DARK ENERGY SURVEY

DES-BRAZIL

LIneA
Laboratório Interinstitucional de e-Astronomia

Dark Energy Survey

Rogerio Rosenfeld

IFT-UNESP

ICTP SAIFR International Centre for Theoretical Physics
South American Institute for Fundamental Research

LIneA

DES review, also work with Fabien Lacasa 1603.00918
Work in progress with Lacasa, Hoffmann and Gaztañaga

SILAFAE
XI SIMPOSIO LATINOAMERICANO DE FÍSICA DE ALTAS ENERGÍAS

Standard Model of Particle Physics works fine but it is unsatisfactory (neutrino masses, dark matter, hierarchy problem, etc). Beyond SM!

Standard Model of Cosmology (ΛCDM) works fine but it is unsatisfatory (value and nature of Λ). Beyond ΛCDM!

Models abound! We have to see what Nature has chosen...

Cosmology has become a data-driven science and entered a precision era.

$t_U = (13.799 \pm 0.021) \times 10^9$ years [used to be $10^{9\pm1}$ years]

Many probes are used to extract information about cosmology.

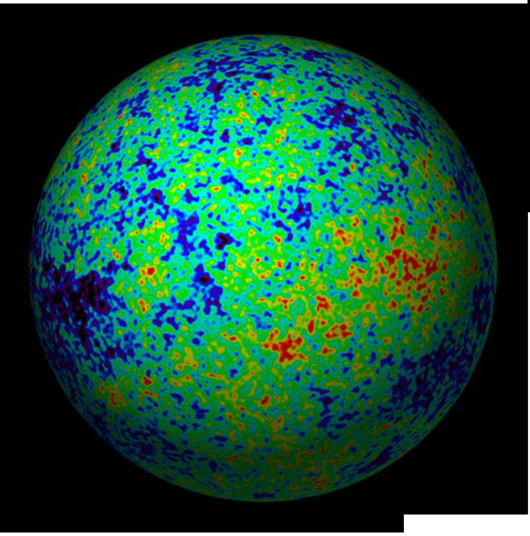
Important to combine them to break degeneracies and improve bounds.

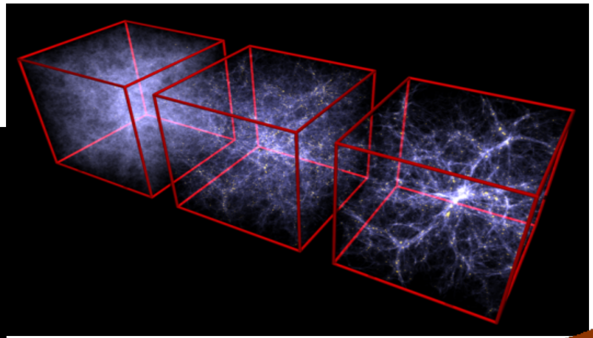
Cosmological probes

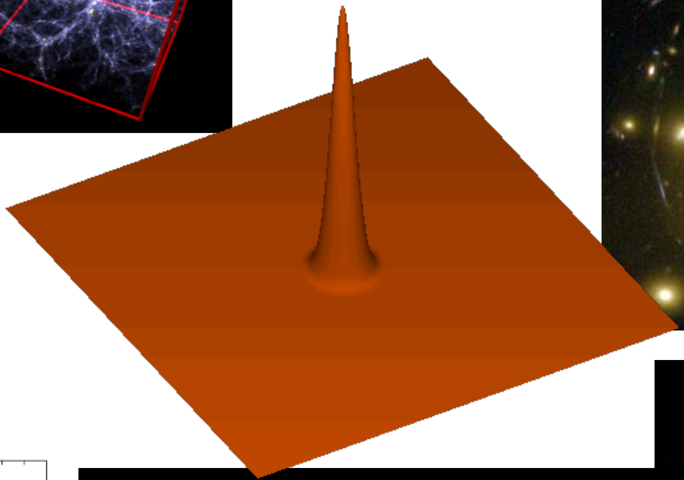
- Cosmic Microwave Background (CMB)
- Big bang nucleosynthesis (BBN)
- Supernovae Ia
- Gravitational lensing
- Number count of clusters of galaxies
- Distribution of galaxies

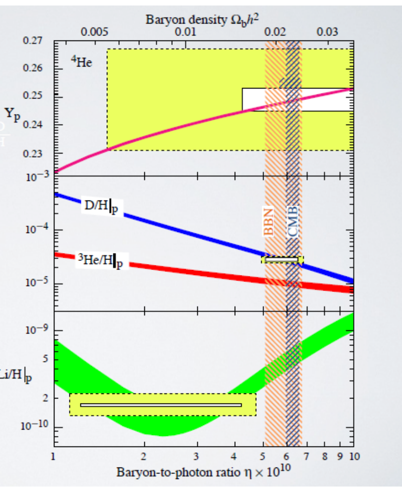
today's talk

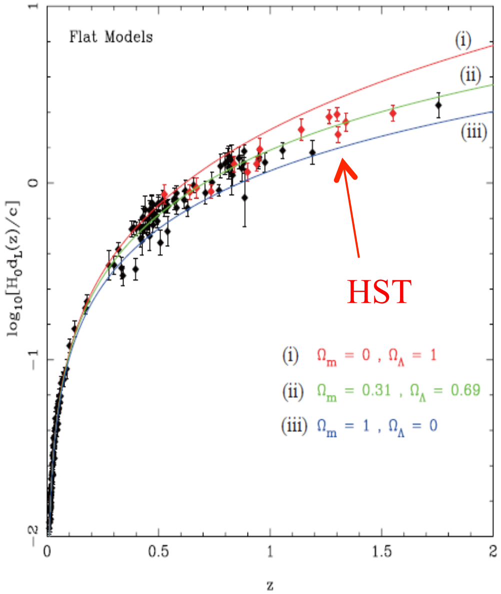
Cosmological probes

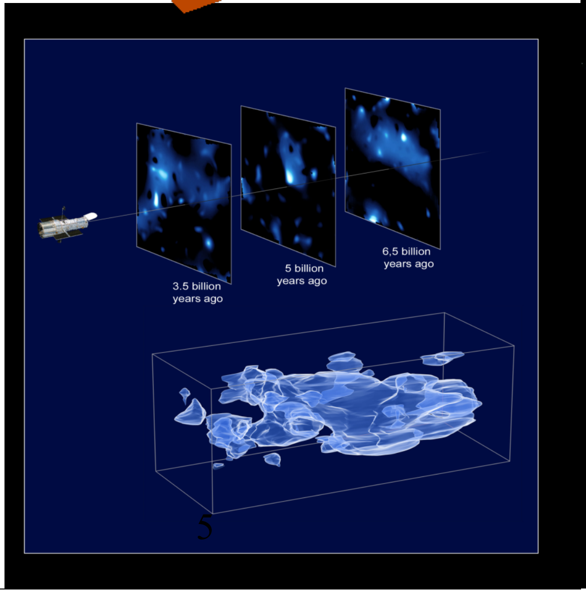


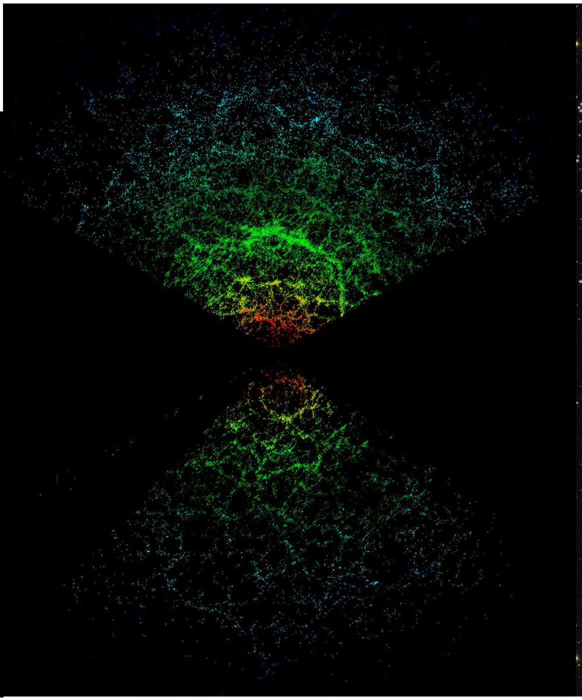












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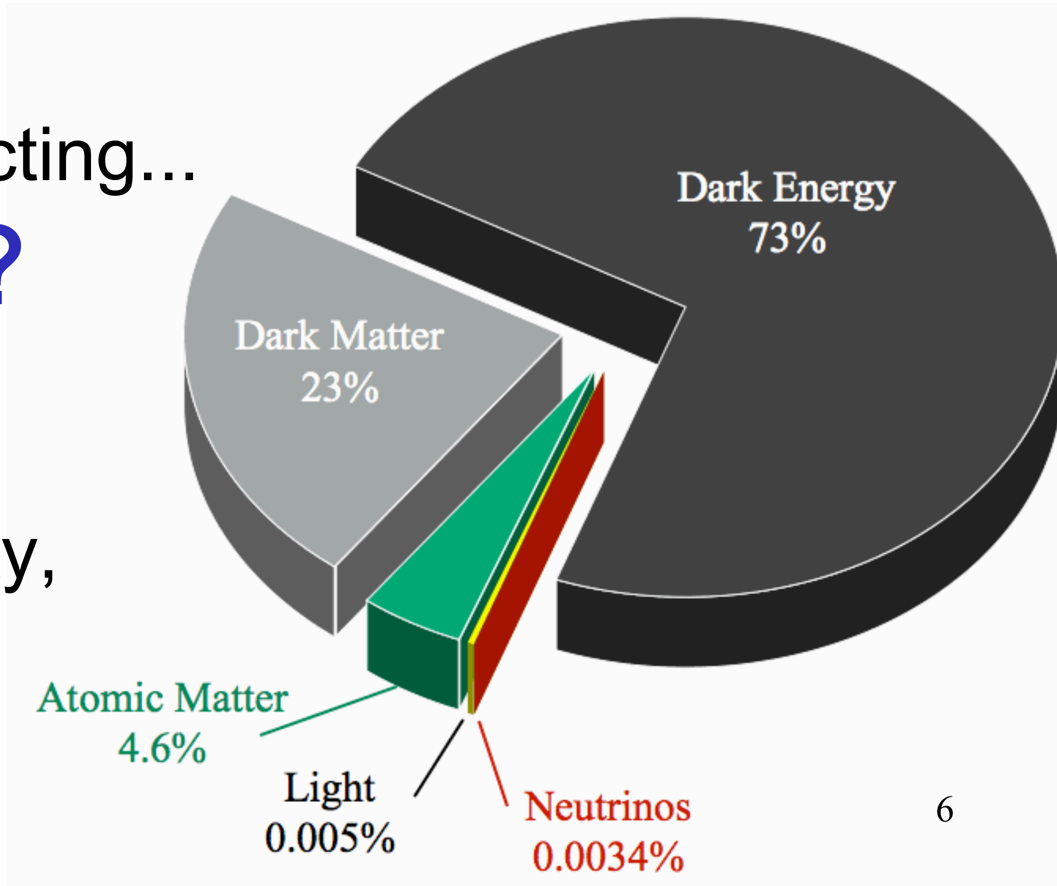
We know that we don't know what 95% of the universe is made of.

What is dark matter?

Cold, warm, fuzzy, self-interacting...

What is dark energy?

New degree of freedom/MG:
Quintessence, galileon, f(R), Hordensky, beyond Hordensky, massive gravity, EFTofDE...
Does it interact with matter?
Does it cluster?



Large scale galaxy surveys are instrumental for the determination of best model for the Universe:

SDSS, BOSS, eBOSS
DES
PAU, J-PAS
DESI
LSST
Euclid ...

Accelerators $\leftrightarrow$ Large scale galaxy surveys analogy:

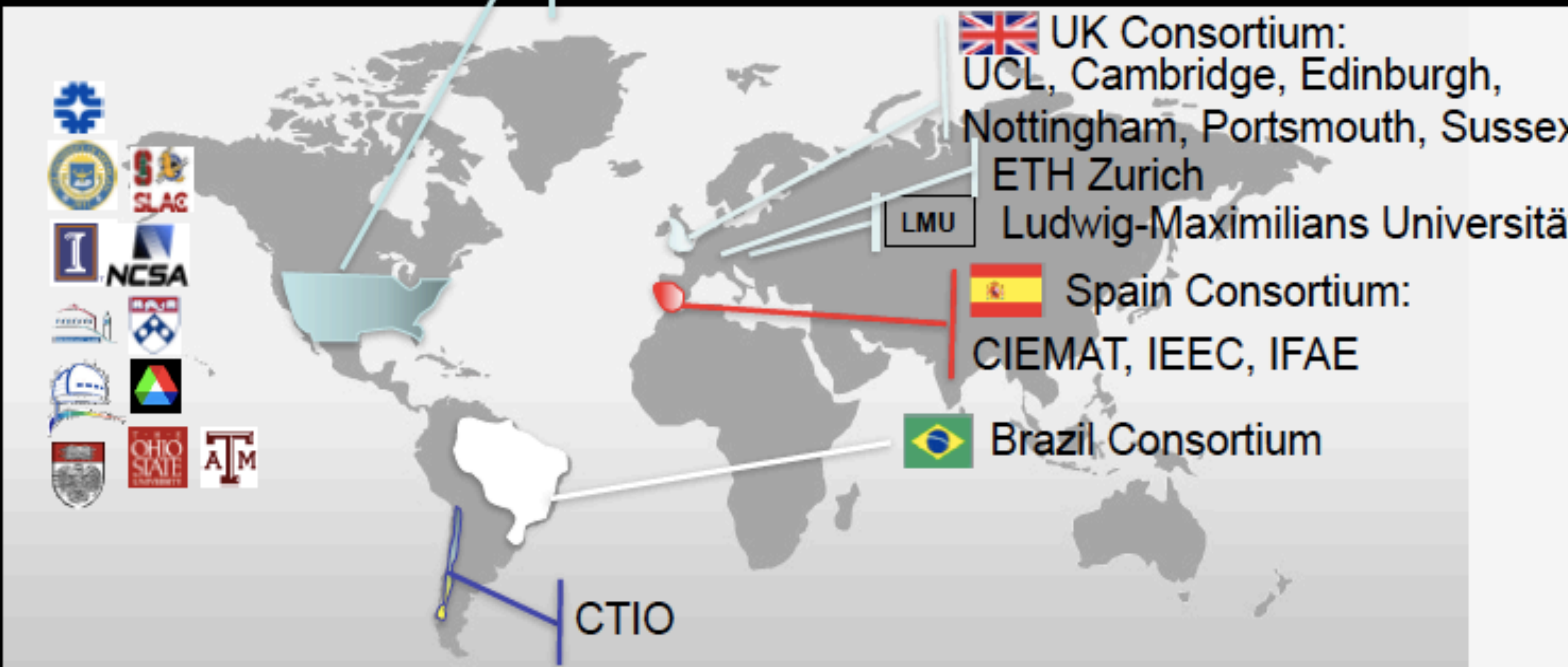
- Energy $\leftrightarrow$ redshift
- Luminosity $\leftrightarrow$ area & observation time
- Energy resolution $\leftrightarrow$ redshift errors
- Energy calibration $\leftrightarrow$ objects with known redshifts
- p_T cuts, etc $\leftrightarrow$ magnitude cuts, mask, etc
- Final data set $\leftrightarrow$ value added catalogs
- Higgs bump hunting $\leftrightarrow$ BAO bump hunting
- PT ok at high E $\leftrightarrow$ PT ok at high z

Dark Energy Survey Collaboration

Josh Frieman – Project Director
John Peoples was 1st director

~300 scientists

Fermilab, UIUC/NCSA, University of Chicago, LBNL, NOAO, University of Michigan, University of Pennsylvania, Argonne National Lab, Ohio State University, Santa-Cruz/SLAC/Stanford, Texas A&M



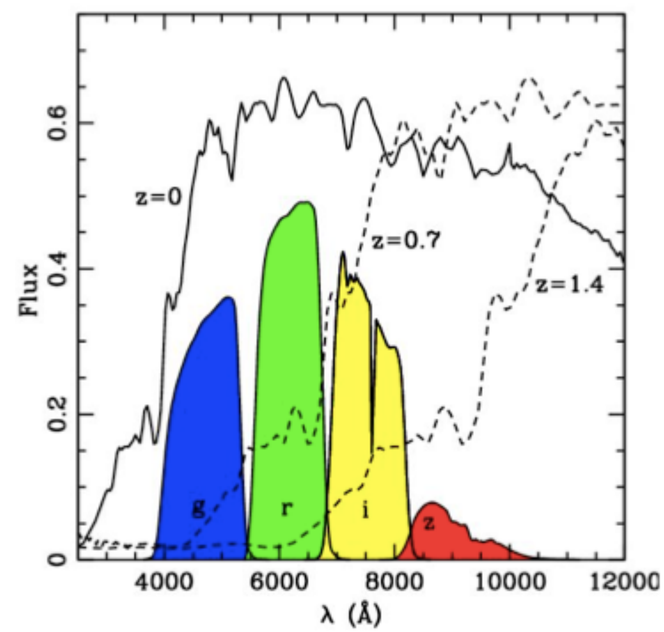
DES-Brazil is a LIneA Project

Laboratório Interinstitucional de e-Astronomia (LIneA)

http://www.linea.gov.br

DES Project

- Survey of 5000 deg^2 (~ 1/8 of the sky)
- 300 millions of galaxies up to z~1.3 (+ 100,000 clusters + 4,000 SN Ia)
- Photometric redshift with 5 filters
- Blanco telescope (4m, CTIO)
- DECam – 62 (+12) CCDs (LBNL) - 570 Megapixels



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DES Project Timeline

NOAO Blanco Announcement of Opportunity 2003

DECam R&D 2004-8

Camera construction 2008-11

First light DECam on telescope September 2012

Science Verification (SV) run: Sept. 2012 - Feb. 2013
First Season (Year 1): Aug. 31, 2013 - Feb. 9, 2014
Second Season (Year 2): Aug. 2014 - Feb. 2015
Third Season (Year 3): Aug. 2015 - Feb. 2016
Fourth Season (Year 4) August 2016 – Feb. 2017

Planning on 5 years of 105-nights each

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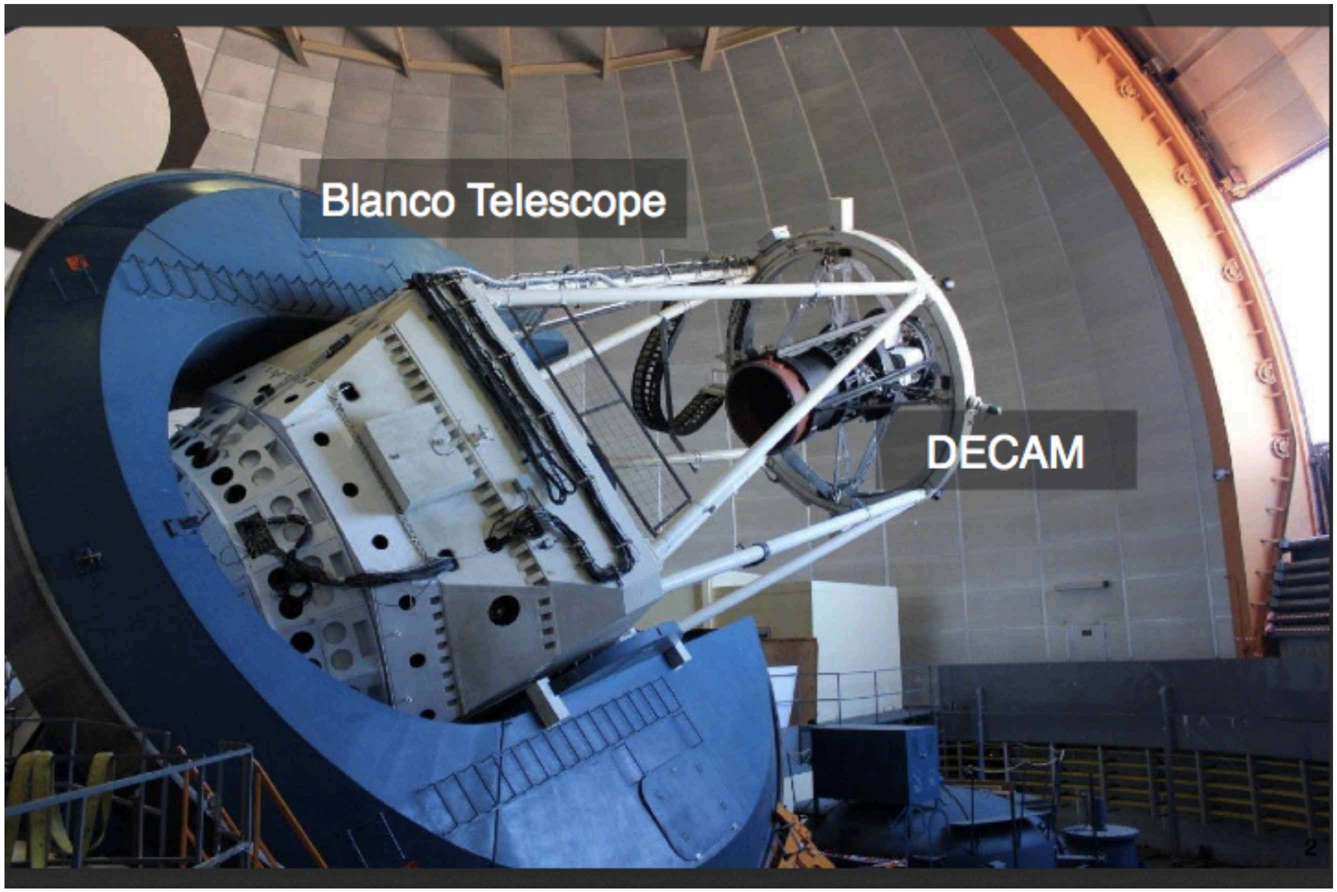
DES site: 4m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile

DECam

Able to see light from more than 100,000 galaxies up to 8 billion light-years away in each snapshot. Weighs ~4 tons!



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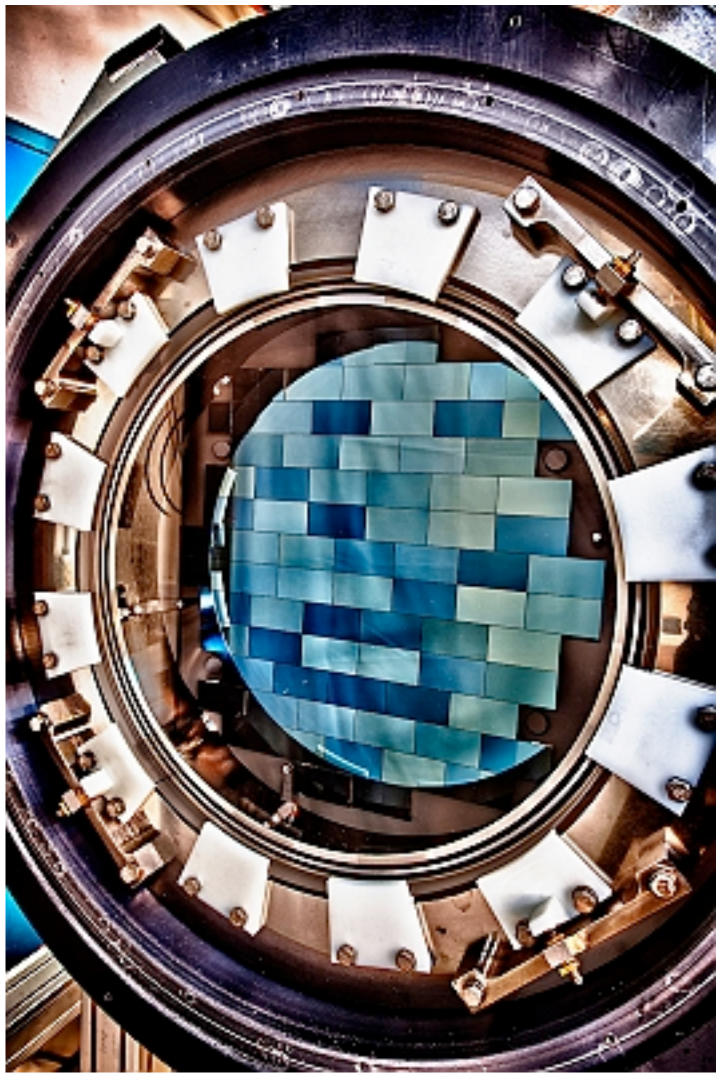
DECam



arXiv:1504.02900

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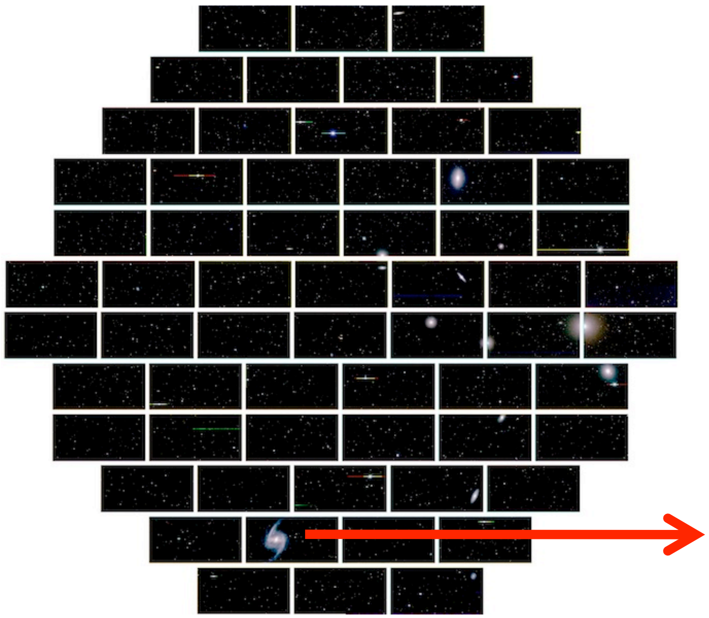

Fornax cluster of galaxies

Barred spiral galaxy NGC 1365 in the Fornax cluster of galaxies

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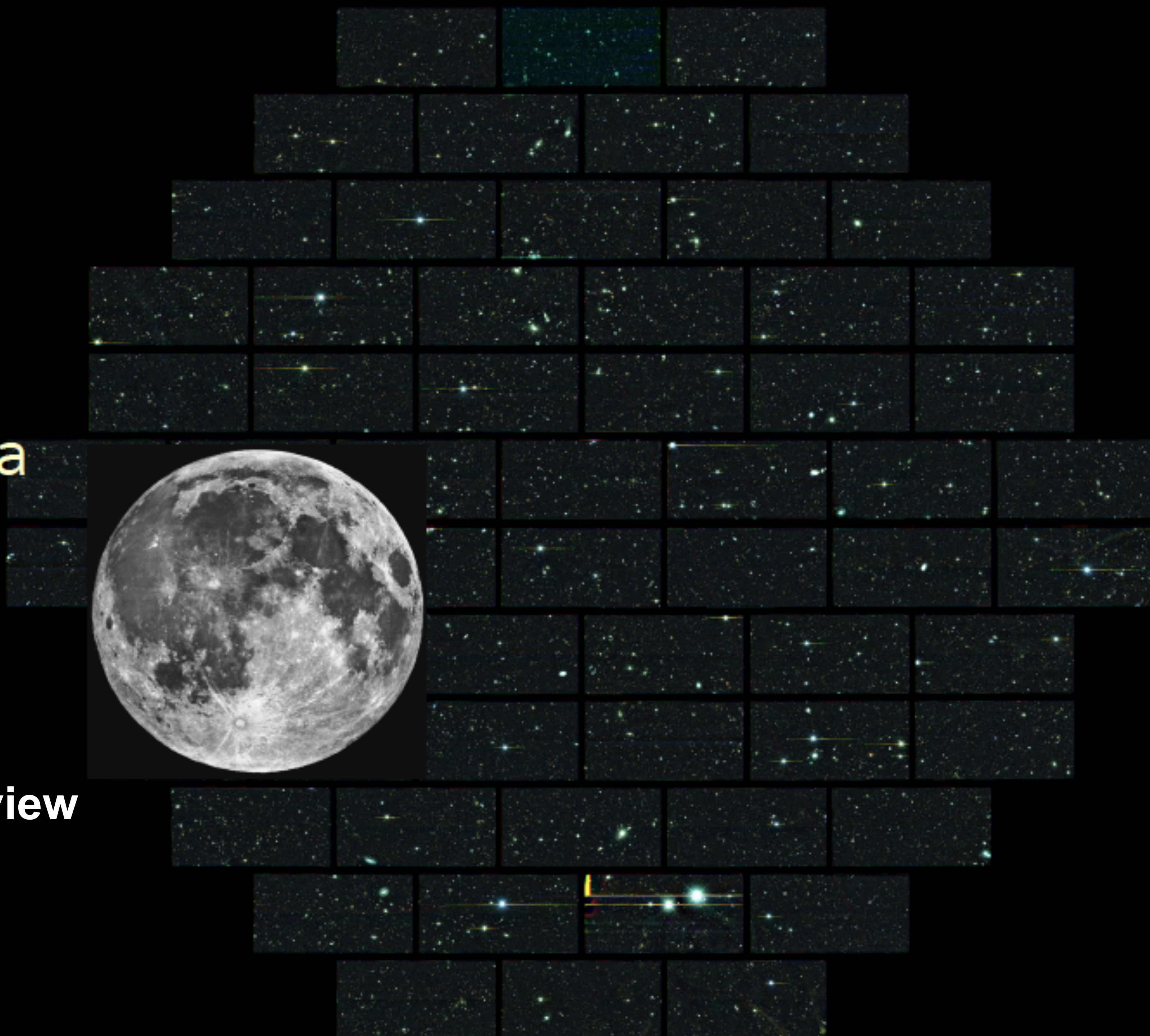
DES SV image of a deep SN field



3 deg^2 field of view

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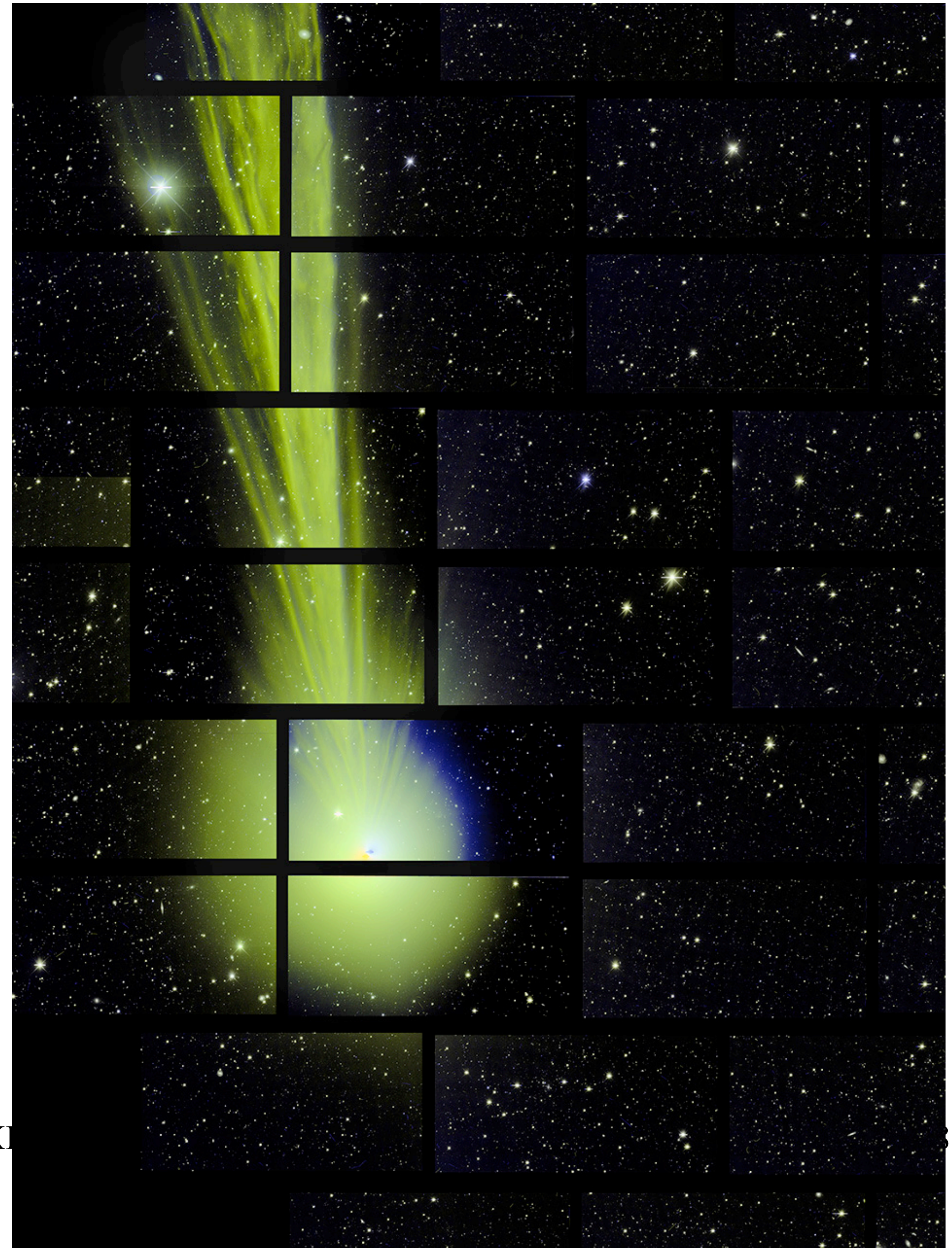
Dark Energy Camera catches breathtaking glimpse of comet Lovejoy

December 27 2014

82 million km away



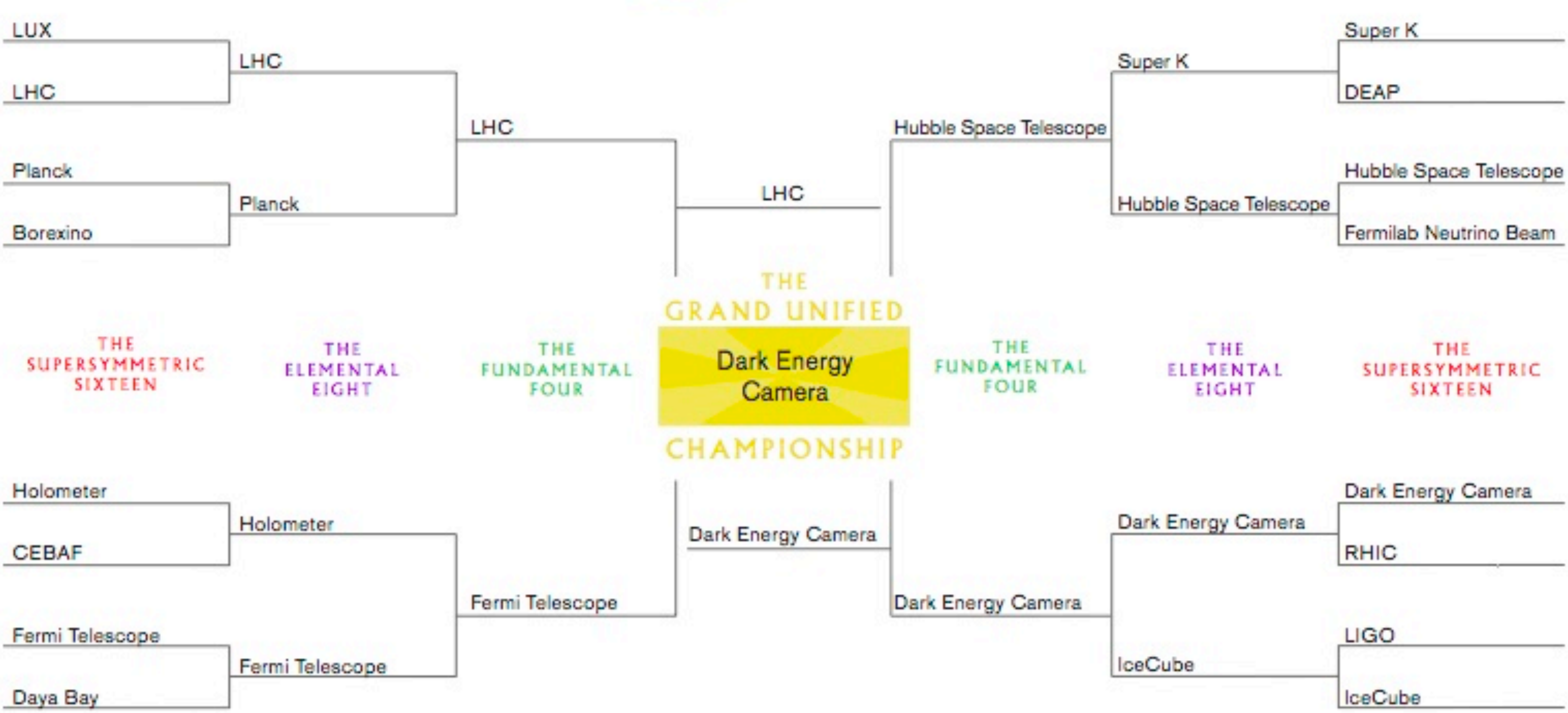
contest

April 06, 2015

Artwork by Sandbox S

Physics Madness Grand Champion

And your 2015 winning physics machine is...



symmetry

www.symmetrymagazine.org

DES Data Management

Each exposure (in a given filter) generates 500Mb

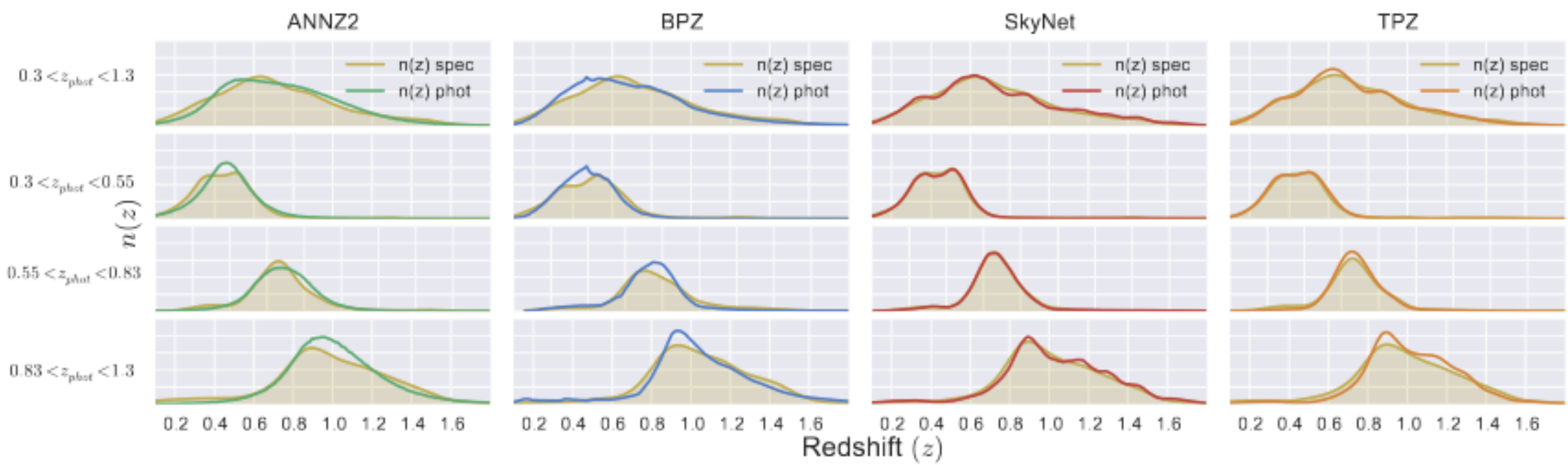
300 exposures/night – 150 Gb/night

Transferred and processed at NCSA in Urbana

Photometric redshift

Single-epoch images are calibrated, background-subtracted, coadded, and processed in \`tiles' (0.75 x 0.75 deg^2) needed to cover the entire DES footprint. A catalogue of objects was extracted from the coadded images using Source Extractor (Sextractor).

Several algorithms to estimate photo-z: machine learning and template based. Must use a probability distribution function to characterize a measurement of the photo-z.



Brazilian infrastructure contribution

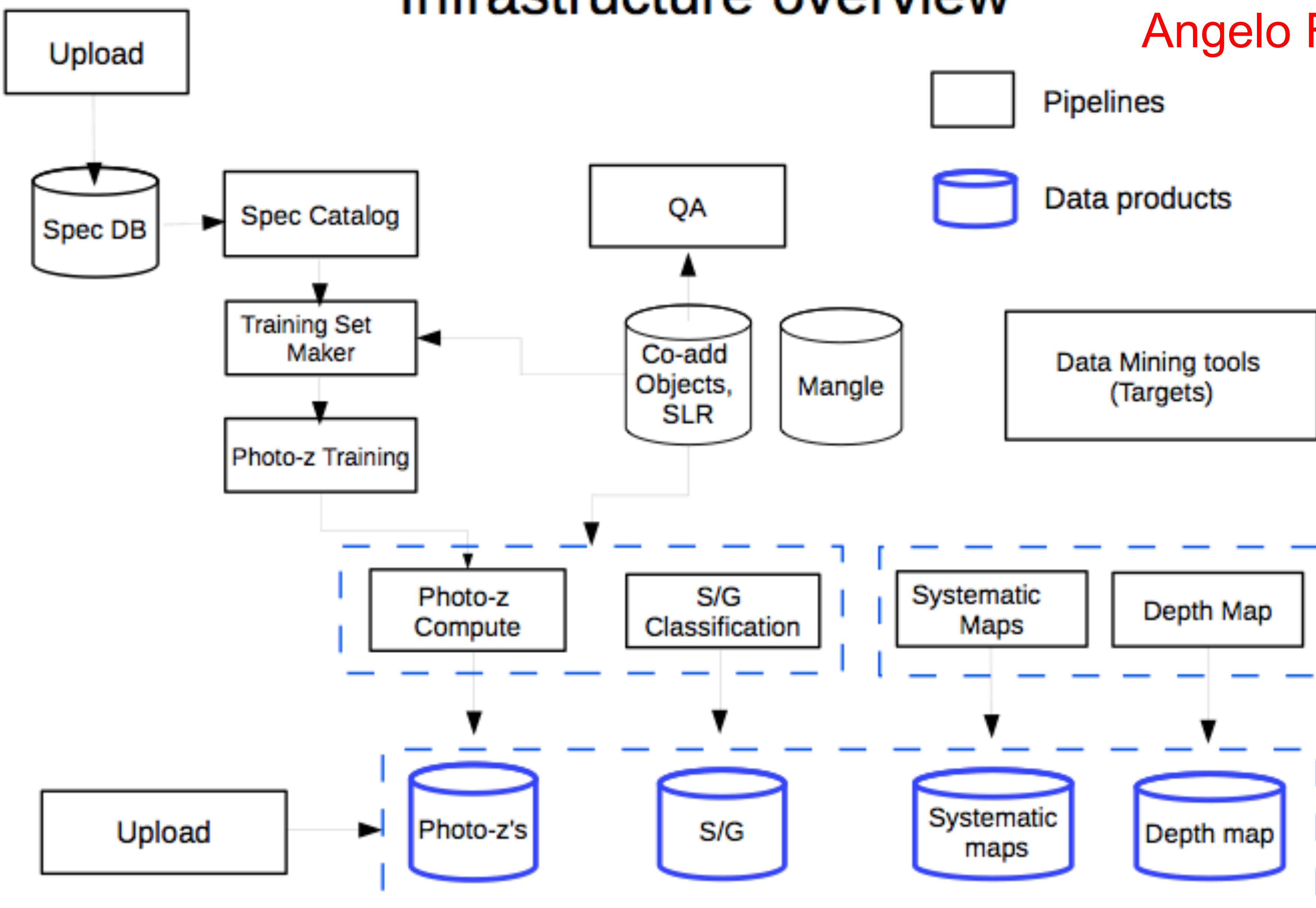
- QuickReduce: software for fast assessment of image quality at CTIO

- The Science Portal: Data Server, Value Added Catalogs and scientific pipelines

Creating a science-ready catalog is the crux: selection of objects, photo-z, systematic effects, …

Infrastructure overview

Angelo Fausti



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https://des-portal.fnal.gov/

Observations | Data Releases | Footprint | Tile Viewer | Catalog Server | User Query | Upload | Help | Rogerio Rosenfeld

Release Notes

DES Science Portal: Data Server

The DES Science Portal hosts tools for Quality Assessment (QA), Value-Added Catalogs (VACs) preparation and Science Analysis.

From the **Data Server** instance @ FNAL you have access to following tools:

- **Observations:** information about DES observations from the Night Summary and Quick Reduce
- **Data Releases:** list of the releases currently installed and associated data
- **Footprint:** spatial coverage and overlapping with external catalogs
- **Tile Viewer:** visual inspection of co-add images and catalogs
- **Catalog Server:** access to VACs produced by the portal, uploaded catalogs, reference catalogs and simulations
- **Science Products:** access to science products produced by the portal or uploaded by other authors

The system is designed to be self-evident, use the help icon "(?)" available on each page.

The Science Portal is a facility developed by LIneA. If you have any question please contact us through the helpdesk@linea.gov.br

Tweets Follow

DES Science Portal @des_portal 14 Jul
A new Upload process was published by Elizabeth Buckley-Geer. des-portal.fnal.gov/VP/getViewProc...

DES Science Portal @des_portal 14 Jul
A new Upload process was published by Elizabeth Buckley-Geer. des-portal.fnal.gov/VP/getViewProc...

DES Science Portal @des_portal 14 Jul
The status of 5.0 (IM3Shape) has been updated to "Do not use".

DES Science Portal @des_portal 8 Jul

Tweet to @des_portal

Science Portal v0.7-2 (Jun 24 2015) Powered by LIneA

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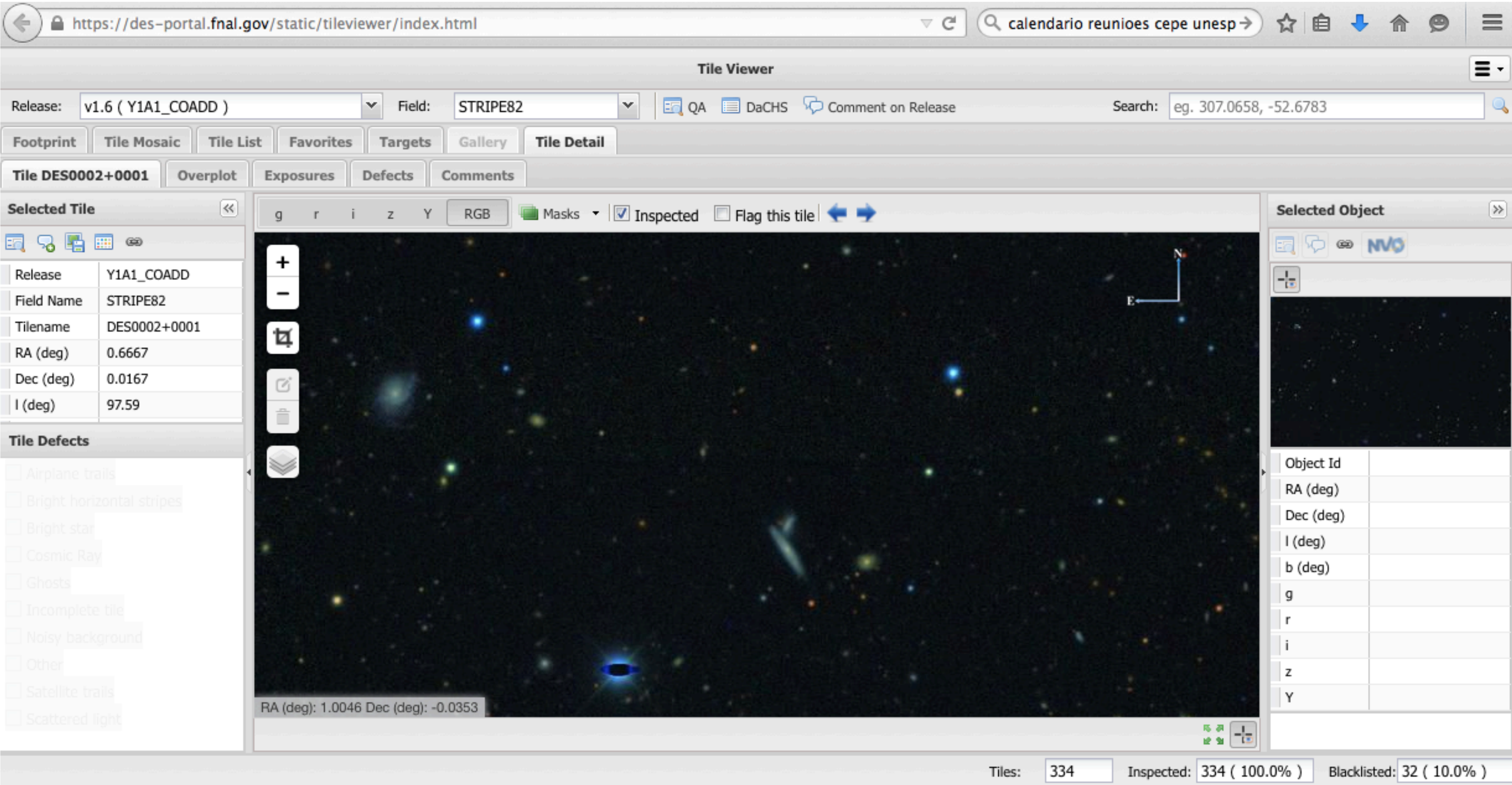
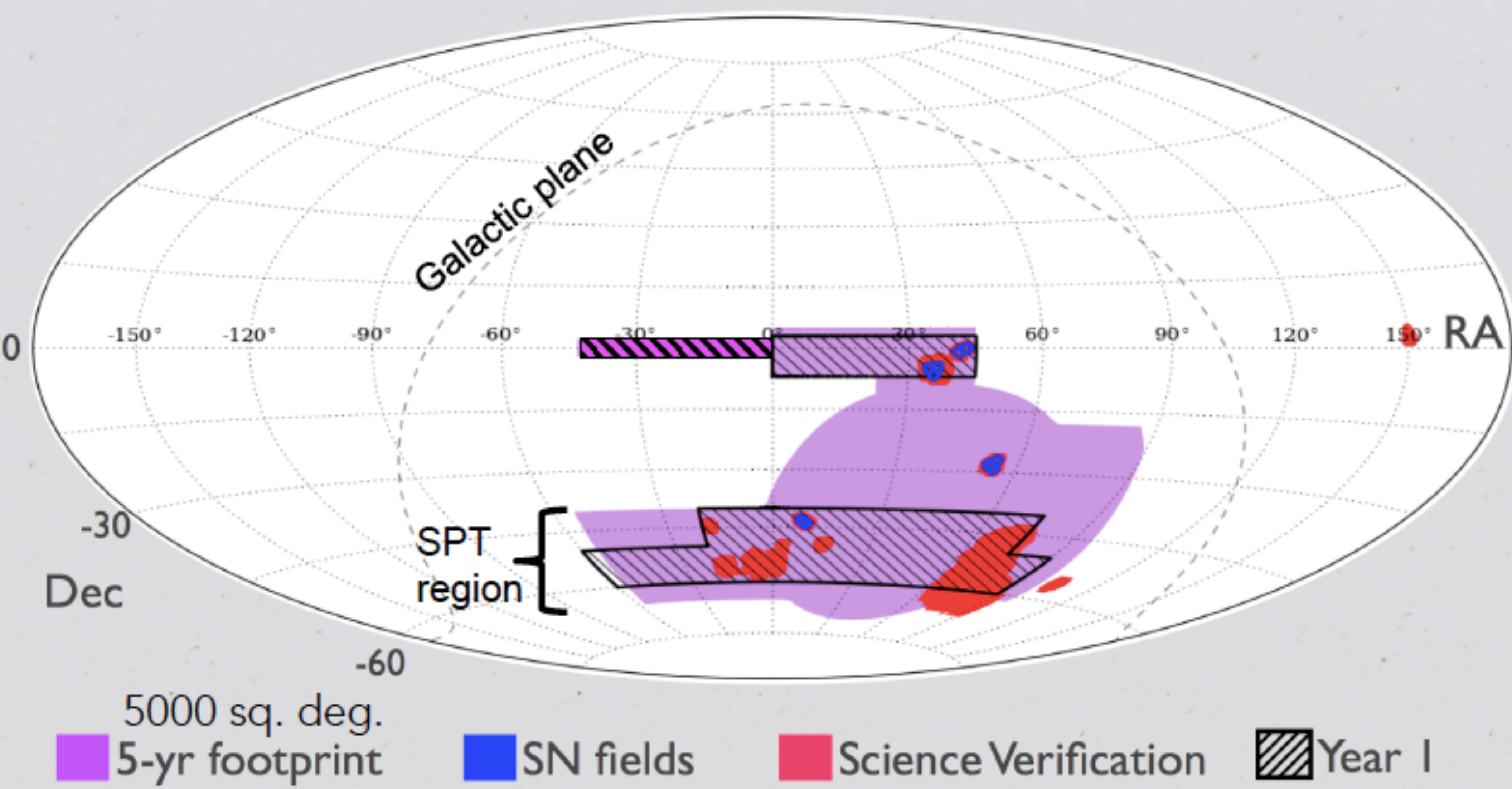
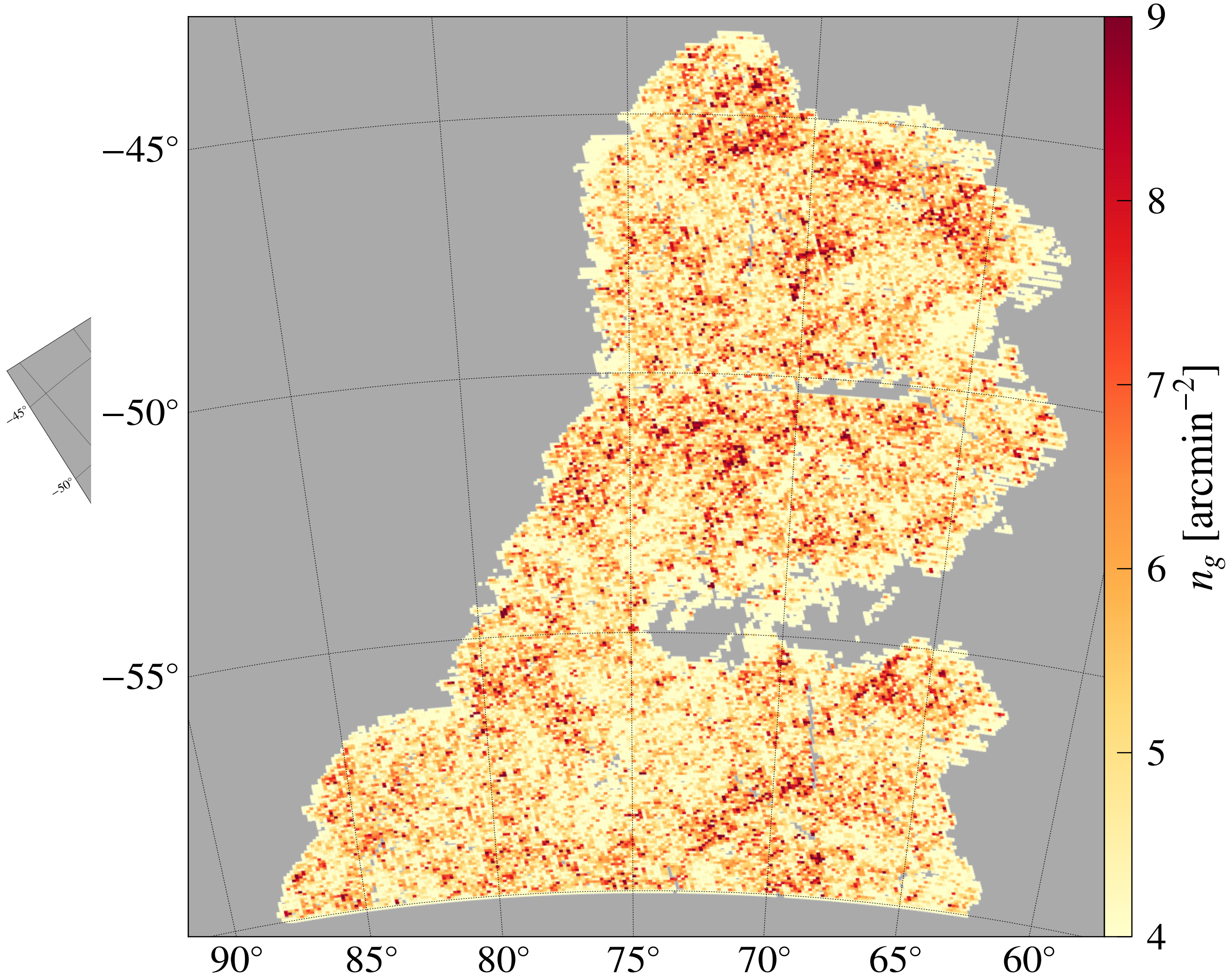


DES Survey Footprint

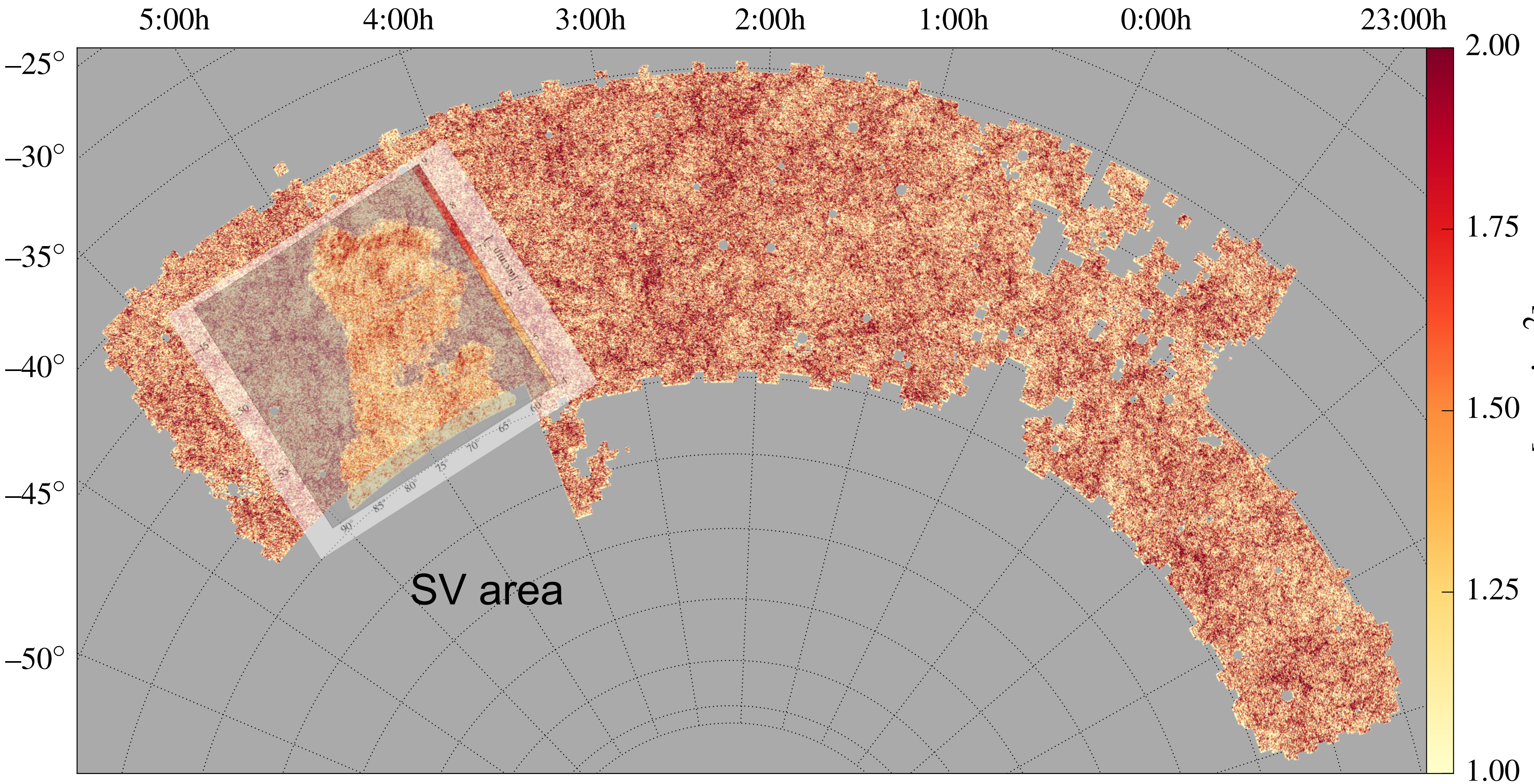


- Science Verification (SV): ~250 sq. deg. to ~full depth; 45 M objects
- Year 1 (Y1): ~2000 sq. deg; overlap SPT, SDSS: 4/10 tilings; 140 M objects

DES SV Galaxy Distribution



DES Year 1 Galaxy Distribution

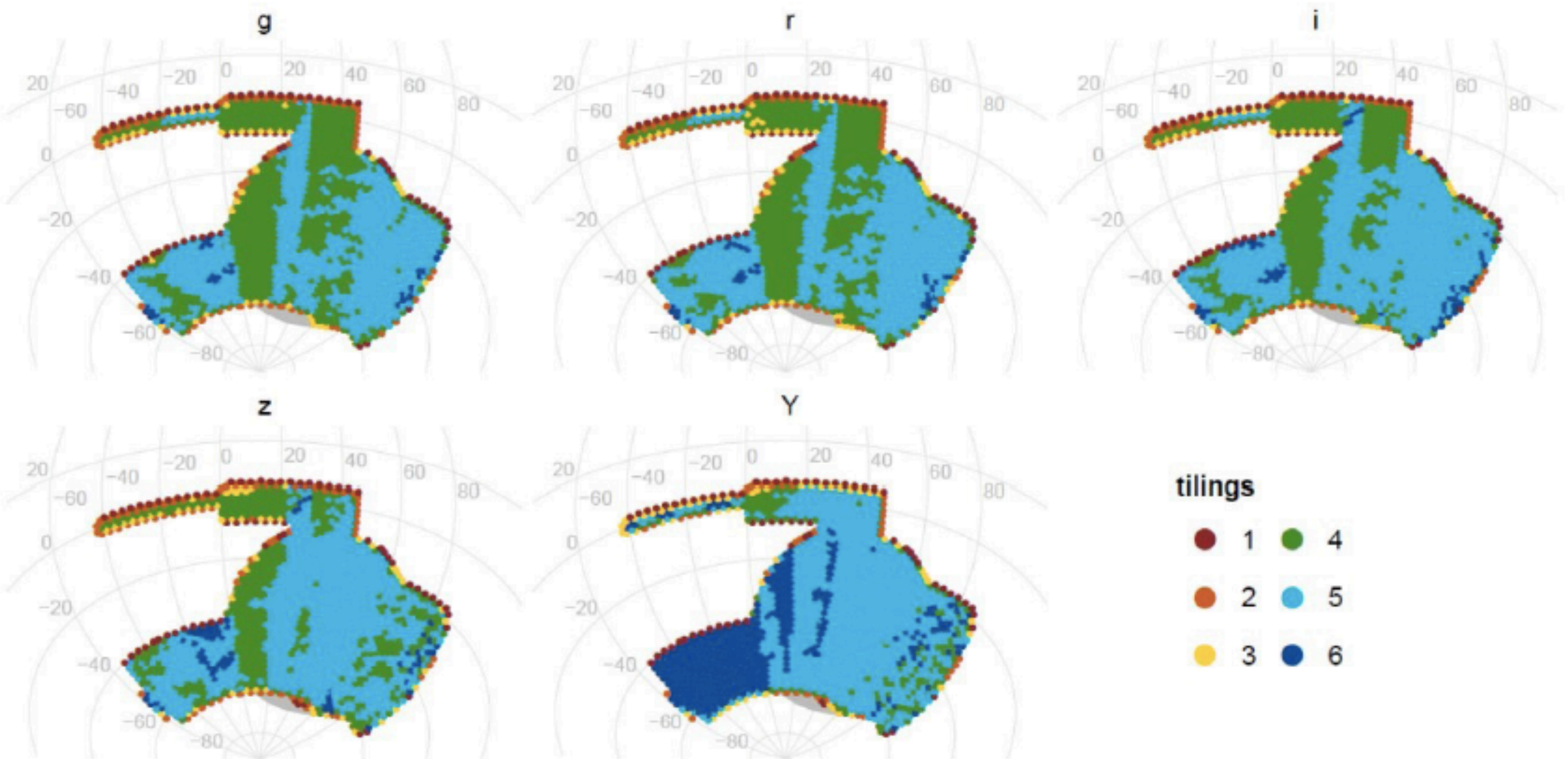


Credit: P. Melchior

DES Y3 ended on february 2016

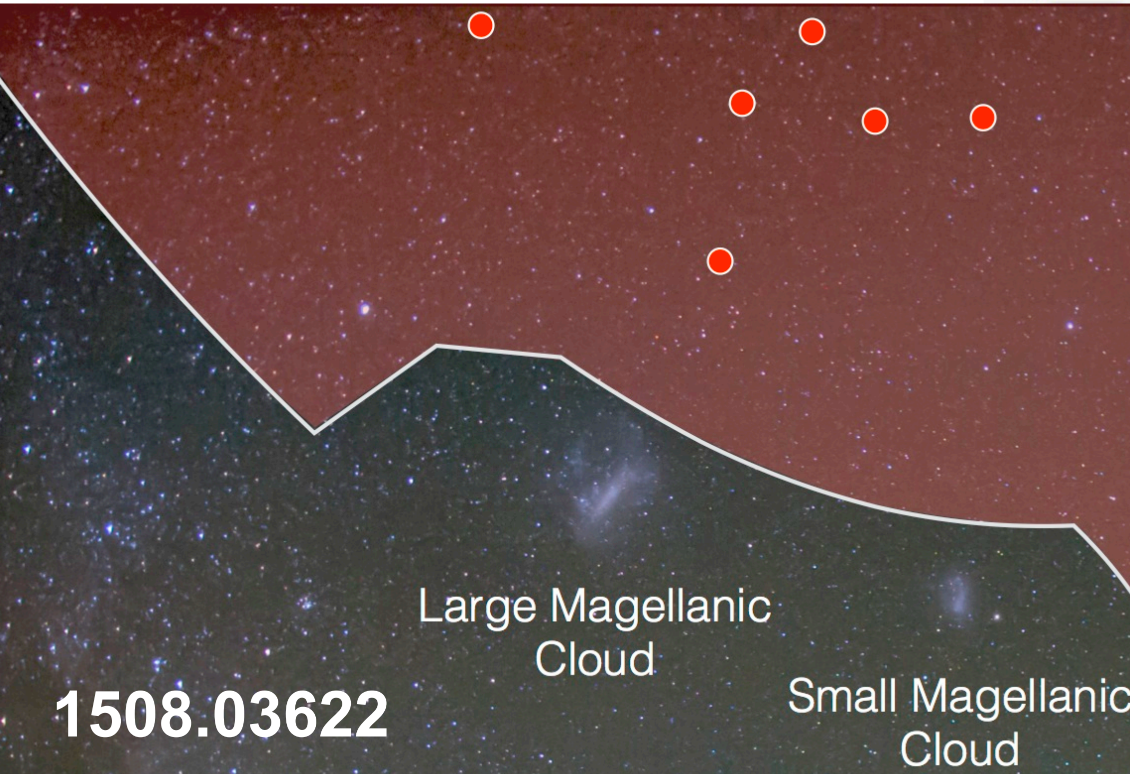
DES is proyected for 5 years , up to 2018

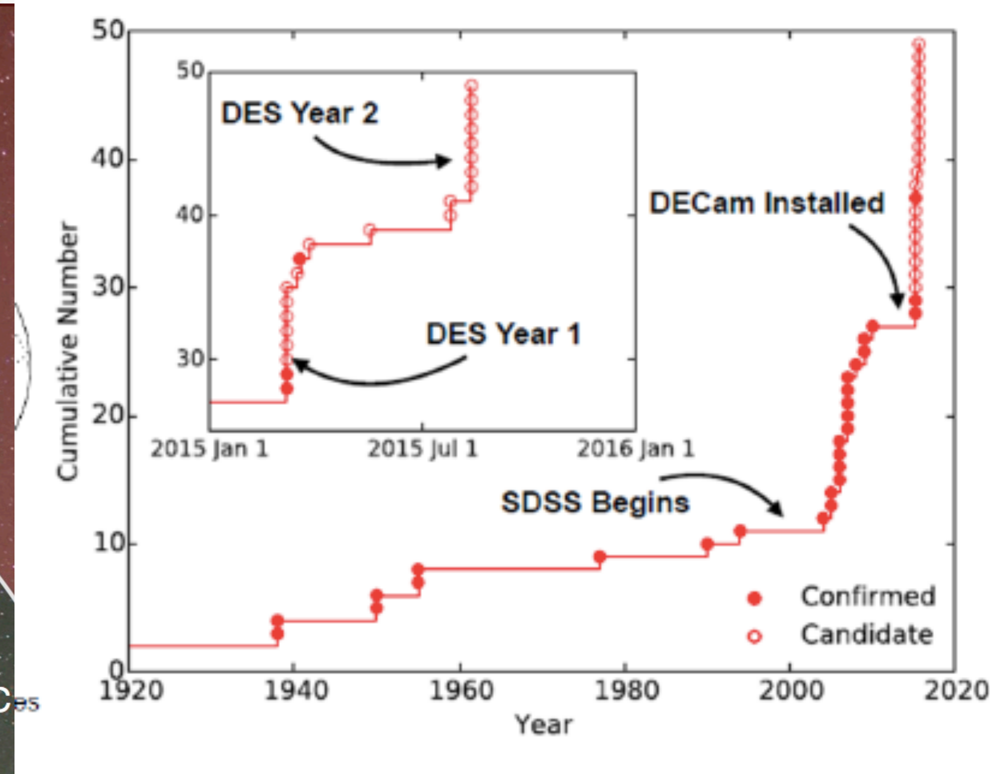
5000 sq-deg already covered, to ~50% of the final projected depth



64 papers: 26 published and 38 submitted (as of May, mostly from SV data)

- Produced the largest contiguous mass map of the Universe;
- Discovered nearly a score of Milky Way dwarf satellites and other Milky Way structures;
- Measured weak lensing cosmic shear, galaxy clustering, and cross-correlations with CMB lensing and with X-ray and SZ-detected clusters;
- Continued to measure light curves for large numbers of type Ia supernovae and discovered a number of super-luminous supernovae including the highest-redshift SLSN so far;
- Discovered a number of redshift z>6 QSOs;
- Discovered a number of strongly lensed galaxies and QSOs;
- Discovered a number of interesting objects in the outer Solar System;
- Searched for optical counterparts of GW events.





1508.03622

17 new dwarf galaxies discovered by DES!

27 known before DES.

Contribution from B. Santiago's team

Joint paper with Fermi-LAT

1503.02632

WIMPs with mass<100 GeV are excluded (thermally produced, model dependent)

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Some highlights: measuring bias

Baryons are only ~ 15% of the total matter in the Universe!

Galaxies are a biased tracer of the total matter distribution.
DES measures the distribution properties of galaxies.

$$\underbrace{\delta_g(\vec{x})}_{\text{galaxy overdensity}} = \underbrace{b(z)}_{\text{bias}}\,\underbrace{\delta(\vec{x})}_{\text{matter overdensity (cosmological model)}}$$

Galaxy clustering, photometric redshifts and diagnosis of systematics in the DES SV data - 1507.0

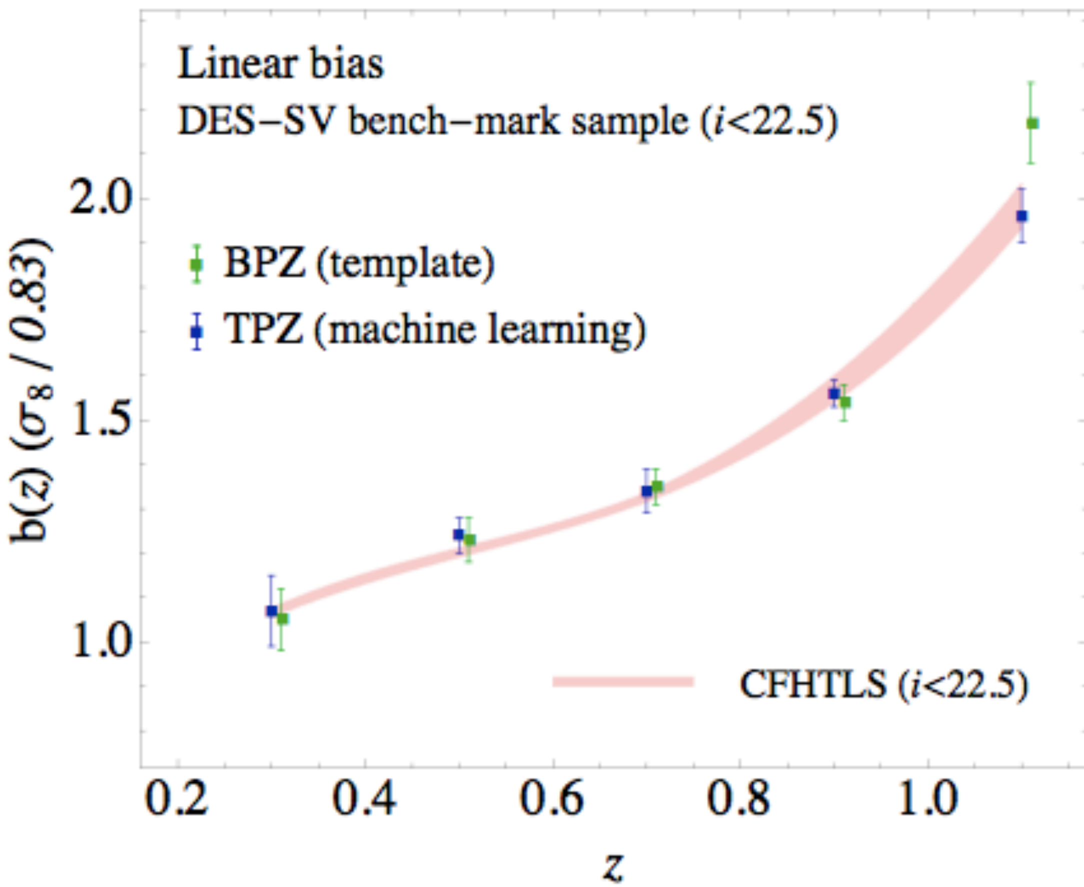


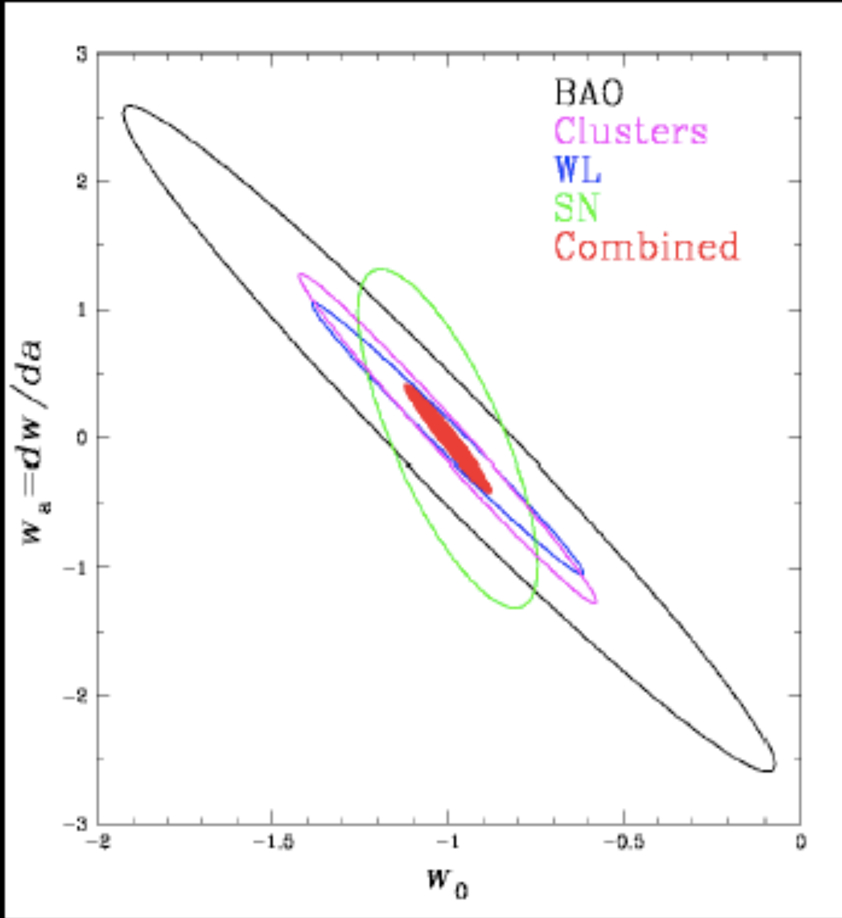
Figure 11. Comparison of the large-scale bias measured in a DES-SV flux limited sample ($i < 22.5$) to equivalent measurements from CFHTLS derived from Coupon et al. (2012). We present DES results for two different photometric redshift catalogs, one obtained using a template method (BPZ), another with a machine learning approach (TPZ). The overall agreement between the two DES samples as a function of redshift is better that 2 per cent for $z < 1$. At $z > 1$ is difference is not statistically significant ($\sim 2\sigma$). This represents a non-trivial test for DES-SV photometric redshift estimation. Our results are also in good agreement with those from CFHTLS, with $\chi^2/d.o.f = 4/5$ for TPZ and $8.7/5$ for BPZ, representing a cross-validation of data quality and sample selection.

DES Science Summary

DARK ENERGY SURVEY

Forecast Constraints on DE Equation of State

$$w(a) = w_0 + w_a(1 - a(t)/a_0)$$



DES forecast

Four Probes of Dark Energy

- Galaxy Clusters
  - Tens of thousands of clusters to z~1
  - Synergy with SPT, VHS
- Weak Lensing
  - Shape and magnification measurements of 200 million galaxies
- Baryon Acoustic Oscillations
  - 300 million galaxies to z = 1 and beyond
- Supernovae
  - 30 sq deg time-domain survey
  - 3500 well-sampled SNe Ia to z ~1

Large Scale Structure

Distribution of galaxies in the universe provide:

- information about growth of perturbations (DE/MG)
- information about dark matter (hot DM is ruled out)
- standard ruler (baryon acoustic oscillation scale)

Large Scale Structure

- The final outcome of DES will be a very large file
- Objects and their characteristics (coordinates, redshift, redshift errors, classification, etc).
- That'll be our basis to extract the cosmology

• From the large file estimate a density field that can describe the galaxy distribution in the survey:

$$\rho(\vec{x})$$

• Fluctuations can be described by a density contrast:

$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

• Fluctuations are a random gaussian field: characterized by its moments – 1pt (average), 2pt (variance), 3pt, ...

$$\langle \delta(\vec{x}) \rangle = 0$$

$$\langle \delta(\vec{x}_1)\delta(\vec{x}_2) \rangle = \xi(\vec{x}_1 - \vec{x}_2) = \xi(|\vec{x}_1 - \vec{x}_2|) = \overbrace{\xi(r)}^{\text{Two-point spatial correlation function}}$$

Homogeneity and isotropy

...

- Interpretation of 2 pt. correlation function: excess (or deficit) of clustering over random at a given scale r

$$dP_{1,2} = (1 + \xi(r))dV_1 dV_2$$

random

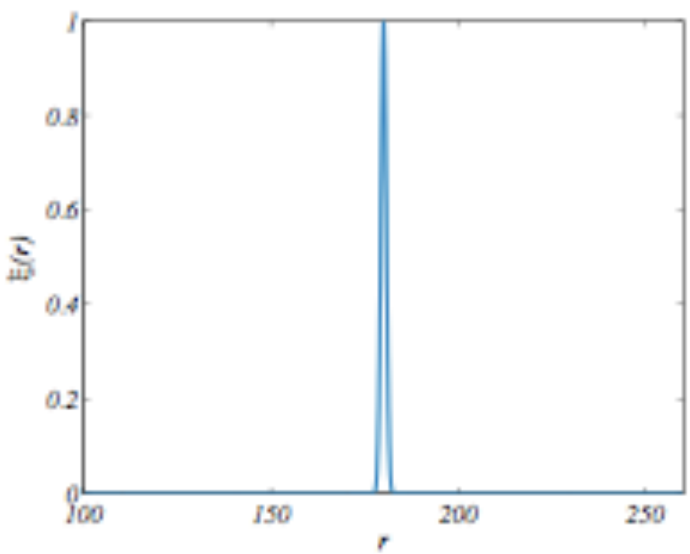
- One can also define a power spectrum:

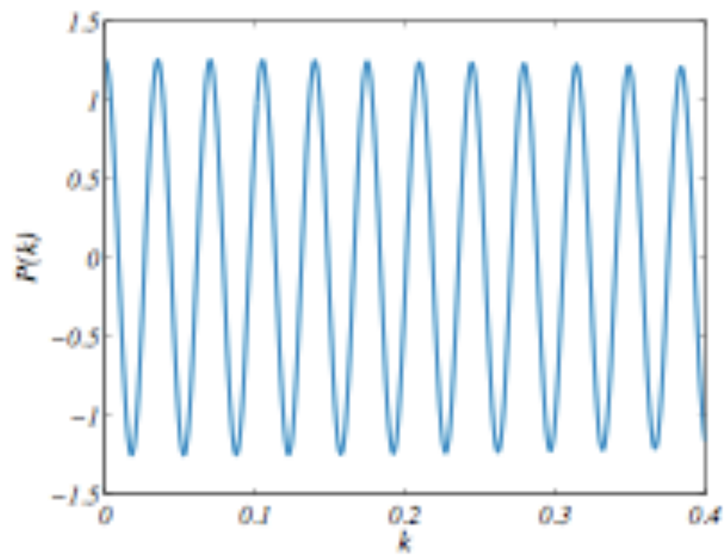
$$P(k) = \int d^3 r \xi(r) e^{i\vec{k}.\vec{r}}$$

• It's possible to work with either spatial correlation function or power spectrum – adv. and disadv.

• Sharp peak in correlation results in oscillations in the power spectrum

$$\xi(r) \approx \delta(r - r_*) \qquad P(k) \approx e^{ikr_*}$$





• In DES we will analyze the angular correlation function/ angular power spectrum because of large redshift uncertainties.

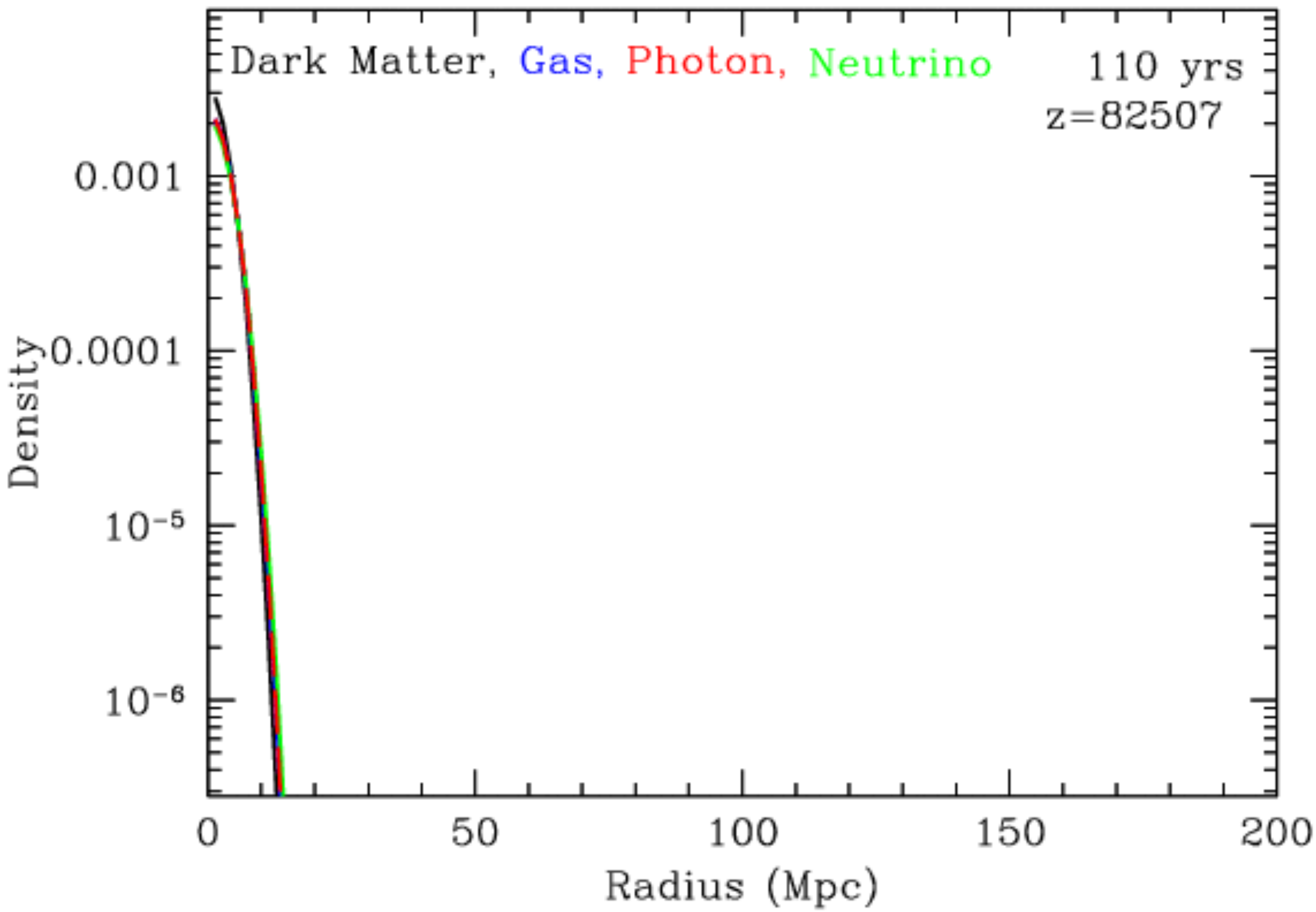
Baryon Acoustic Oscillations

• Should a preferred scale emerge in galaxy distribution? Yes – the sound horizon at decoupling.

• Before recombination, baryons and photons were strongly coupled, forming a single fluid with pressure and speed. Dark matter, neutrinos and other forms were decoupled.

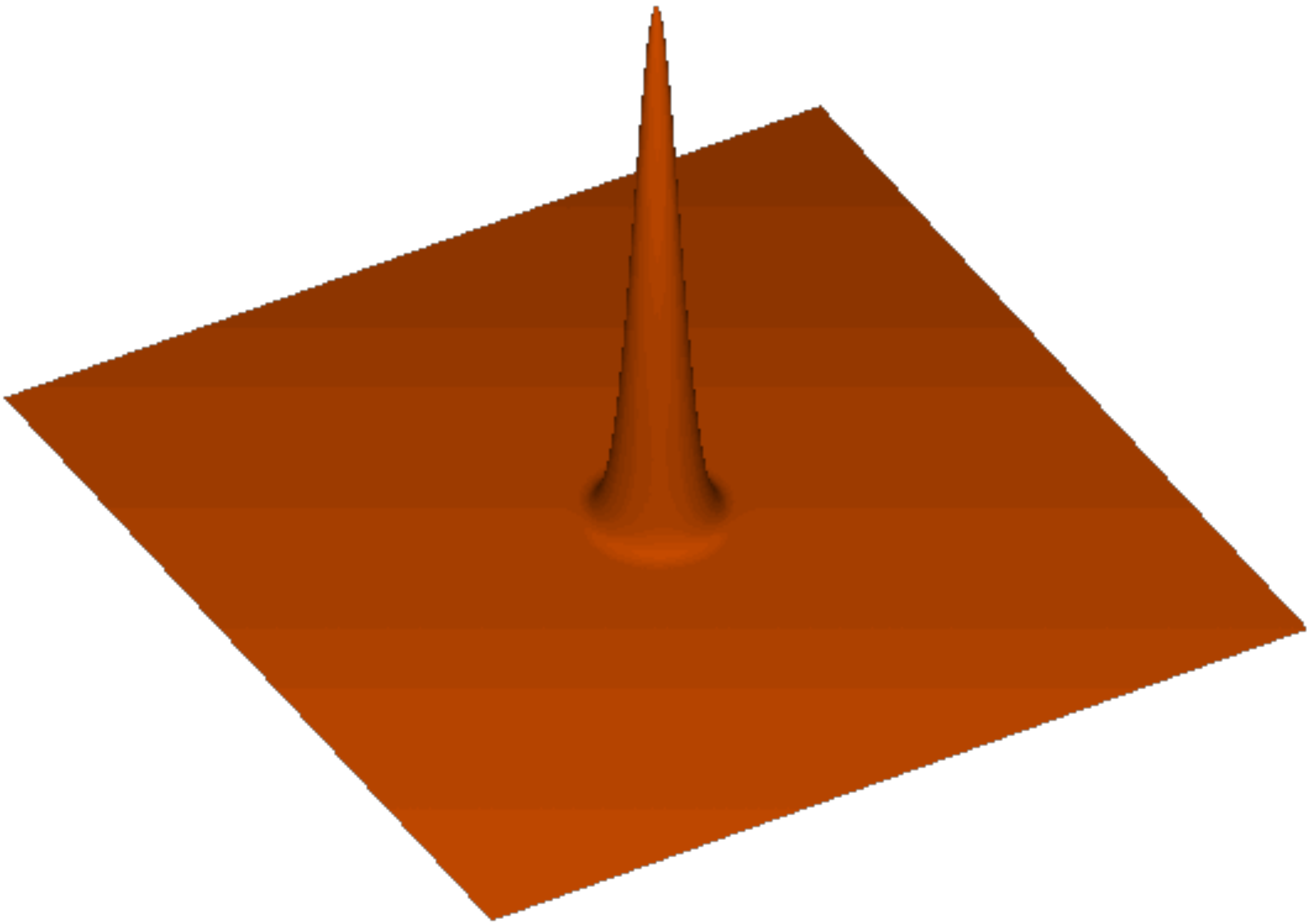
Evolution of one spherical perturbation

Eisenstein



Evolution of one spherical perturbation

Eisenstein



BAO scale

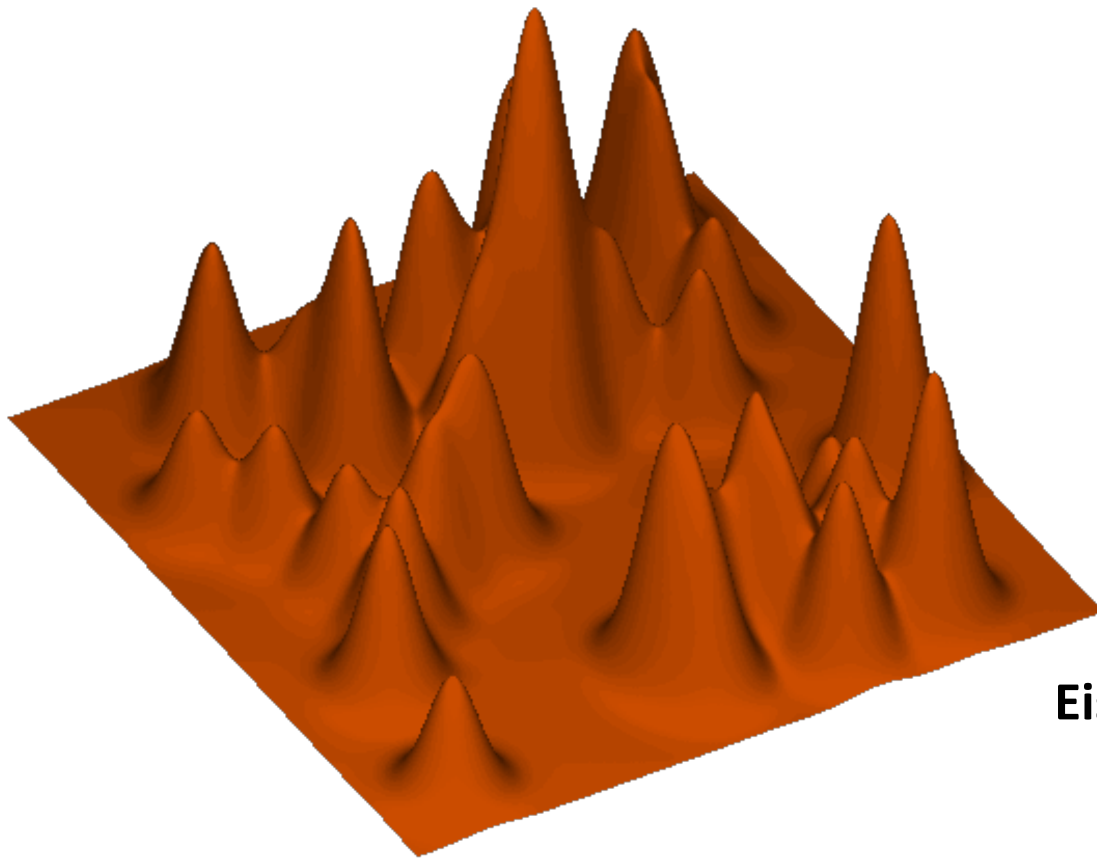
Standard ruler in the sky

$$r_{BAO} = \int_{z_{rec}}^{\infty} \frac{c_s(z)dz}{H(z)} \approx 150 \text{ Mpc}$$

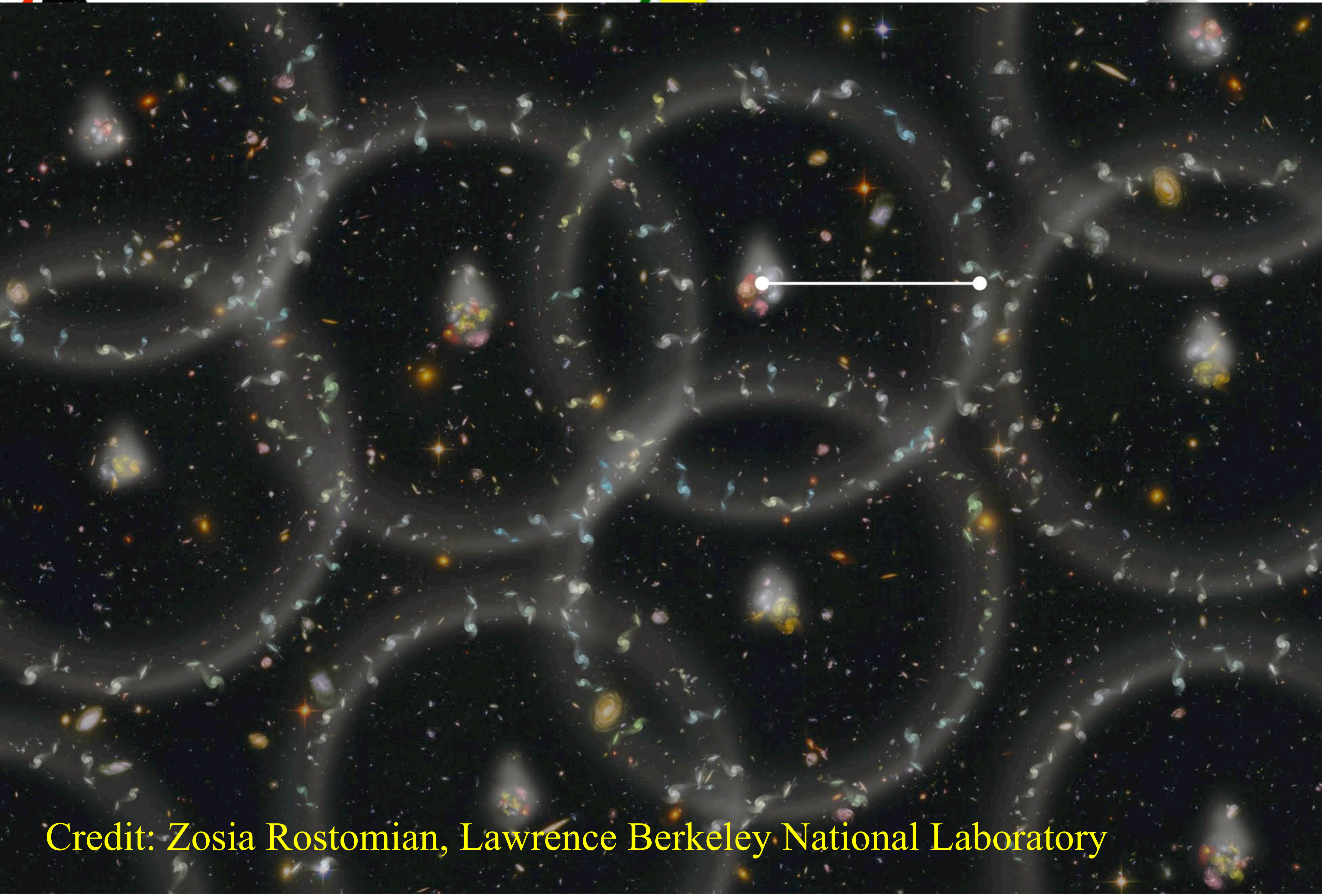
Cosmological parameters

$$c_s^2 = \frac{\partial(p_\gamma + p_b)}{\partial(\rho_\gamma + \rho_b)} \sim \frac{1}{3}$$

Things are more complicated: superposition of shells with different locations and different amplitudes

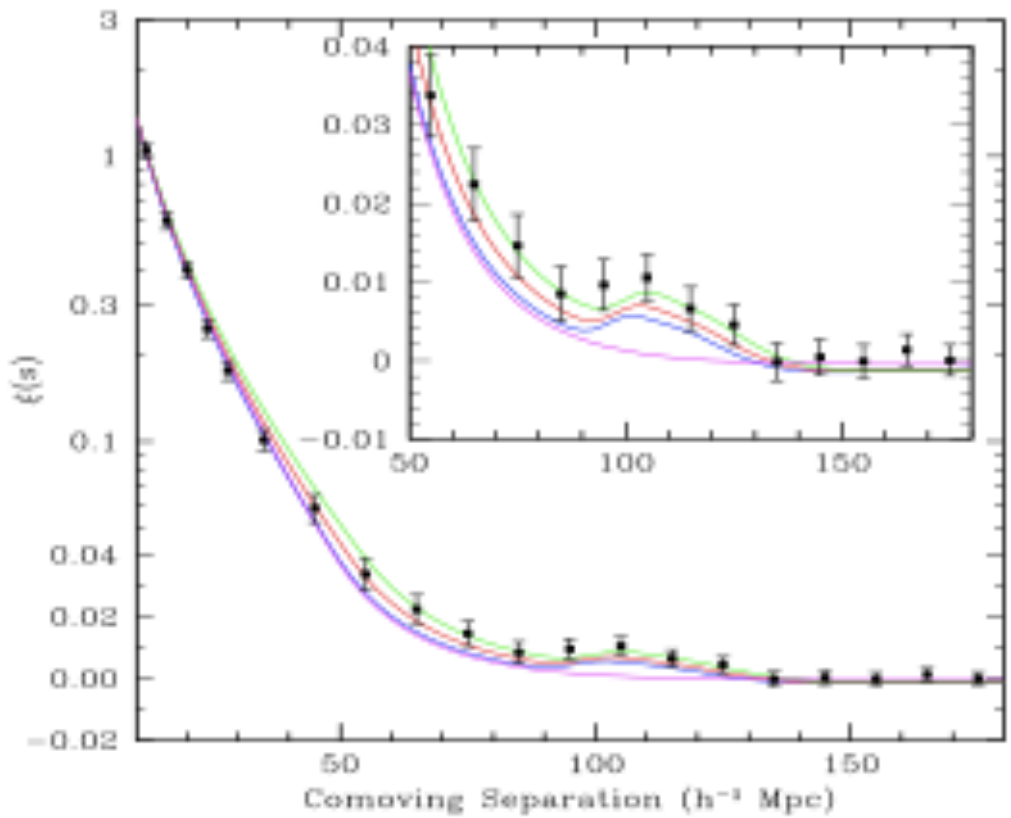


Eisenstein

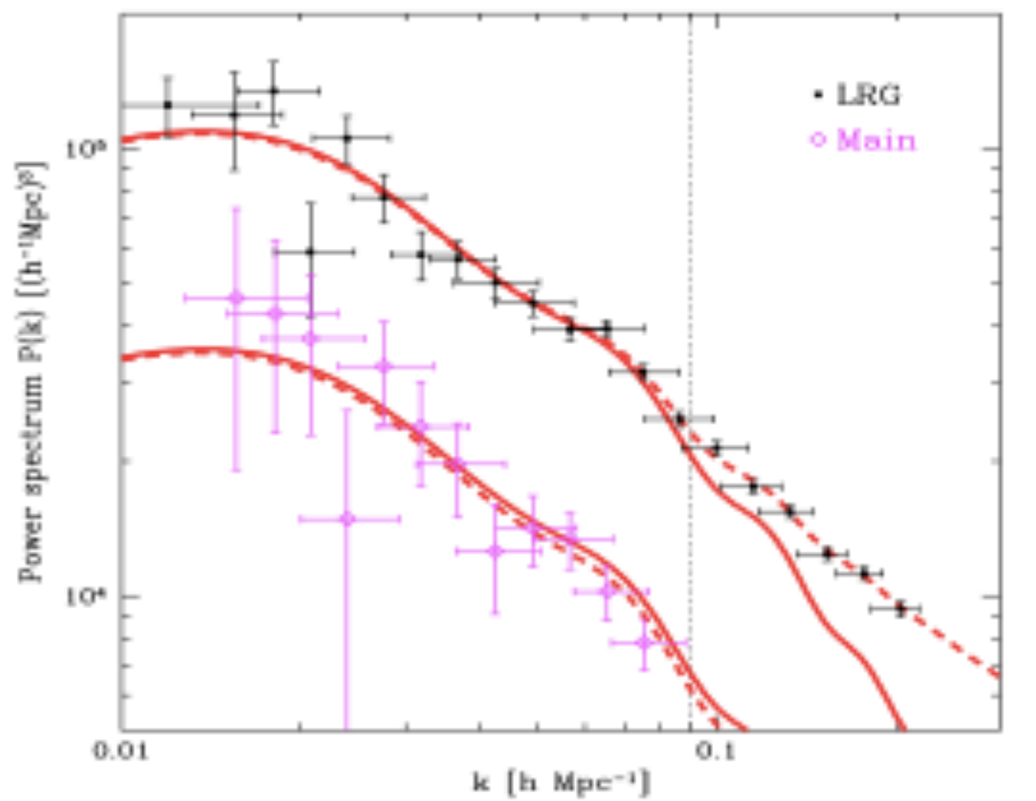


Credit: Zosia Rostomian, Lawrence Berkeley National Laboratory

First detection of BAO features with SDSS data small effect (<few %), difficult measurements **(bump hunting)**



Eisenstein et al (2005)



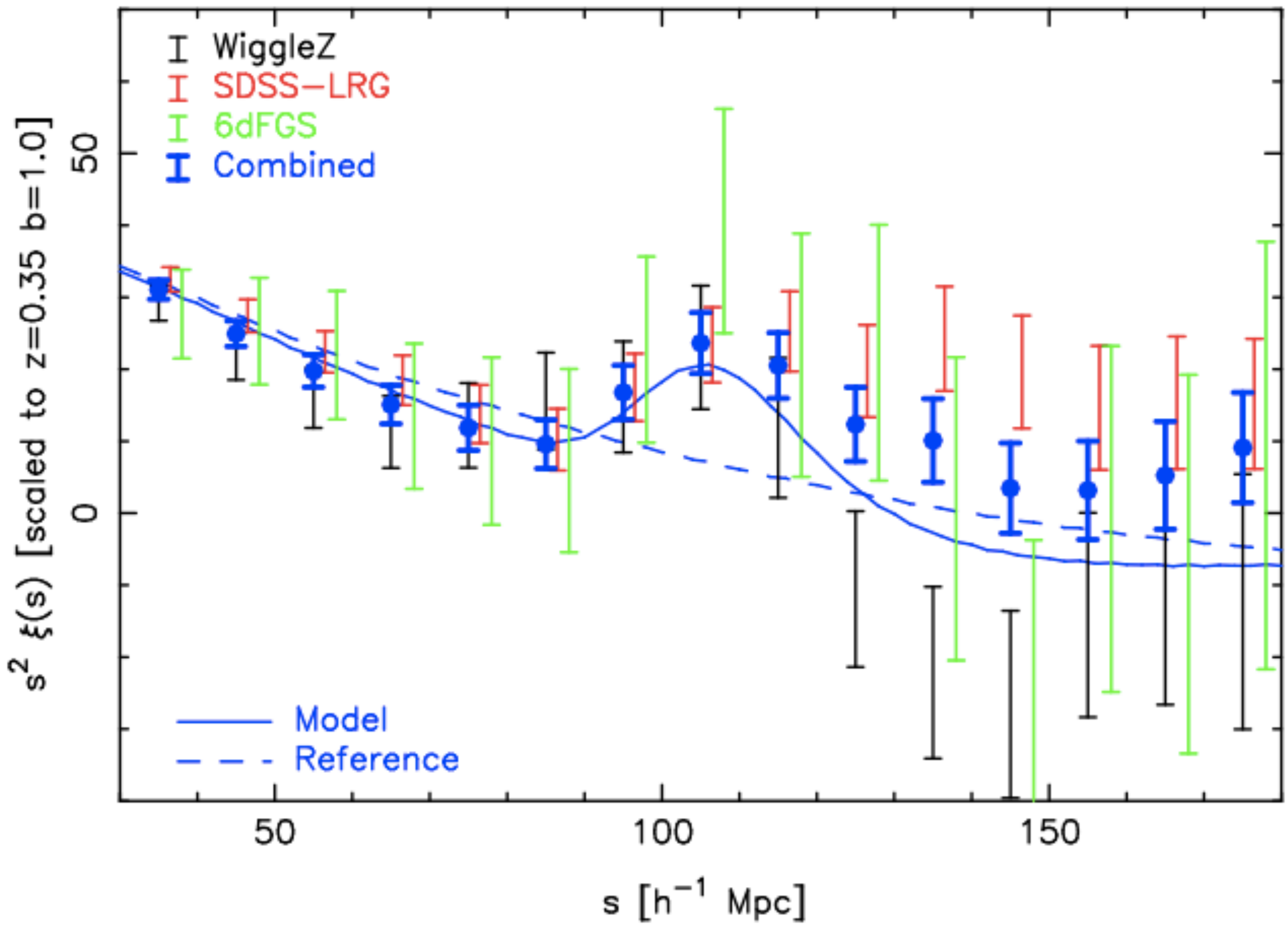
Tegmark et al (2006)

DR3, z ~ 0.35

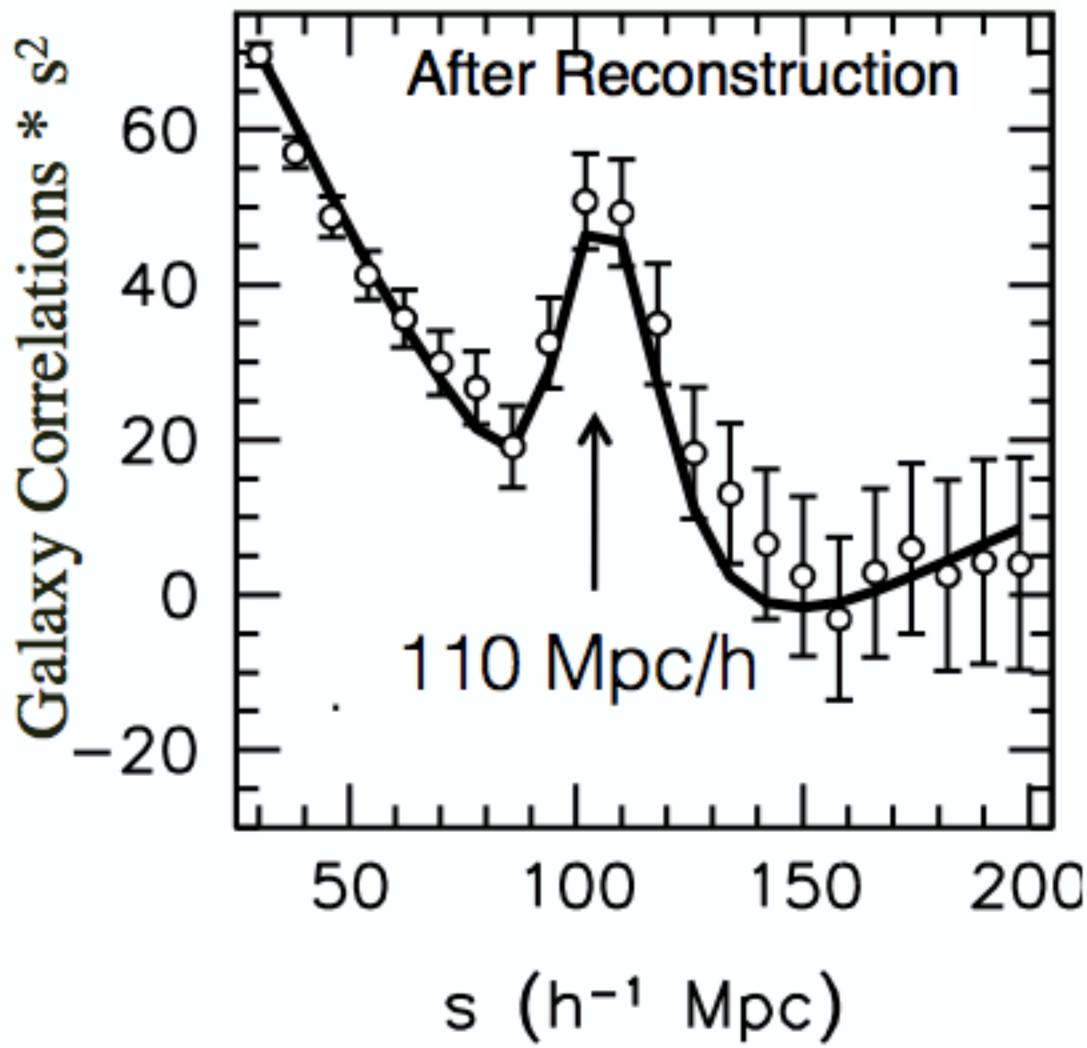
Results from WiggleZ(1108.2635):

(N = 158,741 galaxies in the redshift range 0.2 < z < 1.0)

4.9σ significance

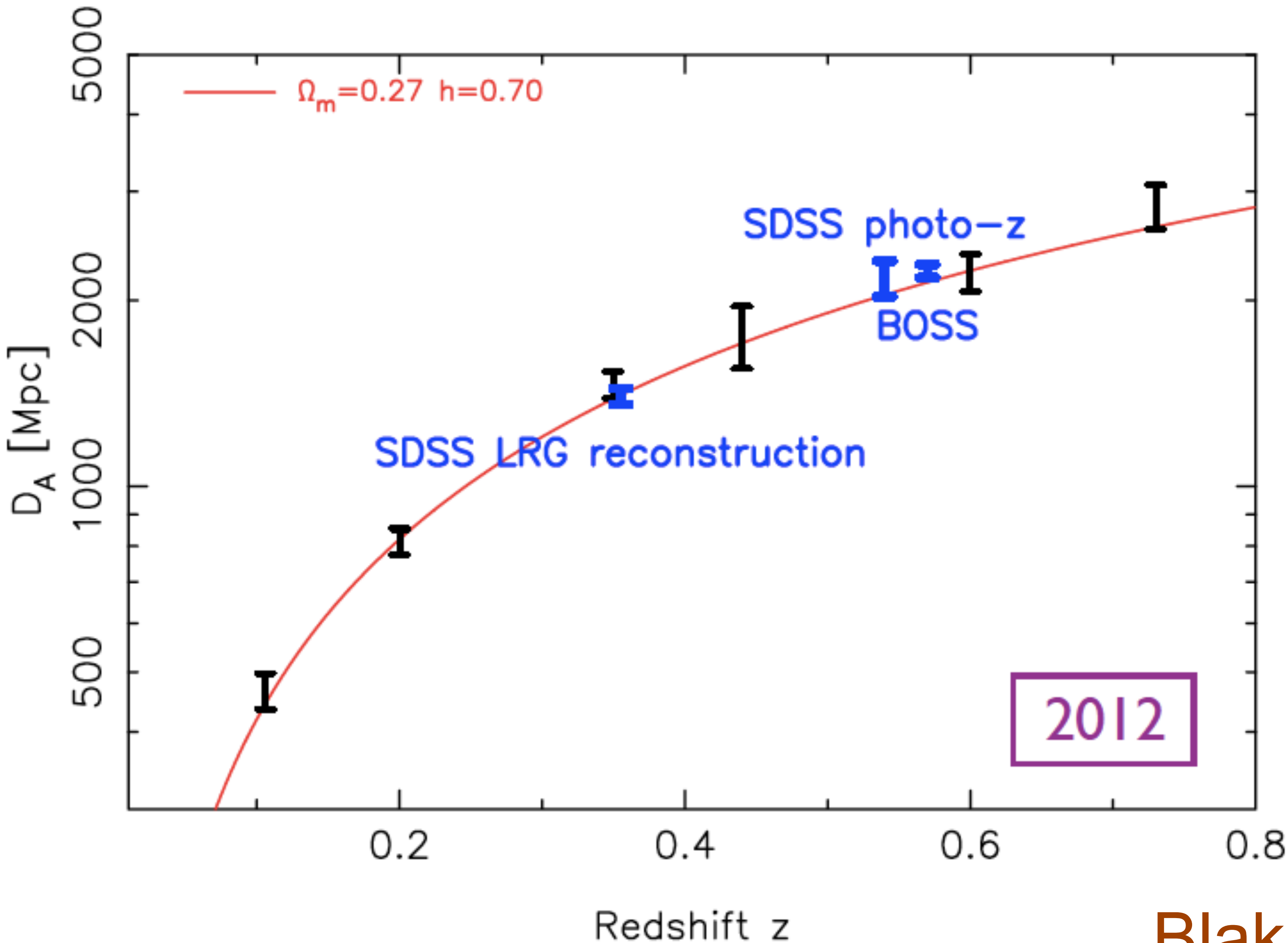


Galaxy 2-point correlation function



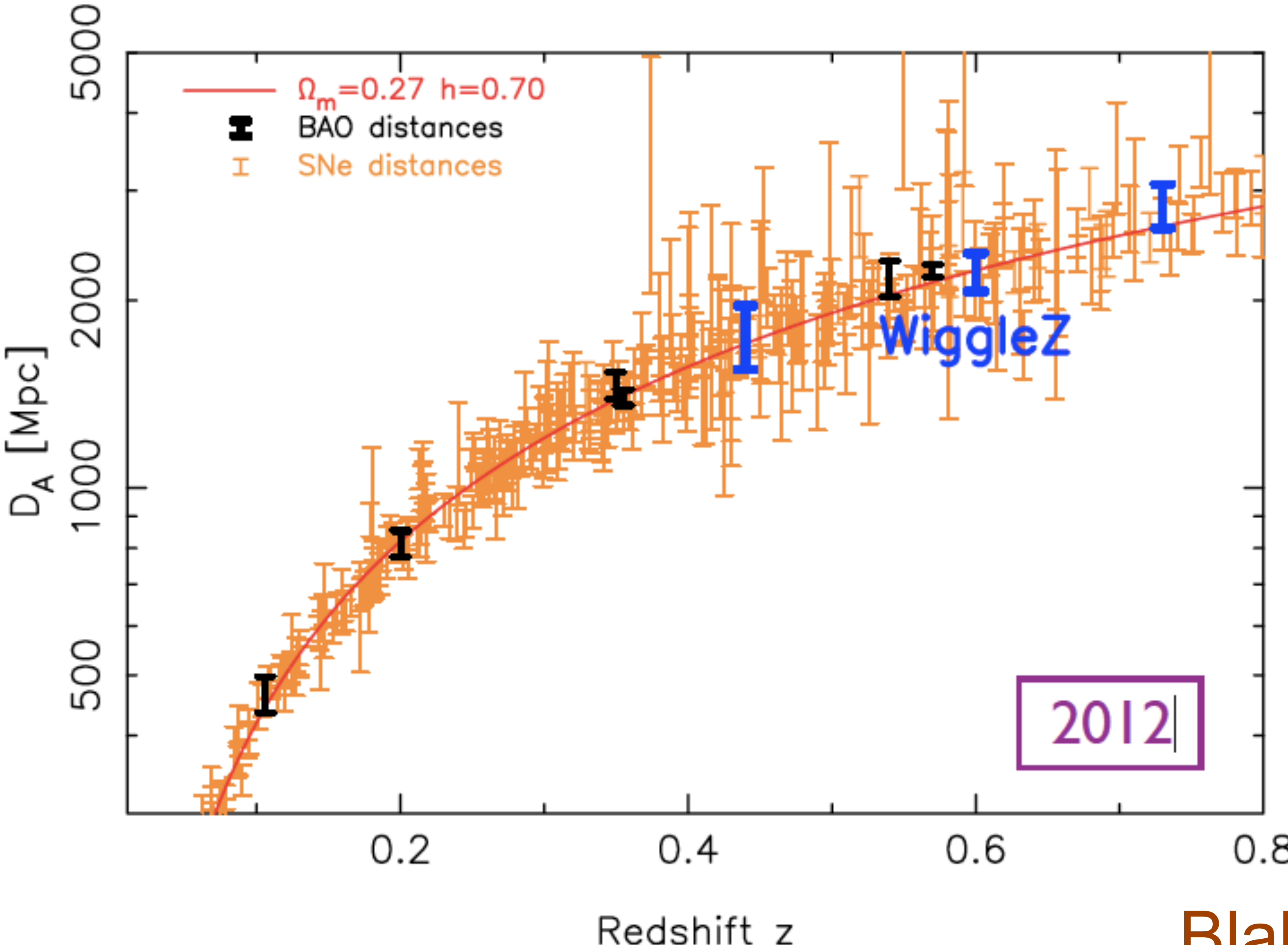
Anderson et al. 2014
Vargas, **Ho** et al. 2015

BAO Hubble diagram



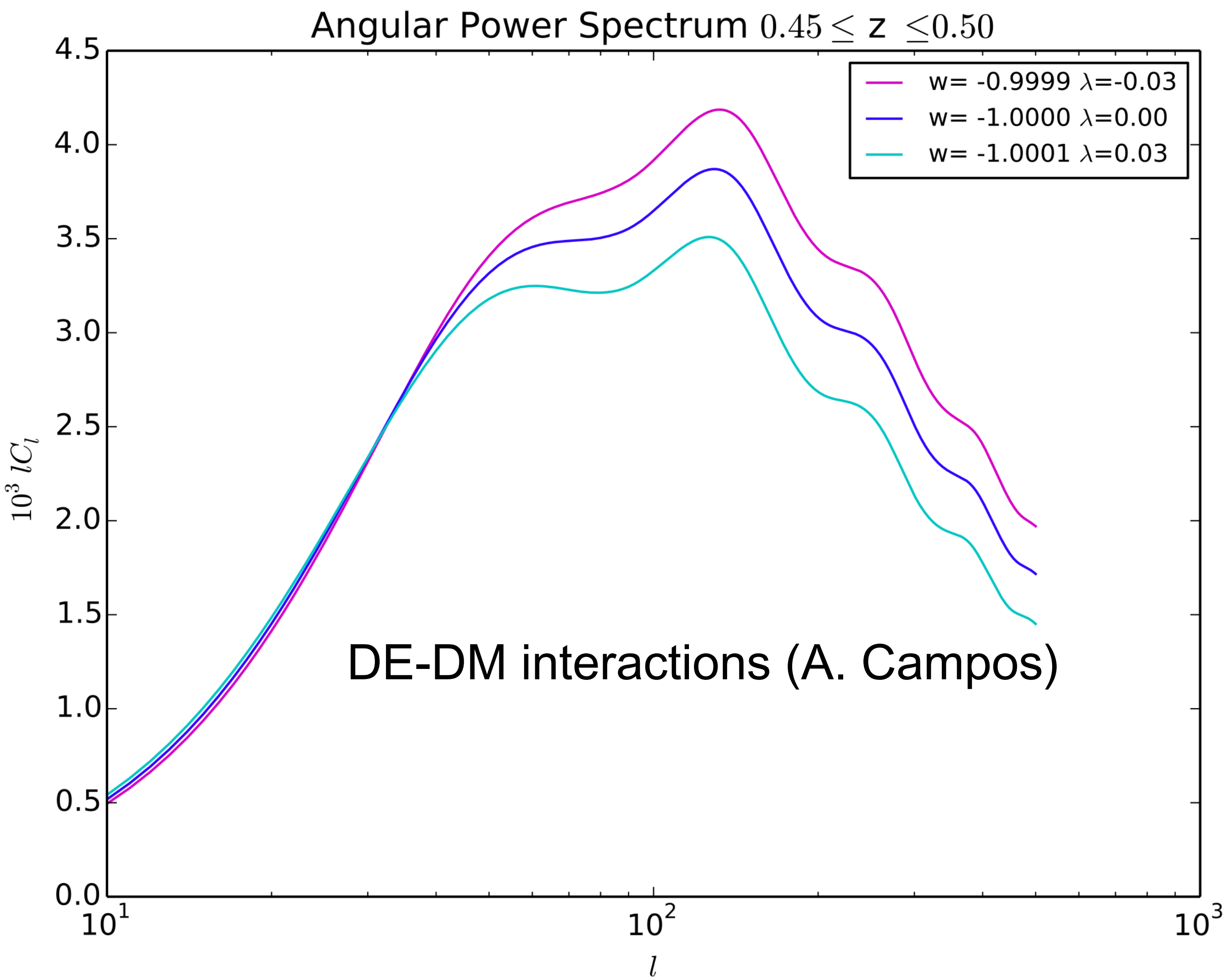
Blake

BAO Hubble diagram

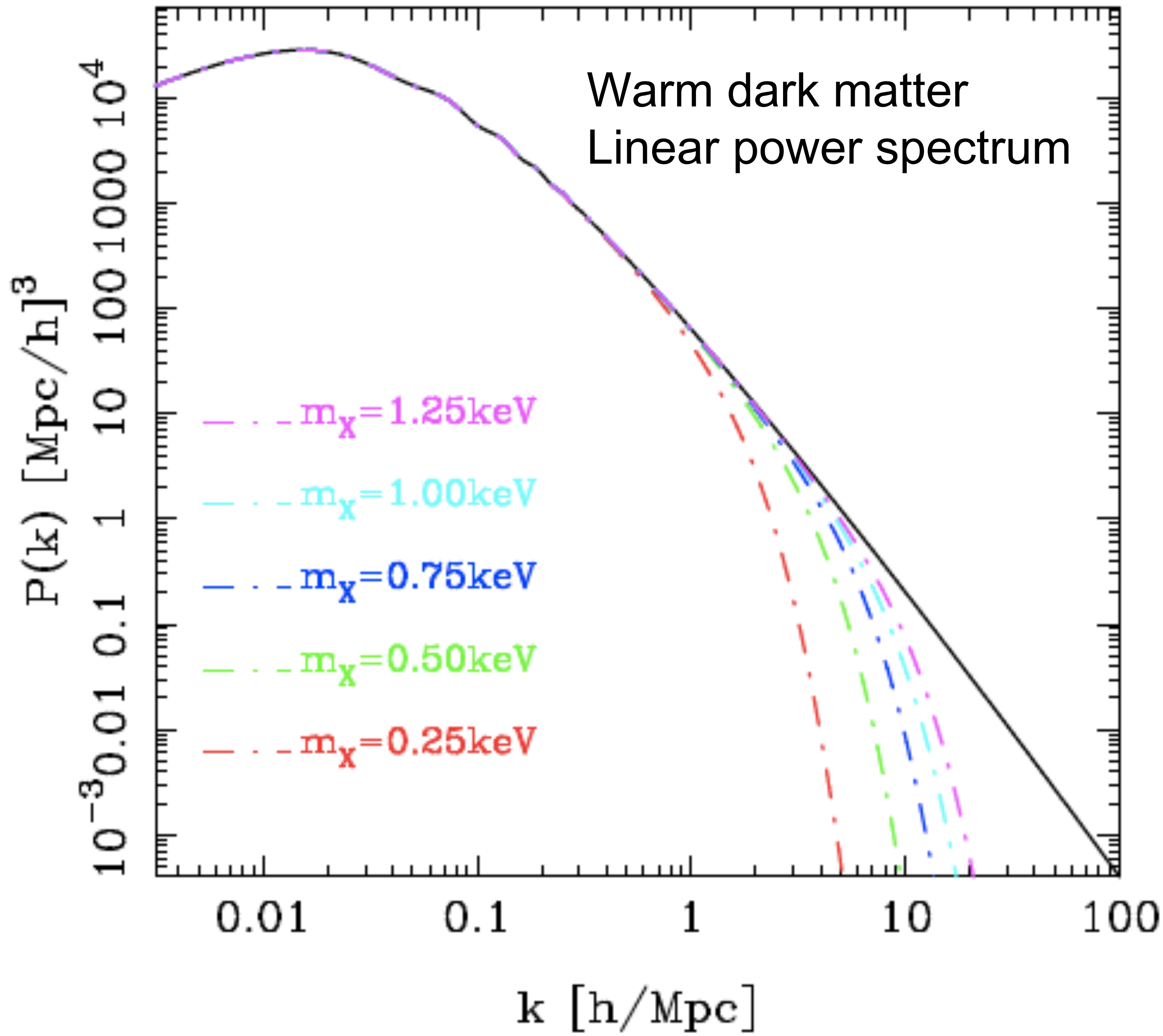


Blake

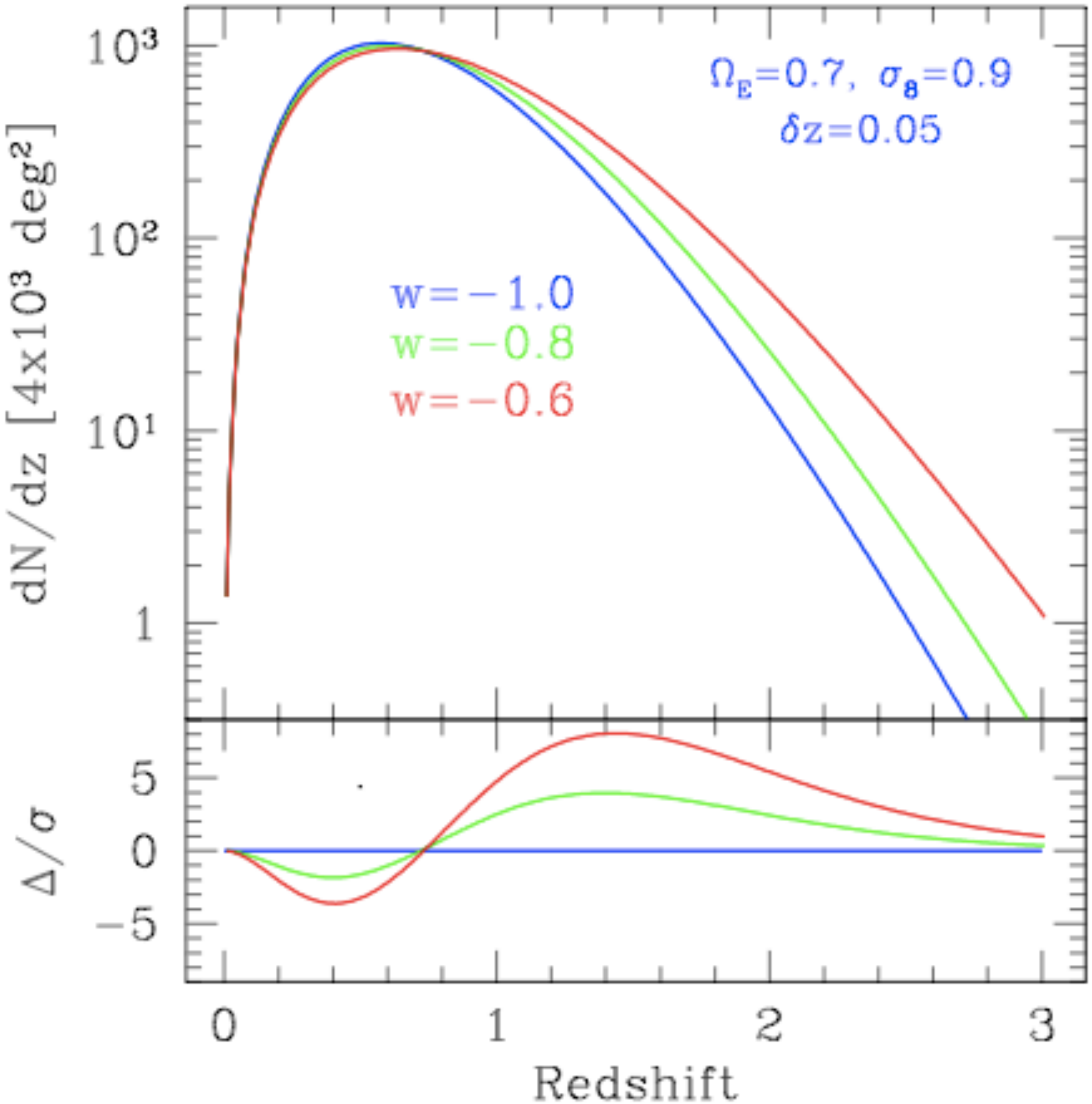
Angular power spectrum is sensitive to new physics



Angular power spectrum is sensitive to new physics



Counts of galaxy clusters are also probes of Dark Energy (probes both geometry and growth):



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However, it is difficult to find clusters and their masses:

Cluster finding algorithms: cluster catalogue already available for SVA – work is ongoing for Y1, Y2, …
Brazilian group working on WAZP

Mass-observable relations:
cross-correlations with gravitational lensing, x-rays, SZ
DES has an agreement with STP (similar region) – see, eg 1603.03904

Constraints at the 5% level on the dark energy equation of state require that systematic biases in the mass estimators must be controlled at better than the ~ 10% level – tough job!

Weak lensing (mass maps) and clusters in DES:

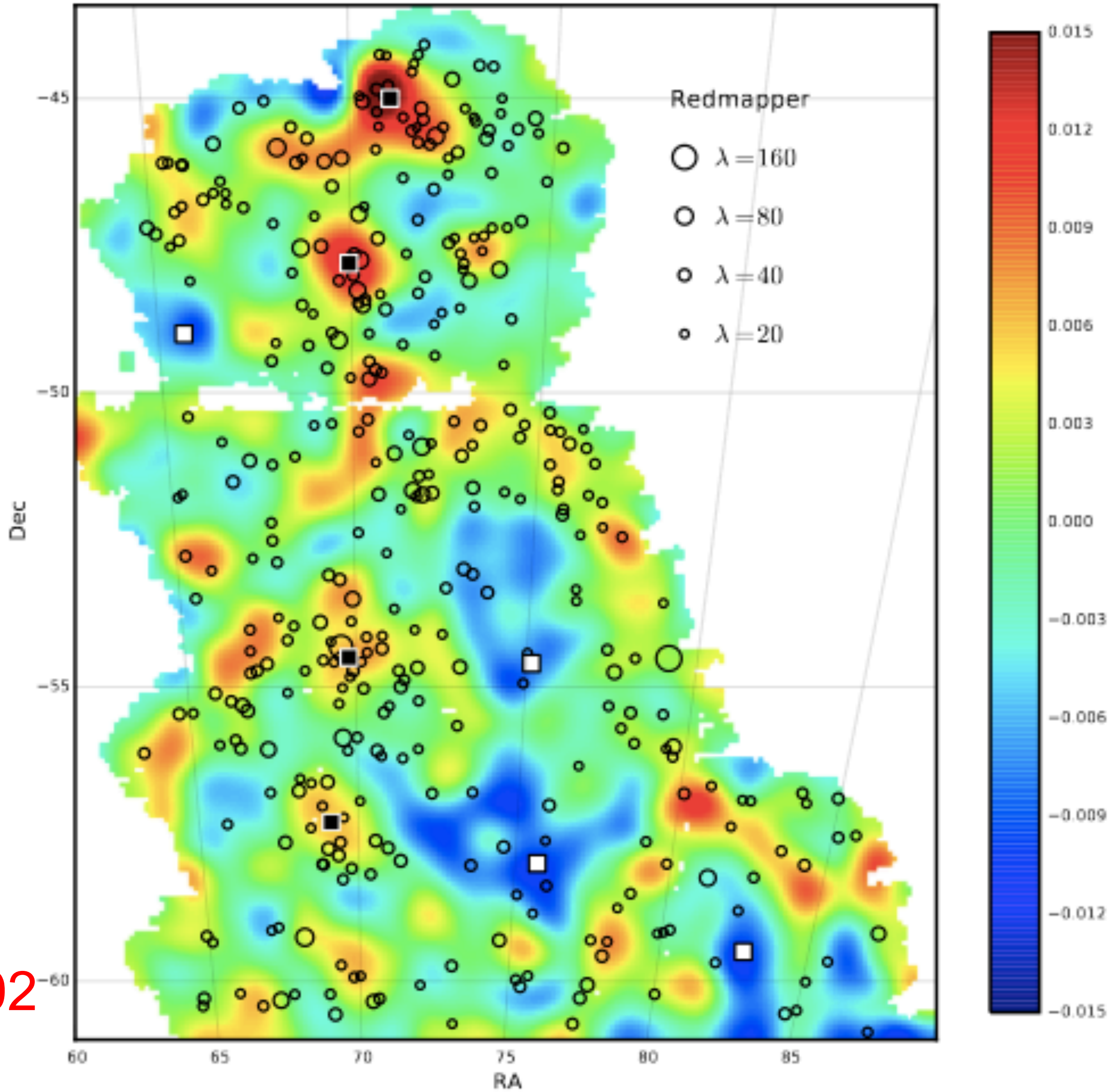


FIG. 4: The DES SV mass map along with foreground galaxy clusters detected using the Redmapper algorithm. The clusters are overlaid as black circles with the size of the circles indicating the richness of the cluster. Only clusters with richness greater than 20 and redshift between 0.1 and 0.5 are shown in the figure. The upper right corner shows the correspondence of the optical richness to the size of the circle in the plot. It can be seen that there is significant correlation between the mass map and the distribution of galaxy clusters. Several superclusters (black squares) and voids (white squares) can be identified in the joint map.

arXiv:1504.03002

We are interested in combining angular power spectrum and cluster number counts to constrain cosmological models and estimate their parameters.

Parameter estimation: likelihood function requires a covariance matrix

Some probes are not independent: need cross-correlations.

Aim of this work: model the covariance matrix for cluster number counts and angular power spectrum

How to estimate covariances?

- Jackknife
- Subsampling
- Bootstrap
- Mocks
- Theoretical covariance (non-gaussian, model dependence, super-sample covariance)

Jury is still out

N. Kokron

Modelling n-point functions

Fabien Lacasa and RR 1603.00918

We want to model the cross-covariance between cluster number counts and the angular correlation function (or the angular power spectrum) of galaxies.

Cluster counts: 1-point function
Cluster count covariance: 2-point function
Correlation function: 2-point function
Cross-covariance: 3-point function
Correlation function covariance: 4-point fct

We actually want to model the full covariance matrix:

$$X = \begin{pmatrix} N_{\mathrm{cl}} \\ C_\ell^{\mathrm{gal}} \end{pmatrix}$$

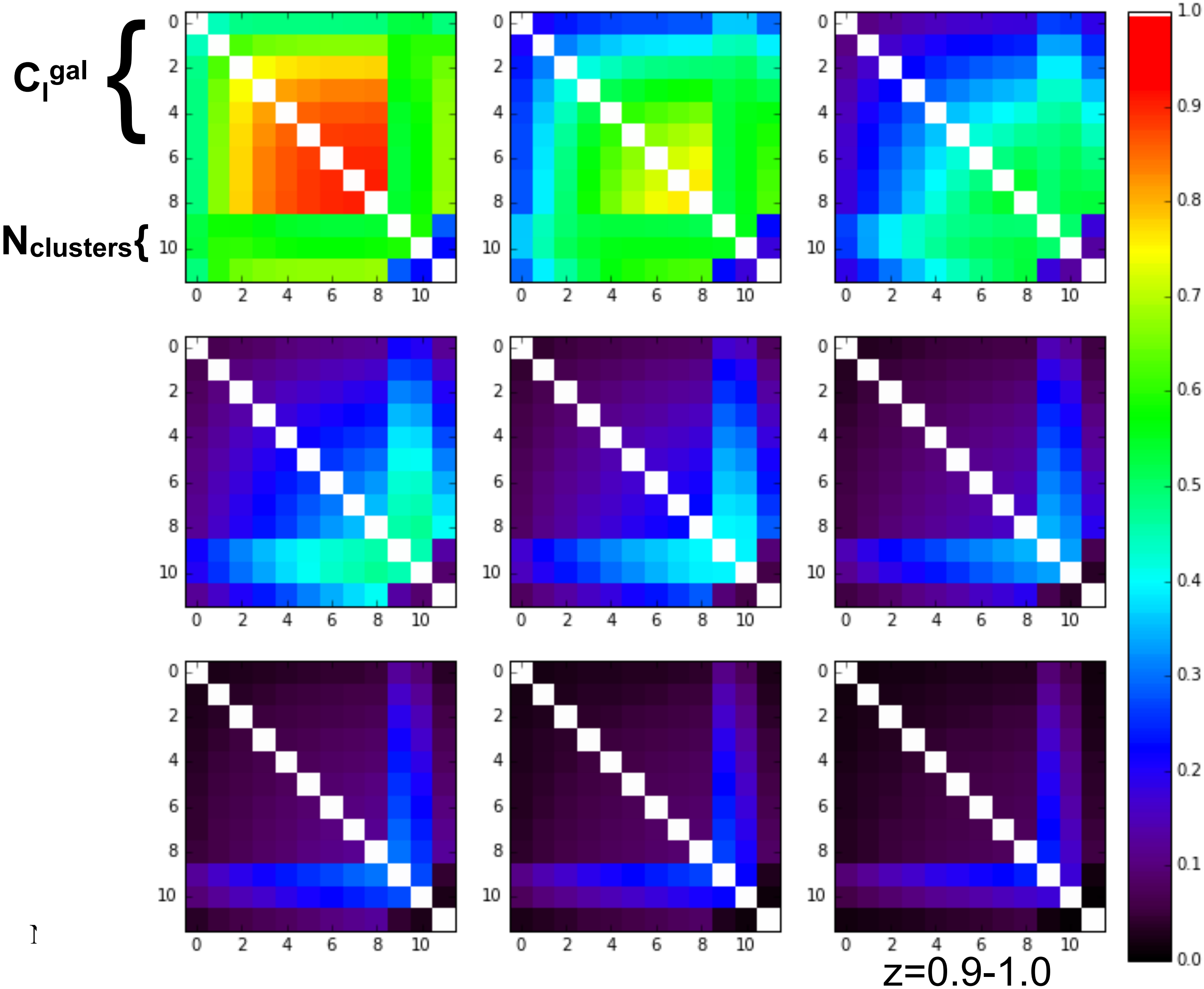
$$\mathrm{Cov}(\hat{X}, \hat{X}) = \begin{pmatrix} \mathrm{Cov}(\hat{N}_{\mathrm{cl}}, \hat{N}_{\mathrm{cl}}) & \mathrm{Cov}(\hat{C}_\ell^{\mathrm{gal}}, \hat{N}_{\mathrm{cl}}) \\ \mathrm{Cov}(\hat{N}_{\mathrm{cl}}, \hat{C}_\ell^{\mathrm{gal}}) & \mathrm{Cov}(\hat{C}_\ell^{\mathrm{gal}}, \hat{C}_\ell^{\mathrm{gal}}) \end{pmatrix}$$

We will use the halo model to compute the n-point functions and a halo occupation distribution (HOD)

$$
\begin{tikzcd}
\text{Halo Model + HOD} \arrow[r, Rightarrow] & \omega(\theta),\ C_l \arrow[d, Leftrightarrow] \\
\text{Halo Model} \arrow[r, Rightarrow] & n(M)
\end{tikzcd}
$$

Joint covariance

Predictions with halo model and HOD



9 redshift bins : Dz=0.1
z=0.1-1

3 mass bins :
DlogM=0.5
logM=14-15.5

9 multipole bins :
Dl=30
l=30-300
(theta~0.6-6 deg)

Cross-covariance is important at all redshifts

Particularly for the smaller angular scales

Conclusions - DES

- Dark Energy Survey fourth season (Y4) is ongoing
- DECam is working to specification
- Pipelines for data analysis are in place (still work to do)
- Catalogue creation for Y1/Y2 in the making
- Some results from the Science Verification data (less than 1/15 of total area already) – catalogues for LSS and shear are fine!
- Expect results from new analysis in early 2017
- Future: DESI (Mexico, Colombia, Brasil) and LSST (Chile, Brasil)

Conclusions

• Nonlinear modelling (in the halo model + HOD approach) of the full covariance matrix involving two main observational probes:
the galaxy angular power spectrum and cluster counts;

• Nongaussian contributions are important at low redshift and small scales;

• Taking into account the cross-correlation does not change significantly the determination of cosmological parameters but can affect the HOD parameters;

• Must take into account more experimental effects: photo-z errors, purity and completeness of a cluster catalog, scatter in cluster mass, etc…

• Method is being tested now in realistic simulations (MICE, with Hoffmann, Lacasa and Gaztañaga) – then apply it to real data!

Keep basic for the moment:

- Full sky
- No redshift uncertainty
- No cluster mass uncertainty

Halo Model

See, e.g., Cooray and Sheth 2002

All mass in the Universe is contained in halos.

Matter correlation on small scales is related to the spatial distribution within the halo: halo profile (use NFW)

Matter correlation on large scales is related to the spatial distribution of halos: halo mass function (e.g. Tinker mass function)

Halo Model

Density at a given position is given by a sum over halos i:

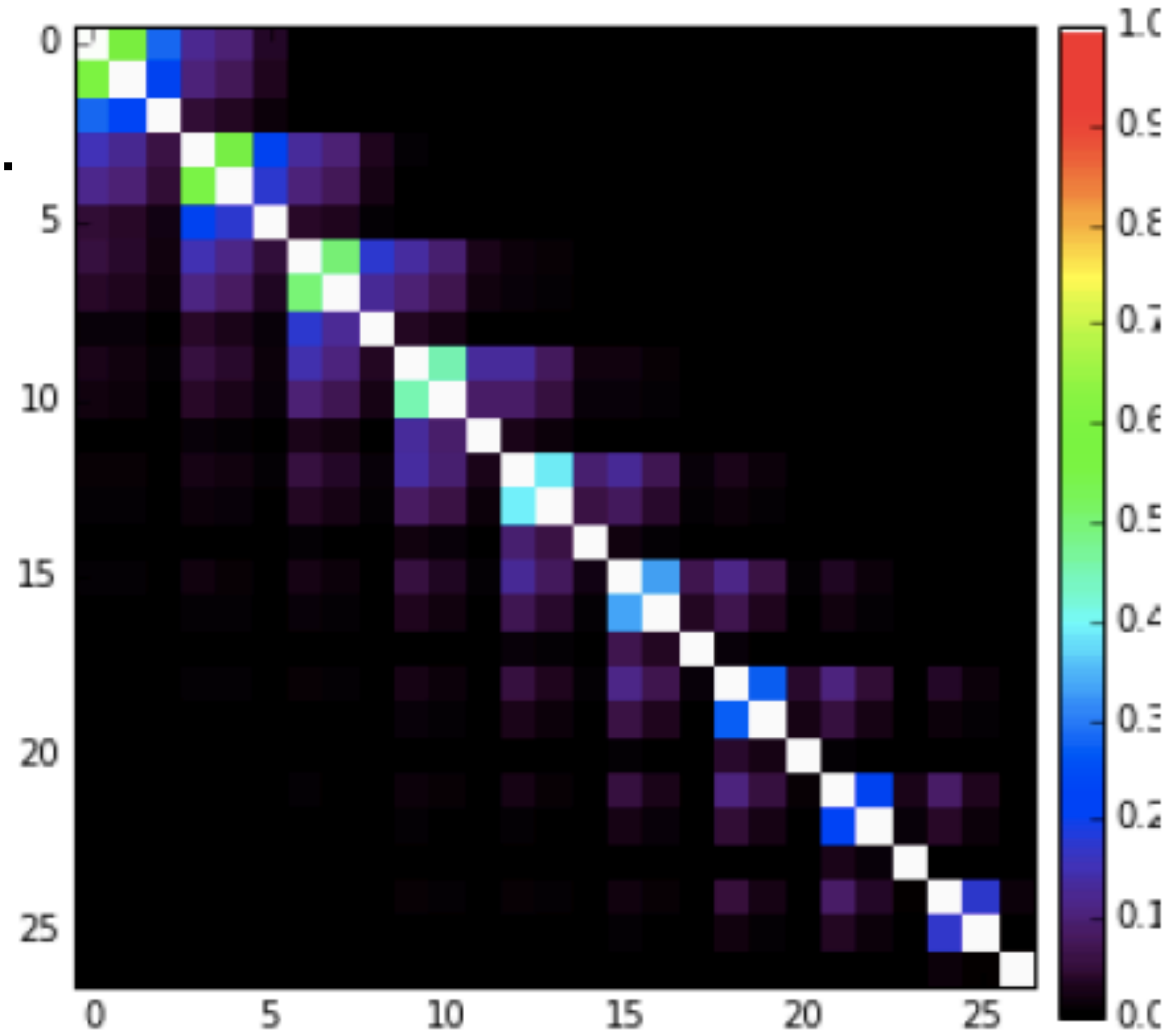
$$\rho(\vec{x}) = \sum_i \underbrace{\rho(\vec{x} - \vec{x}_i | M_i)}$$

Density around halo i ("halo profile")
assumed to depend only on halo mass M_i

Cluster Counts covariance in the Halo Model

Cluster counts covariance (3 bins of mass and 9 redshift bins)
off-diagonal entries from 2-halo contribution

Super sample cov.
is more important
at low z



10^{14}-$10^{14.5}$
$10^{14.5}$-10^{15}
10^{15}-$10^{15.5}$
01.<z<1.0
$\Delta z = 0.1$

Putting galaxies in halos: the halo occupation distribution model (HOD)

Key assumption: number of galaxies N in a halo is a random variable with a pdf that depends only on the halo mass M.

Galaxies are divided into central and satellites, with different pdf's (binomial for centrals and Poisson for satellites).

$$\langle N_g | M \rangle = \langle N_{\rm cen} | M \rangle + \langle N_{\rm sat} | M \rangle$$

Putting galaxies in halos: the halo occupation distribution model (HOD)

We adopt a parametrization with 4 parameters: a mass threshold above which a halo has a large probability of containing a central galaxy, the width of the transition of the central probability, the typical mass above which a halo contains satellite galaxies and the index of the power law for the number of satellites at large halo masses.

These parameters will be either marginalized or estimated in the analysis.

Cross-covariance between APS and cluster counts in the Halo Model + HOD

This cross-covariance will depend on the halo-galaxy-galaxy bispectrum:

$$\langle \delta_h(\vec{k}_1|M_1, z_1)\, \delta_g(\vec{k}_2, z_2)\, \delta_g(\vec{k}_3, z_3)\rangle_c = (2\pi)^3\, \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3)\, B_{\rm hgg}(k_{123}|M_1, z_{123})$$

Cross-covariance between APS and cluster counts in the Halo Model + HOD

Lacasa et al. (2014) proposed a diagrammatic method to compute n-point correlation functions with a set of “Feynman rules”. There are six contributions in this case:

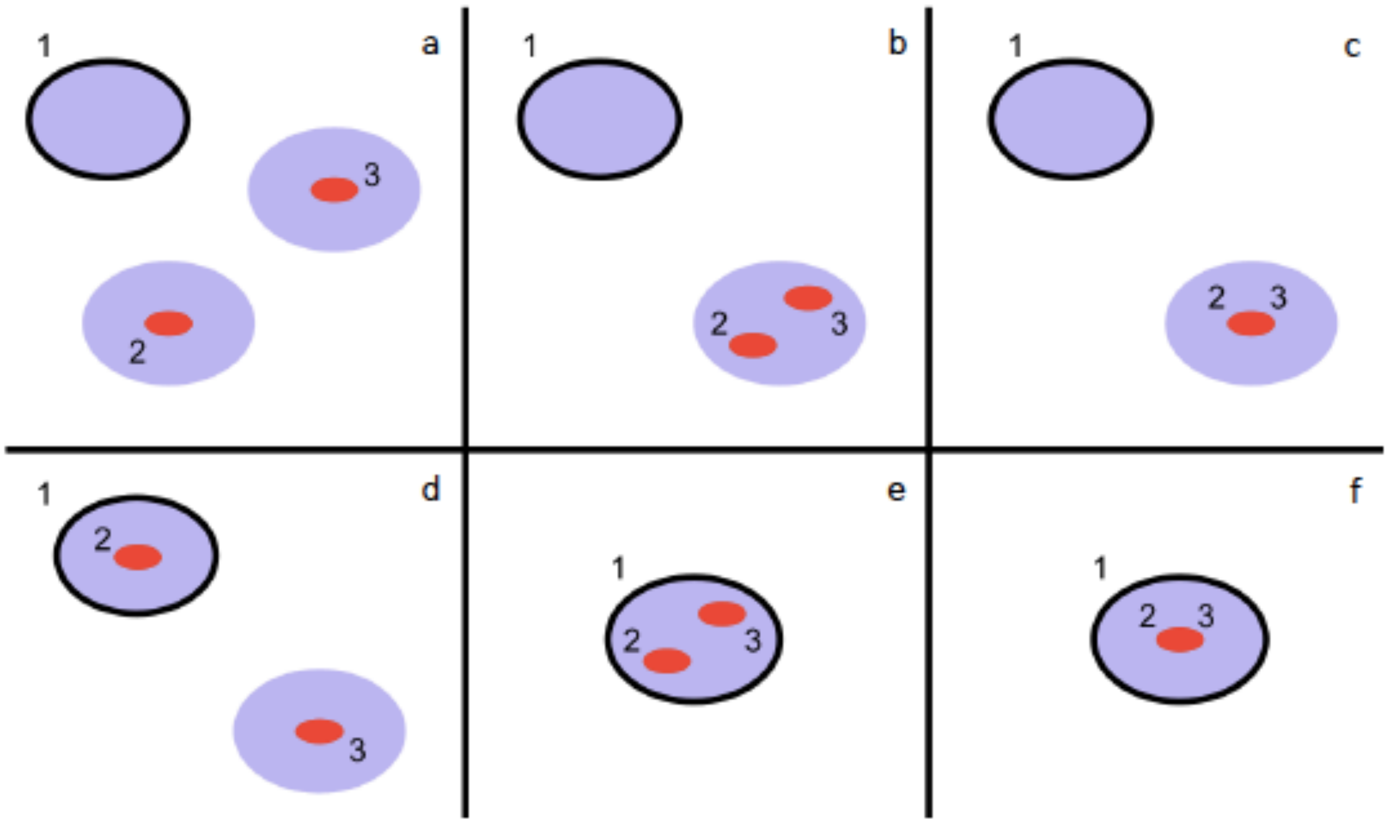


Figure 4. Diagrams for the halo-galaxy-galaxy bispectrum. From left to right and top to bottom : 3h, 2h-1h2g, 2h-1h1g, 2h-2h, 1h2g, 1h1g.

Cross-covariance between APS and cluster counts in the Halo Model + HOD

The perturbation theory term only dominates in certain regimes (high redshift, large scales, small masses). Nonlinear contributions are important!

Covariance of the galaxy APS

It involves a 4-point function. The usual gaussian term comes from the unconnected part:

$$\mathrm{Cov}\left(\hat{C}_\ell^{\mathrm{gal}}(i_z), \hat{C}_{\ell'}^{\mathrm{gal}}(j_z)\right) = \frac{2\; C_\ell^{\mathrm{gal}}(i_z)^2}{2\ell+1}\;\delta_{\ell,\ell'}\;\delta_{i_z,j_z}$$

Covariance of the galaxy APS

Non-gaussian contribution contained in the 2D projected galaxy trispectrum. The 3D galaxy trispectrum has contributions from 14 diagrams and there is no analytical solution for the 2D projection.

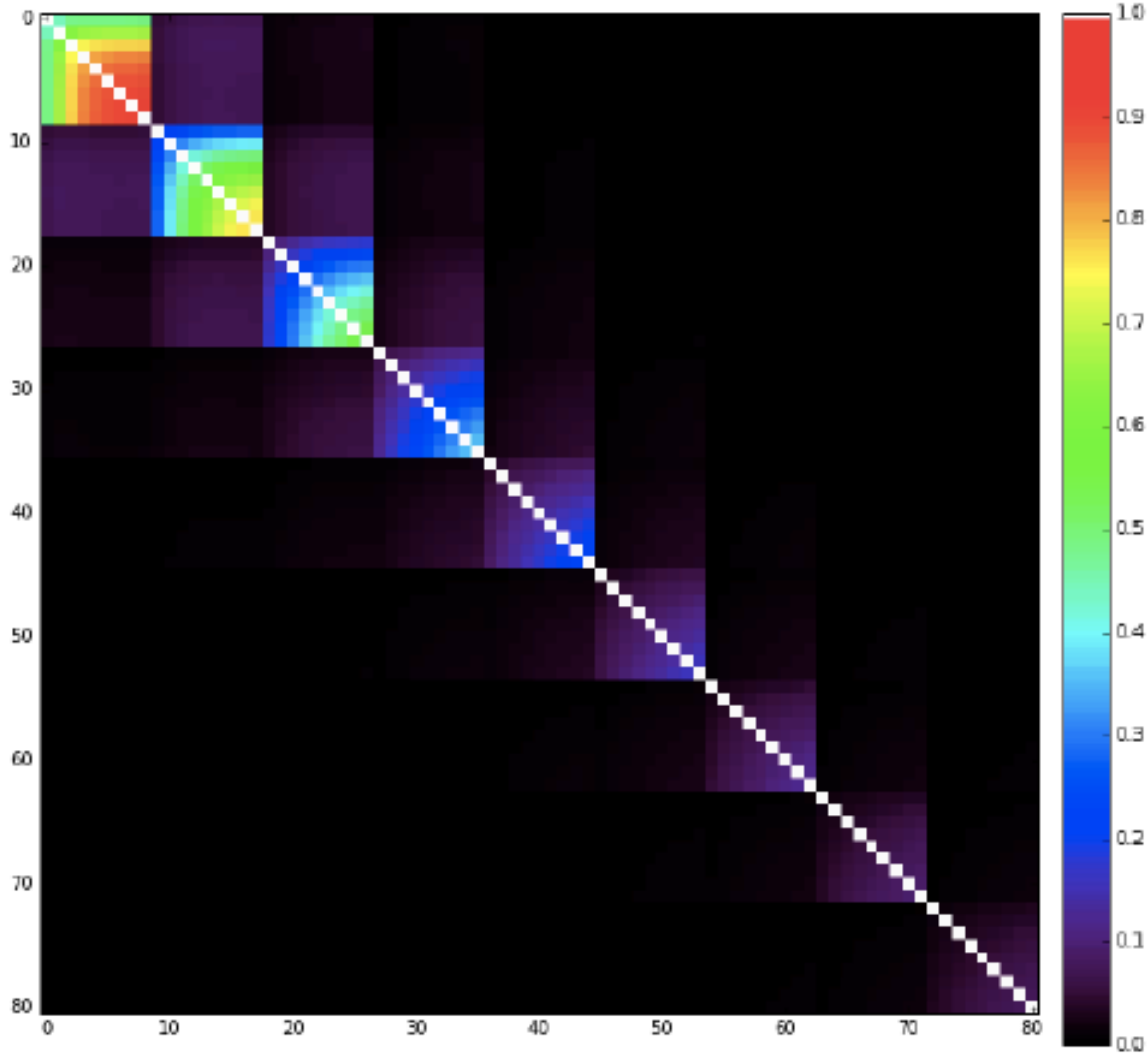
Hence we will keep the gaussian, the 1-halo term and a generalization of the SSC:

$$\mathrm{Cov}_{\mathrm{SSC}}\left(\hat{C}_{\ell}^{\mathrm{gal}}(i_z), \hat{C}_{\ell'}^{\mathrm{gal}}(j_z)\right) \approx \int dV_{12}\, \frac{\partial P_{\mathrm{gal}}(k_{\ell}, z_1)}{\partial \delta_{\mathrm{b}}} \frac{\partial P_{\mathrm{gal}}(k_{\ell'}, z_2)}{\partial \delta_{\mathrm{b}}}\, \sigma^2_{\mathrm{proj}}(z_1, z_2)$$

Covariance of the galaxy APS

l=30-300
in 9 bins of
Δl=30

9 redshift bins
of Δz=0.1
from z=0.1



Impact of including cross-correlation in the determination of parameters

Impact of joint covariance

We adopt:

9 redshift bins ($0.1<z<0.9$, $\Delta z=0.1$)

3 logarithmic mass bins ($14< \mathrm{Log}\, M < 15.5$, $\Delta \mathrm{Log}M=0.5$)

For the multipoles we considered 2 cases:

• Cosmological case (large angular scales)

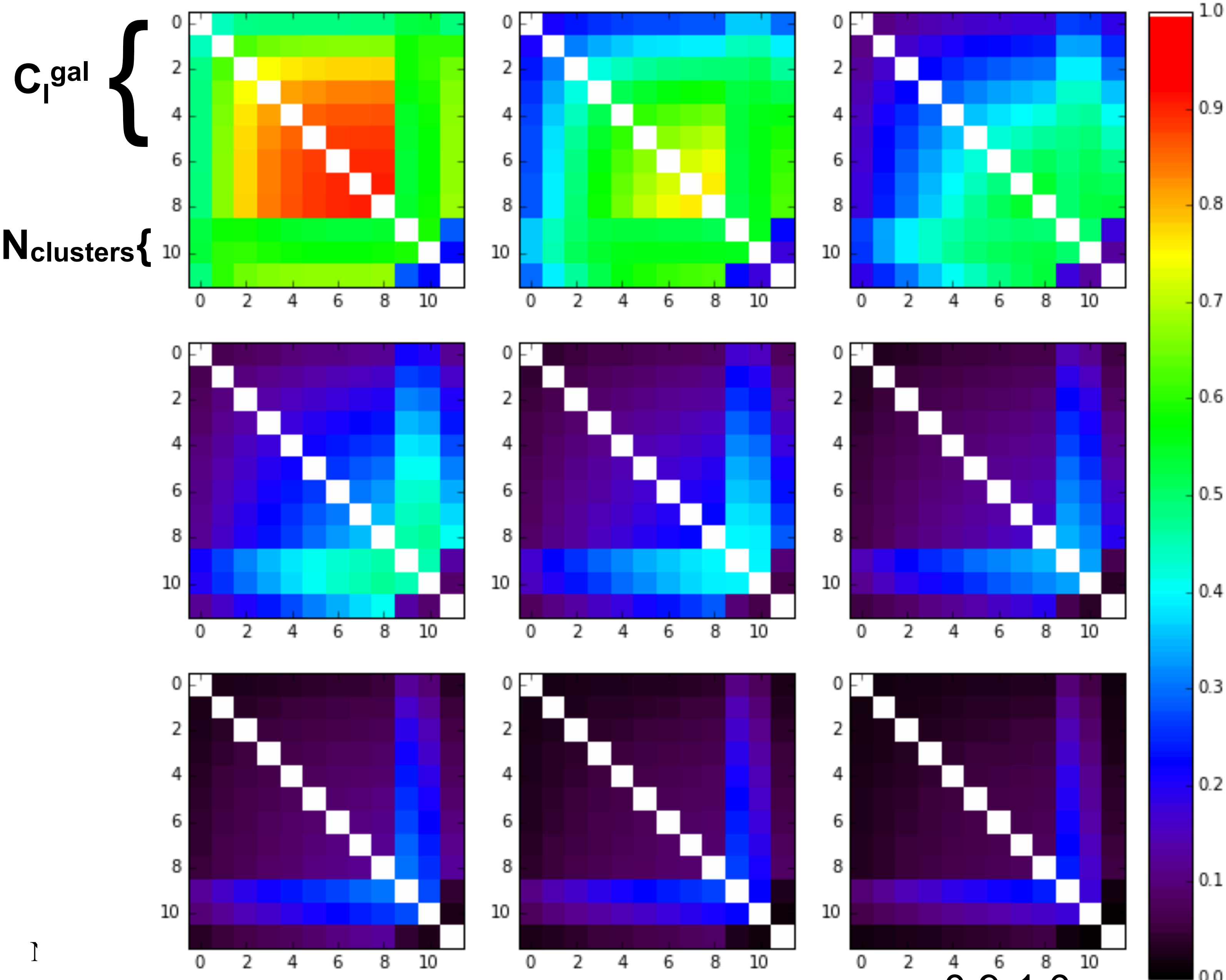
9 bins, $30<l<300$, $\Delta l=30$

• HOD case (small angular scales)

7 bins, $300<l<1000$, $\Delta l=70$

Joint covariance

z=0.1-0.2 z=0.2-0.3 Predictions with halo model and HOD



z=0.9-1.0

9 redshift bins : Dz=0.1
z=0.1-1

3 mass bins :
DlogM=0.5
logM=14-15.5

9 multipole bins :
Dl=30
l=30-300
(theta~0.6-6 deg)

Cross-covariance is important at all redshifts

Particularly for the smaller angular scales

Impact of joint covariance

observable/parameter	σ_8	$\Omega_m h^2$	$w_{\rm DE}$
$C_\ell^{\rm gal}$	10.1 %	8.67 %	36.1 %
$N_{\rm cl}$	1.17 %	4.10 %	7.48 %
joint	0.90 %	3.08 %	6.16 %
independent	0.86 %	2.96 %	5.87 %

Table 2. 1σ marginalised error bars on cosmological parameters in the cosmological case study.

observable / parameter	$\alpha_{\rm sat}$	$\log M_{\rm min}$	$\log M_{\rm sat}$
$C_\ell^{\rm gal}$	7.20 %	0.52 %	0.46 %
joint	1.49 %	0.20 %	0.32 %
independent	2.14 %	0.23 %	0.36 %

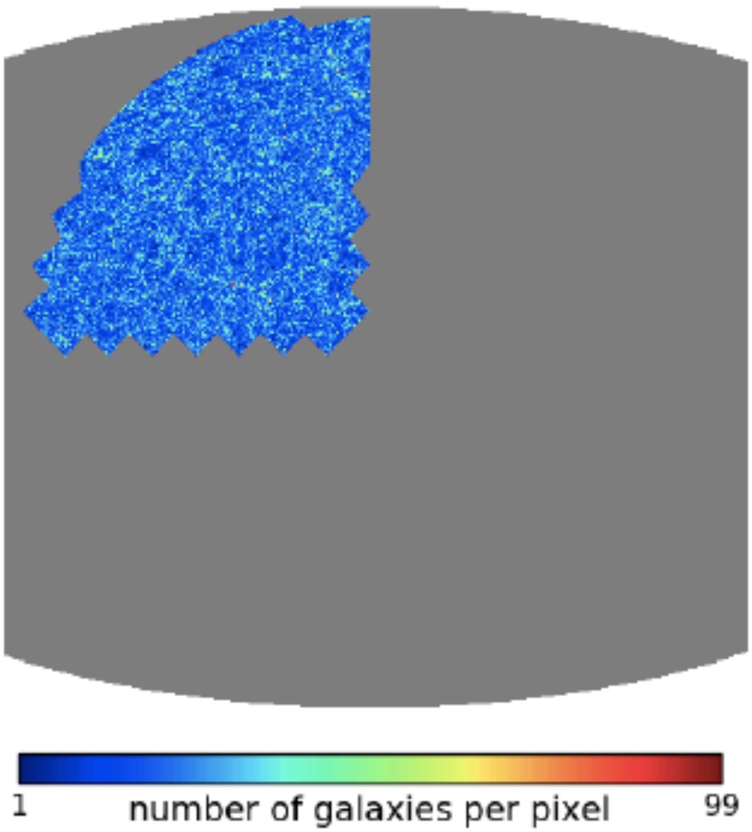
Table 3. 1σ marginalised error bars on HOD parameters in the HOD case study.

Comparison with simulations (prelim.)

- Use MICE simulations
- Introduce cuts in theoretical model – octant, not full sky
- Measurements of Cl's and N_{cl}
- Measurement of Cov(Cl,Cl), Cov(Cl, N_{cl}) and Cov(N_{cl},N_{cl}) using subsamples
- Need a fit to HOD

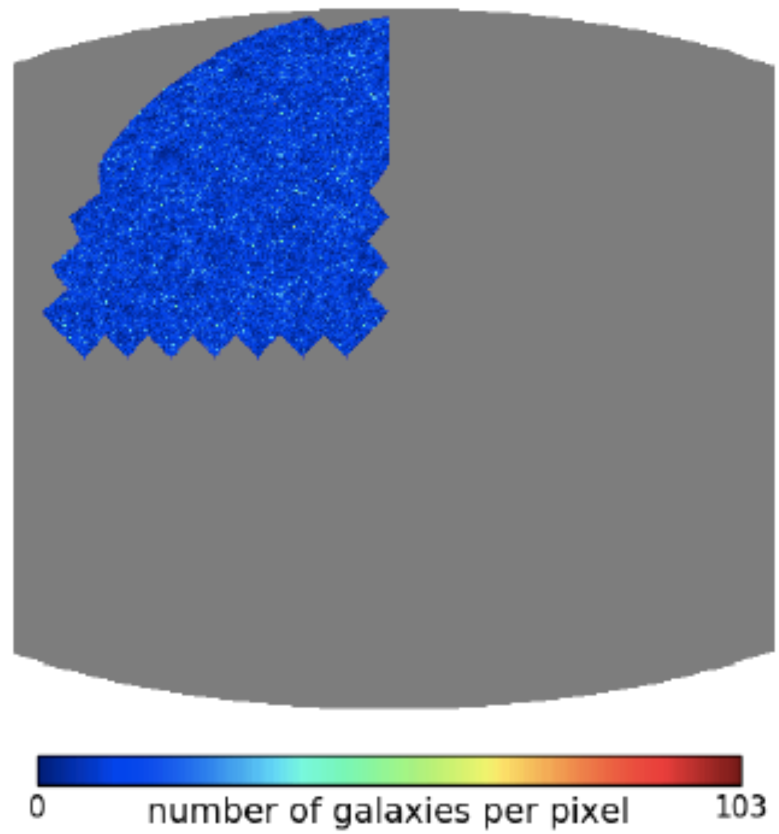
- MICE light cone between $0.5 < z < 0.6$

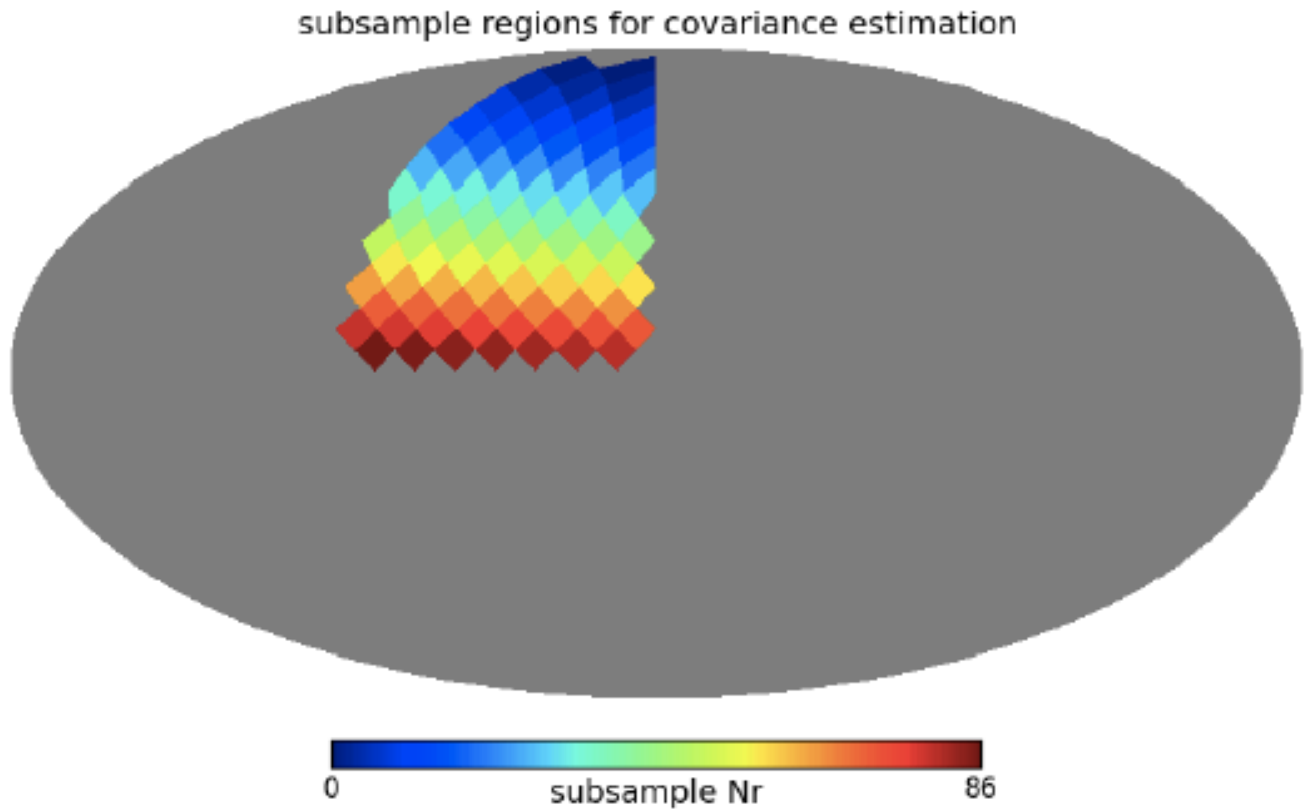
- clusters = FOF haloes (selected as centrals, Np>10)



healpix maps

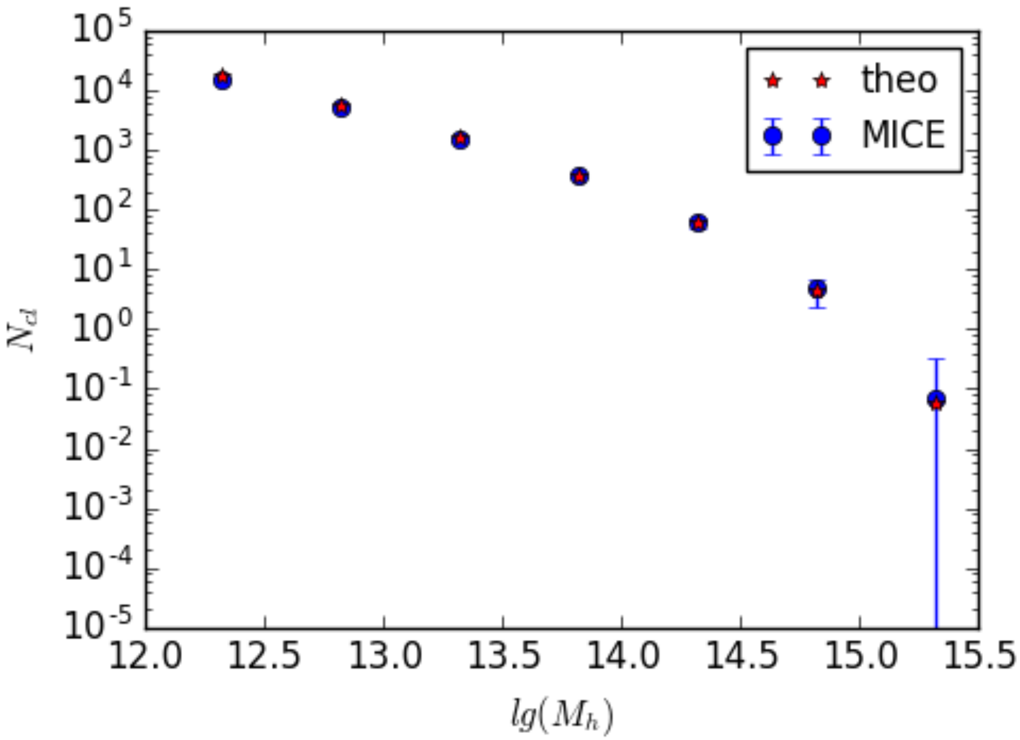
- centrals+satellites (r<22)



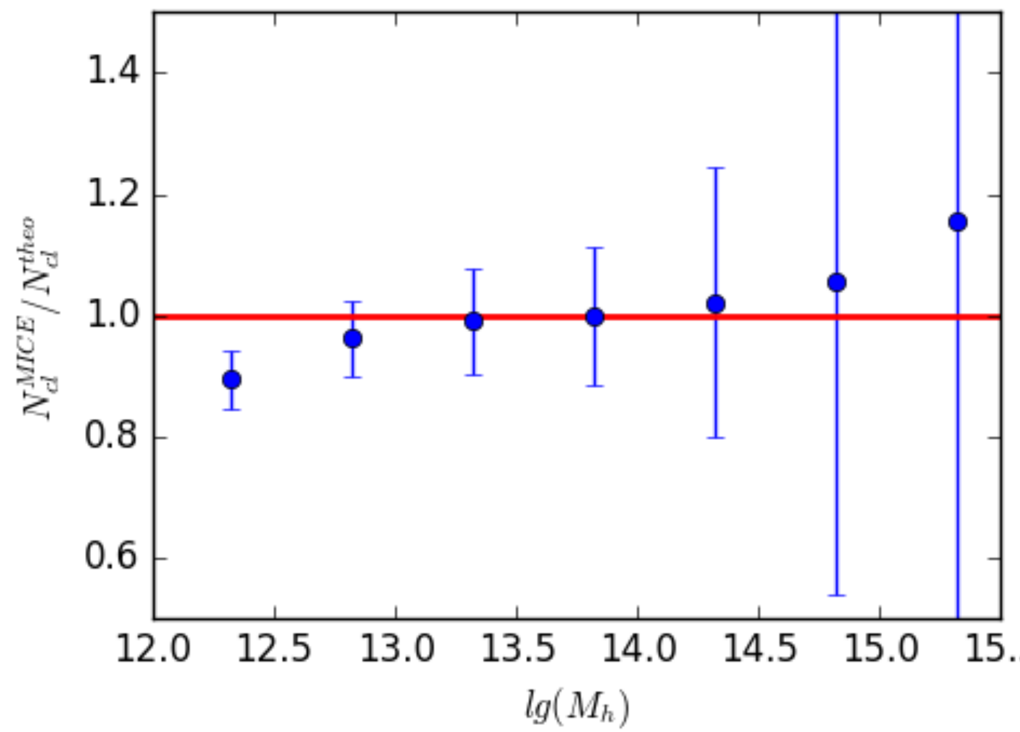


- 87 subsample regions (large healpix pixels)
- regions which exceed area of the octant are excluded

Cluster counts

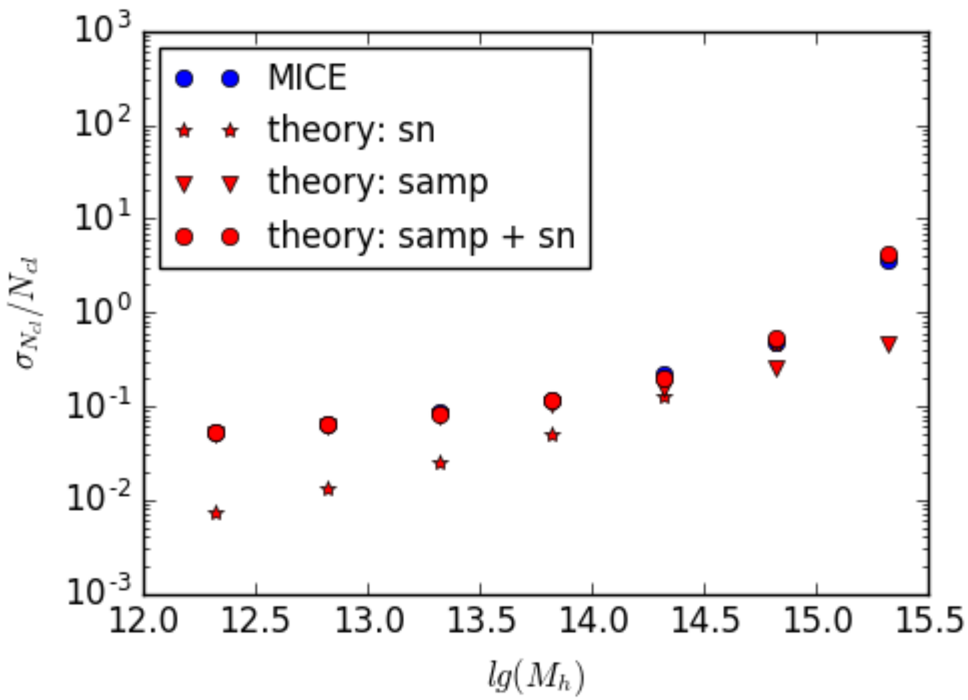


Counts comparison

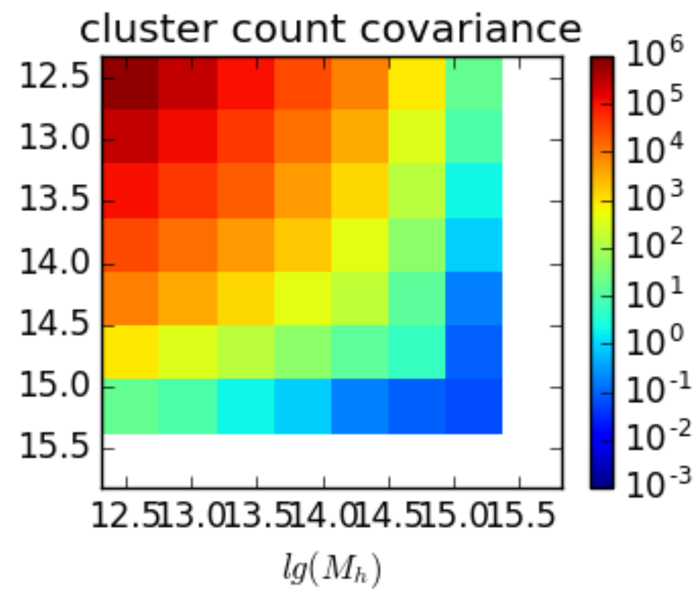


Ratio

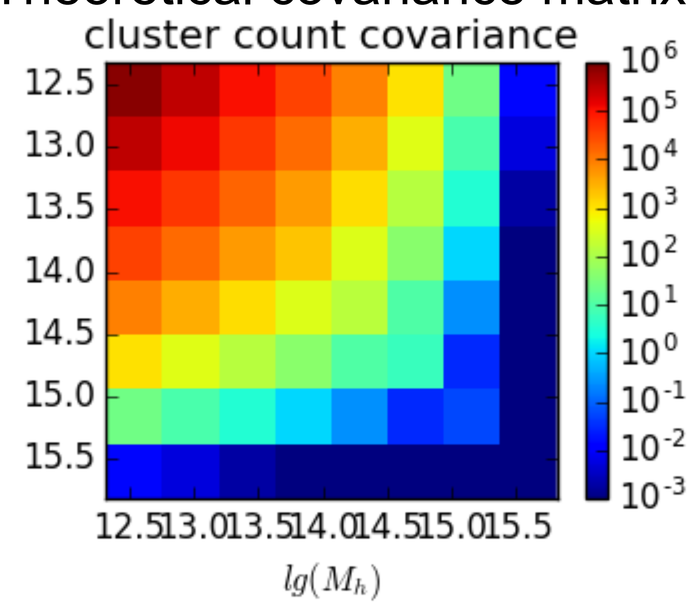
Cluster counts covariance



Measured covariance matrix

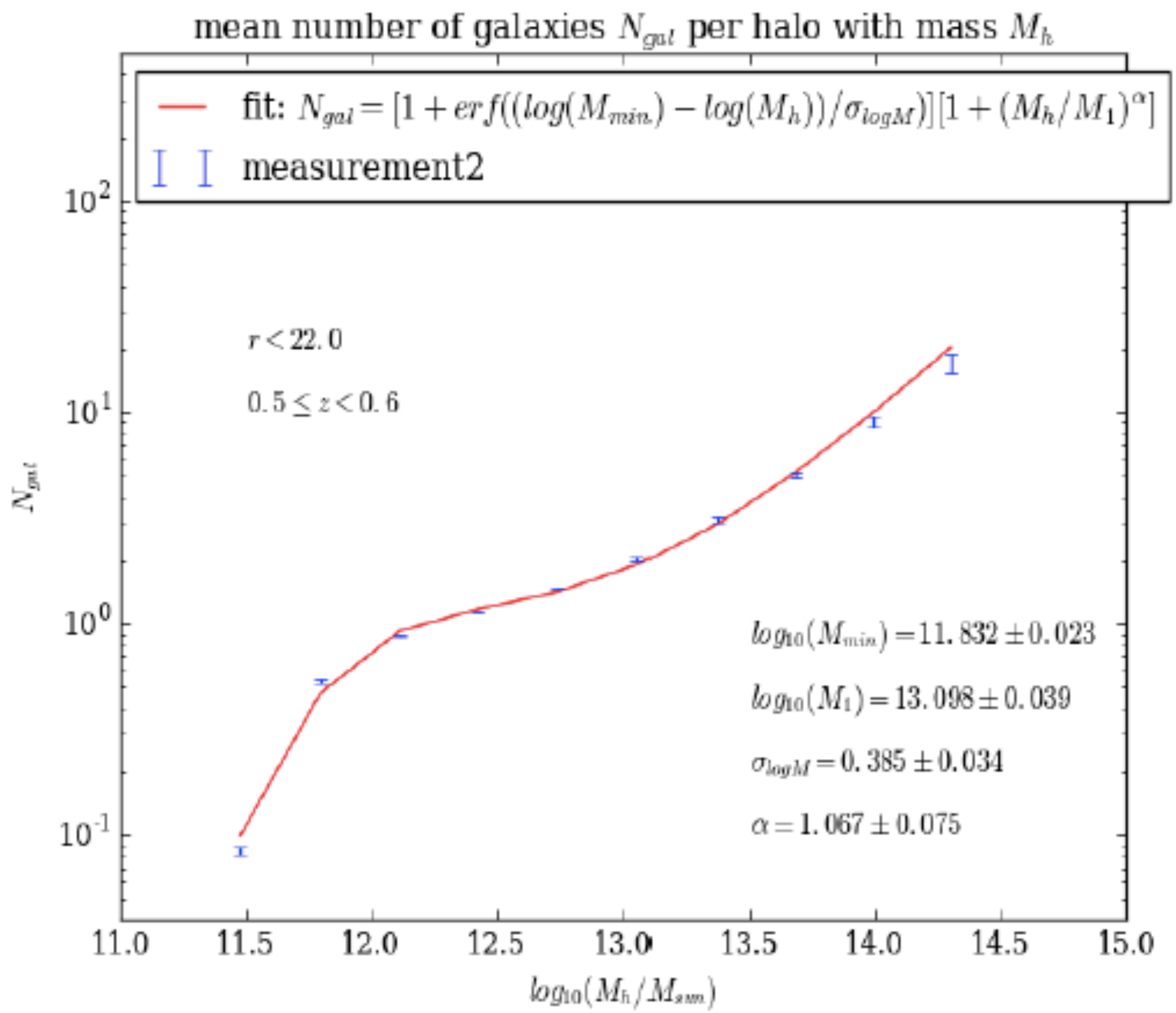


Theoretical covariance matrix



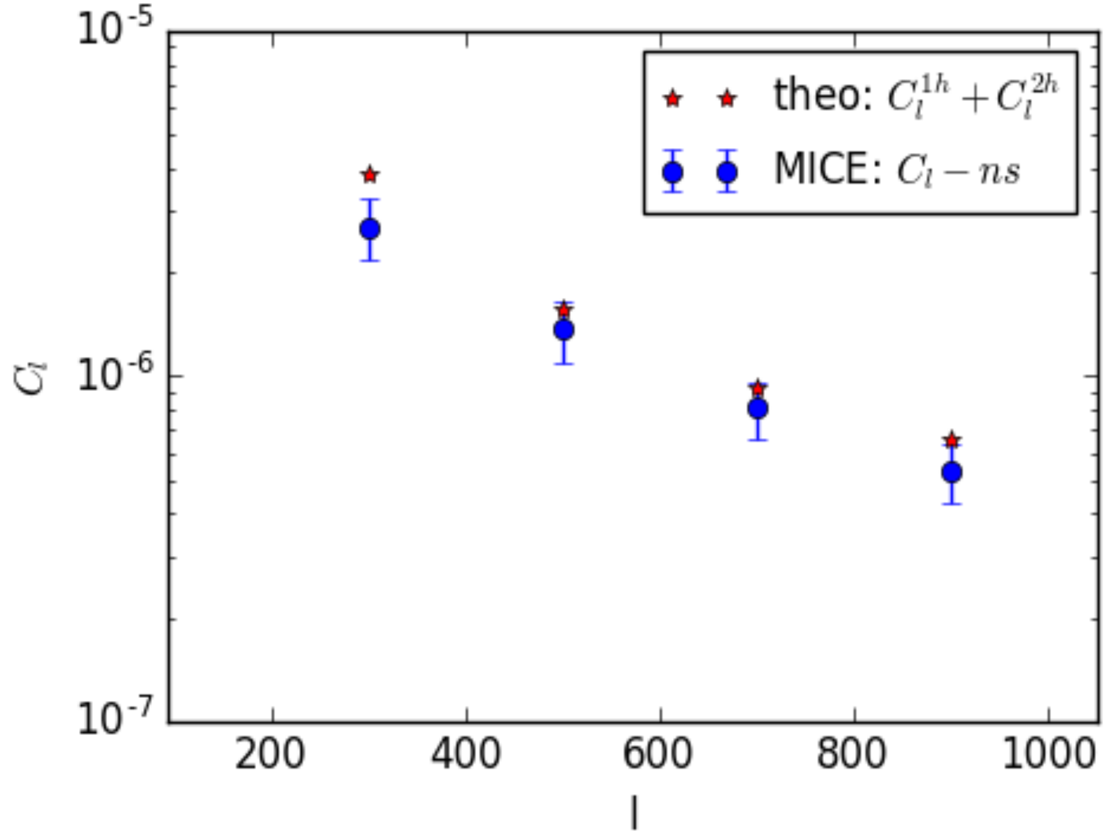
Sample variance dominates at small masses and shot noise dominates for larger masses

HOD fitting for Cl's



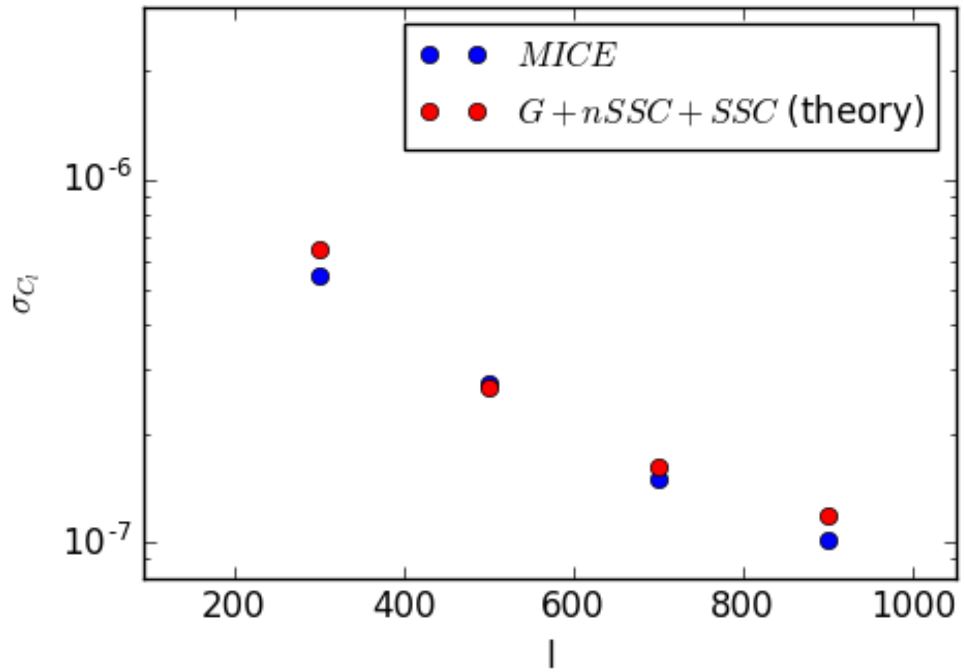
sample:
galtype = 'cent+sat'
no colour selection
r < 22
0.5<z<0.6

Cl's



C(l) comparison

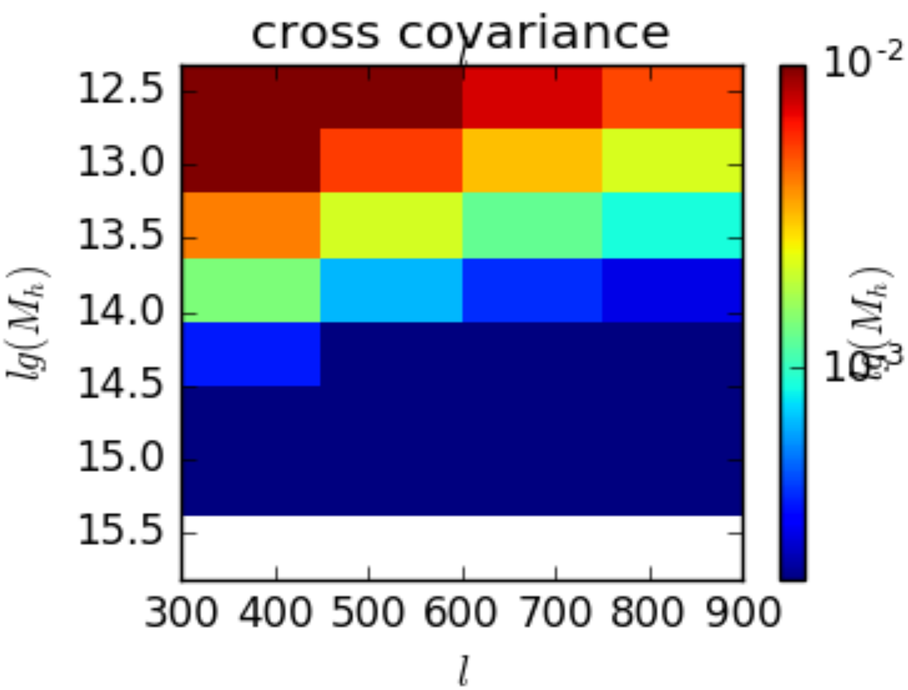
Covariance of Cl's



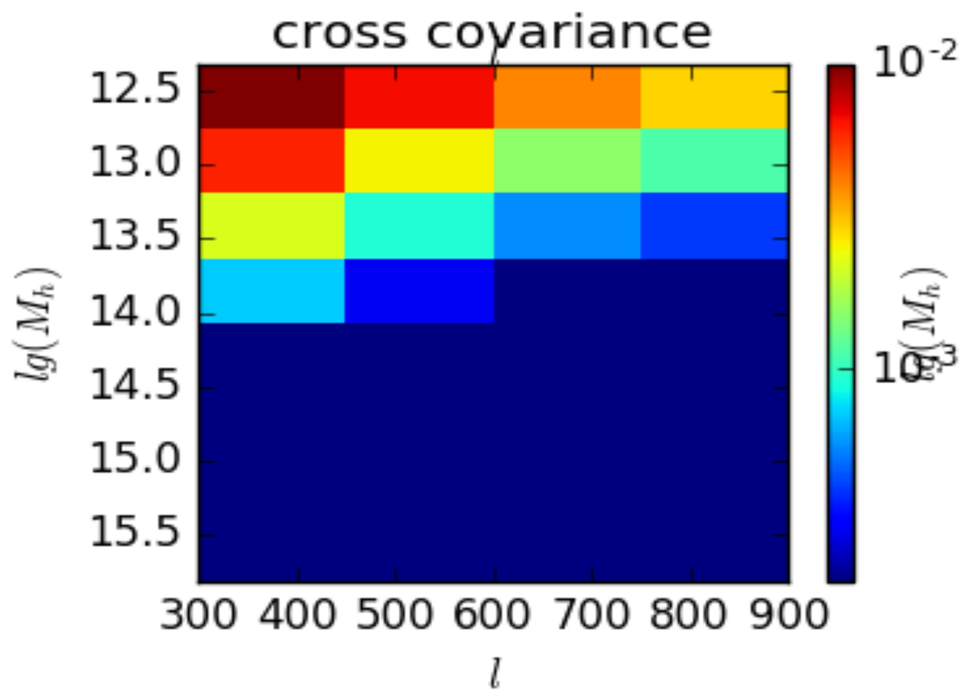
Still some disagreement

Cross covariance

Measured covariance matrix



Theoretical covariance matrix



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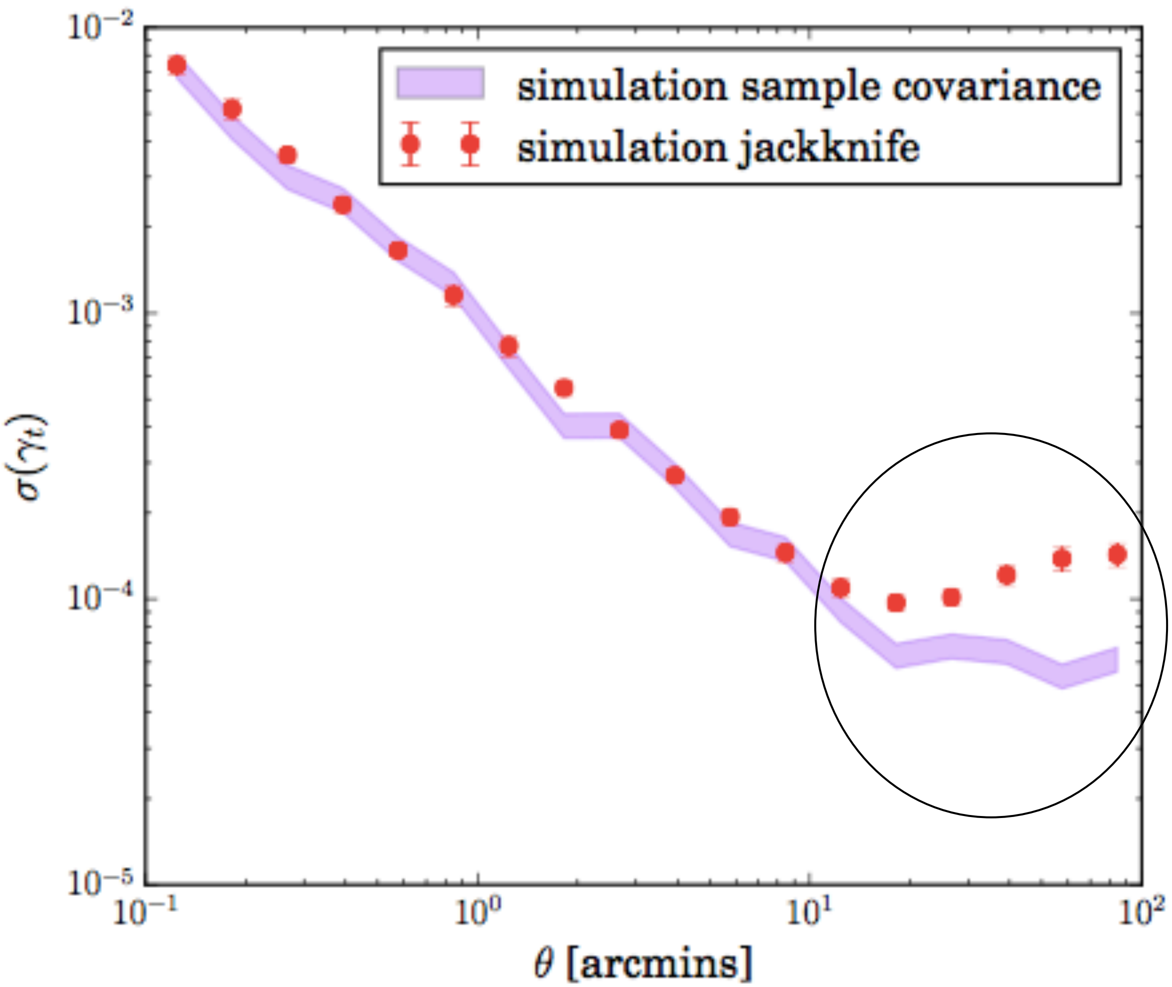
Super sample covariance

DES Galaxy-Galaxy Lensing 13

1603.00918



"Super sample covariance"

Cluster Counts in the Halo Model

Halo mass function (comoving number density of halos per unit mass):

$$\frac{dn_h}{dM} = \langle \sum_i \delta^3(\vec{x} - \vec{x}_i)\delta(M - M_i) \rangle$$

Average cluster number counts:

$$\bar{N}_{\rm cl}(i_M, i_z) = \int_{i_M, i_z} dM\, dV\, \frac{dn_{\rm h}}{dM}$$

Cluster Counts in the Halo Model

Covariance of cluster number counts (in Fourier space):

$$\mathrm{Cov}\left(\hat{N}_{\mathrm{cl}}(i_M, i_z), \hat{N}_{\mathrm{cl}}(j_M, j_z)\right) =$$

$$\int \frac{d^3k}{(2\pi)^3}\, dM_{12}\, dV_{12}\; j_0(kr_1)\, j_0(kr_2)\, \left.\frac{dn_h}{dM}\right|_{M_1, z_1} \left.\frac{dn_h}{dM}\right|_{M_2, z_2} \underbrace{P_{\mathrm{cl}}(k|M_{12}, z_{12})}_{\text{Cluster power spectrum}}$$

$$j_0(x) = \frac{\sin(x)}{x}$$

Cluster Counts in the Halo Model

Covariance of cluster number counts has contributions from 1 and 2 halo terms:

$$\mathrm{Cov}_{1\mathrm{h}}\left(\hat{N}_{\mathrm{cl}}(i_M, i_z), \hat{N}_{\mathrm{cl}}(j_M, j_z)\right) = \delta_{i_M, j_M}\, \delta_{i_z, j_z}\, \frac{\bar{N}_{\mathrm{cl}}(i_M, i_z)}{4\pi}$$

1-halo term: poissonian shot noise

Cluster Counts in the Halo Model

2-halo contribution to the covariance can be conveniently written as (known as sample variance):

$$\mathrm{Cov}_{2\mathrm{h}}\left(\hat{N}_{\mathrm{cl}}(i_M, i_z), \hat{N}_{\mathrm{cl}}(j_M, j_z)\right) = \int dV_{12} \frac{\partial n_h}{\partial \delta_b}(i_M, z_1)\, \frac{\partial n_h}{\partial \delta_b}(j_M, z_2) \sigma^2_{\mathrm{proj}}(z_1, z_2)$$

$$\frac{\partial n_h}{\partial \delta_b}(i_M, z) \equiv \int_{M \in \mathrm{bin}(i_M)} dM\, \frac{dn_h}{dM}\, b_1(M, z)$$

$$\sigma^2_{\mathrm{proj}}(z_1, z_2) \equiv \int \frac{d^3k}{(2\pi)^3}\, j_0(kr_1)\, j_0(kr_2)\, P_{\mathrm{lin}}(k|z_{12})$$

$$j_0(x) = \frac{\sin(x)}{x}$$

related to the covariance of the background density

Cluster Counts in the Halo Model

For numerical results we will use the Tinker halo mass function and the NFW halo density profile. We use as a fiducial model a LCDM with Planck cosmological parameters and a linear power spectrum generated by the Eisenstein-Hu parametrization.

Angular Power Spectrum in the Halo Model

3D galaxy power spectrum written as a sum of 3 terms:

$$P_{\rm gal}(k|z_{12}) = P^{\rm 2h}_{\rm gal}(k|z_{12}) + P^{\rm 1h}_{\rm gal}(k|z_{12}) + P^{\rm shot}_{\rm gal}(k|z_{12})$$

Depends on galaxy bias, mass function, HOD, profiles and DM power spectrum

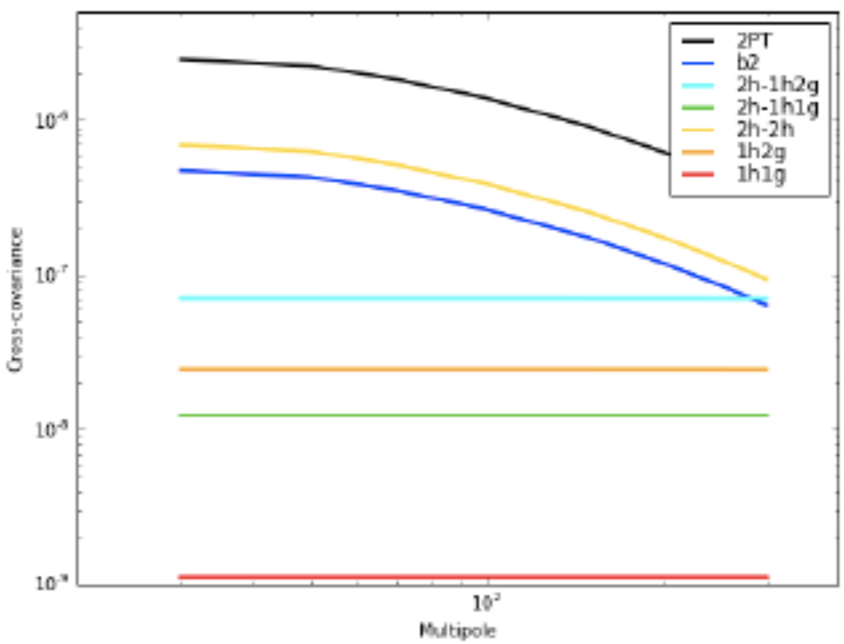
Depends on mass function, HOD and profiles

$$\frac{\delta_{z_1,z_2}}{\overline{n}_{\rm gal}(z_1)}$$

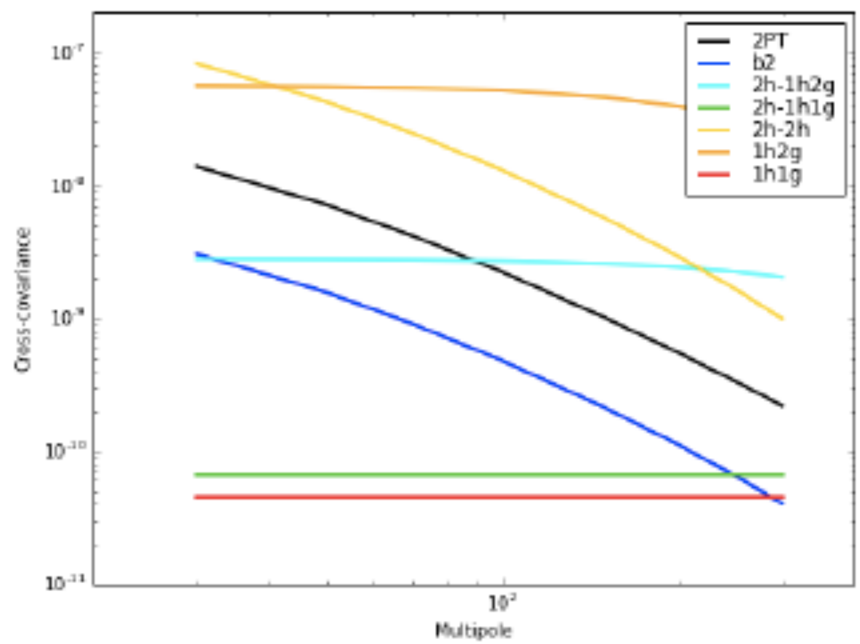
Cross-covariance between APS and cluster counts in the Halo Model + HOD

The perturbation theory term only dominates in certain regimes (high redshift, large scales, small masses). Nonlinear contributions are important!

high redshift, low mass case
0.8<z<0.9 14<logM<14.5



low redshift, high mass case
0.1<z<0.2 15<logM<15.5



Cross-covariance between APS and cluster counts: super-sample covariance

We were able to identify the contribution from super-sample covariance in our approach coming from different terms:

$$\mathrm{Cov}_{\mathrm{SSC}}\left(\hat{N}_{\mathrm{cl}}(i_M, i_z), \hat{C}_\ell^{\mathrm{gal}}(j_z)\right) =$$

$$\int dV_{12}\, \frac{\bar{n}_{\mathrm{gal}}(z_2)^2}{\Delta N_{\mathrm{gal}}(j_z)^2}\, \frac{\partial n_h}{\partial \delta_b}(i_M, z_1)\, \frac{\partial P_{\mathrm{gal}}(k_\ell | z_2)}{\partial \delta_b}\, \sigma^2_{\mathrm{proj}}(z_1, z_2)$$

Our results generalize (for second order bias and galaxy shot noise) the results of Takada and Hu (2013)

Cross-covariance between APS and cluster counts: super-sample covariance

Interpretation

$\frac{\partial P_{\mathrm{gal}}}{\partial \delta_b}$: reaction of galaxy power spectrum to a change in the background density

$\frac{\partial n_h}{\partial \delta_b}$: reaction of cluster counts to a change in the background density

“Unification” of super-sample covariance

We propose that SSC between 2 observables can always be written as

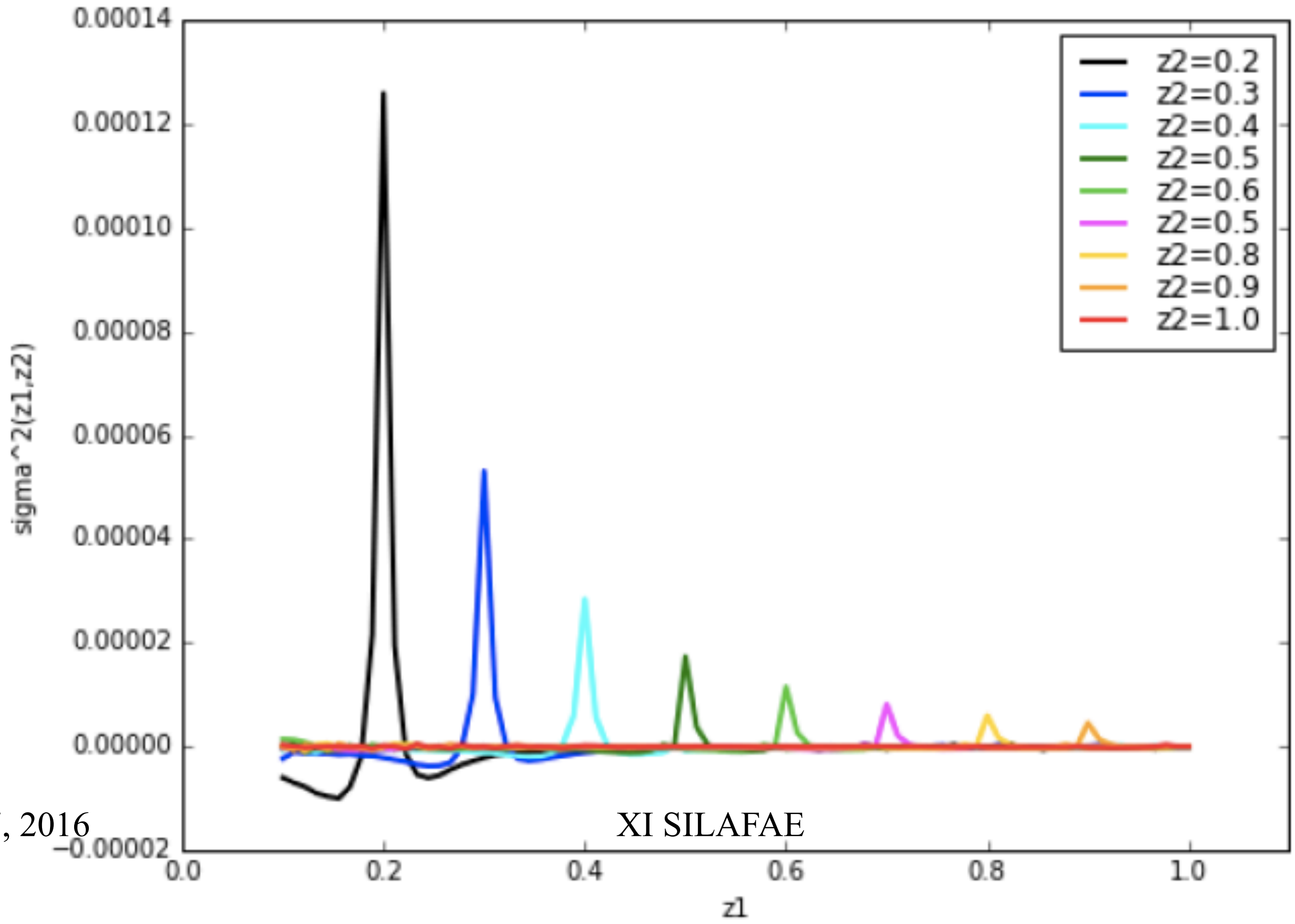
$$\mathrm{Cov}_{\mathrm{SSC}}\left(\mathcal{O}_1, \mathcal{O}_2\right) = \int dV_{12}\, \frac{\partial \mathcal{O}_1}{\partial \delta_b}(z_1)\, \frac{\partial \mathcal{O}_2}{\partial \delta_b}(z_2)\, \sigma^2_{\mathrm{proj}}(z_1, z_2)$$

$\sigma^2_{\mathrm{proj}}(z_1, z_2)$ is related to the covariance of the background density and peaks at $z_1 = z_2$

Covariance of background

$$\sigma^2_{\mathrm{proj}}(z_1, z_2) = \int \frac{\mathrm{d}^3\mathbf{k}}{(2\pi)^3}\, j_0(kr_1)\, j_0(kr_2)\, P_{\mathrm{DM}}(k|z_{12})$$

$$= \langle \delta_{\mathrm{avg}}(z_1)\, \delta_{\mathrm{avg}}(z_2) \rangle_c \quad \text{with} \quad \delta_{\mathrm{avg}}(z) = \int \frac{\mathrm{d}^2\hat{n}}{4\pi}\, \delta(r\hat{n}, z).$$

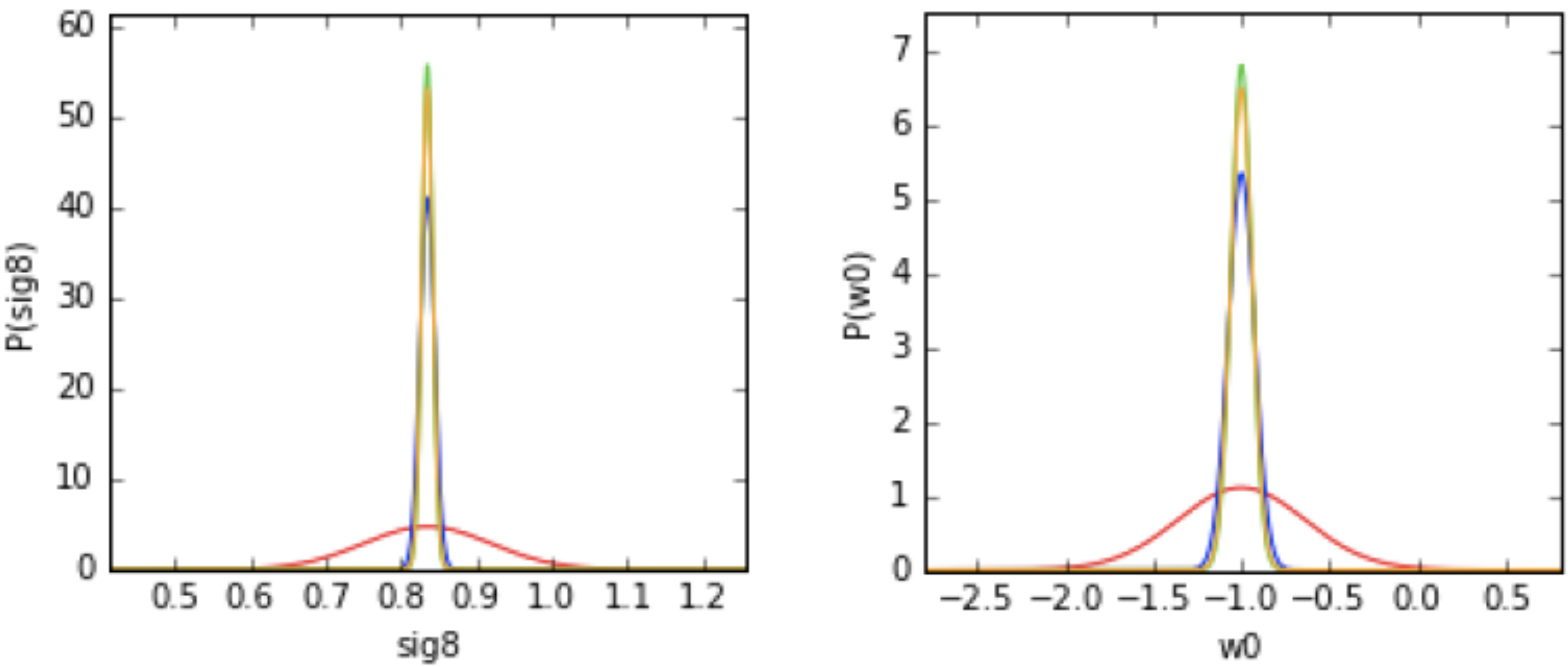


Impact of joint covariance

Perform a Fisher matrix analysis – cosmological case

Red line: APS only
Blue line: cluster counts only
Green line: independent APS and cluster counts
Orange line: full joint APS and cluster counts

Small difference

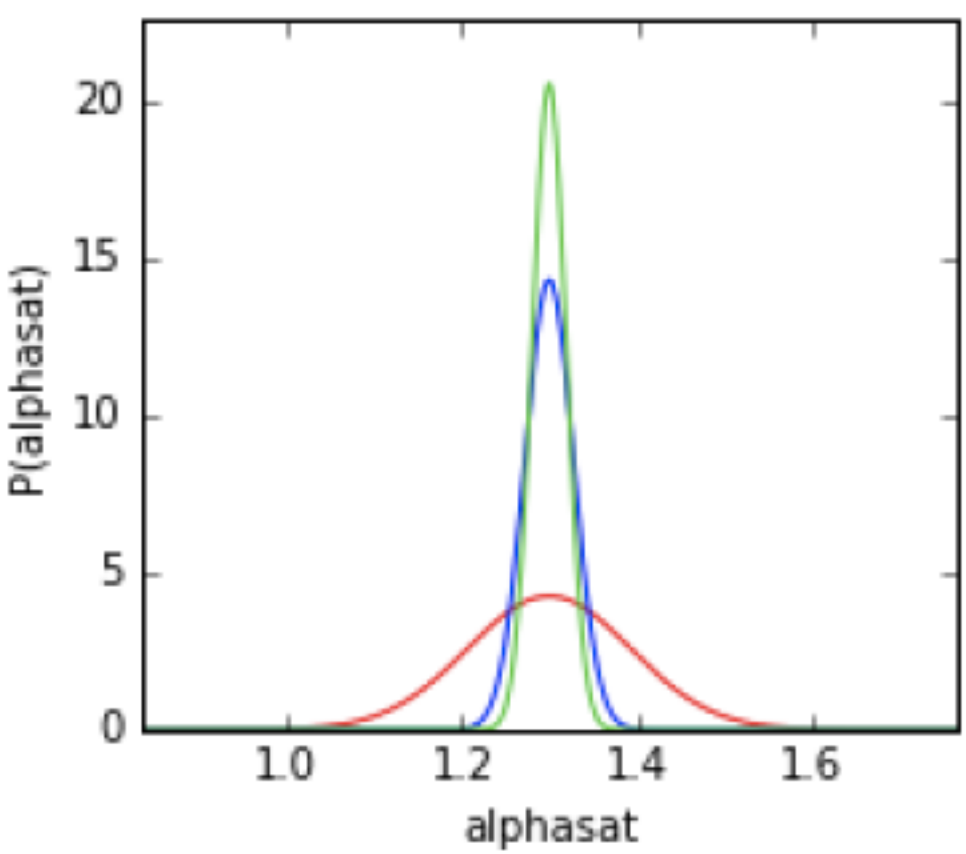


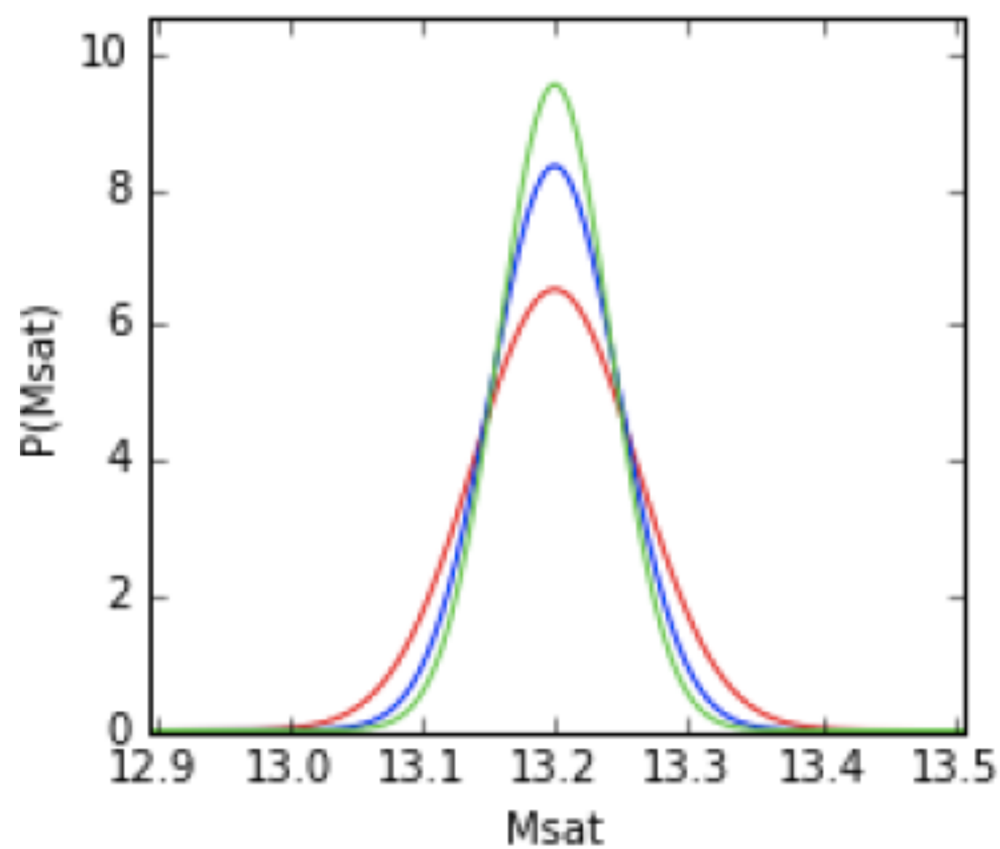
Impact of joint covariance

Perform a Fisher matrix analysis – HOD case
Cluster counts are independent of HOD!

Red line: APS only
Blue line: independent APS and cluster counts
Green line: full joint APS and cluster counts

significant difference





Joint covariance

Cosmological case
9 bins, 30<l<300, Δl=30

HOD case
7 bins, 300<l<1000, Δl=70

Large nongaussianities at small scales and small redshifts