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
Treu+21 2210.10833 mini review
Martin Crocce [talk]
Martin White lectures
Hoekstra [talk]
Heymans+21 [Kids-1000] LCDM
Trost+21 [Kids-1000] beyond LCDM
Mantz+21 cosmology with gas fraction in Galaxy Clusters
Espósito+22
Costanzi+18

DES 3yr results papers https://www.darkenergysurvey.org/des-year-3-cosmology-results-papers/
First lensed Quasar Q0957+561A - Welsh (1979)
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

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

Use GR with line element and Phi Newtonian potential

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

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

\(n > 1\) 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.

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

\[ \alpha = \theta_s + \theta_o \]

\[ \theta_s = \frac{dx}{ds} \bigg|_s \quad \theta_o = -\frac{dx}{ds} \bigg|_o \]

\[ \vec{\alpha} = \int_s^0 ds \vec{\nabla}_\perp n = -\frac{2}{c^2} \int_s^0 ds \vec{\nabla}_\perp \Phi \]

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

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

$$\eta = \frac{D_s}{D_d} \xi - D_{ds} \alpha(\xi)$$

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

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

The mapping from image to source plane is 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 - III
Weak Lensing Basics - IV

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

\( \kappa(\theta) = \frac{\Sigma}{\Sigma_{\text{crit}}} \), \( \Sigma_{\text{crit}} = \frac{c^2}{4\pi G} \frac{D_s}{D_{is} D_{il}} \)

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

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

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

Observable effects:
- Delays
- Deflection
- Distortion
Time delays - I

- Generically, taking into account GR and 3-dim

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

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

Units: \((\text{angle})^2/H_0\)
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

\[ \Rightarrow D_{\Delta t} \propto H_0^{-1} \]

---

**Inference goes this way:**

- Knowledge of \( z_d \) and \( z_s \)
  - (Assuming \( \Omega \))
- Compute \( D_d, D_s, D_{ds} \) as function of \( H_0 \)
- Measure \( \Delta t \)
- Use \( D_{\Delta t} = \frac{c \Delta t_{AB}}{\Delta \Phi_{AB}} \)
- Compute \( \Delta \Phi \)
- To infer \( H_0 \)

**Lens model, knowledge of the mass profile**

\[ \Sigma(\Theta) \approx \int_{l.o.s.} dz \rho(x, y, z) \]
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% $\rightarrow$ 74 pm 6 km/s/Mpc
Deflection - 1

First Derivative = 0

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

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

Units = angles

Notable example CMB lensing - from Blake Sherwin

Replaces the CMB temperature: \( T(\hat{n})_{\text{lensed}} = T(\hat{n} + \mathbf{d}(\hat{n}))_{\text{unlensed}} \)

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

Small ~3 arcminute deflections, coherent on degree scales

Lens "pushes" sources away

radial squeezing:

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

lensing
Distortion - I

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

\[ \frac{\partial \beta}{\partial \theta} = \left( 1 - \frac{\partial^2 \psi}{\partial \theta_x \partial \theta_y} - \frac{\partial^2 \psi}{\partial \theta_y} \right) \]

Units: angle^0

\[ \left| \frac{\partial \beta}{\partial \theta} \right| = \frac{1}{\mu} \]

k is convergence

g is shear

Shearing and magnification

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

Magnification:

\[ \mu = \frac{1}{\det A} = \frac{1}{(1 - \kappa)^2 - |\gamma|^2} = \frac{1}{(1 - \kappa)^2 (1 - |g|^2)} \]
Magnification has two effects:

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

$$n(> S, z) = \frac{1}{\mu(\theta, z)} n_0 \left( \frac{S}{\mu(\theta, z)^2} \right)$$

reduction in volume

increase in flux
Distortion - III

GOAL: get surface density from shear (or convergence)

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

Real Space

\[
\gamma(\theta) = \frac{1}{\pi} \int_{\mathbb{R}^2} d^2\theta' \mathcal{D}(\theta - \theta') \kappa(\theta'), \quad \text{with kernel}
\]
\[
\mathcal{D}(\theta) \equiv \frac{\theta_2^2 - \theta_1^2 - 2i\theta_1\theta_2}{|\theta|^4} = \frac{-1}{(\theta_1 - i\theta_2)^2}
\]

Fourier Space

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

With inversion:

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

where

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

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

Fourier back-transformation then yields

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

Kaiser & Squires (1993)
Distortion - IV

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

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

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.
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 minimal assumptions about the radial matter distribution.
COSMOLOGY WITH WEAK LENSSING
In context

Slide by E. Huff
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 $i < \sim 24$
- **Deep field:** 30 sq. deg. with near-IR YJHK bands, 10x wide field depth
background (source) galaxies

lensed/sheared image of background galaxies

Cosmic Shear
shape (ellipticity) - shape correlation

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

Correlation in the shapes of (source) galaxies

\[ \xi_{\pm} = \langle e_t(\theta')e_t(\theta' + \theta) \rangle - \langle e_x(\theta')e_x(\theta' + \theta) \rangle \]

\[ \propto \sigma_8^2 \]

1x2pt

galaxy clustering

Correlation in the positions of (lens) galaxies

\[ w(\theta) = \langle \delta(\theta')\delta(\theta' + \theta) \rangle \]

\[ \propto b^2 \sigma_8^2 \]

2x2pt

galaxy-galaxy lensing

Correlation between positions of the lenses and shapes of the sources

\[ \gamma_t(\theta) = \langle \delta(\theta')e_t(\theta' + \theta) \rangle \]

\[ \propto b\sigma_8^2 \]

3x2pt

Cosmology!
3x2pt Data-vector

DES uses correlation functions in angular or configuration space.

\[ w^i(\theta) = \sum_{\ell} g_0(\ell, \theta_{\text{min}}, \theta_{\text{max}}) C_{\delta_{\text{obs}} \delta_{\text{obs}}}^{ii}(\ell) \]

\[ \gamma_{t}^{ij}(\theta) = \sum_{\ell} g_2(\ell, \theta_{\text{min}}, \theta_{\text{max}}) C_{\delta_{\text{obs}} E}^{ij}(\ell) \]

\[ \xi_{\pm}^{ij}(\theta) = \sum_{\ell} g_4,\pm(\ell, \theta_{\text{min}}, \theta_{\text{max}}) \left[ C_{E E}^{ij}(\ell) \pm C_{B B}^{ij}(\ell) \right] \]

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

- 4 auto correlation functions for clustering
- 10 bin pars for galaxy-galaxy lensing
- 10 bin pairs for cosmic shear+
- 10 bin pairs for cosmic shear-

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

....but in practice....

- 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 biases $\rightarrow$ 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 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:

\[
\Omega_m = 0.339^{+0.032}_{-0.031} \quad (0.372)
\]

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

In $w$CDM:

\[
\Omega_m = 0.352^{+0.035}_{-0.041} \quad (0.339)
\]

\[
w = -0.98^{+0.32}_{-0.20} \quad (-1.03)
\]
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 3x2pt and Planck CMB at $1.5\sigma$ (p-value=0.13). Cosmic shear only at $2.1\sigma$

Suspiciousness of $0.7\sigma$ (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 LCDM

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

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

Roughly $4\sigma$ smaller than SHOES
Joint constraints

Combining all these data sets we find:

\[
S_8 = 0.812^{+0.008}_{-0.008} \quad (0.815)
\]
\[
\Omega_m = 0.306^{+0.004}_{-0.005} \quad (0.306)
\]

In \(\Lambda\)CDM:
\[
\sigma_8 = 0.804^{+0.008}_{-0.008} \quad (0.807)
\]
\[
h = 0.680^{+0.004}_{-0.003} \quad (0.681)
\]
\[
\sum m_\nu < 0.13 \text{ eV} \quad (95\% \text{ CL})
\]

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
STERILE NEUTRINOS

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

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

- DES 3x2pt
- DES 3x2pt + BAO + RSD + SN
- *Planck*
- *Planck* + BAO + SN
- All data

ACTIVE NEUTRINOS

<table>
<thead>
<tr>
<th>Model</th>
<th>All External</th>
<th>All data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$CDM</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>$w$CDM</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>$w_0 - w_a$</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>$N_{\text{eff}}$</td>
<td>0.14</td>
<td>0.16</td>
</tr>
<tr>
<td>$\Sigma_0 - \mu_0$</td>
<td>0.21</td>
<td>0.14</td>
</tr>
<tr>
<td>Binned $\sigma_8(z)$</td>
<td>0.30</td>
<td>0.20</td>
</tr>
<tr>
<td>$A_L$</td>
<td>0.14</td>
<td>0.19</td>
</tr>
</tbody>
</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.
Cosmology with Galaxy Clusters - I

Concentrations of $\sim 10^3$ galaxies
$\sigma_v \sim 500\text{--}1000$ km/s
Size: $\sim 1\text{--}2$ Mpc
Mass: $\sim 10^{14}\text{--}10^{15}$ Msun
\[ \lambda_i \approx 10 \text{ Mpc} \]
Baryon content:
\[ \text{cosmic share ($\sim 15\%$) in hydrostatic equilibrium} \]
ICM temperature:
\[ T \sim 2\text{--}10 \text{ keV} \]
\[ \text{fully ionized plasma; Thermal bremsstrahlung} \]
\[ n_e \sim 10^{-2}\text{--}10^{-4} \text{ cm}^{-3} \]
\[ L_X \sim n_e^2 V \sim 10^{45} \text{ erg/s} \]
Cosmology with Galaxy Clusters - II

SZ-Clusters

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

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

$\frac{dV}{dz}$: 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]
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

$$f_{\text{gas}}(z, M_{2500}) = \gamma(z, M_{2500}) \frac{\Omega_{\phi}}{\Omega_{m}}$$

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

Mantz+21
Cosmology with Galaxy Clusters - V: constraints from optical clusters

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

→ ~7000 clusters used

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

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

$\sigma_8$ at $\Omega_m = 0.3$

- 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 $s_8$-$\Omega_{m}$: results in agreement with WL
• Again: exciting future: for WL: Euclid and LSST, for GCs: eROSITA, Euclid, Roman telescope.