Welcome back to 8.033!

Alan Guth

Summary of cosmology so far:

Key formula summary

Interpretation of **r**, t, a, comoving

- FRW metric:

$$d\tau^2 = dt^2 - a(t)^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2 \right)$$

- Hubble parameter:

$$H \equiv \frac{\dot{a}}{a}$$

- Dimensionless current Hubble parameter:

$$h \equiv H_0/(100\text{km s}^{-1}\text{Mpc}^{-1}) \approx H_0 \times 9.7846\text{G}$$

- Friedmann equation:

$$\begin{aligned} H^2 &= \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} \\ &= H_0^2 \left[\Omega_\gamma (1+z)^4 + \Omega_\text{m}(1+z)^3 + \Omega_\text{k}(1+z)^2 + \Omega_\Lambda \right] \end{aligned}$$

- Cosmological parameter measurements (2005):
  - $\Omega_b \approx 0.05$,
  - $\Omega_d \approx 0.25$,
  - $\Omega_\Lambda \approx 0.7$,
  - $\Omega_\text{k} \approx 0$,
  - $h \approx 0.70$,
  - $\Omega_\text{m} \equiv \Omega_b + \Omega_d \approx 0.3$,
- Age of the Universe at redshift z:

$$t(z) = \int_z^\infty \frac{dz'}{(1+z')H(z')}$$

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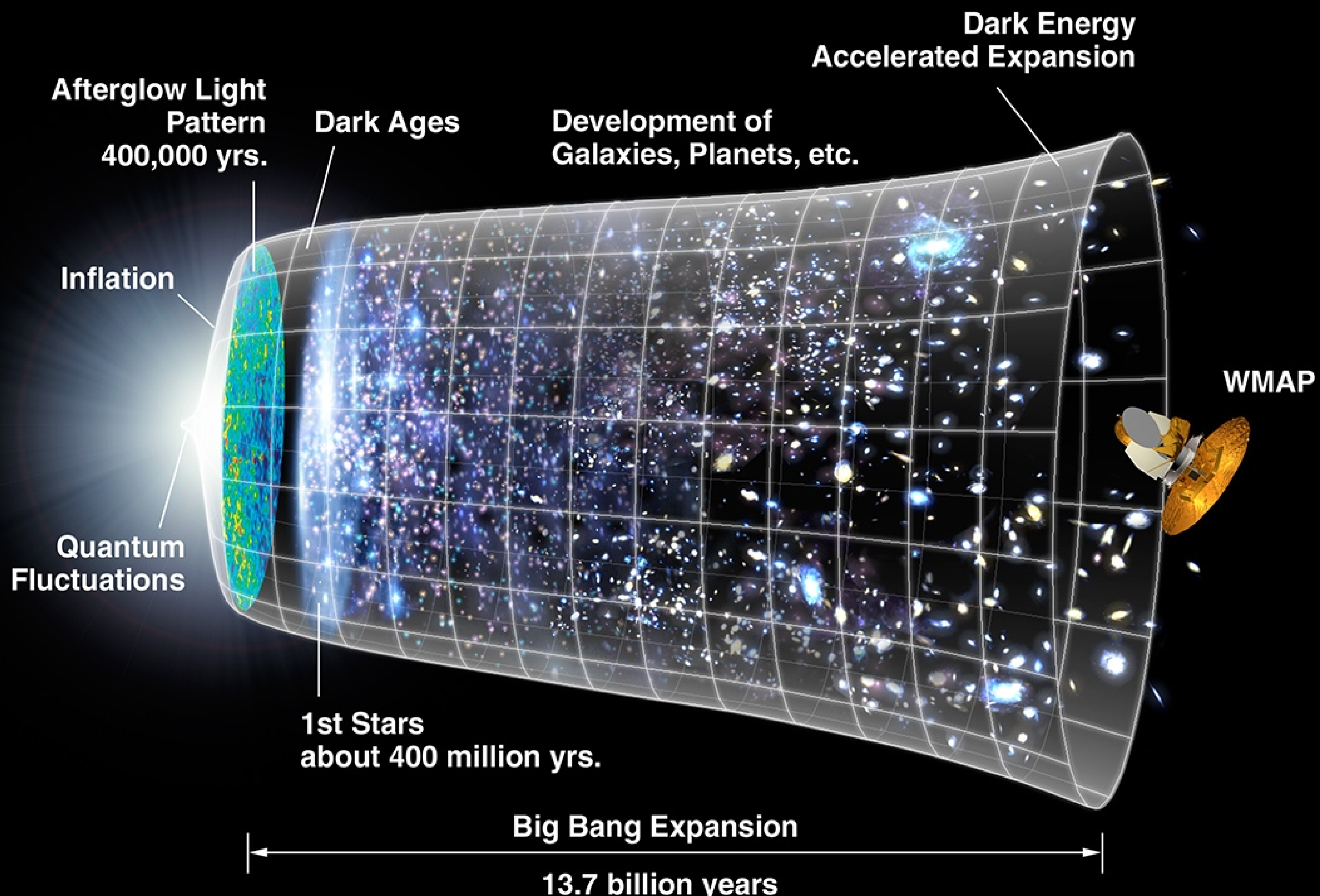


Image courtesy of WMAP/NASA.

Evidence 1:

The Universe *is* expanding!

$v = Hr$

Evidence 2:

Cosmic microwave background exists

$T \approx 2.726K$

Evidence 3:

Big Bang Nucleosynthesis happened

(correctly predicts the abundance of light elements)

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.

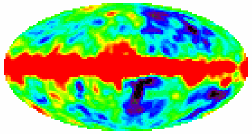
- *Not* evidence for a singularity

MIT Course 8.033, Fall 2006, Lecture 20

Max Tegmark

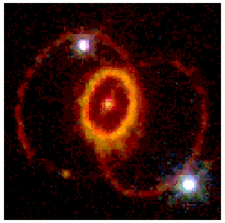
Today's topic: Cosmology roundup

- See nyd_darkenergy.pdf (Thanks Anthony Kesich!)
- Evidence for Big Bang?
- What do we know? Common misconceptions
- What don't we know? Hot research questions
- My "day job"

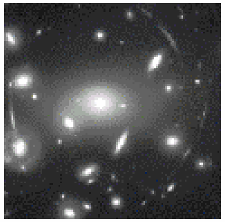


CMB

GALAXY
SURVEYS



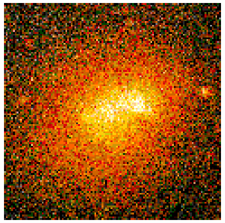
DISTANT
SUPERNOVAE



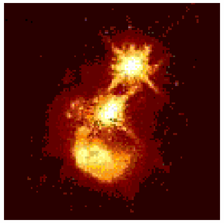
GRAVITATIONAL
LENSING

THE
COSMIC
SMÖRGÅSBORD

BIG BANG
NUCLEOSYNTHESIS



GALAXY
CLUSTERS



LYMAN ALPHA
FOREST

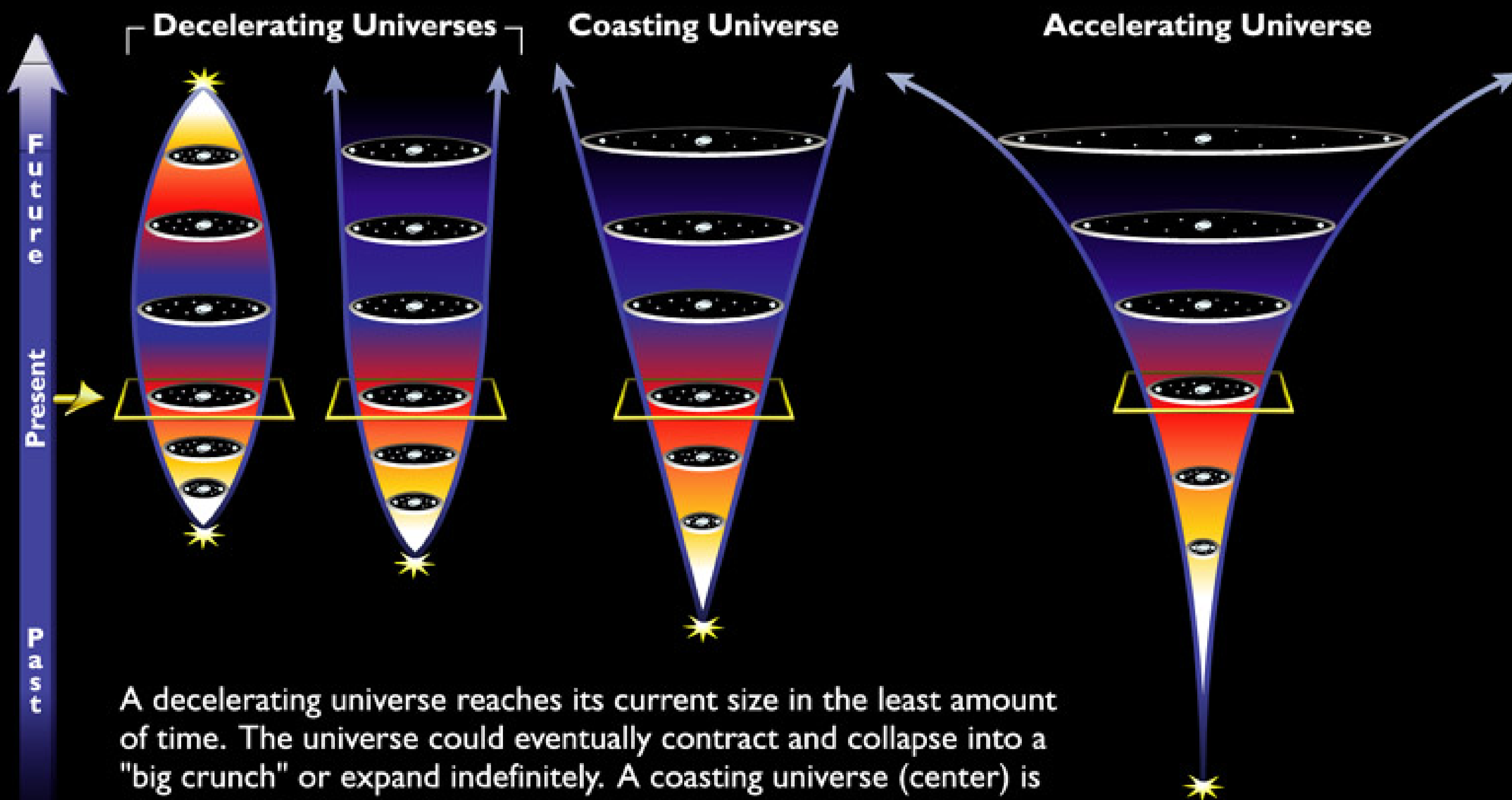
All images courtesy of NASA.

Mysteries for you to solve:

- What is dark matter?
- How did it all begin?
  (buzz word: inflation)
- How will it all end
  (buzz word: dark energy)

Mystery 1: How will it end?

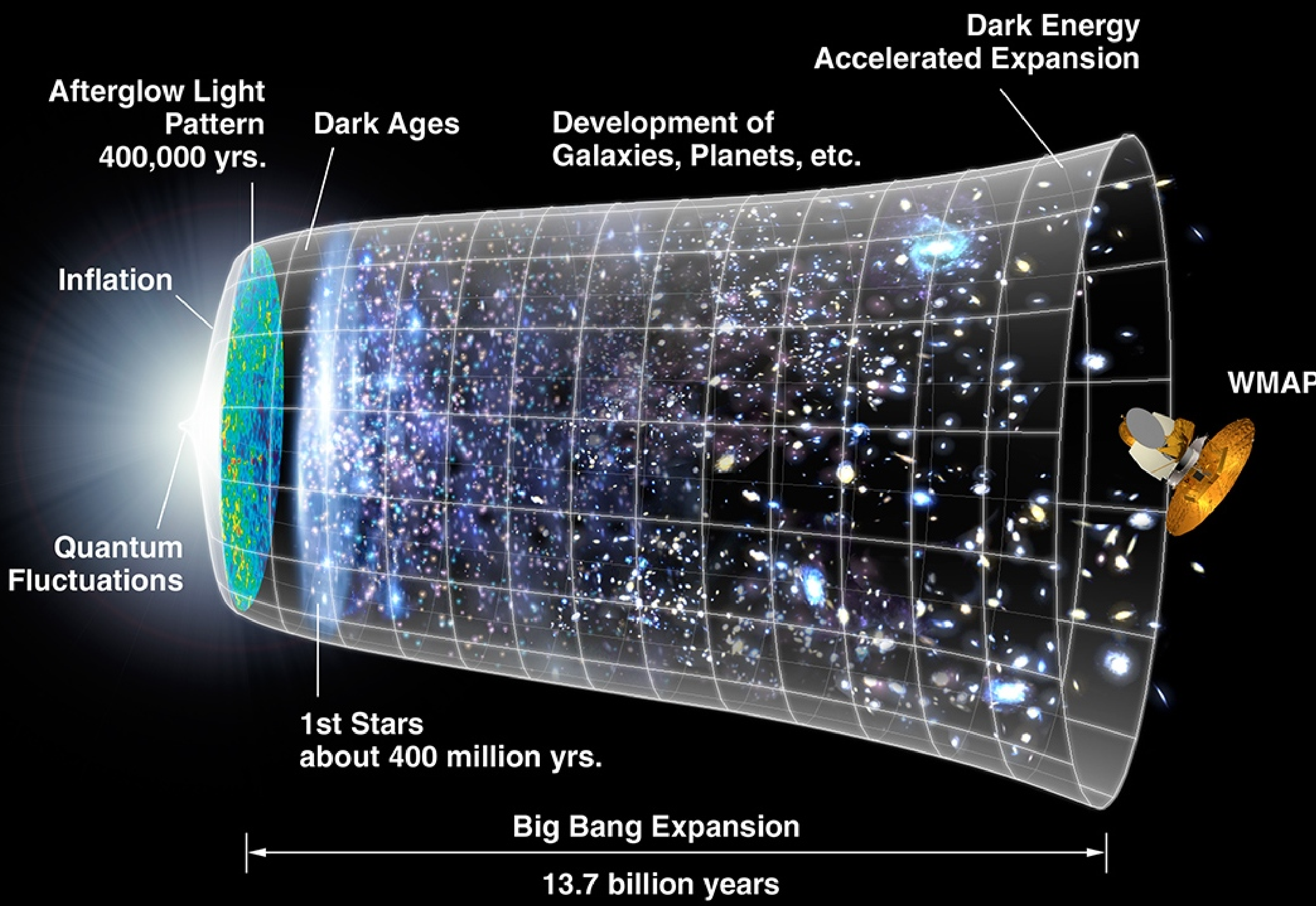
Possible Models of the Expanding Universe



A decelerating universe reaches its current size in the least amount of time. The universe could eventually contract and collapse into a "big crunch" or expand indefinitely. A coasting universe (center) is older than a decelerating universe because it takes more time to reach its present size, and expands forever. An accelerating universe (right) is older still. The rate of expansion actually increases because of a repulsive force that pushes galaxies apart.

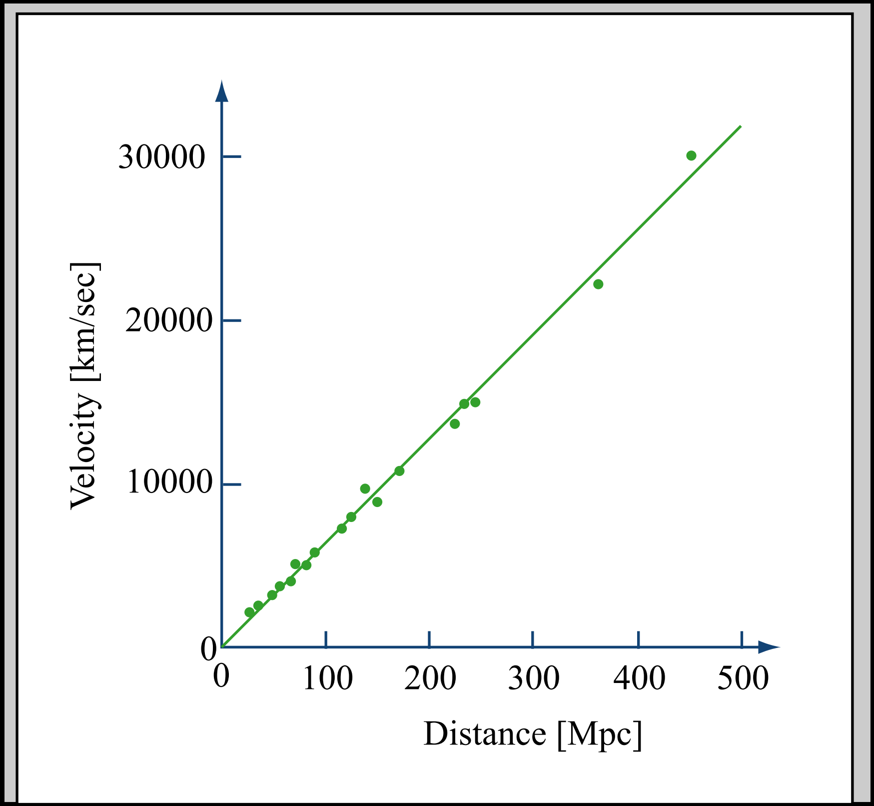
Image courtesy of NASA

Distant light is $\begin{cases} \text{-dimmed} \\ \text{-redshifted} \end{cases}$



Distant light is $\begin{cases} \text{-dimmed} \\ \text{-redshifted} \end{cases}$

Redshift

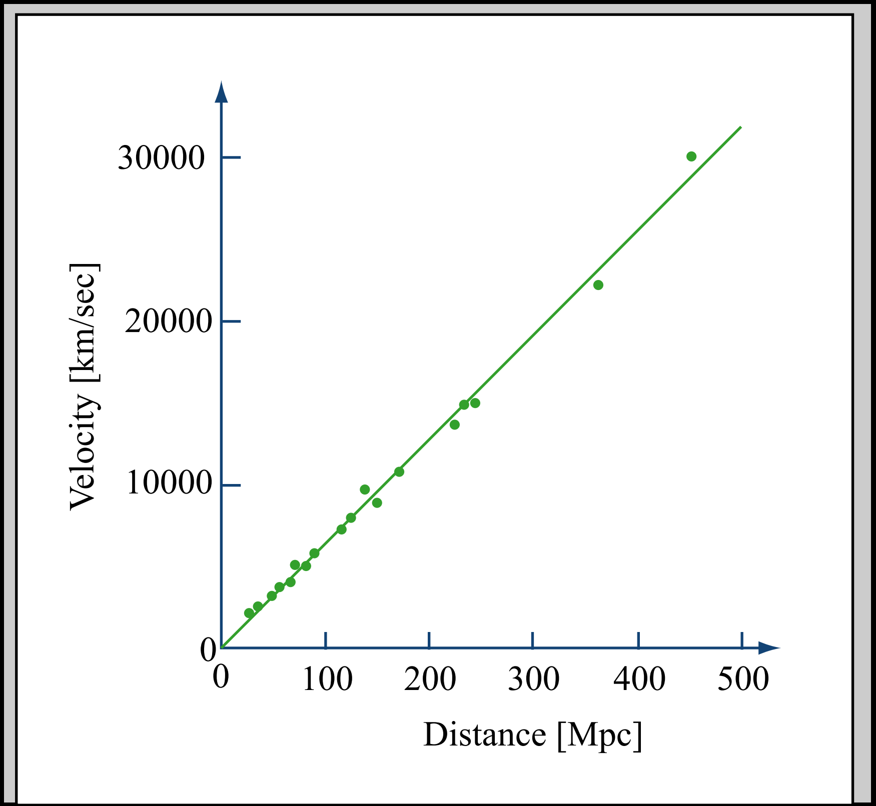


Dimming

Figure by MIT OCW.

Distant light is $\begin{cases} \text{-dimmed} \\ \text{-redshifted} \end{cases}$

Redshift



Dimming

Figure by MIT OCW.

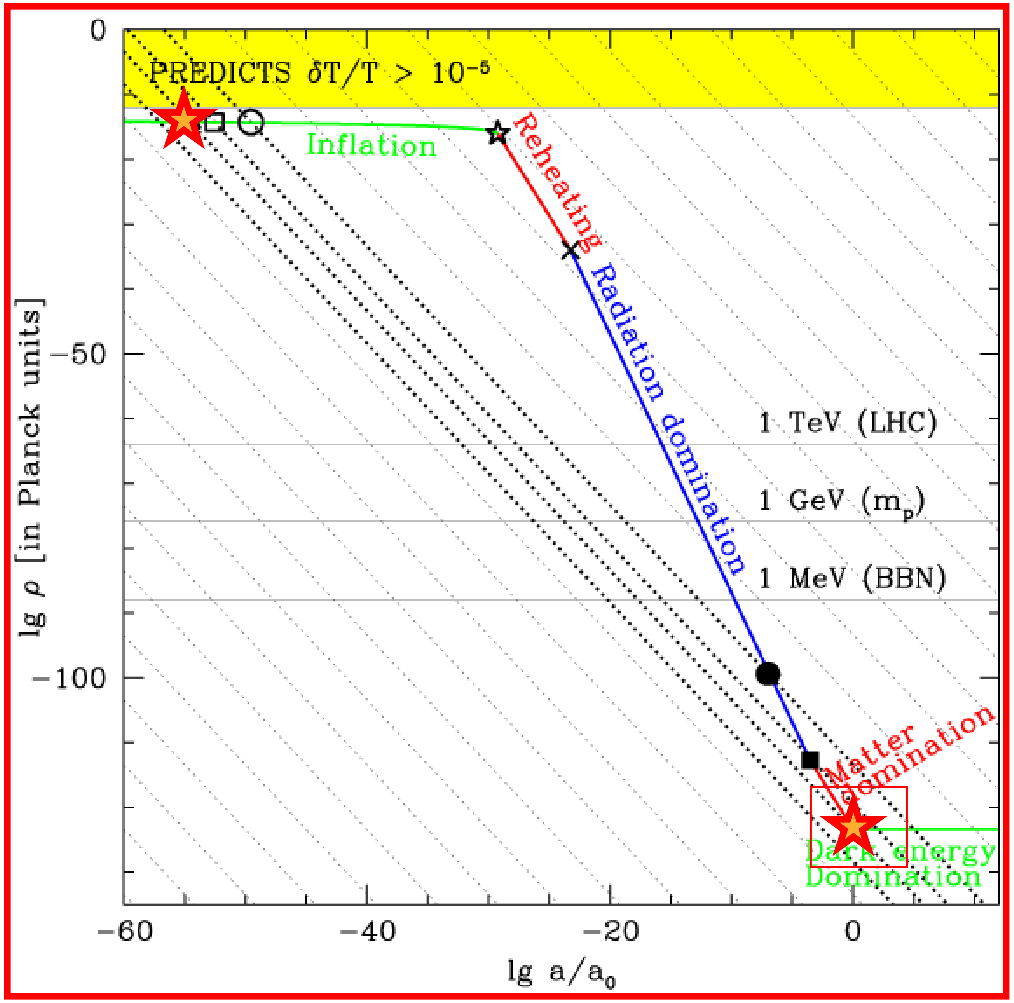
Standard candles, rulers or clocks

Boom
zoom

From Saul Perlmutter's web site

Figure 12 from Reiss et al, "New Hubble Space Telescope Discoveries of Type Ia Supernovae at $z > 1$: Narrowing Constraints on the Early Behavior of Dark Energy." http://arxiv.org/abs/astro-ph/0611572

$$H = d\ln a/dt, \qquad H^2 \propto \rho$$



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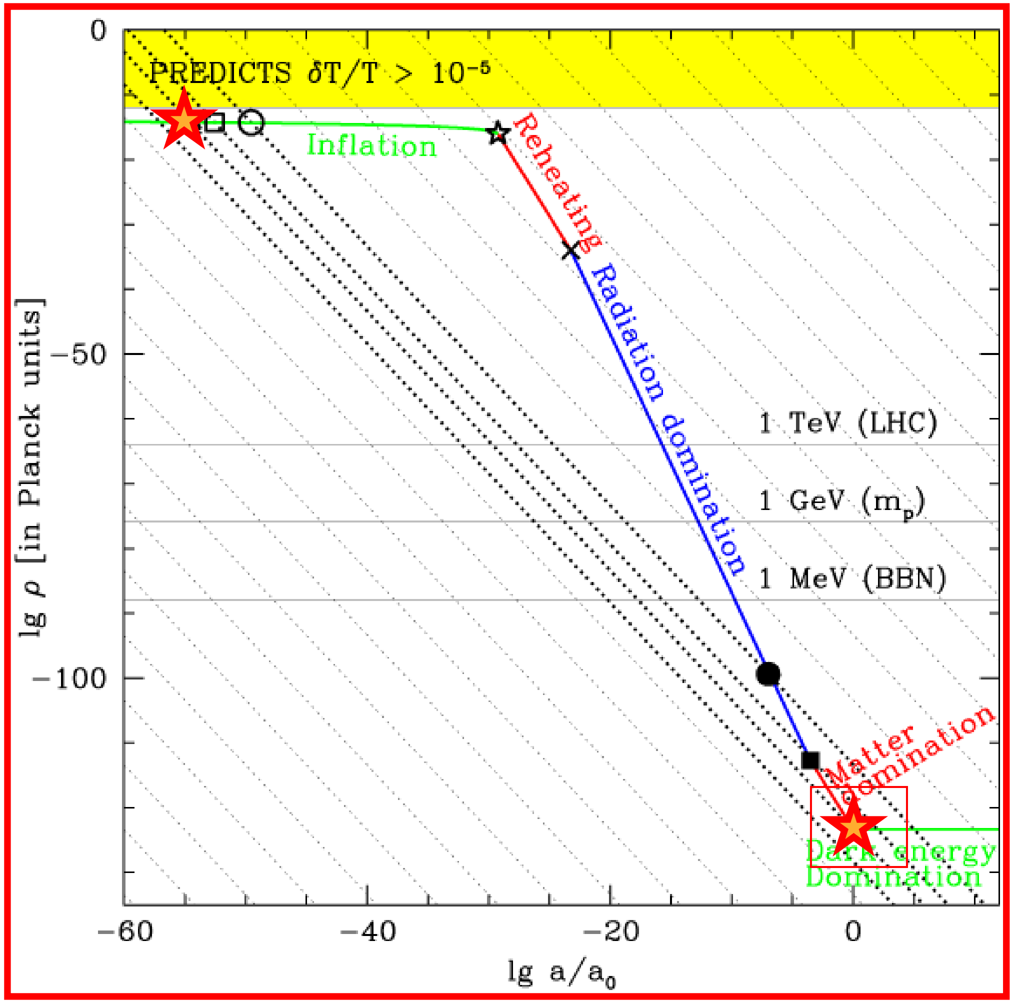


Figure removed due to copyright restrictions.

Figure 1 from Yun Wang & Max Tegmark," New Dark Energy Constraints from Supernovae, Microwave Background, and Galaxy Clustering" *Phys Rev Lett* **92**, 241302 (2004).

Mystery 2: What is dark matter?

Brief History of our Universe

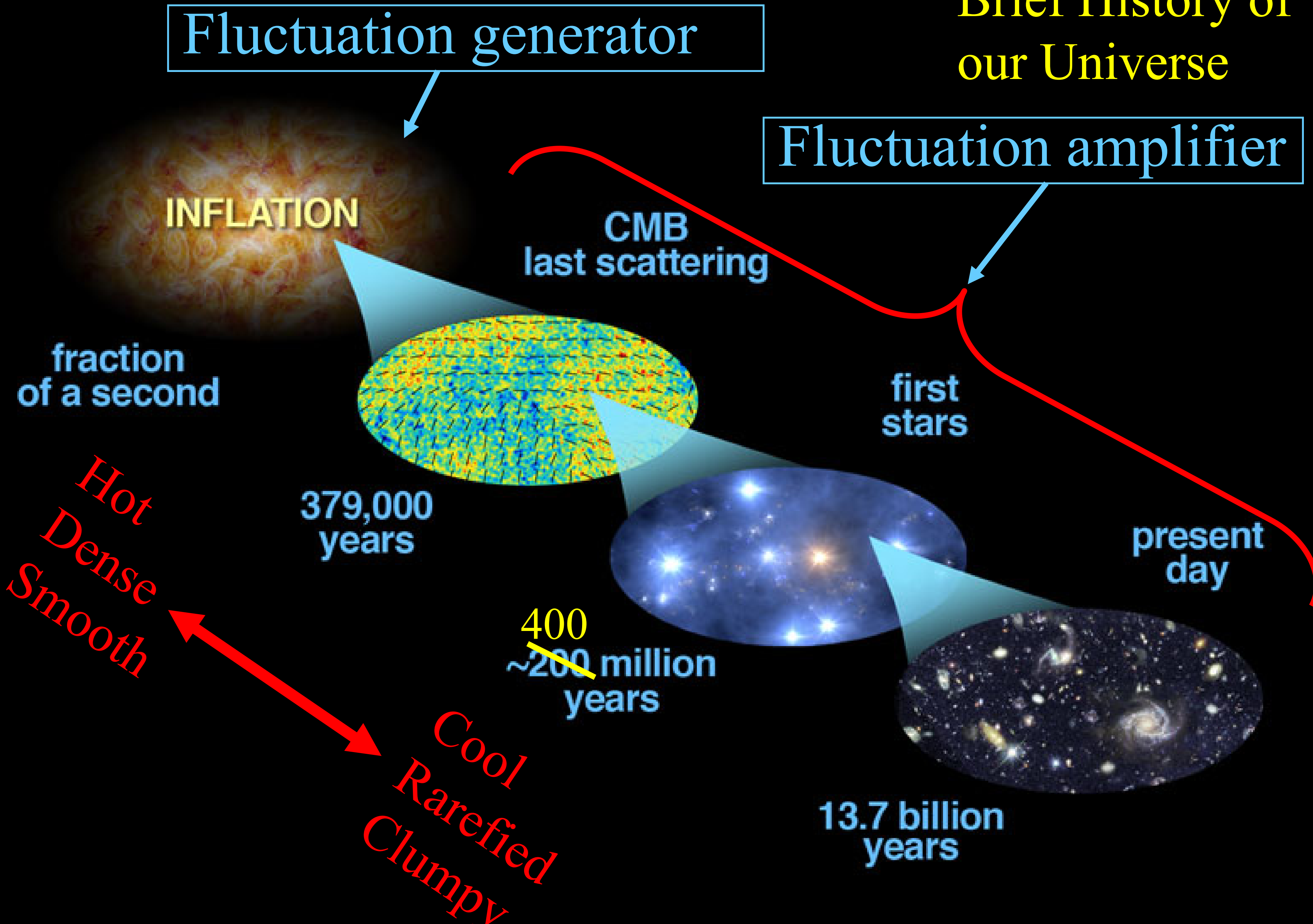


Image courtesy of WMAP/NASA.

What do we want to measure?

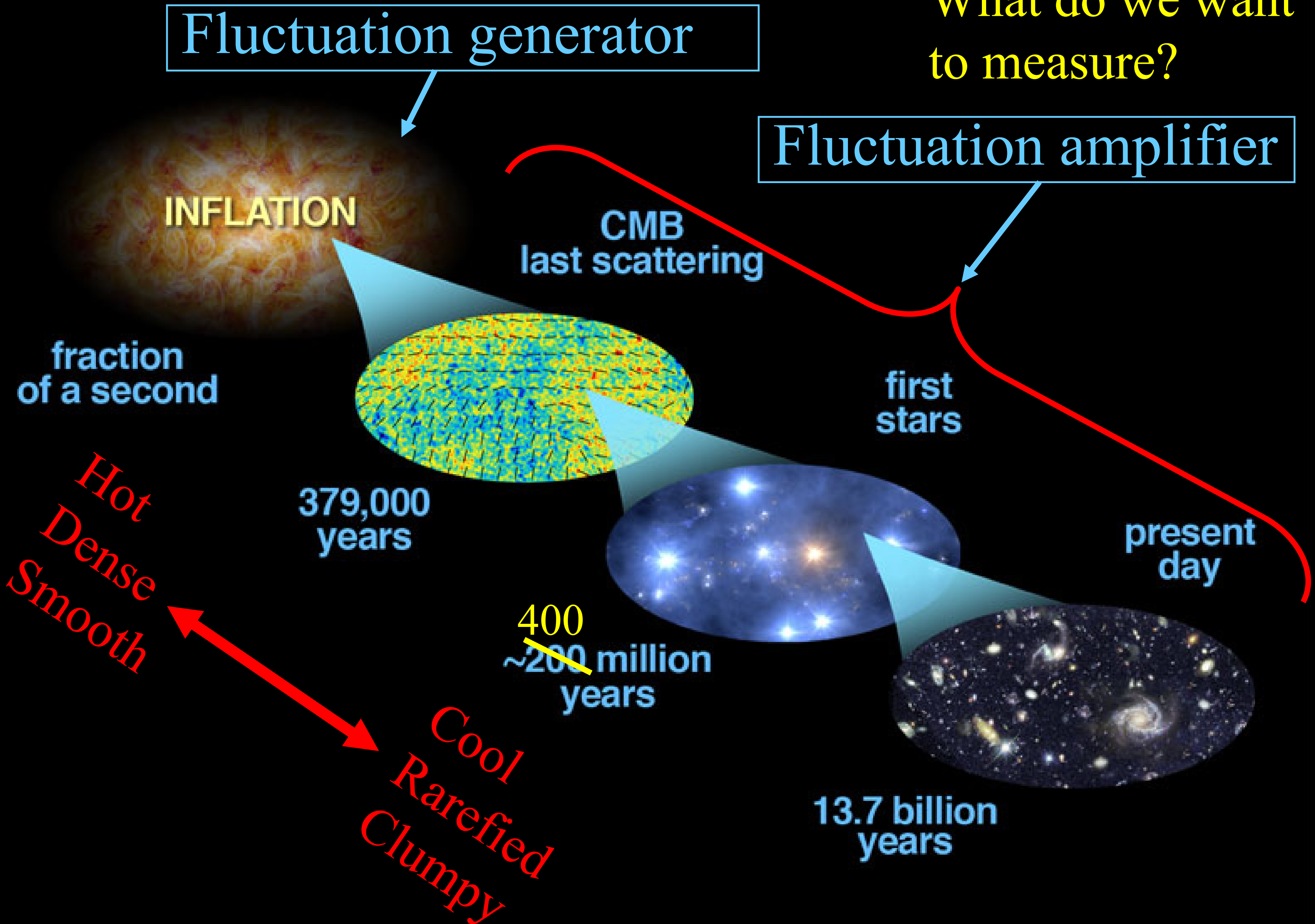


Image courtesy of WMAP/NASA.

Evidence 4:

The fine details of cosmic clumpiness

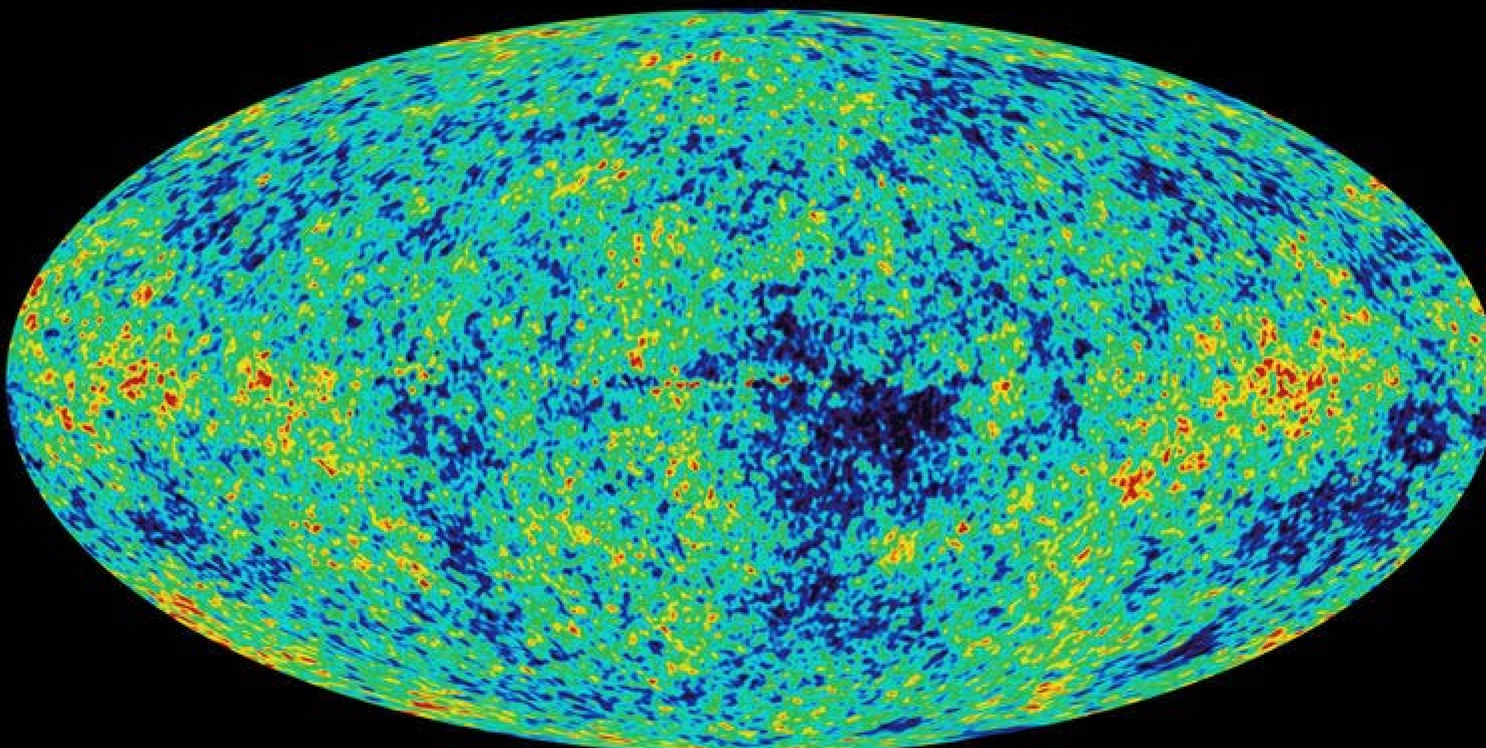
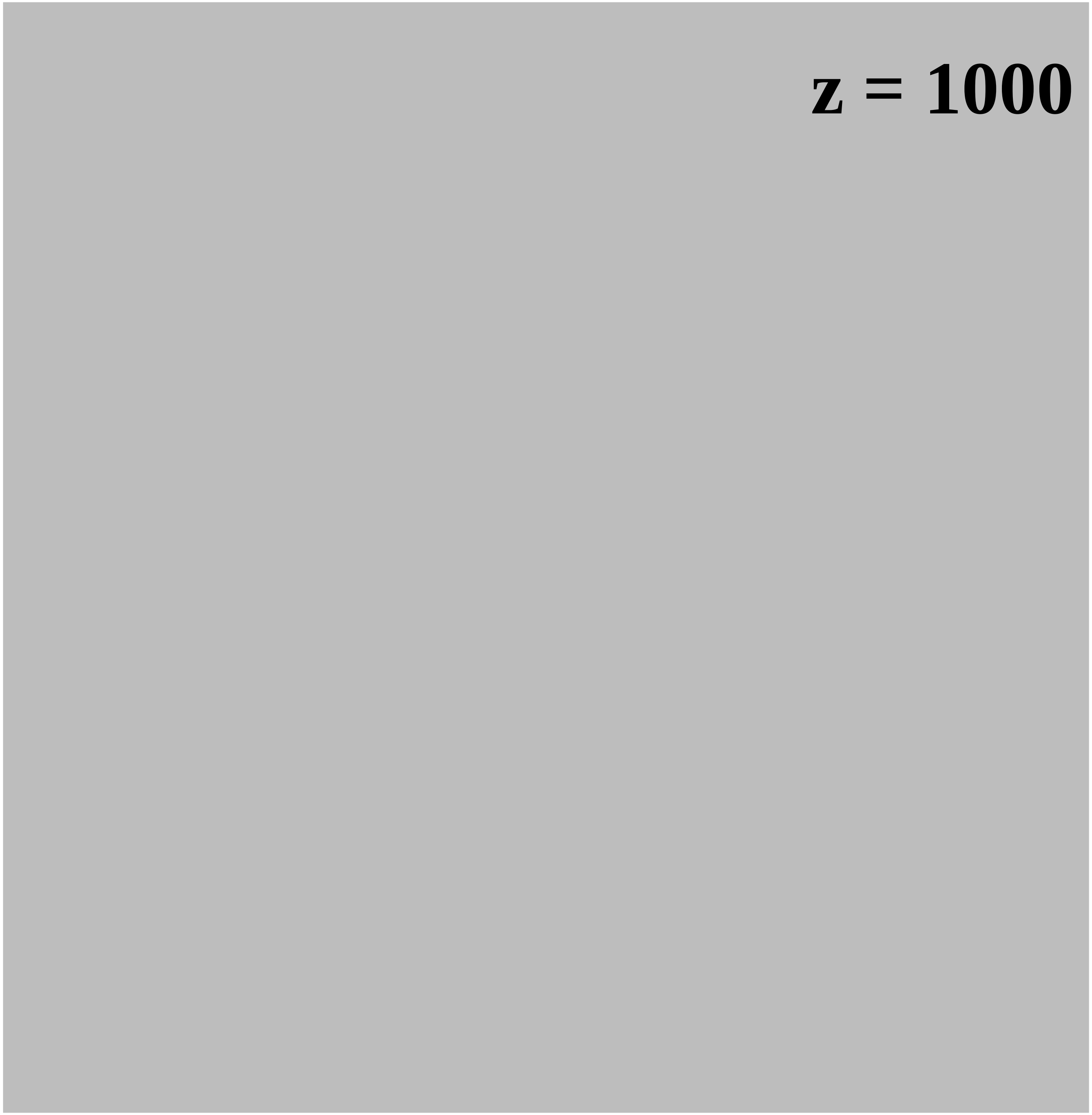
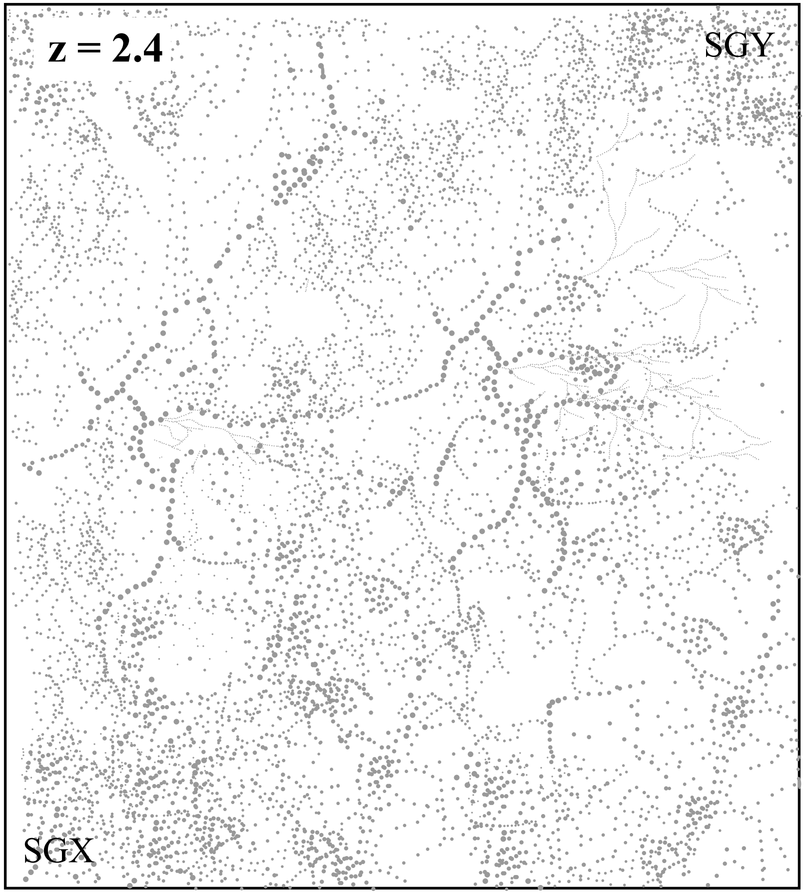


Image courtesy of NASA.


z = 1000

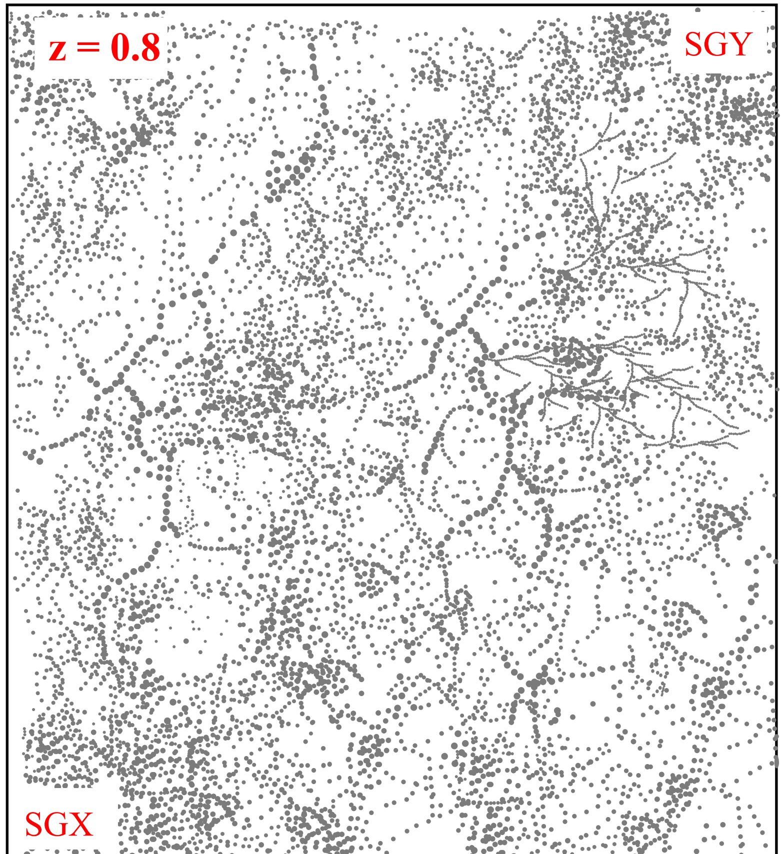
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



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

Figure by MIT OCW.

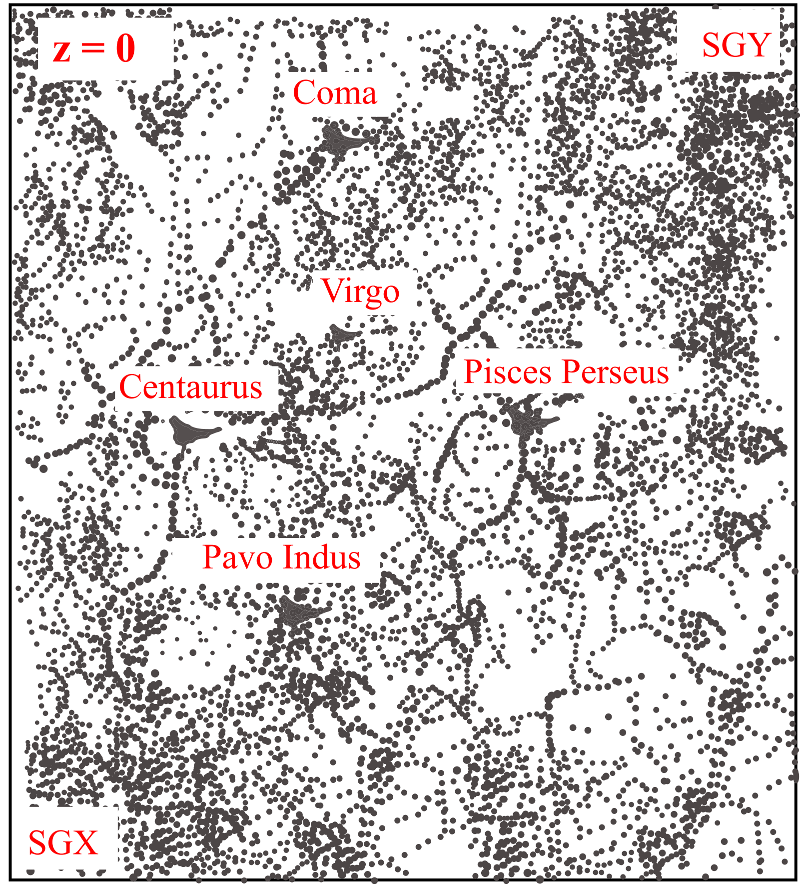
Mathis, Lemson, Springel, Kauffmann, White & Dekel 2001



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

Figure by MIT OCW.

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

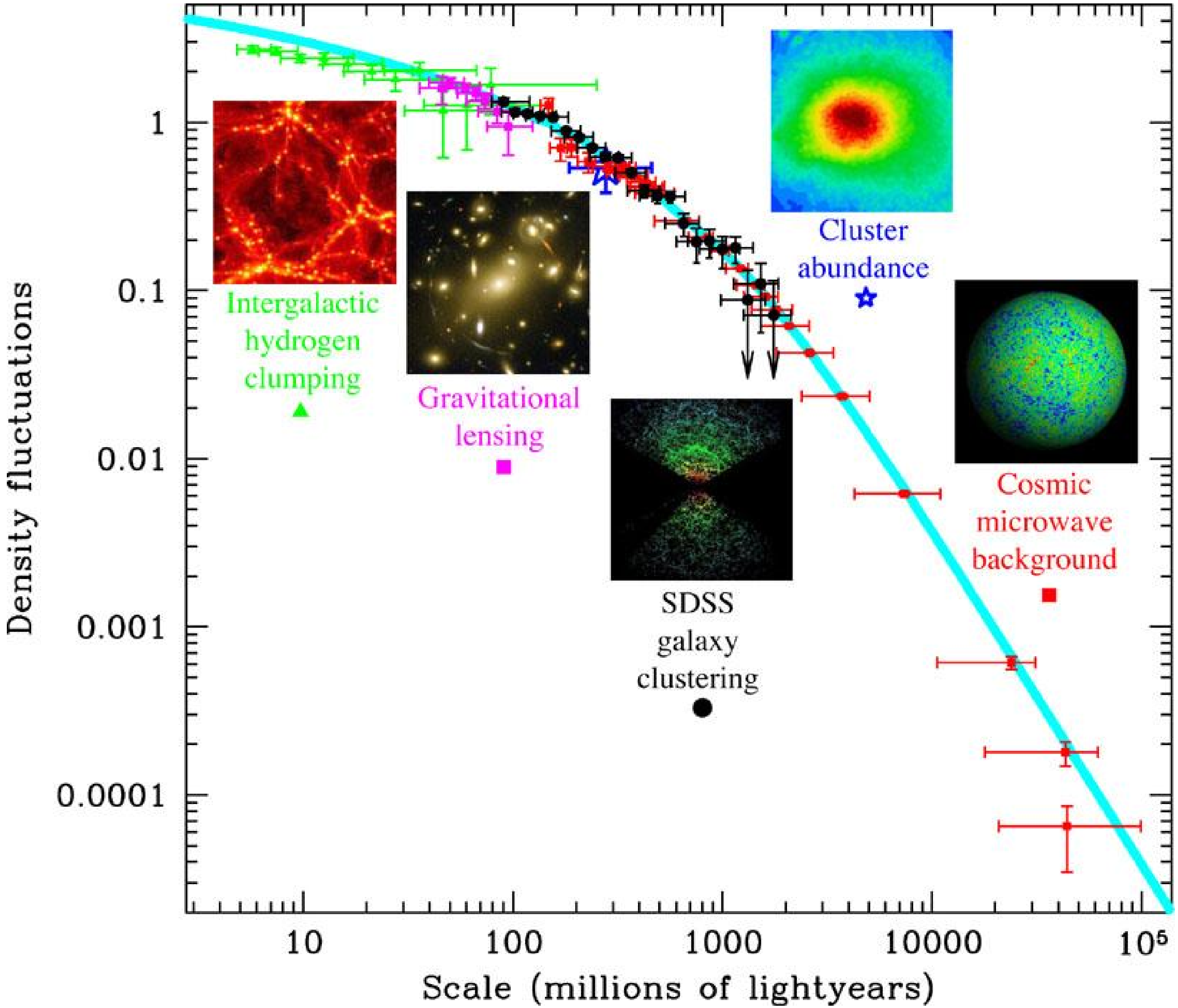


ΛCDM local Universe (Λ= 0.7, Ω = 0.3, h = 0.7)
Constrained within 8000 km/s by the IRAS 1.2 Jy survey

Figure by MIT OCW.

Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

http://www.arxiv.org/abs/astro-ph/0207047



Density fluctuations
1
0.1
0.01
0.001
0.0001
10
100
1000
10000
10⁵
Scale (millions of lightyears)
Intergalactic hydrogen clumping
Gravitational lensing
SDSS galaxy clustering
Cluster abundance
Cosmic microwave background

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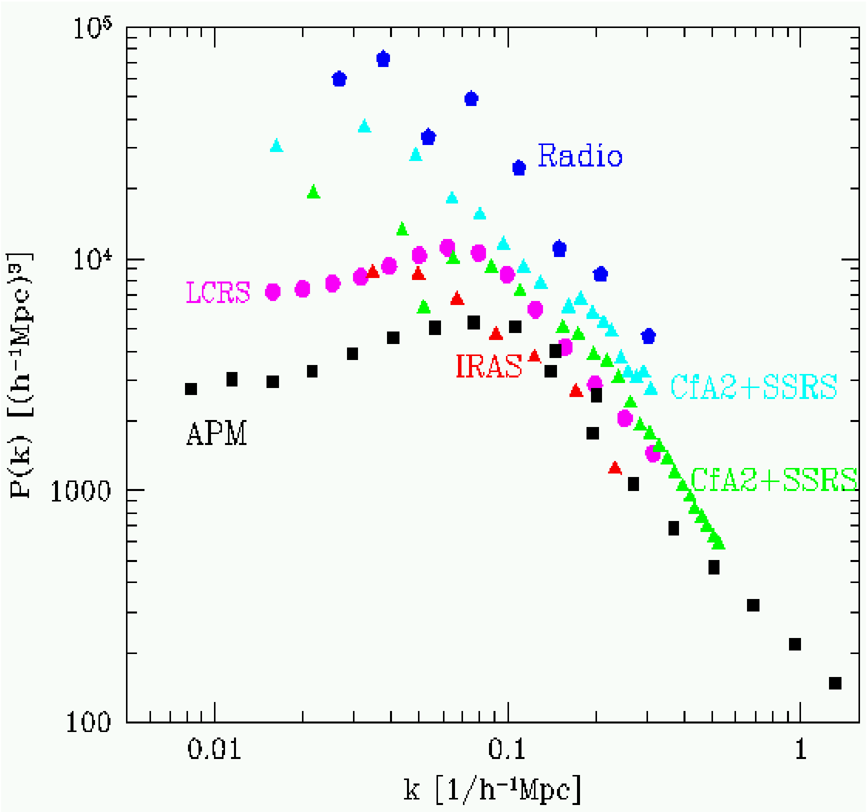

Galaxy power spectrum measurements 1999
(Based on compilation by Michael Vogeley)

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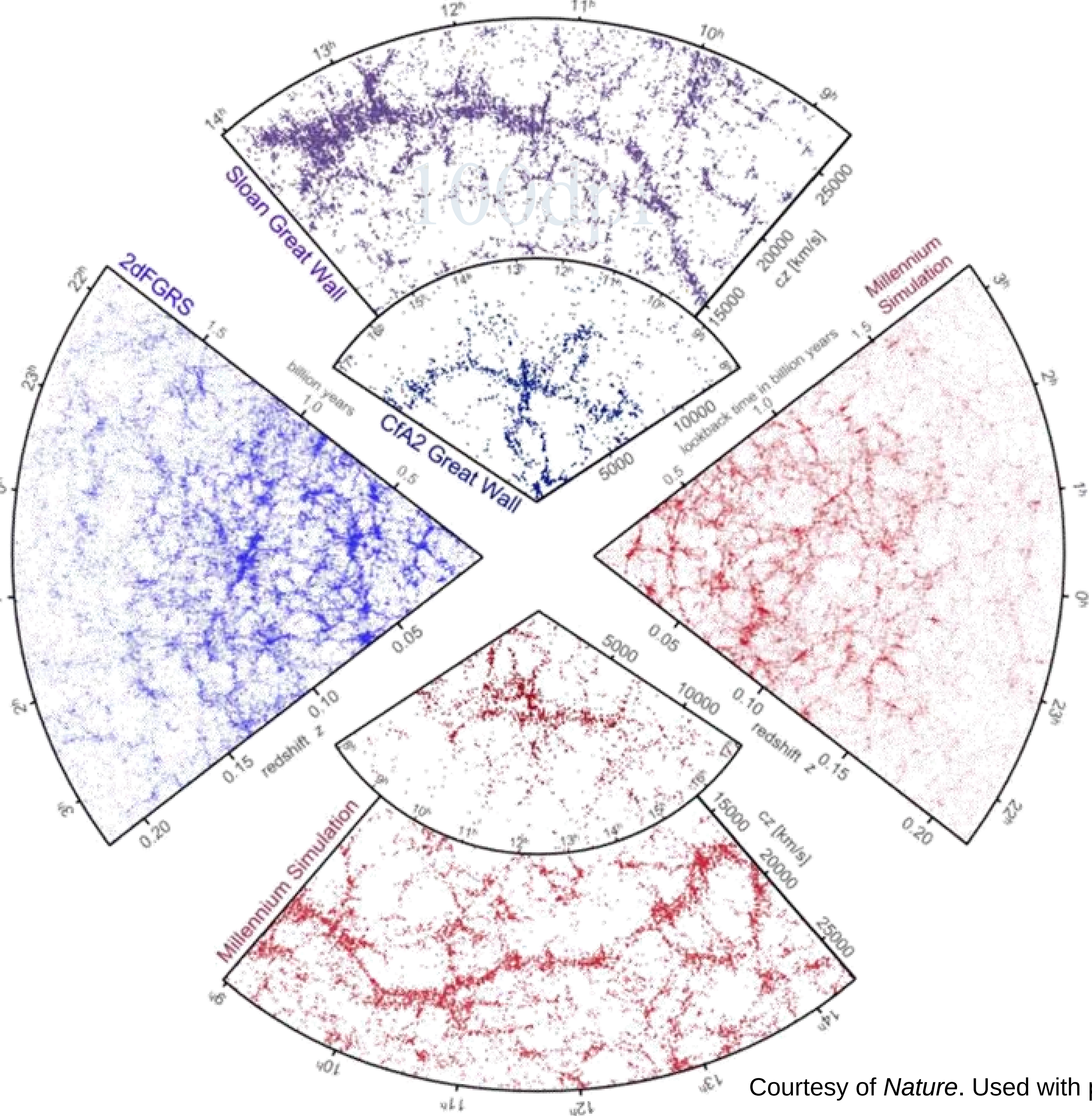
http://www.arxiv.org/abs/astro-ph/0207047

SDSS

Image courtesy of Wikipedia.

Figure removed due to copyright restrictions.

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



Theory and measurement agree!

Figure 4 from Tegmark et al, “Cosmological Constraints from the SDSS Luminous Red Galaxies”,

http://arxiv.org/abs/astro-ph/0608632

Figure 9 from Tegmark & Zaldarriaga, “Separating the Early Universe from the Late Universe: cosmological parameter estimation beyond the black box.”

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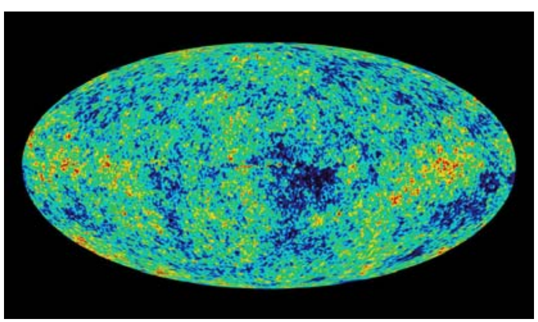
Image courtesy of NASA.

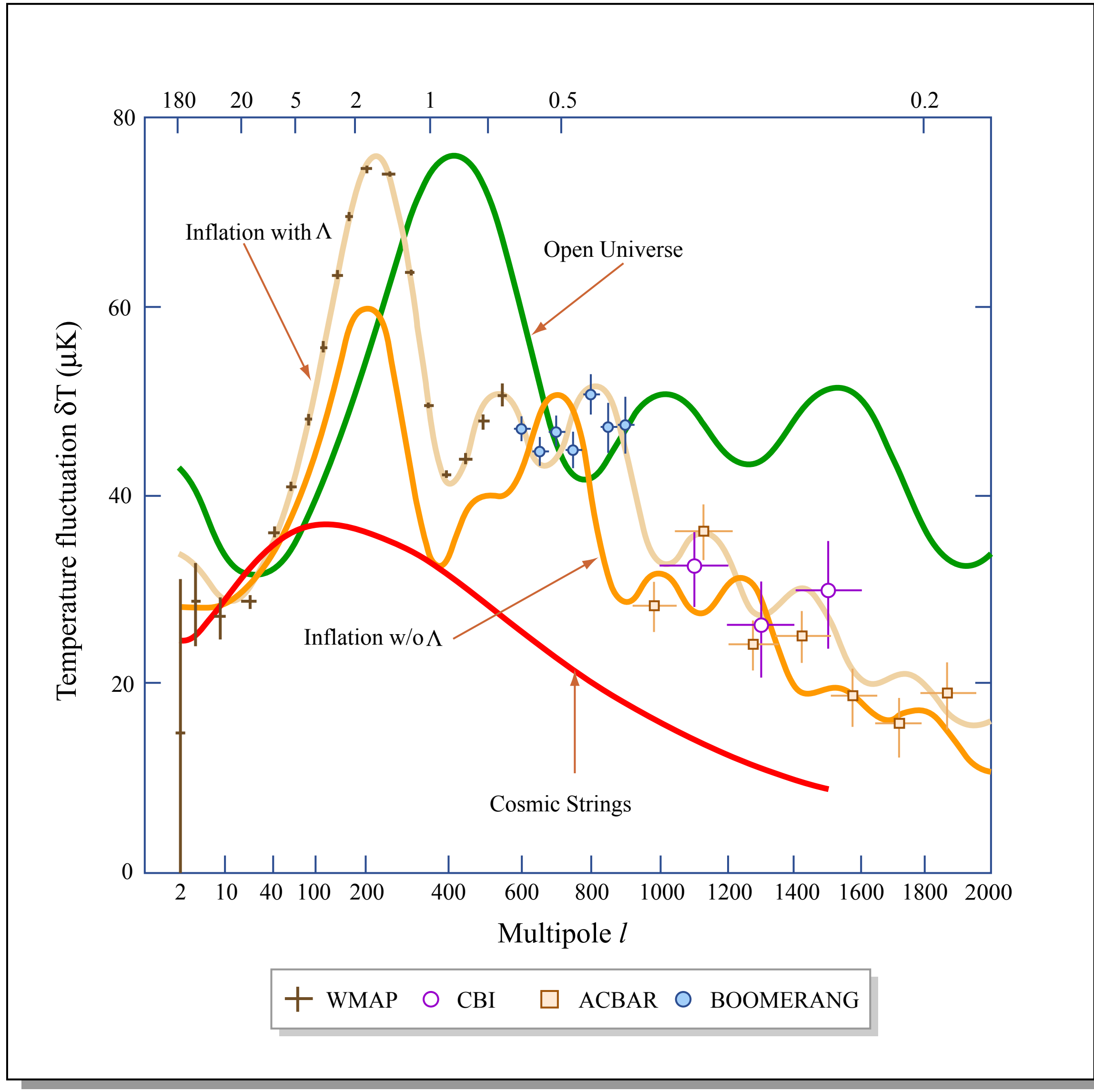

Figure by MIT OCW.

Guth & Kaiser 2005, Science

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LyαF

Lyman Alpha Forest Simulation: Cen et al 2001
astro-ph/0407378

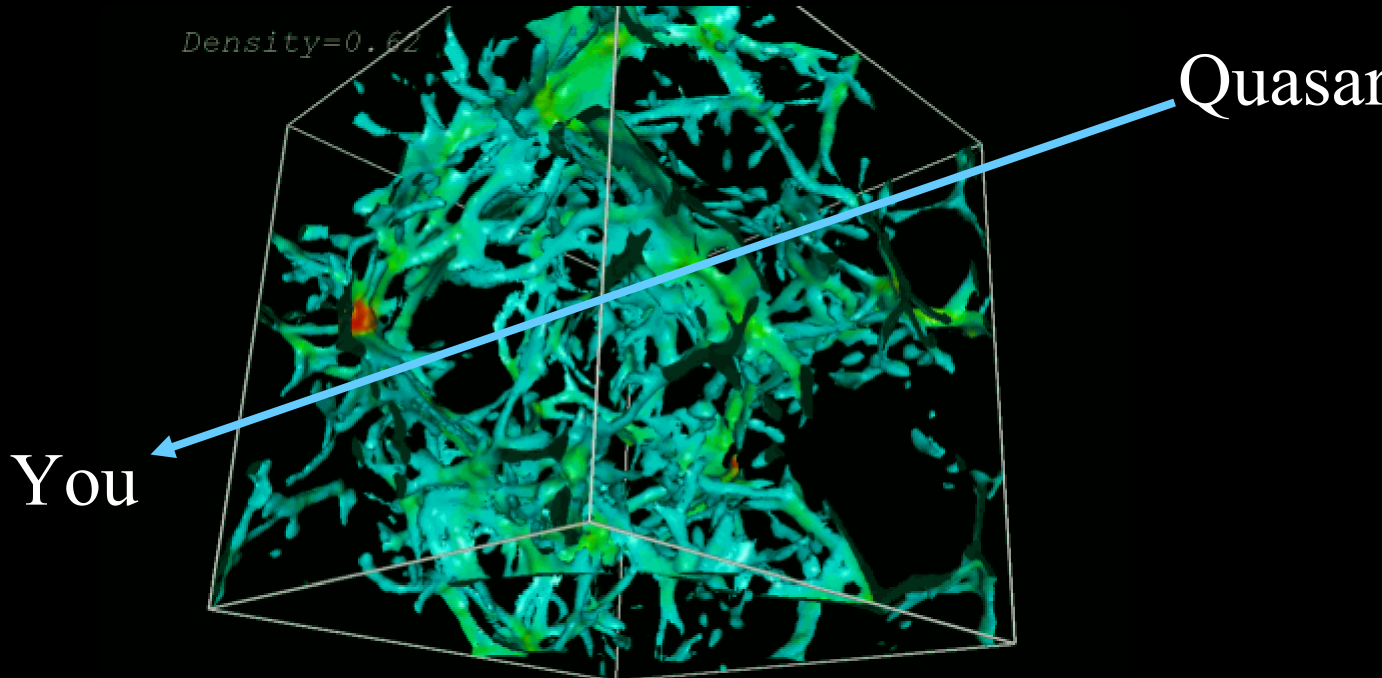

Image courtesy of NASA.

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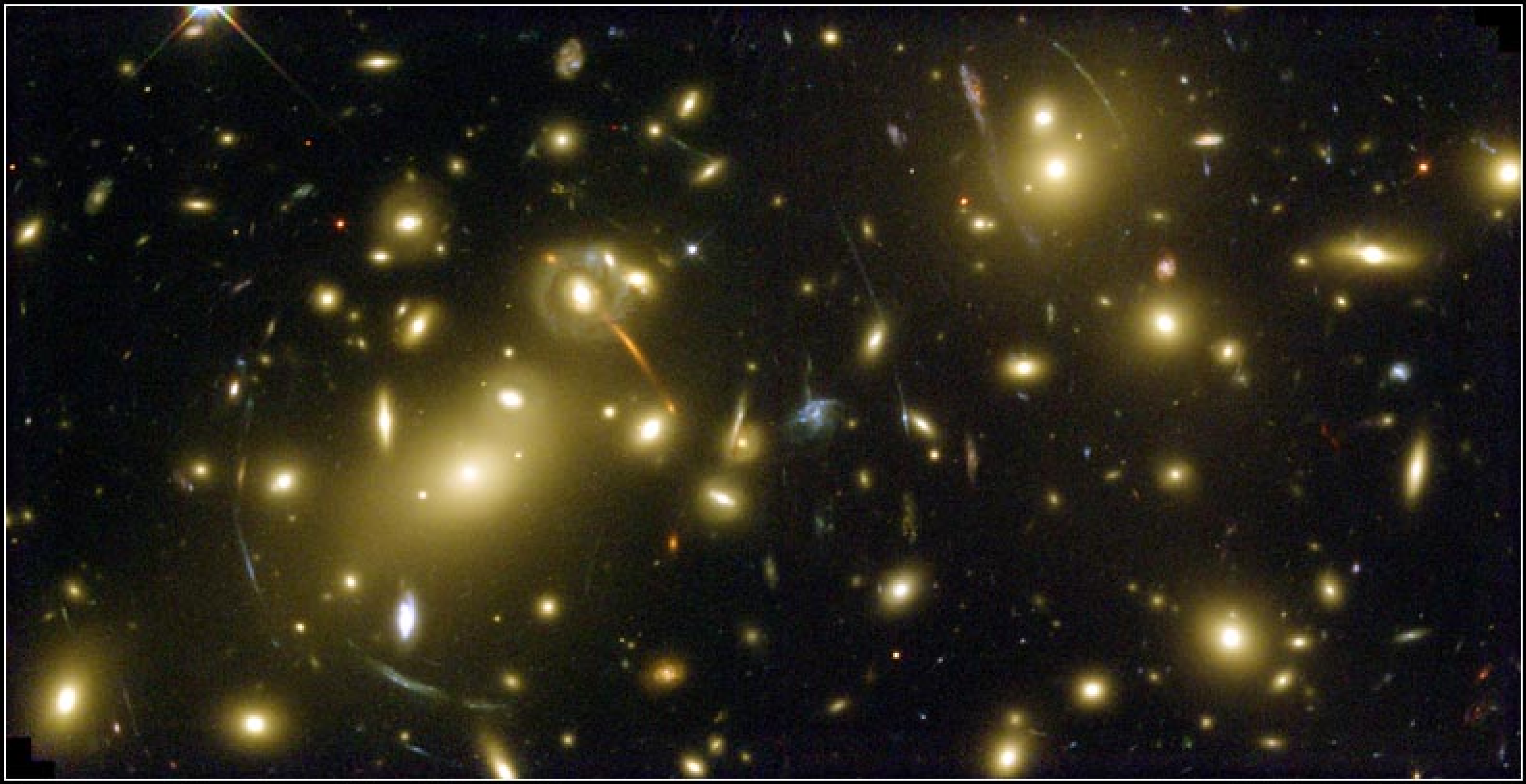
Lensing

Gravitational lensing



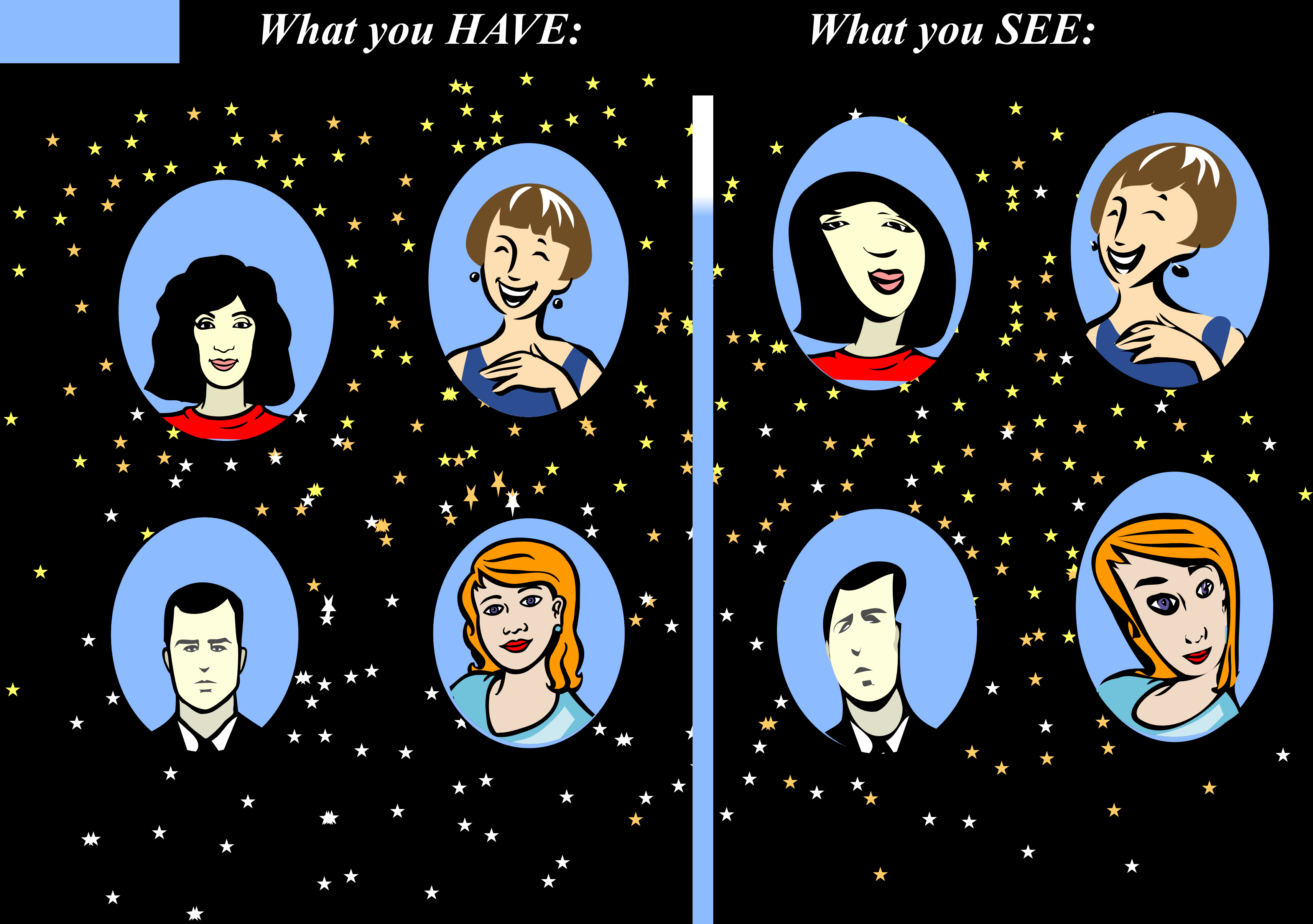
Galaxy Cluster Abell 2218

NASA, A. Fruchter and the ERO Team (STScI, ST-ECF) • STScI-PRC00-08

HST • WFPC2

Image courtesy of NASA.

Lensing



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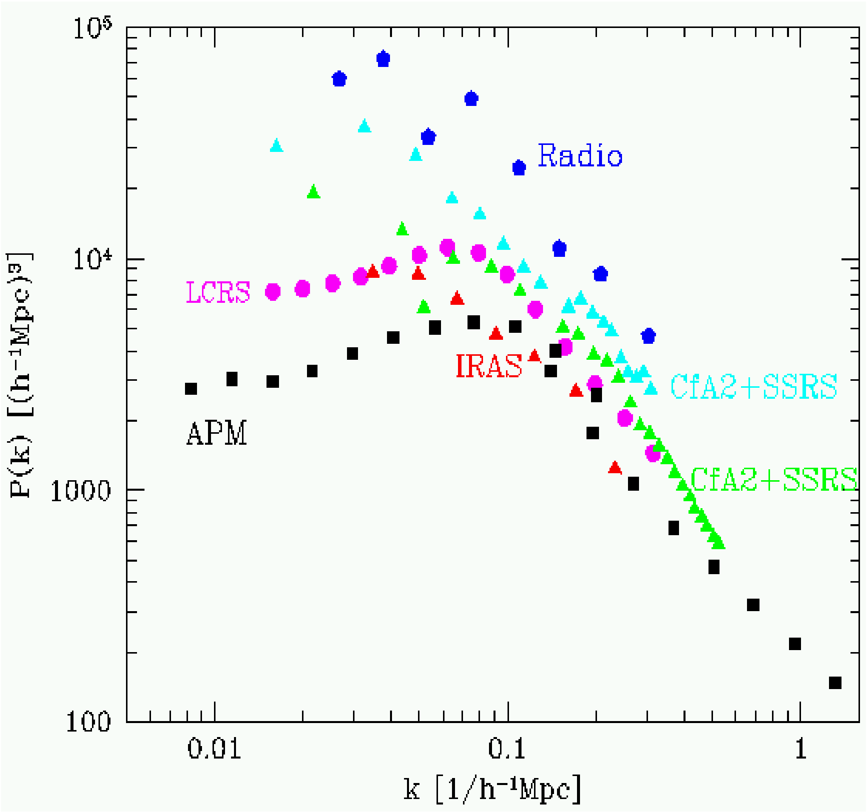

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But the best is yet to come…

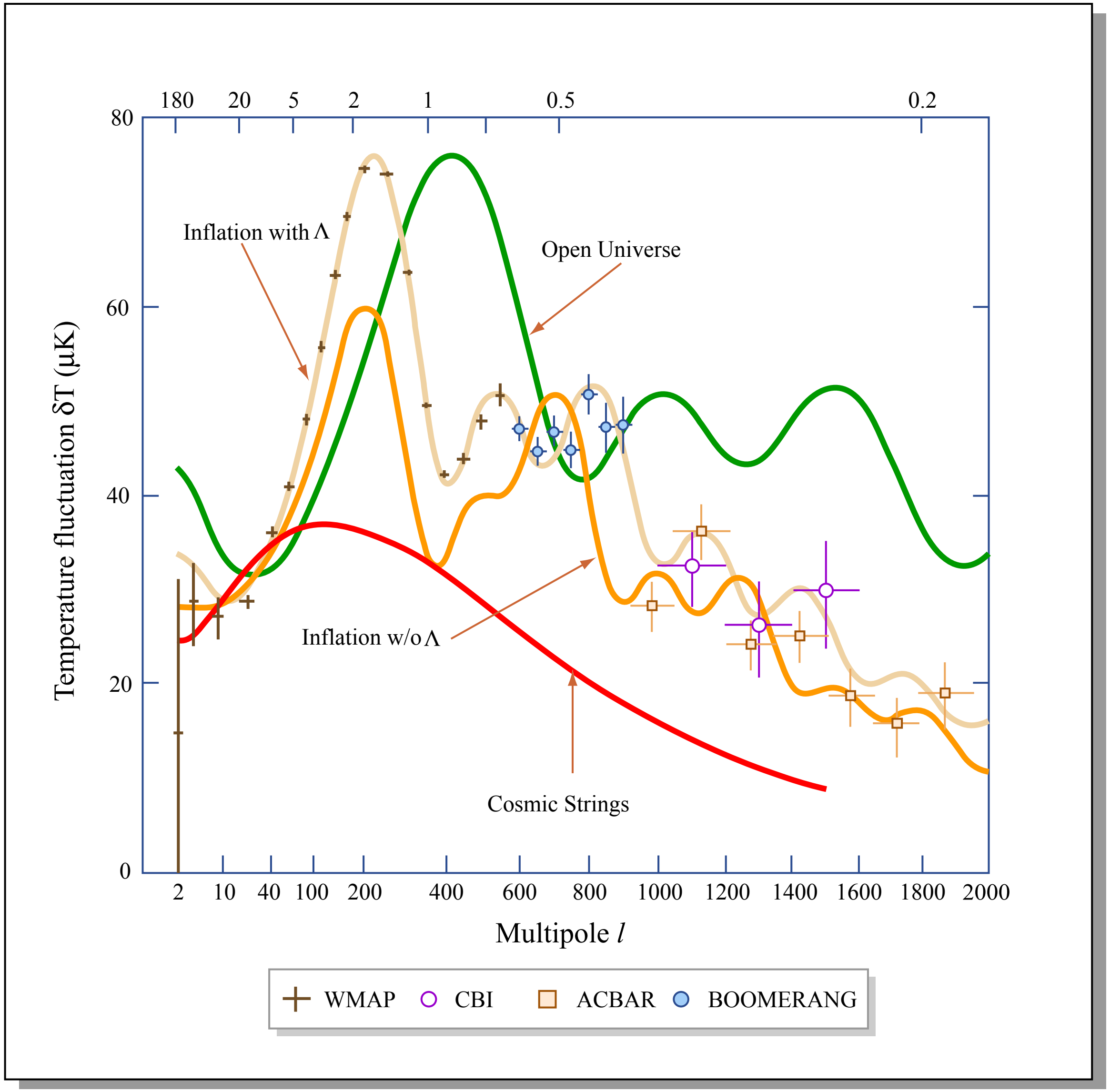


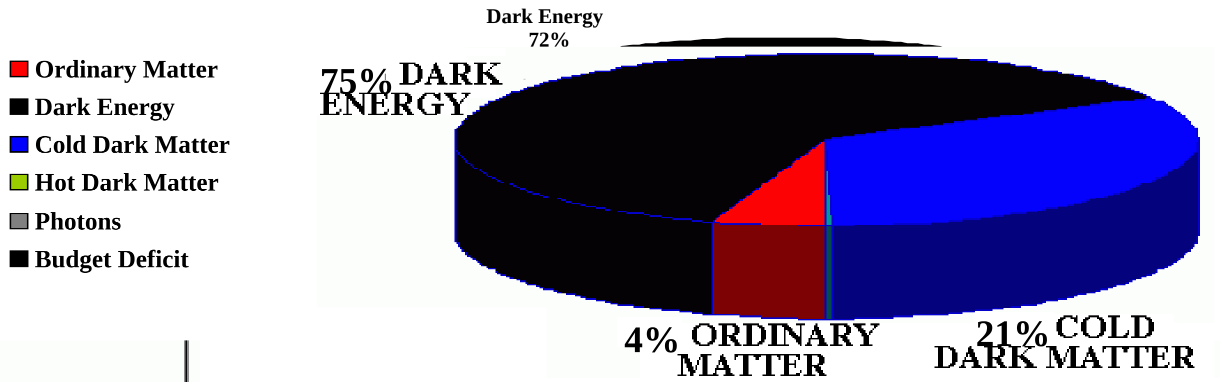
Figure by MIT OCW.

Tegmark & Zaldarriaga, astro-ph/0207047 + updates

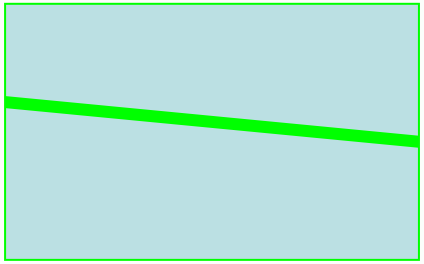
Figure 4 from Guth and Kaiser,
“Inflationary Cosmology: Exploring the Universe from the Smallest to the Largest Scales” (11 February 2005) *Science* **307** (5711), 884.

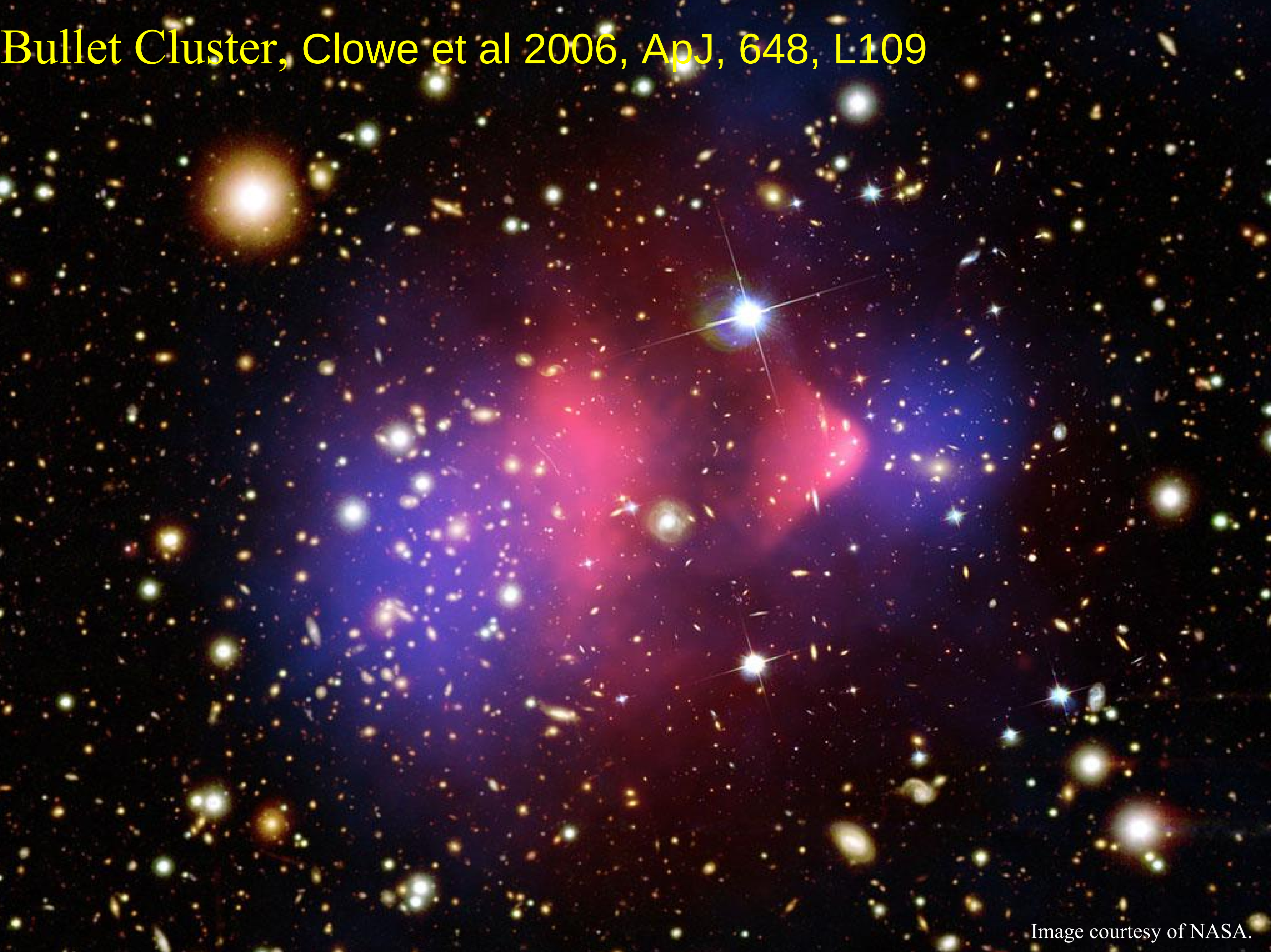
Dark matter par movie

Using WMAP3 + SDSS LRGs:



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




Bullet Cluster, Clowe et al 2006, ApJ, 648, L109
Image courtesy of NASA.

Mystery 3:
How did it begin?

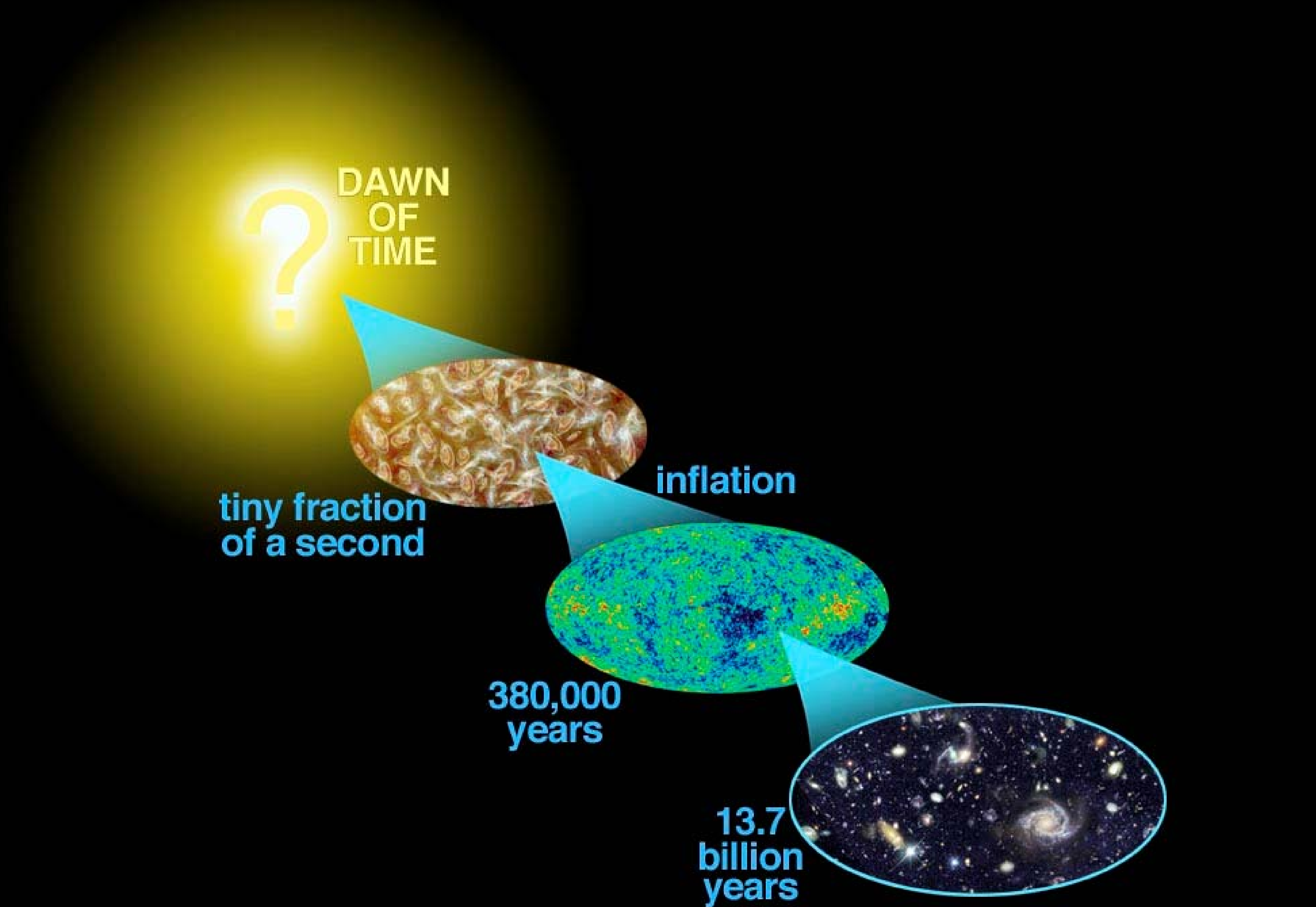
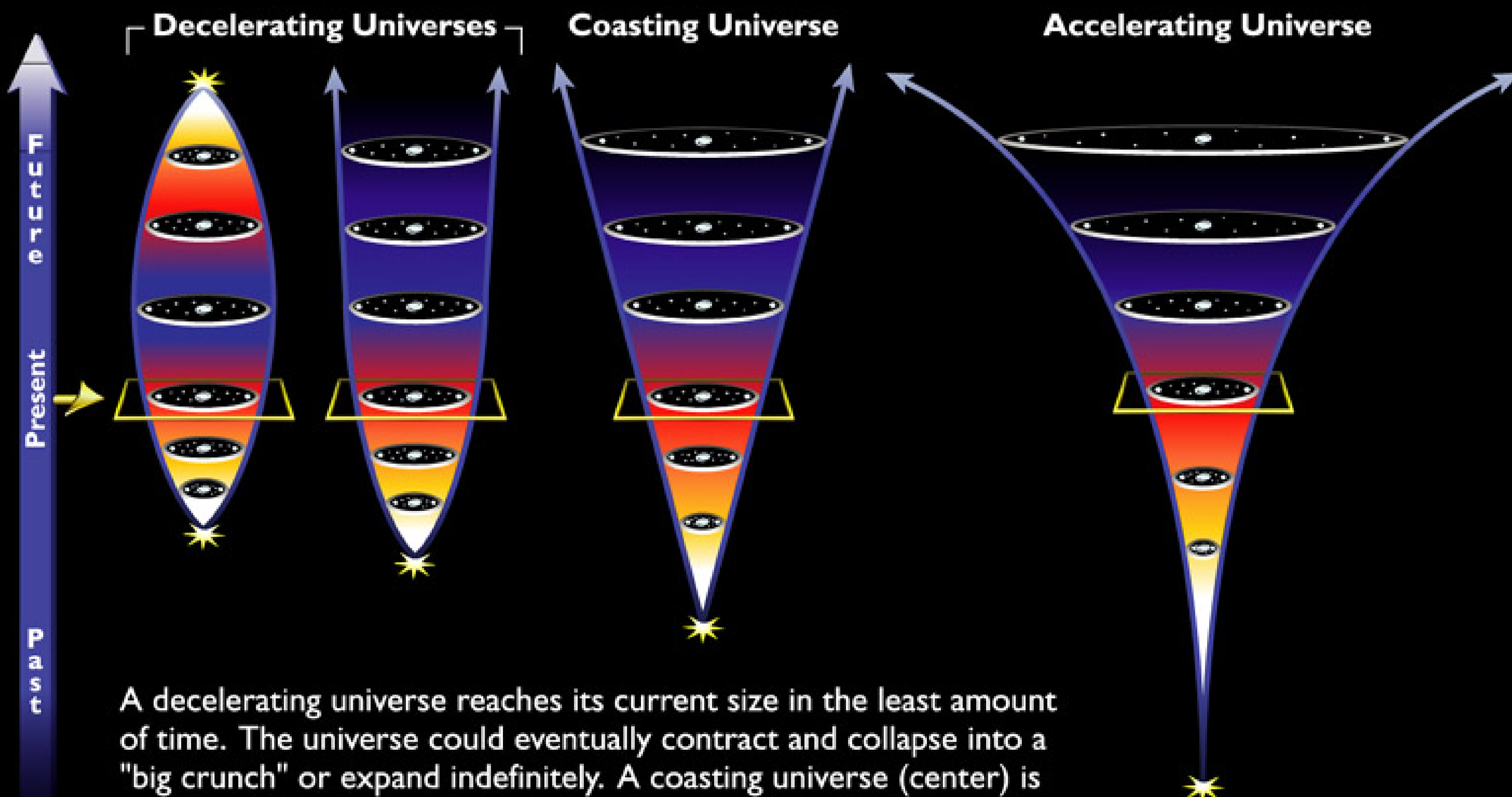


Image courtesy of WMAP/NASA.

Possible Models of the Expanding Universe



A decelerating universe reaches its current size in the least amount of time. The universe could eventually contract and collapse into a "big crunch" or expand indefinitely. A coasting universe (center) is older than a decelerating universe because it takes more time to reach its present size, and expands forever. An accelerating universe (right) is older still. The rate of expansion actually increases because of a repulsive force that pushes galaxies apart.

Image courtesy of STScI/NASA.

$H = d\ln a/dt, \qquad H^2 \propto \rho$

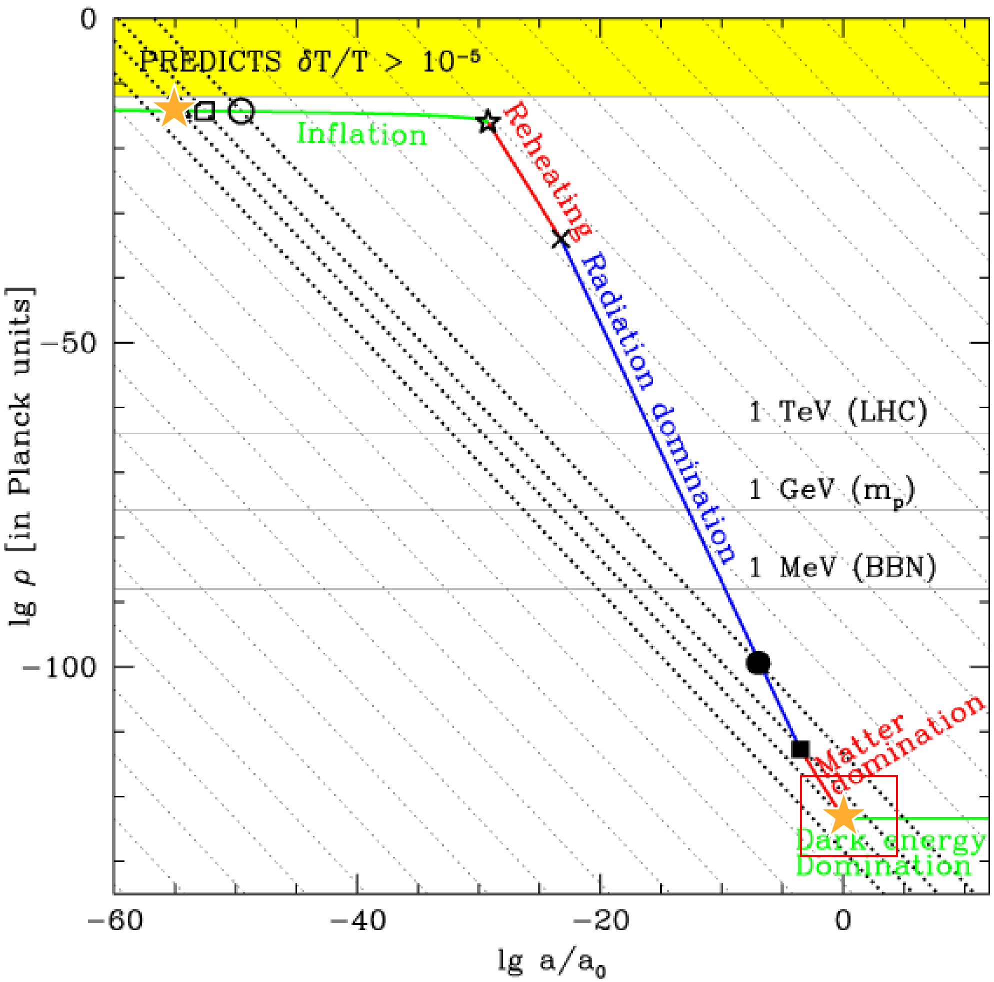


Figure removed due to copyright restrictions.

Figure 1 from Yun Wang & Max Tegmark," New Dark Energy Constraints from Supernovae, Microwave Background, and Galaxy Clustering" *Phys Rev Lett* **92**, 241302 (2004).

Evidence #1 for inflation:

MT et al 2006, astro-ph/0608632

Space is very flat

$$\Omega_{tot} = 1.003 \pm 0.010$$

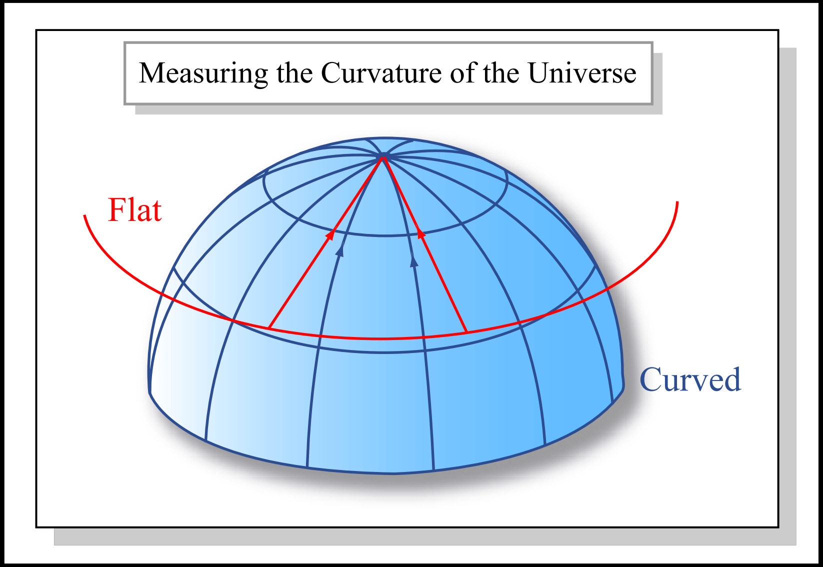


Figure by MIT OCW.

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

Figure 15 from Tegmark et al, “Cosmological Constraints from the SDSS Luminous Red Galaxies”

http://arxiv.org/abs/astro-ph/0608632

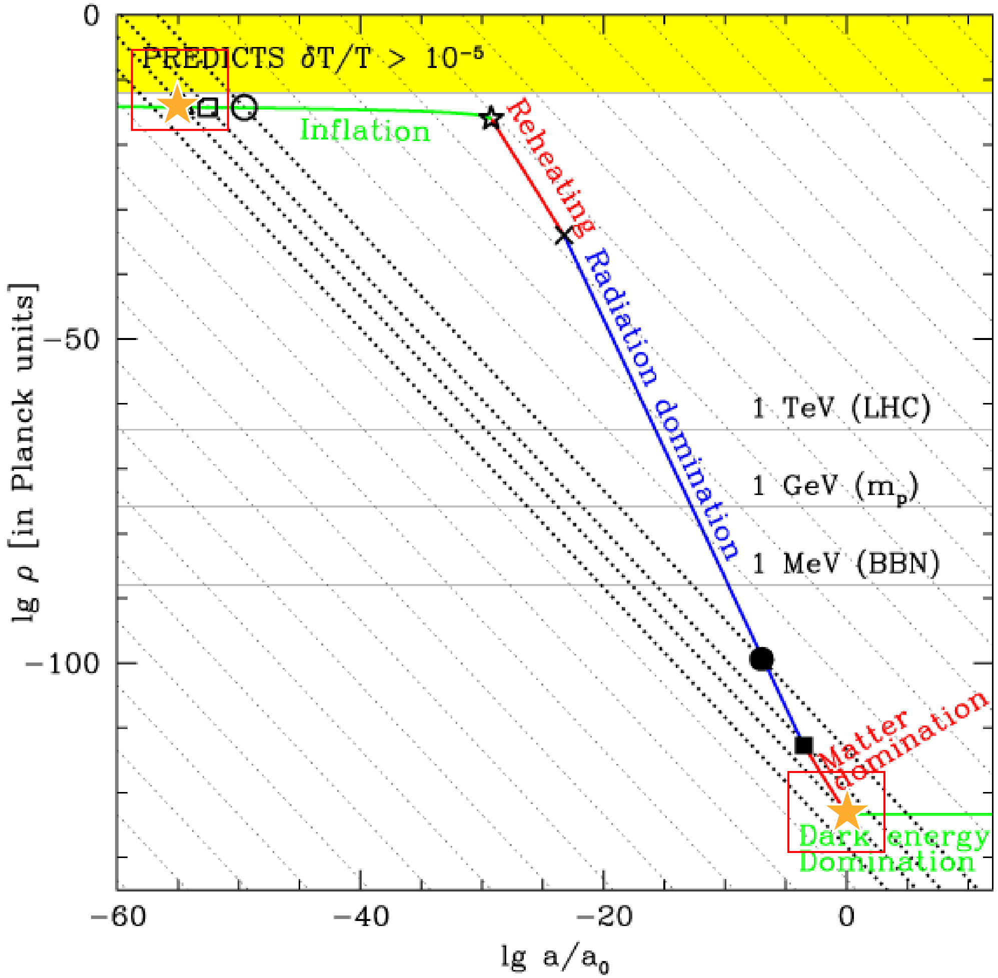


Figure removed due to copyright restrictions.

Figure 1 from Yun Wang & Max Tegmark," New Dark Energy Constraints from Supernovae, Microwave Background, and Galaxy Clustering" *Phys Rev Lett* **92**, 241302 (2004).

What we’ve called “the Big Bang” wasn’t the beginning, but the end…

…of inflation!

Linde, Andrei “The Self-Reproducing Inflationary Universe” Scientific American, Vol. 271, No. 5, pages 48-55, November 1994.

Mysteries for you to solve:

- What is dark matter?
- How did it all begin?
  (buzz word: inflation)
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  (buzz word: dark energy)

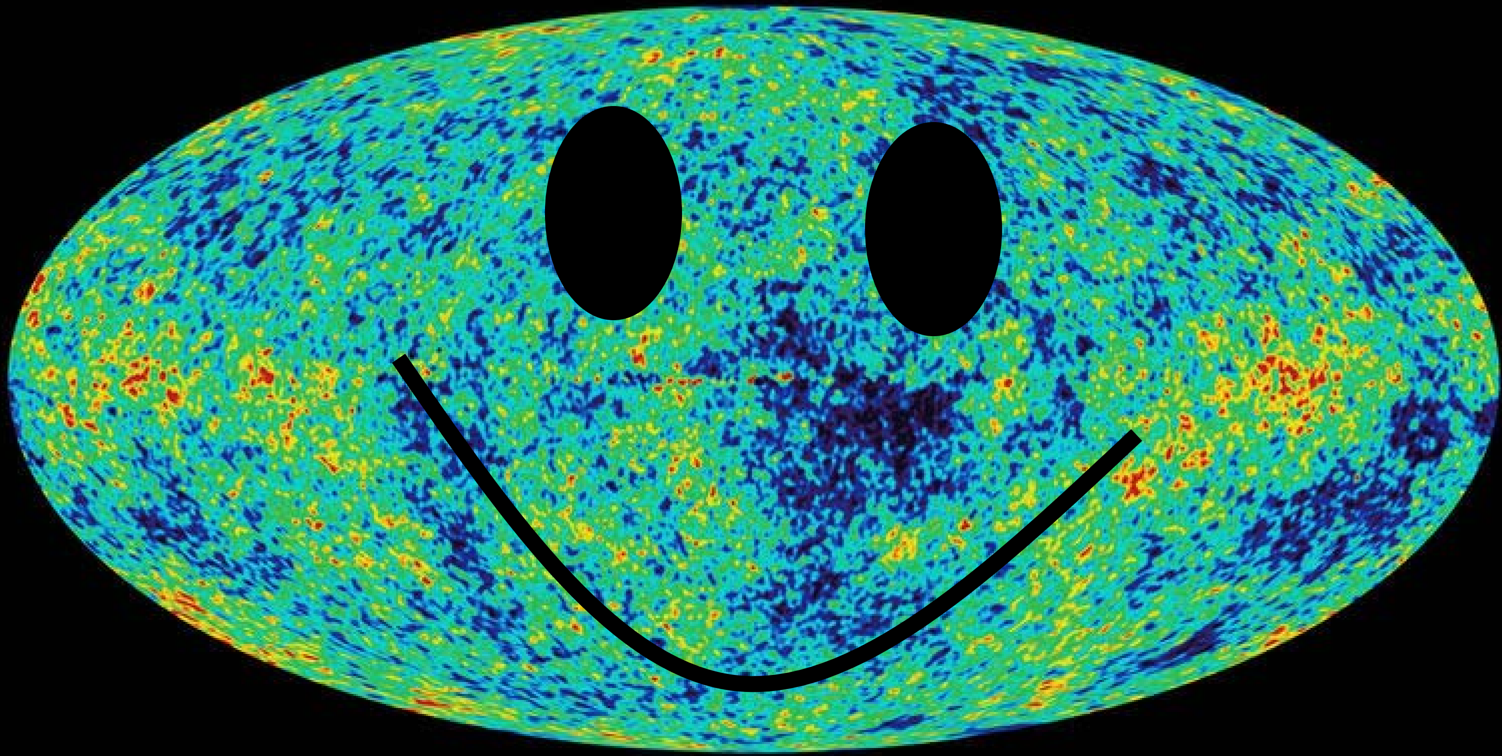

Image courtesy of NASA.

Summary of what we know about our metric.

Coming next…

BLACK HOLES