Large-scale structure and dark energy

Stefanie Phleps

with
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MAX-PLANCK-GESELLSCHAFT

MPE

Outline

- Which are the questions that we would like to answer using LSS
- Challenges in the age of precision cosmology
  - Data
    - Spectroscopy vs. photometric redshifts
  - Theory
    - non-linear clustering growth
    - redshift space distortions
    - (non-linear, scale-dependent, stochastic) galaxy bias
- Methods and surveys which will help answering these questions using clustering measurements
  - BOSS: Constraints on w using correlation function and power spectrum
  - Pan-STARRS: Dealing with photometric redshifts
  - RELFEX: The power spectrum of galaxy clusters
  - VIPERS: Dark energy or dark gravity?

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What can large scale clustering measurements do for cosmology?

- Put constraints on Dark Energy and Dark Gravity
  - Measure the equation of state of DE with Baryonic Acoustic Oscillations (BAOs) as a standard ruler
  - Measure the growth rate function from redshift space distortions
- Measure Ω_k to 0.2% accuracy
- Put constraints on primordial non-Gaussianity (f_{NL}~10)
- Investigate LSS as a function of X
- Galaxy Evolution
- And much, much more...

Challenges in the age of "precision cosmology"

- **Data:**
  - The BAO signal is on very large scales, and it is very small (~2%): need a large volume (in a simulation you would say a box length of more than 1Gpc) and large number statistics
  - Spectroscopy is time-consuming
    - systematics: target selection, fiber collisions, arrangement of slits, S/N
  - Photometric redshifts make a larger volume (depth, number of objects) available
    - systematics: photometric redshifts have much larger errors, need to understand redshift error distribution very well
    - need many more galaxies/much larger volume to make up for the less precise distance measurements
    - impossible to measure growth rate from photometric data
  - Sample selection: since galaxies are biased tracers of the underlying dark matter density field, it is extremely important to choose the sample carefully
    - volume limited! (otherwise introduce scale-dependent luminosity bias)
    - if you want to measure w(z), make sure you compare similar populations

From the ESA-ESO cosmology report:

- 1% error in distance gives 5% error in *w*
- For a spectroscopic survey minimum volume is 5 h^{-3} Gpc^3
- Typical number of galaxies: N = 2000000
- Blake and Bridle 2005: for photometric redshifts need a factor of 10 more (to make up for redshift smearing)

Surveys suited for investigations of LSS

- Photometric surveys:
  - Pan-STARRS
  - DES
  - PAU-BAO
- Spectroscopic surveys:
  - BOSS
  - VIPERS
  - HETDEX
  - WiggleZ
- Future surveys:
  - LAMOST
  - EUCLID
  - LSST

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  - VIPERS
  - HETDEX +RELFEX II (x-ray+spectroscopy)
  - WiggleZ
- Future surveys:
  - LAMOST
  - EUCLID
  - LSST

Challenges in the age of "precision cosmology"

- **Theory:** An accurate measurement of the clustering properties of galaxies (or QSOs, or galaxy clusters) is only one part of the story: We need a precise theoretical prediction as well. This is very complicated, because three effects lead to distortions of the original BAO signal:

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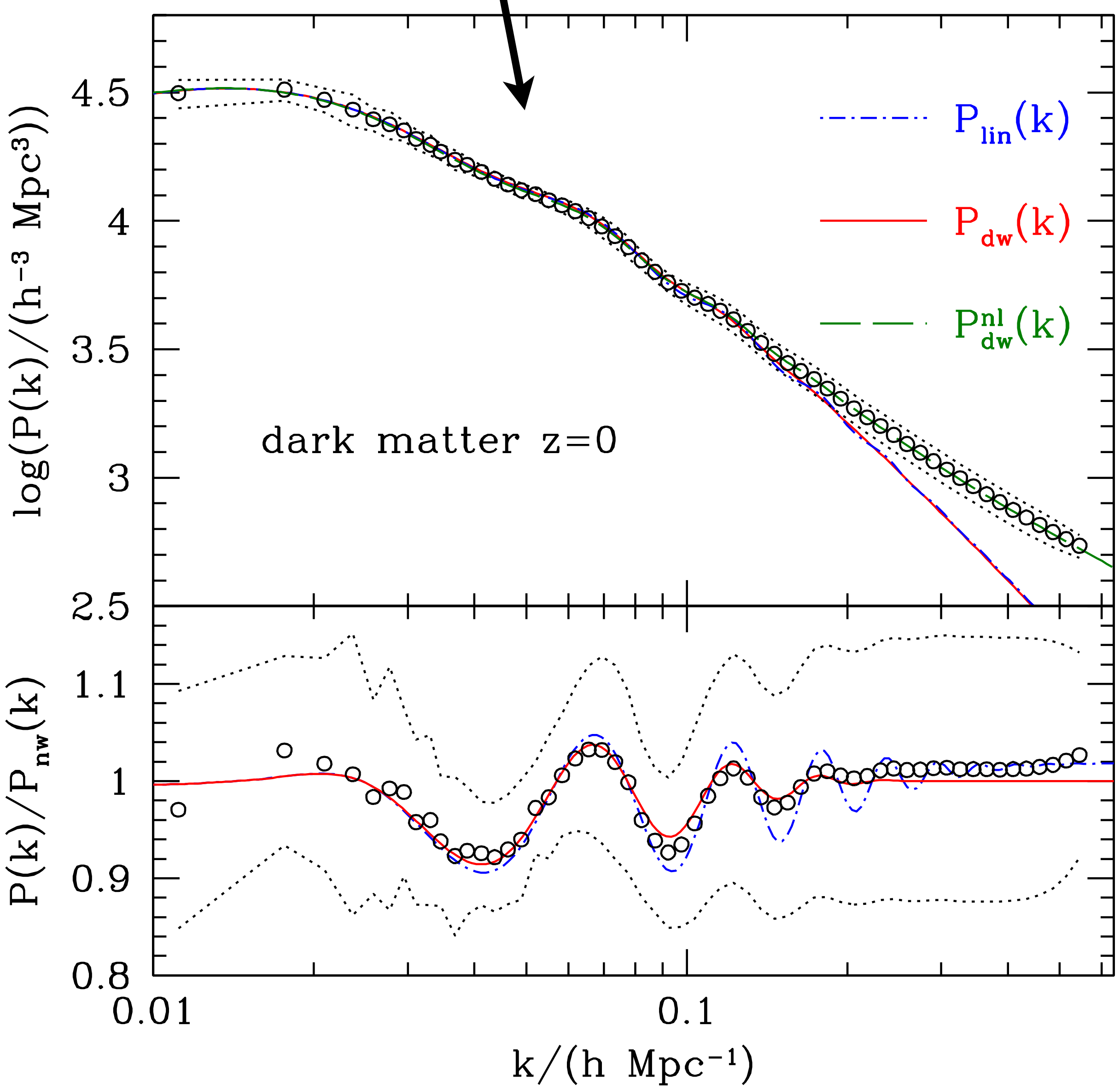
  - non-linear clustering growth
    - Can be tackled by applying renormalised perturbation (Crocce & Scoccimarro 2008, Matsubara 2008) theory to the modeling

Non-linear clustering growth

L-BASICC, a numerical simulation of dark matter (Angulo et al. 2008)

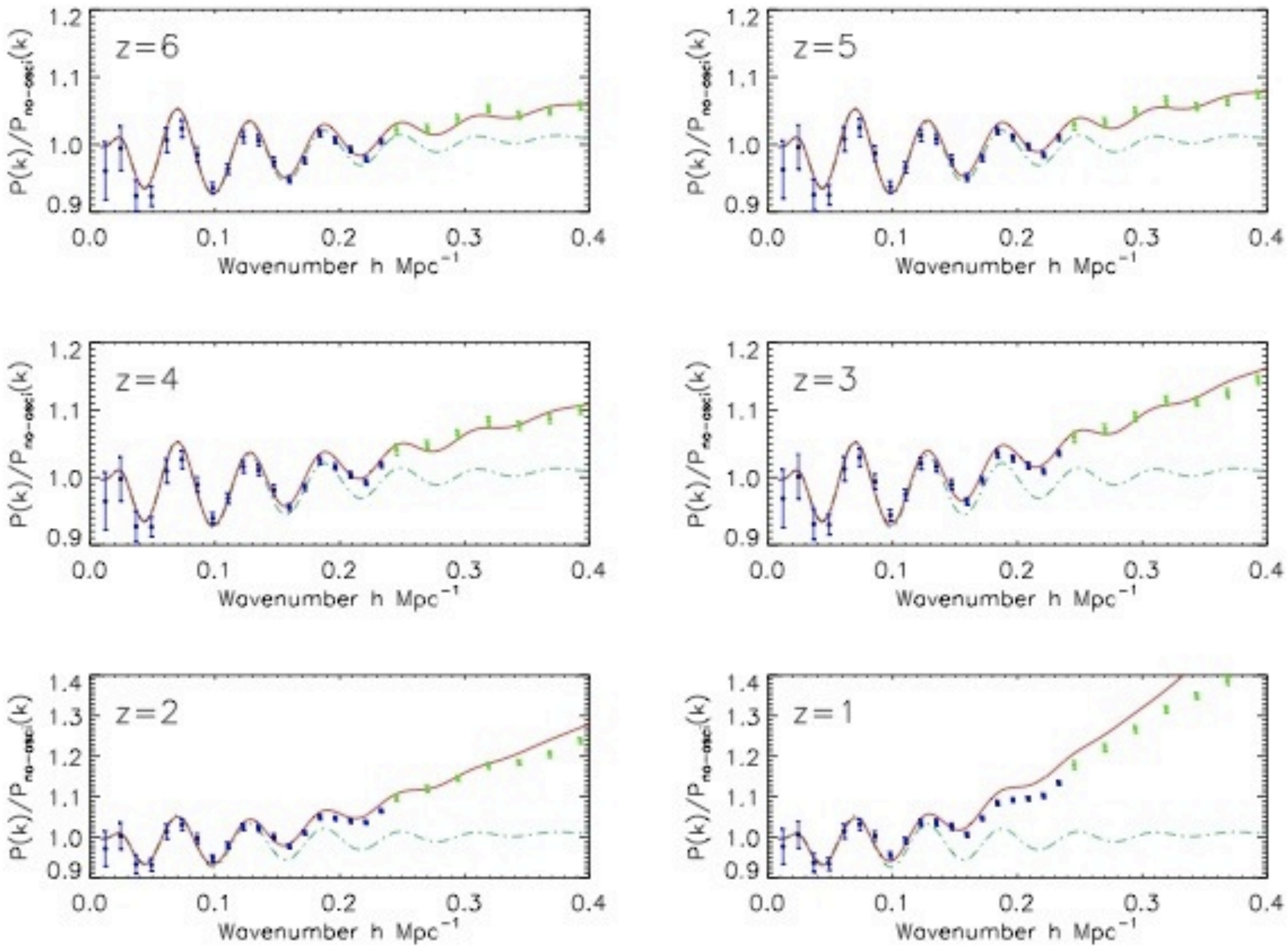


Nonlinear evolution of structure growth has to be taken into account in the modeling of power spectrum or correlation function

The power on small scales is enhanced due to non-linear clustering growth

Sánchez et al. 2008

Non-linear evolution on BAO scales



- Using third-order renormalised perturbation theory we can approximate the effect of non-linear structure growth
- Easier to model at higher redshifts
- There is more:
  - non-linear, scale dependent bias
  - non-linear redshift space distortions

Taken from http://gyudon.as.utexas.edu/~komatsu/presentation/mpe.pdf

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  - non-linear clustering growth
    - Can be tackled by applying renormalised perturbation (Crocce & Scoccimarro 2008, Matsubara 2008) theory to the modeling
  - redshift-space distortions
    - A lot of work still required to understand non-linear effects, both for coherent infall (Kaiser effect) as well as in FoGs (“Fingers of God”)

Redshift space distortions

- Galaxies have peculiar velocities
  - "Fingers of God": Non-linear velocities, hard to model
  - Linear Kaiser effect: Linear velocities, easier to model
  - Non-linear Kaiser effect: extremely difficult to model
- The measured redshift is always a sum of the cosmological redshift and the Doppler redshift coming from the peculiar velocity

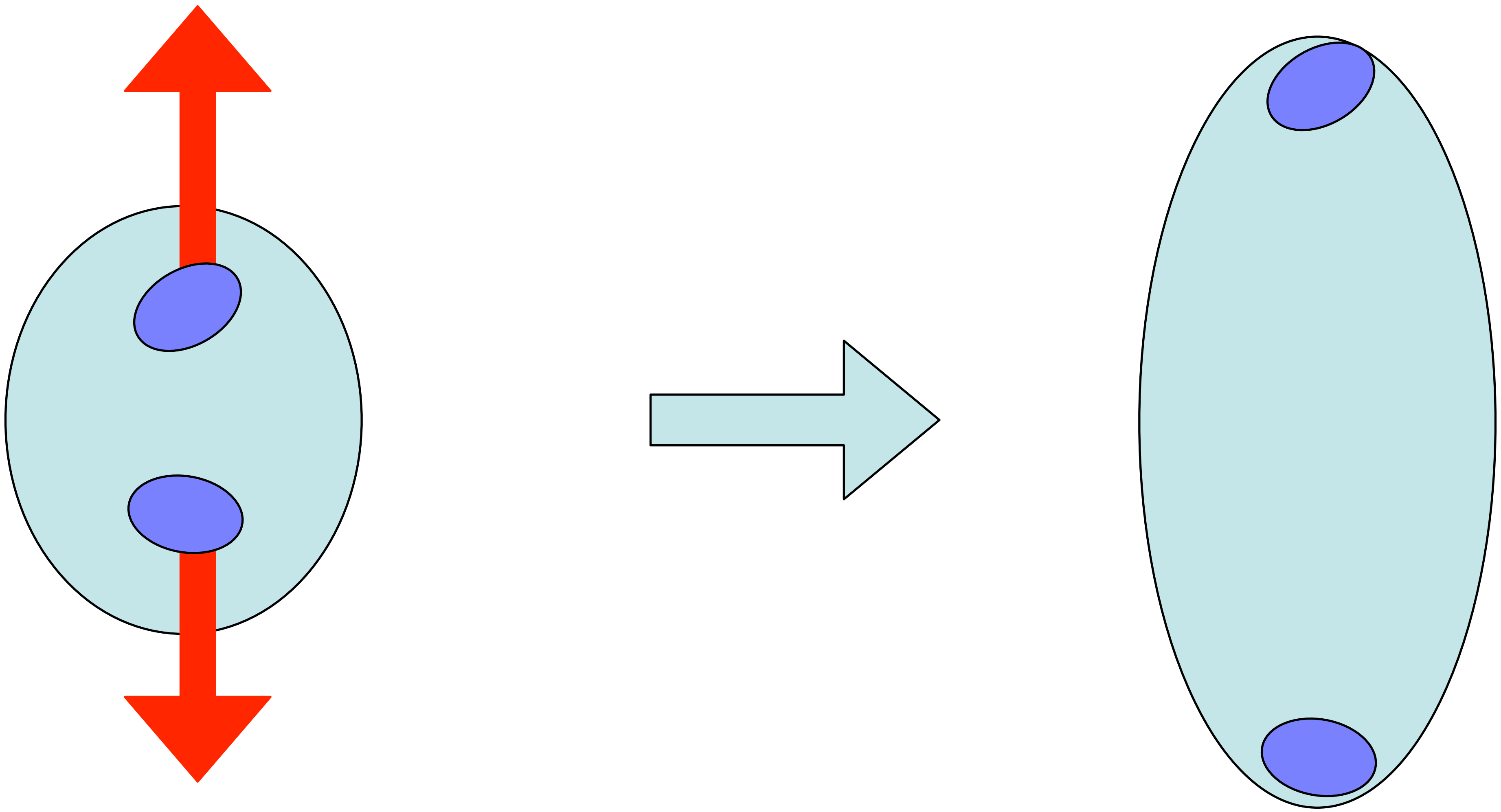
$$z_{obs} = z_{true} + v_{pec}/c$$

- It is impossible to disentangle the two!

Fingers of God

- Galaxies having peculiar velocity components away from us are redshifted, those moving towards us are blueshifted
- In galaxy clusters, galaxies move around in the deep potential well of the mass concentration
- Hence, a cluster appears to be stretched in redshift space

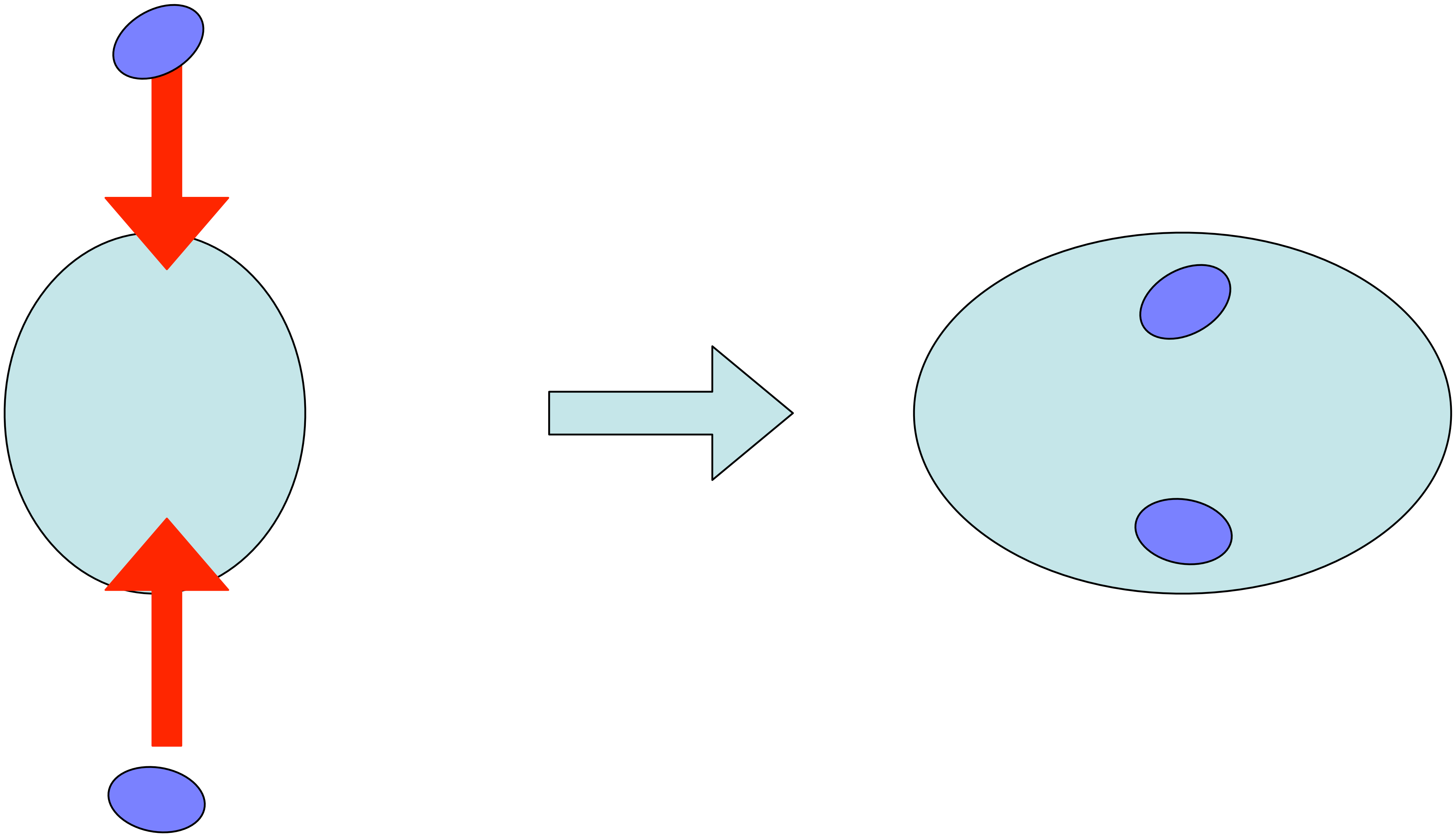
Fingers of God



Real space

Redshift space

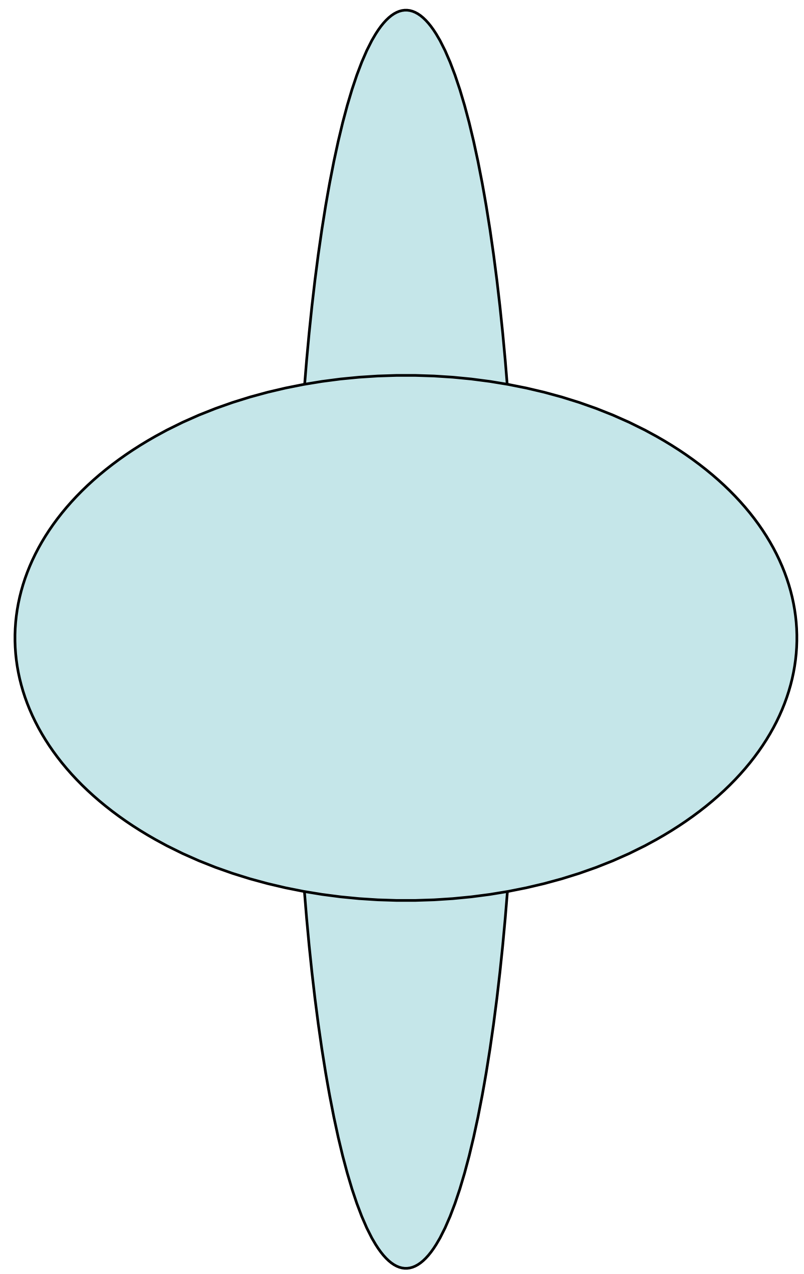
Coherent infall: The *Kaiser effect* (I)



Real space

Redshift space

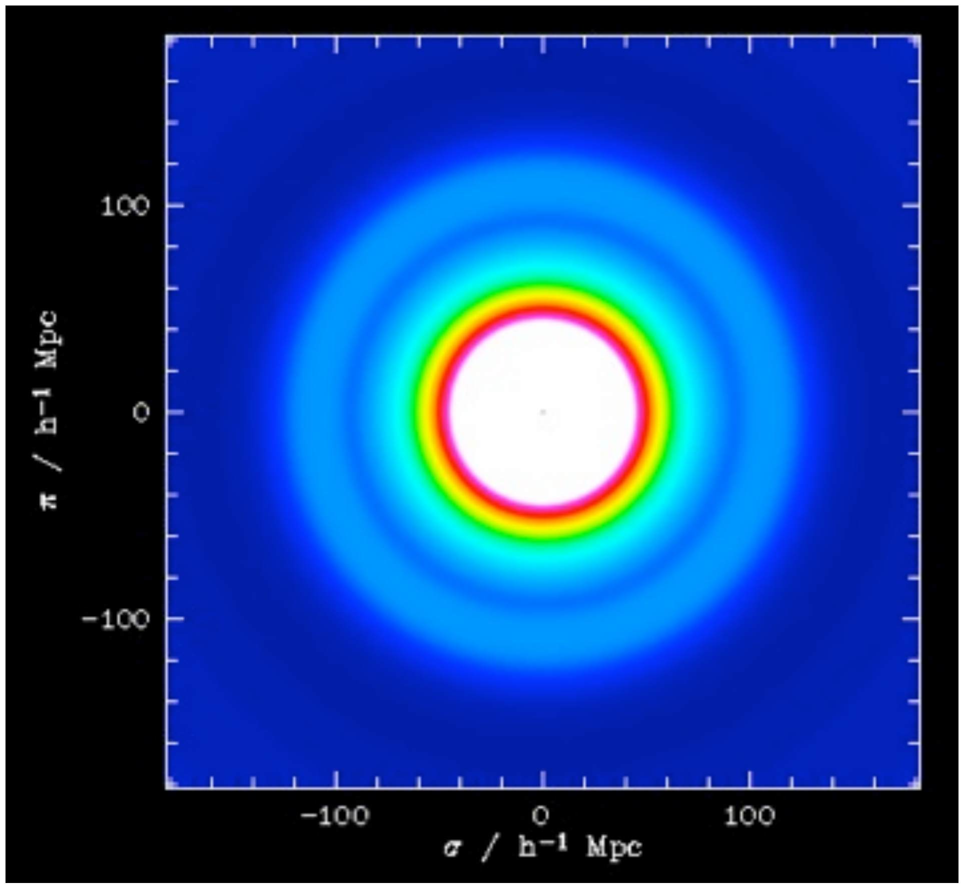
The sum of the two effects (Fingers of God and Kaiser effect):



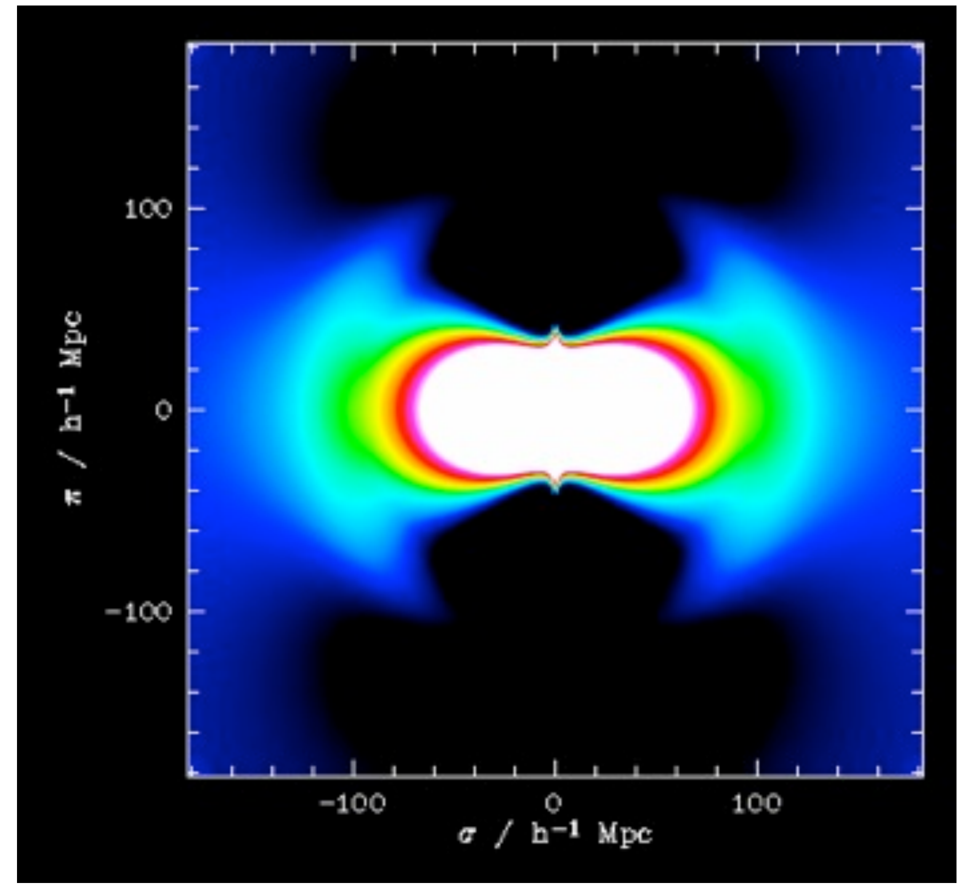
➡ The shape of objects (=distances!) in redshift space is highly distorted!

An analytic prediction for $\xi(r_p,\pi)$ (including non-linear structur growth to 3rd order)

Schlagenhaufer and Phleps



Real space



Redshift space

In real space the signal of the acoustic peak is a ring at $r=106h^{-1}$Mpc.

Redshift space distortions (Fingers of God, Kaiser effect) still act on the scales of the acoustic ring

Challenges in the age of "precision cosmology"

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  - non-linear clustering growth
    - Can be tackled by applying renormalised perturbation (Crocce & Scoccimarro 2008, Matsubara 2008) theory to the modeling
  - redshift-space distortions
    - A lot of work still required to understand non-linear effects, both for coherent infall (Kaiser effect) as well as in FoGs ("Fingers of God")
  - non-linear, possibly scale dependent, stochastic bias ($\xi_{gal}=b^2\xi_{dm}$, $b\neq$const)
    - Can be measured using higher-order clustering statistics, e.g. three-point correlation function or bispectrum

Three point statistics: Bispectrum and three point correlation function

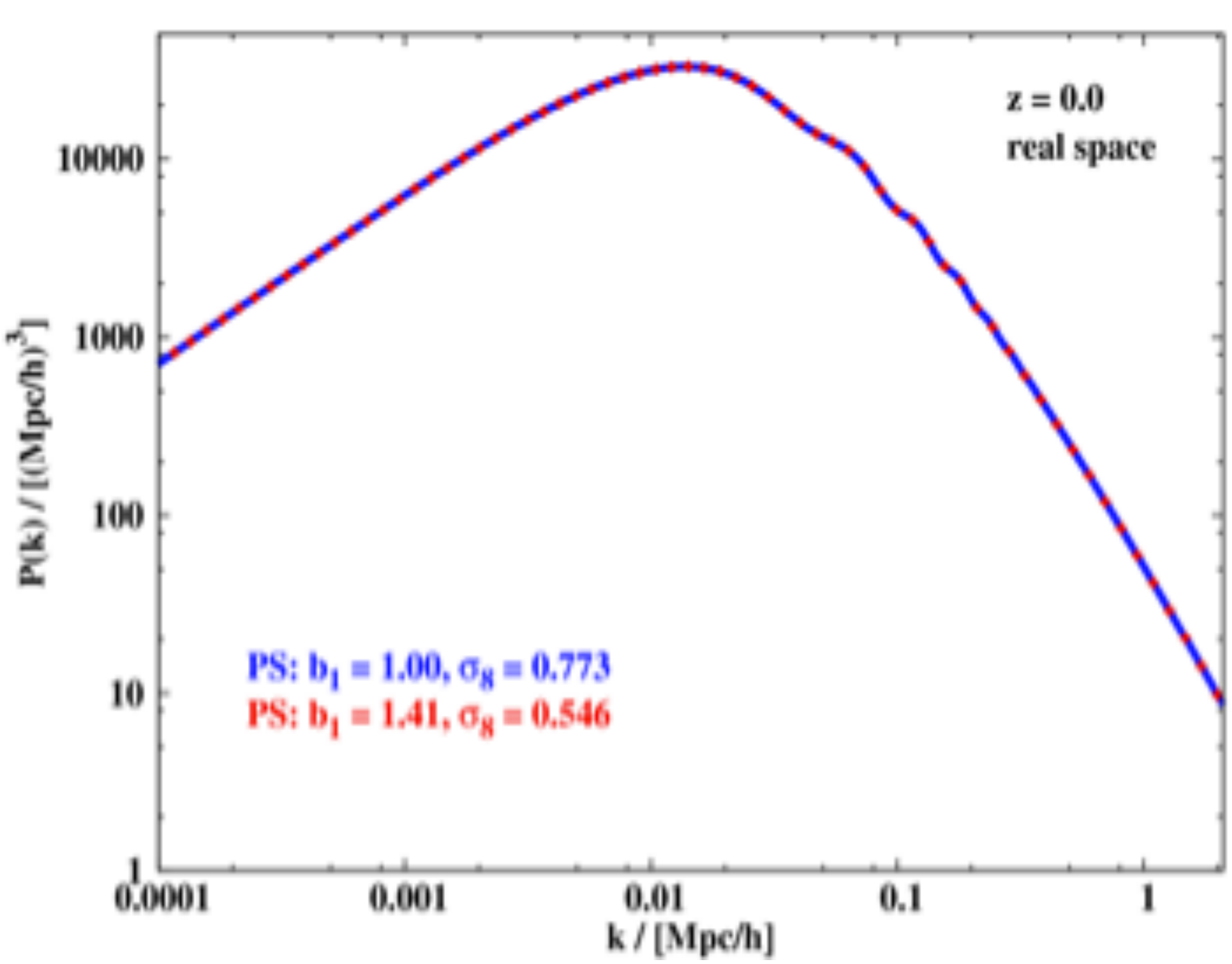
- Why go to higher order statistics?
  - Two-point statistics (two-point correlation function and powerspectrum) are very powerful tools to determine
    - cosmological parameters (e.g. Sánchez 2009)
    - measure growth factor (e.g. Guzzo 2008)
  - Three-point statistics is
    - able to determine linear and quadratic bias (the three point statistics are able to break degeneracy between b_1 and σ_8)

$$\delta_{gal} = b_1 \delta_{DM} + \frac{1}{2} b_2 \delta_{DM}$$

Fry 1996

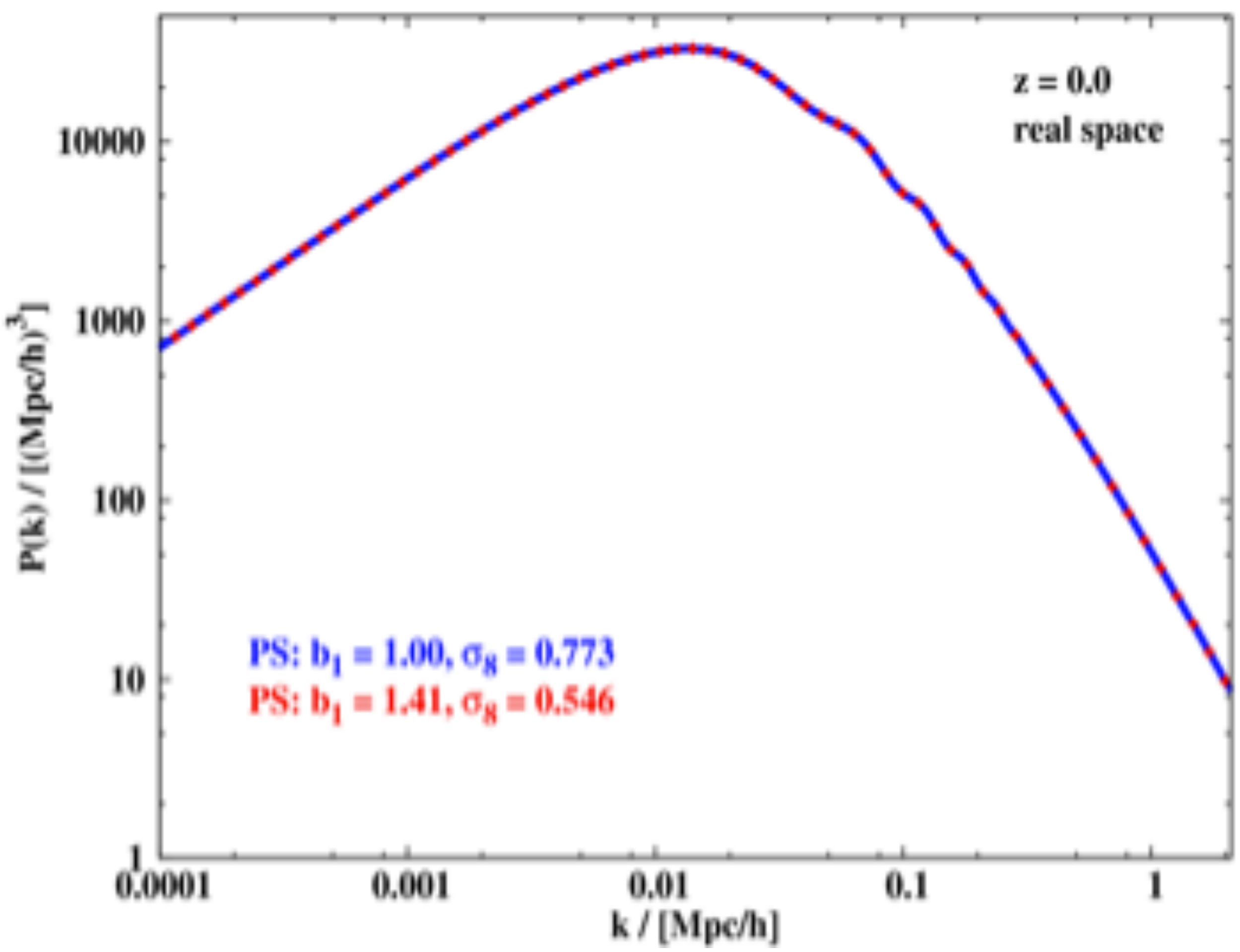
    - sensitive to
      - cosmological parameters
      - non-gaussianities:
        - » non-linear structure growth
        - » primordial

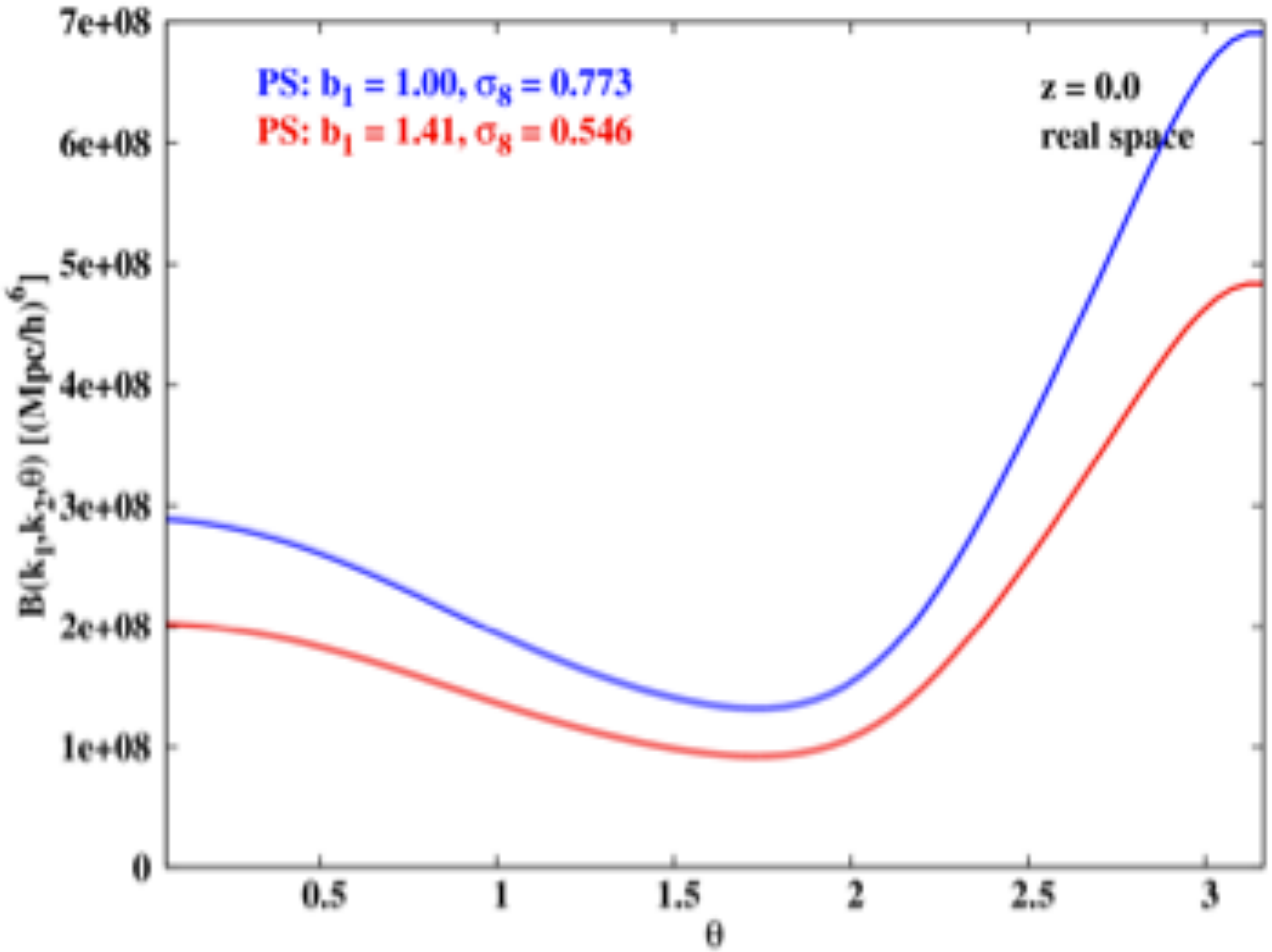
Breaking the degeneracy between bias and σ_8



- power spectra are the same
- b_1 and σ_8 are different

Breaking the degeneracy between bias and σ_8





- power spectra are the same
- b_1 and σ_8 are different
- but three point statistic is able to distinguish the two cases

A measurement of cosmological parameters using the SDSS-DR7 LRG sample (A. Sánchez)

- Model for the full shape of the correlation function, as in Sánchez et al. 2008, 2009:

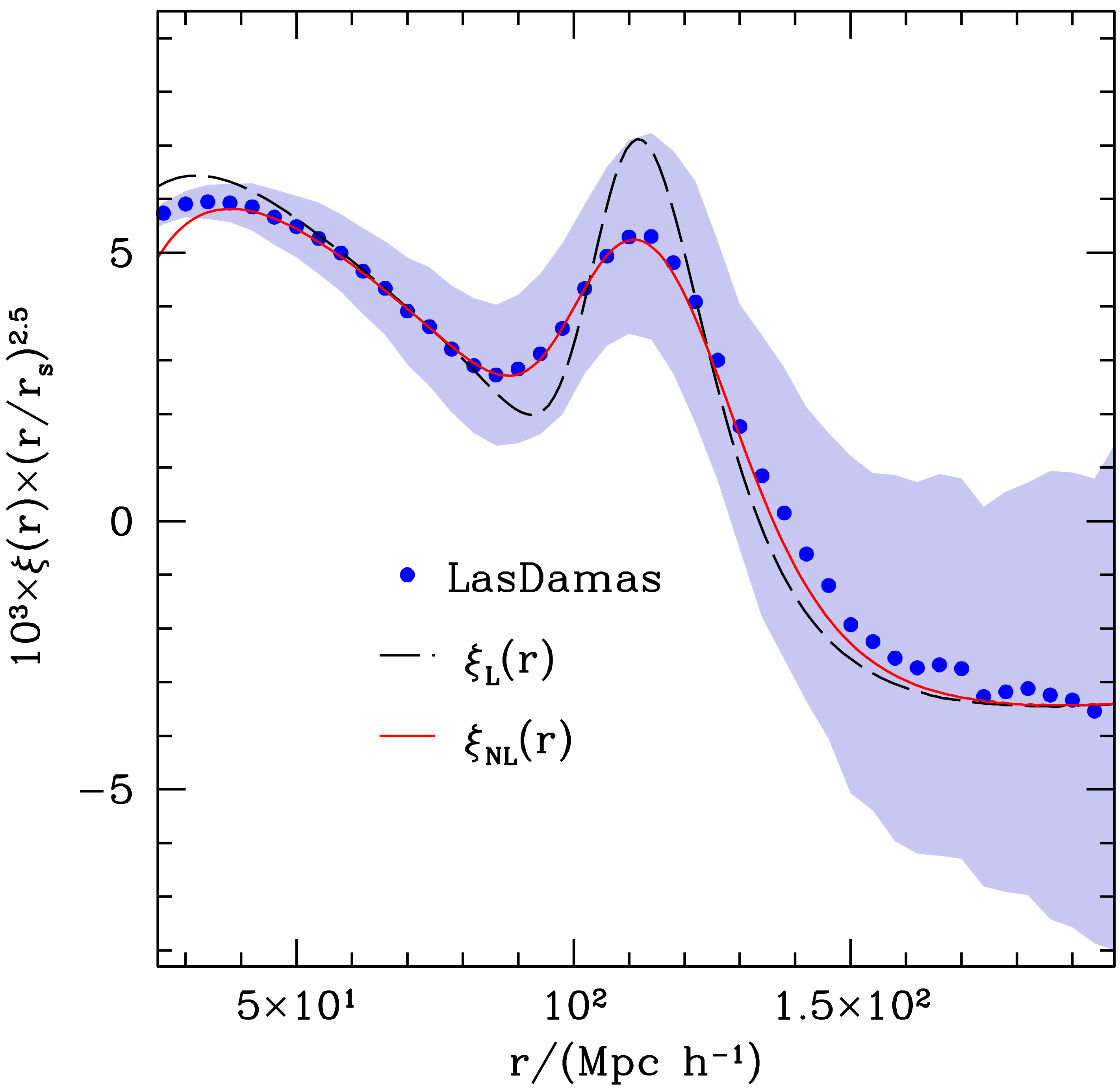
$$\xi_{NL}(r) = b^2\left[\xi_L(r) \otimes \exp\left[-(k_* r^2)\right] + A_{MC}\,\xi_L'(r)\,\xi_L^{(1)}(r)\right]$$

- where b and A_{MC} account for the linear bias as well as the enhanced amplitude due to the Kaiser effect, ξ_L is the linear correlation function, k_* a smoothing kernel parameter, and the second term is primarily motivated by RPT (accounting for mode-mode coupling)
- Use a modified version of the Las Damas (A Large Suite of Dark Matter Simulations) LRG mocks (including angular and radial selection function) to estimate the covariance matrix of the measurement of the real data
- LRG sample from Kazin et al. (2010) for $0.16 < z < 0.44$

The correlation function in the Las Damas SDSS-DR7 LRG mock

http://lss.phy.vanderbilt.edu/lasdamas/mocks.html

Berlind, Busha, Gardner, Manera, McBride, Scoccimarro, van den Bosch, Wechsler



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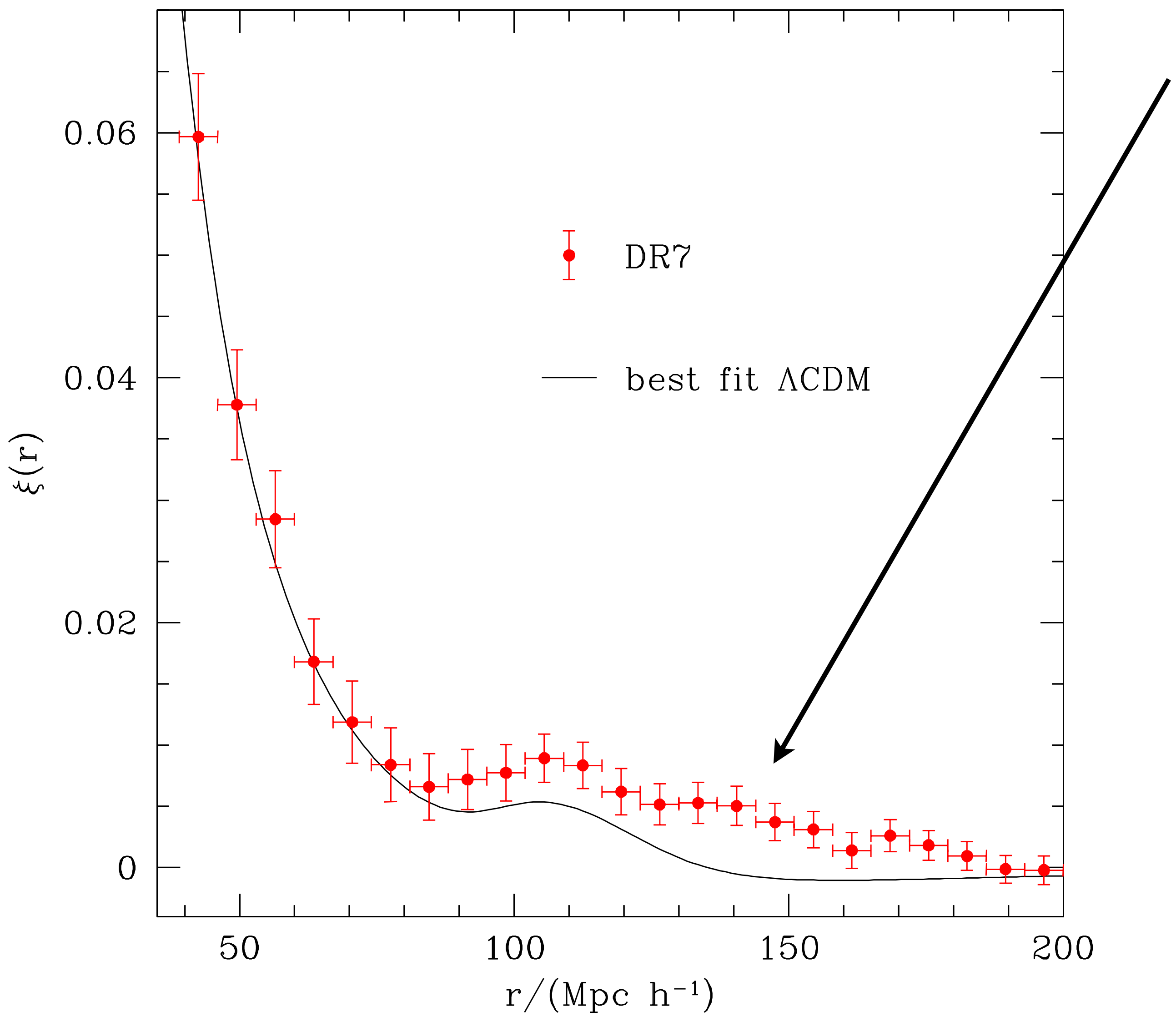

- Unexpected excess power on large scales
- Possible explanations:
  - residual systematic errors
  - cosmic variance
  - large-scale galaxy biasing mechanisms
  - new early-universe physics
  - ...?

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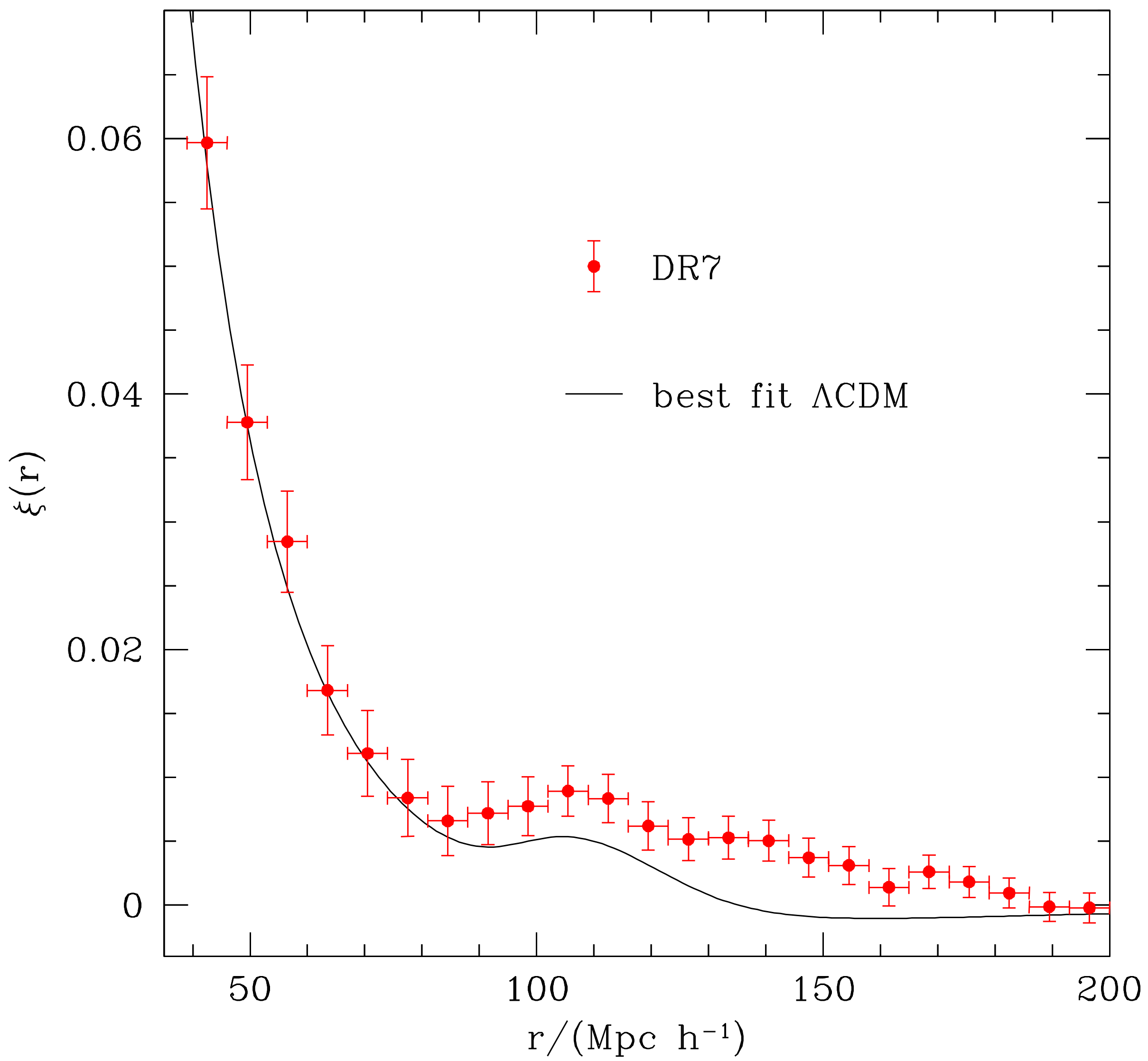
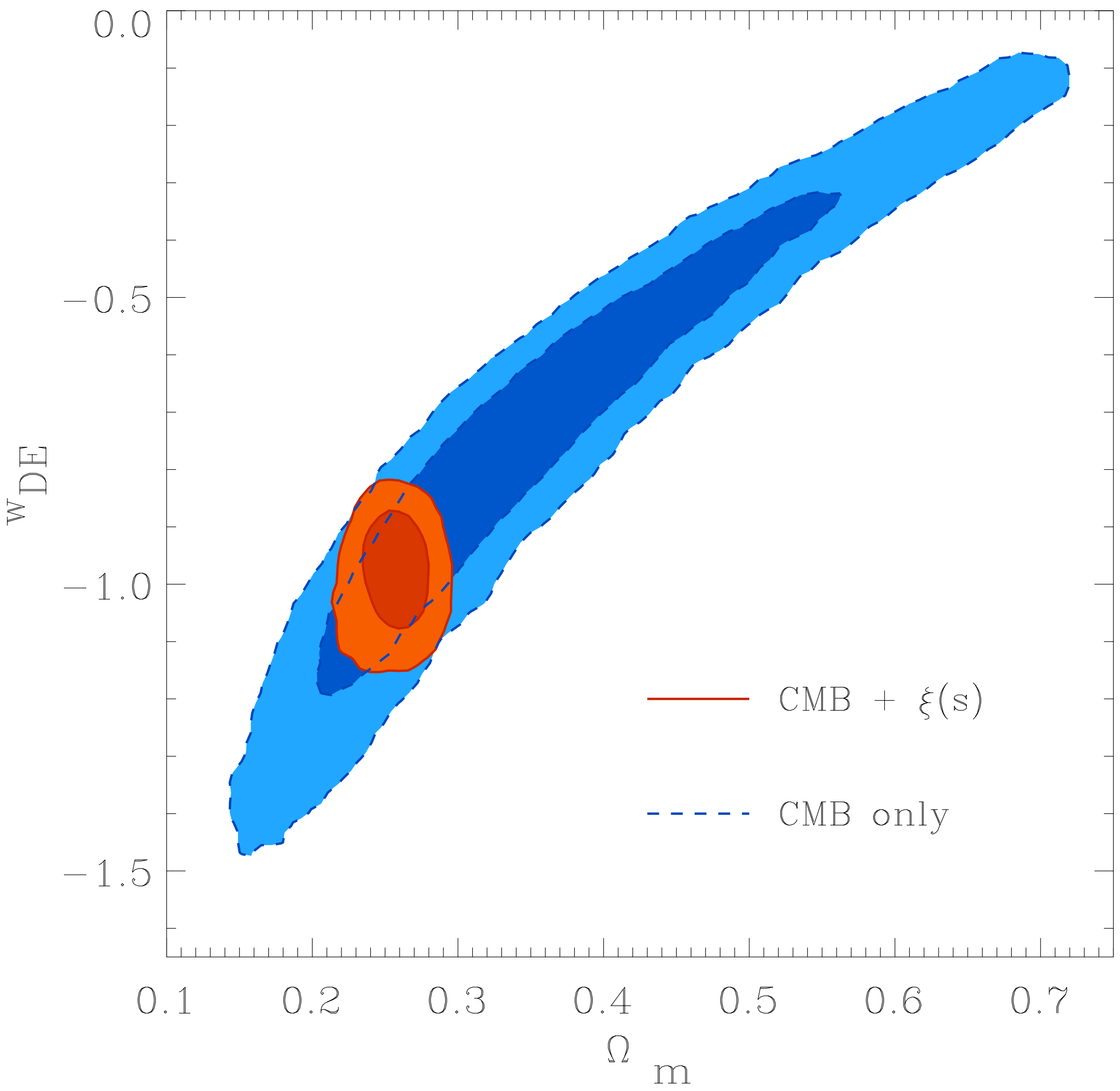


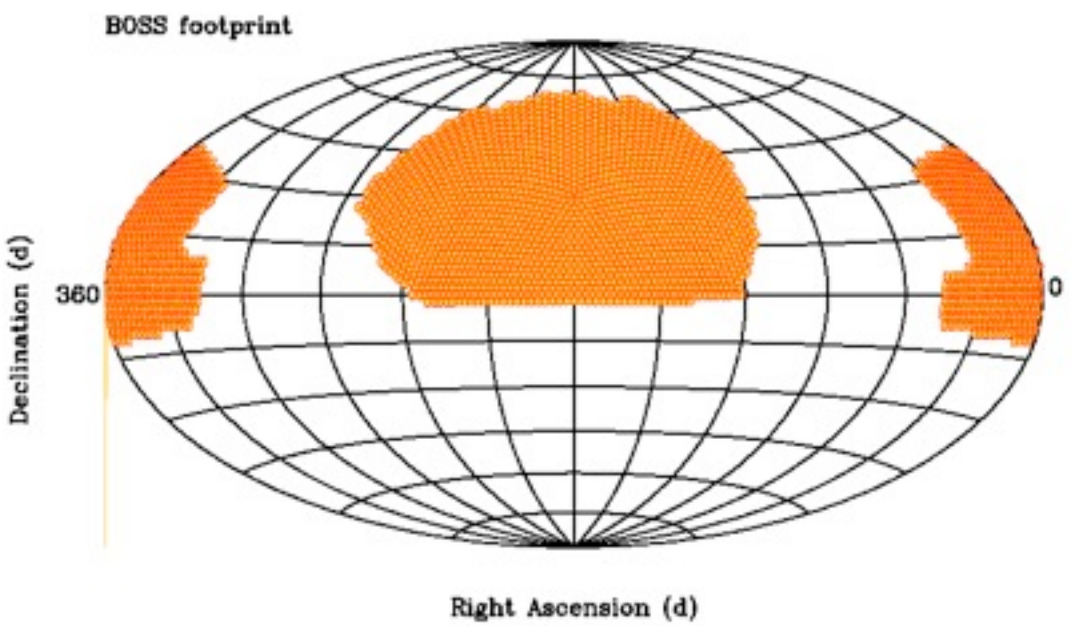


Results for a fit between 40 < r < 200: $w = -1.00 \pm 0.74$

$\Omega_m = 0.255 \pm 0.015$

BOSS
(Baryonic Oscillation Spectroscopic Survey)

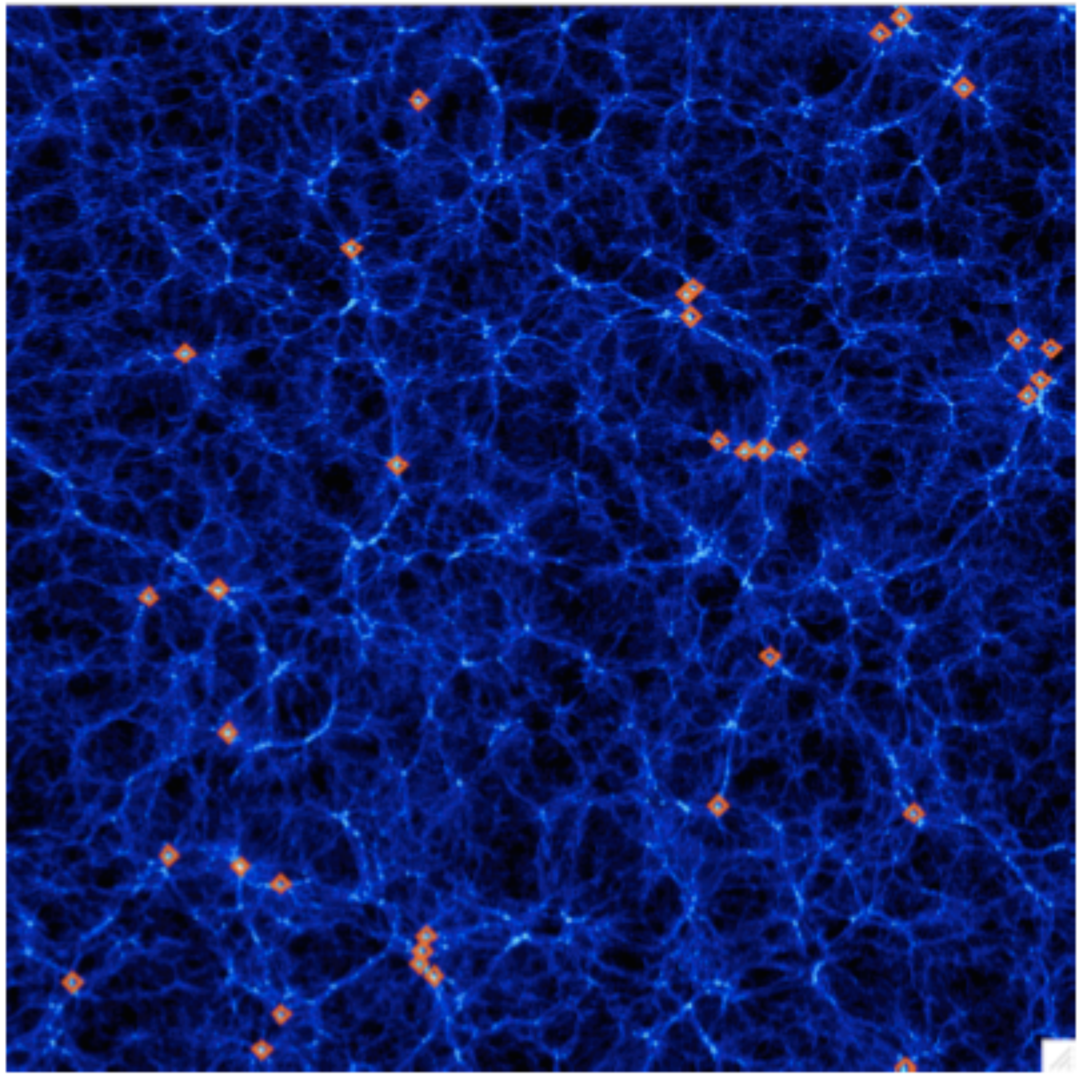
- BOSS is designed to measure the Dark Energy Equation of state using the imprint of BAOs in the galaxy power spectrum (or correlation function). However, a lot of auxiliary science projects possible!
- BOSS is a part of SDSS-III. The other surveys are
  - SEGUE-2 An optical survey to probe the assembly history of the outer Milky Way (formerly known as SEGUE2)
  - APOGEE An infrared survey of the dynamics and chemical evolution of the obscured Galaxy
  - MARVELS A massive multi-object radial velocity planet search (formerly known as ASEPS)
- BOSS has started in autumn 2009, will run until 2014 (total runtime 5 years)
- Area: 10 000 square degrees
- Positions of
  - 1.4 Million LRGs up to z<0.7
  - 160 000 QSOs with 2.3<z<2.8



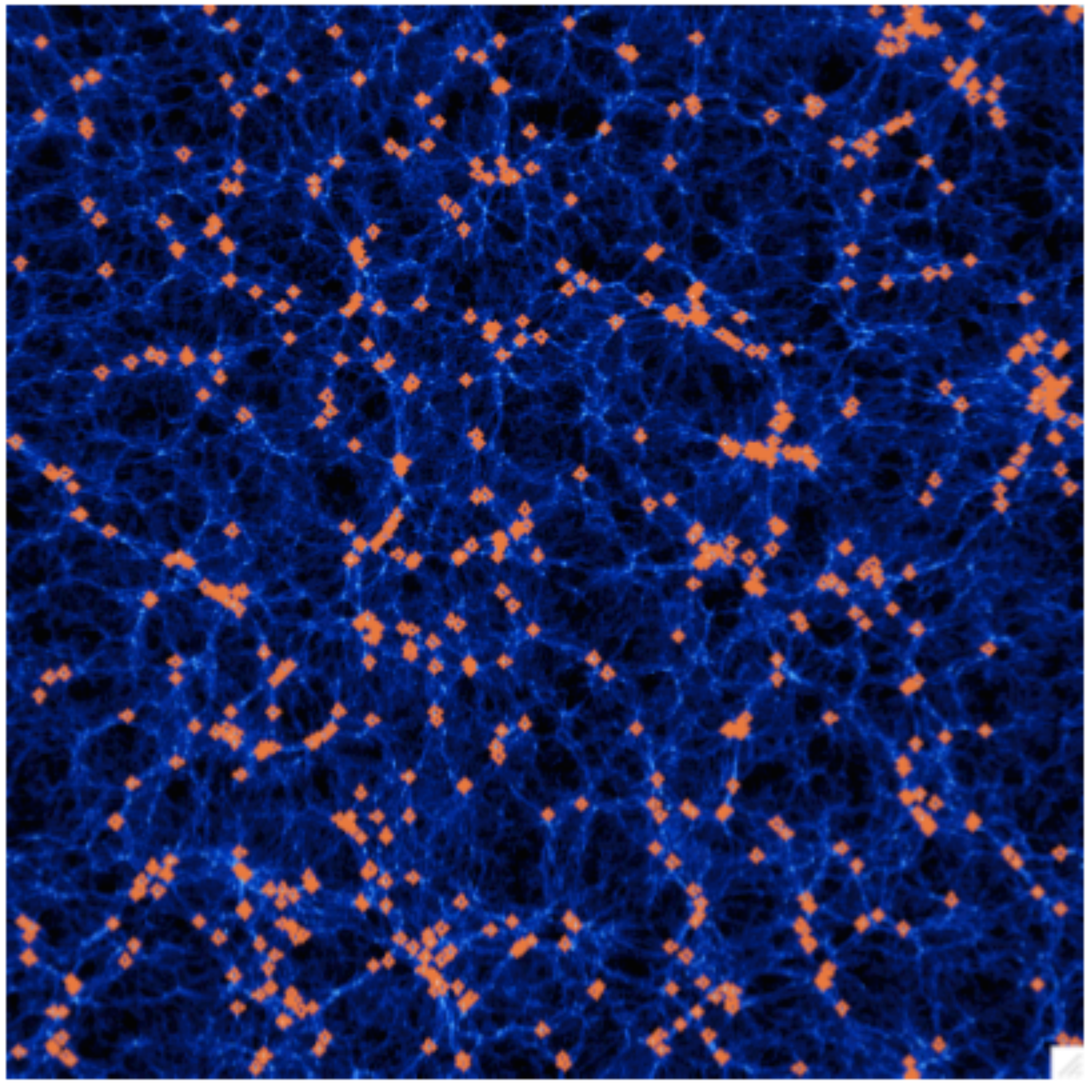
BAOs with the SDSS-III (BOSS)

The cosmic web at $z\sim0.5$, as traced by luminous red galaxies

From the talk of Martin White



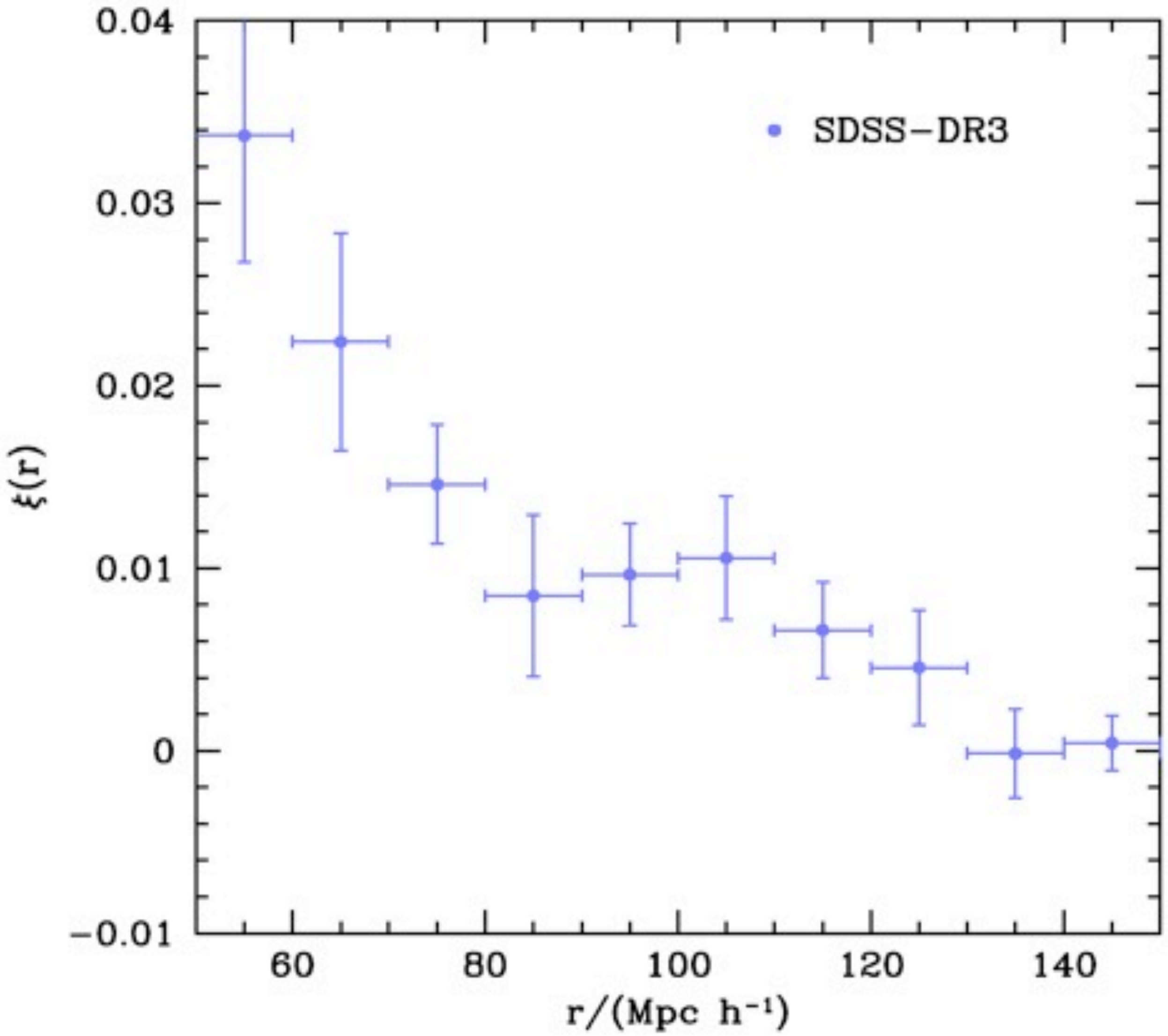
SDSS



BOSS

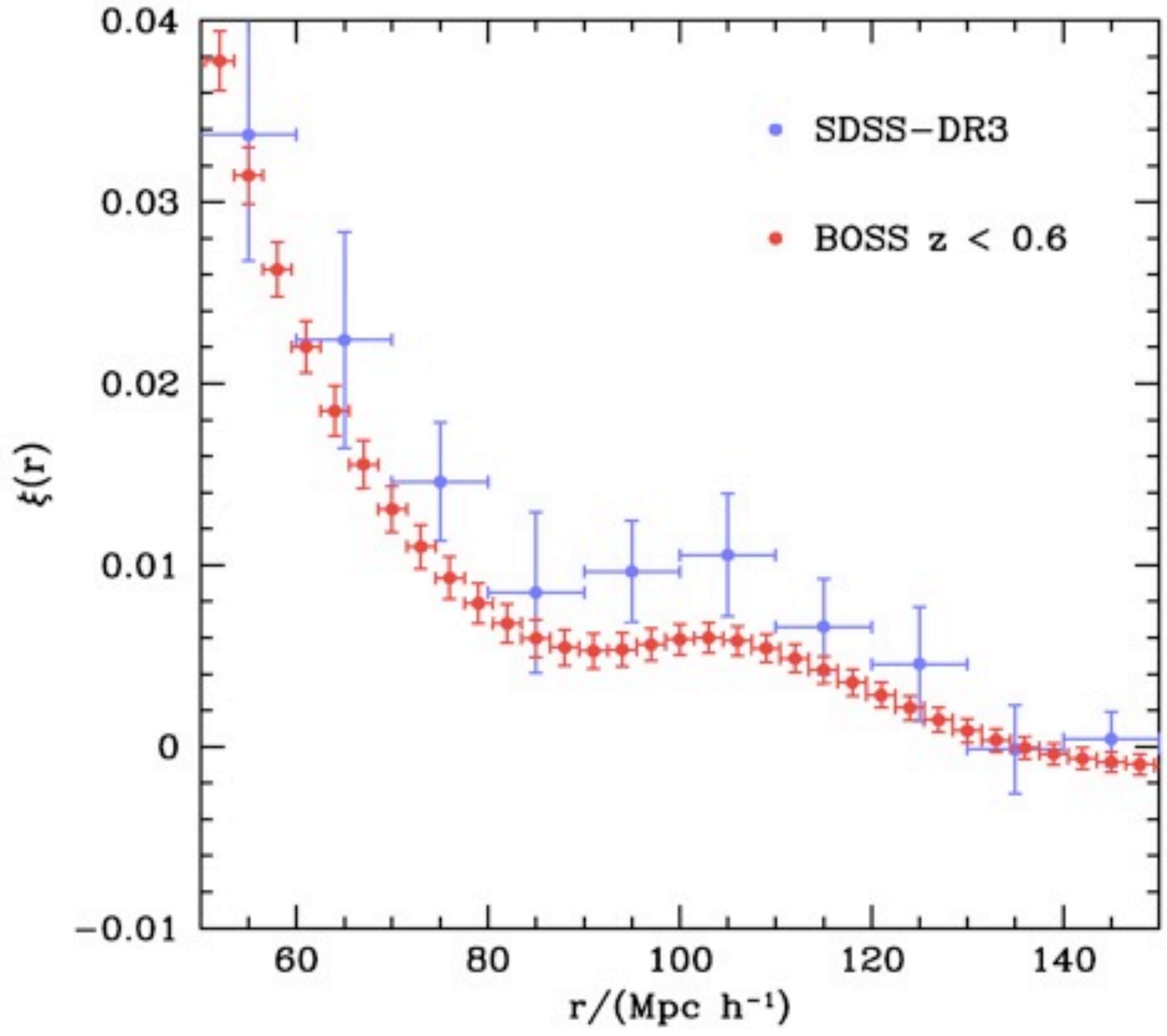
A slice $500h^{-1}$ Mpc across and $10\ h^{-1}$ Mpc thick

What BOSS will be able to do



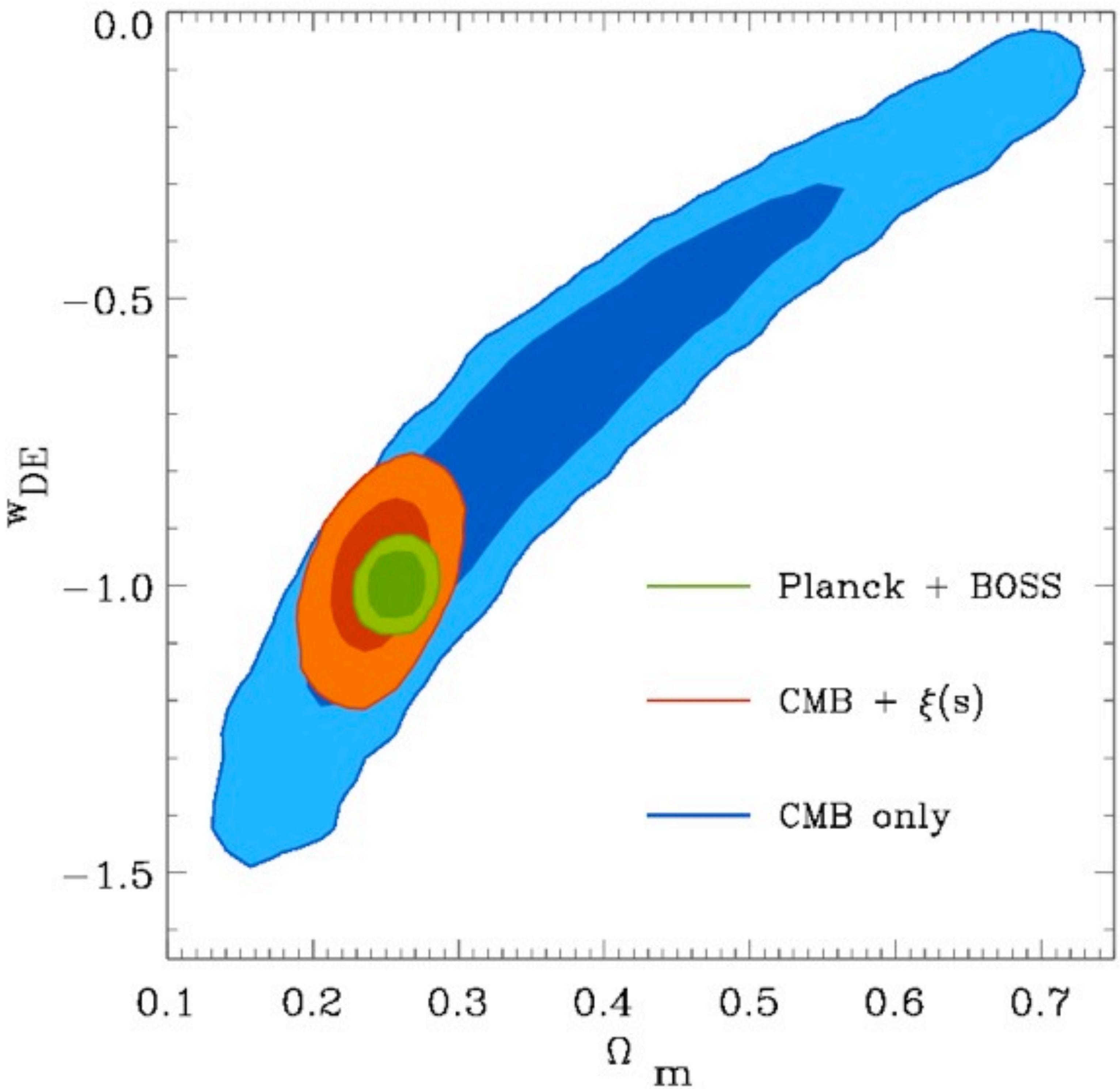
- The first detection of the BAO (Eisenstein et al. 2005)

What BOSS will be able to do



(Sánchez et al.)

Forecasts for BOSS+Planck



Sánchez et al. (2009)

$$\mathbf{P}^{6+w_{\rm DE}}_{\rm varied} \equiv (\omega_{\rm dm}, \omega_{\rm b}, n_{\rm s}, \tau, A_{\rm s}, \Theta, w_{\rm DE})$$

CMB only:

$$\Omega_m = 0.36 \pm 0.12$$
$$w_{DE} = -0.73 \pm 0.30$$

CMB + $\xi(s)$:

$$\Omega_m = 0.245 \pm 0.020$$
$$w_{DE} = -0.988 \pm 0.088$$

Planck + BOSS $\xi(s)$:

$$\Omega_m = 0.2571 \pm 0.0053$$
$$w_{DE} = -1.000 \pm 0.024$$

Correlation Function vs Power Spectrum (e.g. Sánchez et al. 2008)

- Power spectrum:
  - Advantage: Errors are not correlated
  - Disadvantage: Signal is distributed over a large range of modes, low signal-to-noise
    - Very precice modelling of non-linear effects required
- Correlation function:
  - Advantage: Wiggles are condensed into one bump, roughly (but not quite) corresponding to the sound horizon
    - Better signal-to-noise
    - Less effected by scale-dependent effects
  - Disadvantage: Data points and errors are highly correlated

A new model for the full shape of the power spectrum (Montesano, Sánchez & Phleps 2010)

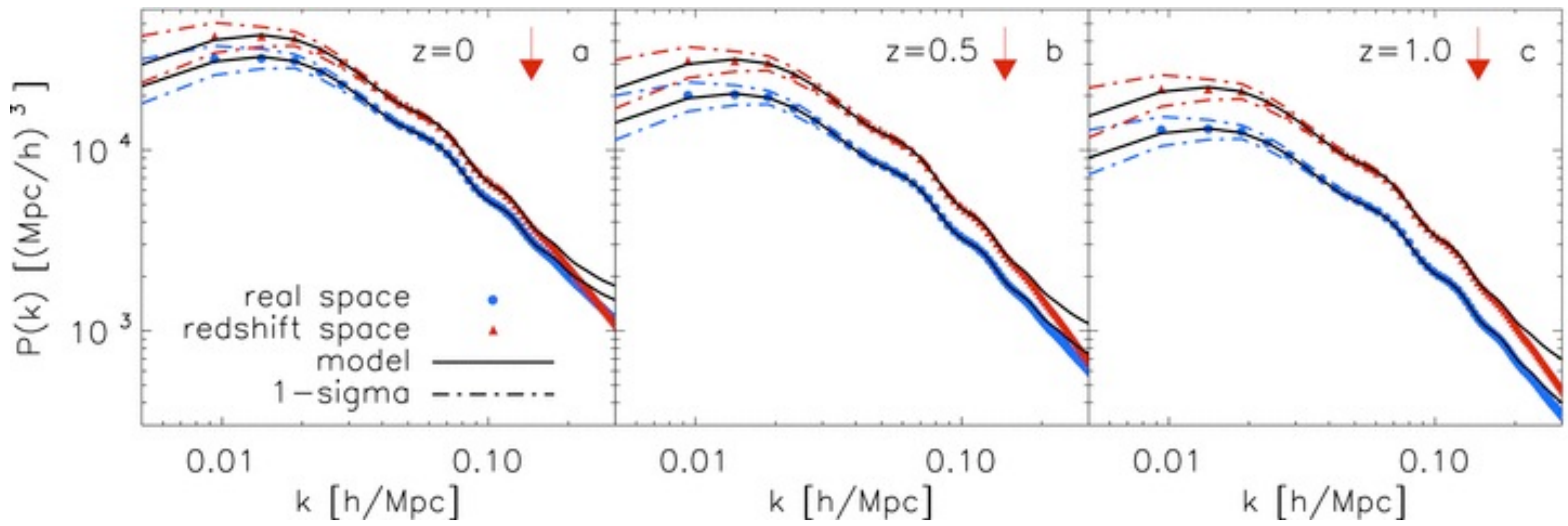
- Same approach as in Sánchez et al. 2008, 2009, but in Fourier space:

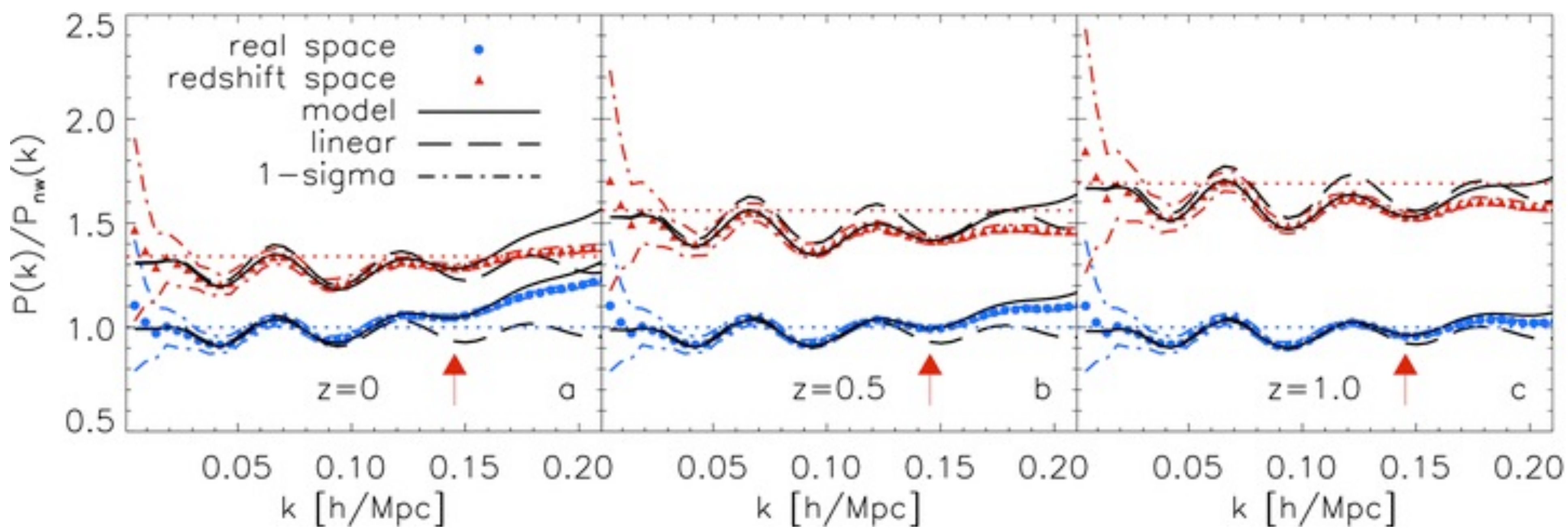
$$P_{NL}(k,z) = b^2\left[\exp\left[-\left(\frac{k}{k_*}\right)^2\right]P_L(k,z) + A_{MC}P_{1loop}(k,z)\right]$$

- Accuracy tested with L-BASICC simulations (Angulo et al. 2008):
  - assume fiducial cosmology for measurement of power spectrum
  - for small deviations away from the true equation of state, the alteration in the measured power spectrum can be represented by a rescaling of the wavenumber from k_{true} to k_{app}
  - introduce a "stretch factor" $\alpha = k_{app}/k_{true}$, which is $\alpha=1$ for an unbiased measurement

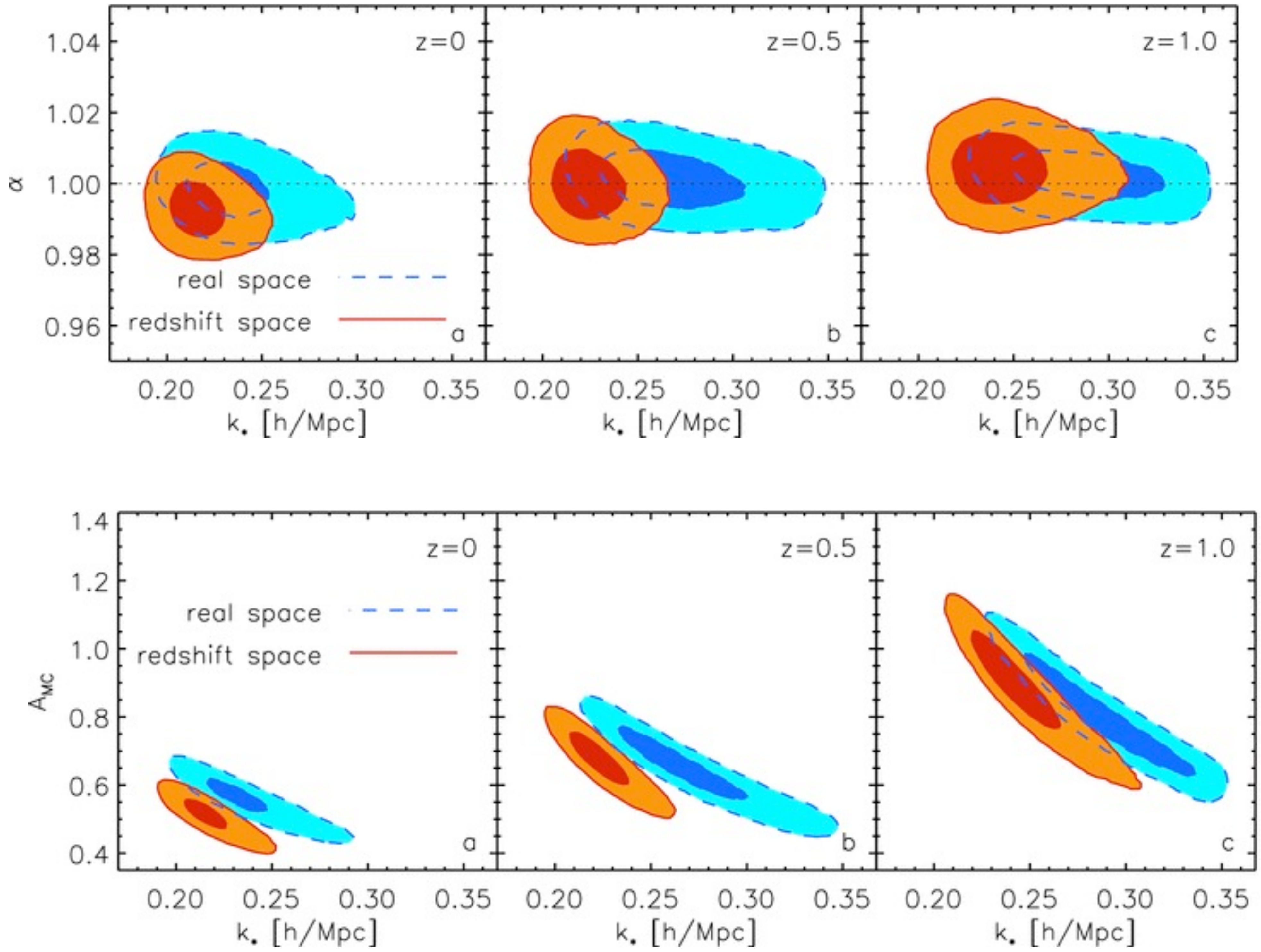
A new model for the full shape of the Power spectrum

Montesano, Sánchez & Phleps 2010, MNRAS





The model provides an unbiased measurement!



Montesano, Sánchez & Phleps 2010, MNRAS

Halo bias

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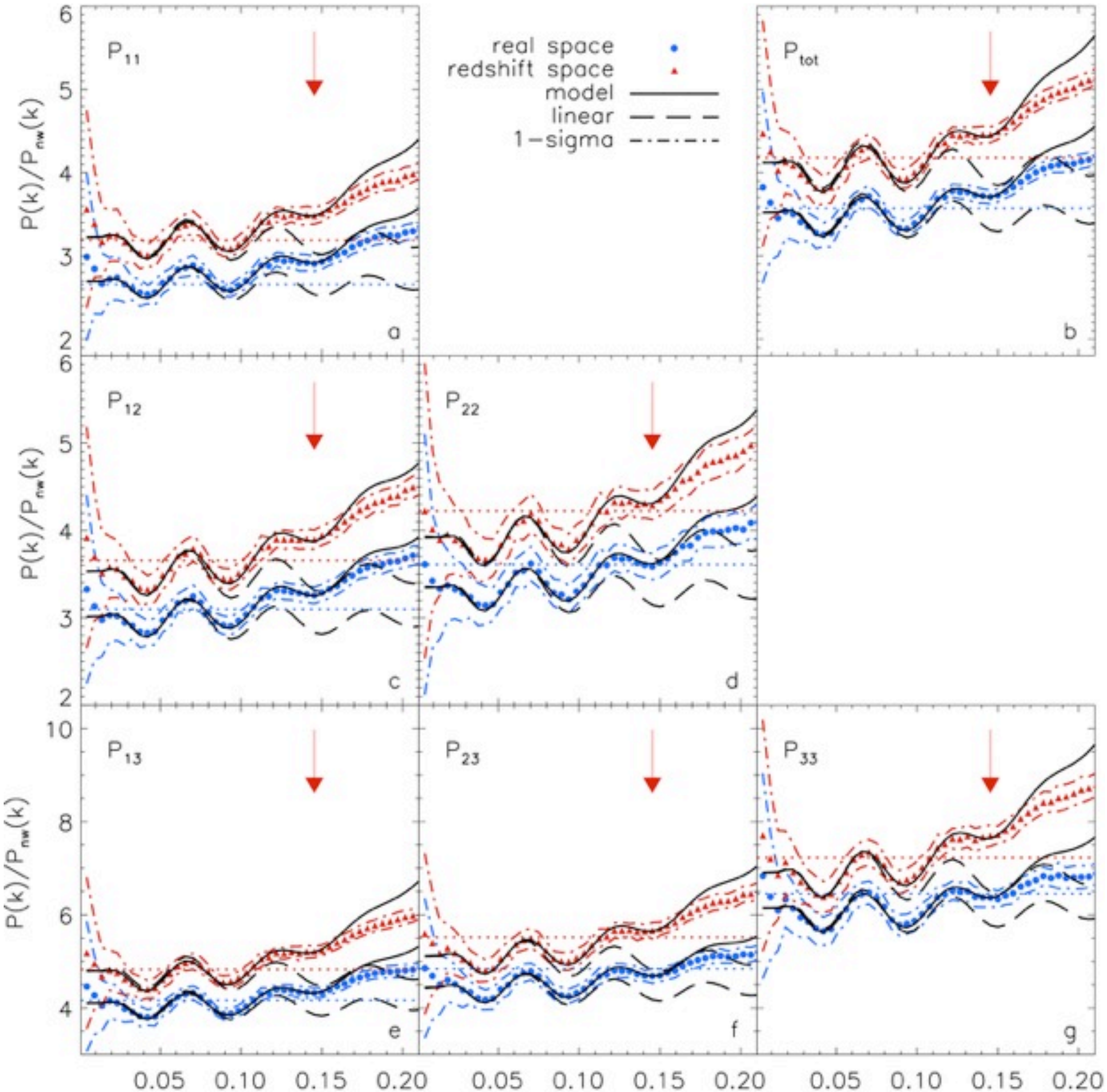

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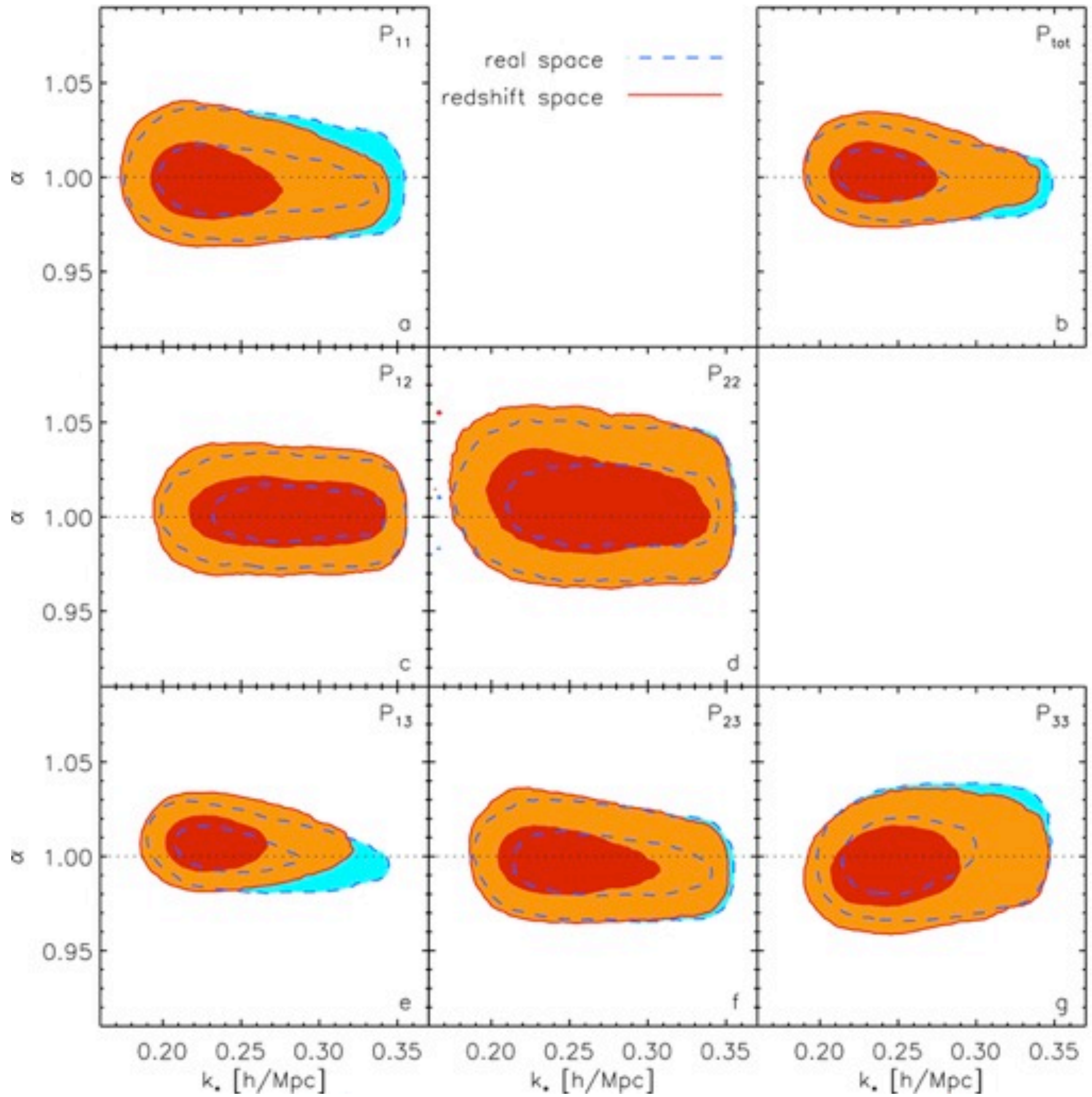
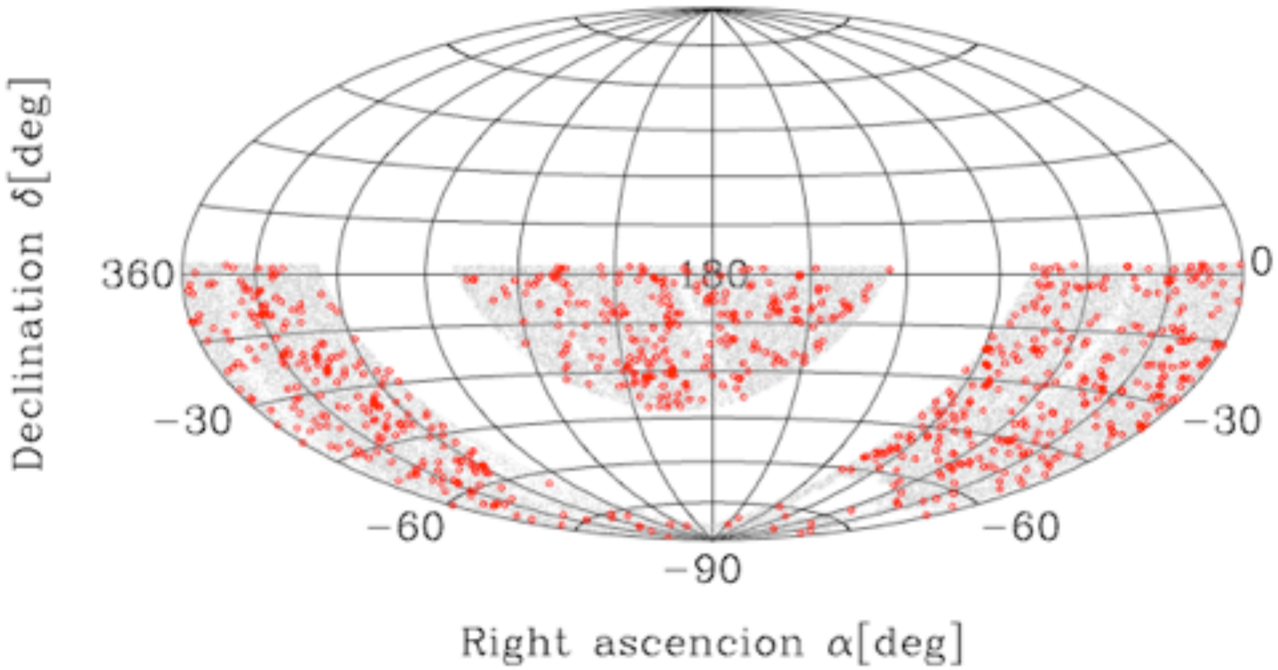


The model can take linear bias into account and still give an unbiased estimate of cosmological parameters!

REFLEX-II
(ROSAT-ESO flux limited X-ray galaxy cluster sample)

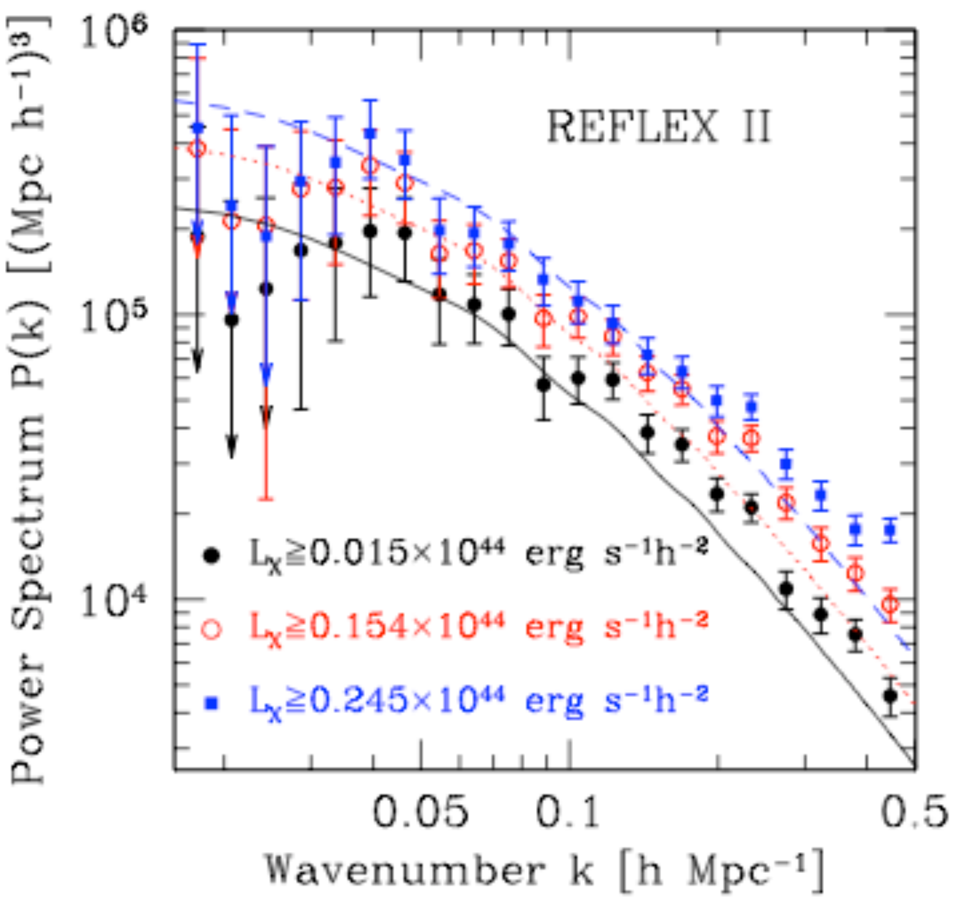
- Flux limit: $F_{lim} = 1.8 \times 10^{-12}$ erg/s/cm2 (0.2 − 4 KeV)

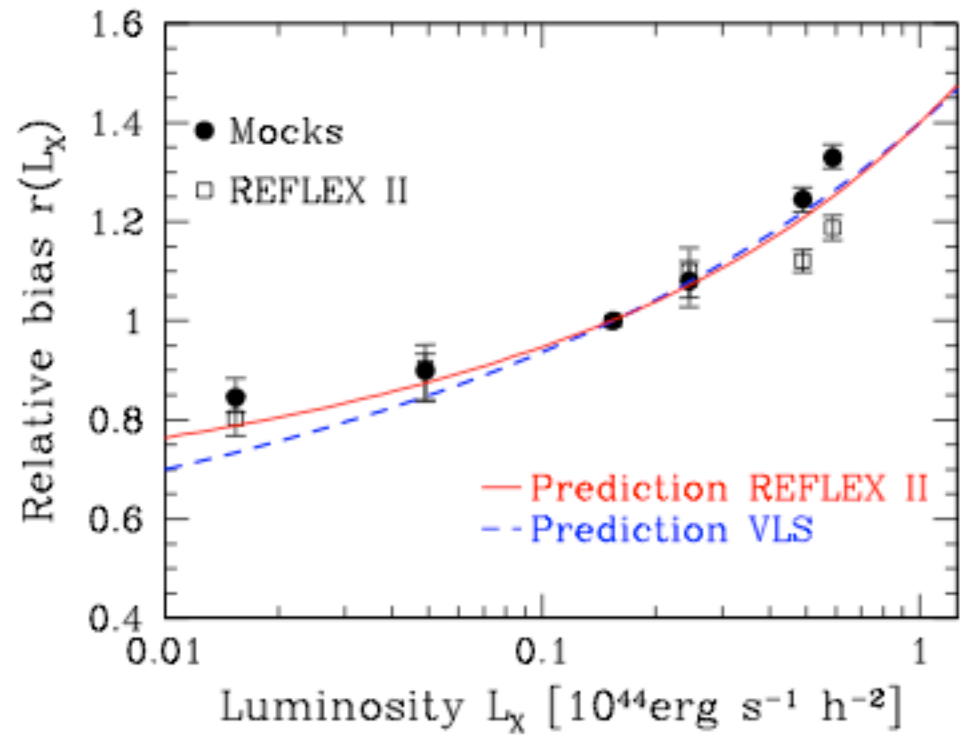


The REFLEX-II footprint

- 911 galaxy clusters found, > 84% of which have spectroscopic redshifts < 0.22 and are well suited for an analysis of their power spectrum
- Effects of luminosity bias and covariance matrices investigated by analysing cluster clustering in 100 REFLEX-II mock catalogues (constructed from the L-BASICC simulations such that the x-ray luminosity function matches the observations)

The power spectrum of the REFLEX-II clusters (Balaguera-Antolínez et al., submitted to MNRAS)





The power spectra of REFLEX-II clusters in three different luminosity bins

Relative bias inferred from the power spectra of the REFLEX-II clusters and the mock clusters

The power spectrum of galaxy clusters (Balaguera-Antolínez et al., submitted to MNRAS)

- In the fitted range the relative luminosity bias is compatible with a scale-independent halo-mass bias
- The growth of the clustering amplitude with luminosity is in agreement with predictions from ΛCDM simulations
- For the first time, a signature of non-linear evolution in the galaxy cluster power spectrum has been detected on scales $k \approx 0.15 h/\mathrm{Mpc}$
- BAOs can not be detected, have to have larger volume and number of clusters
- A first test shows that it can nevertheless be used to infer cosmological parameters

Pan-STARRS

PS1 Science Consortium

Panoramic **S**urvey **T**elescope & **R**apid **R**esponse **S**ystem

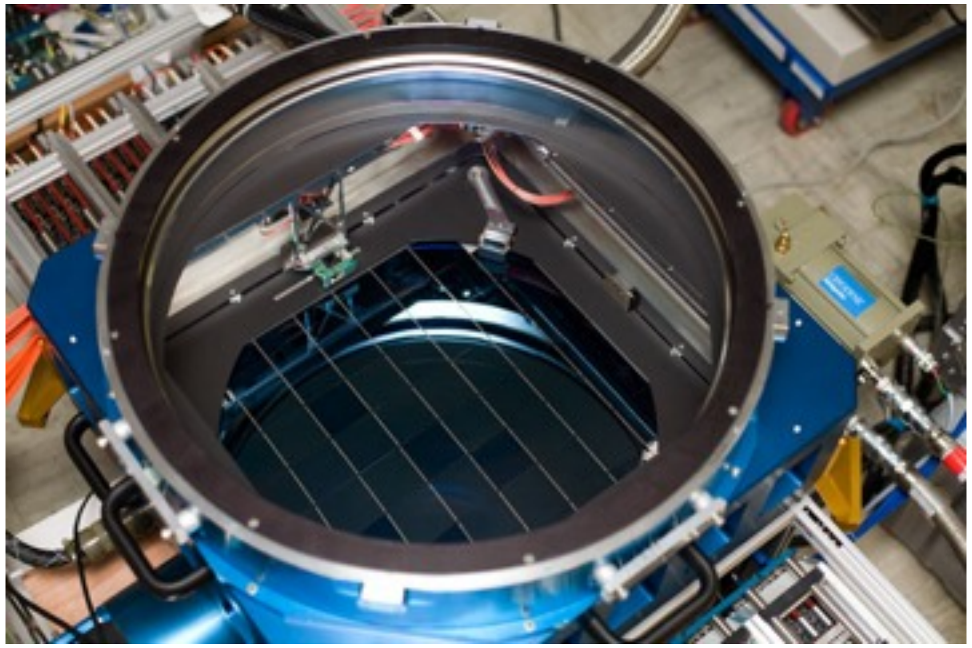
PS1 consortium members

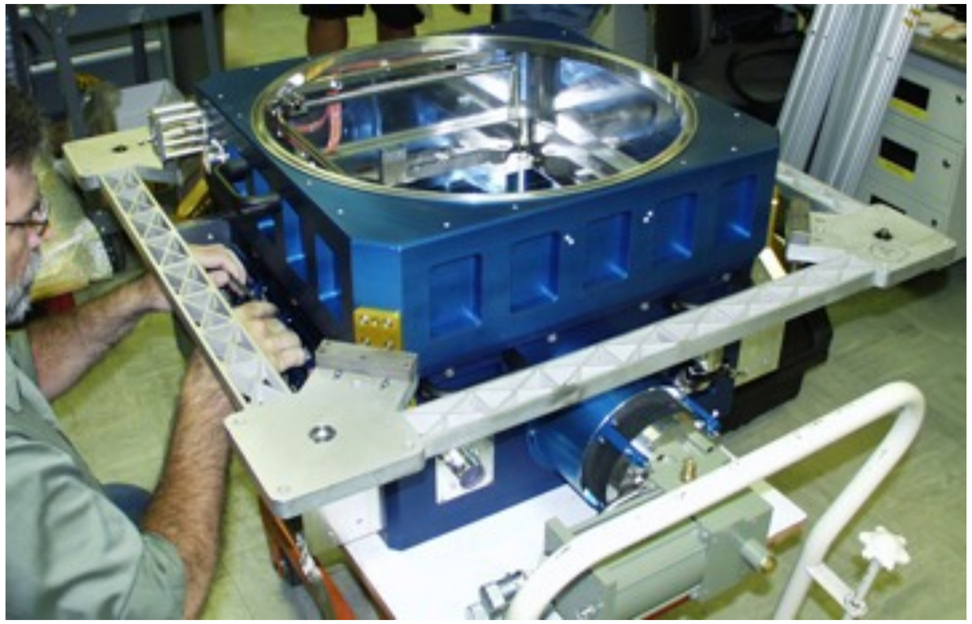
- University of Hawai'i
- UH Institute for Astronomy
- Max Planck Institute for Extraterrestrial Physics
- Max Planck Institute for Astronomy
- Johns Hopkins University, Department of Physics and Astronomy
- Harvard-Smithsonian Center for Astrophysics
- Queen's University Belfast
- University of Edinburgh
- Durham University, Institute for Computational Cosmology
- National Central University, Taiwan
- Las Cumbres Observatory Global Telescope Network

Pan-STARRS
(Panoramic Survey Telescope & Rapid Response System)

- Developed by the University of Hawaii
- One day will consist of four 1.8 m telescopes
- PS1: One 1.8m telescope
- New technology large-fov camera
- Built on Haleakala (on Maui, Hawaii)
- PS1 will be used to make a full-sky survey
- Science observations ongoing since May 2010

The camera





Camera had first light in August 2007

- **New technology wide-field camera with**
  - **1.4 Gigapixels** spread over 40x40 centimeters
  - FOV is 7 sqdeg with 0.3” pixels
  - tip-tilt correction can be done on the chip!

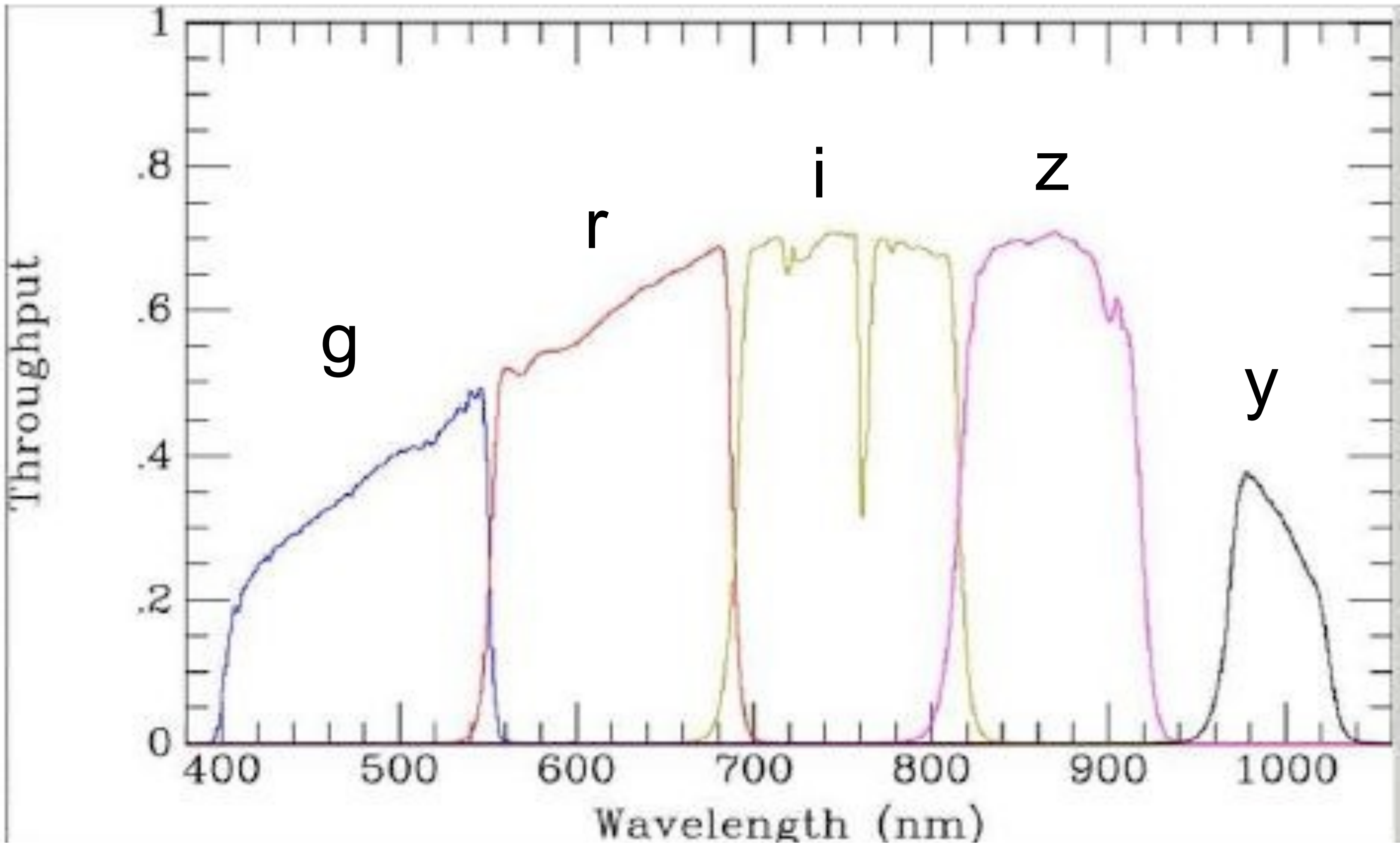
The famous Bonn-Shutter

The famous Bonn-Shutter

- Length: 1.664 m
- Width: 63.2 cm
- Depth: 5 cm
- Shutter aperture: 48 x 48 cm
- Mass: 30 kg
- Has to open and close up to a million times!
- Shortest possible exposure: 300μsec
- Homogeneity of exposure: 0.3% at 0.2sec

PS1SC

The filter system: grizy



Relatively red filter system, good redshifts for red galaxies

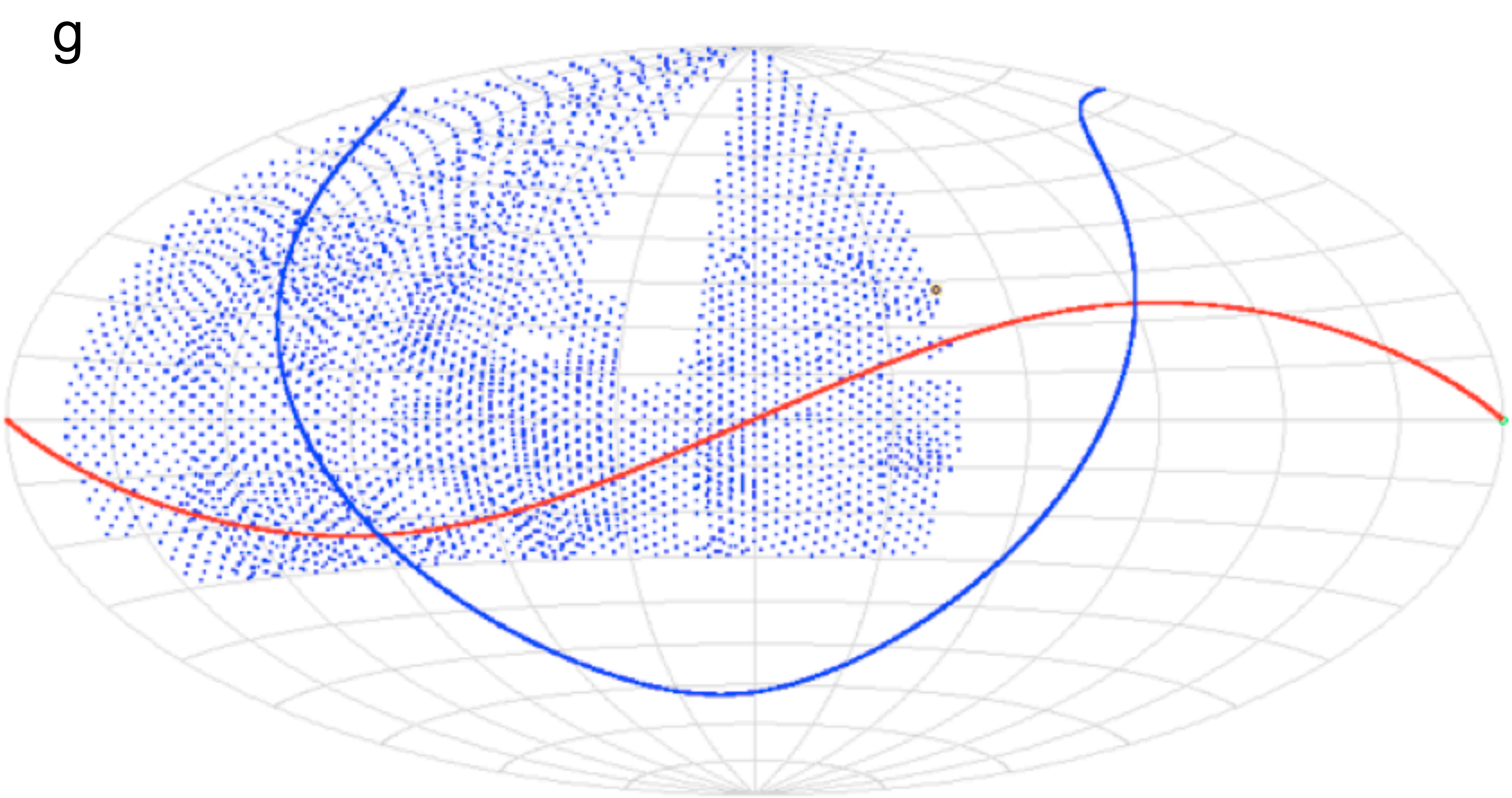
Filter	Bandpass (nm)	m_1 AB mag	μ AB mag/arcsec ^{2}	exposure time in 1st yr (3π) sec	5σ pt. source in 1st yr (3π)	5σ pt. source in 3rd yr (3π)
g	405-550	24.90	21.90	60× 4	24.04	24.66
r	552-689	25.15	20.86	38× 4	23.50	24.11
i	691-815	25.00	20.15	60× 4	23.39	24.00
z	815-915	24.63	19.26	30× 4	22.37	22.98
y	967-1024	23.03	17.98	30× 4	20.91	21.52

The different surveys

- 3π steradian Survey -> 3/4 of the sky!
- Medium Deep survey -> 10 disjoint fields, 7 sqdeg each
- Solar System Sweet Spot Survey
- Stellar Transit Survey
- Deep Survey of M31

- Will make greatest use possible of the synergy with other surveys

Observed footprint as of August 2010



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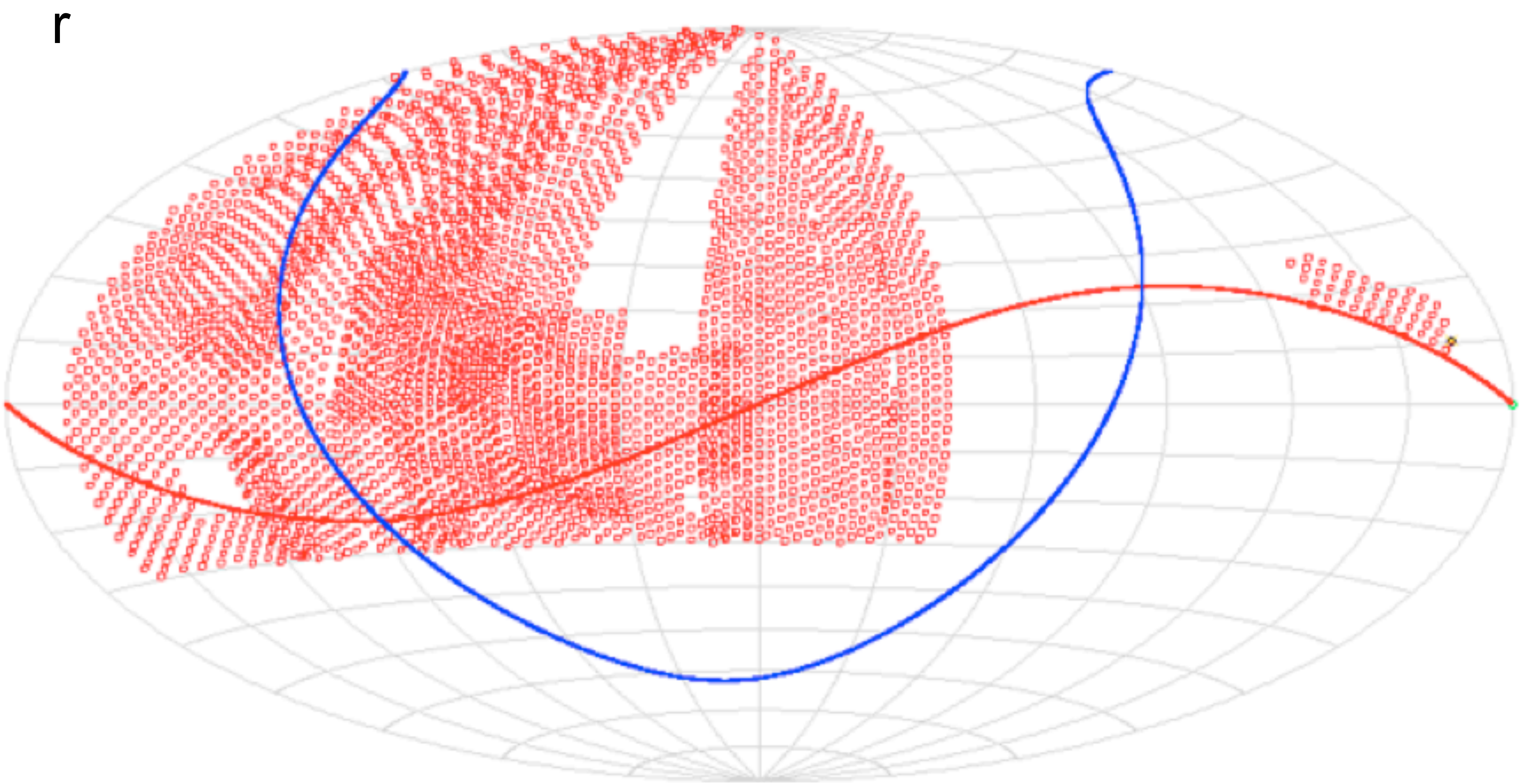

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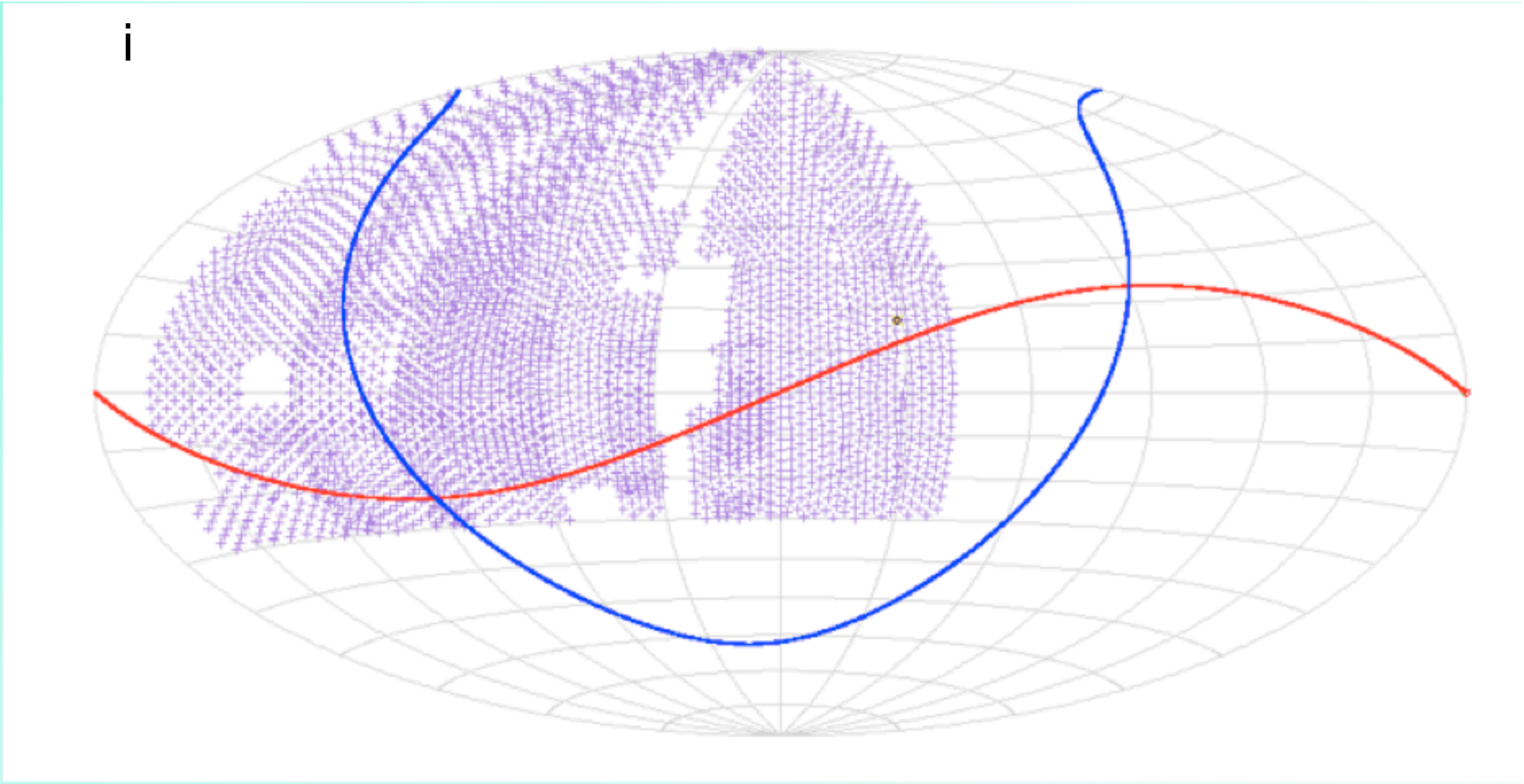

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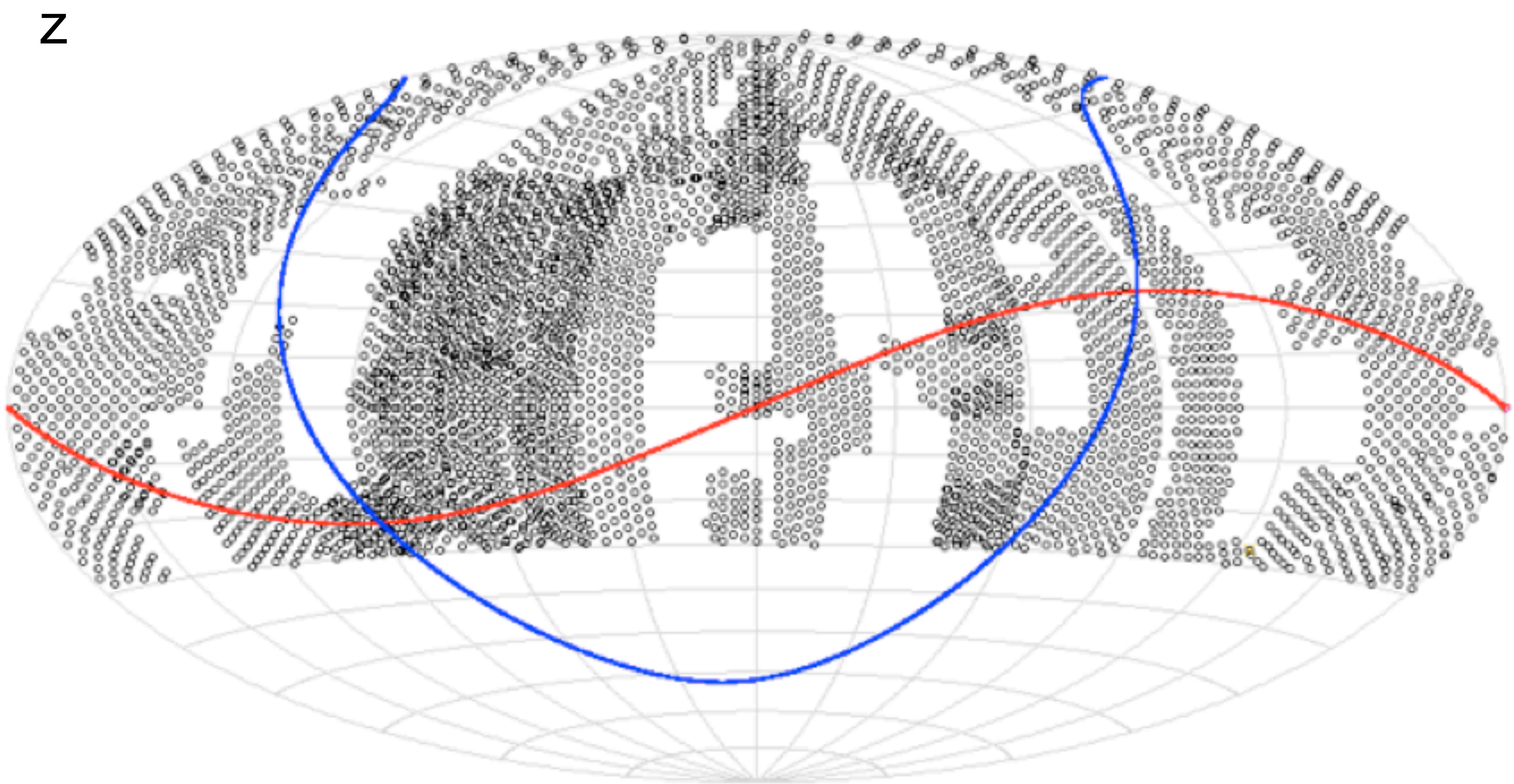

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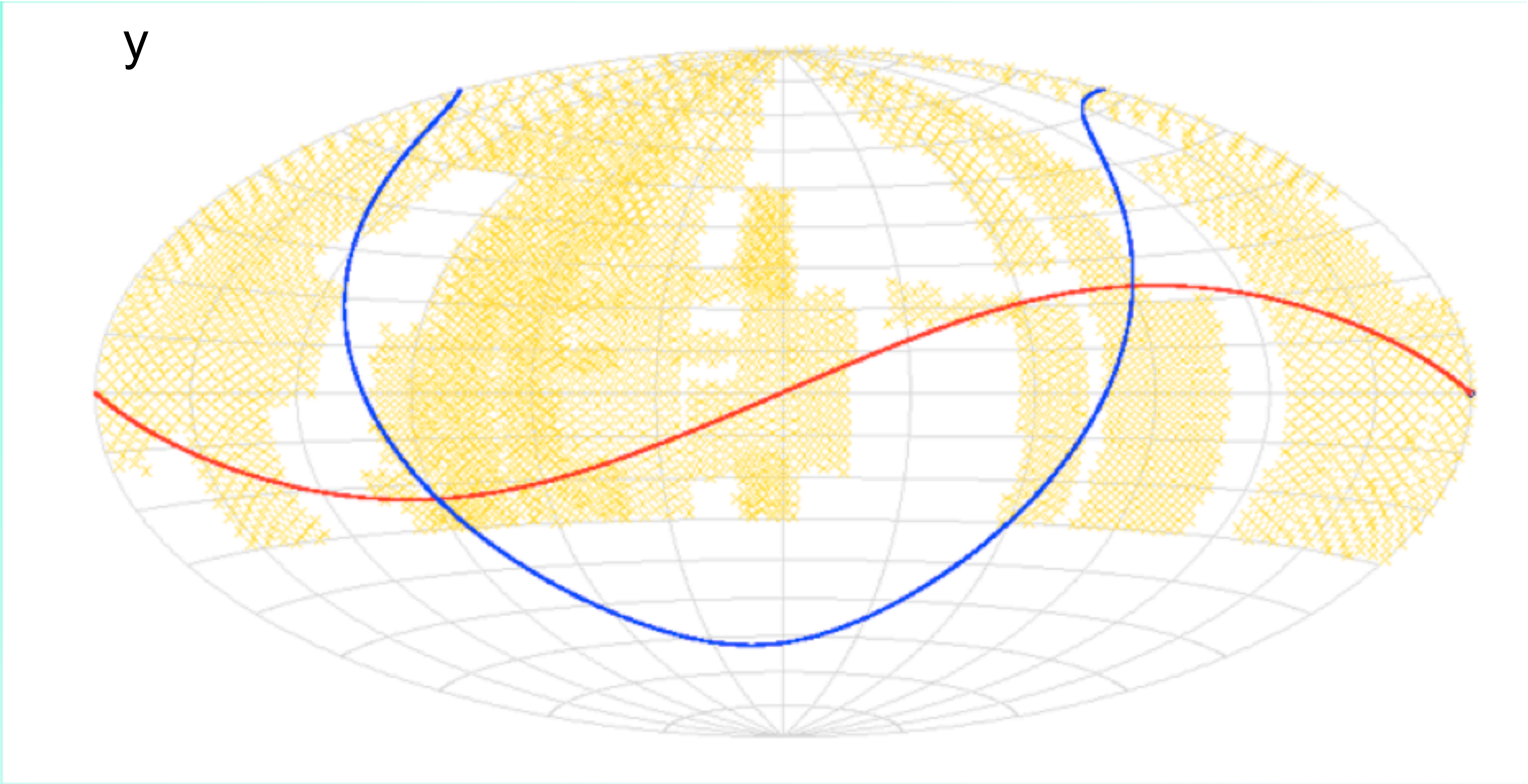
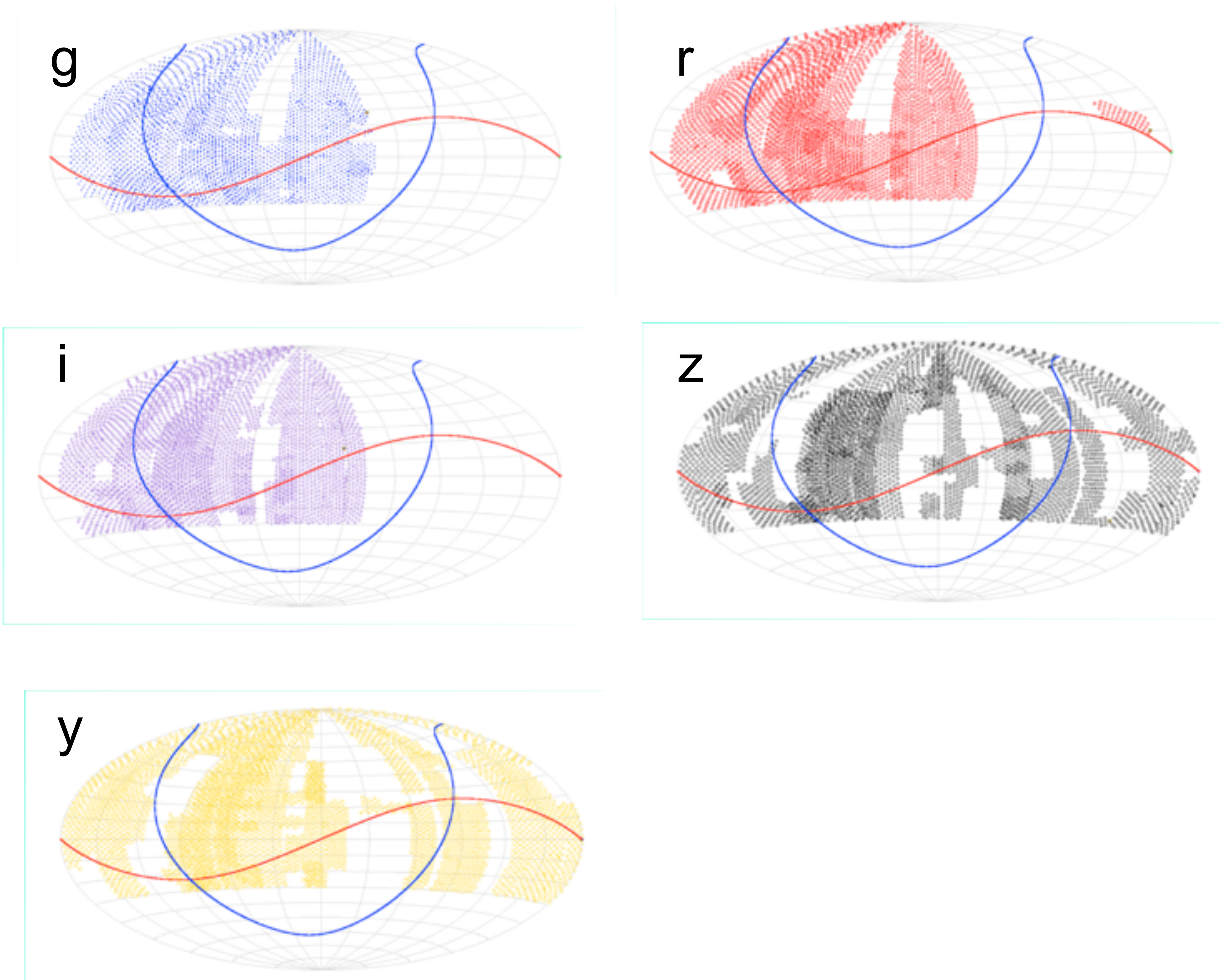
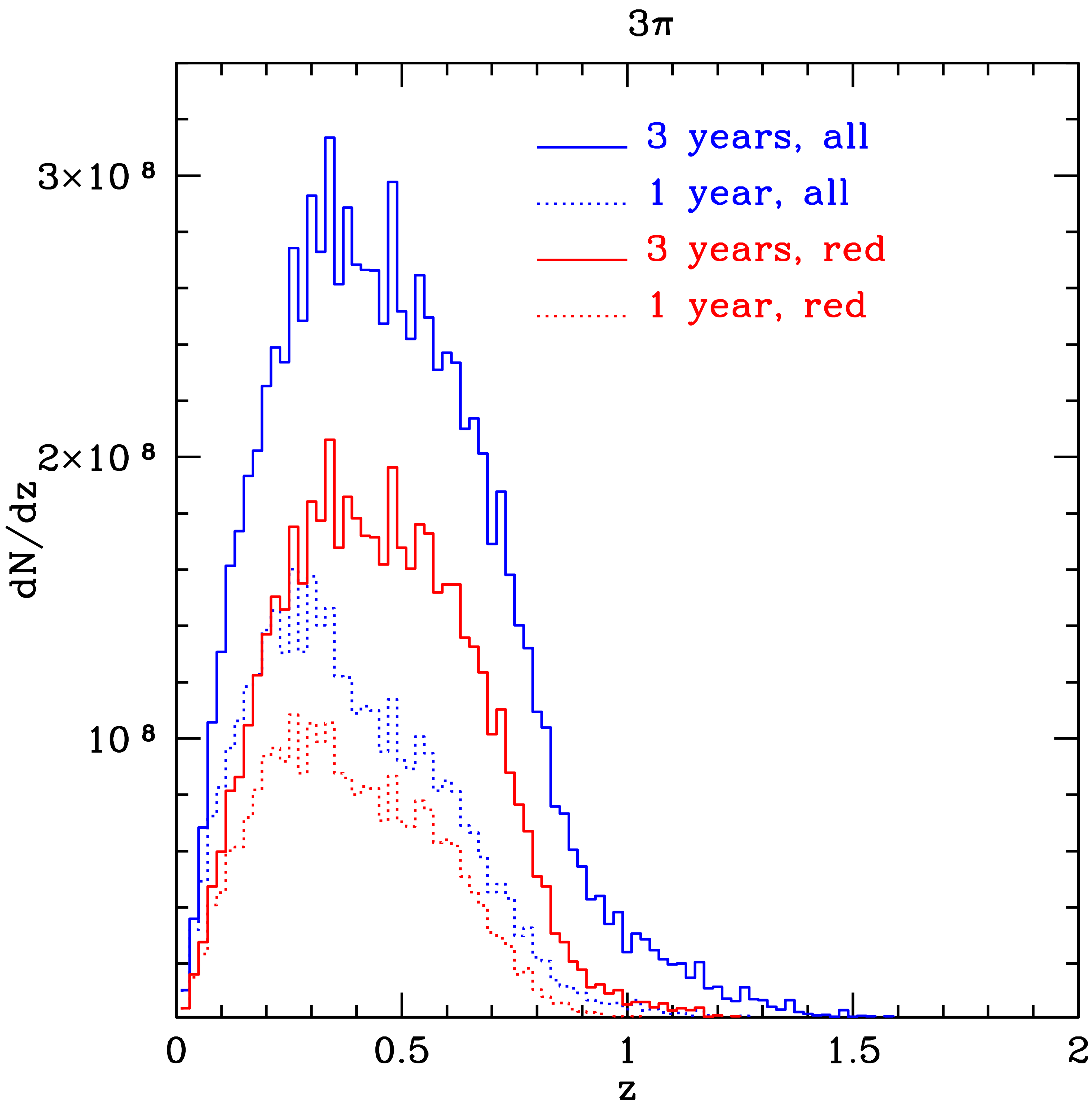


Observed footprint as of August 2010



Redshift distribution of galaxies in the Pan-STARRS 3π survey



Cai et al. 2008

used GALFORM (Bower et al. 2006)

to create a Pan-STARRS mock from the Millennium run (Springel et al. 2005)

numbers extrapolated to 3π

Redshift distribution peaks at z~0.4

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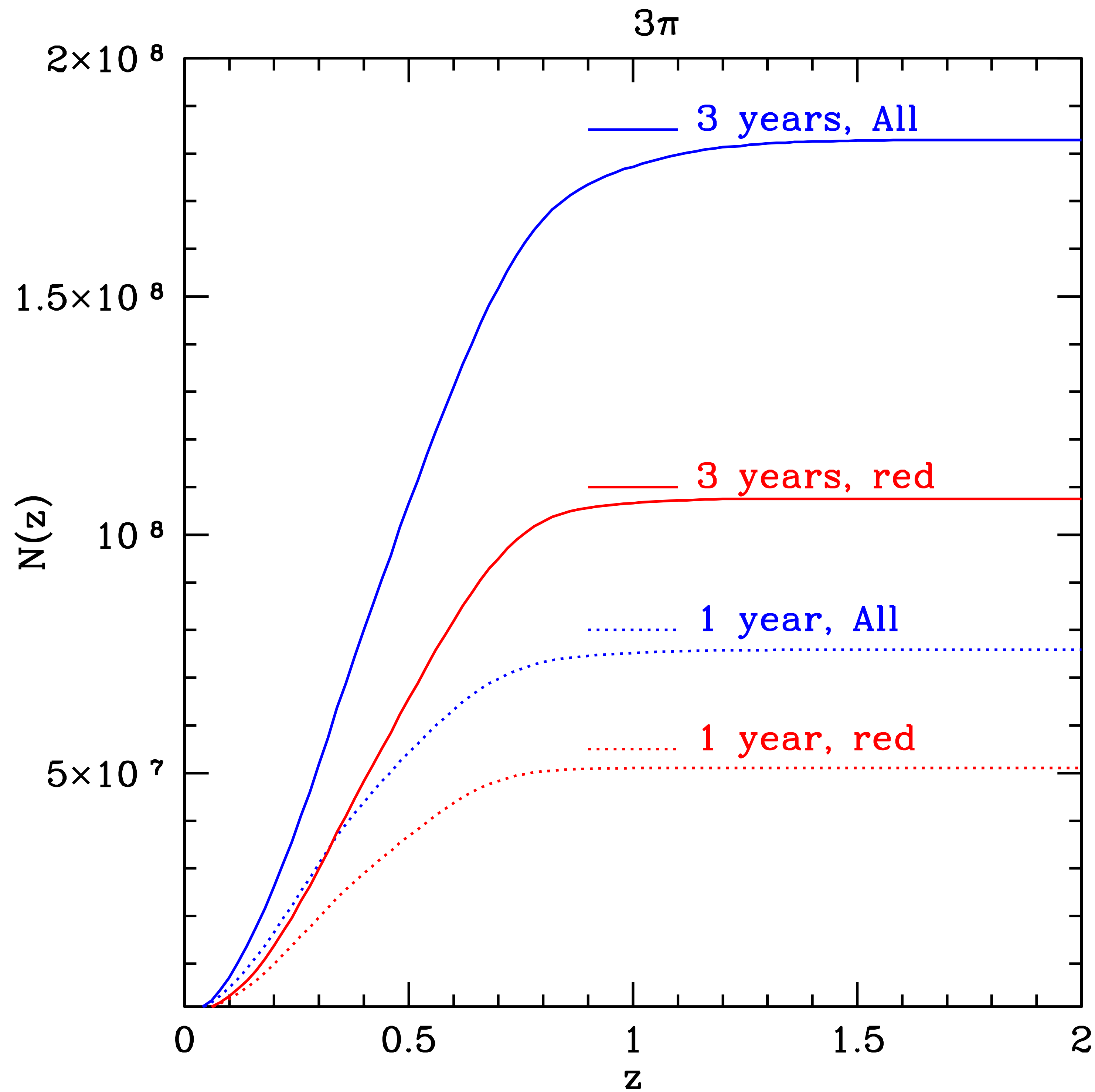

Cai et al. 2008

used GALFORM (Bower et al. 2006)

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numbers extrapolated to 3π

200 million galaxies after 3 years! 100 million LRGS!

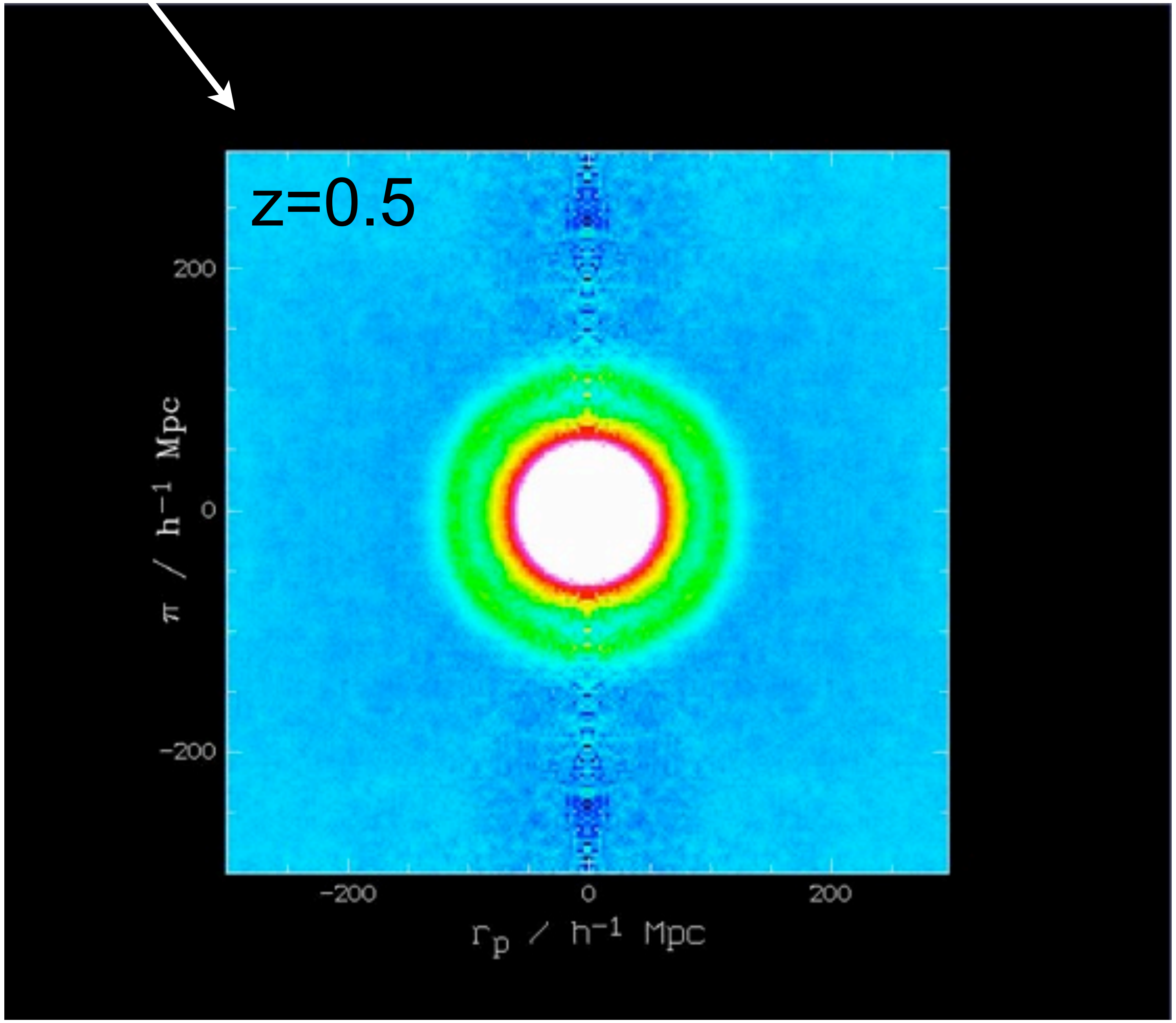
LSS and BAOs in Pan-STARRS

- Huge area, 3π = 30000 square degrees
- Large number of galaxies (200 million up to z=2), expect to find 100 million LRGs (Cai et al. 2008)
- Redshift accuracy can be as small as $\sigma_z/(1+z)=0.03$ for the LRGs, $\sigma_z/(1+z)=0.06$ for the main sample
- However, precision of measurement of w depends critically on knowledge (and size) of redshift errors

$\xi(r_p,\pi)$ in the L-BASICC* simulations

The correlation function split into the direction perpendicular (r_p) and along the line of sight (π)

Real space



L-BASICC: Angulo et al. 2008, 50 x 2.41h^{-3} Gpc^3, $N_{part}=448^3$

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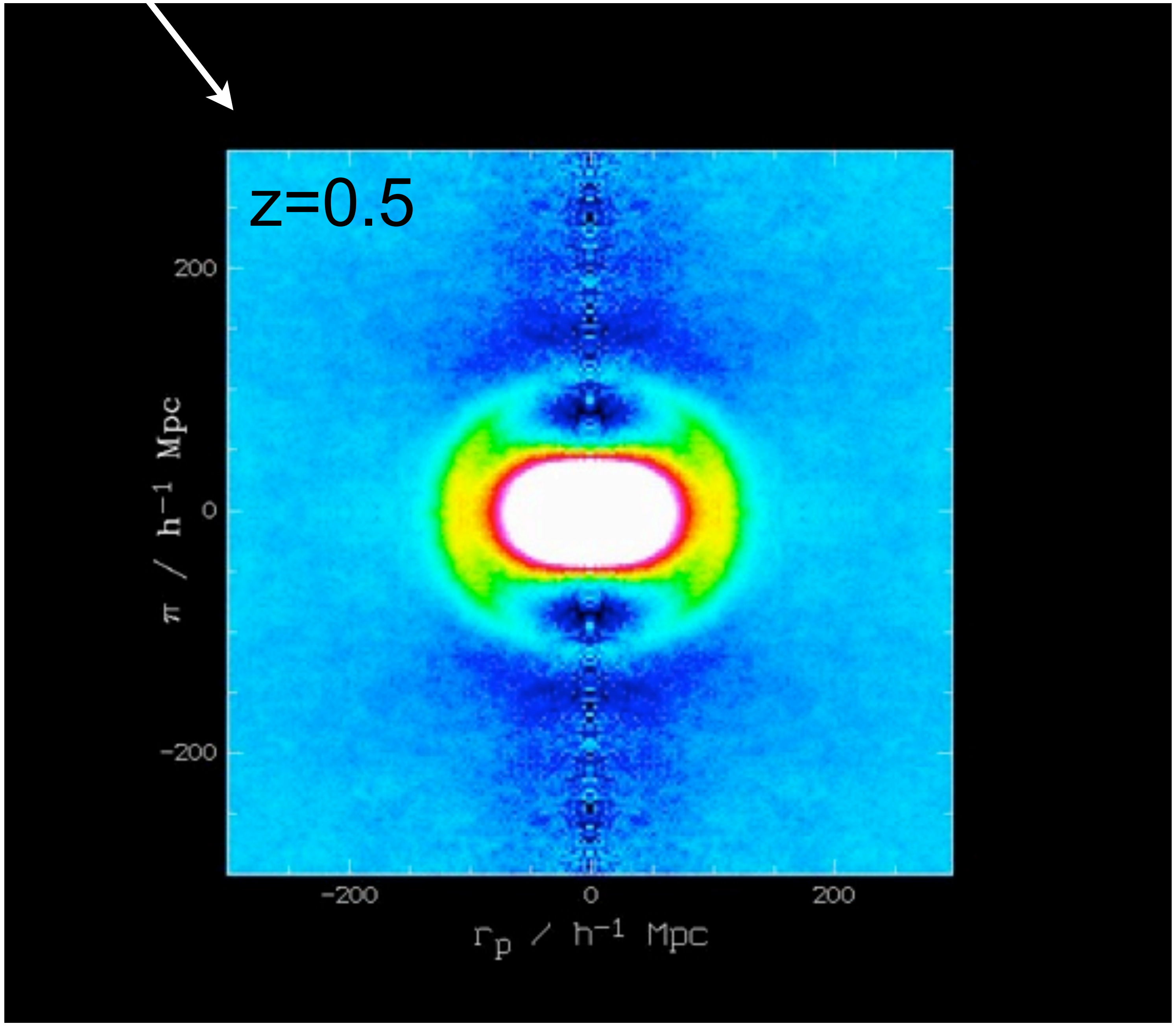

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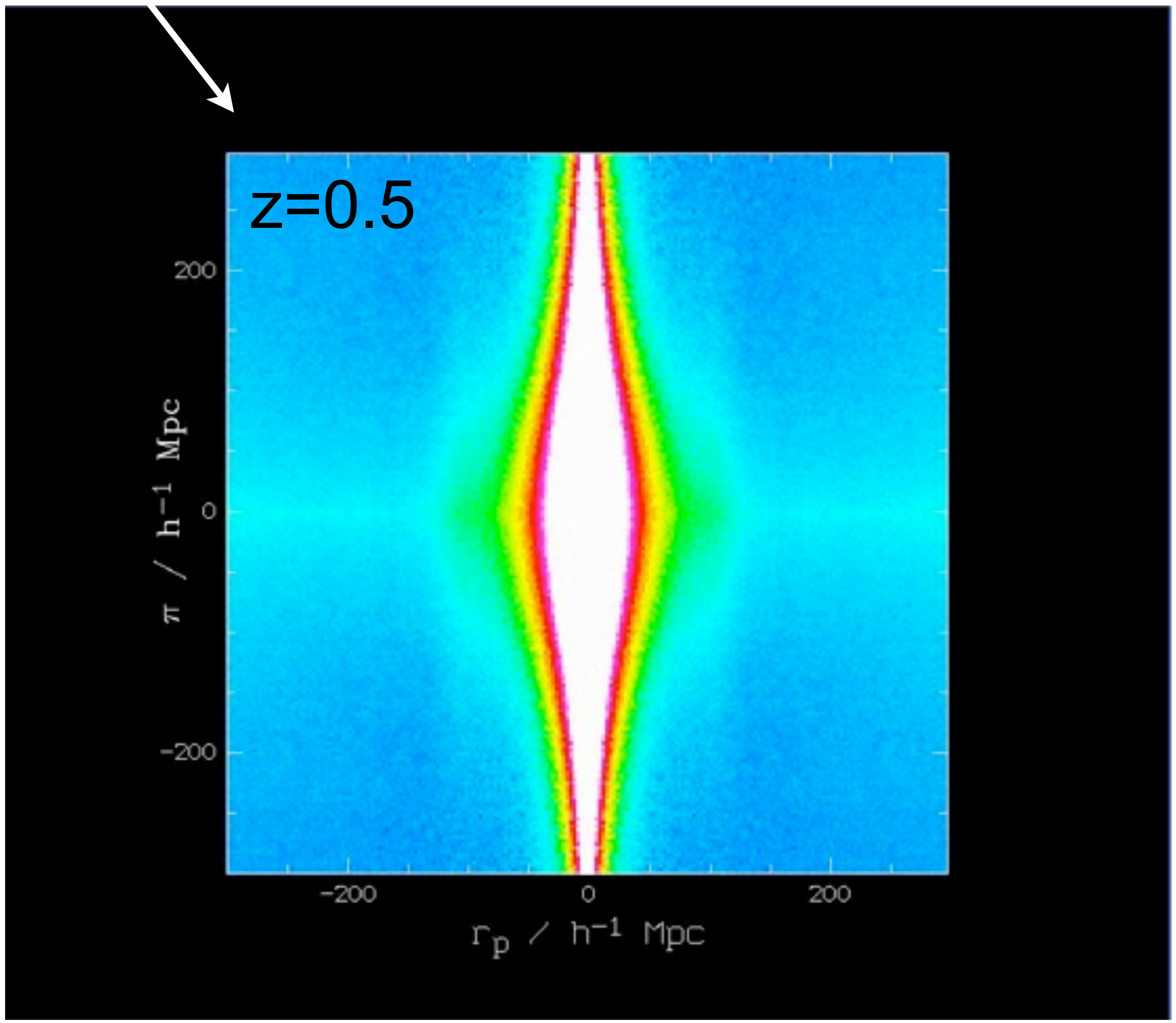
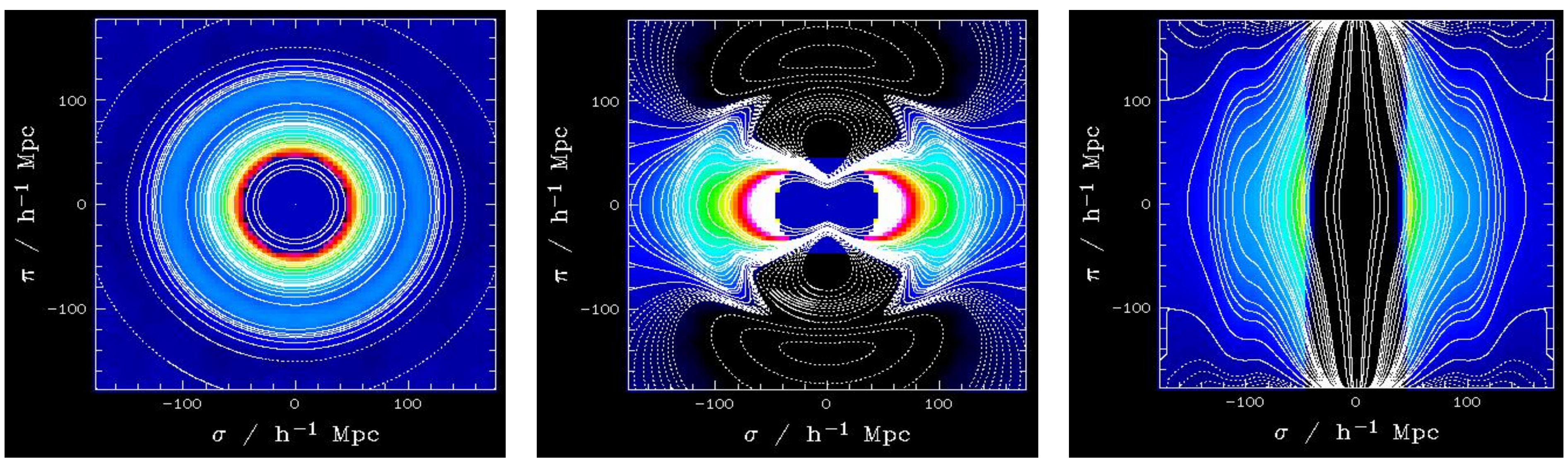


Redshift space and Redshift errors $\sigma_z/(1+z)=0.03$ as expected in photo-z surveys like e.g Pan-STARRS, DES

L-BASICC: Angulo et al. 2008, 50 x 2.41h^{-3} Gpc^3, $N_{part}=448^3$

Measuring w from ξ(rp,π)

- Use a model of $\xi(r_p,\pi)$ using 3rd-order perturbation theory with the same cosmological parameters as the simulation (vary w)
- Include Kaiser-effect and Fingers of God
- Include redshift errors
- Run Monte-Carlo-Markov-Chains to find best-fitting w

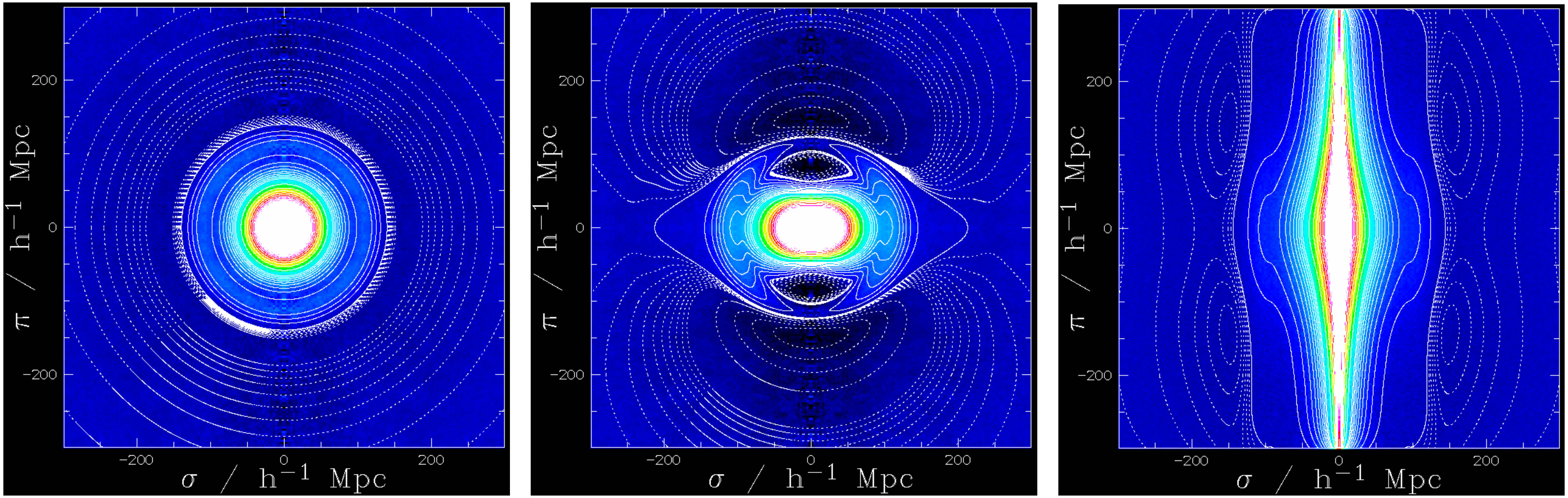


Schlagenhaufer, Phleps & Sánchez

Contours: best-fitting model (for 95 h^{-1} < r_p,π <135 h^{-1} Mpc), ΛCDM at z=0.5

w = -0.992±0.013 -1.002 ± 0.015 -1.011 ± 0.041

Measuring w from ξ(rp,π) in the halo catalogue



- Further complication: halo bias not strictly linear and scale-independent even on BAO scales. Still get good results:

- w= -1.014 +/- 0.021, -1.022 +/- 0.023, -0.998 +/- 0.069

A time dependent equation of state?

- What if w is changing with redshift? Can have complicated time-dependence! (Copeland et al. 2006)
- With Pan-STARRS and BOSS data we can estimate w at a redshift of $z<0.7$
- Have to extend analysis to higher redshifts

→ HETDEX

HETDEX
The Hobby-Eberly Telescope Dark Energy EXperiment

- Led by McDonald Observatory and University of Texas, with participation of USM at LMU, MPE, and AIP.
- Fixed elevation telescope with effective mirror size of 9.2 m
- VIRUS (Visible Integral-field Replicable Unit Spectrograph)
- Spectroscopic redshifts for millions of galaxies at z~3

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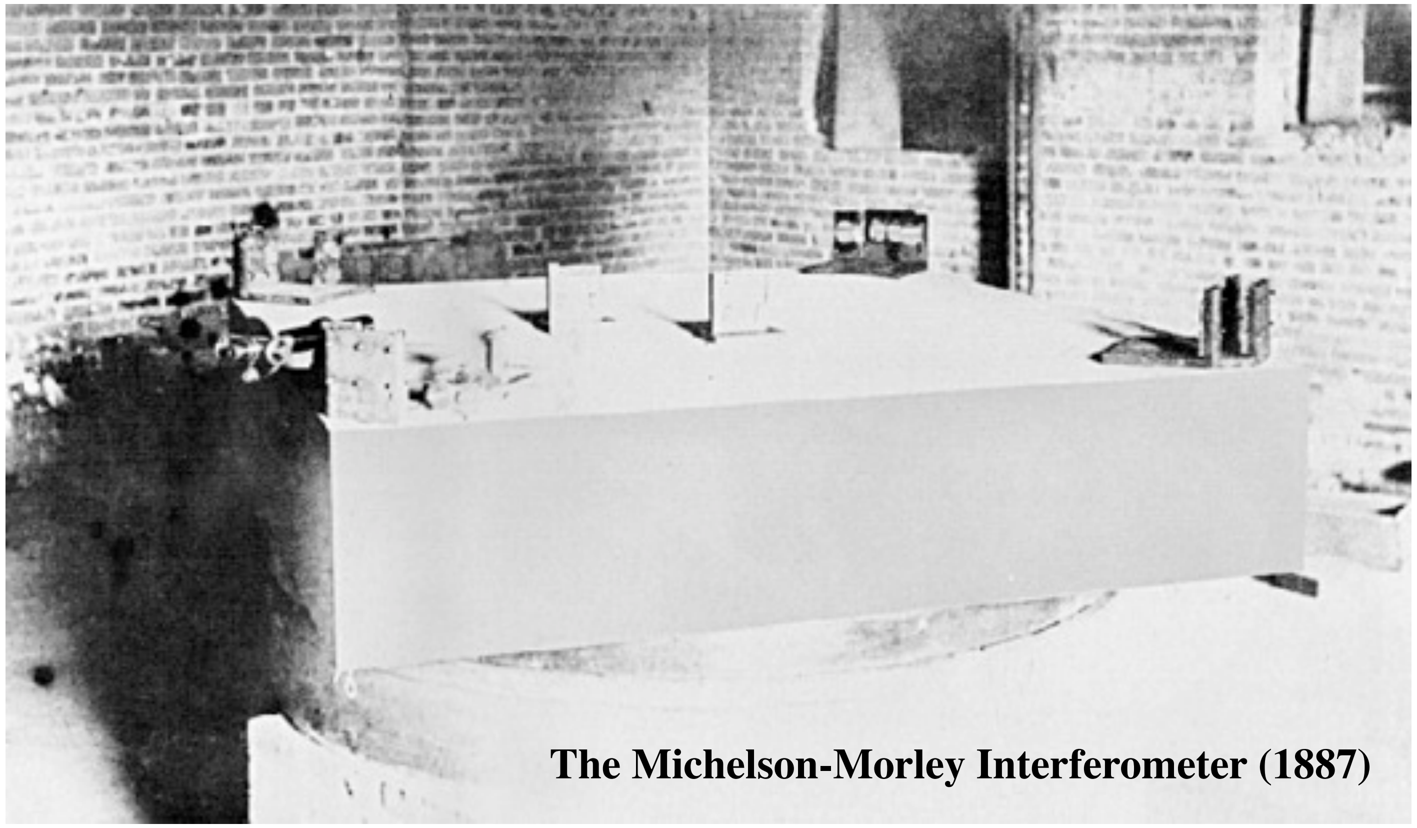
⇨ Measure w at z=3!

But what if...

- ...dark energy does not exist? It wouldn't be the first time the idea of an "aether" filling space will be ruled out...
- However, with geometric tests we will always infer a value for w, by construction of the measurement.



The Michelson-Morley Interferometer (1887)

- This value does not tell us much if we can't rule out other possible explanations, e.g. such as "dark gravity"

→ **We need a "Michelson-Morley experiment"!**

Dark energy or dark gravity?

- Look at Einstein equations:

$$G_{\mu\nu} = 8\pi G(T_{\mu\nu} + T_{\mu\nu}^{dark})$$

Geometry = Normal Energy + Dark Energy

instead:

$$G_{\mu\nu} + G_{\mu\nu}^{dark} = 8\pi G T_{\mu\nu}$$

Geometry + Modified Gravity = Normal Energy

Dark energy or dark gravity?

- Purely geometrical tests like BAOs as a standard ruler can not disentangle the two
- Will always only measure an effective equation of state parameter w_{DEeff}
- For the same w_{DEeff}, if gravity works differently (e.g. in DGP braneworld models), the structure growth will be different
- Compare measurement of growth rate function $f_g(z)$ from
  - the correlation function with prediction for different theories (as in Ross et al. 2007, or Guzzo et al. 2008)
  - galaxy-galaxy-lensing
  - cluster mass function
  - ...

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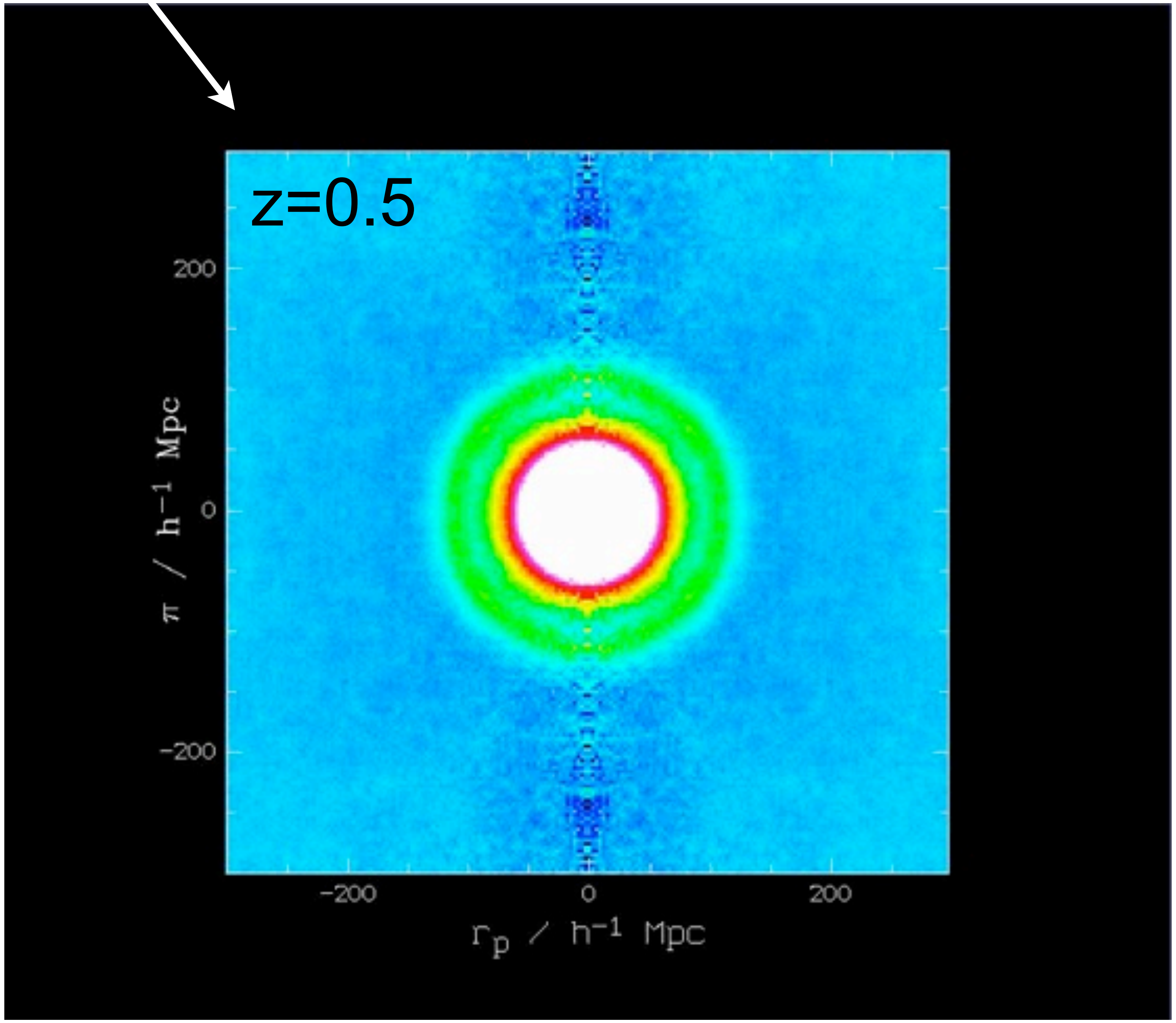
The correlation function split into the direction perpendicular (r_p) and along the line of sight (π)



Real space

L-BASICC: Angulo et al. 2008, 50 x 2.41h^{-3} Gpc^3, $N_{part}=448^3$

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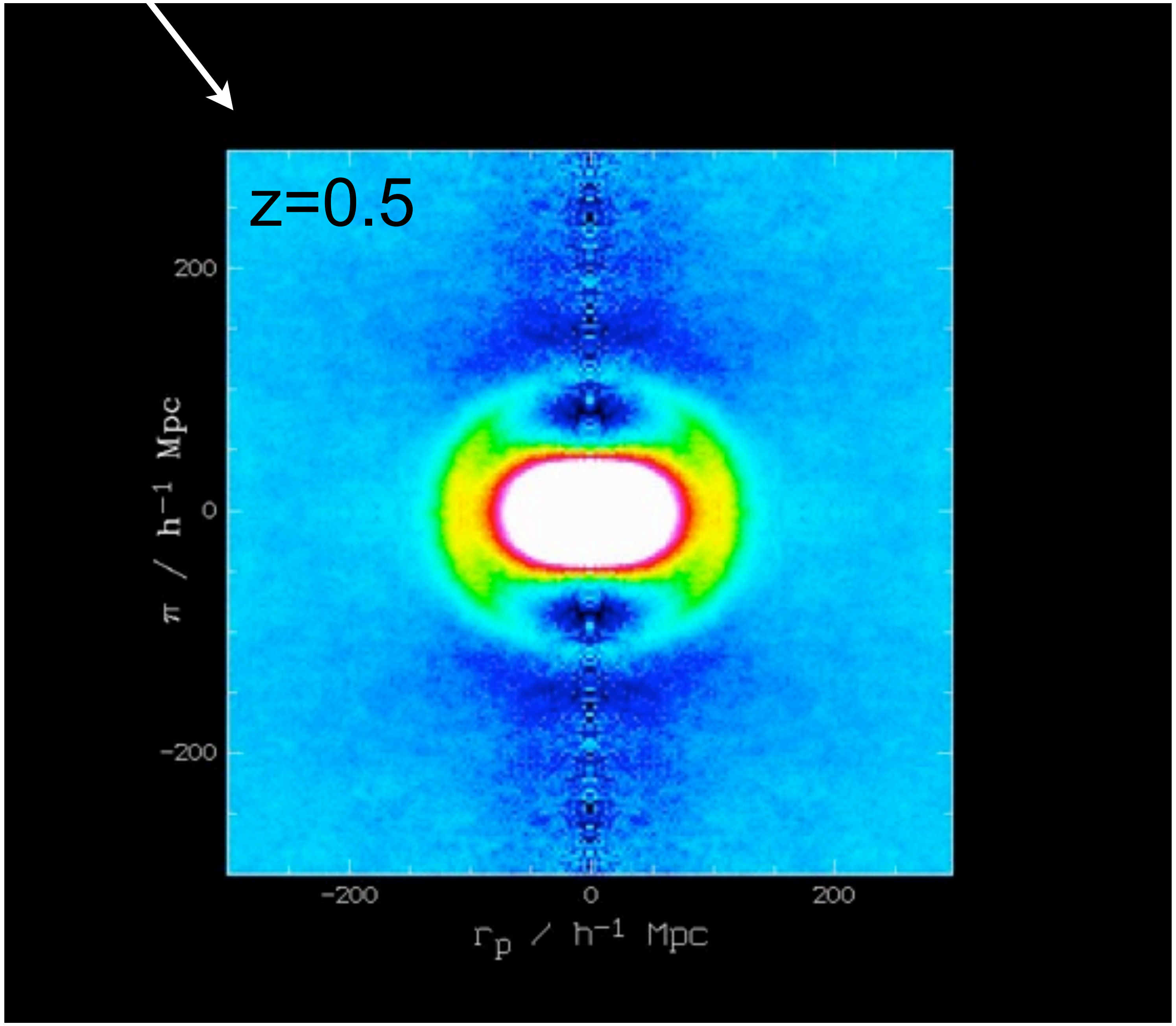

Redshift space

Derive growth rate function from shape of large scale distortions

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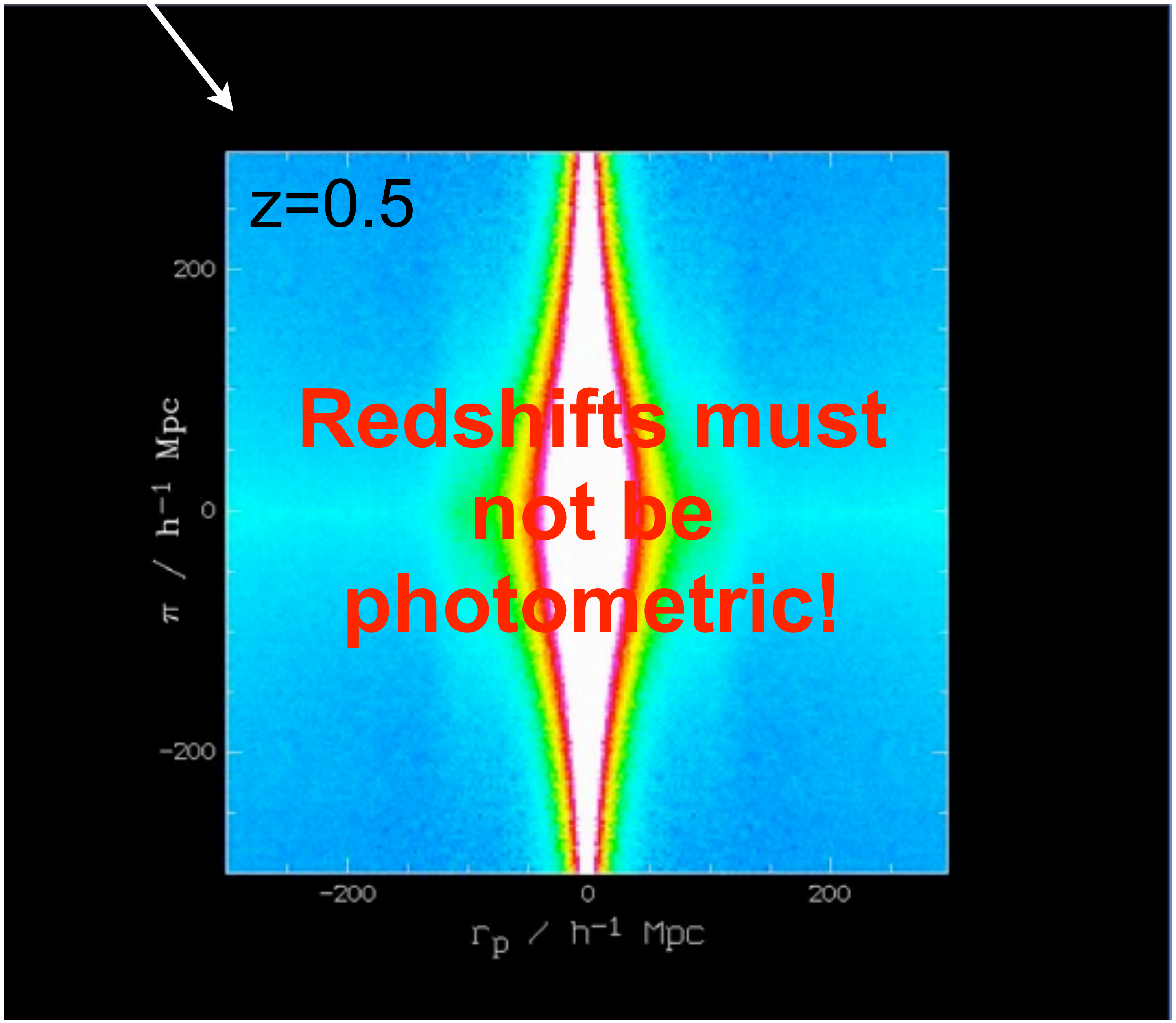

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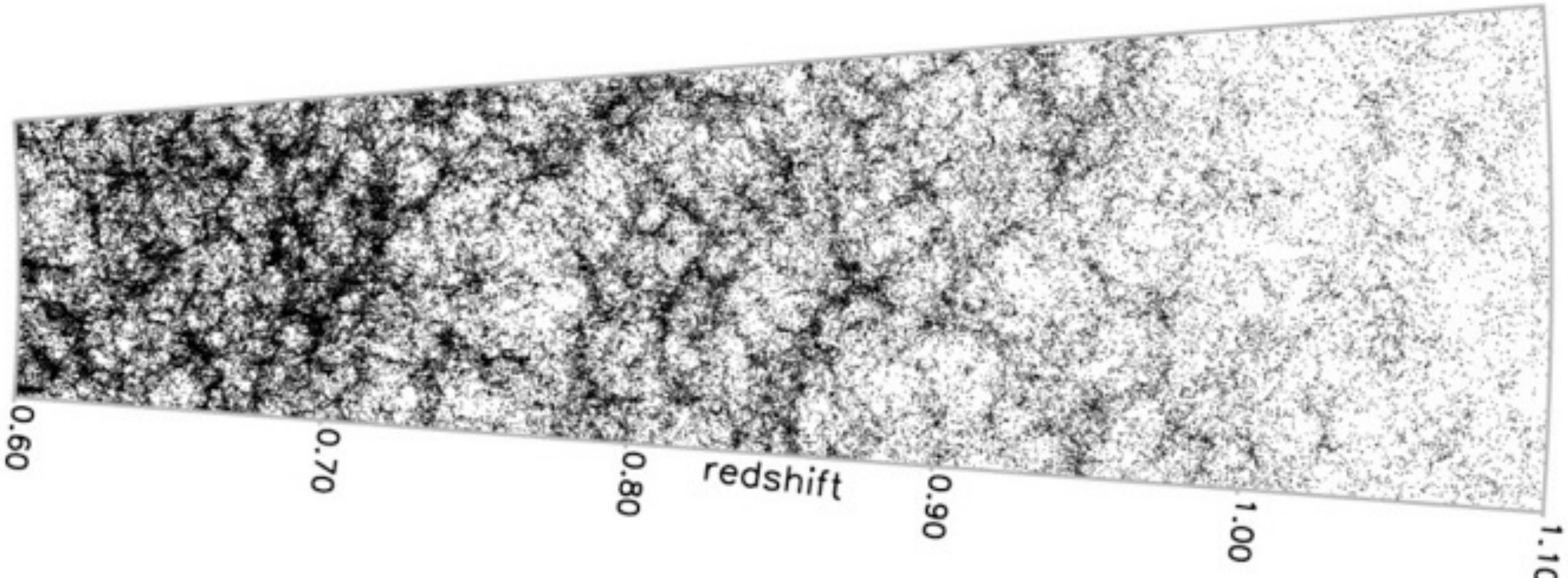
VIPERS
(Vimos Public Extragalactic Redshift Survey)

- ongoing ESO Large Program to map in detail the spatial distribution of galaxies at z~1
- VIPERS is using VIMOS at the VLT to measure 100,000 redshifts for galaxies with red magnitude $I_{AB}<22.5$ over an area of 24 square degrees
- A robust color-color pre-selection allows the survey to focus its measurements on the $0.5 < z < 1.2$ redshift range



Simulated galaxy distribution between $0.6 < z < 1.1$ in the 8 x 2 deg^2 W1 slice of VIPERS, the largest of the two areas surveyed spectroscopically with VIMOS. The transverse linear comoving size of the slice at z = 1 corresponds to ~320 h^{-1} Mpc.

Summary

- Determining cosmological parameters using LSS measurements is challenging:
  - extremely large data sets with well understood systematics required (preferentially spectroscopic)
  - theoretical predictions have to be extremely accurate, however, some important effects are very difficult to model
    - non-linear clustering growth
    - redshift space distortions
    - non-linear, scale dependent, stochastic galaxy biasing
- It is necessary to investigate as many different data sets as possible
  - different samples (red, blue, galaxies, qsos, clusters), in order to understand (relative) biasing
  - and at different redshifts, to measure dw/dt
- with as many different methods as possible, to overcome systematics
  - correlation functions
  - power spectra
  - higher orders

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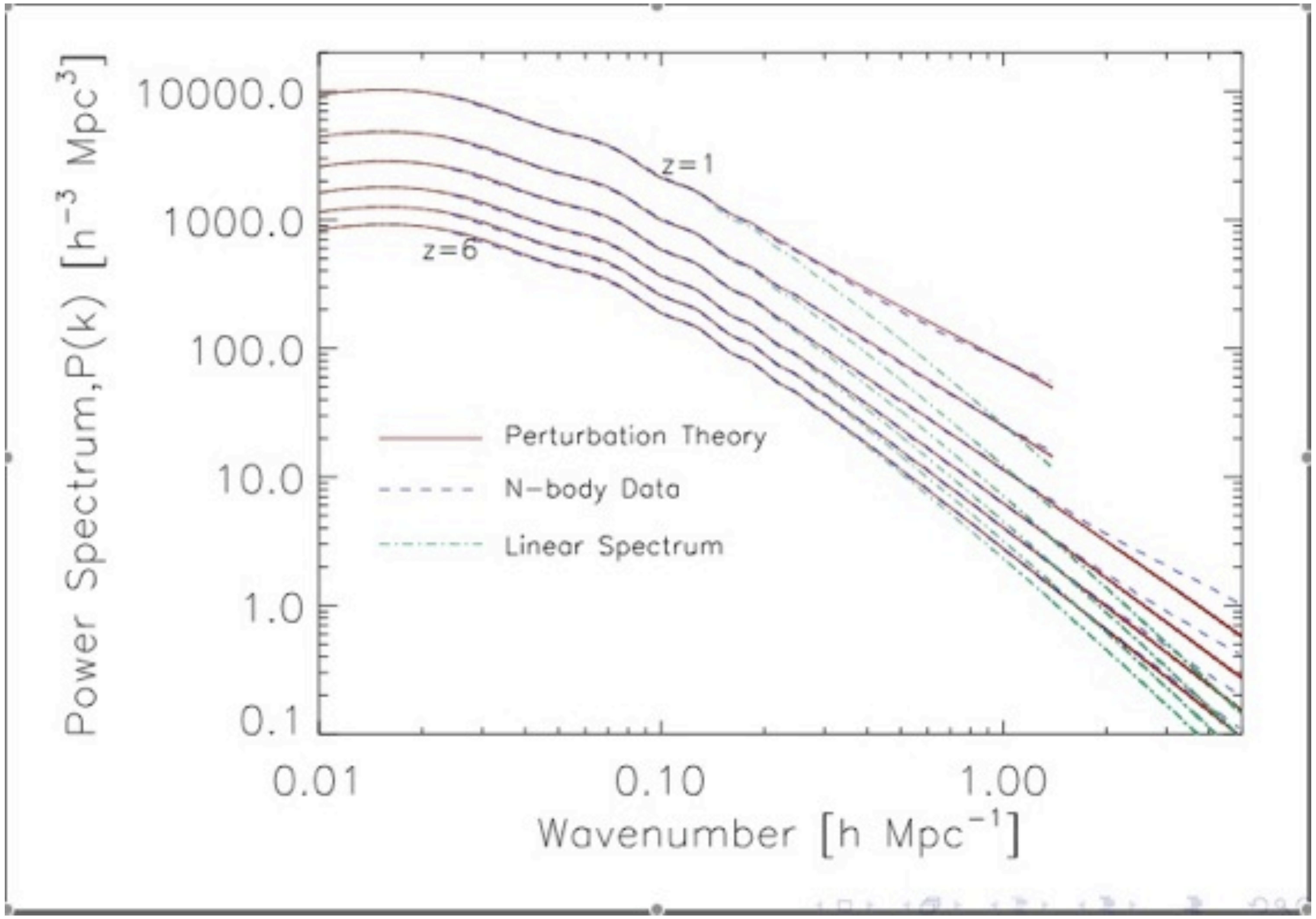
- with as many different methods as possible, to overcome systematics
  - correlation functions
  - power spectra
  - higher orders

+ { SNIa, Lensing, Galaxy Clusters dn/dz }

The big cosmology questions today

- Fundamental question: What is the universe made of?
  - Dark Matter?
  - Dark Energy?
  - Strings?
  - Branes?
  - Higher Dimensions?
- Related and profound problem: Why does the expansion of the universe seem to be accelerating?
  - Dark Energy?
  - Dark Gravity?
  - Backreaction?

Evolution of non-linearities with redshift



- Deviations from linear power spectrum become worse at lower redshifts, and influence increasingly larger scales
- Easier to model observations at higher redshifts (at least z>0.5)
- makes observations more challenging

Taken from http://gyudon.as.utexas.edu/~komatsu/presentation/mpe.pdf

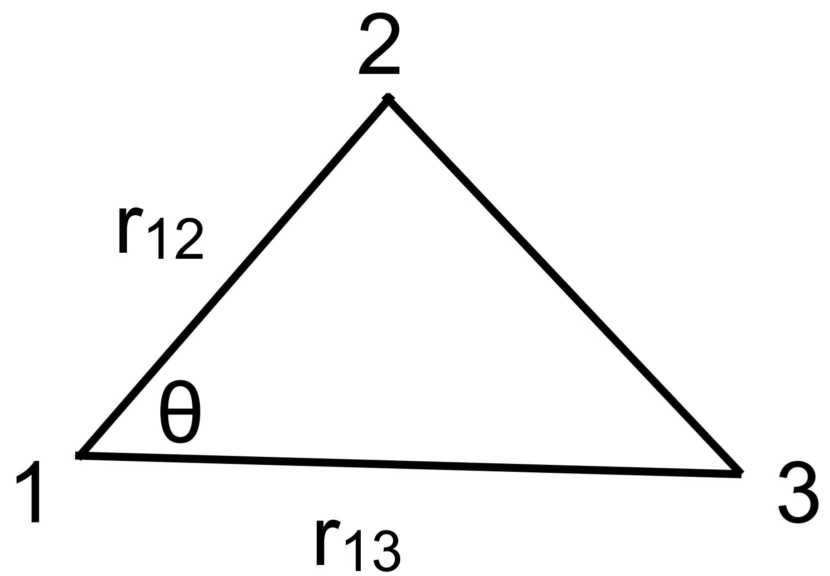
Higher order statistics: The three-point correlation function

- The three point correlation function is the excess probability compared to a Poisson process of finding a closed triangle with side lengths of r_{12} and r_{13} for a given angle θ:

$$dN_{triangle}(r_{12},r_{13},\theta) = N_{gal}^{3}\left[1+\xi(r_{12})+\xi(r_{13})+\xi(r_{23})+\zeta(r_{12},r_{13},\theta)\right]dV_1 dV_2 dV_3$$

- because of
  - isotropy
  - homogeneity

$$\zeta(\vec{r}_1,\vec{r}_2,\vec{r}_3) \rightarrow \zeta(r_{12},r_{13},\theta)$$



The three-point correlation function: relation to underlying dark matter density field

- Measurement sensitive to linear and quadratic bias:

$$\zeta_{gal}(r_{12},r_{13},\theta) = b_1^3\zeta(r_{12},r_{12},\theta) + b_1^2 b_2\left[\xi(r_{12})\xi(r_{13}) + \xi(r_{12})\xi(r_{23}) + \xi(r_{13})\xi(r_{23})\right]$$

- Define the reduced three-point correlation function $Q(r_{12},r_{13},\theta)$:

$$Q(r_{12},r_{13},\theta) = \frac{\zeta(r_{12},r_{13},\theta)}{\xi(r_{12})\xi(r_{13}) + \xi(r_{12})\xi(r_{23}) + \xi(r_{13})\xi(r_{23})}$$

- Which is almost independent of cosmology and time evolution, but sensitiv to the bias:

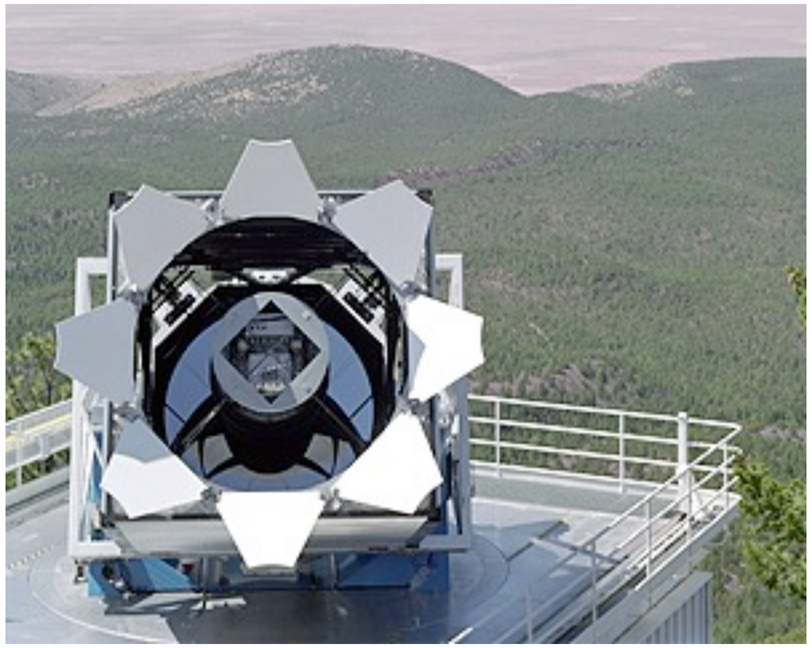
$$Q_{gal}(r_{12},r_{13},\theta) = \frac{Q_{dm}(r_{12},r_{13},\theta)}{b_1} + \frac{b_2}{b_1^2}$$

The Bispectrum

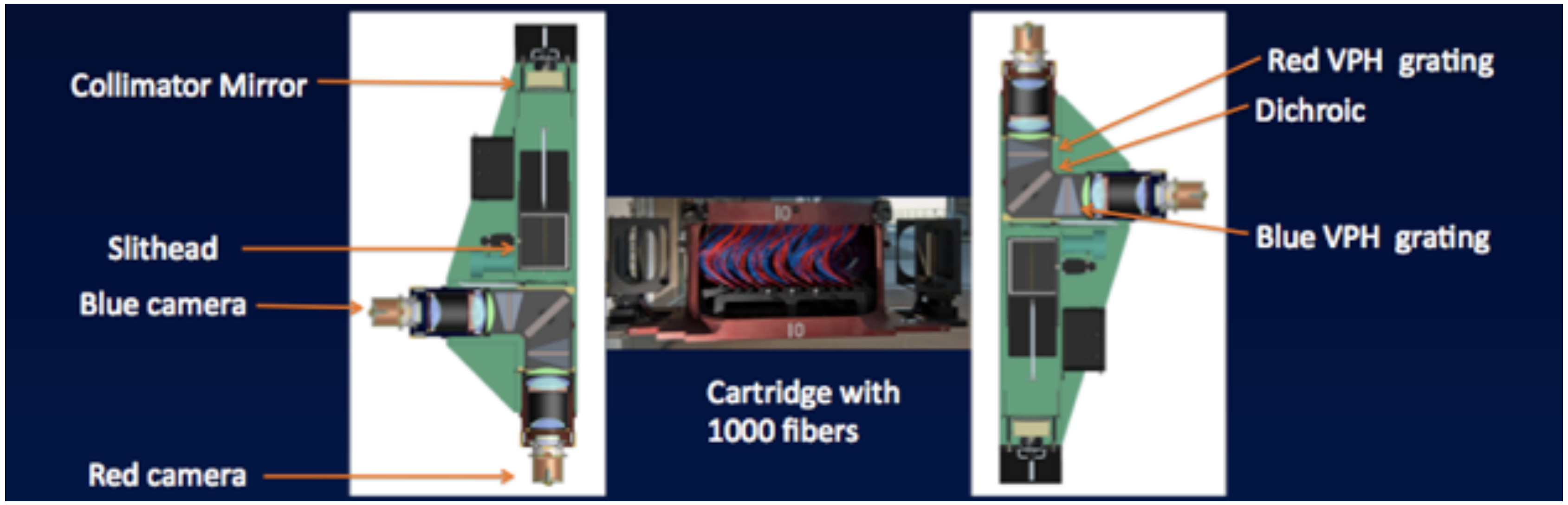
- Fourier counterpart to the three point correlation functions
- easier (faster) to calculate (3ptcf is a N^3-process!) for large amounts of data
- theoretical predictions (2^{nd}-order perturbation theory) easier to calculate in Fourier space
  - convolutions reduce to multiplications
  - Kaiser theory derived in Fourier space, multiplication with $\mu^2=\cos^2(k\ r)$ becomes a differential operator in configuration space
- The reduced Bi-spectrum is defined analogously to the reduced three-point correlation function

Hardware: Telescope, Spectrograph

- BOSS uses the good old SDSS 2.5m telescope on Apache Point Observatory (APO)



- For BOSS, the SDSS spectrograph has been upgraded to
  - extend the wavelength coverage: 3800-6300Å(blue)/5700-9200Å(red) → 3600-6500Å(blue)/5500-10500Å(red)
  - improve throughput:
    - Replace red CCDs w/ red-sensitive LBL/SNAP CCDs, making it possible to go to higher-z for luminous red galaxies (LRGs)
    - Replace blue CCDs w/ UV-sensitive e2v CCDs, making it possible for Lyα at z=2.15 →3.5
  - and increase the number of fibers: 3” x 640 → 2” x 1000
- Observe an additional 2000 square degrees at the SGP



Observing strategy and data releases

- **Imaging**: BOSS imaging complete November 18th 2009
- **Spectroscopy**: Commissioning has started in September 2009, science observations have officially started January 2010
- Future Data releases:
  – DR8: full BOSS Imaging
    - July 2010 collaboration
    - Dec 2010 public DR8
  – DR9: first year BOSS spectroscopy
    - July 2011 preliminary DR9 (“data sweeps” available somewhere on the webpage)
    - Jan 2012 collaboration DR9
    - July 2012 public DR9 release

VIPERS status as of 27.9.2010

- 18586 redshifts measured
- covered area: 22.3%
- stellar contamination: 576 (3.1 %)

- Eventually this is going to be the “2dF at z=1”! Great data set!

- However, area not quite large enough to measure BAOs. But there is more to cosmology than just measuring w! Actually, the survey was **designed to measure the growth rate.**