Physics of the Large Scale Structure

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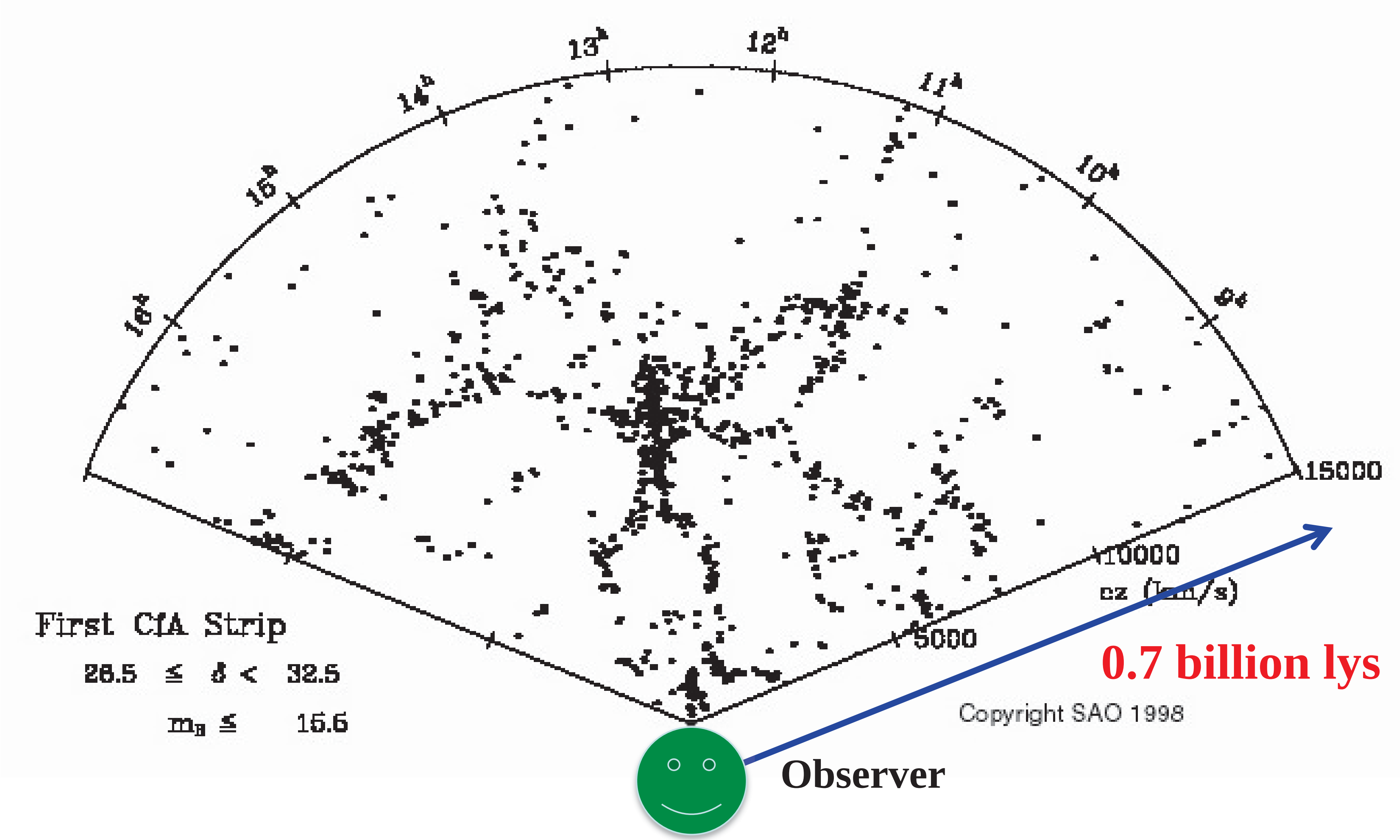
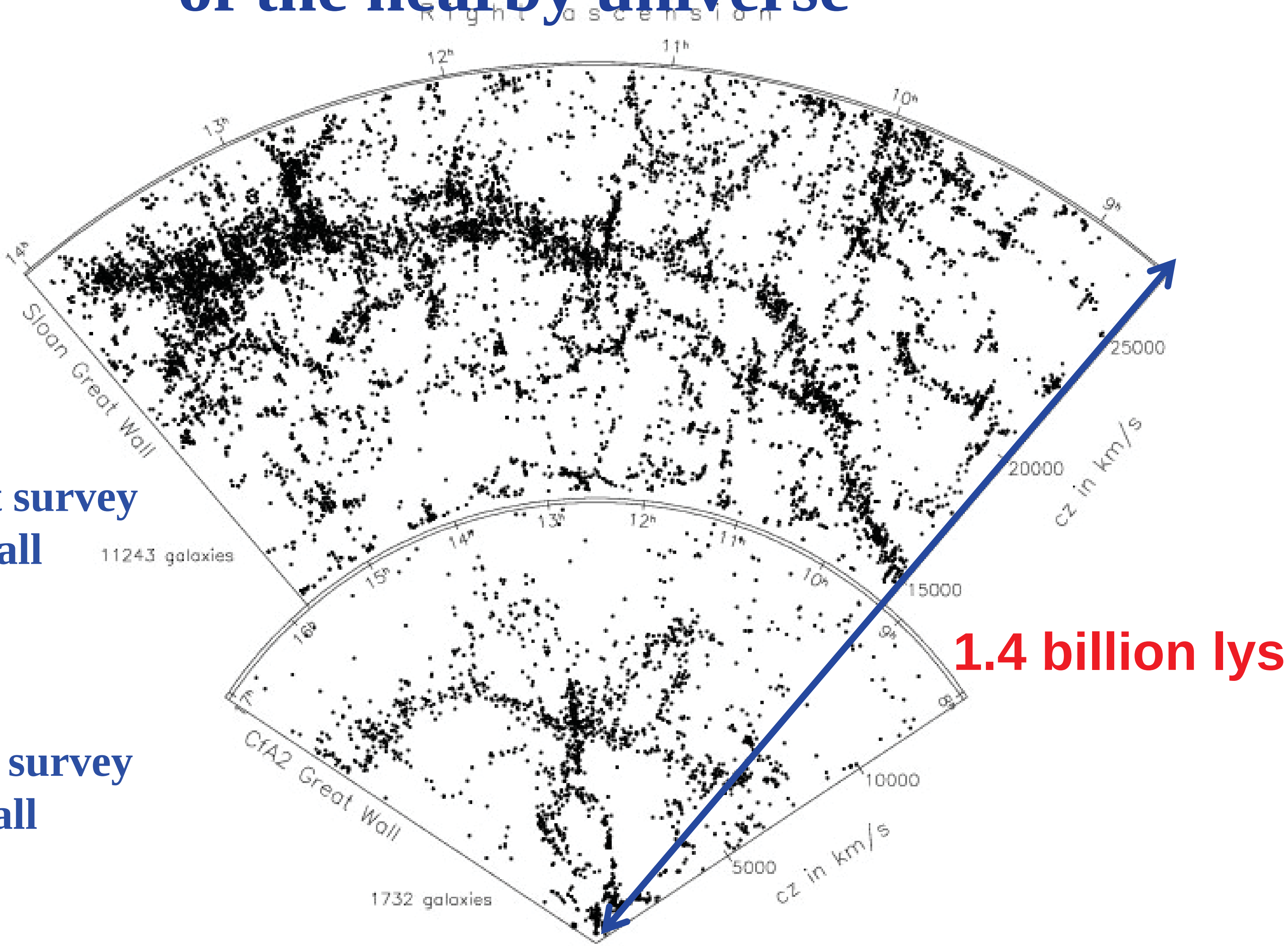
The observed galaxy distribution of the nearby universe



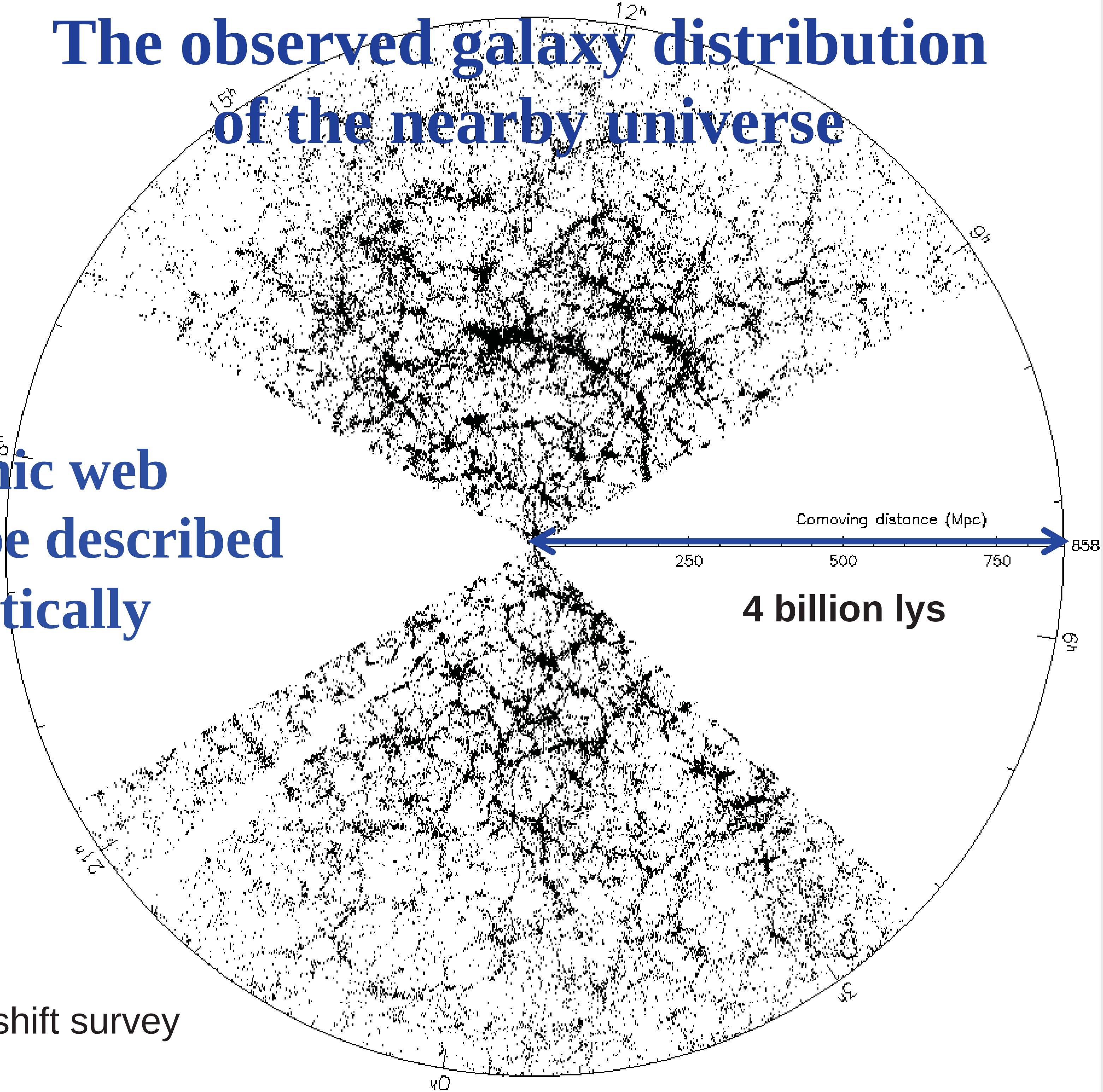
The observed galaxy distribution of the nearby universe

SDSS redshift survey
Sloan great wall

CfA2 redshift survey
CfA2 great wall



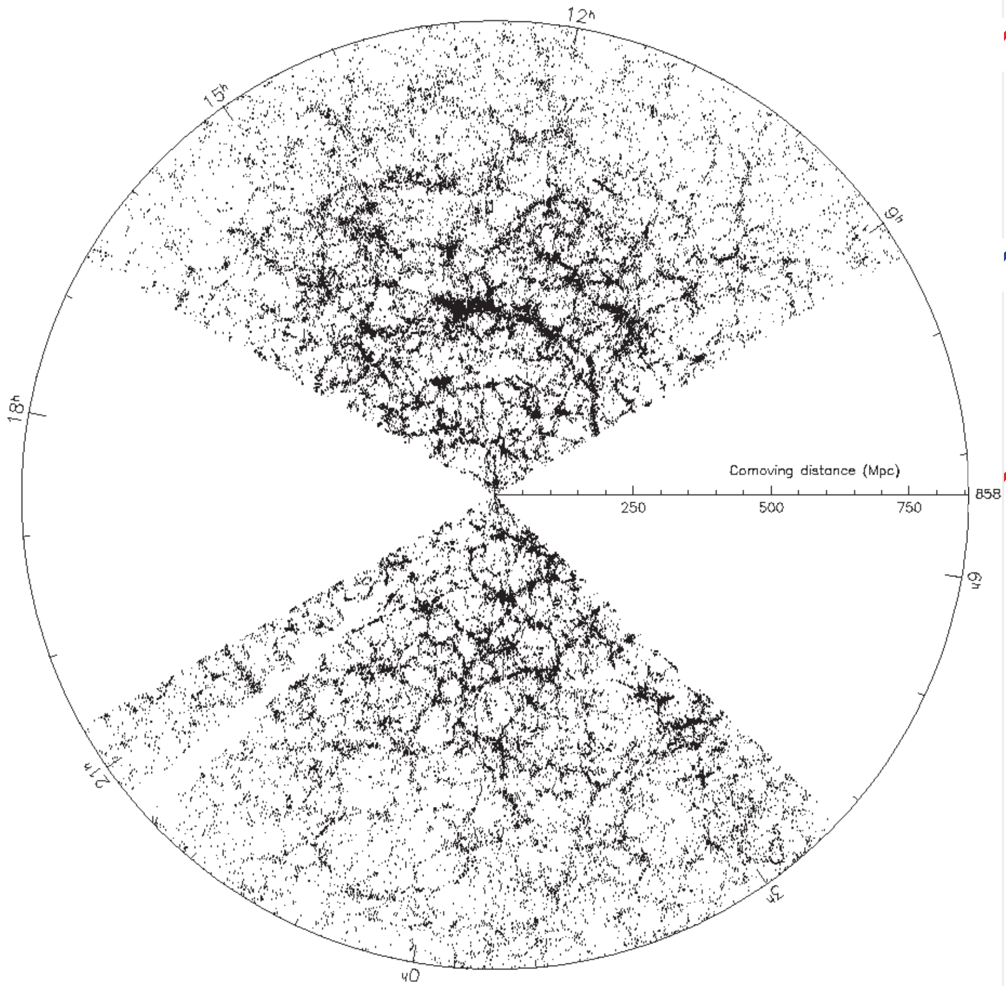
The observed galaxy distribution of the nearby universe



Cosmic web can be described statistically

SDSS redshift survey

What is the large scale structure?



Large scale structure

- **Intrinsic inhomogeneities**
  - ✓ Not illusion of observation
- **beyond randomness**
  - ✓ Not fluke of randomness
- **At >~ Mpc scale**
  - ✓ Not internal structure of galaxies
  - ✓ Not distribution at specific region (since we do not know the initial condition)
  - ✓ Ensemble average –> volume average

The large scale structure of the universe

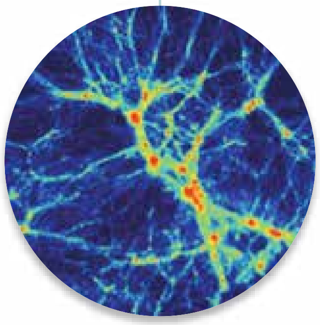
Fundamental physics

Precision modeling

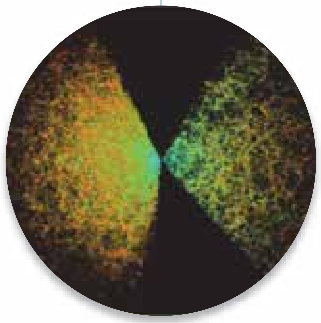
Precision measurement

LSS

Galaxy clustering, weak lensing, clusters, void, SZ, ISW, peculiar velocities, etc.



Dark matter



Baryons

The large scale structure of the universe

Part 1:

- **Deciphering the large scale structure (LSS)**
  - **With statistics and physics**

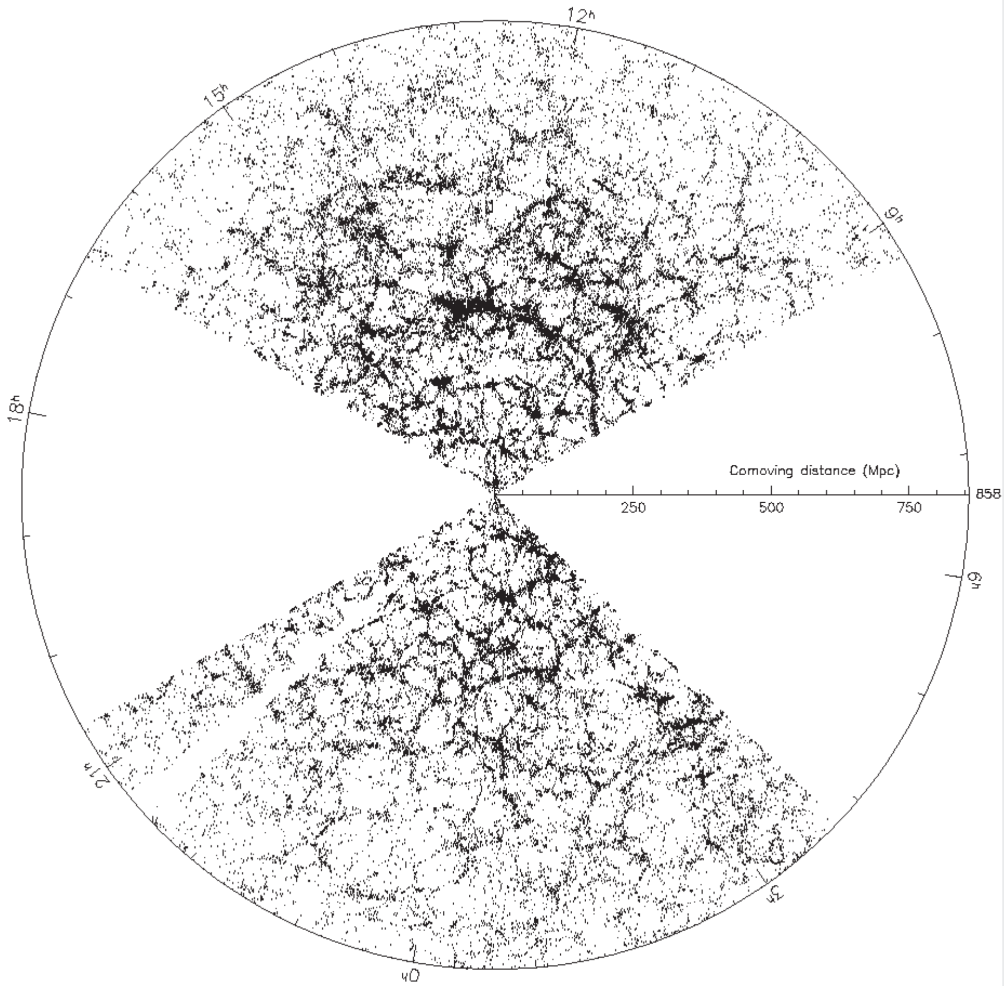
Part 2:

- **Tracers of LSS**
  - **Broadband power spectrum, BAO, redshift distortion, weak lensing, SZ effect, etc.**

Part 3

- **Synergies of LSS tracers**
  - **Probe DM, DE, MG, neutrino, etc.**
  - **Reduce statistical errors**
  - **Control systematic errors**

How to describe the large scale structure?

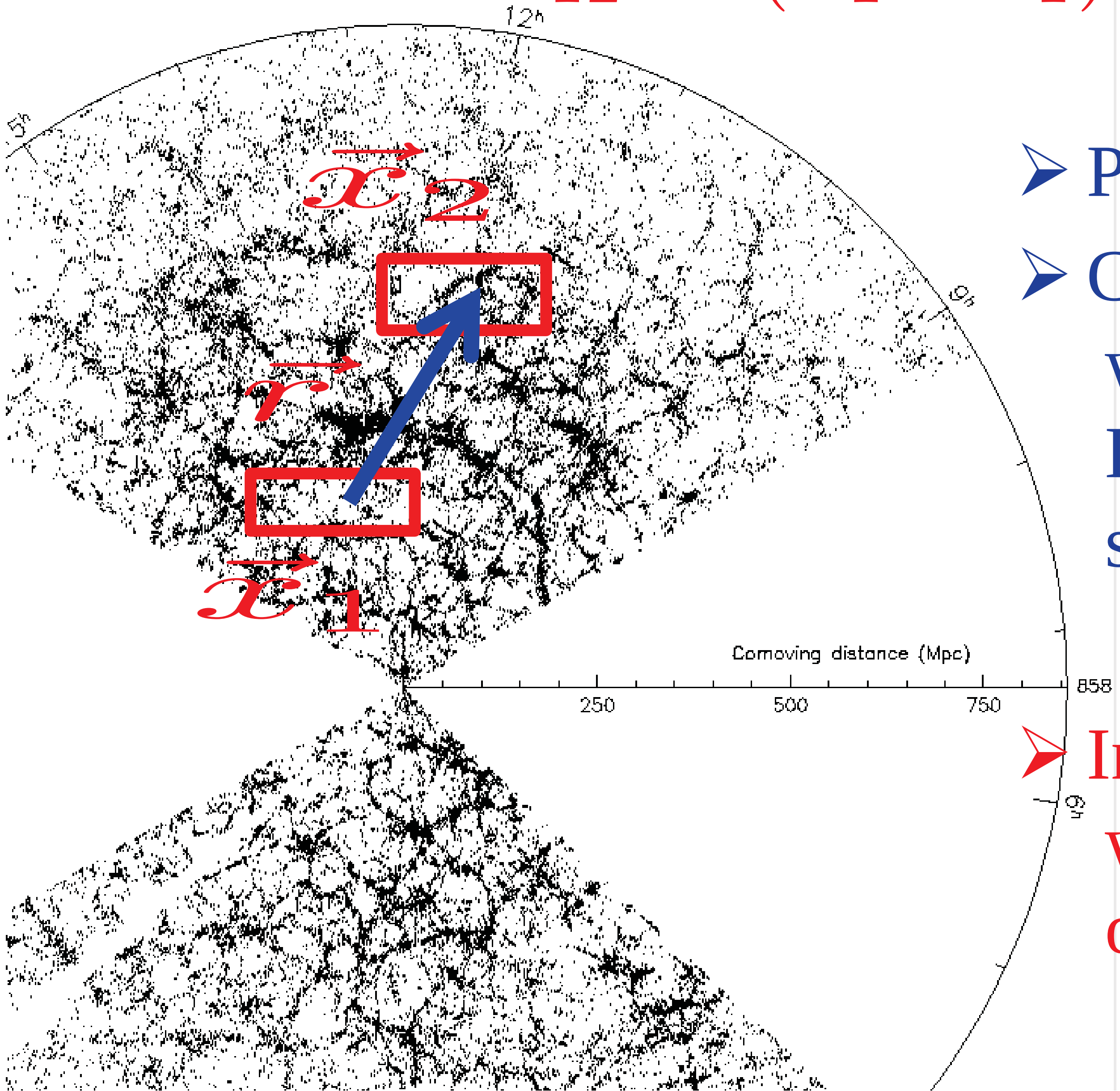


With statistics!

- N-point correlation functions and their Fourier transforms
  - 2-point correlation– power spectrum
- N-point joint PDF
- Peak analysis
- Topological descriptions: Minkowski functionals (and genus in particular), etc.

Two−point correlation function

$$P_{12} = (\bar{n}_1 d^3 x_1)(\bar{n}_2 d^3 x_2)\left[1 + \xi(\mathbf{r})\right]$$



- P_{12}: pairs of galaxies
- Correlation function.: what beyond average. Depends on the pair separation vector **r**.

- In real measurement, we have to eliminate observational effect

Correlation function: correlated feild

$$P_{12} = (\bar{n}_1 d^3 x_1)(\bar{n}_2 d^3 x_2)\left[1 + \xi(\mathbf{r})\right]$$

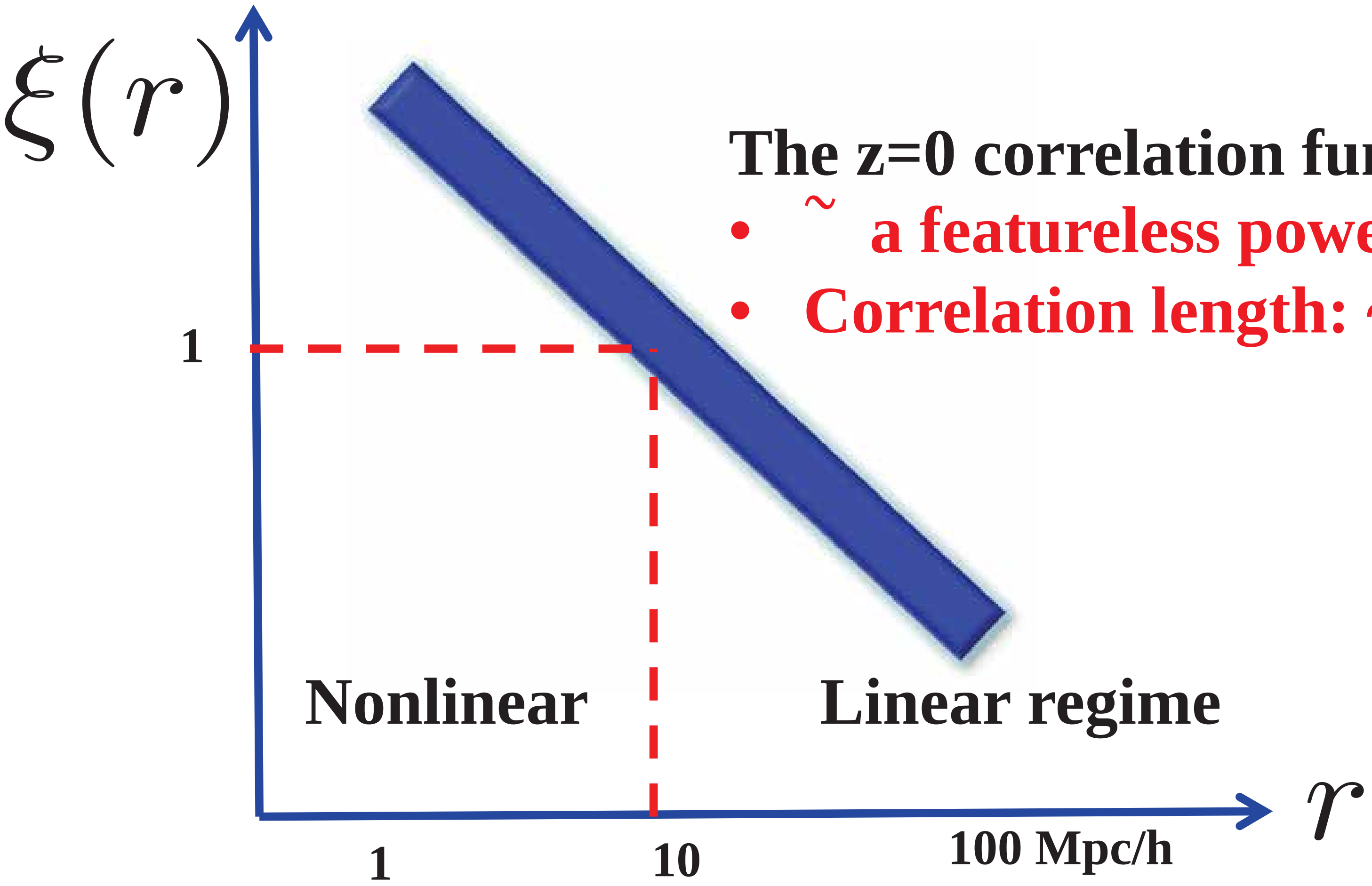
The overdensity field $$\delta(\vec{x}) \equiv \frac{n(\vec{x}) - \langle n \rangle}{\langle n \rangle}$$

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

The observed galaxy correlation function

Smaller scale measurement: requires high number denisty

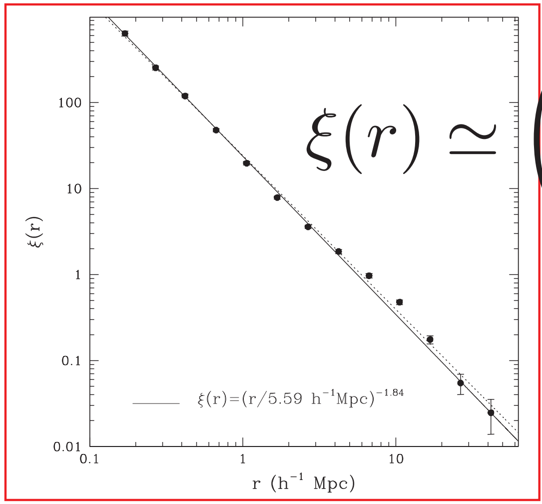
Larger scale measurement: requires large volume



The z=0 correlation function:

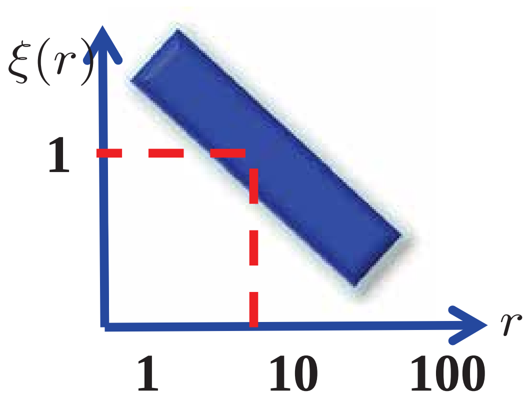
- **~ a featureless power-law**
- **Correlation length: ~5 Mpc/h**

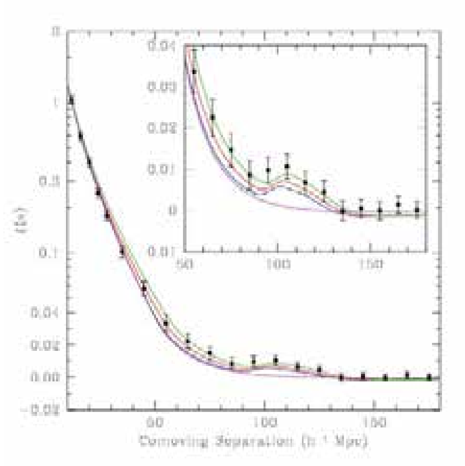
Features in the galaxy correlation function



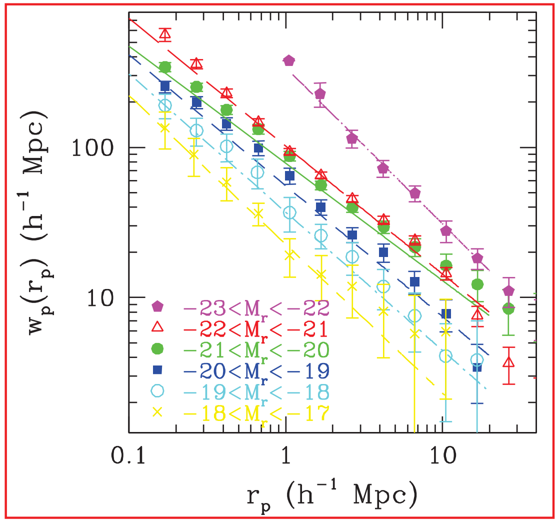
$$\xi(r) \simeq \left(\frac{r}{r_0}\right)^{\sim -1.8}$$

e. g. Zehavi+, 2004

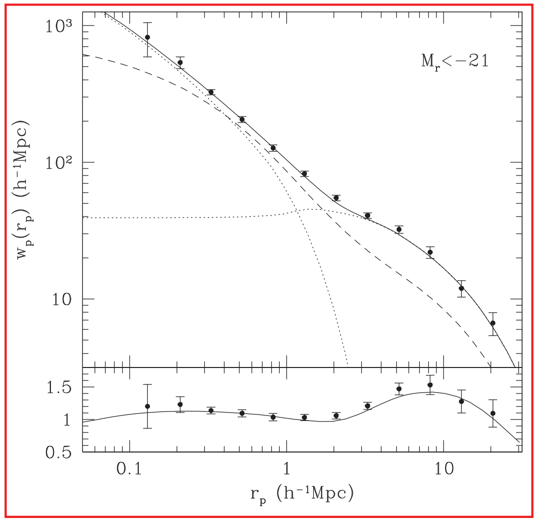




Bump at 100 Mpc/h
e. g. Eisenstein+, 2005

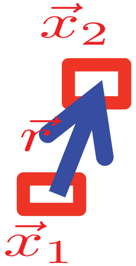


Type dependence.
e. g. Zehavi+, 2004



Deviation from power-law
e. g. Zehavi+, 2003

Closer look at the correlation function



$$P_{12} = (\bar{n}_1 d^3 x_1)(\bar{n}_2 d^3 x_2)\,[1 + \xi(\mathbf{r})]$$

$$P_{12}(\vec{x}_1, \vec{x}_2) = (\bar{n}_1 d^3 x_1)(\bar{n} d^3 x_2)[1 + \xi(\vec{r} \equiv \vec{x}_2 - \vec{\mathbf{x}}_1, \vec{x}_1)]$$

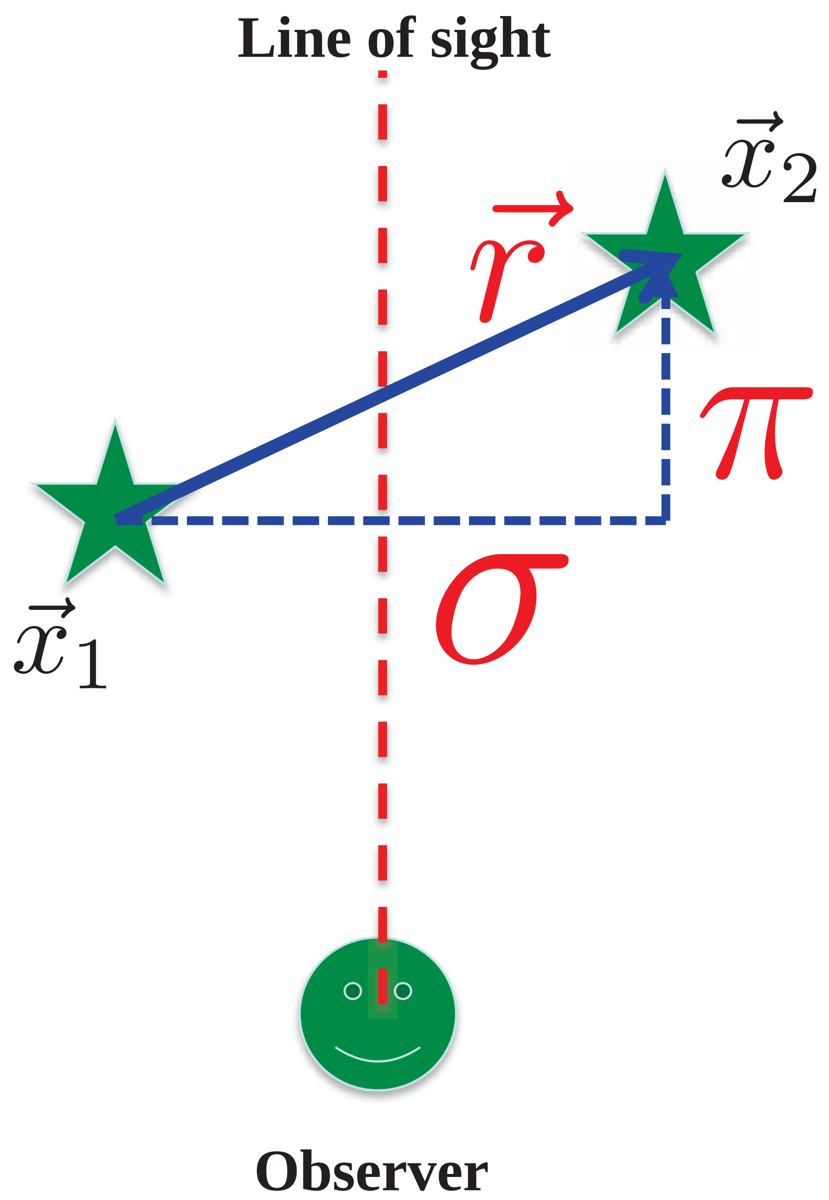
Our universe should be homogeneous

$$\xi(\vec{r} \equiv \vec{x}_2 - \vec{\mathbf{x}}_1, \vec{x}_1) \rightarrow \xi(\vec{r} \equiv \vec{x}_2 - \vec{\mathbf{x}}_1)$$

Our universe should be isotropic

$$\xi(\vec{r} \equiv \vec{x}_2 - \vec{x}_1) \rightarrow \xi(r)$$

More features: anisotropies



$$\xi(\vec{r}) = \xi(\sigma, \pi)$$

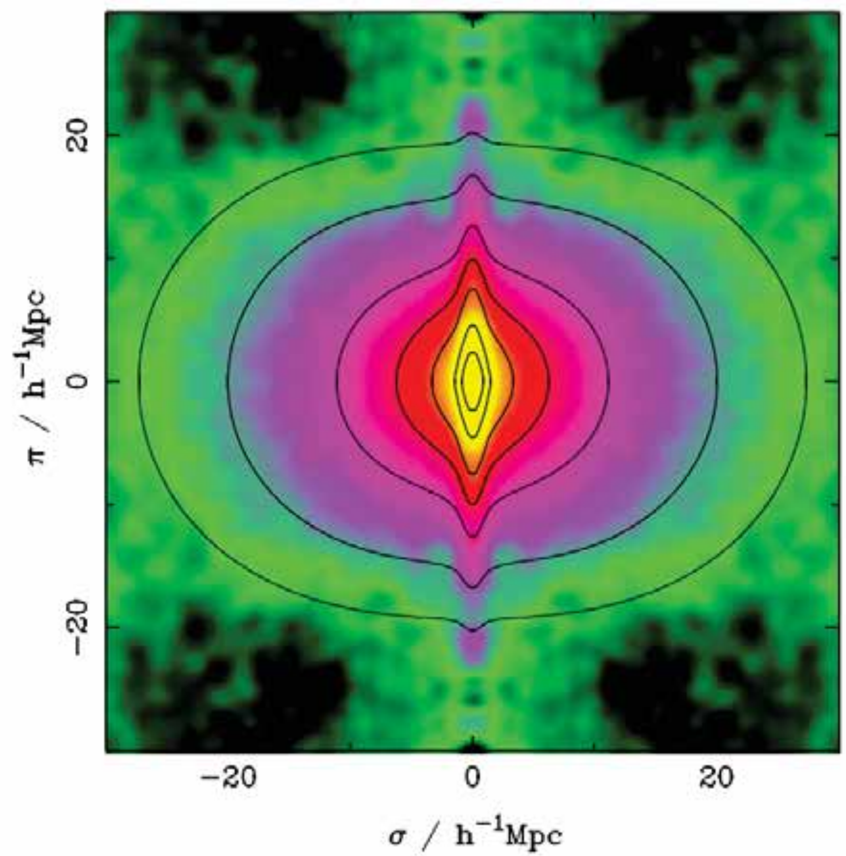
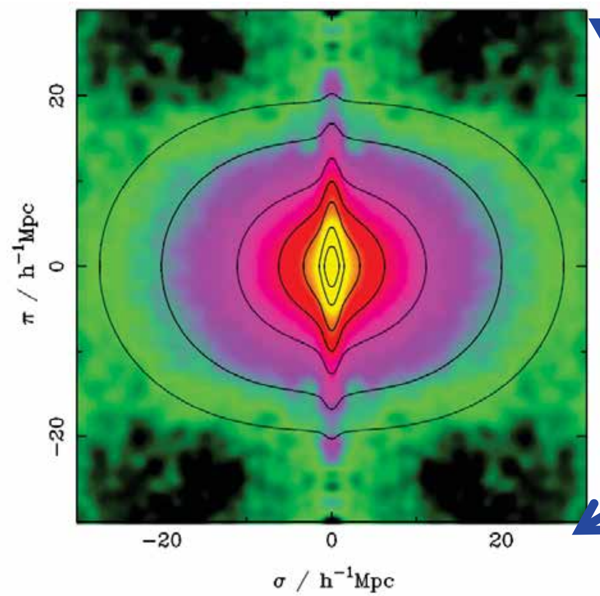


Figure 2 The redshift-space correlation function for the 2dFGRS, $\xi(\sigma, \pi)$, plotted as a function of transverse (σ) and radial (π) pair separation. The function was estimated by counting pairs in boxes of side $0.2\,h^{-1}$ Mpc (assuming an $\Omega = 1$ geometry), and then smoothing with a Gaussian of rms width $0.5\,h^{-1}$ Mpc.

e.g. Peacock+, 2001,
with 141,000 2dF galaxies

More features: anisotropies

$$\xi(\vec{r}) = \xi(\sigma, \pi)$$



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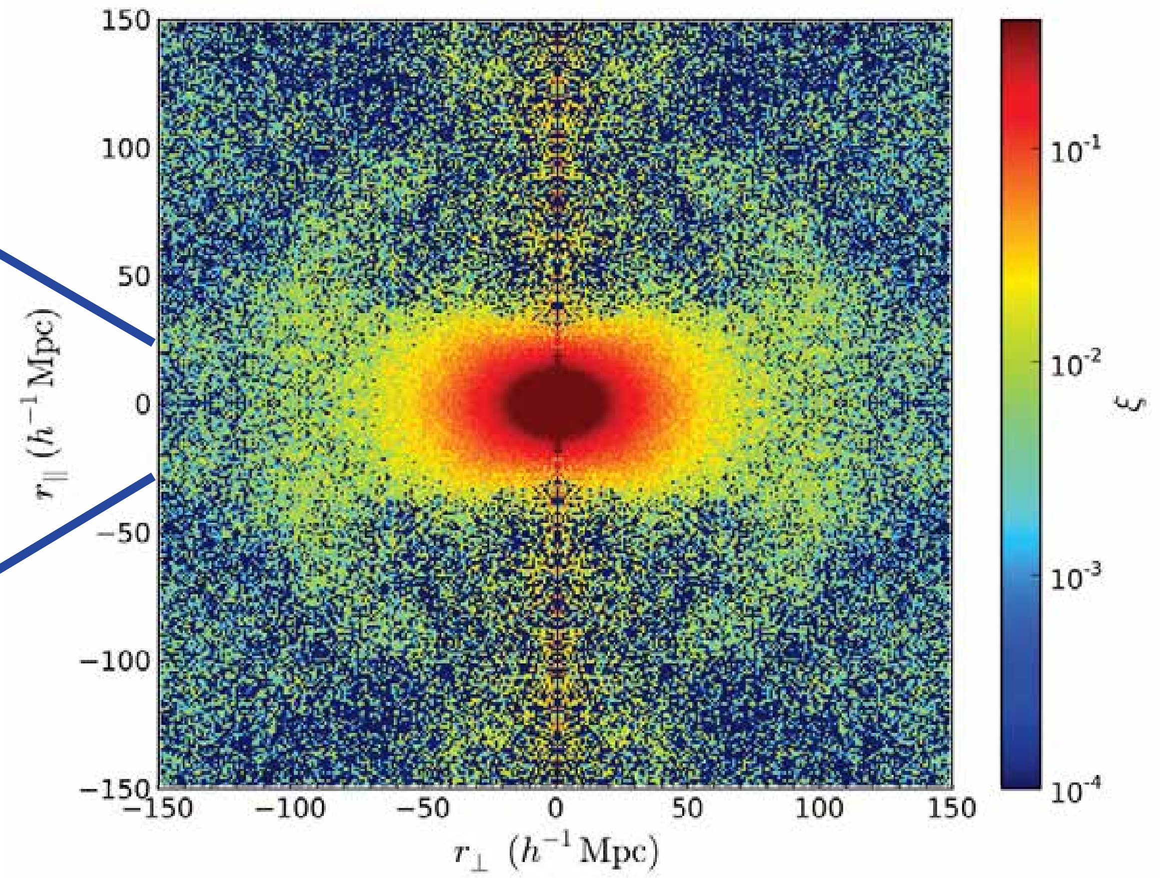
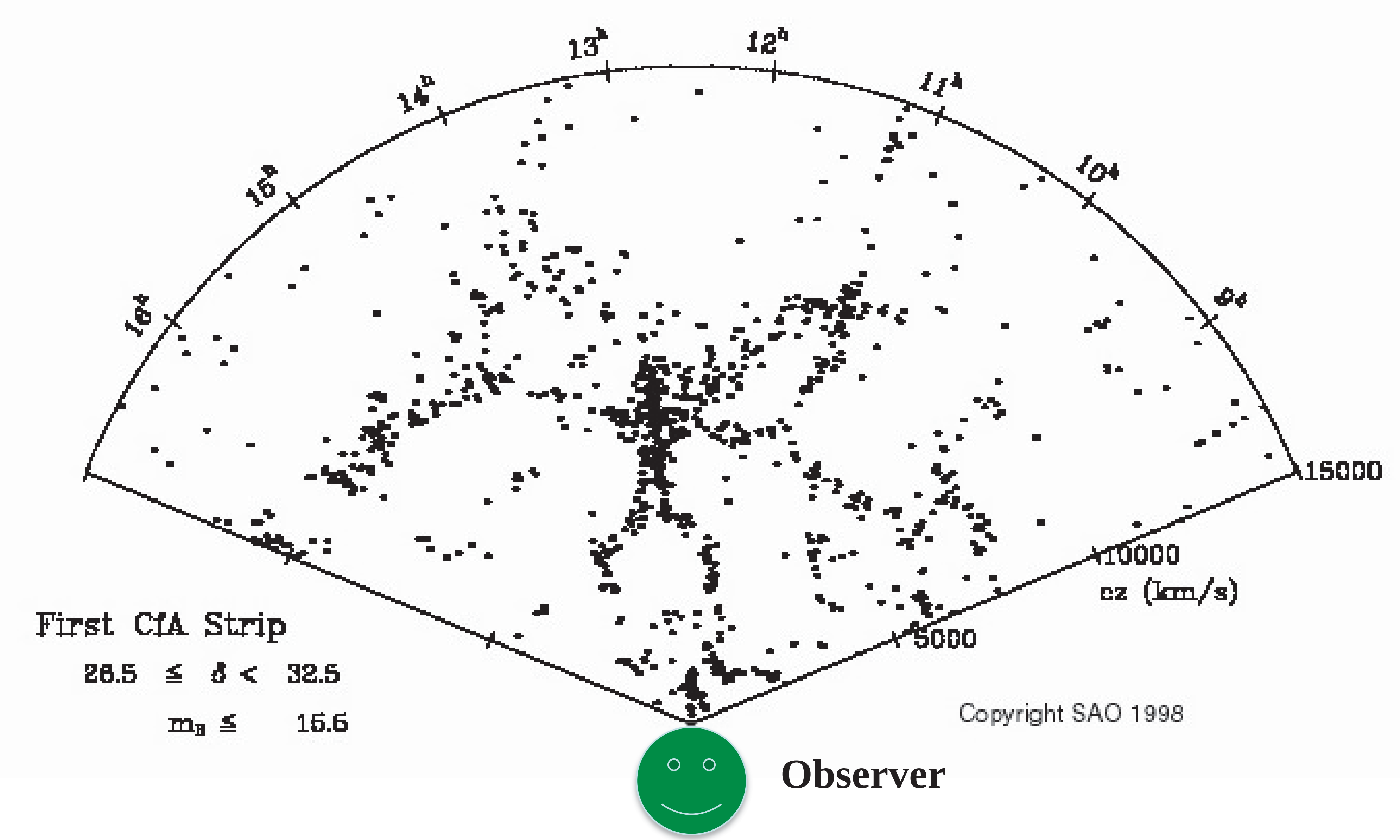


e.g. Peacock+, 2001,
with 141,000 2dF galaxies

2010+: larger scale coverage, higher accuracy
e.g. Li+, 2016, with 0.5M BOSS galaxies

Some anisotropies are so prominent that we can simply see by eyes in 1980s!



Correlation function –> Power spectrum

$$\delta(\vec{x}) \equiv \frac{n(\vec{x}) - \langle n \rangle}{\langle n \rangle}$$

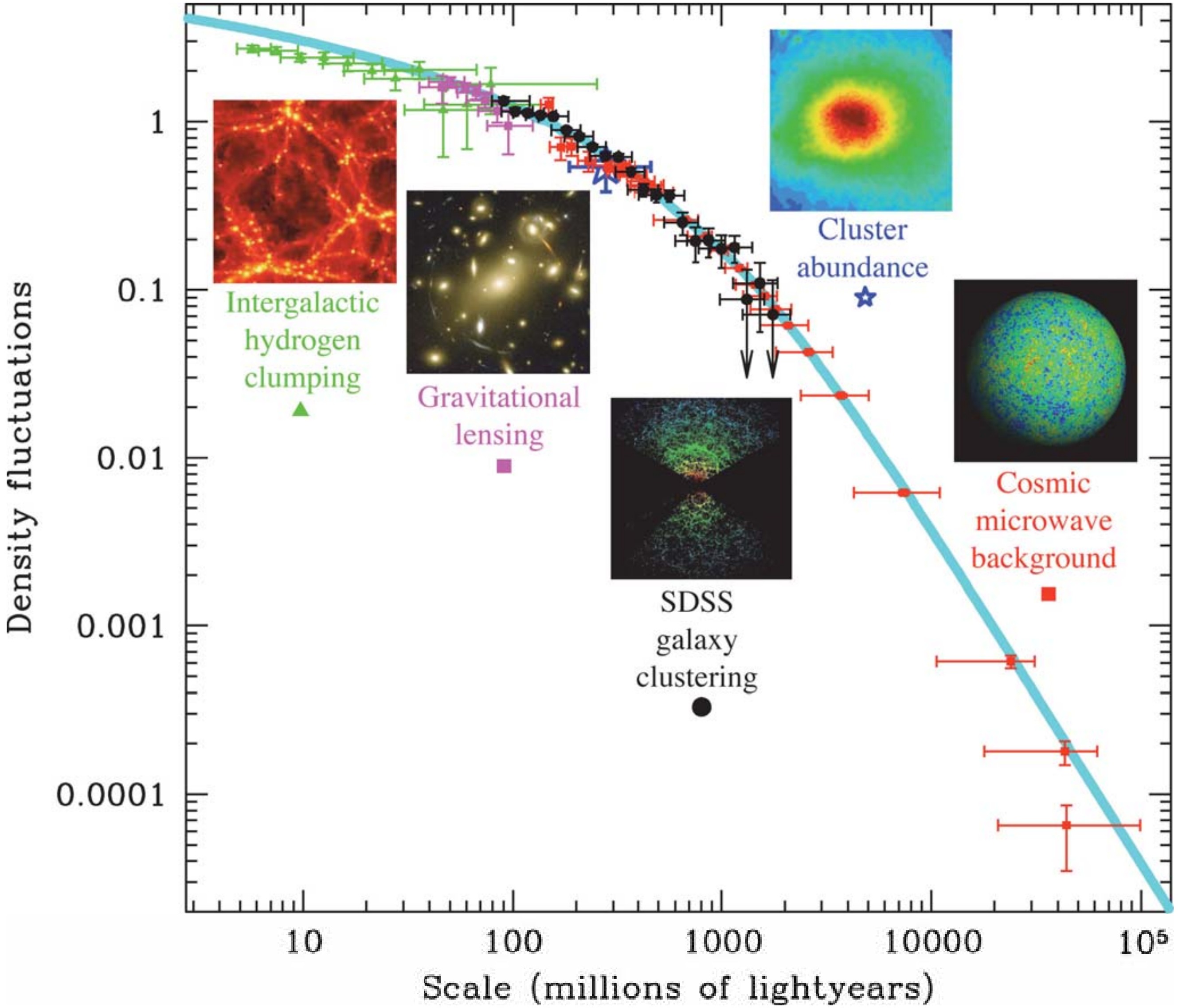
$$\delta(\vec{k}) \equiv \int d^3x \delta(\vec{x}) e^{i\vec{k}\cdot\vec{x}}$$

homogeneity

$$\langle \delta(\vec{k}) \delta(\vec{k}') \rangle = (2\pi)^3 \delta_{3D}(\vec{k} + \vec{k}') P(\vec{k})$$

$$P(\vec{k}) = \int d^3r \xi(\vec{r}) e^{i\vec{k}\cdot\vec{r}}$$

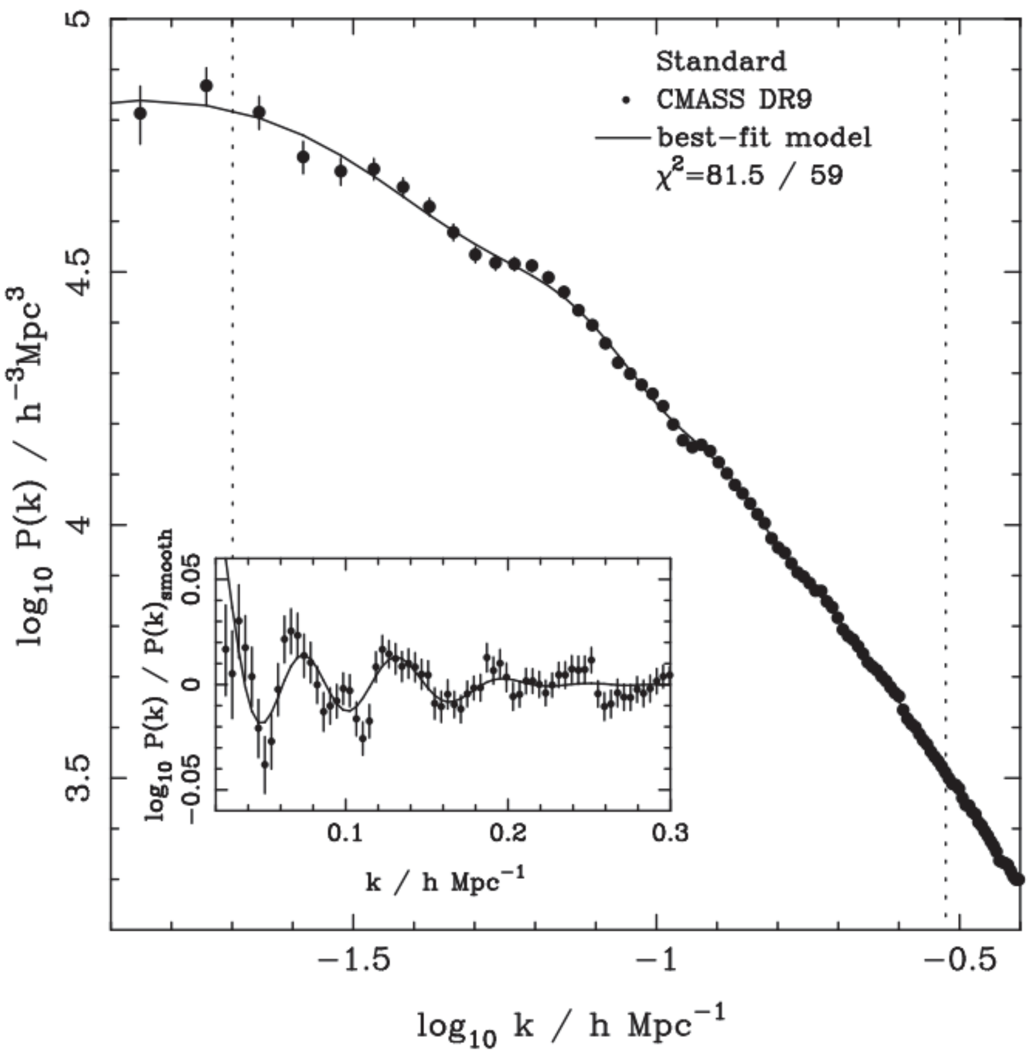
Rich features in the power spectrum



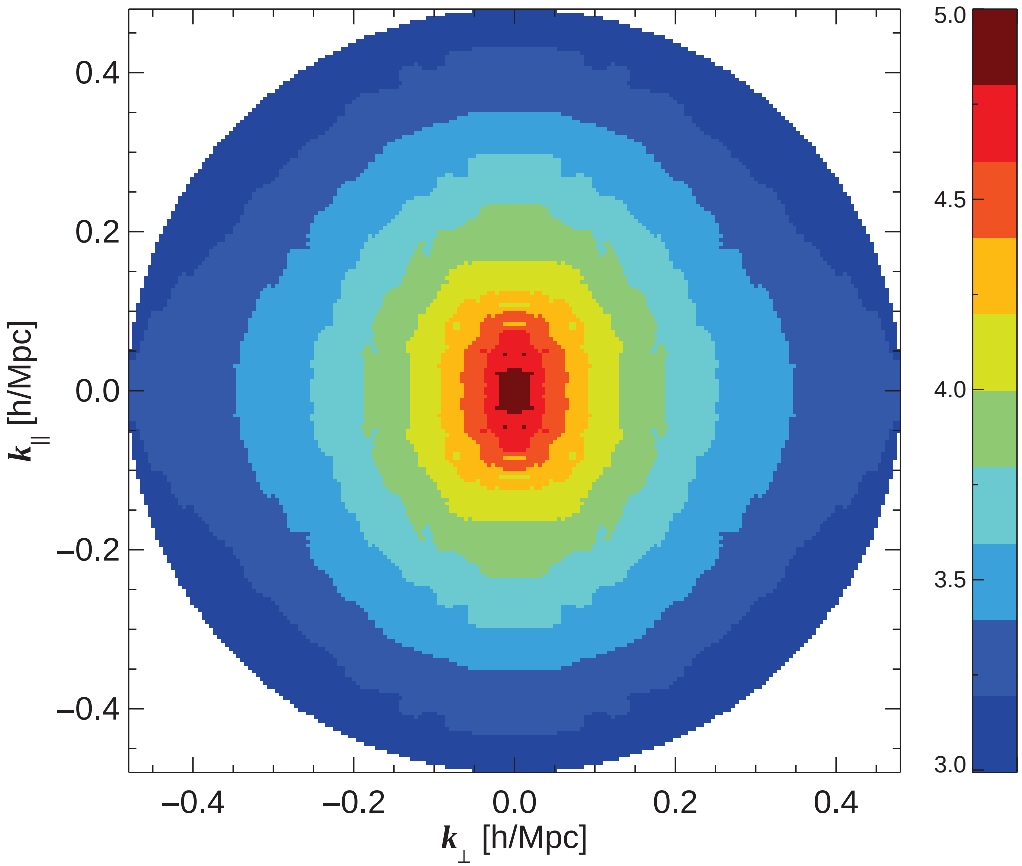
Tegmark

Rich features in the power spectrum

$$P(k) \equiv P(|\vec{k}|)$$



$$P(\vec{k})$$



DR11 e.g. Li+ 2016

Even more features:
“abnormal” correlation at horizon scales

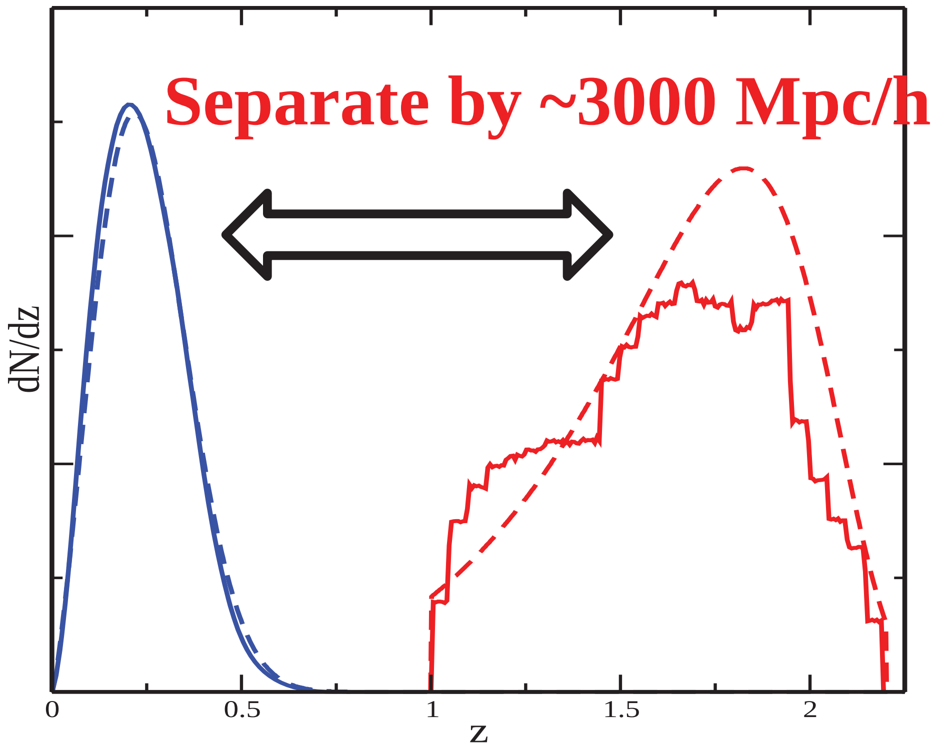
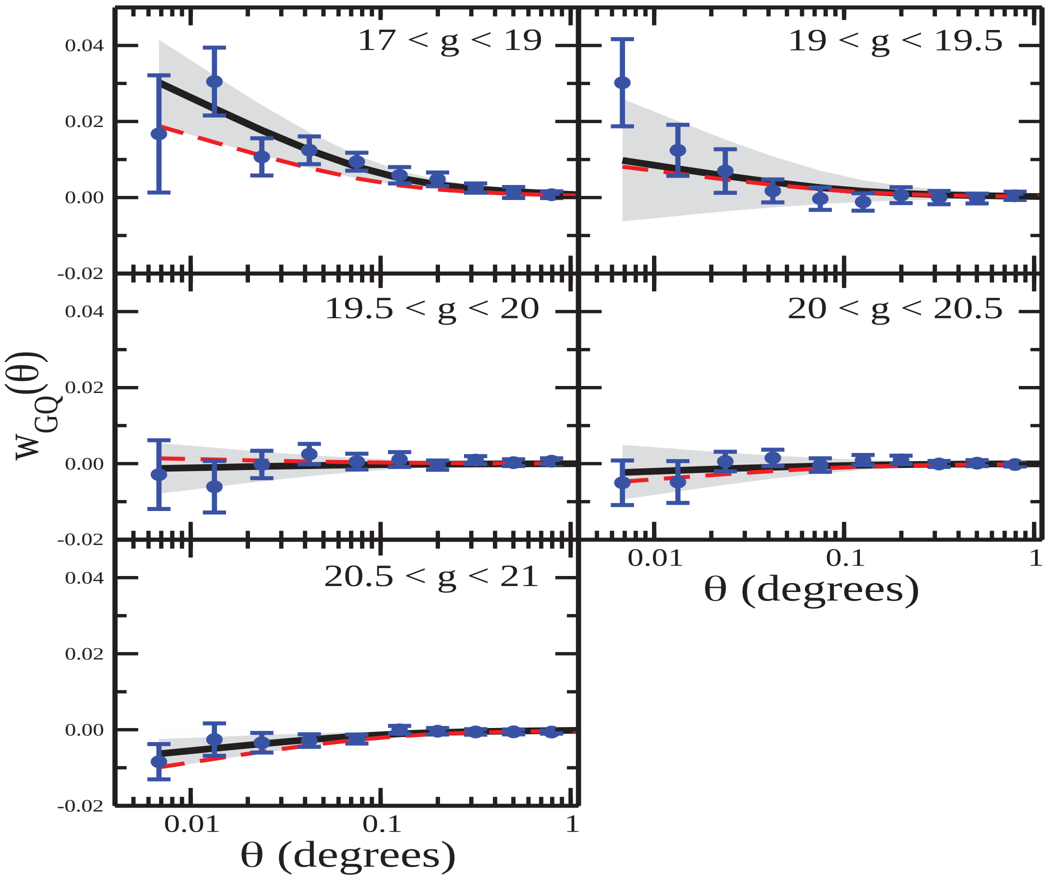


FIG. 1.— Galaxy redshift distribution from applying our $17 < r < 21$ magnitude limit to the CNOC2 luminosity function and quasar redshift distribution inferred from quasar photometric redshifts (solid lines). The fitted redshift distributions from Equation 8 are shown with dashed lines. In all cases, the amplitude scaling is arbitrary.



Non-vanishing correlation! First detected by Scranton+, 2005 at ~10sigma and then by other data

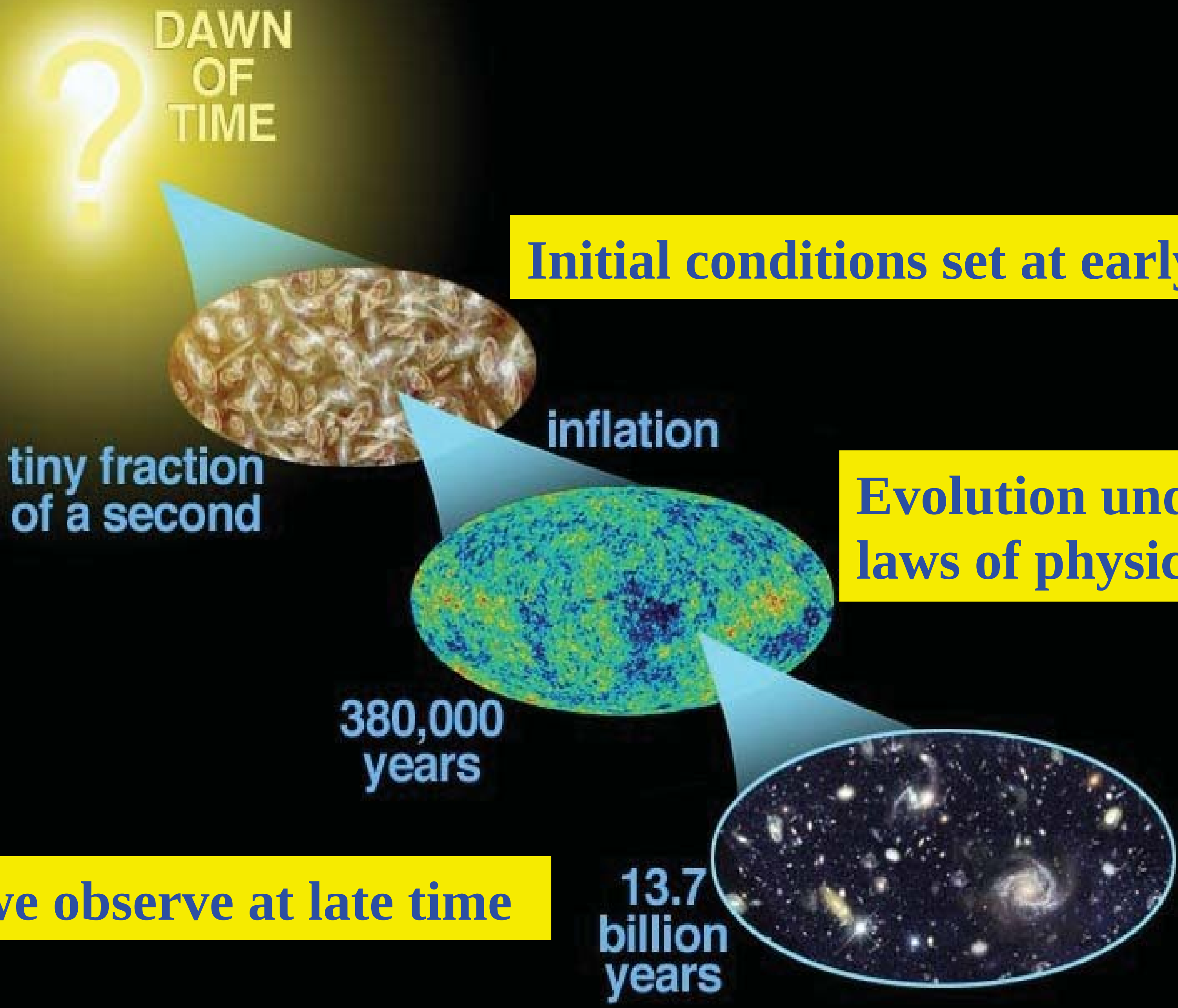
Even more features:
"abnormal" correlation at horizon scales

Galaxies at z~1 CMB at z~1100

Separate by ~6000 Mpc/h

Non-vanishing correlation detected at ~4sigma,
by NVSS/SDSS/WISE +WMAP/Planck

Understanding LSS with physics



Initial conditions set at early time

Evolution under laws of physics

LSS we observe at late time

Understanding LSS with physics

Initial fluctuations

$$P(k) \propto k^{\simeq 0.96}$$

Linear perturbation

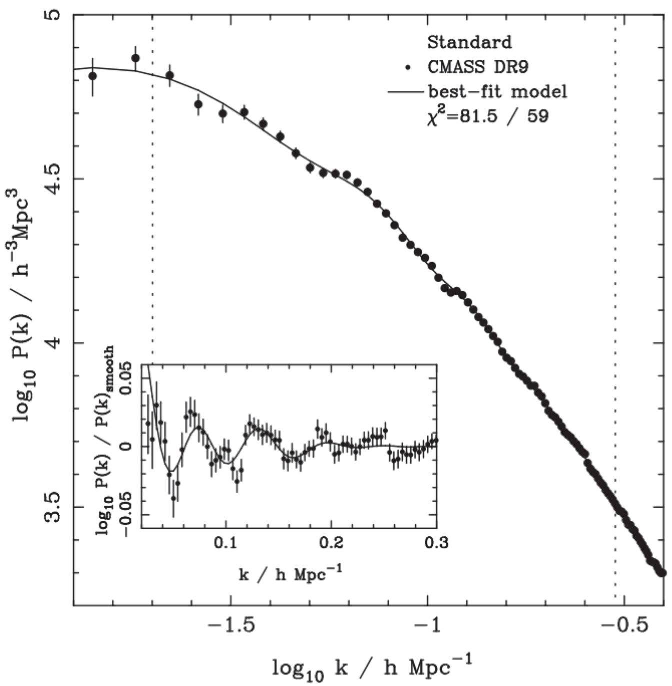
Boltzmann equation

Fluctuations at $z \sim 100$

$$P(k) \propto k^{0.96} \text{ at } k \to 0$$

$$P(k) \propto k^{0.96-4} \text{ at } k \to \infty$$

- **High order perturbation theory**
- **Halo model, Effective field theory of LSS**



- **N-body simulations**
- **Hydrodynamic simulations**
- **Semi-analytical models**
- **Halo occupation distribution, Conditional luminosity function**

Movies of simulation:

The Millennium

The Elucid project

Complexities to understand LSS

- **Task: evolve the universe from z~100 to z~0**
- **Complexities**
  - **Dark matter, baryons, photons, neutrinos, dark energy**
  - **Gravity: nonlinear evolution at $<\sim 10$ Mpc/h under gravity, GR effect at $>\sim 10^3$ Mpc/h**
  - **Non-gravitational forces: gastrophysics, galaxy formation and feedback**
  - **Mapping underlying matter/energy into observable signals (galaxy distribution, galaxies shapes, secondary CMB, etc.)**
  - **Eliminating observational contaminations in the desired cosmological signals**

An example of simplified treatment

- Set neutrinos=0, photons=0.
- Neglect gastrophysics of baryons. Then only gravity. Baryons behave the same as DM
- Assume smooth dark energy. Then DE only affects the expansion. Assume DE=Lambda
- Assume flatness

The universe to evolve

- Dark matter (=DM+baryons), Lambda
- Flat
- gravity

Two steps

- Step 1: evolution of the dark matter field
  - Large scales: linear perturbation (GR effect can be included too)
  - Intermediate scales: spherical collapse
  - Small scales (and actually all scales): N-body simulations

- Step 2: identify virialized regions (dark matter halos) and put galaxies in
  - Halo mass function, halo bias/spatial clustering
  - Halo occupation distribution/Conditional luminosity function (the number of galaxies as a function of halo mass)

Step 1: linear evolution

$$G_{\mu\nu}(g_{\mu\nu}) = T_{\mu\nu}$$ **Nonlinear differential equation**

$$g_{\mu\nu} = g_{\mu\nu}^{FRW} + h_{\mu\nu}$$ **Perturb around the background**

$$G_{\mu\nu}(g_{\mu\nu}^{FRW}) + \frac{\partial G_{\mu\nu}}{\partial g_{\alpha\beta}} h_{\alpha\beta} = T_{\mu\nu} - \frac{1}{2}\frac{\partial^2 G_{\mu\nu}}{\partial g_{\alpha\beta}\partial g_{\chi\delta}} h_{\alpha\beta} h_{\chi\delta} + \cdots$$

Neglect high order perturbation terms

$$ds^2 = -(1+2\psi)dt^2 + a^2(1+2\phi)\sum_i dx^{i,2}$$

$$T_{\mu\nu} = \rho U_\mu U_\nu \quad (P=0)$$

$$\rho = \bar{\rho}(1+\delta)$$

Step 1: linear evolution: Lambda: sub-horizon

$$H^2(a) = H_0^2(\Omega_m a^{-3} + \Omega_\Lambda)$$

$$\frac{d^2\delta}{da^2} + \frac{d\delta}{da}\left(\frac{dH/da}{H} + \frac{3}{a}\right) - \frac{3}{2}\frac{H_0^2\Omega_m}{H^2 a^3}\frac{\delta}{a^2} = 0$$

Linear growth factor

$$\delta(\vec{x}, a) \propto \left[H \int_0^a \frac{da}{H^3 a^3}\right] \delta(\vec{x}, a = 0)$$

Heath 1977

Carroll, Press & Turner (1992)

$$D(a) \simeq \frac{5\Omega_M(a)a}{2}\left[\Omega_M(a)^{4/7} - \Omega_\Lambda(a) + \left(1 + \frac{\Omega_M(a)}{2}\right)\left(1 + \frac{\Omega_\Lambda(a)}{70}\right)\right]^{-1}$$

From sub-horizon to super-horizon

$$(\nabla^2 + 3K)\phi - 3a^2H^2(\phi' a + \phi) = 4\pi G\bar{\rho}_m a^2 \delta_m,$$

GR effect

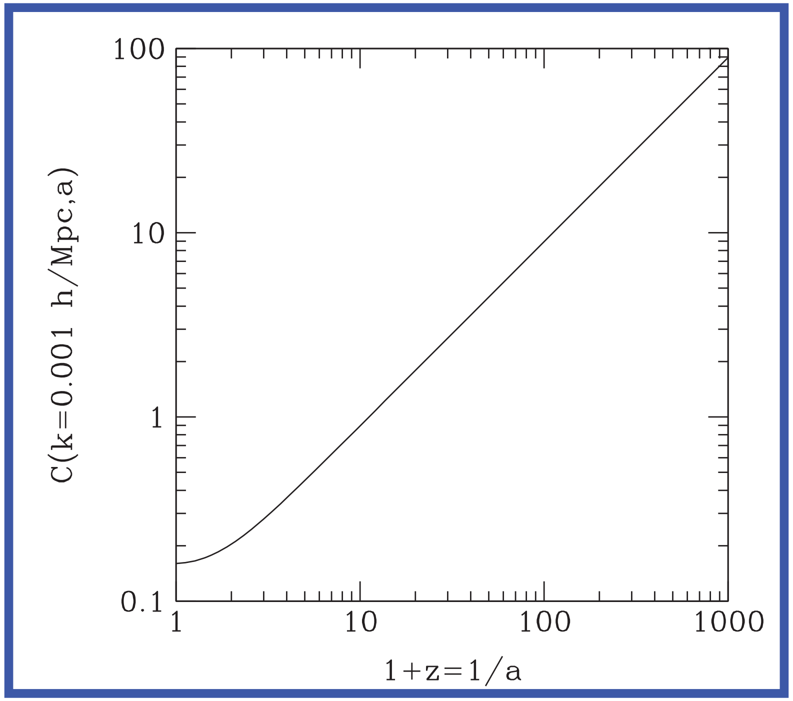
$$aH(\phi' a + \phi) = 4\pi G\bar{\rho}_m a^2 W,$$

$$\delta'_m = \frac{\nabla^2 W}{a^2 H} + 3\phi'.$$

GR effect

$$\tilde{\delta}_m \propto \left[H \int_0^a \frac{da}{H^3 a^3}\right] \times [1 + C(k, a)].$$

$$C(k,a) = \frac{3a^2H^2}{k^2}\left(\frac{H'a}{H} + \frac{1/H^3a^2}{\int_0^a da/H^3a^3}\right)$$
$$= \frac{a^2(H/H_0)^2}{3(k \times 10^3 h^{-1}\ \mathrm{Mpc})^2}\left(\frac{H'a}{H} + \frac{1/H^3a^2}{\int_0^a da/H^3a^3}\right).$$



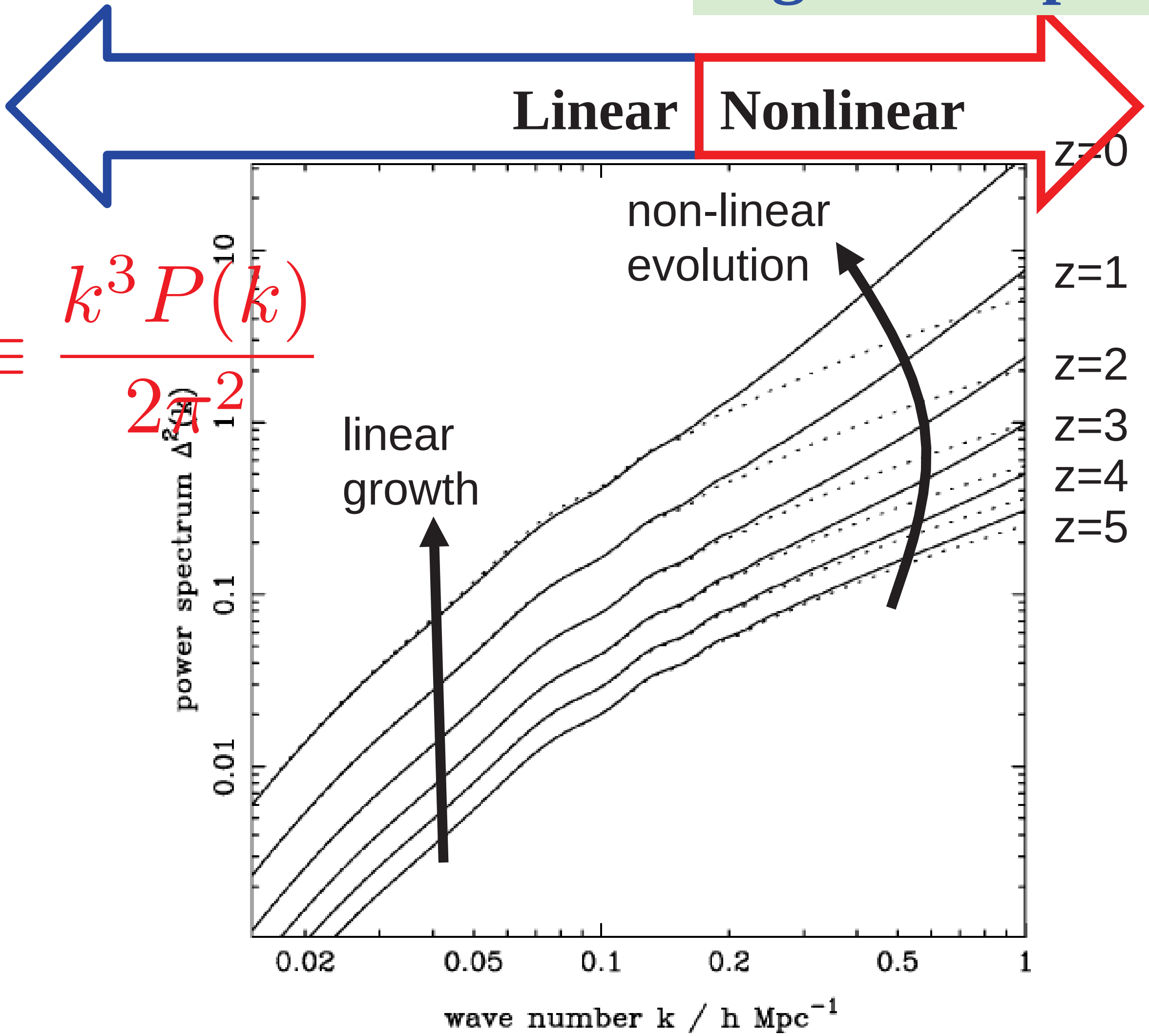
ZPJ 2011

From linear to nonlinear scales

Halo model, halofit, EFT, etc.

high order pt, simulations

$$\Delta^2(k) \equiv \frac{k^3 P(k)}{2\pi^2}$$



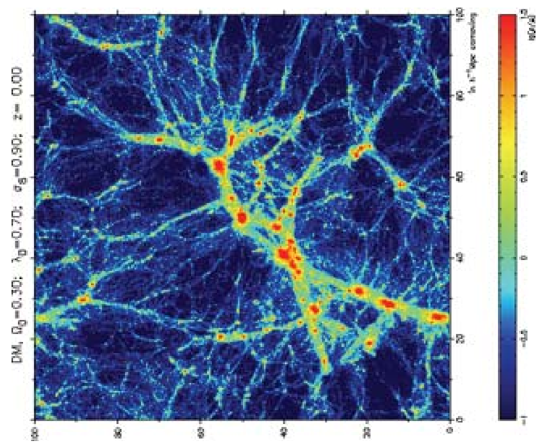
N-body simulations today

~10-10^4 Mpc/h

~$10^{9\text{-}12}$ particles

~$10^{2\text{-}4}$ cpus

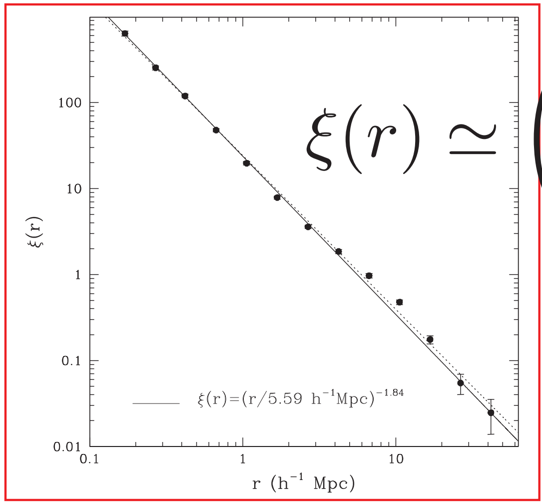
~days-months



Credit: Percival's lectures

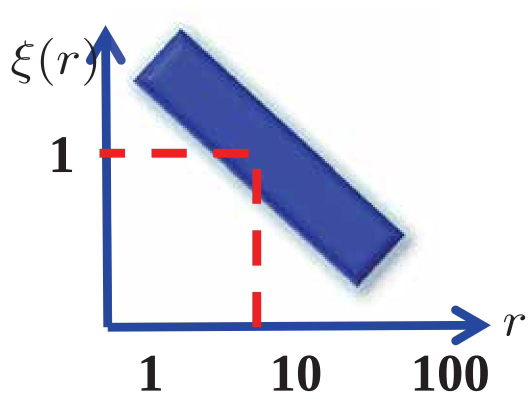
Can it explain the observed galaxy clustering?

Some but not all!

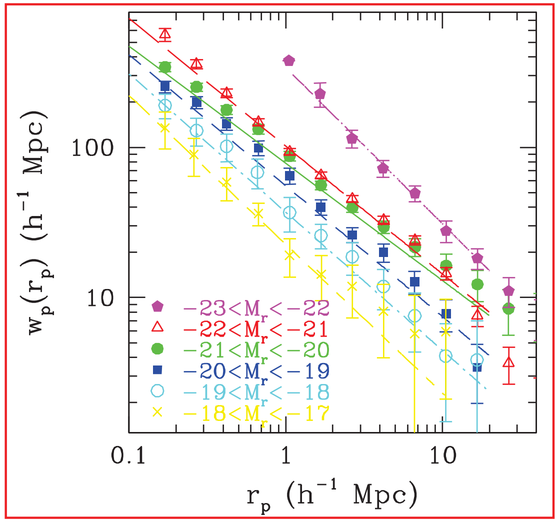


$$\xi(r) \simeq \left(\frac{r}{r_0}\right)^{\sim -1.8}$$

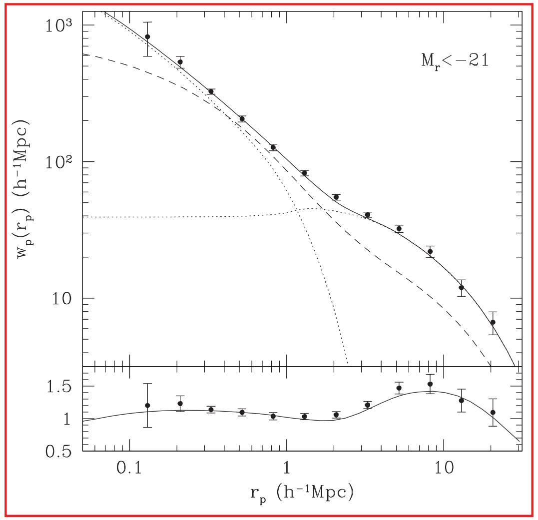
e. g. Zehavi+, 2004



Bump at 100 Mpc/h
e. g. Eisenstein+, 2005



Type dependence.
e. g. Zehavi+, 2004

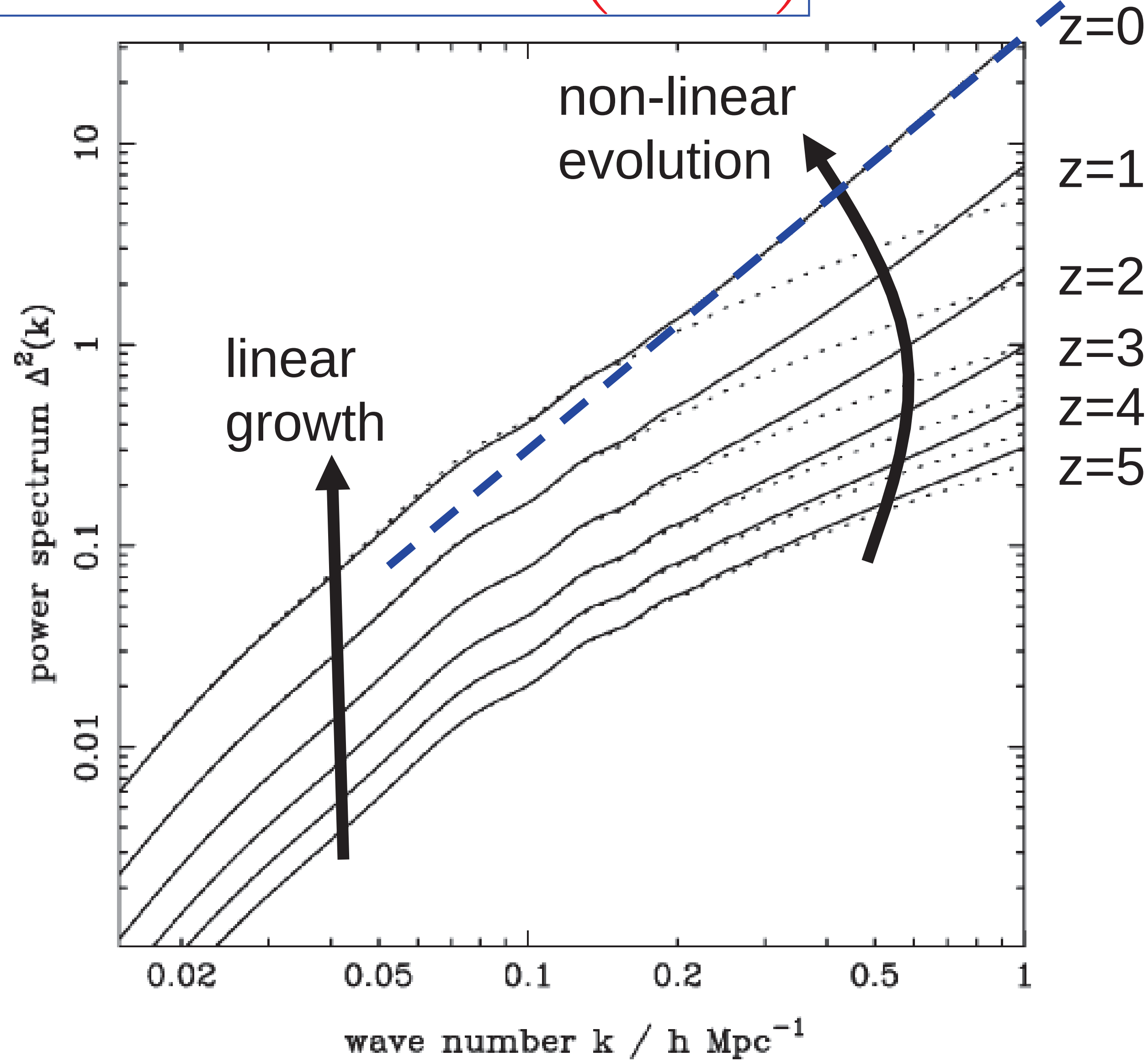


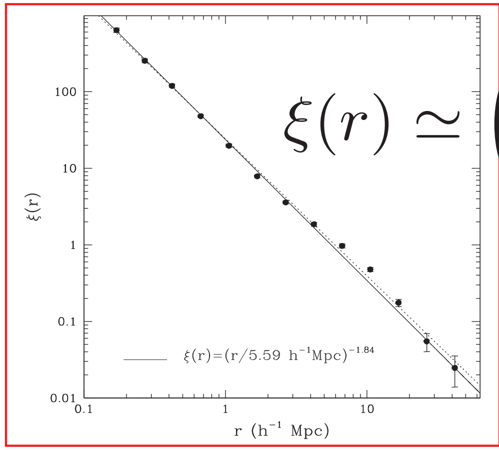
Deviation from power-law
e. g. Zehavi+, 2003

The power-law correlation at ~1 Mpc/h

$$\Delta^2(k) \equiv \frac{k^3 P(k)}{2\pi^2} \sim \xi\left(r \sim \frac{1}{k}\right)$$

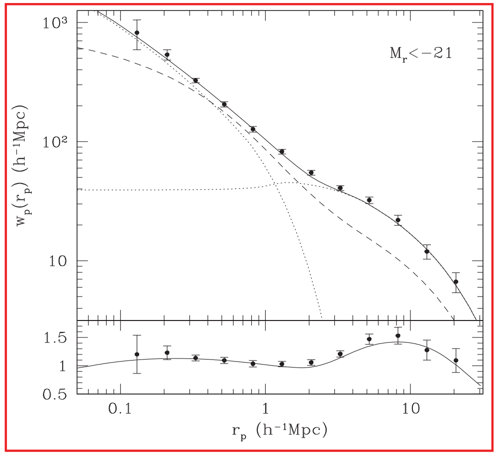
$$\Rightarrow \xi(r) \sim r^{\sim -1.8}$$





$$\xi(r) \simeq \left(\frac{r}{r_0}\right)^{\sim -1}$$

e. g. Zehavi+, 2004



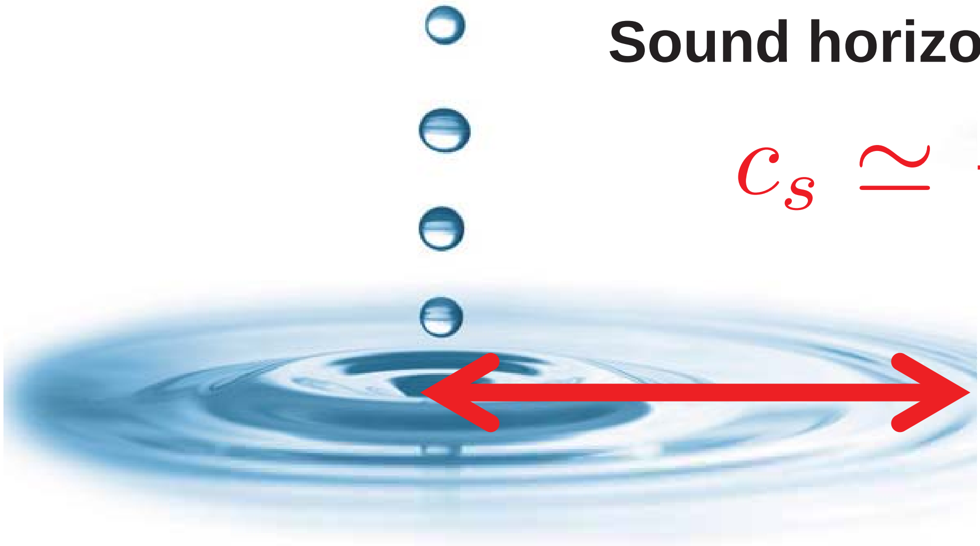
Deviation from power-law
e. g. Zehavi+, 2003

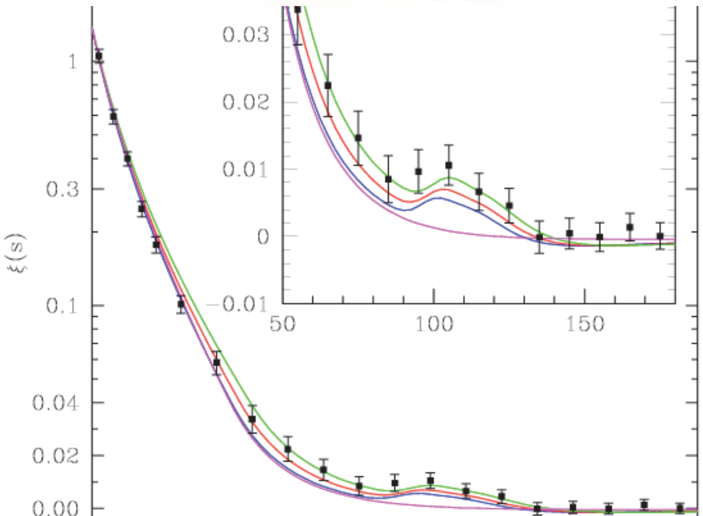
What about the bump at ~100 Mpc/h?

Baryon acoustic oscillations

Sound horizon at decoupling

$$c_s \simeq \frac{c}{\sqrt{3}}$$





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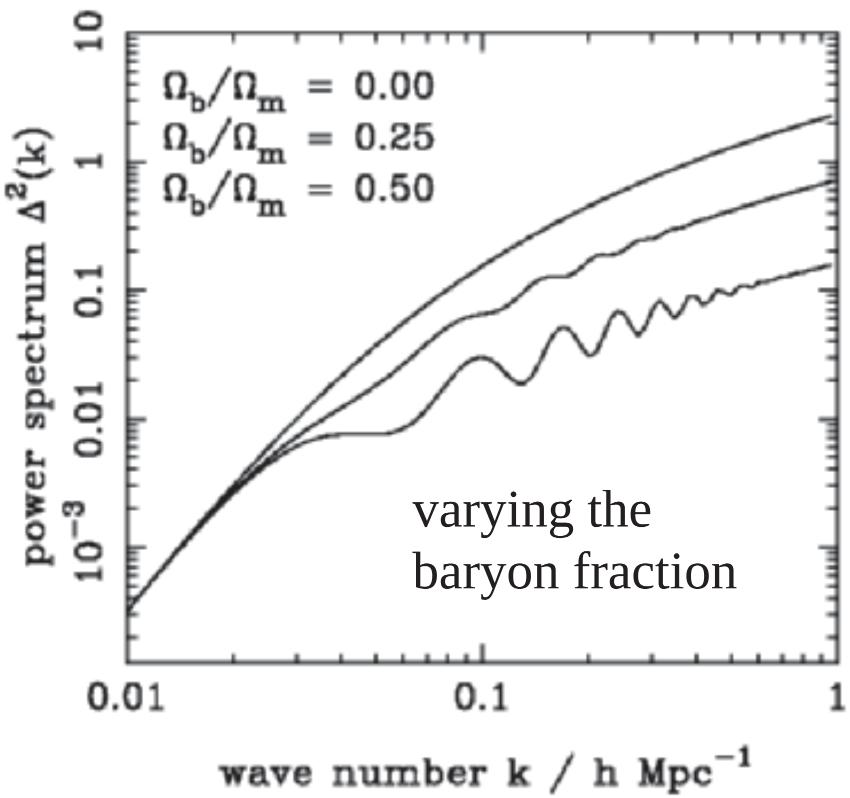
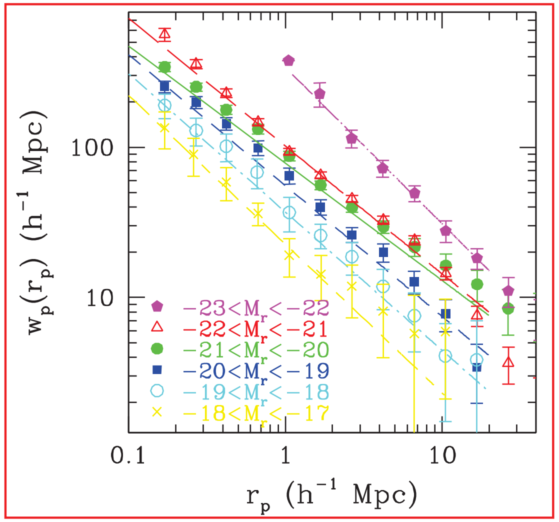
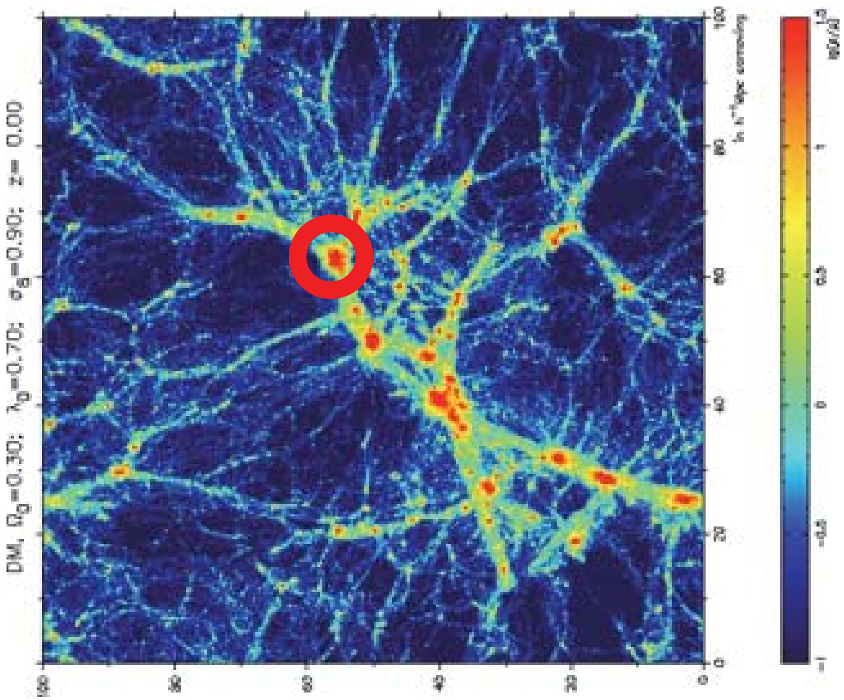
e. g. Eisenstein+, 2005

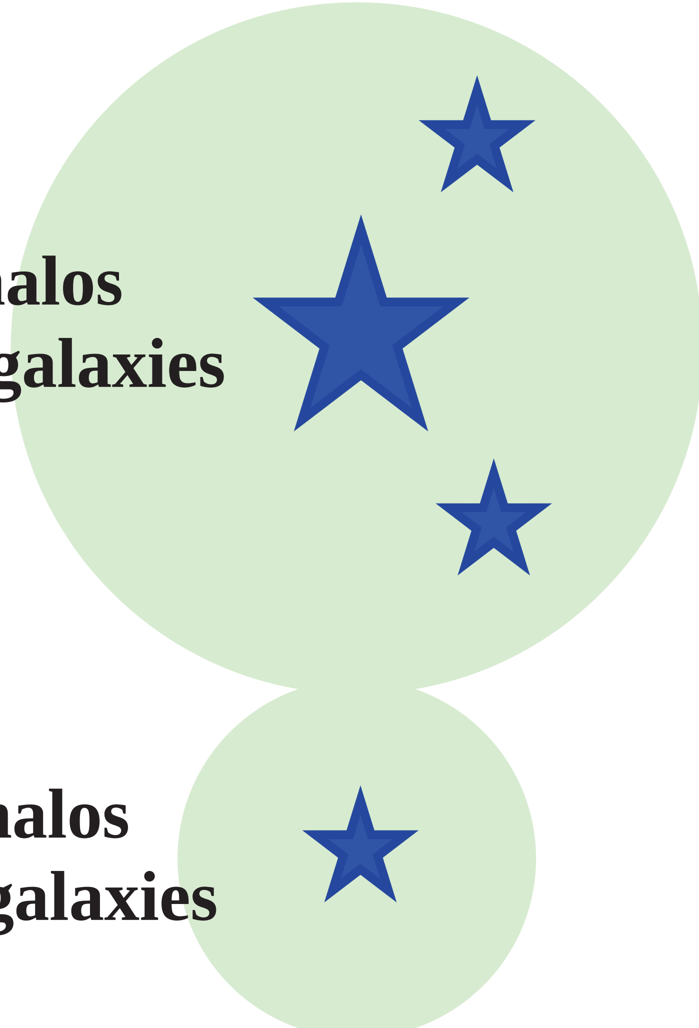




A missing ingredient

Type dependence.
e. g. Zehavi+, 2004

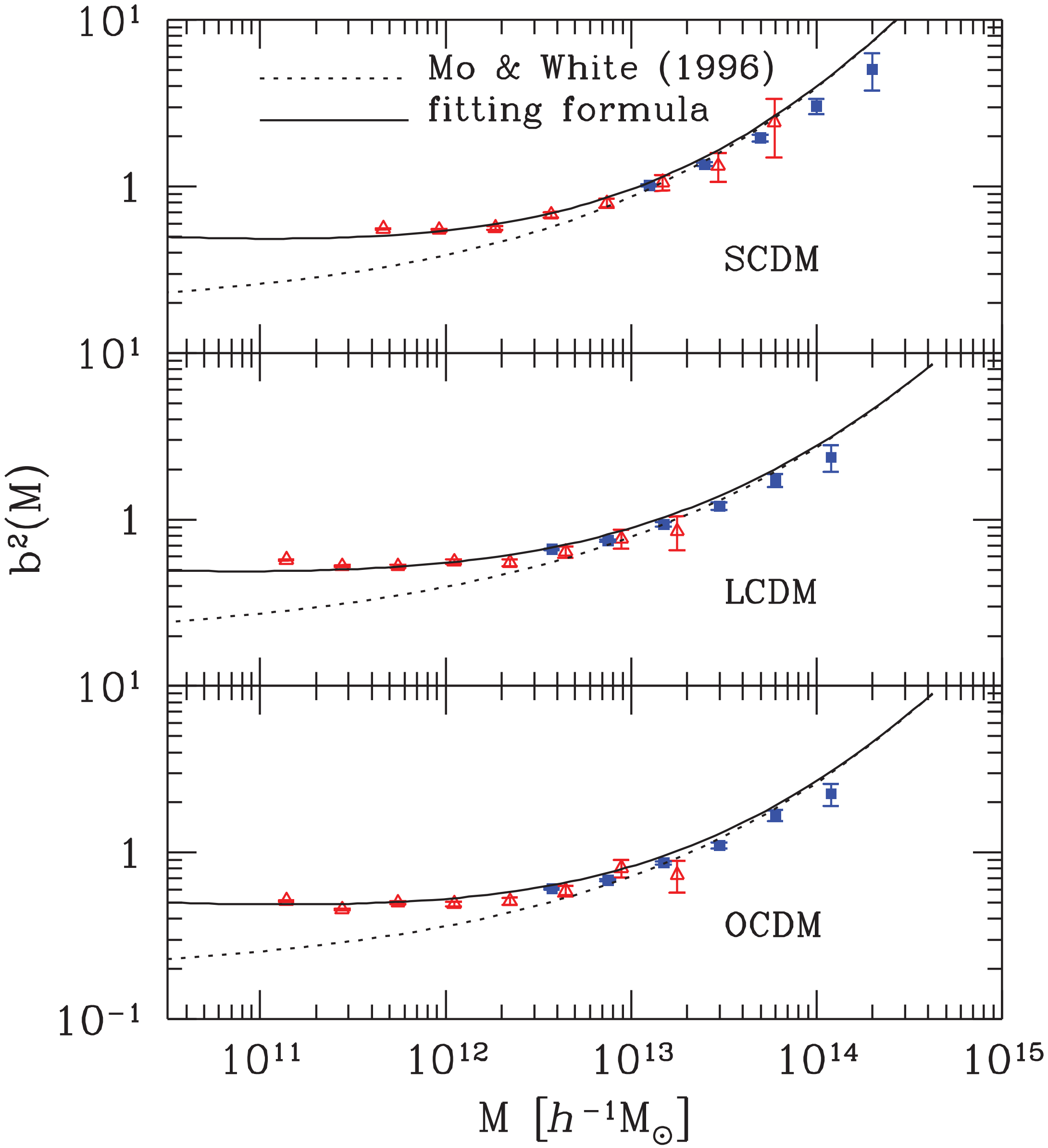




Larger DM halos
More/larger galaxies

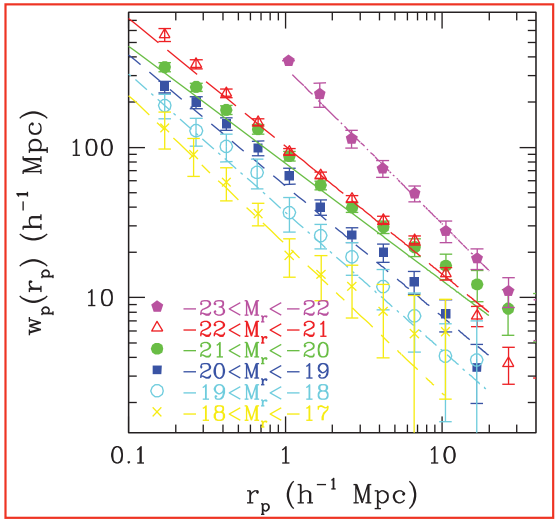
Smaller DM halos
Less/smaller galaxies

Bias



Jing 1998

$$\xi_{\rm halo} = b^2(M)\xi_{\rm DM}$$



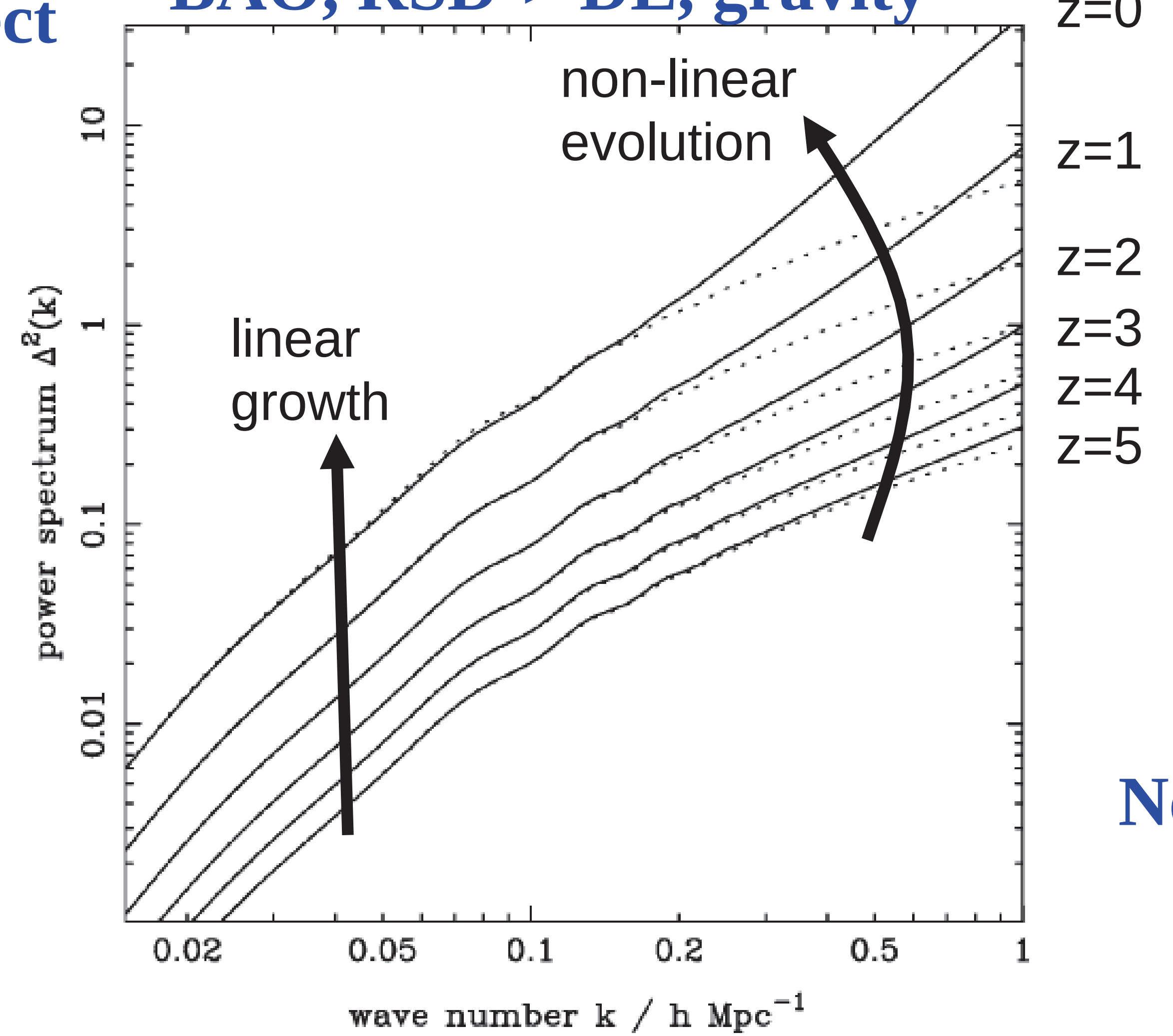
Type dependence.
e. g. Zehavi+, 2004

Rich cosmological information

Large scale — small scale

GR effect
PNG

BAO, RSD-> DE, gravity



Neutrinos, DM

Cosmic magnification (weak lensing)