Latest Results from Cosmological probes

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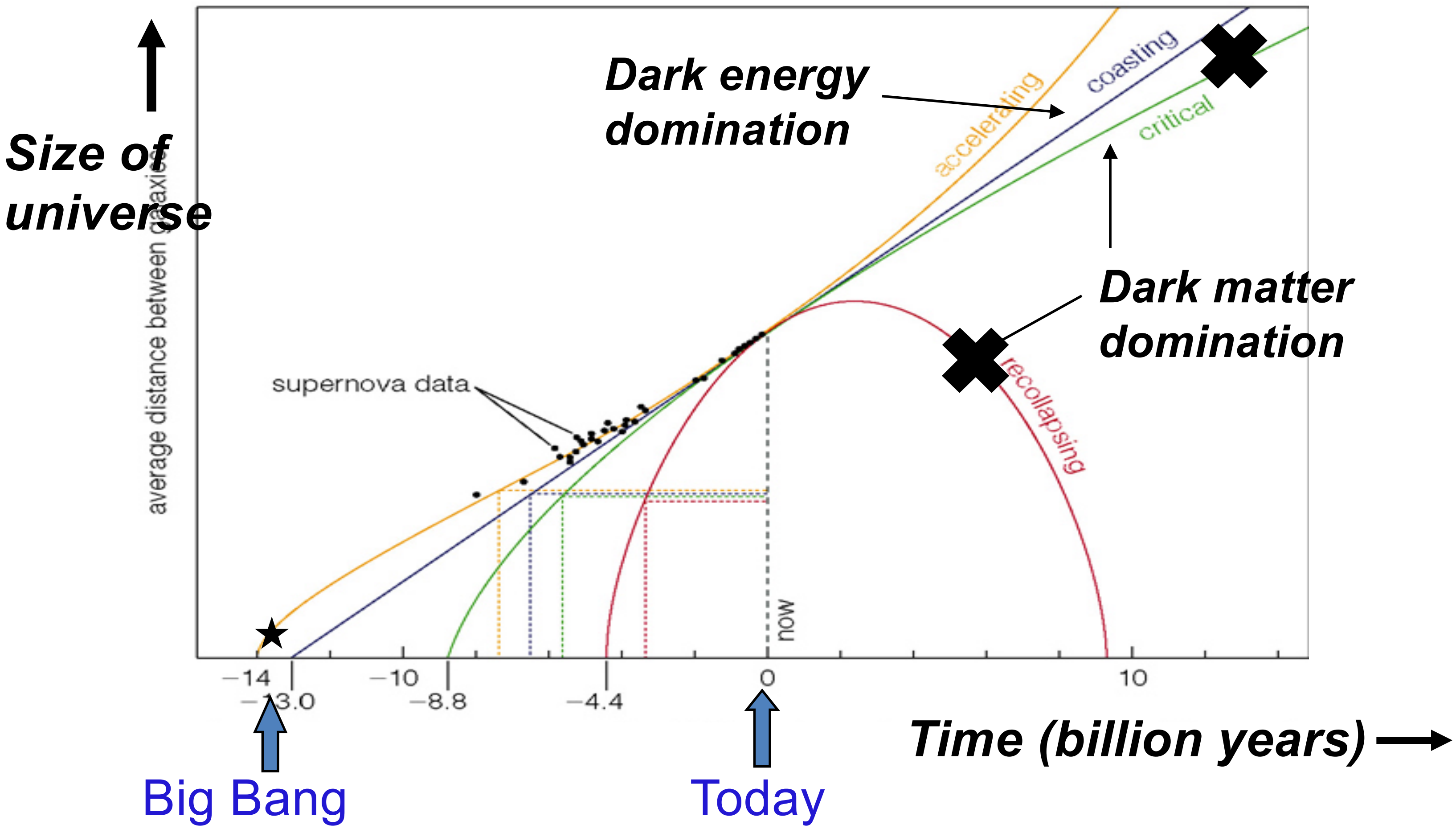
Big Questions in Cosmology

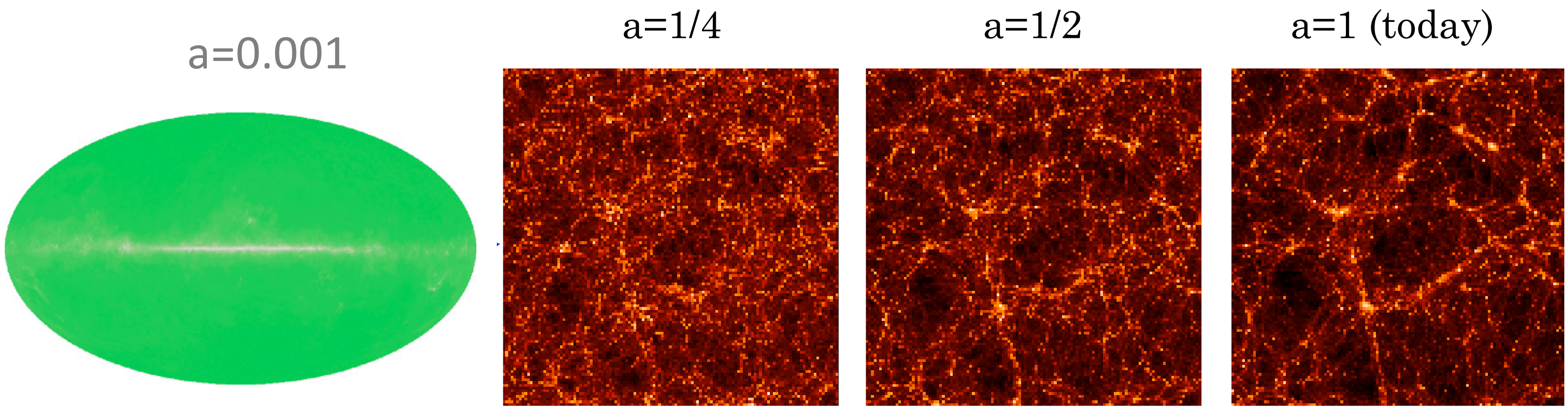
- What was the pre-Big Bang universe like?
- What is the origin of structure?
- What are dark matter and dark energy?
- Where is the universe headed?

A brief history of our universe



Cosmology probes: geometry and growth

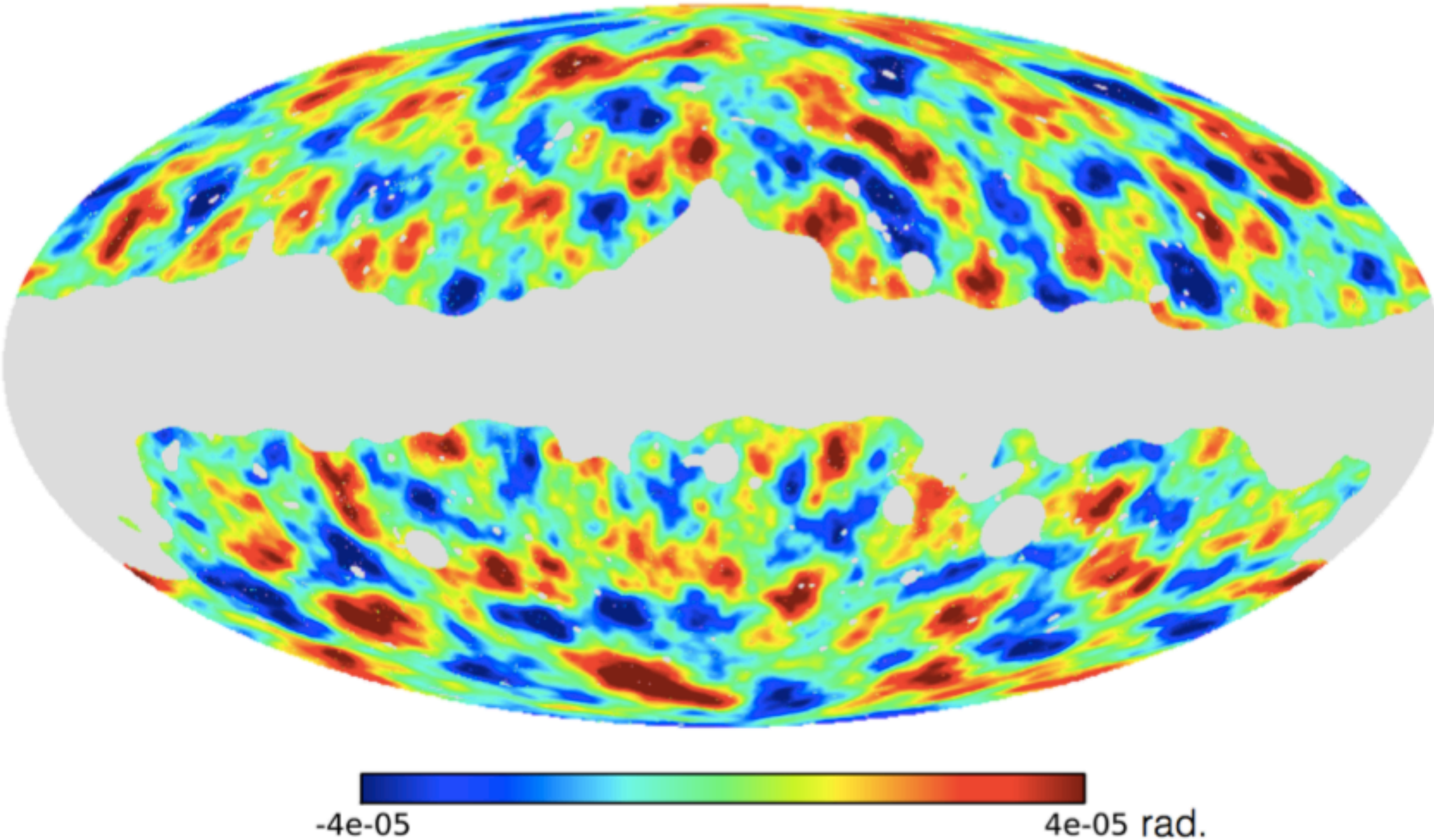
- Geometry: Distance-Redshift relation D(z), Expansion rate H(z)
- Growth: Fluctuations in temperature, mass, gas and galaxies



- The power spectrum of fluctuation in the Cosmic Microwave Background (CMB) temperature and polarization: t ~ 400,000 years
  – Tilt (inflation), locations of peaks (geometry), damping tail (neutrinos)
- Late time universe probes of geometry and growth: t ~ 1-14 billion years

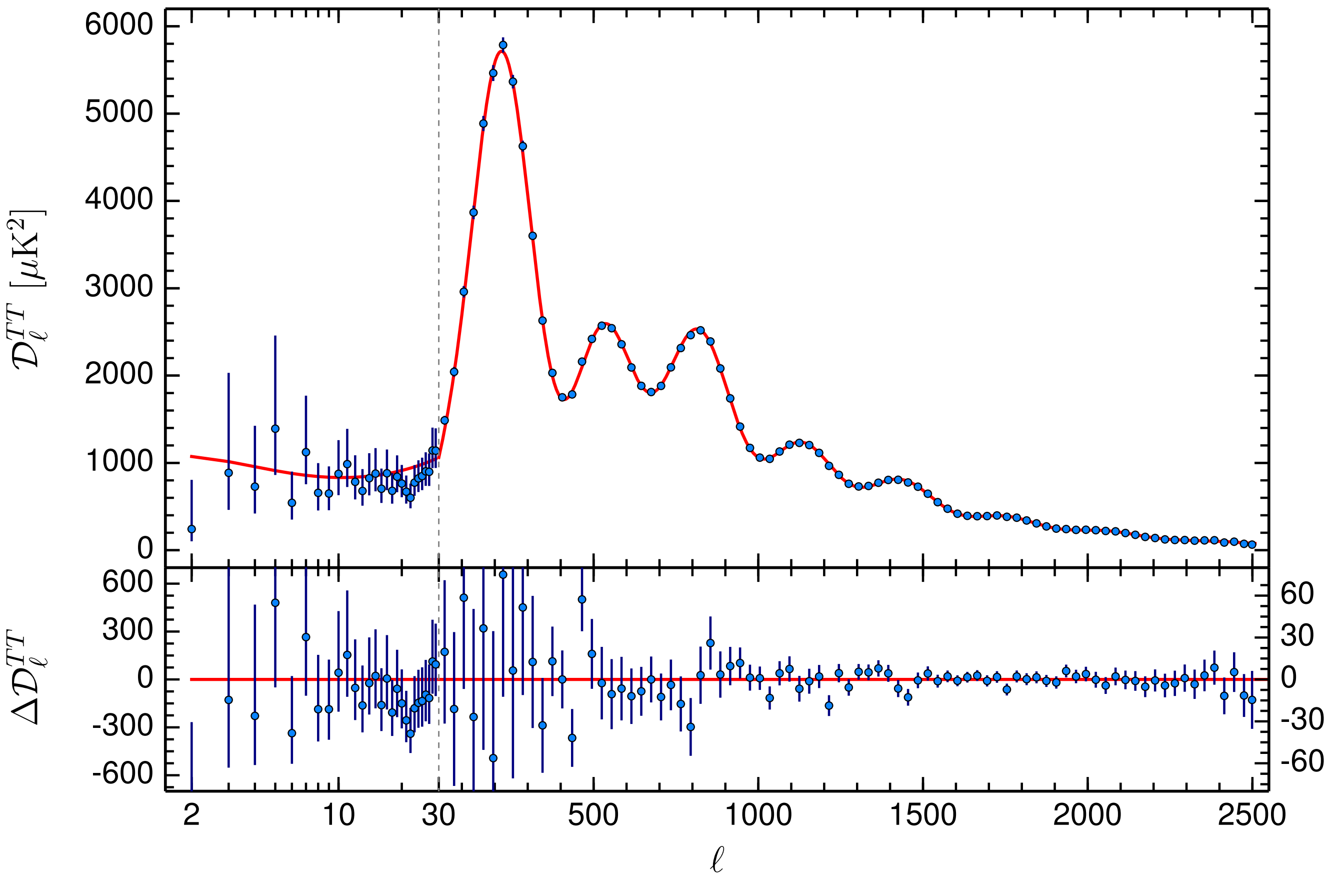
  - Combining CMB with late time data provides huge lever arm in scale and time: tests of inflation, dark energy, massive neutrinos, dark sector interactions

Cosmic Microwave Background Temperature



Planck satellite, arXiv:1502.01589

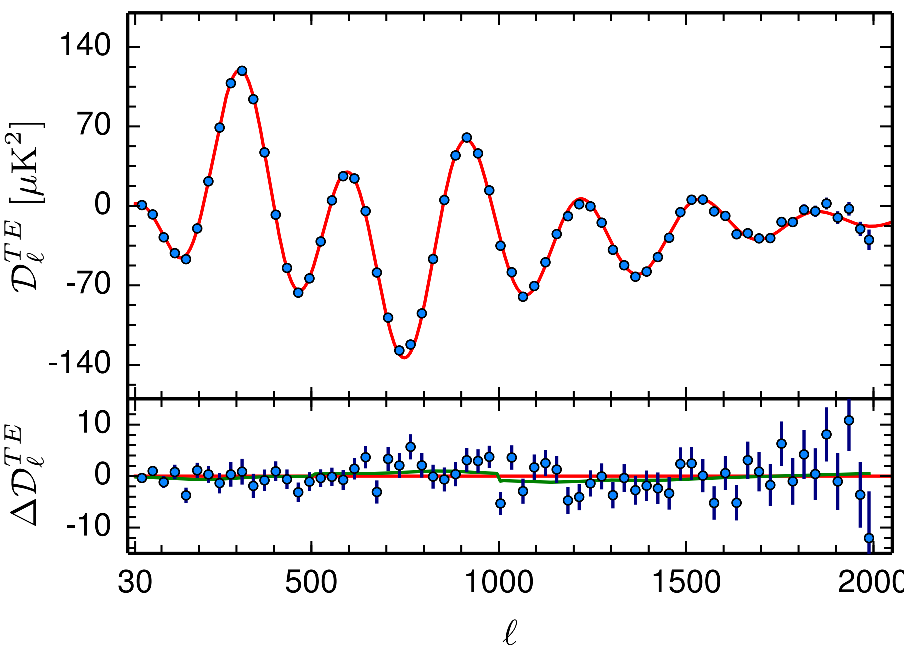
CMB temperature power spectrum

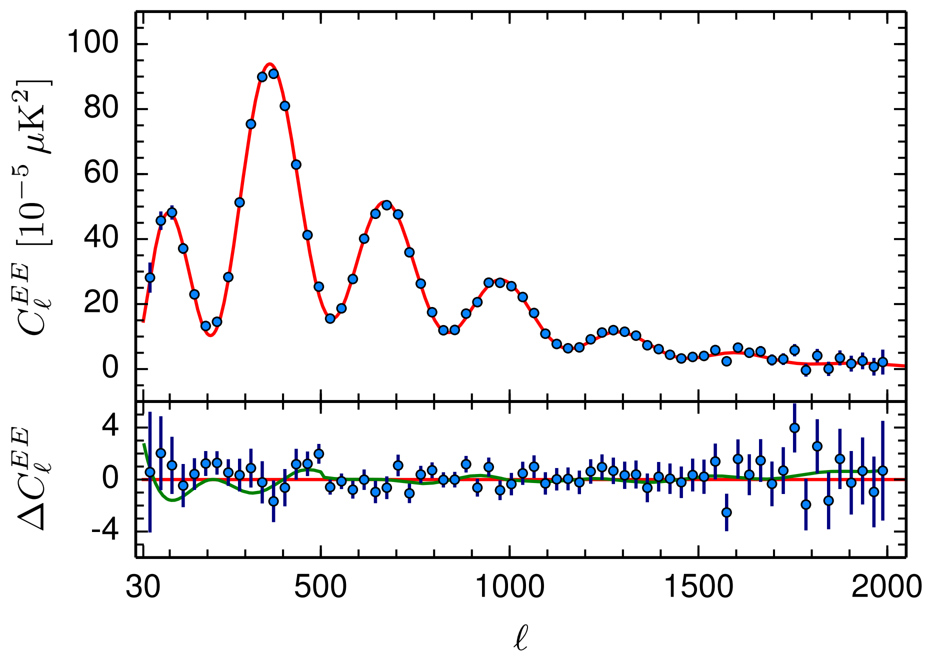


Power spectrum of temperature fluctuations from the Planck satellite

arXiv:1502.01589

CMB Polarization power spectra

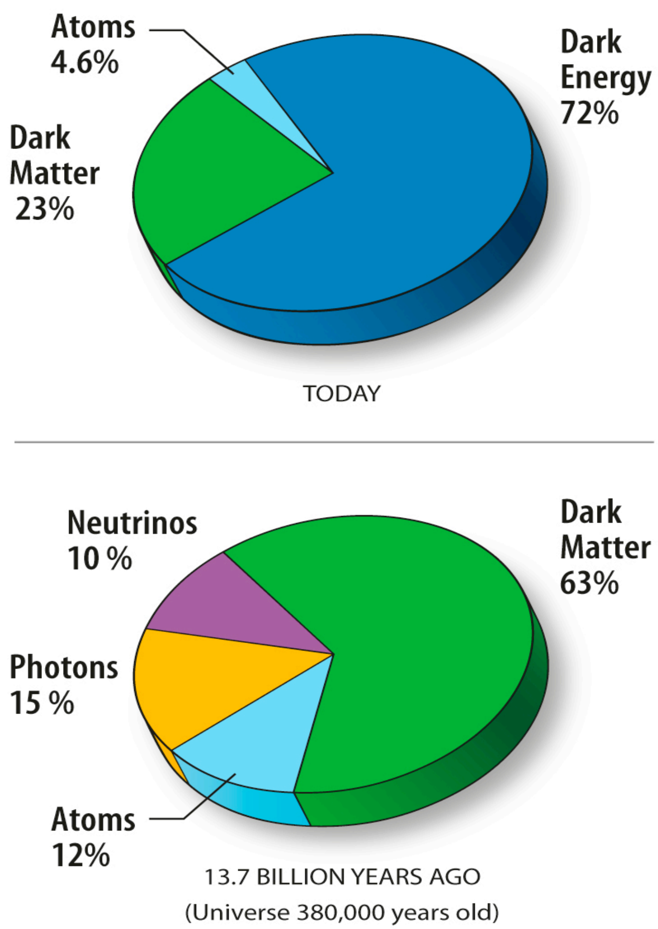




Power spectrum of polarization fluctuations from the Planck satellite

arXiv:1502.01589

From the CMB to the late universe: Energy budget over cosmic time

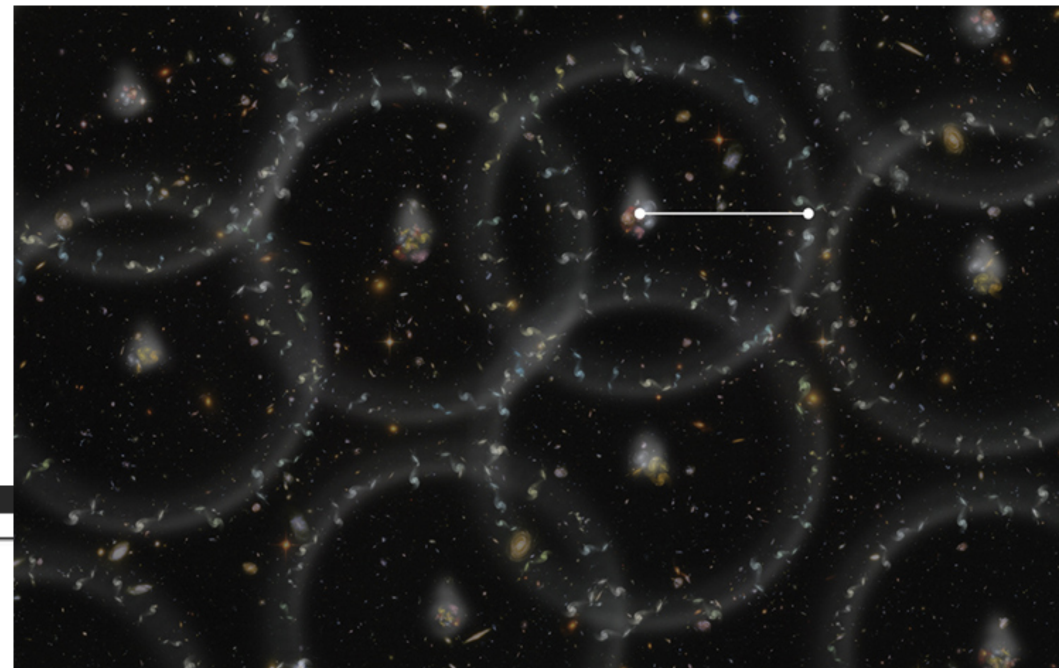


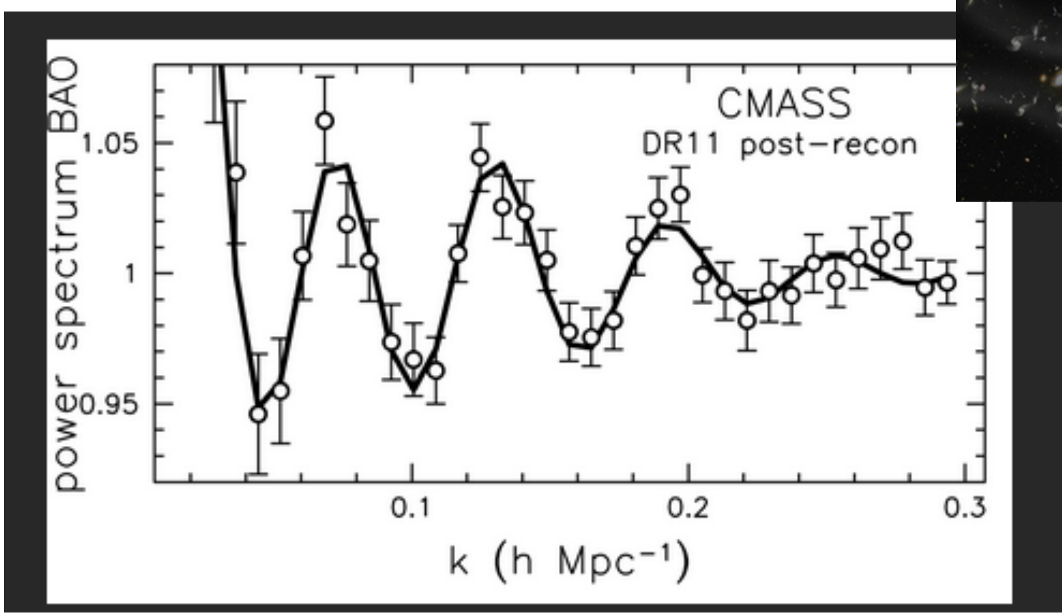
WMAP web site

Cosmology probes: late times

Probe	**Physical Observable**	**Sensitivity to Dark Energy or Modified Gravity**
Weak Lensing *Imaging*	Coherent distortions in galaxy shapes	Geometry and Growth of structure (projected)
Large-Scale Structure *Spectroscopic*	Power spectrum of galaxy distribution	Geometry (BAO) and Growth
Galaxy Clusters *Imaging + SZ/Xray*	Abundance of massive clusters	Geometry and Growth
Type Ia Supernovae *Imaging + Spectra*	Fluxes of standard candles	Geometry
Strong lensing *Imaging + Spectra*	Time delays	Geometry

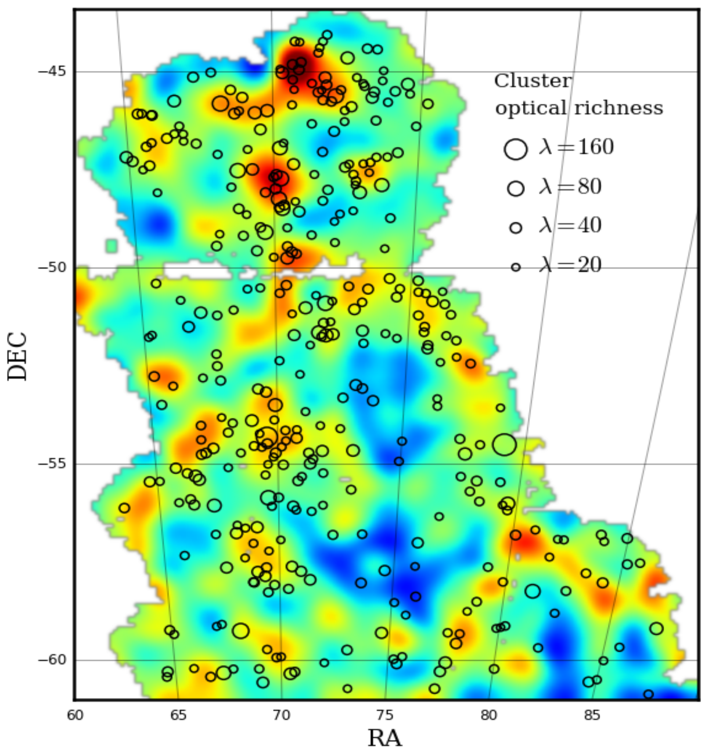
Baryon wiggles in the galaxy distribution



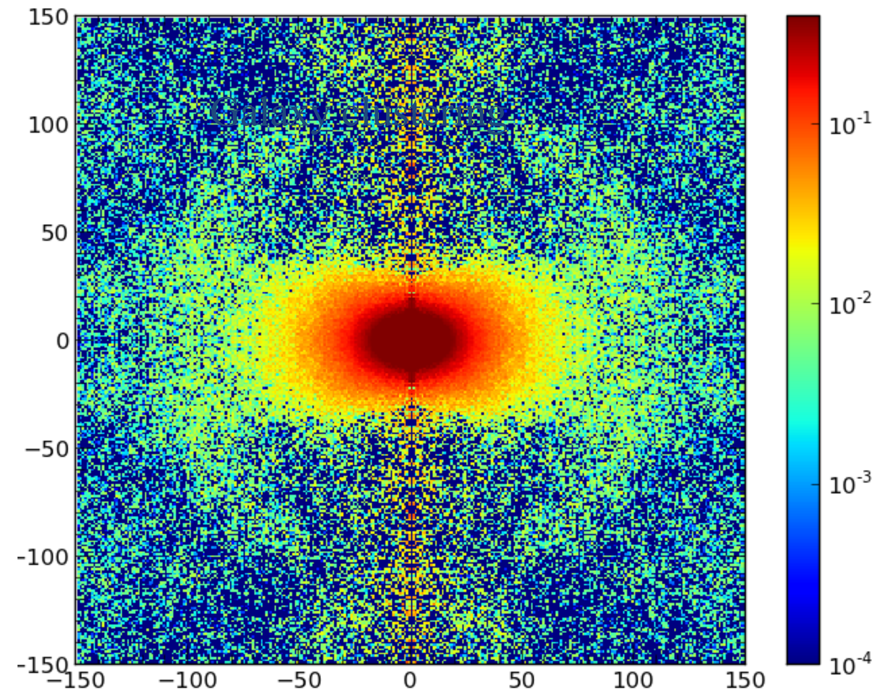


Anderson et al 2013, BOSS survey

Growth of structure



Gravitational Lensing



Galaxy distribution in redshift space

- Growth of structure: Galaxy clustering; Galaxy Clusters; Lensing; 21cm…
- CMB+low-z universe: generally consistent with inflation, and Λ-CDM
- Gome intriguing hints of deviation exist; tests will get much sharper in the next years

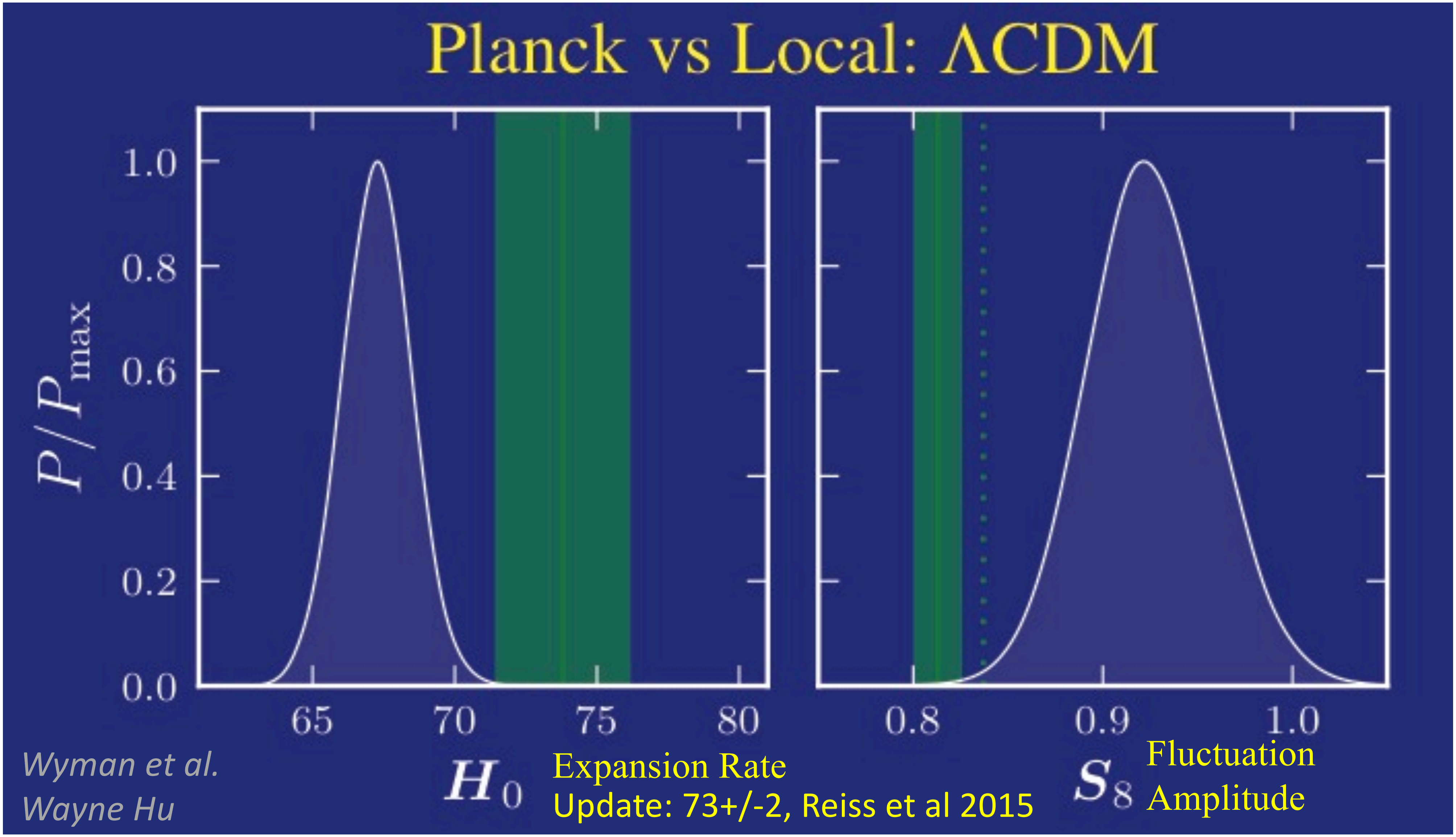
The parameters of the standard model

Parameter	[1] *Planck* TT+lowP
$\Omega_b h^2$	0.02222 ± 0.00023
$\Omega_c h^2$	0.1197 ± 0.0022
$100\theta_{MC}$	1.04085 ± 0.00047
τ	0.078 ± 0.019
$\ln(10^{10} A_s)$	3.089 ± 0.036
n_s	0.9655 ± 0.0062
H_0	67.31 ± 0.96
Ω_m	0.315 ± 0.013
σ_8	0.829 ± 0.014
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014

Present day parameters assuming ΛCDM (H_0, Ω_m, σ_8)

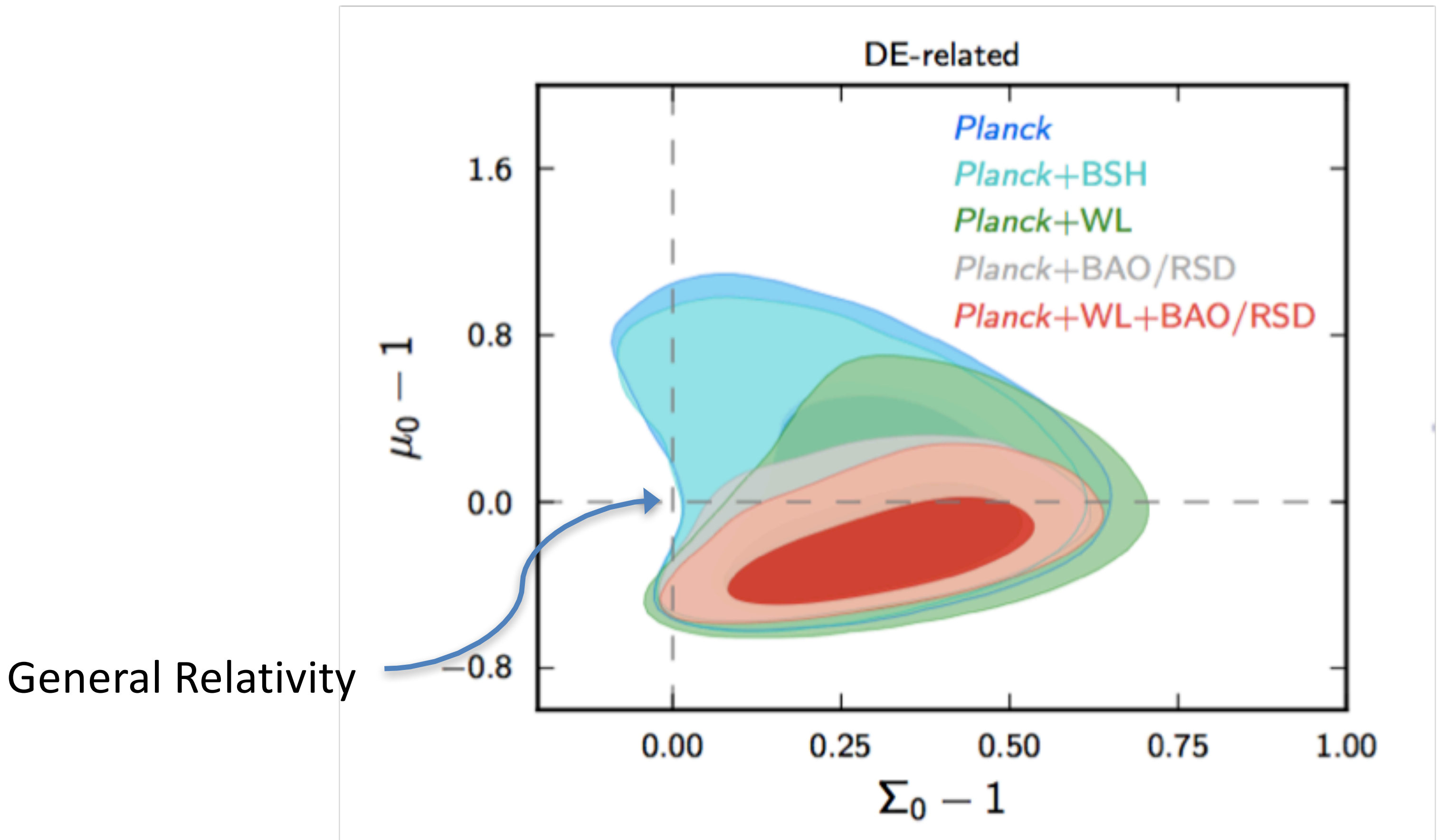
- Consistent with a spatially flat, GR+LambdaCDM universe
- H_0 (expansion rate), Ω_m (mass density) and σ_8 (amplitude of fluctuations): compare extrapolation of CMB to present day measurements – discrepancy signals breakdown of standard model!
- Sum of neutrino masses < 0.2 eV (Planck + BOSS)

(Mild) tension in cosmology data



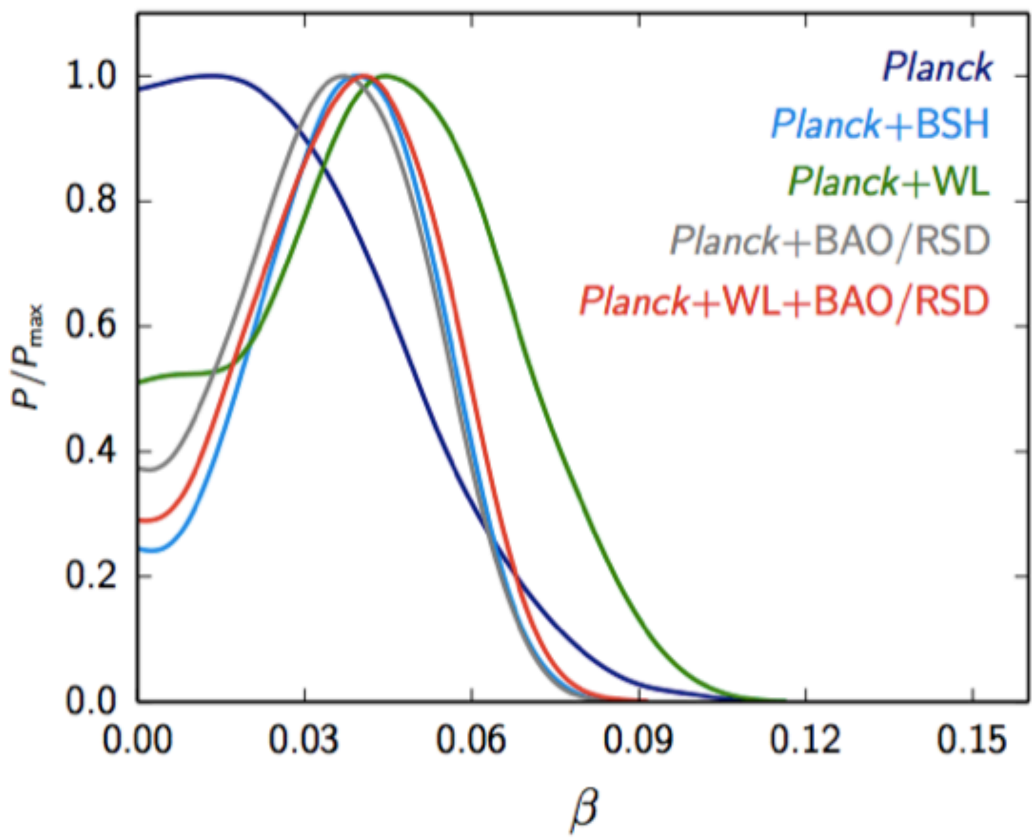
Extrapolation from CMB to present disagrees with low-z measurements in *some* cases.

(Mild) tension in cosmology data: metric potentials in the Poisson eqn



Planck collaboration, 2015

(Mild) tension in cosmology data: coupling of dark energy-dark matter



Planck collaboration, 2015

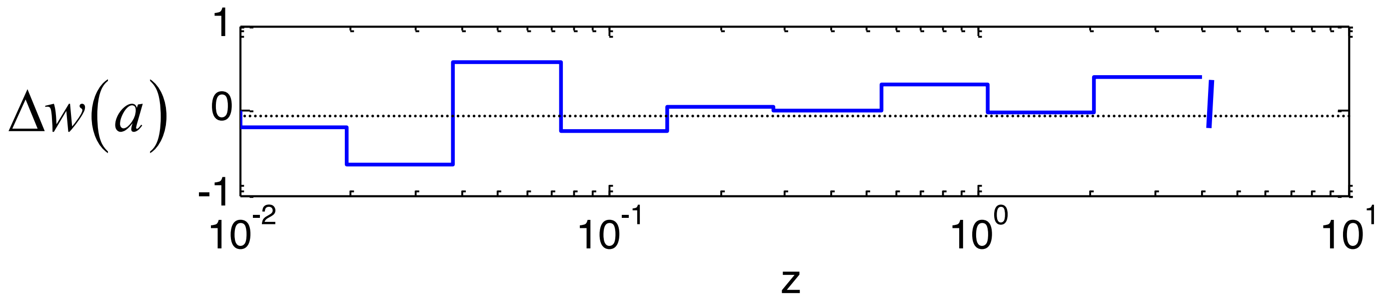
– Overview of cosmology

– Beyond the standard model

– New tests of gravity

– Results from the Dark Energy Survey

Beyond Λ



- Is dark energy constant in redshift?
- Is dark energy spatially clustered or anisotropic?
- Are there couplings/interactions between dark energy, dark matter, baryons?
- Is it dark energy or modified gravity?

New degrees of freedom in the universe

- Theorem: Cosmological constant is the `unique' large distance modification to GR that does not introduce any new degrees of freedom

- Dynamical models of Dark Energy or Modified Gravity invoke new degrees of freedom (also arise in string theory, higher dimension theories…).

- Modified gravity (MG) theories typically invoke a scalar field coupled non-minimally to gravity. The scalar enhances the gravitational potential
  ➡ observable effects on all scales, mm to Gpc!

- In addition
  - Dark energy and dark matter can directly couple to standard model particles, leading to other 5th force-like effects.
  - Dark matter particles may have self-interactions

Modified gravity and scalar fields

- Consider a scalar $\phi = \phi_b + \delta\phi$ coupled to the energy density ρ.
- Since it is light, the long range, scalar force inside the solar system must be suppressed to satisfy tests of the equivalence principle and GR.
- In the last decade, some natural ways to achieve this have been realized by theories designed to produce cosmic acceleration.
- The generic form of the equation of motion for $\delta\phi$ is:

$$Z(\phi_b,\rho_b)\left[\frac{d^2\delta\phi}{dt^2}-c_s^2\frac{d^2\delta\phi}{dx^2}\right]+m^2(\phi_b,\rho_b)\delta\phi=\beta(\phi_b,\rho_b)G_{\rm Newton}\delta\rho$$

kinetic term

mass term
(range of interaction)

coupling to matter

A. Tolley

Screening: how to hide enhanced gravity

$$\delta F \approx \frac{M_a M_b G}{r^2} \frac{\beta^2(\phi_b, \rho_b)}{\sqrt{Z}(\phi_b, \rho_b) c_s(\phi_b, \rho_b)} \exp(-m(\phi_b, \rho_b) r)$$

To keep force enhancement small, this term must be small.
Only 3 options!

(a) Coupling ***β*** is small (Symmetron)
(b) Mass ***m*** is large (Chameleon)
(c) Kinetic term ***Z*** is large (Vainshtein)

- The three mechanisms of screening lead to distinct observable effects as one transitions from MG on large scales to GR well inside galaxies
- A successful MG theory must incorporate a screening
- The parameters that observations constrain:
  - coupling ***β*** & mass ***m*** (the range of the scalar force λ)

Signatures of modified gravity

- Unscreened environments in the universe will show these signatures of gravity: from cosmological scales to nearby galaxies

$$ds^2 = -(1+2\psi)dt^2 + (1-2\phi)a^2(t)d\mathbf{x}^2$$

- GR: $\Psi = \Phi$. MG: $\Psi \neq \Phi$.
- Generically extra scalar field enhances forces on stars and galaxies
  - *acceleration* $= -\nabla \Psi = -\nabla (\Psi_S + \Psi_N)$

- Photons respond to the sum ($\Psi + \Phi$) which is typically unaltered
  - Dynamical masses are larger than Lensing (true) masses

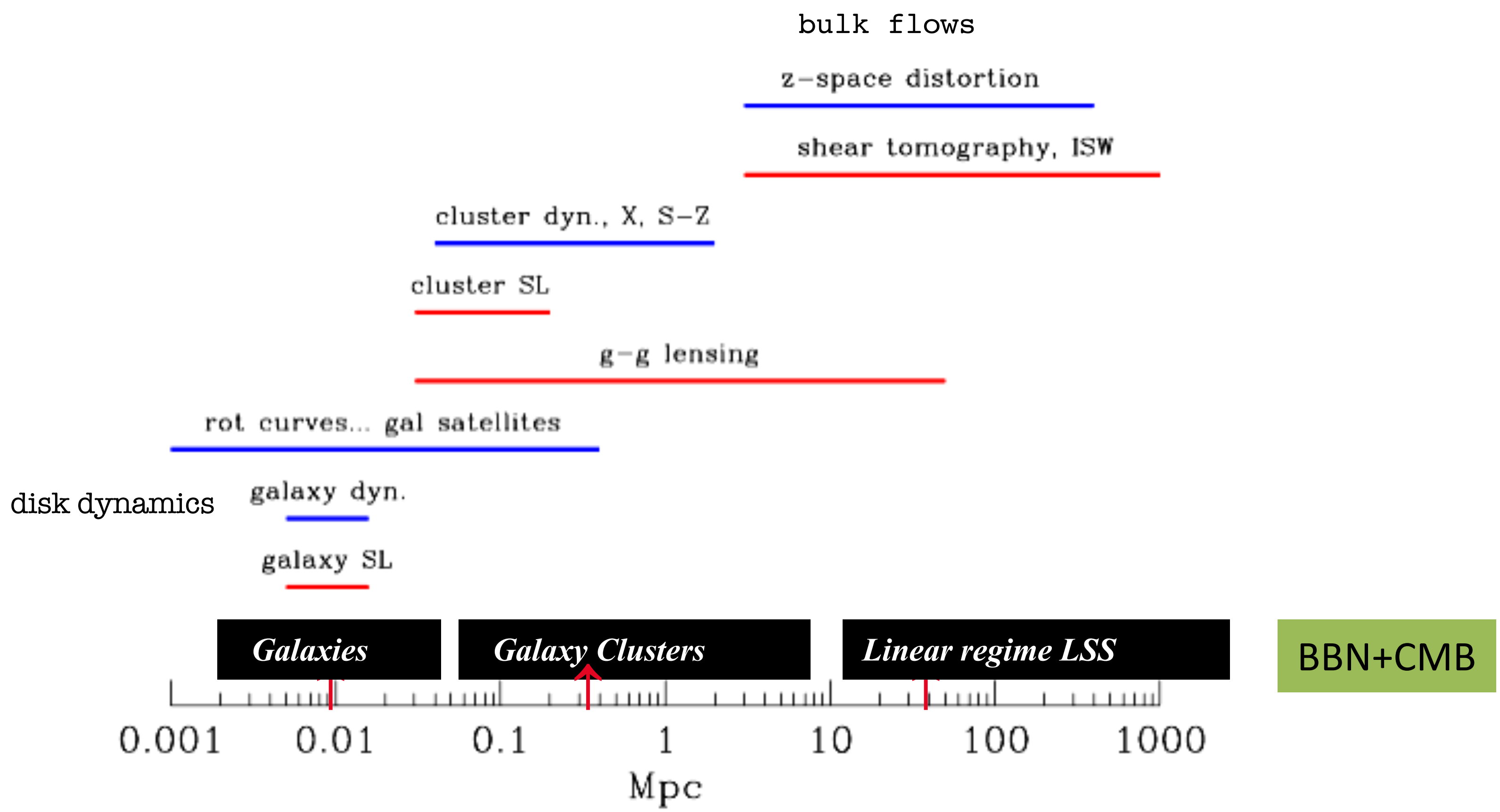
Einstein ring test of gravity

ψ/ϕ = 1.01+/-0.05 from Einstein Rings + velocity dispersion

Bolton et al 2006; Schwab, Bolton, Rappaport 2010

Tests on large scales will be carried out with upcoming surveys

Tests of gravity and the dark sector



Dynamical probes (blue) measure Newtonian potential ψ

Lensing and ISW (red) measures $\phi + \psi$

BJ & Khoury 2010; Joyce, BJ, Khoury, Trodden 2014; BJ et al, Snowmass report 2013

- Overview of cosmology
- Beyond the standard model
- New tests of gravity
- Results from the Dark Energy Survey

Gravitational Lensing

Unlensed

Lensed

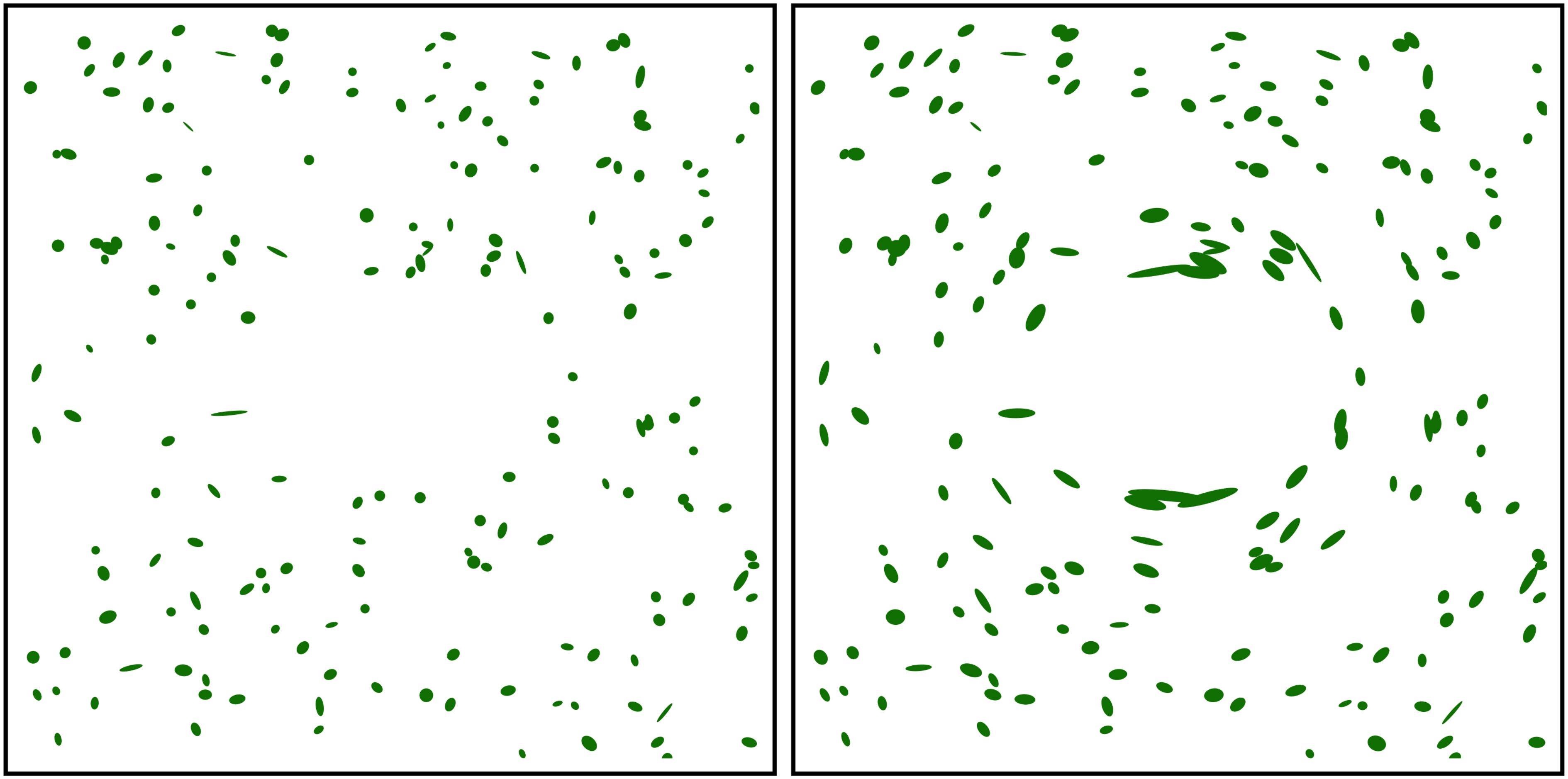
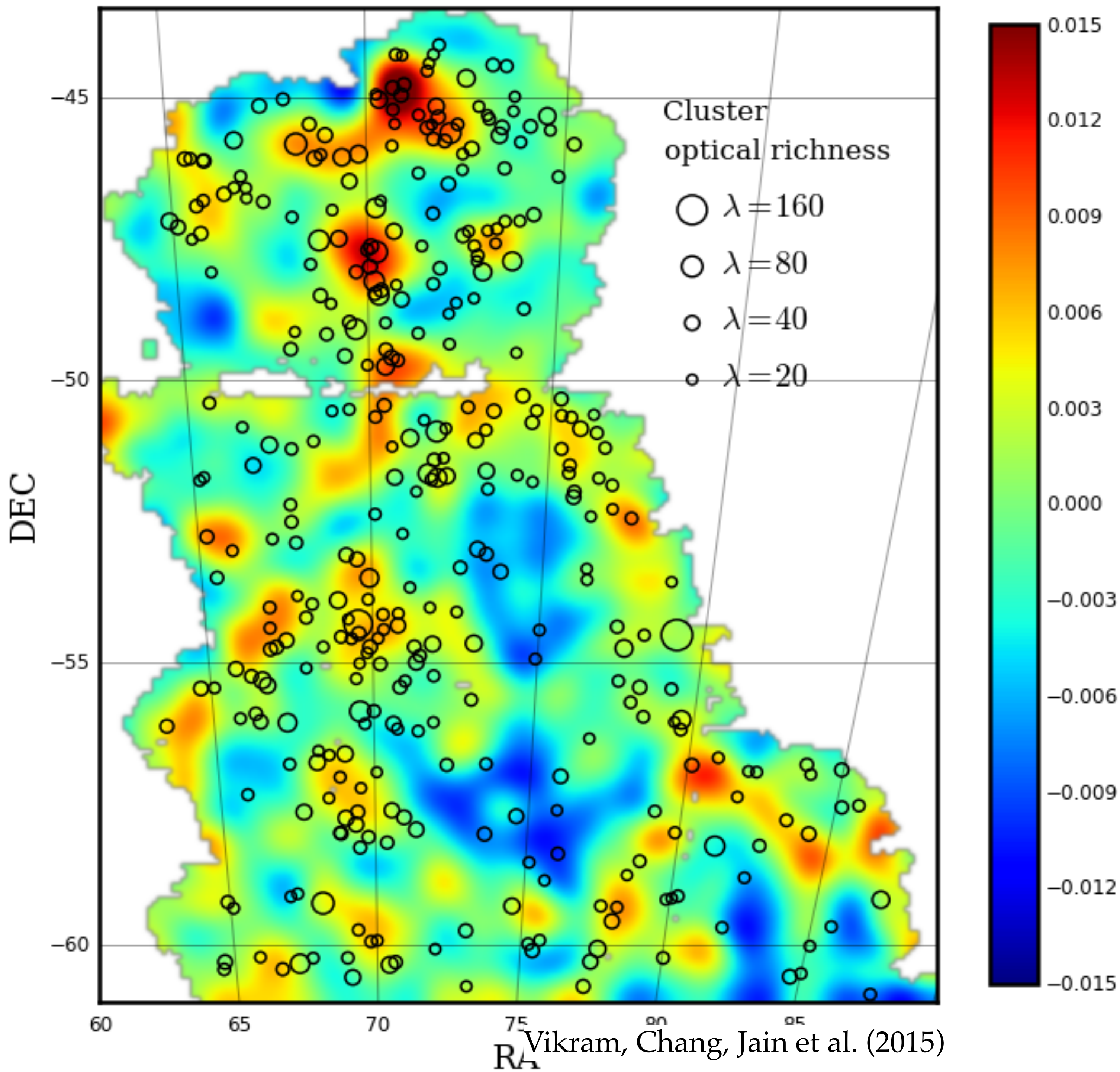


Image credit:
Jim Bosch

Mass and Light



Vikram, Chang, Jain et al. (2015)

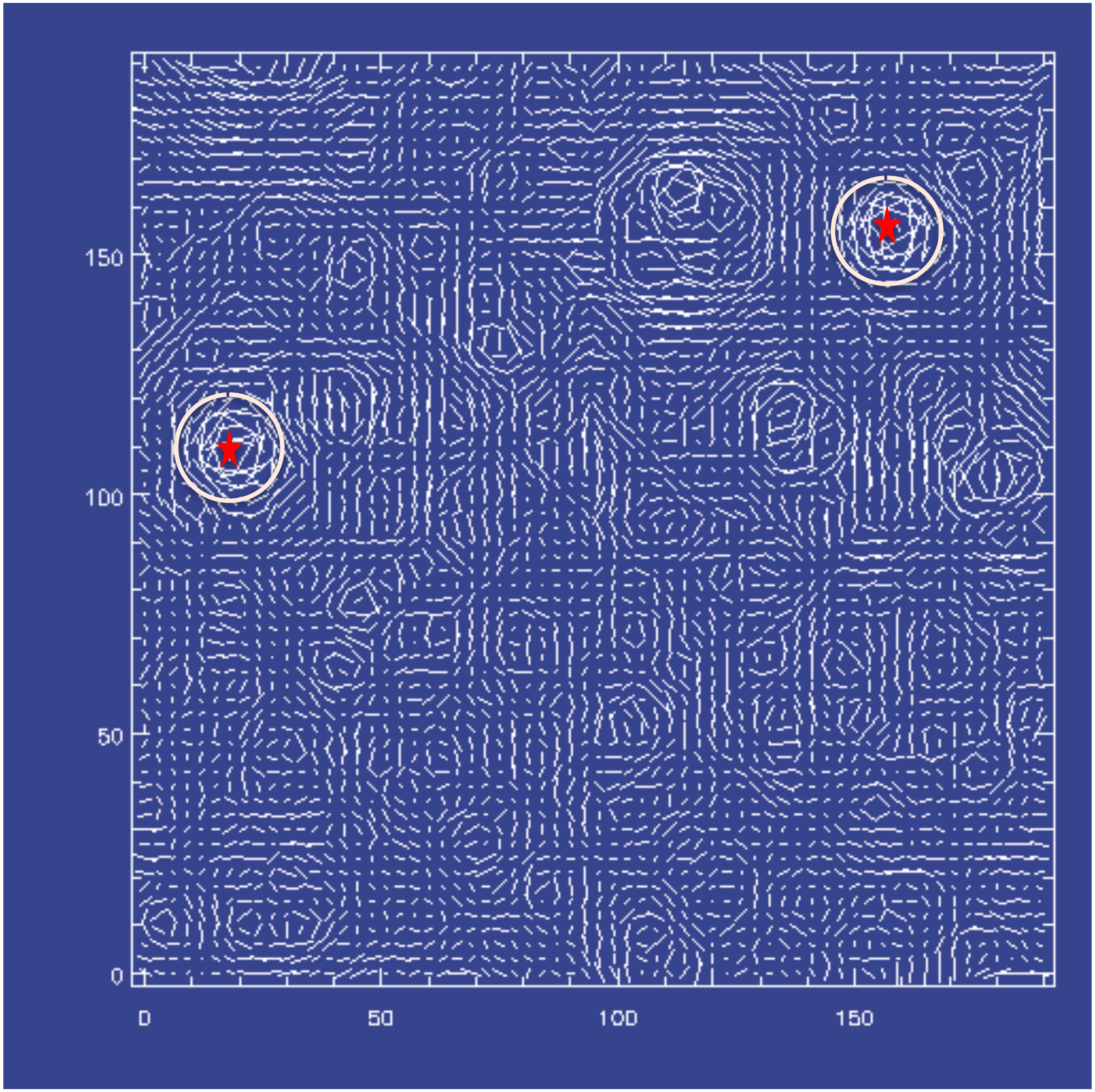
Questions about Halos and Voids

- What is the edge of a dark matter halo?
- How round and smooth are halos?
- How empty are voids? Do they cluster?

For the first time we are able to measure both the light and the mass – and answer these questions.

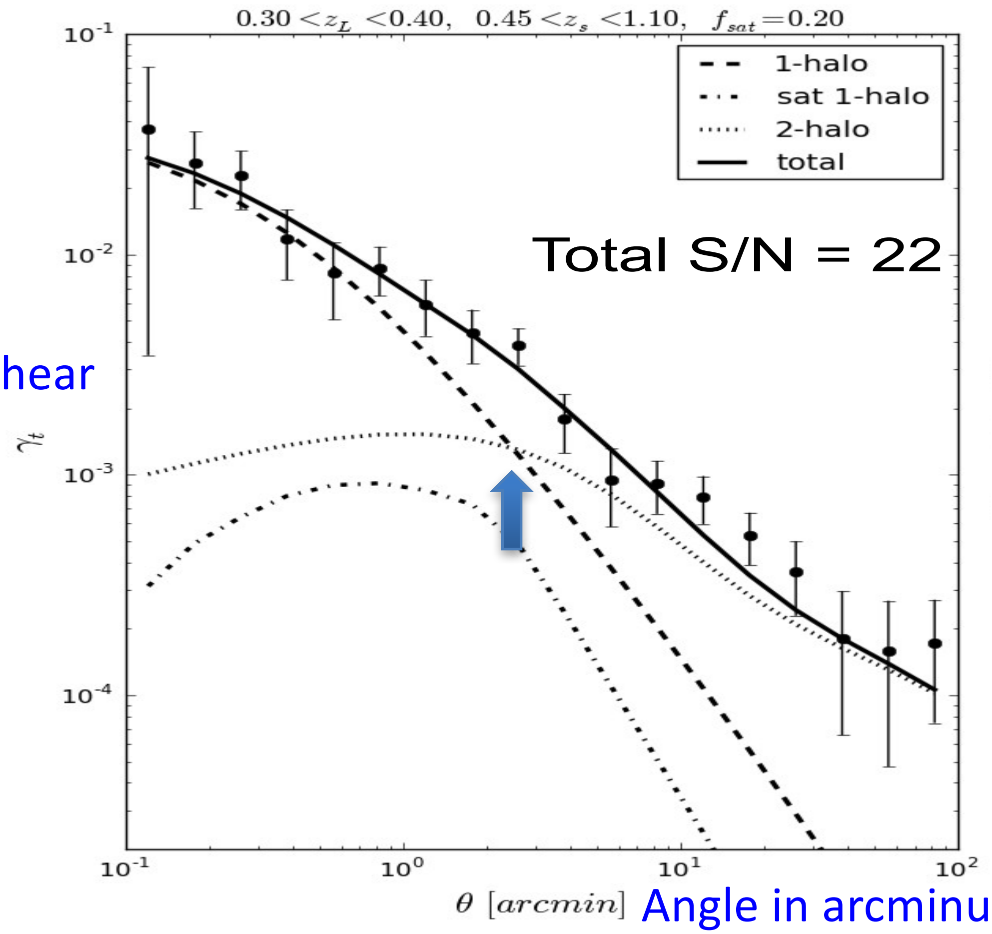
These small scale measurements enable new tests of fundamental physics.

Mass profiles via shear cross-correlations



Halo mass profile

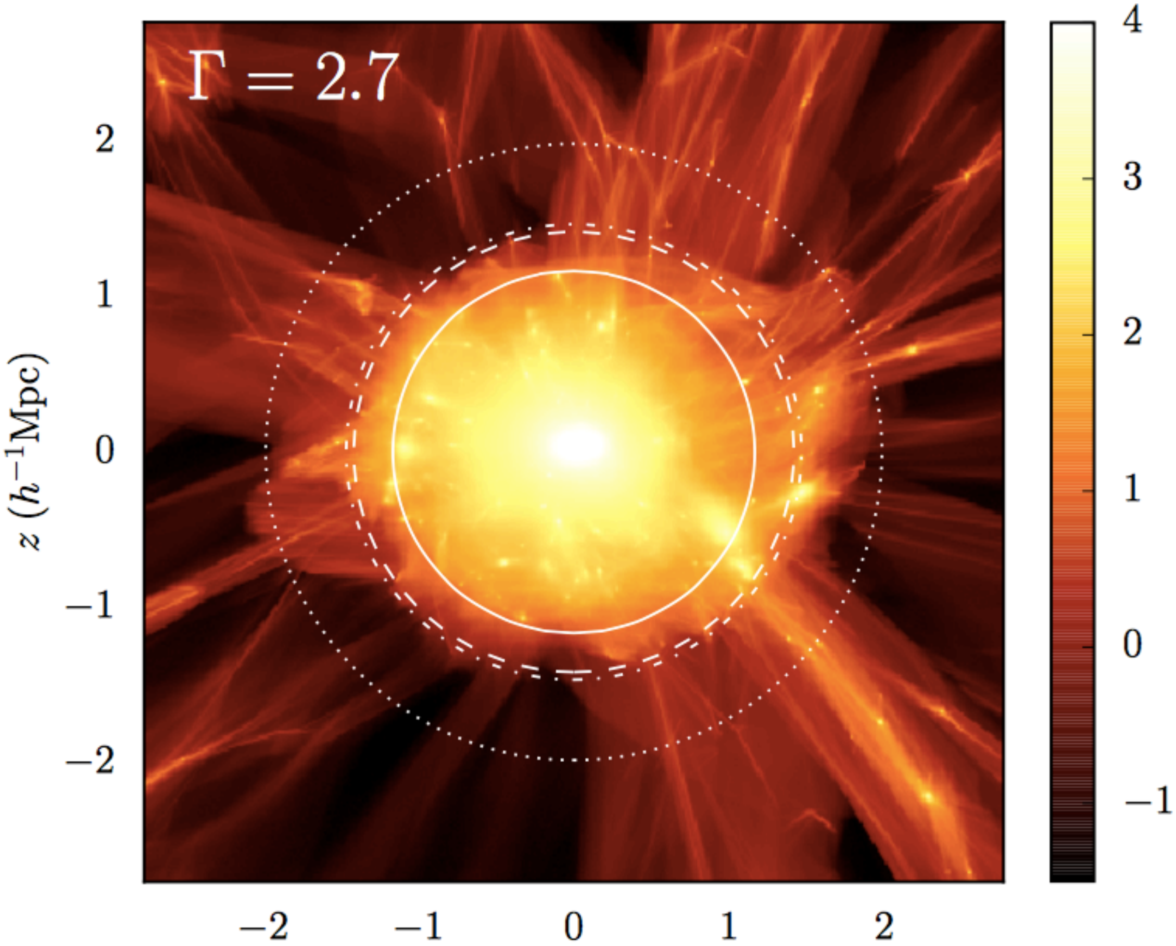
Tangential shear



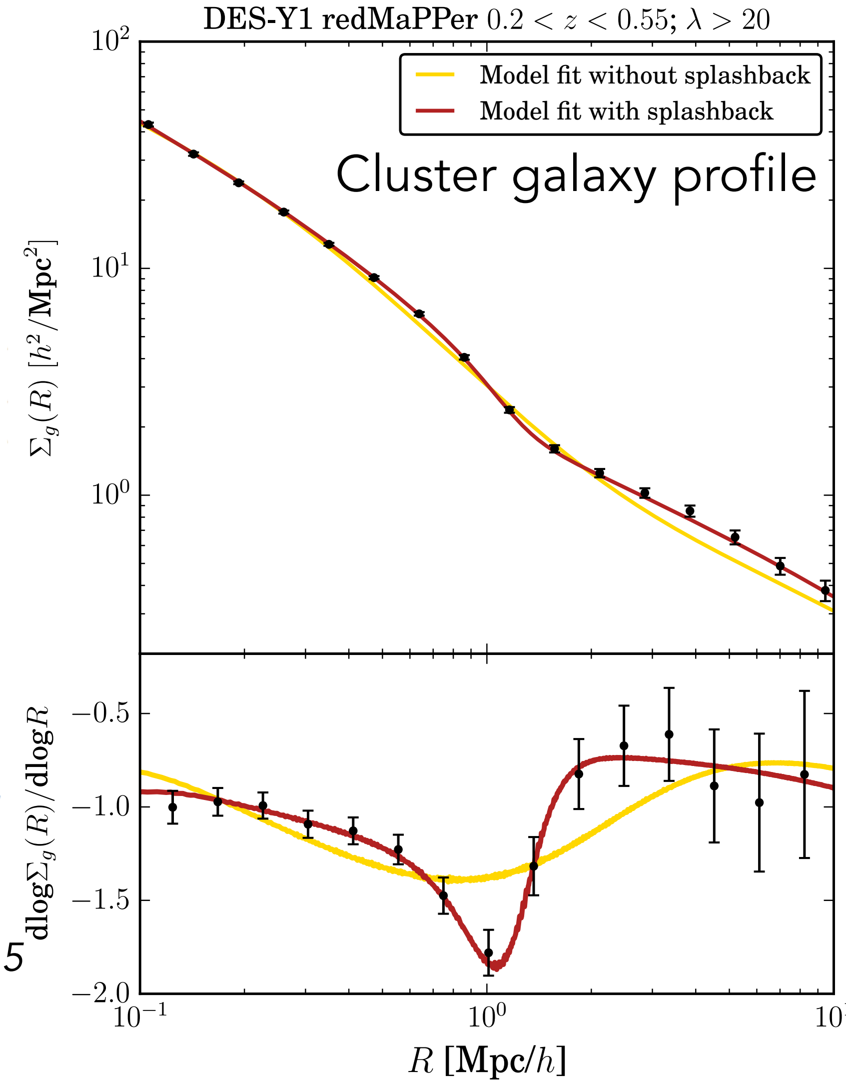
Angle in arcminutes

Measurement and modeling of halo mass profiles: 1 and 2-halo terms
Clampitt et al 2016 (DES collaboration)

The edge of halos



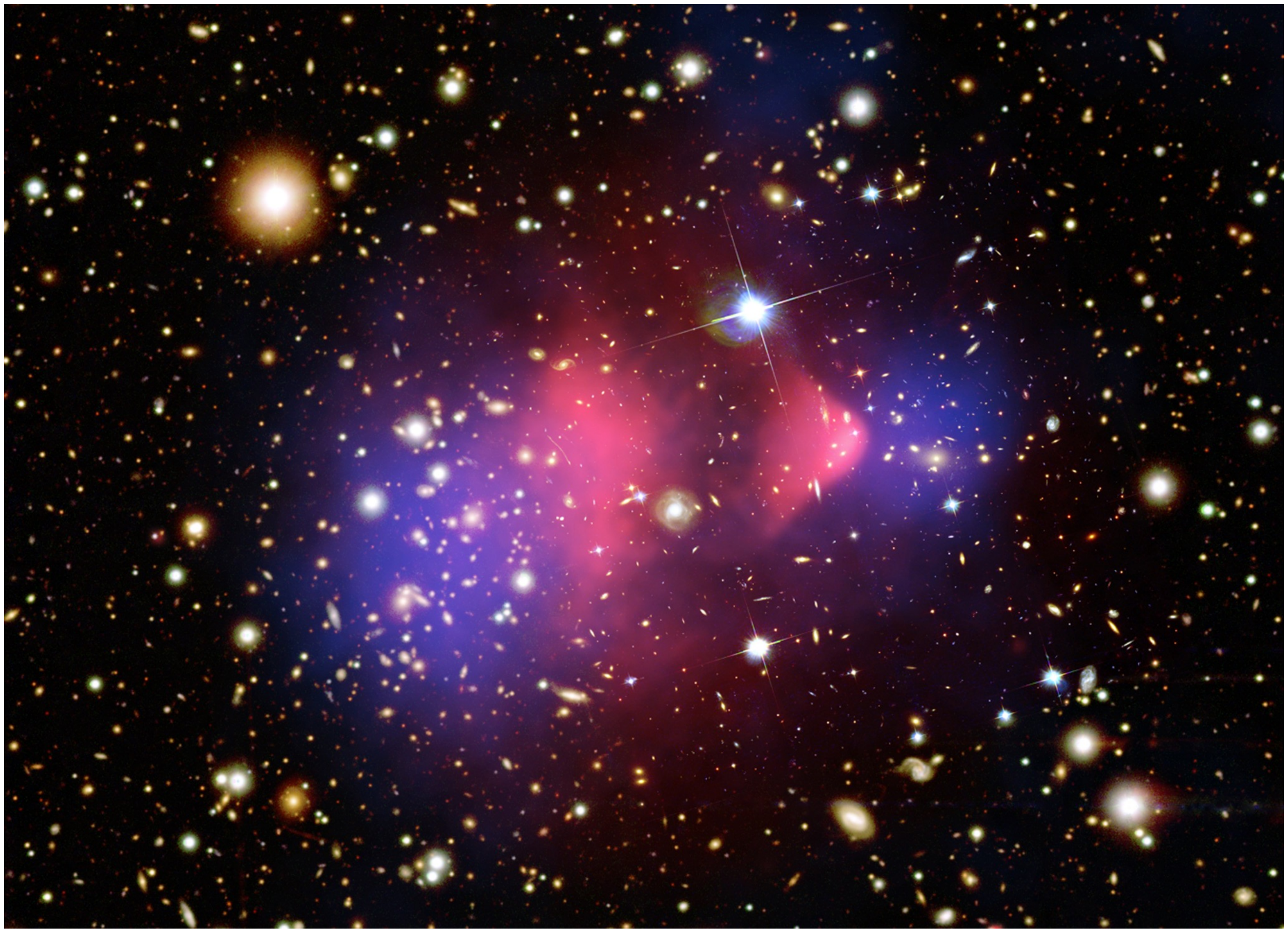
More,Diemer,Kravtsov 2015
Diemer, Kravtsov 2014



Splashback: radius at which accreted matter reaches apocenter

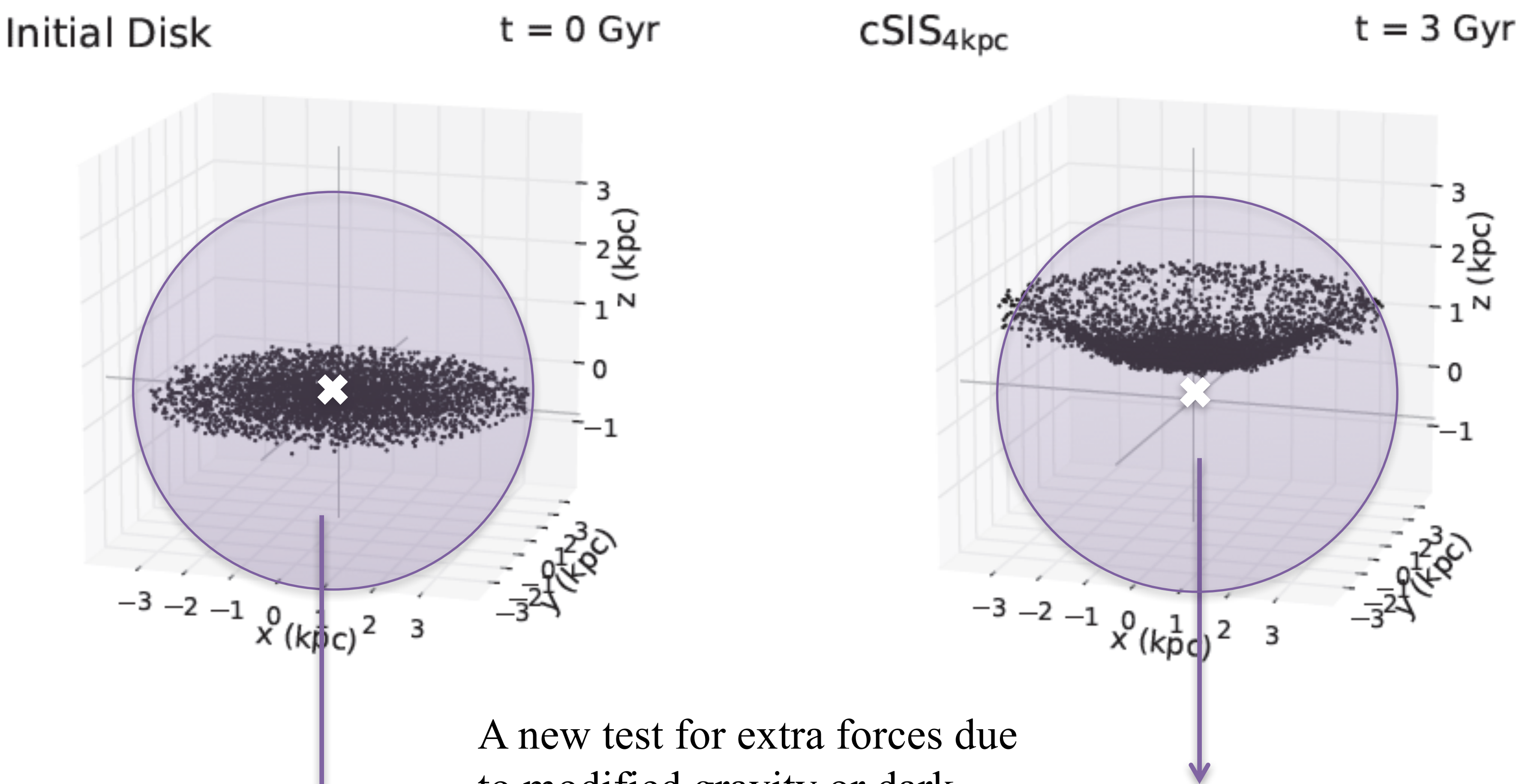
Baxter, Chang, Sanchez, BJ, DES collab.
More et al 2016

Dark matter self-interaction: Bullet cluster



Coincidence of dark matter and stars: sigma/m < 1 cm^2/g

Disk galaxies and dark interactions



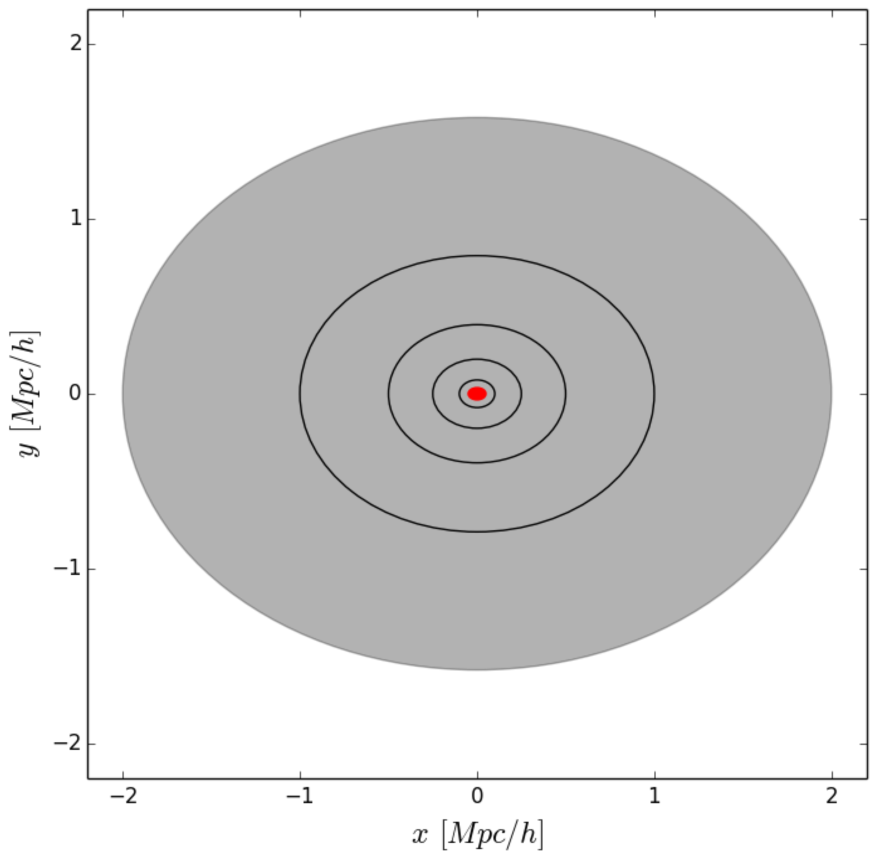
A new test for extra forces due to modified gravity or dark matter self-interactions

BJ & VanderPlas 2011

Secco et al, in preparation

How round are halos?

halo ellipticity, gravity and dark matter



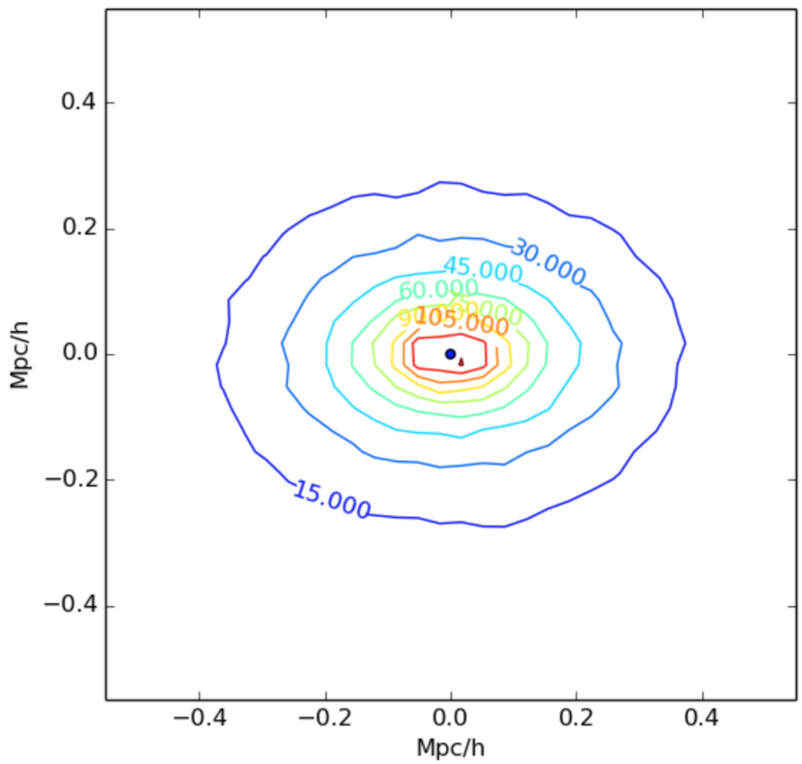
For typical galaxies, the halo virial radius is ~20x larger than the visible stars.

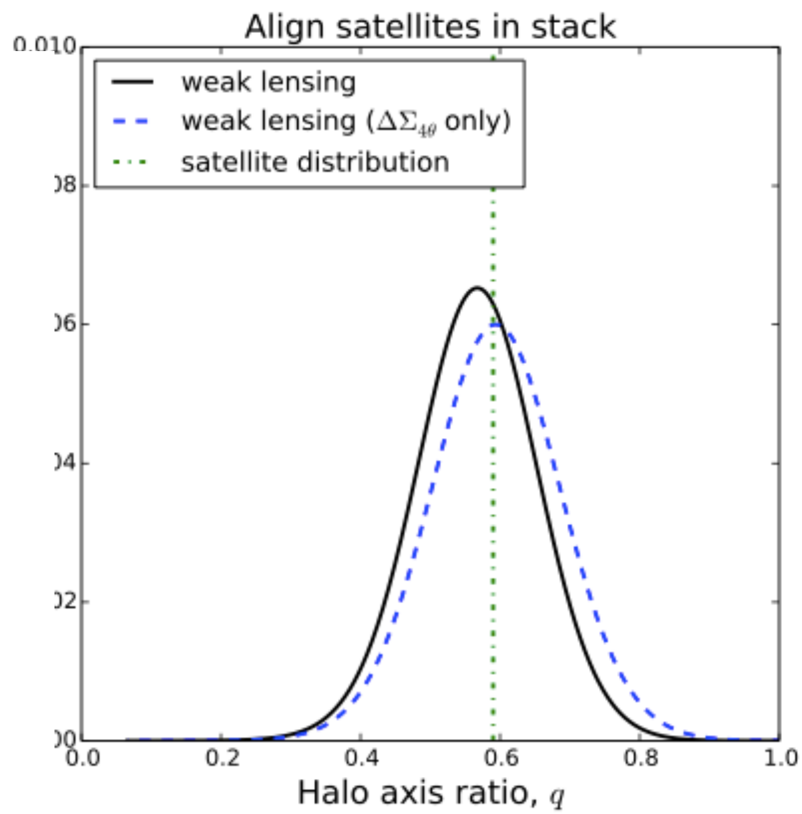
- How elliptical are the density contours?
- How do they change with radius?
- How do they relate to the light?

- Some attempts to modify gravity produce rounder contours with increasing radius.
- Other theories involve self-interacting dark matter, which makes the halo rounder at small radii.

Galaxy Cluster Halos

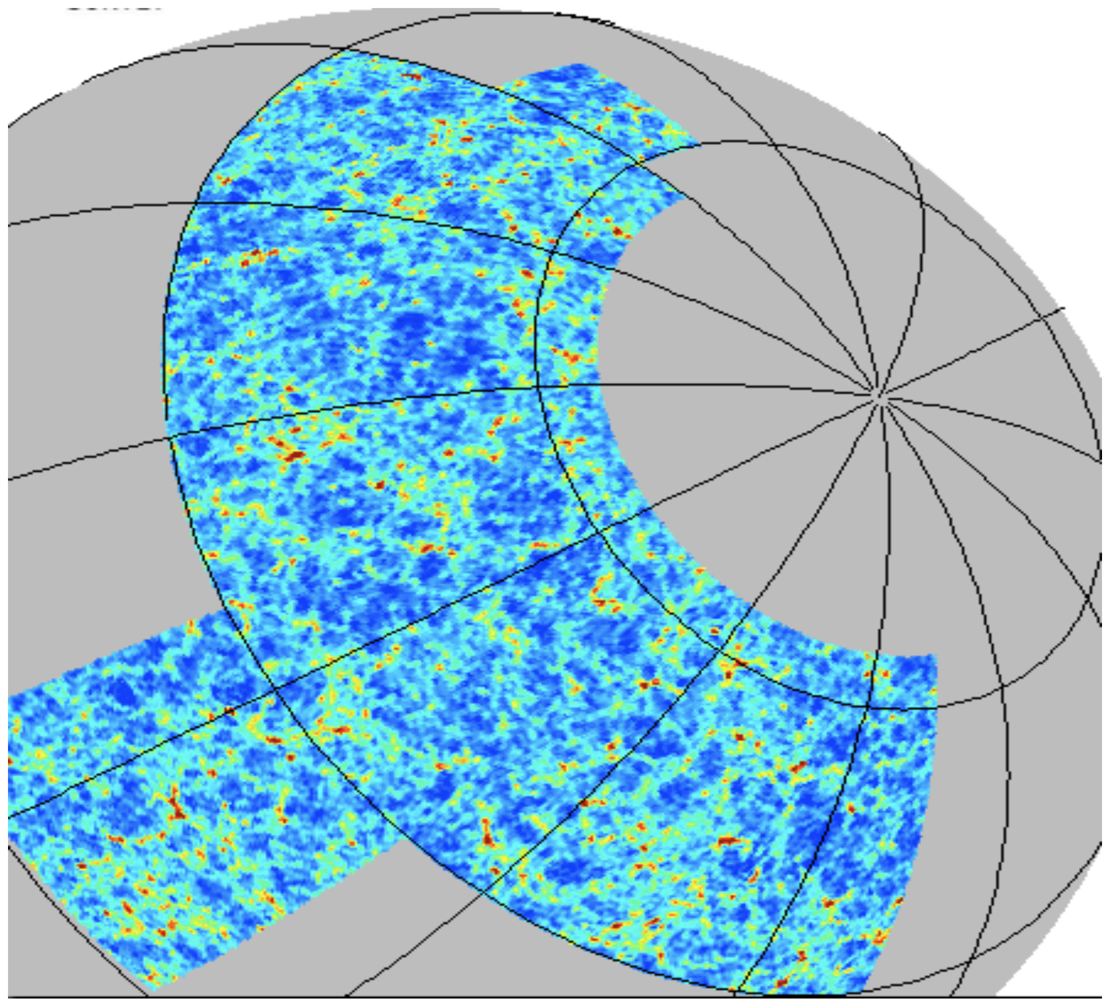
- We used a new estimator to measure halo ellipticity using lensing.
- The best fit axis ratio for these redMaPPer clusters is 0.6. Nearly 5-sigma detection.
- Galaxy halo shapes -- in progress..





Clampitt and BJ, 2015

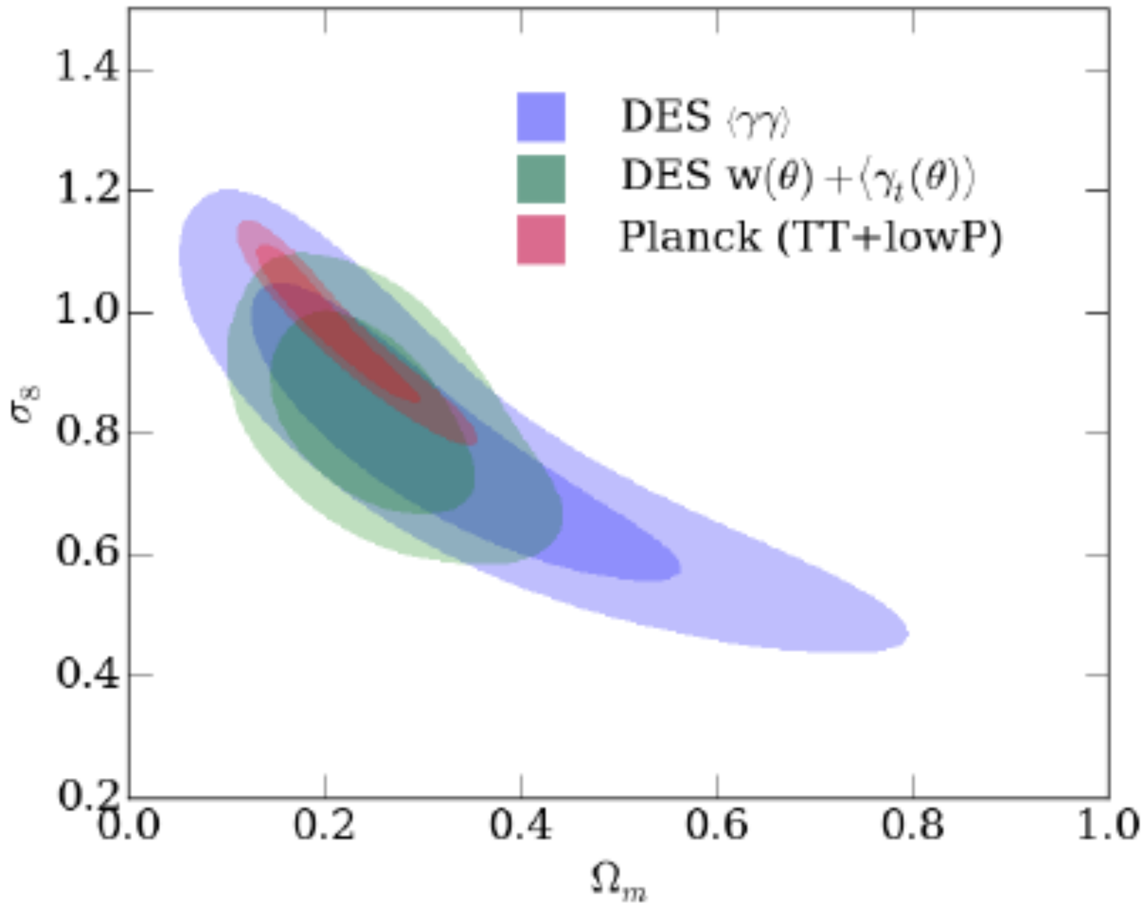
Dark Energy Survey



•500 Mpix camera for Cerro Tololo 4-meter telescope

•5-year, 5000-square-degree: 2+ years completed

Galaxy clustering + Lensing

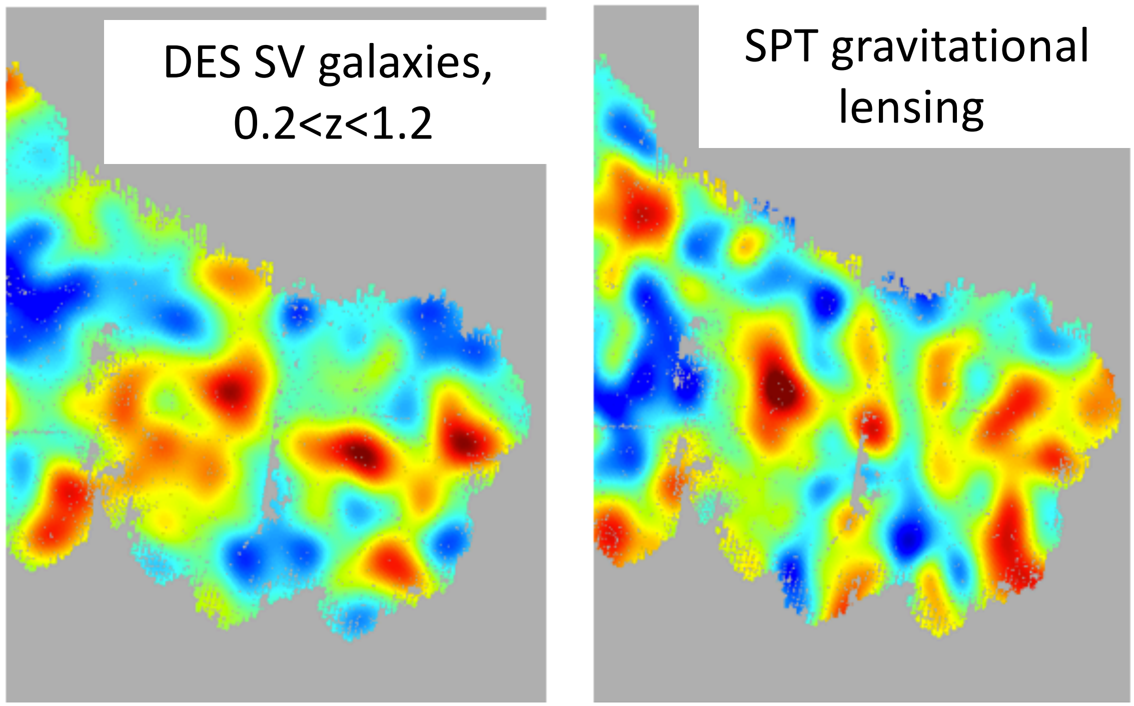


Constraints on the amplitude of mass fluctuations

Kwan et al, DES Collaboration 2016; Cacciato et al 2012; van den Bosch et al 2012; Mandelbaum et al 2012…

New analyses with DES are underway….including the impact of massive neutrinos on the matter and galaxy distribution

Galaxies x CMB



Giannantonio et al 2015; Saro et al 2015; Kirk et al 2016; Baxter et al 2016

Outlook

- With Galaxy + CMB surveys we are testing many aspects of the GR-ΛCDM model.
- New measurements of large-scale correlations, as well as the interior of galaxy halos and voids, help test galaxy formation theories and dark sector interactions.
- Surveys that will be completed or mature in the next 5 years:
  - Imaging surveys: DES, KiDS, HSC…
  - Spectroscopic surveys: +PFS, Hetdex, DESI…
  - CMB experiments: next generation SPT, ACT, Simons Observatory…
  - 21cm surveys: CHIME, HERA…
- 2020's: LSST, Euclid, WFIRST, SKA, CMB-S4 …