Cosmology through the Large-Scale Structure of the Universe

Eyal Kazin

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illustration by Sam Moorfield

What does everybody in this room have in common?

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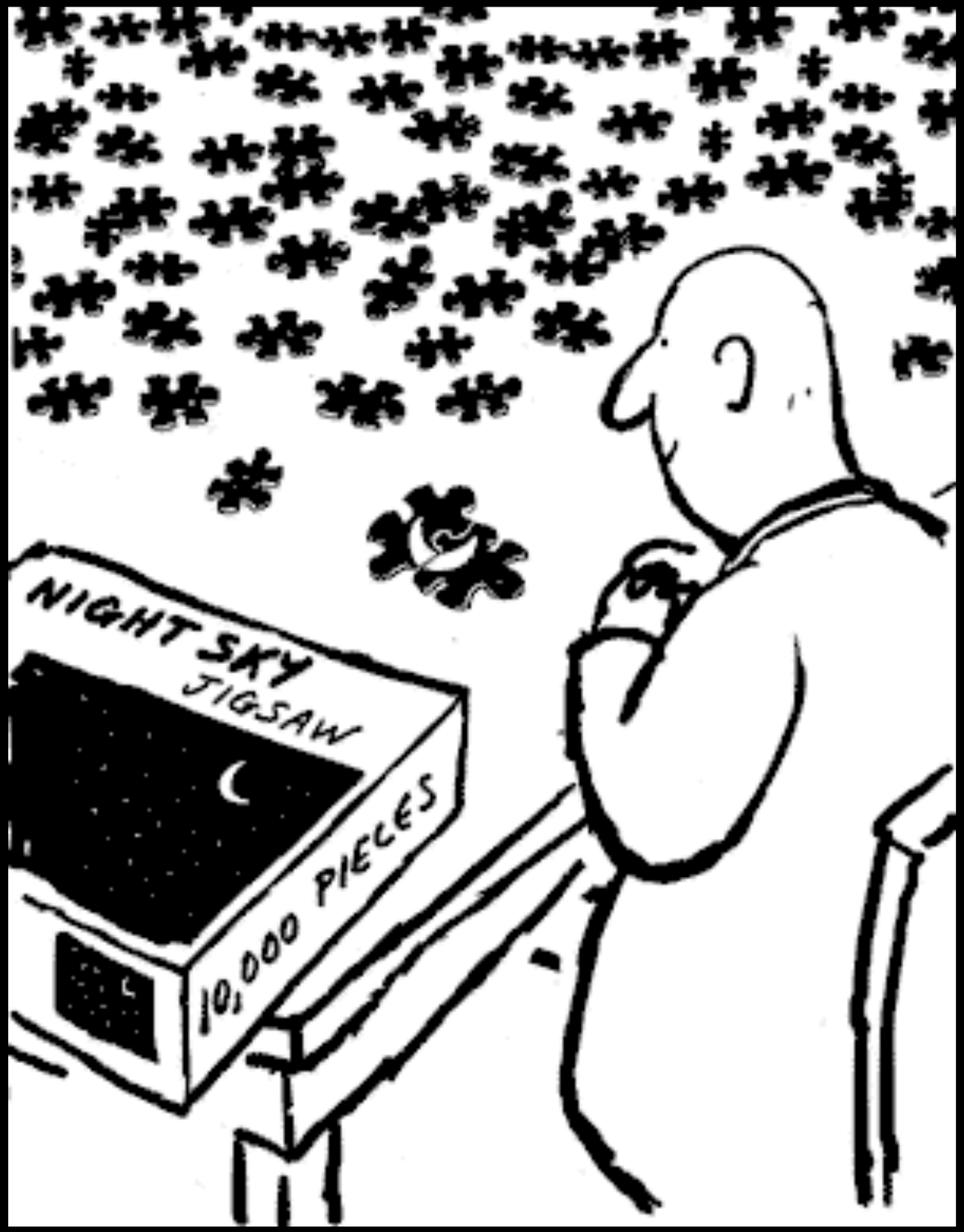
What does everybody in this room have in common?

We get pleasure from solving puzzles.



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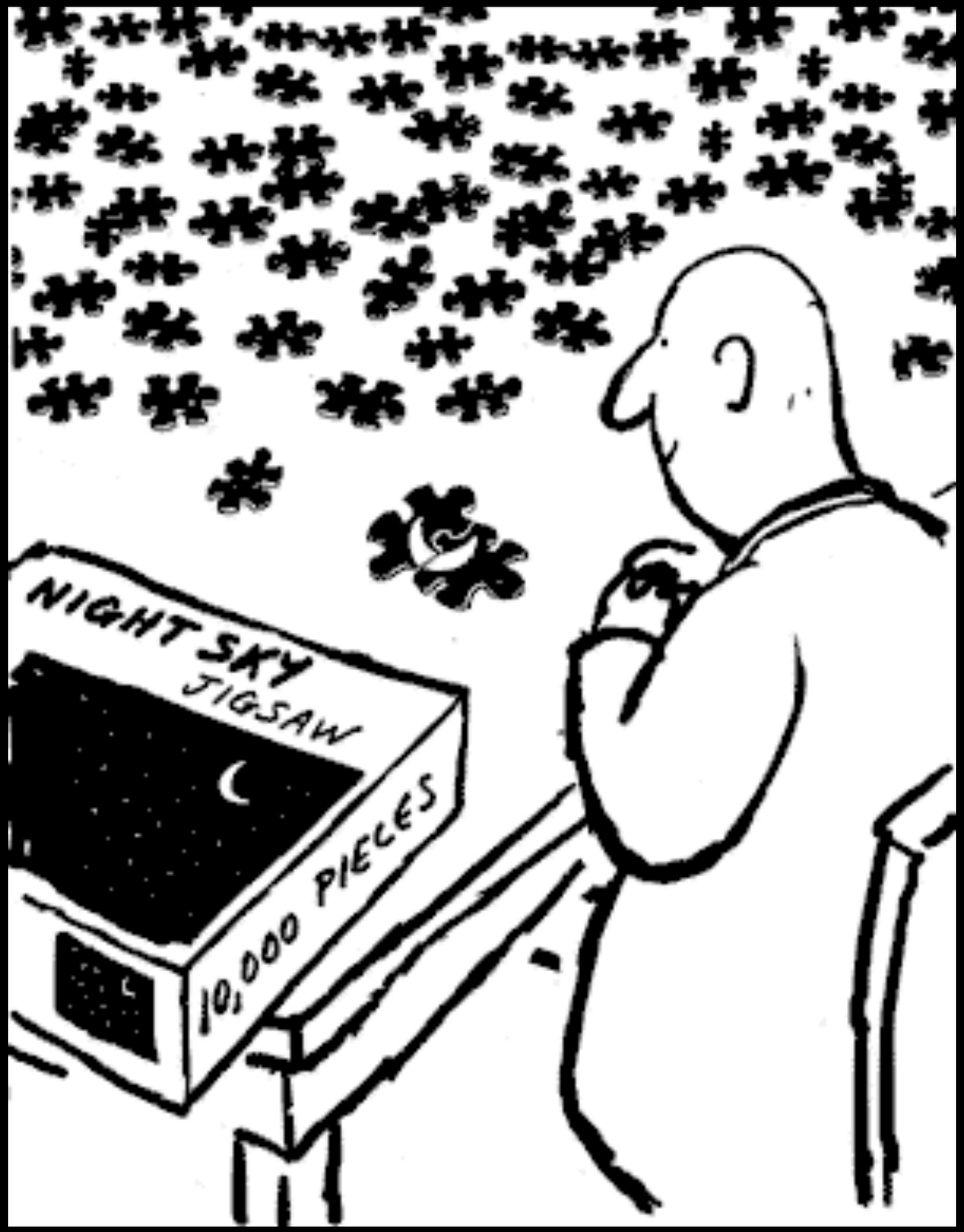
To solve a puzzle, we need information to analyze, and would like to compare results to fundamental ideas.



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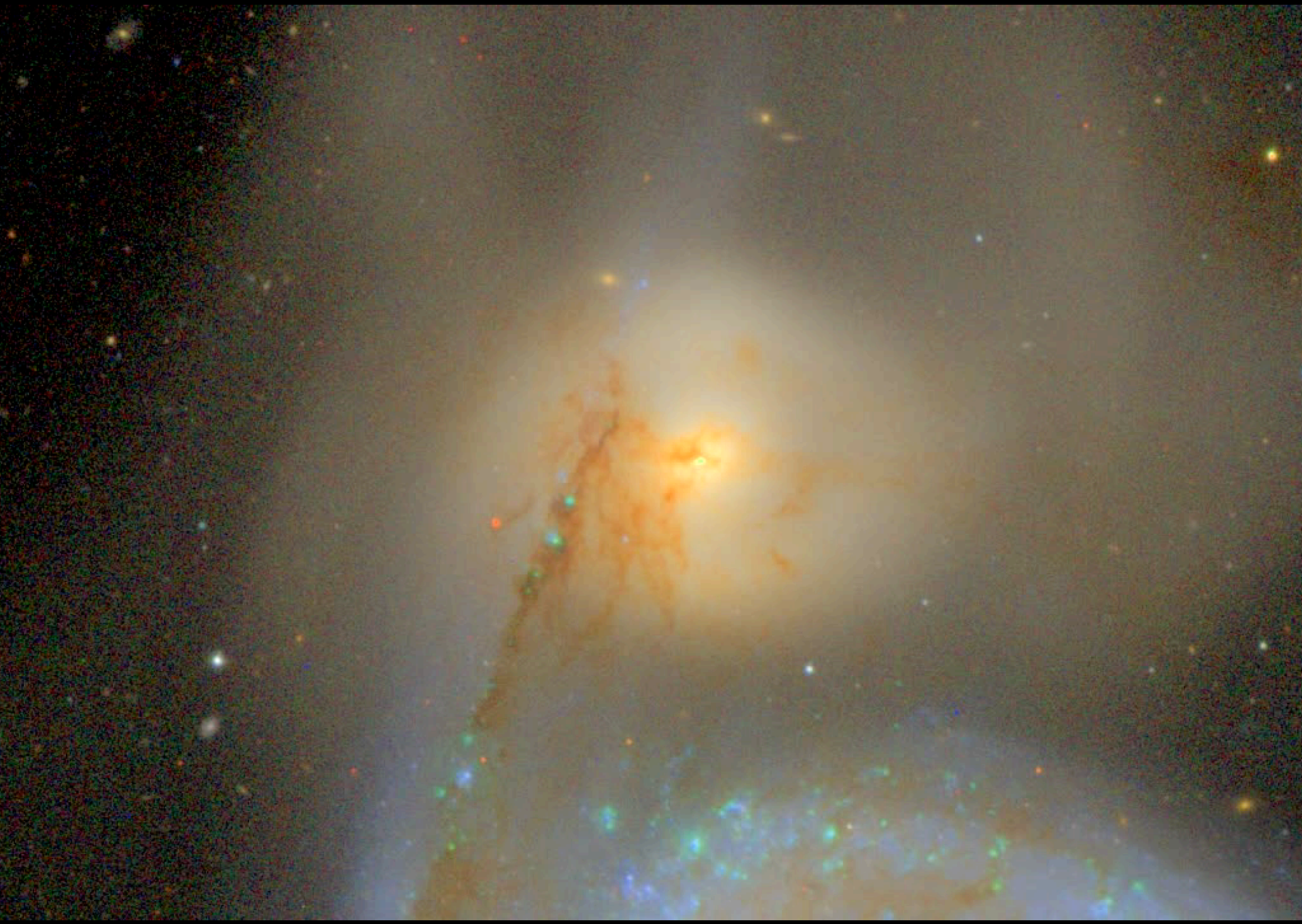

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from LSS we measure the cosmic expansion, gravity on large-scales

1100

Redshift

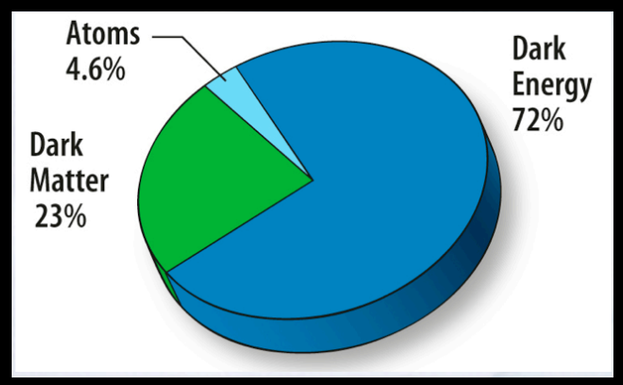
0.1 0.2 0.3 0.4 0.6 0.8 1.0 1.5 2 3 6 20

Lookback Time (Billions of years)

1 2 3 4 5 6 7 8 9 10 11 12 13

Earth,
Right here
Right Now

a lot of cosmological information



DM simulation, Kim et al. (2009)

13.3

Cosmic Microwave Background

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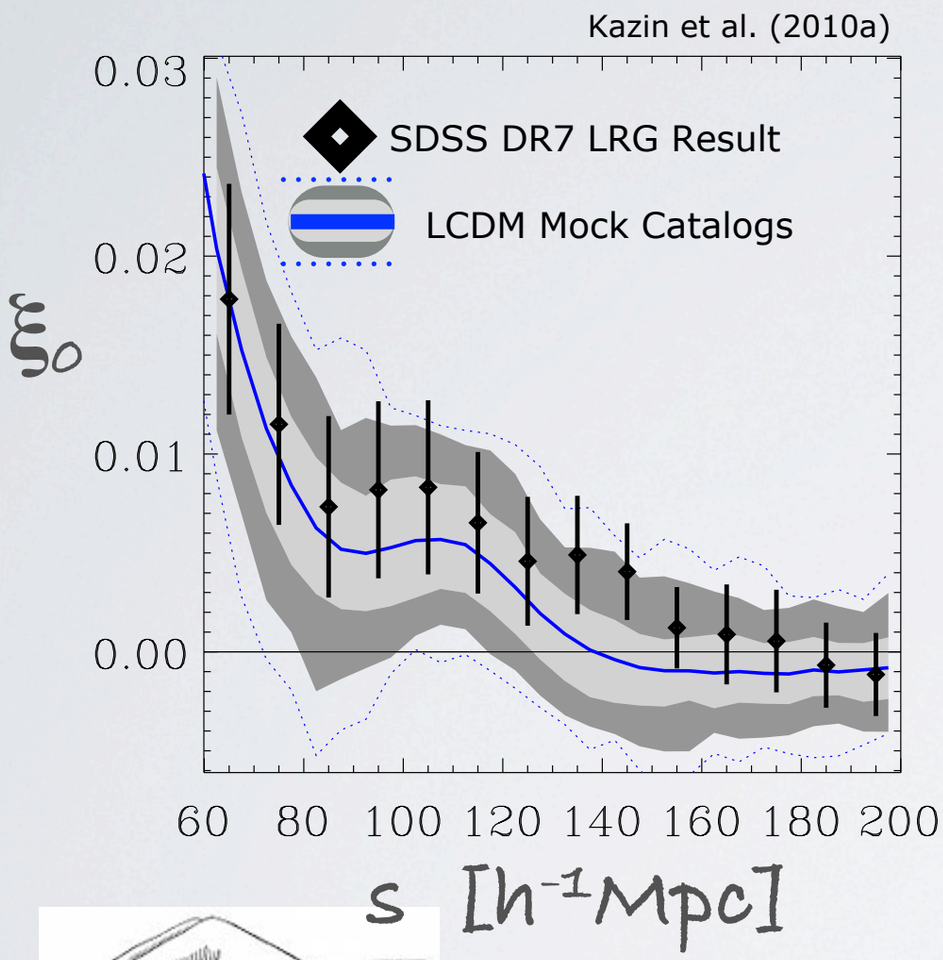
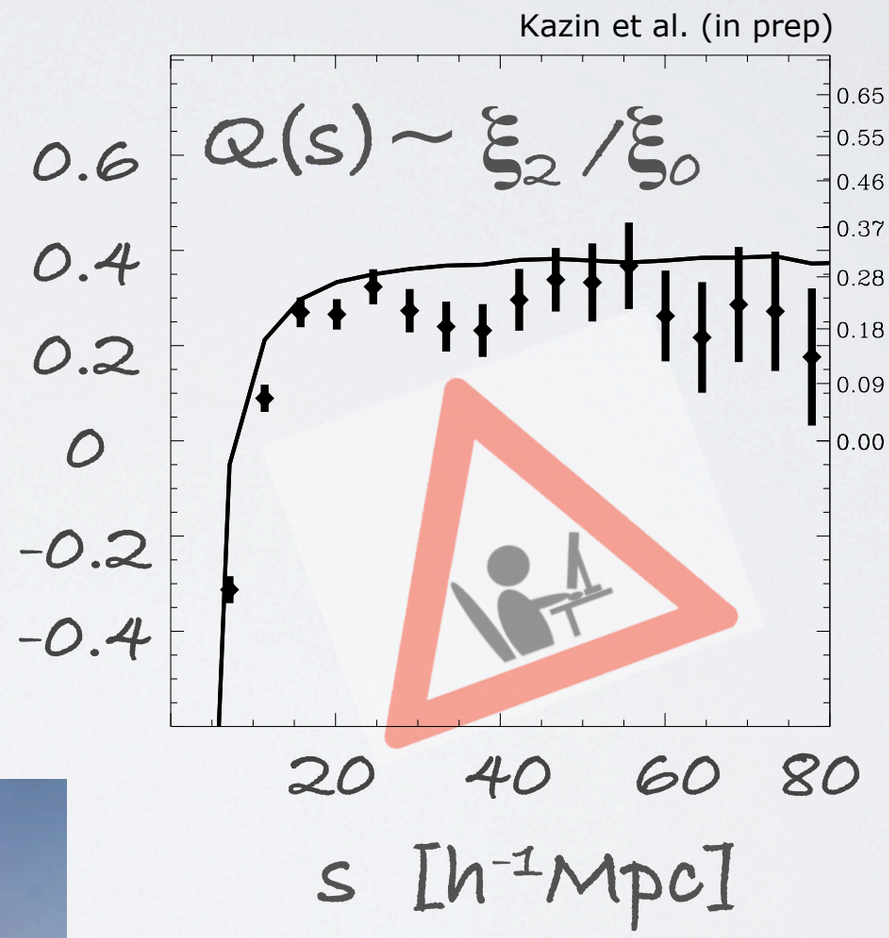
My Cosmological Tool Box

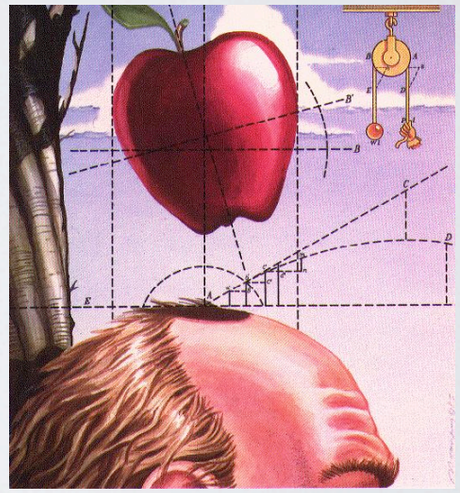
The Baryonic Acoustic Feature
Testing Geometry

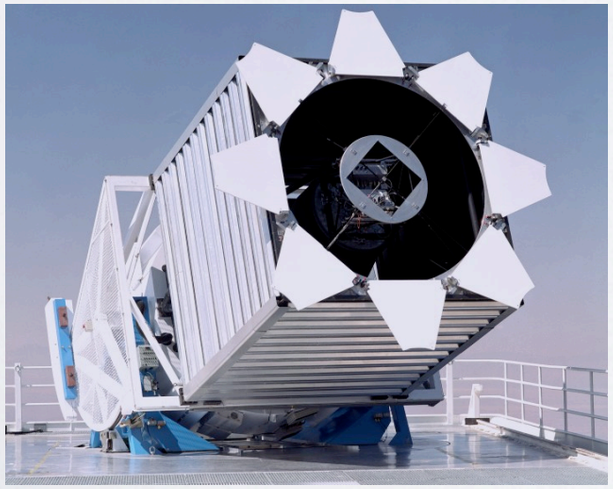


z-Distortions
Testing Gravity



$\beta \approx \Omega_M^{\gamma}(z)/b_1$





The Sloan Digital Sky Survey (SDSS)

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physicists & astronomers

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Newtonian Gravity

Moon & Tides

(I hope Bill O'Reilly is not in the audience... we wouldn't want miss-communication ...)

Einstein's General Relativity

Mercury's precession

?

Dark Matter

??

Dark Energy

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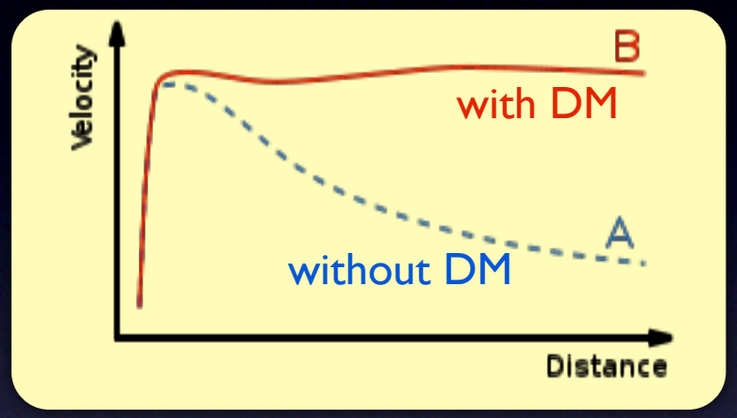
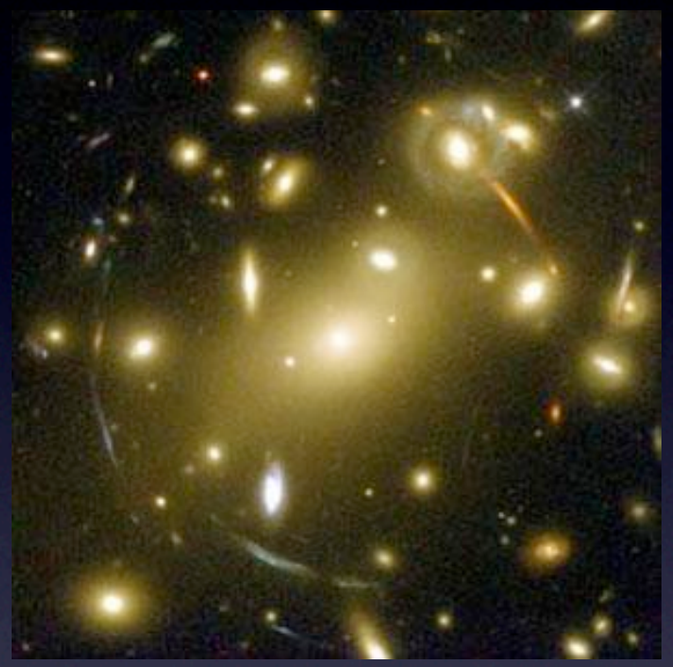
Why believe in DM?

signature observed in many gravitational probes

Galaxy Rotation Curves

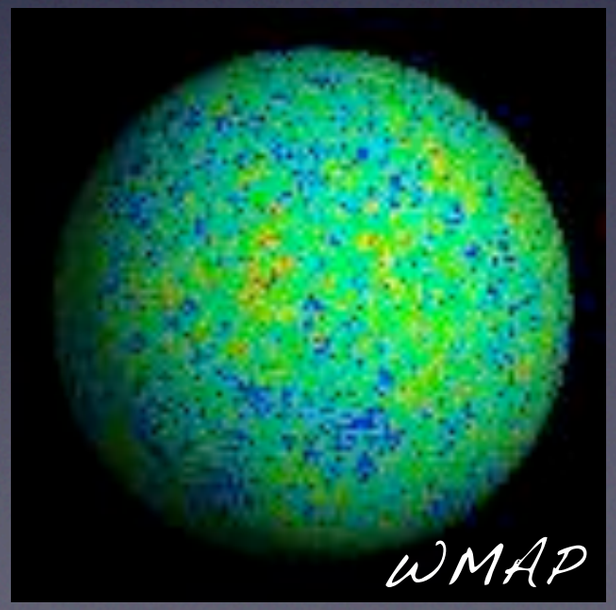


Gravitational Lensing

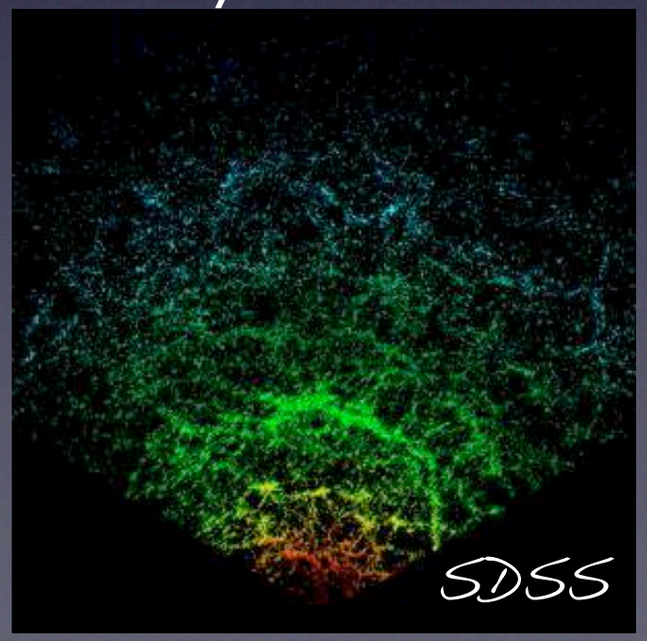


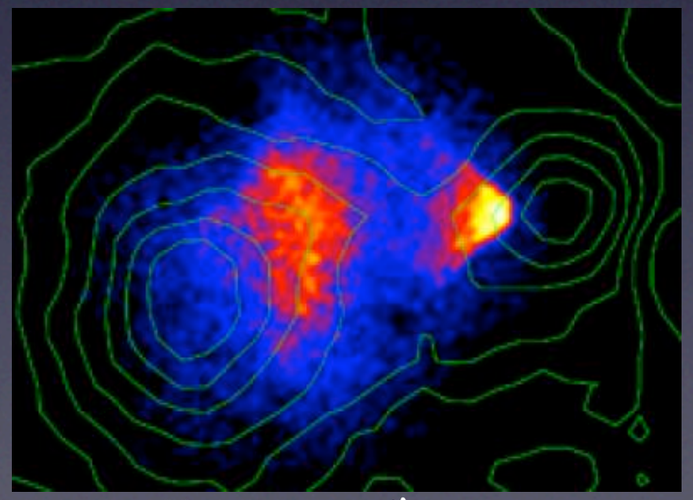
Galaxy Clusters

Cosmic Microwave Background



Galaxy Distribution





the "Bullet" Cluster

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A (brief) history of (our understanding of) the cosmic expansion

- 1925: Friedman applies GR on Universe -- it could potentially expand!

- 1929: Hubble's distance-velocity correlation -- the Universe is expanding?
- 1949: Fred Hoyle ridicules the expansion idea coining it the``Big Bang''

- 1968: Penzias & Wilson detect the predicted Cosmic Microwave Background -- first smoking gun for expansion!
- 1998: Reis et al. and Perlmutter et al. measure SNe distance-redshift -- the observed Universe is accelerating!

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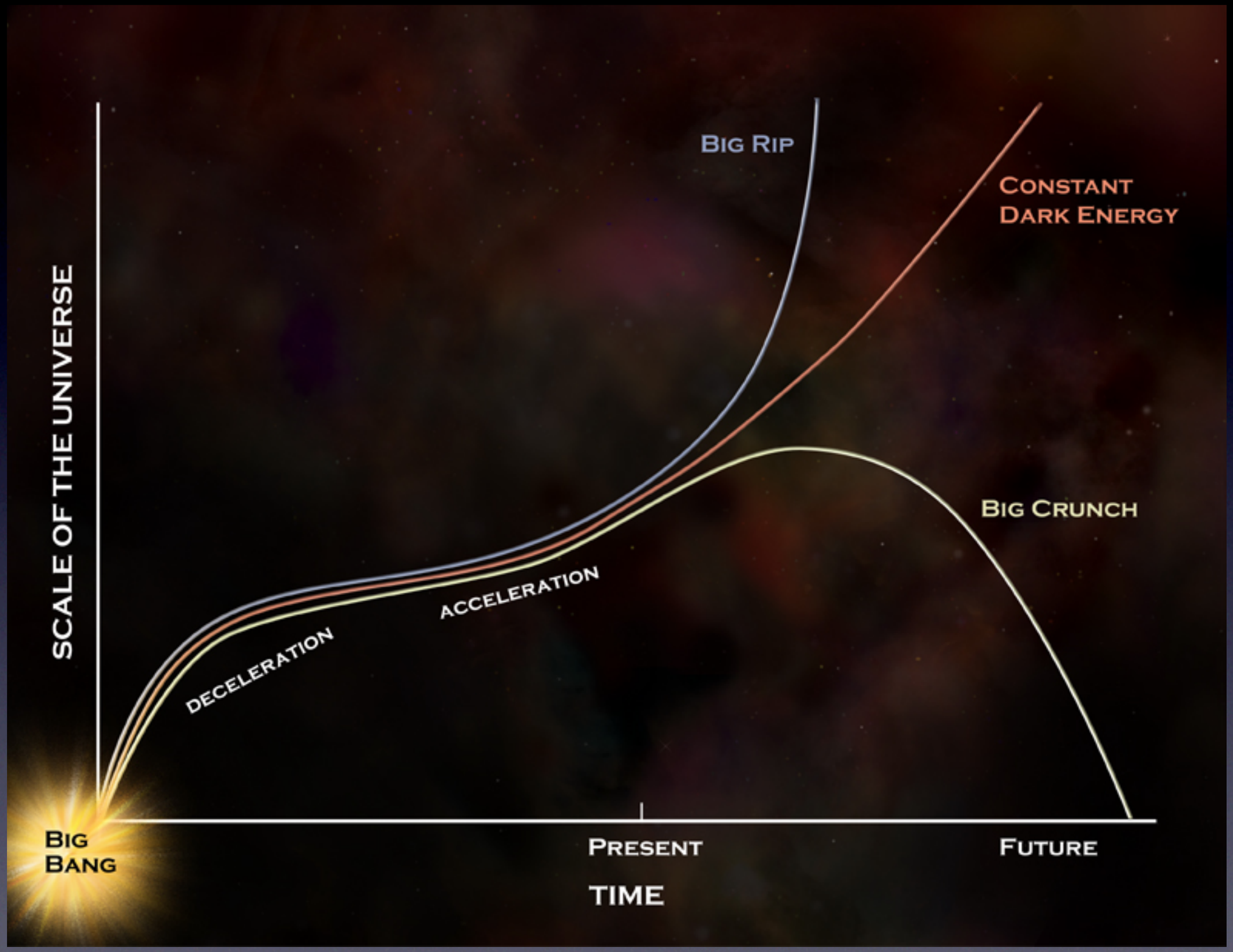
The Accelerating Universe?

When?

- Now! In the last 7.7 (of 13.6) Gyr
- Inflation era (t<<1 sec after Big Bang)



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The Accelerating Universe?

When?

- Now! In the last 7.7 (of 13.6) Gyr
- Inflation era (t<<1 sec after Big Bang)

Why? Current best guesses:

- Cosmological Constant (Dark Energy)
- Modified Gravity (breakdown of GR?)

How do we measure?

- By measuring large-scale geometry

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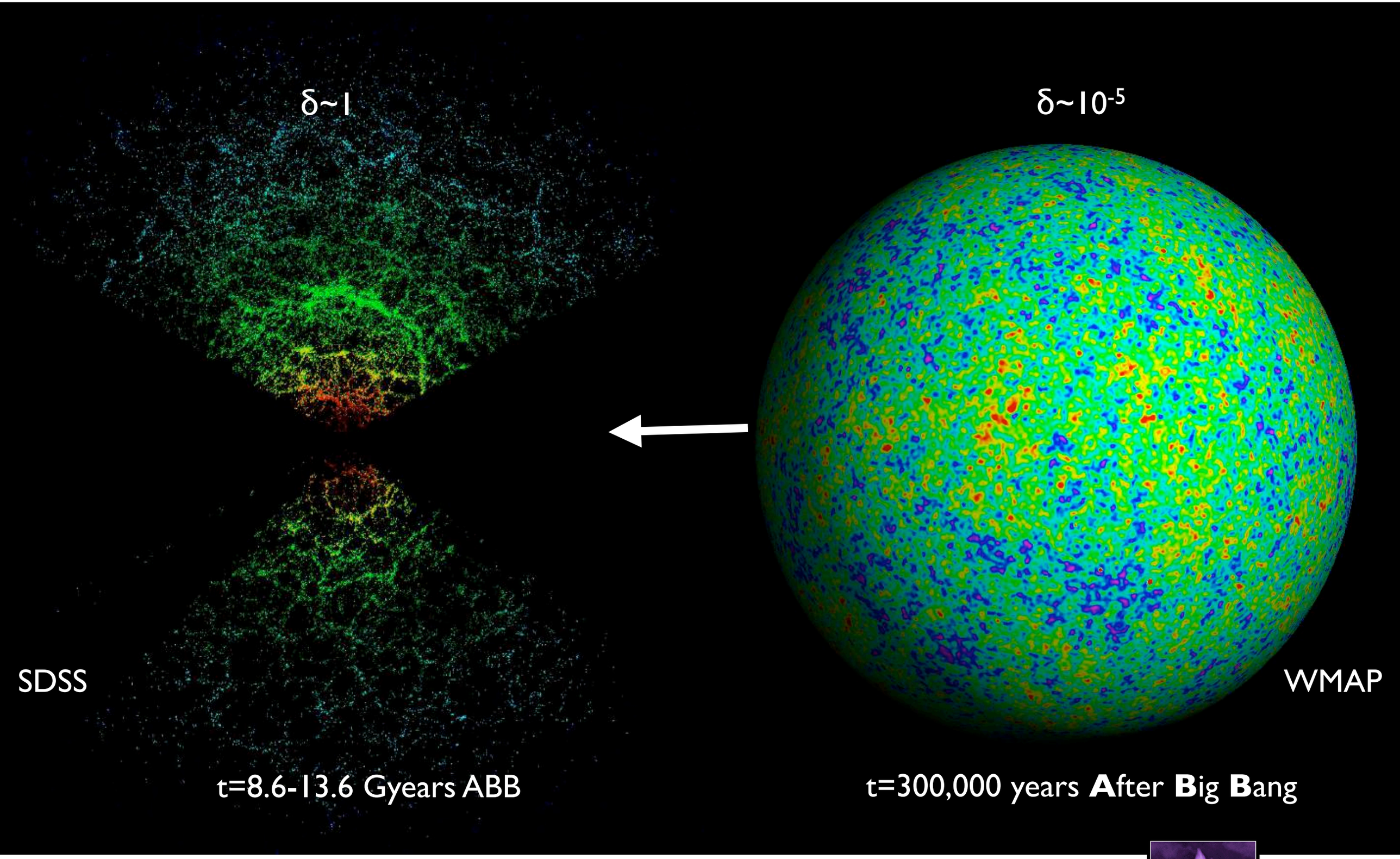
Large-Scale Structure



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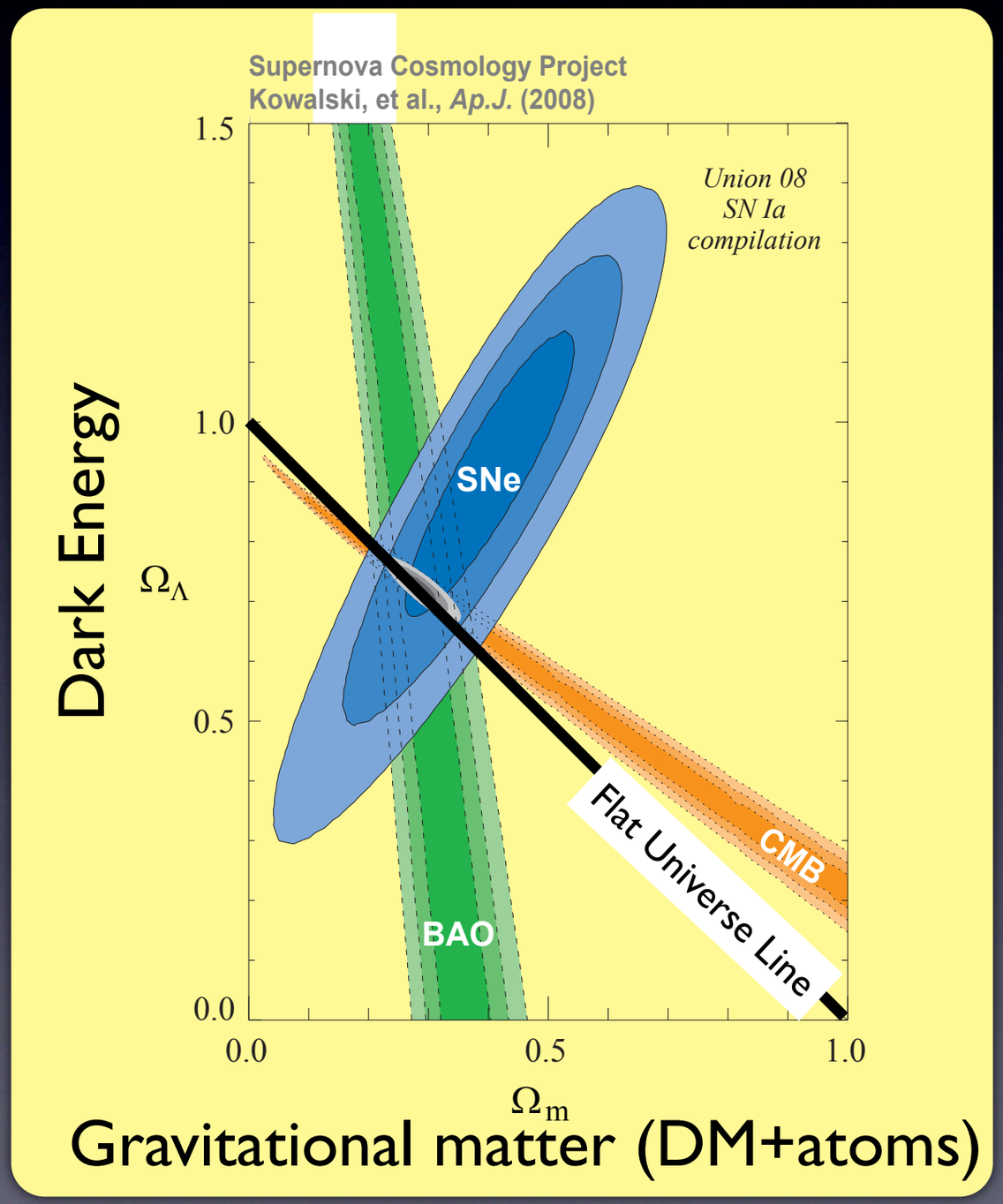
ΛCDM- the *standard* theory

in the age of precision science



CDM- cold dark matter,
``seen'' gravitationally

Λ- dark energy,
explaining the cosmic acceleration

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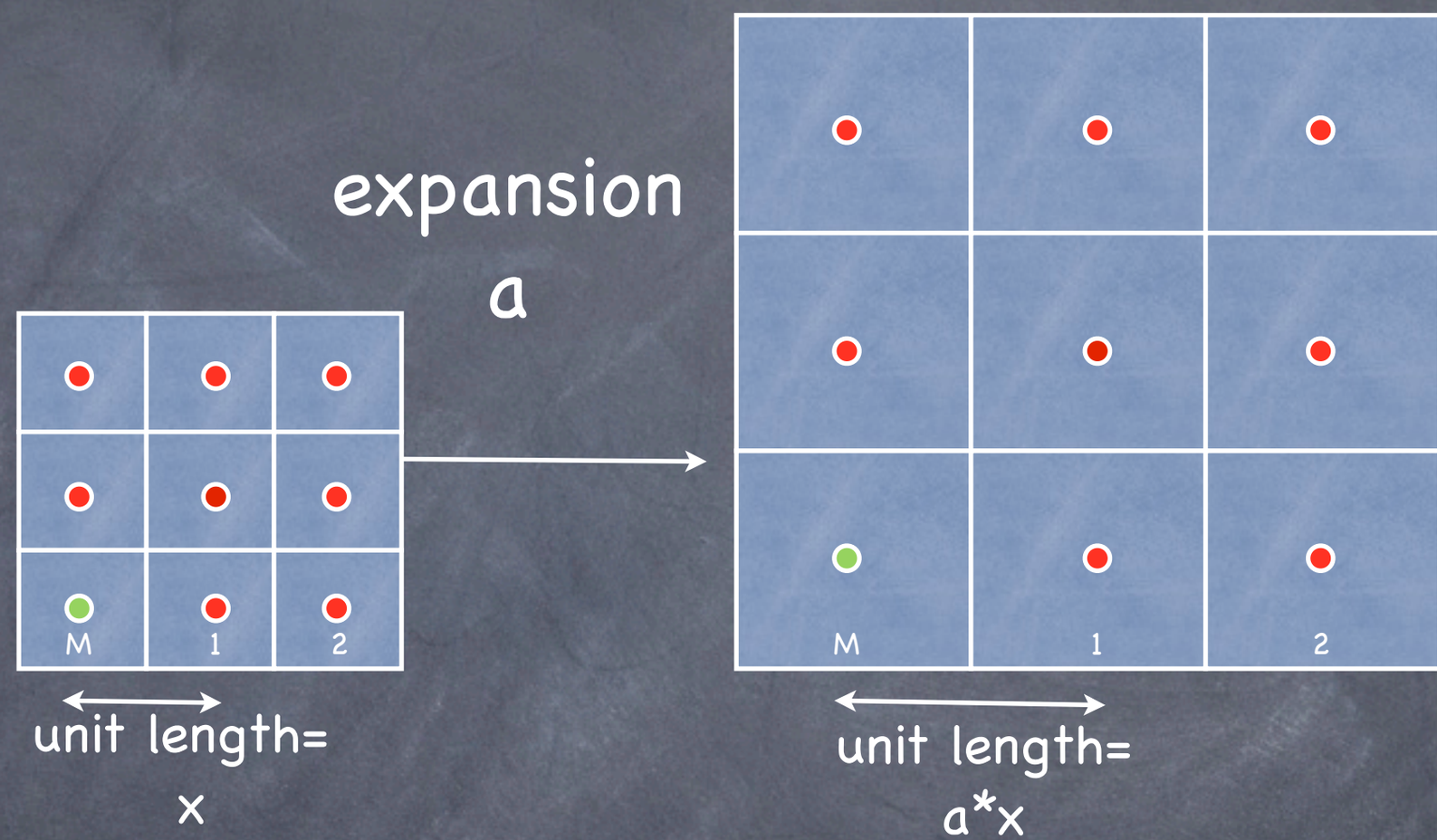
Cosmologist Jargon

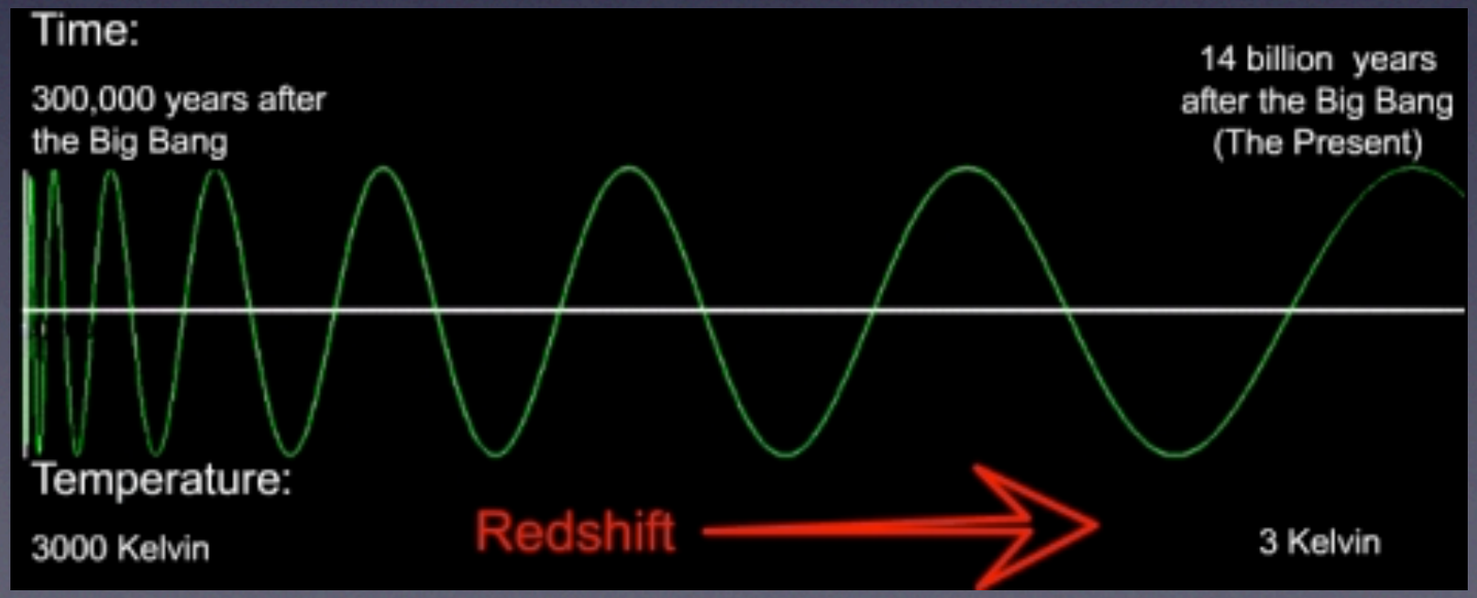
- comoving distance

Comoving Distance Units



Cosmologist Jargon

- comoving distance
- distance units: par-sec (pc) = 3.26 ly; h^{-1}Mpc
- redshifts z~ look back time, look back distance
- baryons = regular matter = electrons, protons



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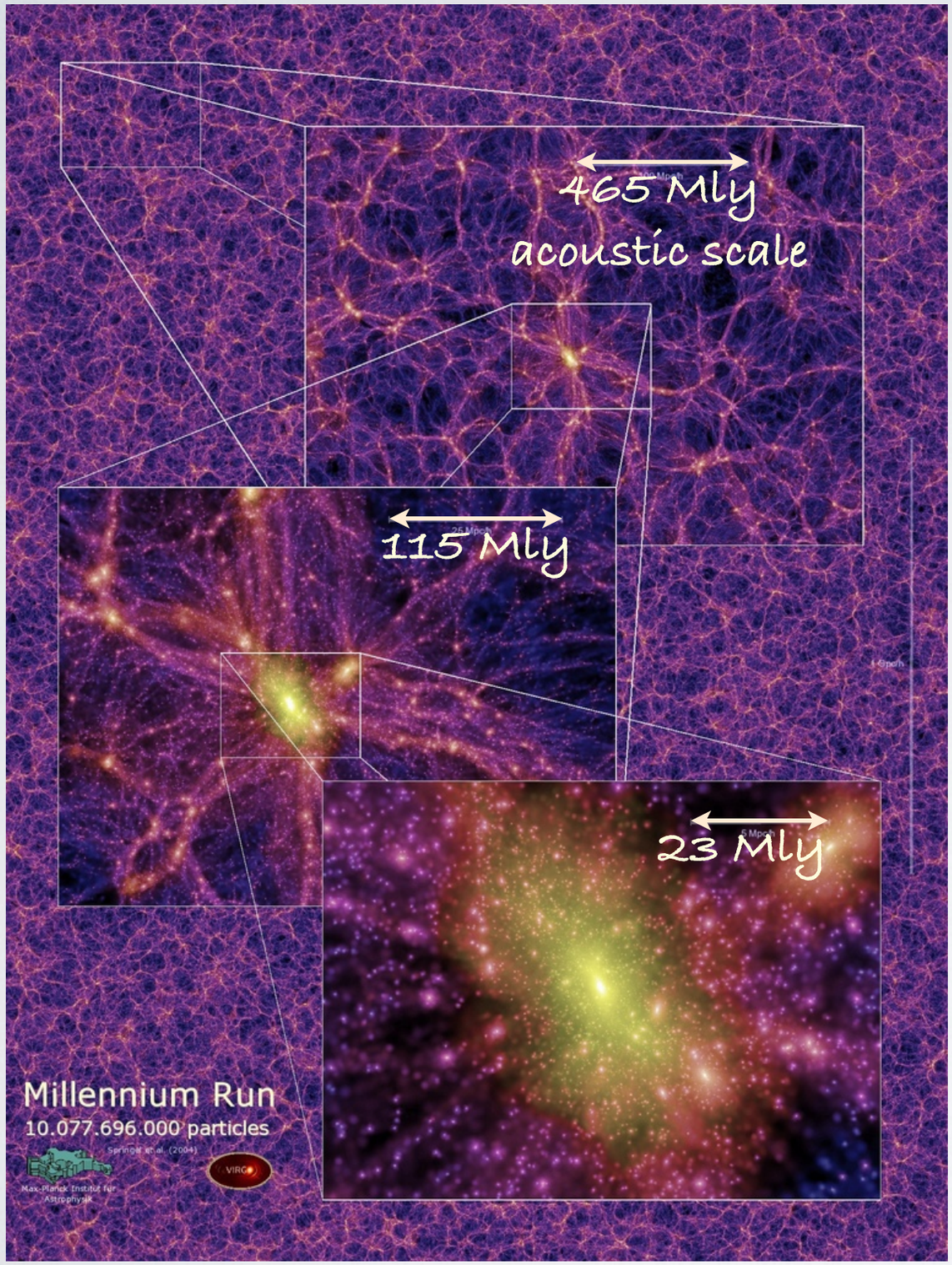
Large-Scale Structure



Springel et al. (2005)

The Millennium Simulation Project

Dark Matter Distribution

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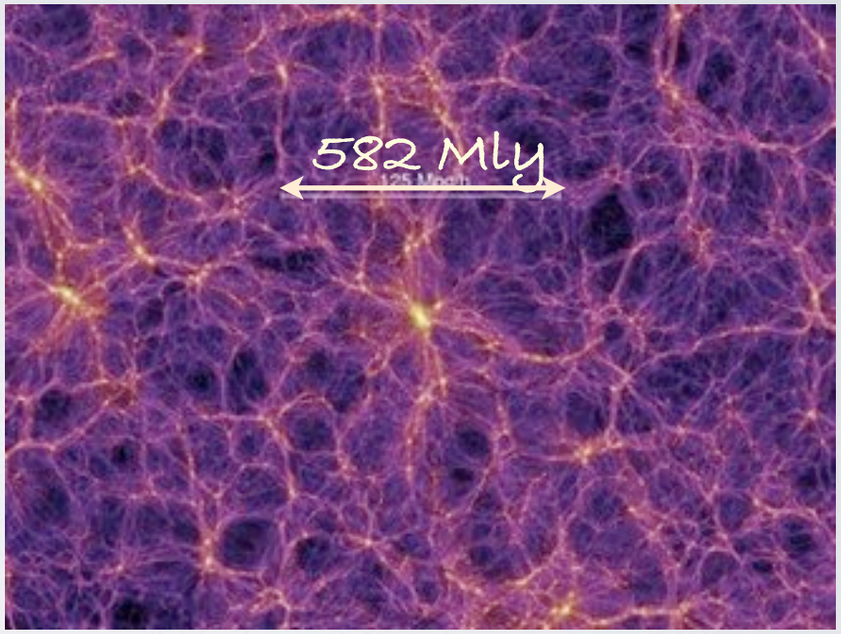
Quantifying Clustering

$$\varrho(x) = \bar{\varrho}(1+\delta(x))$$

ϱ- density

δ- overdensity

$\delta \geq -1$

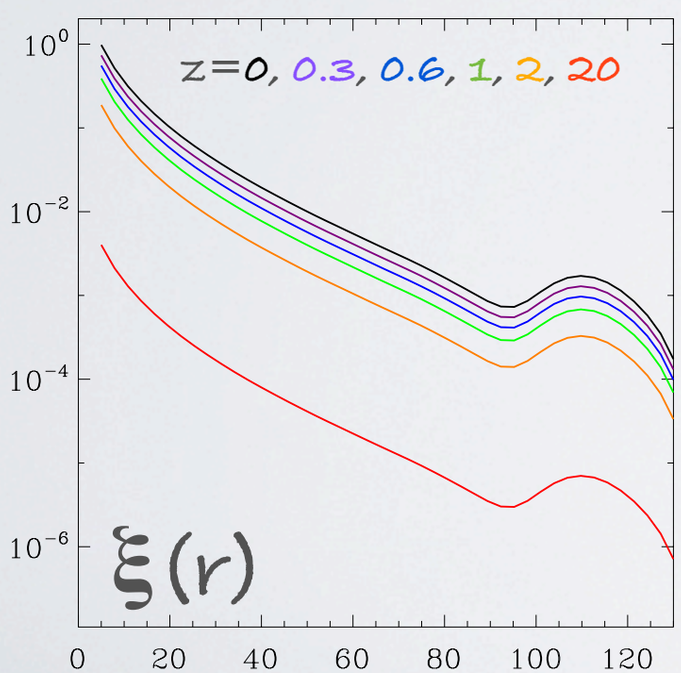


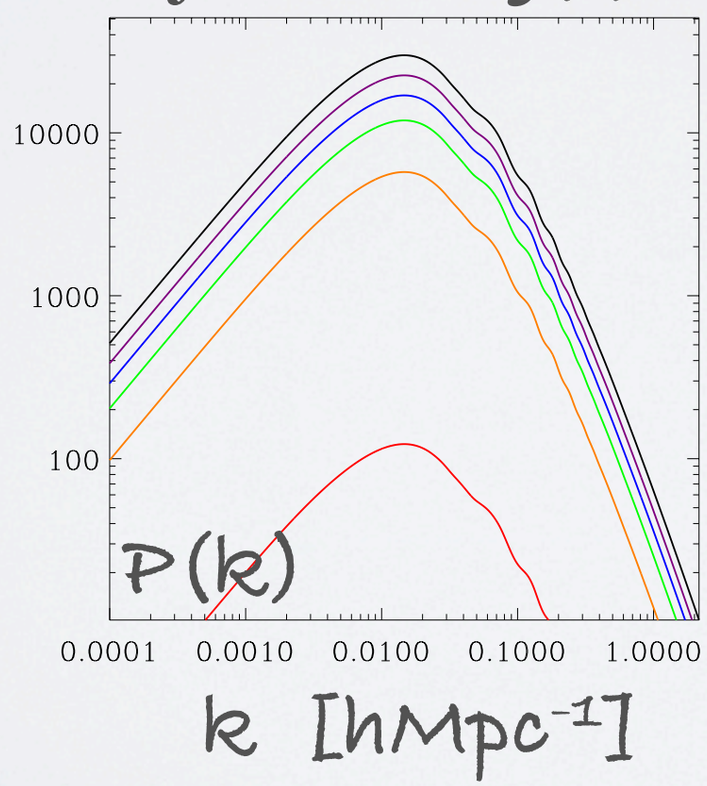
Springel et al. (2005)

2 point functions

correlation function $\xi(r) \equiv \langle \delta(x)\delta(x+r) \rangle_{volume}$

Power Spectrum $P(k) \equiv \int d^3x e^{-ikr} \xi(r)$





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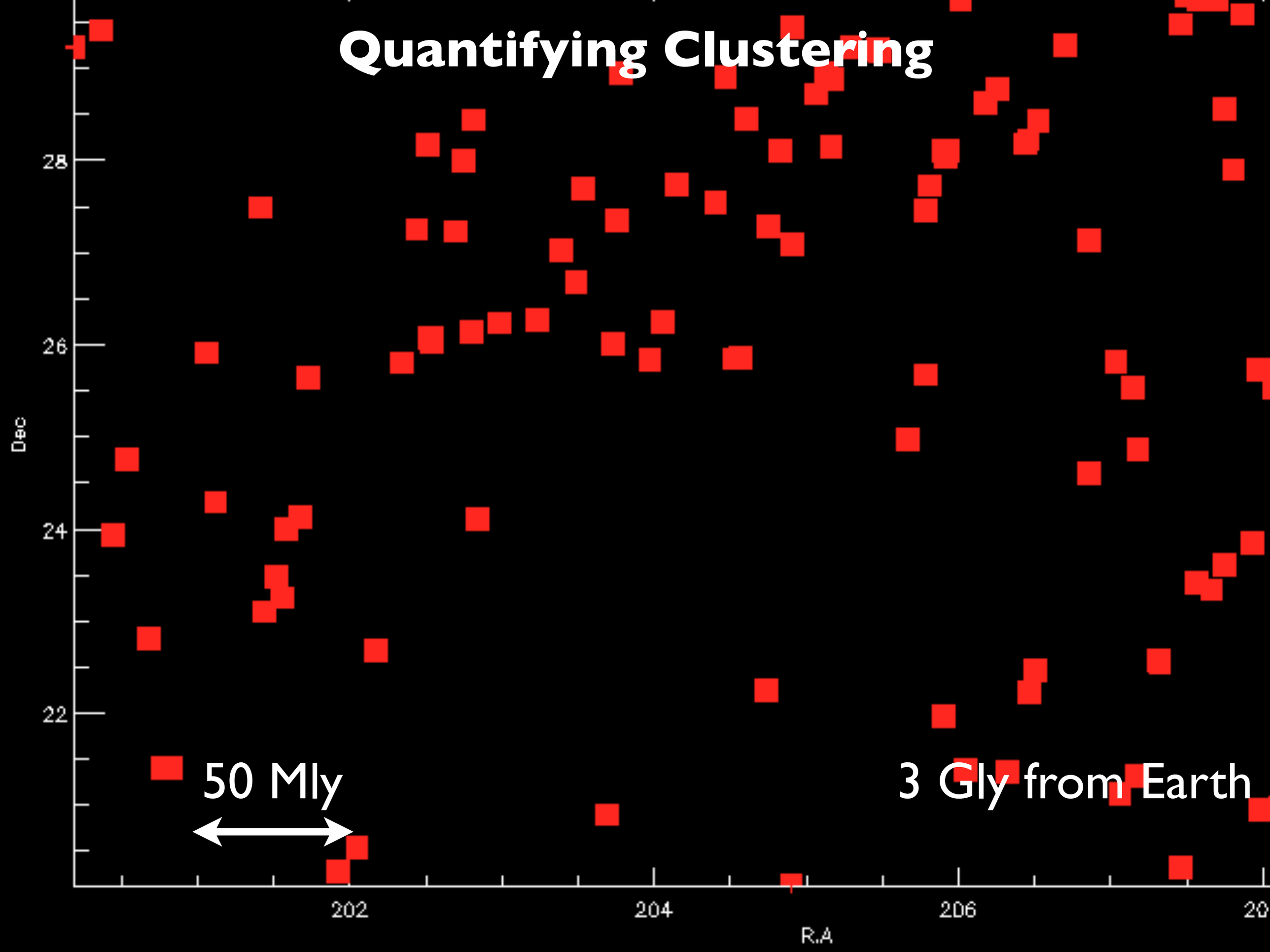
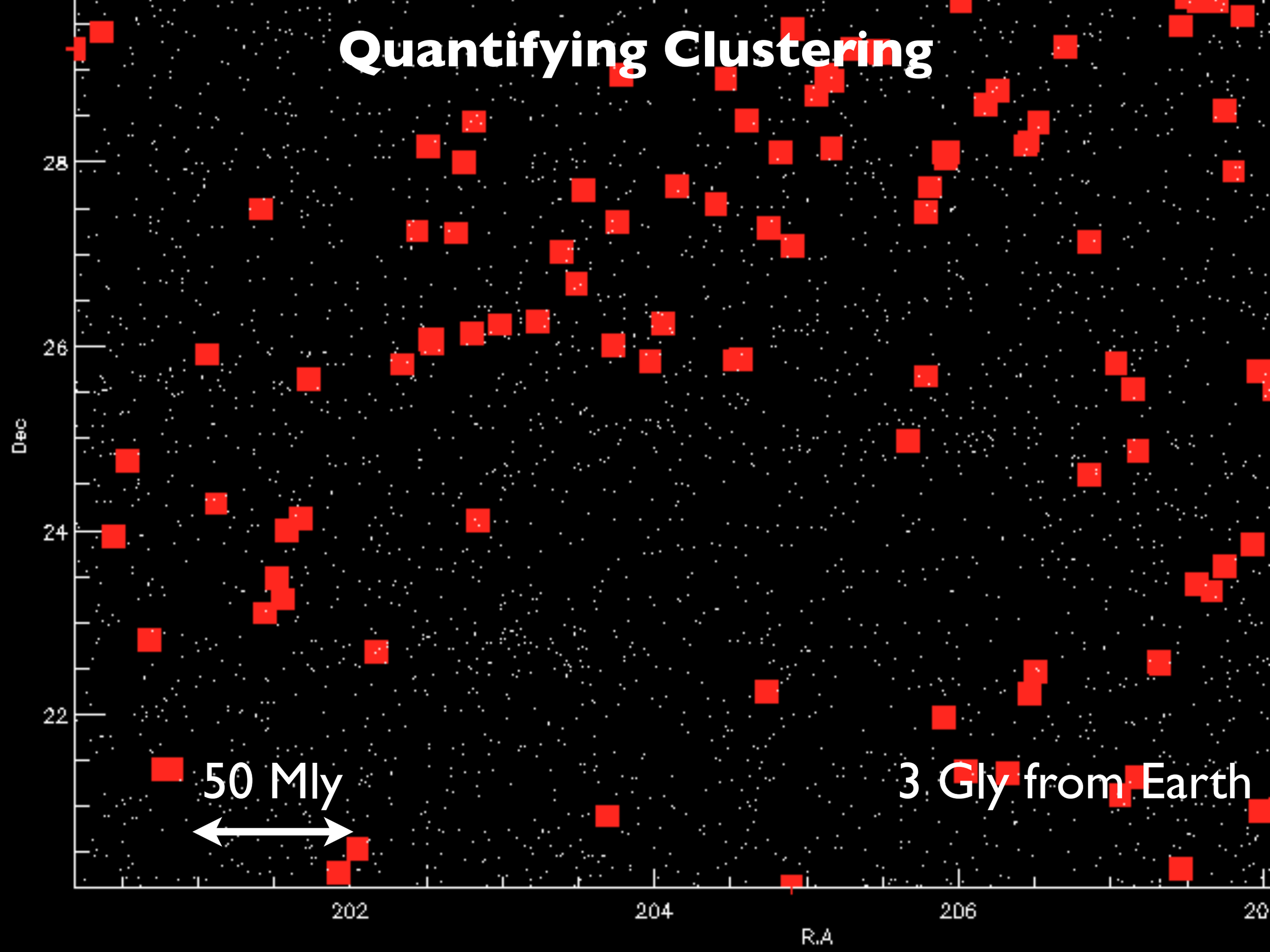
Quantifying Clustering



Quantifying Clustering



Quantifying Clustering

correlation function

$$\xi(r) \equiv \langle \delta(x)\delta(x+r) \rangle_{volume}$$

To deal with point ``dots'' and boundary conditions, we compare data to random point distribution:

$$\xi(r) = DD/RR - 1$$

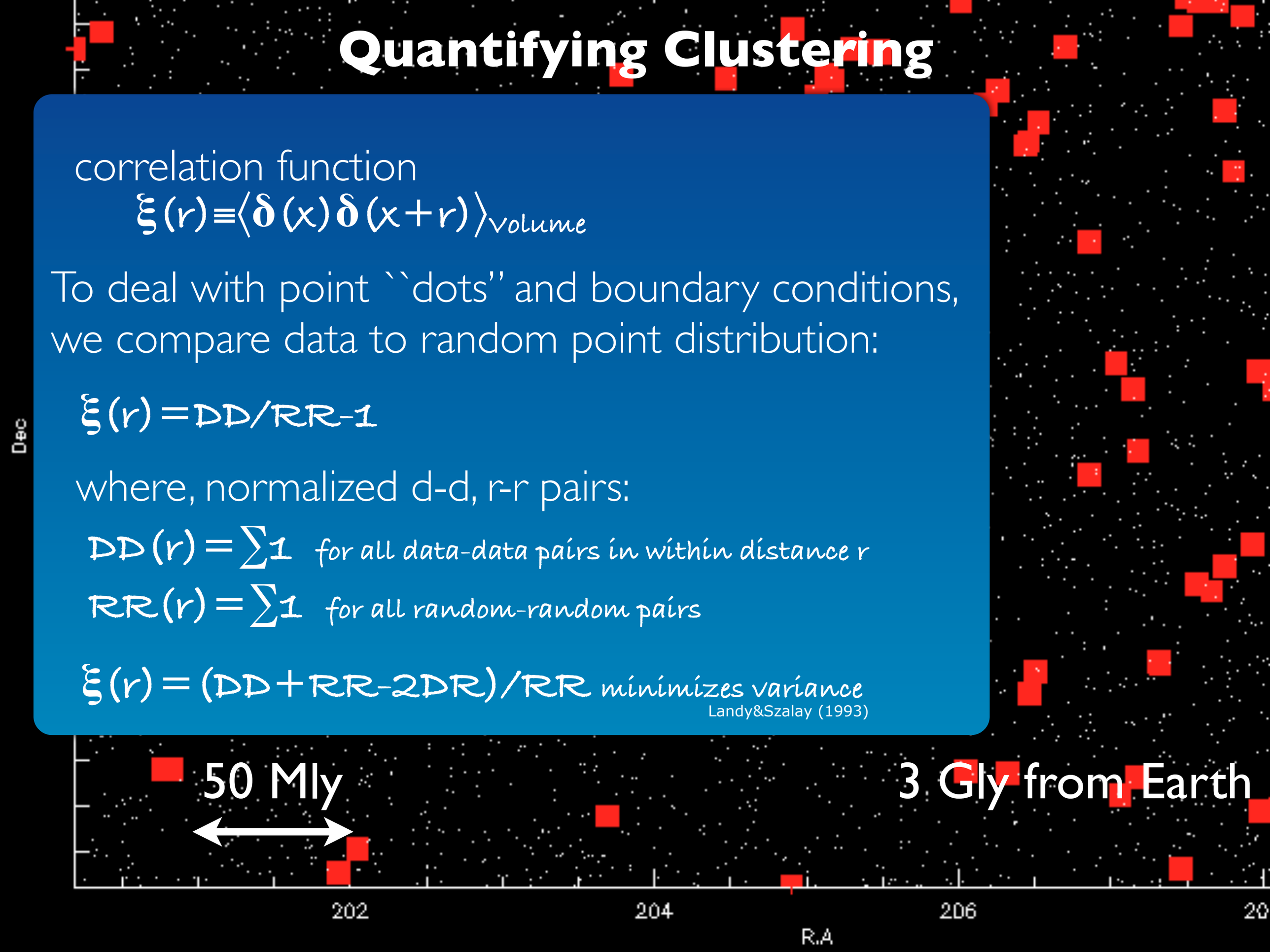
where, normalized d-d, r-r pairs:

$DD(r) = \sum 1$ *for all data-data pairs in within distance r*

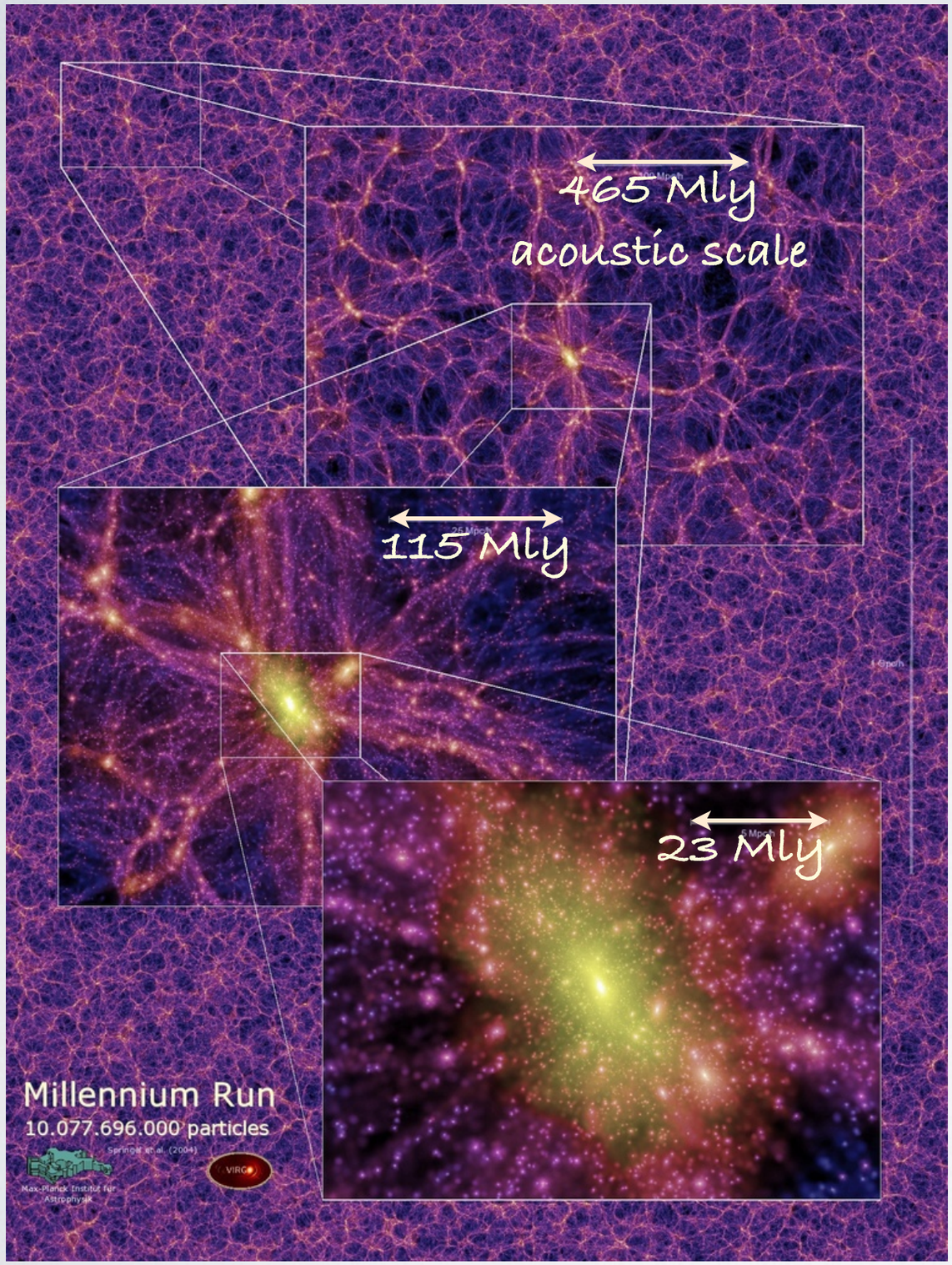
$RR(r) = \sum 1$ *for all random-random pairs*

$\xi(r) = (DD + RR - 2DR)/RR$ *minimizes variance*

Landy&Szalay (1993)



Large-Scale Structure



Springel et al. (2005)

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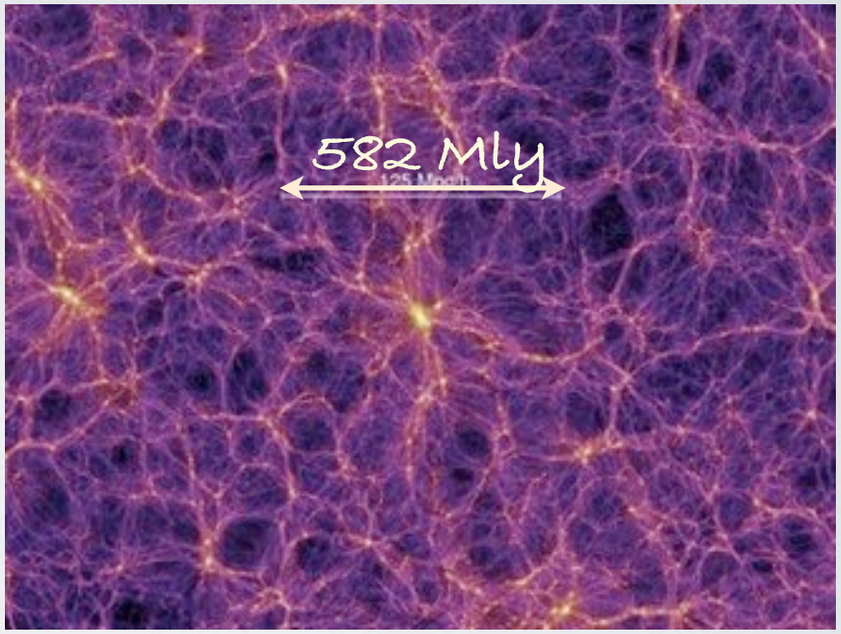
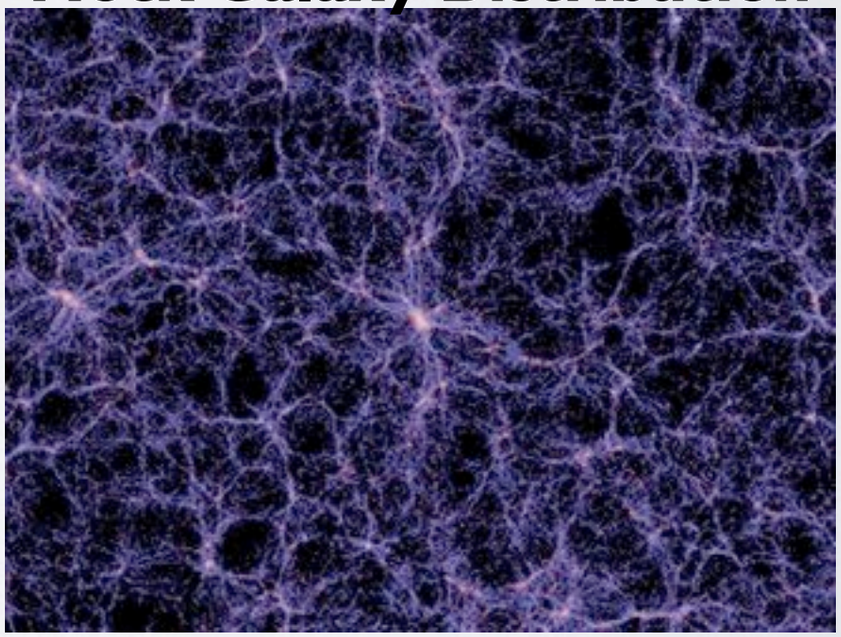


Mock Galaxy Distribution

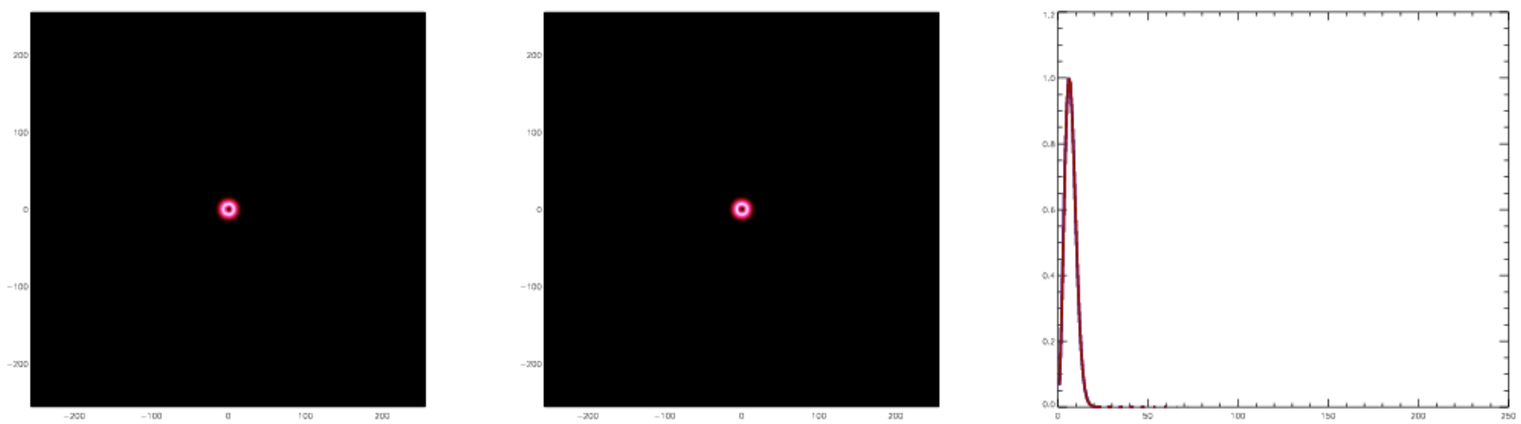


Springel et al. (2005)

from talk by Martin White

The acoustic wave

An initial perturbation in otherwise uniform plasma,
consisting of DM, electrons + protons, radiations (photons)



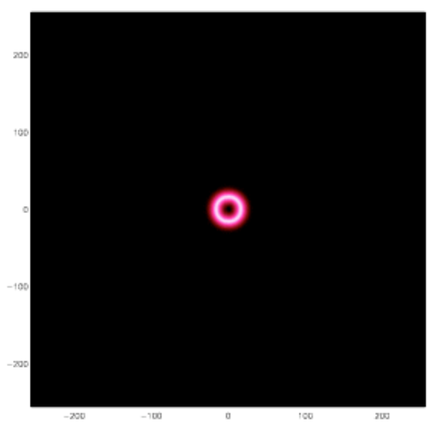
Baryons Photons Mass profile

Eisenstein, Seo & White (2006)

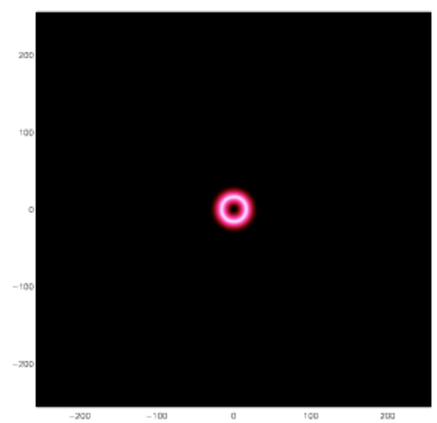
from talk by Martin White

The acoustic wave

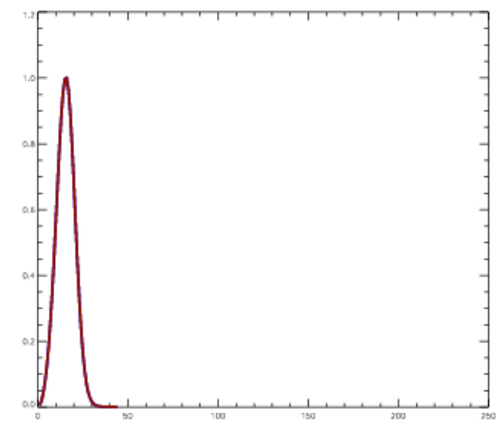
Photons pressure electrons, which pull protons. This plasma fluid propagates in acoustic fashion in a shell from origin.



Baryons



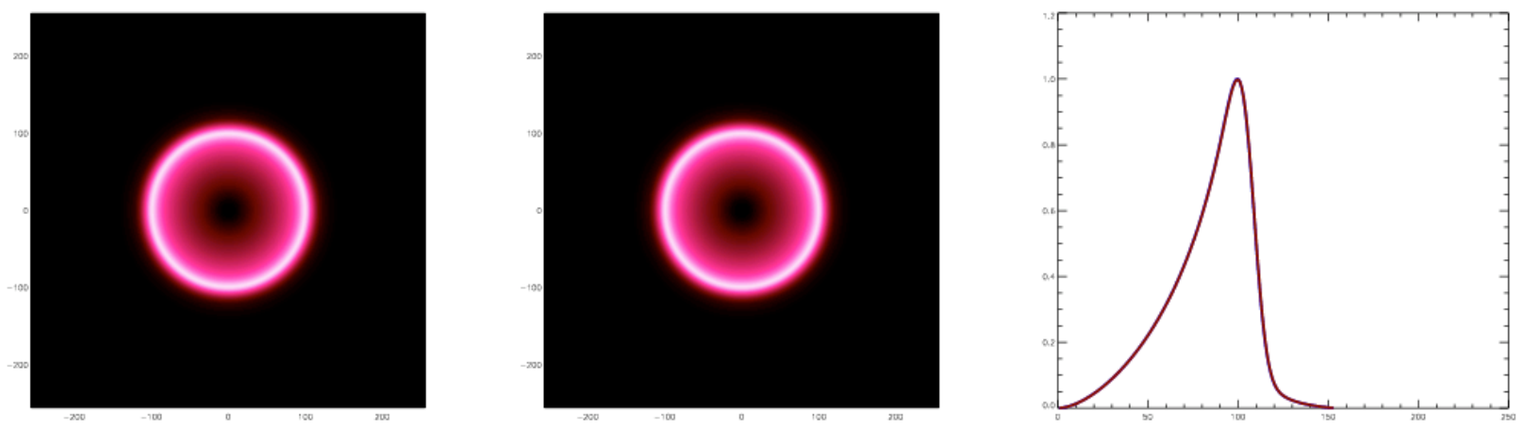
Photons



from talk by Martin White

The acoustic wave

Acoustic wave propagates for 100,000 years.

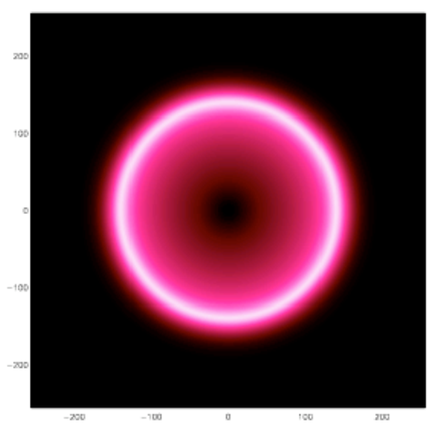


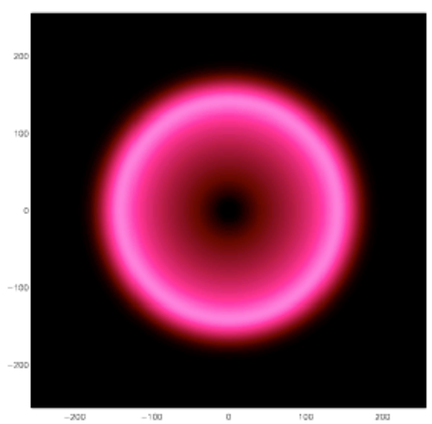
from talk by Martin White

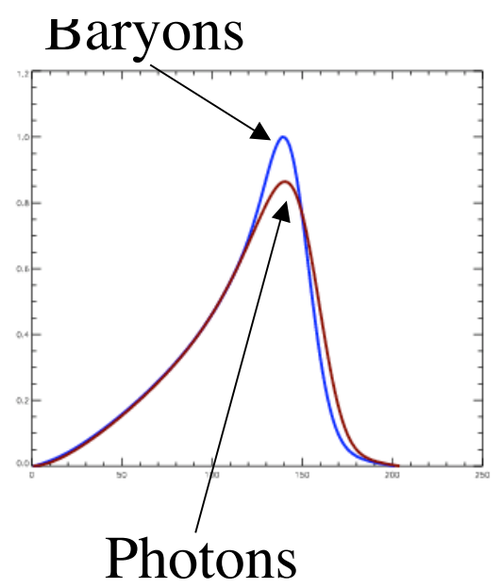
~300,000 yr ABB

The acoustic wave

After 10^5 years, first Hydrogen forms, and photons decoupled.
Atoms eventually come to a halt.

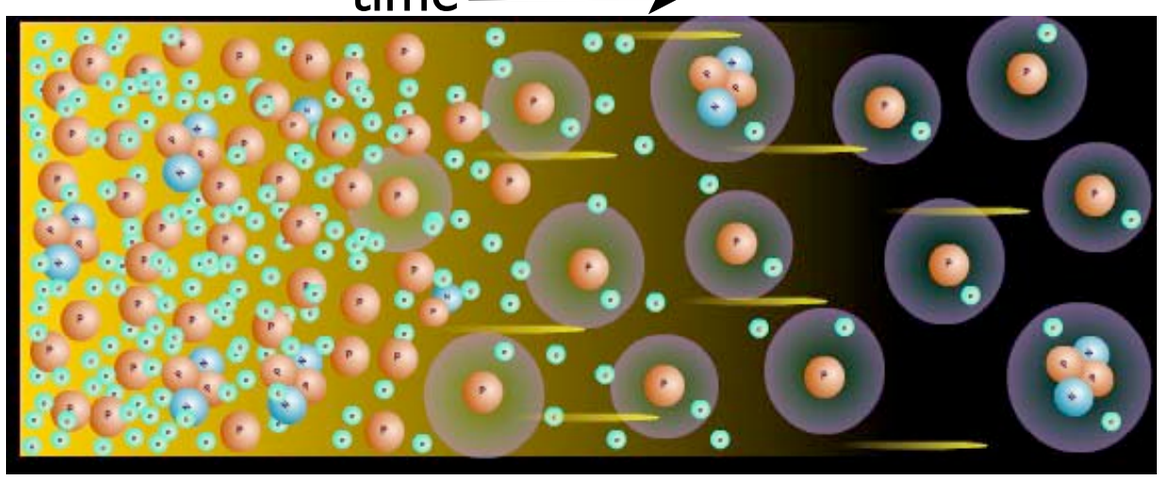






time →

opaque Universe

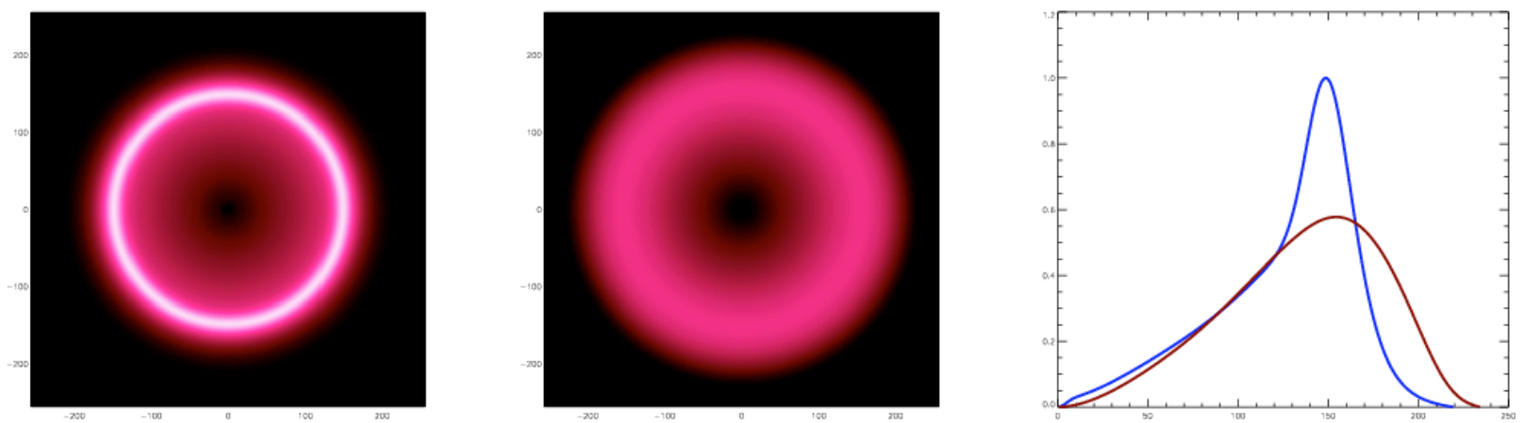


transparent Universe

from talk by Martin White

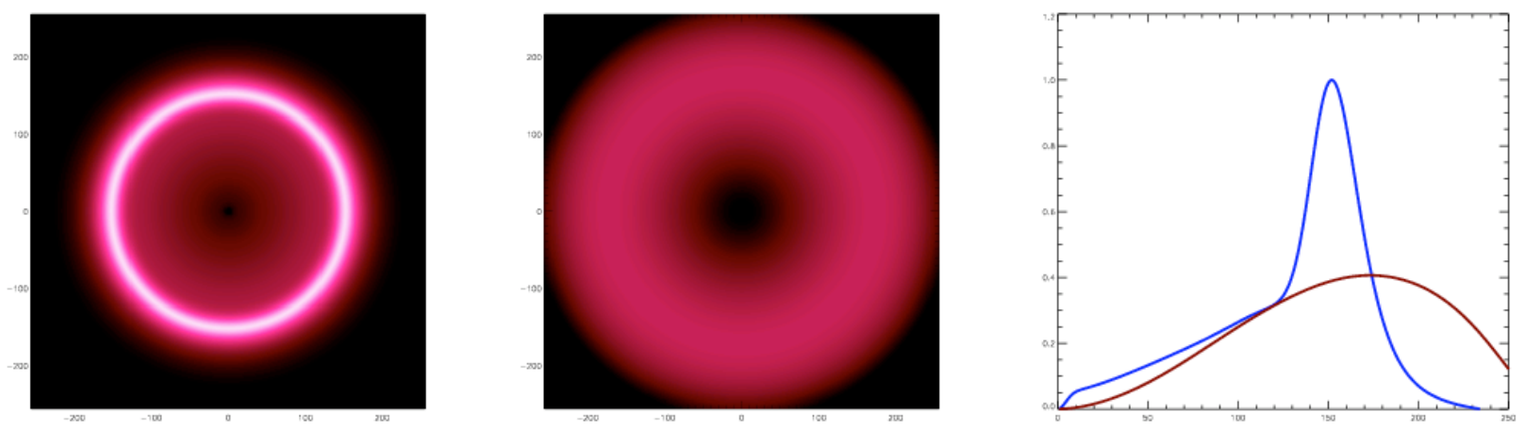
The acoustic wave

The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.



from talk by Martin White

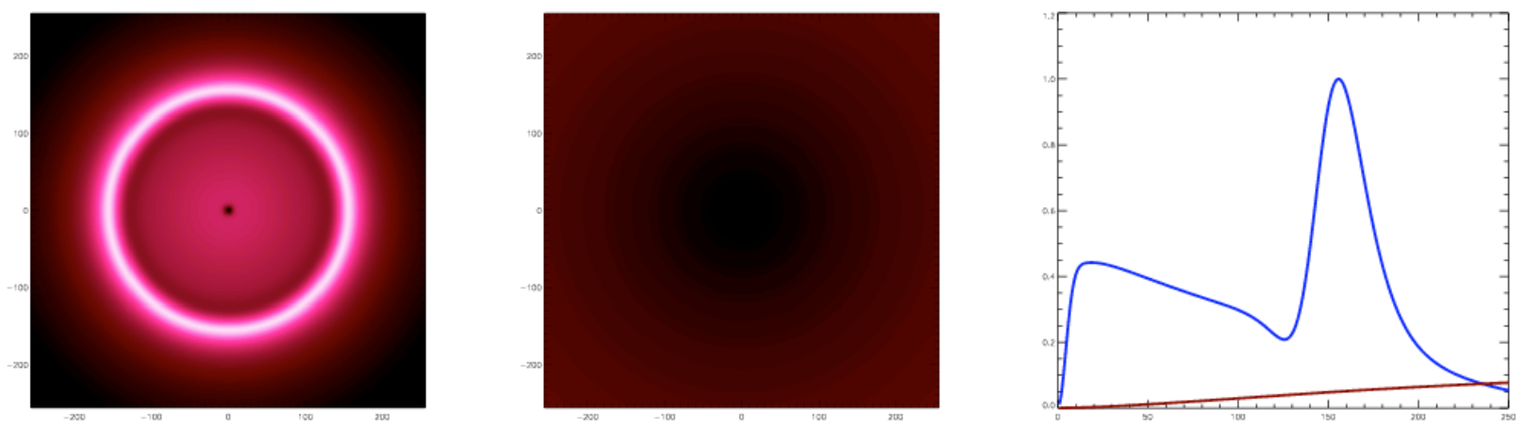
The acoustic wave



from talk by Martin White

The acoustic wave

The photons have become almost completely uniform, but the baryons remain overdense in a shell 100Mpc in radius.
In addition, the large gravitational potential well which we started with starts to draw material back into it.

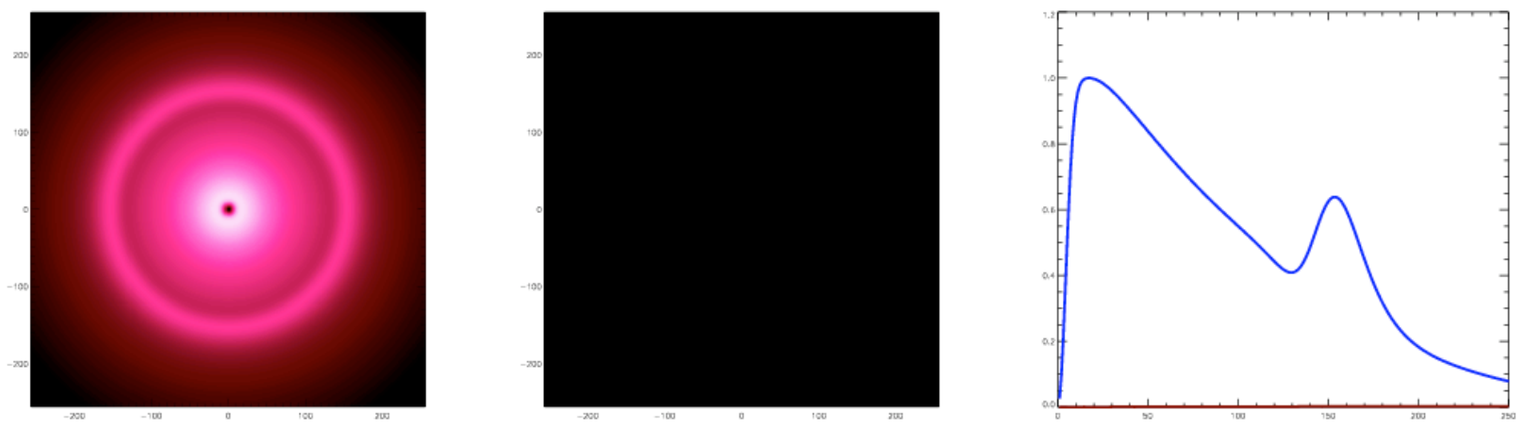


from talk by Martin White

The acoustic wave

As the perturbation grows by ~10^3 the baryons and DM reach equilibrium densities in the ratio Ω_b/Ω_m.

The final configuration is our original peak at the center (which we put in by hand) and an "echo" in a shell roughly 100Mpc in radius with width ~10%.

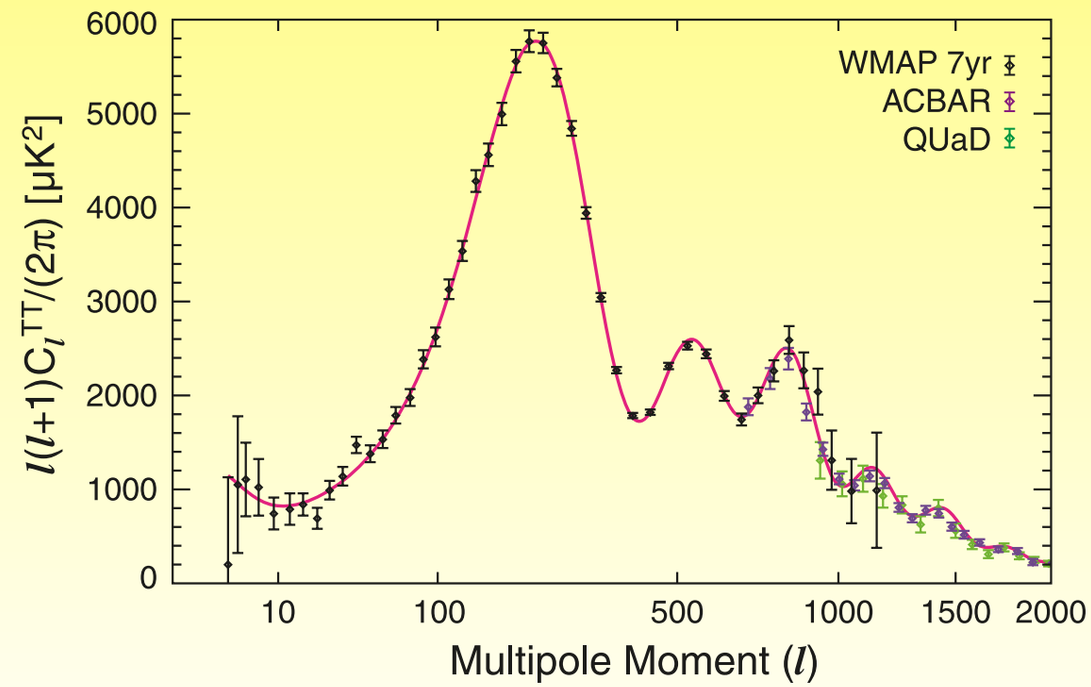


The Baryonic Acoustic Feature

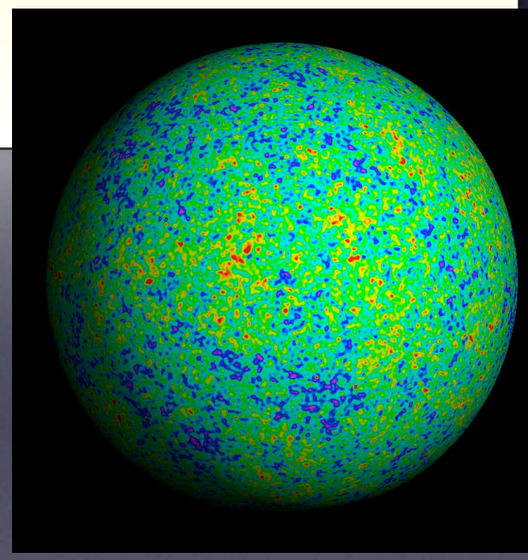
Feature in the early universe:

CMB Temperature Fluctuations

Larson et al. (2010)



z~1100
t~300,000 years ABB



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The Baryonic Acoustic Feature

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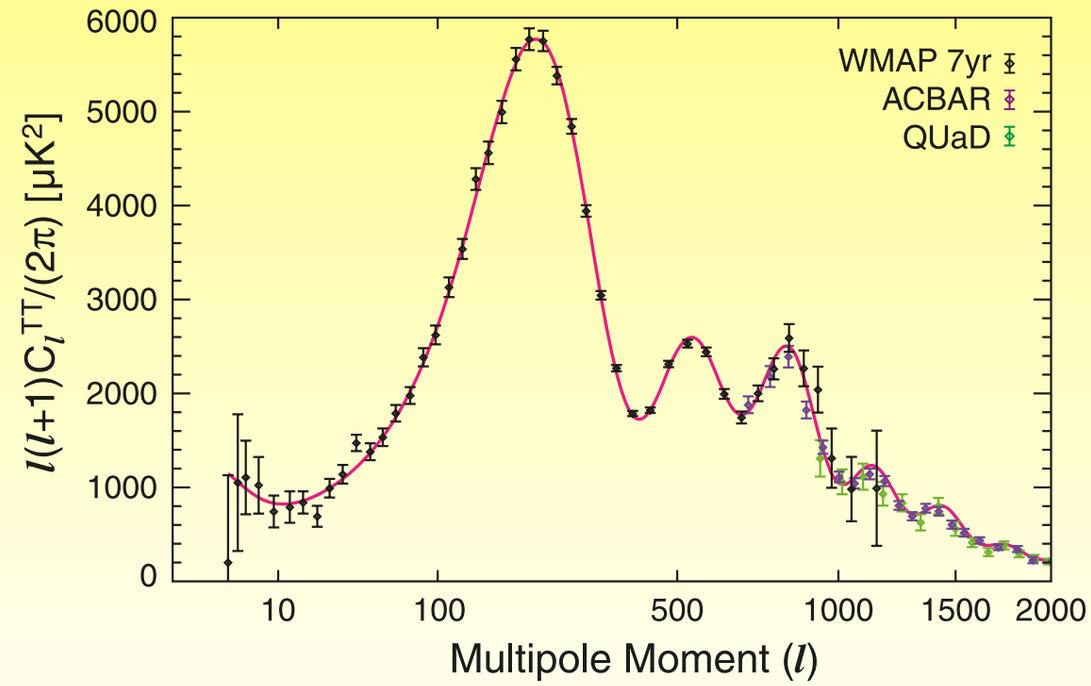
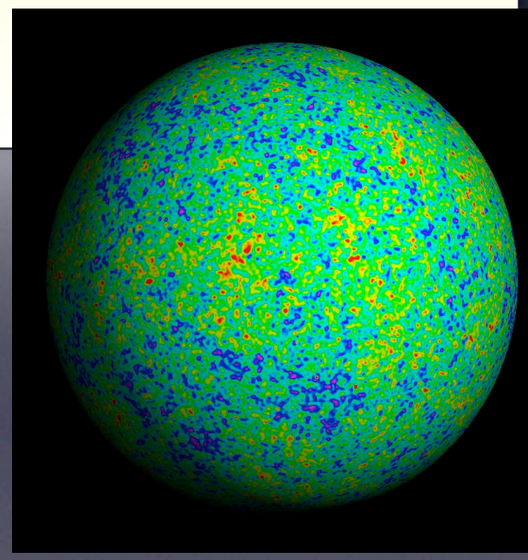


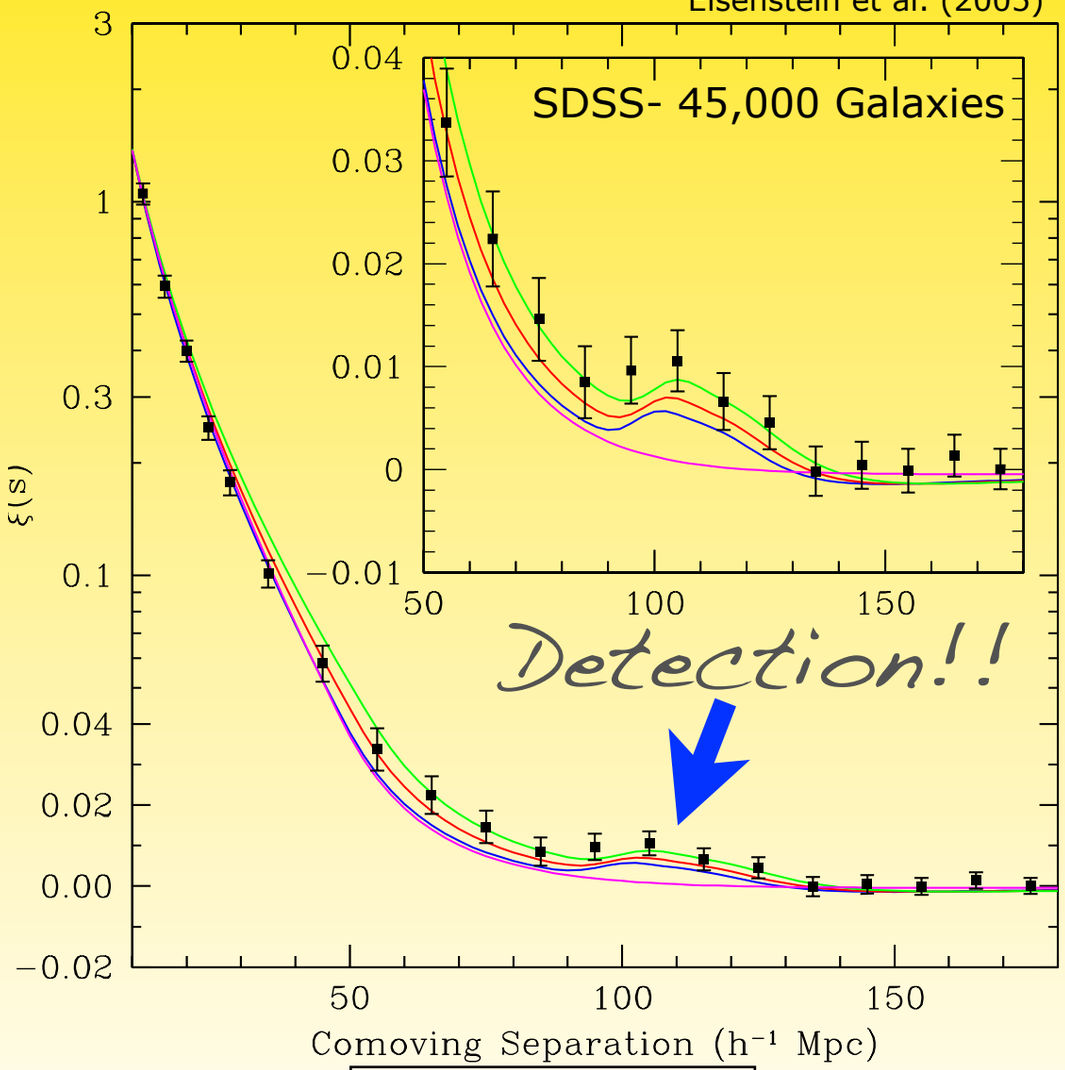
z~1100
t~300,000 years ABB



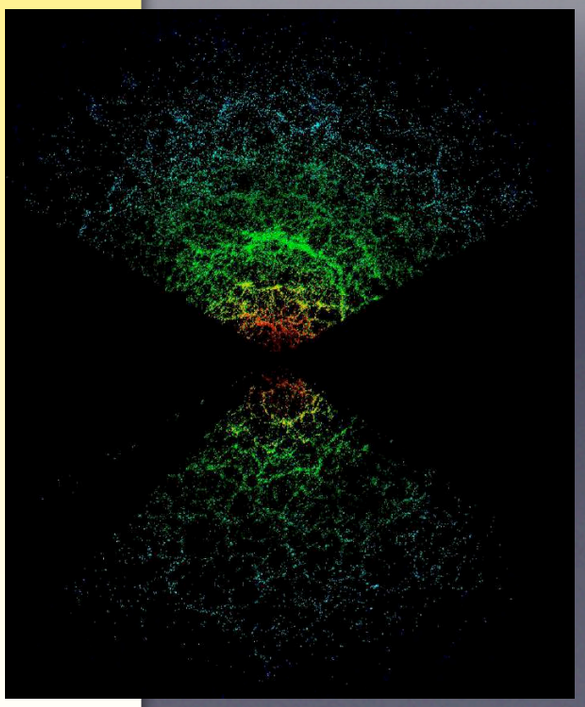
Feature in the recent universe:

Distribution of Galaxies

Eisenstein et al. (2005)



z~0.35
t~9.8G years ABB



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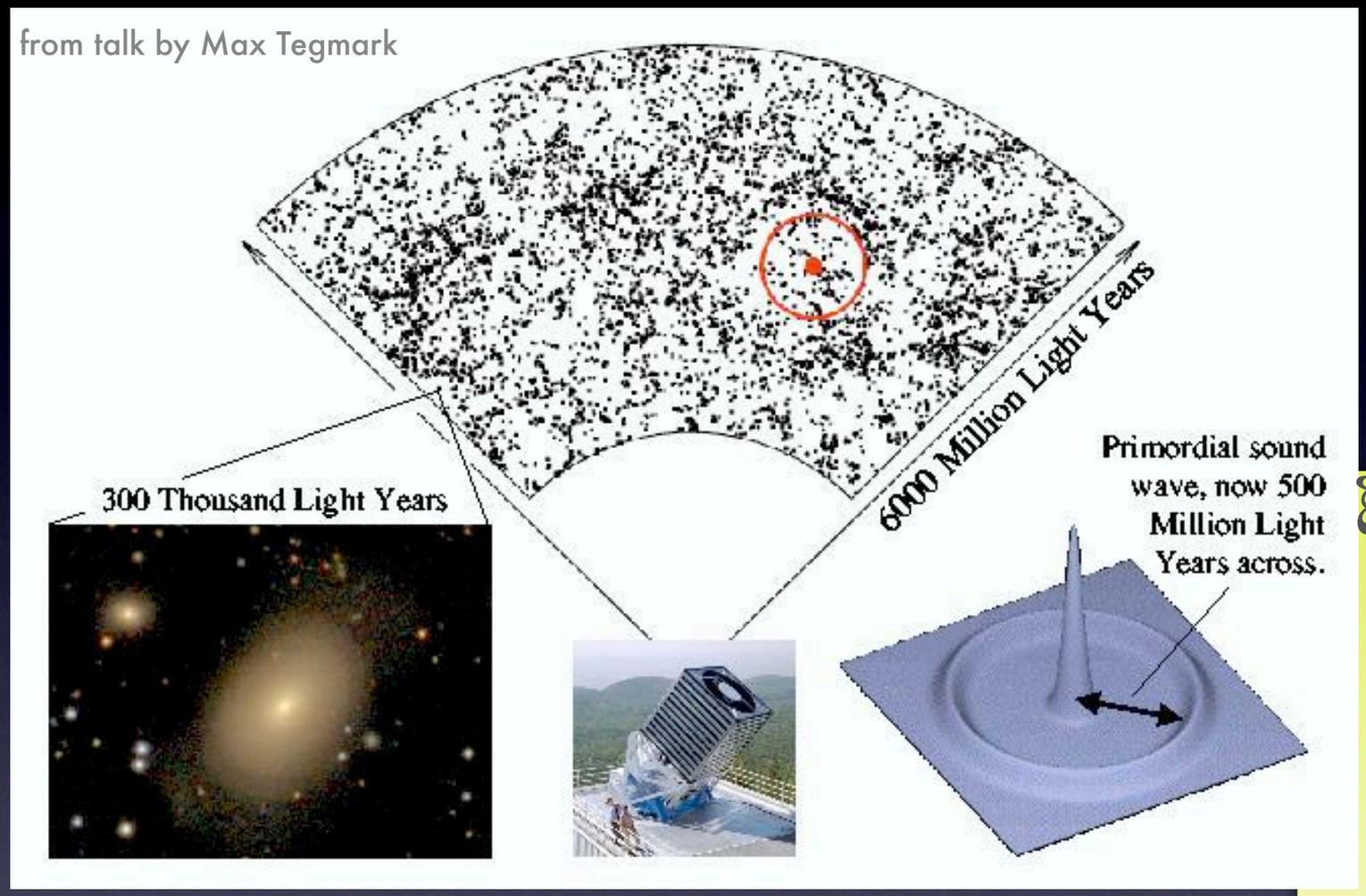
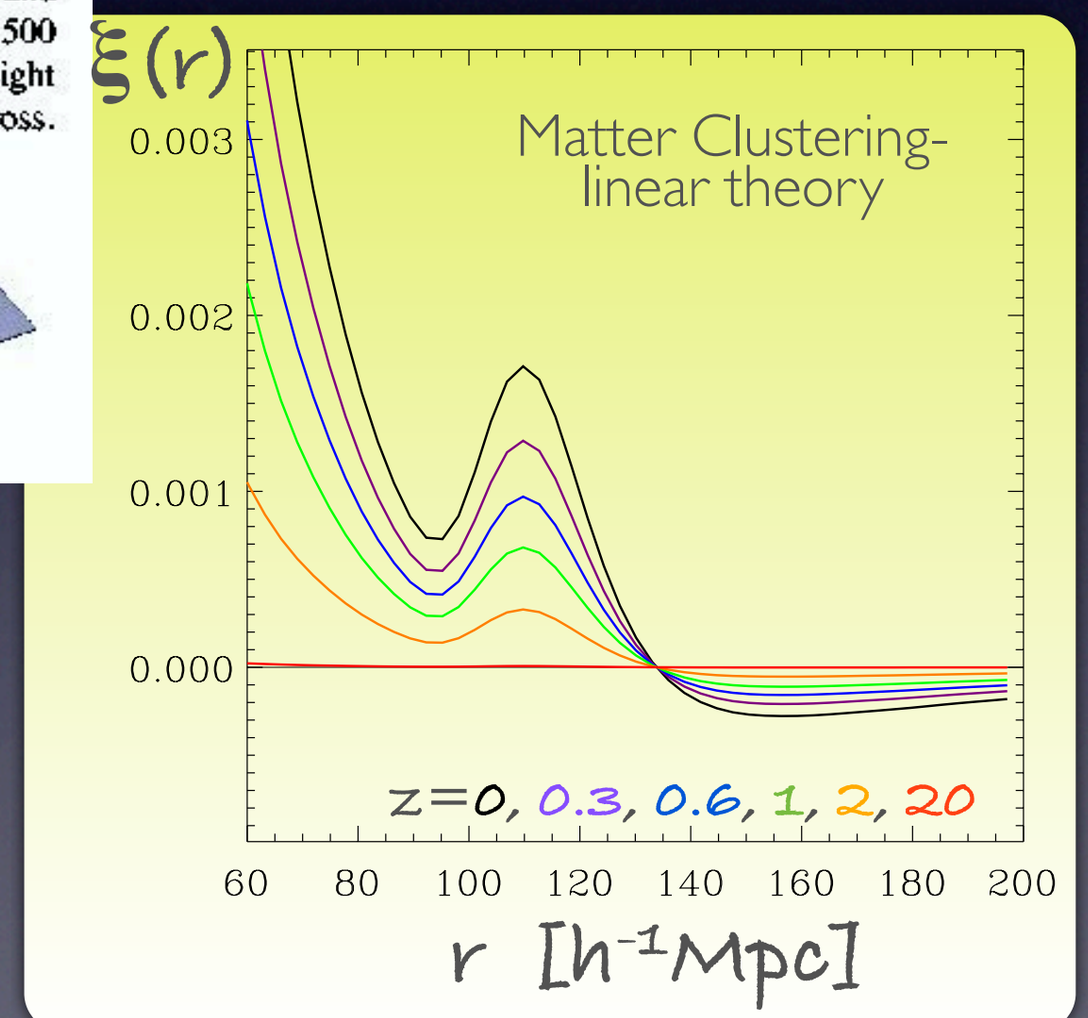
The Baryonic Acoustic Feature





- A firm prediction of ΛCDM
- A ``standard ruler''

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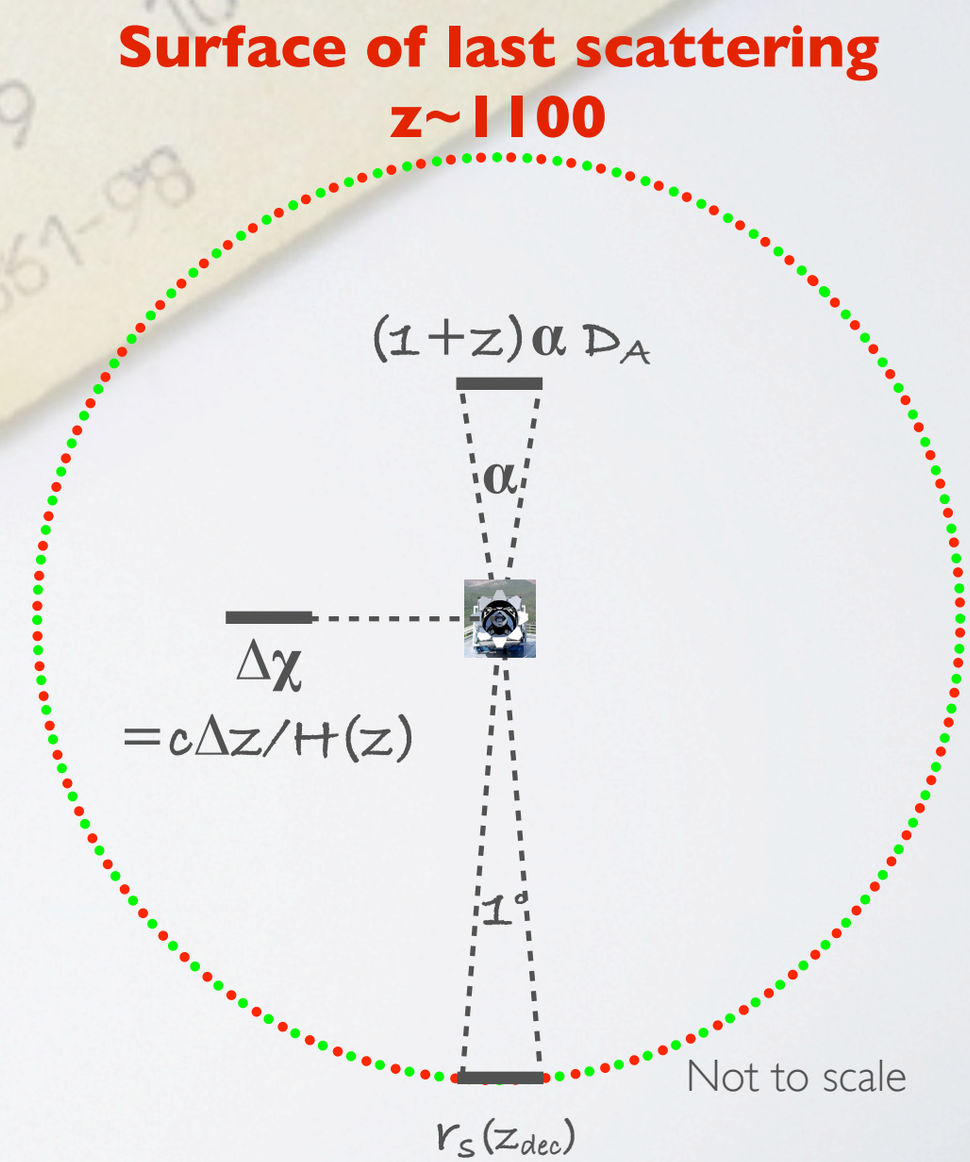
The Baryonic Acoustic Feature as a Standard Ruler

- Early Universe (z_{dec}~1090):
  CMB temp fluctuations determines
  r_s~479M light-year ($\delta r_s/r_s$~1.3%; **WMAP-5** Komatsu et al. 2009)

- Late Universe :
  SDSS-II, -III
  Luminous Red Galaxies (z~ 0.3, 0.6)
  QSOs Lyman-α Forest (z>2.5)
  Galaxy Clusters

  Wiggle-Z
  Blue Galaxies (z~ 0.2, 0.4, 0.6, 0.8)



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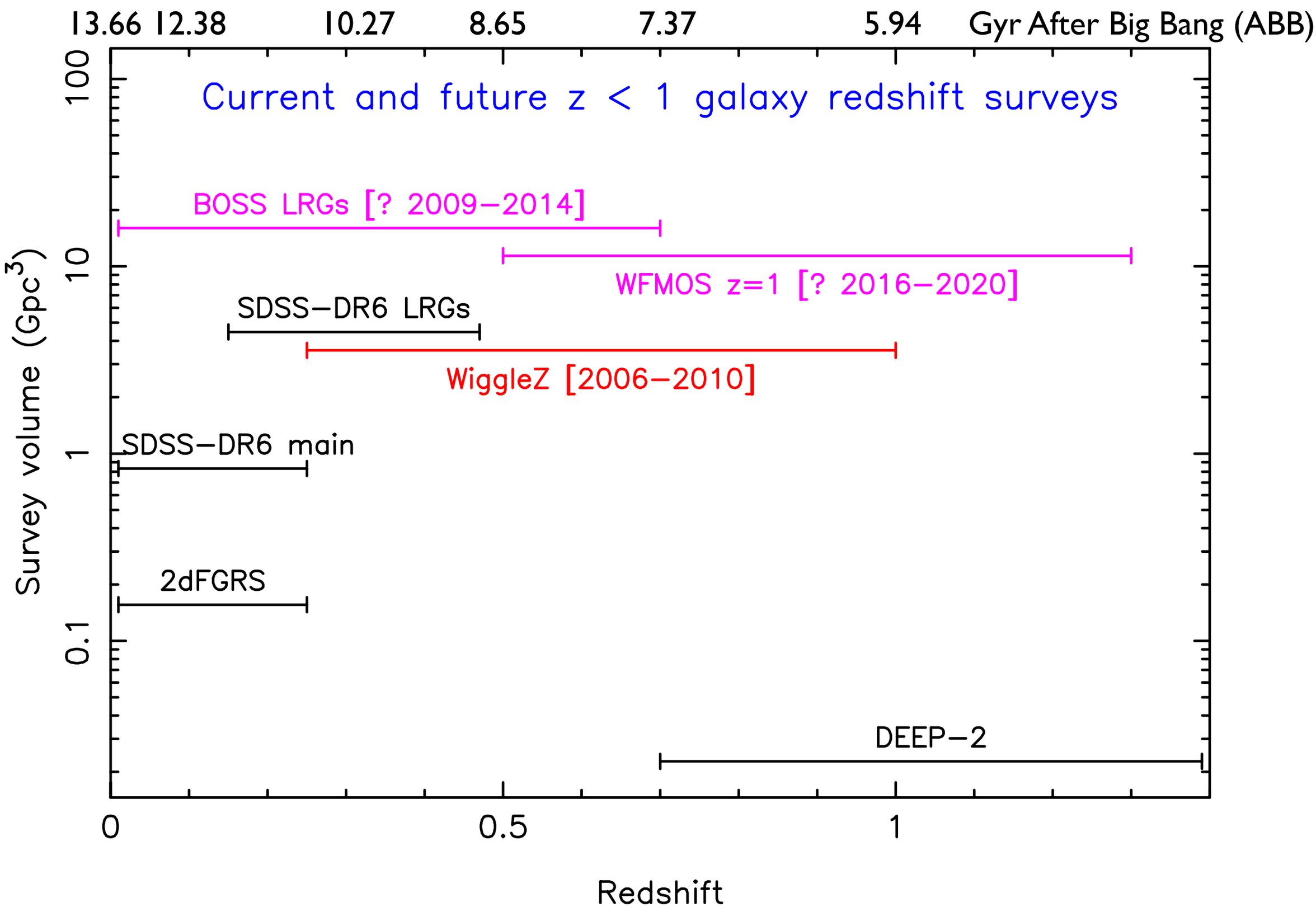
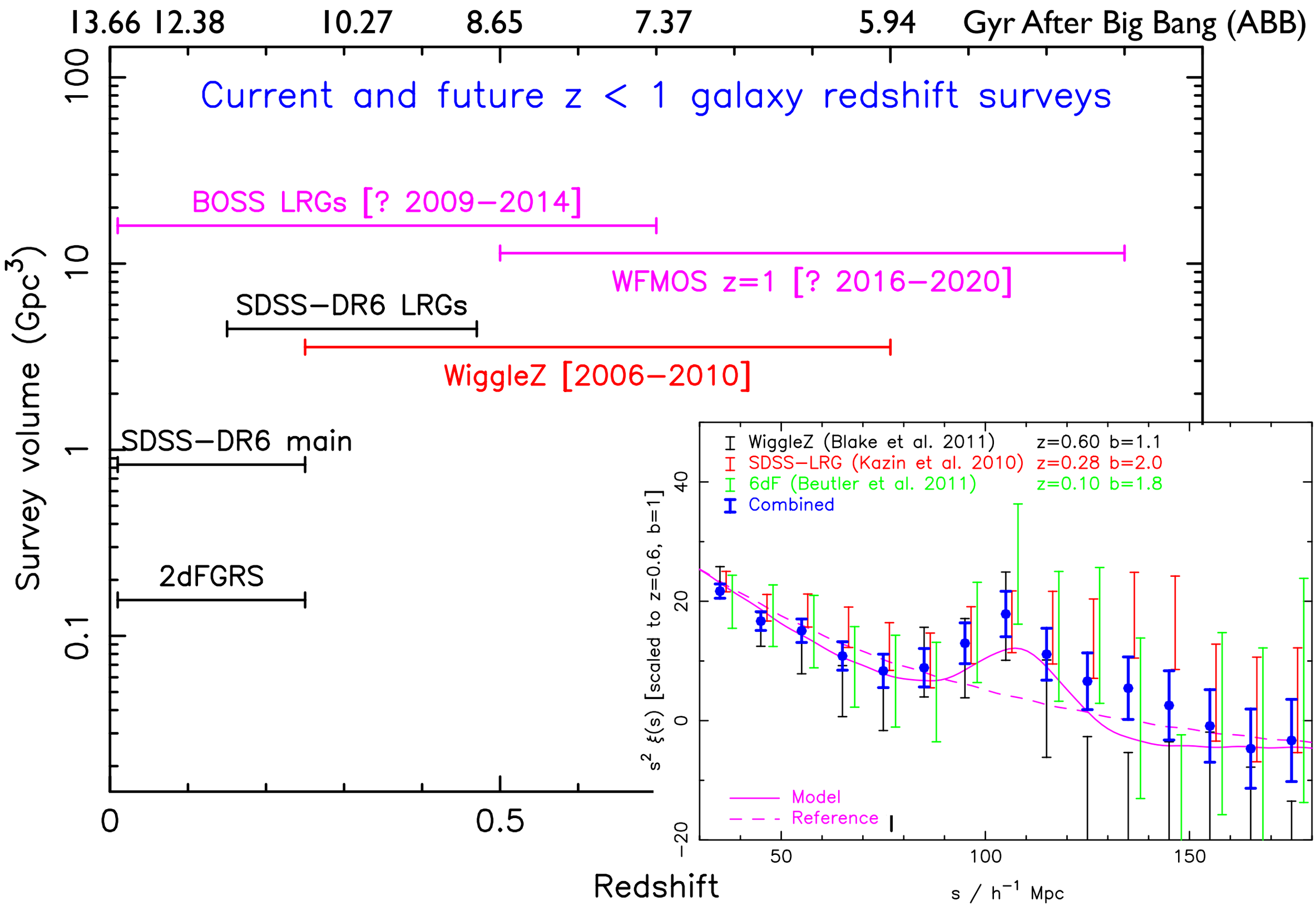
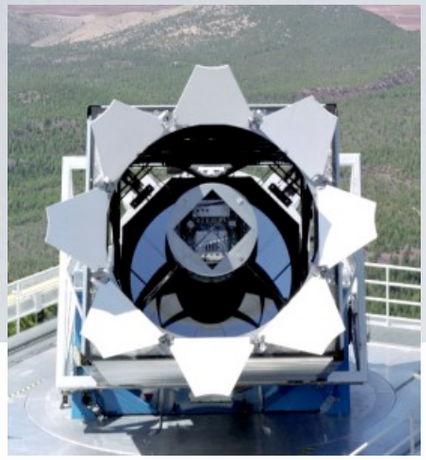
from talk by Chris Blake

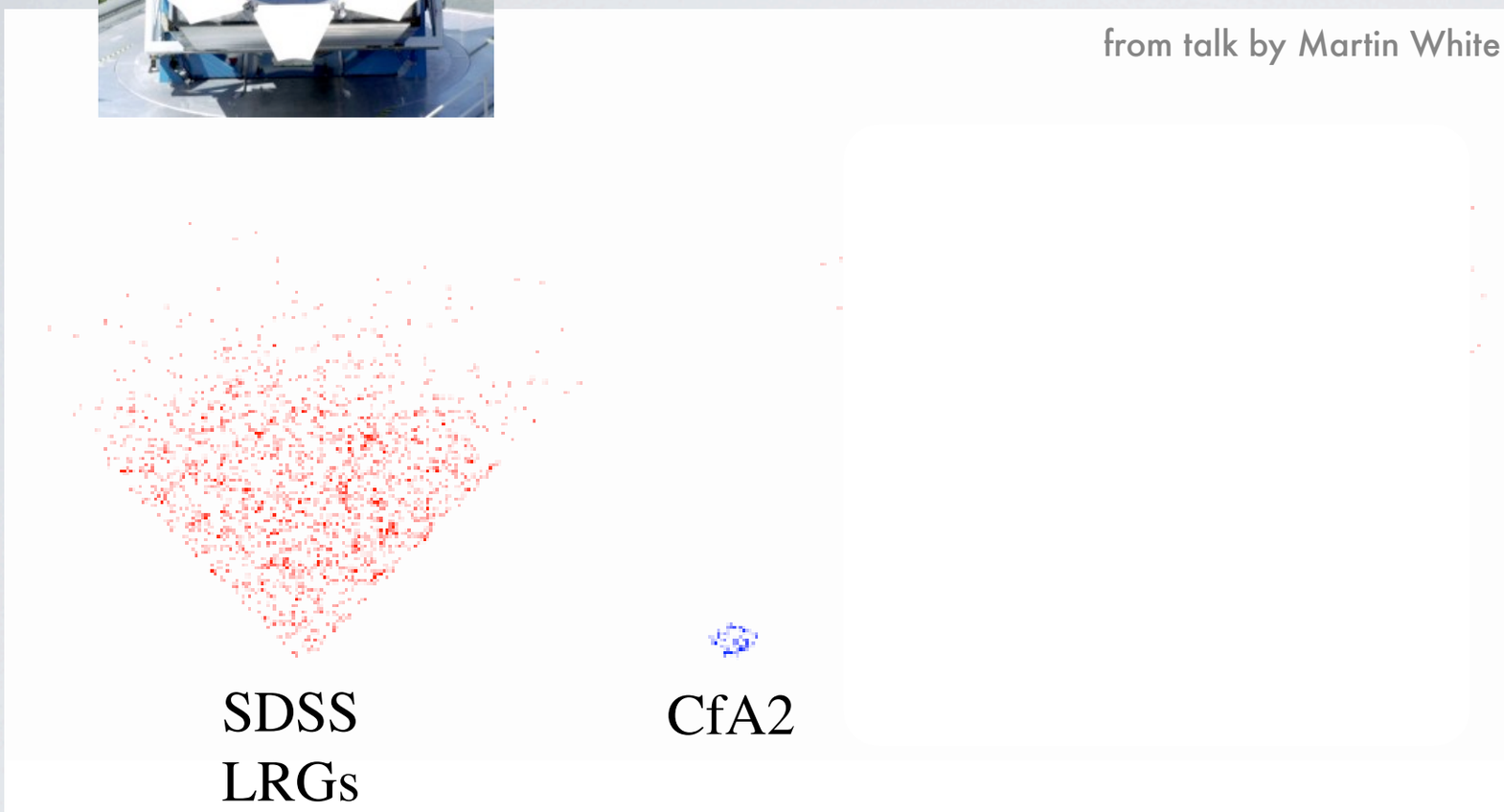


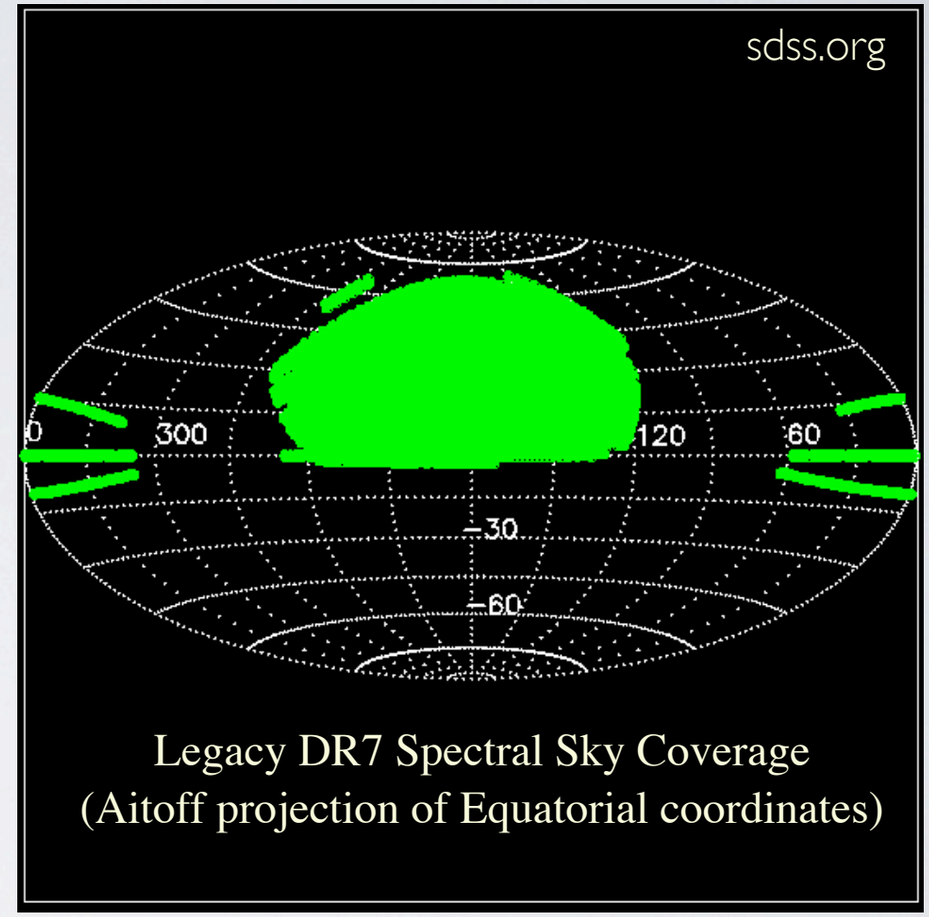
from talk by Chris Blake





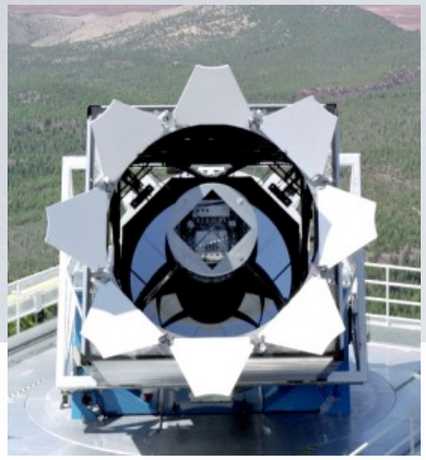
The Sloan Digital Sky Survey Luminous Galaxy Sample



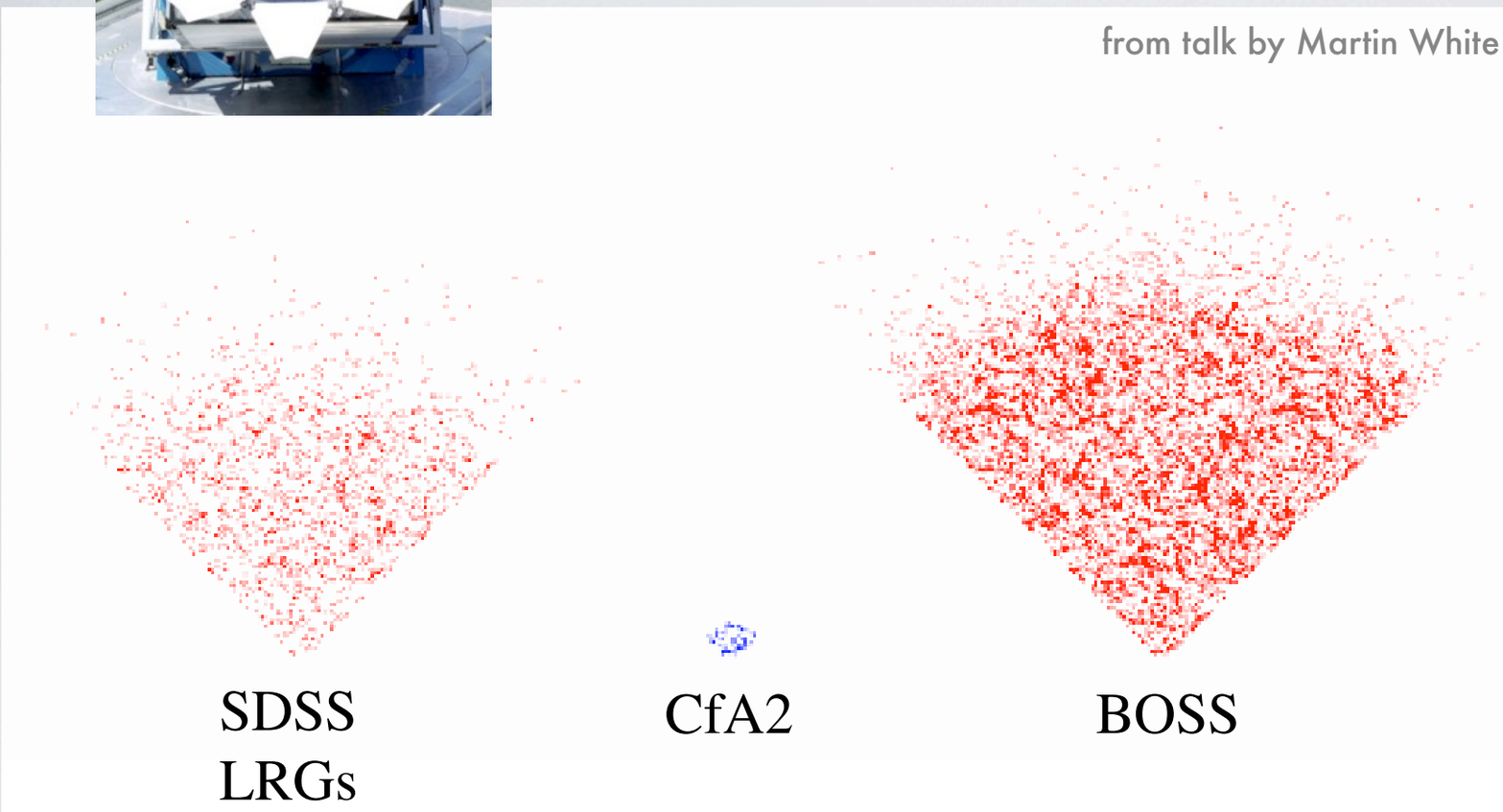


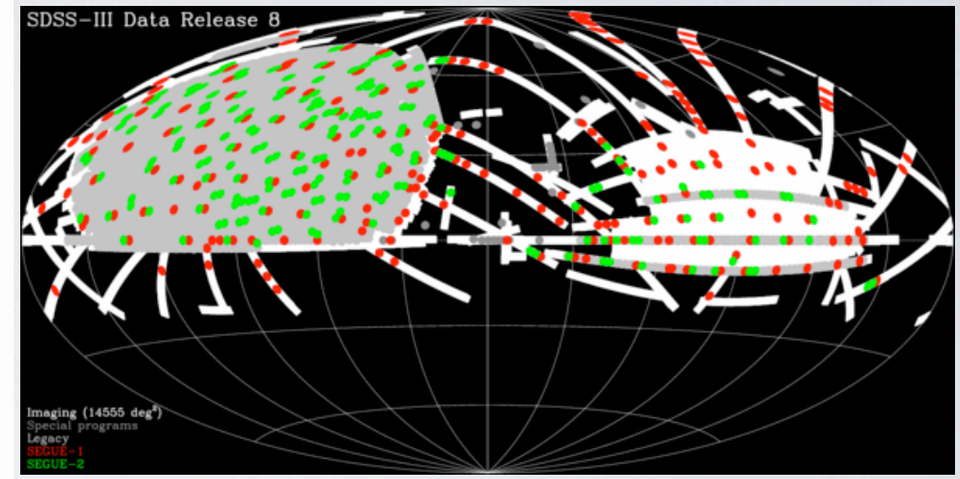
- >100,00 luminous galaxies
- look-back time ~4.8Gyr (z<0.47)
- Sky Coverage ~1/5

sample available at: **http://cosmo.nyu.edu/~eak306/SDSS-LRG.html**



The Sloan Digital Sky Survey Luminous Galaxy Sample





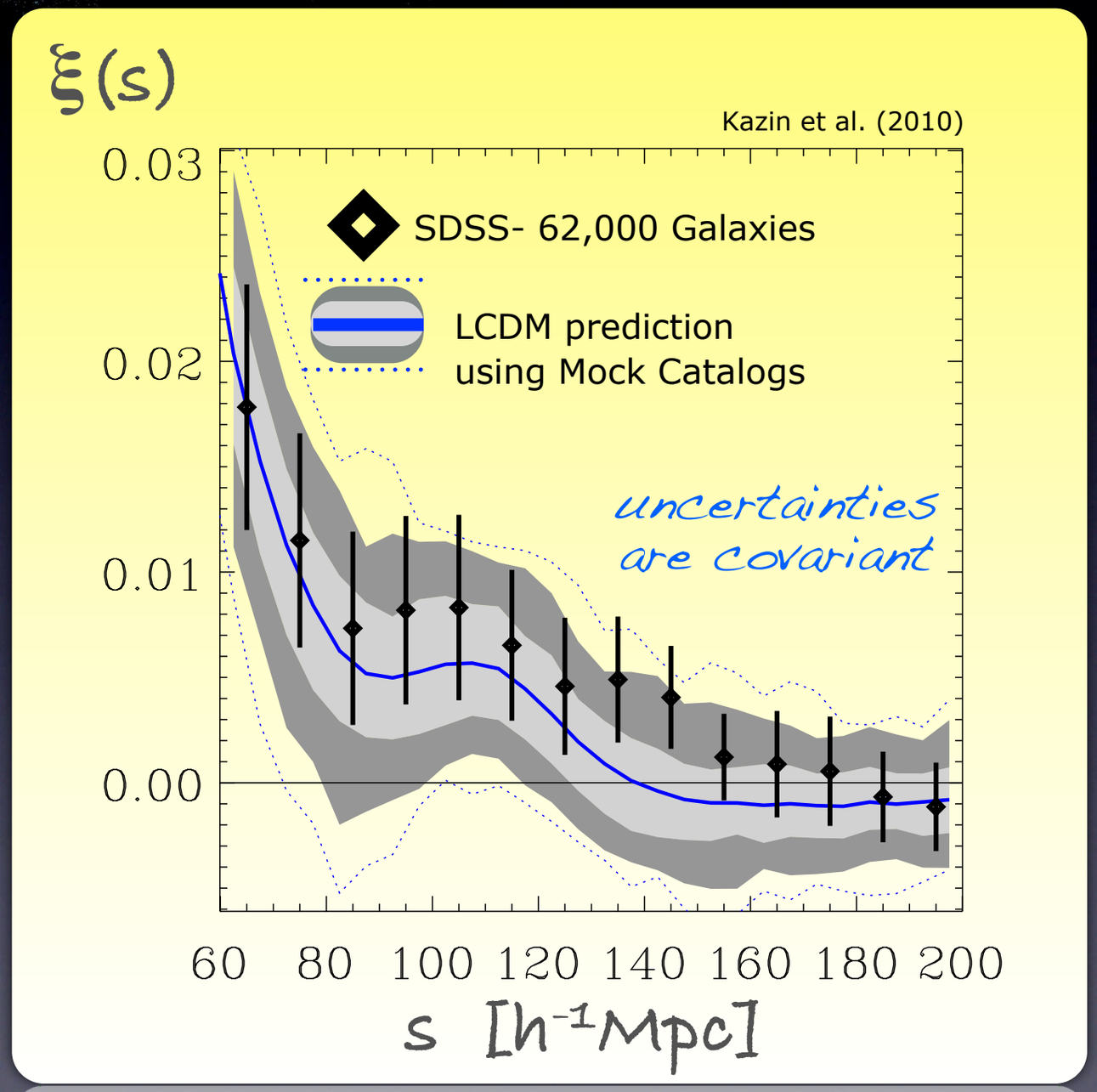
- >100,00 luminous galaxies
- look-back time ~4.8Gyr (z<0.47)
- Sky Coverage ~1/5

BOSS LRGs (exp 2014)

- >1.2M galaxies
- ~6.8Gyr (z<0.8)
- Sky Coverage ~1/4
- 3 times as dense

sample available at: **http://cosmo.nyu.edu/~eak306/SDSS-LRG.html**

The Baryonic Acoustic Feature in the SDSS Galaxy Sample



z~0.28

t~10.5G years ABB

Using peak position (@ ~ 0.5Gly), we calaculate the distance to ~ 3.6Gly to an accuracy of ~3.5%!

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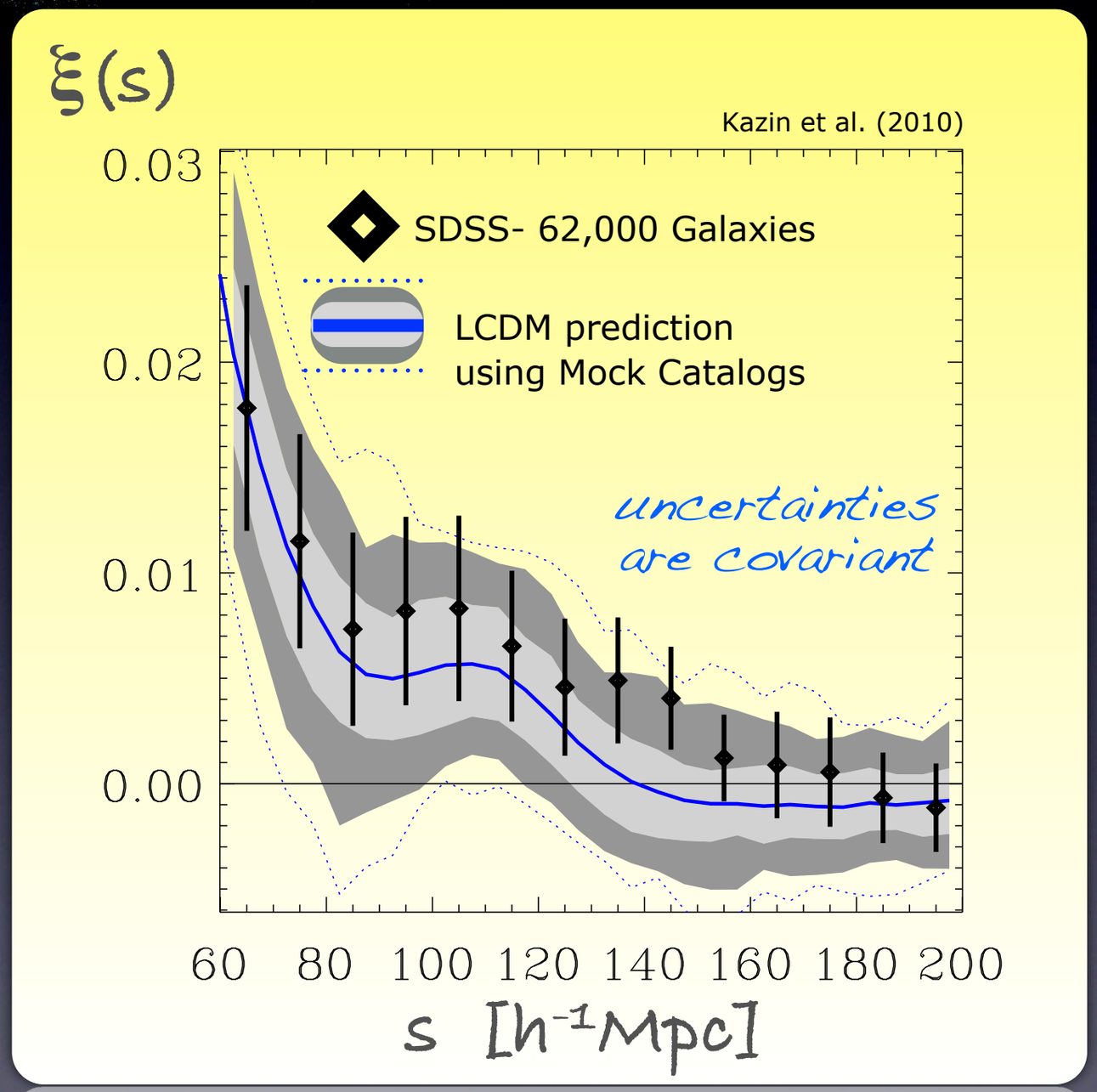
The Baryonic Acoustic Feature in the SDSS Galaxy Sample



Cosmic variance

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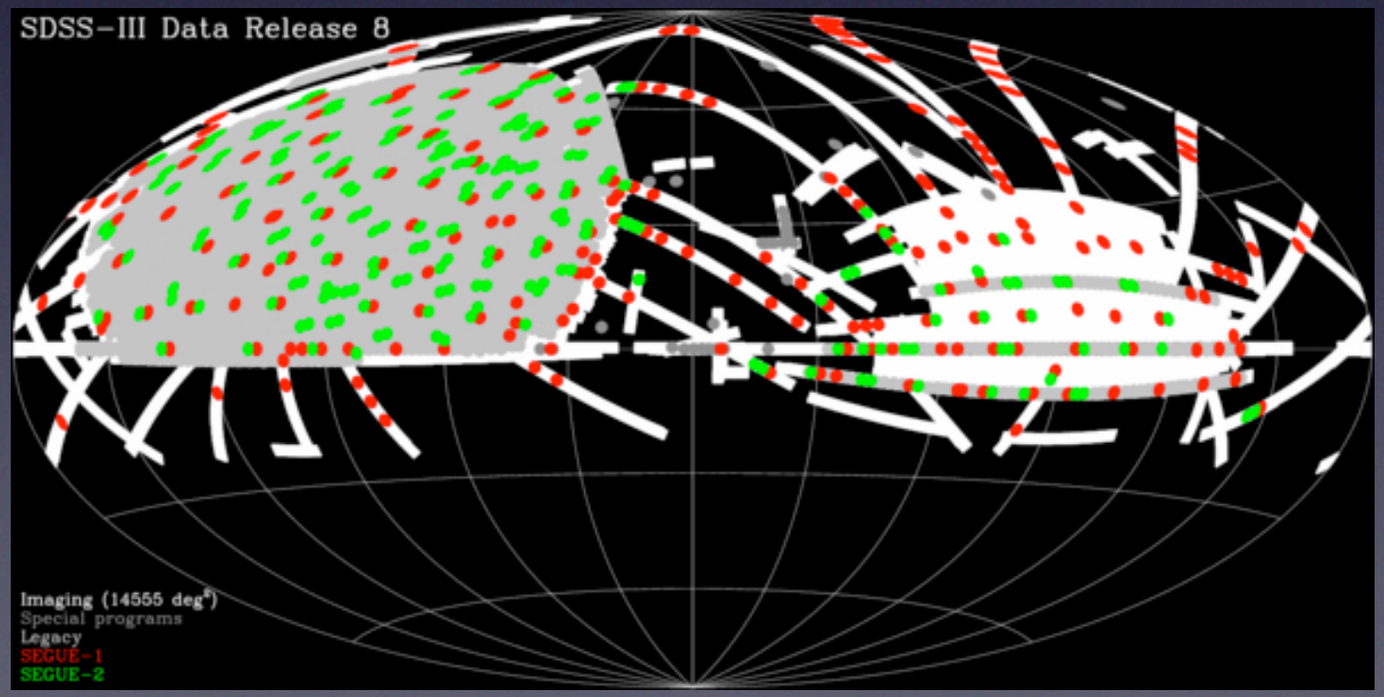
www.sdss3.org

Sloan Digital Sky Survey

2.5m designated telescope,
Apache Point, NM

Final Imaging released in January 11'



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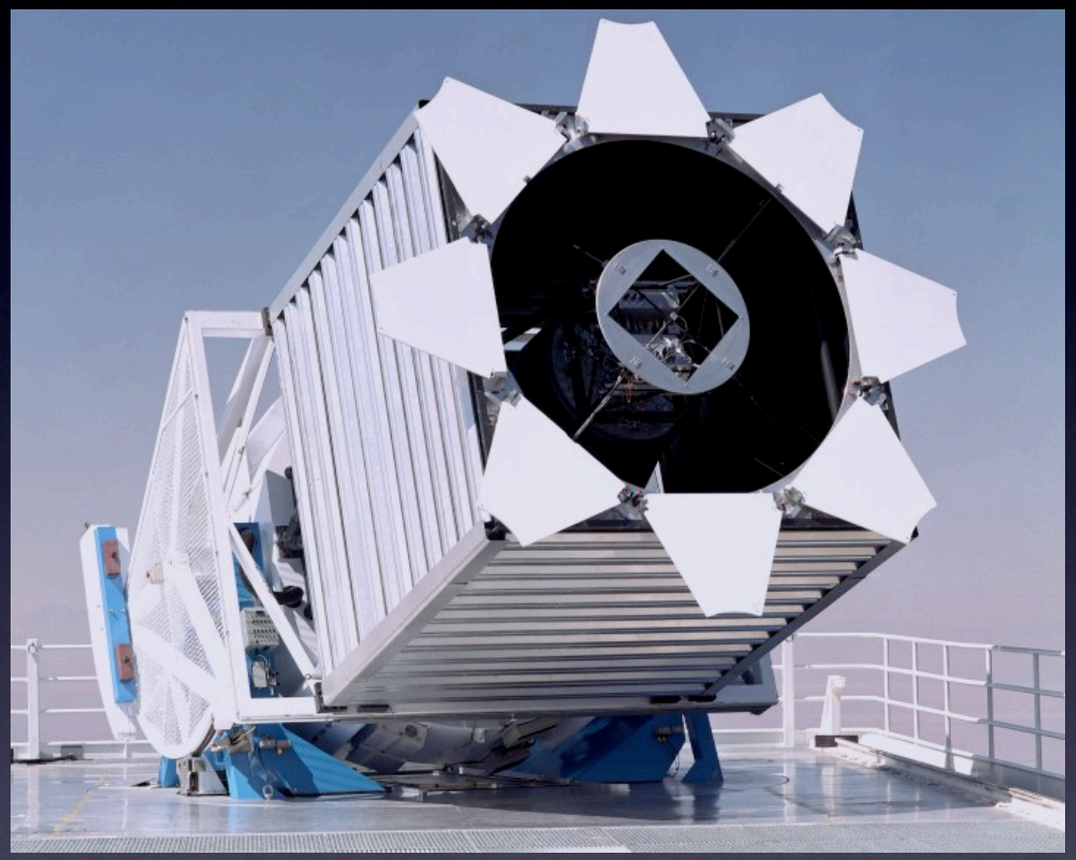
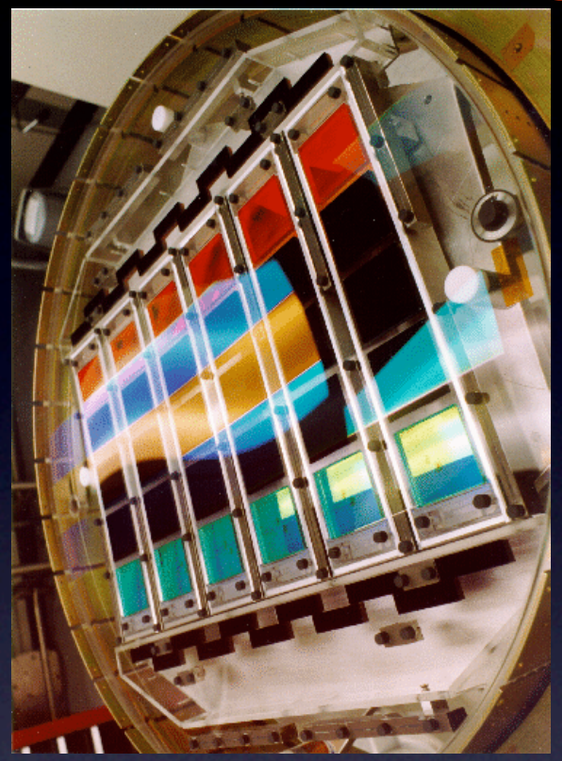
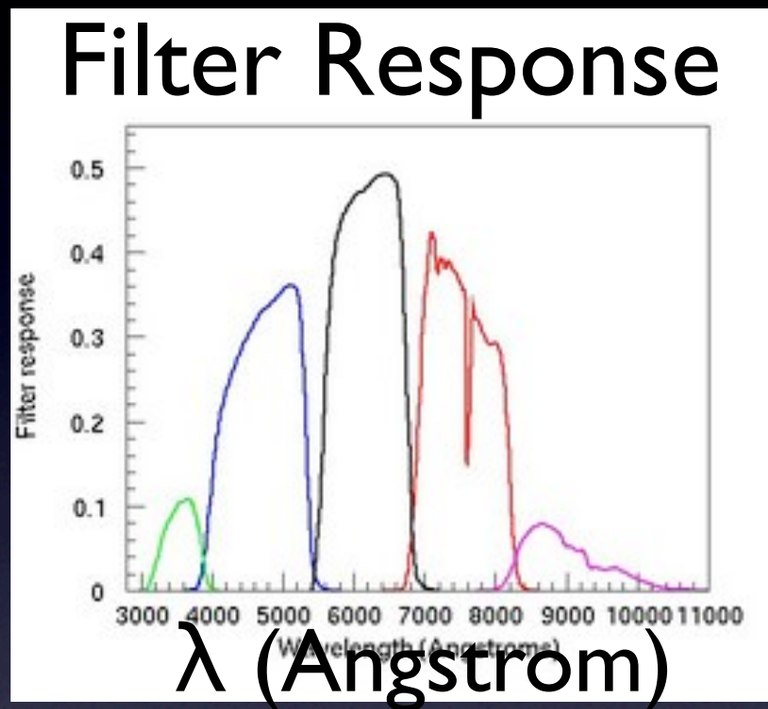
Sloan Digital Sky Survey- Imaging

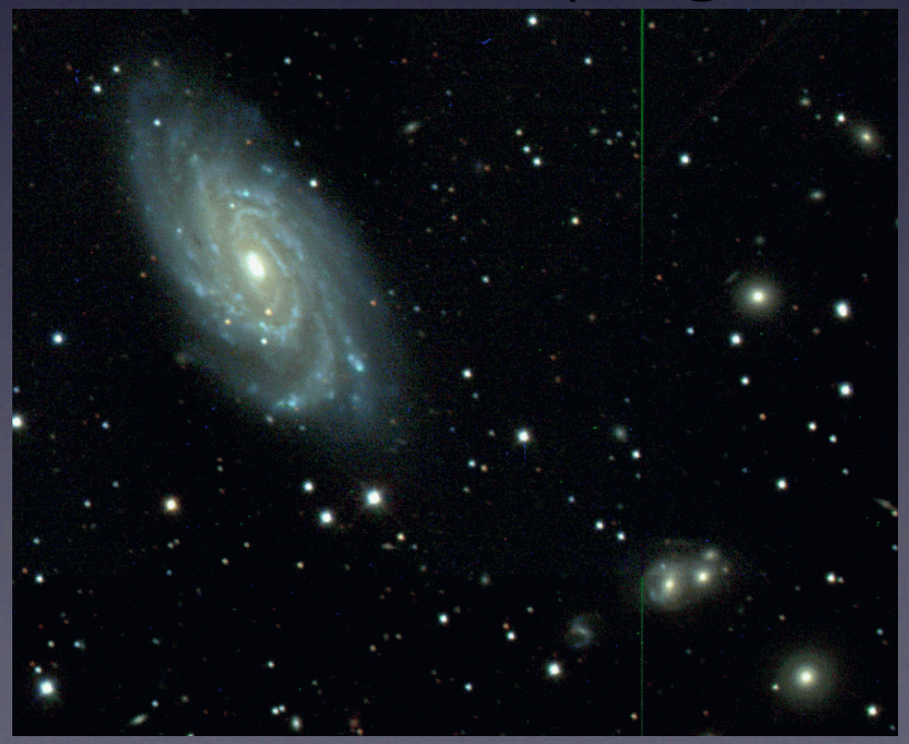
14,555 deg^2 (~35% of sky)

30 2MX2M pixel CCDs









images ➢ 2D mapping

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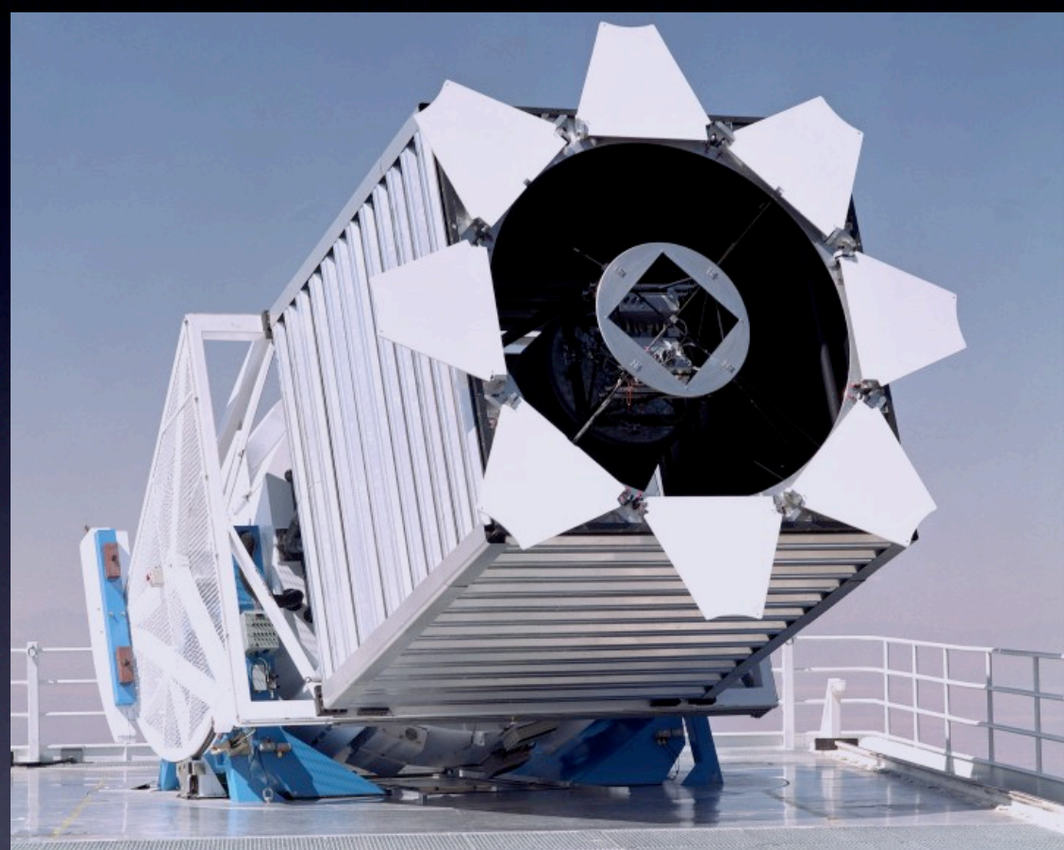
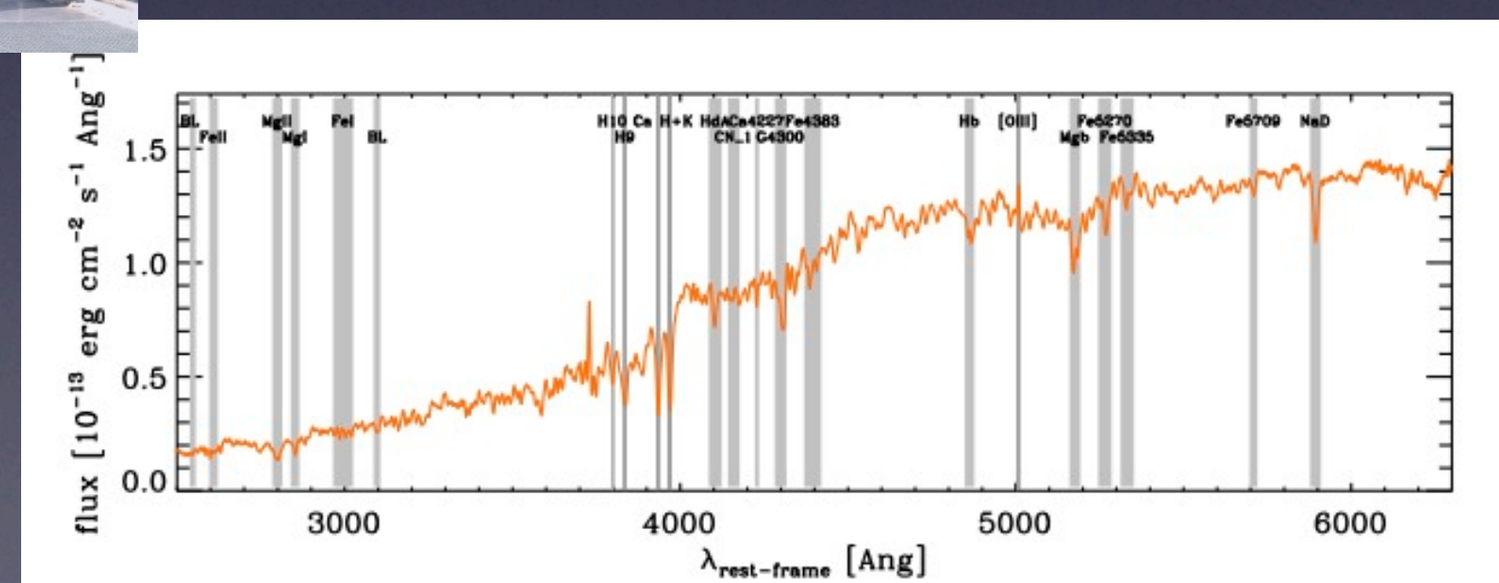
Sloan Digital Sky Survey- Spectroscopy

9274 deg^2 (22% of sky)



1000 fiber plugs connecting between spectrograph and plate

spectra
➢ redshift
➢ distance
(3D mapping)



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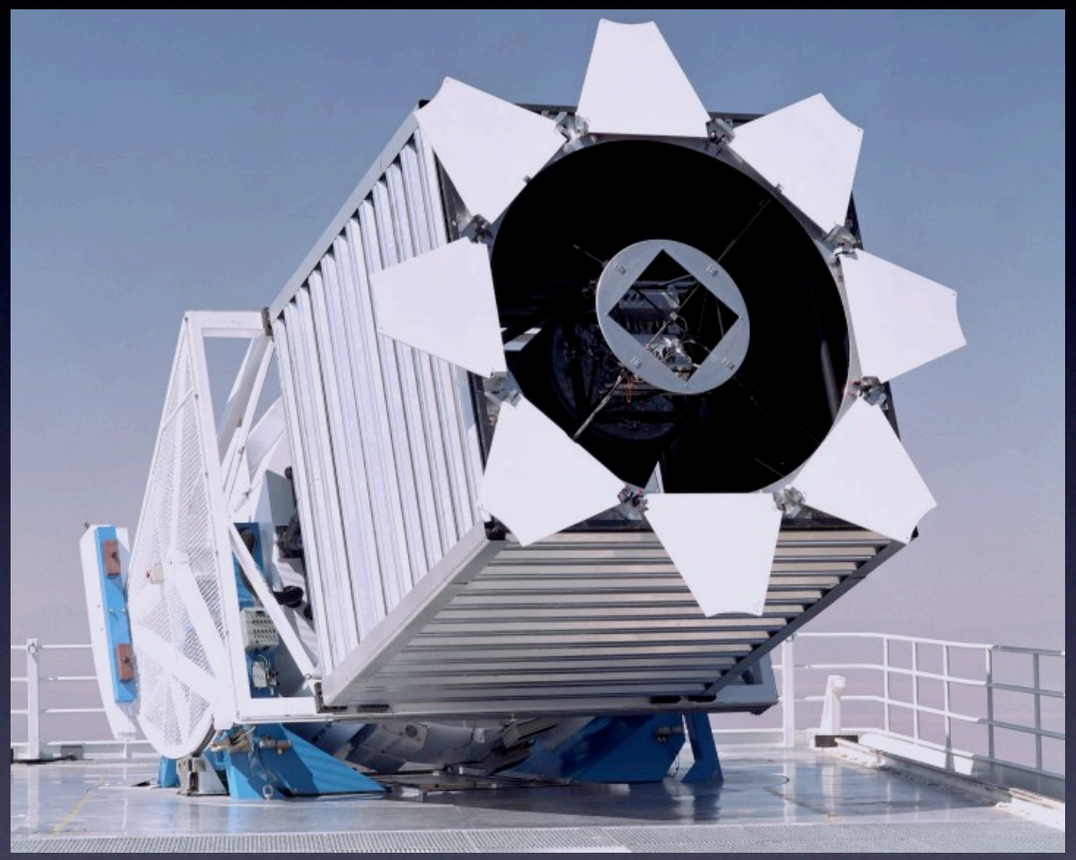
www.sdss3.org

Sloan Digital Sky Survey- in numbers



Data Release 8
(publicly available since Jan 2011):

Imaging: 469 Million objects
60 Terabytes

Spectra: 1.6 Million objects
Galaxies 860 thousand
Quasars 116 thousand
Stars 521 thousand
Unclassified 37 thousand
(Sky 93 thousand)
5.5 Terabytes

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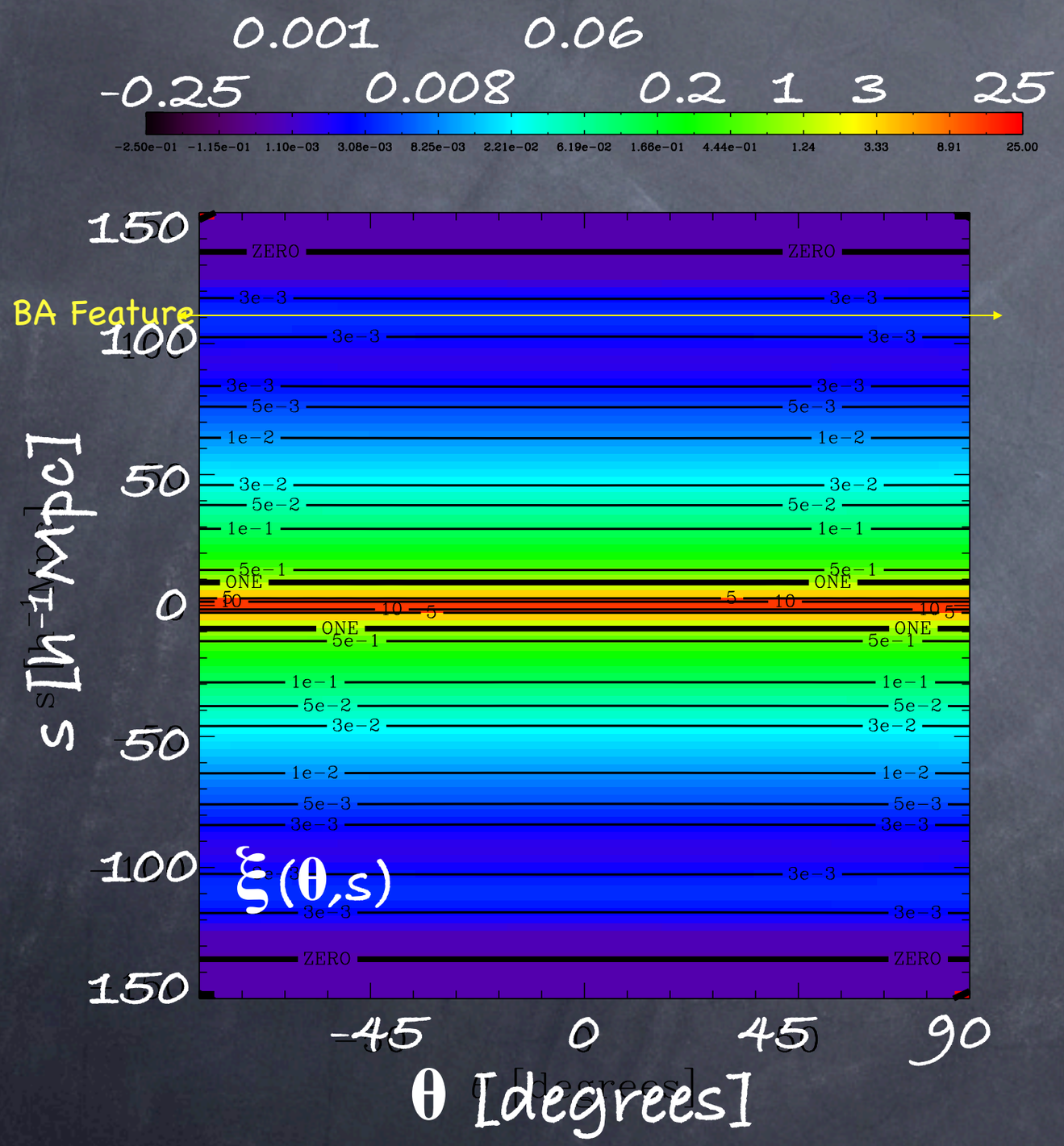
Clustering as Function of Angle



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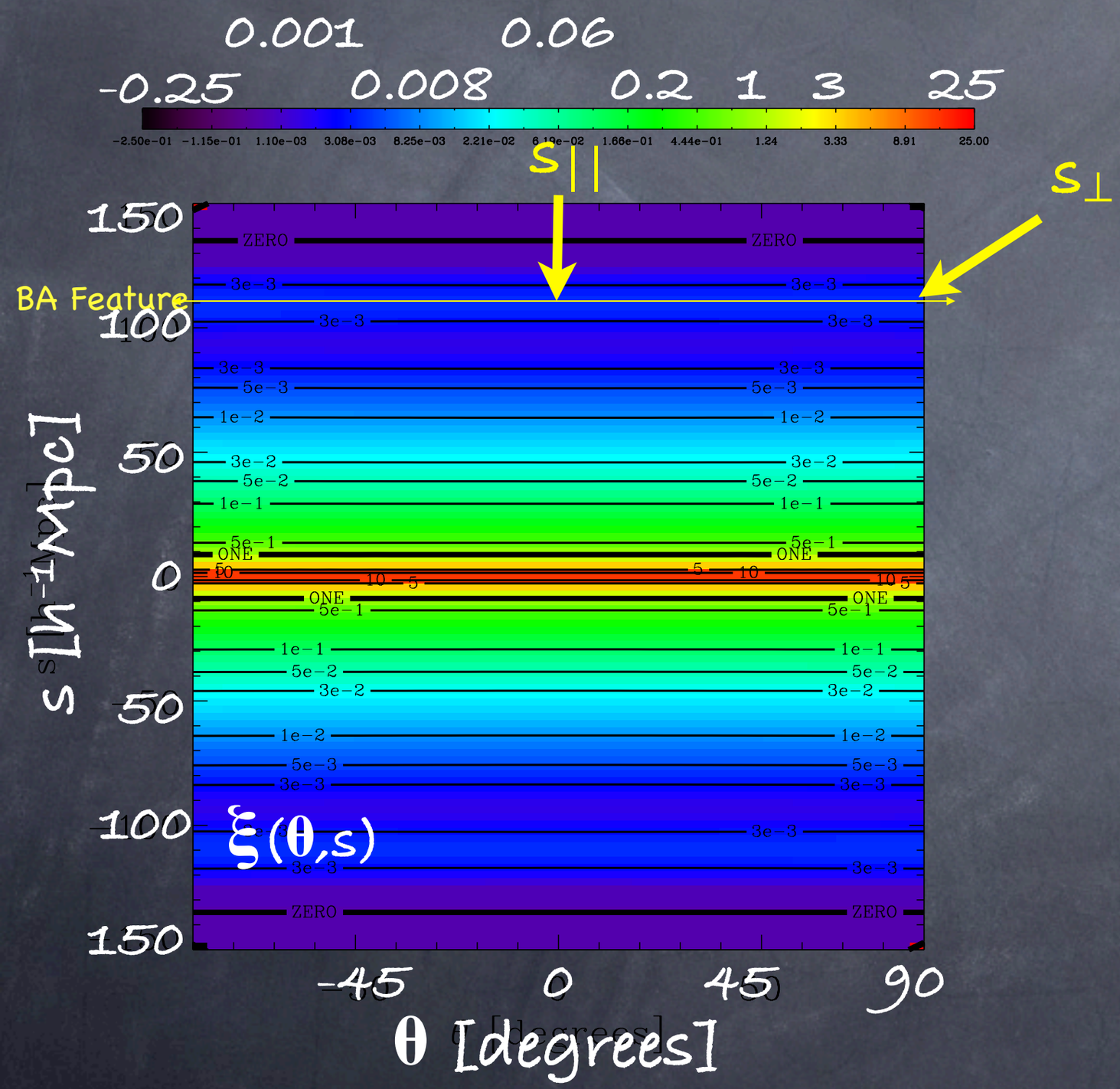
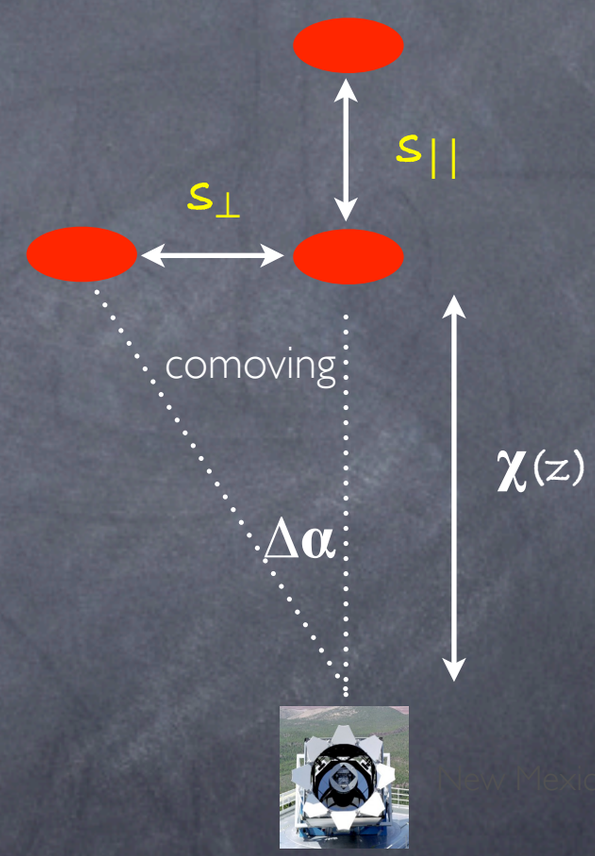
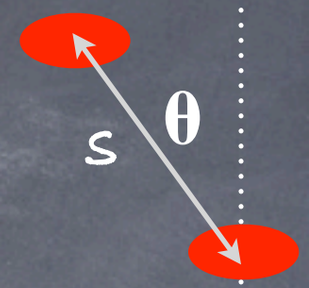
Clustering as Function of Angle

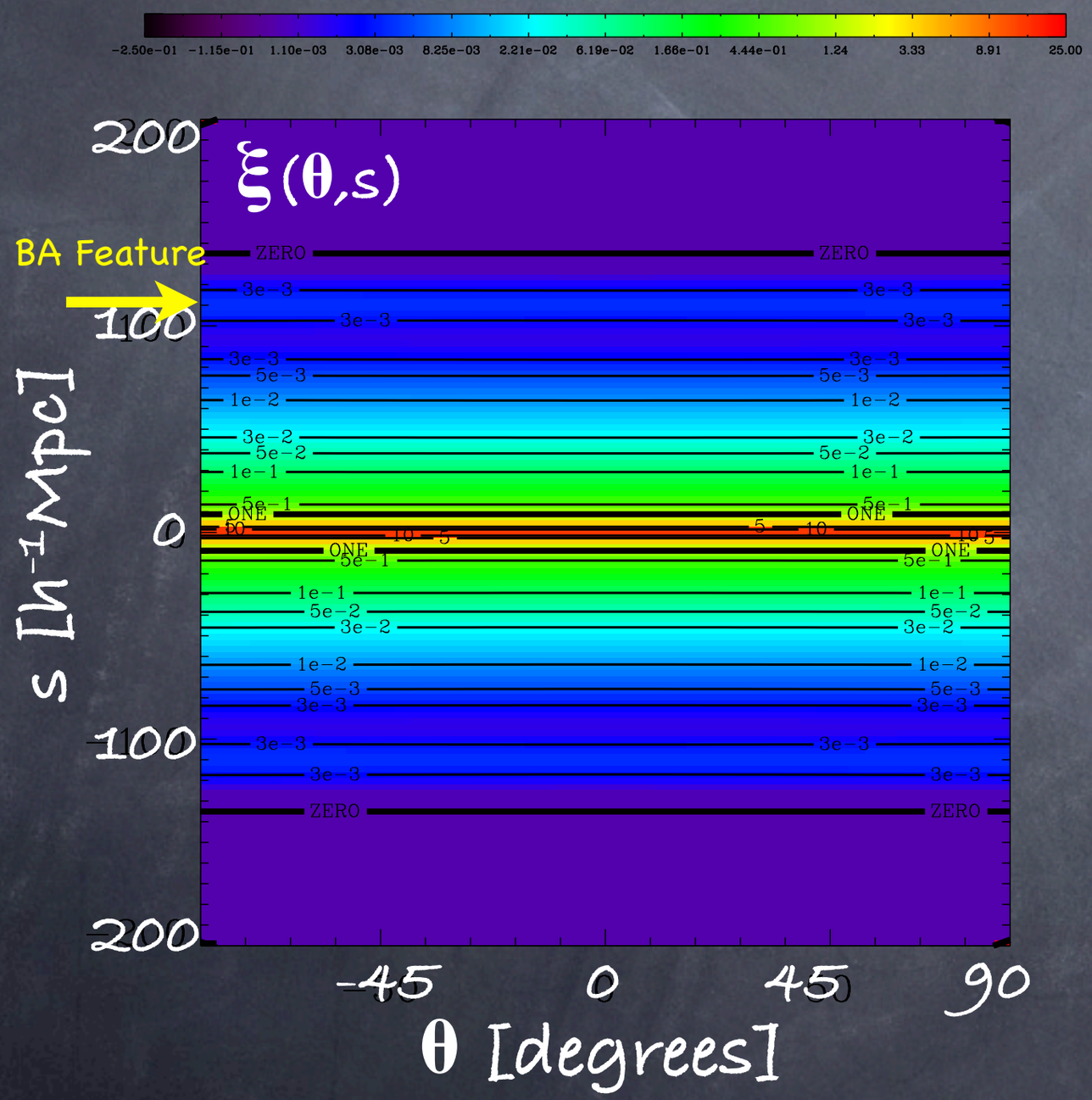




Clustering as Function of Polar Angle



no dynamical distortions
(linear theory)



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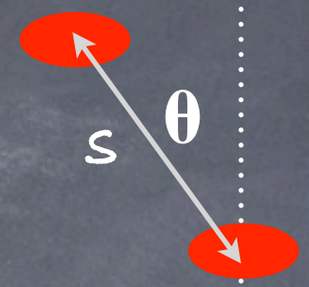
Clustering as Function of Polar Angle



no dynamical distortions
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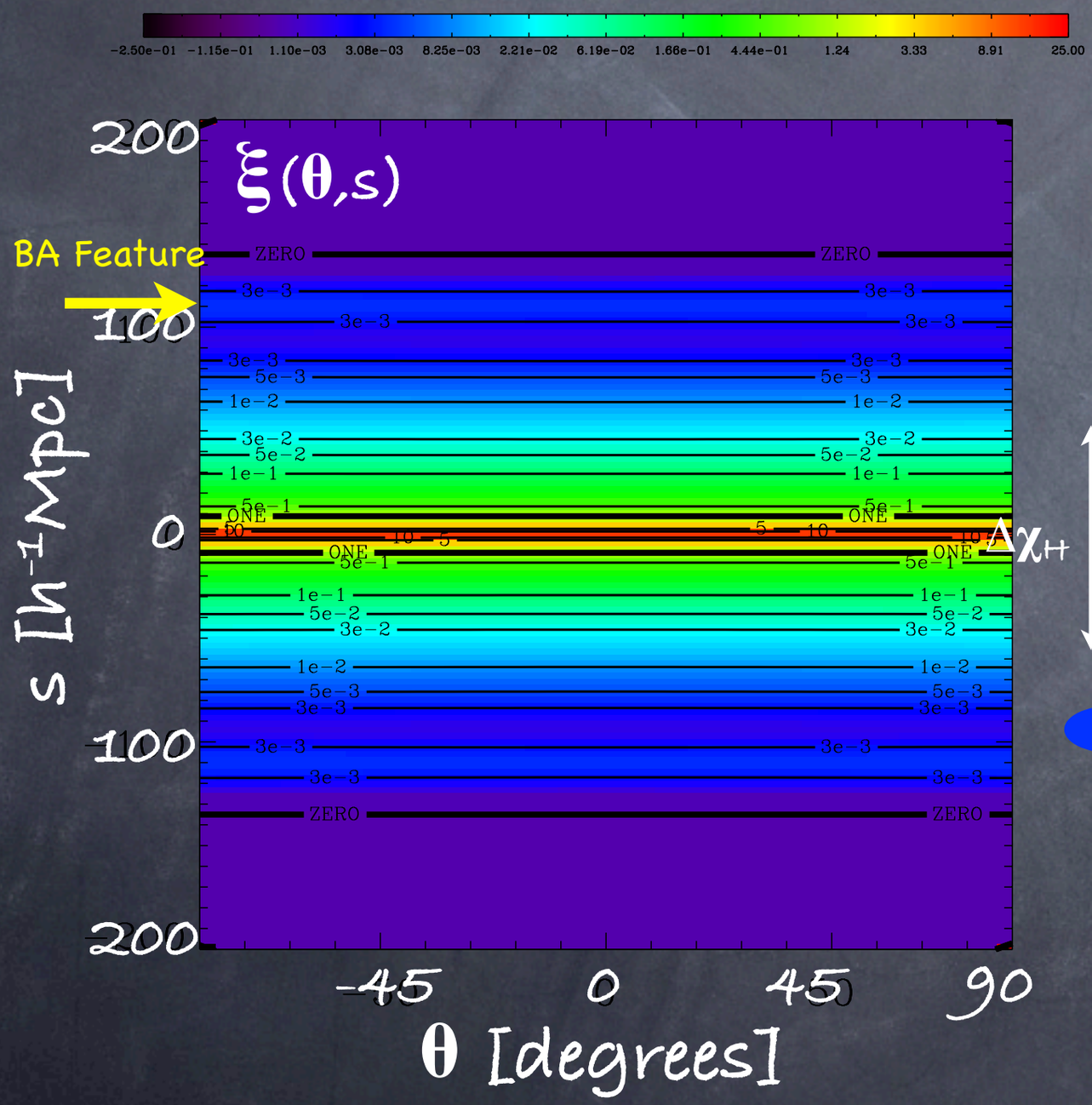
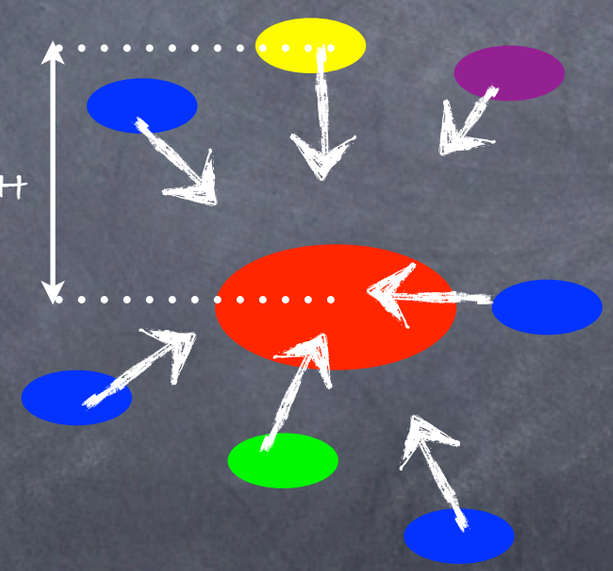
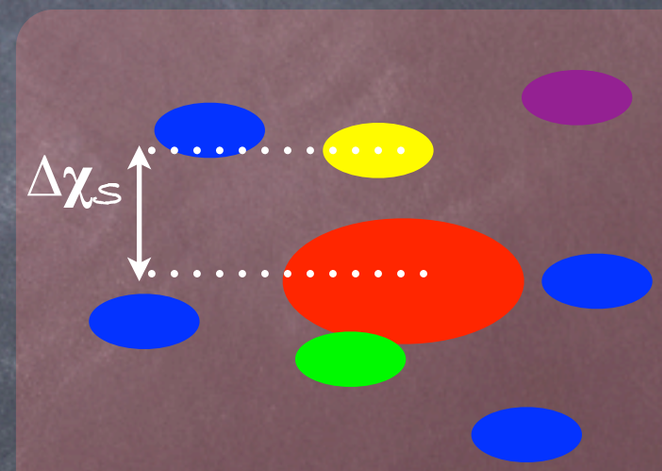




Real Space



Redshift Space

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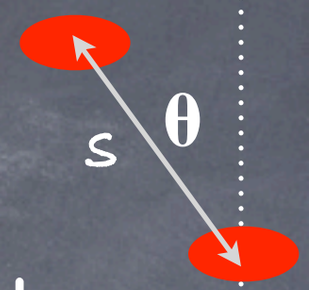
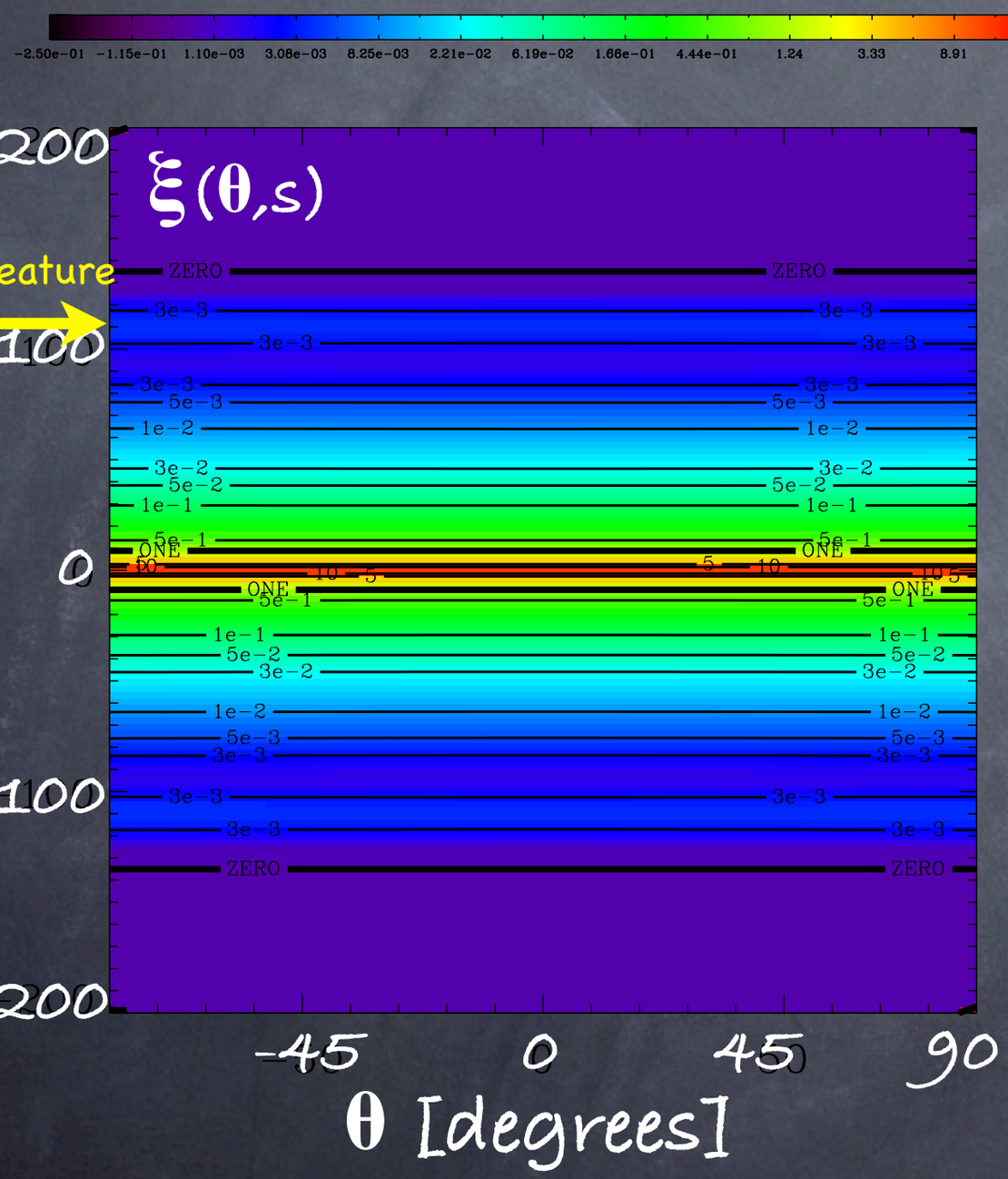
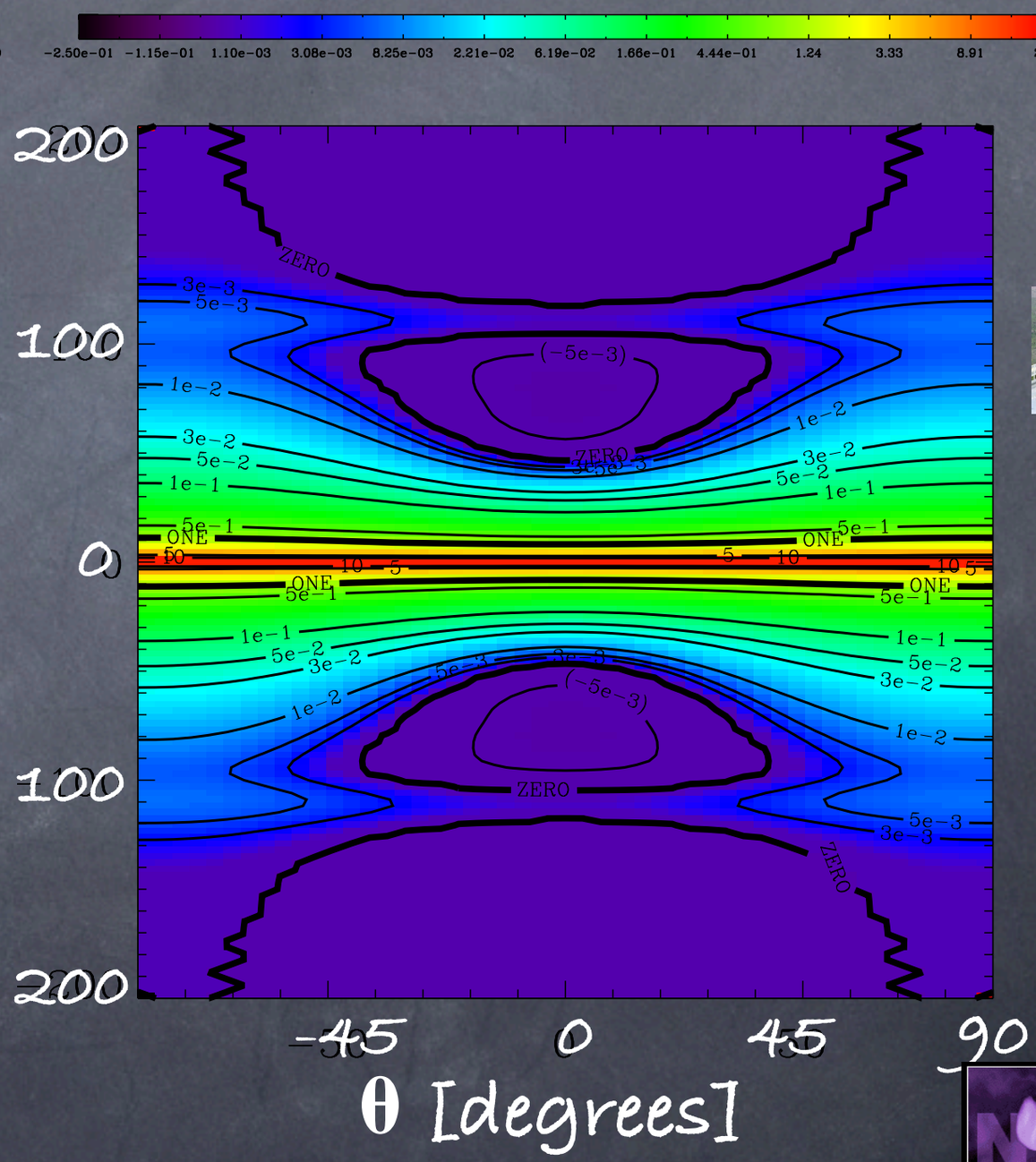
Clustering as Function of Polar Angle



no dynamical distortions
(linear theory)



squashing effect only
(linear theory)



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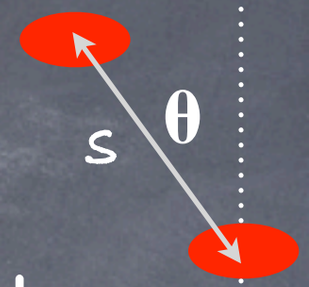
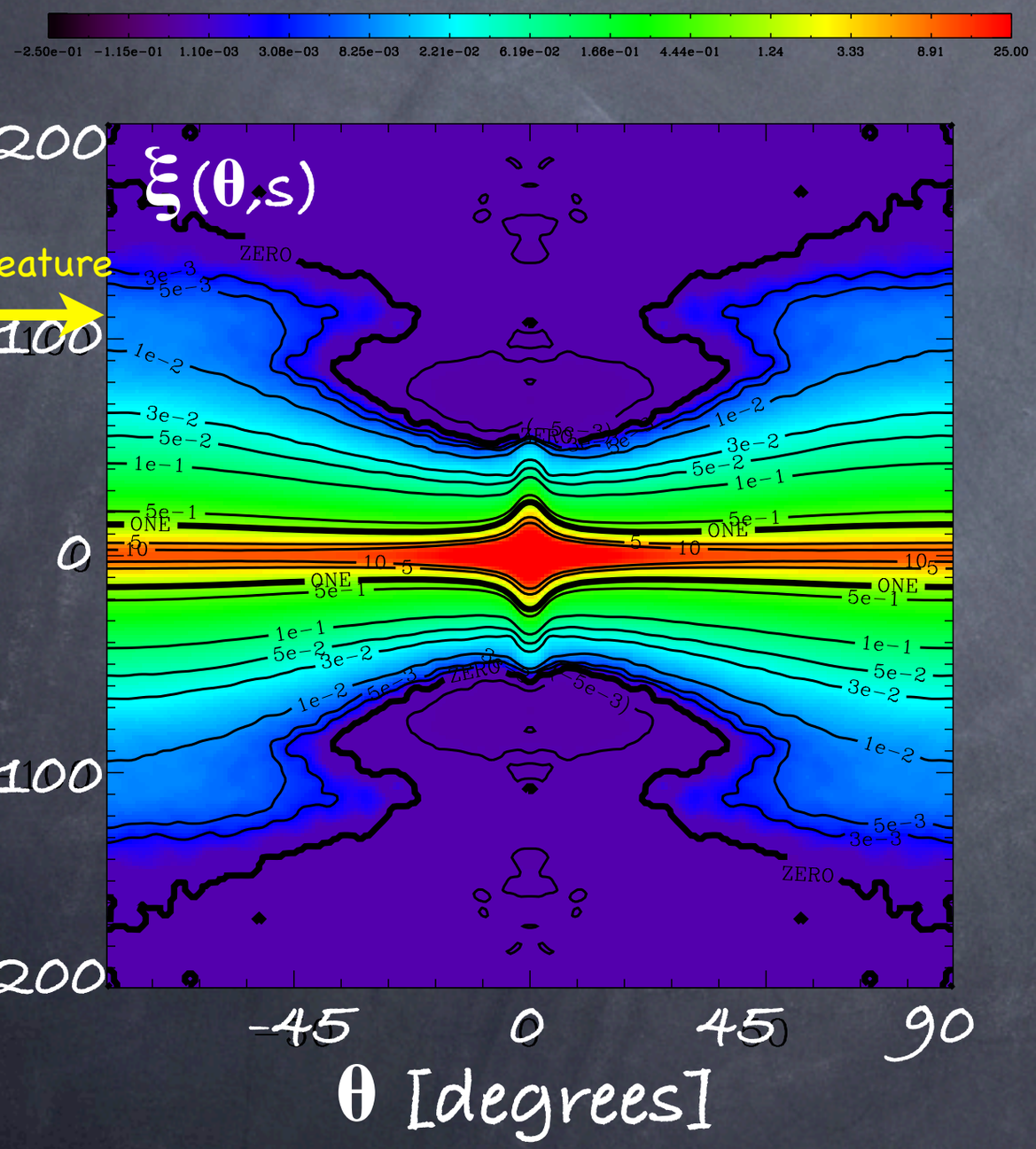
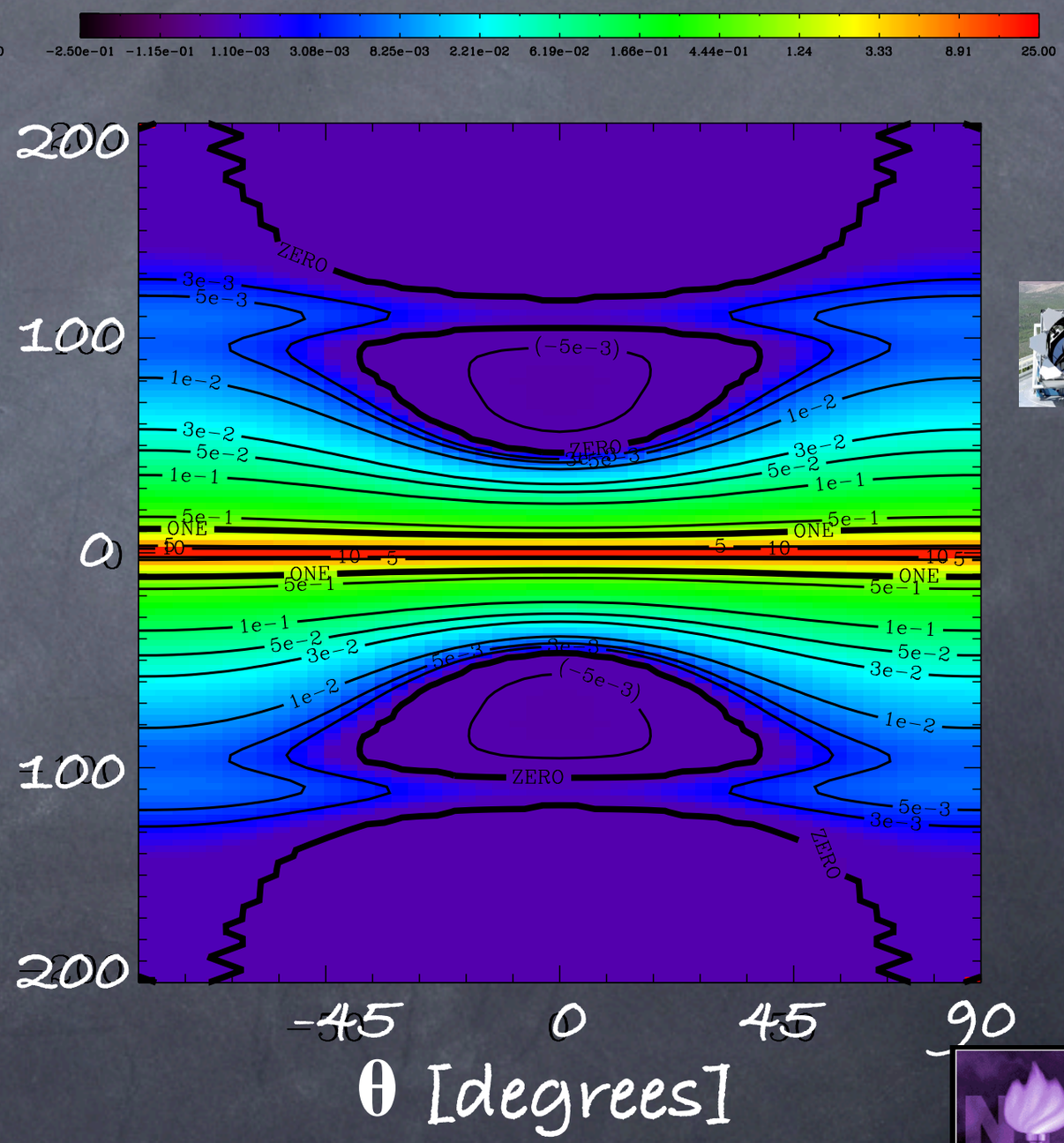
Clustering as Function of Polar Angle

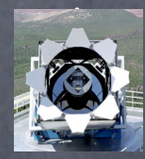


redshift distortions
(N-body simluated mock catalogs)



squashing effect only
(linear theory)





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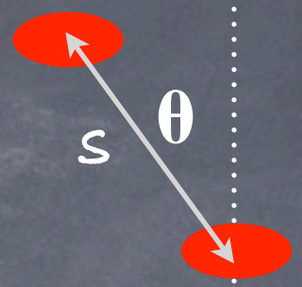
Clustering as Function of Polar Angle



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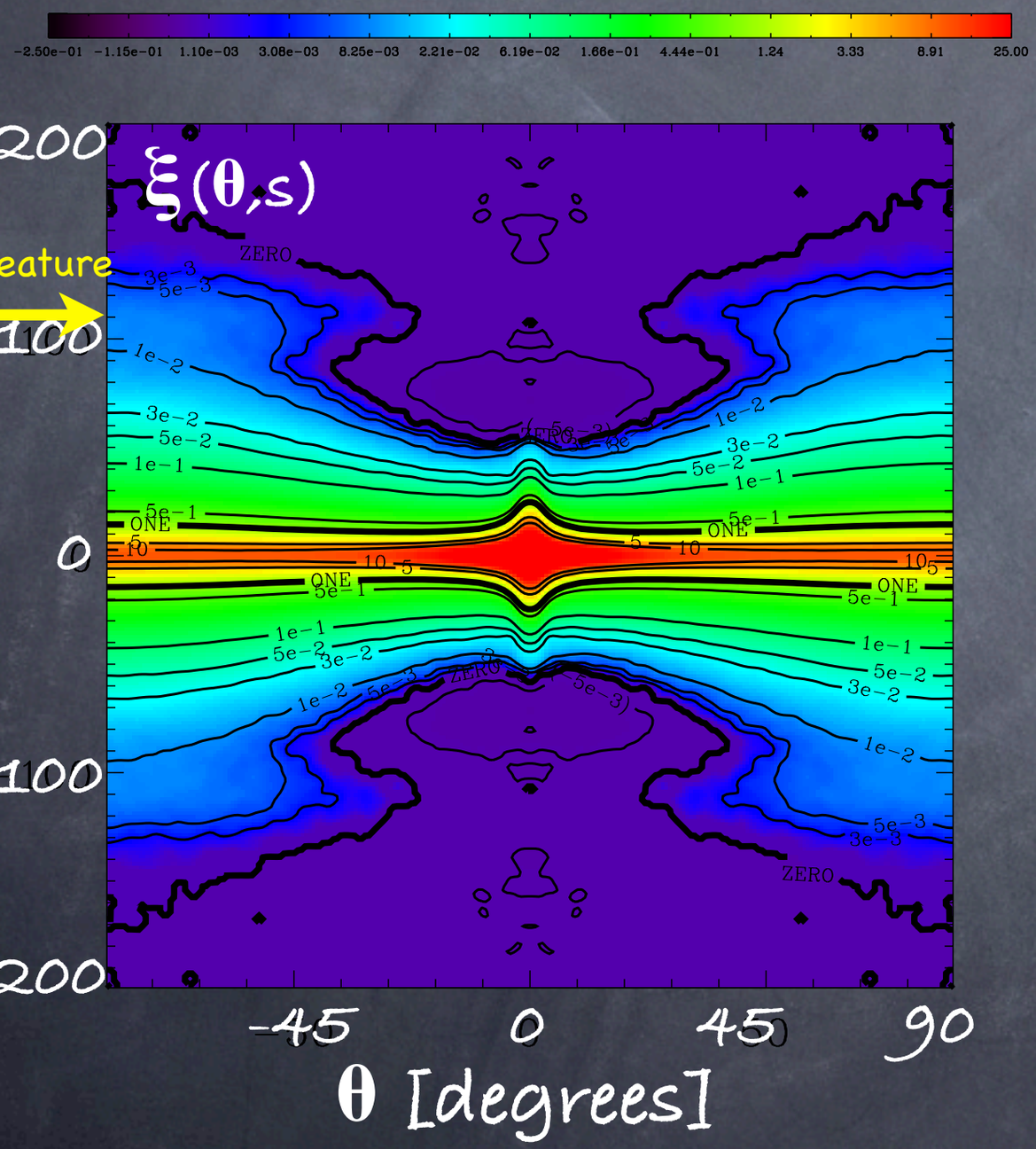
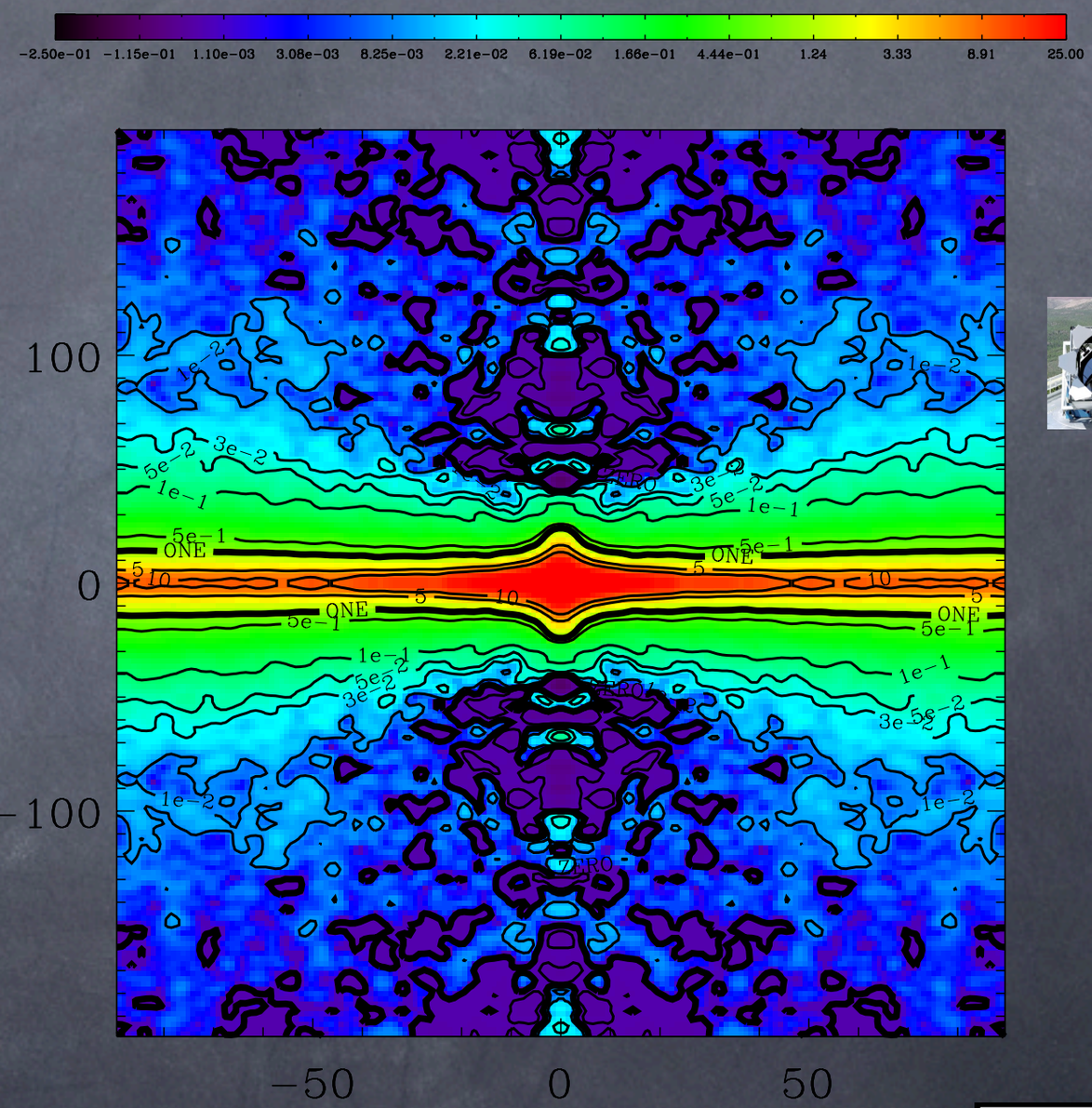


SDSS-II Results (0.16<z<0.47)



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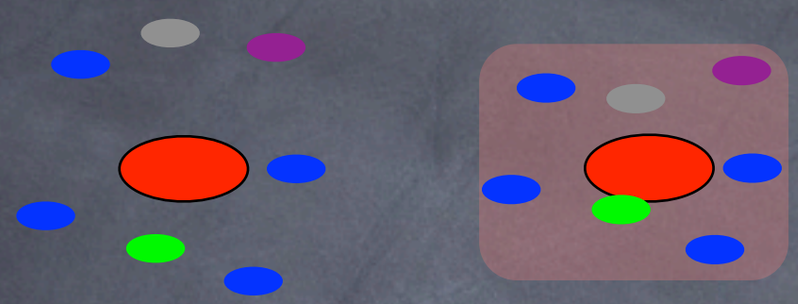
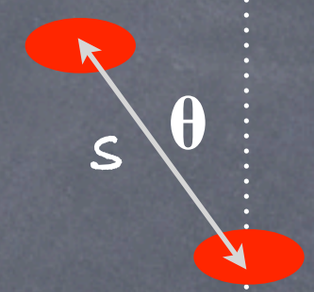
Testing Gravity through the Squashing Effect





- Galaxy dynamics is caused by gravity.
- Gravity strength depends on matter abudance.
- Hence squashing effect can be used to measure matter abundance (Ω_M).
- Alternatively, assuming Ω_M, it can be used to test gravity.

squashing parameter

$$\beta \propto \Omega_M^{\gamma}$$

growth index

ΛCDM (GR): $\gamma \sim 0.56$

DGP (alternative theory): $\gamma \sim 0.68$

Quadrupole Test: No dependence on scale!

$$Q \equiv \xi_2(r)/\xi_0(r) = (4/3\beta + 4/7\beta^2)/(1 + 2/3\beta + 1/5\beta^2)$$

quadrupole/monopole

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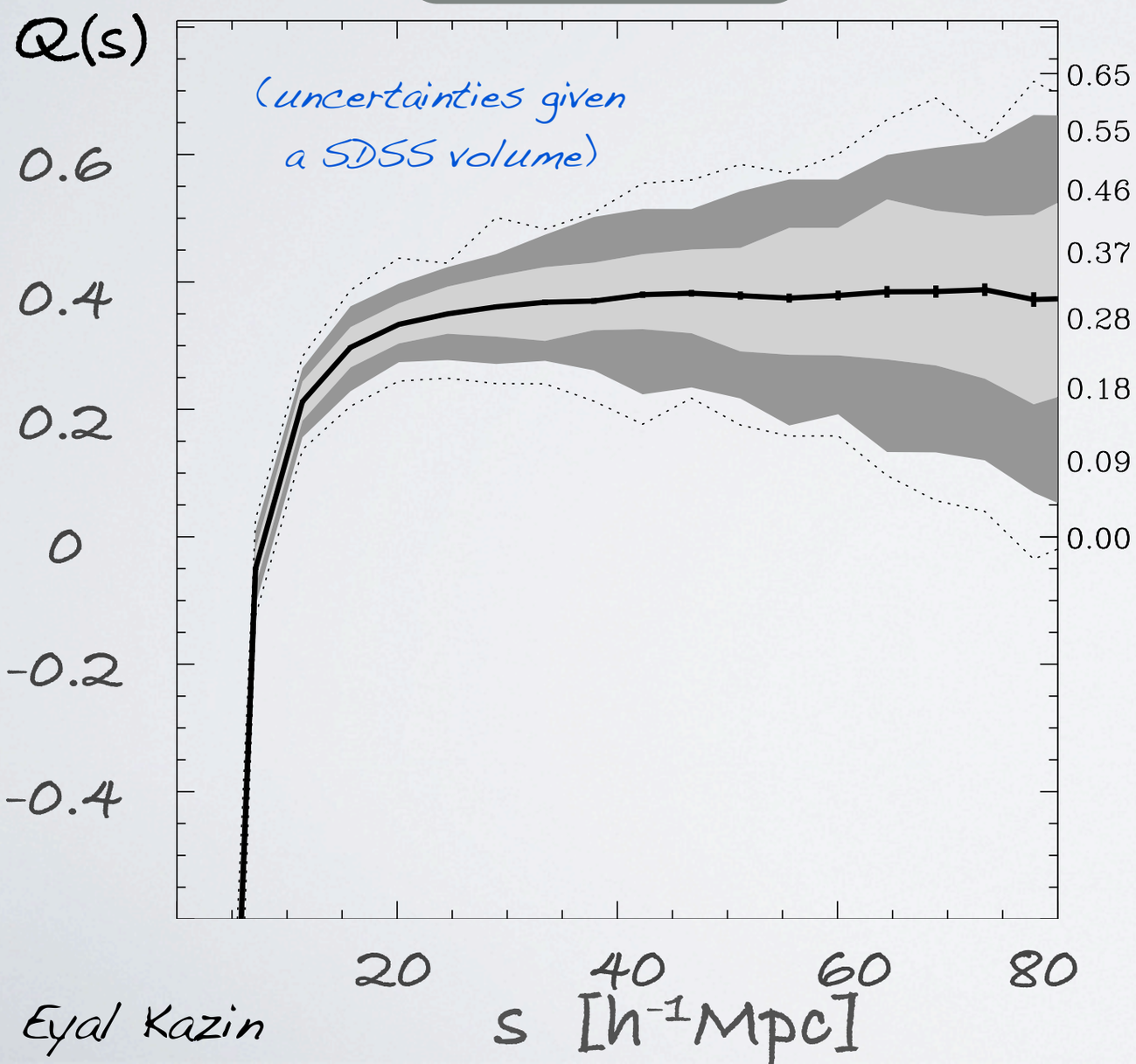
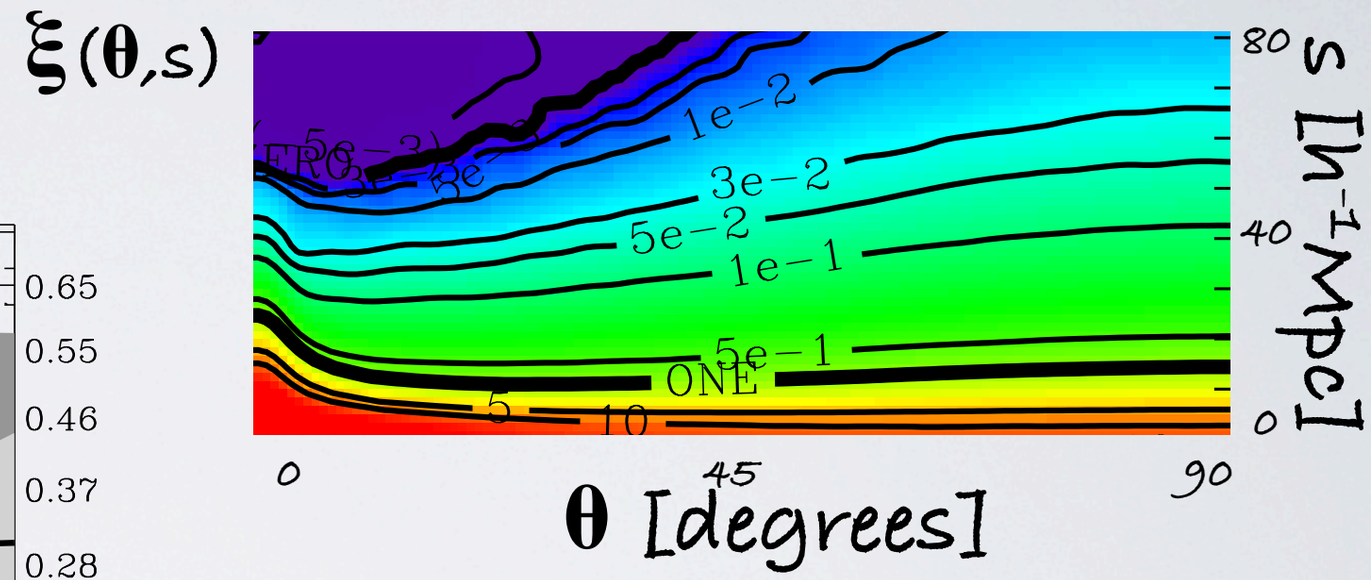
β through the Quadrupole Test
N-Body Simulations (Mock Surveys)

$$Q \sim \xi_2(s) / \xi_0(s) = (4/3\beta + 4/7\beta^2)/(1 + 2/3\beta + 1/5\beta^2)$$

Mock Galaxies,
Not observation!!





$$\beta \approx \Omega_M^{\gamma}(z)/b_1$$

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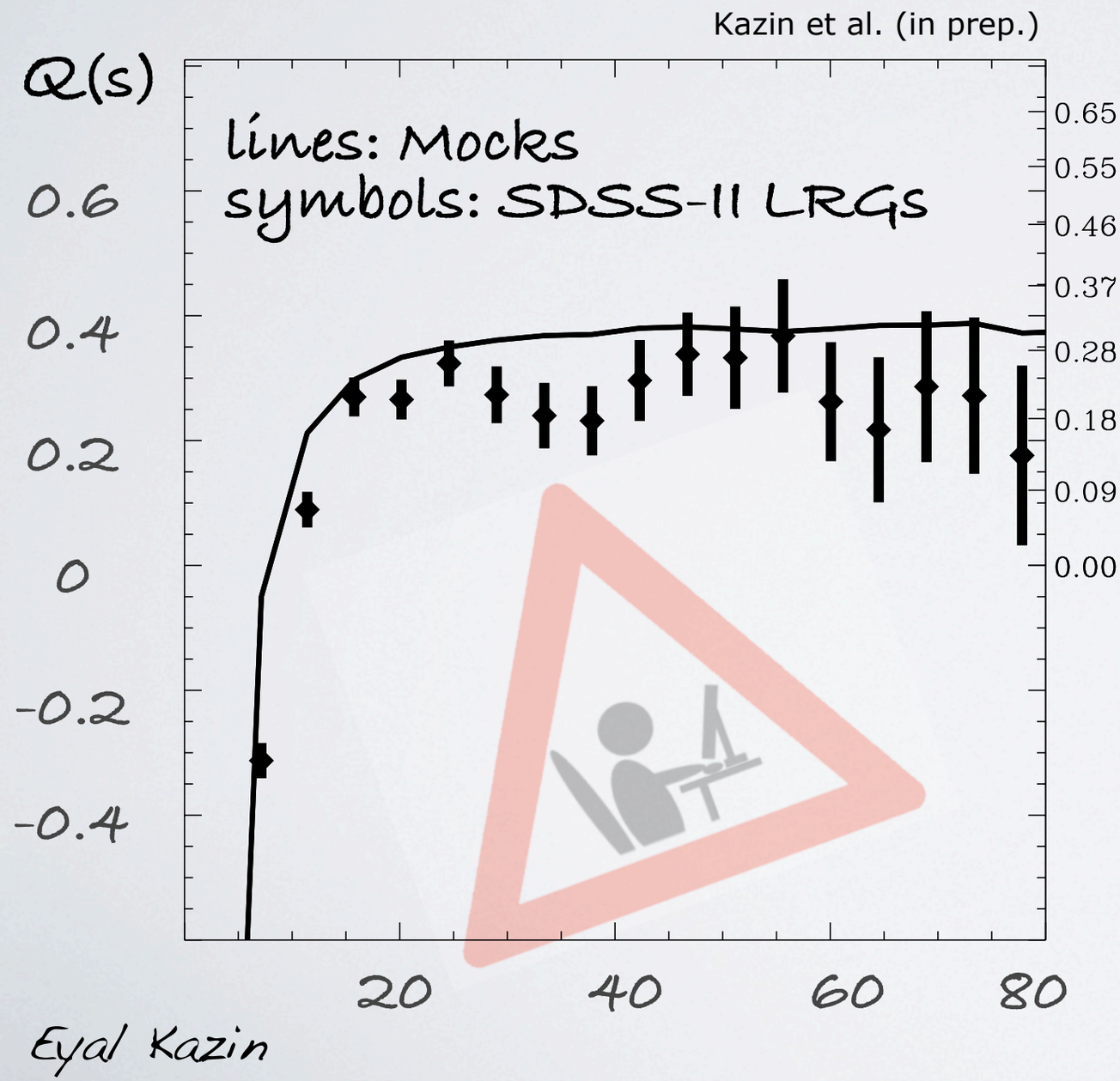
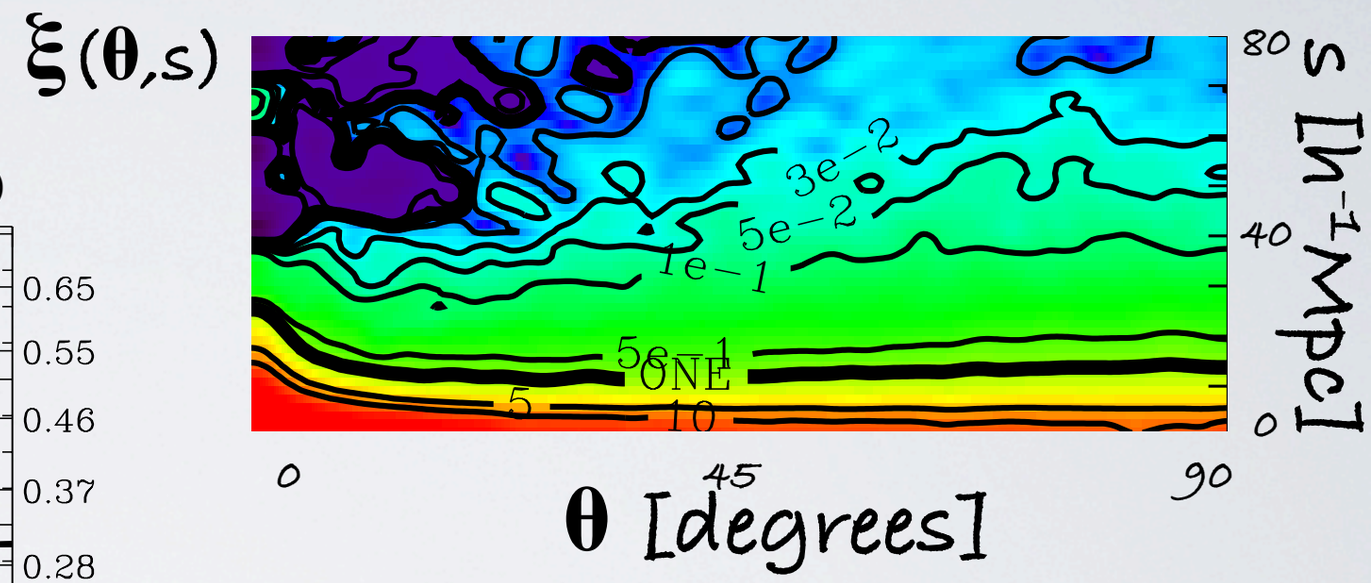
β through the Quadrupole Test
SDSS-II Results

$$Q \sim \xi_2(s) / \xi_0(s) = (4/3\beta + 4/7\beta^2)/(1 + 2/3\beta + 1/5\beta^2)$$





$$\beta \approx \Omega_M^{\gamma}(z)/b_1$$

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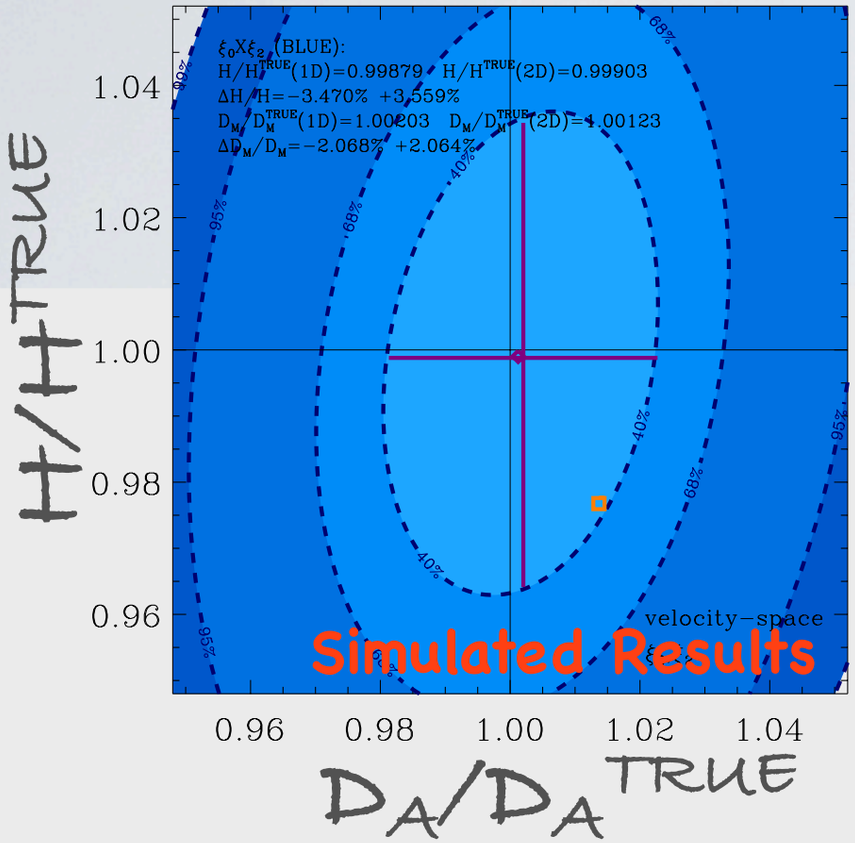
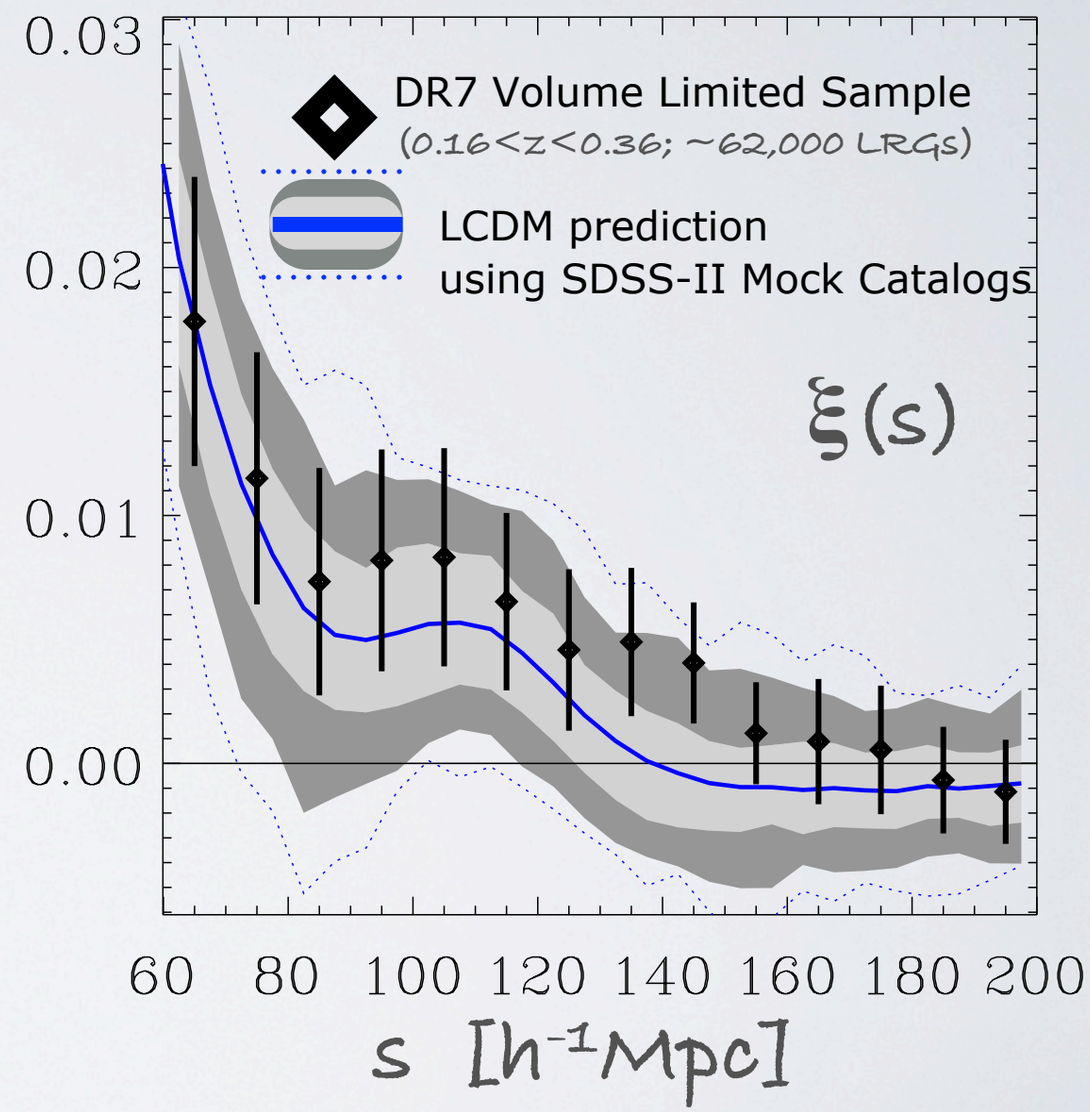
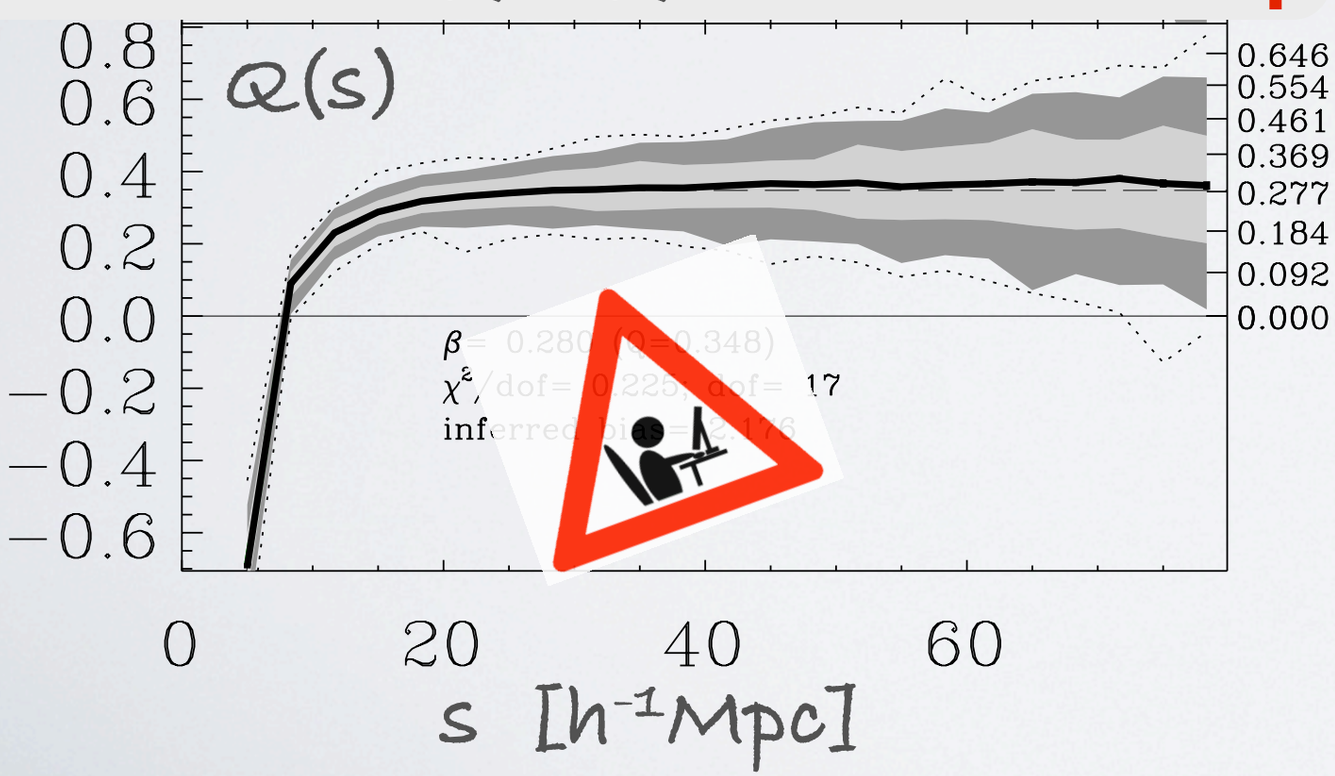
BOSS- Substantially Improving Our Cosmological Tools



SDSS-II



β



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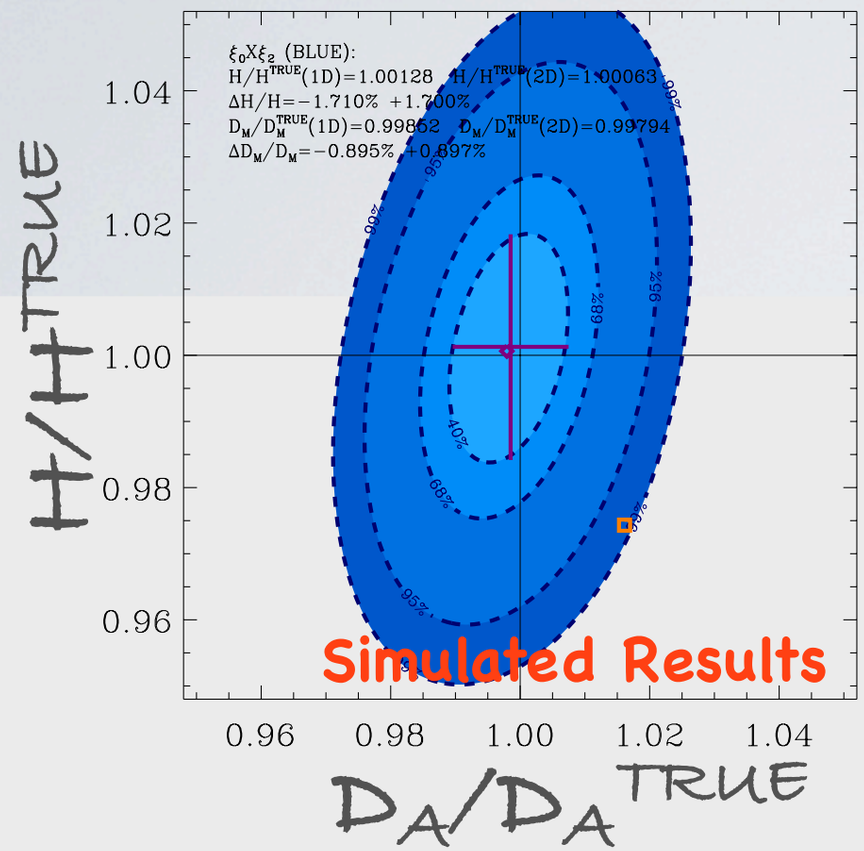
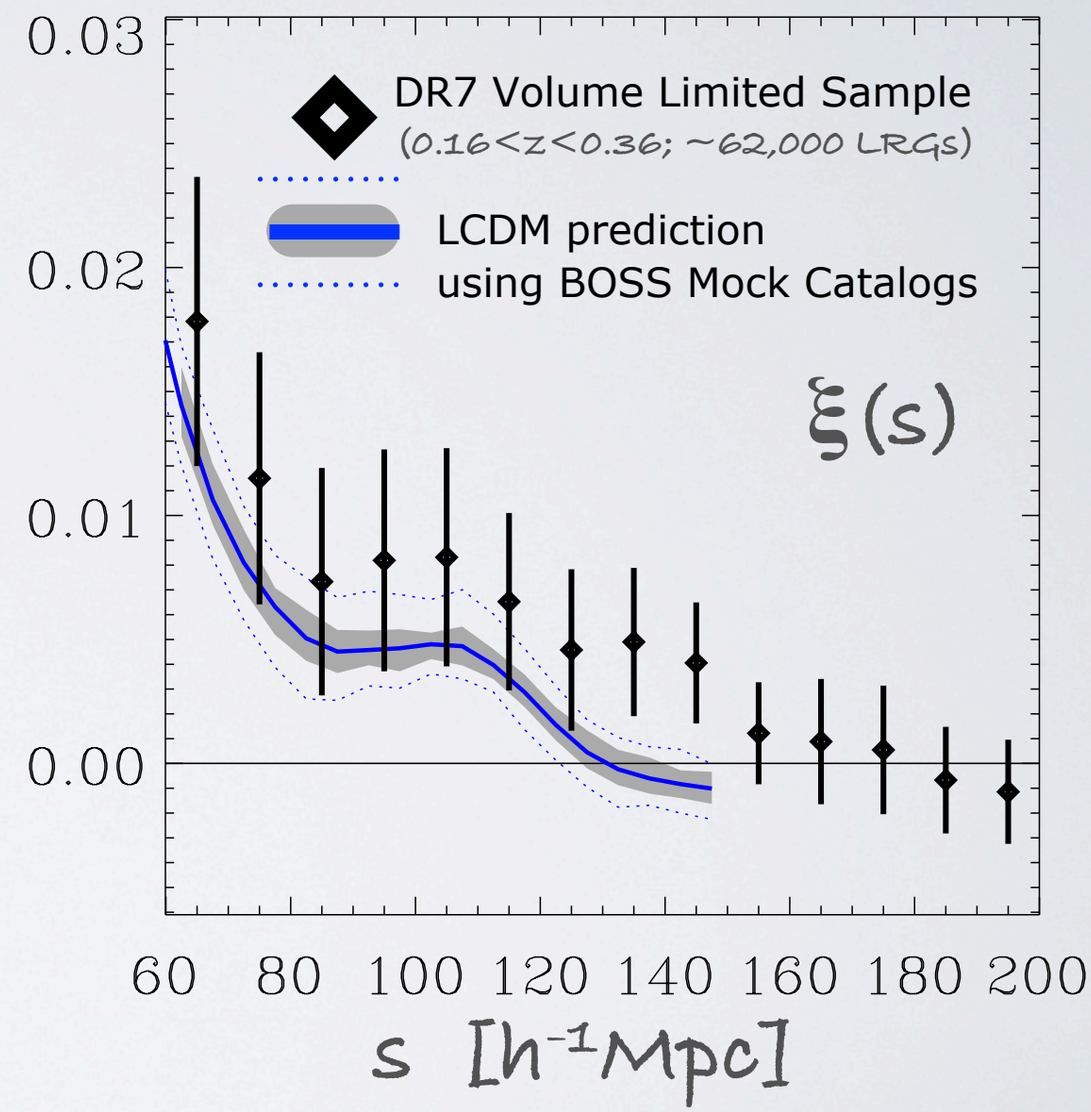
BOSS- Substantially Improving Our Cosmological Tools



SDSS-III



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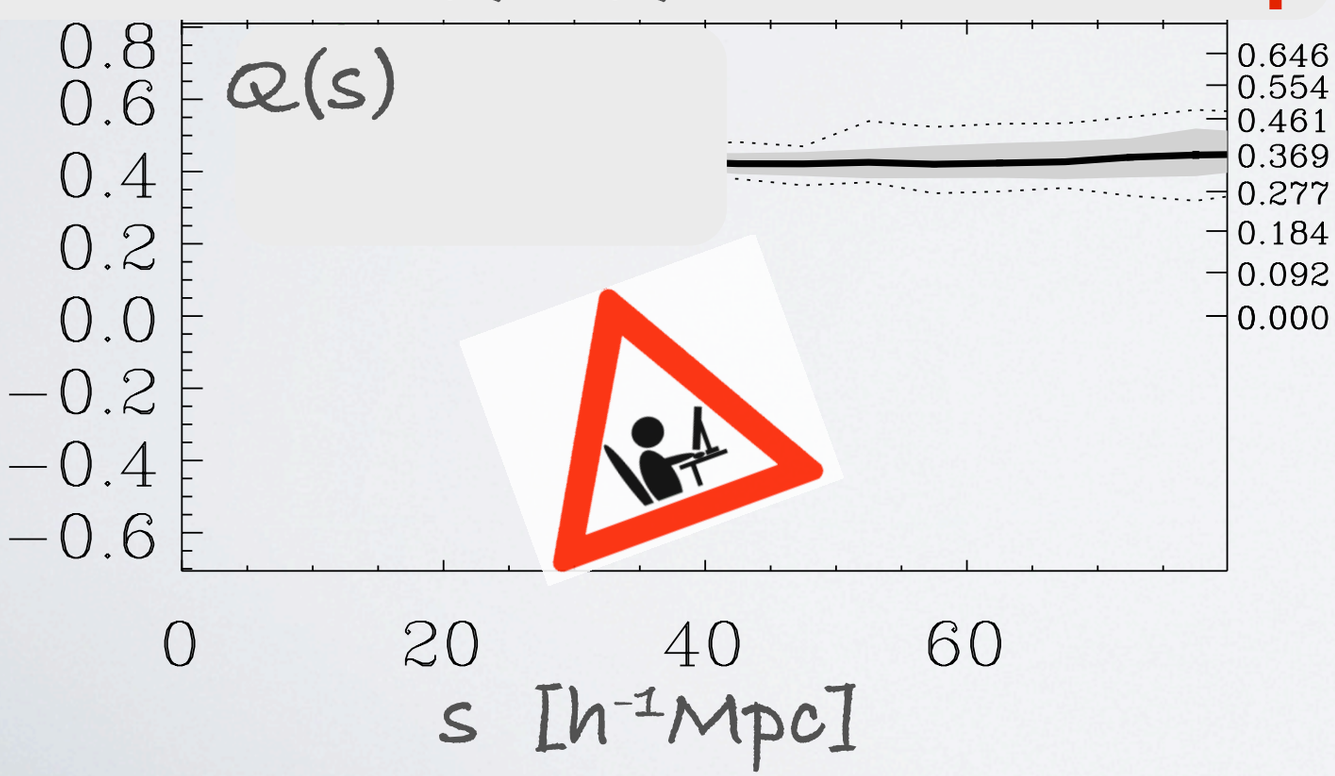

Eyal Kazin

Cosmology through the Large-Scale Structure of the Universe

Eyal Kazin

New York University

CCPP
CENTER FOR COSMOLOGY AND PARTICLE PHYSICS

illustration by Sam Moorfield

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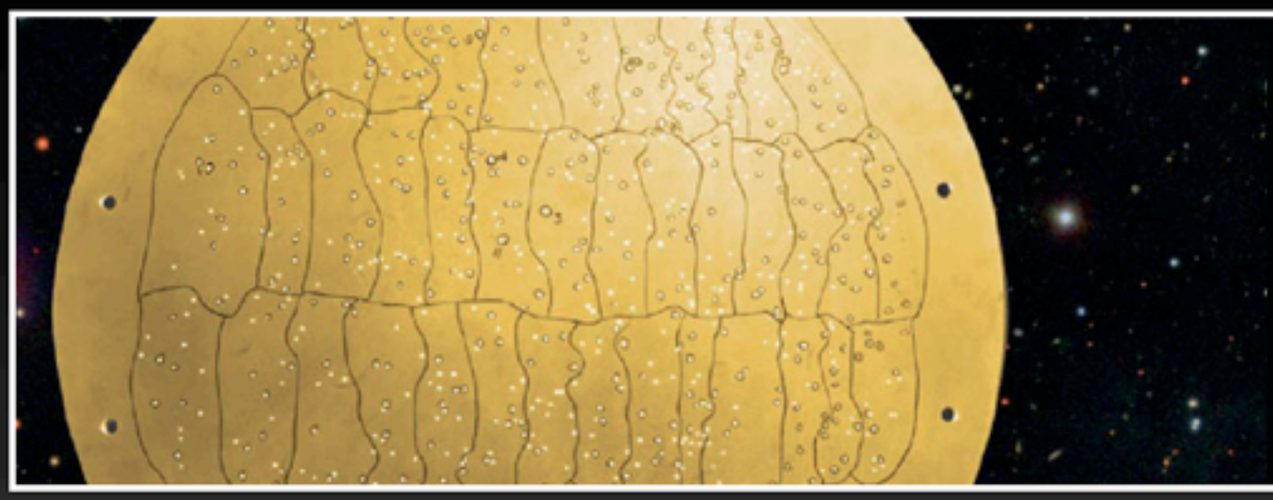

SDSS-III

Massive Spectroscopic Surveys of the Distant Universe, the Milky Way Galaxy and Extrasolar Planetary Systems

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SDSS-III BOSS SEGUE-2 APOGEE MARVELS

SDSS-III

Building on the legacy of the Sloan Digital Sky Survey (SDSS) and SDSS-II, the SDSS-III Collaboration is carrying out a program of four surveys to map the structure and dynamics of the Milky Way, to find and characterize extrasolar planetary systems, and to understand dark energy and the nature of the universe.

Between 2008 and 2014, SDSS-III's four surveys are using Apache Point Observatory's 2.5-meter telescope. SDSS-III will continue the SDSS tradition of public data releases, with the first release scheduled for January 2011. The survey will also continue its commitment to making its data available and useful to students, teachers, and citizen scientists.

The SDSS-III Collaboration includes many institutions from around the globe. Inquiries from interested parties to join the collaboration are welcome. For a detailed description of SDSS-III, see the Project Description, available as a PDF document.

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