Lensing measurements of galaxies, voids and the CMB

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The Dark Energy Survey:
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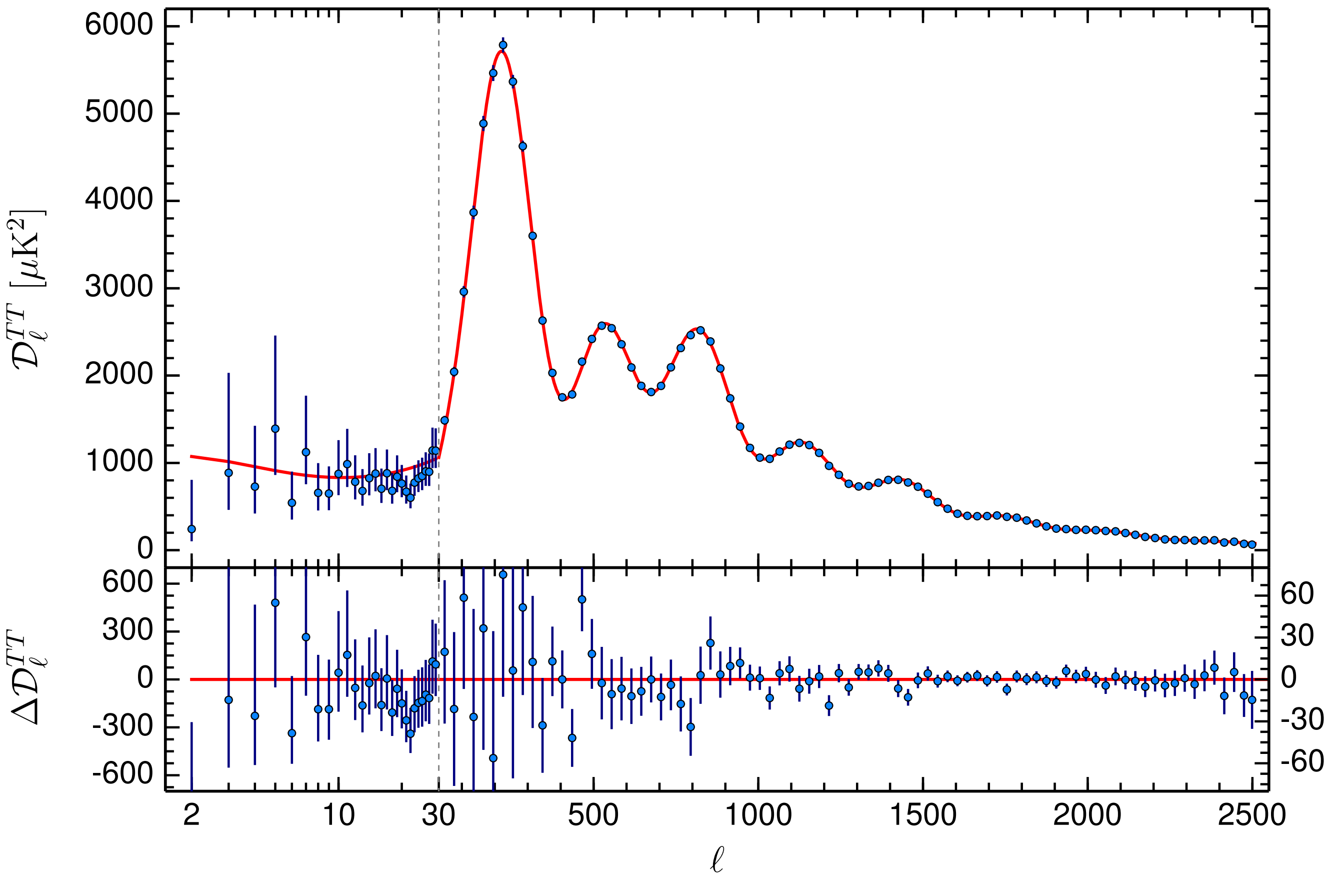
Outline

- Cosmology today
- Beyond the standard model
- Lensing by halos and voids
- Cosmological weak lensing

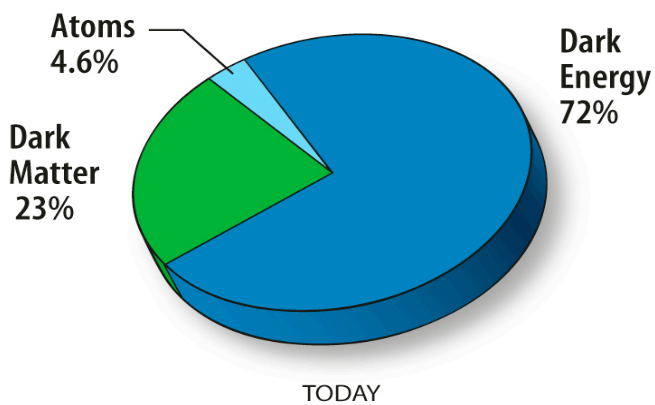
Cosmic Microwave Background

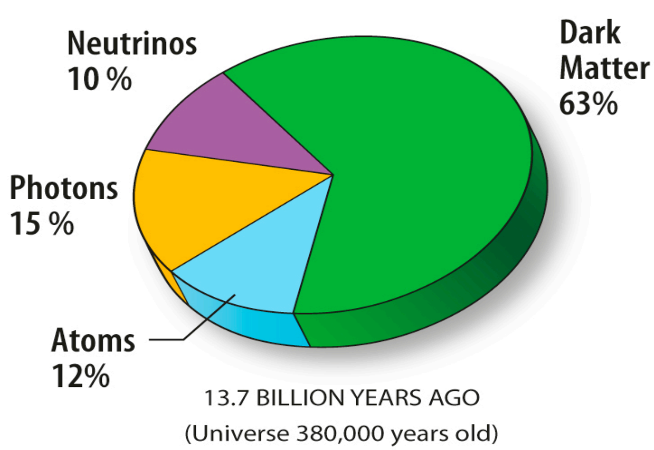


Power spectrum of temperature fluctuations from the Planck satellite

arXiv:1502.01589

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

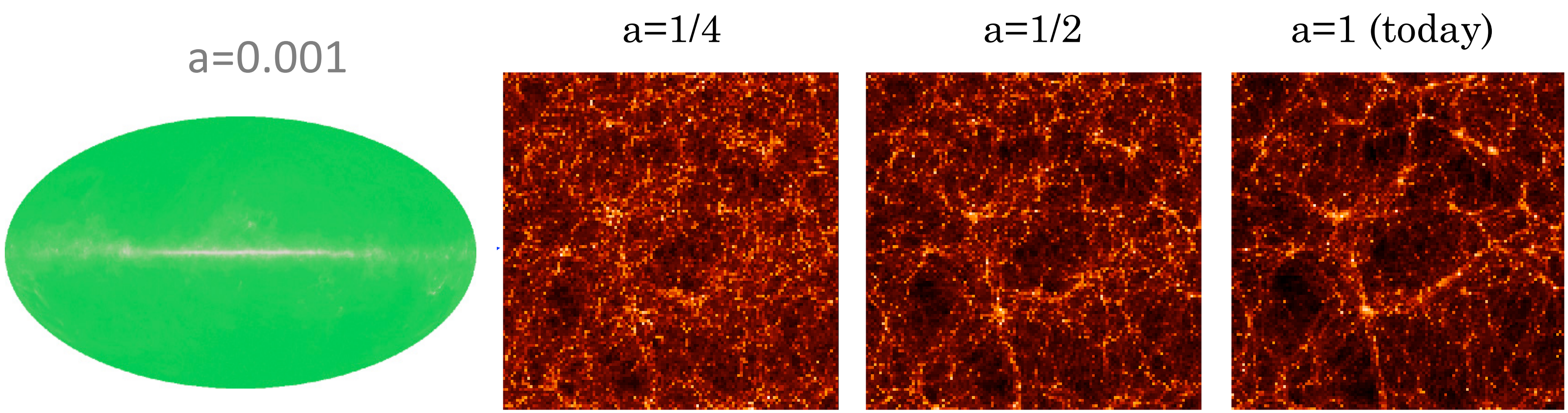




WMAP web site

Cosmology probes: geometry and growth

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



- 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

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

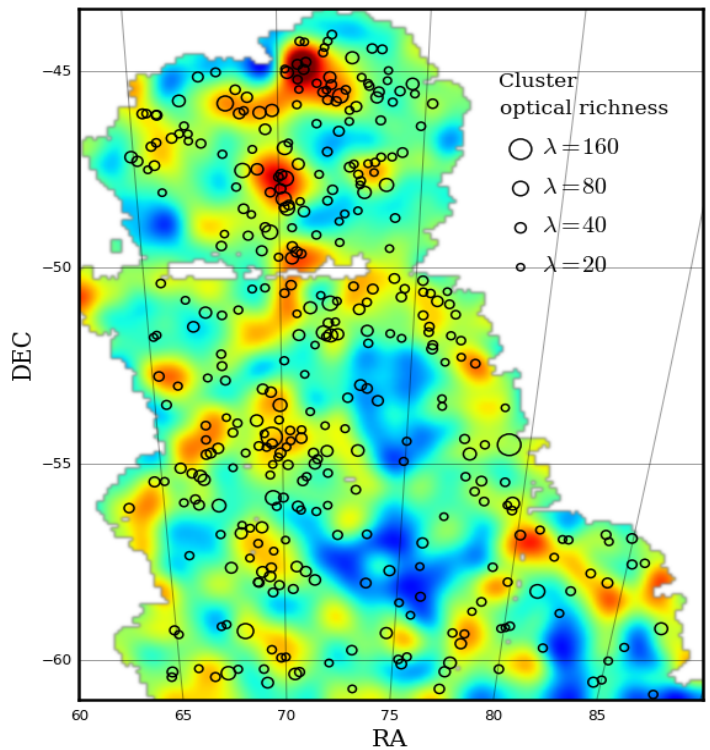
Present day parameters assuming ΛCDM

- H_0 (expansion rate), Ω_m (mass density) and σ_8 (amplitude of fluctuations)
- Compare extrapolation of CMB to present day measurements – discrepancy signals breakdown of smooth dark energy model! Three examples follow..

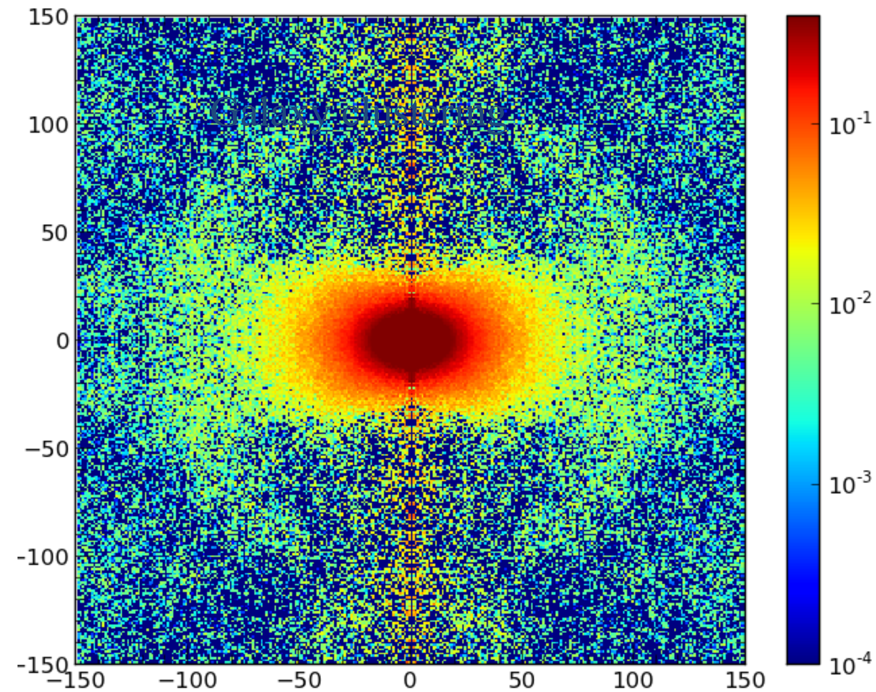
Cosmology probes: late times

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

Growth of structure



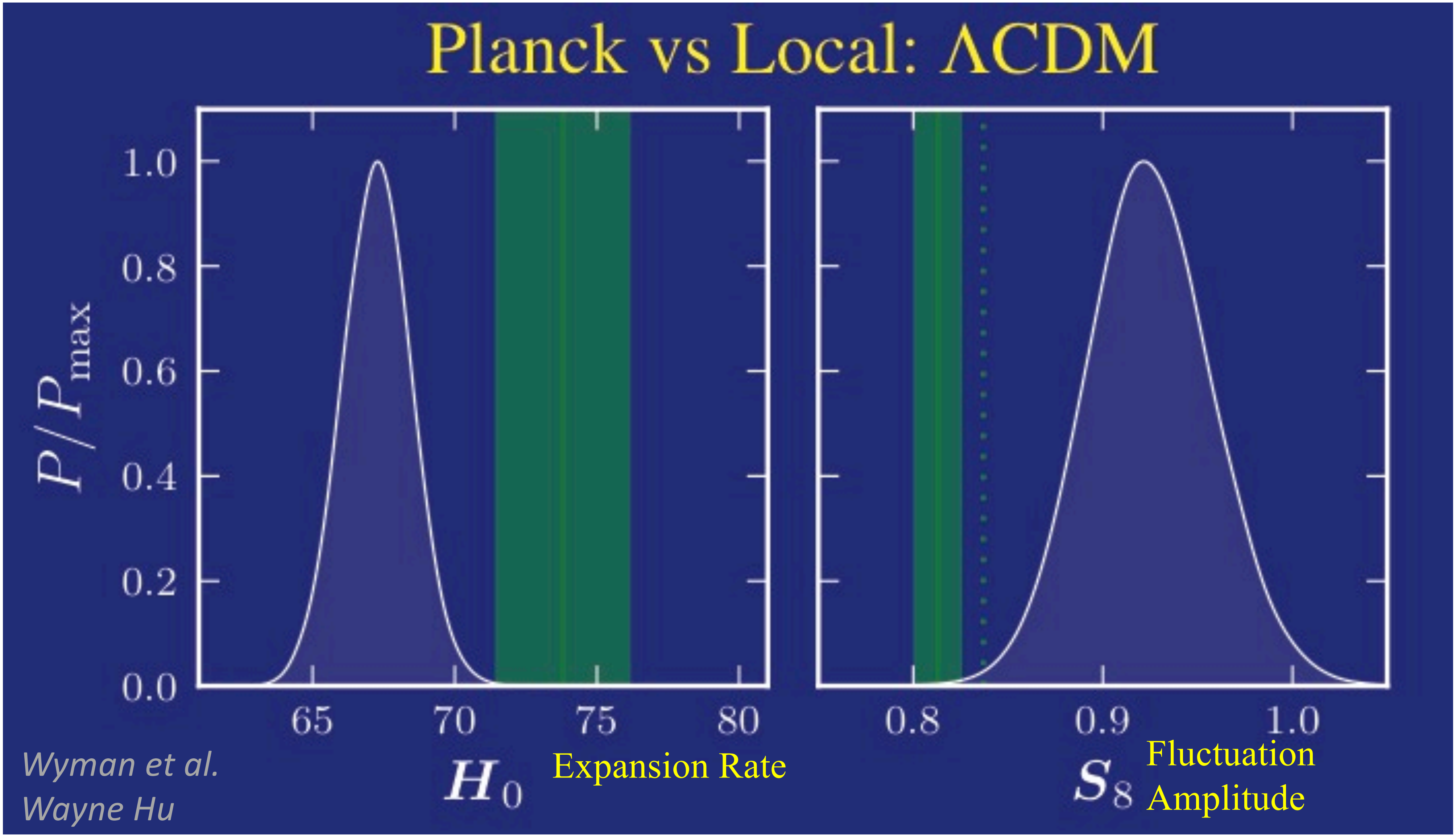
Gravitational Lensing



Galaxy distribution in redshift space

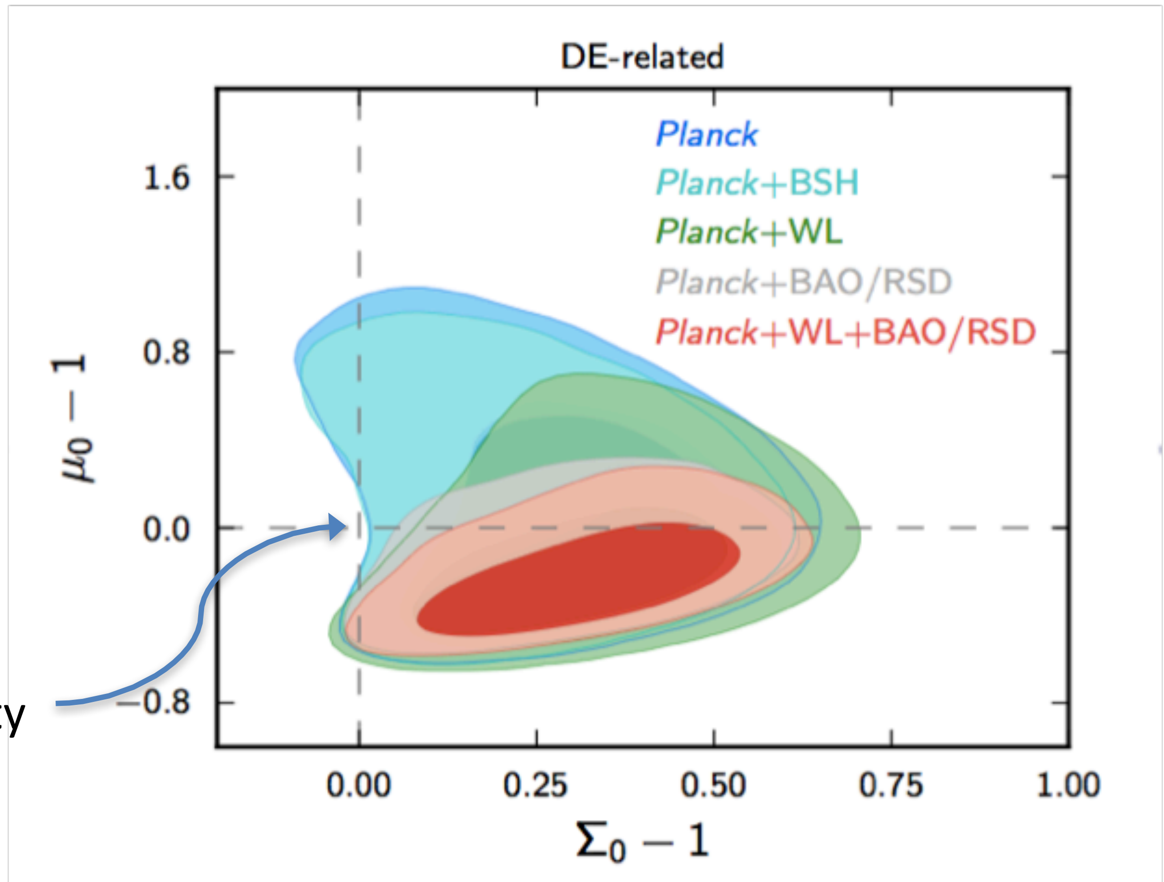
- Growth of structure: Galaxy clustering; Galaxy Clusters; Lensing; 21cm…
- CMB+low-z universe: generally consistent with inflation, and Λ-CDM
- Some intriguing hints of deviation exist; tests will get much sharper in the next years

(Mild) tension in cosmology data



Extrapolation from CMB to present disagrees with low-z measurements

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



General Relativity

Similar findings in dark energy-matter coupling

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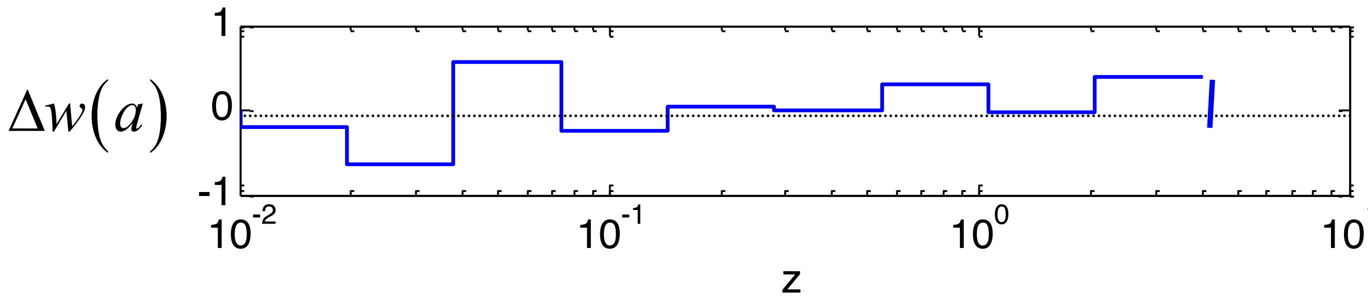
Beyond Λ



- Is dark energy constant in redshift?
- Is dark energy spatially clustered or anisotropic?
- Are there couplings 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:

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

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* = $-\nabla\Psi = -\nabla(\Psi_S + \Psi_N)$
  - This enhances effective G & velocities by O(10%)
- 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

Modified Gravity

how cosmological effects show up inside galaxies

• Enhanced forces can alter the luminosities, colors and ages of stars in unscreened galaxies.

Chang & Hui 2010; Davis et al 2011; BJ, Vikram, Sakstein 2012

• Dark matter and gas clouds are diffuse; stars are compact; black holes have no hair -> should feel the fifth/scalar force differently

Hui, Nicolis & Stubbs 2009; BJ & VanderPlas 2011; Hui &Nicolis 2012

Pulsating stars and distances

- Cepheids are 3-10 $M_\odot$ giant stars that pulsate over days to weeks. The period P and luminosity L are tightly related -> distance indicator

  - Pulsation time period

  $$P \sim 1/\sqrt{G\rho}$$

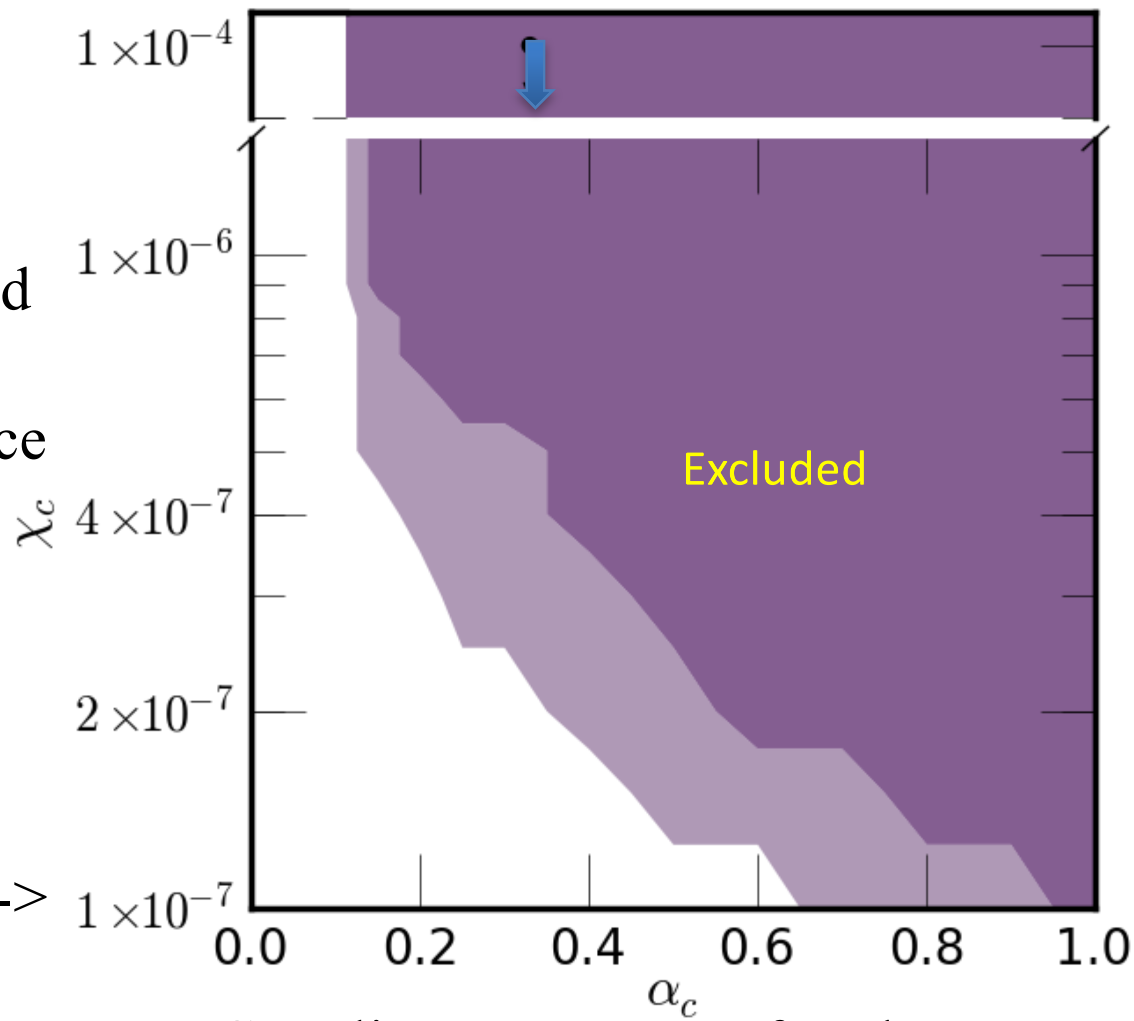
  Scalar force enhances G -> lowers P -> underestimate distance.

- Use relative measurements of distances via cepheids and other methods -> the distance-redshift relation becomes a test of gravity!

Constraints on chameleon/f(R) theories

Background field
or
Range of 5th force

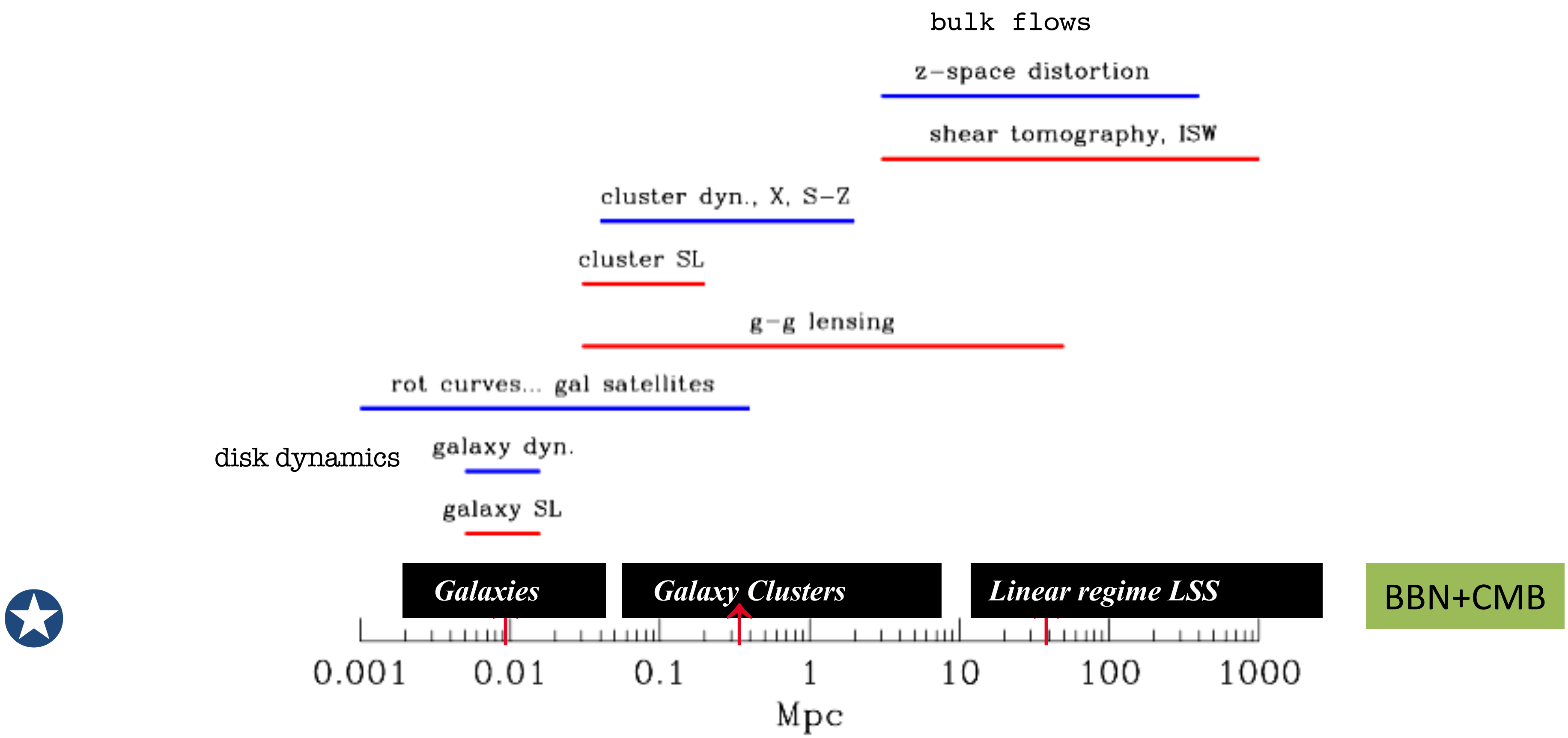
1 Mpc<->



Coupling parameter of scalar to matter

BJ, Vikram, Sakstein 2012

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

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Gravitational Lensing

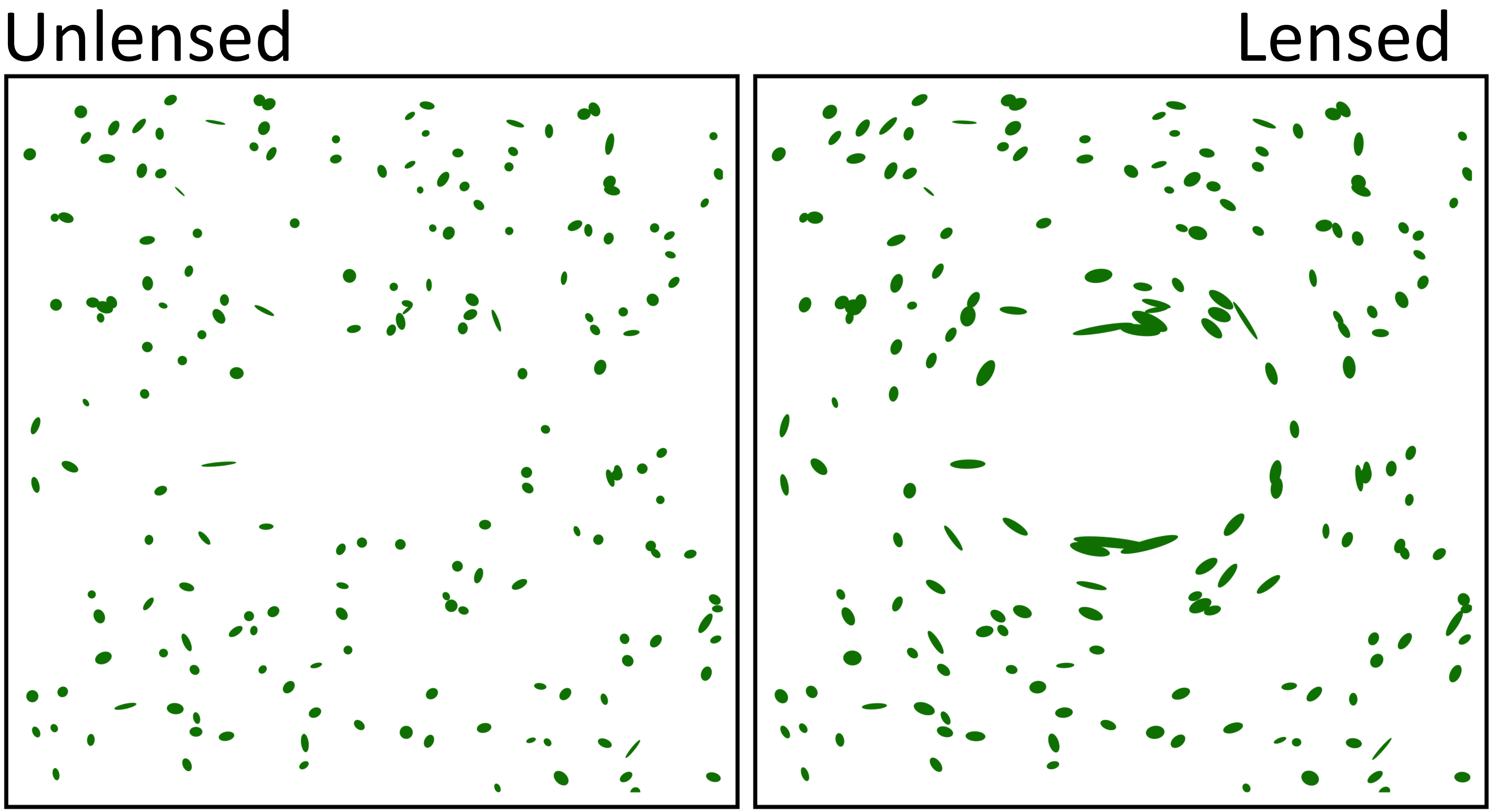
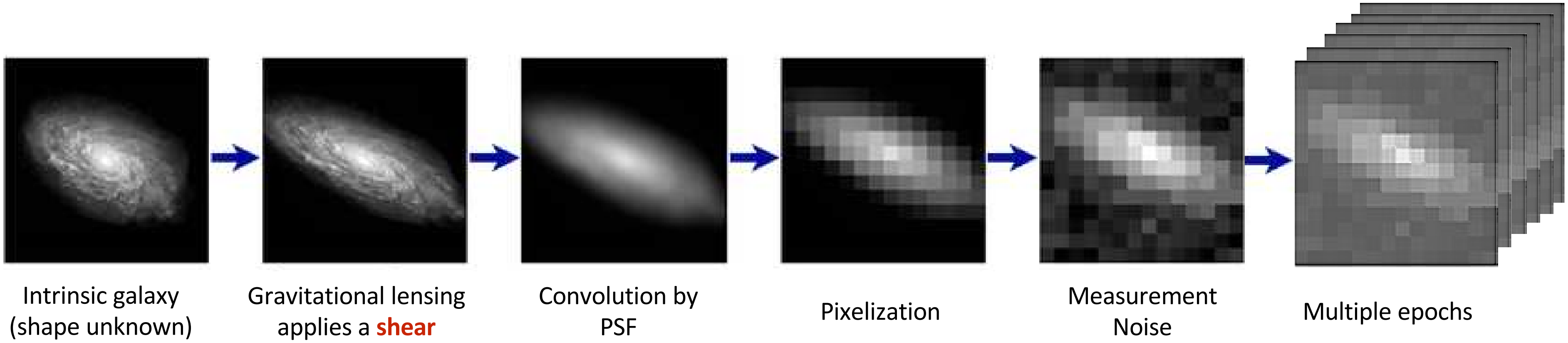


Image credit:
Jim Bosch

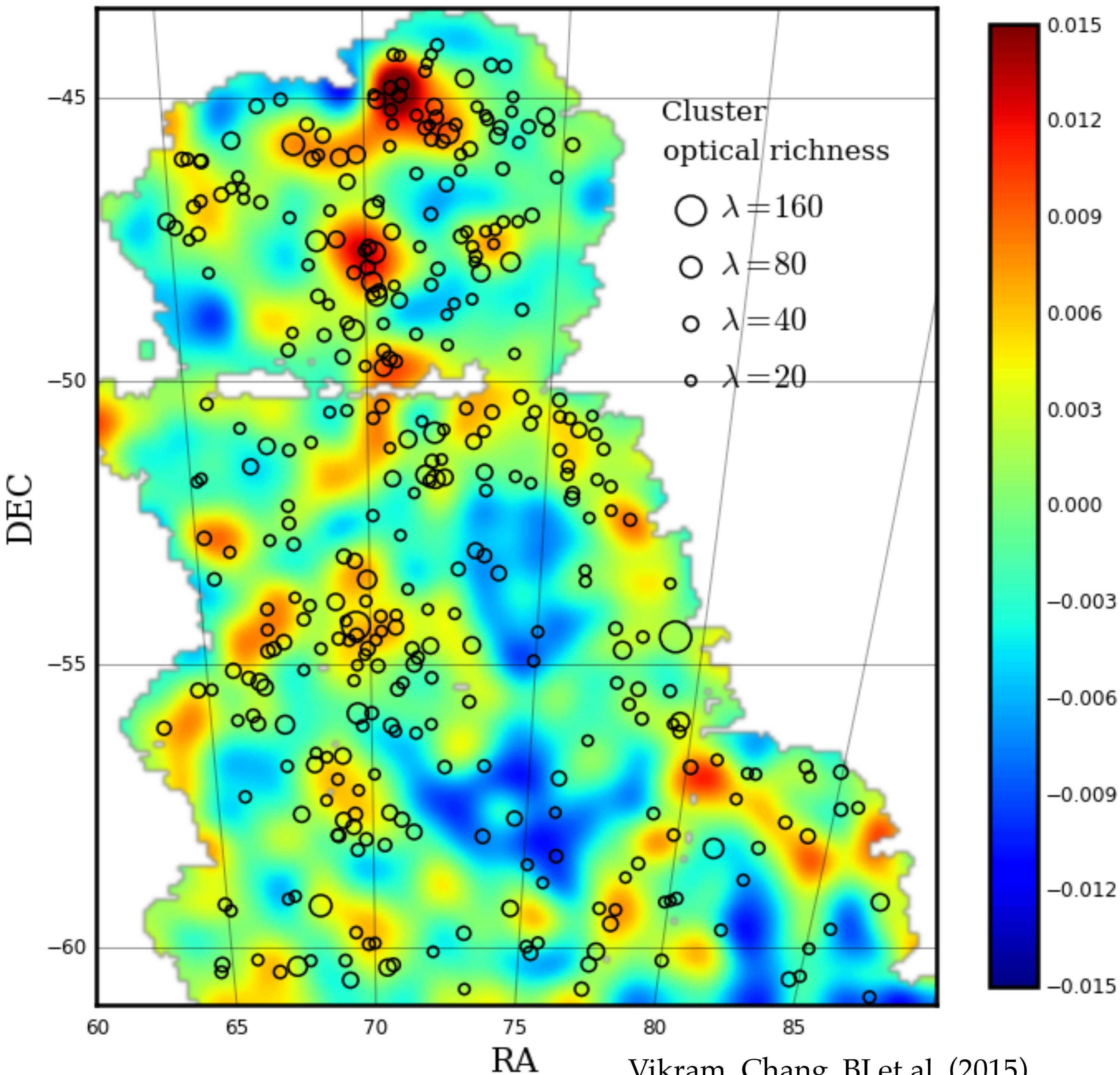
Weak Lensing



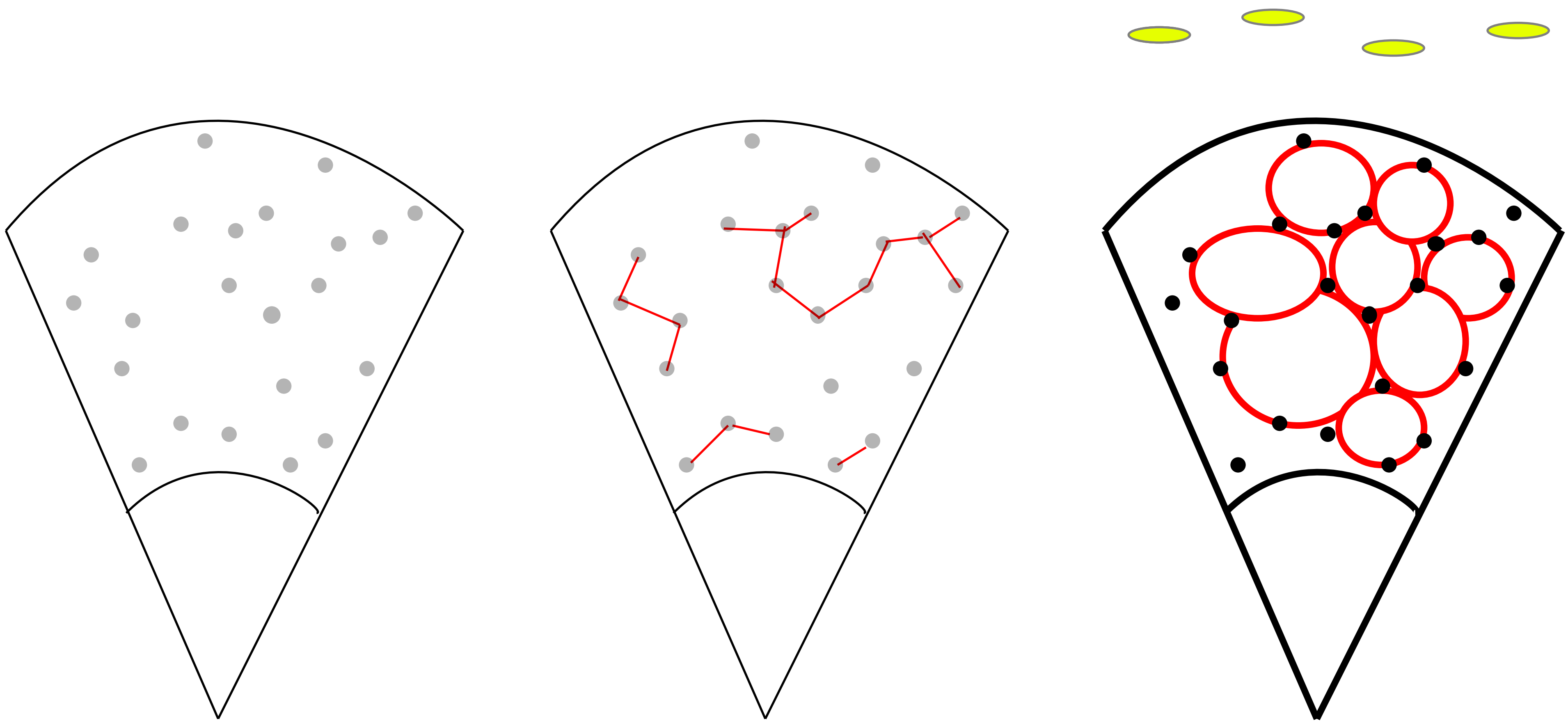
Galaxy with a 10% lensing shear and real-world effects. *Great3 handbook*

We have measured 0.01% shears using ~20 million galaxy images from the Sloan survey (SDSS) and the Dark Energy Survey (DES).

Mass and Light



Vikram, Chang, BJ et al. (2015)



Halos Filaments Voids

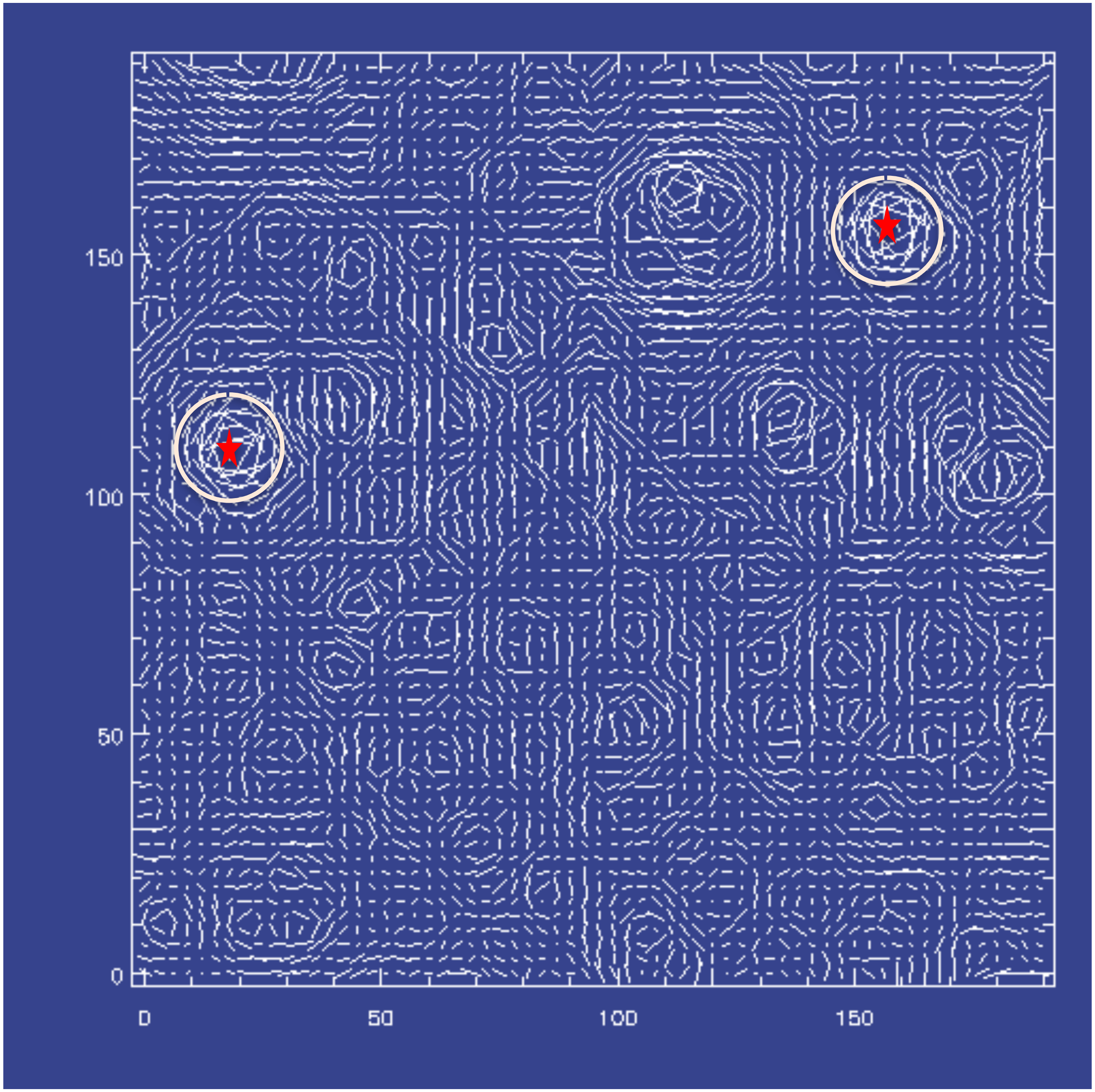
Basic Questions

- 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.

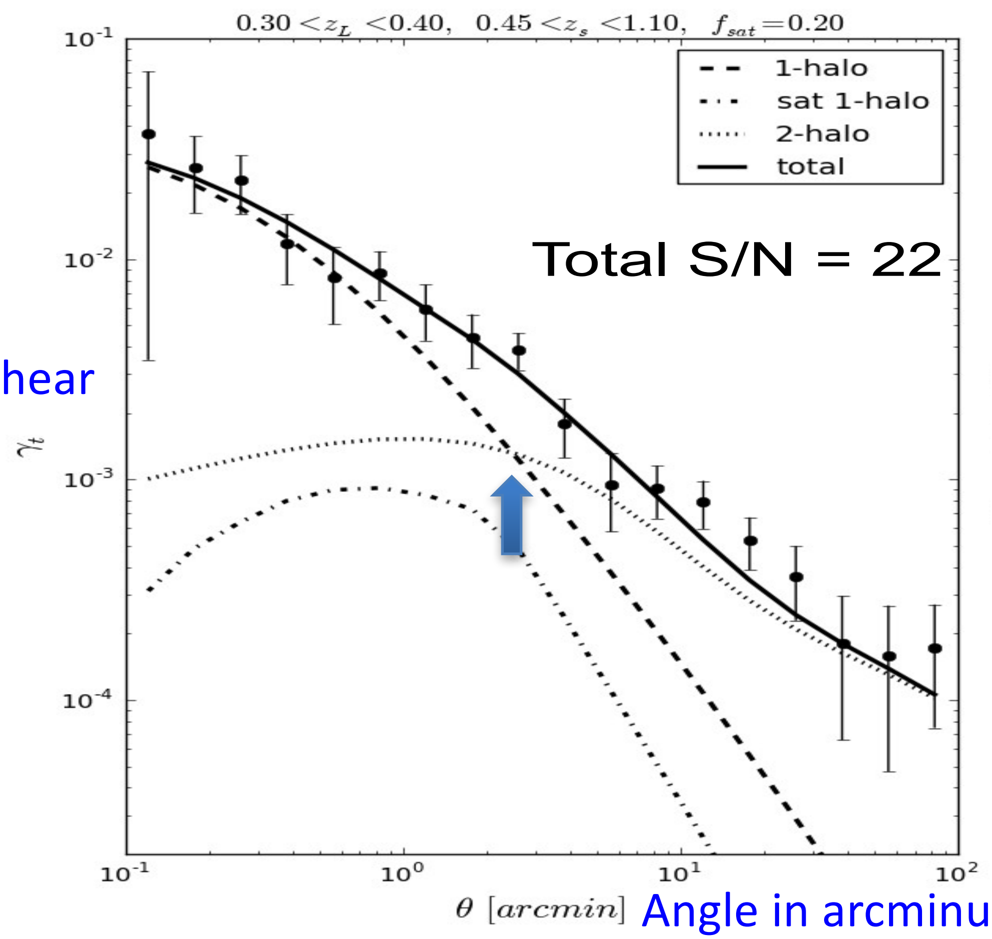
These small scale measurements enable new tests of fundamental physics.

Mass profiles via shear cross-correlations



Halo mass profile

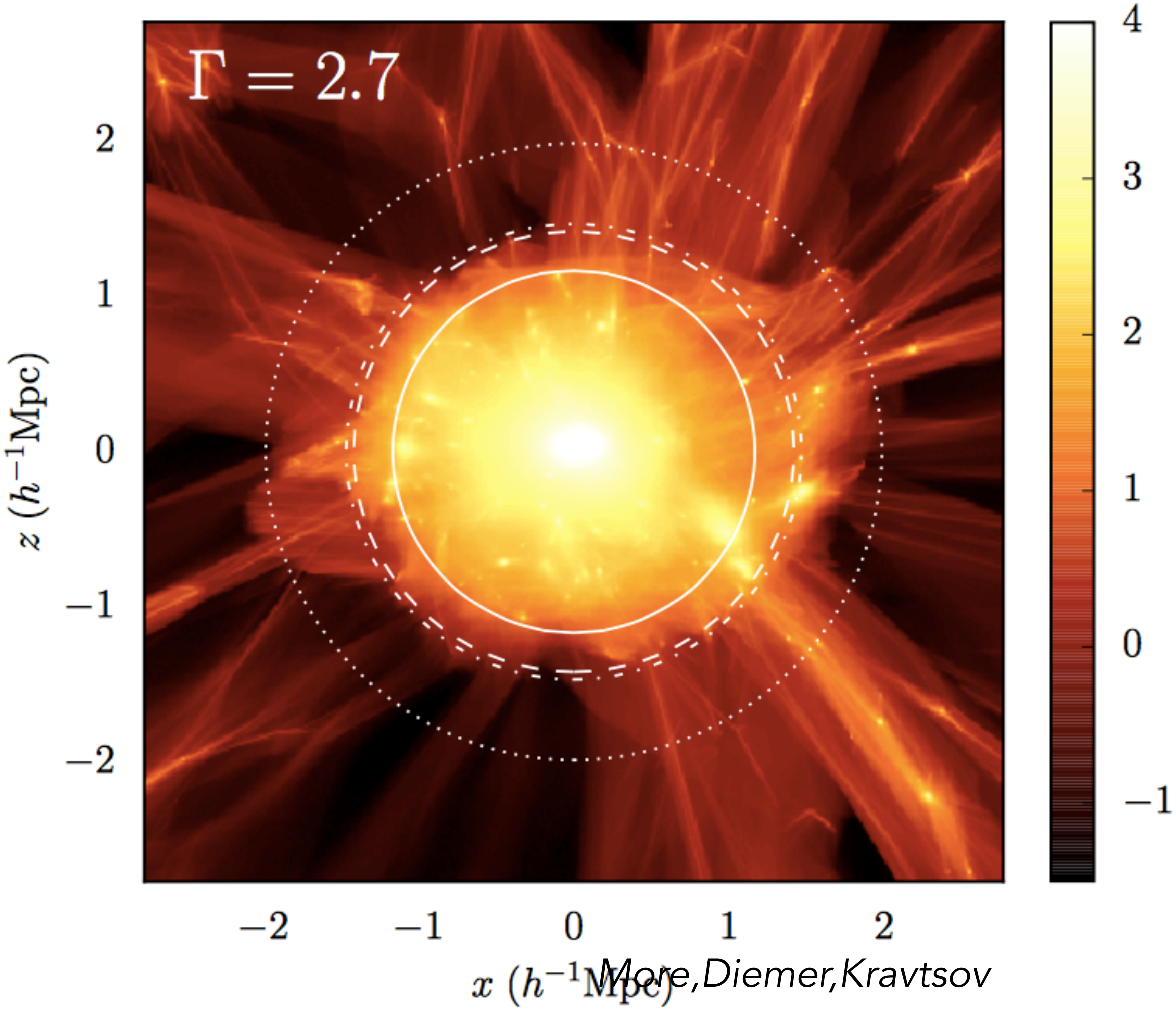
Tangential shear



Angle in arcminutes

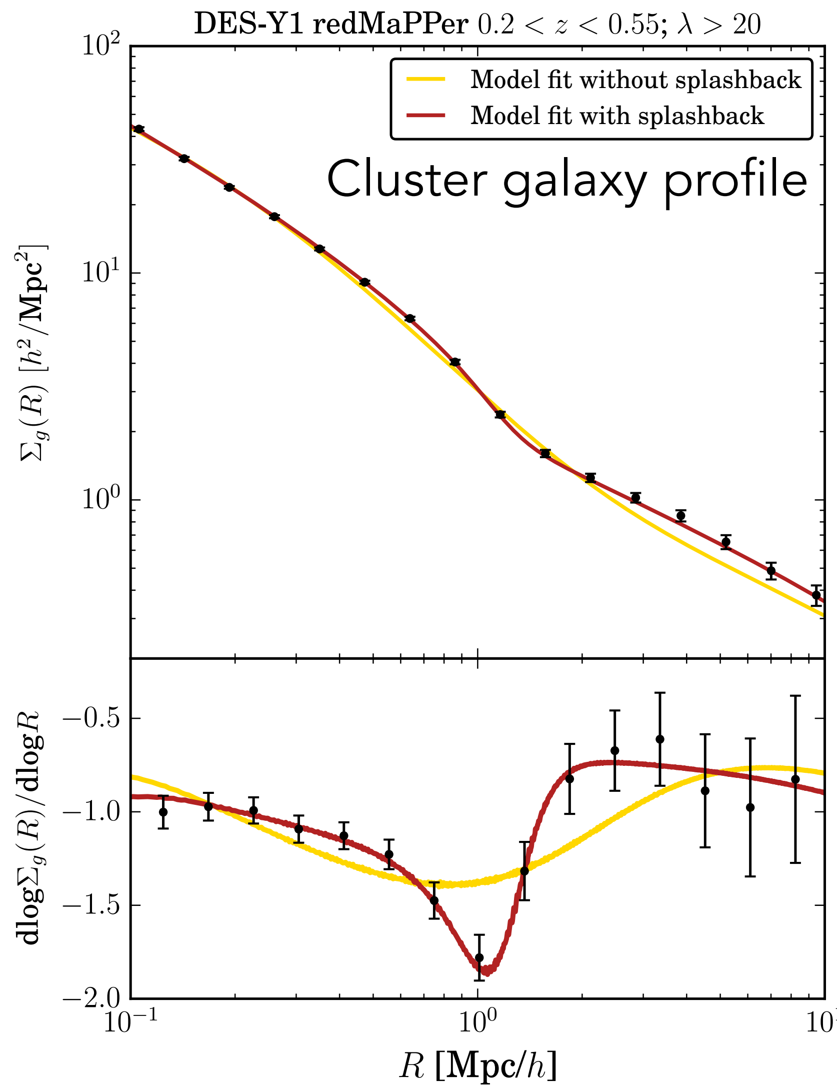
Measurement and modeling of halo mass profiles: 1 and 2-halo terms
Clampitt et al 2016 (DES collaboration)

The edge of halos



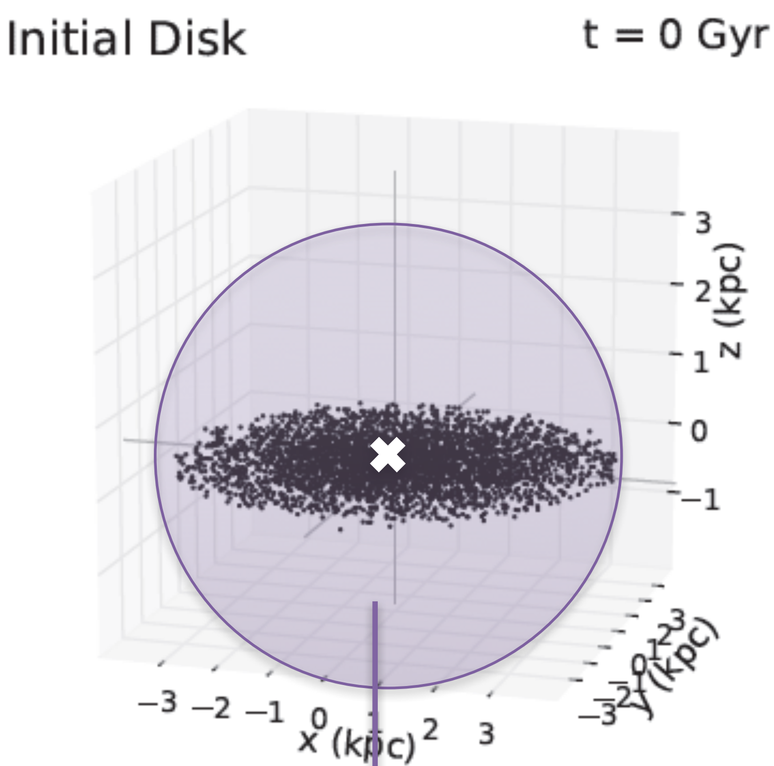
More,Diemer,Kravtsov

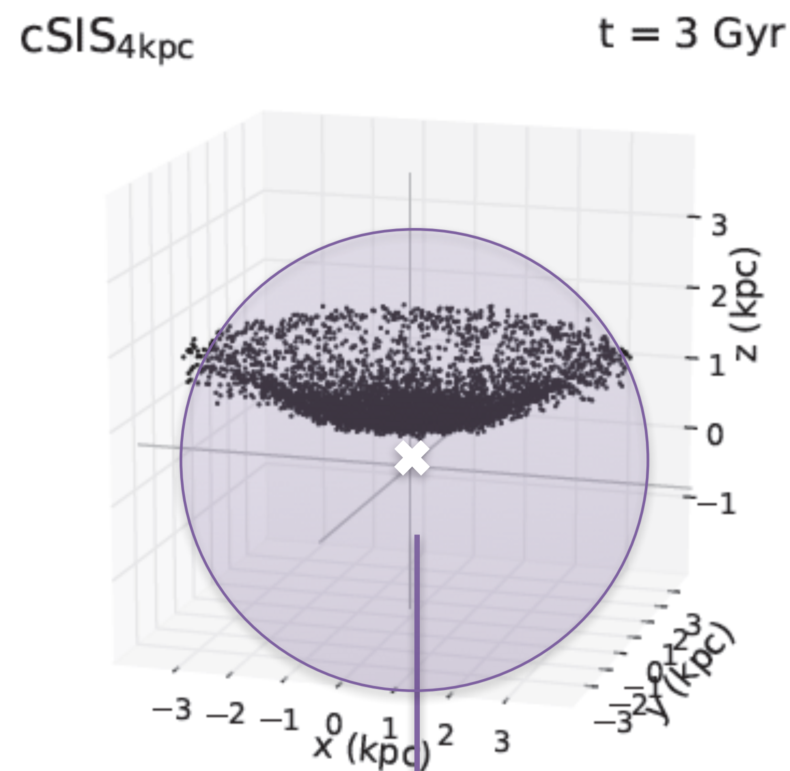
Splashback: radius at which accreted matter reaches apocenter

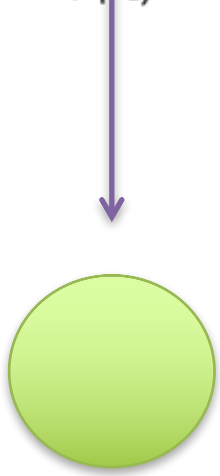


Baxter, Chang, Sanchez, BJ, DES collab.
More et al 2016

Disk galaxies and dark interactions



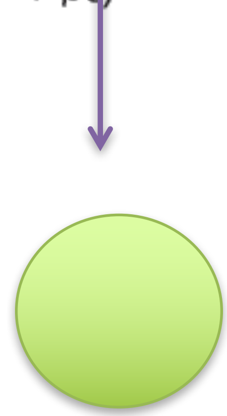




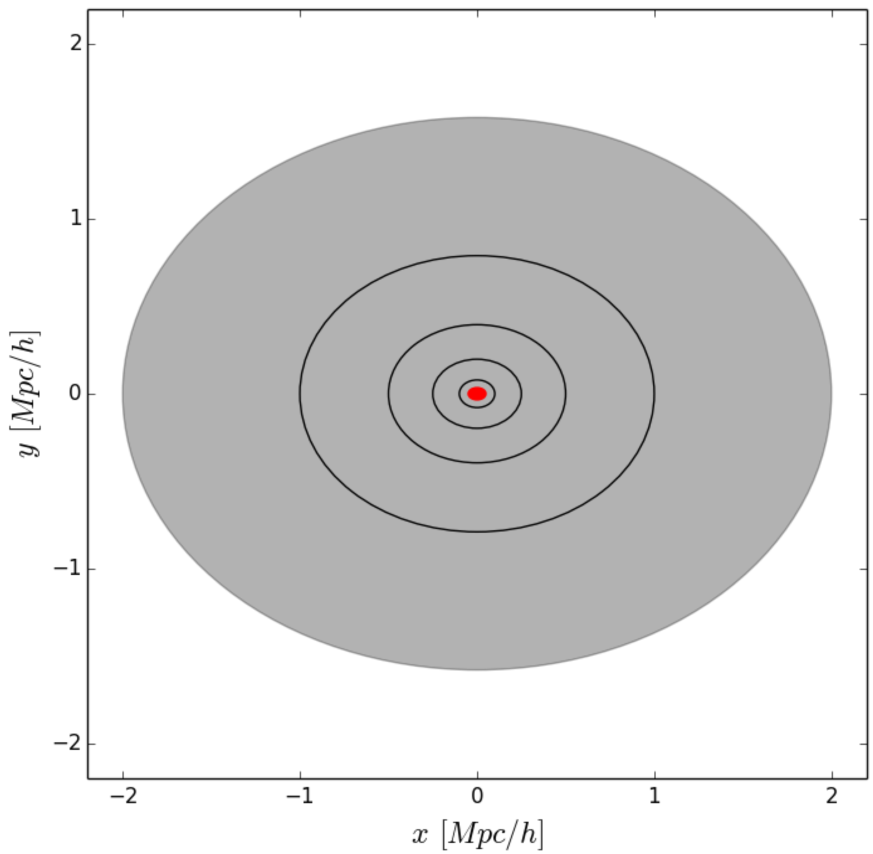
A new test for extra forces due to modified gravity or dark matter self-interactions

BJ & VanderPlas 2011

Secco et al in preparation



How round are halos?: halo ellipticity, gravity and dark matter



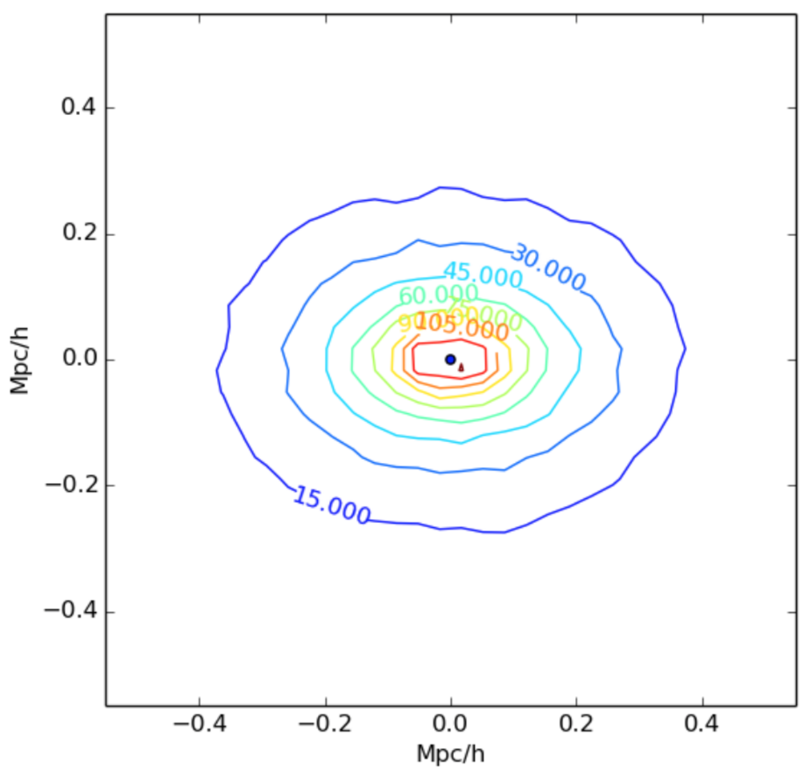
For typical galaxies, the halo virial radius is ~20x larger than the visible stars.

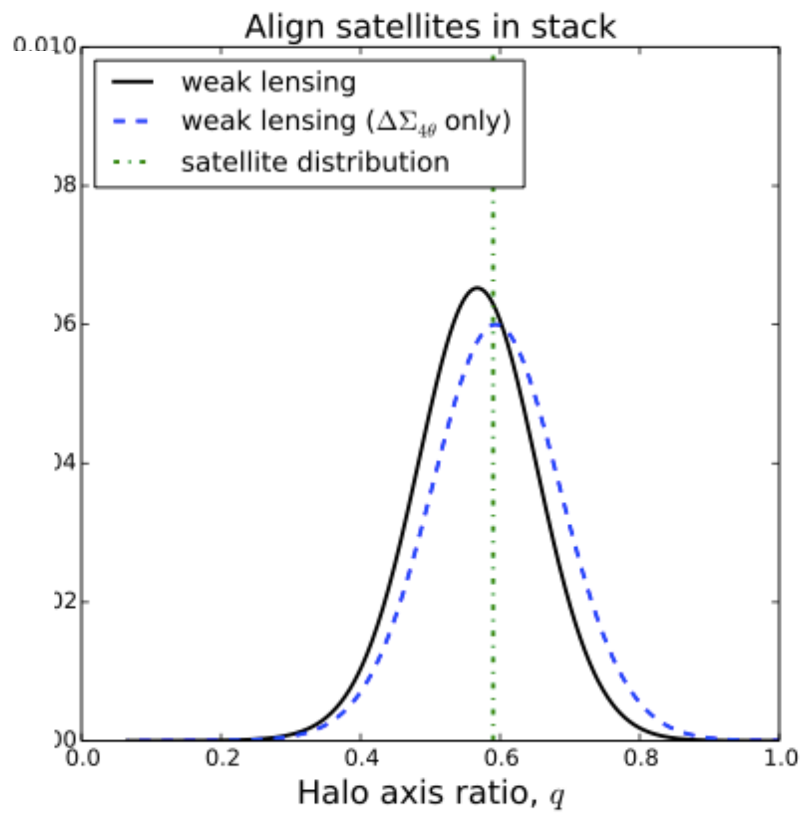
- How elliptical are the density contours?
- How do they change with radius?
- How do they relate to the light?

- 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.

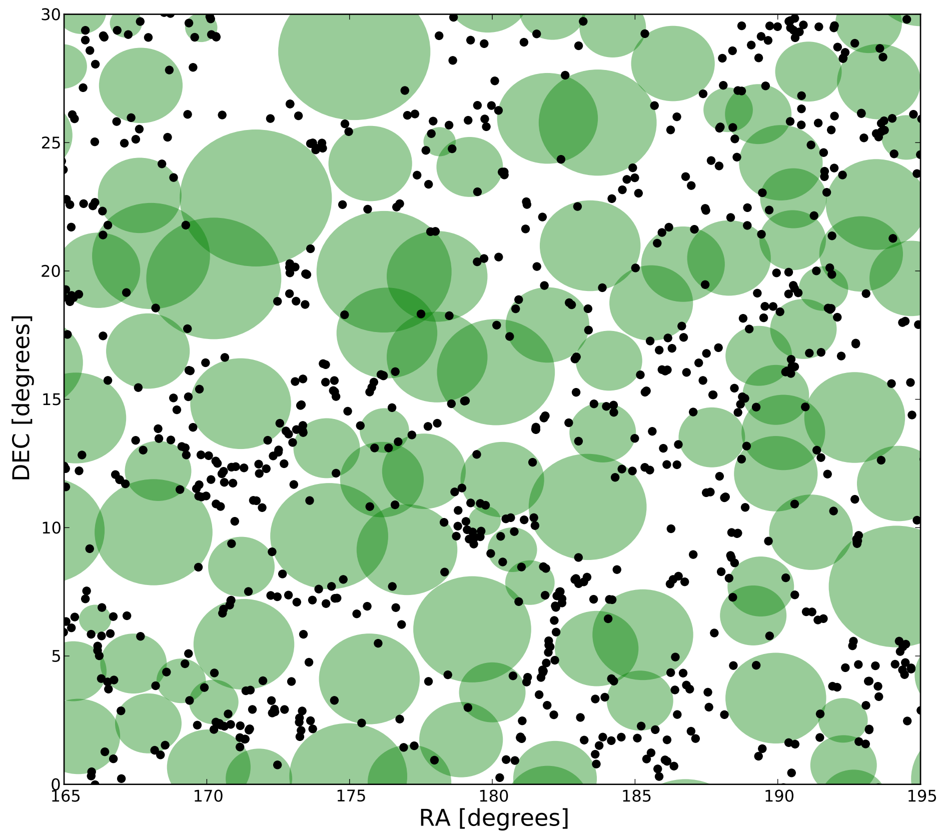
Galaxy Cluster Halos

- 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.
- Satellite galaxies are an excellent tracer of halo shape. BCG’s – significant misalignment.
- Galaxy halo shapes -- in progress..

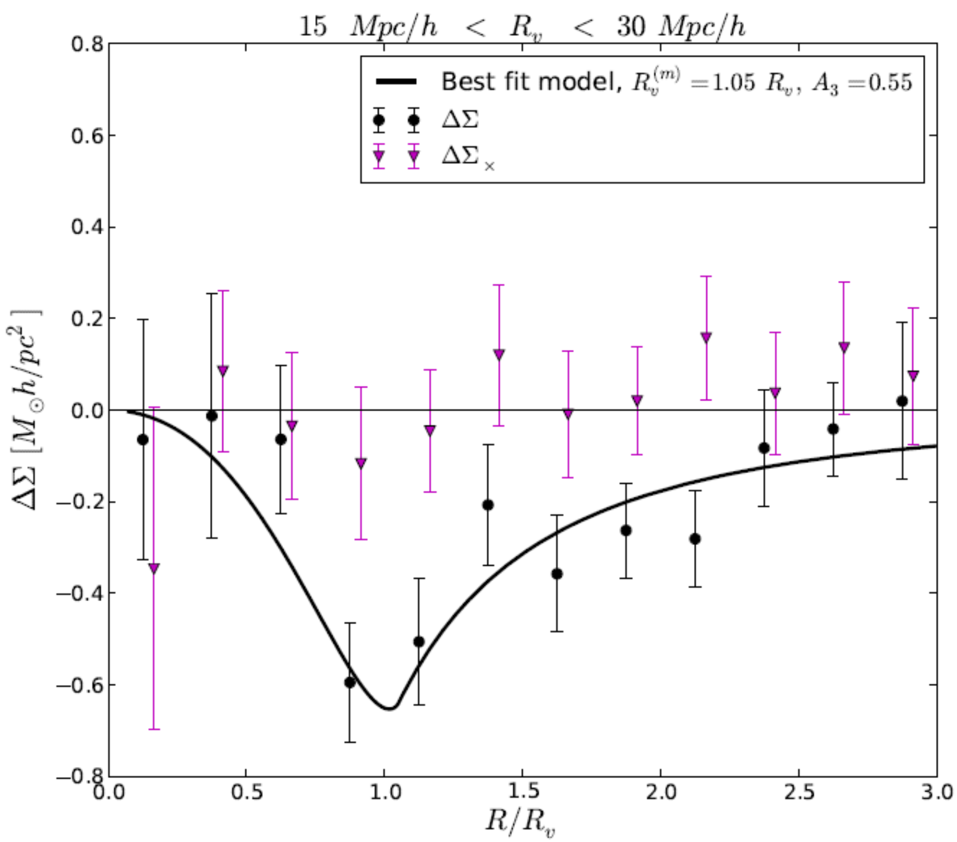


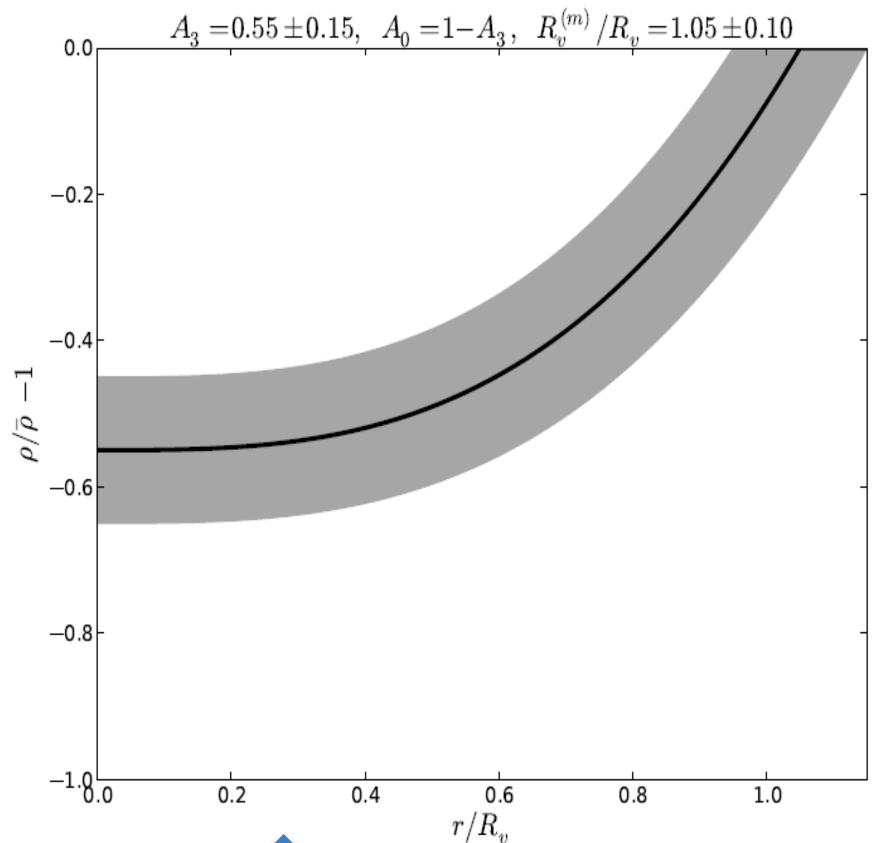


Voids in SDSS: Galaxies in a slice



Void lensing

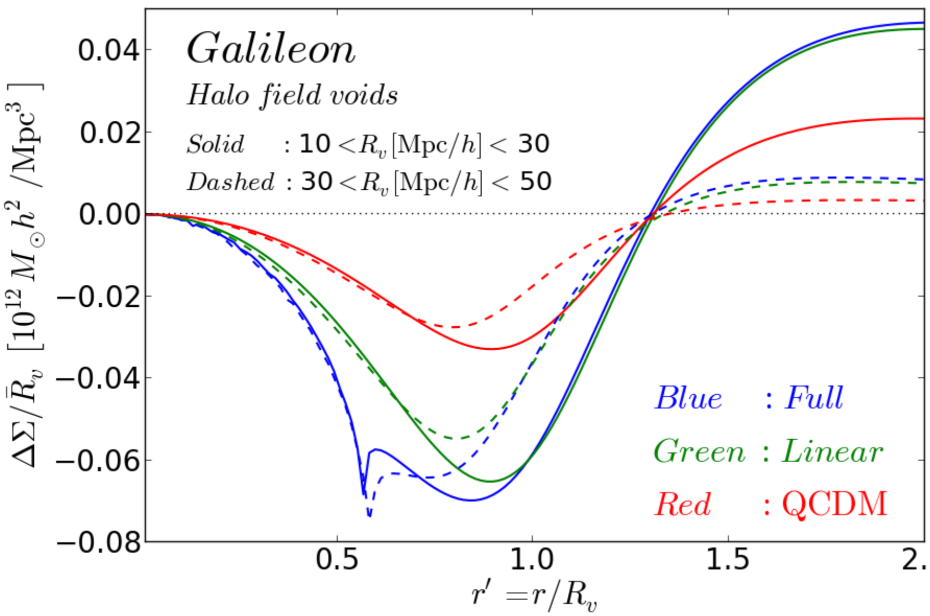




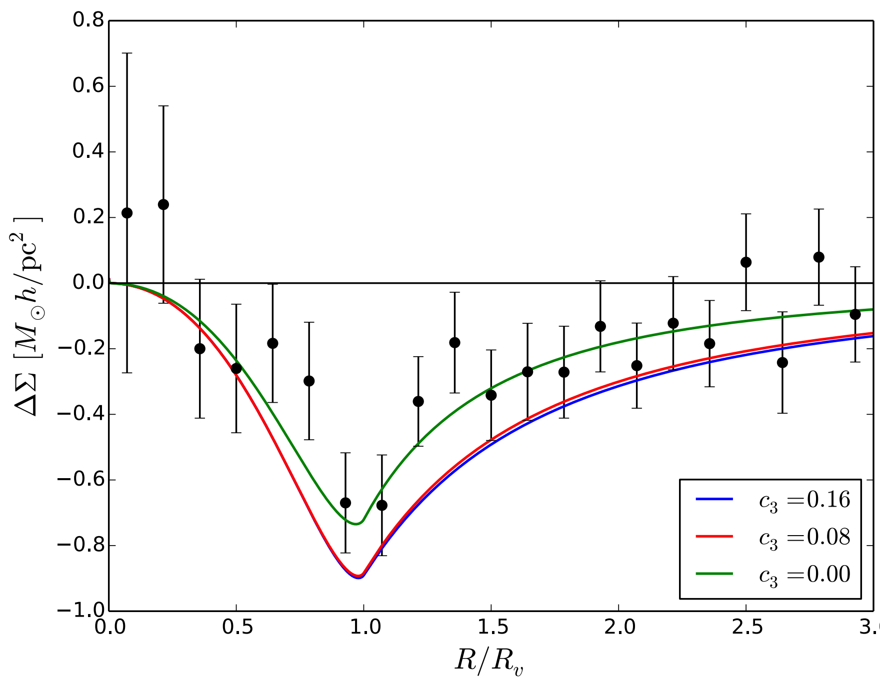
The lensing profile and the inferred 3d density profile of voids.
The measured shear signal is at the 0.01% level!

Clampitt and Jain 2014

Voids in modified gravity



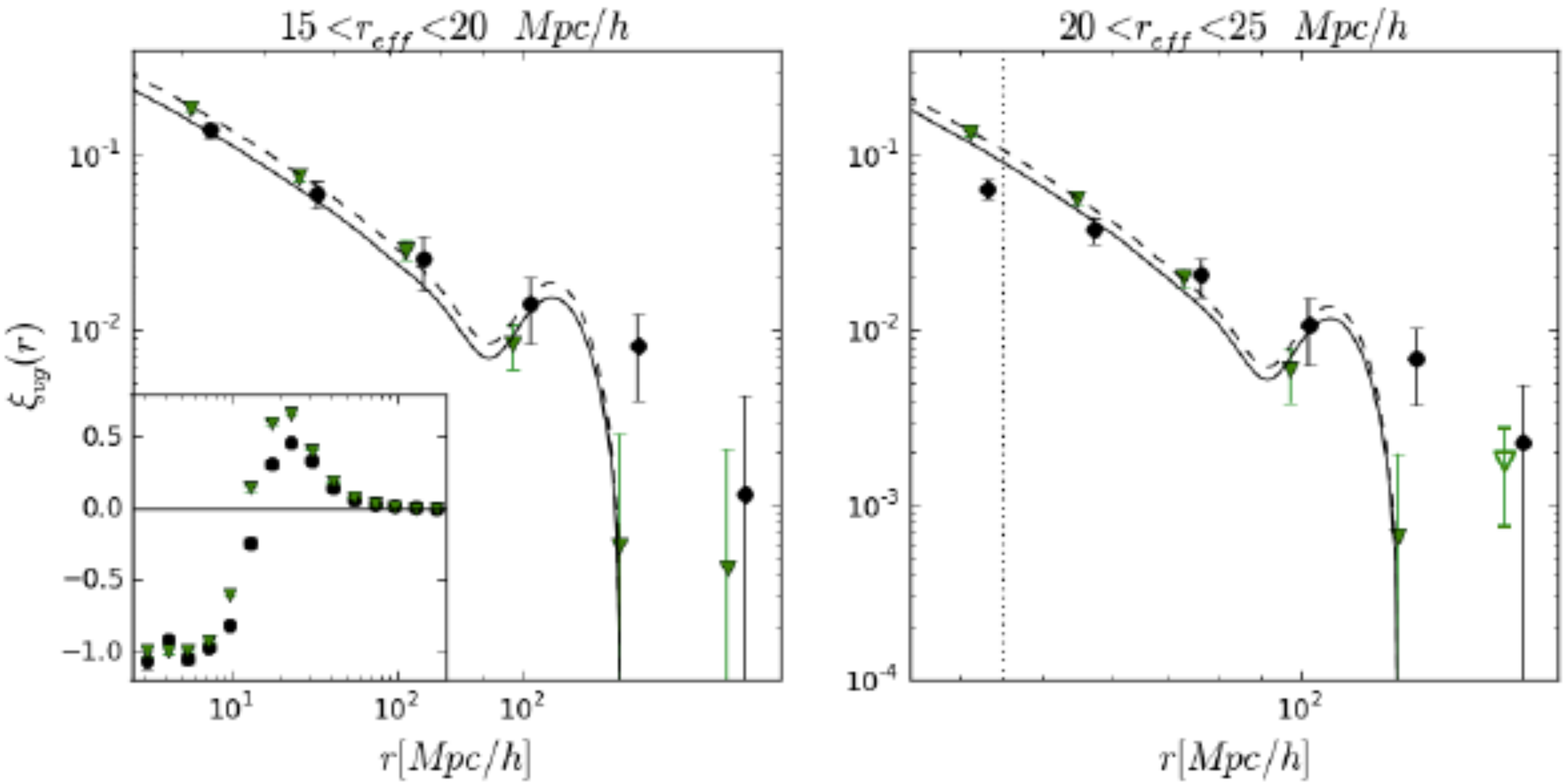
Barreira et al, 2015



Clampitt et al, in prep.

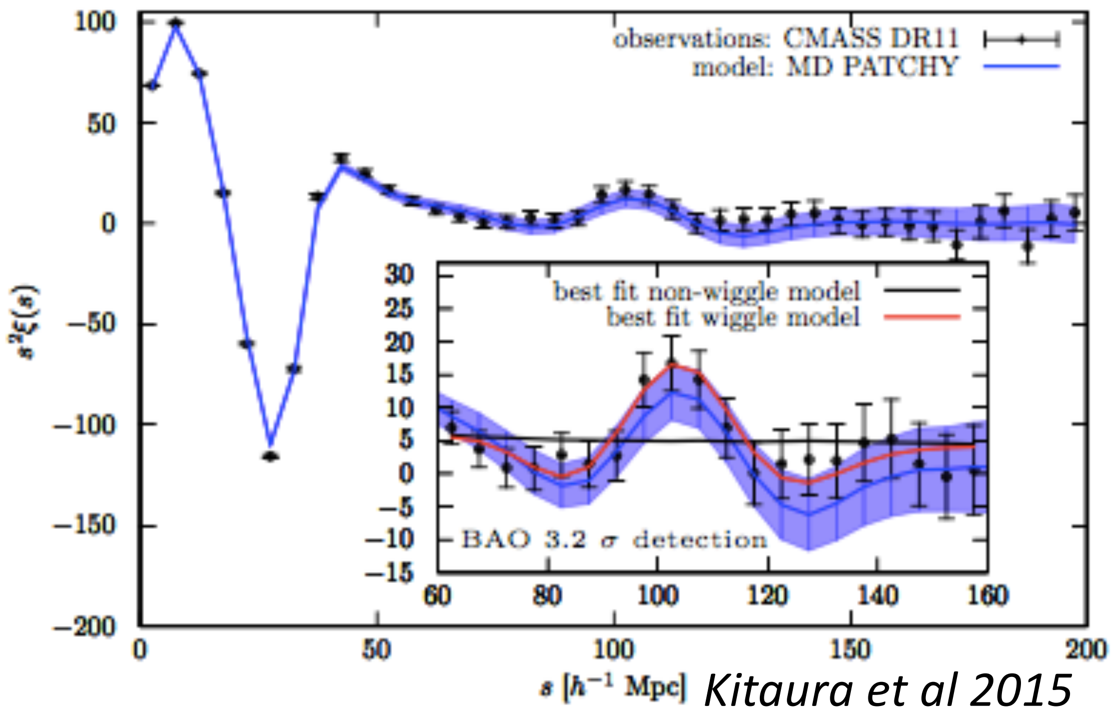
The modified gravity signature in voids is typically much larger than in halos!

Void-galaxy correlations



The clustering of voids and galaxies around them. *Clampitt, Sanchez, Jain 2015*

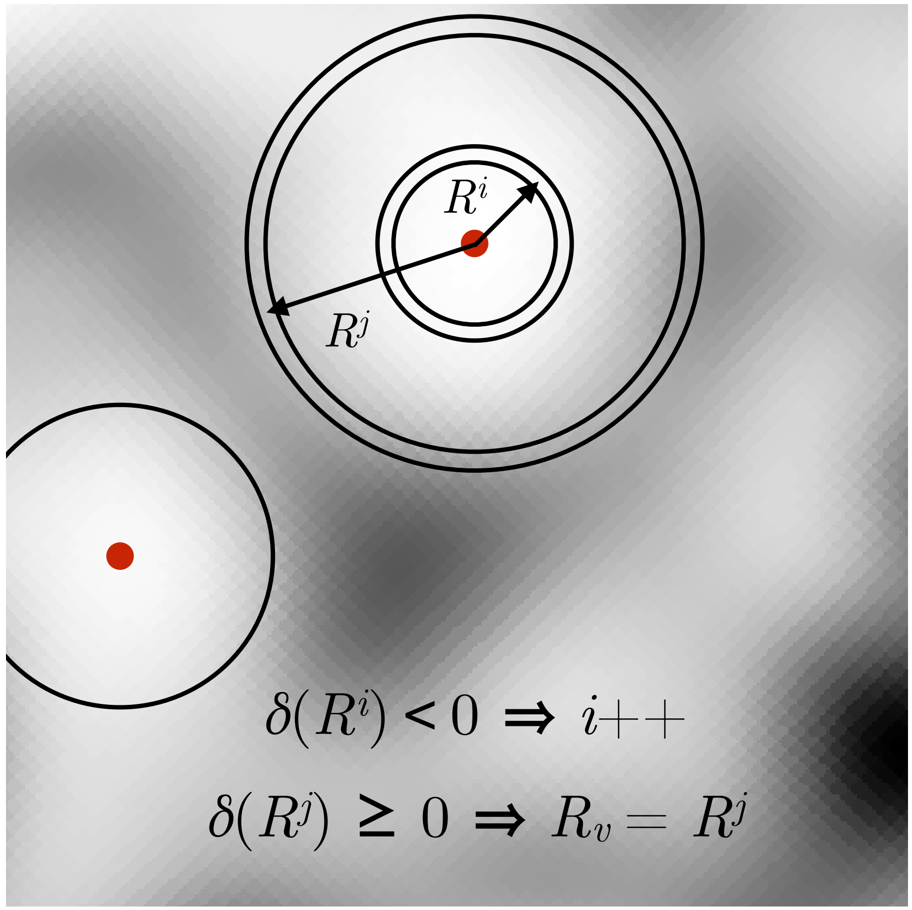
Void-void clustering: BAO!



Kitaura et al 2015

Several cosmological applications of voids are being developed.
Key question: what can we test with voids that isn't already tested using galaxies and clusters? Gravity, neutrinos…

Voids in imaging galaxy surveys



- New void finder for photoz data.
- Lensing and ISW analyses in progress
  Sanchez et al, in preparation

Summary: halos and voids

- Halo boundary: detection of the sharp edge of halos
- Halo ellipticity: measurements of how ellipticity changes with radius
- Voids: mass profiles inside voids, and clustering on large-scales

- Applications to galaxy-formation and dark sector interactions!

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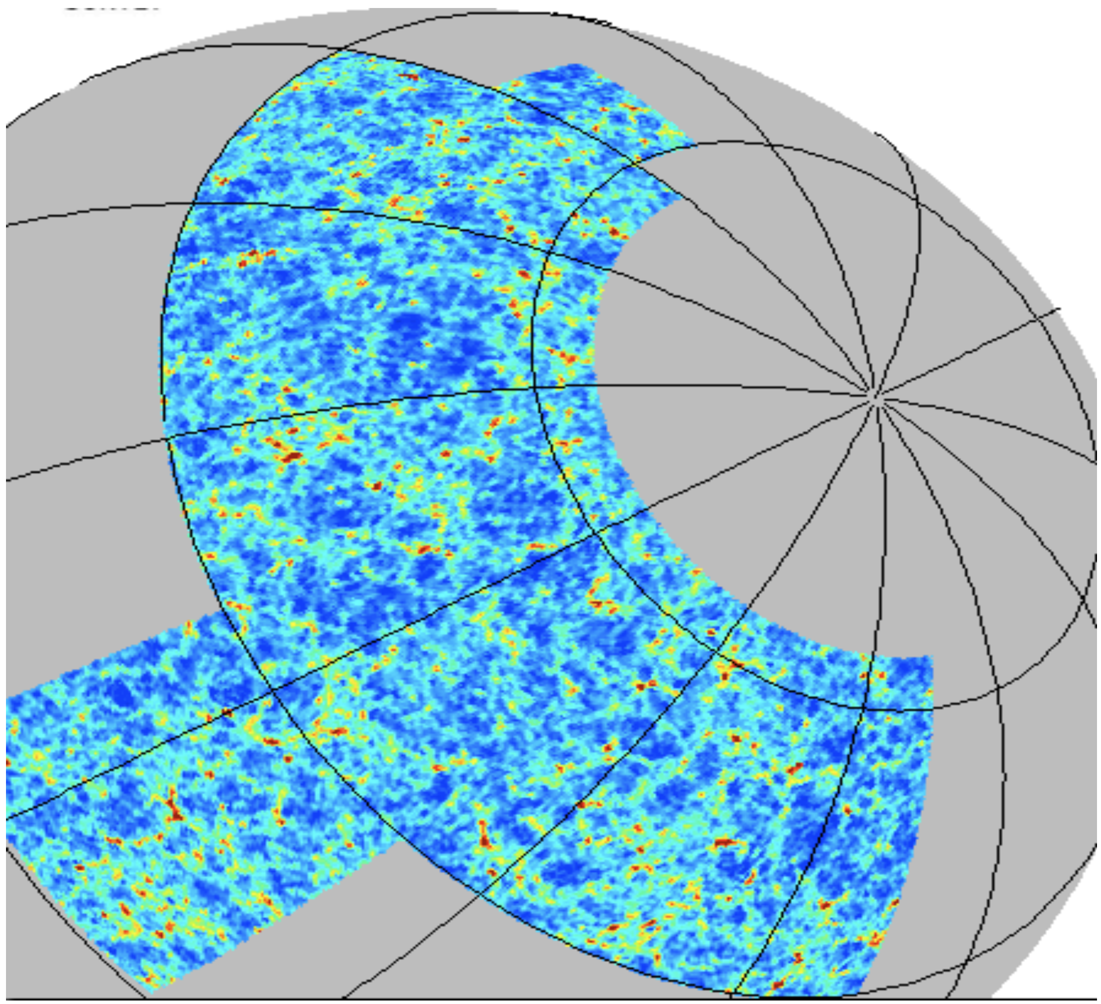
Dark Energy Survey

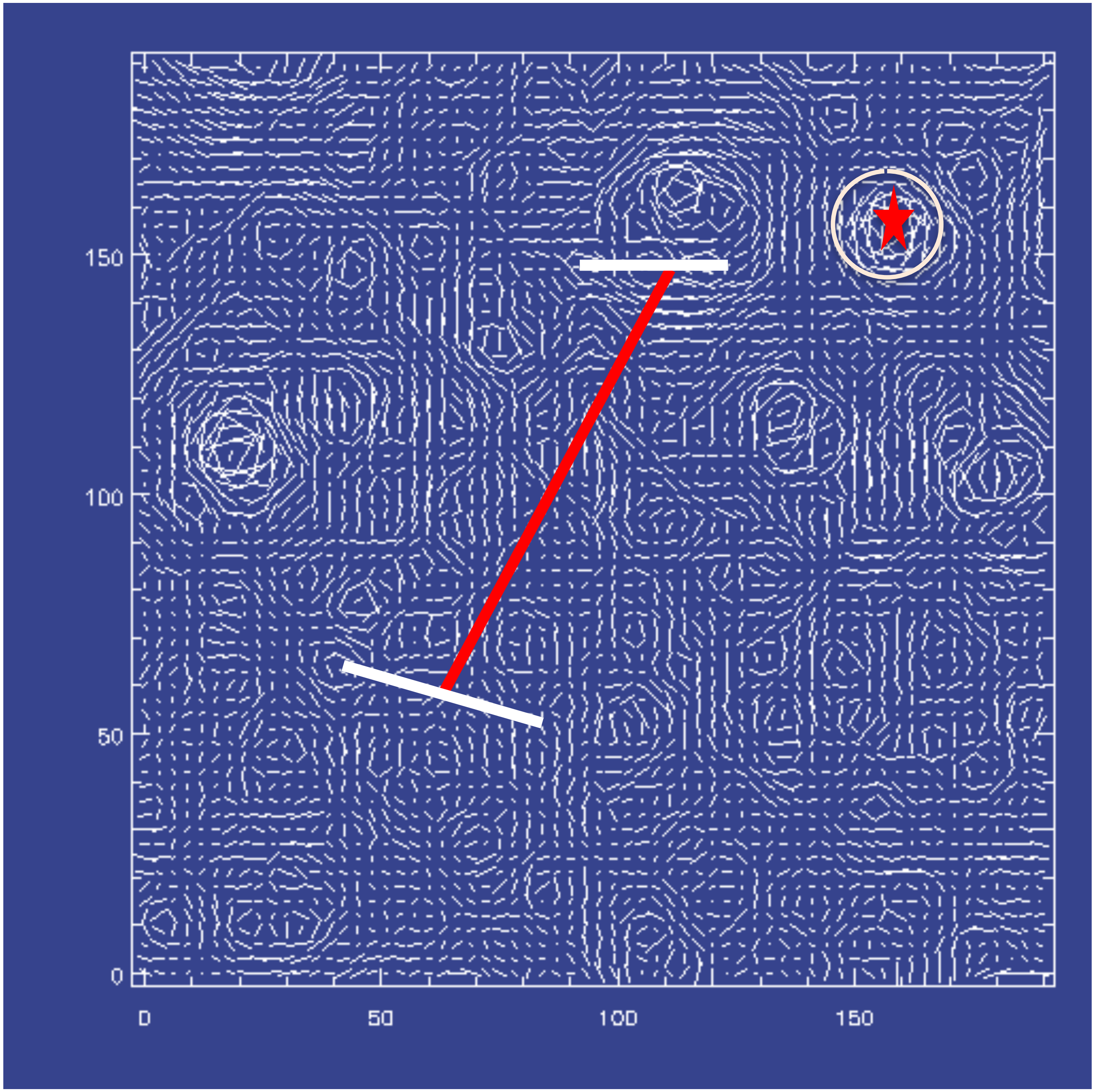


•500 Mpix camera for Cerro Tololo 4-meter telescope

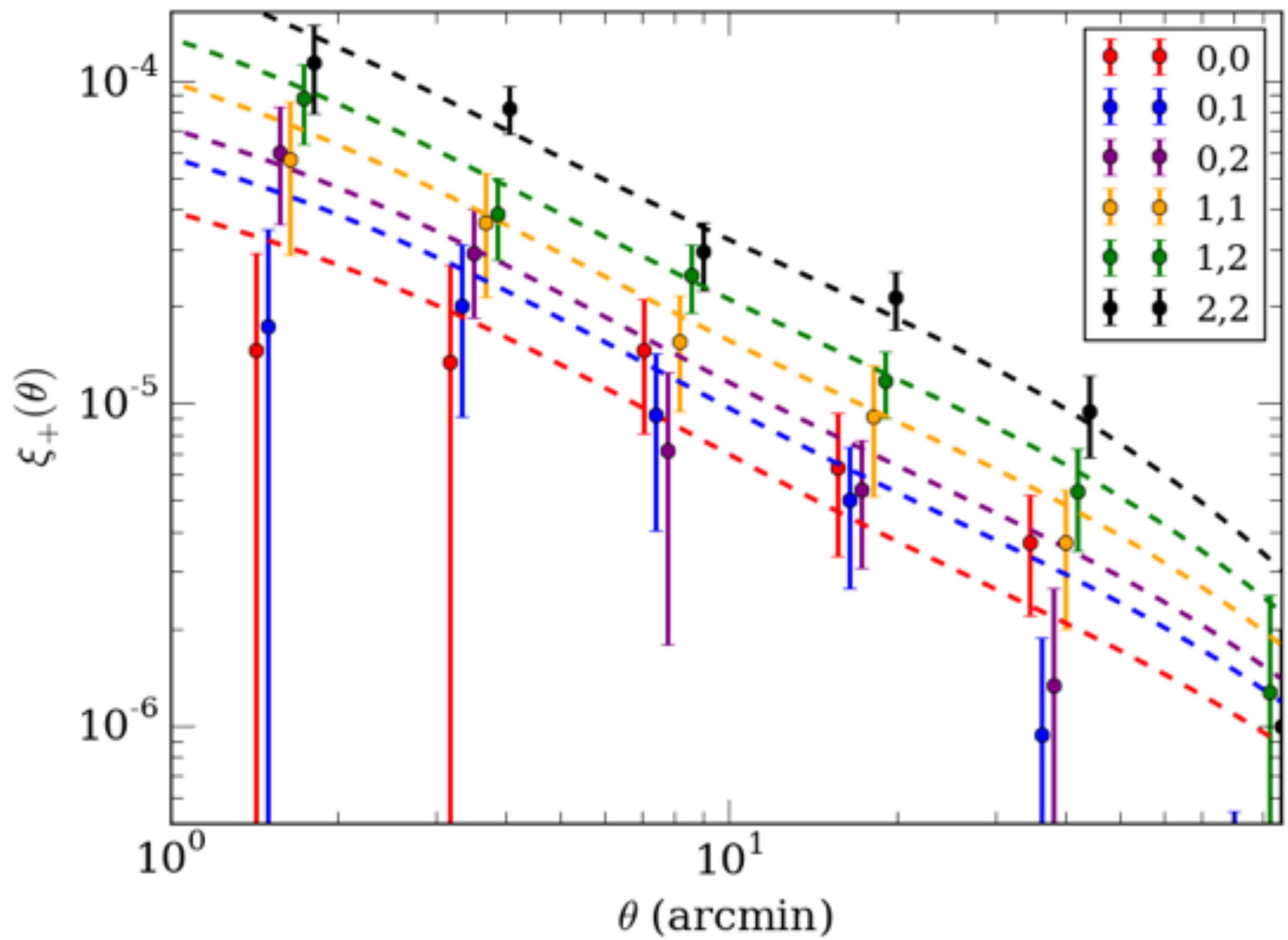
•5-year, 5000-square-degree: 2+ years completed

•Designed to overlap with the SPT CMB survey

Shear auto and cross-correlations

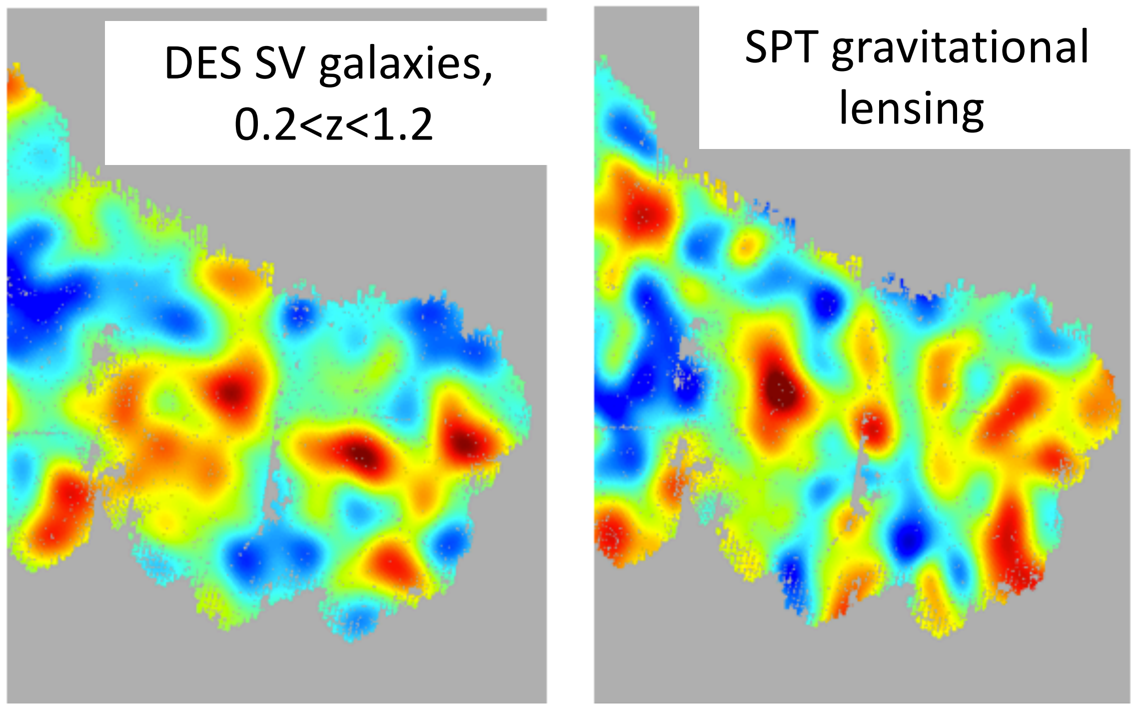


Cosmic shear tomography



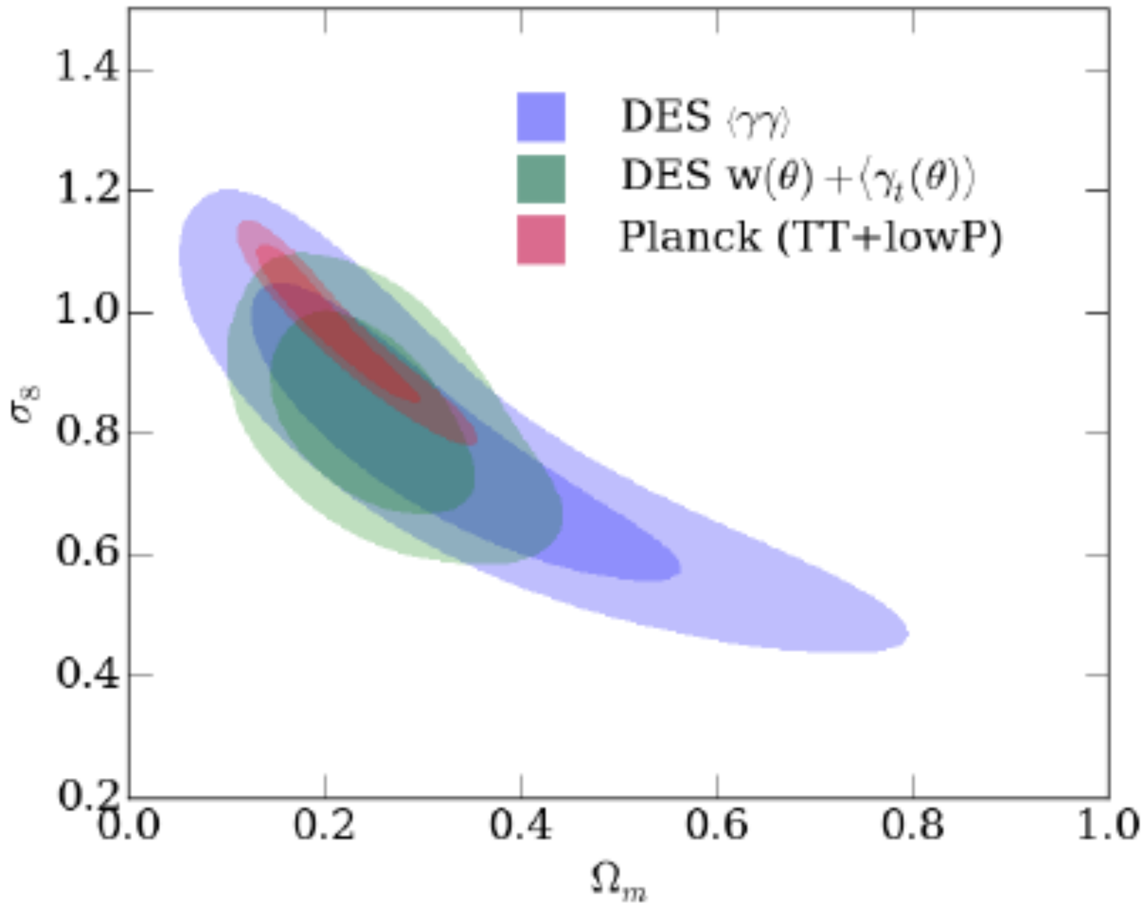
Becker et al 2015 (DES collaboration)

Galaxies x CMB



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

Galaxy clustering + Lensing

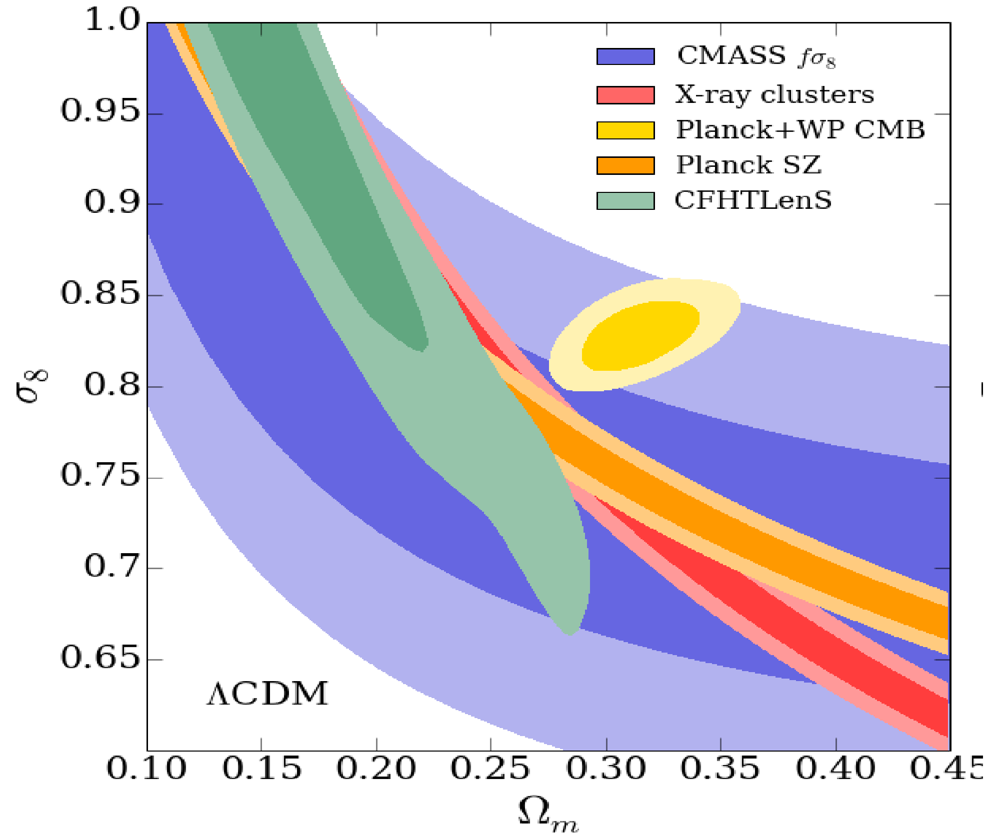


Constraints on the amplitude of mass fluctuations

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 vs. CMB



- Amplitude at late times/small scales is lower than inferred from CMB
- More data needed!

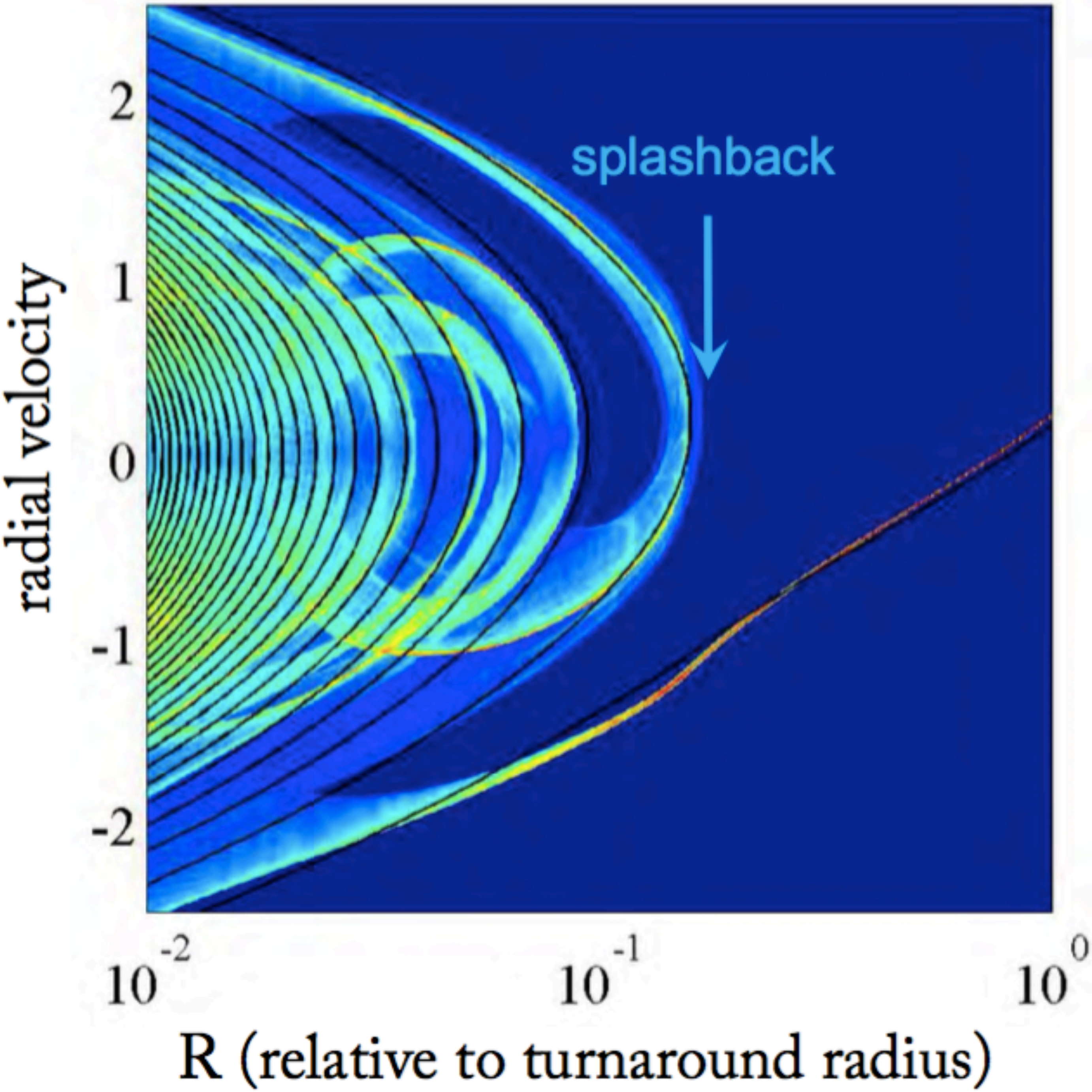
Maccrann,, Zuntz, Bridle, BJ, Becker 2014; BOSS, Planck papers

Outlook

- Year 1-3 DES data is about 10x the size of results shown here. 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 …

Spare slides

Spare



Adhikari et al. (2014)