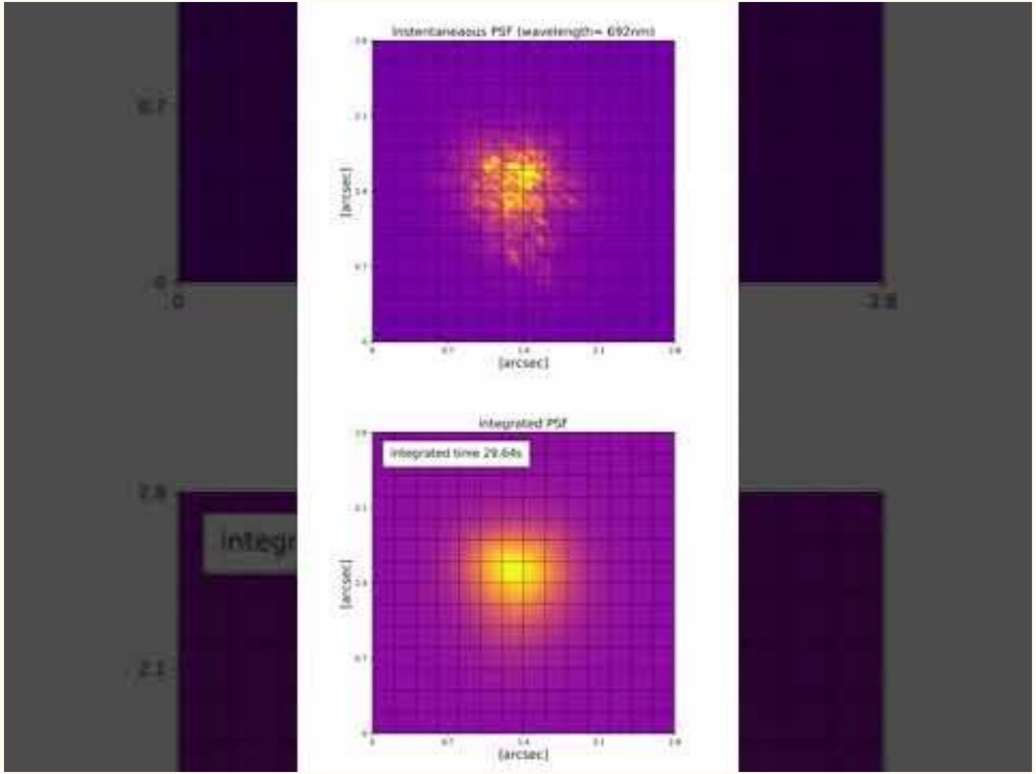
LSST PSF systematics

PF Léget and J Meyers

PSFs are complicated!

- Roughly a convolution between
  - Atmosphere
  - Optics
  - Sensor
  - Other
    - Vibrations/tracking
    - Dome seeing
    - Polishing errors
    - ...
- Varies with
  - Field angle
  - Wavelength
  - Flux

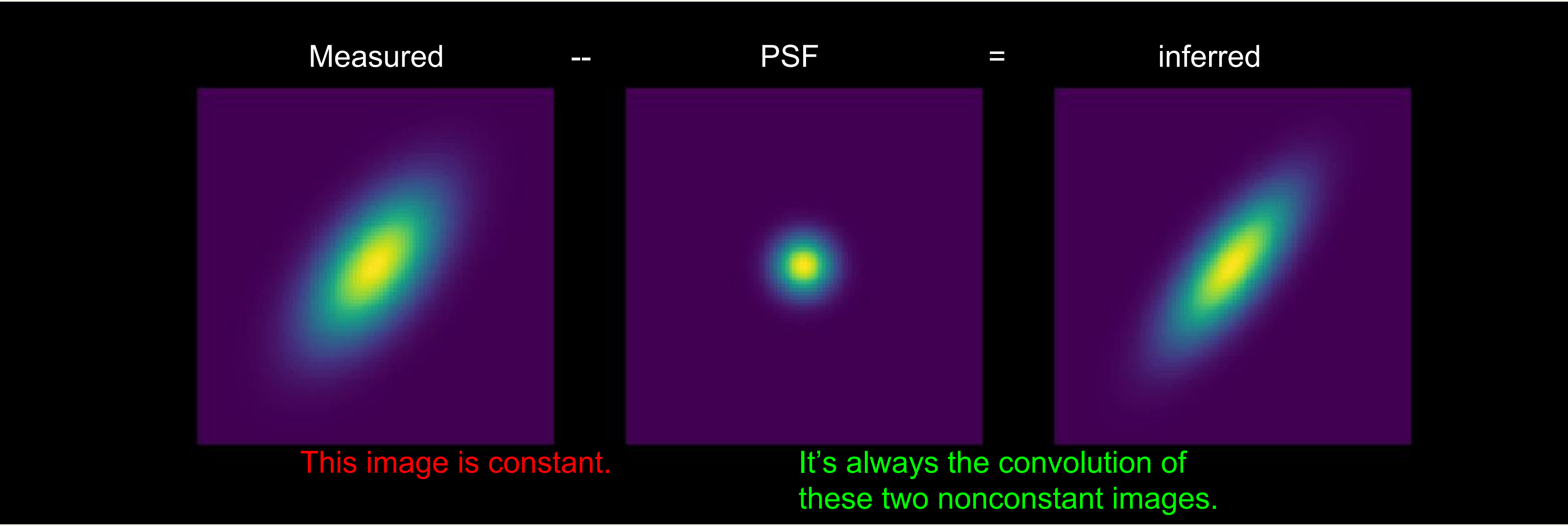
PSFs & Atmospheric contribution



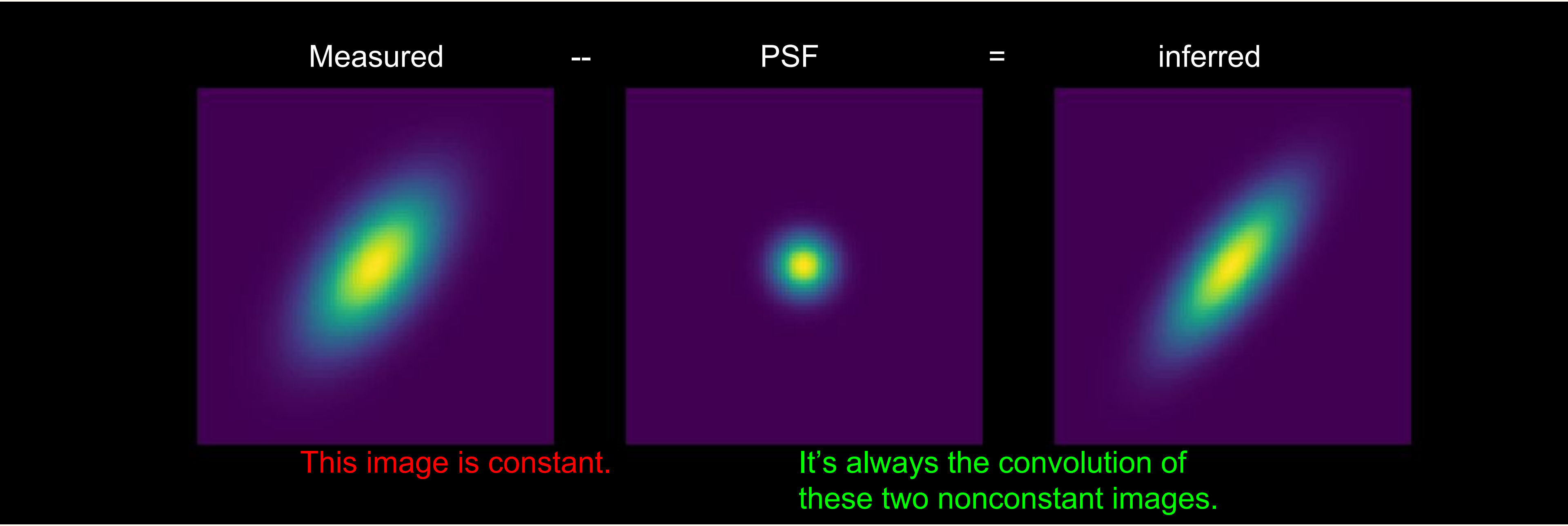
- What does the atmospheric PSF looks like?
- High resolution movies of bright stars taken on Gemini South with the Differential Speckle Survey Instrument
- 0.011 arcsec / pixel (LSST 0.2 arcsec / pixel)
- Exposure time of 60 ms with 2 ms of readout
- See Hébert++ 2018 for more details

PSF effect on weak lensing

Galaxy shape errors from PSF size errors



Galaxy shape errors from PSF ellipticity errors



PSF errors maths for cosmic shear

Note: there are O(1) factors floating around that I'm not being careful with...

- Start with 2nd moment description of size and ellipticity:

$$T = I_{xx} + I_{yy} \qquad\qquad e = \frac{I_{xx} - I_{yy}}{T} + i\frac{2I_{xy}}{T}$$

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- Propagate errors in PSF size and ellipticity assuming 2nd moments add under convolution (Paulin-Henriksson++ 2008):

PSF size residual

PSF ellipticity residual

$$\underline{\delta e_{g,\mathrm{sys}}} = (e_g - e_P)\left(\frac{T_P}{T_g}\right)\frac{\boxed{\delta T_P}}{T_P} - \left(\frac{T_P}{T_g}\right)\boxed{\delta e_P}$$

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$$\underline{\delta e_{g,\mathrm{sys}}} = (e_g - e_P)\left(\frac{T_P}{T_g}\right)\frac{\overbrace{\boxed{\delta T_P}}^{\text{PSF size residual}}}{T_P} - \left(\frac{T_P}{T_g}\right)\overbrace{\boxed{\delta e_P}}^{\text{PSF ellipticity residual}}$$

- Feed the above into the expression for the galaxy ellipticity correlation function.

$$\hat{\xi}_+(\theta) = \left\langle \left(e_g + \underline{\delta e_{g,\mathrm{sys}}}\right)^* \cdot \left(e_g + \underline{\delta e_{g,\mathrm{sys}}}\right) \right\rangle_\theta$$

PSF error => Correlation function error

Rowe10, Jarvis++16

$$\hat{\xi}_+(\theta) = \xi_+(\theta) + 2\left\langle e_g^* \cdot \delta e_{g,\mathrm{sys}} \right\rangle_\theta + \left\langle \delta e_{g,\mathrm{sys}}^* \cdot \delta e_{g,\mathrm{sys}} \right\rangle_\theta$$

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- Aside: PSF leakage - PSF ellipticity “leaks” into estimated galaxy ellipticity for many shear estimators

$$\langle e_g \rangle = (1+m) g_{\mathrm{true}} + \boxed{\alpha} e_P + c$$

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- Expand second term

$$\underbrace{\left\langle e_g^* \cdot \delta e_{g,\mathrm{sys}} \right\rangle_\theta} = \underbrace{\left\langle \frac{T_P}{T_g} \frac{\delta T_P}{T_P} \right\rangle}_{\text{Mean size error}} \xi_+(\theta) - \boxed{\alpha} \left\langle \frac{T_P}{T_g} \right\rangle \left[\underbrace{\left\langle e_P^* \cdot e_P \frac{\delta T_P}{T_P} \right\rangle_\theta}_{\rho_5(\theta)} + \underbrace{\langle e_P^* \cdot \delta e_P \rangle_\theta}_{\rho_2(\theta)} \right]$$

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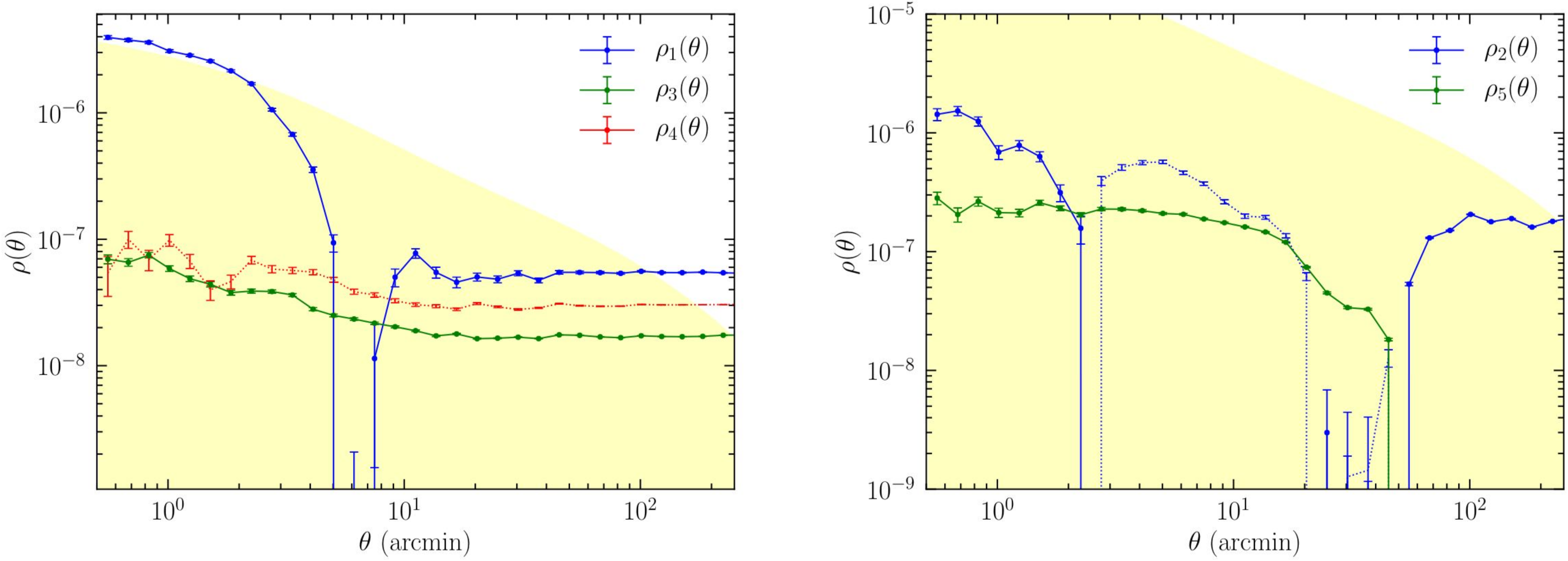
- Expand third term

$$\underbrace{\left\langle \delta e_{g,\mathrm{sys}}^* \cdot \delta e_{g,\mathrm{sys}} \right\rangle_\theta} = \left\langle \frac{T_P}{T_g} \right\rangle^2 \left[\underbrace{\left\langle e_P^* \frac{\delta T_P}{T_P} \cdot e_P \frac{\delta T_P}{T_P} \right\rangle_\theta}_{\rho_3(\theta)} + 2 \underbrace{\left\langle e_P^* \frac{\delta T_P}{T_P} \cdot \delta e_P \right\rangle_\theta}_{\rho_4(\theta)} + \underbrace{\langle \delta e_P^* \cdot \delta e_P \rangle_\theta}_{\rho_1(\theta)} + \mathcal{O}\left(\mathrm{small}^3\right) \right]$$

ρ statistics for DES Y1

- Yellow background is a rough guideline for tolerable systematics.
- Note: a more accurate, but similarly motivated, treatment of PSF error propagation is illustrated in Appendix A of Troxel++17 and in Zuntz++17.

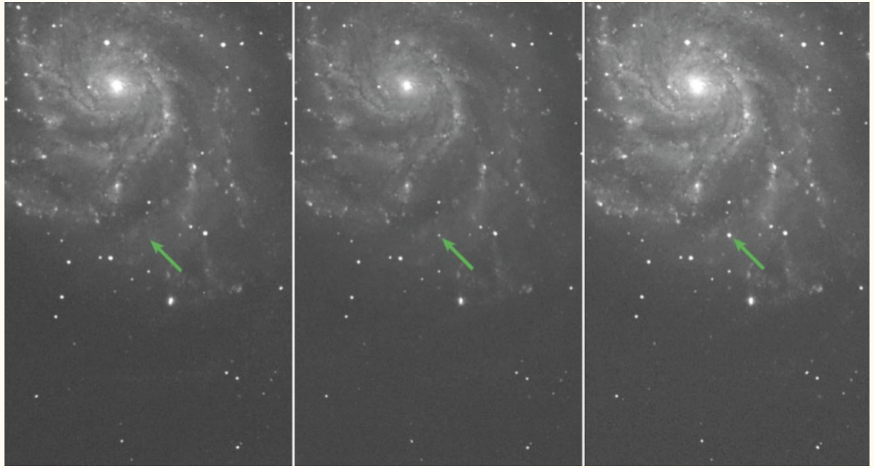
Zuntz++17



PSF effect on SNe Ia

Why PSF matters for SNIa

SN2011 fe (Nugent++ 2011)



- SNIa are another key probe for DESC
- Where PSF matters for SNIa cosmology → Light-Curve extraction & photometric calibration with tertiary stars
- Main problem → Difference between PSF of tertiary stars (bright) and PSF of SNIa (fainter)

Why PSF matters for SNIa

- Light Curve extraction principle (see Astier++ 2013 for more information):

Model = Time evolving point source + constant structure background

$$M_{t,p} = f_t \times \phi(\mathbf{x}_p - \mathbf{x}_{sn}) + [gal_{ref} \otimes K_t] + s_t$$

Model for epoch t and pixel p

Flux of the SNIa at epoch t

PSF at epoch t

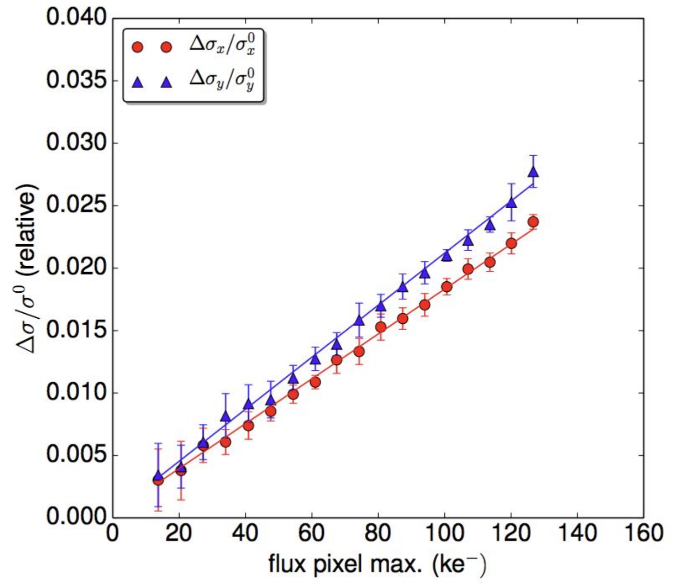
Galaxy modeled in the same pixel map as the images with the best seeing

Convolution kernel to match the reference image PSF and flux scale to the PSF of image t.

- Same modeling applied for both the SNIa and tertiary stars that will be used to calibrate SNIa flux
- Flux calibration of SNIa consists of computing ratio of PSF between SNIa and tertiary stars
- Need a linear relation between bright tertiary stars and faint SNIa

Why PSF matters for SNIa

Guyonnet++ 2015

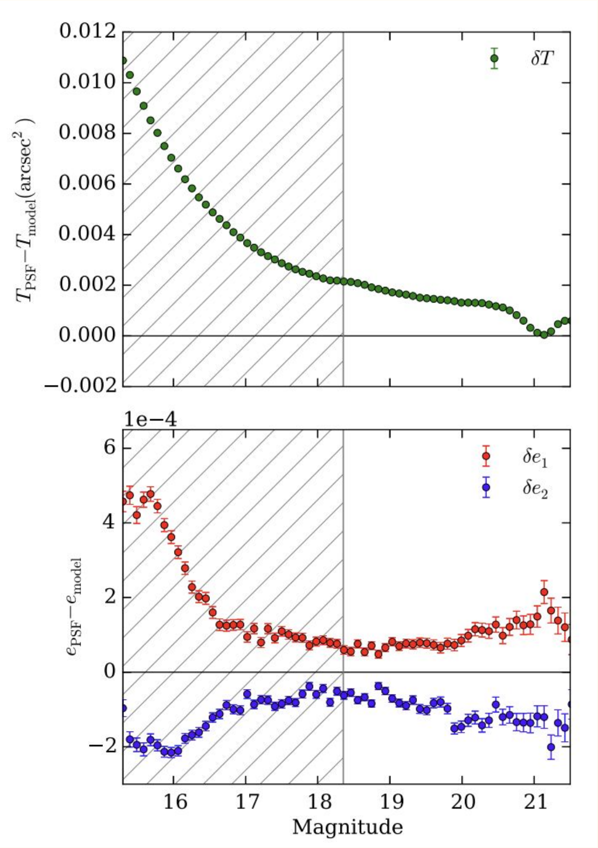


(b) LSST - E2V 250 - Spots 900 nm

- Brighter Fatter effect (Antilogus++ 2014 ; Guyonnet++ 2015)
  - Sizes of the PSF of tertiary stars are larger
  - than PSF at SNIa location
  - Introduces nonlinearities in the calibration
  - Difference of 2-3% in size of the PSF
  - Flux estimation bias (what matters for SNIa)
  - Shape and ellipticity bias (what matters for WL)

Why PSF matters for SNIa

Jarvis++ 2016



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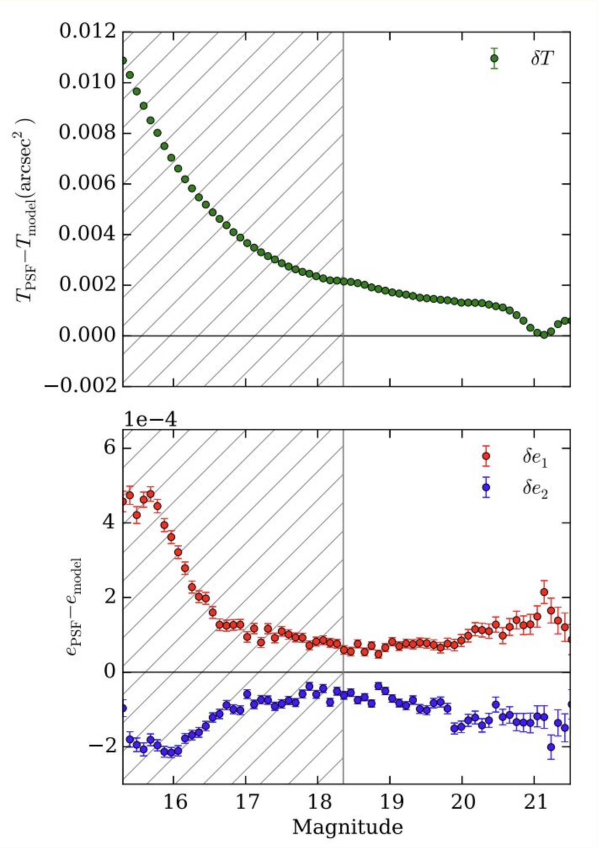

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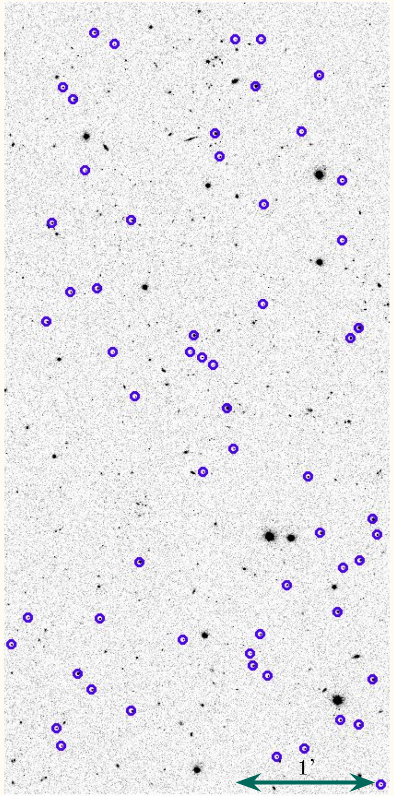
Needs to be corrected to avoid bias in flux that evolves with redshift...

PSF modeling

PSF modeling from (bright) stars

SUBARU-HSC image from one CCD



- Basic sketch for modeling PSF
- First-step: Finding the stars in the image

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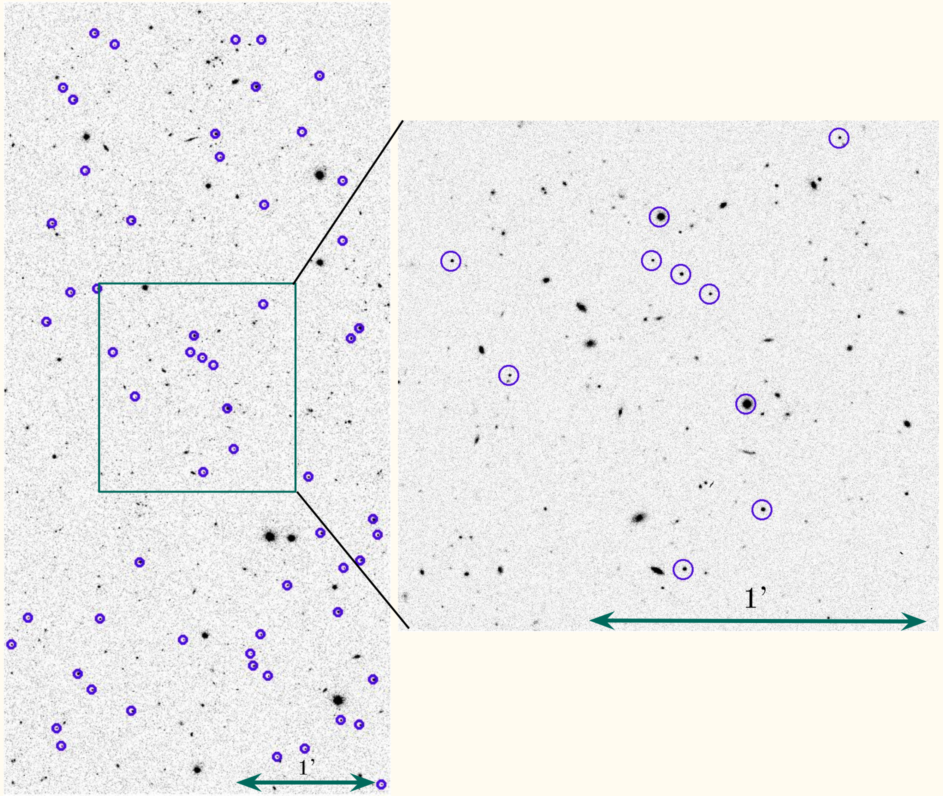

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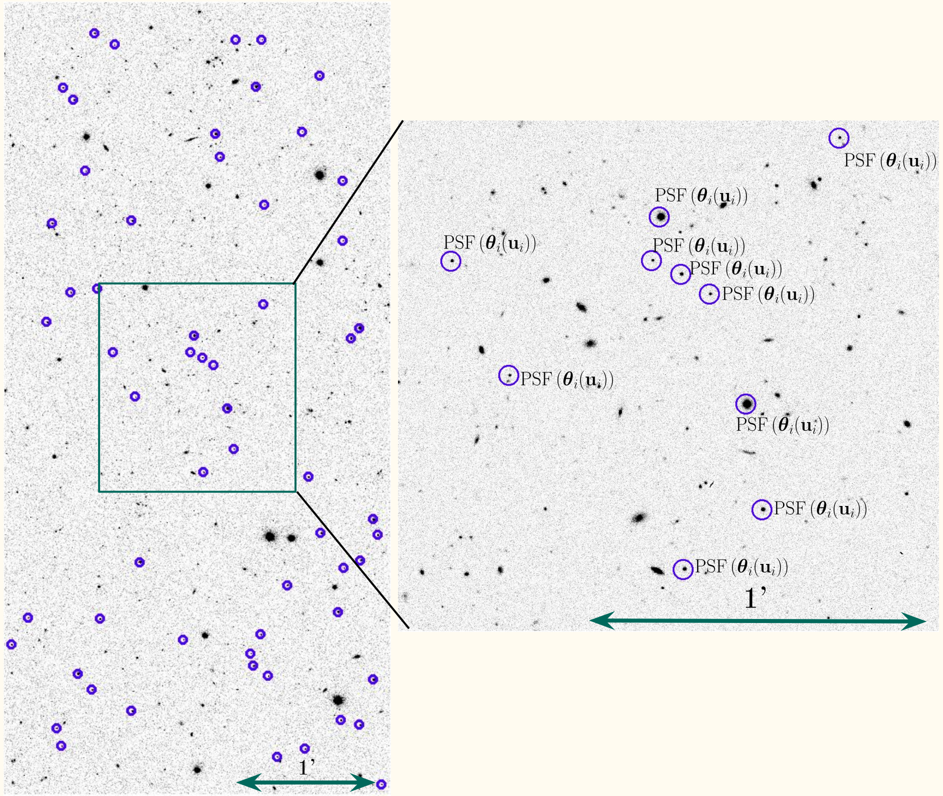

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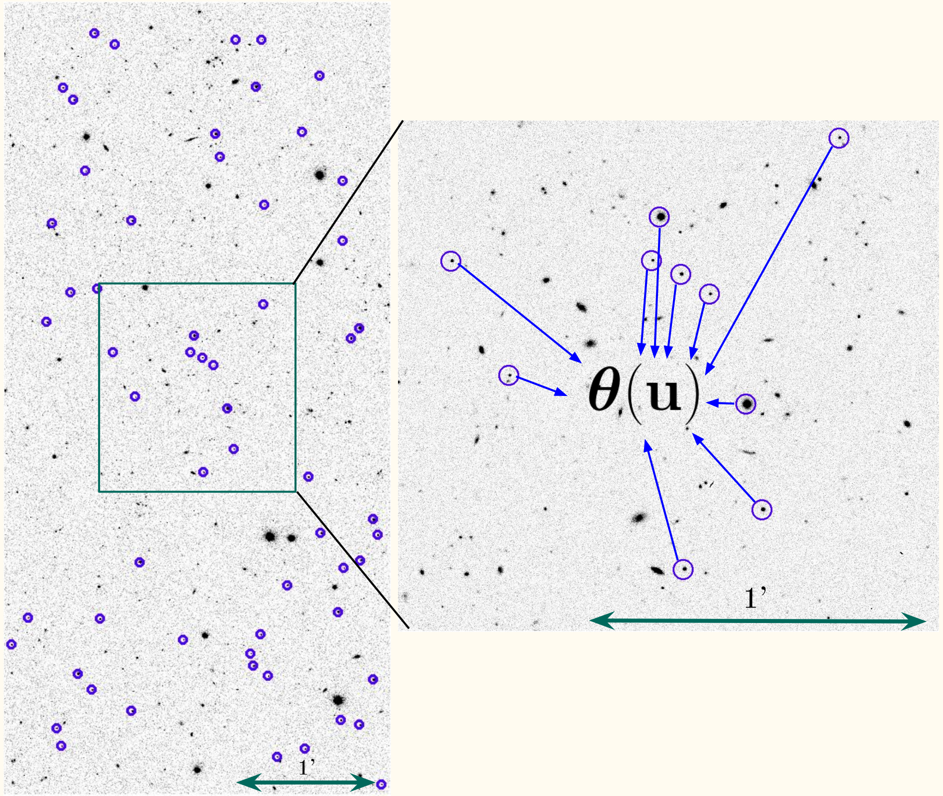

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- Third step: interpolate $\boldsymbol{\theta}(\mathbf{u})$ to new location (galaxy position, SNIa position, ...)

Get a PSF model:

- PSF ~ Optic + Atmosphere + Sensor
- Because of chip gaps it is hard to simultaneously model the full focal plane PSF
- Current PSF algorithms model each CCD separately to avoid dealing with CCD chip gap
- Consequently the model would be empirical as in current methods used
- E.g. :
    - PSFex (Bertin 2011)
    - Piff with the PixelGrid model (Piff on github)
    - The SNLS PSF (Astier++ 2013)

Get a PSF model: With basis functions (per CCD)

Example of Pixel basis based PSF: The SNLS PSF model (see Astier++ 2013):

PSF profile ~ Analytical part to described the core of the PSF $+$ Pixel basis functions to describe residuals of the PSF

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$$I(\mathbf{x}) \sim \mathrm{Moffat}\left(\alpha(\mathbf{x}), g_1(\mathbf{x}), g_2(\mathbf{x})\right) \;+\; \mathbf{R}_0 \;+\; \mathbf{R}_x \times x \;+\; \mathbf{R}_y \times y \;+\; \ldots$$

Second moment of the Moffat profile (size, ellipticity)

Pixel basis (size ~ 5 times the seeing) to describe the residuals around the Moffat profile

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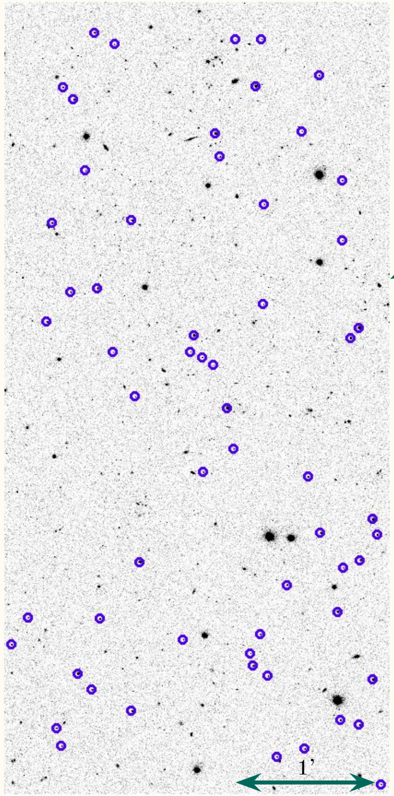
Pixel basis (size ~ 5 times the seeing) to describe the residuals around the Moffat profile

Interpolated with polynomial function (order 1 for SNLS)

PSF modeling from (bright) stars

SUBARU-HSC image from one CCD

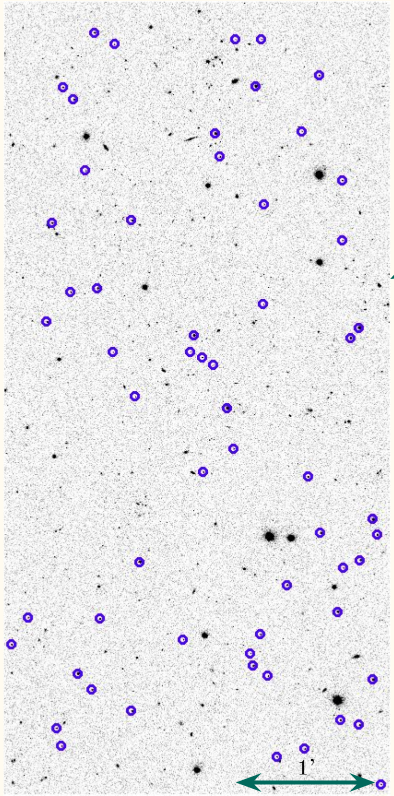


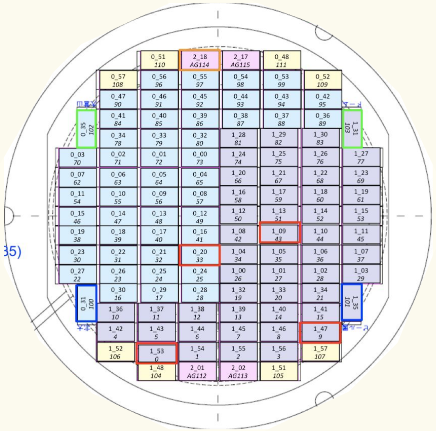
Problem of PSF model :

- For galaxy on the edge of the CCD, how to extrapolate the PSF parameters?
- Atmosphere introduces correlation bigger than the CCD chip...

PSF modeling from (bright) stars

SUBARU-HSC image from one CCD





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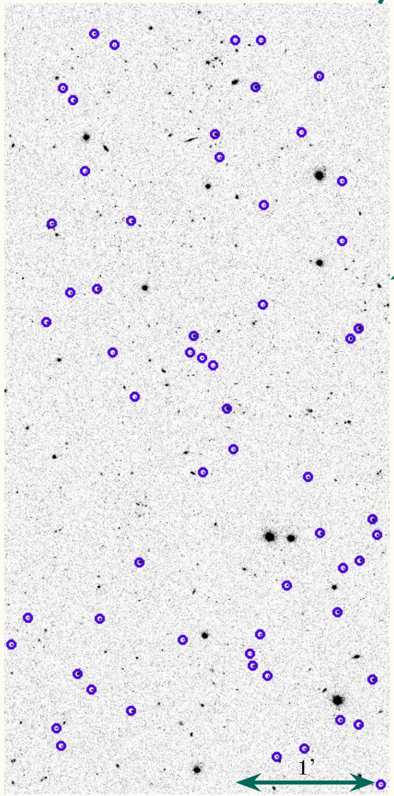

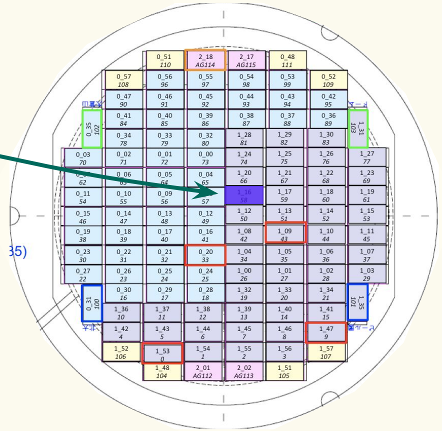

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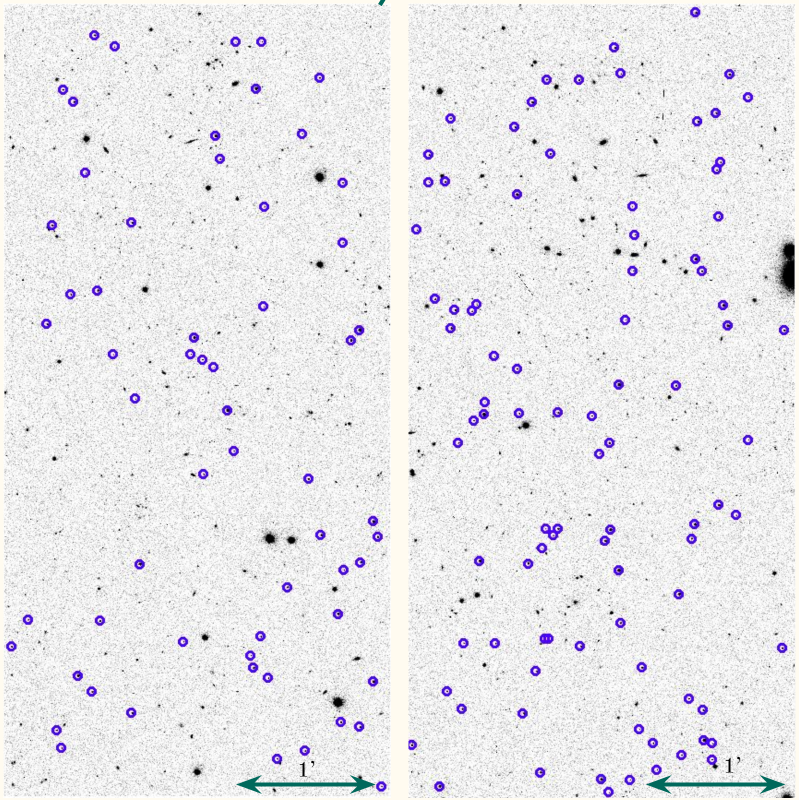
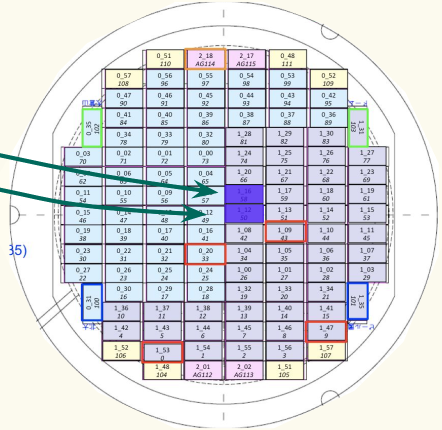


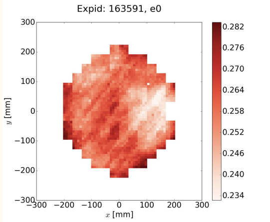
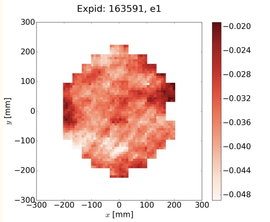
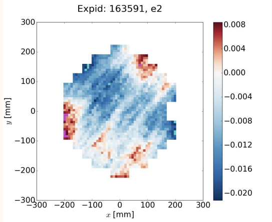


- Solution: Used stars from CCD nearby to get the spatial information of the PSF that are bigger than one CCD chip.

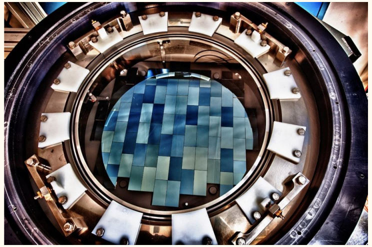
- Problem: Deal with CCD gap

PSF modeling with physics (on the F.o.V.)

For a given exposure

Davis++ 2016	PSF size	PSF ellipticity 1	PSF ellipticity 2
Total PSF			

The Dark Energy Camera



- Due to the atmosphere there are spatial correlation that are larger than chip size

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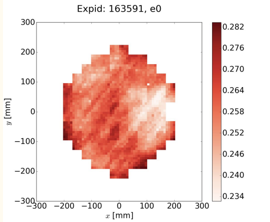
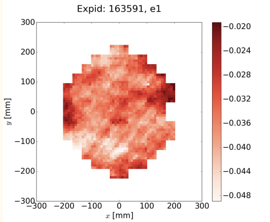
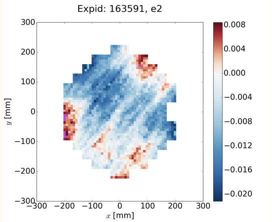
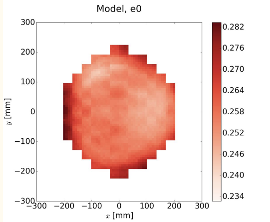
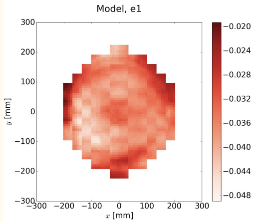
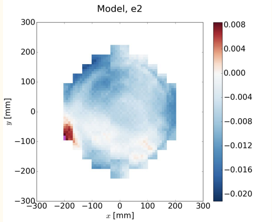
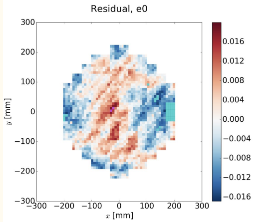
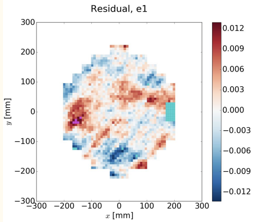
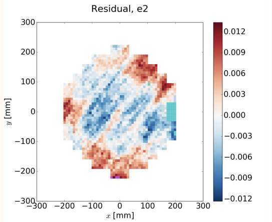
Total PSF			
Optical PSF			
Atmospheric PSF			

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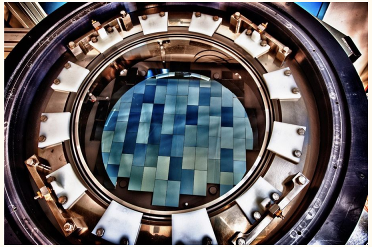

- Due to the atmosphere there are spatial correlation that are larger than chip size

- If you have an optical model, it will allowed to separate the optical part from the atmospheric part and to modeled the spatial variation of the PSF through the F.o.V.

PSF modeling with physics (on the F.o.V.)

PSF profile ~ Optical part of the PSF As a Fraunhofer Diffraction $\otimes$ Atmospheric part of the PSF as an elliptical Kolmogorov profile

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PSF profile ~ Optical part of the PSF As a Fraunhofer Diffraction $\bigotimes$ Atmospheric part of the PSF as an elliptical Kolmogorov profile

$$I(\mathbf{u}) \sim |F\{P(\boldsymbol{\theta})e^{\frac{2\pi i W(\boldsymbol{\theta})}{\lambda}}\}| \otimes K(\alpha(\mathbf{u}), g_1(\mathbf{u}), g_2(\mathbf{u}))$$

Pupil function

Wavefront

Second moment of the Kolmogorov profile (size, ellipticity)

Wavefront described with Double Zernike polynomial function

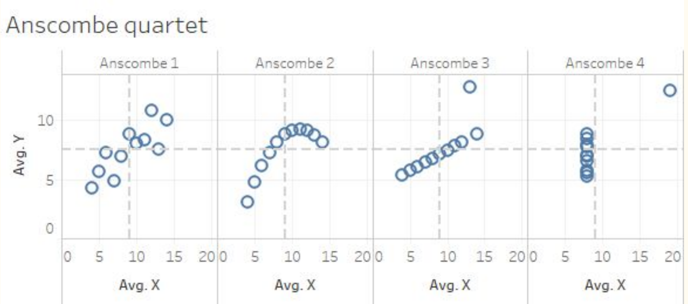
Spatial variation across the full F.o.V. of the atmosphere are described with gaussian processes

Other things to worry about

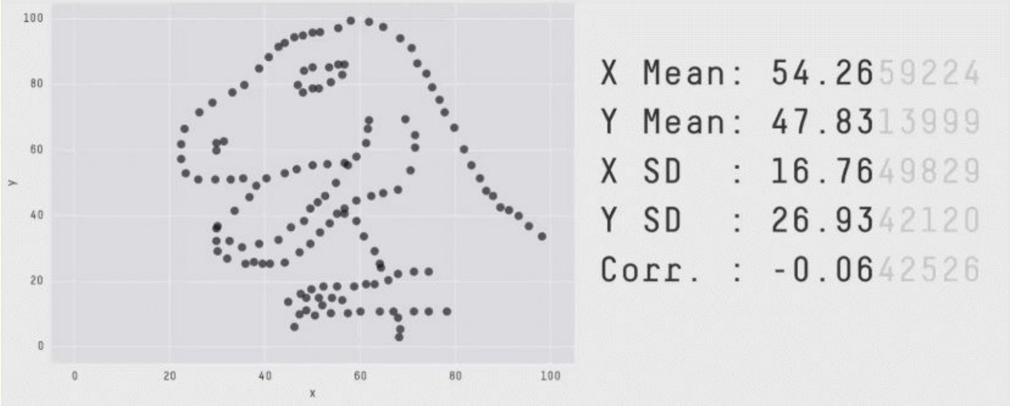
Higher order moments

- Second moment diagnostics (including ρ-stats, anything with T_P, e_P, ...) can't diagnose problems with higher order moments.
- Because we effectively use **weighted** moments, there is leakage from higher order down to second moments.
- Implies 2nd moment summary statistics are insufficient! Important to plot your data! (PSF model/image +residuals in this case).

Each Anscombe 1973 dataset has identical 1st/2nd moments



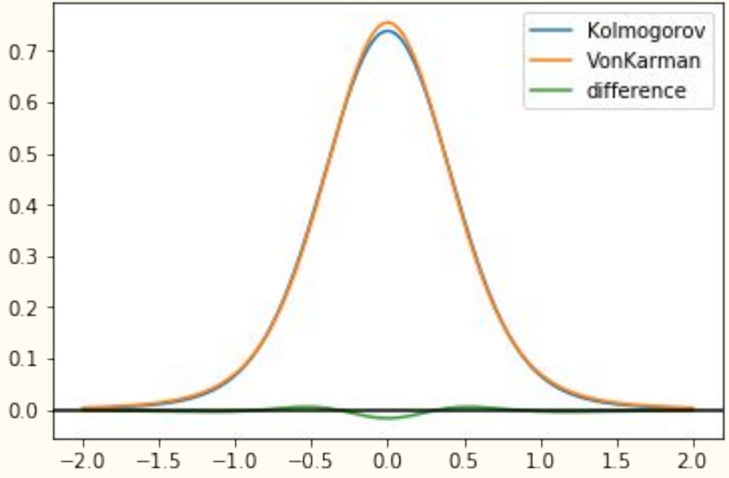
Also the datasaurus dozen. Beware the datasaurus!!

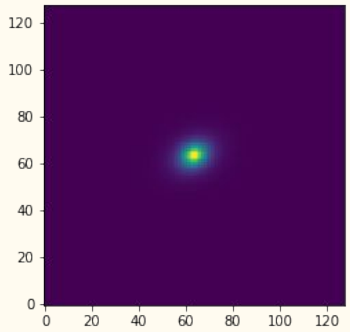


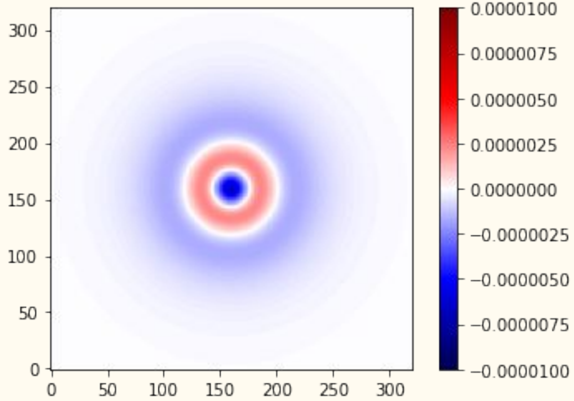
https://www.autodeskresearch.com/publications/samestats

Higher order moments (quick test)

- True PSF Kolmogorov PSF
  - Circular, FWHM=0.8 arcsec
- Engineered VonKarman PSF with L_0=25m and **same HSM moments.**
- Sersic galaxy:
  - n=1.5
  - HLR=0.8 arcsec
  - e=(0.2, 0.3)
- Convolve galaxy with Kolmogorov PSF
- Use HSM with both PSFs to infer Δe, find $\Delta e/e$ = (0.009, 0.009)
- PSF photometry with wrong PSF, find $\Delta f/f$ = 0.0009
- Lots of ways to extend this.



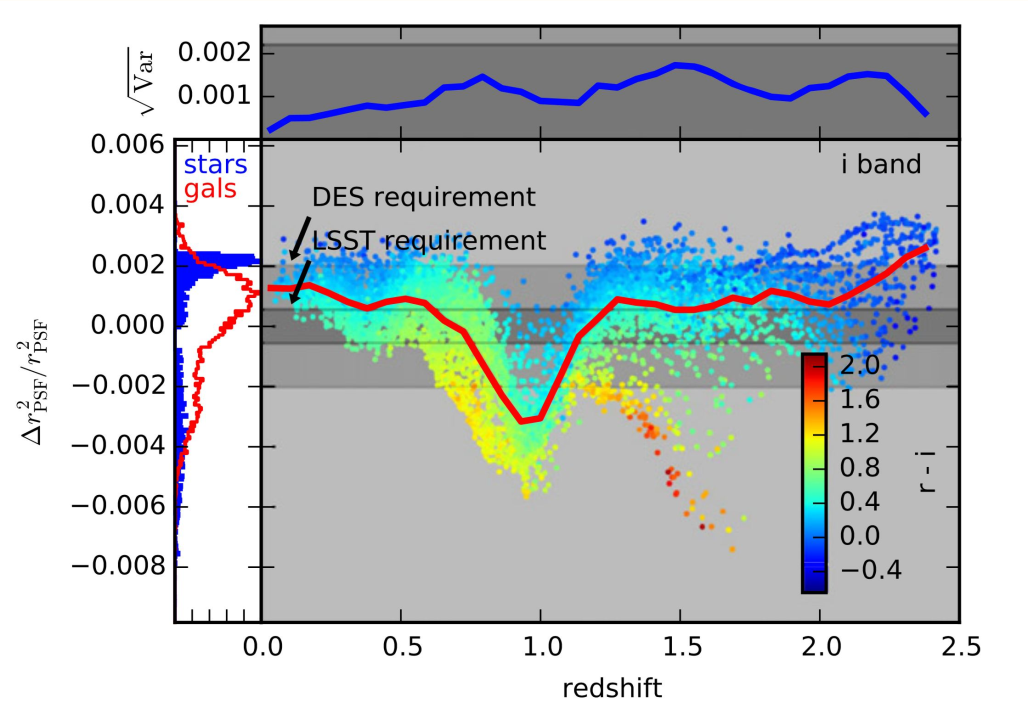




Chromatic Errors

- Many origins
  - Atmosphere: DCR and seeing
  - Optics
  - Sensors
- Effect depends on stellar/galaxy SEDs
- May be possible to mitigate if can discover SEDs and chromatic PSF dependence. (Meyers & Burchat 2015)
- But, it's hard to determine the exact chromatic PSF dependence. May be possible to infer from data? (Carlsten++ 2018)

Chromatic error just from (old model of) chromatic seeing



Meyers & Burchat 2015

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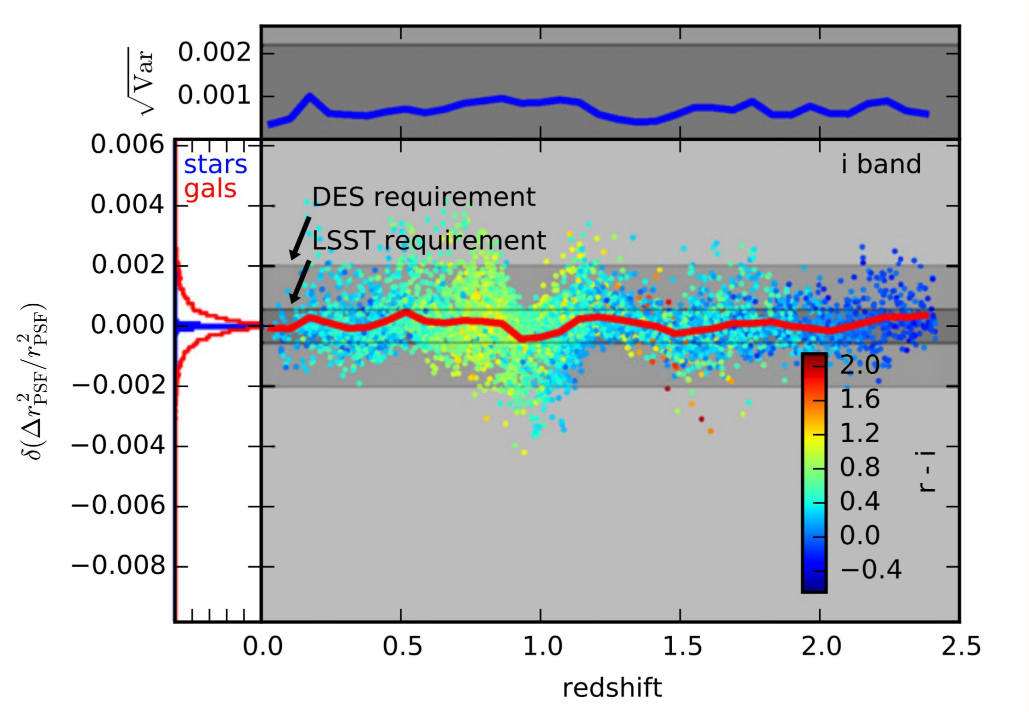
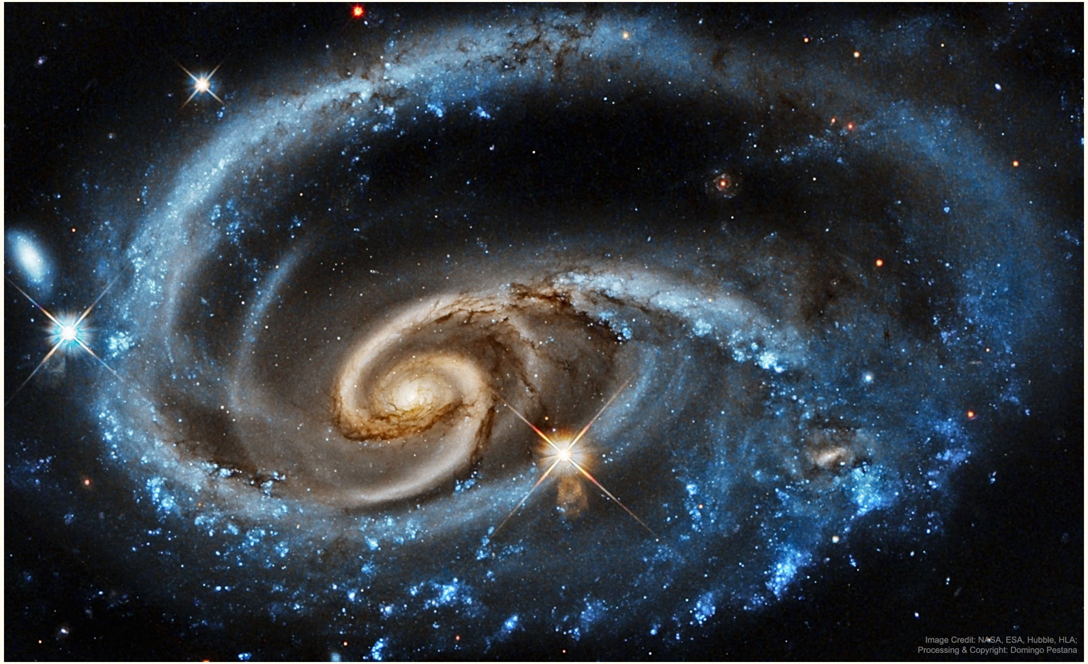


Meyers & Burchat 2015

Color gradients

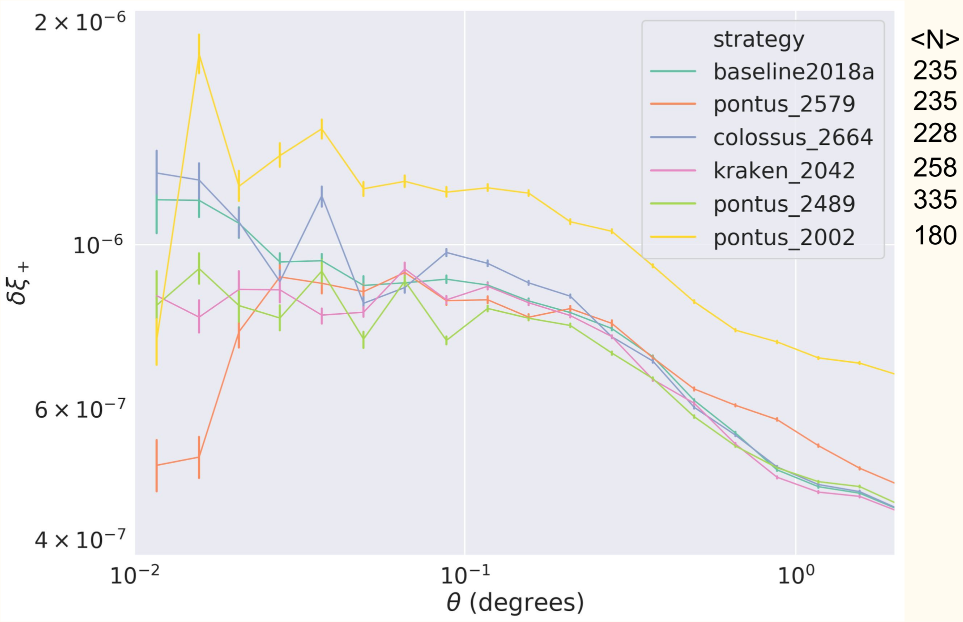
- Galaxies are composed of many different SEDs => many different PSFs
- Using a single "effective" PSF during inference can introduce a bias (Semboloni++12).
- (Kamath++ in prep) uses HST V+I images to find that bias for brightish (to HST) galaxies is limited to m~0.0009 for LSST.
- Room for more investigation at fainter magnitudes though.



https://apod.nasa.gov/apod/ap170510.html

Survey Strategy mitigation

- Some biases that are fixed to the focal plane (e.g., anisotroptic BF-effect, optics), or fixed in alt-az coords (DCR) may be mitigated by carefully considering the observing strategy.
    - x, y, θ dithers are good!
- (Almoubayyed++ in prep.) propagated some simple models through the rho statistics to estimate $\delta\xi_+$ for different strategies; found that more visits allow systematics to better decorrelate (also see [observing strategy white paper](#)).



Almoubayyed++ in prep

The Future

Speculations

- Can we marginalize over 2-pt function systematic if we know the form of the 2-pt function of PSF ellipticity residuals?
- How does blending mix with PSF systematics?
- How does image stacking mix with PSF systematics?
- Can we model the PSF probabilistically, maybe push to fainter magnitudes?
- Can we usefully constrain ΔPSF using difference imaging?

Imagine we observed this collection of galaxies at high redshift,
Could we handle the color gradients, blending, and chromatic PSF?

https://apod.nasa.gov/apod/ap140327.html

Conclusions

- PSFs are complicated
- PSFs affect almost all measurements
- PSFs are not a solved problem
- Need to continue to
  - find ways to measure, propagate and set requirements on PSF accuracy
  - develop PSF modeling algorithms, including ones that are based on physics
  - develop other PSF systematic mitigation strategies