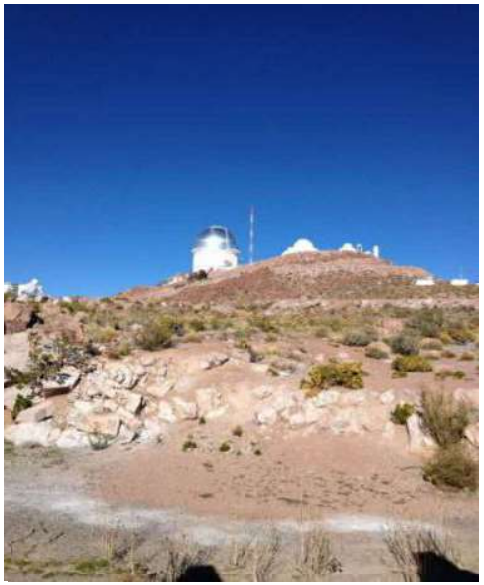
100 Years of the Cosmological Constant: What's Next?

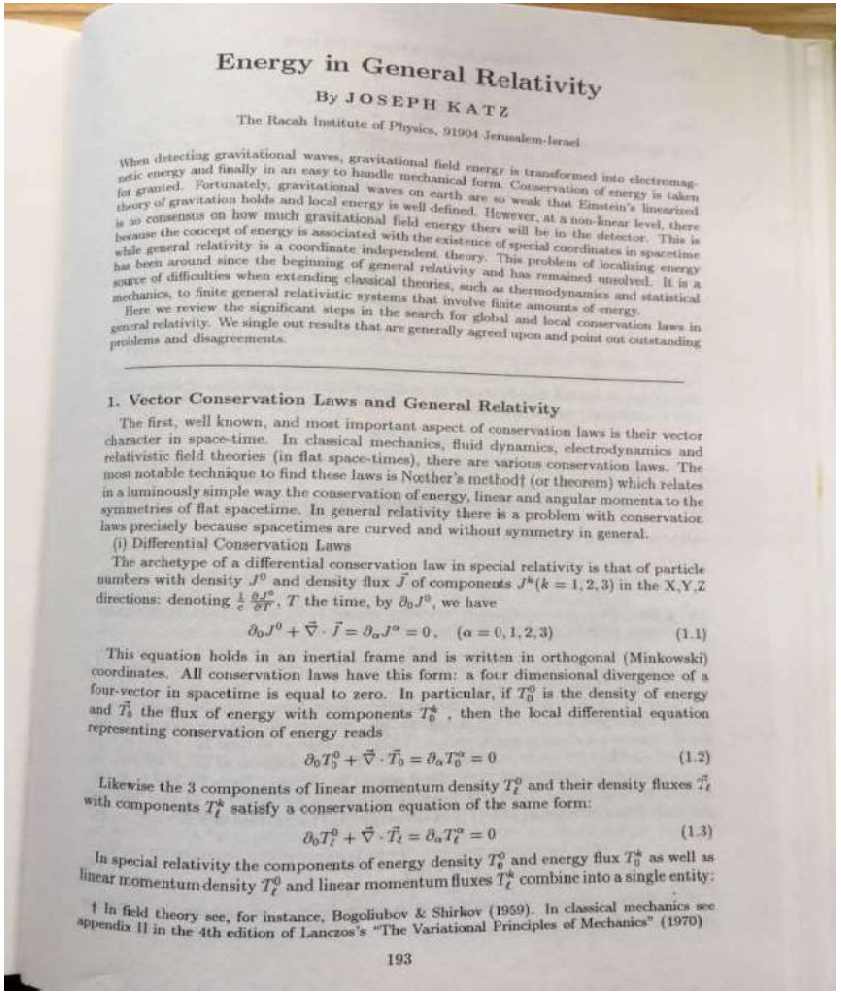
Ofer Lahav (University College London)

DES@Blanco-Chile



HST CLASH

Joseph Katz



Energy in General Relativity

By JOSEPH KATZ

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When detecting gravitational waves, gravitational field energy is transformed into electromagnetic energy and finally in an easy to handle mechanical form. Conservation of energy is taken for granted. Fortunately, gravitational waves on earth are so weak that Einstein's linearized theory of gravitation holds and local energy is well defined. However, at a non-linear level, there is no consensus on how much gravitational field energy there will be in the detector. This is because the concept of energy is associated with the existence of special coordinates in spacetime while general relativity is a coordinate independent theory. This problem of localizing energy has been around since the beginning of general relativity and has remained unsolved. It is a source of difficulties when extending classical theories, such as thermodynamics and statistical mechanics, to finite general relativistic systems that involve finite amounts of energy.

Here we review the significant steps in the search for global and local conservation laws in general relativity. We single out results that are generally agreed upon and point out outstanding problems and disagreements.

1. Vector Conservation Laws and General Relativity

The first, well known, and most important aspect of conservation laws is their vector character in space-time. In classical mechanics, fluid dynamics, electrodynamics and relativistic field theories (in flat space-times), there are various conservation laws. The most notable technique to find these laws is Noether's method† (or theorem) which relates in a luminously simple way the conservation of energy, linear and angular momenta to the symmetries of flat spacetime. In general relativity there is a problem with conservation laws precisely because spacetimes are curved and without symmetry in general.

(i) Differential Conservation Laws

The archetype of a differential conservation law in special relativity is that of particle numbers with density J^0 and density flux $\vec{J}$ of components $J^k (k = 1, 2, 3)$ in the X,Y,Z directions: denoting $\frac{1}{c}\frac{\partial x^0}{\partial T}$, T the time, by $\partial_0 J^0$, we have

$$\partial_0 J^0 + \vec{\nabla} \cdot \vec{J} = \partial_\alpha J^\alpha = 0, \quad (\alpha = 0, 1, 2, 3) \tag{1.1}$$

This equation holds in an inertial frame and is written in orthogonal (Minkowski) coordinates. All conservation laws have this form: a four dimensional divergence of a four-vector in spacetime is equal to zero. In particular, if T_0^0 is the density of energy and $\vec{T}_k$ the flux of energy with components T_0^k, then the local differential equation representing conservation of energy reads

$$\partial_0 T_0^0 + \vec{\nabla} \cdot \vec{T}_0 = \partial_\alpha T_0^\alpha = 0 \tag{1.2}$$

Likewise the 3 components of linear momentum density T_ℓ^0 and their density fluxes $\vec{T}_\ell$ with components T_ℓ^k satisfy a conservation equation of the same form:

$$\partial_0 T_\ell^0 + \vec{\nabla} \cdot \vec{T}_\ell = \partial_\alpha T_\ell^\alpha = 0 \tag{1.3}$$

In special relativity the components of energy density T_0^0 and energy flux T_0^k as well as linear momentum density T_ℓ^0 and linear momentum fluxes T_ℓ^k combine into a single entity:

† In field theory see, for instance, Bogoliubov & Shirkov (1959). In classical mechanics see appendix II in the 4th edition of Lanczos's "The Variational Principles of Mechanics" (1970)

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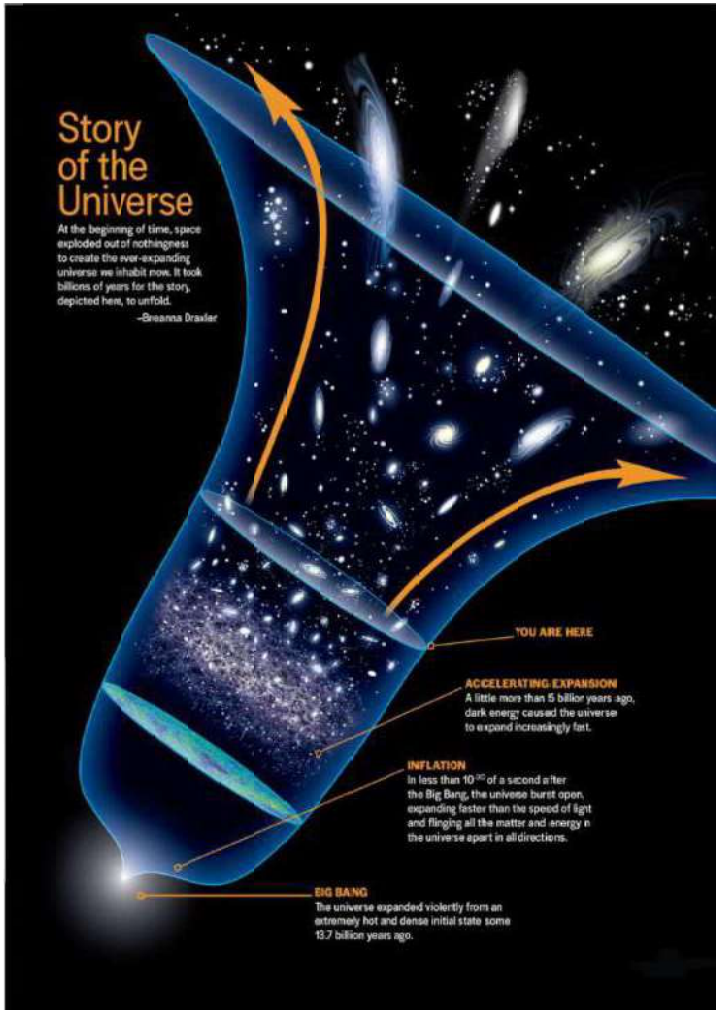
J. Katz, in the DLB@60 book (1995)

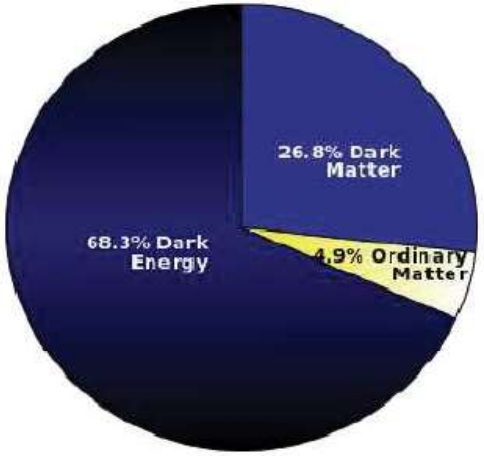
Ruth Yardeni-Katz (1986)

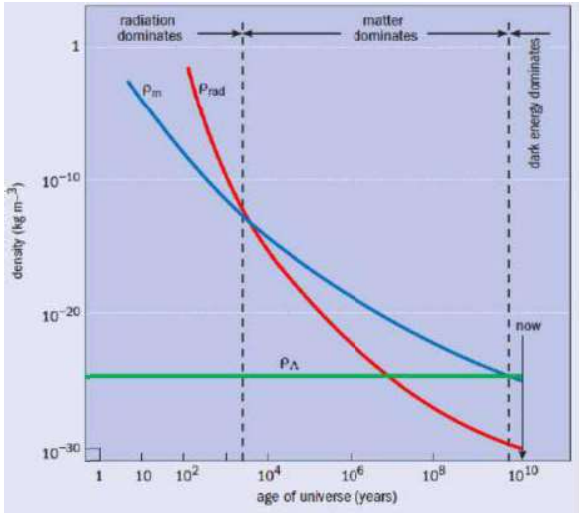
Outline

- 100 years of Λ
- Λ on Mpc scales
- The Dark Energy Survey
- More than Dark Energy:
- Gravitational Wave follow-ups
- The era of Big Data

What accelerates the Universe?







"a simple but strange universe"

100 years of Lambda


142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

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

Modified Newtonian

$$\nabla^2\phi - \lambda\phi = 4\pi\kappa\rho$$

Modified GR

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa\left(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T\right)$$

In a static universe:

$$\lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2}.$$

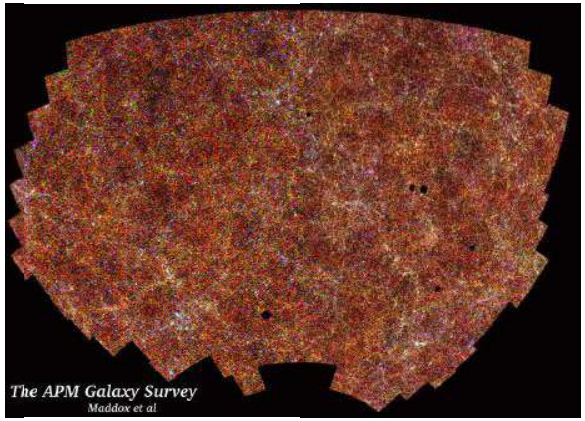
Einstein (February 1917)
See review O'Raifeartaigh et al. (1701.07261)

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

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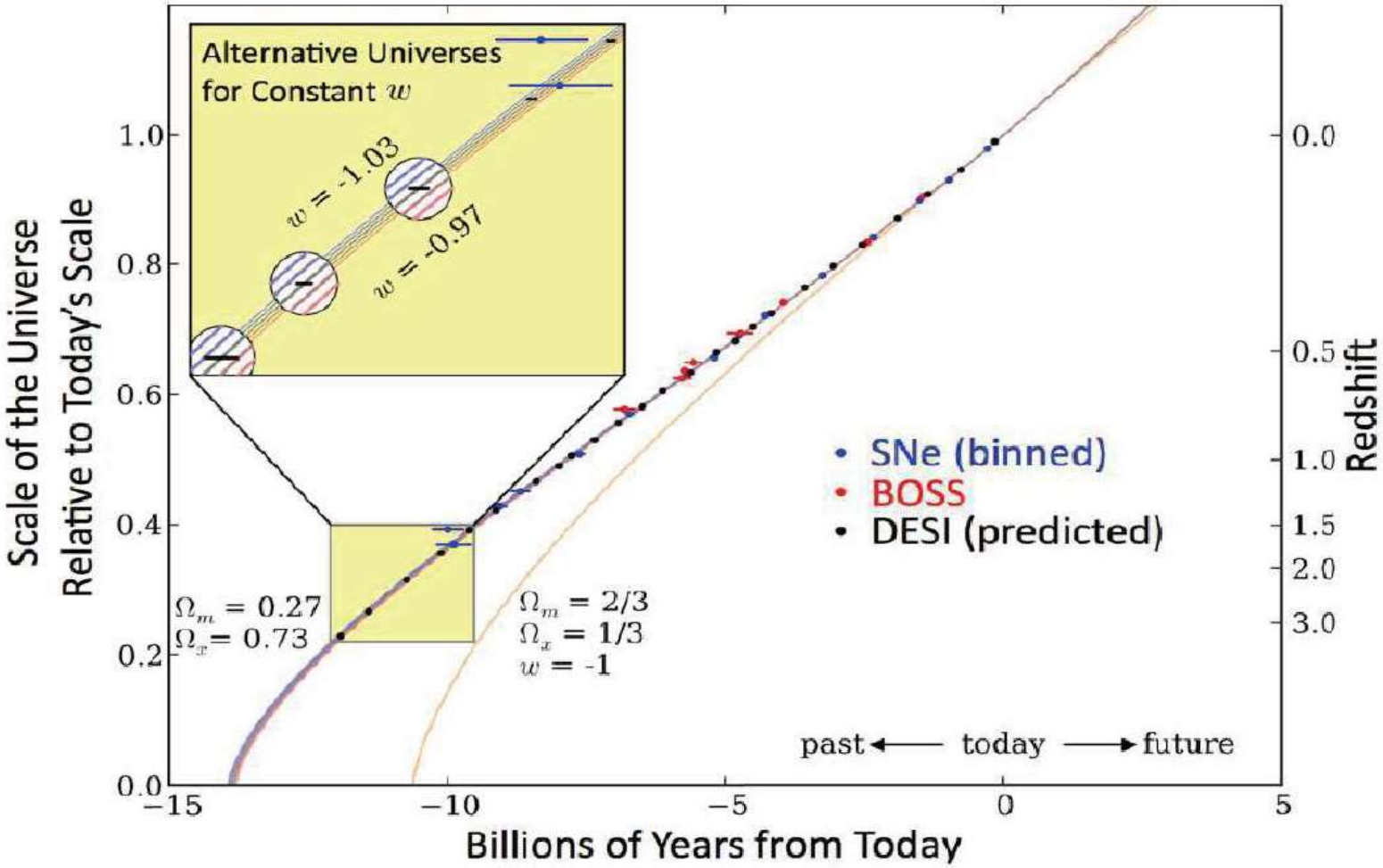
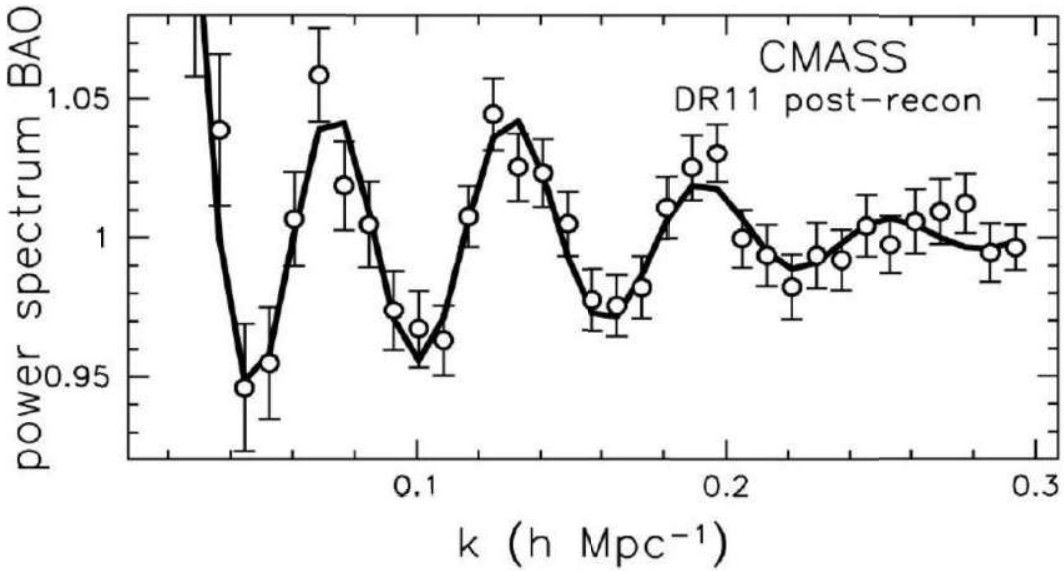
THE cold dark matter (CDM) model[1–4] for the formation and distribution of galaxies in a universe with exactly the critical density is theoretically appealing and has proved to be durable, but recent work[5–8] suggests that there is more cosmological structure on very large scales ($l > 10\ h^{-1}$ 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.

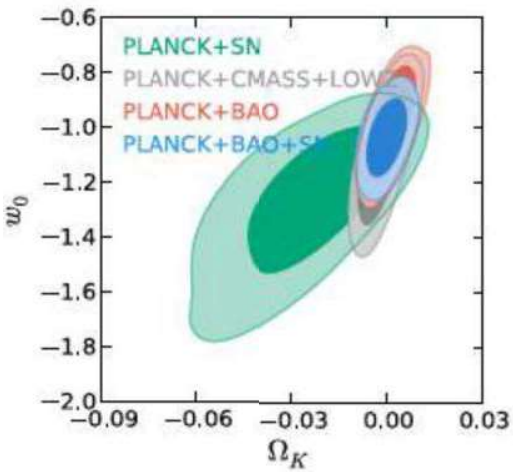
Other pre-SNIa papers : Peebles (1984). Weinberg (1989), OL, Lilje, Primack & Rees. (1991), White et al. (1993), Ostriker et al. (1995),…

Measuring the acceleration of the Universe

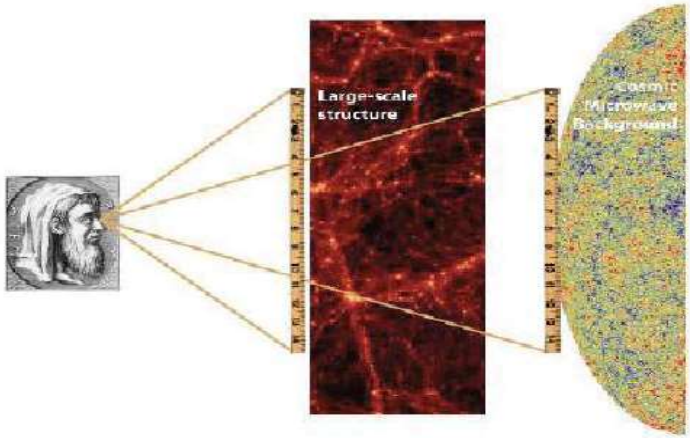


1% distances with Baryonic Acoustic Oscillations

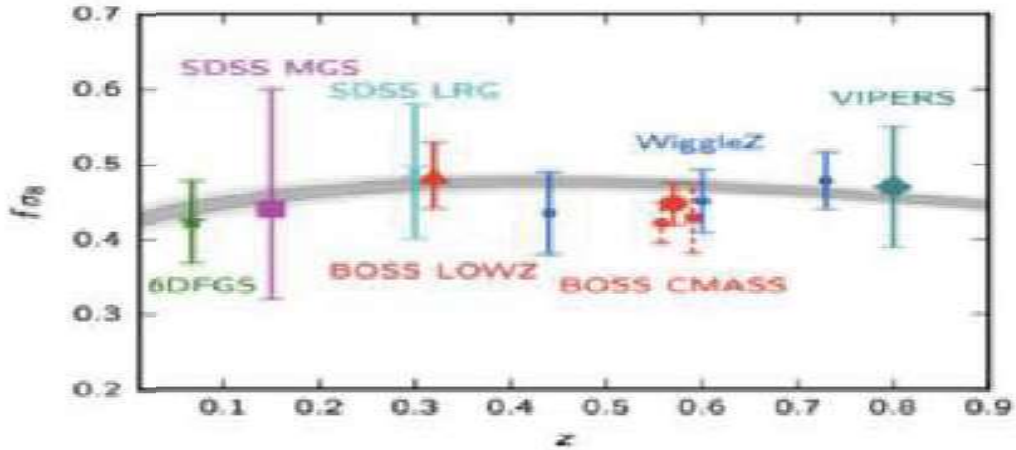




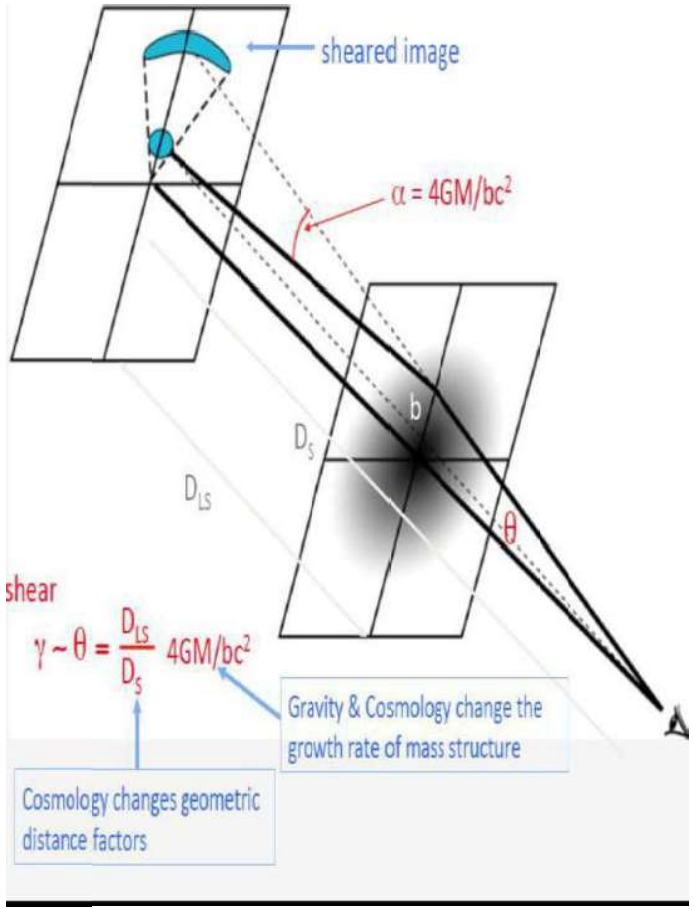
BOSS - Anderson et al (2013)



Growth of structure
galaxy surveys vs. Planck



Gravitational Lensing: Weak and Strong



HST CLASH cluster MACS1206

So what is Dark Energy?

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

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

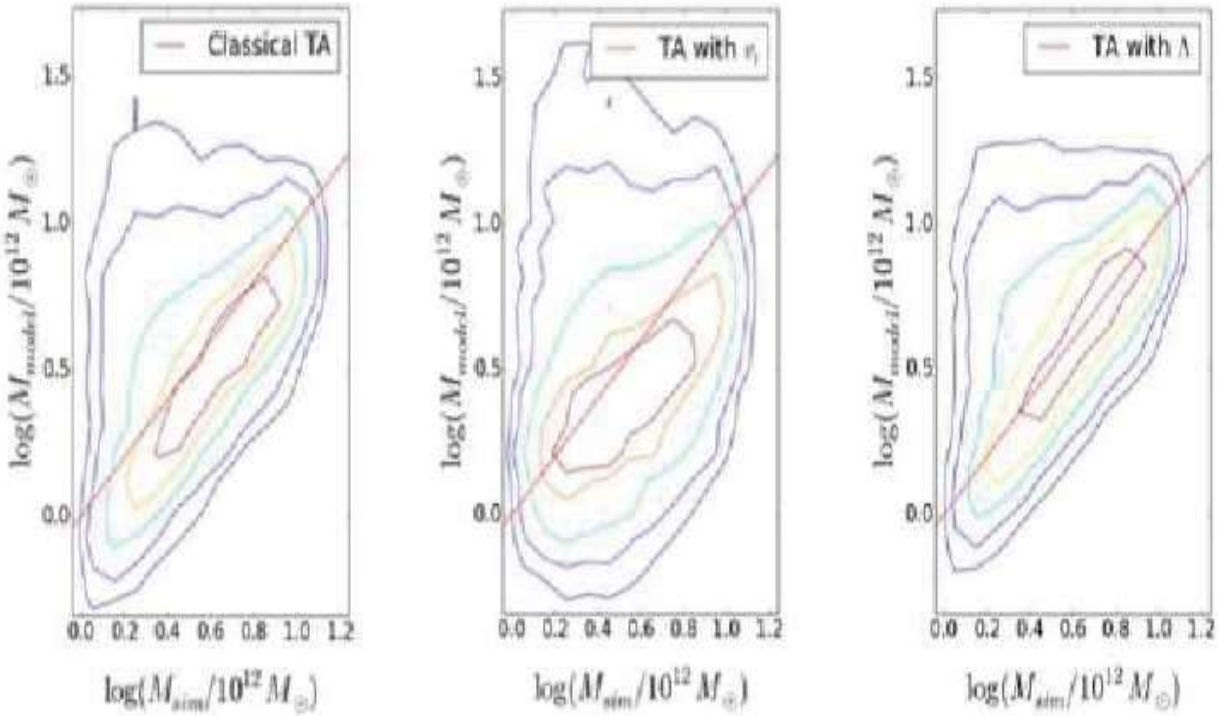
$$M = (4.73 +- 1.03) \times 10^{12}\ M_{sun}$$

- 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

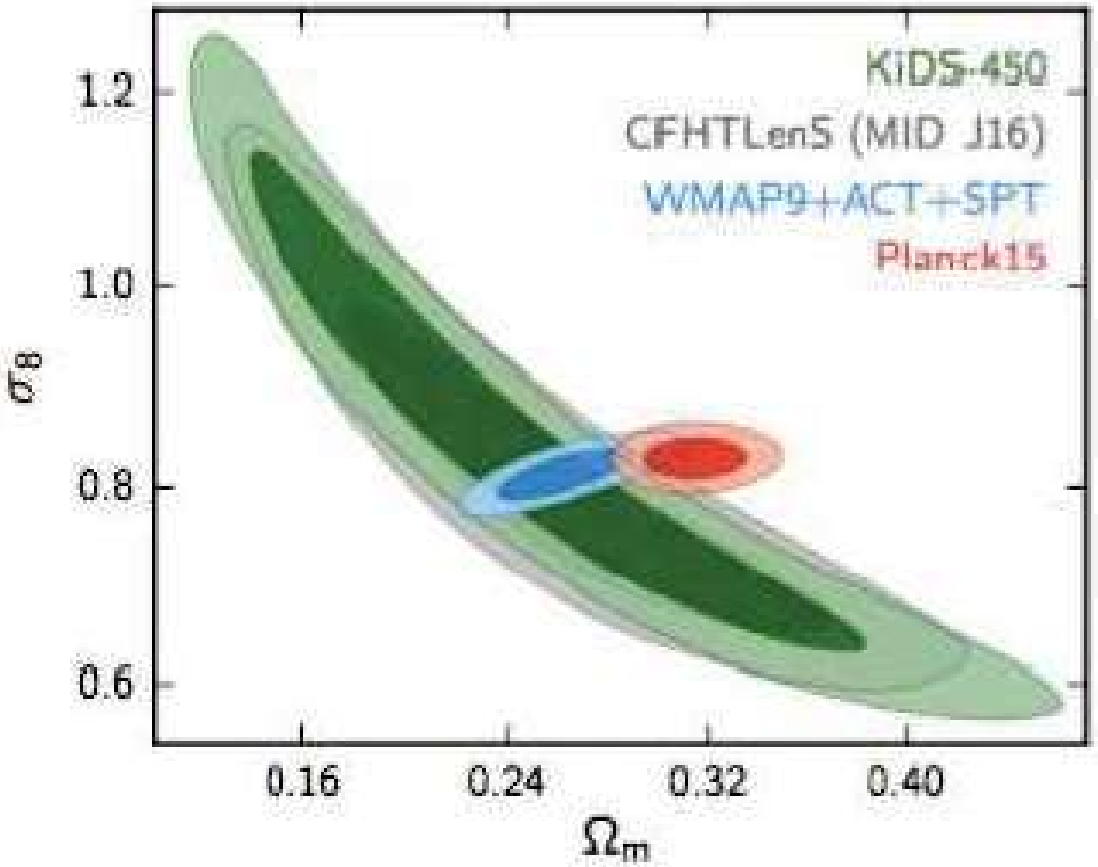


McLeod, Libeskind, Hoffman & OL (arXiv:1606.02694)

Tension in LCDM?

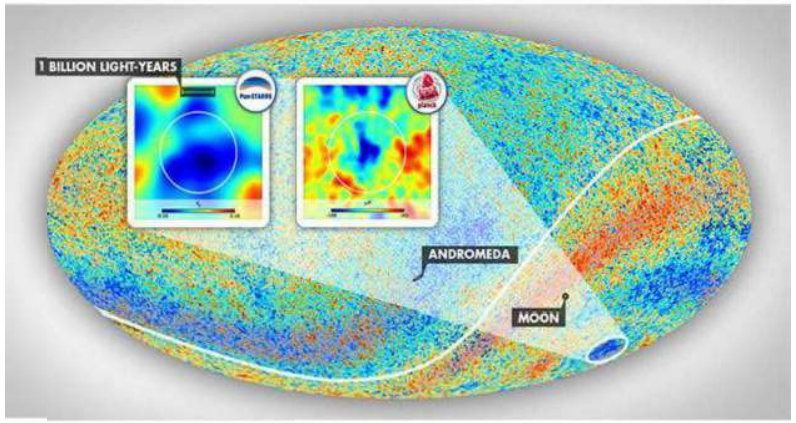
- h = 0.67 (Planck) or 0.73 (SN) ?
- The amplitude Sigma8 in Planck vs WL
- Anomalies: the CMB Cold spot
- Tests of GR on large scales => Modified Gravity?

KidS 450 sq deg: tension with Planck 2015?

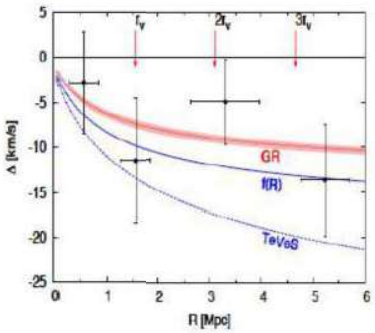


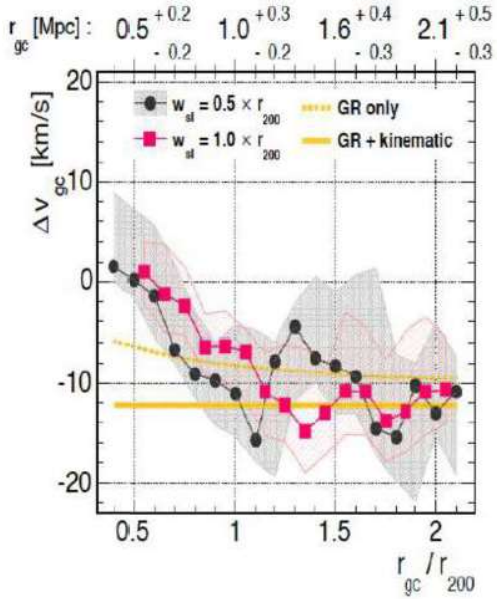
Hildebrandt et al. (2016)

Testing GR:
Gravitational redshifts in Clusters
ISW&RS effects in the CMB



The CMB Cold Spot & supervoid





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

Szapudi et al. (2015)
Nadathur et al. (2014)
Naidoo, Benoit-Levy & OL (2015, 2017)

Wojtak et al. (2011)
Sadeh, Lerh & OL (2015)

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 + …

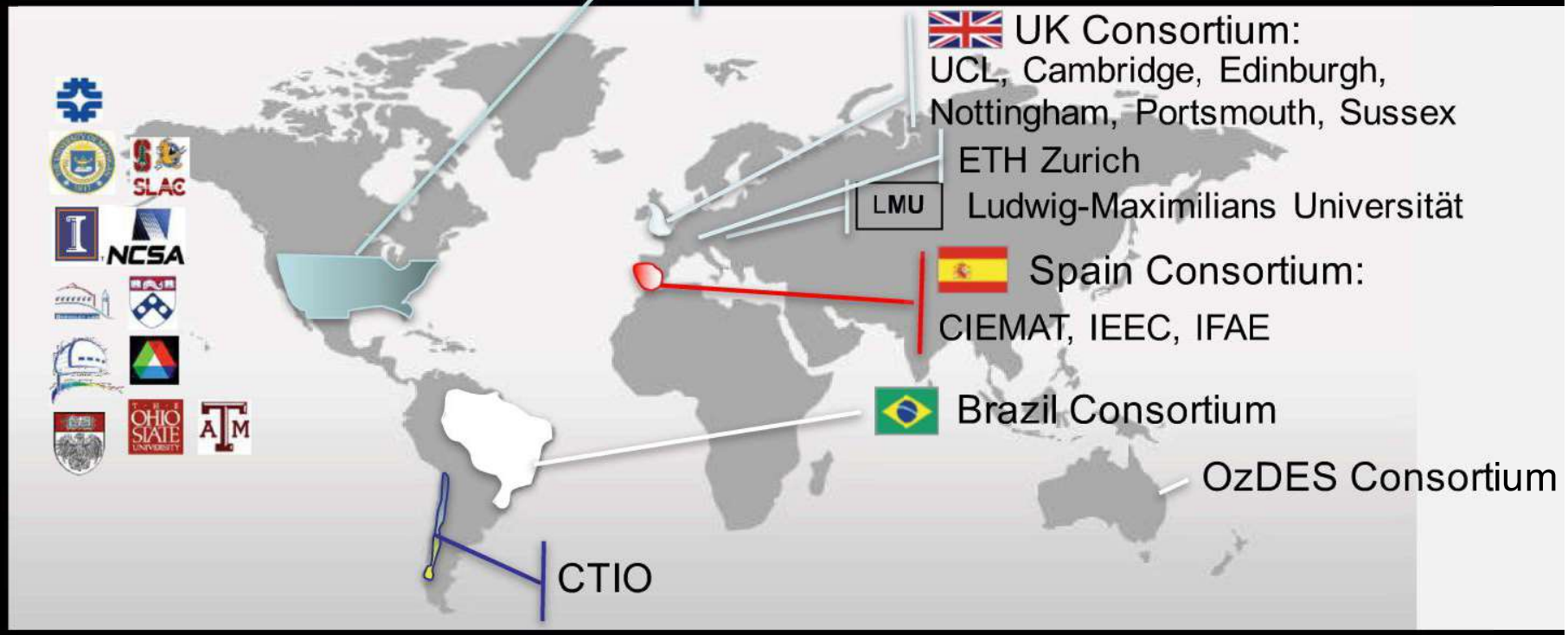
- Science Verification (SV): 250 sq deg to full depth
- Y1: approx 2000 sq deg 40% of depth.
  Median seeing FWHM approx 0.9”
  (as required for WL in riz)
- Y2: approx remaining 3000 sq deg same depth
- Y3: done
- Y4: done

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

Dark Energy Survey Collaboration

~400 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

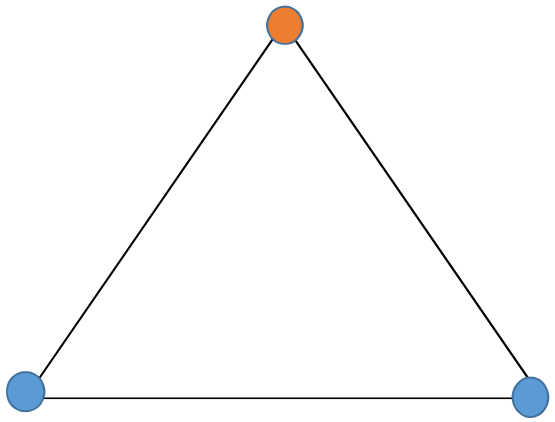


DES@UCL

28 Feb 2017

Mass-Light Correlations

DES galaxies per type (main/red)

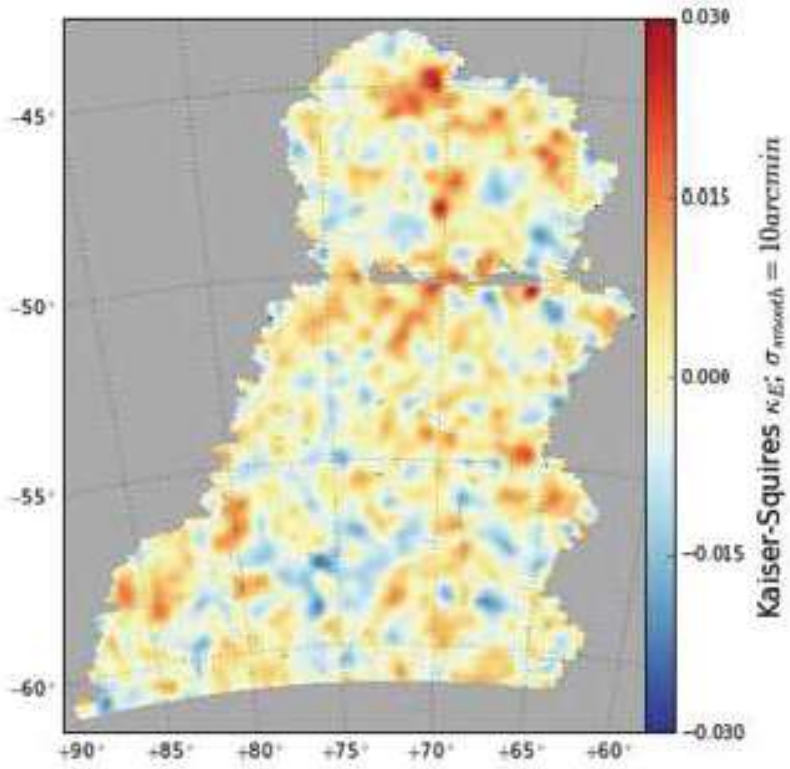


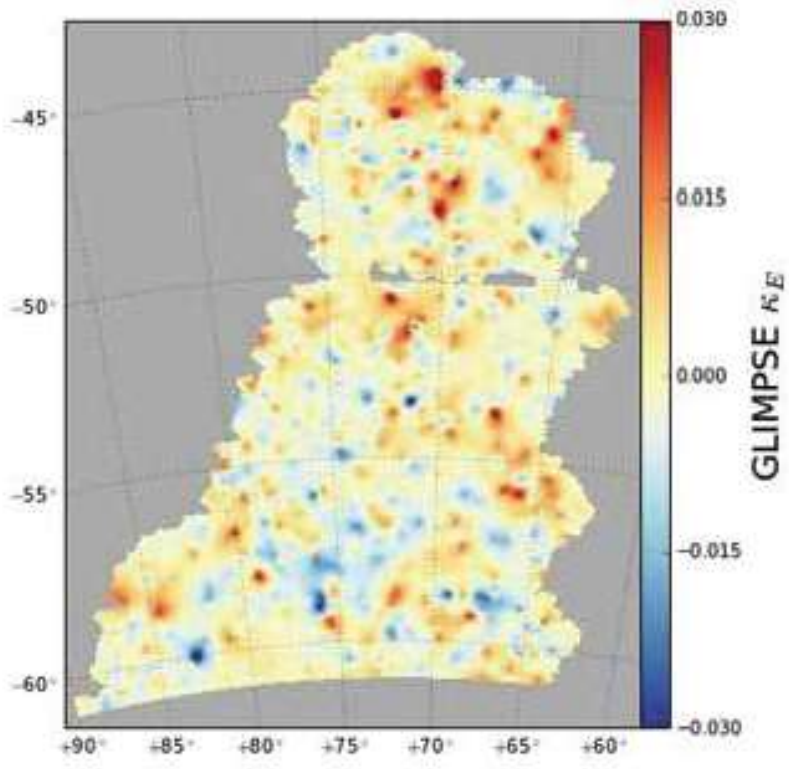
Mass from
DES Weak Lensing

Mass from
CMB (Planck/SPT) Weak Lensing

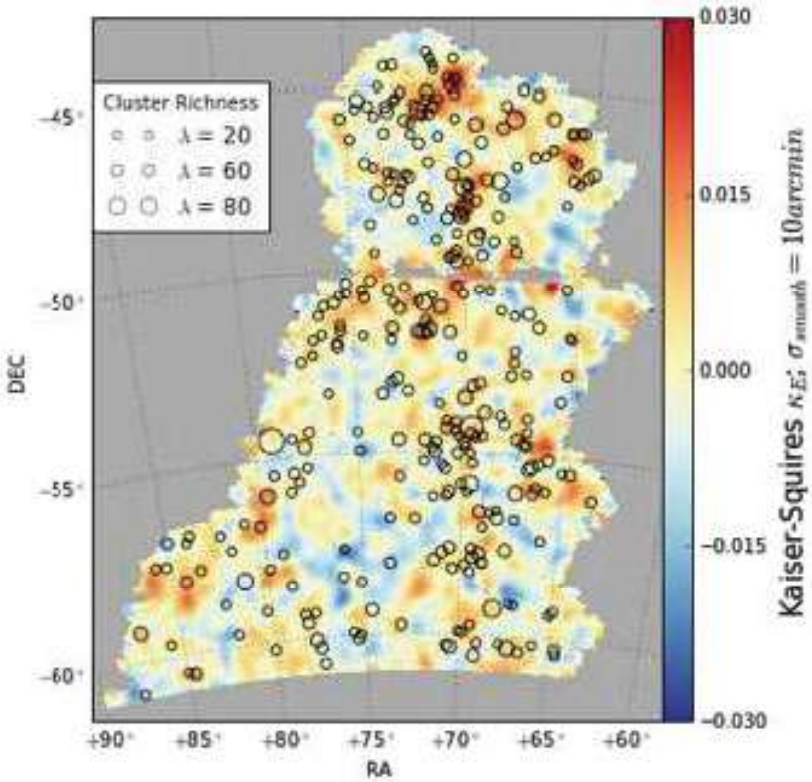
1

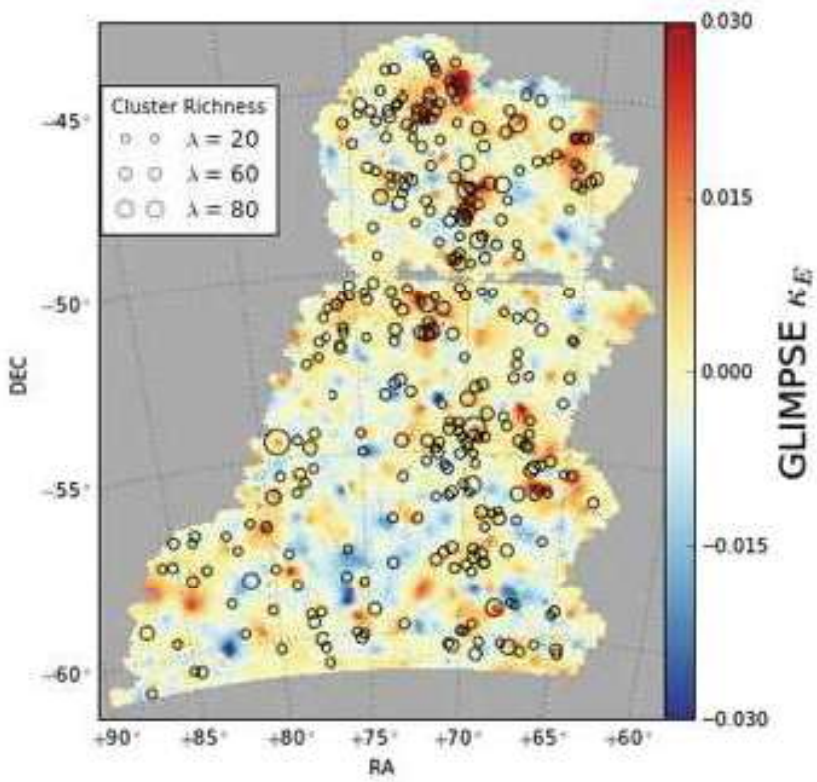
WL mass map from DES SV





WL mass map from DES SV

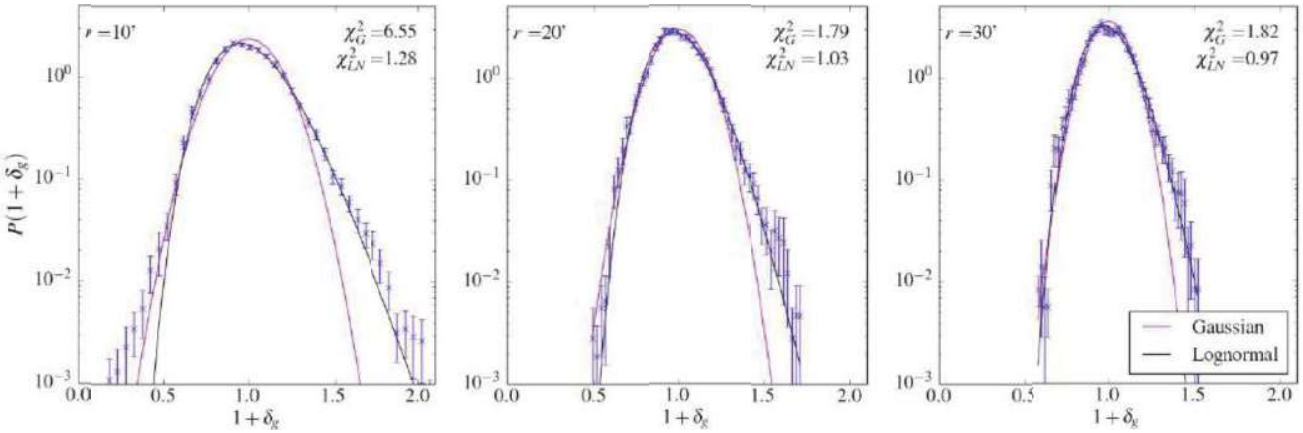




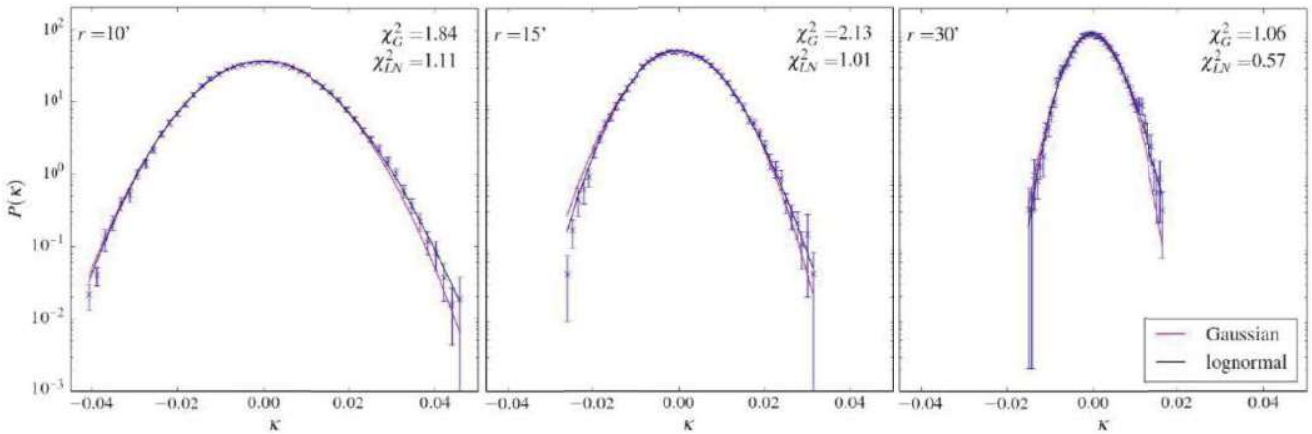
Chang et al. (2016)

Jeffrey et al. (in prep)

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



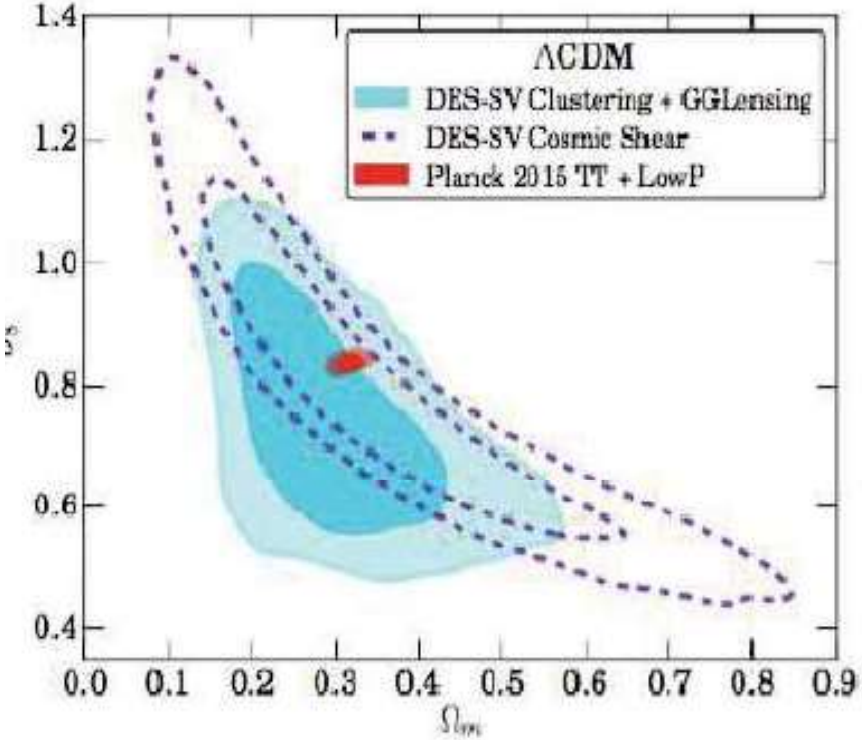
- Lognormal better than Gaussian, all scales

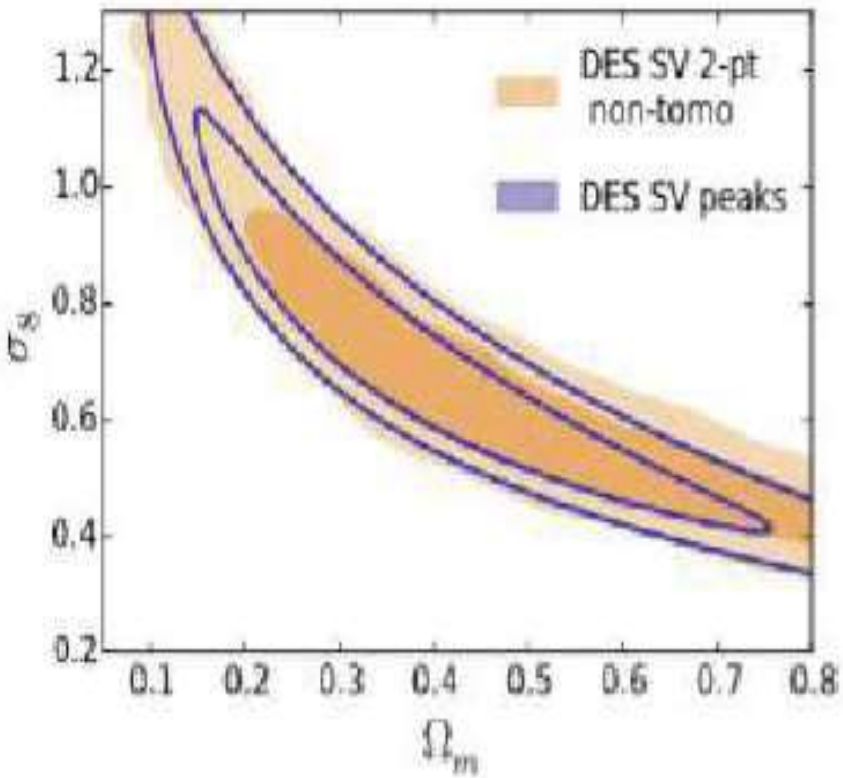


- Lognormal better than Gaussian at scales < 20 arcmin (< 5 Mpc/h)

Clerkin et al. (arXiv:1605.02036)

Testing LCDM with DES Weak Lensing and clustering

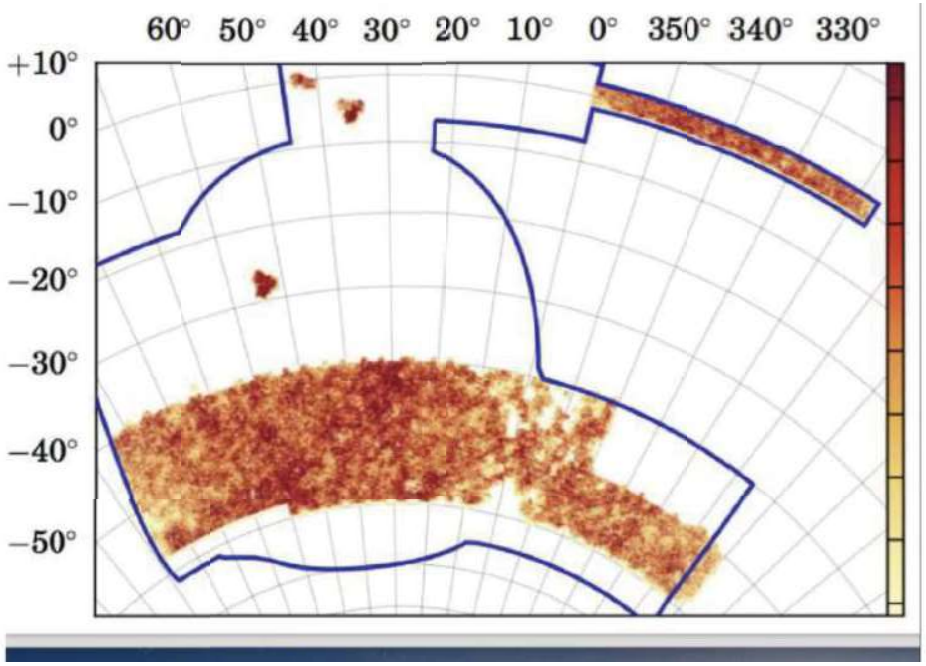




Kwan et al. 1604.07871
(dashed line: DES Collaboration 1507.05552)

Kacprzak et al. 1603.05040

Year 1 papers soon – stay tuned!

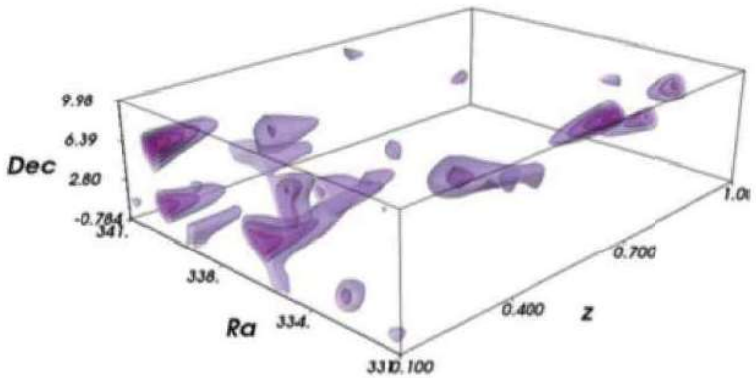


- WL: About 35M galaxies with shape measurements over (in riz)1300 sq deg
- 10 times SV in both galaxies and in area
- cf. KiDS, HSC
- 3 times 2pt functions: gal-gal, gal-shear, shear-shear

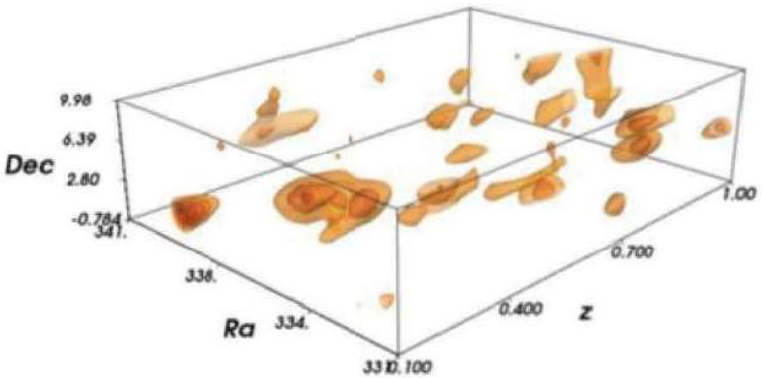
Subaru HSC mass maps

(167 sq deg; 25 galaxies per sq arc min)

Mass from WL



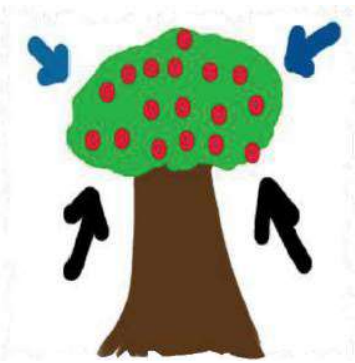
Light from LRG stellar mass



arXiv:1705.06792

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



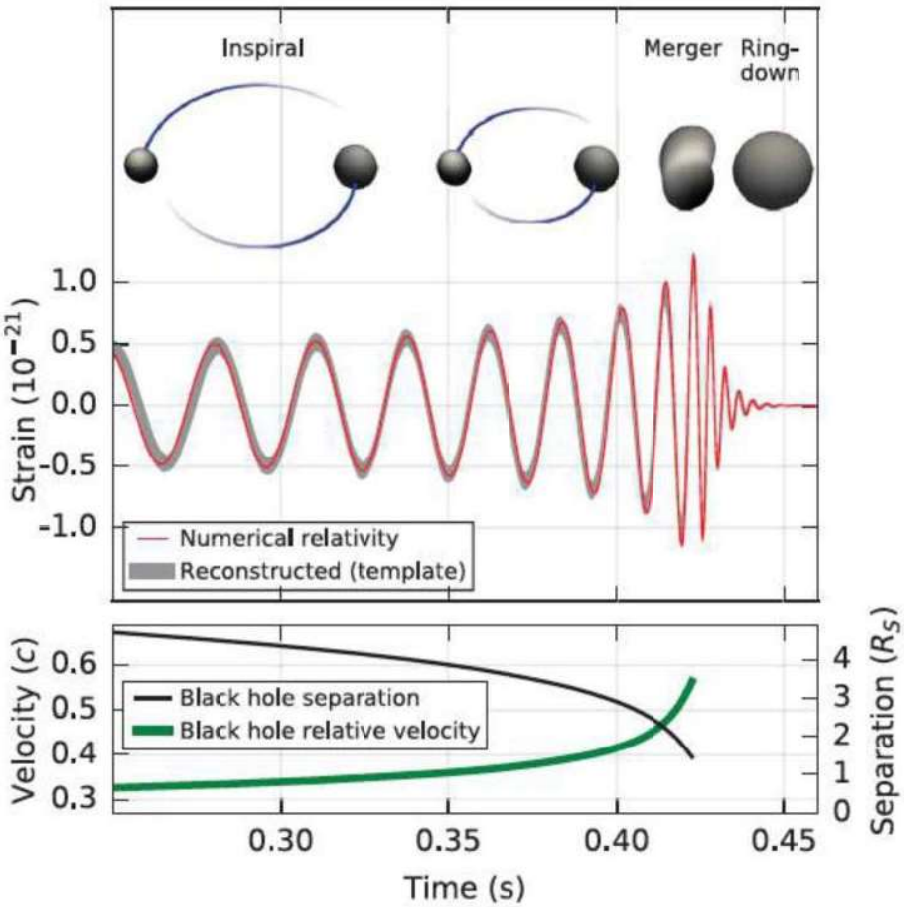
Low and high hanging fruit

Non-DE Overview (arXiv:1601.000329, MNRAS 2016)

DES Non—DE Overview
arXiv:1601.00329

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

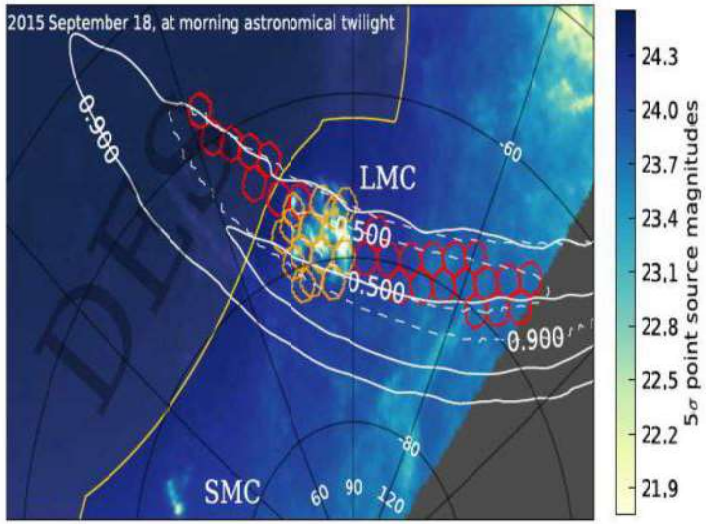
The new window of Gravitational Waves



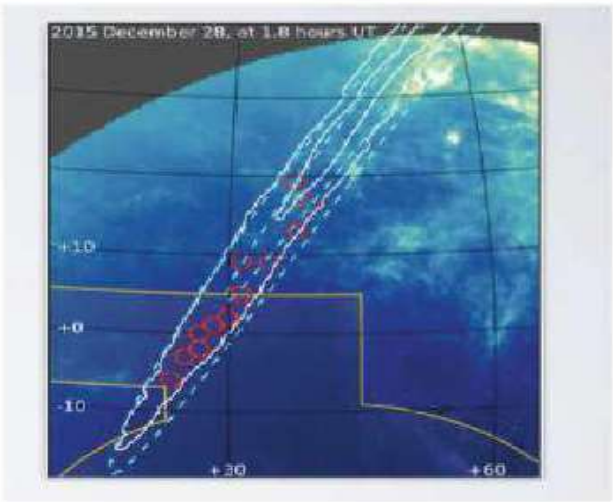
LIGO collaboration 2016

DES LIGO GW follow ups

GW150914



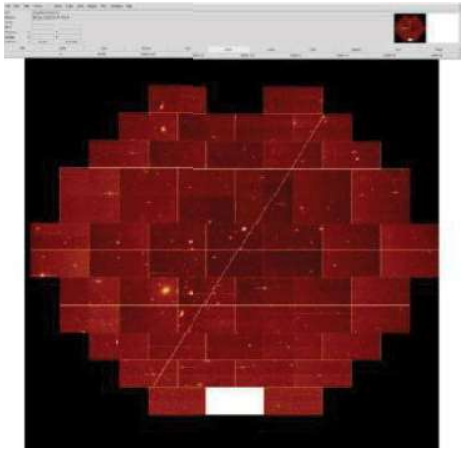
GW151226



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

Cowperthwaite et al. (2016)

DES observing run in Sep 2015: on the night of 16 Sep a LIGO trigger, but a mag 8.3 earthquake!



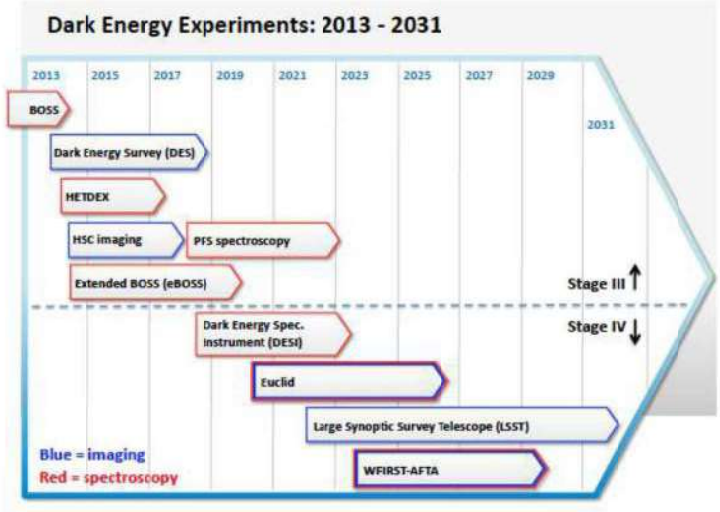
DES LIGO GW follow ups

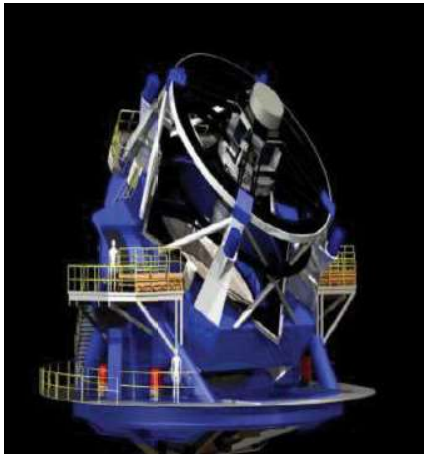
- So far DES followed up 2 out of the 3 GW events, both BH-BH mergers: no detections
- Current theoretical paradigm is that BH-BH mergers have no EM counterparts, but other models are being considered.
- DES search is sensitive to NS-NS and NS-BH out to 200 Mpc.
- The current main limitation is the poor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

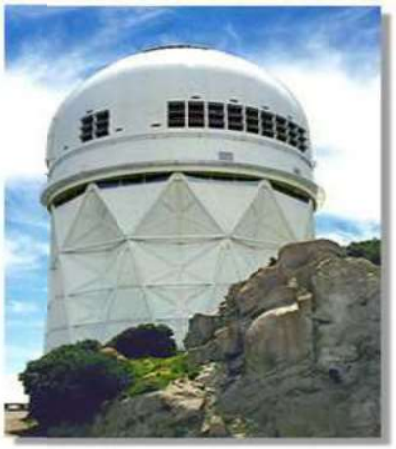
The DES followup strategy

- DES: wide-field, large aperture, red-sensitive CCD
- Aim at observations within 24hr of trigger
- For GW150914: 102 sq deg observed, in 28 fields (90 sec) + 20 fields in the (5 sec) in the LMC [search for core-collapse events, eg redupergiants progenitors]
- For GW151226: 36 sq deg
- Employ templates and difference imaging pipeline
- Spinoffs: detection of other objects with time variability; preparations for the LSST era.

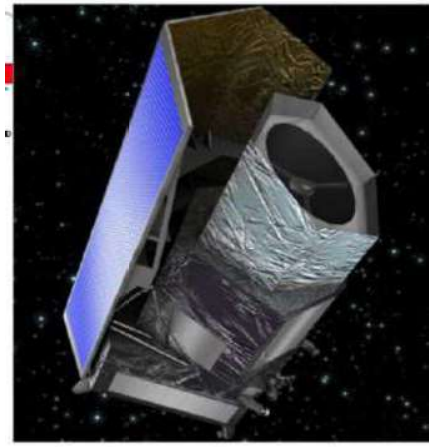
The era of DESI, Euclid, LSST,…





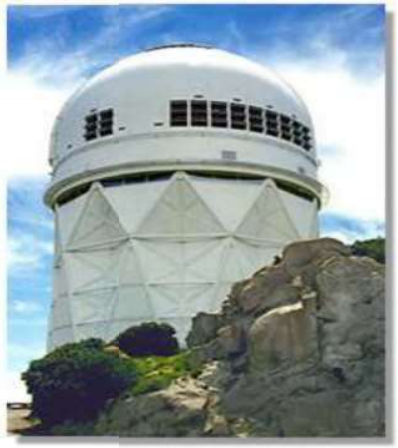


Mayall 4-Meter Telescope

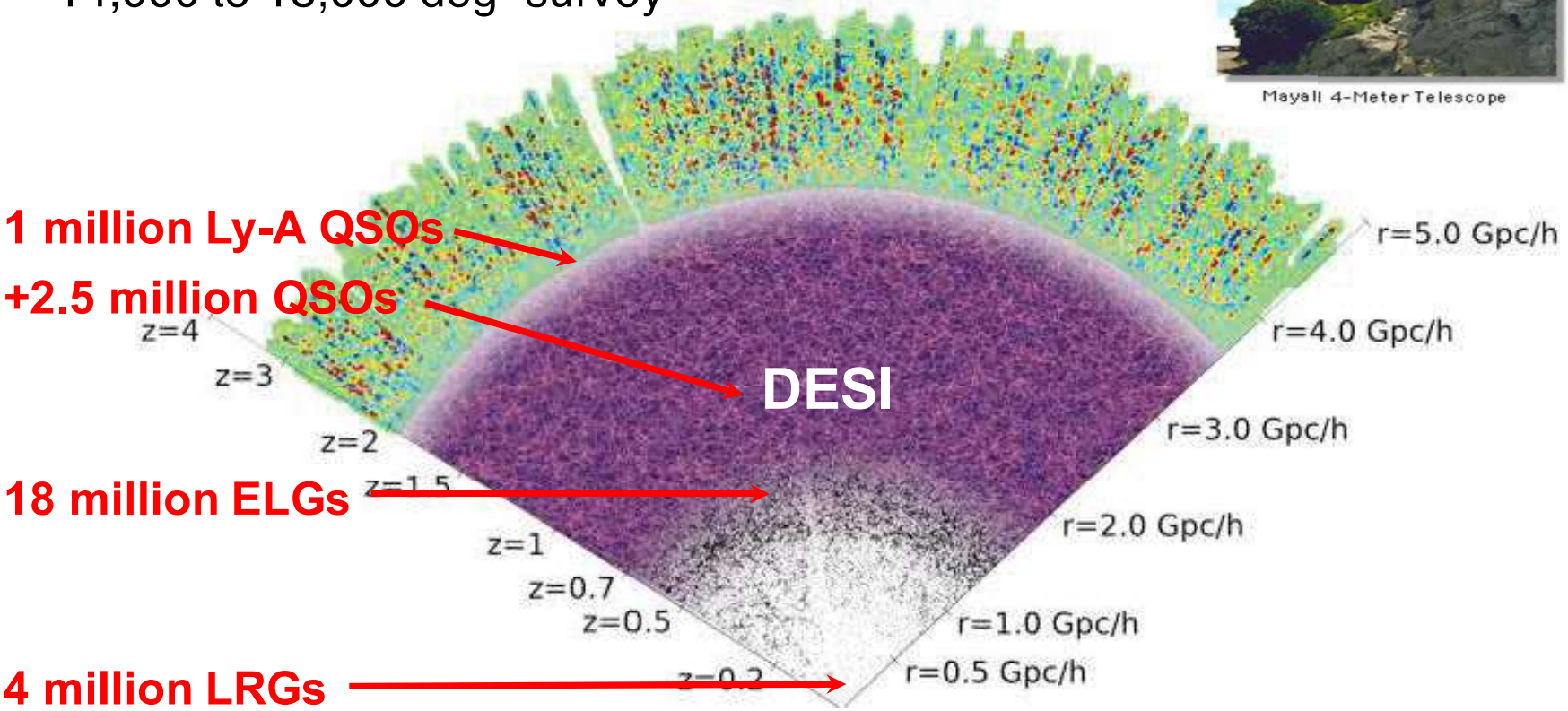


Dark Energy Spectroscopic Instrument (DESI) – 10 times BOSS

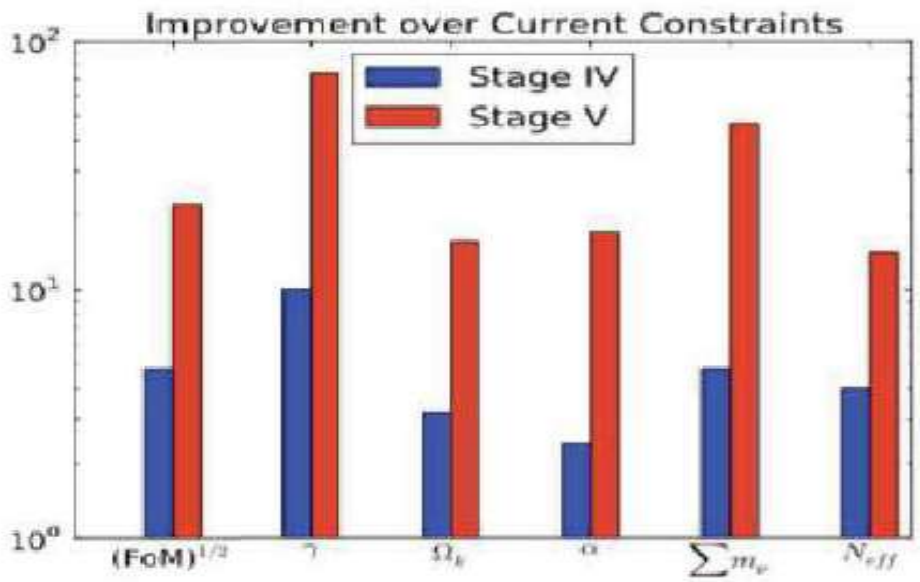
Mayall telescope available up to 100% of dark time,
5000 fibres, 20min base integration time
> 20 million targets
14,000 to 18,000 deg^2 survey



Mayall 4-Meter Telescope

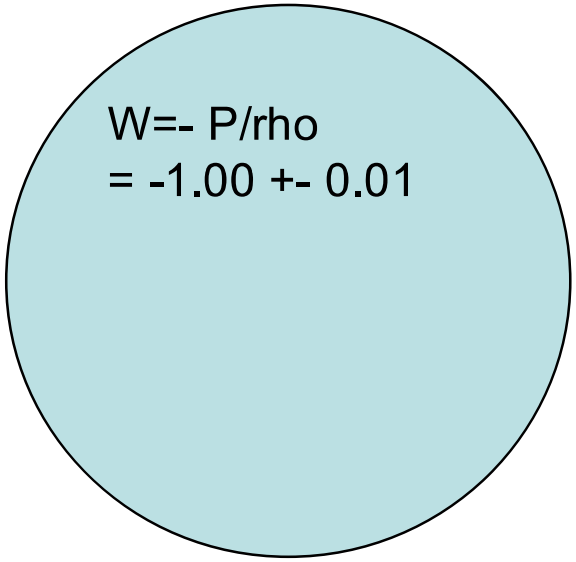


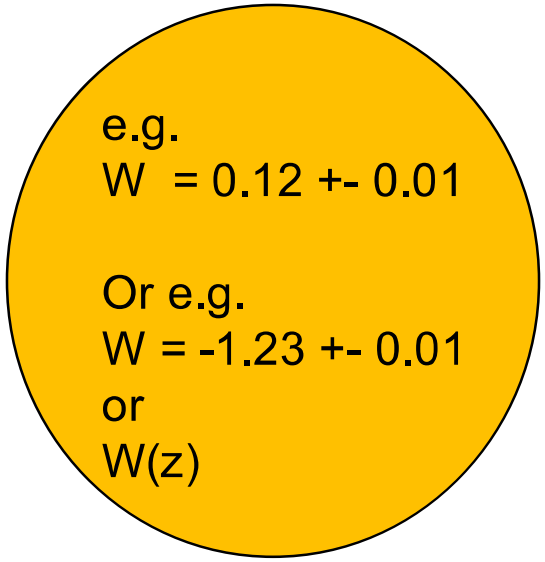
Cosmic Vision forecast

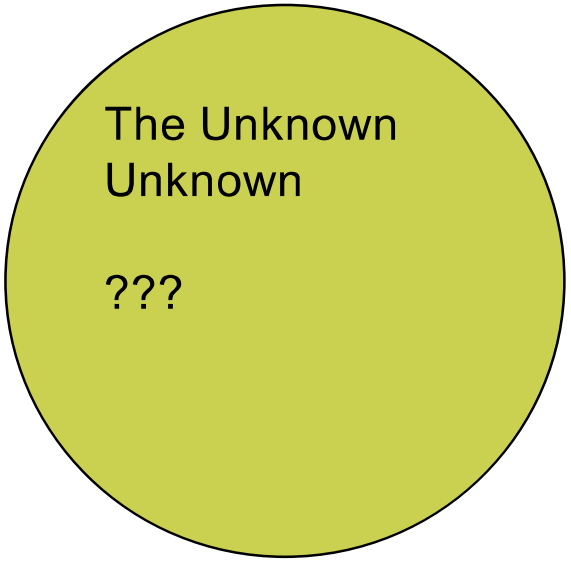


arXiv:1604.07626

Possible outcomes of ongoing and future surveys







Back to Lambda

Back to fundamental Physics

Anthropic Principle?

‘Accuracy’ vs ‘Precision’

Back to systematics/Astrophysics

Then fundamental Physics

A new paradigm shift?

Big Data in Astrophysics and HEP

- Google: 3.5 Billion Google searches per day
- LHC: 600 Million collisions per second
  (only 100 per second are 'interesting')

- SDSS: 200 Giga(10^9) Bytes per night
- DES: 1 Tera (10^{12}) Bytes per night
- LSST: 15 Tera Bytes per night
- SKA: 1 Peta (10^{15}) Bytes per day

Big numbers

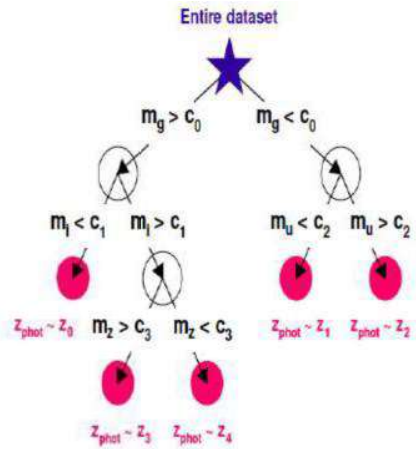
- Exo-planets: 9-1 (+1?) +2000+…
- Gaia: 1B stars
- DES: 300M galaxies
- Euclid/LSST: 1B galaxies
- Simulations: N-body, Hydro

(many times the data)

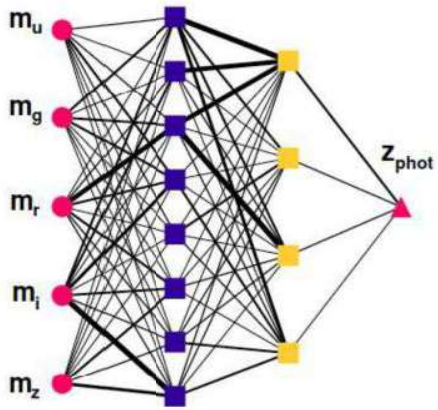
Data Intensive Science @ UCL

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

33 PhD students; first PhD intake Sep 2017
20 industry partners



Decision Trees



Artificial Neural Networks

Summary

- 25 years of LCDM: supported by most observations.
- Important to test LCDM further (local dynamics, CMB Cold Spot, gravitational redshift)
- DES does “see” DM, and good correlations between DM and galaxies.
- DES on the path to DE from LSS, WL, Clusters & SN Ia (+ cross correlations).
- DES: successor of APM, 2dF & SDSS;

  precursor of LSST, DESI, Euclid and WFIRST; Big Data
- What are the prospects for a new paradigm shift, beyond LCDM, eg w(z) or ModGrav ?