Vera Rubin Observatory & LSST
Possible synergies with
21cm Intensity Mapping surveys

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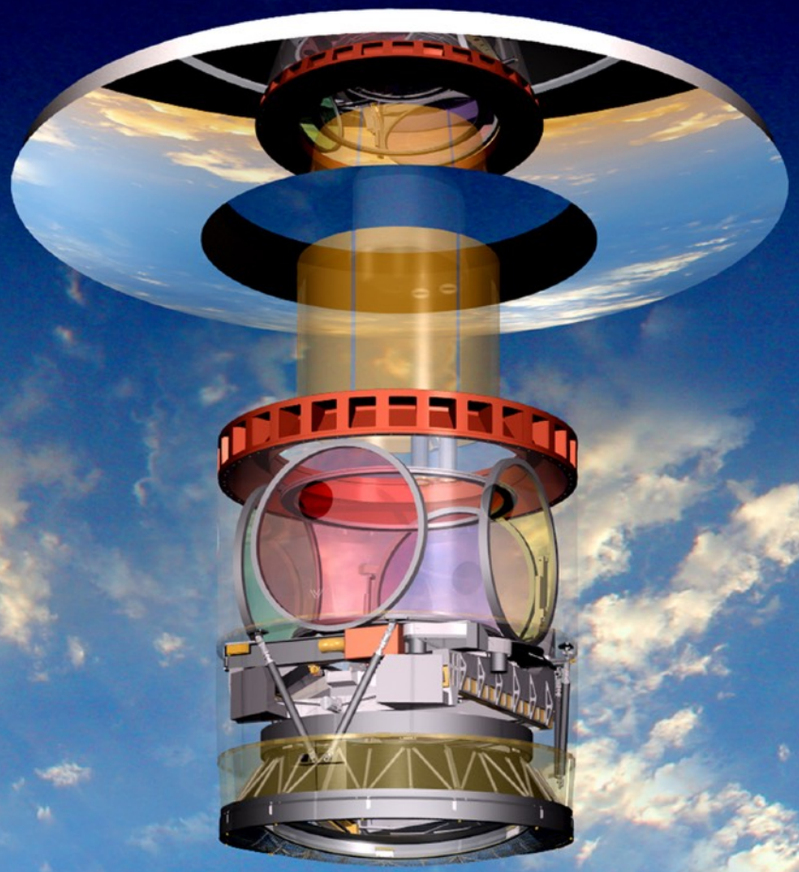
21cm Cosmology Workshop 2023, Northeastern Univ. & NAOC, Shenyang, China

July 2023

- Vera Rubin Observatory
  - Telescope and camera
  - LSST (Legacy Survey of Space and Time) Survey strategy
  - Photometric calibration and AuxTel
- Time domain astrophysics, transients and Fink
- Science with Rubin/LSST
  - Cosmology and DESC
  - Photometric redshifts & BAO's
- Possible synergies with 21cm IM surveys



Vera C Rubin Observatory

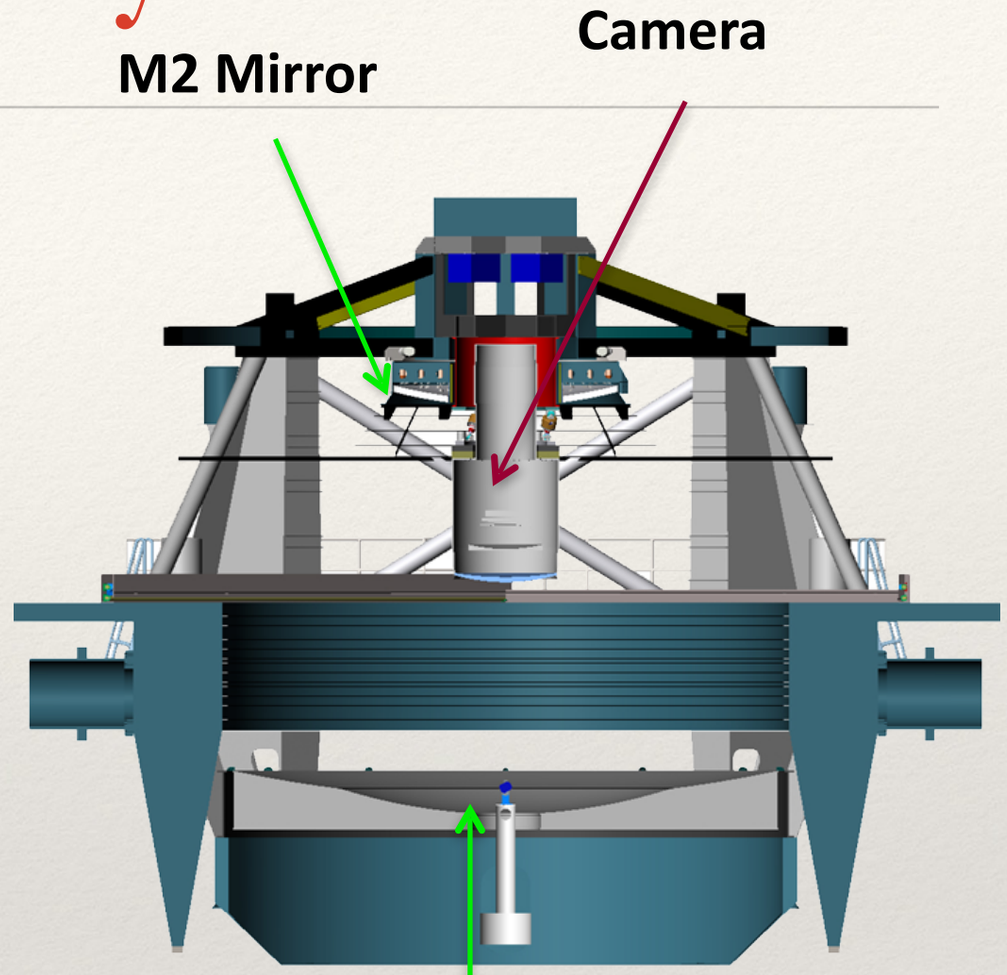
LSST (Legacy Survey of Space and Time)

Wide … Fast … Deep

Rubin Observatory / LSST

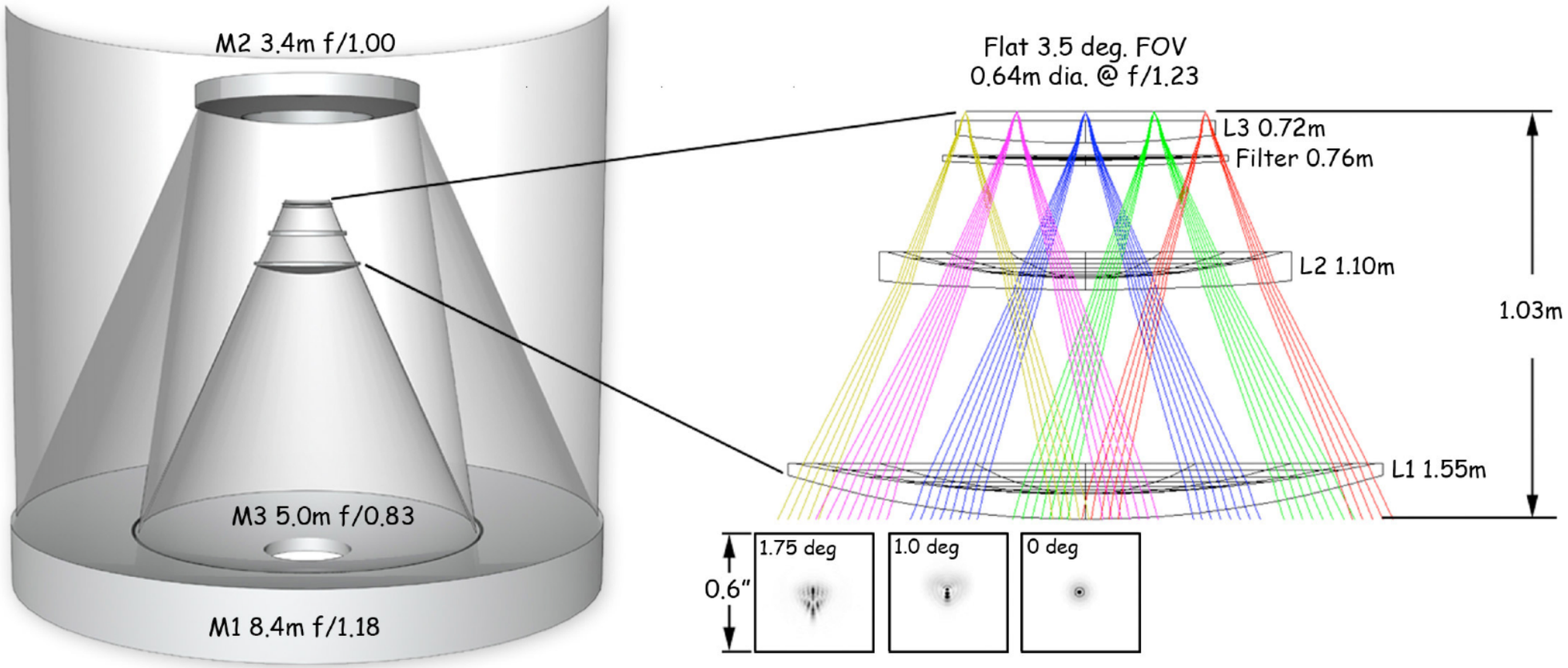
- Optical telescope **8.4 m diameter**
- Wide-field camera : **3.5°, 3.2 Gpixels**
- 6 wide-band filters **u g r i z y**
- Galaxies: r_{lim}=**27.5** after 10 year coadd.
- Final catalogue: **10^{10} galaxies, 10^{10} stars**
- Final database **15 PetaBytes**
- Weak lensing up to **z ~ 3**
- 2,500,000 SNIa up to **z ~ 1**
- BAO: 3.10^9 galaxies up to **z ~ 3**
- Transients with alerts (**2.10^6/night**)
- See LSST science-book in **http://www.lsst.org**

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

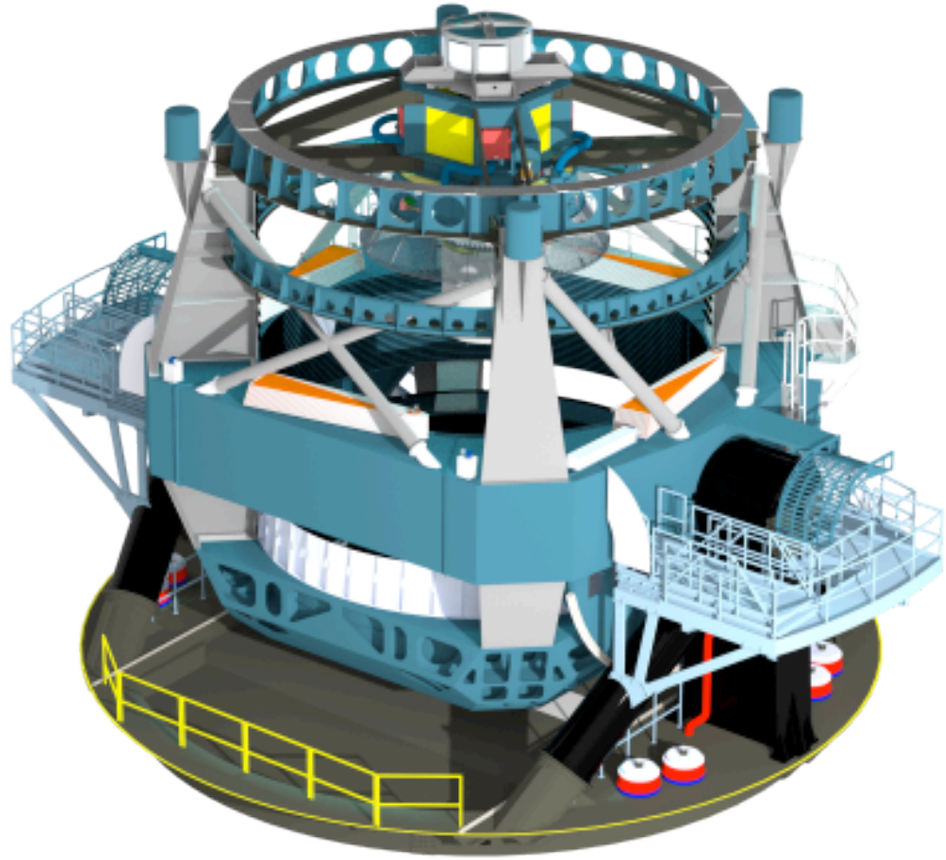


http://www.lsst.org/

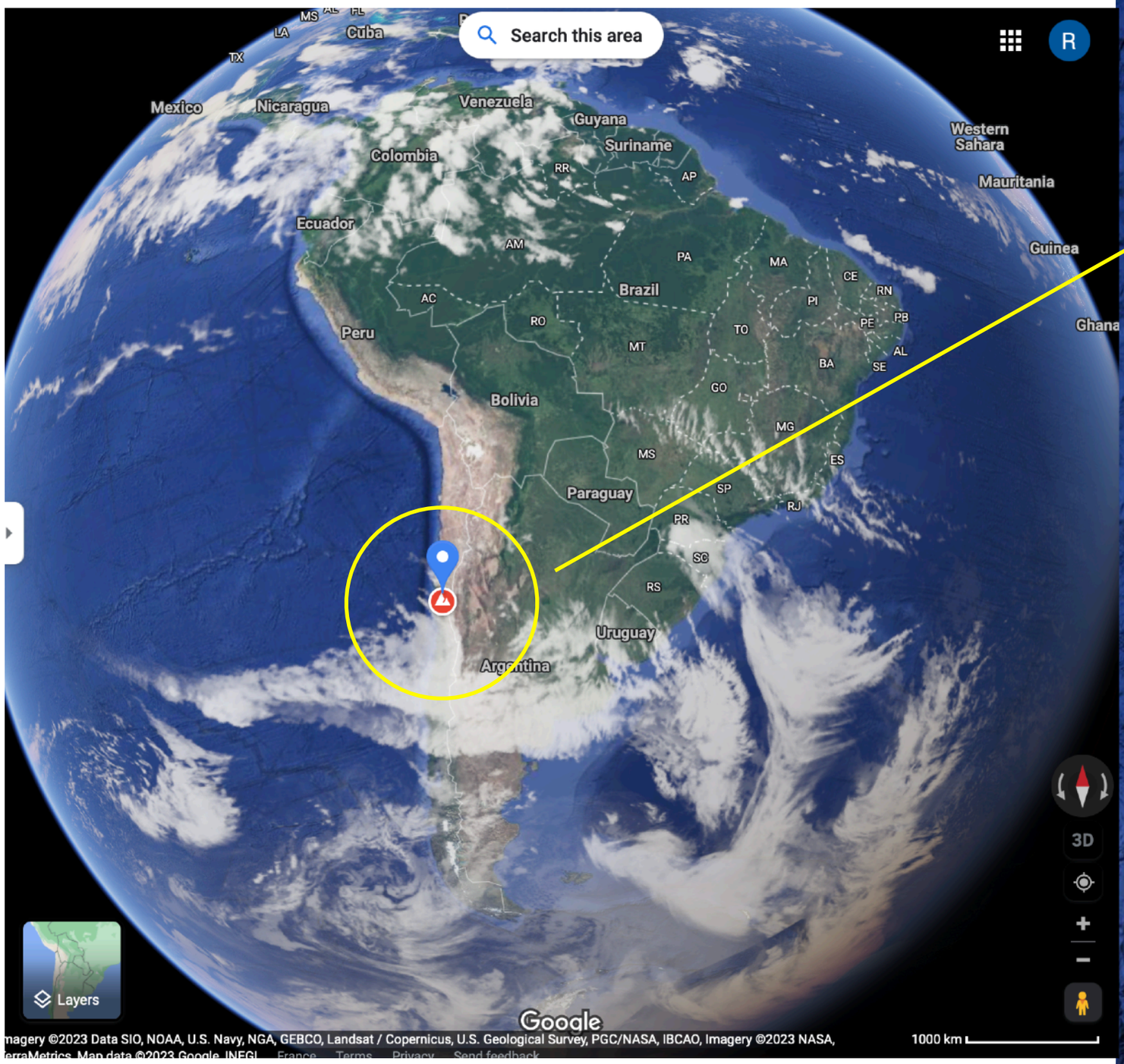
VERA C. RUBIN OBSERVATORY

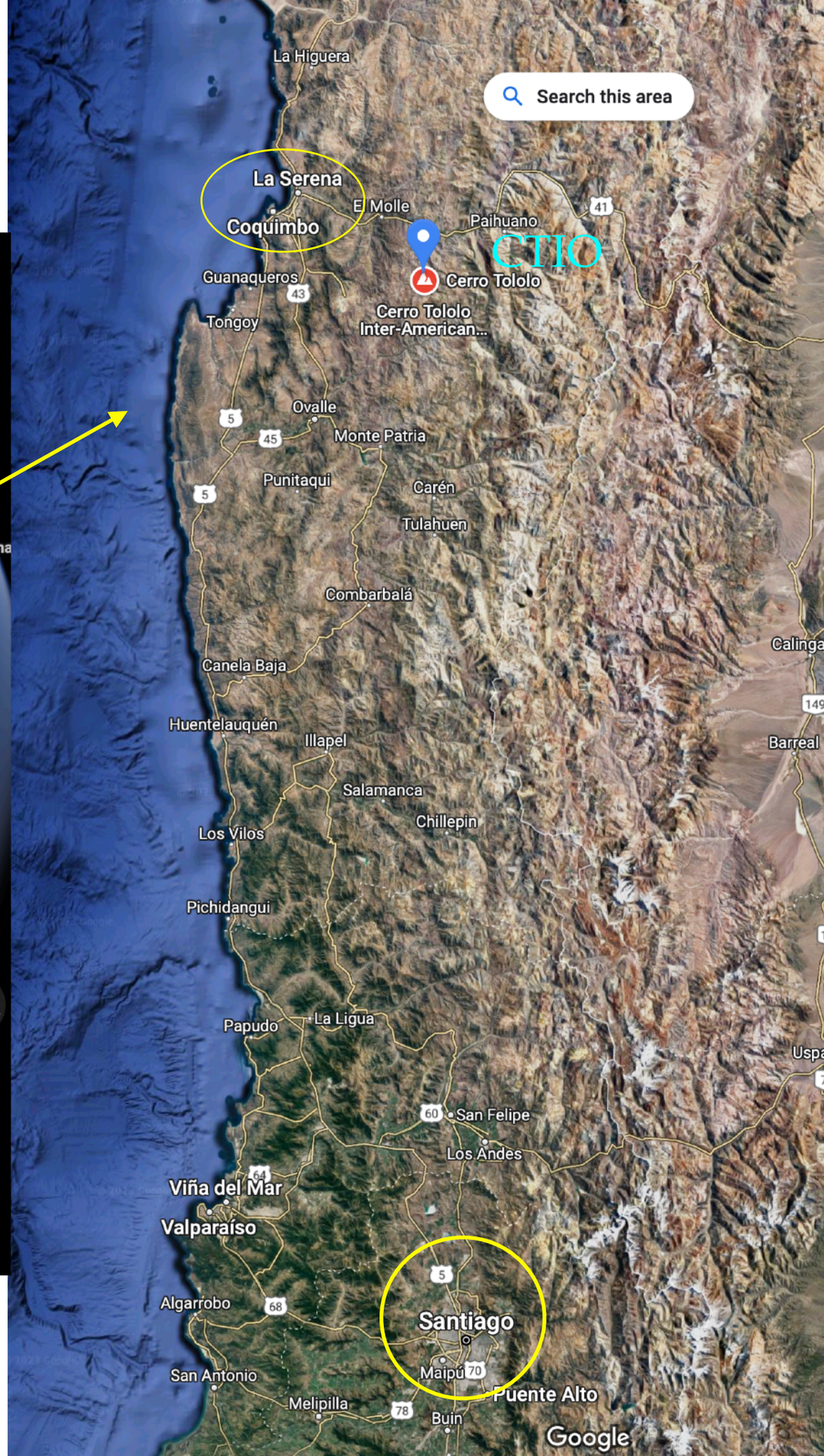


Vera Rubin Telescope
Compact telescope
3 mirror + camera entrance lens
With M1-M3 on the same substrate
Very large field of view



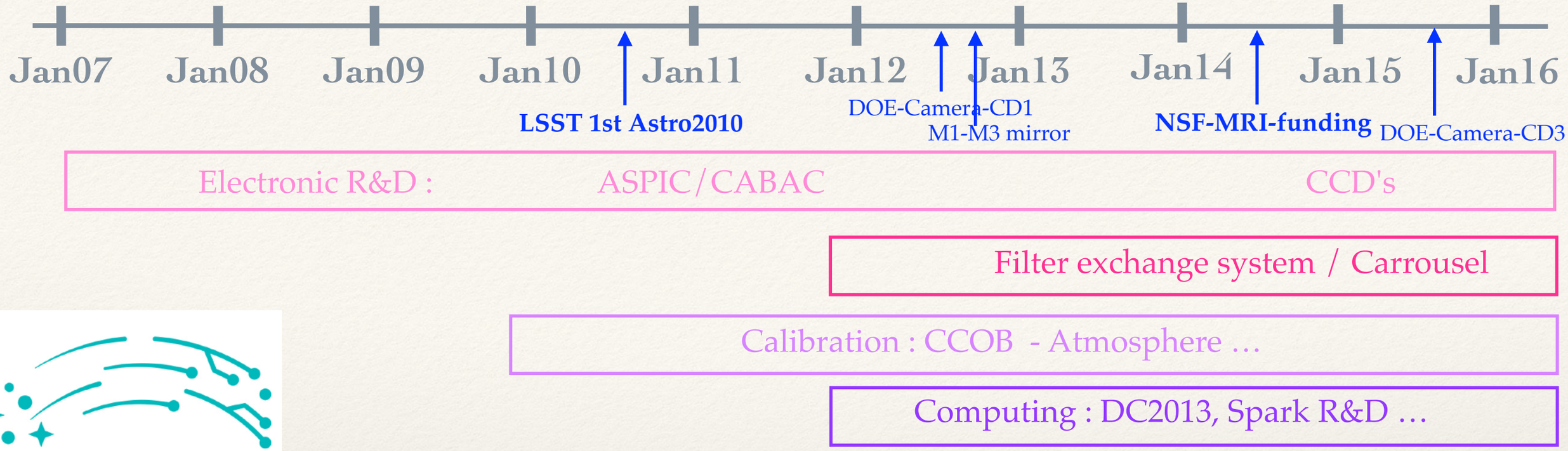
VRO at Cerro Pachon, in Chile





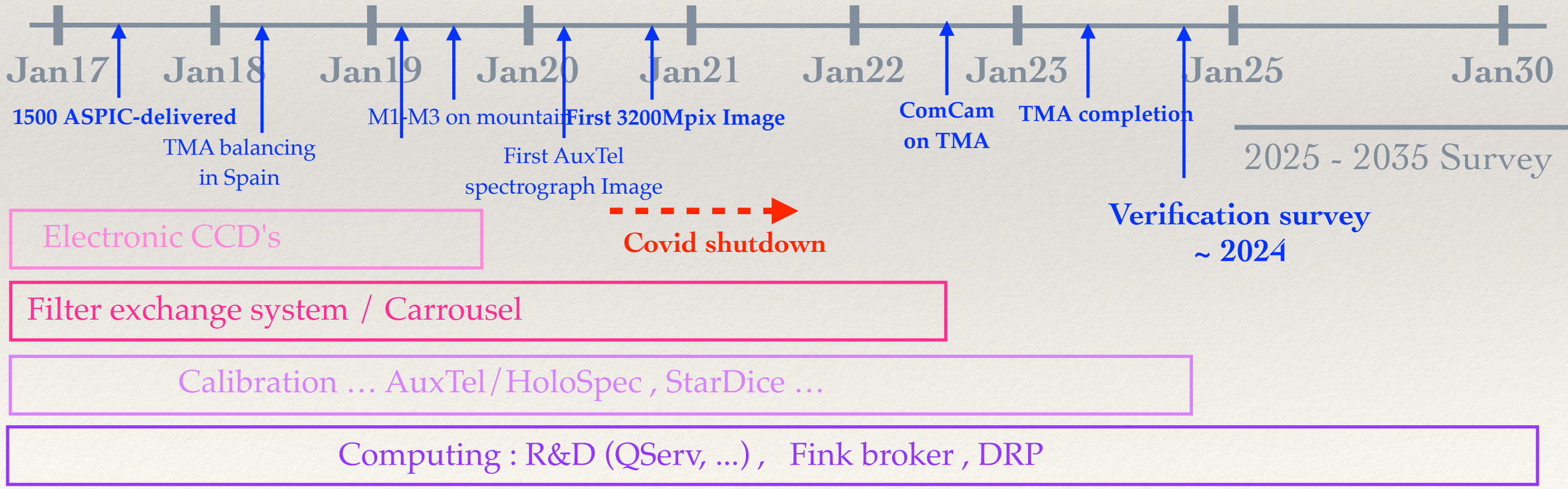
VRO at Cerro Pachon, in Chile

Drone view (2021)



Rubin / LSST development history

(A French biased view - boxes : French contributions)

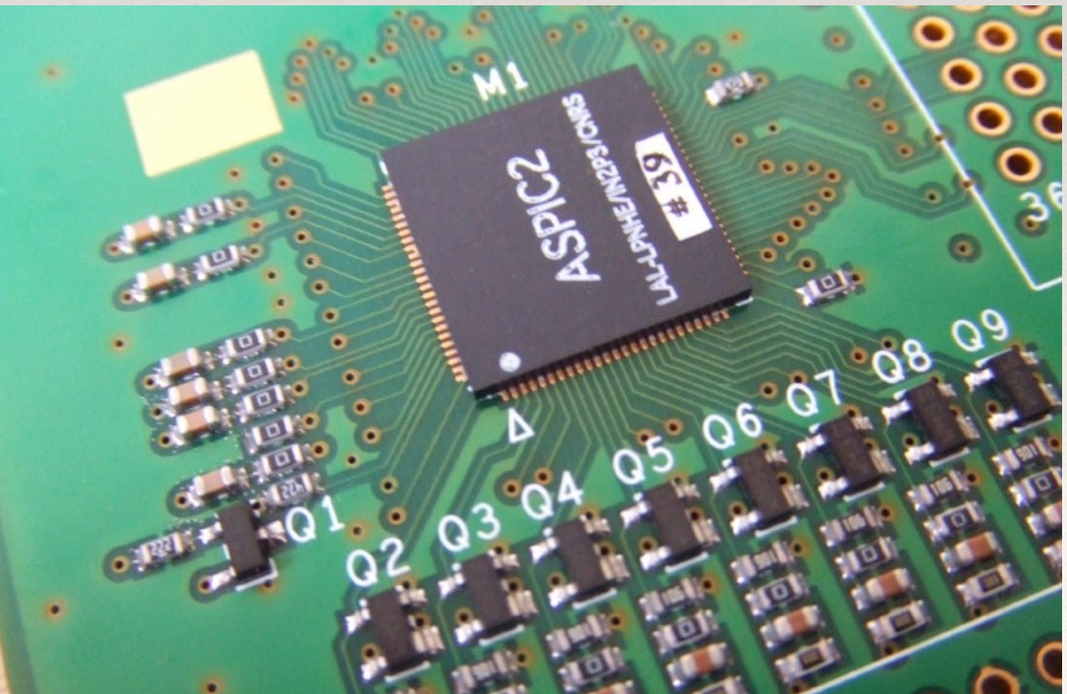


Check Rubin/LSST project site :
https://project.lsst.org/blogs/lsstpo#

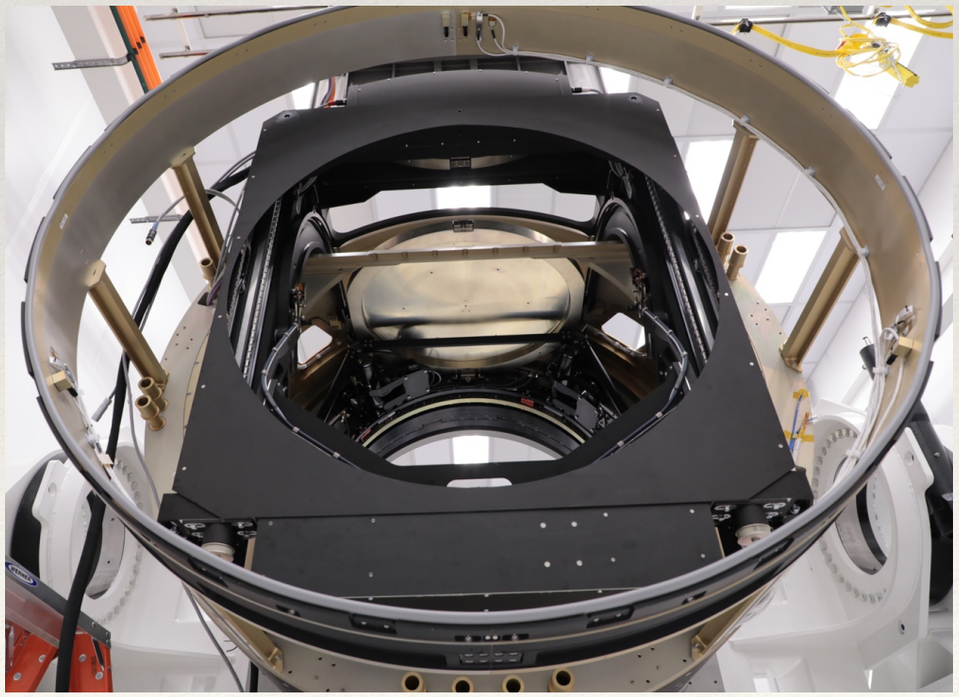
Rubin / LSST development history (a French biased view)

- End of 1990's : LSST concept and initial design
- 2007: French LSST consortium created by three IN2P3 labs: LAL, LPNHE & APC
- 2007 : Start of R&D in electronics (camera readout system) in France
- ***Aug. 2010 : LSST ranked first in the US Astro2020 decadal survey*** - https://www.lsst.org/sites/default/files/docs/NAS_pr_8-10.pdf
- ***April 2014 : LSST NSF-MRI funding / official construction started*** - https://www.lsst.org/enews/issue/volume-7-number-3
- 2010 : start of work on the filter exchange system in France
- 2012- : Start of LSST-computing activities in France
- 2015 : Calibration and impact of atmosphere
- 2017 : **Holospec** , holographic disperser for AuxTel, Sparc R&D
- 2019 : **Fink** broker initiative

2nd version of the ASPIC chip, ASPIC4 for the LSST-Cam readout



Autochanger / carrousel mounted on the camera body



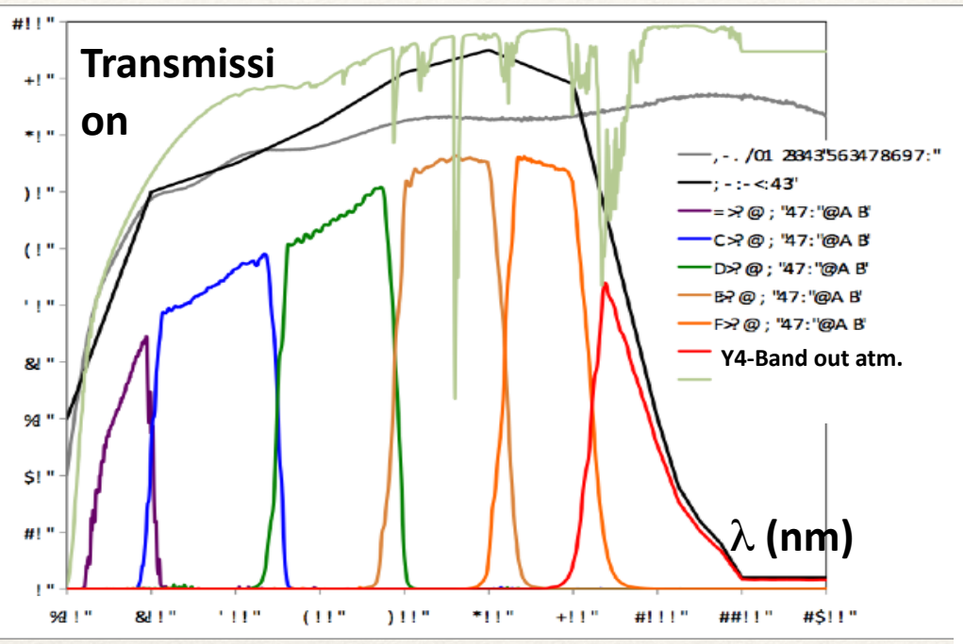
https://hal.science/hal-03838583/document

VRO : telescope & dome view

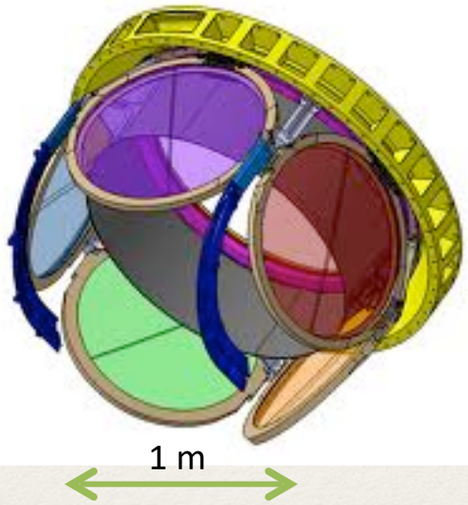
© Vera Rubin Observatory

Rubin Dome fly over - February 2023 (video)

Camera

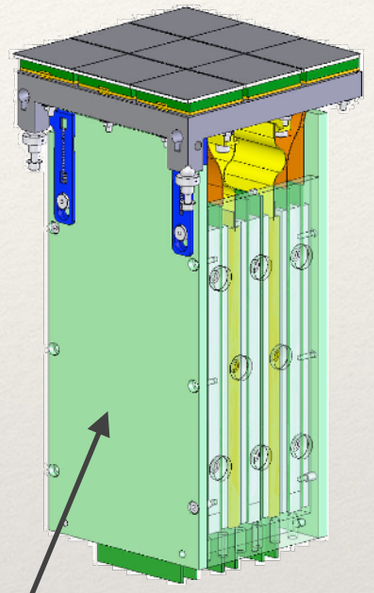


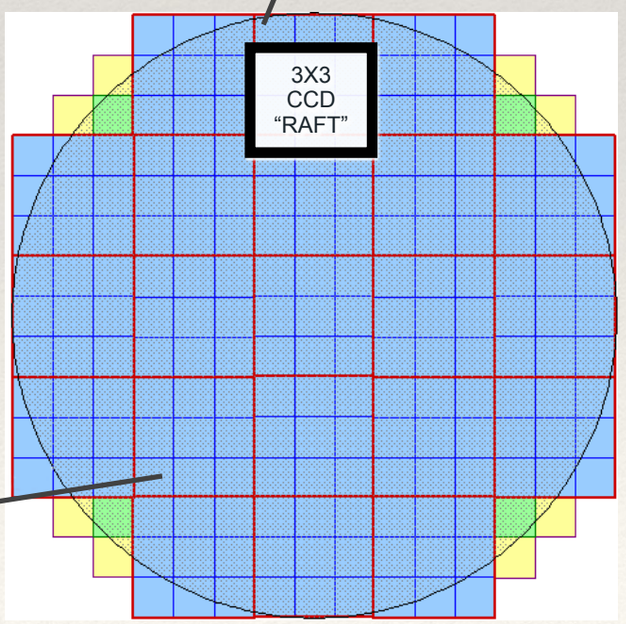
- 3.2 Gigapixels
- 0.2 arcsec pixels
- 9.6 square degree FOV
- 2 second readout
- 6 filters
- 1.65mx3.7m, 3000 kg



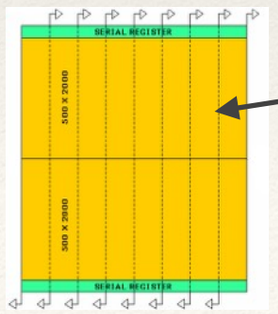
189 Science CCD
4000 X 4000 10μm pixels

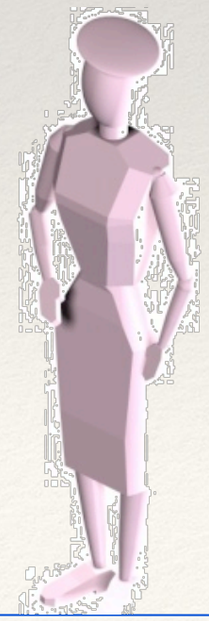
A raft
3x3 CCD
144 MPixels





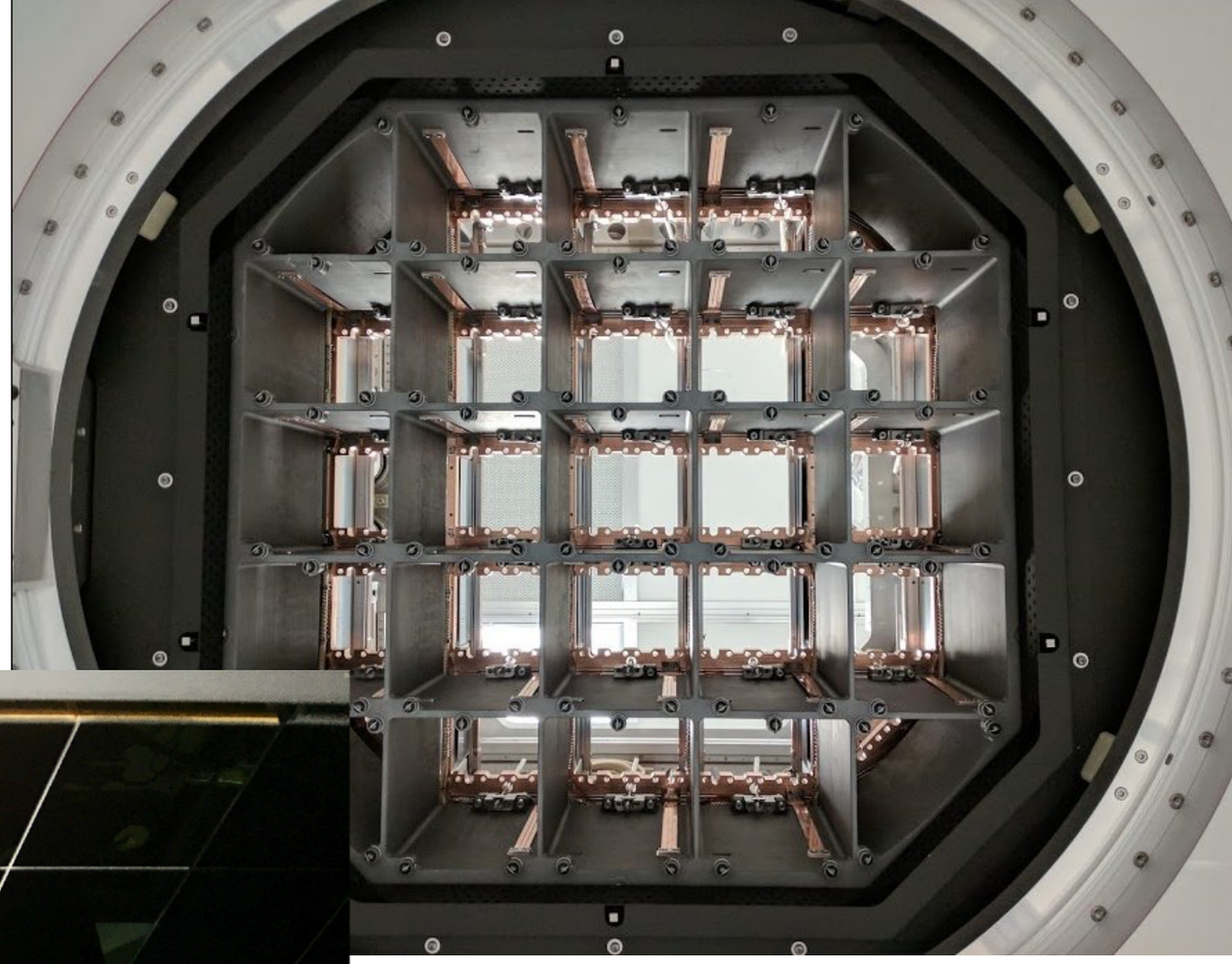
Segmented CCD
16 segments of 1M
pixels





1.65 m
5'-5"

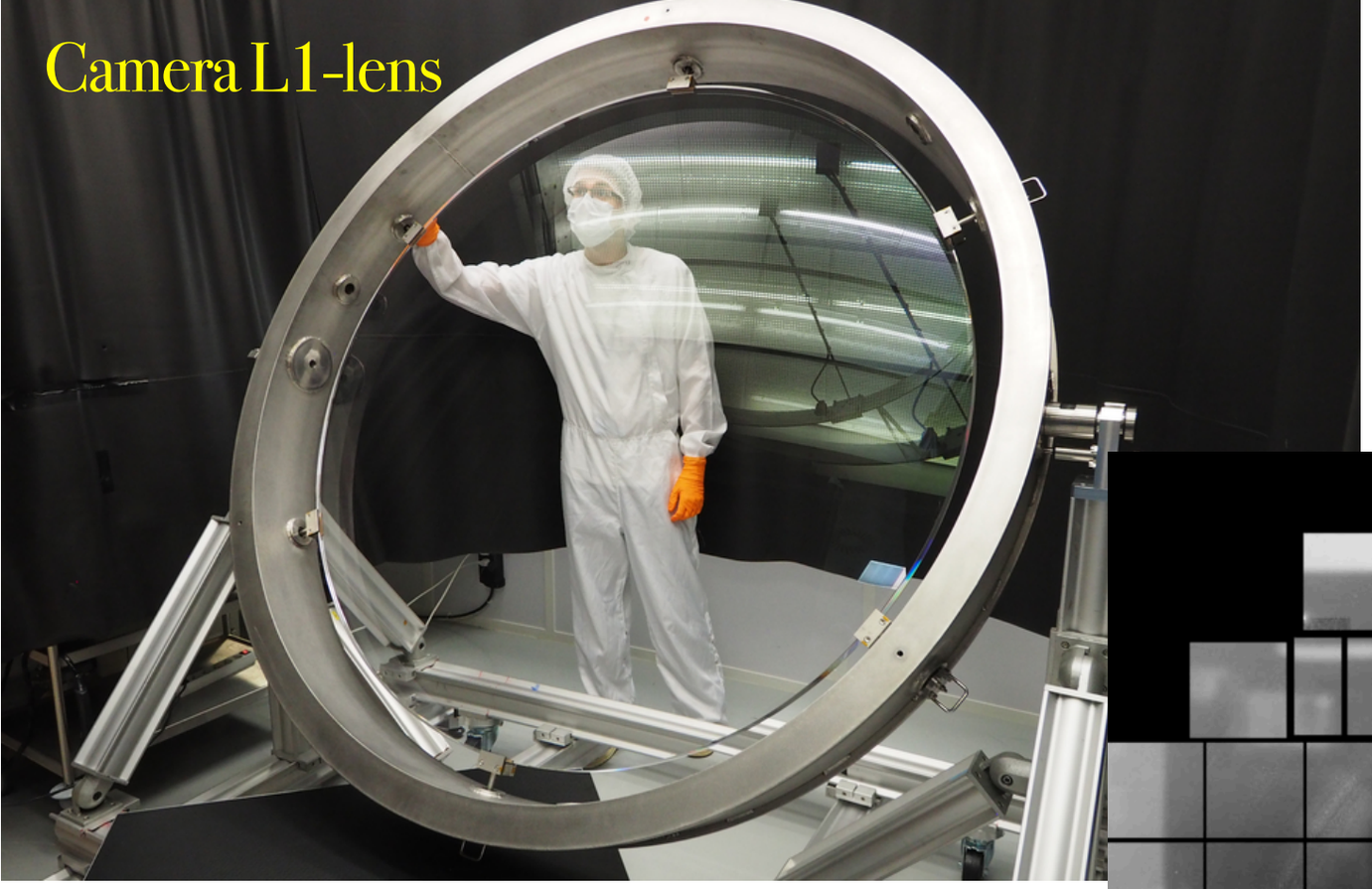
LSST camera



9th raft inserted

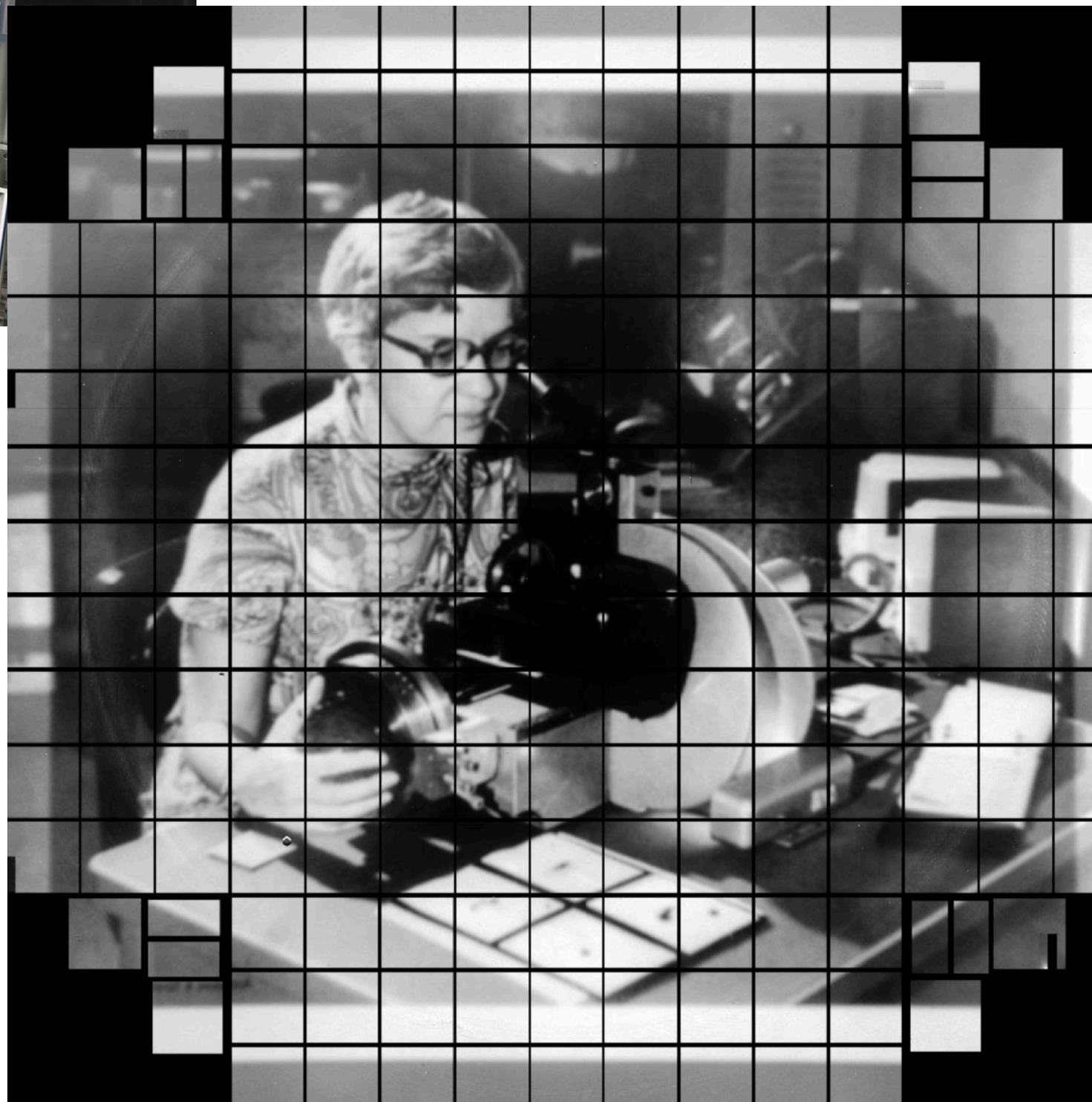
September 2019

SLAC



First 3200 Pixel
LSST-Cam image.

© Vera Rubin Observatory & SLAC

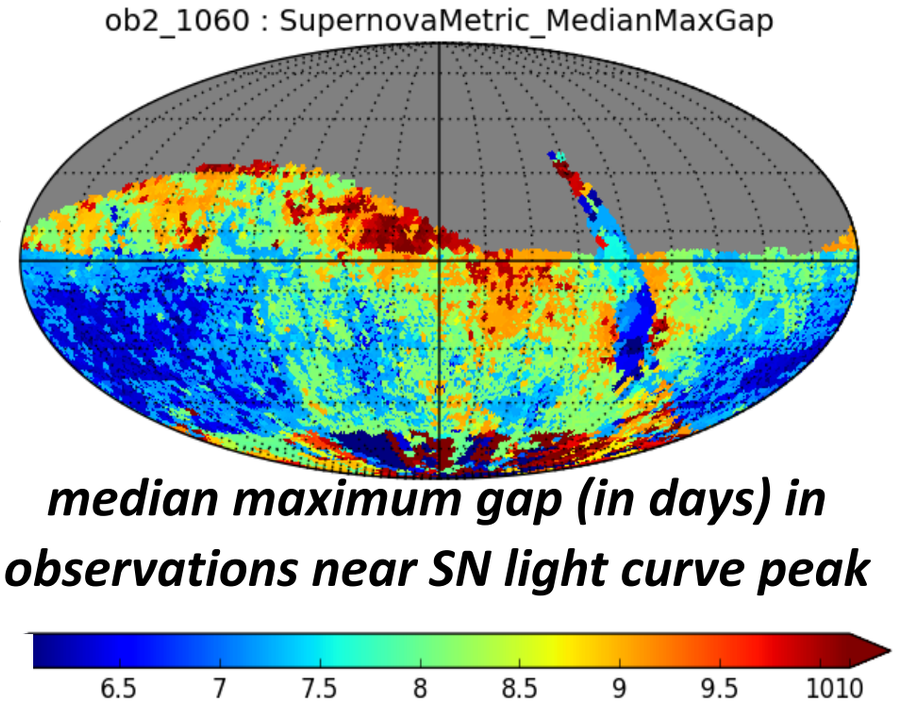


LSST survey

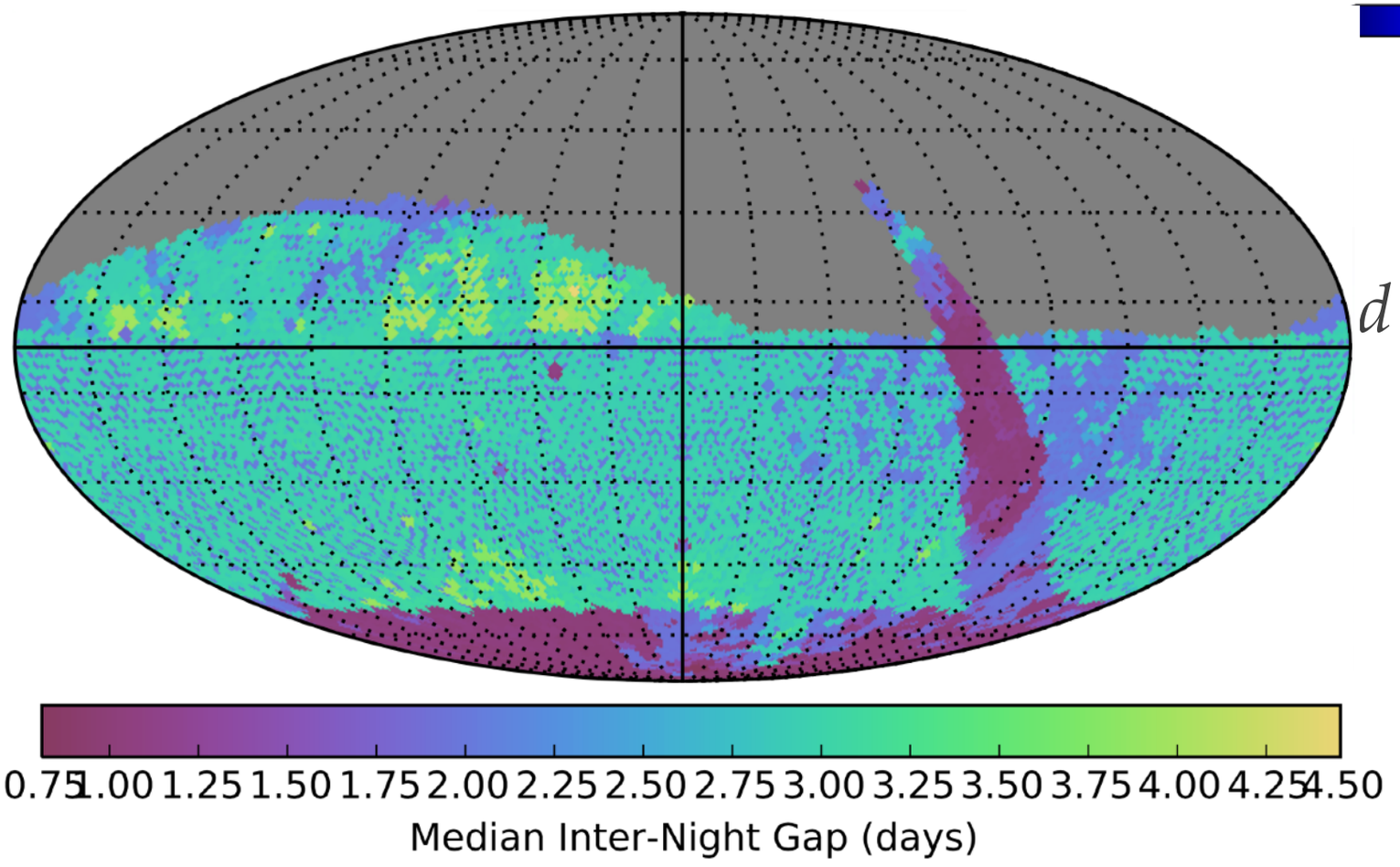
LSST "mission"

« 4D » object mapping (stars, galaxies...) of 18,000 sq. deg. to an uniform depth (>25 in i-band magnitude

- (α,δ) positions on the sky
- Photometric redshifts z
- Time variations



median maximum gap (in days) in observations near SN light curve peak



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Other survey modes

~10% of time ~1h/night
Very Deep + fast time domain + special zones (ecliptic, galactic plane, Magellanic clouds)

Observing strategy (I)

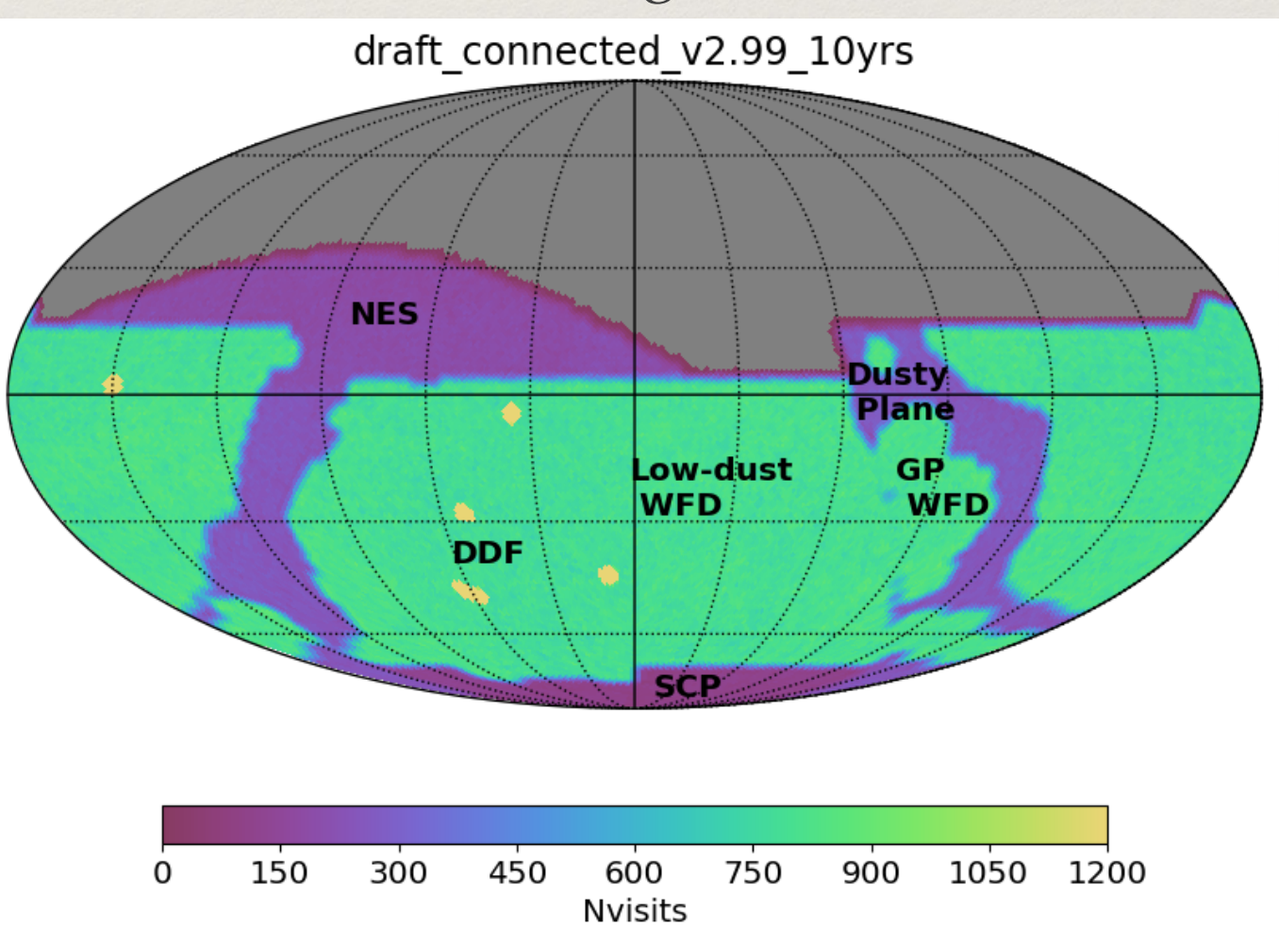
- Main survey : uniform multi-band survey of a large fraction of the sky (Wide Fast Deep survey WFD), about 18000 sq.deg
- Deep Drilling Fields (DDF) : Cosmos, XMM-LSS, Chandra W-CDF-S …

arXiv:2206.06432

- Microsurveys (less than 3% of the time) : Microlensing (high cadence in SMC, bulge w/ Roman) , Virgo cluster local groups …
- ToO : Target of opportunity
- Rolling search cadence (optimisation for SN detection and light-curve measurement)

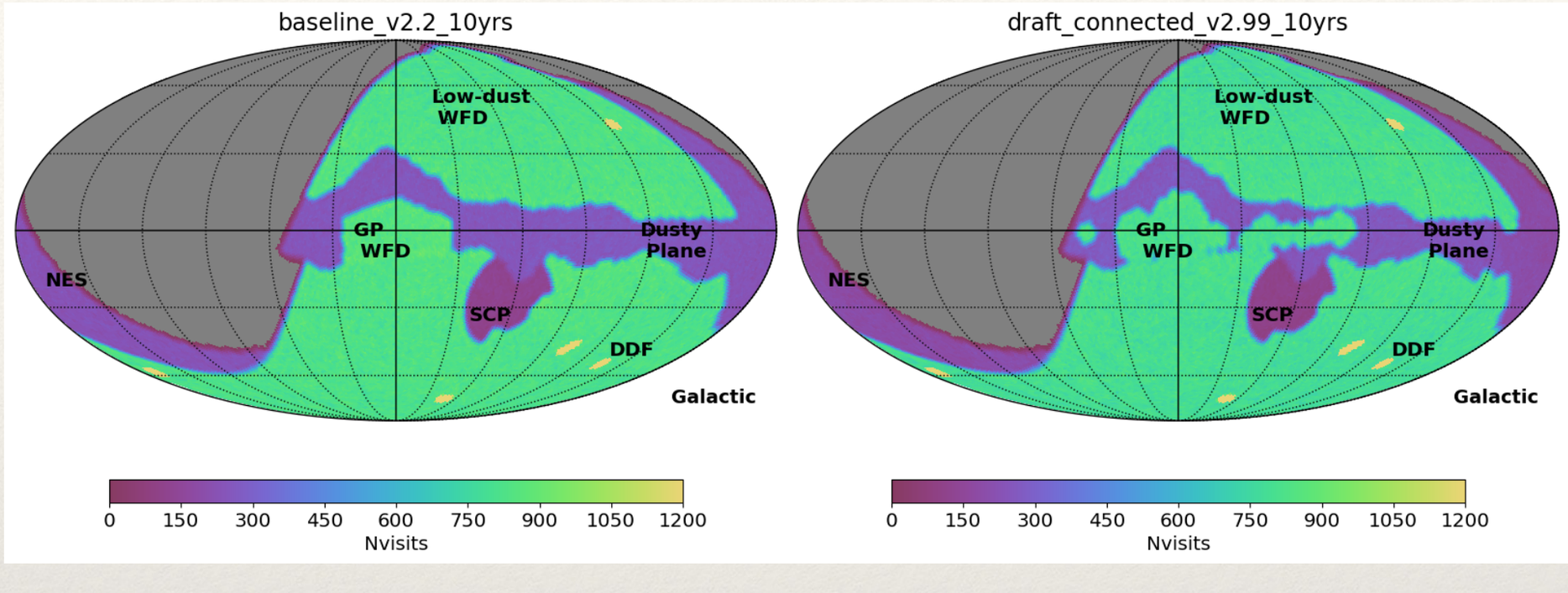
LSST sky coverage in Equatorial coordinates (number of visits)

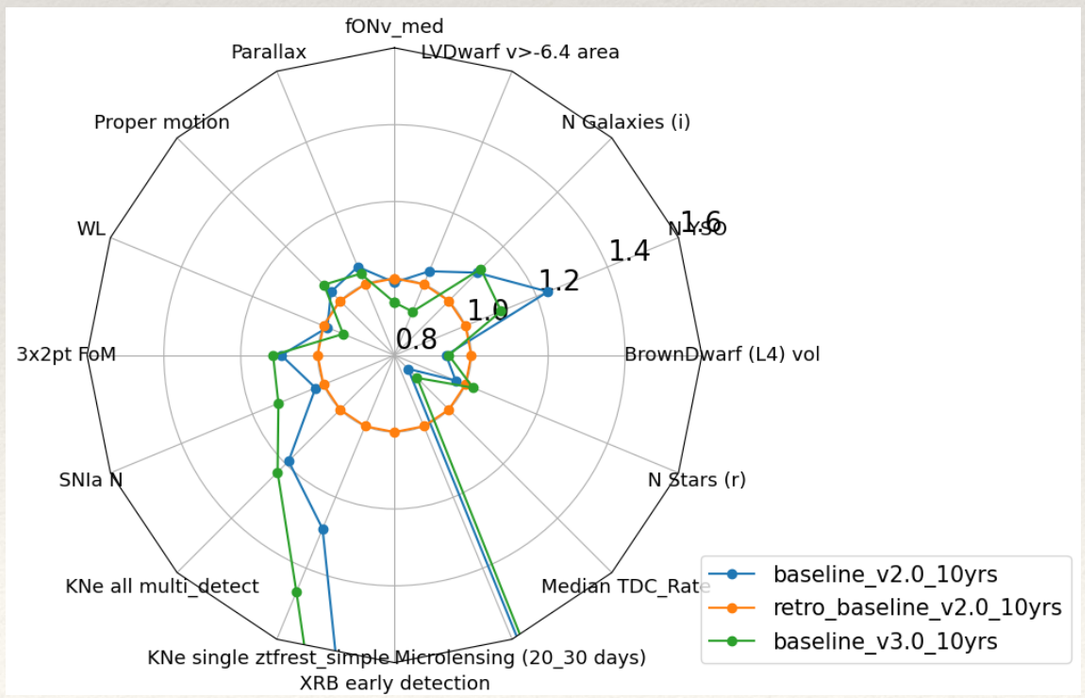
Survey cadence optimisation recommendations

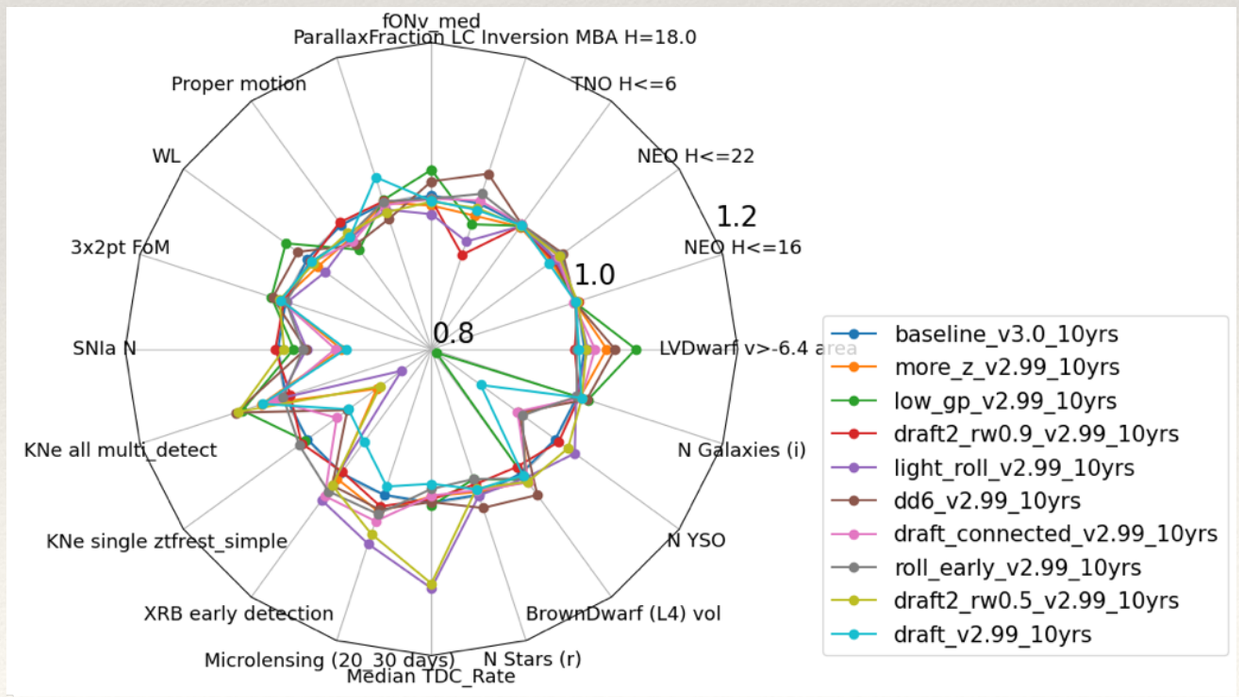


Observing strategy (II)

Survey cadence optimisation recommendations





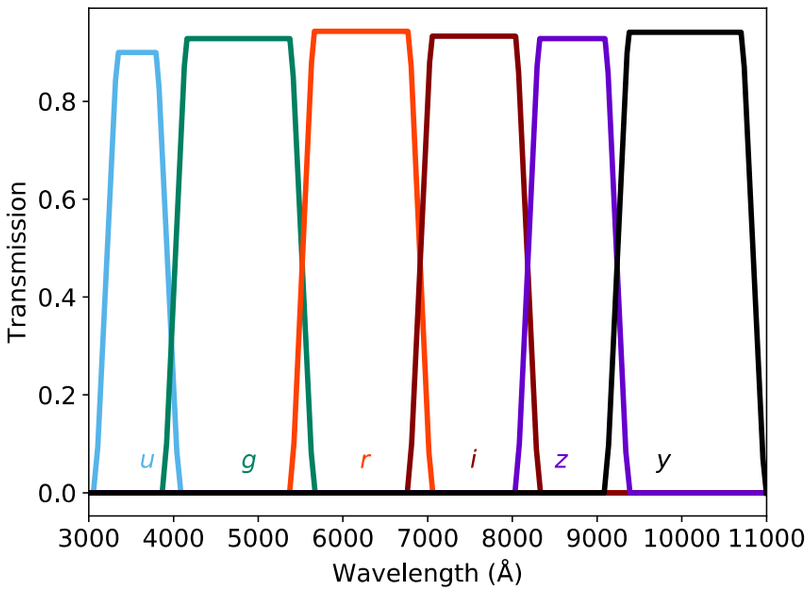


Photometric Calibration and AuxTel

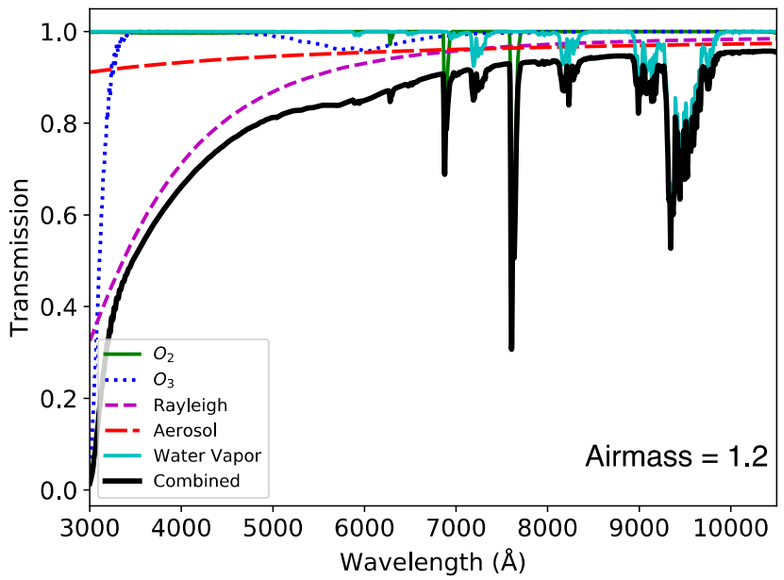
Photometric calibration

- Survey uniformity is crucial for most LSST analysis → relative calibration
- Insure spatial repeatability, as well as repeatability in time e.g slides by E. Rykoff (2020)
- LSST needs a very good relative pass-band calibration, both for photoZ and for SNIa science
- Photometric calibration targeted at the milli-mag level (10^{-3})
- Several initiatives targeting absolute calibration, linking on sky measurements to physical photometric standards (StarDice …) e.g slides by M. Betoul (2023)
- VRO has a dedicated telescope, equipped with a slit-less spectrograph (**AuxTel**) to monitor the atmosphere and provide grey absorption and atmospheric correction for bandpasses

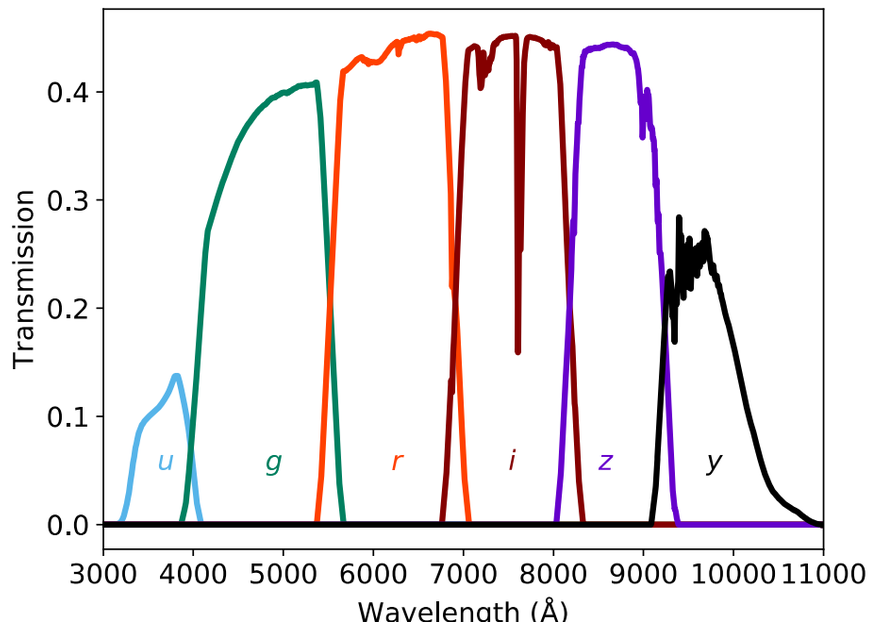
Nominal LSST filters



Atmospheric transmission



Nominal passbands
(mirrors+filters+lenses+CCD's+**atmosphere**)



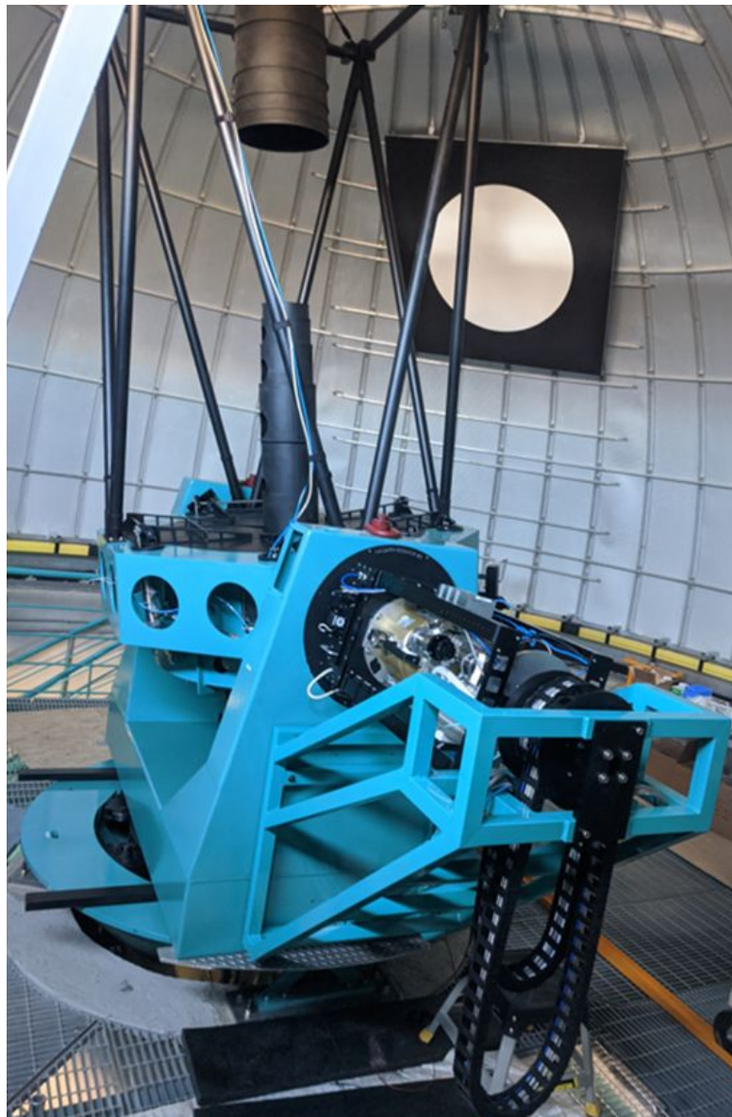
AuxTel / HoloSpec

- Edgar J. Smith (/Calypso) 1.2 m telescope, refurbished in Tucson
- Camera, combined with filter and disperser, making the LATISS (LSST Atmospheric Imager and Slit-less Spectrograph, built at Harvard (C. Stubbs et al.)

e.g slides at VRO PCW (2022)

- LATISS installed in January 2020 - and shares some of the main telescope command/control and Data Acquisition software -
- Uses a Ronchi grating (baseline) , and an optimised holographic disperser, designed and built in France (LAL/IJCLab, M. Moniez et al.)
- Ongoing observations with AuxTel/HoloSpec and Spectractor (data reduction pipeline)

AuxTel / Calibration hill

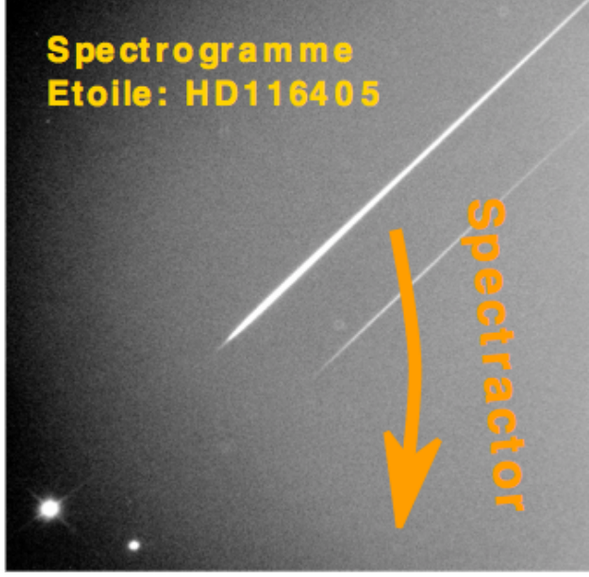


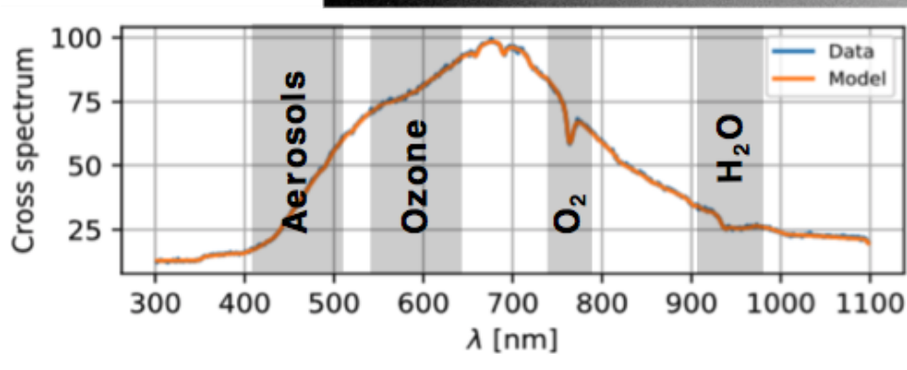
AuxTel in its dome

HoloSpec / Spectractor

- **Holospec** (M. Moniez LAL/IJCLab) : A hologram replacing the grating for a spectrograph in a convergent beam.
- Corrects for distortions and defocusing of a standard grating in a non planar beam
- First prototypes tested at CTIO in 2017, final version characterised in LPNHE (Paris) in 2020, chipped to Chile in Dec 2020
- **Spectractor** (J. Neveu IJCLab/LPNHE) : software tool to extract spectra from AuxTel images

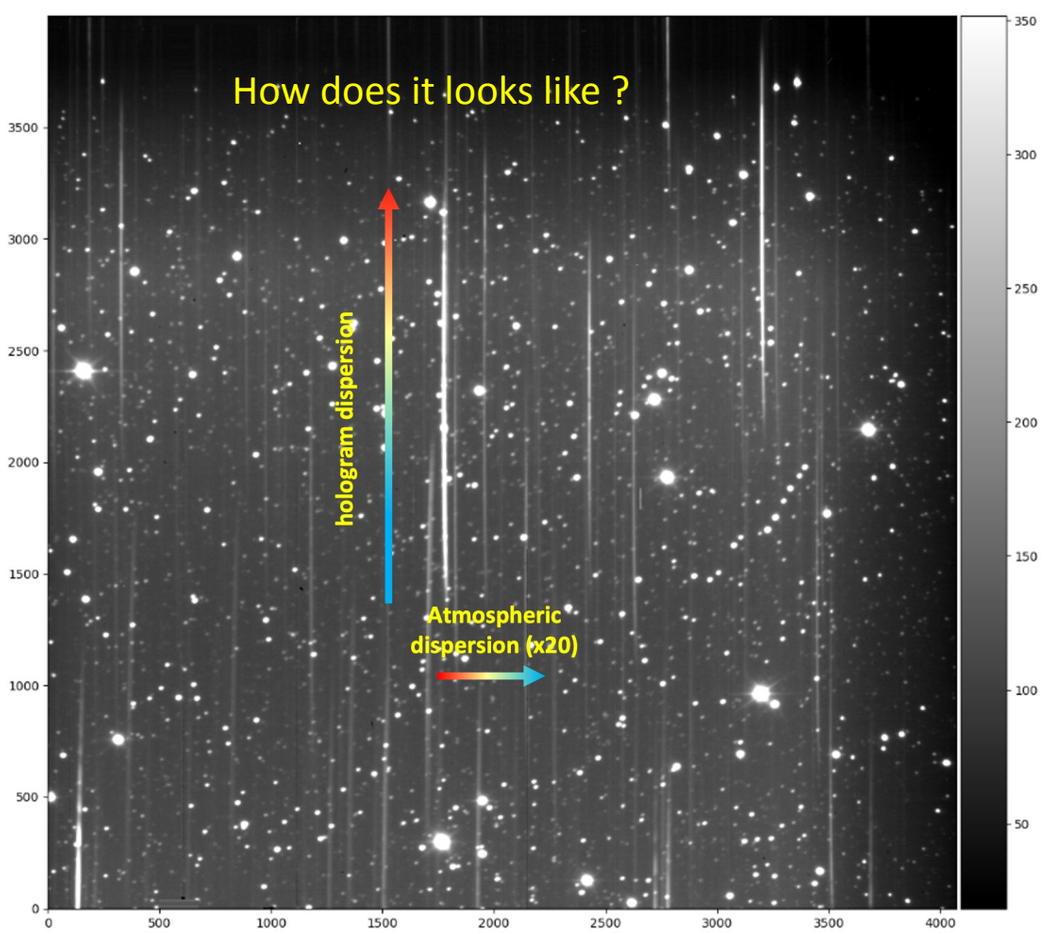
see slides by M.Monroy (LSST-France 2023)



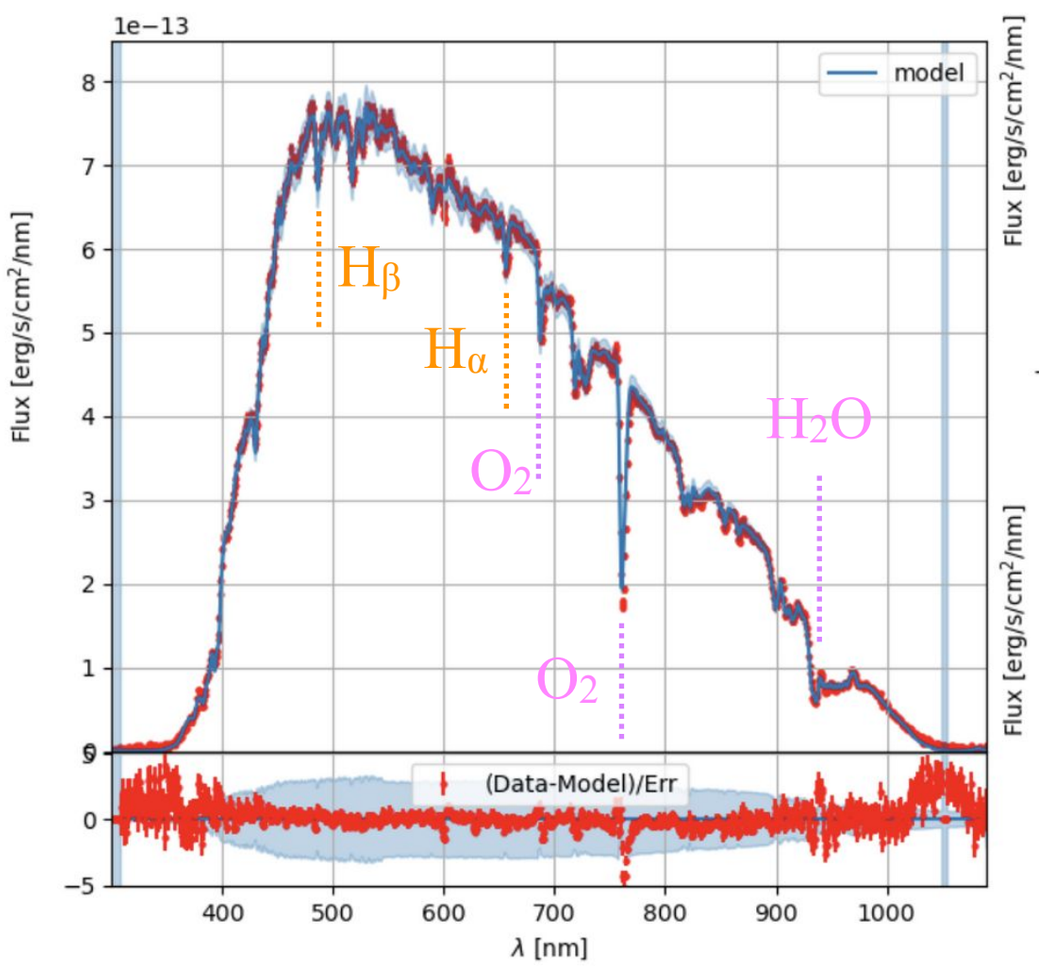


O_2, H_2O : line features
Aerosols, Ozone : broadband

Holospec image



Extracted Spectra

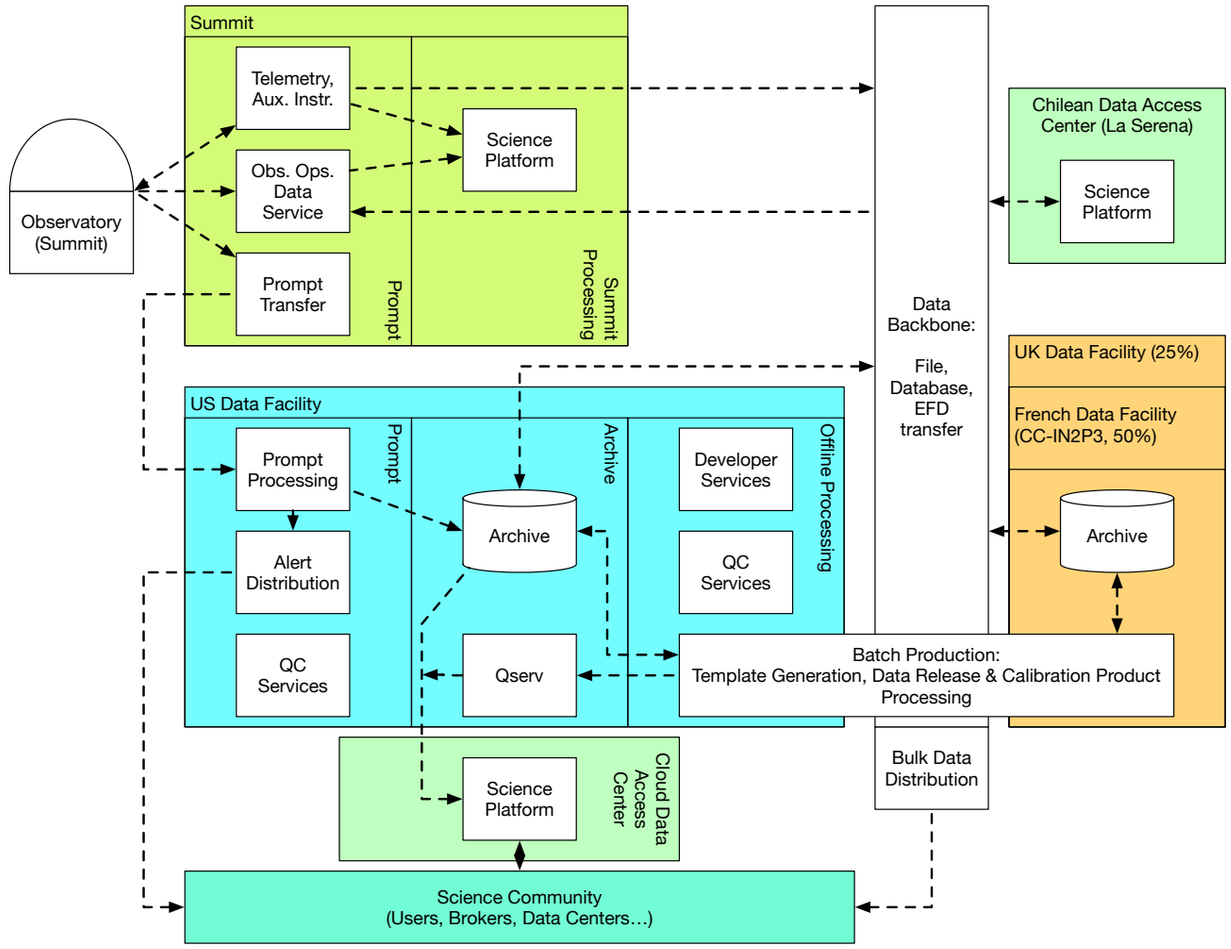


Time domain astronomy

Transients and fink

Rubin Observatory/LSST data processing

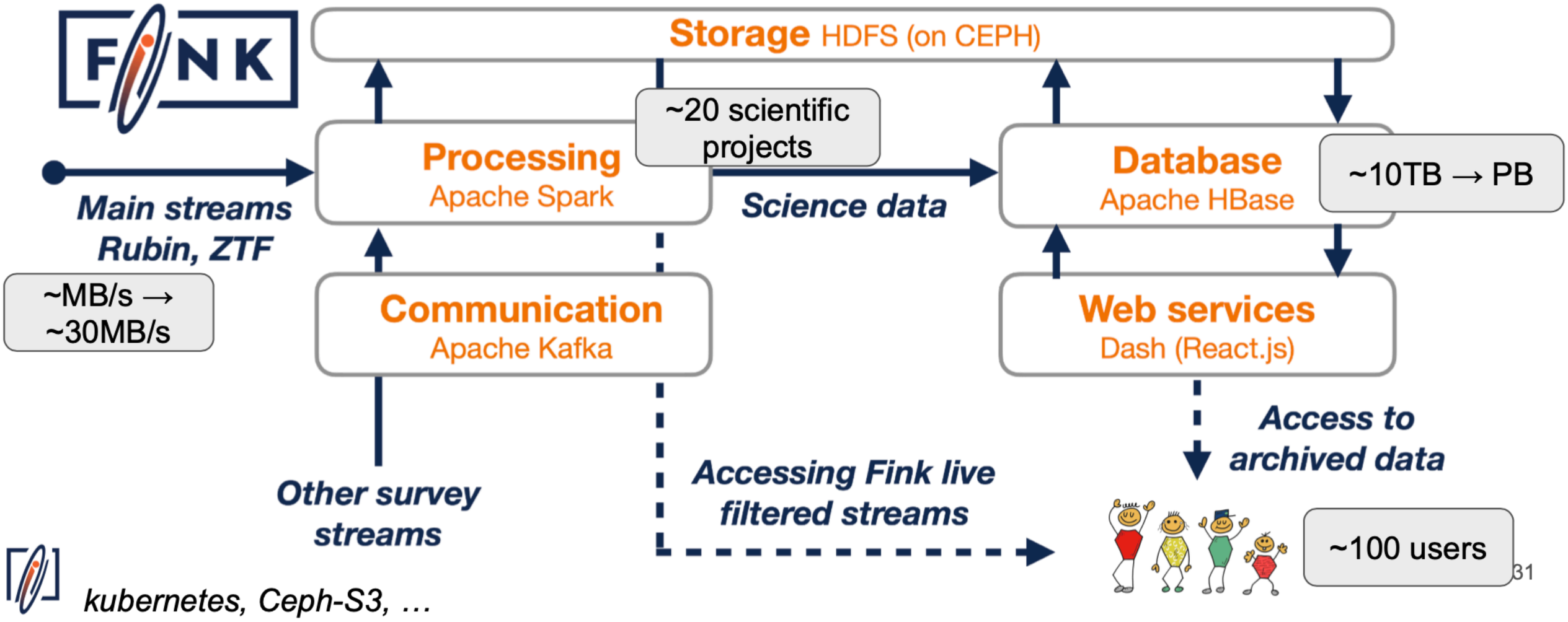
- VRO will take short exposure images (~30 s)
- Any part of the surveyed area will be visited every few nights (5-10 nights)
- With more than 10 GB/image, the data stream will represent about 20 TB / night
- The complete data set will be processed to produce the source catalog for the annual **DRP** (Data Release Processing)
- In addition, the images taken each night are processed by the Alert or **Prompt** processing pipeline, through Difference Image Analysis to search for variabilities in sky
- The alert stream is distributed to a limited number of alert brokers, with about 10 million alerts / night
- Images from each visit processed and alerts distributed within minutes of taken exposures



arXiv:2211.13611

Fink @ VirtualData

Deployed on the VirtualData cloud since 2019 (~200 vCPUs, 35TB storage)



Fink broker :

Receive alerts from Rubin/LSST

Gather additional information for the alert source

Apply additional filter , redistribute the alerts to users

Possibility to add user defined filters

See e.g. slides by J. Peloton (03/2023)

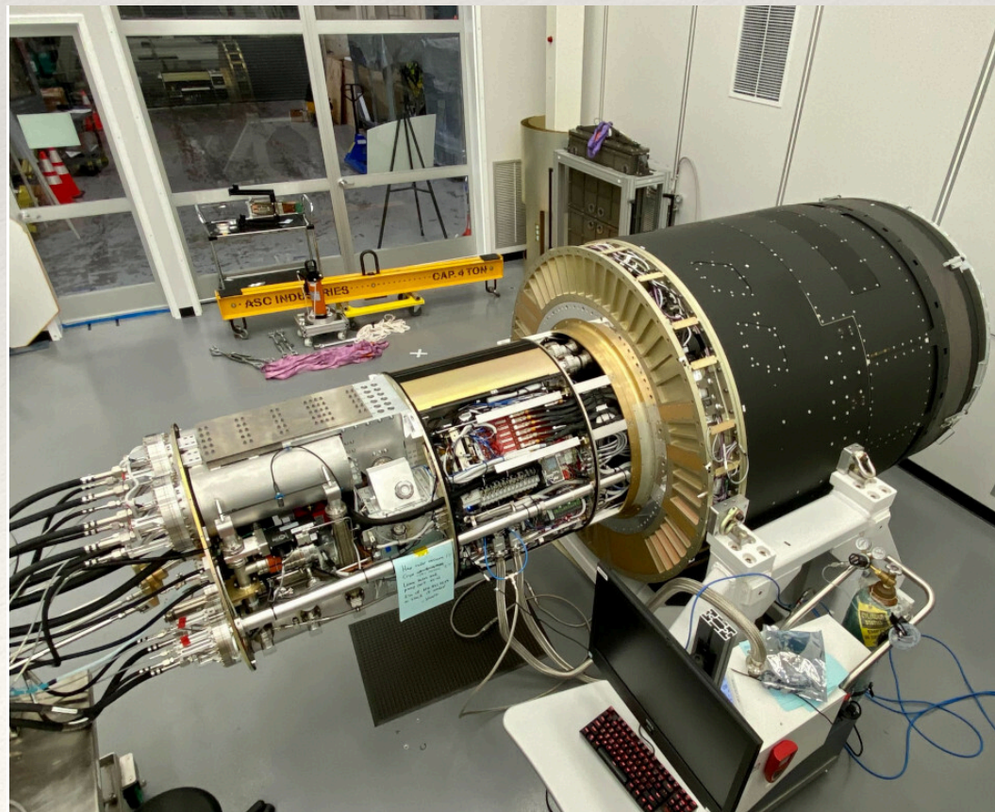
Or slides by M. Pruzhinskaya (06/2023)

Science with Vera Rubin Observatory / LSST

VRO recent and future milestones

- Spring 2023 : Dome aluminium cladding , TMA complete, Engineering data flowing to USDF
- Spring/Summer 2023 : M1-M3 mirror cell assembly testing on summit
- Summer 2023: Camera calibration ongoing at SLAC with CCOB
- March 2024 : Dome complete
- July 2024 : LSST-Cam ready for sky photons
- October 2024 : first light
- Feb 2025 : completion of Science validation survey
- March 2025 : start of VRO/LSST 10 year sky survey

Camera and its wiring at SLAC
(spring 2023)



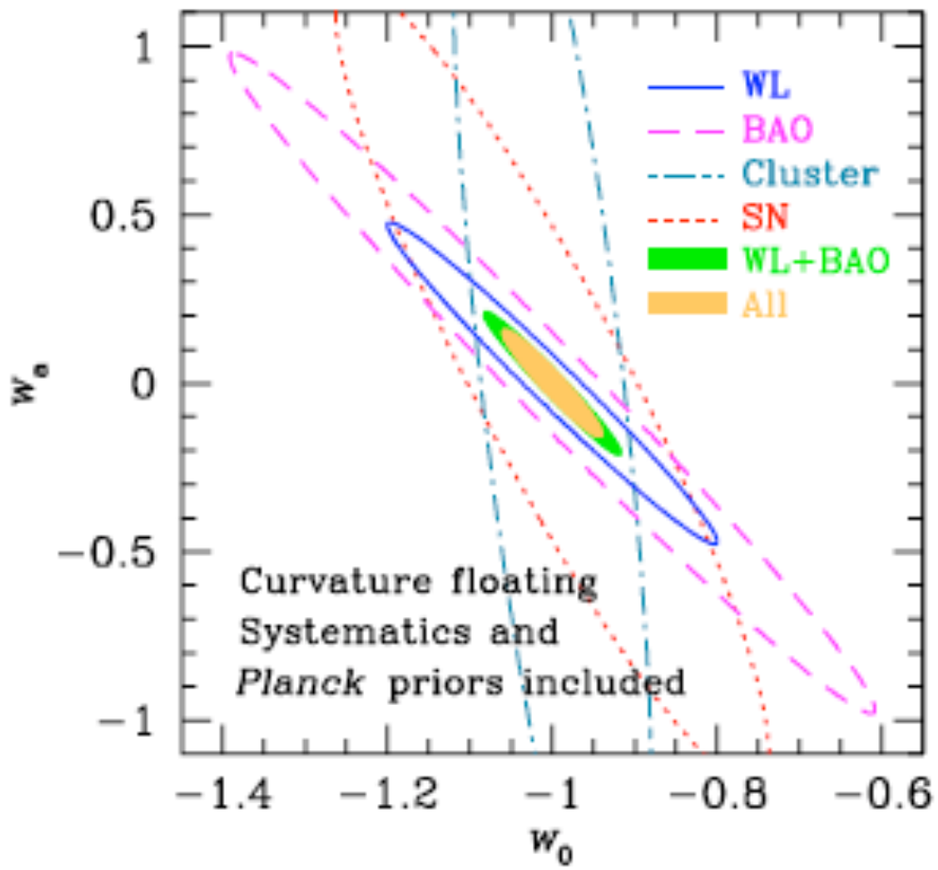
Science enabled by VRO / LSST

LSST Science Book - https://www.lsst.org/scientists/scibook

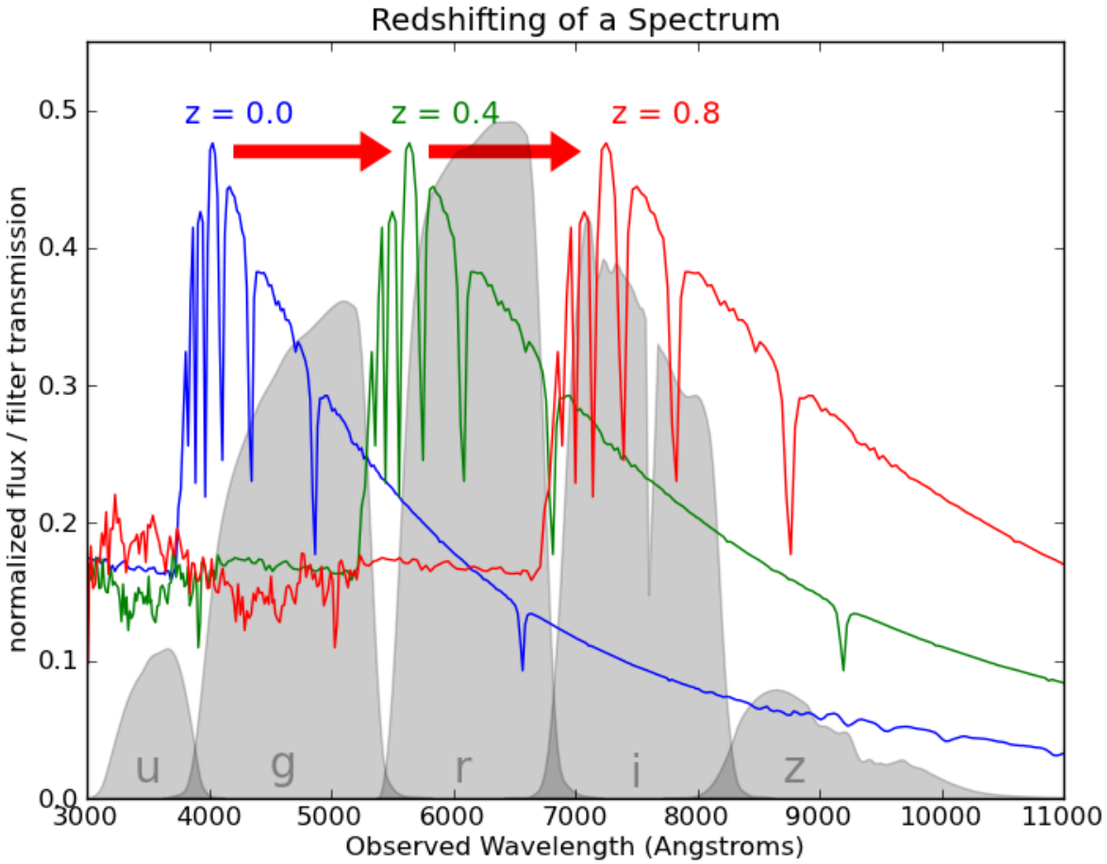
- Moving sources, Solar system science
- Time domain astrophysics :
  - Novae, Supernovae, GRB's
  - Microlensing
- Mapping the Milky Way : Galactic structure and tidal streams
- Galaxies : *The Rubin Galaxies Collaboration*
- **Cosmology , Dark Energy and Dark matter:** *DESC*
  - Weak lensing and strong lensing
  - Clusters
  - Supernovae
  - LSS , LSS x WL

PhotoZ

DESC: Dark Energy Science Collaboration

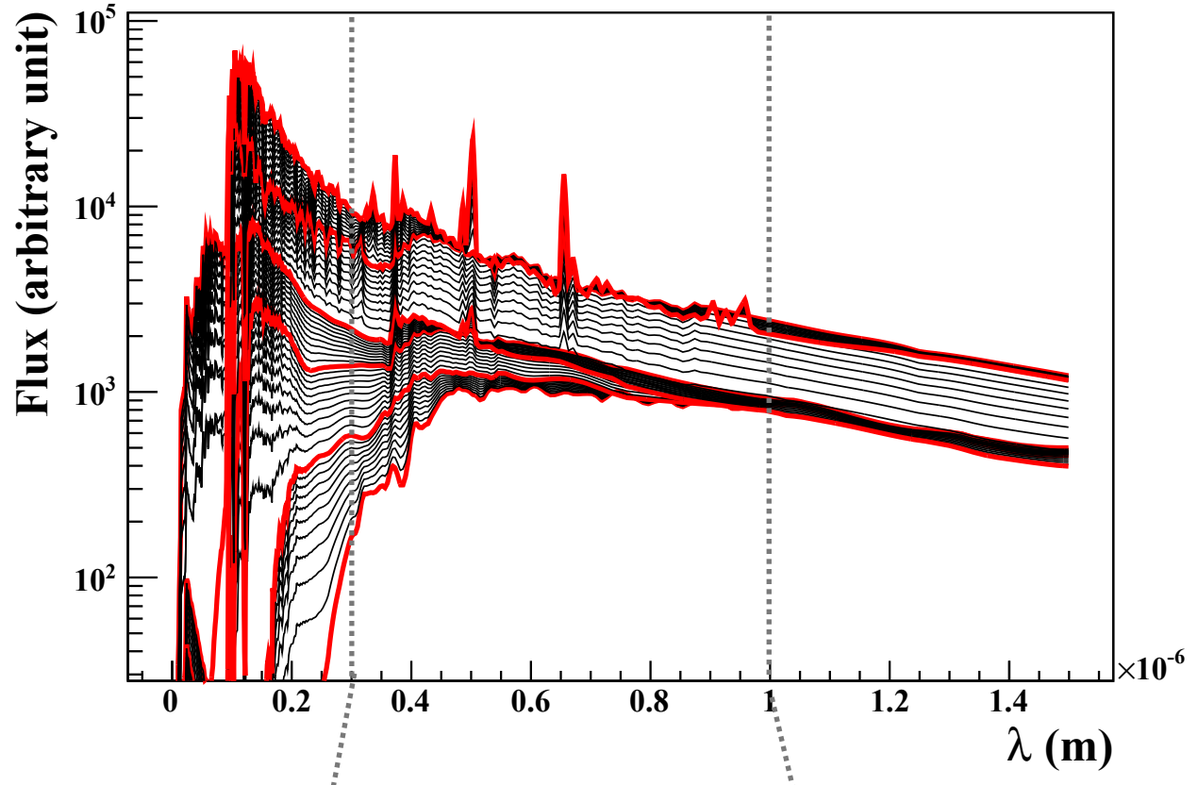


PhotoZ basics

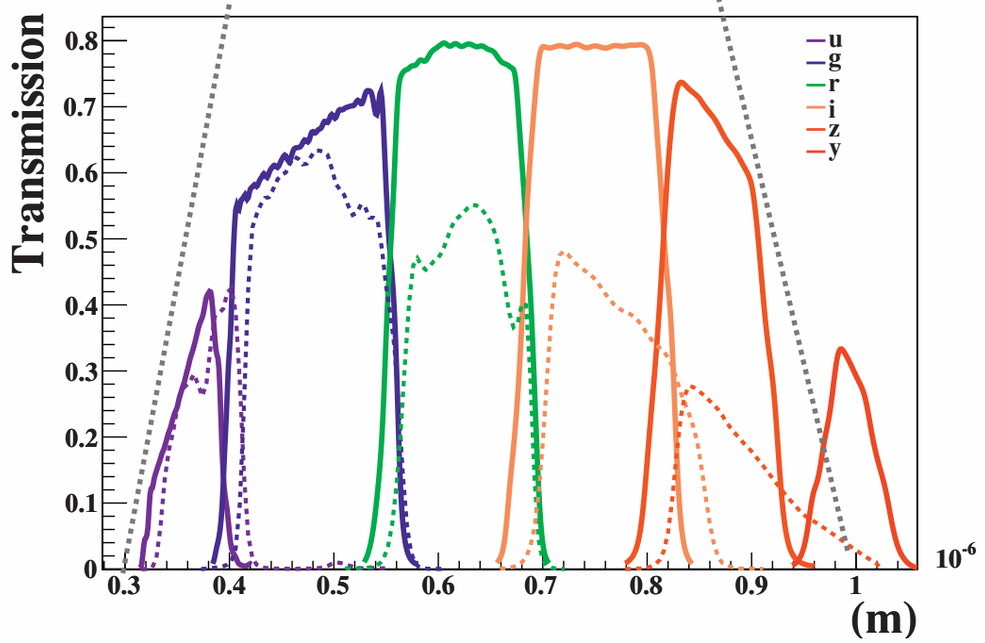


© Image source:

Typical galaxy SED's



LSST bands



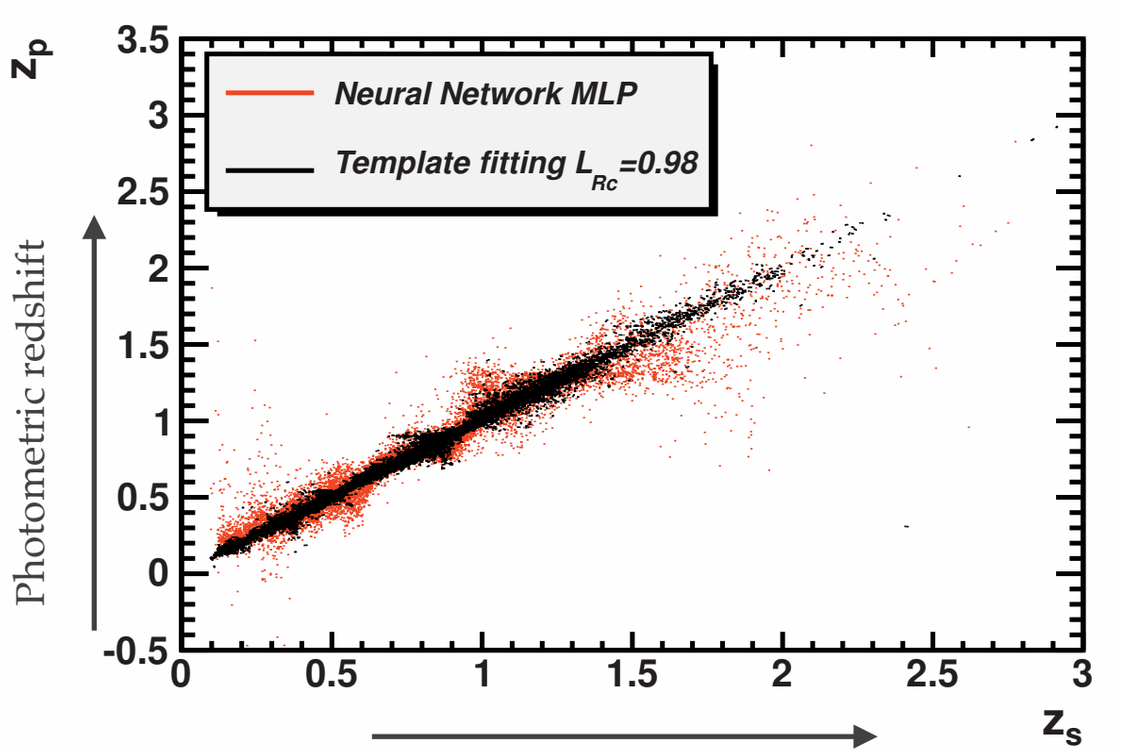
Gorecki A. et al, A&A 2014 , arXiv:1301.3010

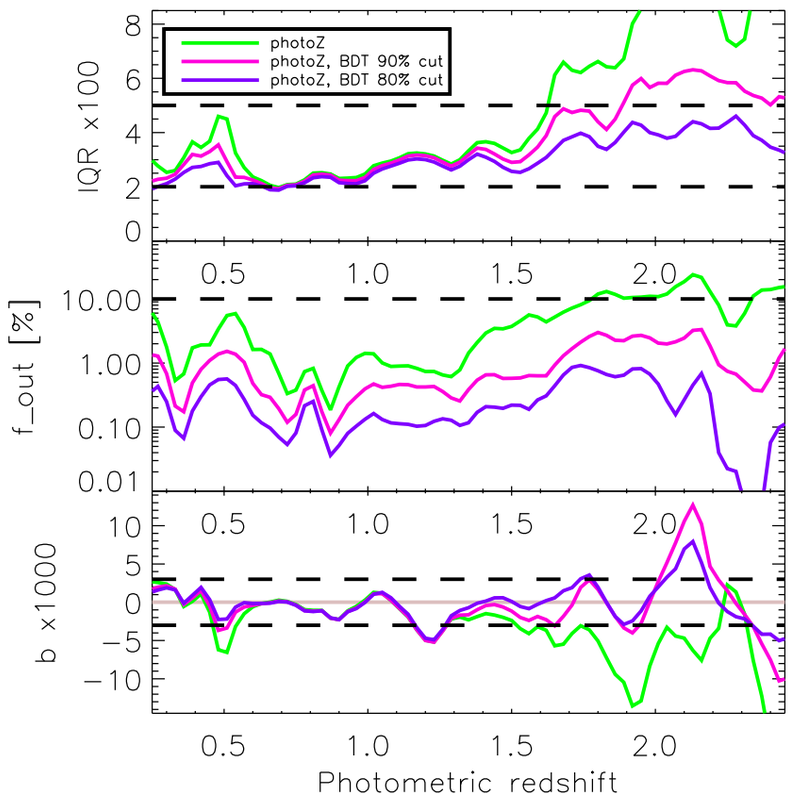
Photometric redshifts

- LSST is a 6-band photometric survey and most of the cosmology and extra-galactic science will rely on the photo-metric determination of redshifts
- PhotoZ determination relies mainly on colour changes as the galaxy SED's shifts through different filters as the redshift increases
- Two broad categories of PhotoZ codes, using Machine Learning (ML) and Neural Networks (NN), OR through template (galaxy SED) fitting (TF)
- ML/NN : needs a photometric catalog with spectroscopic redshifts (training data set) that matches the complete photometric catalog - major challenge for LSST
- ML/NN methods are often able to optimise the use of available information
- Template based : need to have representative galaxy SED libraries, and understand the astrophysical effects (& cosmology), and the evolution with redshift - Training data set would be used for validation
- Template based methods use the accumulated *human* knowledge (physics) to extend photo-z determination beyond parameters (magnitudes, redshift …) covered by the training set
- Increasing the available number of photometric bands, both toward UV and in the InfraRed (IR) enhances significantly the PhotoZ performance
- Synergies with other optical surveys , such as Euclid, or Roman
- Spectroscopic surveys (DESI …) will be used for the calibration through cross-correlations

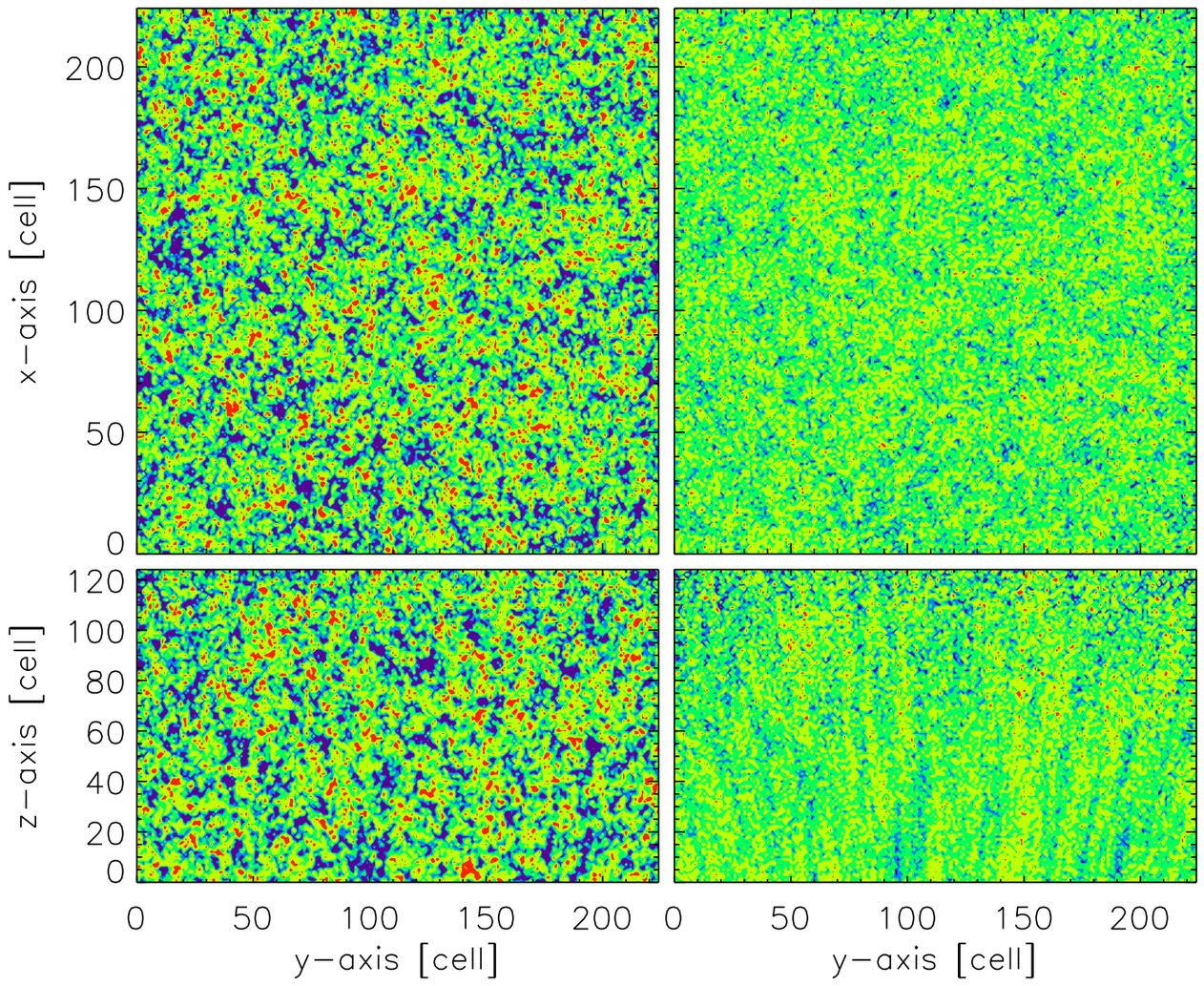
Photo-z & BAO's in LSST (I)

Gorecki A. et al, A&A 2014 , arXiv:1301.3010





Smearing effect of Photo-z on LSS



with spectroscopic redshift

with photometric BDT 80% redshift

Ansari R. et al, A&A 2019 , arXiv:1902.03004

Photo-z performance (LSST goals)

$e_z = (z_s - z_p)/(1 + z_s)$

e_z IQR ≤ 0.05,

Less than 10% outliers ($e_z > 0.15$)

Photo-z & BAO's in LSST (II)

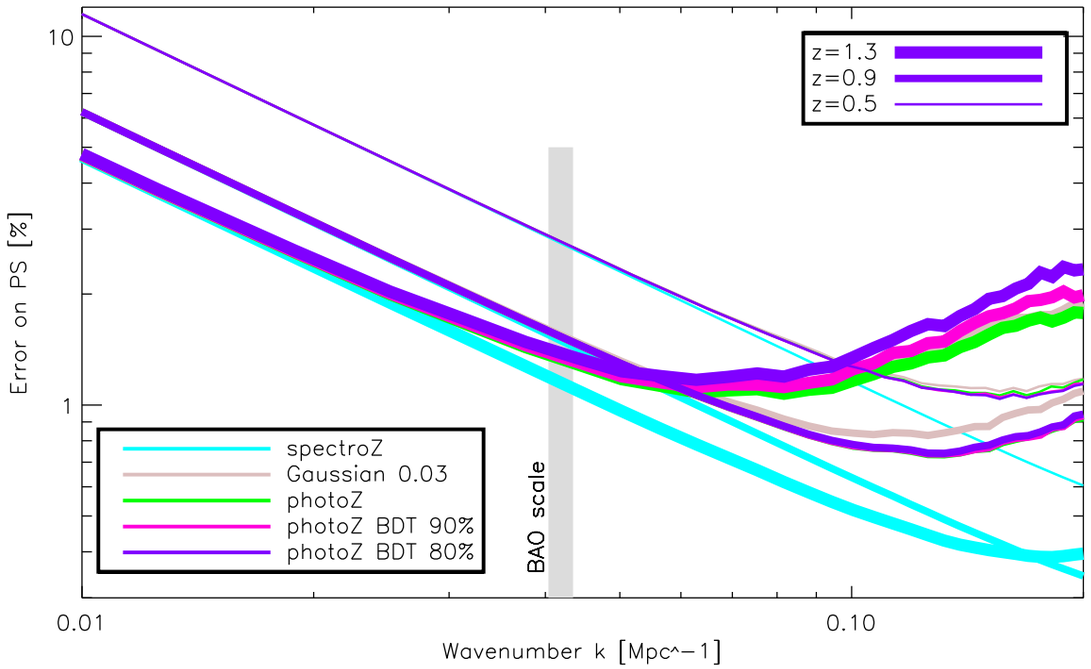


Fig. 10. Fractional statistical error $\sigma_P/P(k)$ of the recovered power spectra P_D in percent. Colours identify the different redshift error models, while the grid redshifts are distinguished by different line thicknesses. The light grey area shows the wave number corresponding to the BAO scale.

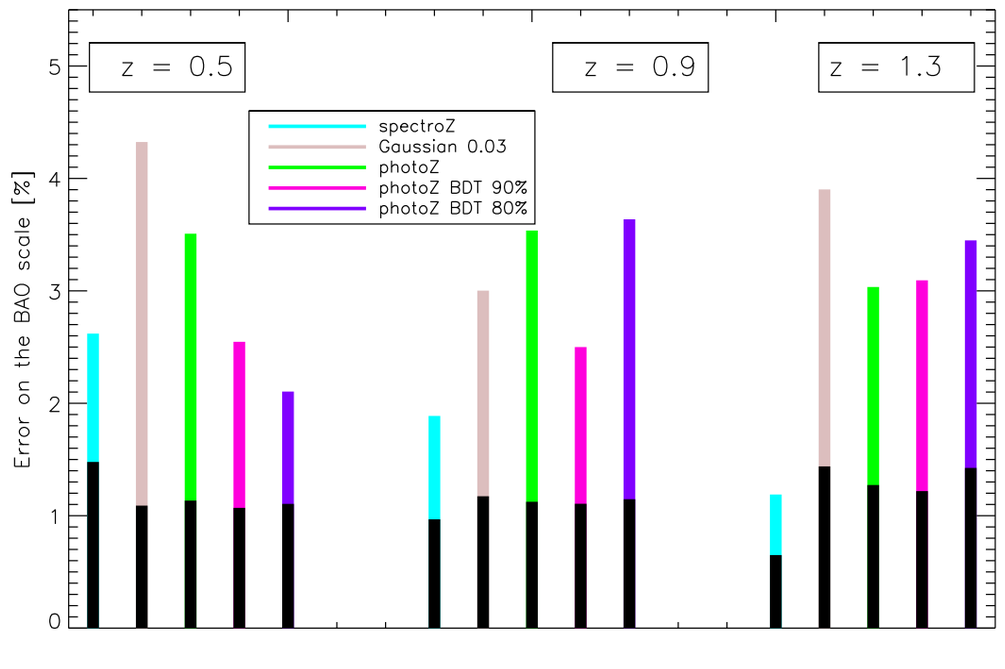


Fig. 12. Relative errors on the BAO scale fitted from the power spectra for each redshift and each error model. The black bars are the results using the k-range $[0.03-0.1]\,\mathrm{Mpc}^{-1}$ while the colour bars are the results using the k-range $[0.02-0.07]\,\mathrm{Mpc}^{-1}$.

Still possible to recover the isotropic BAO scale with <5% accuracy thanks to the large number of galaxies

BAO scale would be an important LSS and Photo-z check in LSST

Ansari R. … C. Renault et al, A&A 2019 , arXiv:1902.03004

Synergy with 21cm Intensity Mapping

Optical surveys

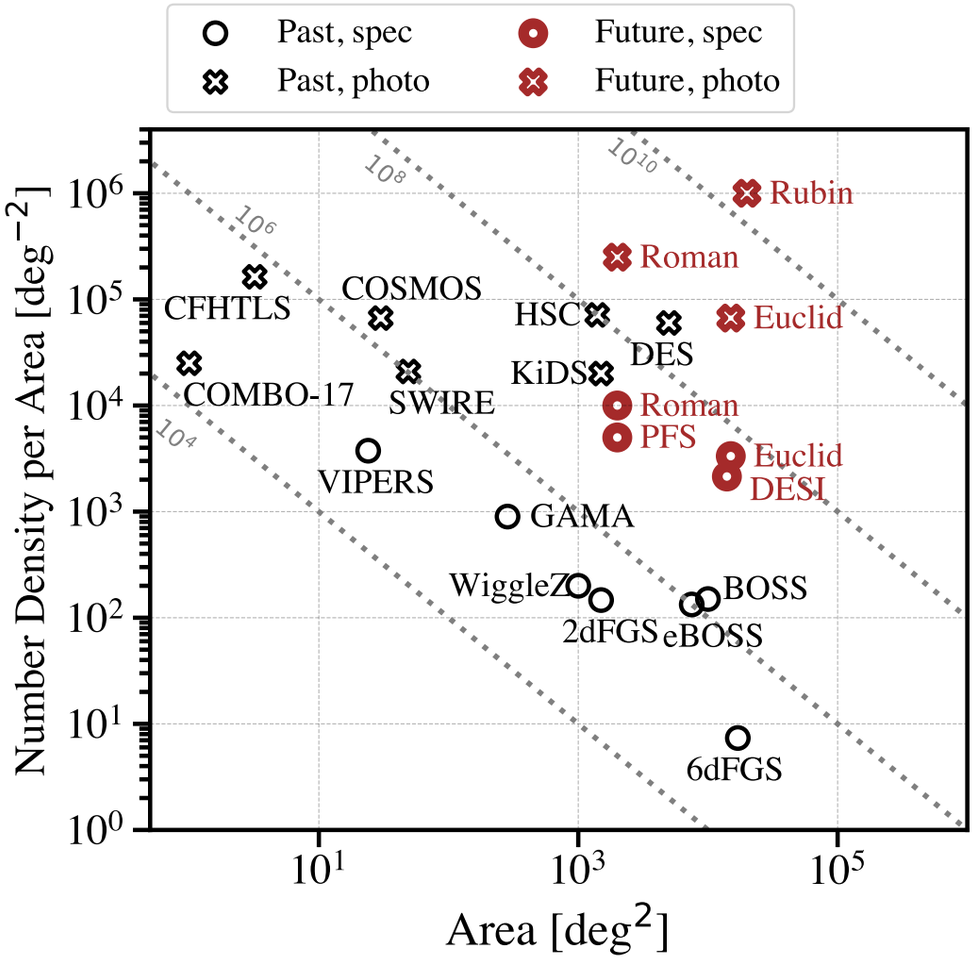


Figure 14. Landscape of past (black) and current/future galaxy surveys (red) for galaxy number density per area as a function of the survey area. Photometric surveys are crosses and spectroscopic surveys are open circles. The grey dotted lines corresponds to 10^4, 10^6, 10^8, and 10^{10} galaxies. Overall, the current/future surveys cover a larger area with a higher number density per area.

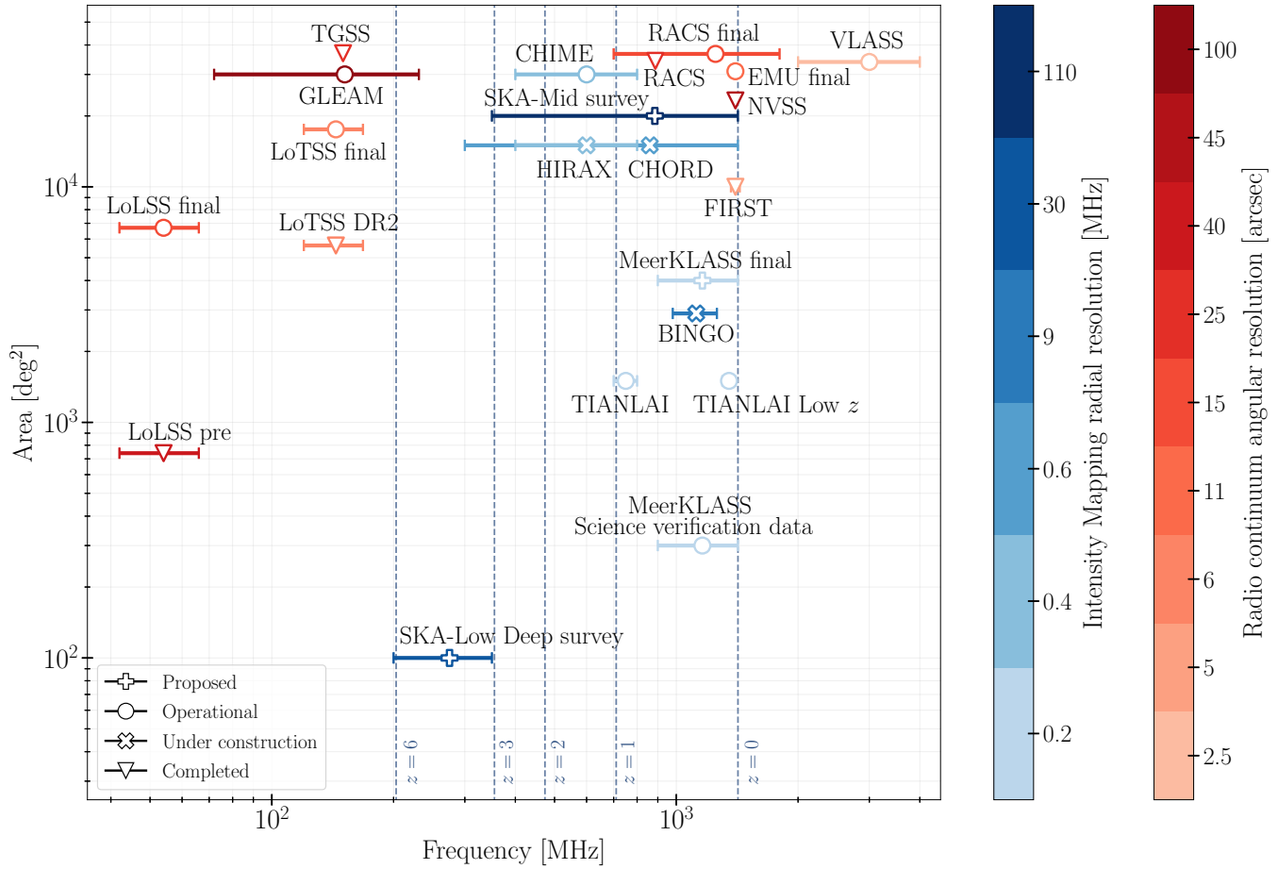
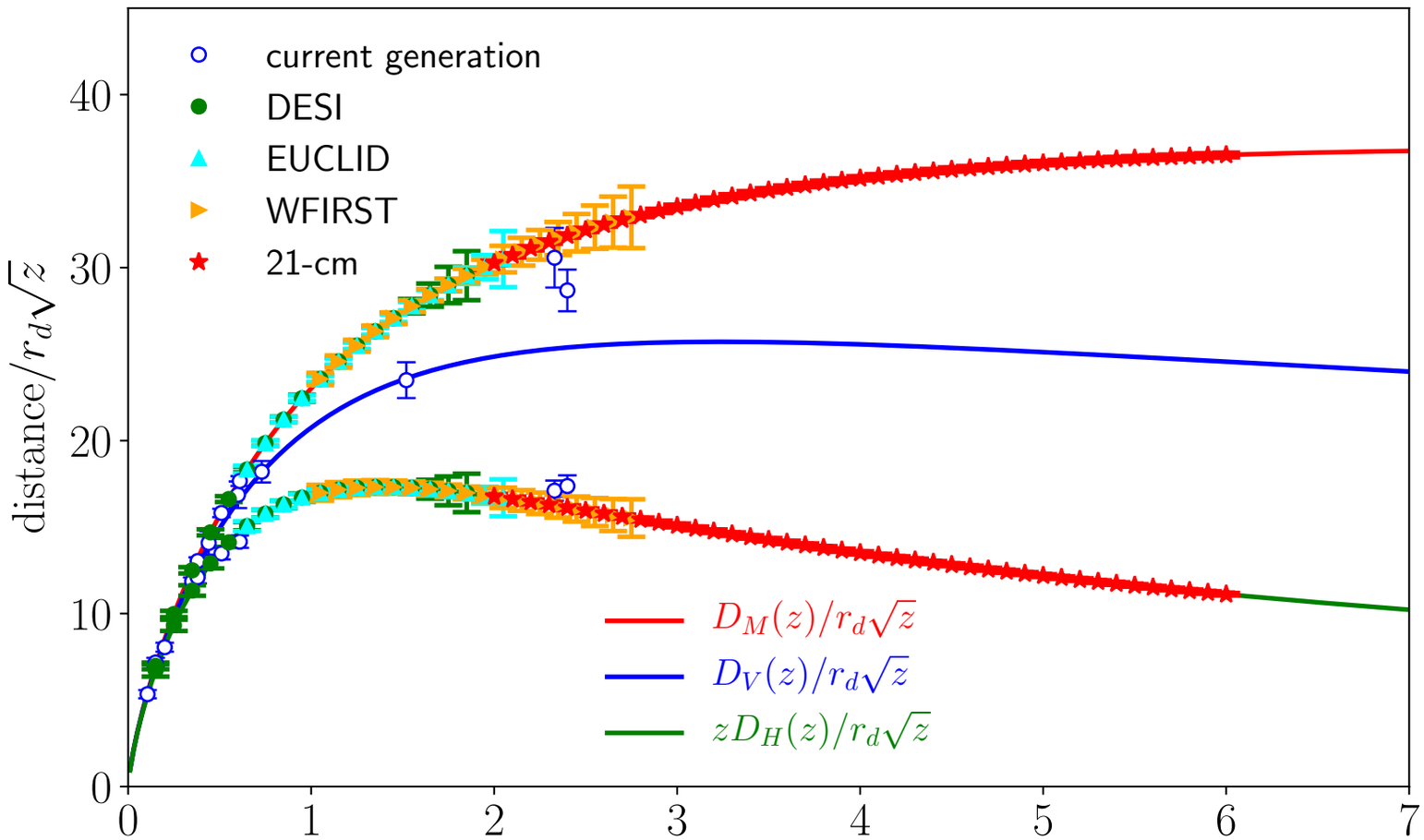
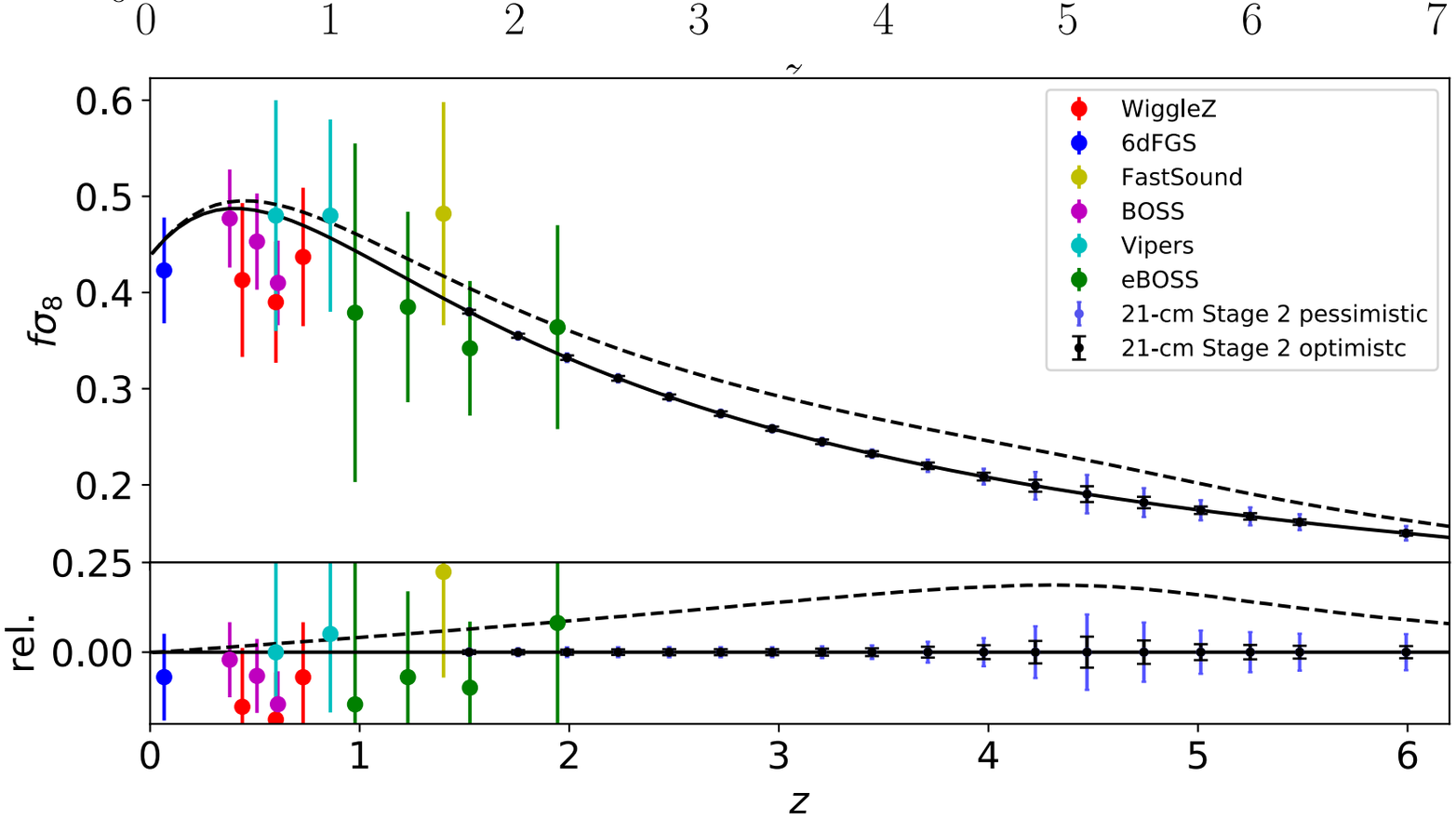


Figure 15. A summary of radio surveys. The warm red colours denote the radio continuum maps while the cold blue colours represent the 21 cm intensity mapping. The error bars show the frequency ranges for each of the instruments or surveys. While the advantage of radio surveys is their high-angular resolutions, the surveys that measure the 21 cm signal possess good high-radial resolution, i.e., the frequency and its corresponding redshifts (dashed blue vertical lines). We mark the two kinds of resolutions as different colour gradients.

Radio surveys

Hou, Bautista, Berti et al. arXiv:2306.13726





Cosmic Visions A. Slosar et al &RA , arXiv:1810.09572

PUMA like futuristic survey

Many others (forecasts, phenomenology …)
Random selection

Karagiannis et al, arXiv:1911.03964

Santos et al, arXiv:1501.03989

Villaescusa et al, arXiv:1609.00019

Villaescusa et al, arXiv:1804.09180

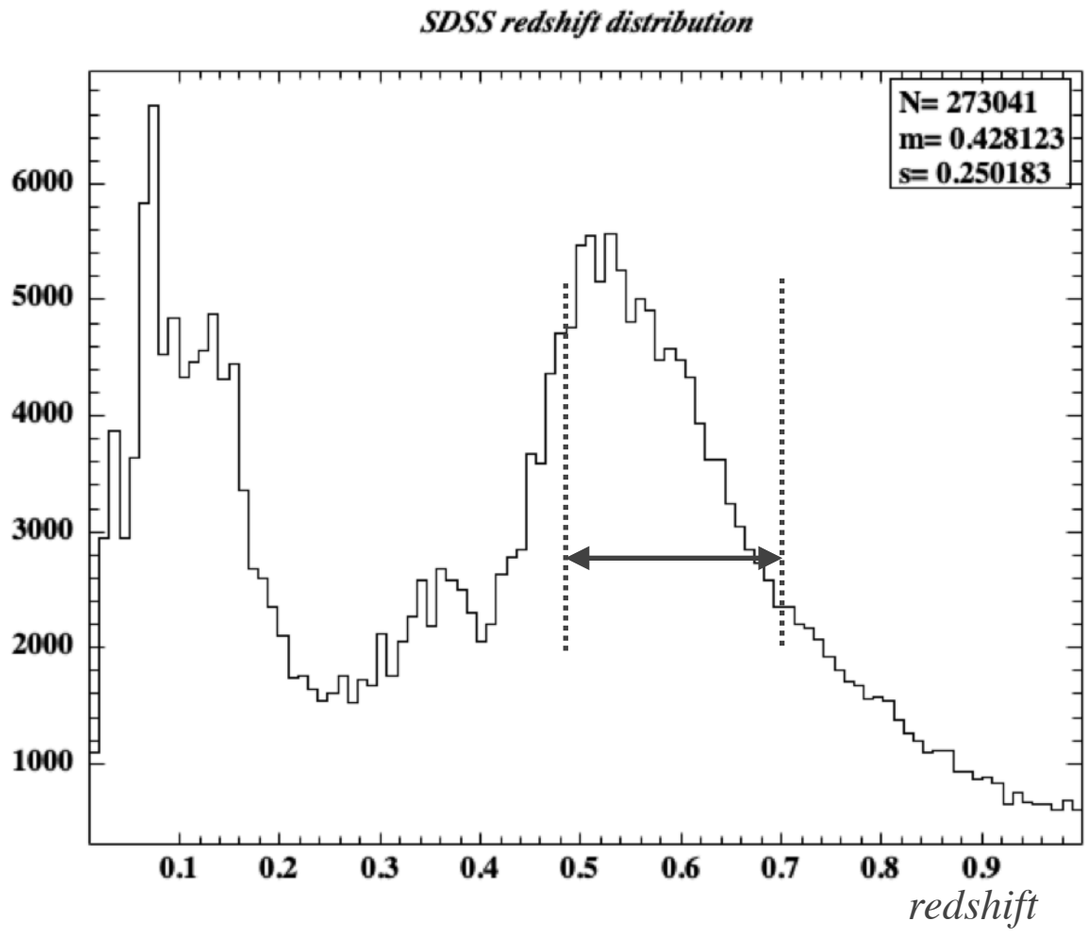
Witzemann et al, arXiv:1711.02179

Chen et al, arXiv:2010.07985

SKA-WG , Bacon et al. arXiv:1811.02743

Back to PhotoZ's

- External spectre-photometric datasets will be used for training purposes
- Rubin/LSST will also need external data sets with spectroscopic information to cross check and **Calibrate** photo-z's have to check the
- Cross-correlations with spectroscopic catalogs, such as the DESI catalog will be used for this purpose
- However, 21 cm intensity maps could provide alternative datasets to calibrate Rubin photo-z's



A preliminary study of this possibility
Simulation over about 2500 sq.deg.
~80 deg in ra, ~50 deg in dec
centered on ra=180, dec=40

Use of SDSS galaxies in the redshift range $0.5<z<0.7$ to create a fiducial LSS mass density contrast ($\delta\varrho/\varrho$)

$z \in [0.5,0.7]$ corresponds to 840-950 MHz for the redshifted 21cm, 3D maps with 0.25 deg. angular resolution and 1 MHz along frequency

21cm IM x LSST-like galaxy with photo-z catalog (I)

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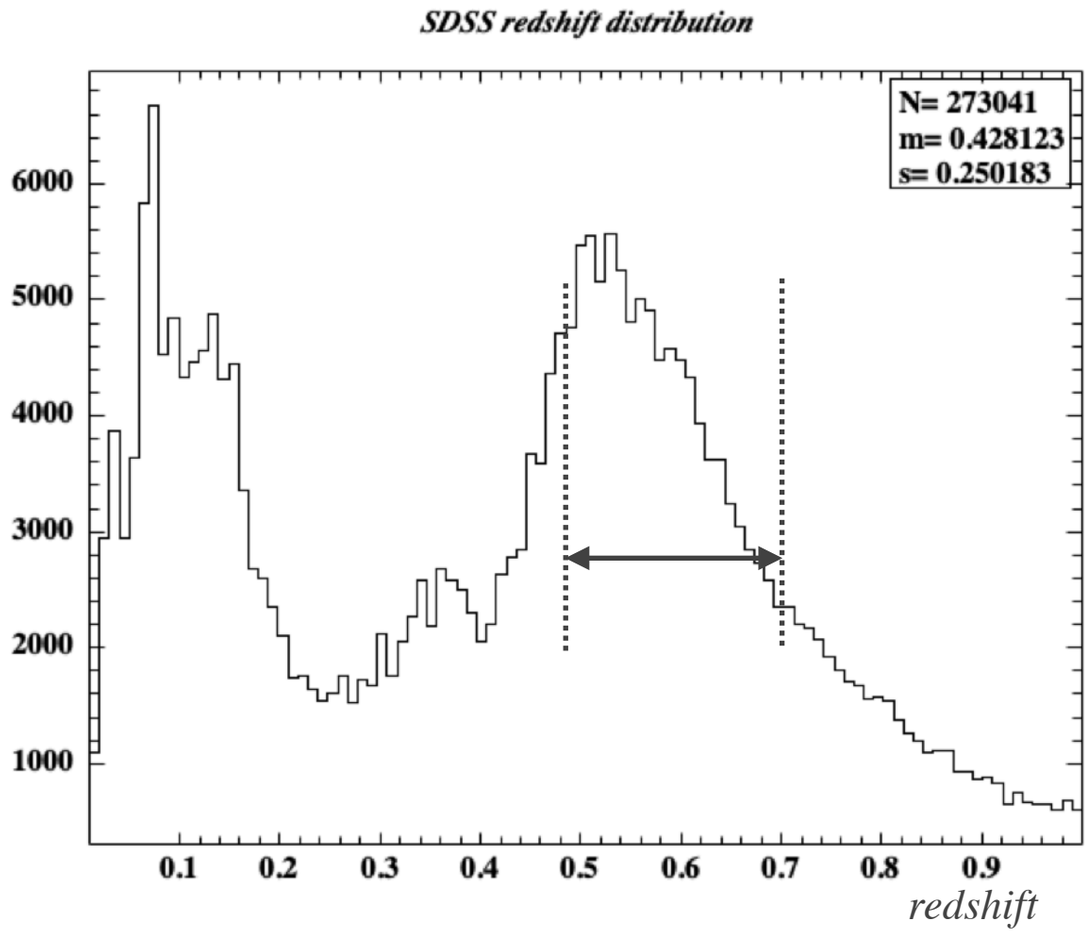

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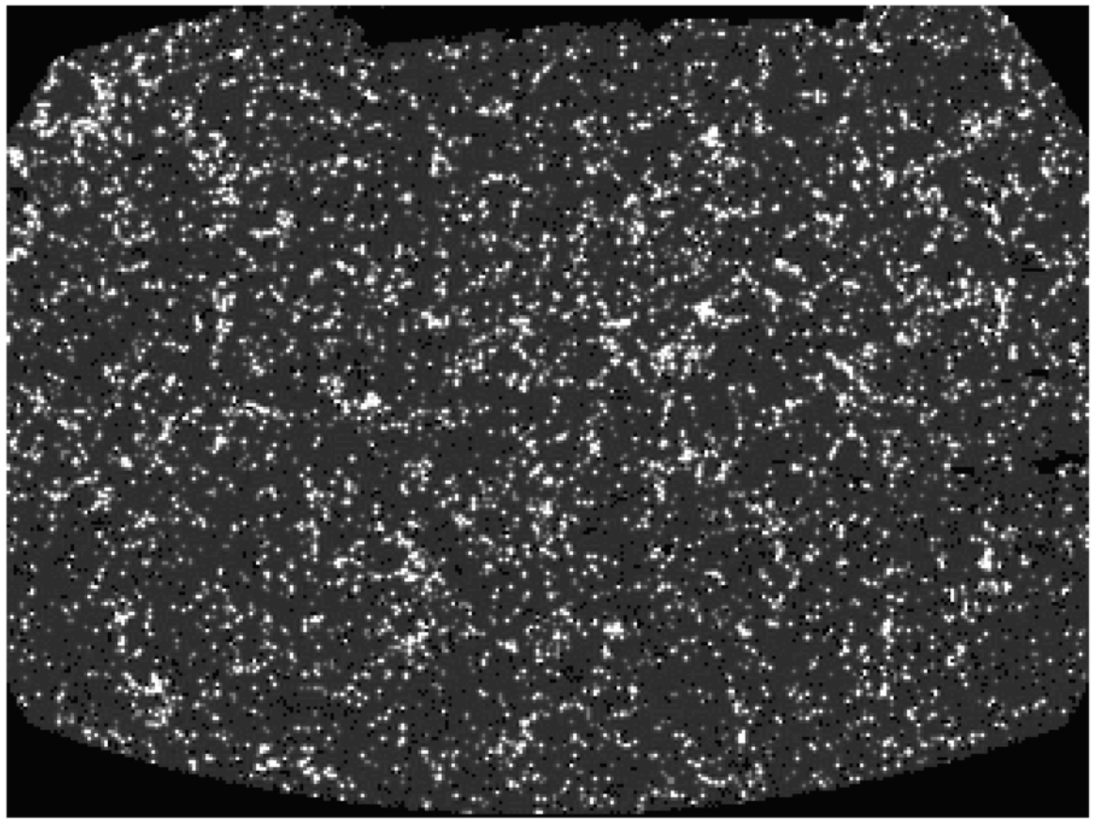
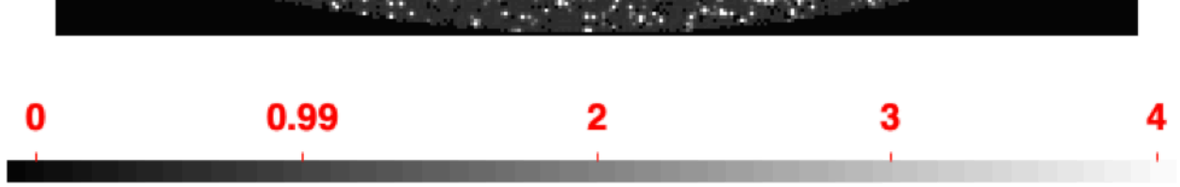
A slice at z ~ 0.6

α (~80 deg)

δ (~50 deg)

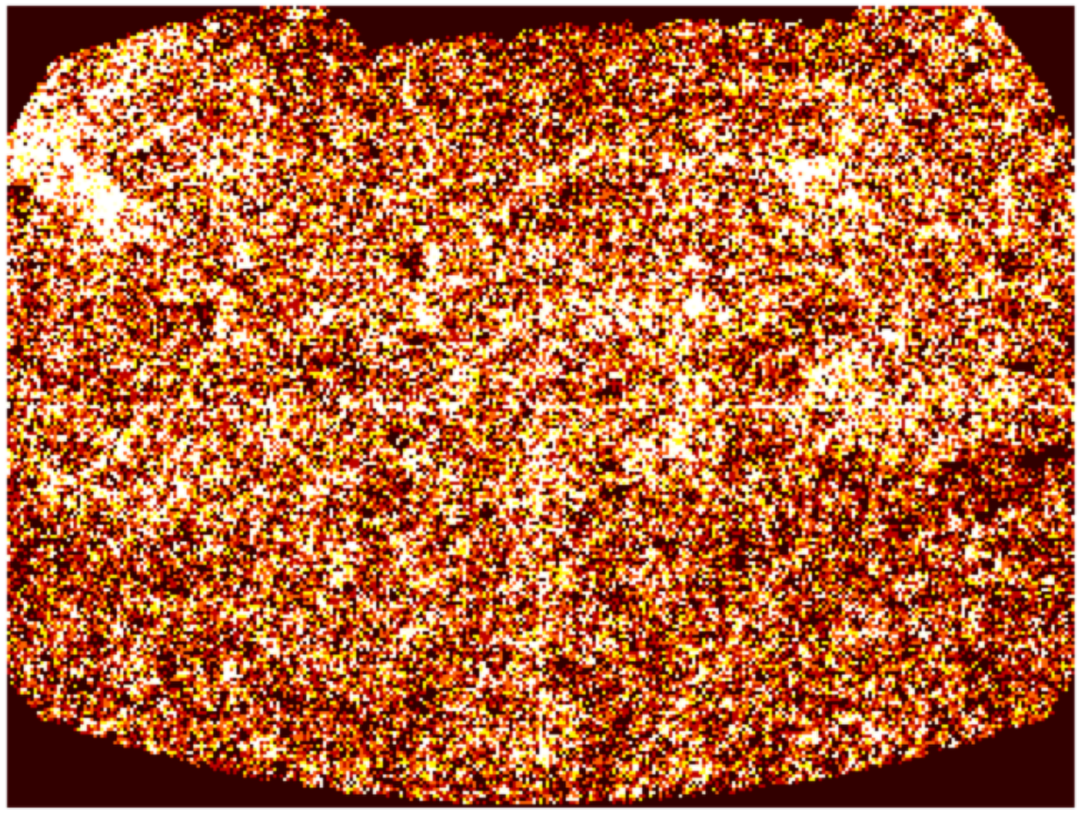




Galaxy Density contrast

$n_g/\bar{n}$

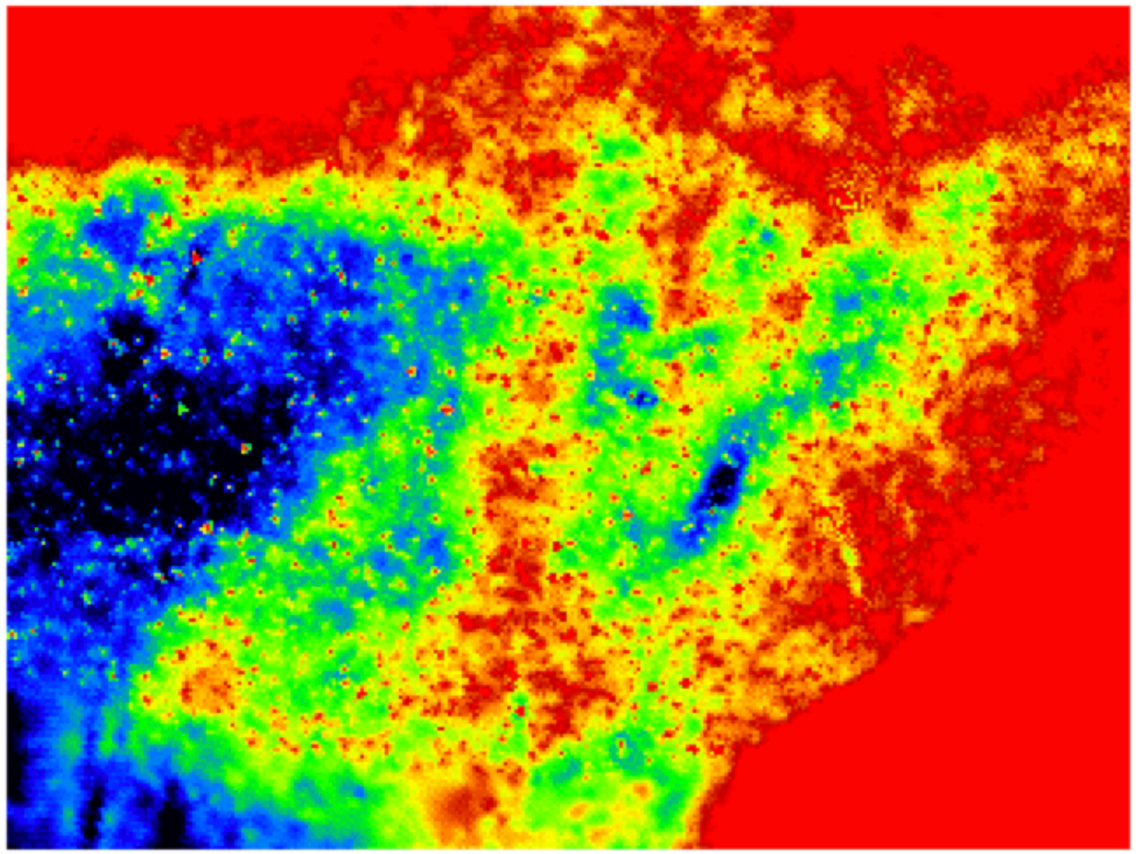
Photo-z smearing



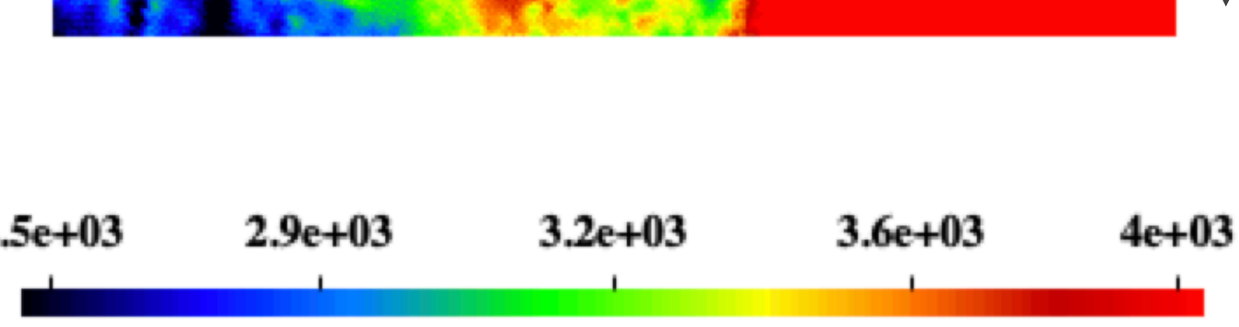
Slice of $\rho/\bar{\rho}$

Generated from SDSS galaxies
+ filtering to get $\sigma_8 \lesssim 1$

α (~80 deg)

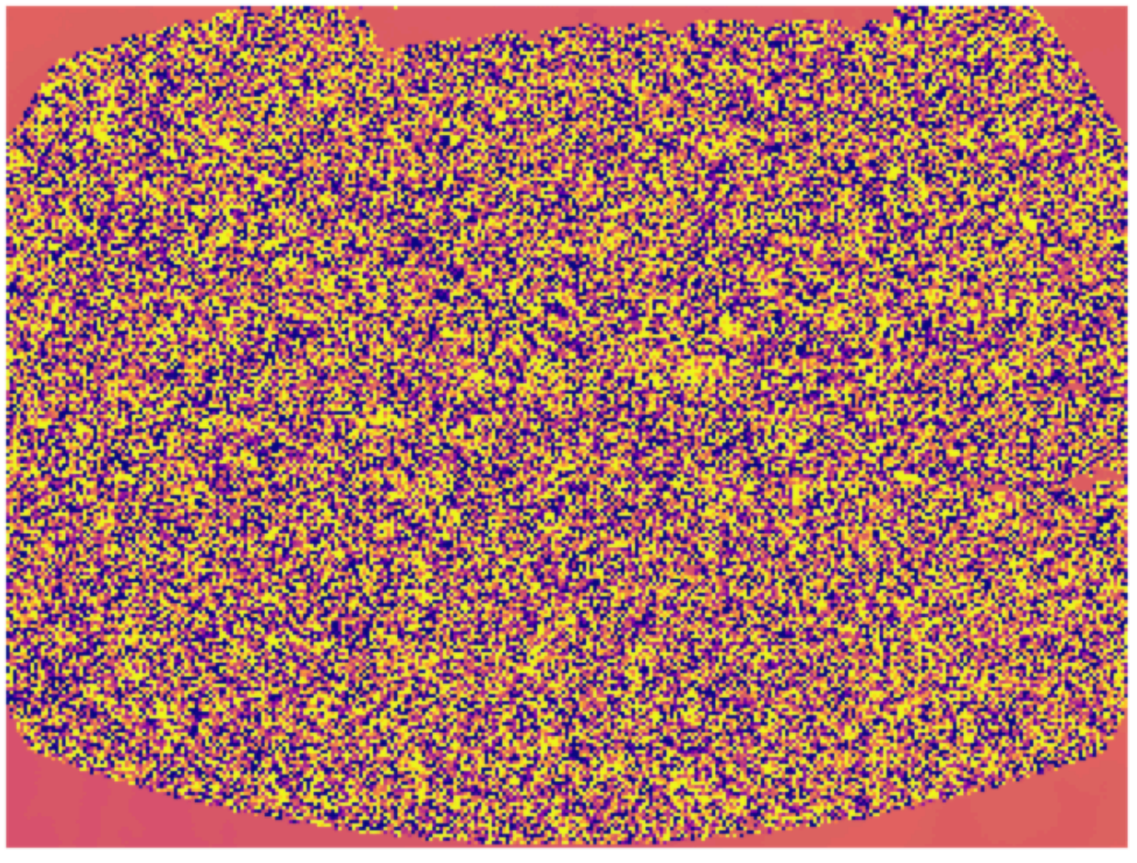


δ (~50 deg)



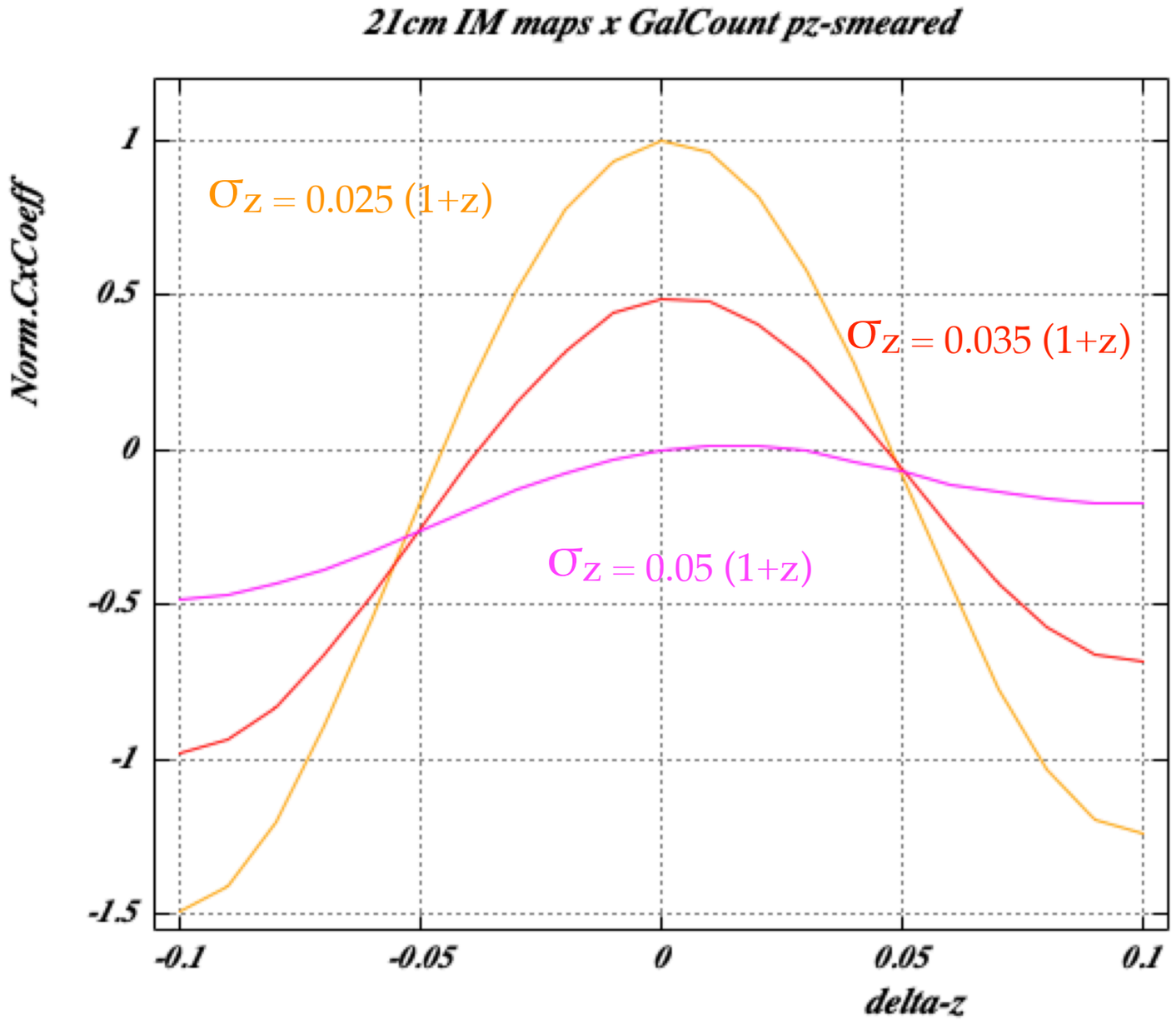
Corresponding radio sky
(temperature in mK)

T_{21} , after foreground subtraction , in mK
(noise dominated , $\sigma_n = 0.5$ mK)



21cm IM x LSST-like galaxy with photo-z catalog (II)

- Project galaxies into 3D map, 0.25 deg angular resolution, and 1 MHz along frequency or redshift
- Compute average cross-correlation, along the frequency axis for all sky directions (320 x 240 pixels)
- Check how the cross-correlation coefficient changes with an offset (shift) in the photo-z distribution
- Sky foreground Synchrotron + NVSS sources, a gaussian frequency dependent beam , corresponding to a dish D ~ 35 m
- 0.5 mK noise / 0.25 x 0.25 deg2 x 1 MHz pixel



END

Rubin Observatory

Telescope and summit

August 2020