Cosmology and Particle Physics

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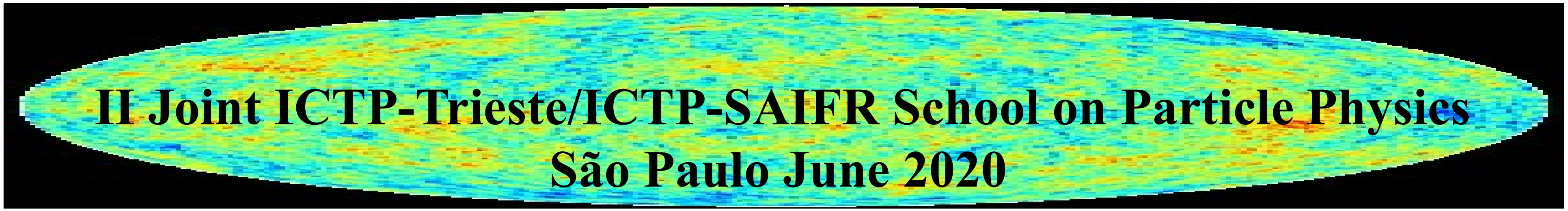
Lecture I: The average Universe

Lecture II: Origins

Lecture III: The perturbed Universe



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 – COBE sattelite) and were tiny:

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

The Nobel Prize in Physics 2006

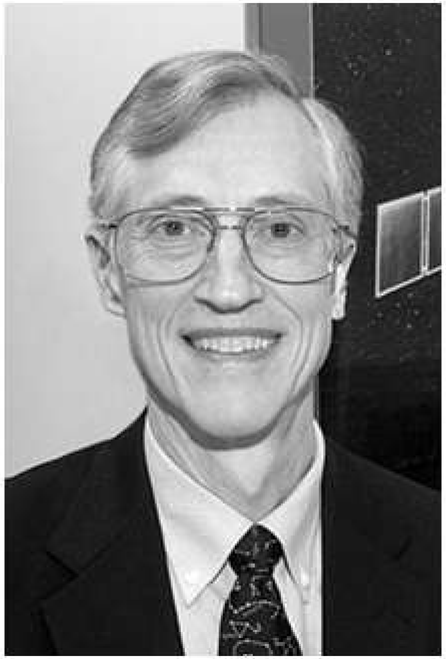


Photo: P. Izzo

John C. Mather

Prize share: 1/2

Photo: J. Bauer

George F. Smoot

Prize share: 1/2

The Nobel Prize in Physics 2006 was awarded jointly to John C. Mather and George F. Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."

Evolution of perturbations

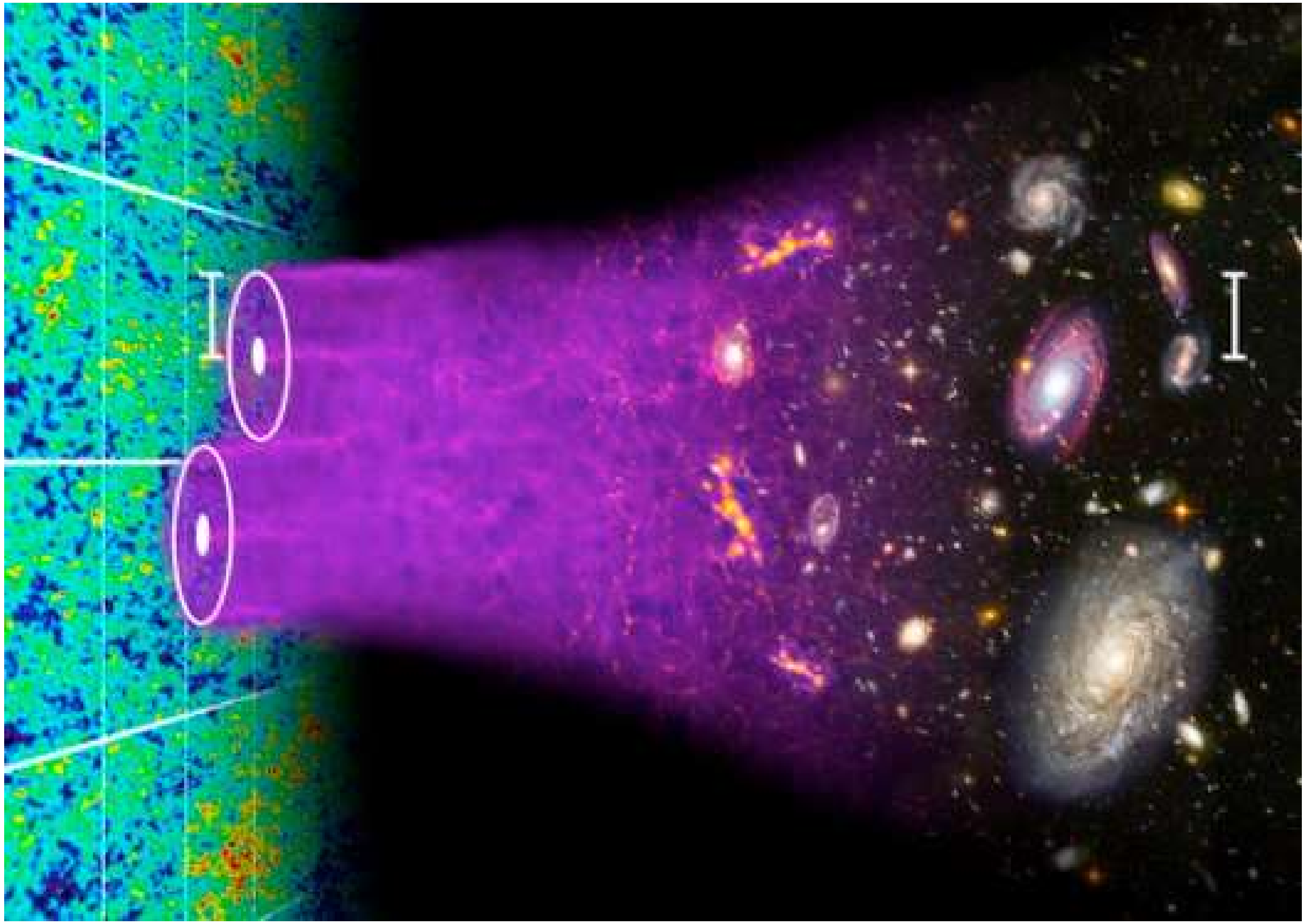


Illustration courtesy of Chris Blake and Sam Moorfield

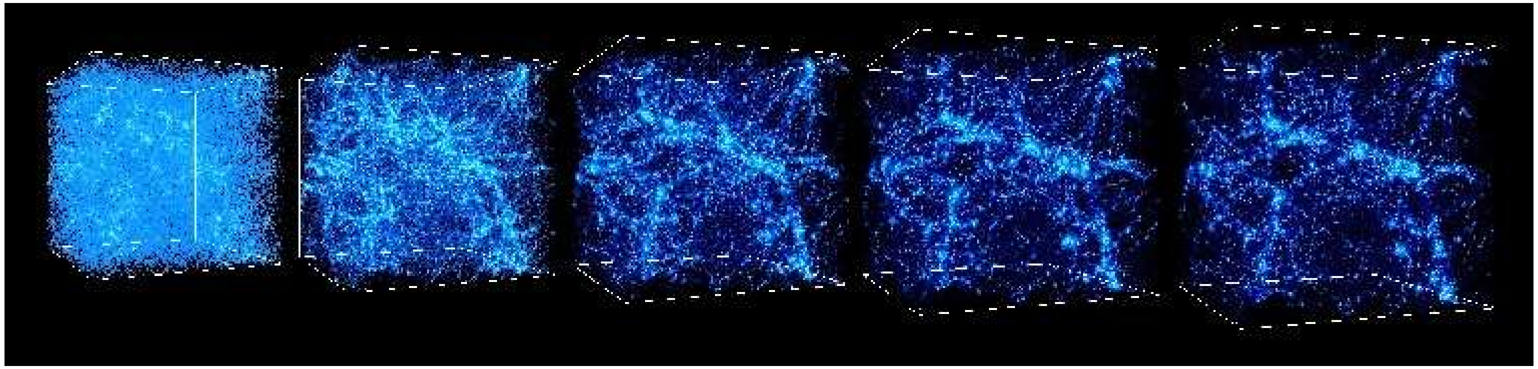
Evolution of perturbations:

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

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

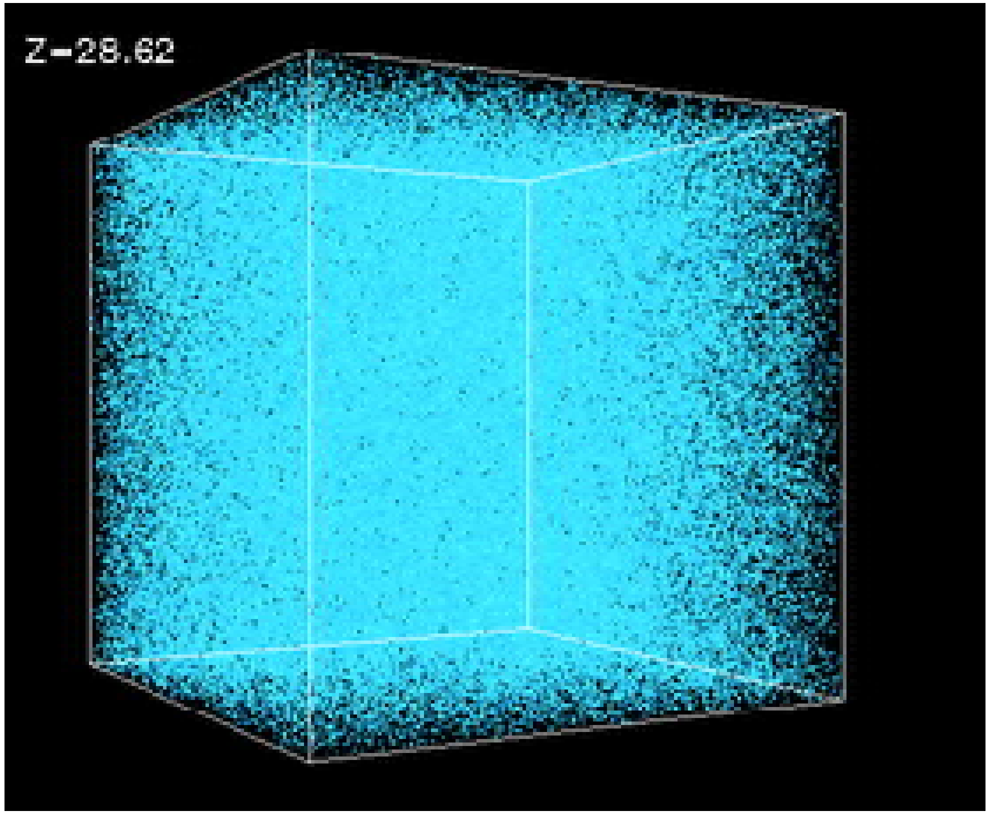
Universe in a box (A. Kravtsov)



The frames show the evolution of structures in a 43 Mpc box from redshift of 10 to the present epoch (from left to right). Notice that structure formation freezes in the late Universe due to the dominance of dark energy (comoving coordinates are used).

Large scale structure: N-body simulations

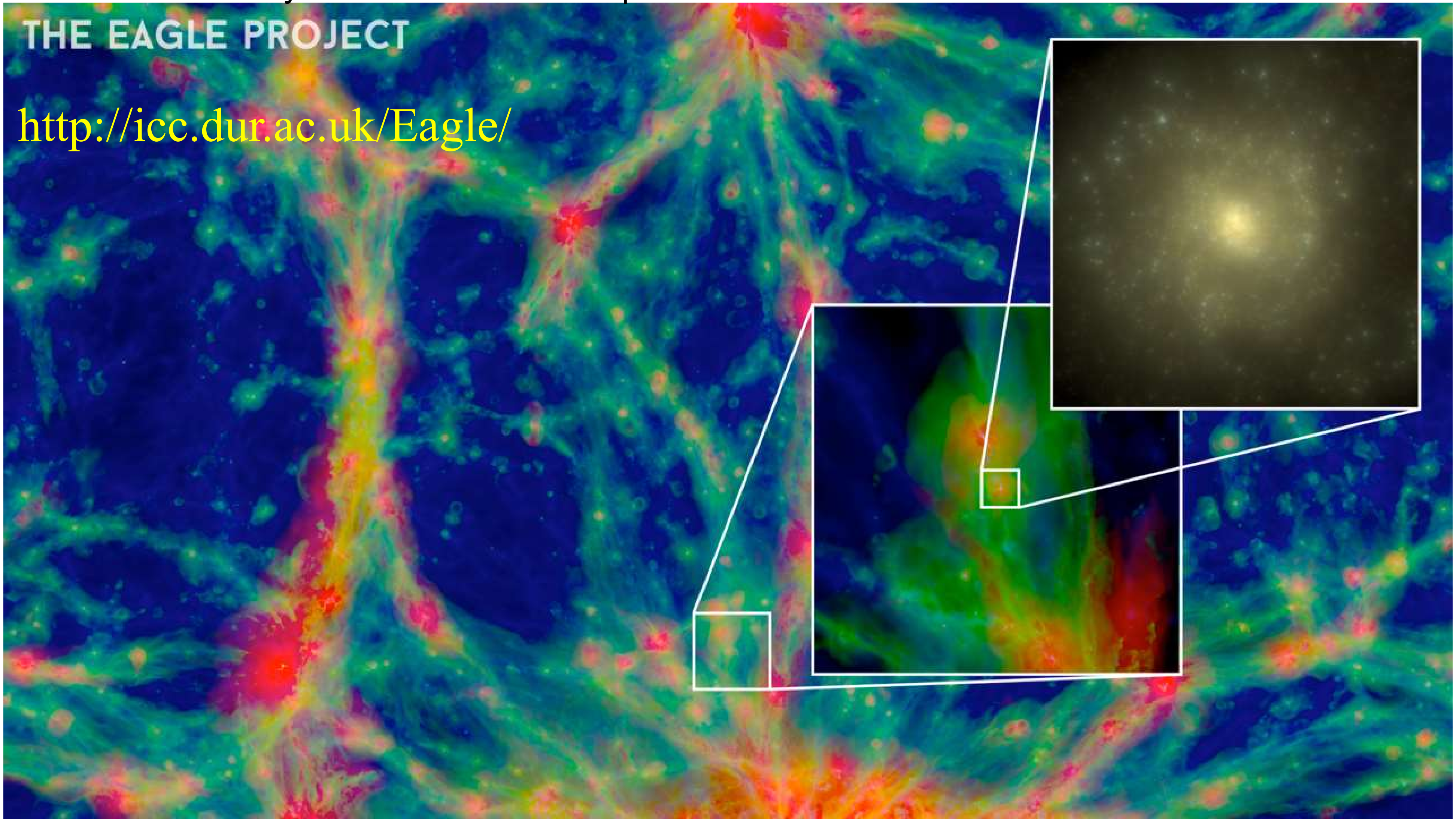
Universe in a box (A. Kravtsov)



http://cosmicweb.uchicago.edu/filaments.html

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.

The EAGLE simulation is one of the largest cosmological hydrodynamical simulations ever, using nearly 7 billion particles to model the physics.The image below is a slice through the simulation volume, with the intergalactic hot gas with T> 100,000K, and is contained with dark matter structures that host galaxies. Such hot gas can be detected in X-rays. The insets zoom into a galaxy like the Milky Way, showing first its gas, and then its beautiful stellar disc: it looks remarkably similar to observed spirals.



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

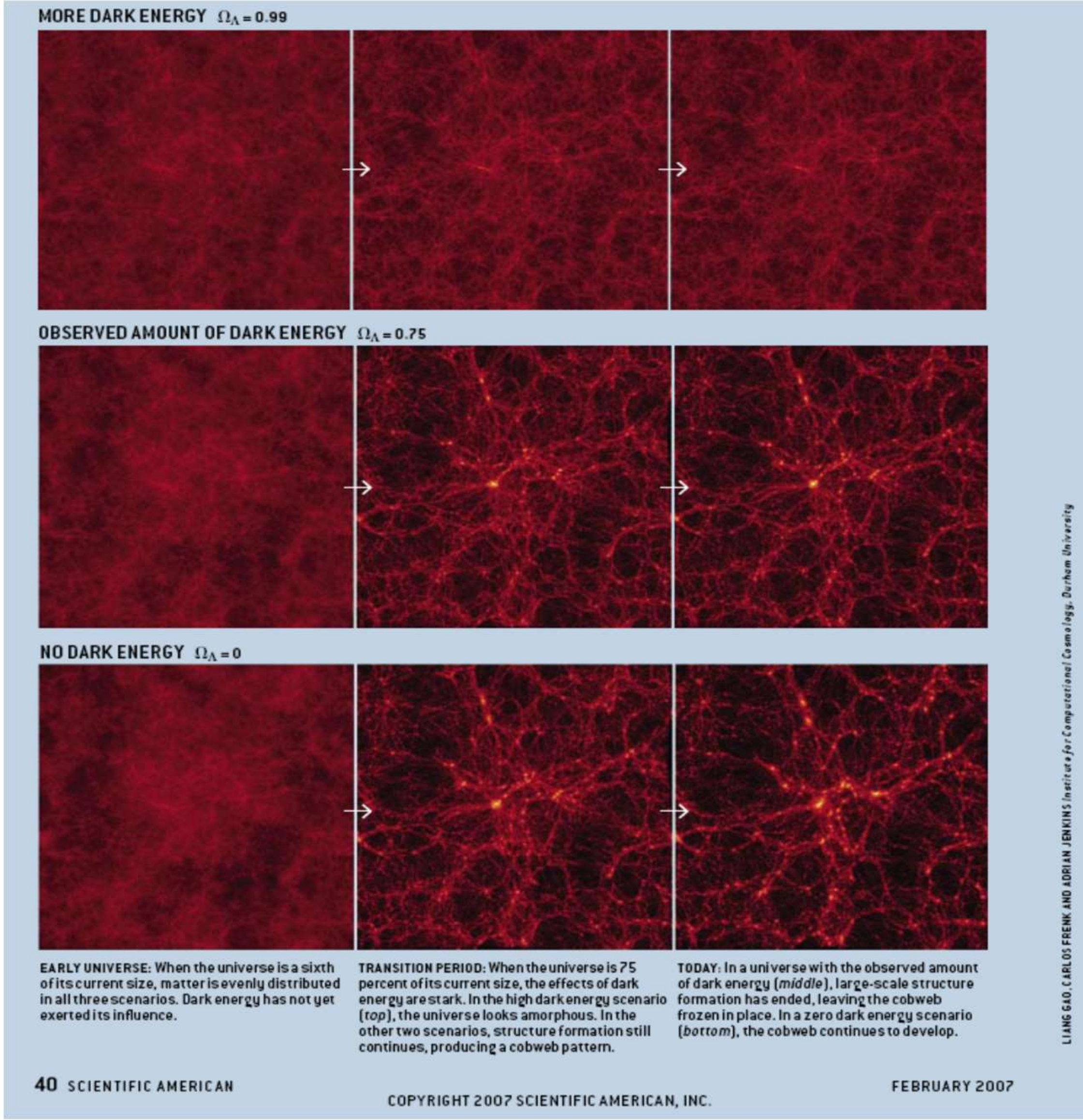
$$\boxed{\delta_m \propto a(t)}$$

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)



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

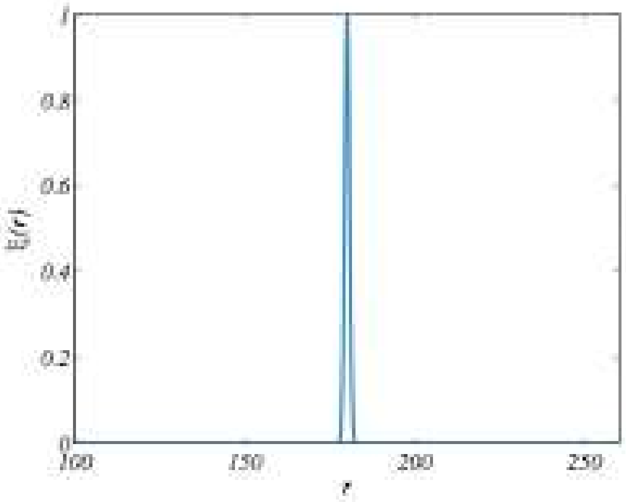
One can also define a power spectrum:

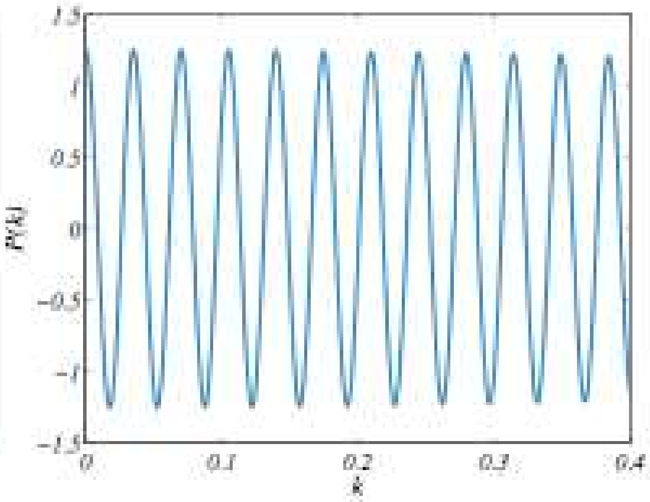
$$P(k) = \int d^3r \xi(r) e^{i\vec{k}.\vec{r}}$$

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

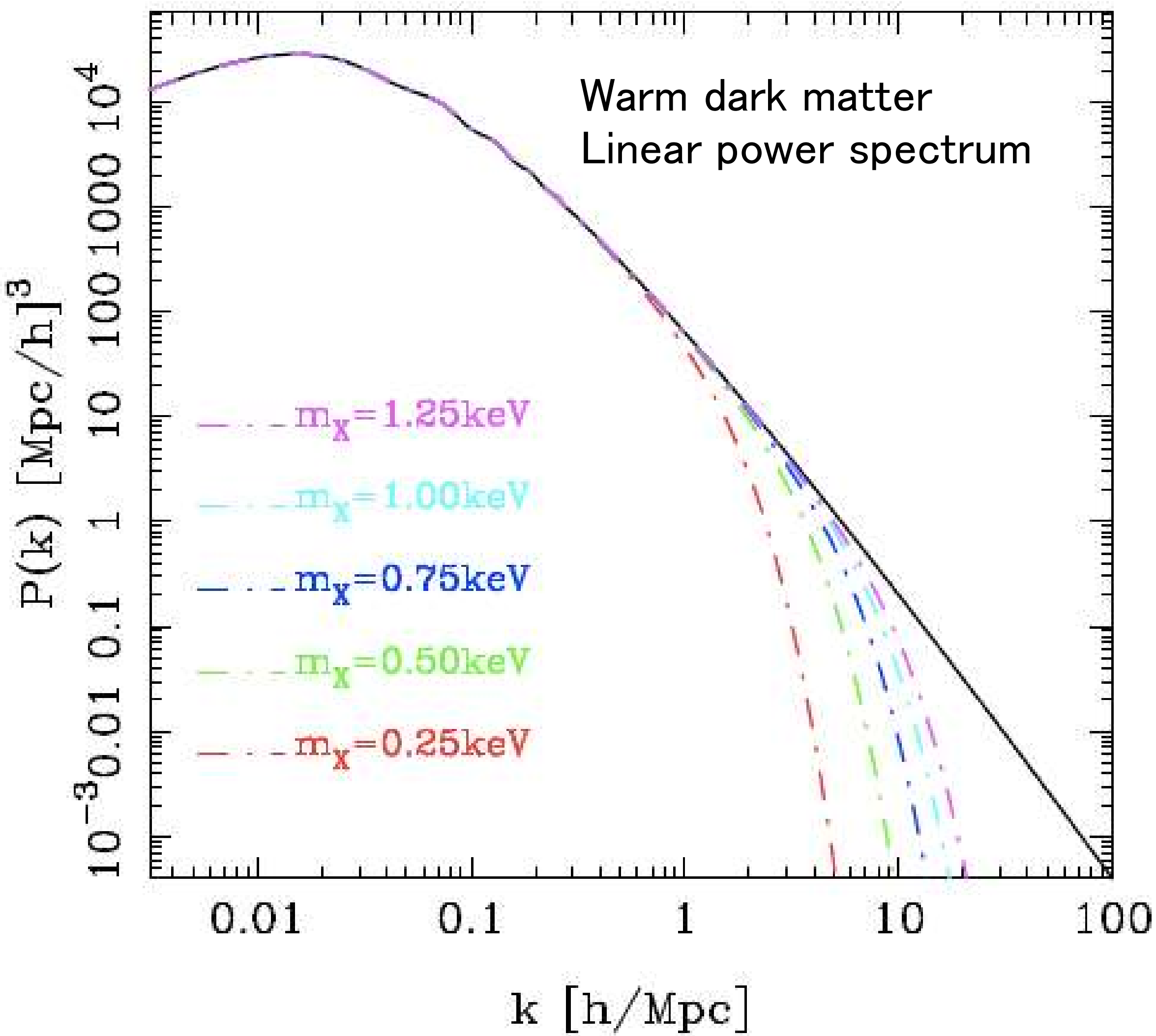
Sharp peak in correlation results in oscillations in the power spectrum

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





Power spectrum is sensitive to new physics

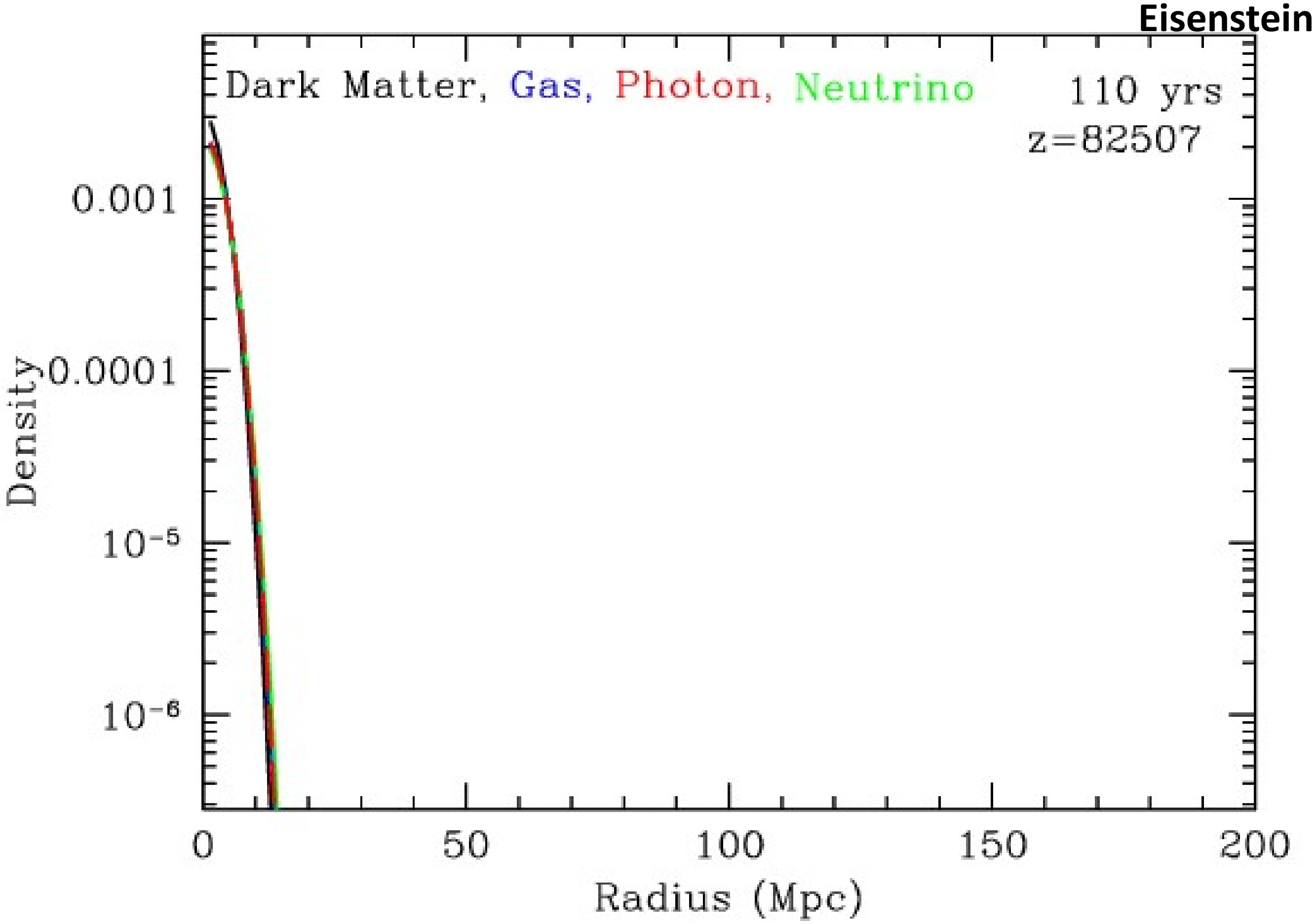


III.4-Baryon acoustic oscillation

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

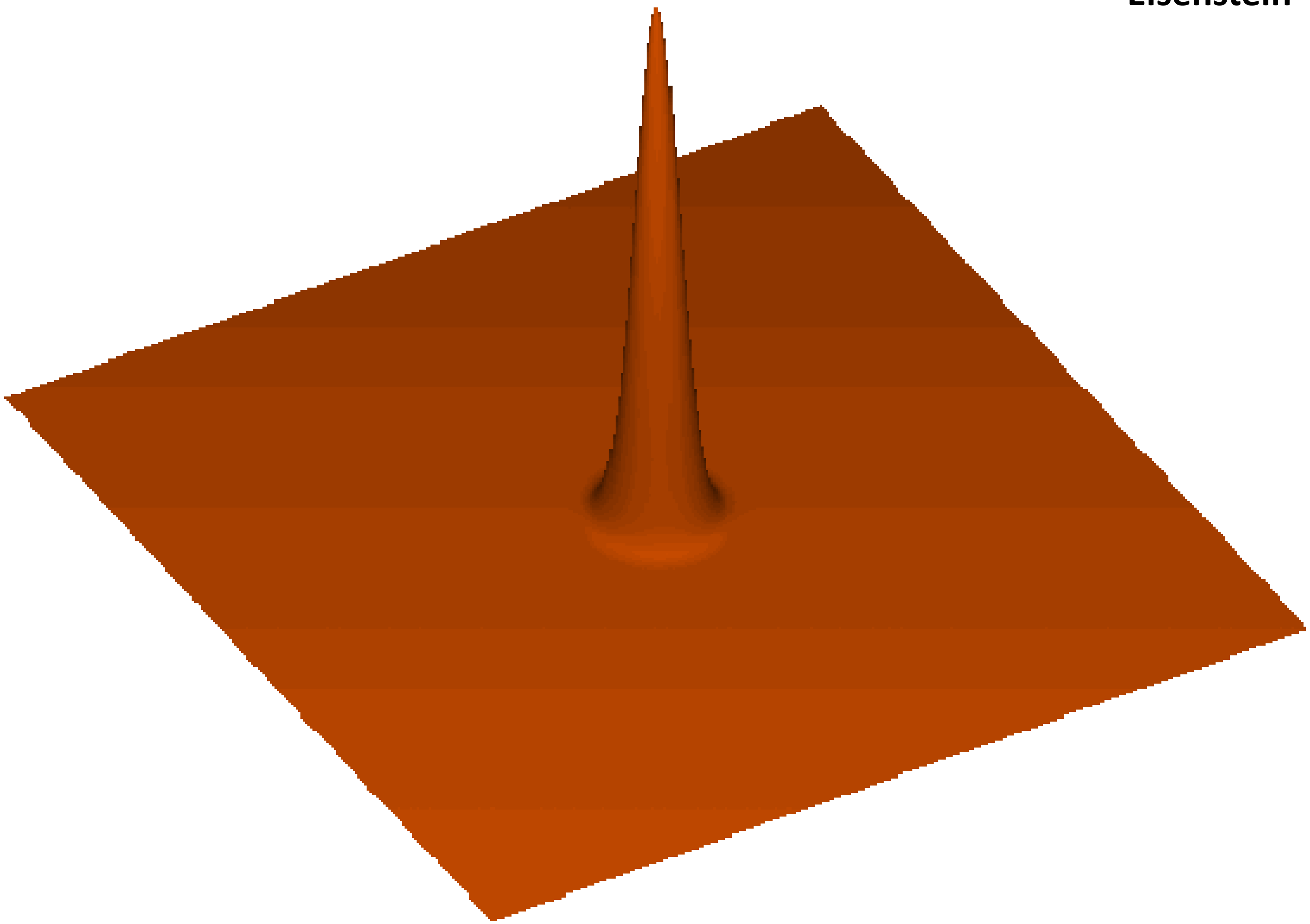
Before recombination, baryons and photons were strongly coupled, forming a single fluid with pressure and speed. Dark matter, neutrinos and other forms were decoupled.

Evolution of one spherical perturbation



Evolution of one spherical perturbation

Eisenstein



BAO scale

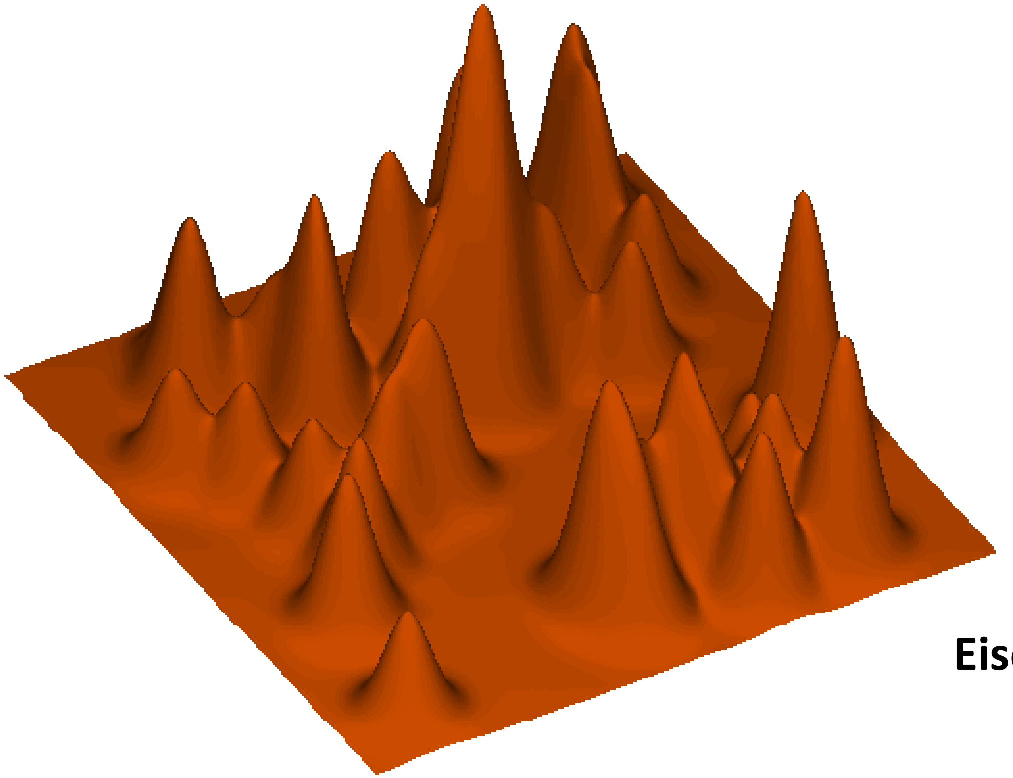
Standard ruler in the sky

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

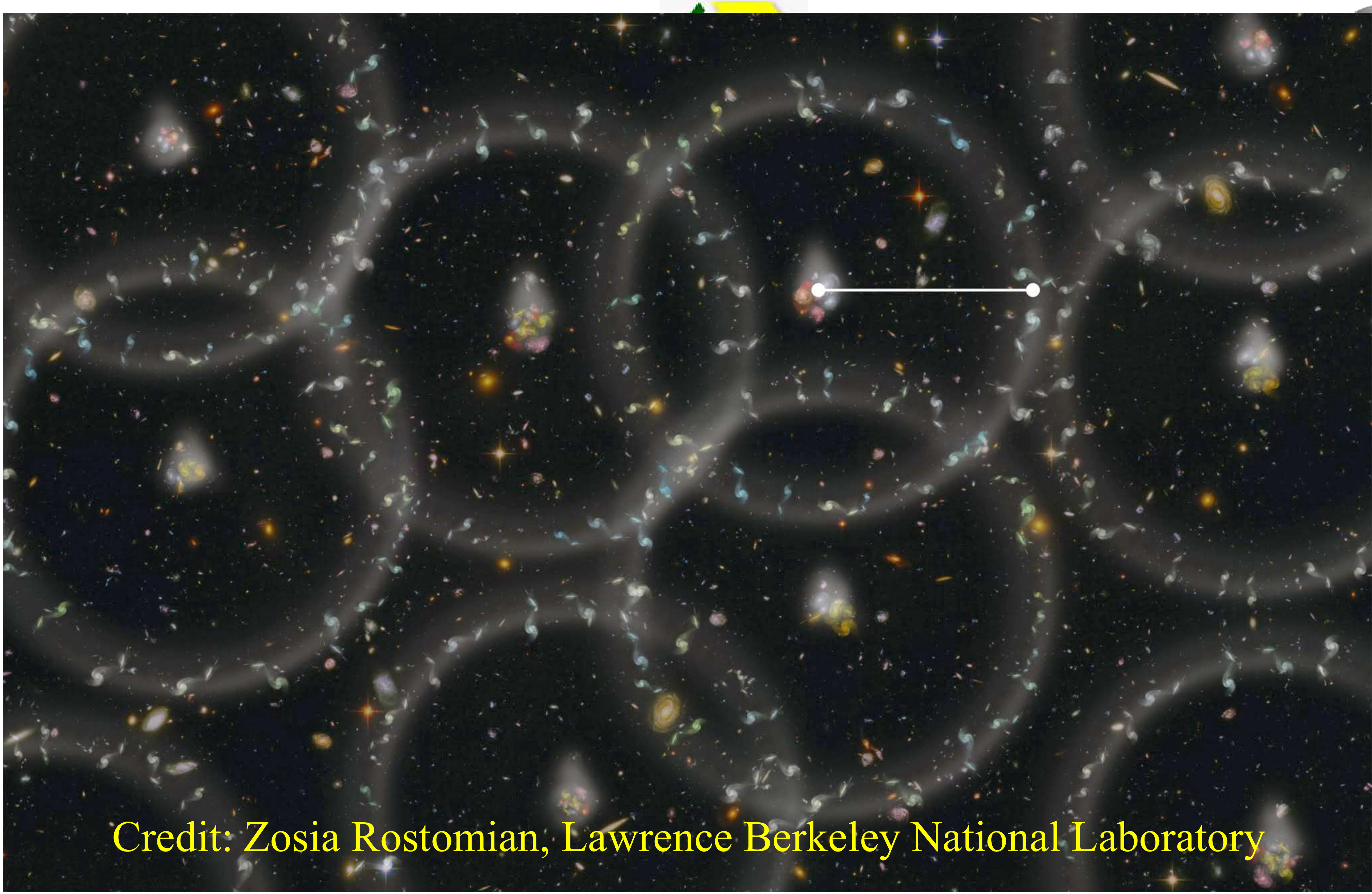
Cosmological parameters

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

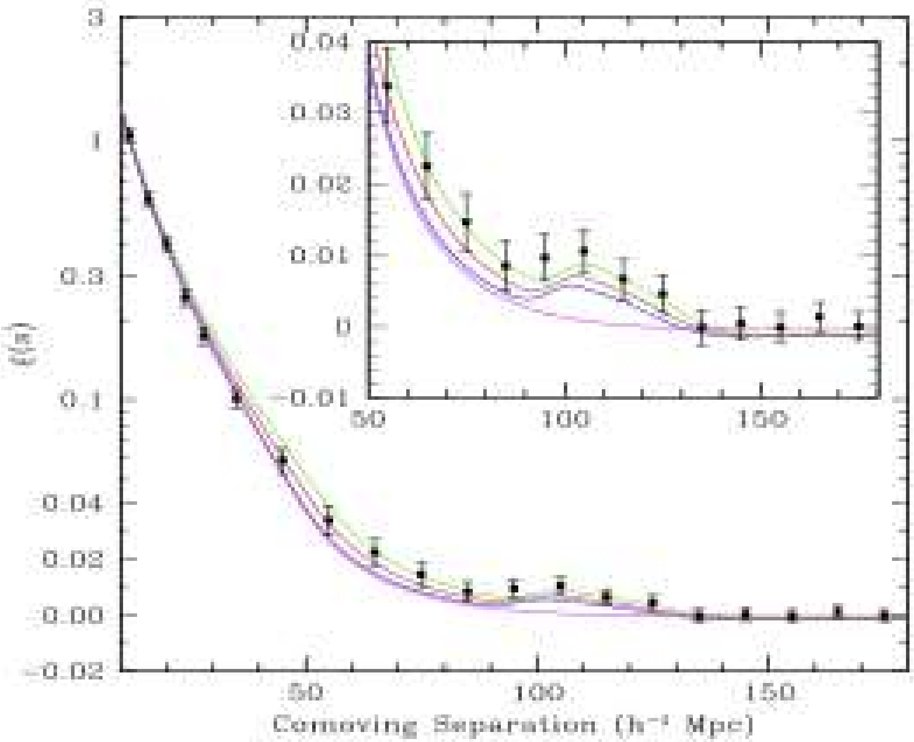
Things are more complicated: superposition of shells with different locations and different amplitudes



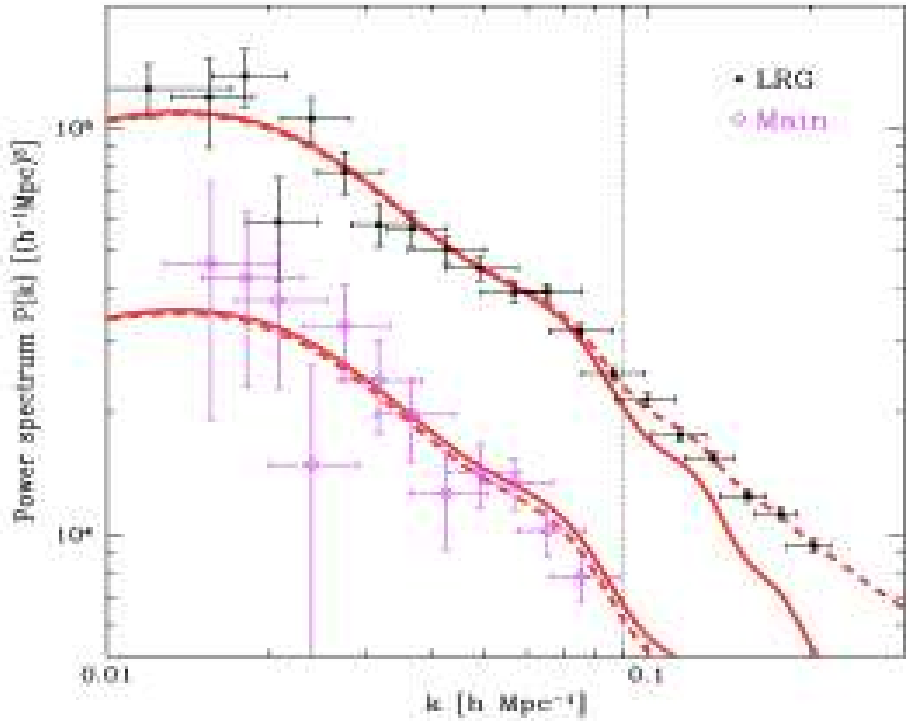
Eisenstein


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)



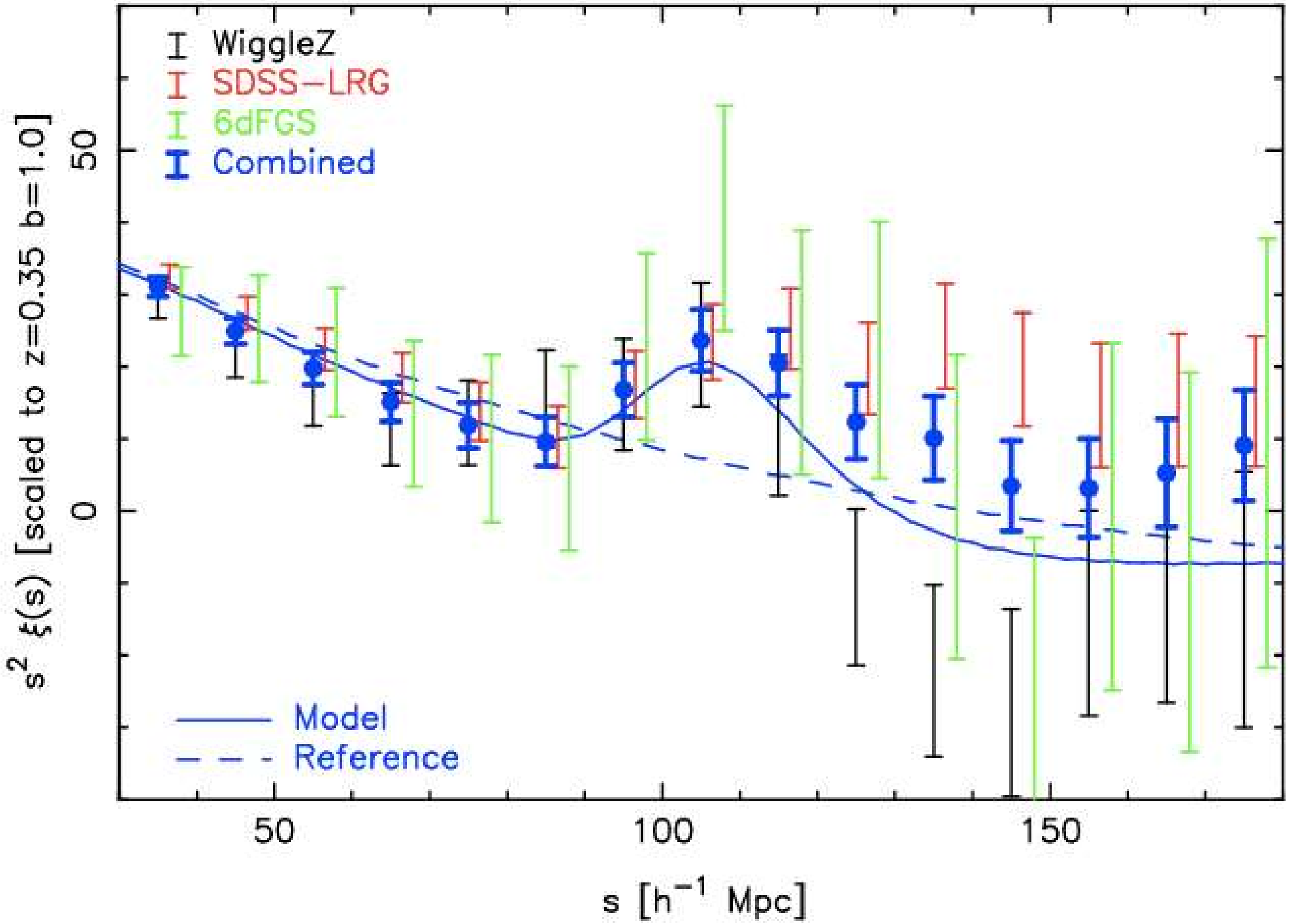
Tegmark et al (2006)

DR3, z ~ 0.35

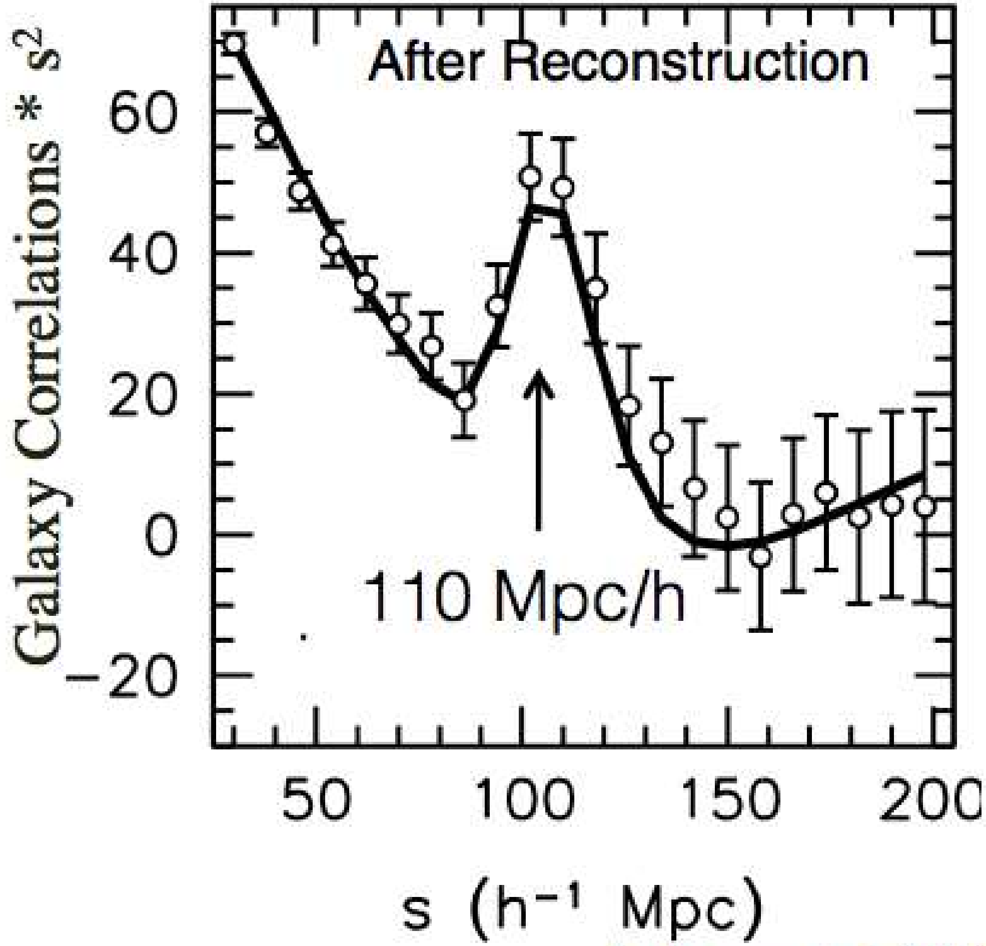
Results from WiggleZ(1108.2635):

(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

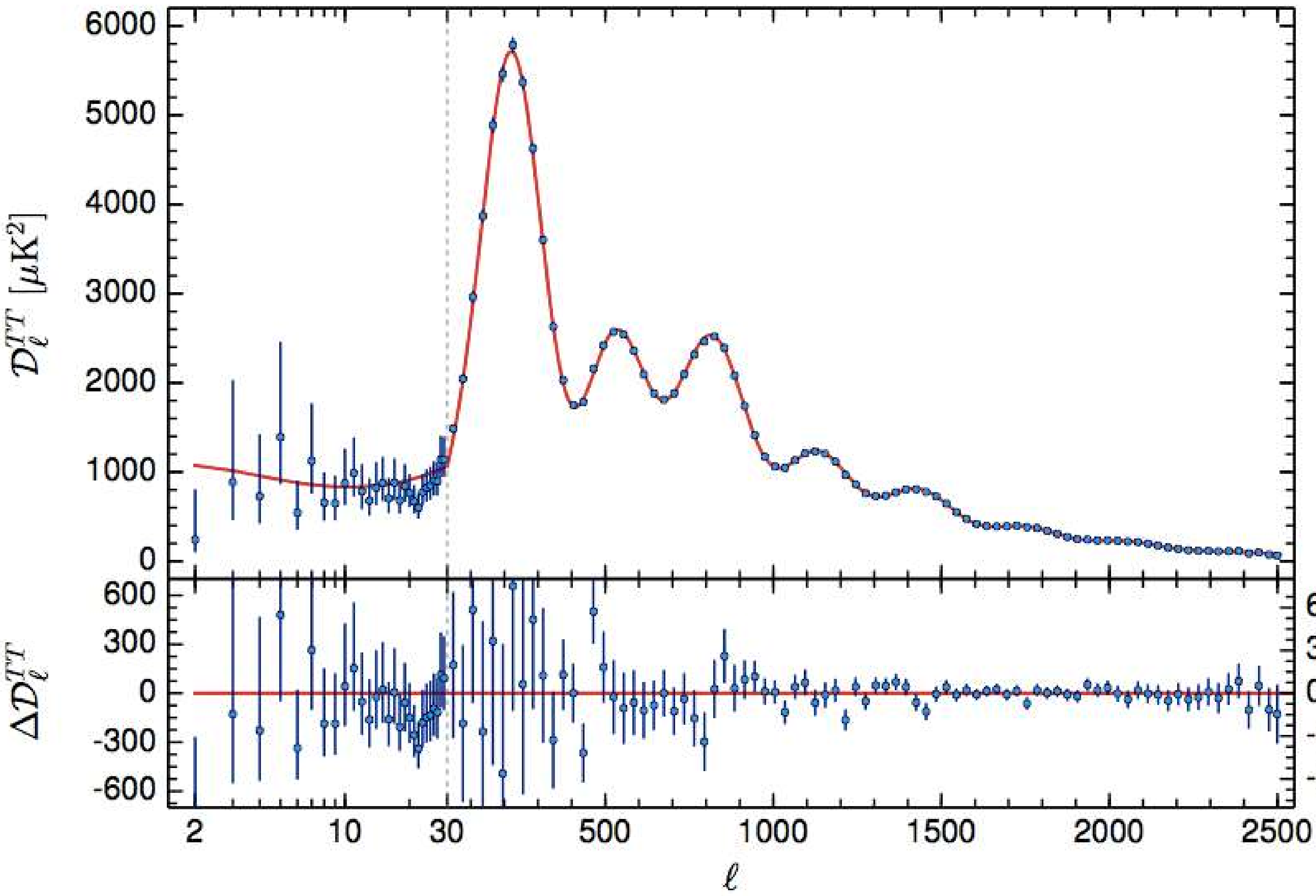
III.5 – The six-parameter Universe

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,Ω_b,Ω_{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	$-1.54^{+0.62}_{-0.50}$	$-1.41^{+0.64}_{-0.56}$	$-1.006^{+0.085}_{-0.091}$	$-1.55^{+0.58}_{-0.48}$	$-1.42^{+0.62}_{-0.56}$	$-1.019^{+0.075}_{-0.080}$

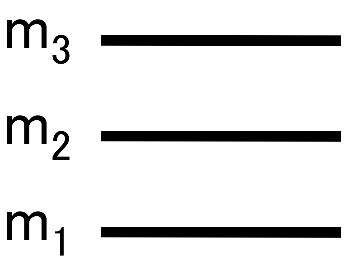
Neutrino masses in cosmology

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

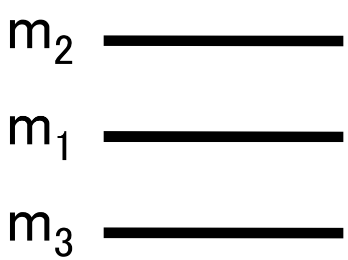
These experiments are sensitive only to the squared-mass differences:

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

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]

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

Sum of neutrino masses can be written as
(for the different hierarchies):

$$\sum m_\nu^{NH} = m_0^\nu + \sqrt{\Delta m_{21}^2 + (m_0^\nu)^2} + \sqrt{|\Delta m_{31}^2| + (m_0^\nu)^2}$$

$$\sum m_\nu^{IH} = m_0^\nu + \sqrt{|\Delta m_{31}^2| + (m_0^\nu)^2} + \sqrt{|\Delta m_{31}^2| + \Delta m_{21}^2 + (m_0^\nu)^2}.$$

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

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

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].

On The Upper Bound of Neutrino Masses from Combined Cosmological Observations and Particle Physics Experiments – 1811.02578 : impact of priors on neutrino mass determination

TABLE I. Neutrino mass models considered in this work, the neutrino parameters sampled, and the 95% CI upper bounds on both $\sum m_\nu$ and m_0^ν. Results were obtained using a combination of BOSS LSS C_ℓs, Planck CMB temperature and polarization, Planck lensing, Type Ia SuperNovae from Pantheon, and BBN measurements of D/H data. Models 1-4 also include constraints from oscillation experiments.

Model	Description	ν-Parameters	$\sum m_\nu$ [95% CI]	m_0^ν [95% CI]
1	Both hierarchies, m_0^ν-parametrization, sampling $\lvert\Delta m_{31}^2\rvert$ and Δm_{21}^2 from Gaussian priors.	m_0^ν, $\mathcal{H}$, $\lvert\Delta m_{31}^2\rvert$, Δm_{21}^2	< 0.264 eV	< 0.081 eV
2	Both hierarchies, m_0^ν-parametrization with $\lvert\Delta m_{31}^2\rvert$ and Δm_{21}^2 fixed to their central value.	m_0^ν, $\mathcal{H}$	< 0.275 eV	< 0.086 eV
3	NH, m_0^ν-parametrization, fixed mass splittings.	m_0^ν	< 0.261 eV	< 0.085 eV
4	IH, m_0^ν-parametrization, fixed mass splittings.	m_0^ν	< 0.256 eV	< 0.078 eV
5	NH approximation, $N_\nu = 1$.	$\sum m_\nu$	< 0.154 eV	–
6	IH approximation, $N_\nu = 2$.	$\sum m_\nu$	< 0.215 eV	–
7	Degenerated masses approximation, $N_\nu = 3$.	$\sum m_\nu$	< 0.270 eV	–
8	No massive neutrinos, i.e., $N_\nu = 0$	–	–	–
9	Fixed to NH's lower bound, $\sum m_\nu = 0.06$ eV	–	–	–

Usual analysis

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 $\leftrightarrow$ 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

John Peoples was 1st director
Josh Frieman – 2nd director
Rich Kron – current 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

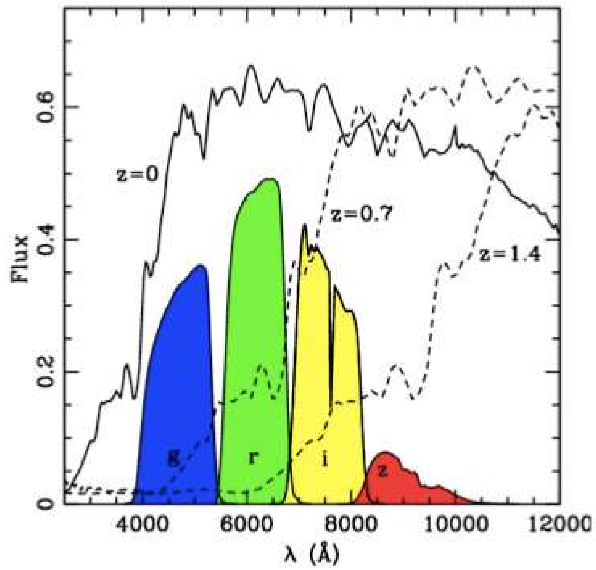
DES-Brazil is a LIneA Project

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



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

Observations ended in January 9, 2019

DES-BRAZIL

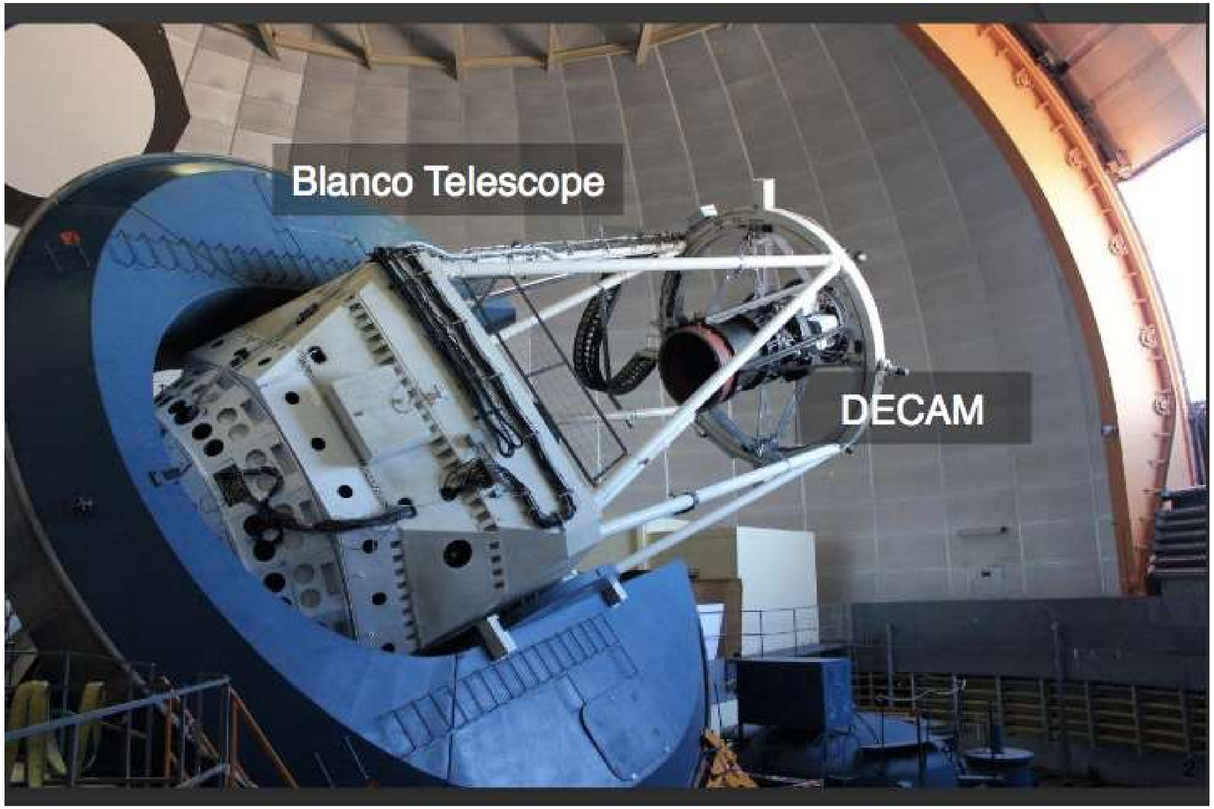
LIneA

Laboratório Interinstitucional de e-Astr

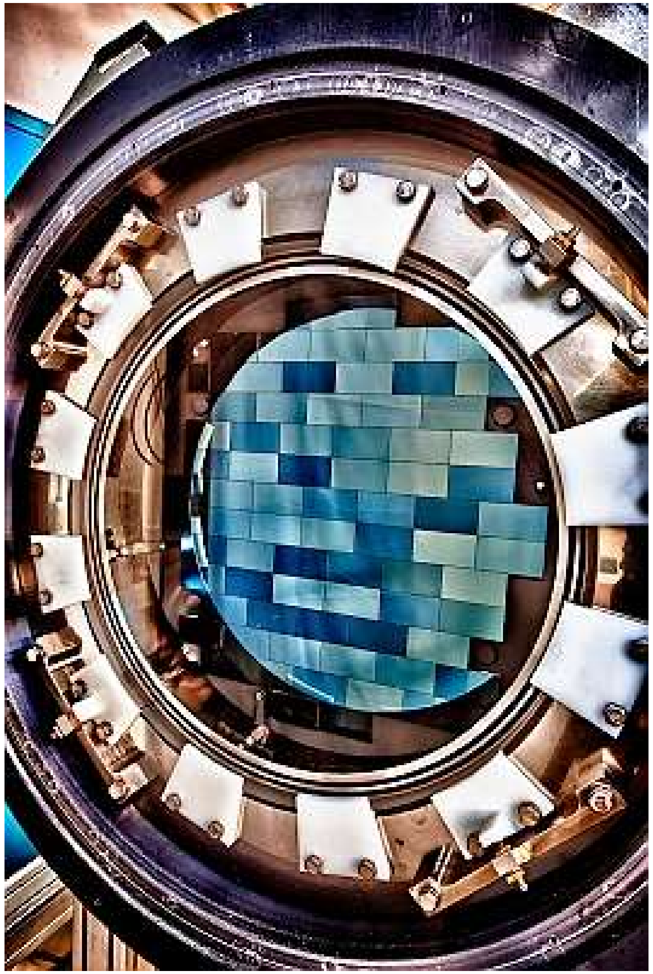
DES site: 4m Blanco telescope at the Cerro Tololo Inter-American Observatory (CTIO) in Chile

DECam

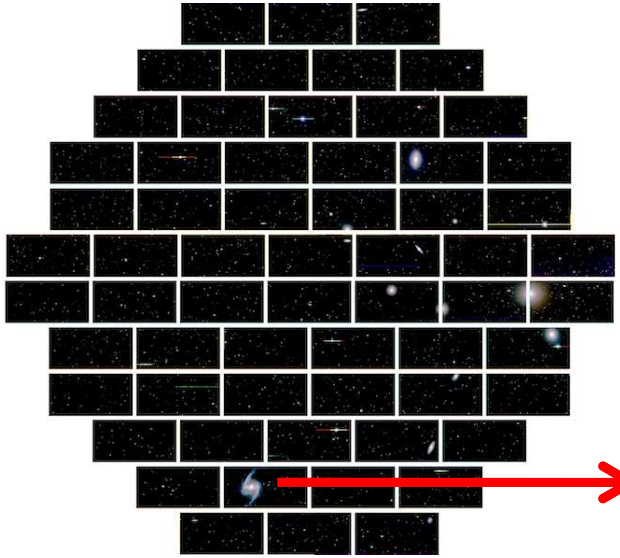
Able to see light from more than 100,000 galaxies up to 8 billion light-years away in each snapshot. Weighs ~4 tons!



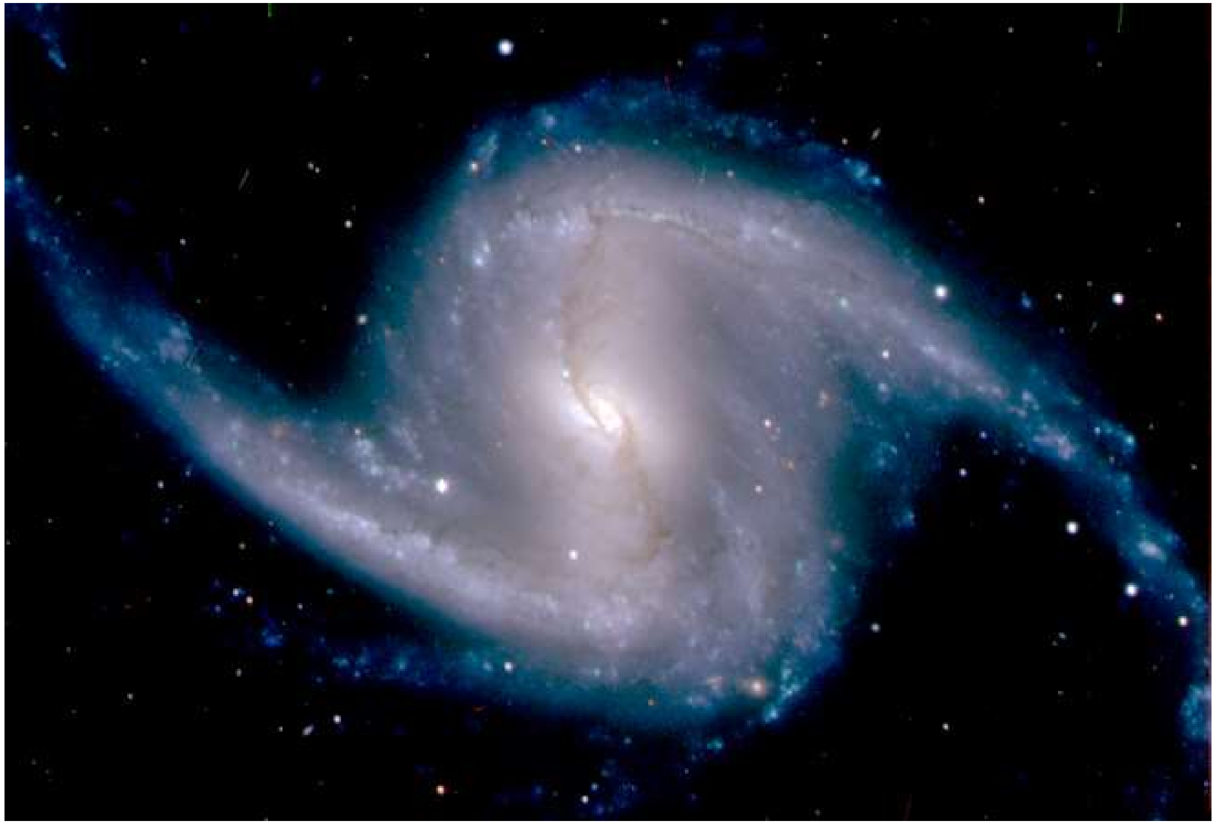
DECam



arXiv:1504.02900



Fornax cluster of galaxies



Barred spiral galaxy NGC 1365 in the Fornax cluster of galaxies

DARK ENERGY SURVEY

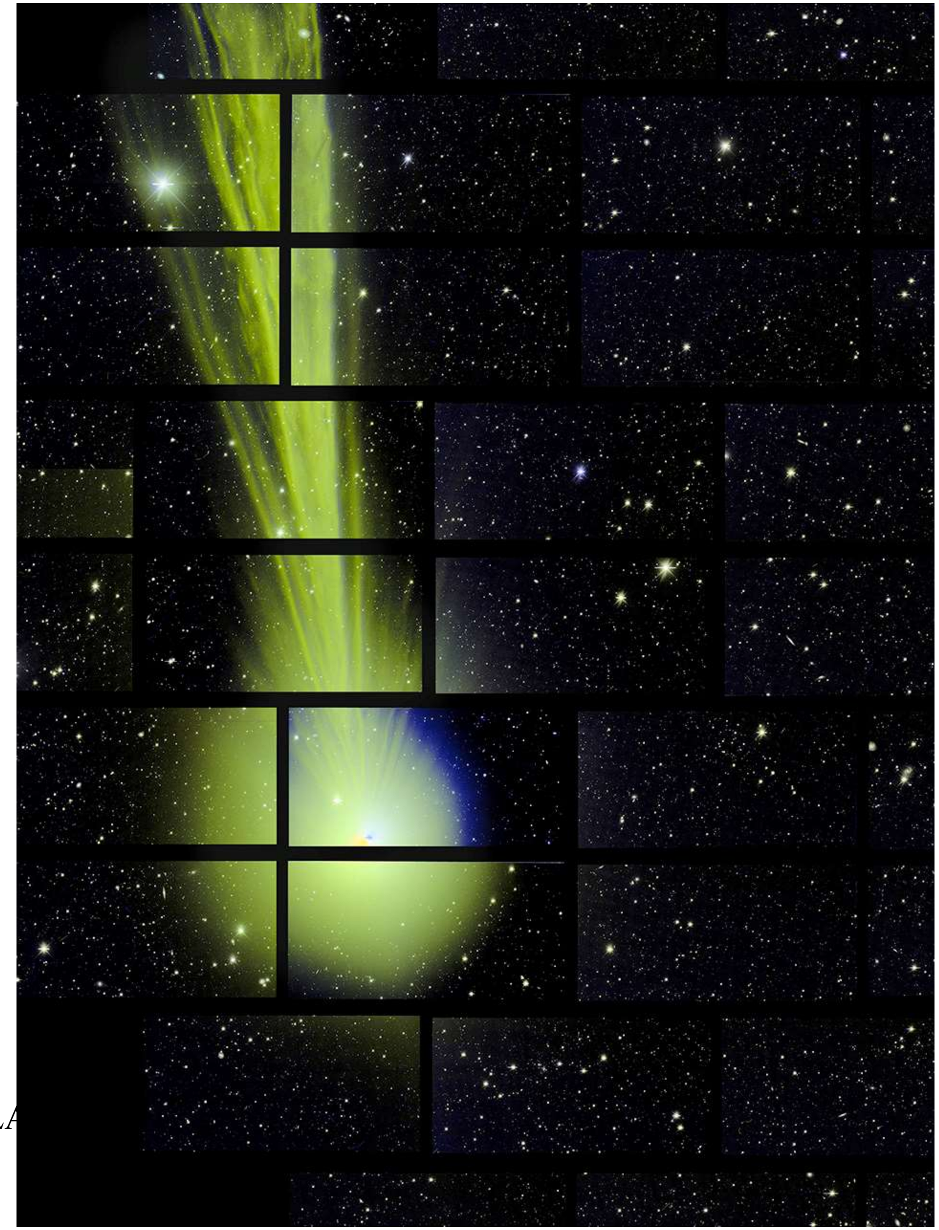
DES SV image of a deep SN field

3 deg^2 field of view

Dark Energy Camera catches breathtaking glimpse of comet Lovejoy

December 27 2014

82 million km away



DES Data Management

Each exposure (in a given filter) generates 500Mb

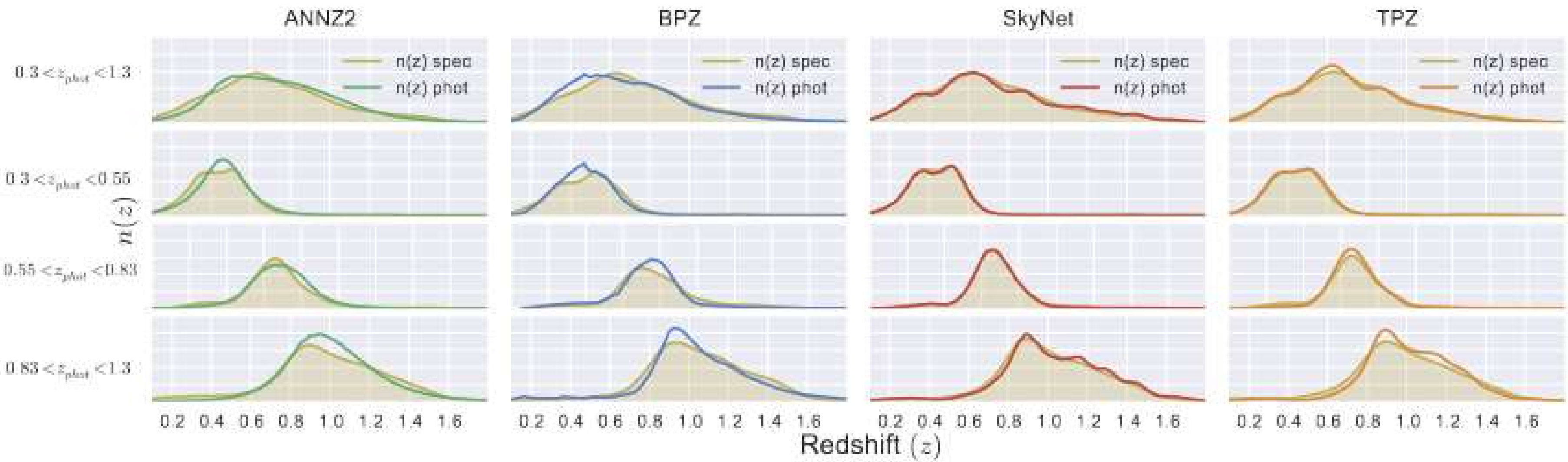
300 exposures/night – 150 Gb/night

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

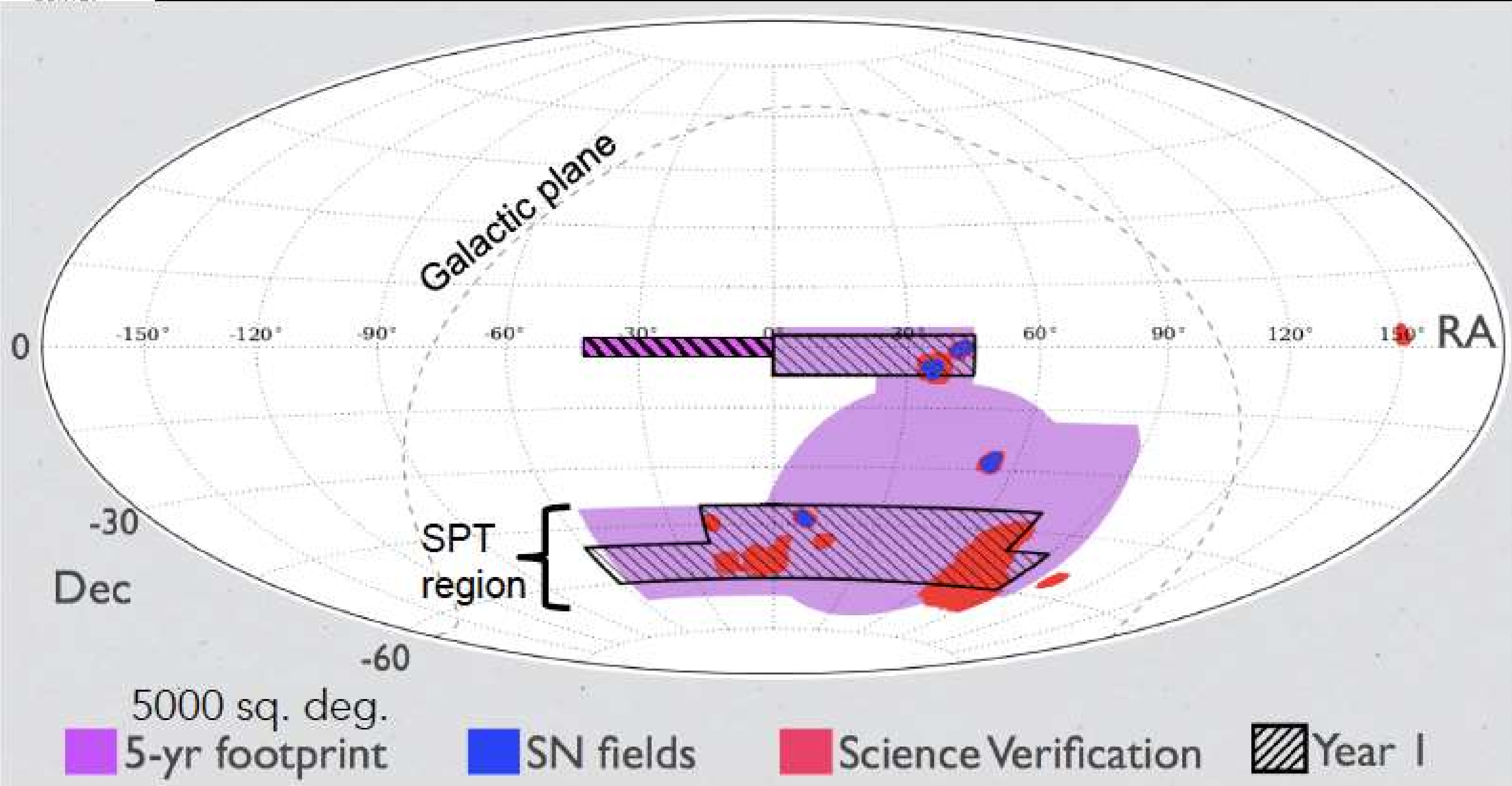
• QuickReduce: software for fast assessment of image quality at CTIO

• 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, …

DES Survey Footprint

DARK ENERGY SURVEY

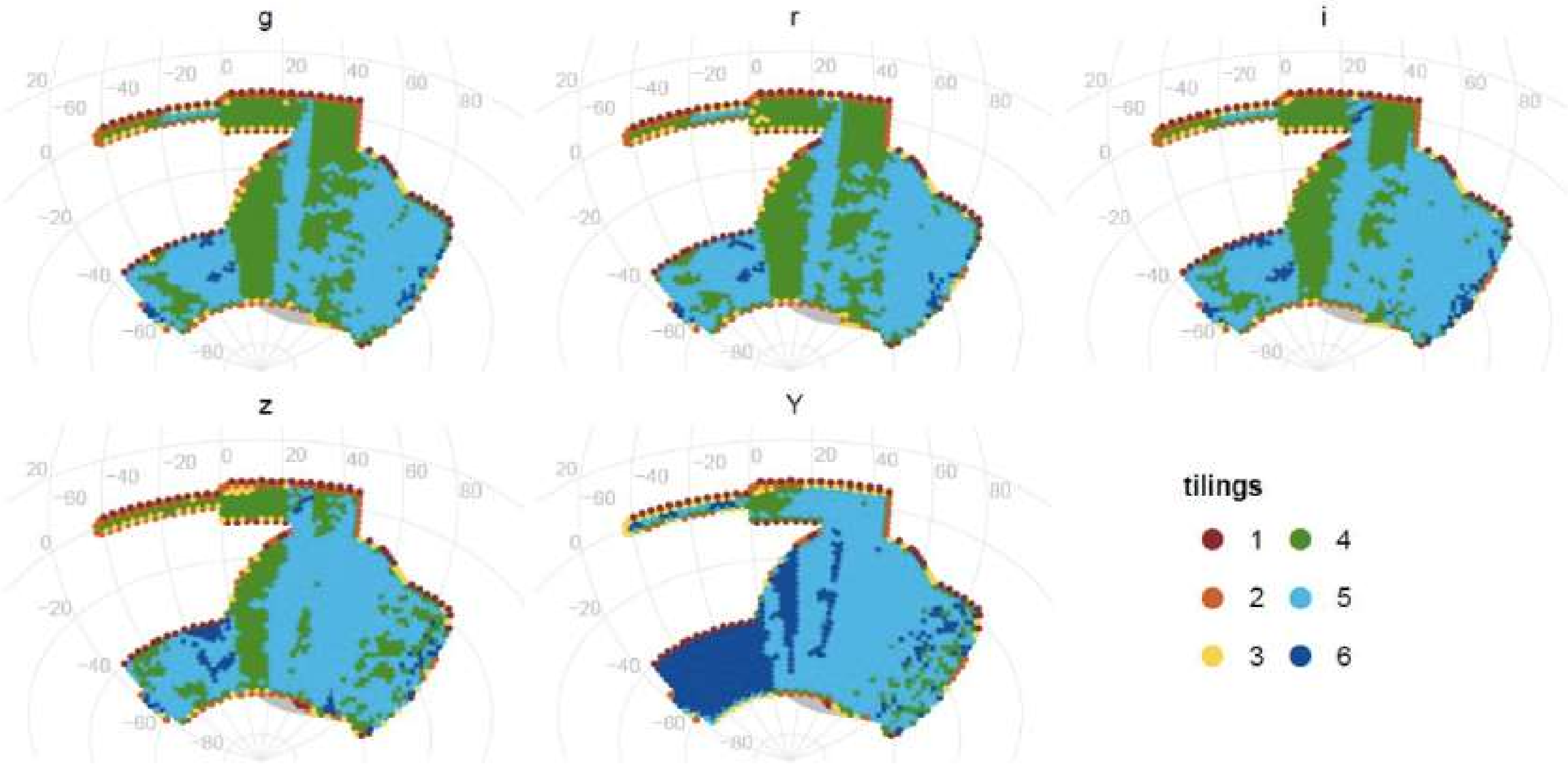


- Science Verification (SV): ~250 sq. deg. to ~full depth; 45 M objects
- Year 1 (Y1): ~2000 sq. deg; overlap SPT, SDSS: 4/10 tilings; 140 M objects

DES Y3 ended on february 2016

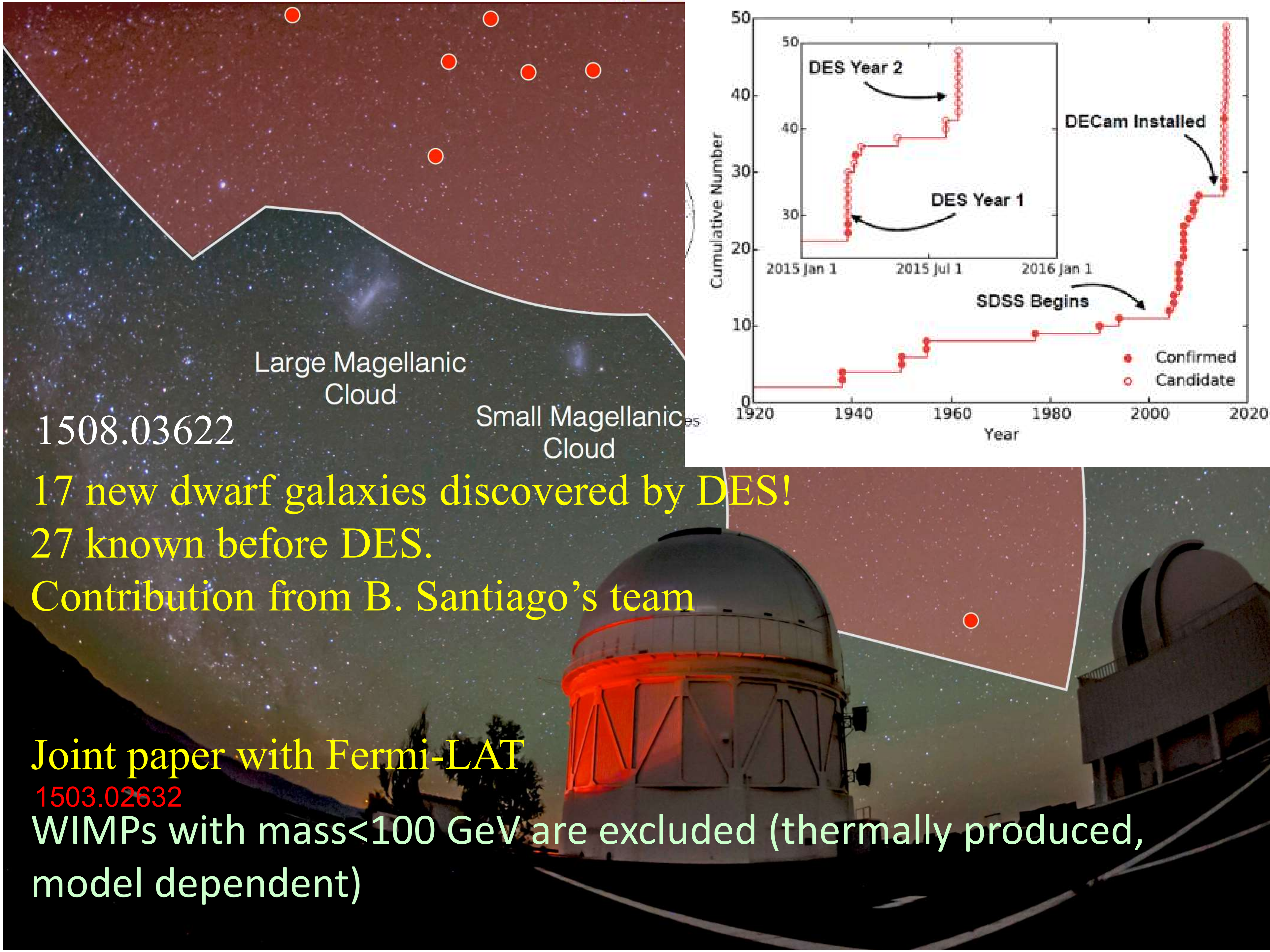
DES is proyected for 5 years , up to 2018

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



~300 papers:

- 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;
- 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

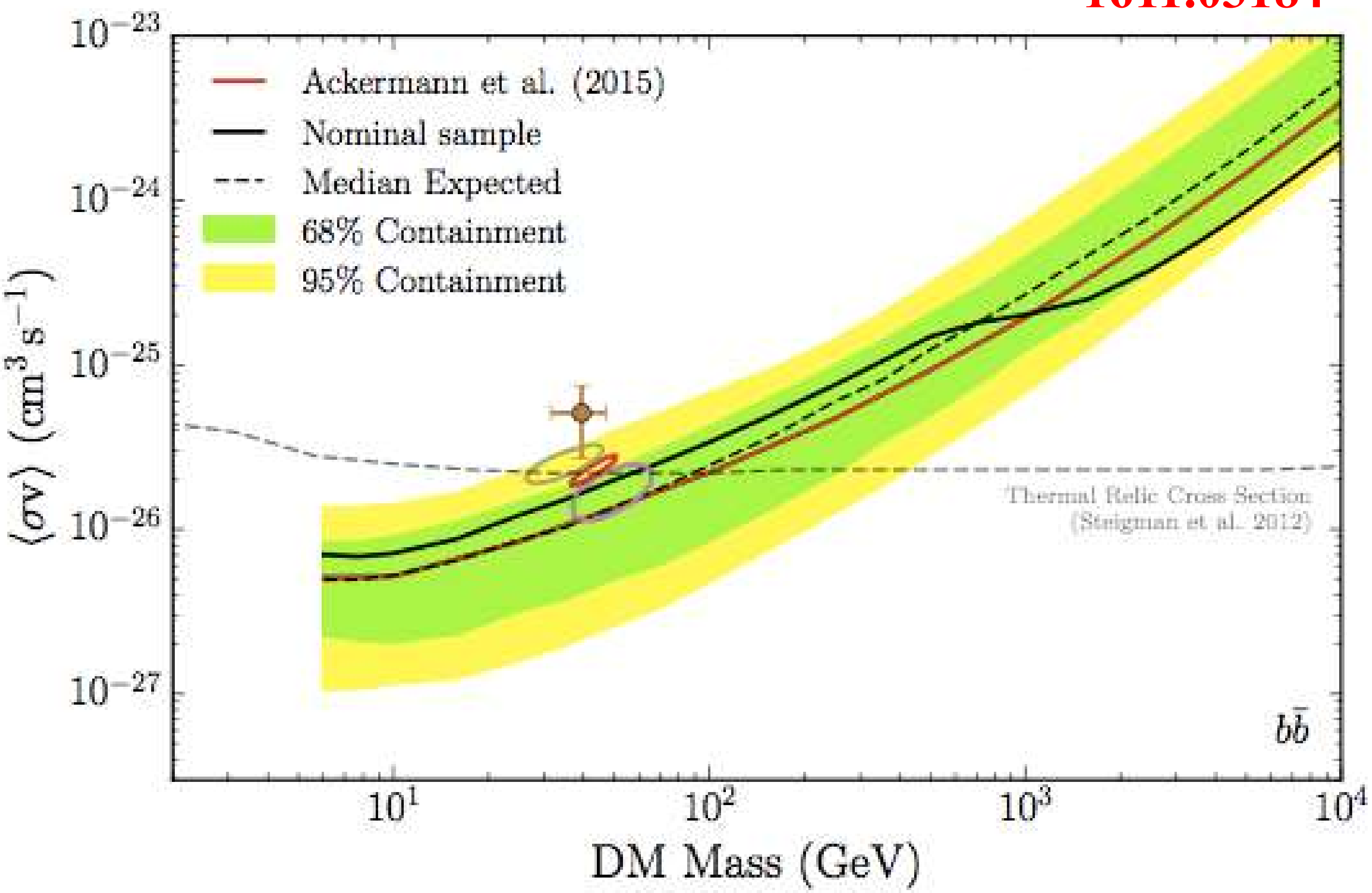
Joint paper with Fermi-LAT

1503.02632

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

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

1611.03184



III.6.1- Getting Cosmological Parameters in DES

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:

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

Theoretical prediction depends on the model and its parameters.

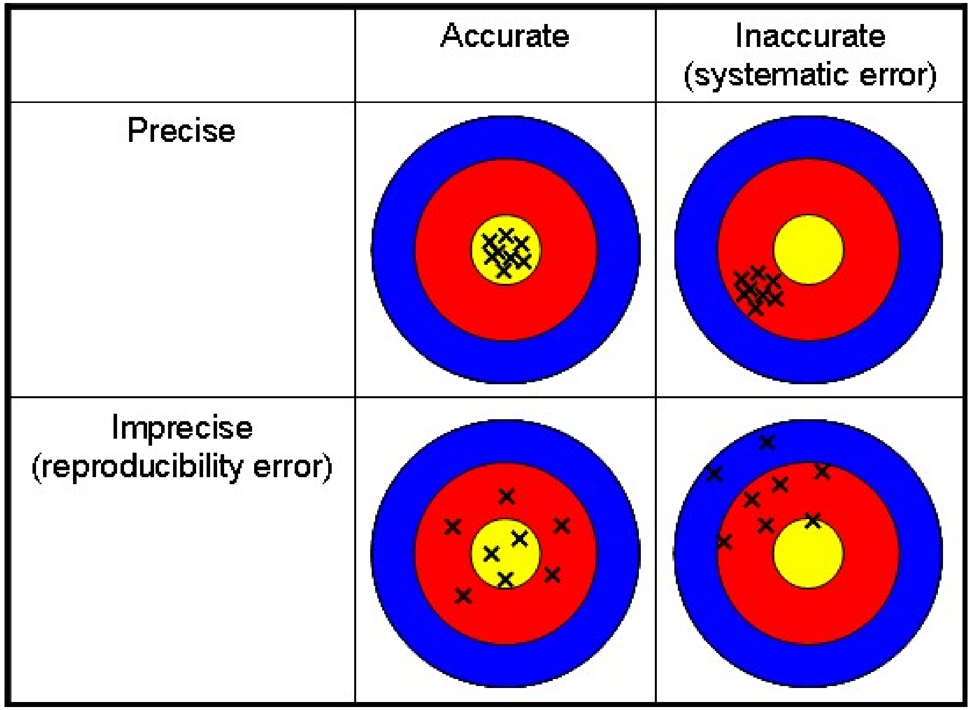
Observations depend on the experiment.

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

Best model: maximize likelihood

Sounds pretty easy!

Precision vs Accuracy



I’ll briefly describe two cosmological analysis of DES first year data:

- Baryon Acoustic Oscillation

- Main analysis combining galaxy distribution and galaxy weak lensing

III.6.2- BAO in 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.

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

We need to model the galaxy angular power spectrum. Model will depend on parameters that will be estimated with a given likelihood.

The theoretical modelling is far from trivial. Will discuss a couple of issues.

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 methods, simulations, EFT

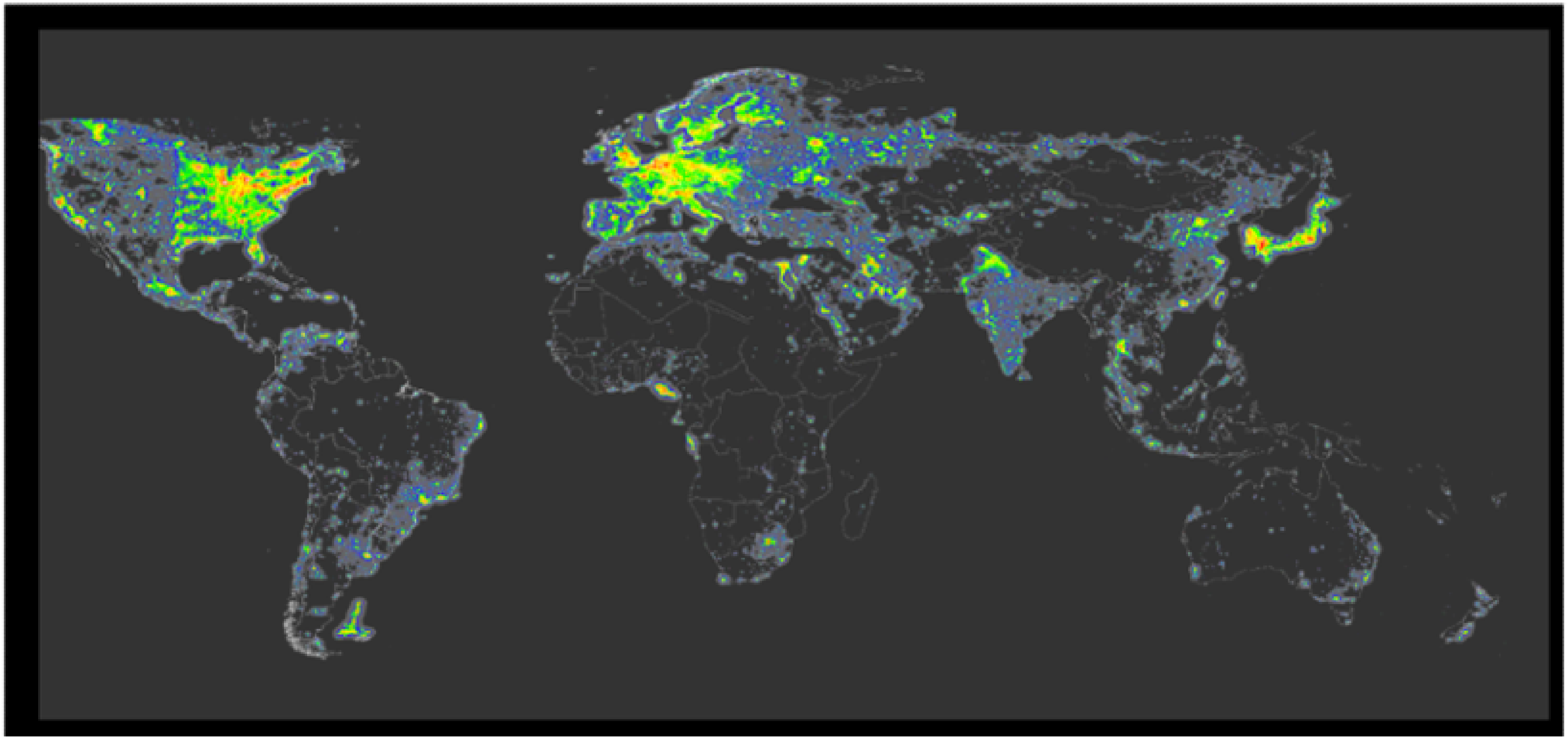
. One must correct for the so-called redshift space distortions – proper motions of objects

. 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

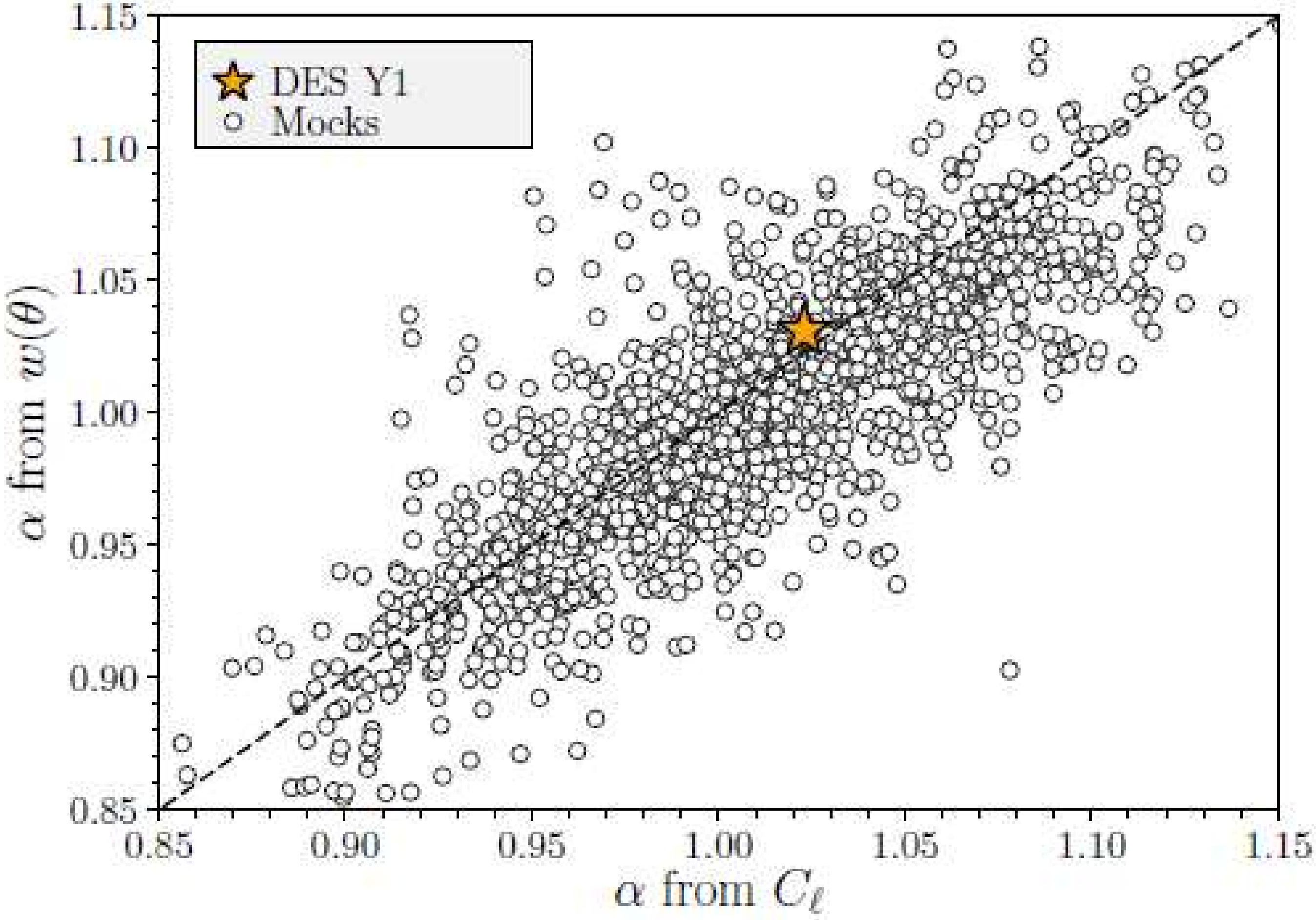
BAO position estimated using a template-based method:

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

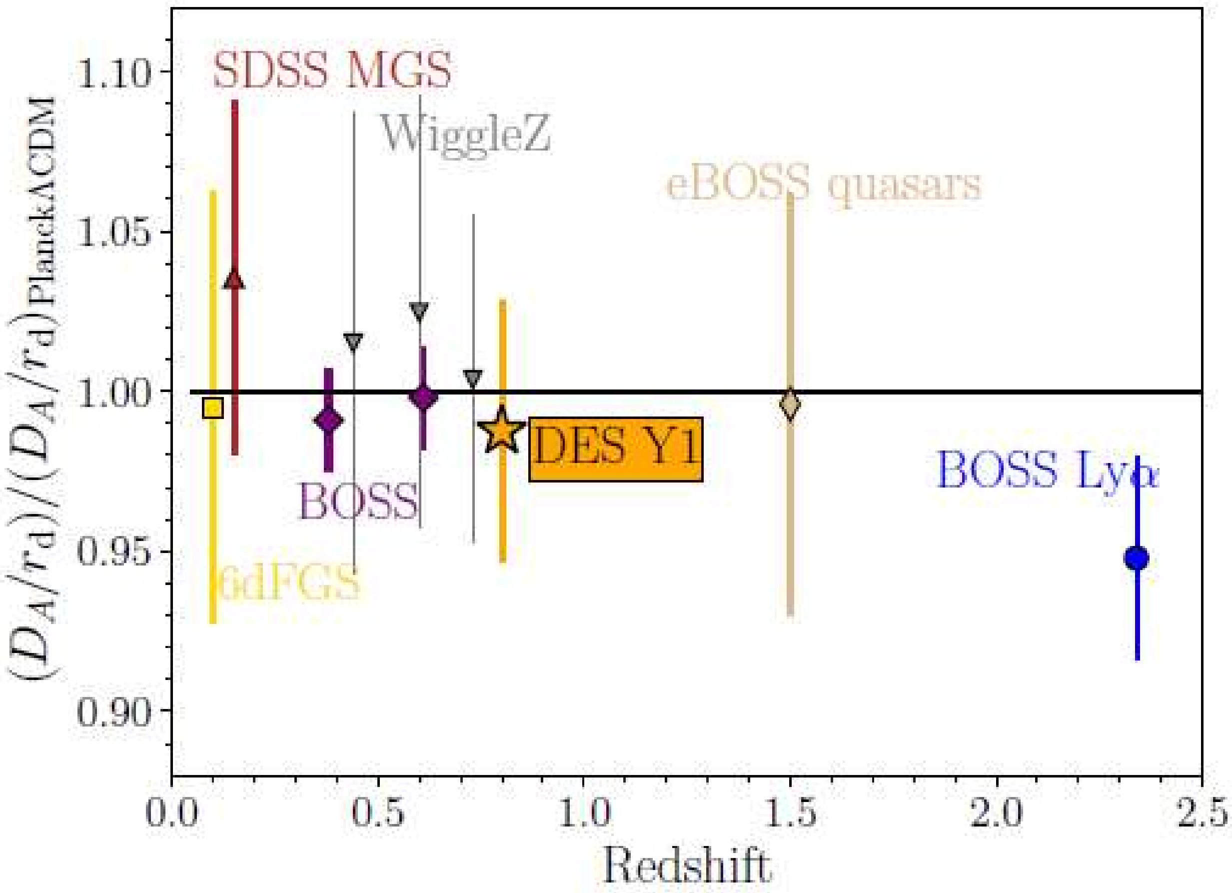
Parameter α determines the shift in the BAO position with respect to a fiducial cosmology:

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

Comparison of measurements using real space and harmonic space in mocks and in real data – consistent!!



The money plot



III.6.3- DES main results for Y1

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

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)	
$\Delta z_{\rm l}^1$	Gauss $(0.001, 0.008)$
$\Delta z_{\rm l}^2$	Gauss $(0.002, 0.007)$
$\Delta z_{\rm l}^3$	Gauss $(0.001, 0.007)$
$\Delta z_{\rm l}^4$	Gauss $(0.003, 0.01)$
$\Delta z_{\rm l}^5$	Gauss $(0.0, 0.01)$
Source photo-z shift	
$\Delta z_{\rm s}^1$	Gauss $(-0.001, 0.016)$
$\Delta z_{\rm s}^2$	Gauss $(-0.019, 0.013)$
$\Delta z_{\rm s}^3$	Gauss $(+0.009, 0.011)$
$\Delta z_{\rm s}^4$	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!

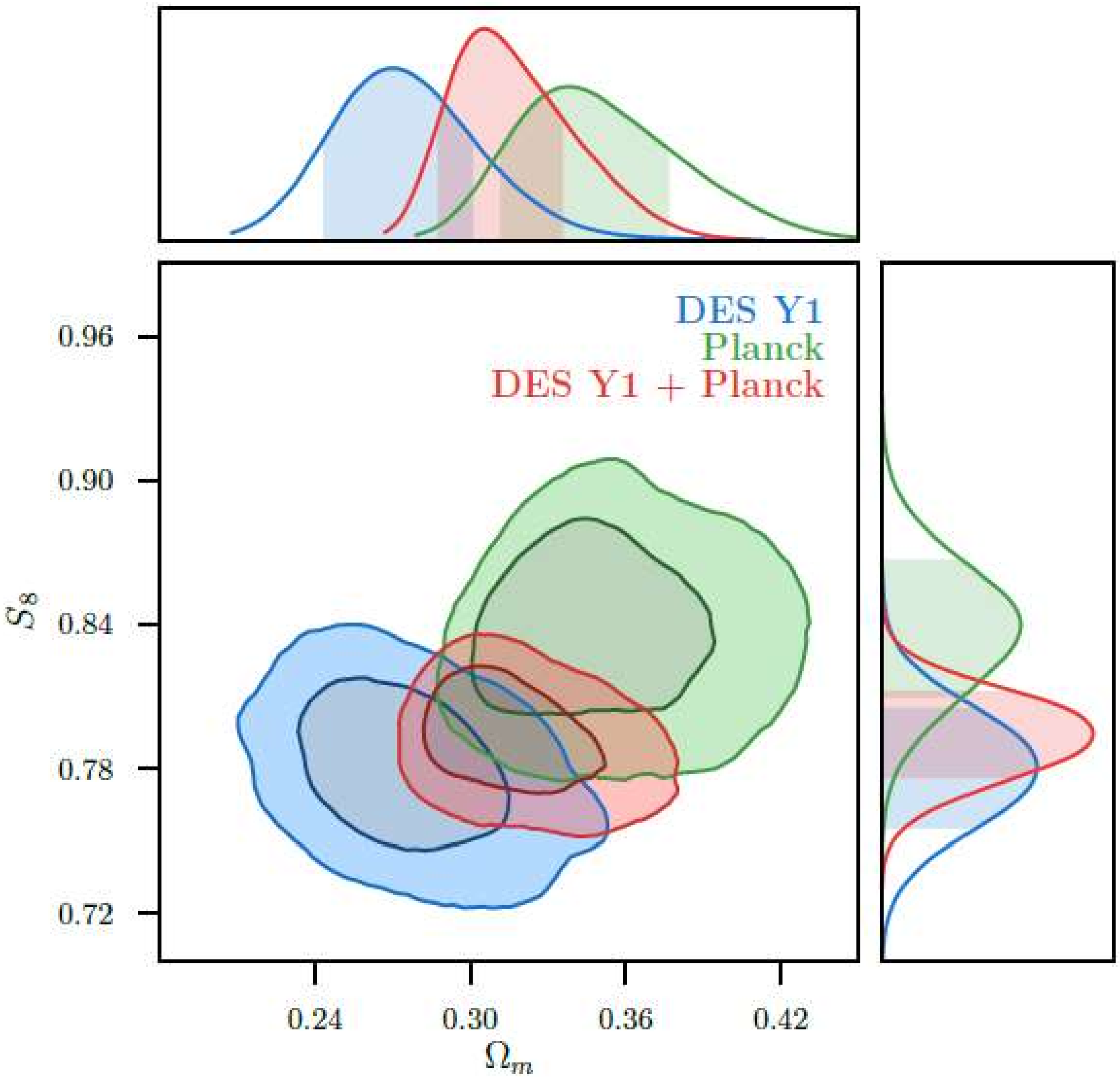
Data vectors were defined using scale cuts to mitigate non-linear bias effects.

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.

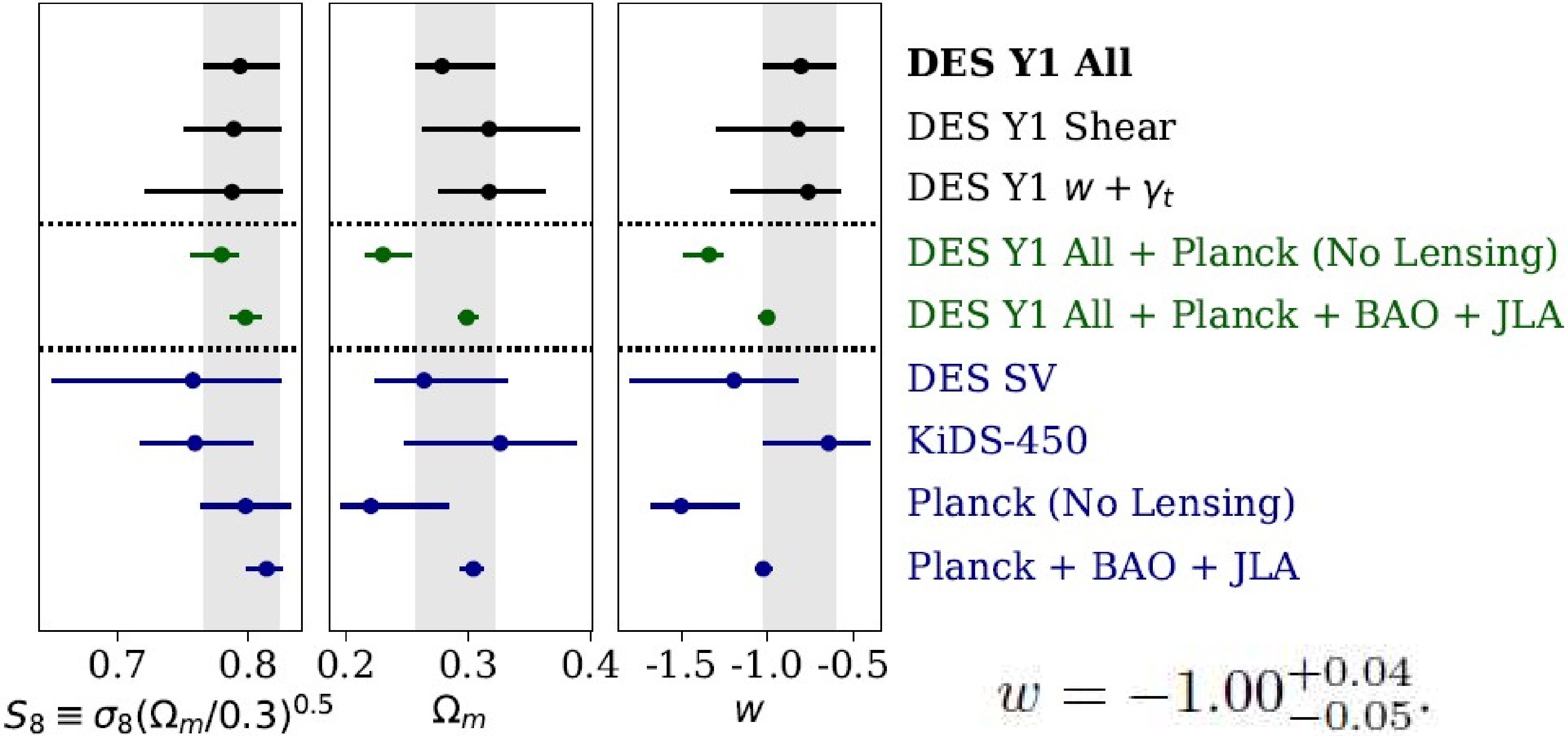
2 models were analyzed: ΛCDM and wCDM

ΛCDM



For the 1st time results from late universe are comparable with results from CMB!! Early fluctuations turn into galaxies!

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	$[-3.0, 3.0]$

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Near future

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

CONCLUSION

- 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!