INTRO

FUNDAMENTAL PHYSICAL TESTS "BEFORE" GALAXIES ARE FORMED IN THE POST-REIONIZATION UNIVERSE

INTENSITY MAPPING
IGM

GALAXY CLUSTERING: DYNAMICAL AND GEOMETRICAL PROBE

WEAK LENSING

GALAXY CLUSTERS

PLAN

CONNECTIONS

FABIO FINELLI: CMB x LSS

KFIR BLUM: SMALLER SCALES PROPERTIES OF GALAXIES

LUCA AMENDOLA: MODIFICATION OF GRAVITY/DARK ENERGY

OLGA MENA: NEUTRINOS

TRACY SLATYER: DARK MATTER
WEAK (and partly STRONG) LENSING

Hoekstra & Jain 2008
Wong et al. 2019 - HoliCow time delays results
Birrer+22 Time delays
Treu+21 2210.10833 mini review
Martin Crocce [talk]
Martin White lectures
Hoekstra [talk]
Heymans+21 [Kids-1000] LCDM
Troster+21 [Kids-1000] beyond LCDM
Mantz+21 cosmology with gas fraction in Galaxy Clusters
Esposito+22 Galaxy Clusters and IGM
Costanzi+18 DES Galaxy Cluster number counts
DES 3yr results papers https://www.darkenergysurvey.org/des-year-3-cosmology-results-papers/
First lensed Quasar Q0957+561A - Welsh (1979)
Rauch, Becker, MV +05
SMACS 0723, known as Webb's First Deep Field
11/07/22
Assumptions:
1) Gravitational field is weak
2) Deflection angles are small
3) Deflection happens at scales << scale of the Universe

Optics in the context of geometrically thin lenses

Use GR with line element and Phi Newtonian potential

\[ d\tau^2 = (c^2 + 2\Phi)dt^2 - \frac{(1 - 2\Phi / c^2)}{c^2 + 2\Phi}ds^2 \]

Use Fermat principle \( d\tau = 0 \)

\[ dt = \sqrt{\frac{1 - 2\Phi / c^2}{c^2 + 2\Phi}} ds = \frac{1}{c} \left( 1 - \frac{2\Phi}{c^2} \right) ds = \frac{n}{c} ds \]

\( n > 1 \) is an index of refraction produced by the Newtoniana potential
Weak Lensing Basics - II

Photons will follow a path for which the light travel time is stationary to small changes in the path.

\[ t = \frac{1}{c} \int n \cdot ds \]

\[ \mathbf{\alpha} = \int_s^0 ds \nabla_{\perp} n = -\frac{2}{c^2} \int_s^0 ds \nabla_{\perp} \Phi \]

\[ \Phi(\mathbf{x}) = -G \int d^3 x' \frac{\rho(x')}{|\mathbf{x} - \mathbf{x}'|} \]

\[ \alpha(\mathbf{x}) = -\frac{4G}{c^2} \nabla \int d^2 x' \Sigma(x') \ln |\mathbf{x} - \mathbf{x}'| \]
The lens equation

\[ \eta = \frac{D_s}{D_d} \xi - D_{ds} \hat{\alpha}(\xi) \]

\[ \eta = D_s \beta \quad \text{and} \quad \xi = D_d \theta \]

\[ \beta = \theta - \frac{D_{ds}}{D_s} \hat{\alpha}(D_d \theta) \equiv \theta - \alpha(\theta) \]

The mapping from image to source plane is relatively easy. This is not the case for the mapping from source to image plane:

A source with true position will be observed at all positions that satisfy the lens equation. Multiple solutions are possible: a single source can be observed at several positions on the sky ... and this is used to measure H0 from time delays! :-)}
Weak Lensing Basics - IV

convergence (dimensionless)

\[ \kappa(\theta) = \frac{\Sigma}{\Sigma_{\text{crit}}}, \quad \Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_s}{D_{ls} D_l} \]

Redshift of sources has to be known: spectroscopy too expensive
photometry is good

\[ \alpha(\theta) = \frac{1}{\pi} \int d^2 \vartheta \cdot \kappa(\vartheta) \frac{\theta - \vartheta}{|\theta - \vartheta|^2} = \nabla \Psi(\theta) \]

deflection angle

\[ \Psi(\theta) = \frac{1}{\pi} \int d^2 \vartheta \cdot \kappa(\vartheta) \ln |\theta - \vartheta| \]
gravitational lens potential

\[ \nabla^2 \Psi(\theta) = 2\kappa(\theta) \]

which satisfies Poisson-like equation

Observable effects:
- Delays
- Deflection
- Distortion
Fermat’s principle
rays of light traverse the path of stationary optical length with respect to variations of the path

- Generically, taking into account GR and 3-dim

\[
t(\Theta) = \frac{D_{\Delta l}}{c} \cdot \Phi(\Theta, \vec{\beta})
\]

where \( \Phi = \frac{1}{2}(\Theta - \vec{\beta})^2 - \psi(\Theta) \) and \( D_{\Delta l} \equiv (1 + z_d) \frac{D_d D_s}{D_{ds}} \)

Units: (angle)^2/H0
The time delay between two paths is then
\[ \Delta t_{AB} = \frac{D_{\Delta t}}{c} \cdot \Delta \Phi_{AB} \]

- \( D_{\Delta t} = (1 + z_d) \frac{D_d D_s}{D_{ds}} \). \( D \)'s are angular-diameter distances
  \[ \Rightarrow D_{\Delta t} \propto H_0^{-1} \]

---

Knowledge of \( z_d \) and \( z_s \)

(Assuming \( \Omega \))

Compute \( D_d, D_s, D_{ds} \) as func of \( H_0 \)

Measure \( \Delta t \)

Use \( D_{\Delta t} = \frac{c \Delta t_{AB}}{\Delta \Phi_{AB}} \) to infer \( H_0 \)

Inference goes this way:

Lens model, knowledge of the mass profile

Compute \( \Delta \Phi \)

\[ \Sigma(\Theta) \approx \int_{\text{I.o.S.}} dz \rho(x, y, z) \]
2.4% error bar on $H_0$
5.3 sigma away from Planck value

NOTE:
Modelling of the gravitational potential

With a more flexible parametrization, $H_0$ is only constrained if the measured time delays and imaging data are supplemented by stellar kinematics. Applying this extremely conservative choice to the TDCOSMO sample of 7 lenses increases the uncertainty on $H_0$ from 2% to 8% --> 74 pm 6 km/s/Mpc
Deflection - I

First Derivative = 0

\[ \vec{\nabla}_T = 0 \]

\[ \vec{\theta} - \vec{\beta} - \vec{\nabla}_2D = 0 \]

Units=angles

Notable example CMB lensing - from Blake Sherwin

\[ |d(\hat{n})|_{\text{filt}} \]

remaps the CMB temperature:

\[ T(\hat{n})_{\text{lensed}} = T(\hat{n} + d(\hat{n}))_{\text{unlensed}} \]

small \( \sim 3 \) arcminute deflections, coherent on degree scales

\[ \nabla \cdot d(\hat{n}) = \int_0^{r_{\text{CMB}}} \int_{\text{density}} \nabla^\text{geometry} dr W(r) \delta(\hat{n}, r) \]

Lens “pushes” sources away

radial squeezing:
The effect of lensing is to remap the images of extended sources, while conserving surface brightness.

\[
I(\theta) = I^{(s)}[\beta(\theta)]
\]

\[
I(\theta) = I^{(s)}[\beta_0 + \mathcal{A}(\theta_0) \cdot (\theta - \theta_0)]
\]

\[
\mathcal{A}(\theta) = (1 - \kappa) \begin{pmatrix} 1 - g_1 & -g_2 \\ -g_2 & 1 + g_1 \end{pmatrix}, \text{ where } g(\theta) = \frac{\gamma(\theta)}{[1 - \kappa(\theta)]}
\]

Lensed image of a small circular source is an ellipse

Shearing and magnification

Reduced shear: \( g_i = \frac{\gamma_i}{(1 - \kappa)} \)

Magnification:

\[
\mu = \frac{1}{\det \mathcal{A}} = \frac{1}{(1 - \kappa)^2 - |\gamma|^2} = \frac{1}{(1 - \kappa)^2 (1 - |g|^2)}
\]

Axis ratio of ellipse:

\[
\frac{b}{a} = \frac{R}{(1 - \kappa)(1 + |g|)} / \frac{R}{(1 - \kappa)(1 - |g|)} = \frac{1 - |g|}{1 + |g|}
\]
Magnification has two effects:

- true survey area is $1/\mu$ times larger
- objects are $\mu$ times larger/brighter

$$n(S, z) = \frac{1}{\mu(\theta, z)} n_0 \left( \frac{S}{\mu(\theta, z)} \right)$$
**Distortion - III**

GOAL: get surface density from shear (or convergence)

Note that shear and convergence are related

\[
\Psi(\theta) = \frac{1}{\pi} \int d^2 \theta \cdot \kappa(\theta) \ln |\theta - \theta'|
\]

\[
\vec{\alpha}(\theta) = \nabla \Psi(\theta)
\]

\[
\nabla^2 \Psi(\theta) = 2\kappa(\theta)
\]

\[
\gamma_1 = \frac{1}{2} \left( \frac{\partial^2 \Psi}{\partial^2 x_1} - \frac{\partial^2 \Psi}{\partial^2 x_2} \right)
\]

\[
\gamma_2 = \frac{\partial^2 \Psi}{\partial x_1 \partial x_2}
\]

**Real Space**

\[
\gamma(\theta) = \frac{1}{\pi} \int_{\mathbb{R}^2} d^2 \theta' D(\theta - \theta') \kappa(\theta') , \quad \text{with kernel}
\]

\[
D(\theta) \equiv \frac{\theta_2^2 - \theta_1^2 - 2i\theta_1 \theta_2}{|\theta|^4} = -\frac{1}{(\theta_1 - i\theta_2)^2}.
\]

**Fourier Space**

\[
\tilde{\gamma}(\ell) = \pi^{-1} \hat{D}(\ell) \hat{\kappa}(\ell) \quad \text{for} \quad \ell \neq 0
\]

With inversion:

\[
\hat{\kappa}(\ell) = \pi^{-1} \tilde{\gamma}(\ell) \hat{D}^*(\ell) \quad \text{for} \quad \ell \neq 0
\]

Where

\[
\hat{D}(\ell) = \frac{\pi \left( \ell_1^2 - \ell_2^2 + 2i\ell_1 \ell_2 \right)}{|\ell|^2}
\]

was used (this implies \( D D^* = \pi^2 \)).

Fourier back-transformation then yields

\[
\kappa(\theta) - \kappa_0 = \frac{1}{\pi} \int_{\mathbb{R}^2} d^2 \theta' D^*(\theta - \theta') \gamma(\theta')
\]

Kaiser & Squires (1993)
The shearing of images is a spin-2 field. It is useful to spend some time on the description of spin-2 fields.

\[ \gamma_1 > 0 \quad \gamma_1 < 0 \quad \gamma_2 > 0 \quad \gamma_2 < 0 \]

Rotating the coordinate system counterclockwise by \( \phi \) changes

\[ \gamma_1 + i \gamma_2 \rightarrow (\gamma_1 + i \gamma_2) e^{-2i\phi} \]

Keeping track of that phase as we rotate coordinates, the Fourier decomposition can be written in terms of real functions \( \varepsilon \) and \( \beta \) as

\[ (\gamma_1 + i \gamma_2)(x) \equiv \int \frac{d^2k}{(2\pi)^2} \left[ \varepsilon(k) + i \beta(k) \right] e^{2i\phi_k} e^{i\vec{k} \cdot \vec{x}} \]

where \( \varepsilon \) is parity even and \( \beta \) is parity odd.

The \( E \)-mode is simply \( \kappa \) -- tangential shear around overdensities.

The \( B \)-mode is very small for gravitational lensing -- “swirling” around overdensities.
Distortion - IV

\[ \langle \epsilon(l)\epsilon(l') \rangle = (2\pi)^2 \delta(l - l') C_l^{EE} \]
\[ \langle \beta(l)\beta(l') \rangle = (2\pi)^2 \delta(l - l') C_l^{BB} \]
\[ \langle \epsilon(l)\beta(l') \rangle = (2\pi)^2 \delta(l - l') C_l^{EB} \]

Using Gauss theorem

\[ \langle \gamma_t \rangle(\theta) = \kappa(\theta) - \langle \kappa \rangle(\theta) \]

The tangential shear provides a direct measure of the **mass contrast**. It is a **local** measurement. This can be used to estimate projected masses within a radius with few assumptions about the radial matter distribution.
**Convergence Power Spectrum**

The convergence power spectrum is defined as,

\[
\langle \tilde{\kappa}(\ell) \tilde{\kappa}^*(\ell') \rangle = (2\pi)^2 \delta_D(\ell - \ell') \, P_{\kappa}(\ell)
\]

And is related to the 3D mass power spectrum as,

\[
P_{\kappa}(\ell) = \frac{9}{4} \Omega_m^2 \left( \frac{H_0}{c} \right)^4 \int_0^{\chi_{\infty}} d\chi \frac{g^2(\chi)}{a^2(\chi)} P_\delta \left( k = \frac{\ell}{\chi}, \chi \right)
\]

Limber approximation

Cooray & Hu 2001
COSMOLOGY WITH WEAK LENSING
In context

Slide by E. Huff

Survey area (deg²)

Completed:
2005 2009  Ongoing

Beginning science operations:
2022 2023 2026
The Dark Energy Survey (DES)

- 570 Megapixel camera for the Blanco 4m telescope in Chile.
- Observed in 5 imaging bands (grizY) : photometric redshifts
- Full survey 758 nights (2013-19)
- **This talk**  DES Y3 (2013-16).
- **Wide field**: 5000 sq. deg. with limiting depth i <~ 24
- **Deep field**: 30 sq. deg. with near-IR YJHK bands, 10x wide field depth

courtesy of Martin Crocce
Cosmic Shear

shape (ellipticity) - shape correlation

$$\xi \sim \langle e(\theta')e(\theta + \theta) \rangle$$
cosmic shear

\[ \xi_\pm = \langle e_t(\theta')e_t(\theta' + \theta) \rangle \]
\[ - \langle e_x(\theta')e_x(\theta' + \theta) \rangle \]
\[ \propto \sigma_8^2 \]

1x2pt
galaxy clustering

\[ w(\theta) = \langle \delta(\theta')\delta(\theta' + \theta) \rangle \]
\[ \propto b^2 \sigma_8^2 \]

2x2pt
galaxy-galaxy lensing

\[ \gamma_t(\theta) = \langle \delta(\theta')e_t(\theta' + \theta) \rangle \]
\[ \propto b \sigma_8^2 \]

3x2pt

courtesy of Martin Crocce
**3x2pt Data-vector**

DES uses correlation functions in angular or configuration space.

\[
\begin{align*}
\hat{w}^i(\theta) &= \sum_{\ell} \mathcal{G}_0 (\ell, \theta_{\text{min}}, \theta_{\text{max}}) \, C_{\delta\delta}^{ij}(\ell) \\
\hat{\gamma}_t^{ij}(\theta) &= \sum_{\ell} \mathcal{G}_2 (\ell, \theta_{\text{min}}, \theta_{\text{max}}) \, C_{\delta\delta}^{ij}(\ell) \\
\hat{\xi}^{ij}_\pm(\theta) &= \sum_{\ell} \mathcal{G}_4,\pm (\ell, \theta_{\text{min}}, \theta_{\text{max}}) \left[ C_{\eta\eta}^{ij}(\ell) \pm C_{BB}^{ij}(\ell) \right]
\end{align*}
\]

From 4 lens and 4 source tomographic bins we get \( \hat{D} \equiv \{ \hat{w}^i(\theta), \hat{\gamma}_t^{ij}(\theta), \hat{\xi}^{ij}_\pm(\theta) \} \)

- 4 auto correlation functions for clustering
- 10 bin paris for galaxy-galaxy lensing
- 10 bin pairs fro cosmic shear+ and 10 bin pairs for cosmic shear-

462 data-points after scale-cuts with a total S/N = 87 (twice DESY1)

\( G_0, G_2, G_4 \) are analytical function that take into account projections of lensing on the sphere see Stebbins 1996

\( \xi^{ij}_\pm(\theta) = \langle \epsilon_t \epsilon_t \pm \epsilon_x \epsilon_x \rangle(\theta) \).
How beautiful!!!

....but in practice....

“I know I’m out of touch with reality. That’s my best stress-management technique!”
- Linear galaxy bias only valid on large scales
- Galaxies intrinsically aligned (not randomly oriented)
- Estimating galaxy distances through photometric redshifts in few bands
- Measuring and deconvolving the Point Spread Functions (PSF)
- Shear estimations bias calibration with image simulations
- Galaxy images blend
- Blending couples with photometric redshifts
- Galaxy images are taken with a wide range of observing conditions
- Observing conditions imprint large-scale density fluctuations
3x2pt Data + Model fit

cosmic shear Amon, + (2021), Secco, Samuroff, + (2021)
galaxy-galaxy lensing Prat, + (2021)
galaxy clustering Rodriguez-Monroy, + (2021)
Internal consistency

Two correlated cosmological probes:

1. **Cosmic shear** (blue)
2. **Galaxy clustering** and **tangential shear** (orange)

We find consistency between them.

**Cosmic shear** most sensitive to clustering amplitude.

**Galaxy clustering** and **tangential shear** more sensitive to total matter density.
DES only 3x2pt results

We combine these into the \textbf{3x2pt} probe of large-scale structure.

A factor of 2.1 improvement in signal-to-noise from DES Year 1 (and in the $\sigma_8 - \Omega_m$ plane).

\[
S_8 = 0.776^{+0.017}_{-0.017} \quad (0.776)
\]

In $\Lambda$CDM: \quad $\Omega_m = 0.339^{+0.032}_{-0.031} \quad (0.372)$

\[
\sigma_8 = 0.733^{+0.039}_{-0.049} \quad (0.696)
\]

In $w$CDM: \quad $\Omega_m = 0.352^{+0.035}_{-0.041} \quad (0.339)$

\[
w = -0.98^{+0.32}_{-0.20} \quad (-1.03)
\]
**Low-z vs High-z in $\Lambda$CDM**

We test the robustness of $\Lambda$CDM by comparing measurements of the clustering amplitude at low-redshift to the prediction from the cosmic microwave background (CMB) at high-redshift.

We find no significant evidence of inconsistency between DES Y3 3×2pt and Planck CMB at 1.5σ (p-value=0.13). Cosmic shear only at 2.1σ Suspiciousness of 0.7σ (p-value = 0.48).

Roughly similar as in DESY1 but with an increase in precision in both probes.
The *Hubble* parameter tension

Local measurements of $h$, e.g. from Cepheids variable stars (SHOES collab.), with MIRA variable stars, masers, strong lensing time delays, etc tend to find higher $h$ values than derived by CMB observations at high-$z$ assuming $\Lambda$CDM

**BAO+BBN+DES** 3x2 similar constraining power as *Planck* CMB, all combined leads to

$$ h = 0.680^{+0.004}_{-0.003} $$

Roughly 4σ smaller than SHOES
Joint constraints

Combining all these data sets we find:

In $\Lambda$CDM:

\[
S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)
\]

\[
\Omega_m = 0.306^{+0.004}_{-0.005} \quad (0.306)
\]

\[
\sigma_8 = 0.804^{+0.008}_{-0.008} \quad (0.807)
\]

\[
h = 0.680^{+0.004}_{-0.003} \quad (0.681)
\]

\[
\sum m_\nu < 0.13 \text{ eV} \quad (95\% \text{ CL})
\]

In $w$CDM:

\[
\sigma_8 = 0.810^{+0.010}_{-0.009} \quad (0.804).
\]

\[
\Omega_m = 0.302^{+0.006}_{-0.006} \quad (0.298).
\]

\[
w = -1.03^{+0.03}_{-0.03} \quad (-1.00)
\]
DARK ENERGY with DES 3yr

Pivot: z~0.3

arXiv:2207.05766
### Neutrinos

**Sterile Neutrinos**

\[
k_{fs} = \frac{0.8 h \text{Mpc}^{-1}}{\sqrt{1 + z}} \left( \frac{m_{\text{eff}}}{(1\text{eV})\Delta N_{\text{eff}}} \right)
\]

**Active Neutrinos**

\[
\Delta N_{\text{eff}} > 0.047
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>All External</th>
<th>All data</th>
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<tbody>
<tr>
<td>(\Lambda\text{CDM})</td>
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<td>0.14</td>
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<tr>
<td>(w\text{CDM})</td>
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<td>0.19</td>
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<td>(w_0-w_a)</td>
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<td>(\Omega_k)</td>
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<td>(N_{\text{eff}})</td>
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<td>(\Sigma_0-\mu_0)</td>
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<tr>
<td>Binned (\sigma_8(z))</td>
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</tr>
<tr>
<td>(A_L)</td>
<td>0.14</td>
<td>0.19</td>
</tr>
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</table>
Modification of gravity and evolution of growth
We find that the $\sim 3\sigma$ tension with Planck CMB data that was found in Asgari et al. (2021) and Heymans et al. (2021) is not resolved by either extending the parameter space beyond flat $\Lambda$CDM, or by restricting it through fixing the amplitude of the primordial power spectrum to the Planck best-fit value.
On the degeneracy between baryon feedback and massive neutrinos as probed by matter clustering and weak lensing

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Baryons? Neutrinos? to ease the "tensions"......
Concentrations of $\sim 10^3$ galaxies
$\sigma_v \sim 500-1000$ km/s
Size: $\sim 1$-$2$ Mpc
Mass: $\sim 10^{14}$-$10^{15}$ Msun
$\Rightarrow \lambda_i \approx 10$ Mpc
Baryon content:
$\Rightarrow$ cosmic share ($\sim 15\%$) in hydrostatic equilibrium
ICM temperature:
$\Rightarrow T \sim 2$-$10$ keV
$\Rightarrow$ fully ionized plasma; Thermal bremsstrahlung
$\Rightarrow n_e \sim 10^{-2}$-$10^{-4}$ cm$^{-3}$
$\Rightarrow L_X \sim n_e^2 V \sim 10^{45}$ erg/s

Physical properties of GCs as inferred from optical and X-ray observations
Cosmology with Galaxy Clusters - II

SZ-Clusters

- Signal virtually independent of redshift
- Proportional to the l.o.s. integration of neTe ~ pressure
- Wider dynamic range accessible compared to X-rays
- We are now in the era of SZ cluster cosmology (e.g. ACT, SPT, Planck)

Inverse Compton scattering of CMB photons off the ICM electrons
Cosmology with Galaxy Clusters - III

What do we need to do cosmology with GCs? 1) robust cluster catalogs with large z leverage (with well understood purity and completeness; look for e.g. DES, SPT-3G, eROSITA, Euclid) 2. accurate absolute mass calibration (from weak lensing or X-ray once bHE is better characterized) 3. sufficiently low-scatter mass proxy information (mainly from X-ray and SZ follow-up; optical is more expensive and still affected from large scatter)

\[
\frac{dN(X,z)}{dXdz} = \frac{dV}{dz} f(X,z) \int_0^{\infty} \frac{dn(M,z)}{dM} \frac{dp(X|M,z)}{dX} dM
\]

dV/dz: volume [priors from BAO, SN, CMB
f(X,z) observational strategy - selection function
dn/dM cosmology Mass function
dp/dX - astrophysics [from sims/mocks/observations]

σ₈ Ωₘ⁰.5 ~ const
Cosmology with Galaxy Clusters - IV: constraints from gas fractions

~ 40 X-ray Clusters - measurement of $f_{\text{gas}}$
from hydrostatic equilibrium
sample of relaxed and hot GCs from Chandra
also some WL mass estimates to further constrain the model

$$f_{\text{gas}}(z, M_{2500}) = \gamma(z, M_{2500}) \frac{\Omega_D}{\Omega_m},$$

$$\gamma(z, M_{2500}) = \gamma_0 (1 + \gamma_1 z) \left( \frac{M_{2500}}{3 \times 10^{14} M_\odot} \right)^{\alpha}$$

Mantz+21
Costanzi+2018: abundance and weak-lensing of RedMapper clusters from SDSS \((z=0.1-0.3)\)

\[ S_8 \equiv \sigma_8 (\Omega_m/0.3)^{0.5} = 0.79^{+0.05}_{-0.04}. \]

No evidence of tension with CMB constraints and constraints from other cluster catalogues
Cosmology with Galaxy Clusters - VI: constraints from SZ cluster

Bocquet+2018: cluster counts in the SPT-SZ survey (z=0.25-1.75)
→ 377 clusters used, supplemented by HST+Magellan WL mass and Chandra X-ray observations

$$\Omega_m = 0.276 \pm 0.047$$
$$\sigma_8 = 0.781 \pm 0.037$$

- Allow neutrino mass to be a free parameter
- Test of growth of structure in agreement with GR
Cosmology with Galaxy Clusters

XXL (Pacaud+18)
HIFLUGCS MF+fgas (Schellenberger+17)
HIFLUGCS MF (Schellenberger+17)
RASS+WtG MF+fgas (Mantz+15)
SPT (Bocquet+18)
SPT (de Haan+16)
Planck 2015 (XXIV)
ACT (Hasselfield+13)
SDSS (Costanzi+18)
HSC Y-1 (Hikage+18)
DES Y-1 (Abbott+18)
KiDS+VIKING (Hildebrandt+18)
KiDS+GAMA (van Uitert+18)
KiDS-450 (Hildebrandt+17)
Planck 2018 (VI)
Planck 2015 (XIII)
WMAP9 (Hinshaw+13)
Cosmology with Galaxy Clusters and the IGM - new tension???

Esposito+22 w

Detection signal noise-ratio vs Cluster Mass

\[
\ln(\zeta) = \ln A_{SZ} + B_{SZ} \ln \left( \frac{M_{500} h_{70}}{4.3 \times 10^{14} M_\odot} \right) + C_{SZ} \ln \left( \frac{E(z)}{E(0.6)} \right)
\]
Lensing and Clusters - Summary

- Weak gravitational lensing: fundamental cosmological observables which, unlike galaxy clustering and similarly to Lyman-alpha, allows access to non-linear scales
- Tremendous progress in the last decade: KiDS, DES, CFHTLens. Mathematically very neat modelling, in practice much harder
- Probe of structure growth: some $S_8$ tension seems to be present
- Galaxy Cluster number counts also very important to constrain $s_8$-Omegam: results in agreement with WL
- Again: exciting future: for WL: Euclid and LSST, for GCs: eROSITA, Euclid, Roman telescope.