Galaxy clustering in Pan-STARRS

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Outline

- Pan-STARRS
  – Telescope
  – Camera, Shutter, Filters
  – Science
- LSS and BAOs
  – Power spectrum
  – Correlation function
  – Spherical harmonics
- Summary

Pan-STARRS

PS1 Science Consortium

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

PS1 consortium members

Max Planck Institute for Astronomy

University of Hawai'i

UH Institute for Astronomy

Max Planck Institute for Extraterrestrial Physics

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

- Pan-STARRS is developed by the University of Hawaii
- One day Pan-STARRS will be a system of four 1.8m telescopes that will survey the entire visible sky (3π) in five filters (grizy)
- New technology wide-field camera with
  - 1.4 Gigapixels spread over 40x40 centimeters
  - FOV is 7 sqdeg with 0.3” pixels
  - tip-tilt correction on the chip!

Pan-STARRS1: The prototype

- One 1.8m telescope
- Built on Haleakala (on Maui, Hawaii)
- PS1 will allow us to test all the technology that is being developed for Pan-STARRS, including the telescope design, the cameras and the data reduction software.
- PS1 will be used to make a full-sky survey
- Science observations will start in early January 2009

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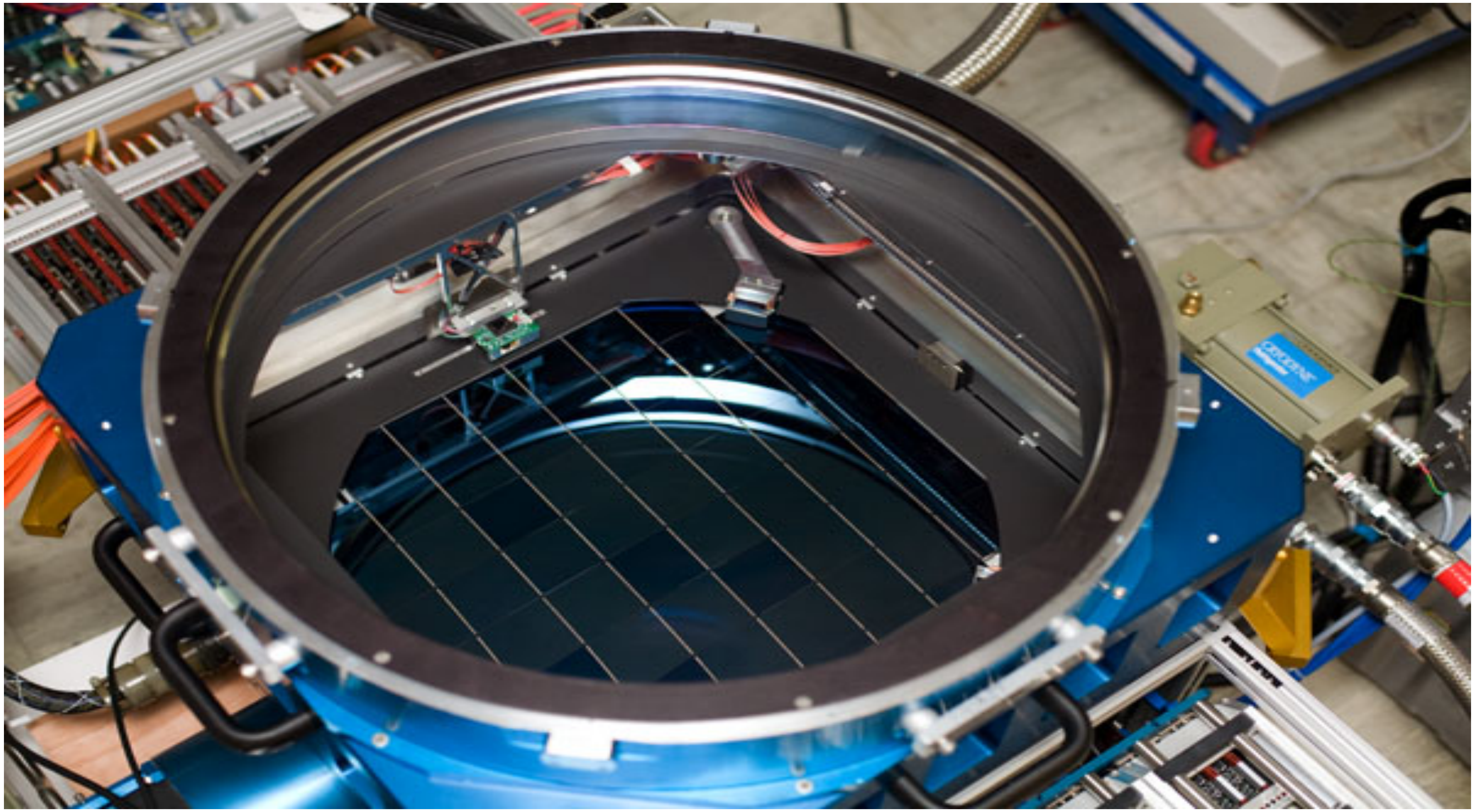
The camera

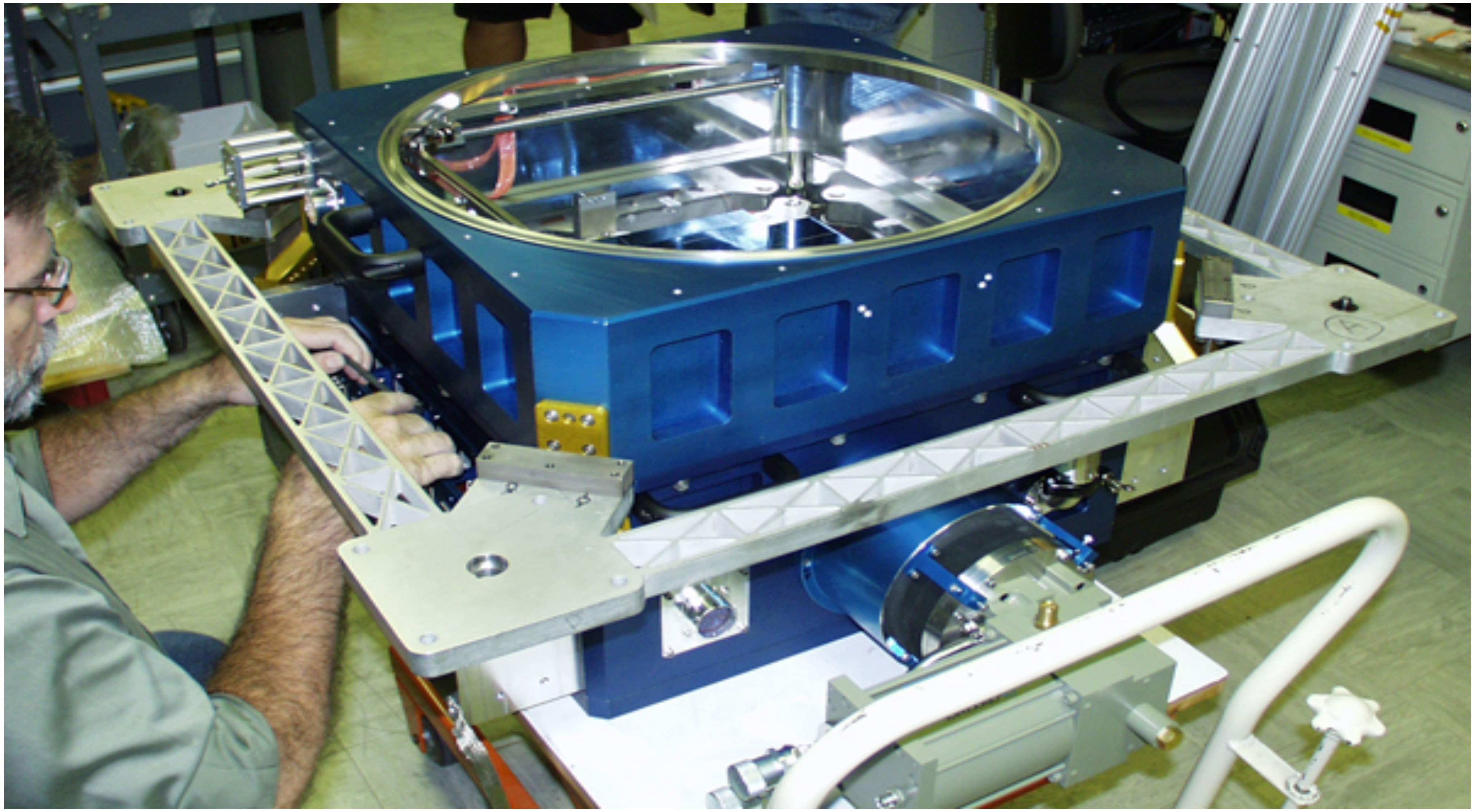
- Consists of an array of 64x64 CCDs
- Each CCD has 600x600 pixels
- A total of 1.4 Gigapixels spread over 40x40 centimeters
- Orthogonal transfer allows for a shift of the image during the observation -> tip-tilt correction on the chip
- Expected data flow: 50Tbytes/month

The camera



Camera had first light in August 2007

The camera



Camera had first light in August 2007

The famous Bonn-Shutter

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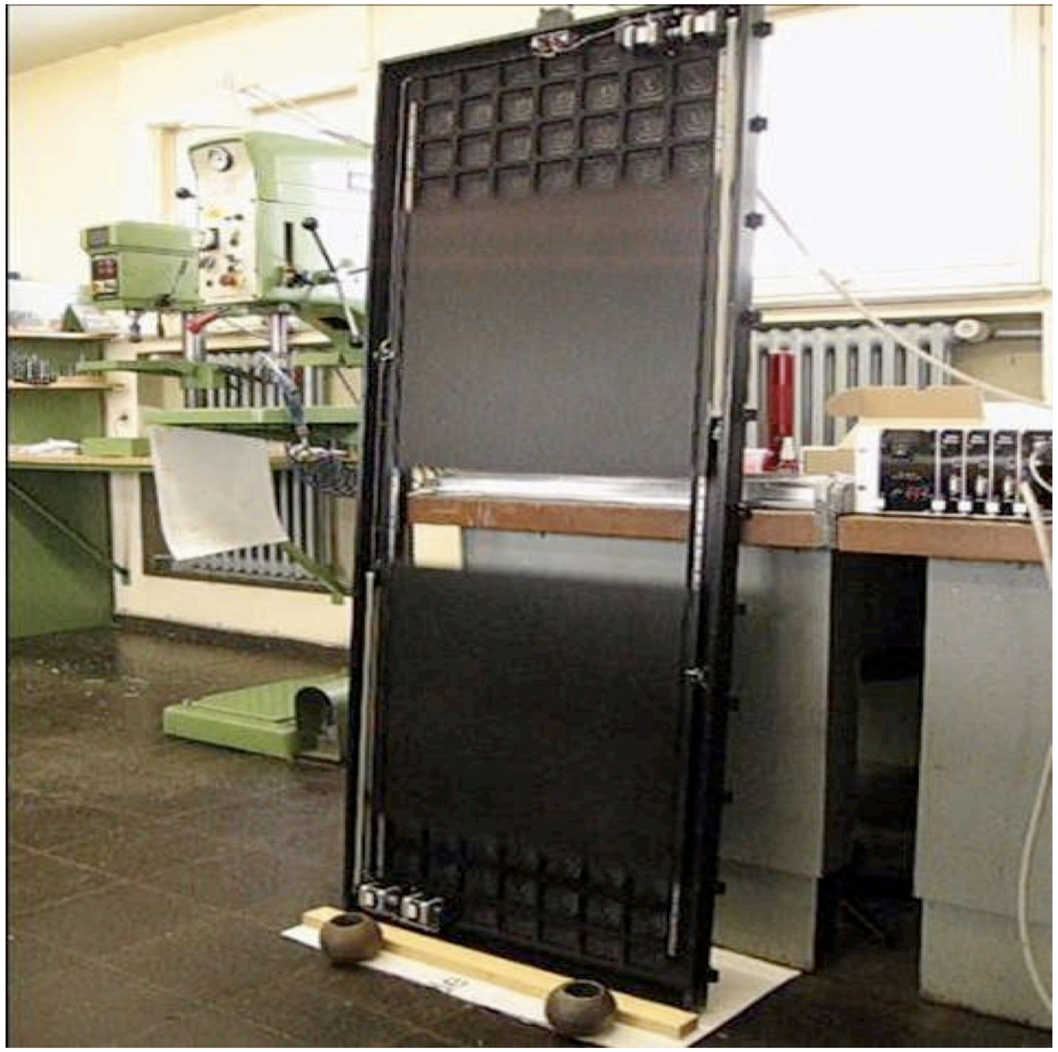
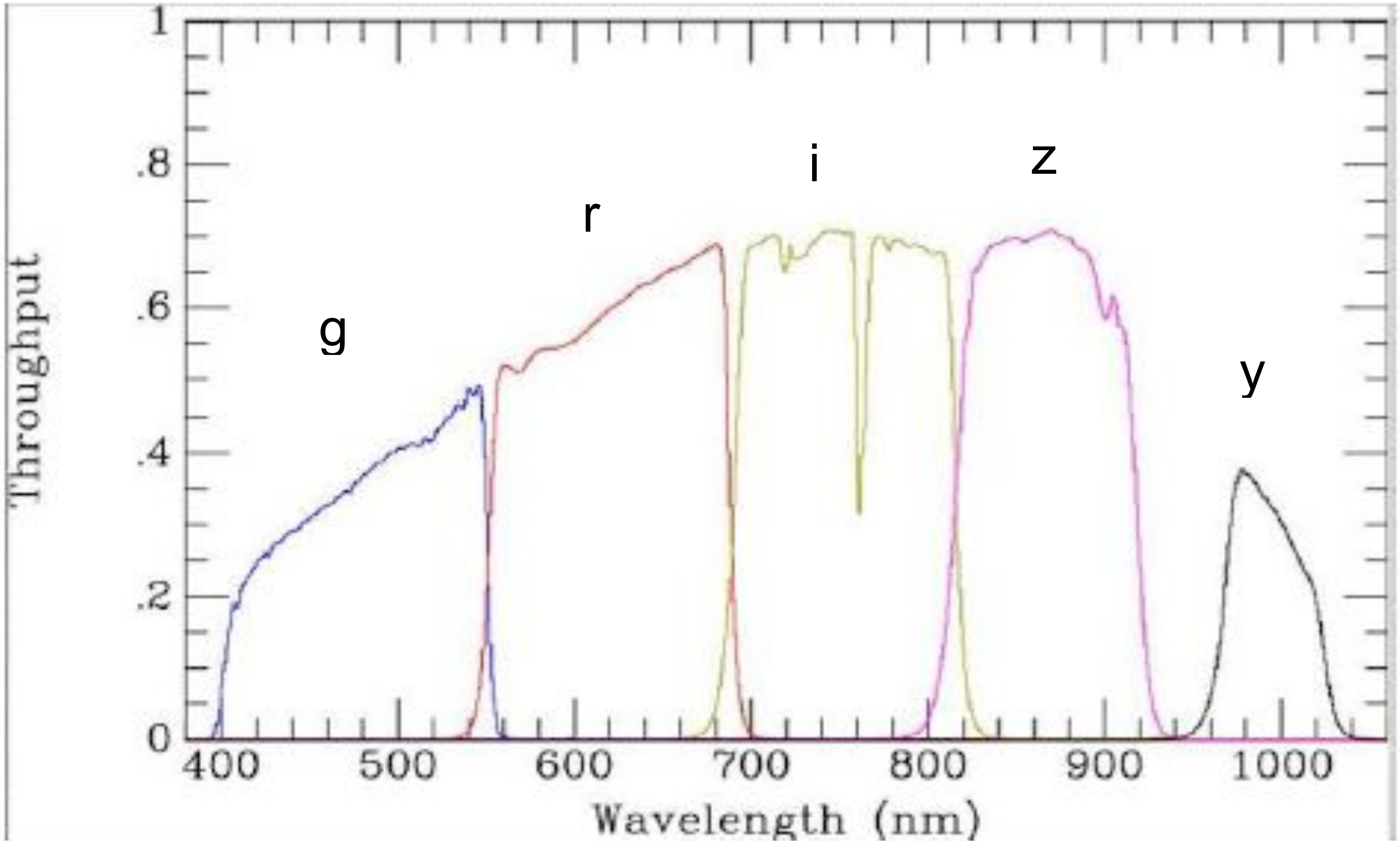
The famous Bonn-Shutter

- 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



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

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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

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The different key projects

- KP1: Populations of objects in the Inner Solar System
- KP2: Populations of objects in the Outer Solar System
- KP3: Low-Mass Stars, Brown Dwarfs, and Young Stellar Objects
- KP4: Search for Exo-Planets and dedicated Stellar Transits
- KP5: Structure of the Milky Way and the Local Group
- KP6: A Dedicated Deep Survey of M31
- KP7: Massive Stars and Supernova Progenitors
- KP8: Cosmology Investigations with Variables and Explosive Transients
- KP9: Galaxy Evolution
- KP10: Active Galactic Nuclei and High Redshift Quasars
- KP11: Cosmological Lensing
- KP12: Large Scale Structure

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- KP11: Cosmological Lensing
- KP12: Large Scale Structure (Shaun Cole and Stefanie Phleps)

Key Project 12: Large Scale Structure

- People (N=123): Angulo, R.; Antolinez, Andres Balaguera; Baugh, C.M.; Bell, Eric; Bender, Ralf; Bennett, Charles L.; Best, P.N.; Bielby, Rich; Blindert, Kris; Bower, R. G.; Braglia, Filiberto; Brimioulle, Fabrice; Budavari, Tamas; Bunk, Wolfram; Burgett, W.S.; Burwitz, Vadim; Cai, Y.C.; Carliles, Sam; Carlson, Arthur; Chambers, K. C.; Chen, A. B.; Chen, W. P.; Chiang, Po-Shih; Chieuh, Tzi-hong; Cirasuolo, Michele; Coleman, Paul; Cole, Shaun; Connelly, Jennifer; Drory, N.; Ebeling, Harold; Edge, A. C.; Eke, V.R.; Erwin, Peter; Fassbender, Rene; Ferguson, Henry C.; Finkbeiner, Douglas P.; Finoguenov, Alexis; Frenk, Carlos S.; Gal, R.R.; Geach, James; Gerhard, Ortwin; Giodini, Stefania; Gonzalez, Juan Esteban; Granett, B.R.; Halkola, Aleksi; Heavens, A.F.; Heckman, Tim; Heinis, Sebastien; Henry, Pat; High, Will; Hofbauer, Florian; Hopp, Ulrich; Huang, Lijin; Huchra, John; Hwang, Chorng-Yuan; James, J. Berian; Jenkins, Adrian; Johnson, Olivia; Kaiser, N.; Khochfar, S; Köhler, R; Lacey, C.G.; Lemson, Gerrard; Lin, Lihwai; Lopes, P. A.; Lucey, John; Lynn, Stuart; Magnier, Eugene A.; Mann, R.G.; Meiksin, A.A.; Meneux, Baptiste; Miller, Neal; Montesano, Francesco; Morris, Simon L.; Murphy, D.N.A.; Murray, S. S.; Neyrinck, Mark; Nishioka, Hiroaki; Norberg, P.; Panter, Ben; Papai, Peter; Parkinson, Hannah R.; Peacock, J.A.; Phleps, Stefanie; Pierini, Daniele; Pope, Adrian; Pratt, Gabriel W.; Rath, Christoph; Robaina, Aday; Roeser, Herrmann-Josef; Rykoff, Eli; Saglia, R.P.; Sanchez, Ariel; Santos, Joana; Sawangwit, Utane; Schlagenhaufer, Holger; Schneider, Peter; Seitz, Stella; Shanks, T.; Sharples, R.M.; Simon, P.; Simpson, F.; Skibba, Ramin; Smail, Ian; Smith, Russell J.; Specian, Mike; Stubbs, C.W.; Swinbank, A. M.; Szalay, Alex; Szapudi, Istvan; Tagidzeh, Manu; Taylor, A.N.; Theuns, Tom; Tocchini, Domenico; van den Bosch, Frank C.; van der Wel, Arjen; Voges, Wolfgang; Wake, D. A.; West, M.J.; White, Simon; Wilman, D.J.; Yip, Ching-Wa; Zibetti, Stefano

Key Project 12: Large Scale Structure

- Catalogue construction
  - mock catalogues Carlton Baugh and Frank van den Bosch
  - redshift catalogues Roberto Saglia and Dave Wilman
- LSS and BAOs Shaun Cole, Stefanie Phleps and Alex Szalay
- Higher order clustering statistics Istvan Szapudi
- CMB foregrounds from LSS Carlos Frenk and John Peacock
- Clustering as a function of X Stefanie Phleps and Frank van den Bosch
- Galaxy clusters Hans Böhringer and Richard Bower

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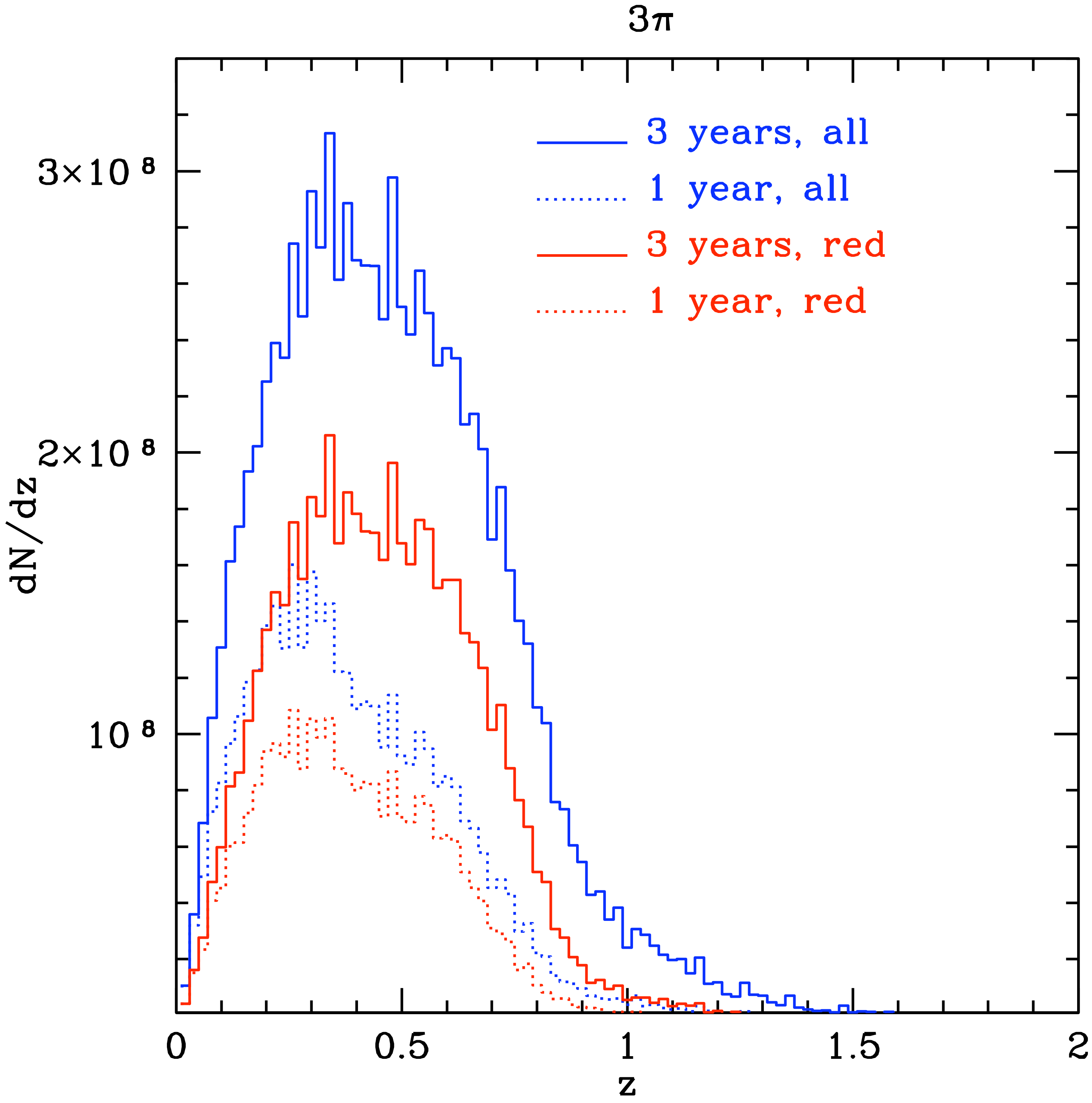
Redshift distribution of galaxies in the Pan-STARRS 3π survey



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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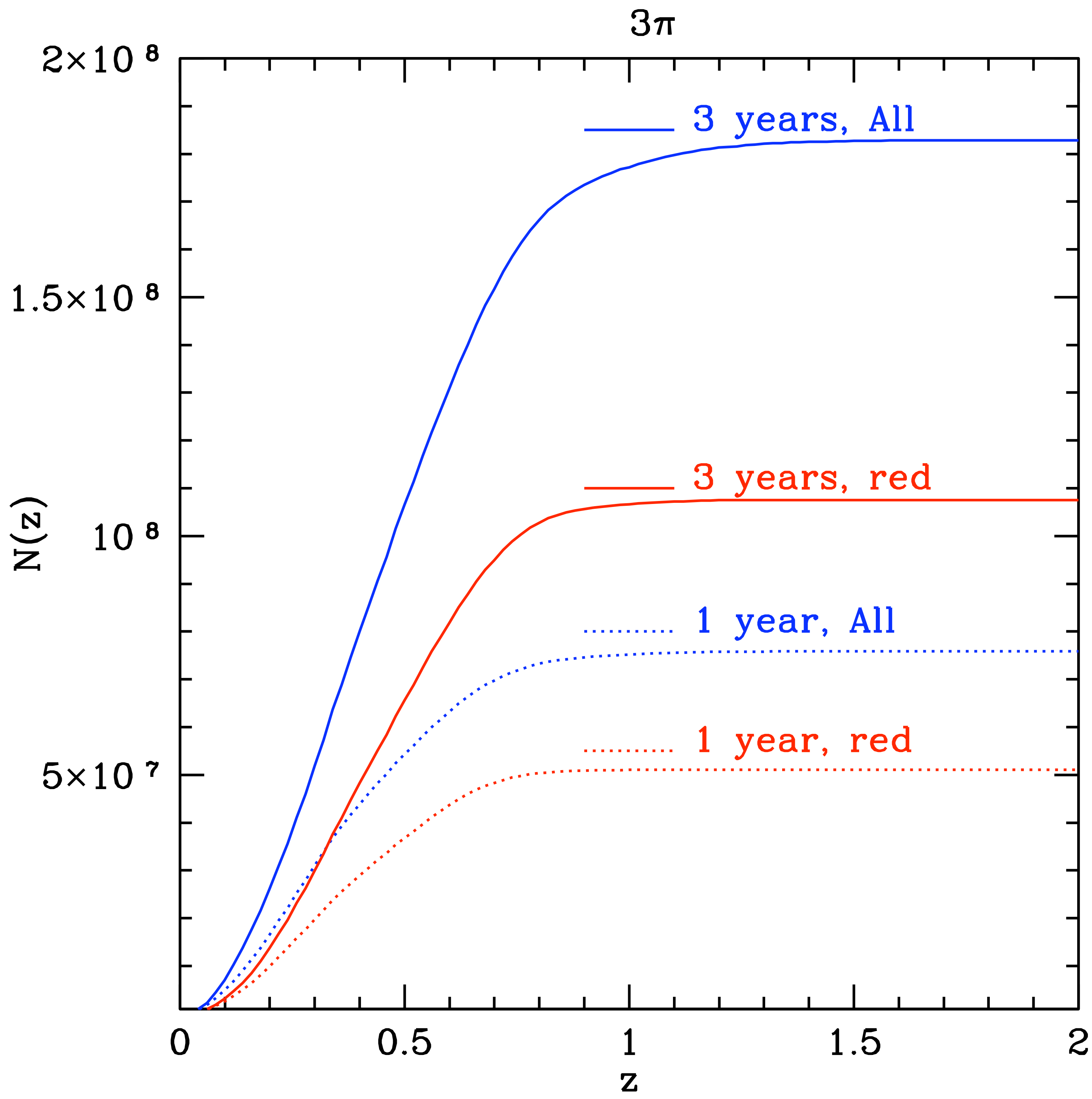

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numbers extrapolated to 3π

200 million galaxies after 3 years! 100 million LRGS!

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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

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Methods to detect BAOs

- Power spectrum (see Angulo et al. 2008, Sánchez et al. 2008, Cai et al. 2008, and see poster by F. Montesano)
- Correlation function (see poster by H. Schlagenhaufer)
  - $w(r_p)$
  - $\xi(r_p,\pi)$
- Spherical Harmonics (A. Balaguera-Antolínez)
- Higher order statistics

Correlation Function vs Power Spectrum

(Sánchez et al. 2008, see poster outside!)

- 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

See Shaun's talk this morning

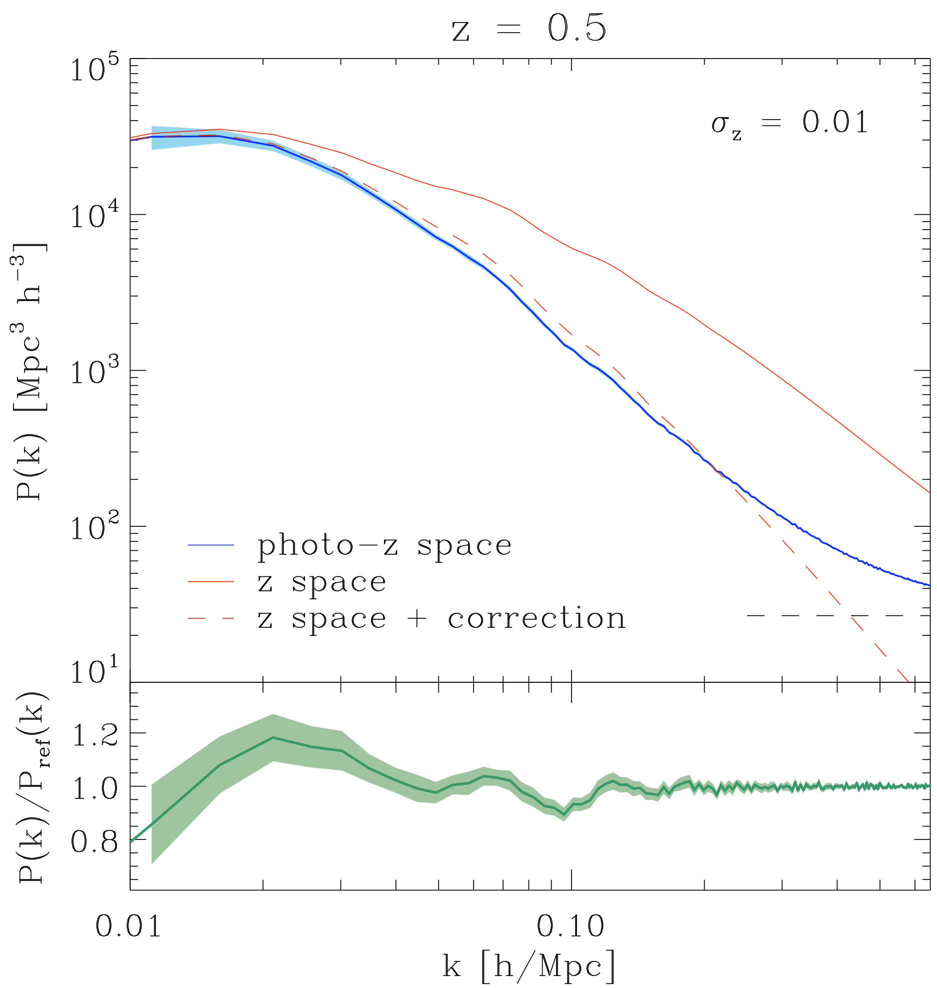
L-BASICC

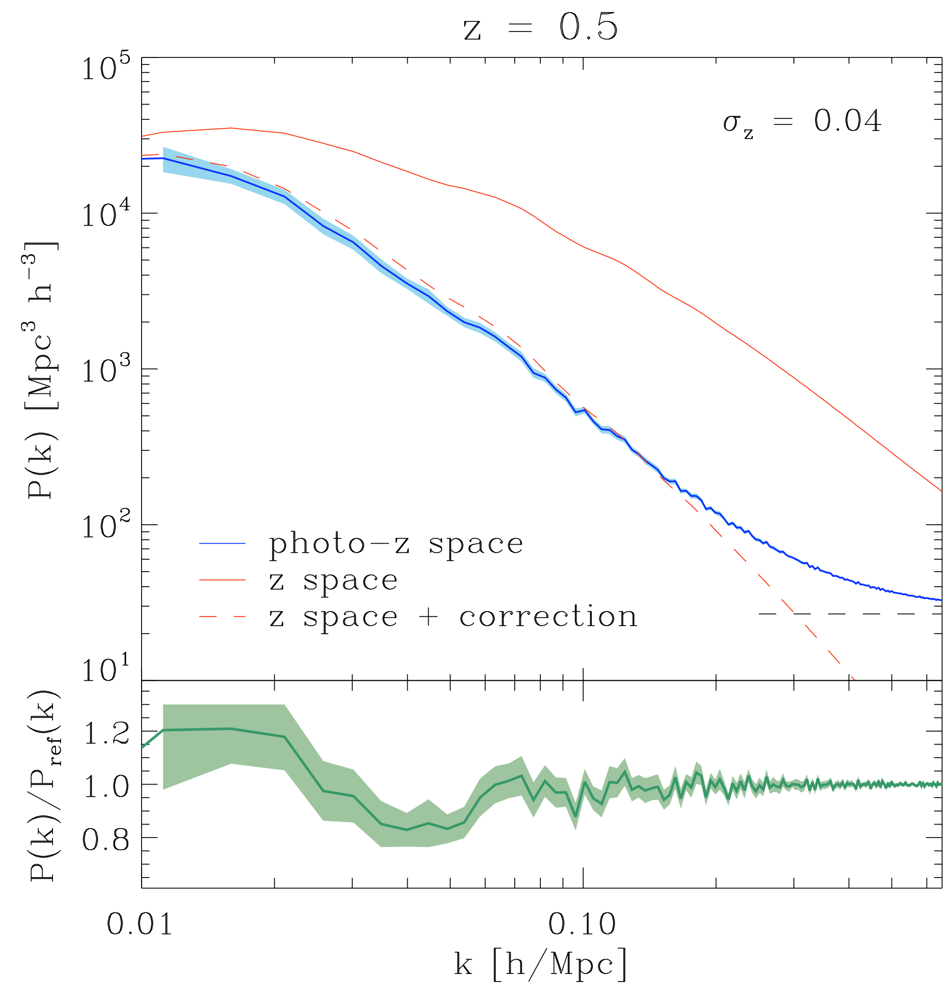
(Angulo et al. 2008)

- **L**ow-resolution version of **BASICC**, the **B**aryon **A**coustic **S**imulation at the **ICC** (**I**nstitute for **C**omputational **C**osmology, Durham)
- 50 realisations of a simulation box, each with
  - L=1340 h^{-1} Mpc (V=2.41h^{-3} Gpc^3)
  - N=448^3
  - Resolution: 1.8 x 10^{12} M_{sun}/particle
  - A minium of 10 particles forms a halo - can resolve haloes with M= 1.8 x 10^{13} M_{sun}
  - Same cosmology as Millennium run (Ω_m=0.25, Ω_Λ=0.75, h=0.73, n=, σ=0.9)

The power spectrum

Theoretical prediction: $P_{pz}(k) = P_z(k)\frac{\sqrt{\pi}}{2}\frac{Erf(k\sigma_z)}{k\sigma_z}$

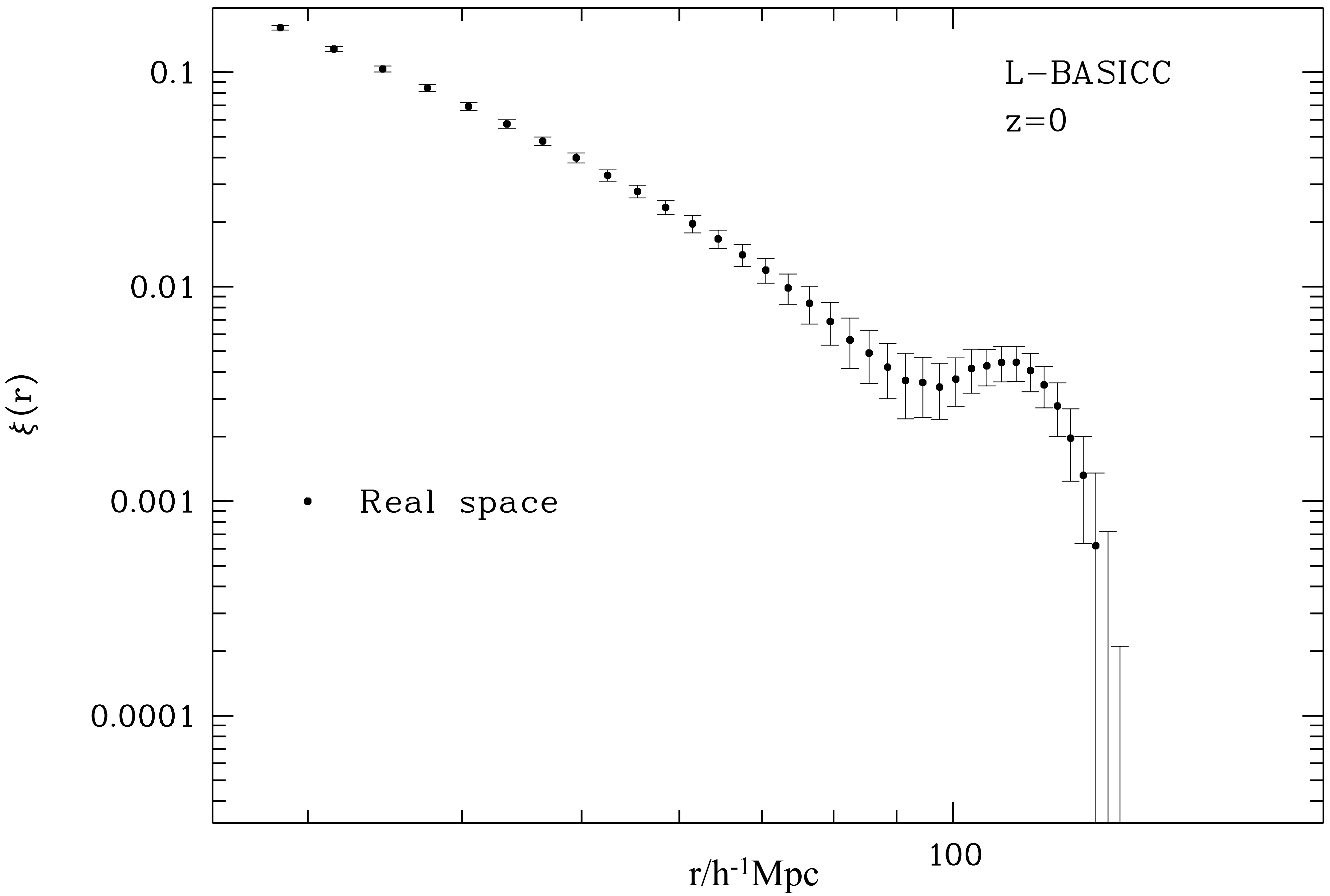




Cai et al. 2008 took L-BASICCs to simulate the effect of redshift errors on the power spectrum

They find that PS1 will achieve the same accuracy in the measurement of the scale of the BAOs (and hence in w_{DE}) as a spectroscopic survey containing 20 million galaxies -> which is not feasible for some time!

BAOs in the correlation function
(of dark halos in the L-BASICC simulation)



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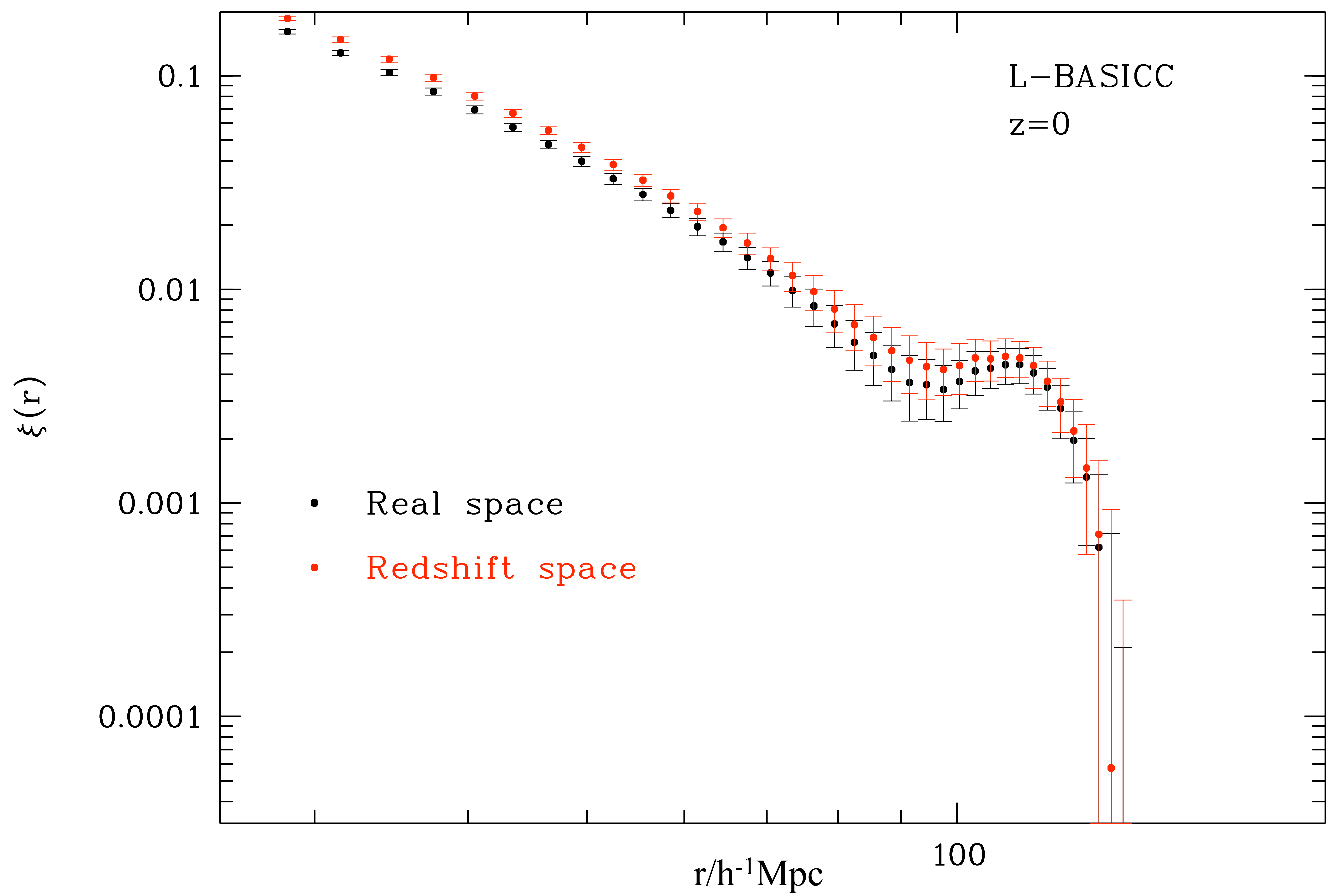

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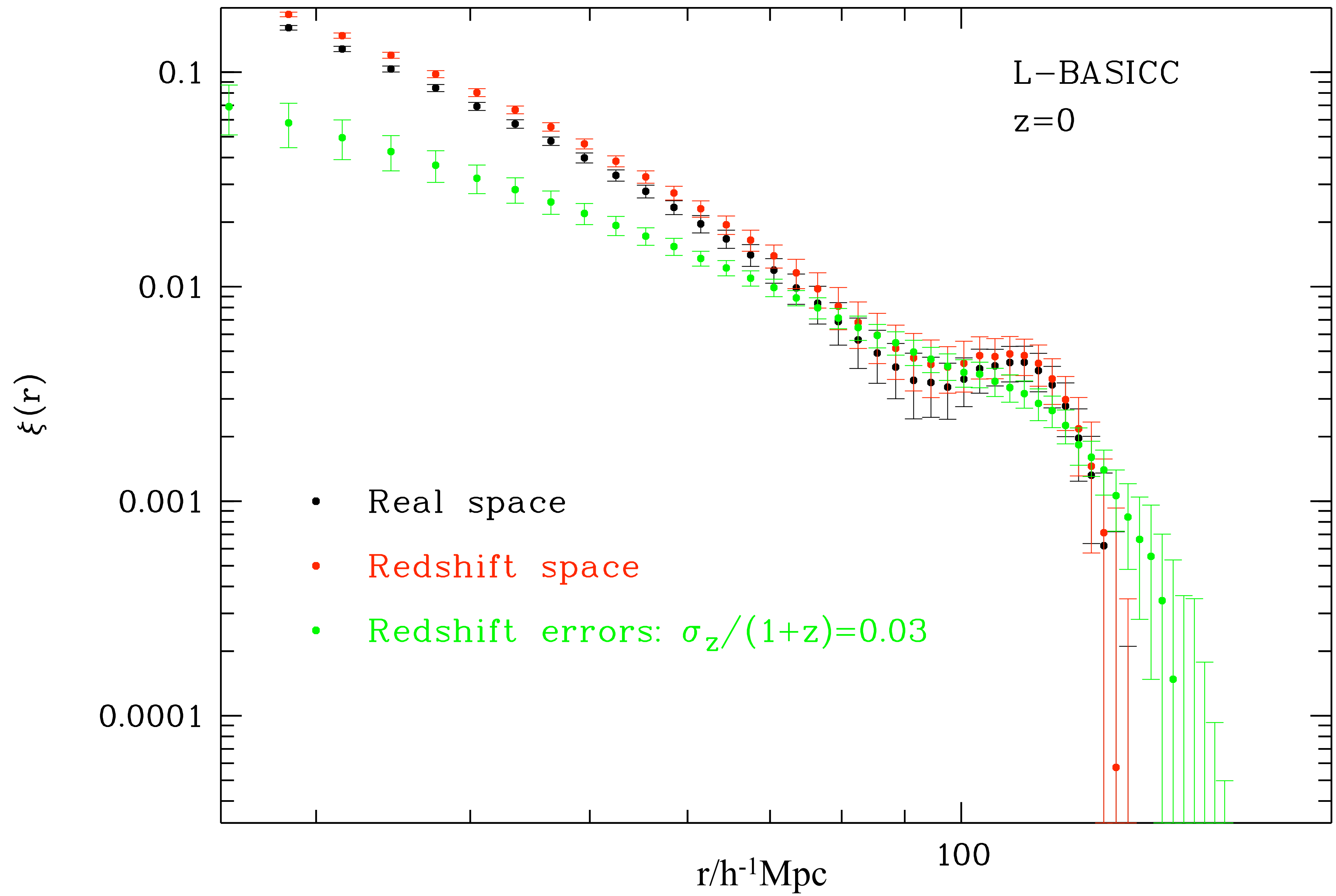

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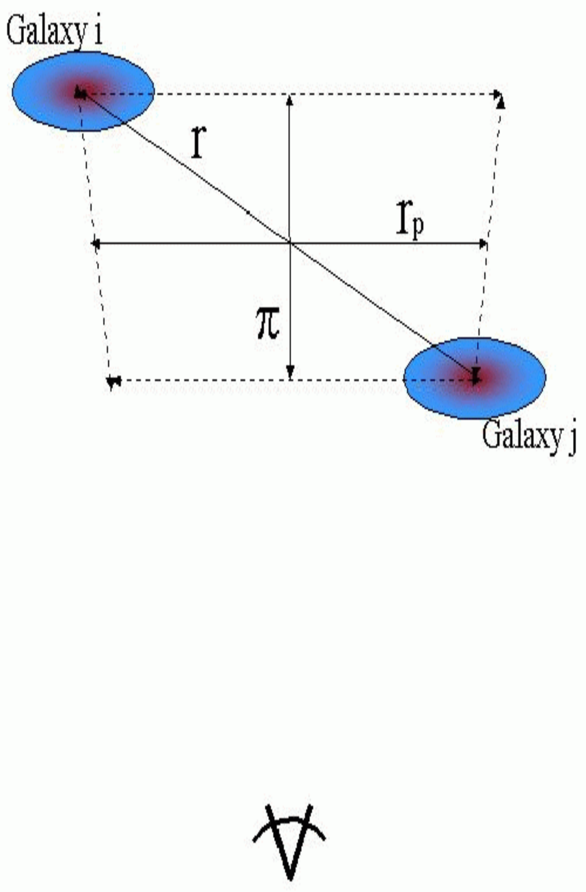
The projected correlation function

- If **redshift errors** are not negligible (e.g. in Pan-STARRS), we can calculate $\xi(r_p,\pi)$, or from there the **projected correlation function, $w(r_p)$**:

$$w(r_p) = 2\int_0^{\infty} \xi\left[\left(r_p^2 + \pi^2\right)^{1/2}\right] d\pi$$

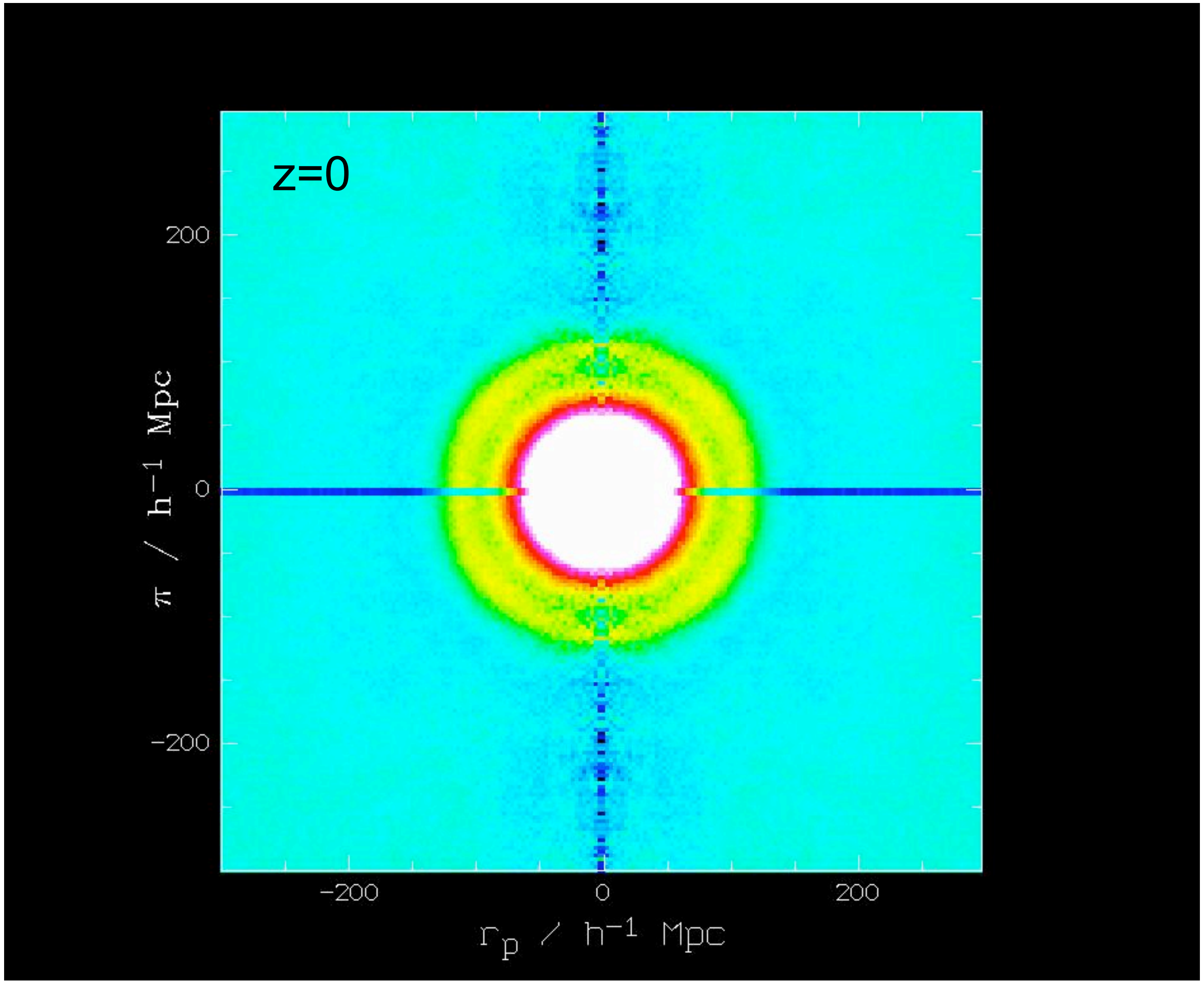
$$= 2\int_{r_p}^{\infty} \xi(r)\left(r^2 - r_p^2\right)^{-1/2} dr$$



r_p: projected distance between pairs of galaxies,

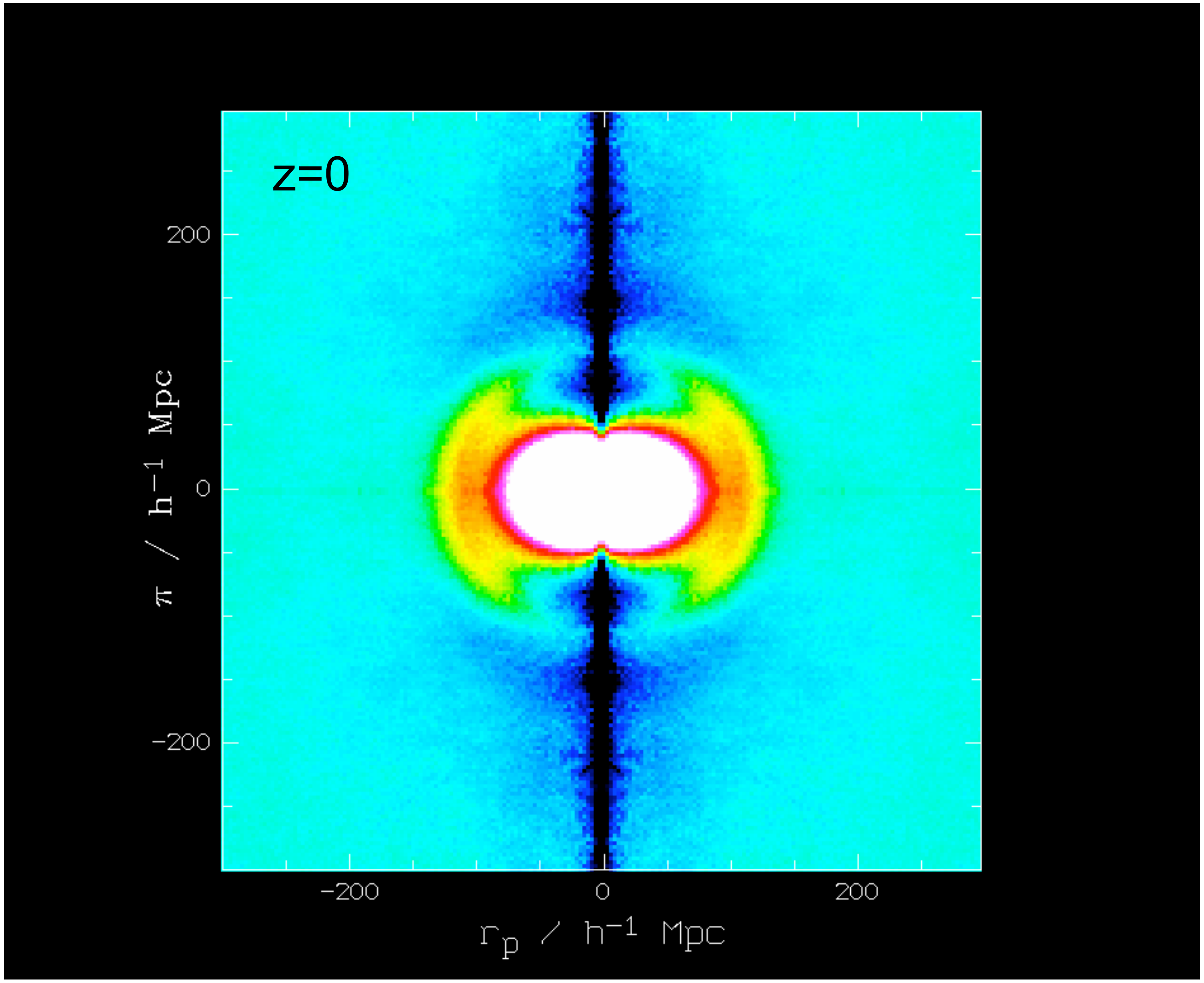
π: distance parallel to the line of sight

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



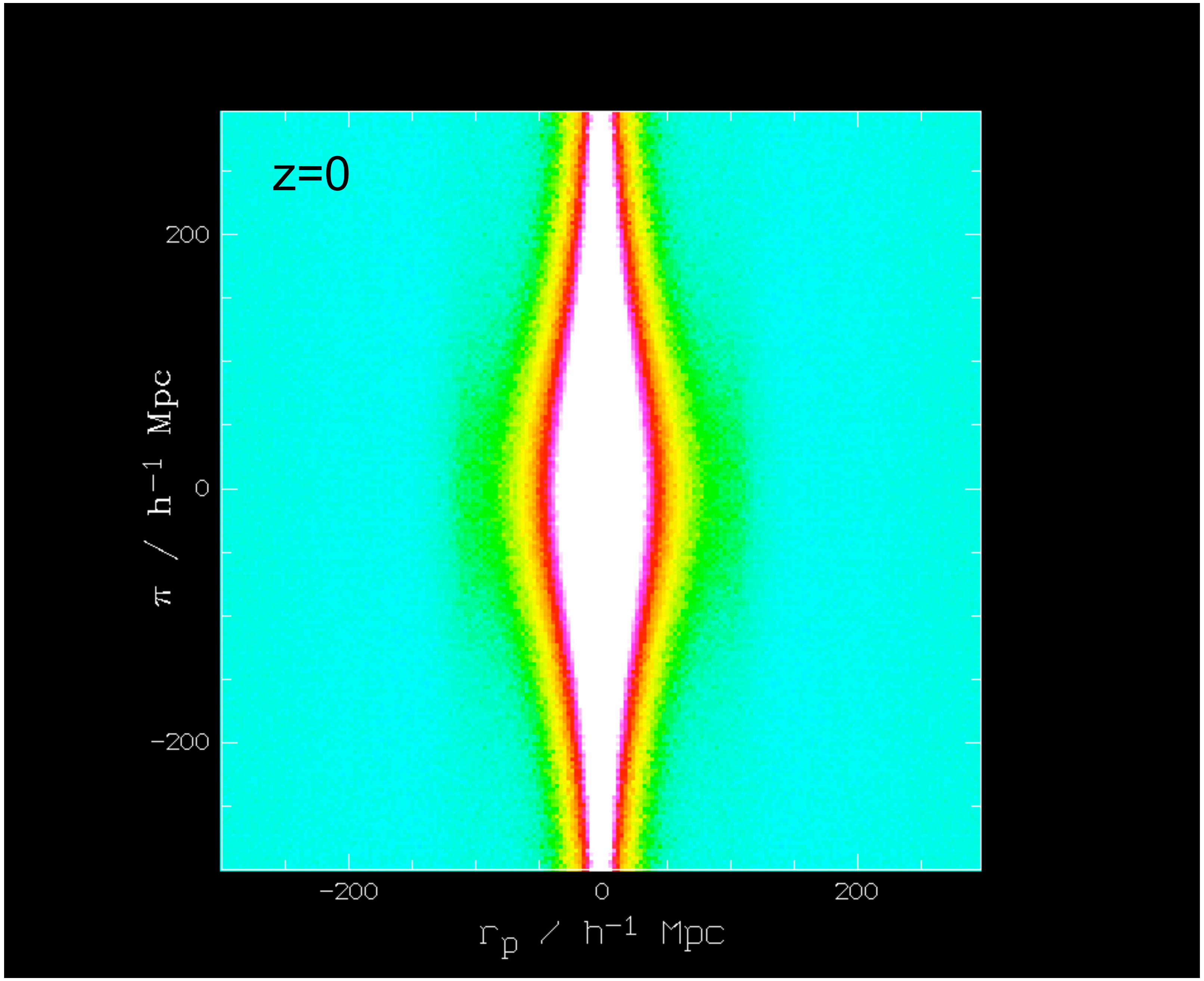
Real space

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



Redshift space

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

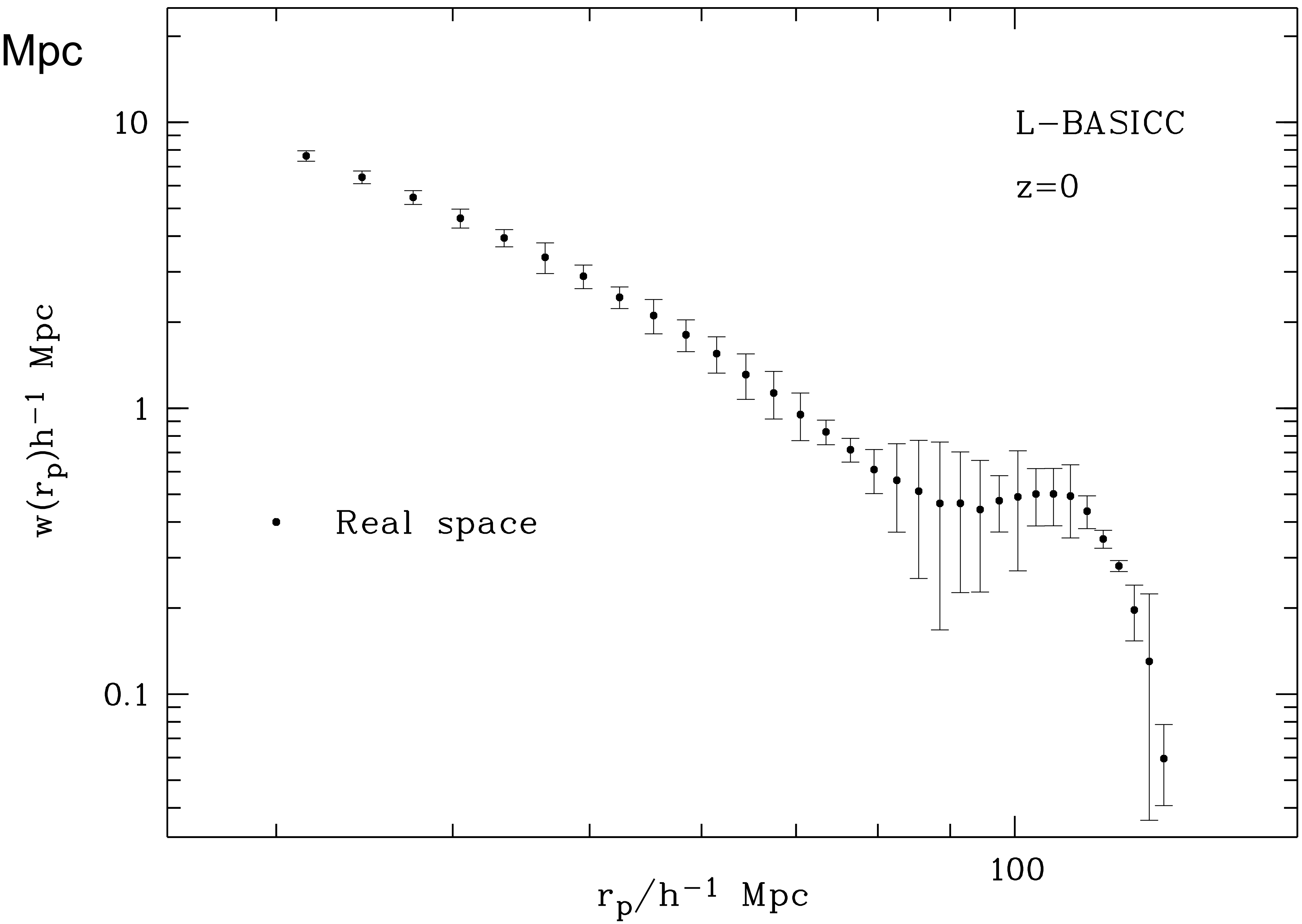


Redshift space and

Redshift errors $\sigma_z/(1+z)=0.03$

The acoustic peak in $w(r_p)$:

π_{max}=60 h^{-1}Mpc



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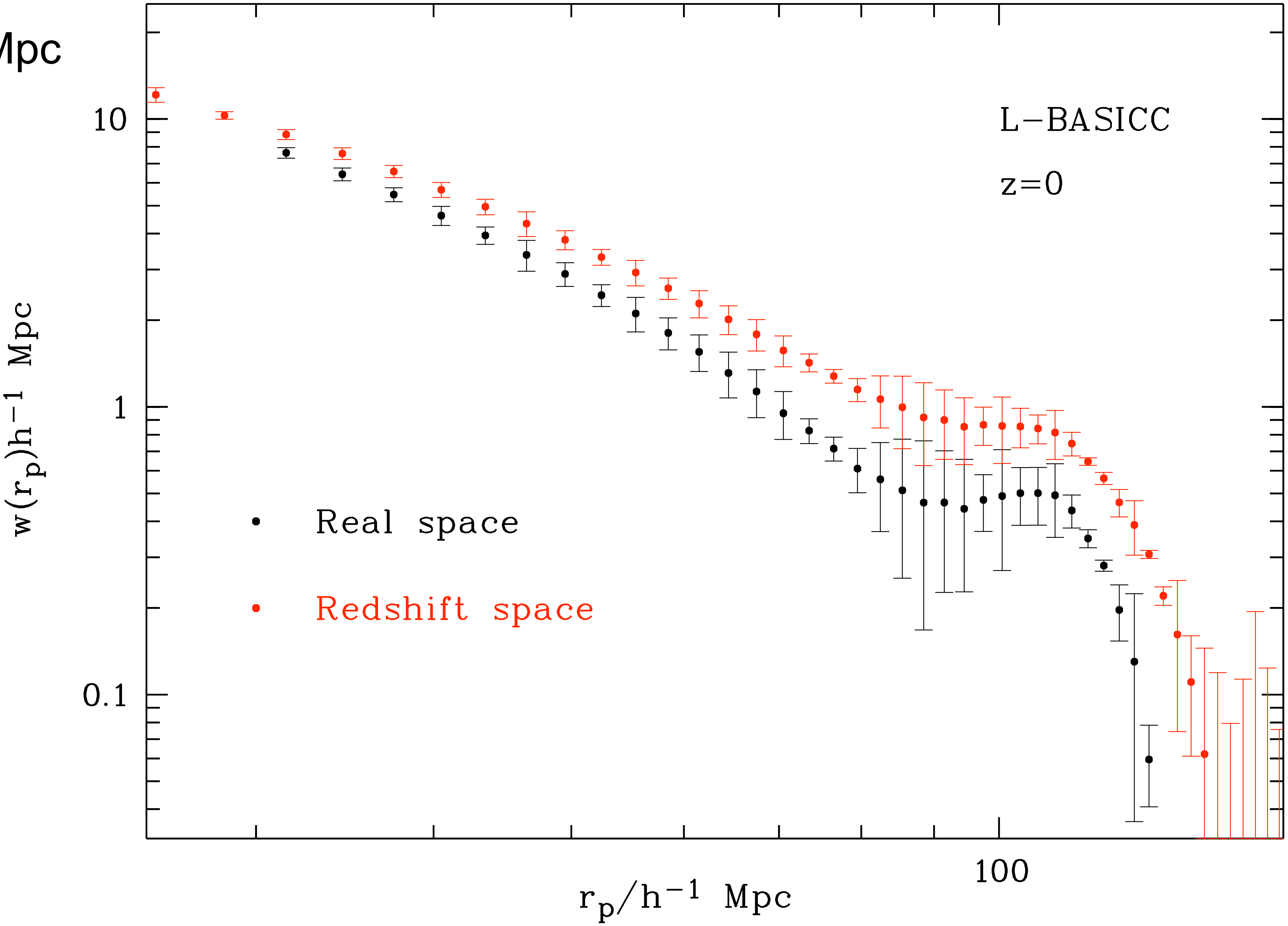

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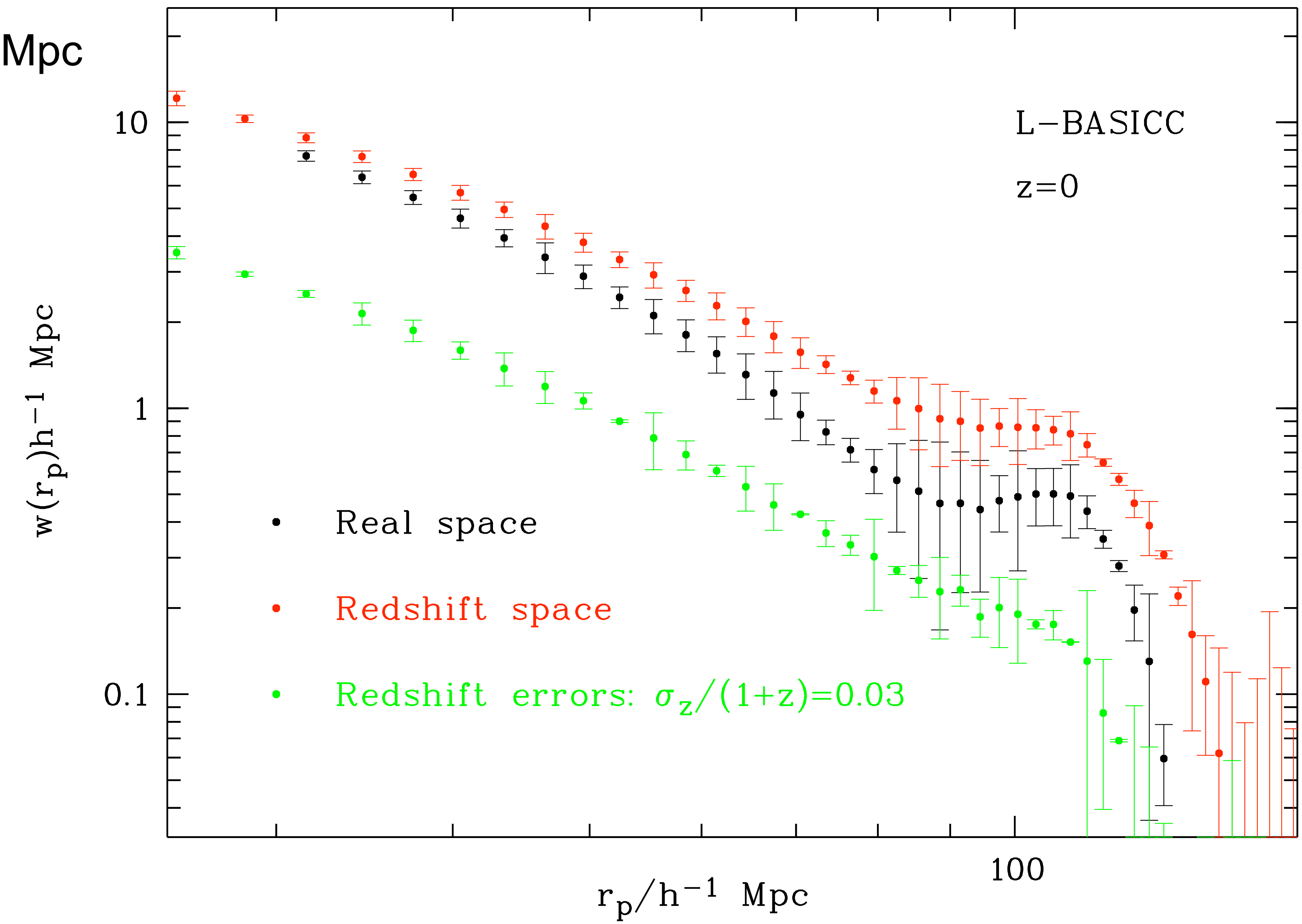
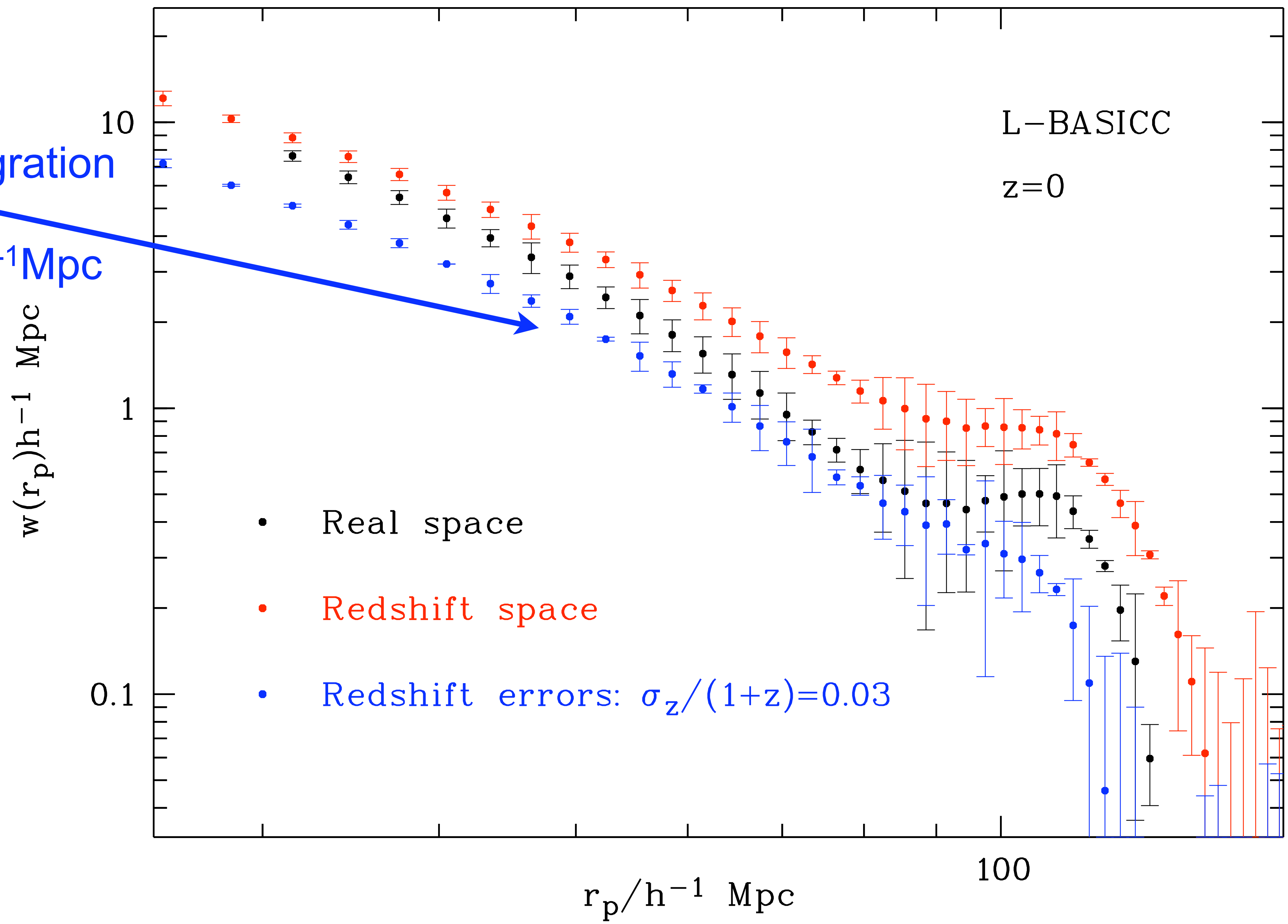


The acoustic peak in $w(r_p)$:

Larger integration limits!
π_{max}=120 h^{-1}Mpc



$w(r_p)$ vs $\xi(r_p,\pi)$

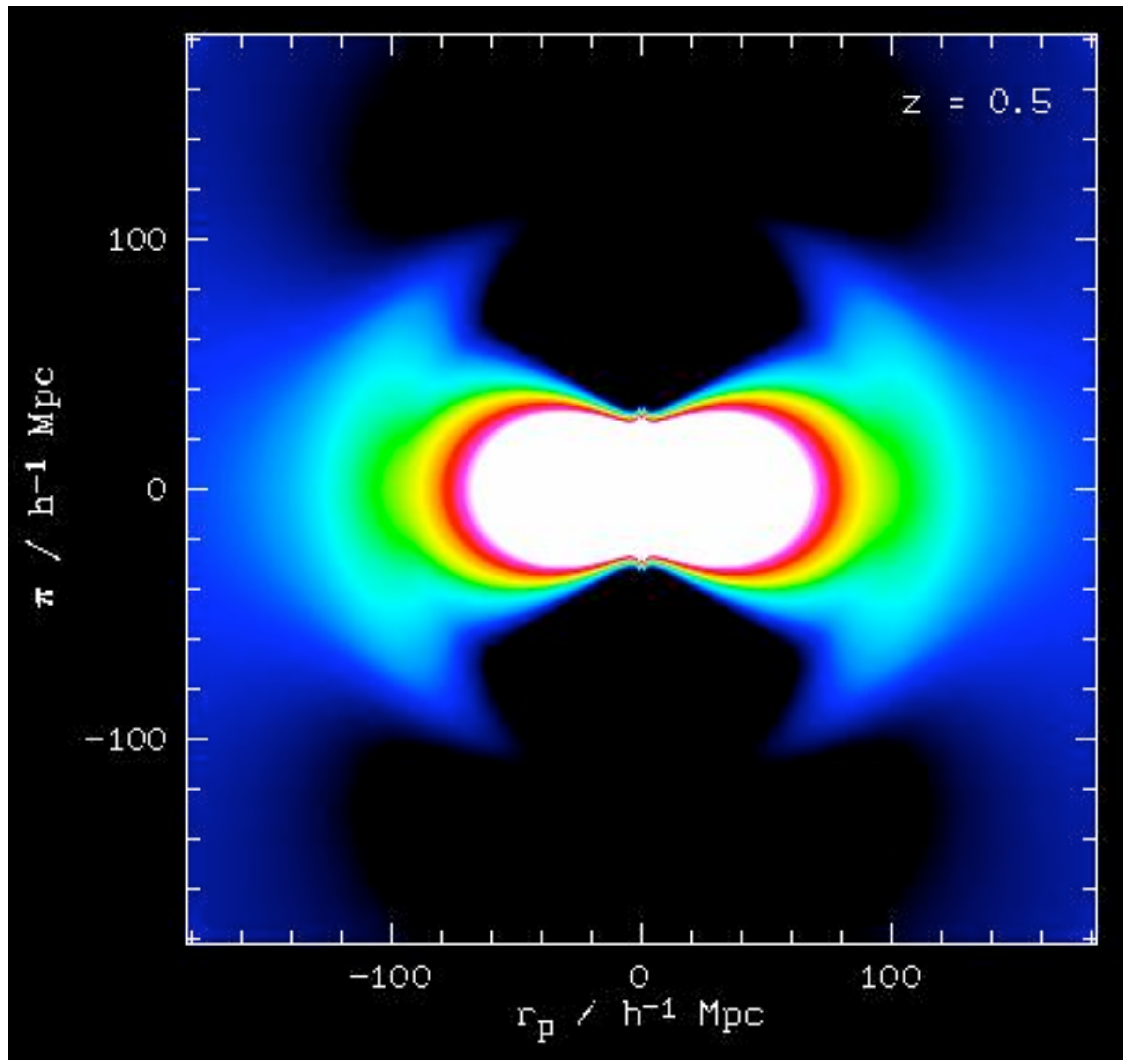
- If you were able to integrate $\xi(r_p,\pi)$ out to infinity, you should be able to recapture the full signal
- In practice this is impossible!
  - the choice of the integration limits influences the result!
- w_{DE} is also encoded in the redshift space distortions (Guzzo et al. 2008), can make use of the full shape of $\xi(r_p,\pi)$!
- redshift space distortions have to be modelled very carefully

→ **There is more information in $\xi(r_p,\pi)$!**

A model for $\xi(r_p, \pi)$

This model includes:

- nonlinear clustering growth (3rd order perturbation theory)
- Kaiser boost on large scales
- Fingers of god



Courtesy: Holger Schlagenhaufer

A model for $\xi(r_p,\pi)$

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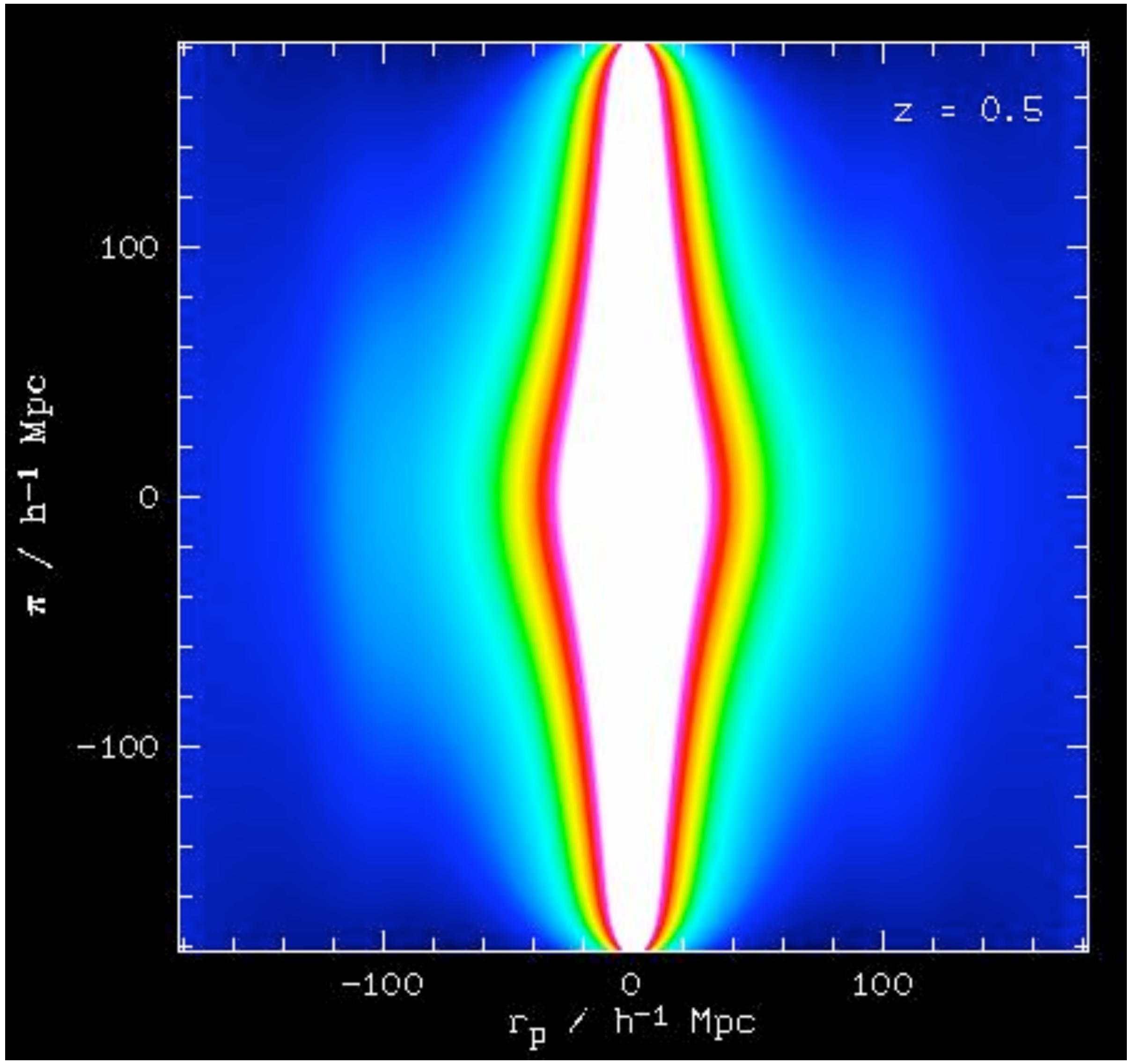
And redshift errors $\sigma_z/(1+z)=0.03$



Fitting the model $\xi(r_p,\pi)$ to the Pan-STARRS 3π data, we will be able to measure w_{DE} with an accuracy of ~3% (extrapolated from comparison with L-BASICC)

Have to improve description of non-linear clustering growth! (See poster by Holger)

Courtesy: Holger Schlagenhaufer

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The power spectrum vs spherical harmonics

- “Problem”: Fourier decomposition in plane waves not possible, redshift-space distortions not parallell
- Solution: A spherical harmonic analysis of redshift space (Heavens and Taylor 1995, 1997)
- Inclusion of redshift errors in spherical Bessel functions (Balaguera-Antolínez, Phleps and Schuecker)

Spherical Harmonics

Andrés Balaguera-Antolínez (PhD project)

- Natural complete set of eigenfunctions (of Laplace operator) on the sphere
- Tangential and radial effects can be treated separately (radial direction: use spherical Bessel functions)
- Useful for large sky coverage

Ideal for Pan-STARRS!

Spherical Harmonics

Andrés Balaguera-Antolínez (PhD project)

- Expand the galaxy density field:

$$\hat{\delta}_{lm}(k) = \sqrt{\frac{2}{\pi}}\int d^3r\,\delta(r)\,j_l(kr)\,Y^*_{lm}(\hat{r})$$

- Then

$$\left\langle \delta_{lmn}\delta^*_{l'm'n'} \right\rangle = S^{lmn}_{l'm'n'} + N^{lmn}_{l'm'n'}$$

Signal Shot Noise

- With

$$\boxed{S^{lmn}_{l'm'n'} = \sum_{l''m''n''} W^{lmn}_{l''m''n''} W^{*l'm'n'}_{l''m''n''} f^{ln''}_{l'n'} f^{l'n''}_{l'n'} P(k_{ln''})}$$

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What else?

- We can compare clustering of different galaxy types (in the PS1 MDS) to measure the biasing
- Calculate all sorts of higher order statistics (bi-spectrum, three-point correlation function, scaling indices, Minkowsky functionals...) in order to get a grip on the evolution of non-linearities and biasing, investigate signature of BAOs in higher order statistics
- Combine with HETDEX (measurement at z=3)

Summary

- Pan-STARRS covers the largest contiguous area on the sky in the optical up to now
- Observations in five filters give redshift errors of about 3% for ~100 million luminous red galaxies up to $z=1.2$
- We can use the large volume to calculate correlation functions, power spectra, and spherical harmonics
- Measure scale of the BAOs
- and hence the equation of state of Dark Energy at $z<1$ with at least 3% accuracy