Commissioning of the Vera C. Rubin Observatory and Weak Gravitational Lensing

Pierre-François Léget

Associate Research Scholar @ Princeton University

VERA C. RUBIN OBSERVATORY

U.S. National Science Foundation

U.S. DEPARTMENT of ENERGY | Office of Science

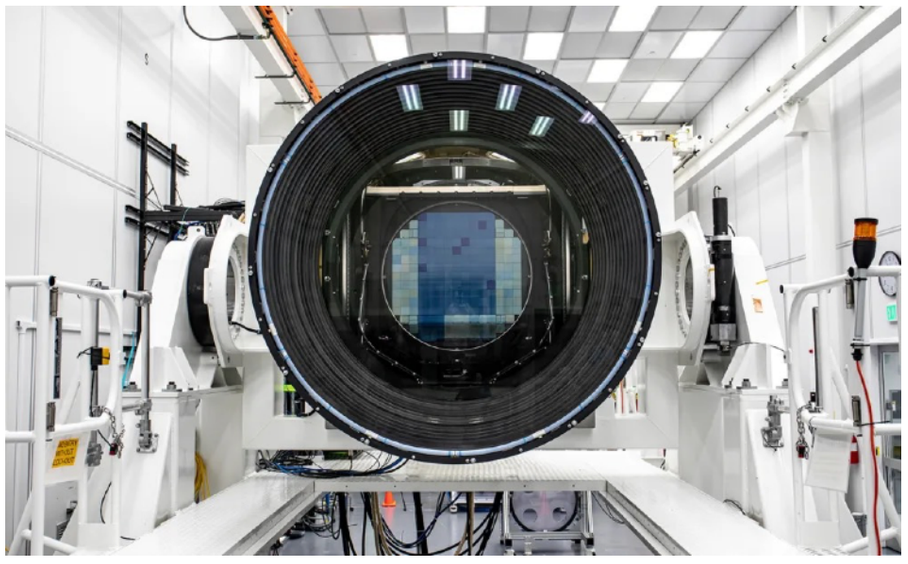
Credit: NSF–DOE Rubin Observatory/NOIRLab/SLAC/AURA/P. Lago

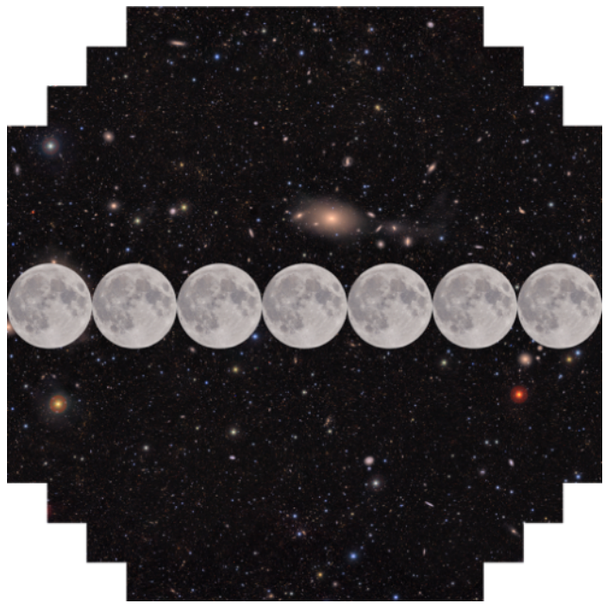
The Vera C. Rubin Observatory

- Rubin Observatory at Cerro Pachón, a mountain in Chile at 2,663 meters
- M1 + M3 : 8.4 meters

The Camera (CCDs)

- 189 Science CCD (3.2 Gigapixels total) with ~10 square degrees FoV

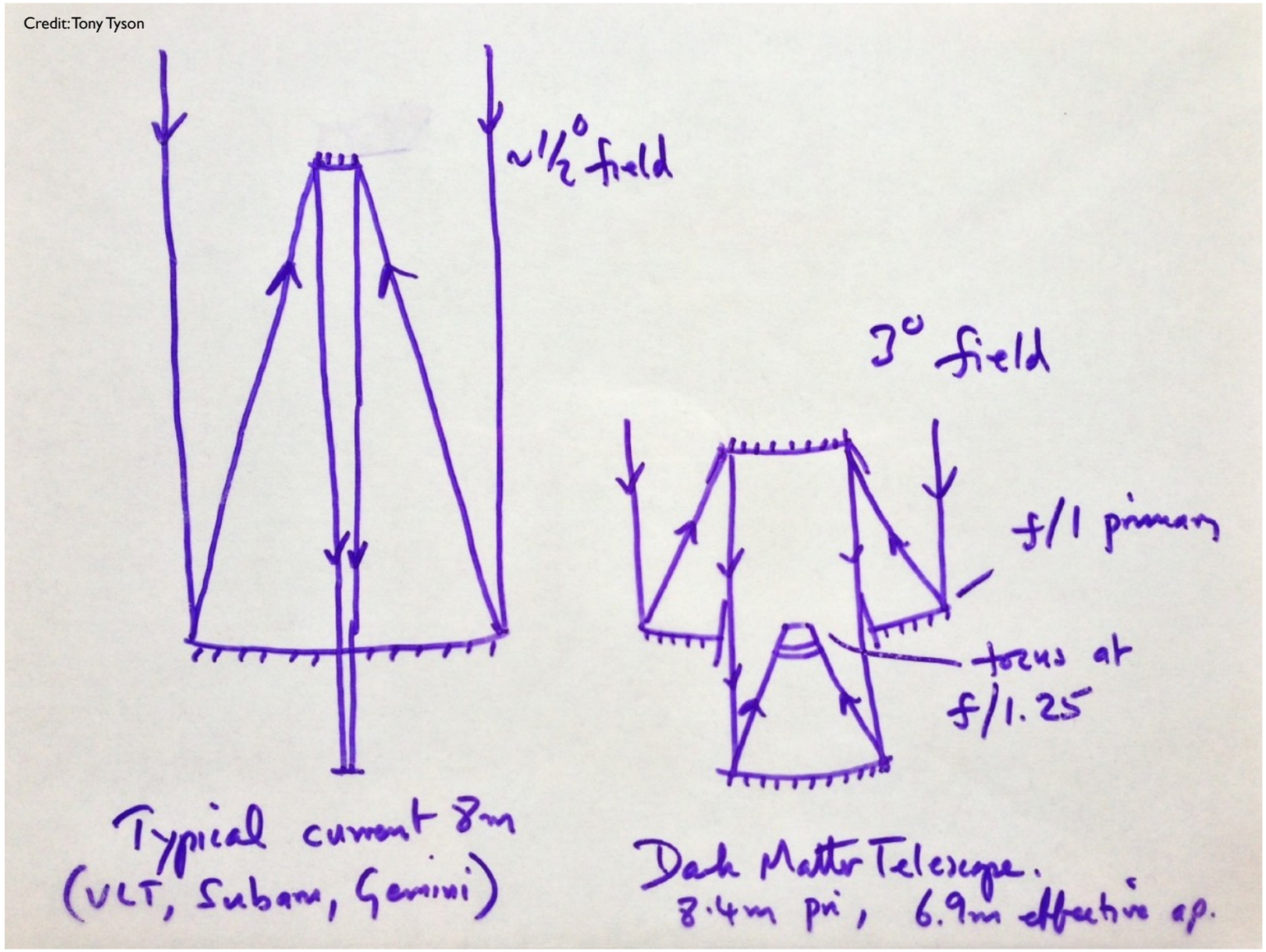




Primary Science Targets:

- Dark Energy & Dark Matter
- The "Changing" Sky
- The Solar System
- The Milky Way

Selected timeline of the Rubin Observatory



The Dark Matter Telescope optical design on a "real" slide

From Tony Tyson in end of 1990 beginning of 2000

Main purpose is weak gravitational lensing

~2000 first concept

Selected timeline of the Rubin Observatory

Credit: NSF–DOE Vera C. Rubin Observatory/NOIRLab/SLAC/NSF/DOE/AURA

First stone in 2015, start of the construction of the project

Now the project is named the Large Synoptic Survey Telescope (LSST).

~2000 first concept

2015 first stone

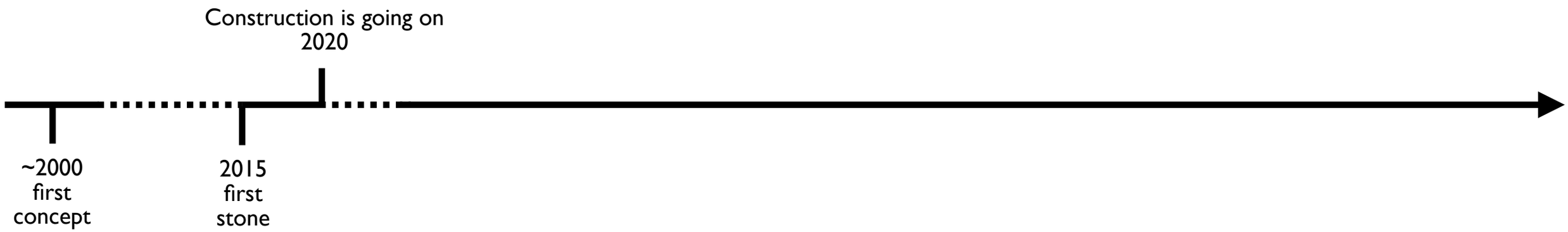
Selected timeline of the Rubin Observatory

State of the construction back in February 2020

Now the project is called the Vera C. Rubin Observatory and the survey from the the Rubin Observatory is called the "Legacy Survey of Space and Time"

In a slide deck I found from me in beginning of March 2020 I was saying "First light in 2021"

Well something happened in 2020…



Selected timeline of the Rubin Observatory

First light of LSSTCam started in April 2025

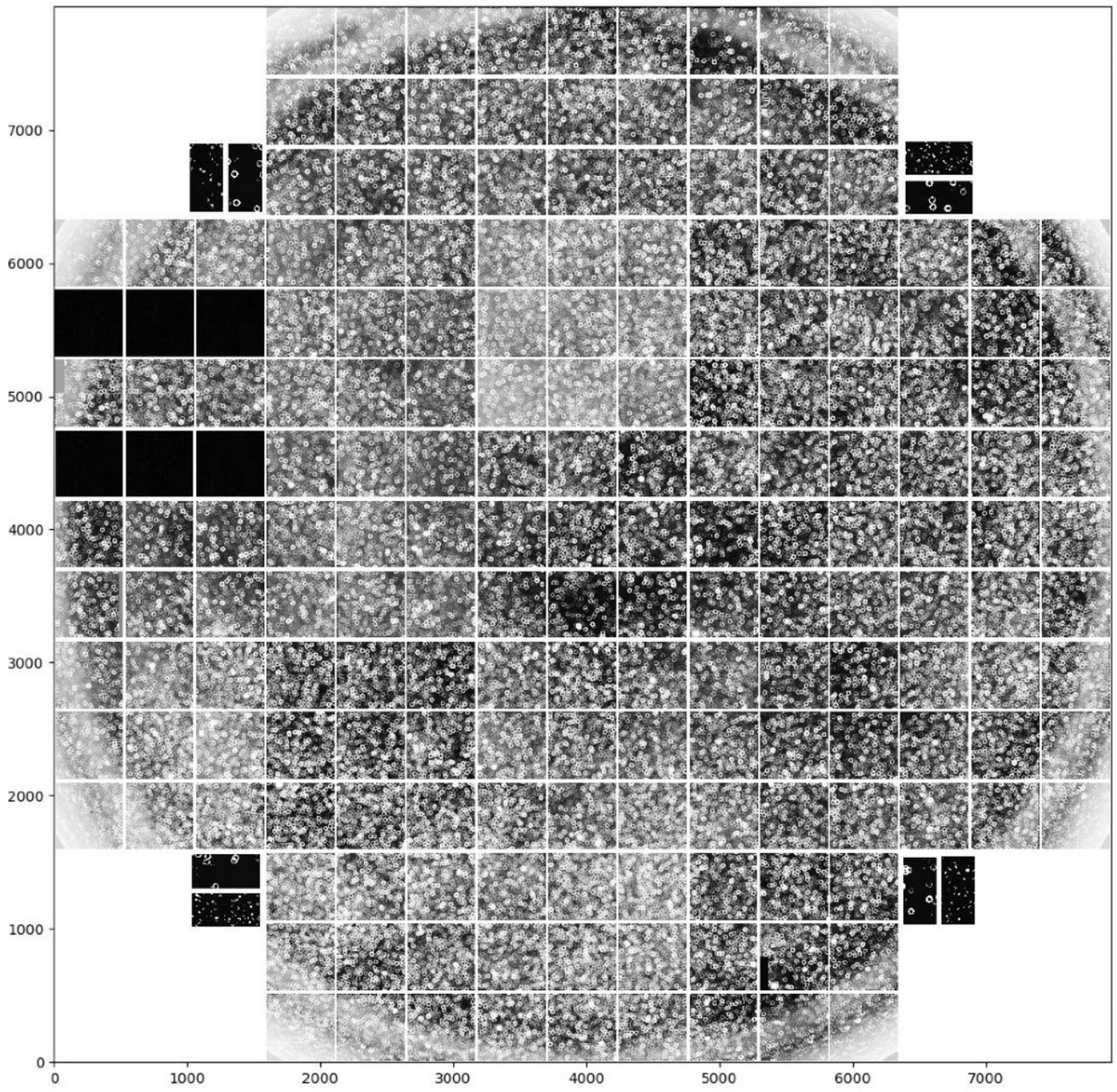
Construction is going on 2020

~2000 first concept

2015 first stone

April 2025 first light

Selected timeline of the Rubin Observatory



First image (visit) with LSSTCam with photons coming from the sky

What is going on? Let's zoom in…

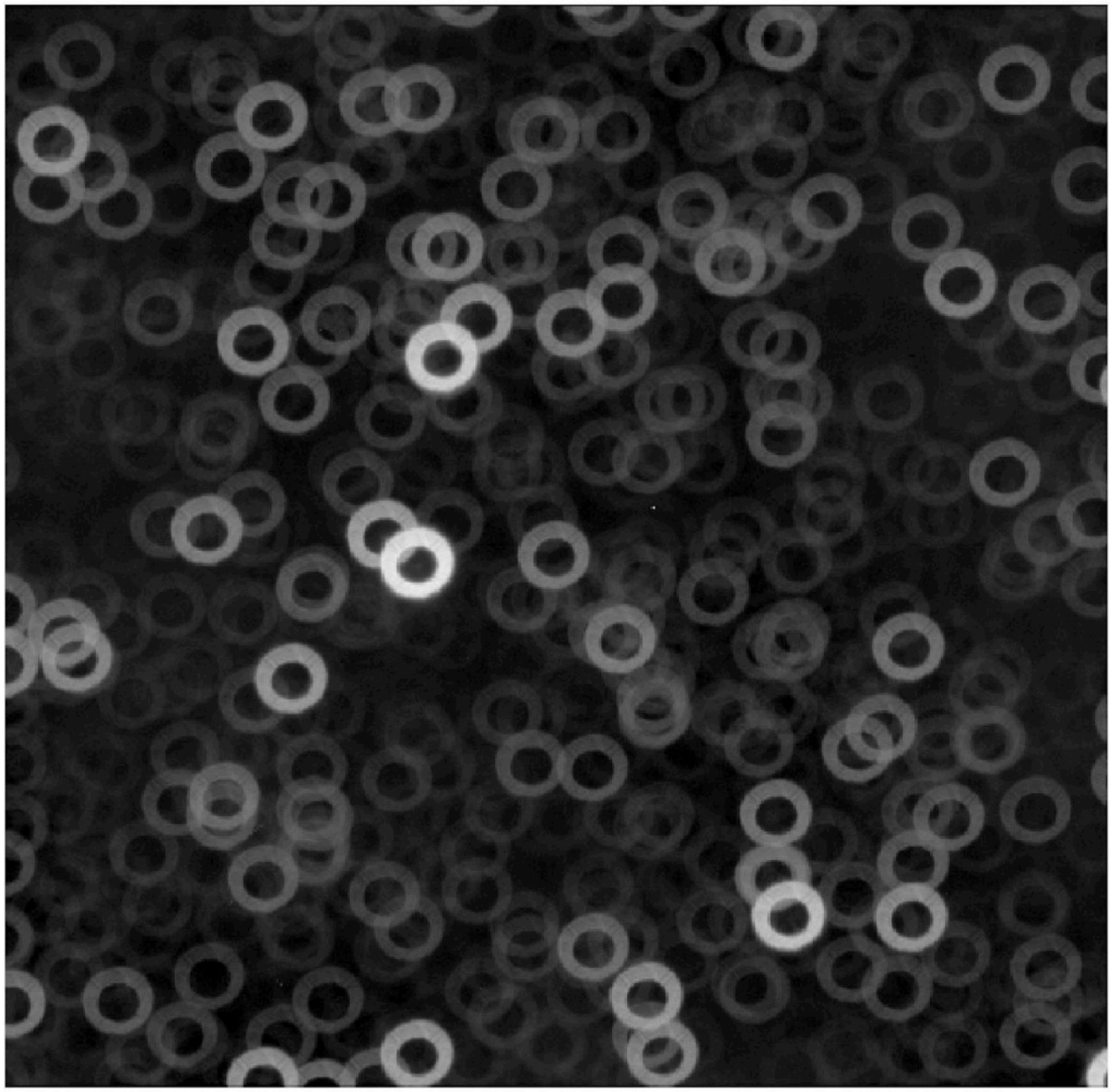
Construction is going on 2020

~2000 first concept

2015 first stone

April 2025 first light

Selected timeline of the Rubin Observatory



Ok object from the sky looks like donuts but why?

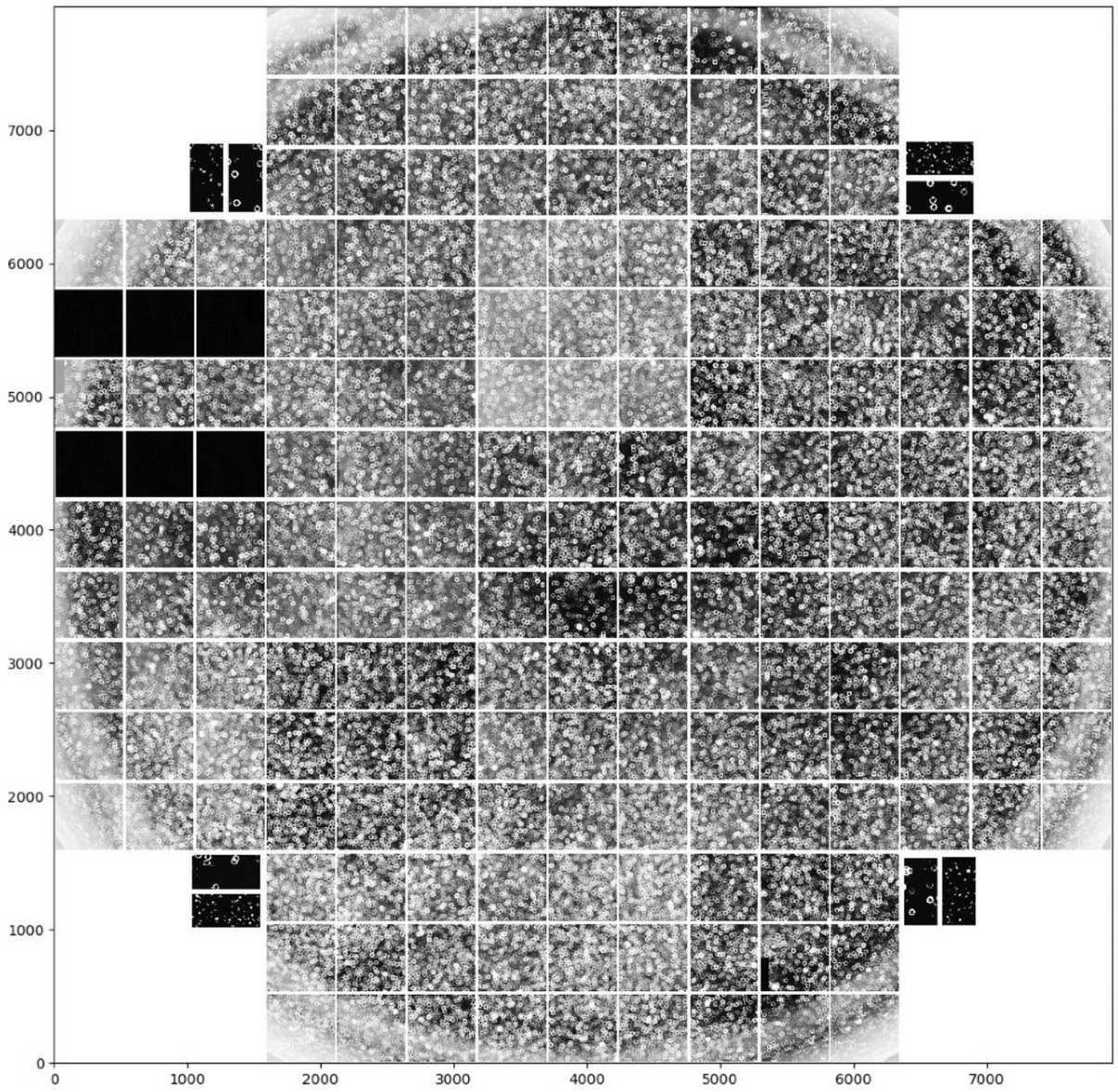
Construction is going on
2020

~2000
first
concept

2015
first
stone

April 2025
first light

Selected timeline of the Rubin Observatory



So the telescope is out of focus, how do we move forward ?

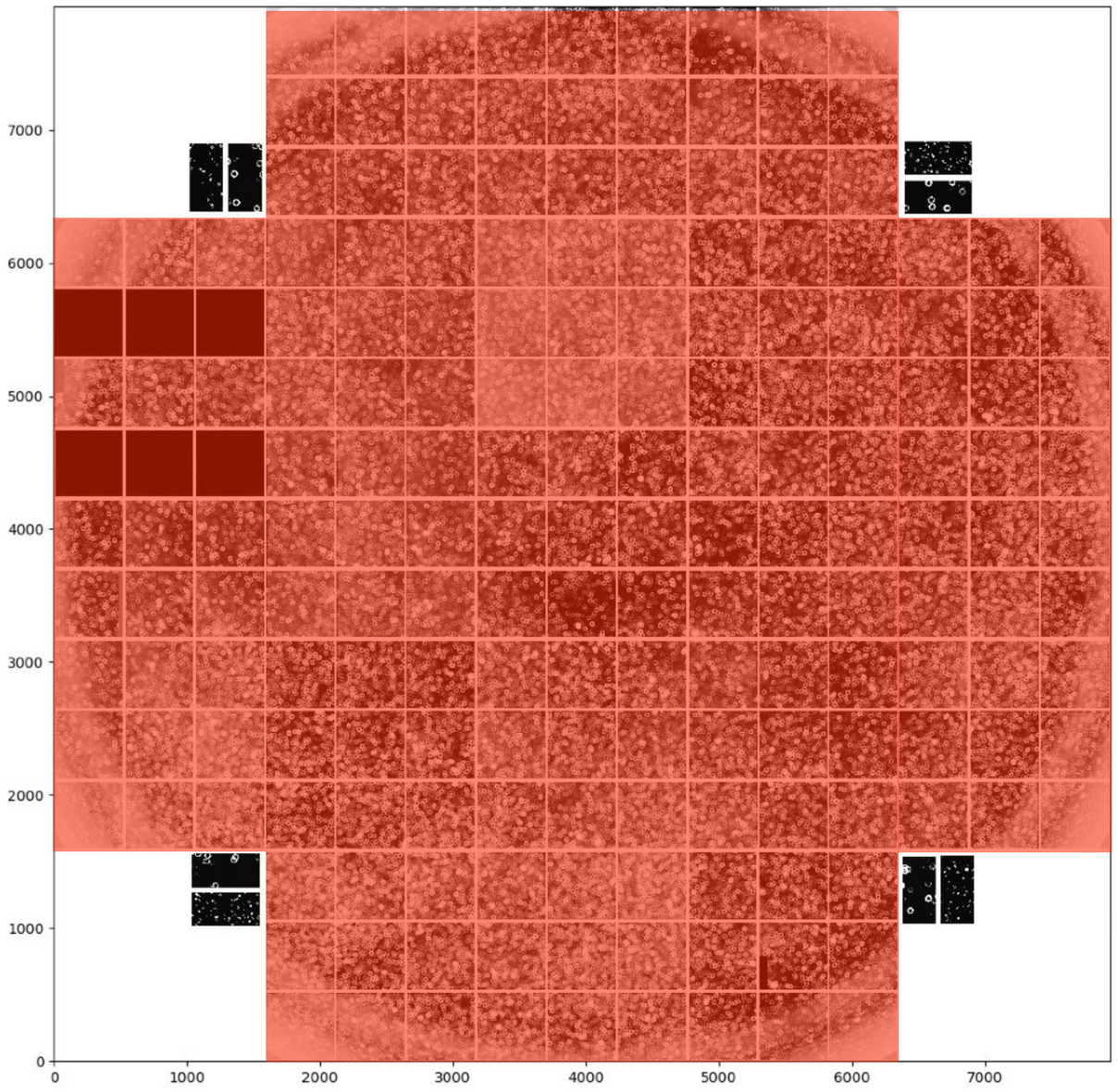
Construction is going on 2020

~2000 first concept

2015 first stone

April 2025 first light

Selected timeline of the Rubin Observatory



So the telescope is out of focus, how do we move forward ?

Science sensors / CCDs

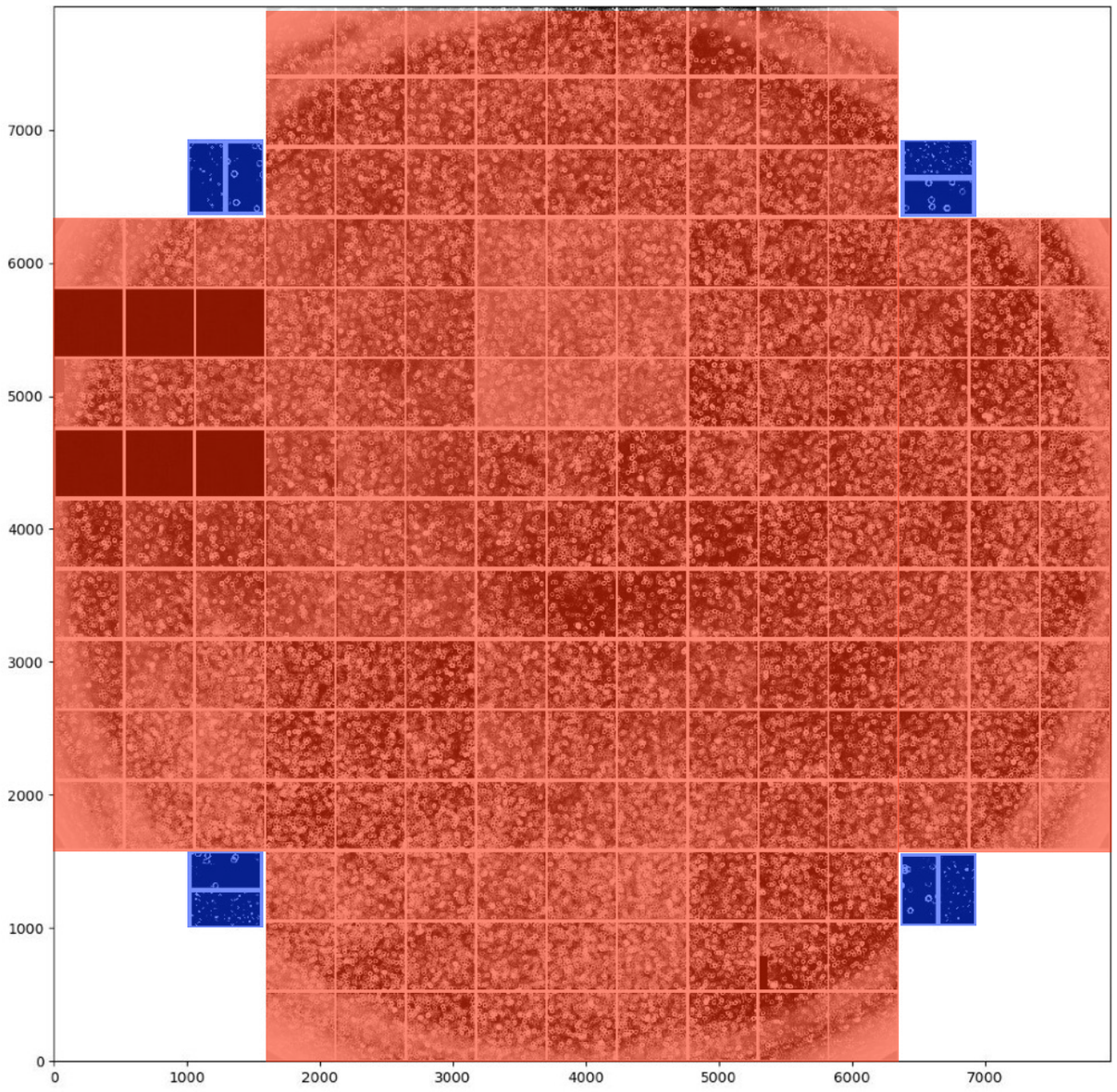
Construction is going on 2020

~2000 first concept

2015 first stone

April 2025 first light

Selected timeline of the Rubin Observatory



So the telescope is out of focus, how do we move forward ?

Science sensors / CCDs

Wavefront sensors / CCDs:

On purpose in/out of focus imagers, where you will have always donuts —> Donuts tell us how to move the optical system put the telescope in focus and minimize optical aberration.

It is the Active Optical System (AOS)

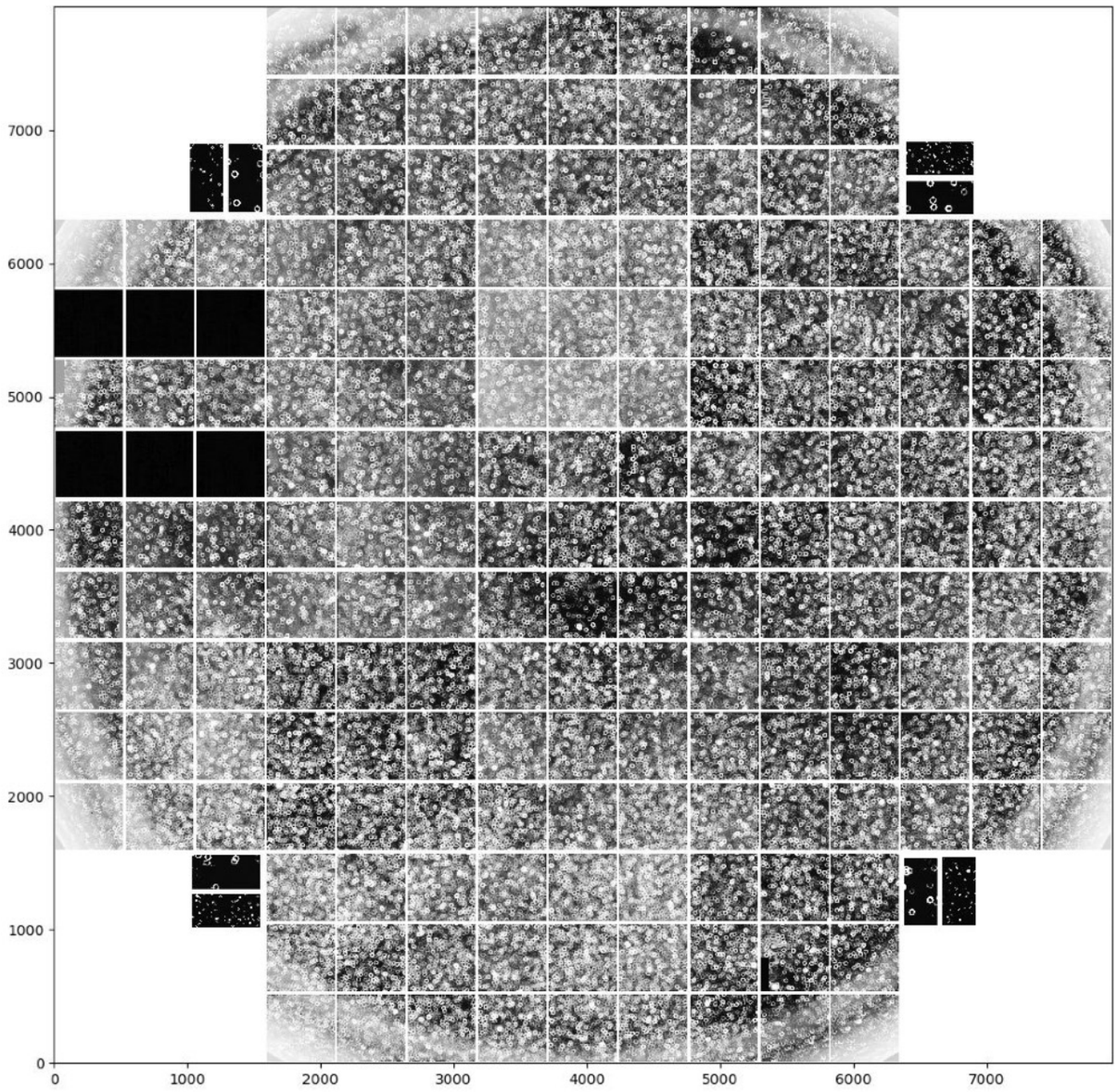
Construction is going on 2020

~2000 first concept

2015 first stone

April 2025 first light

Selected timeline of the Rubin Observatory



Let the AOS to do its magic!

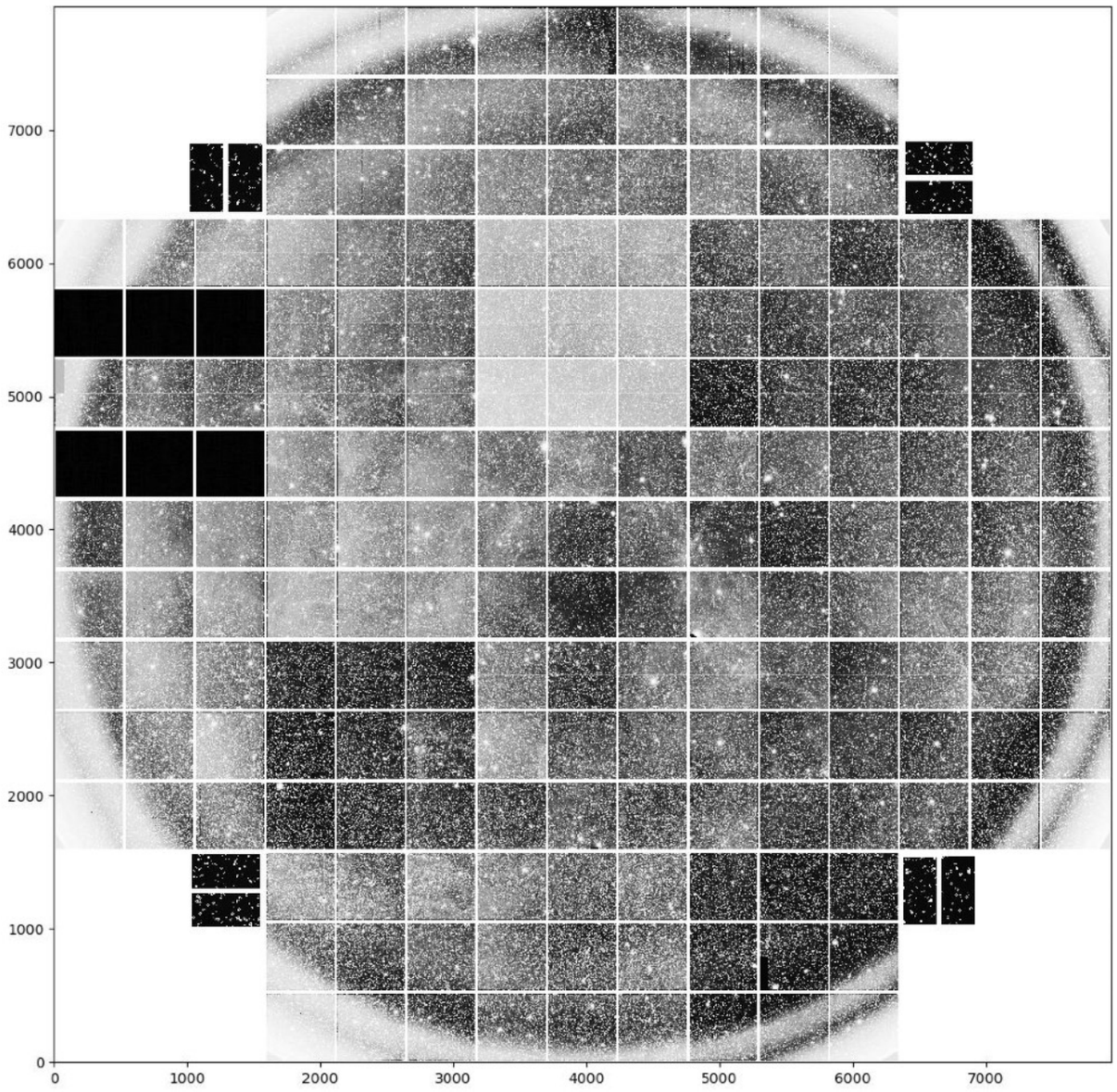
Construction is going on
2020

~2000
first
concept

2015
first
stone

April 2025
first light

Selected timeline of the Rubin Observatory



Let the AOS to do its magic!

Hooray!

This is the raw image, let the image processing do its magic now!

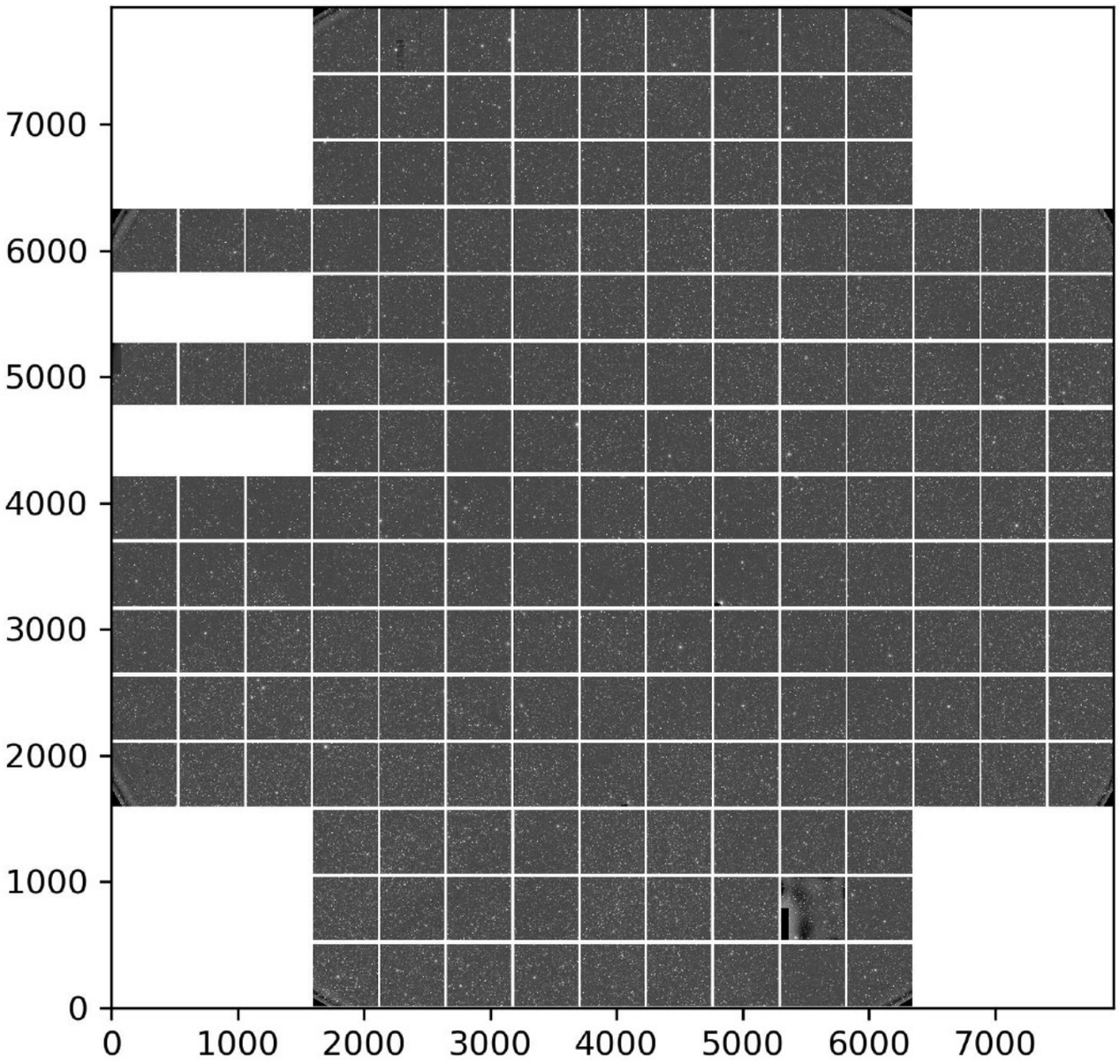
Construction is going on 2020

~2000 first concept

2015 first stone

April 2025 first light

Selected timeline of the Rubin Observatory



Let the AOS to do its magic!

Hooray!

This is the raw image, let the image processing do its magic now!

Hooray!

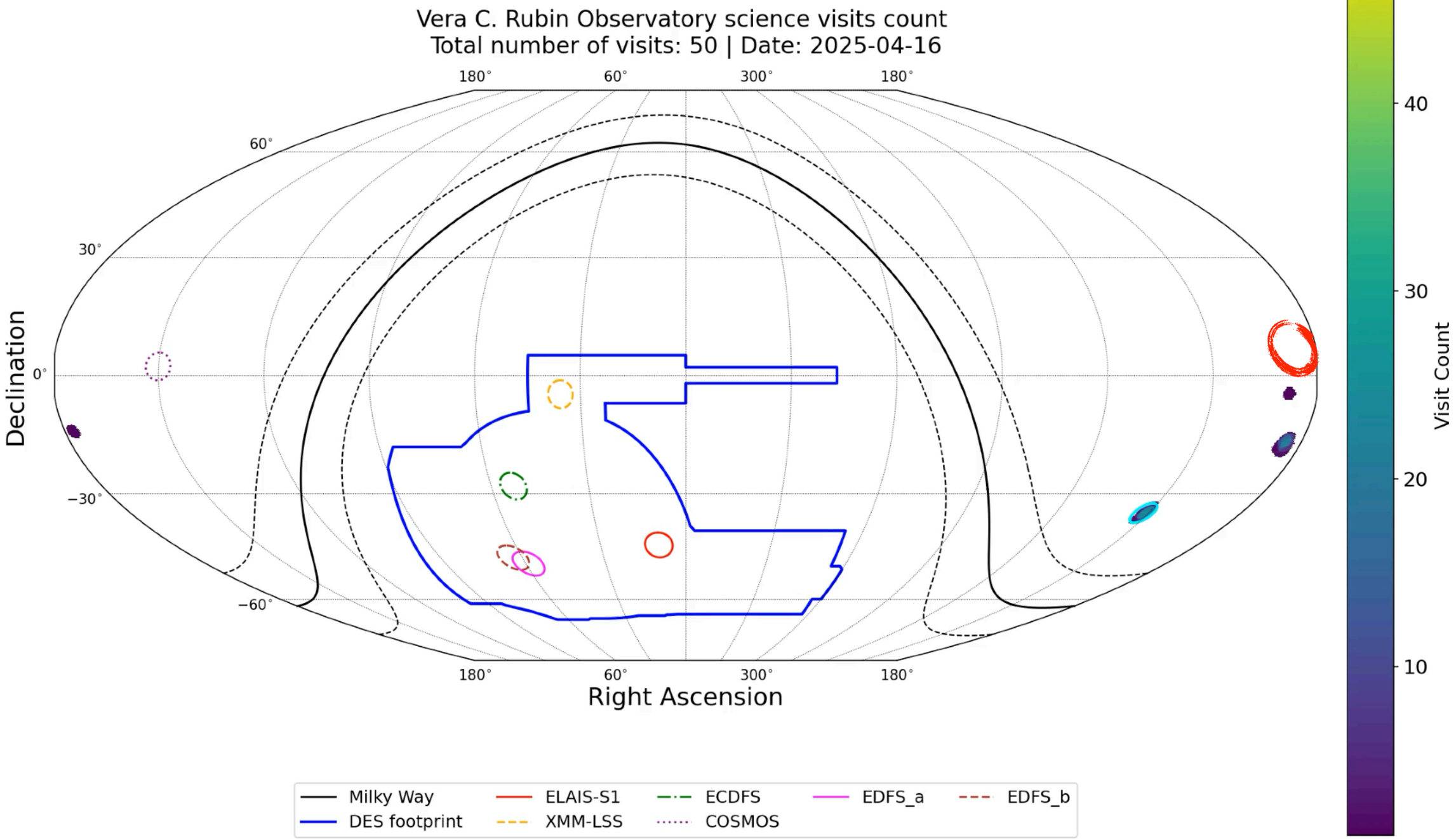
Construction is going on 2020

~2000 first concept

2015 first stone

April 2025 first light

Selected timeline of the Rubin Observatory



~2000
first
concept

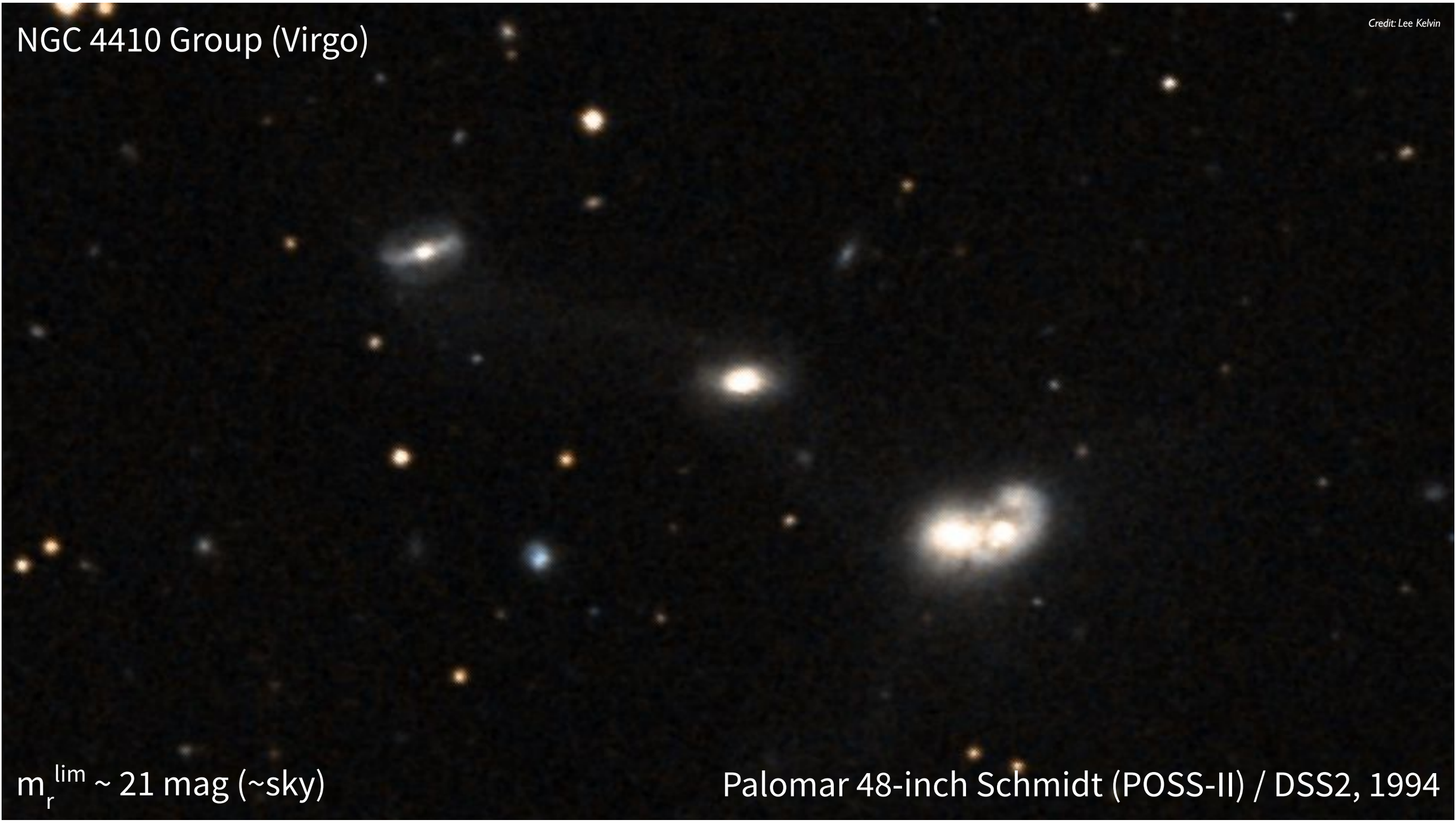
2015
first
stone

Construction is going on
2020

April 2025
first light

First look event
June 2025

Selected timeline of the Rubin Observatory



Construction is going on
2020

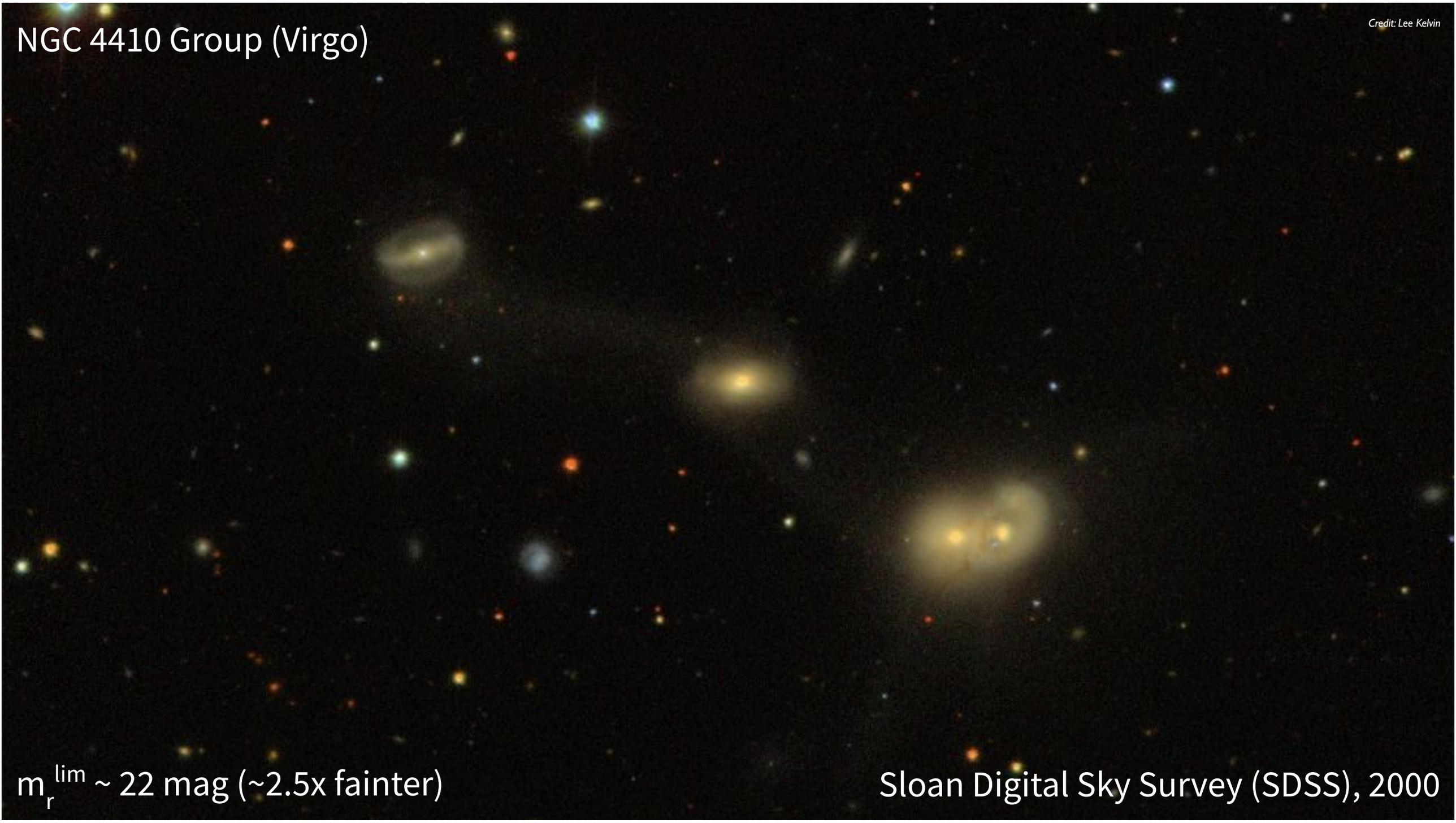
First look event
June 2025

~2000
first
concept

2015
first
stone

April 2025
first light

Selected timeline of the Rubin Observatory



Construction is going on
2020

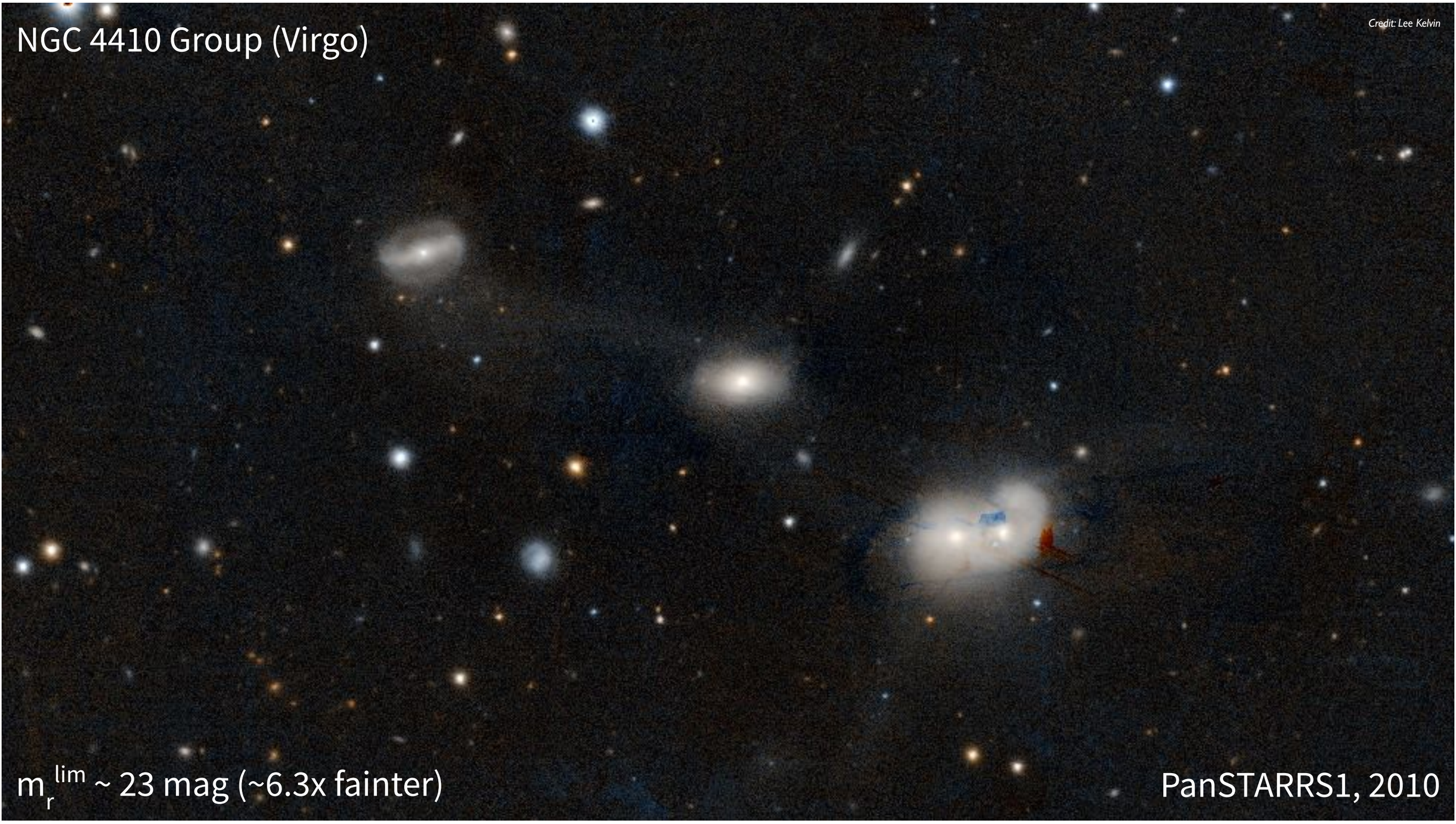
First look event
June 2025

~2000
first
concept

2015
first
stone

April 2025
first light

Selected timeline of the Rubin Observatory



~2000
first
concept

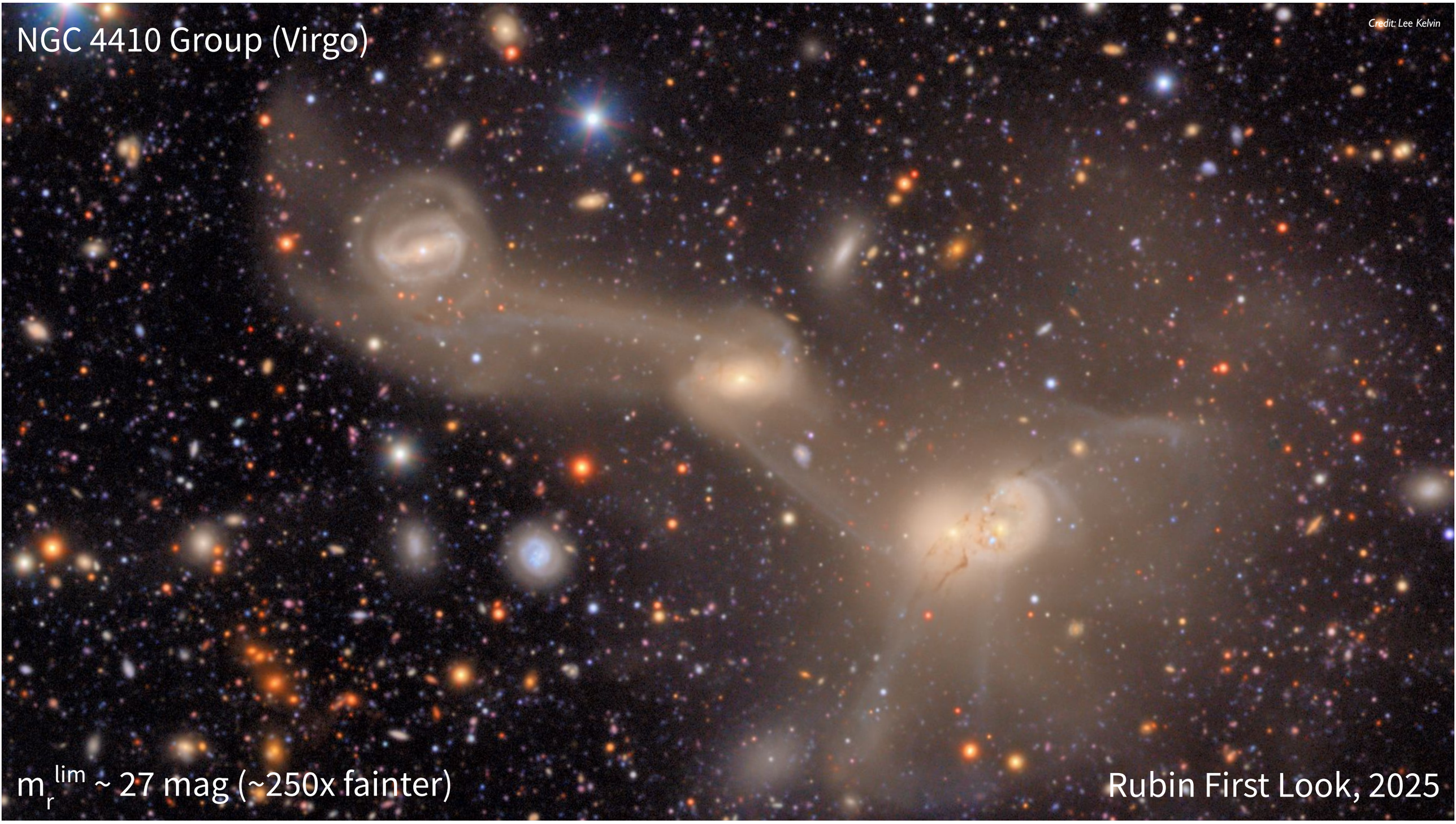
2015
first
stone

Construction is going on
2020

April 2025
first light

First look event
June 2025

Selected timeline of the Rubin Observatory



~2000
first
concept

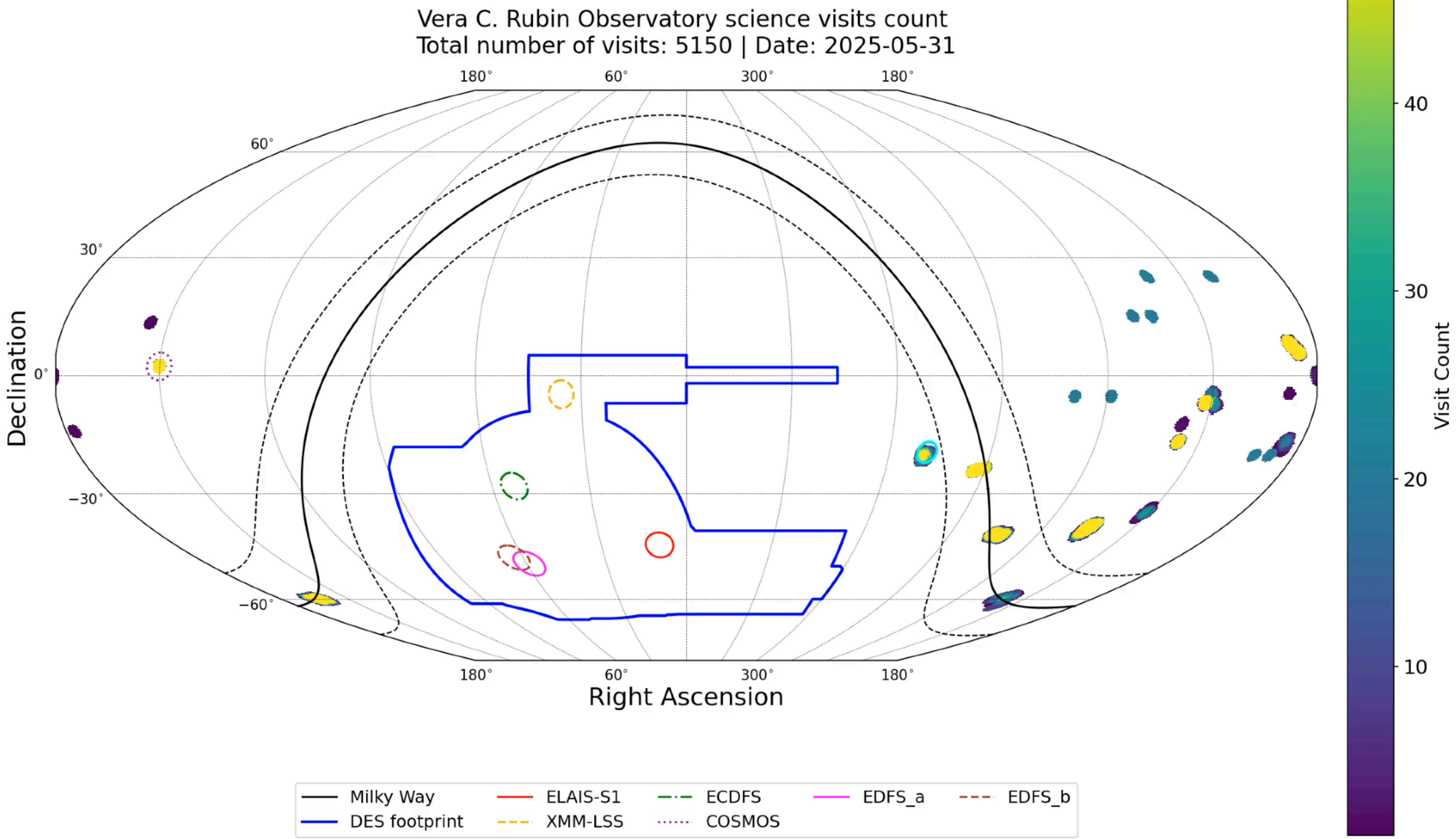
2015
first
stone

Construction is going on
2020

April 2025
first light

First look event
June 2025

Selected timeline of the Rubin Observatory



Construction is going on
2020

First look event
June 2025

Alert system is enable
for the public
February 2026

Data Preview 2 is public
~mid 2026

~2000
first
concept

2015
first
stone

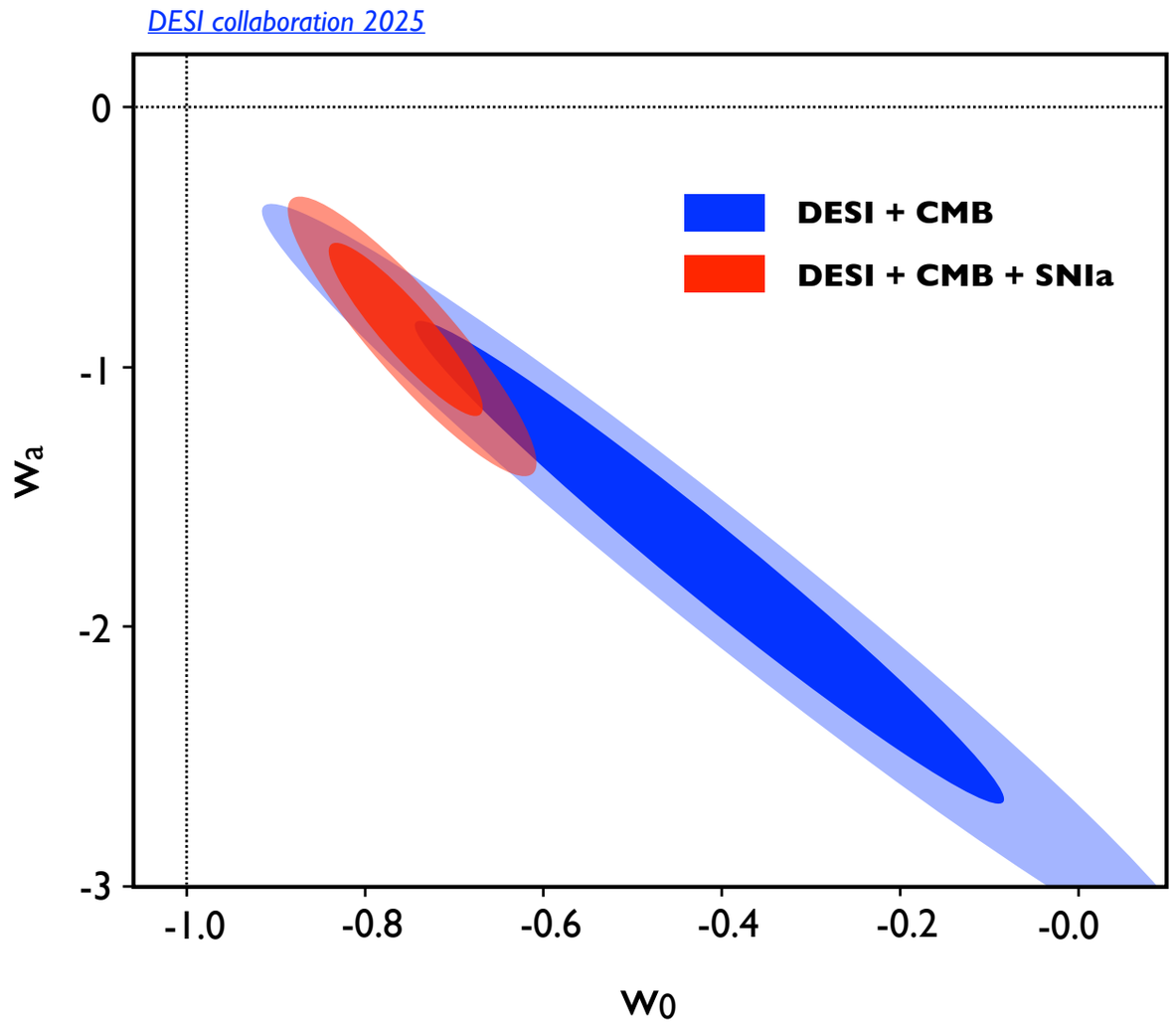
April 2025
first light

January 2026
Data Preview 2 data set will stop here

? 2026
LSST start

Dark Energy and the Vera Rubin Observatory

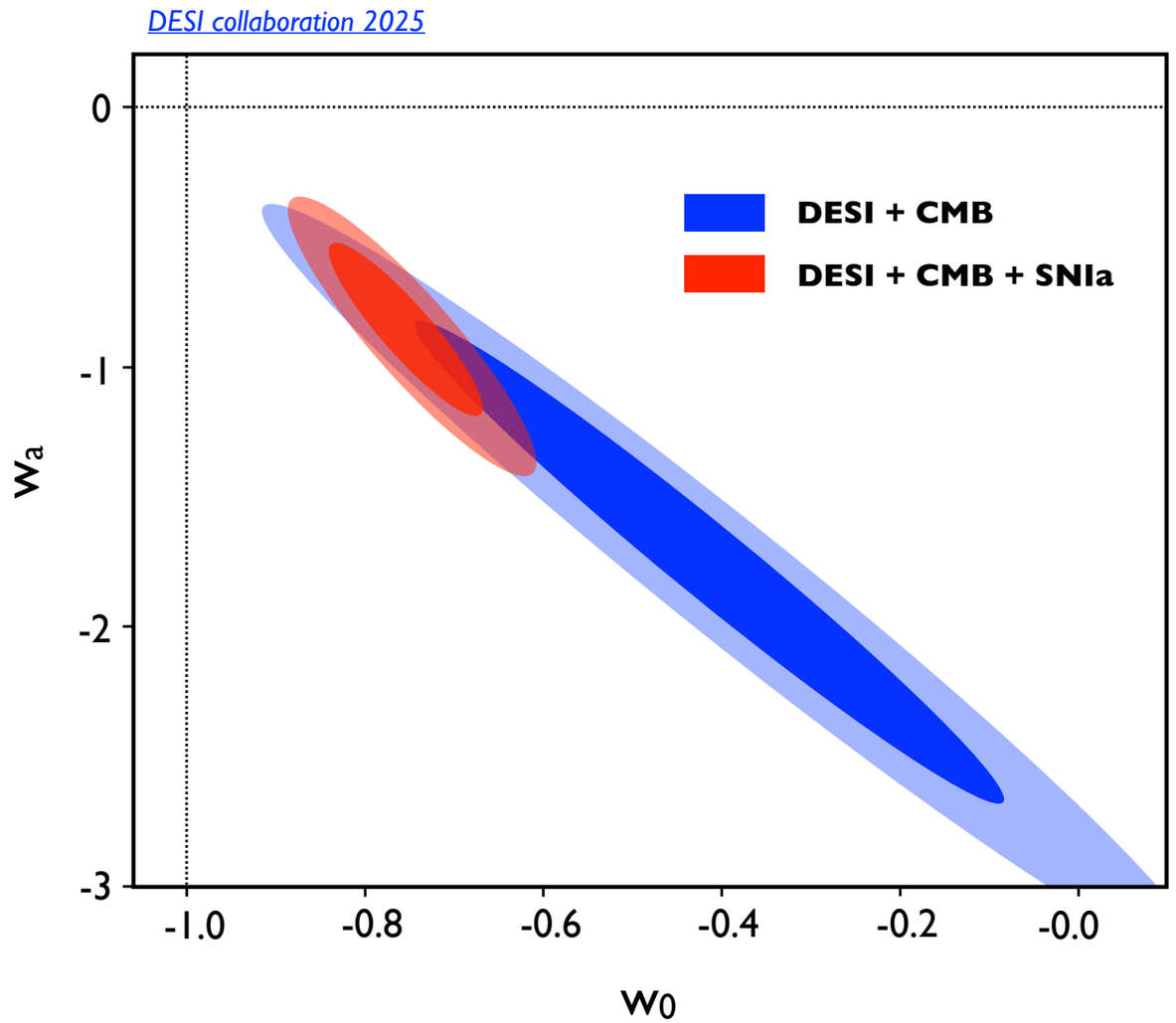
- The question is what is the nature of Dark Energy?
- First evidence of time evolving Dark Energy with DESI (+ CMB + SNIa)!



Dark Energy and the Vera Rubin Observatory

- The question is what is the nature of Dark Energy?
- First evidence of time evolving Dark Energy with DESI (+ CMB + SNIa)!

What next generation survey, like the Vera Rubin Observatory have to say about this?



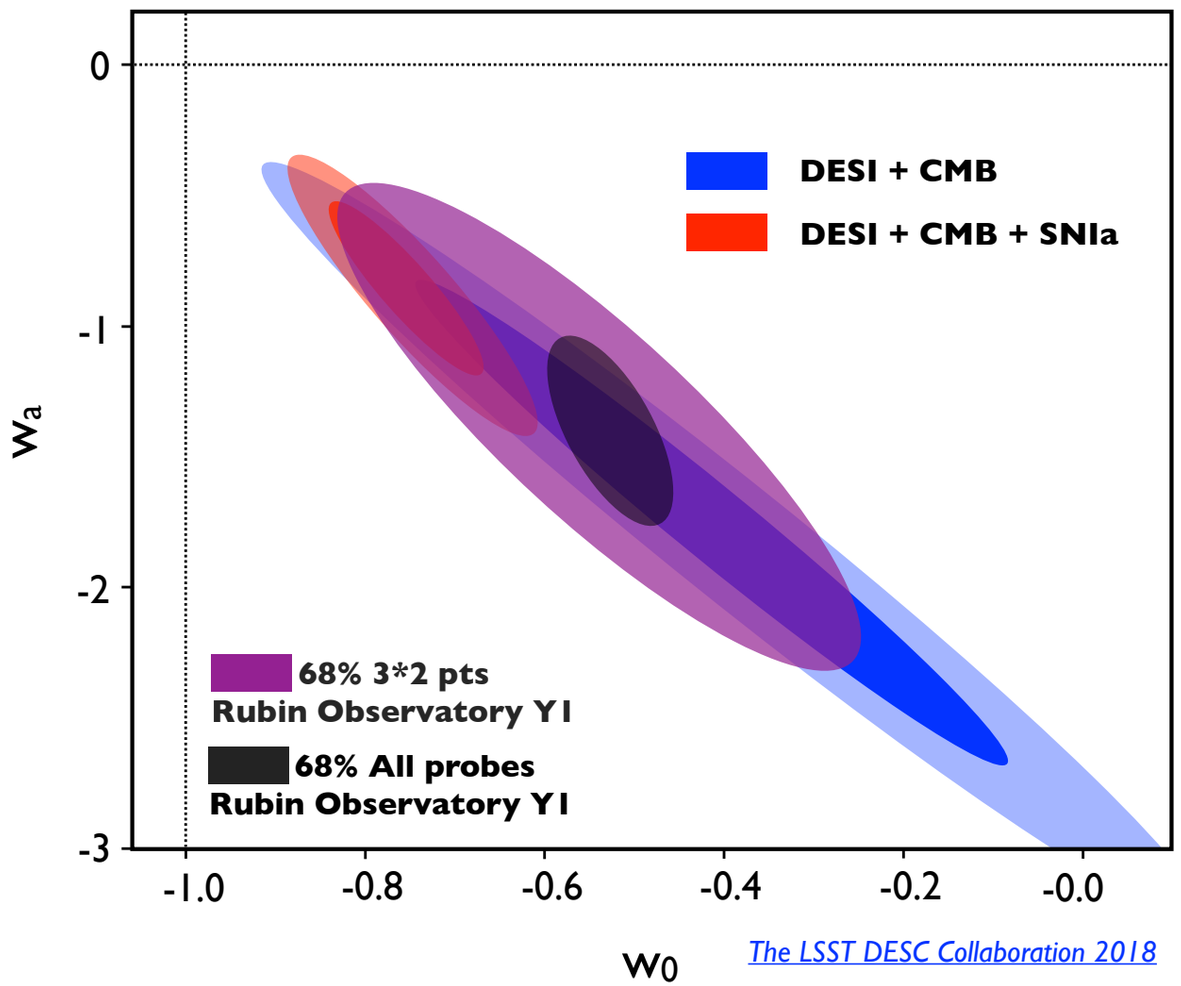
Dark Energy and the Vera Rubin Observatory

- The question is what is the nature of Dark Energy?
- First evidence of time evolving Dark Energy with DESI (+ CMB + SNIa)!

What next generation survey, like the Vera Rubin Observatory have to say about this?

- The best constrain alone is from the 3x2-points correlation function analysis.
- Can do multi joint constraint

DESI collaboration 2025



The LSST DESC Collaboration 2018

Dark Energy and the Vera Rubin Observatory

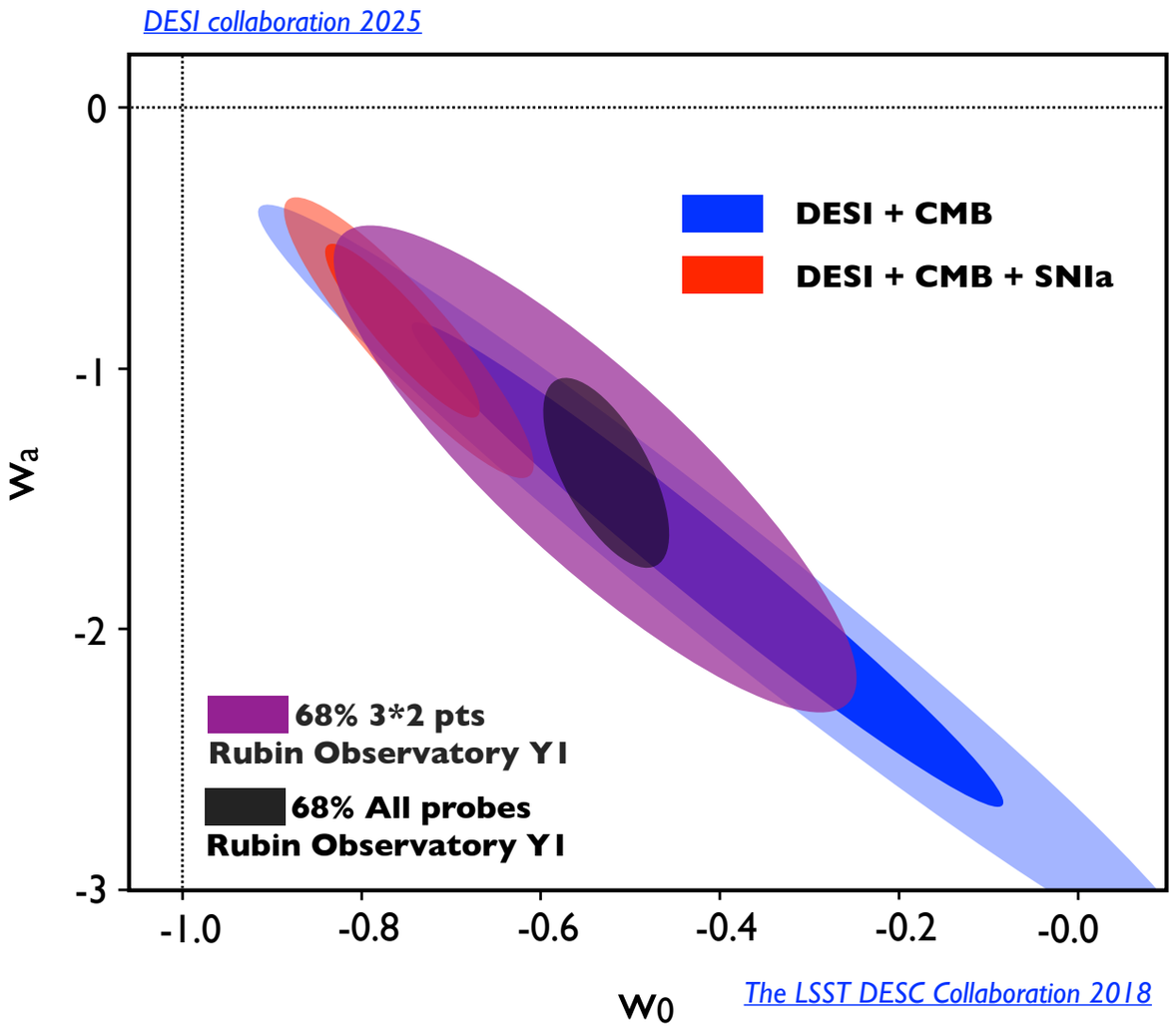
- The question is what is the nature of Dark Energy?
- First evidence of time evolving Dark Energy with DESI (+ CMB + SNIa)!

What next generation survey, like the Vera Rubin Observatory have to say about this?

- The best constrain alone is from the 3x2-points correlation function analysis.
- Can do multi joint constraint

IF systematics are under control (Not yet in the pocket!)

DESI collaboration 2025



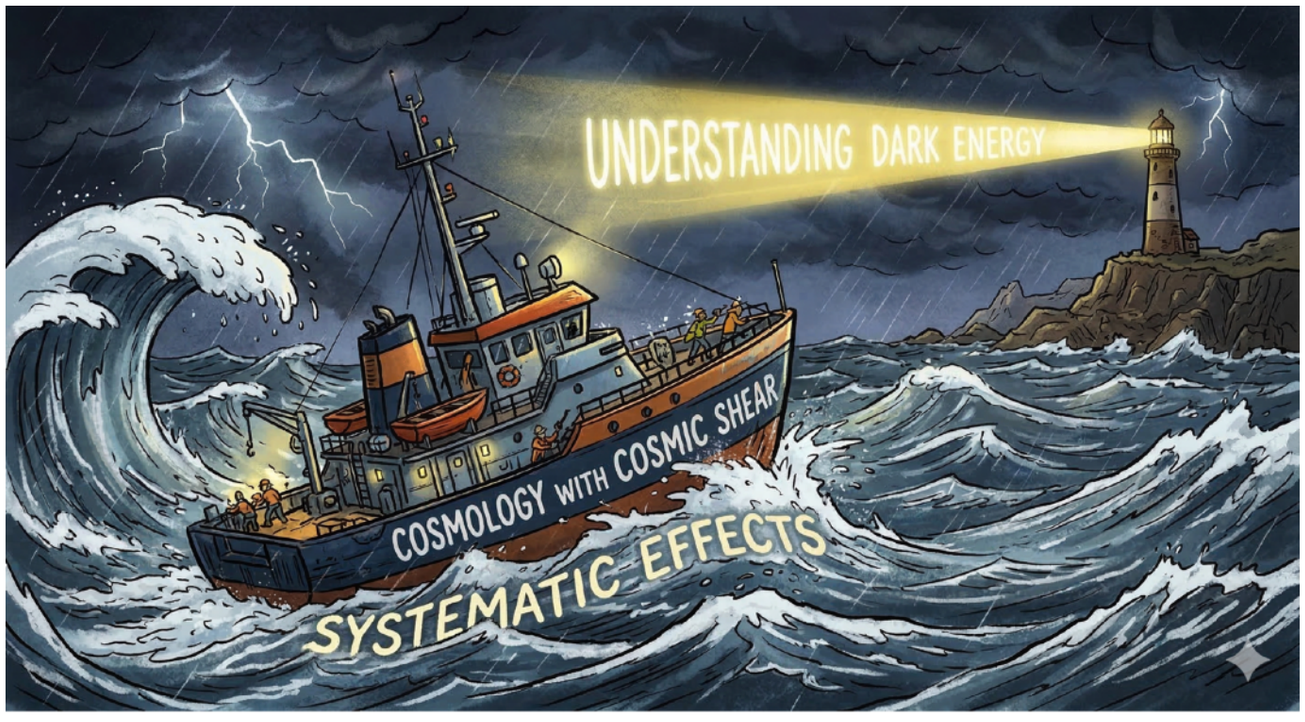
The LSST DESC Collaboration 2018

On Cosmology with cosmic shear

Spatial correlation of galaxy shape
==
Cosmology

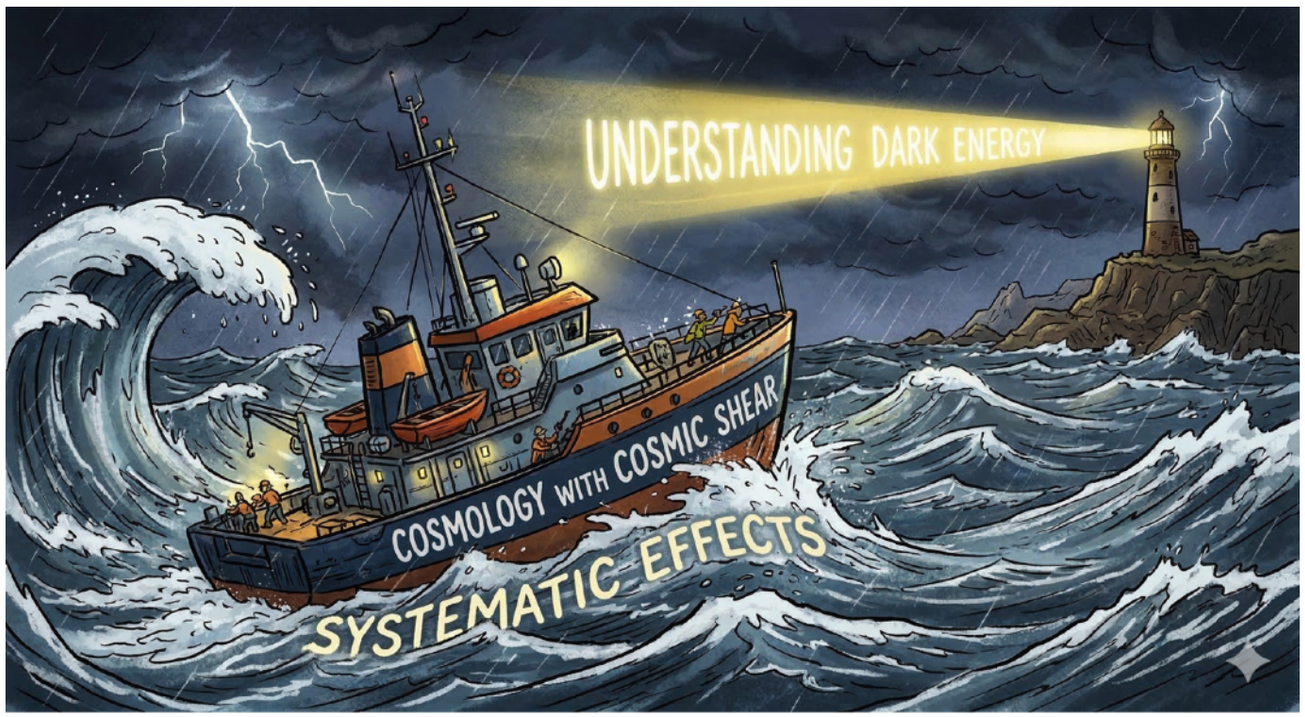
On Cosmology with cosmic shear

Spatial correlation of galaxy shape
==
Cosmology



On Cosmology with cosmic shear

Spatial correlation of galaxy shape
==
Cosmology

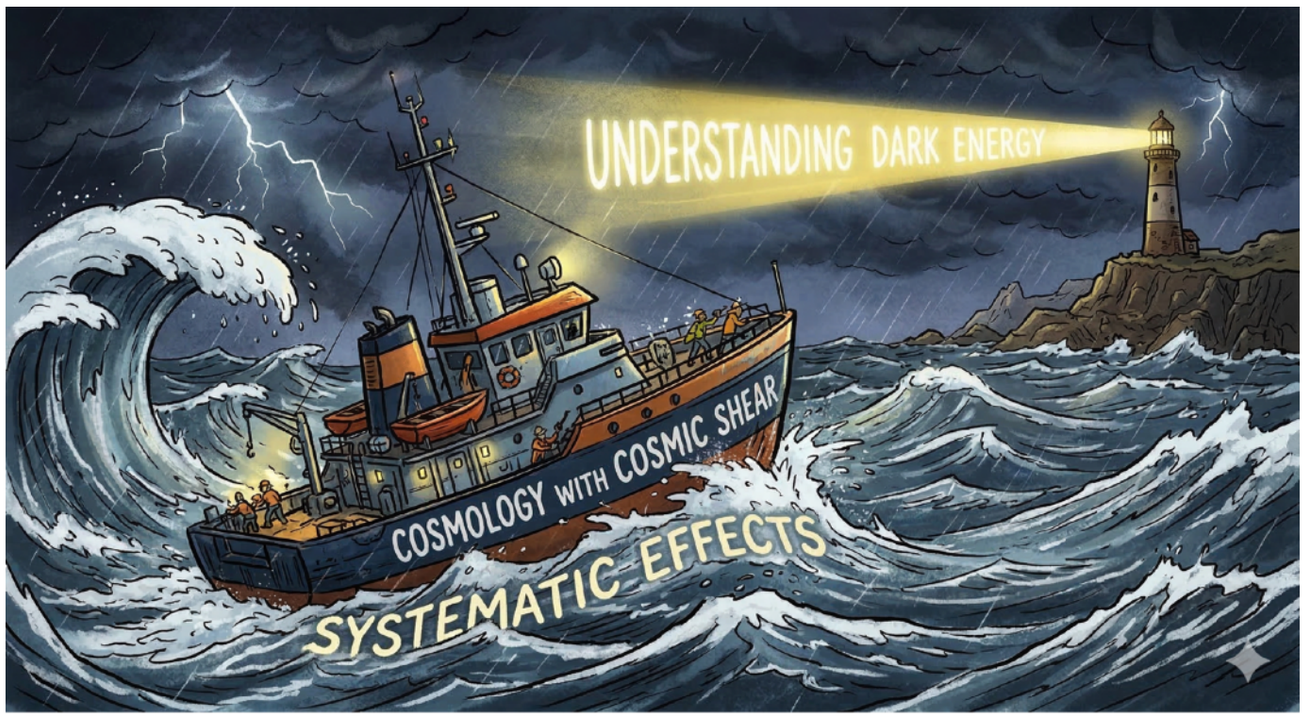


Systematic effect on shear measurement

- PSF modeling
- Shear estimation
- Photometric redshift
- Intrinsic alignement
- …

On Cosmology with cosmic shear

Spatial correlation of galaxy shape
==
Cosmology

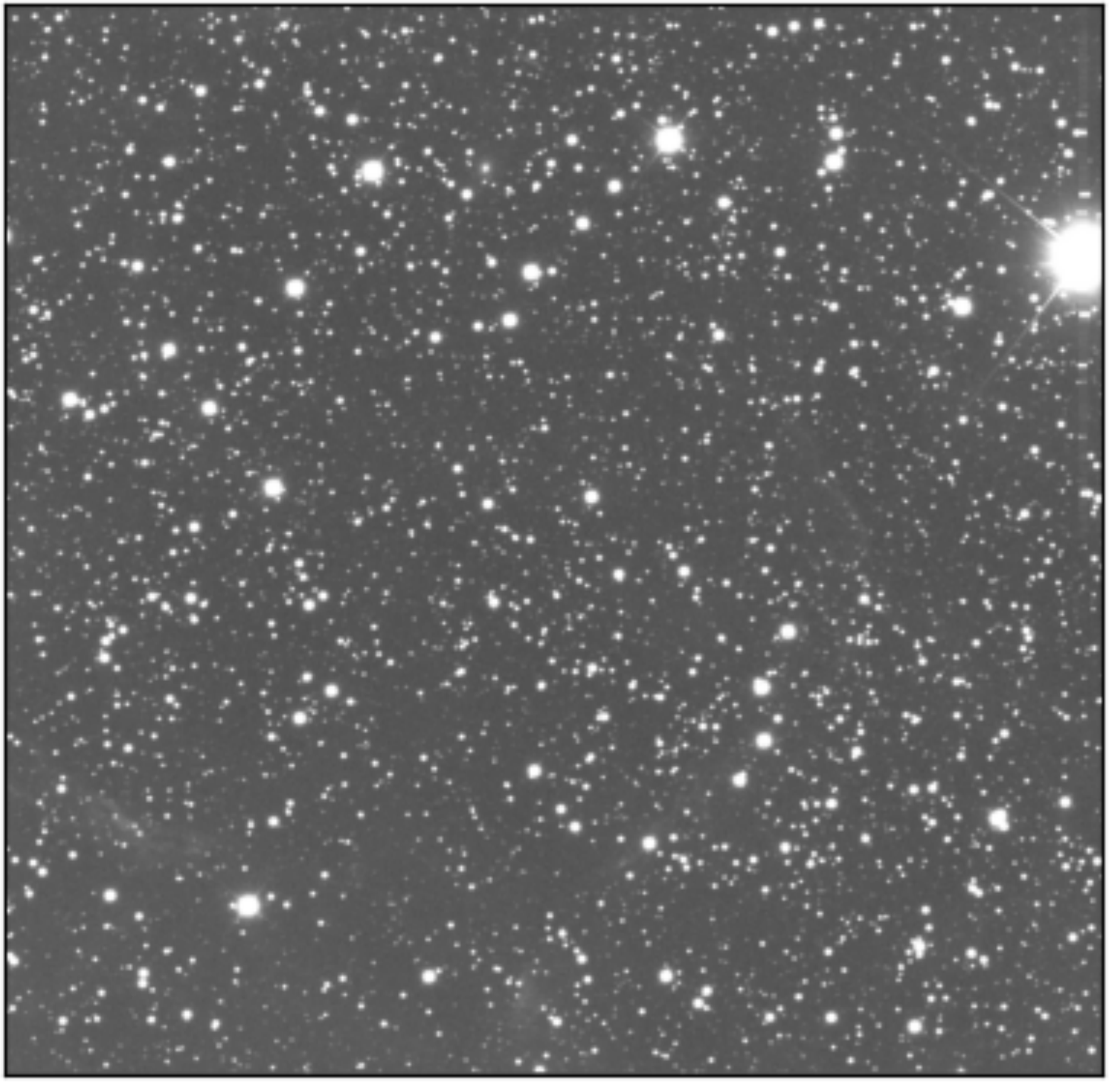


Systematic effect on shear measurement

- Image quality
- PSF modeling
- Shear estimation
- Photometric redshift
- Intrinsic alignement
- …

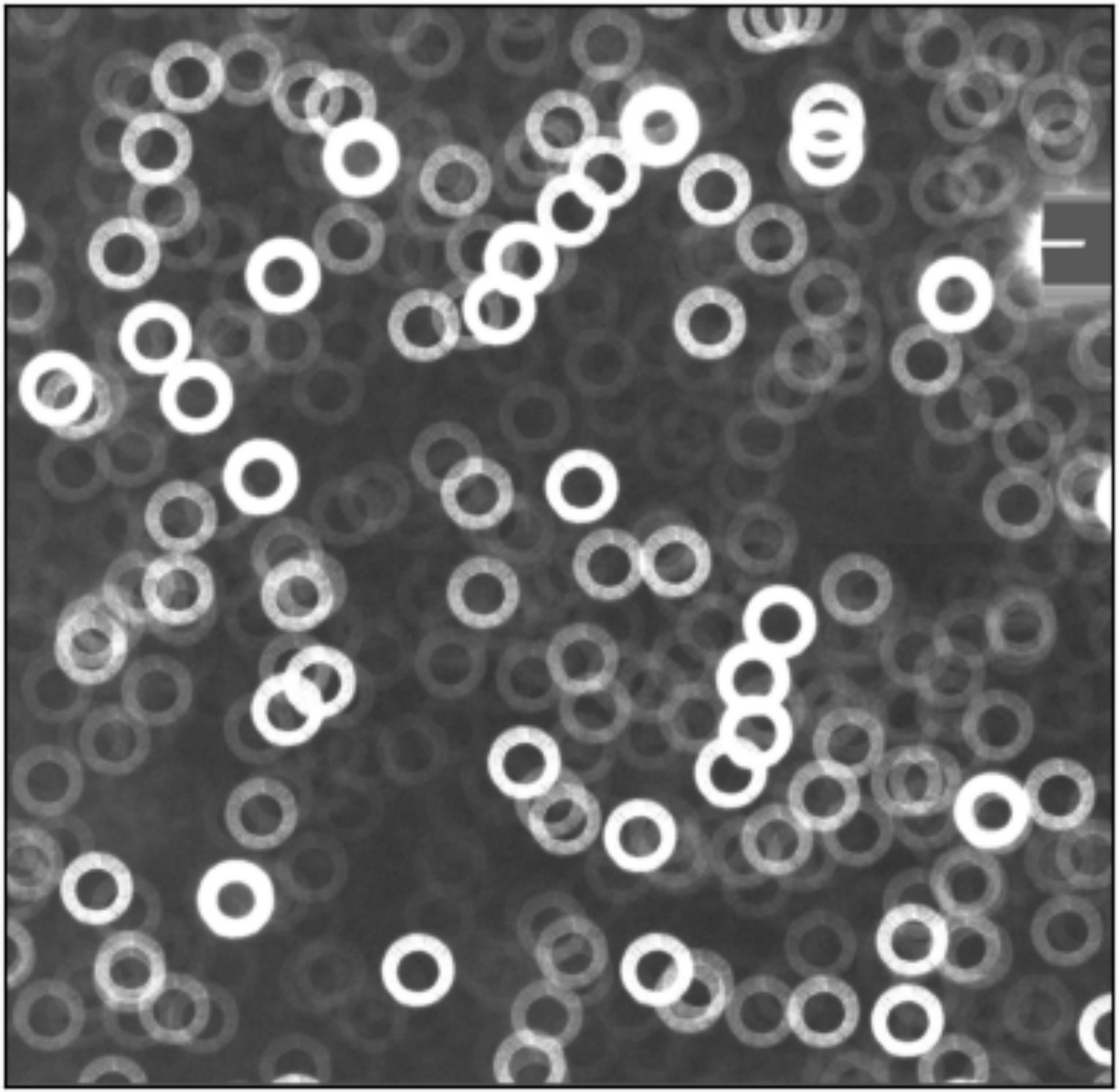
- Right now the main bottle neck for weak-lensing, is the image quality and modeling it.

On delivered Image Quality (IQ):



In focus image

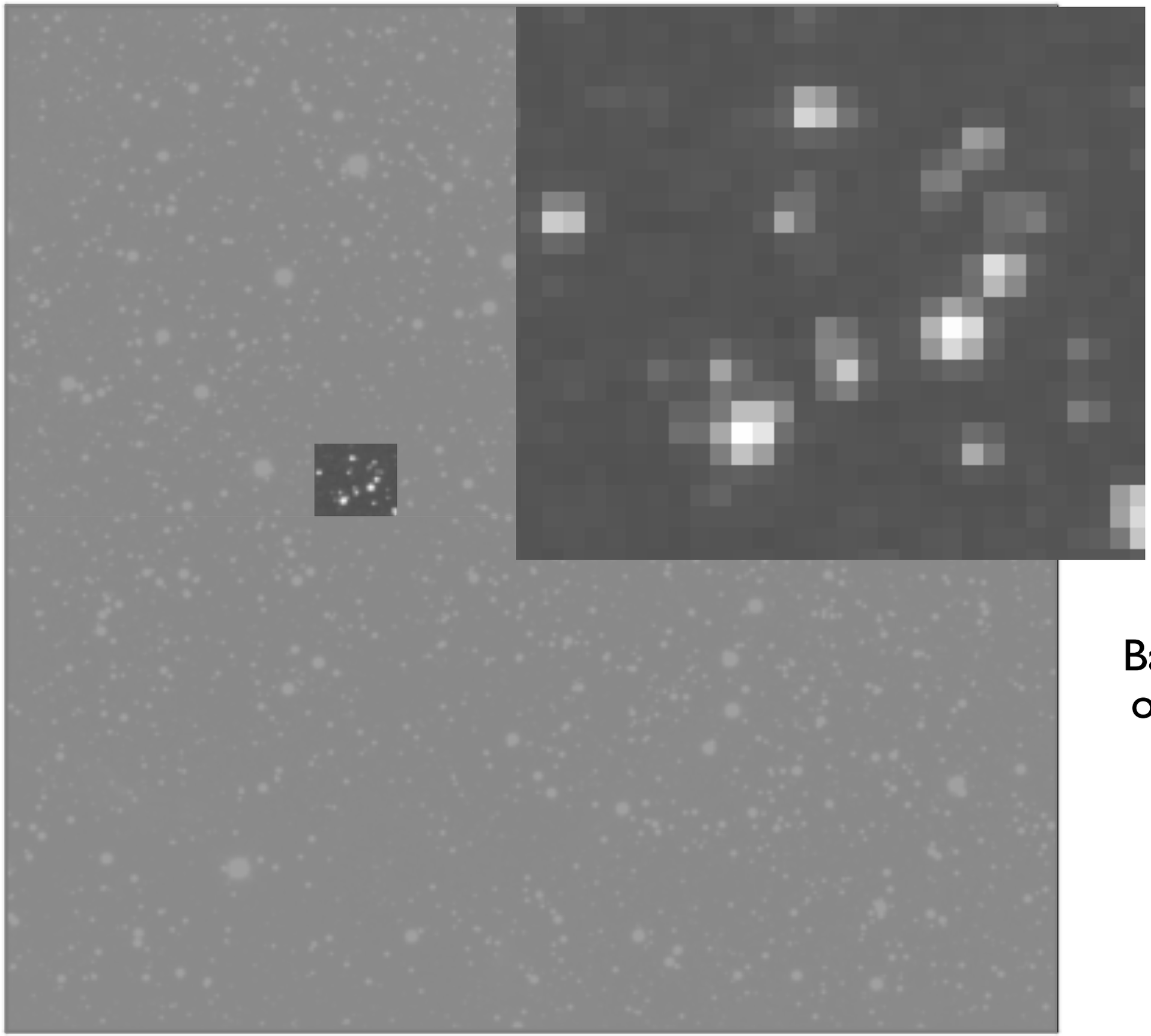
On delivered Image Quality (IQ):



Out of focus image on the same part of the sky

Bad IQ —> Less object detected

On delivered Image Quality (IQ):

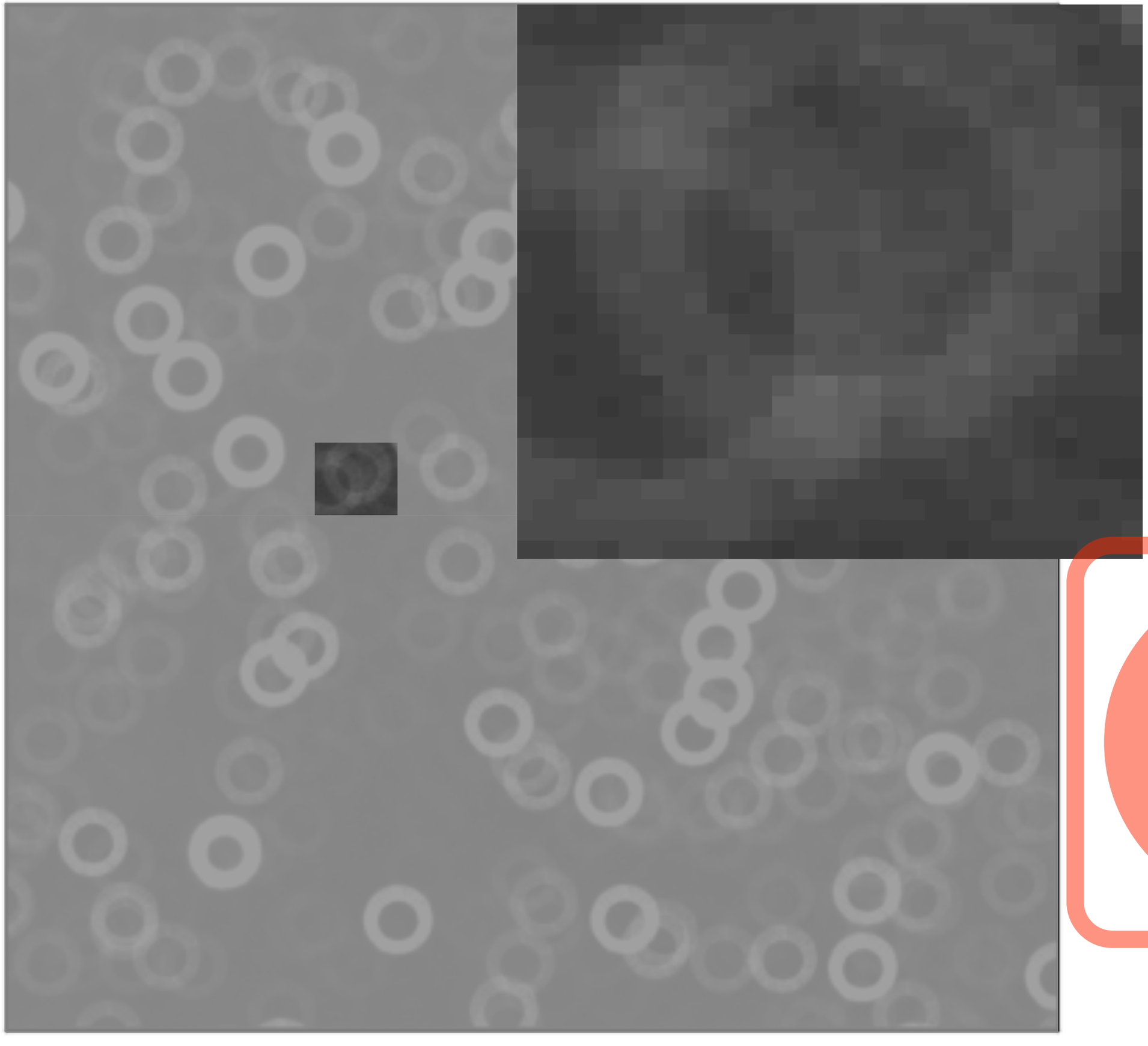


In focus image

14 sources with good IQ

Bad IQ —> Less object detected

On delivered Image Quality (IQ):



Out of focus image

2 sources
with bad IQ

We are out
of target

On Point Spread Function (PSF):

Image before going through:

- The Atmosphere
- The Optics of the Telescope
- The Sensors

$$I(x, y) = \tilde{I}(x, y) * PSF(x, y)$$

Observed image

Blurring kernel that describe how a point source reacts to:

- The Atmosphere
- The Optics of the Telescope
- The Sensors

On Point Spread Function (PSF):

General case:

Observed image — "True image" — Blurring kernel / PSF

$$I(x, y) = \tilde{I}(x, y) * PSF(x, y)$$

Measured on detector — Unknown — Unknown

On Point Spread Function (PSF):

Case where the "True image" is a star:

Observed image — "True image" A star — Blurring kernel / PSF

$$I(x, y) = \delta(x, y) * PSF(x, y)$$

Measured on detector — Dirac delta function — Unknown

δ

On Point Spread Function (PSF):

Case where the "True image" is a star:

Observed image Blurring kernel / PSF

$$I(x, y) = PSF(x, y)$$

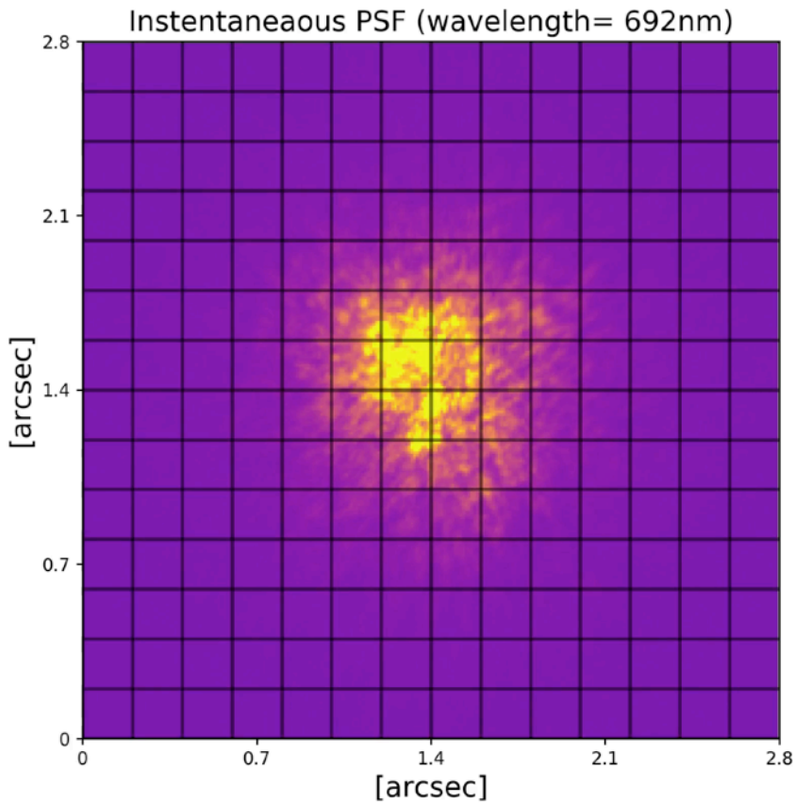
Measured on detector known

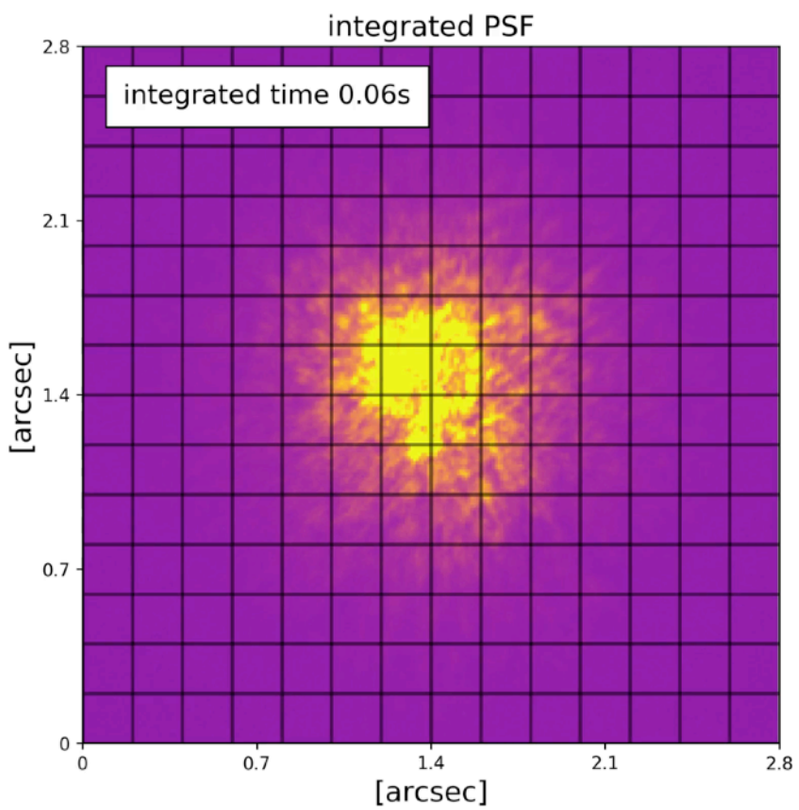
δ

On Point Spread Function (PSF):

- PSF ~ How a light point source reacts once it goes through all of these:
  - The Atmosphere
  - The Optics of the Telescope

On Point Spread Function (PSF):





- PSF ~ How a light point source reacts once it goes through all of these:
  - The Atmosphere
  - The Optics of the Telescope

- What does the real atmospheric PSF really look like ?

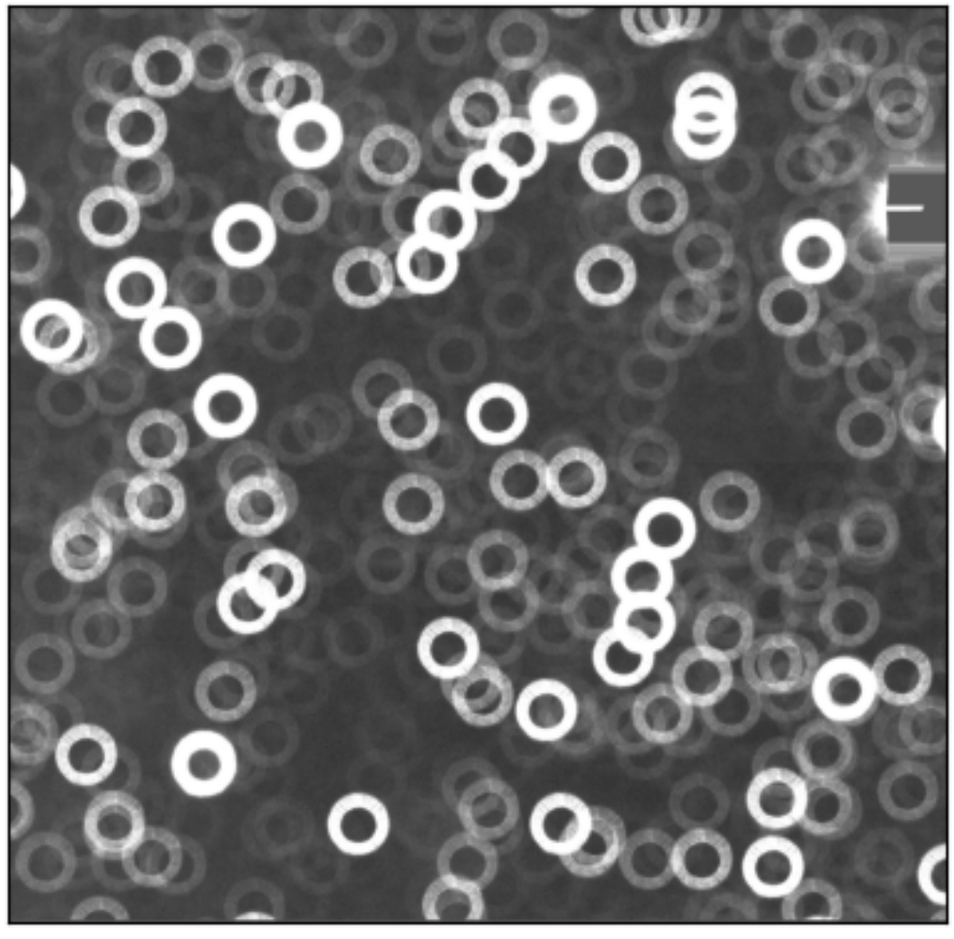
- High definition movies of bright stars taken on Gemini South with the Differential Speckle Survey Instrument

- 0.011 arcsec / pixel (LSSTCam 0.2 arcsec / pixel)

- Exposure time of 60 ms with 2 ms of readout

- See Hébert et al. 2018

On Point Spread Function (PSF):

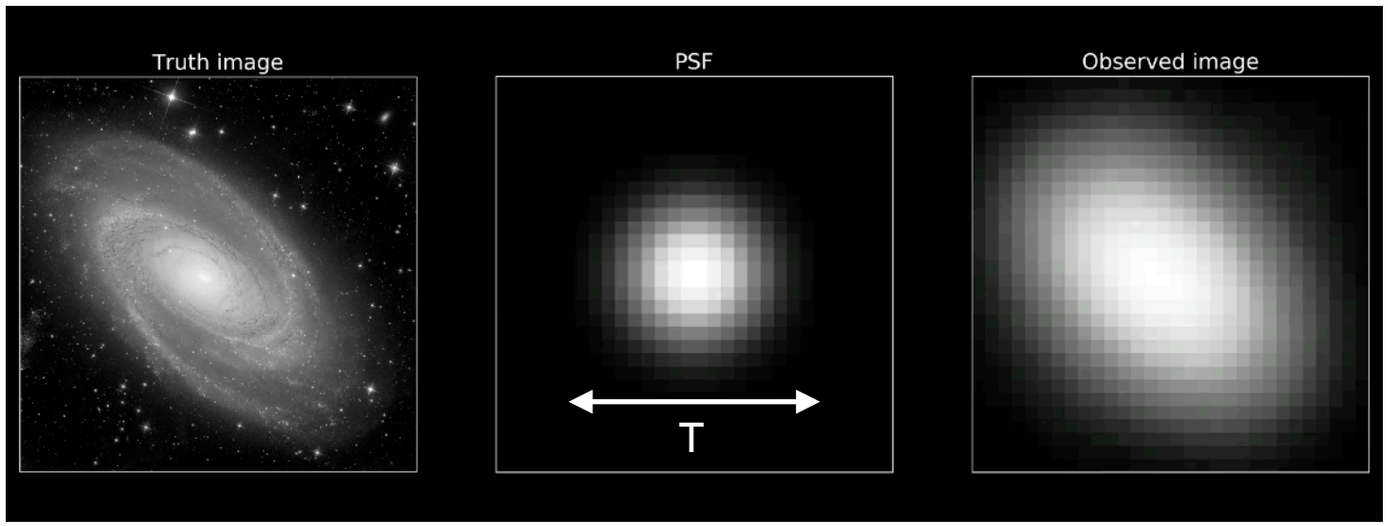


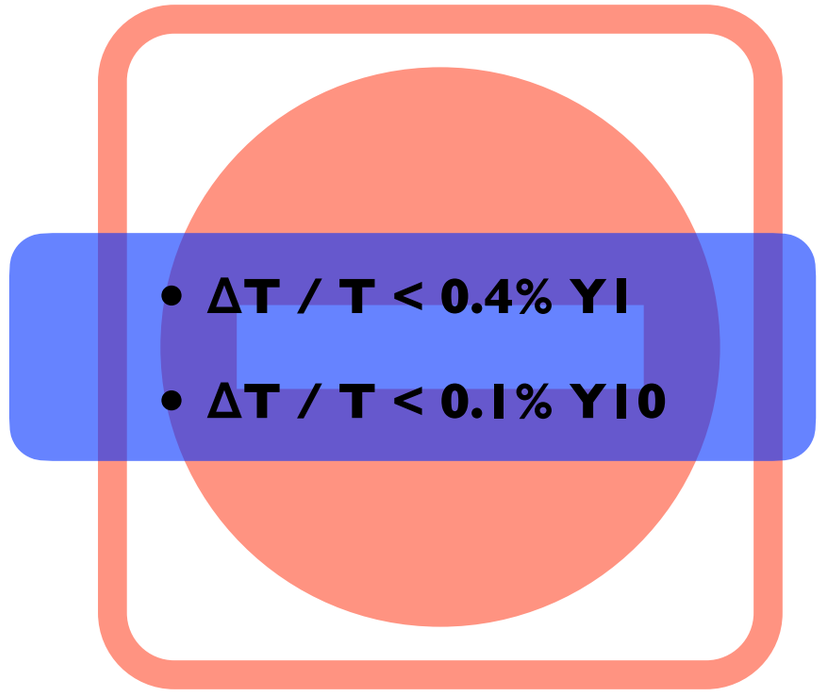
- PSF ~ How a light point source reacts once it goes through all of these:
  - The Atmosphere
  - The Optics of the Telescope

- Hardcore case of donuts like PSF because the telescope is out of focus.

On Point Spread Function (PSF):

PSF matters in most of science case especially weak lensing





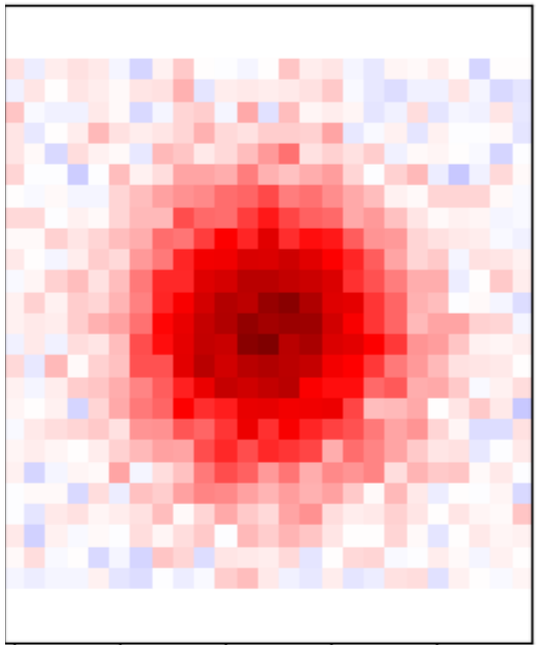
- `T` —> PSF size

- `ΔT / T  = T_star - T_psf / T_star` —> PSF size residuals

On DP2 PSF model at single visit:

How PSF modeling looks like on a single star of LSSTCam

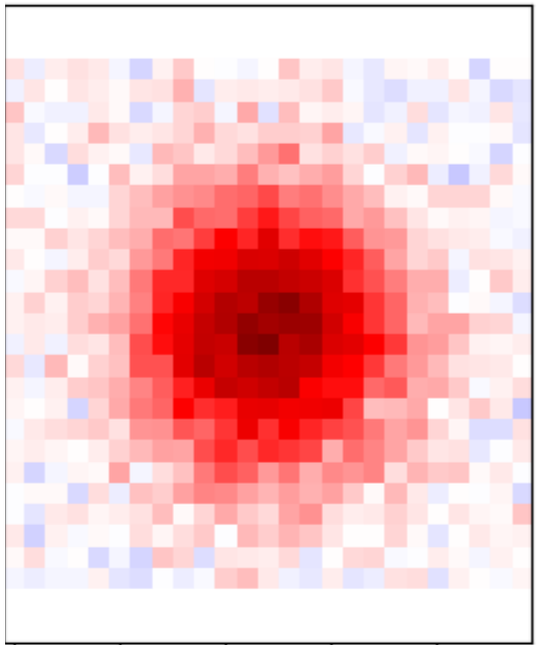
Observed stars



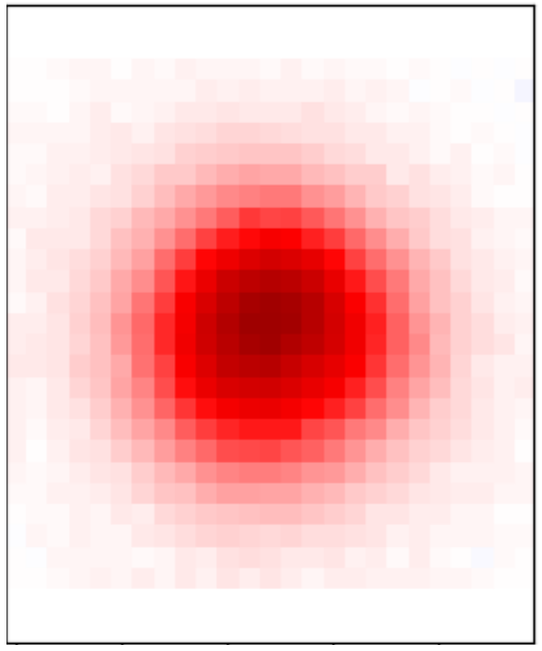
On DP2 PSF model at single visit:

How PSF modeling looks like on a single star of LSSTCam

Observed stars



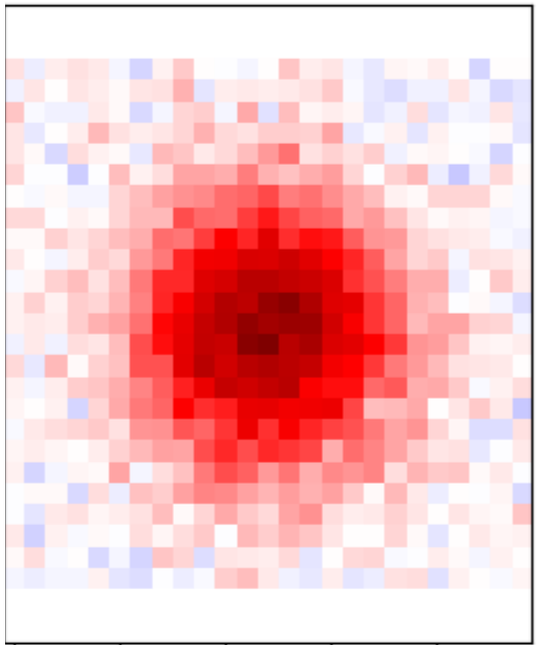
PSF model



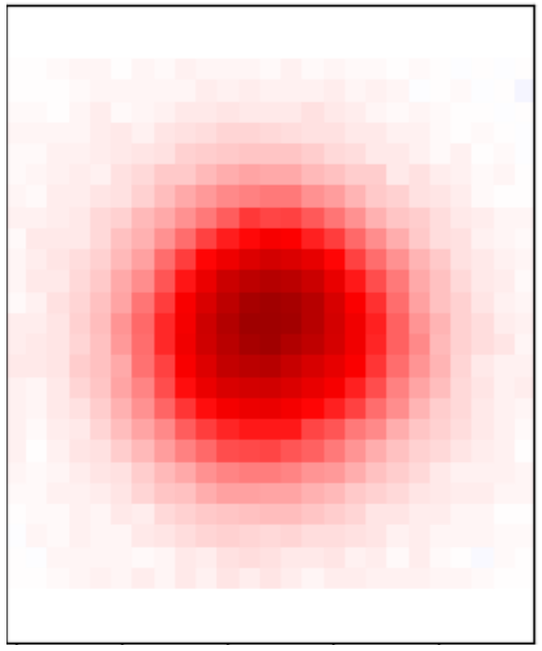
On DP2 PSF model at single visit:

How PSF modeling looks like on a single star of LSSTCam

Observed stars



PSF model



Model:

Lanczos interpolation (Sinus cardinal function basis)

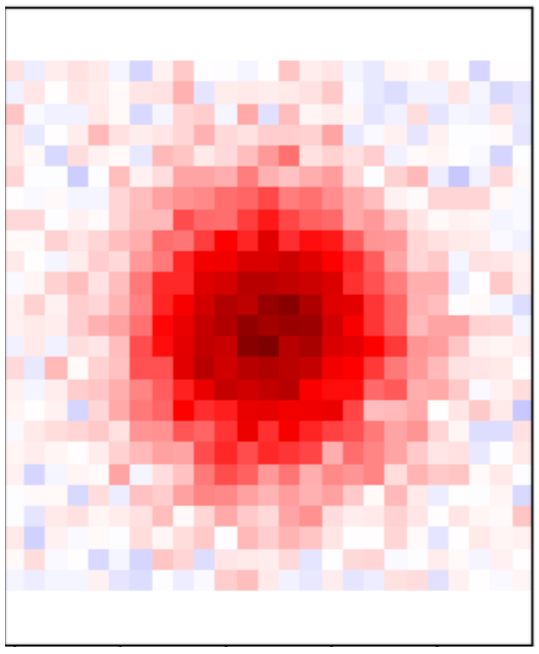
+

Polynomial function to interpolate the coefficient of the Sinc basis

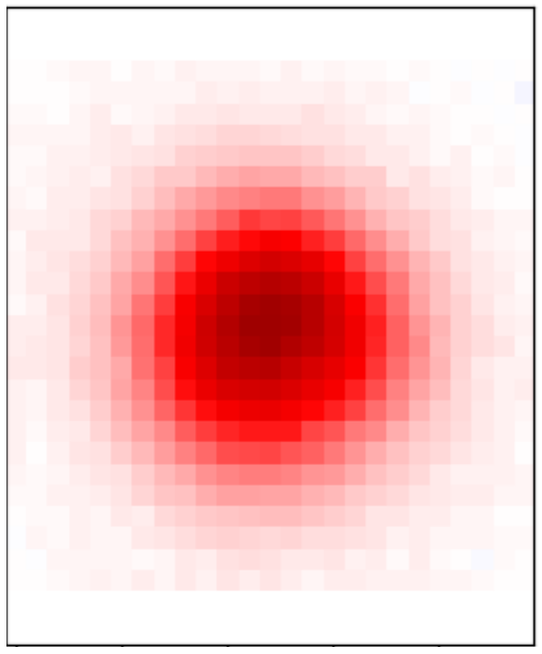
On DP2 PSF model at single visit:

How PSF modeling looks like on a single star of LSSTCam

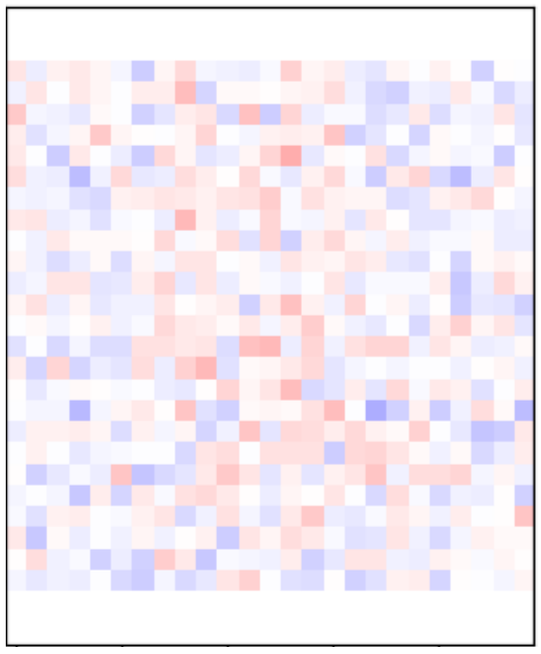
Observed stars



PSF model



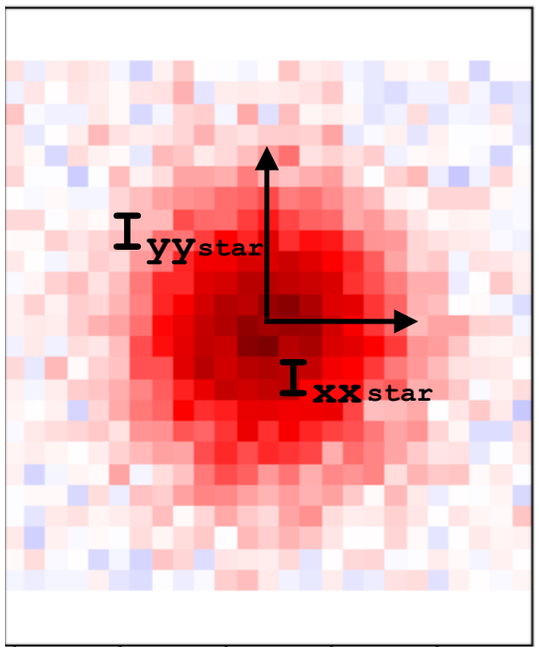
Residuals



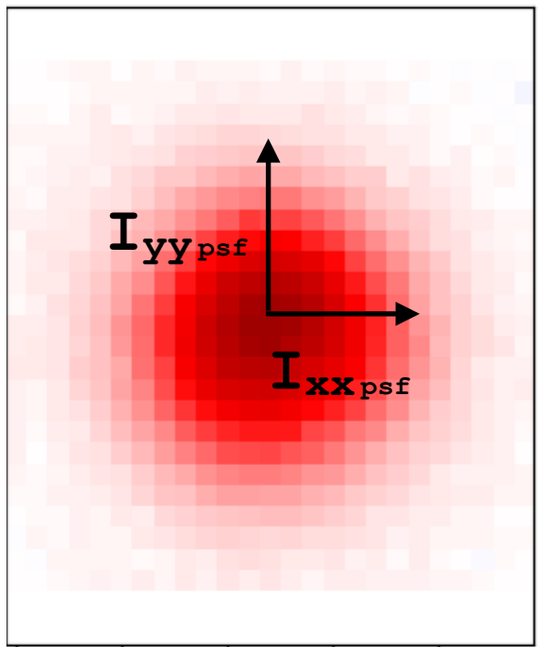
On DP2 PSF model at single visit:

How PSF modeling looks like on a single star of LSSTCam

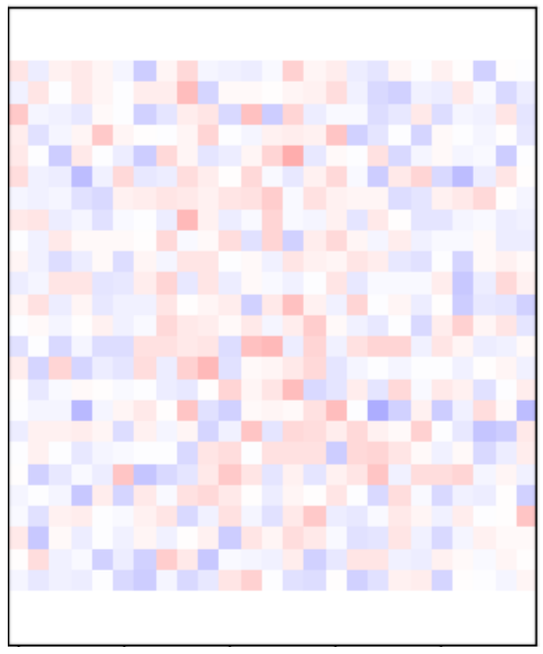
Observed stars



PSF model



Residuals



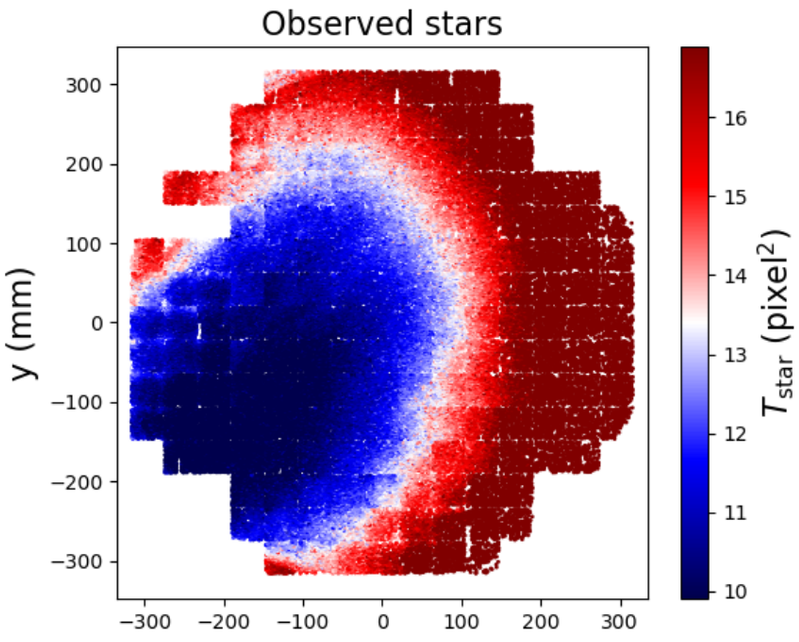
- $T = I_{xx} + I_{yy}$ —> PSF size

- $\Delta T / T = T_{star} - T_{psf} / T_{star}$ —> PSF size residuals

How this looks like in the camera plane?

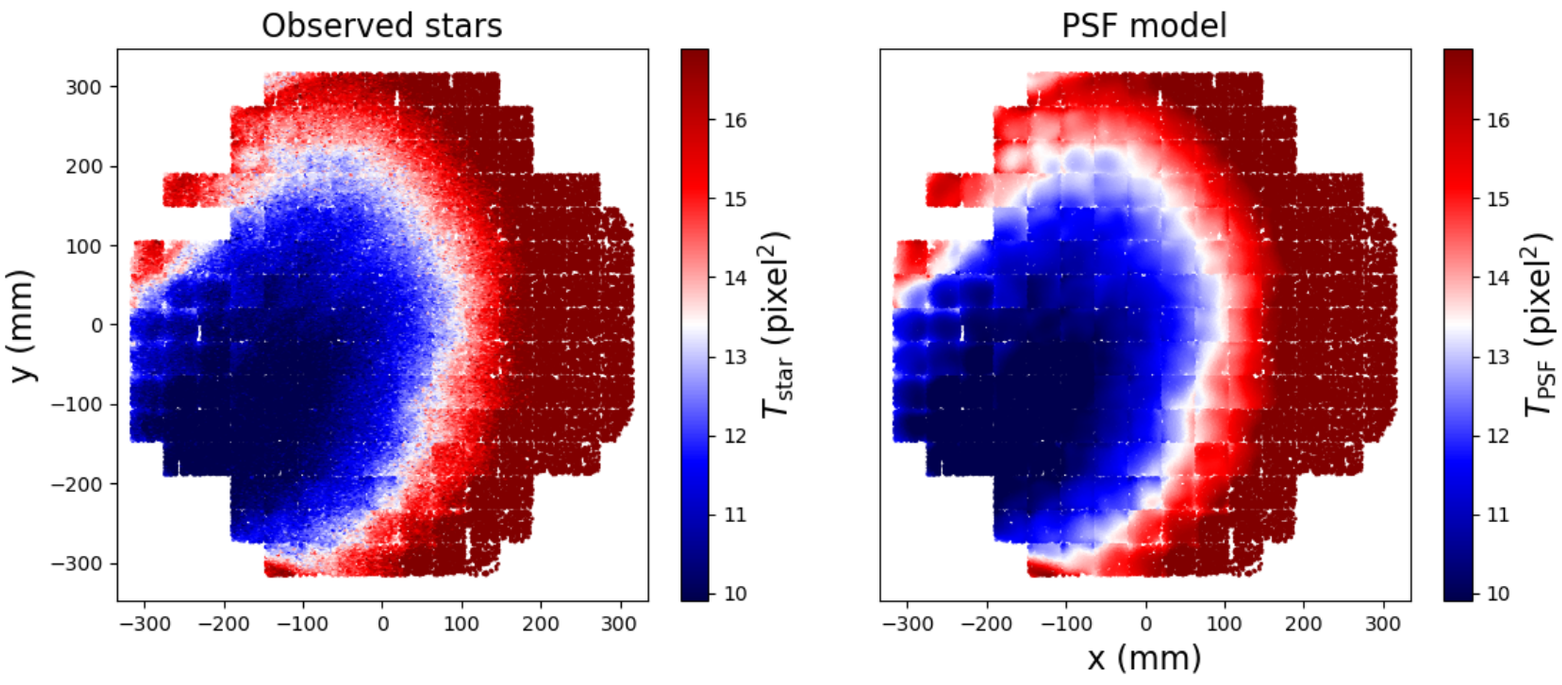
On DP2 PSF model at single visit:

How PSF modeling looks like on a single image/visit of LSSTCam



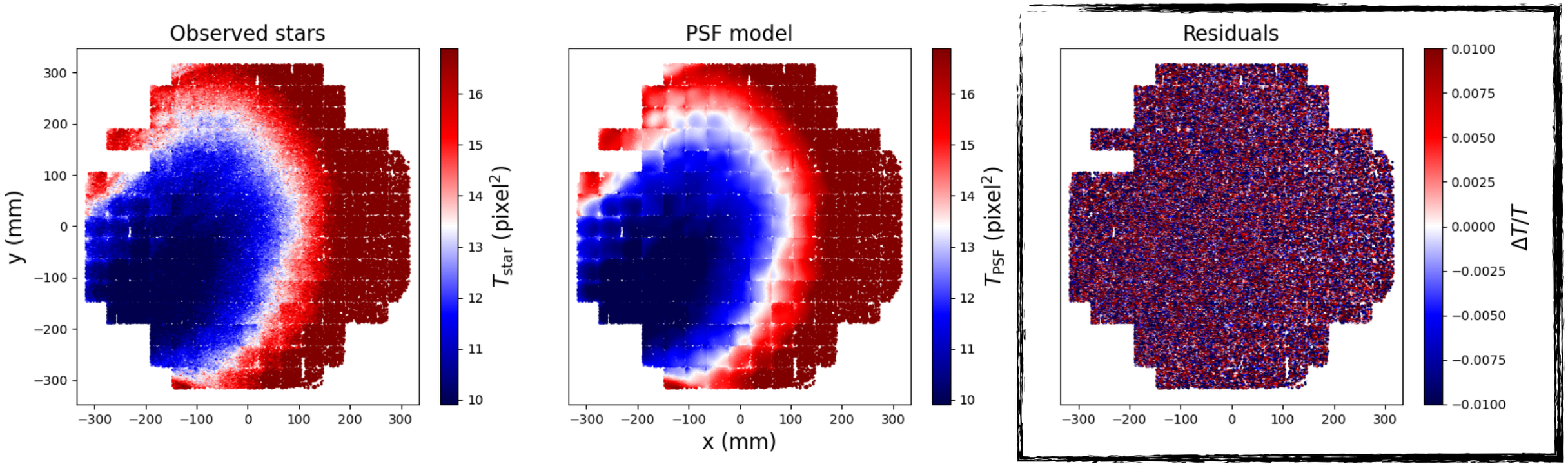
On DP2 PSF model at single visit:

How PSF modeling looks like on a single image/visit of LSSTCam



On DP2 PSF model at single visit:

How PSF modeling looks like on a single image/visit of LSSTCam



Lets stack PSF size residuals on a batch of visits

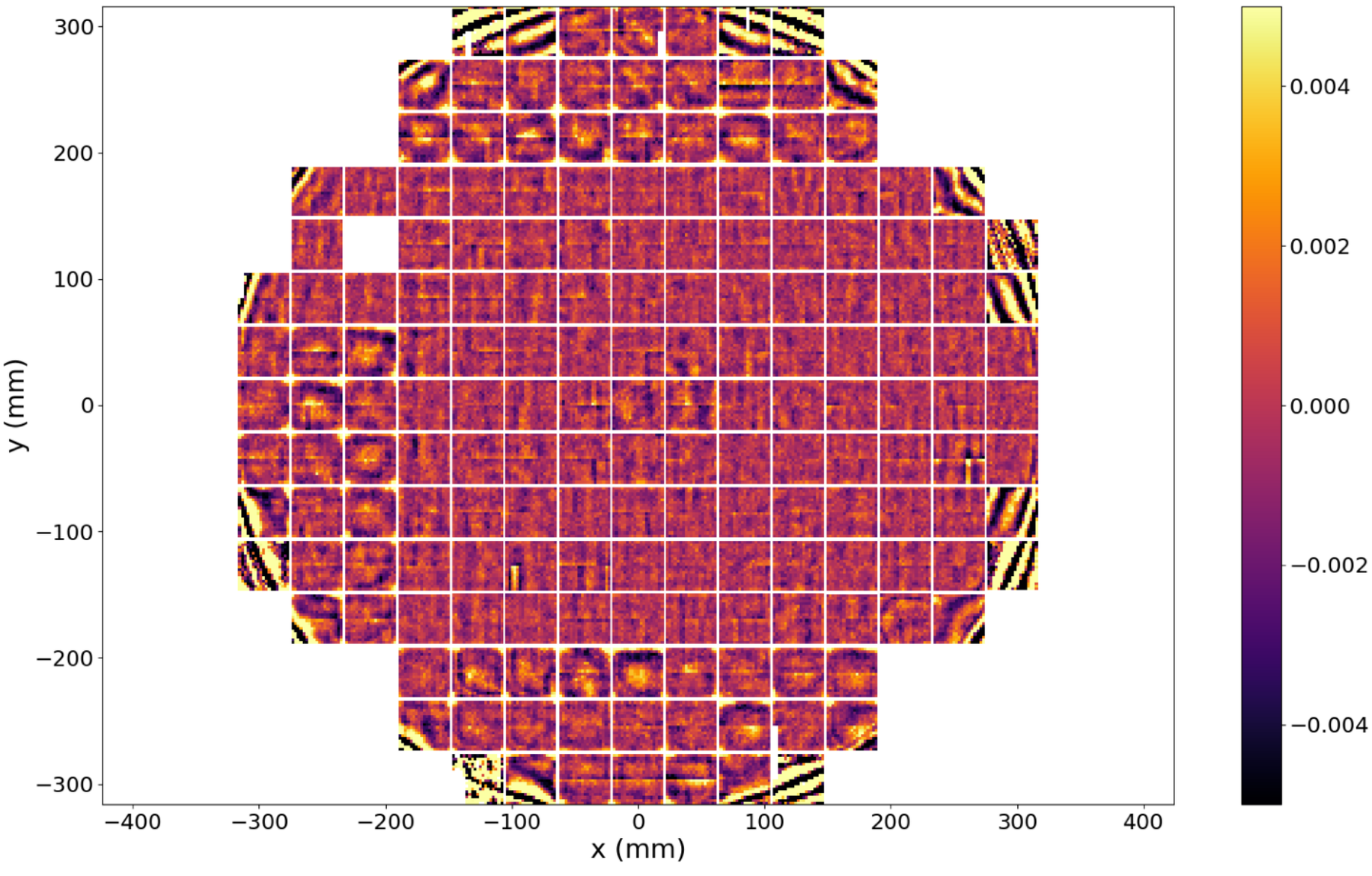
DP2 PSF characterization

Stack ΔT / T on 3k visits (I had only that up to January 2026)

DP2 PSF characterization

Stack ΔT / T on 3k visits (I had only that up to January 2026)

A lot of things are going on 😱

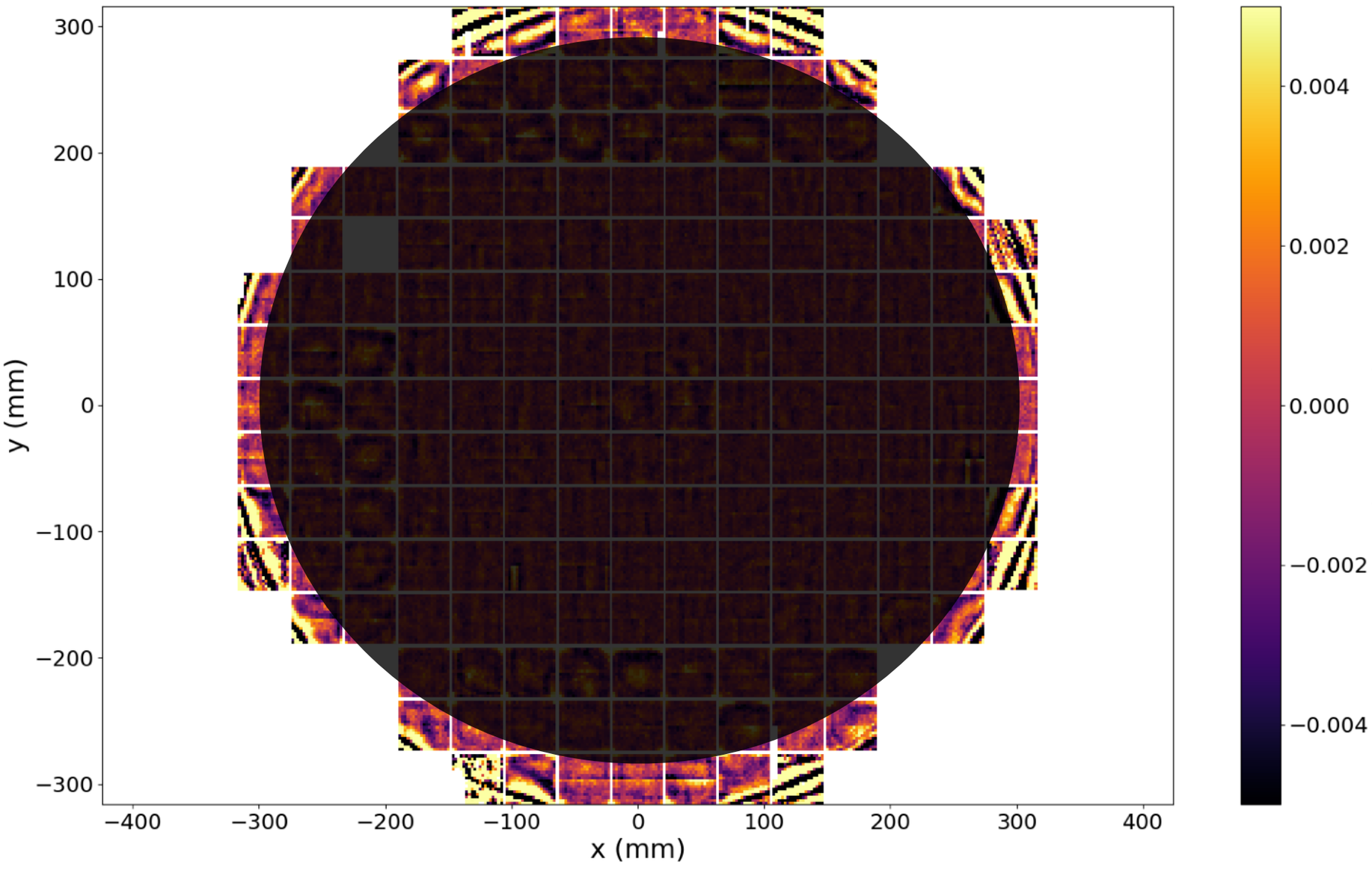


DP2 PSF characterization

Stack ΔT / T on 3k visits (I had only that up to January 2026)

- Ring on the edge

A lot of things are going on 😱

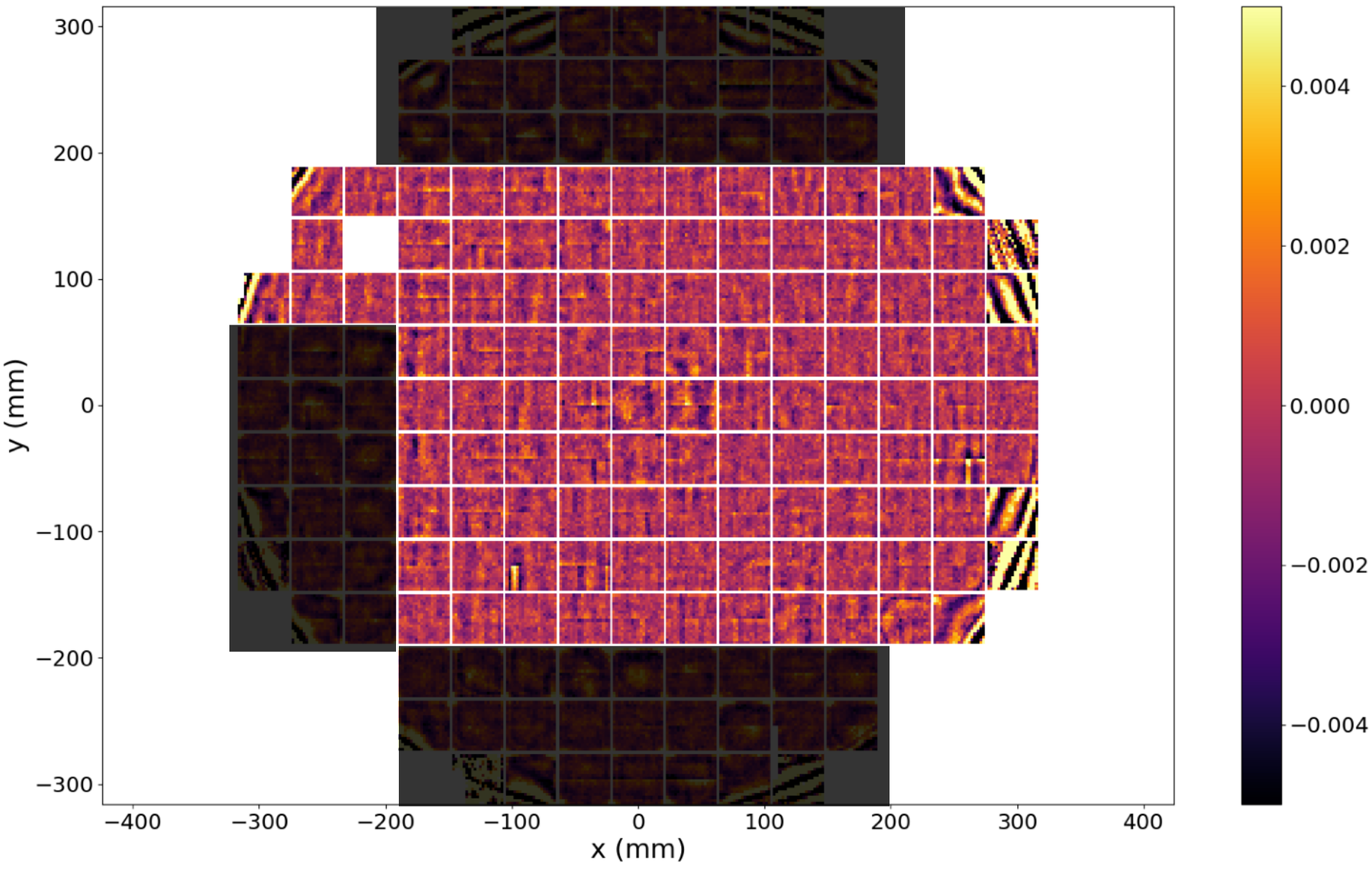


DP2 PSF characterization

Stack ΔT / T on 3k visits (I had only that up to January 2026)

- Ring on the edge
- E2V's Amp offset

A lot of things are going on 😱

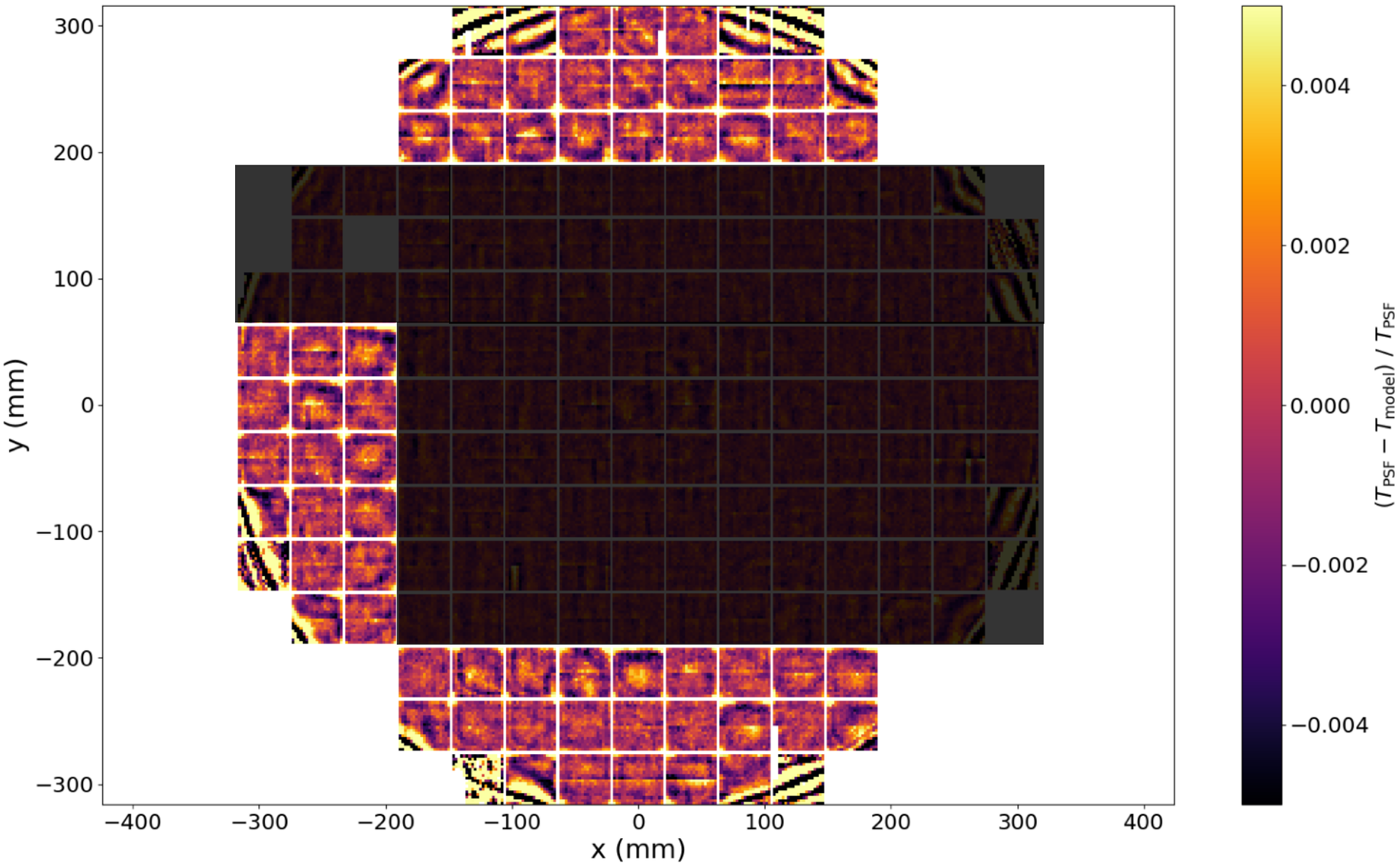


DP2 PSF characterization

Stack ΔT / T on 3k visits (I had only that up to January 2026)

- Ring on the edge
- E2V's Amp offset
- ITL's "blob"

A lot of things are going on 😱

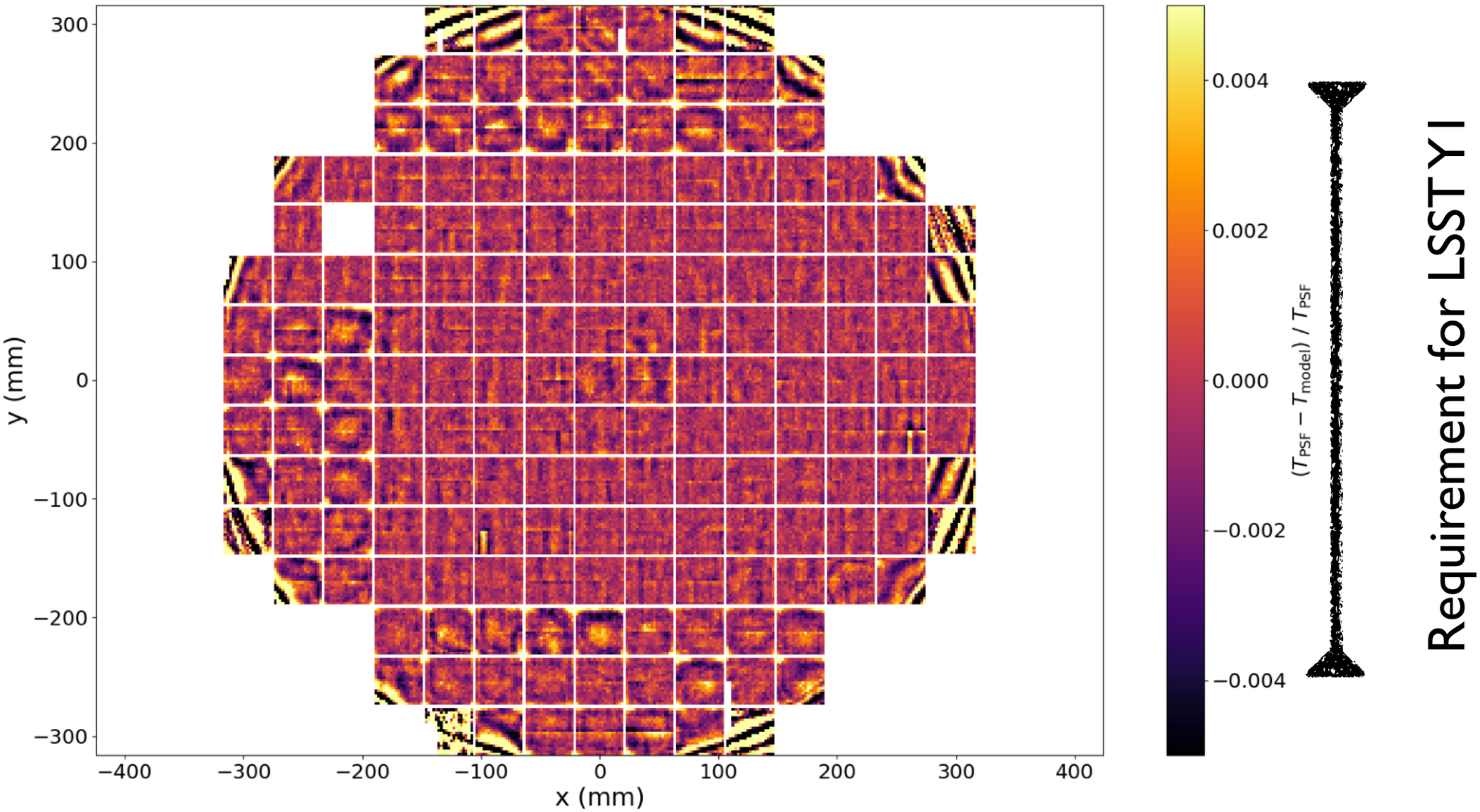


DP2 PSF characterization

Stack ΔT / T on 3k visits (I had only that up to January 2026)

- Ring on the edge
- E2V's Amp offset
- ITL's "blob"

A lot of things are going on 😱



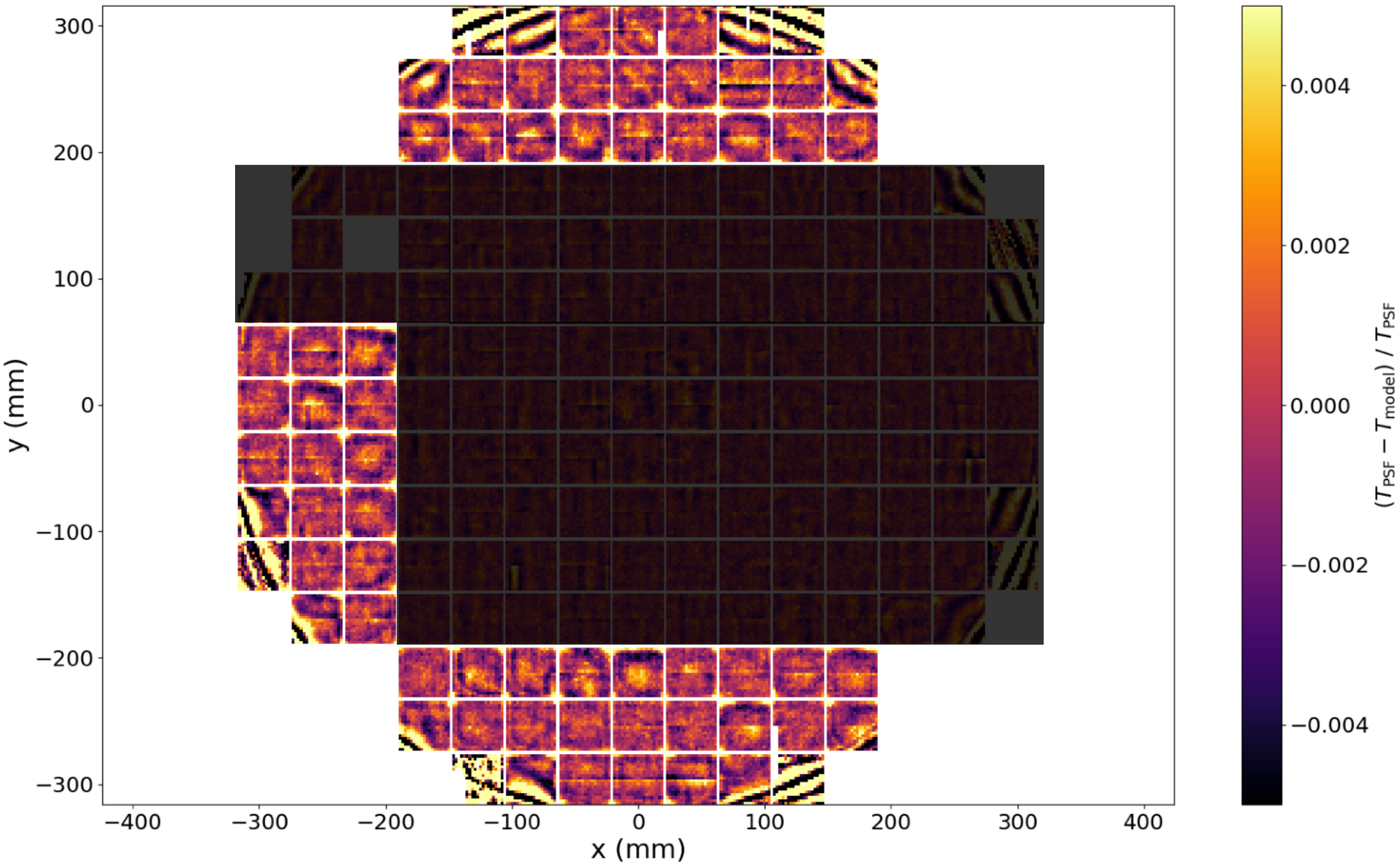
How do we improve this to reach cosmic shear requirement ?

DP2 PSF characterization

Stack ΔT / T on 3k visits (I had only that up to January 2026)

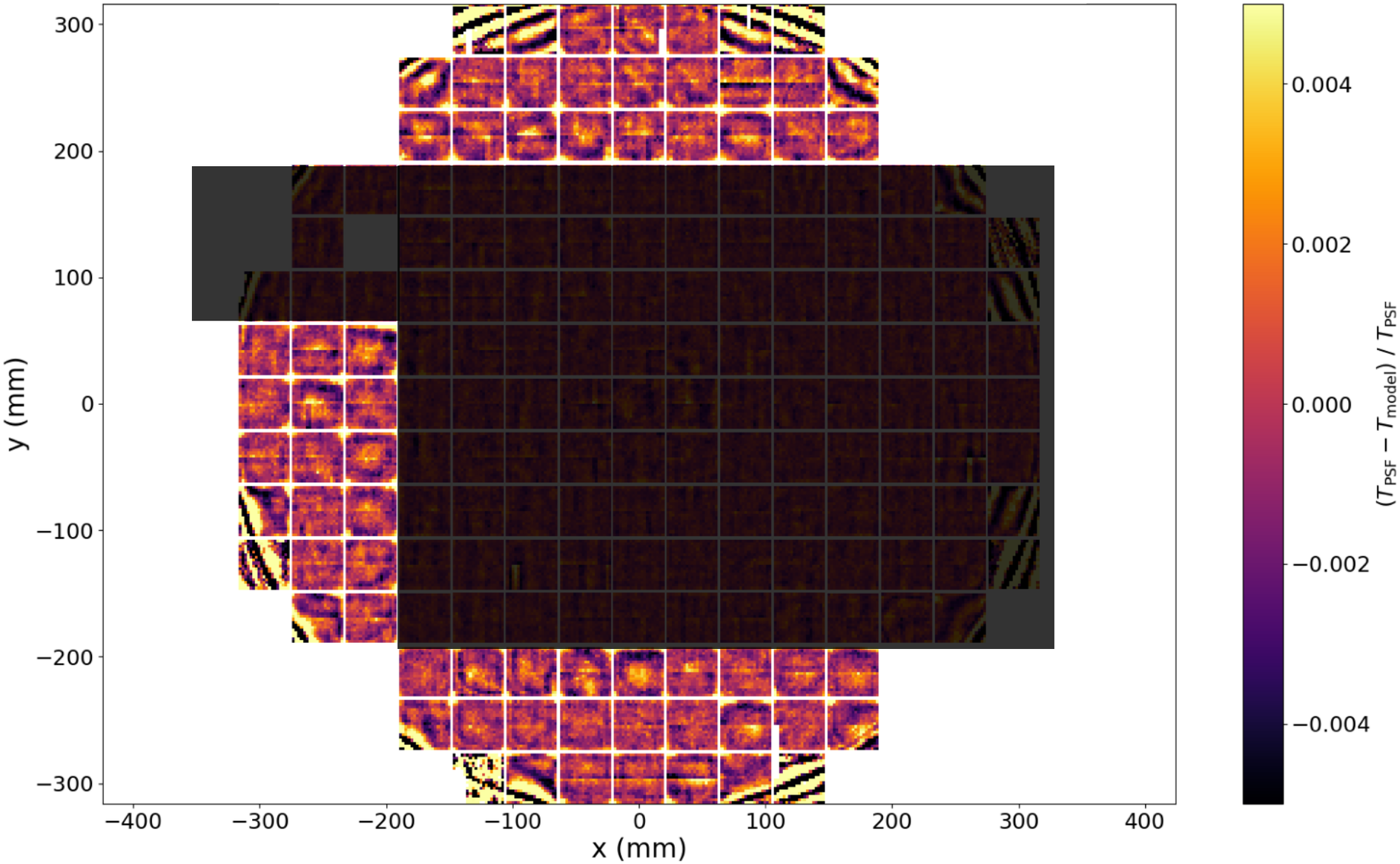
- Ring on the edge
- E2V's Amp offset
- ITL's "blob"

A lot of things are going on 😱



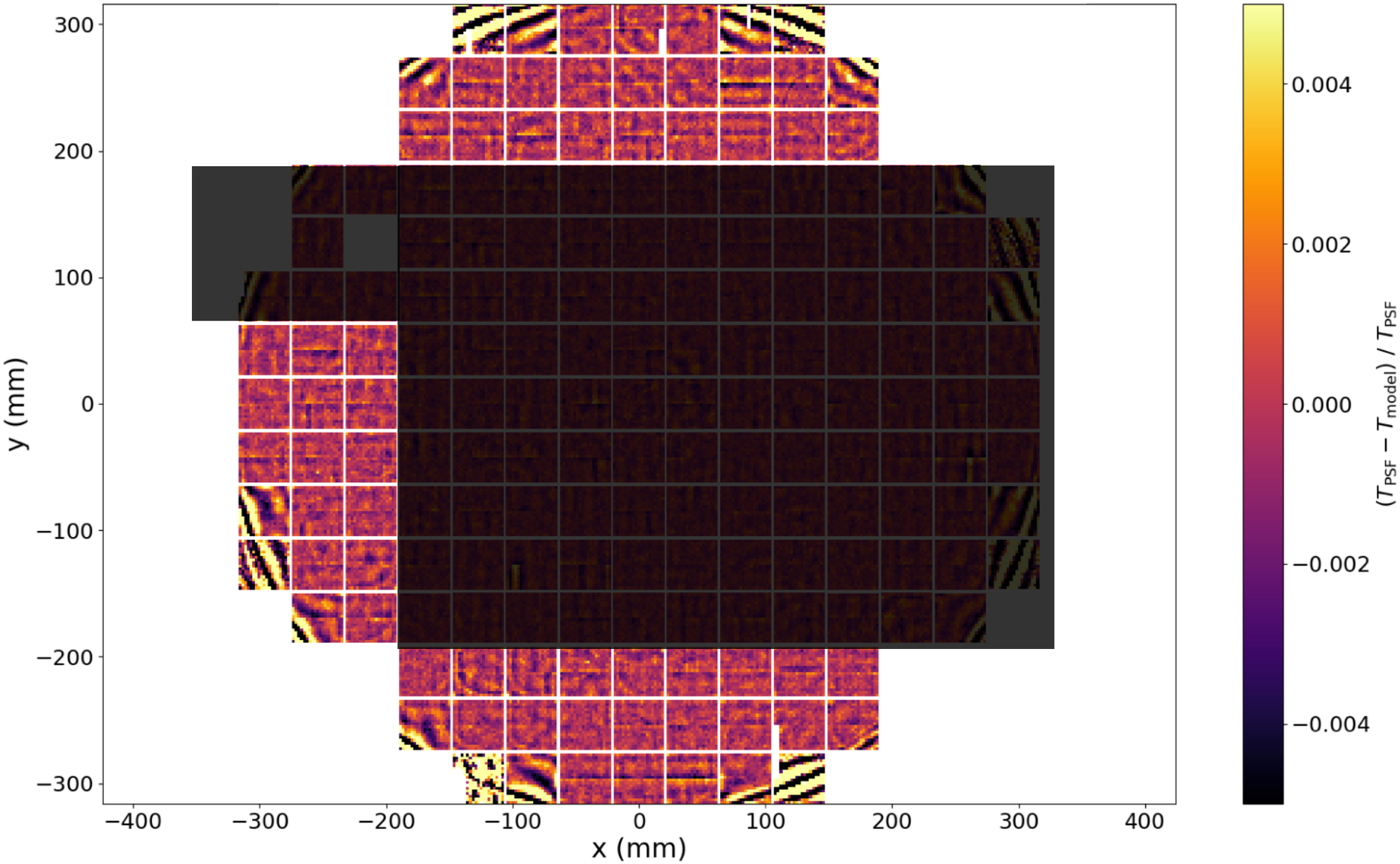
How do we improve this to reach cosmic shear requirement ?

On ITL “blob” or is my telescope in focus?:



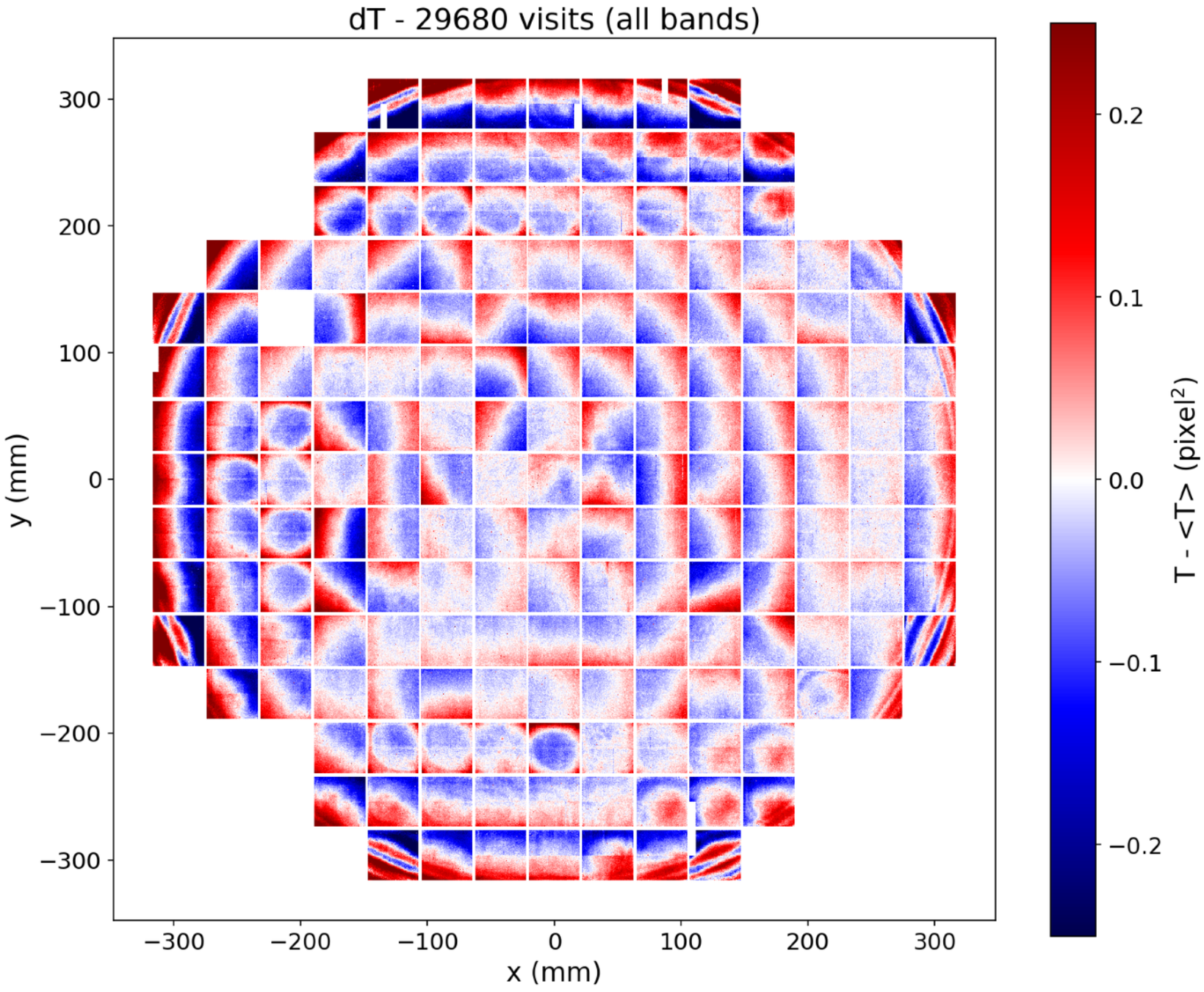
- Blob pattern on ITL chip ? Where it is coming from ?

On ITL “blob” or is my telescope in focus?:



- Blob pattern on ITL chip ? Where it is coming from ?
- Switch to 4th order polynomial looks to solve the problem.

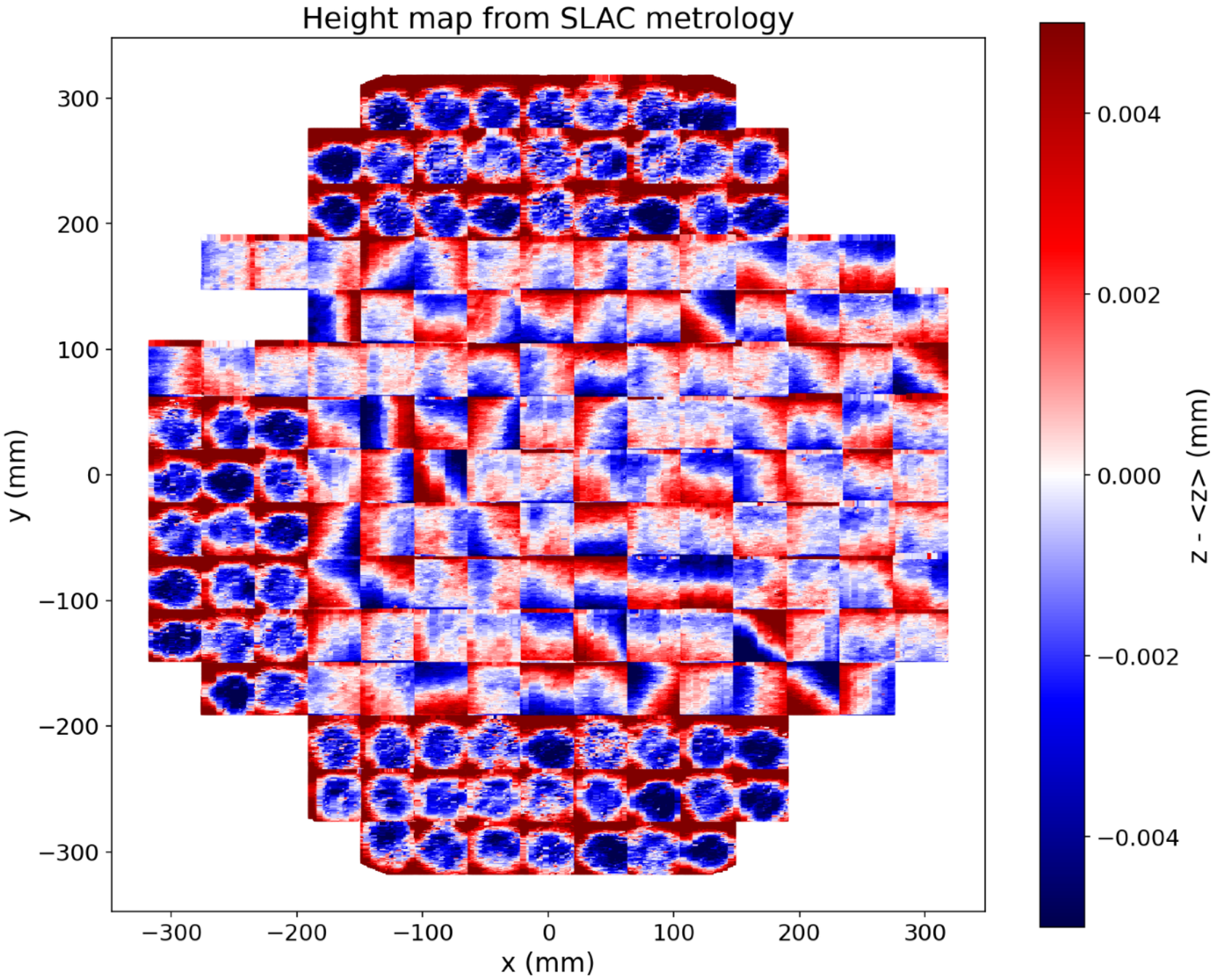
On ITL “blob” or is my telescope in focus?:



- Lets remove the interpolation to see what is going on

Average PSF/star size from on sky measurement with a 0th order polynomial interpolation

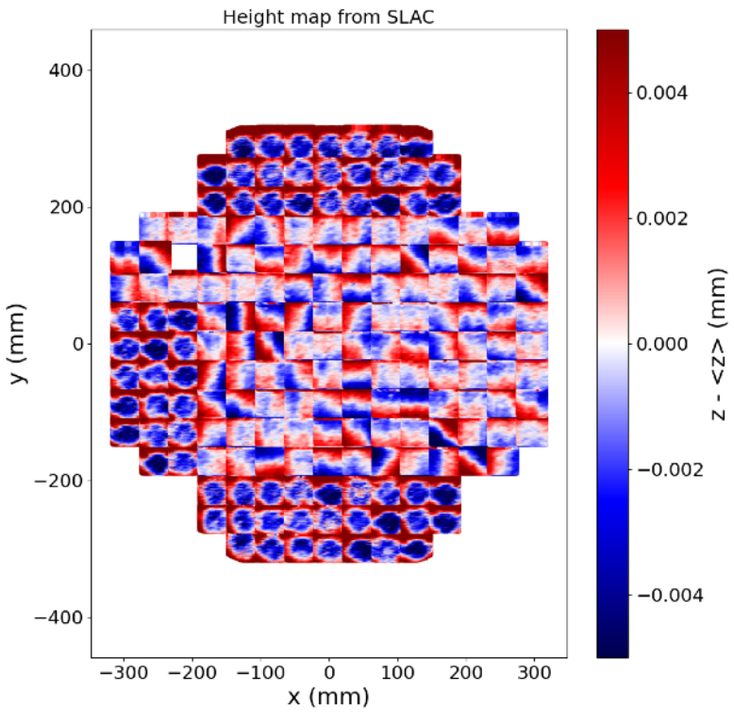
On ITL “blob” or is my telescope in focus?:

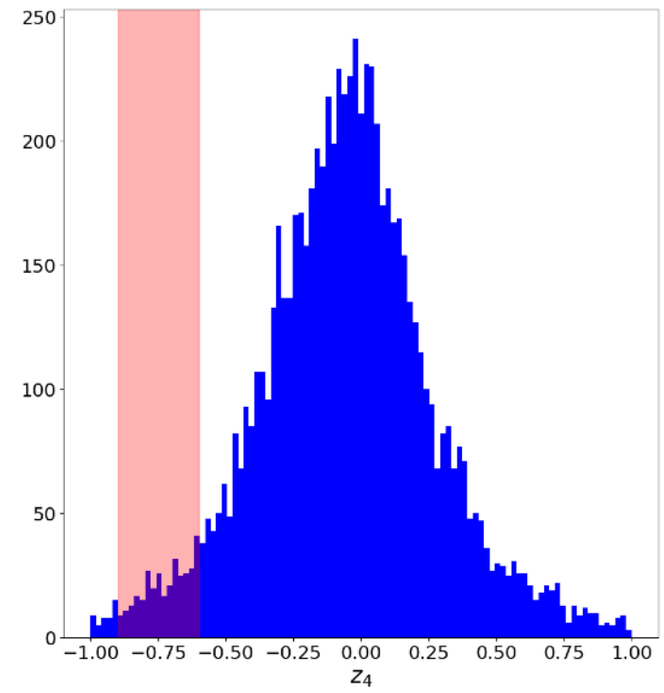


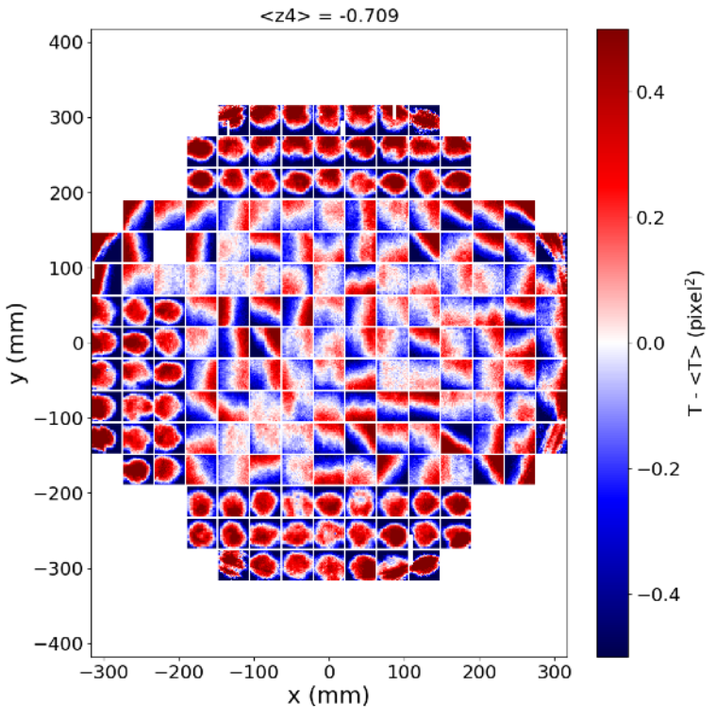
- Height CCD map is imprinted into star (and galaxy) shape
- But why ? —> need to look at AOS

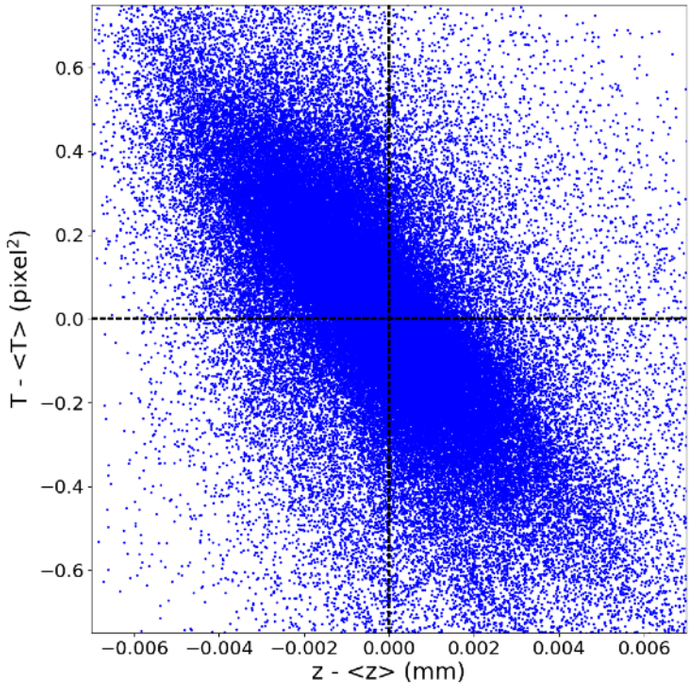
Height measurement of Focal plane @ SLAC

On ITL “blob” or is my telescope in focus?:



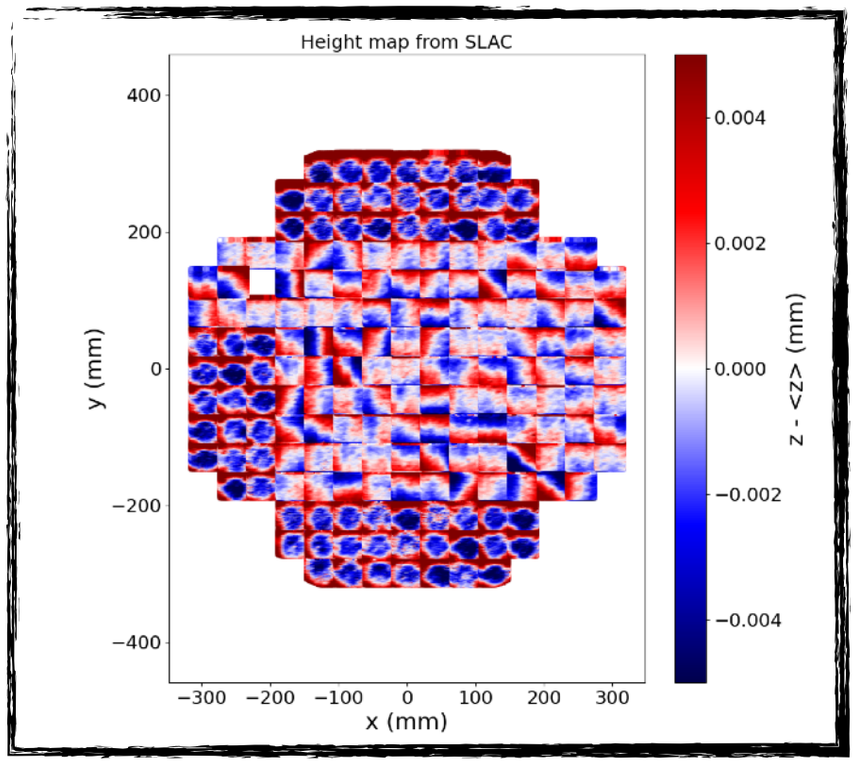


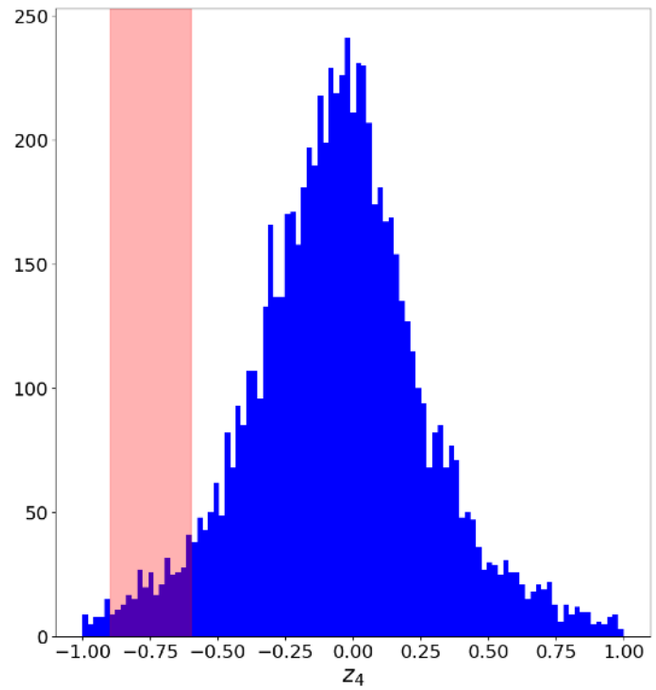


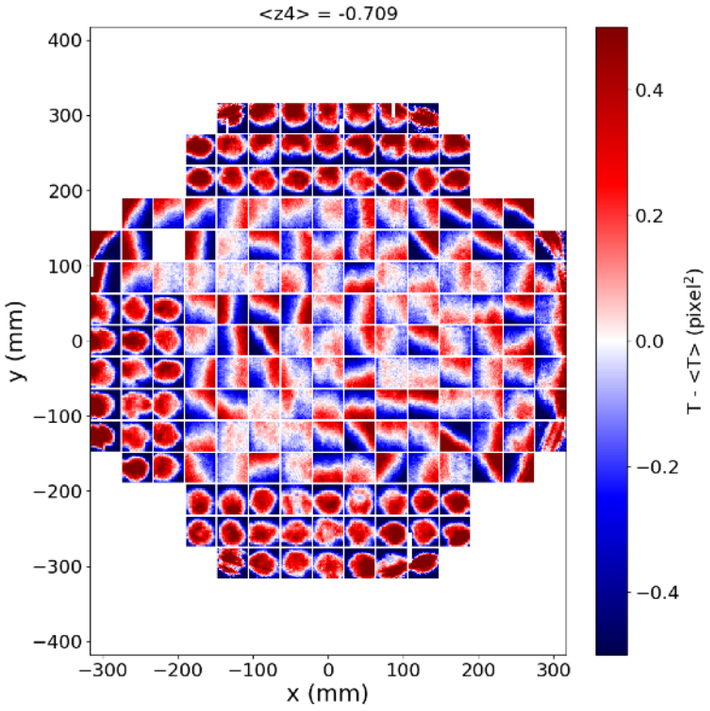


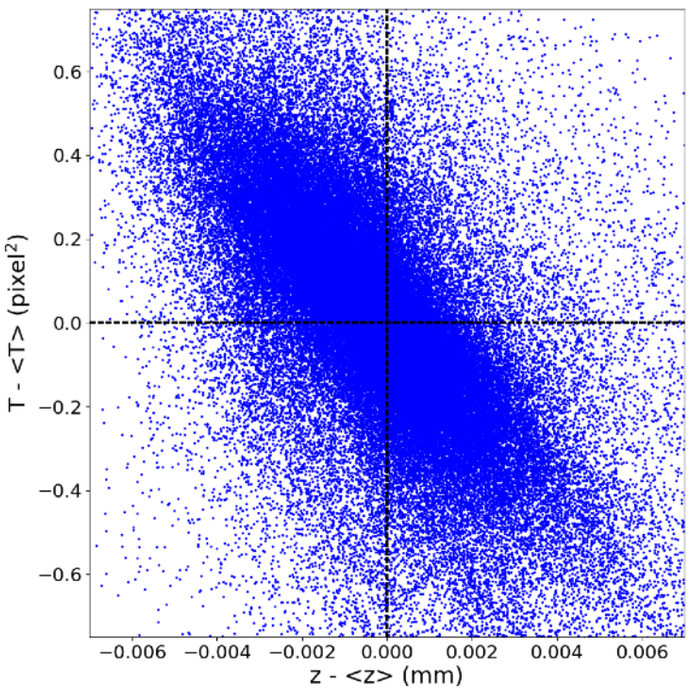
On ITL “blob” or is my telescope in focus?:

- Height map measured at SLAC



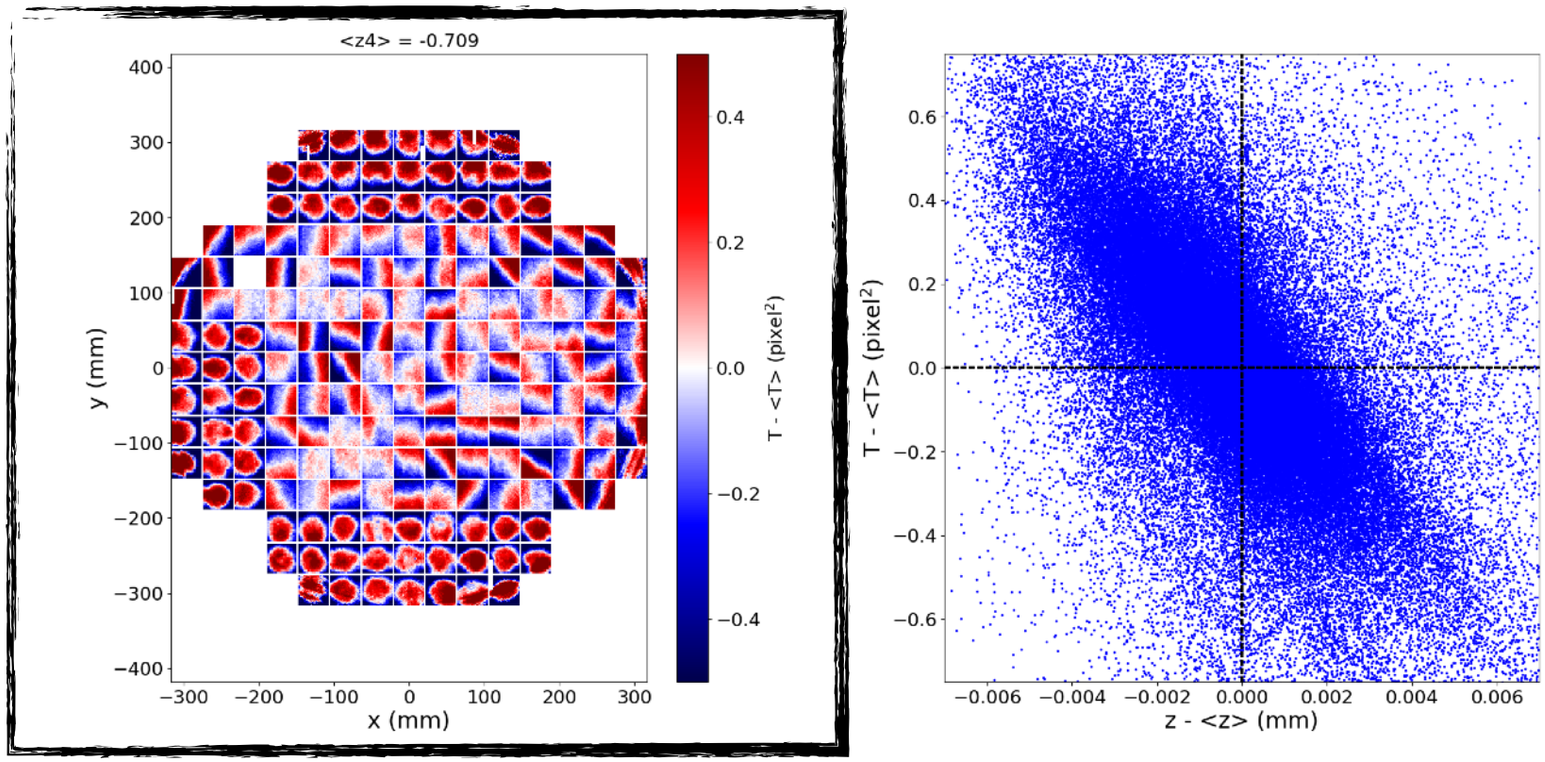






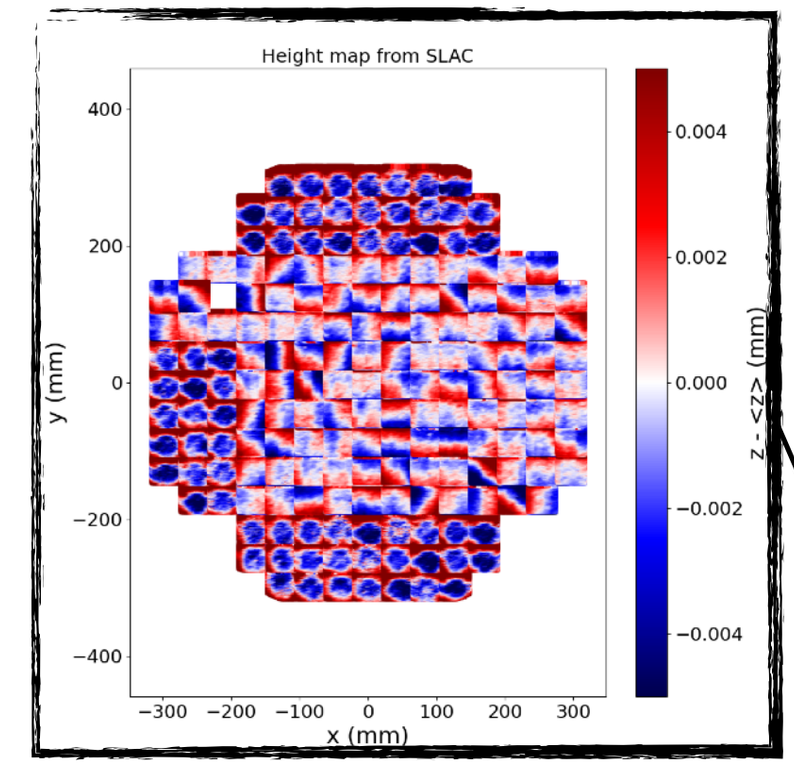
On ITL “blob” or is my telescope in focus?:

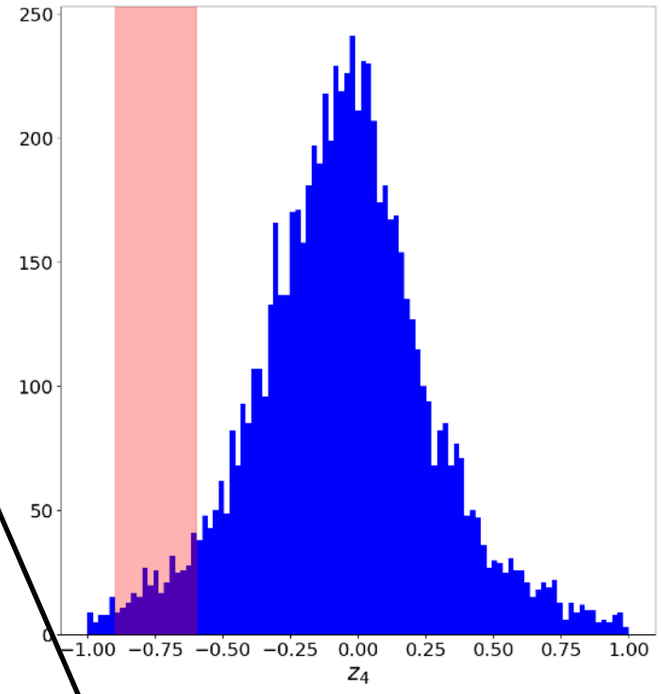
- PSF size residuals after a 0th order polynomial
- Compute in a bin of z4 (focus parameter in AOS from donuts measurement on wavefront)



On ITL “blob” or is my telescope in focus?:

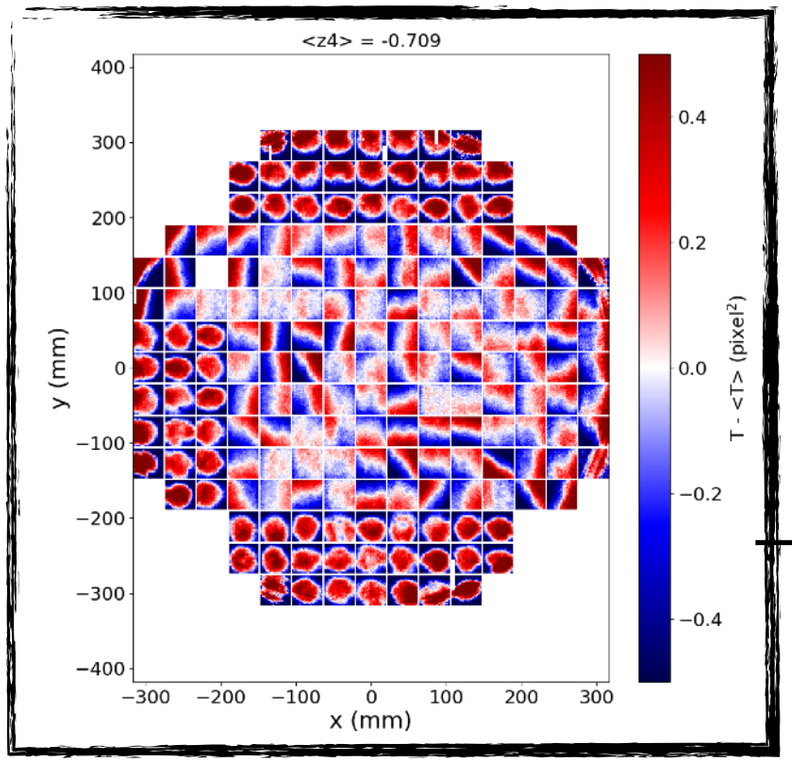
- PSF size vs Height map for the current z4 bin

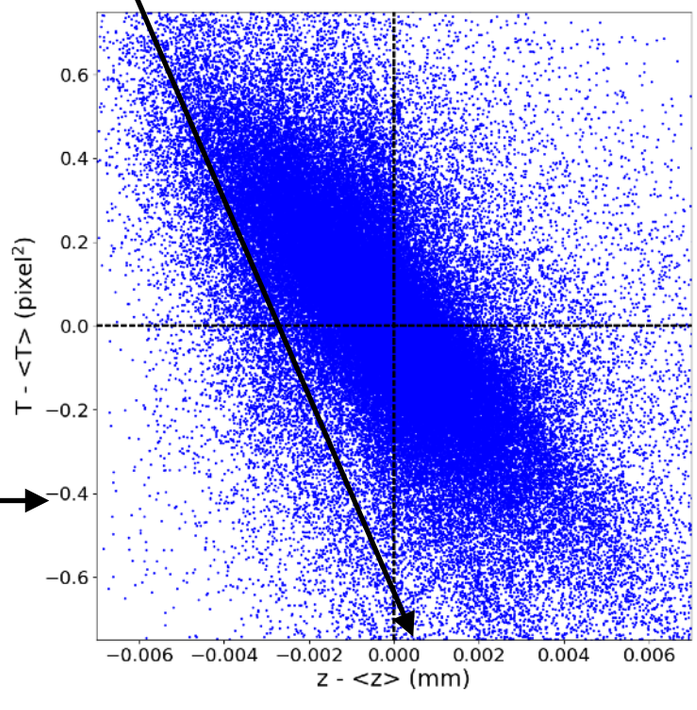




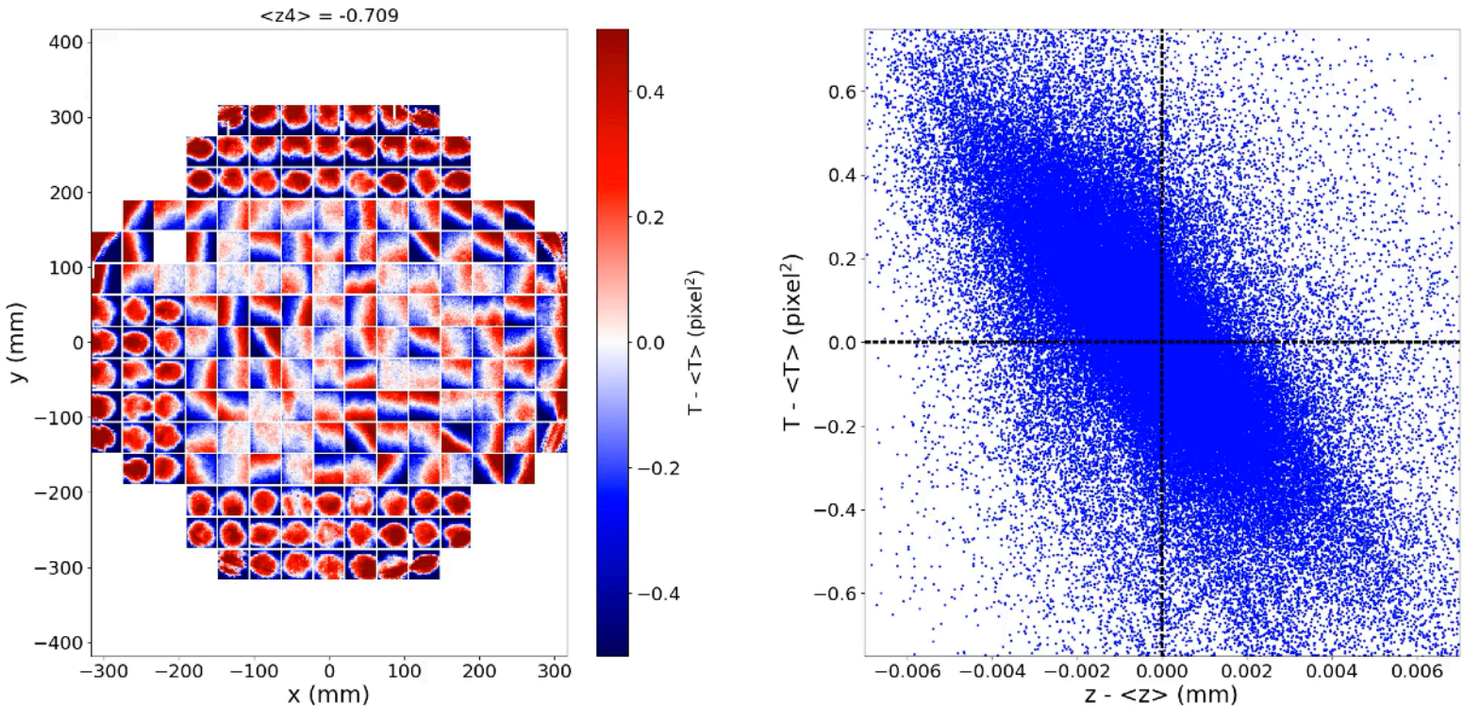
- Lets do a z4 sweep

- Here for all visits from DP2 in i-band



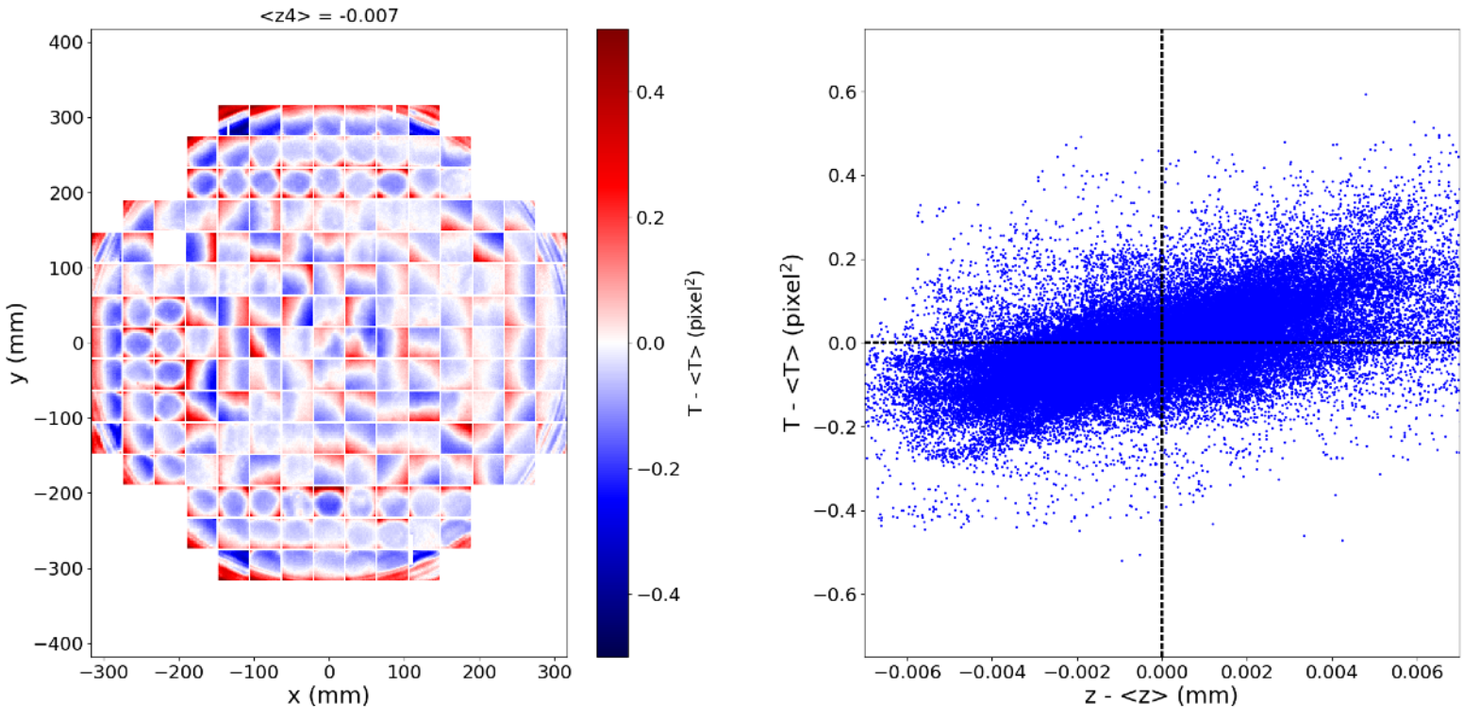


On ITL “blob” or is my telescope in focus?:



On ITL “blob” or is my telescope in focus?:

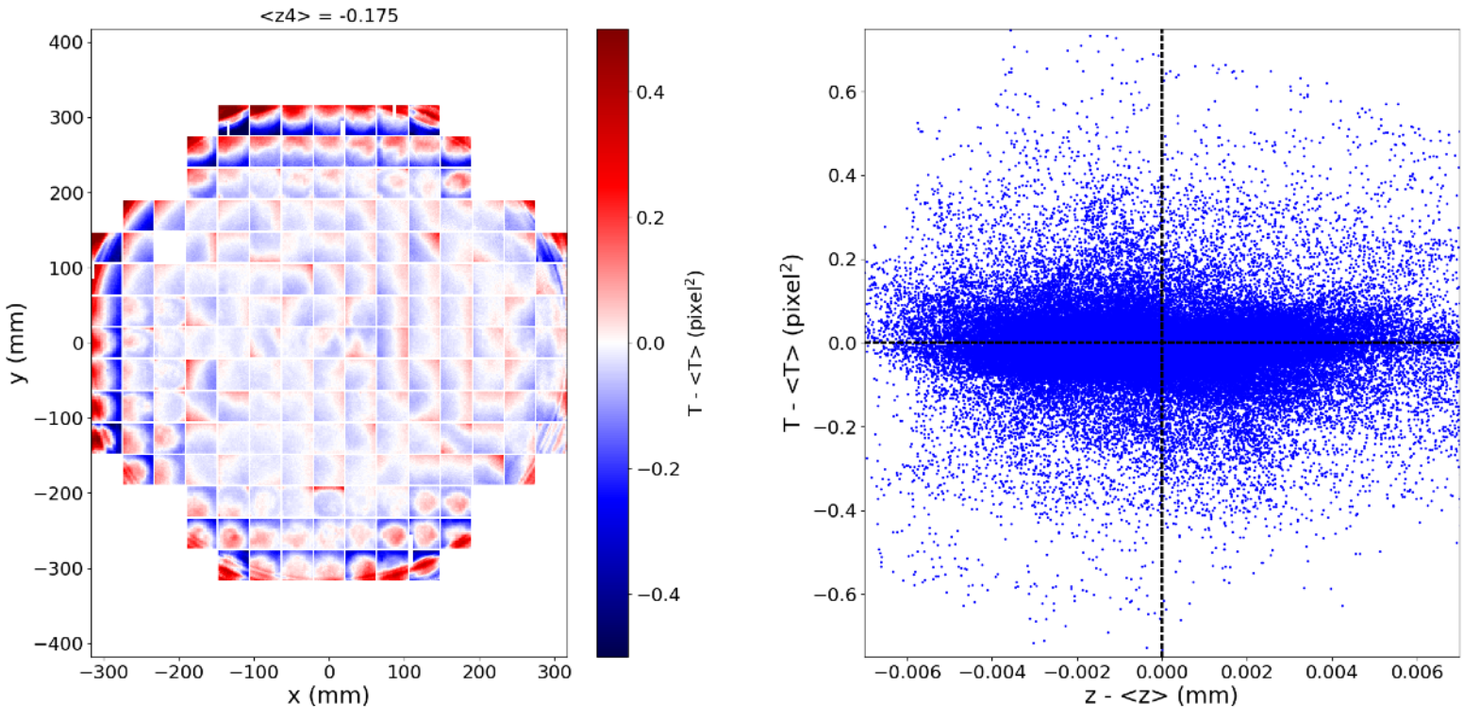
Out of focus



On ITL “blob” or is my telescope in focus?:

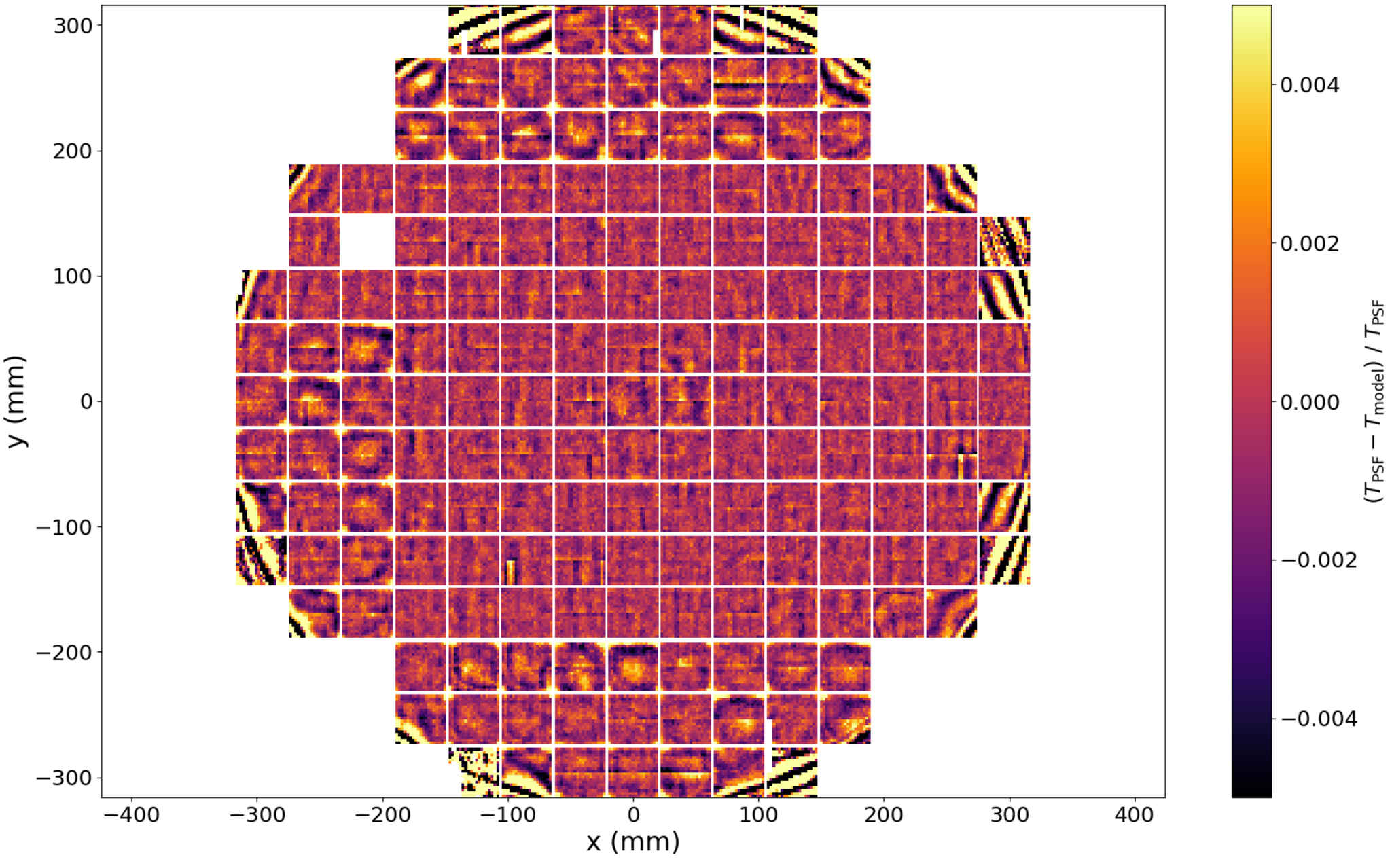
- AOS run with the right offset since mid December

In focus



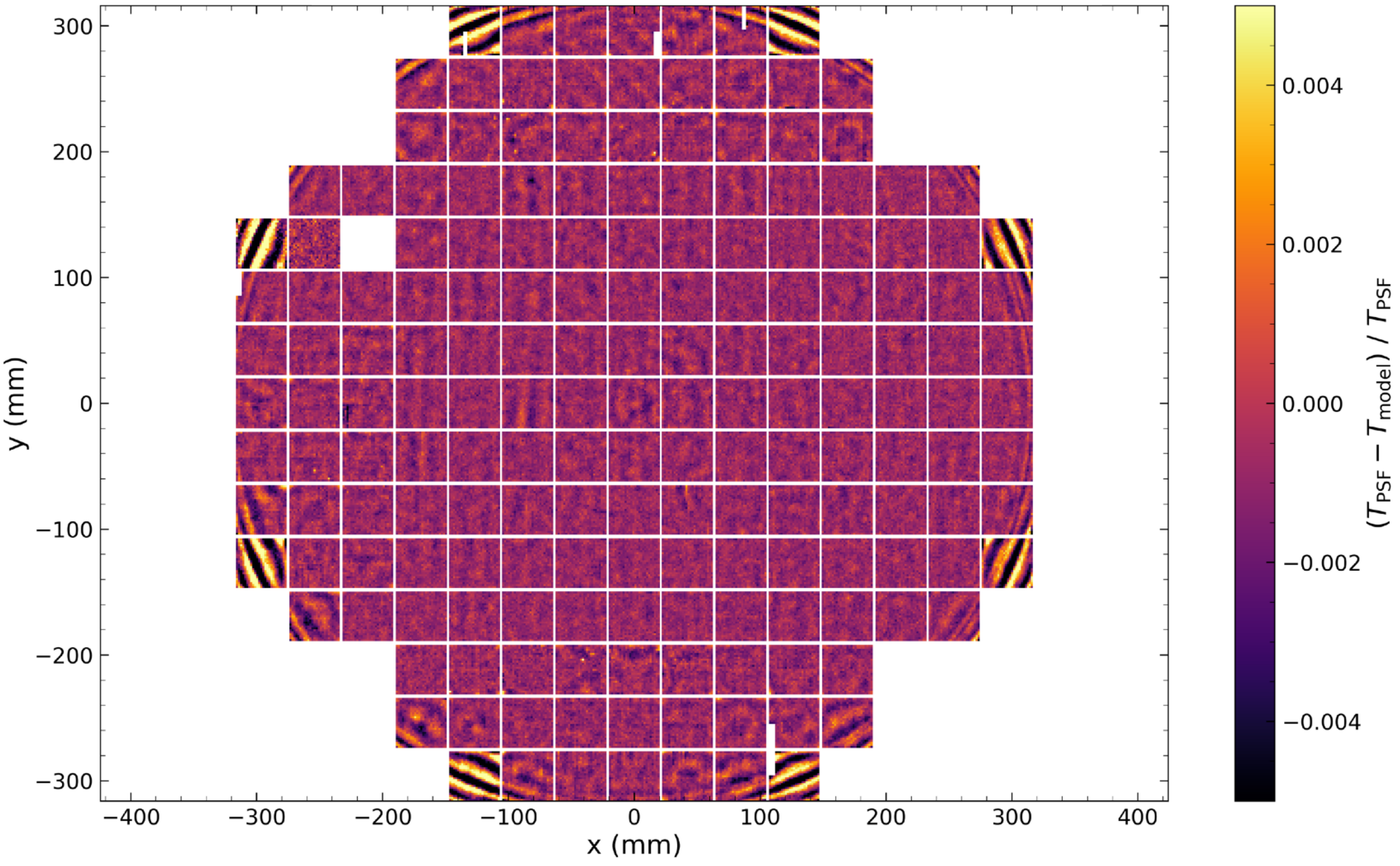
On PSF Characterization

State of PSF modeling in June 2025 (~3k visits)



On PSF Characterization

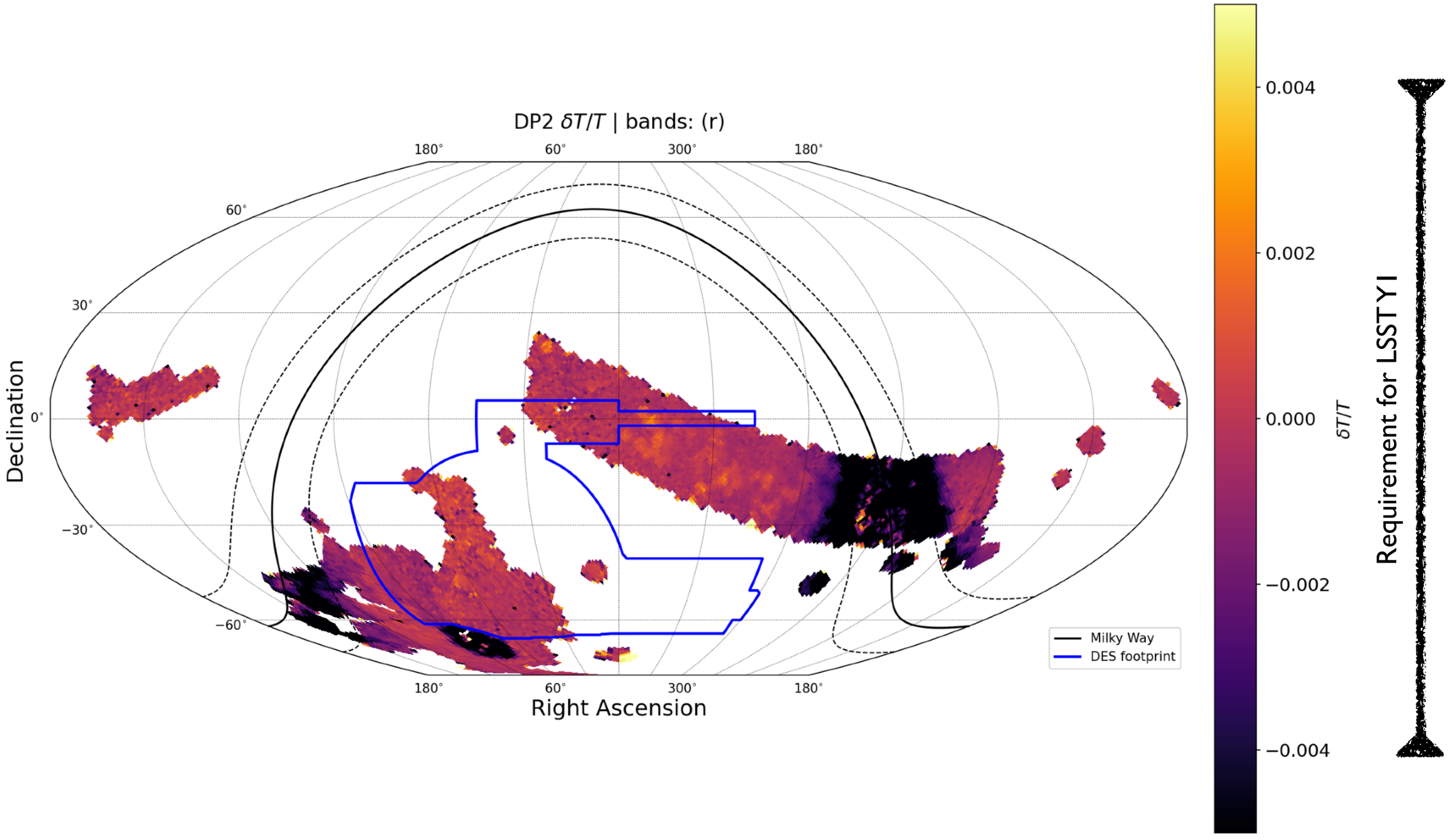
State of PSF modeling in January 2026 (~3k visits)



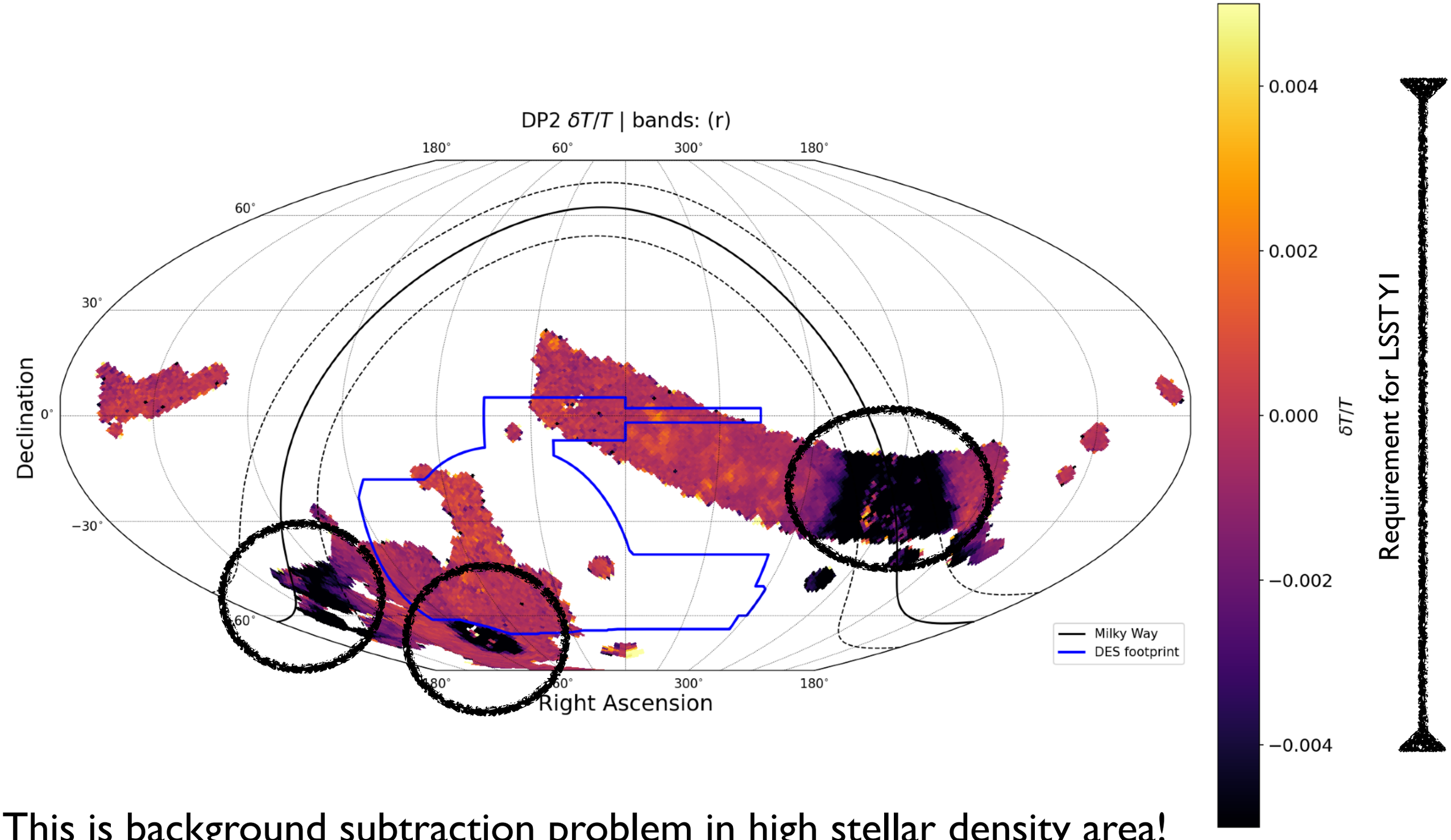
Are we good now 👀 ?

The answer is in the sky!

Are we good now on PSF modeling?



Are we good now on PSF modeling?

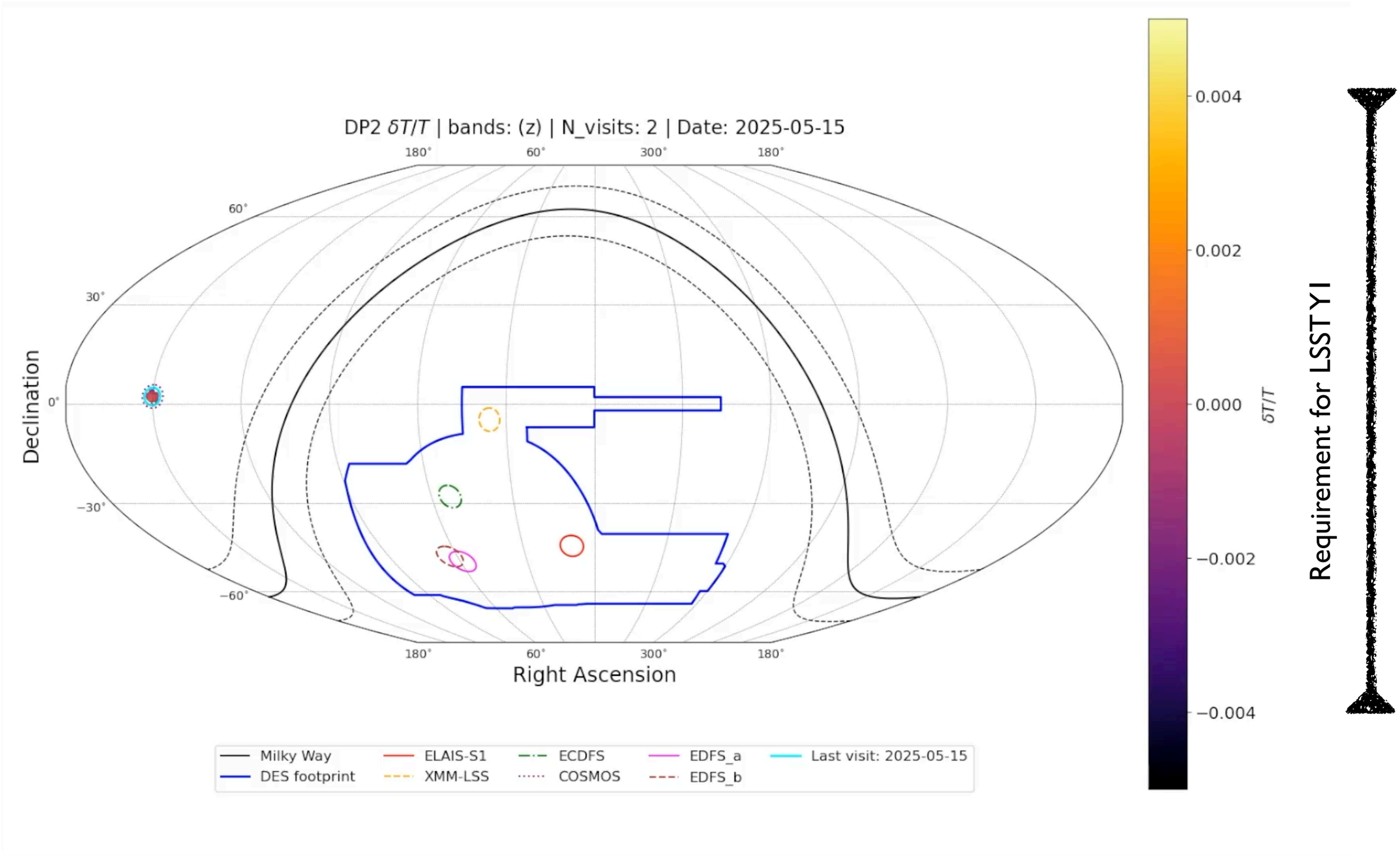


This is background subtraction problem in high stellar density area!

Looks to be in previous survey

We might have a solution for this but need to implement it!

Are we good now on PSF modeling?



Bad PSF residuals correlate with bad stellar density and some outlier visits

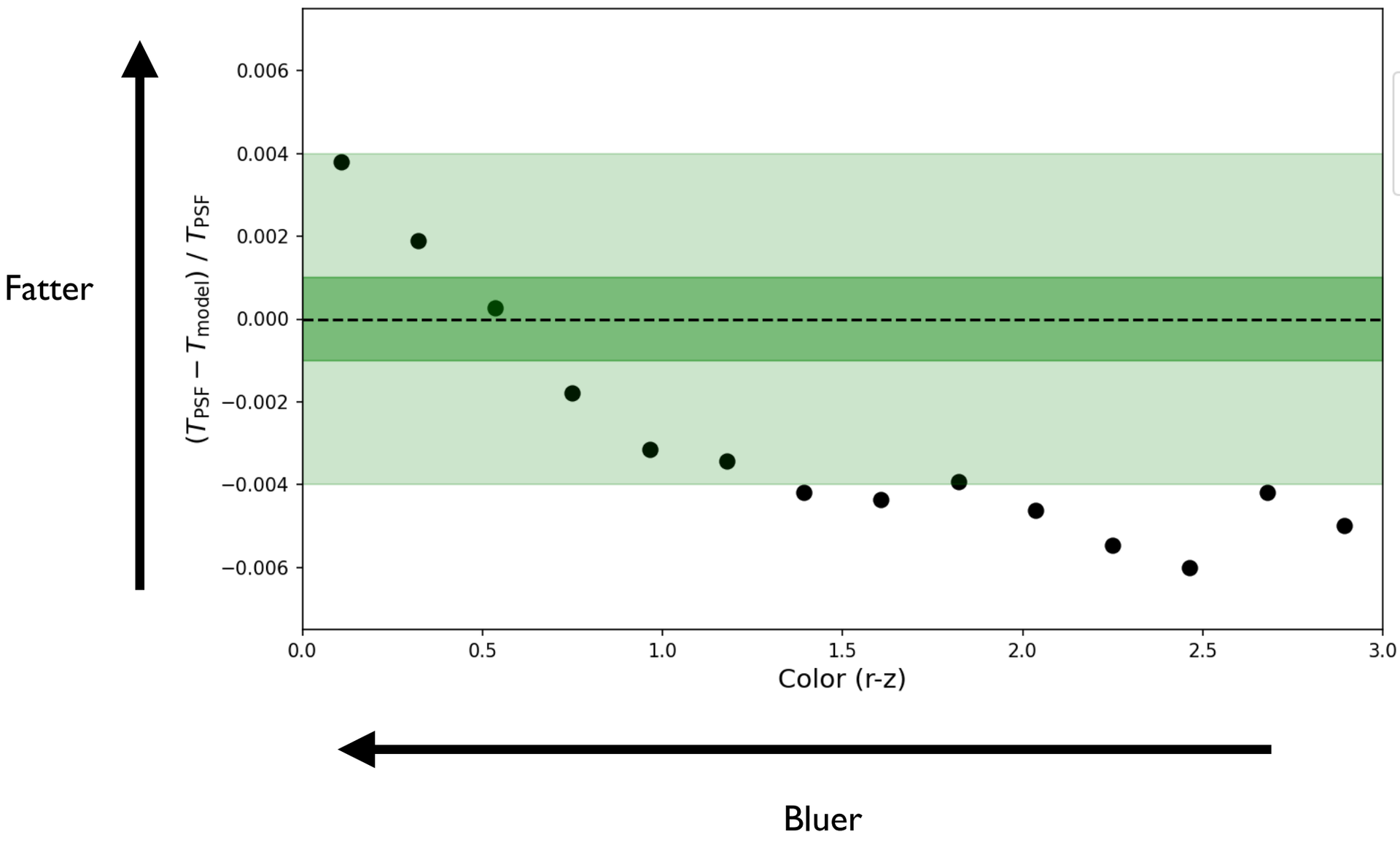
Are we good now on PSF modeling?

Improve PSF modeling in two known areas:

Are we good now on PSF modeling?

Improve PSF modeling in two known areas: On chromatic PSF

"Bluer-Fatter" effect because of Differential Chromatic Refraction

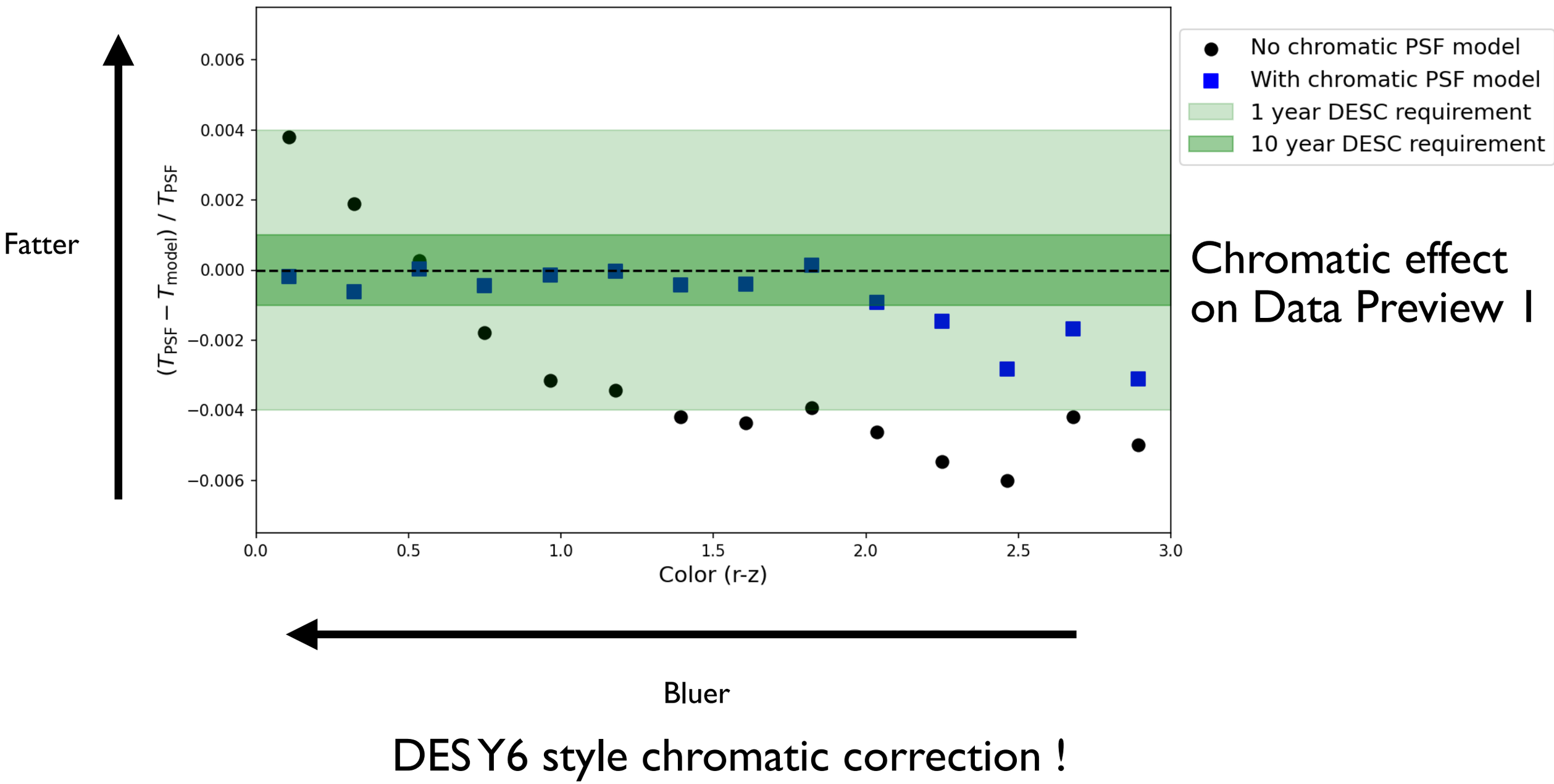


Chromatic effect on Data Preview 1

Are we good now on PSF modeling?

Improve PSF modeling in two known areas: On chromatic PSF

"Bluer-Fatter" effect because of Differential Chromatic Refraction



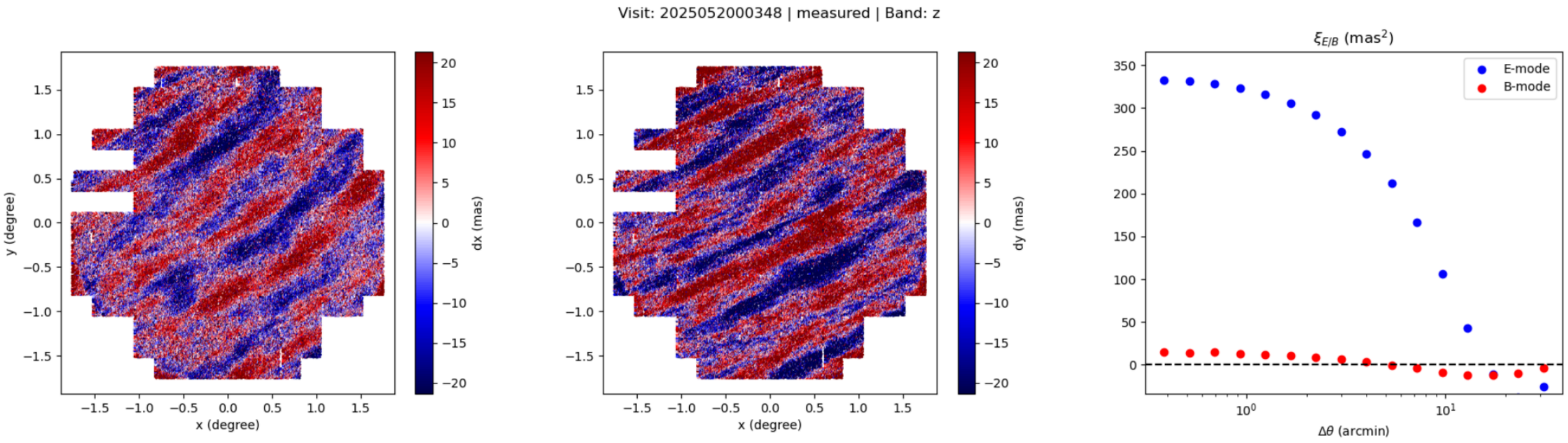
Chromatic effect on Data Preview 1

DES Y6 style chromatic correction !

Are we good now on PSF modeling?

Improve PSF modeling in two known areas: Introducing Astrometric distortion

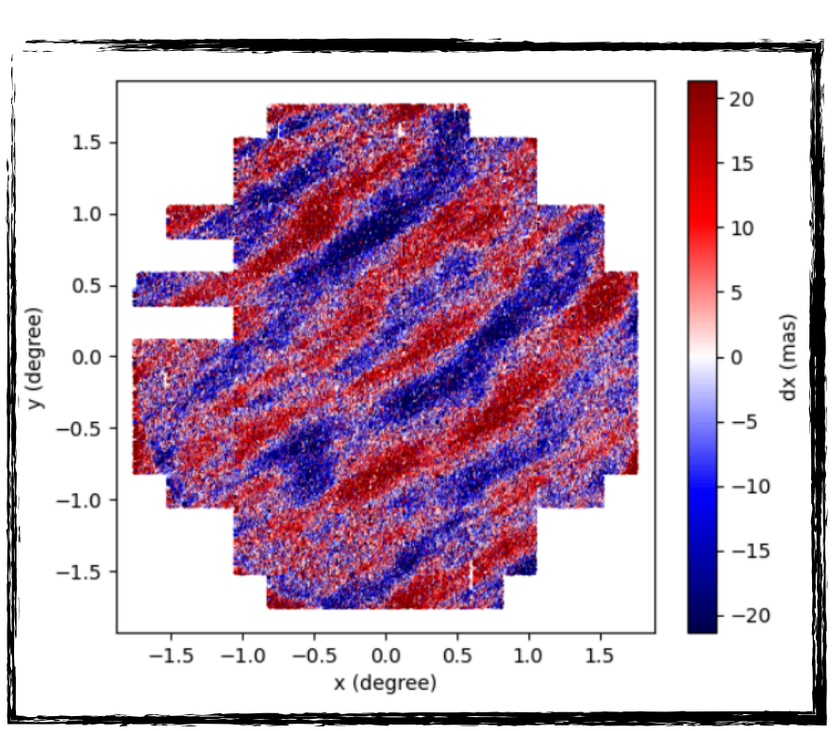
Residual position (astrometric) distortion

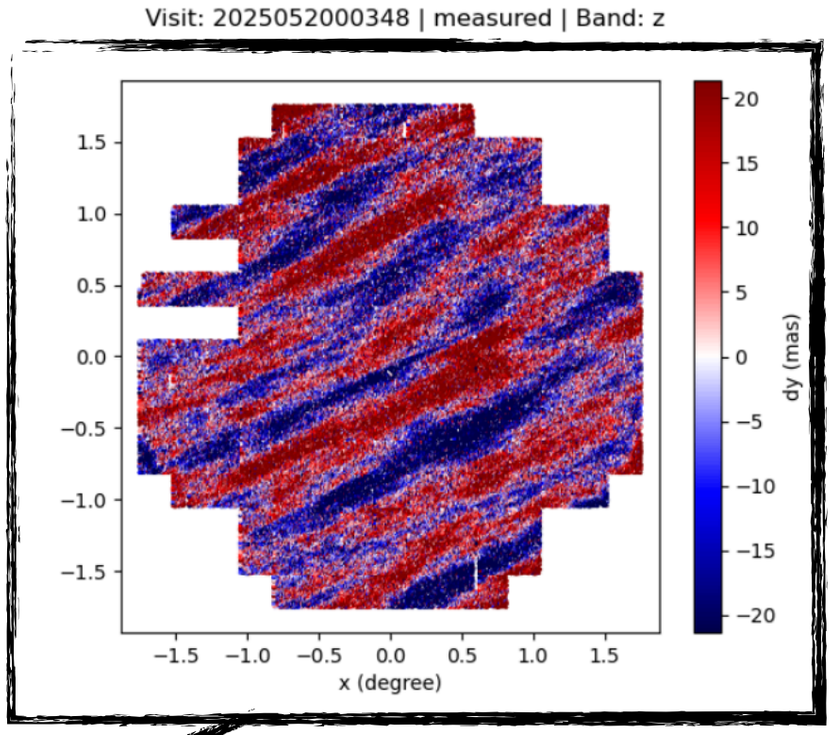


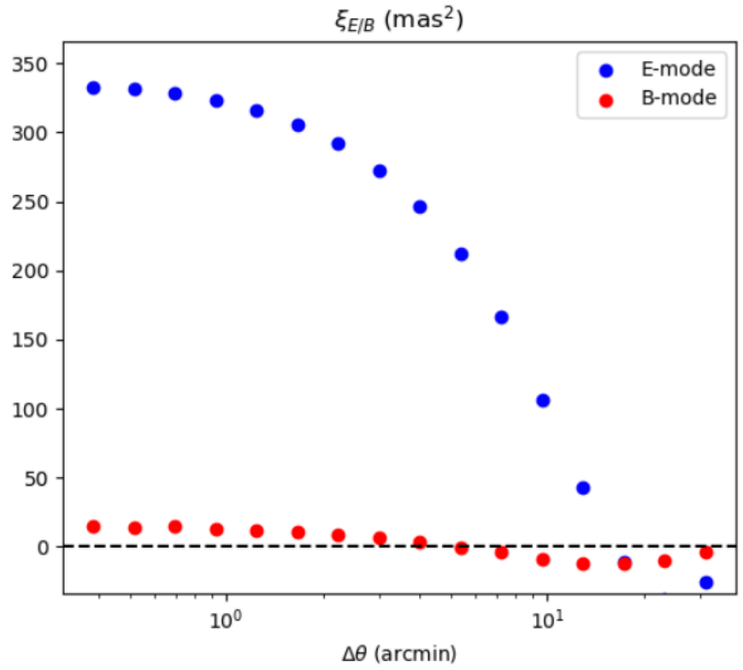
Are we good now on PSF modeling?

Improve PSF modeling in two known areas: Introducing Astrometric distortion

Residual position (astrometric) distortion





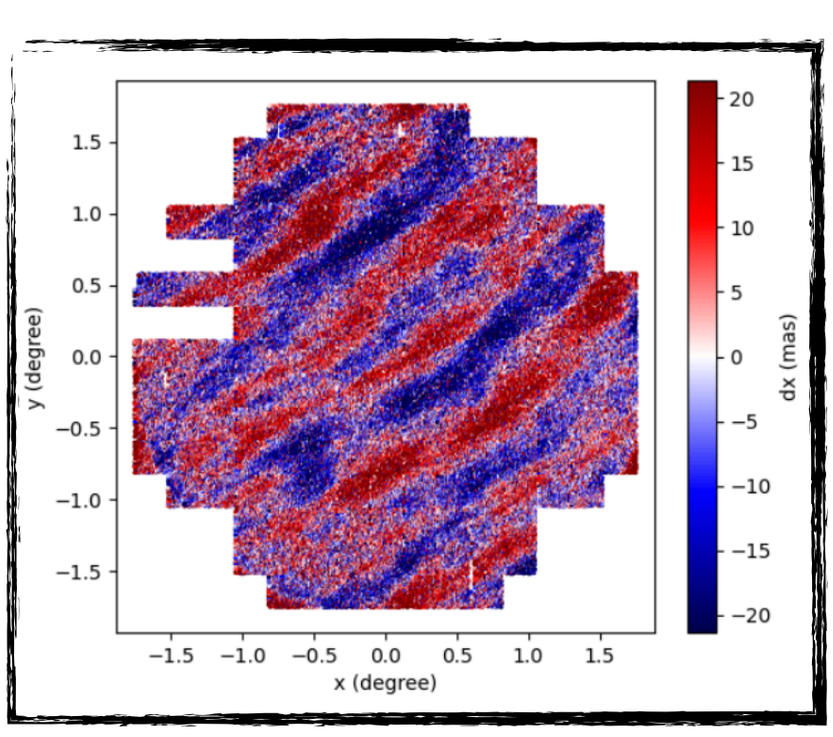


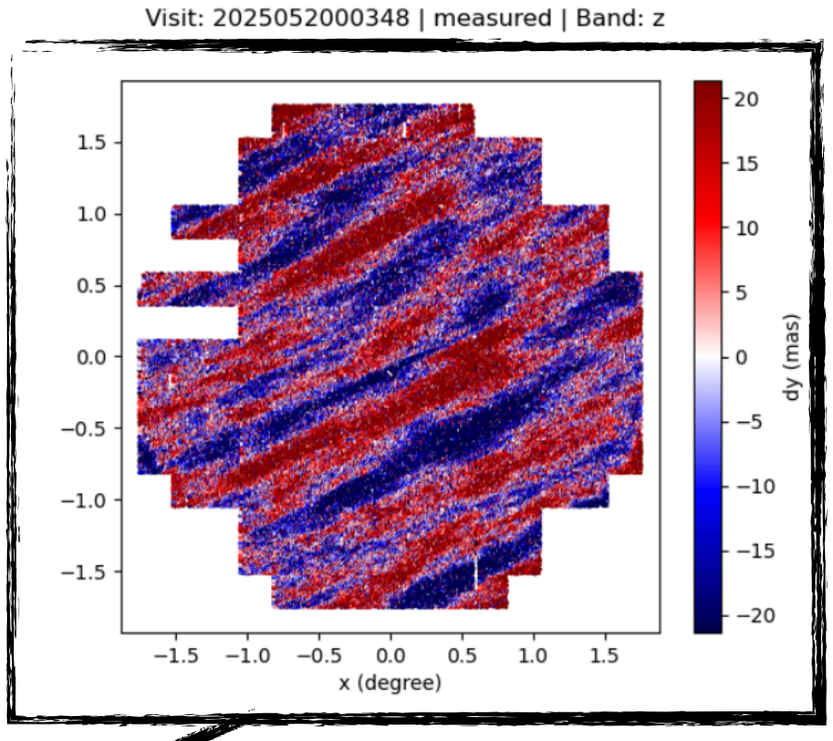
Position distortion for a single visit

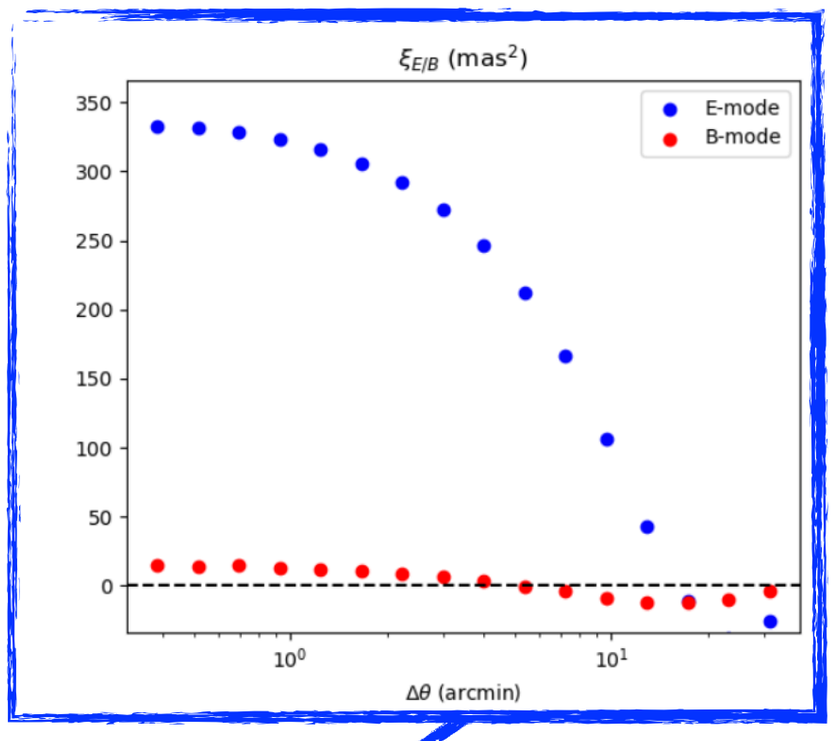
Are we good now on PSF modeling?

Improve PSF modeling in two known areas: Introducing Astrometric distortion

Residual position (astrometric) distortion







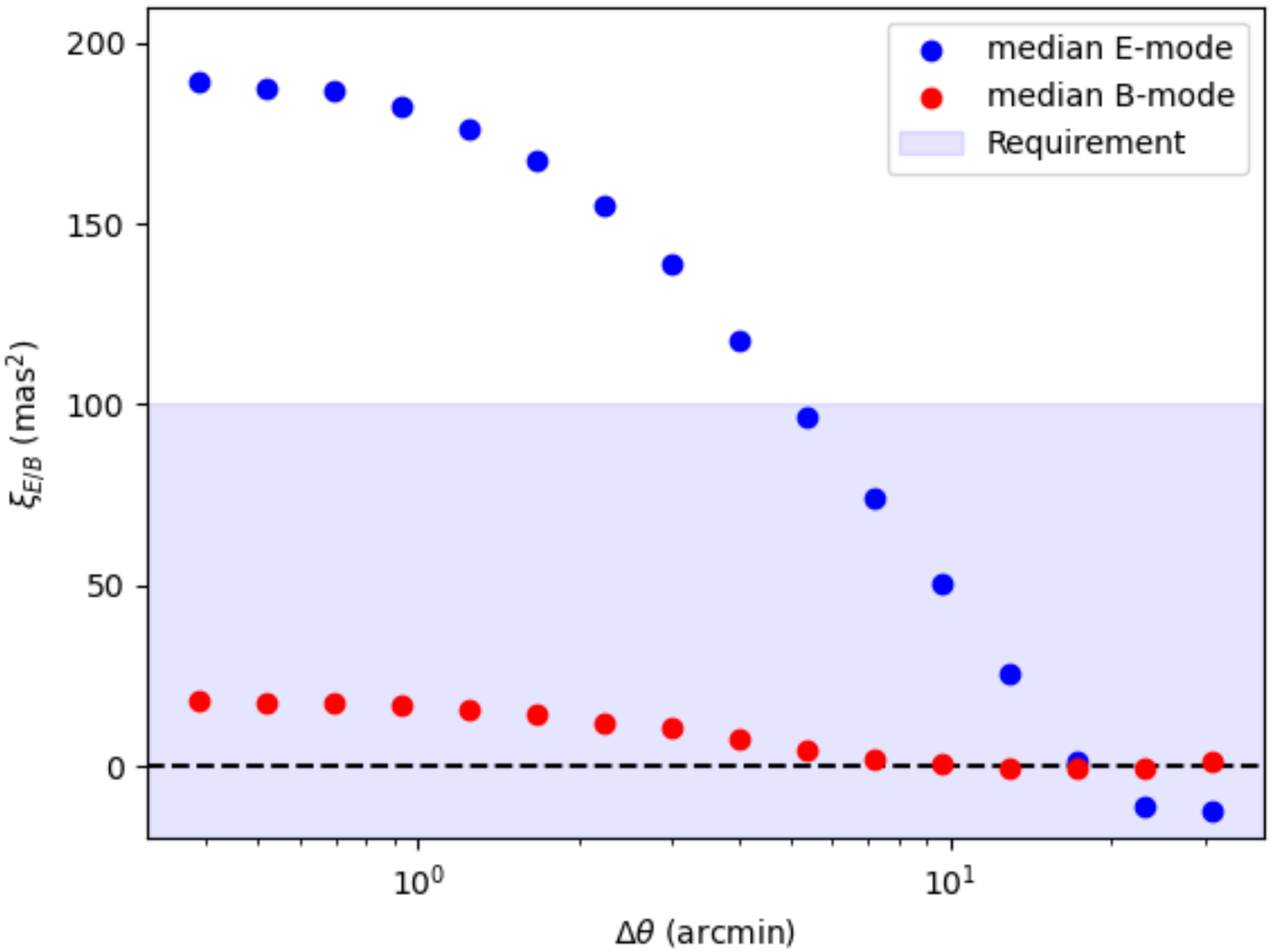
Position distortion for a single visit

Curl free (E) and divergence free (B) correlation function of the vector field

Only E-mode —> Turbulence from Earth atmosphere.

Are we good now on PSF modeling?

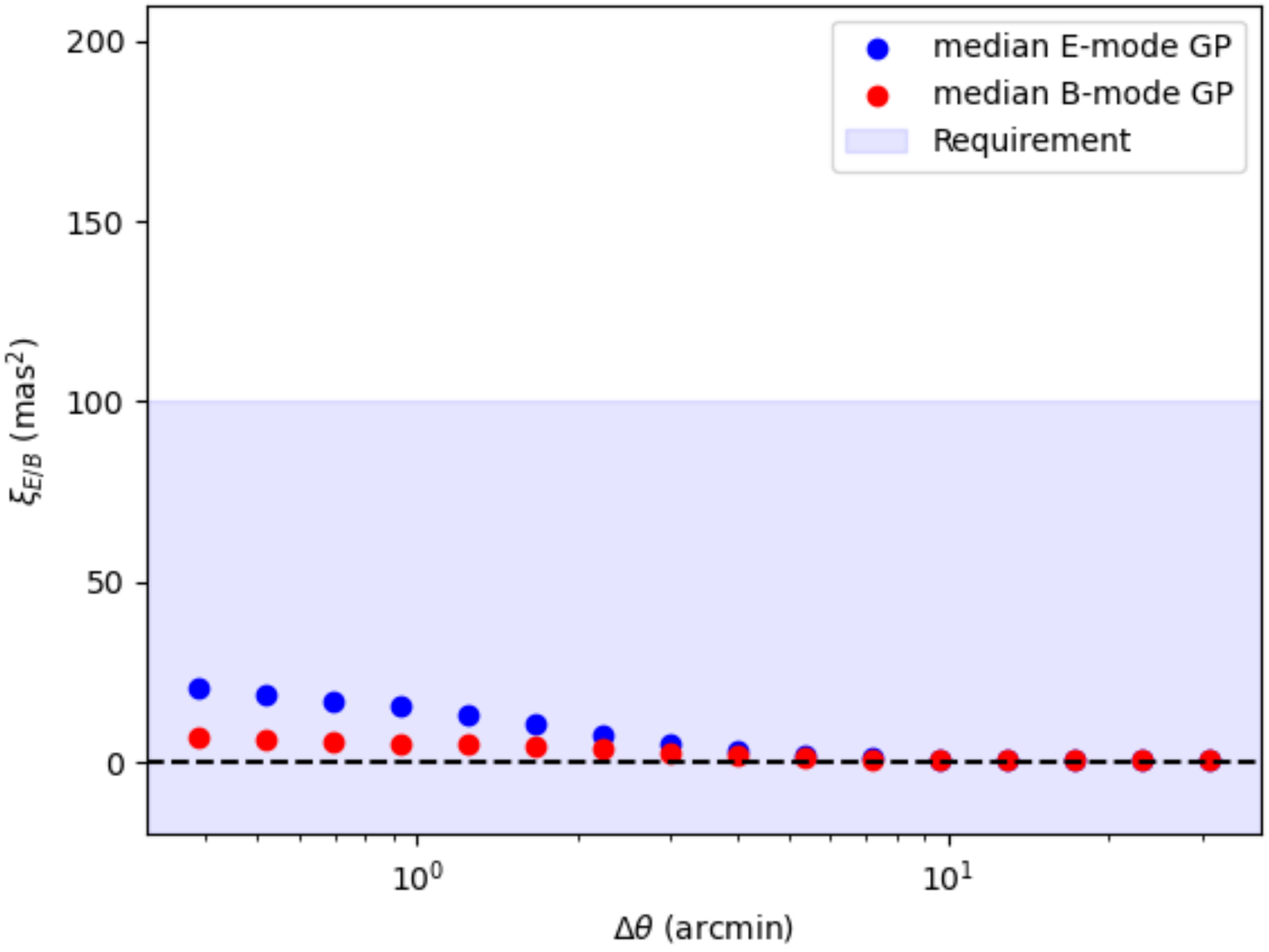
Improve PSF modeling in two known areas: Introducing Astrometric distortion



Median E and B mode for LSSTCam

Are we good now on PSF modeling?

Improve PSF modeling in two known areas: Introducing Astrometric distortion



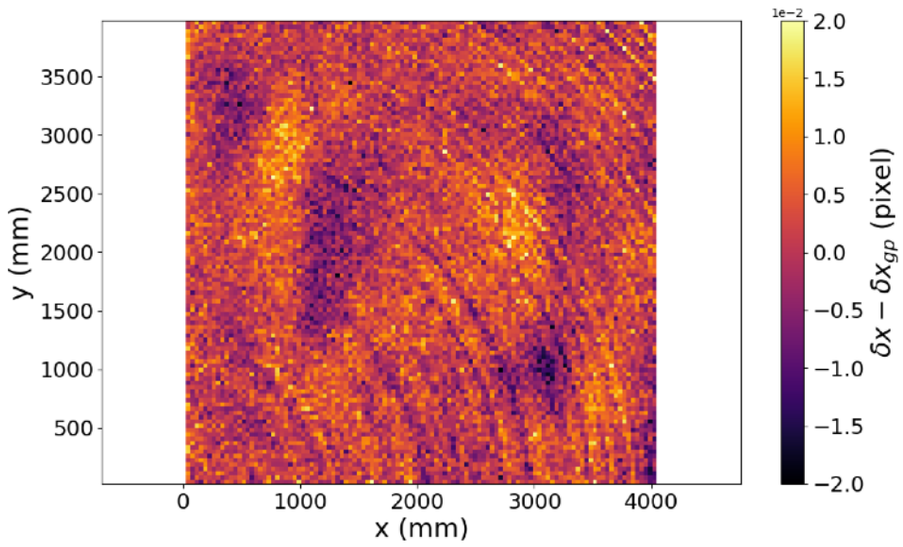
Median E and B mode for LSSTCam

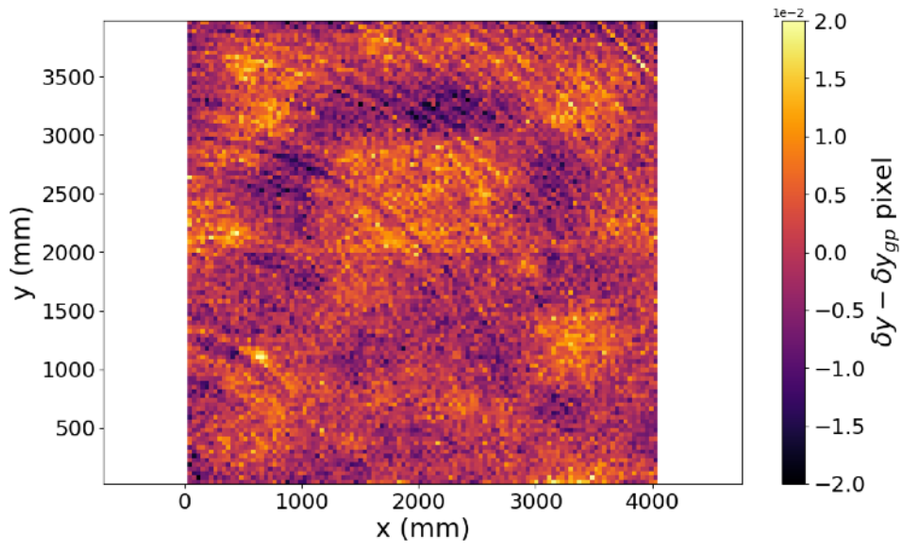
After Gaussian Process modeling with a turbulence kernel (Von Kármán)

Are we good now on PSF modeling?

Improve PSF modeling in two known areas: Introducing Astrometric distortion

Once the atmosphere removed we can see sensor defect in position distortion

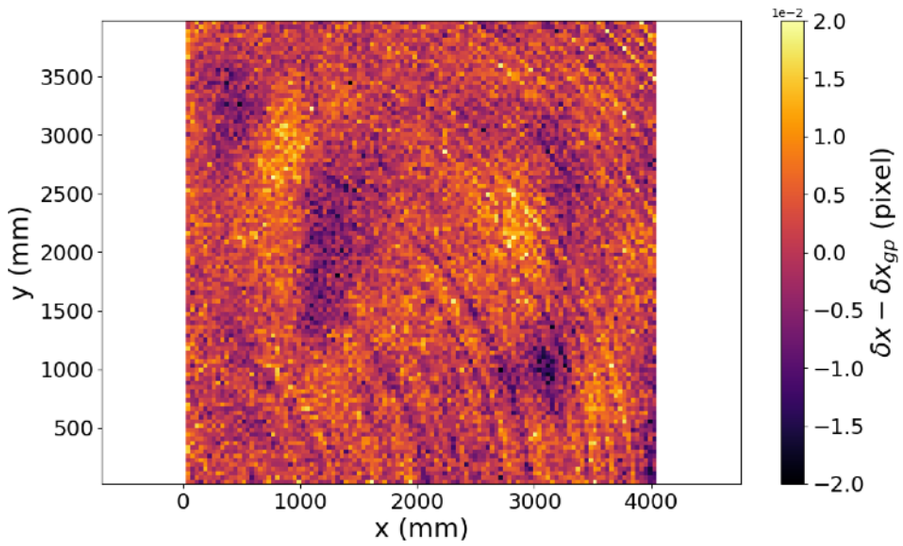


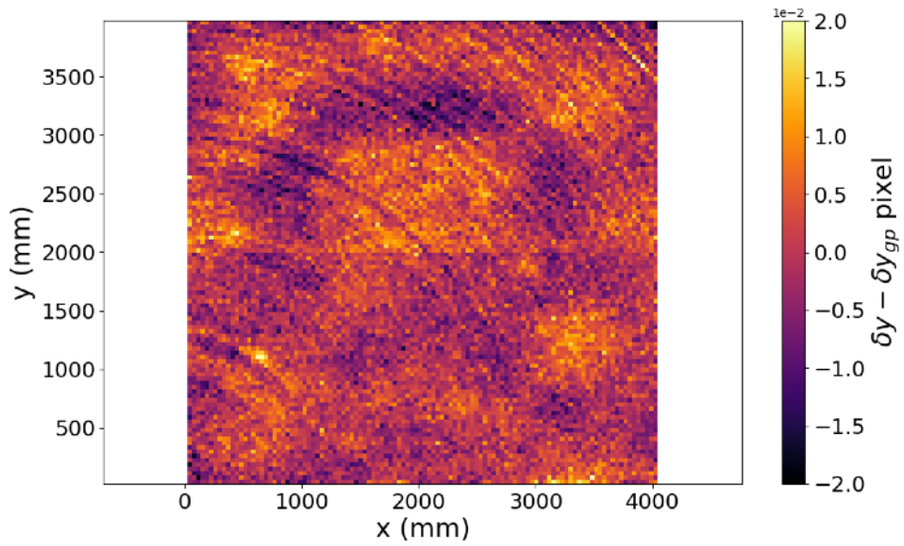


Are we good now on PSF modeling?

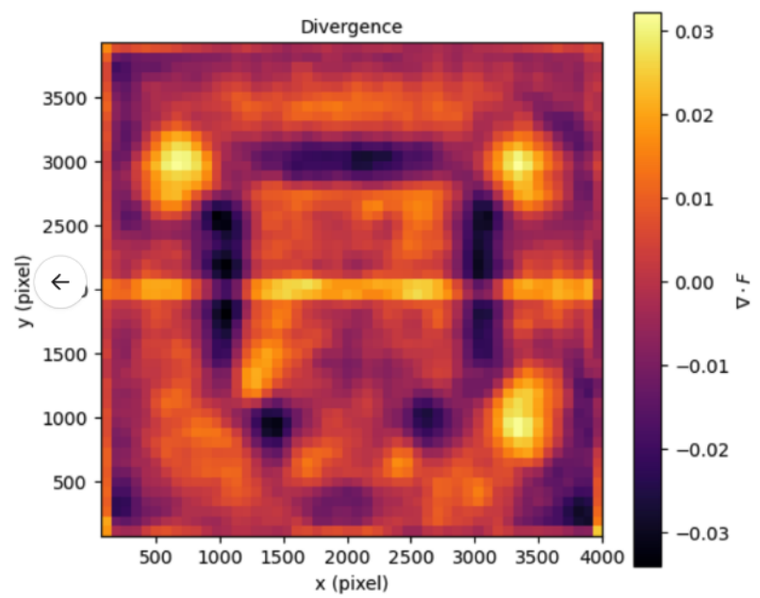
Improve PSF modeling in two known areas: Introducing Astrometric distortion

Once the atmosphere removed we can see sensor defect in position distortion





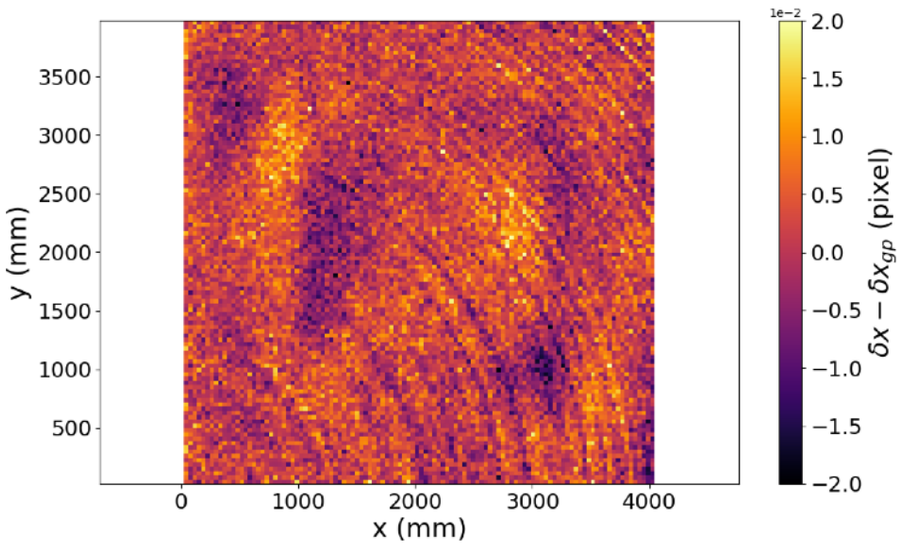
Lets take the divergence

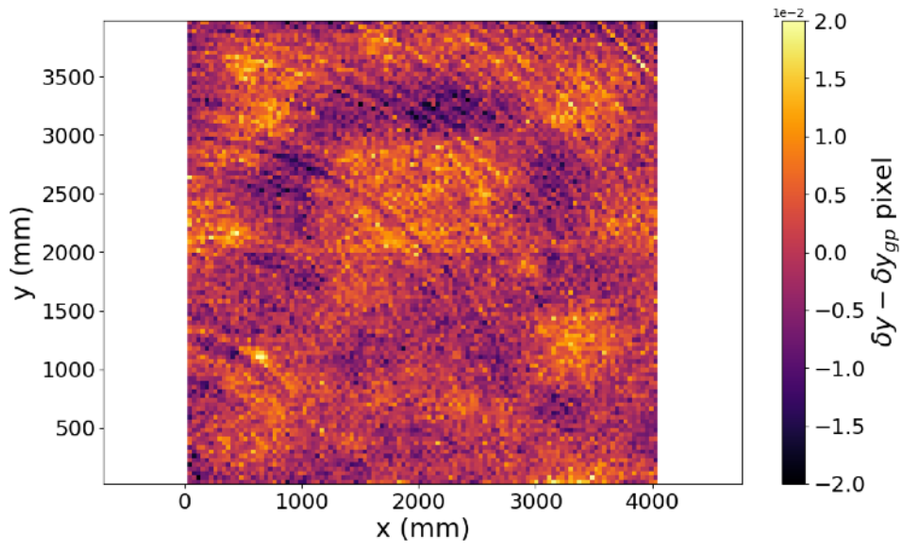


Are we good now on PSF modeling?

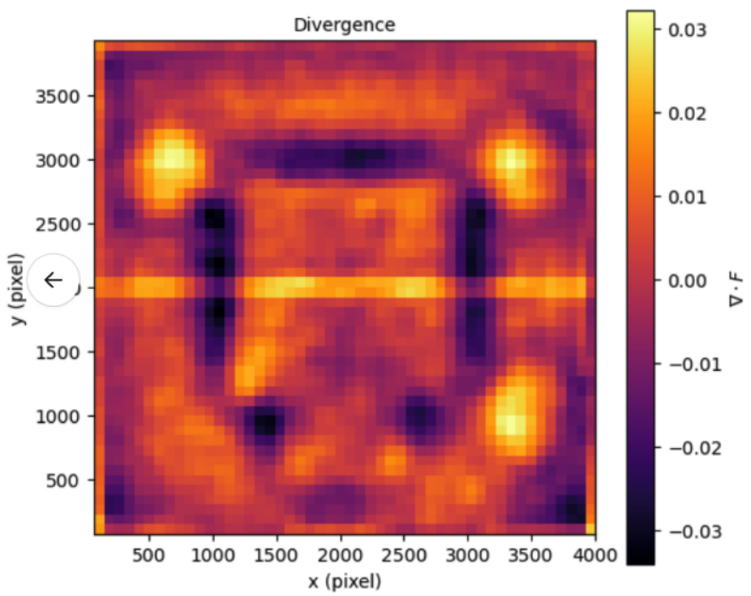
Improve PSF modeling in two known areas: Introducing Astrometric distortion

Once the atmosphere removed we can see sensor defect in position distortion

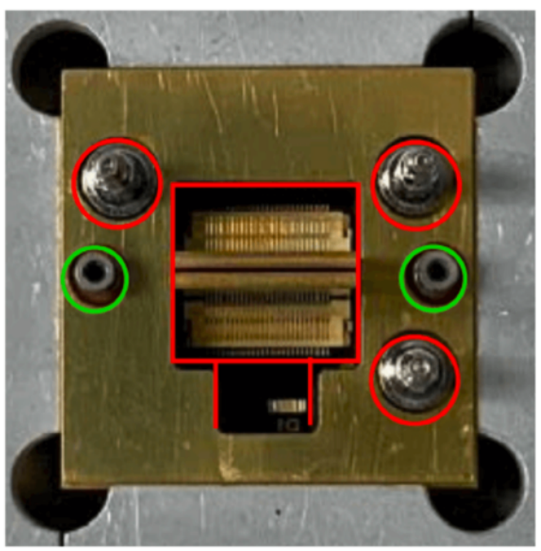




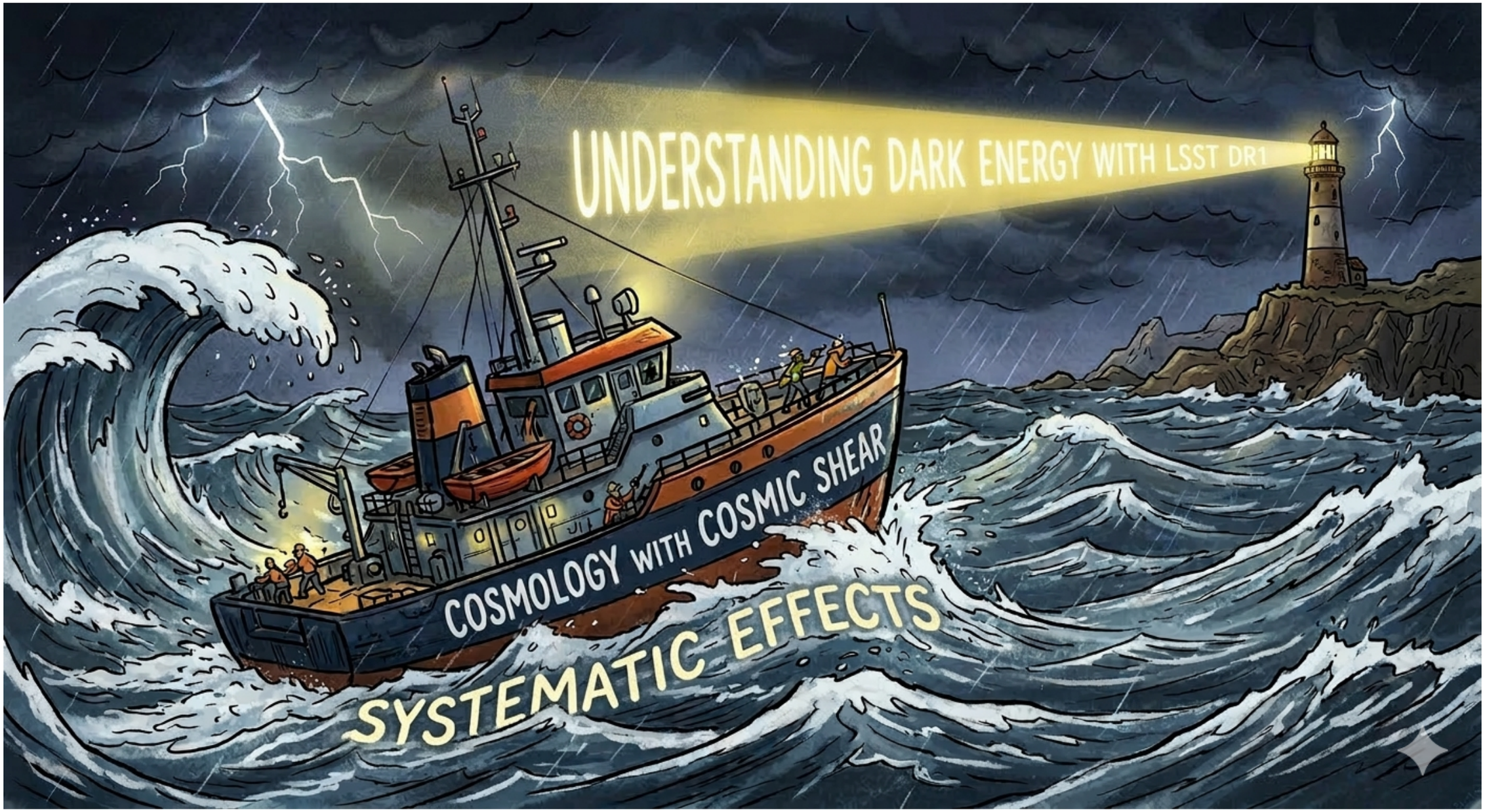
Lets take the divergence



Looks like the sensor support!

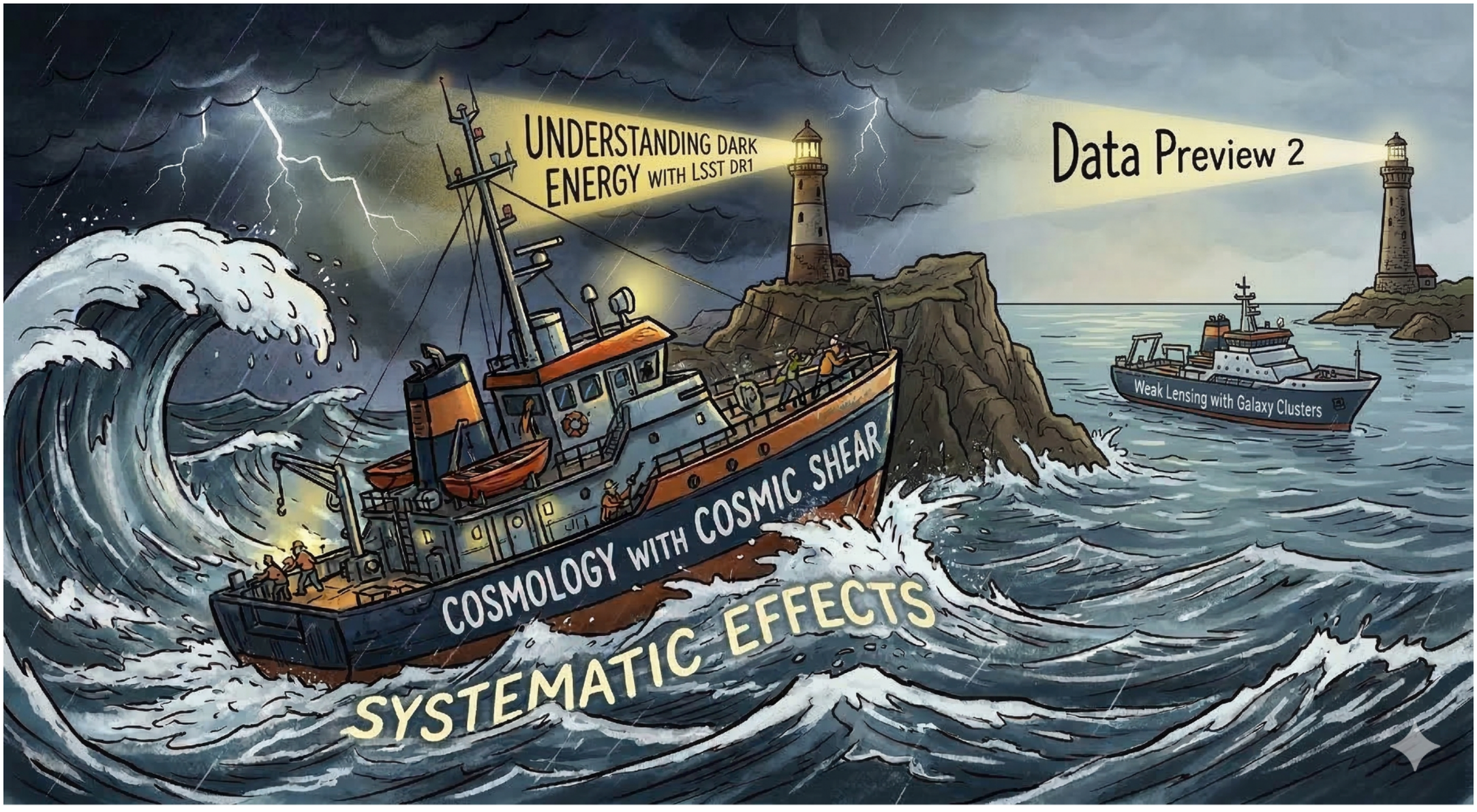


Weak lensing with DP2?



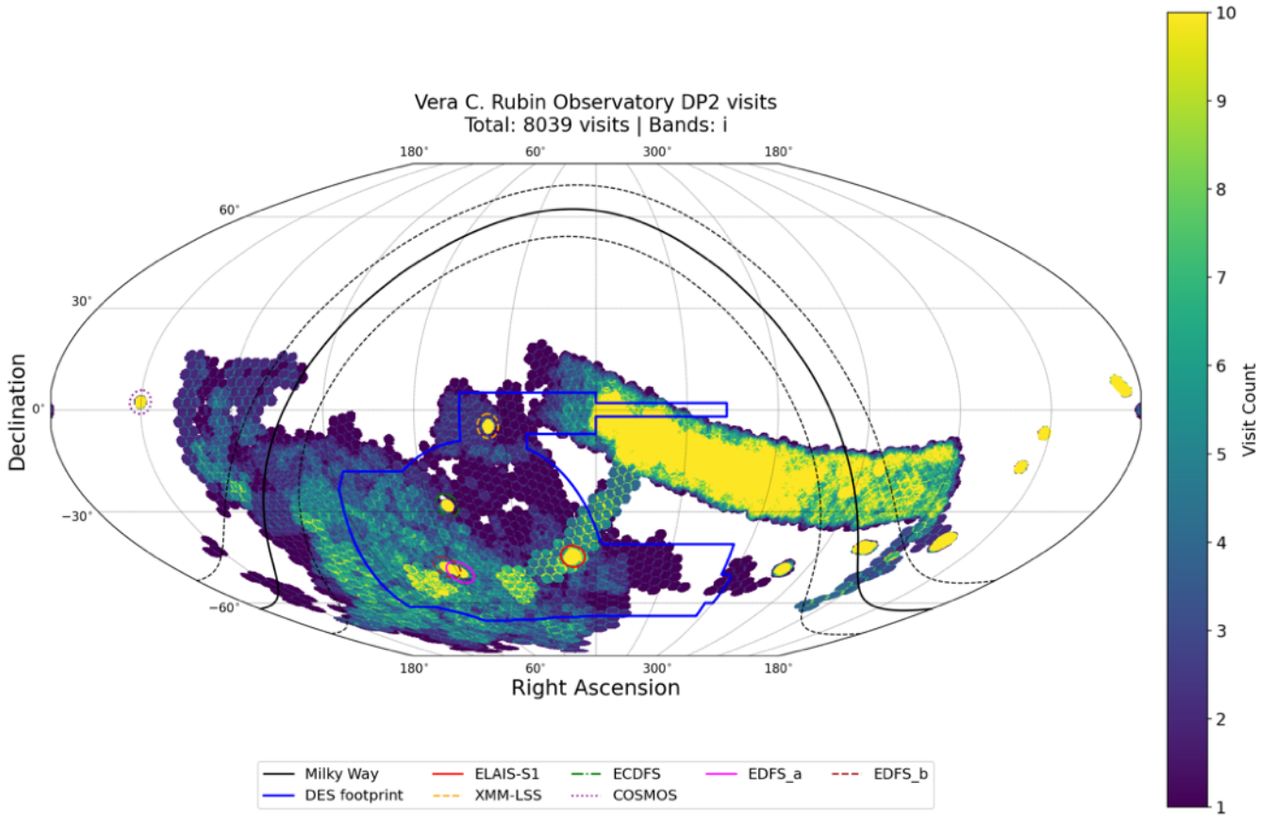
Systematic of cosmic shear are hard but we are going through the storm to reach the first cosmic shear analysis with LSST!

Weak lensing with DP2?



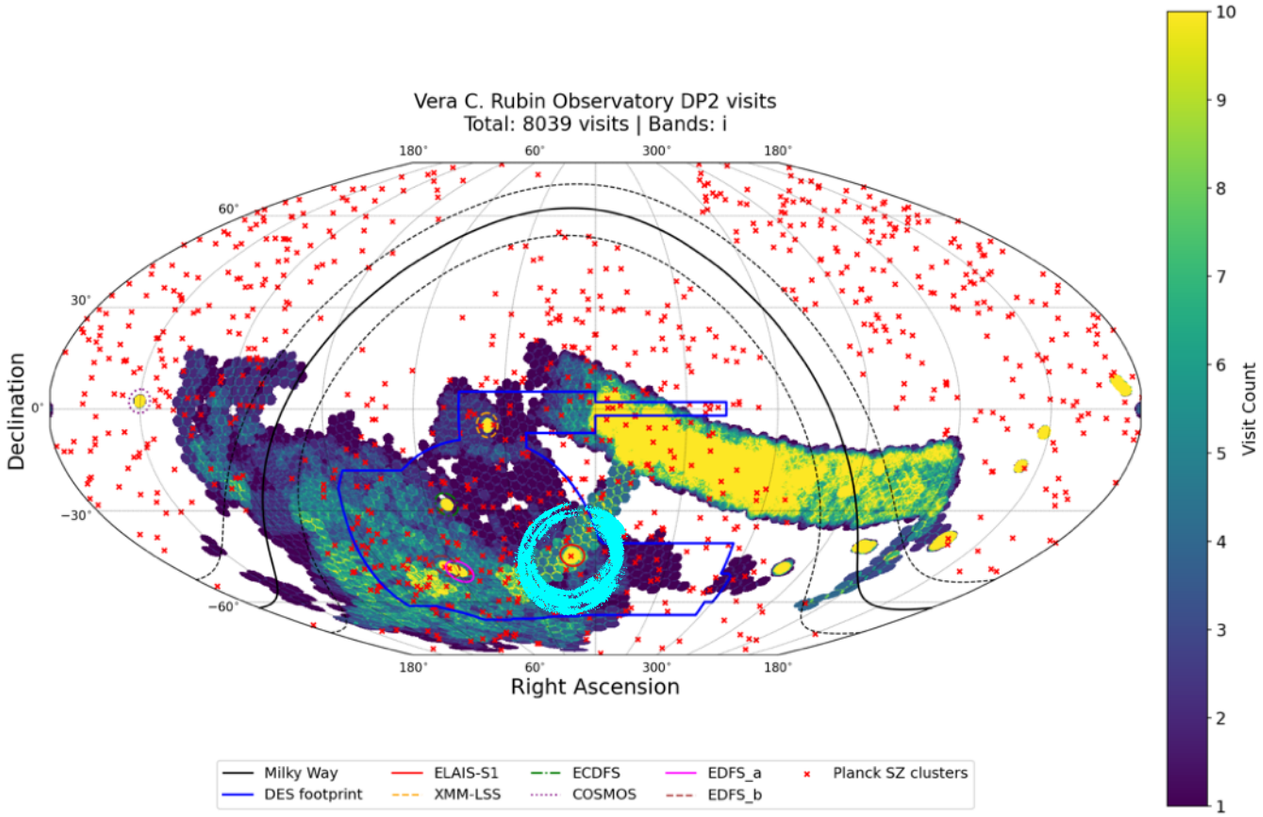
But weak lensing can be study also on Galaxy cluster with the up-coming public data release in 2026 !

On weak lensing with Galaxy clusters in DP2



DP2 footprint in i-band

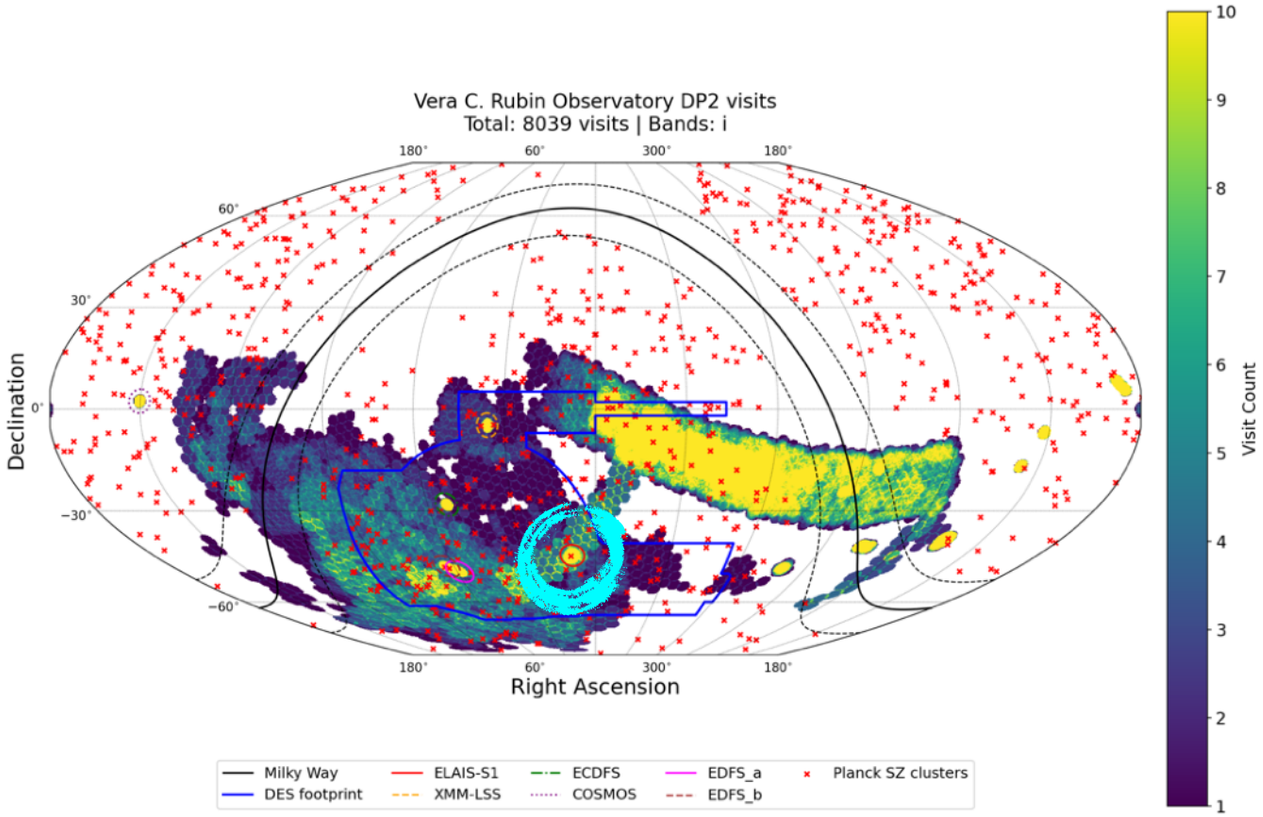
On weak lensing with Galaxy clusters in DP2



DP2 footprint in i-band

Sunyaev-Zeldovich Galaxy Cluster from Planck (redshift in 0.1 and 1)

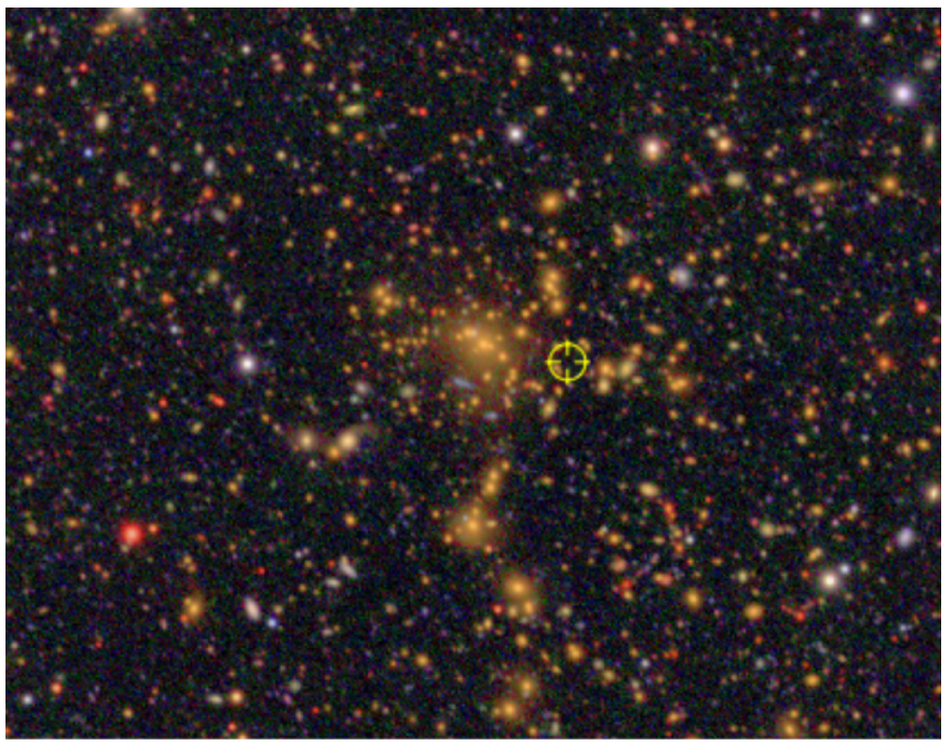
On weak lensing with Galaxy clusters in DP2



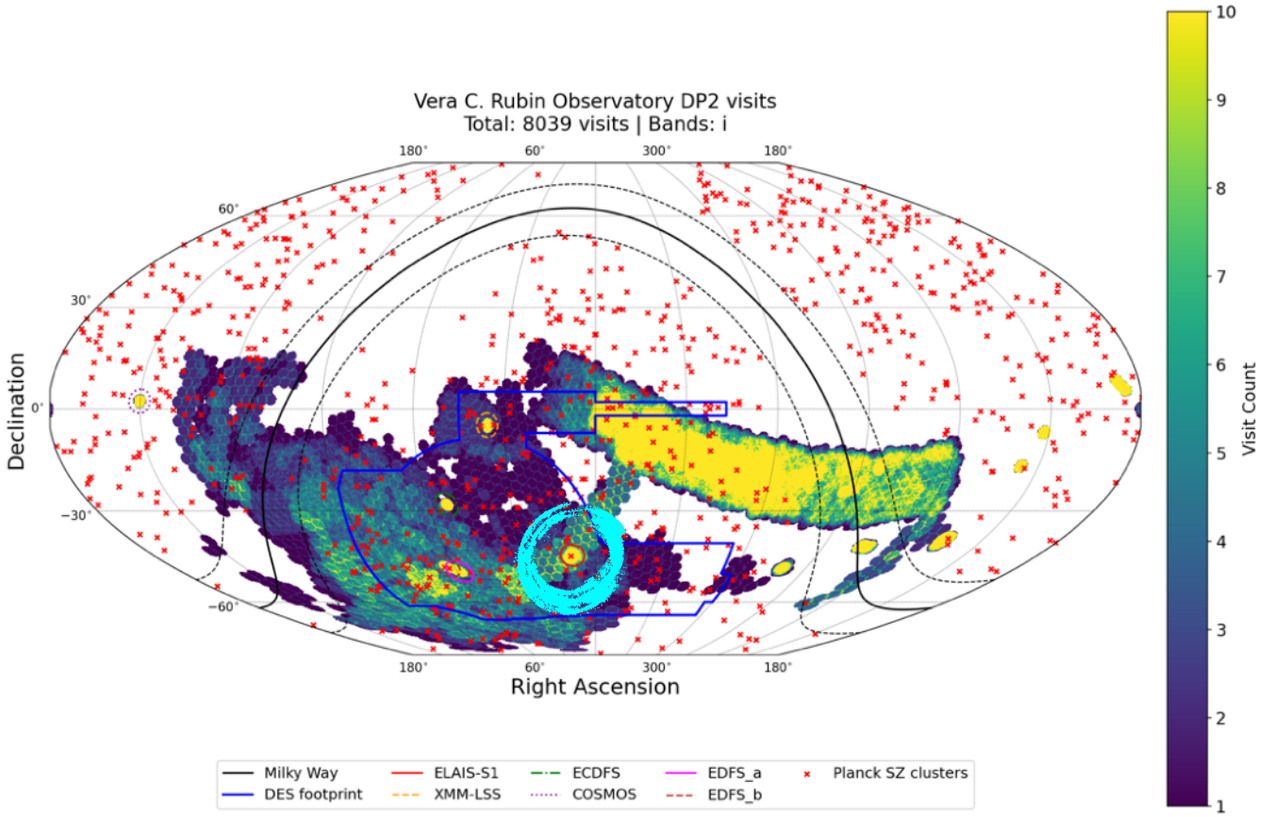
DP2 footprint in i-band

Sunyaev-Zeldovich Galaxy Cluster from Planck (redshift in 0.1 and 1)

PSZ2 G309.43-72.86 that is at a redshift of 0.35 and with SZ mass of 5.82 * 10^14 solar masses



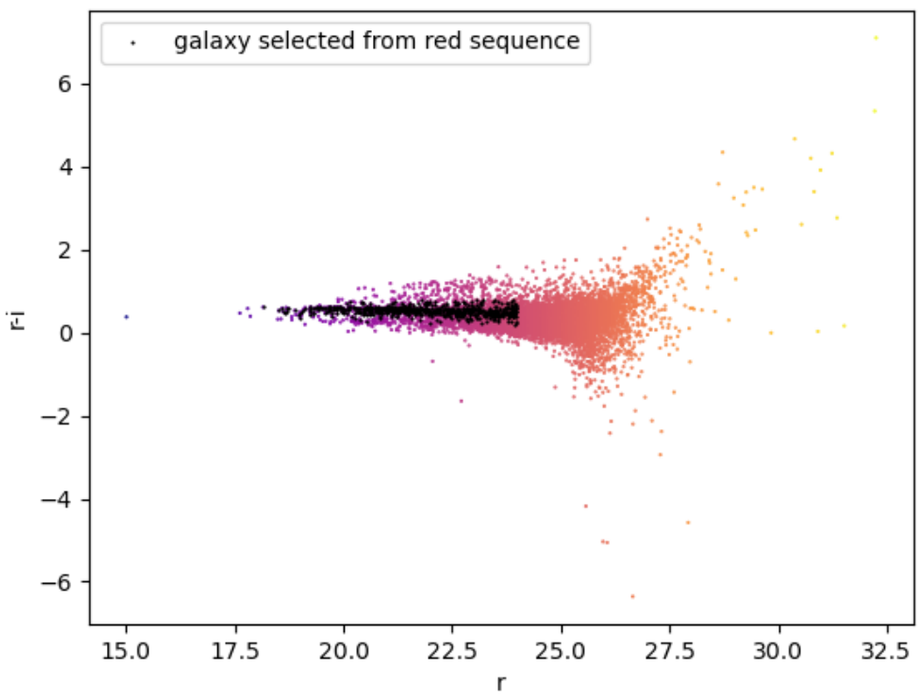
On weak lensing with Galaxy clusters in DP2



DP2 footprint in i-band

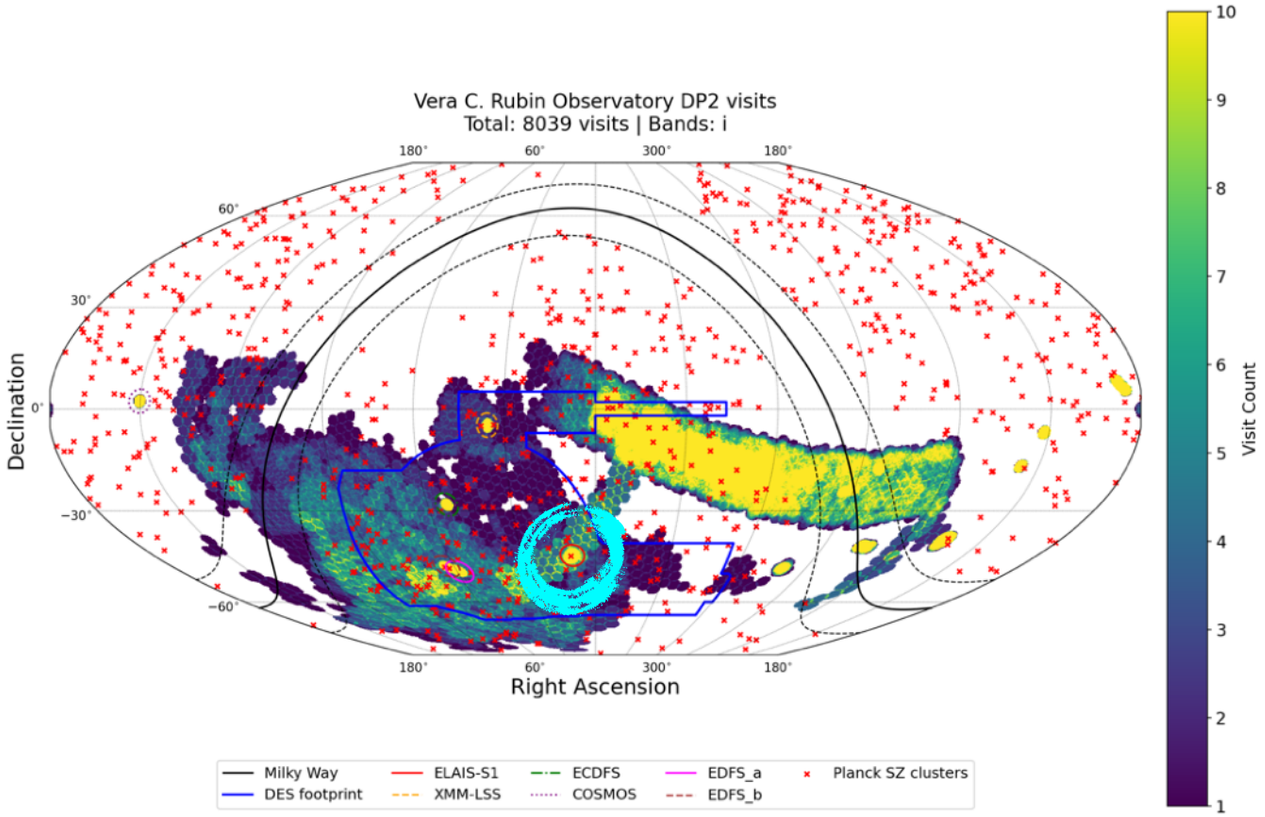
Sunyaev-Zeldovich Galaxy Cluster from Planck (redshift in 0.1 and 1)

PSZ2 G309.43-72.86 that is at a redshift of 0.35 and with SZ mass of 5.82 * 10^14 solar masses



Select galaxy that belong to the cluster with red sequence

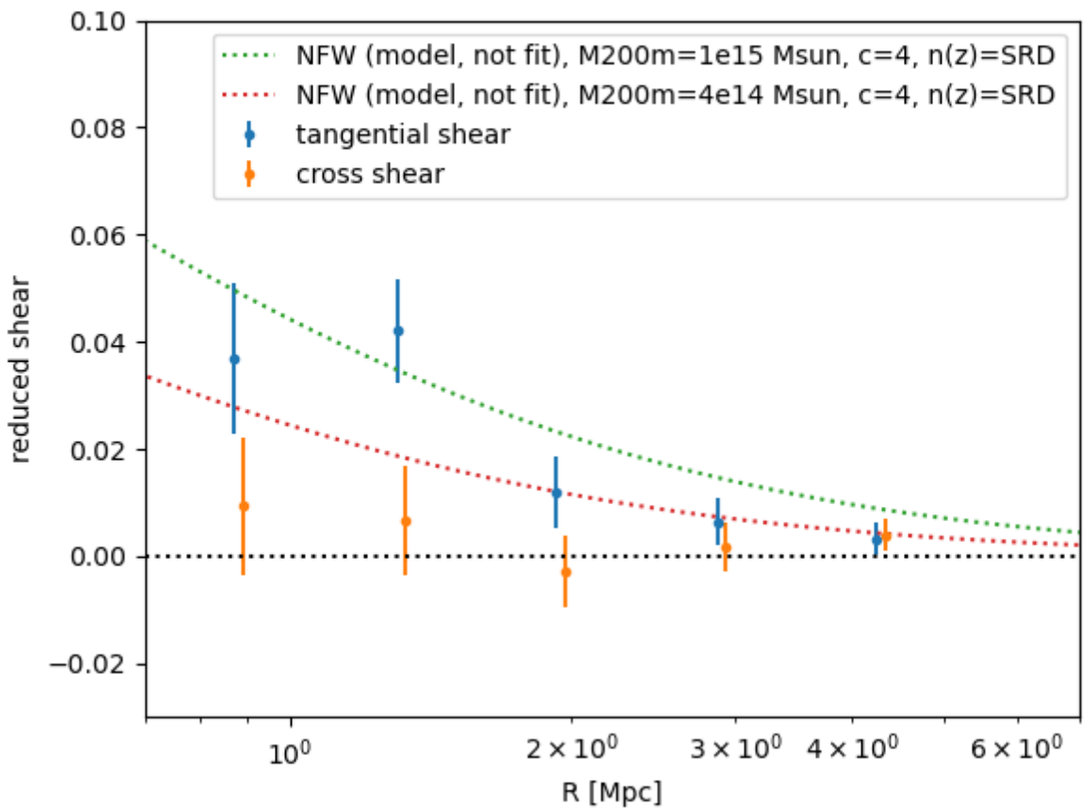
On weak lensing with Galaxy clusters in DP2



DP2 footprint in i-band

Sunyaev-Zeldovich Galaxy Cluster from Planck (redshift in 0.1 and 1)

PSZ2 G309.43-72.86 that is at a redshift of 0.35 and with SZ mass of 5.82 * 10^14 solar masses



Select galaxy that belong to the cluster with red sequence

First detection of the weak lensing signal with LSSTCam!

MERCI !

Credit: NSF–DOE Vera C. Rubin Observatory/NOIRLab/SLAC/NSF/DOE/AURA/P. Horálek