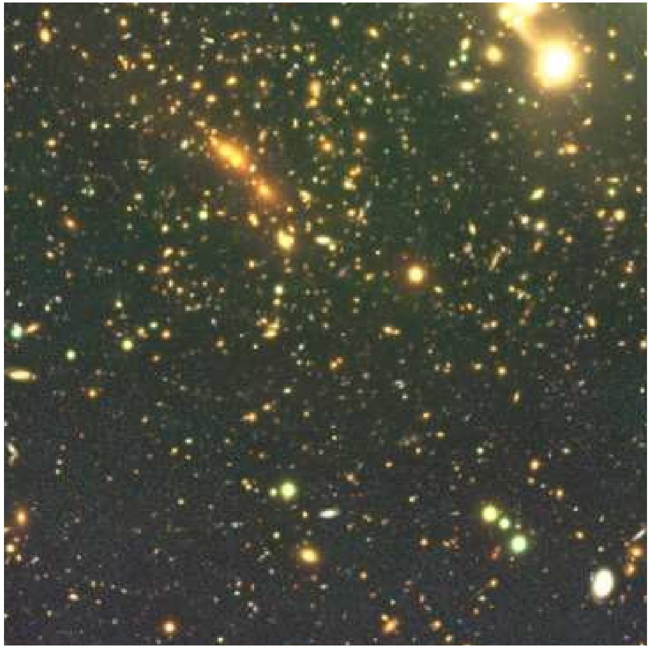
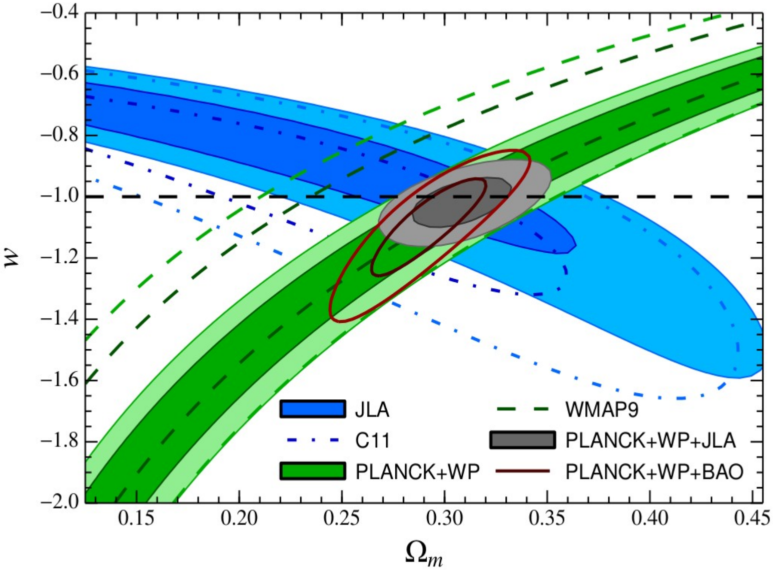
Imaging Dark Energy

Pierre Astier (LPNHE/IN2P3/CNRS, SU, Paris)



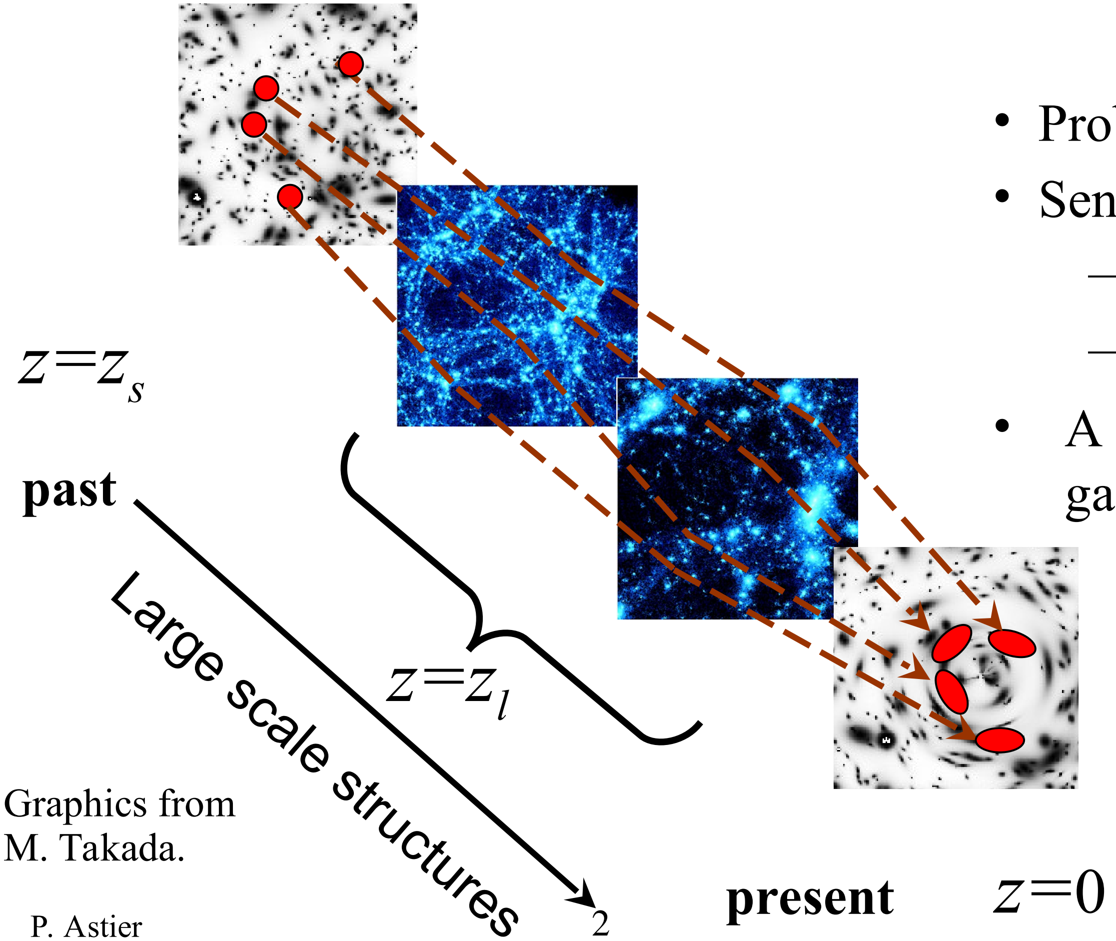
International Conference on the Physics of the Two Infinities



Kyoto, March 2023

Cosmic shear

- Distortion of background galaxy shapes due to intervening masses.
- Probes matter (dark or not)
- Sensitive to :
  - structures
  - distances
- A ~1% effect : one needs millions of galaxies to measure it.



Graphics from M. Takada.

Observables :
- ellipticity
- orientation

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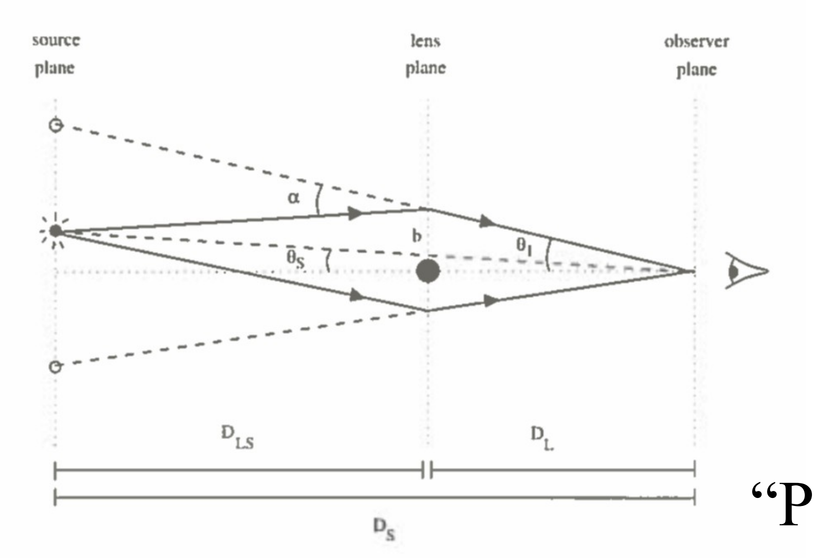
Relation with the sources of gravitation



Cosmological physics (Peacock).

$$\theta_I - \theta_S = \frac{D_{LS}}{D_S}\alpha = \nabla_\theta \psi(\theta_I)$$

Deflection potential

"Poisson equation" :

$$\nabla^2_\theta \psi = \frac{8\pi G}{c^2}\int \frac{D_L D_{LS}}{D_S}\rho d\ell$$

- All observables derive from a scalar field: the "projected mass"
- Shear correlations are related to mass density correlation function

What can we learn from cosmic shear ?

$$H^2(z) = H_0^2\left[\Omega_M(1+z)^3 + \Omega_{DE}\right]$$

$$\delta \equiv \frac{\delta\rho}{<\rho>}$$

$$d(z) = \int_0^z \frac{dz'}{H(z')}$$

$$\ddot{\delta} + 2H(z)\dot{\delta} = 4\pi G\rho_M\delta$$

- Constrain Dark Energy:
  - From the redshift evolution of density contrast
  - From distances that enter into the distortion prediction
- Test GR on large scales: (> 10^{12} solar system scale)
  - Test if the evolution of structure formation and the expansion history (from shear, supernovae or BAO) tell the same story.
  - Requires shear in redshift slices.

Observations requirements

- A lot of galaxies:
  - The signal is ~ 1% ellipticity, galaxy images have a ~25% ellipticity
  - This implies deep images using a wide-field imager on a large telescope
- Stars (!):
  - Required to get the shape distortions due to the telescope & the atmosphere. Known as the Point Spread Function (PSF).
- (Photometric) redshifts:
  - The expected shear signal depends on the source redshift.
  - Need multi-band imaging (typically 5 bands or more) to infer redshift.

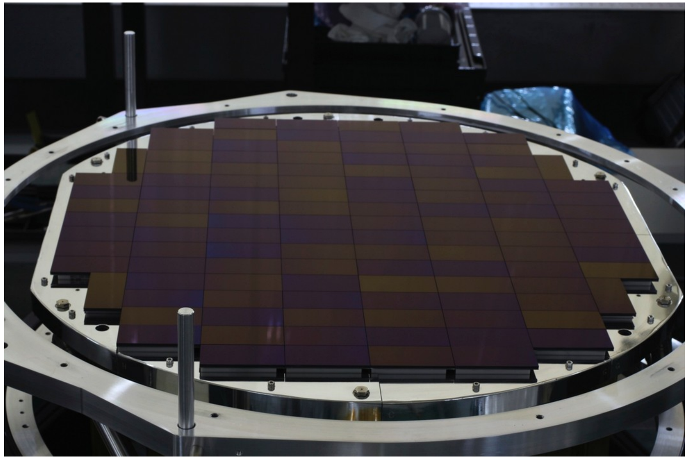
Cosmic shear: the three threats

- The shear estimator:
  - One cannot express uniquely the expected galaxy image given the shear → a whole suite of estimators, challenges, ….
  - The whole thing relies on empirical (mostly ad hoc) PSF estimation from stars. One extra difficulty: the brighter-fatter effect.

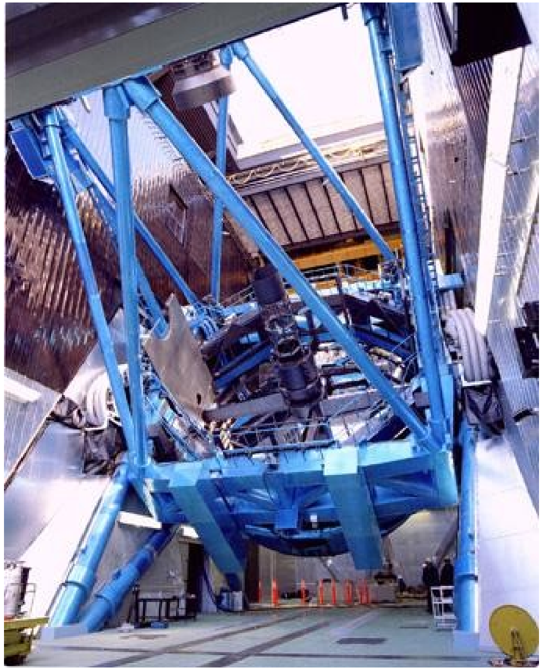
- Intrinsic alignments: (neighbor galaxies may align naturally)
  - Accounted for using ad hoc models, but there is safe information in cross-correlations of shear at sufficiently different redshifts.

- Photo-z: (guessing galaxy redshifts from colors)
  - Calibration from a sample of spectroscopic redshifts is the life line.
  - DESI, PFS and 4Most will hopefully deliver those en masse

Hyper Suprime-Cam on the Subaru telescope



104 2kx4k CCDs: 840 Mpix
1.8 deg^2
First light in 2012



8.2 m primary mirror on the Mauna Kea

The Subaru Strategic Program:

330 nights (done)
3 data releases (17,19,21)

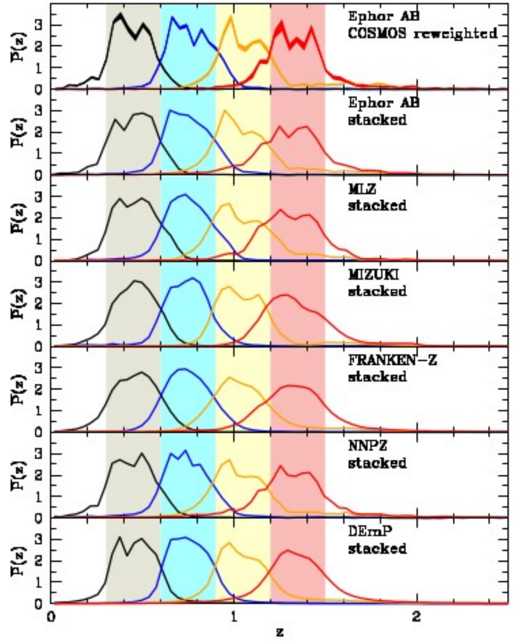
	Area (deg^2)	bands
Wide	1400	grizy
Deep	27	grizy+4NB
Ultra-deep	3.6	grizy+4NB

First HSC cosmic shear analysis

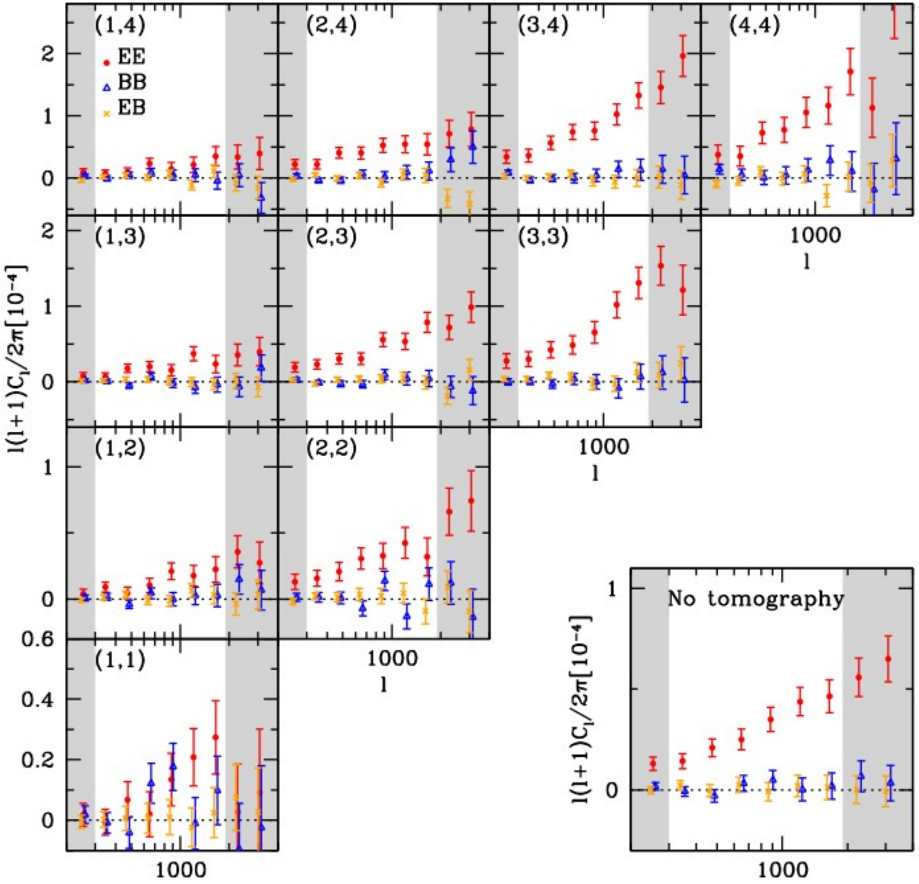
. Japan (2019) 71 (2), 43 (1–44)
doi: 10.1093/pasj/psz010
ublication Date: 2019 March 6

Cosmology from cosmic shear power spectra with Subaru Hyper Suprime-Cam first-year data

Chiaki Hikage,[1,*] Masamune Oguri,[1,2,3] Takashi Hamana,[4] Surhud More,[1,5] Rachel Mandelbaum,[6] Masahiro Takada,[1] Fabian Köhlinger,[1] Hironao Miyatake,[1,7,8,9] Atsushi J. Nishizawa,[7,8] Hiroaki Aihara,[1,3] Robert Armstrong,[10] James Bosch,[11] Jean Coupon,[12] Anne Ducout,[1]



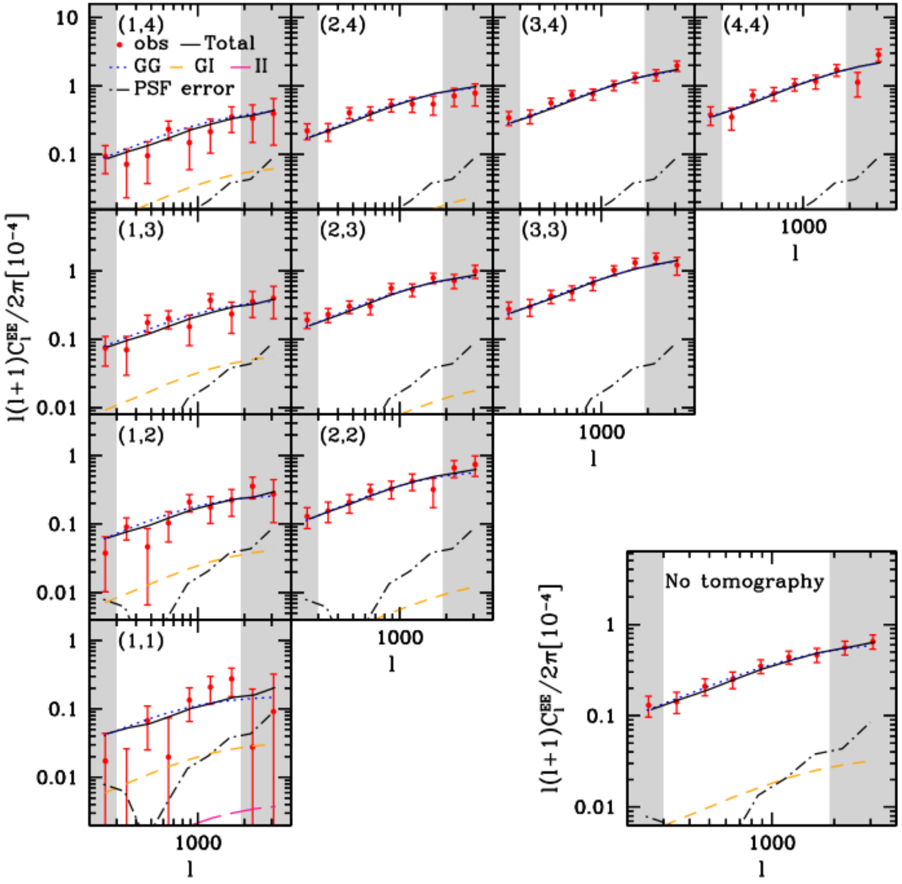
Assessment of the redshift distributions of photo-z bins

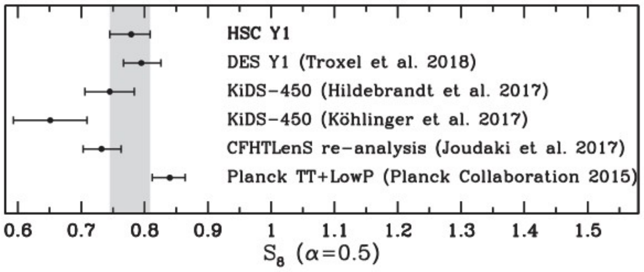


Basic figures:

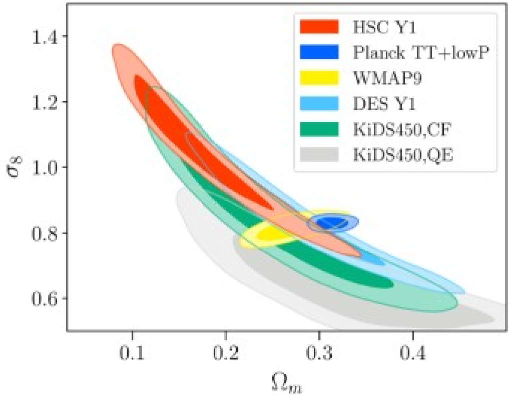
- 137 deg^2
- i<24.5
- 17 galaxies/arcmin^2

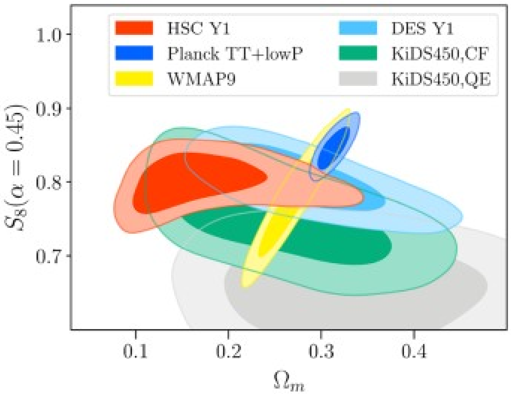
Measured shear ~~correlations~~ cross-power spectra.
B modes compatible with 0



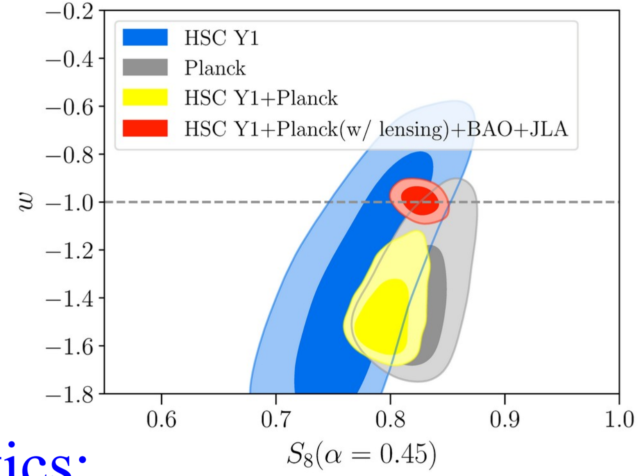


P.





(1809.09148,
See also
1906.06041)



Main systematics:

shear scale : ~1%

PSF size : 1-10% of shear signal

Photo-z : ~ 0.01-0.04 *(1+z)

Second SSP cosmic shear sample

- 3rd year shear catalog is out : 2107.00136
  - 433 deg^2, i<24.5, ~20 galaxies/arcmin^2
  - Improved PSF modeling and tests
  - Systematics within bounds for the statistics in hand.
  - Cosmology expected very soon.

The three-year shear catalog of the Subaru Hyper Suprime-Cam SSP Survey

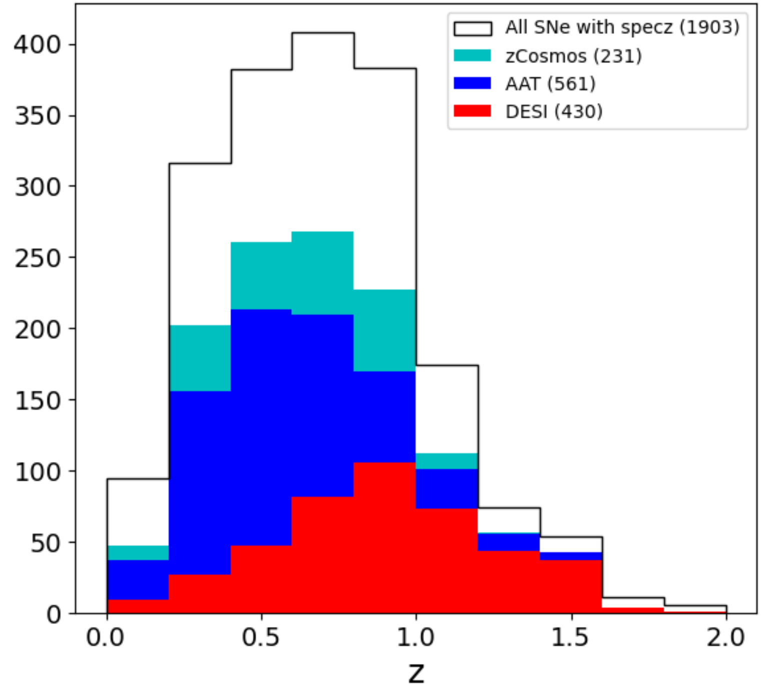
Xiangchong Li[1,2,11], Hironao Miyatake[3,4,5,1,6], Wentao Luo[7,1], Surhud More[8,1], Masamune Oguri[9,2,1], Takashi Hamana[10], Rachel Mandelbaum[11], Masato Shirasaki[10,12], Masahiro Takada[1], Robert Armstrong[13], Arun Kannawadi[14], Satoshi Takita[15,10], Satoshi Miyazaki[10,16], Atsushi J. Nishizawa[4], Andrés A. Plazas Malagón[14], Michael A. Strauss[14], Masayuki Tanaka[10,16] and Naoki Yoshida[1,2,9]

Supernova Strategic Program (HSC again)

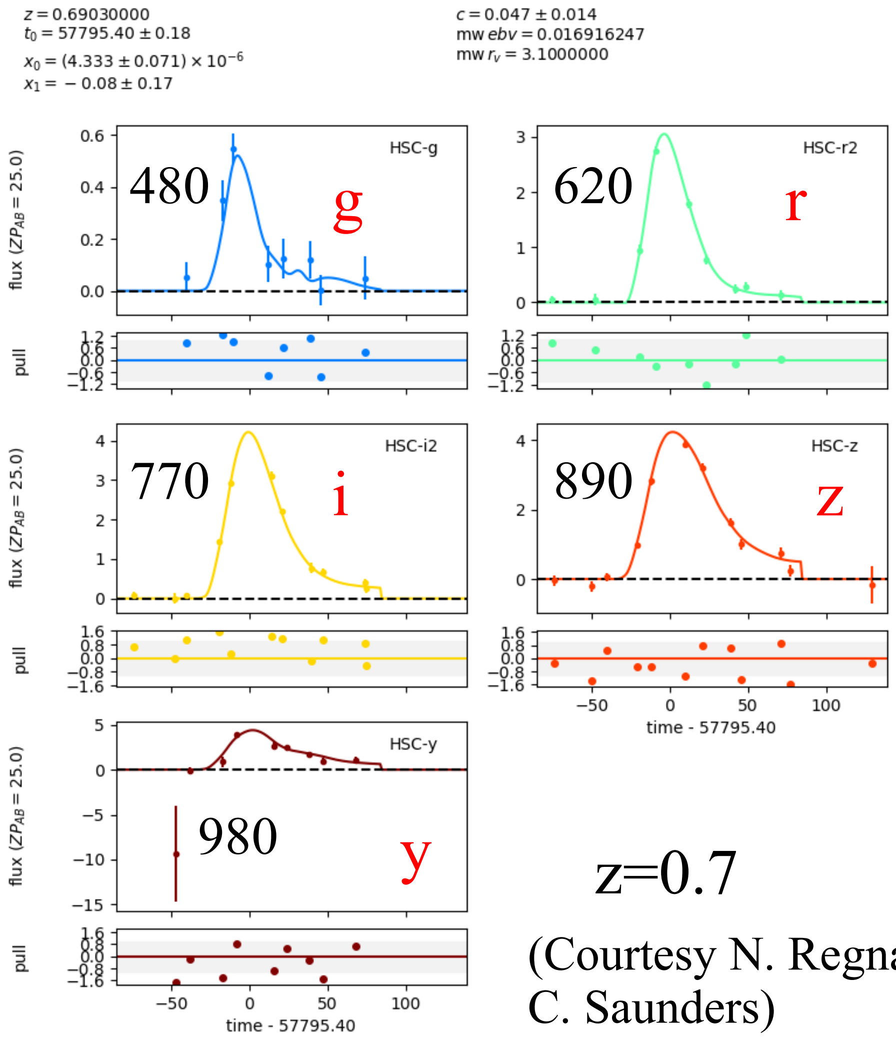
- Use the SSP ultra-deep sequenced survey to detect and measure type Ia supernovae (mostly on 2 HSC pointings).
- The observing plan allows to detect events at z>~1.3
- For those, estimating distances requires observer NIR bands (>1μm)
- An HST large program was awarded for NIR photometry (PI: N. Suzuki)
- Photometry observations are over, host galaxy redshifts are underway (from Subaru, AAT, DESI, and archives). In practice, bright events get redshifts before faint ones.

Supernova light curves

Spectroscopic redshift campaigns have been successful. Most of the redshifts are host galaxy redshifts.

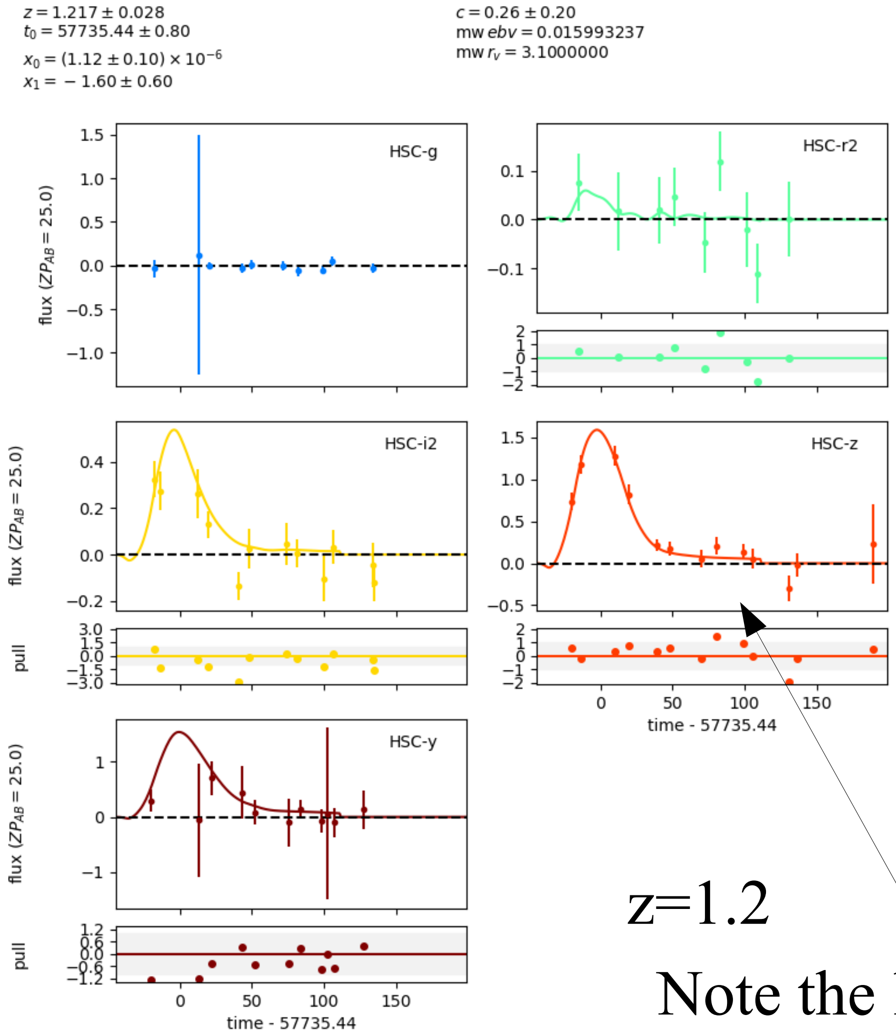


(Courtesy N. Suzuki)

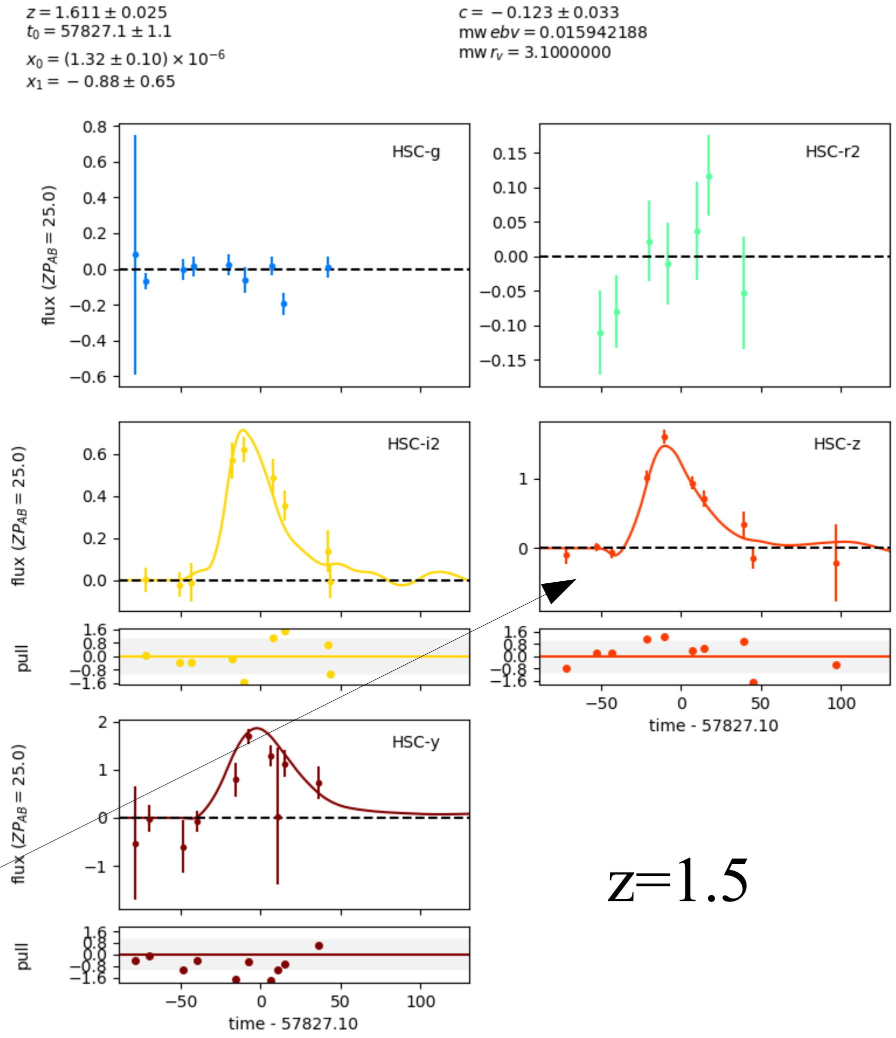


z=0.7

(Courtesy N. Regnault, C. Saunders)



z=1.2



z=1.5

Note the large S/N at this high z

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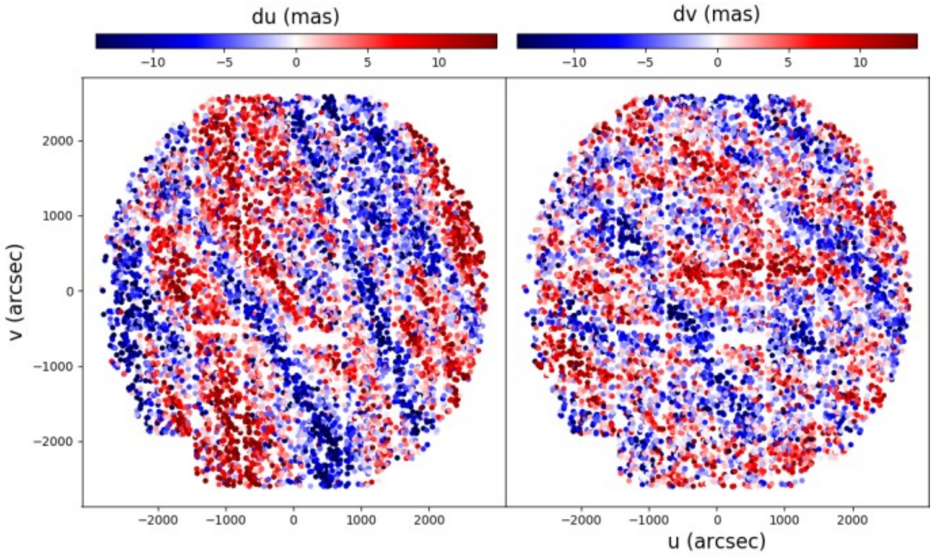
Status of Supernova Strategic Program

- Photometric calibration is solved
- Photometry of supernovae is done
  - including many subtle corrections (non-linearity, brighter-fatter)
- Calibration transfer to supernovae underway
- Do not know yet how many events have good enough lightcurves.
- Expect distances this year.

En route for Rubin

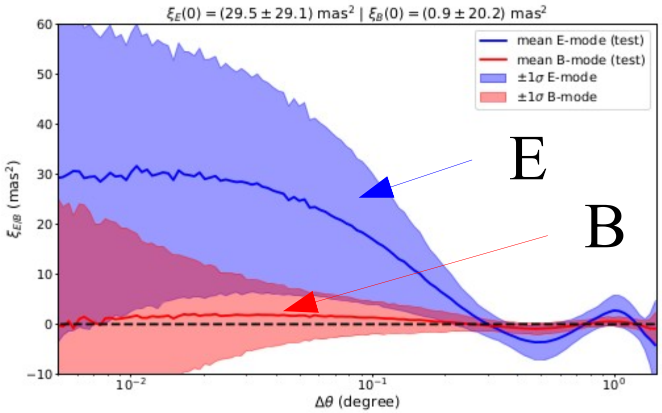
- The SSP data is the best possible training for Rubin/LSST.
- The Dark Energy Survey is also a very active playground from which many developments are being transferred to Rubin.
- Most of the cosmic shear results are obtained with moderate systematics margins: improvements are still needed.
- A few illustrations follow….

Atmosphere also perturbs objects positions (astrometry)

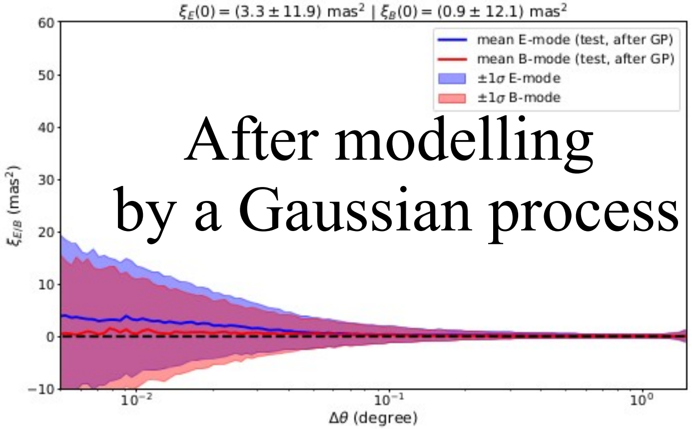


Position offsets (x,y) of
astronomical objects from
a single exposure of
HSC/Subaru (300 s)
→ coherent shifts of ~5 mas

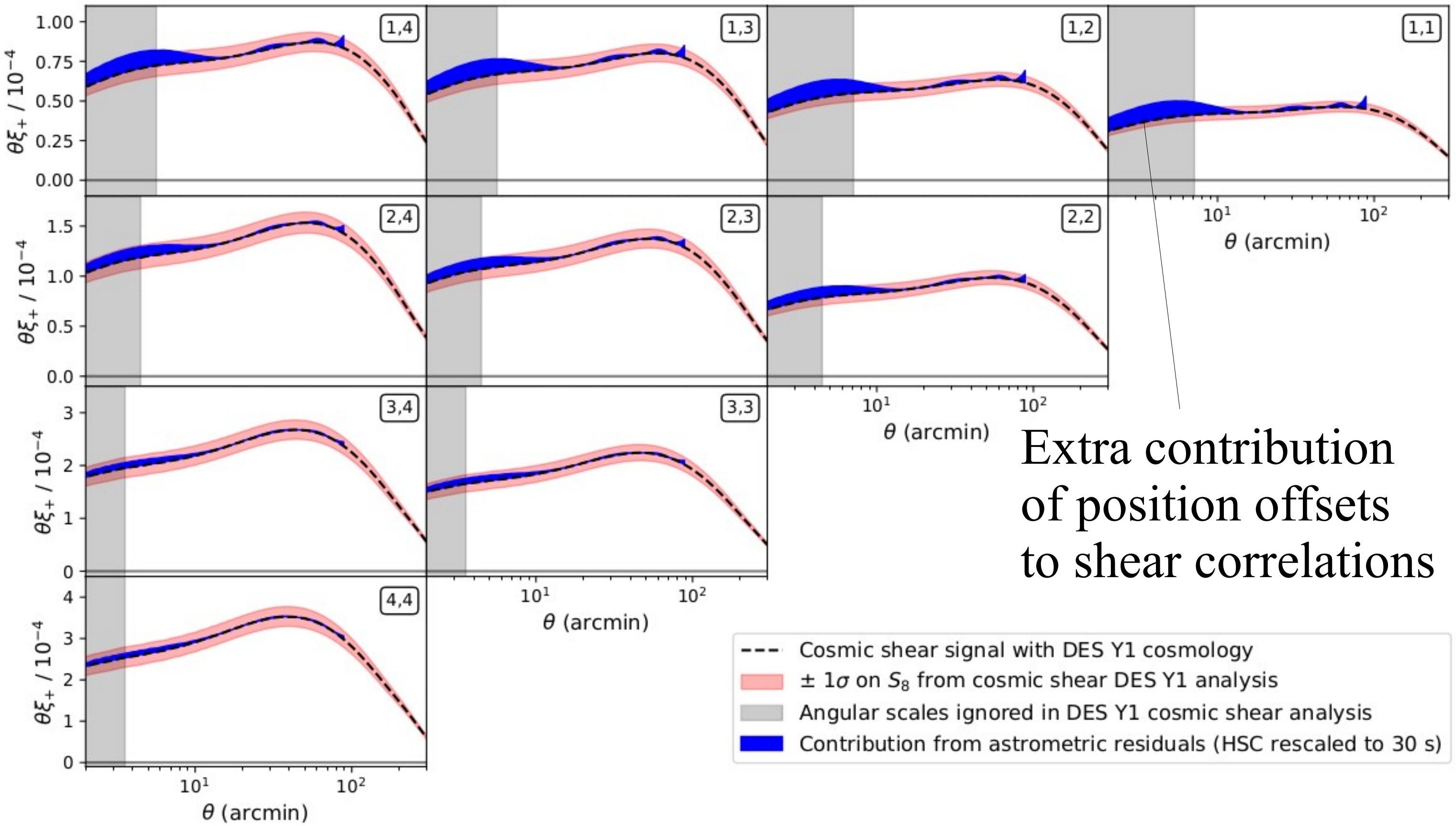
2103.09881



Correlation function:
The absence of B modes
indicates that the
displacement field is the
gradient of a scalar:
the refraction index.



Effect for Rubin ? very large



Extra contribution of position offsets to shear correlations

T_{exp}: 300s → 30 s

The contribution of position offsets to shear correlation is multiplied by 100

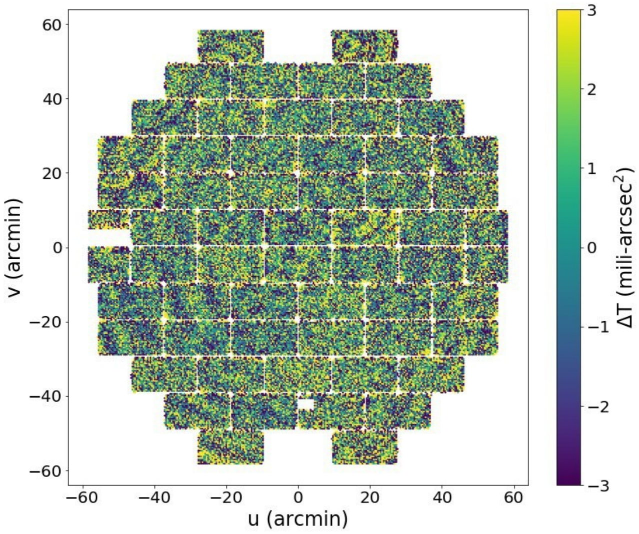
Correction is mandatory

Any shear estimator relies on a PSF model

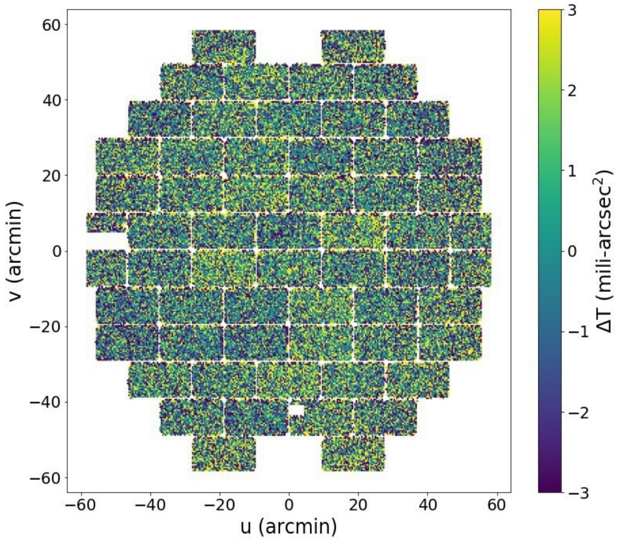
State of the art : PIFF (2011.04409), developed for DES/LSST
- Introduced for DES year 3 shear analysis.
- Models optical distortions from physics models
- Models atmospheric distortions using Gaussian processes
- Spurious shear correlations reduced by a factor of 10 w.r.t DES year 1.

Average PSF size residuals

Standard way



Gaussian process interpolation



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The brighter-fatter effect

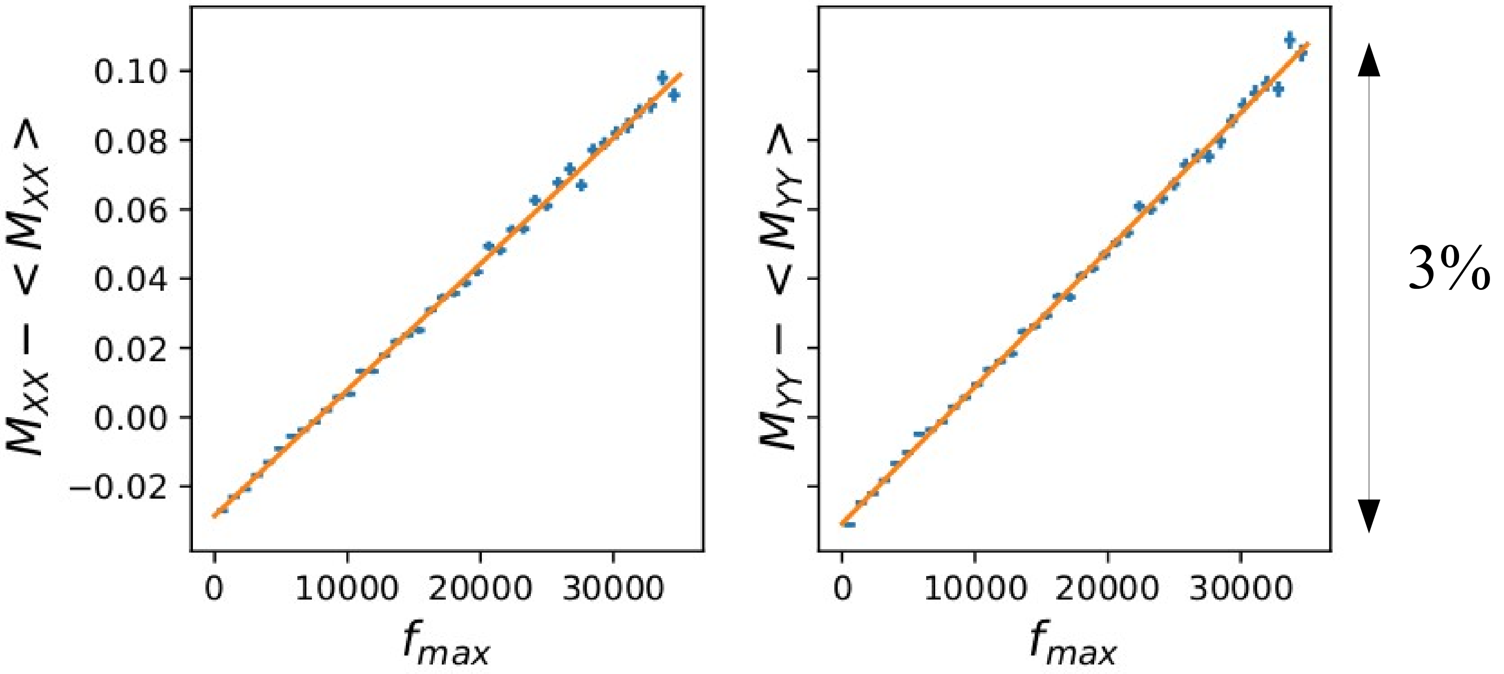
Star images on CCDs are not self-similar with flux

One cannot safely use bright stars to model the system response for faint objects

Killer for at least cosmic shear and supernovae

Due to interactions of charges in the CCD

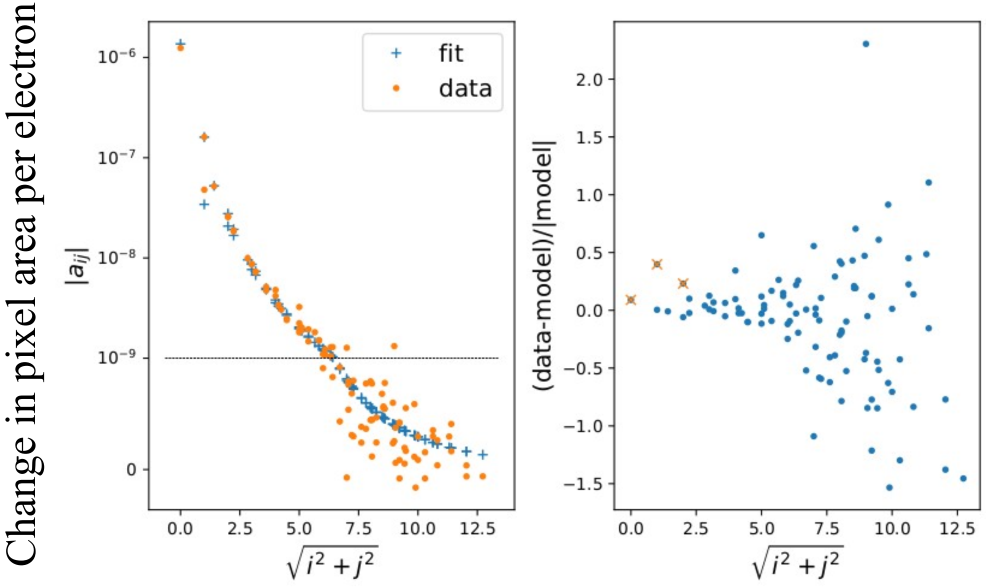
Variation of second moments of stars as a function of peak flux



Measurement on HSC.

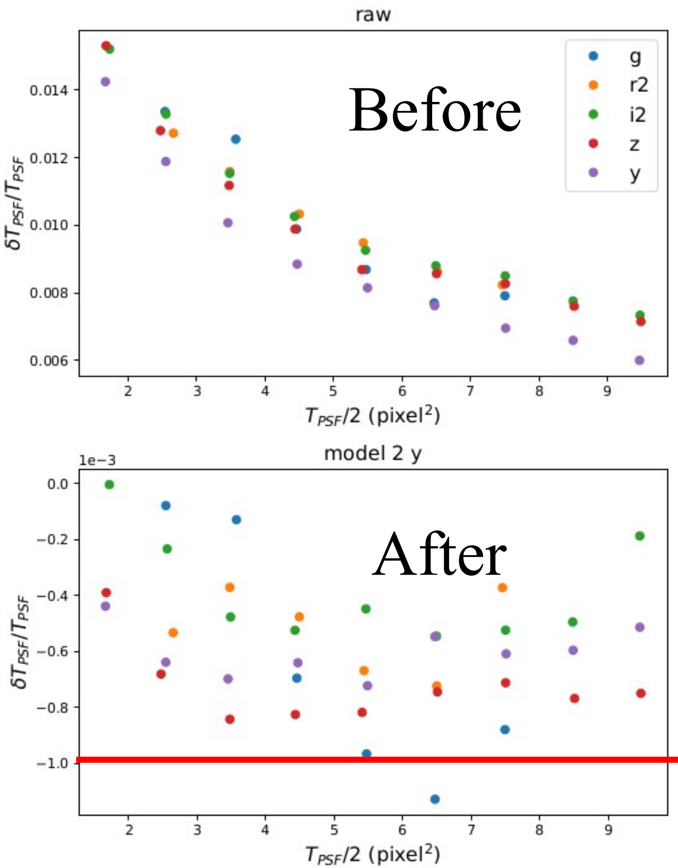
1: Derive from flatfield statistics the changes in pixel area due to charges stored in the CCD.!

2: Fit an electrostatic CCD model:



2301.03274

3: Correct HSC science images and check:



Relative PSF sizes

LSST 10 years requirement

Image quality

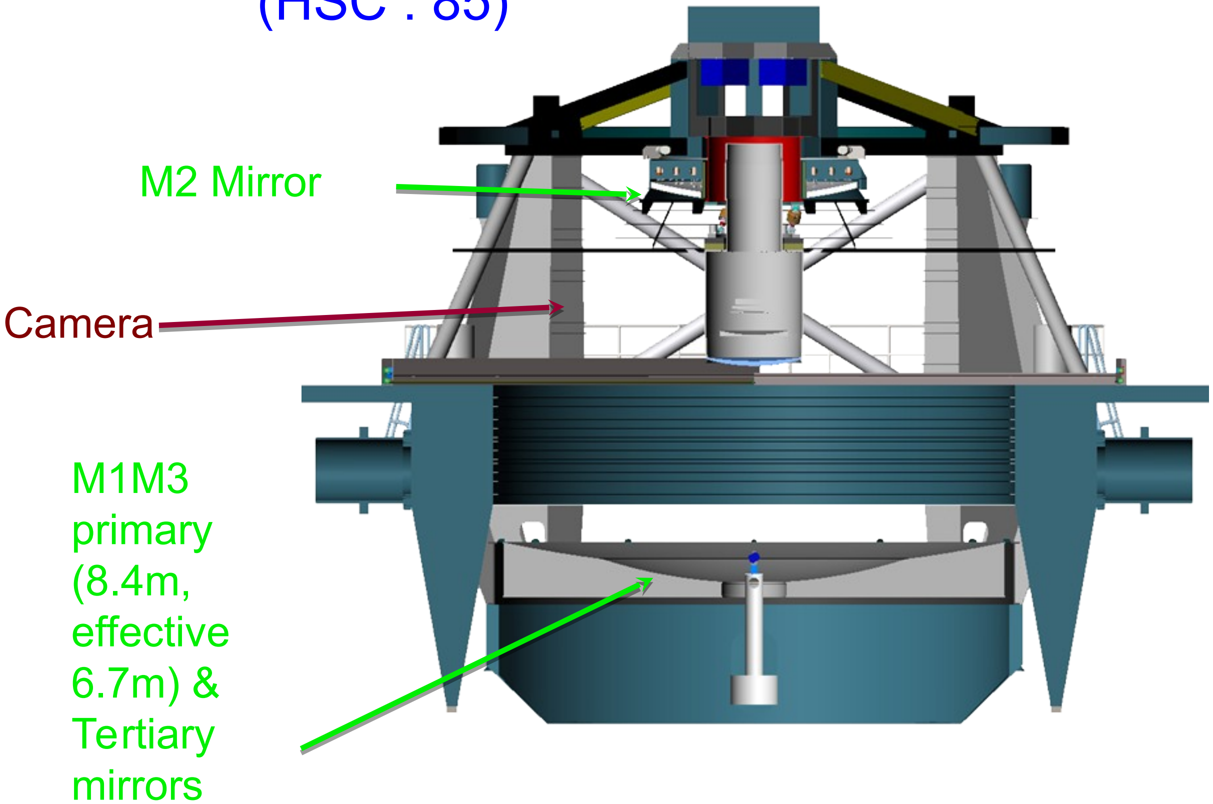
Rubin observatory (aka LSST) in a nutshell

- Rubin is an integrated survey system designed to conduct a decade-long, deep, wide, fast time-domain survey of the optical sky. It consists of an 8-meter class wide-field ground based telescope, a 3.2 Gpix camera, and an automated data processing system.
- Over a decade of operations the Rubin survey will acquire, process, and make available a collection of over 5 million images and catalogs with more than 37 billion objects and 7 trillion sources. Tens of billions of time-domain events will be detect and alerted on in real-time.
- Rubin will enable a wide variety of complementary scientific investigations, utilizing a common database and alert stream. These range from searches for small bodies in the Solar System to precision astrometry of the outer regions of the Galaxy to systematic monitoring for transient phenomena in the optical sky. Rubin will also provide crucial constraints on our understanding of the nature of dark energy and dark matter.

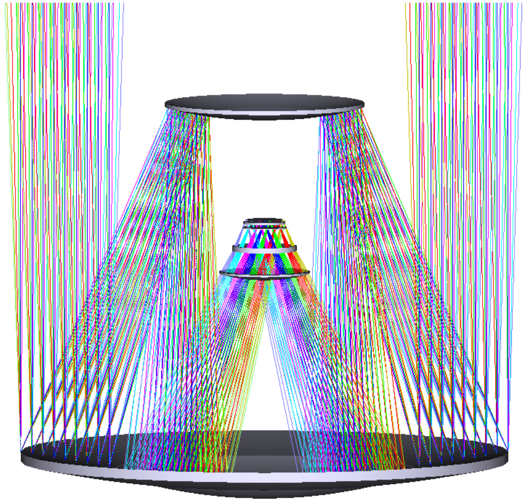
LSST : Wide , Deep and Fast (1/2)

Telescope Mount Enables Fast Slew and Settle

LSST Etendue : 319 m² deg²
(HSC : 85)



Modified Paul-Baker Optical Design



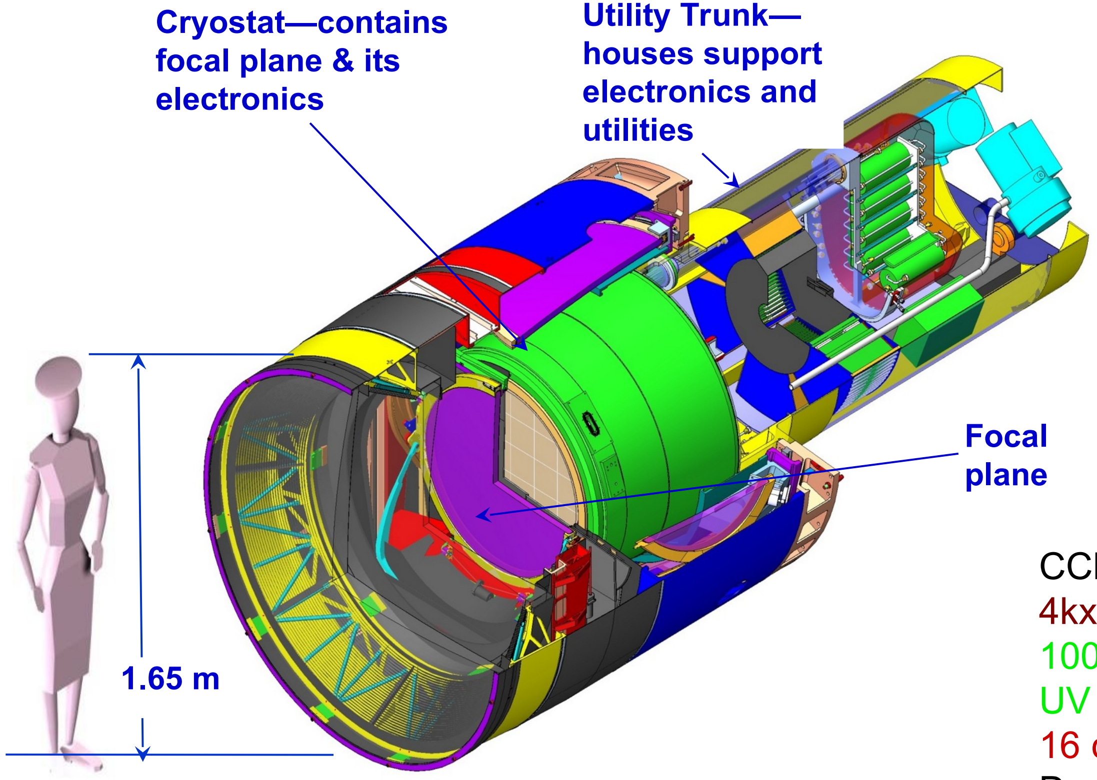
- **Points to new positions in the sky every 39 seconds**
- **Tracks during exposures and slews 3.5° to adjacent fields in ~ 4 seconds**

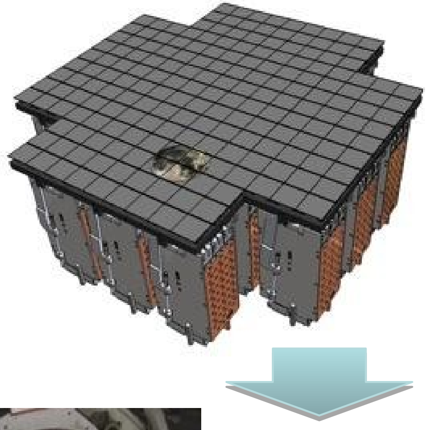
LSST : Wide , Deep and Fast (2/2)

Field of view : 3.5 deg (9.6 deg^2)

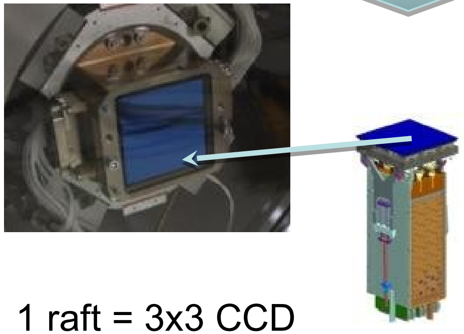
Focal plane diameter : 64 cm ; 189 science CCD (21 rafts)

3024 readout channels; >3 10^9 pixels ; Readout in 2s

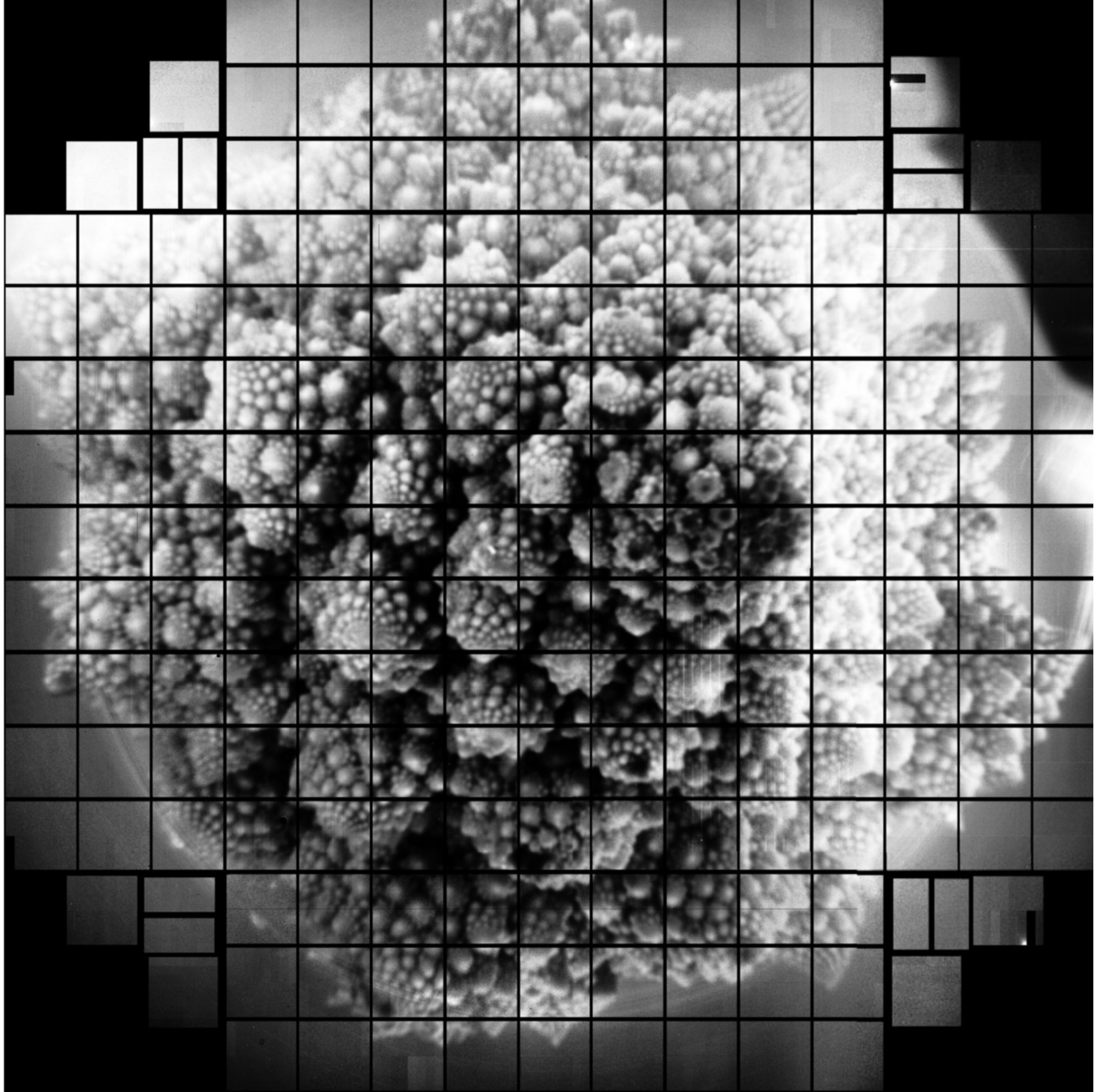




CCD :
4kx4k , 10 µm pixels
100 µm deep depleted
UV to IR sensitive
16 channels output
Designed for LSST



1 raft = 3x3 CCD
150 M pixels

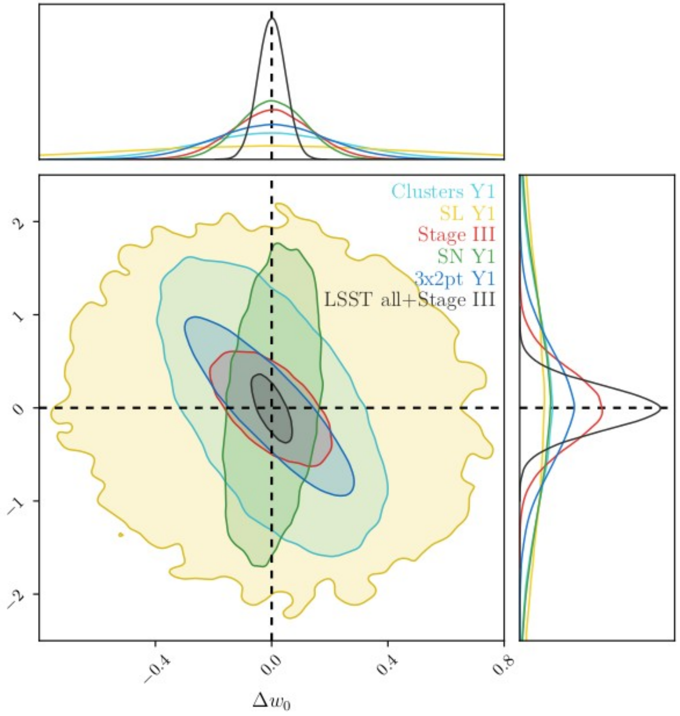


Pinhole image of a romanesco cabbage (!)

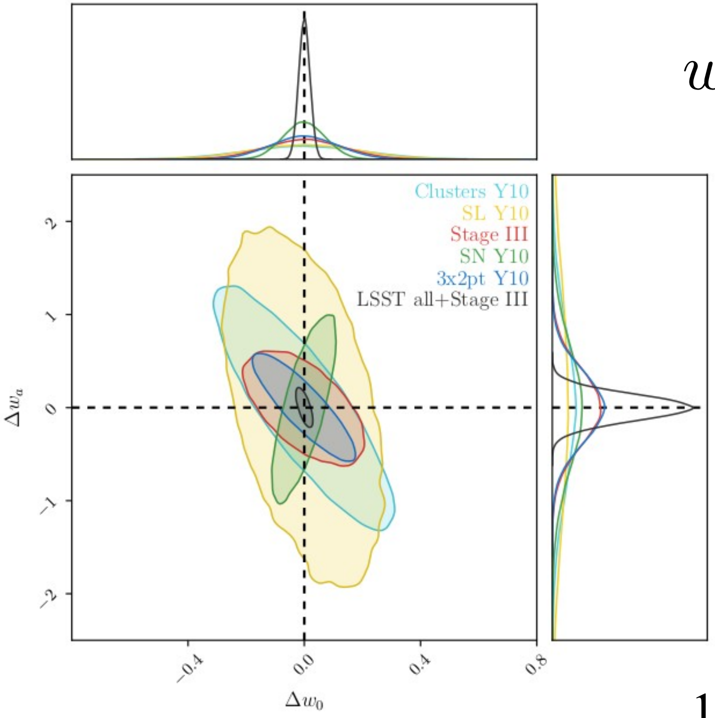
Neighbors:
- CTIO 4m
- Gemini
  south

Anticipated Rubin dark energy constraints

1 year



10 years



Parametrization :

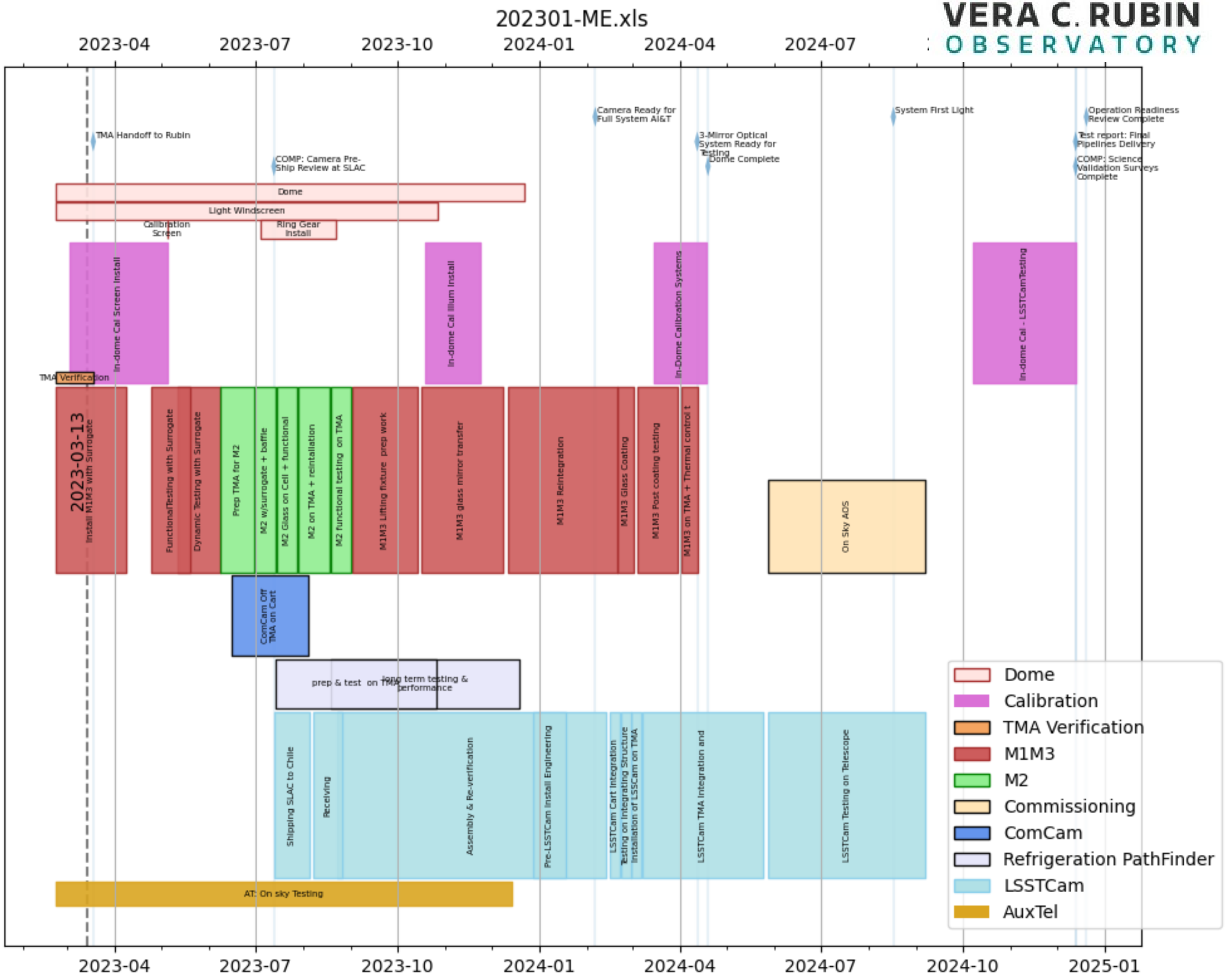
$$w(z) = w_0 + w_a \frac{z}{1+z}$$

Constant w
to ~ 2 %

1809.01669

When is first light ?

- 2023-03-17 :
  - Telescope handoff to Rubin
- 2023-07-12 :
  - Camera Pre-Ship Review
- 2024-02-05 :
  - Camera Ready for Full System AI&T
- 2024-04-11 :
  - 3-Mirror Optical System Ready for Testing
- 2024-04-18 :
  - Dome Complete
- 2024-08-16 :
  - System First Light



From Now to Rubin:

	Now	Goal	How
Photometric Calibration (SNe)	0.5%	0.1%	Laboratory standards
Filter bandpasses (SNe)	1nm	0.1 nm	In situ measurement
Scale error of shear estimator	1%	0.1%	- Higher S/N cut - Image-based simulations
PSF size	~0.3%	0.1%	Physics in PSF model (PIFF)
Photo-z	0.01 to 0.02(1+z)	0.001	- More spectroscopic data - Mix with correlation-based approaches

Summary/conclusions

- Cosmic shear is arguably the best Dark Energy probe, but its full potential is not reached yet
  - New results tend to improve methodologies
- Comparing the histories of expansion and growth rate is a powerful test of GR on large spatial scales.
- Both cosmic shear and distances to supernovae require improvements of reduction methods or calibration sources
- Expectations :
  - SSP year 3 cosmic shear cosmology within weeks.
  - Distances : SSP supernovae and DESI Hubble diagrams in ~ 1 y.
  - First Rubin sky images in ~ 18 months.