Towards precision cosmology with Rubin Observatory galaxy clusters

Marina Ricci
Postoc @ LAPP

The Bullet cluster
Credits : Markevitch, Clowe et al

Content

- Observationnal cosmology with galaxy clusters
- Preparing Rubin Obs. LSST cluster cosmology
- Exploiting multi-wavelength synergies
- Summary & take home messages

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- **Observationnal cosmology with galaxy clusters**
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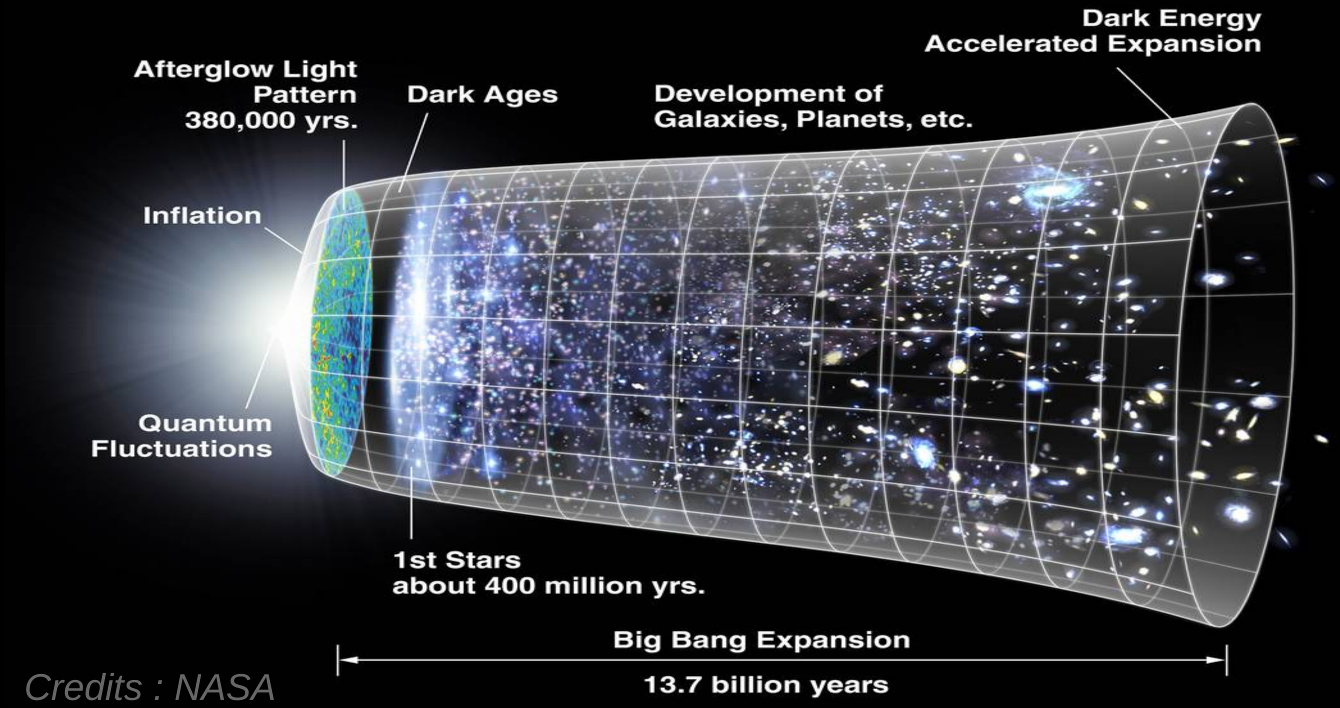
Our current understanding of the Universe

Cosmology: study of the structure and evolution of the Universe



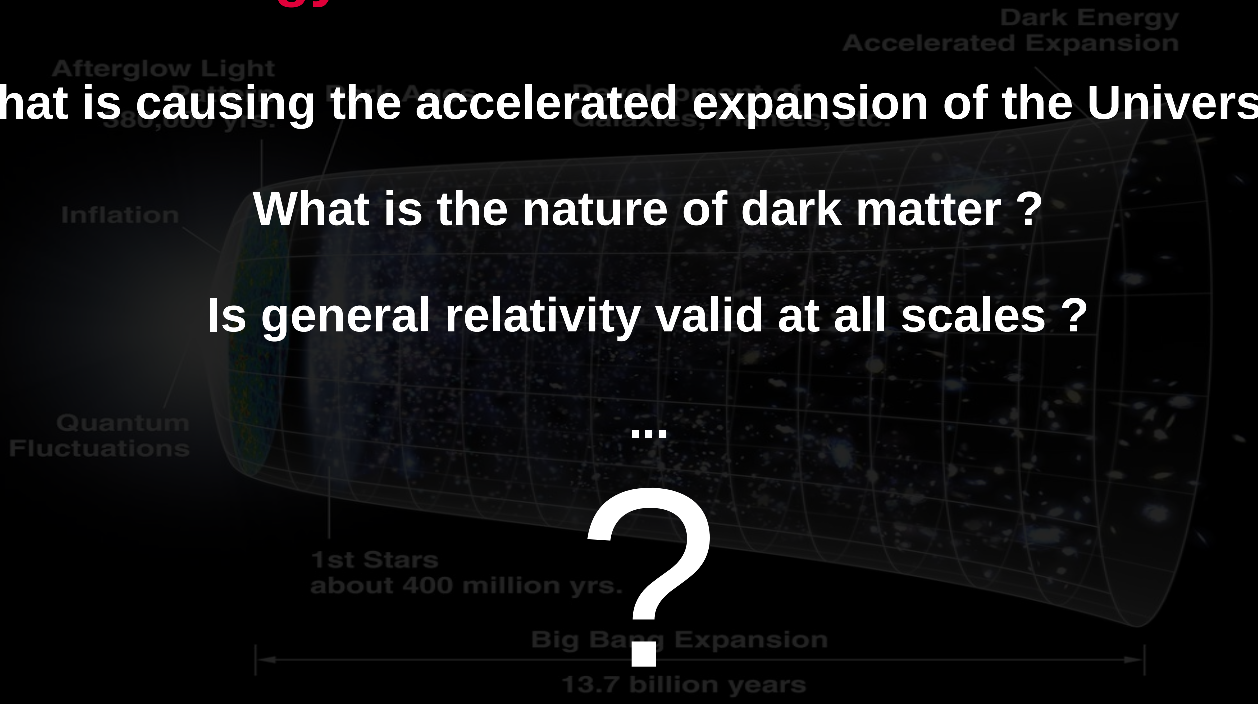
Credits : NASA

Cosmological models described by a set of parameters that can be measured

Our current understanding of the Universe

Our current cosmological model stipulates that

95 % of the energy in the Universe is in a unknown form



What is causing the accelerated expansion of the Universe ?

What is the nature of dark matter ?

Is general relativity valid at all scales ?

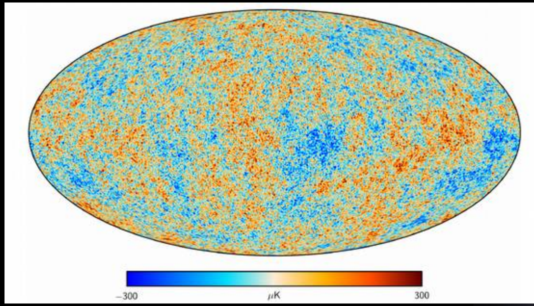
...

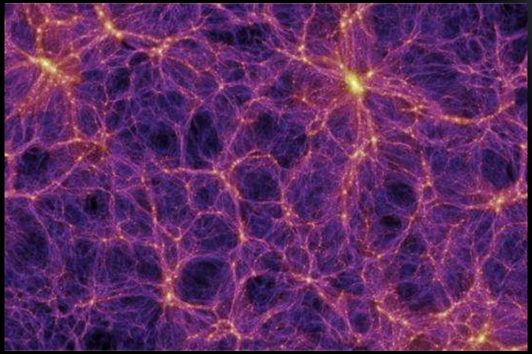
?

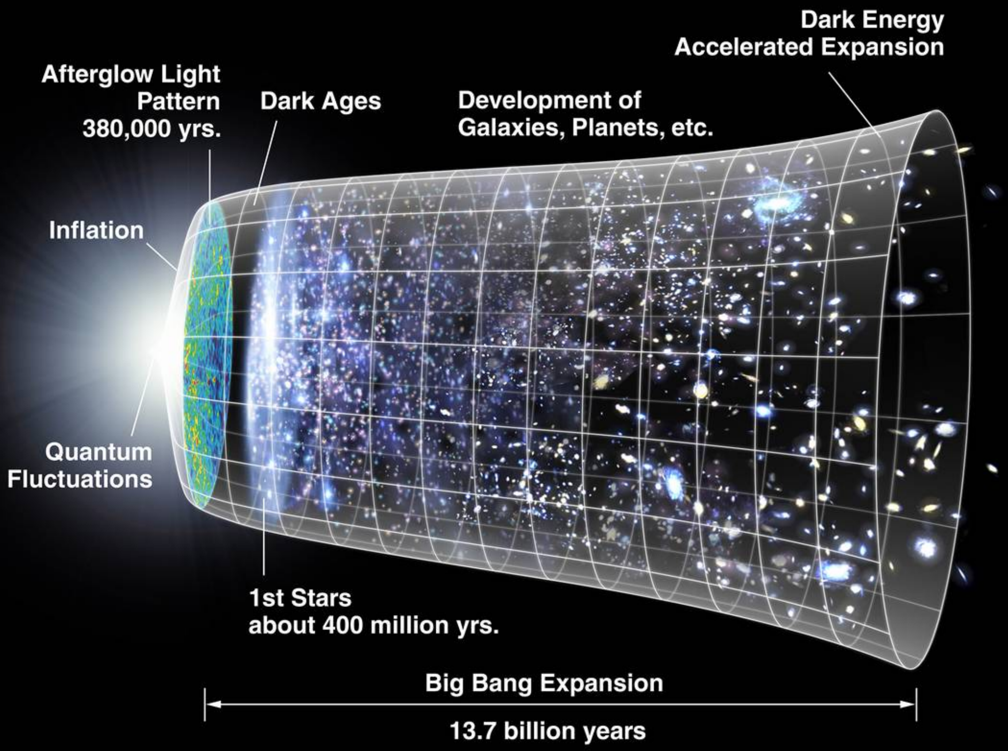
We need to **confront theories to observations of “cosmological probes”**

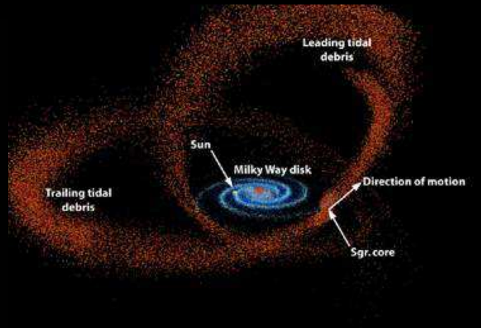
Our current understanding of the Universe

Many cosmological probes: different phenomena / time of evolution / physical scales





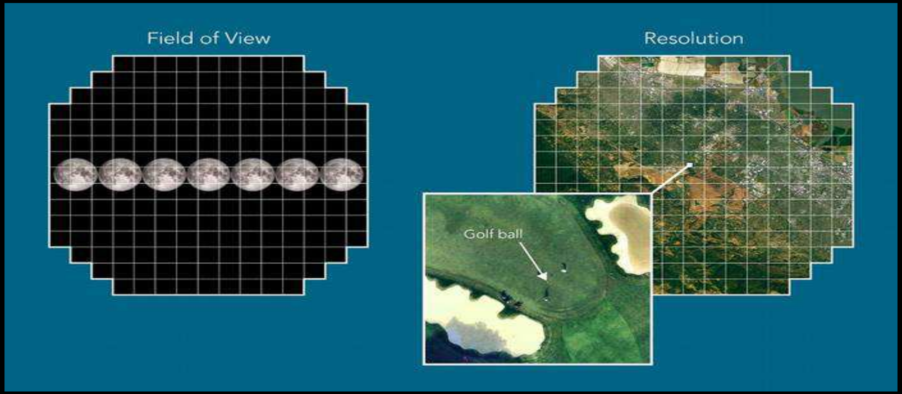




Coherent obs. & modeling of multiple probes to shed light on cosmological ‘mysteries’

The Rubin Obs. Legacy Survey of Space and Time

LSST Project/NSF/AURA



6 bands optical telescope (ugrizy)

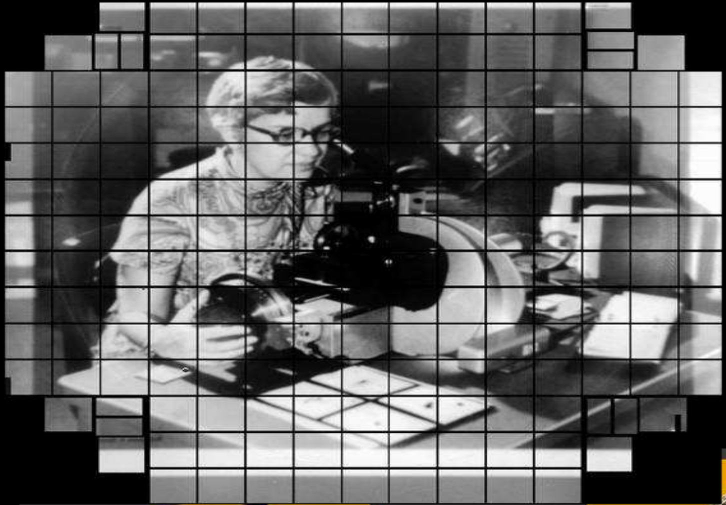
- Primary miror : 8.4 m
- FoV : 3.5 deg

Wide, Fast, Deep Survey :

- ~18 000 deg2 up to *r ~ 27 (10 years)*
- footprint imaged every ~3 nights

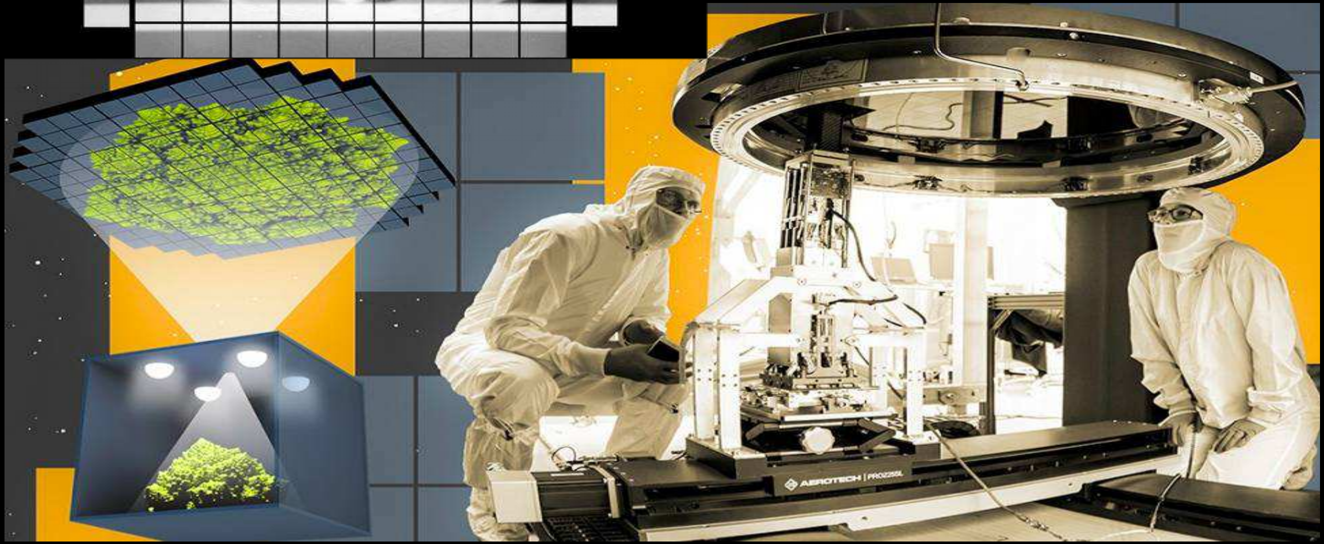
One of the main goal : **Understand the origin of Dark Energy & Dark Matter**

The Rubin Obs. Legacy Survey of Space and Time

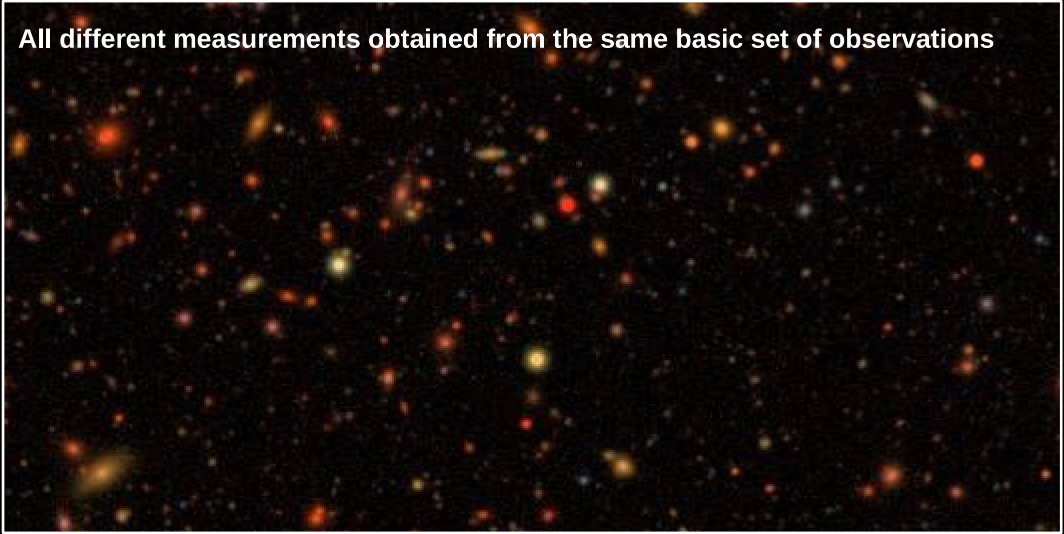


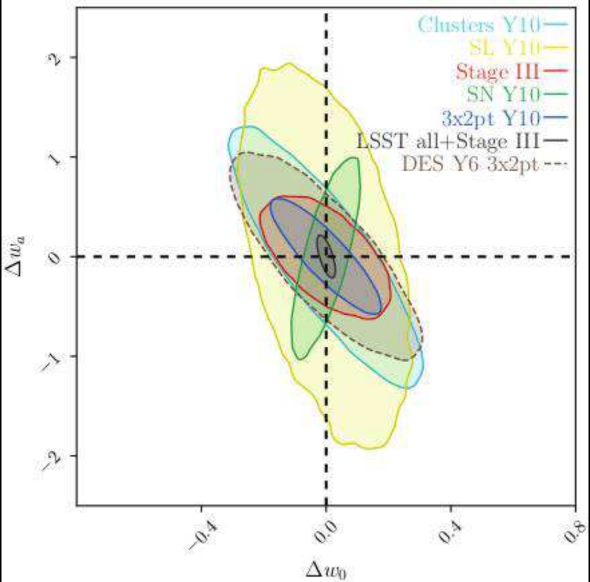
Project status :

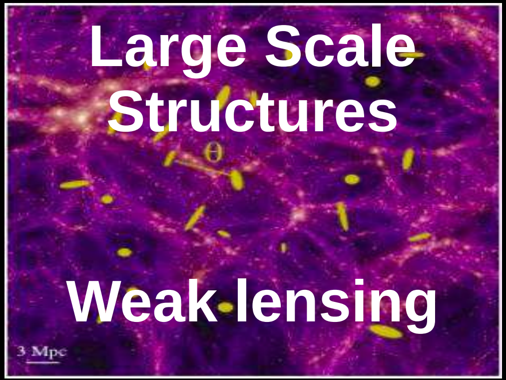
- US / Chile / Fr : builder countries (Fr : camera & computing at CC)
- Survey expected start : ~ 2023
- Largest ever image recently taken with the camera !
- ~ 20 TB of raw data each night, 50 % processed at CC



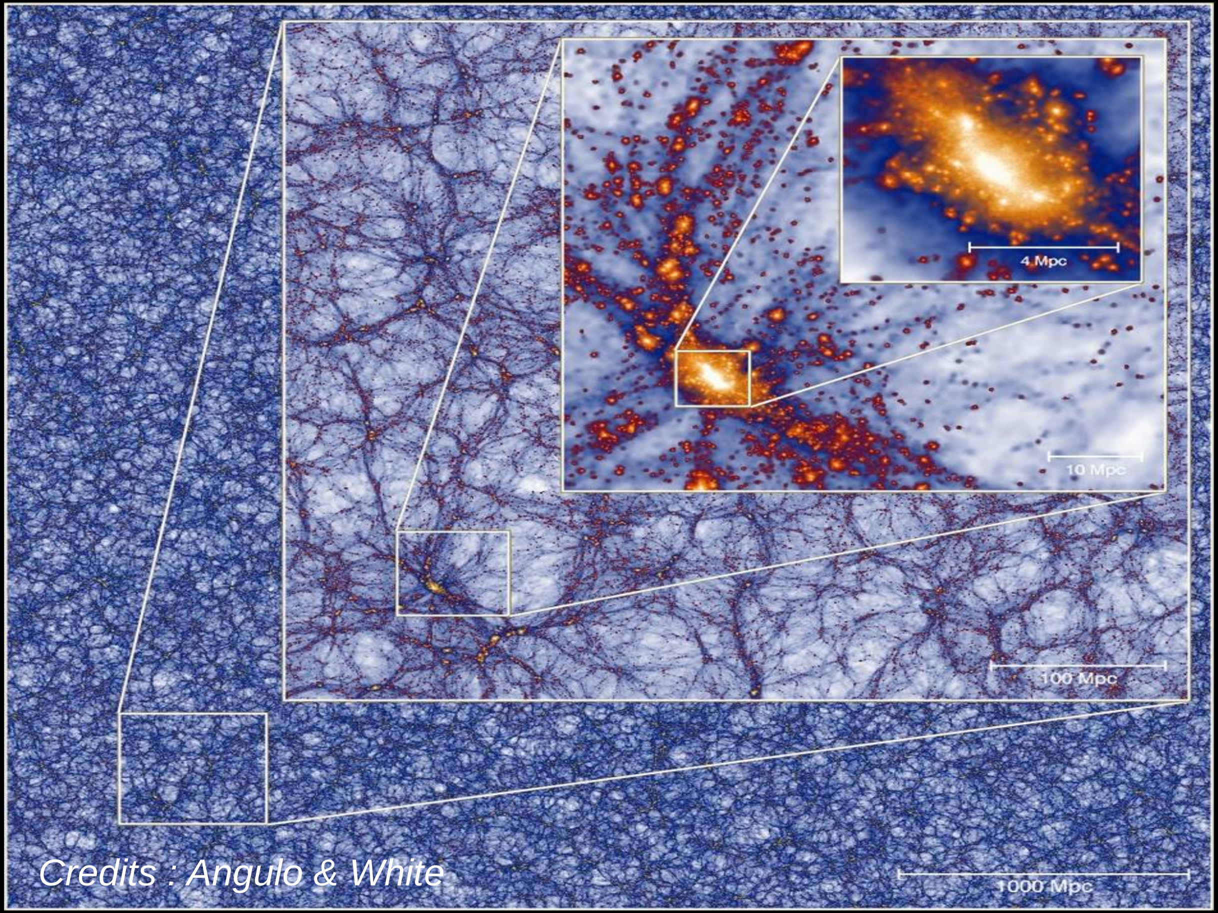
The LSST Dark Energy Science Collaboration







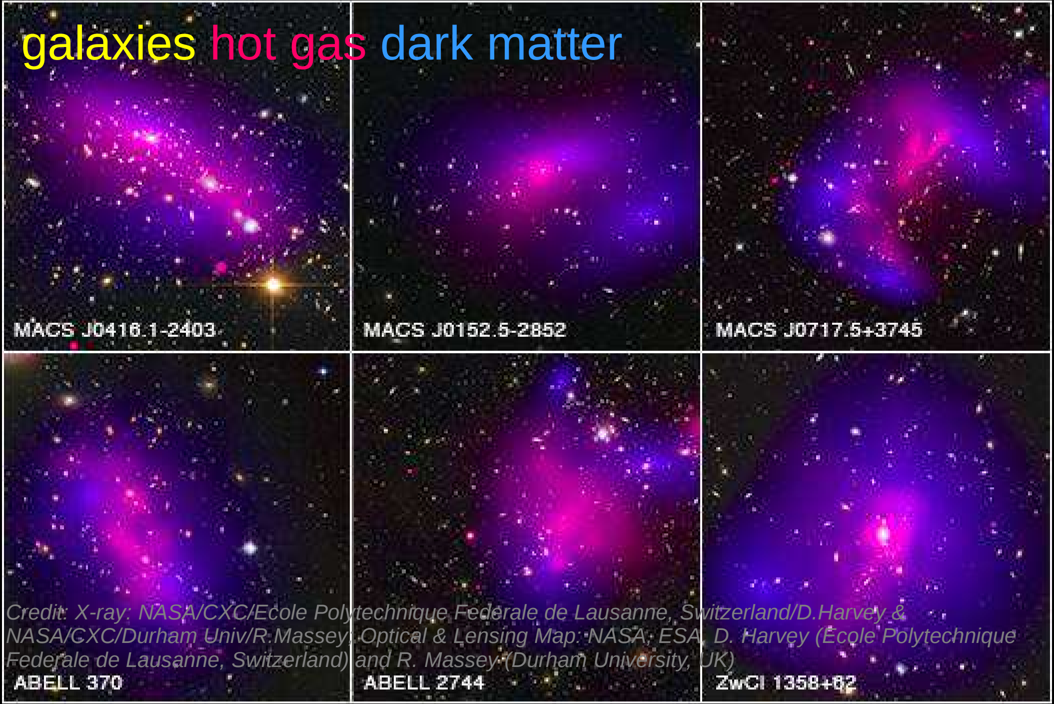
Clusters as tracers of the matter distribution



- **most massive objects** that collapsed under their own gravity
  - typical mass : ~$10^{14\text{-}15}$ M_{sun}
  - typical size : ~1 Mpc (~$3\text{x}10^6$ l.y.)
- **peaks in the matter density field**

➔ **powerful cosmological probes**

Observing galaxy clusters



~ 5 % of galaxies

- **Optical/IR : stellar light emission**
- FIR to mm : dust emission
- Radio/X-ray : black hole accretion

~ 15 % of hot gas

- **X-ray : thermal bremsstrahlung**
- **mm : Sunyaev-Zel’dovich effect**
- Radio: non thermal processes

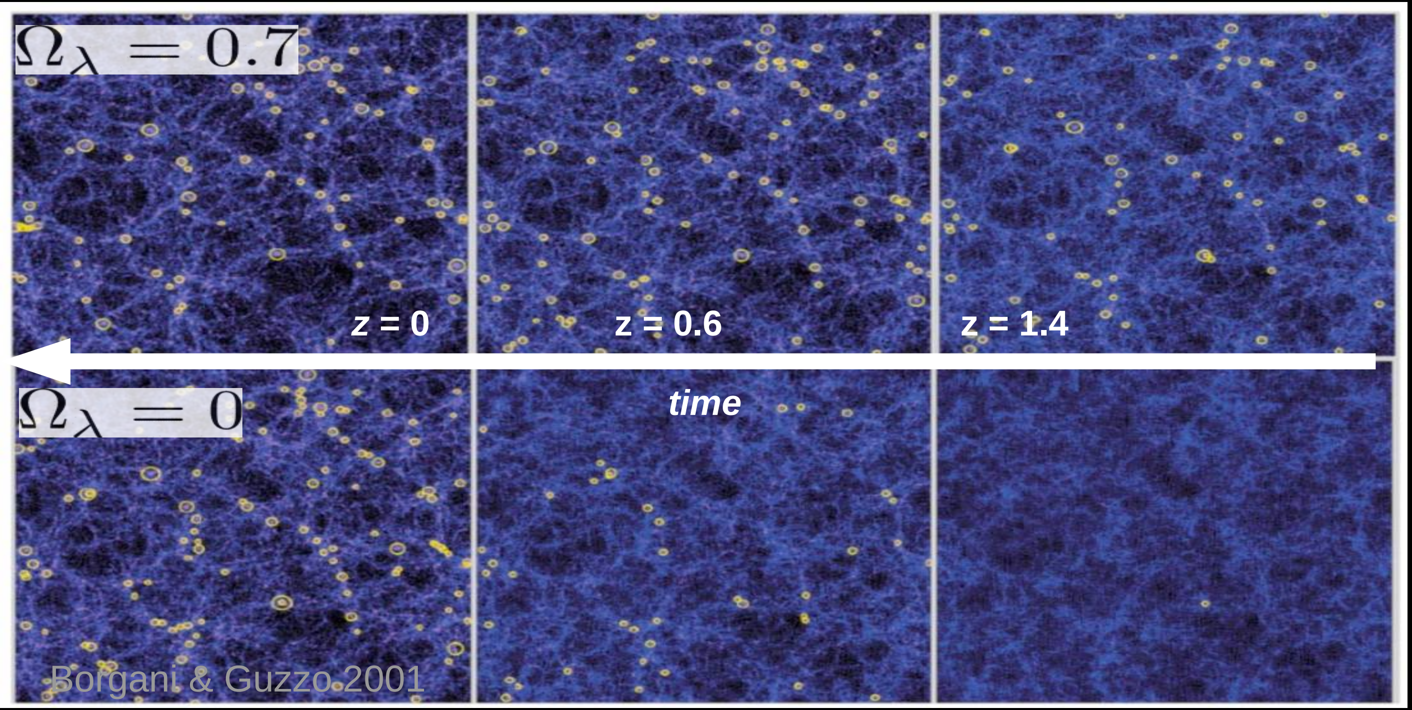
~ 80 % of dark Matter

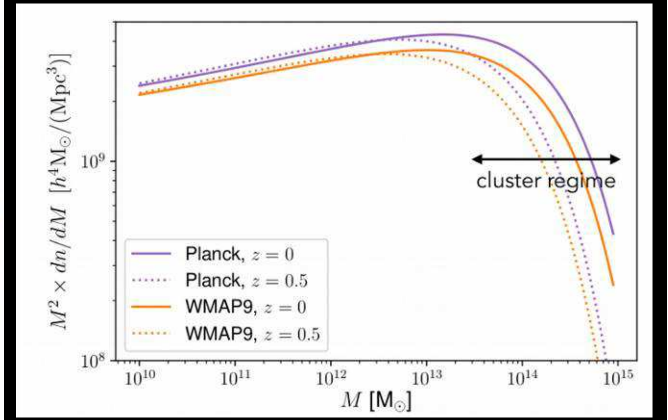
- Indirectly accessible from **gravitational lensing**

The majority of the mass of a galaxy cluster is not directly observable

Clusters counts as cosmological probe

The number of clusters as a function of mass and z can be used to **constrain cosmology**



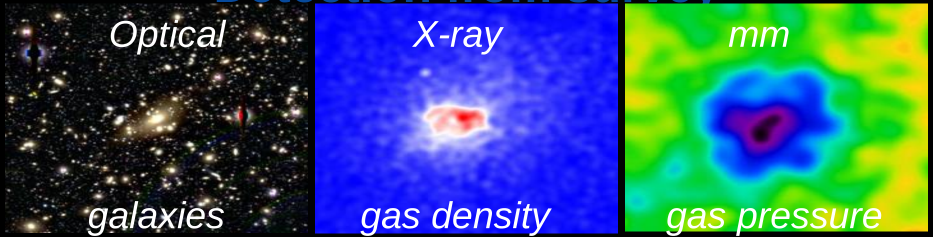


- **Growth of structures**
- **Gravitation law**
- **Dark energy**
- **Neutrino masses**

Other methods also sensitive to dark matter properties, expansion rate, structure formation scenario...

Constructing a cosmological cluster sample

Detection from survey



Selection function

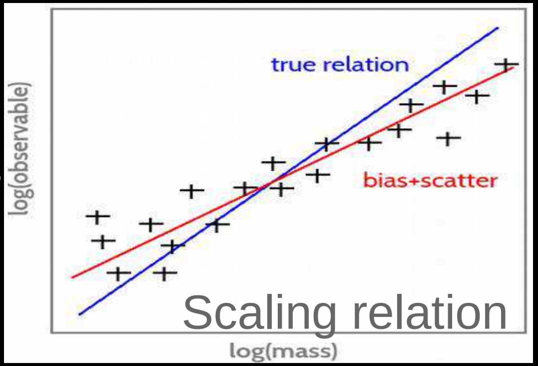
Representativity of detected clusters wrt the underlying population

Cluster catalogue

Mass determination

Observable : e.g. richness, L_x, SZ flux

Calibration from sub-samples with mass measured via e.g. gravitational lensing



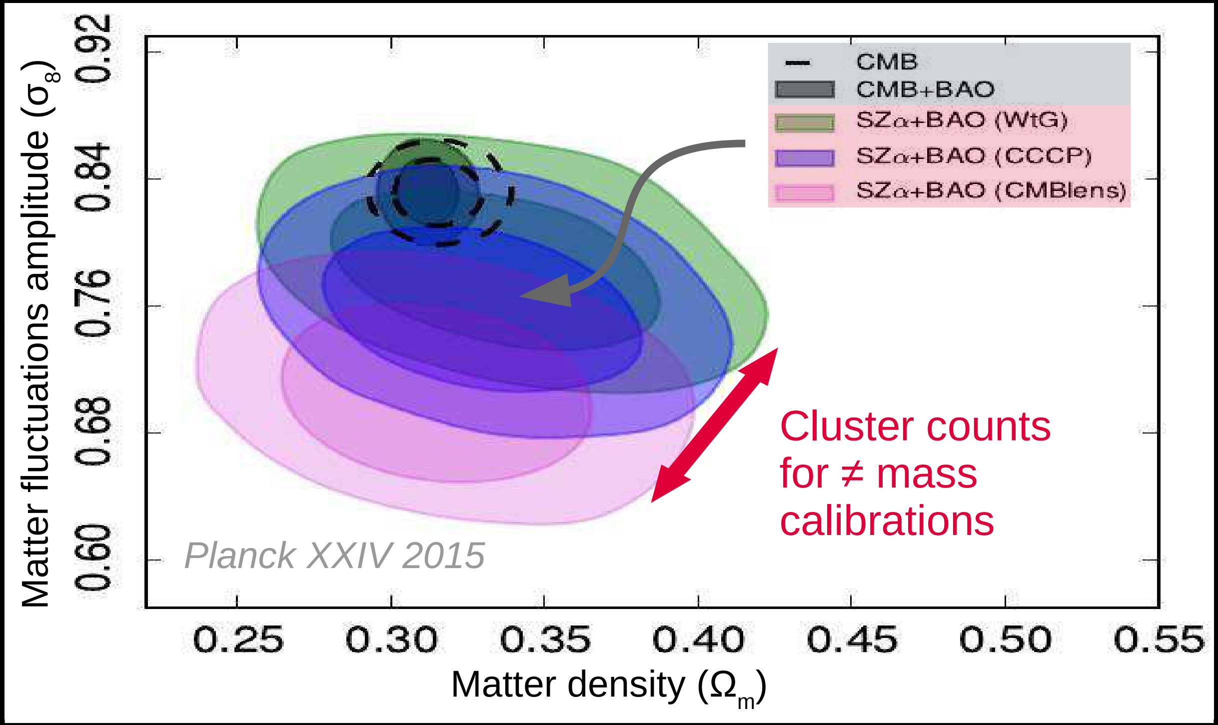
Redshift determination

possible internally (in optical/IR) or via follow-ups

The selection function and the mass determination are critical aspects

Status of cluster cosmology

- **Deficit in clusters counts** wrt expectations from early Universe probe
➤ **Tensions** between cosmological parameter constraints from CMB and clusters



Breakdown of our cosmological model or **mismodelling of cluster physics** ?

Current/future large cluster surveys

Several highly complementary surveys tracing ≠ cluster components, with ≠ systematics

Need to control detection, mass and redshift determination & selection function in the **X-ray, optical/NIR and mm**

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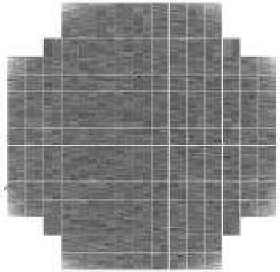
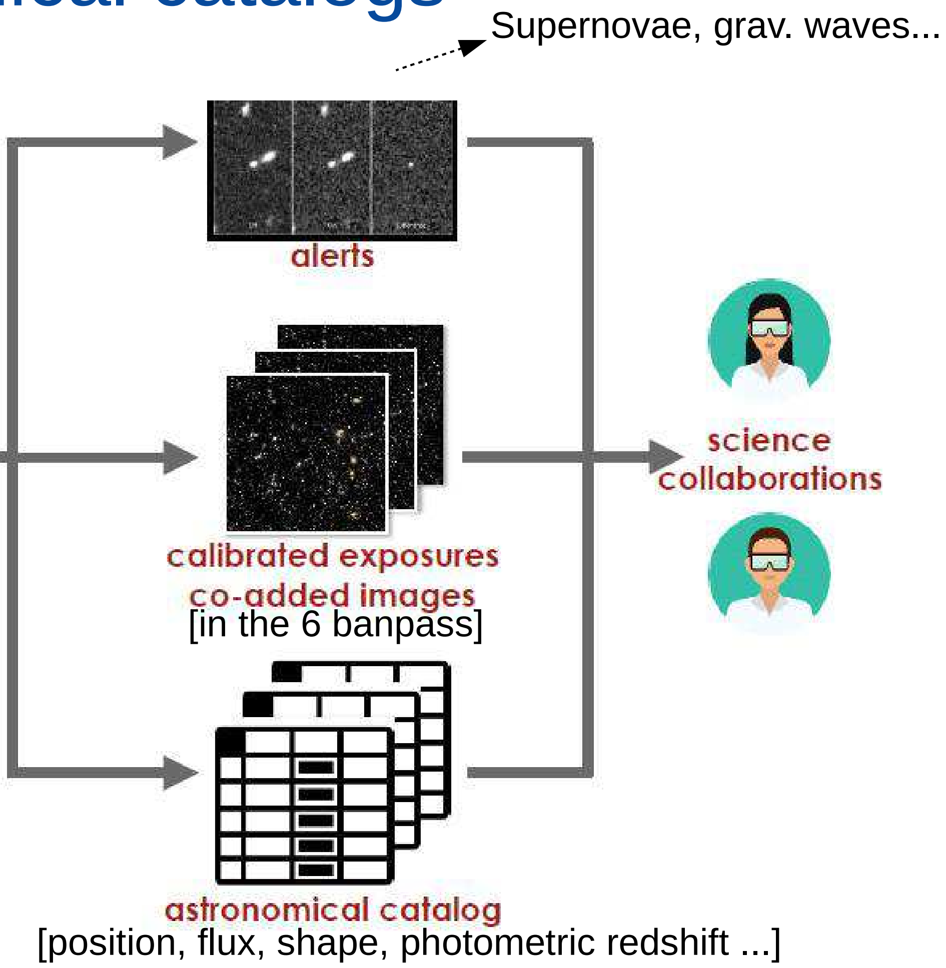
From LSST images to astronomical catalogs

Very complex pipelines at each processing step





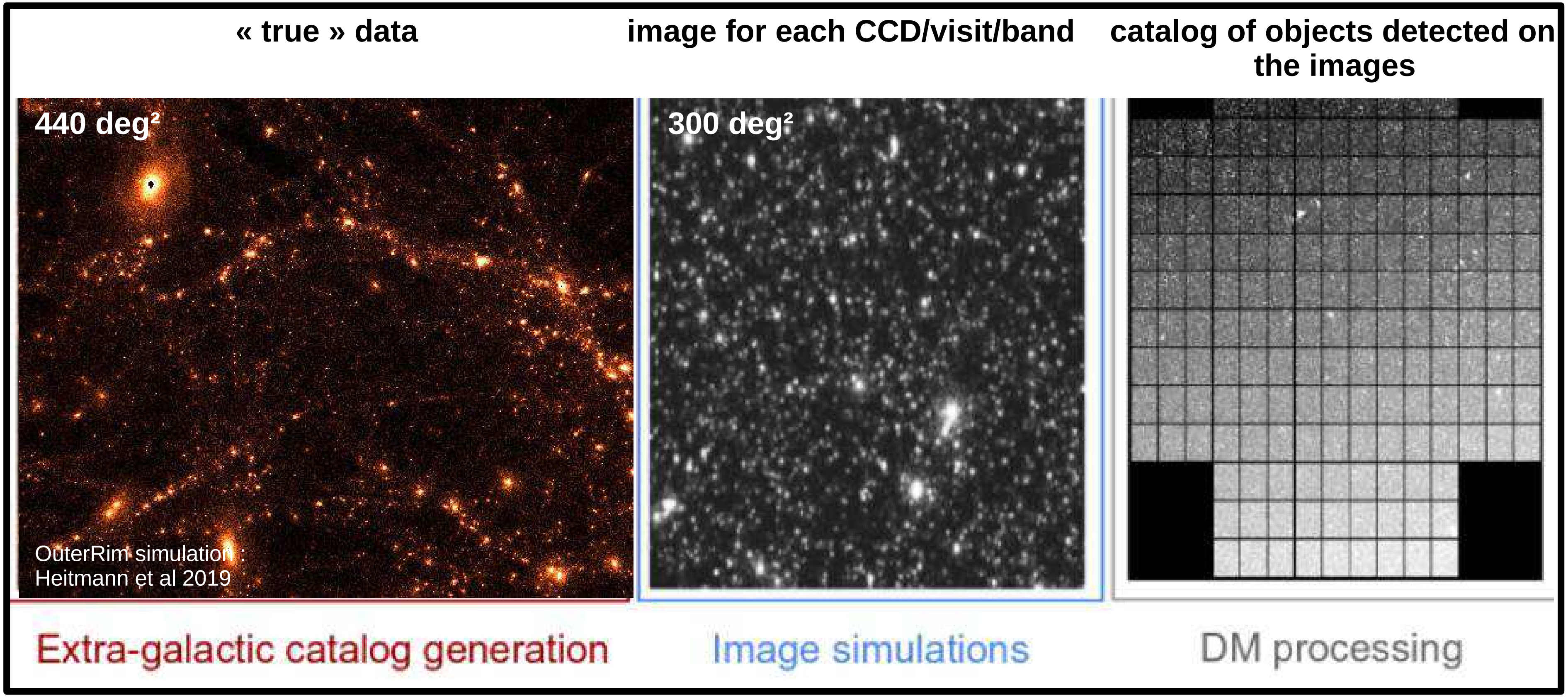
LSST aims to deliver a catalog of 20 billion galaxies and 17 billion stars with their associated physical properties

credits : F. Hernandez

The LSST DESC DC2 Simulated Sky Survey

[LSST DESC 2020, Korytov et al. 2019]

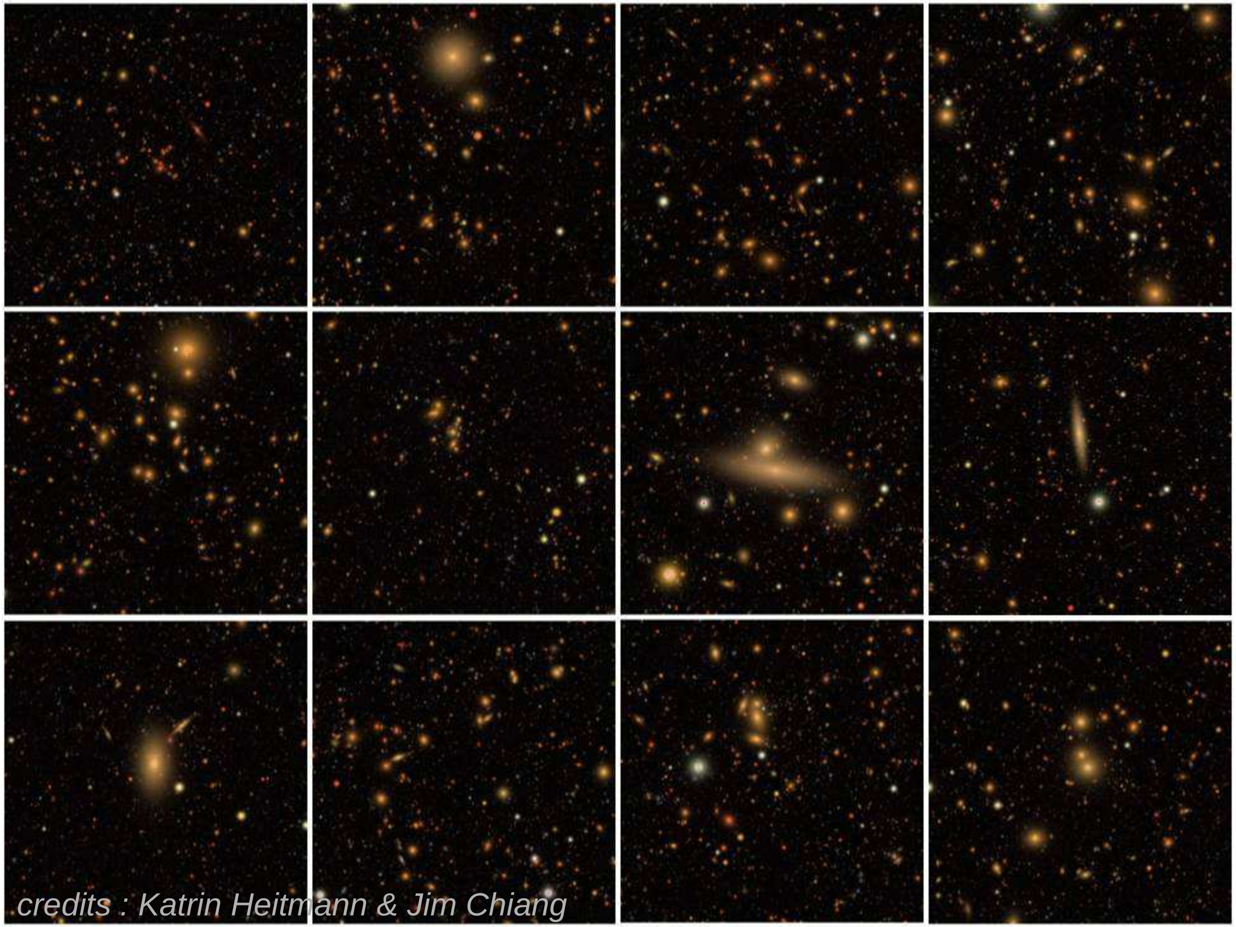
- end-to-end simulation to get pipelines ready and computing infrastructure to scale
- needed representativity wrt true data : continuous validation effort



credit : Katrin Heitmann

The LSST DESC DC2 Simulated Sky Survey

A gallery of zoom-in images from the DC2 simulation

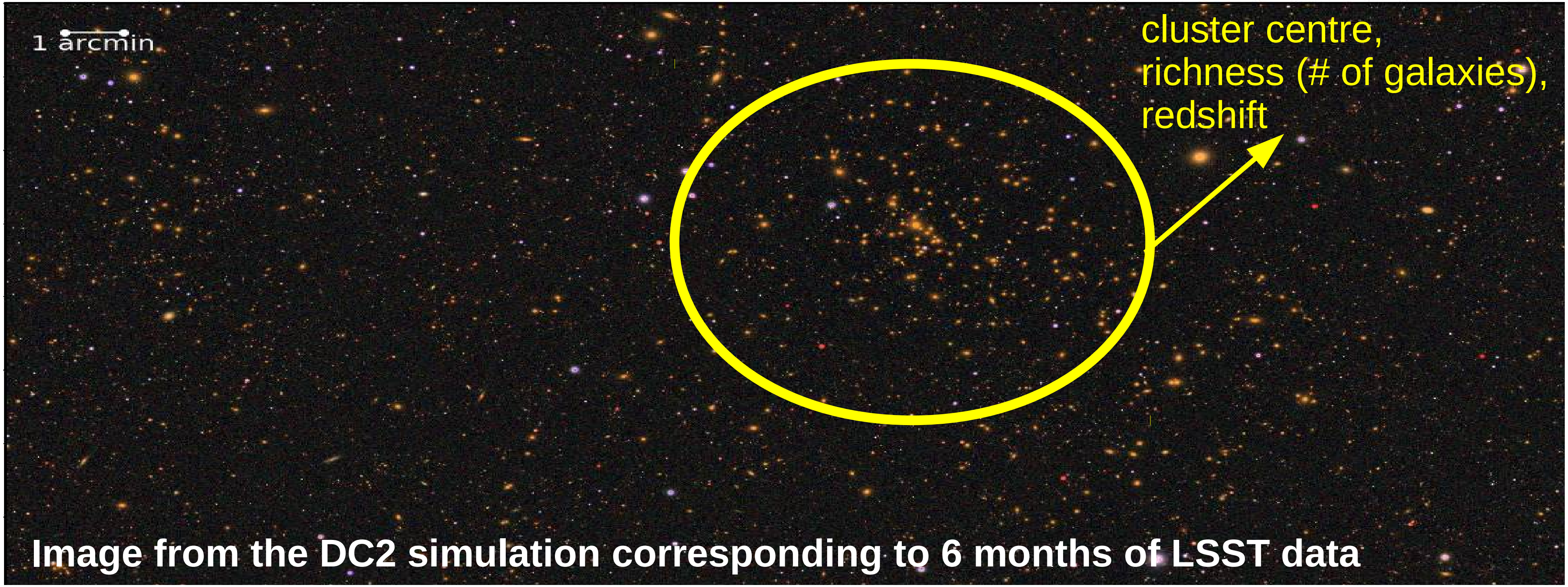


[LSST DESC 2020, Korytov et al. 2019]

5 years of LSST data

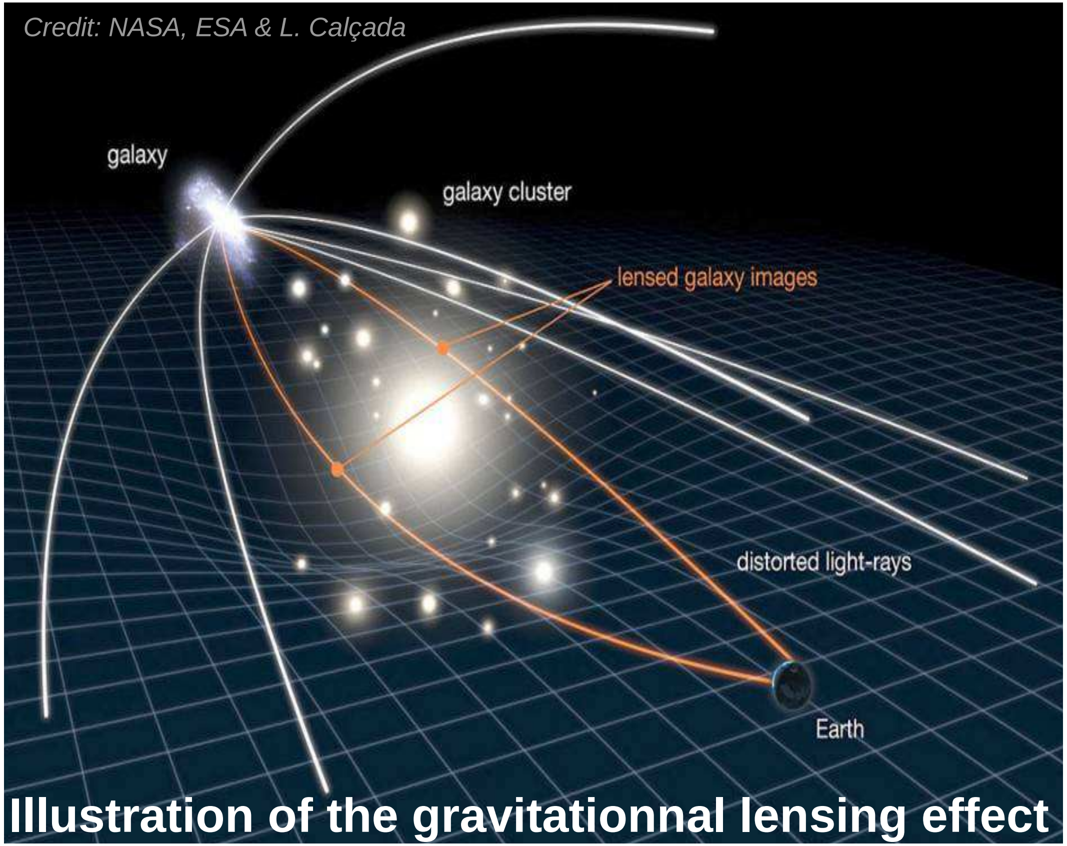
The LSST DESC cluster cosmological pipeline

- 1) **Cluster detection** from galaxy catalogs and measurements of their redshift and richness



The LSST DESC cluster cosmological pipeline

- 1) Cluster detection from galaxy catalogs and measurements of their redshift and richness
- 2) **Calibration of the richness-mass relation** via gravitationnal lensing measurements



The LSST DESC cluster cosmological pipeline

- 1) Cluster detection from galaxy catalogs and measurements of their redshift and richness
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Shear :

$$\gamma(\boldsymbol{\theta})$$

- **changes sources shapes**
- sensitive to the differential mass density

$$\gamma_t(\theta) \propto \Delta\Sigma(\theta)$$

Magnification :

$$\mu(\boldsymbol{\theta}) = \frac{1}{[1-\kappa(\boldsymbol{\theta})]^2 - |\gamma(\boldsymbol{\theta})|^2}$$

- **changes apparent solid angle & increases the flux of sources**
- sensitive to the mass density

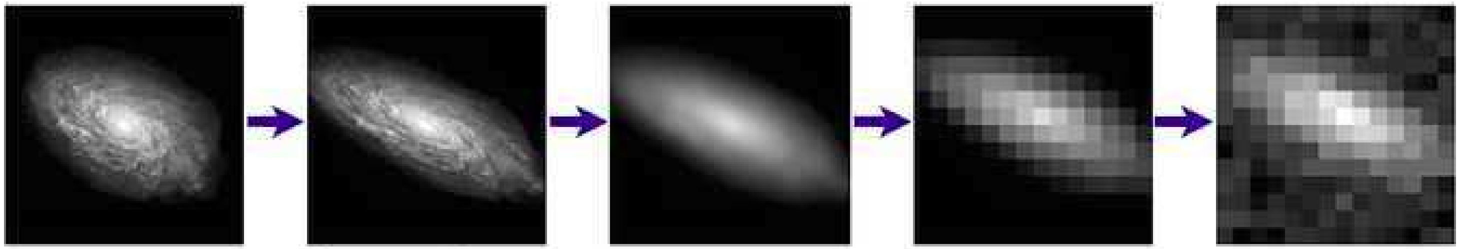
$$\mu(\theta) \propto \Sigma(\theta)$$

The LSST DESC cluster cosmological pipeline

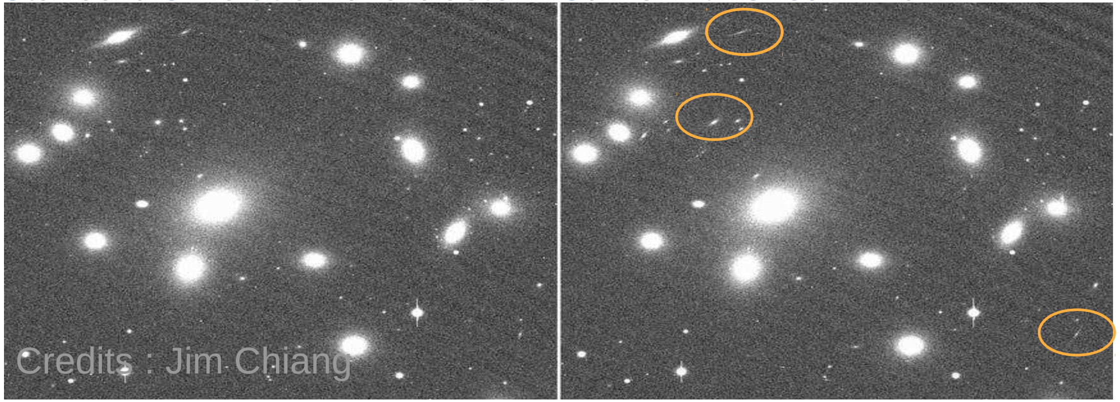
- 1) Cluster detection from galaxy catalogs and measurements of their redshift and richness
- 2) **Calibration of the richness-mass relation** via gravitationnal lensing measurements

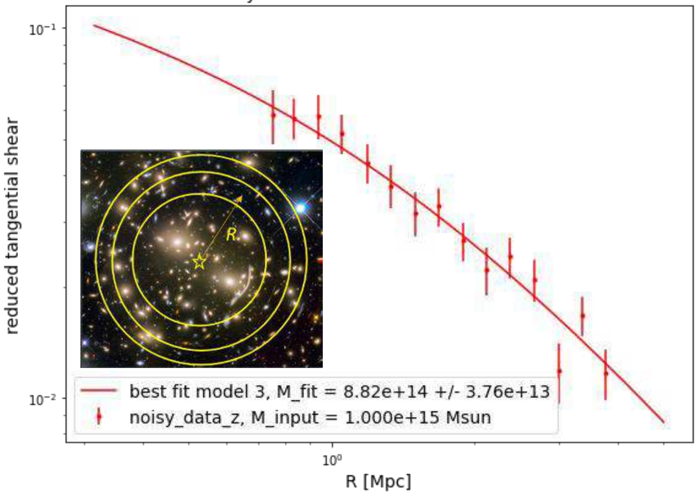
Shear :

- change in source shape
- tiny effect : measure statistically by averaging many galaxies
- hypothese : intrinsic shapes are random
- shear profile around clusters informs about their mass profiles



Standard simulation of a cluster   Same with shear x 10





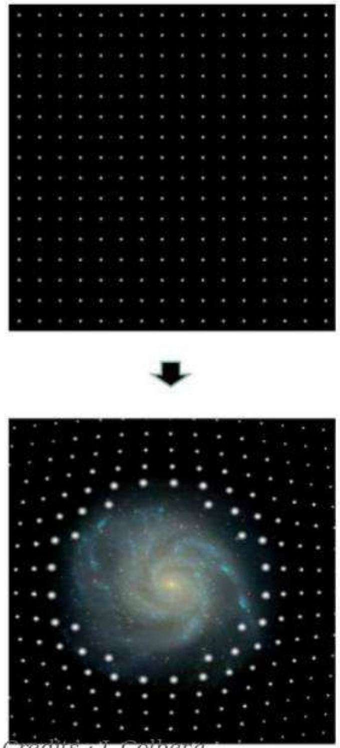
WL shear requires very accurate photometry

The LSST DESC cluster cosmological pipeline

- 1) Cluster detection from galaxy catalogs and measurements of their redshift and richness
- 2) **Calibration of the richness-mass relation** via gravitationnal lensing measurements

Magnification :

changes the apparent source number density, measurable from the **cross-correlation function of cluster and backgroud source positions**



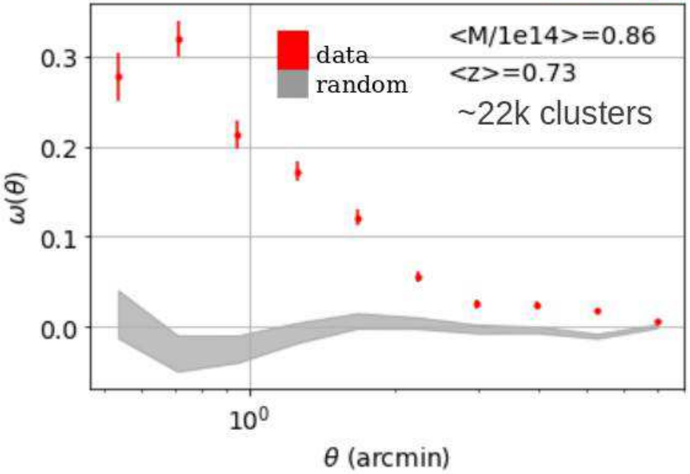
Credits : J. Colberg, R. Scranton, R. Lupton, SDSS

lensed → $n(>f)$; *unlensed* → n_0

$$n(>f) = \frac{1}{\mu} n_0 \left(> \frac{f}{\mu}\right)$$

$\frac{1}{\mu}$: dilution of the source density due to the dilatation of the solid angle

$\left(> \frac{f}{\mu}\right)$: diminution of the minimum detectable flux



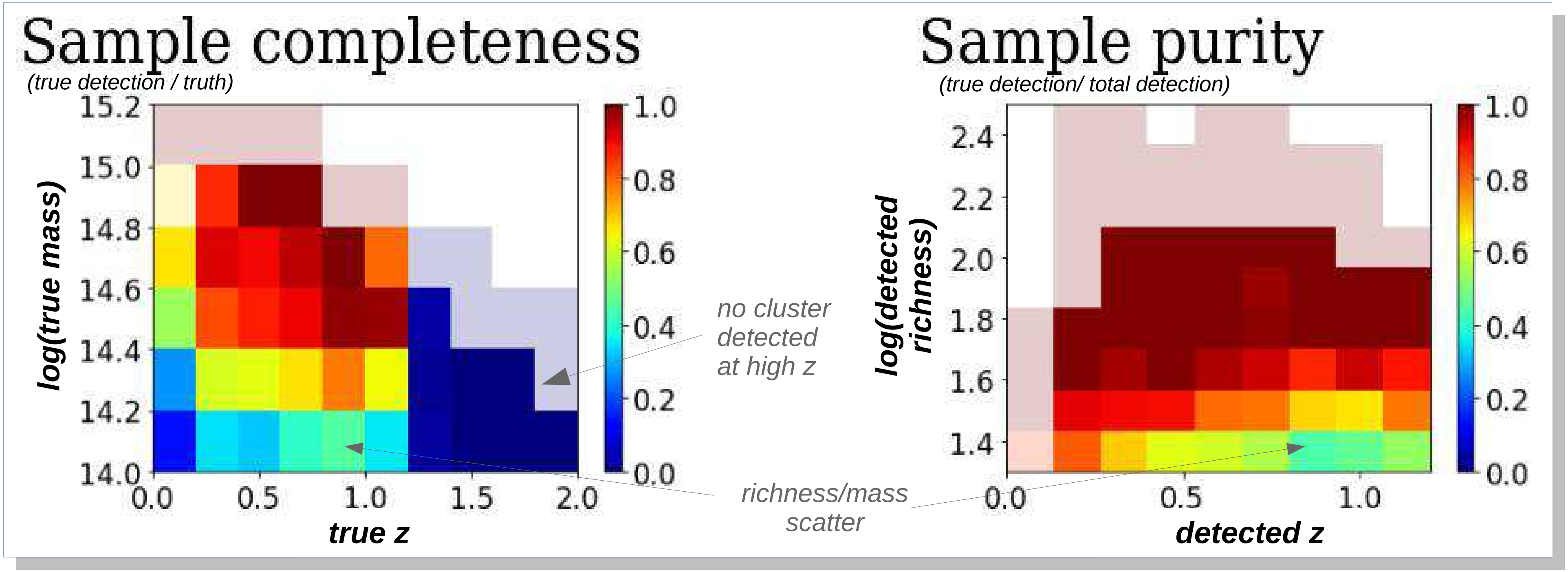
Cross-correlation function between background galaxies and clusters in DC2 as a function of angular separation

- measurements only requires knowledge about the flux and number counts of unlensed objects : easier to get than the shape

Magnification effect : precious alternative probe of clusters masses

The LSST DESC cluster cosmological pipeline

- 1) Cluster detection from galaxy catalogs and measurements of their redshift and richness
- 2) Calibration of the richness-mass relation via gravitationnal lensing measurements
- 3) Characterization of the **sample selection function** (completeness, purity ...)



Characterization of the cluster sample detected with the redMaPPer algorithm, evaluated on the DESC DC2 simulation

The LSST DESC cluster cosmological pipeline

- 1) Cluster detection from galaxy catalogs and measurements of their redshift and richness
- 2) Calibration of the richness-mass relation via gravitationnal lensing measurements
- 3) Characterization of the sample selection function (purity, completeness ...)
- 4) **Statistical modeling** of data/theory to get **cosmological constraints**

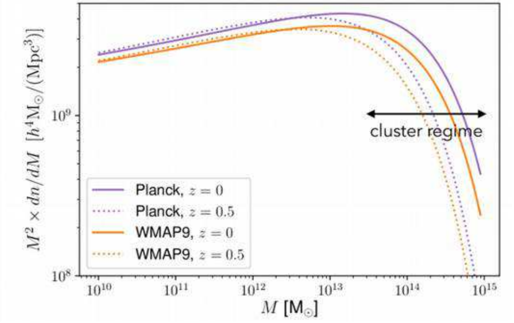
Observations — Predictions

$$\frac{dN}{dzd\Omega} = \frac{dV_C}{dzd\Omega}(z) \int \hat{\chi}(\mathcal{O}, z, \vec{u}) d\mathcal{O} \int P(\mathcal{O}|M,z) \frac{dn(M,z)}{dM} dM$$

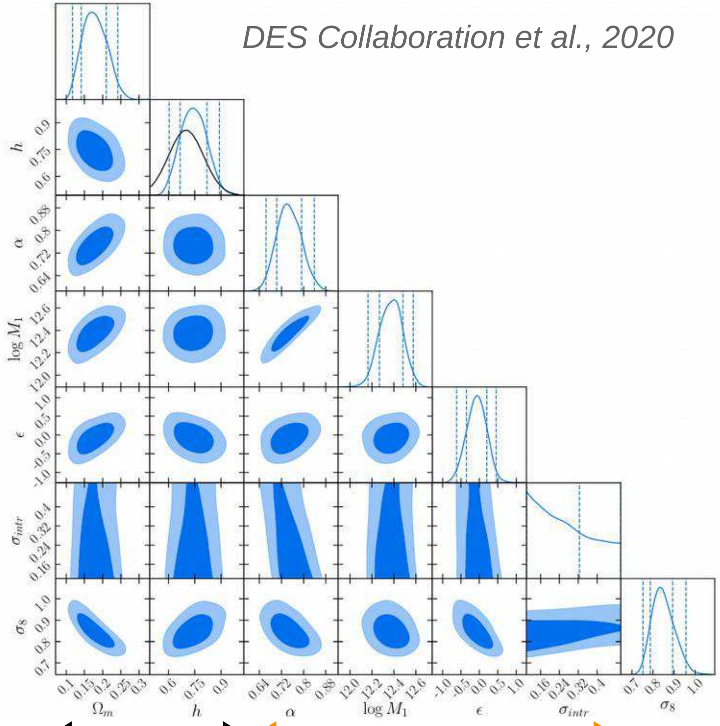
Obervationnal effects

- Detection and selection function
- Observable (richness)
- Mass-observable relation
- Redshift determination

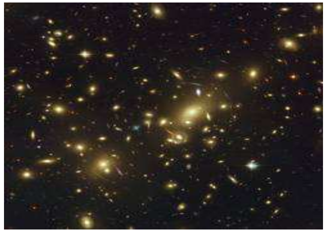
Theoretical models



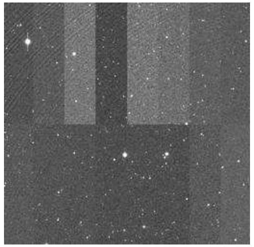
DES Collaboration et al., 2020



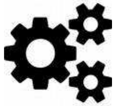
Preparing Rubin Obs. LSST cluster cosmology : summary



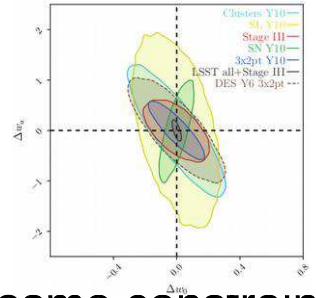
cosmo probe



raw images



astro catalogs



cosmo constraints

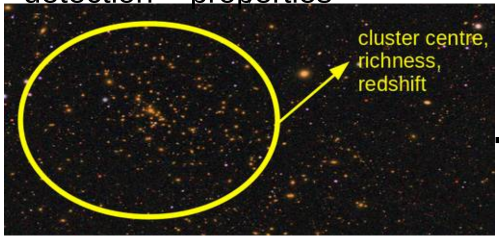
dedicated simulation : DC2

cosmo probe =
galaxy cluster

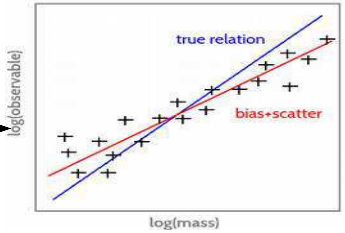
+ precise understanding of astrophysics

+ sims and external data

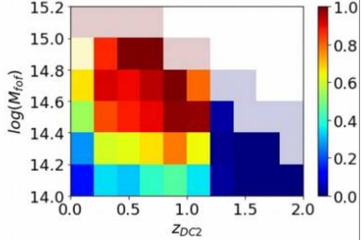
detection + properties



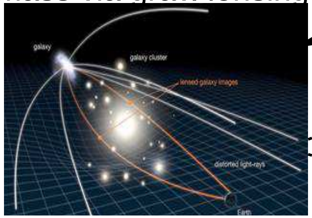
mass - richness relation



selection function



mass via grav. lensing



shear

magnification

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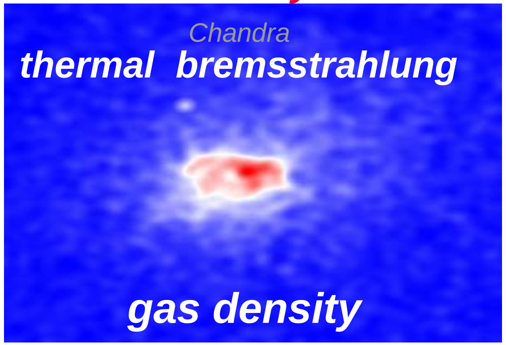
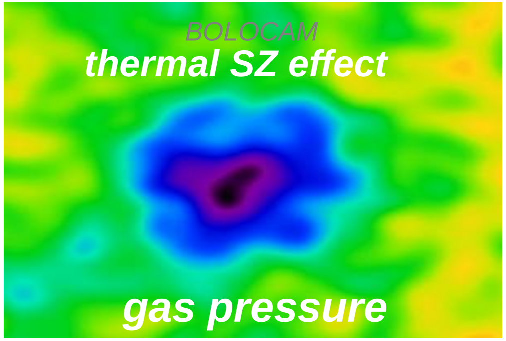
Exploiting multi-wavelength synergies

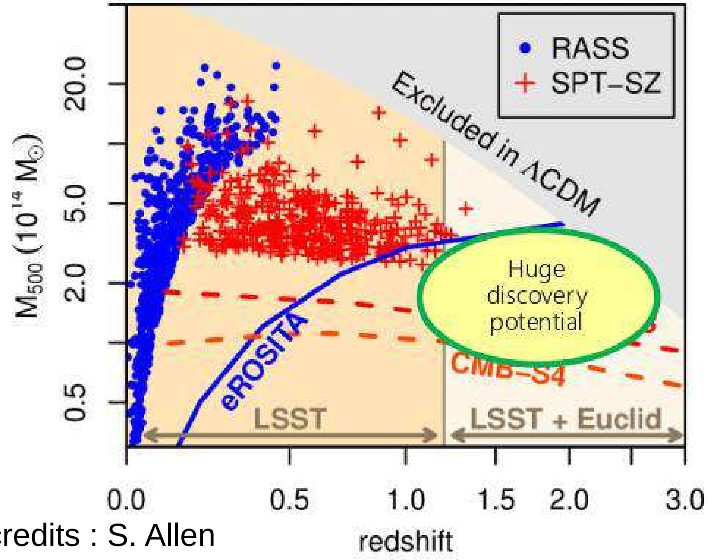
optical/IR

X-ray



mm





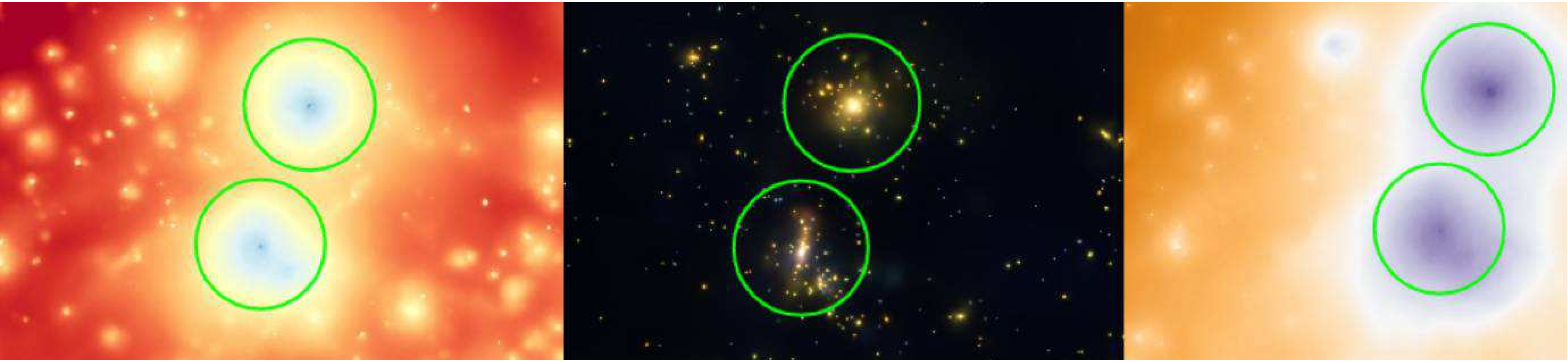
credits : S. Allen

- cluster : **multi-wavelength objects**
- each λ trace **different components** with **different systematics :** comparison crucial to understand cluster physics + tackle biases
- Need of **large cluster samples & dedicated follow-up**

Combining data from different instruments at both survey and individual scales is key

Multi-wavelength simulations : a ‘baryon pasting’ approach

Cosmological analyses rely on simulated datasets to understand the DM - gas - galaxy connection



Ideal simulations :
- up to large scales
- include dark matter, gas & galaxies
- accurate cluster observables
- different cosmo and physics
- mimick different instruments

Extremely computationally intensive

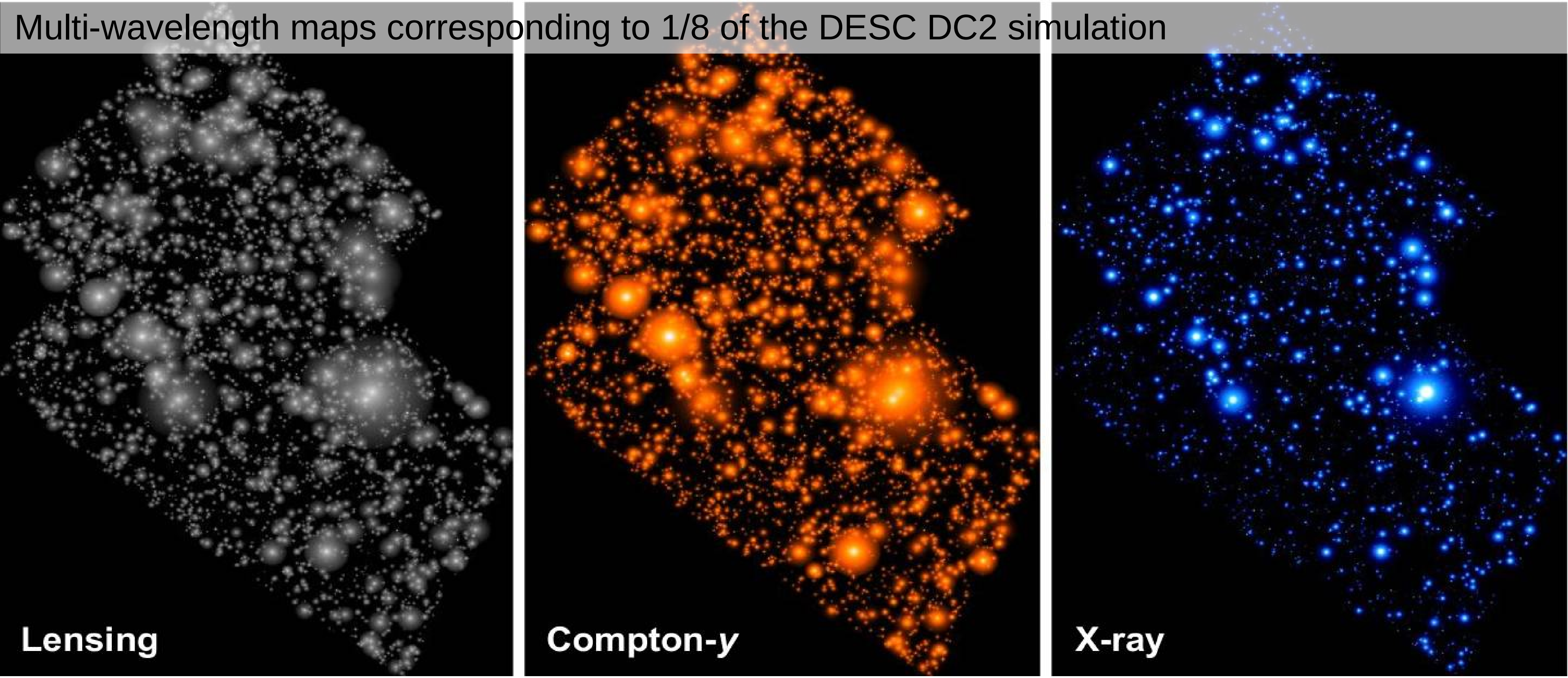
‘Baryon pasting’ approach :
- ‘pasting’ gas properties on DM halos (then particules)
- allow to simply include many observationnal aspects
- gas model validated on data and other sims
- produce different observables, including mock sky maps

‘cheap’ multi-wavelenght simulations based on gas model

Multi-wavelength simulated views of the Rubin Sky

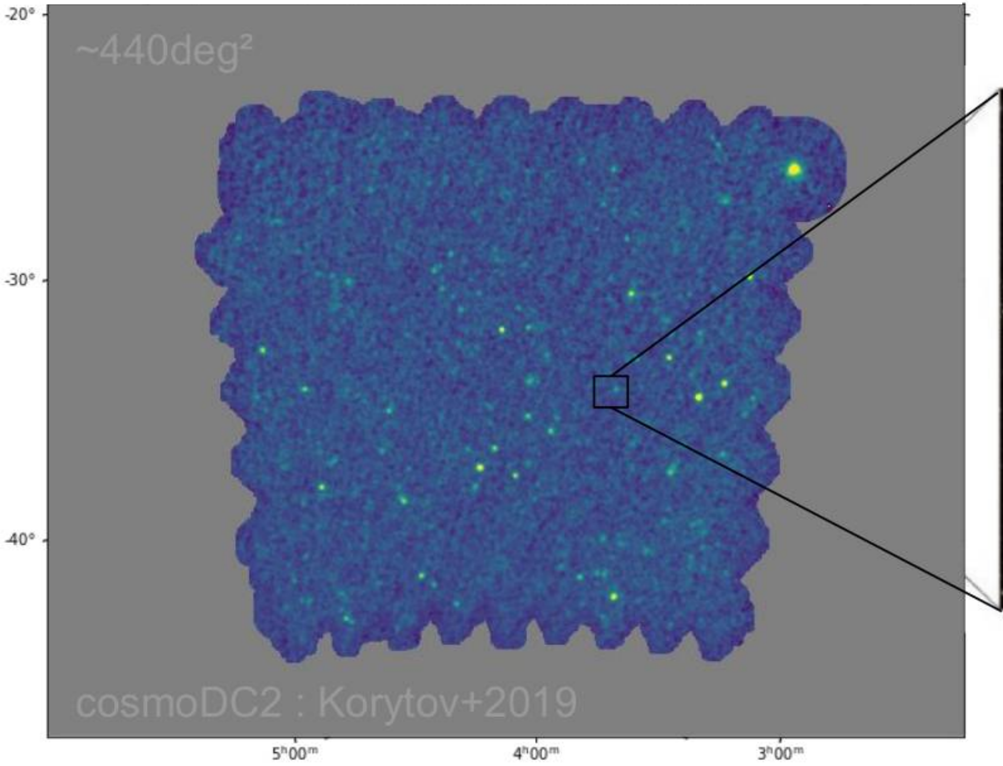
Project : obtain X-ray & mm simulated view of the Rubin Obs. sky to developp multi-wavelength analyses

Multi-wavelength maps corresponding to 1/8 of the DESC DC2 simulation

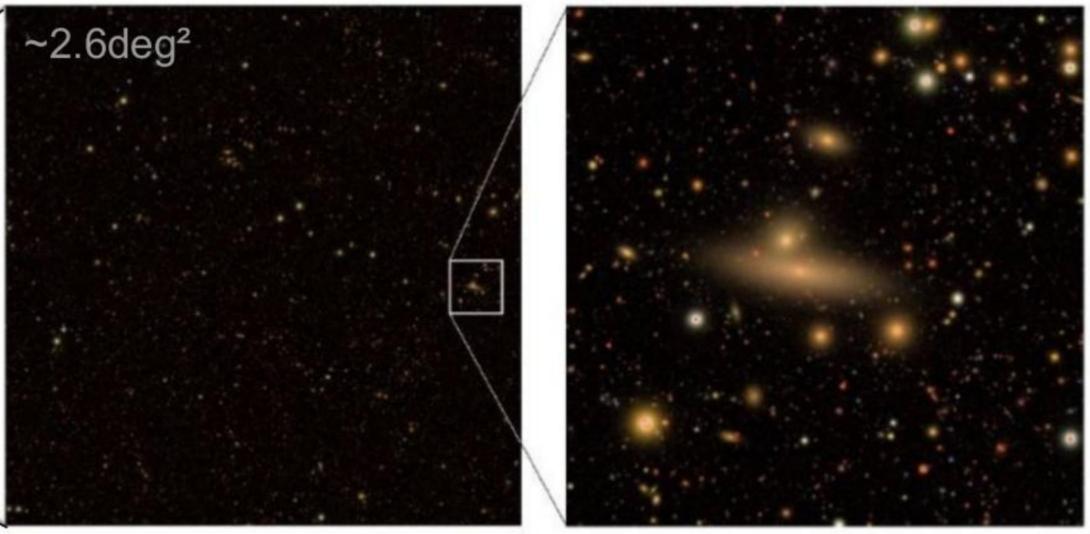


Multi-wavelength simulated views of the Rubin Sky

map of the DC2 lightcone as seen by Planck



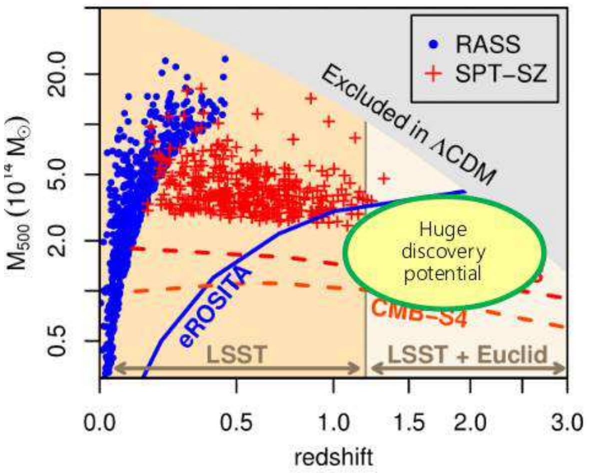
zoom on an image from the DC2 simulation



LSST DESC et al. 2020

Applications : multi-wavelength mass-observable relations, detection, selection functions, cross-correlations...

Multi-wavelength in-depth analysis of ‘extreme’ clusters



- Understanding clusters physics up to high redshift and down to low mass is important for cosmology :
  - bulk of the detected systems
  - high leverage to constrain cosmo and astro
  - good test-beds for cluster physics modeling

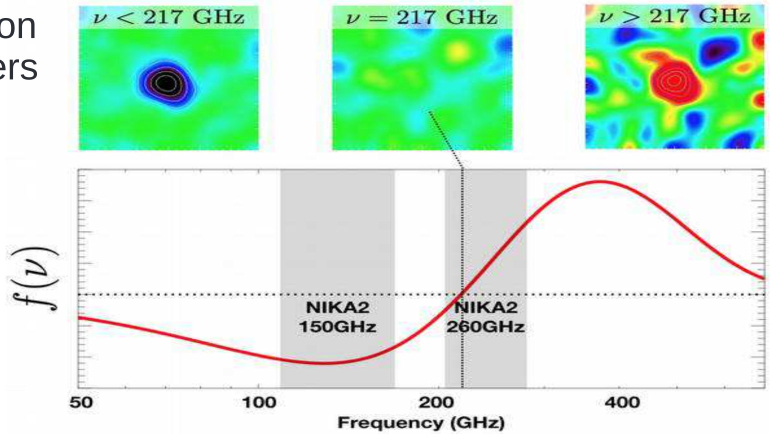
Project : SZ follow-up observation of 3 z~1 low mass clusters detected in X-ray

- **Sunyaev-Zel’dovich (SZ) effect** : inverse Compton scattering of CMB photons with electrons in clusters

$$\Delta I_{SZ} \propto f(\nu) \int P_e$$

- ➢ **independent of *z***
- ➢ sensitive to integrated **pressure**
- ➢ SZ flux tracks **total mass**

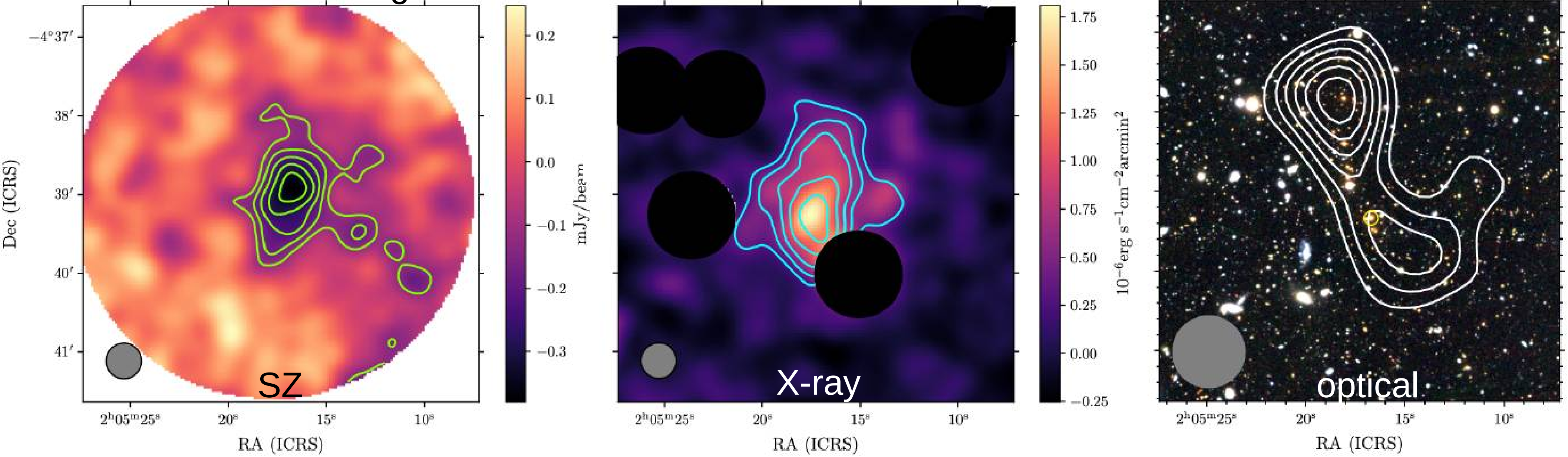
Resolved SZ observations allow to probe the gas pressure structure



Multi-wavelength in-depth analysis of ‘extreme’ clusters

View of one of the 3 targeted cluster :

Ricci, Adam et al. 2020

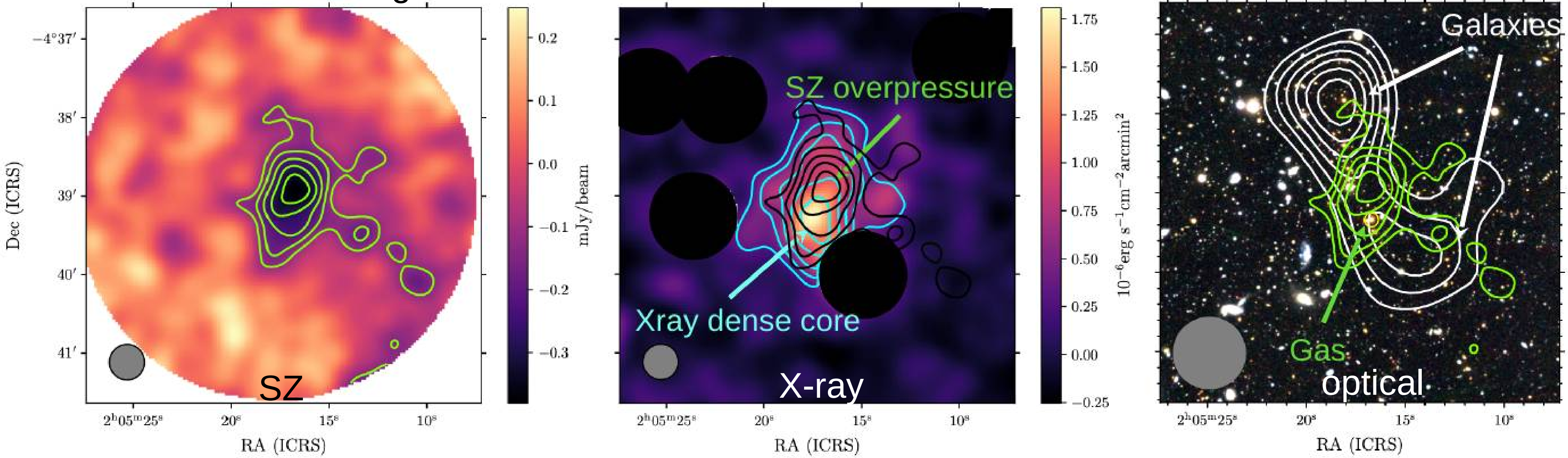


SZ + X-ray+optical mapping allow a good physical understanding

Multi-wavelength in-depth analysis of 'extreme' clusters

View of one of the 3 targeted cluster :

Ricci, Adam et al. 2020



SZ + X-ray+optical mapping allow a good physical understanding

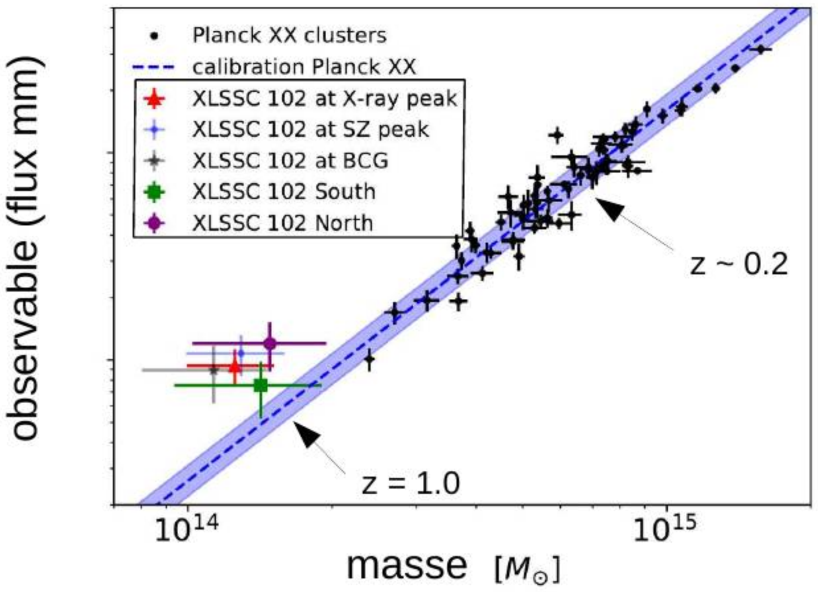
- Large scale X/SZ agreement, but local deviations due to substructures
- Huge ICM/galaxies offset

A low mass Bullet cluster at z~1

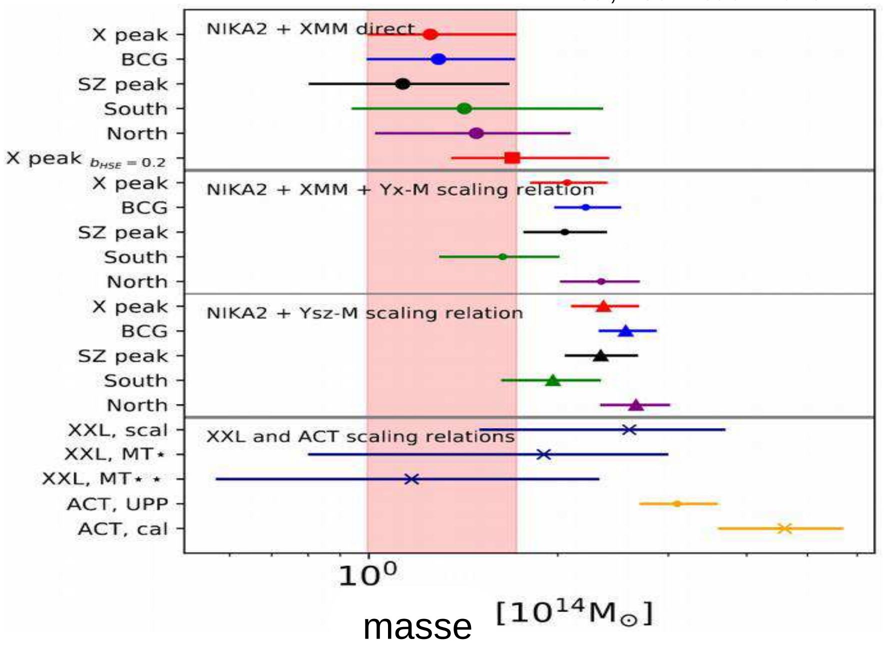
Multi-wavelength in-depth analysis of ‘extreme’ clusters

Comparison of global properties to what expected from low redshift and higher mass systems

Ricci, Adam et al. 2020



Ricci, Adam et al. 2020

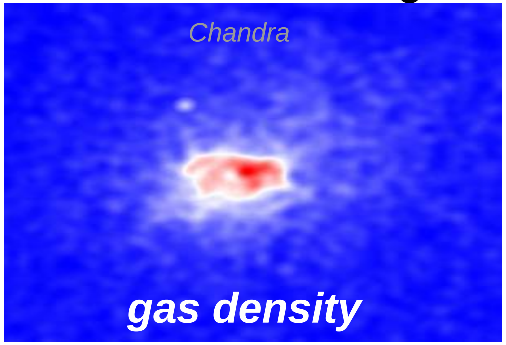


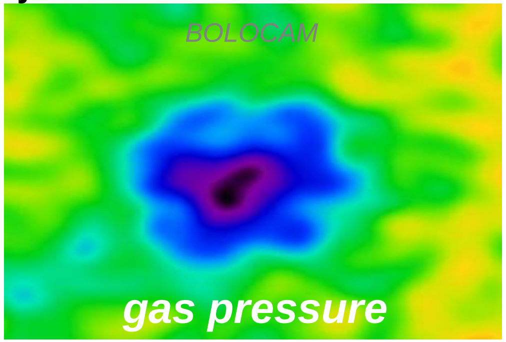
- No strong deviation on the mass-observable relation
- Effect of the internal structure on the mass measurements
- Different compatible mass estimates, but scatter

Standard evolution seems to hold for this extreme system, but more clusters needed to validate

Exploiting multi-wavelength synergies : summary

clusters : multi-wavelength objects



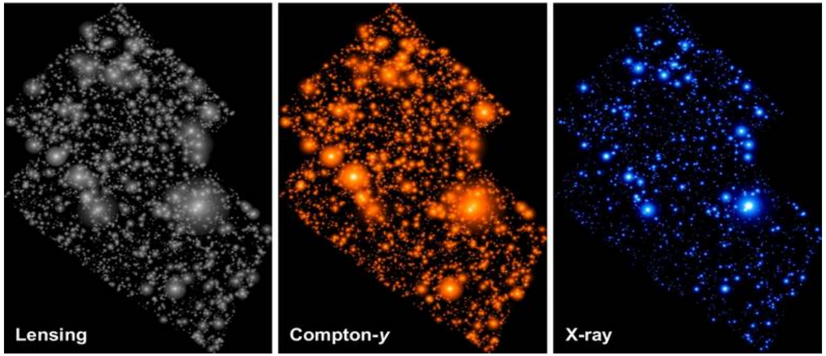


At large scale

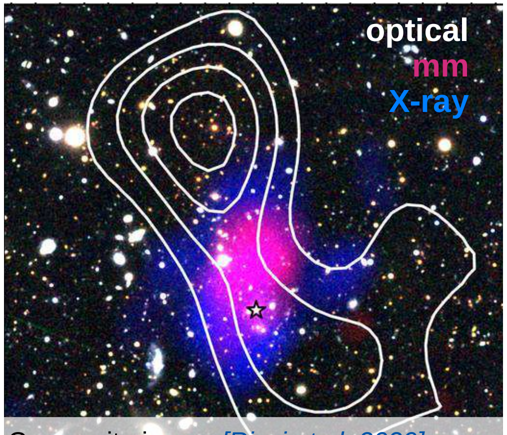
cosmo analyses need to combine data from different instruments

At individual cluster scale

Multi-wavelength simulated views of the Rubin Sky



Multi-wavelength in-depth analysis of 'extreme' clusters



Composite image *[Ricci et al. 2020]*

Content

- Observationnal cosmology with galaxy clusters
- Preparing Rubin Obs. LSST cluster cosmology
- Exploiting multi-wavelength synergies
- **Summary & take home messages**

Summary & take home messages

- **Large optical telescope** at the era of big data, to shed light on **cosmological mysteries** (and more)
- **Project in its last preparation stage,** first data expected in ~3 yrs
- Science pipeline curently developped using pathfinder data and **dedicated simulations**

- Powerfull tools to **test cosmological models**
- **Rich laboratories** to understand the **complex physics of the dark matter, gas and galaxy connection**
- Cosmo analyses **dominated by systematics** from astro processes : **combining data and sims at different wavelenghts/scales** is key

Thank you for your attention !

LSST Project/NSF/AURA

additional

Abell 2218 at z = 0.18

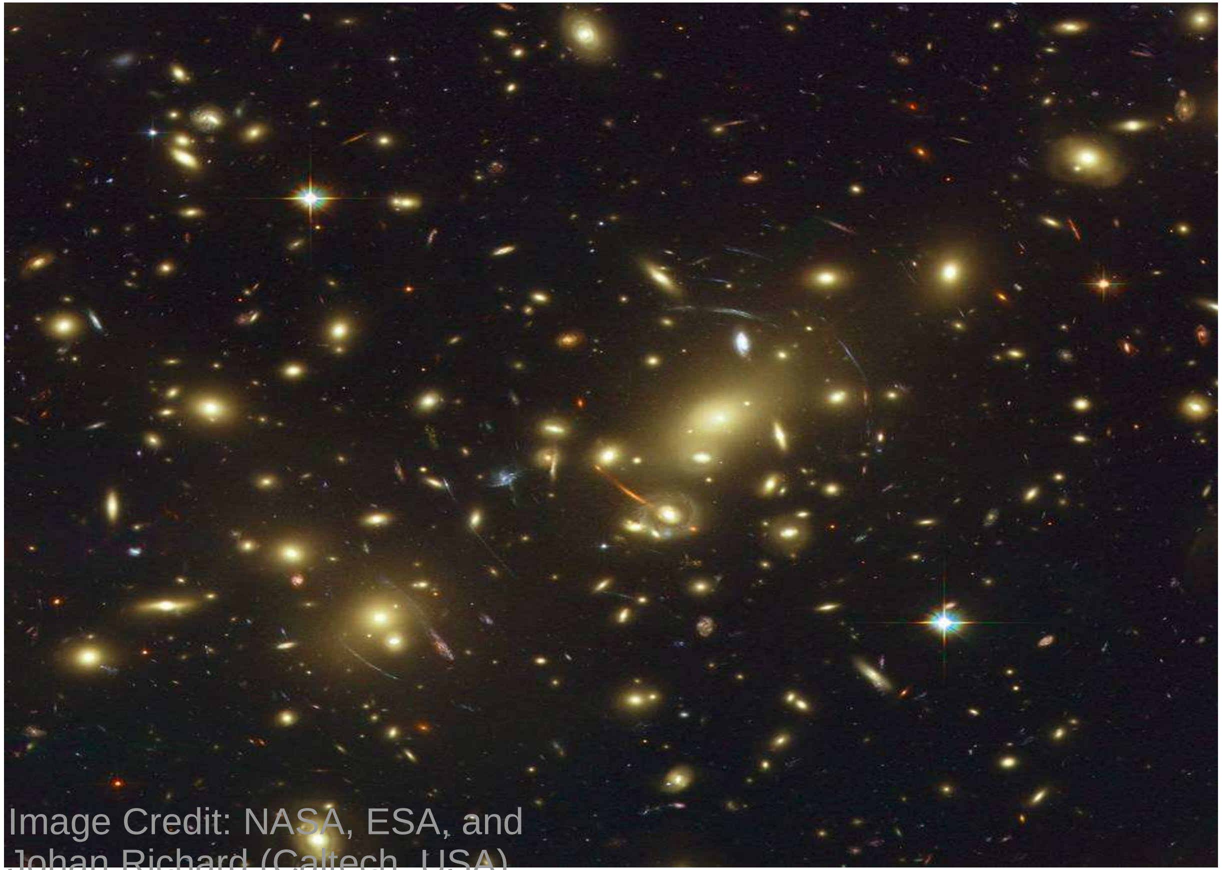
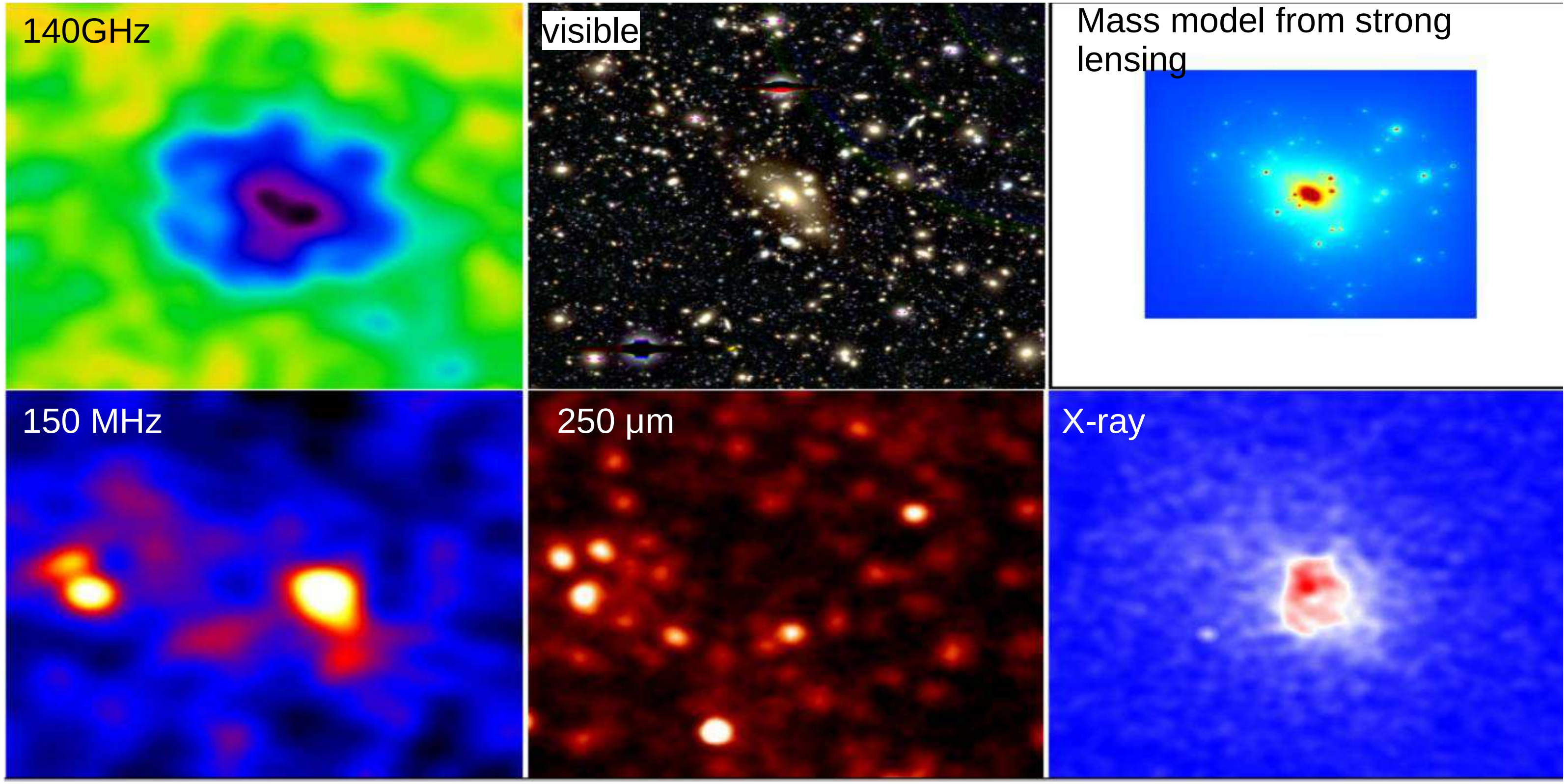


Image Credit: NASA, ESA, and Johan Richard (Caltech, USA)

additional

Abell 209, a massive merging cluster at z=0.206



additional

The number of clusters as a function of mass and z can be used to **constrain cosmology**

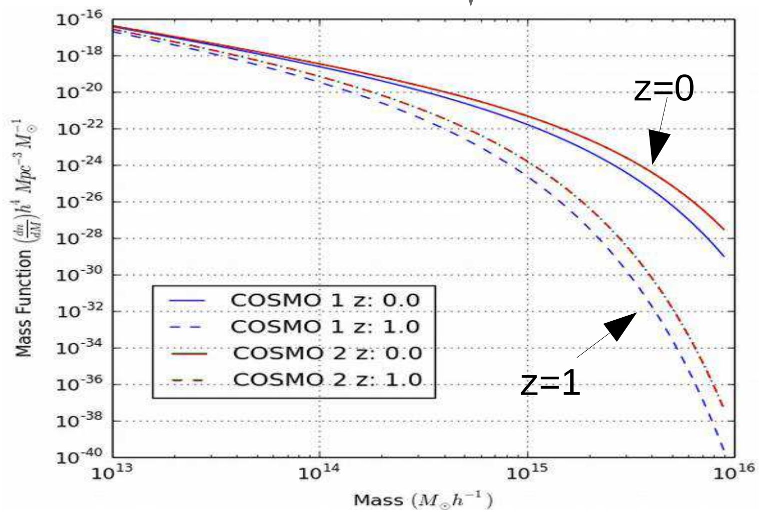
Observations — Predictions

$$\frac{dN}{dz d\Omega} = \frac{dV_C}{dz d\Omega}(z) \int \hat{\chi}(\mathcal{O}, z, \vec{u}) d\mathcal{O} \int P(\mathcal{O}|M, z) \frac{dn(M,z)}{dM} dM$$

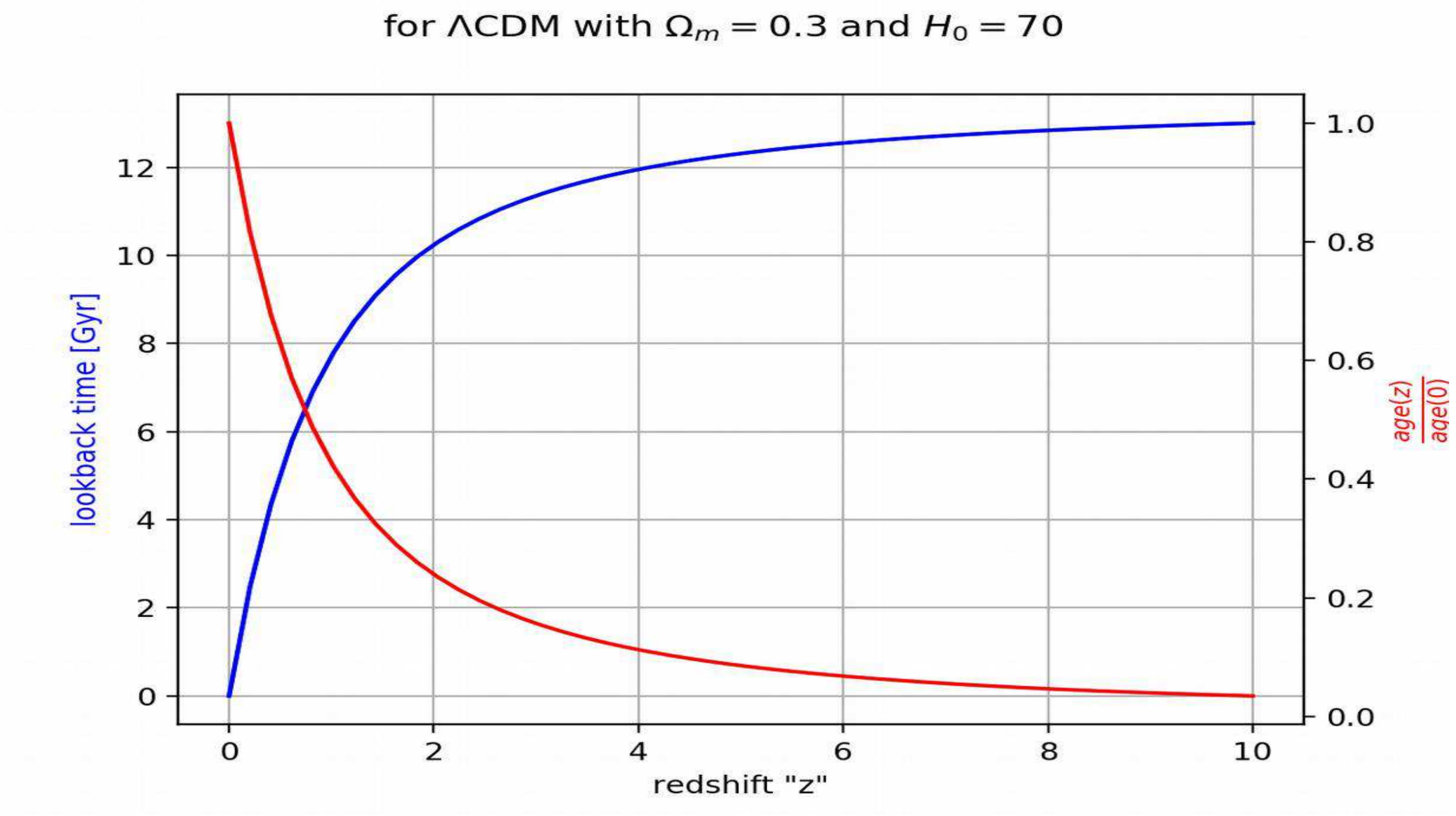
Observational effects

Detection and selection function
Observable (mass proxy)
Mass-observable relations
Redshift determination

theory

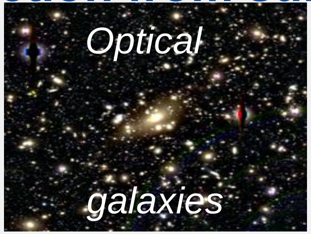


additional


for ΛCDM with $\Omega_m = 0.3$ and $H_0 = 70$
lookback time [Gyr]
$\frac{age(z)}{age(0)}$
redshift "z"
0
2
4
6
8
10
12
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10

Constructing a cosmological cluster sample

Detection from survey



Selection function

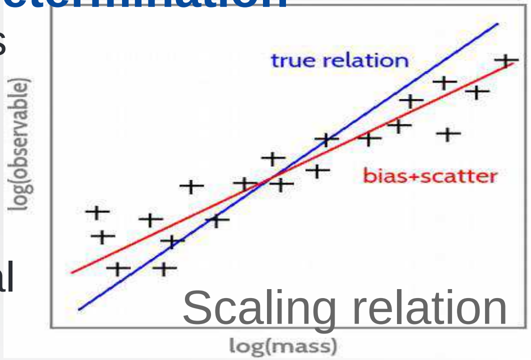
By comparison to simulations and other instruments

LSST cluster cosmo sample

Mass determination

Observable: richness (# of galaxies)

Mass calibration via gravitational lensing (+ scatter via external data)



Redshift determination

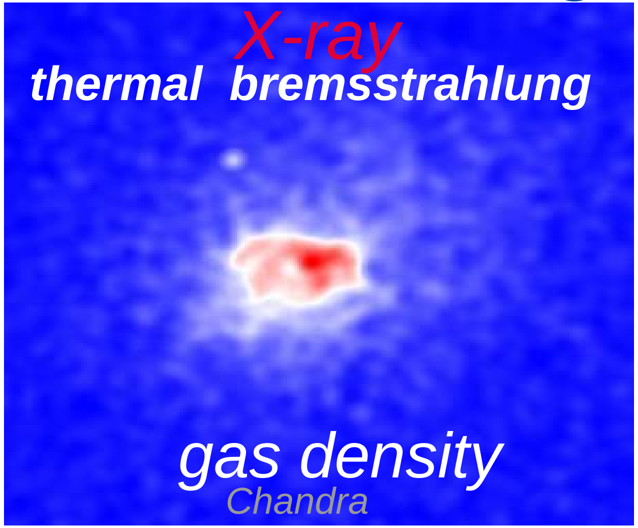
internaly : photo-z calibrated with spectro

The selection function and the mass determination are critical aspects

Exploiting multi-wavelength synergies

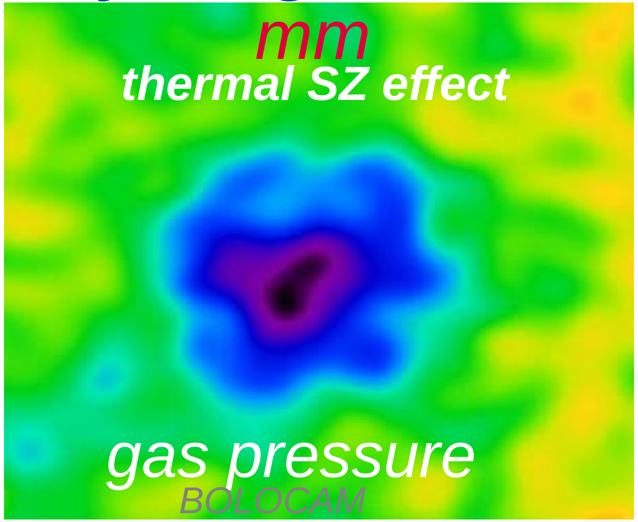
- ✔ down to low masses
- ✔ *z* determination from photometry
- ✔ mass from shear & magnification

- ✗ projection effects
- ✗ miscentering



- ✔ trace virialised structure
- ✔ mass from hydrostatic eq.

- ✗ AGN contamination
- ✗ redshift from spectro only



- ✔ no redshift dimming of flux
- ✔ trace virialised structure
- ✔ ~ mass selected samples

- ✗ radio source and CIB/CMB contamination
- ✗ no redshift determination

Comparing the properties of clusters at different wavelengths is critical