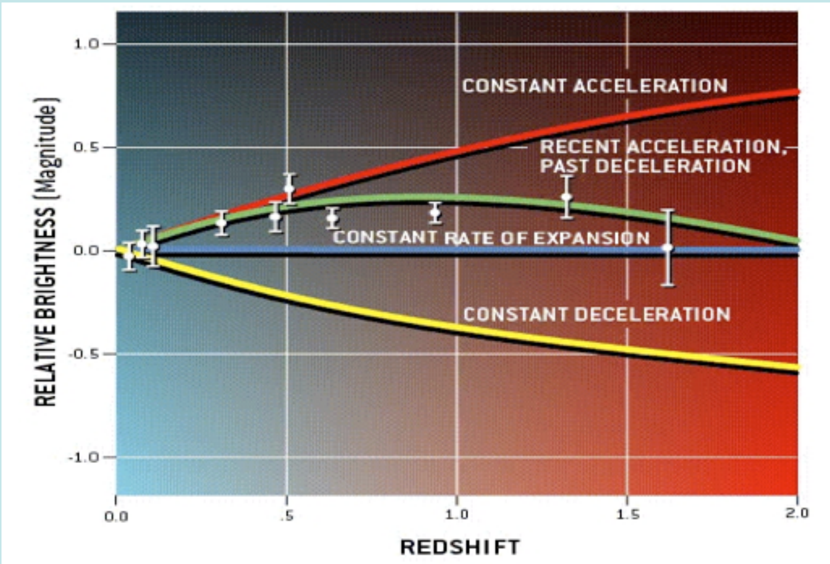
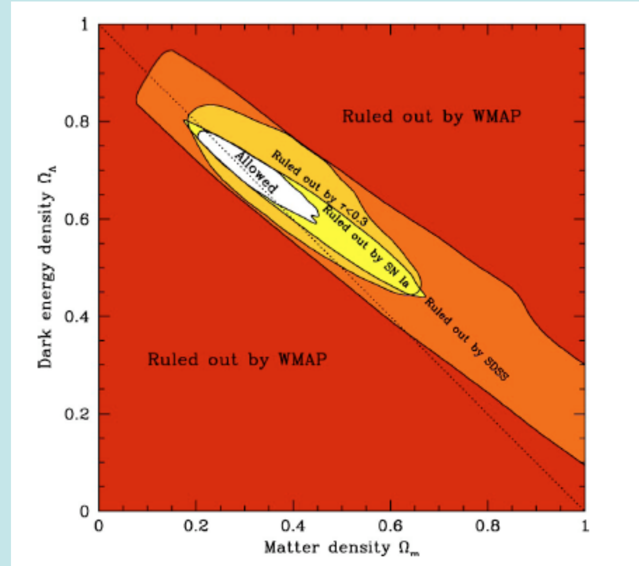
The current status and challenges in cosmology: a brief preview of coming attractions*

Priya Natarajan (Yale)
Philosophy of Cosmology Summer School
Santa Cruz, June – July 2013

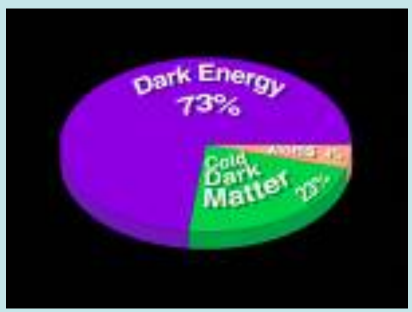
* forthcoming lectures by Joel Primack & Anthony Aguirre

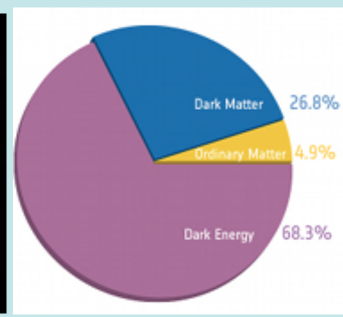
Composition of the Cosmos

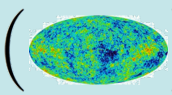




Compelling cosmological evidence for non-baryonic DM

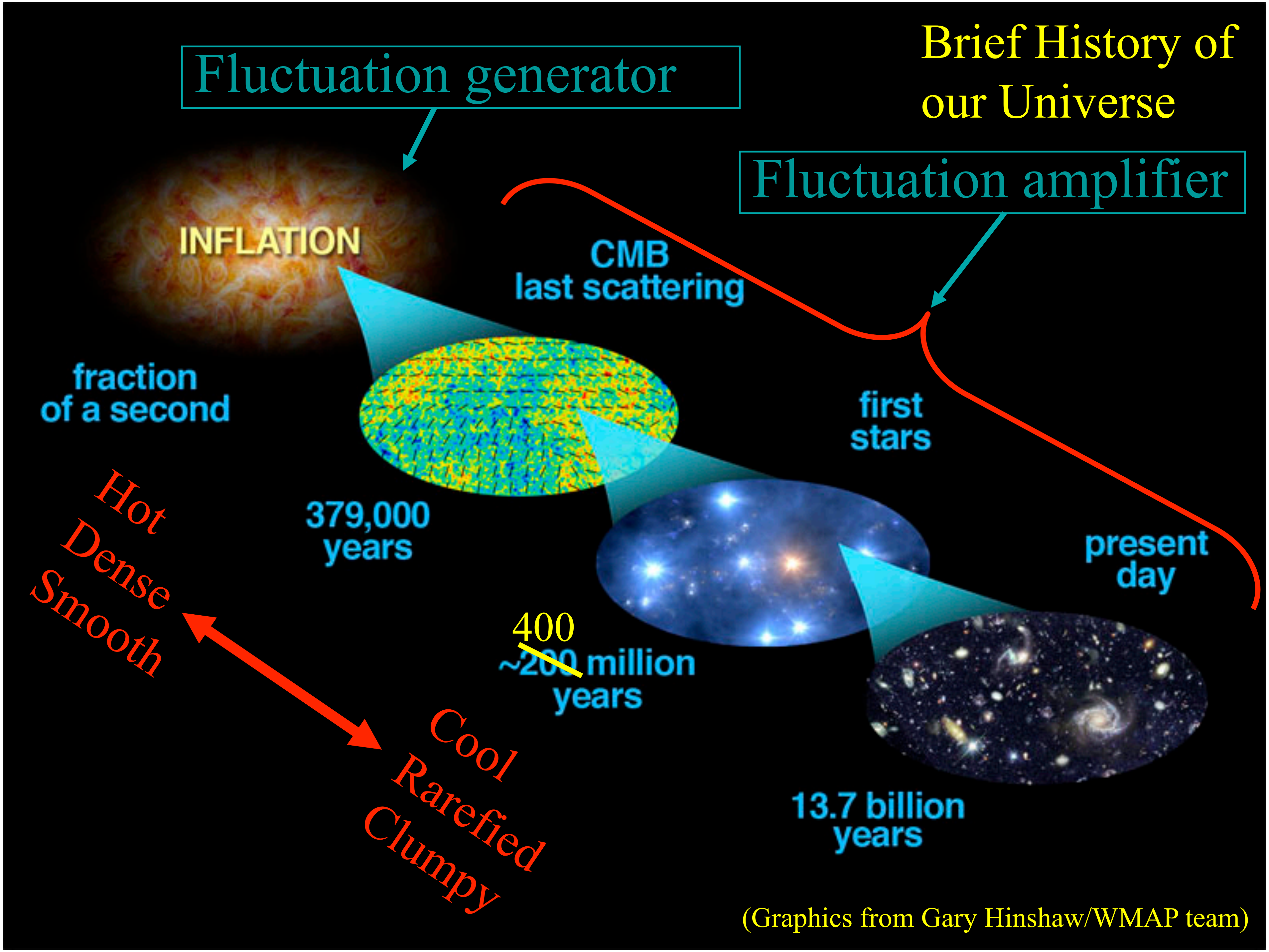




$\Omega_d h^2($  $) = 0.113$

WIMPS: Weakly Interacting Massive Particles - the lightest neutralino, motivated by SUSY, mean scattering time-scale longer than Hubble time

Riess+ 98 Perlmutter +99; Tegmark+ 03; Spergel+ 03; 06; WMAP, SDSS, 2dF


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

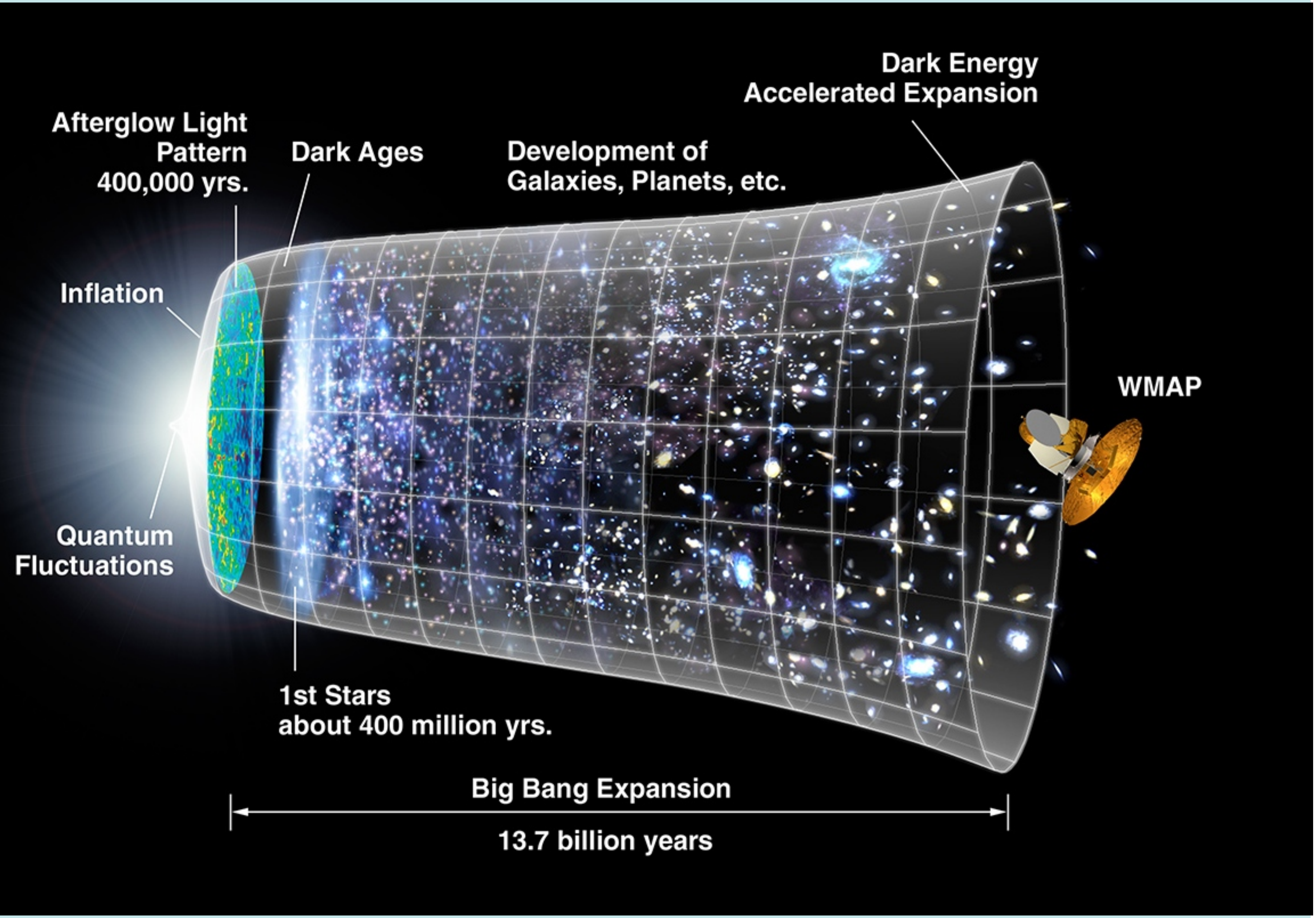
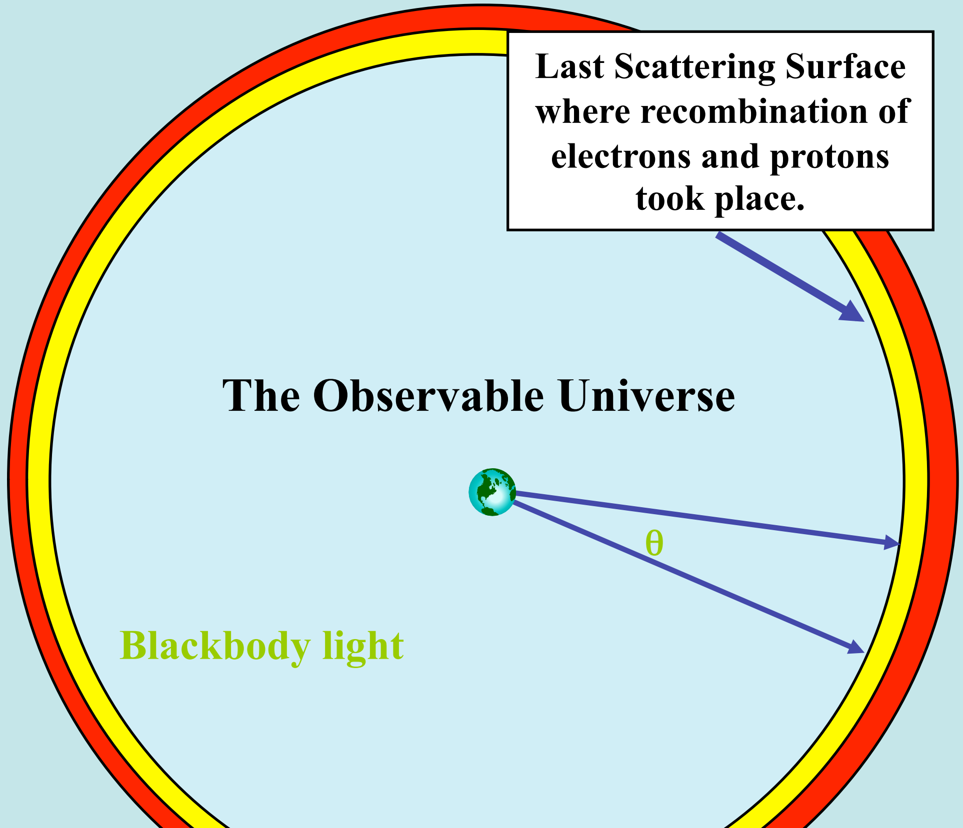


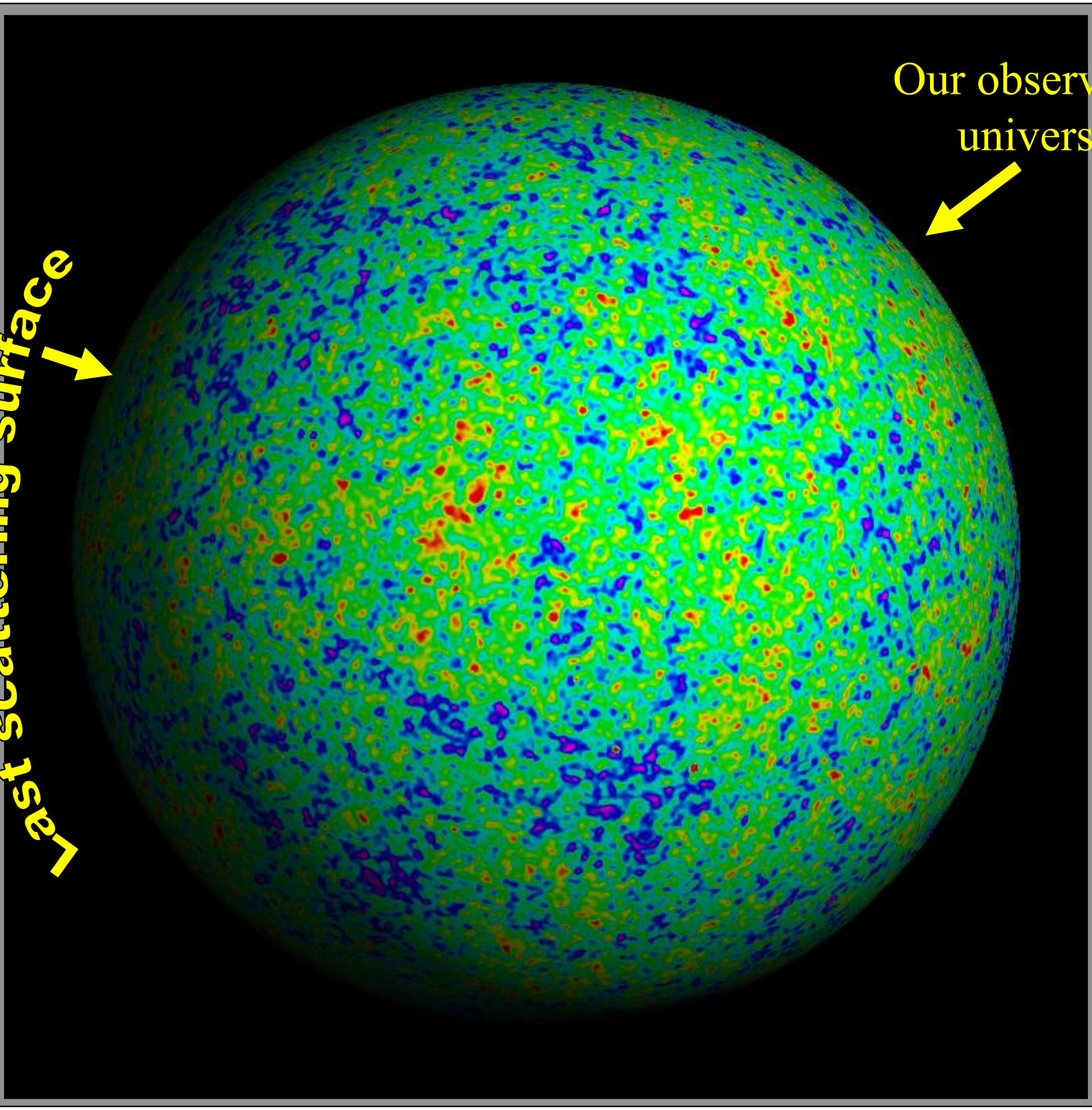
Figure from WMAP team

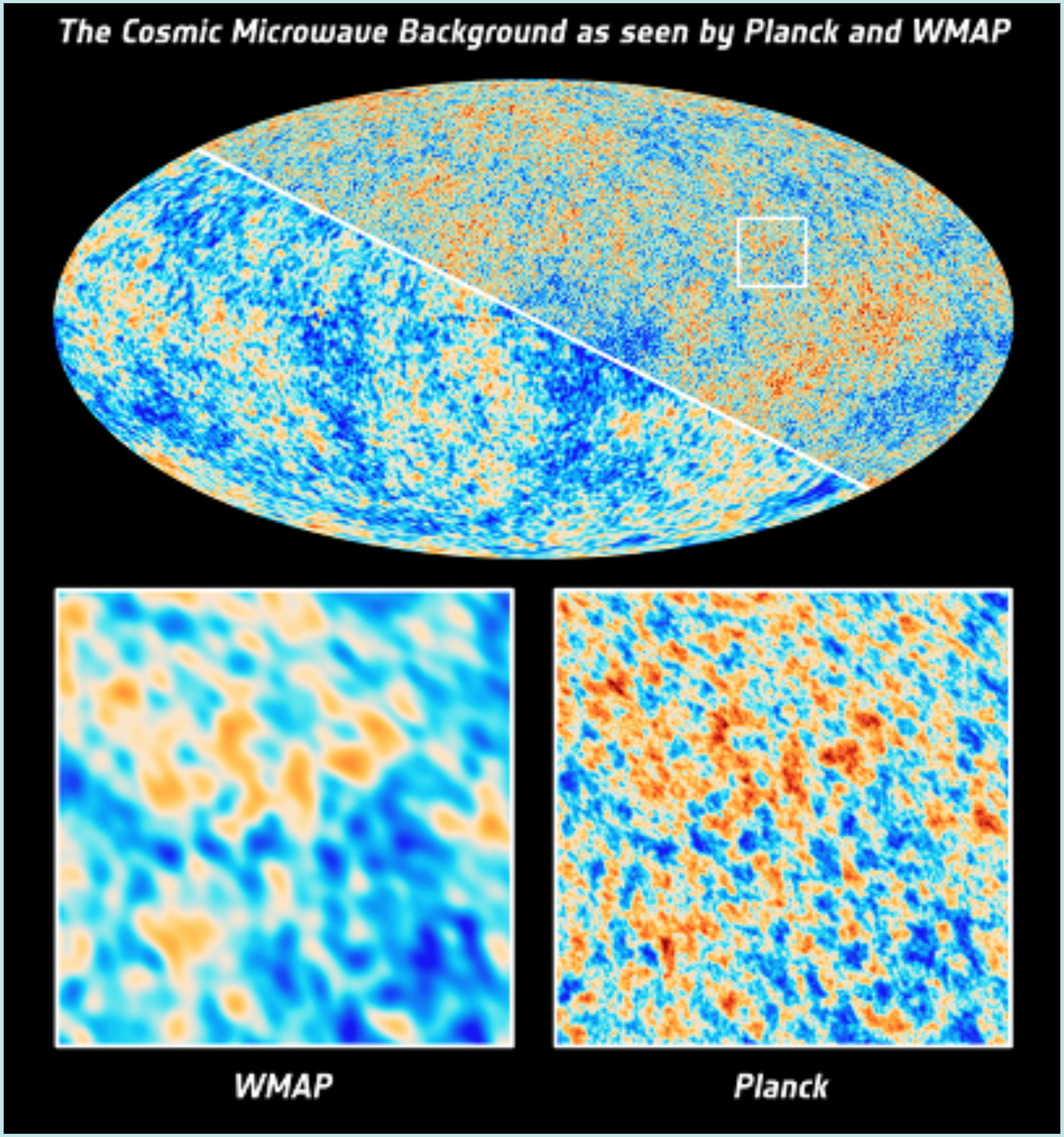
Reconciling COBE and Large Scale Structure

- COBE observations
  - constrain density variations on 7° scale on surface of last scattering
  - these scales correspond to distances of billions of light years today
- Nearby universe
  - largest regions probed have scales of several billion light years
  - need to probe many regions of this size to study density variations
- There exists a hierarchy of structures over a vast range of scales
  - galaxies
  - groups of galaxies
  - clusters of galaxies
  - superclusters of galaxies
  - sheets and filaments



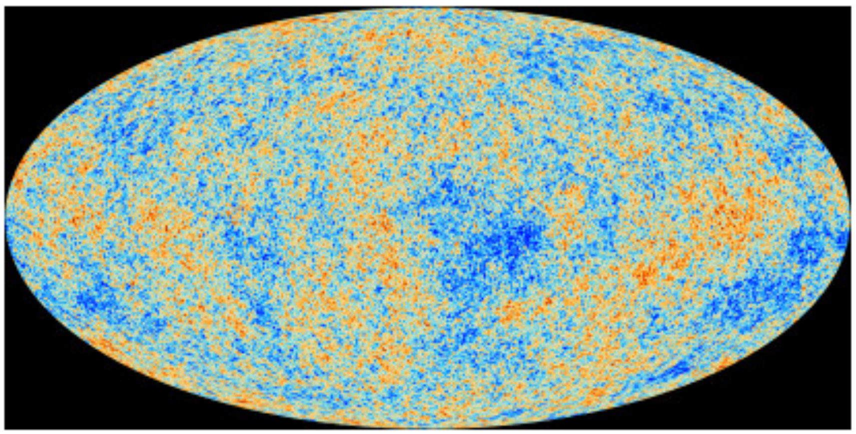
WMAP & PLANCK constrain the CMB temperature on a wide range of scales. From ~ 1 degree -the angular scale that corresponds to a distance on the last scattering surface, a time when the universe was ~500,000 years old. Accounting for the expansion of the universe, this scale corresponds to billions of light years in the nearby universe.


Our observable universe
Last scattering surface


The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

How well is the LCDM theory tested?

COSMIC MICROWAVE BACKGROUND SEEN BY PLANCK

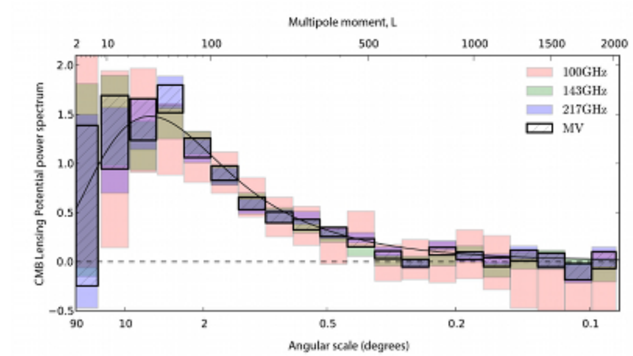


Date: 21 March 2013

Satellite: Planck

Depicts: Cosmic Microwave Background

PLANCK'S GRAVITATIONAL LENSING POWER SPECTRUM



Date: 02 April 2013

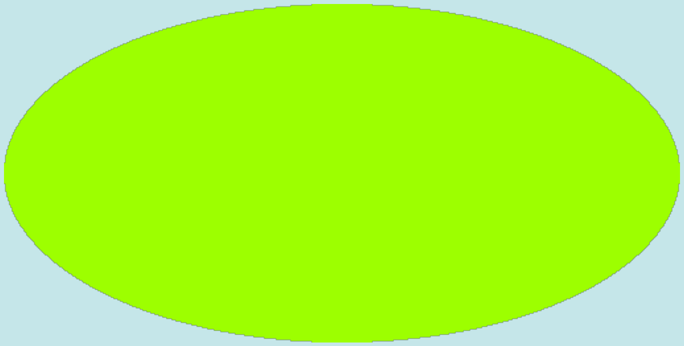
Satellite: Planck

Depicts: Gravitational lensing power spectrum obtained from Planck data

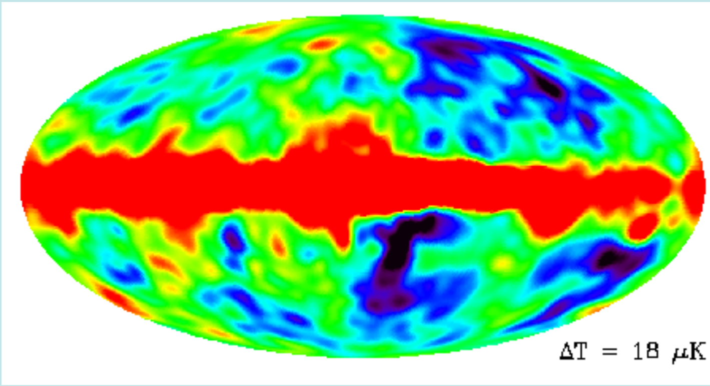
The Early Universe Was Very Homogeneous

- The Cosmic Background Explorer (COBE) – the first instrument
  - measured the temperature of the CMB
    - satellite- all sky
    - DMR: temperature measurements with 7^{o} beam
    - FIRAS: CMB has blackbody spectrum with T=2.728+/-0.004 Kelvin
  - variation amplitude is 30+/-3μK
  - LATER MISSIONS WMAP & PLANCK HAVE NOT ALTERED OUR UNDERSTANDING FUNDAMENTALLY (more precision measurements)

- Homogeneous early universe
  - CMB tells us about nature of universe at time of recombination
  - recombination occurs when universe is ~500,000 years old
  - overdense region contains hotter gas
  - photons are gravitationally redshifted as they escape these overdense regions
  - density uniform to ~1 part in 100,000

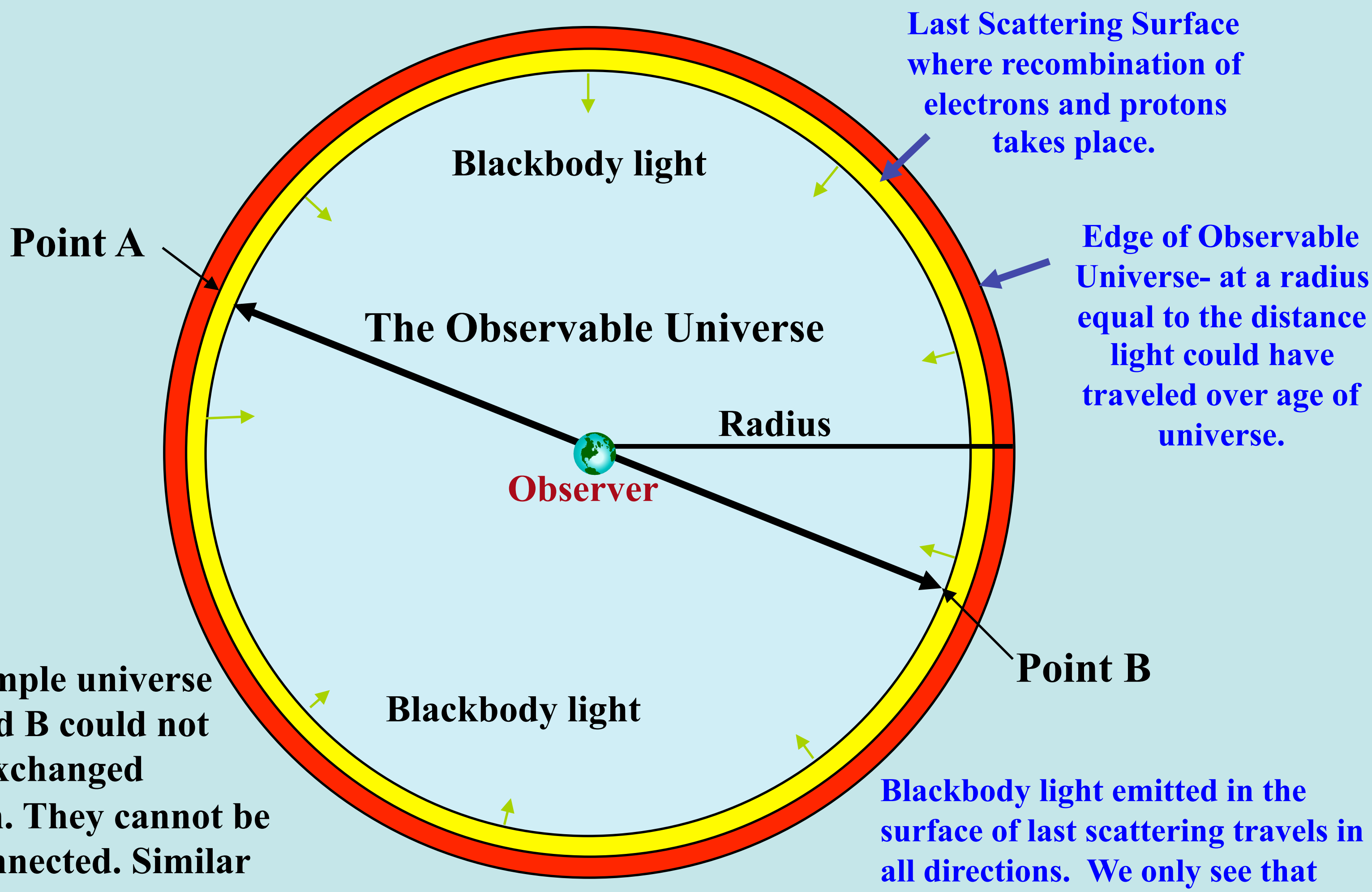


Temperature range 0-4 Kelvin



Dipole removed but emission from galaxy still present

The Horizon Problem

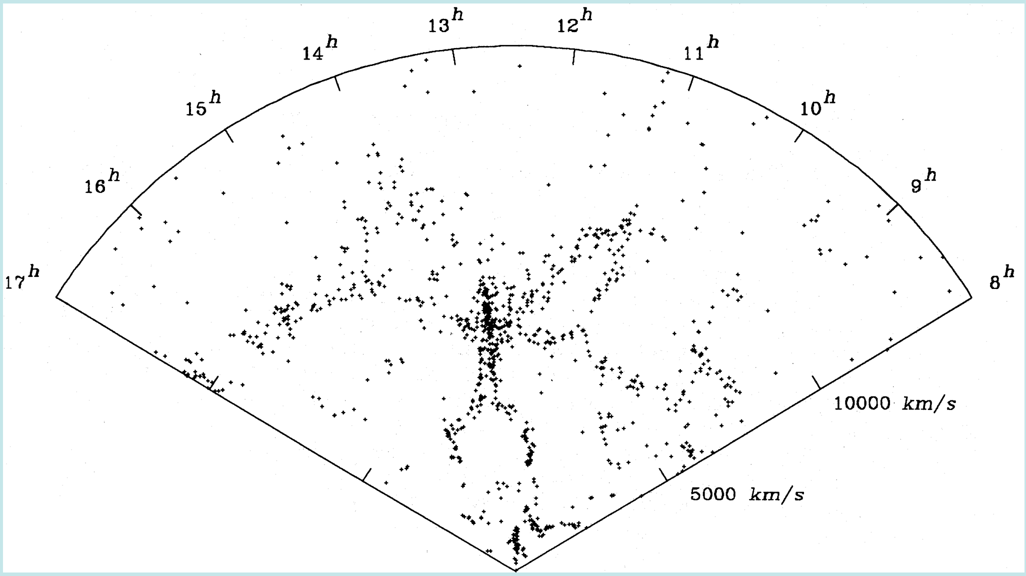


Within a simple universe Points A and B could not have ever exchanged information. They cannot be causally connected. Similar CMB temperatures at these points would be coincidental, or result from initial conditions.

Blackbody light emitted in the surface of last scattering travels in all directions. We only see that portion which happens to set off in a direction that leads it into one of our detectors.

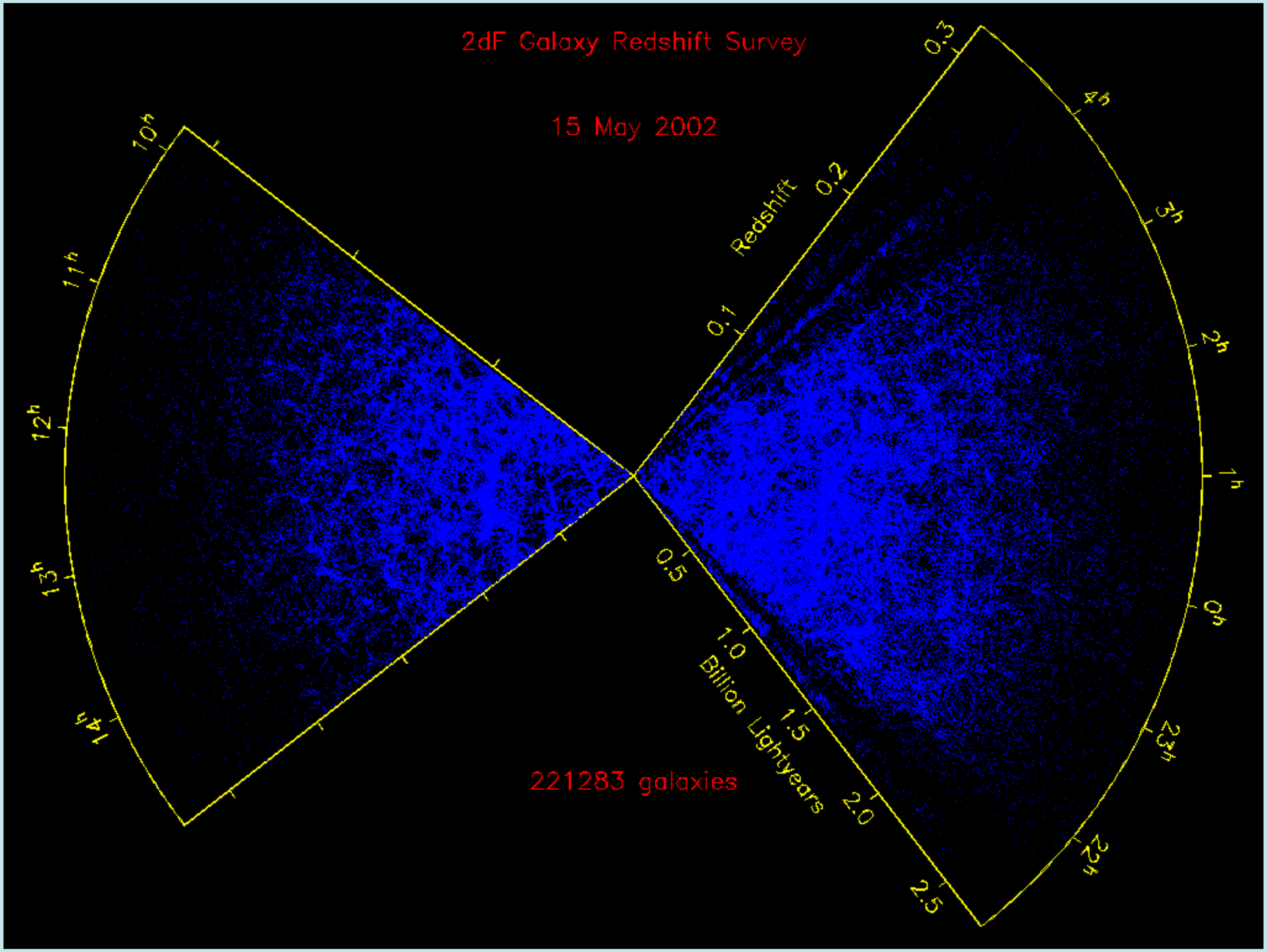
de Lapparent, Geller & Huchra, ApJ 1986

The Nearby Universe is Inhomogeneous



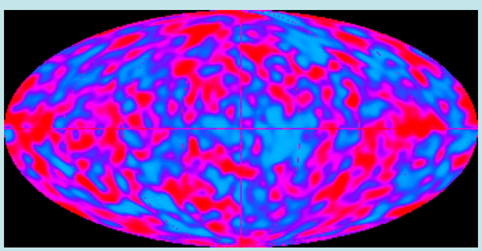
- Large Scale Structure Revealed by Maps of Nearby Universe
  - First slice of the Center for Astrophysics redshift survey
  - 6°x100° slice containing 1,061 galaxies brighter than B=15.5 mags
  - Slice is ~ 1 billion light years deep

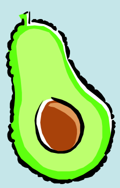
Large scale structure - on smaller scales galaxies show a rich structure, measured using redshift surveys



Primer

- CMB constraints on early universe
  - Connecting temperature and density
- How do nearby structures arise?
  - A day in the life of a perturbation
- A statistical description of structures
  - Structure over a range of scales
  - Power spectrum of fluctuations
- Predicting structure in the nearby universe
  - Numerical structure formation simulations
- Observing the seeds of structure formation





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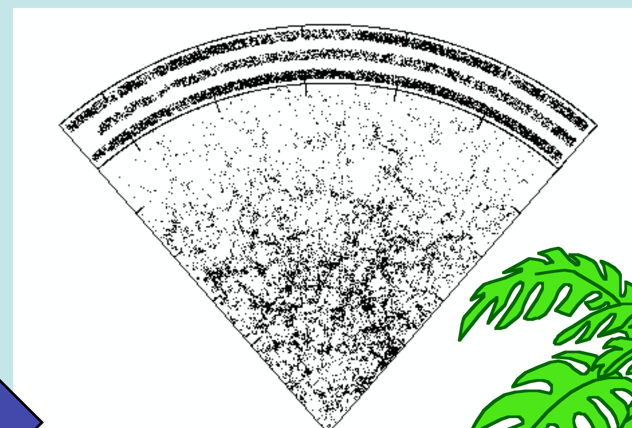
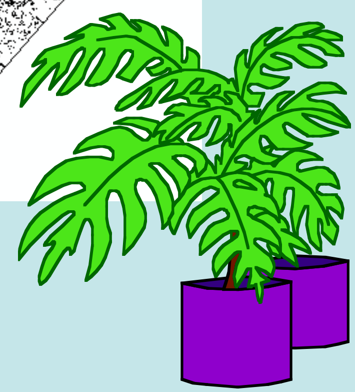
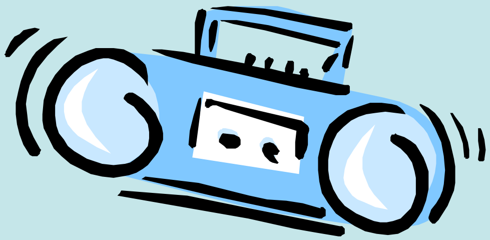




From Homogeneity to Structure

- Structure Evolution is a Basic Component of the Big Bang model
  - Reasonably well constrained observationally modulo relation between mass and light
  - sensitive to cosmological parameters and the nature of dark matter
    - can provide way of addressing these outstanding issues

- Gravity amplifies inhomogeneities, even in an expanding universe

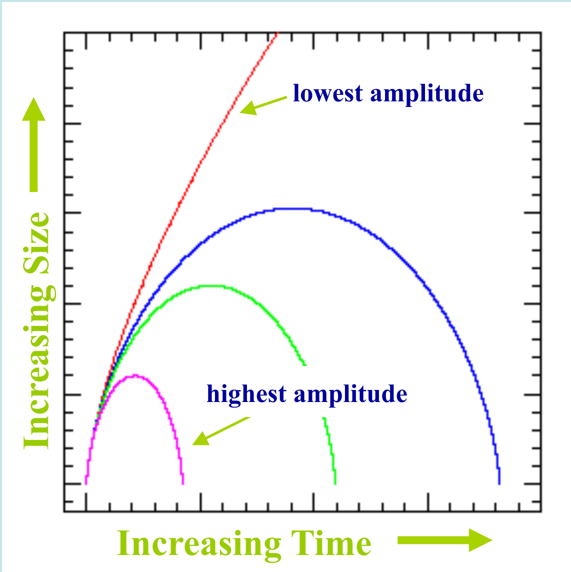


Gravitational Instability

- Small departures from uniformity are amplified in an expanding universe
  - Overdense regions
    - experience greater deceleration of expansion
    - leads to greater overdensity
    - expand more slowly than typical part of the universe
    - eventually collapse if sufficiently overdense
  - Underdense regions
    - experience less deceleration of expansion
    - leads to even larger underdensities
    - regions expand faster than typical part of the universe
    - underdense regions grow and form voids

- General relativity provides solutions for the evolution of density perturbations
  - Overdensity of very small perturbations grows linearly with the expansion of the universe until perturbations become large

Life and Times of 4 Density Perturbations



In reality, there are fluctuations on all scales

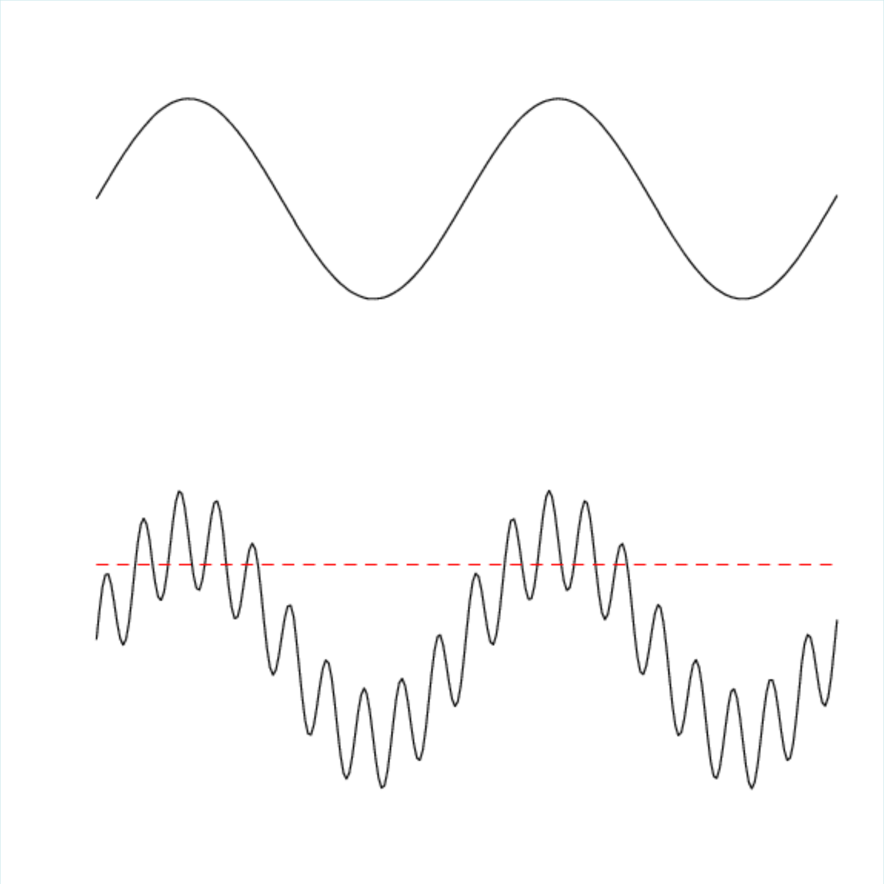
Relative amplitudes described by a **power spectrum**, which can be predicted for a particular cosmological model

Evolution of the fluctuations to form large scale structure can be studied using numerical simulations

In cold dark matter models, build-up of structure is hierarchical or `bottom-up' - small objects form earliest and then merge to form larger ones. Clusters are relatively recently formed structures.

Small fluctuations seen in the CMB are amplified by gravity during the expansion of the Universe:

- Galaxies form in dense regions
- Clusters form from exceptionally overdense regions
- Schematically easy to see why galaxies are then clustered



Suppose initial density has fluctuations on many scales (here, just two!)

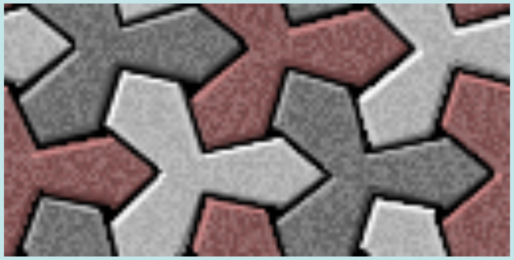
If galaxies or clusters form when the density is above a threshold value, they will preferentially form close together

-> link between initial conditions and current observations

Comparing Structures at a Different Place and Time

- Large scale structure observations tell us about structure in the nearby, 13 billion year old universe
- COBE observations tell us about structure at a distant location when the universe was only ~500,000 years old
- Structure formation models connect these two observations
  - Models need not produce replicas of local structure
  - Models must produce local structure with properties similar to those observed
    - require a statistical description of structure: the power spectrum

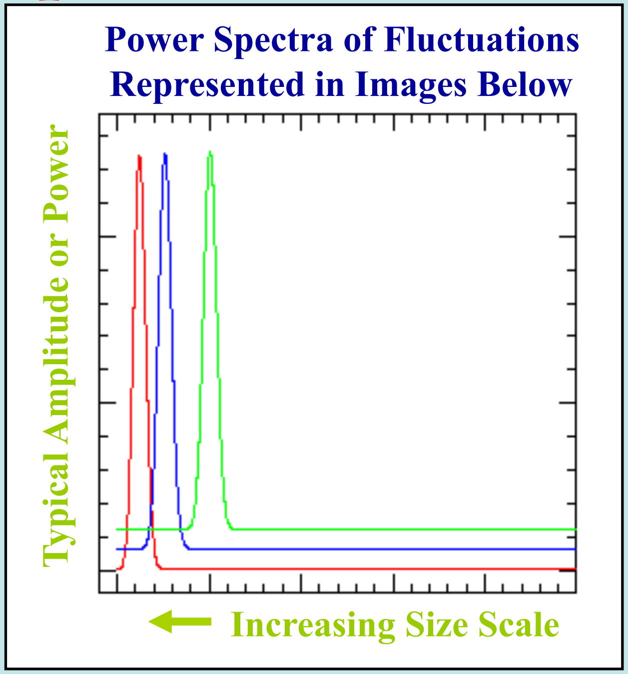
- Think of structures as arrangements or superpositions of many structures, each with a particular size scale

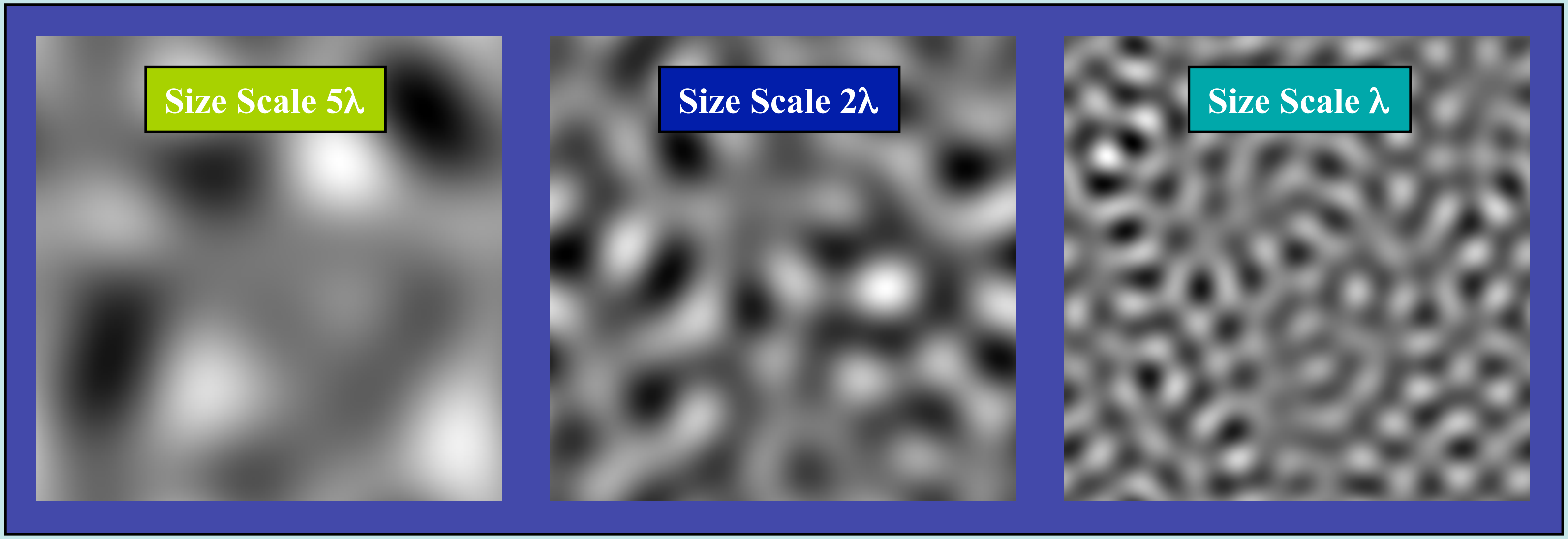


- Power spectrum describes the typical amplitude of a density perturbation as a function of the length scale of the perturbation

Images of Structures on Specific Scales

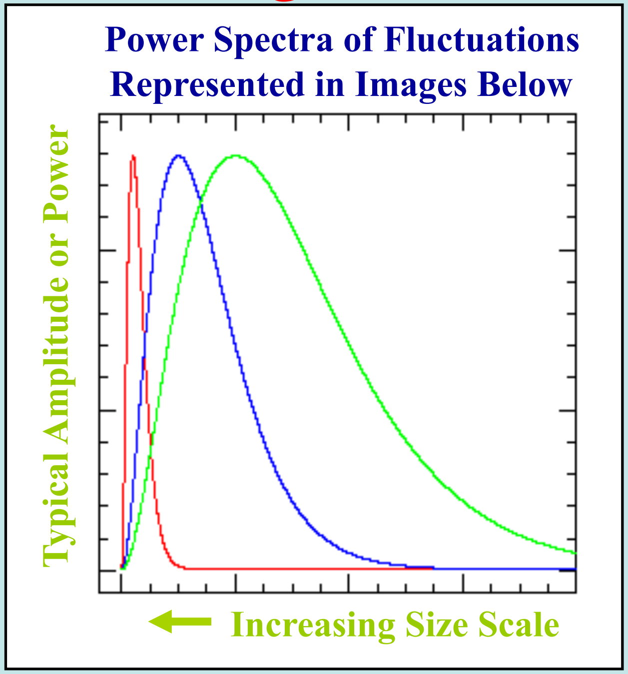
- Brightness fluctuations in images
  - can be described by powerspectrum
    - note plot of three power spectra and corresponding images
  - all images can be decomposed into a superposition of structures on different scales
    - power spectrum encodes decomposition
    - provides typical fluctuation amplitude for a range of scales
  - Fourier transform of image yields the power spectrum

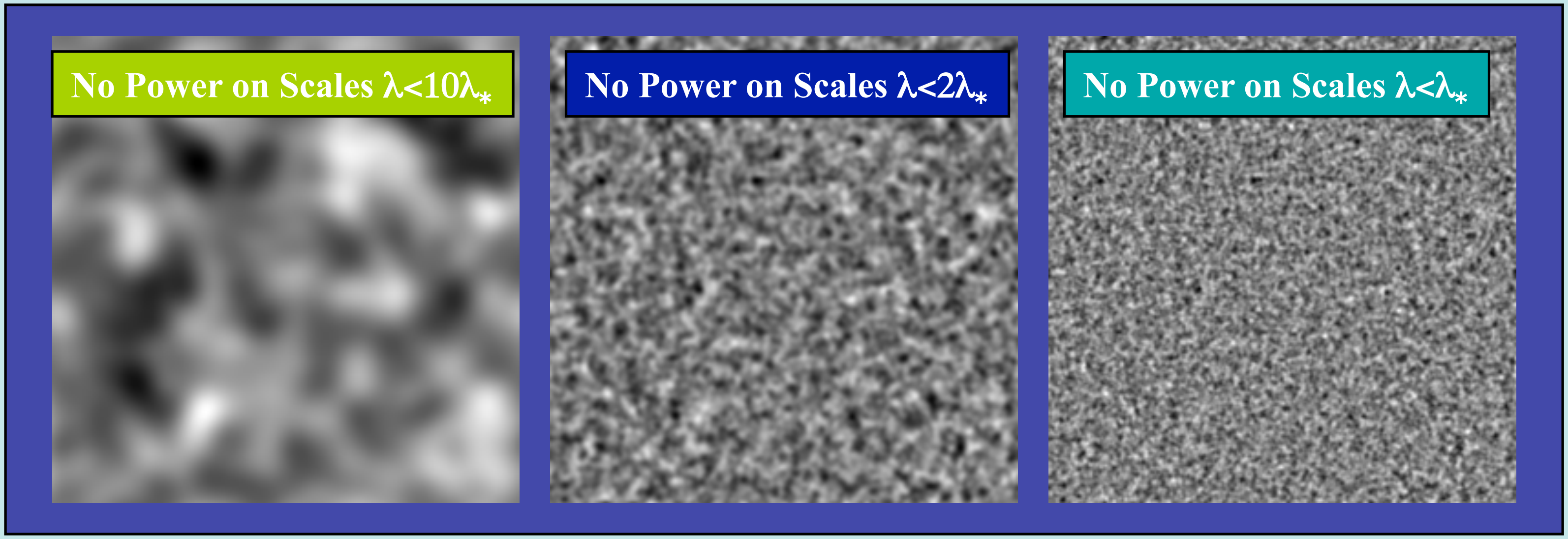




Images of Structures on a Broad Range of Scales

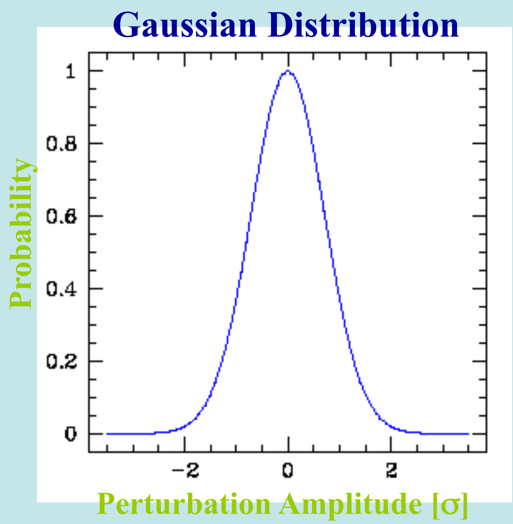
- Image decomposition
  - typically images contain power over a broad range of scales, rather than at very specific scales
    - note plot of three power spectra and corresponding images
- Density fluctuations in the Universe
  - inflation predicts power on all scales
  - on each scale the fluctuations are Gaussian distributed with a characteristic amplitude
    - overdense/underdense regions equally likely

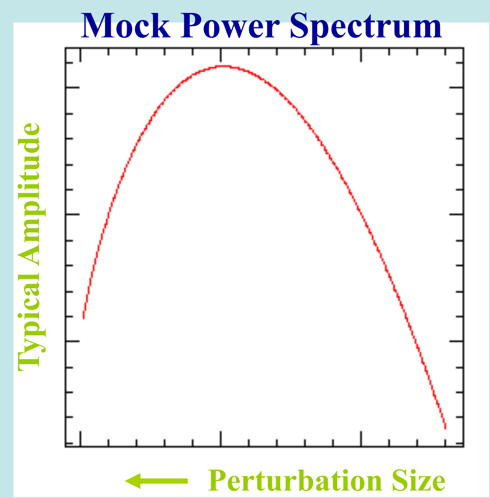




Describing Density Fluctuations in the Universe

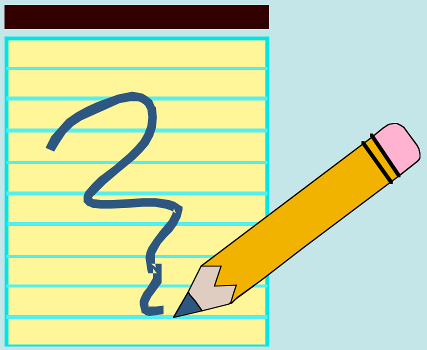
- Power spectra provide a quantitative description of density fluctuations in our universe
  - inflation predicts an initially Gaussian distribution of density fluctuations on each scale
    - arise from quantum processes in the early universe
    - typical amplitude on each scale need not be the same
  - initial fluctuations then grow or are erased depending on the physical conditions
- Observations of the temperature fluctuations in the CMB
  - provide direct measurements of the density fluctuations when the universe was ~500,000 years old
  - COBE measurements on scales larger than 7 degrees
- Observations of the distribution of galaxies in the nearby universe
  - provide direct measurements of the density fluctuations when the universe is 13 billion years old
  - current accurate measurements lie between scales of 1 and several hundred million light years
- Structure formation models
  - can we produce structure like that we see today from a universe that is consistent with the CMB observations when it was ~500,000 years old?





Calculating Structure Formation

- Must evolve density perturbations in time using gravity



- How complicated is gravity?
  - can calculate orbit of single planet around massive star by hand
  - it's even possible to calculate by hand the perturbations to the planetary orbit due to other planets!
    - French mathematicians/astronomers excelled at this in their time
  - the dynamics of many-body systems quickly becomes intractable

- Fast computers to the rescue!
  - several billion particle simulations are the state of the art BOLSHOI LCDM simulations (Details in Joel's talk)

Numerical Structure Formation Simulations

- Model matter in universe as collection of particles that interact gravitationally (and perhaps hydrodynamically)
- several billion particles is current state of the art (Joel's lectures)
  - one chooses particle mass by choosing a simulation volume
    - total mass in simulation volume divided by particle mass
    - all information about structure on mass scales of the particle and smaller is lost!
  - for cosmological simulations the typical particle mass is around the mass of a galaxy or somewhat less (~10^{12} solar masses)
    - all the wonderfully complex activity in a galaxy is ignored
    - galaxy described by 7 numbers: mass, location and velocity!
- Simulation process
  - distribute particles in early universe
    - typically after recombination, during dark ages at t_{age}~100 million year
  - account for underlying expansion and turn gravity loose!
    - calculate where each particle would be some time δt later, where dt is around 10 million years
    - repeat these integration steps until time equal to the age of the universe has ellapsed
    - Presto! Instant universe
- Compare properties of simulated universe with those of the observed universe!

What is a cosmological simulation?

- Ingridients
- Initial fluctuation spectrum
- Spatial and temporal evolution
- Evolution under gravity
- Statistics of underlying distribution
- Ansatz to relate DM and galaxies
- Comparison with observed galaxy distribution

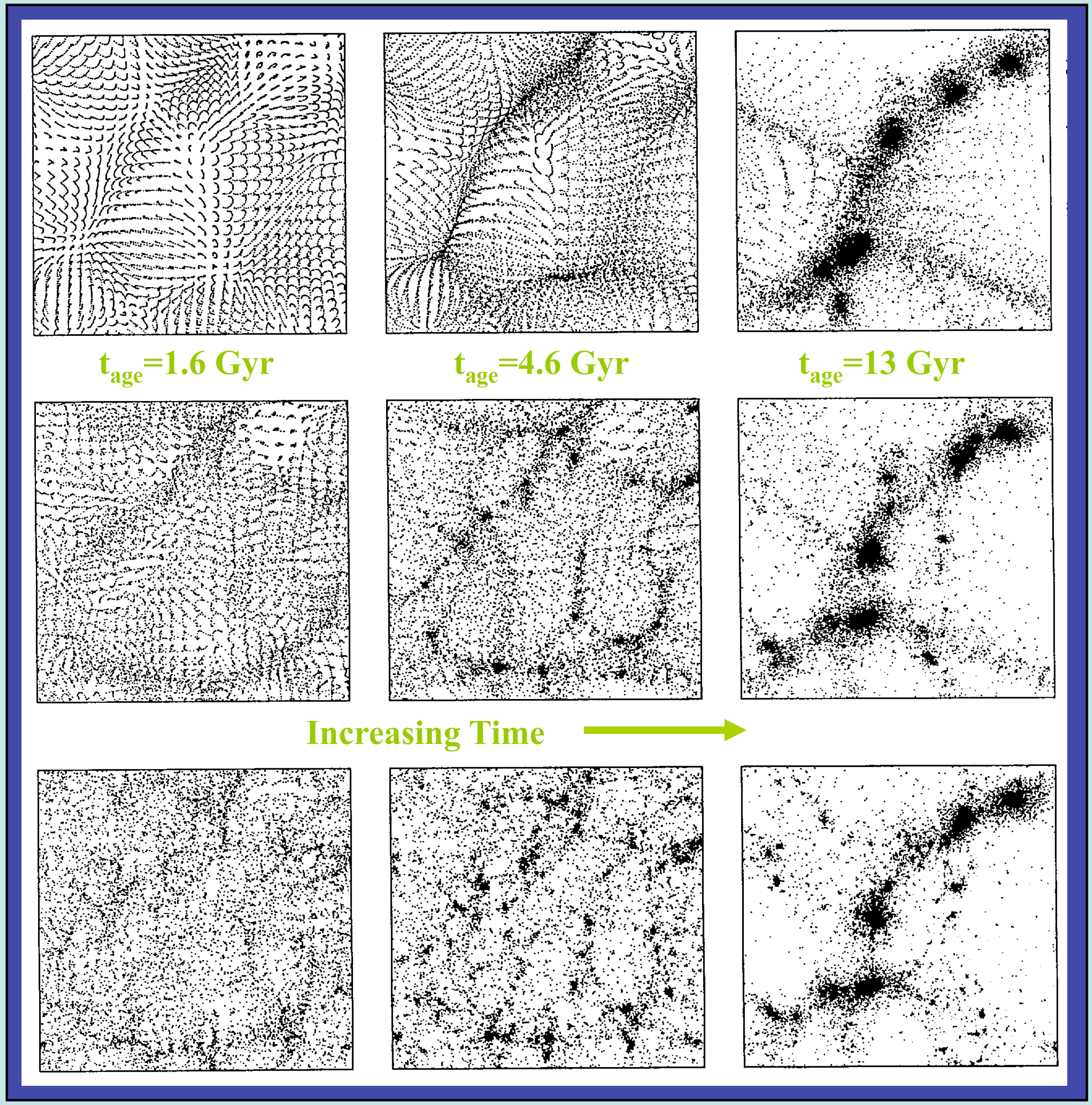
Schweber & Wachter 2000; Keller 2001; Ruphy 2010; Yanoff & Weirich 2010

Evolution of Density Perturbations

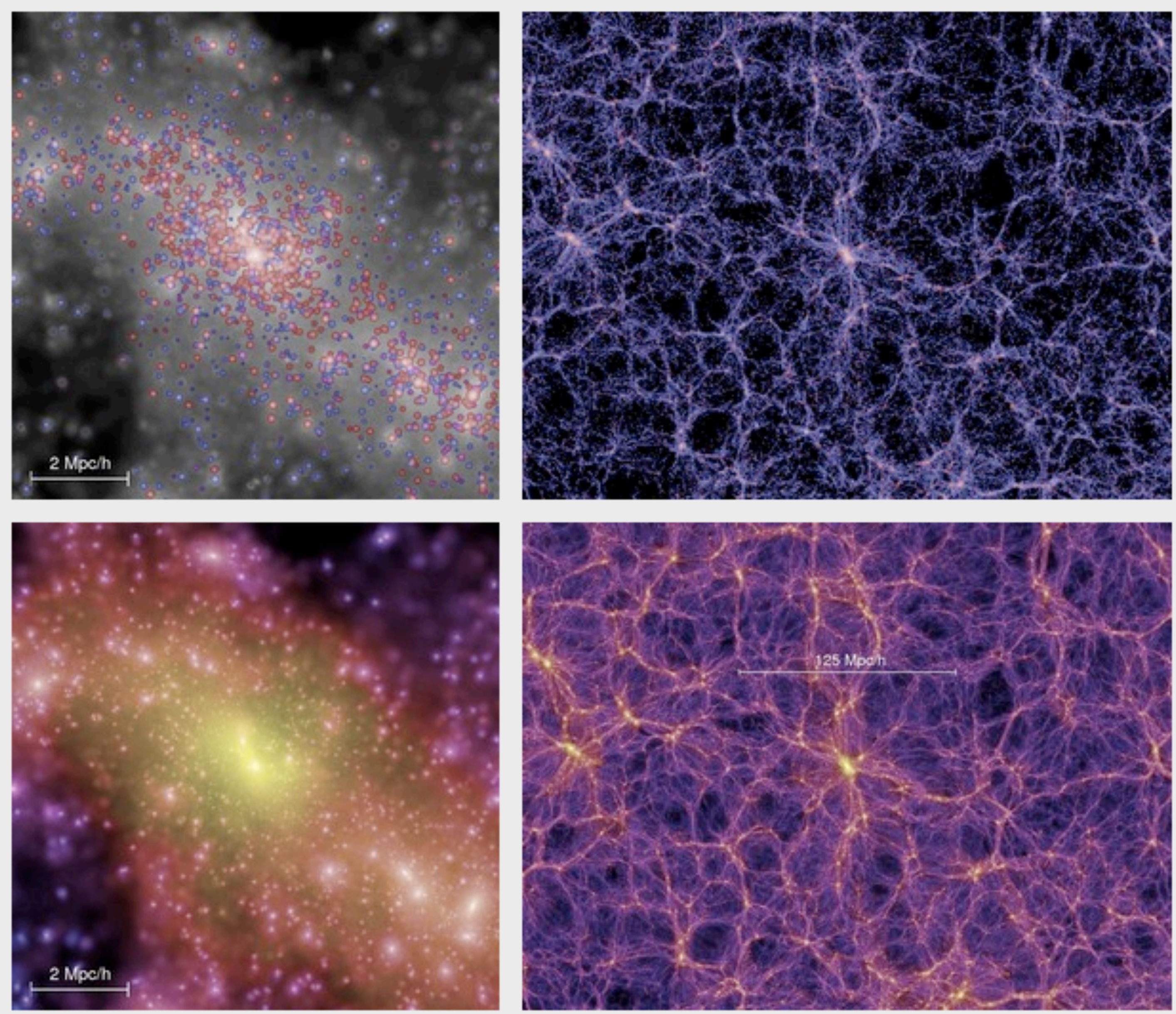
Least Small
Scale Power

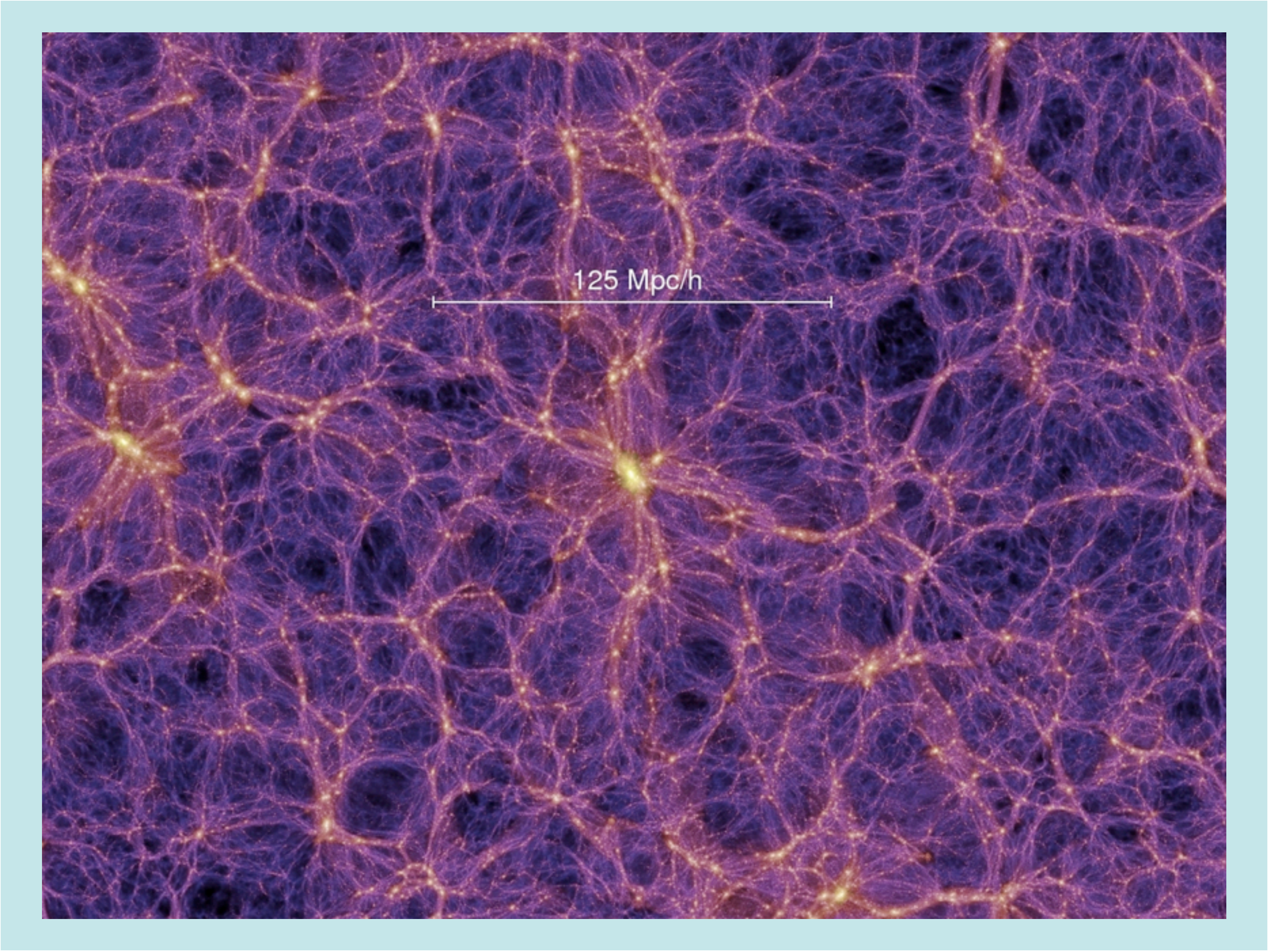
Simulations of three different models, each described by a different spectrum of initial density fluctuations.

Increasing Small Scale Power



Most Small
Scale Power


2 Mpc/h
2 Mpc/h
125 Mpc/h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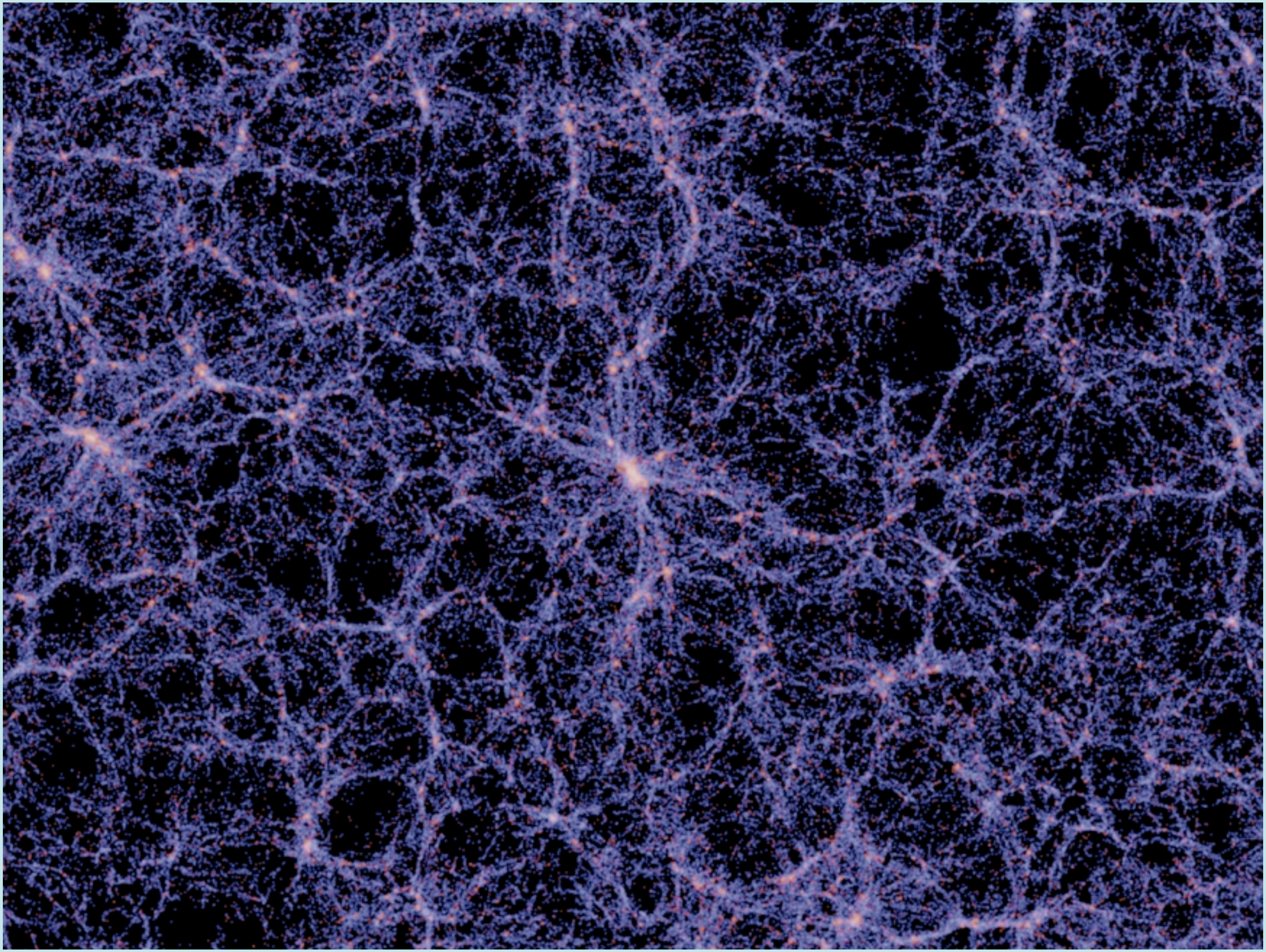
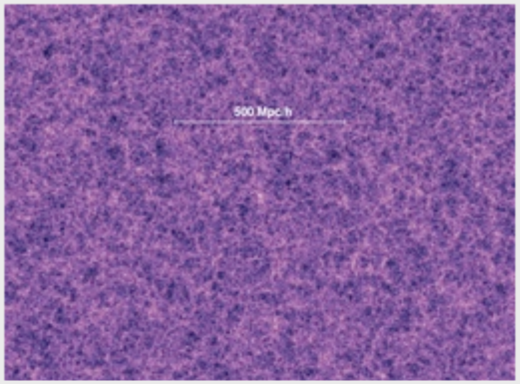
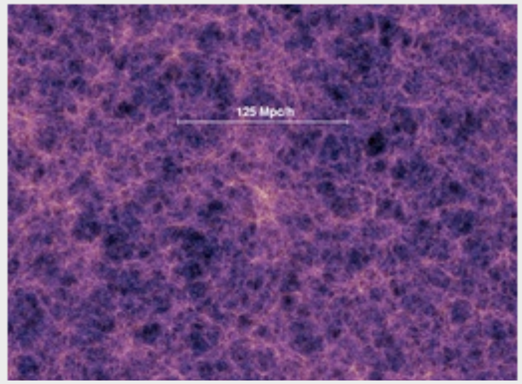
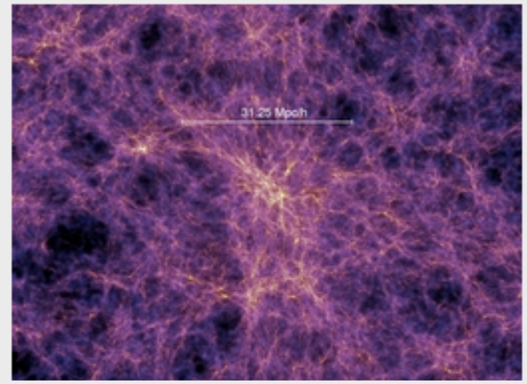


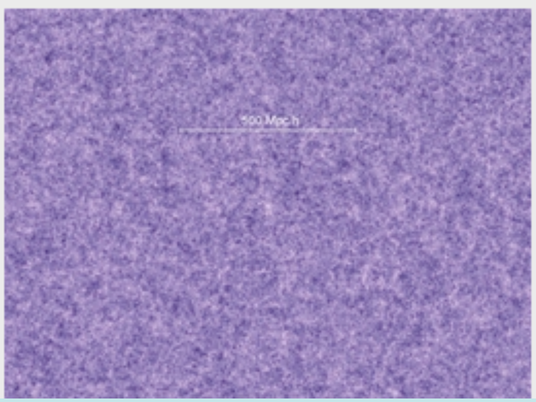
Redshift z=5.7 (t = 1.0 Gyr)

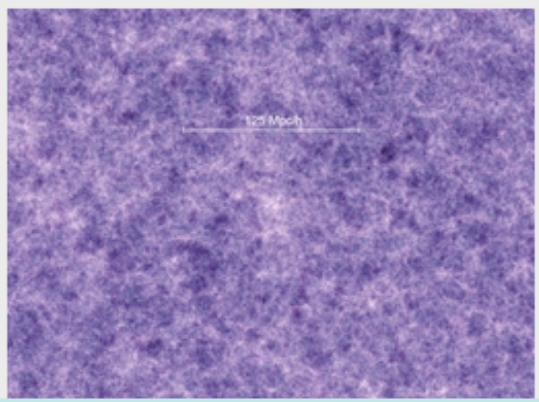


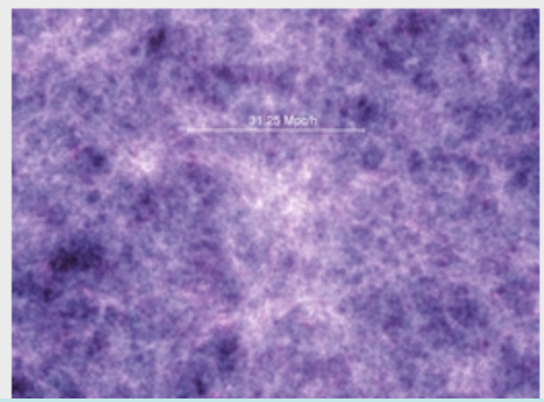




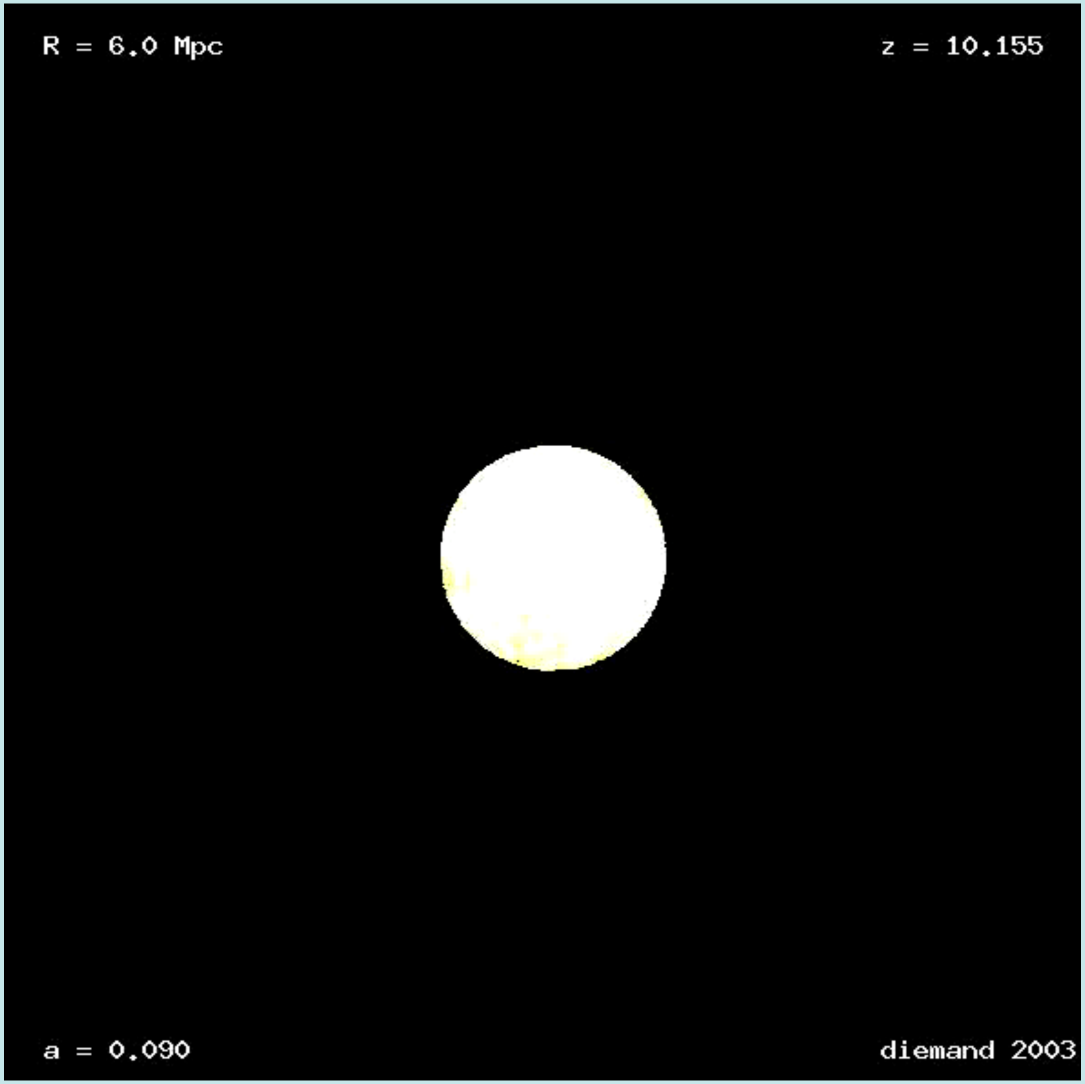
Redshift z=18.3 (t = 0.21 Gyr)



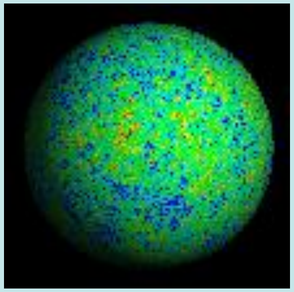




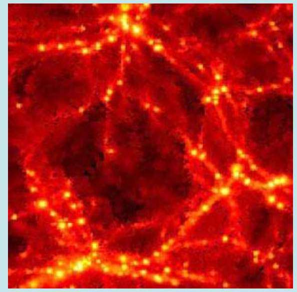
NUMERICAL SIMULATIONS



CMBR



Lyman alpha forest



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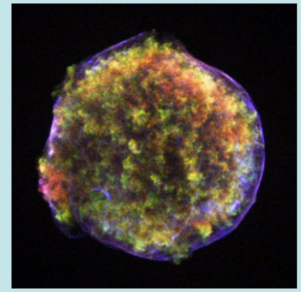
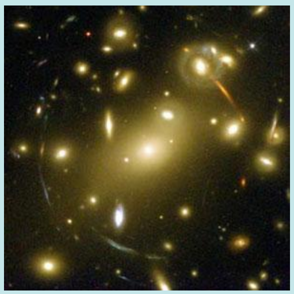
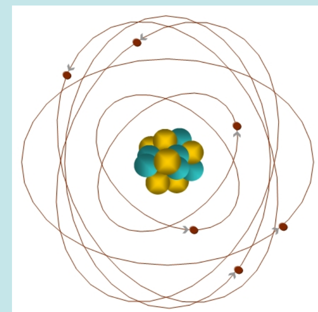




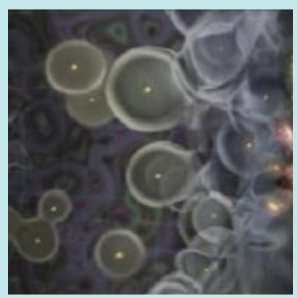
Gravitational Lensing

Cosmological Probes

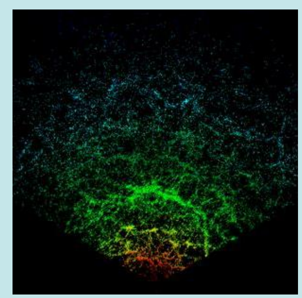


Primordial Nucleosynthesis

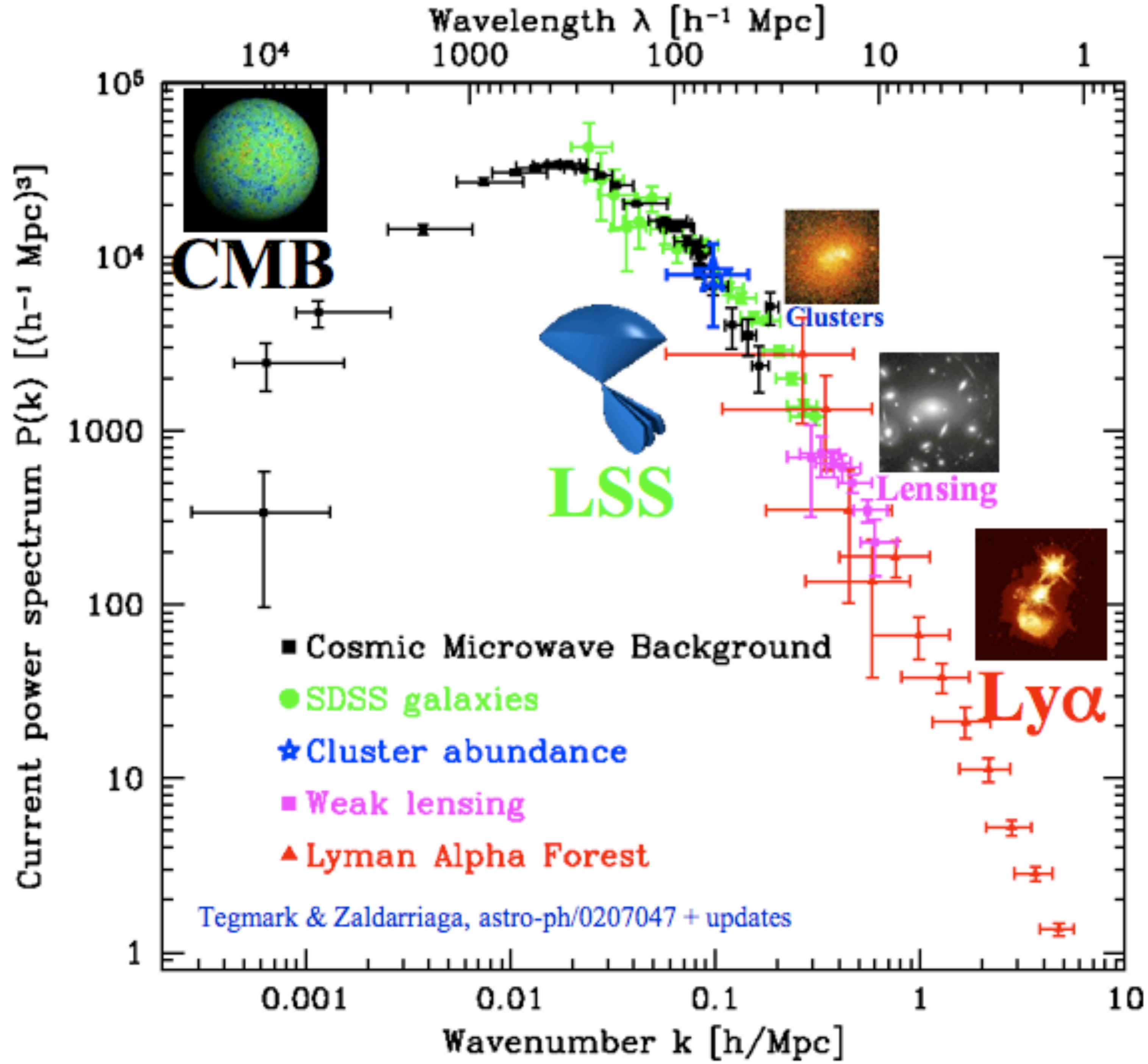
Galaxy clusters



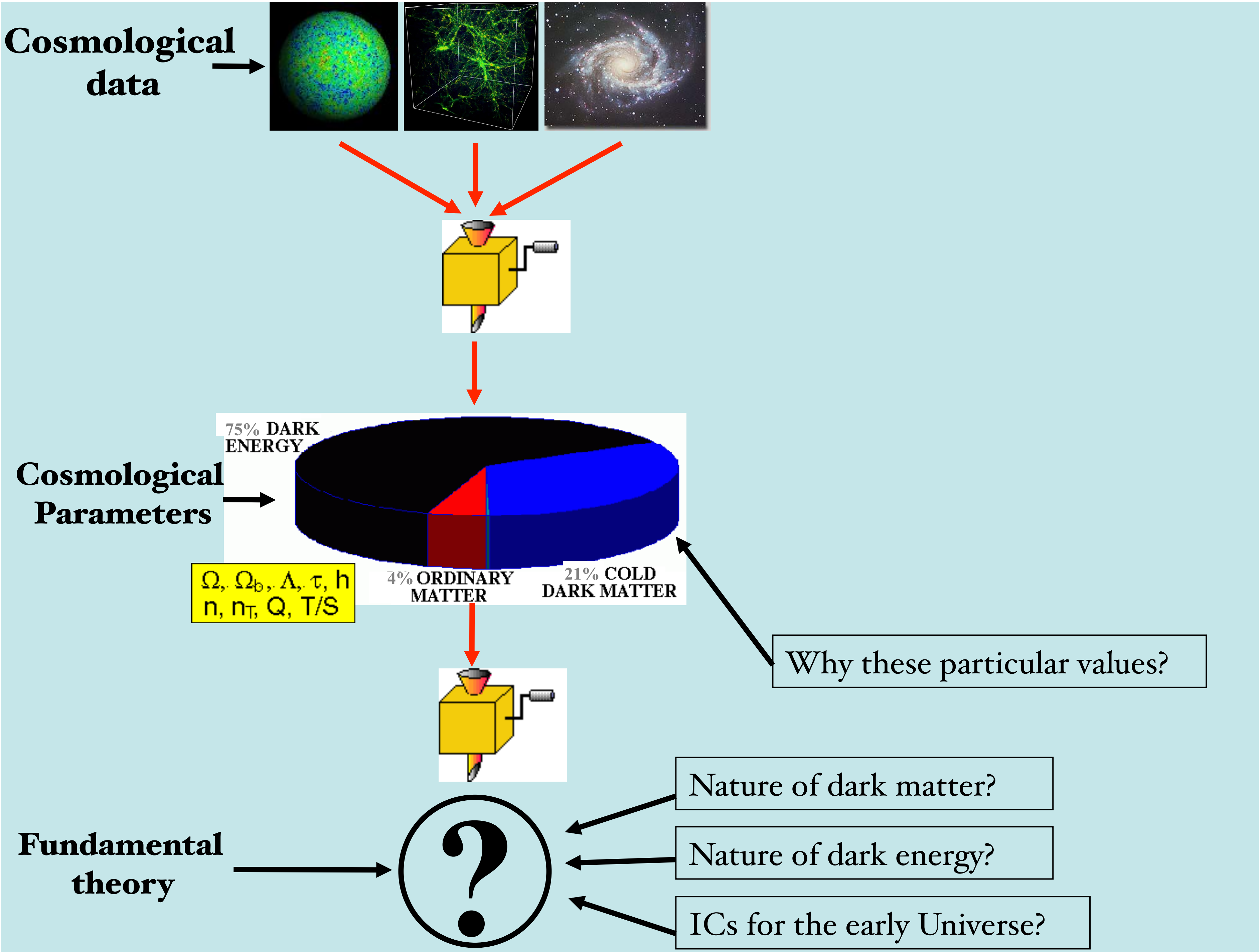
21 cm mapping



Galaxy Surveys



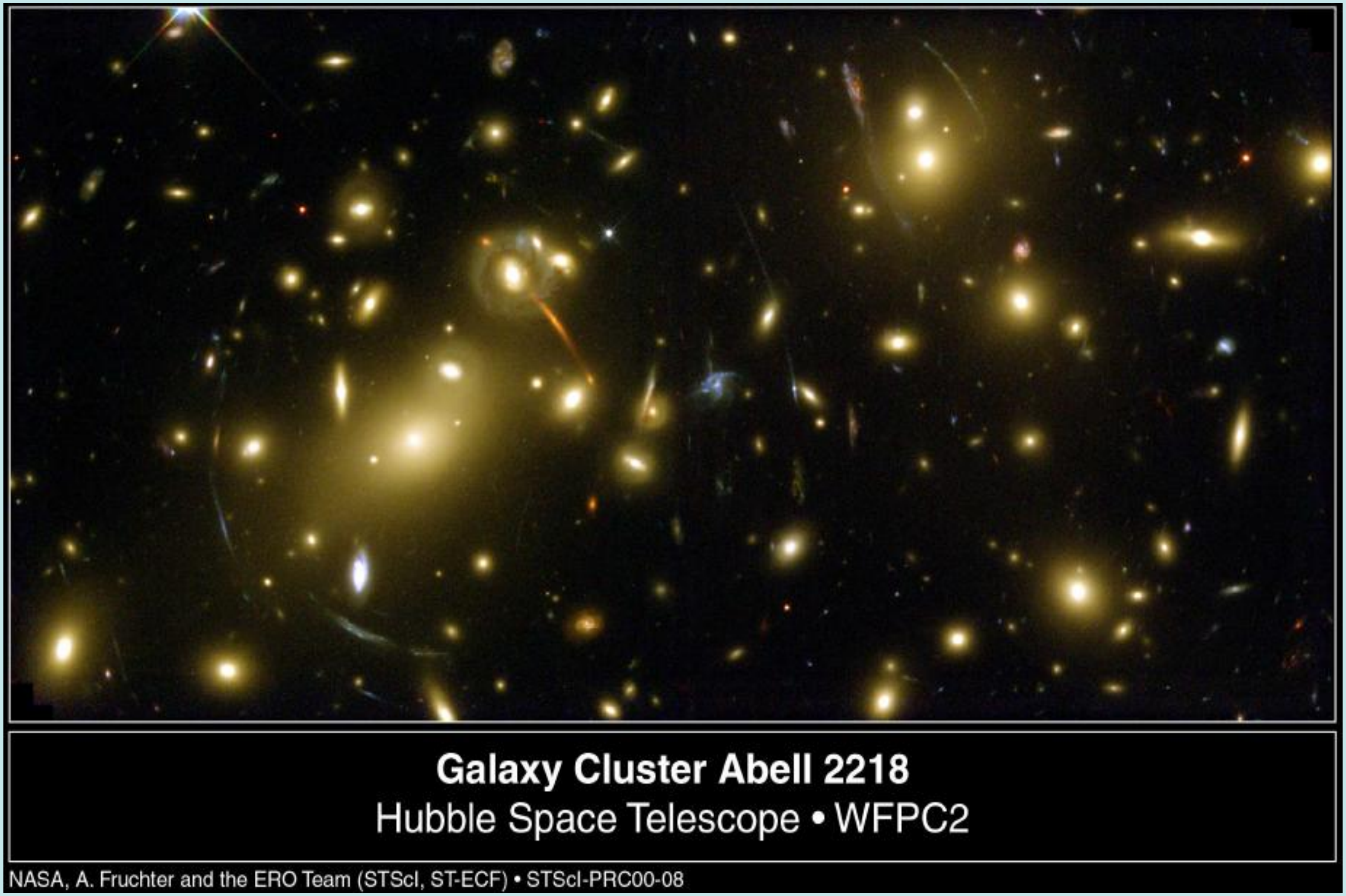
Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
CMB
LSS
Clusters
Lensing
Lyα
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
Tegmark & Zaldarriaga, astro-ph/0207047 + updates
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]



Cosmological data
75% DARK ENERGY
Cosmological Parameters
Ω, Ω_b, Λ, τ, h
n, n_T, Q, T/S
4% ORDINARY MATTER
21% COLD DARK MATTER
Why these particular values?
Nature of dark matter?
Nature of dark energy?
ICs for the early Universe?
Fundamental theory
?

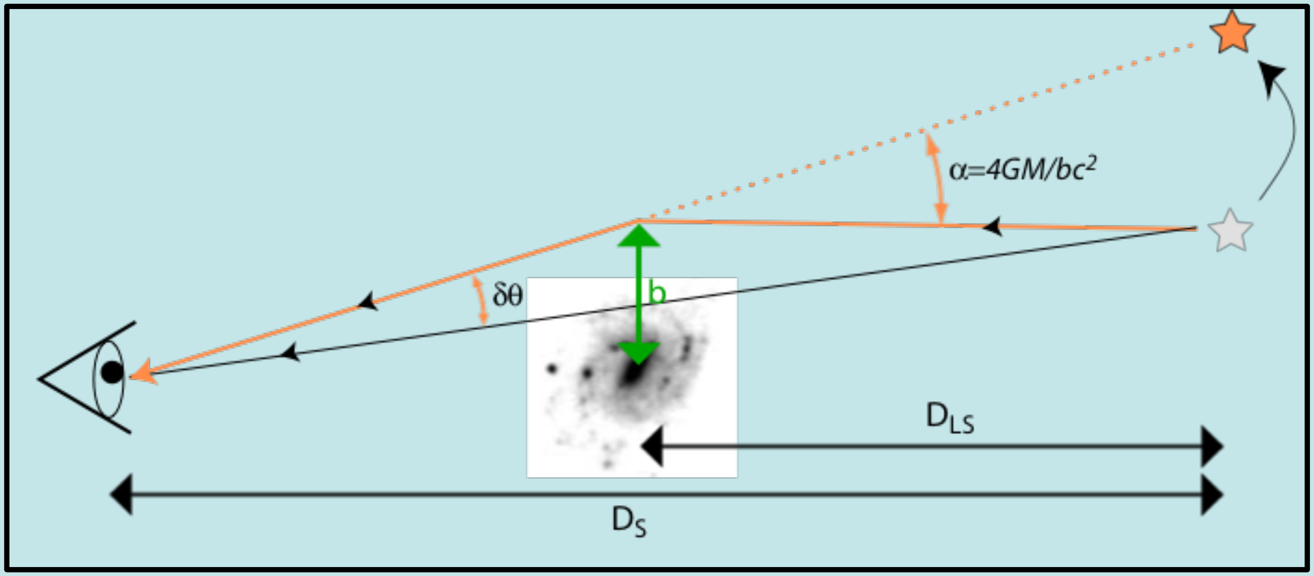
CONSTRAINING DARK MATTER & DARK ENERGY

power of gravitational lensing



~1% of mass in galaxies, ~10% of mass is hot gas, rest is DM

Measuring lensing signals



$$\delta\theta = \frac{4GM}{bc^2}\,\frac{D_{LS}}{D_S}$$

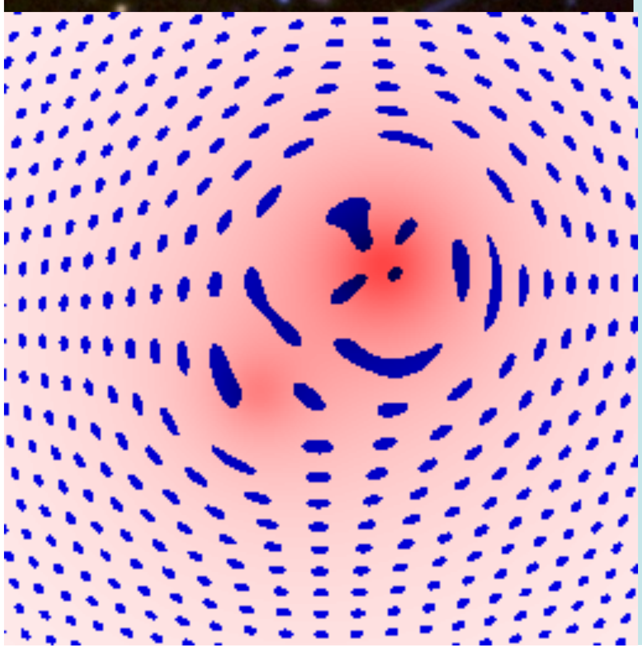
We observe this deflection angle (more precisely, gradients of the deflection angle).

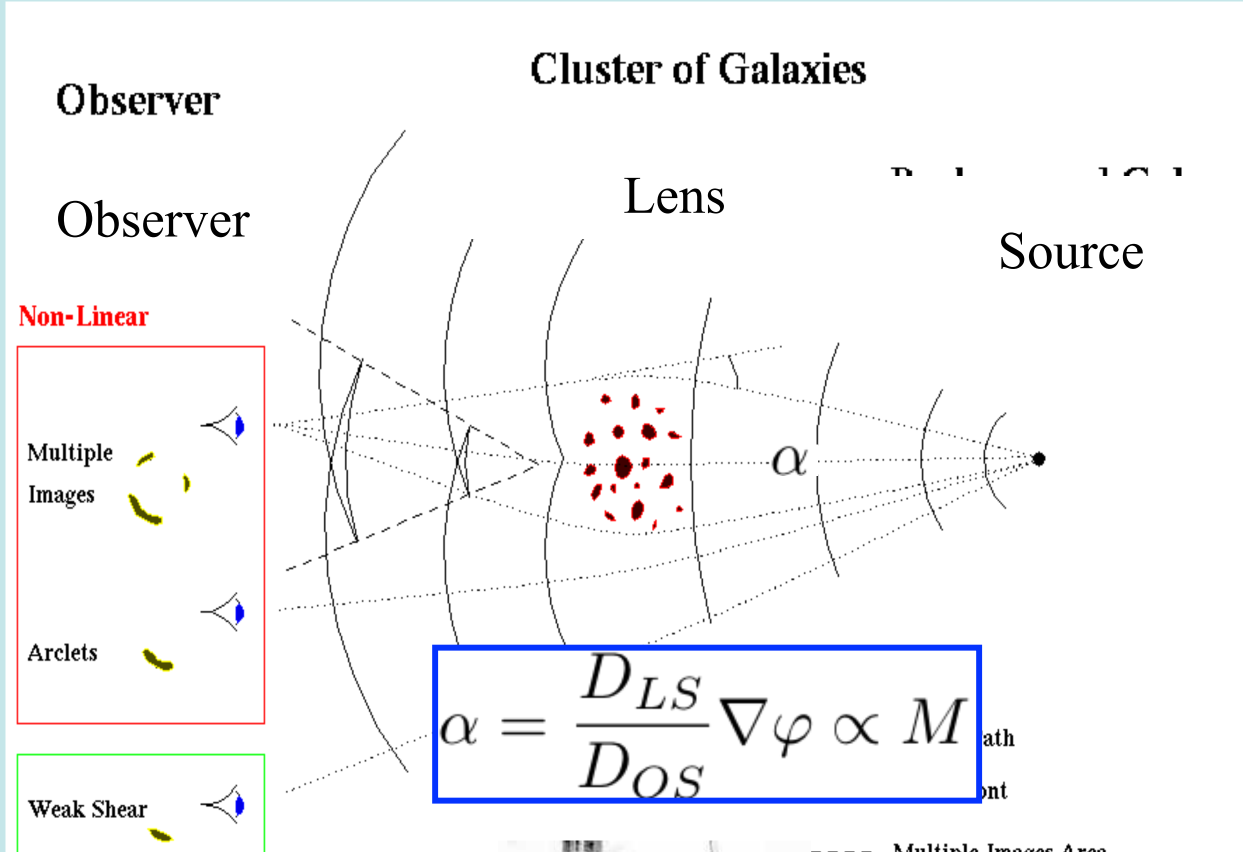
Cosmology changes growth rate of mass structures in the Universe.

Cosmology changes the geometric distance factors.

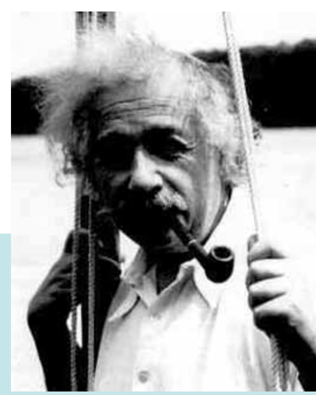
The deflection is proportional to the mass

Blandford & Narayan 92; Schneider Ehlers & Falco 92; Bartelmann & Narayan 97; Kneib & PN 10

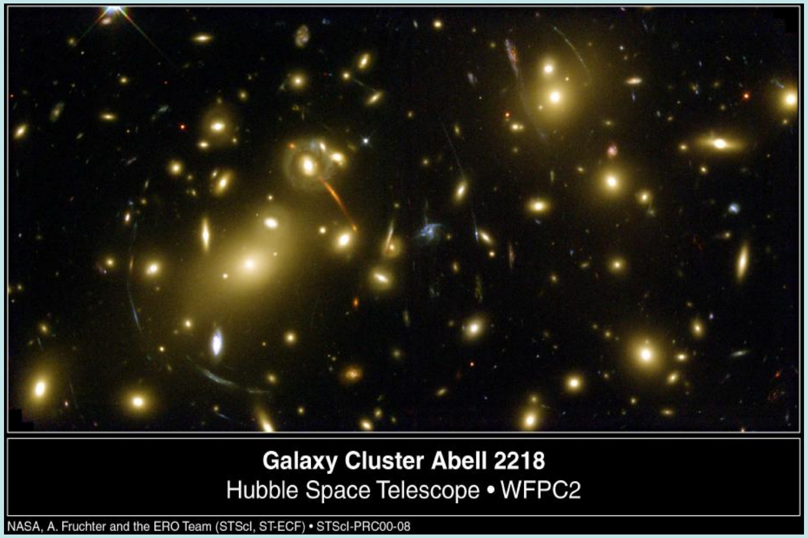


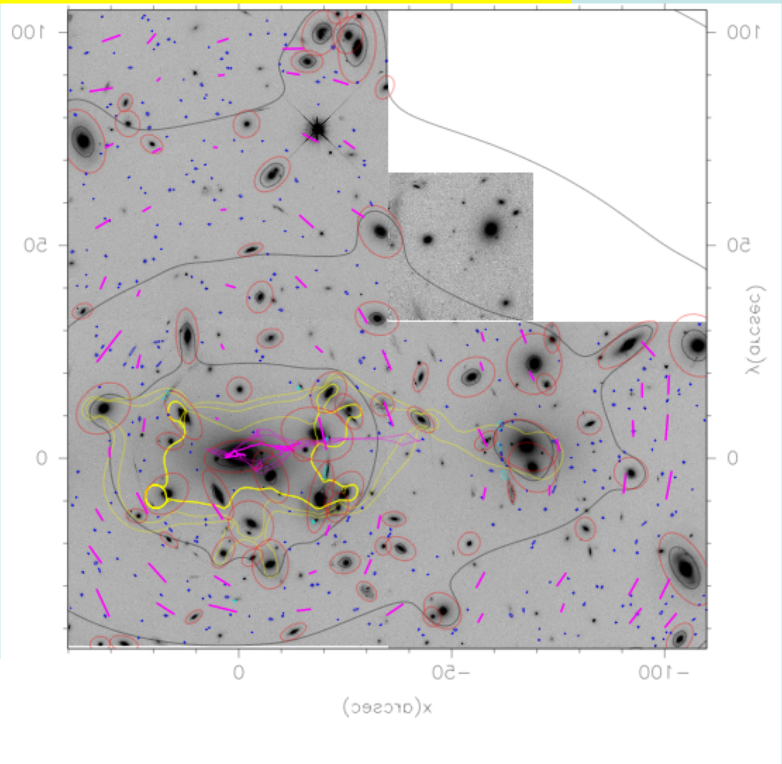


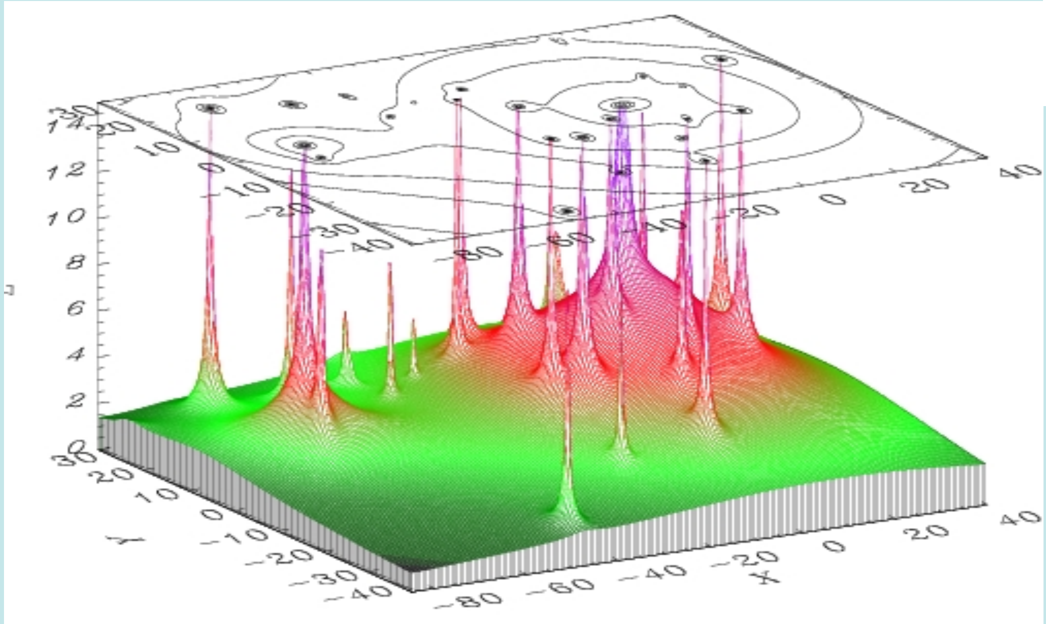
$$\boxed{\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi \propto M}$$



Dark Matter Maps



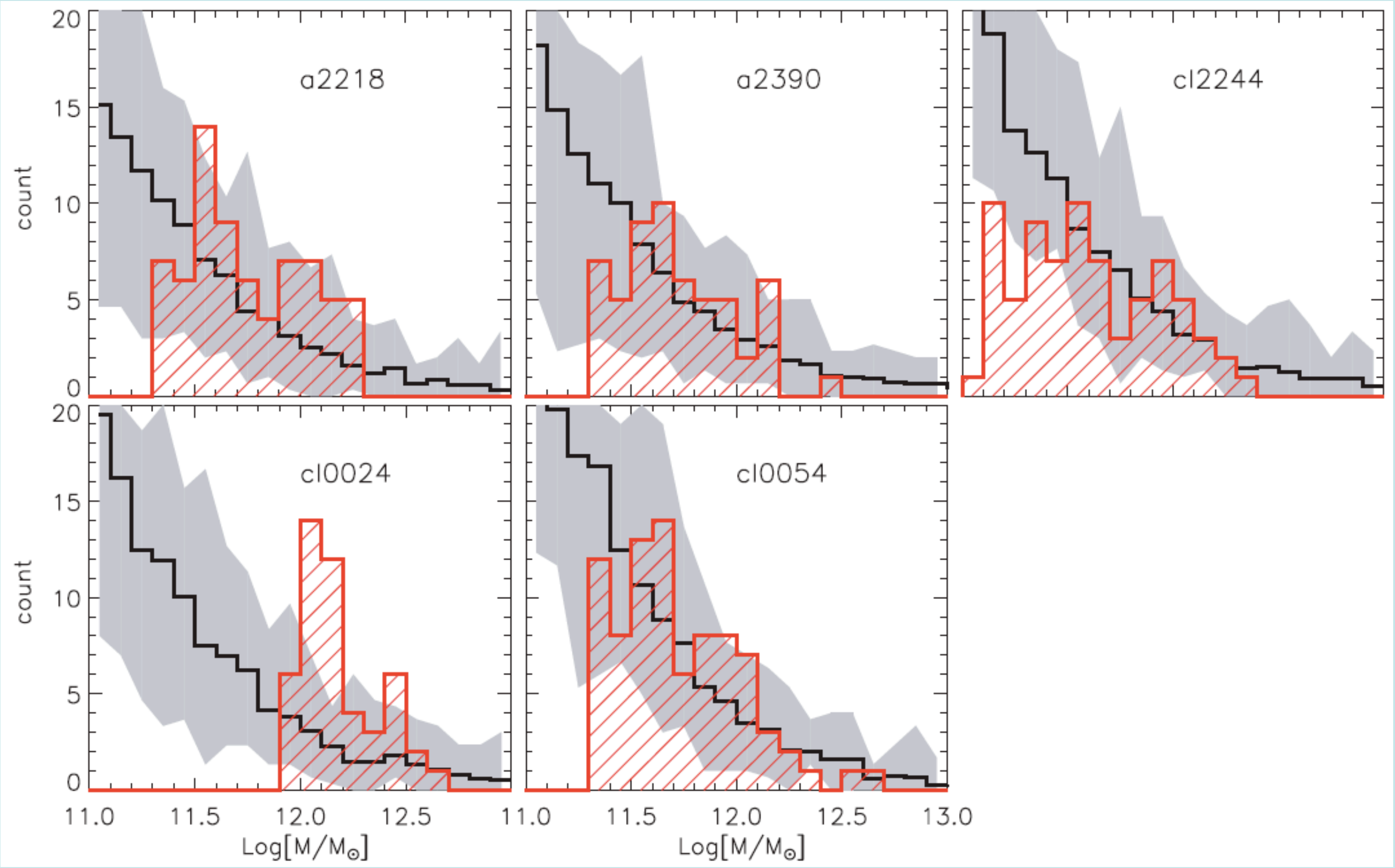




PN+ 02; 06

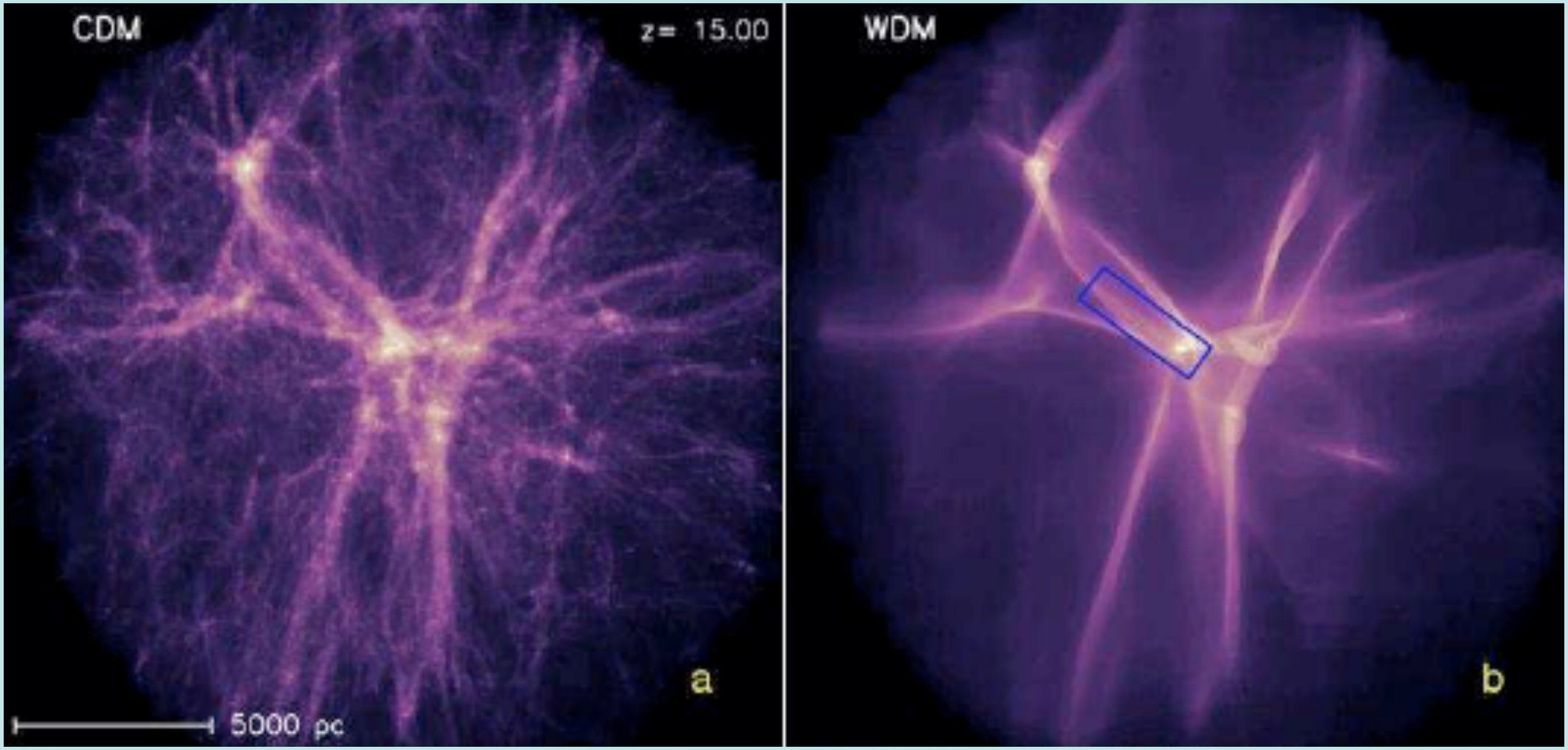
Comparison with LCDM clusters in the Millenium Run

The subhalo mass function



Springel+ 05
PN, De Lucia & Springel 07
PN+ 09

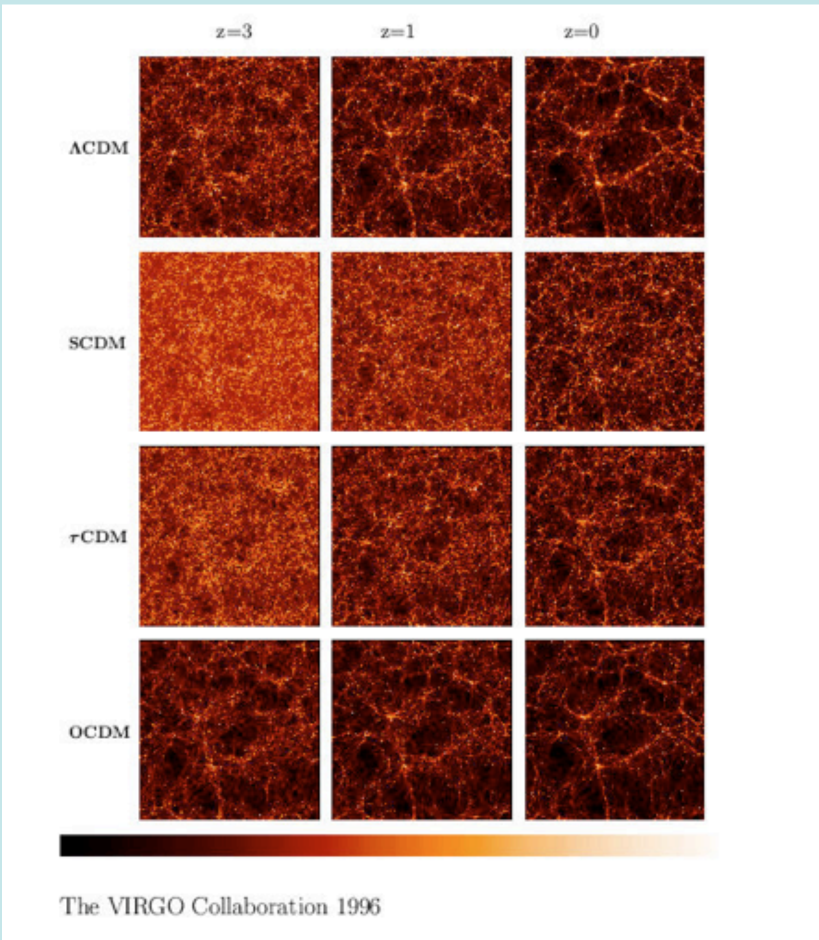
LCDM is consistent with lensing observations at present

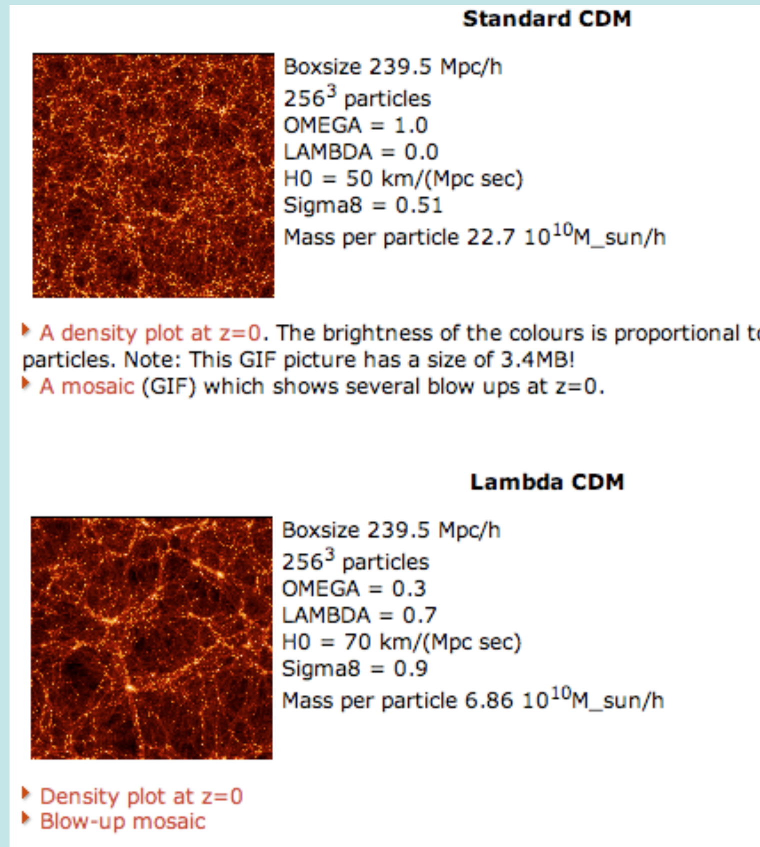


COLD DARK MATTER WARM DARK MATTER

However can we ever rule out theories and LCDM in particular? Not really.....no compelling alternative

Can cosmological simulations help us validate cosmological theories?





Why do we need to simulate in cosmology?

- Inability to perform any other kind of controlled experiments
- Provides a temporal realization of a complex process
- Enables comparison with observed reality
- Relationship between models and reality

Parker 2009; Yanoff & Weirich 2010

How do cosmological simulations differ from experiments?

- Experiments epistemically privileged due to their materiality
- More concrete relationship with reality
- Unique-ness easier to establish and quantify

- Challenging to compare to reality

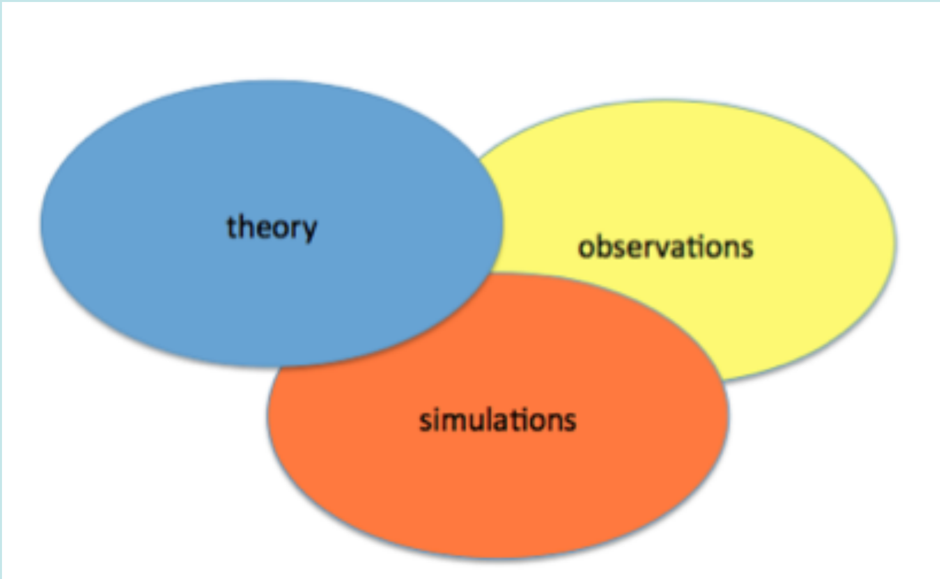
Schweber & Wachter 2000; Keller 2000; Ruphy 2010; Yanoff & Weinrich 2010

What sets cosmological simulations apart?

- Special properties of the Universe - the Universe itself cannot be subjected to physical experimentation
- Cannot be observationally compared to other Universes
- The concept of any laws of physics that apply to only one object are questionable
- The concept of probability is problematic in the context of the existence of one object
- The interpretation and comparison of observations with simulations requires further assumptions

Scientific uses of cosmological simulations

- Proof/Validation
- Explanation, either full or partial
- Prediction
- Substitute for controlled experiments



Requires us to expand our notion of how a theory or explanation can be tested, verified and accepted

Key philosophical problems with simulations as generators of and testers of theories

- The underdetermination of cosmological models by all possible evidence that an observer can hope to collect
- The failure of predictability in most cosmological models
- Limits on testing theories that arise from cosmic variance (and what does cosmic variance mean anyway)
- Simulations versus observations - what are we testing?
- Methodological, Epistemic, Semantic problems….
- Relationship between simulations and the models that they rely on
- Are simulations truly descriptive, representational and inferential?
- How radically have simulations transformed cosmology?

How transformative have cosmological simulations been?

- Have transformed a wide range of scientific practices, multi-disciplinary in impact
- Have catalyzed the formation of a new professional class of simulators in cosmology
- Have catalyzed dramatic intellectual changes
- Can we discriminate between theories?
- Role of technology and the history of the development of computational sciences
- Testing plausibility of models, Bayesian inference….
- Have been revolutionary

Winsberg 2011

EXPANDING OUR NOTION OF WHAT COUNTS AS AN EXPLANATION

- Simulations of the universe and theories of what happened before the BB (initial conditions....)

  both require redefining our notion of what is a valid explanation and how a theory can be verified

Can a test validate a theory whose extrapolation can be test even though it cannot be? (Aguirre's lectures)

Challenges

- No controlled experiments can be performed
- Uniqueness – cannot compare with other universes, poses problem for probabilistic claims
- Epistemic limitations – limits of our knowledge of physics relevant to the early universe
- Issue of origins – testable physics cannot explain the initial state, no information available
- Anthropic issues – ultimate causation, laws of physics
- The multiverse hypothesis – possible existence impossible to prove, torques the very nature of explanation (on what constitutes an acceptable one)
- Gaps in current understanding – dynamical matter composition at early and late times is unknown, nature of the laws of physics