Cosmology in the era of large galaxy surveys

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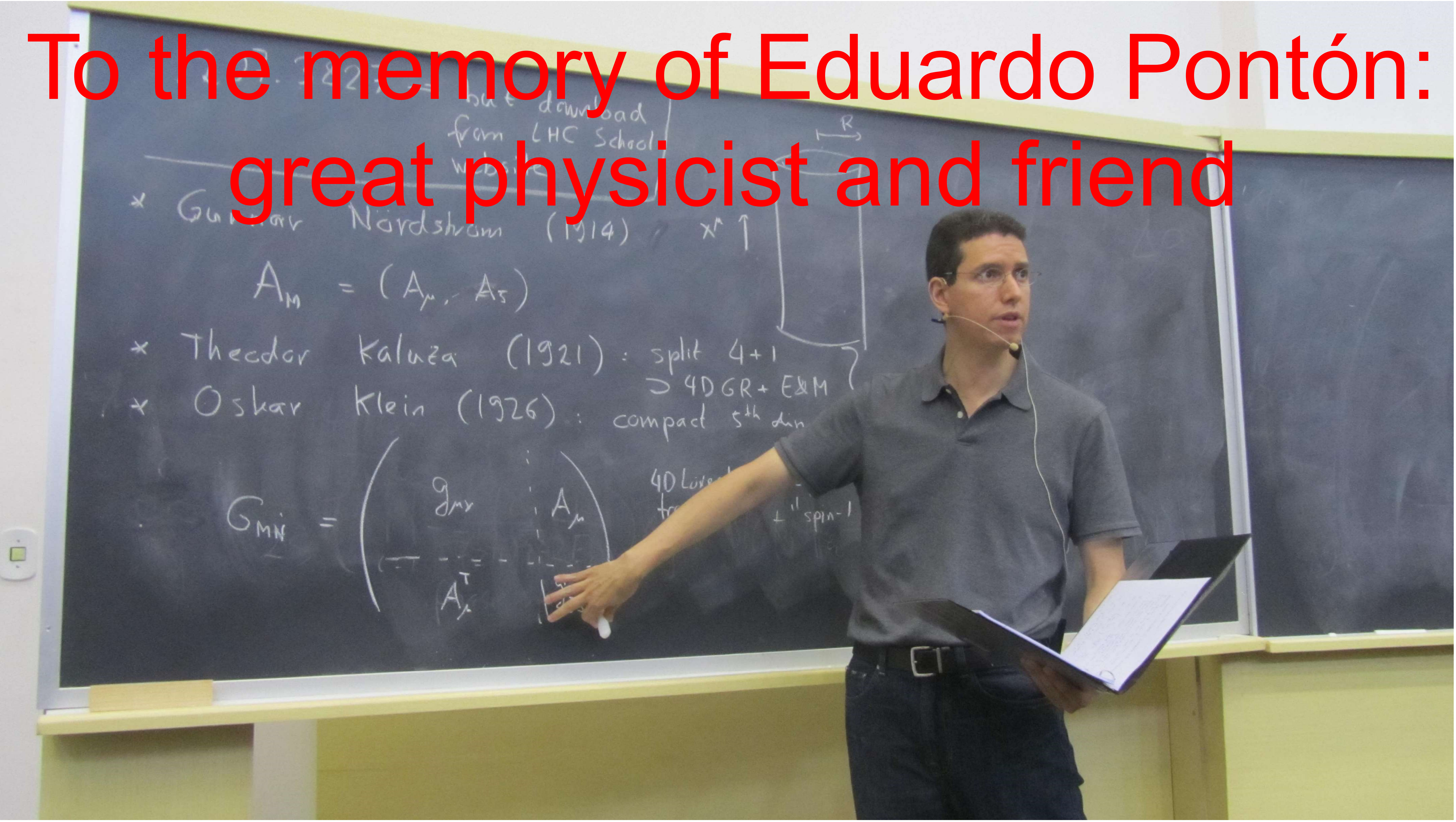
ICTP SAIFR International Centre for Theoretical Physics South American Institute for Fundamental Research

LIneA

Dark Energy Survey collaboration

COMHEP

To the memory of Eduardo Pontón: great physicist and friend



Plan:

0 – Introduction

1– From probes to answers

2 – Perturbations in the Universe

3 – The 3d power spectrum

4 - Baryon acoustic oscillations

5 – Observations: the Dark Energy Survey

6 – DES highlights and challenges

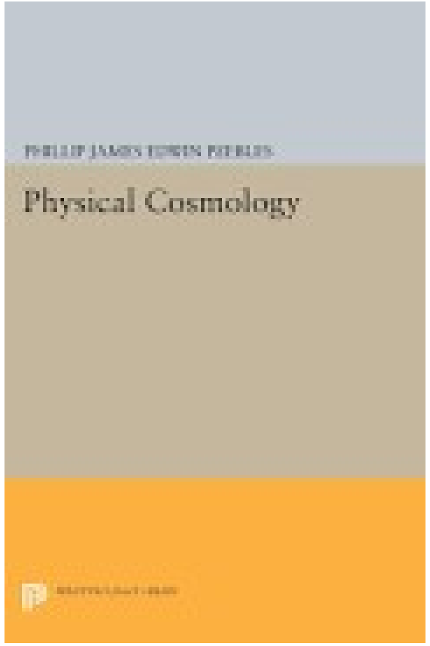
7 – A glimpse into the future & Conclusions

0 – Introduction

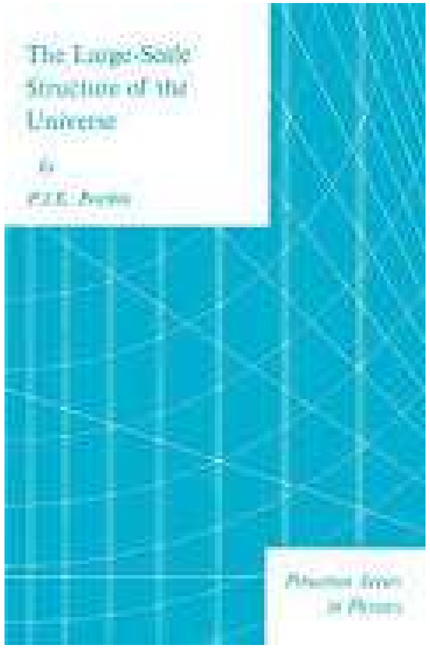
Cosmology in the last decades has become a respectable, data-driven science. Cosmological parameters are now measured with great precision.

t_U= (13.799±0.021)x10^9 years [used to be $10^{9\pm1}$ years]

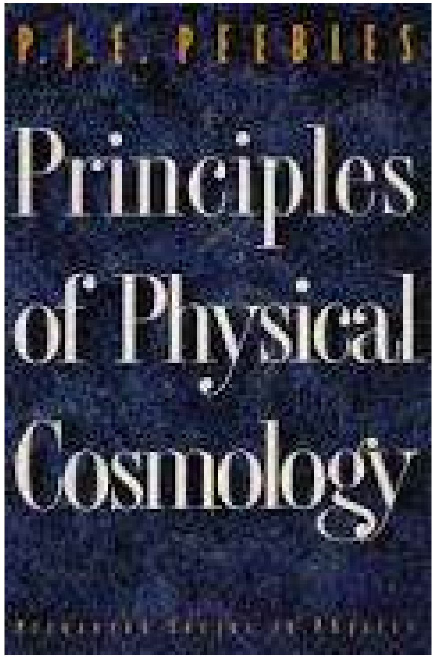
One person had a fundamental role in changing cosmology into a respectable science: James Peebles



1971



1980



1993

The Nobel Prize in Physics 2019

Phillip James Edwin Peebles

Ill. Niklas Elmehed. © Nobel Media.

James Peebles

Prize share: 1/2

Ill. Niklas Elmehed. © Nobel Media.

Michel Mayor

Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media.

Didier Queloz

Prize share: 1/4

The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" with one half to James Peebles "for theoretical discoveries in physical cosmology", the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

Many cosmological probes

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

Large Surveys

A Standard Cosmological Model has emerged: flat ΛCDM

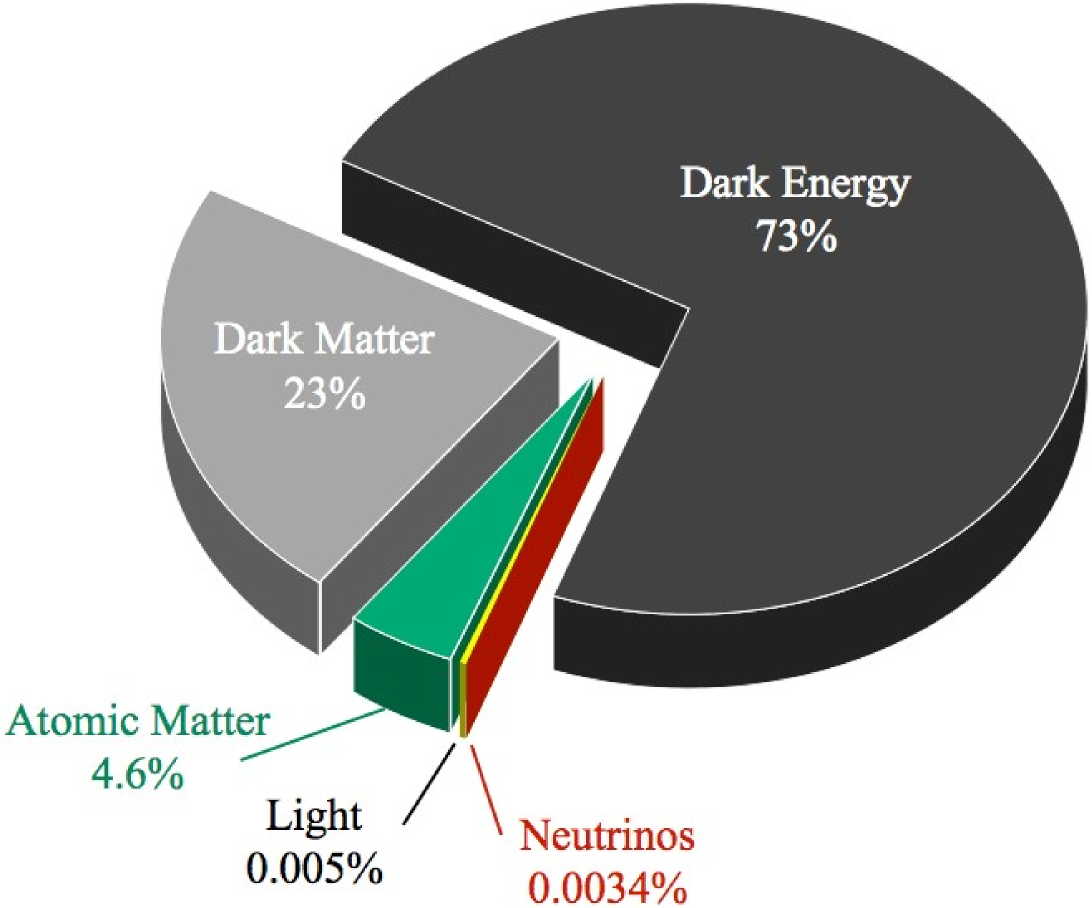
Many questions:

What is dark matter?

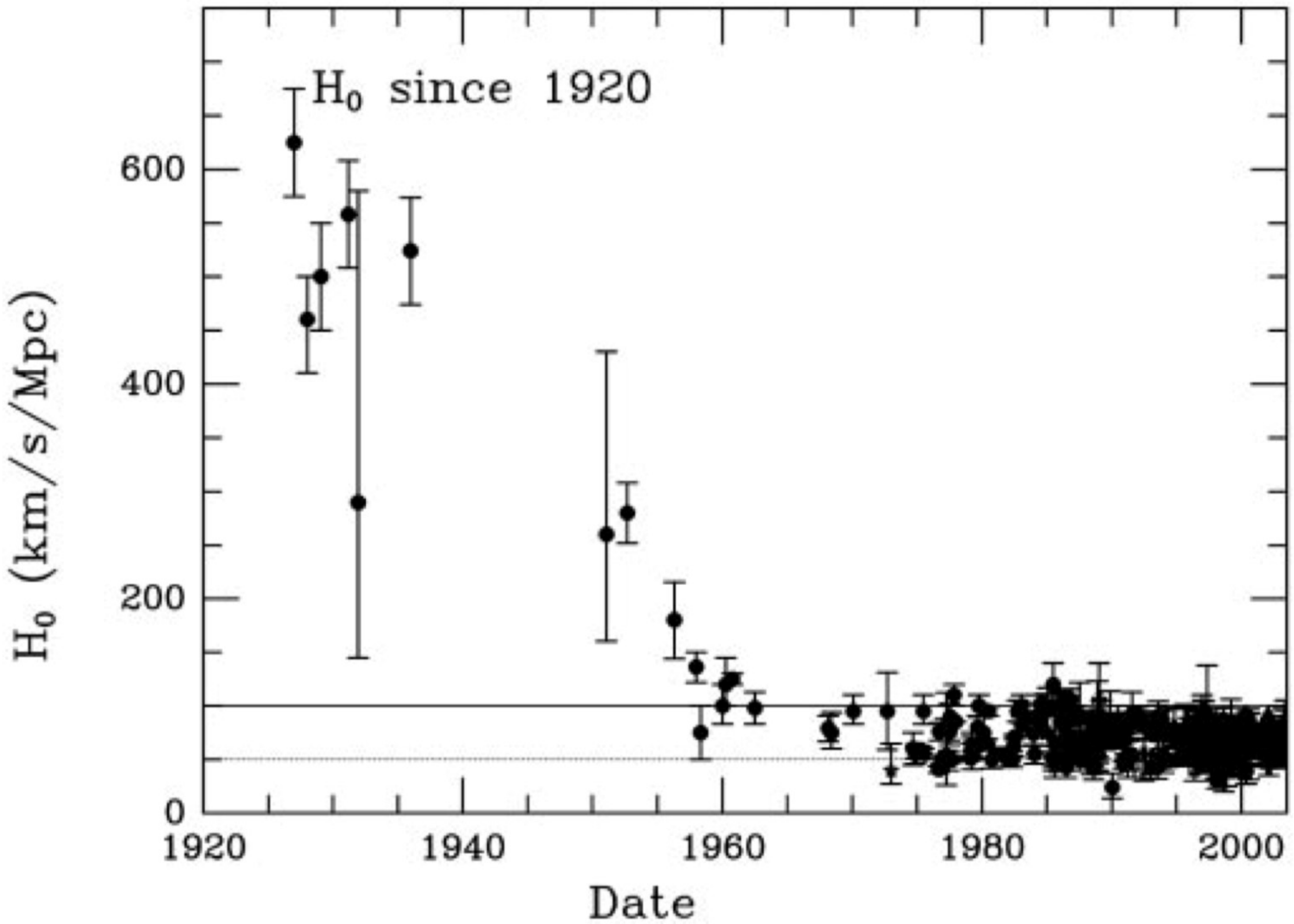
Cold, warm, fuzzy, self-interacting...

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?



Historical evolution of the measured values of the Hubble constant: H_0= 50-100 km/s/Mpc

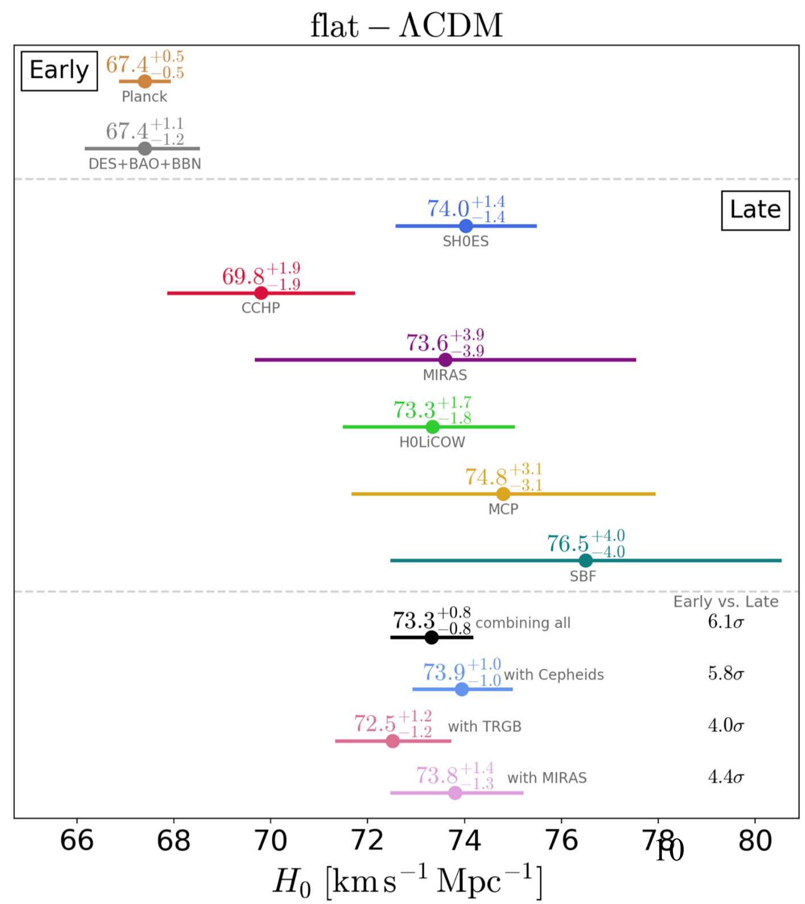


1907.10625

H_0 with precision <2%

~5σ tension

First cracks in ΛCDM?



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...

1- From probes to answers

The main goal is to determine what is the best model that describes our Universe.

Easy steps:

. Pick a probe

. Pick a model

. Compute predictions from the model for a given set of parameters

. Get some data

. Compare model predictions with data

. Find the best model with the corresponding values of parameters

Put all steps together in the so-called likelihood function:

$$\mathcal{L}(\{p\}) \propto \exp\left\{-\frac{1}{2}\left(\mathcal{O}^{\rm th} - \mathcal{O}^{\rm obs}\right)^T_i \mathrm{Cov}^{-1}_{ij} \left(\mathcal{O}^{\rm th} - \mathcal{O}^{\rm obs}\right)_j\right\}$$

Theoretical prediction depends on the model and its parameters.

Observations depend on the experiment.

The covariance matrix basically reflects the uncertainty in the experimental measurement.

Best parameters given a model: maximize likelihood

Challenges:

Theoretical predictions are difficult (nonlinear physics, baryons, ...)

Observations are subject to systematic and model uncertainties – nuisance parameters.

How to estimate the covariance matrix? Theoretical, from simulations, from data, ...

Computational: how to study a ~30 dimensional parameter space?

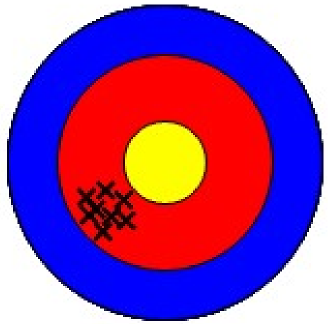
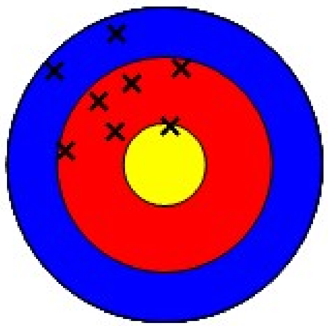
Example from a Dark Energy survey 3x2pt analysis

7 Cosmological Parameters (flat wCDM model)

Parameter	Prior
Cosmology	
Ω_m	flat (0.1, 0.9)
A_s	flat $(5 \times 10^{-10}, 5 \times 10^{-9})$
n_s	flat (0.87, 1.07)
Ω_b	flat (0.03, 0.07)
h	flat (0.55, 0.91)
$\Omega_\nu h^2$	flat$(5 \times 10^{-4}, 10^{-2})$
w	flat $(-2, -0.33)$
Lens Galaxy Bias	
$b_i(i = 1, 5)$	flat (0.8, 3.0)
Intrinsic Alignment	
$A_{\mathrm{IA}}(z) = A_{\mathrm{IA}}[(1+z)/1.62]^{\eta_{\mathrm{IA}}}$	
A_{IA}	flat $(-5, 5)$
η_{IA}	flat $(-5, 5)$
Lens photo-z shift (red sequence)	
Δz_1^1	Gauss (0.001, 0.008)
Δz_1^2	Gauss (0.002, 0.007)
Δz_1^3	Gauss (0.001, 0.007)
Δz_1^4	Gauss (0.003, 0.01)
Δz_1^5	Gauss (0.0, 0.01)
Source photo-z shift	
Δz_s^1	Gauss $(-0.001, 0.016)$
Δz_s^2	Gauss $(-0.019, 0.013)$
Δz_s^3	Gauss $(+0.009, 0.011)$
Δz_s^4	Gauss $(-0.018, 0.022)$
Shear calibration	
$m^i_{\mathrm{METACALIBRATION}}(i = 1, 4)$	Gauss (0.012, 0.023)
$m^i_{\mathrm{IM3SHAPE}}(i = 1, 4)$	Gauss (0.0, 0.035)

20 Nuisance Parameters

Precision versus Accuracy

	Accurate	Inaccurate (systematic error)
Precise		
Imprecise (reproducibility error)		

2- Perturbations in the Universe

Inflation generates small (gaussian, adiabatic, nearly scale-invariant) density perturbations in the early Universe.

These perturbations grew with gravity and originated the structures we now observe.

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

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

Evolution of perturbations

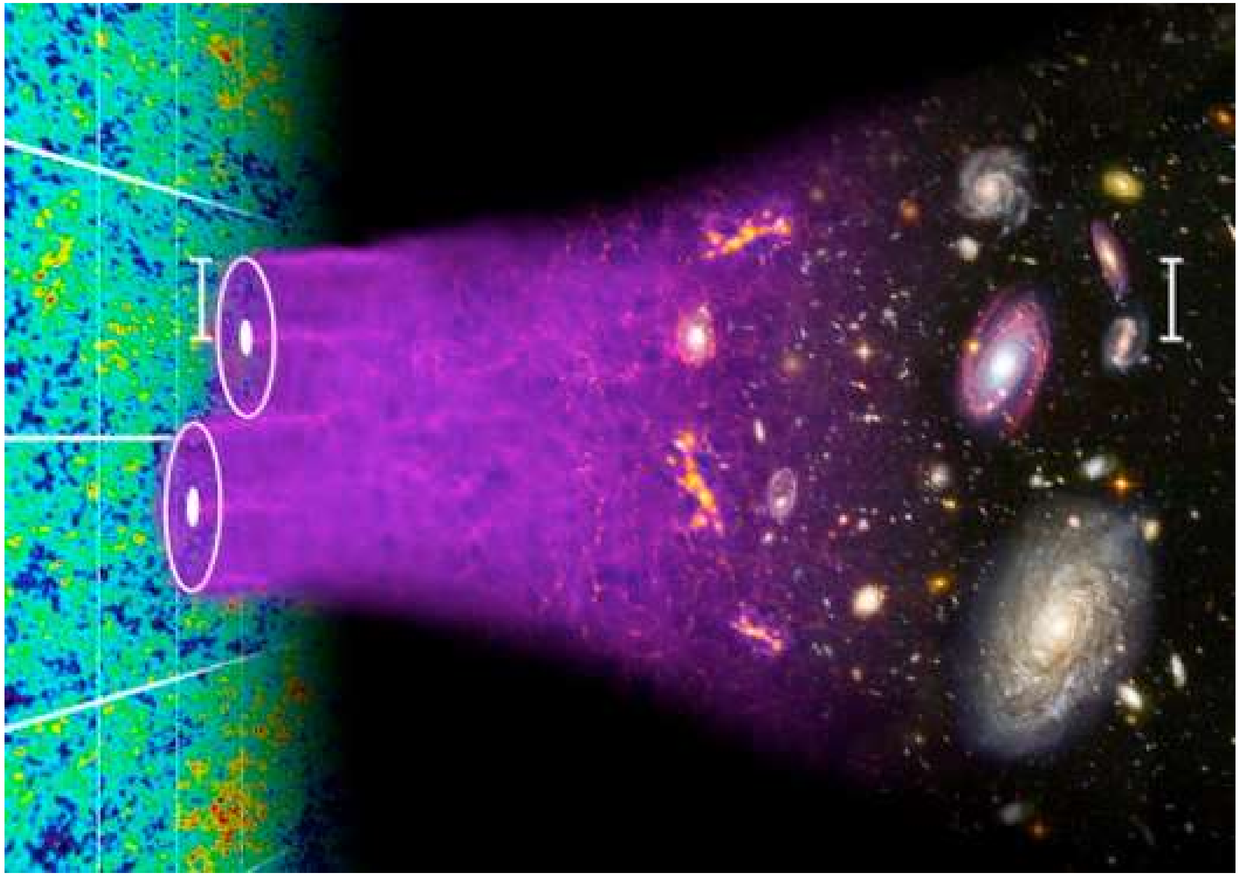


Illustration by Chris Blake and Sam Moorfield

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 dominant(and easy to simulate since it is dissipationless). Baryons are complicated but essential.

Linear perturbations are much easier to compute – CAMB, CLASS,…

Semi-analytical methods for nonlinear evolution of perturbations:

Halo model

EFTofLSS

Resummed perturbation theory

Halo model motivated fits to simulations (HALOFIT)

Emulators

3- The 3d 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

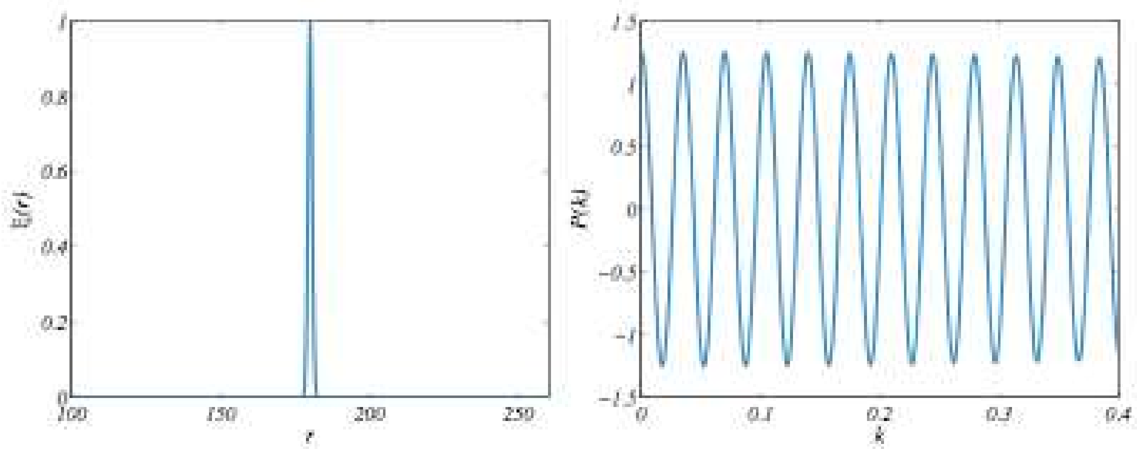
One can also define the power spectrum:

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

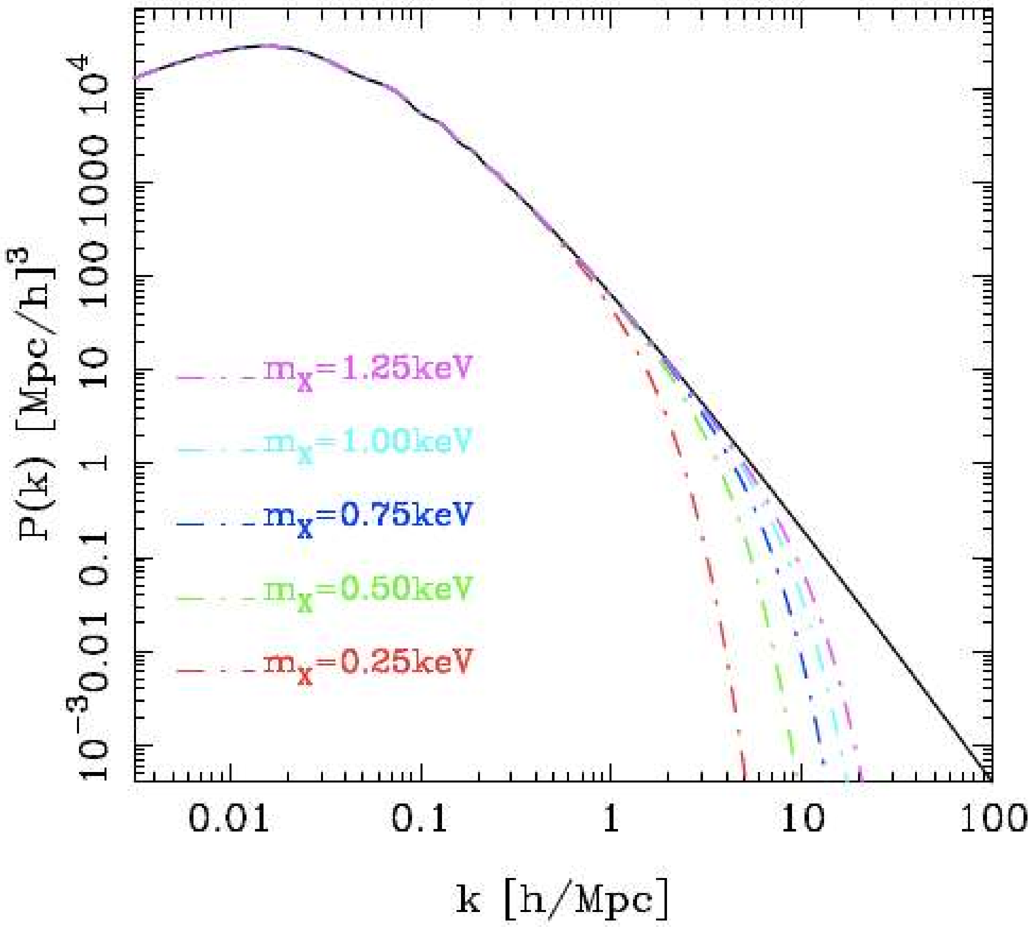
It is possible to work with either spatial correlation function or power spectrum – advantages and disadvantages

Sharp peak in correlation results in oscillations in the power spectrum

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

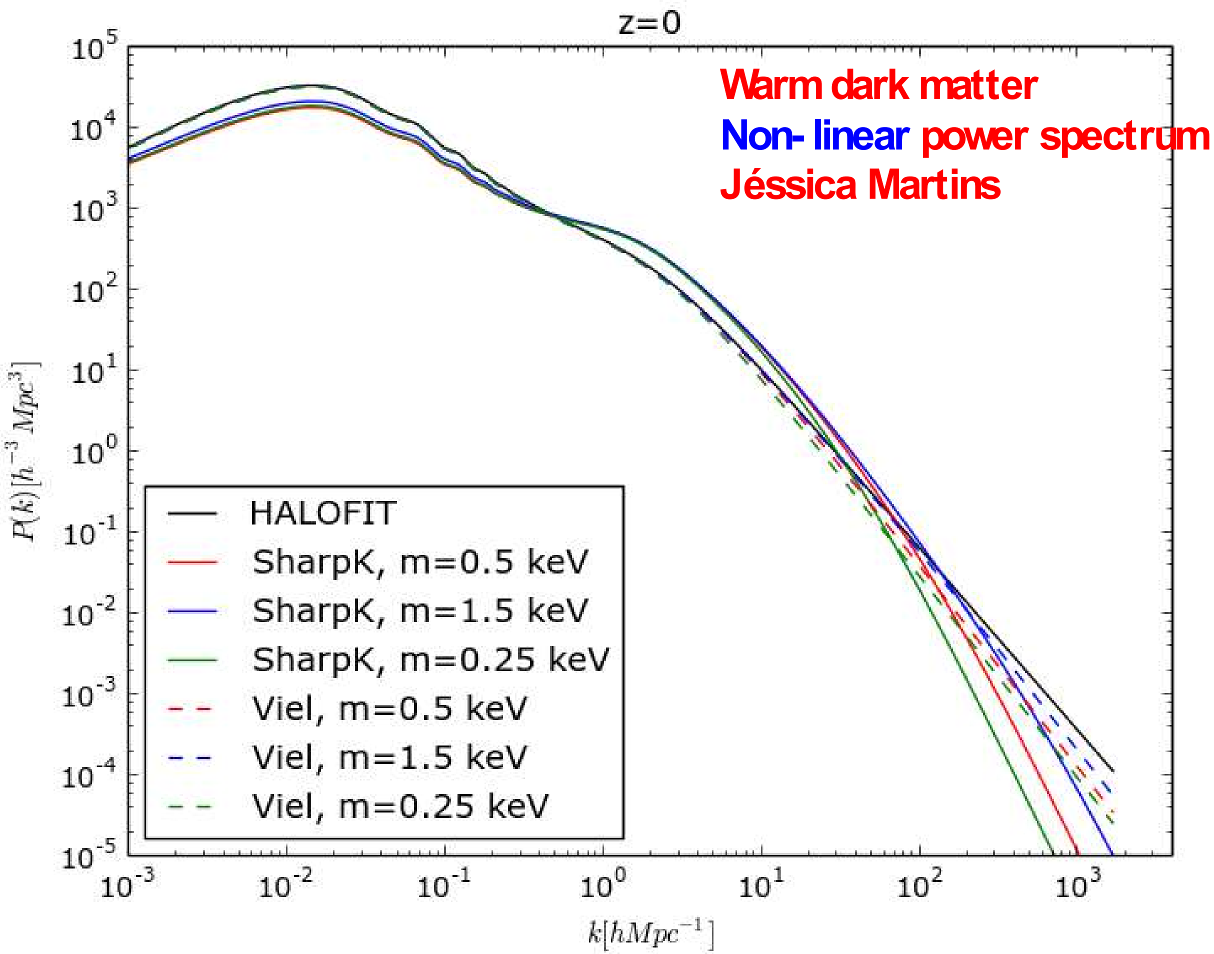


Power spectrum is sensitive to new physics



Warm dark matter
Linear power spectrum

Power spectrum is sensitive to new physics



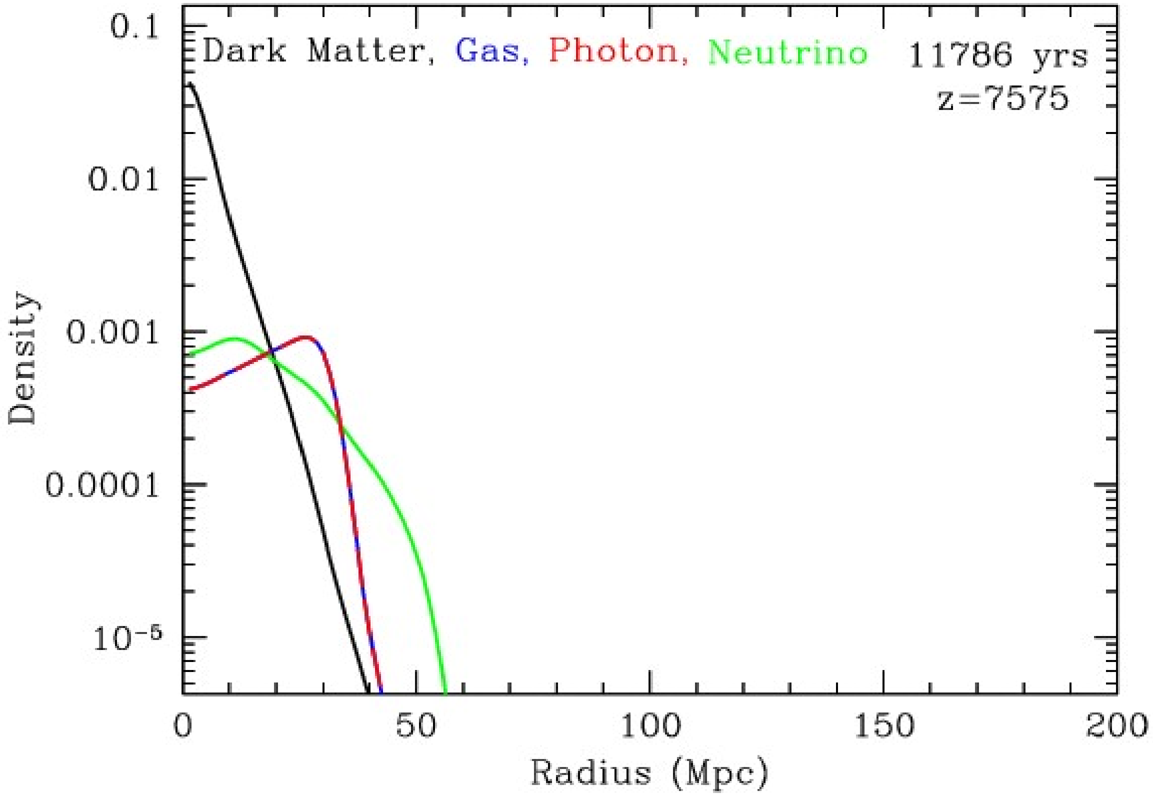
4-Baryon acoustic oscillation

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.

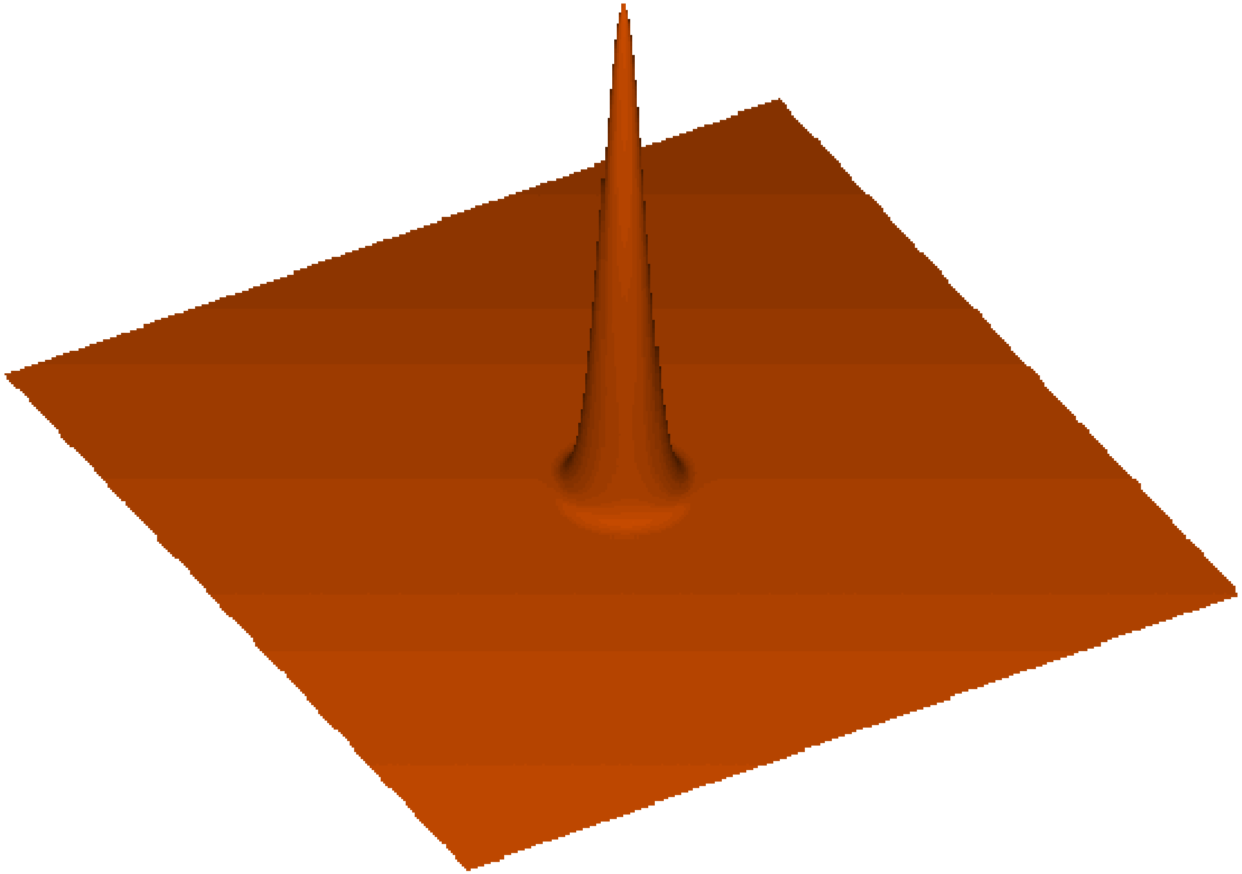
Evolution of one spherical perturbation

Eisenstein



Evolution of one spherical perturbation

Eisenstein



BAO scale

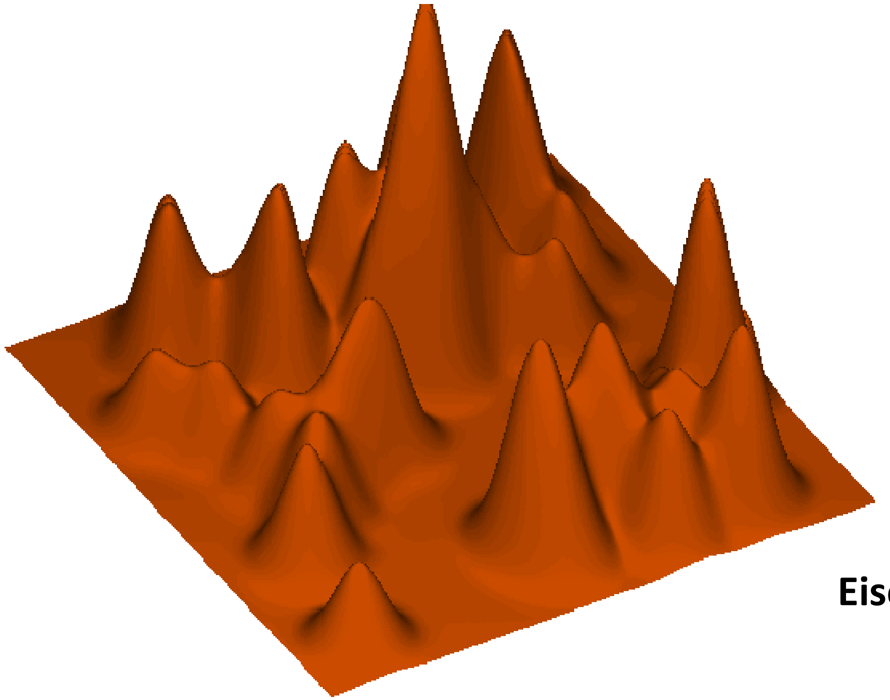
Standard ruler in the sky

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

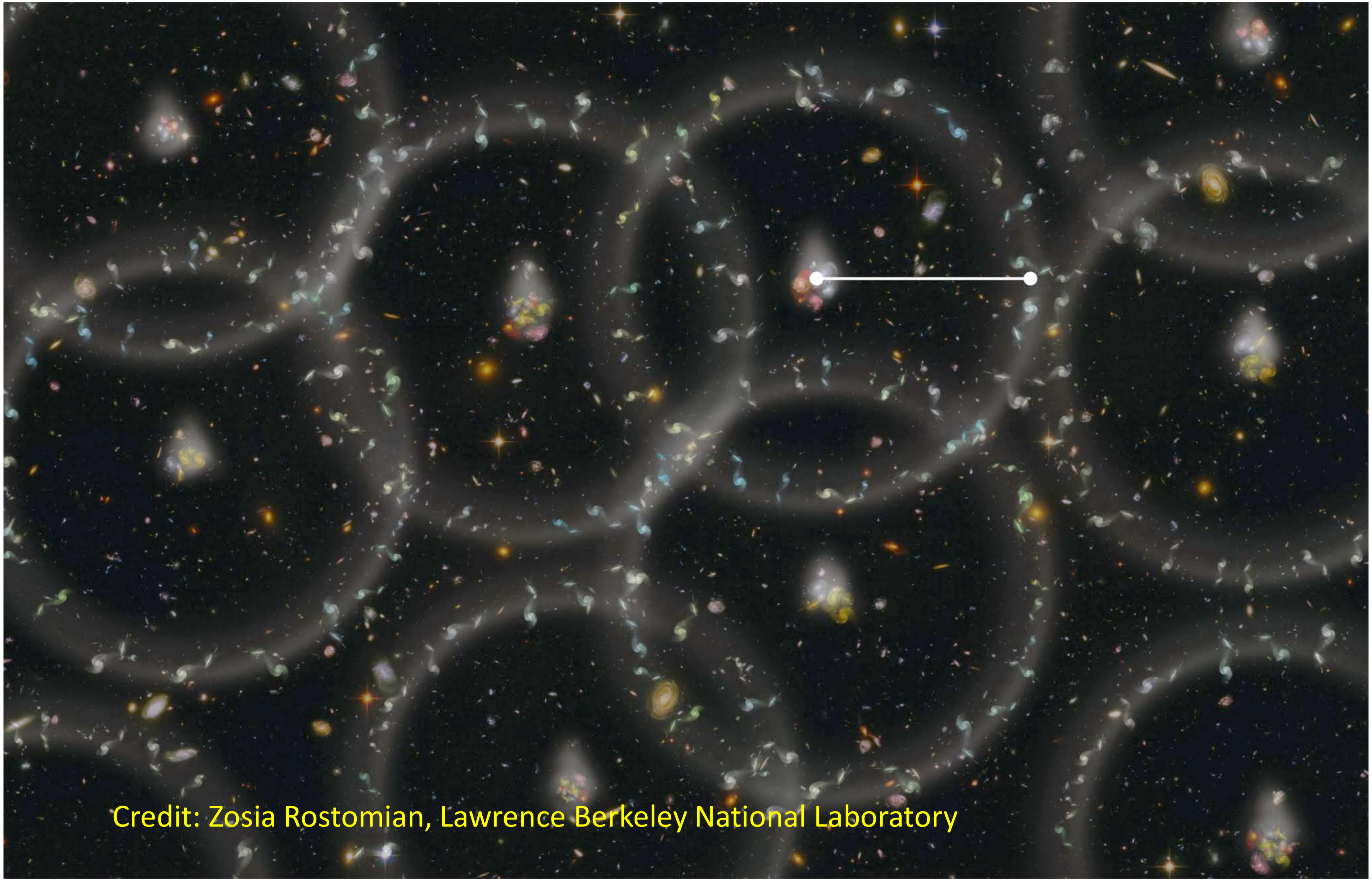
Cosmological parameters

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

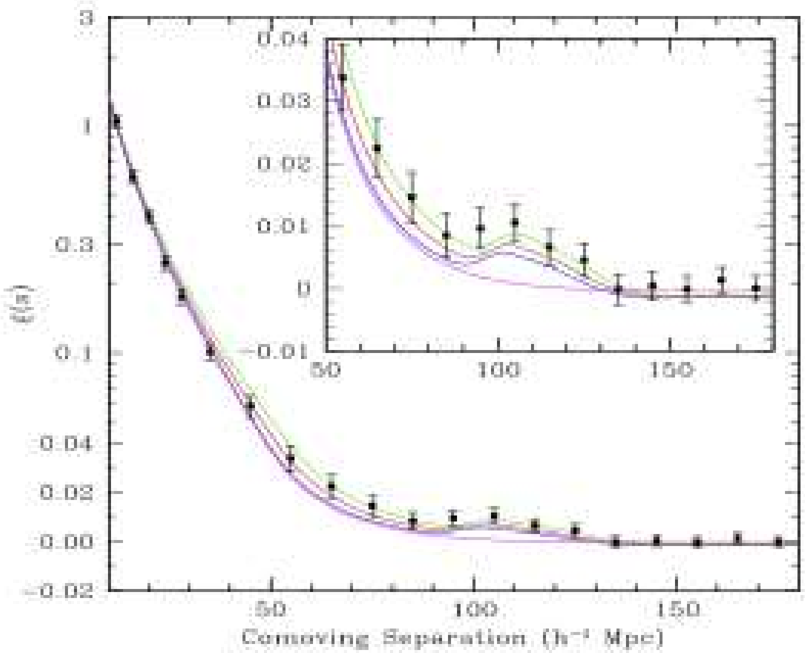
Things are more complicated: superposition of shells with different locations and different amplitudes



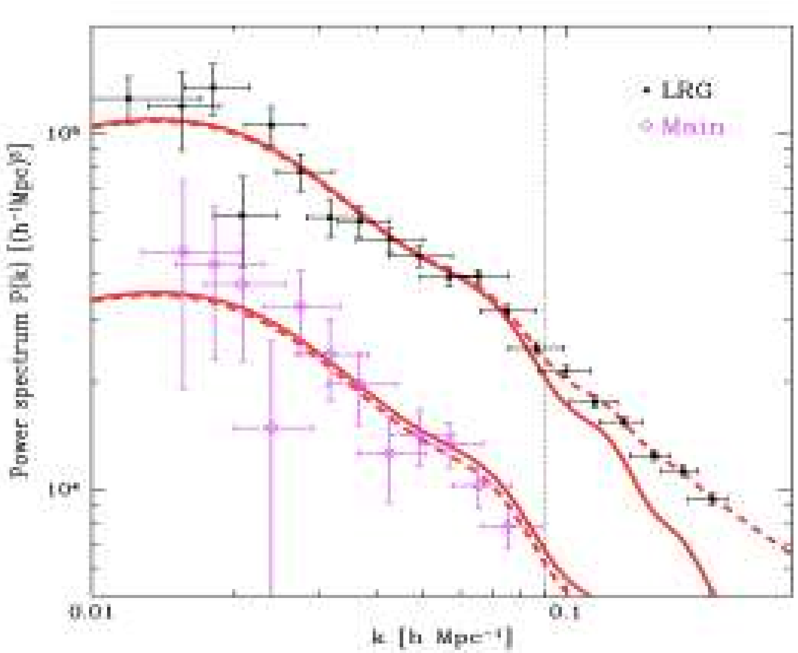
Eisenstein


Credit: Zosia Rostomian, Lawrence Berkeley National Laboratory

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



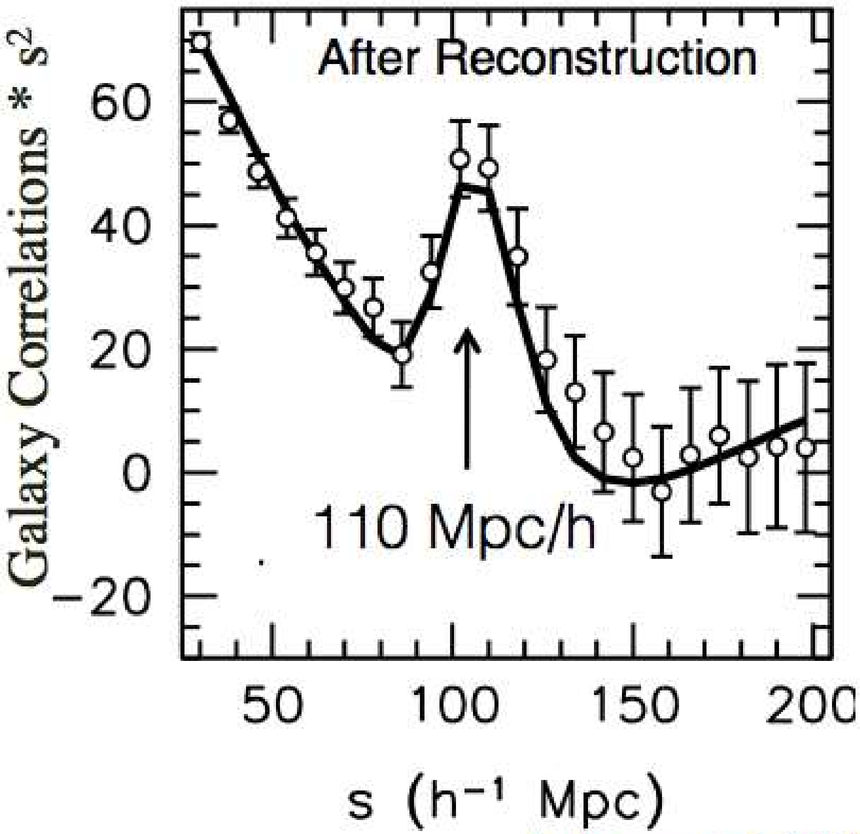
Eisenstein et al (2005)



Tegmark et al (2006)

DR3, z ~ 0.35

Galaxy 2‐point correlation function



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

5- Observations: the case of DES

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

SDSS, BOSS, eBOSS
KiDS
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

DARK ENERGY SURVEY

John Peoples - 1st Director
Josh Frieman – 2nd Director
Richard Kron – 3rd 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

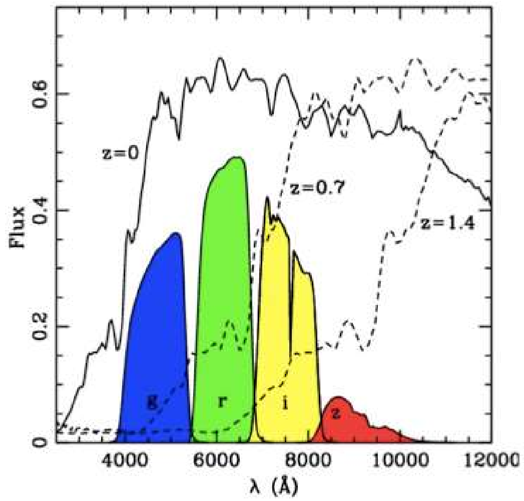
Laboratório Interinstitucional de e-Astronomia (LIneA)

http://www.linea.gov.br

Recently approved INCT of the e-Universe

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

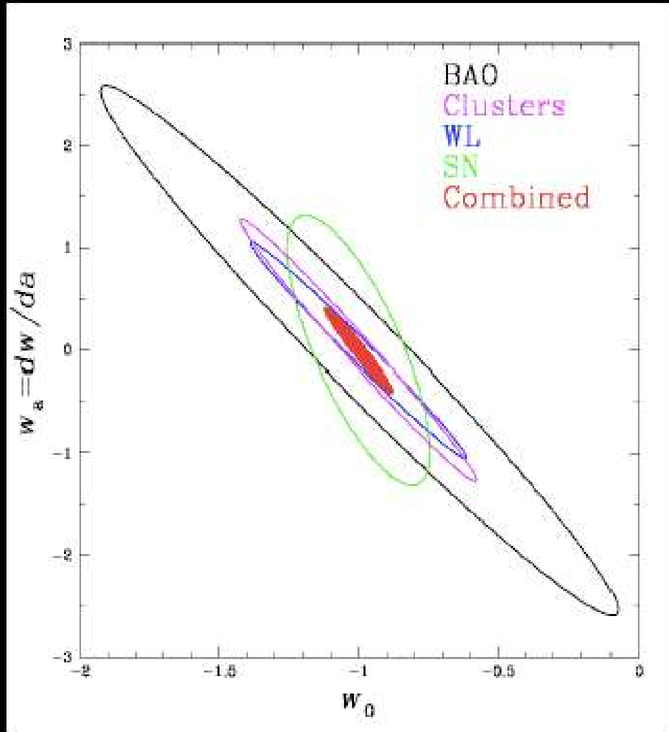


DES Science Summary

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

12

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

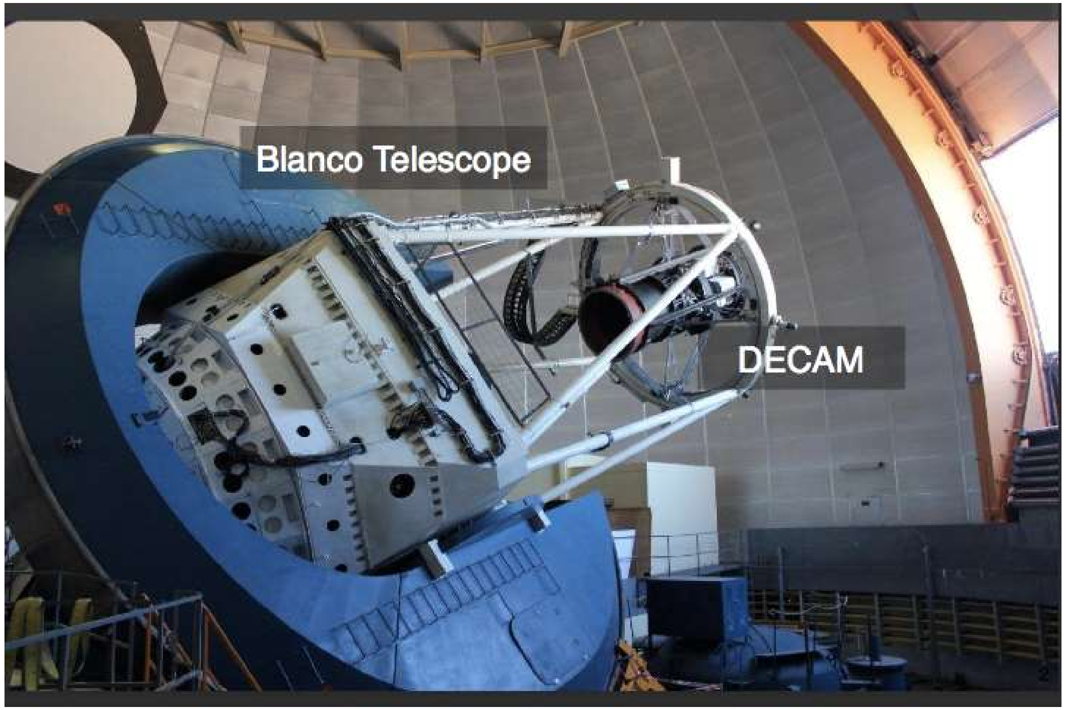
Science Verification (SV) run: Sept. 2012 - Feb. 2013
First Season (Year 1): Aug. 31, 2013 - Feb. 9, 2014
Second Season (Year 2): Aug. 2014 - Feb. 2015
Third Season (Year 3): Aug. 2015 - Feb. 2016
Fourth Season (Year 4) August 2016 – Feb. 2017
Fifth Season (Year 5) August 2017 – Feb. 2018
5 ½ Season – Finished January 2019

Planned 5 years of 105-nights each

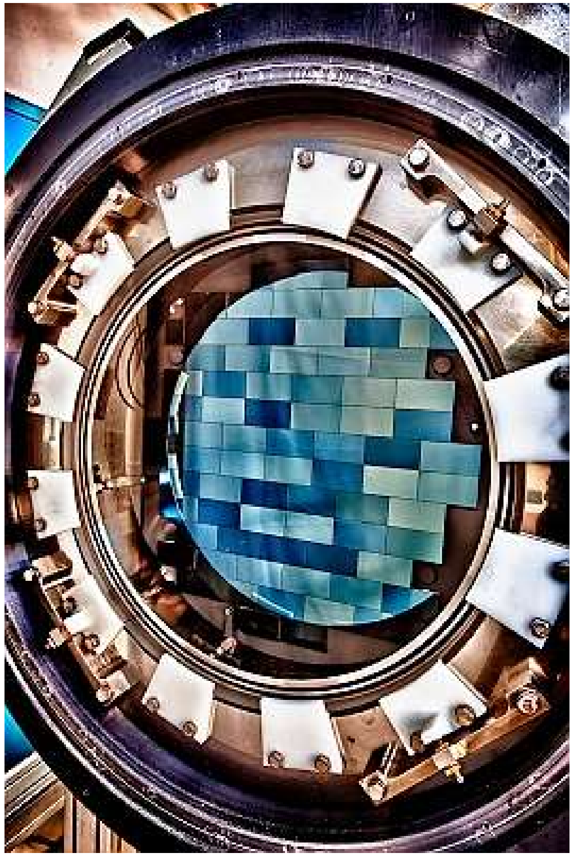
DES site: 4m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile

DECam

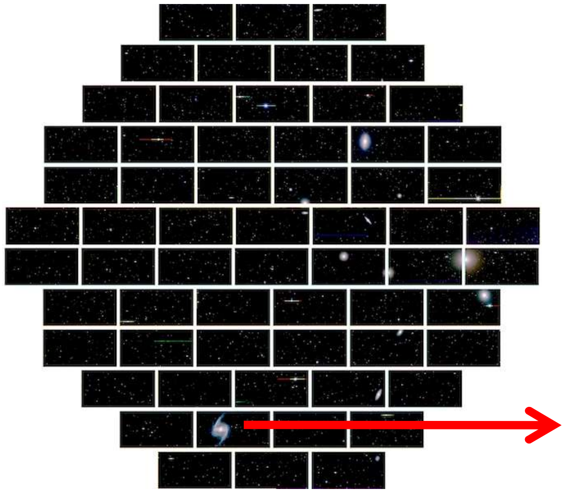
Able to see light from more than 100,000 galaxies up to 8 billion light-years away in each snapshot. Weighs ~4 tons!



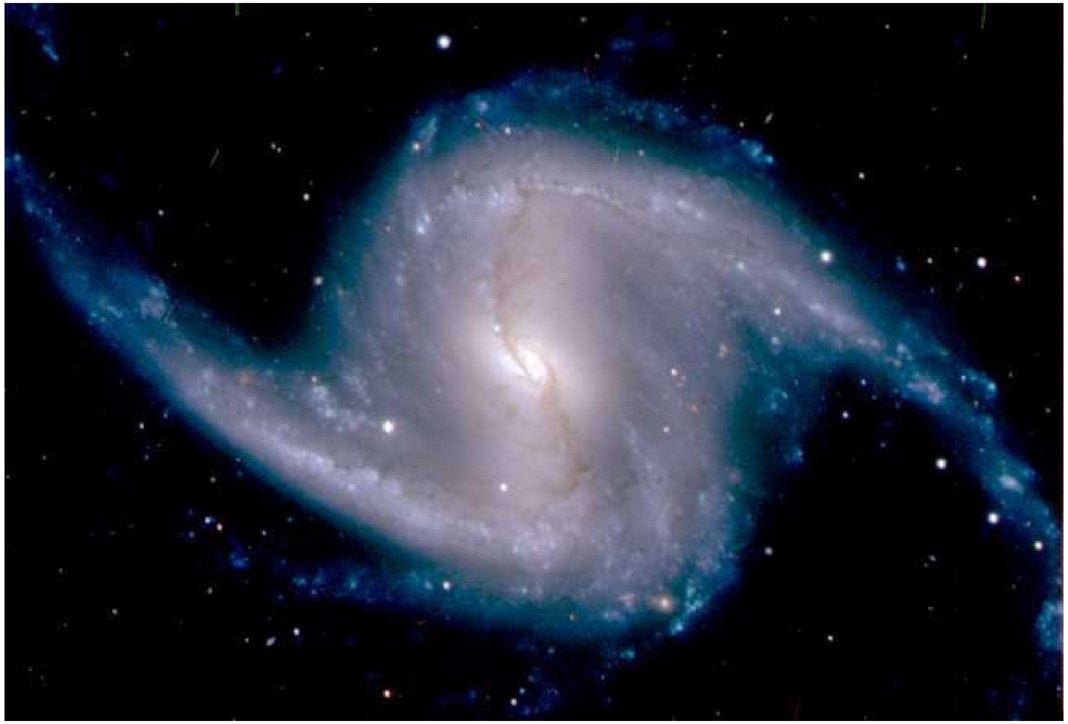
DECam



arXiv:1504.02900

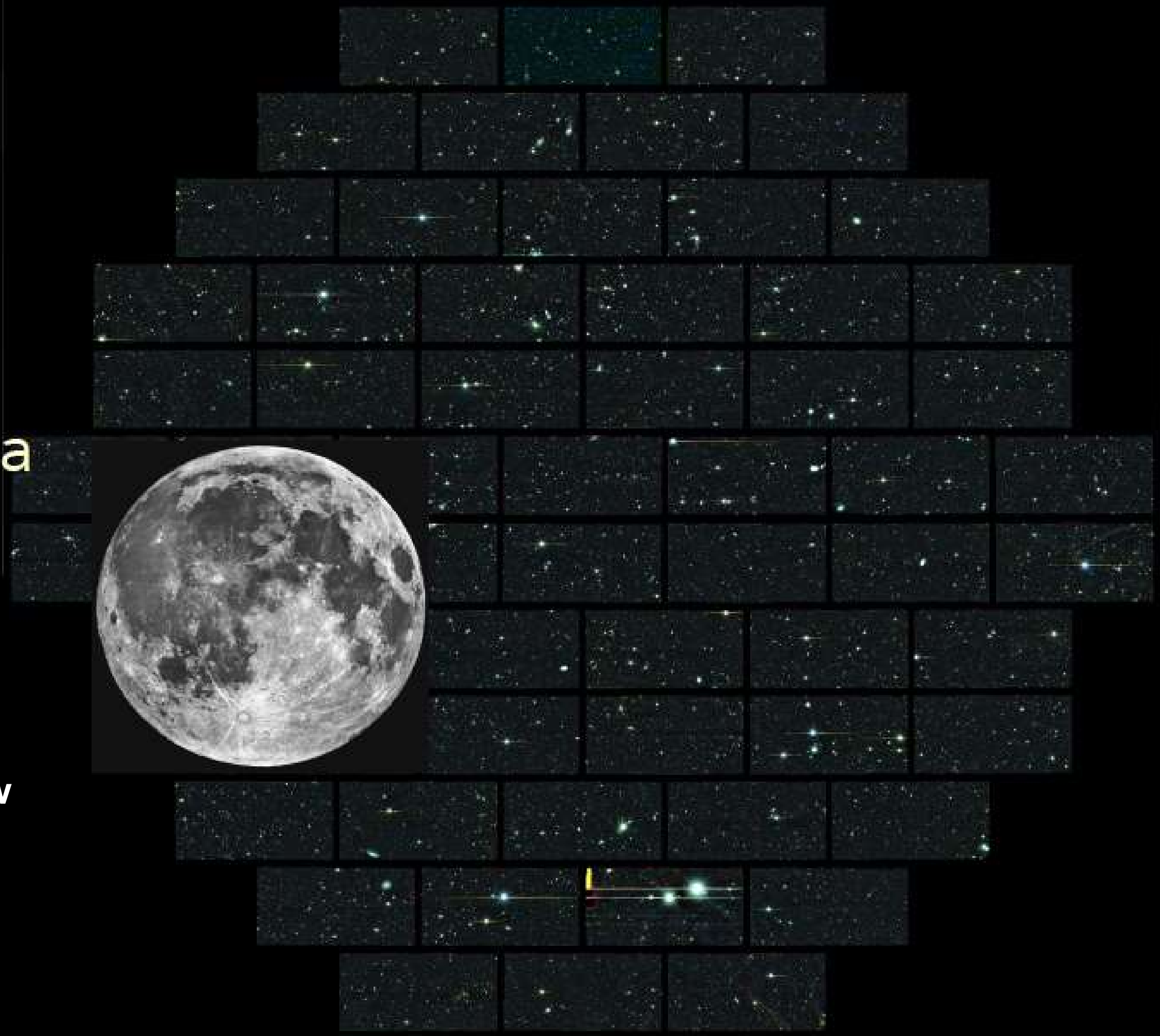


Fornax cluster of galaxies



Barred spiral galaxy NGC 1365 in the Fornax cluster of galaxies

DES SV image of a deep SN field

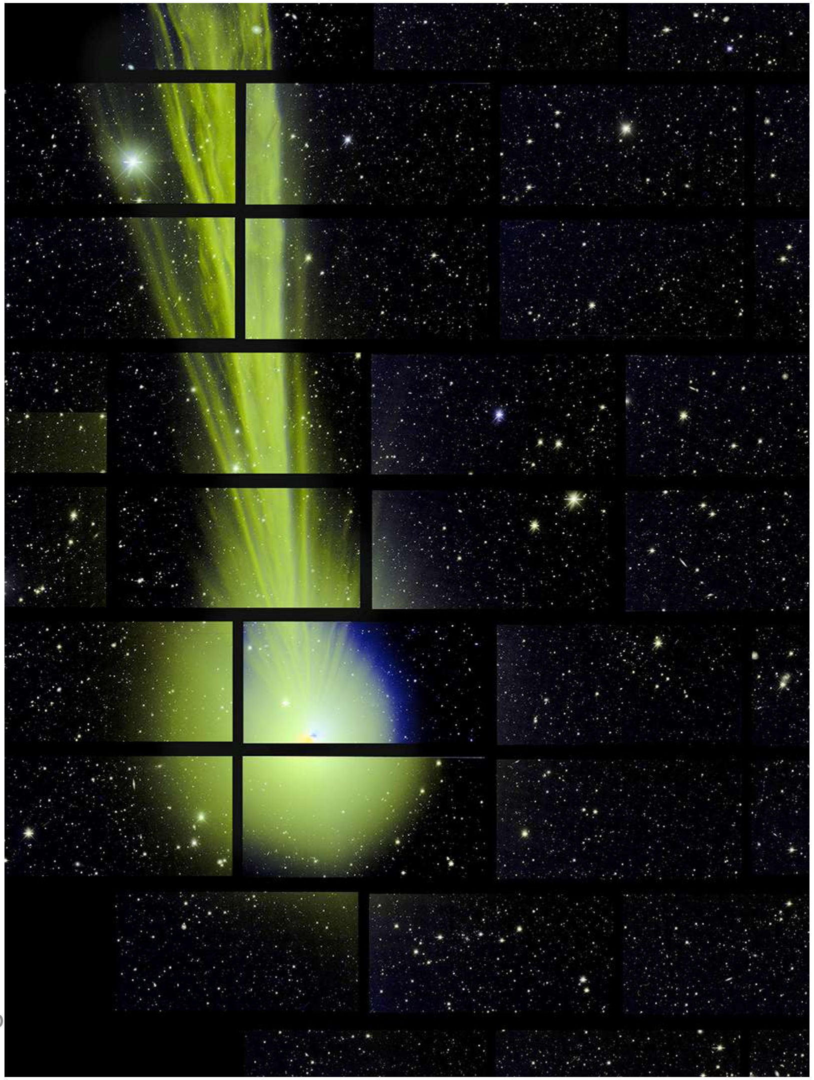


3 deg^2 field of view

Dark Energy Camera catches breathtaking glimpse of comet Lovejoy

December 27 2014

82 million km away



Co

DES Data Management

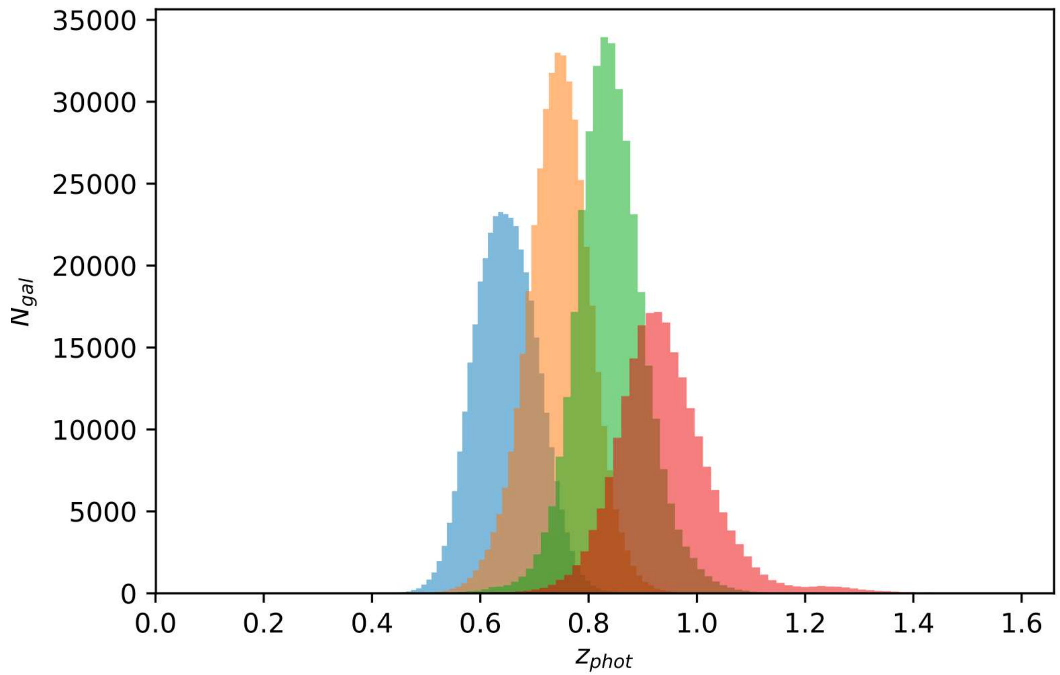
Each exposure (in a given filter) generates 500Mb

300 exposures/night – 150 Gb/night

Transferred and processed at NCSA in Urbana

Photometric redshift

Typical photo-z distribution in 4 bins (BPZ) – selection function

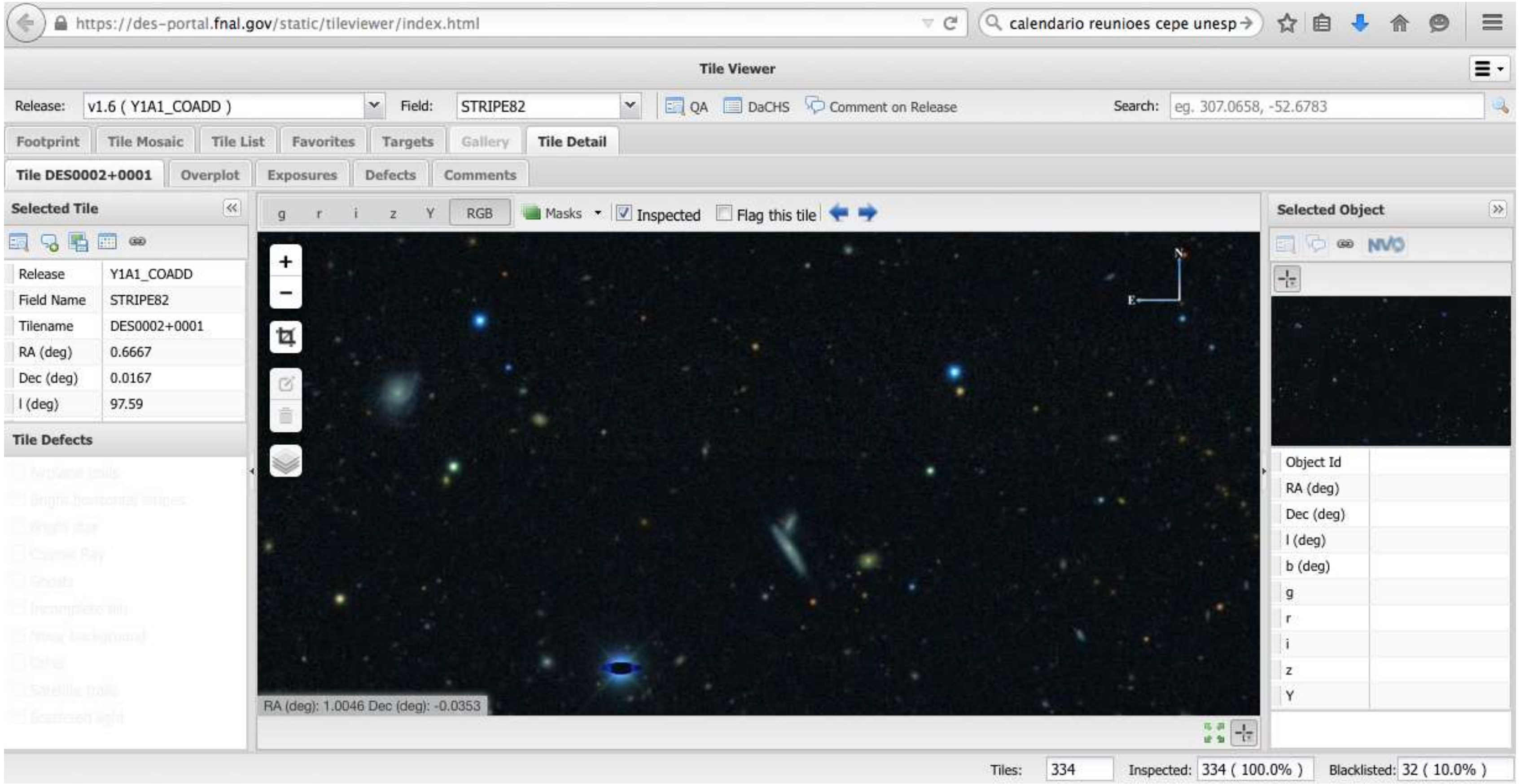


Brazilian infrastructure contribution

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

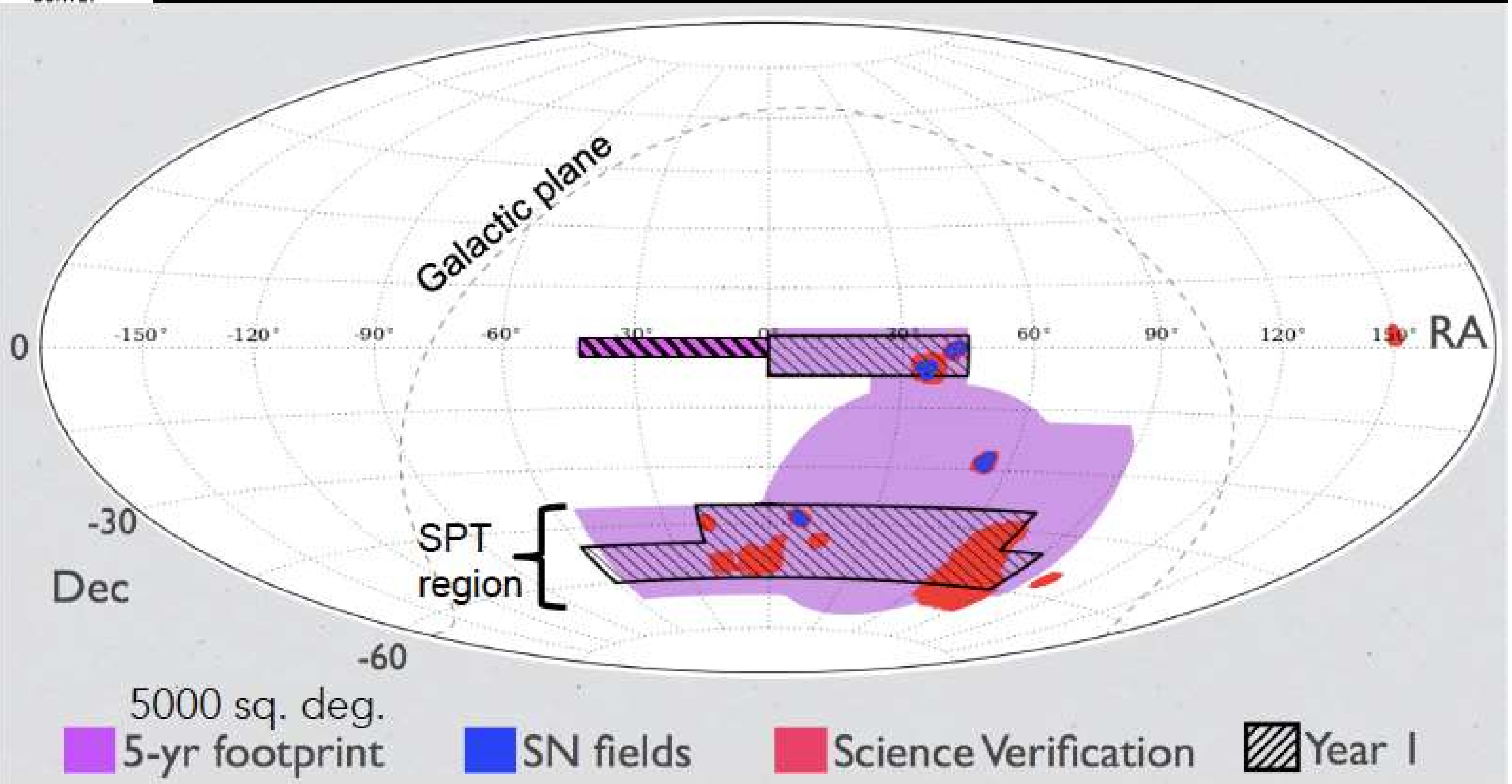
• The Science Portal: Data Server, Value Added Catalogs and scientific pipelines

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


https://des-portal.fnal.gov/static/tileviewer/index.html
Tile Viewer
Release: v1.6 (Y1A1_COADD)
Field: STRIPE82
QA
DaCHS
Comment on Release
Search: eg. 307.0658, -52.6783
Footprint
Tile Mosaic
Tile List
Favorites
Targets
Gallery
Tile Detail
Tile DES0002+0001
Overplot
Exposures
Defects
Comments
Selected Tile
Release Y1A1_COADD
Field Name STRIPE82
Tilename DES0002+0001
RA (deg) 0.6667
Dec (deg) 0.0167
l (deg) 97.59
Tile Defects
g r i z Y RGB
Masks
Inspected
Flag this tile
RA (deg): 1.0046 Dec (deg): -0.0353
Selected Object
Object Id
RA (deg)
Dec (deg)
l (deg)
b (deg)
g
r
i
z
Y
Tiles: 334
Inspected: 334 (100.0%)
Blacklisted: 32 (10.0%)

DES SURVEY FOOTPRINT

DARK ENERGY SURVEY



- 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

6- DES highlights and challenges

A number of results were already obtained.

I will highlight some but concentrate on these Y1 results:

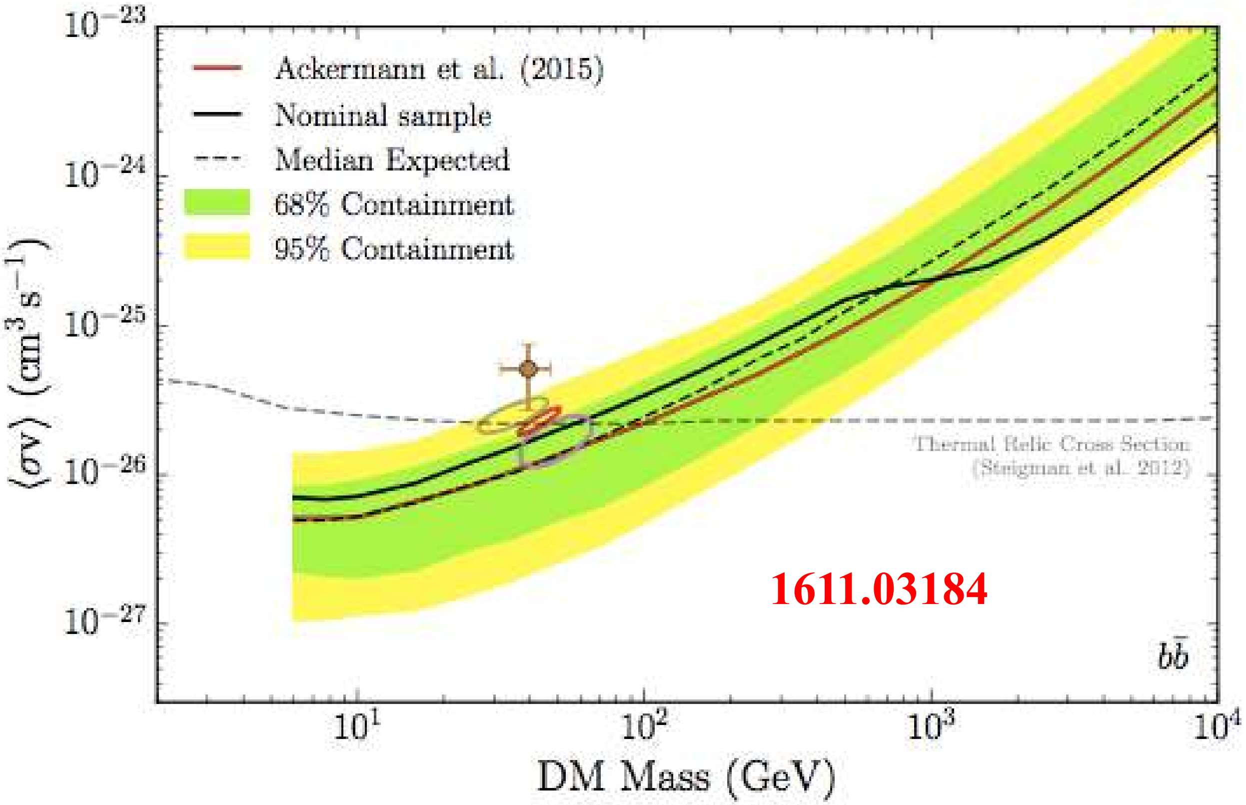
- BAO
- Galaxy clustering + weak lensing
- Beyond LCDM
- Preliminary work on Generalized Dark Matter

> 200 papers

- Produced the largest contiguous mass map of the Universe;
- Discovered 17 new 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;
- Measured 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;
- Found optical counterparts of GW events – led by a brazilian.

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

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



BAO using the angular power spectrum: Camacho et al 1807.10163

Estimations of the galaxy angular power spectrum.

First decompose the projected 2-dimensional galaxy overdensity in a given redshift bin in spherical harmonics as:

$$\delta_{\rm gal}(\hat{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{m=l} a_{lm} Y_{lm}(\hat{n})$$

The angular power spectrum C_l can be estimated (in full sky) as:

$$\hat{C}_l = \frac{1}{2l+1} \sum_{m=-l}^{m=l} |a_{lm}|^2$$

We compute the coefficients a_{lm} from the pixelized density contrast maps using the *anafast* code contained in HEALPiX.

The measurements must take into account the fact that the survey is not performed in full sky – there is a *mask*

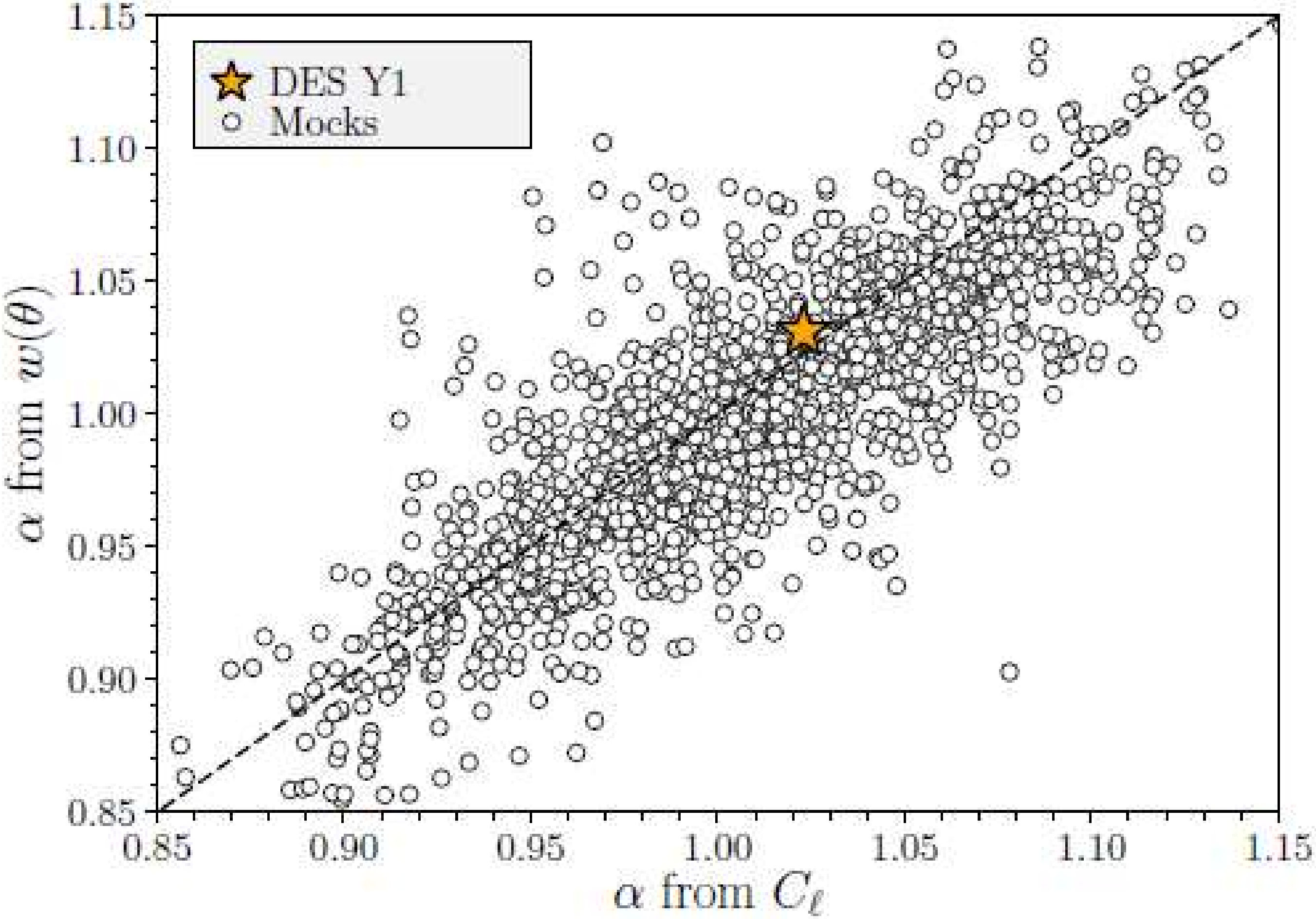
Mask affects the estimator: we use the so-called pseudo-C_l method (developed in CMB)

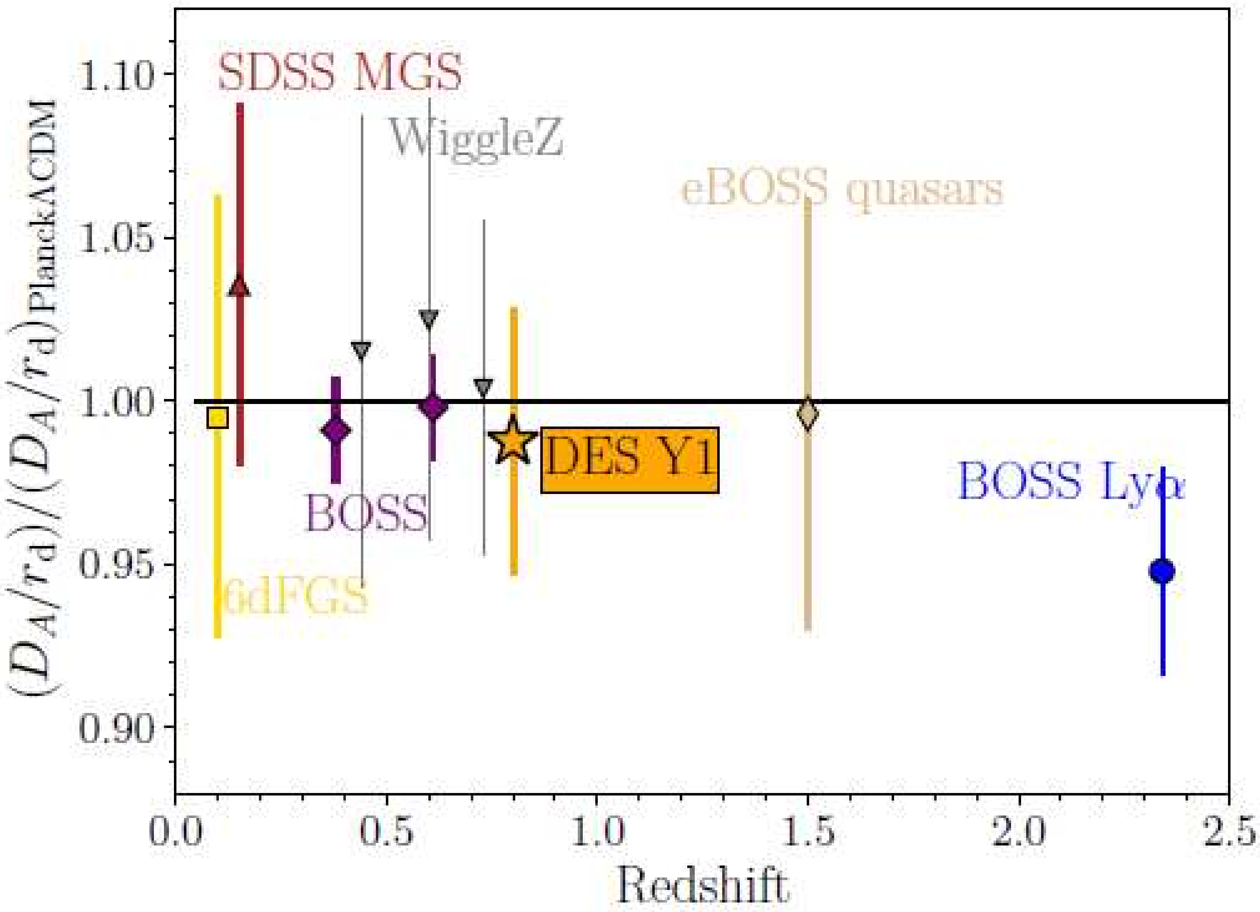
Mask is provided by the collaboration taking into account data quality and systematic effects (eg airmass).
Effective area of full survey is expected to be 5000 deg^2
Y1 ~ 1000 deg^2

Covariance matrix estimated from 1800 mocks (but resulted in large chi2) – also estimate theoretically from HALOFIT including mask effects.

Parameter α determines the shift in the BAO position with respect to a fiducial cosmology:

$$\alpha = \frac{(D_A(z)/r_d)}{(D_A(z)/r_d)_{\rm fid}}$$




SDSS MGS
WiggleZ
eBOSS quasars
DES Y1
BOSS
BOSS Lyα
6dFGS
1.10
1.05
1.00
0.95
0.90
$(D_A/r_d)/(D_A/r_d)_{\text{Planck}\Lambda\text{CDM}}$
0.0
0.5
1.0
1.5
2.0
2.5
Redshift

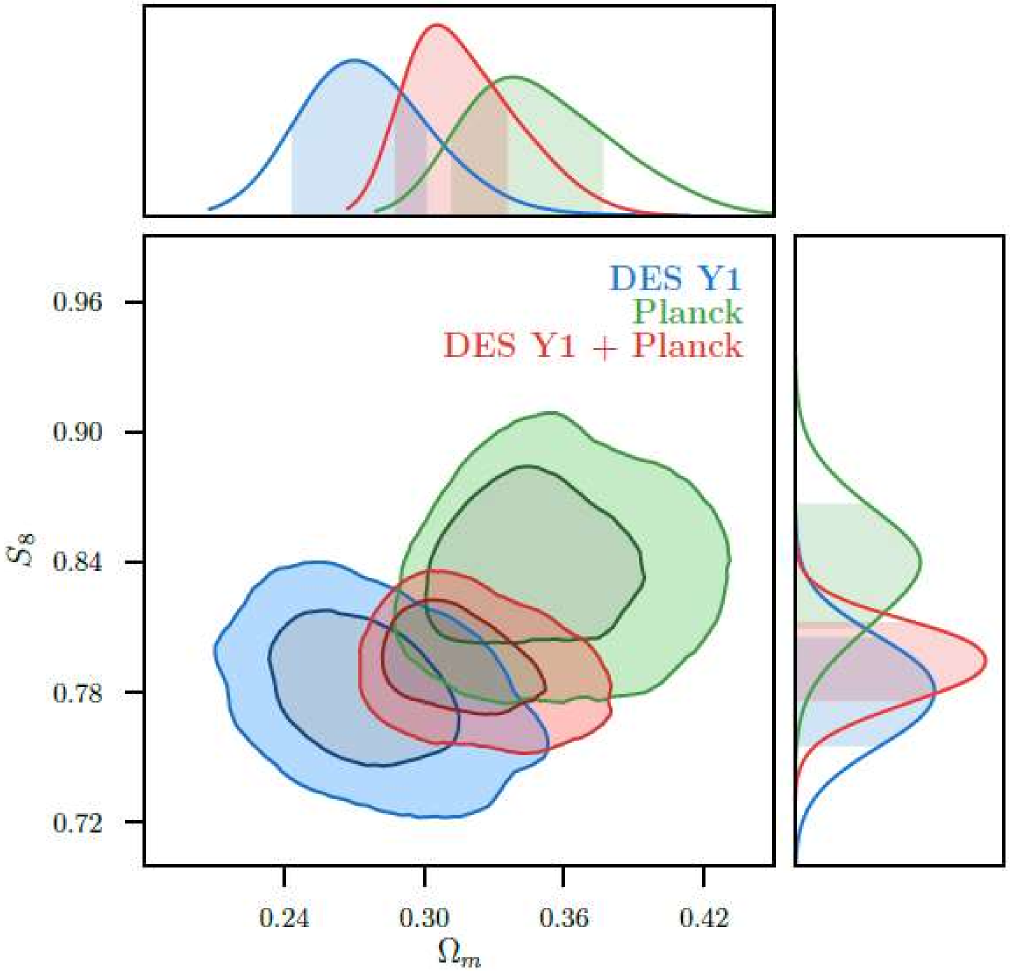
Main result: Galaxy clustering + weak lensing

Main paper: 1708.01530

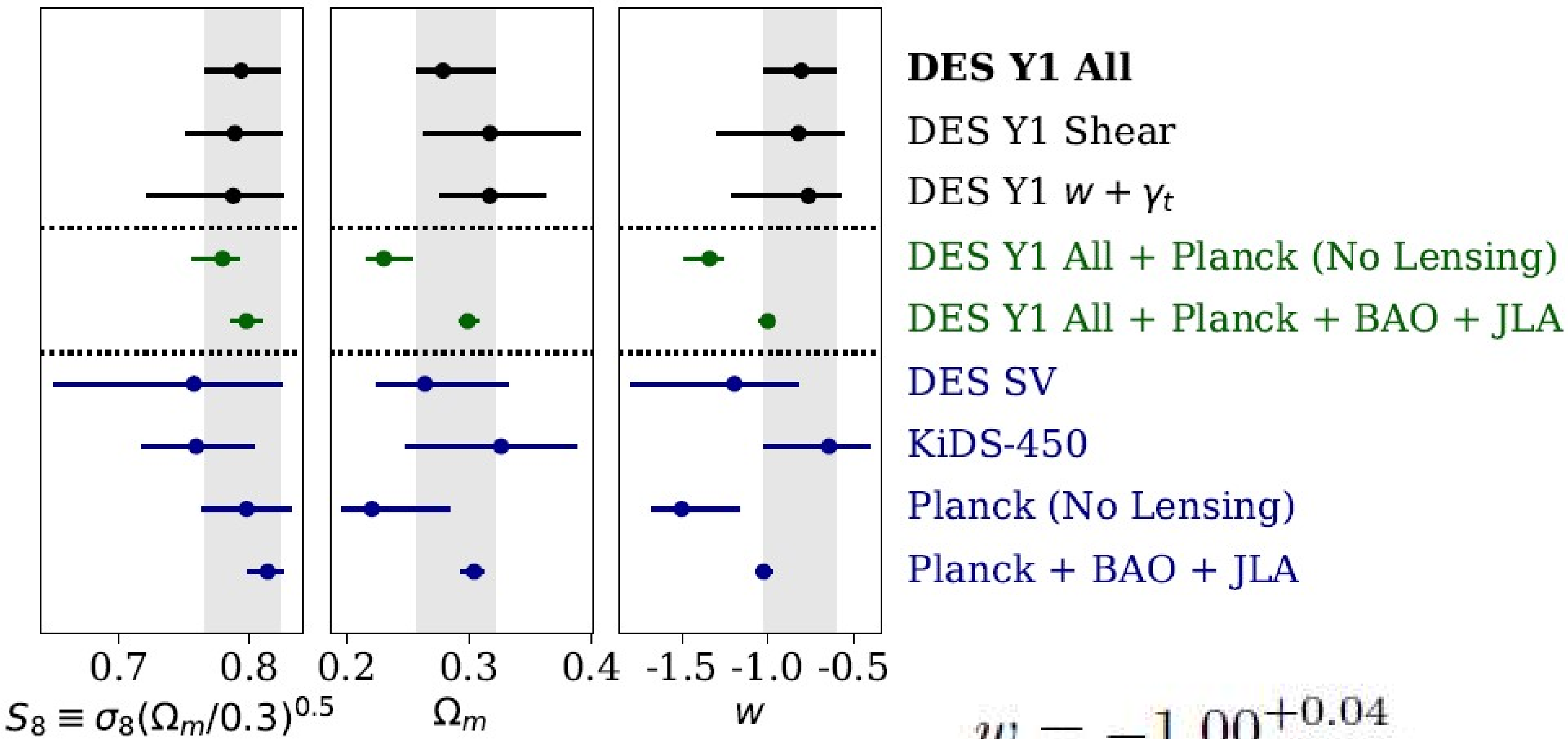
Uses 2 galaxy samples:

- “Shape catalogue”: 26M galaxies for cosmic shear measurements (source galaxies) divided into 4 redshift bins
- “Position catalogue”: 650,000 luminous red galaxies (lens galaxies) for clustering measurements divided into 5 redshift bins

ΛCDM


DES Y1
Planck
DES Y1 + Planck
0.96
0.90
0.84
0.78
0.72
S_8
0.24
0.30
0.36
0.42
Ω_m

wCDM



$$w = -1.00^{+0.04}_{-0.05}.$$

There goes the Nobel prize... (S. Dodelson)

Beyond wCDM: "Extensions paper" - 1810.02499

Four extensions:

1. Spatial curvature
2. The effective number of neutrinos species
3. Time-varying equation-of-state of dark energy: $w(a) = w_0 + (1-a)\, w_a$
4. Tests of gravity

ΛCDM Extension	Parameter	Flat Prior
Curvature	Ω_k	$[-0.25, 0.25]$
Number relativistic species	$N_{\rm eff}$	$[3.0, 7.0]$
Dynamical dark energy	w_0	$[-2.0, -0.33]$
	w_a	$[-3.0, 3.0]$
Modified gravity	Σ_0	$[-3.0, 3.0]$
	μ_0	$[-3.0, 3.0]$

Generalized Dark Matter (GDM): work in progress

Otávio Alonso – MSc student + F. Oliveira + I. Tutusaus

GDM was introduced by W. Hu in 1998.
Most general way to parametrize dark matter.

General Relativity: $g_{\mu\nu} \longleftrightarrow T_{\mu\nu}$

For a homogeneous and isotropic universe: only one function must be specified for the description of a fluid – the equation of state $w(a) = p(a)/\rho(a)$

However, in the description of perturbations one needs more information. How many degrees of freedom in GR?

General Relativity:
$g_{\mu\nu}$: 10 functions
$T_{\mu\nu}$: 10 functions
Einstein's equation: 10 equations
General coordinate invariance: 4 "gauge" relations

6 physical degrees of freedom!

One can choose the 6 physical degrees of freedom to be related to the components of the perturbed $T_{\mu\nu}$

Furthermore, perturbations can be divided into scalar, vector and tensor perturbations. For galaxy formation we are interested only in scalar perturbations.

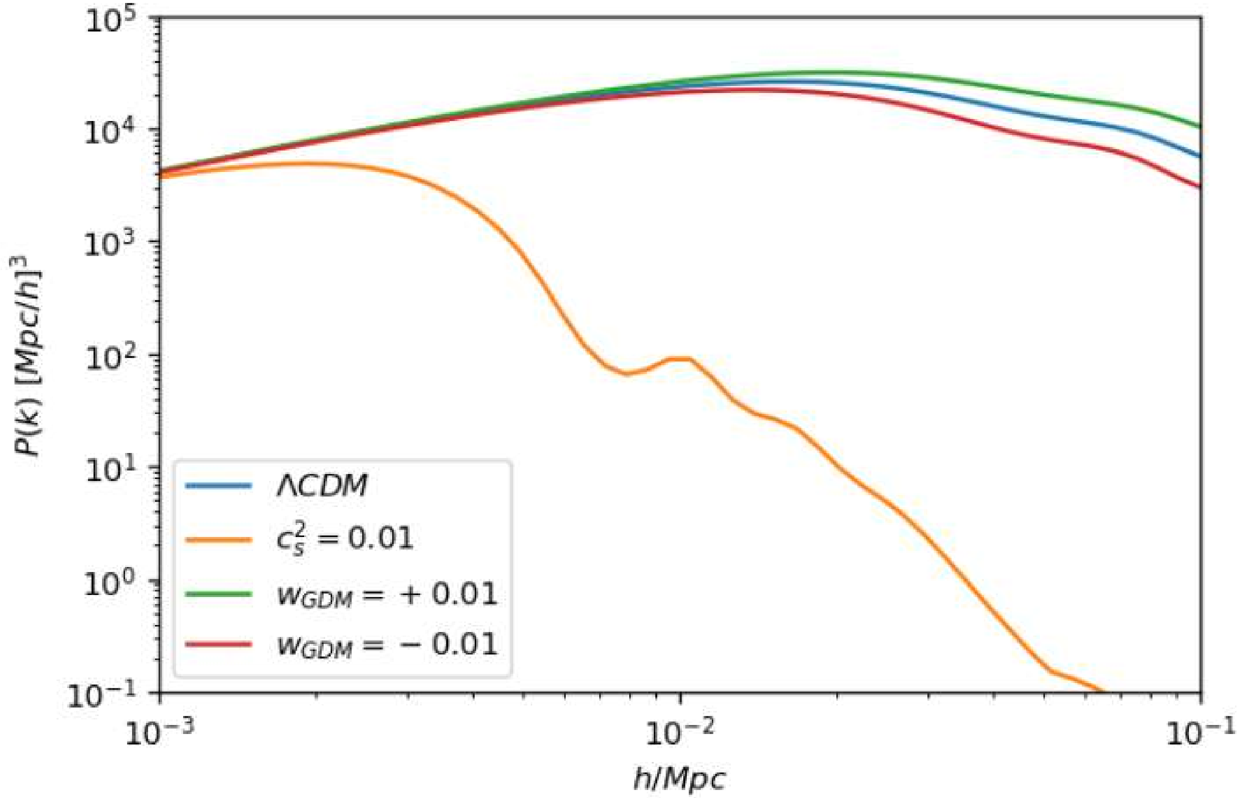
It can be shown that scalar perturbations can be fully described by 2 functions: they can be chosen to be the non-adiabatic speed of sound and a viscosity term (Hu 1998)

Generalized DM parametrized by:

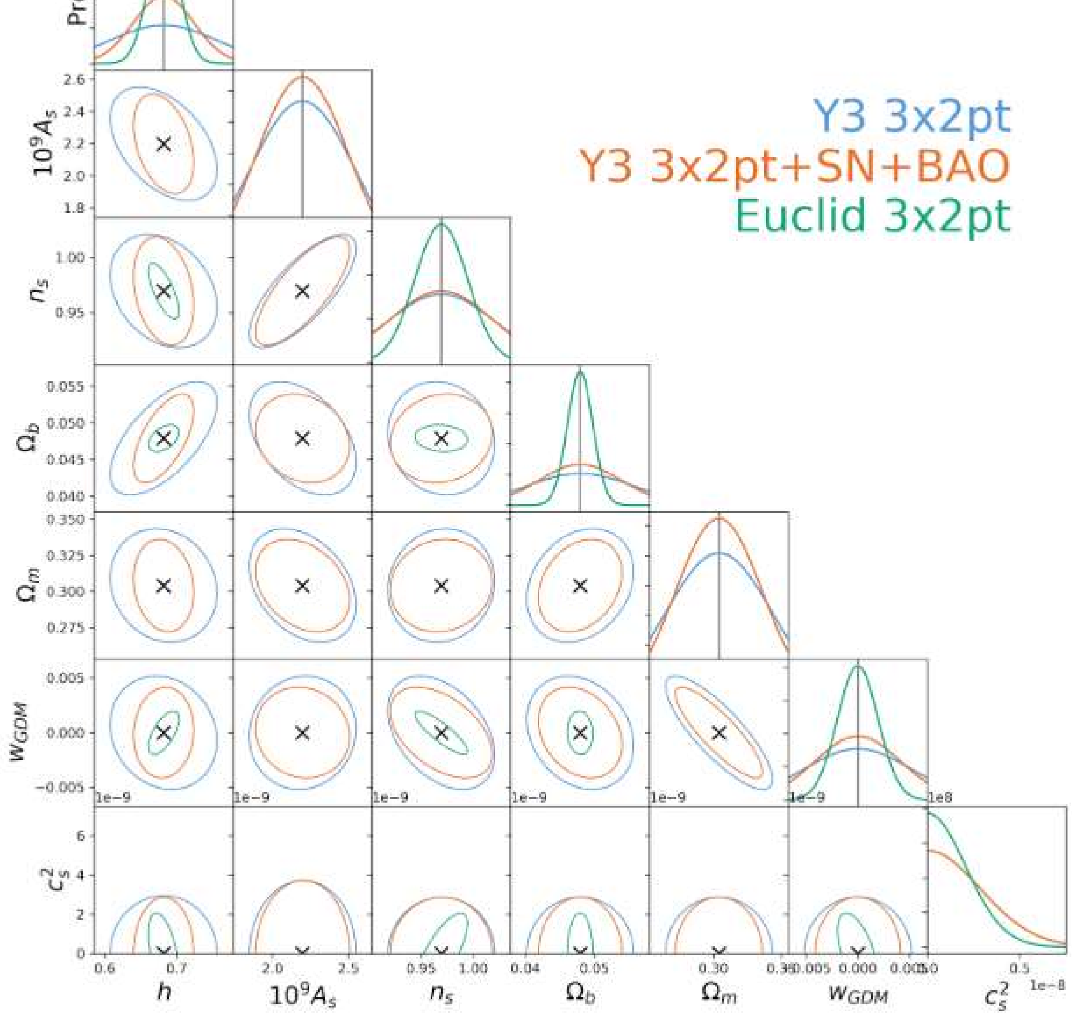
$$w(a), \quad c_s^2(k,a), \quad c_{\rm vis}^2(k,a)$$

Linear perturbation equations for GDM introduced in CLASS

How does GDM affect the matter power spectrum?



Fisher forecast



2 GDM parameters: w_{GDM}, c_s^2

Modified CLASS by Isaac Tutusaus.

Fisher forecast using:

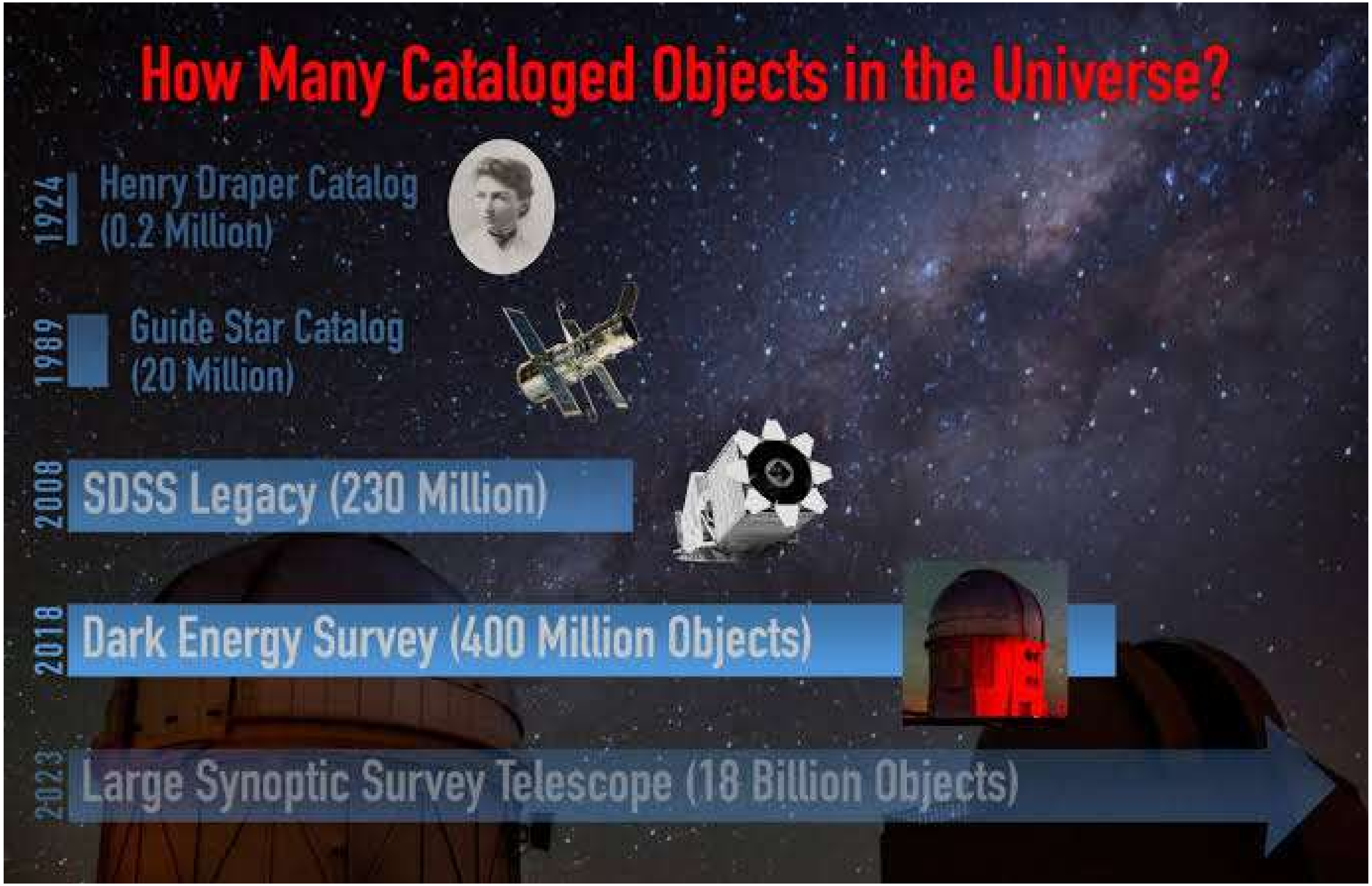
DES Y3 simulated covariance matrix
Gaussian+shot noise, uses cosmolike
Cosmology: planck best fit, LCDM, TT only

DES Y1 scale cuts

Ongoing: **simulated likelihood analysis.**

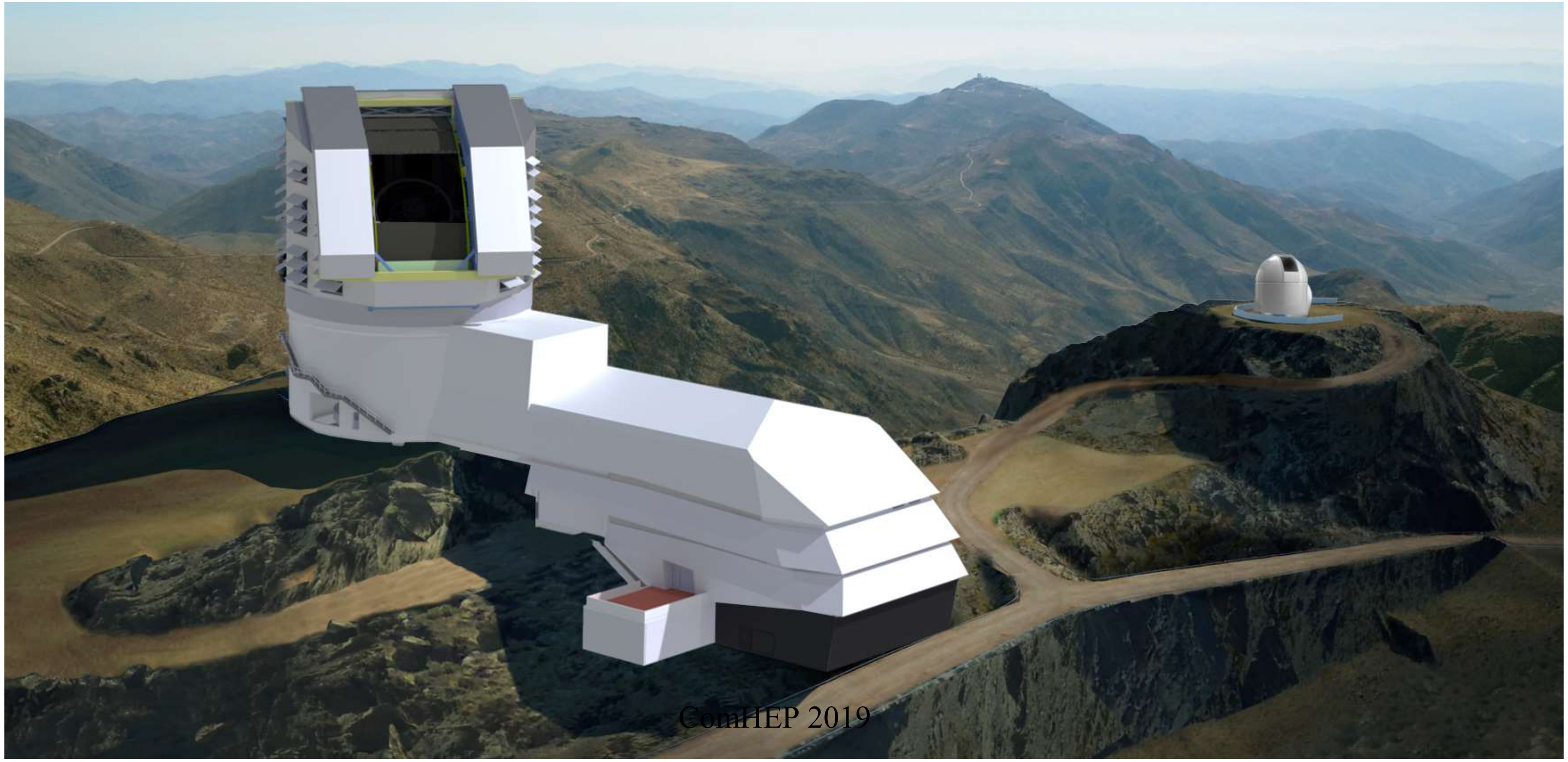
DES Y3 simulated datavector
(simulated_redmagic_hd3_hl2_sourcesy3_cosmo-ptt_cov-cosmolikeG.fits)
Fiducial Planck cosmology

7- Glimpses at the Future and Conclusions



The Future: LSST

Large Synoptic Survey Telescope
Brazil has 10 PIs



The goal of the Large Synoptic Survey Telescope (LSST) project is to conduct a 10-year survey of the sky that will deliver a 500 petabyte set of images and data products that will address some of the most pressing questions about the structure and evolution of the universe and the objects in it. The LSST survey is designed to address four science areas:

- Understanding the Mysterious Dark Matter and Dark Energy
- Hazardous Asteroids and the Remote Solar System
- The Transient Optical Sky
- The Formation and Structure of the Milky Way

White paper: Probing the fundamental nature of dark matter with LSST

1902.01055

Very active Dark Matter working group in LSST

CONCLUSIONS

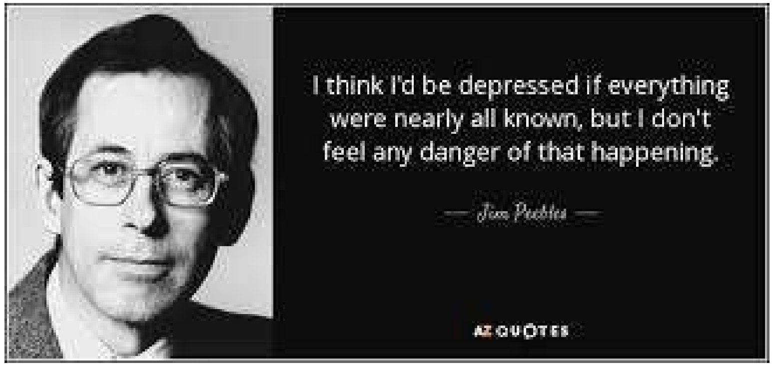
- Cosmology has become a precision, data driven Science – Jim Peebles is one of the main responsibles

- Cosmology tests models of fundamental physics (eg are studying WDM and DM-DE interaction)

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

- Y1 DES analysis finished – Y3 under way

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



On behalf of the participants:

Thank you to the organizers for this very nice meeting!