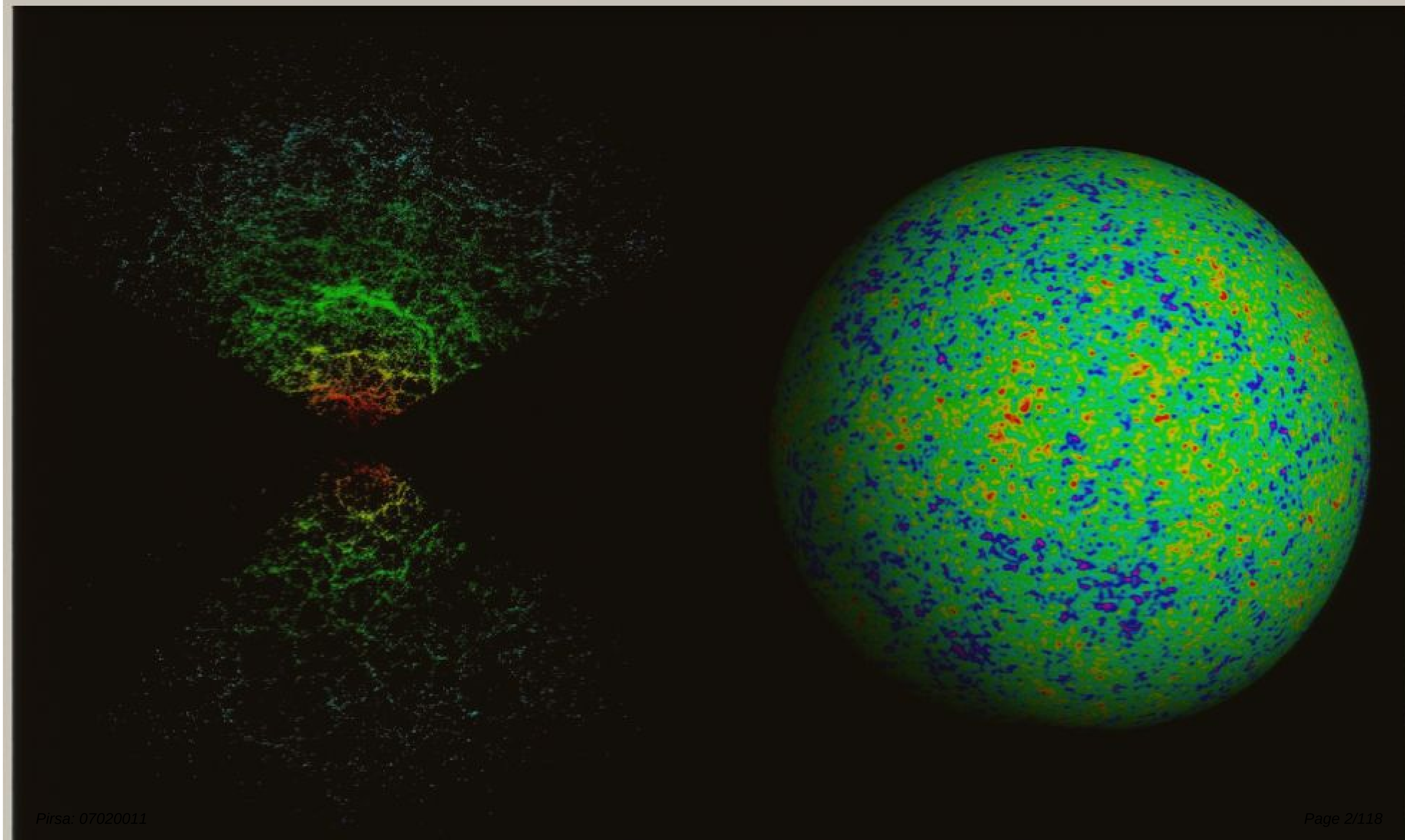
Title: New cosmic maps & measurements

Date: Feb 01, 2007 11:00 AM

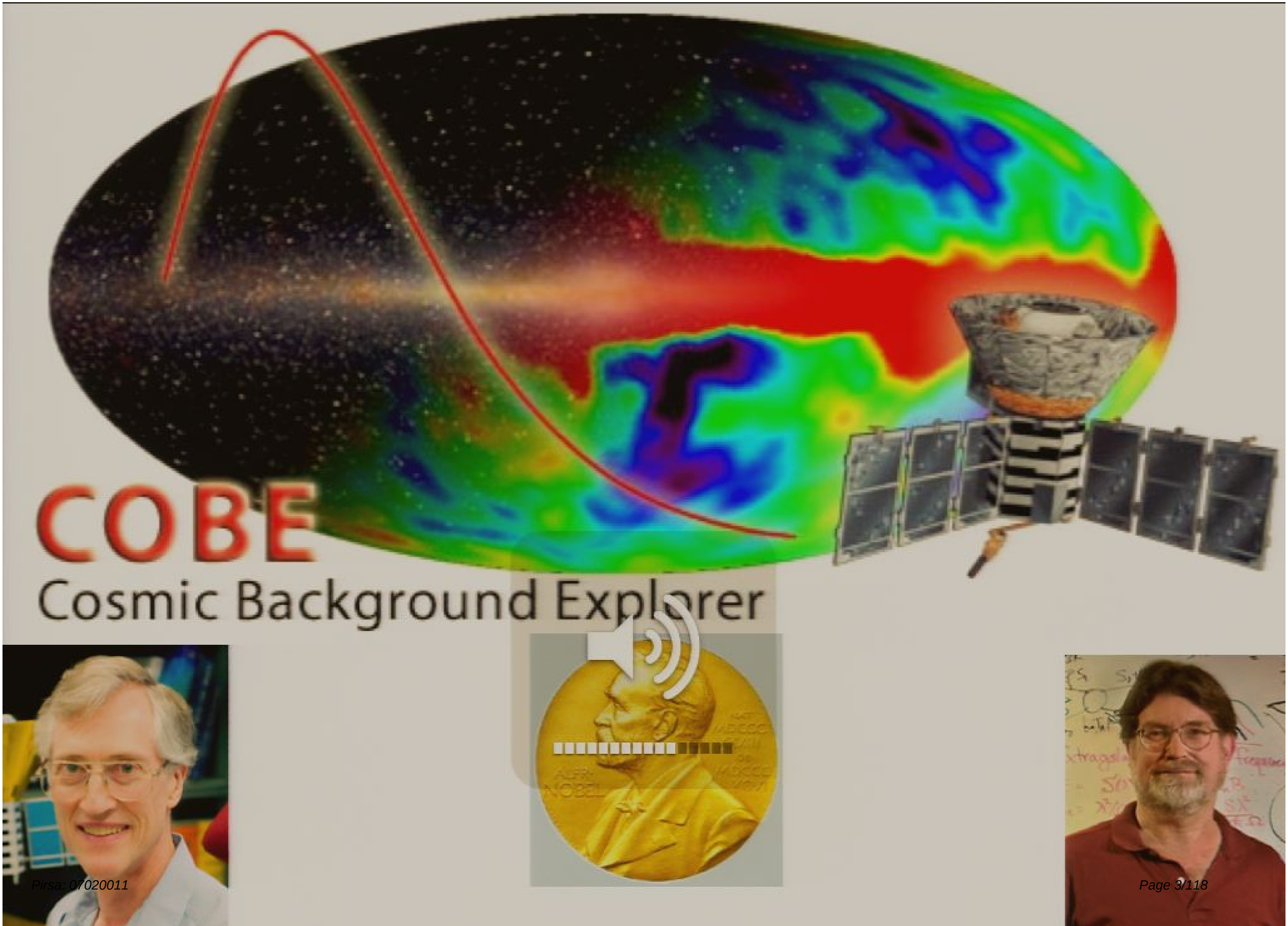
URL: http://pirsa.org/07020011

Abstract: I first summarize how the recent avalanche of precision measurements involving the cosmic microwave background, galaxy clustering, the Lyman alpha forest, gravitational lensing, supernovae Ia and other tools probes has transformed our understanding of our universe. I then discuss key open problems such as the nature of dark matter, dark energy and the early universe.

New cosmic maps & measurements



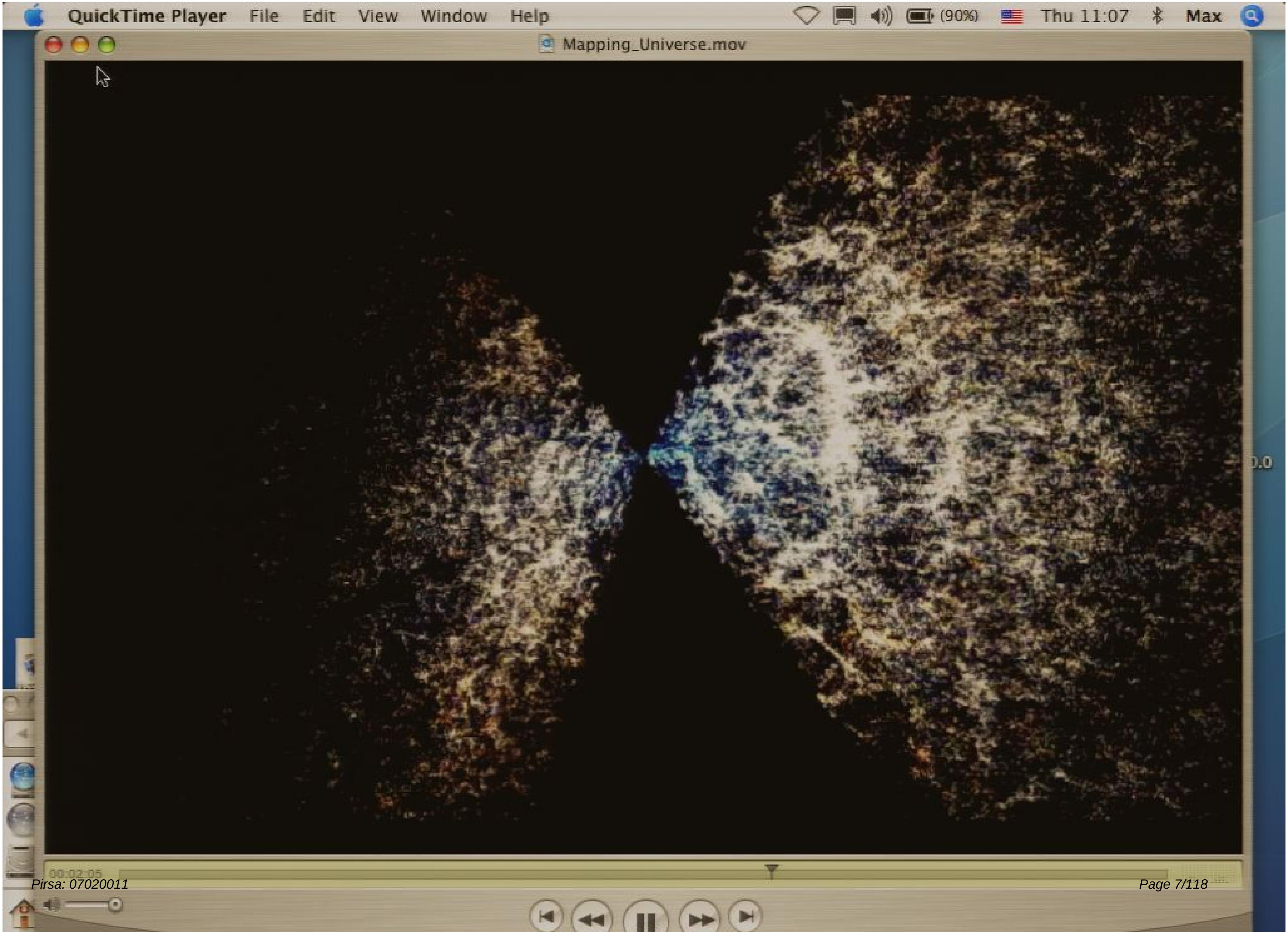
Max Tegmark, MIT

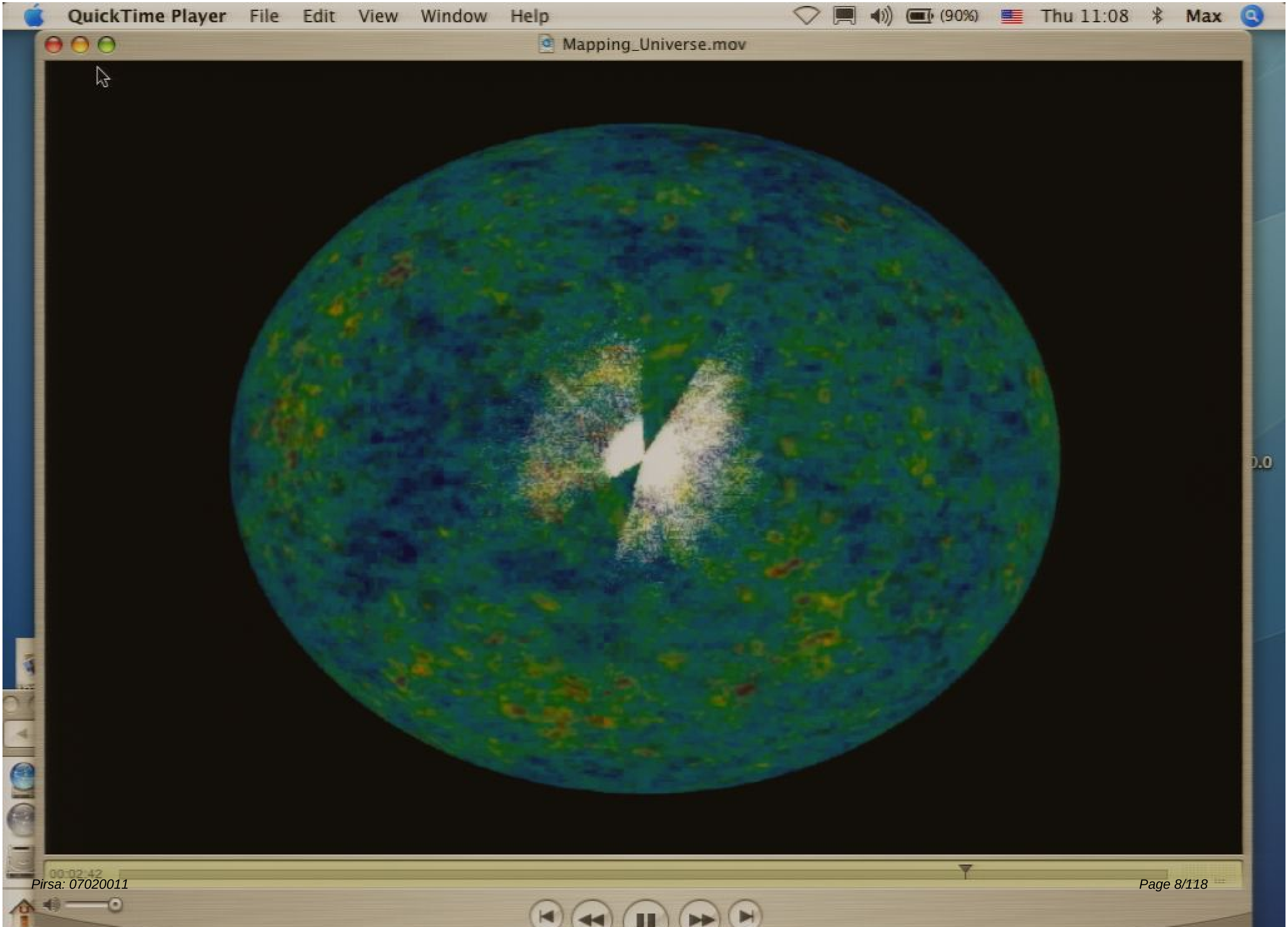

COBE
Cosmic Background Explorer

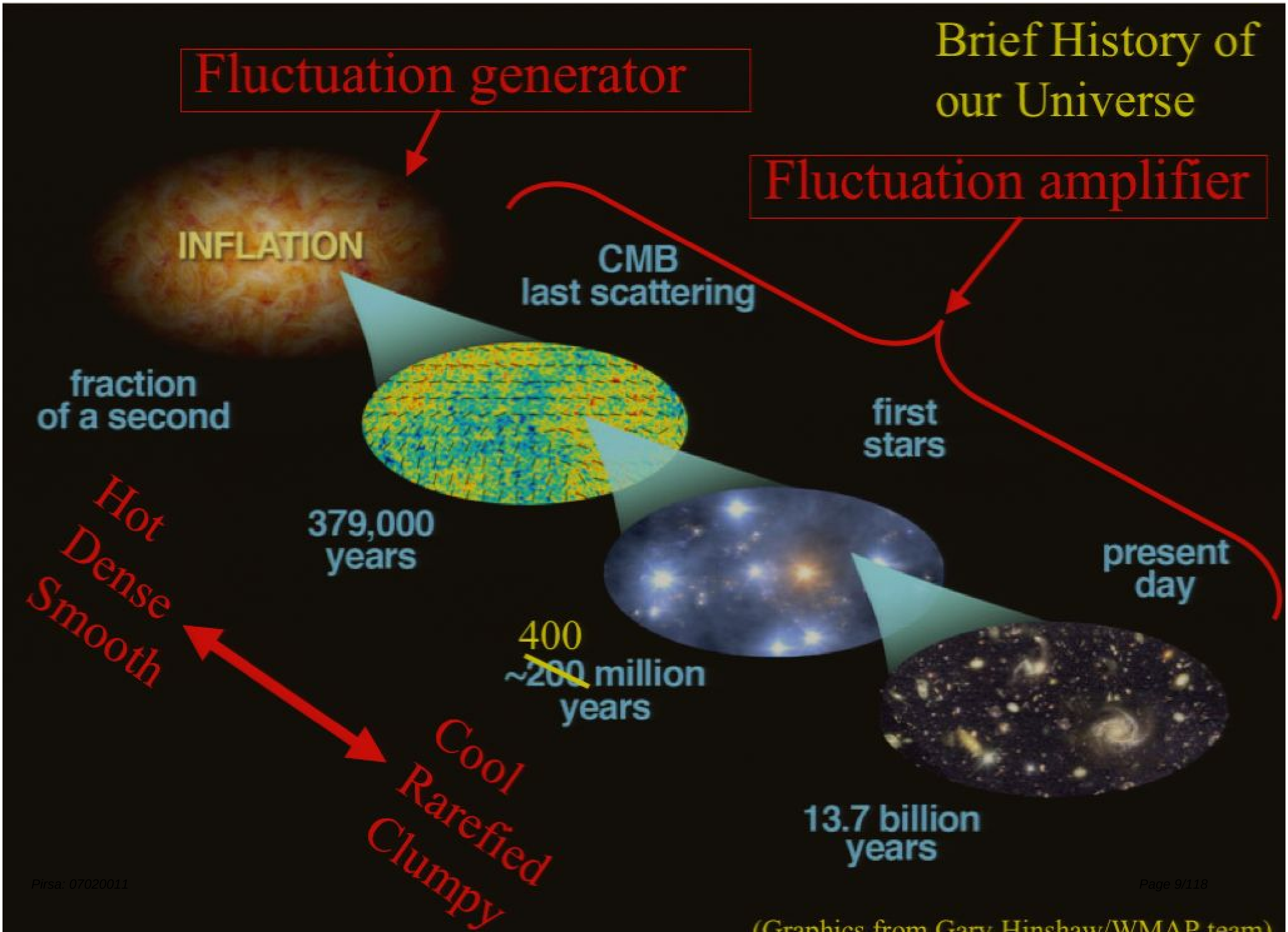
What have we learned?

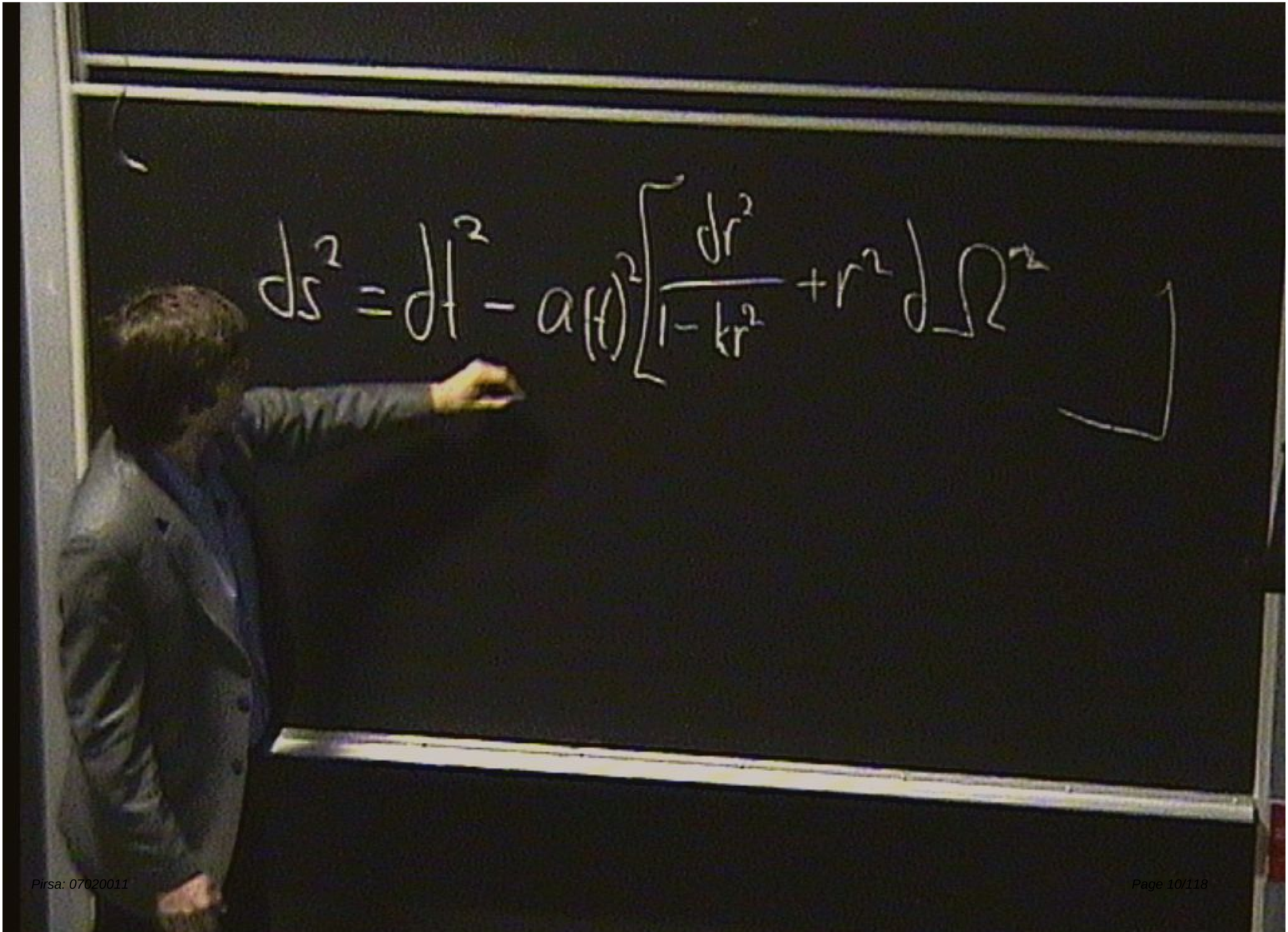

QuickTime Player
File
Edit
View
Window
Help
(91%)
Thu 11:06
Max
Mapping_Universe.mov


QuickTime Player
File
Edit
View
Window
Help
(91%)
Thu 11:06
Max
Mapping_Universe.mov

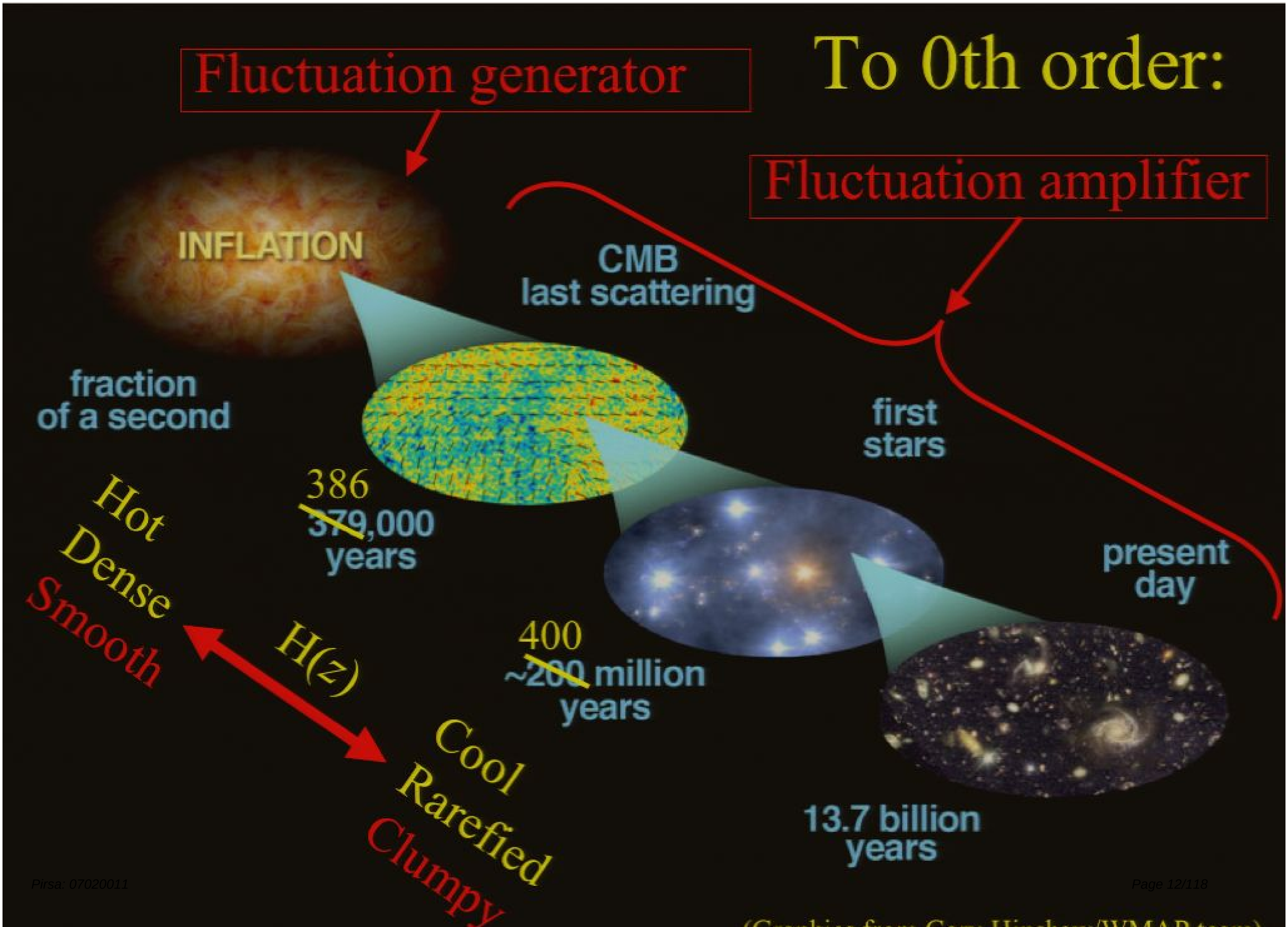

QuickTime Player
File
Edit
View
Window
Help
(90%)
Thu 11:07
Max
Mapping_Universe.mov


QuickTime Player File Edit View Window Help
(90%) Thu 11:08 Max
Mapping_Universe.mov

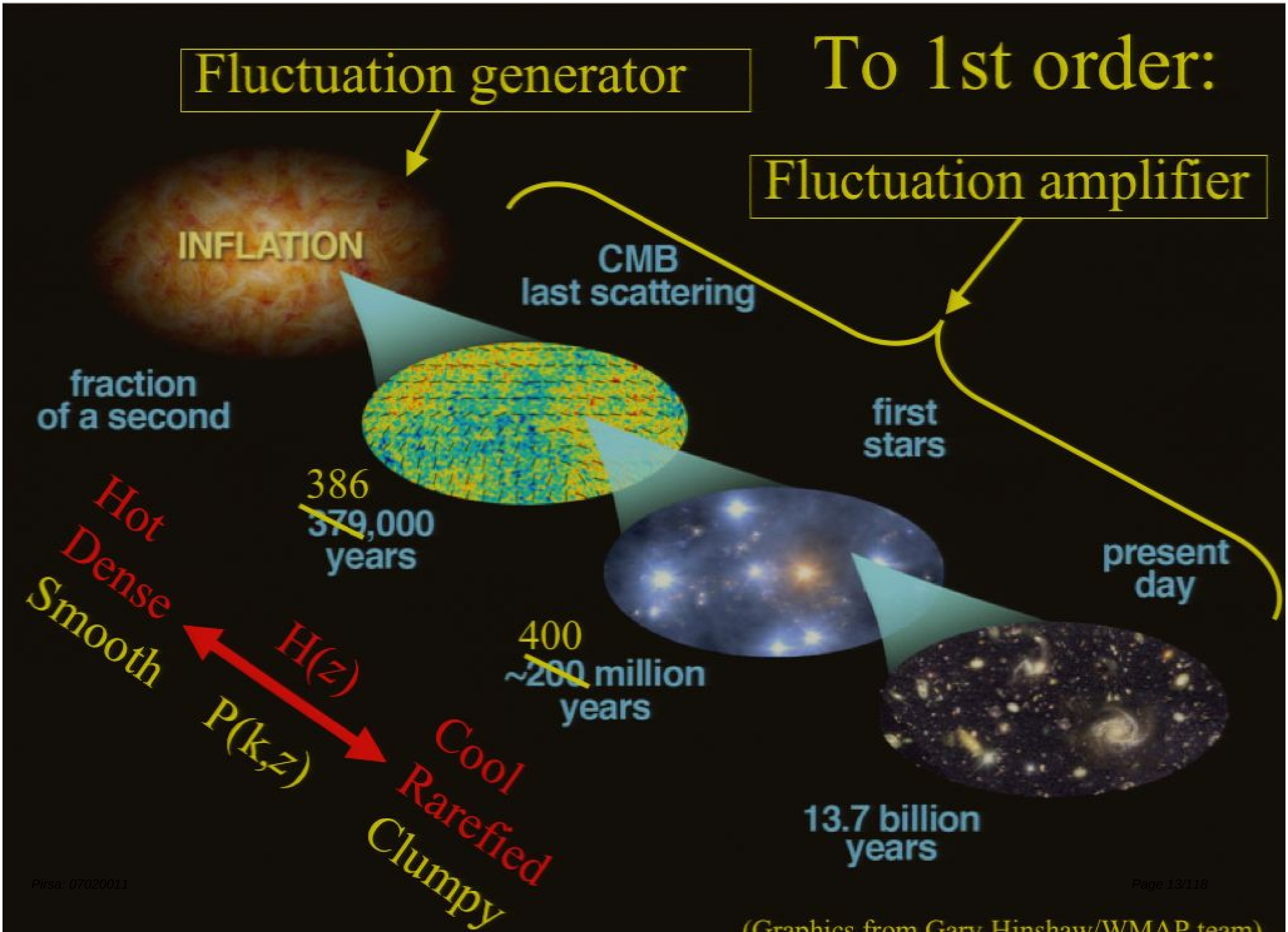

Brief History of our Universe
Fluctuation generator
Fluctuation amplifier
INFLATION
CMB last scattering
fraction of a second
first stars
379,000 years
present day
Hot Dense Smooth
400
~~~200~~ million years
Cool Rarefied Clumpy
13.7 billion years
(Graphics from Gary Hinshaw/WMAP team)
~~~


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

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



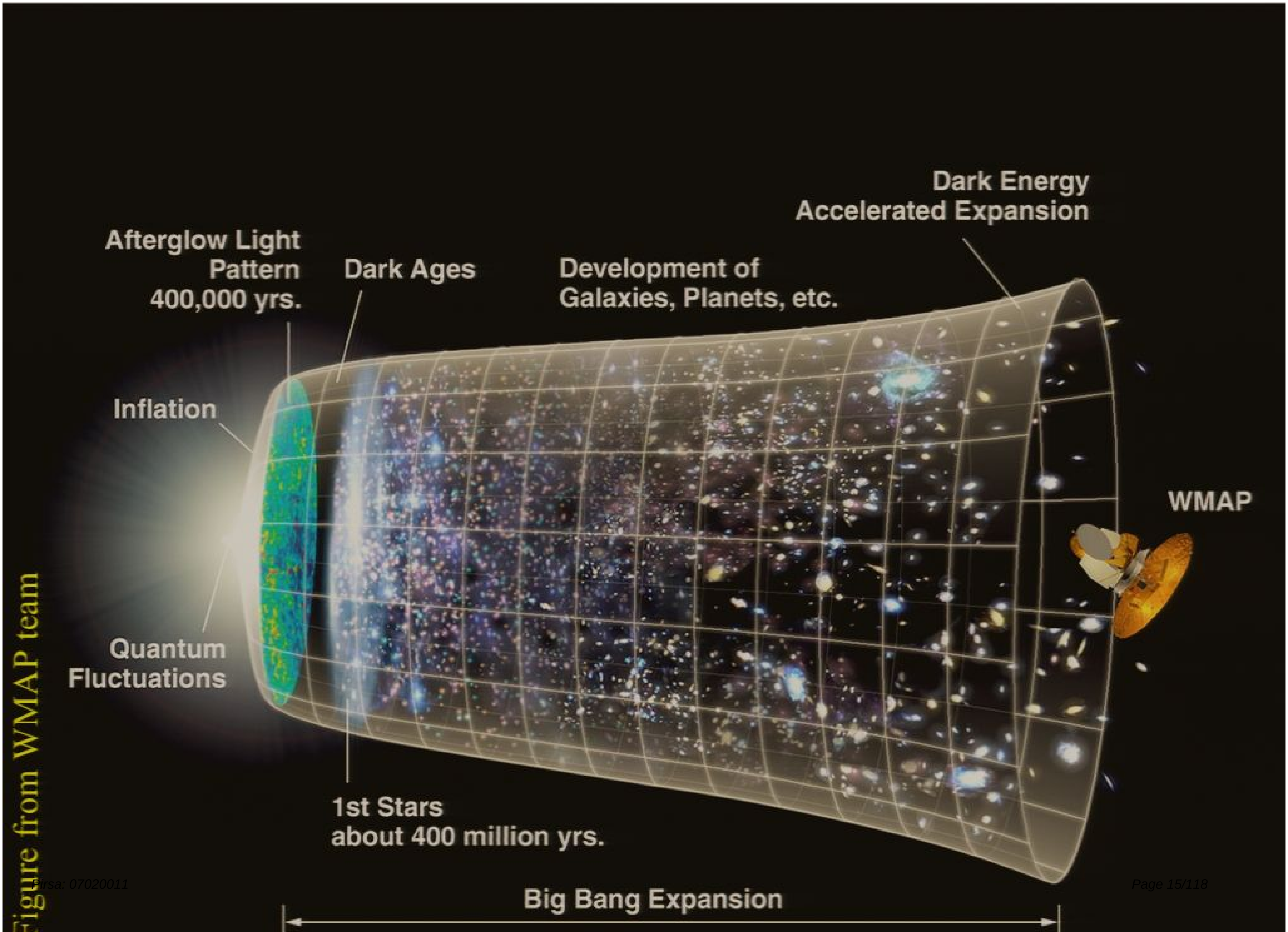
To 0th order:
Fluctuation generator
Fluctuation amplifier
INFLATION
CMB
last scattering
fraction
of a second
first
stars
present
day
386
~~379~~,000
years
400
~~~~200~~ million
years
13.7 billion
years
Hot
Dense
Smooth
H(z)
Cool
Rarefied
Clumpy
(Graphics from Gary Hinshaw/WMAP team)
~~~~


To 1st order:
Fluctuation generator
Fluctuation amplifier
INFLATION
CMB
last scattering
fraction
of a second
first
stars
386
~~379,000~~
years
present
day
400
~~~200~~ million
years
13.7 billion
years
Hot
Dense
Smooth
H(z)
P(k,z)
Cool
Rarefied
Clumpy
(Graphics from Gary Hinshaw/WMAP team)
~~~

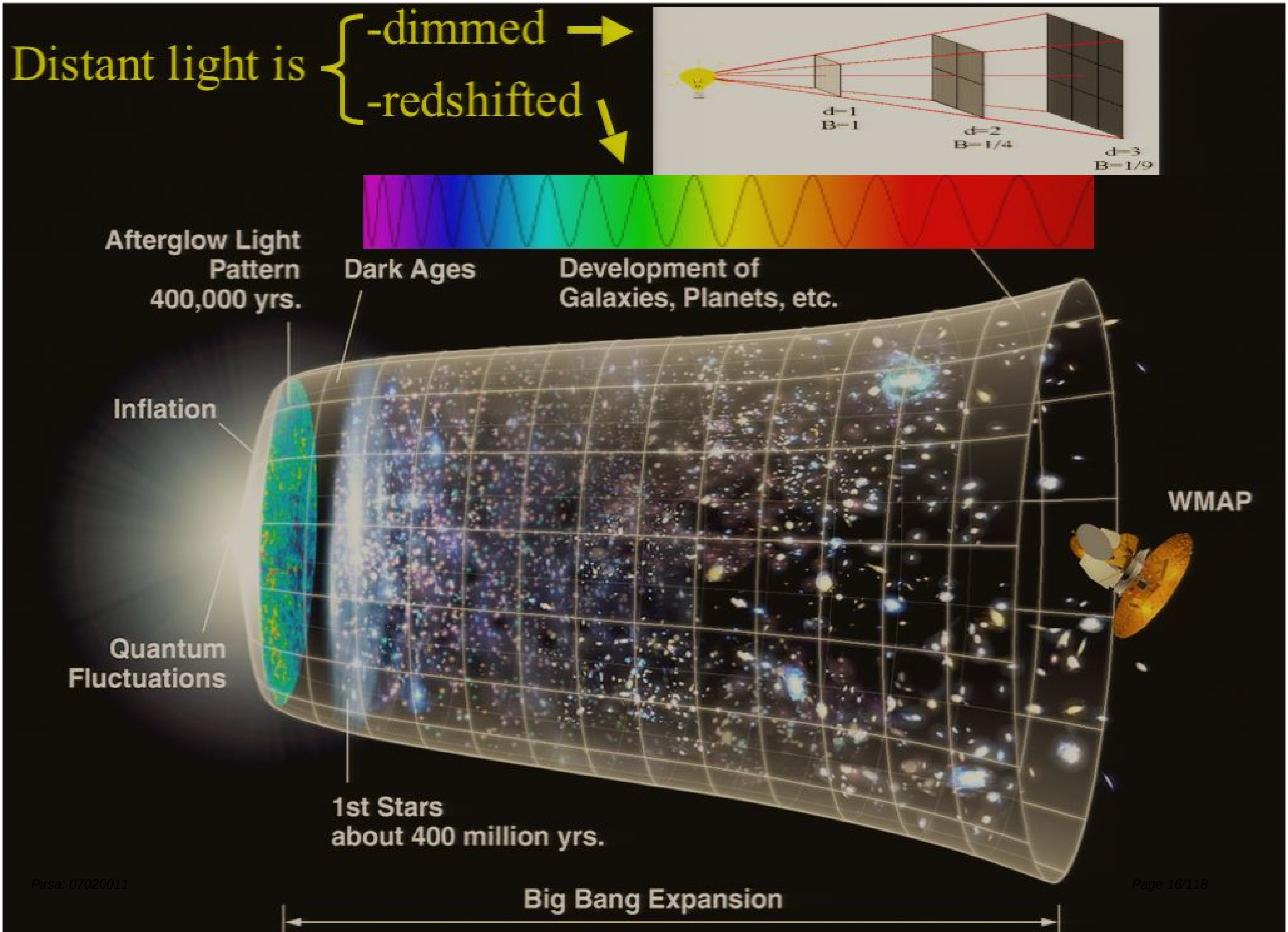
0th order:

Measuring Expansion:

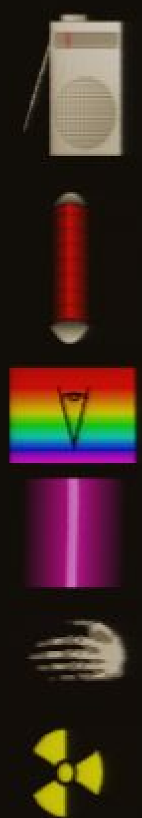
$a(t) \iff H(z)$

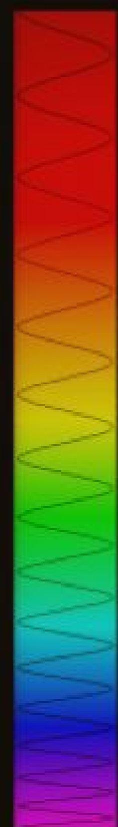


Dark Energy Accelerated Expansion
Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
Figure from WMAP team

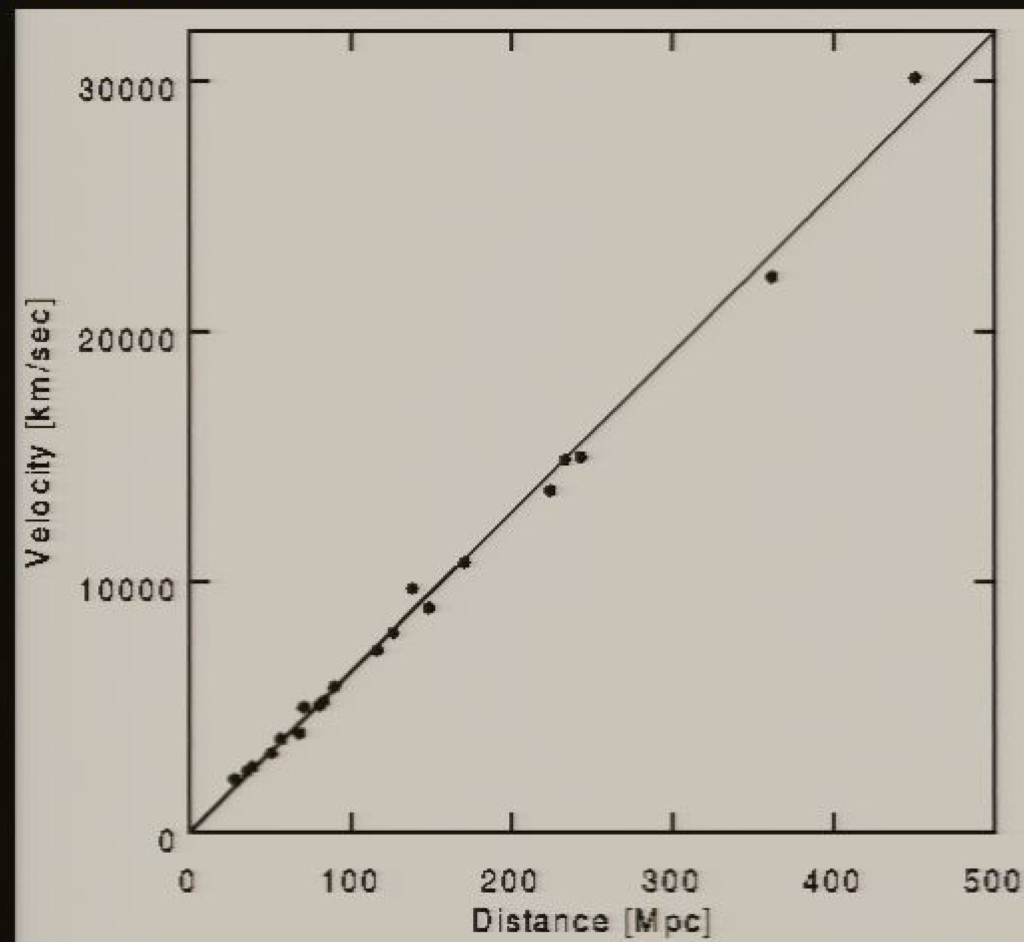

Distant light is
-dimmed
-redshifted
d=1
B=1
d=2
B=1/4
d=3
B=1/9
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion

Distant light is -dimmed
-redshifted

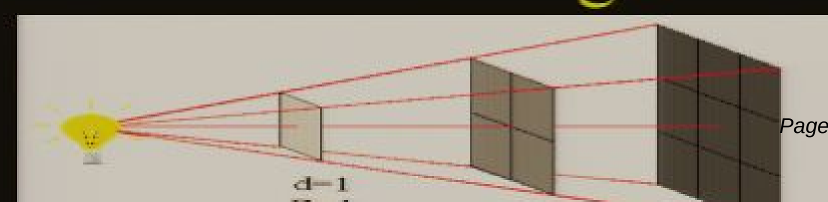




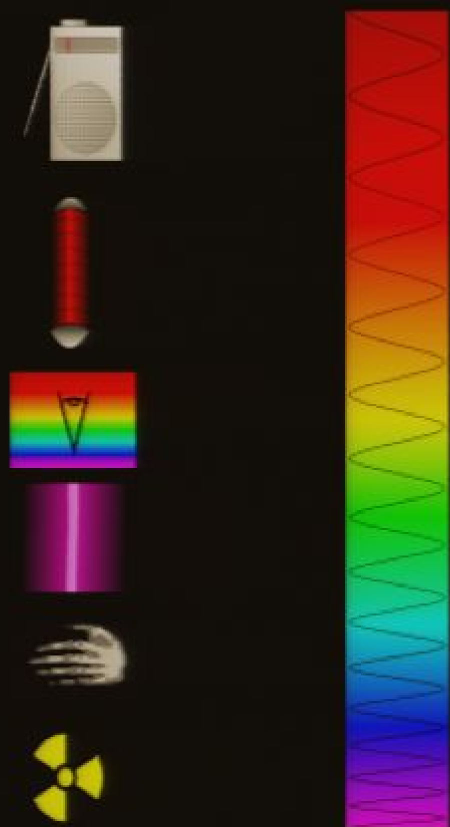
Redshift



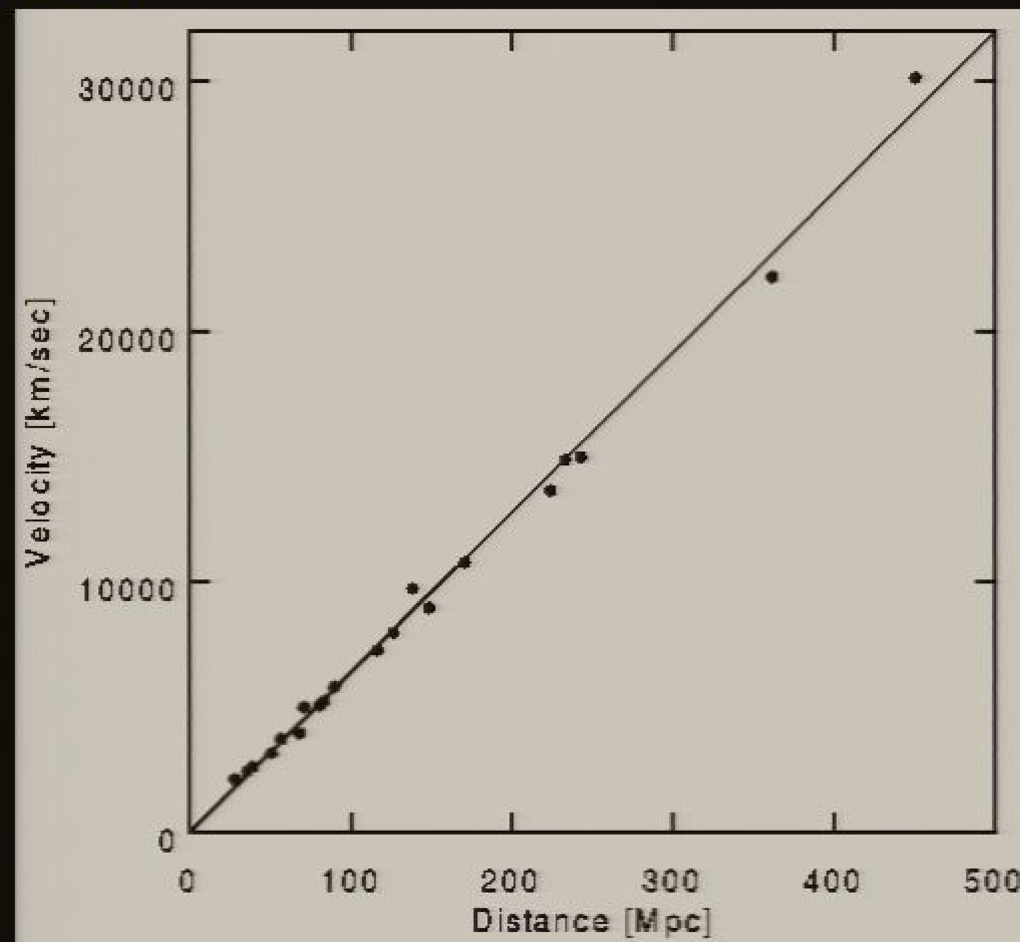
Dimming



Distant light is { -dimmed
-redshifted

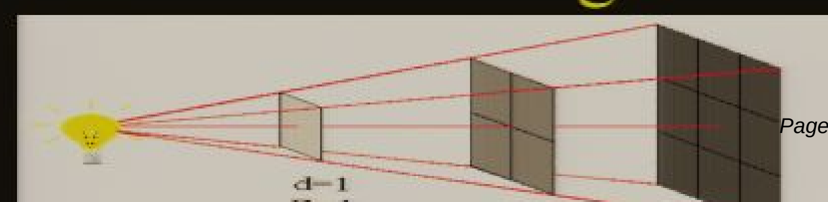


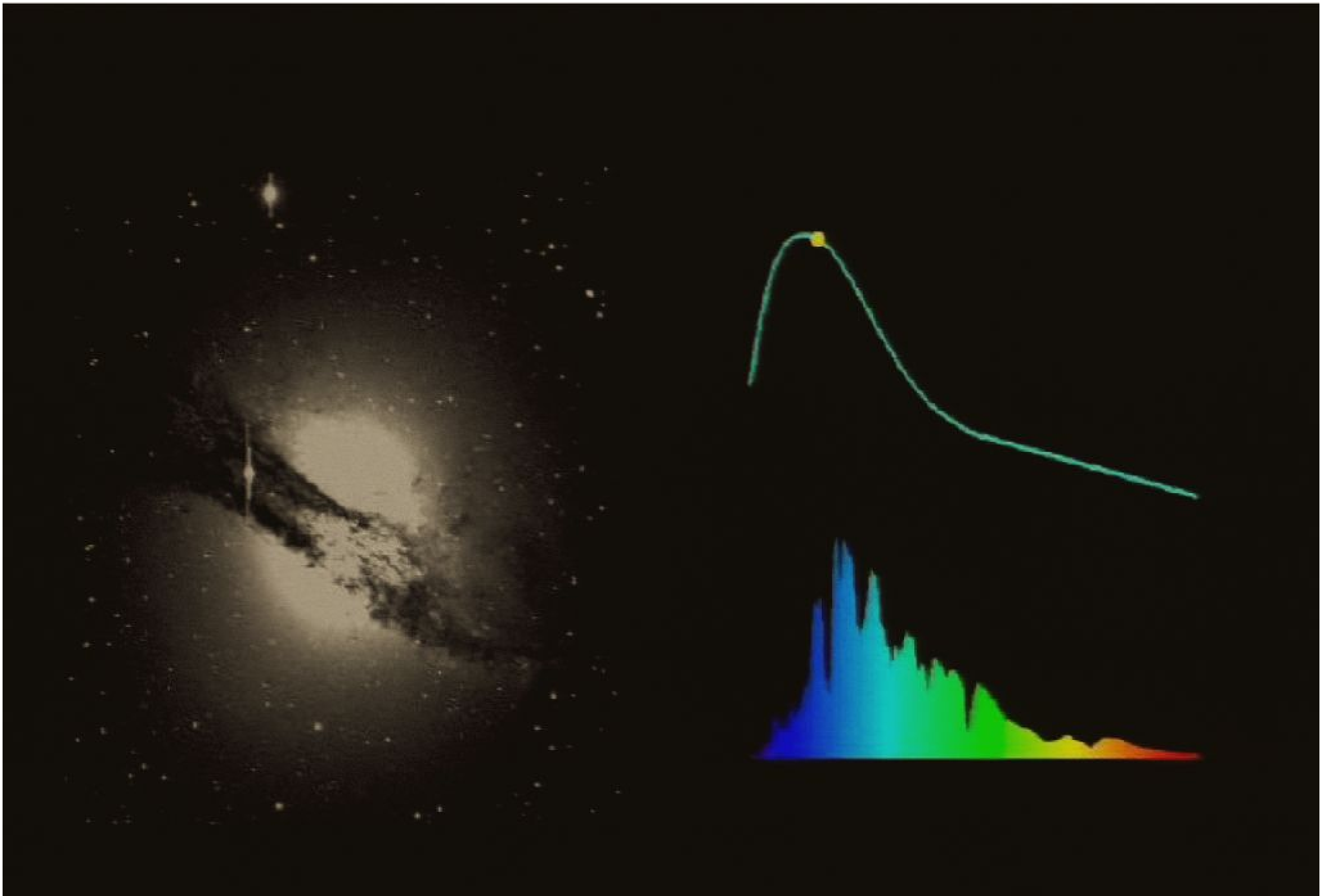
Redshift



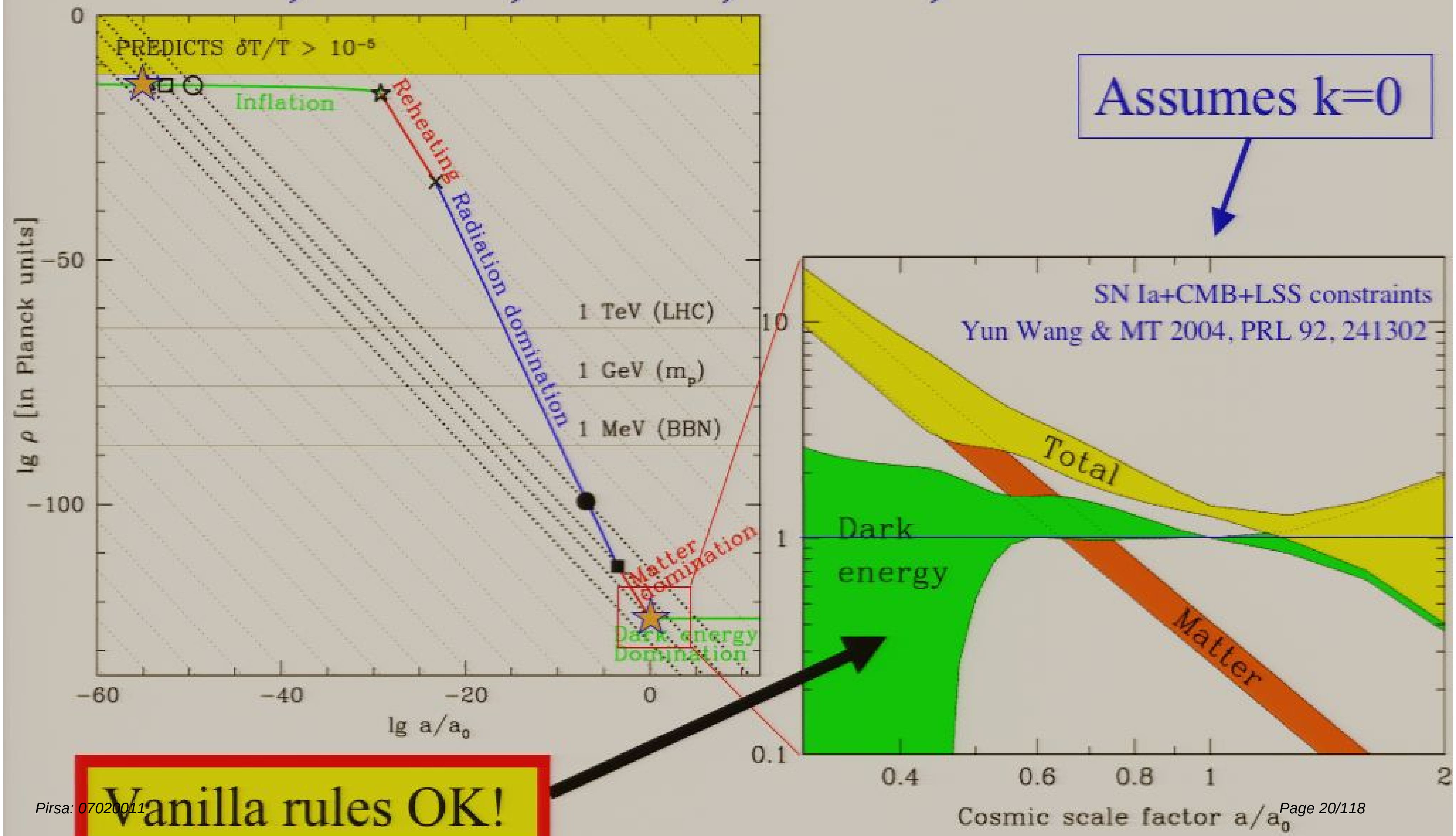
Dimming

Standard candles,
rulers or clocks



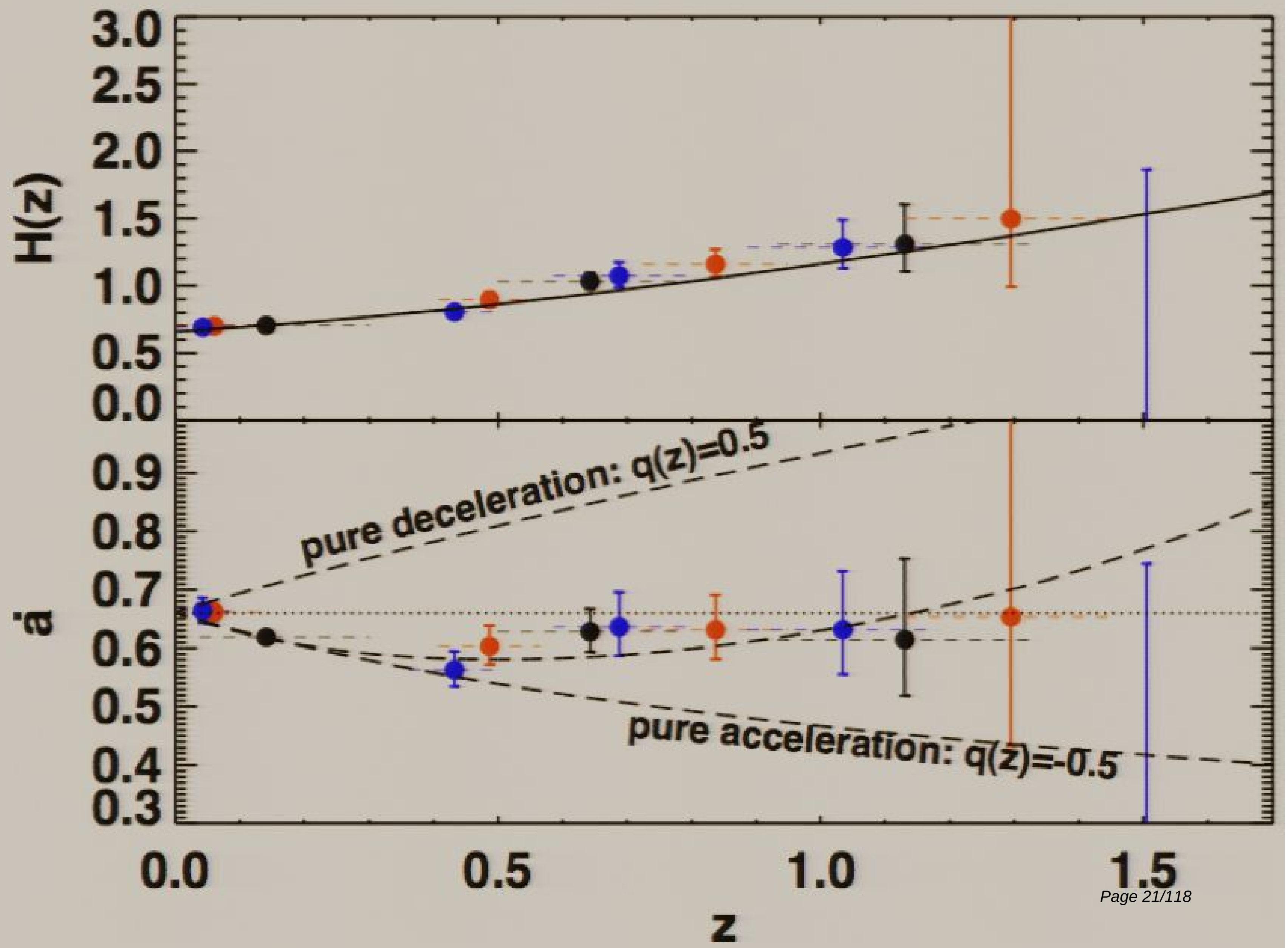


What we've learned about H(z) from SN Ia, CMB, BAO, BBN, etc:

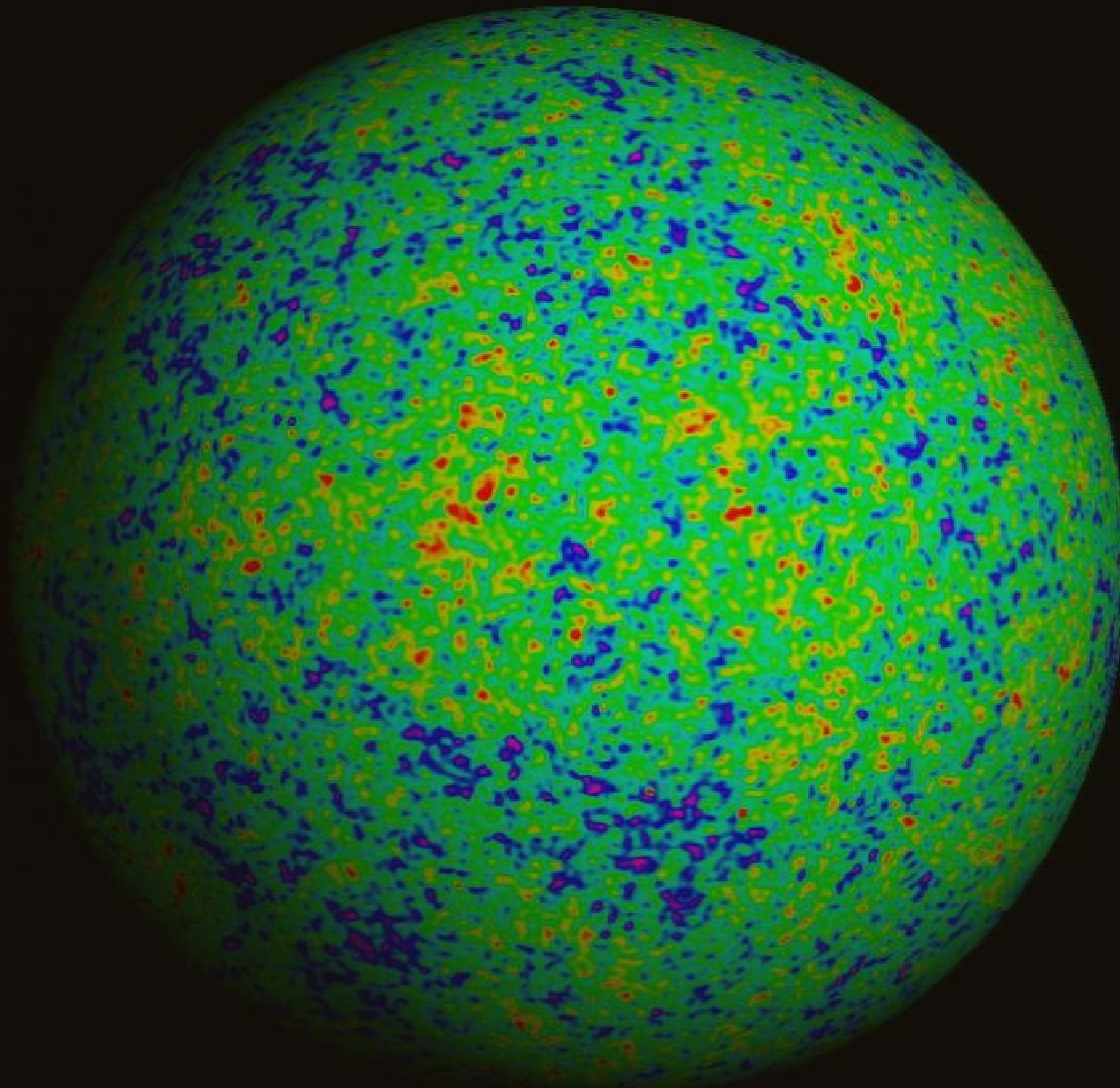


Vanilla rules OK!

Riess et al, astro-ph/0611572



1st order: measuring clustering

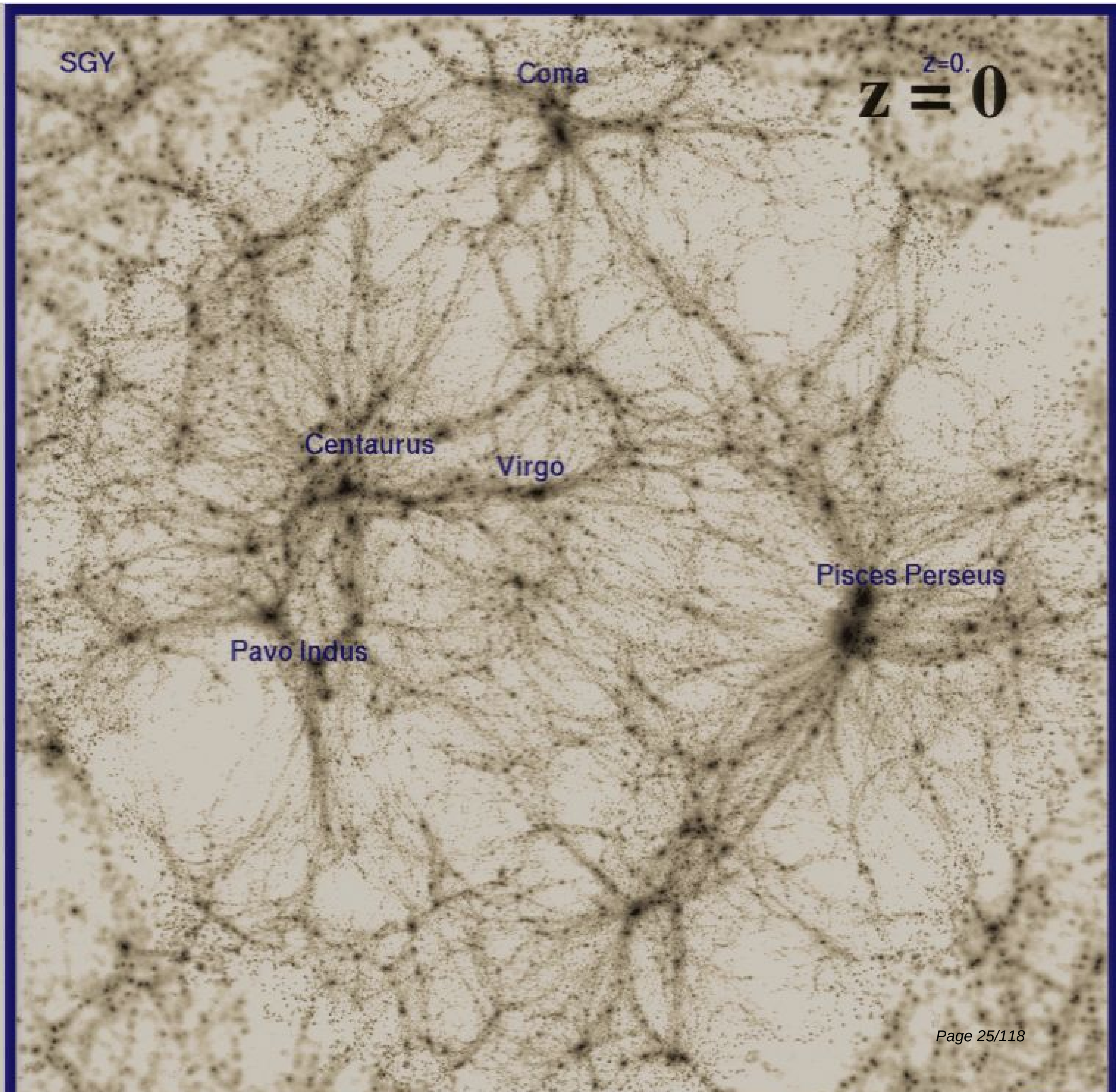


Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496

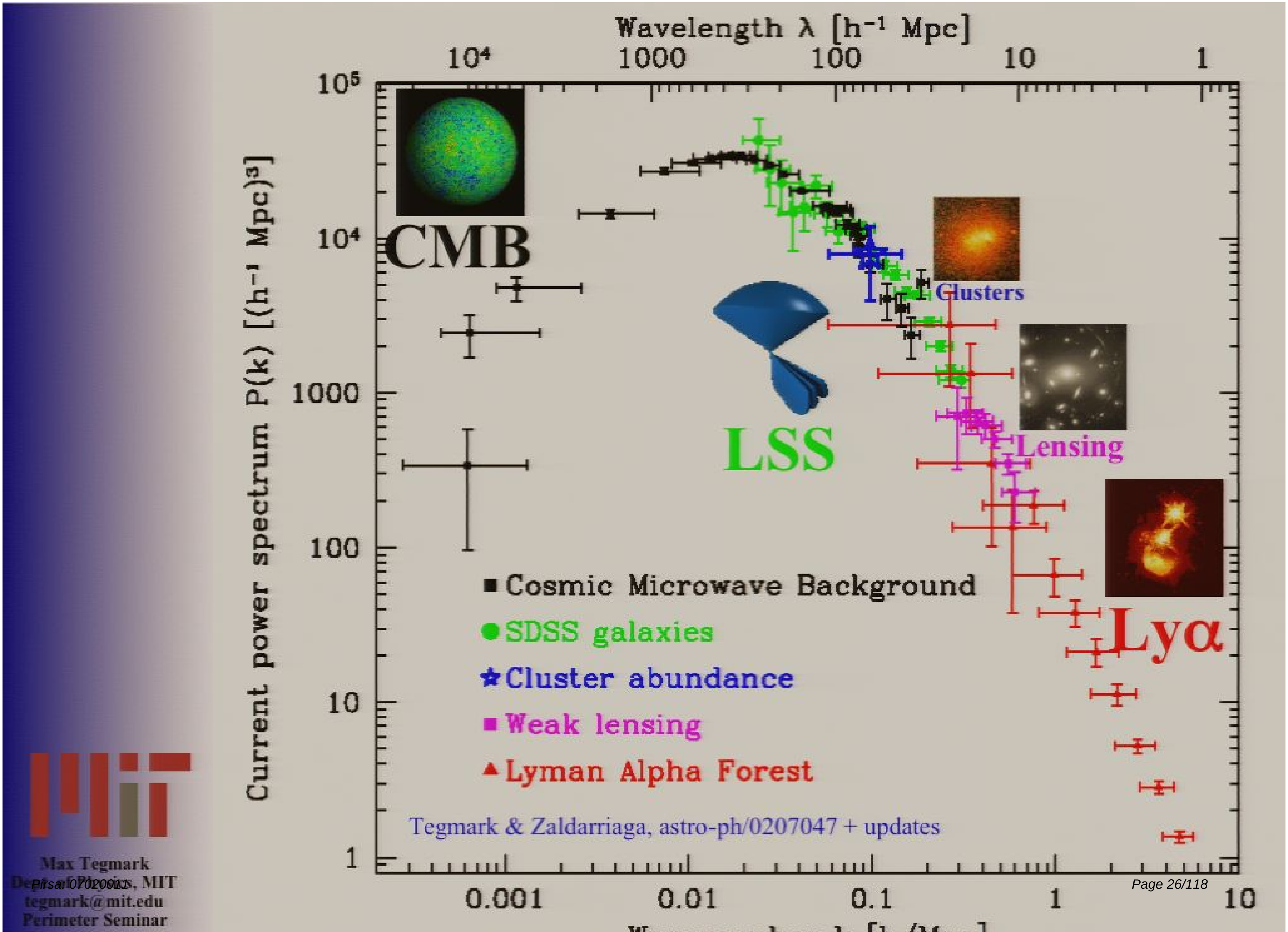
z = 1000

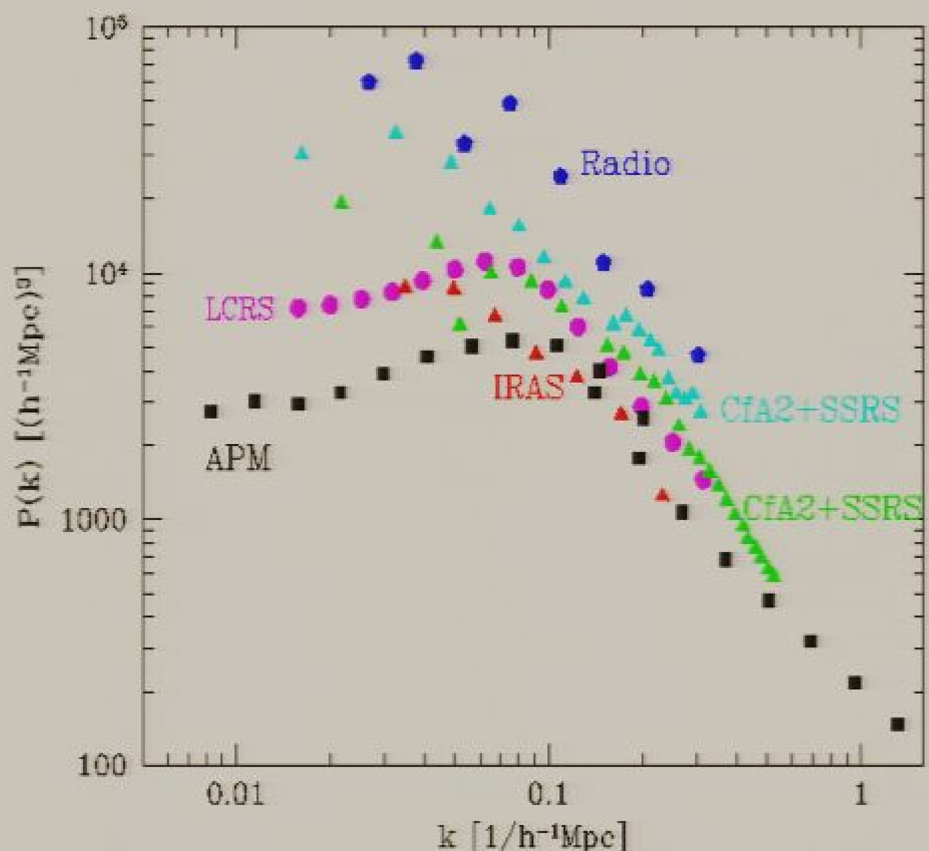
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

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



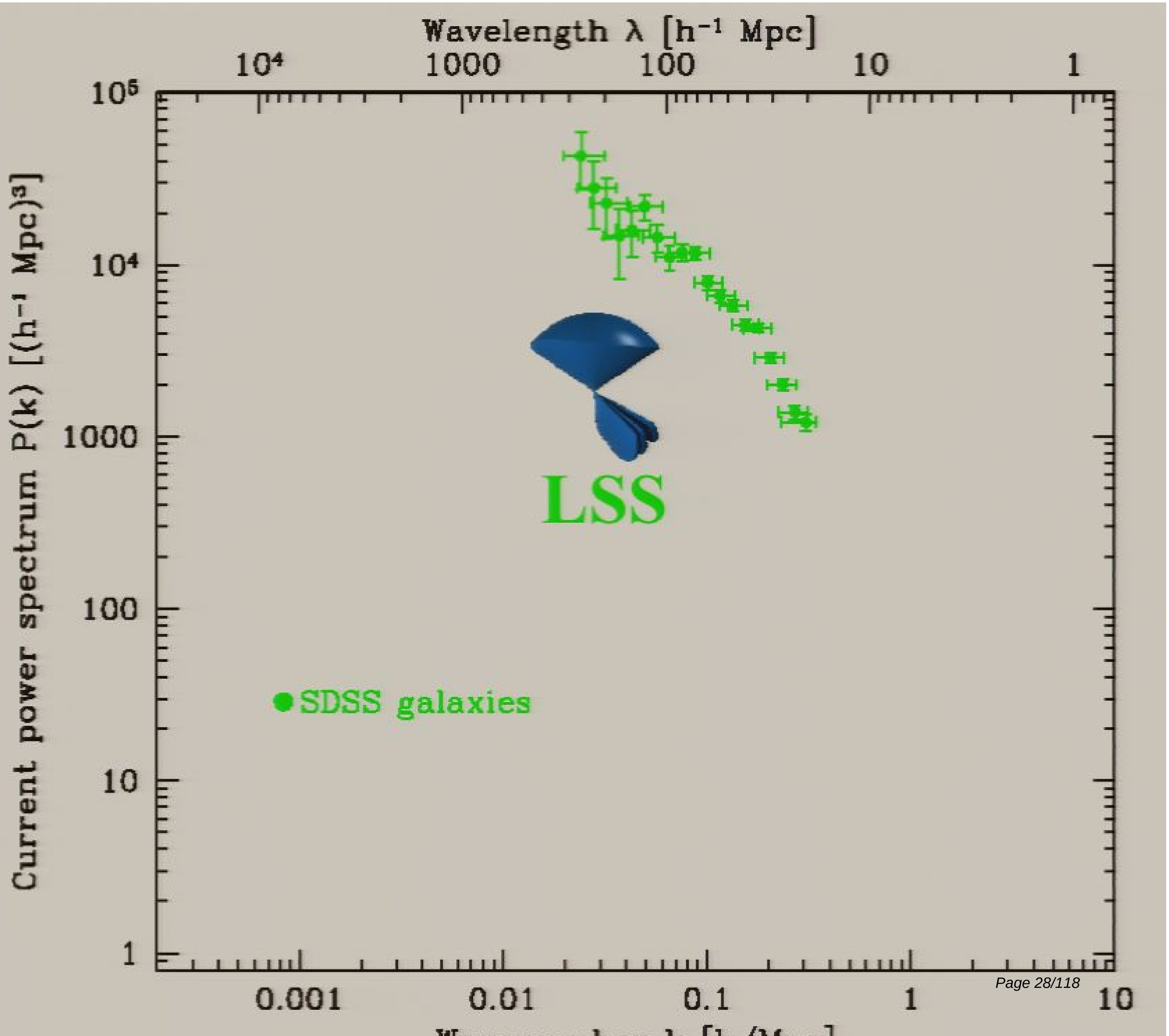
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
CMB
LSS
Clusters
Lensing
Lyα
■ Cosmic Microwave Background
● SDSS galaxies
★ Cluster abundance
■ Weak lensing
▲ Lyman Alpha Forest
Tegmark & Zaldarriaga, astro-ph/0207047 + updates
0.001
0.01
0.1
1
10
Max Tegmark
Dept of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

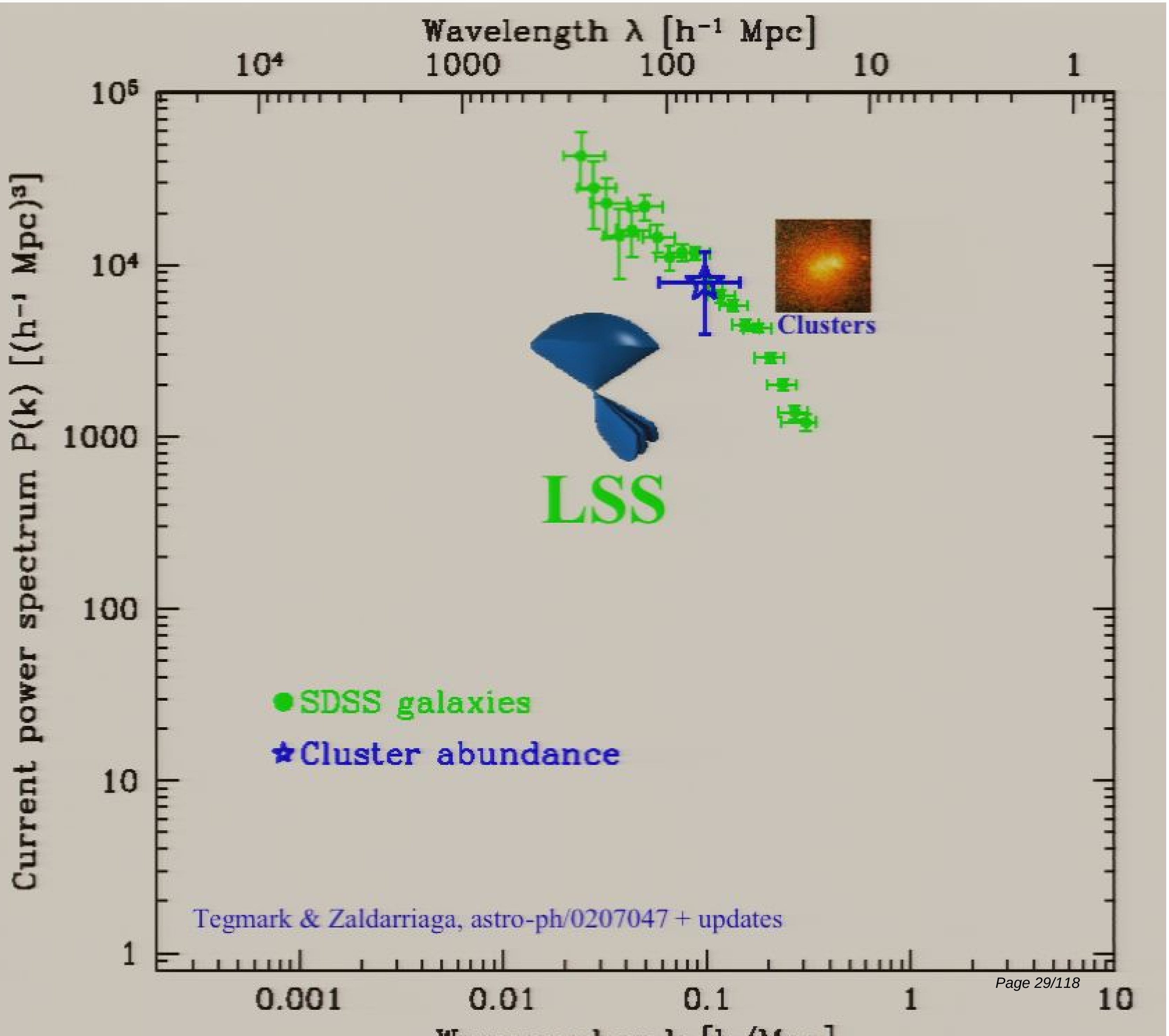


Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

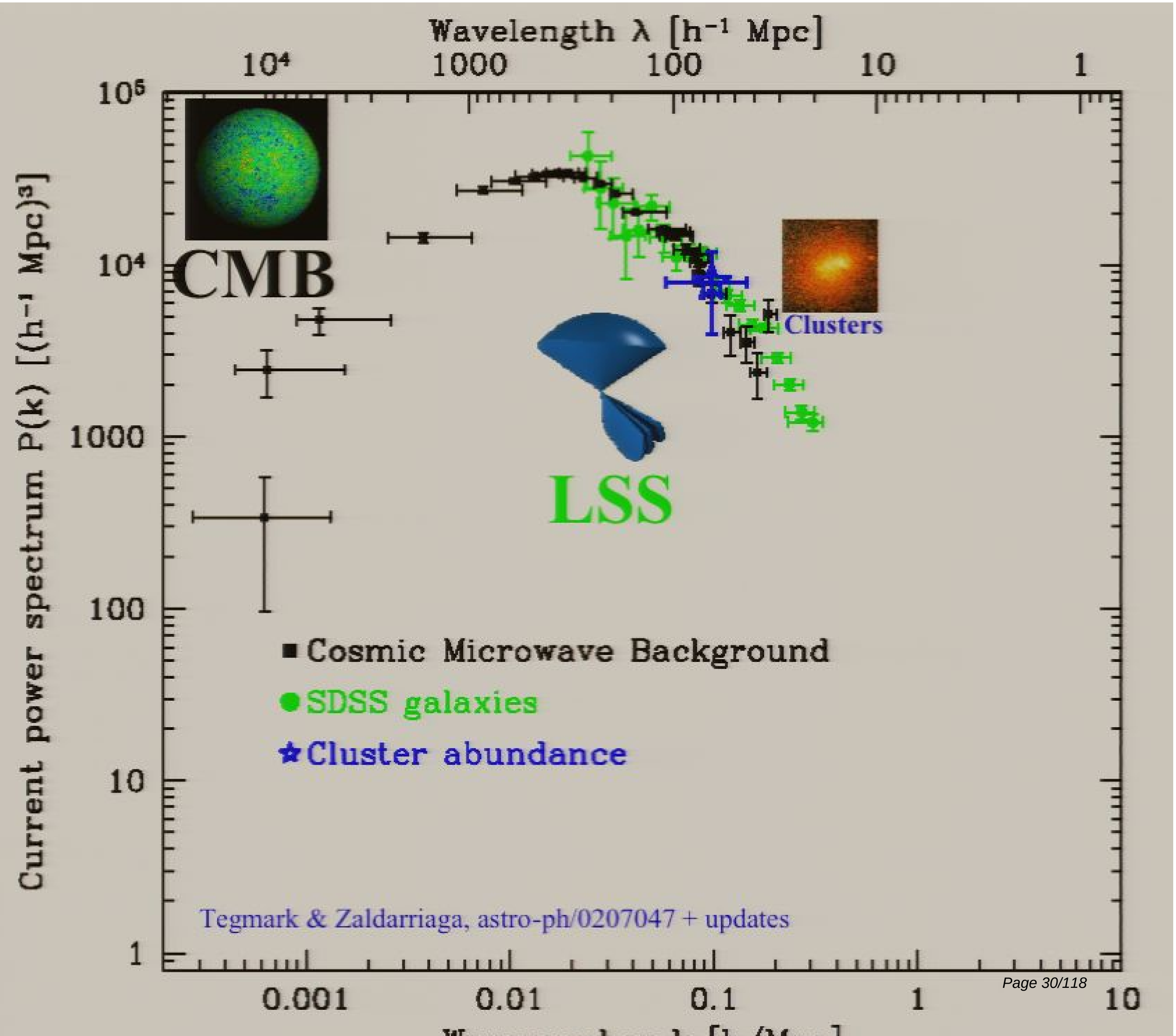
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar



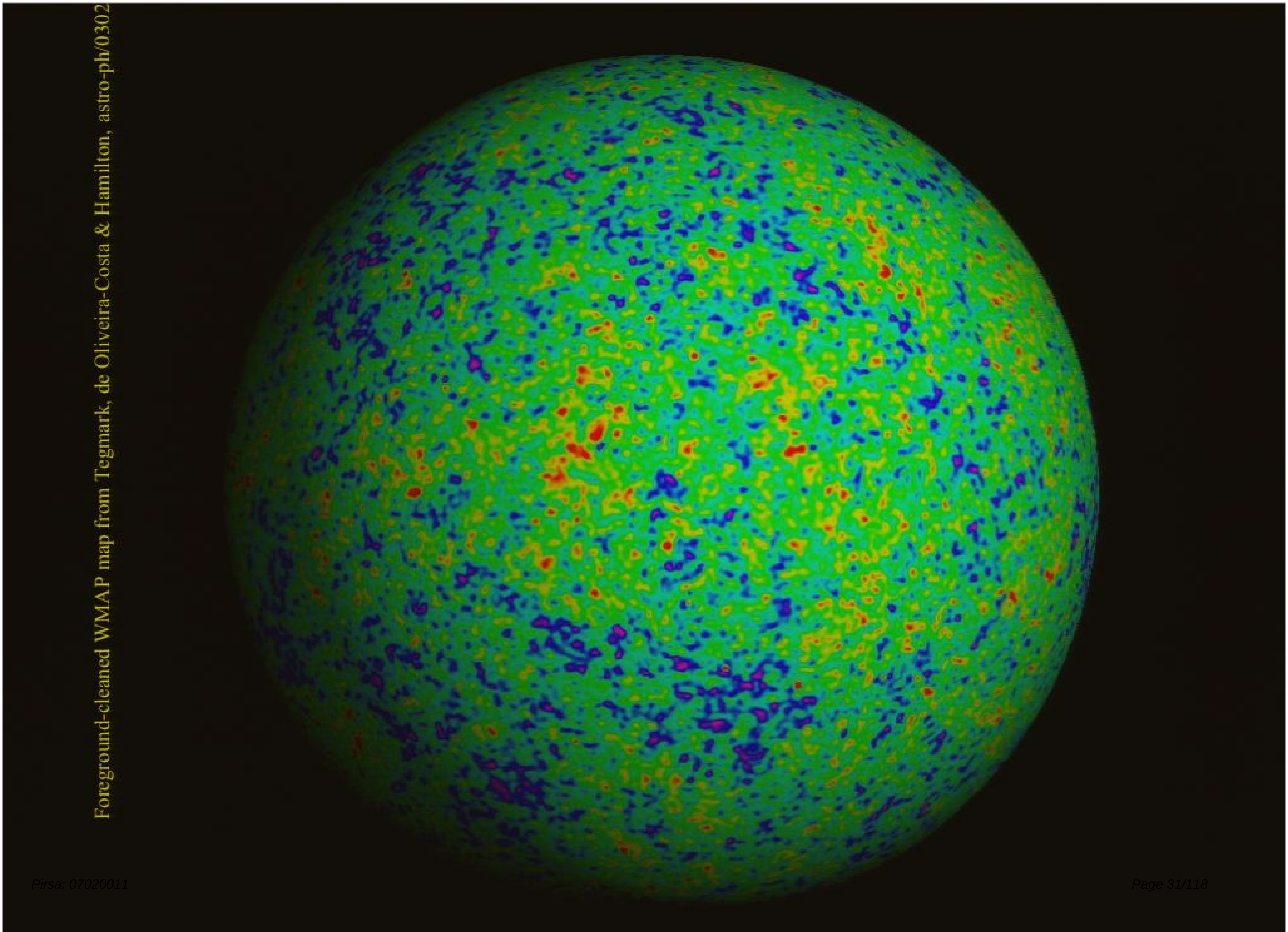
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

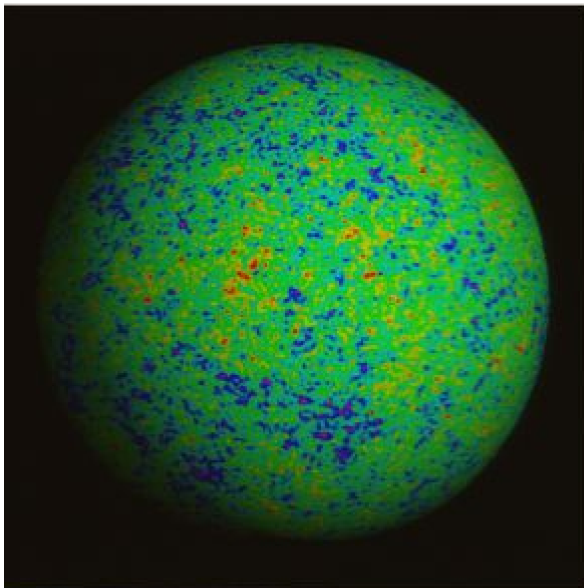


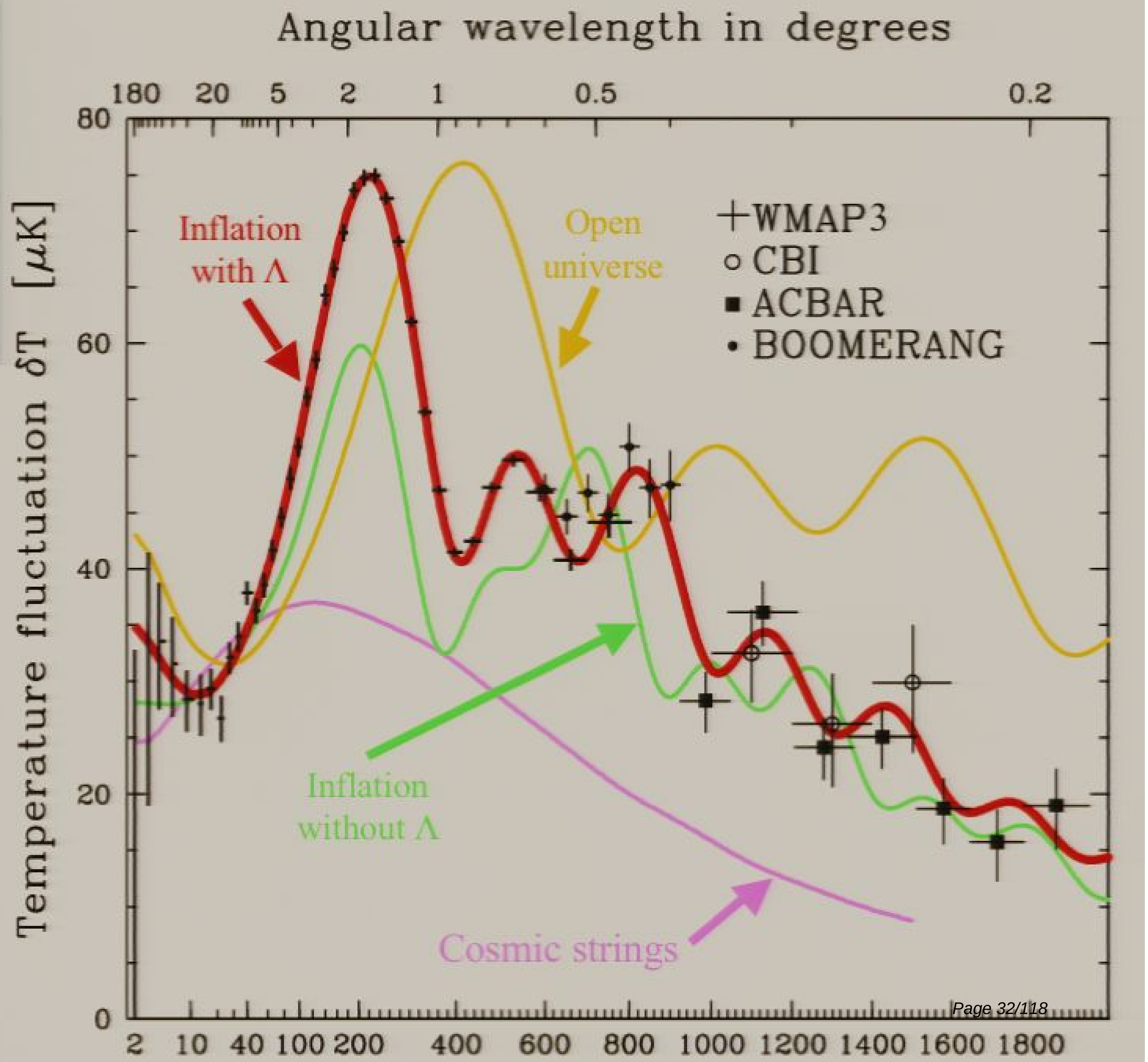
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar



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

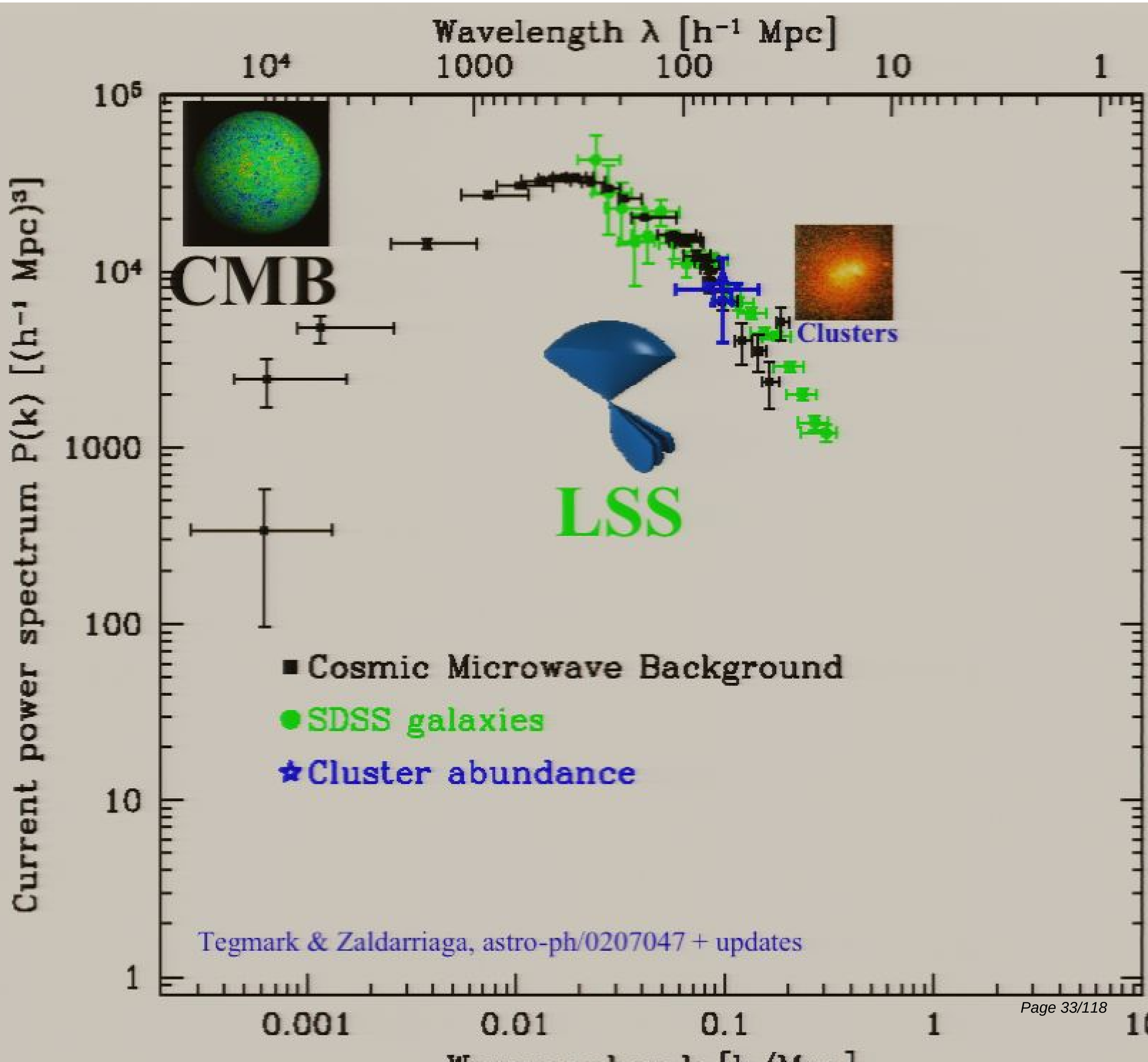

Foreground-cleaned WMAP map from Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302





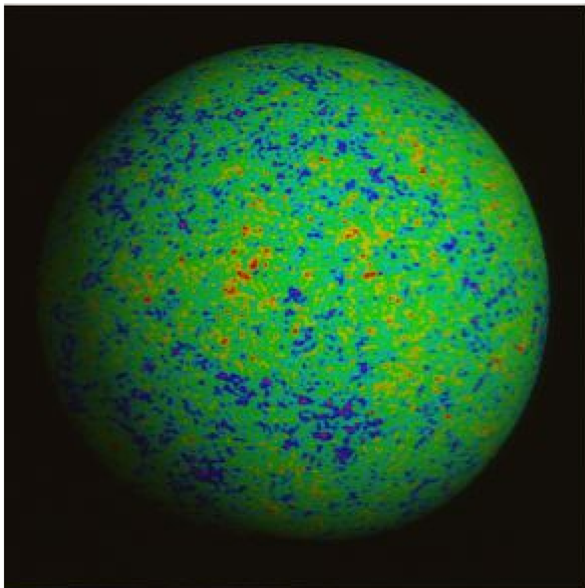
uth & Kaiser 2005 (Science) + WMAP3

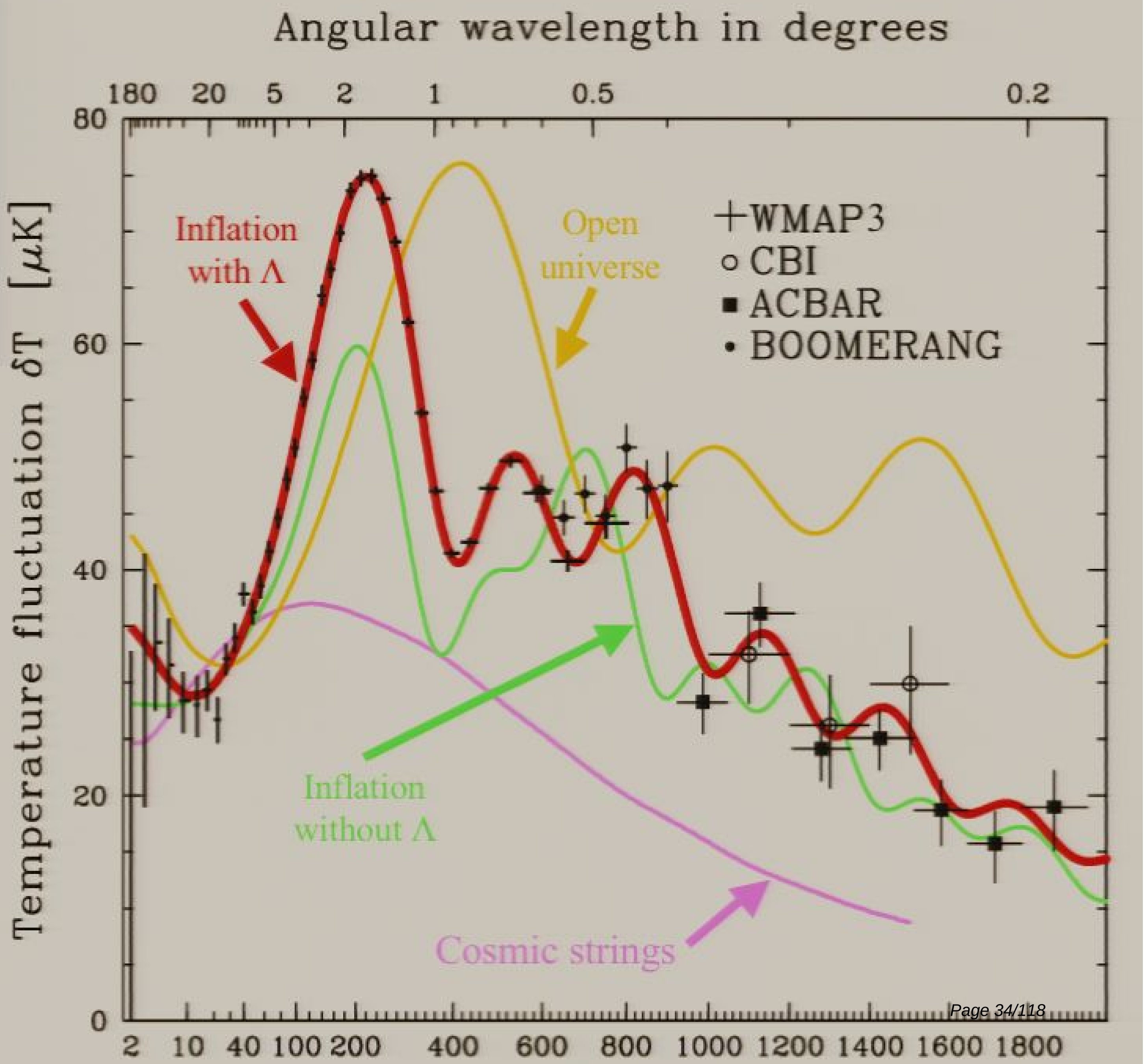
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar



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

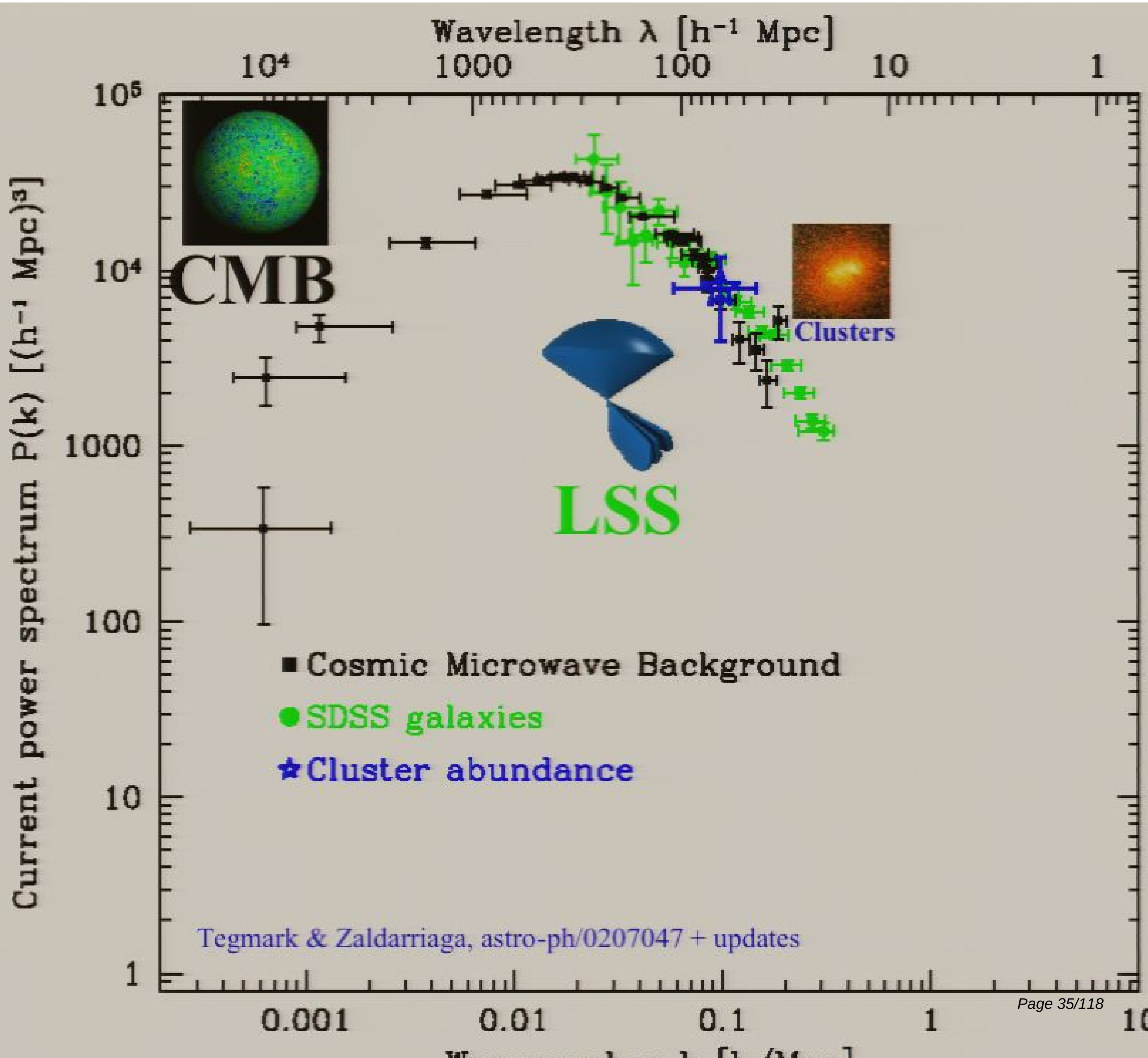
Perimeter Seminar



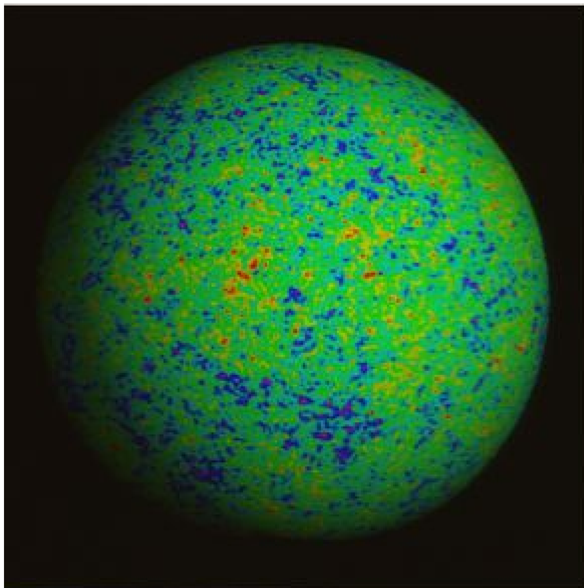


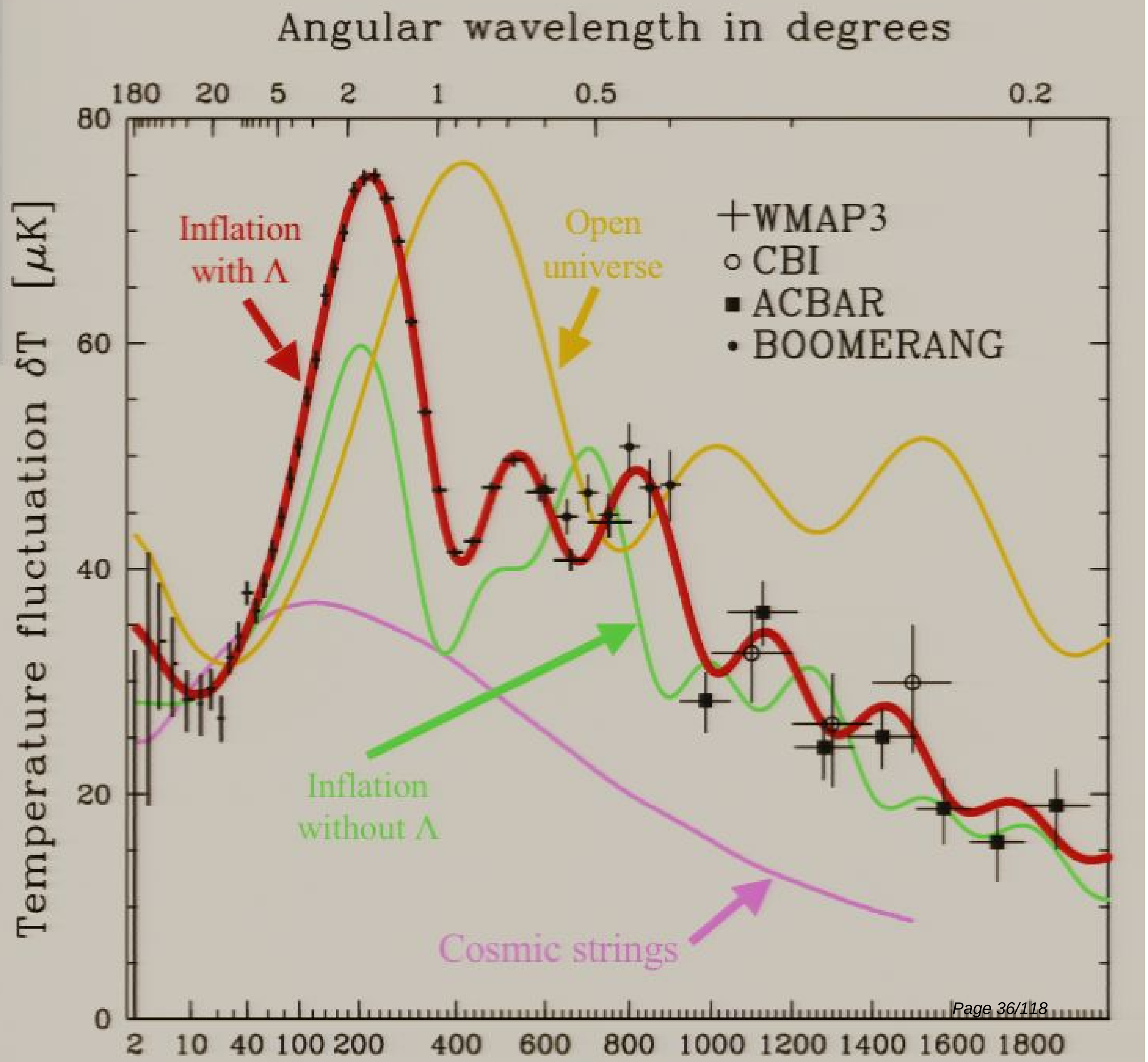
uth & Kaiser 2005 (Science) + WMAP3

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



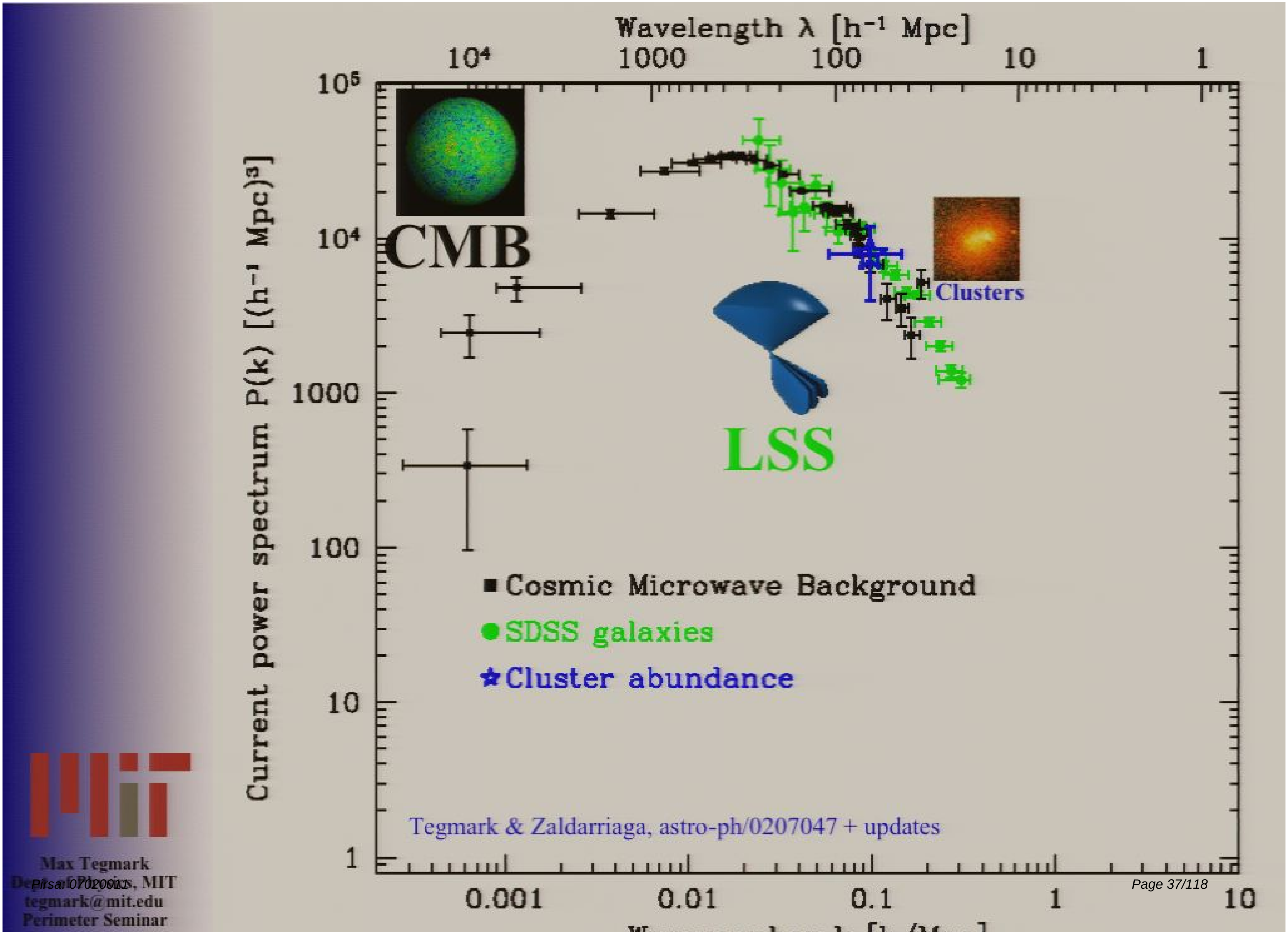
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

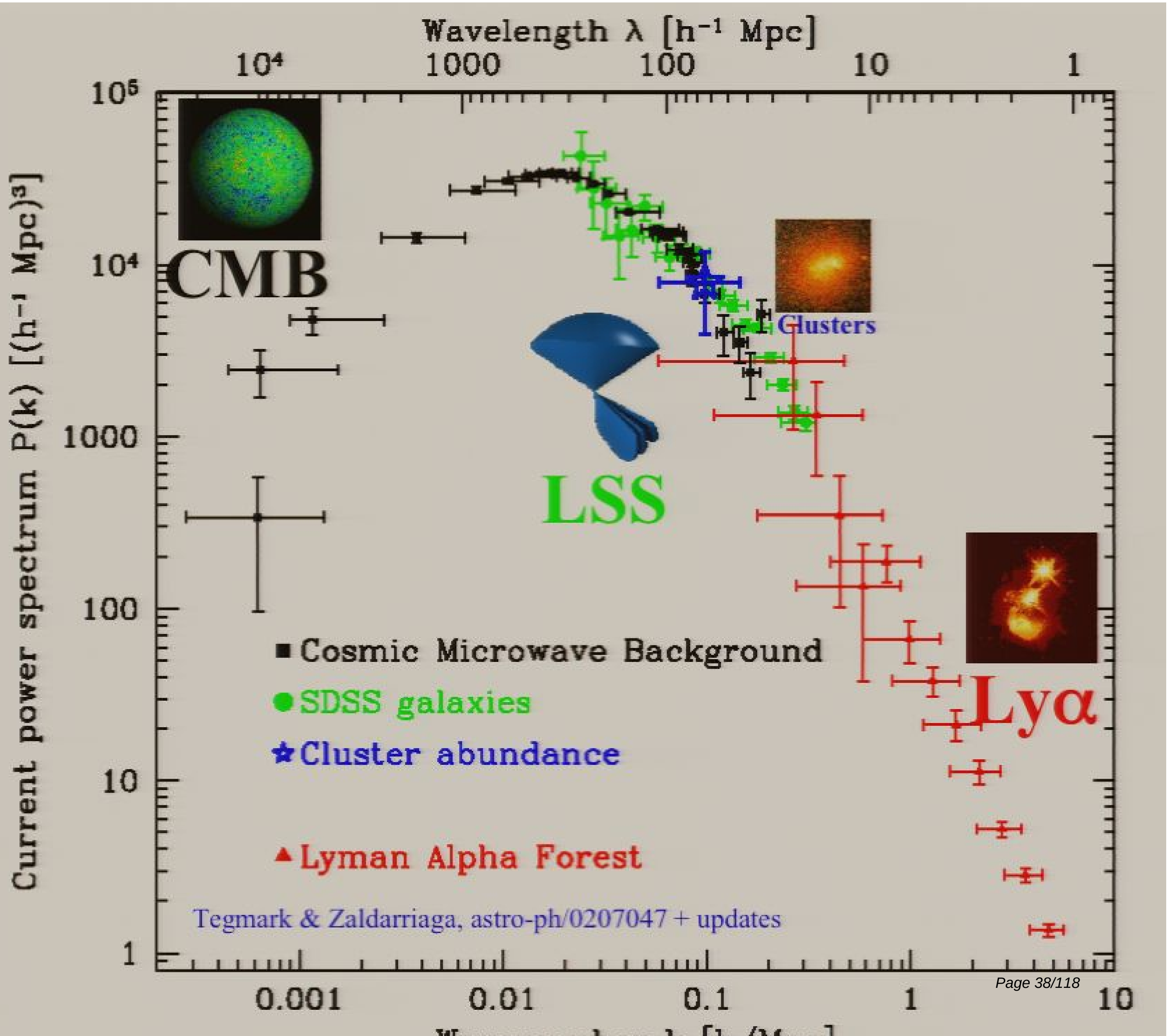




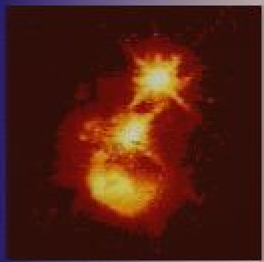
uth & Kaiser 2005 (Science) + WMAP3

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


Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
CMB
Clusters
LSS
■ Cosmic Microwave Background
● SDSS galaxies
★ Cluster abundance
Tegmark & Zaldarriaga, astro-ph/0207047 + updates
0.001
0.01
0.1
1
10
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

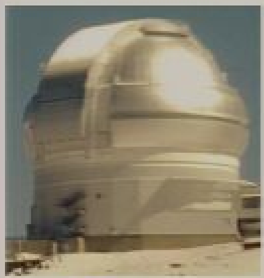


Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar



LyαF

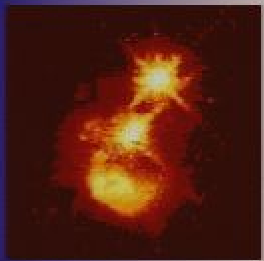
Quasar



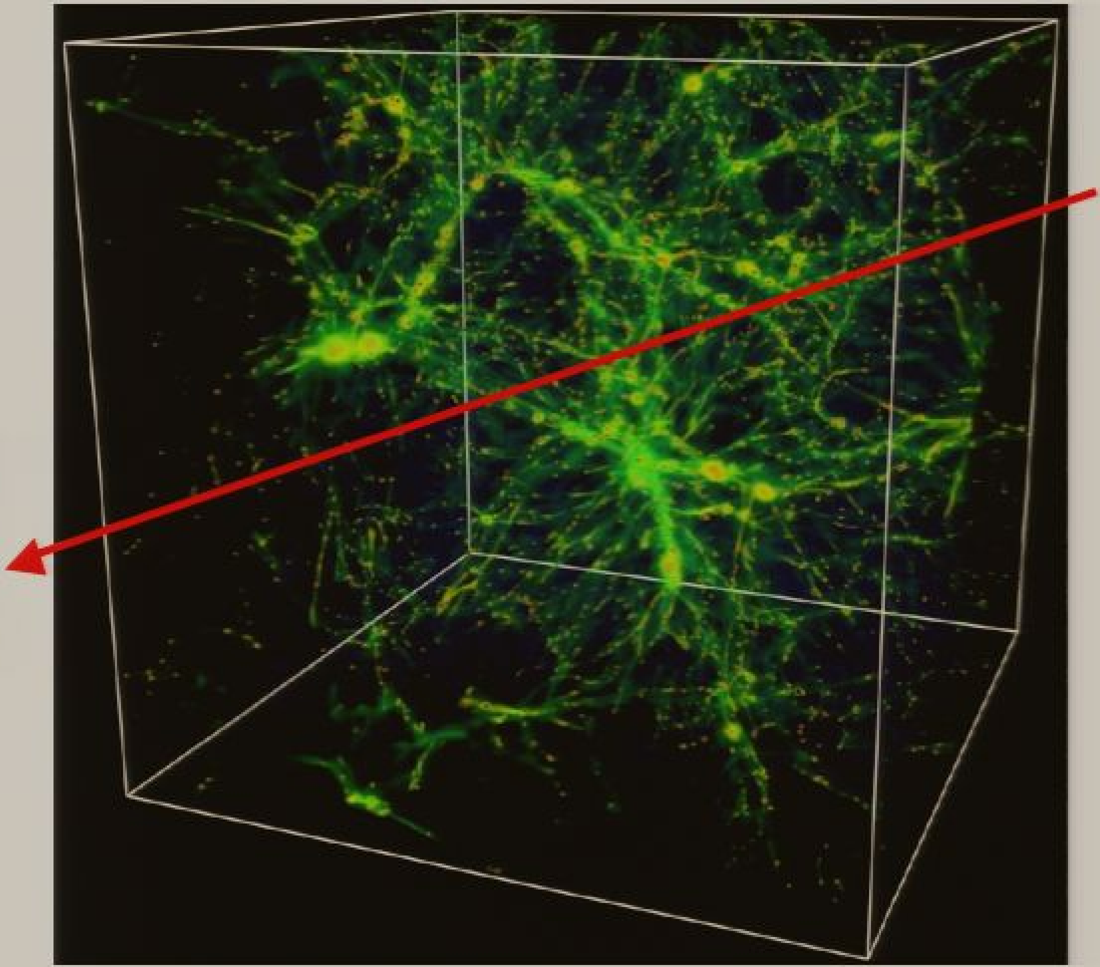
You

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

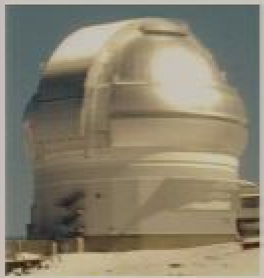
Lyman Alpha Forest Simulation: Cen et al 2001



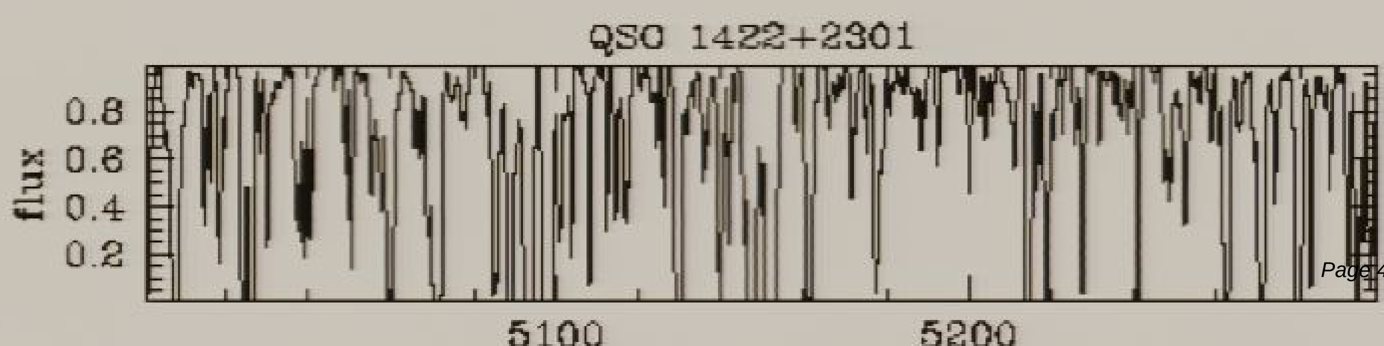
LyαF



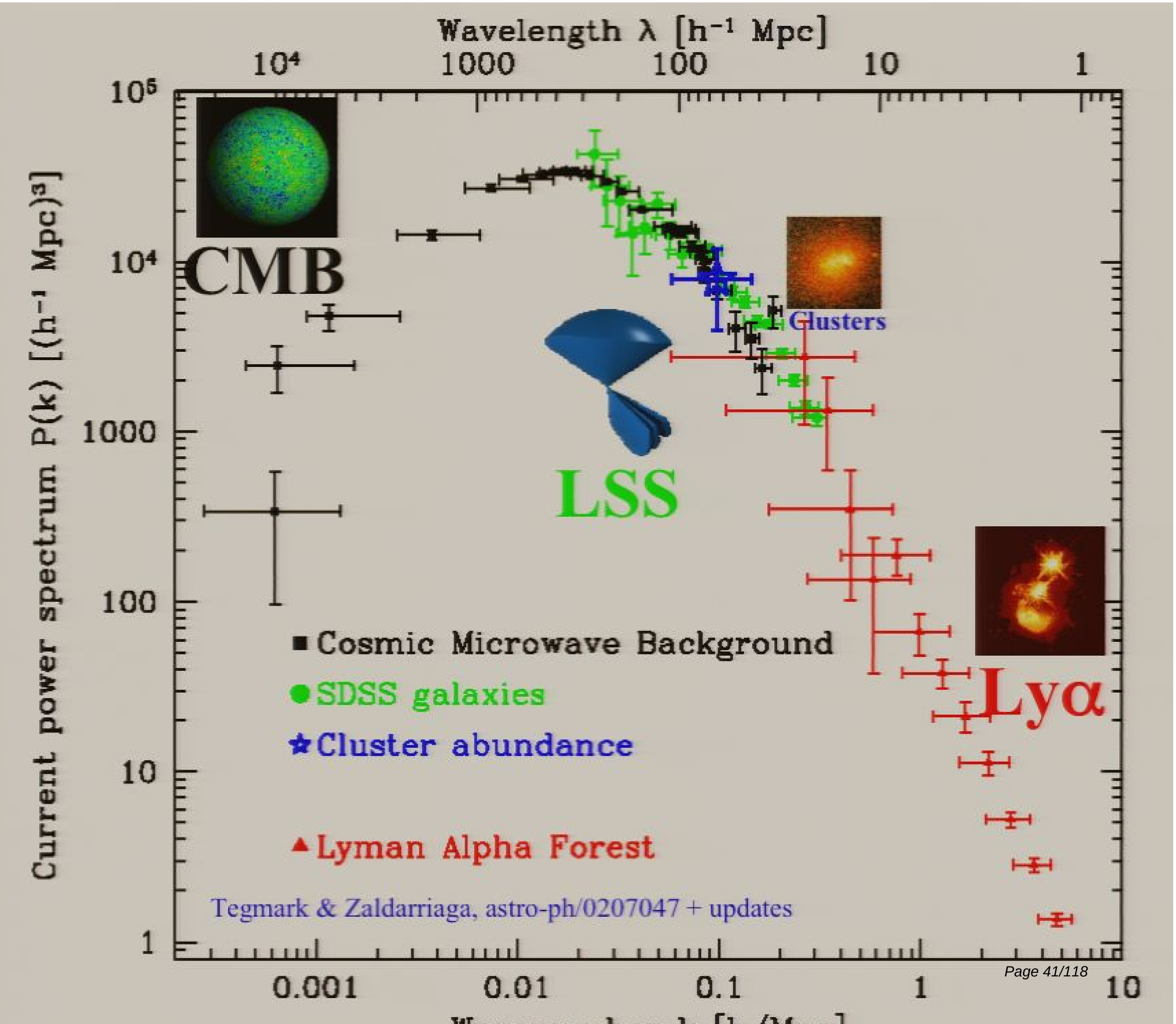
Quasar



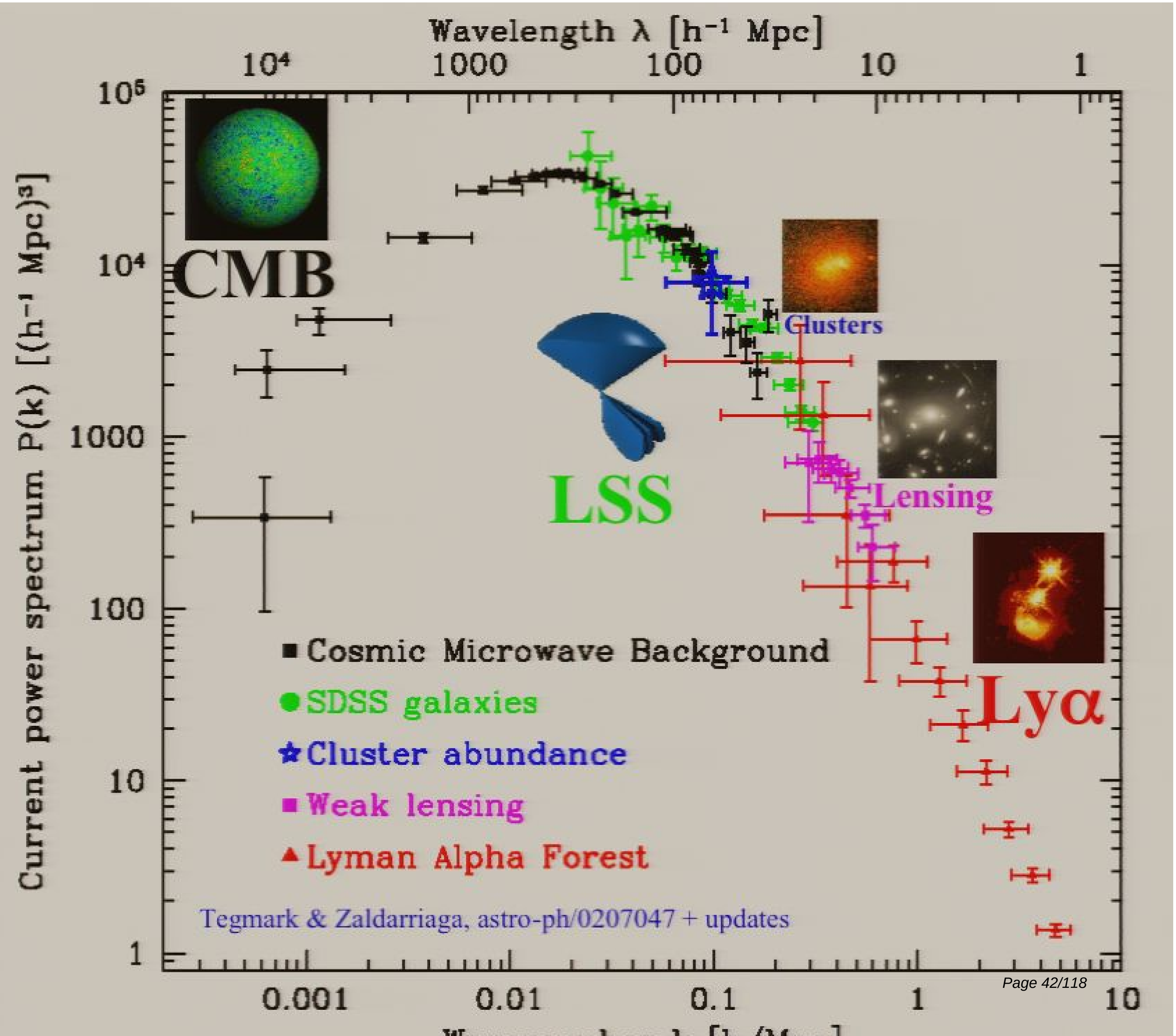
You



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



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

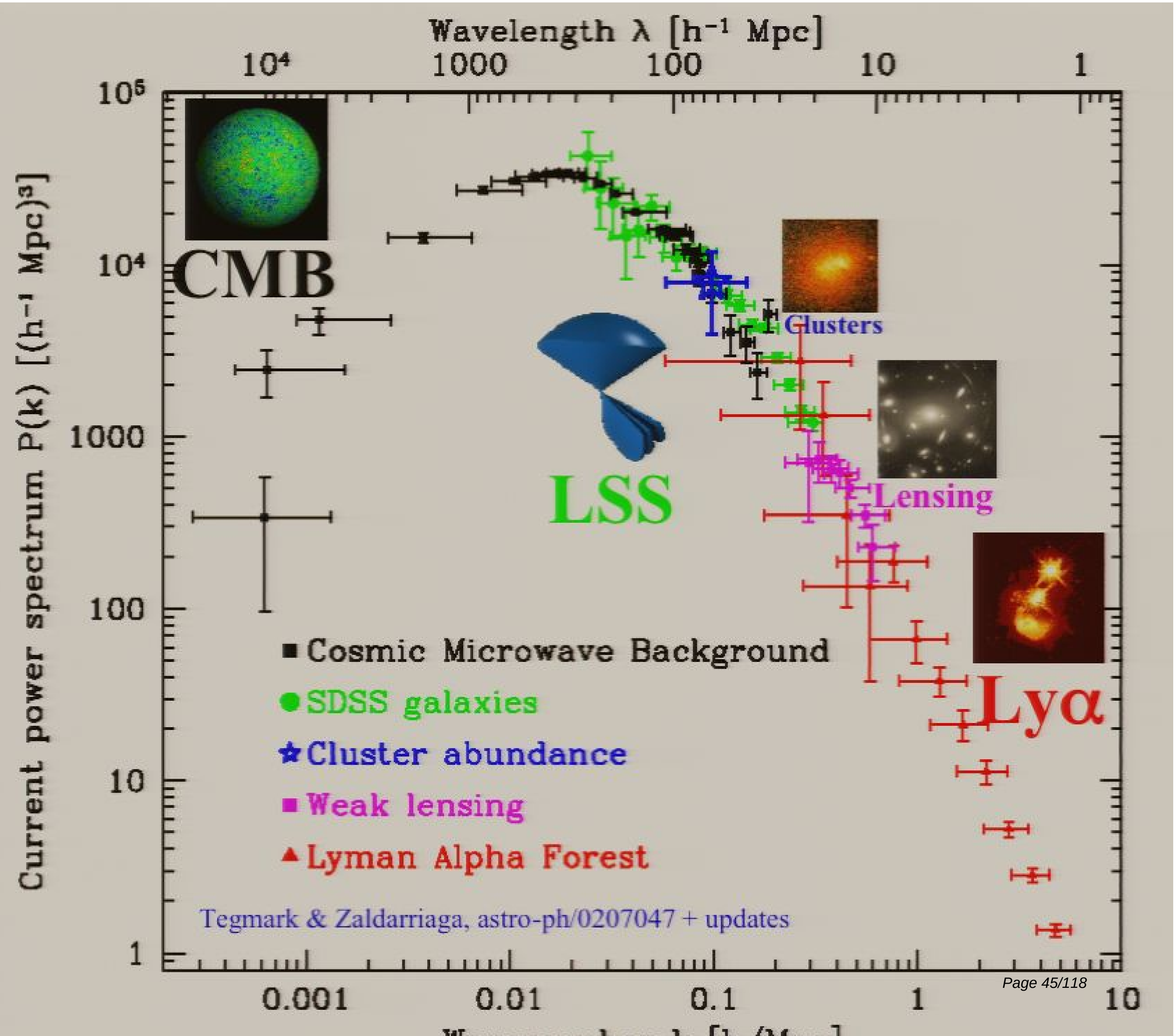


Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

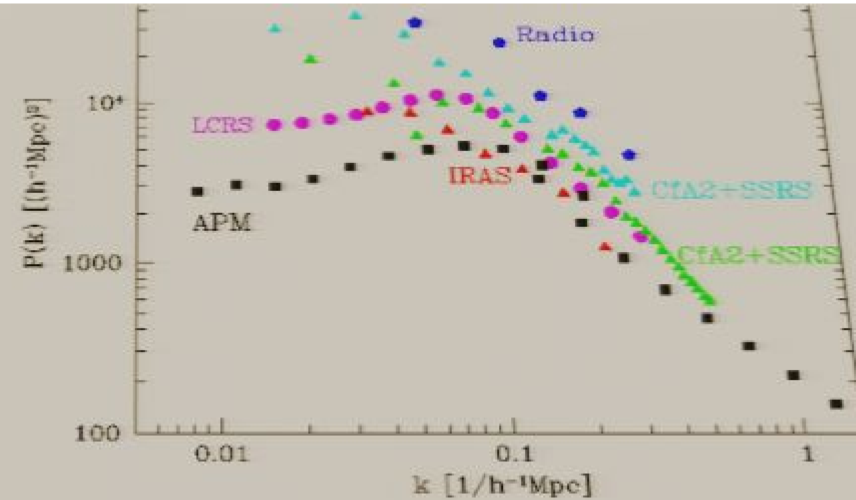
GRAVITATIONAL LENSING:
A1689 imaged by Hubble ACS, Broadhurst et al 2004

Lensing

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

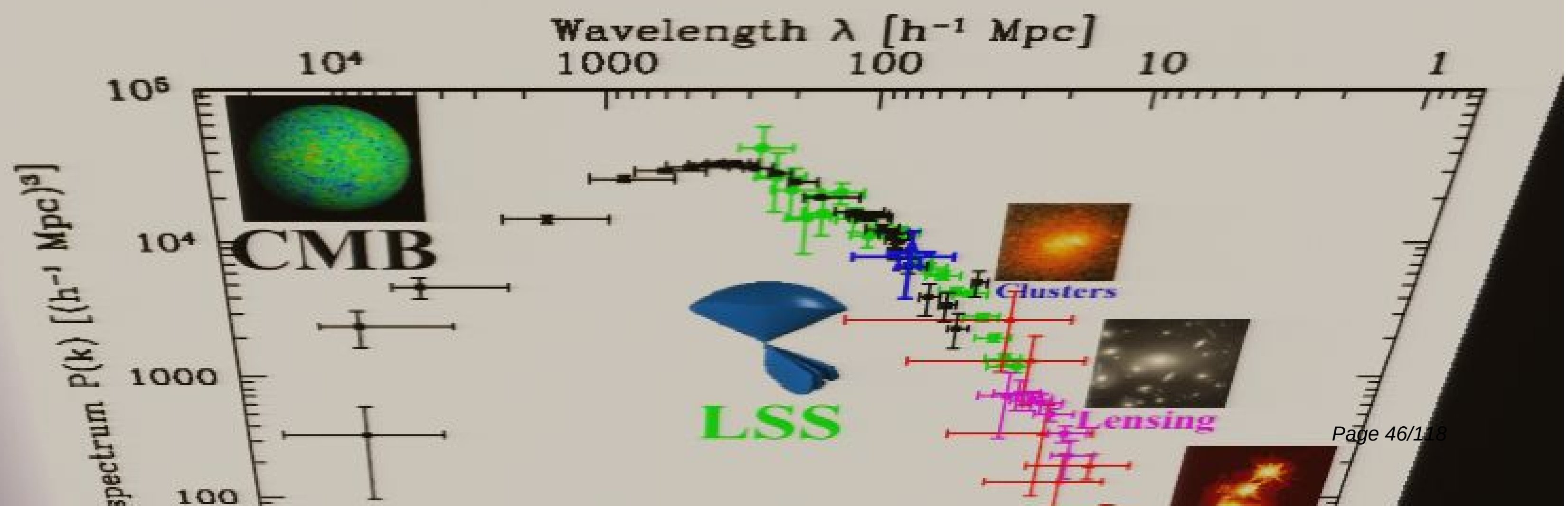


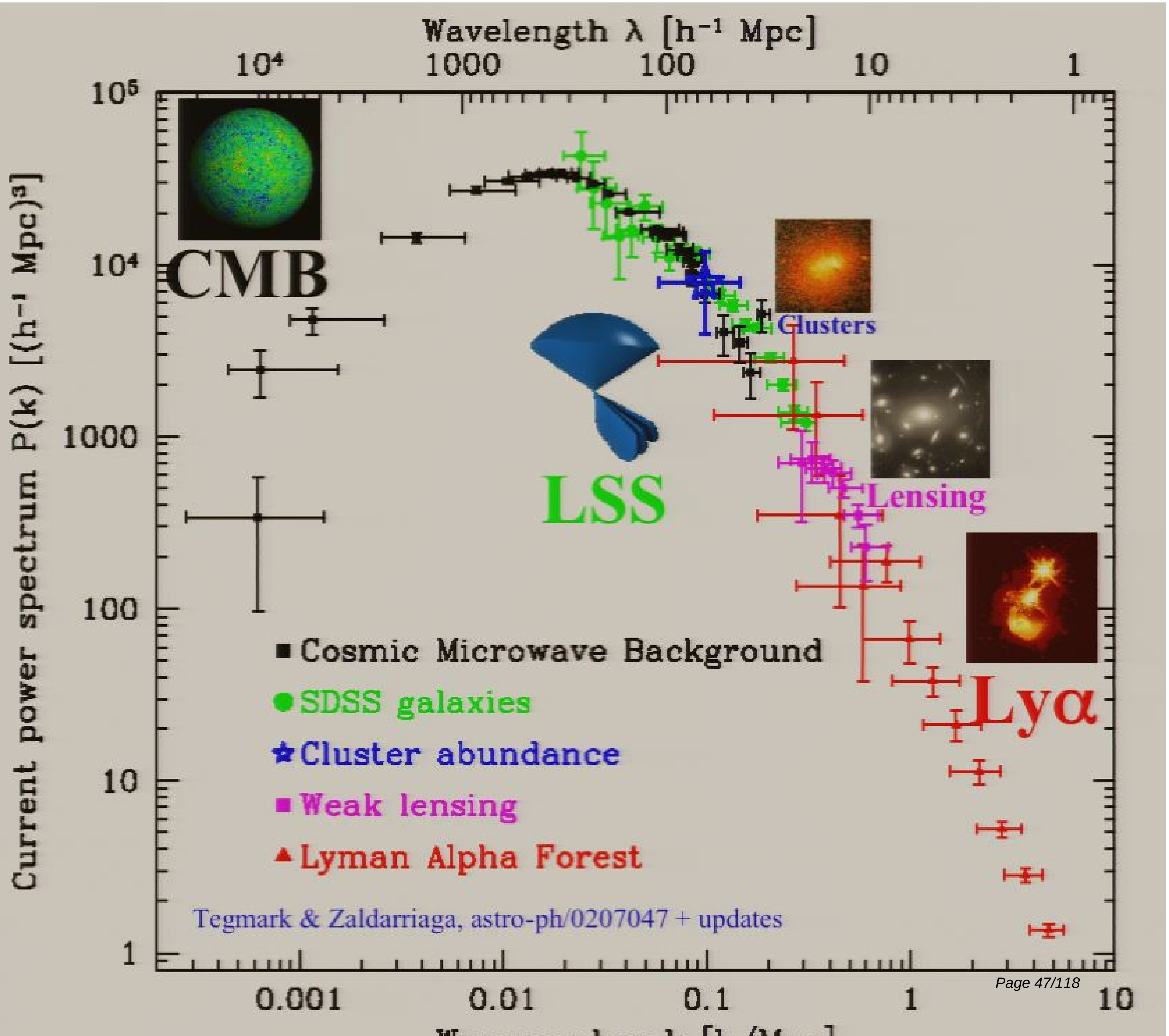
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar



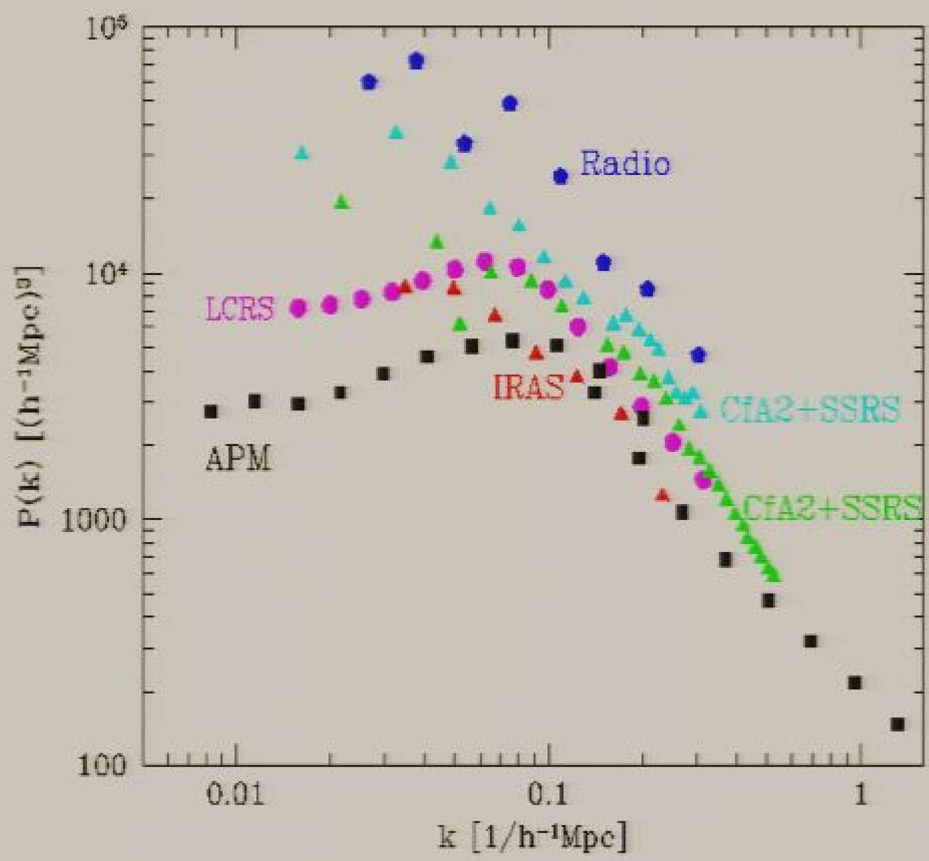
Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar
February 1, 2007



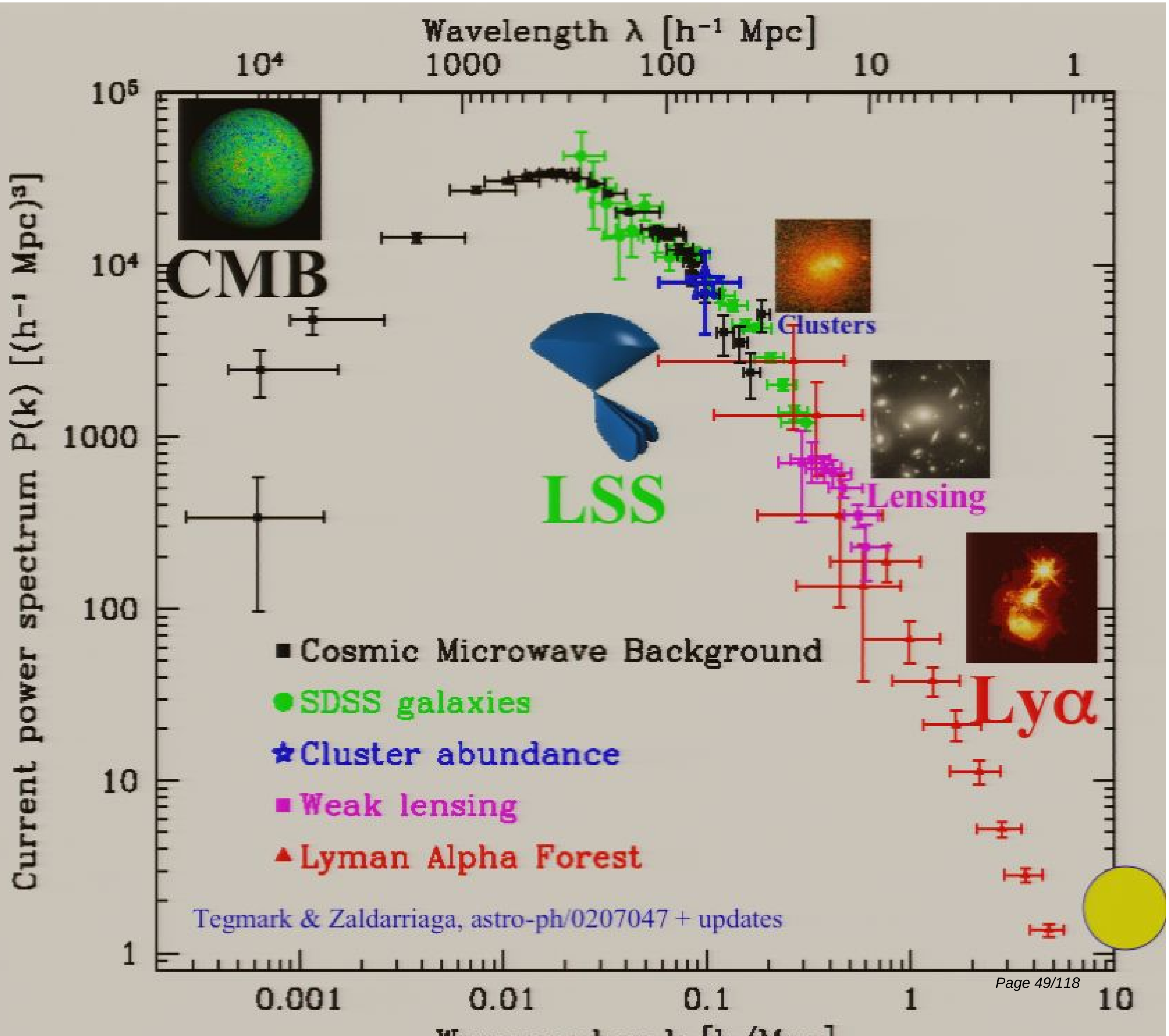


Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar



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

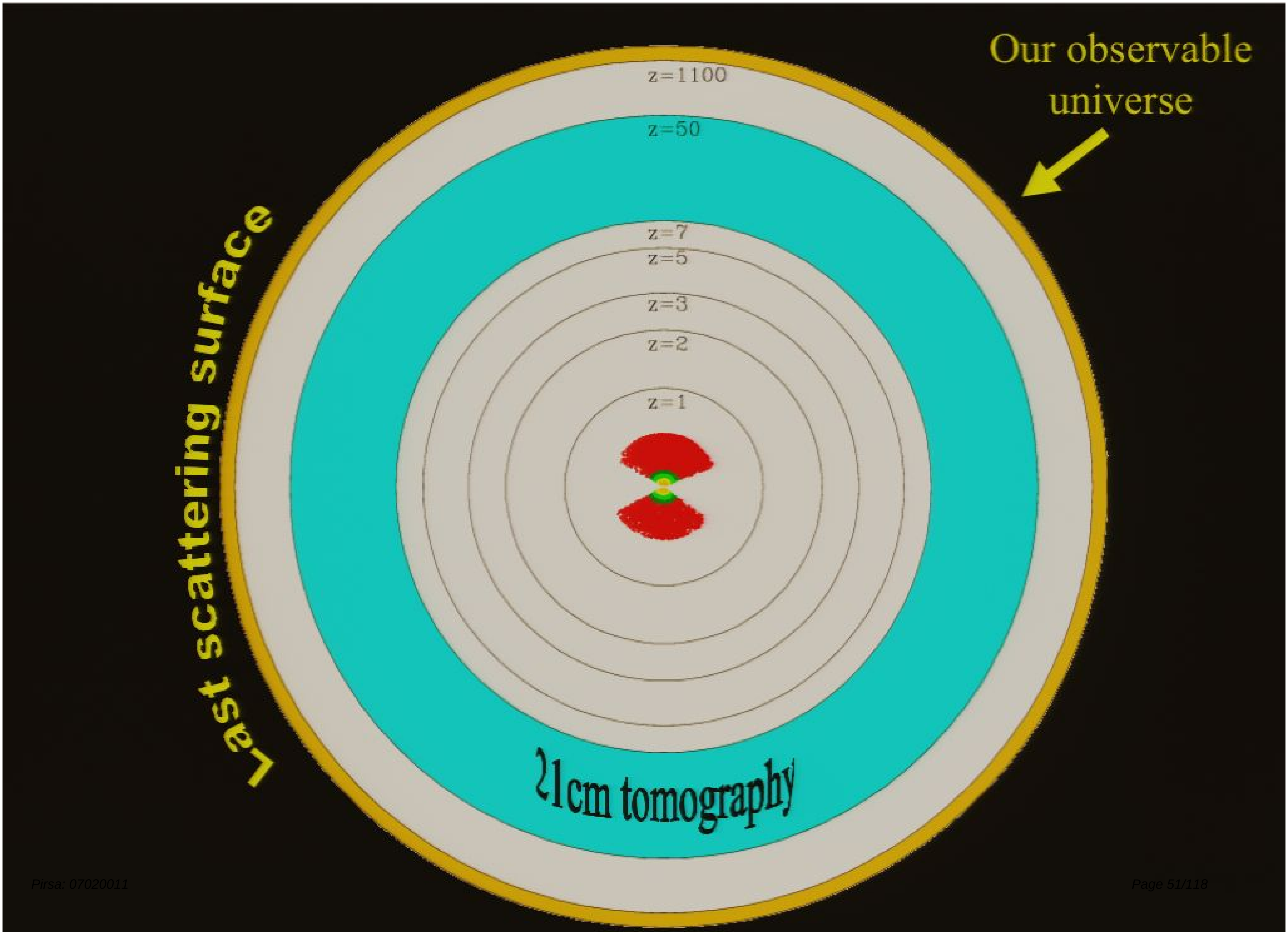
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar



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

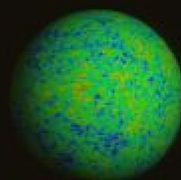
But the best is yet to come…

Precision, 21cm tomography, …


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

Summary:
WHAT DO WE REALLY KNOW?

Evidence for Big Bang:

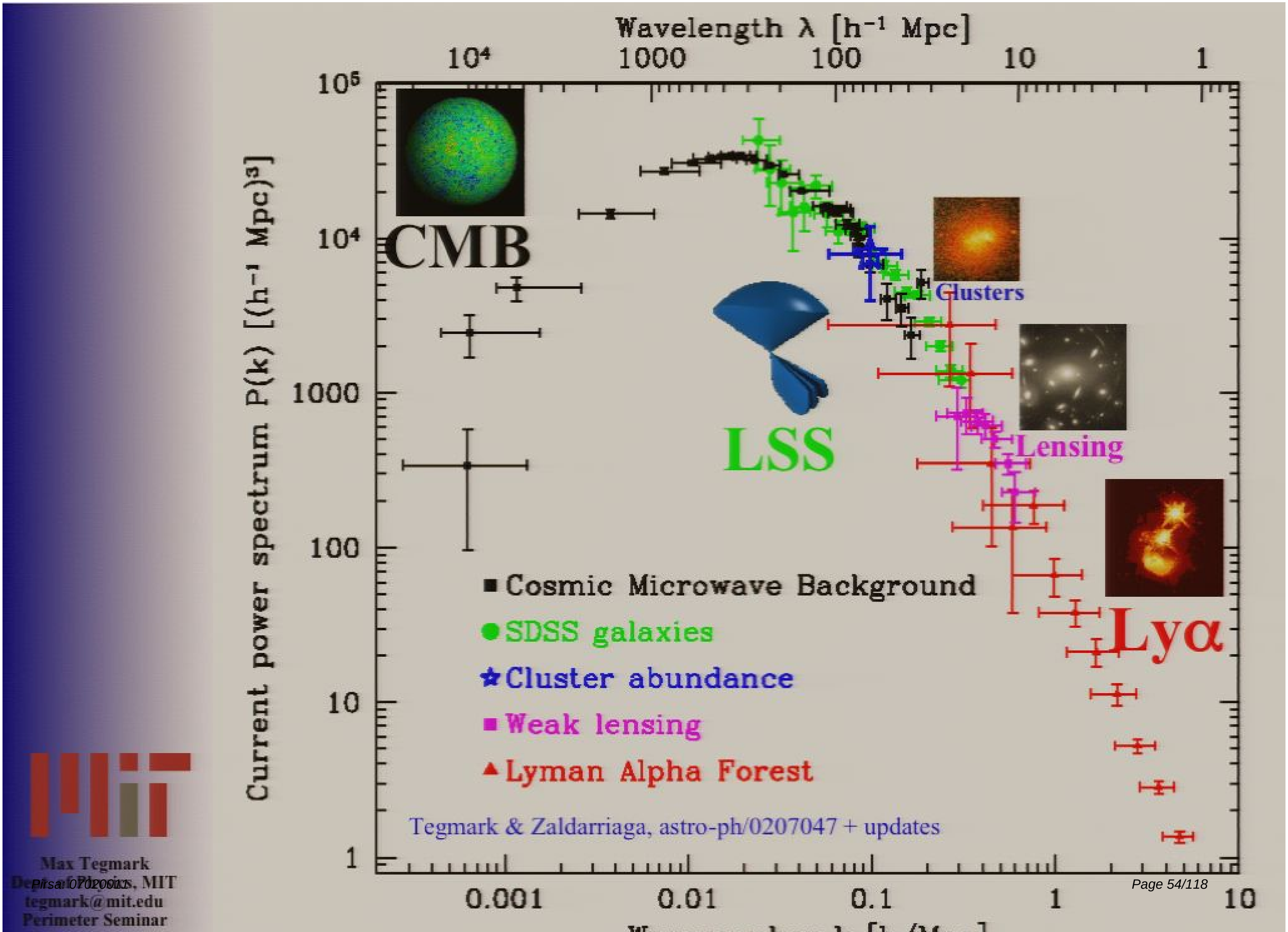
- Observed galaxy recession (Hubble's law)
- Existence of CMB 
- Correct predictions of big bang nucleosynthesis
- Darkness of night sky! (Olber)
- Distant objects look younger

Plenty enough bang for most people to call "big"…

Evidence for *what*, exactly?

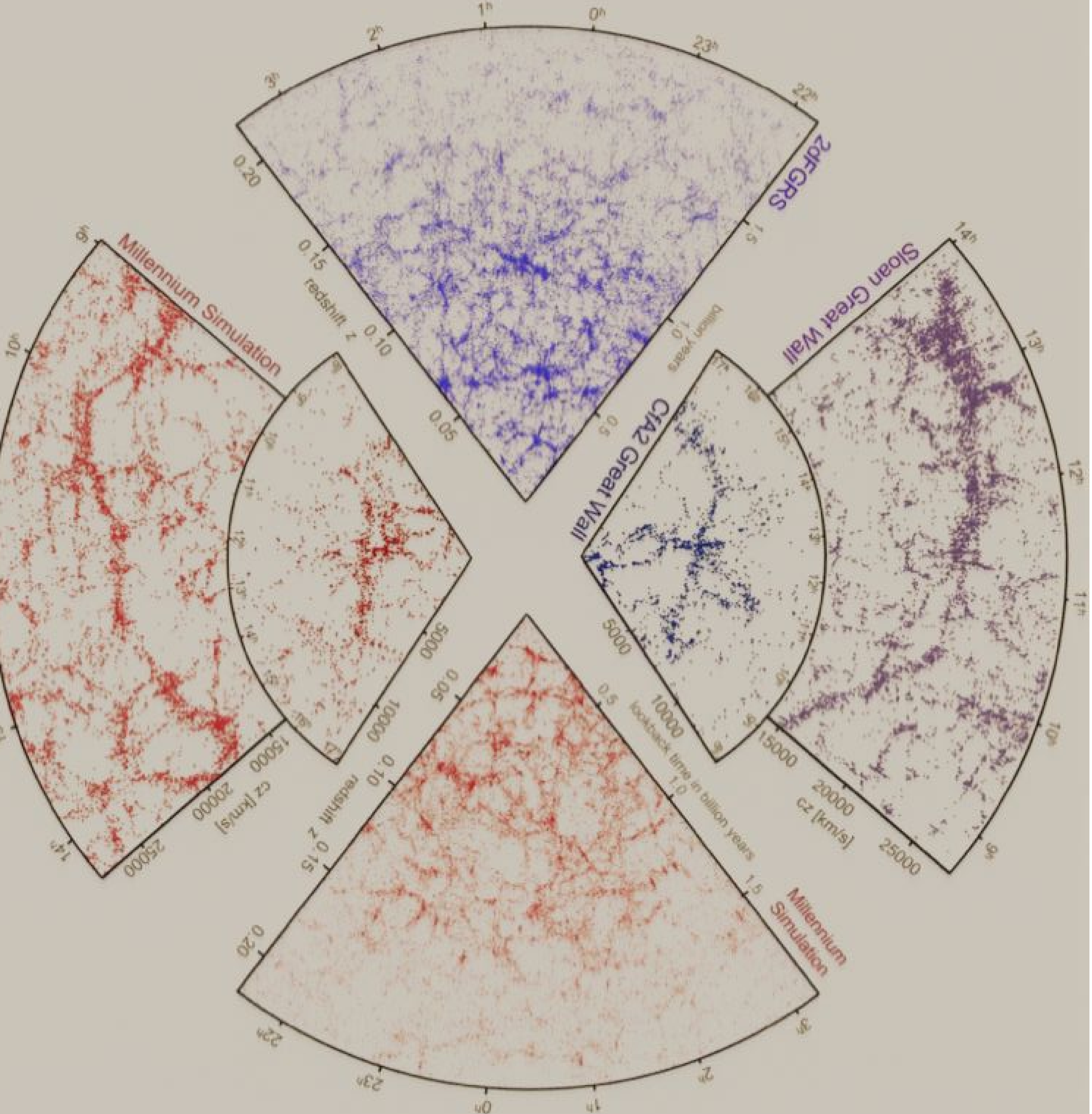
Our entire observable universe was once as hot as the core of the Sun, doubling its size in a under a second.

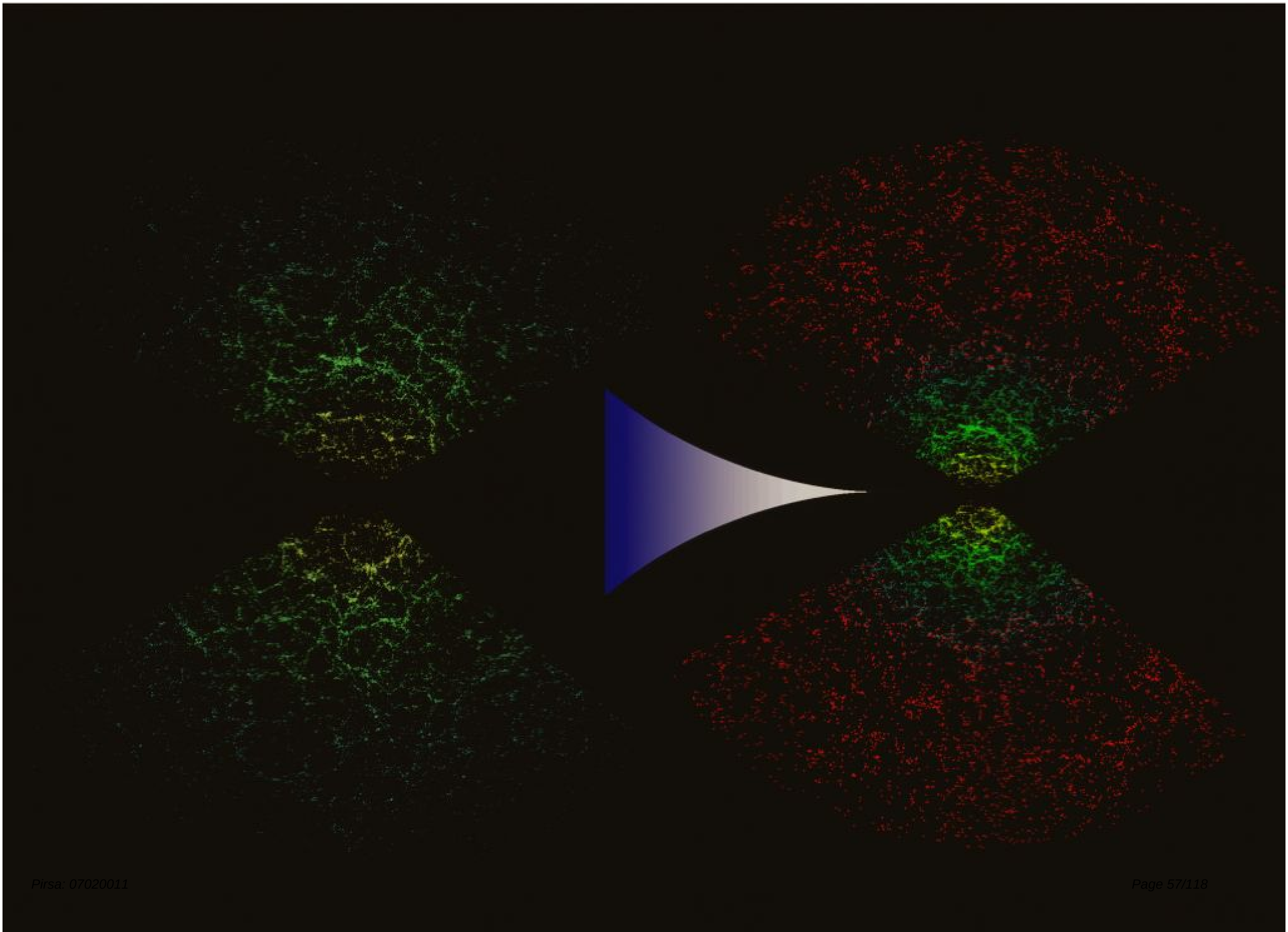
- *Not* evidence for a singularity

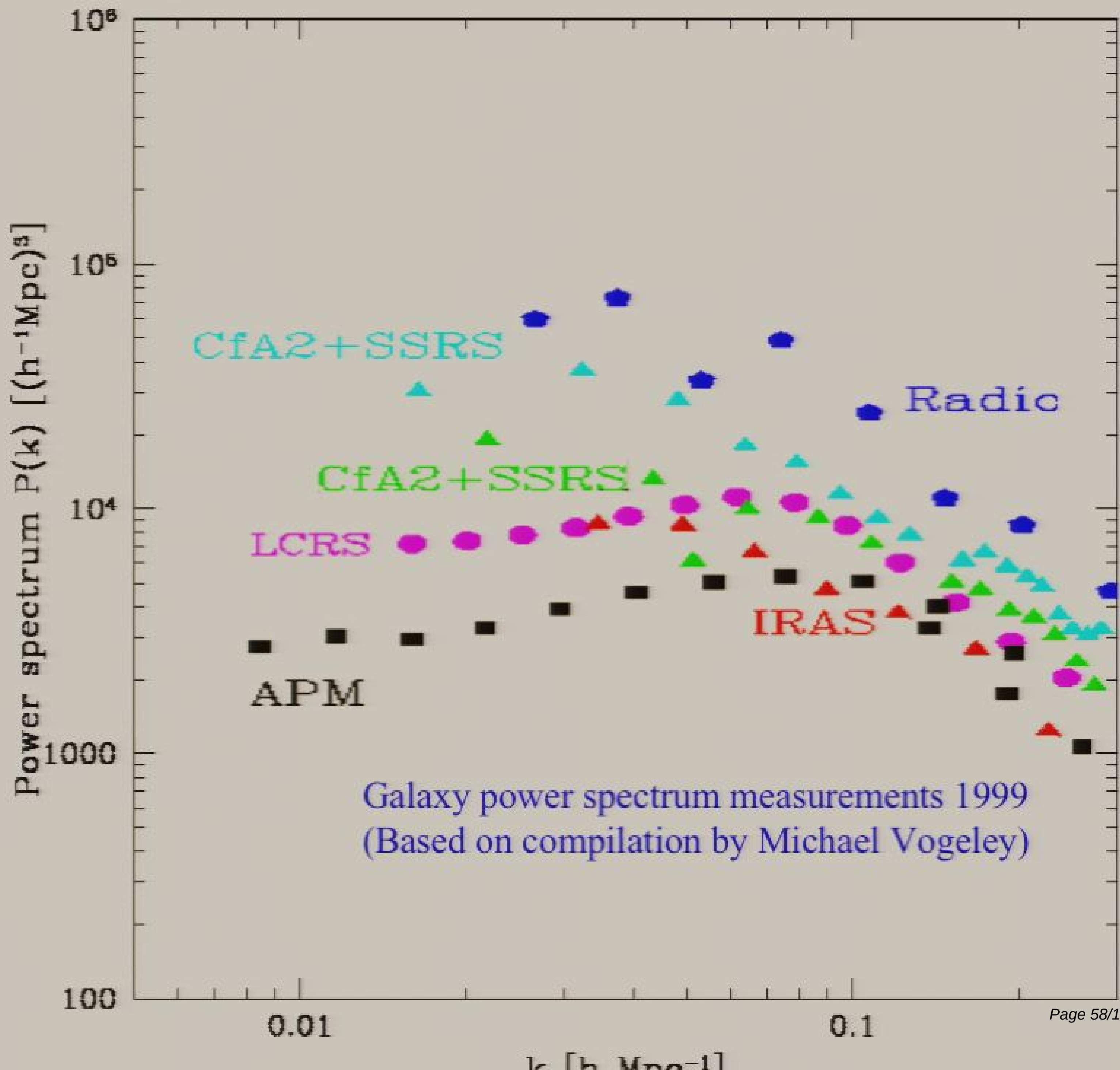

Wavelength λ [h⁻¹ Mpc]
Current power spectrum P(k) [(h⁻¹ Mpc)³]
CMB
LSS
Clusters
Lensing
Lyα
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
Tegmark & Zaldarriaga, astro-ph/0207047 + updates
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

Galaxy clustering progress

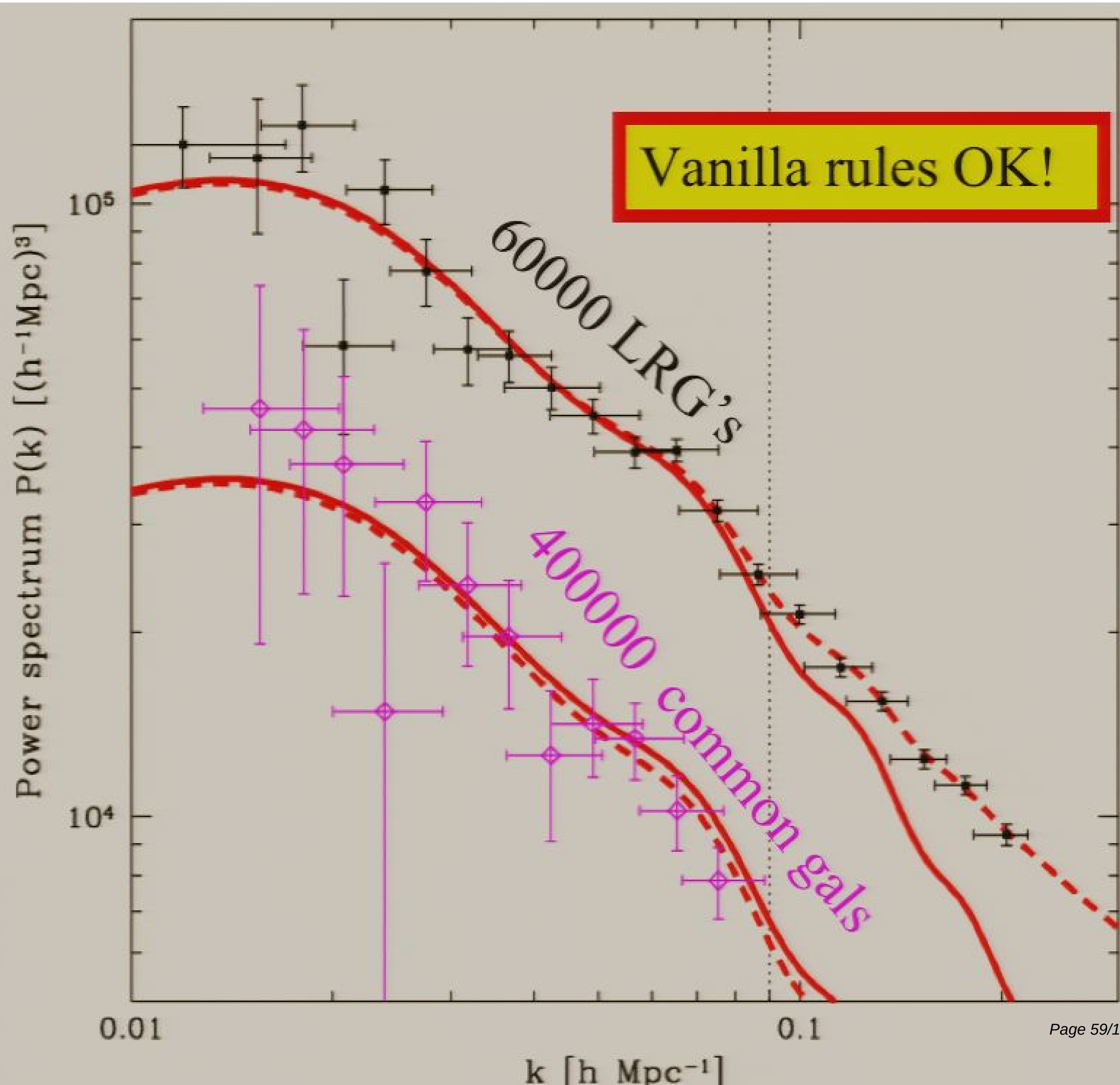
Springel, Frenk & White 2006, Nature, 440, 11







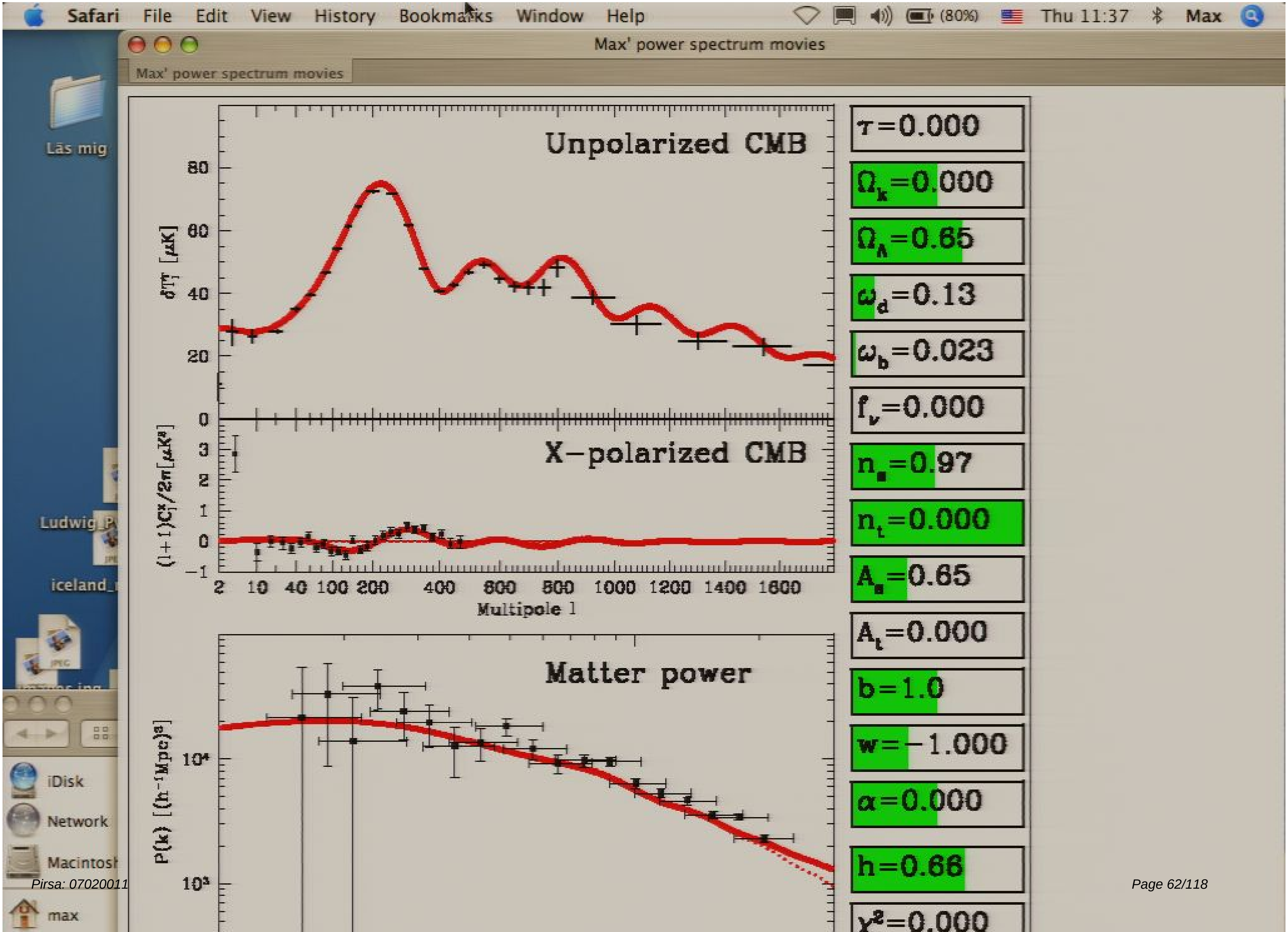
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

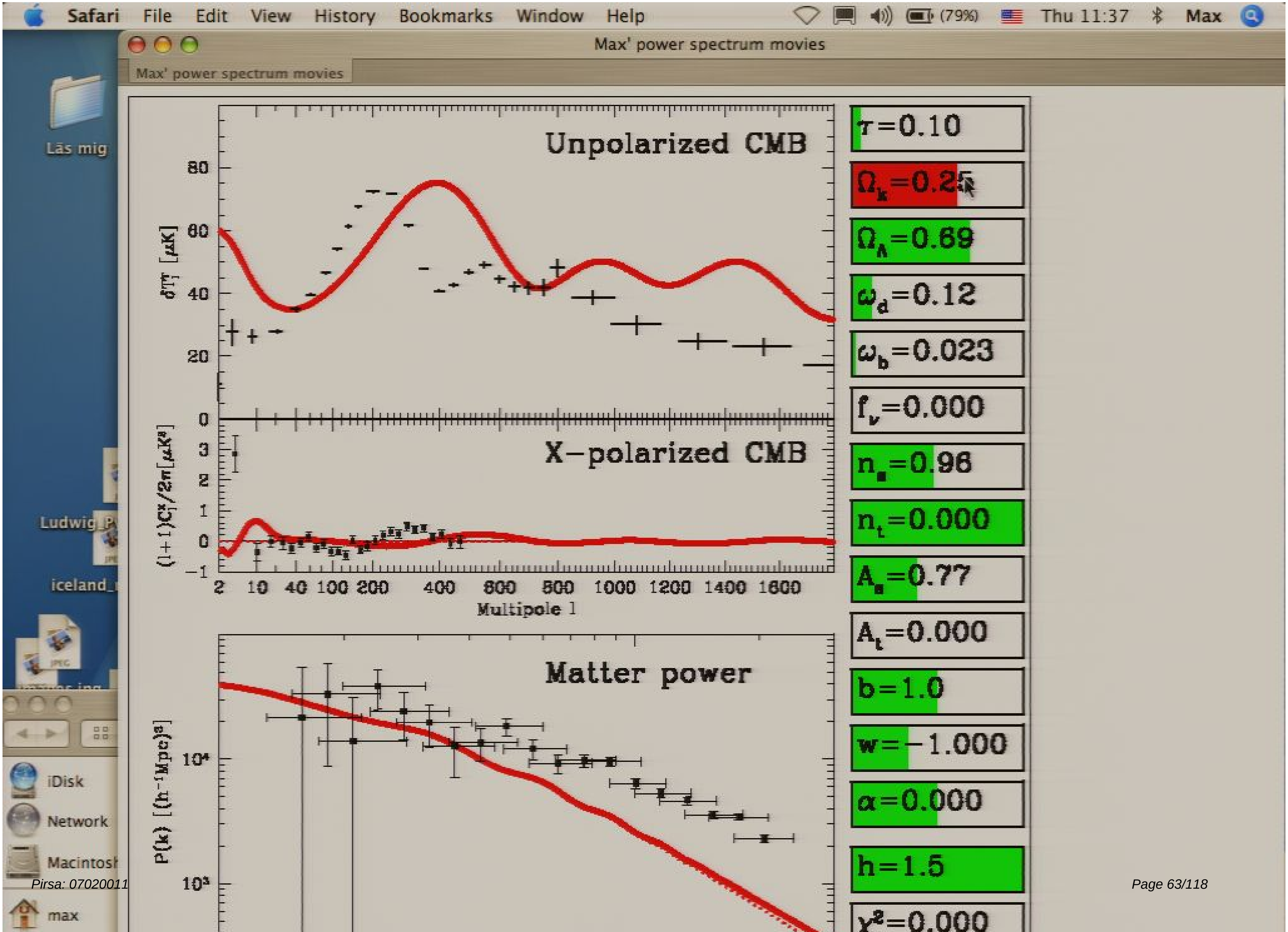


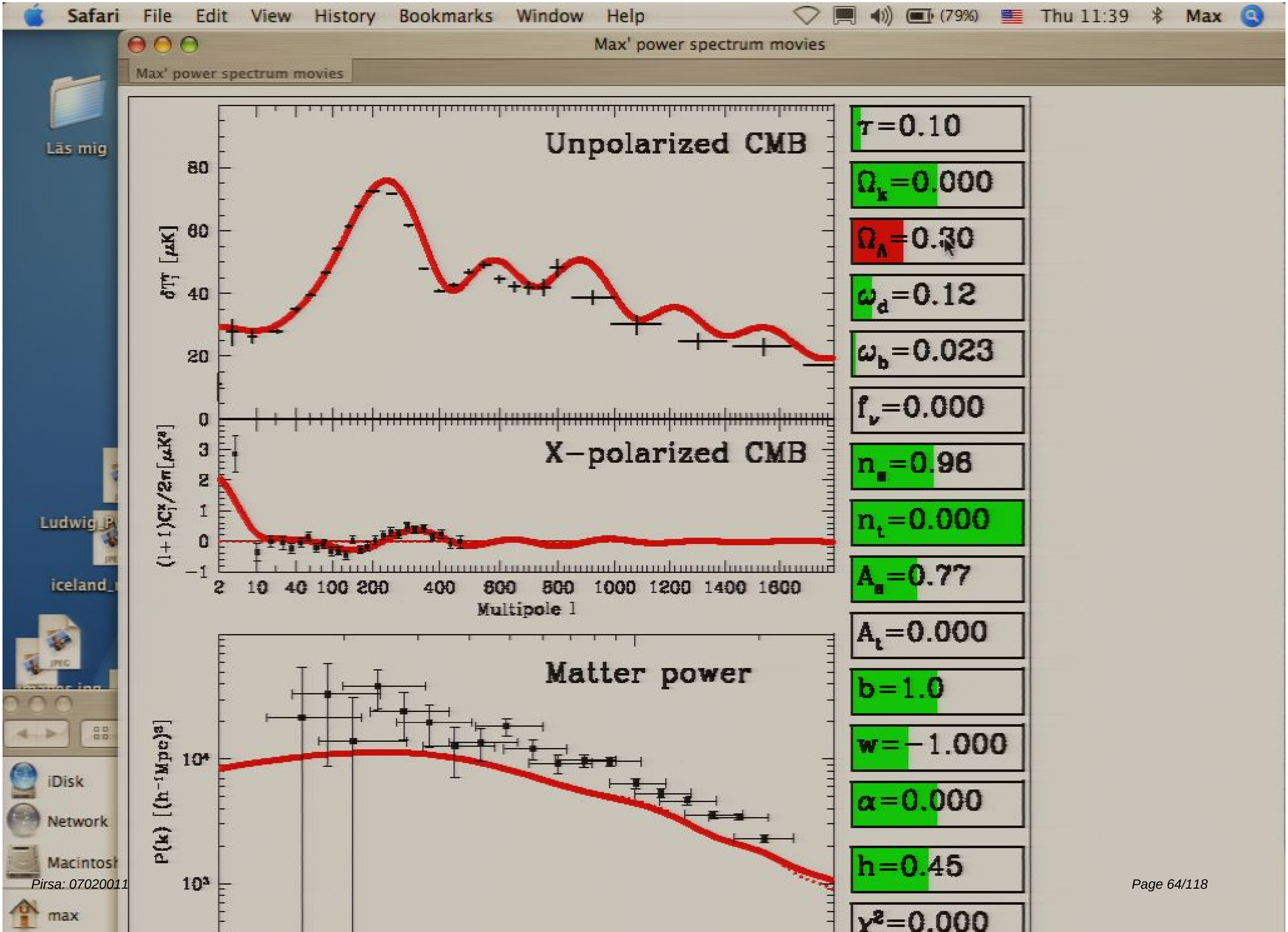
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

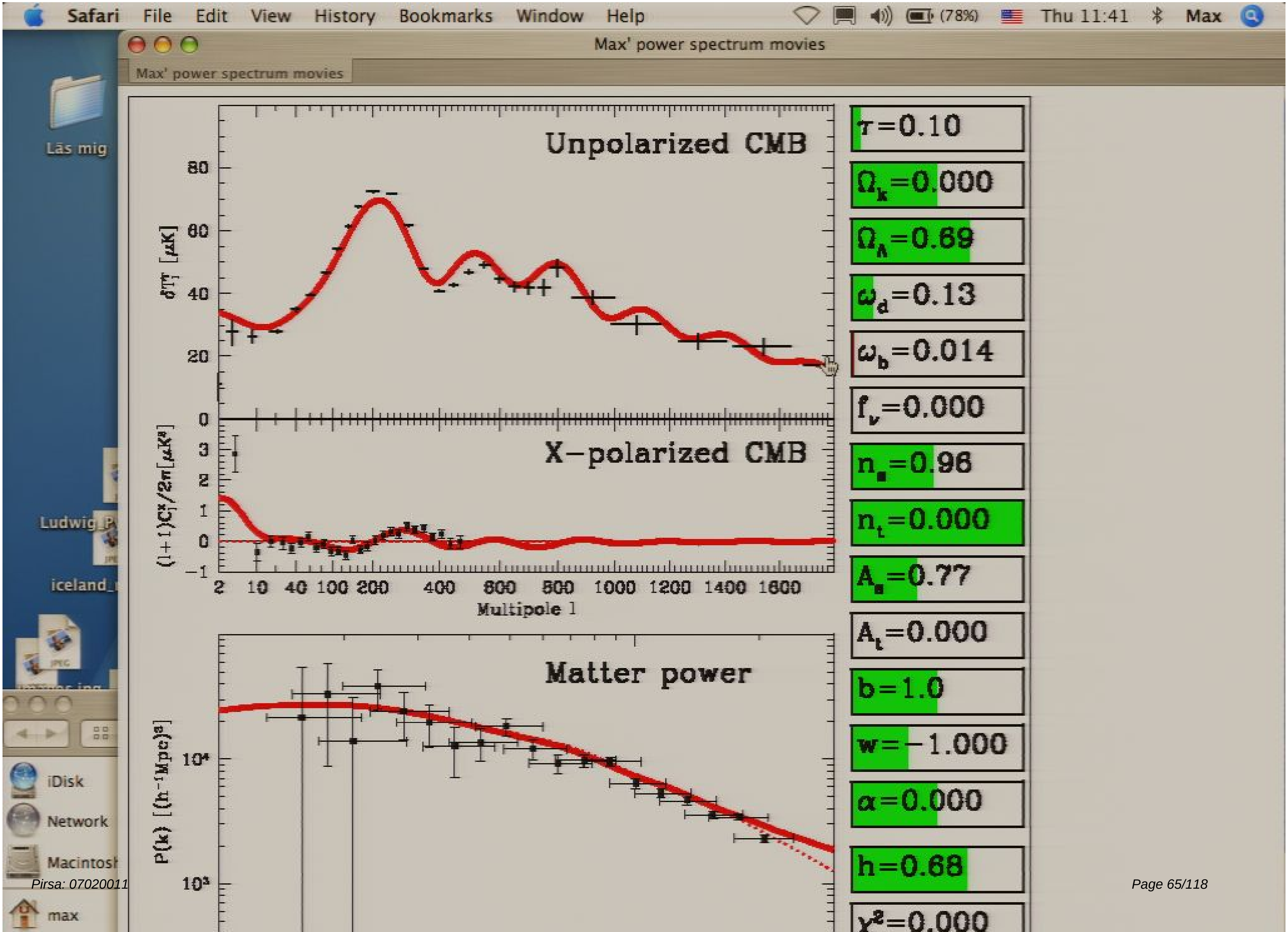
Cosmological parameters

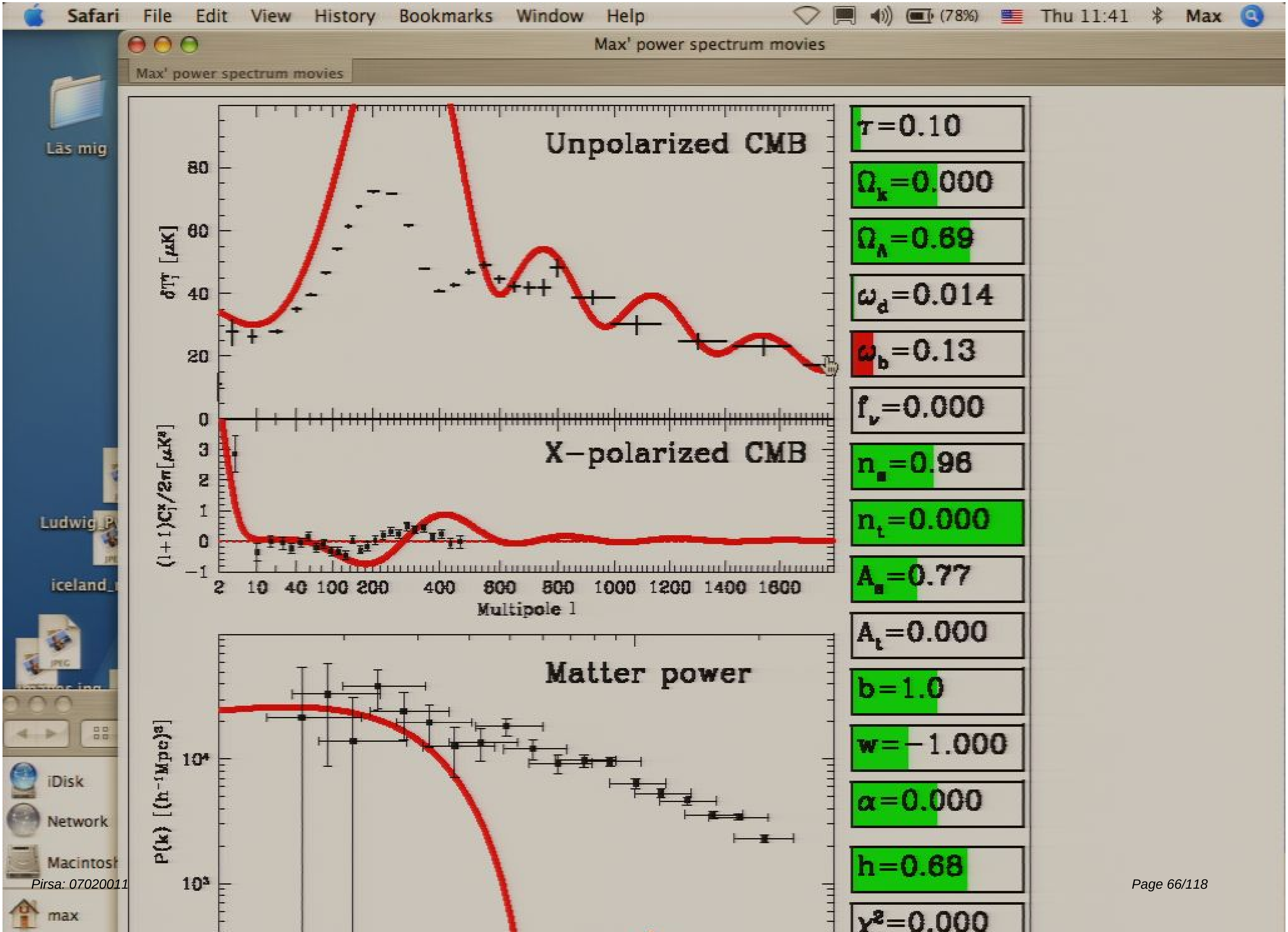
par movies

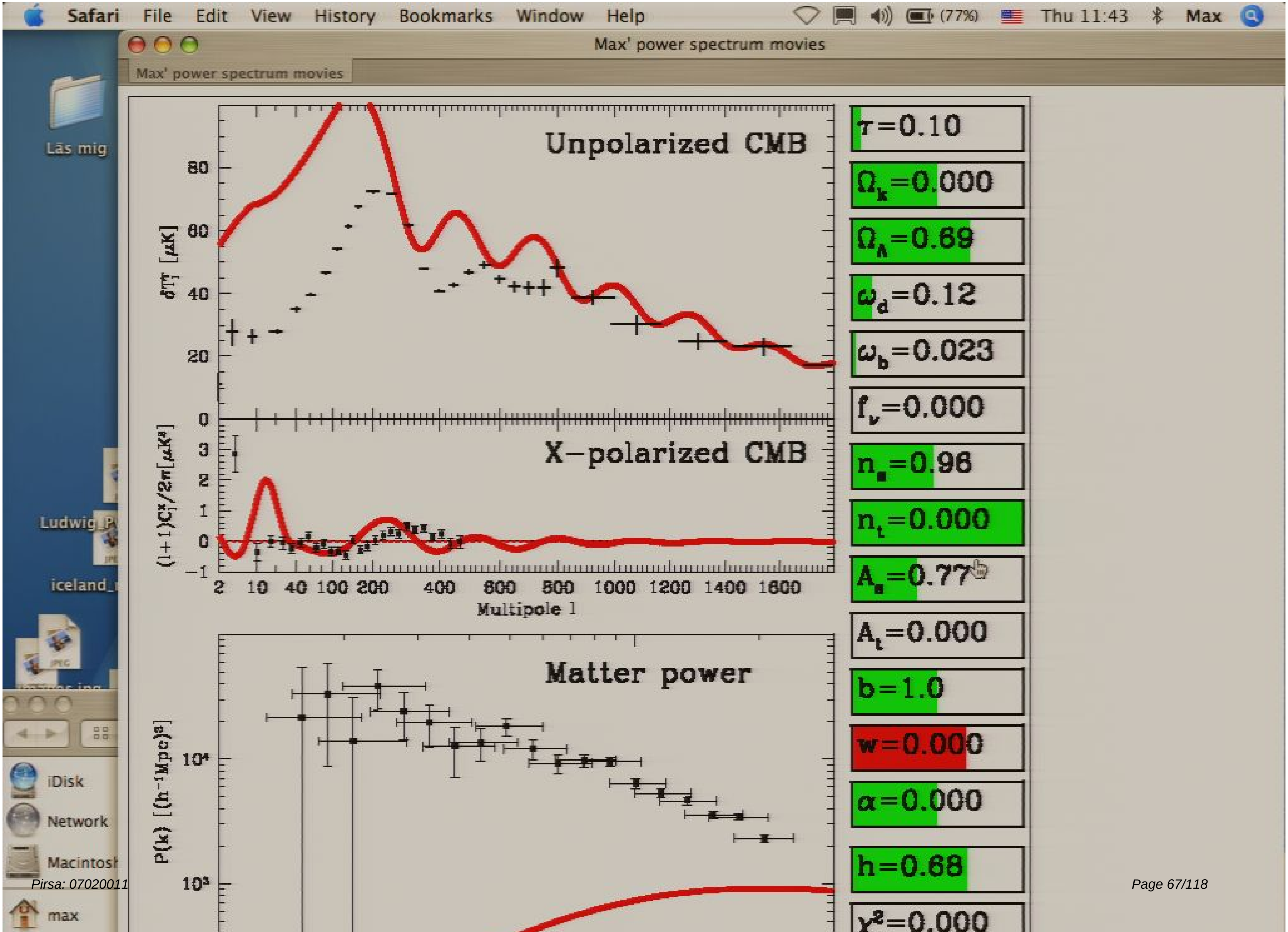

Safari File Edit View History Bookmarks Window Help
(80%) Thu 11:37 Max
Max' power spectrum movies
Unpolarized CMB
X−polarized CMB
Multipole l
Matter power
P(k) [(h⁻¹Mpc)³]
τ=0.000
Ωk=0.000
ΩΛ=0.65
ωd=0.13
ωb=0.023
fν=0.000
ns=0.97
nt=0.000
As=0.65
At=0.000
b=1.0
w=−1.000
α=0.000
h=0.66
χ²=0.000
iDisk
Network
max

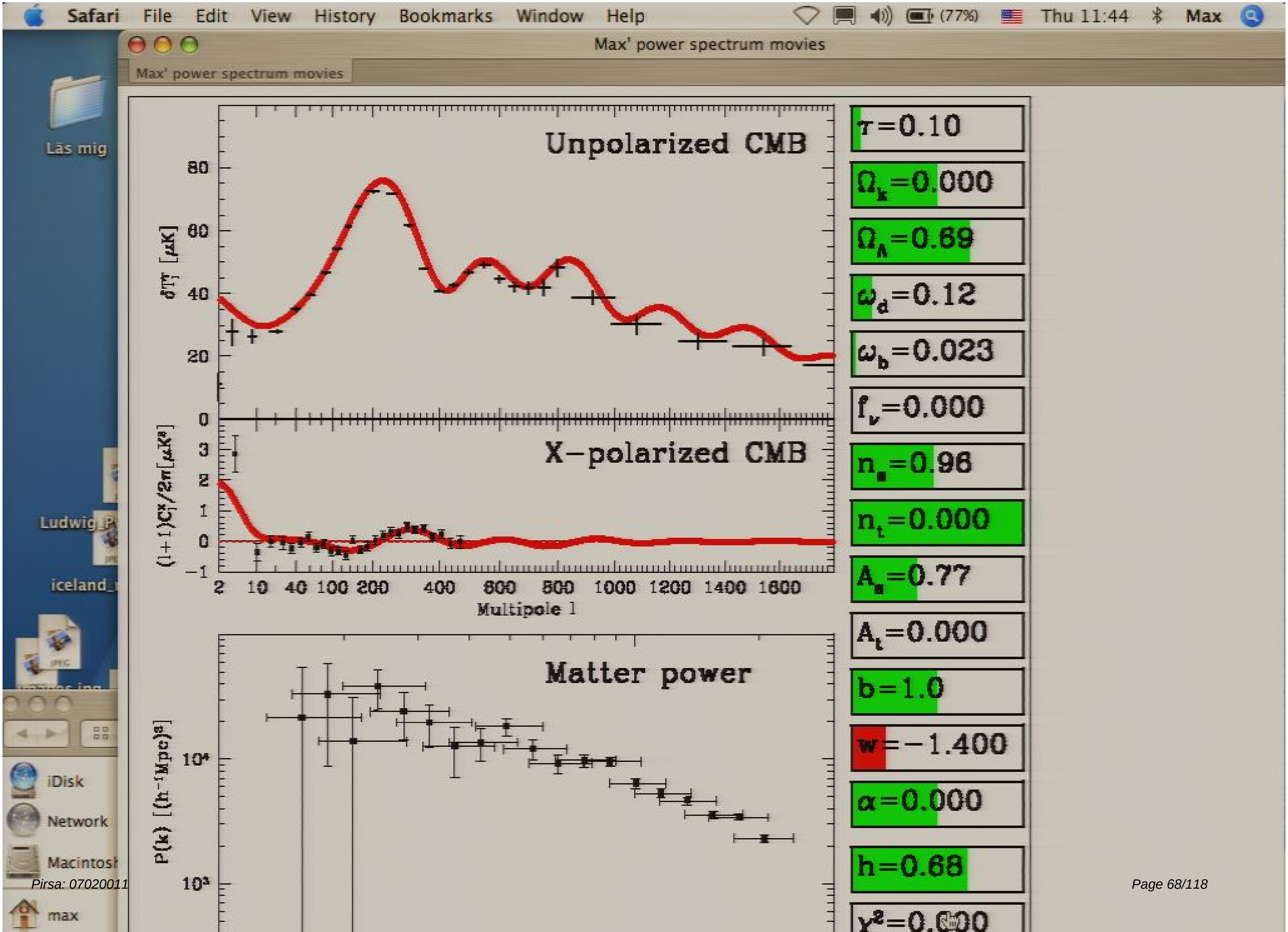

Safari File Edit View History Bookmarks Window Help
(79%) Thu 11:37 Max
Max' power spectrum movies
Max' power spectrum movies
Läs mig
iDisk
Network
max
Unpolarized CMB
X−polarized CMB
Multipole l
Matter power
τ=0.10
Ωk=0.25
ΩΛ=0.69
ωd=0.12
ωb=0.023
fν=0.000
ns=0.96
nt=0.000
As=0.77
At=0.000
b=1.0
w=−1.000
α=0.000
h=1.5
χ²=0.000

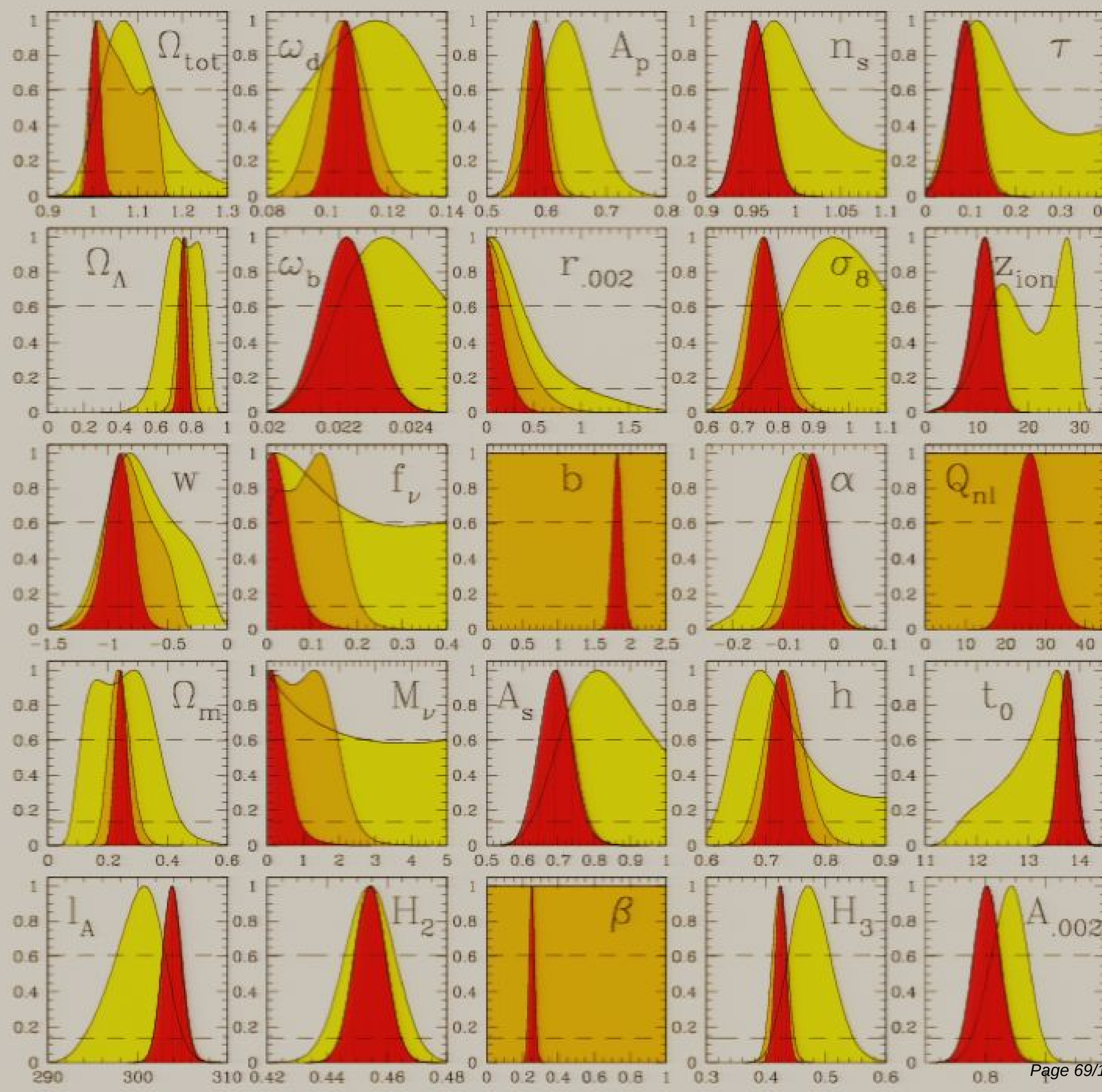

Safari File Edit View History Bookmarks Window Help
(79%)
Thu 11:39
Max
Max' power spectrum movies
Max' power spectrum movies
Läs mig
Unpolarized CMB
X−polarized CMB
Multipole l
Matter power
τ=0.10
Ωk=0.000
ΩΛ=0.30
ωd=0.12
ωb=0.023
fν=0.000
ns=0.96
nt=0.000
As=0.77
At=0.000
b=1.0
w=−1.000
α=0.000
h=0.45
χ²=0.000
iDisk
Network
max


Safari File Edit View History Bookmarks Window Help
(78%) Thu 11:41 Max
Max' power spectrum movies
Läs mig
Unpolarized CMB
X−polarized CMB
Multipole l
Matter power
P(k) [(h⁻¹Mpc)³]
τ=0.10
Ω_k=0.000
Ω_Λ=0.69
ω_d=0.13
ω_b=0.014
f_ν=0.000
n_s=0.96
n_t=0.000
A_s=0.77
A_t=0.000
b=1.0
w=−1.000
α=0.000
h=0.68
χ²=0.000
iDisk
Network
max


Safari File Edit View History Bookmarks Window Help
(78%) Thu 11:41 Max
Max' power spectrum movies
Max' power spectrum movies
Läs mig
iDisk
Network
Macintosh
max
Unpolarized CMB
X−polarized CMB
Multipole l
Matter power
τ=0.10
Ωk=0.000
ΩΛ=0.69
ωd=0.014
ωb=0.13
fν=0.000
ns=0.96
nt=0.000
As=0.77
At=0.000
b=1.0
w=−1.000
α=0.000
h=0.68
χ²=0.000

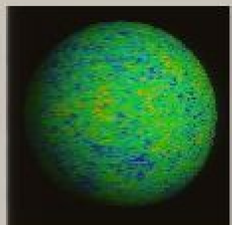

Safari File Edit View History Bookmarks Window Help
Thu 11:43
Max
Max' power spectrum movies
Max' power spectrum movies
Unpolarized CMB
X−polarized CMB
Multipole l
Matter power
τ=0.10
Ω_k=0.000
Ω_Λ=0.69
ω_d=0.12
ω_b=0.023
f_ν=0.000
n_s=0.96
n_t=0.000
A_s=0.77
A_t=0.000
b=1.0
w=0.000
α=0.000
h=0.68
χ²=0.000
iDisk
Network
max


Safari File Edit View History Bookmarks Window Help
(77%) Thu 11:44 Max
Max' power spectrum movies
Max' power spectrum movies
Läs mig
iDisk
Network
Macintosh
max
Unpolarized CMB
X−polarized CMB
Multipole l
Matter power
τ=0.10
Ω_k=0.000
Ω_Λ=0.69
ω_d=0.12
ω_b=0.023
f_ν=0.000
n_s=0.96
n_t=0.000
A_s=0.77
A_t=0.000
b=1.0
w=−1.400
α=0.000
h=0.68



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

Perimeter Seminar



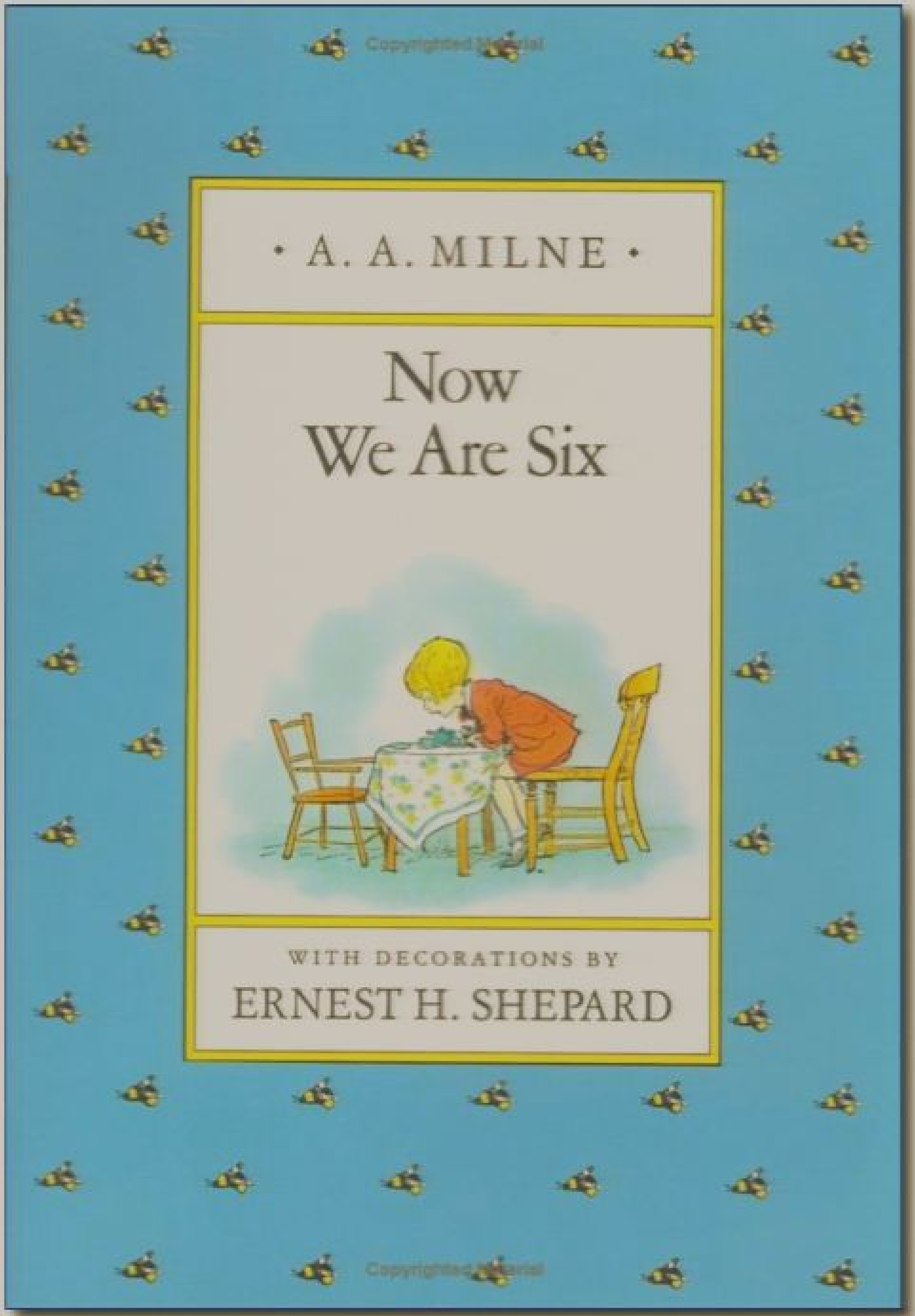
CMB

+

LSS

Parameter	Value	Meaning	Definition
Matter budget parameters:			
Ω_{tot}	[illegible]	Total density/critical density	[illegible]
Ω_Λ	[illegible]	Dark energy density parameter	[illegible]
ω_b	[illegible]	Baryon density	[illegible]
ω_c	[illegible]	Cold dark matter density	[illegible]
ω_ν	[illegible]	Massive neutrino density	[illegible]
w	[illegible]	Dark energy equation of state	[illegible]
Seed fluctuation parameters:			
A_s	[illegible]	Scalar fluctuation amplitude	[illegible]
r	[illegible]	Tensor-to-scalar ratio	[illegible]
n_s	[illegible]	Scalar spectral index	[illegible]
$n_t + 1$	[illegible]	Tensor spectral index	[illegible]
α	[illegible]	Running of spectral index	[illegible]
Nuisance parameters:			
τ	[illegible]	Reionization optical depth	
b	[illegible]	Galaxy bias factor	[illegible]
Q_{nl}	[illegible]	Nonlinear correction parameter [20]	[illegible]
Other popular parameters (determined by those above):			
h	[illegible]	Hubble parameter	[illegible]
Ω_m	[illegible]	Matter density/critical density	[illegible]
Ω_b	[illegible]	Baryon density/critical density	[illegible]
Ω_c	[illegible]	CDM density/critical density	[illegible]
Ω_ν	[illegible]	Neutrino density/critical density	[illegible]
Ω_k	[illegible]	Spatial curvature	[illegible]
ω_m	[illegible]	Matter density	[illegible]
f_ν	[illegible]	Dark matter neutrino fraction	[illegible]
A_t	[illegible]	Tensor fluctuation amplitude	[illegible]
M_ν	[illegible]	Sum of neutrino masses	[illegible]
[illegible]	[illegible]	WMAP3 normalization parameter	[illegible]
[illegible]	[illegible]	Tensor-to-scalar ratio (WMAP3)	[illegible]
σ_8	[illegible]	Density fluctuation amplitude	[illegible]
[illegible]	[illegible]	Velocity fluctuation amplitude	
Cosmic history parameters:			
z_{eq}	[illegible]	Matter-radiation Equality redshift	[illegible]
z_{rec}	[illegible]	Recombination redshift	[illegible]
z_{ion}	[illegible]	Reionization redshift (abrupt)	[illegible]
z_{acc}	[illegible]	Acceleration redshift	[illegible]
t_{eq}	[illegible]	Matter-radiation Equality time	[illegible]
t_{rec}	[illegible]	Recombination time	[illegible]
t_{ion}	[illegible]	Reionization time	[illegible]
t_{acc}	[illegible]	Acceleration time	[illegible]
t_{now}	[illegible]	Age of Universe now	[illegible]
Fundamental parameters (independent of observing epoch):			
Q	[illegible]	Primordial fluctuation amplitude	[illegible]
κ	[illegible]	Dimensionless spatial curvature [108]	[illegible]
ρ_Λ	[illegible]	Dark energy density	[illegible]
ρ_{halo}	[illegible]	Halo formation density	[illegible]
ξ	[illegible]	Matter mass per photon	[illegible]
ξ_b	[illegible]	Baryon mass per photon	[illegible]
ξ_c	[illegible]	CDM mass per photon	[illegible]
ξ_ν	[illegible]	Neutrino mass per photon	[illegible]
η	[illegible]	Baryon/photon ratio	[illegible]
A_λ	[illegible]	Expansion during matter domination	[illegible]
σ^*_{gal}	[illegible]	Seed amplitude on galaxy scale	[illegible]
CMB phenomenology parameters:			
A_{peak}	[illegible]	Amplitude on CMB peak scales	[illegible]
A_{pivot}	[illegible]	Amplitude at pivot point	[illegible]
H_1	[illegible]	1st CMB peak ratio	[illegible]
H_2	[illegible]	2nd to 1st CMB peak ratio	[illegible]
H_3	[illegible]	3rd to 1st CMB peak ratio	[illegible]
$d_A(z_{rec})$	[illegible]	Comoving angular diameter distance to CMB	[illegible]
$r_s(z_{rec})$	[illegible]	Comoving sound horizon scale	[illegible]
r_{damp}	[illegible]	Comoving acoustic damping scale	[illegible]
Θ_s	[illegible]	CMB acoustic angular scale fit (degrees)	[illegible]
ℓ_A	[illegible]	CMB acoustic angular scale	[illegible]

(Universe fact sheet handout)



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

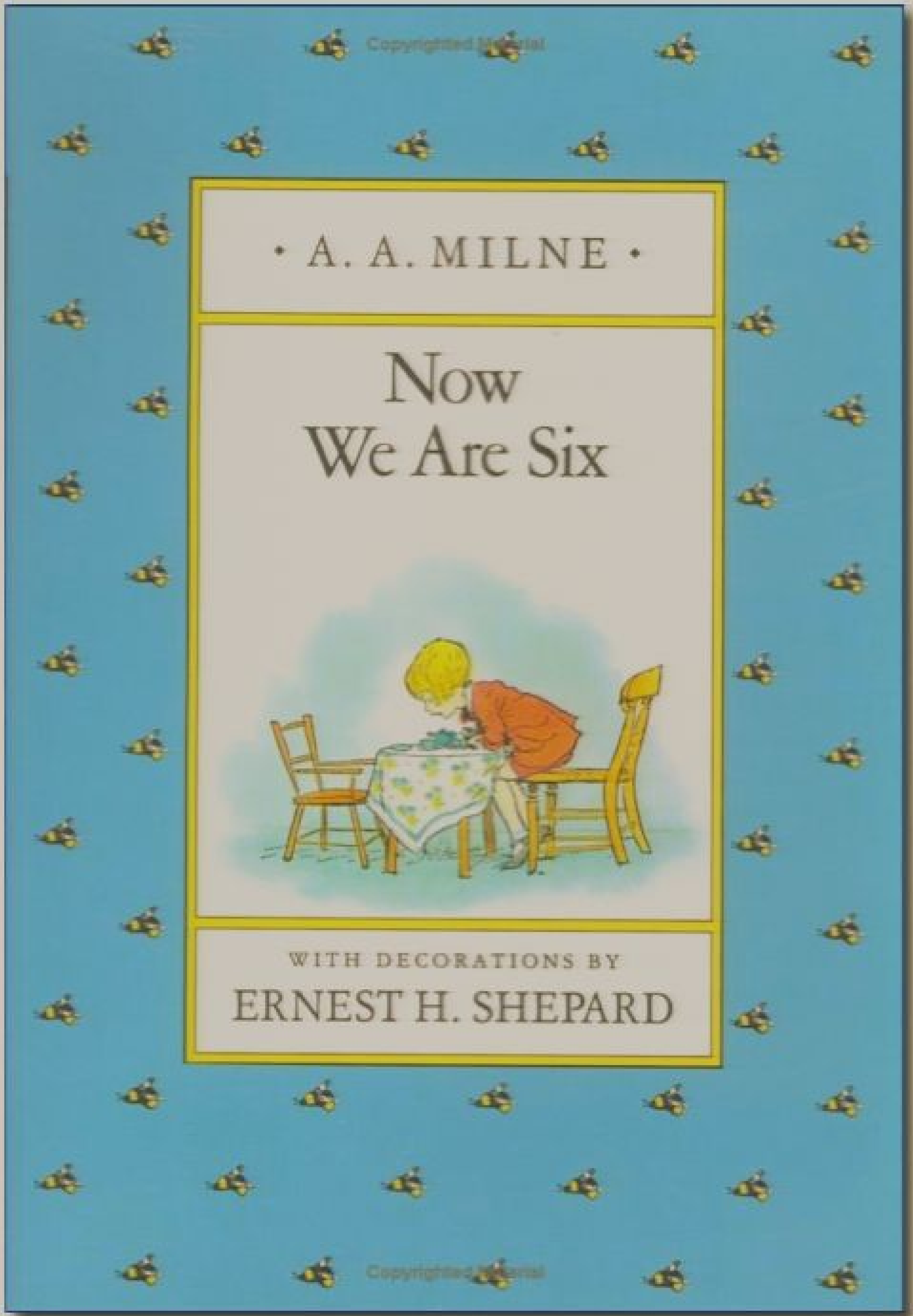
σ_8

Ω_Λ

ω_m

ω_b

τ

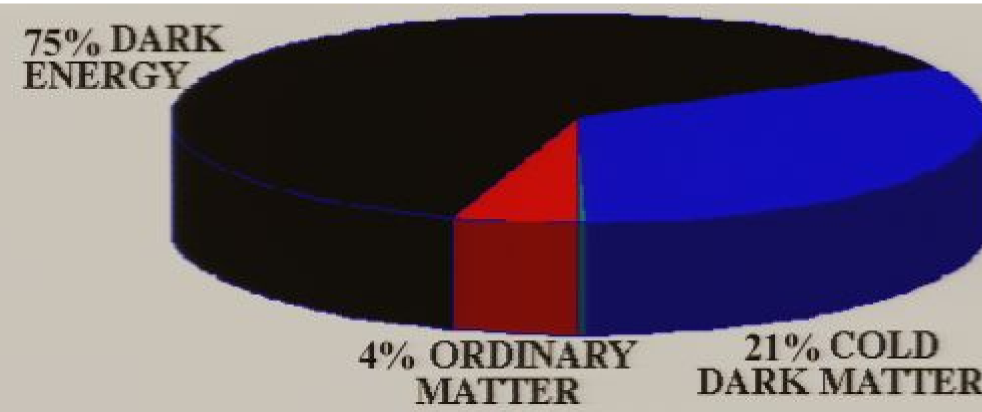


n_s

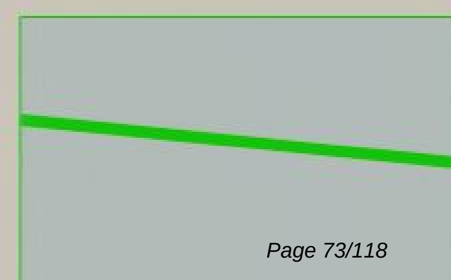
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

Using WMAP3 + SDSS LRGs:

- Ordinary Matter
- Dark Energy
- Cold Dark Matter
- Hot Dark Matter
- Photons
- Budget Deficit

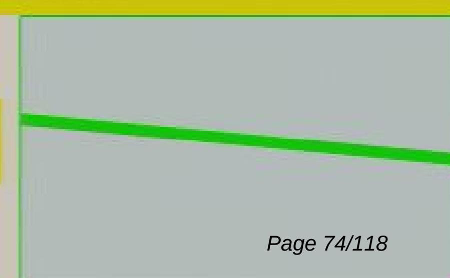


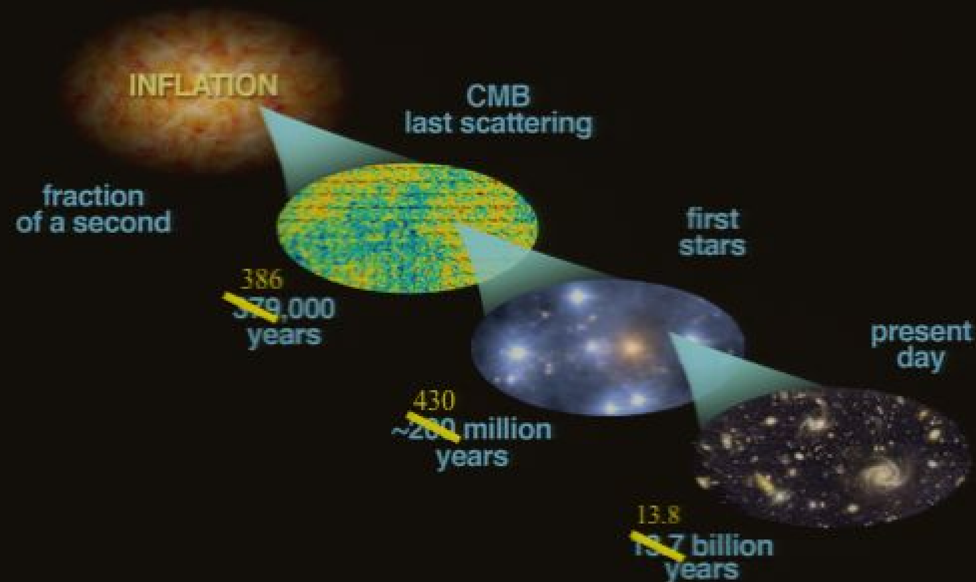
Parameter	Value	
Matter budget parameters:		
Ω_{tot}	$1.003^{+0.010}_{-0.009}$	Total density/critical density
Ω_Λ	$0.761^{+0.017}_{-0.018}$	Dark energy density parameter
ω_b	$0.0222^{+0.0007}_{-0.0007}$	Baryon density
ω_c	$0.1050^{+0.0041}_{-0.0040}$	Cold dark matter density
ω_ν	< 0.010 (95%)	Massive neutrino density
w	$-0.941^{+0.087}_{-0.101}$	Dark energy equation of state
Seed fluctuation parameters:		
A_s	$0.690^{+0.045}_{-0.044}$	Scalar fluctuation amplitude
r	< 0.30 (95%)	Tensor-to-scalar ratio
n_s	$0.953^{+0.016}_{-0.016}$	Scalar spectral index
$n_t + 1$	$0.9861^{+0.0096}_{-0.0142}$	Tensor spectral index
α	$-0.040^{+0.027}_{-0.027}$	Running of spectral index



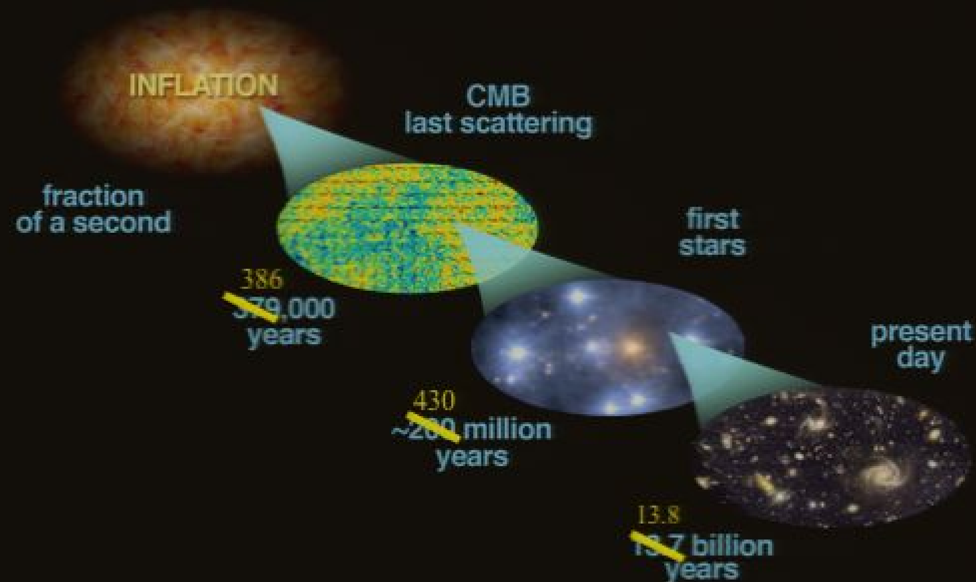
No strong evidence against "vanilla":

Parameter	Value	Meaning
Matter budget parameters:		
Ω_{tot}	1	Total density/critical density
Ω_Λ	$0.755^{+0.019}_{-0.021}$	Dark energy density parameter
ω_d	$0.1065^{+0.0045}_{-0.0044}$	Dark matter density
ω_b	$0.0222^{+0.0007}_{-0.0007}$	Baryon density
ω_ν	0	Massive neutrino density
w	–1	Dark energy equation of state
Seed fluctuation parameters:		
A_s	$0.693^{+0.045}_{-0.045}$	Scalar fluctuation amplitude
r	0	Tensor-to-scalar ratio
n_s	$0.953^{+0.016}_{-0.016}$	Scalar spectral index
n_t+1		Tensor spectral index
α	0	Running of spectral index





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



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

Other popular parameters (determined by those above):		
h	$0.730^{+0.019}_{-0.019}$	Hubble parameter
Ω_m	$0.239^{+0.018}_{-0.017}$	Matter density/critical density
Ω_b	$0.0416^{+0.0019}_{-0.0018}$	Baryon density/critical density
Ω_c	$0.197^{+0.016}_{-0.015}$	CDM density/critical density
Ω_ν	$< 0.024\,(95\%)$	Neutrino density/critical density
Ω_k	$-0.0030^{+0.0095}_{-0.0102}$	Spatial curvature
ω_m	$0.1272^{+0.0044}_{-0.0043}$	Matter density
f_ν	$< 0.090\,(95\%)$	Dark matter neutrino fraction
A_t	$< 0.21\,(95\%)$	Tensor fluctuation amplitude
M_ν	$< 0.94\,(95\%)$ eV	Sum of neutrino masses
$A_{.002}$	$0.801^{+0.042}_{-0.043}$	WMAP3 normalization parameter
$r_{.002}$	$< 0.33\,(95\%)$	Tensor-to-scalar ratio (WMAP3)
σ_8	$0.756^{+0.035}_{-0.035}$	Density fluctuation amplitude
$\sigma_8\Omega_m^{0.6}$	$0.320^{+0.024}_{-0.023}$	Velocity fluctuation amplitude

Fundamental parameters (independent of observing epoch):		
Q	$1.945^{+0.051}_{-0.053} \times 10^{-5}$	Primordial fluctuation amplitude
κ	$1.3^{+3.7}_{-4.3} \times 10^{-61}$	Dimensionless spatial curvature [110]
ρ_Λ	$1.48^{+0.11}_{-0.11} \times 10^{-123} \rho_{\rm Pl}$	Dark energy density
$\rho_{\rm halo}$	$6.6^{+1.2}_{-1.0} \times 10^{-123} \rho_{\rm Pl}$	Halo formation density
ξ	$3.26^{+0.11}_{-0.11}$ eV	Matter mass per photon
ξ_b	$0.569^{+0.018}_{-0.018}$ eV	Baryon mass per photon
ξ_c	$2.69^{+0.11}_{-0.10}$ eV	CDM mass per photon
ξ_ν	< 0.26 (95%) eV	Neutrino mass per photon
η	$6.06^{+0.20}_{-0.19} \times 10^{-10}$	Baryon/photon ratio
A_Λ	2077^{+135}_{-125}	Expansion during matter domination
$\sigma^*_{\rm gal}$	$0.561^{+0.024}_{-0.023} \times 10^{-3}$	Seed amplitude on galaxy scale

Other popular parameters (determined by those above):		
h	$0.730^{+0.019}_{-0.019}$	Hubble parameter
Ω_m	$0.239^{+0.018}_{-0.017}$	Matter density/critical density
Ω_b	$0.0416^{+0.0019}_{-0.0018}$	Baryon density/critical density
Ω_c	$0.197^{+0.016}_{-0.015}$	CDM density/critical density
Ω_ν	< 0.024 (95%)	Neutrino density/critical density
Ω_k	$-0.0030^{+0.0095}_{-0.0102}$	Spatial curvature
ω_m	$0.1272^{+0.0044}_{-0.0043}$	Matter density
f_ν	< 0.090 (95%)	Dark matter neutrino fraction
A_t	< 0.21 (95%)	Tensor fluctuation amplitude
M_ν	< 0.94 (95%) eV	Sum of neutrino masses
$A_{.002}$	$0.801^{+0.042}_{-0.043}$	WMAP3 normalization parameter
$r_{.002}$	< 0.33 (95%)	Tensor-to-scalar ratio (WMAP3)
σ_8	$0.756^{+0.035}_{-0.035}$	Density fluctuation amplitude
$\sigma_8\Omega_m^{0.6}$	$0.320^{+0.024}_{-0.023}$	Velocity fluctuation amplitude

Fundamental parameters (independent of observing epoch):		
Q	$1.945^{+0.051}_{-0.053} \times 10^{-5}$	Primordial fluctuation amplitude
κ	$1.3^{+3.7}_{-4.3} \times 10^{-61}$	Dimensionless spatial curvature [110]
ρ_Λ	$1.48^{+0.11}_{-0.11} \times 10^{-123} \rho_{\rm Pl}$	Dark energy density
$\rho_{\rm halo}$	$6.6^{+1.2}_{-1.0} \times 10^{-123} \rho_{\rm Pl}$	Halo formation density
ξ	$3.26^{+0.11}_{-0.11}$ eV	Matter mass per photon
ξ_b	$0.569^{+0.018}_{-0.018}$ eV	Baryon mass per photon
ξ_c	$2.69^{+0.11}_{-0.10}$ eV	CDM mass per photon
ξ_ν	< 0.26 (95%) eV	Neutrino mass per photon
η	$6.06^{+0.20}_{-0.19} \times 10^{-10}$	Baryon/photon ratio
A_Λ	2077^{+135}_{-125}	Expansion during matter domination
$\sigma^*_{\rm gal}$	$0.561^{+0.024}_{-0.023} \times 10^{-3}$	Seed amplitude on galaxy scale

Standard model parameters:

Particle physics

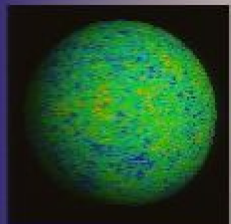
Cosmology

Required

Optional

Parameter	Meaning	Measured value
g	Weak coupling constant at M_Z	0.6425
θ_W	Weinberg angle	0.4908
g_s	Strong coupling constant	≈ 1.2
μ^2	Quadratic Higgs coefficient	$\sim -10^{-33}$
λ	Quartic Higgs coefficient	~ 17
G_e	Electron Yukawa coupling	2.94×10^{-6}
G_μ	Muon Yukawa coupling	0.000607
G_τ	Tauon Yukawa coupling	0.0102156233
G_u	Up quark Yukawa coupling	0.000016 ± 0.000007
G_d	Down quark Yukawa coupling	0.00003 ± 0.00002
G_c	Charm quark Yukawa coupling	0.0072 ± 0.0006
G_s	Strange quark Yukawa coupling	0.0006 ± 0.0002
G_t	Top quark Yukawa coupling	1.002 ± 0.029
G_b	Bottom quark Yukawa coupling	0.026 ± 0.003
$\sin\theta_{12}$	Quark CKM matrix angle	0.2243 ± 0.0016
$\sin\theta_{23}$	Quark CKM matrix angle	0.0413 ± 0.0015
$\sin\theta_{13}$	Quark CKM matrix angle	0.0037 ± 0.0005
δ_{13}	Quark CKM matrix phase	1.05 ± 0.24
$\theta_{\rm qcd}$	CP-violating QCD vacuum phase	$< 10^{-9}$
G_{ν_e}	Electron neutrino Yukawa coupling	$< 1.7 \times 10^{-11}$
G_{ν_μ}	Muon neutrino Yukawa coupling	$< 1.1 \times 10^{-6}$
G_{ν_τ}	Tau neutrino Yukawa coupling	< 0.10
...	Neutrino mixing parameters	
ρ_Λ	Dark energy density	$(9.3 \pm 2.5) \times 10^{-124}$
ξ_b	Baryon mass per photon ρ_b/n_γ	$(0.49 \pm 0.03) \times 10^{-28}$
ξ_c	Cold dark matter mass per photon ρ_c/n_γ	$(2.7 \pm 0.2) \times 10^{-28}$
ξ_ν	Neutrino mass per photon $\rho_\nu/n_\gamma = \frac{3}{11}\sum m_{\nu_i}$	$< 0.9 \times 10^{-28}$
Q	Scalar fluctuation amplitude δ_H on horizon	$(2.0 \pm 0.2) \times 10^{-5}$
n_s	Scalar spectral index	0.98 ± 0.02
α_n	Running of spectral index $dn_s/d\ln k$	$\lvert\alpha\rvert \lesssim 0.01$
r	Tensor-to-scalar ratio $(Q_t/Q)^2$	$\lesssim 0.36$
n_t	Tensor spectral index	Unconstrained
$\Omega_{\rm tot}$	Spatial curvature	1.01 ± 0.02
w	Dark energy equation of state	-1 ± 0.1

$C = \hbar = G = k_b = q_e = 1$

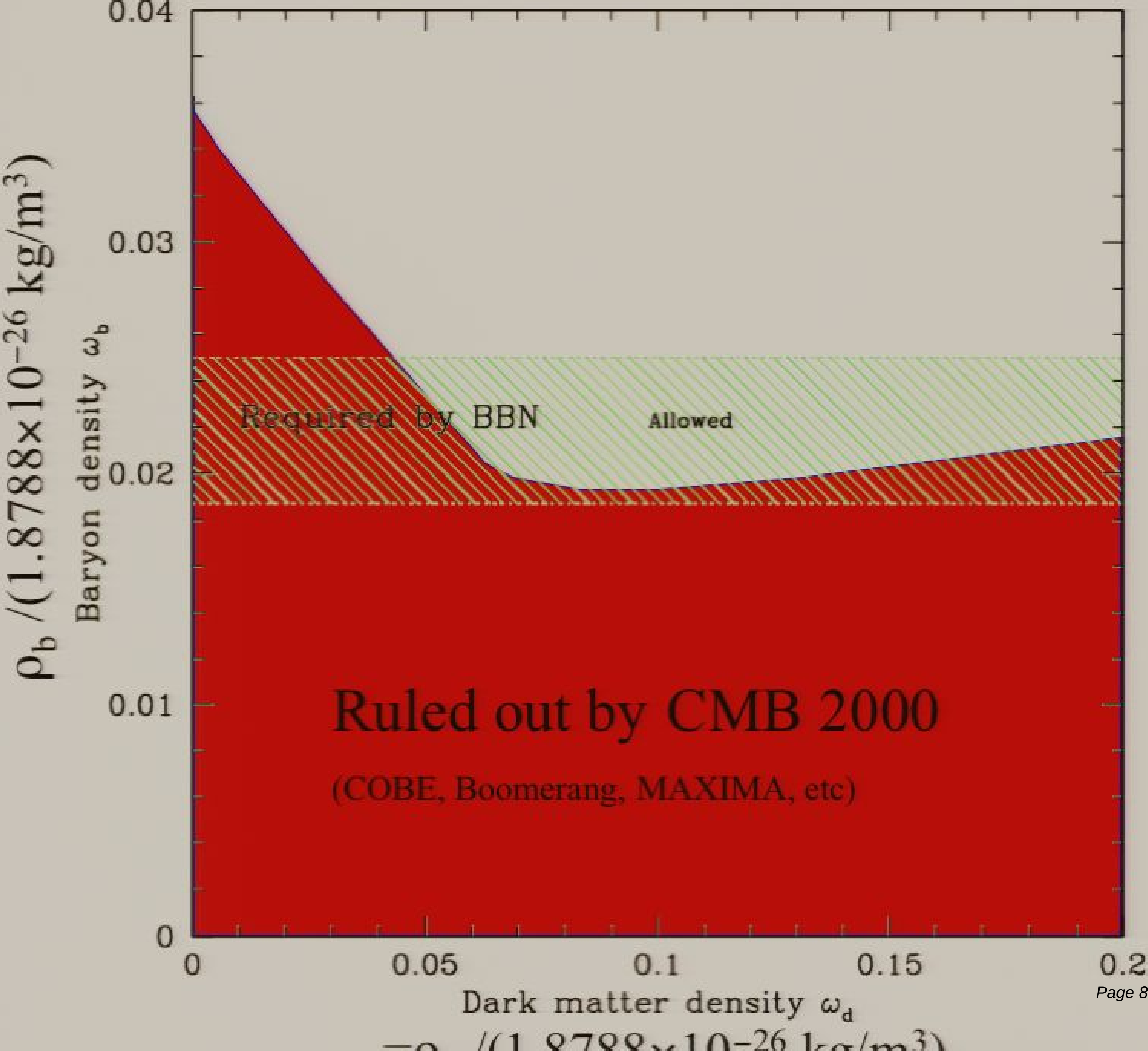


CMB

+

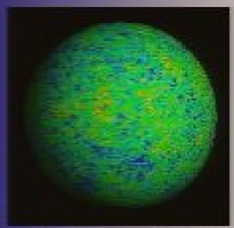
P(k)

How much dark matter is there?



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

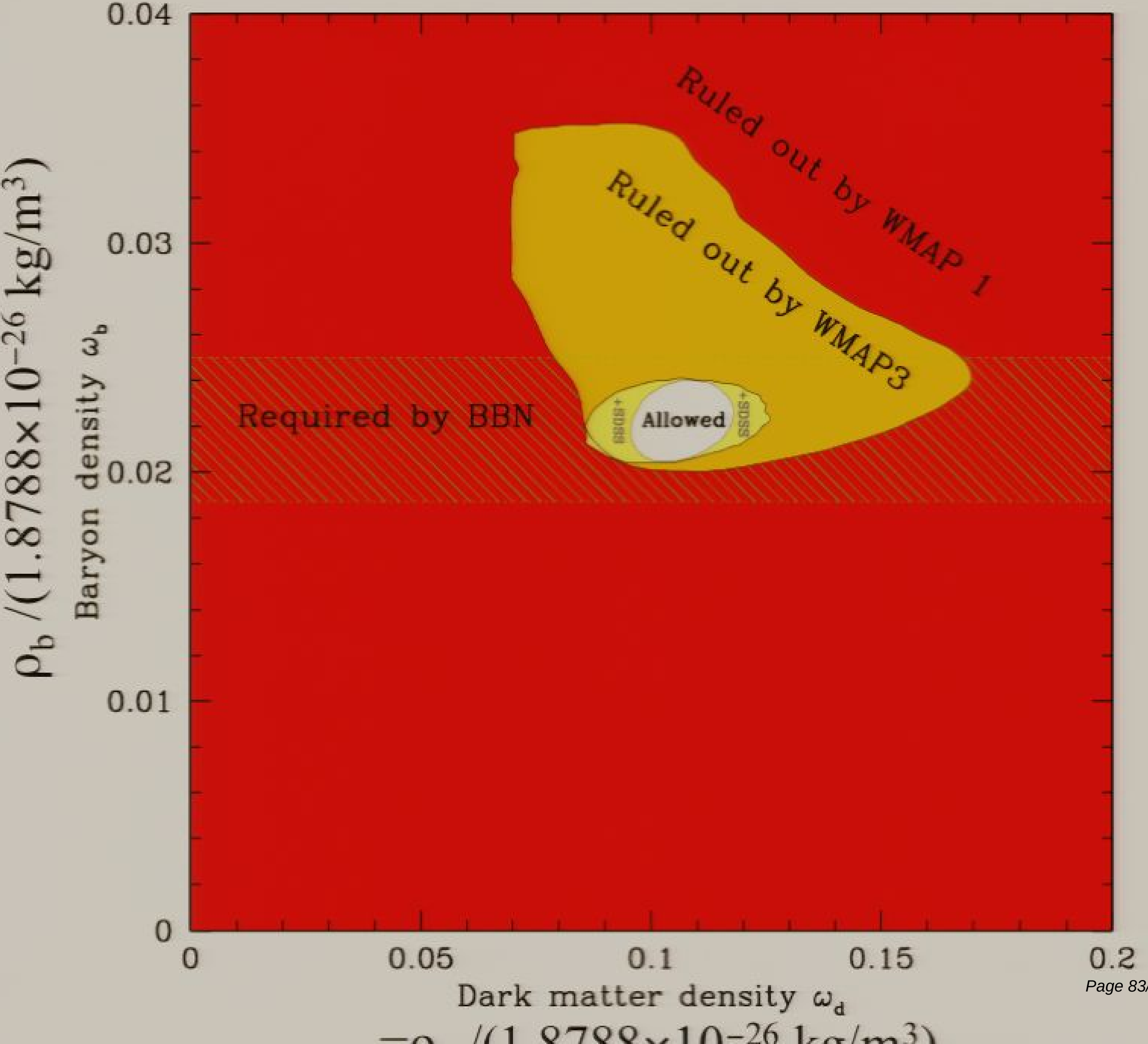
How much dark matter is there?



CMB

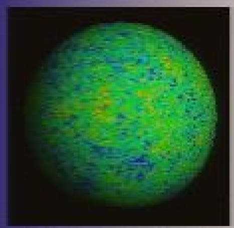
+

P(k)



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

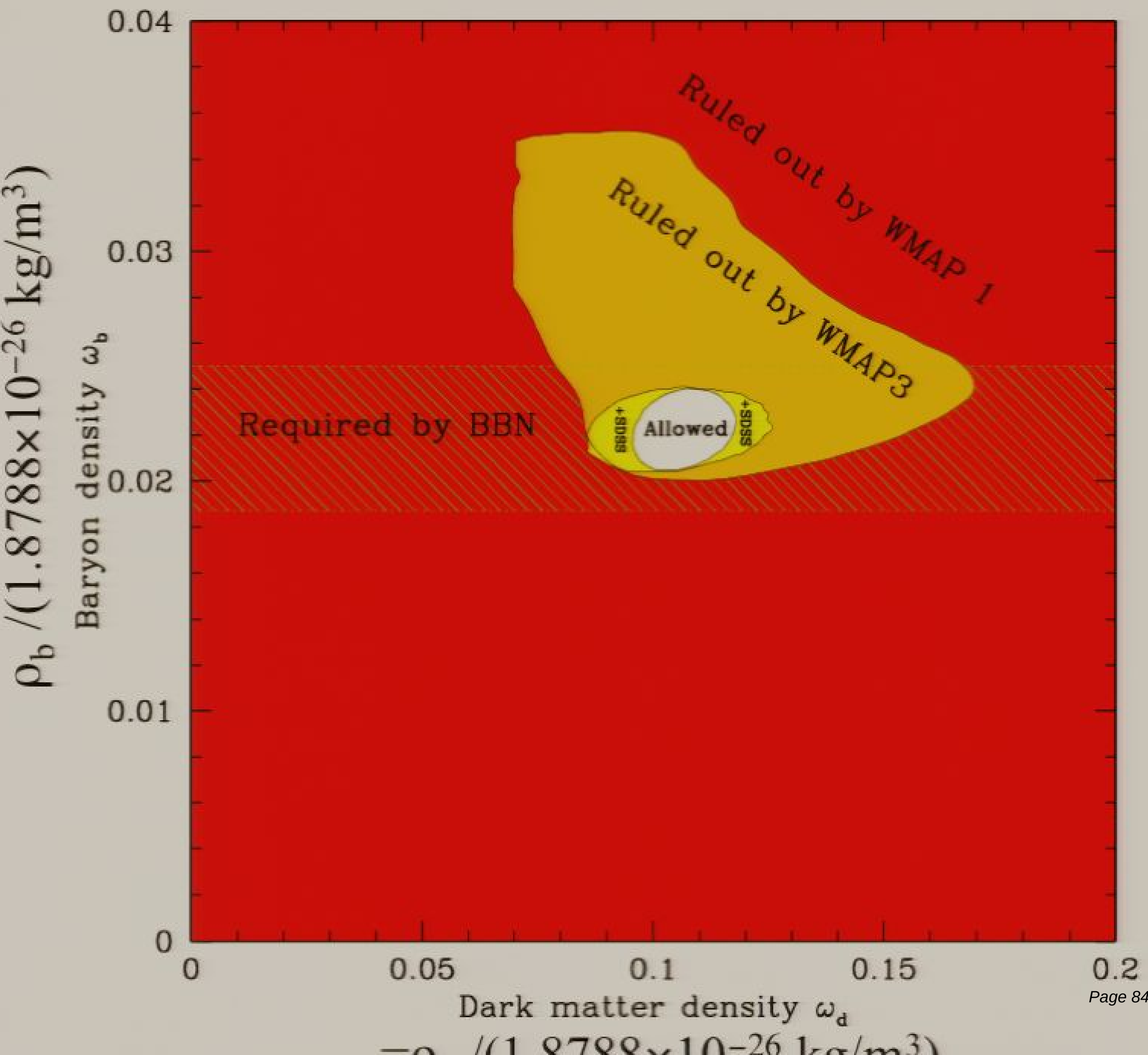
How much dark matter is there?



CMB

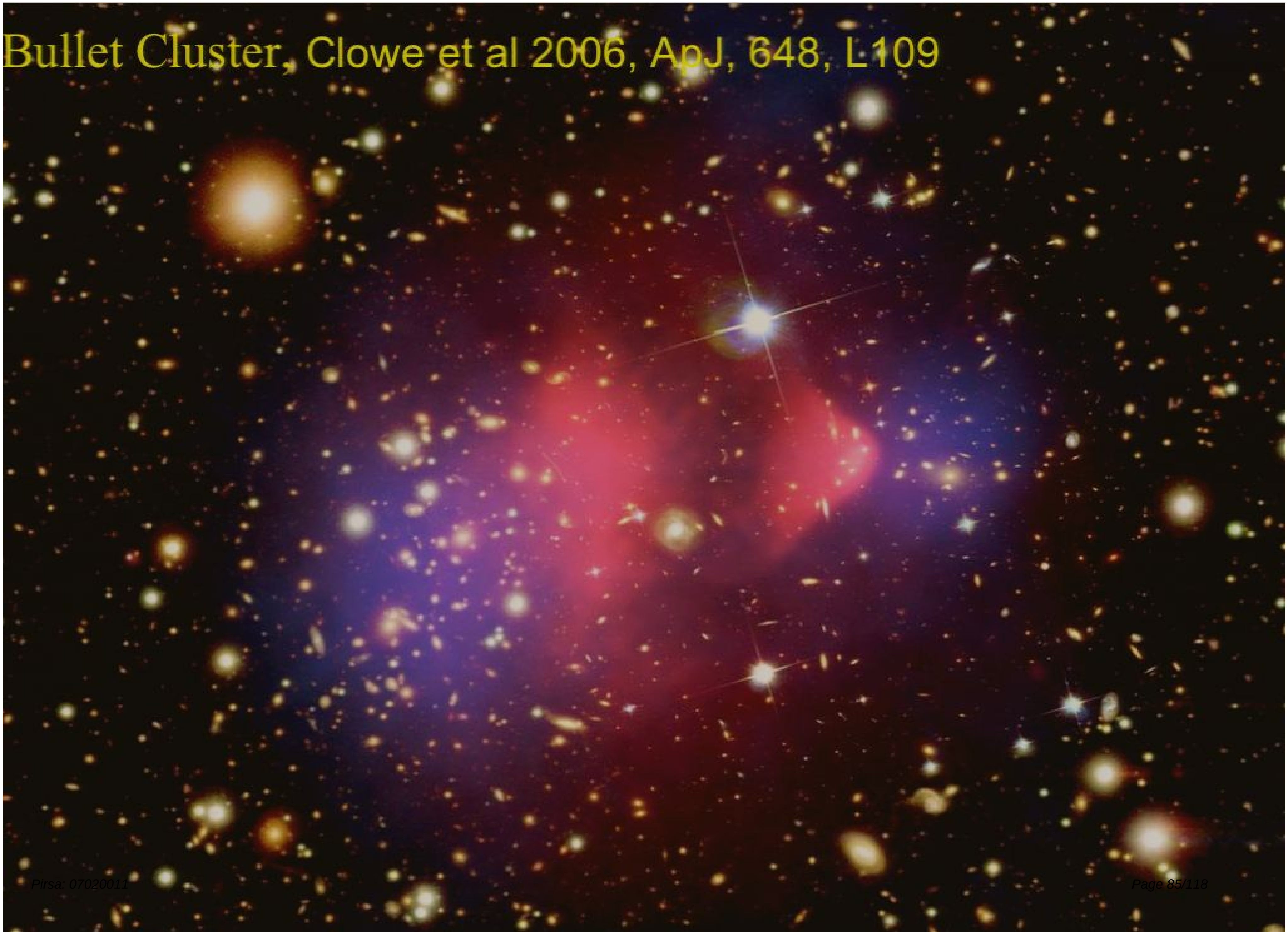
+

P(k)



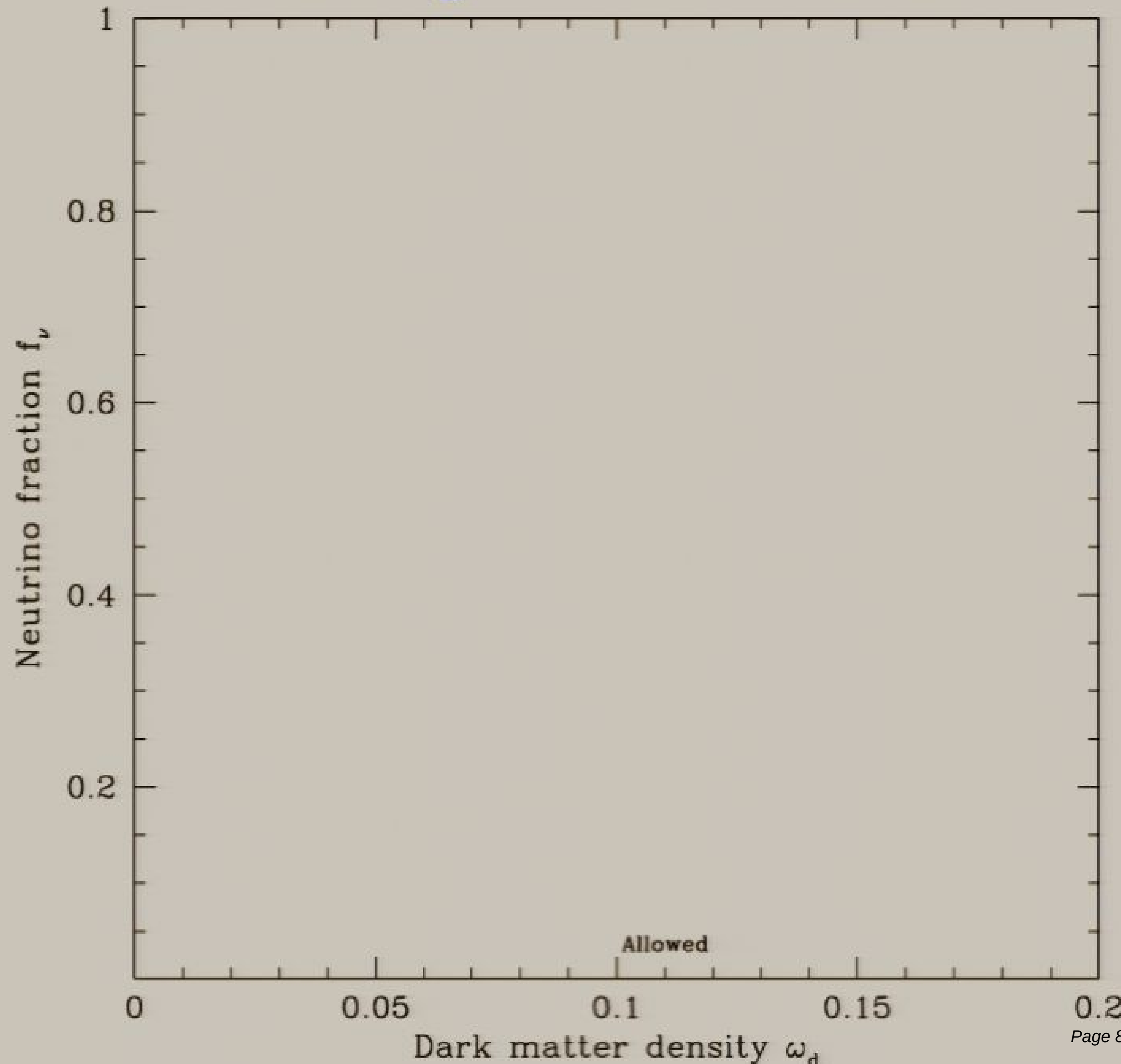
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

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



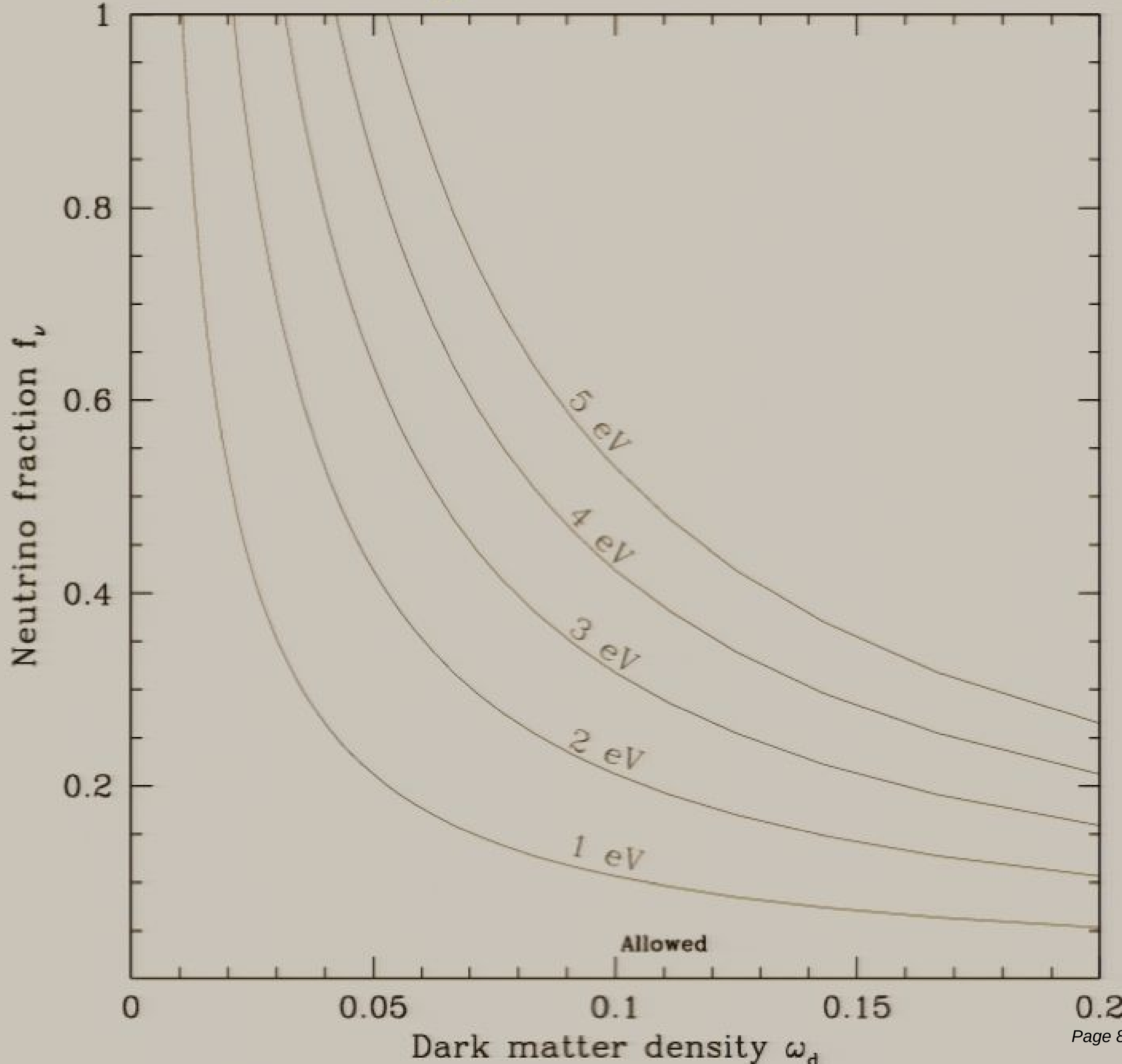
Neutrinos

Cosmological neutrino bounds



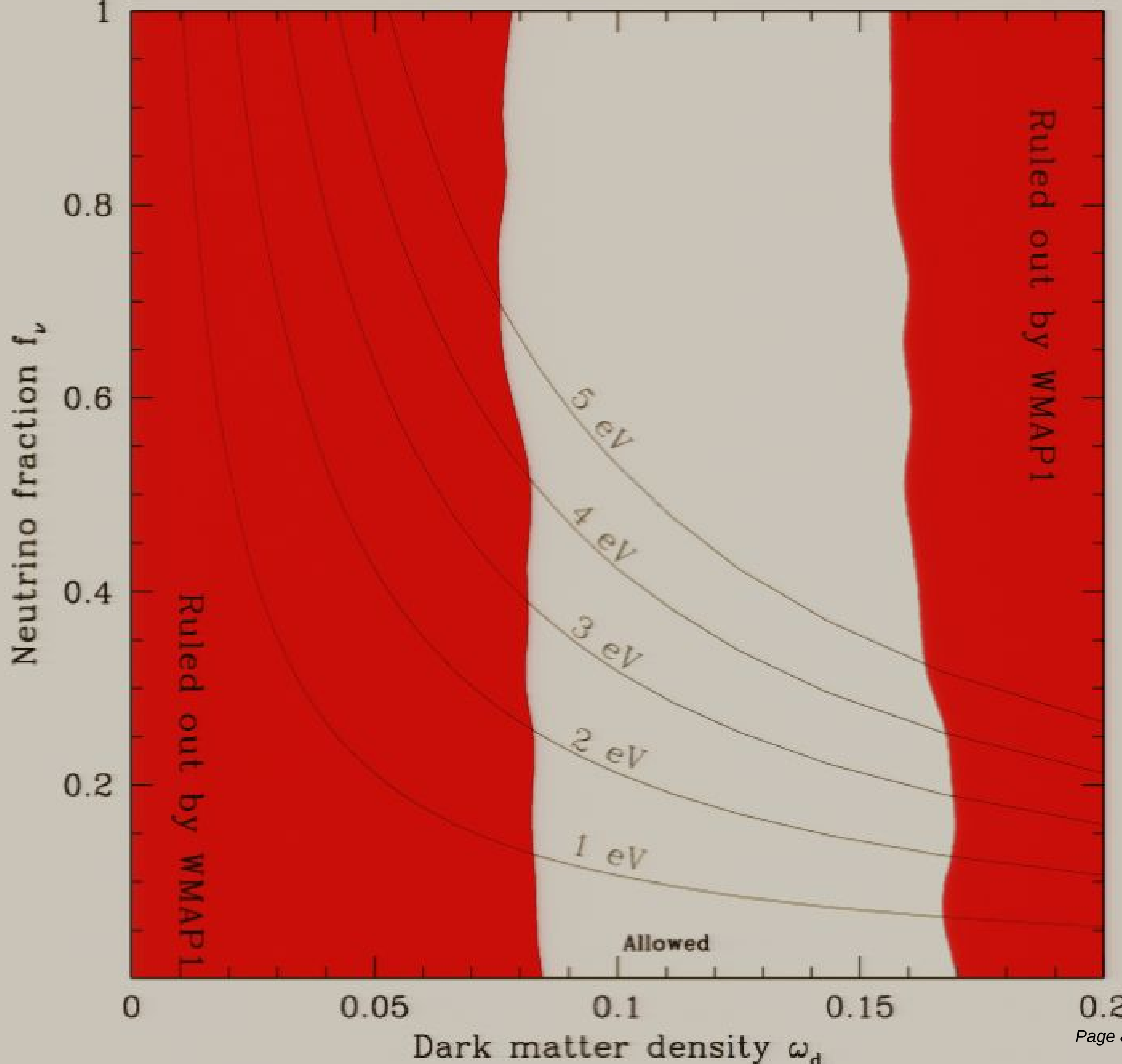
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

Cosmological neutrino bounds



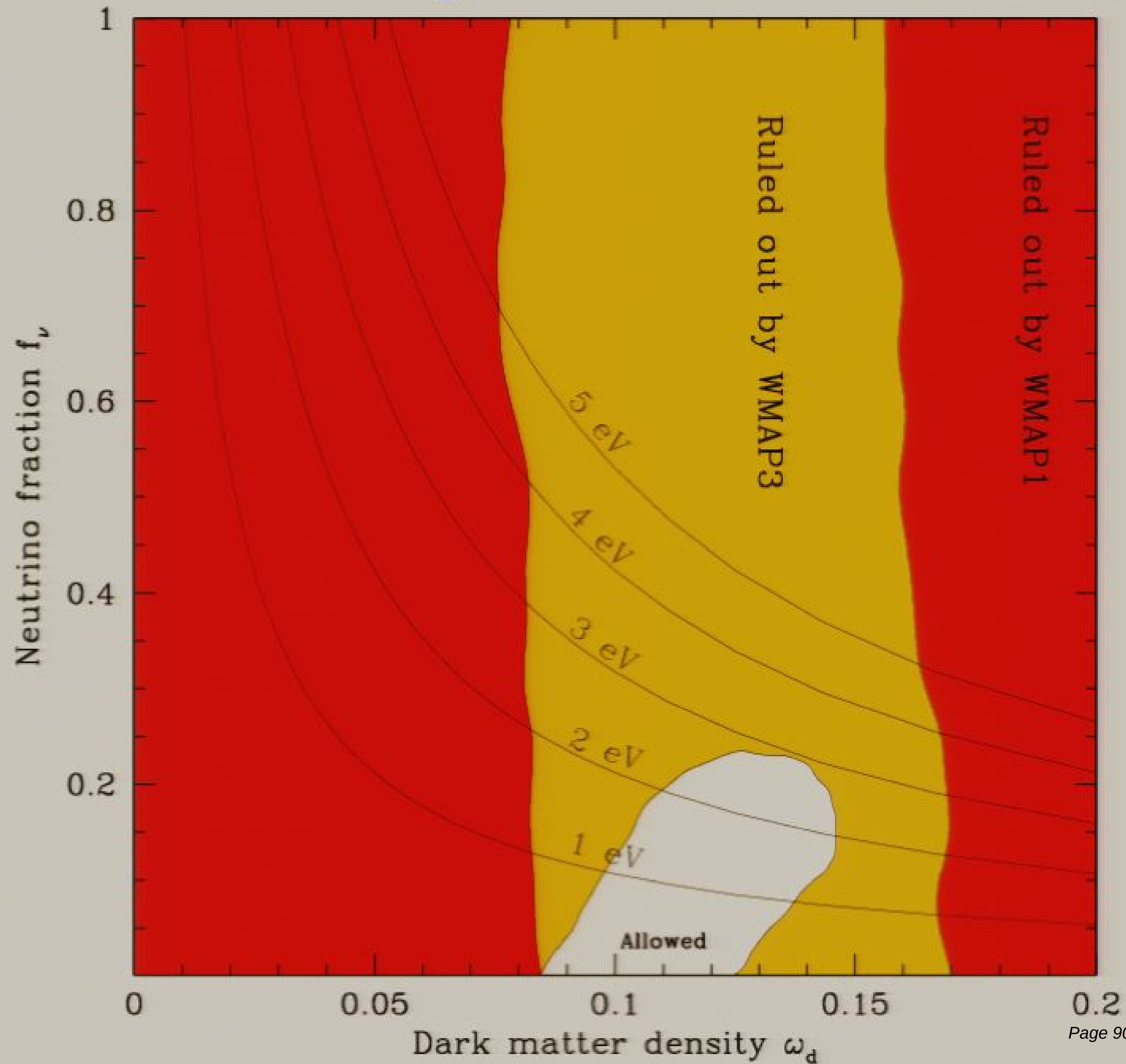
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

Cosmological neutrino bounds



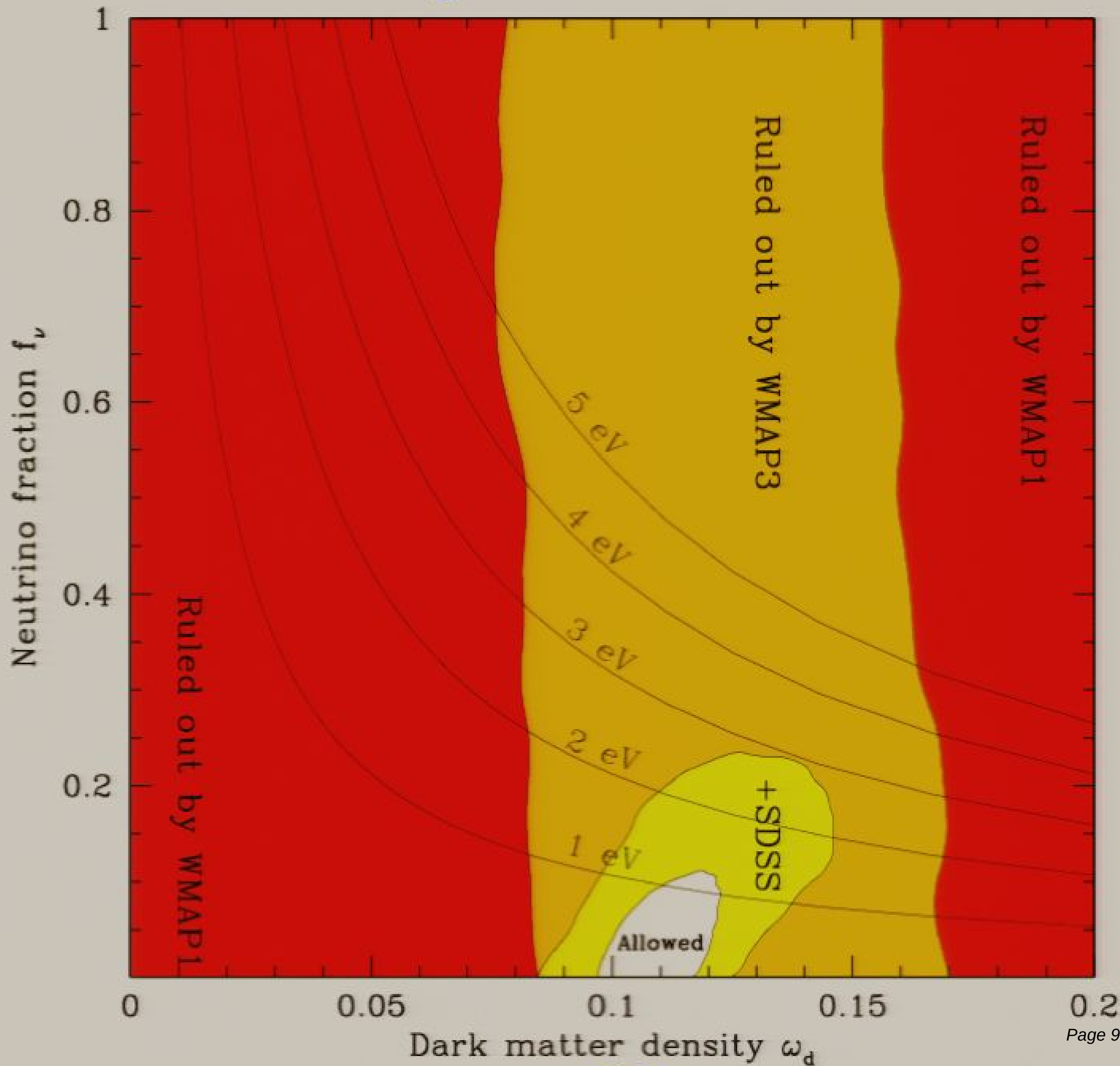
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

Cosmological neutrino bounds



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

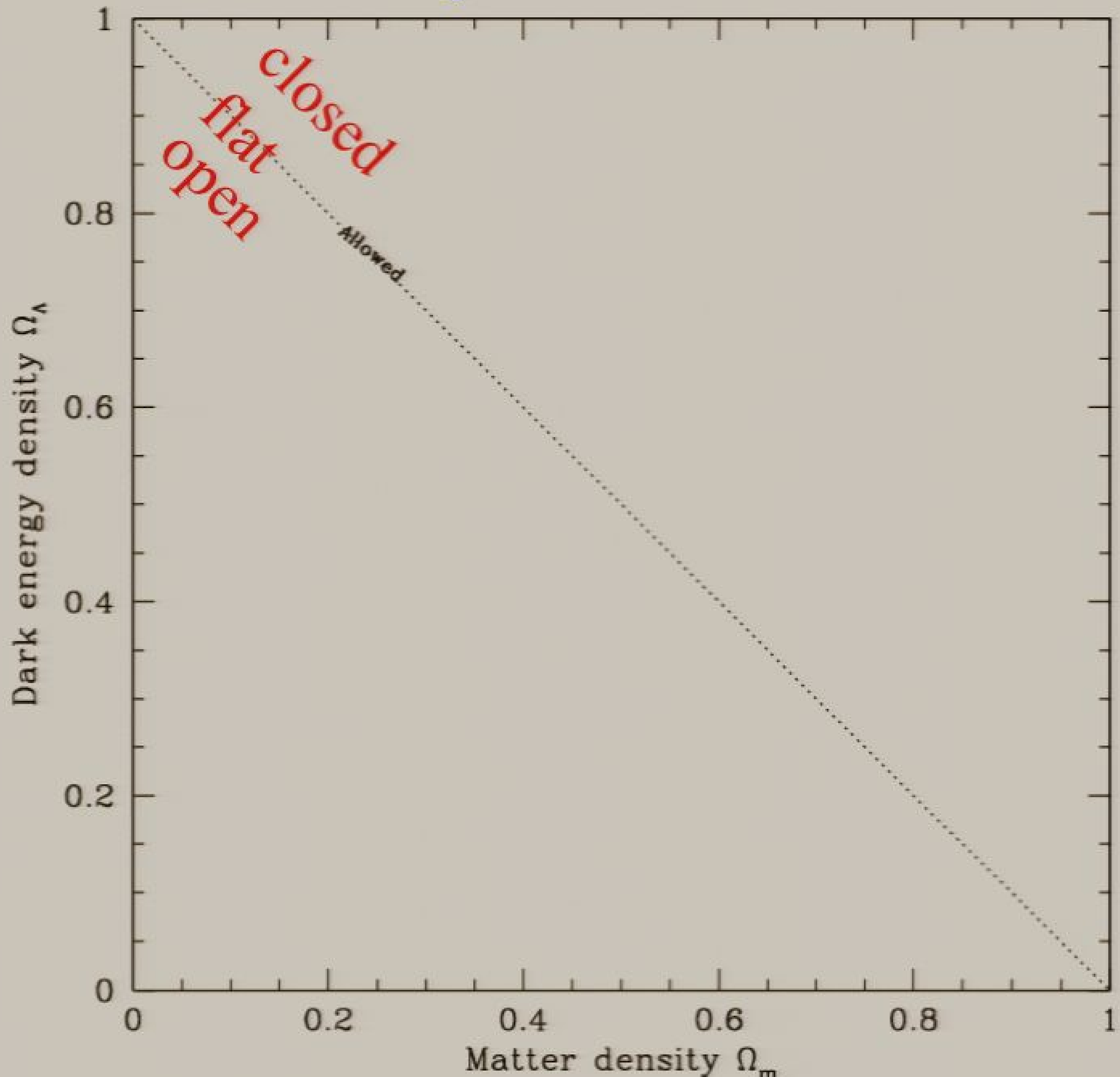
Cosmological neutrino bounds



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

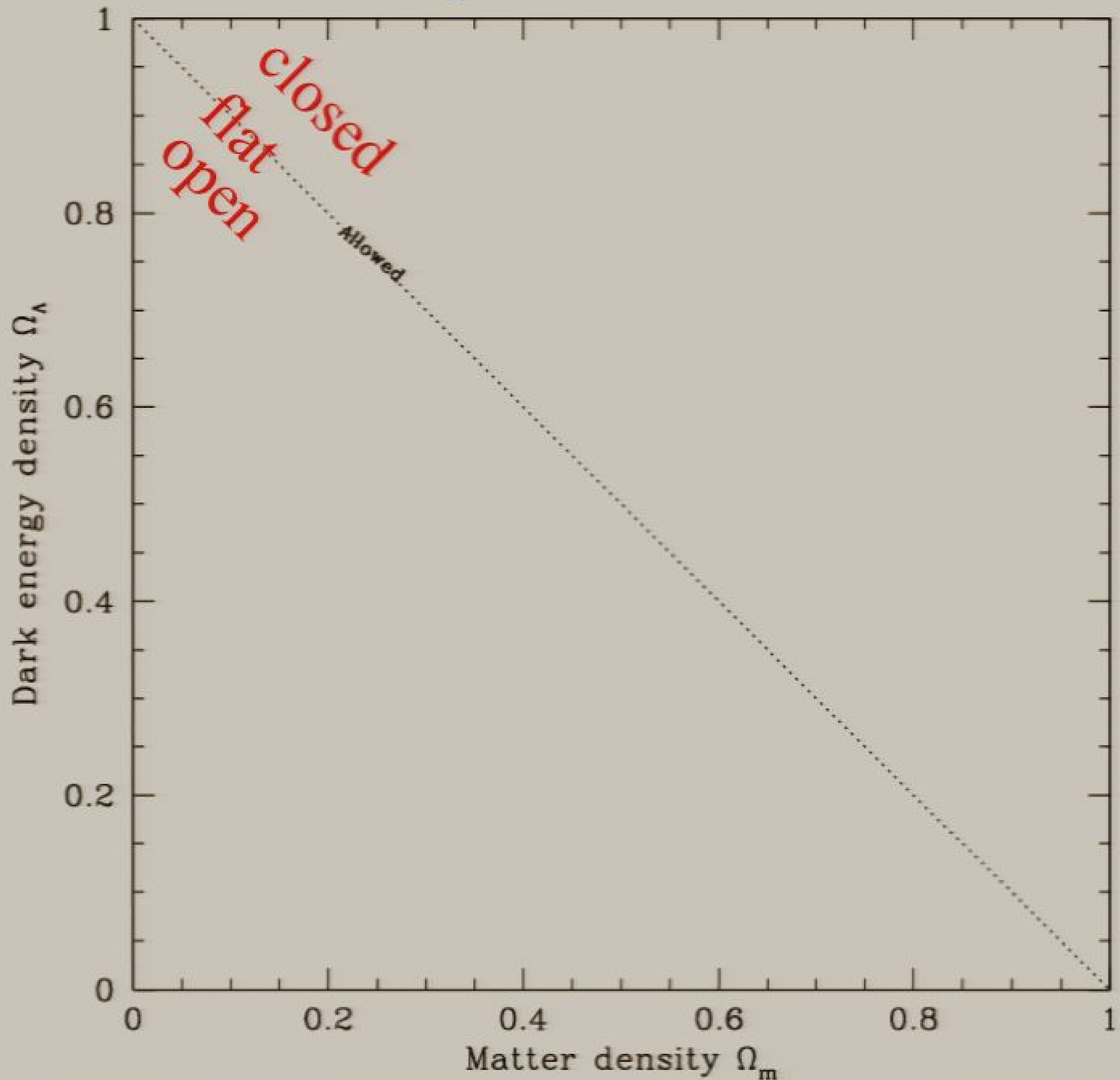
Inflation

How flat is space?



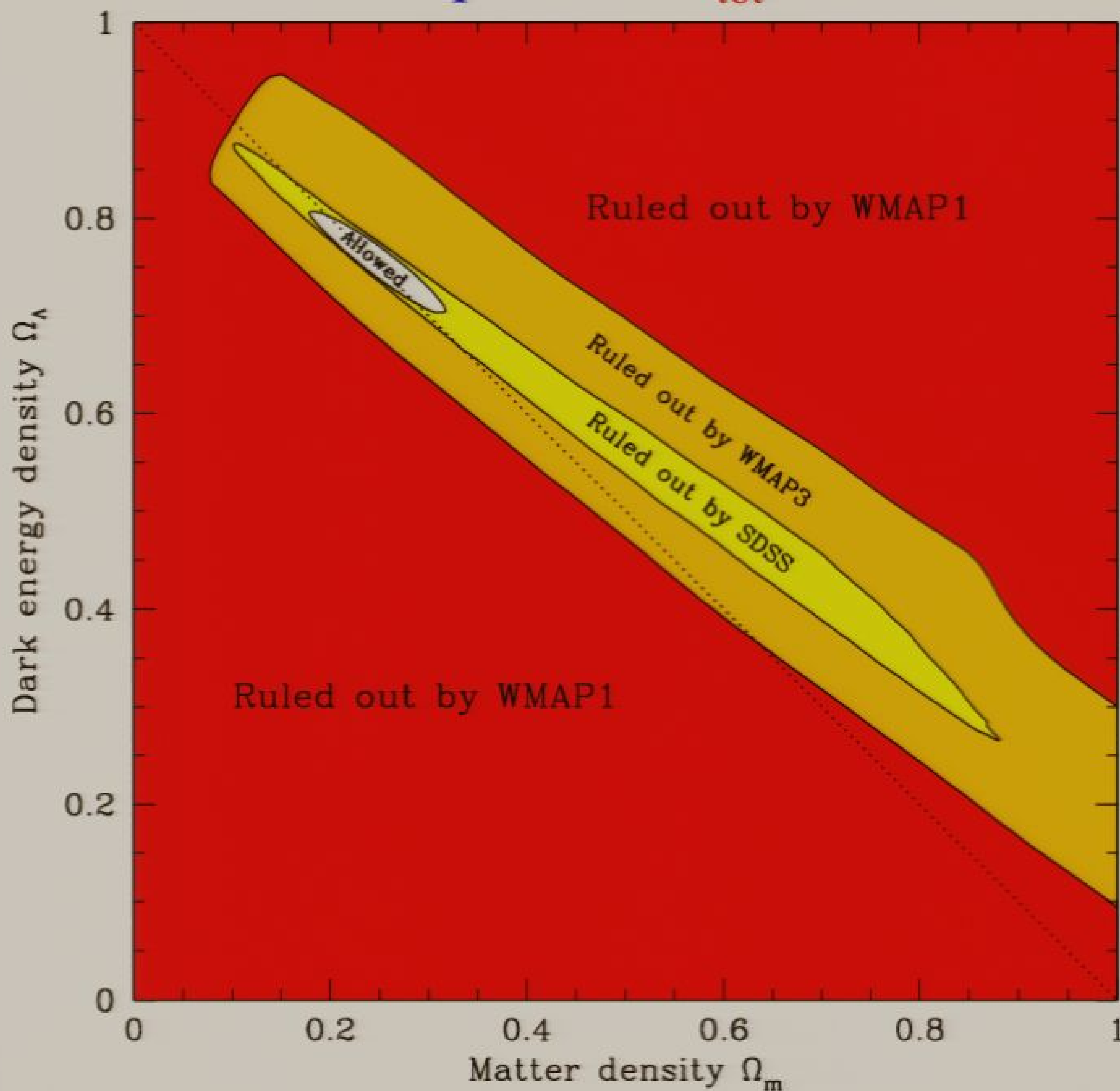
Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

How flat is space?

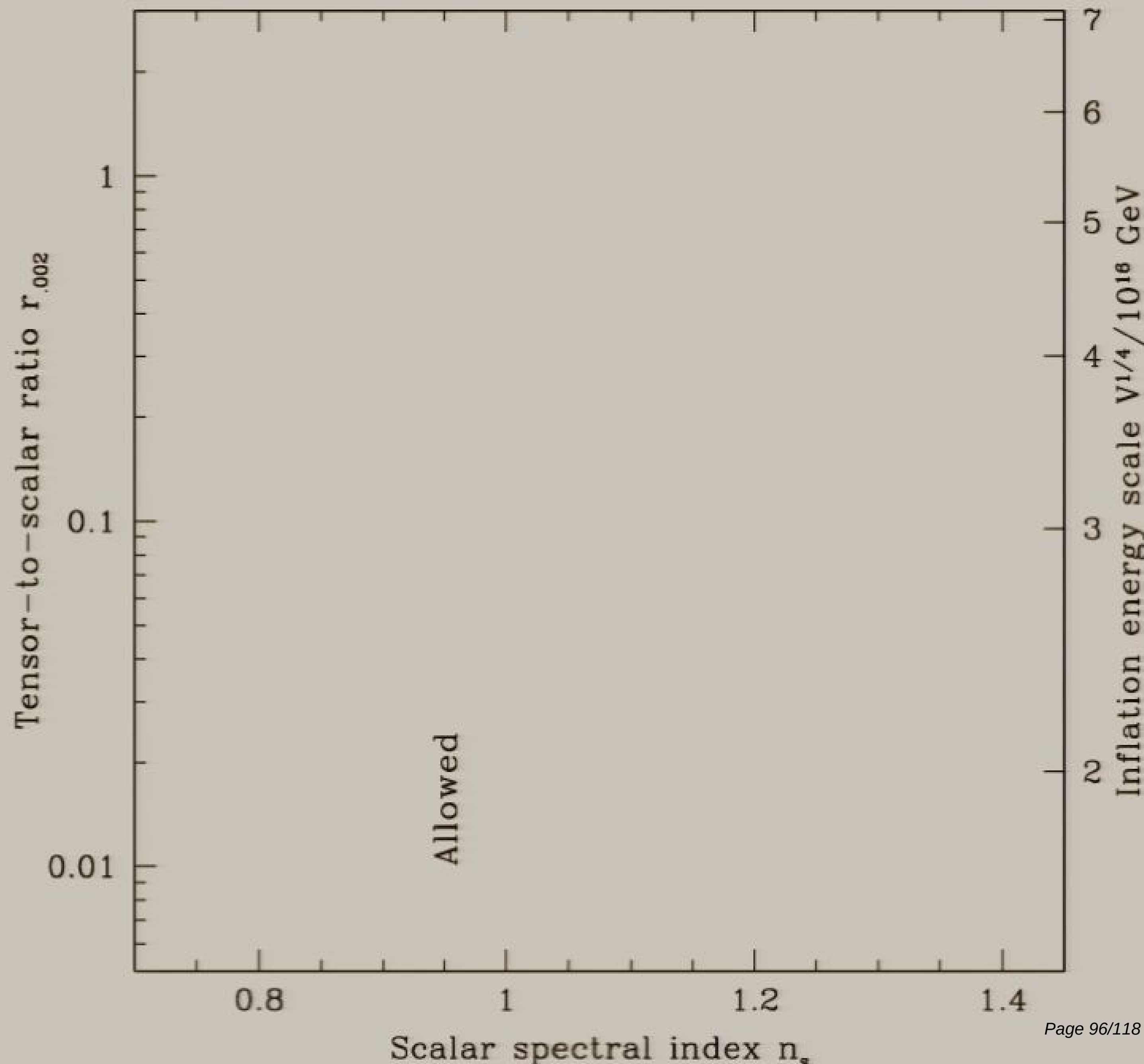


Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

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



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

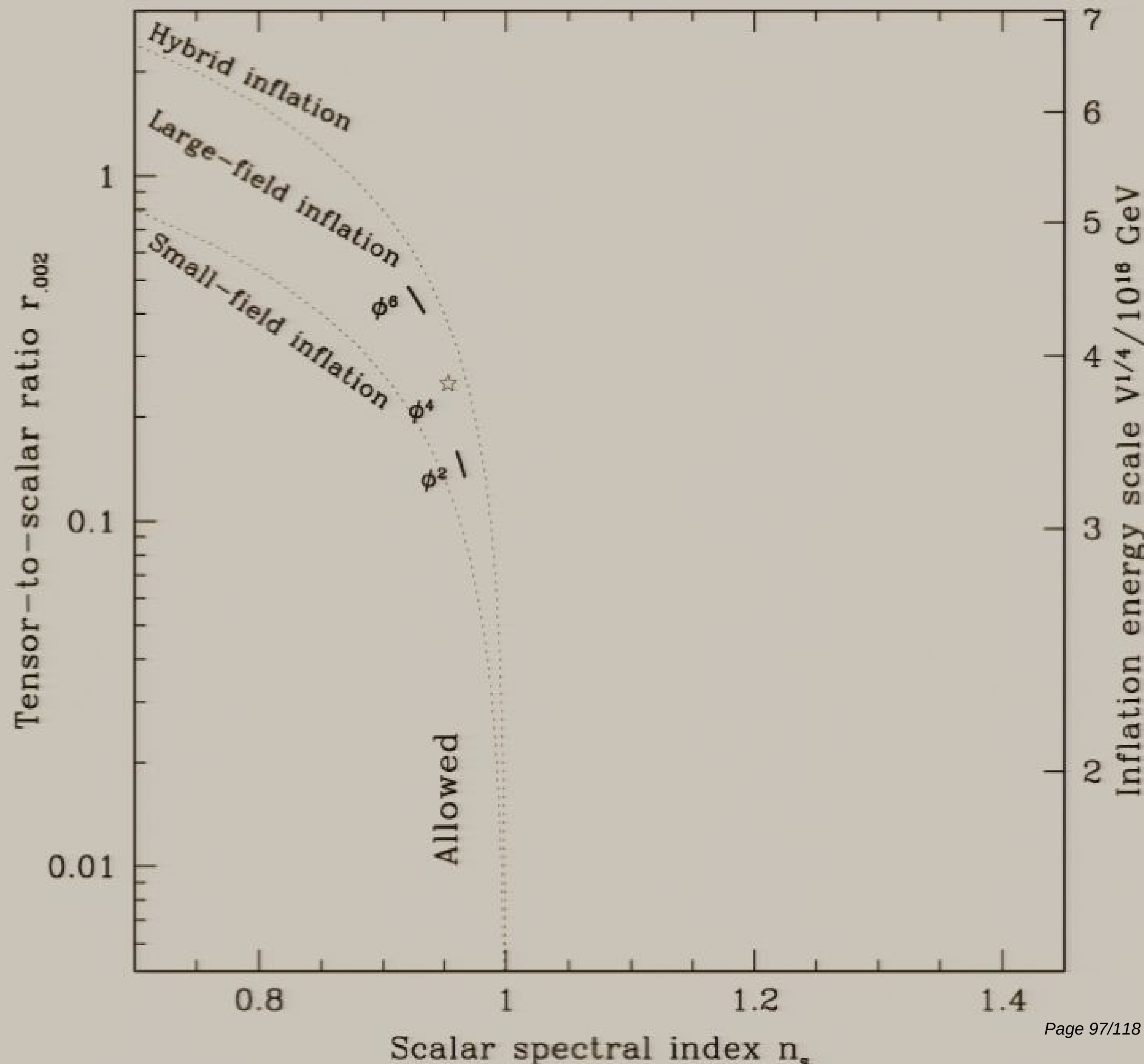


Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

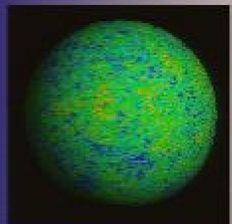
CMB

+

LSS

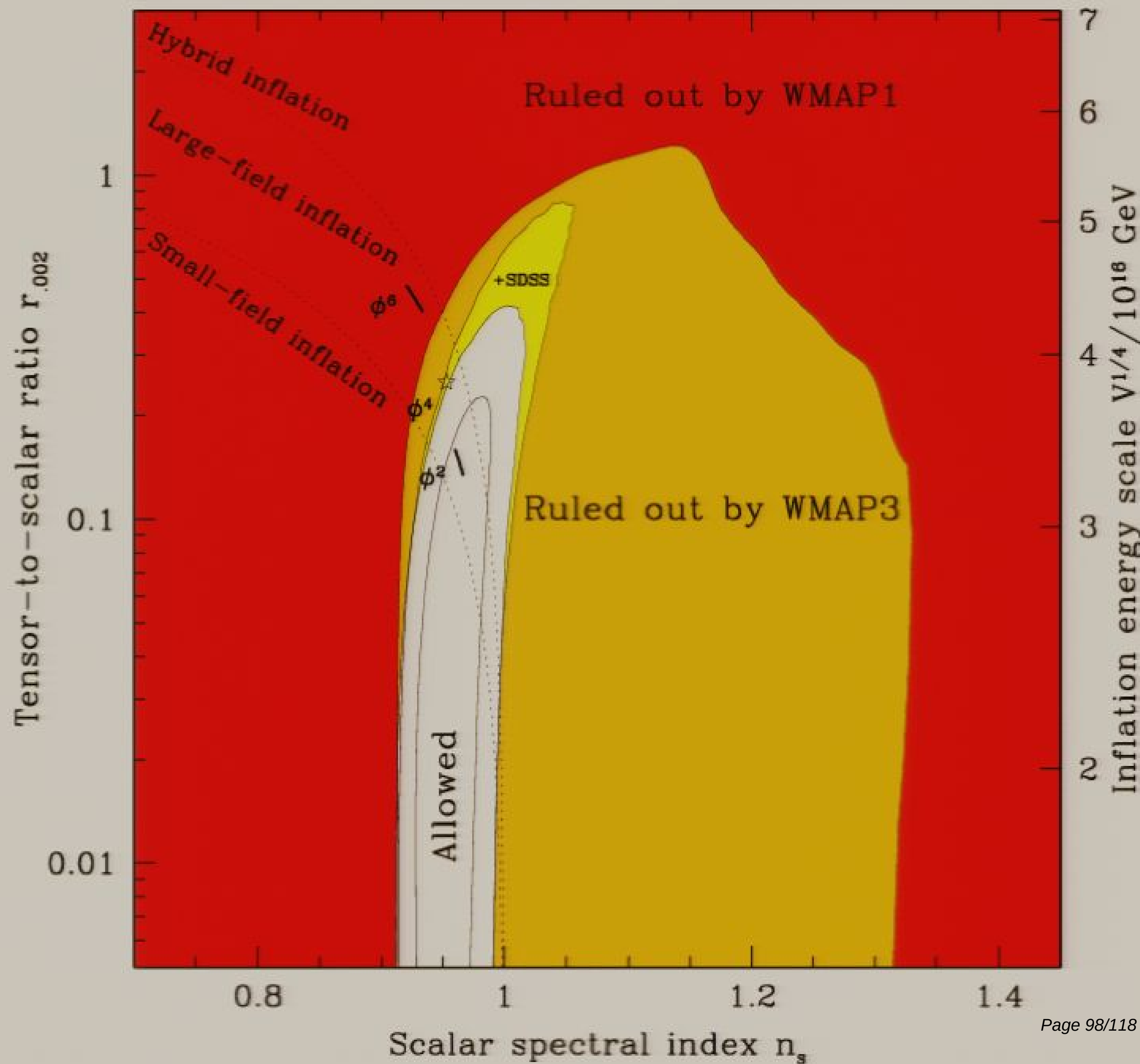


Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar



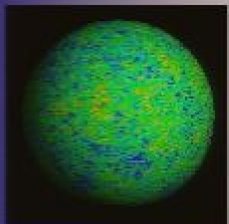
CMB
+

LSS



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

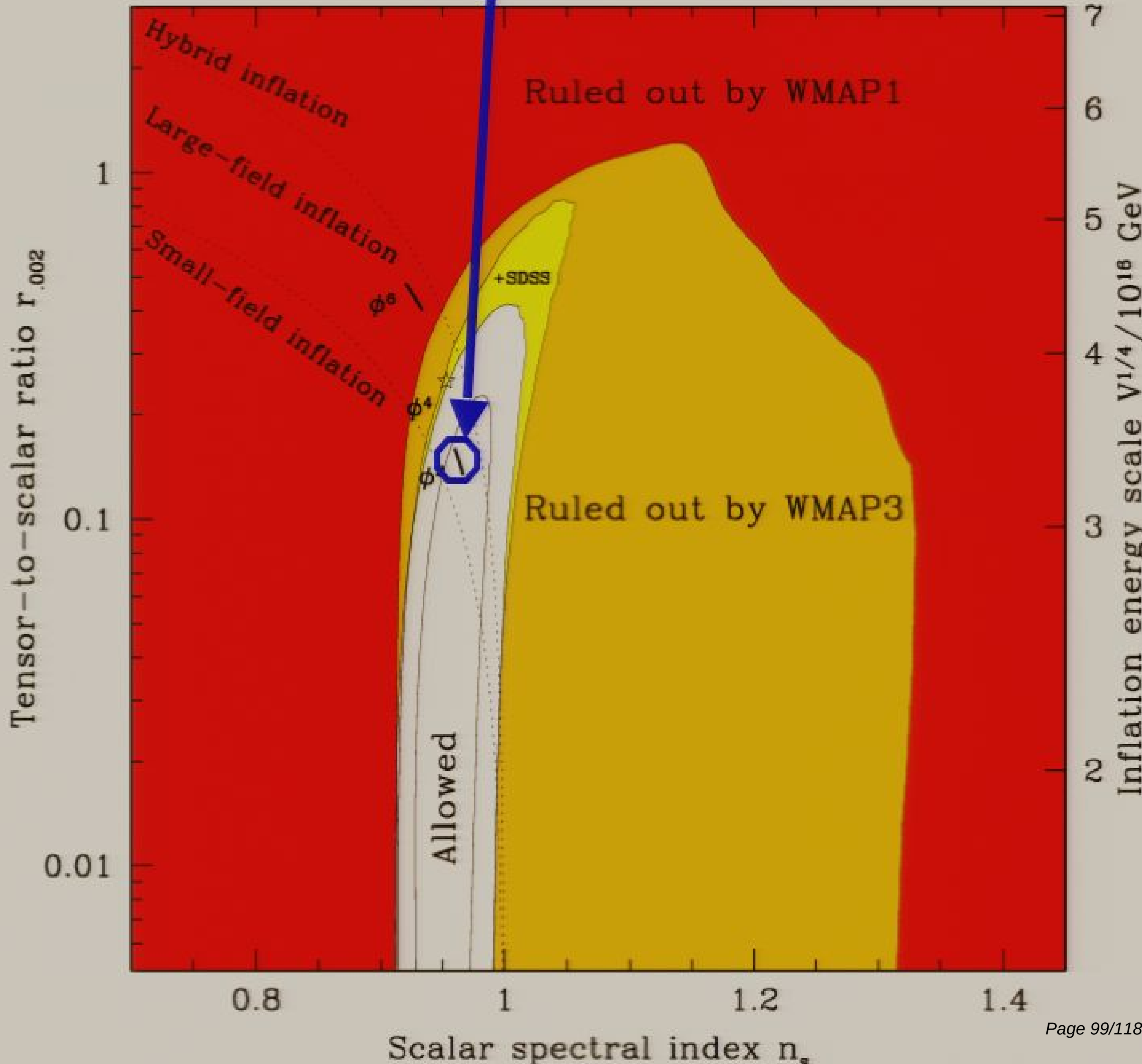
Planck + SDSS: Δn=0.008, Δr=0.012



CMB

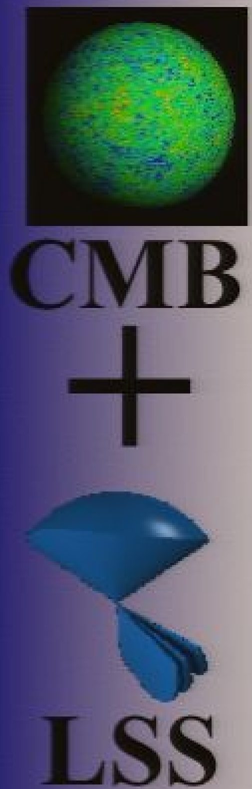
+

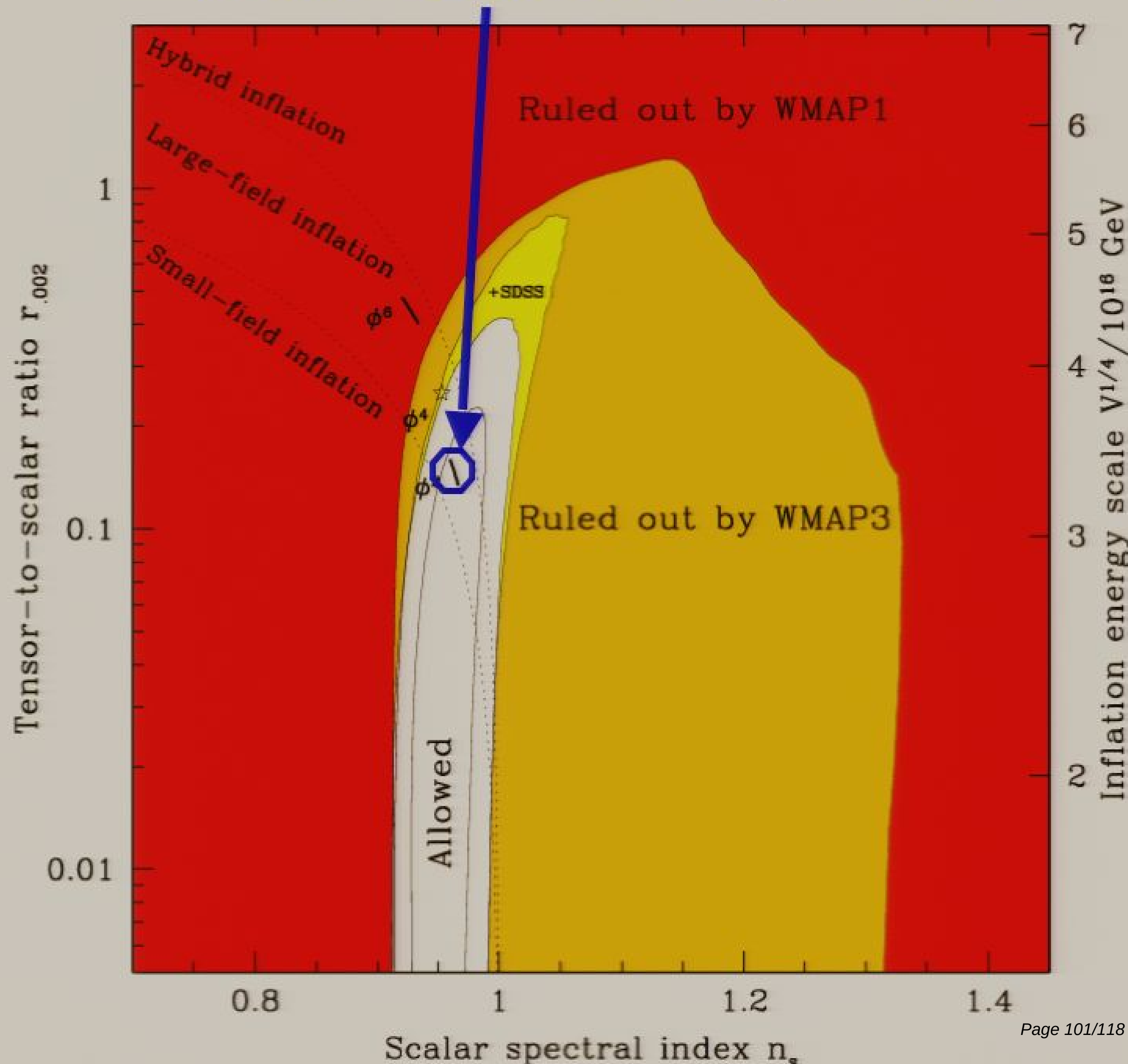
LSS



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

Planck + SDSS: Δn=0.008, Δr=0.012



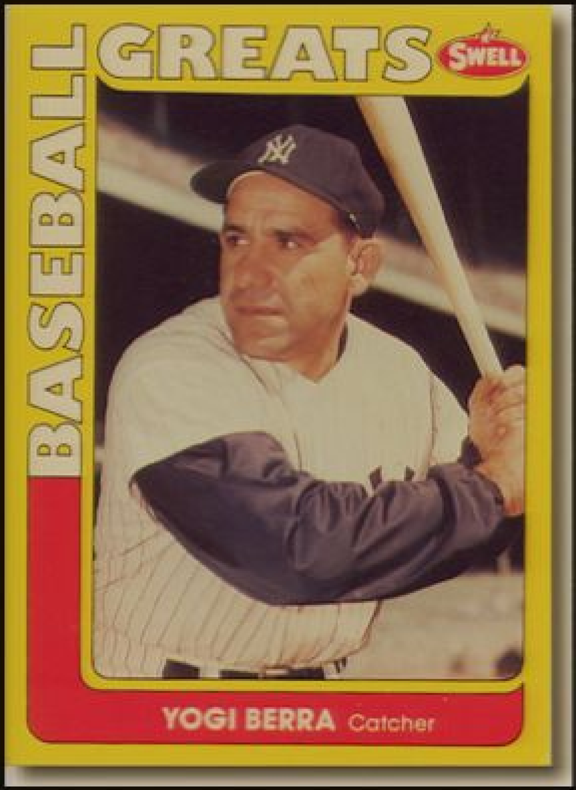


Max Tegmark
Dept. of Physics, MIT
tegmark@mit.edu
Perimeter Seminar

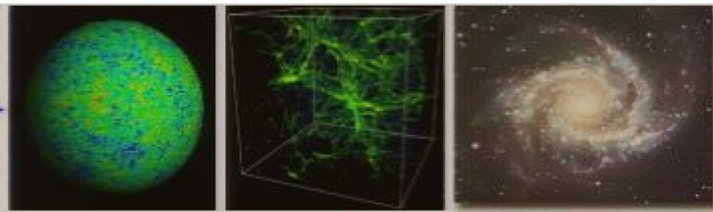
THE FUTURE

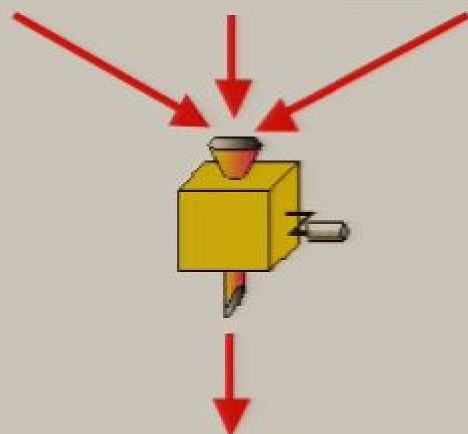
It's tough to make predictions,
especially about the future.

Yogi Berra



Cosmological data

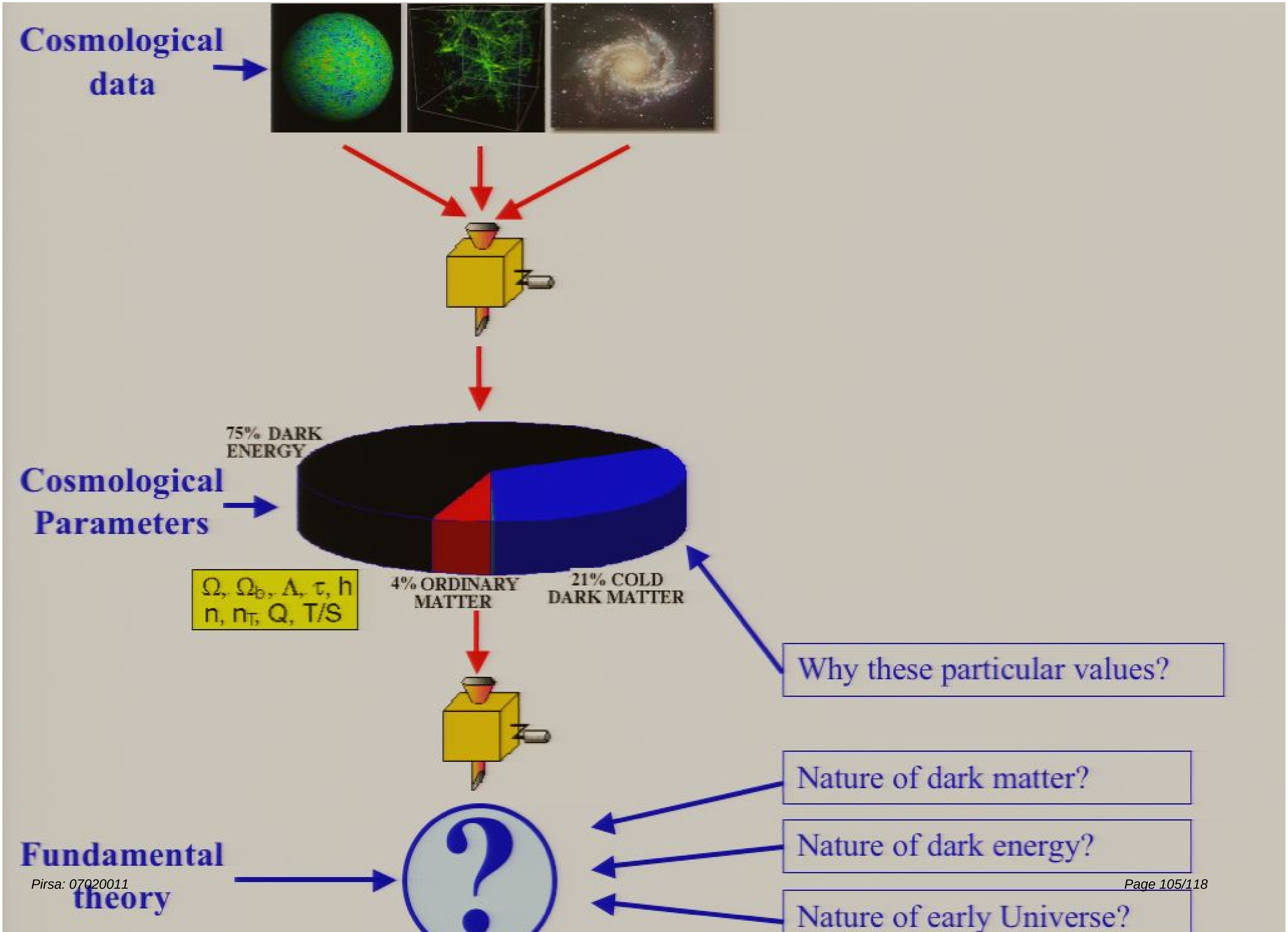




Cosmological Parameters

Ω, Ω_b, A, τ, h
n, n_T, Q, T/S


McDonald's
BILLIONS AND BILLIONS SERVED
DRIVE-THRU
BURRITOS .99
NOW HIRING LOSERS
$6 A HOUR


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?
Nature of dark matter?
Nature of dark energy?
Nature of early Universe?
Fundamental theory
?

DARK ENERGY SUMMARY:

Observation:

- Still no observed departures from "vanilla"
- #1 goal is searching for *any* non-vanilla behavior (density changing with time, clustering) (ne mind w' *etc*)

Theory:

- Zillions of papers and models, wide open:
  - cosmological constant + ground state density?
  - evolving scalar field?
  - modified gravity?
- The least unsuccessful solution to the coincidence problem is probably anthropic - but fails if Q or dark matter density i variable

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

DARK MATTER SUMMARY:

Observation:

- Still no observed departures from "vanilla" - observing this would be sensational (non-vanilla fluctuation growth, evidence of interaction)
- Indirect detection possible from annihilation
- Direct detection experiments may succeed
- LHC may discover SUSY

Theory:

- Zillions of papers and models, wide open:

  - WIMP?

  - axion?

  - modified gravity??

- Why is its density comparable to that for baryons?

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

INFLATION SUMMARY:

Observation:

- Predictions of flatness and near-vanilla confirmed
- Still no observed departures from "vanilla", i.e.,
  - departure from scale invariance
  - gravitational waves
  - non-Gaussianity
  - isocurvature
- Sensitivity will continuing to improve dramatically

Theory:

- Zillions of papers and models, wide open. But essentially all predict at least one kind of observable non-vanilla behavior.
- Inflation can be realized in string-theory landscape context
- Open problem how to compute probabilities

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

Table 1: Rough classification of inflation models.

Fluctuation generation phase	Fluctuation source	Clock evolution	Inflation ending	Inflation model	Observable: Gravitational waves	Non-scale invariance	Non-Gaussianity	Iso-curvature
Expansion	Mainly clock field	Standard kinetic term	Clock field	Classic	+	+	-	-
			Other	Hybrid	-	+	-	?
		Other dynamics		DBI	+	+	+	?
				Ghost	-	-	+	?
	Other			Multi-field	+	+	-?	?
				VDR	-	+	+	?
				Curvaton	-	+	+	?
Contraction				Ekpyrotic	-	+	-	-
				Pre-BB	+	?	?	?

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

INFLATION SUMMARY:

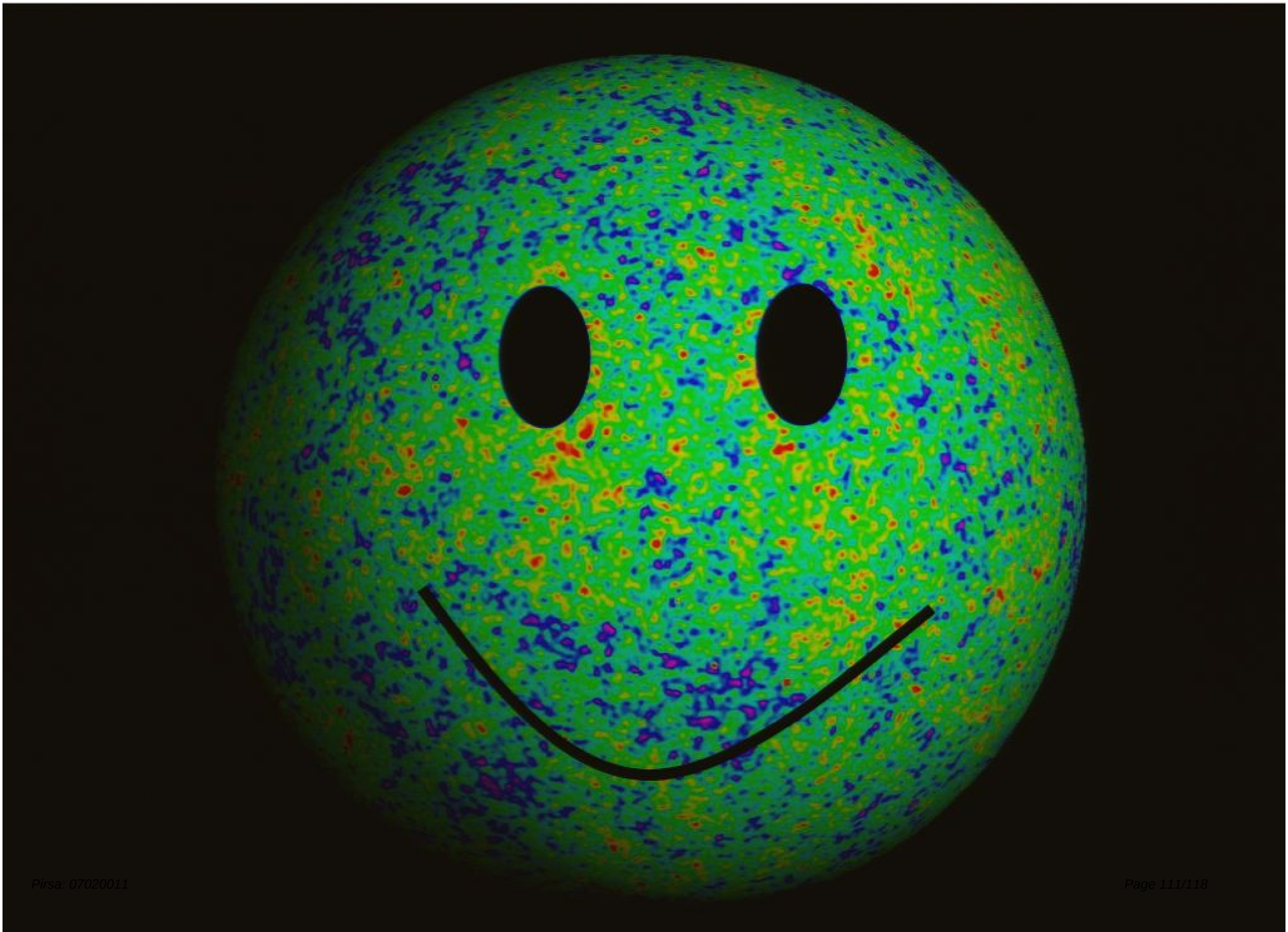
Observation:

- Predictions of flatness and near-vanilla confirmed
- Still no observed departures from "vanilla", i.e.,
  - departure from scale invariance
  - gravitational waves
  - non-Gaussianity
  - isocurvature
- Sensitivity will continuing to improve dramatically

Theory:

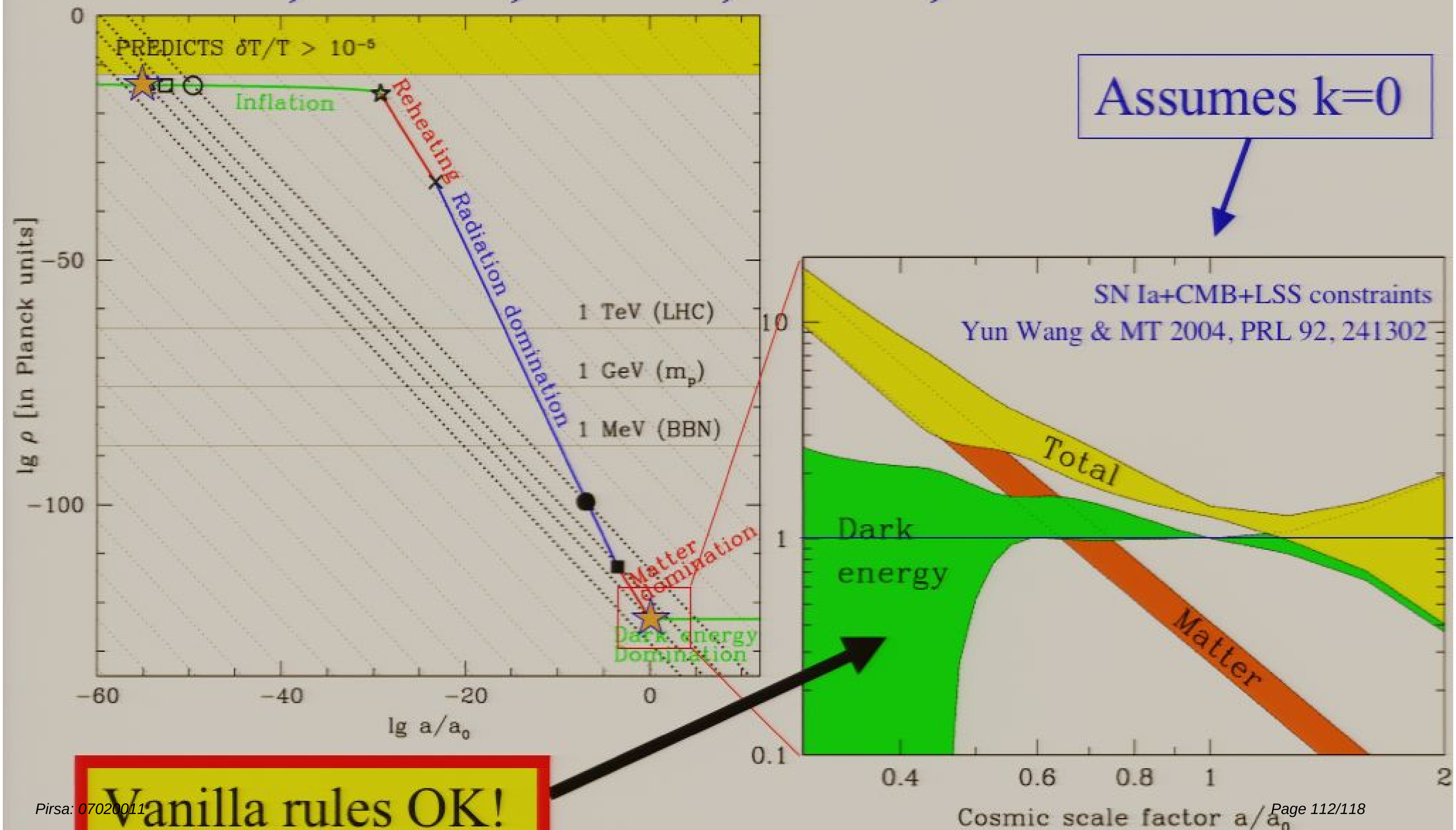
- Zillions of papers and models, wide open. But essentially all predict at least one kind of observable non-vanilla behavior.
- Inflation can be realized in string-theory landscape context
- Open problem how to compute probabilities

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

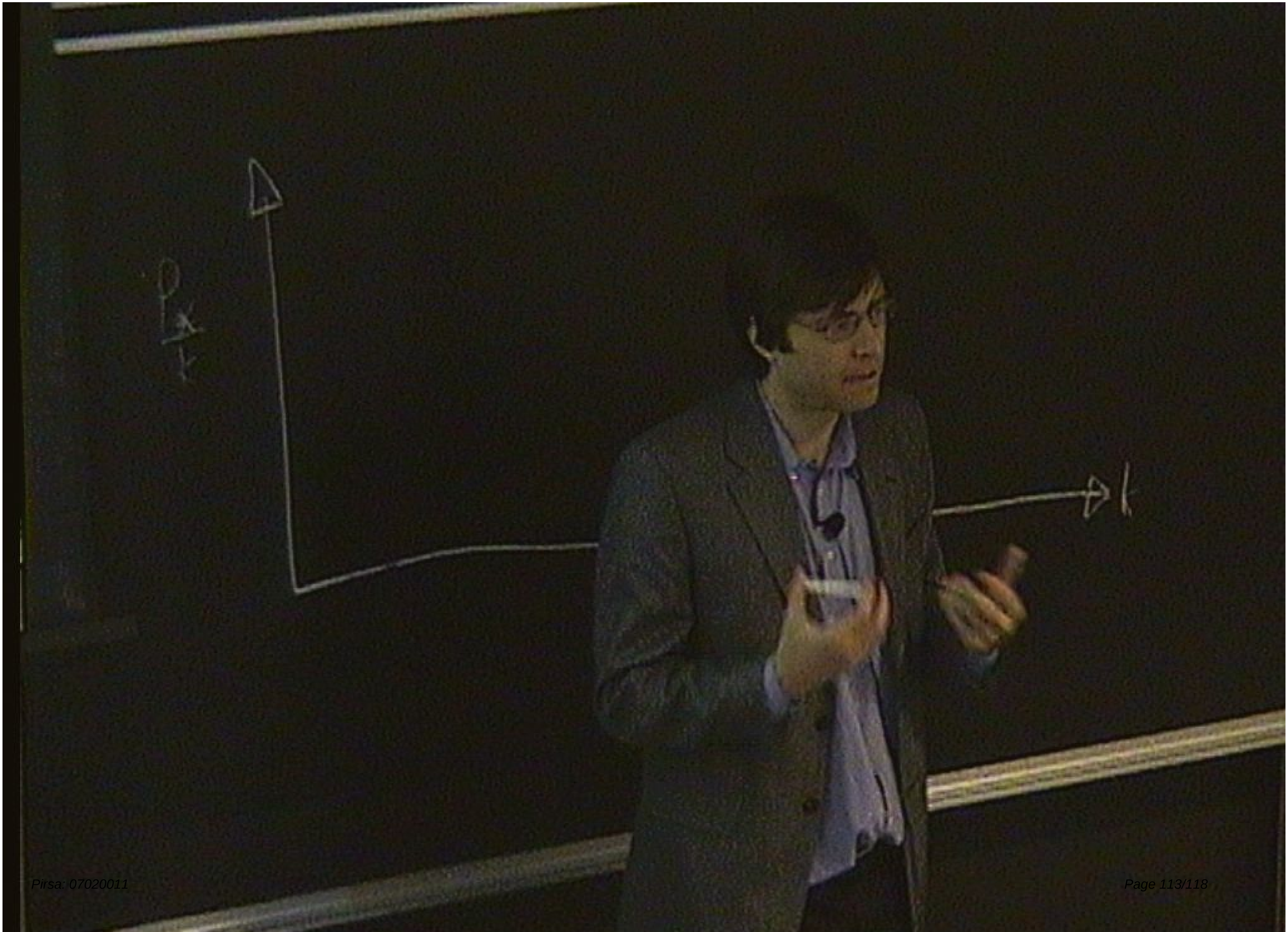


What we've learned about H(z) from SN Ia, CMB, BAO, BBN, etc:

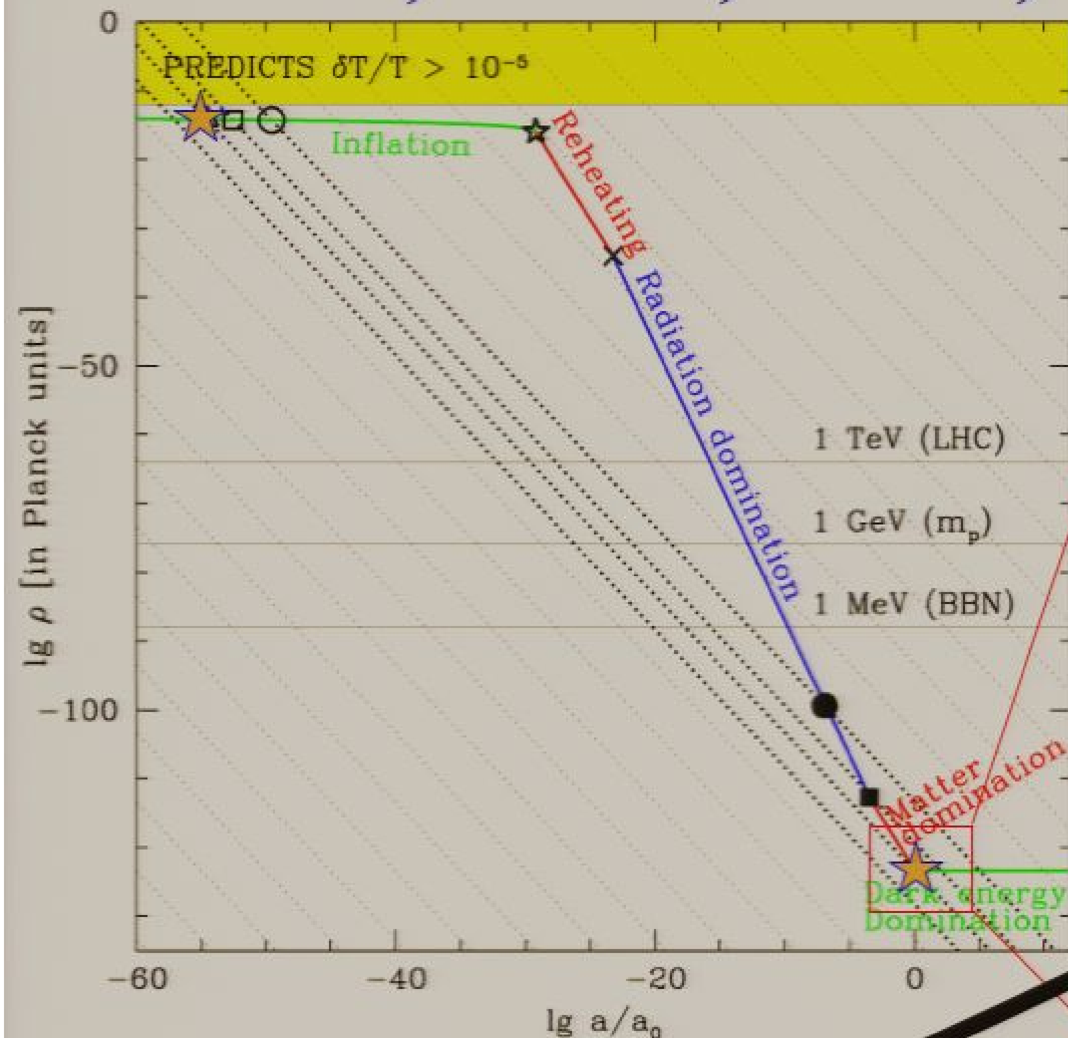
Assumes k=0



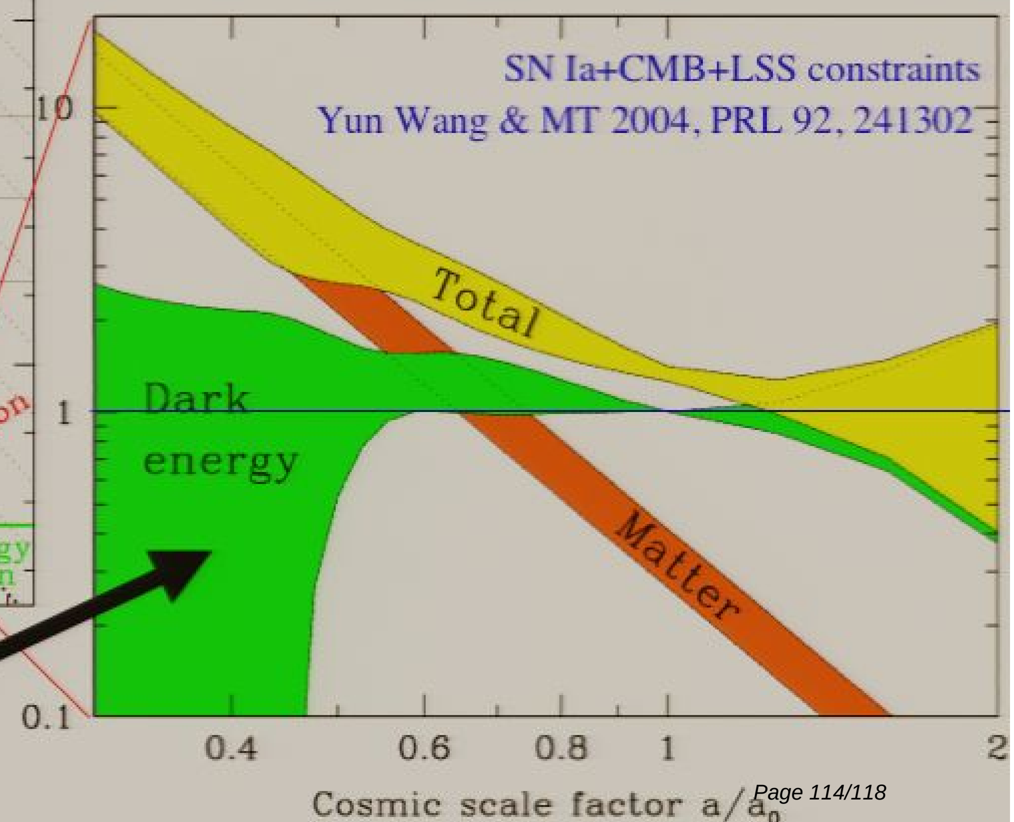
Vanilla rules OK!



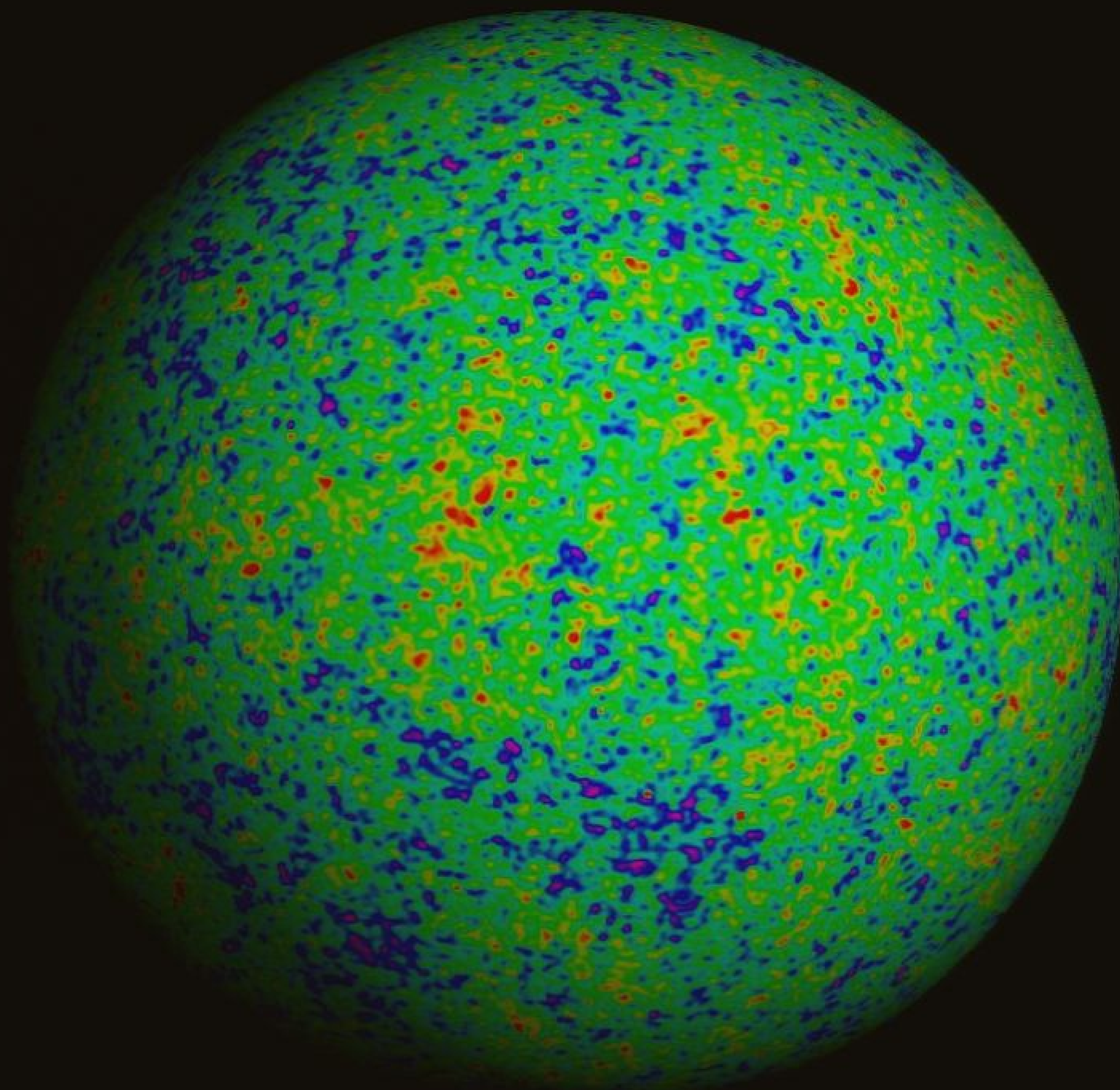
What we've learned about H(z) from SN Ia, CMB, BAO, BBN, etc:



Assumes k=0

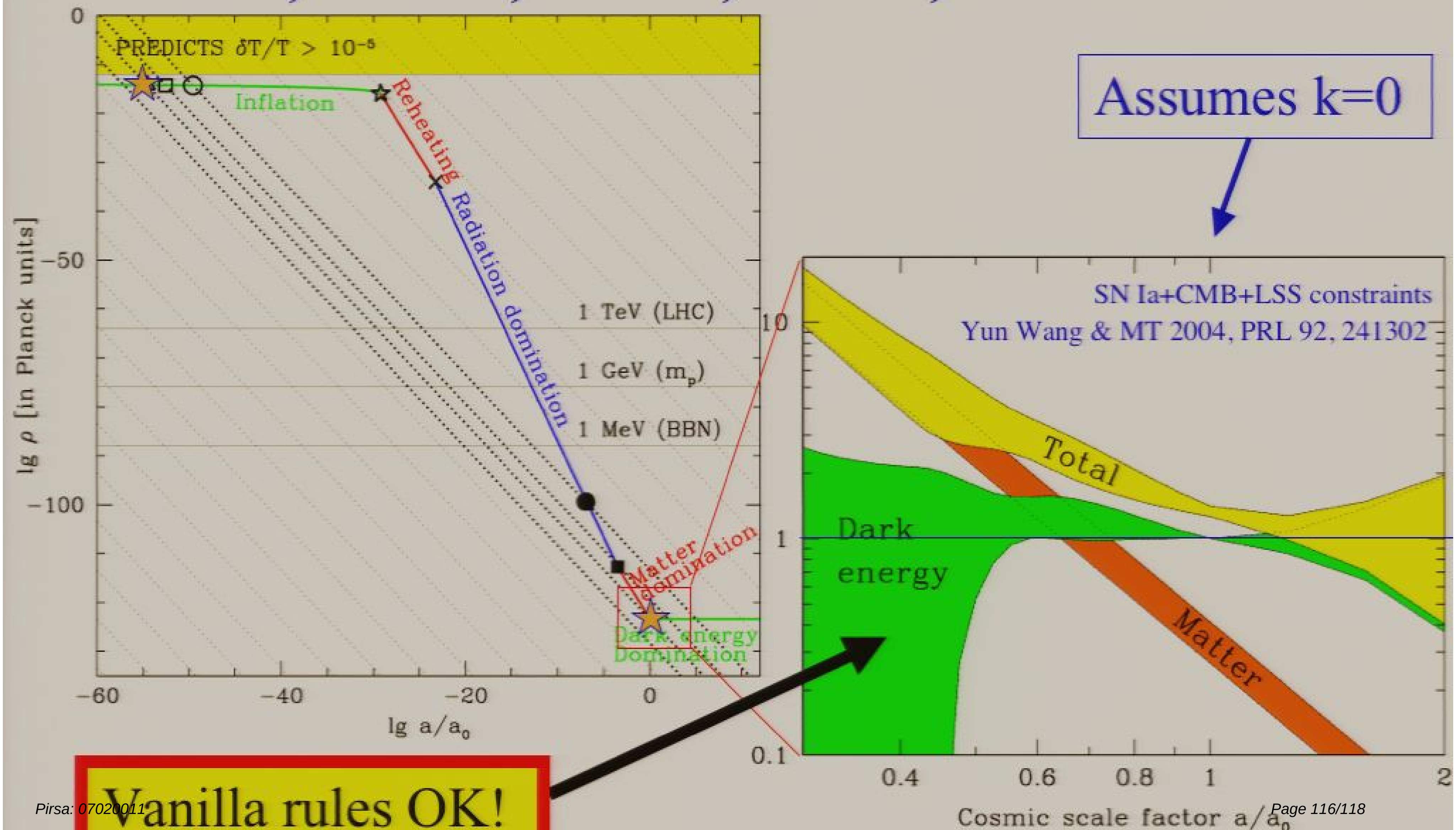


Vanilla rules OK!



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

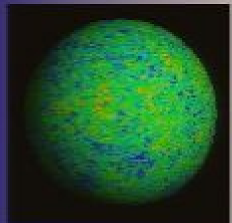
What we've learned about H(z) from SN Ia, CMB, BAO, BBN, etc:



Assumes k=0

Vanilla rules OK!

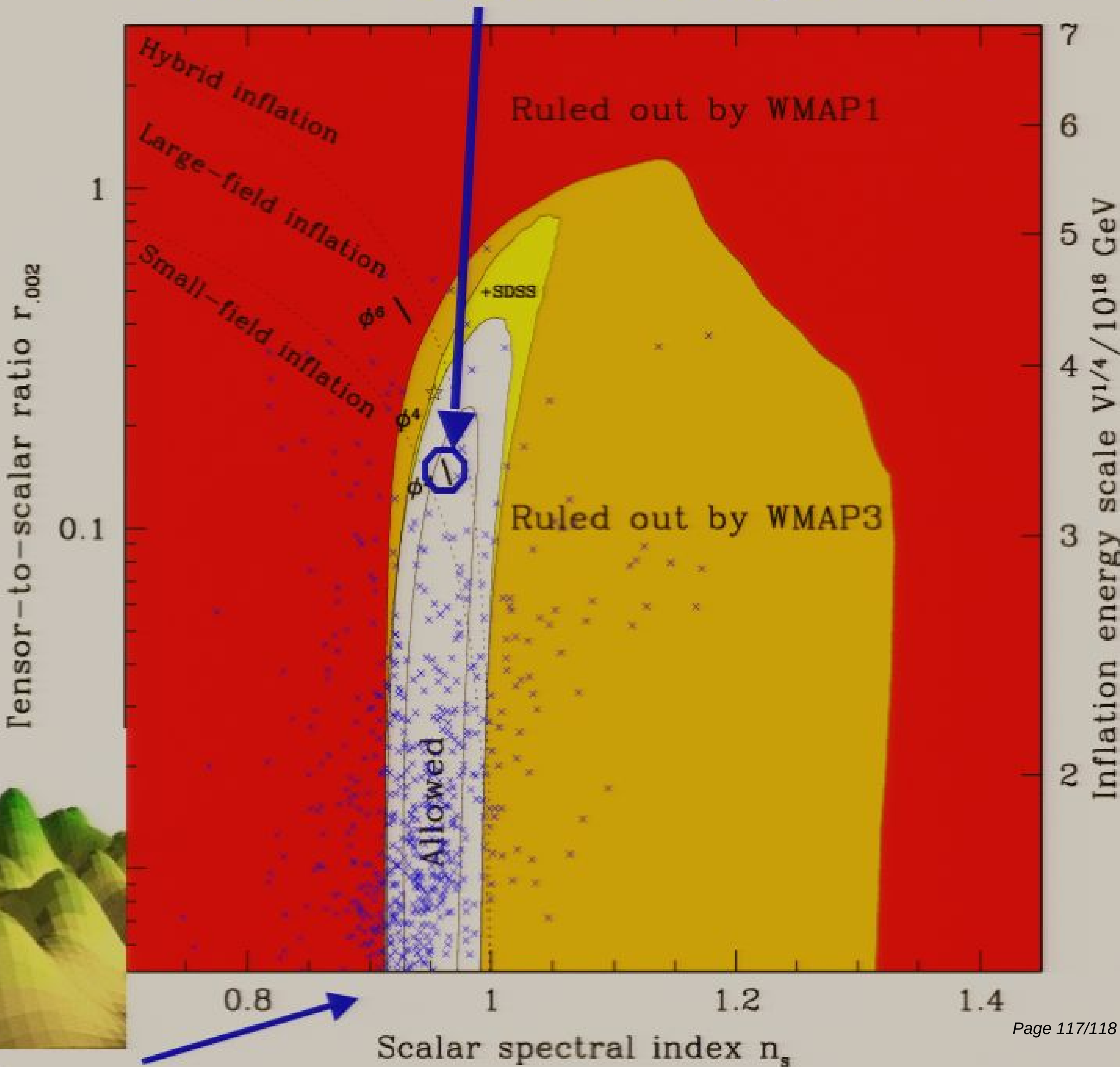
Planck + SDSS: $\Delta n=0.008$, $\Delta r=0.012$



CMB

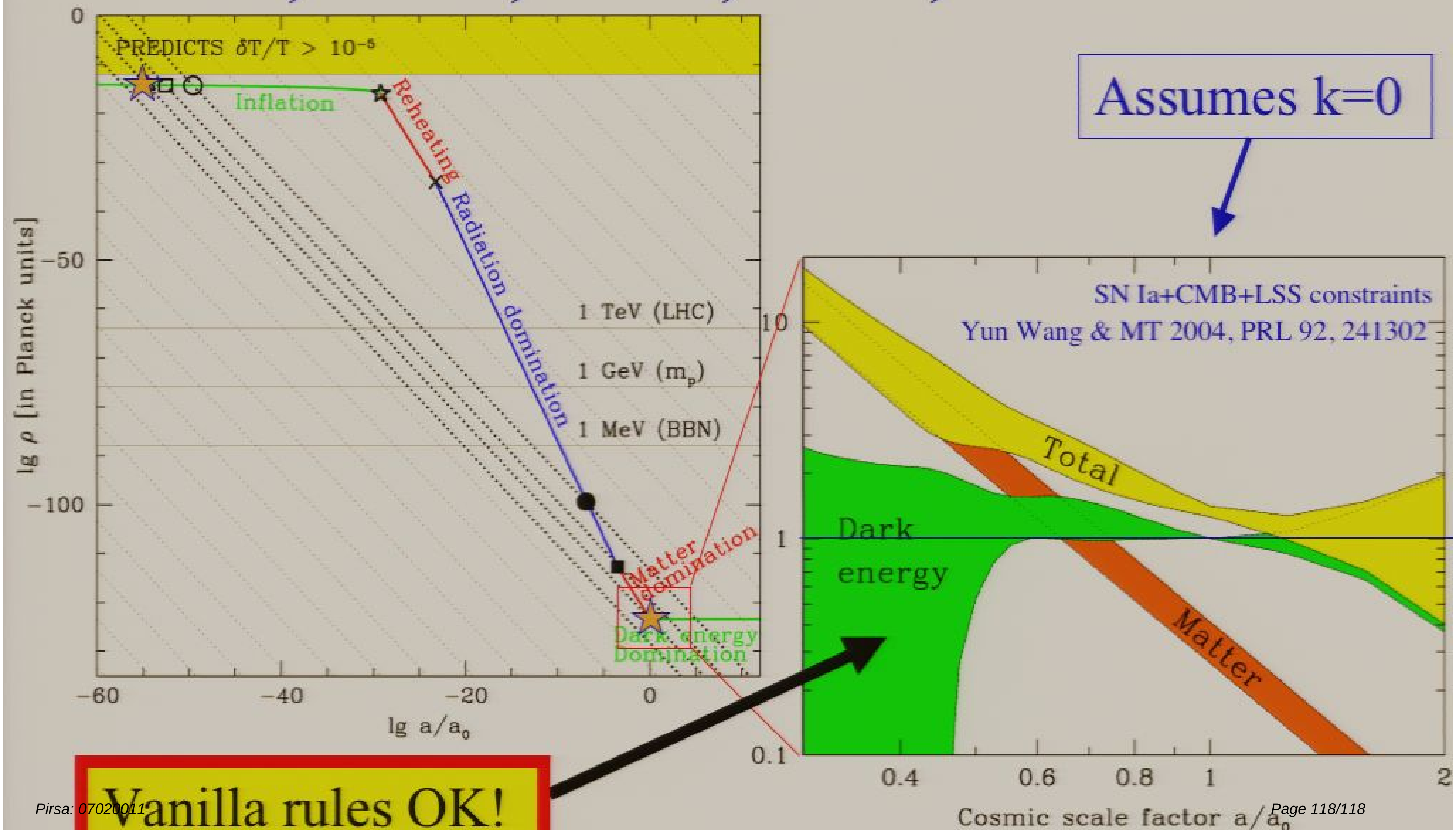
+

LSS



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

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



Assumes k=0

Vanilla rules OK!