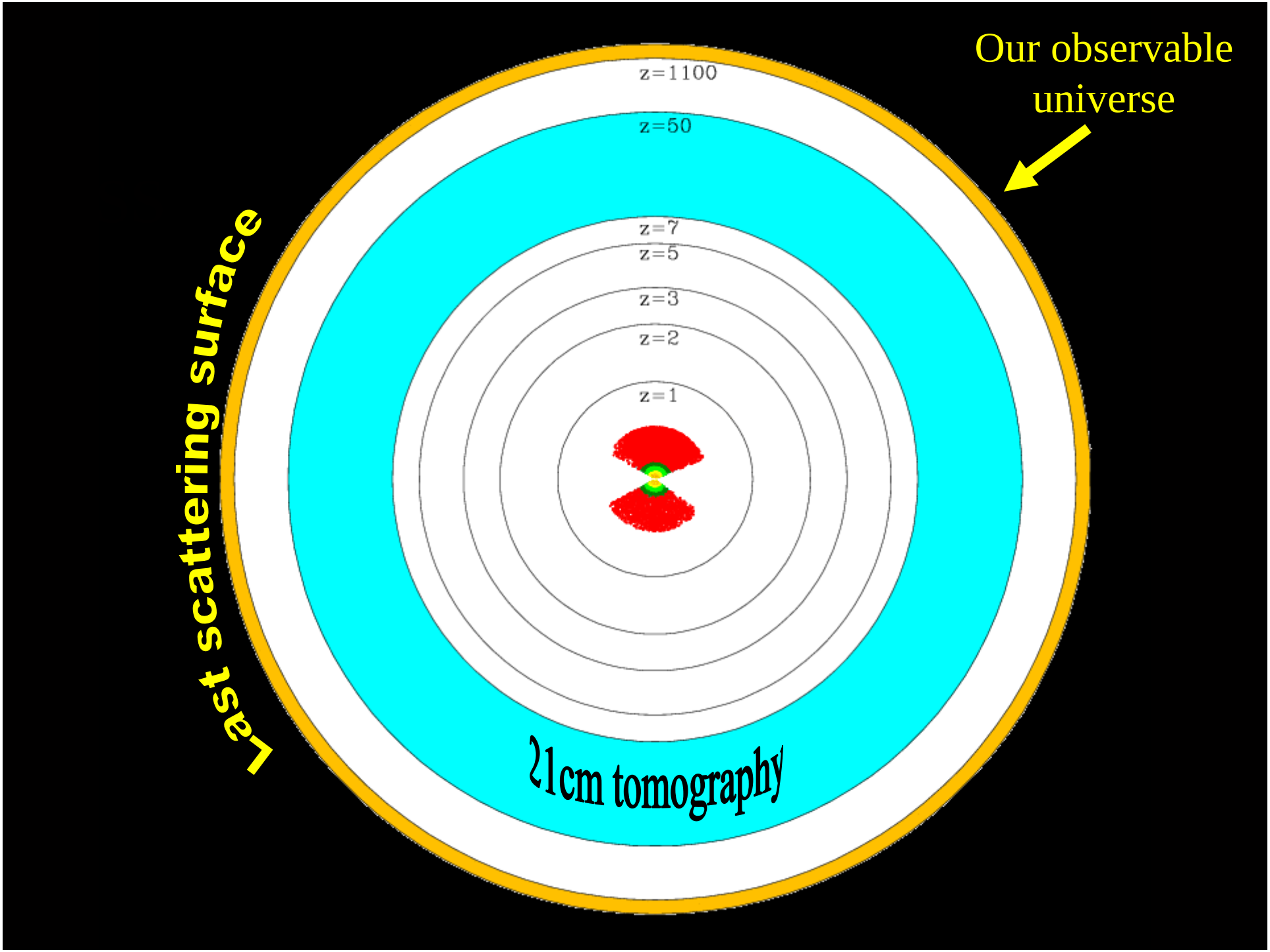
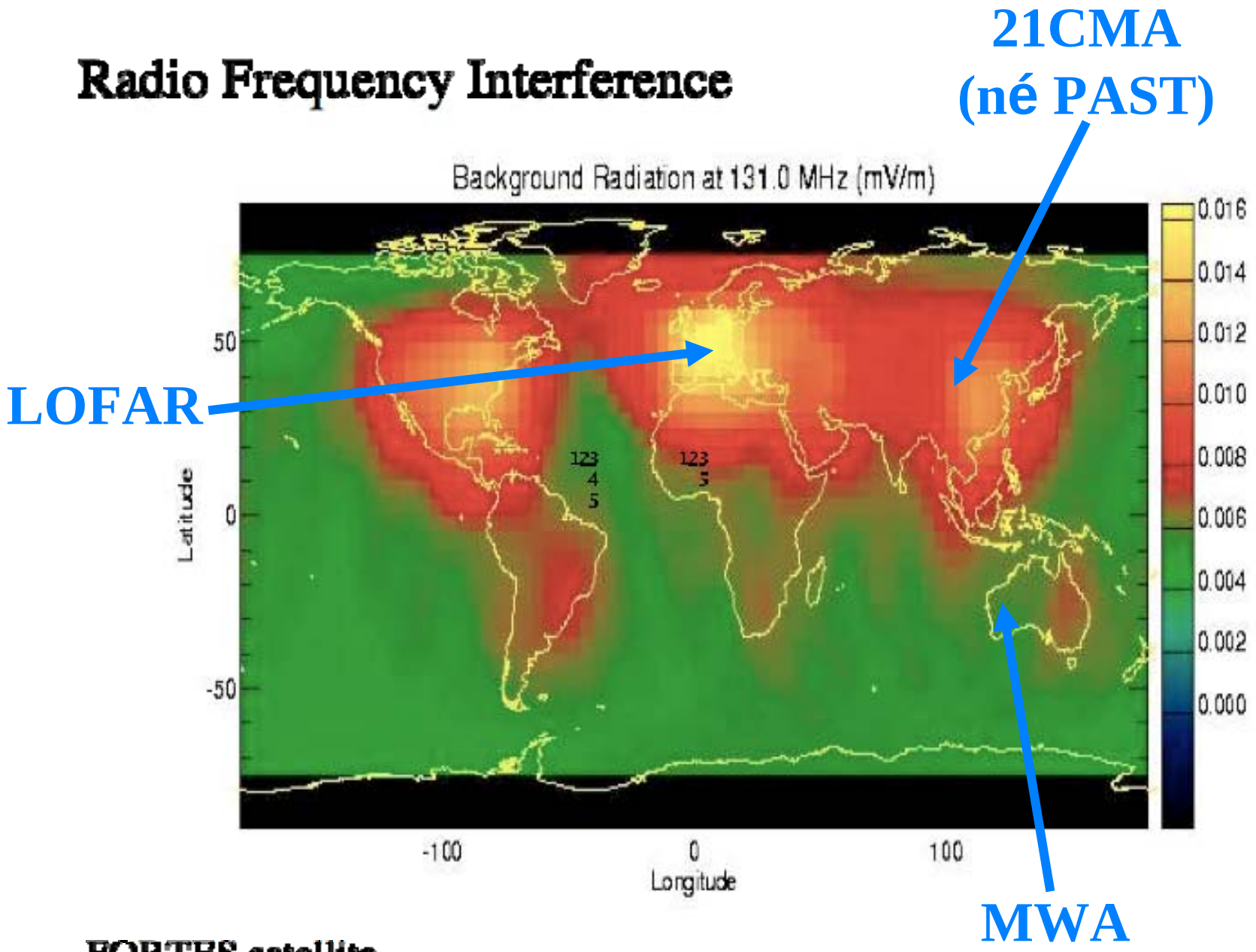

Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496
Last scattering surface
Our observable universe


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

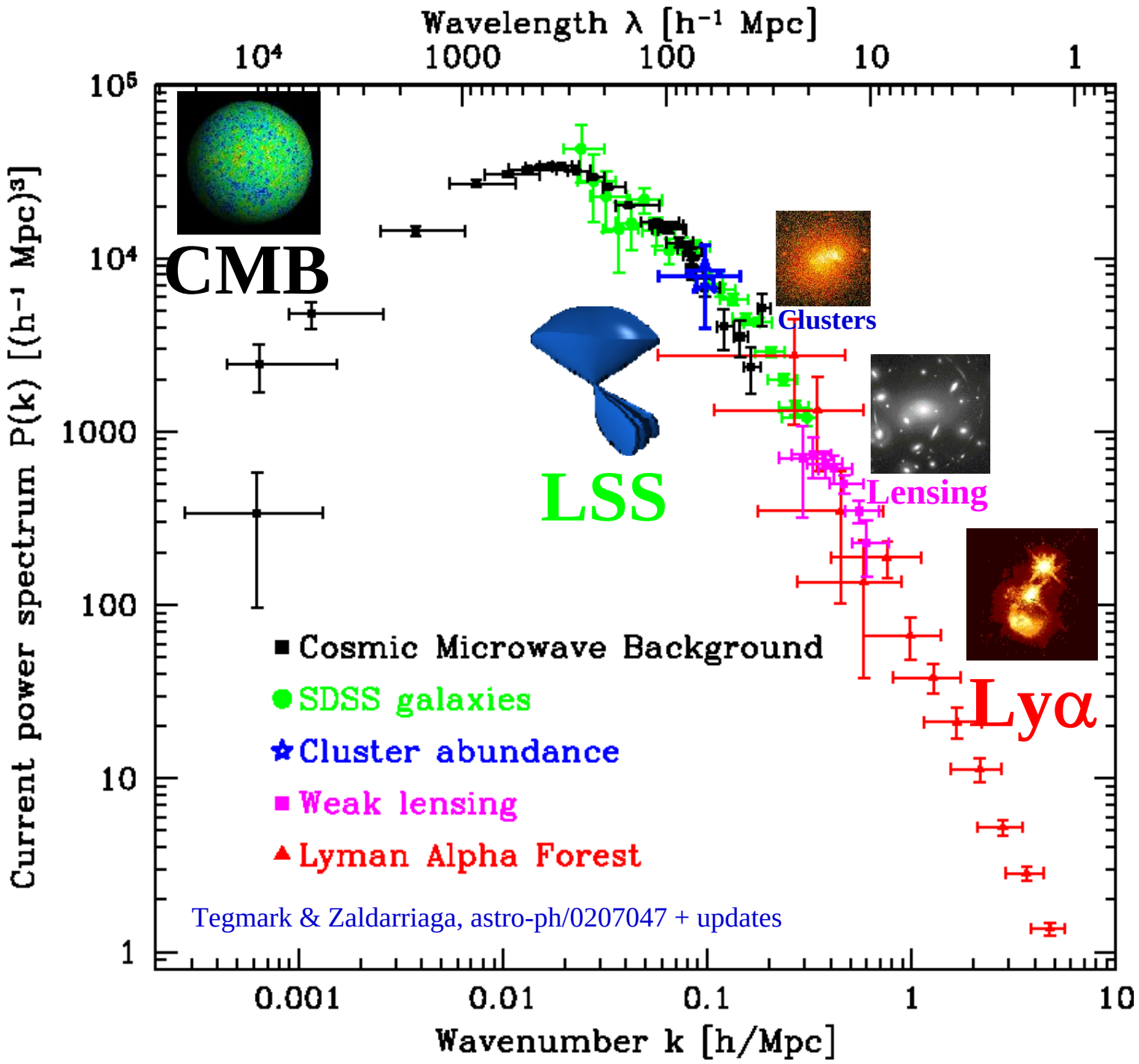
Now 3 funded 21 cm tomography experiments:



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 systems



Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu

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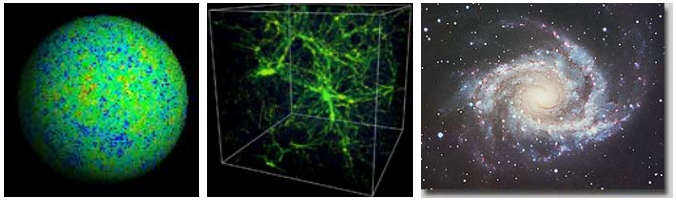
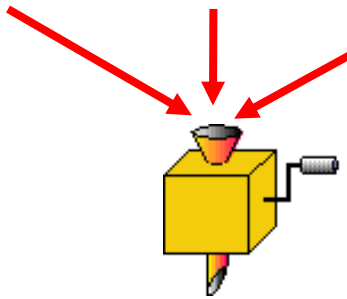
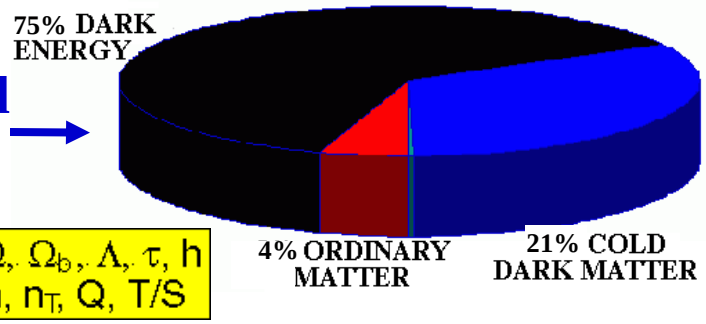
Cosmological data



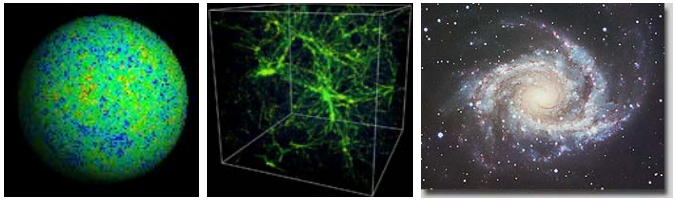


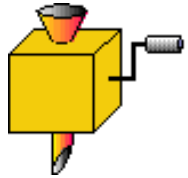
Cosmological Parameters



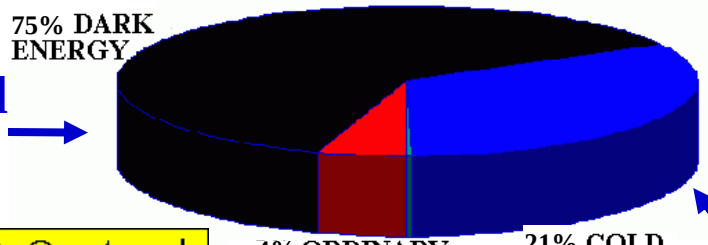
$\Omega, \Omega_b, \Lambda, \tau, h$
$n, n_T, Q, T/S$

Cosmological data



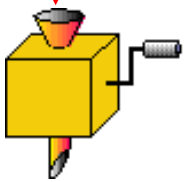


Cosmological Parameters



$\Omega, \Omega_b, \Lambda, \tau, h$
$n, n_T, Q, T/S$

Why these particular values?



Fundamental theory

Nature of dark matter?
- P(k,z)
- Substructure

Nature of dark energy?

Nature of early Universe?