Galaxy cluster cosmology with LSST

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What is Cosmology — and Why Study It?

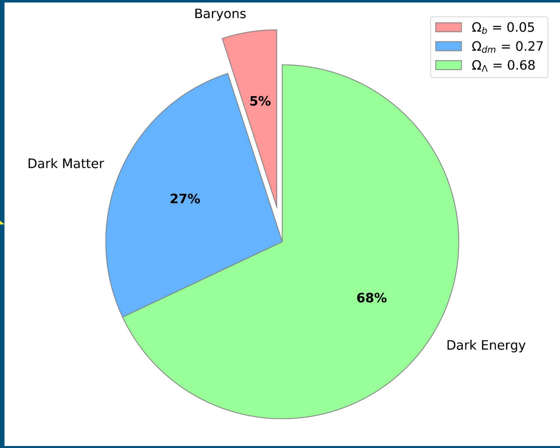
- Cosmology is the scientific study of the universe as a whole — its origin, evolution, structure, and ultimate fate.
  - We want to explain the structure of the Universe on the scale of galaxies and beyond
- Current model is the ΛCDM:
  - Cold dark matter, radiation, curvature, dark energy and baryons

How did structures form?

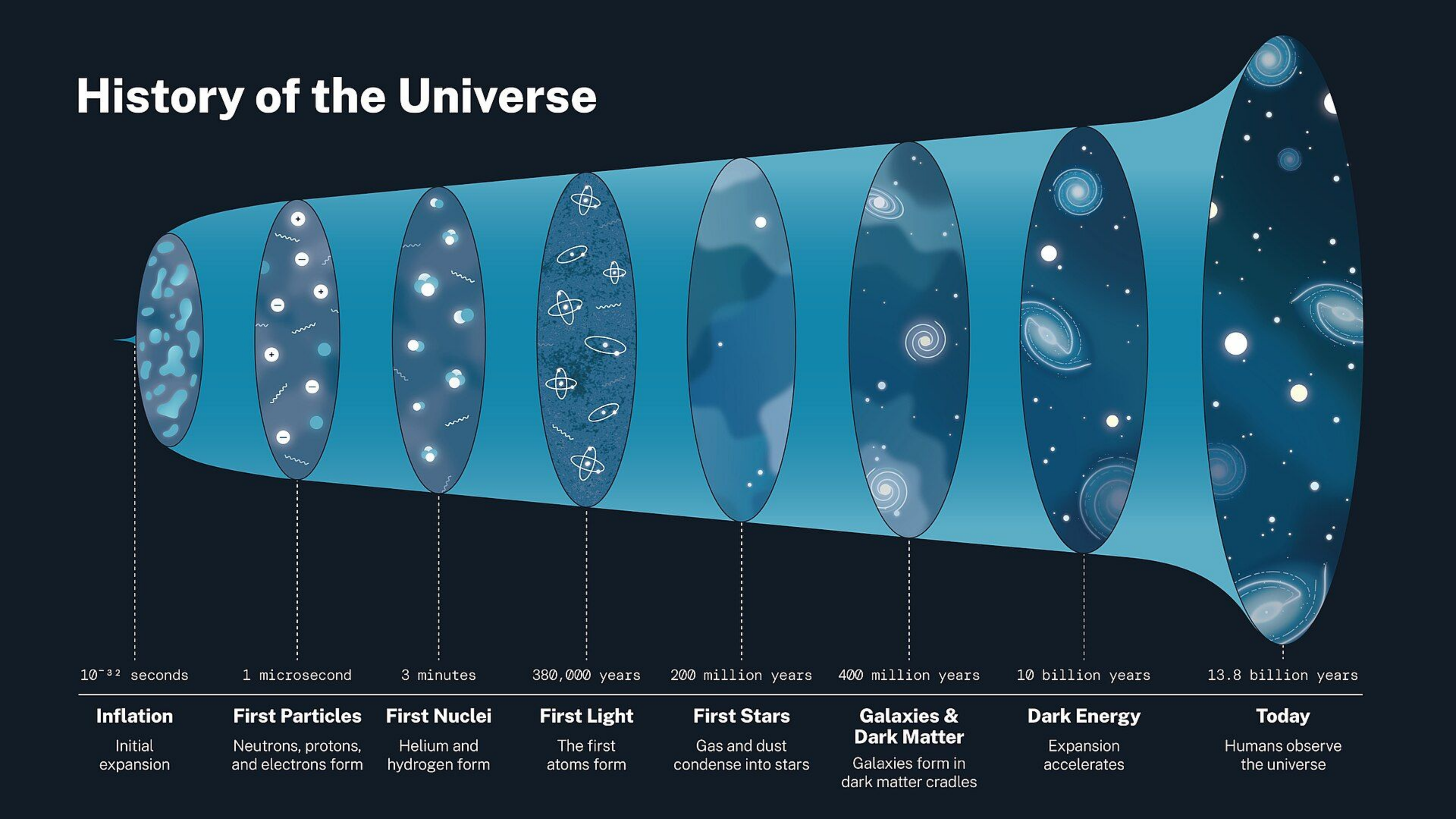
What is the universe made of?

What is the ultimate fate of our universe?

What were the initial conditions after the Big Bang?



Fractions of the energy density content of the universe regarding the ΛCDM


History of the Universe
10^{-32} seconds
1 microsecond
3 minutes
380,000 years
200 million years
400 million years
10 billion years
13.8 billion years
Inflation
Initial expansion
First Particles
Neutrons, protons, and electrons form
First Nuclei
Helium and hydrogen form
First Light
The first atoms form
First Stars
Gas and dust condense into stars
Galaxies & Dark Matter
Galaxies form in dark matter cradles
Dark Energy
Expansion accelerates
Today
Humans observe the universe

Sky surveys

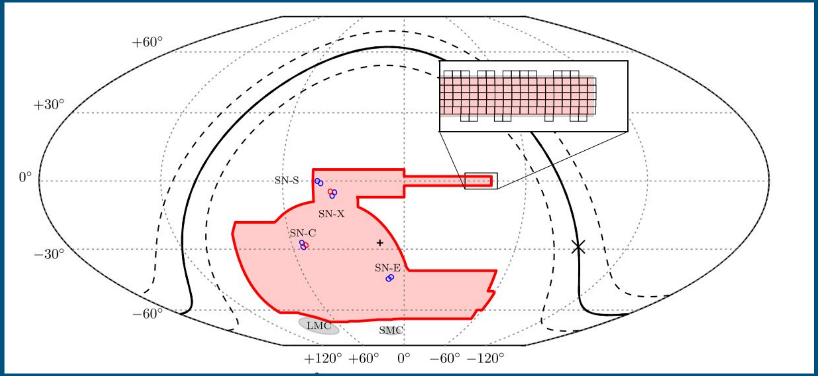
Sky surveys → Scan the universe to characterize different objects

Classified in regard to their scientific motivation and strategy (wavelength, spectroscopy, …)

Some examples are:

- Optical → Image based surveys
- Infrared → Good for exoplanets and cool clouds of cosmic dust
- Gamma-ray → Gamma-ray spectroscopy. Good for supernovae and particles falling into black holes
- Multi-wavelength, etc.

Image of the sky from the Dark energy Survey



Dark energy Survey footprint

How to do cosmology with sky surveys?

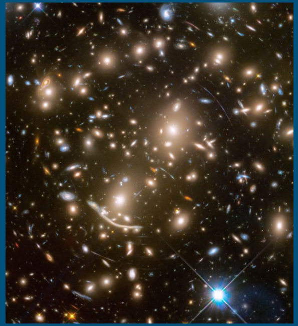
1. **Choose probes of the Universe:**
   - Galaxy clusters, Type Ia supernovae, Weak lensing, BAO, CMB

2. **Develop theoretical predictions:**
   - Use cosmological models (ΛCDM) to predict how these observables behave.

3. **Compare theory with observations:**
   - Collect data from telescopes and surveys
   - Measure what we can directly observe; use **proxies** for quantities we cannot measure directly

4. **Perform likelihood inference:**
   - Treat the unknowns statistically (we cannot control everything)
   - Constrain cosmological parameters $\theta = (H_0, \boldsymbol{\Omega}, \sigma_8, \ldots)$

$$L(D|\vec{\theta}) = exp^{(\text{Data vector})^T \text{Cov}(\text{Theory vector}(\vec{\theta}))}$$



The massive galaxy cluster Abell 370

We cannot measure directly:
- masses
- Dark matter
- initial density fluctuations

Legacy Survey of Space and Time (LSST)

Twilight photo of Rubin Observatory, in Cerro Pachón, Chile

LSST Camera at SLAC, US

Legacy Survey of Space and Time (LSST)

The Survey

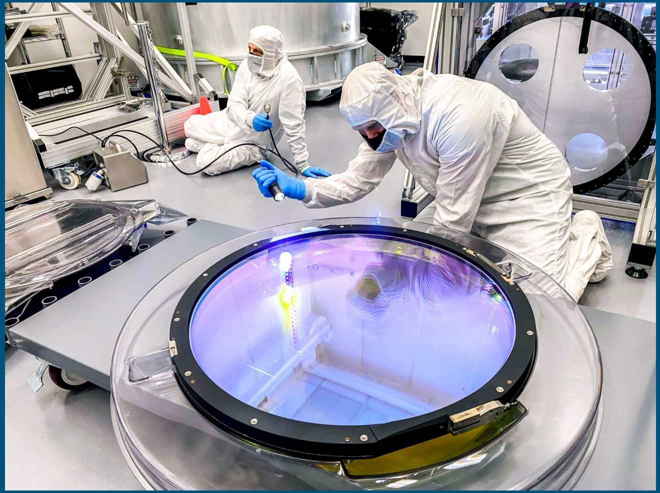
- 10-year survey covering the entire visible southern sky (~18,000 deg^2)
- Entire sky imaged every 3 nights → dynamic “video of the Universe”

Telescope & Camera:

- 3.2 Gpx digital camera (largest ever built)
- 9.6 deg^2 field of view per exposure
- 3-mirror design + rapid filter change system

Filters & Observing

- 6 filters: *u, g, r, i, z, y* (covering ultraviolet to near-infrared)
- Short exposures (15–30 sec), combined for deep images



One of the 6 huge filters for the Rubin Observatory LSST Camera being inspected at SLAC National Accelerator Laboratory.

Main Probes

Weak Lensing(3x2)	Galaxy clustering	Galaxy CLusters	Supernovae	Strong lensing

Started recently: Entering full survey mode now!!

Links:

https://skyviewer.app/explorer

https://rubinobservatory.org/gallery/collections/first-look-gallery

SCAN ME

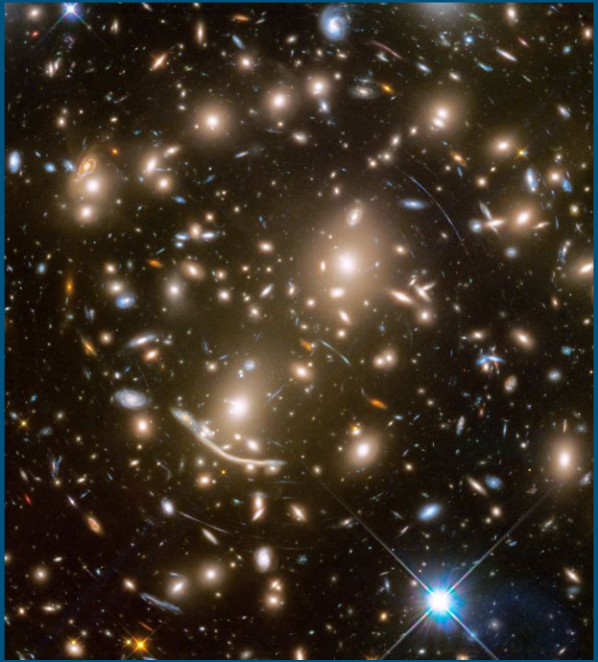
Galaxy Clusters

Galaxy Clusters are Largest gravitationally bound structures in the Universe

- ➔ Galaxies, plus hot gas and dark matter
- ➔ They are 80 -85% dark matter, 10 - 15% gas and 1-5% stars

Act as **cosmic probe** for studying:

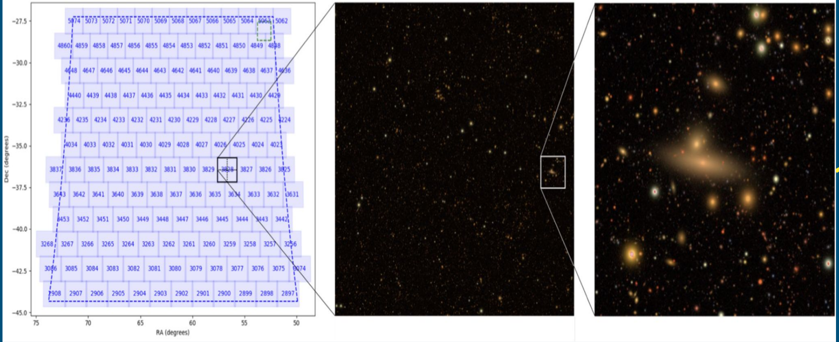
- Dark matter (through gravitational lensing)
- Large-scale structure formation
- Baryonic physics (hot intracluster medium)
- Cosmologial parameters (cluster counts, mass function)

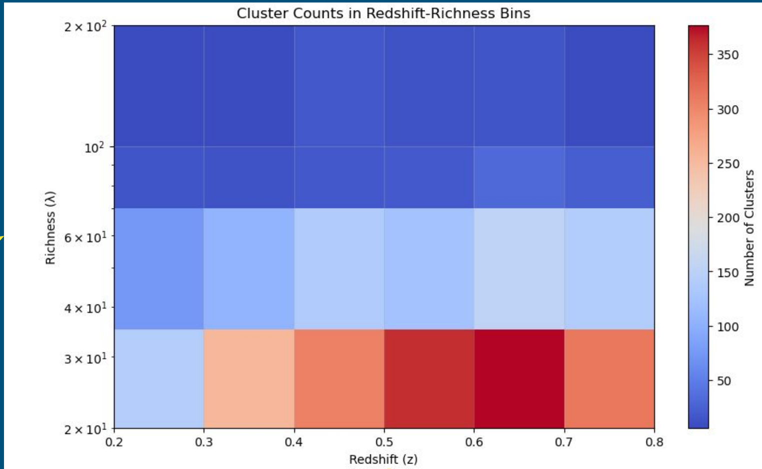


The massive galaxy cluster Abell 370 as seen by Hubble Space Telescope

Cosmology with Cluster counts

One measurement with galaxy clusters is simply to count how many of them we have in the Universe mapped by the survey



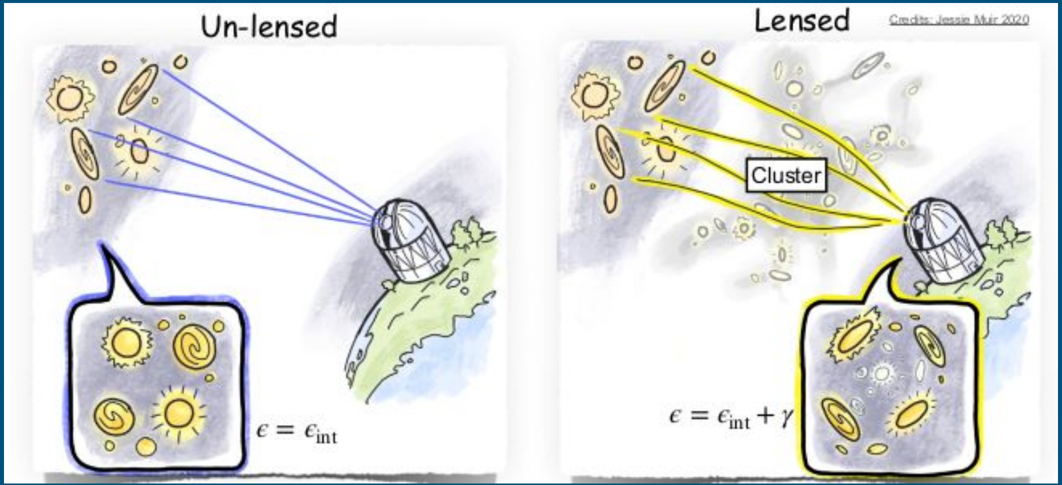


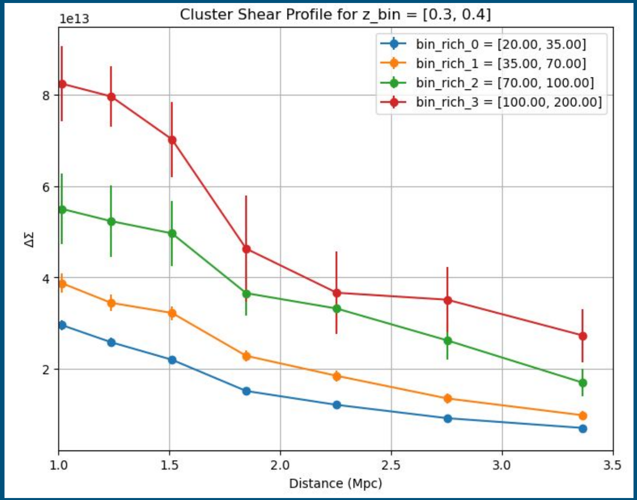
Abundance given by

$$\frac{\partial^2 N_{\rm obs}^{\rm clusters}}{\partial \mathcal{O} \partial z} \propto \int dm \underbrace{\frac{\partial^2 N_{\rm th}^{\rm halo}(m,z)}{\partial m \partial z}}_{\rm HMF} \underbrace{P(\mathcal{O}\,|\,m,z)}_{\rm MOR}$$

➔ Current precision limited mainly by **uncertainties in the mass–observable relation (MOR)**

Weak Lensing and Galaxy Clusters



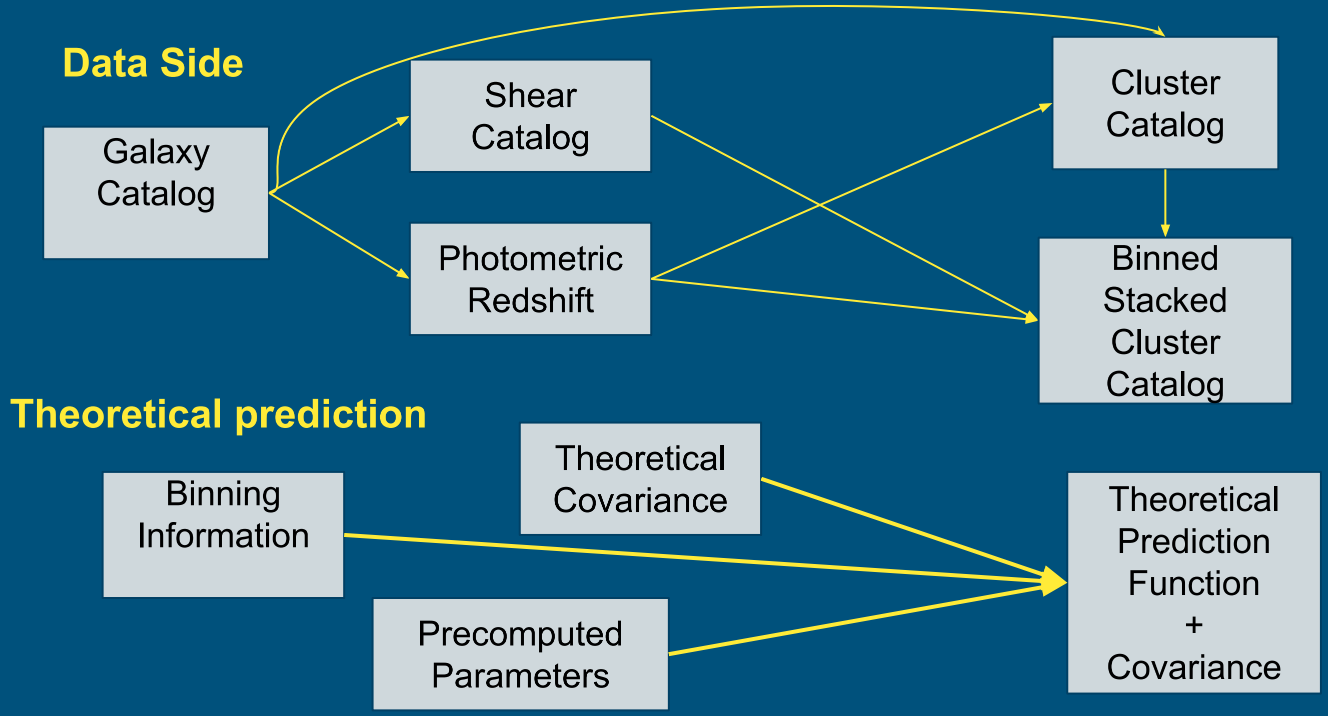


- Weak Lensing maps the invisible dark matter halo
- Massive clusters bend light from more distant background galaxies
- Shape distortions in background galaxies (shear): $\varepsilon = \varepsilon_{int} + \gamma$

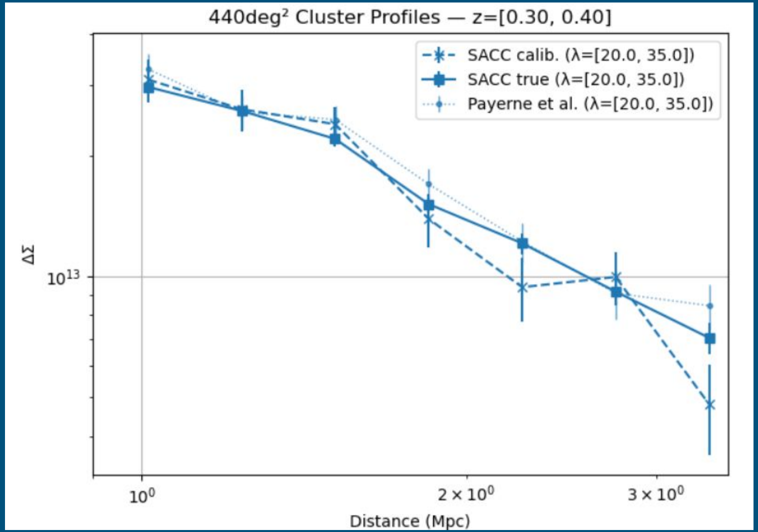
- Local average over many galaxies
- $\gamma \propto M_{cluster}$
- Signal decreases with distance from cluster center

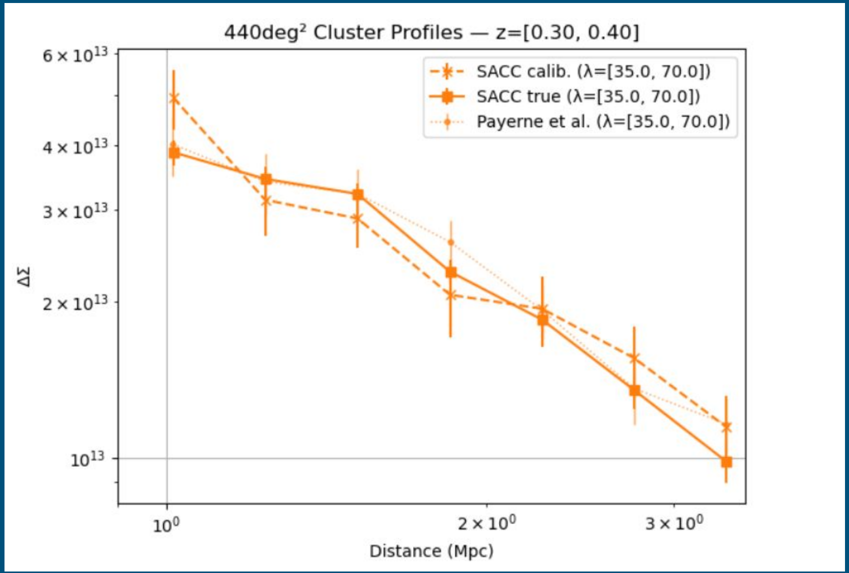
Cluster Pipeline

➔ A primary goal is to obtain constraints on Ω_m and σ_8 from the ΛCDM model



CLPipeline full chain analysis with cosmoDC2 - Preliminary tests





Source Selection

- ➔ r < 26.9 , i<26.2 , z<25.5. Similar to expected magnitude depth for 10-Year LSST with SNR=4
- ➔ Behind: $z_{cosmoDC2} > z_{cl} + 0.2$
- ➔ σ_{SN}= 0.26

Weak Lensing Profile

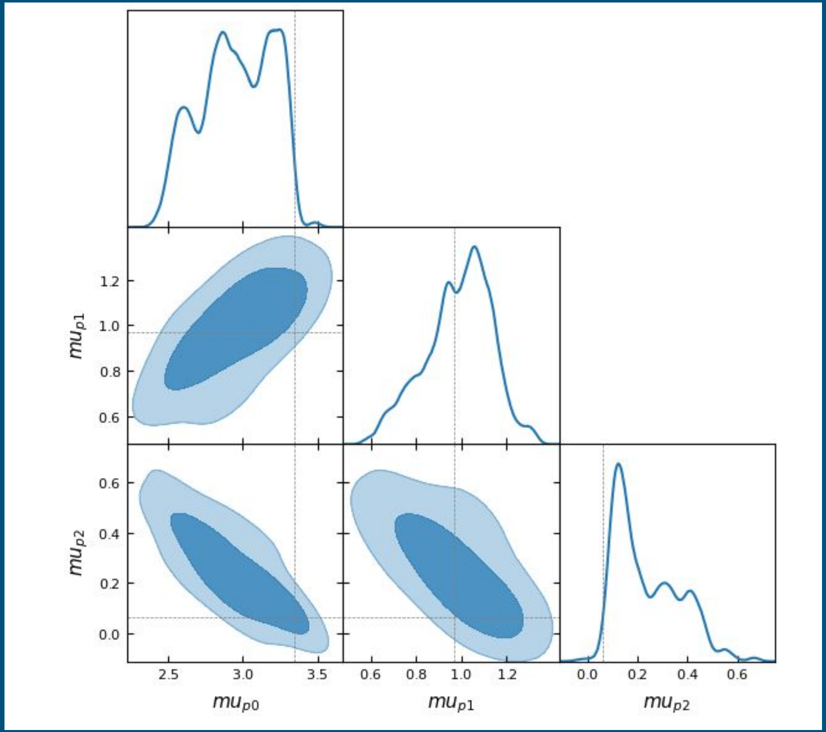
- ➔ Richness and redshift bins
- ➔ R ∈ [1.0, 3.5] Mpc
- ➔ z < 0.8

Constraints on the MOR from MCMC sampling

Run parameters

- ➔ Chains have 30% burn in
- ➔ Results have 2000 samples
- ➔ Emcee sampler
- ➔ 20 walkers

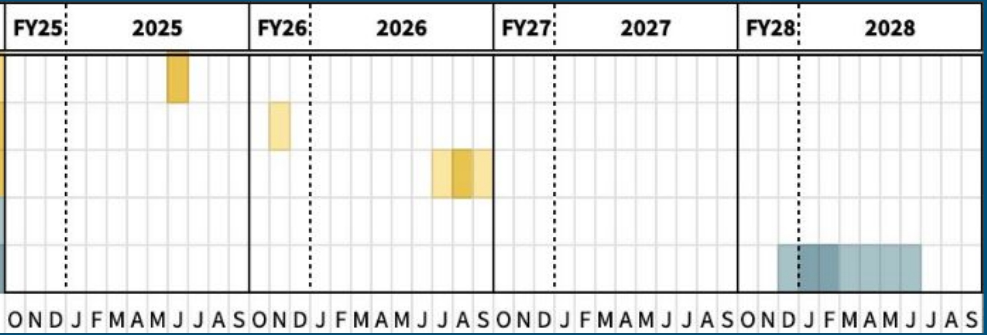
<u>The fiducial values from the matched cluster and halo catalogs are within the 2σ contours</u>



Fiducial

$$\mu_{p0} = 3.35 \pm 0.01$$
$$\mu_{p1} = 0.96 \pm 0.02$$
$$\mu_{p2} = 0.06 \pm 0.08$$

Option 2: No DR1, Augmented DP2		Date Range
DP1	ComCam Data	June 2025
SVY	Start of Survey	November 2025
DP2	SV plus 2 month Nov/Dec extension	Jul 2026 - Sep 2026
No DR1		
DR2	LSST Year 1 Data, 2 month delay	Dec 2027 - Jun 2028



Cluster Pipeline Validation on Simulation

1. **Mass + Abundance on ideal simulation (cosmoDC2)**
2. **Shear + Abundance on cosmoDC2**

Using the ideal dataset allow us to validate step by step adding complexity to the analysis

3. **Shear + Abundance on less ideal simulation (DC2)**

Simulated dataset that mimic data from images. It will allow us to test systematics

Conclusion

- Cluster cosmology will be a key probe for LSST
- The pipeline is on the final touches to be ready for an initial analysis
- In this presentation, I showed plots using the ideal dataset already
- We are ready to perform the pipeline validation and prepare for the upcoming LSST datasets (cosmoDC2 and DC2)
- We also have an ongoing project on the first data preview
- Joint probe analysis will push further to test the cosmological model