If the Universe is the answer what is the question?

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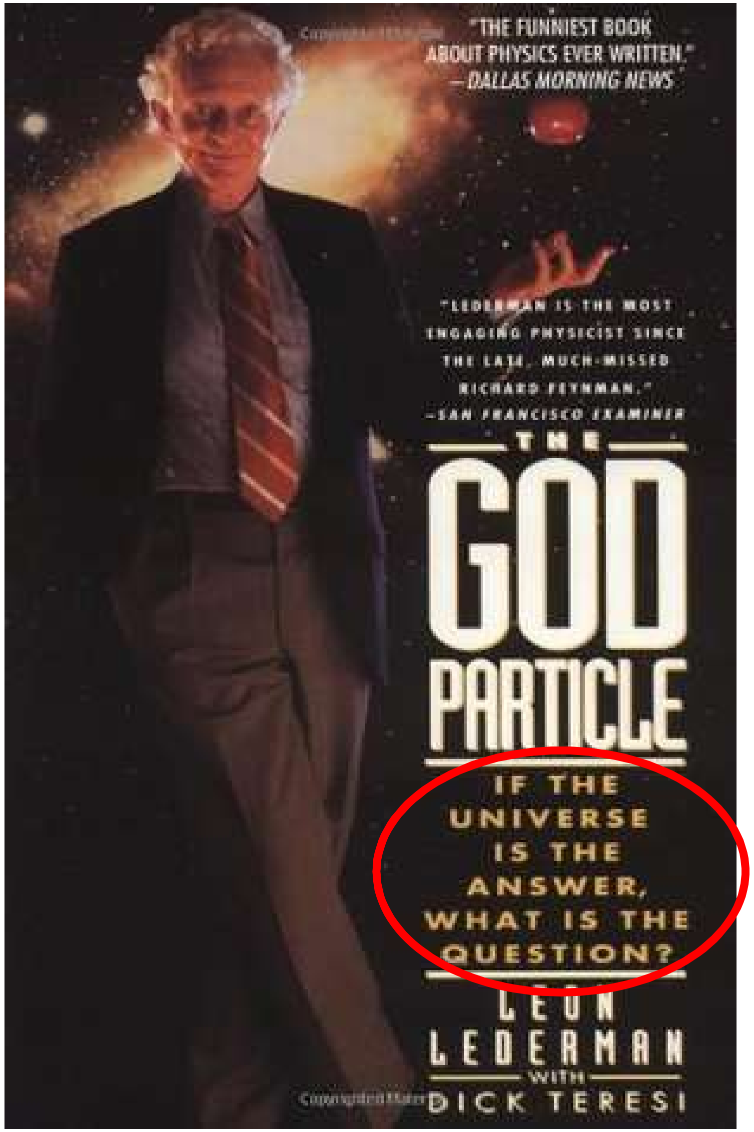
Dark Energy Survey collaboration

SILAFAE 2018 – Lima – Peru



Leon Max Lederman (July 15, 1922 – October 3, 2018)

Started the cosmology group at Fermilab

SDSS and DES

Plan:

0 – Introduction

1– From probes to answers

2 – Perturbations in the Universe

3 – The 3d power spectrum

4 - Baryon acoustic oscillations

5 – Angular power spectrum: theory

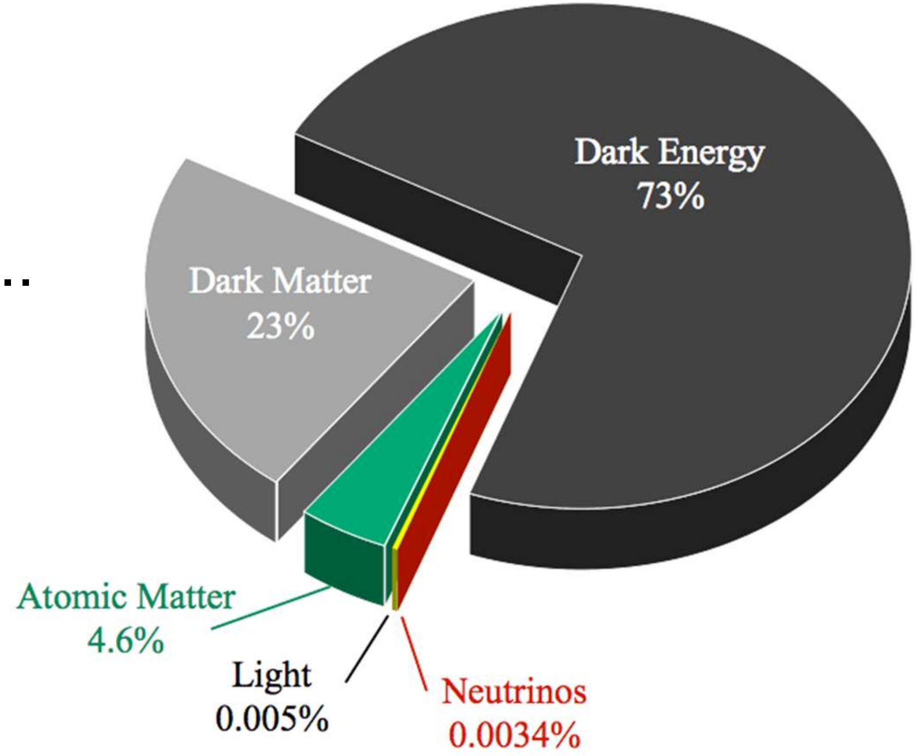
6 – Observations: the Dark Energy Survey

7 – DES highlights and challenges

8 – Coda

0 – Introduction

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?

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.

$t_U = (13.799 \pm 0.021) \times 10^9$ 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.

Some 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

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:

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

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 model: maximize likelihood

Sounds pretty easy!

2- Perturbations in the Universe

Inflation generated small 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

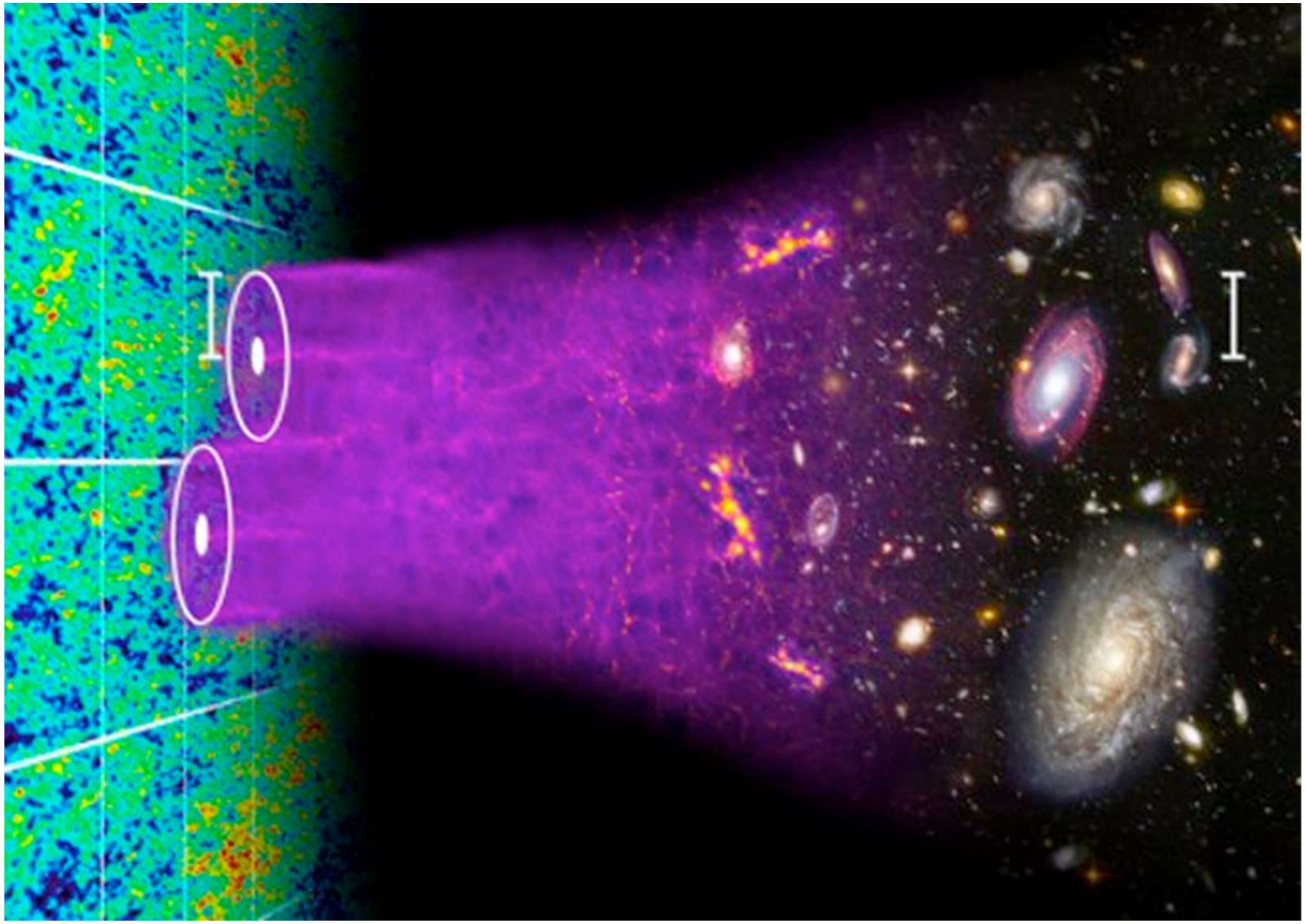


Illustration by Chris Blake and Sam Moorfield

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.

Semi-analytical methods for nonlinear evolution of perturbations:

Halo model

EFTofLSS

Resummed perturbation theory

Halo model motivated fits to simulations (HALOFIT)

One can 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

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

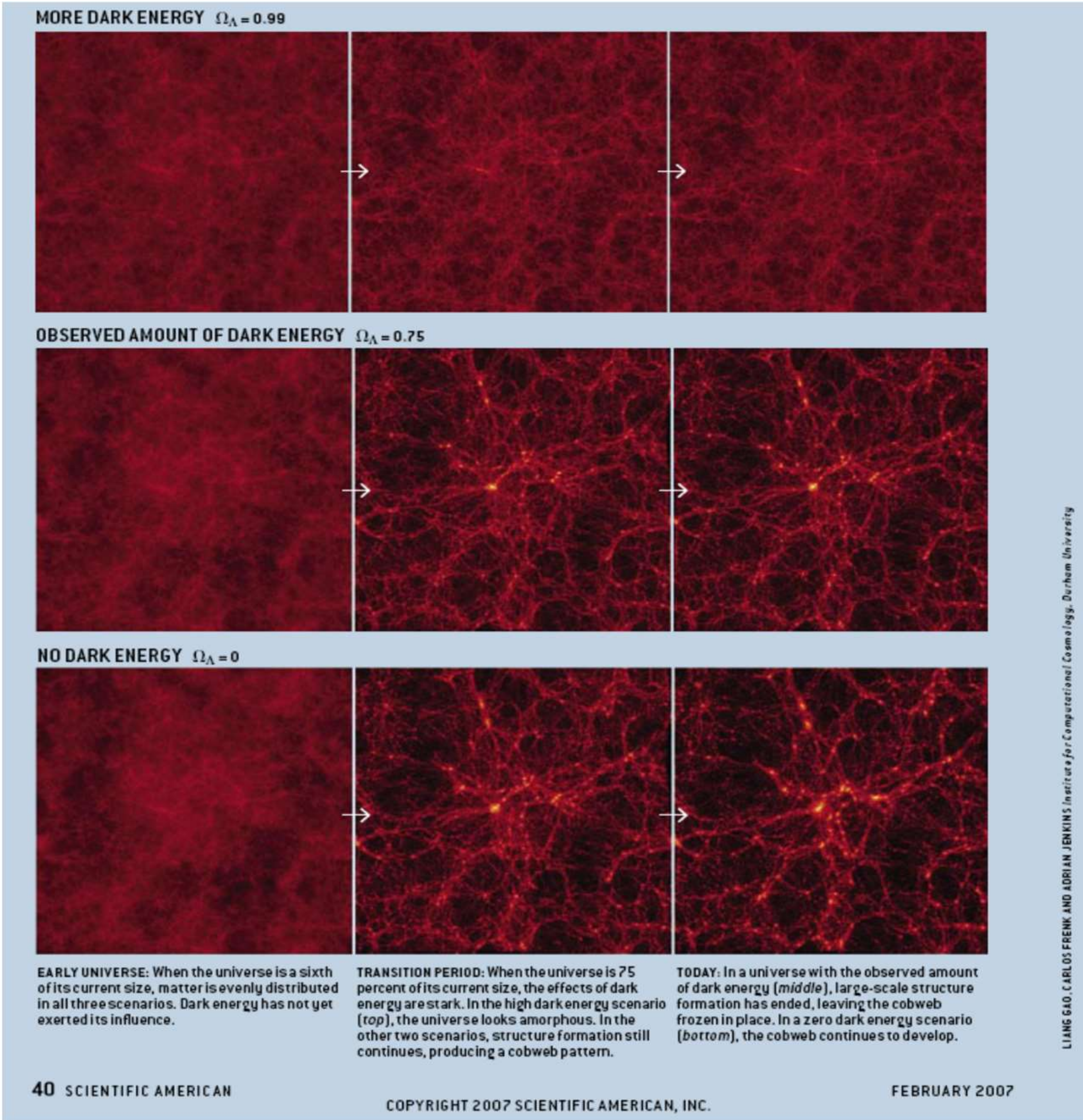
and that in a Λ-dominated universe

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

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

Dark energy suppresses structure formation

(Weinberg's anthropic argument)



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

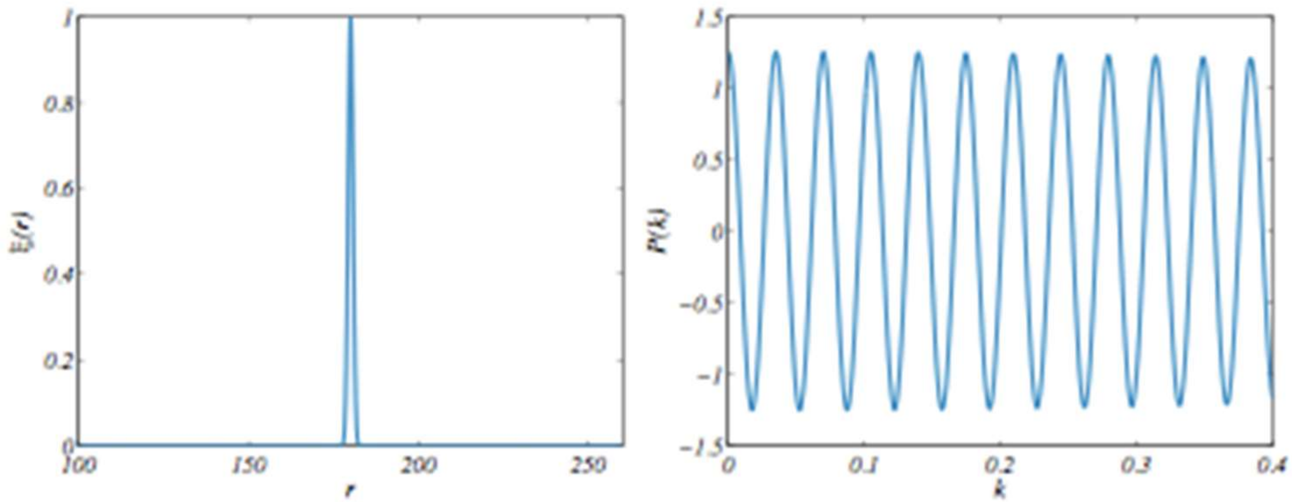
One can also define a power spectrum:

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

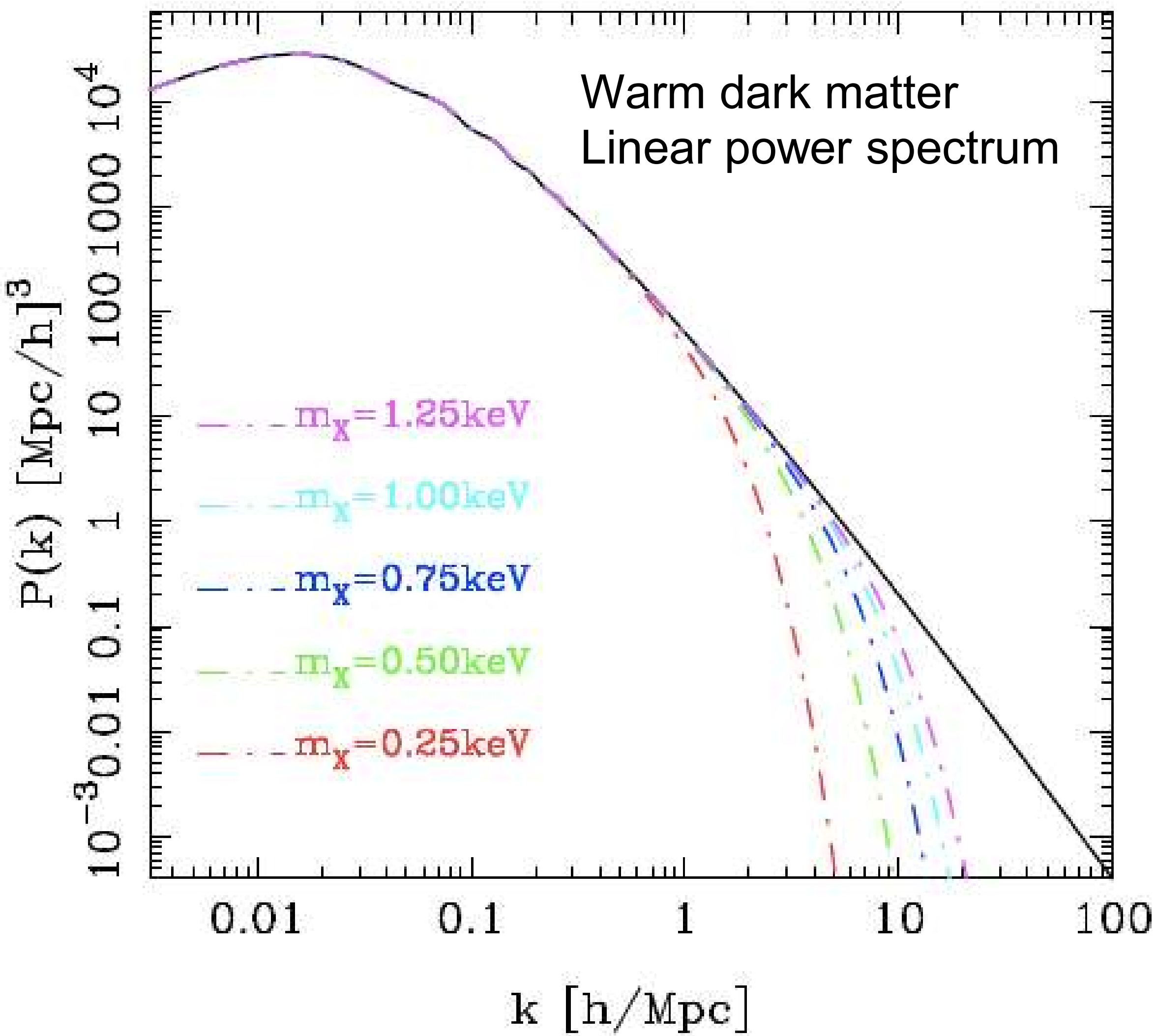
It's possible to work with either spatial correlation function or power spectrum – advantages and disadvantages

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



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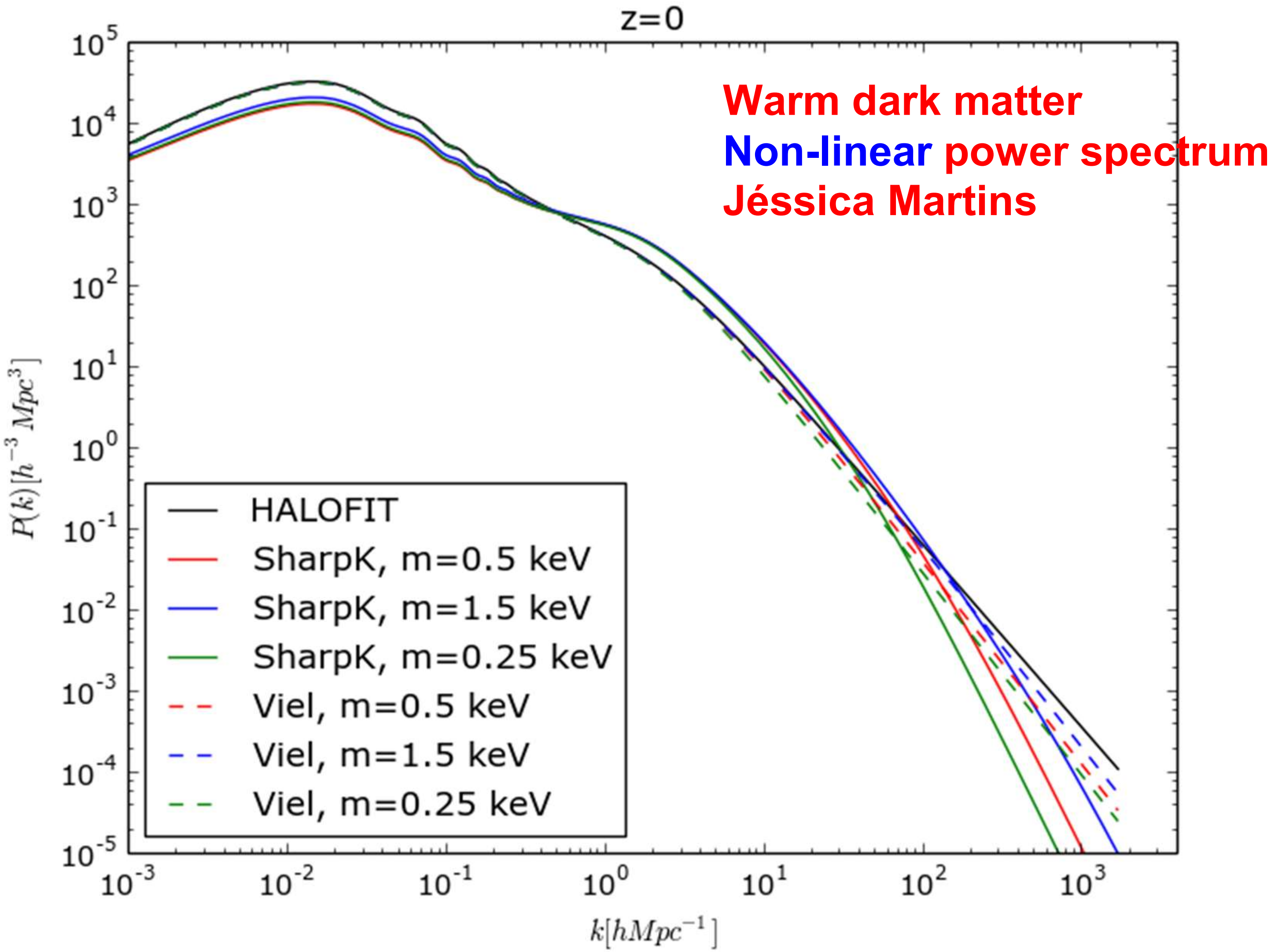
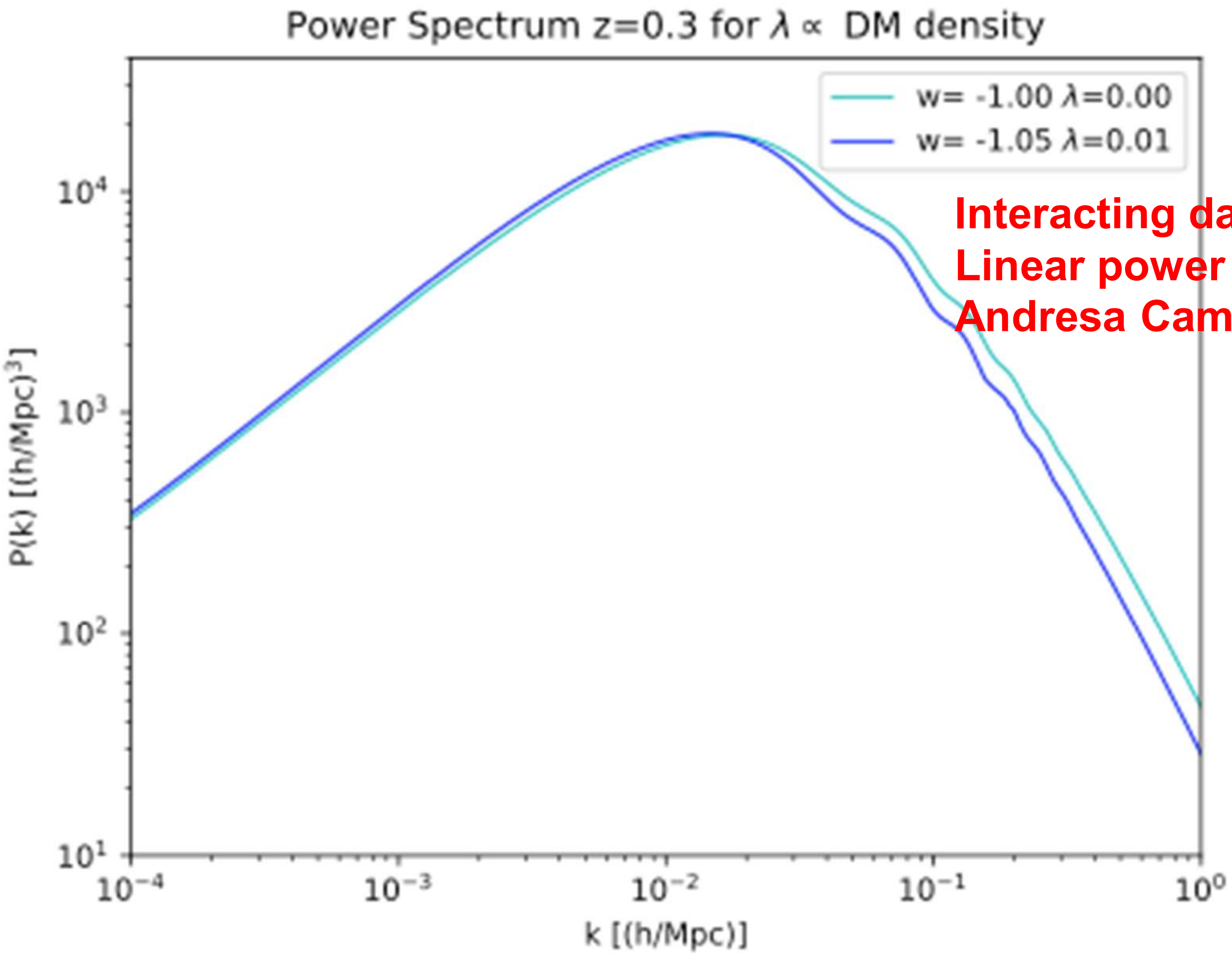


Power spectrum is sensitive to new physics



Interacting dark matter-dark energy
Linear power spectrum
Andresa Campos

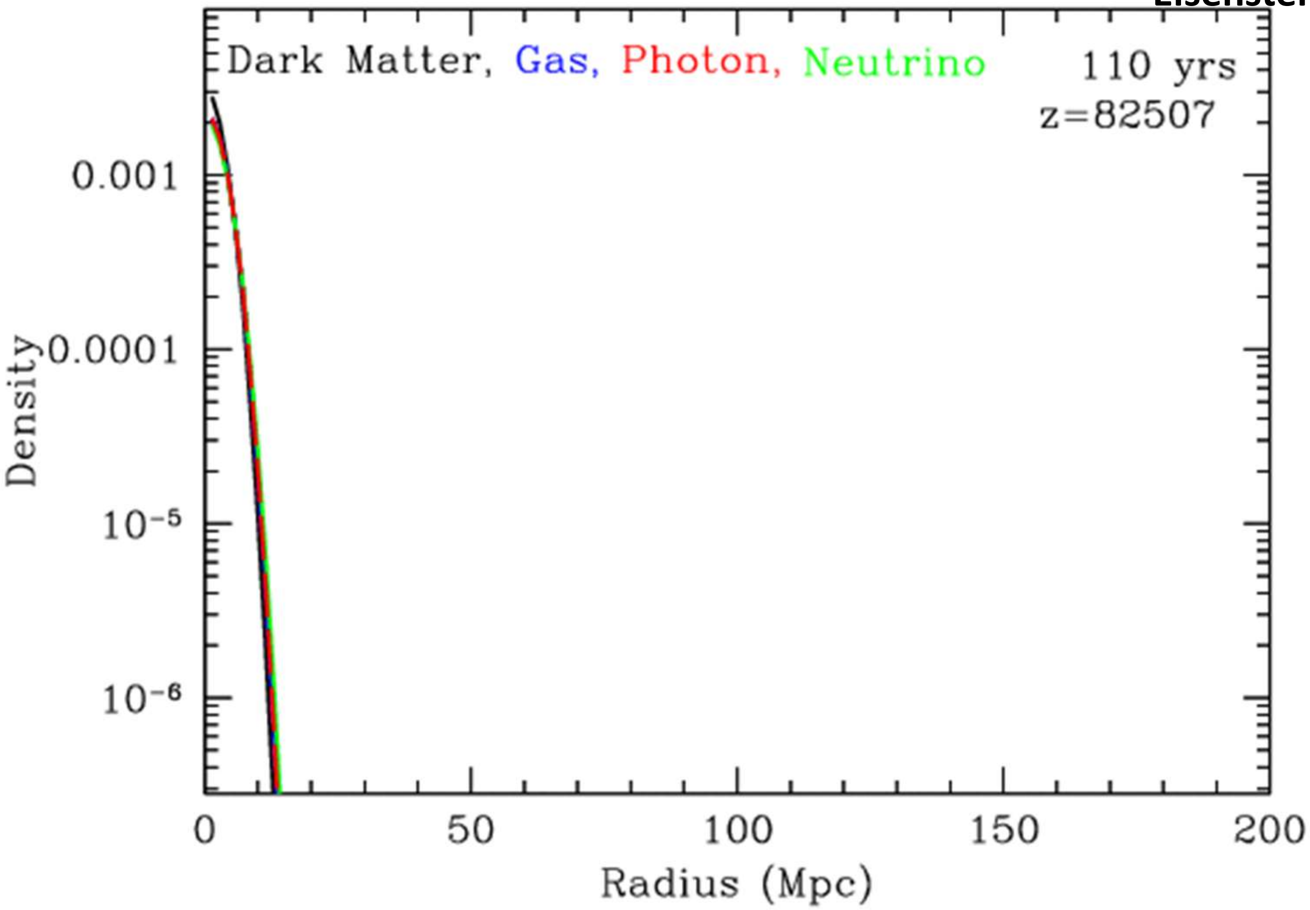
4- Baryon acoustic oscillation

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

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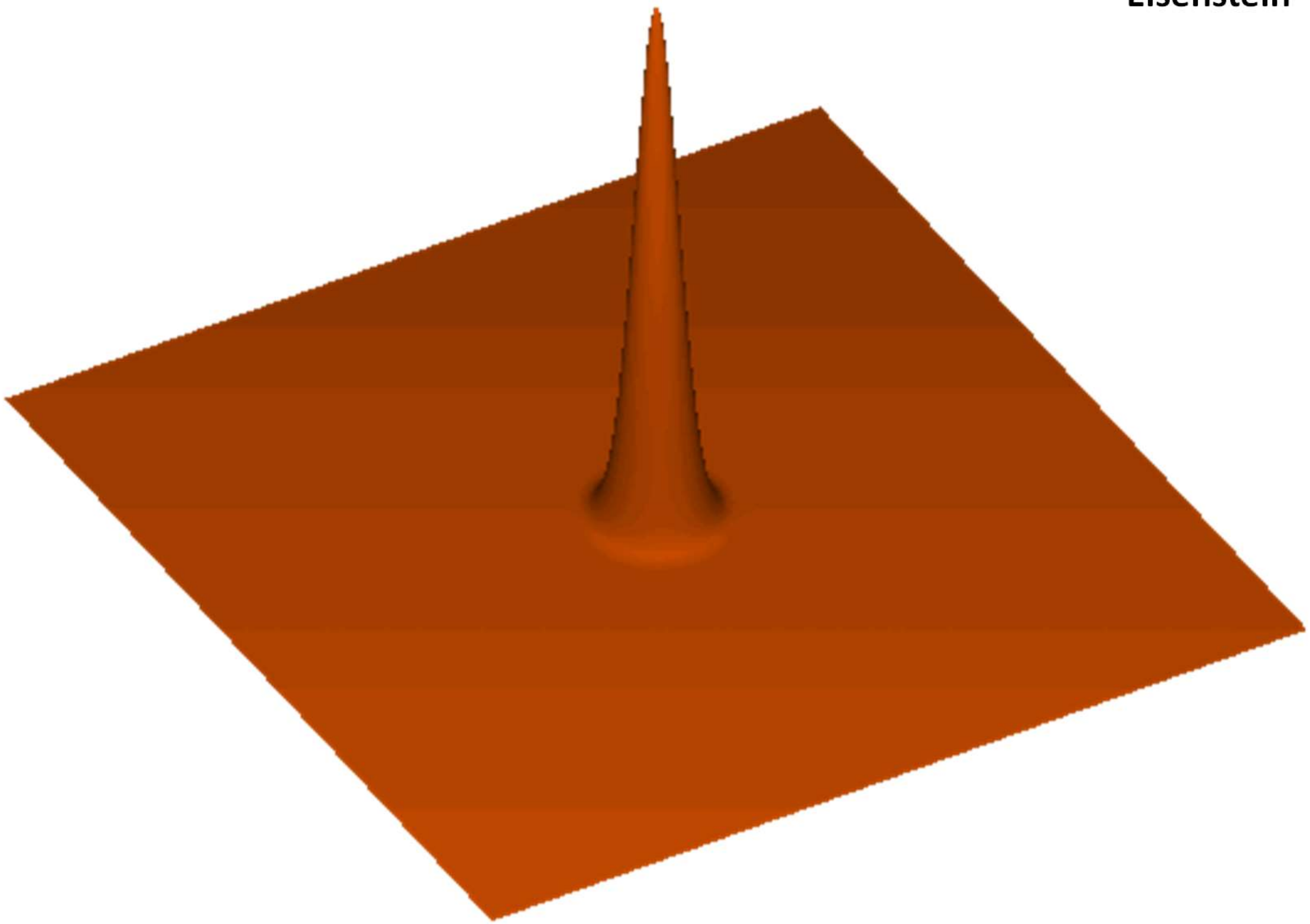


BAO scale

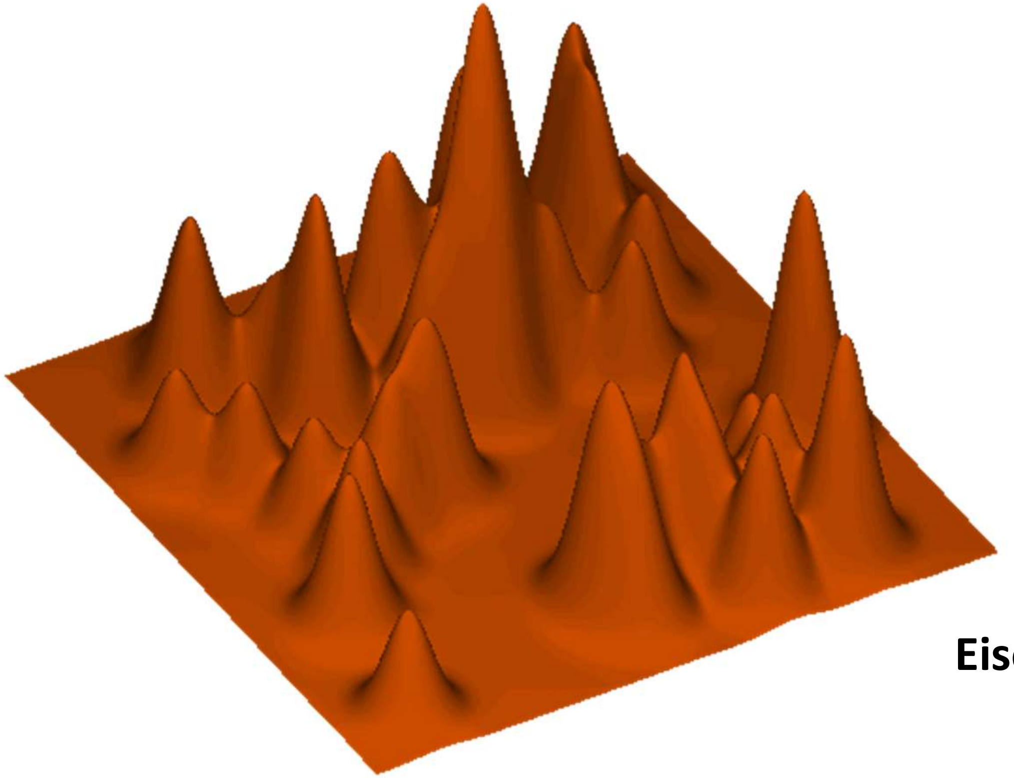
Standard ruler in the sky

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

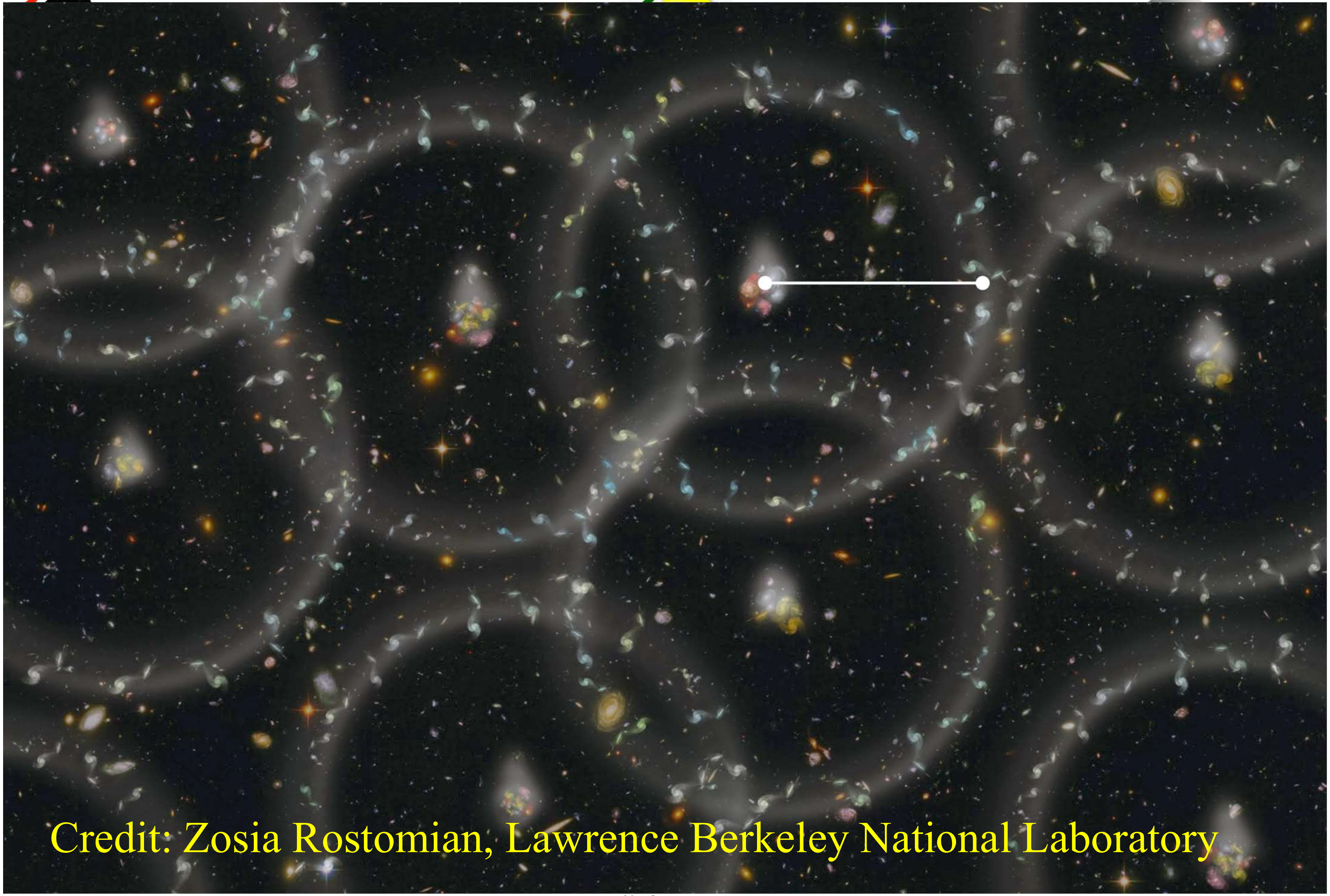
Cosmological parameters

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

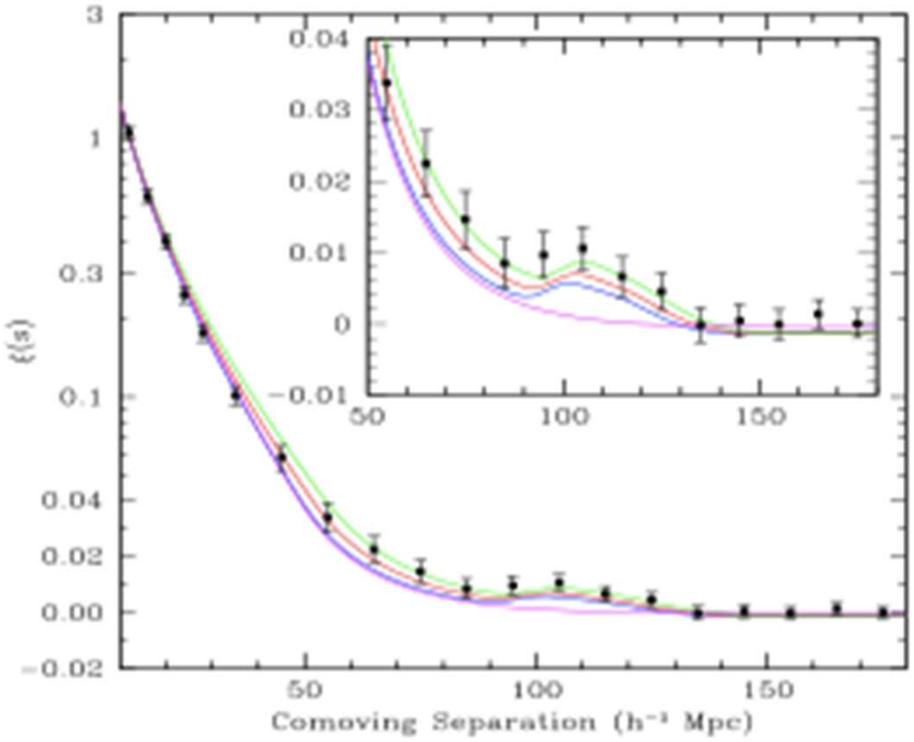
Things are more complicated: superposition of shells with different locations and different amplitudes



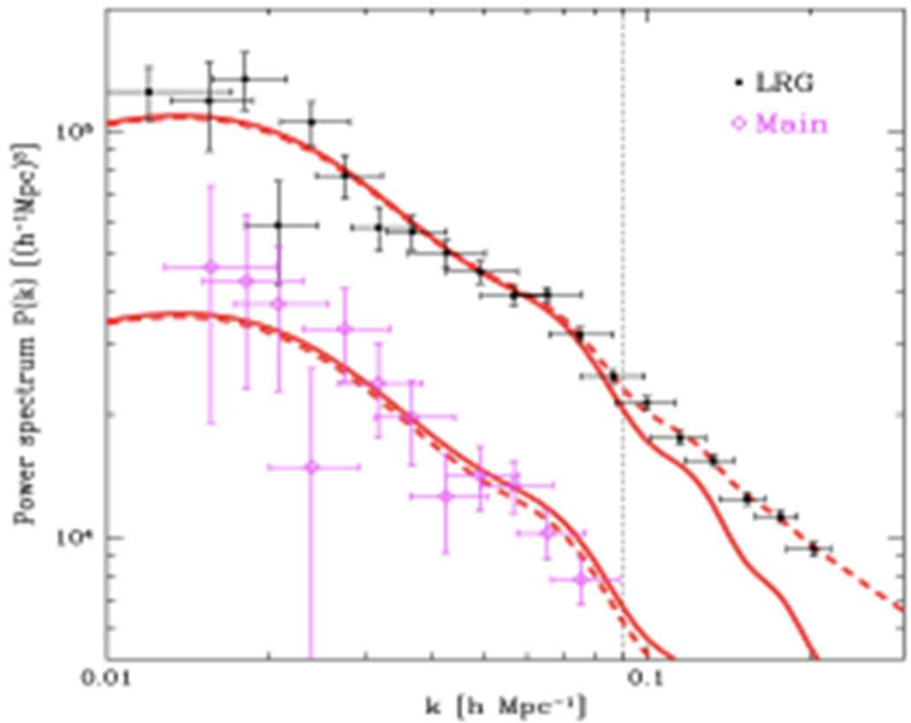
Eisenstein


Credit: Zosia Rostomian, Lawrence Berkeley National Laboratory

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



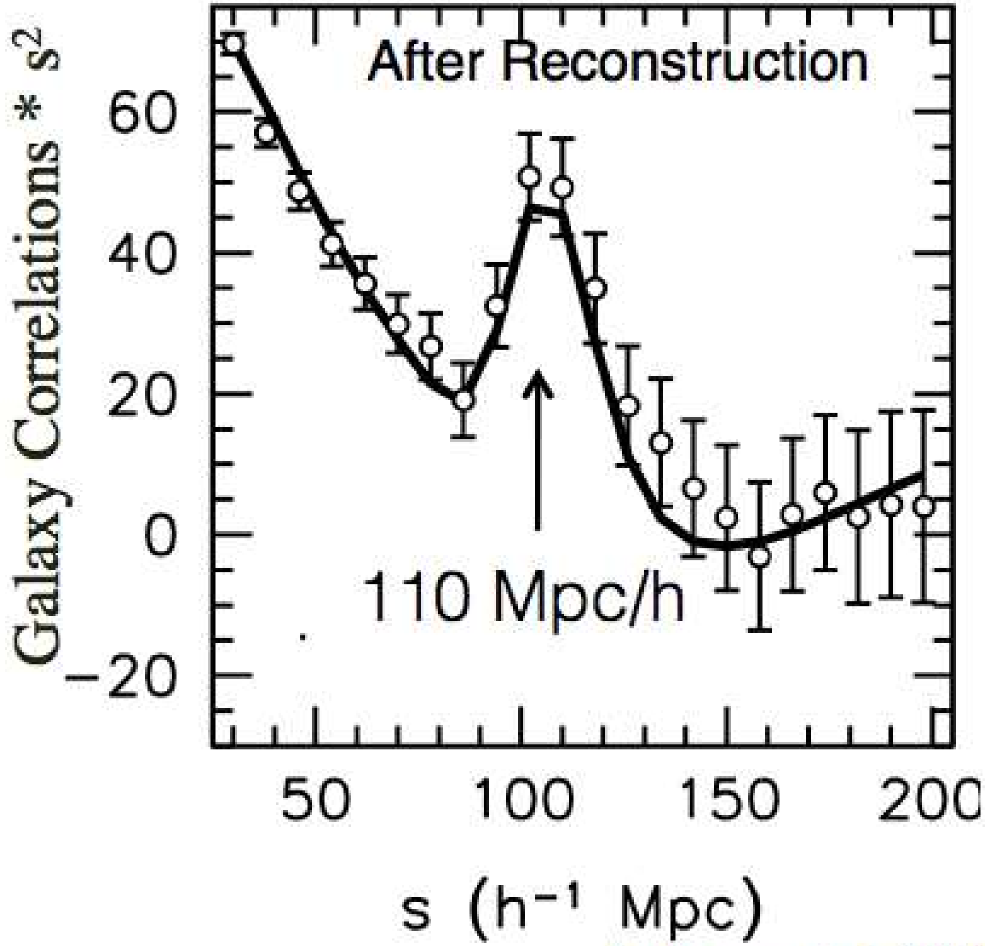
Eisenstein et al (2005)



Tegmark et al (2006)

DR3, z ~ 0.35

Galaxy 2-point correlation function



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

5- Angular power spectrum: theory

Some surveys have poor redshift determination and it is convenient to project the 3d matter density contrast into spherical shells in a given redshift bin and expand it in spherical harmonics:

$$\sigma_i(\hat{n}) = \int dz \phi_i(z) \delta(\hat{n}, z) = \sum_{lm} a_{lm} Y_{lm}(\hat{n})$$

Selection function (given by experiment)

The angular power spectrum C_l is defined as:

$$\langle a_{lm} a^*_{l'm'} \rangle = \delta_{ll'} \delta_{mm'} C_l$$

It is not difficult to show that the angular power spectrum C_l is related to the 3d power spectrum by:

$$C_l^{ij} = \frac{2}{\pi} \int dk k^2 P(k) \psi_l^i(k) \psi_l^j(k)$$

$$\psi_l^i(k) = \int dz \phi^i(z) j_l(kr(z))$$

Why is it difficult to compute the angular power spectrum in a given model:

. To compute the linear P(k) in a new physics model one has to solve a complicated set of Boltzmann equations (CAMB, CLASS) to evolve an initial P(k)

. Non-linear power spectrum is very difficult to obtain – semi-analytic mthods, simulations, EFT

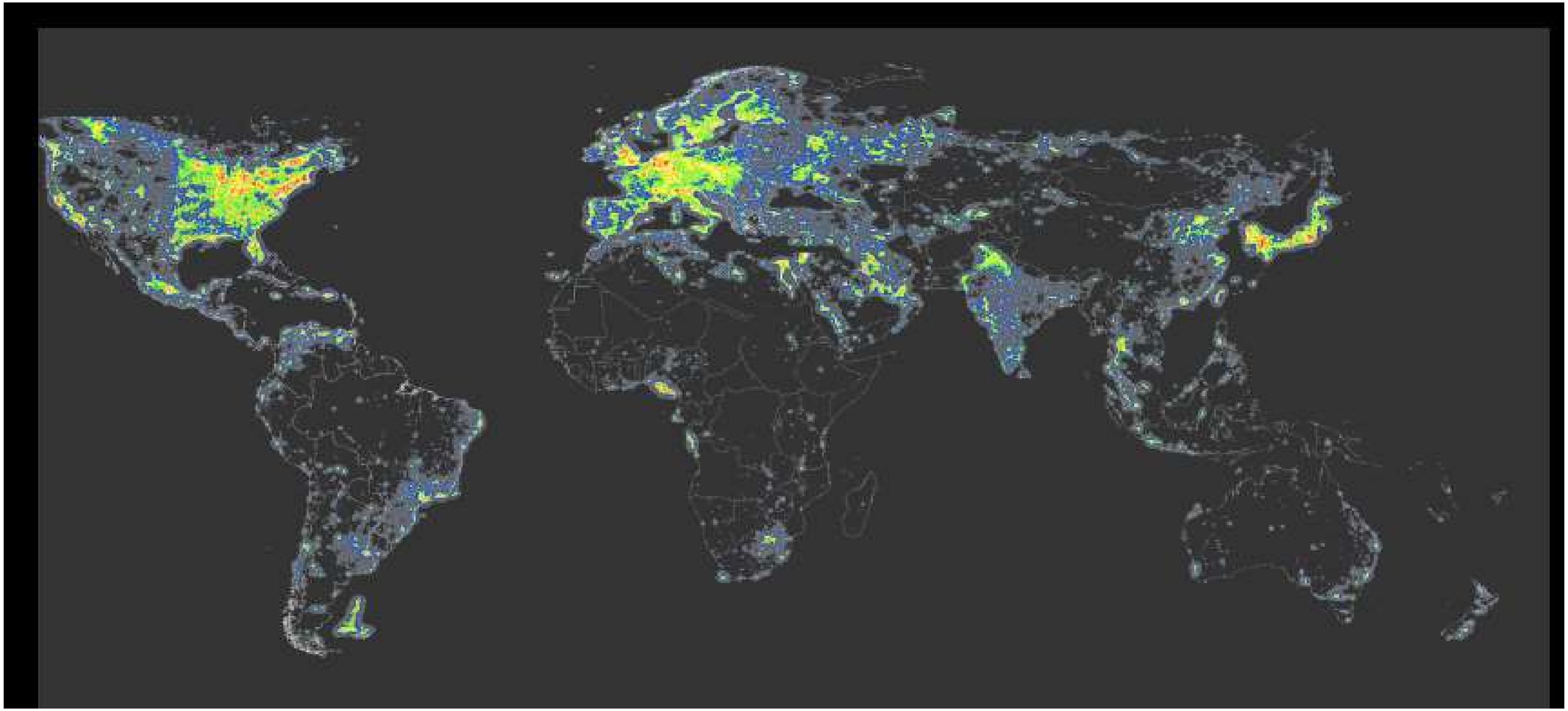
. One must correct for the so-called redshift space distortions – proper motions of objects

. Redshift measurement has large errors that have to be modelled (photometric redshift)

We observe galaxies (baryons) since they emit light.

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.



Linear bias model
(relation between galaxy density and dark matter density):

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

galaxy overdensity

bias

matter overdensity
(theory from a cosmological model)

Linear bias: another free parameter

6- 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 ...

linea.gov.br

LIneA
Laboratório Interinstitucional de e-Astronomia

INCT do e-Universo

Início | Sobre | Ciência ▾ | Data Center ▾ | Software ▾ | Serviços ▾ | Divulgação ▾ | Colaboradores ▾ | Contatos ▾ | Oportunidades

O que é o LIneA

É um laboratório interinstitucional apoiado pelo Observatório Nacional (ON), o Laboratório Nacional de Computação Científica (LNCC), e a Rede Nacional de Ensino e Pesquisa (RNP), que foi criado com a finalidade de dar suporte à participação brasileira em levantamentos astronômicos gerando grandes volumes de dados. Para alcançar os objetivos científicos destes projetos, o LIneA gerencia toda uma infraestrutura de armazenamento, processamento, análise e distribuição de dados astronômicos e desenvolve tecnologia para lidar com os desafios de projetos envolvendo Big Data. Participam do LIneA pesquisadores e técnicos dos institutos do MCTI mencionados acima, além de professores de universidades.

Missão

- Dar apoio logístico e financeiro para a participação de cientistas e estudantes em grandes projetos internacionais.
- Implantar e manter um Centro de Dados Astronômico para facilitar a exploração científica dos dados provenientes destes experimentos bem como de outras fontes que possam complementar estes dados.
- Desenvolver e manter um portal científico para a validação e mineração de dados e para conduzir de forma eficiente a análise científica destes grandes acervos.
- Ajudar na formação de jovens pesquisadores e na sua preparação para atuar pró-ativamente em grandes colaborações internacionais.
- Ajudar na formação de tecnologistas para lidar com projetos de Big Data.
- Contribuir na divulgação dos resultados de pesquisa para o grande público.
- Apoiar o trabalho técnico/científico sendo desenvolvido no INCT do e-Universo.

Dark Energy Survey

O levantamento Dark Energy Survey (DES) tem por objetivo estudar a natureza da energia escura, uma componente descoberta recentemente, que representa da ordem de 70% do conteúdo do Universo, sendo esta energia a suposta responsável pela aceleração de sua expansão. O projeto procura determinar a abundância da energia escura e...

INCT do e-Universo

O Laboratório Interinstitucional de e-Astronomia (LIneA) surgiu em 2010 com a missão de estimular e coordenar a participação de pesquisadores brasileiros em grandes mapeamentos do Universo, realizados por consórcios internacionais, visando estudos em Astrofísica e Cosmologia. Assim como fez junto à colaboração do DES-Brazil, pelo qual pesquisadores (mais pós-docs e...

Large Synoptic Survey Telescope

O Large Synoptic Survey Telescope (LSST) é um telescópio sendo construído em Cerro Pachón no Chile. Previsto para entrar em operação no início da próxima década, o LSST irá mapear em seis bandas, quase a metade do céu por um período de 10 anos. O telescópio com um diâmetro de 8,4 metros...

Sloan Digital Sky Survey – III

O projeto Sloan Digital Sky Survey – III (SDSS-III) é uma colaboração internacional, que produziu vários levantamentos espectroscópicos de extensas regiões do céu, criando amostras estatísticas sem precedentes para estudos em diferentes áreas. As observações se encerraram em 2014, mas análises científicas ainda continuam sendo feitas. Quatro grandes temas são...

Sloan Digital Sky Survey – IV

O projeto Sloan Digital Sky Survey – IV (SDSS-IV) é continuação do trabalho feito no SDSS-III. Em particular, dois dos levantamentos (eBOSS e APOGEE-2) são extensões naturais de levantamentos realizados no SDSS-III. O projeto inclui ainda, um novo levantamento (MaNGA) de 10.000 galáxias próximas utilizando pacotes de fibra óptica que...

Transneptunian Occultation Network

Objetos transnetunianos (TNOs) constituem uma população de pequenos corpos planetários situados além da órbita de Netuno, ou seja, estão afastados do Sol mais de 30 vezes a distância que separa a Terra do Sol (cerca de 150 milhões de quilômetros). Isto faz com que tais objetos tenham sofrido poucas alterações...

Distribution of galaxies in the universe provide:

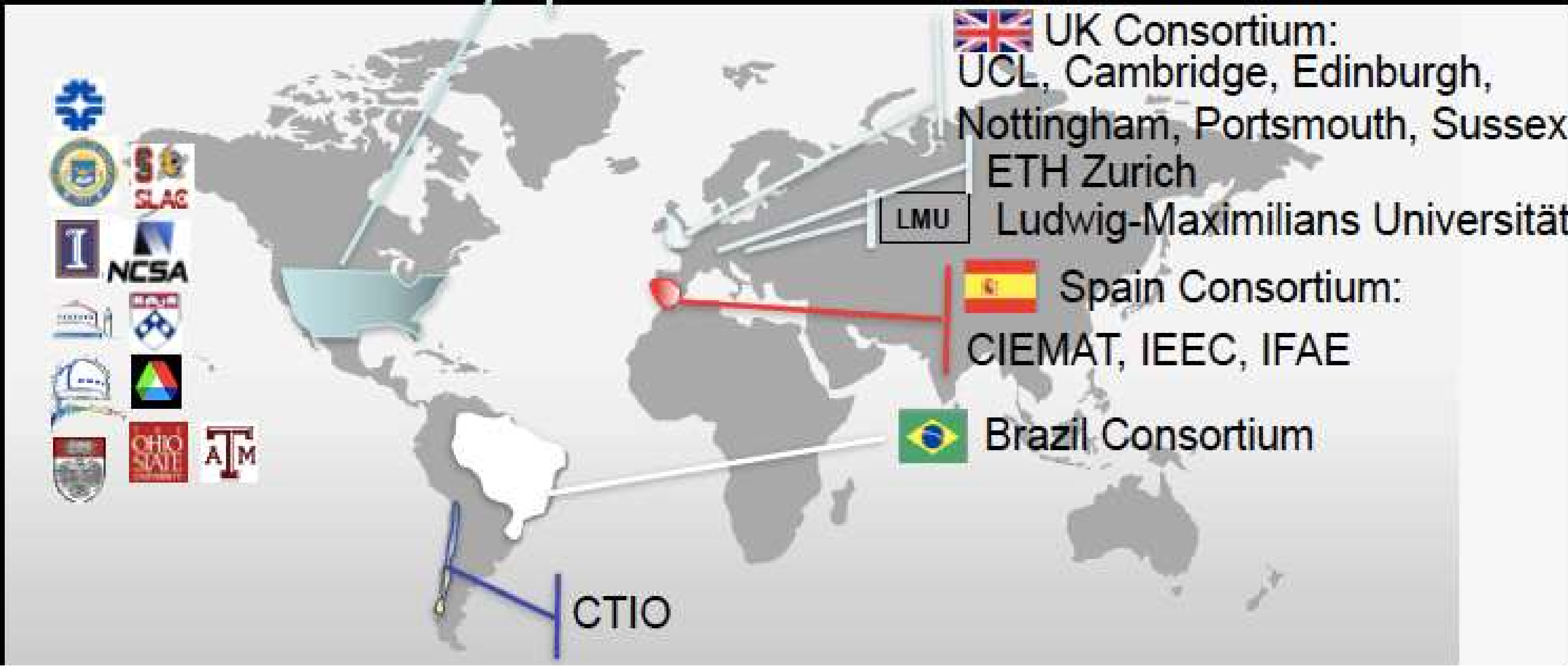
- information about growth of perturbations (DE/MG)
- information about dark matter (hot DM is ruled out)
- standard ruler (baryon acoustic oscillation scale)

Dark Energy Survey Collaboration

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 Science Summary

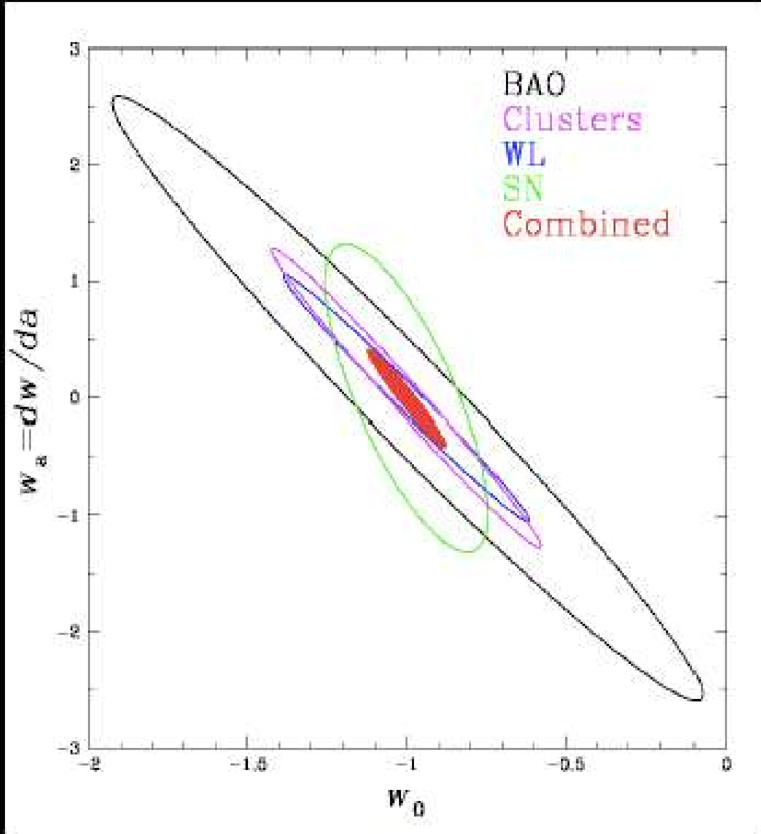
DARK ENERGY SURVEY

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

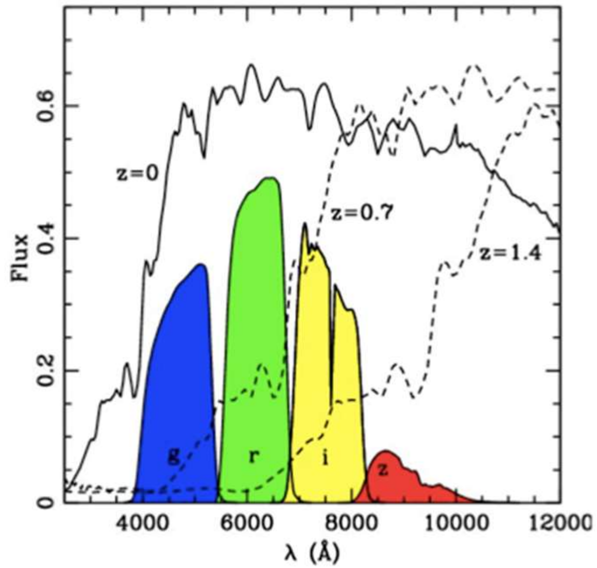
$$w(a) = w_0 + w_a(1 - a(t)/a_0)$$



DES forecast

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 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 – Finishes January 2019

Planned 5 years of 105-nights each

DARK ENERGY SURVEY

DES-BRAZIL

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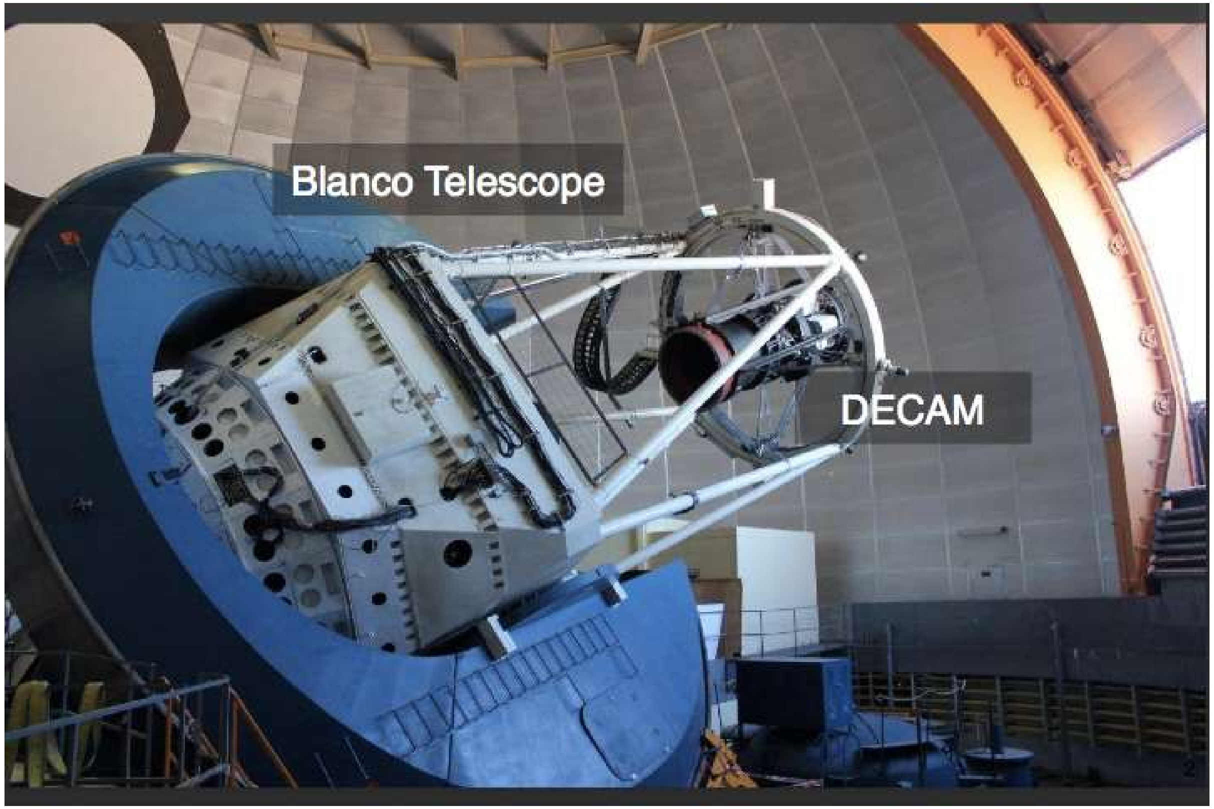
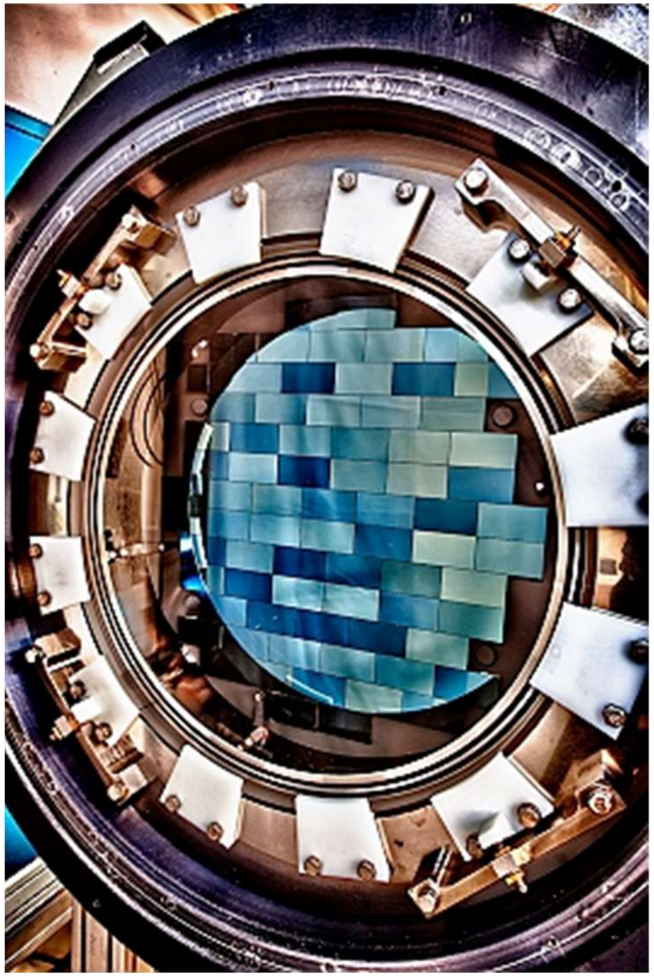
DES site: 4m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile

DECam

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



DECam



arXiv:1504.02900

DARK ENERGY SURVEY

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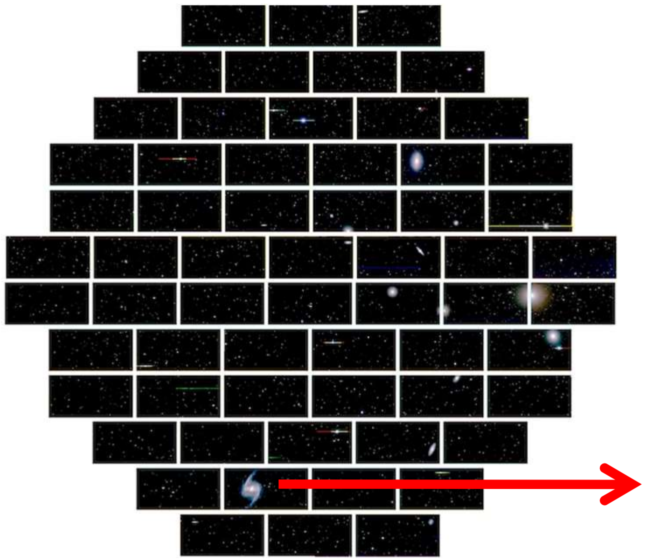
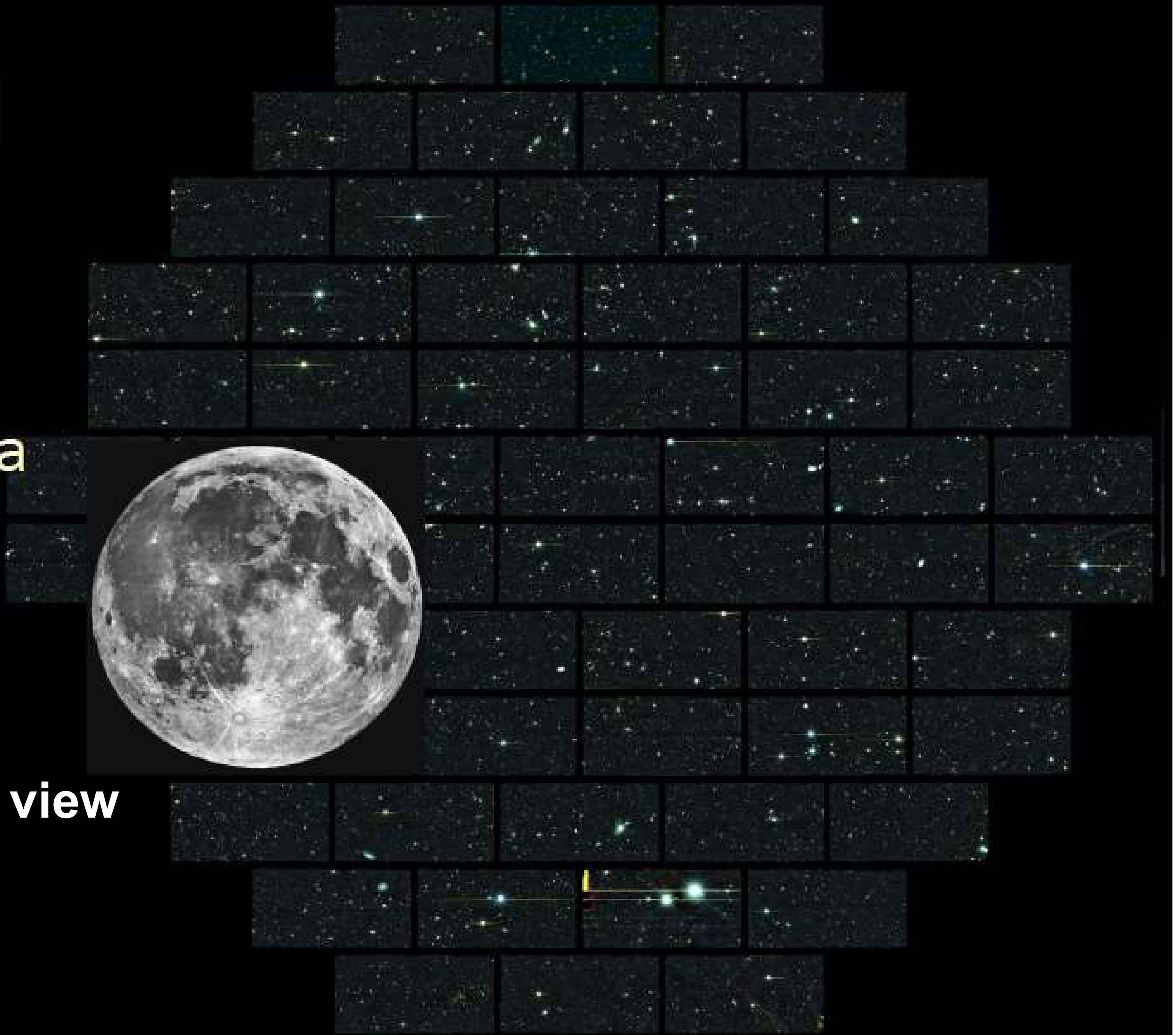


Fornax cluster of galaxies

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 SURVEY

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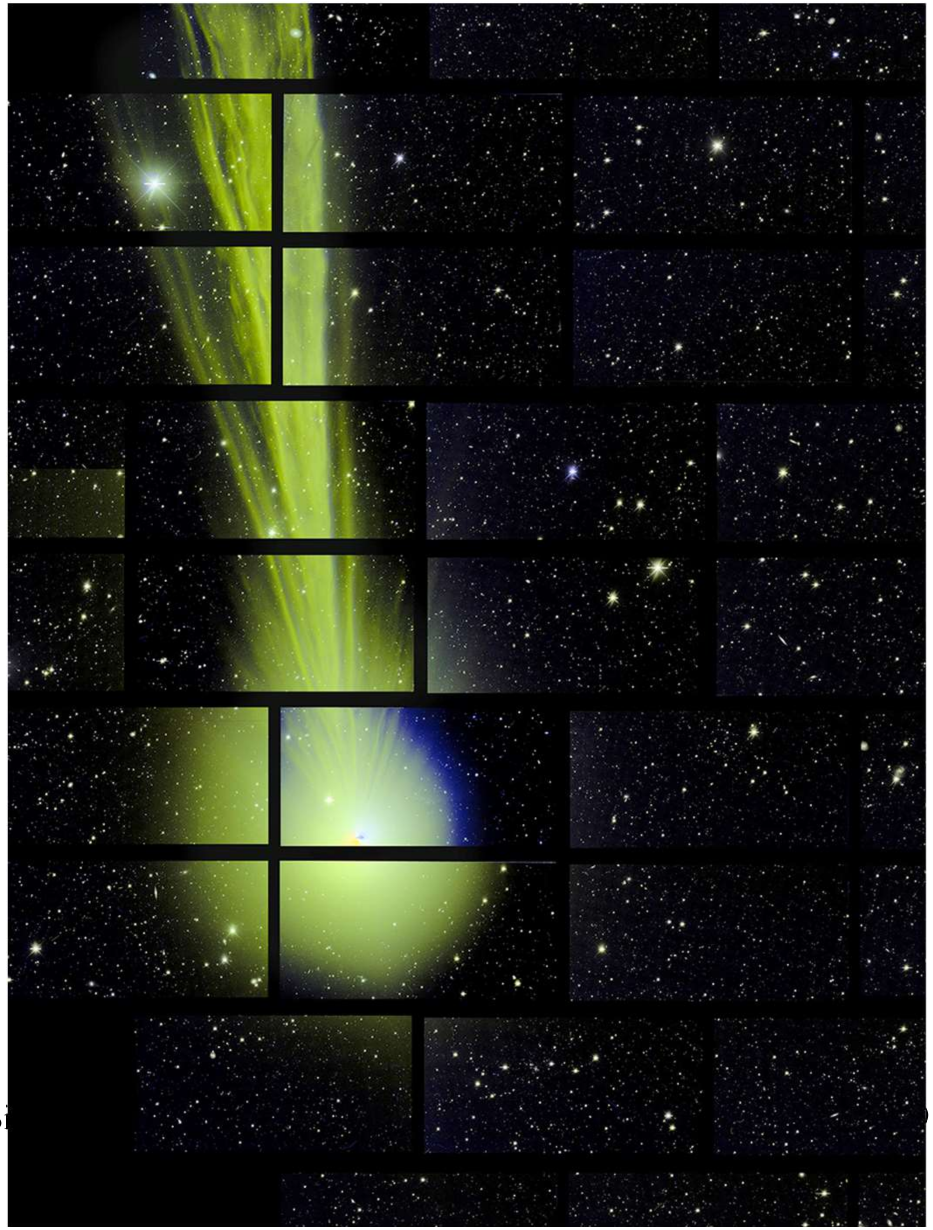
Dark Energy Camera catches breathtaking glimpse of comet Lovejoy

December 27 2014

82 million km away



DES Data Management

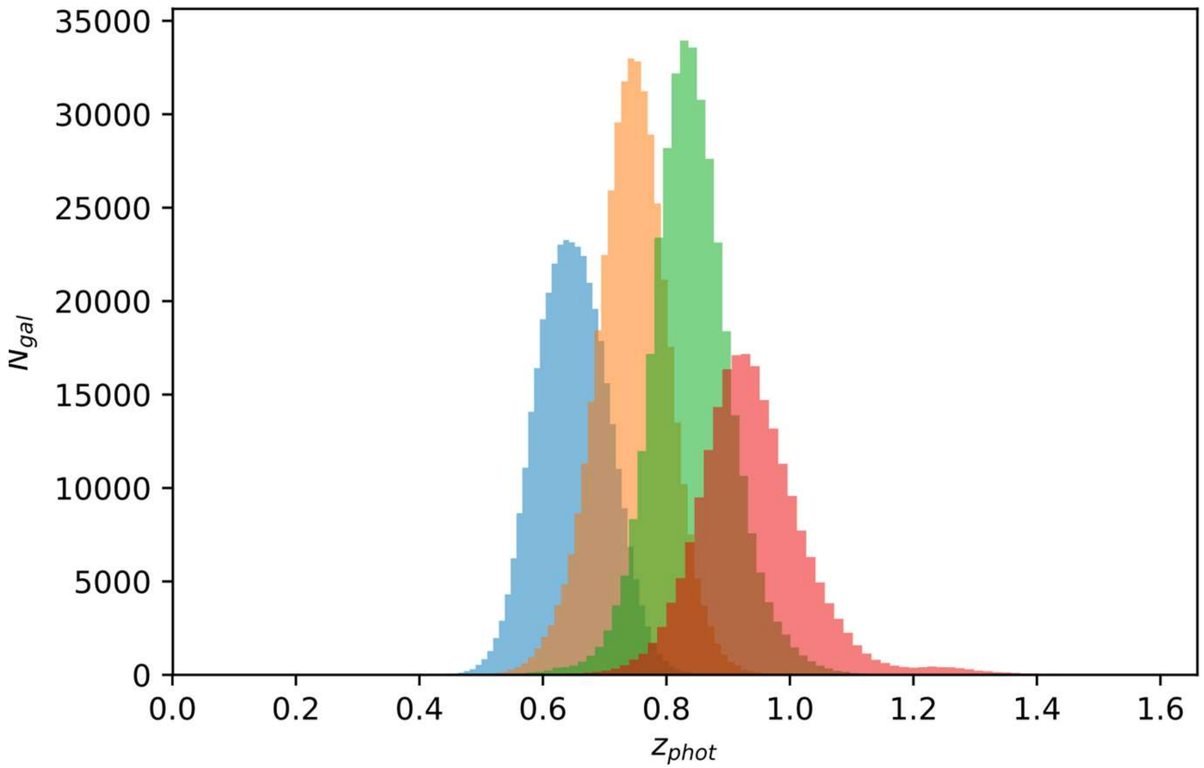
Each exposure (in a given filter) generates 500Mb

300 exposures/night – 150 Gb/night

Transferred and processed at NCSA in Urbana

Photometric redshift

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



DARK ENERGY SURVEY

DES-BRAZIL

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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, …

DARK ENERGY SURVEY

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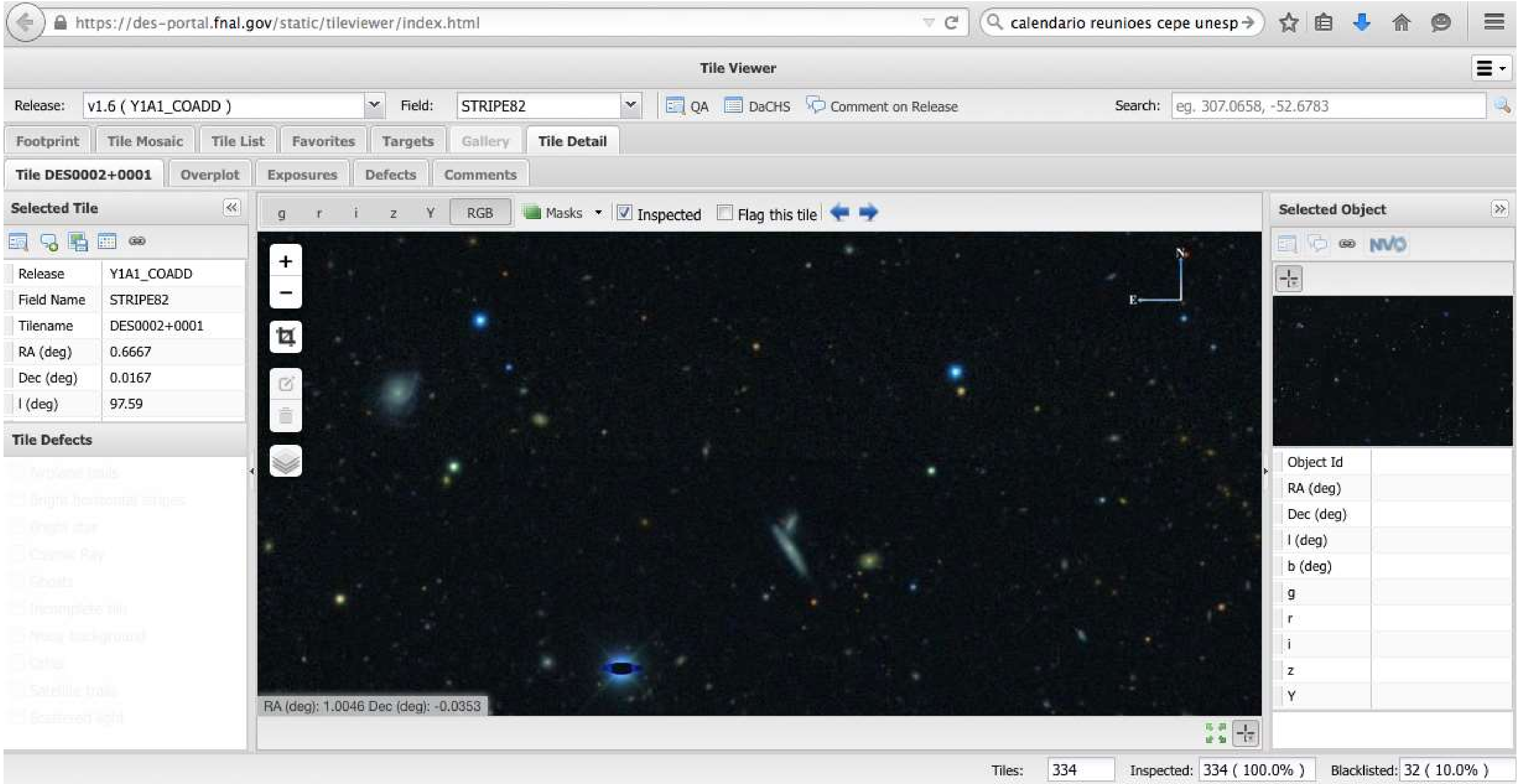
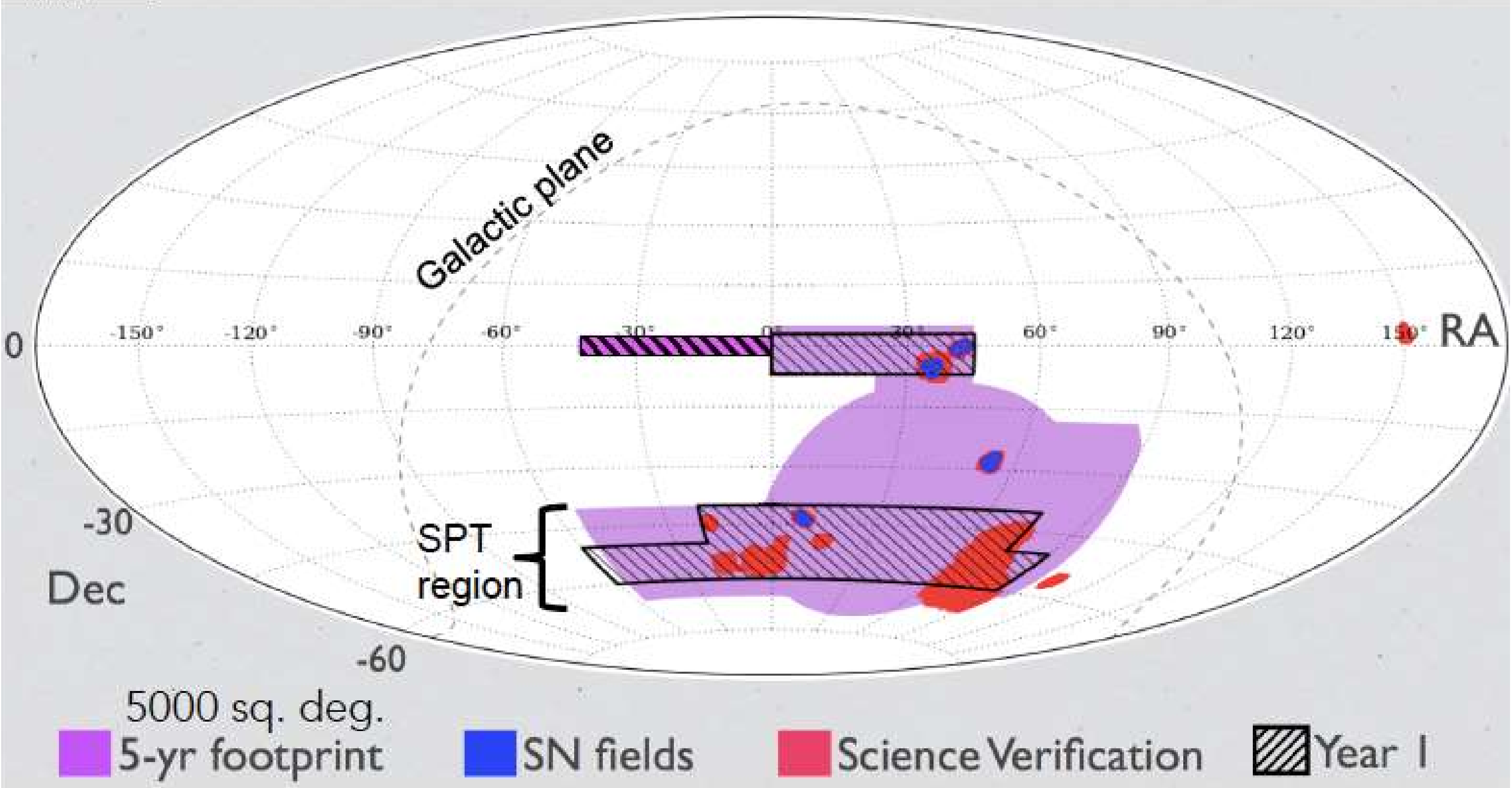


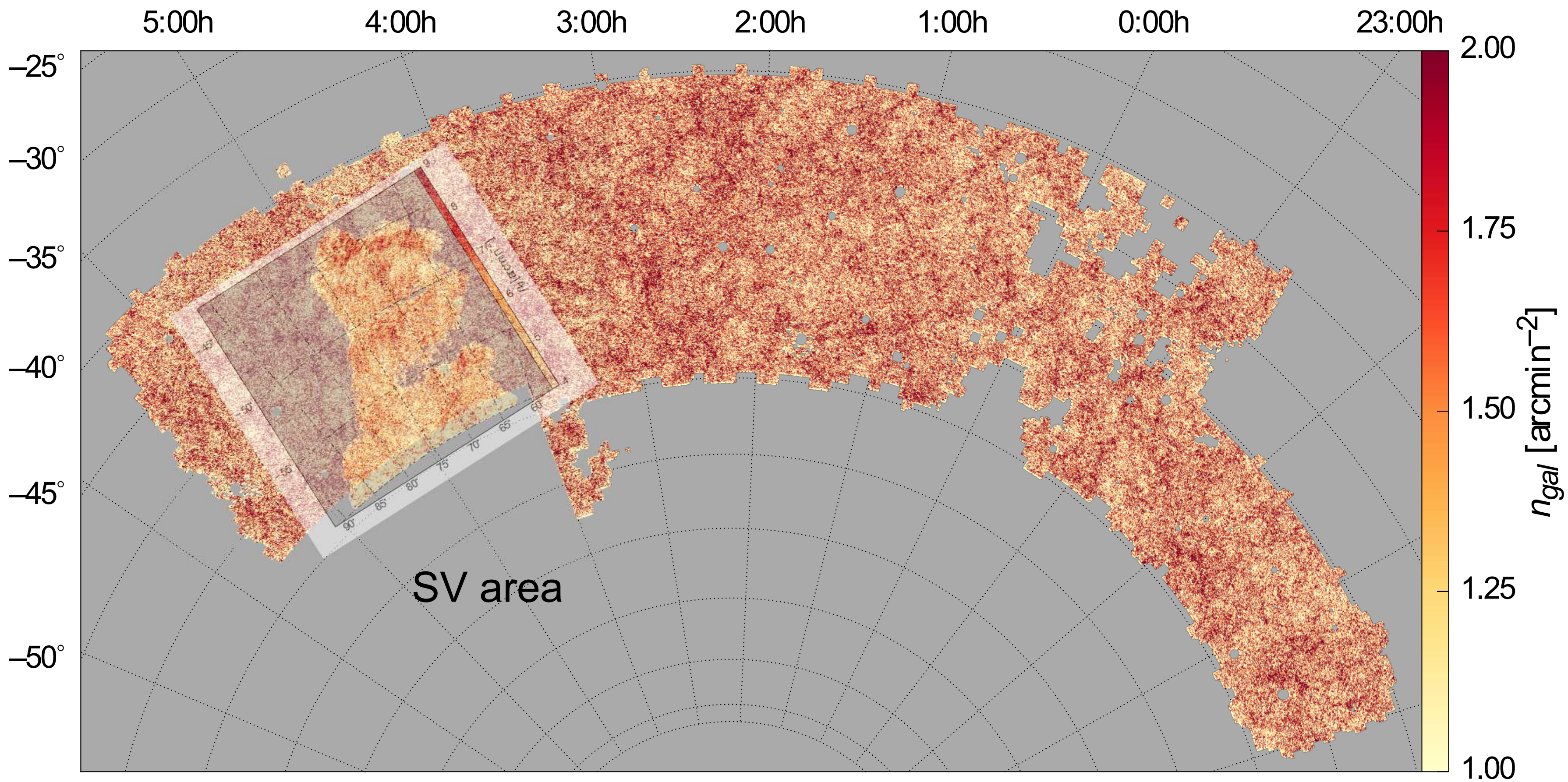
DARK ENERGY SURVEY

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 Year 1 Galaxy Distribution

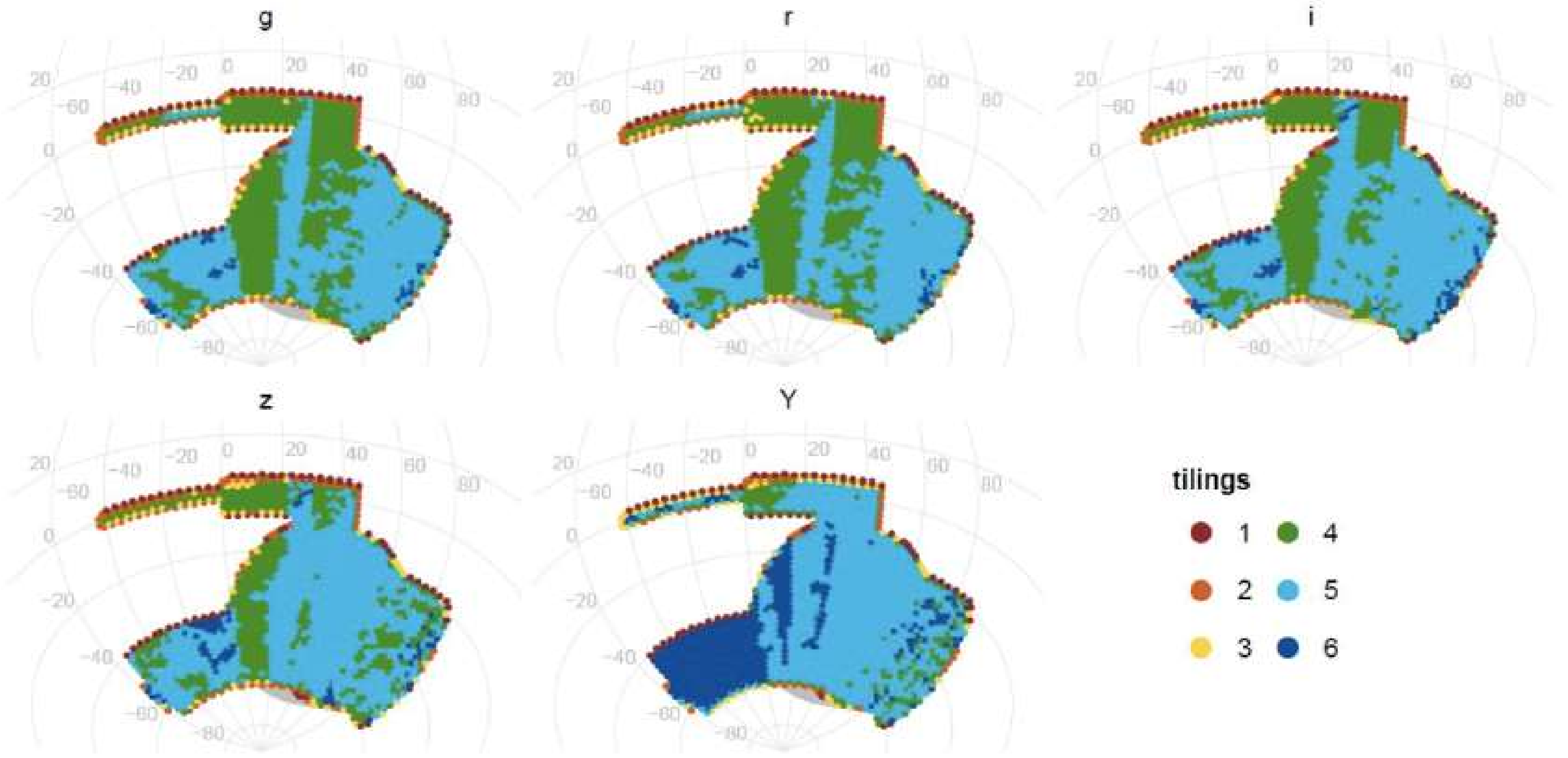


Credit: P. Melchior

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



7- 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

DARK ENERGY SURVEY

DES-BRAZIL

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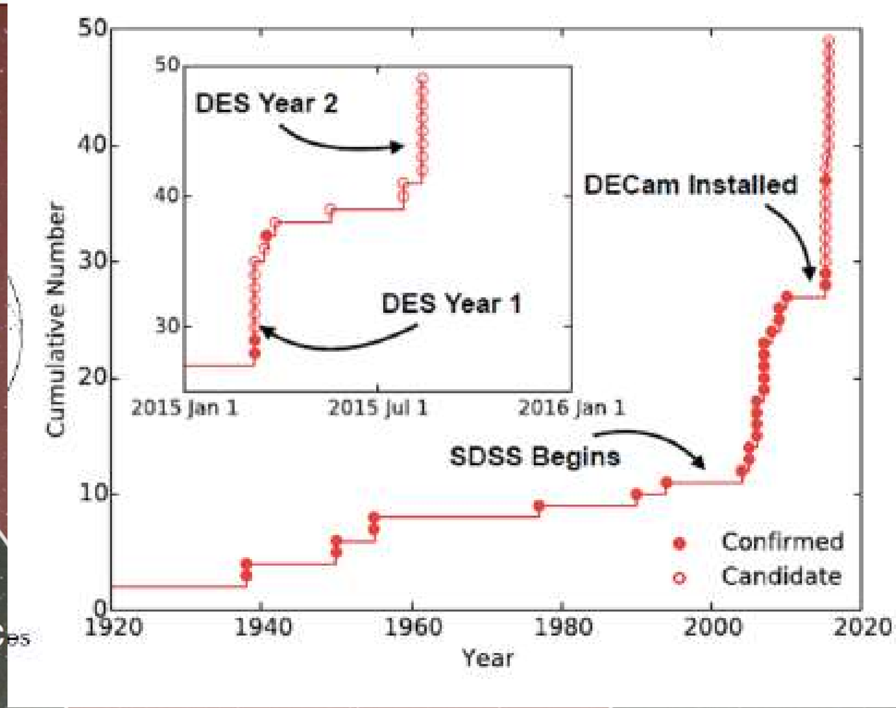
64 papers: 26 published and 38 submitted (not updated)

- 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;
- 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.



1508.03622

17 new dwarf galaxies discovered by DES!

27 known before DES.

Contribution from B. Santiago’s team

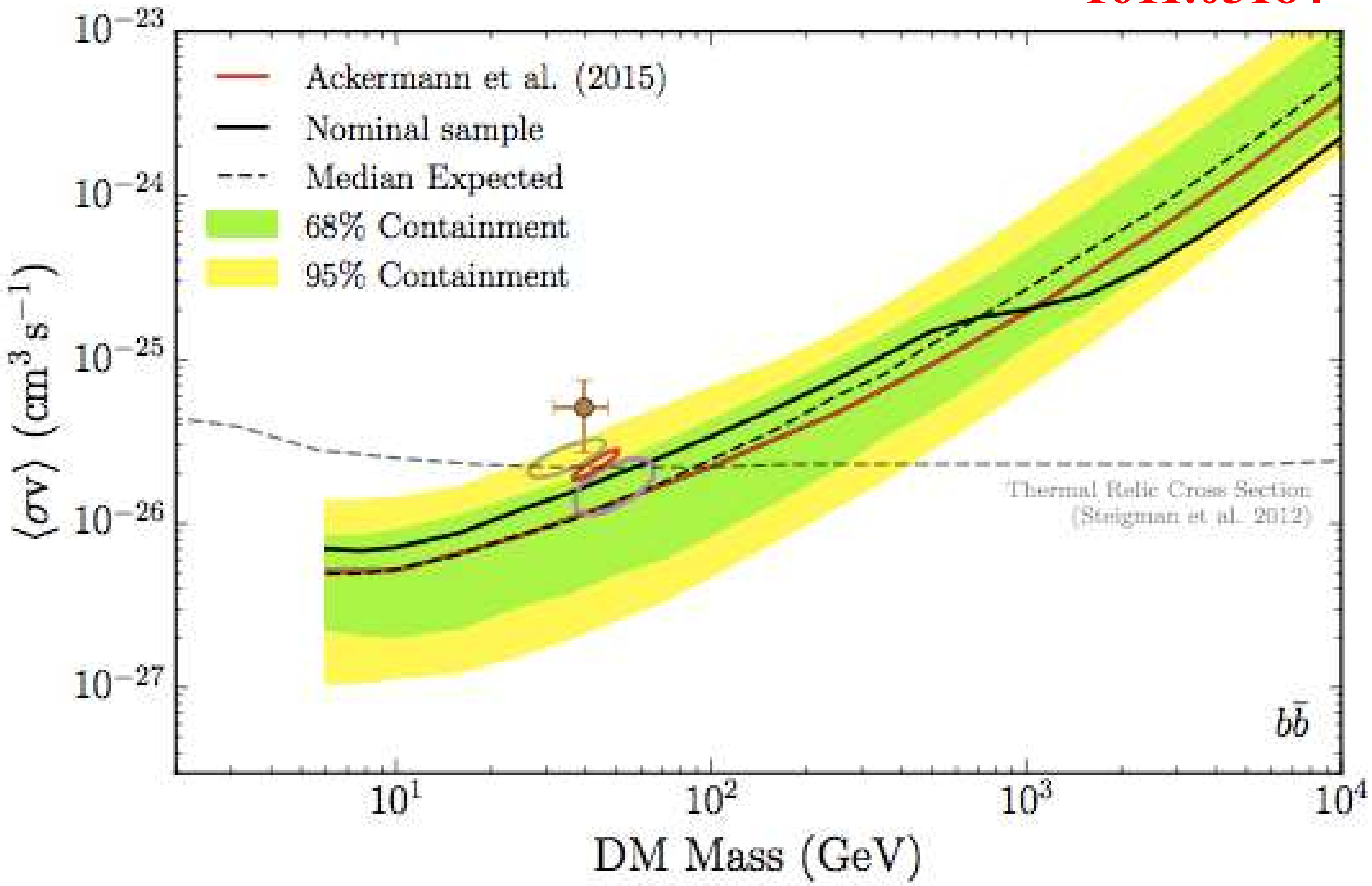
Joint paper with Fermi-LAT

1503.02632

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

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

1611.03184



7.1- BAO@DES

BAO main paper: 1712.06209

Three diferente analysis:

- Real space angular correlation function
- Harmonic space power spectrum – our contribution
- Comoving transverse separation

Identify the BAO signature in the DES Y1data, and use it to place constraints on the comoving angular diameter distance to the effective redshift of the sample.

BAO main paper: 1712.06209

Steps:

- Determine a sample (catalogue) – based on color and magnitude cuts that optimize the BAO signal
- Minimize systematic errors (stellar contamination, seen, etc)
- Measure redshift and divide sample into redshift bins
- Define (bins in angle, bins in l's) and measure data vector
- Estimate covariance matrix (1800 Halogen mocks)
- Show robustness/goodness of measurements

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:

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

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

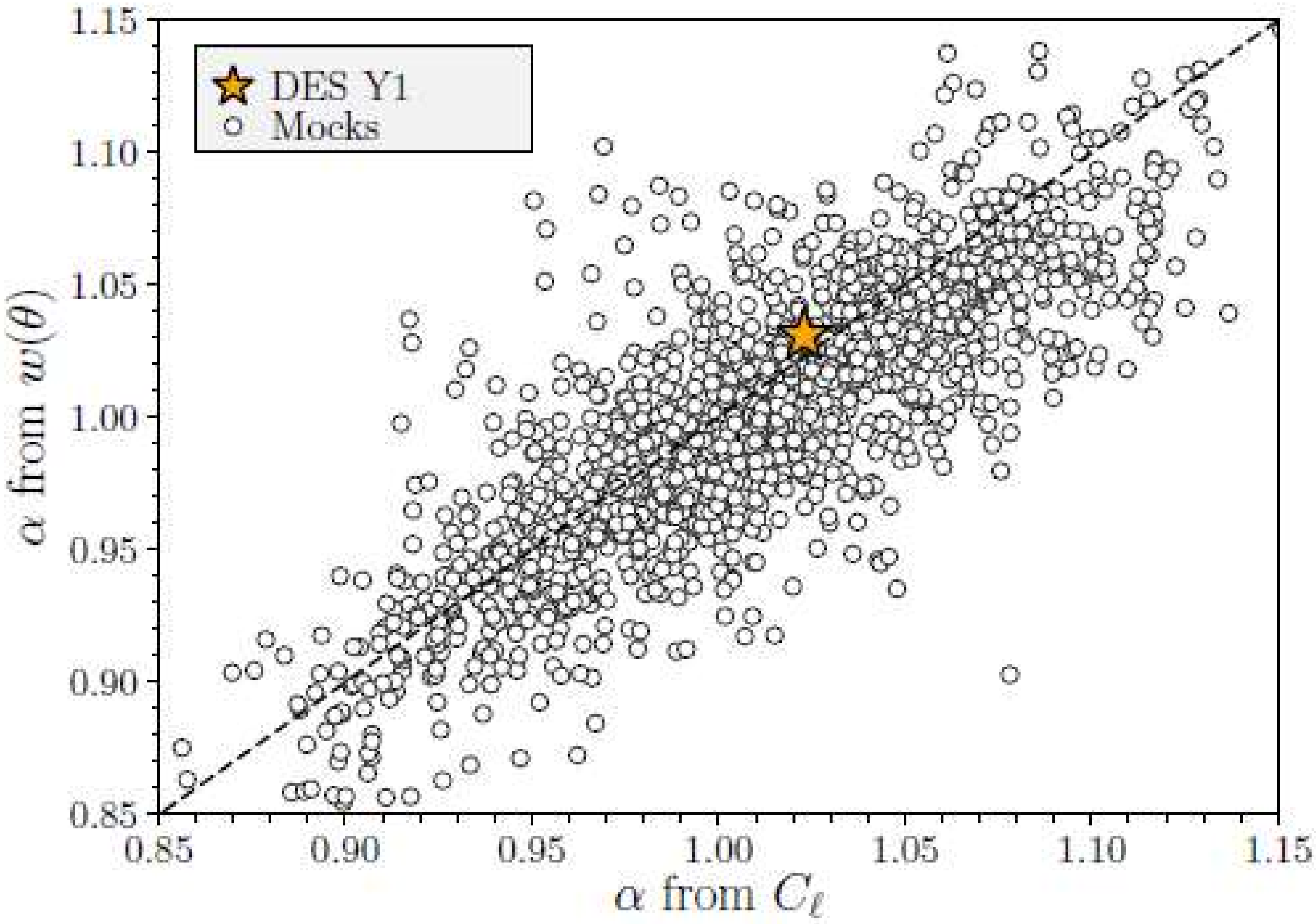
Covariance matrix estimated from 1800 mocks (but resulted in large chi2) – also estimate theoretically from HALOFIT including mask effects.

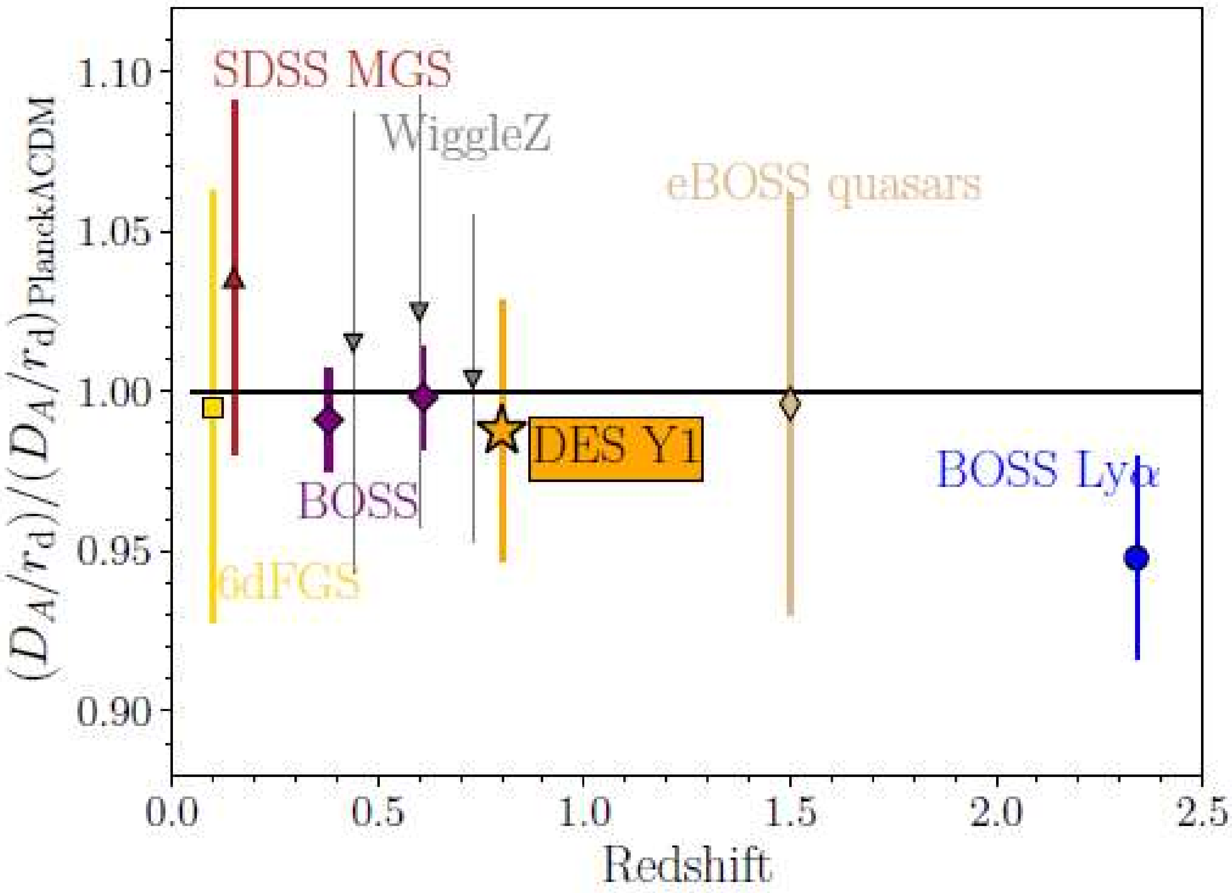
BAO position estimated using a template-based method:

$$C(\ell) \quad = \quad B_0\, C^{\rm temp}(\ell/\alpha) + A_0 + A_1 \ell + A_2/\ell^2$$

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

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


DES Y1
Mocks
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.85
0.90
0.95
1.00
1.05
1.10
1.15
α from $w(\theta)$
α from C_ℓ



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

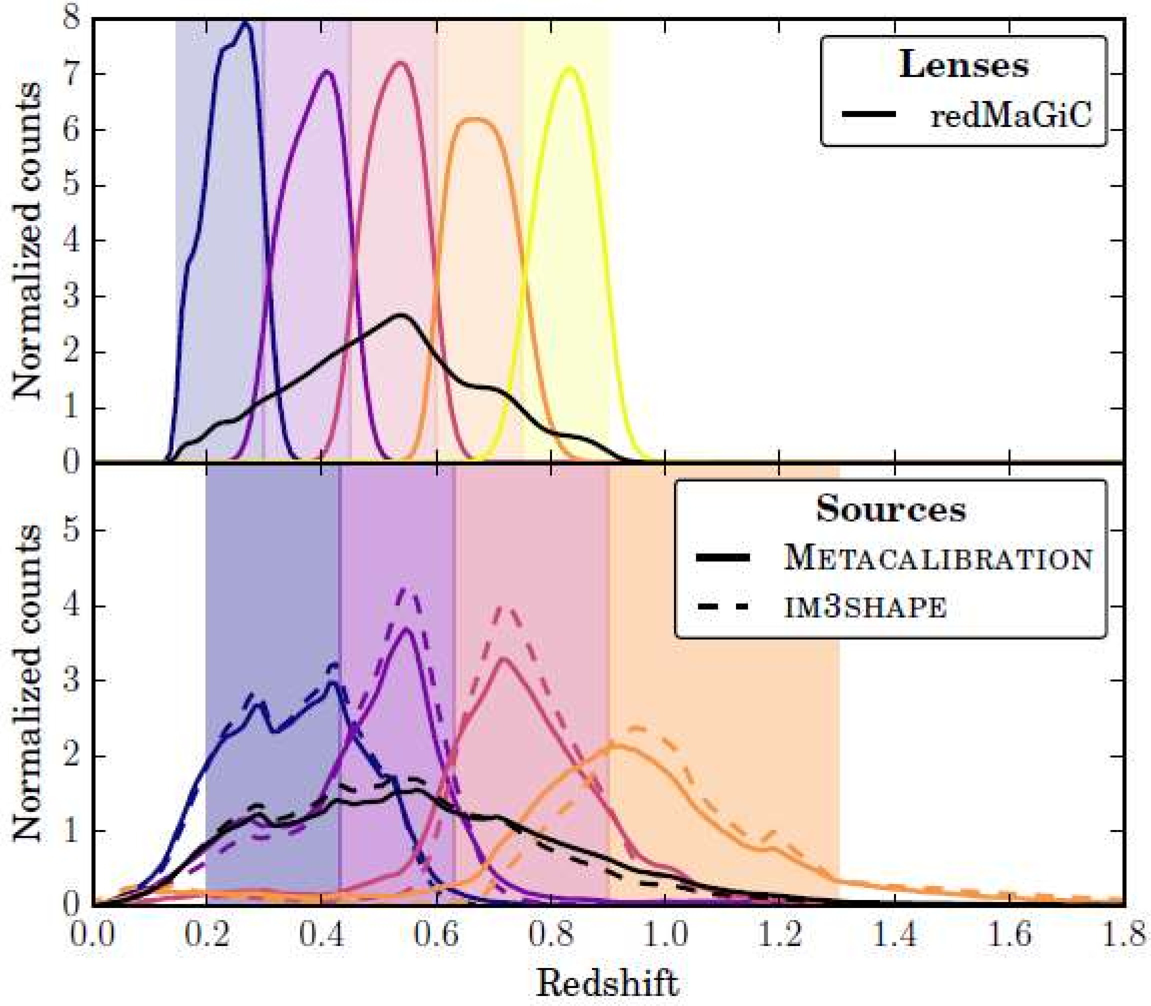
7.2- Main result: Galaxy clustering + weak lensing

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

Redshift distributions of the 2 samples



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	
$A_{\rm IA}(z) = A_{\rm IA}[(1+z)/1.62]^{\eta_{\rm IA}}$	
$A_{\rm IA}$	flat (−5, 5)
$\eta_{\rm IA}$	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	
$m^i_{\rm METACALIBRATION} (i = 1, 4)$	Gauss (0.012, 0.023)
$m^i_{\rm IM3SHAPE} (i = 1, 4)$	Gauss (0.0, 0.035)

20 Nuisance Parameters

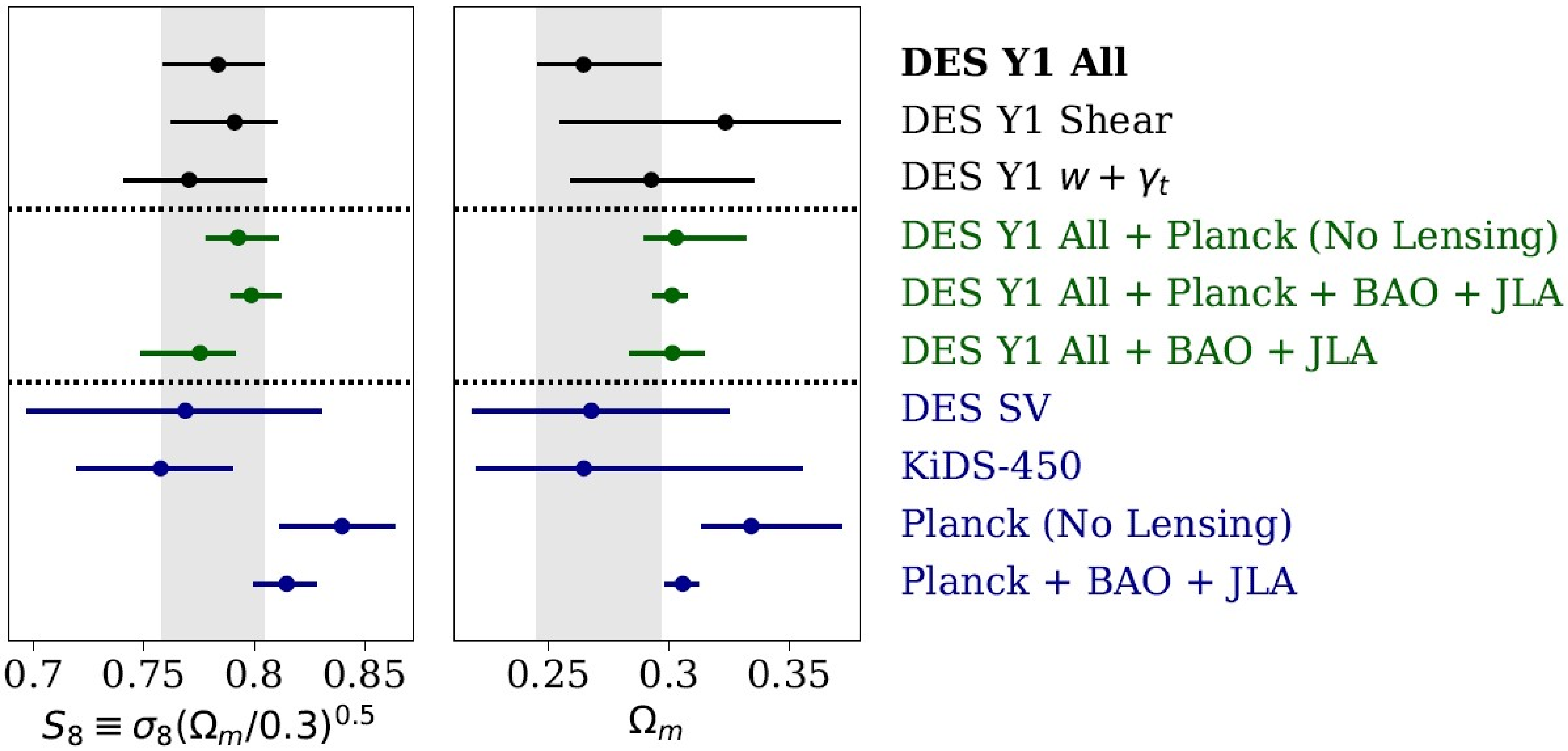
Data vectors were defined using scale cuts to mitigate non-linear bias effects.

Uses a theoretical (halo-model based) Covariance Matrix: CosmoLike (457x457) validated with 800 lognormal mocks – our contribution.

2 main parameters were measured: the total matter density and the amplitude of perturbations at a scale of 8 Mpc.

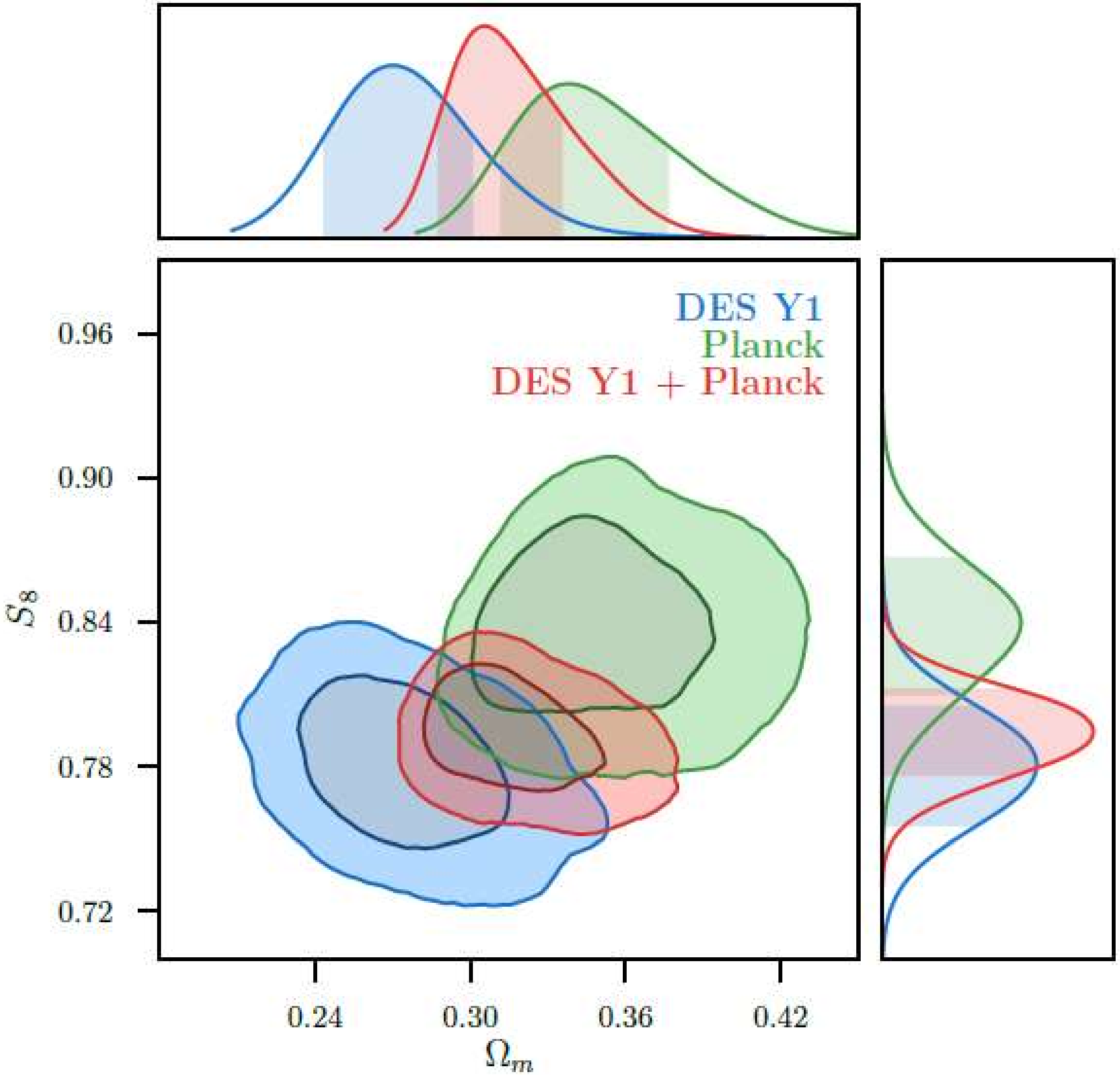
2 models were analyzed: ΛCDM and wCDM

ΛCDM



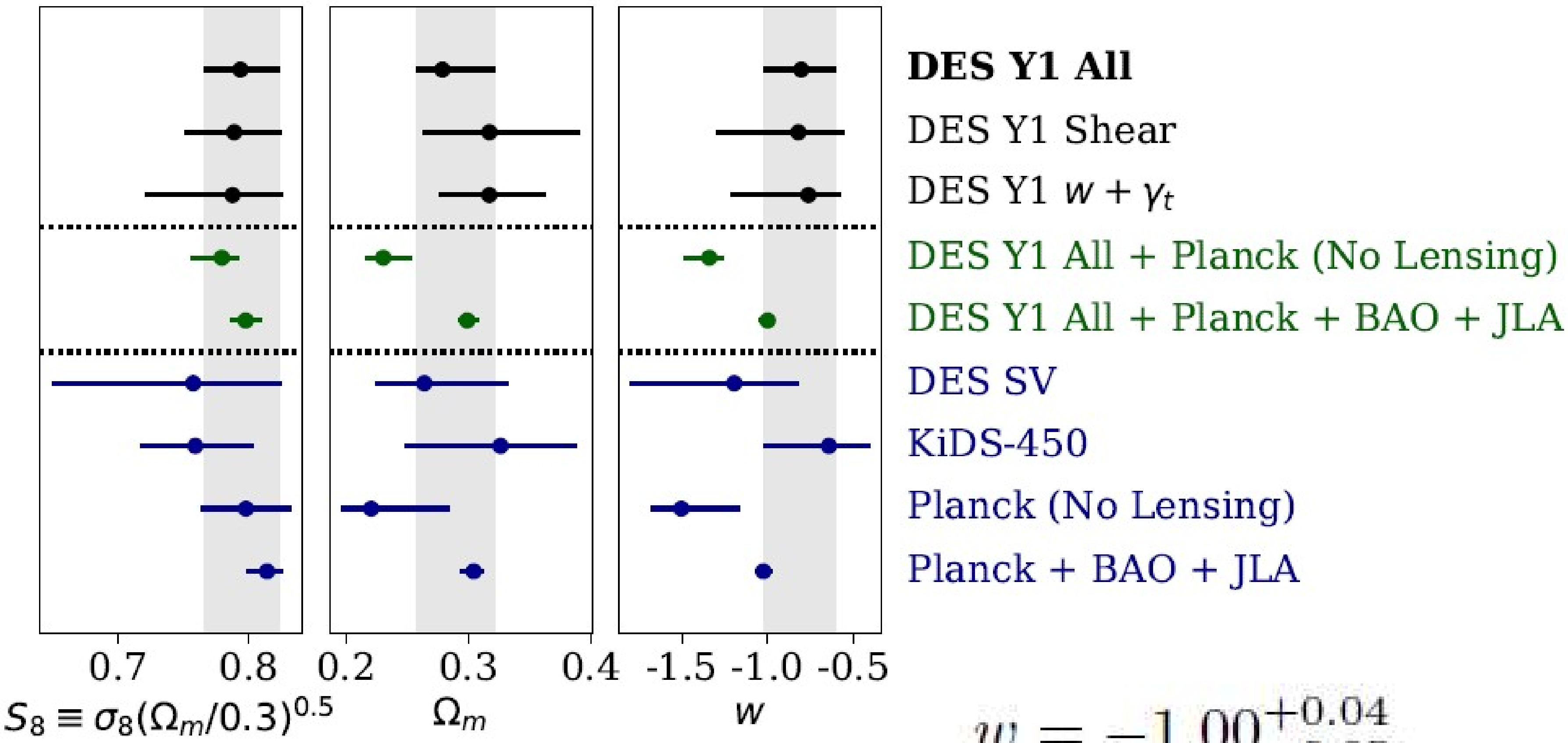
0.7
0.75
0.8
0.85
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$
0.25
0.3
0.35
Ω_m
DES Y1 All
DES Y1 Shear
DES Y1 $w + \gamma_t$
DES Y1 All + Planck (No Lensing)
DES Y1 All + Planck + BAO + JLA
DES Y1 All + BAO + JLA
DES SV
KiDS-450
Planck (No Lensing)
Planck + BAO + JLA

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



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

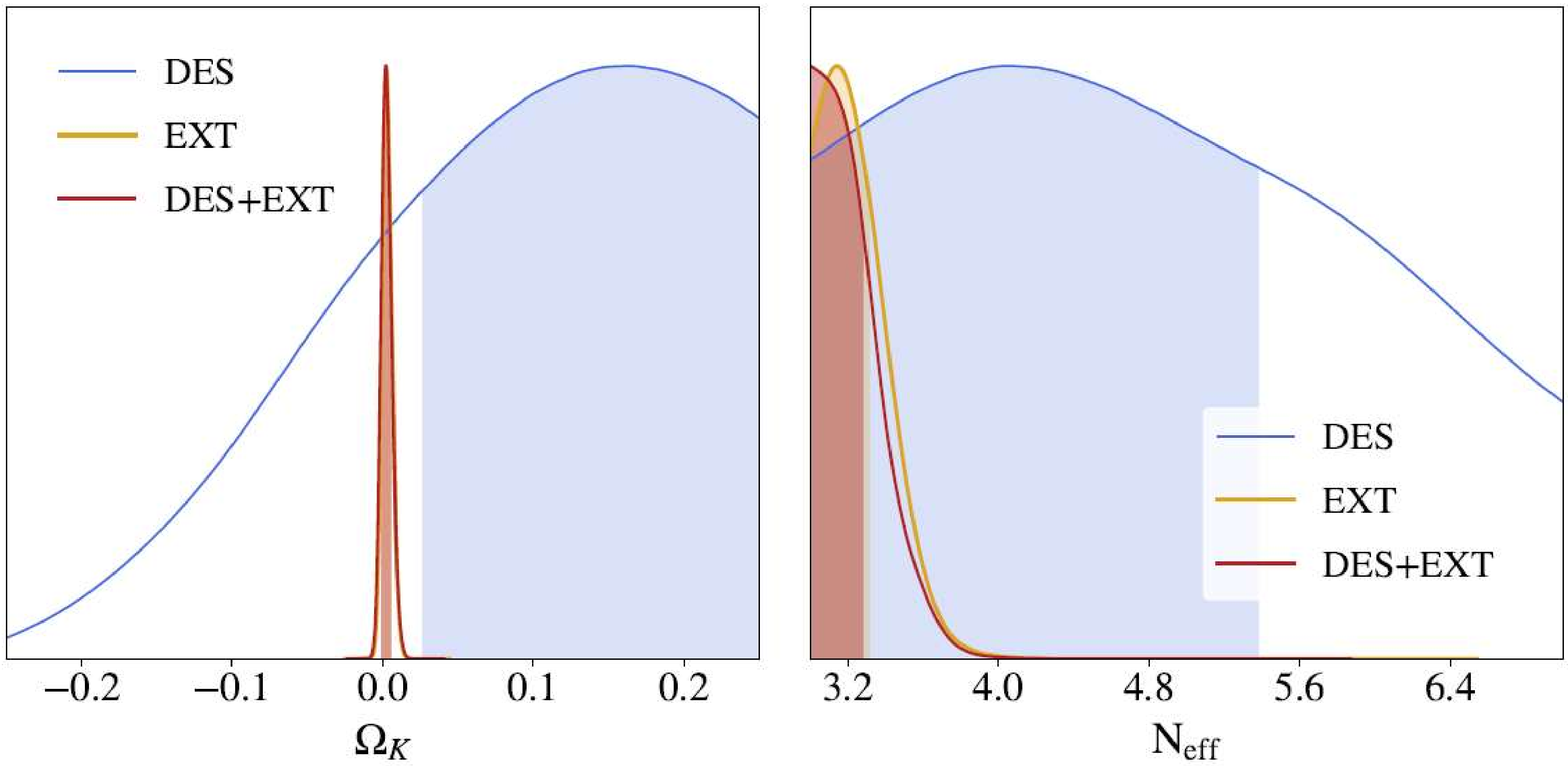
There goes the Nobel prize... (S. Dodelson)

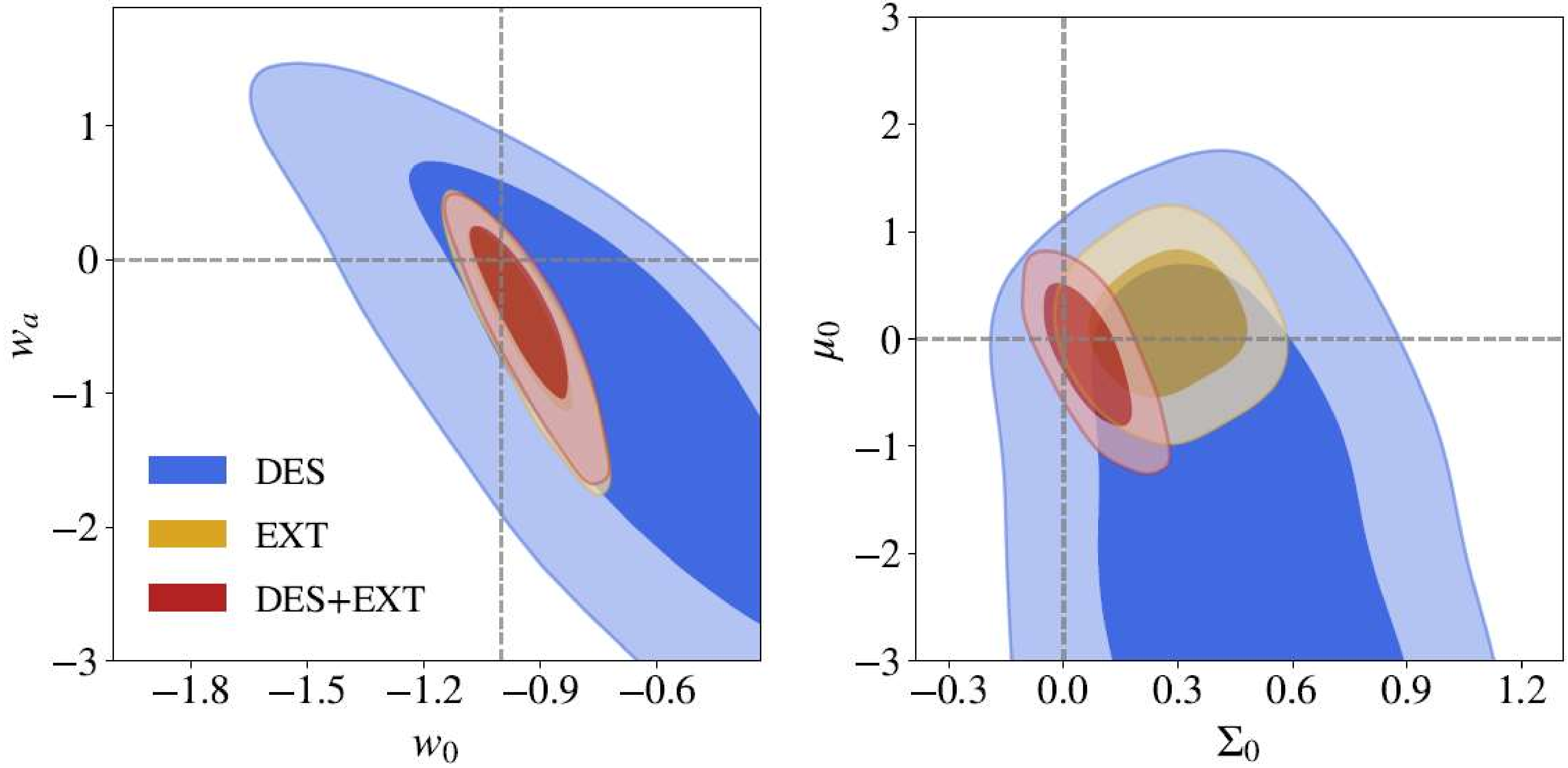
Beyond wCDM: “Extensions paper” - 1810.02499

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	$[-3.0, 3.0]$


DES
EXT
DES+EXT
−0.2
−0.1
0.0
0.1
0.2
Ω_K
DES
EXT
DES+EXT
3.2
4.0
4.8
5.6
6.4
$N_{\rm eff}$



w_a
1
0
−1
−2
−3
−1.8
−1.5
−1.2
−0.9
−0.6
w_0
DES
EXT
DES+EXT
μ_0
3
2
1
0
−1
−2
−3
−0.3
0.0
0.3
0.6
0.9
1.2
Σ_0

7.3- Challenges

- Cosmology from cluster counts:

cluster finding algorithms (RedMapper), mass-richness calibration, etc – coming!

- Including cluster counts in a joint analysis: 3x2pt+1
- SNIa cosmology just finished:

  First Cosmology Results using Type Ia Supernovae from the DES: Constraints on Cosmological Parameters - 1811.02374

- Going to smaller scales:

better modelling of bias and baryons – precision!

- Alternative covariances
- Check for non-gaussian likelihoods

8 - CODA

- Cosmology has become a precision, data driven science

- 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!