Cosmology and Particle Physics

Rogerio Rosenfeld
IFT-UNESP & ICTP-SAIFR & LIneA

Lecture I: The average Universe
Lecture II: Origins
→ Lecture III: The perturbed Universe

9th CLASHEP

San Juan del Rio, Mexico, 8–21 March 2017

Plan:

III.1 – Growth of perturbations

III.2 – Perturbations in a newtonian universe

III.3 – The power spectrum

III.4 – Baryon acoustic oscillations

III.5 – The six-parameter universe

III.6 – Observations: the case of DES

III.1- Growth of perturbations

Inflation generated small density perturbations in the early Universe.

These perturbations grew and originated the structures we now observe.

These early fluctuations were detected for the first time in the cosmic microwave background (~1991) and were tiny:

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} \simeq 10^{-5}$$

Evolution of perturbations

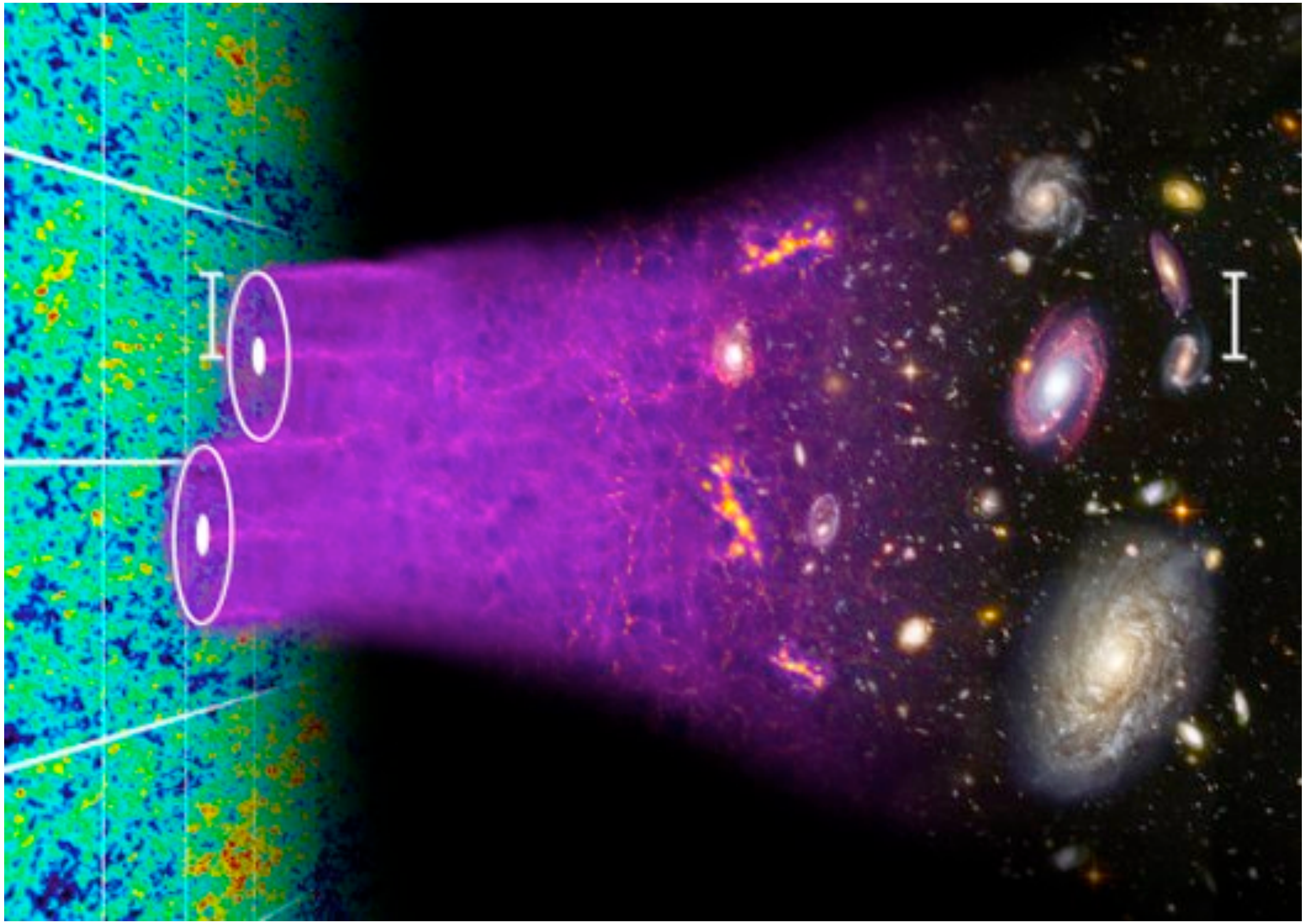


Illustration courtesy of Chris Blake and Sam Moorfield

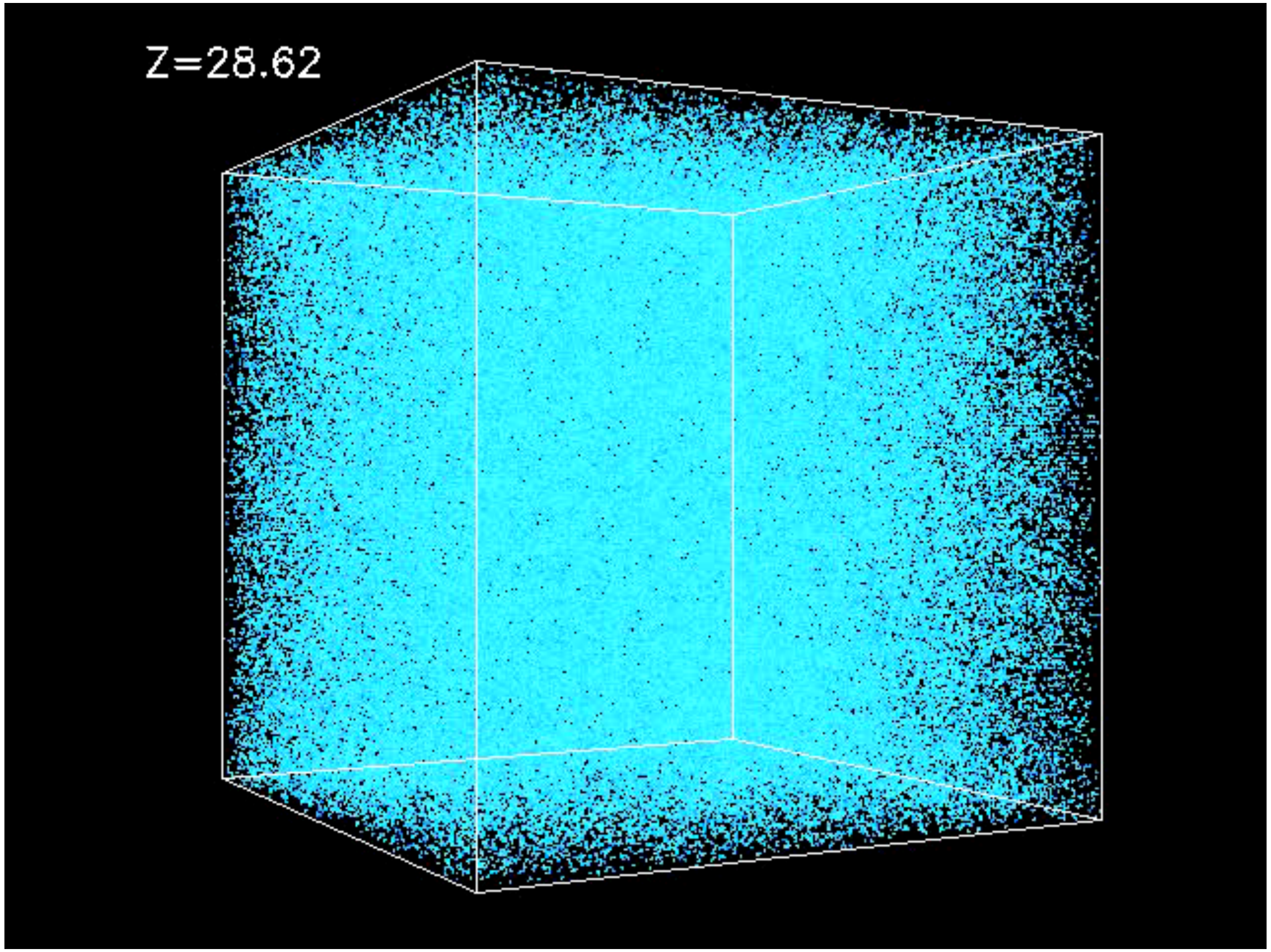
Evolution of perturbations:

$$\delta G_{\mu\nu} = 8\pi G \delta T_{\mu\nu}$$

It is not possible to fully describe the non-linear regime analytically in GR:
large numerical simulations are necessary (Millenium, MICE, etc…) – and are done using Newtonian physics. Sometimes only cold dark matter is considered because it is dissipationless. Baryons are complicated but important.

Large scale structure: N-body simulations

Universe in a box (A. Kravtsov)



The movie illustrates the formation formation of clusters and large-scale filaments in the Cold Dark Matter model with dark energy. Evolution of structures in a 43 Mpc box from redshift of 30 to the present epoch . At the initial epoch (z=30), when the age of the Universe was less than 1% of its current age, distribution of matter appears to be uniform. As time goes on, the fluctuations grow resulting in a wealth of structures from the smallest bright clumps which have sizes and masses similar to those of galaxies to the dark large filaments.

III.2- Perturbations in a newtonian Universe

Perturbations can be analytically studied when they are small – use perturbation theory.

This can be done in full GR.

At scales smaller than the Hubble radius and for non-relativistic matter one can simplify the problem and use Newtonian physics:

Fluid dynamics in an expanding universe

Fluid dynamics: consider a fluid element with mass density ρ and velocity u at a position r and a time t:

• continuity equation (conservation of matter)

$$\partial_t \rho = -\vec{\nabla}_r \cdot (\rho \vec{u})$$

• Euler equation ("F=ma")

$$(\partial_t + \vec{u} \cdot \vec{\nabla}_r)\vec{u} = -\frac{\vec{\nabla}_r P}{\rho} - \vec{\nabla}_r \Phi$$

• Poisson equation (density is the source of gravity)

$$\nabla_r^2 \Phi = 4\pi G \rho$$

In an expanding universe it is convenient to use comoving coordinates x:

$$\vec{r}(t) = a(t)\vec{x}$$

and velocities can be written as:

$$\vec{u}(t) = \dot{\vec{r}}(t) = \dot{a}(t)\vec{x} + a\dot{\vec{x}} = \frac{\dot{a}}{a}\vec{r} + \vec{v} = H\vec{r} + \vec{v}$$

Hubble flow

Peculiar velocity

Consider small perturbations around the background (average) values:

$$\rho(\vec{r},t) = \bar{\rho}(t) + \delta\rho(\vec{r},t)$$

$$P(\vec{r},t) = \bar{P}(t) + \delta P(\vec{r},t)$$

$$\vec{u}(\vec{r},t) = \bar{\vec{u}}(t) + \delta\vec{u}(\vec{r},t)$$

$$\Phi(\vec{r},t) = \bar{\Phi}(t) + \delta\Phi(\vec{r},t)$$

Using the linearized equations one can derive a single equation for the evolution of the matter (P=0) density perturbation:

$$\delta_m = \frac{\rho_m - \bar{\rho}_m}{\bar{\rho}_m}$$

$$\ddot{\delta}_m + 2H\dot{\delta}_m - \frac{3}{2}H^2\Omega_m(t)\delta_m = 0$$

Ex. 1: Show that in a matter dominated universe

$$\Omega_m = 1,\ a(t) \propto t^{2/3},\ H = \frac{2}{3t}$$

the matter density perturbation grows as

$$\boxed{\delta_m \propto a(t)}$$

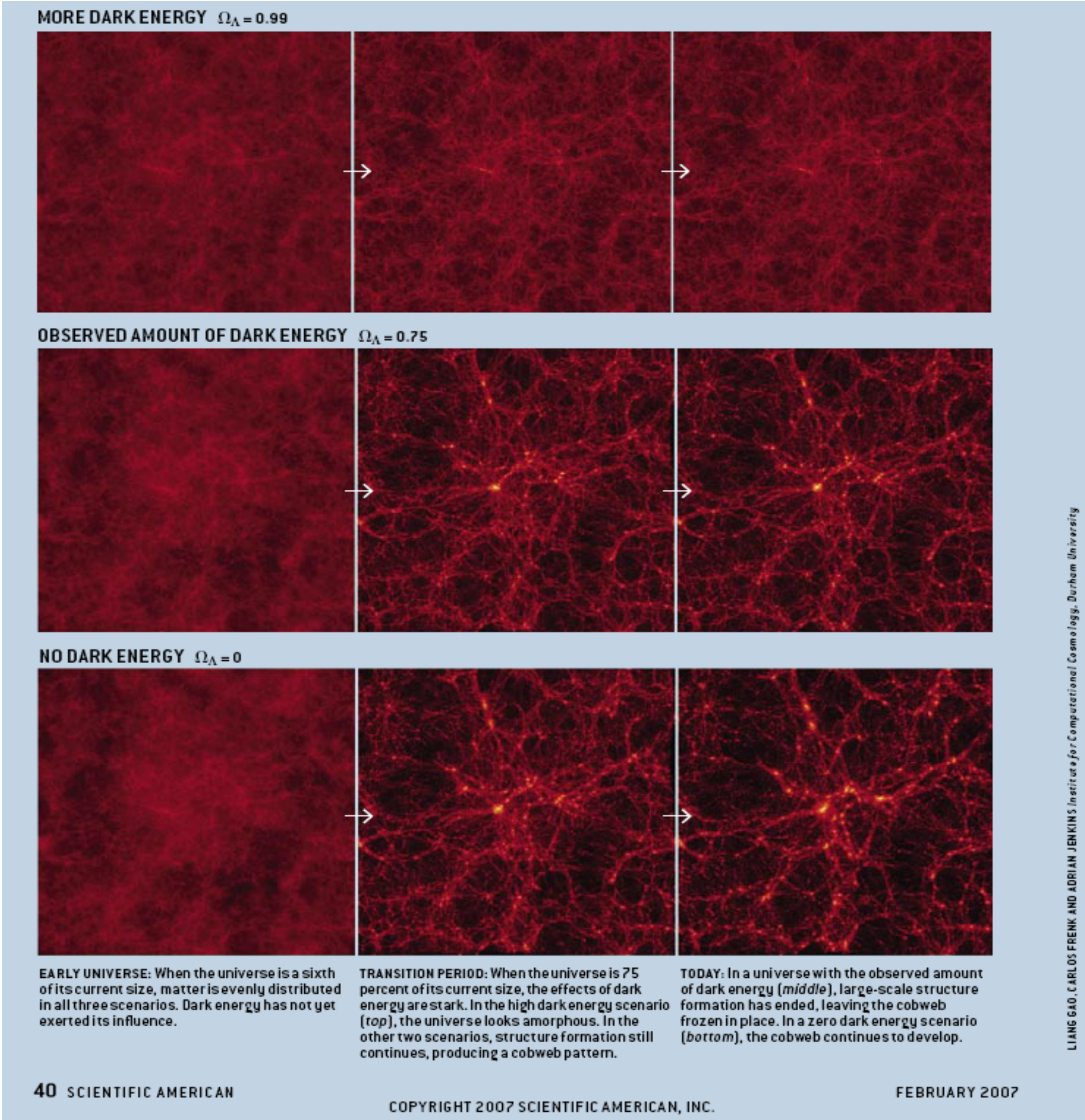
and that in a Λ-dominated universe

$$\Omega_m = 0,\ a(t) \propto e^{Ht},\ H = \text{const}$$

$$\boxed{\delta_m = \text{const}}$$

Dark energy suppresses structure formation

(Weinberg's anthropic argument)



CHRISTOPHER J. CONSELICE

III.3- The power spectrum

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, ...

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

Two-point spatial correlation function

$$\langle \delta(\vec{x}_1)\delta(\vec{x}_2) \rangle = \xi(\vec{x}_1 - \vec{x}_2) = \xi(|\vec{x}_1 - \vec{x}_2|) = \xi(r)$$

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

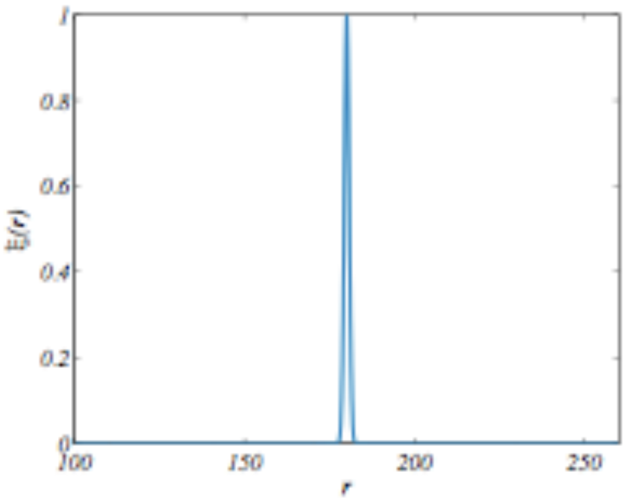
One can also define a power spectrum:

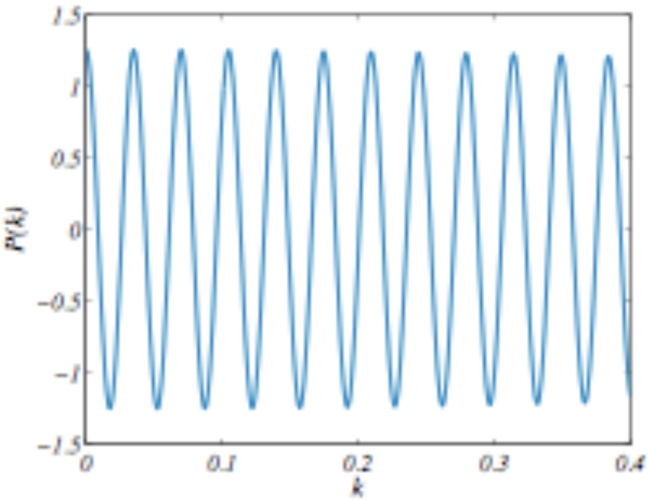
$$P(k) = \int d^3 r \xi(r) e^{i\vec{k}.\vec{r}}$$

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

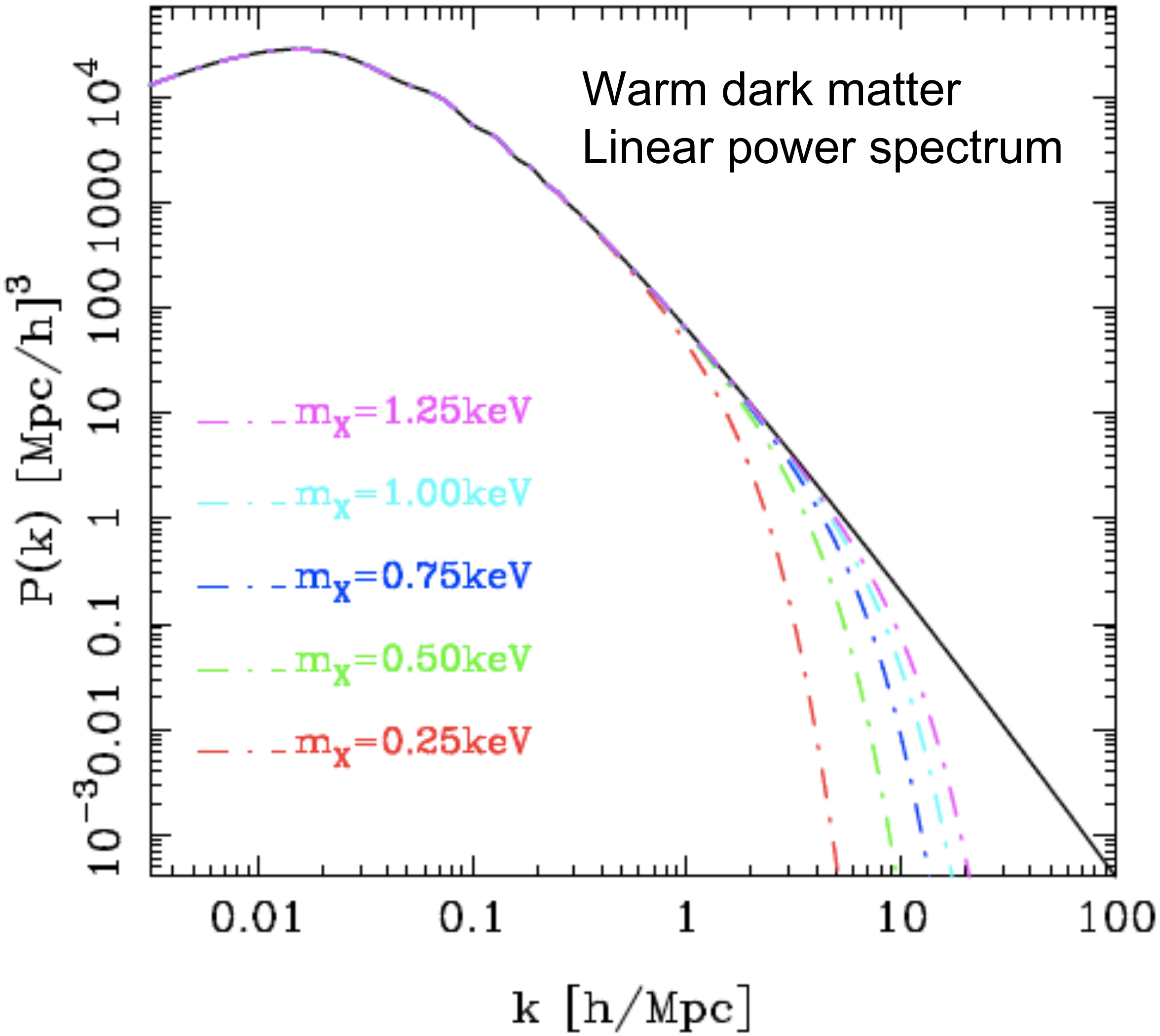
Sharp peak in correlation results in oscillations in the power spectrum

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





Power spectrum is sensitive to new physics



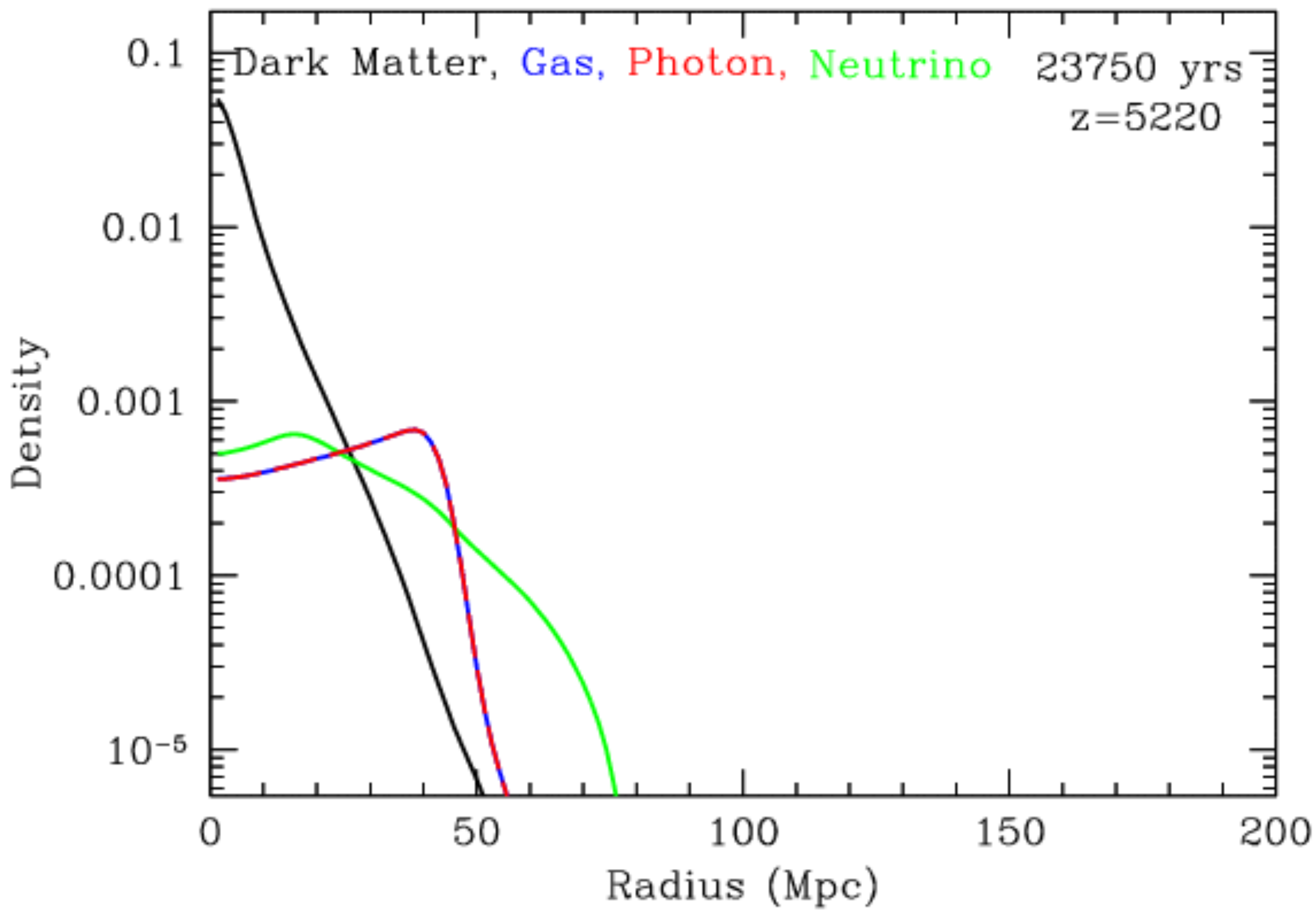
III.4- Baryon acoustic oscillation

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.

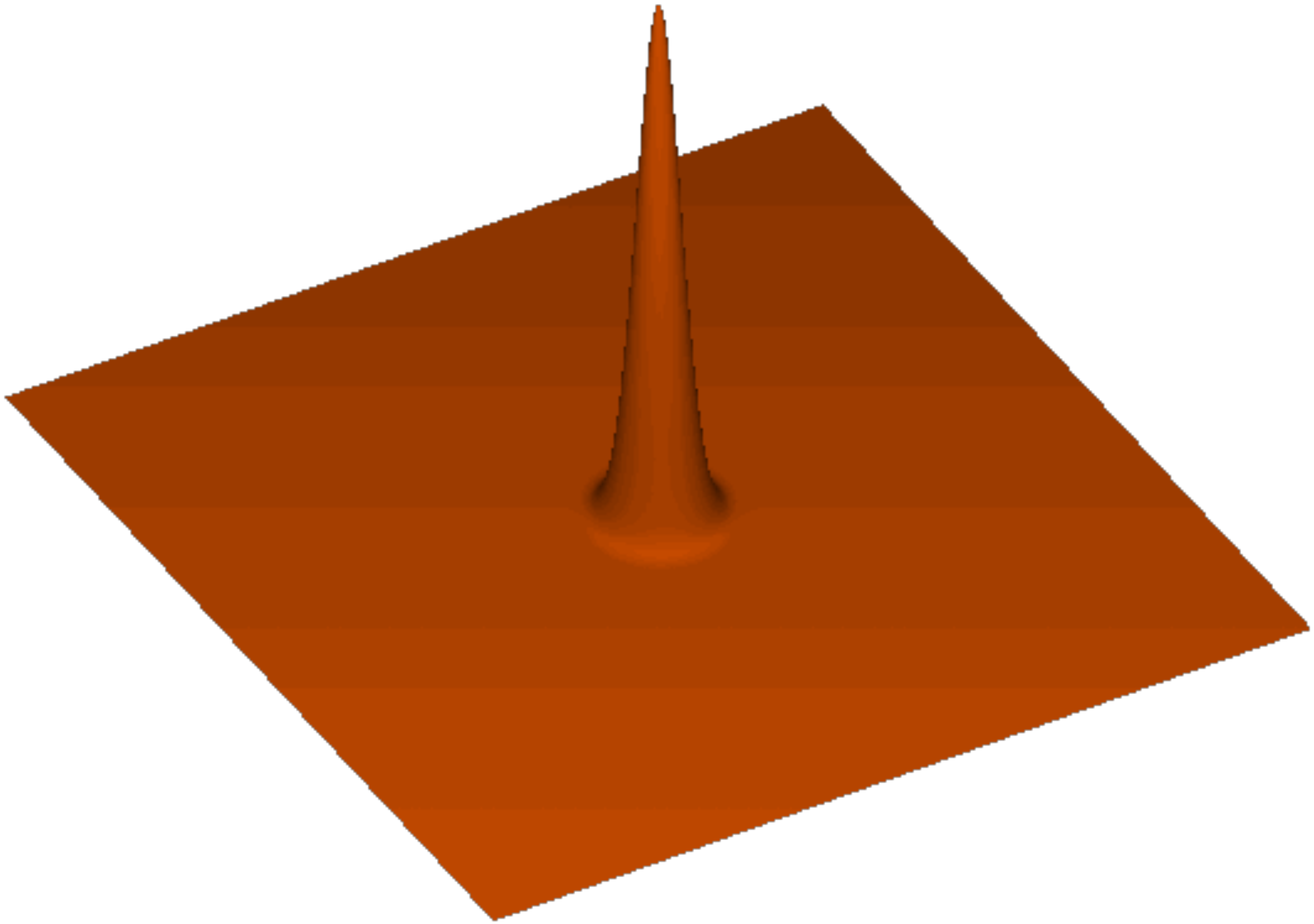
Evolution of one spherical perturbation

Eisenstein



Evolution of one spherical perturbation

Eisenstein



BAO scale

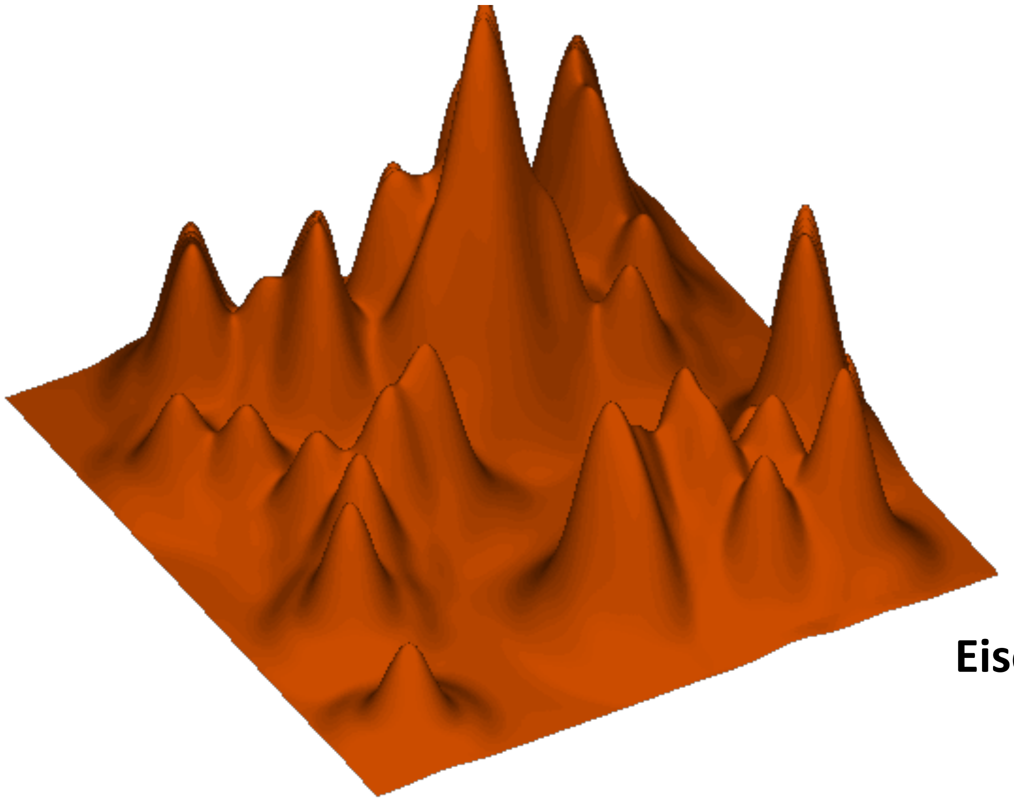
Standard ruler in the sky

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

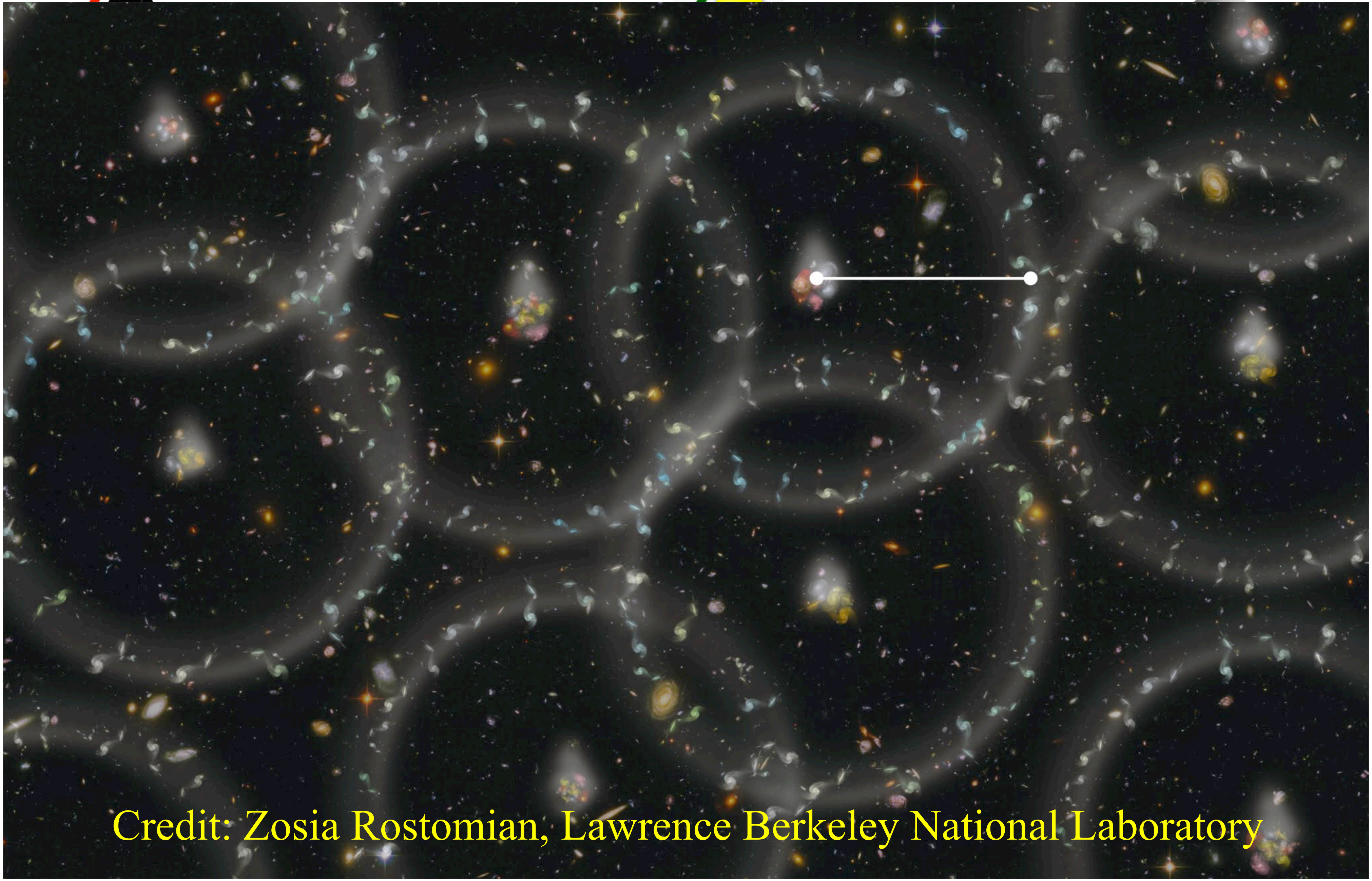
Cosmological parameters

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

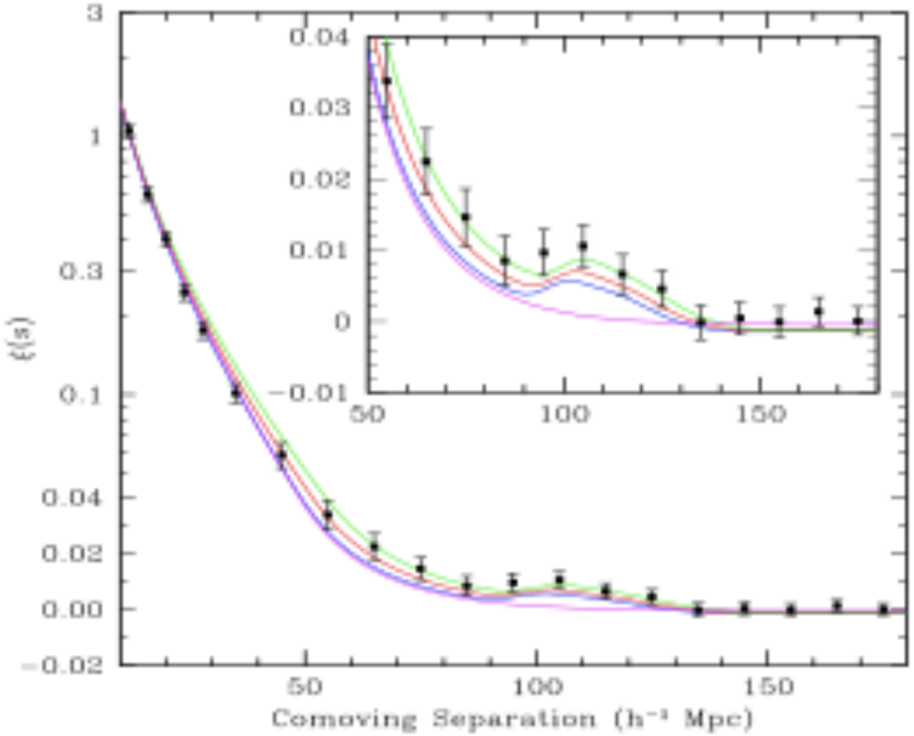
Things are more complicated: superposition of shells with different locations and different amplitudes



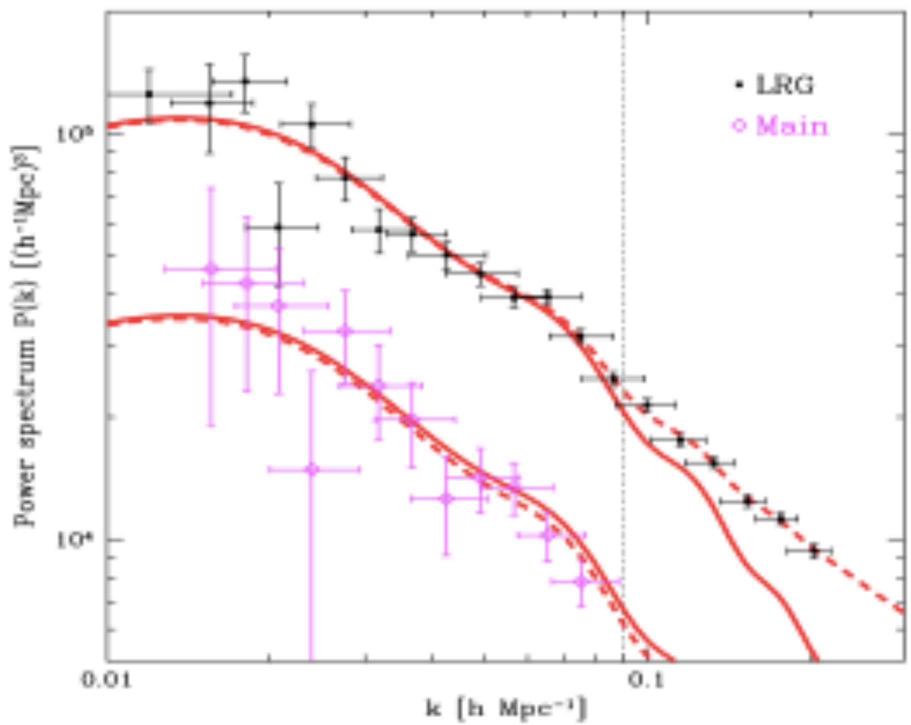
Eisenstein


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)



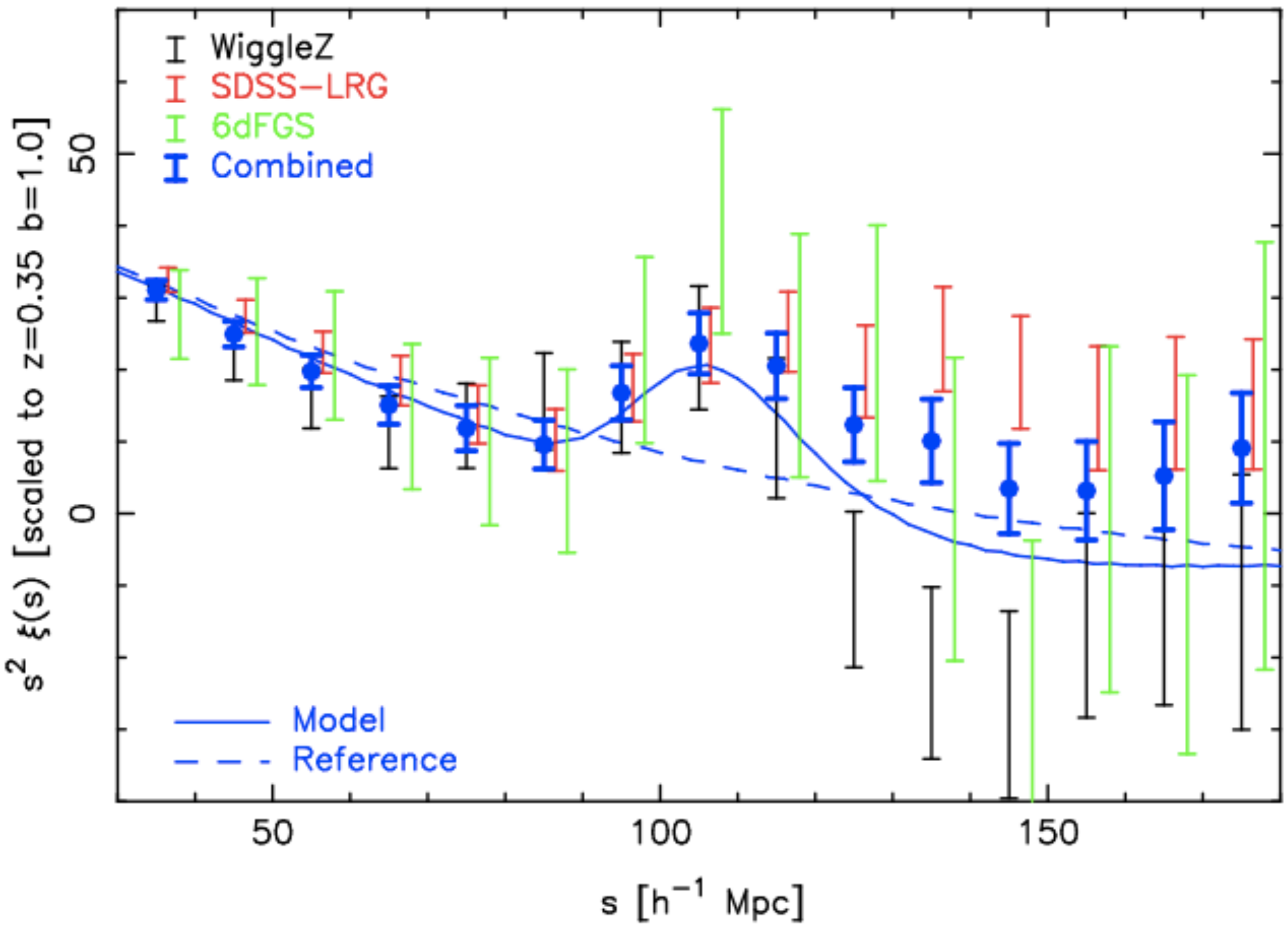
Tegmark et al (2006)

DR3, z ~ 0.35

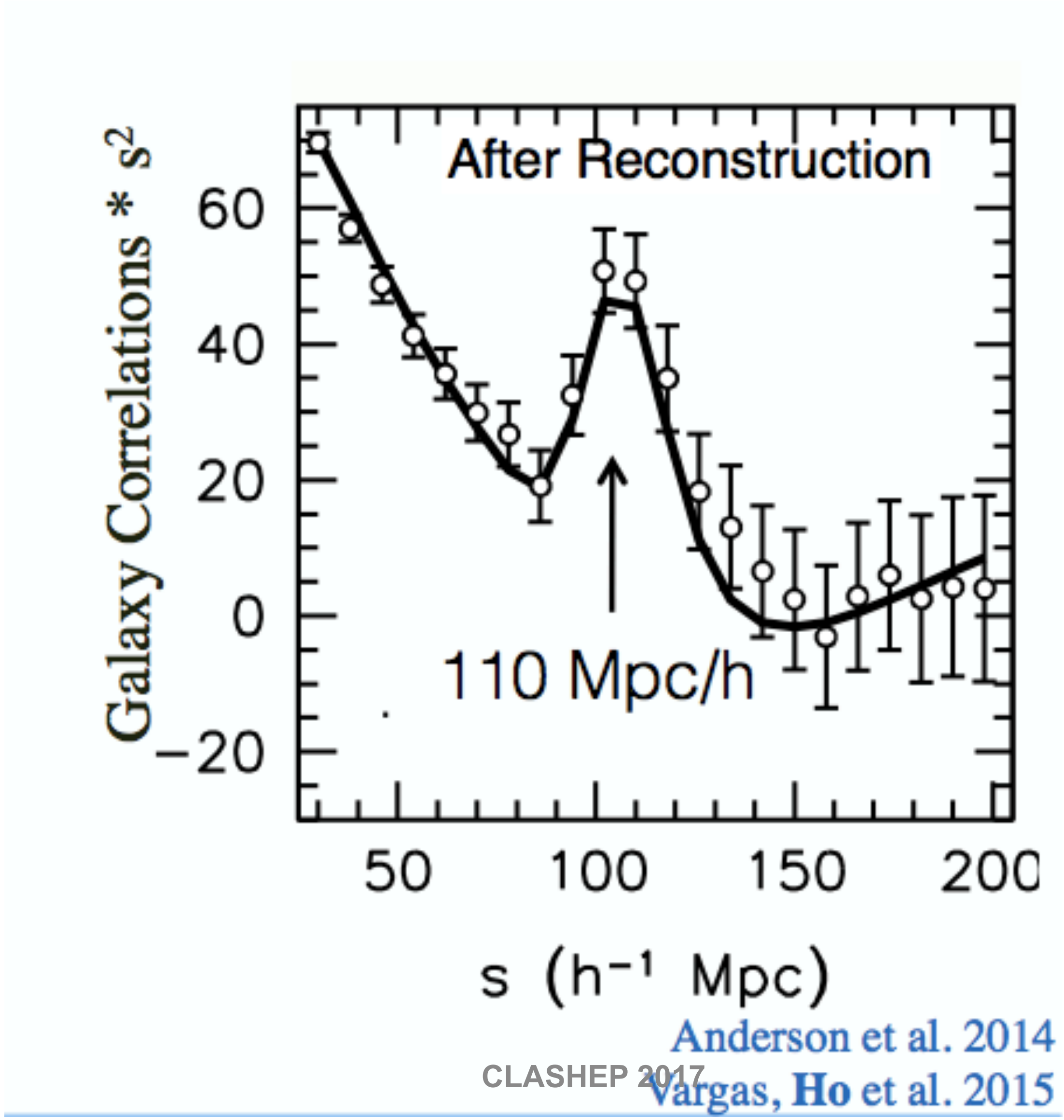
Results from WiggleZ(1108.2635):

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

4.9σ significance



Galaxy 2-point correlation function



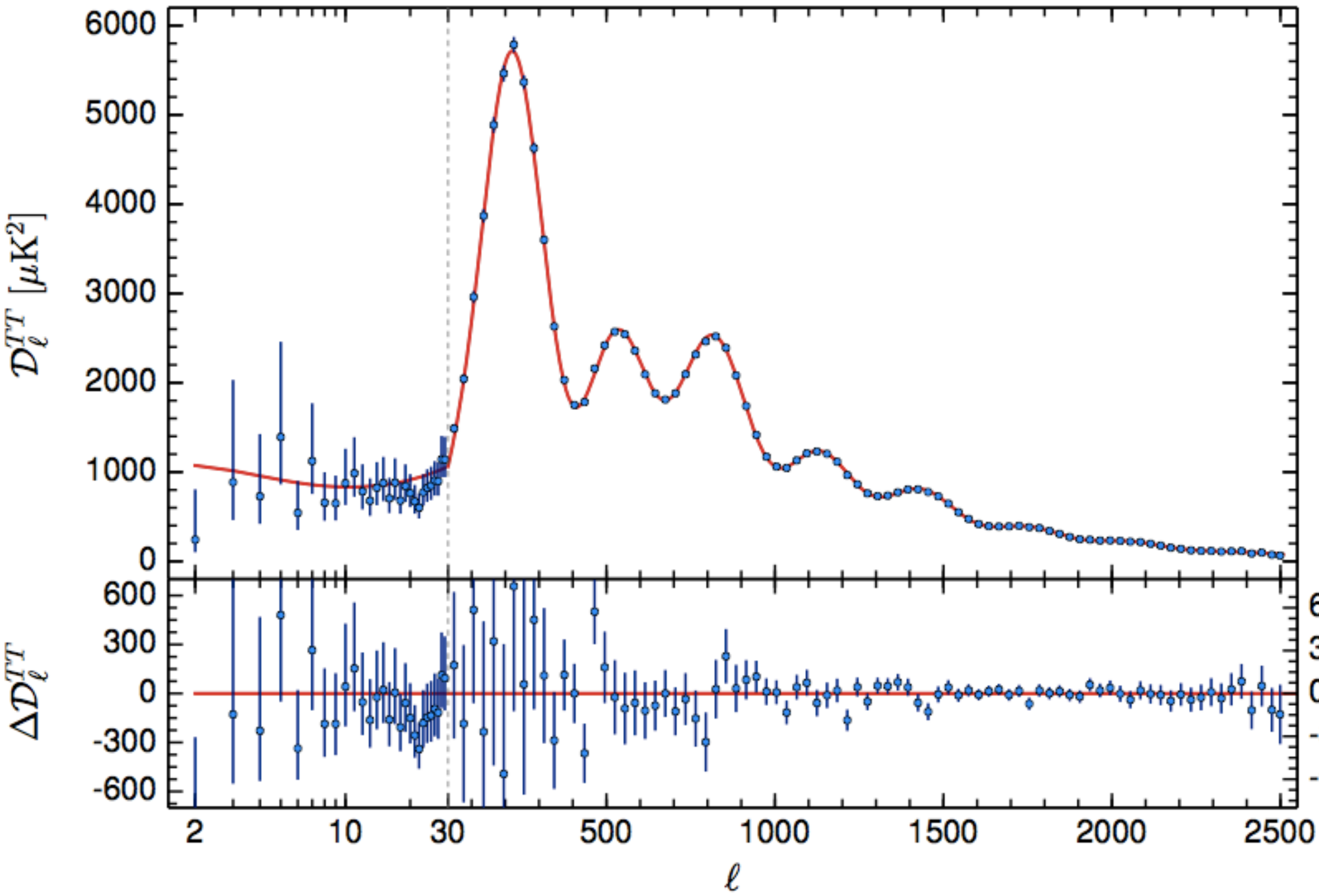
III.5- The six-parameter Universe

Standard cosmological model used by Planck:
spatially-flat ΛCDM cosmology with a power-law spectrum of scalar perturbations.

Baseline parameters: H_0,$A_{s,}$$n_s$,$\Omega_b$,$\Omega_{cdm}$, optical depth.

Beyond baseline parameters:
$\Sigma\ m_{\nu i}$, w, Ω_k,

Planck (1502.01589)



Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062

Table 5. Constraints on 1-parameter extensions to the base ΛCDM model for combinations of *Planck* power spectra, *Planck* lensing, and external data (BAO+JLA+H_0, denoted "ext"). All limits and confidence regions quoted here are 95 %.

Parameter	TT	TT+lensing	TT+lensing+ext	TT, TE, EE	TT, TE, EE+lensing	TT, TE, EE+lensing+ext
Ω_K	$-0.052^{+0.049}_{-0.055}$	$-0.005^{+0.016}_{-0.017}$	$-0.0001^{+0.0054}_{-0.0052}$	$-0.040^{+0.038}_{-0.041}$	$-0.004^{+0.015}_{-0.015}$	$0.0008^{+0.0040}_{-0.0039}$
Σm_ν [eV]	< 0.715	< 0.675	< 0.234	< 0.492	< 0.589	< 0.194
N_{eff}	$3.13^{+0.64}_{-0.63}$	$3.13^{+0.62}_{-0.61}$	$3.15^{+0.41}_{-0.40}$	$2.99^{+0.41}_{-0.39}$	$2.94^{+0.38}_{-0.38}$	$3.04^{+0.33}_{-0.33}$
Y_P	$0.252^{+0.041}_{-0.042}$	$0.251^{+0.040}_{-0.039}$	$0.251^{+0.035}_{-0.036}$	$0.250^{+0.026}_{-0.027}$	$0.247^{+0.026}_{-0.027}$	$0.249^{+0.025}_{-0.026}$
$dn_s/d\ln k$	$-0.008^{+0.016}_{-0.016}$	$-0.003^{+0.015}_{-0.015}$	$-0.003^{+0.015}_{-0.014}$	$-0.006^{+0.014}_{-0.014}$	$-0.002^{+0.013}_{-0.013}$	$-0.002^{+0.013}_{-0.013}$
$r_{0.002}$	< 0.103	< 0.114	< 0.114	< 0.0987	< 0.112	< 0.113
w	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$

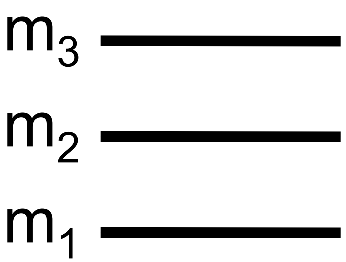
Neutrino masses in cosmology

Neutrino oscillations experiments have determined that neutrinos have mass – mass eigenstates are denoted by m_1, m_2 and m_3.

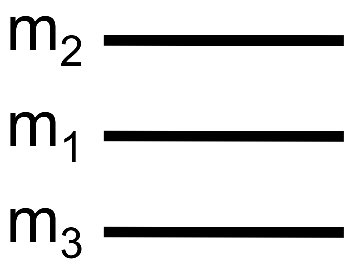
These experiments are sensitive only to the squared-mass differences:

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

It is still an open question the ordering (or hierarchy) of the neutrino mass eigenstates:



Normal hierarchy



Inverted hierarchy

Cosmology is sensitive to the sum of neutrino masses (CMB, damping of small scale fluctuations due to free-streaming) :

$$\Sigma = \sum_{i=1}^{3} m_i$$

Official Planck bound (assuming a 6-parameter ΛCDM models) combining with BAO+SN+H_0:

$$\Sigma < 0.23 \text{ eV } @95\%\text{CL}$$

but there are claims of more stringent bound [1511.05983]

$$\Sigma < 0.13 \text{ eV } @95\%\text{CL}$$

It is interesting to notice that Σ depends on the neutrino mass hierarchy. From the oscillation data:

$$\Sigma \geq \begin{cases} 58.5 \pm 0.48 \text{ meV} & \text{(NH)} \\ 98.6 \pm 0.85 \text{ meV} & \text{(IH)} \end{cases}$$

The equality is attained when the lightest mass is zero.

Therefore if from cosmology one finds $\Sigma < 0.098$ eV then one can say that the inverted hierarchy is excluded.

Again there are claims of strong evidence (in the bayesian sense) for normal hierarchy [1703.03425].

III.6- Observations: the case of DES

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 ...

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)

Accelerators ↔ Large scale galaxy surveys analogy:

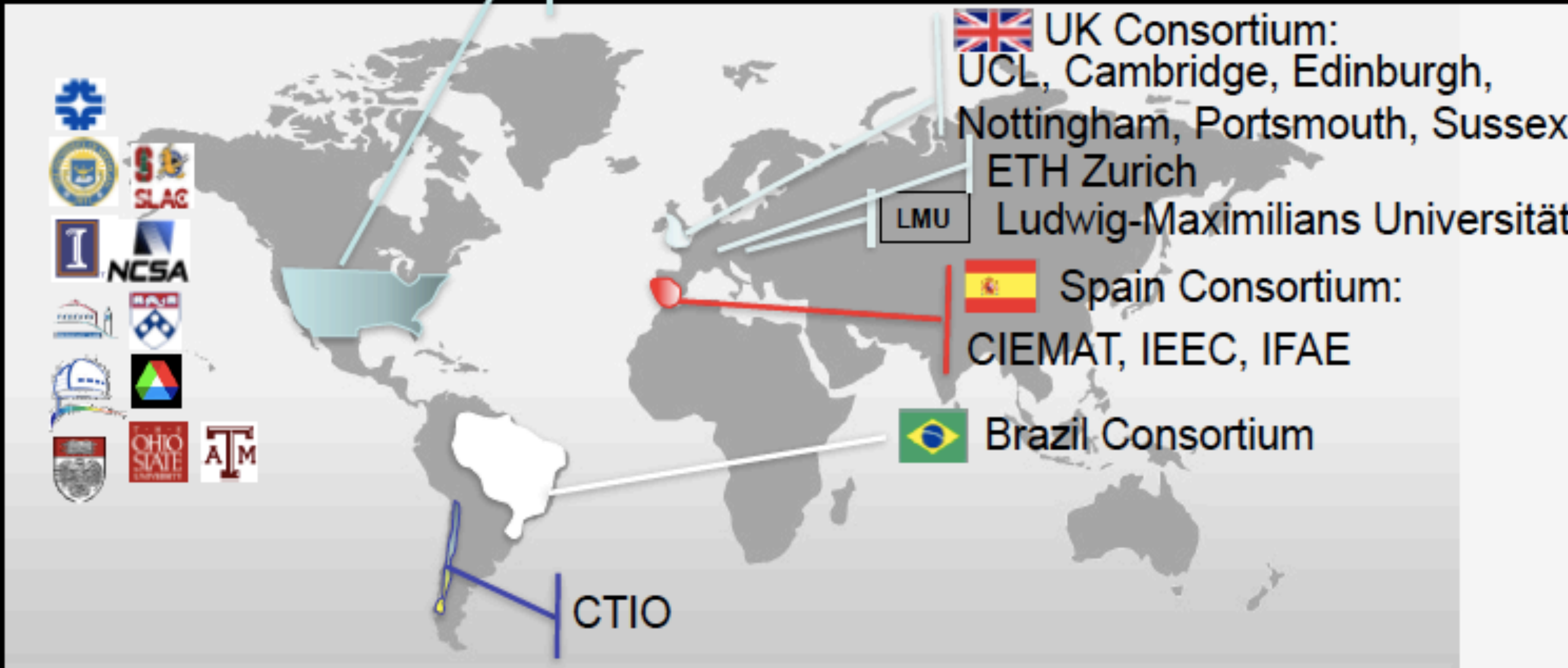
- Energy ↔ redshift
- Luminosity ↔ area & observation time
- Energy resolution ↔ redshift errors
- Energy calibration ↔ objects with known redshifts
- p_T cuts, etc ↔ magnitude cuts, mask, etc
- Final data set ↔ value added catalogs
- Higgs bump hunting ↔ BAO bump hunting
- PT ok at high E ↔ PT ok at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



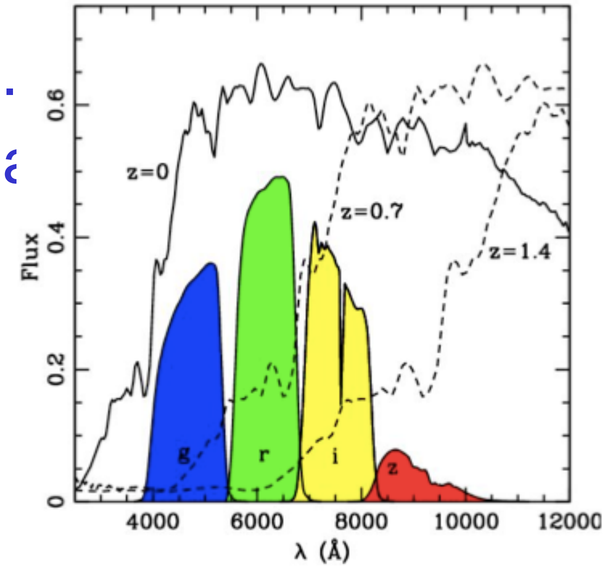
DES-Brazil is a LIneA Project

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.
  (+ 100,000 clusters + 4,000 SN Ia
- Photometric redshift with 5 filters
- Blanco telescope (4m, CTIO)
- DECam – 62 (+12) CCDs (LBNL) - 570 Megapixels



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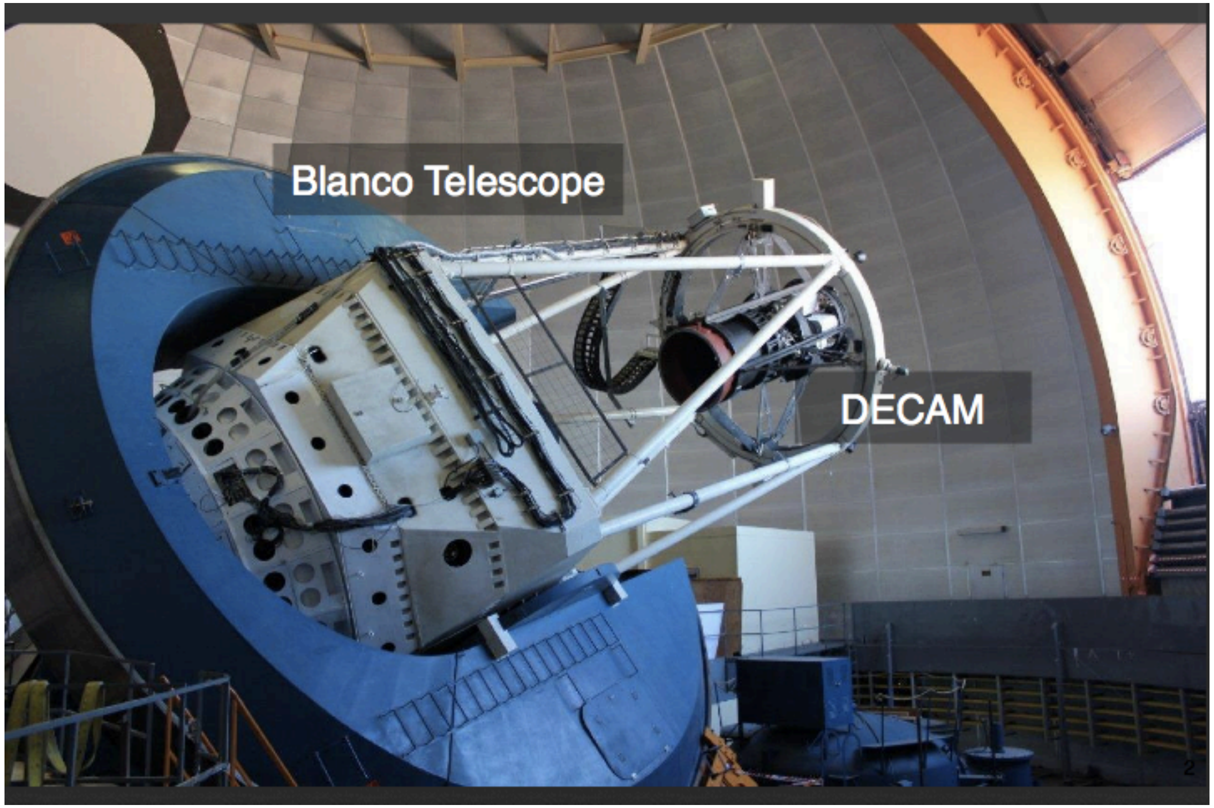
DES site: 4m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile

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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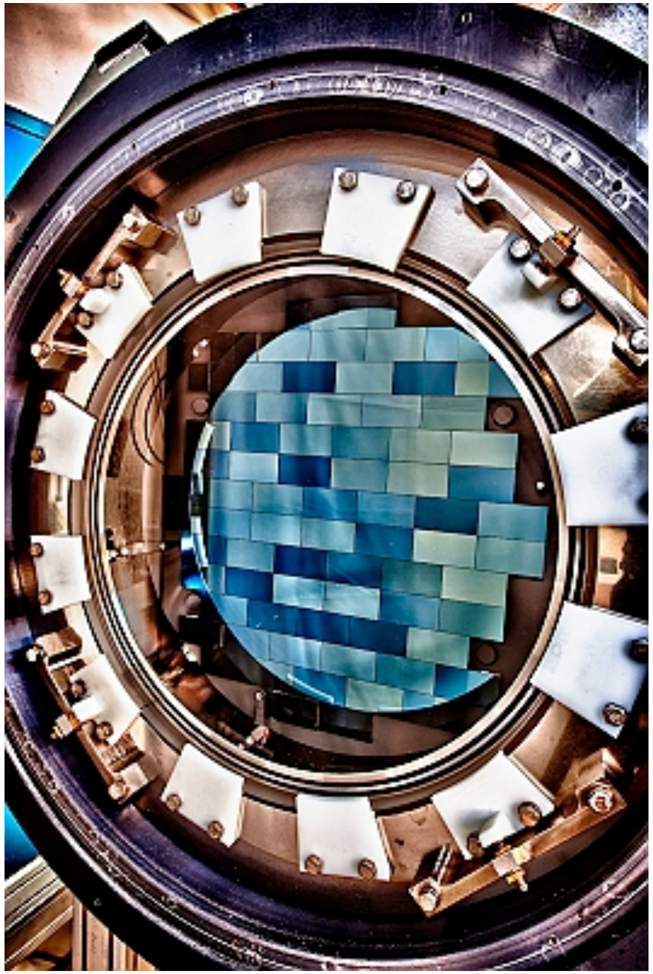
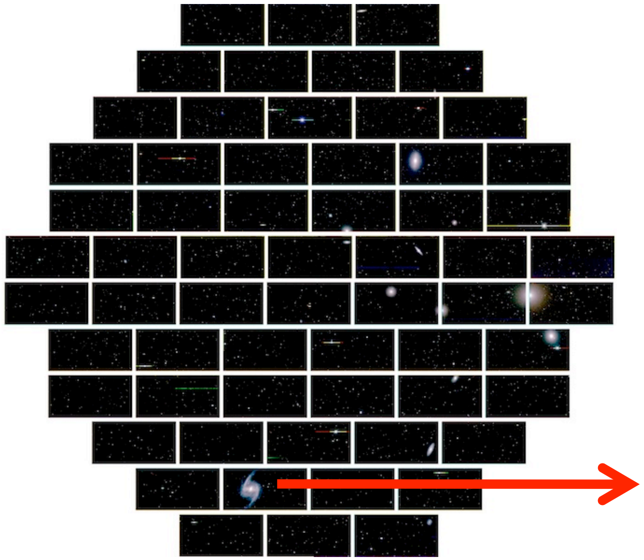
DECam



arXiv:1504.02900



Fornax cluster of galaxies

Barred spiral galaxy NGC 1365 in the Fornax cluster of galaxies

DES SV image of a deep SN field

3 deg^2 field of view

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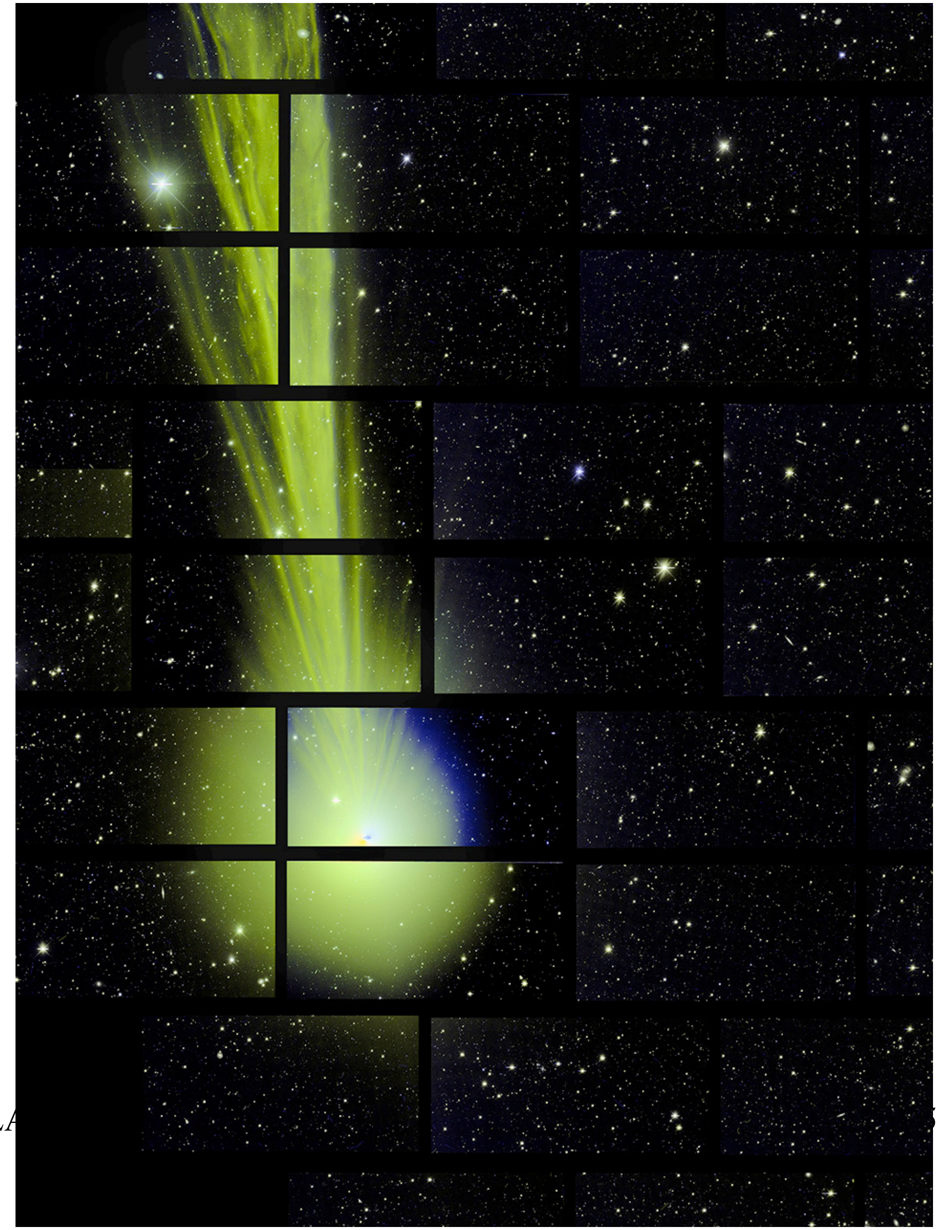
Dark Energy Camera catches breathtaking glimpse of comet Lovejoy

December 27 2014

82 million km away



DES Data Management

Each exposure (in a given filter) generates 500Mb

300 exposures/night – 150 Gb/night

Transferred and processed at NCSA in Urbana

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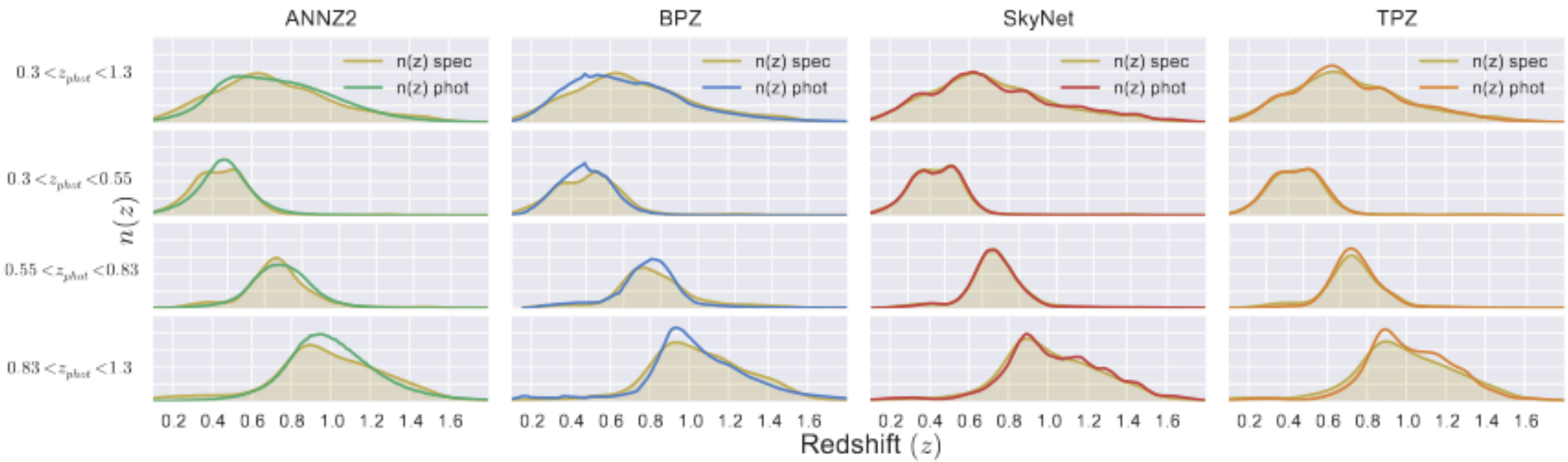
Photometric redshift

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.



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Brazilian infrastructure contribution

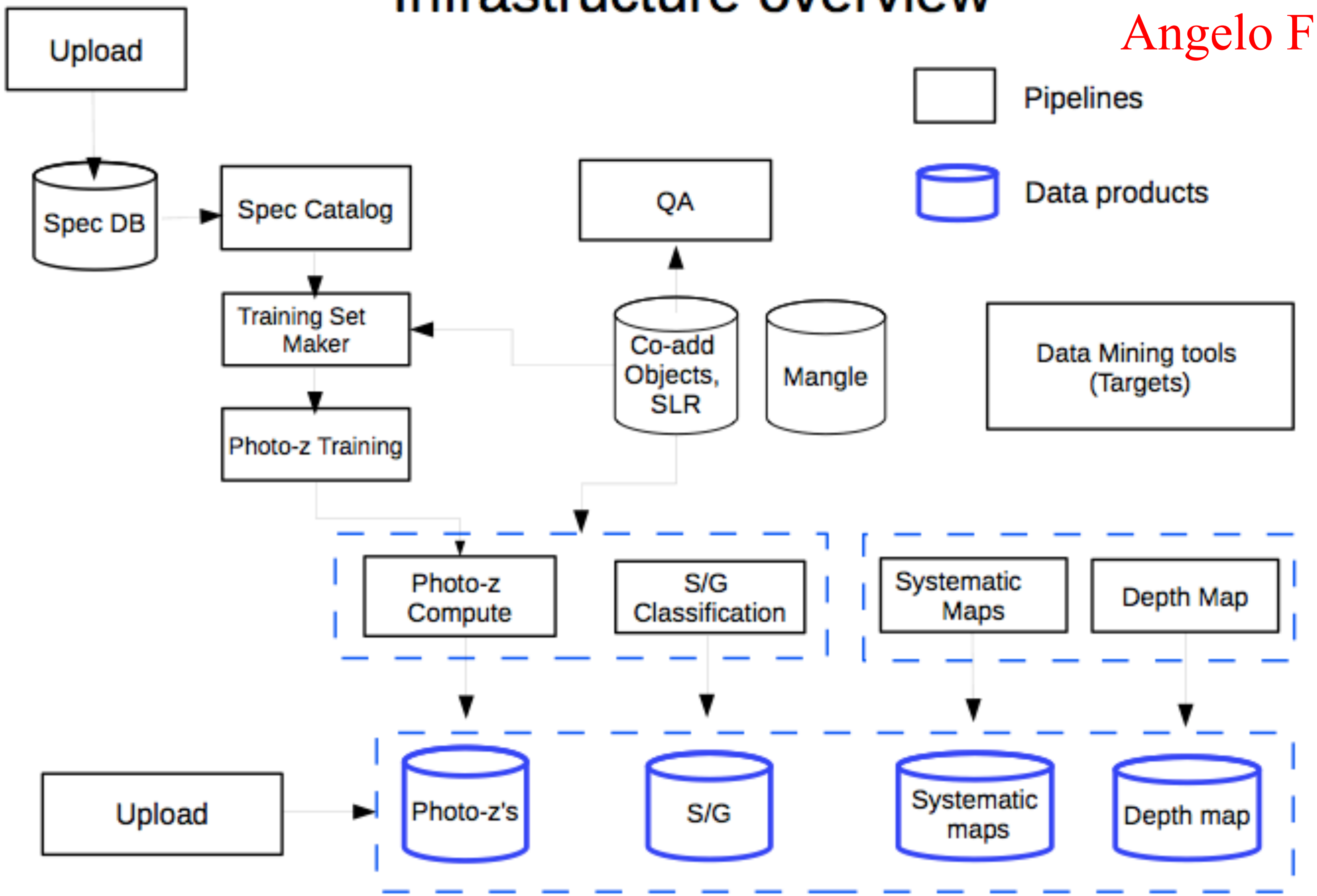
- QuickReduce: software for fast assessment of image quality at CTIO

- 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…

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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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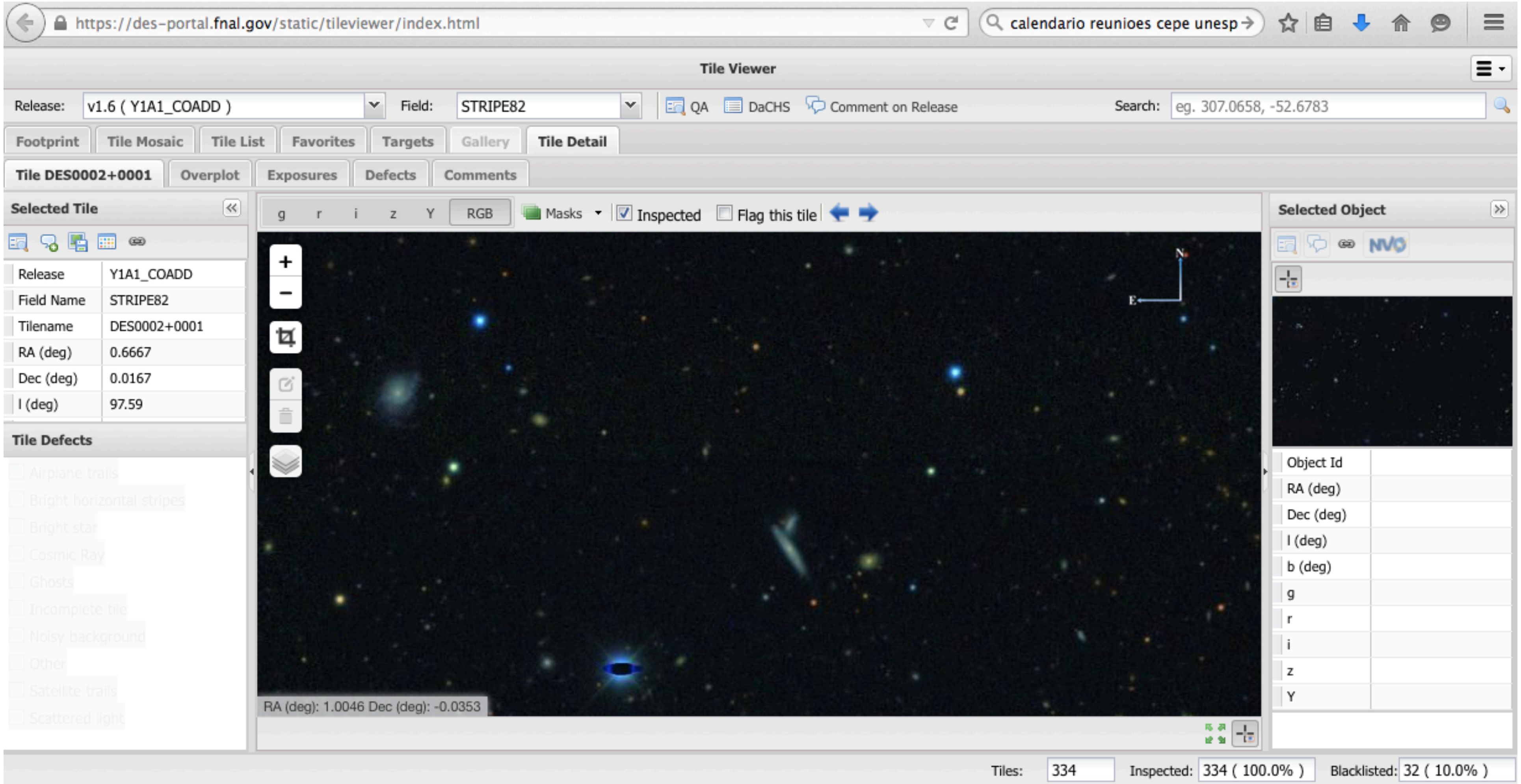
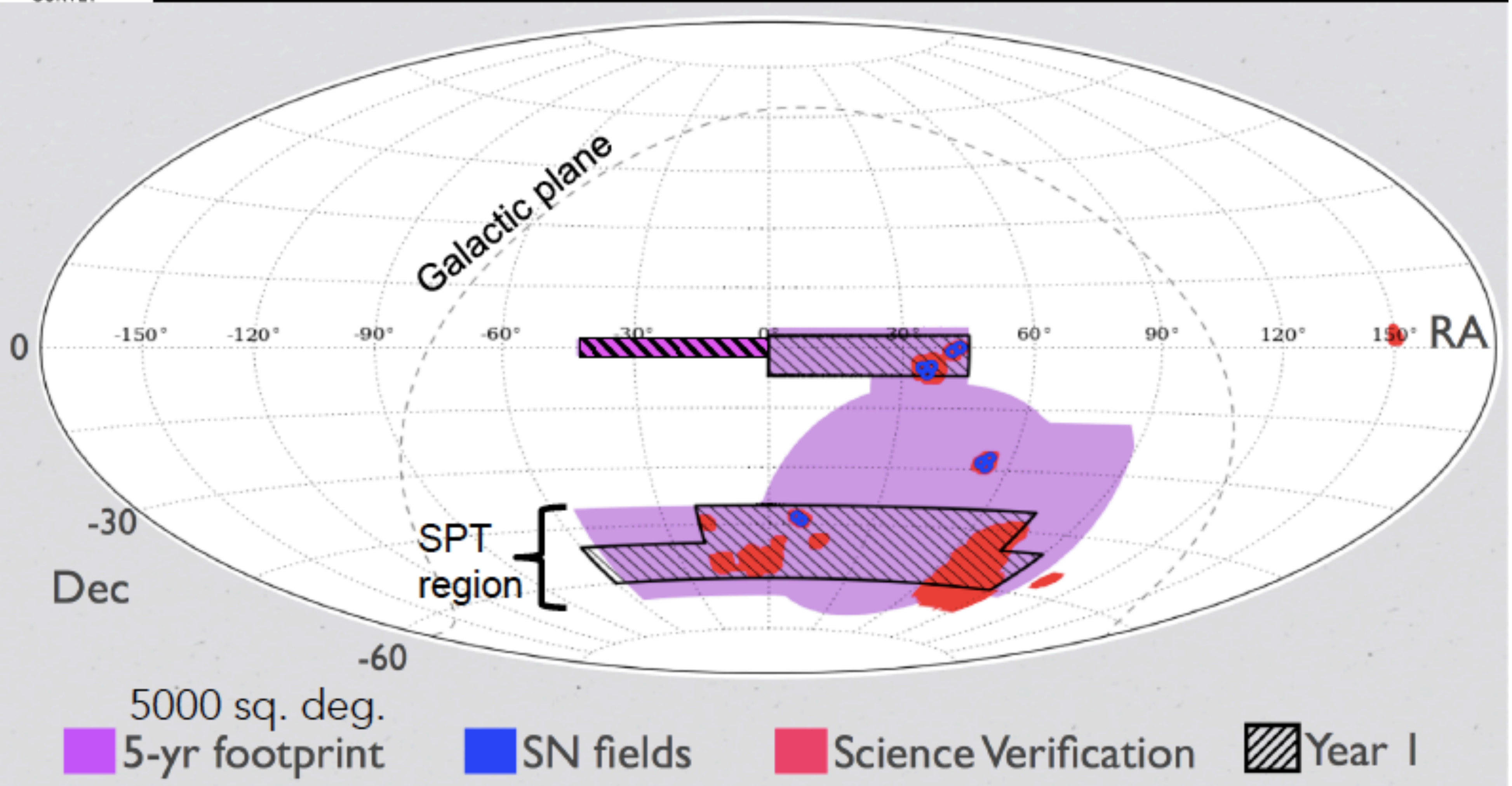
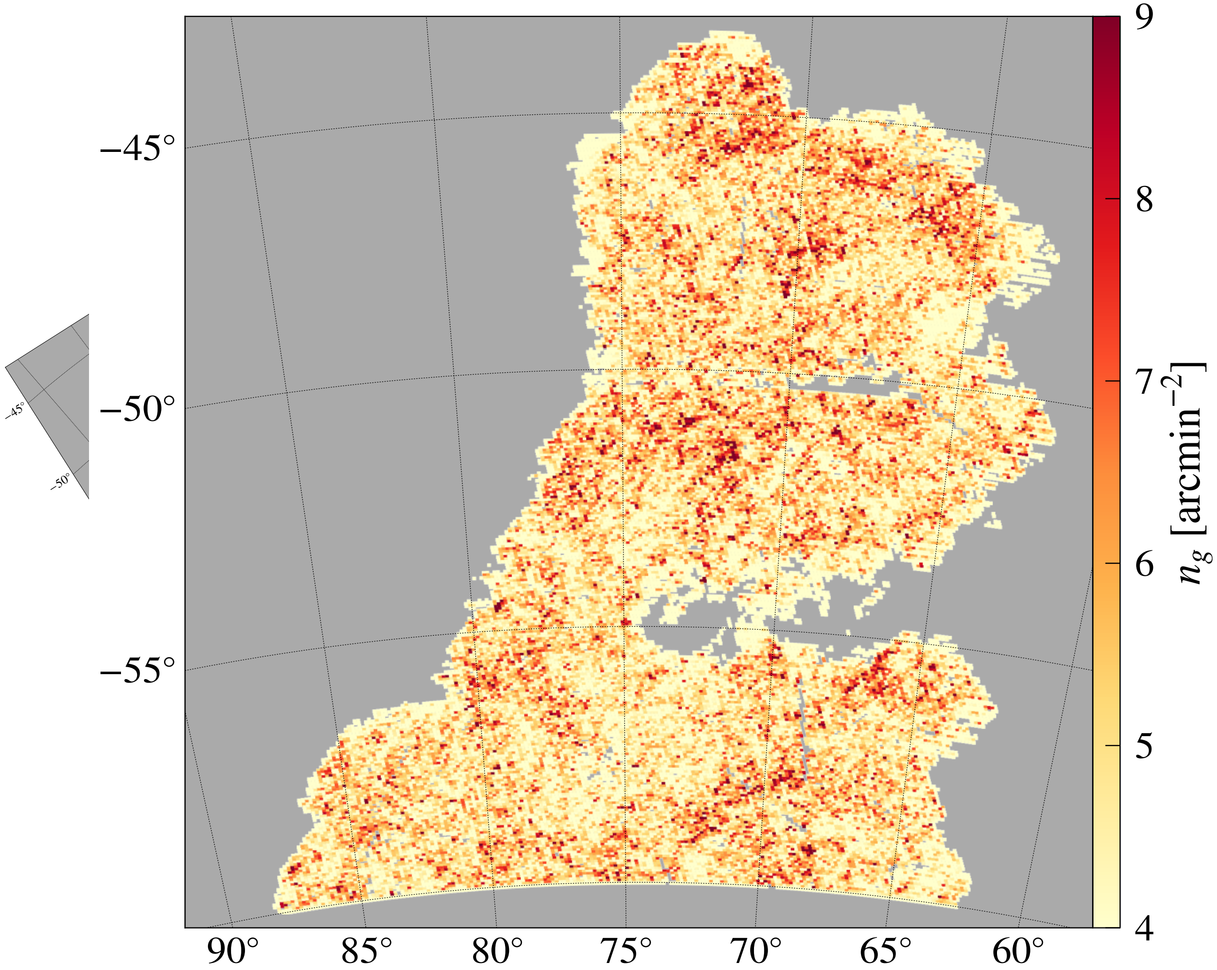


DES Survey Footprint

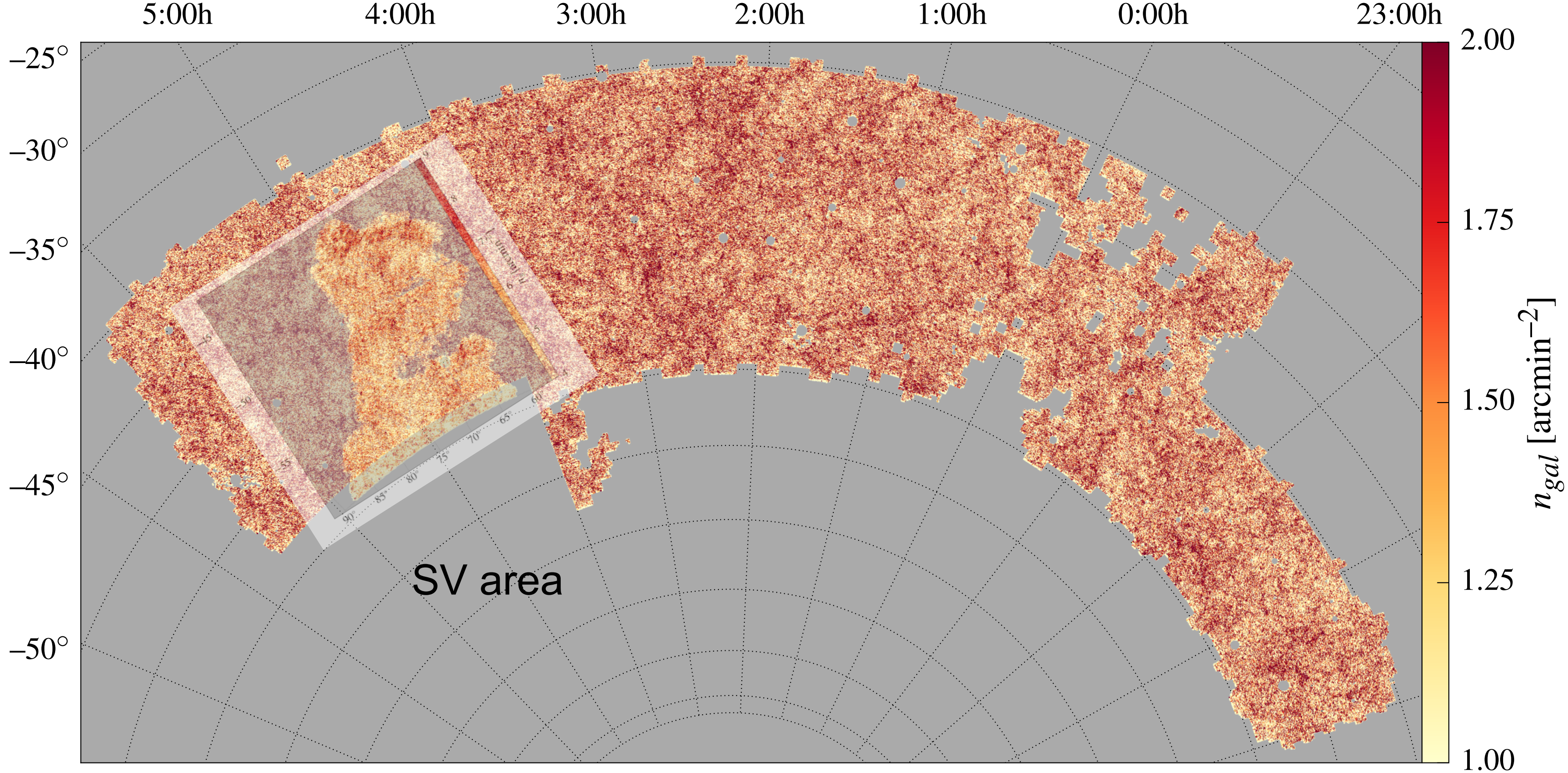


- Science Verification (SV): ~250 sq. deg. to ~full depth; 45 M objects
- Year 1 (Y1): ~2000 sq. deg; overlap SPT, SDSS: 4/10 tilings; 140 M objects

DES SV Galaxy Distribution



DES Year 1 Galaxy Distribution

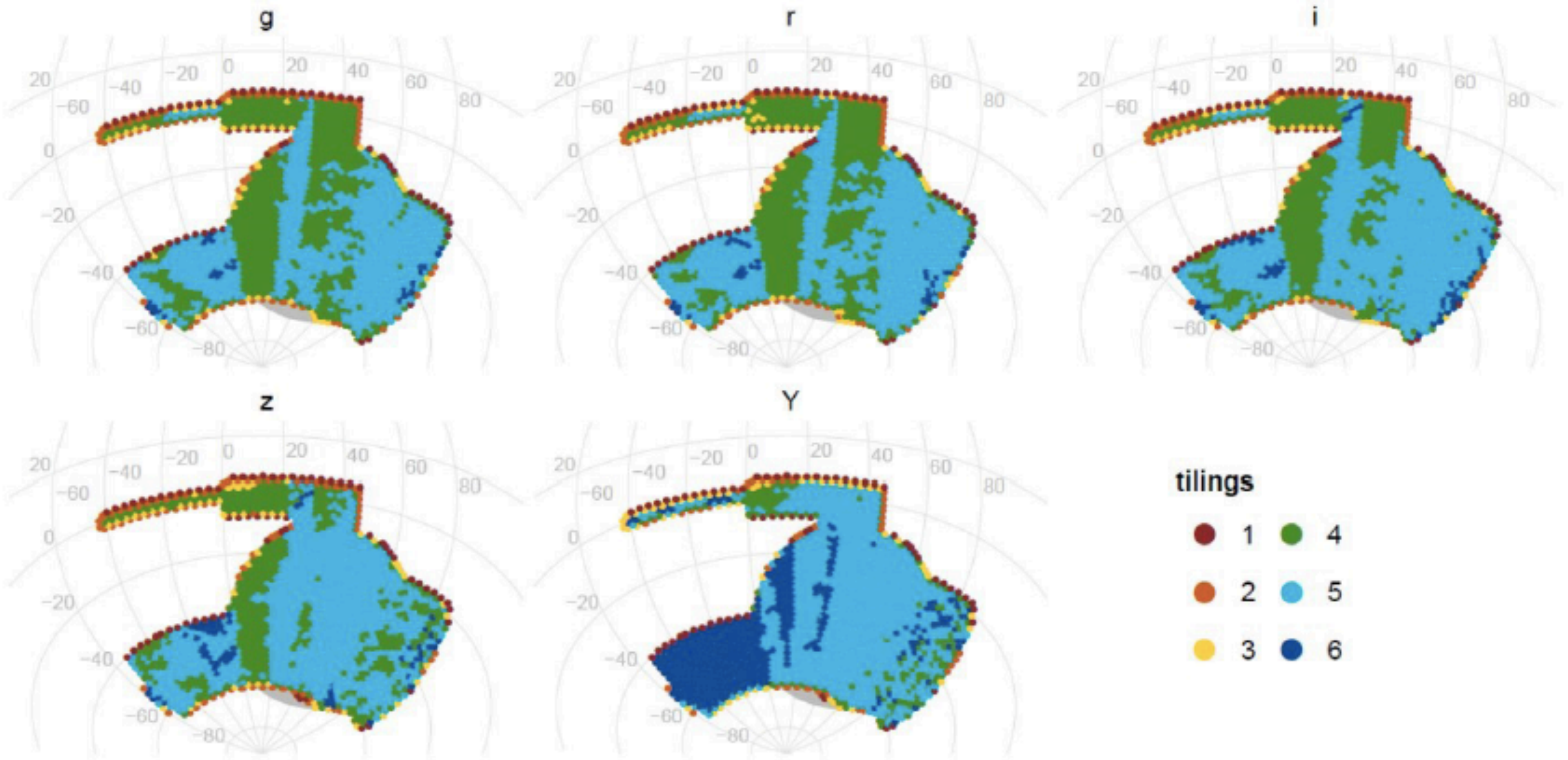


Credit: P. Melchior

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



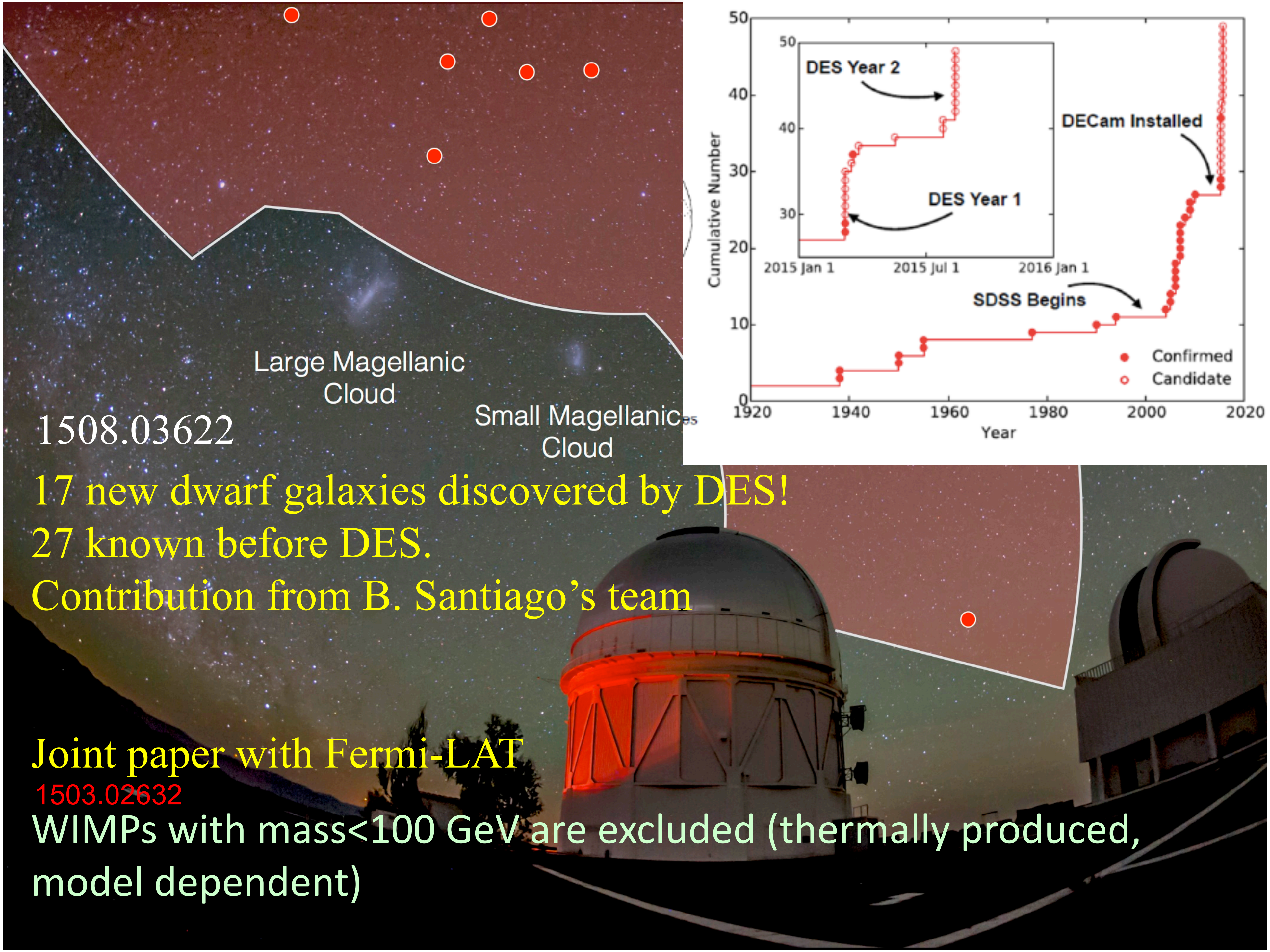
DARK ENERGY SURVEY

DES-BRAZIL

LIneA
Laboratório Interinstitucional de e-Astronomia

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

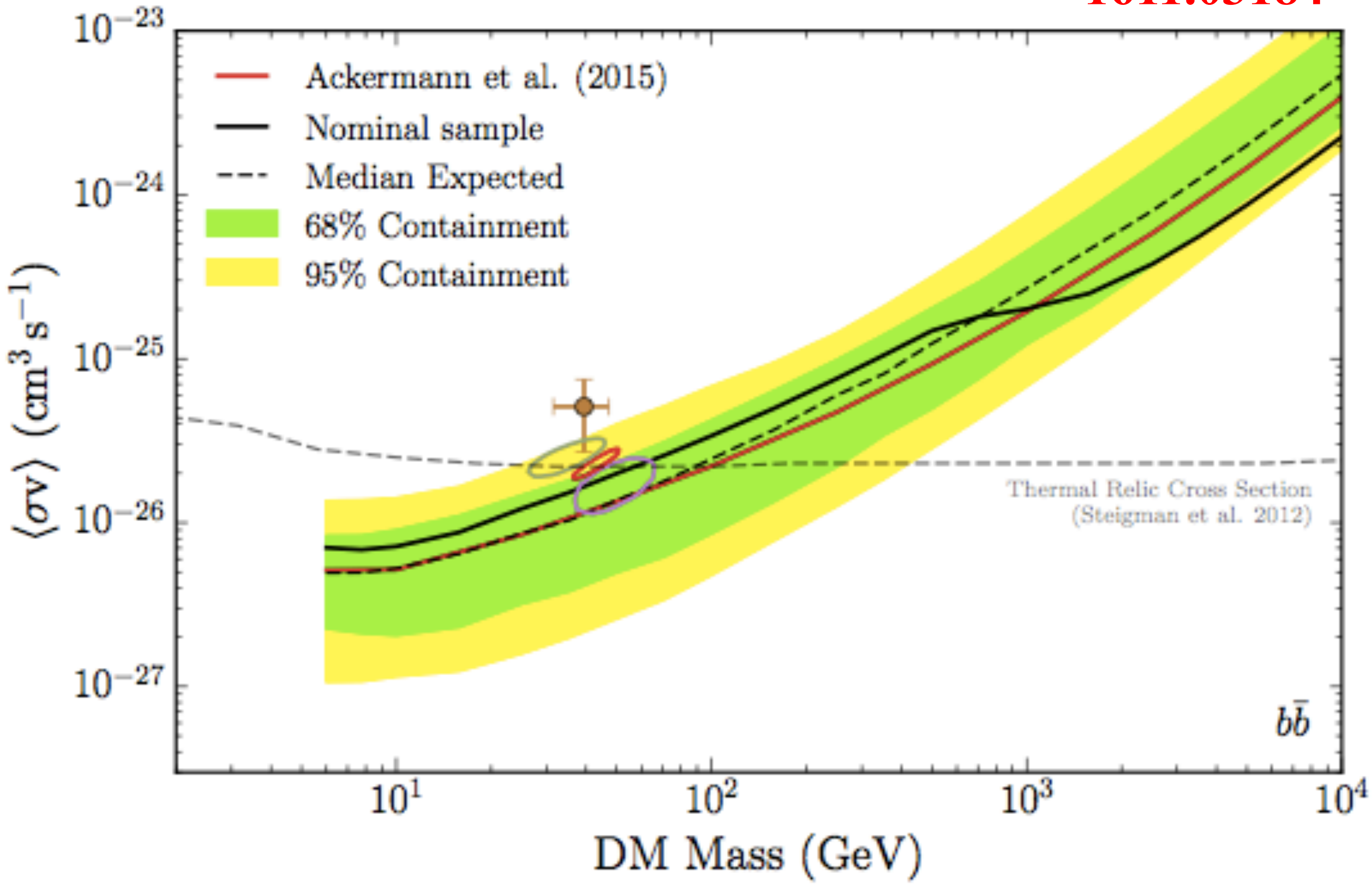
Joint paper with Fermi-LAT

1503.02632

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

Recent results from Fermi-LAT & DES using 45 dwarf Milky Way satellite galaxies (rich in dark matter)

1611.03184



DARK ENERGY SURVEY

DES-BRAZIL

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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.

$$\delta_g(\vec{x}) = b(z)\delta(\vec{x})$$

galaxy overdensity

matter overdensity (cosmological model)

bias

DARK ENERGY SURVEY

DES-BRAZIL

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Galaxy clustering, photometric redshifts and diagnosis of systematics in the DES SV data - 1507.05360

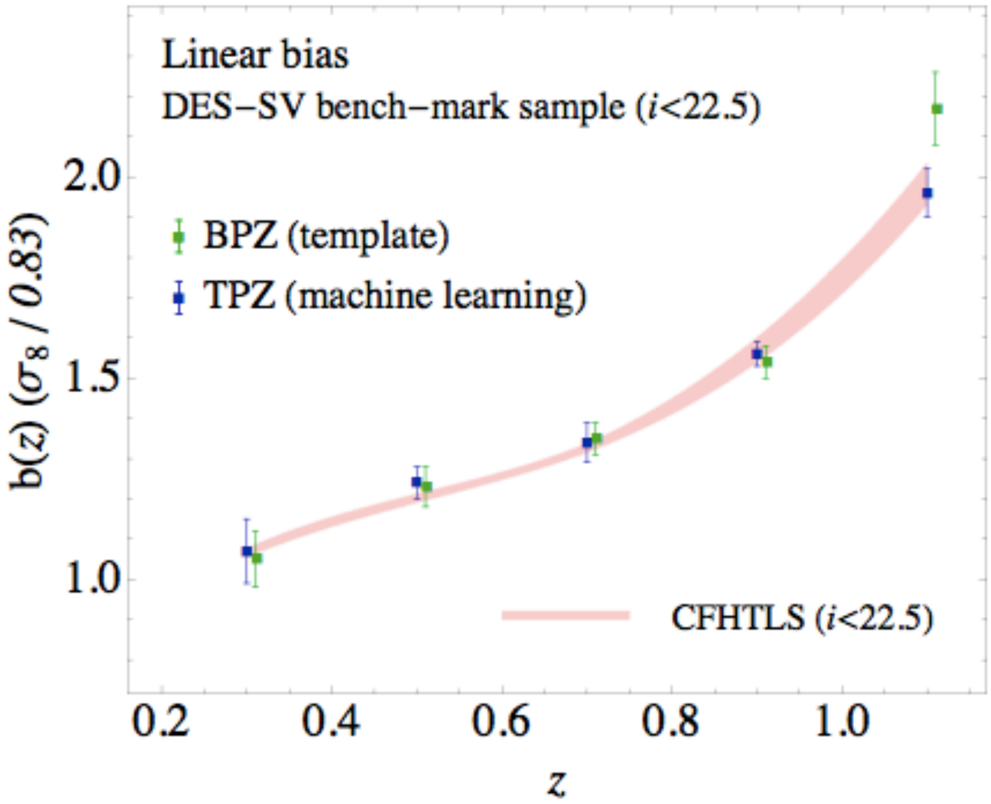


Figure 11. Comparison of the large-scale bias measured in a DES-SV flux limited sample ($i < 22.5$) to equivalent measurements from CFHTLS derived from Coupon et al. (2012). We present DES results for two different photometric redshift catalogs, one obtained using a template method (BPZ), another with 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

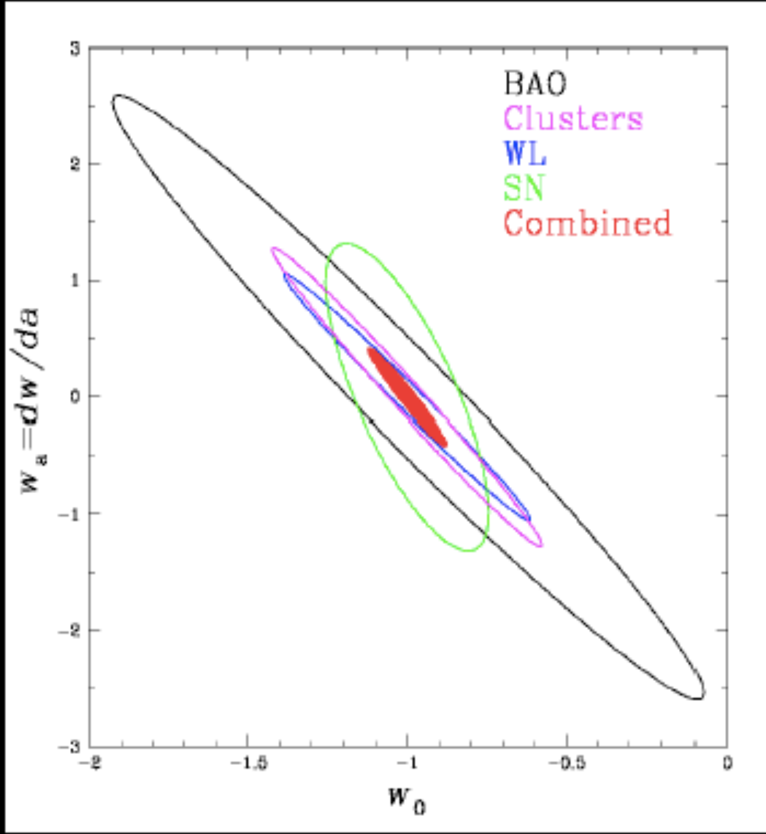
DARK ENERGY SURVEY

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

Forecast Constraints on DE Equation of State

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



DES forecast

CODA

- Cosmology has become a precision, data driven science

- Cosmology tests models of particle physicss

- New experiments are taking data now and many are planned (DESI, LSST, Euclid, ...)

- It is an exciting time – let's hope for more surprises!