VIMOS (ESO)

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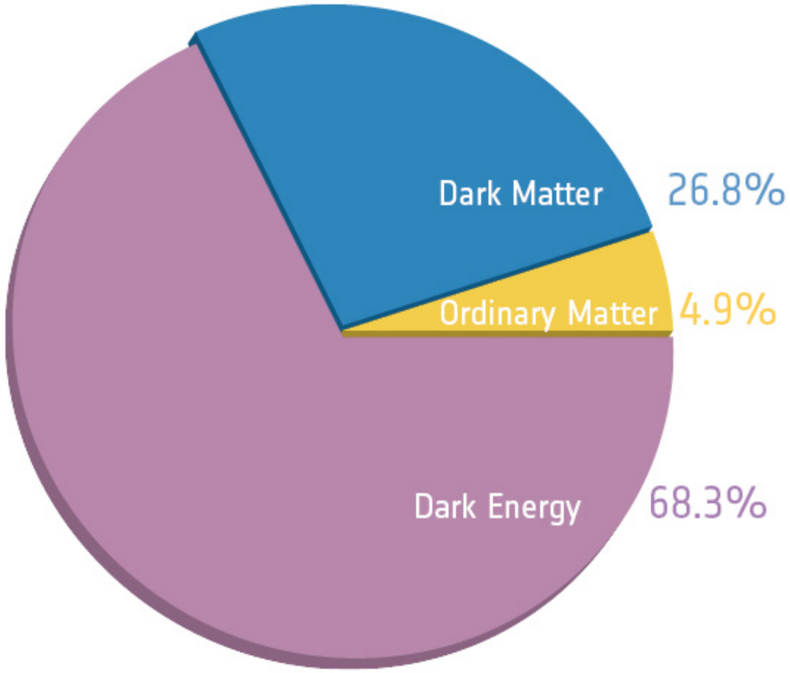
# Cosmology with galaxy clusters in the Rubin/LSST era

Constantin Payerne, supervisor: Céline Combet (équipe DARK)
Laboratoire de Physique Subatomique et de Cosmologie, Grenoble




(Planck CMB, 2018)

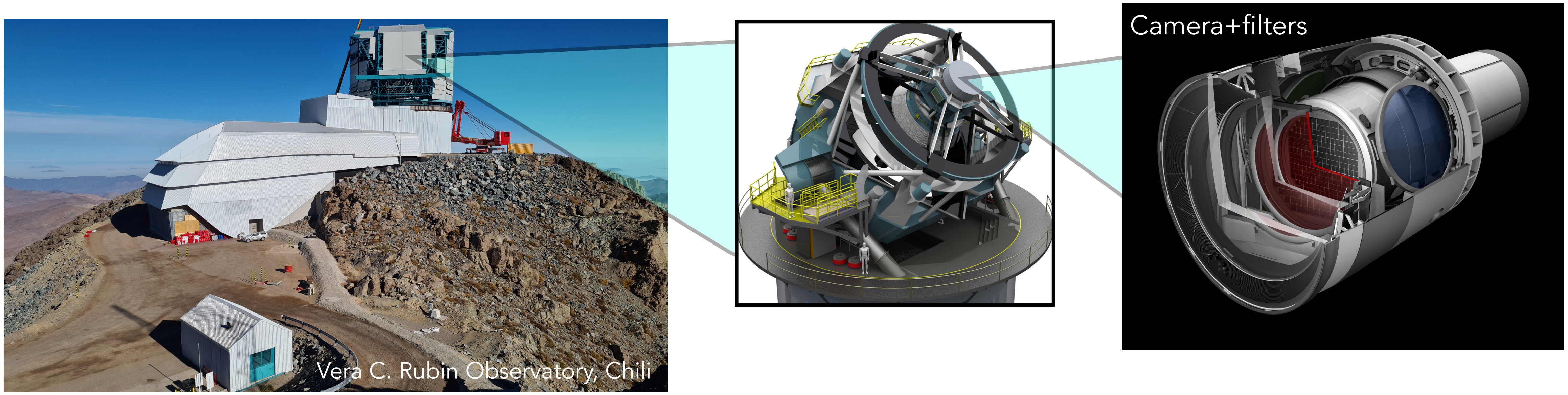
Only $\sim$ 5 % of matter content is baryonic matter
$\sim$ 95 % is unknown

**Two hypothetical components:**

1. Dark matter: attractive effect on dynamics of the Universe

2. Dark energy: acts as a negative pressure in the Universe, responsible for the current accelerated expansion

→ To constrain the properties of dark matter and dark energy is one of the goals of modern cosmology

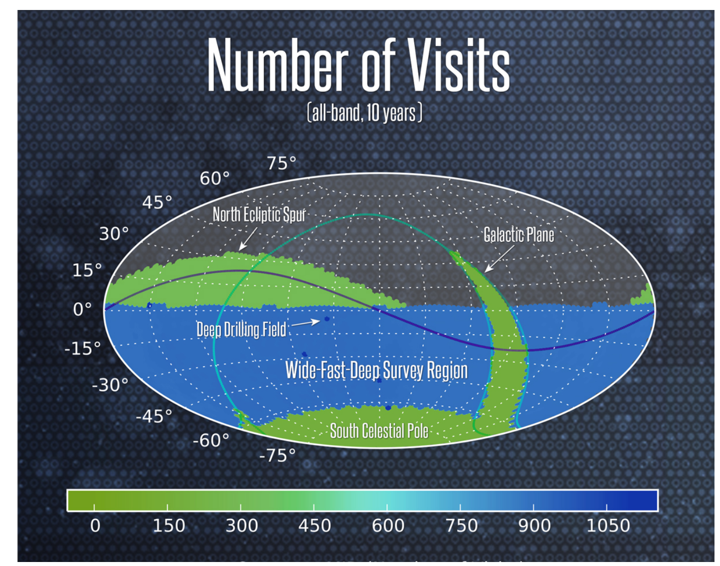



**Rubin observatory:**

- 8 meter wide mirror
- CCD camera with 3 billions pixels
- 6 optical filters

**LSST - Legacy Survey of Space and Time:**

- Sky area: 18 000 deg$^2$
- LSST: 10 years optical survey
- Observation of $\sim$ 10 billion galaxies



www.lsst.org

**DESC collaboration: study the nature of dark matter and dark energy via**

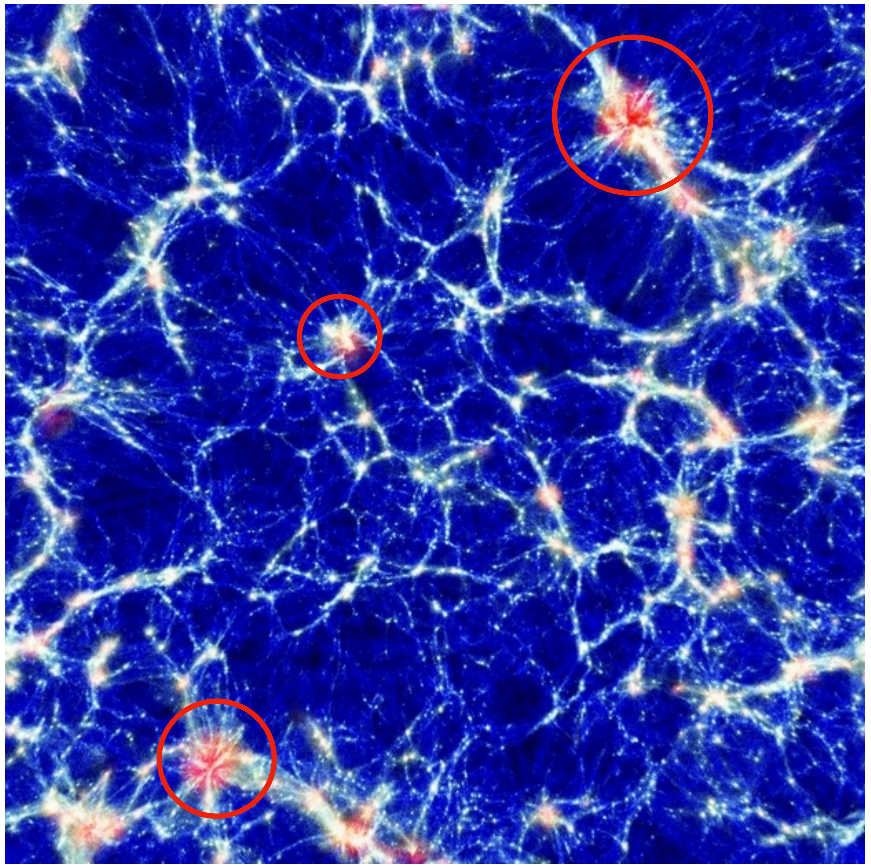
- Weak gravitational lensing
- Spatial distribution of galaxies
- Type 1a supernovae
- Galaxy clusters

LSST DESC
Dark Energy Science Collaboration

**Are the largest gravitationally bound objects in the Universe**

- Form within the largest dark matter halos
- $M > 10^{14}\ M_{\odot}$
- size of $\approx 1$ Mpc ( $= 3.10^{19}$ km)
- Recently formed object, redshift $z \leq 2$: Final step of hierarchical large scale structure formation

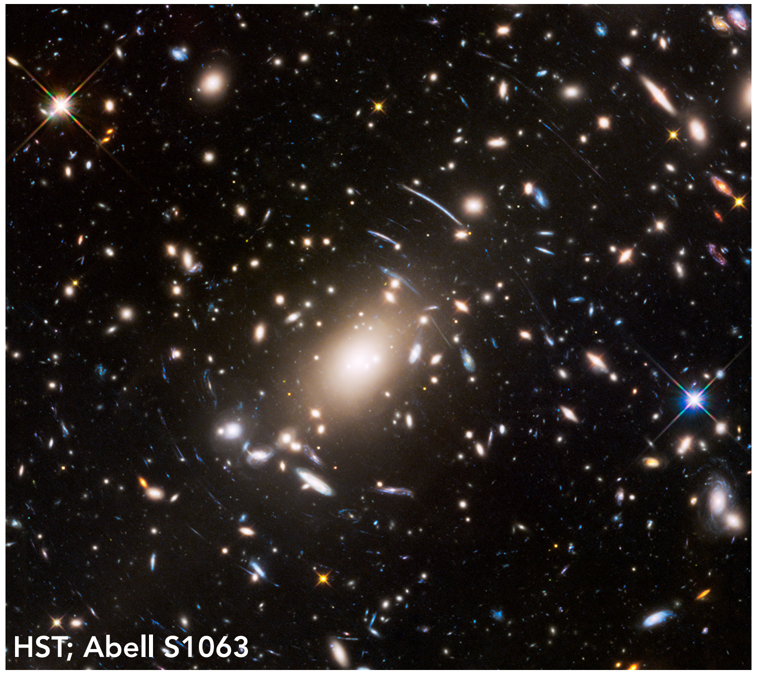
Redshift $z \sim$ distance $\sim$ look in the past



Numerical simulations Credits: Klaus Dolag

**Are multi-composite systems, contributions to the total mass:**

- $\approx$ 5% of galaxies (Optical/Near Infra-Red)
- $\approx$ 15% of hot gas ($10^7 - 10^8$ Kelvin) (X-ray, mm)
- $\approx$ 80% of dark matter
  - *"invisible"*, indirectly accessible from gravitational lensing

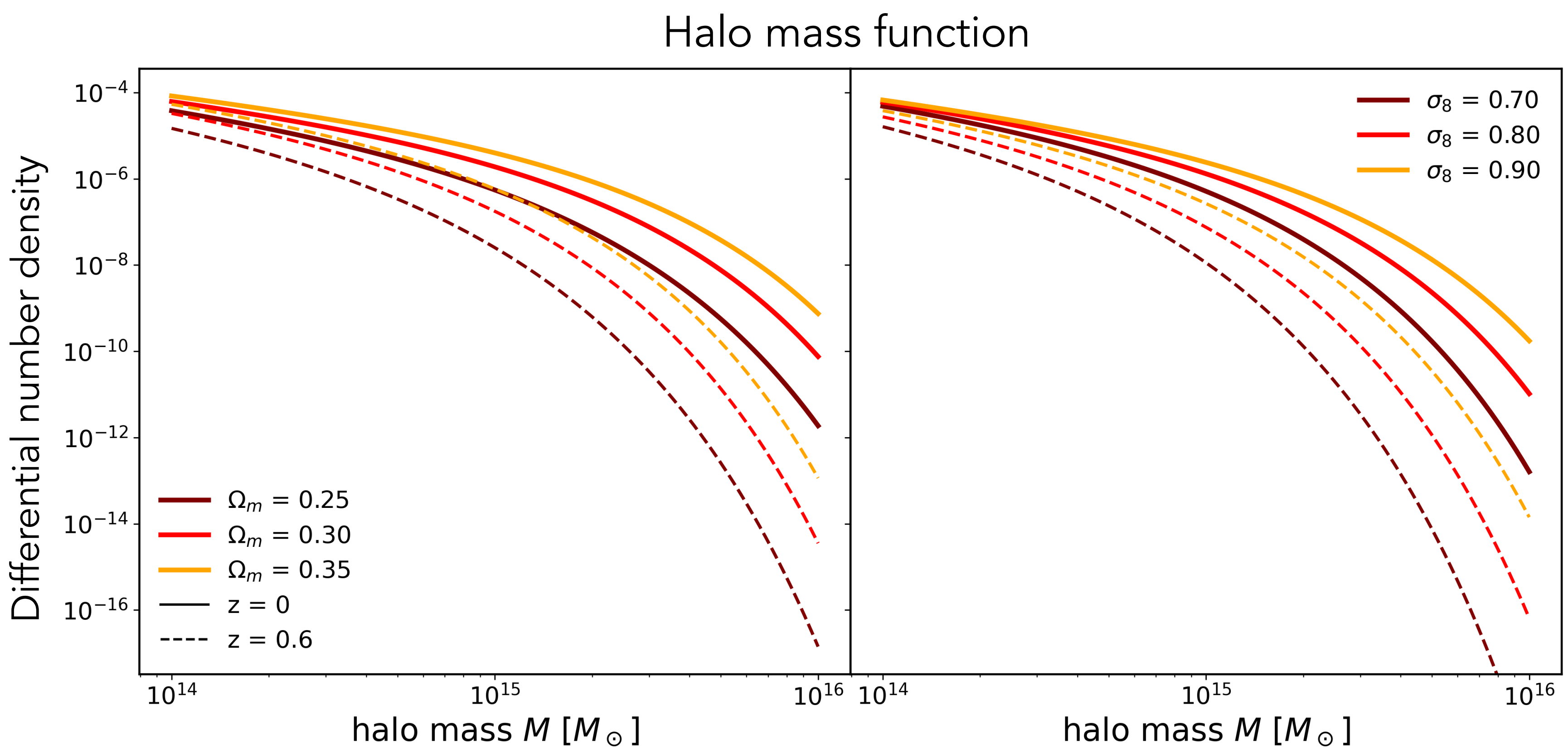



→ Galaxy clusters are tracers of the matter density field in the Universe

→ Galaxy clusters are tracers of the matter density field

**Mass and redshift distribution of galaxy clusters is highly sensitive to cosmology**

- Amount of matter $\Omega_m$ and of dark energy
- Fluctuation of matter density field $\sigma_8$



Cluster abundance: count galaxy clusters in bins of redshift and mass

$$N(z_\alpha, m_\beta) = \Omega_s \int_{z_1}^{z_2} dz \int_{m_1}^{m_2} dm \frac{dn(m,z)}{dm} \frac{d^2V(z)}{dz d\Omega}$$

Halo mass function ($\Omega_m$, $\sigma_8$)

Comoving volume (geometry of the Universe)

Mass is not an observable

We do not detect all galaxy clusters

count in bins of redshift and richness $\lambda$: count of member galaxies

$$N(z_\alpha, \lambda_\beta) = \Omega_s \int_{z_1}^{z_2} dz \int_{\lambda_1}^{\lambda_2} d\lambda\, \Phi(\lambda, z) \int_{m_{\min}}^{m_{\max}} dm \frac{dn(m,z)}{dm} P(\lambda\,|\,m,z) \frac{d^2V(z)}{dz d\Omega}$$

Selection function

Mass-richness relation

Mass function

Mass function
+
Mass-richness relation
+
Selection function

- Selection function depends on detection strategy
- Mass-richness relation can be calibrated using weak lensing

**Some recent cluster abundance analysis at optical wavelength:**

| Survey | Sky area (deg2) | Nb of clusters | Redshift range |
|---|---|---|---|
| SDSS (2019) | 10 000 | 8 000 | [0.10 - 0.33] |
| KiDs (2021) | 400 | 3 700 | [0.1 - 0.6] |
| DES Y1 (2021) | 1800 | 7 000 | [0.20 - 0.65] |

$\sim 10^3$ clusters

Upcoming optical surveys LSST/Euclid: $\sim 100\ 000$ clusters → **systematics ≫ statistical effects**

**The calibration of the mass-richness relation is crucial for cluster count cosmology**

DES Y1:

- Tensions driven by the calibration of the mass-richness relation
- Found $\sim 4\sigma$ tension with other probes

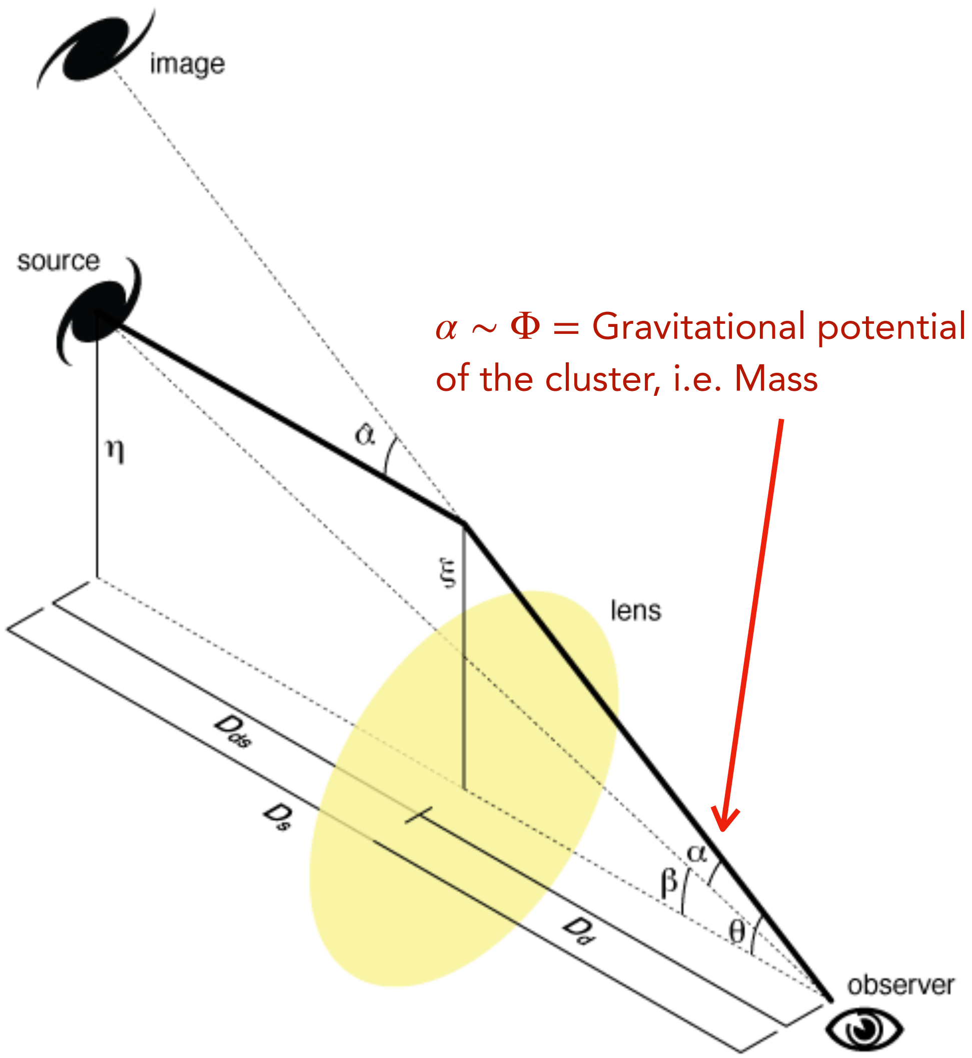
→ **weak lensing is the main tool to calibrate mass-richness relation**

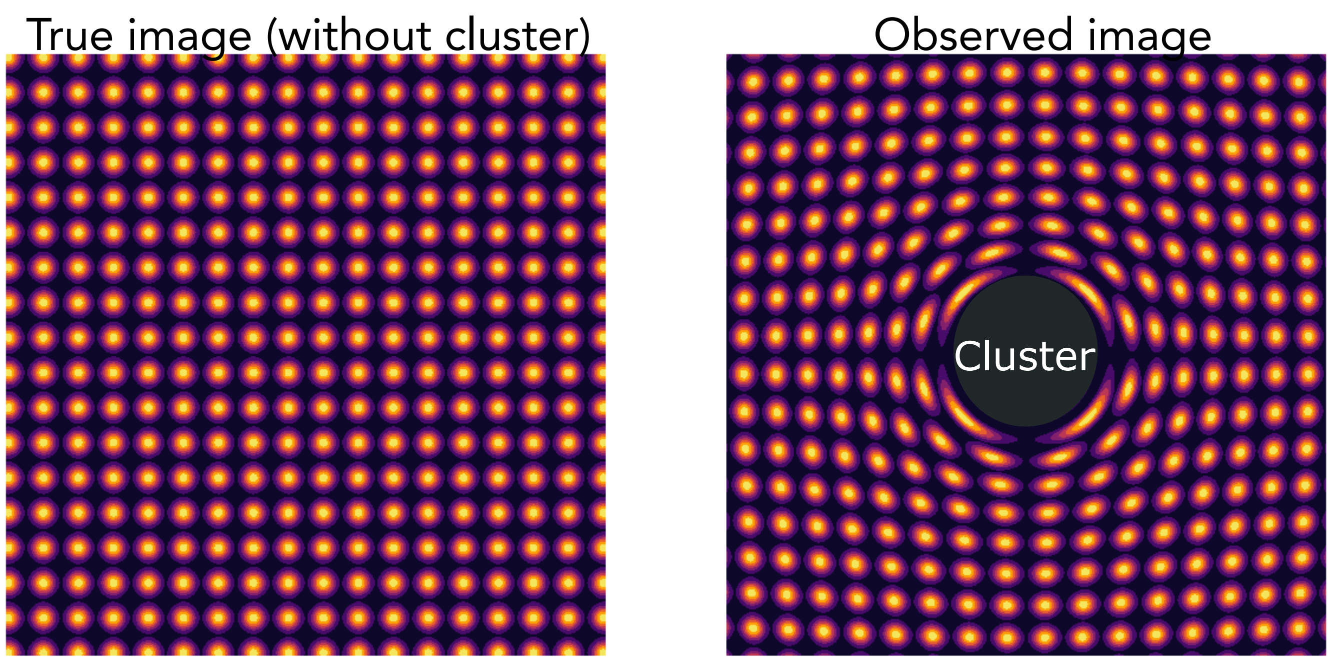
**Weak lensing:**

- Induces deviation of light rays coming from a background source (galaxy) by the potential of the cluster

**Two effects on background sources:**

1. Magnification: modifies location and magnitude of sources
2. Deformation: modifies the observed background galaxy shapes $\sim \gamma$




Effect of a point mass distribution on a distribution of spherical objects

→ Galaxy shapes can be used to measure the shear

**Shear from galaxy shapes**

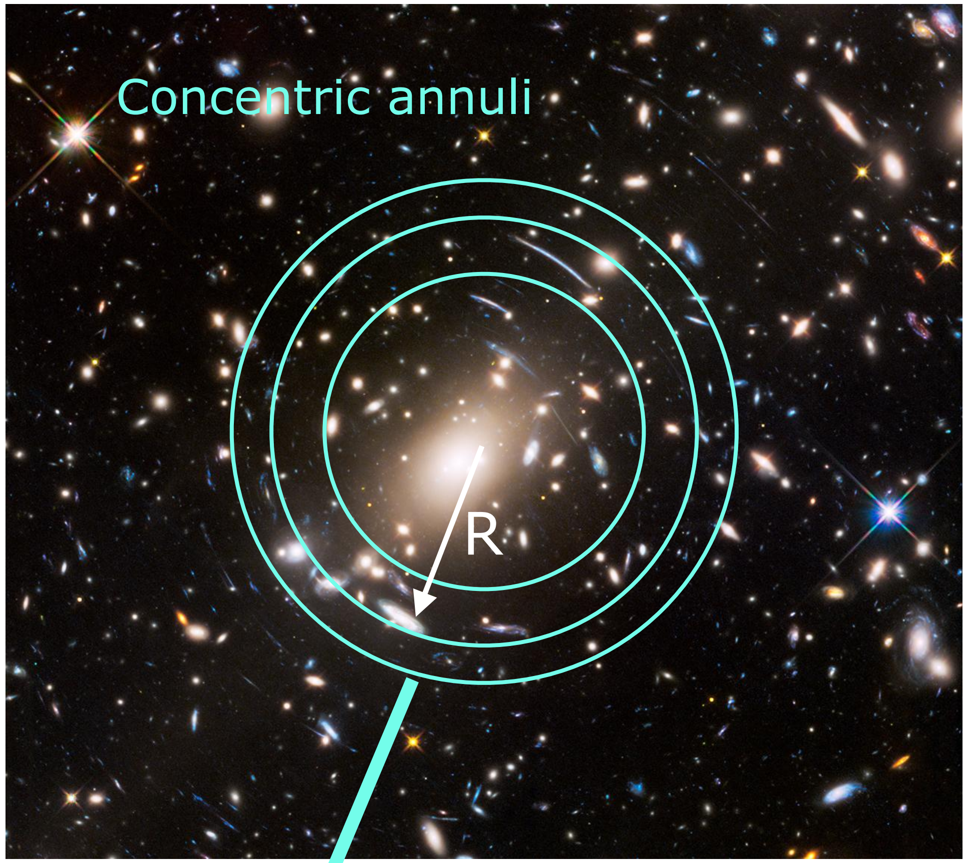
- The ellipticity of galaxies is linked to the weak lensing *shear*

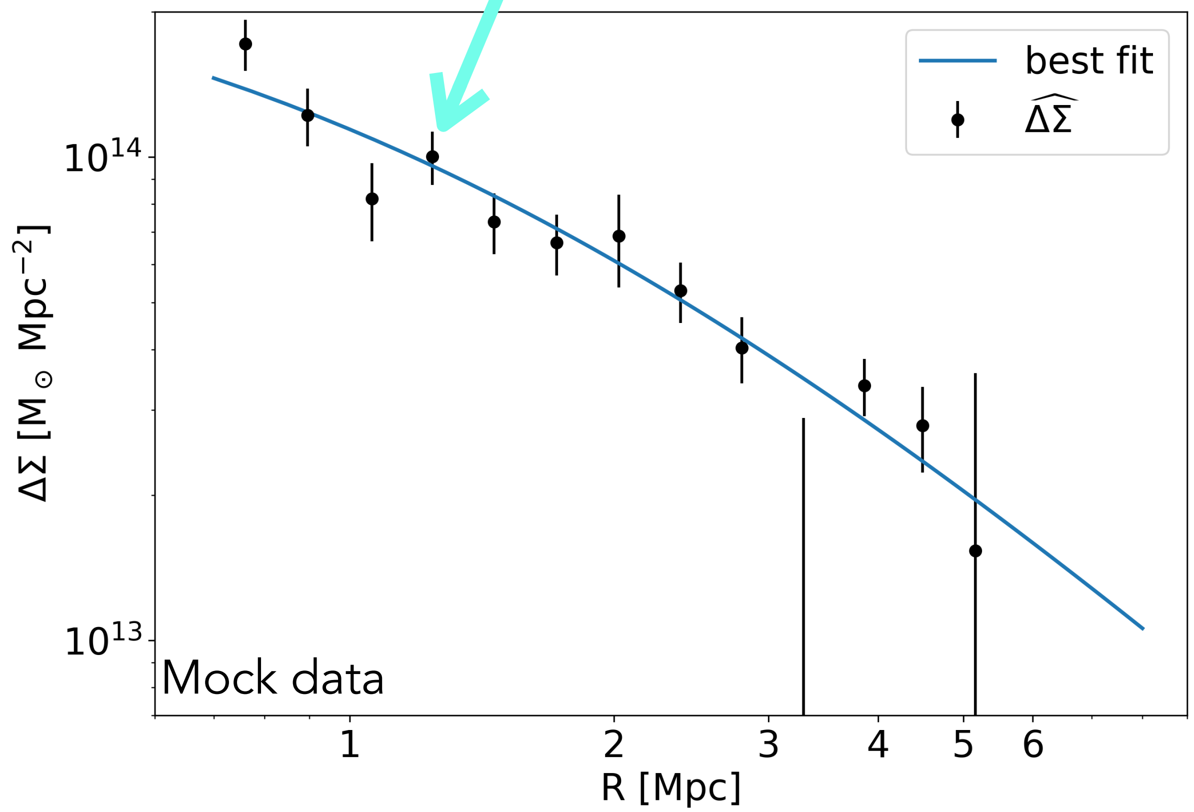
$$\epsilon^{\rm obs} \approx \epsilon^{\rm int} + \gamma(R)$$

- We estimate the excess surface density

$$\widehat{\Delta\Sigma}(R, z_{\rm l}) = \langle \Sigma_{\rm crit}(z_{\rm gal}, z_{\rm l})\ \epsilon_{+}^{\rm obs} \rangle$$

Critical surface mass density — *Tangential* ellipticity




**From weak lensing to cluster mass …**

$\Delta\Sigma(R)$ depends on $\Sigma(R) = \int_{-\infty}^{+\infty} dz\ \rho_{3d}(r)$

Integration along the line of sight

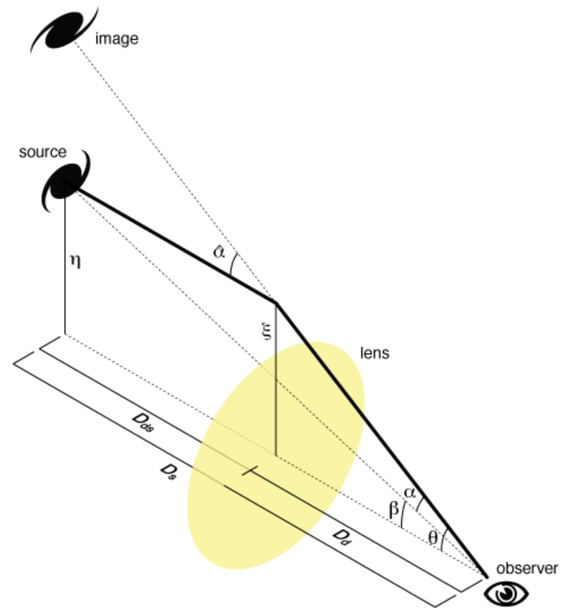
$\rho_{3d}(r)$ : cluster $M$ and intrinsic properties, and contribution from neighbouring halos

Fit of $\Delta\Sigma \rightarrow$ mass $M$

1. Introduction
    1. Cosmology with LSST
    2. Cosmology with galaxy clusters
2. Weak gravitational lensing
3. Application to DESC simulations
4. Conclusions and perspectives

**Data Challenge 2:**

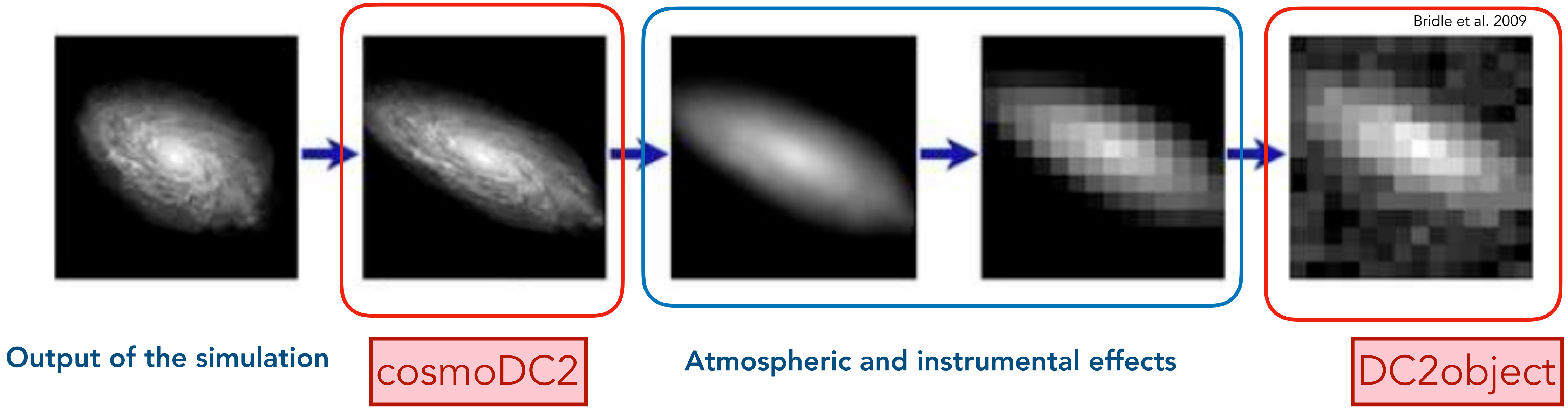
- Dark matter N-body simulation of large scale structure formation $\sim 400$ deg$^2$
- Identified dark matter halos, filled with galaxies




**Lens catalogs:**

- Dark matter halos (with "true" masses and redshifts)
- Detected galaxy clusters (with observed richnesses and observed redshifts)

**Background source catalogs:**




Add lensing effect, "true" redshifts, ideal shapes, magnitudes, etc.

measured objects, measured shapes, measured magnitudes, etc.

**First step:** Extract background galaxy catalogs for each lens

$$N(z_\alpha, \lambda_\beta) = \Omega_s \int_{z_1}^{z_2} dz \int_{\lambda_1}^{\lambda_2} d\lambda \; \Phi(\lambda, z) \int_{m_{\min}}^{m_{\max}} dm \frac{dn(m,z)}{dm} P(\lambda \,|\, m, z) \frac{d^2V(z)}{dz d\Omega}$$

Calibration with weak lensing $\Delta\Sigma$

**Objectives:**

1. DESC-CLMM: Develop functionalities for the estimation of $\Delta\Sigma$
2. DC2 dataset: Test possible sources of systematics on the mass-richness relation

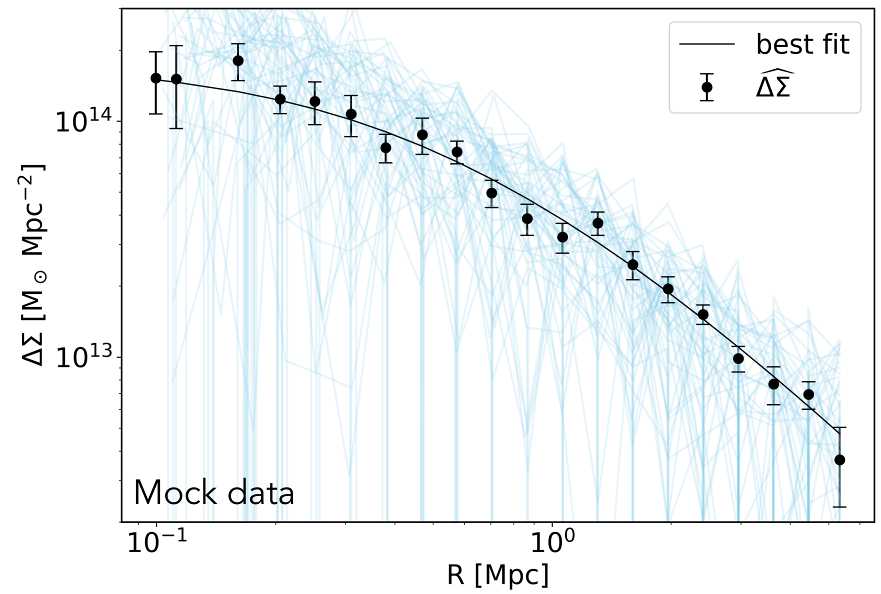
With DC2 data

**Stacked $\Delta\Sigma$ around many galaxy clusters:**

- The individual $\widehat{\Delta\Sigma}$ very noisy → stack $\widehat{\Delta\Sigma}$ (high SNR)

$$\widehat{\Delta\Sigma}(R) = \frac{1}{\sum_{\rm l,gal=1} w_{\rm l,gal}} \sum_{\rm l,gal=1} w_{\rm l,gal} \widehat{\Sigma_{\rm crit}}(z_{\rm gal}, z_{\rm l})\, \epsilon_+^{\rm gal}$$

∈ shape measurement errors + photometric redshift + noise



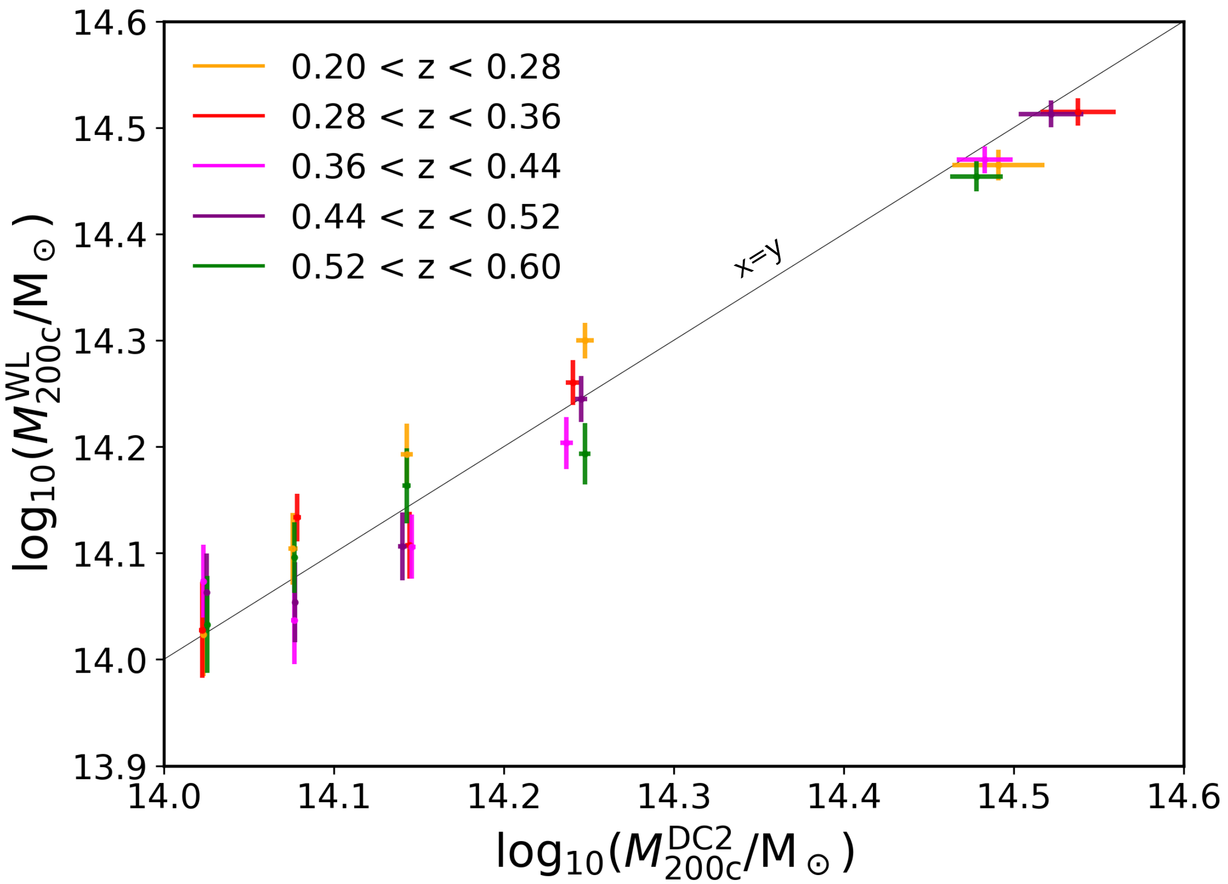

- **Implementation in DESC-CLMM code** (Aguena et al., 2021)

**Validation of the stacked shear analysis:**

- in bins of redshift and "true" mass
- Significant contribution in the **DC2 validation paper** (Kovacs *et al.*, 2021)

Here $M_{\rm WL}$ vs $M_{\rm true}$ → $M_{\rm WL}$ vs $\lambda$

$M_{\rm WL}$ of cosmoDC2 dark matter halos



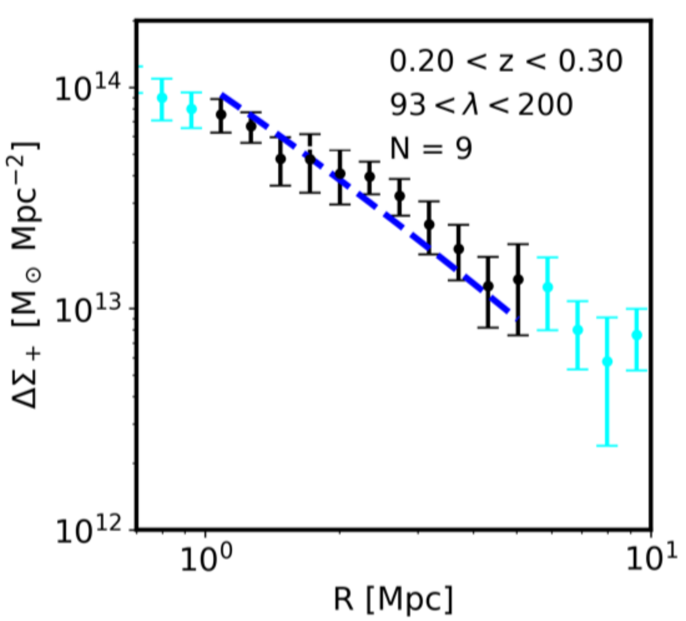
**redMaPPer galaxy cluster catalog**

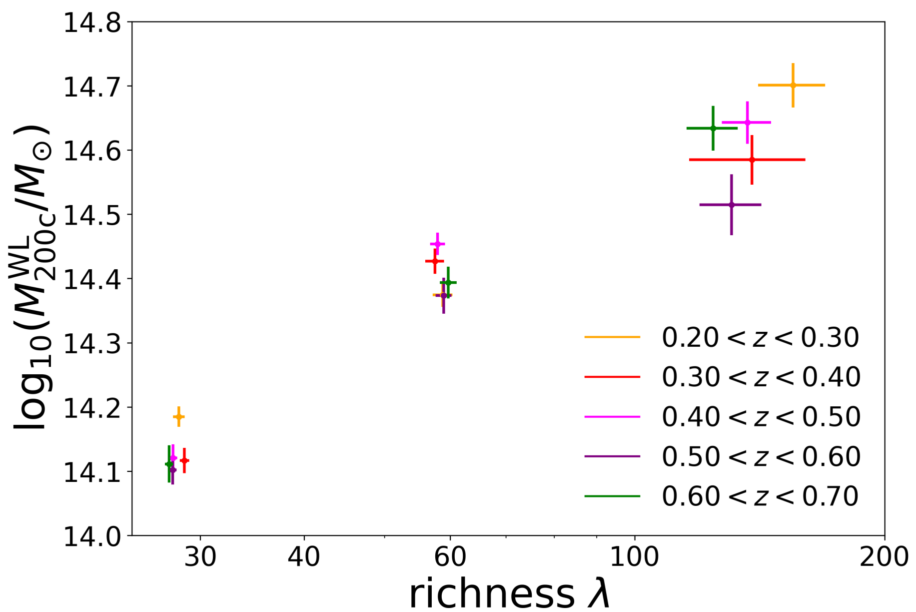
- 4000 clusters
- Output:
  - cluster sky position
  - redshift
  - richness $\lambda \sim$ number of galaxies within the cluster

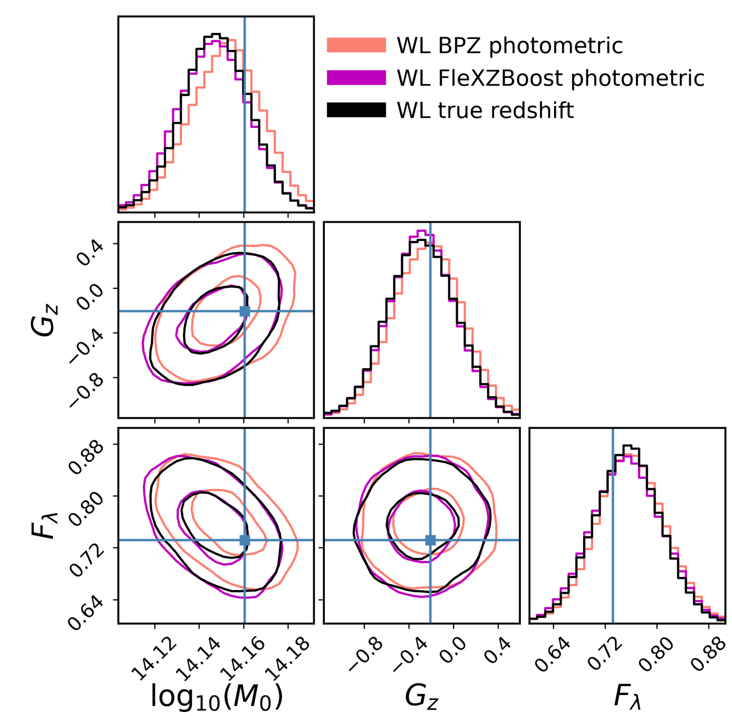
**Methodology: from weak lensing to mass-richness relation**

Shear profile estimation → Fit $M_{\rm WL}$ in redshift-richness bins → (Markov chain Monte-Carlo) → Constrain mass-richness relation

$$\langle M \,|\, \lambda, z\rangle \propto M_0\ (1+z)^{G_z}\ \lambda^{F_\lambda}$$



**Test the impact of various possible sources of systematics on** $\langle M_{\rm WL}\,|\,\lambda, z\rangle$

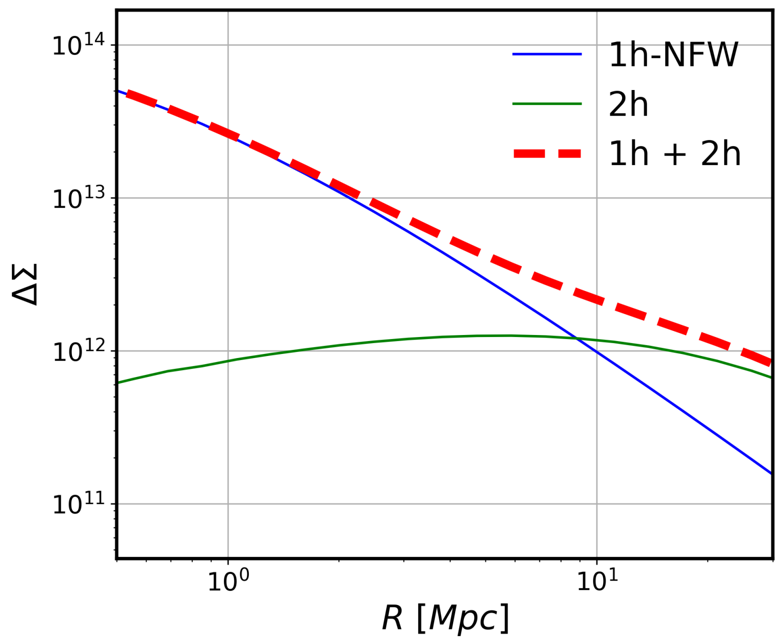
1. Effect of modelling choices
2. Effect of photometric redshift
3. Effect of shape measurement

$M_{\rm WL}$ obtained from Model $\Delta\Sigma$ + Data $\widehat{\Delta\Sigma}(R, z_{\rm l}) = \langle \Sigma_{\rm crit}(z_{\rm gal}, z_{\rm l})\ \epsilon_+^{\rm obs}\rangle$

By matching "true" masses and detected richnesses → *fiducial* constraints of $\langle M_{\rm true}\,|\,\lambda, z\rangle$

**Different contributions in** $\Delta\Sigma(R) = \Delta\Sigma_{1h}(R) + \Delta\Sigma_{2h}(R)$

1. $\Delta\Sigma_{1h}$: Intrinsic properties - mass $M$, concentration $c$ ($R \leq 5$ Mpc)
2. $\Delta\Sigma_{2h}$: Neighbouring halos ($R \geq 5$ Mpc)




**1-halo term** $\Delta\Sigma_{1h}$

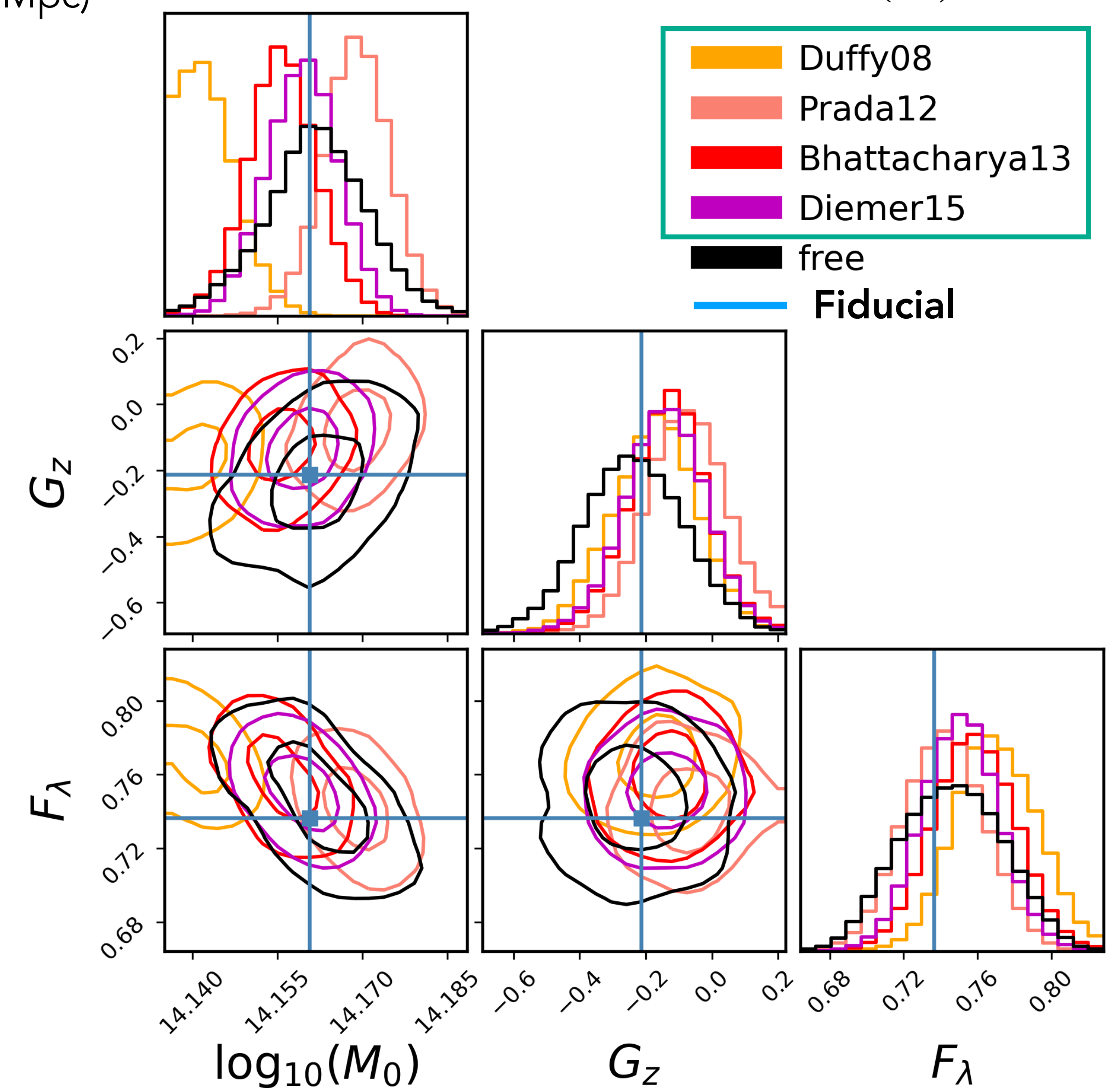
- $c(M)$ relation frequently used
- Results might be sensitive to $c(M)$ choices

**This work:**

- Tests of various $c(M)$ up to $\langle M_{WL} | \lambda, z \rangle$
- Smaller error-bars, but may bias results (ex: Duffy08)

→ letting the concentration free appears to be a good compromise

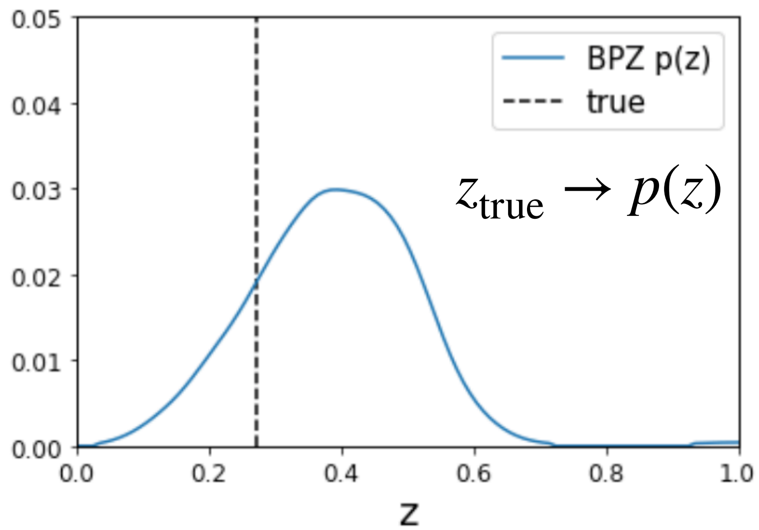
Different $c(M)$




Joint Posterior distribution of $\log_{10}(M_0), F_\lambda, G_z$

**Photometric redshifts:**

- Are reconstructed from magnitudes in each filter

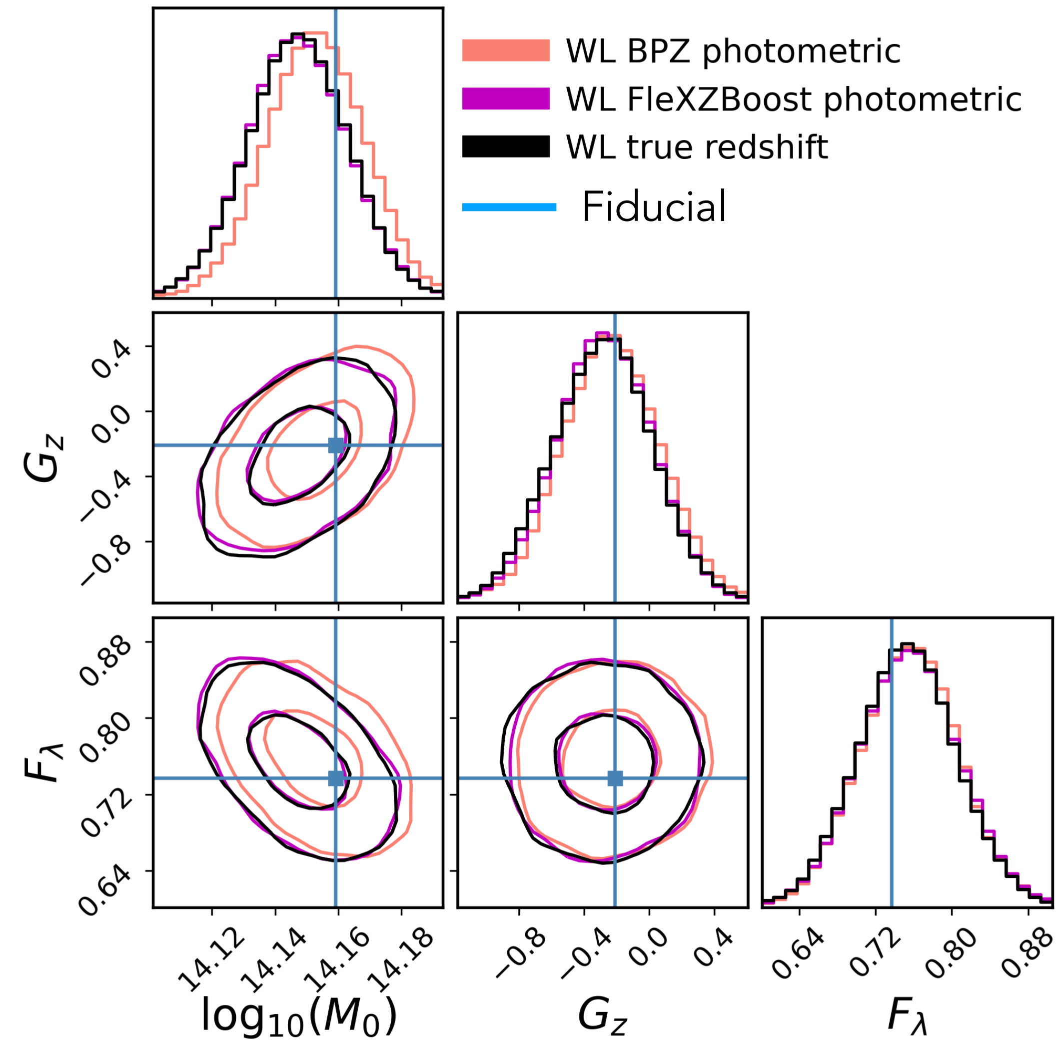



**Affects the weak lensing weights** $\to M_{\rm WL}$

$$w_{\rm l,gal} \propto \left(\int_{z_l}^{+\infty} dz_{\rm gal}\; p(z_{\rm gal})\; \Sigma_{\rm crit}(z_{\rm gal}, z_l)^{-1}\right)^2$$

**This work:**

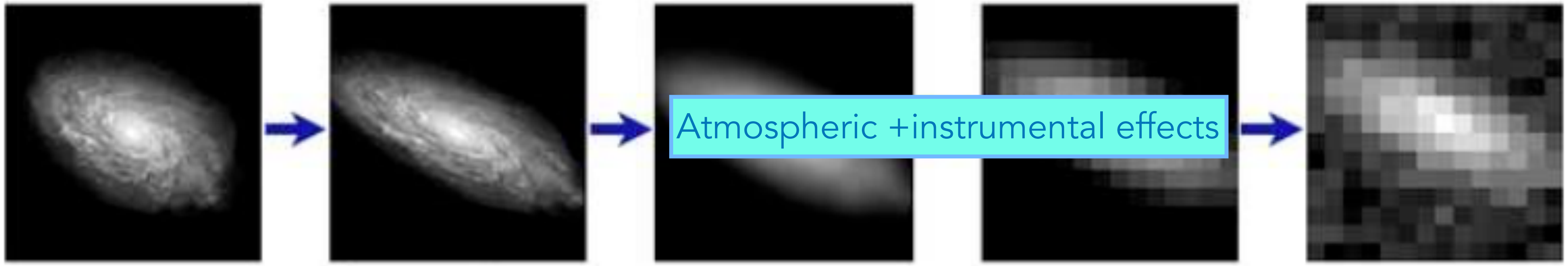
- 2 different algorithms: BPZ, FleXZboost
- Good agreement with ideal redshifts
- Here, cosmoDC2 magnitudes → Ongoing tests on DC2object magnitudes ("realistic" magnitudes)




Joint Posterior distribution of $\log_{10}(M_0), F_\lambda, G_z$

$\langle M_{\rm WL}\,|\,\lambda, z\rangle$ not sensitive to photometric redshifts

# Shape catalogs in DC2 dataset




cosmoDC2

DC2object

"true" redshifts, true shapes, true magnitudes, etc.

DC2object:

- Detected objects → less objects
- Measured magnitudes
- Measured shapes: 2 different algorithms - HSM, and Metacalibration

Delivers un-calibrated shapes

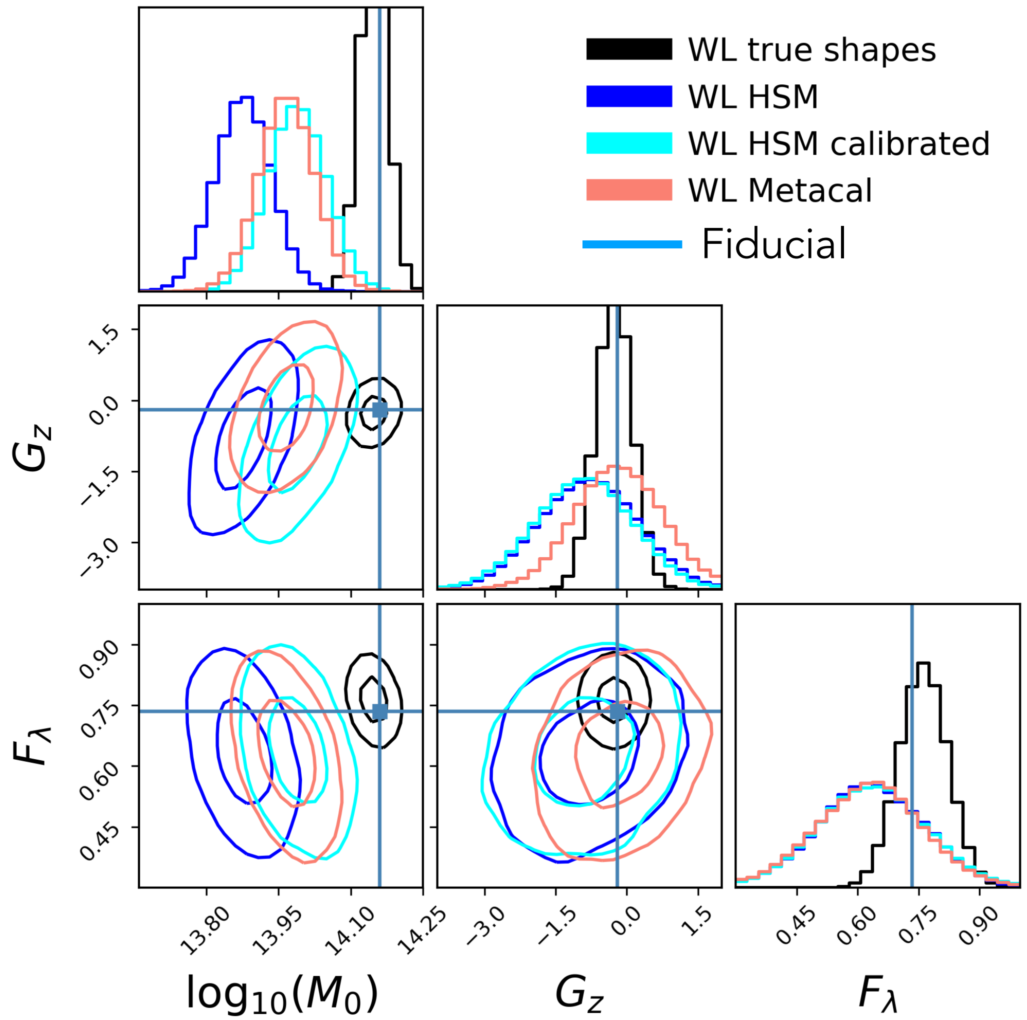
Self-calibrated method

HSM:

- *By hand* calibration procedure: $\epsilon_{\rm obs} \to \epsilon_{\rm true}$
- Unfortunately, still high tension $\log_{10}(M_0)$
- Ongoing works to solve this issue

Metacalibration:

- Surprising tension on $\log_{10}(M_0)$
- Highlight problems with the run of Metacalibration
- Noticed independently from other probes within DESC
- Mitigation effort in progress within DESC




Joint Posterior distribution of $\log_{10}(M_0), F_\lambda, G_z$

→ use of measured shapes + less galaxies increase error bars

# Conclusions

$$N(z_\alpha, \lambda_\beta) = \Omega_s \int_{z_1}^{z_2} dz \int_{\lambda_1}^{\lambda_2} d\lambda\ \Phi(\lambda, z) \int_{m_{\min}}^{m_{\max}} dm \frac{dn(m,z)}{dm} P(\lambda\,|\,m, z) \frac{d^2V(z)}{dz d\Omega}$$

Mass-richness relation

**Conclusions:**

1. Weak lensing is the main tool to constrain mass-richness relation
2. Weak lensing mass is affected by different systematics:
    A. Modelling: free concentration is a good compromise
    B. Photometric redshift: no sizeable impact
    C. Shape measurement + less objects: increases error bars, still need to understand calibration

**Work within DESC Collaboration**

1. Refereed DESC notes on mass-richness relation in DC2
    1. Effect of photometric redshifts and shape measurements
    2. Effect of modelling choices
2. → paper in prep.
3. Co-author of DESC CLMM v1.0 (Aguena et al. 2021)
4. Co-author of the cosmoDC2 validation paper (Kovacs et al. 2021)

**Using DESC tools**

CLMM (data analysis + prediction)
CCL (prediction)
GCRCatalogs (read galaxy catalogs)
…

$$N(z_\alpha, \lambda_\beta) = \Omega_s \int_{z_1}^{z_2} dz \int_{\lambda_1}^{\lambda_2} d\lambda \; \Phi(\lambda, z) \int_{m_{\min}}^{m_{\max}} dm \frac{dn(m,z)}{dm} P(\lambda \,|\, m, z) \frac{d^2V(z)}{dz d\Omega}$$

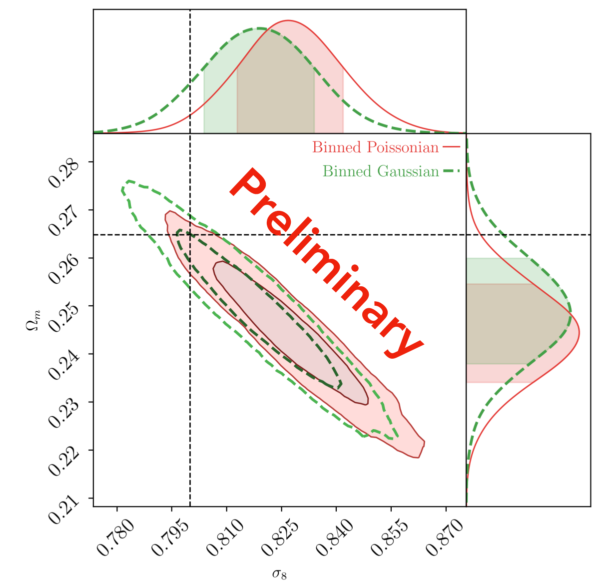
Mass-richness relation

Cluster abundance cosmology → From galaxy cluster catalog to cosmological parameters

**Developing DESC cluster abundance software**

- Prediction of cluster abundance
- Estimation/prediction of covariance matrix
- Likelihood implementation

→ test changes of $\langle M_{\rm WL} \,|\, \lambda, z\rangle$ on cosmological parameter estimation




**Which likelihood for cluster count cosmology ?**

- Project with Calum Murray