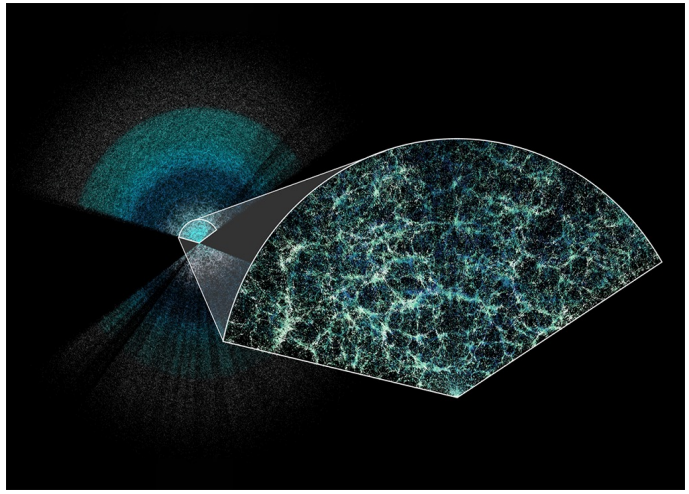
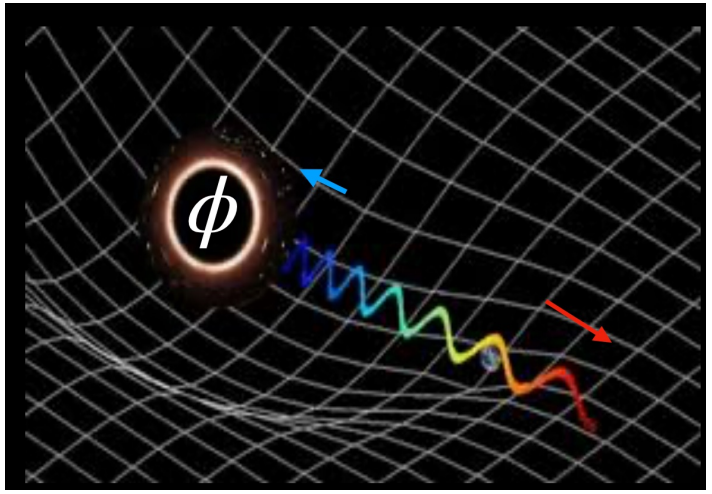
Gravitational Redshift of Galaxies in Clusters





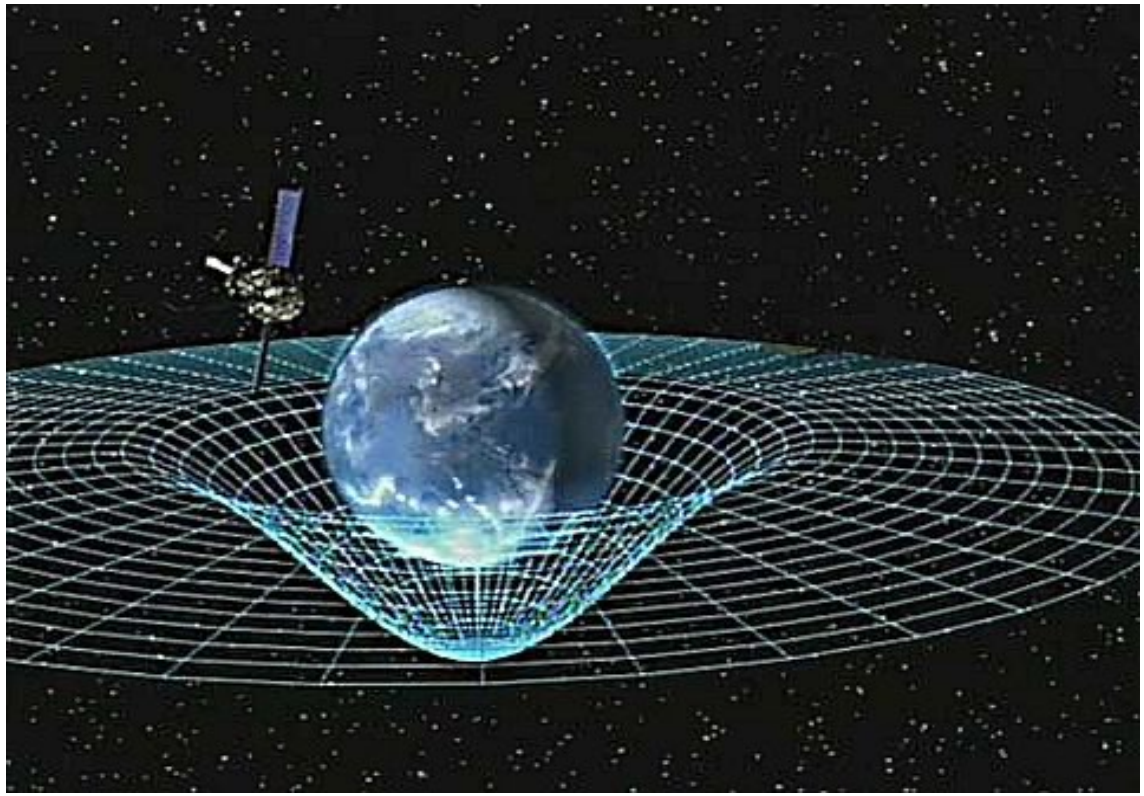
Ofer Lahav (UCL)

UCL CDT DIS

Outline

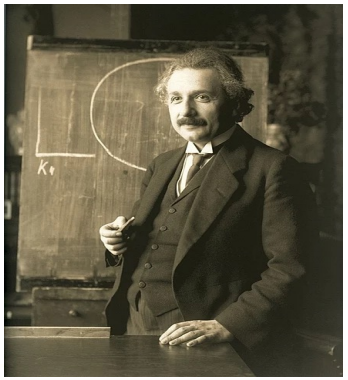
- The landscape of galaxy surveys
- Testing GR with SNIa (DES) and BAO (DESI)
- Gravitational Redshifts (Grav-z) of galaxies in clusters
- Prospects for Grav-z from DESI

Einstein's General Relativity (1915)

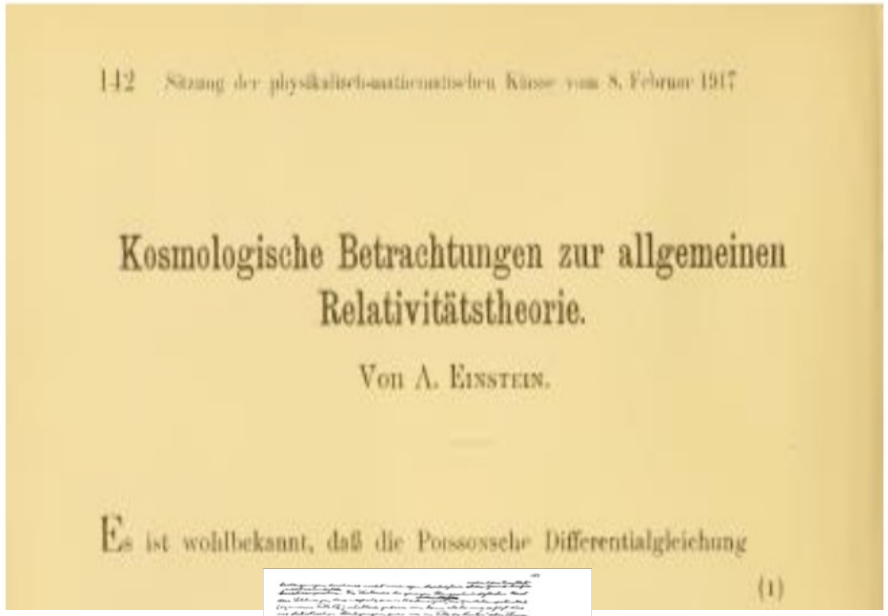


- Matter tells space-time how to curve.
- Space-time tells matter how to move.

John Wheeler



Einstein's 1917 Lambda



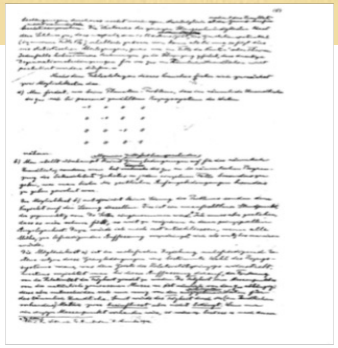
142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Es ist wohlbekannt, daß die Possonsche Differentialgleichung

(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)

English translation: http://einsteinpapers.press.princeton.edu/vol6-trans/433?ajax

See review O'Raifeartaigh et al. (1701.07261)

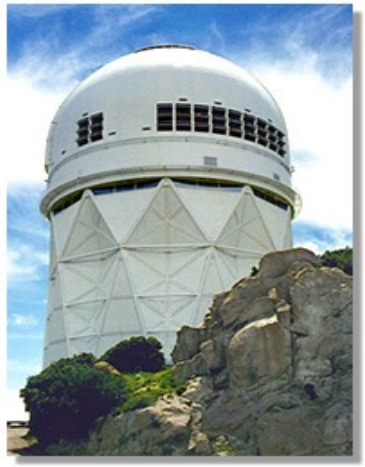
Big Data in Astronomy

Survey	Data per night/day	Galaxies	Cost	Scientists
DES	1 TeraB	~300 Million (all observed)	~$100M	~400
DESI	40 GigaB	~40 Million (being observed)	~$100M	~900
Rubin-LSST	15 TeraB	~Billions	~$1.0B	~1000
Euclid	850 GigaB	~Billions	~$1.5B	~1500
SKA	1 PetaB	~Billions	~$1.3B	~1000

How many surveys should one join?

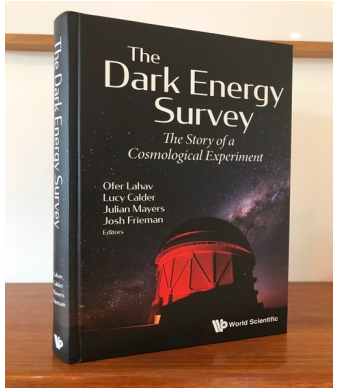
The tale of two surveys:

Dark Energy Survey (DES) &
Dark Energy Spectroscopic Instrument (DESI)



Mayall 4-Meter Telescope

- Modern instruments on old twin 4m telescopes:
  DES (imaging) on Blanco (Chile) and DESI (spectroscopy)
  on the Mayall (Kitt Peak)
- DES Fermilab-led; DESI LBL-led & international partners
- UCL built both optical correctors

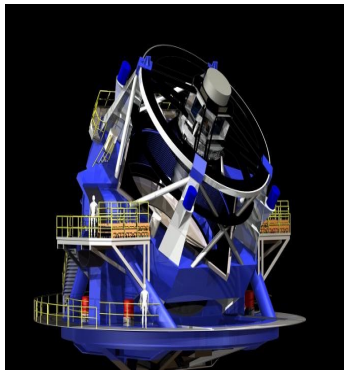


- DES completed 6 seasons in 2019 →
  300M galaxy images and thousands of SN
- DESI started observations in 2020
  40M galaxy+qso spectra

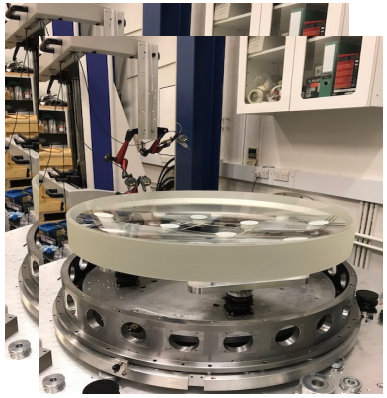
Galaxy Surveys

KiDS

DES



Rubin-LSST



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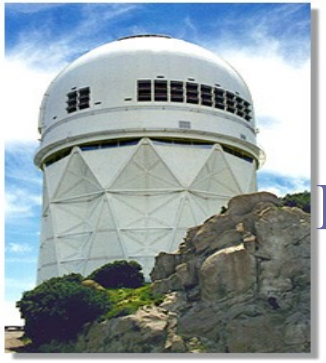
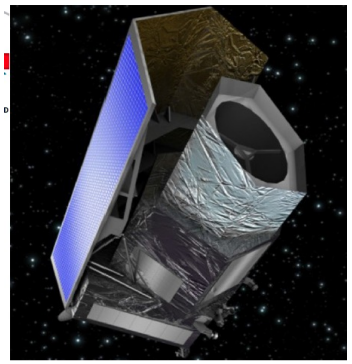
1 of 6 DESI lenses at UCL



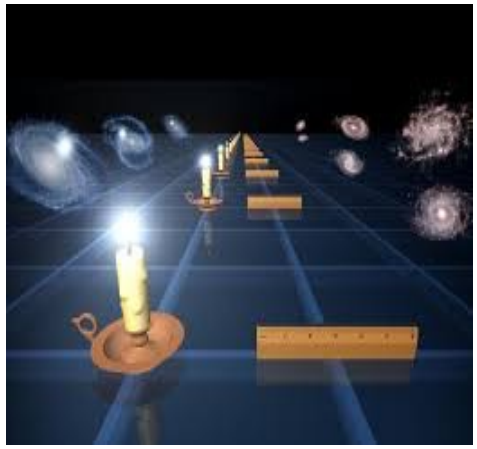
Mayall 4-Meter Telescope

DESI

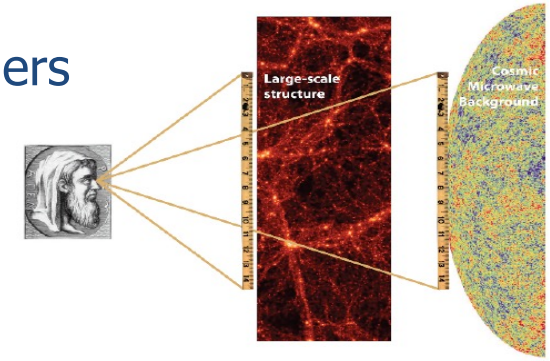


Euclid

Key Probes of Dark Energy: expansion and growth of structure

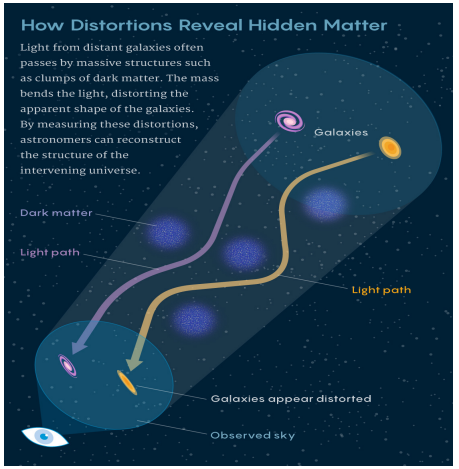


Standard Candles and Rulers



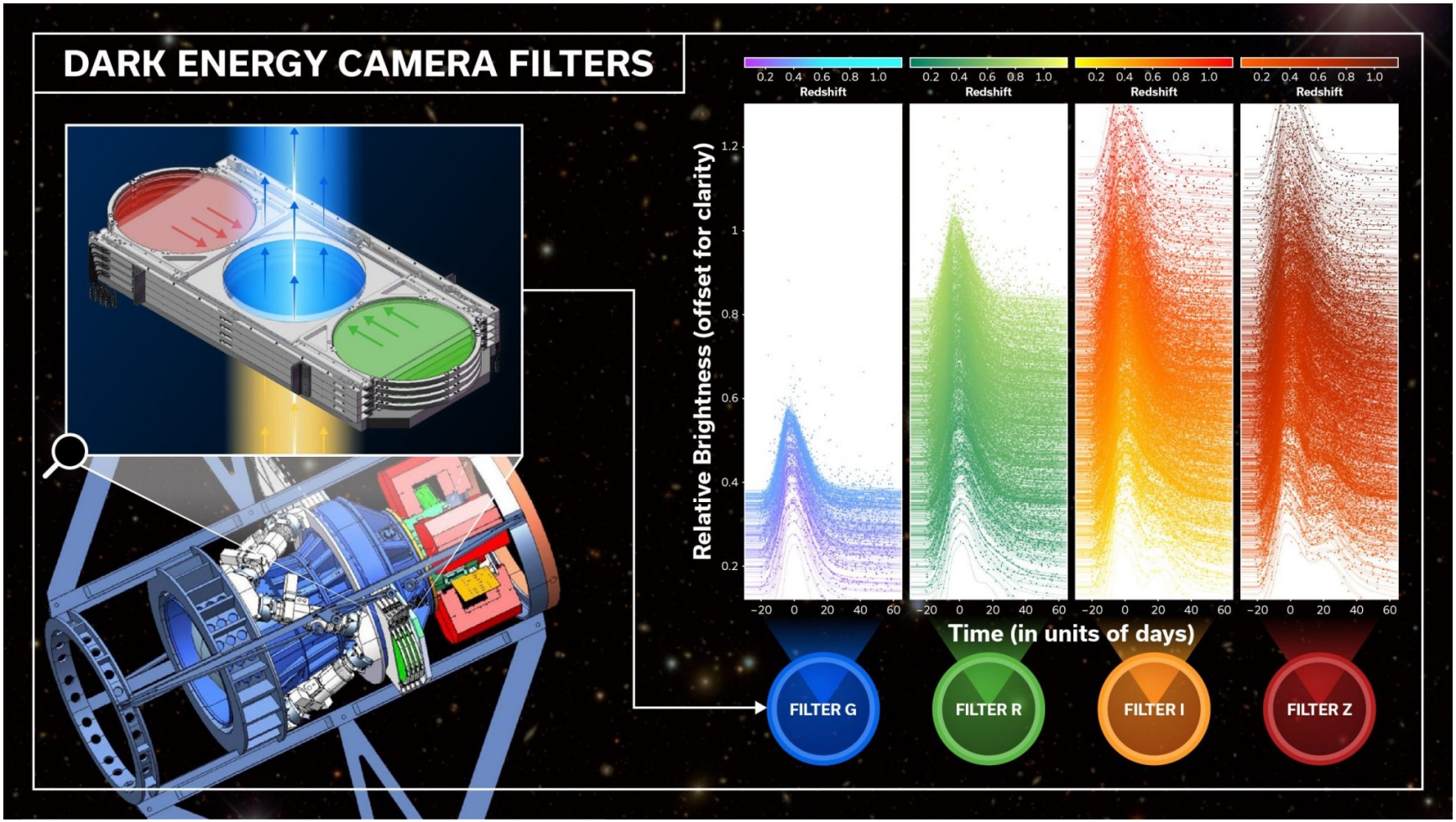
Clusters

Weak Lensing

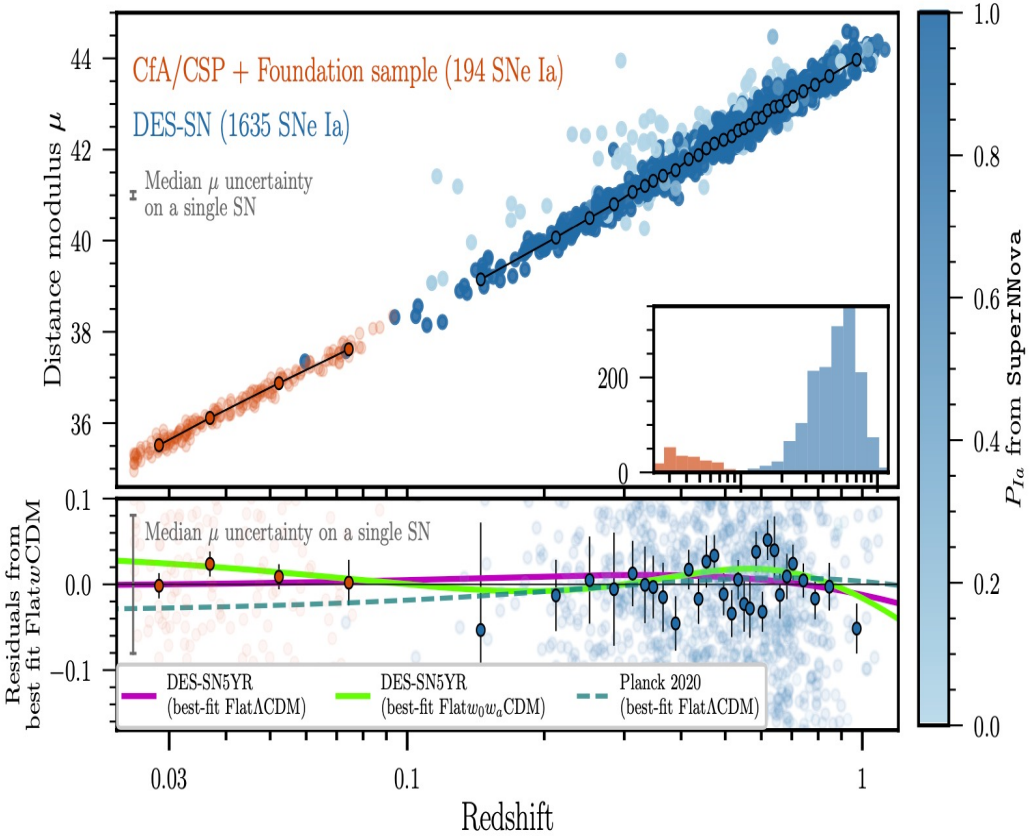


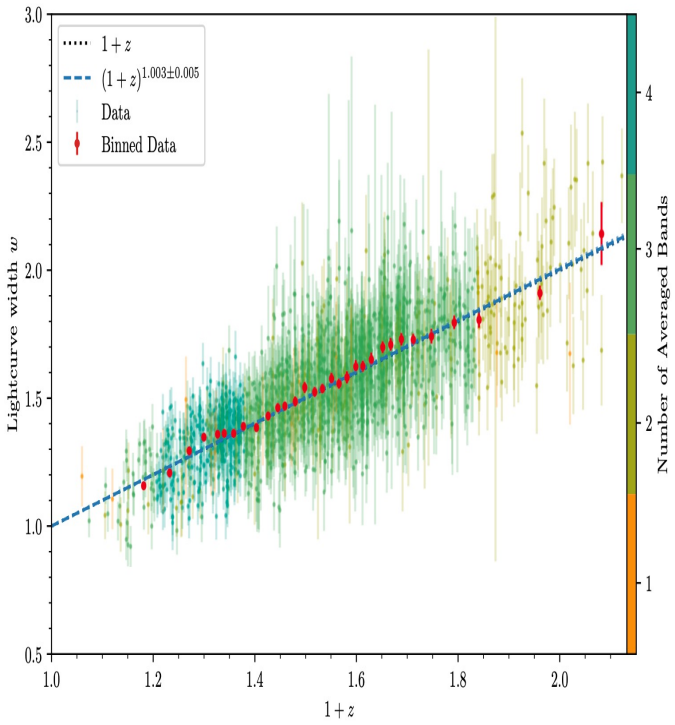
JWST image

1500 DES Yr5, Supernovae Ia



Results from
1500 DES Supernovae Ia (Yr5, Jan 2024)





(1+z) time dilation in SN Ia light curve width

Einstein was right!

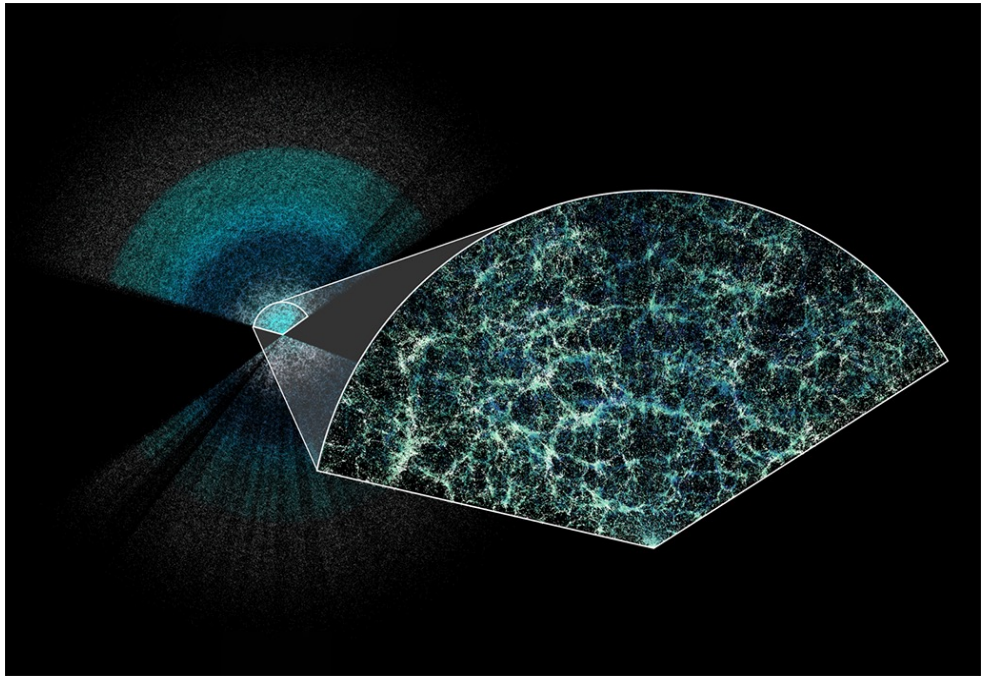
arXiv:2401.02929

From DES SN+ 3x2pt + SDSS BAO + Planck

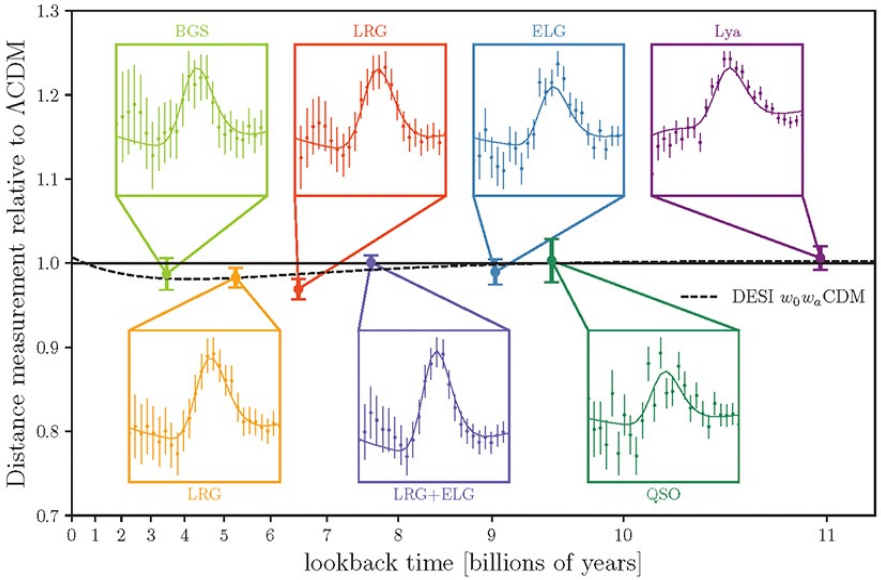
$$(\Omega_{\rm M}, w) = (0.321 \pm 0.007, -0.941 \pm 0.026).$$

White & DES, arXiv:2406.05050

DESI Y1 BAO results (April 2024)



arXiv:2404.03002



The measurement of the dark energy equation of state w is a key science goal of DESI. Assuming the wCDM model where the equation-of-state parameter is constant in time, we find $w = -0.99^{+0.15}_{-0.13}$ from DESI alone, and $w = -0.997 \pm 0.025$ from the combination of DESI BAO, CMB, and SN Ia results from the Pantheon+ compilation, in good consistency with ΛCDM. This result does not appreciably change when the Pantheon+ data are replaced

Consistent with LCDM, but time variation of w is still possible

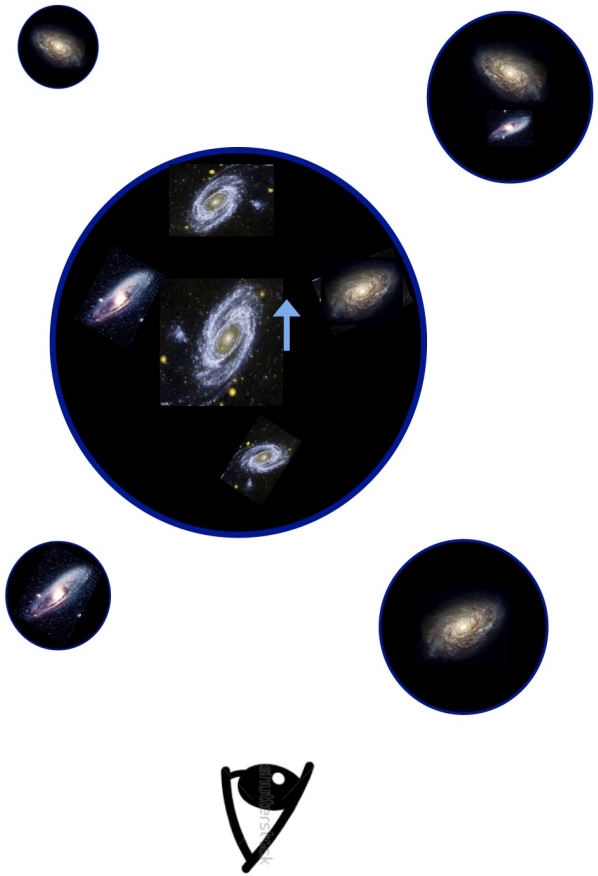
Einstein was right that Lambda exists, but at a different value!
(accelerated rather than static universe)

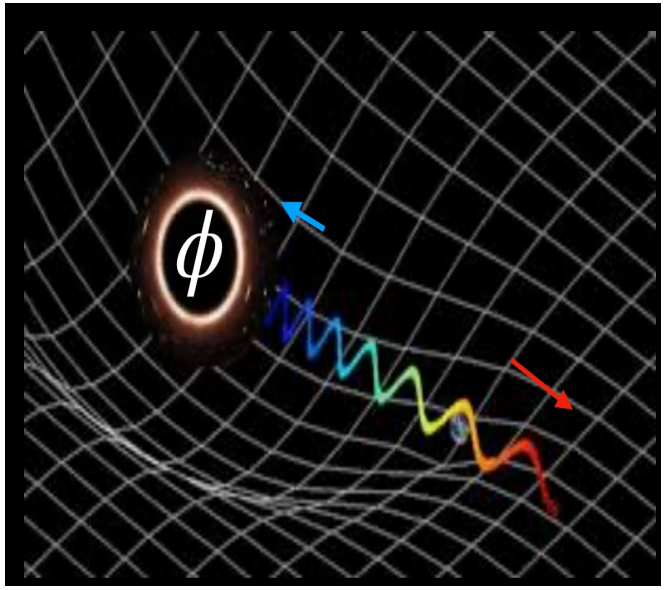
The speed of GW from GW170817

- Time delay of 1.7 second between the Gamma Ray Burst and the GW event
- This implies $|c_{GW} - c_{Light}| / c_{Light} < 10^{-15}$
- Einstein was right again!
- This rules out some (but not all) modified gravity models

Abbott et al, ApJ Lett, 2017
arXiv:1710.05834

Grav-z in clusters: another test of GR, on Mpc scales

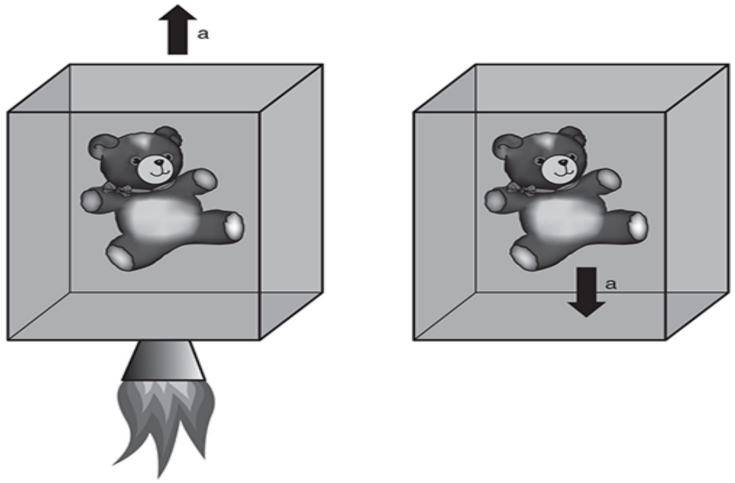




$$z_g = \frac{\Delta\lambda}{\lambda} - \simeq \frac{\Delta\phi}{c^2}$$

The Equivalence Principle in clusters: do we test the EP or GR?

Credit: Ryden's book

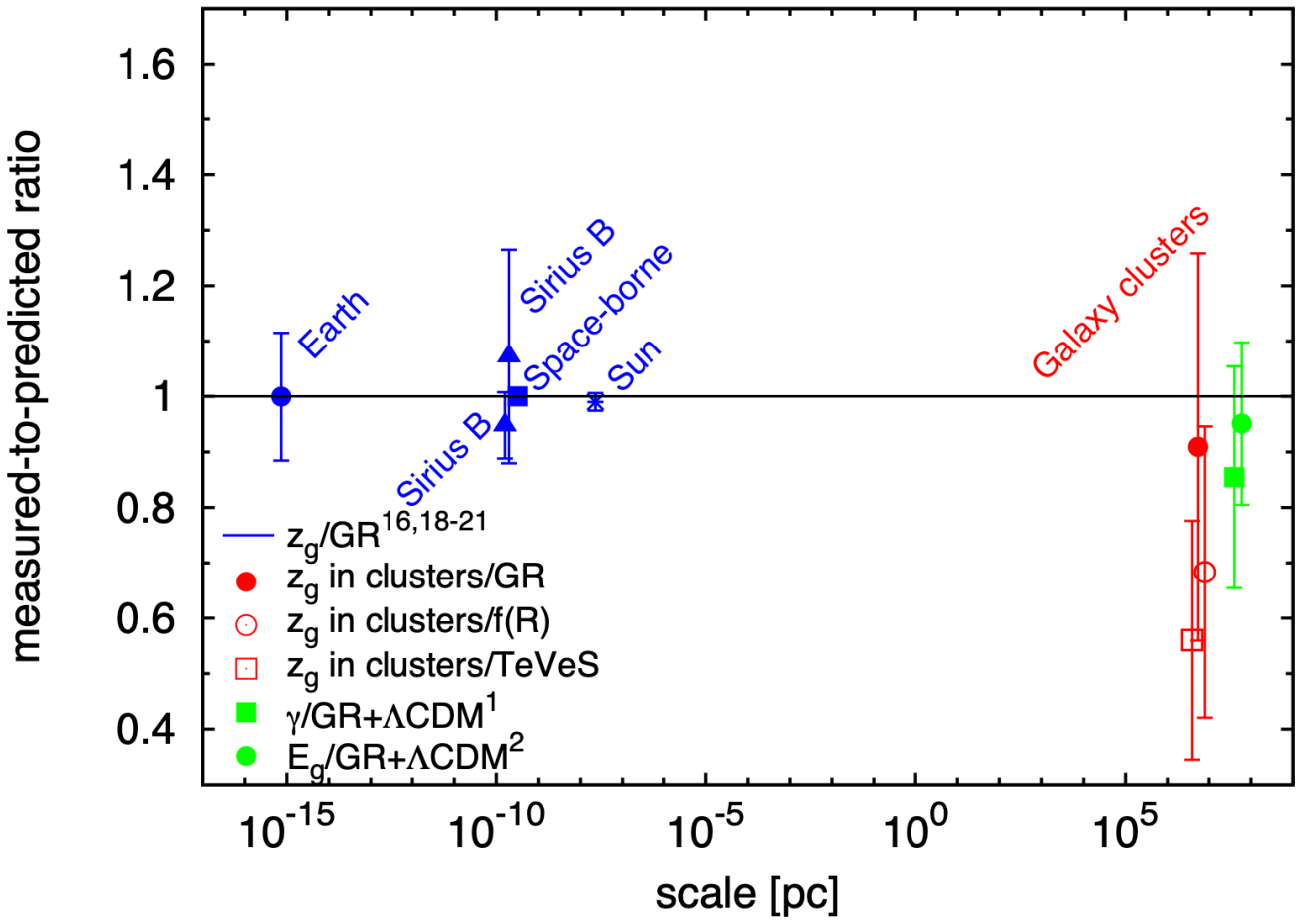


JWST cluster

- GR: Galaxy motions and gravitational redshift of photons experience the same underlying gravitational potential.
- However, there are non-GR models that assume the EP.

e.g. Wojtak et al. (2011); Bekenstein & Sanders (2011); Bonvin & Fleury (2018)

Grav-z vs. scale



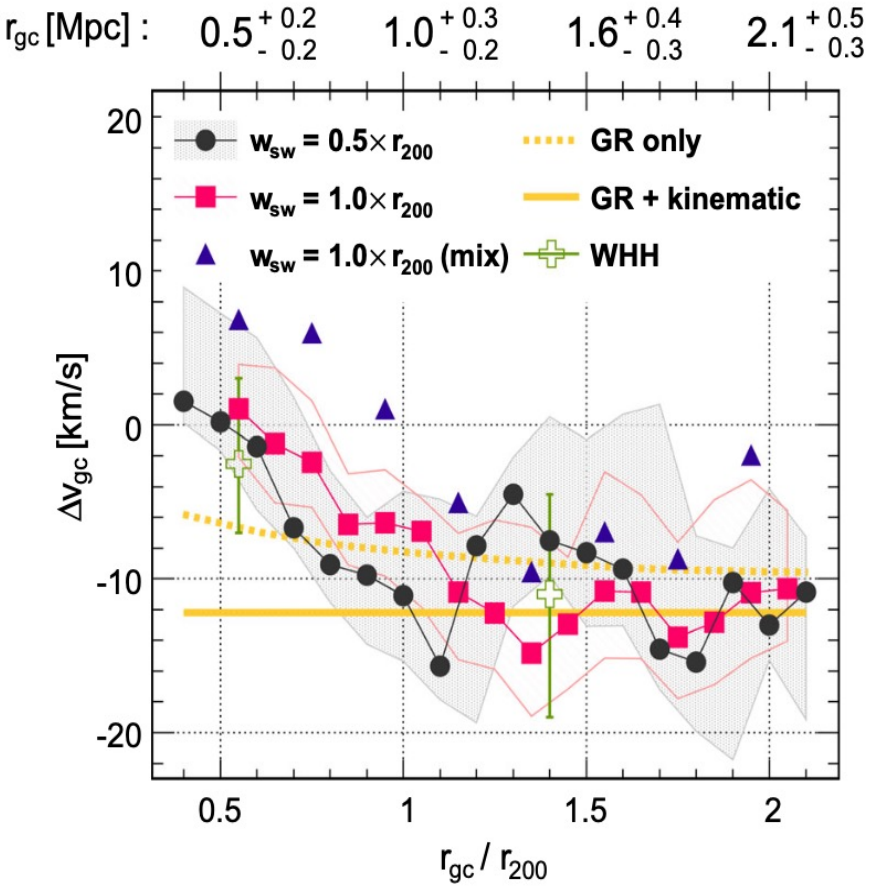
Wojtak et al. (2011)

Grav-z results

Authors	Galaxies Associated with the clusters	clusters	Δ (km/sec)
Wojtak+ 2011	125k	7.8k	-7.7 +-3.0
Sadeh+ 2015	60.6k	12.6k	-11 (+7,-5)
Mephta+ 2021	10k	2.5k	-13.5 (+- 4.7)
Rosesselli+ 2022	50k	3k	-11.4 (+-3.3)
DESI	500k	25k	In prep

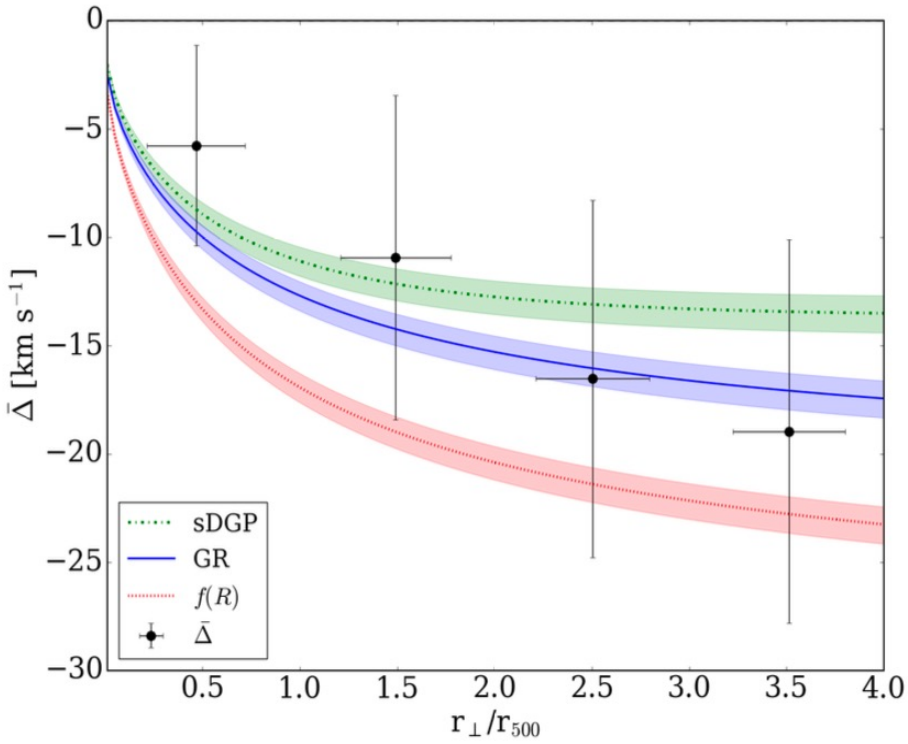
$\Delta = cz_g$ may depend on cluster mass and redshift range

Grav-z results from SDSS



Sadeh, Feng & OL (2016)

$$\Delta_1(r_{\rm gc}) = \frac{2}{c\Sigma(r_{\rm gc})} \int_{r_{\rm gc}}^{\infty} [\Phi(r) - \Phi(0)] \frac{\rho(r) r}{\sqrt{r^2 - r_{\rm gc}^2}} dr$$



Rosselli+ (2022)

Other effects

(Kaiser 2013, Zaho+ 2013)

- Transverse Doppler effect
- Light-cone effect
- Surface brightness modulation effect

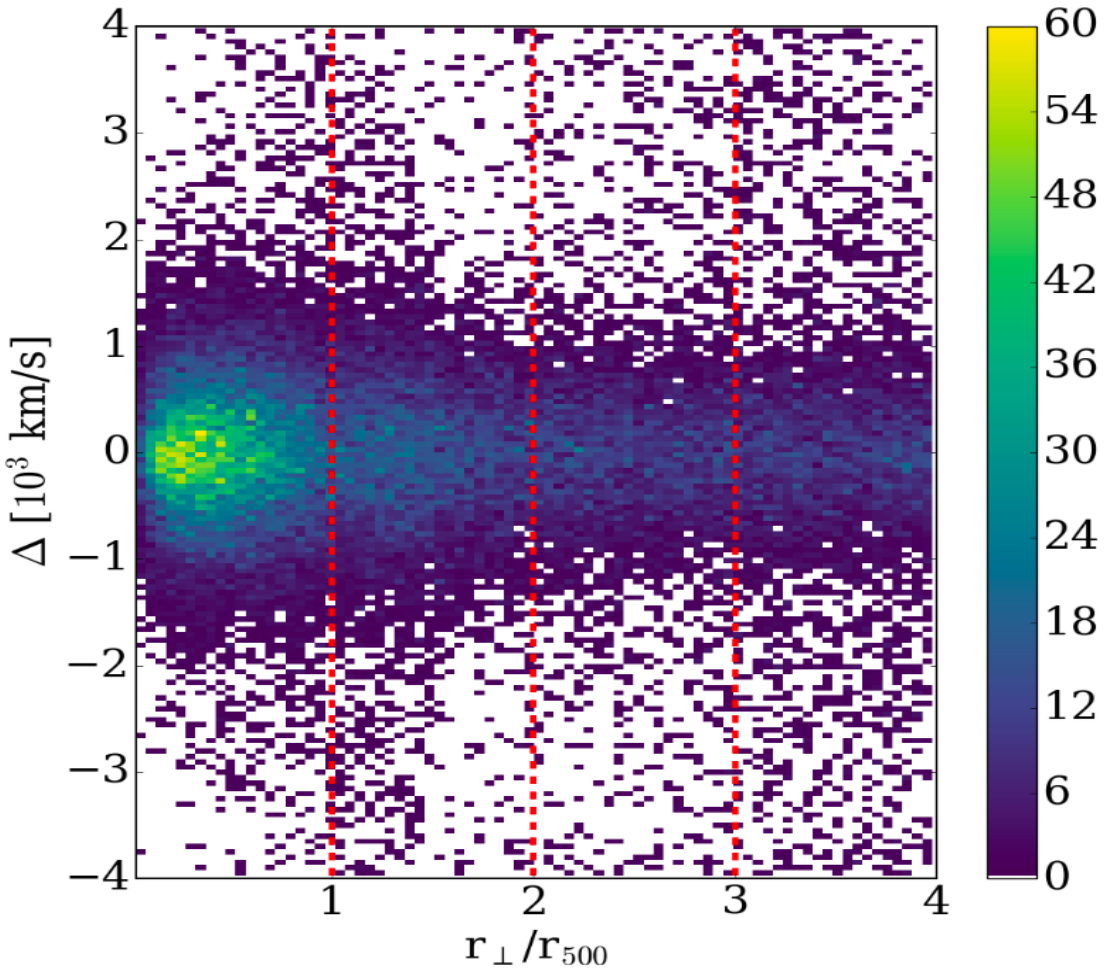
$$1 + z_{\rm pec} \simeq 1 + \frac{v_{\rm los}}{c} + \frac{1}{2}\frac{v^2}{c^2}$$

$$\bar{\Delta} = \bar{\Delta}_{\rm gz} + \bar{\Delta}_{\rm TD} + \bar{\Delta}_{\rm LC} + \bar{\Delta}_{\rm SB}$$

Systematics in Grav-z

- Cluster definition and centre
- galaxy cluster membership
- Redshift uncertainties
- Stacking
- Theoretical uncertainties

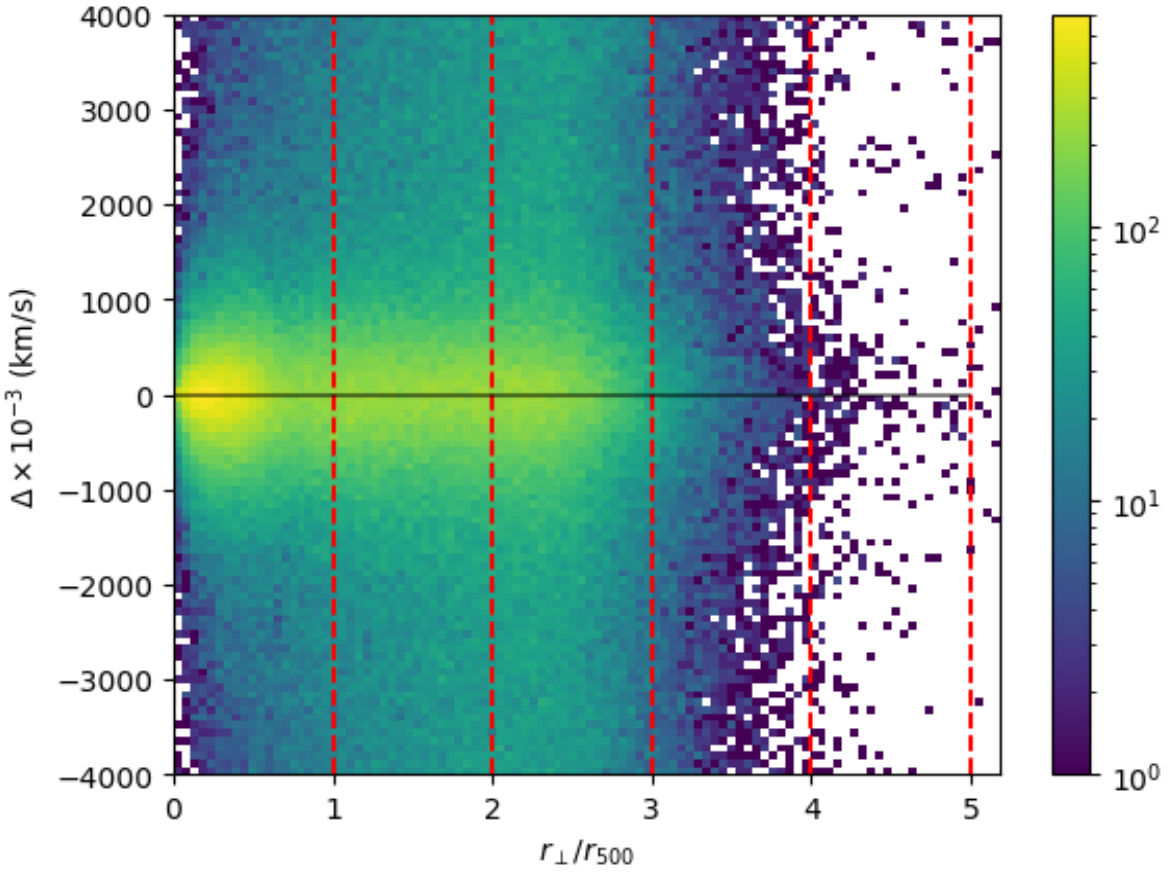
Phase-space diagram from SDSS



Rosselli et al. (2011)

Stacked 3k clusters, with 50k associated galaxies

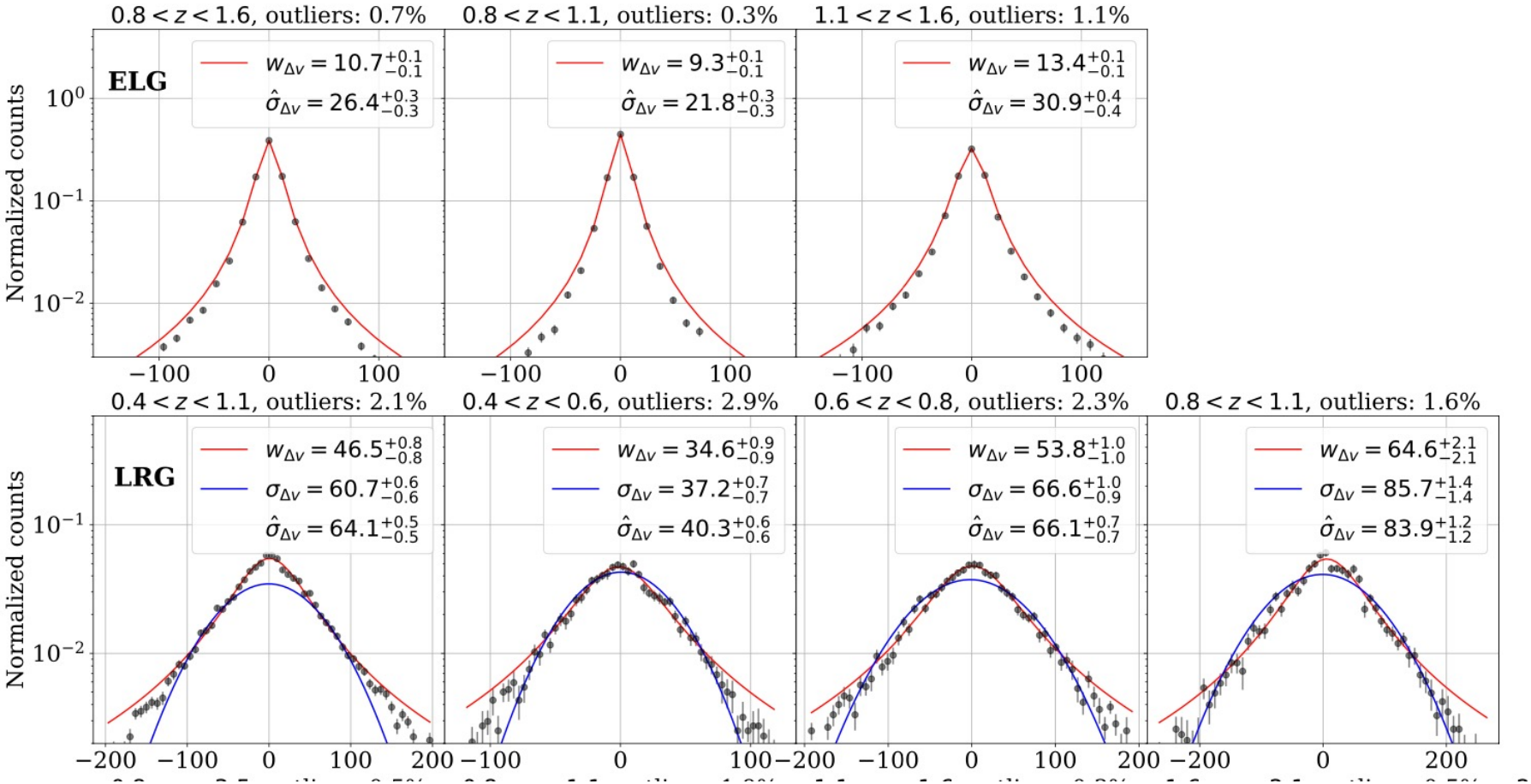
Phase-space diagram from DESI Yr1



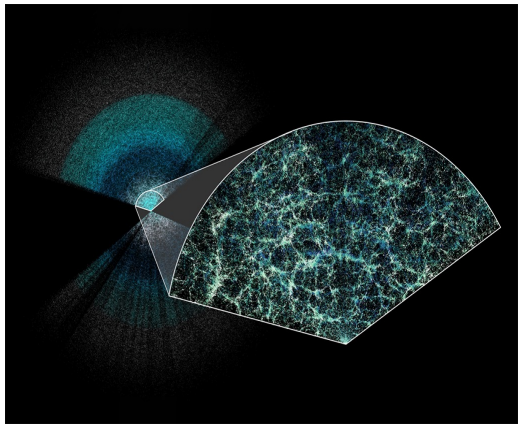
Williamson, Manera, Kololgi, OL & DESI collabaoration (project 236, in prep)

Stacked 25k clusters, with 500k associated galaxies

DESI redshift errors from repeat observations



Yu et al., arXiv:2306.06313



Application to DESI

- 25k Clusters
- 500k galaxies as cluster members
- Improves S/N by a factor 3 wrt to SDSS samples
- Phase space diagram for DESI is in place
- Controlling systematics
- Nearly there with results for the shift Δ!

Summary

- So far, cosmological surveys are spectacularly consistent with GR (subject to some ‘tensions’).
- Several measurements of gravitational redshift in clusters using SDSS are consistent with GR/EP a for shift of about ~10 km/sec on Mpc scale.
- Understanding systematics is crucial.
- Measurement from DESI is nearly there.
- Check consistency with relativistic corrections in the field.
- New tests of GR/EP are needed!