Cosmic Microwave Background Radiation +

Large Scale Structure

Layout of the Course

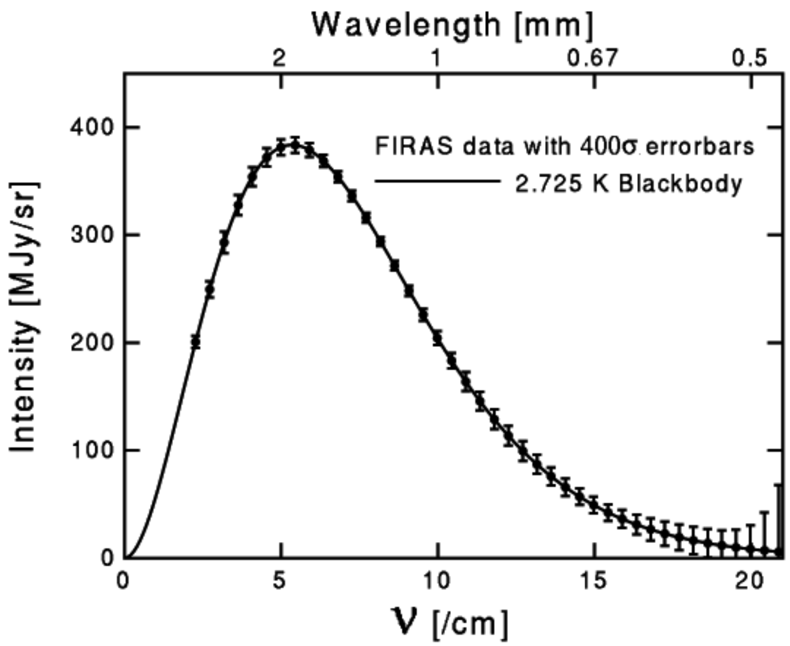
Feb 5: Introduction / Overview / General Concepts
Feb 12: Age of Universe / Distance Ladder / Hubble Constant
Feb 19: Distance Ladder / Hubble Constant / Distance Measures
Feb 26: Distance Measures / SNe science / Baryonic Content
Mar 4: Baryon Content / Dark Matter Content of Universe
Mar 11: Cosmic Microwave Background
Mar 18: Cosmic Microwave Background / Large Scale Structure
Mar 25: Baryon Acoustic Oscillations / Dark Energy / Clusters
Apr 1: No Class
Apr 8: Clusters / Cosmic Shear
Apr 15: Dark Energy Missions / Review for Final Exam

May 13: Final Exam

This Week

Review Material from Last Week

Photons from the CMB have a spectral energy distribution which is almost a perfect black body.



Cosmic Microwave Background is Isotropic

Isotropic to one part in 10^5

CMB radiation became decoupled from matter during recombination era (z~1100)

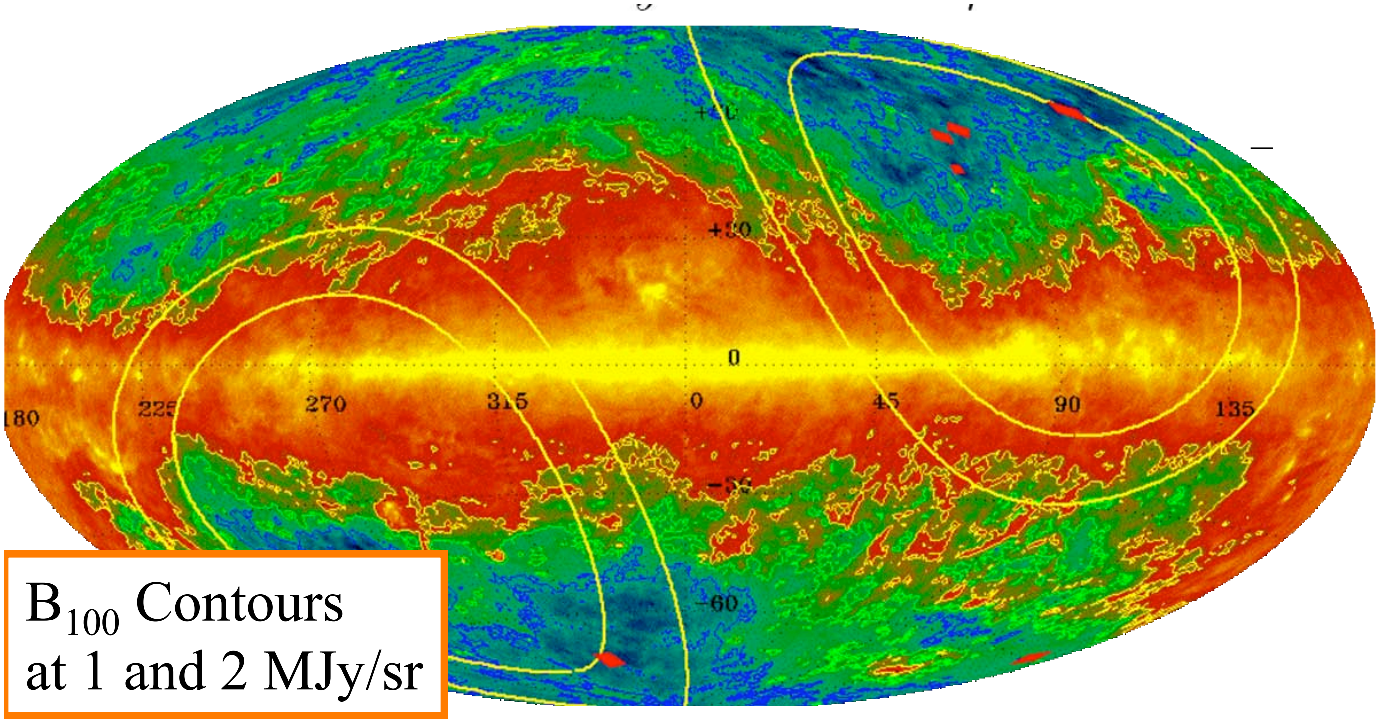
Ionized Plasma →	Neutral Gas
(z > 1100)	(z < 1100)
< 380,000 years	> 380,000 years
Temperature > 3600 K	Temperature < 3600 K
Hydrogen ionized	Hydrogen neutral
Photons Thomson-scattering off of the ionized hydrogen	Almost no free electrons
	Photons unbound from plasma

Substantial Foreground Light

One Example is Infrared Cirrus:

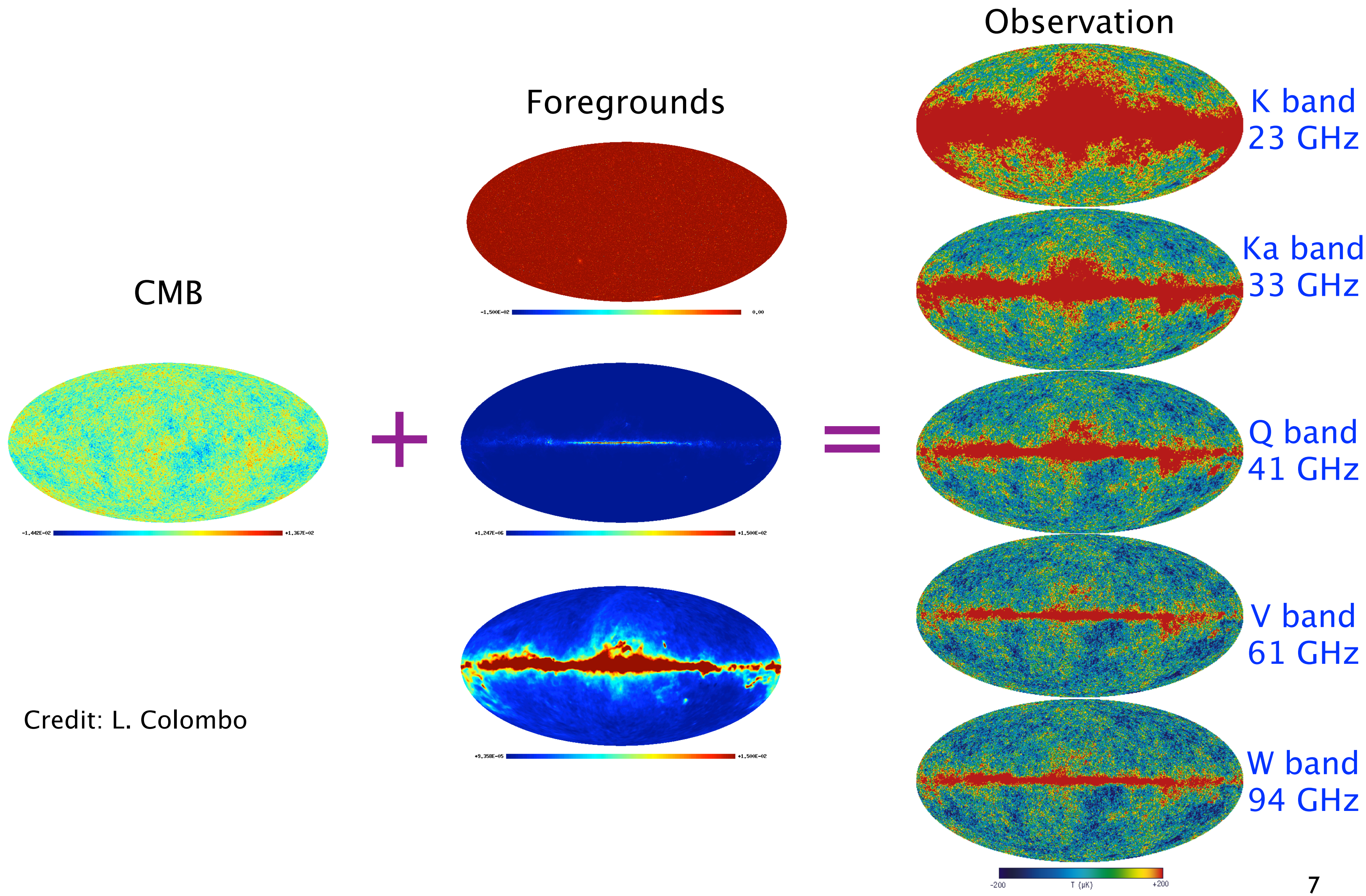
-- Interstellar dust in our galaxy is heated by the interstellar radiation field.

-- Emission depends on galaxy latitute and is significant longward of 60 μm



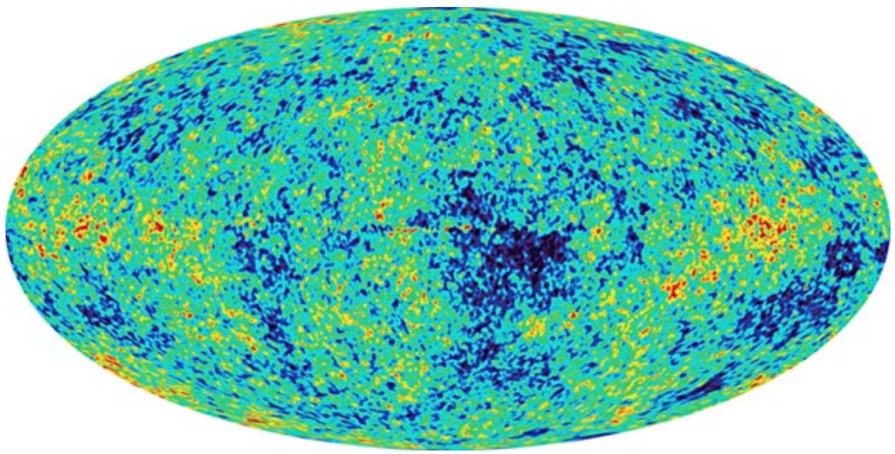
Other Examples are Synchrotron (from supernovae remnants) and Free-free Emission (from ionized regions around hot stars)

Using unique multiwavelength signatures of the CMB and the foreground, find the right linear combination to match the multi-wavelength observations

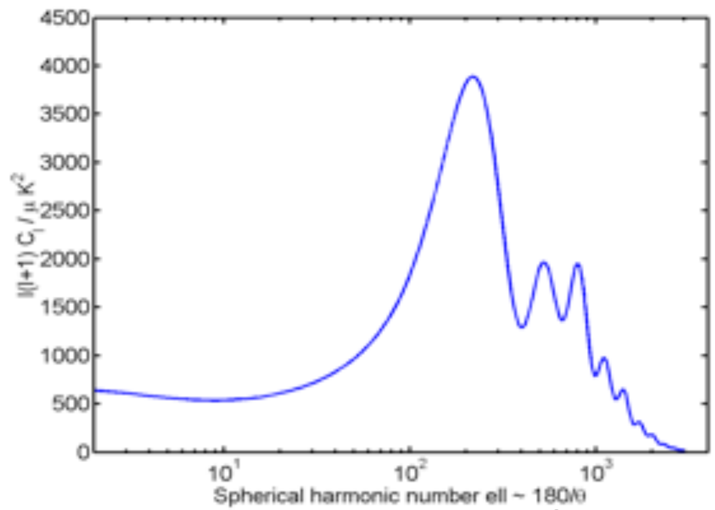


Power Spectra Derived from Fluctuations in CMB

-- Use the spherical harmonic expansion to construct a power spectrum to describe anisotropies of the CMB on the sky



Power Spectrum



l = 180 / θ

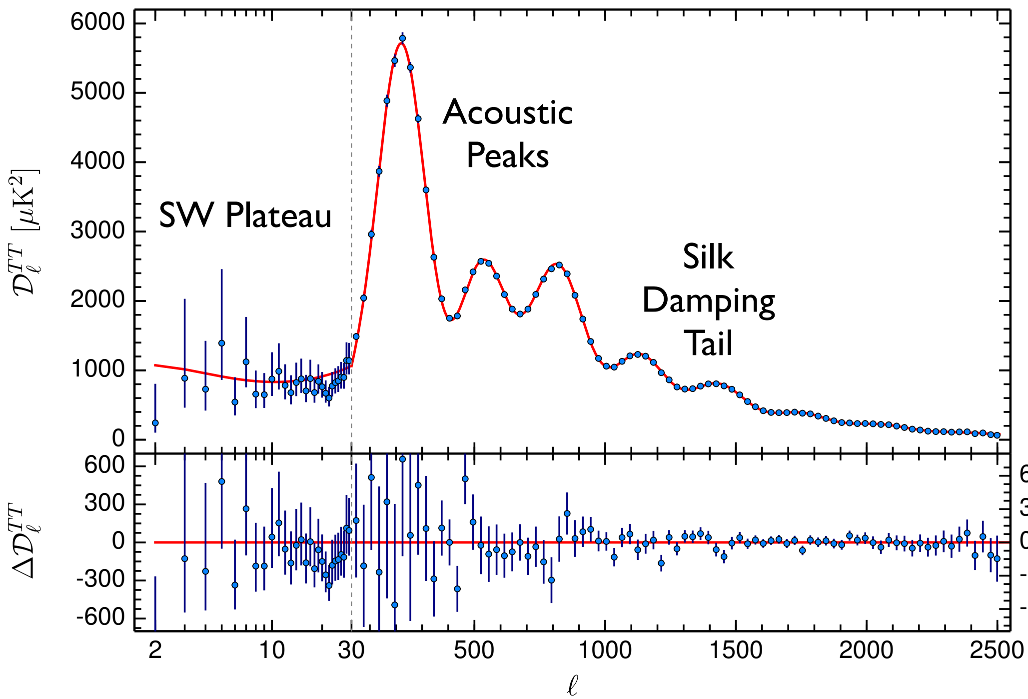
Expansion:

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell} a_{\ell m} Y_m^{\ell}(\theta,\phi)$$

After deriving the a_{lm} coefficients from the data, determine the statistical average

$$c_\ell = \langle |a_{\ell m}| \rangle^2$$

Cosmic Microwave Background



Sachs-Wolfe Plateau: Constrain normalization of primordial power spectrum

1st acoustic peak: Measure Angular Diameter Distance to Last Scattering Surface

Ratio of Even and Odd Acoustic Peaks: Probe Baryon Content

Ratio of Amplitude of 3rd to 1st Acoustic Peak: Matter Content

High Frequency Modes: Silk Damping...

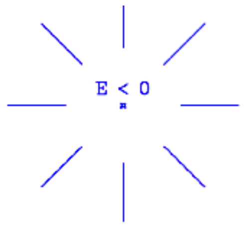
How CMB light can be broken down?

Measure Temperature and Polarization of Light

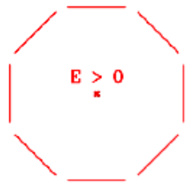
90% of the photons in the CMB are unpolarized; this leaves 10% which is polarized.

One tends to break down the polarization map into two modes
(Helmholtz-Hodge theorem)

E-modes



hot spots

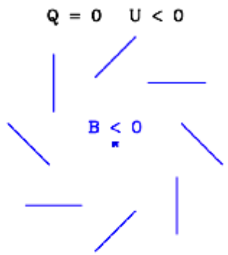


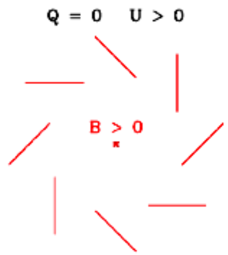
cold spots

E-modes are curl free and can be written as the gradient of a potential

$\nabla \times E = 0$

B-modes





B-modes have no divergence.

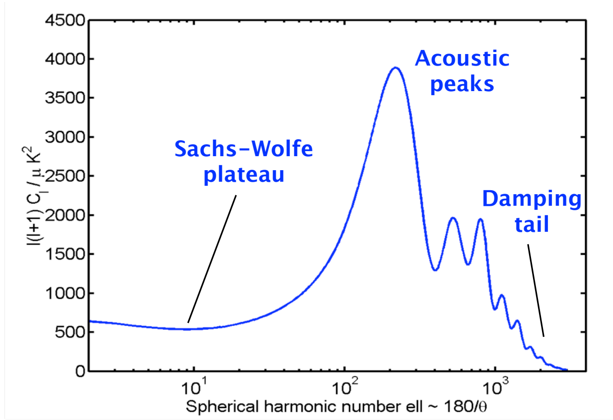
$\nabla \cdot B = 0$

The terms E and B modes simply reflect the general form of the polarization fields and are in analogy with similar fields in electromagnetism. However, they have no direct relation with electric or magnetic fields

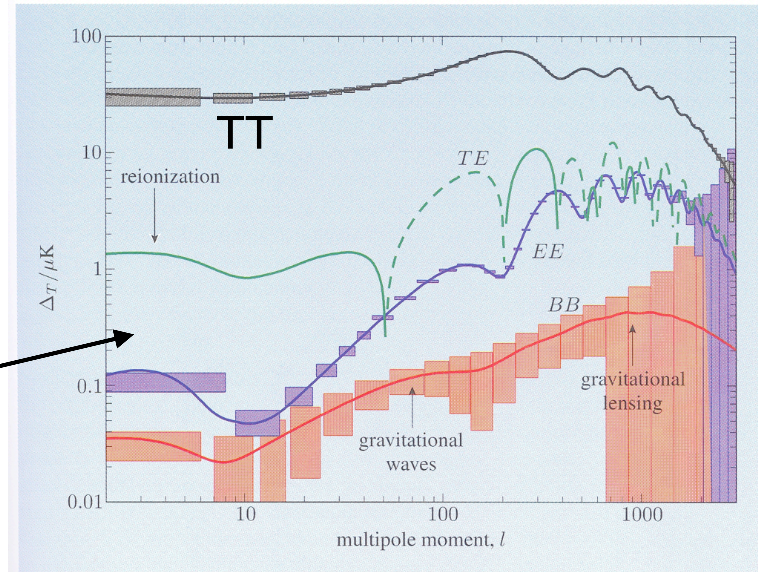
Why look at the polarized light separately?

1) teaches us new things.. 2) tests our assumptions...

Using the polarization information, we can form an angular power spectrum using not only the temperature information:



Forming additional power and cross spectra from E and B polarisation information, i.e., TE, EE, and BB, we have the following:

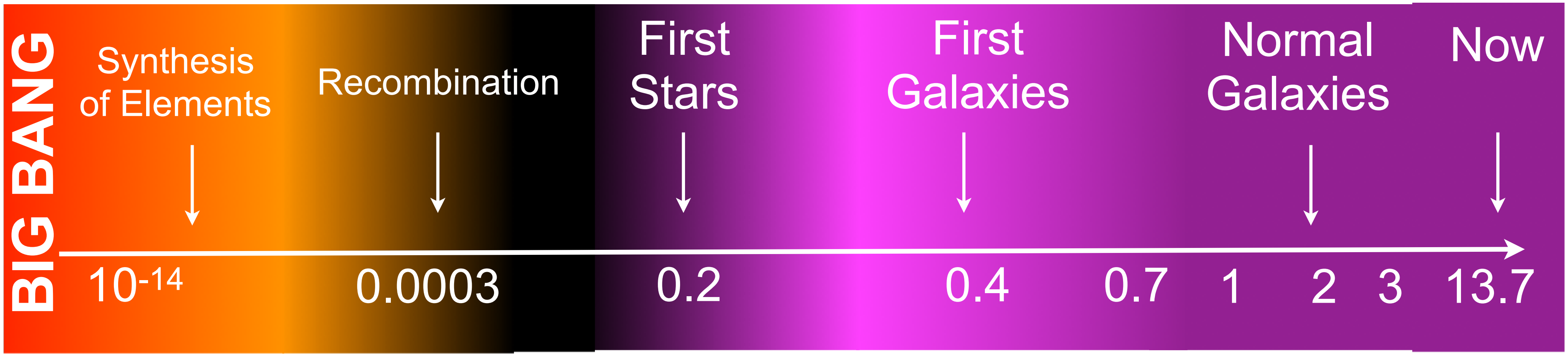


Note how the amplitude of the cross-spectra using polarisation are less by factors of 10 to 1000.

New Material

What new information do the TE, EE, and BB spectra provide?

Allows us to answer question how long did hydrogen in the universe in a neutral state, i.e., from 400,000 yrs after Big Bang to 1 Gyr

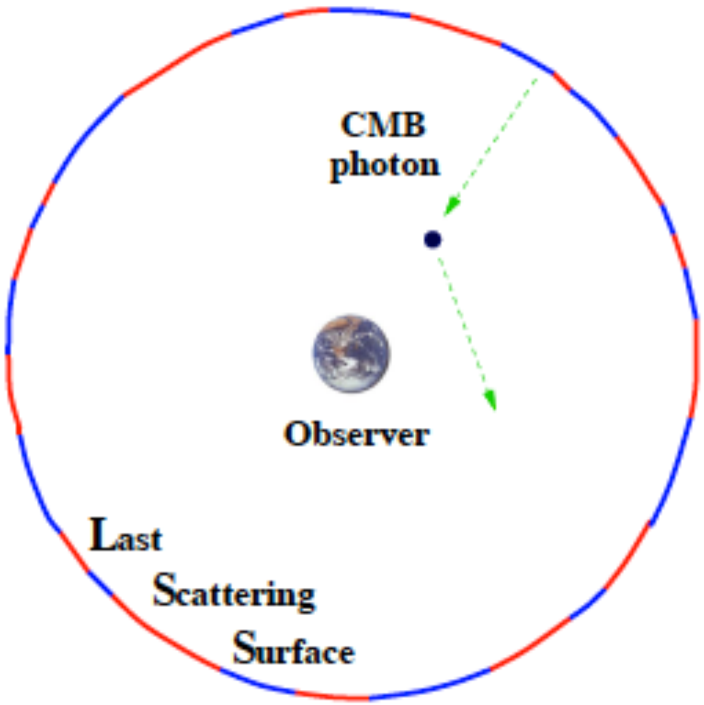


state of hydrogen

ionized → ← neutral → ← ionized

What new information do the TE, EE, and BB spectra provide?

The microwave background helps us answer this question -- since photons from the microwave background scatter off of ionized elecrons in the universe

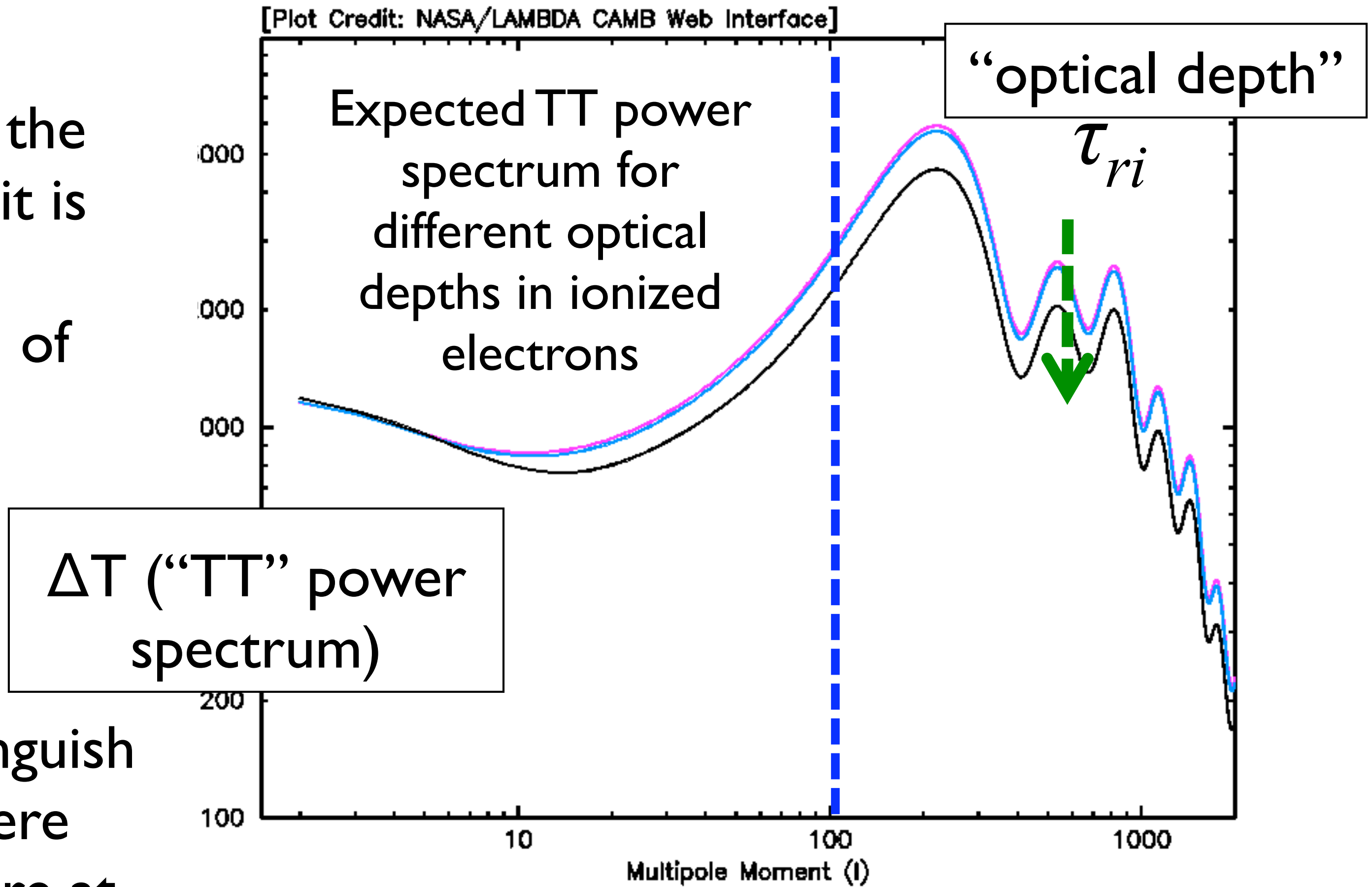


Obviously, the longer the hydrogen remains in an ionized state, the more photons from the CMB we would expect to be scattered.

Credit: Porciano

What new information do the TE, EE, and BB spectra provide?

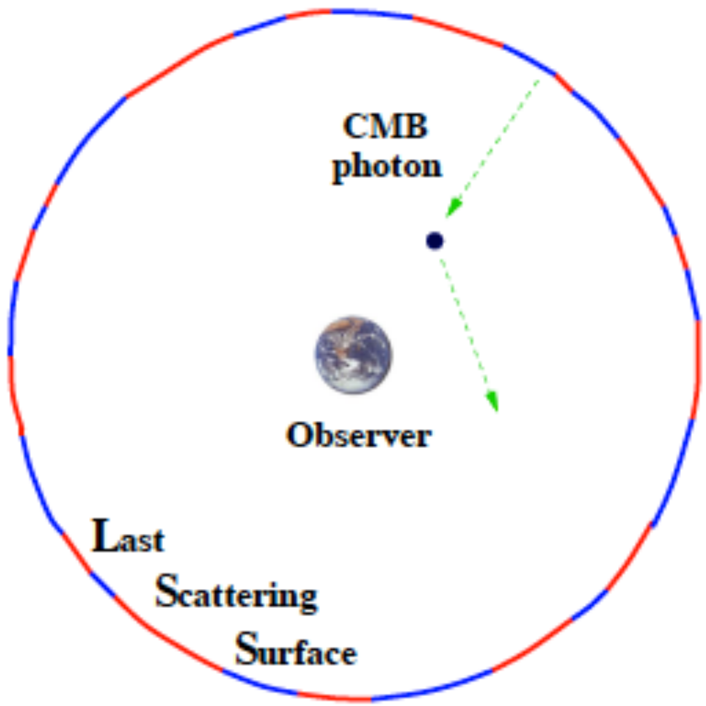
Information about reionization is present in the TT power spectrum, but it is degenerate with the underlying normalisation of the power spectrum.



Difficult to know to distinguish between scenarios where universe had less structure at early times and where the apparent structure washed out by Thomson scattering.

What new information do the TE, EE, and BB spectra provide?

Since photons from the CMB are expected to have a certain polarization symmetry relative to the temperature structure of the CMB and this polarization would be mixed up if they are scattered by intervening matter, we can learn about the intervening ionized hydrogen

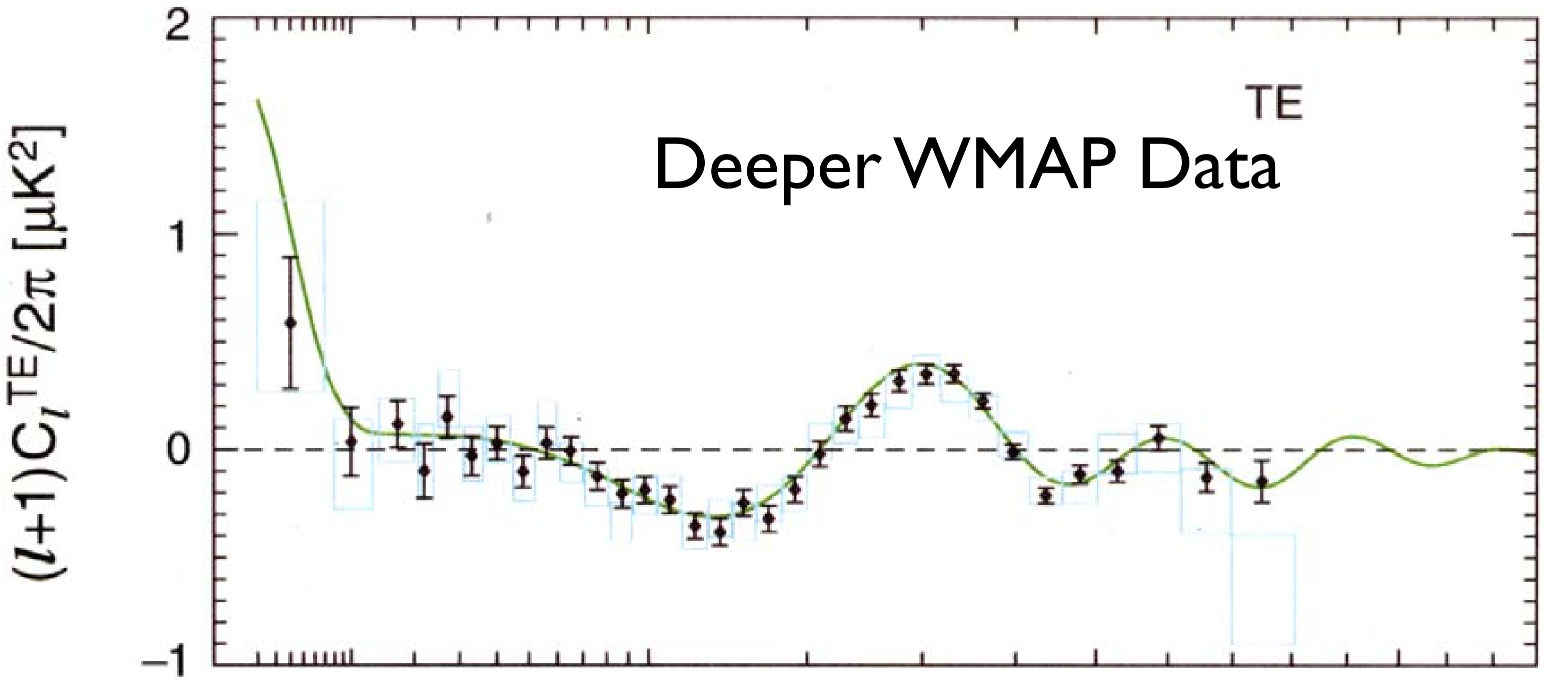


Measurements show that ~10% of CMB photons are so scattered

Credit: Porciano

What new information do the TE, EE, and BB spectra provide?

By looking at the polarization data, we can attempt to answer this question -- since the polarization of photons unscattered by ions in the intervening space will have different properties than those that are scattered.



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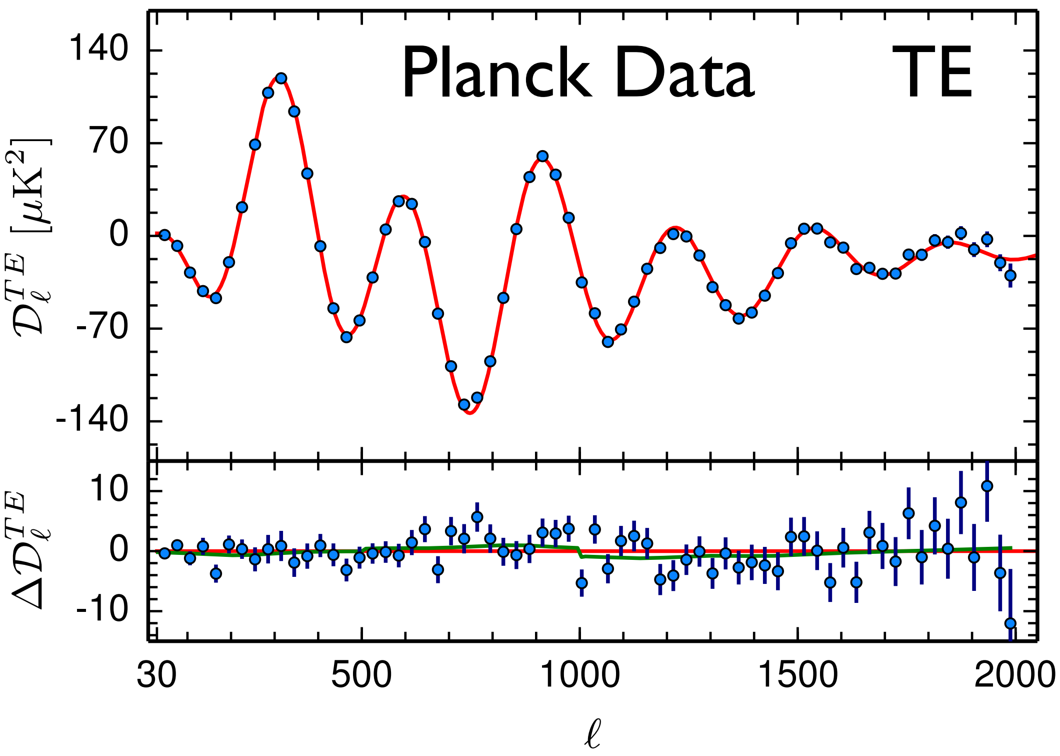

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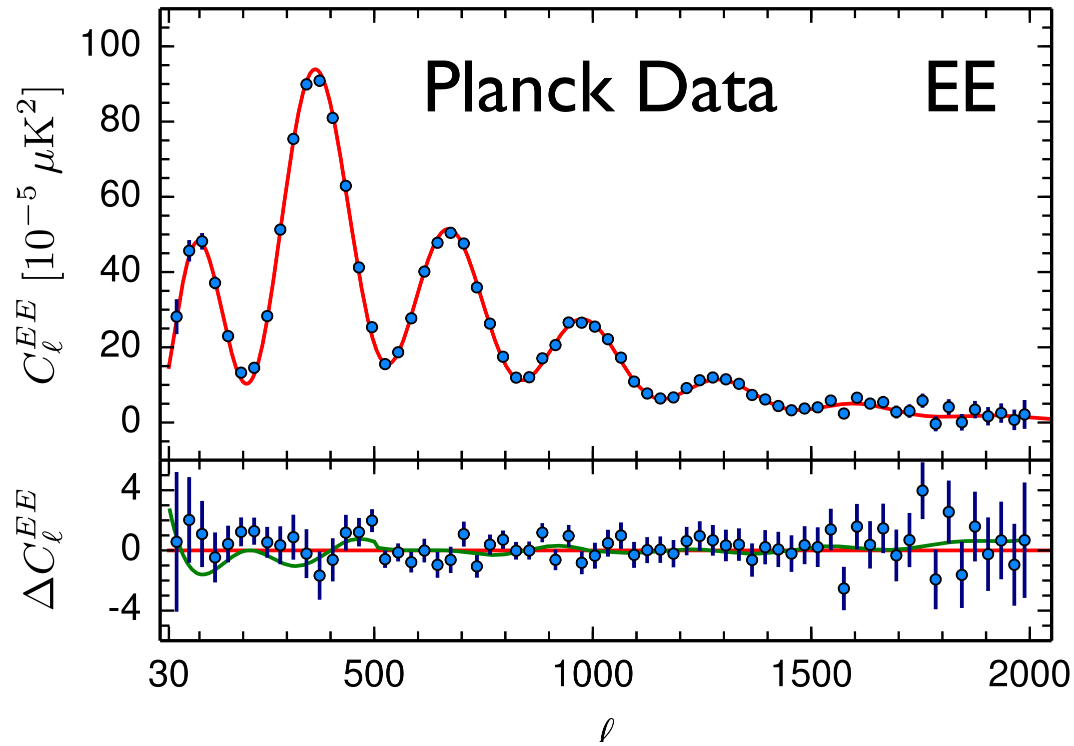

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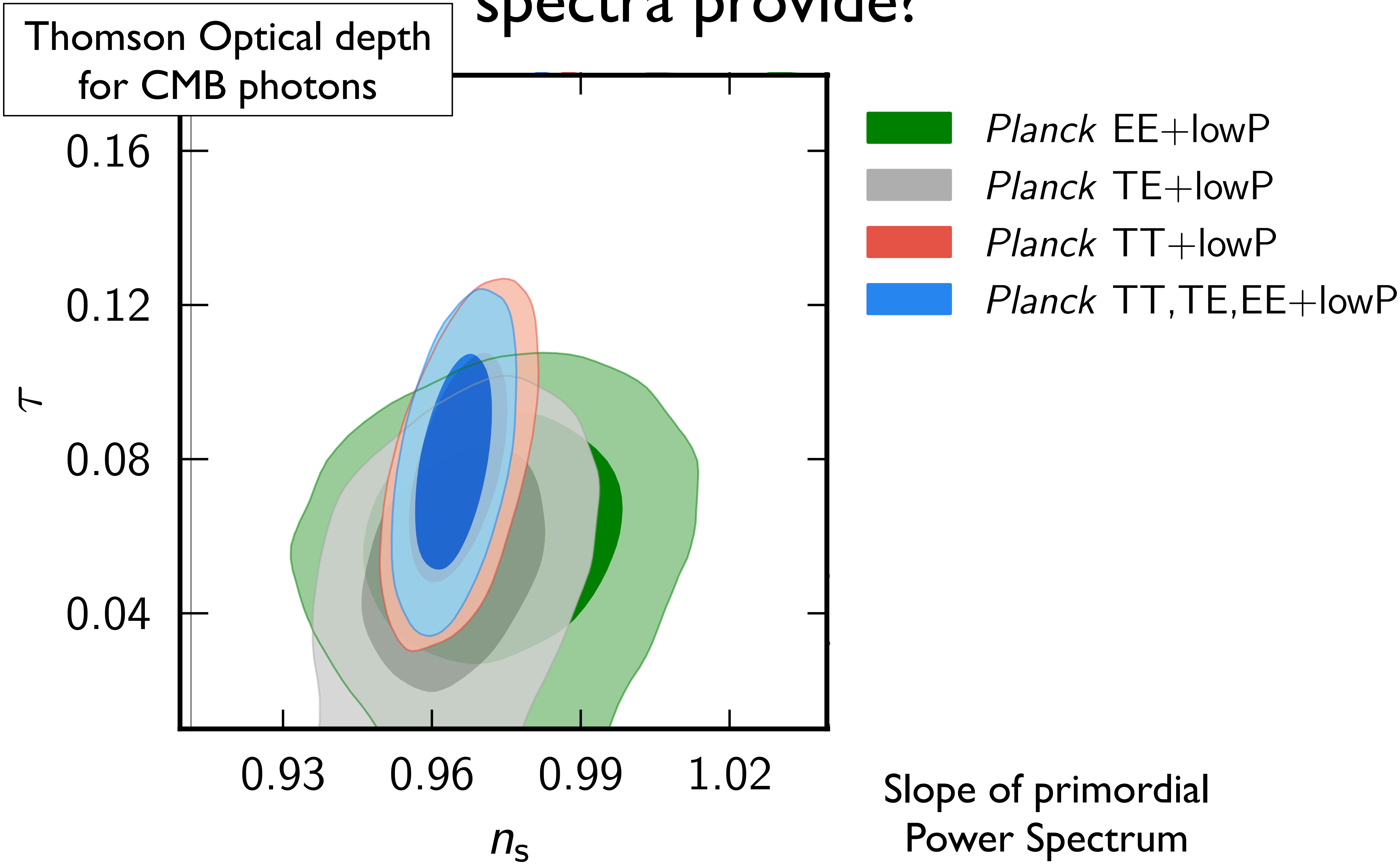
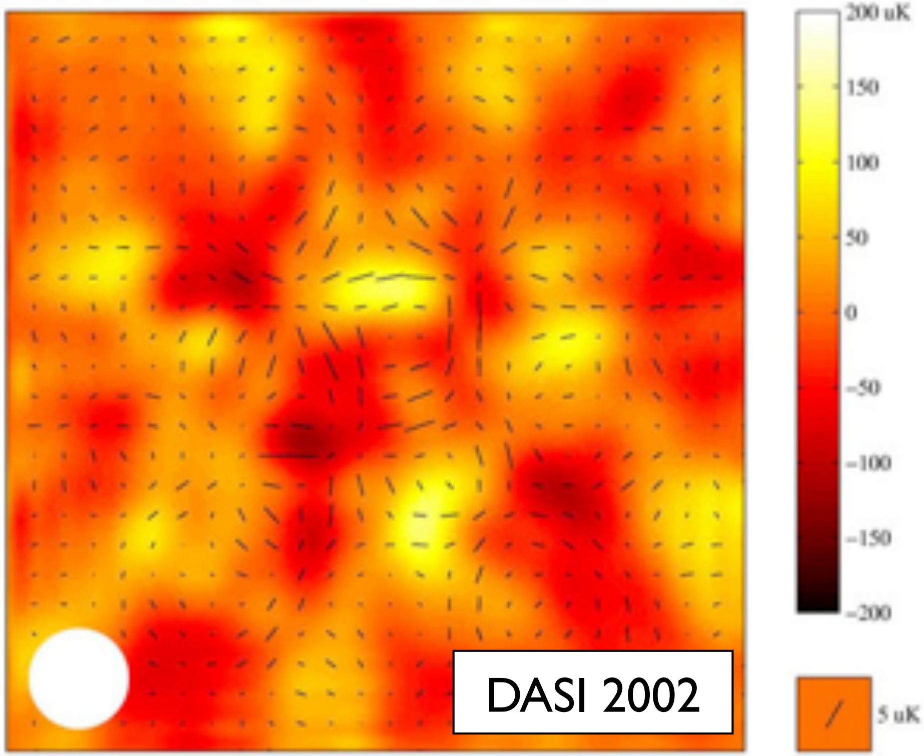


First detection of polarization in CMB

-- DASI South Pole experiment (interferometer) first to detect E mode polarization (2002)

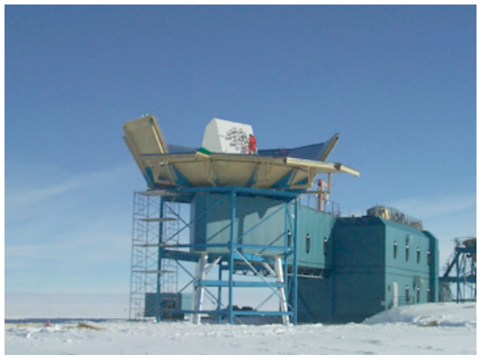
-- This was followed by WMAP reporting a measure of the C_{TE} power spectrum at low angular scales

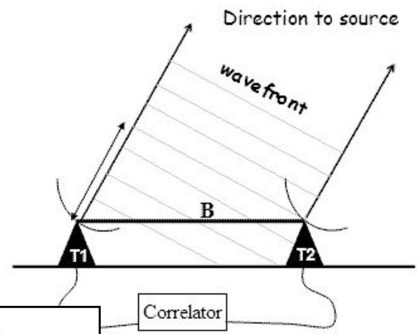
-- Measurements of the E-mode polarization also made with CARMAP, MAXIPOL, and QUAD



Map is 5 degrees square

interferometer: collect coherent signals over certain angular scale on sky


DASI in South Pole



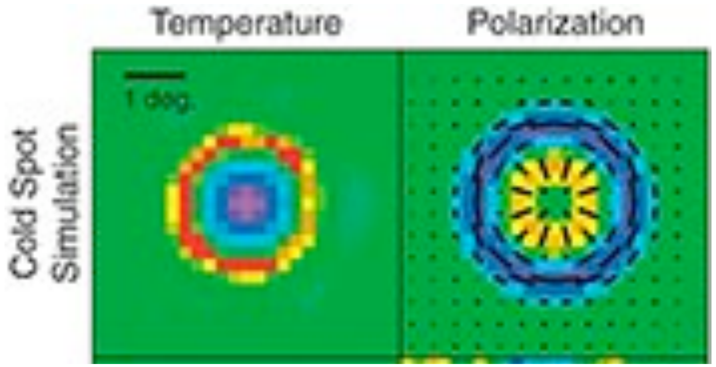
Credit: Basu

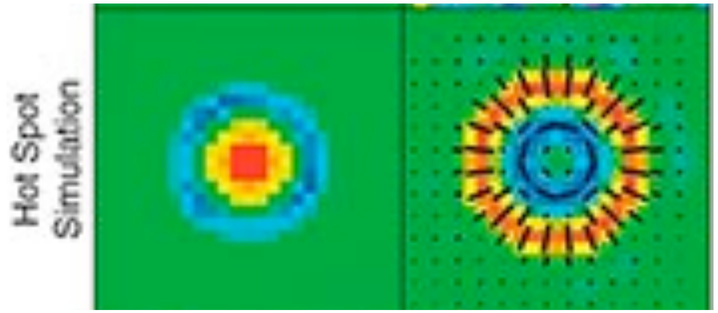
It is interesting that we can actually test whether our understanding of the polarization of CMB is correct

Around cold or hot spots, we expect a certain structure to the polarization signal

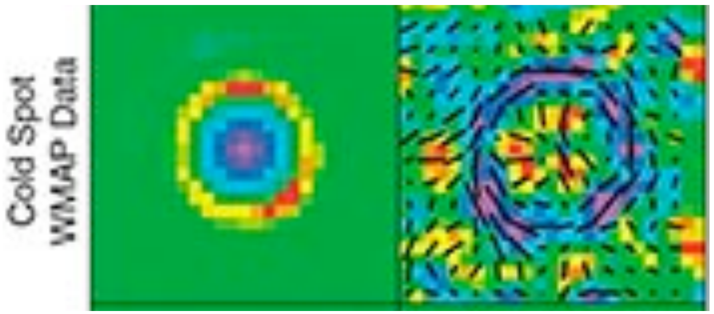
Can test this by looking at the polarization signal around hot or cold spots in the observations.

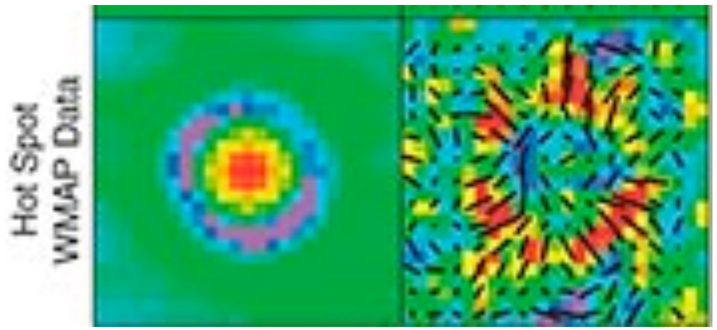
From theory





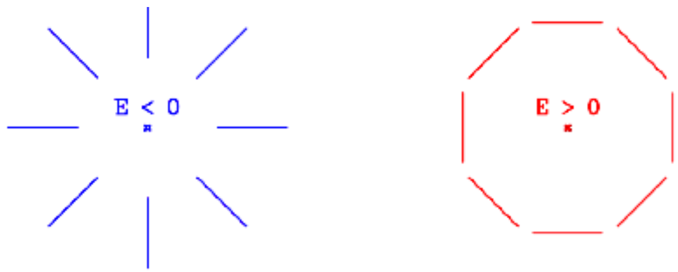
As observed by WMAP





One tends to break down the polarization map into two modes

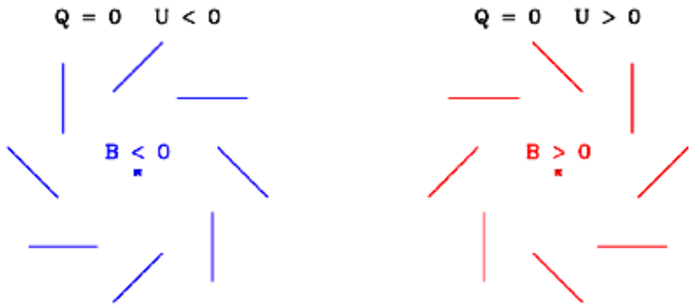
E-modes



hot spots cold spots

E-modes are curl free and can be written as the gradient of a potential

B-modes



B-modes are curl free and can be written as the gradient of a potential

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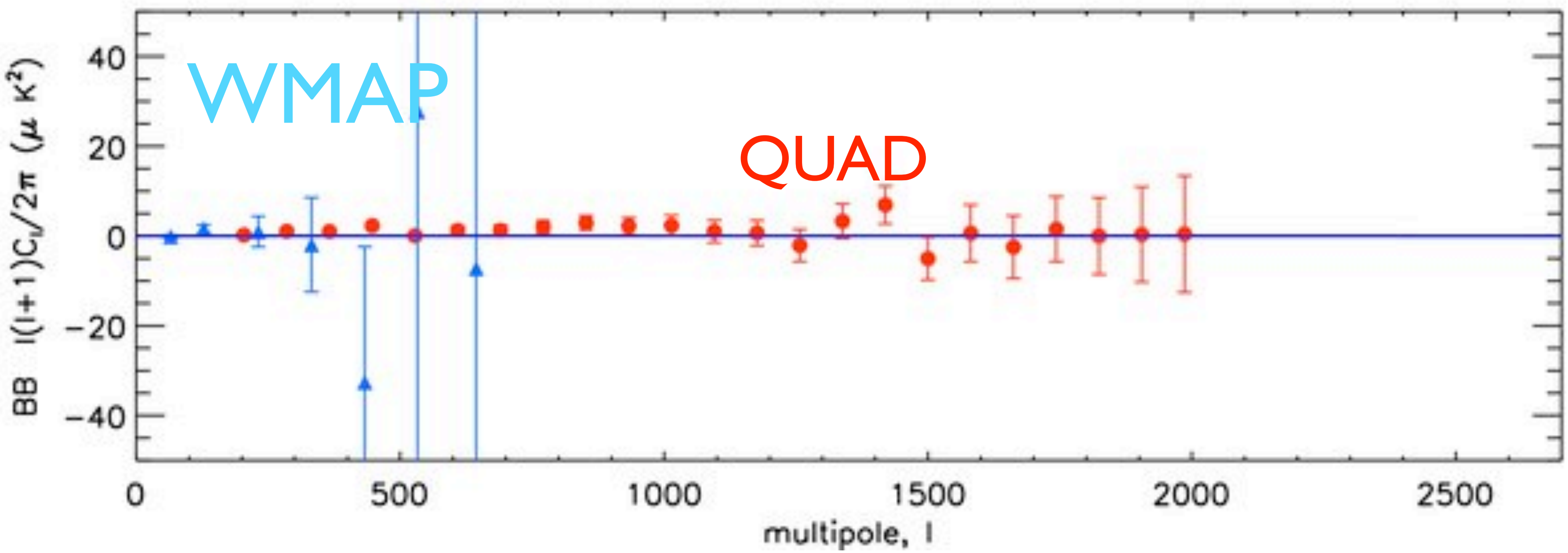
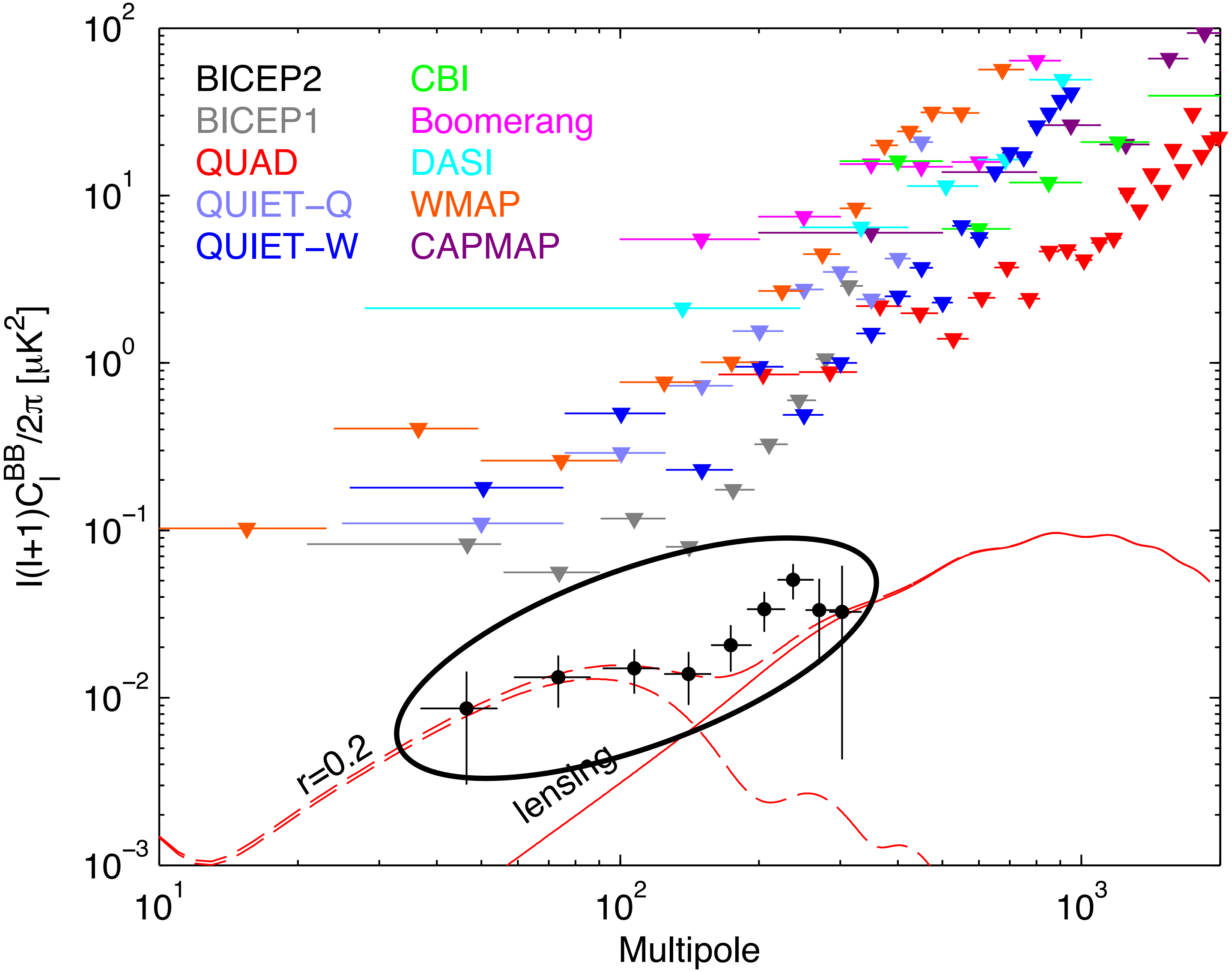
No power in BB power spectrum detected as of 2013 -- goal of Planck!



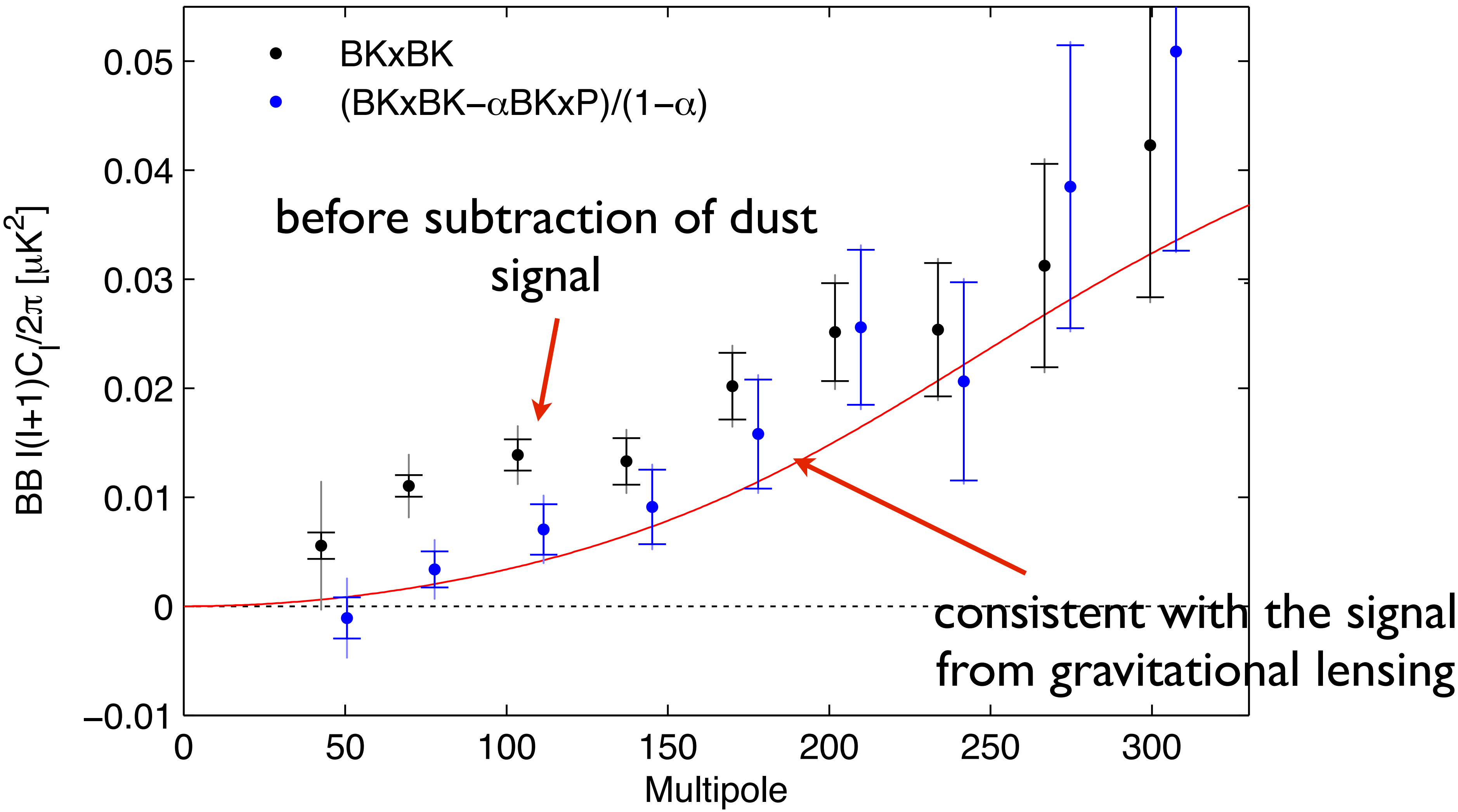
Was expected to the smoking gun test of inflation -- since the signal is expected to originate from gravity waves (from inflation) -- signal on smaller scales comes from gravitational lensing

Significant BB signal detected by BICEP II!



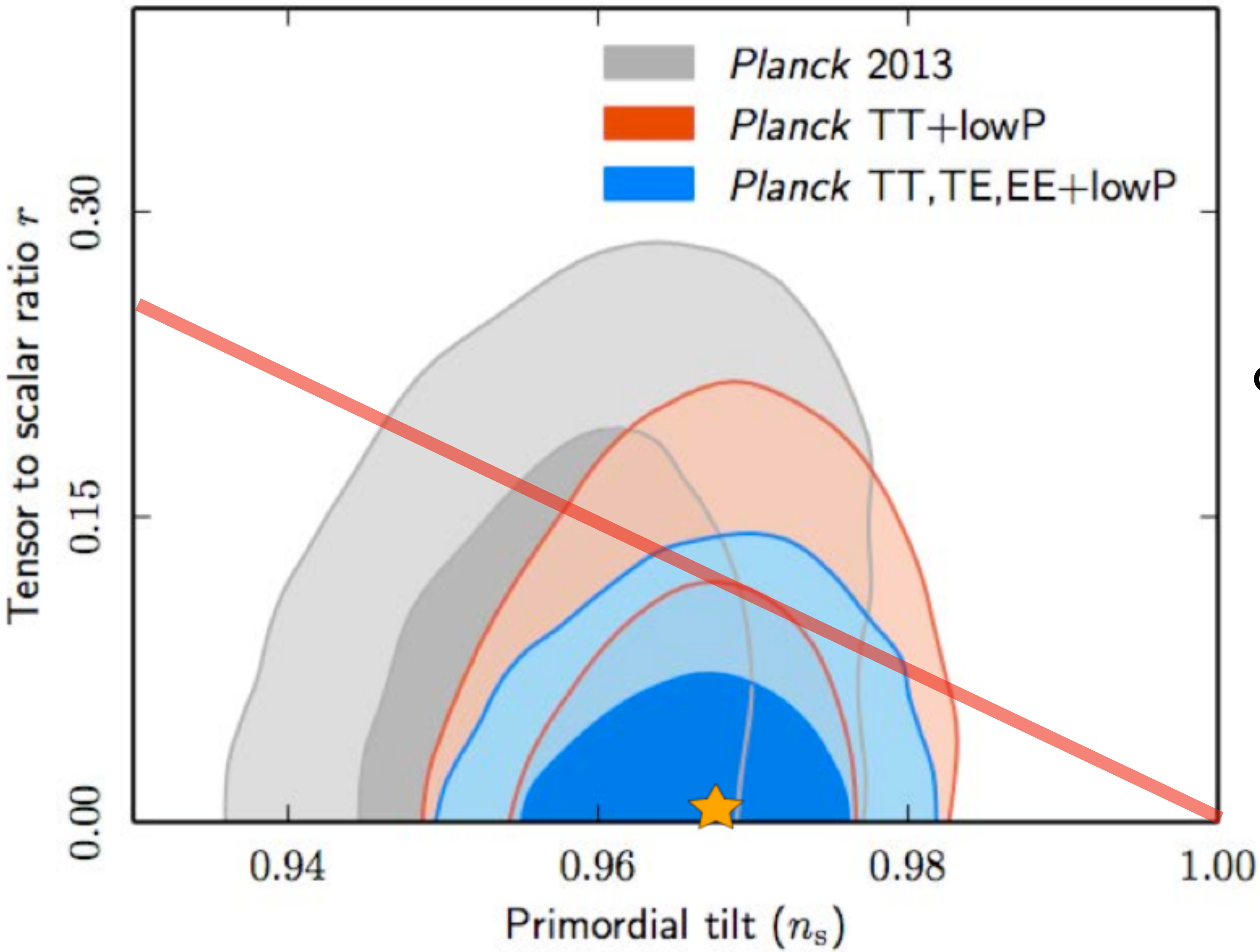
BICEP2 results show a positive detection of BB modes. Attempted fit to gravity waves from inflation... Lensing contributes at small scales

But current BB signal from BICEP II appears consistent with arising from dust in our own galaxy..



Credit: BICEP/Keck Collaboration

Current constraints on BB allow us to set constraints on r, the ratio of power tensor-to-scalar modes.



For simplest inflation models, there is a relationship between the tilt of the primordial power spectrum And the tensor-to-scalar ratio r.

$r = 8(1\text{-}n_s)$

=> r = 0.1-0.3

Planck - BICEP-II/Keck Joint Results

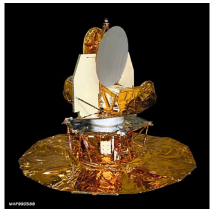
Ruled out at 95% confidence

Both WMAP + Planck have provided us with an immense amount of information on the cosmological parameters

Constraints on the cosmological parameters from WMAP observations (7-year)

WMAP launched June 2001

Credit: NASA



Note the same dual receivers as COBE. This design, added with the very stable conditions at the L2, minimizes the "1/f noise" in amplifiers and receivers.

Thus after 7 years, the data can still be added and noise lowered (of course, the improvement will be marginal).

WMAP Cosmological Parameters

Model: lcdm+sz+lens

Data: wmap7

$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	$1-n_s$	0.037 ± 0.014
$1-n_s$	$0.0079 < 1-n_s < 0.0642$ (95% CL)	$A_{\rm BAO}(z=0.35)$	$0.463^{+0.021}_{-0.020}$
C_{220}	5763^{+38}_{-40}	$d_A(z_{\rm eq})$	14281^{+158}_{-161} Mpc
$d_A(z_*)$	14116^{+160}_{-163} Mpc	$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
h	0.710 ± 0.025	H_0	71.0 ± 2.5 km/s/Mpc
$k_{\rm eq}$	$0.00974^{+0.00041}_{-0.00040}$	$\ell_{\rm eq}$	137.5 ± 4.3
ℓ_*	302.44 ± 0.80	n_s	0.963 ± 0.014
Ω_b	0.0449 ± 0.0028	$\Omega_b h^2$	$0.02258^{+0.00057}_{-0.00056}$
Ω_c	0.222 ± 0.026	$\Omega_c h^2$	0.1109 ± 0.0056
Ω_Λ	0.734 ± 0.029	Ω_m	0.266 ± 0.029
$\Omega_m h^2$	$0.1334^{+0.0056}_{-0.0055}$	$r_{\rm hor}(z_{\rm dec})$	285.5 ± 3.0 Mpc
$r_s(z_d)$	153.2 ± 1.7 Mpc	$r_s(z_d)/D_v(z=0.2)$	$0.1922^{+0.0072}_{-0.0073}$
$r_s(z_d)/D_v(z=0.35)$	$0.1153^{+0.0038}_{-0.0039}$	$r_s(z_*)$	$146.6^{+1.5}_{-1.6}$ Mpc
R	1.719 ± 0.019	σ_8	0.801 ± 0.030
$A_{\rm SZ}$	$0.97^{+0.68}_{-0.97}$	t_0	13.75 ± 0.13 Gyr
τ	0.088 ± 0.015	θ_*	0.010388 ± 0.000027
θ_*	$0.5952 \pm 0.0016\ ^\circ$	t_*	379164^{+5187}_{-5243} yr
$z_{\rm dec}$	1088.2 ± 1.2	z_d	1020.3 ± 1.4
$z_{\rm eq}$	3196^{+134}_{-133}	$z_{\rm reion}$	10.5 ± 1.2
z_*	$1090.79^{+0.94}_{-0.92}$		

Constraints on the cosmological parameters from Planck observations (final results)

2010-2014: The Planck satellite

Credit: ESA

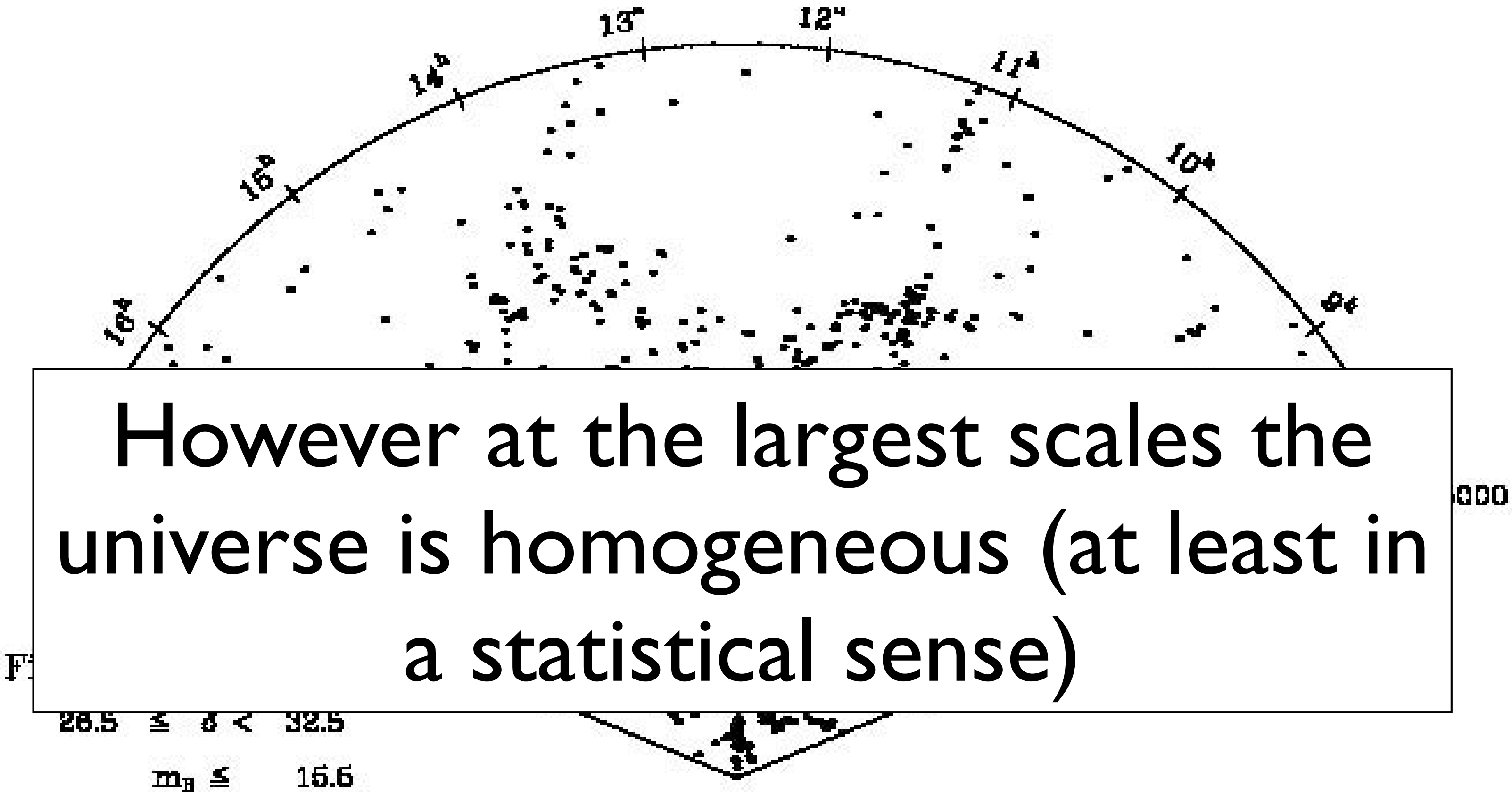
Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}] . .	66.88 ± 0.92	68.44 ± 0.91	69.9 ± 2.7	67.27 ± 0.60	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.679 ± 0.013	0.699 ± 0.012	$0.711^{+0.033}_{-0.026}$	0.6834 ± 0.0084	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.321 ± 0.013	0.301 ± 0.012	$0.289^{+0.026}_{-0.033}$	0.3166 ± 0.0084	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1434 ± 0.0020	0.1408 ± 0.0019	$0.1404^{+0.0034}_{-0.0039}$	0.1432 ± 0.0013	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09589 ± 0.00046	0.09635 ± 0.00051	$0.0981^{+0.0016}_{-0.0018}$	0.09633 ± 0.00029	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8118 ± 0.0089	0.793 ± 0.011	0.796 ± 0.018	0.8120 ± 0.0073	0.8111 ± 0.0060	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$.	0.840 ± 0.024	0.794 ± 0.024	$0.781^{+0.052}_{-0.060}$	0.834 ± 0.016	0.832 ± 0.013	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.611 ± 0.012	0.587 ± 0.012	0.583 ± 0.027	0.6090 ± 0.0081	0.6078 ± 0.0064	0.6051 ± 0.0058
z_{re}	7.50 ± 0.82	$7.11^{+0.91}_{-0.75}$	$7.10^{+0.87}_{-0.73}$	7.68 ± 0.79	7.67 ± 0.73	7.82 ± 0.71
$10^9 A_s$	2.092 ± 0.034	2.045 ± 0.041	2.116 ± 0.047	$2.101^{+0.031}_{-0.034}$	2.100 ± 0.030	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.884 ± 0.014	1.851 ± 0.018	1.904 ± 0.024	1.884 ± 0.012	1.883 ± 0.011	1.881 ± 0.010
Age [Gyr]	13.830 ± 0.037	13.761 ± 0.038	$13.64^{+0.16}_{-0.14}$	13.800 ± 0.024	13.797 ± 0.023	13.787 ± 0.020
z_*	1090.30 ± 0.41	1089.57 ± 0.42	$1087.8^{+1.6}_{-1.7}$	1089.95 ± 0.27	1089.92 ± 0.25	1089.80 ± 0.21
r_* [Mpc]	144.46 ± 0.48	144.95 ± 0.48	144.29 ± 0.64	144.39 ± 0.30	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04097 ± 0.00046	1.04156 ± 0.00049	1.04001 ± 0.00086	1.04109 ± 0.00030	1.04110 ± 0.00031	1.04119 ± 0.00029
z_{drag}	1059.39 ± 0.46	1060.03 ± 0.54	1063.2 ± 2.4	1059.93 ± 0.30	1059.94 ± 0.30	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.48	147.59 ± 0.49	146.46 ± 0.70	147.05 ± 0.30	147.09 ± 0.26	147.21 ± 0.23
k_D [Mpc^{-1}]	0.14054 ± 0.00052	0.14043 ± 0.00057	0.1426 ± 0.0012	0.14090 ± 0.00032	0.14087 ± 0.00030	0.14078 ± 0.00028
z_{eq}	3411 ± 48	3349 ± 46	3340^{+81}_{-92}	3407 ± 31	3402 ± 26	3387 ± 21
k_{eq} [Mpc^{-1}]	0.01041 ± 0.00014	0.01022 ± 0.00014	$0.01019^{+0.00025}_{-0.00028}$	0.010398 ± 0.000094	0.010384 ± 0.000081	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4483 ± 0.0046	0.4547 ± 0.0045	0.4562 ± 0.0092	0.4490 ± 0.0030	0.4494 ± 0.0026	0.4509 ± 0.0020
f_{2000}^{143}	31.2 ± 3.0			29.5 ± 2.7	29.6 ± 2.8	29.4 ± 2.7
$f_{2000}^{143\times217}$	33.6 ± 2.0			32.2 ± 1.9	32.3 ± 1.9	32.1 ± 1.9
f_{2000}^{217}	108.2 ± 1.9			107.0 ± 1.8	107.1 ± 1.8	106.9 ± 1.8

So what can we learn from the spatial distribution of galaxies on the sky?

In forming the Big Bang model of the universe and the Friedmann equations, one thing we assumed is that the universe is isotropic and homogeneous

This is true in a statistical sense

But as you all know it isn't



However at the largest scales the universe is homogeneous (at least in a statistical sense)

Spatial Distribution of Galaxies on some part of sky

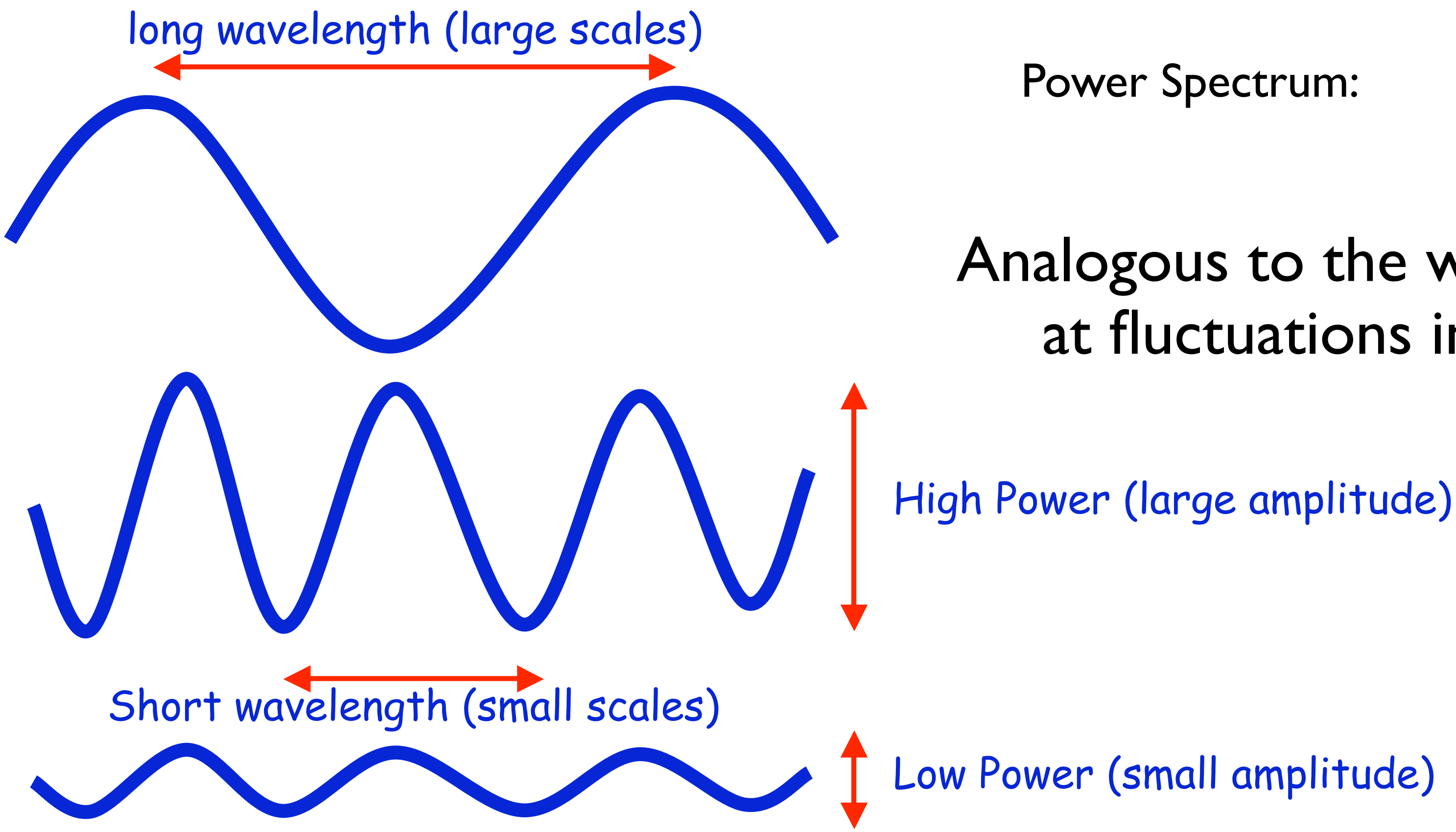
How do we express this spatial structure (density perturbations in the universe)?

Convenient to express it in terms of Fourier modes:

Subtract off mean density: $\delta(\vec{r}) = \frac{\rho - \bar{\rho}}{\bar{\rho}} = \frac{\Delta\rho}{\bar{\rho}}$

Fourier Transform: $\delta_k = \sum \delta(\vec{r}) e^{-i\mathbf{k}\bullet\mathbf{r}}$

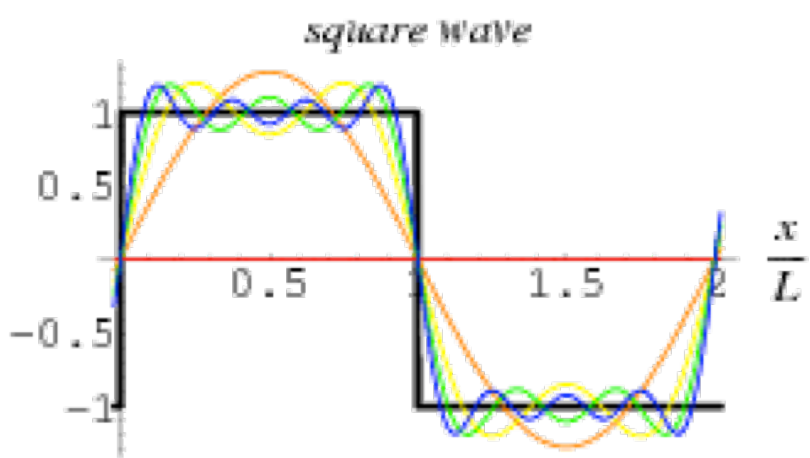
Power Spectrum: $P(k) = \langle |\delta_k|^2 \rangle$

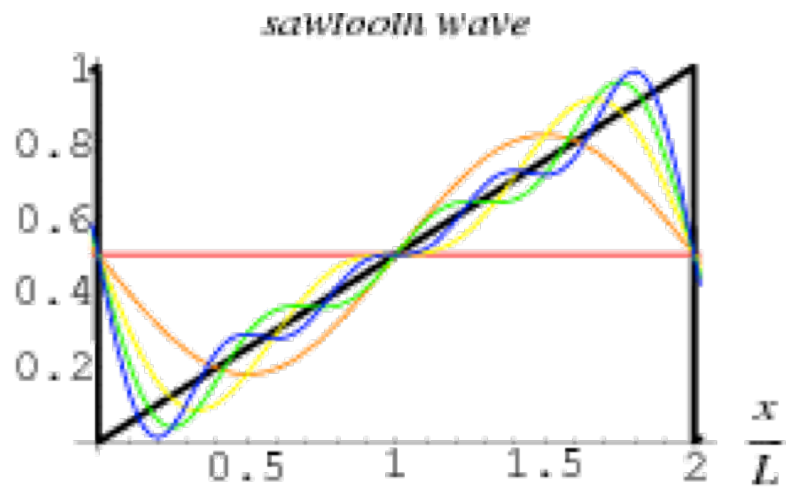


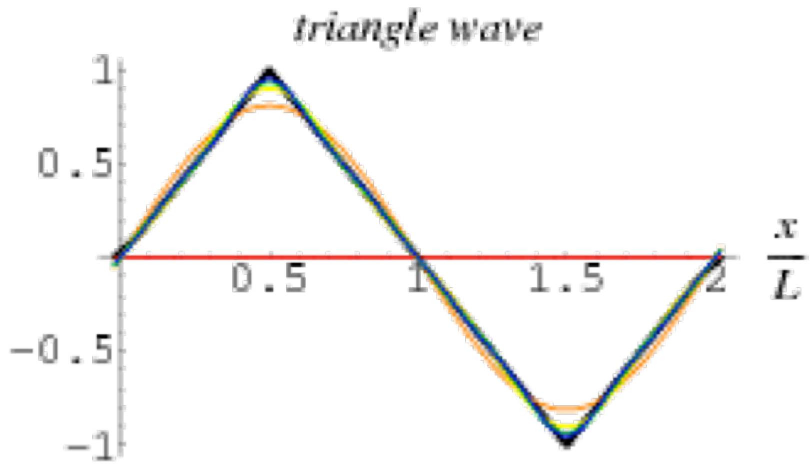
Analogous to the way we looked at fluctuations in the CMB

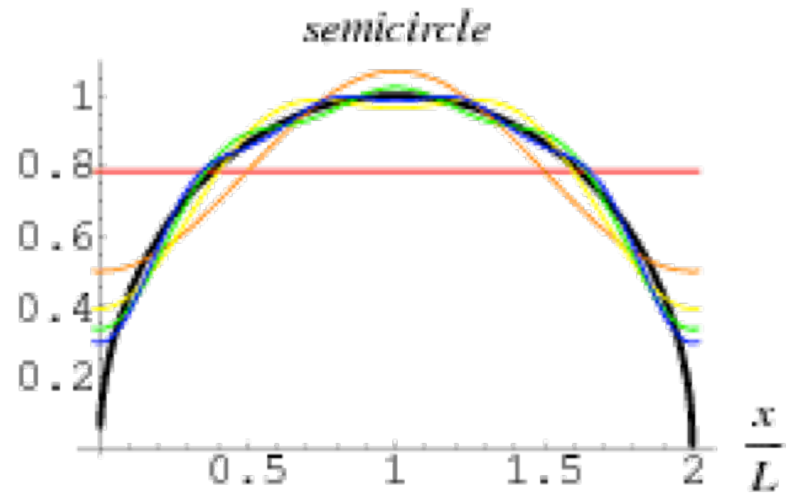
Similar concept to Fourier Series

-- Most of you are probably familiar with the fact that one can use a fourier series to represent an arbitrary one-dimensional function









Can express structure in universe in terms of power spectrum

What is the primordial power spectrum?

What is the primordial power spectrum?

The initial power spectrum of fluctuations is the following:

$$P_0(k) = A\, k^{n_s}$$

A is the normalization and n_s is the power-law slope. From inflation, n_s is thought to be almost exactly equal to one. This is the Harrison-Zeldovich power spectrum.

A power law makes sense for the primordial power spectrum since it has no characteristic scale.

What is the primordial power spectrum?

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Density Fluctuations in Universe expected to be Gaussian, homogeneous, isotropic (modes are uncorrelated)

$$\wp(\delta) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left(\frac{\delta}{2\sigma^2}\right)}$$

Gaussian-random field

all information in power spectrum

What is the primordial power spectrum?

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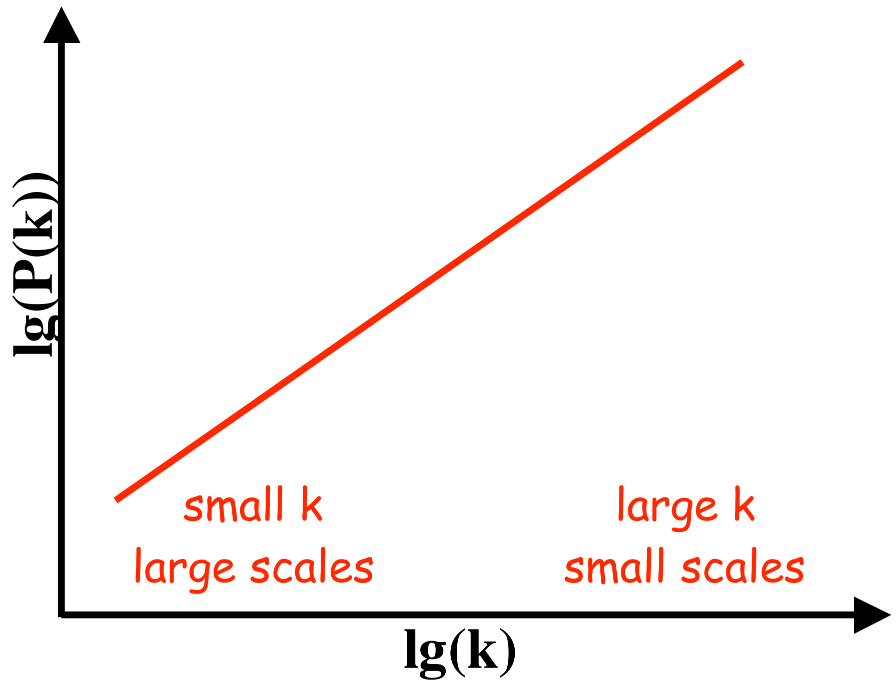


Credit: Pearson

To simplest approximation, it can be expressed in terms of growing modes...

$$P(k, t) = D_+^2(t)\, P(k, t_0) =: D_+^2(t)\, P_0(k)$$

where P(k,t) is the power spectrum at some later time and D(t) is the growth factor.

In the linear growth regime (before modes start turning around and collapsing and virializing), the time t and mode k are totally separable in the above equation.

How fast does the power spectrum grow?

During the epoch where radiation dominates the energy density ($z > 3500$), no significant growth in structure occurs -- except at scales larger than the horizon, where the growth goes as R^2 (R = scale of universe)

During the epoch where matter dominates ($z < 3500$), the growth goes as R (R = scale of universe)

How fast does the power spectrum grow?

During the epoch where radiation dominates the energy density ($z > 3500$), no significant growth in structure occurs -- except at scales larger than the horizon, where the growth goes as R^2 (R = scale of universe)

Implication is that growth in causally connected regions (i.e., within the horizon) will not grow at early times

But structure at large scales (super horizon scale) will grow

Recall from earlier in semester

Epoch of Matter-Radiation Equality (z=3500)

Energy Density in Dark Energy

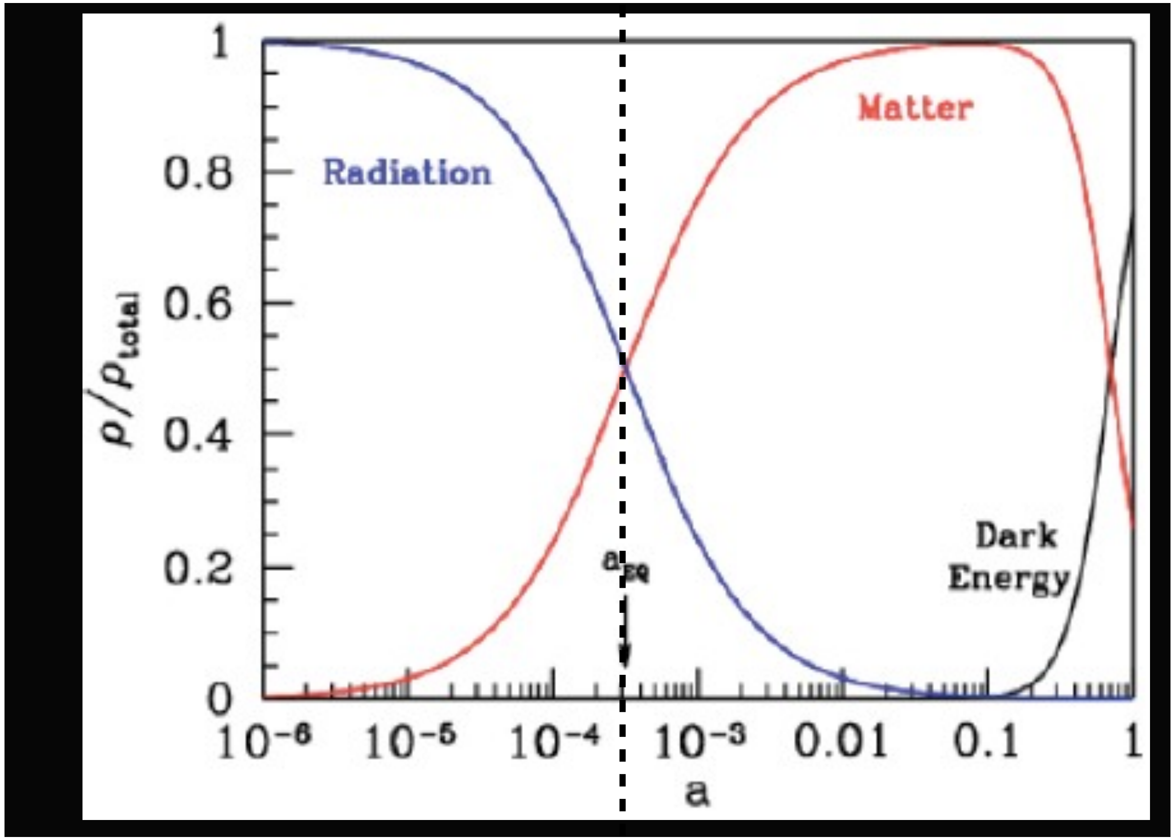
$\Lambda = \text{const}$ (dominant at late times)

Energy Density in Matter

$\rho_m \propto R^{-3}$

Energy Density in Radiation

$\rho_r \propto R^{-4}$ (dominant at earliest times)



P(k) below horizon does not grow

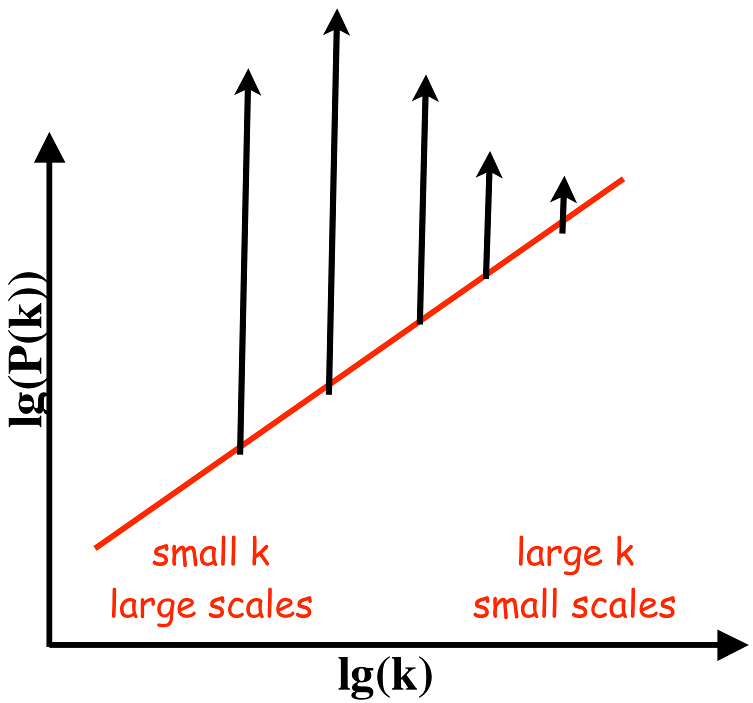
P(k) can grow

What is the primordial power spectrum?

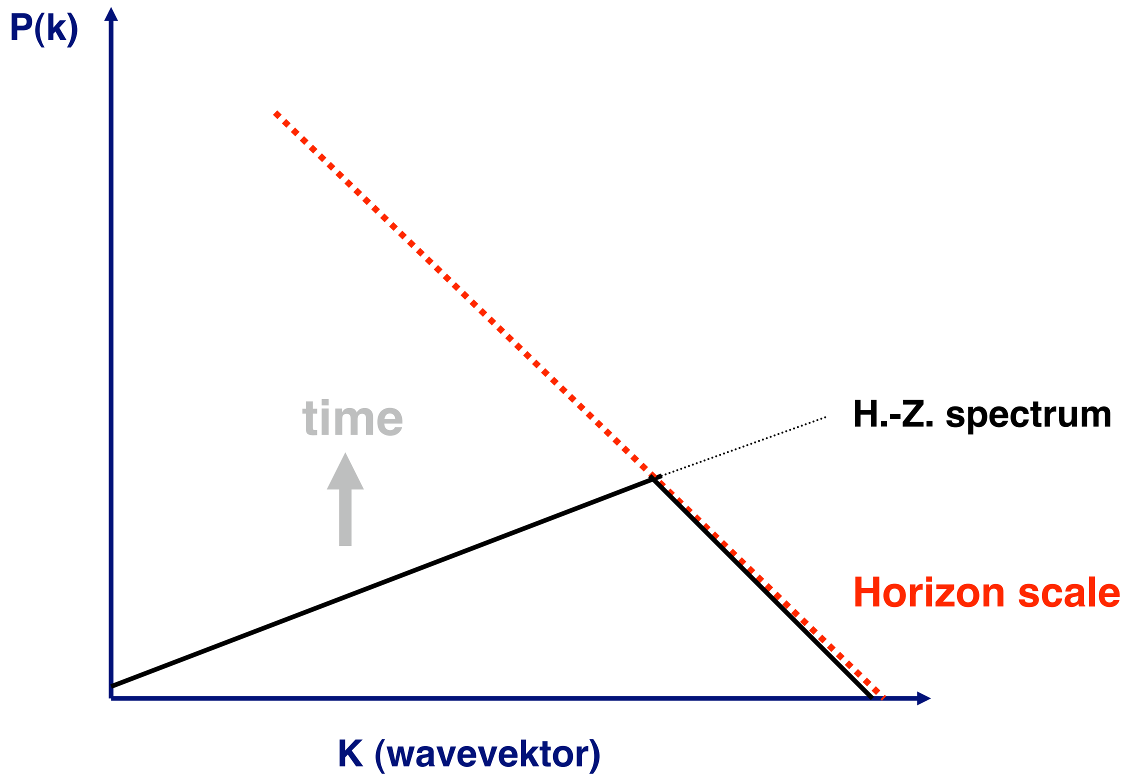
The initial power spectrum of fluctuations is the following:

$$P_0(k) = A\, k^{n_s}$$

Therefore we could expect P(k) at large scales to grow much more than at small scales



Evolution of the Matter Power Spectrum

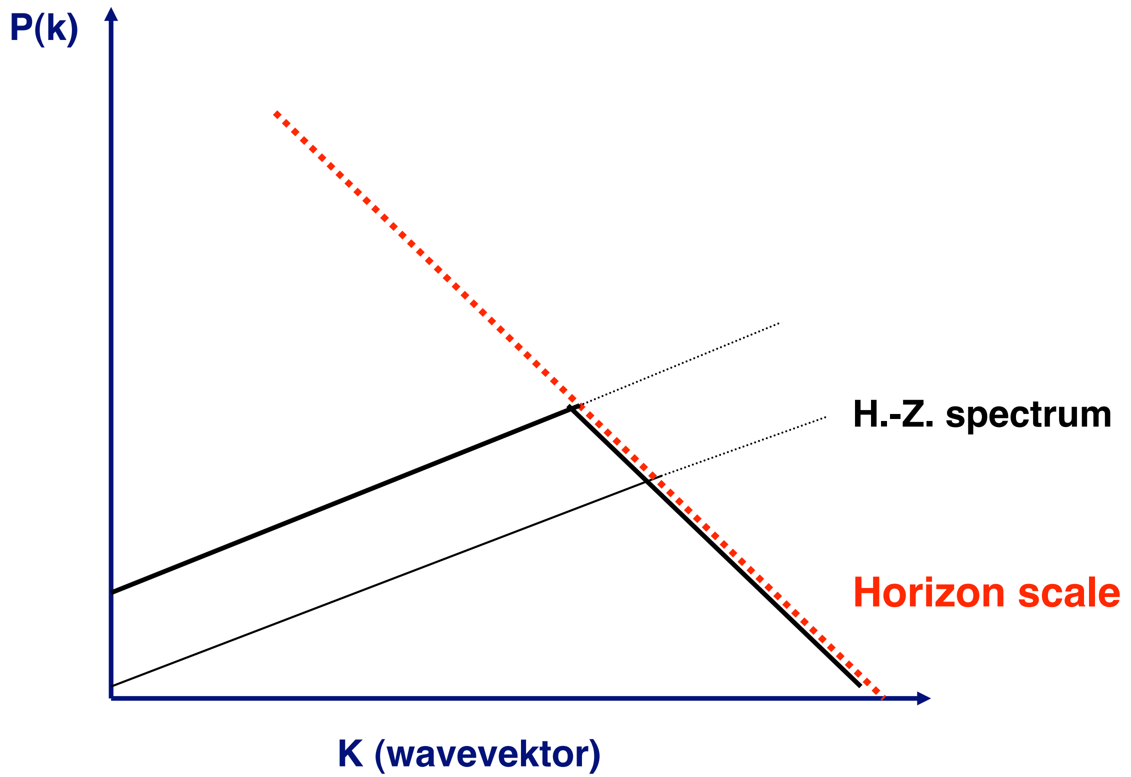


large scales
small k

small scales
large k

Credit: Bohringer

Evolution of the Matter Power Spectrum



large scales
small k

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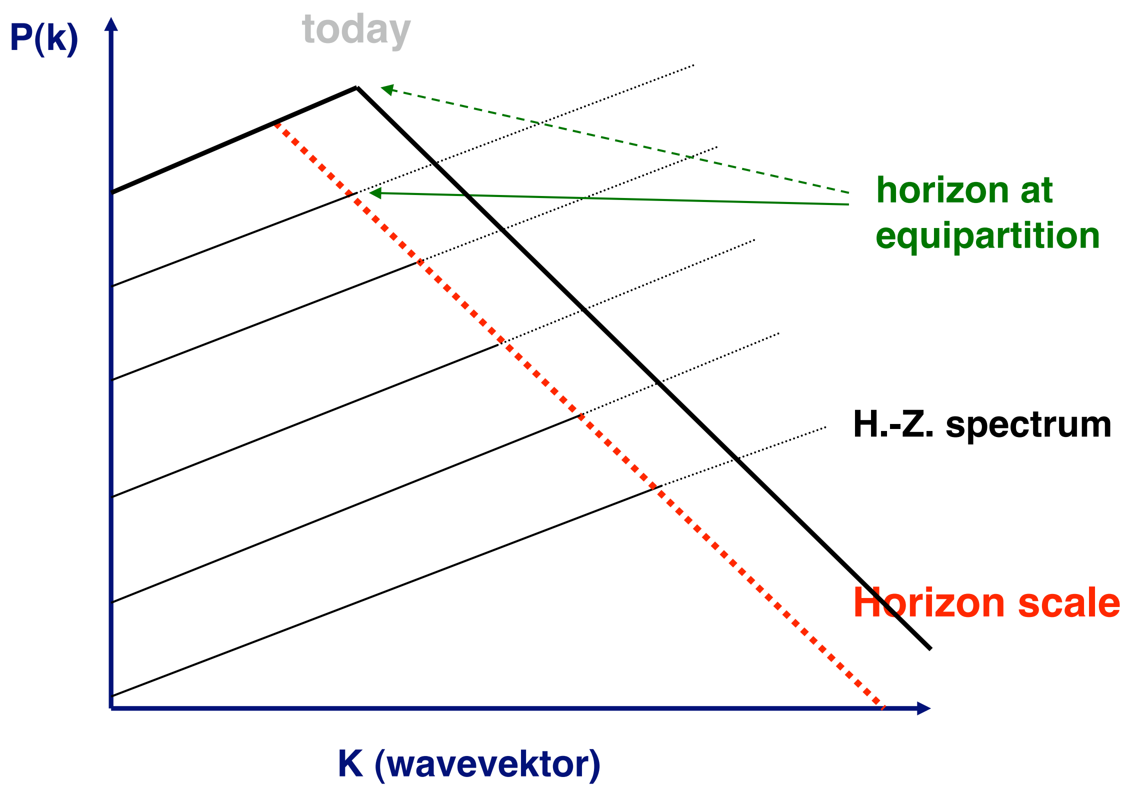
large k

Credit: Bohringer

Evolution of the Matter Power Spectrum



large scales
small k

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large k

Credit: Bohringer

What is the primordial power spectrum?

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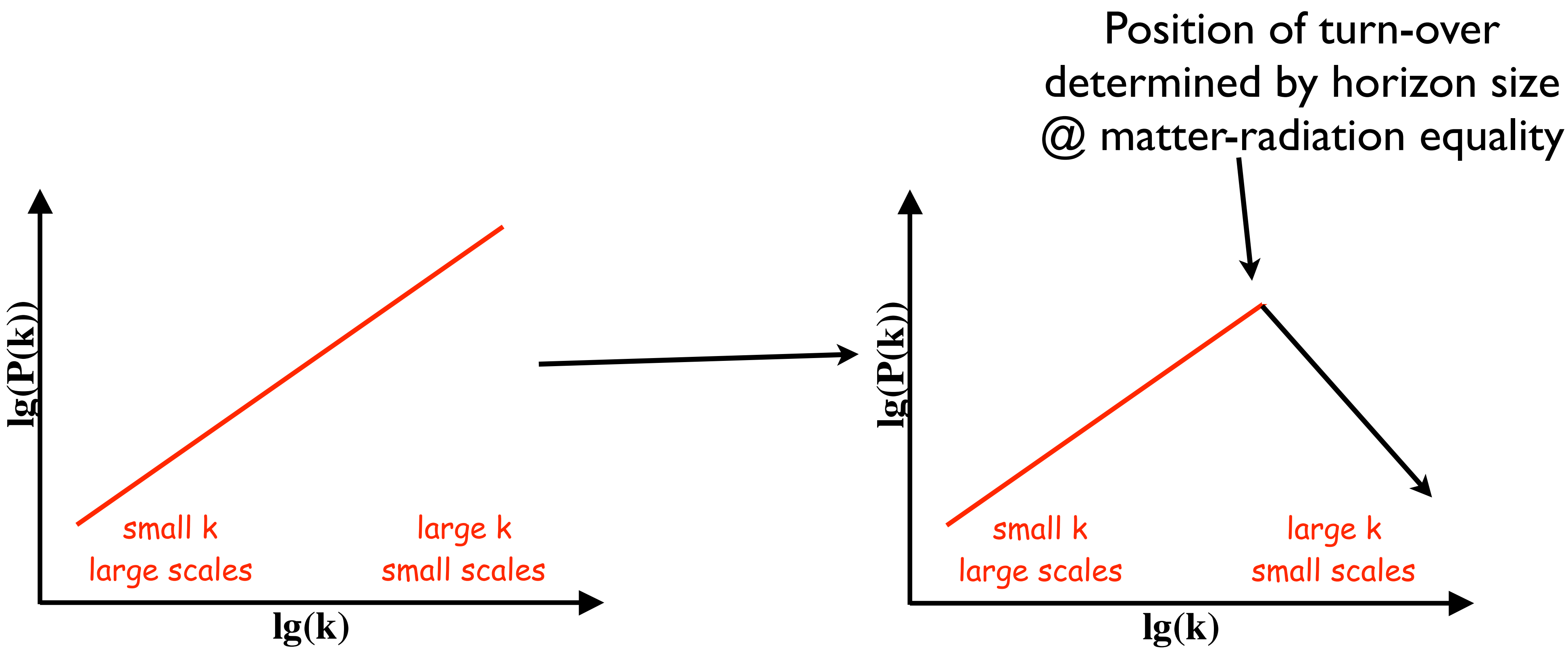


How does the power spectrum grow after the point of matter-radiation equality?

The power spectrum grows in proportion to R the size of the universe (won't derive this for you -- it is done in Joop's origin and evolution of universe)

How does one treat this formally?

Formally, one utilizes a transfer function to include these physics:

$$P_0(k) = A\, k^{n_s}\, T^2(k)$$

where T(k) is the transfer function.

The transfer function T(k) depends on the cosmological model and in particular on the quantity $\Gamma = \Omega_m h$. Γ is called the shape parameter.

The transfer function T(k) includes all physics involved in the growth of the primordial power spectrum to after recombination (and so some additional physics beyond what I mentioned)

How does one treat this formally?

Formally, one utilizes a transfer function to include these physics:

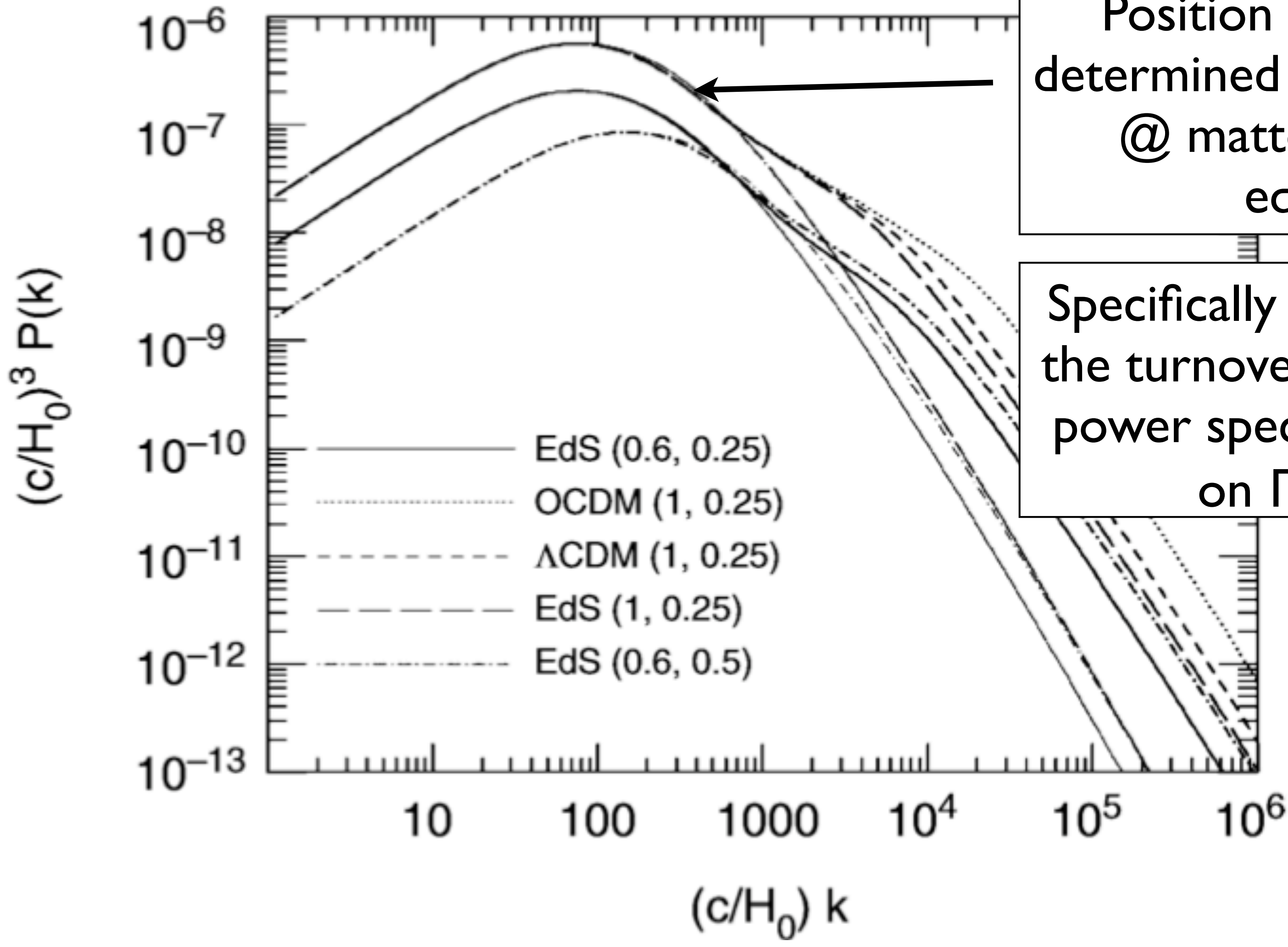
$$P_0(k) = A\, k^{n_s}\, T^2(k)$$

where T(k) is the transfer function.

Other important effects to include are the free streaming of relativistic matter/radiation (energy density in relativistic components of universe at recombination) which washes out power at small scales

Other important effects to include are baryons falling into the dark matter potential after recombination.

What does the matter power spectrum look like when all of these effects are included?

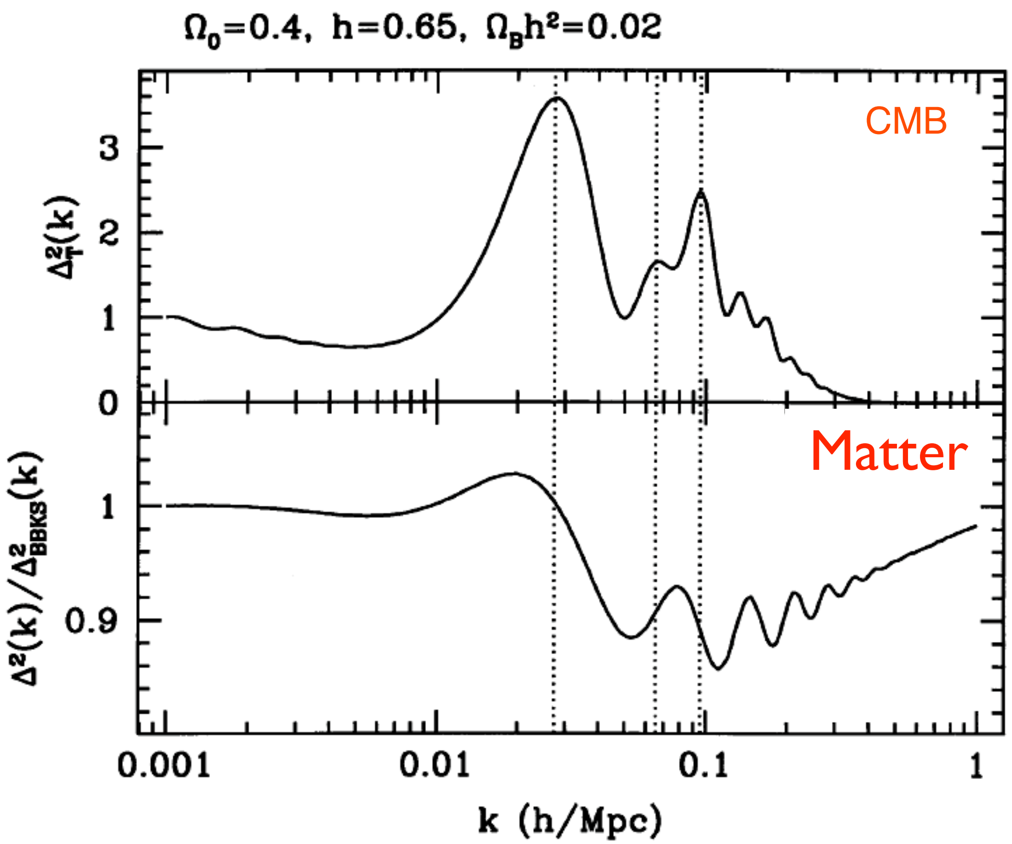


Position of turn-over determined by horizon size @ matter-radiation equality

Specifically the position of the turnover in the matter power spectrum depends on $\Gamma = \Omega_m h$

How does the CMB and large scale structure fit into this?

Matter Power Spectrum after Dividing Out Rough Shape

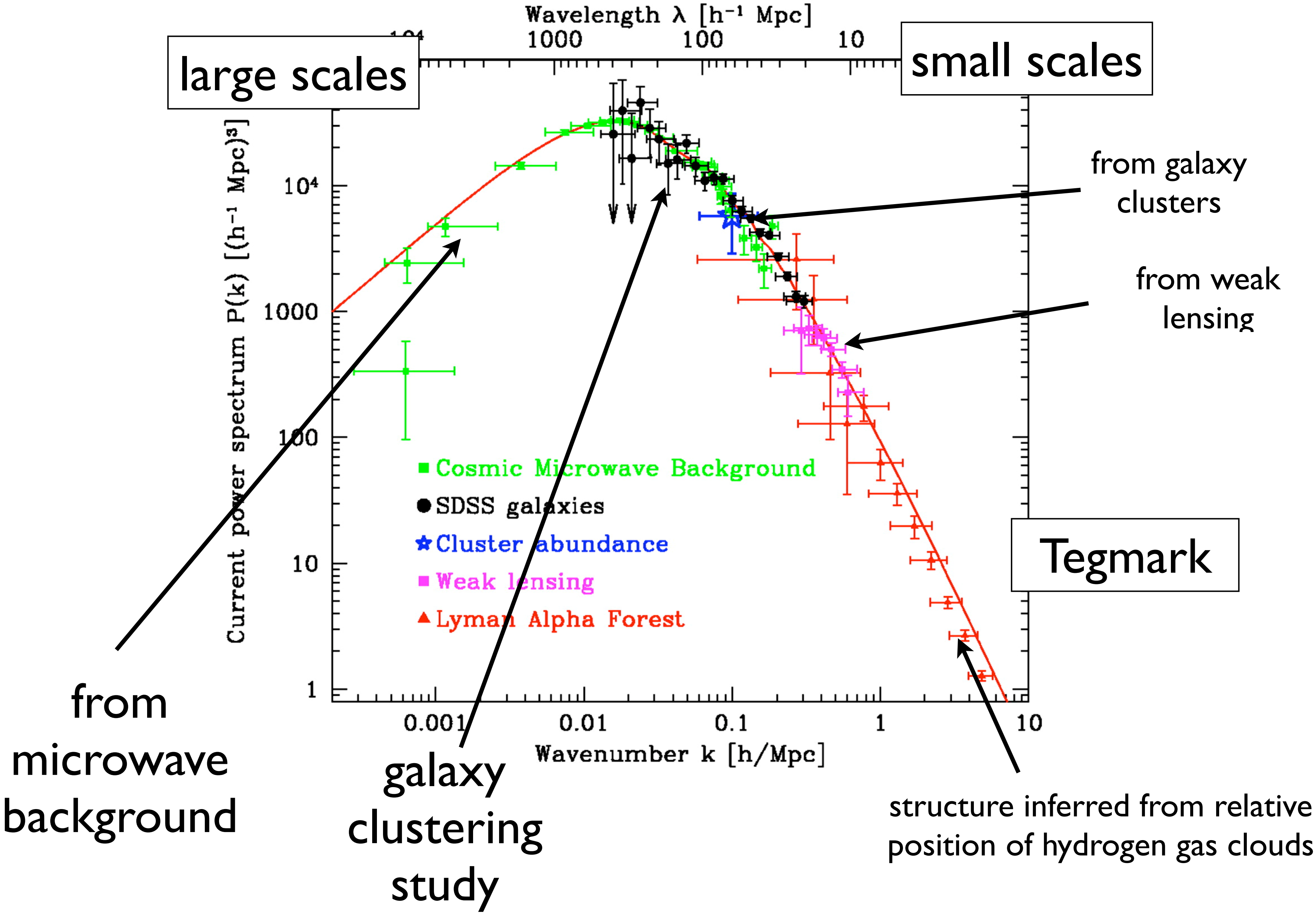


CMB and LSS out of phase

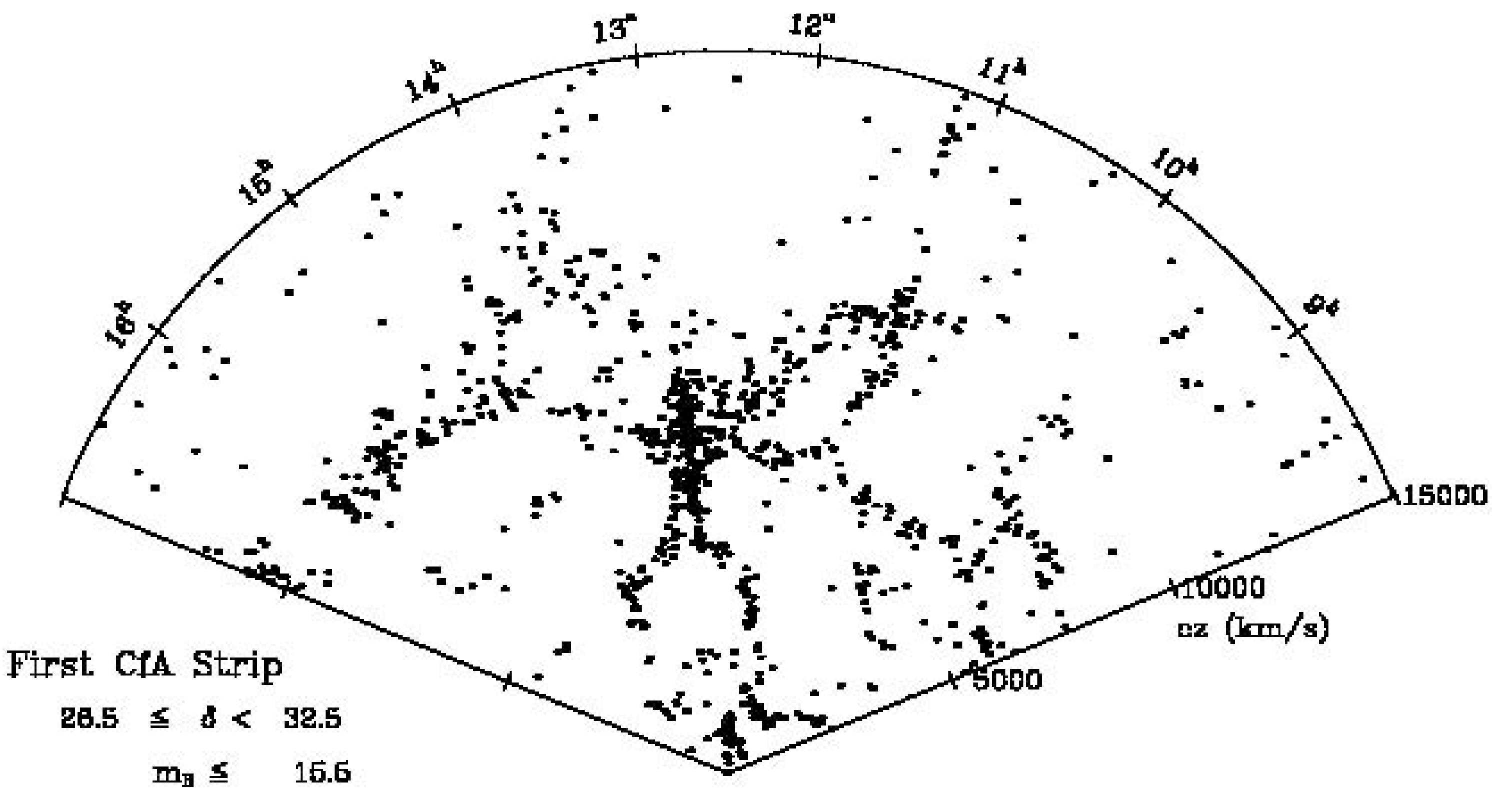
LSS amplitude smaller than CMB

The matter power spectrum is one of the most important parameters to derive in observational cosmology.

Different techniques/sources probe different regimes in matter power spectrum

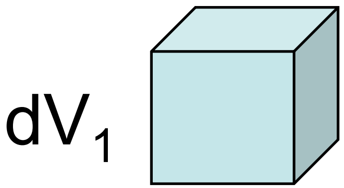


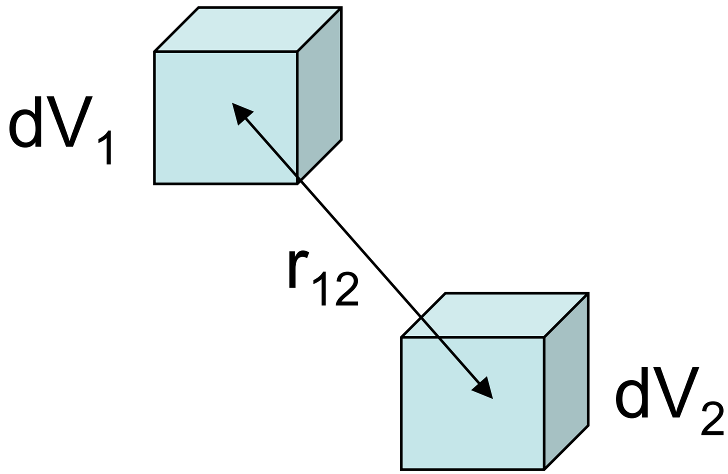
We can derive the matter power spectrum from the clustering of galaxies on sky



We quantify clustering in terms of correlation functions

The Correlation function ξ tells us -- given the existence of a galaxy in some volume dV_1 -- how much more likely we are to find a nearby galaxy at some distance r_{12}





$$dP_1 = n\, dV_1$$

$$dP_{12} = n^2\,(1 + \xi(r_{12}))\, dV_1\, dV_2$$

n = average density of galaxies

Why do we care about correlation functions?

The power spectrum is the Fourier transform of the correlation function ξ

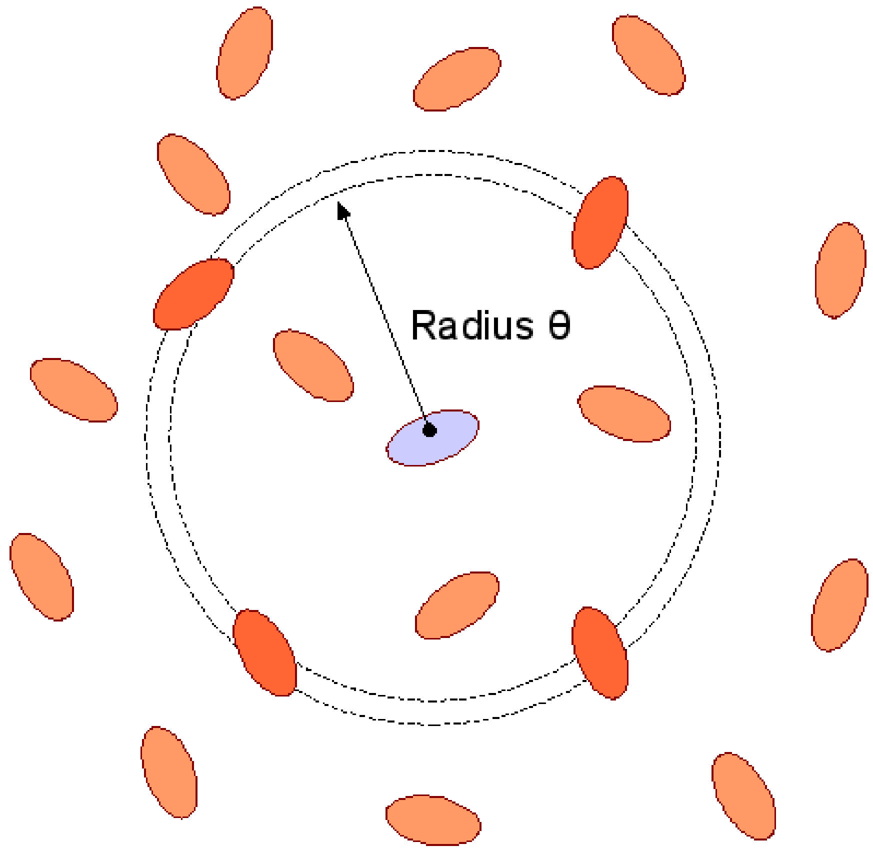
$$P(k) = \int \xi(r) e^{ik \bullet r} d^3 r \equiv \int \xi(r) \frac{\sin(kr)}{r} dr$$

We quantify clustering in terms of correlation functions

The Correlation function ξ is calculated by examining the distances between every pair of galaxies in a survey and comparing it to a random distribution

$\xi(r) > -1$ since probability always positive

$\xi(r) \rightarrow 0$ at $r \rightarrow \infty$



Correlations between points can be determined by counting pairs.

We quantify clustering in terms of correlation functions

One estimates the correlation function by comparing the number of sources seen at a given distance r and angle in the data D and comparing it to a purely random distribution R:

Standard Estimator : $w(r) = (2DD/DR) - 1$

Landy & Szalay- SL Estimator : $w(r) = (DD - 2DR + RR)/RR$

Smaller uncertainties on large scales

Hamilton Estimator : $w(r) = 4(DD\text{x}DR)/(DR^2 - 1)$

We quantify clustering in terms of correlation functions

The Correlation function ξ is typically parametrized as a power-law in radius:

$$\xi_{\mathrm{g}}(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

Typical values for γ are 1.8. r_0 is known as the correlation length and it tells us the typical distance from a source we can expect a large enhancement in neighboring sources

We quantify clustering in terms of correlation functions

The Correlation function ξ is typically parametrized as a power-law in radius:

$$\xi_{\mathrm{g}}(r) = \left(\frac{r}{r_0}\right)^{-\gamma}$$

Red galaxies have a larger correlation length than blue galaxies. Typical r_0's for red galaxies at 5 h^{-1}Mpc and for blue galaxies 3 h^{-1}Mpc.

What are the typical properties of the correlation function?

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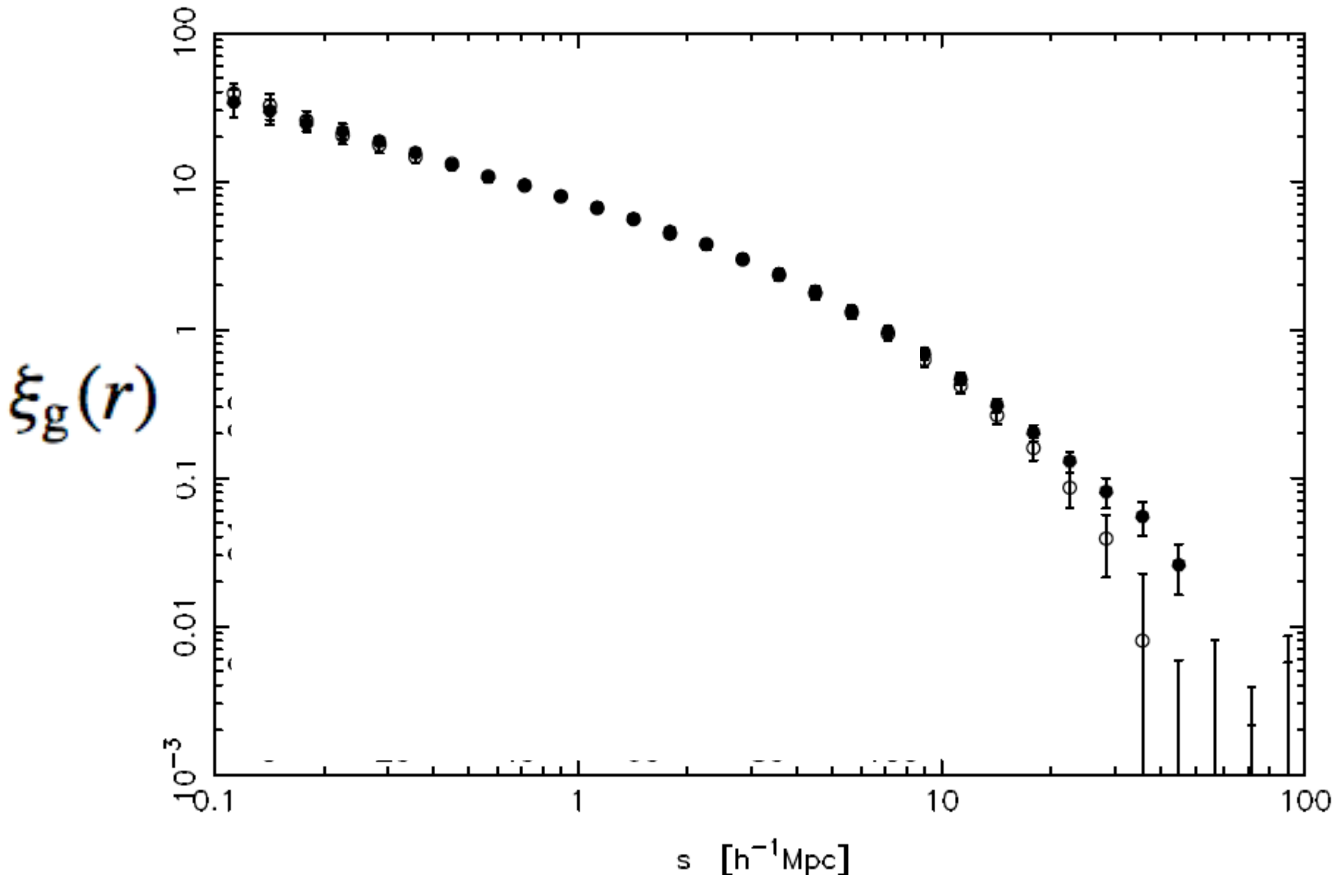
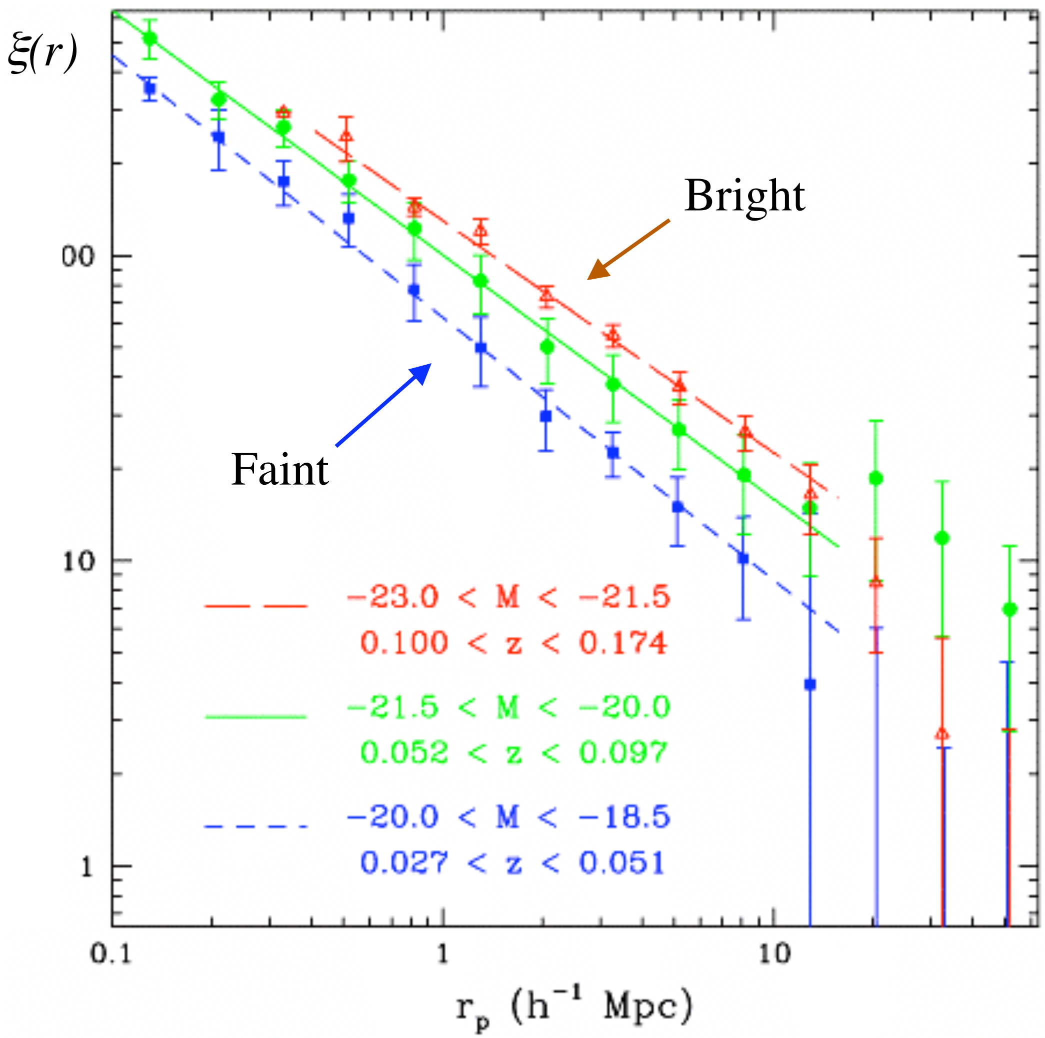


What are the typical properties of the correlation function?

Brighter, more massive galaxies have a larger correlation length than fainter, lower mass galaxies:



Red galaxies have a larger correlation length than blue galaxies. Typical r_0's for red galaxies at 5 h^{-1}Mpc and for blue galaxies 3 h^{-1}Mpc.

The different clustering properties of these galaxies tell us something about how they form

Angular Correlation Function

The Correlation function ξ that I've described thus far is the spatial correlation function.

There's also an angular correlation function $w(\theta)$ that one can measure -- when one knows the position of the sources on the sky and does not know their redshift

It makes sense that you could use the position of sources on the sky -- even without redshift information -- to measure clustering since if sources are close to each other in 3-dimensional space -- they will be close to each other in 2-dimensional space

Angular Correlation Function

It makes sense that you could use the position of sources on the sky -- even without redshift information -- to measure clustering since if sources are close to each other in 3-dimensional space -- they will be close to each

Of course, the observed clustering will be diluted depending on how large the redshift dimension is to one's samples

Angular Correlation Function

Therefore we can go from the angular correlation function to a spatial correlation function, but there's not *if* we know the distribution of galaxies in redshift.

There's a well-known equation called Limber's equation that relates the angular correlation function w(θ) to the spatial correlation function ξ(r)

$$w(\theta) = \int \mathrm{d}z\, p^2(z) \int \mathrm{d}(\Delta z)\ \times \xi_{\mathrm{g}} \left(\sqrt{[D_{\mathrm{A}}(z)\theta]^2 + \left(\frac{\mathrm{d}D}{\mathrm{d}z}\right)^2 (\Delta z)^2} \right)$$

where $D_A(z)$ is the angular diameter distance and p(z) is the redshift distribution of the sources.

Other Techniques for Quantifying Clustering

Of course, there are other techniques as well for quantifying clustering... counts in cells, void probability functions

Counts In Cell -- Divide the Space into Discrete Grid Points "Cells" and Calculate the Variation in the # of Sources per Grid Point

Void Probability Function -- Probability of Finding Zero Galaxies in a Volume of Radius R

We quantify clustering in terms of correlation functions

But we need samples of galaxies to derive these correlation functions...

How do we compile these samples?

How do we compile these samples?

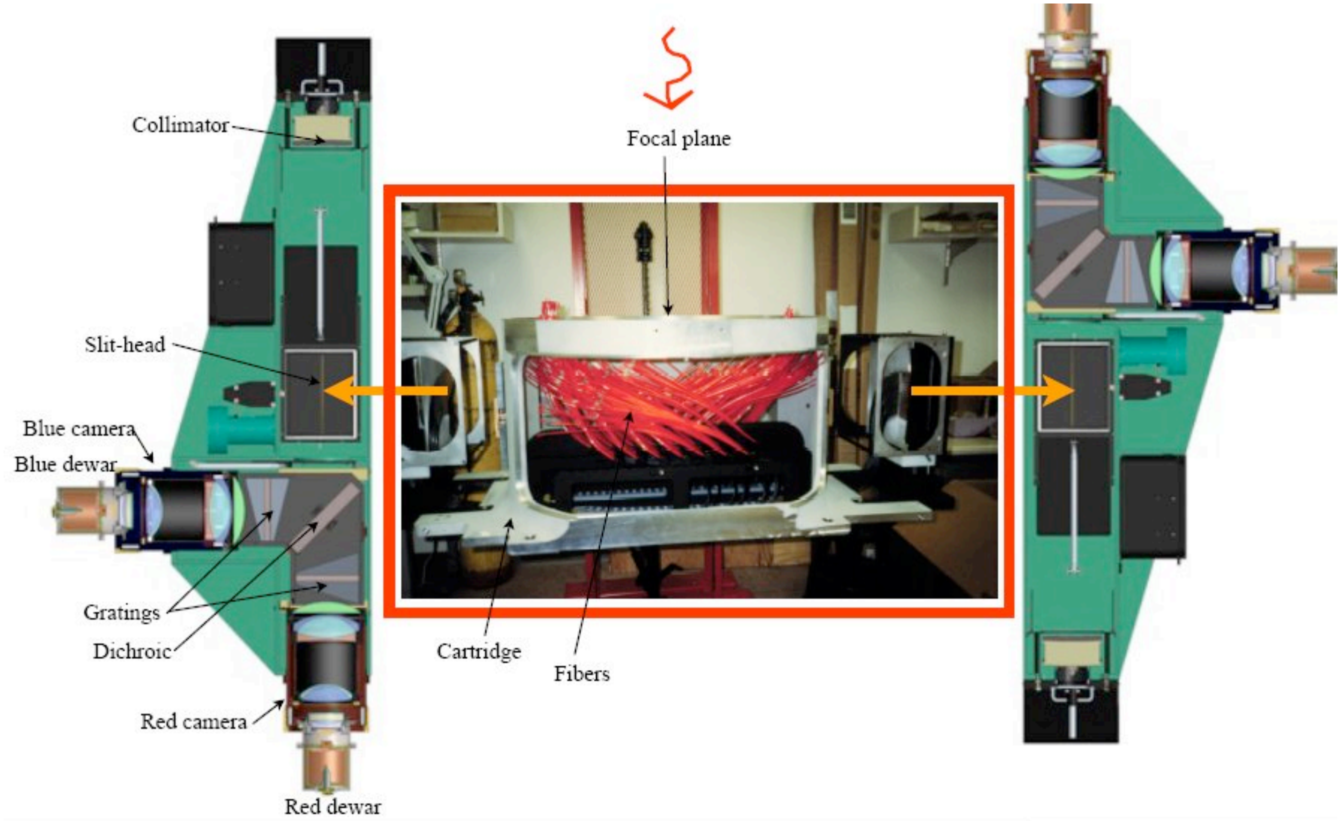
I. Obtaining multi-colour images of a large area of the sky

II. Create a catalogue and then select the sources over some range of brightness (and perhaps using some other criteria)

III. Measure redshifts for sources (to add third dimension)

How do we obtain redshifts for large numbers of sources?

(using a fiber)

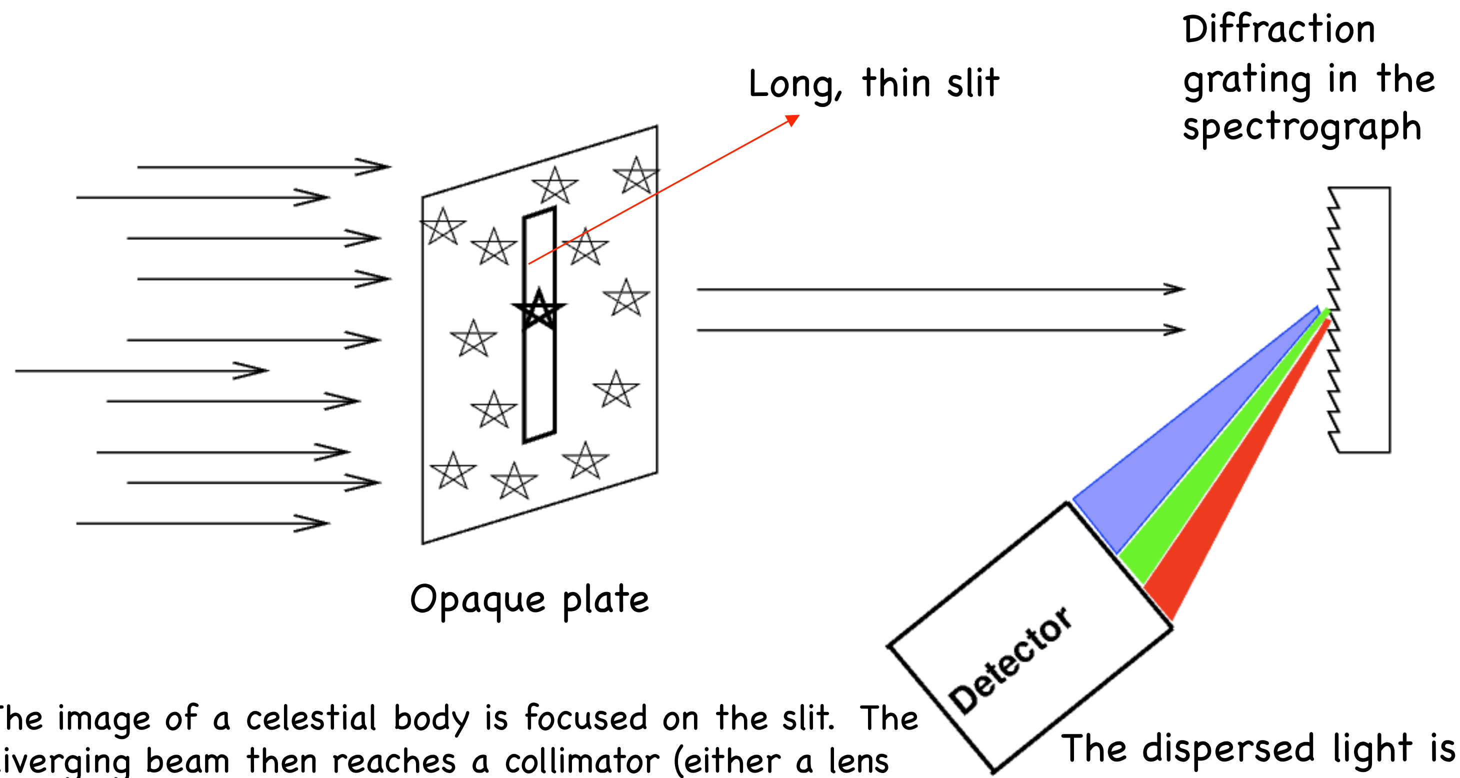


Why use fibers?

Can obtain spectra of > 100s of galaxies or stars per field by packing fibers closely

How do we obtain redshifts for large numbers of sources?

(using a slit)



The image of a celestial body is focused on the slit. The diverging beam then reaches a collimator (either a lens or a mirror - not shown -). This produces parallel light which is then dispersed by a diffraction grating.

The dispersed light is imaged on a detector (typically a CCD)

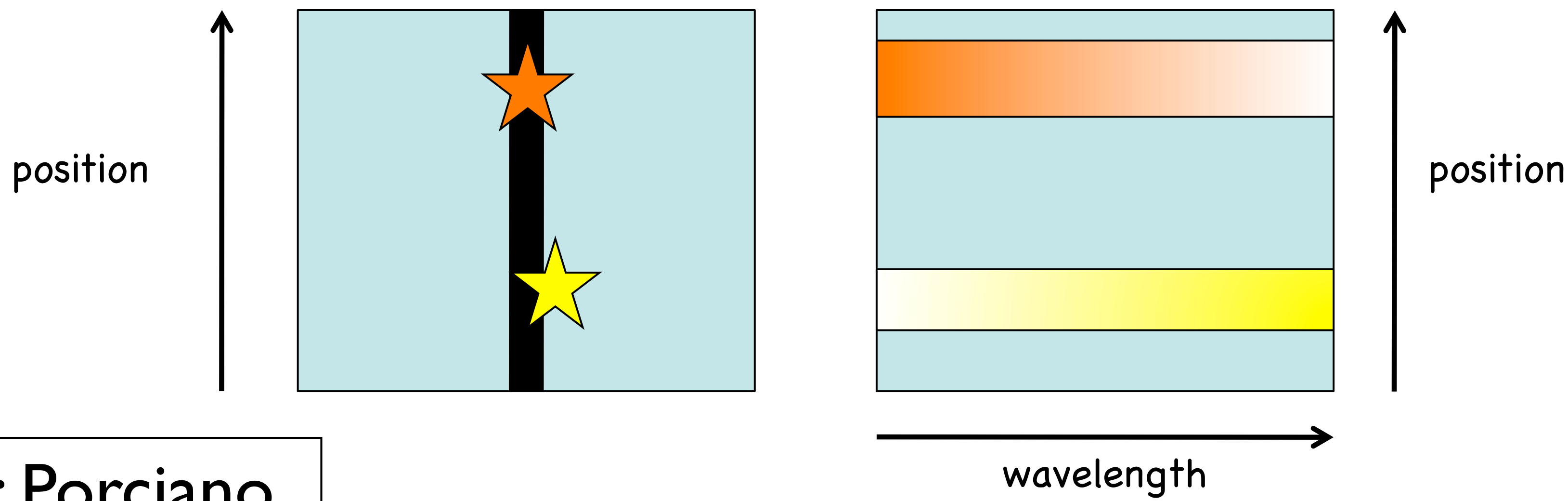
credit: Porciano

How do we obtain redshifts for large numbers of sources?

(using a slit)

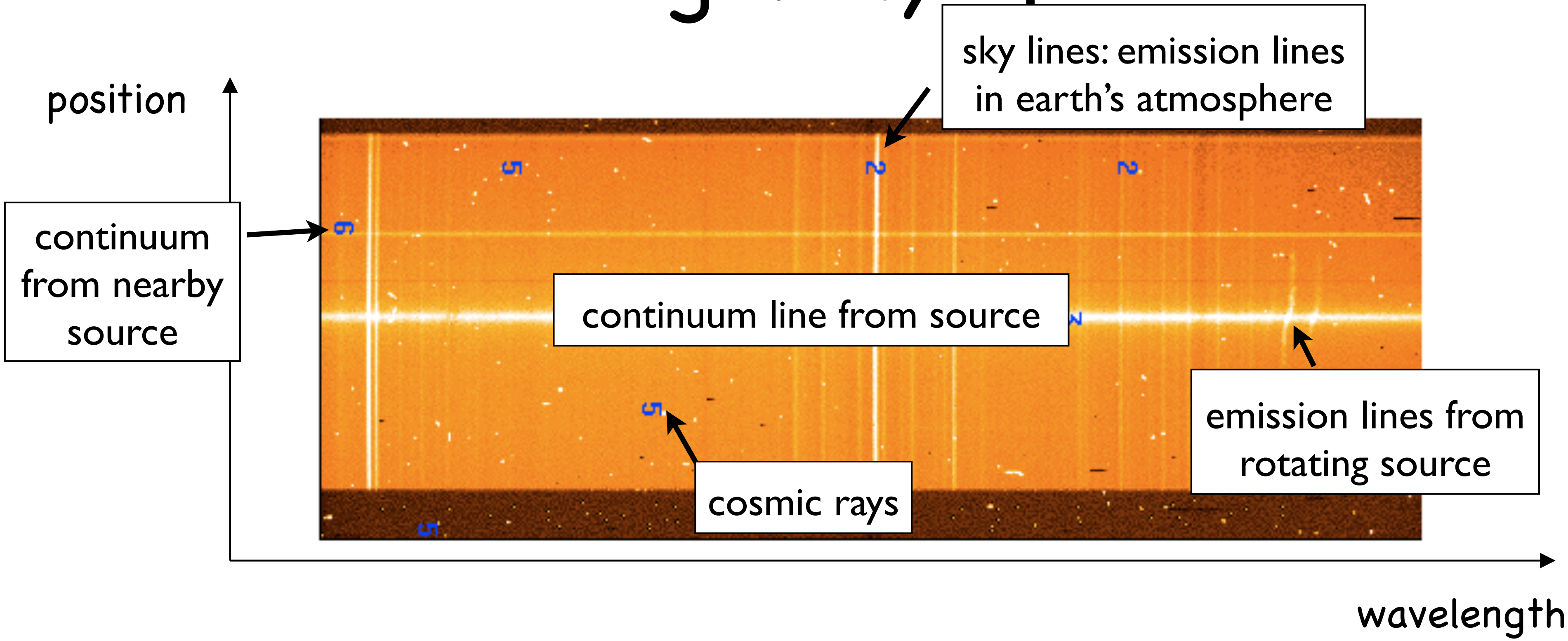
- Why using a slit? To keep out as much as background light as possible

- How does the output look like? 2D spectrum



credit: Porciano

A raw galaxy spectrum



- This is the typical output of a spectrograph mounted on a telescope.

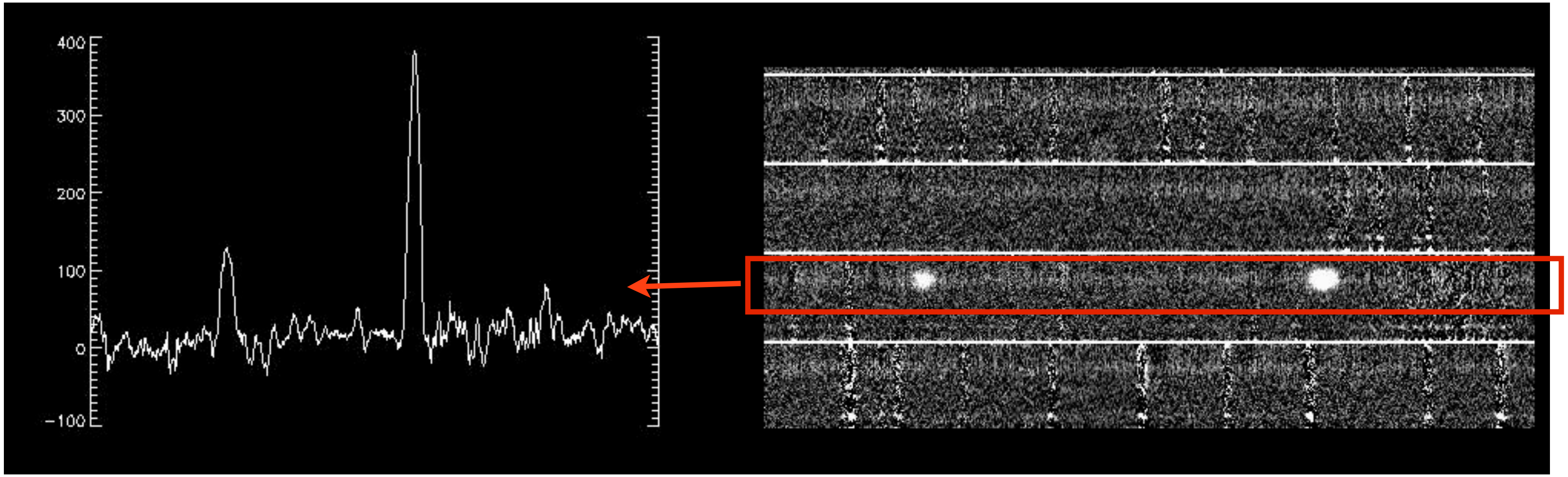
- Can you identify the origin of the different features?

credit: Porciano

Typically these two-dimensional spectra are converted into one-dimensional spectra

1D spectrum

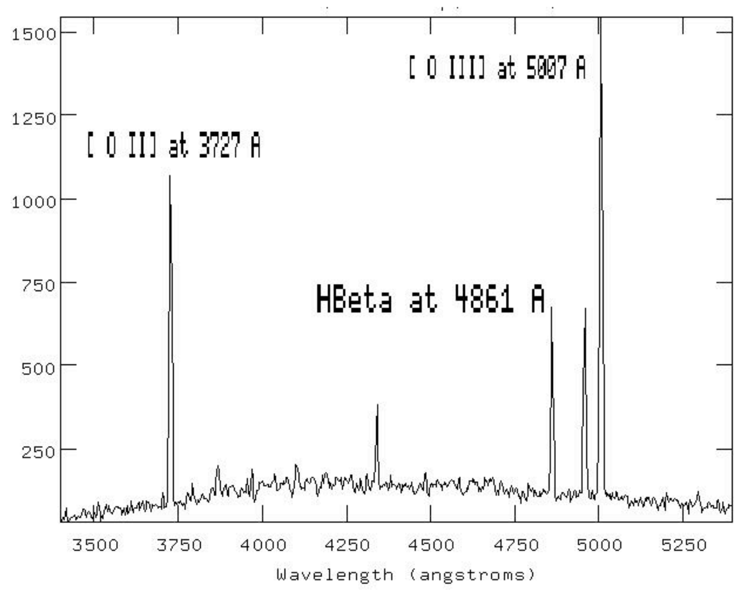
2D spectrum



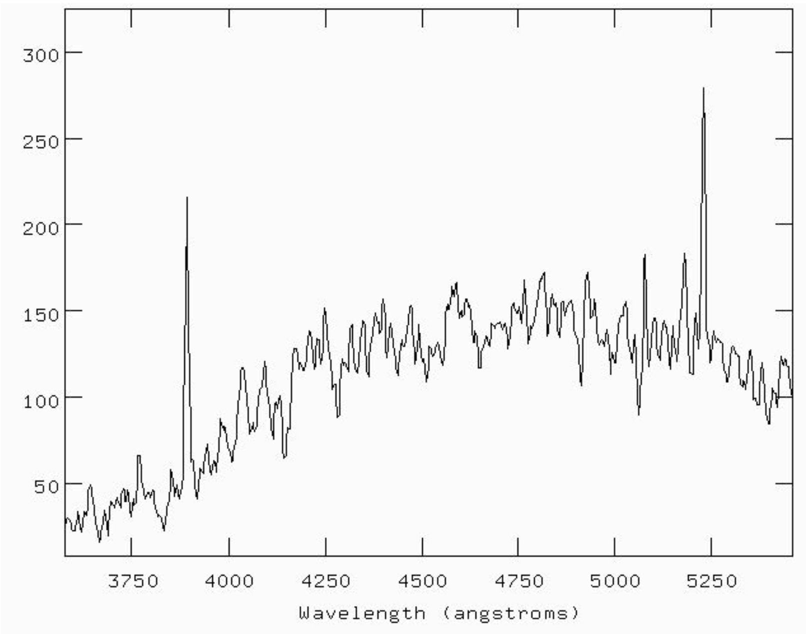
wavelength

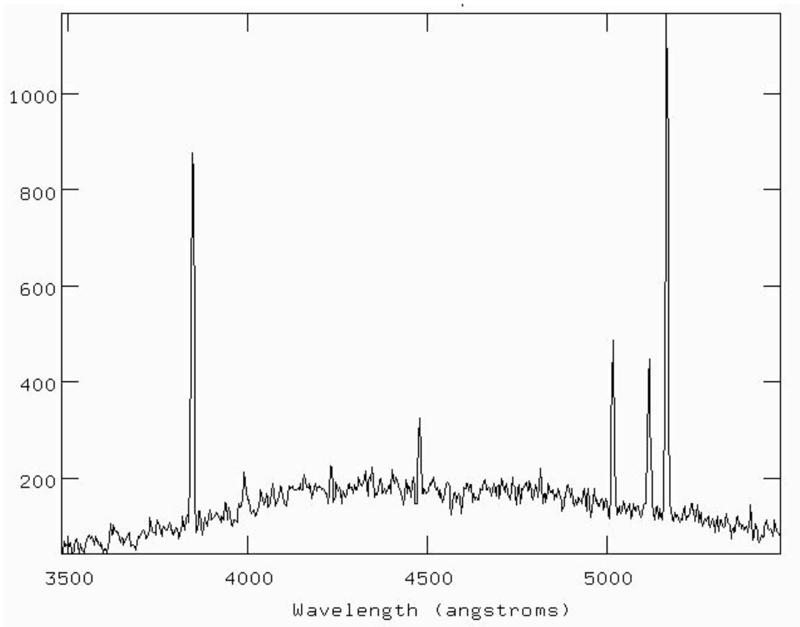
credit: Porciano

Measuring galaxy redshifts



Template spectrum at z=0





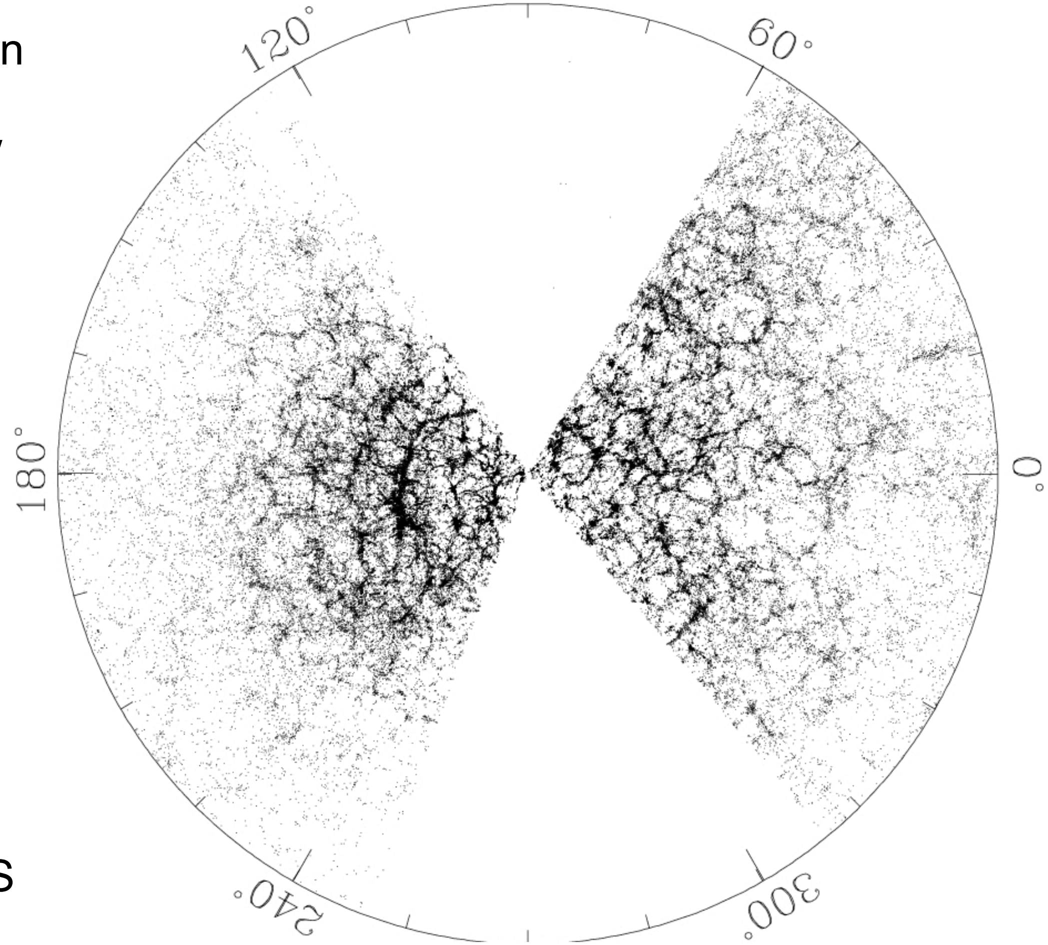
Measure redshifts by comparing with unredshifted template spectrum

credit: Porciano

Massive redshift surveys

- Multifibre technology, digitalization and multiobject spectrographs now allow us to measure redshift of millions of galaxies on a time scale of a few years.

- Recently completed or ongoing surveys: (local) 2dF, SDSS, 6dF (high-z) VVDS, DEEP2, zCOSMOS



credit: Porciano

The Sloan Digital Sky Survey

- Over eight years of operation (SDSS I, 2000-2005; SDSS II, 2005-2008; SDSS III, 2008-2014)

- It used a dedicated 2.5m telescope at Apache Point Observatory (New Mexico) equipped with 2 special purpose instruments: a 120 Mpixel camera imaging 1.5 sq. deg. of the sky at a time (8 times the area of the full moon); a pair of spectrographs fed by optical fibers (640 objects per pointing)

- It obtained deep multi-color images (u,g,r,i,z) covering more than a quarter of the sky (8,400 square degrees)

- Created 3D maps containing more than 930,000 galaxies and more than 120,000 quasars (in 5,700 square degrees)

credit: Porciano

What science do astronomers do with these big surveys?

measure many, many things...

- Luminosity function and number densities
- Group and cluster catalogs (FoF, Voronoi, BCG)

- The density field
- Reconstruct the linear density field (time machine)

- Counts in cells
- Measure 2-point, 3-point correlation function
- Measure power spectrum, bispectrum
- Topological invariants: Minkowski functionals (mean genus, void probability function)

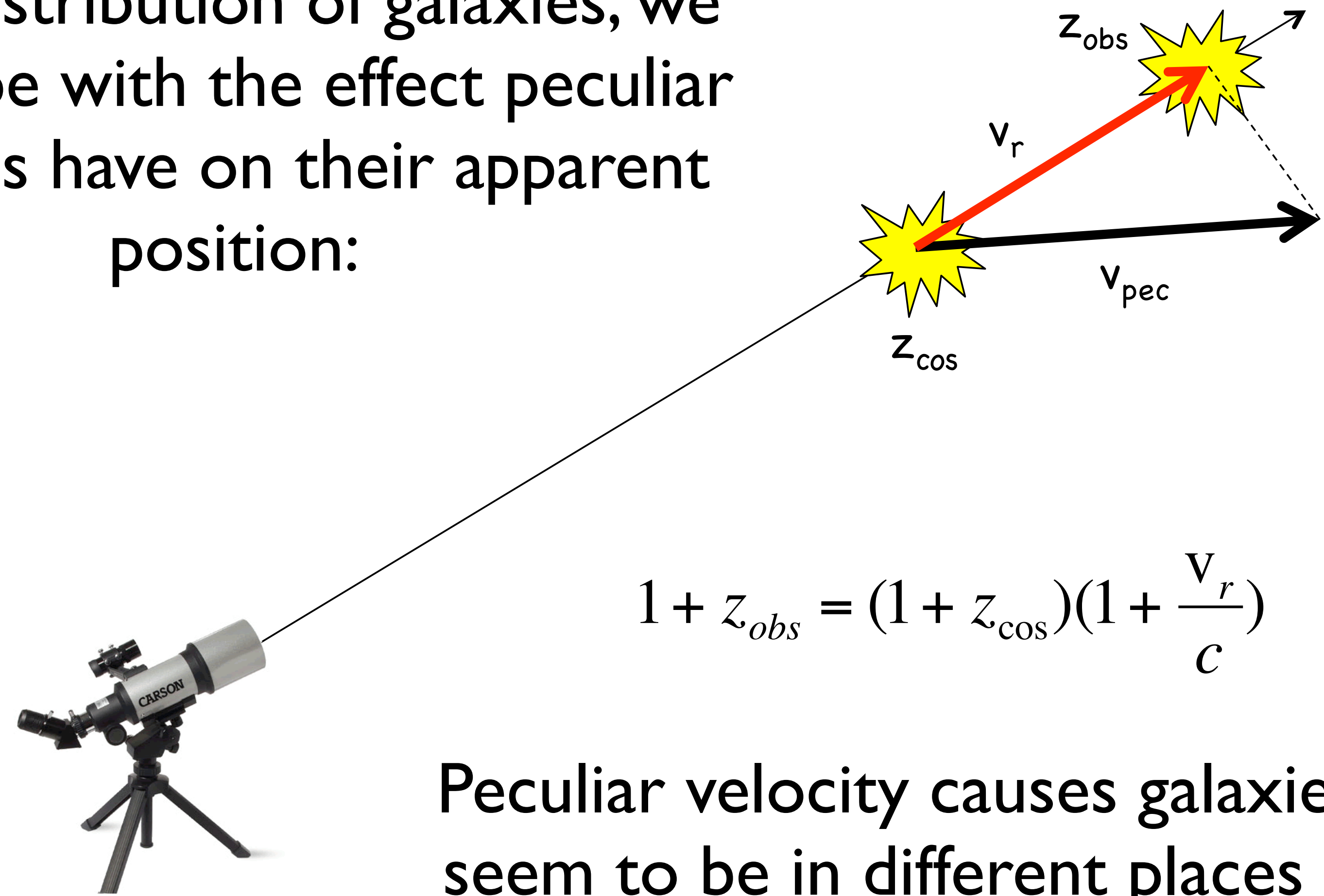
credit: Porciano

However there are a number of important complications...

Complication #1: Redshift Distortions

Redshift Space Distortions

When mapping the three-dimensional spatial distribution of galaxies, we must cope with the effect peculiar velocities have on their apparent position:



$$1 + z_{obs} = (1 + z_{\cos})(1 + \frac{v_r}{c})$$

Peculiar velocity causes galaxies to seem to be in different places that they really are

credit: Porciano

Redshift Space Distortions

For example, let's say we're looking at two galaxies which are the same distance from us, but one is moving towards us and the other is moving away

REALITY

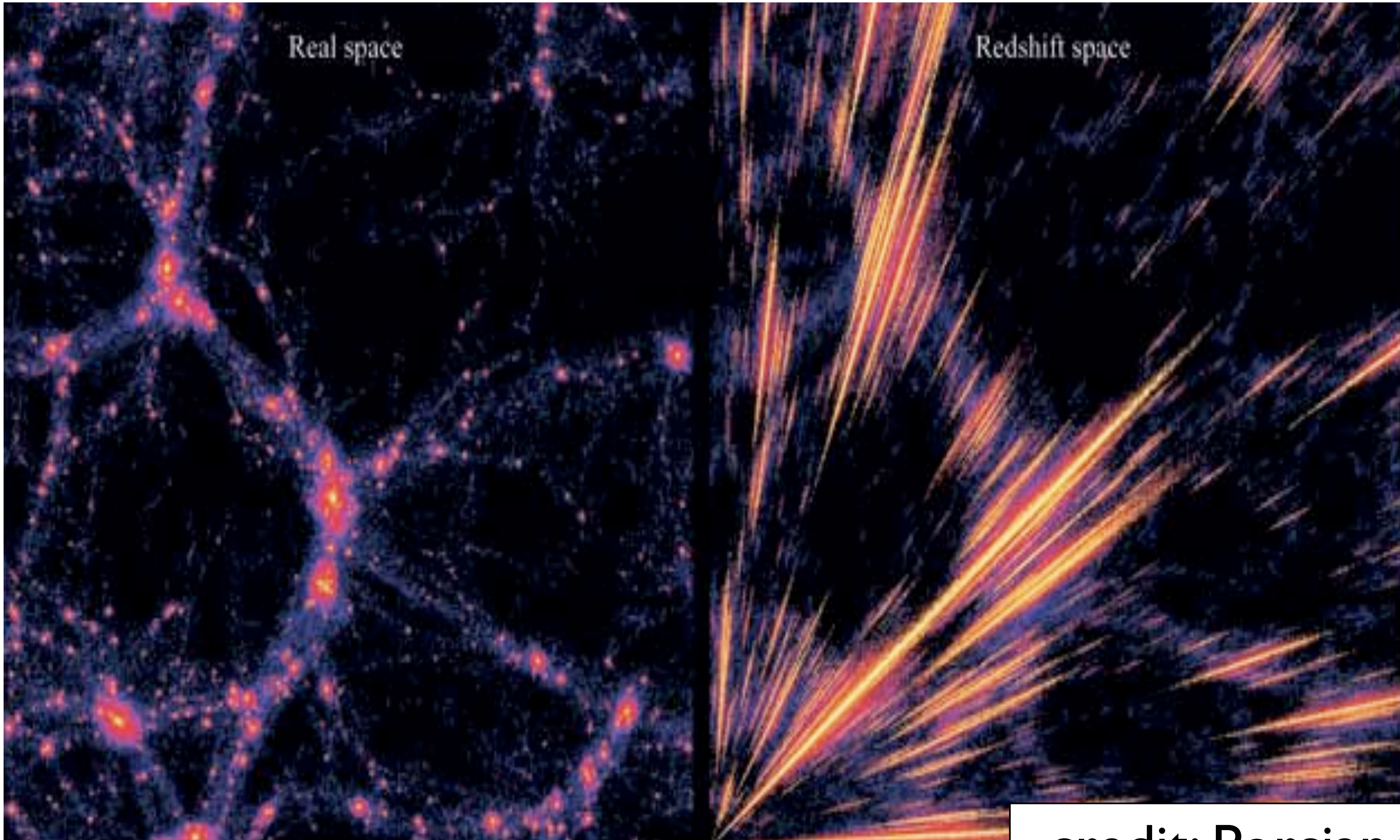
APPEARANCE

doppler shift changes the apparent position of galaxies along line of sight

==> cannot infer exact distribution of galaxies in real space (peculiar velocity and distance along line of sight degenerate)

Illustration of Redshift Space Distortions

Real Space | Redshift Space

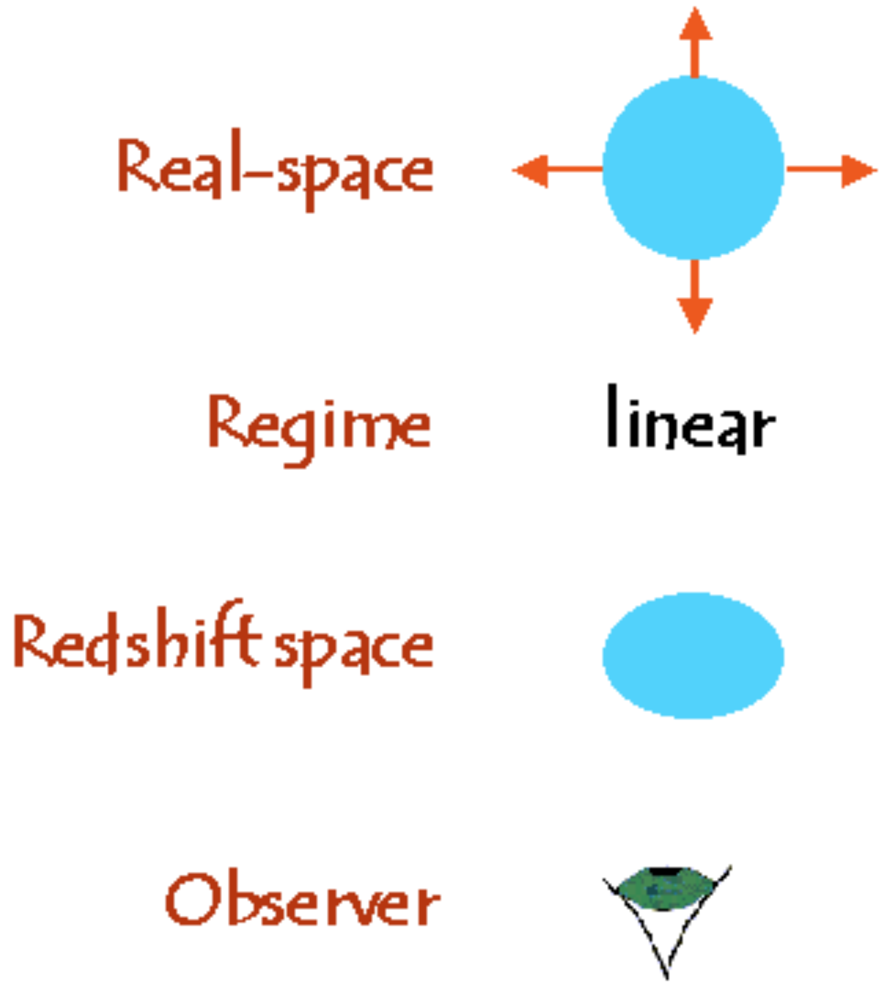


credit: Porciano

Redshift Space Distortions

So what sort of effects would we expect the peculiar velocities of galaxies to have on the spatial positioning of galaxies?

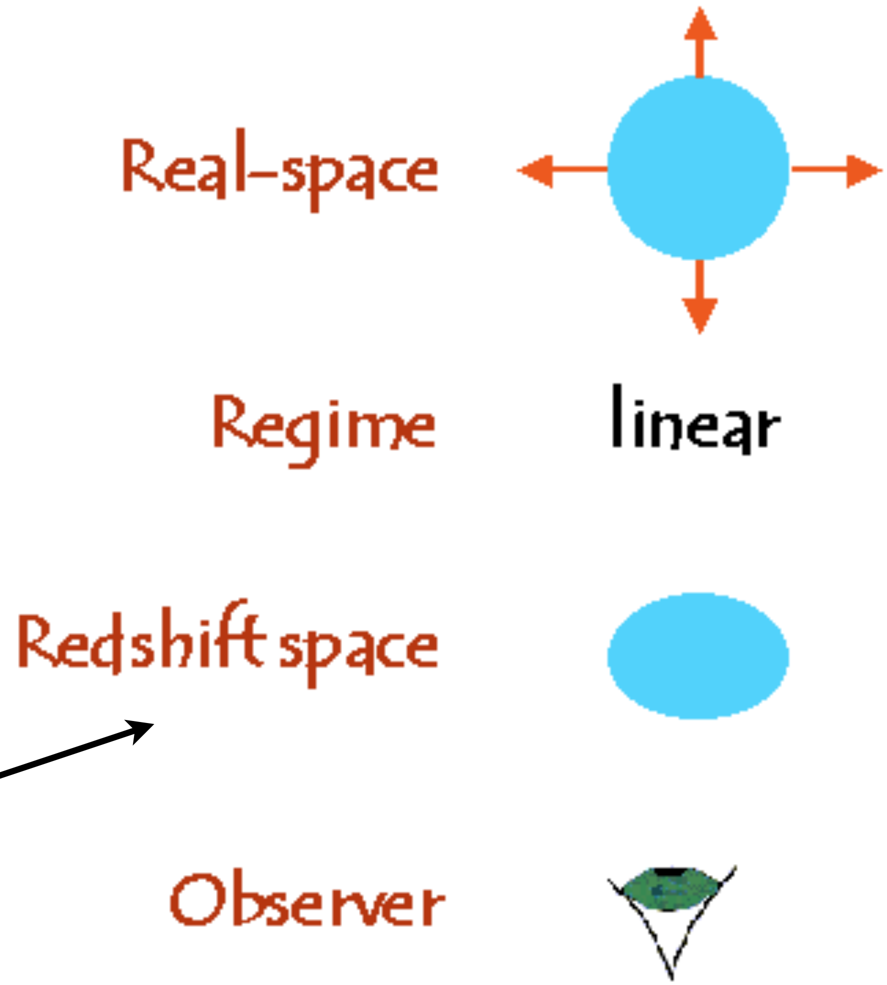
Let's say we have a group of galaxies which are still expanding with the Hubble flow... and have not quite started to turn around...



credit: Porciano

Redshift Space Distortions

What would the appearance of this structure appear to be in redshift and angular space? It is shown to the right.

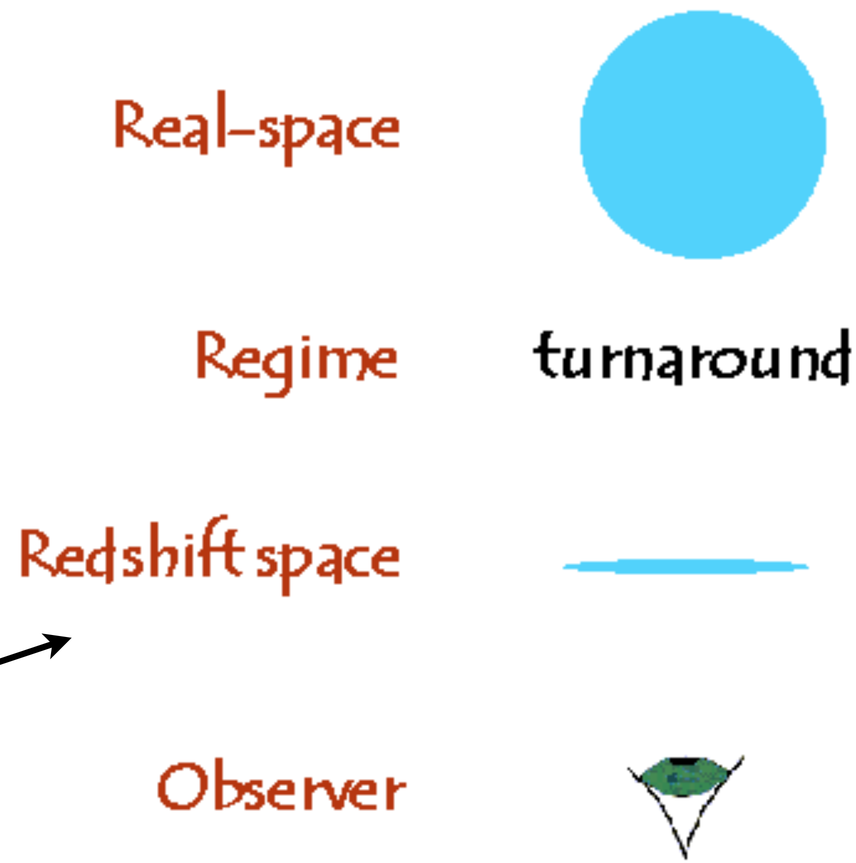


Gravity has slowed Hubble flow slightly.... This is why compressed in redshift space...

credit: Porciano

Redshift Space Distortions

What about a little later on in the evolution of a structure when it starts to turn around (from gravity)?



Doppler shift cancels cosmological redshift

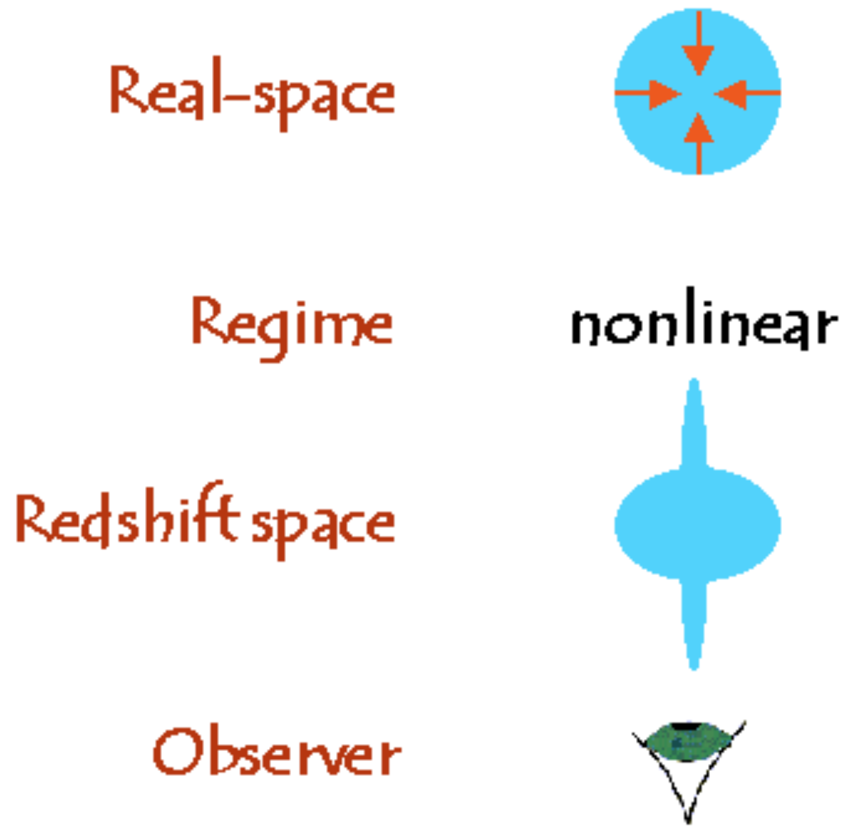
credit: Porciano

Redshift Space Distortions

And a little later on in the evolution when the structure has collapsed?

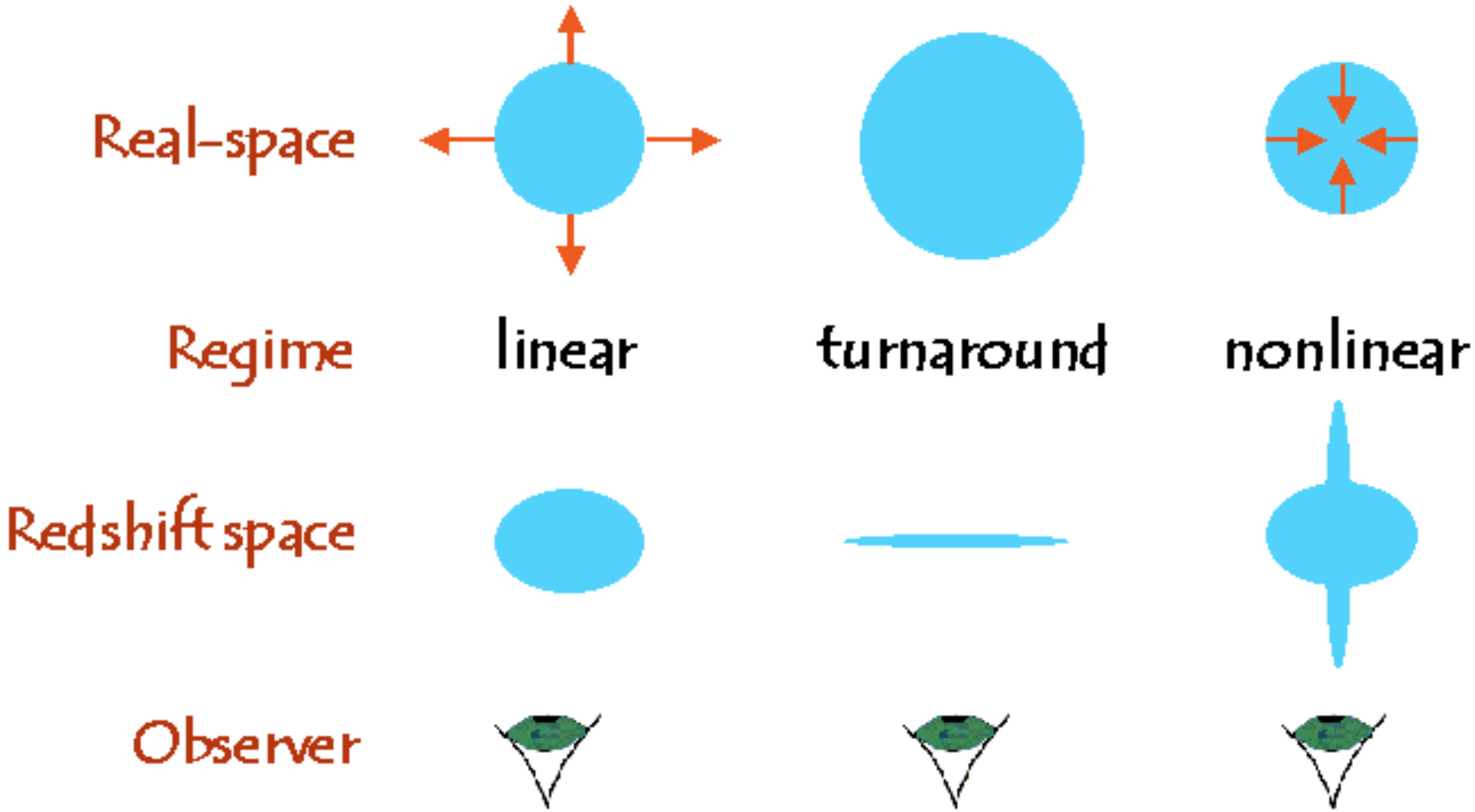
This apparent structure is called a finger of God... and is evident whenever one has a galaxy cluster

This finger of God is due to the substantial speeds with galaxies within clusters move around (often ~700-1000 km/s)



credit: Porciano

Redshift Space Distortions



credit: Porciano

Redshift Space Distortions

Typically, one looks at the spatial positioning of galaxies in this angle - redshift space as shown to the right:

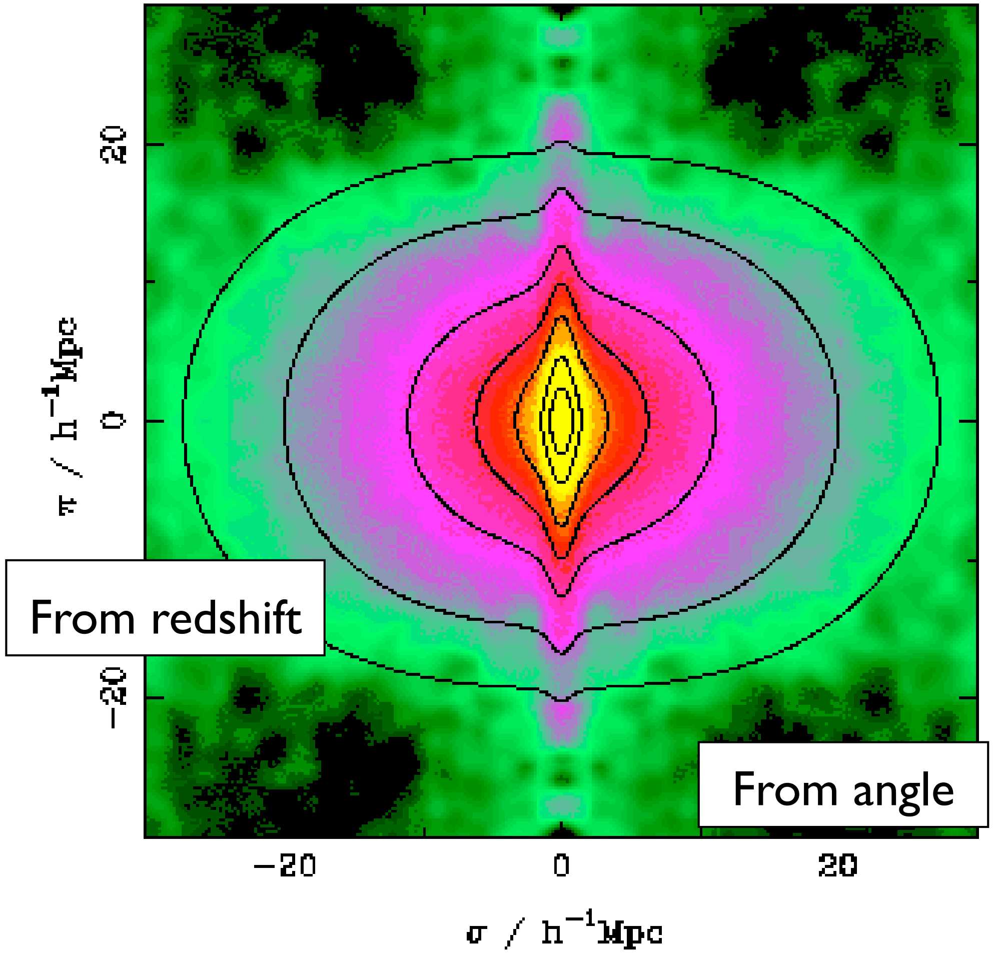
σ is the apparent position of the galaxy in physical space based on the observed angle

$$\sigma = \Delta\theta \, (D_A)$$

π is the apparent position of the galaxy in physical space based on the observed redshift

$$\pi \equiv \frac{c \, \Delta z}{H_0}$$

$\xi(\sigma,\pi)$

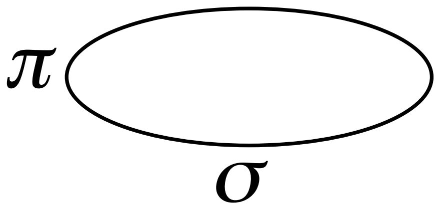


Hawkins et al. 2002

Redshift Space Distortions

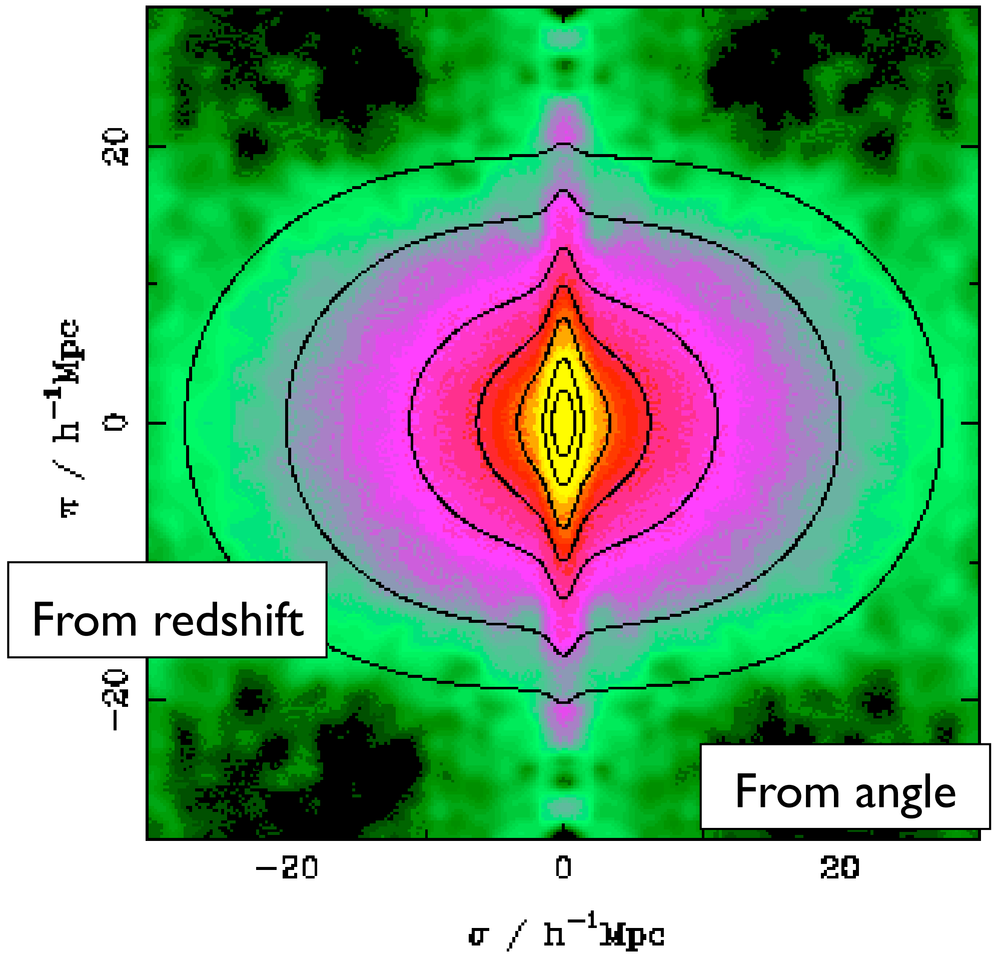
Why is this distribution not circularly symmetric?

The flattening along the π (redshift) direction is due to galaxies on the near and far sides of an overdensity falling back towards that overdensity



Infall velocity squashes π
"Kaiser effect"

ξ(σ,π)

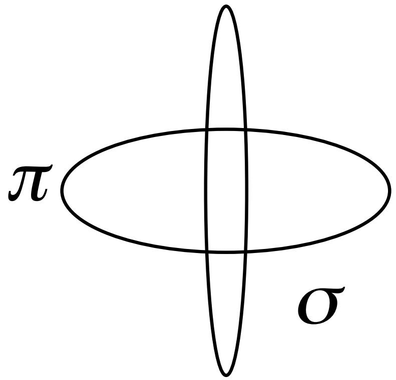


Hawkins et al. 2002

Redshift Space Distortions

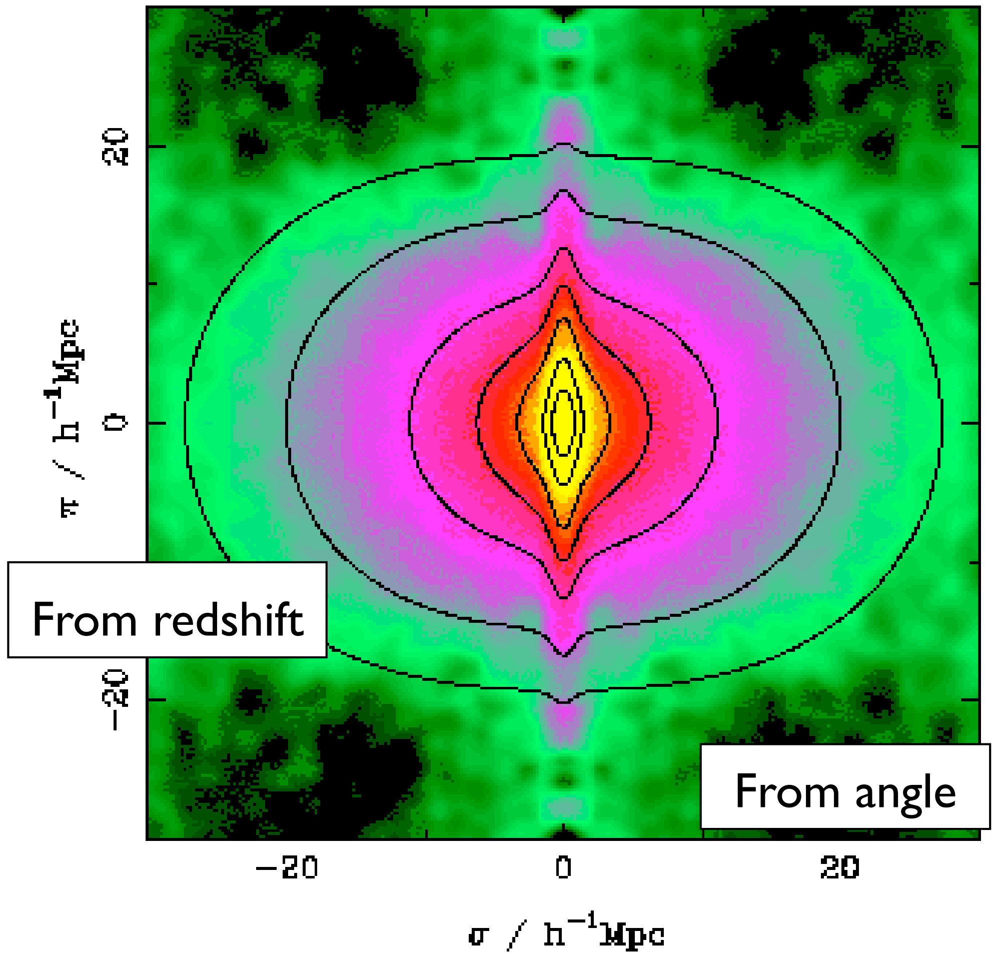
Why is this distribution not circularly symmetric?

Fingers of God results from the high internal motions within massive cluster type regions of universe



$V \sim (GM/r)^{1/2}$

$\xi(\sigma,\pi)$



Hawkins et al. 2002

Redshift Space Distortions

From the Kaiser effect, it is actually possible to learn about the total amount of dark matter in universe

Basically this is because a higher dark matter mass density means that galaxies will be falling faster towards each other

The predicted two point correlation function -- shown in the previous plots -- can be shown to be dependent on a parameter known as β

$$\beta \equiv \frac{\Omega_M^{\ 0.6}}{b} = 0.43 \pm 0.07$$

b = bias parameter > 1

(equivalent to $\Omega_M = 0.24 \pm 0.07$)

Looking at Kaiser effect is just another way of getting at the dark matter content of universe

In a previous lecture, I discussed deriving this based on a velocity flow model of local universe

There, the dark matter content was inferred by looking at the overall convergence in the velocity flow (i.e., the strength of the "attractors" in flow provide measure of the total mass density in universe)

Inferences for the dark matter content from velocity flows

One can also use the peculiar velocities (bulk flows) of galaxies in the nearby universe to estimate the amount of dark matter in the universe

This is because the peculiar velocities are set by the matter within the universe -- which causes galaxies to fall towards each other.

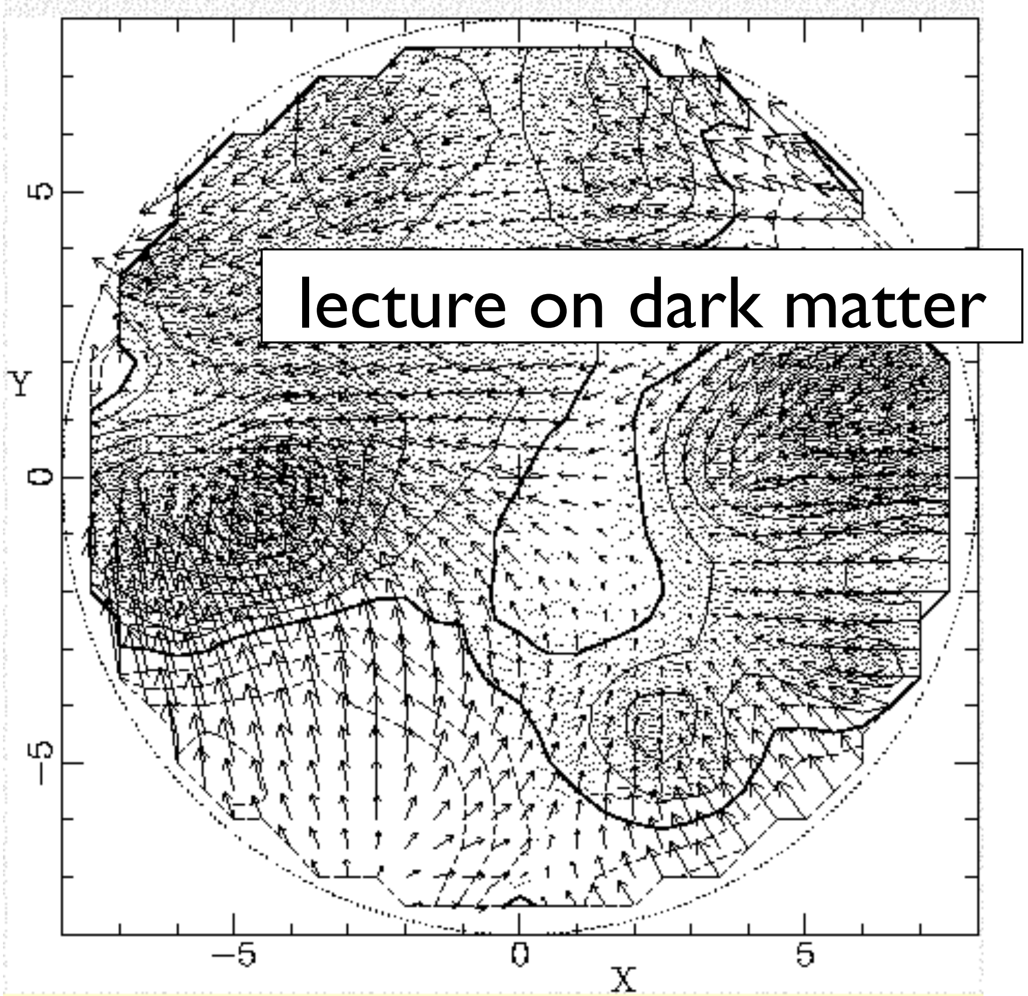
An approximate equation to describe this is the following:

$$\nabla \cdot v = -\Omega_M^{0.6}\,\delta_M$$

convergence points for fluid flow

gravitational mass

Velocity flow model in the nearby universe



Complication #2

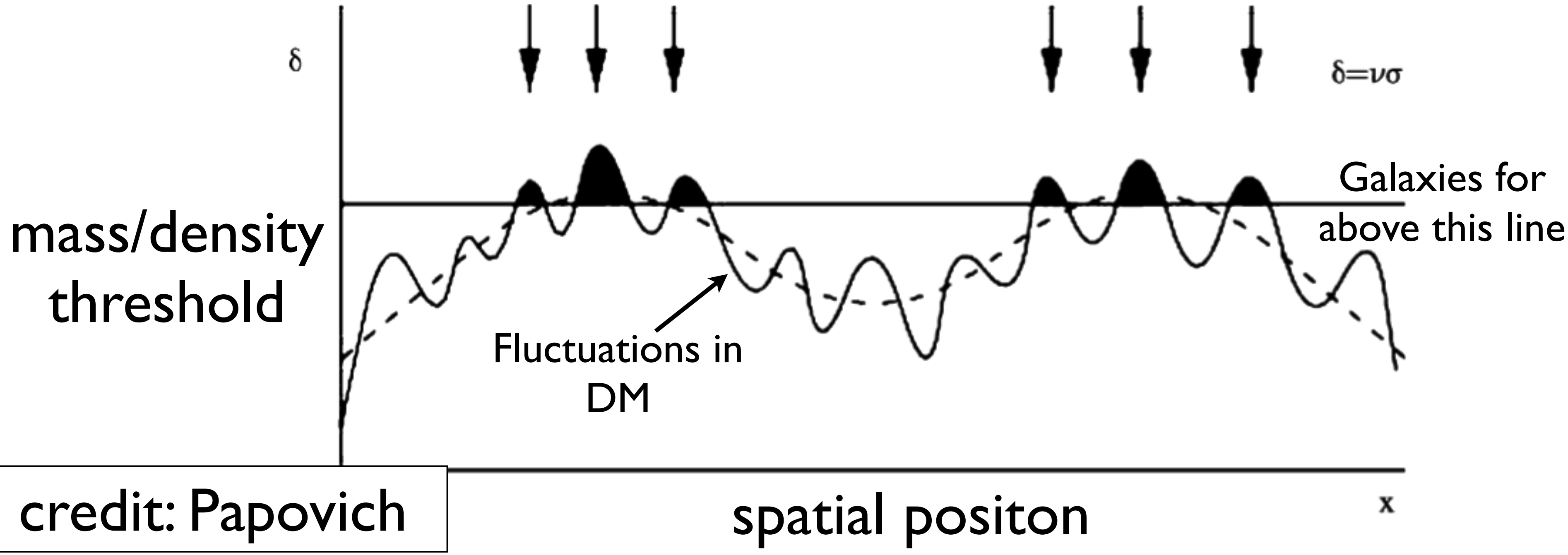
Galaxy Bias

(how well do galaxies trace the underlying perturbations in the matter?)

Galaxy Bias

-- The galaxies we observe do not perfectly trace the underlying mass distribution in the universe (i.e., light does not trace mass)

-- Expect galaxies to be found preferentially in the most prominent high-mass peaks



credit: Papovich

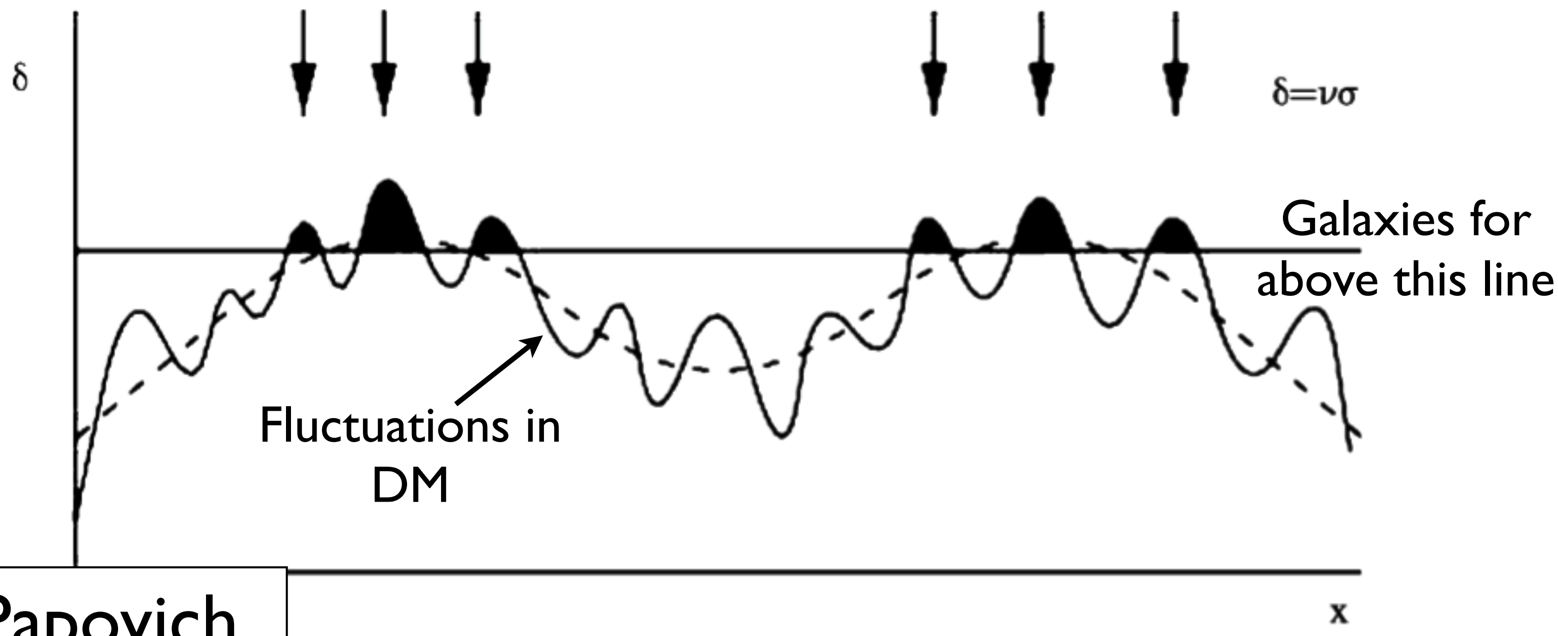
Galaxy Bias

-- Express fluctuations in the number of observed galaxies in terms of fluctuations in the mass density times biasing factor:

$$\delta_g := \frac{\Delta n}{\bar{n}} = b \frac{\Delta \rho}{\bar{\rho}} = b\,\delta$$

(linear bias, in general, more complicated)

In general, bias b >= 1



credit: Papovich

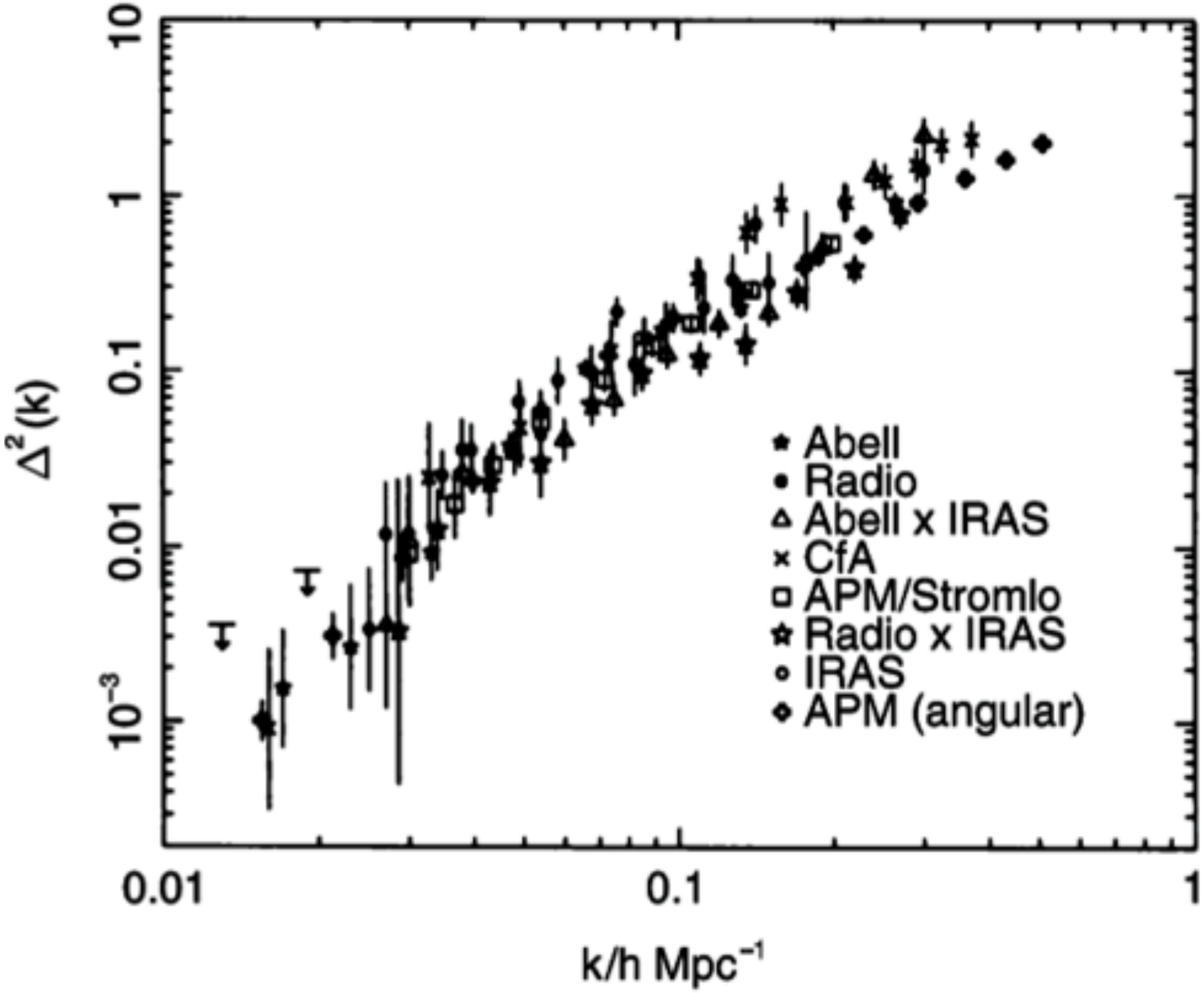
We’re discussed how to measure the matter power spectrum from the correlation function

We’re also discussed two complications in recovering the matter power spectrum from the correlation function

1. Redshift Space Distortions
2. Galaxy Biasing

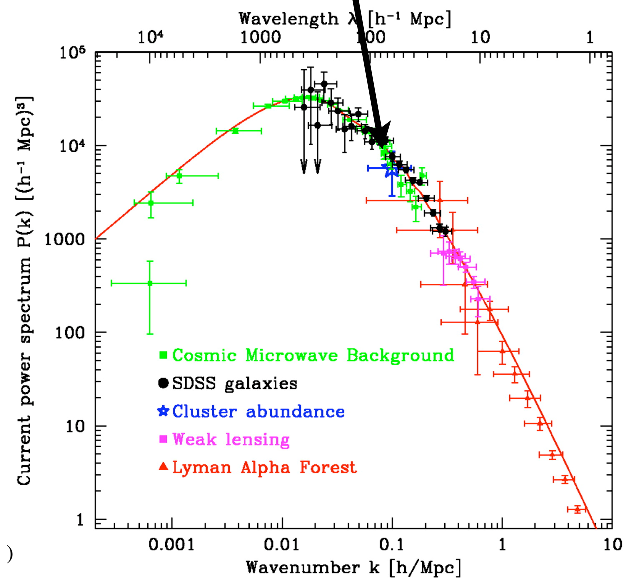
After coping with the above effects, we can measure the matter power spectrum

What does an extracted power spectrum look like?



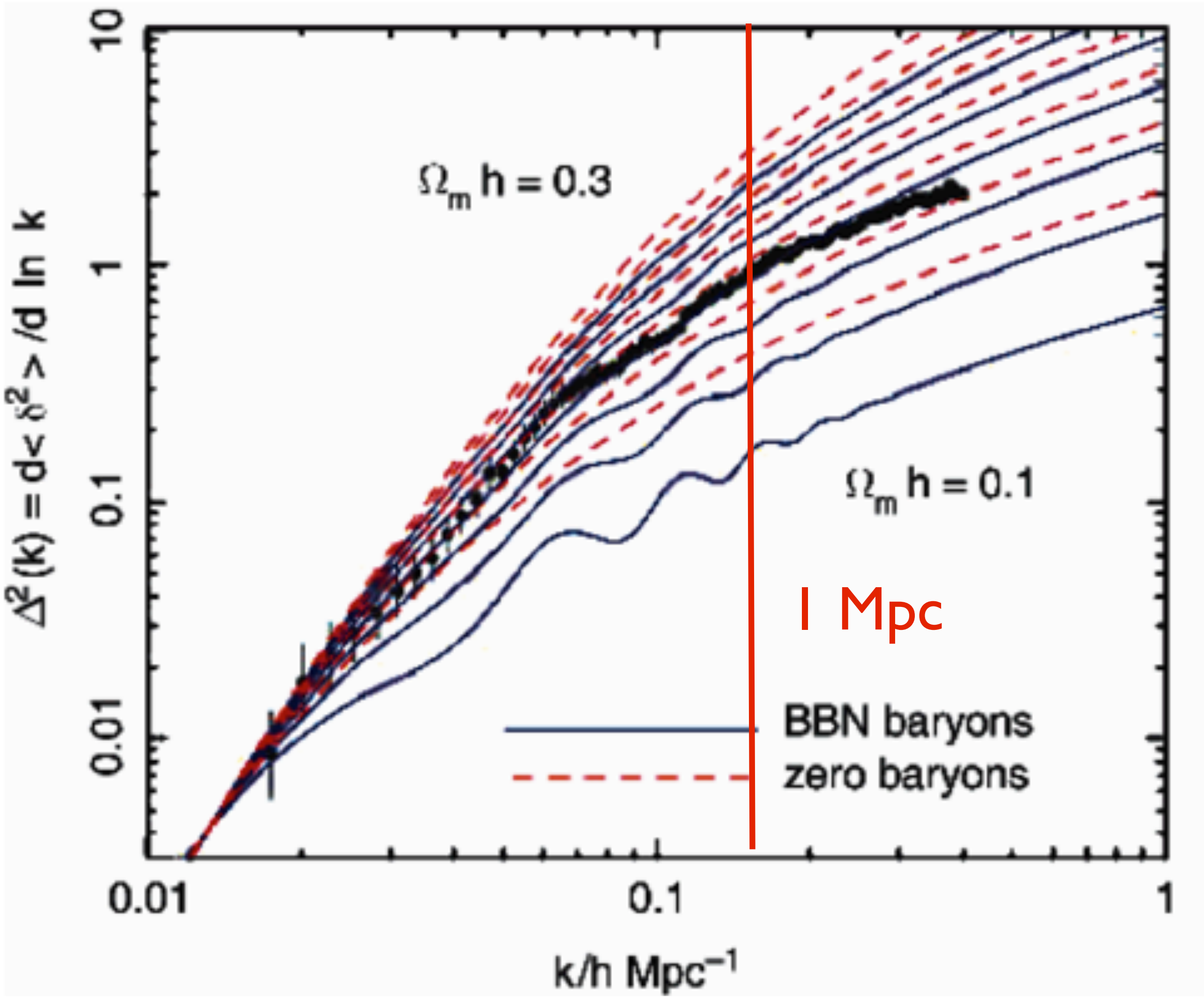
Measurements of $\Delta^2 = k^3 P(k)$

Differs from the matter power spectrum shown earlier due to k^3 term



What does the power spectrum teach us about the cosmological parameters?

Compare observed power spectrum with that found in simulations



Biggest constraint is on Ω_m h

due to its role in determining time of matter-radiation equality

also can constrain Ω_b

Peacock 2003, astro-ph/0309240 and Peacock 2001, astro-ph/0105450.

Implications for Cosmological Parameters

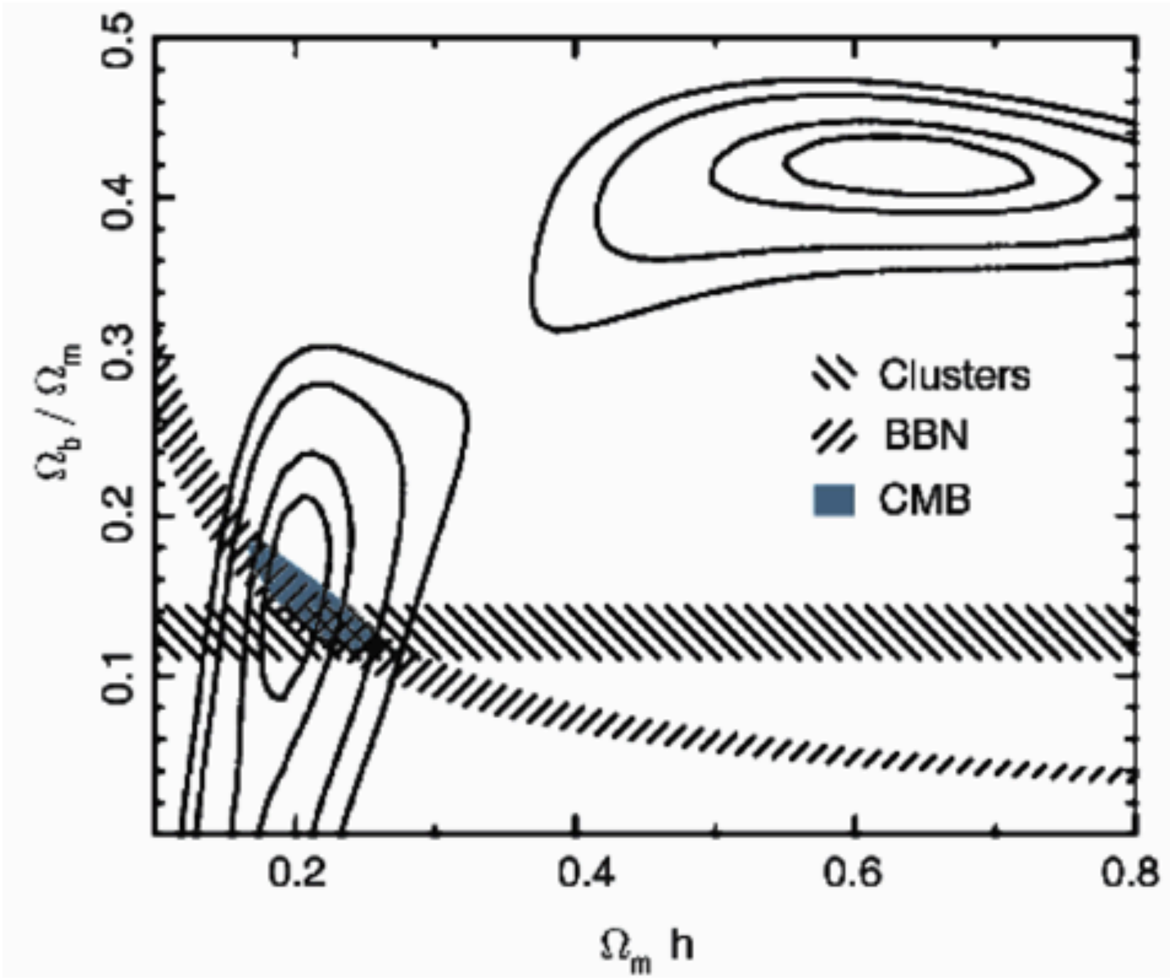
Can use comparison to constrain cosmological parameters!

Allowed solutions are bimodal, but we can eliminate one of solutions using other constraints

$\Omega_m h = 0.2$
$\Rightarrow \Omega_m = 0.3$

$\Omega_b = 0.04$

Yet another constraint on the baryonic density of universe!



Peacock 2003, astro-ph/0309240 and Peacock 2001, astro-ph/0105450.

How do we normalize the power spectrum?

We parameterize this using the σ_8 parameter

While deriving correlation function and Power spectrum from galaxy survey, one thing we are particularly interested in is the normalization of the power spectrum

$$P_0(k) = A\,k^{n_s}$$

(related to the A parameter here)
($n_s = 1$)

This is defined using this parameter σ_8 (intended to represent the root-mean-squared fluctuations in a 8 h^{-1}Mpc volume):

$$\sigma_{8,\mathrm{g}}^2 := \left\langle \left(\frac{\Delta n}{\bar{n}} \right)^2 \right\rangle_8 \approx 1$$

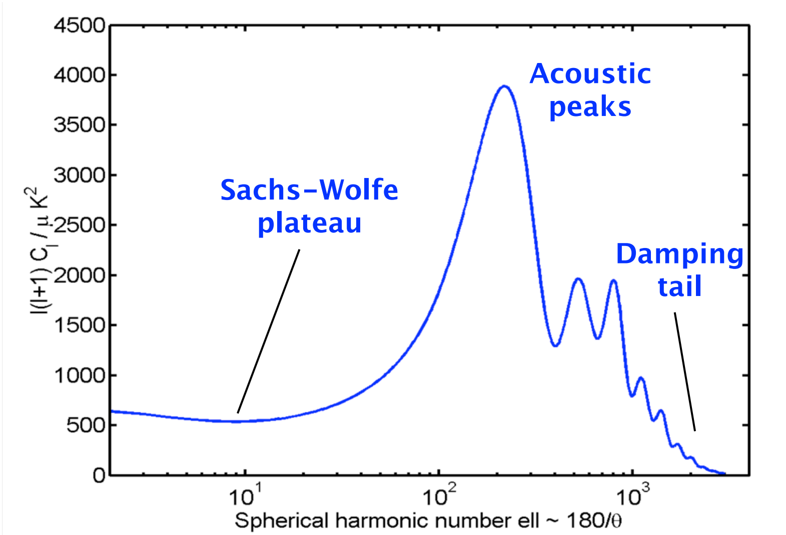
(8 h^{-1} Mpc was chosen because appeared close to 1)

Size of density fluctuations in a volume really defines the amplitude of power spectrum

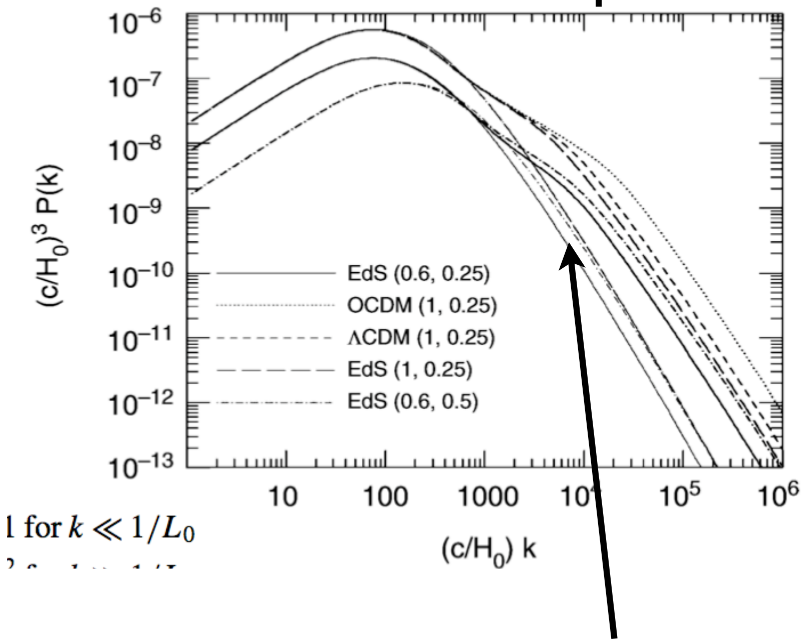
What effect do baryons have on the matter power spectrum?

Just like in the CMB, baryons impart acoustic oscillations on matter power spectrum

CMB Power Spectrum

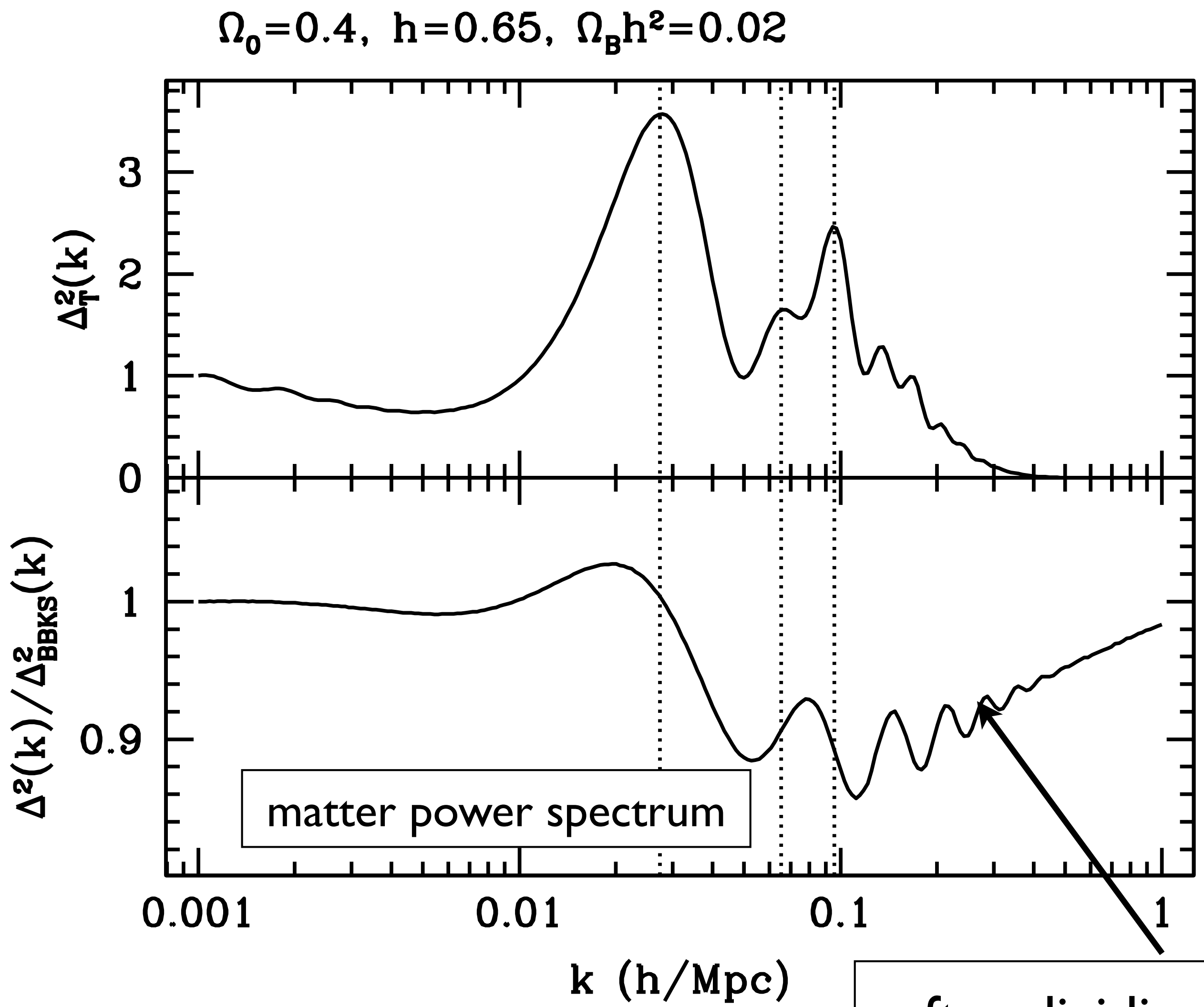


Matter Power Spectrum



Has small acoustic oscillations in the matter power spectrum

Here are the CMB and matter power spectrum overlaid one over top of the other



CMB and LSS peaks are out of phase

Acoustic peaks in CMB are much more prominent

after dividing out overall shape

note $k = 2\pi$/length (a wavenumber)

This makes the acoustic peaks more obvious

Meiksin et al. 1999

But where do these acoustic peaks come from?

Between $z = 3500$ (when universe became matter dominated) and $z = 1080$ (photons and baryons decoupled):

Perturbations in baryonic material cannot grow (being coupled to radiation) and will just oscillate

baryonic material ⇒ no growth

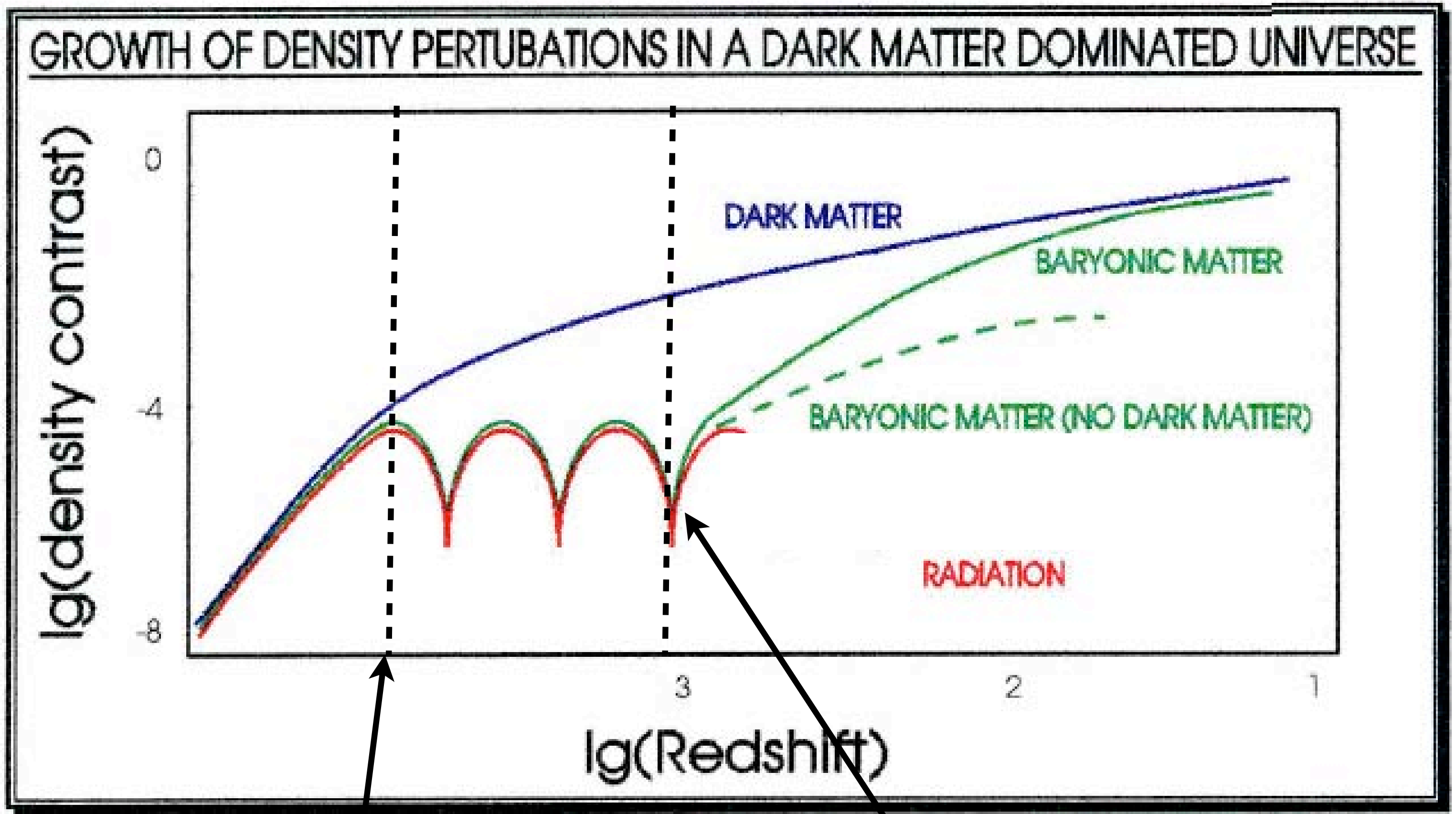
Perturbations in dark material can grow (not being coupled to the radiation)

dark matter ⇒ growth

As a result, perturbations in dark matter get a head start

But where do these acoustic peaks come from?

here's an illustration (notice difference between dark matter and baryonic matter)



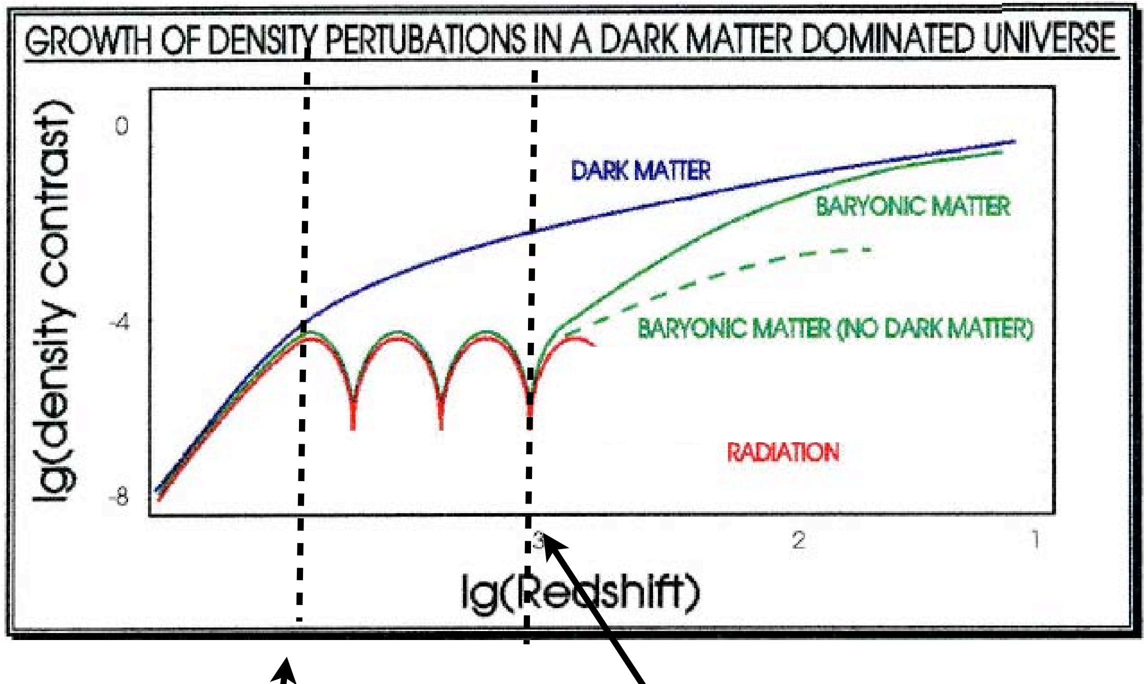
matter-radiation equality

decoupling

credit: Pearson

But where do these acoustic peaks come from?

here's an illustration (notice difference between dark matter and baryonic matter)



matter-radiation equality

decoupling

Before decoupling, perturbations in dark matter are able to grow, but perturbations in baryons are not.

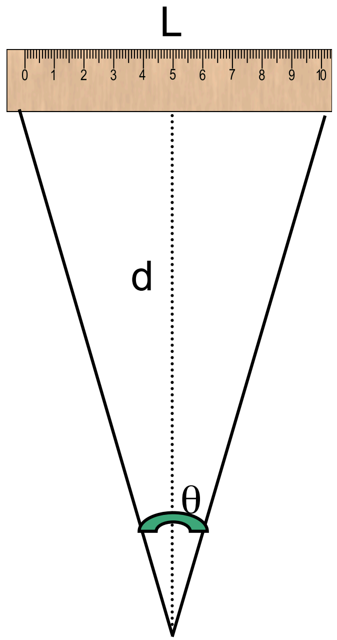
After decoupling, baryons fall into overdensities from dark matter.

But, in doing so, they affect the dark matter; they add the oscillatory ringing structure to larger perturbations defined by dark matter

Why do we care about these small oscillations in matter power spectrum caused by baryons?

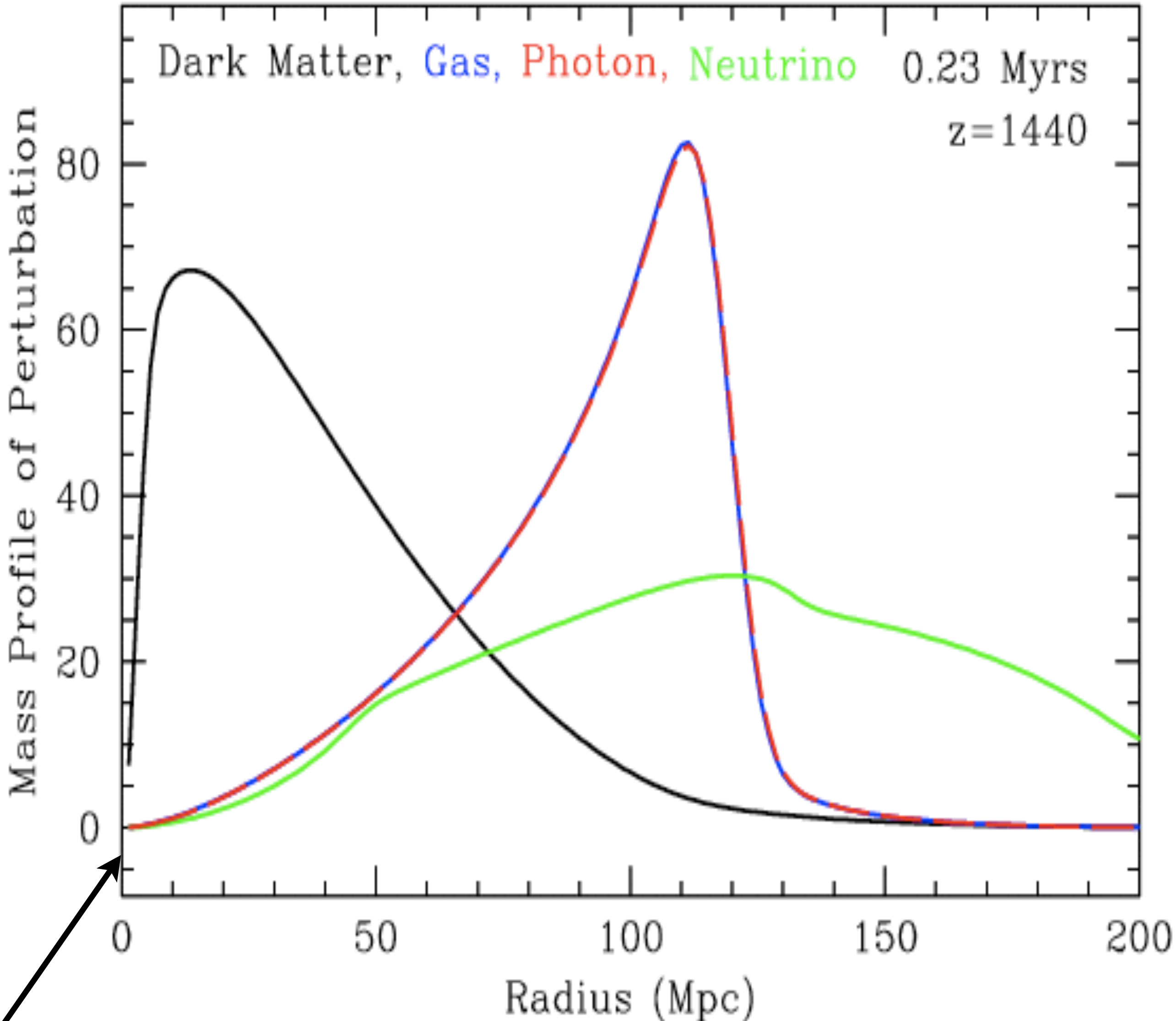
These oscillations cause there to be preferential structure at a certain comoving physical scale!

It provides us with a standard rod again that we can use to learn about the universe!



We can therefore do a galaxy survey at any epoch or redshift, measure the power spectrum, and look for the acoustic peak from baryons!

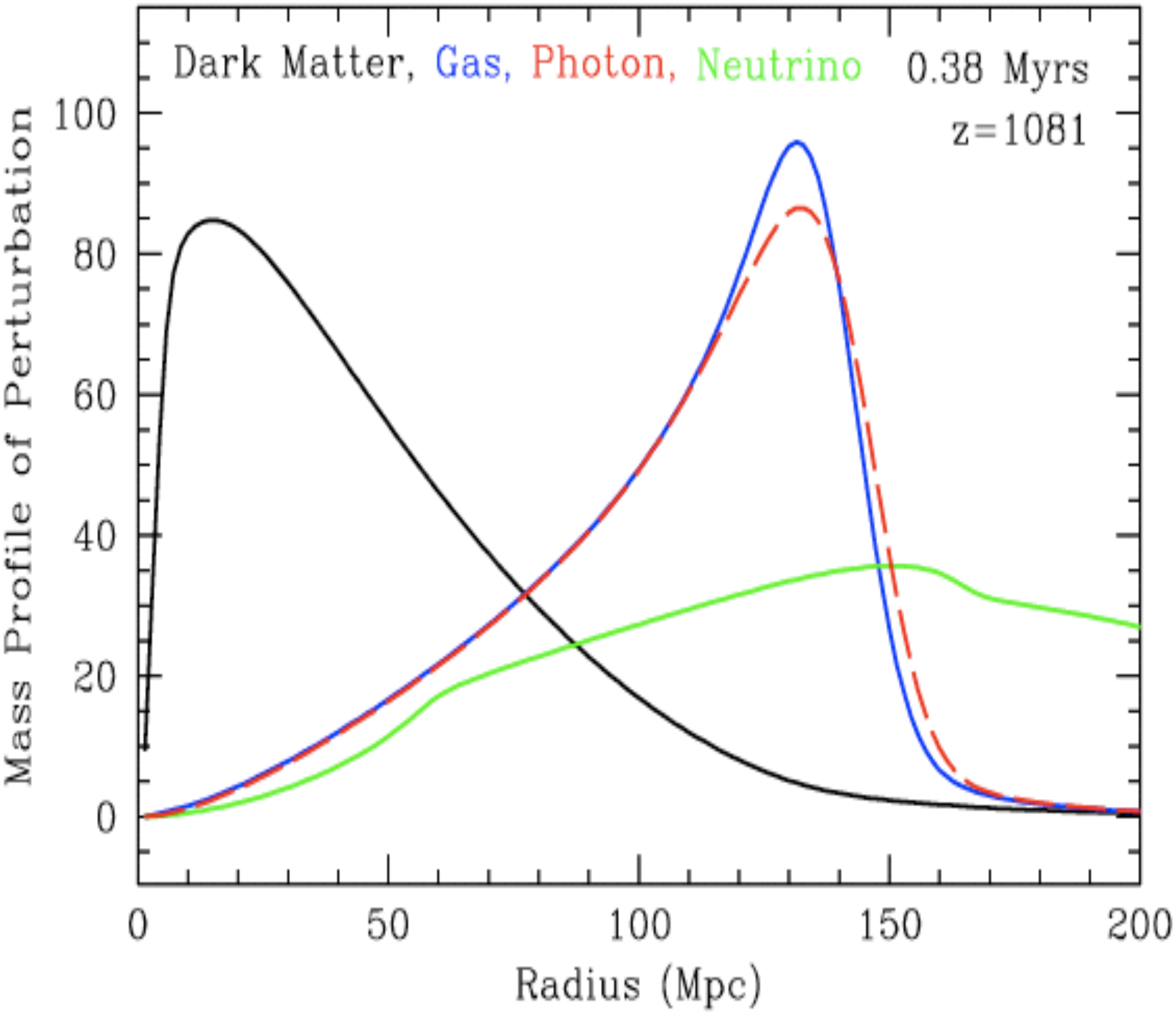
It will define same comoving scale at all epochs!



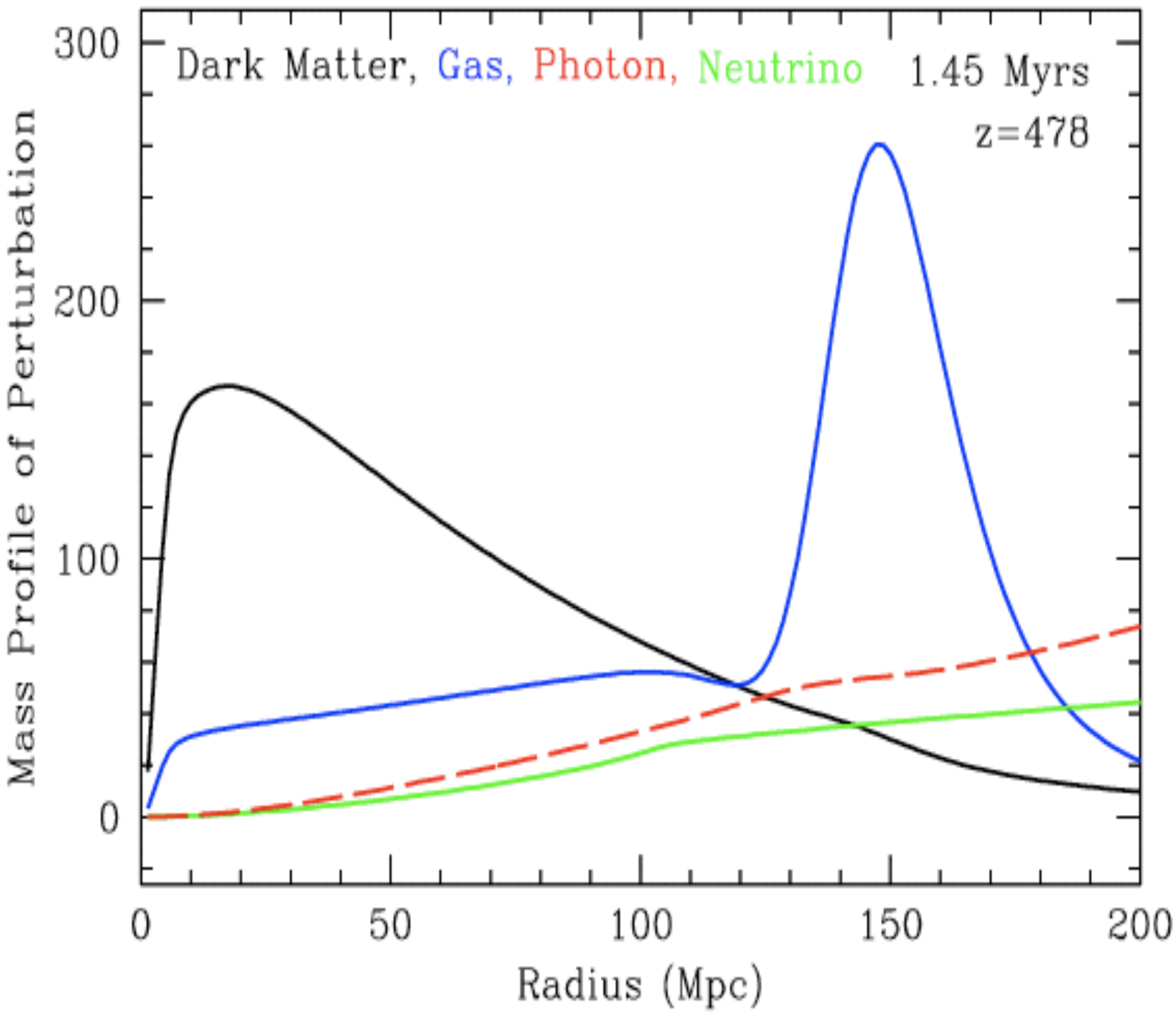
imagine we have a overdensity here at time t = 0

dark matter will fall towards it

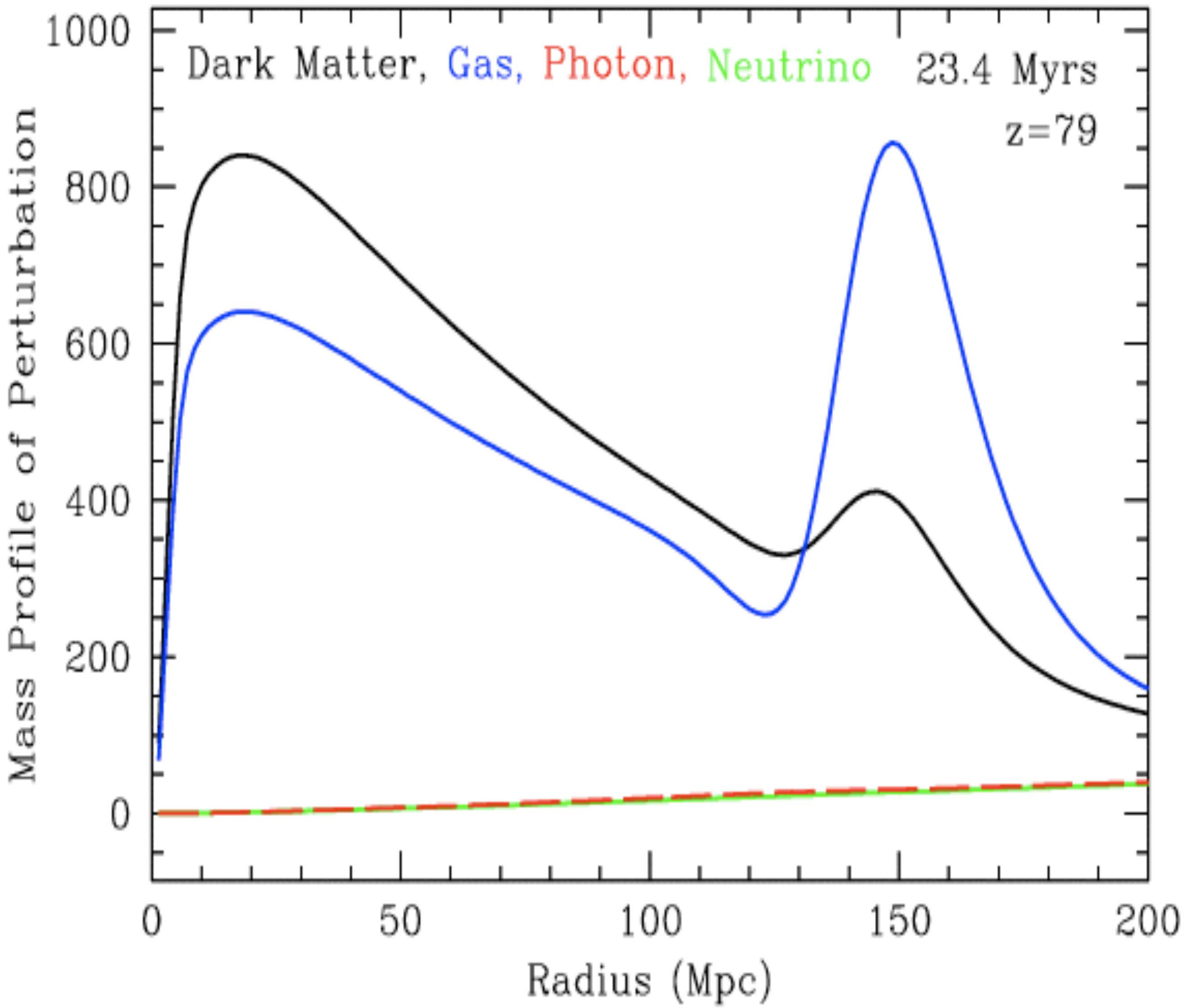
but baryons and radiation will bounce



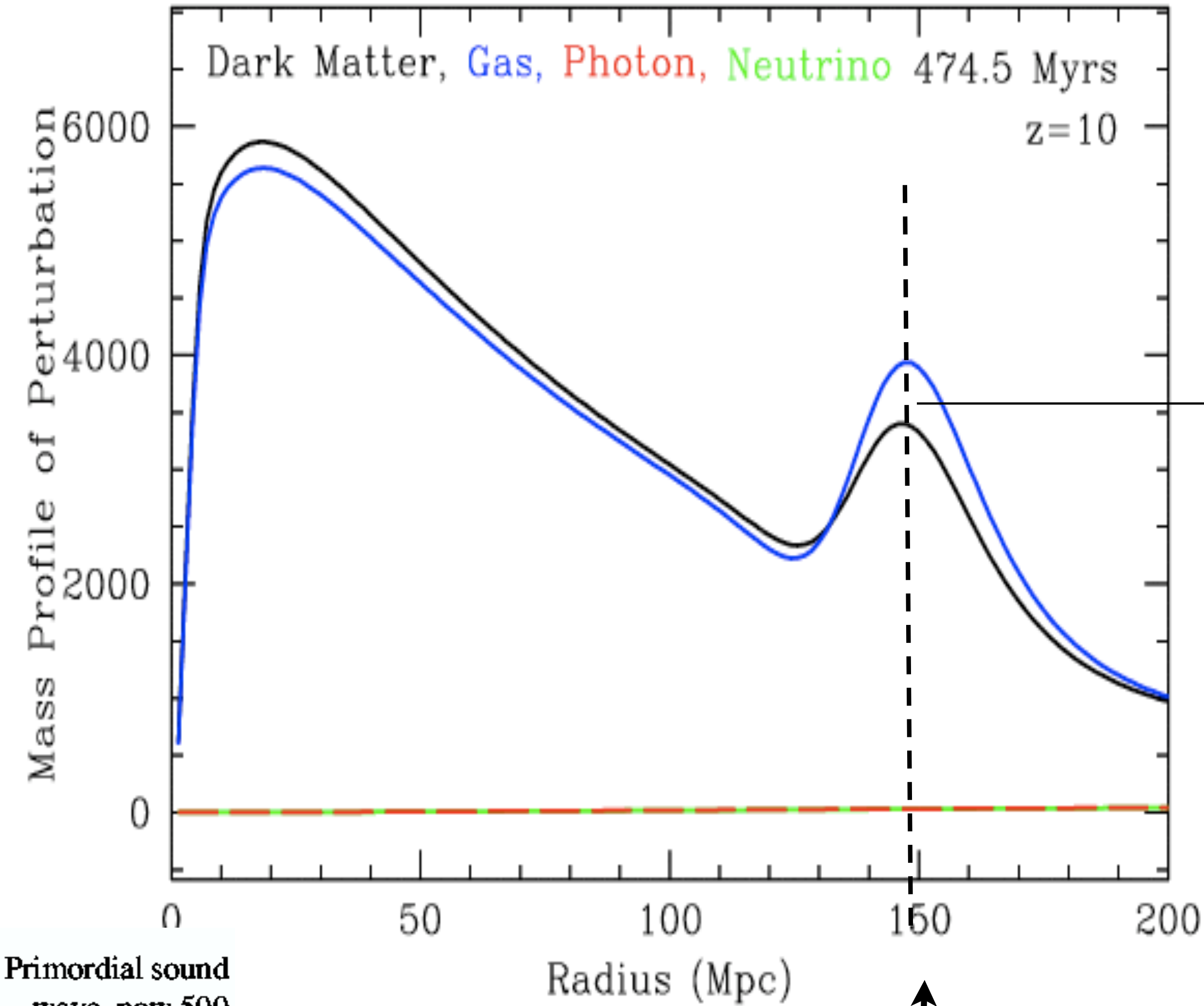
Dark Matter, Gas, Photon, Neutrino
0.38 Myrs
z=1081
Mass Profile of Perturbation
Radius (Mpc)
0
20
40
60
80
100
0
50
100
150
200



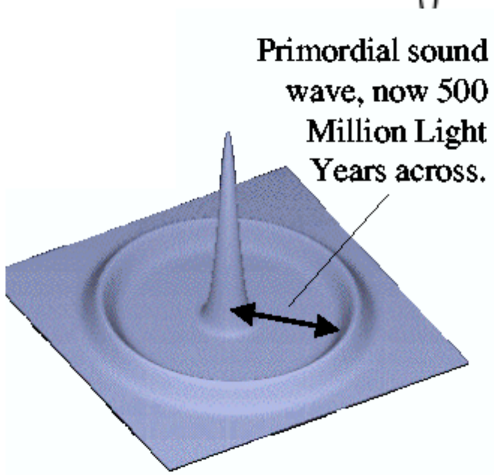
Dark Matter, Gas, Photon, Neutrino
1.45 Myrs
z=478
Mass Profile of Perturbation
Radius (Mpc)
0
100
200
300
0
50
100
150
200



Dark Matter, Gas, Photon, Neutrino
23.4 Myrs
z=79
Mass Profile of Perturbation
Radius (Mpc)
0
200
400
600
800
1000
0
50
100
150
200



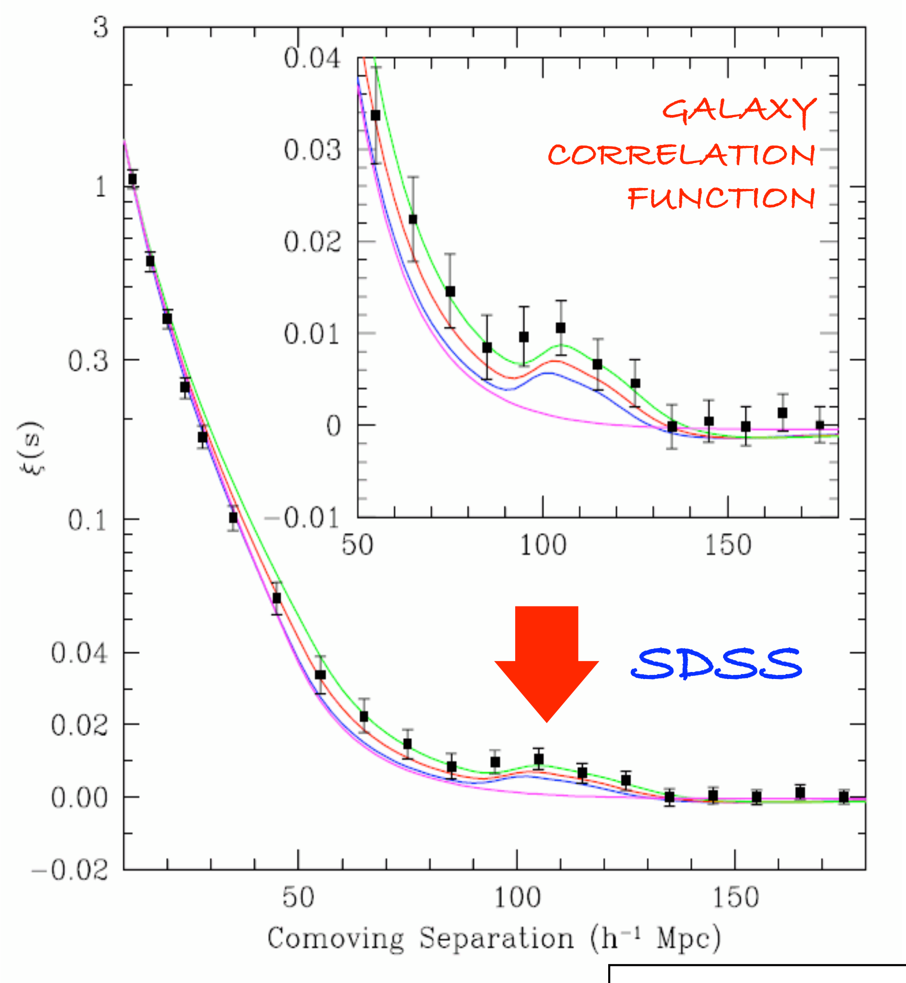
Sound horizon at matter-radiation decoupling



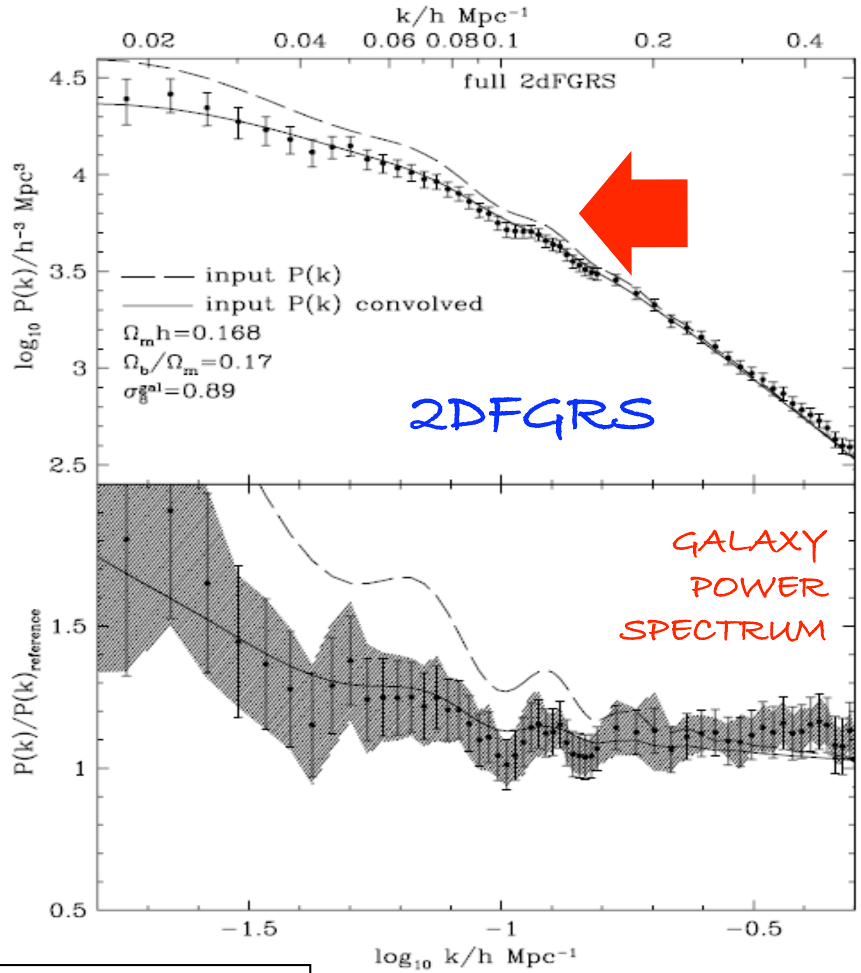
this bump is at 150 Mpc!

By measuring the correlation function for a galaxy survey we can look for this bump (from baryon acoustic oscillations)

SDSS: EISENSTEIN ET AL. (2005)



2DFGRS: COLE ET AL. (2005)



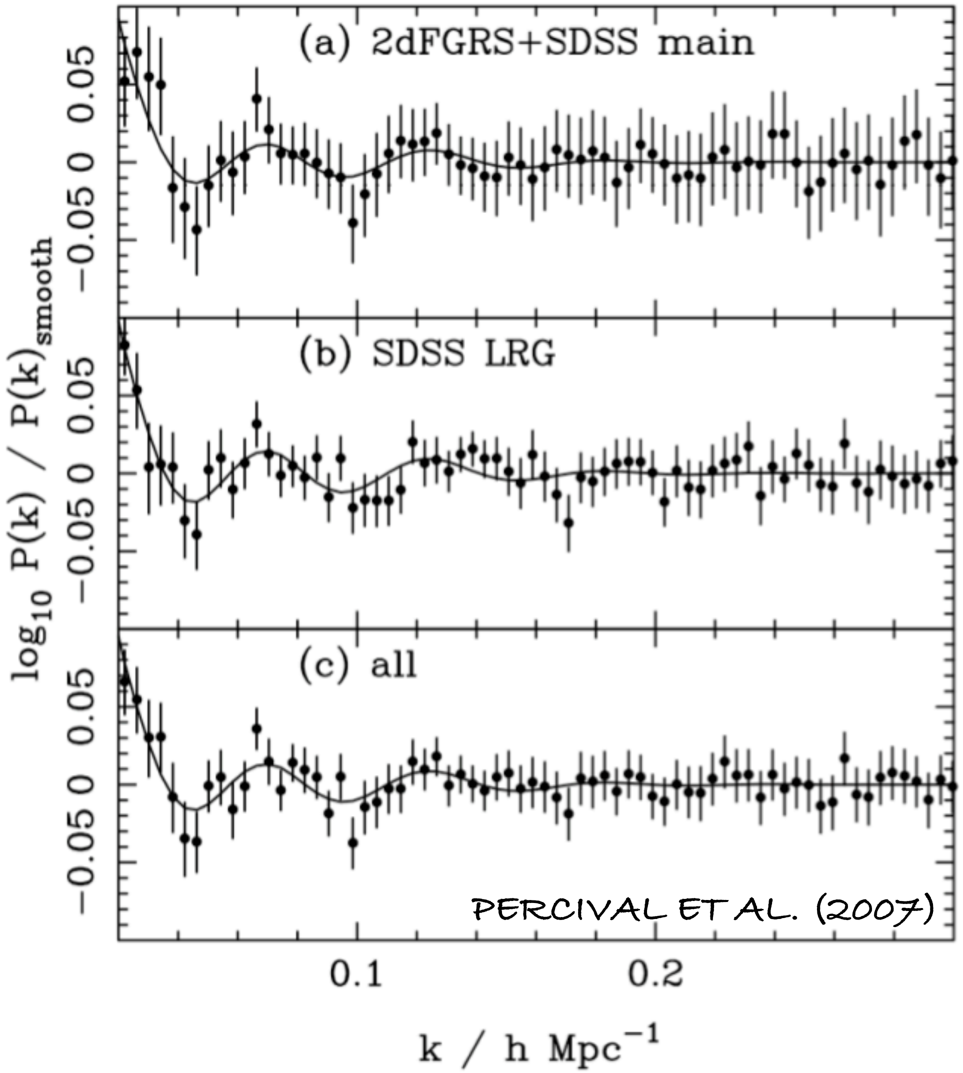
First Measurements

More recent State-of-the-art measurements of the baryonic acoustic oscillations

Detected at 99.74% confidence!

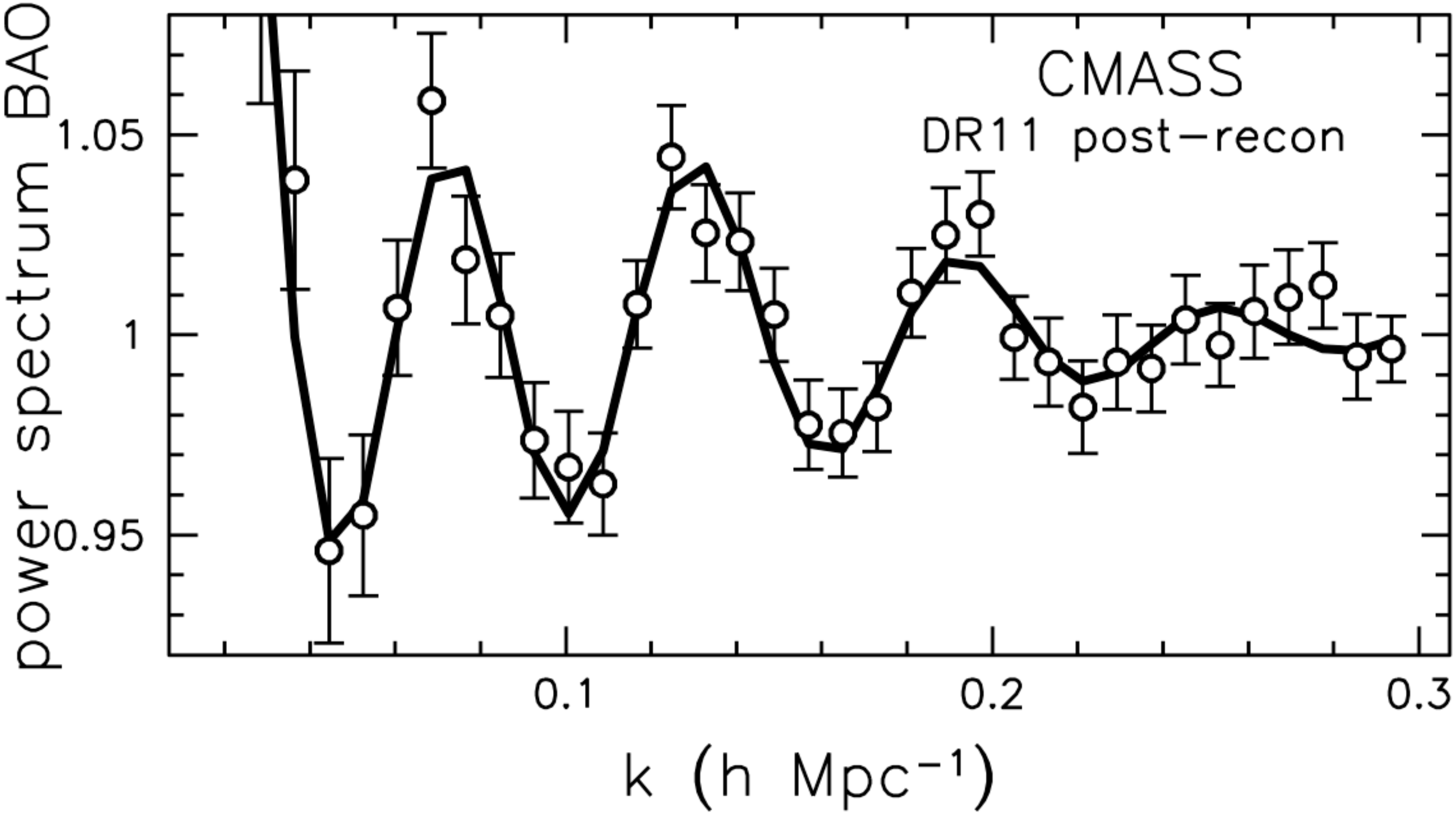
$\Omega_m = 0.256 \pm 0.027$

Allows us to examine same basic standard rod at both z = 0.35 and z = 1100 (CMB)



Now the BAO technique has been used out to z>~0.6...

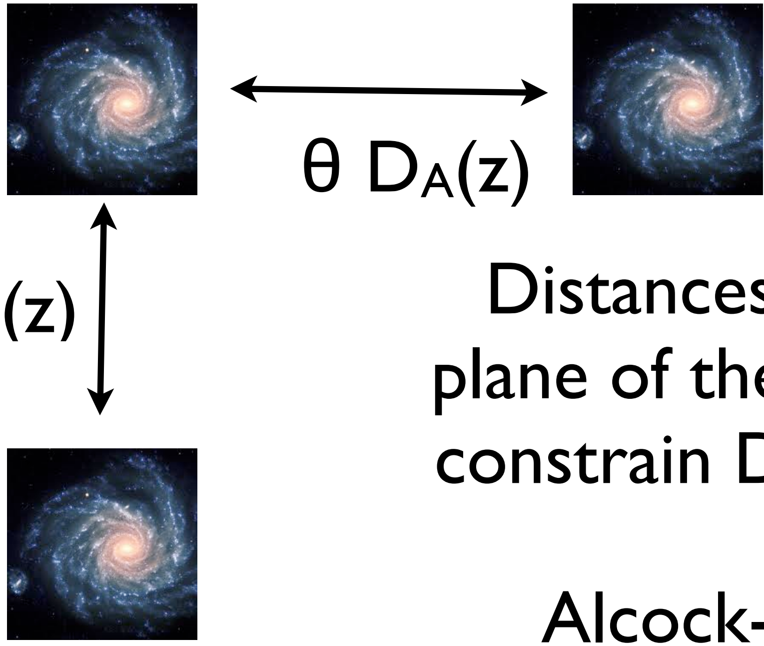
Results of BOSS survey at z~0.55



Anderson+2013

The Baryon Acoustic Oscillation Method can be used to look for structure in the plane of the sky, but also along the line of sight

Observables of interest for constraining the cosmology: $D_A(z)$, $H(z)$



Distances in plane of the sky constrain $D_A(z)$

Distances along line of sight constrain $H(z)$

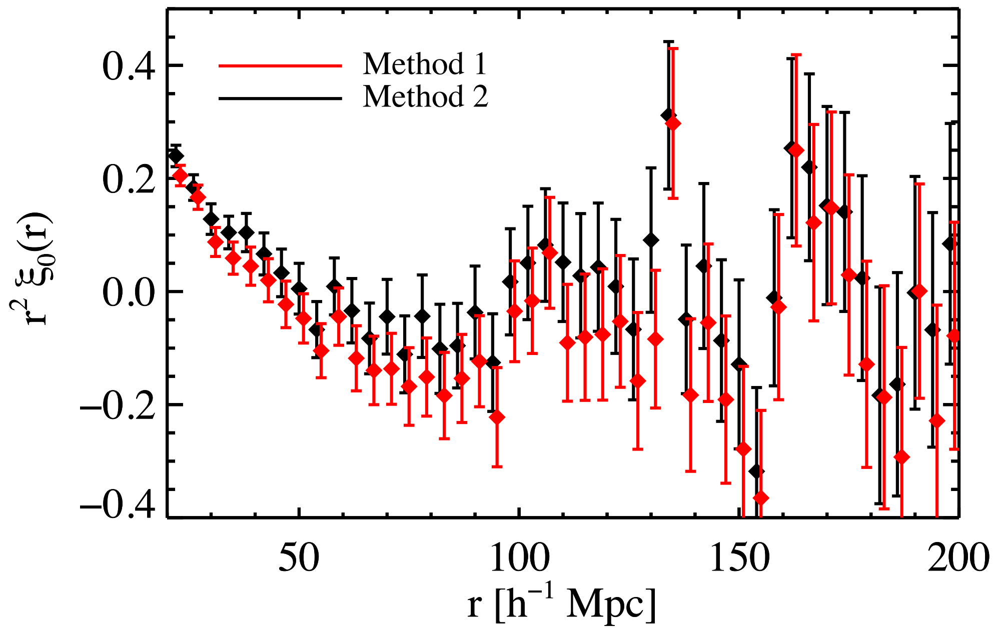
Alcock-Paczynski constraints

telescope

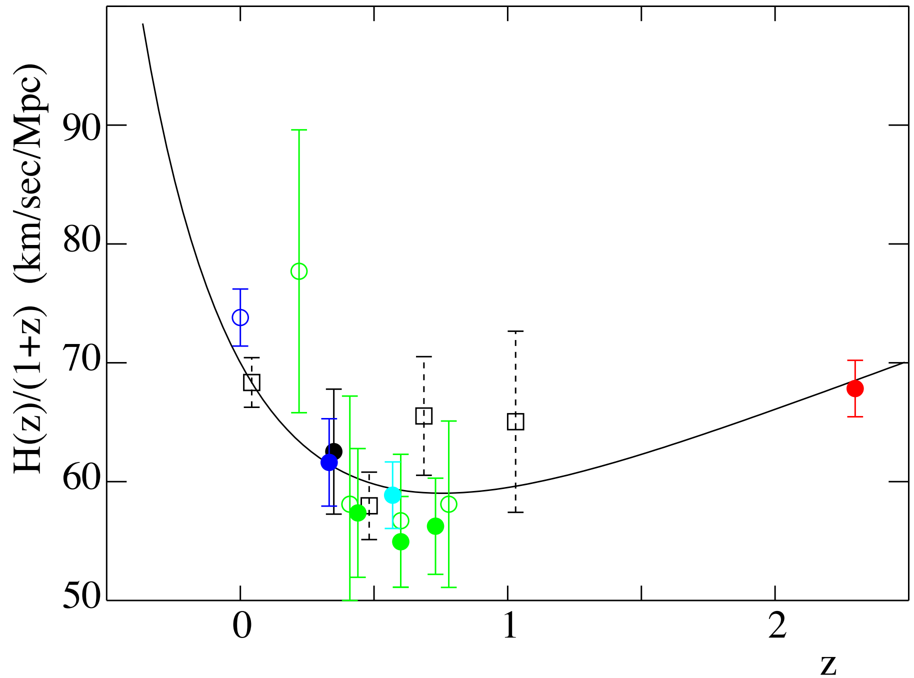
both length scales must be the same

BAO have also been used to constrain H(z)... amazing out to z~2.3...

Power spectrum measured for absorption lines from gas at z~2.3 in z~2.5 quasars



Constraints on the evolution of the Hubble parameter to z~2.3



Busca+2013