100 Years of the Cosmological Constant Λ : what's next?

Ofer Lahav (University College London)

DES@Blanco-Chile

HST CLASH

Outline

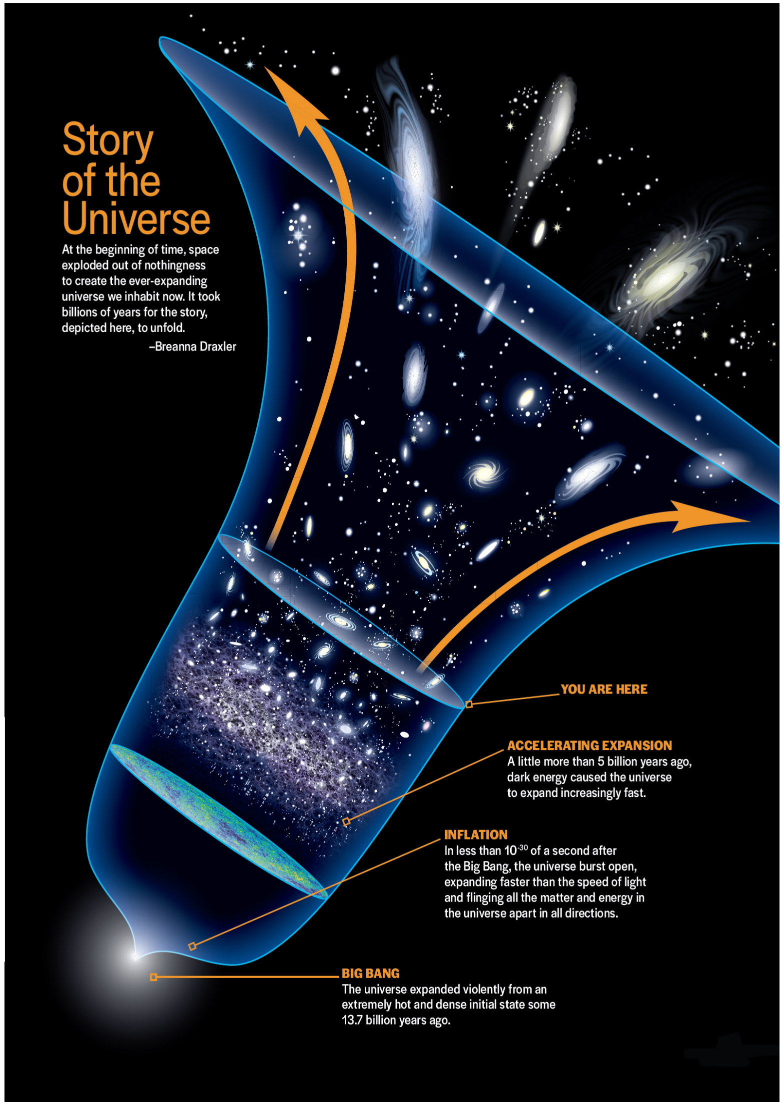
- 100 years of Λ
- Λ on Mpc scales: Machine Learning for Local Group modelling
- The Dark Energy Survey:

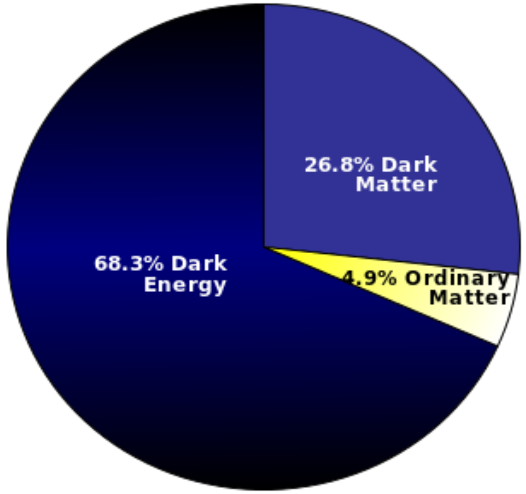
  status of observations and new results
- The CMB Cold Spot revisited
- More than Dark Energy:

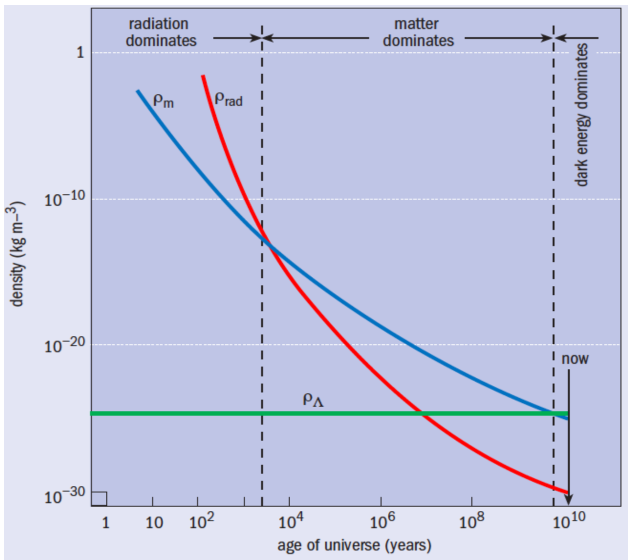
  from search for Planet 9

  to Gravitational Wave follow-ups

What accelerates the Universe?





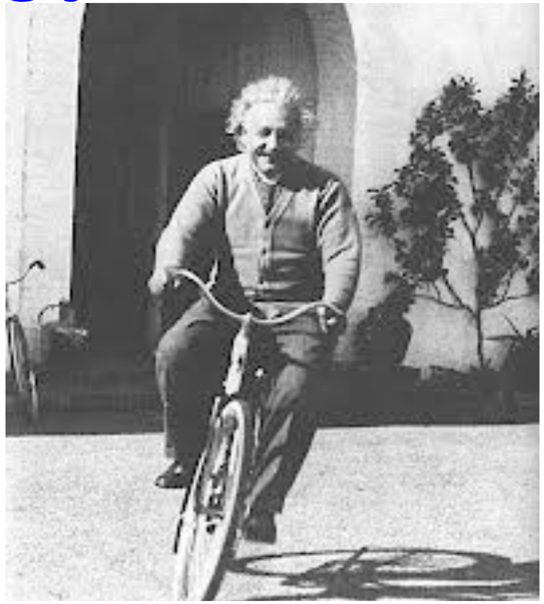


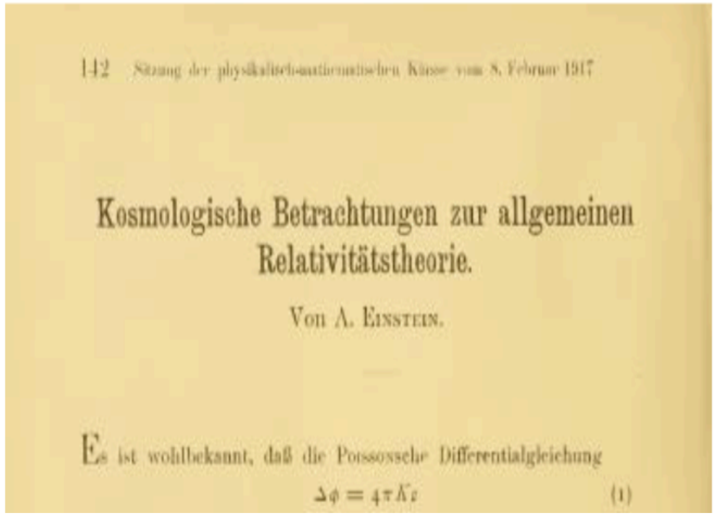
LCDM is “a simple but strange universe” (since 1990)

100 Years of Λ:
What is Dark Energy?

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Systematics mimic DE?
- Lambda-CDM, EoS w = -1.00?
- Dynamical scalar field w(z)?
- Signatures of modified gravity?
- Inhomogeneous Universe?
- Multi-verse?
- An unknown unknown??





142 [illegible] 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

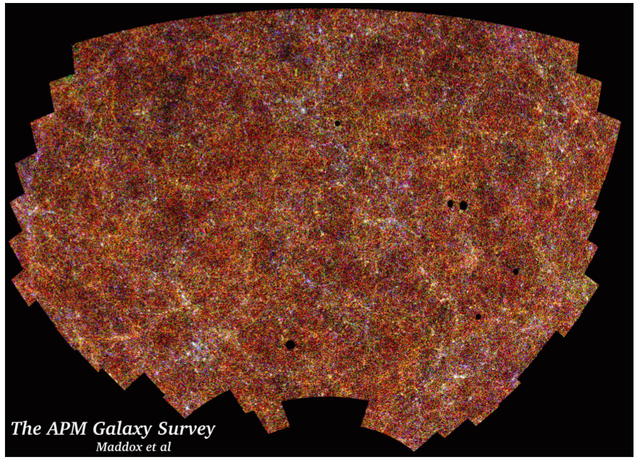
Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\varrho \qquad (1)$$

Einstein's Λ paper (February 1917)

Lambda from the APM galaxy clustering (1990)

$\Omega_\Lambda = 1 - 0.2 = 0.8$



letters to nature

Nature **348**, 705 - 707 (27 December 1990); doi:10.1038/348705a0

The cosmological constant and cold dark matter

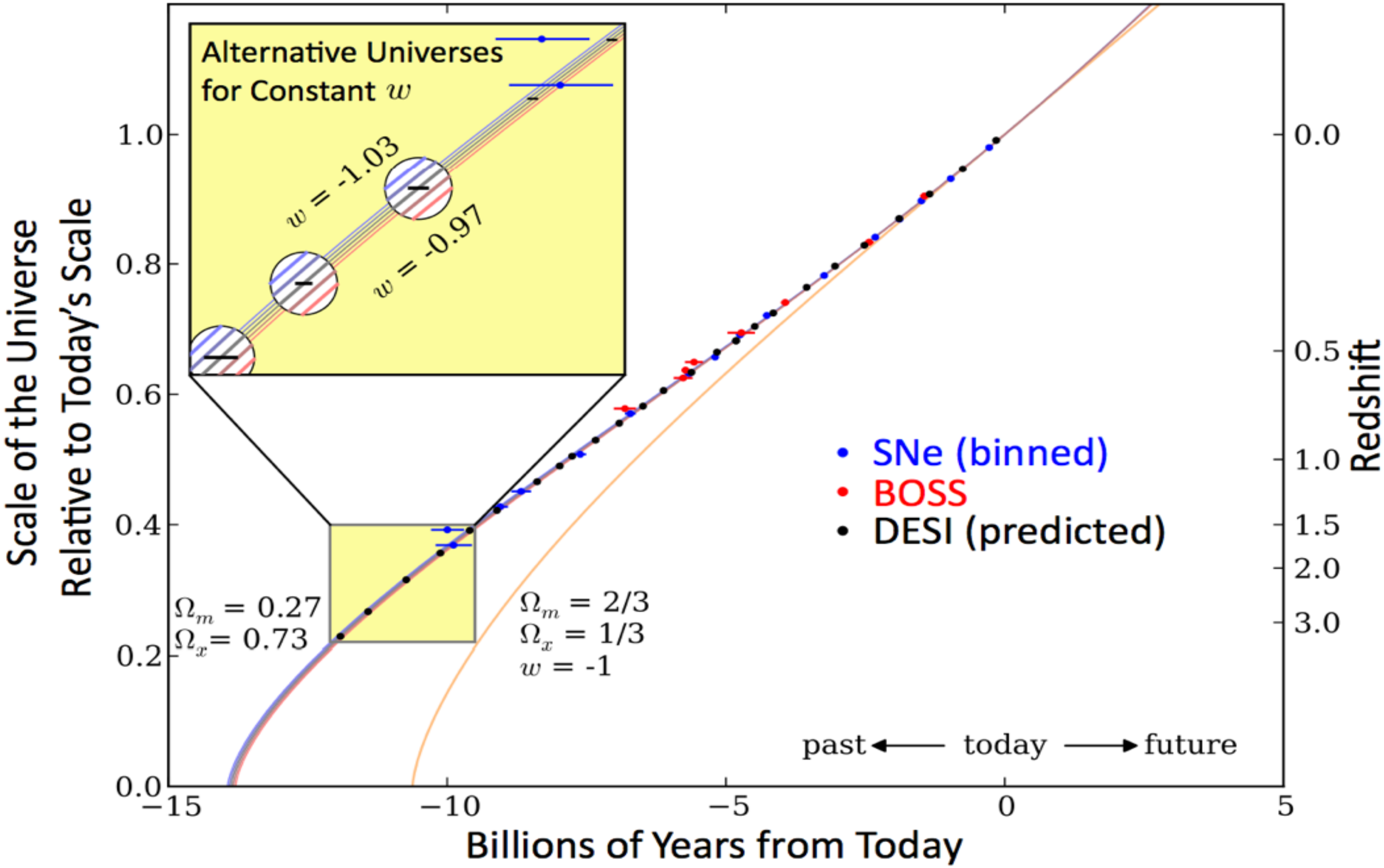
G. EFSTATHIOU, W. J. SUTHERLAND & S. J. MADDOX

Department of Physics, University of Oxford, Oxford 0X1 3RH, UK

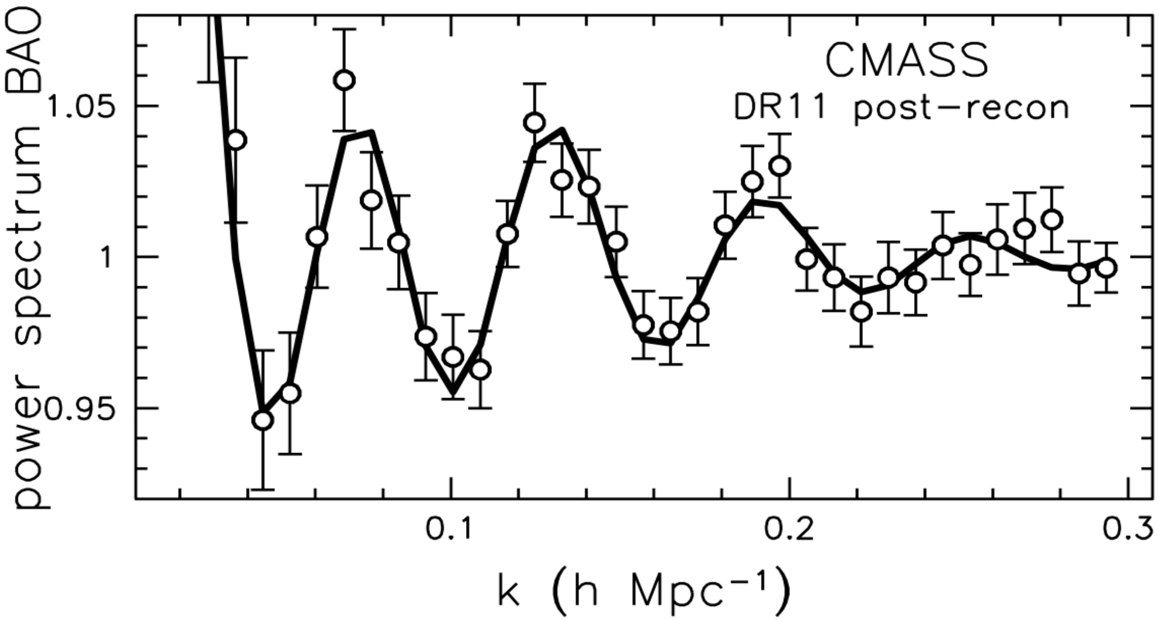
THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales ($l > 10\ h^{-1}$ Mpc, where h is the Hubble constant H_0 in units of 100 km s^{-1} Mpc^{-1}) than simple versions of the CDM theory predict. We argue here that the successes of the CDM theory can be retained and the new observations accommodated in a spatially flat cosmology in which as much as 80% of the critical density is provided by a positive cosmological constant, which is dynamically equivalent to endowing the vacuum with a non-zero energy density. In such a universe, expansion was dominated by CDM until a recent epoch, but is now governed by the cosmological constant. As well as explaining large-scale structure, a cosmological constant can account for the lack of fluctuations in the microwave background and the large number of certain kinds of object found at high redshift.

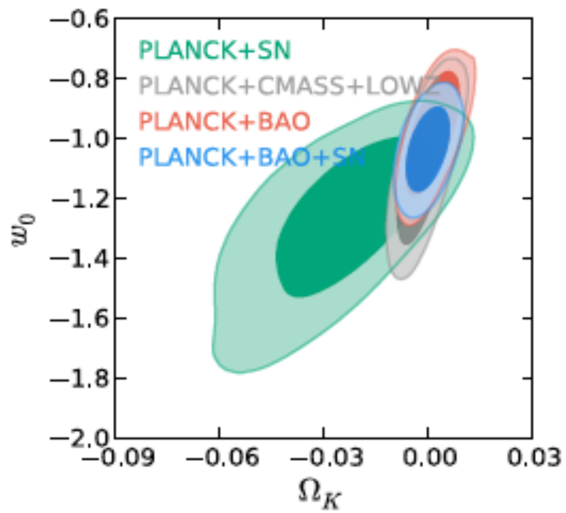
Other pre-SNIa papers : Peebles (1984). Weinberg (1989), OL, Lilje, Primack & Rees. (1991), White et al. (1993), Ostriker et al. (1995),…

Measuring the acceleration of the Universe

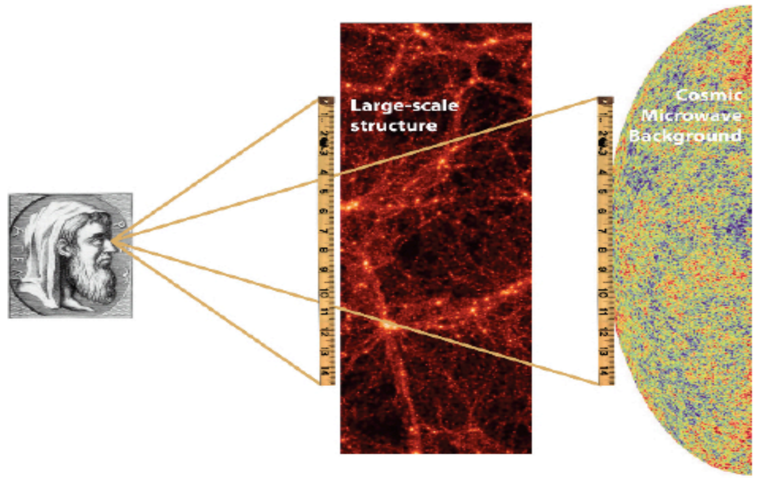


1% distances with Baryonic Acoustic Oscillations



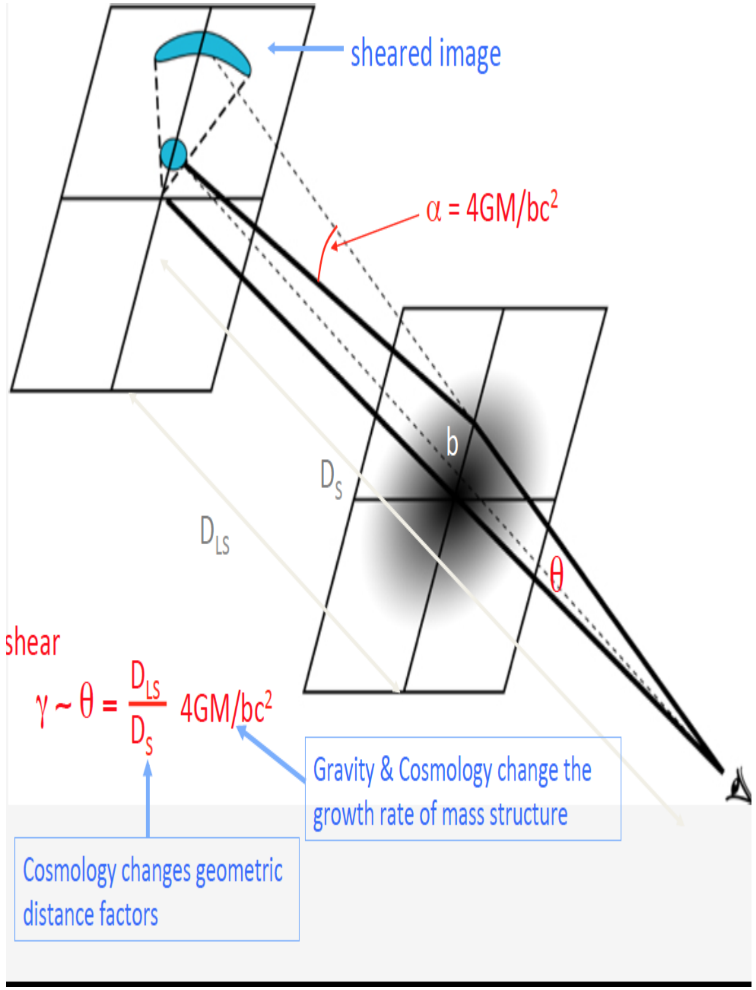


BOSS - Anderson et al (2013)



Gravitational Lensing: Weak and Strong

HST CLASH cluster MACS1206



Paradigm shifts:
a new entity or a new theory?

Phenomenon	New Entity	New theory
Uranus' orbit	Neptune	(Bessel's specific gravity ruled out)
Mercury's orbit	(Hypothetical planet Vulcan ruled out)	General Relativity
Beta decay	Neutrino	(violation of angular momentum ruled out)
Galaxy flat rotation curves	Dark Matter?	Modified Newtonian Dynamics?
Accelerating universe (SN Ia and other data)	Dark Energy?	Modified General Relativity?

OL & Michela Massimi (A&G 2014)
Lucy Calder & OL (Physics World 2010)

Weighing the Local Group in the presence of Dark Energy

$$a = -GM/r^2 + \Lambda/3 \; r$$

- At present the Milky Way and Andromeda galaxies are separated by r=770 kpc and are “falling” towards each other at v=109 km/sec.
- Given the age of the universe t=13.8 Gyr and Dark Energy fraction of 70% we find that the mass is

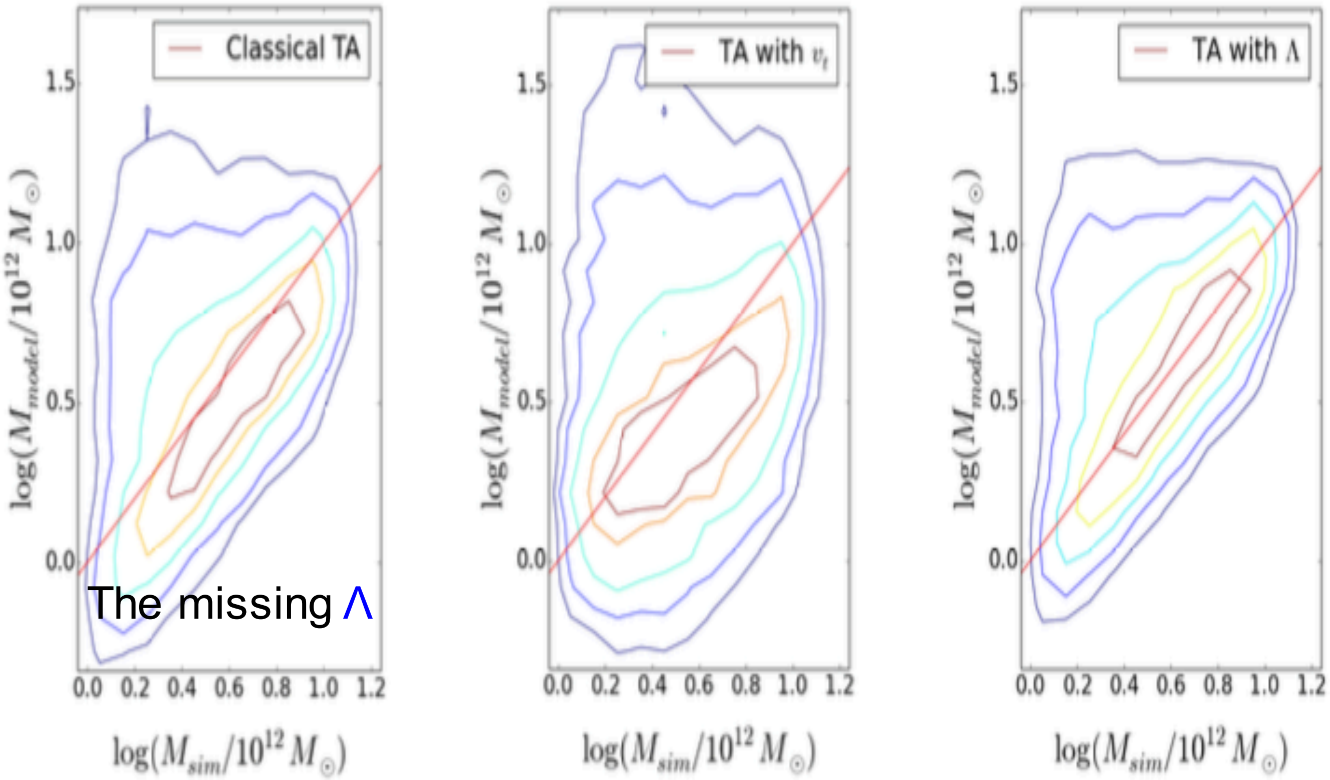
$M = (4.73 \pm 1.03) \times 10^{12} M_{sun}$

- 13% more than in the absence of Dark Energy

Without Λ: Kahn & Waltjer (1959), Lynden-Bell (1981), Raychaudhury & Lynden-Bell (1989)

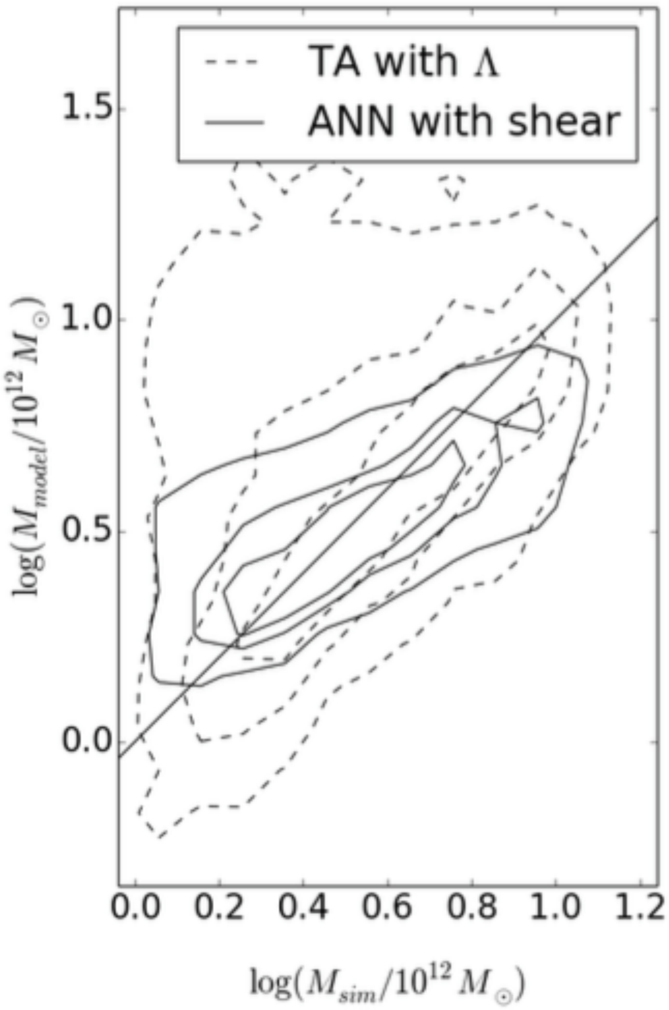
With Λ: Binney & Tremaine (2008), Partridge, OL & Hoffman (2012), McLeod et al. (2017)

30k LG-like pairs in MultiDark simulations



McLeod, Libeskind, Hoffman & OL (arXiv:1606.02694)

LG mass with Machine Learning: adding velocity shear



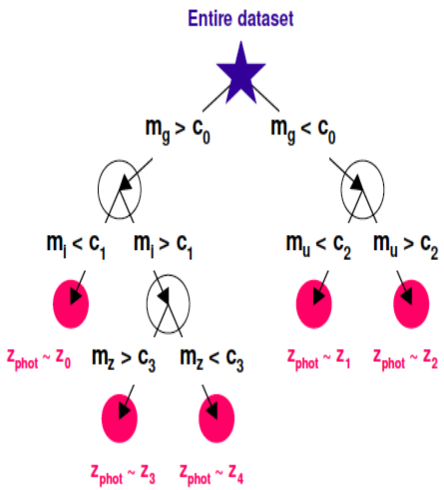
$$\Sigma_{ij} = -\frac{1}{2H_0}\left(\frac{\partial v_i}{\partial r_j} + \frac{\partial v_j}{\partial r_i}\right)$$

	M_{LG} / $10^{12} M_{\odot}$		
Model	(vdM. 2008)	(vdM. 2012)	(Sal. 2015)
TA_{Λ}	$5.8^{+1.0+4.7}_{-0.9-3.0}$	$4.7^{+0.7+3.9}_{-0.6-2.4}$	$3.8^{+1.1+3.1}_{-0.9-2.0}$
ANN	$3.7^{+0.3+1.5}_{-0.3-1.5}$	$3.6^{+0.3+1.4}_{-0.3-1.4}$	$3.3^{+0.6+2.0}_{-0.5-1.5}$
ANN + Shear	$6.1^{+1.1+1.6}_{-1.1-1.8}$	$4.9^{+0.8+1.3}_{-0.8-1.4}$	$3.6^{+1.3+1.7}_{-1.1-1.5}$
Bayesian	$3.4^{+1.9}_{-1.2}$	$3.1^{+1.3}_{-1.0}$	$3.4^{+2.3}_{-1.3}$

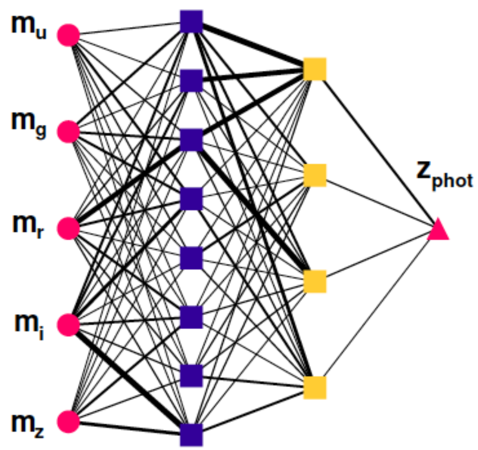
Machine Learning in Cosmology

New STFC-funded UCL's Centre for Doctoral Training in Data Intensive Science
http://www.hep.ucl.ac.uk/cdt-dis/

(over 30 PhD students; first PhD intake Sep 2017)



Decision Trees



Artificial Neural Networks

The Dark Energy Survey

- Multi-probe approach
  Wide field: Galaxy Clustering, Weak Lensing, Cluster Counts
  Time domain: Supernovae

- Survey strategy
  300 million photometric redshifts (grizY)
  over 5000 deg^2
  + 3500 SN Ia (over 27 sq deg fields)
  overlap with VHS + SPT+ OzDES + …

- Science Verification (SV): 250 sq deg to full depth
- Y1: approx 2000 sq deg 40% of depth.
  Median seeing FWHM approx 0.9”
  (as required for WL in riz)
- Y2: approx remaining 3000 sq deg same depth
- Y3: done
- Y4: done

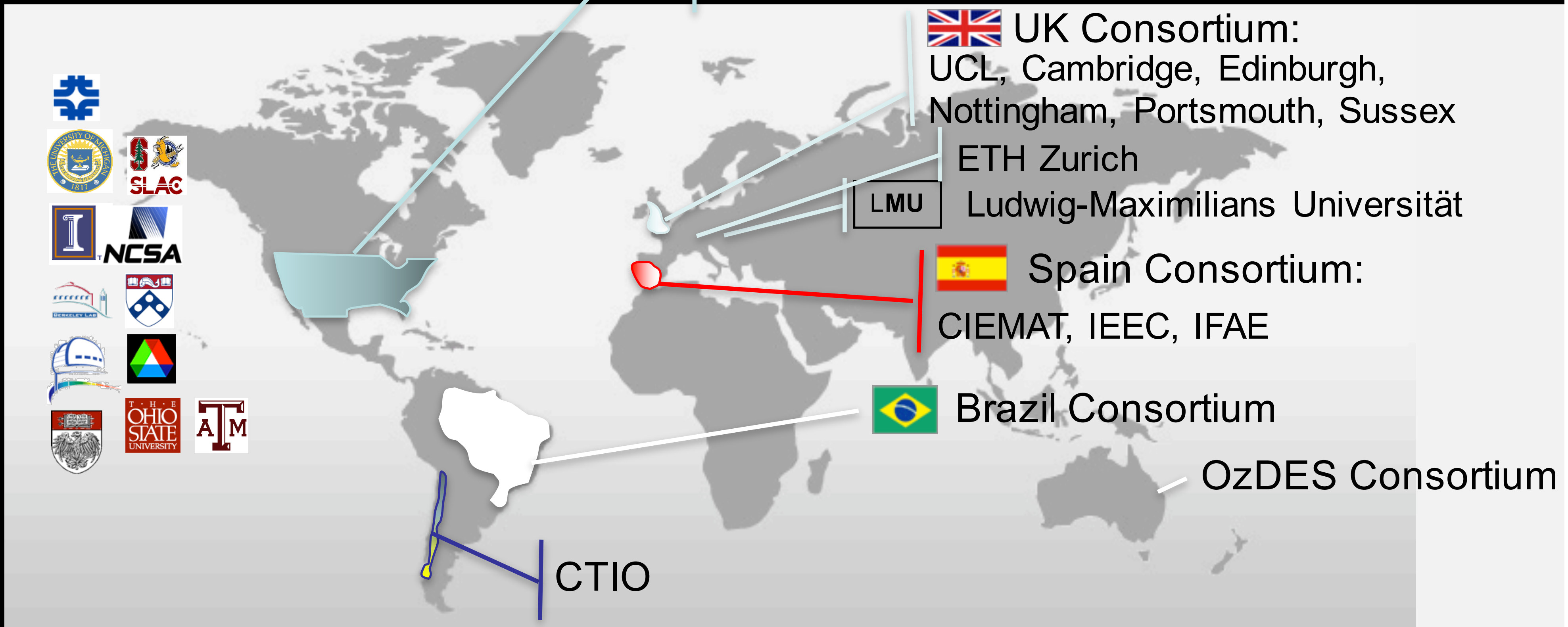
- The DES journey started in 2003
- Nearly about 4/5 of the programme done
- Over 90 DES papers on the arXiv

DARK ENERGY SURVEY

Dark Energy Survey Collaboration

~500 scientists from 7 nations

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

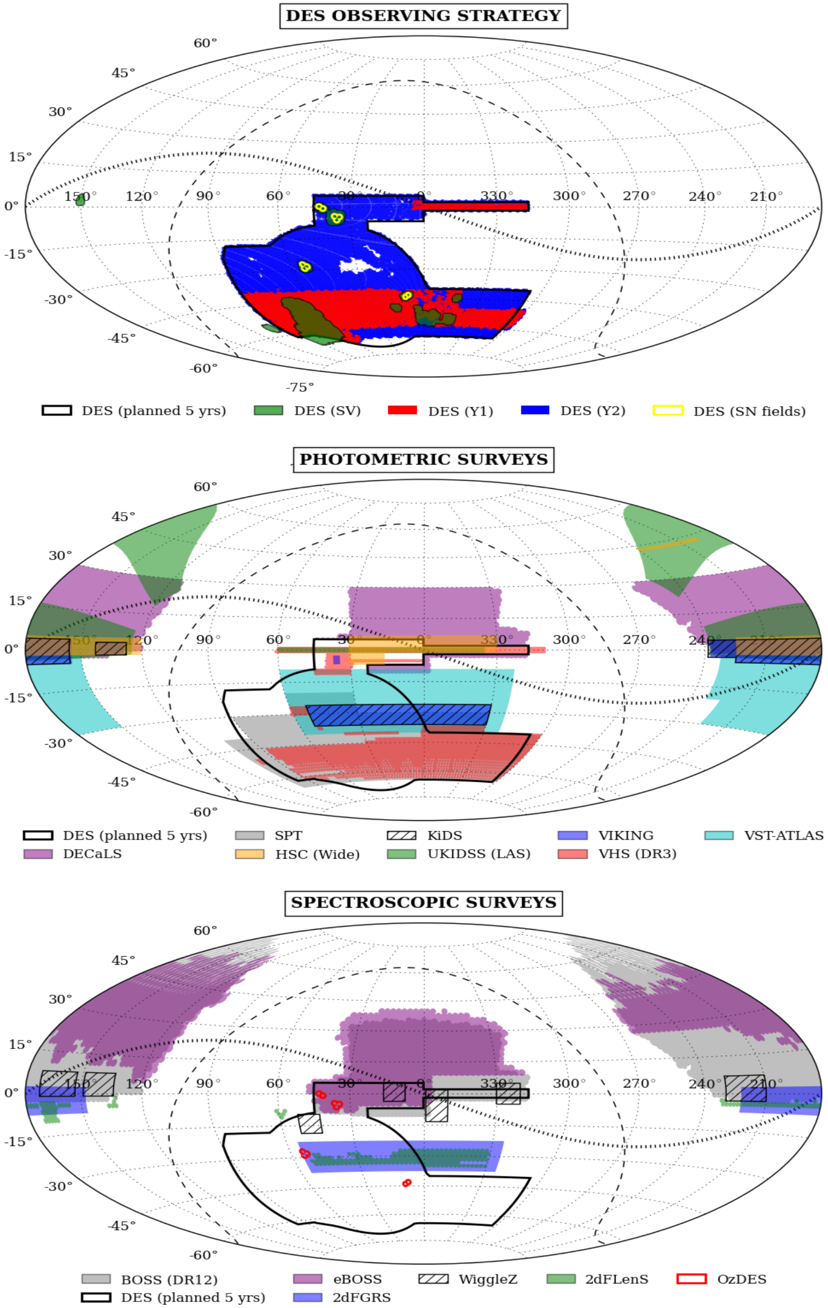


DES@UCL

28 Feb 2017

DES Footprint

Non-DE overview, MNRAS, 460, 1270 (2016)



Overlapping Imaging Surveys

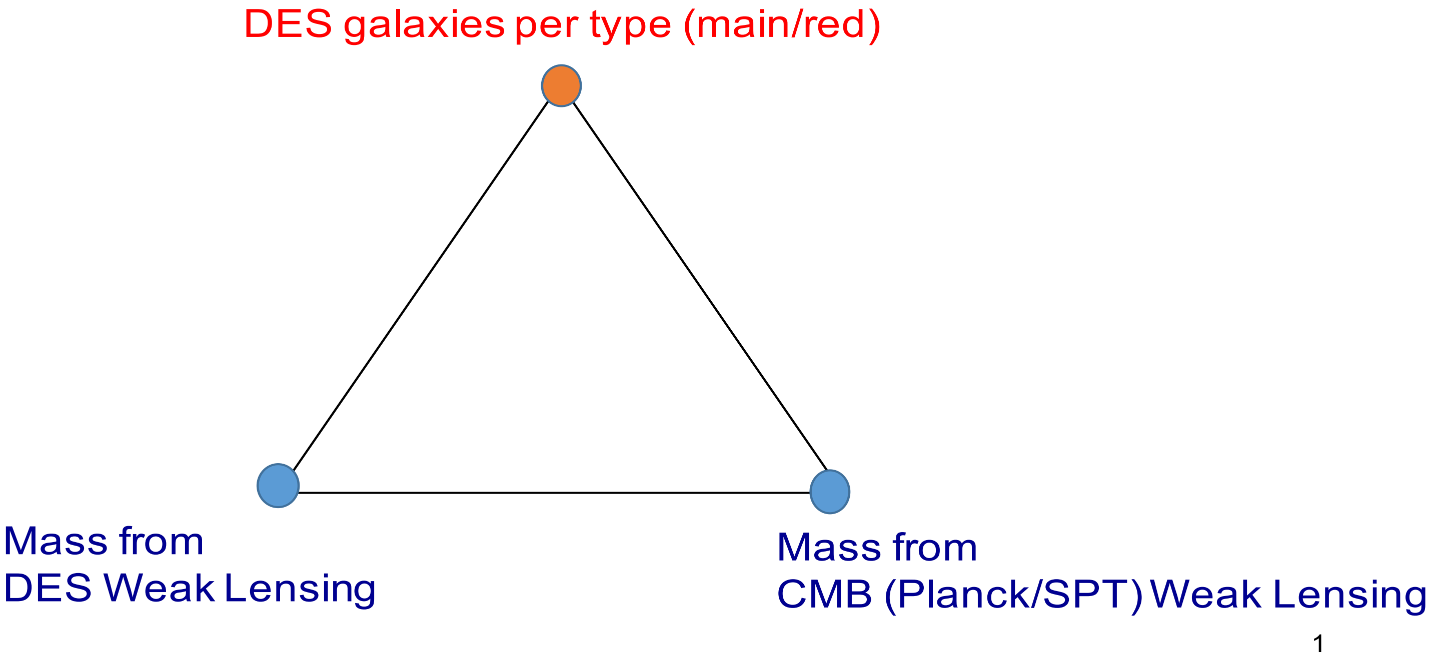
Overlapping Spectroscopic Surveys

Credit: Alex Merson (UCL)

Objects	As of Dec 2015	Expected from full 5yr DES
Galaxies with photo-z (> 10 sigma)	7M (SV), 100M (Y1+Y2),	300M
Galaxies with shapes	3M (SV), 80M (Y1+Y2)	200M
Galaxy clusters (lambda>5)	150K (Y1+Y2)	380K
SN Ia SLSN	1000 2 + confirmed + candidates	Thousands 15-20
New Milky Way companions	17	25
QSO's at z> 6 Lensed QSO's	1 + confirmed + candidates 2 + candidates	375 100 (i<21)
Stars (> 10 sigma)	2M (SV), 30M (Y1+Y2)	100M
Solar System: Trans Neptunian Objects Jupiter Trojans Main Belt asteroids Kuiper Belt Objects	32 in SN fields + 2 in the WF 19 300K (Y1+Y2)	50 + many more in the wide field 500-1000

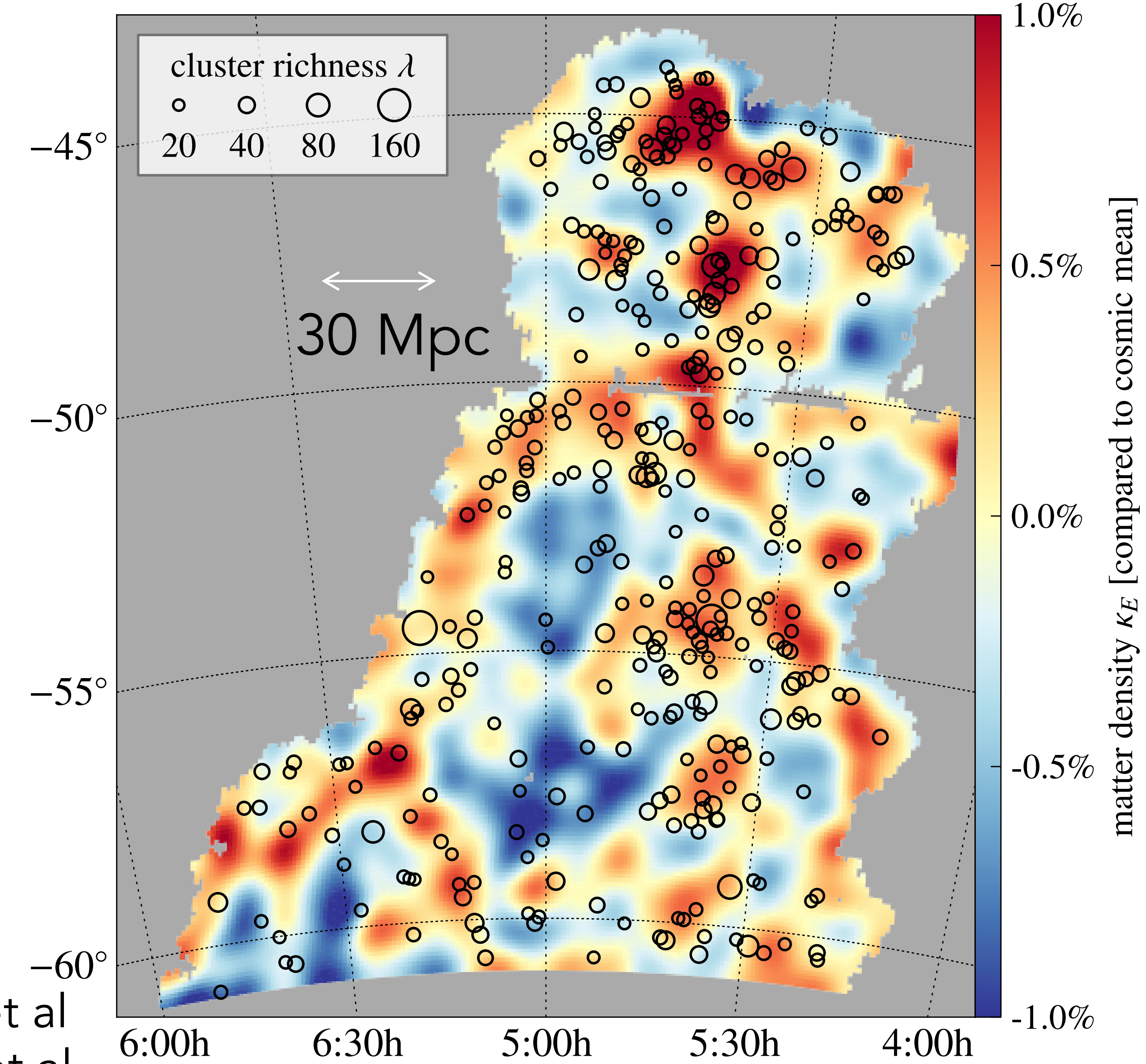
DES Non—DE Overview
arXiv:1601.00329

Mass-Light Correlations



DES Mass Map from Weak Lensing

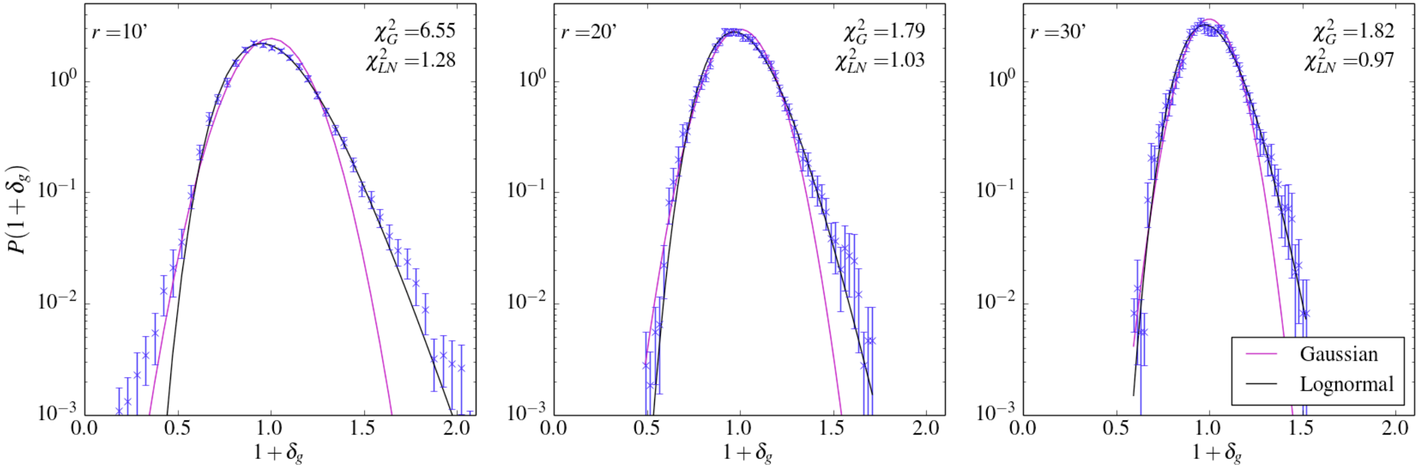
DARK ENERGY SURVEY



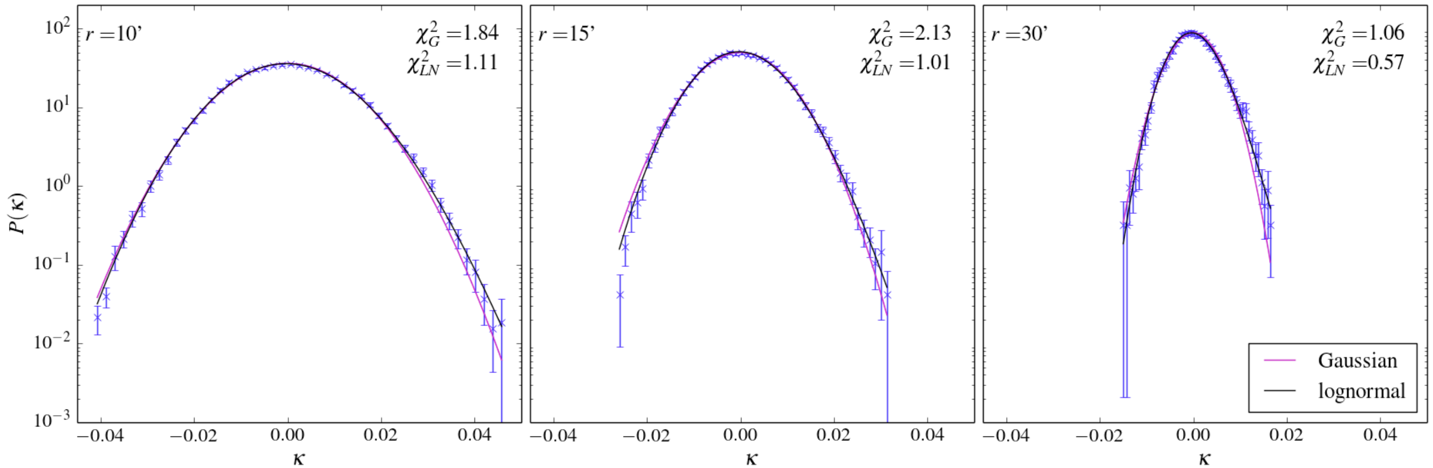
Galaxy clusters

Chang, et al
Vikram, et al

DES galaxy and kappa pdf: Log Normal? Or a better model?



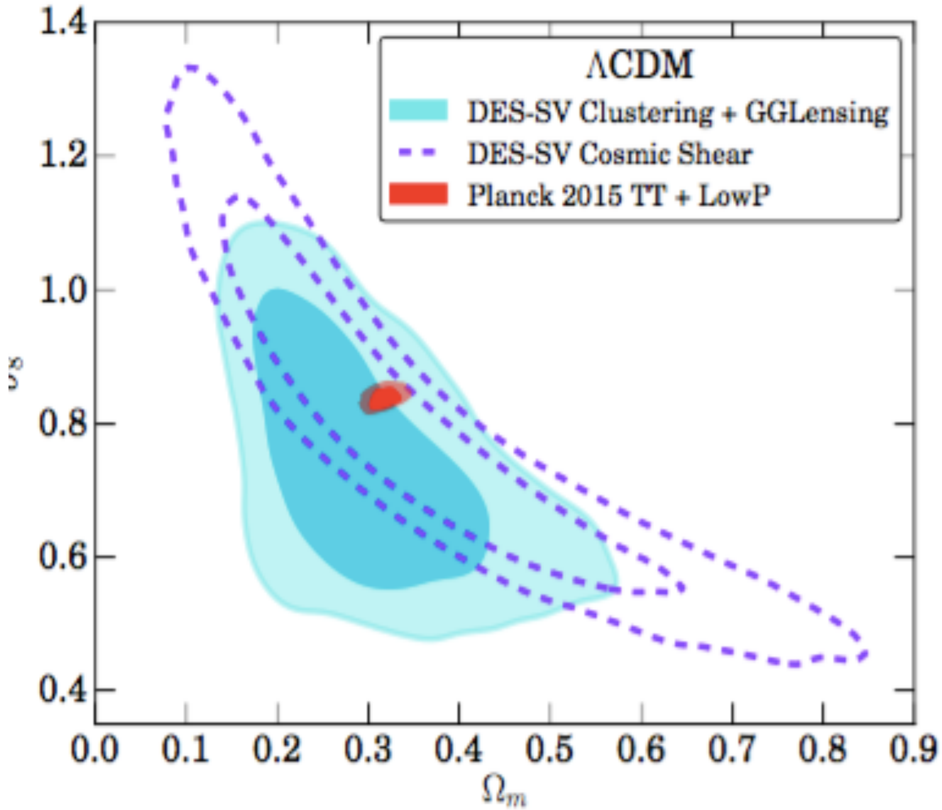
- Lognormal better than Gaussian, all scales

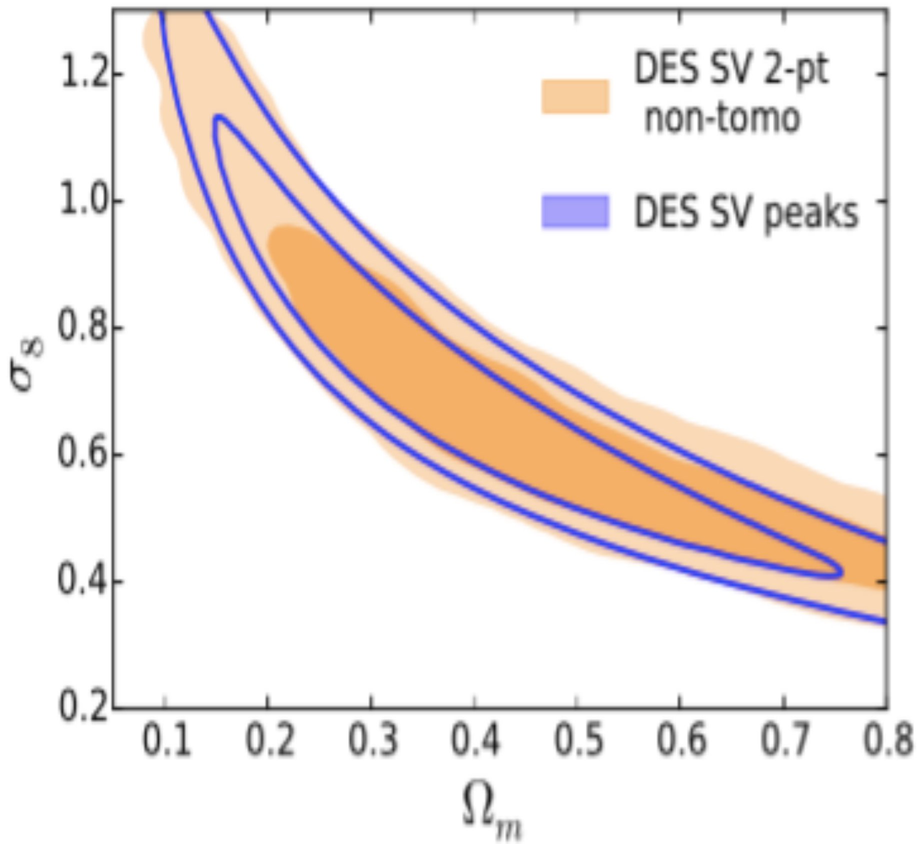


- Lognormal better than Gaussian at scales < 20 arcmin (< 5 Mpc/h)

Clerkin et al. (arXiv:1605.02036)

Testing LCDM with DES Weak Lensing and clustering



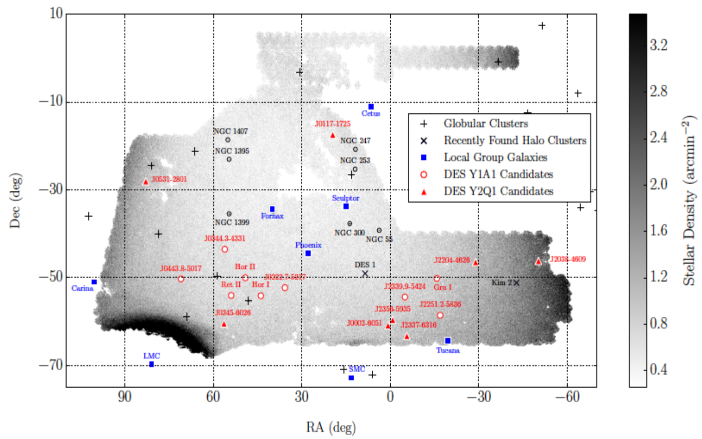


Kwan et al. 1604.07871
(dashed line: DES Collaboration 1507.05552)

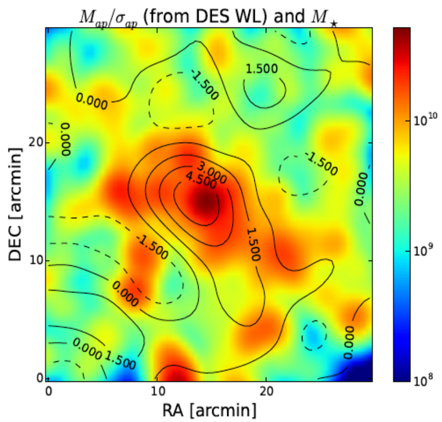
Kacprzak et al. 1603.05040

What have we learned from DES on Dark Matter? (from galactic to Gpc scales)

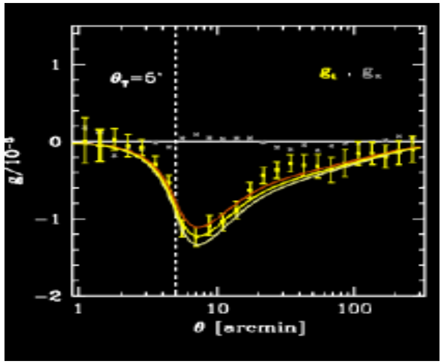
- Mass maps from WL
- The shear correlations as expected in LCDM (with sigma_8 = 0.8)
- Galaxies trace the dark matter fluctuations (esp clusters and voids) from both DES WL and CMB WL
- New 'clustered' 17 MW companions qualitatively fit into the scenario of hierarchical LSS formation
- Dwarfs are DM dominated (e.g. M/L = 470 $(M/L)_{\odot}$ for Ret2)
- But the Nature of the DM still unknown (only upper limits on gamma ray emission)



17 New MW companions from DES (in red) (Drlica-Wagner et al.)

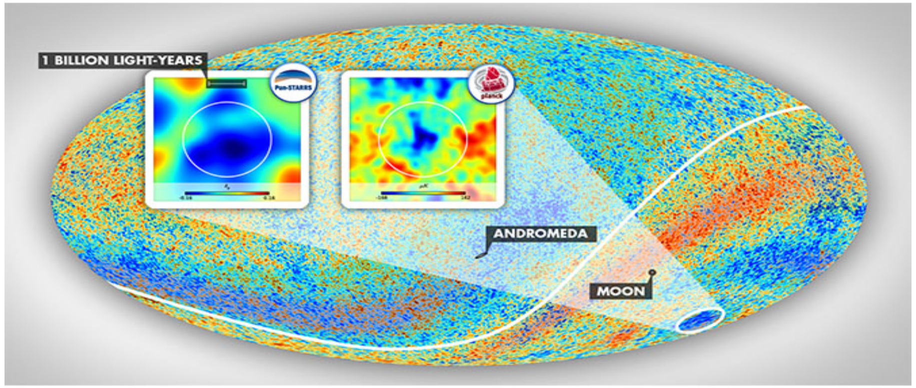


RXJ224: WL DM (contours) vs stellar mass (Melchior et al, Palmese et al)



WL by troughs (voids)in the galaxy distribution (Gruen et al.)

Could a void explain the CMB Cold Spot?

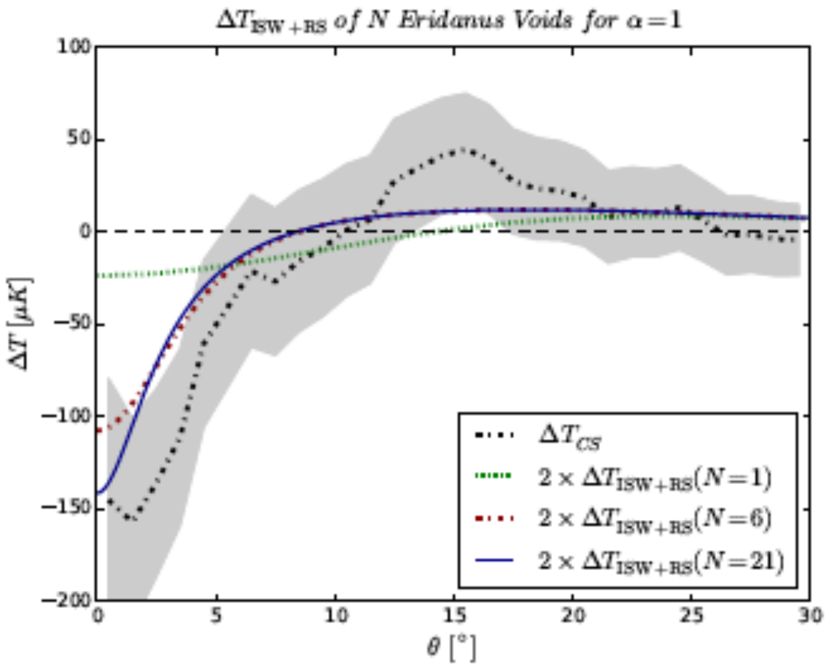


δT = -150 μK,
detected by WMAP & Planck
2-3 sigma if a Gaussian fluctuation

- A super-void with $\boldsymbol{\delta}_m$= -0.4, R = 220 Mpc/h, z = 0.2 found in the direction of the Cold Spot. e.g. Szapudi et al. (2015), Nadathur et al. (2014)
- But ISW & Rees-Sciama can only account for a fraction of it.

But note the effect of CMB masking, reducing the CS significance from 2.2 to 1.9 sigma (Naidoo, Benoit-Levy & OL, 1703.07894)

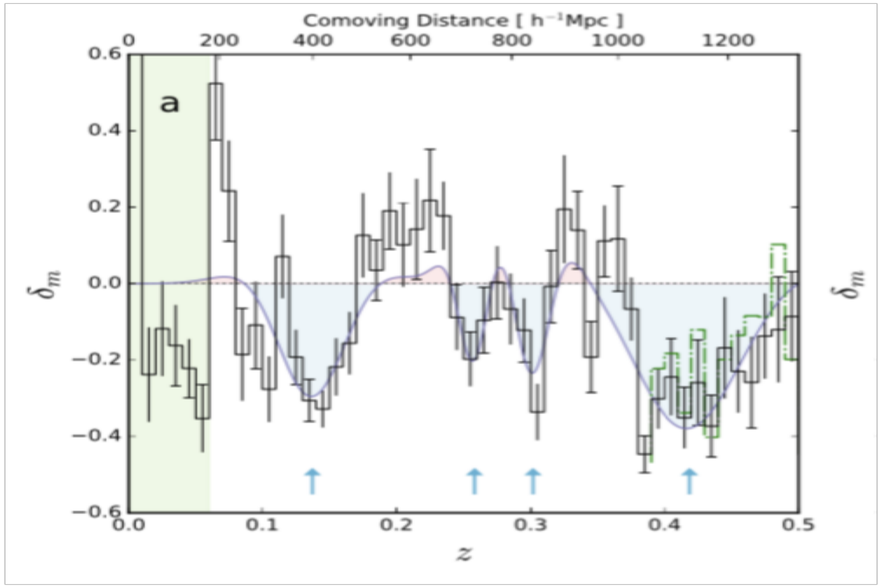
Cold Spot Temperature profiles assuming a multi-void array along the LOS



The tension between the CMB CS and LCDM can be reduced if a multi-void array in the cosmic web is taken into account, but big voids would also be in tension with LCDM

Naidoo, Benoit-Levy, OL (arXiv 1512.02694)

Mapping voids in the CS direction



- 2dF-VST Atlas (2CSz)
- 7000 spectroscopic redshifts at z < 0.4
- Voids found at

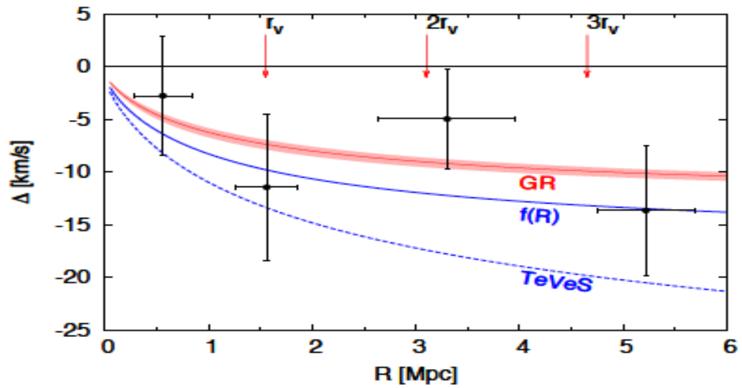
  z=0.14, 0.26 and 0.30

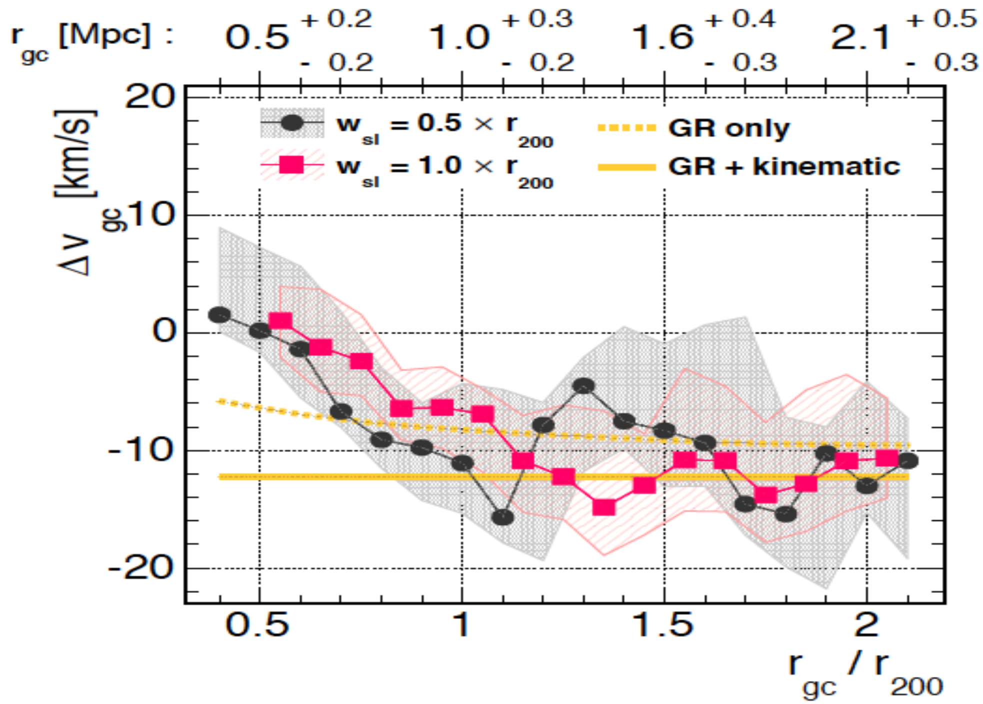
  (and possibly at 0.43)

Mackenzie, Shanks et al. (1704.03814)

These voids are insufficient to explain the CS via ISW in LCDM

Testing GR: Gravitational redshifts in Clusters





► $\Delta v_{gc} = -11^{+7}_{-5}$ km/s (for $1 < r_{gc}/r_{200} < 2.5$)

Wojtak et al. (2011)

Sadeh, Fen & OL (PRL. 2015)

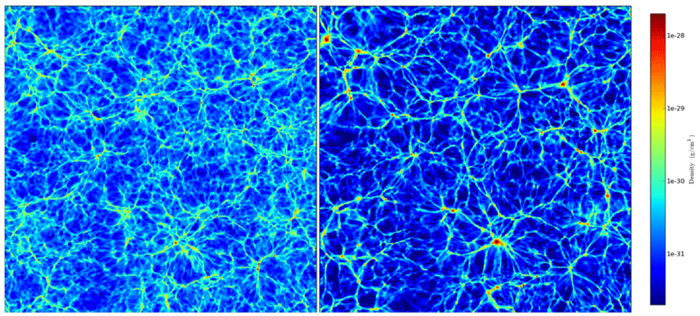
Neutrino mass from surveys

- What is the absolute sum of neutrino mass?

(given the lower limit 0.06 eV from oscillations)
Upper limit on neutrino mass dropped by a factor 10 over past 15 years: from about 2eV to 0.2eV.
Can the mass be MEASURED from surveys?

- What is the hierarchy – Normal or Inverted?
- Is $N_{eff} = 3.046$,

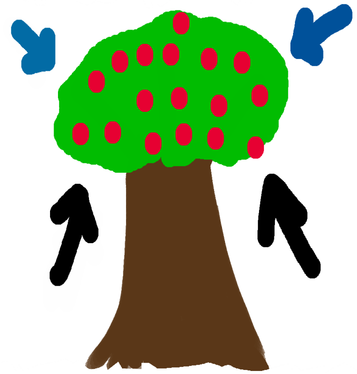
or larger (Sterile neutrino /'dark radiation')?

- Is the neutrino its anti-particle?
- 

Structure is 'washed out' with massive neutrinos

DES: more than Dark Energy

- Solar system objects
- MW, dwarf satellites, LMC
- Galaxy evolution (including biasing and intrinsic alignments)
- Strong lensing
- QSOs (+ lensed QSOs)
- Super-luminous SN
- Gravitational wave follow ups

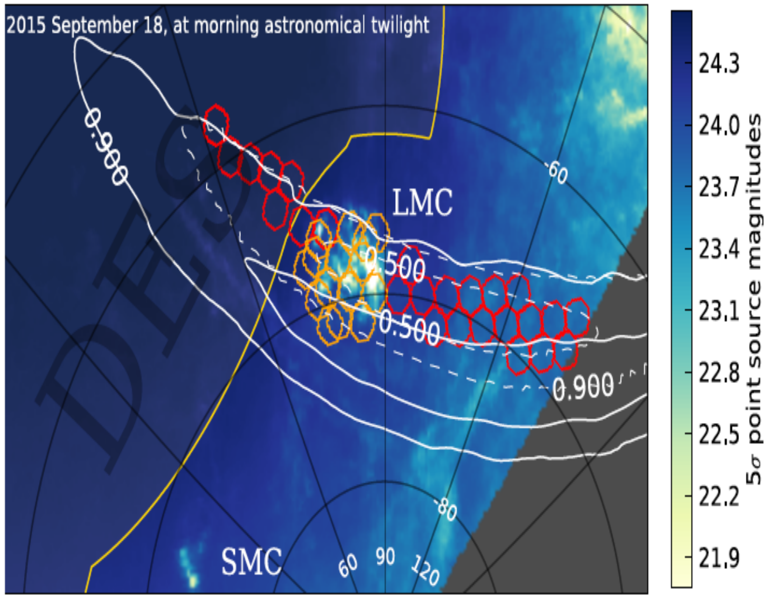


Low and high hanging fruit

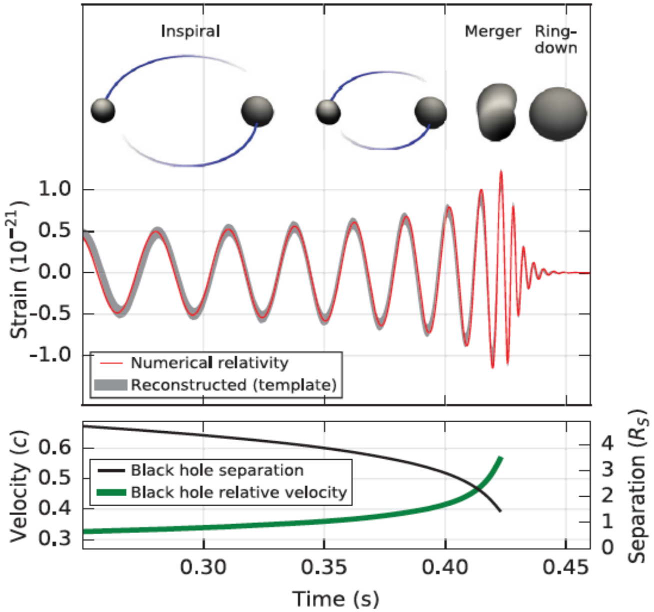
Non-DE Overview (arXiv:1601.000329 V2)

LIGO Gravitational Waves and DES follow ups

GW150914



Soares-Santos et al. (2016)
Annis et al. (2016)
Abbott et al. (2016)

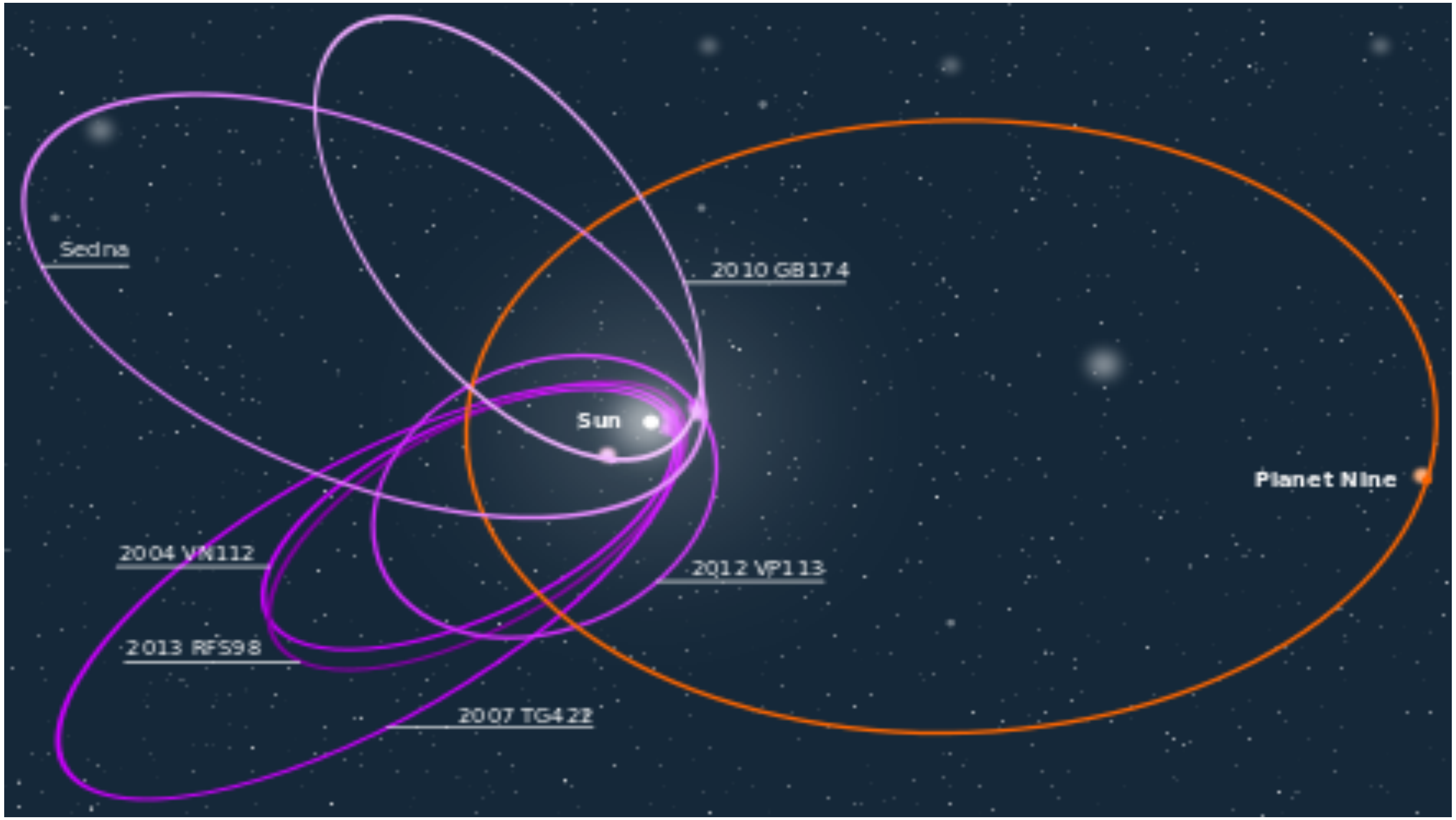


LIGO collaboration 2016

DES LIGO GW follow ups

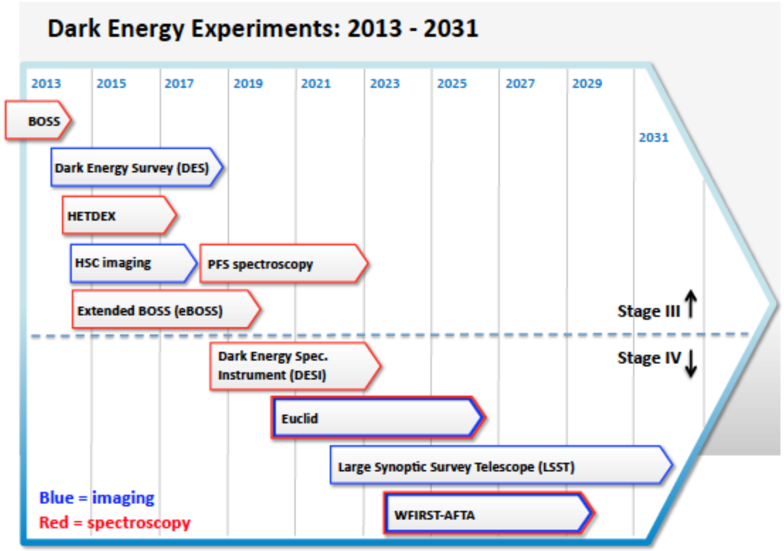
- So far DES followed up 2 out of the 3 GW events, both BH-BH mergers: no detections
- Current theoretical paradigm is that BH-BH mergers have no EM counterparts, but other models are being considered.
- DES search is sensitive to NS-NS and NS-BH out to 200 Mpc.
- The current main limitation is the poor angular localization (until Virgo and other GW experiments come online).

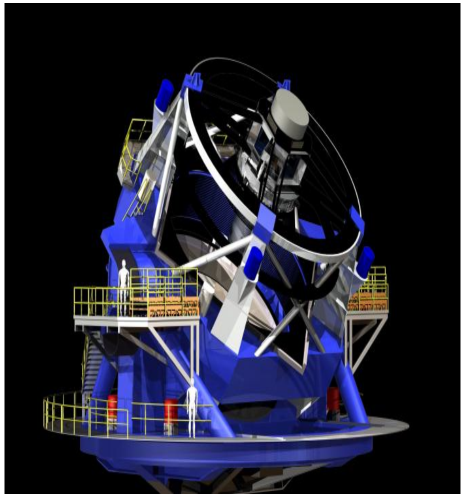
The search for Planet 9
(one of the 6 minor planets discovered by DES)

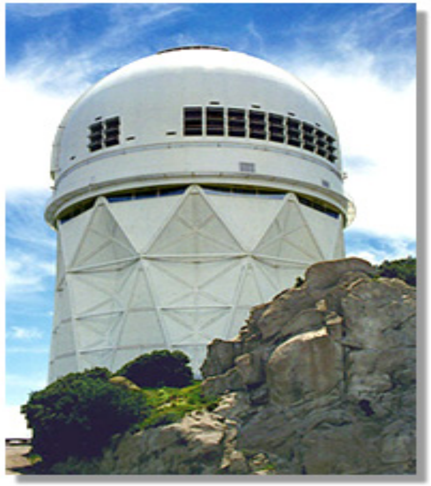


David Gerdes et al, DES TMO WG

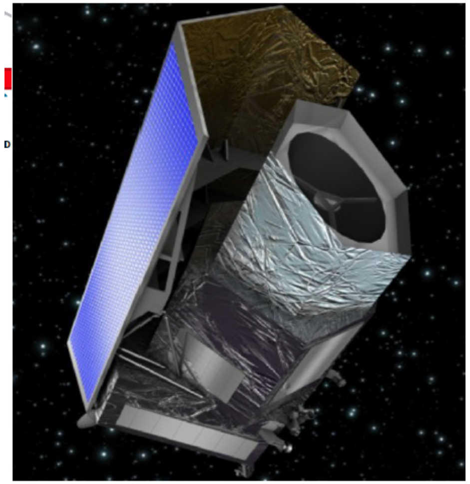
The era of DESI, Euclid, LSST,...





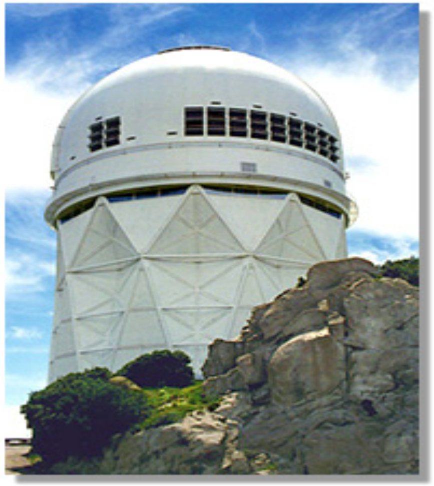


Mayall 4-Meter Telescope

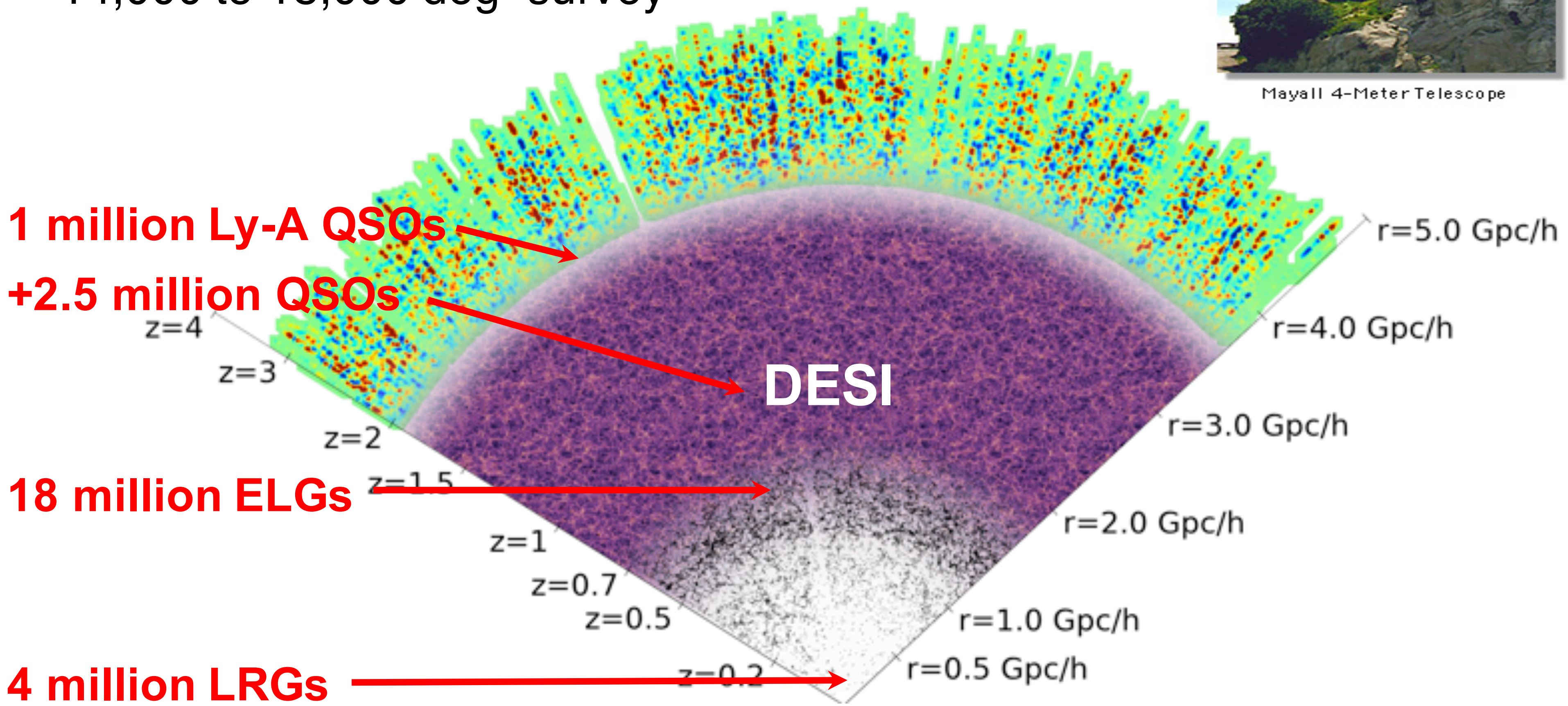


Dark Energy Spectroscopic Instrument (DESI) – 10 times BOSS

Mayall telescope available up to 100% of dark time,
5000 fibres, 20min base integration time
> 20 million targets
14,000 to 18,000 deg^2 survey



Mayall 4-Meter Telescope



Summary

- 25 years of Λ+CDM: supported by most observations, but what is Λ or DE?
- It is important to have new tests of DE (e.g. local dynamics, CMB Cold Spot, gravitational redshift).
- DES does “see” Dark Matter, and good correlations between DM and galaxies.
- DES is on the path to measure DE.
- What are the prospects for a new paradigm shift, beyond Λ+CDM with DESI, LSST, Euclid, WFIRST?