Wavelength dependent PSFs

Josh Meyers

Chromaticity

Sources

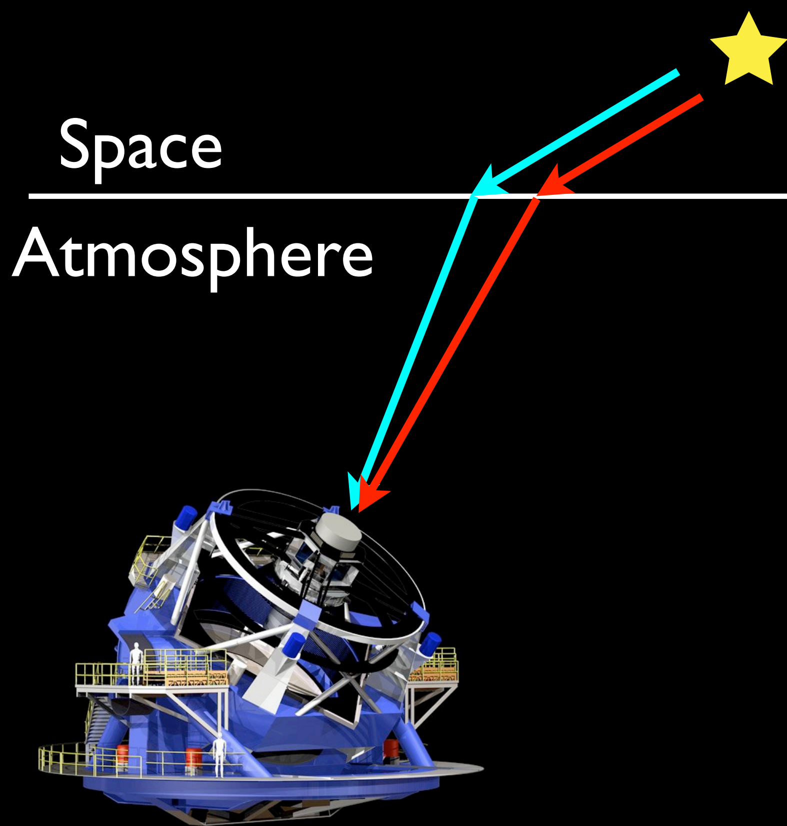
- atmosphere
  - differential chromatic refraction (DCR)
  - seeing
- telescope optics
- sensor

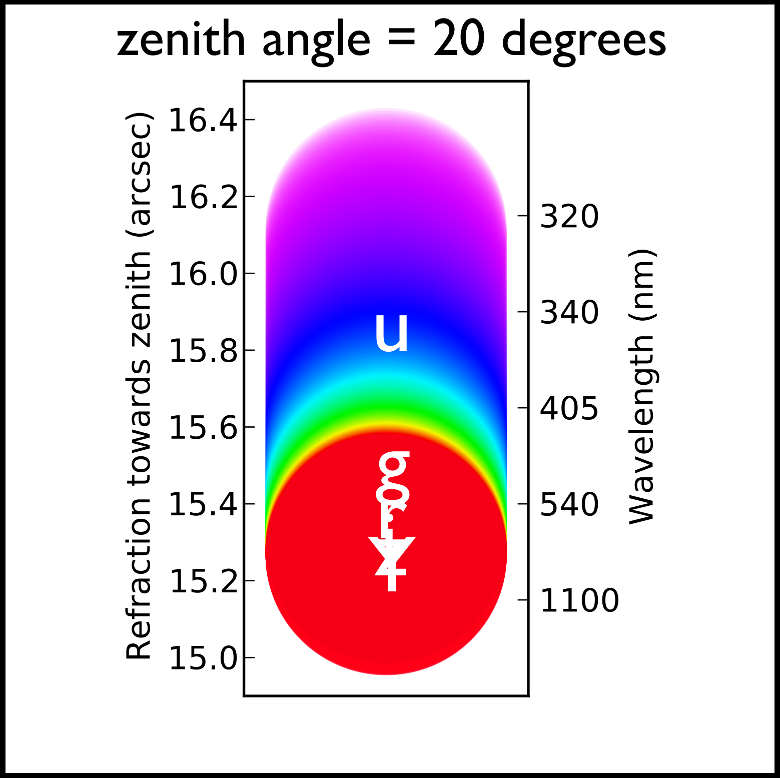
Techniques for study

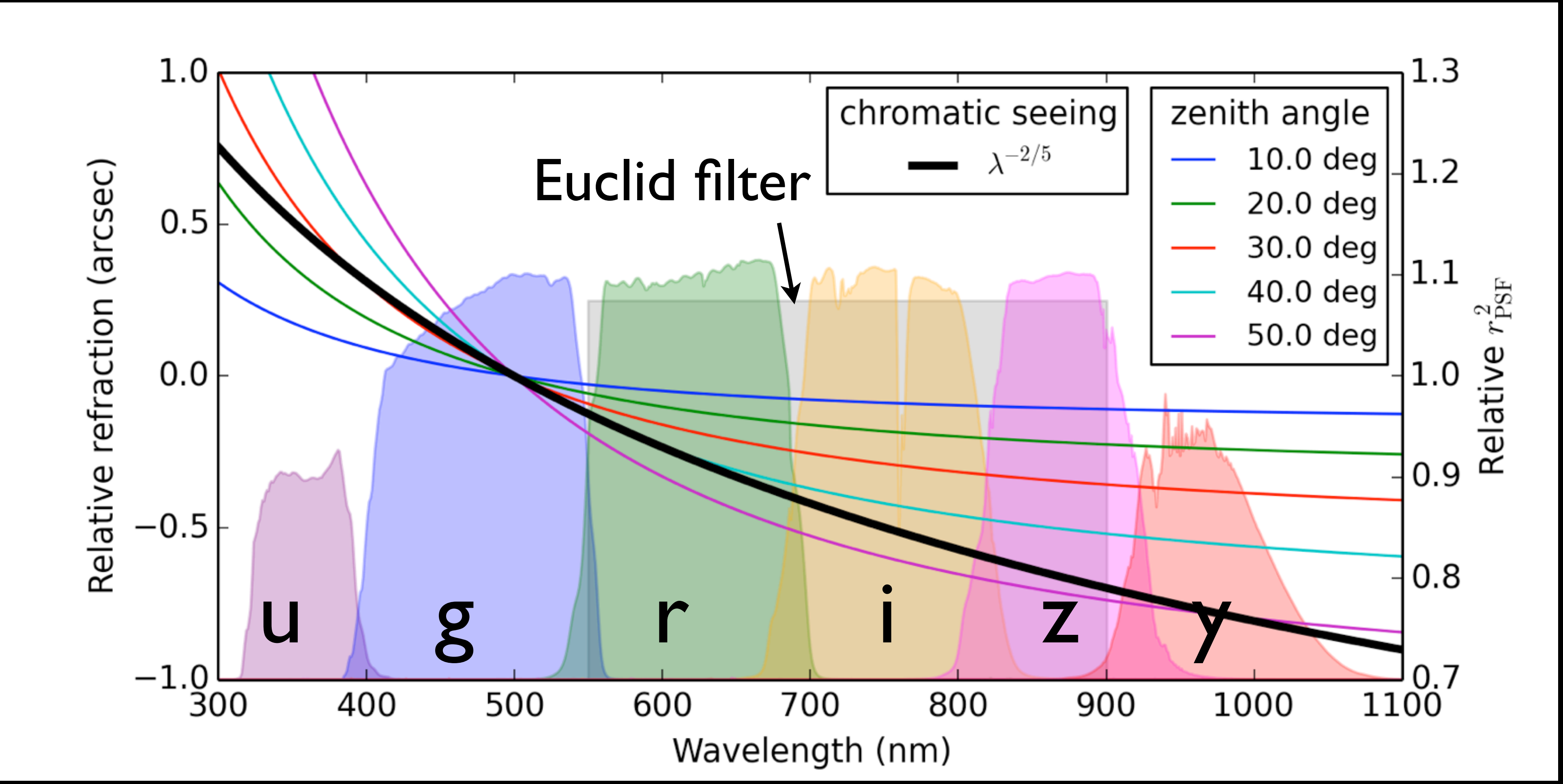
- analytic formulae
- GalSim “ring test” simulations
- photon-by-photon Monte Carlo (PhoSim)

Differential Chromatic Refraction

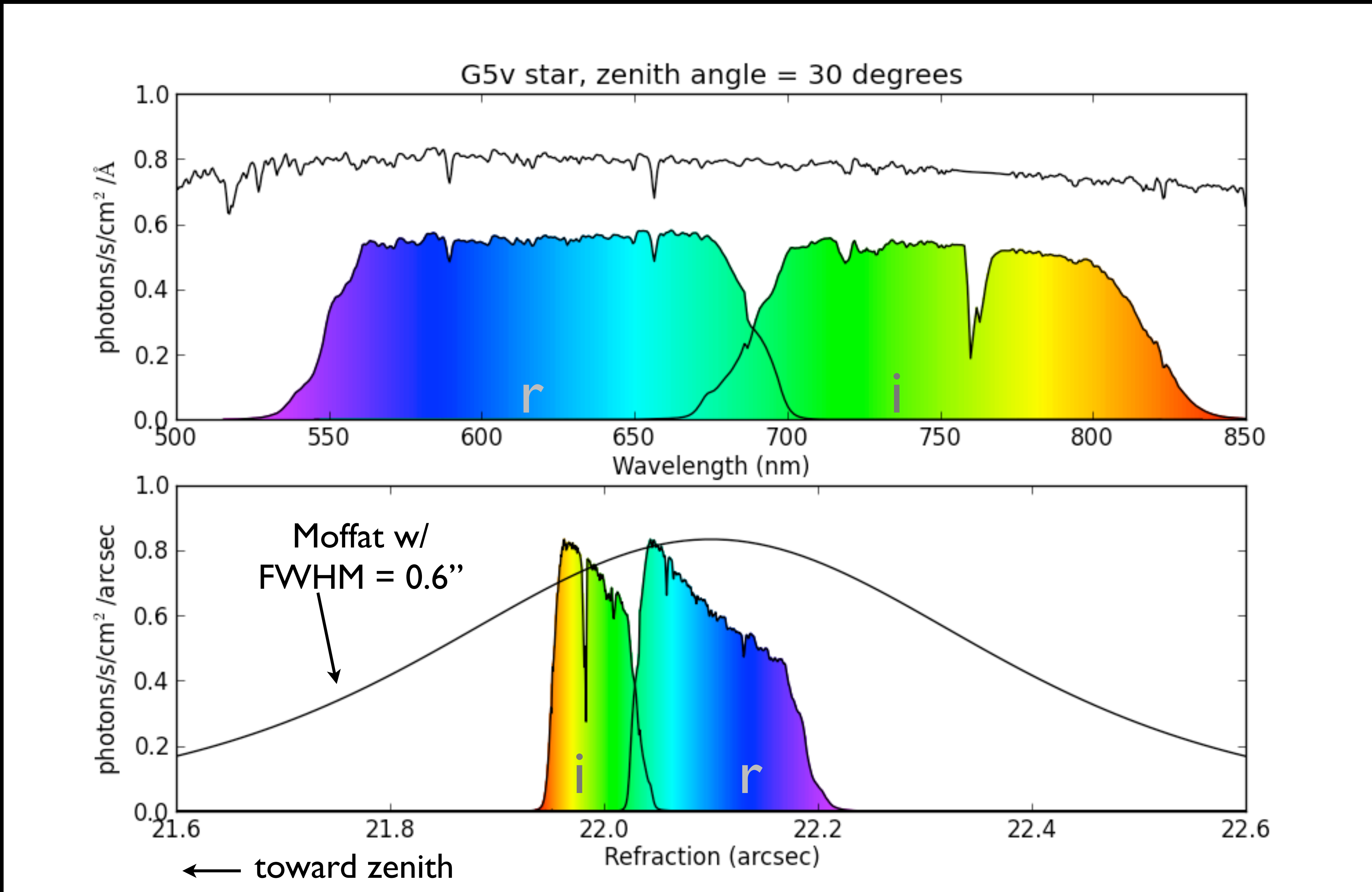
cf. Plazas & Bernstein 2012







Where the photons land on the focal plane



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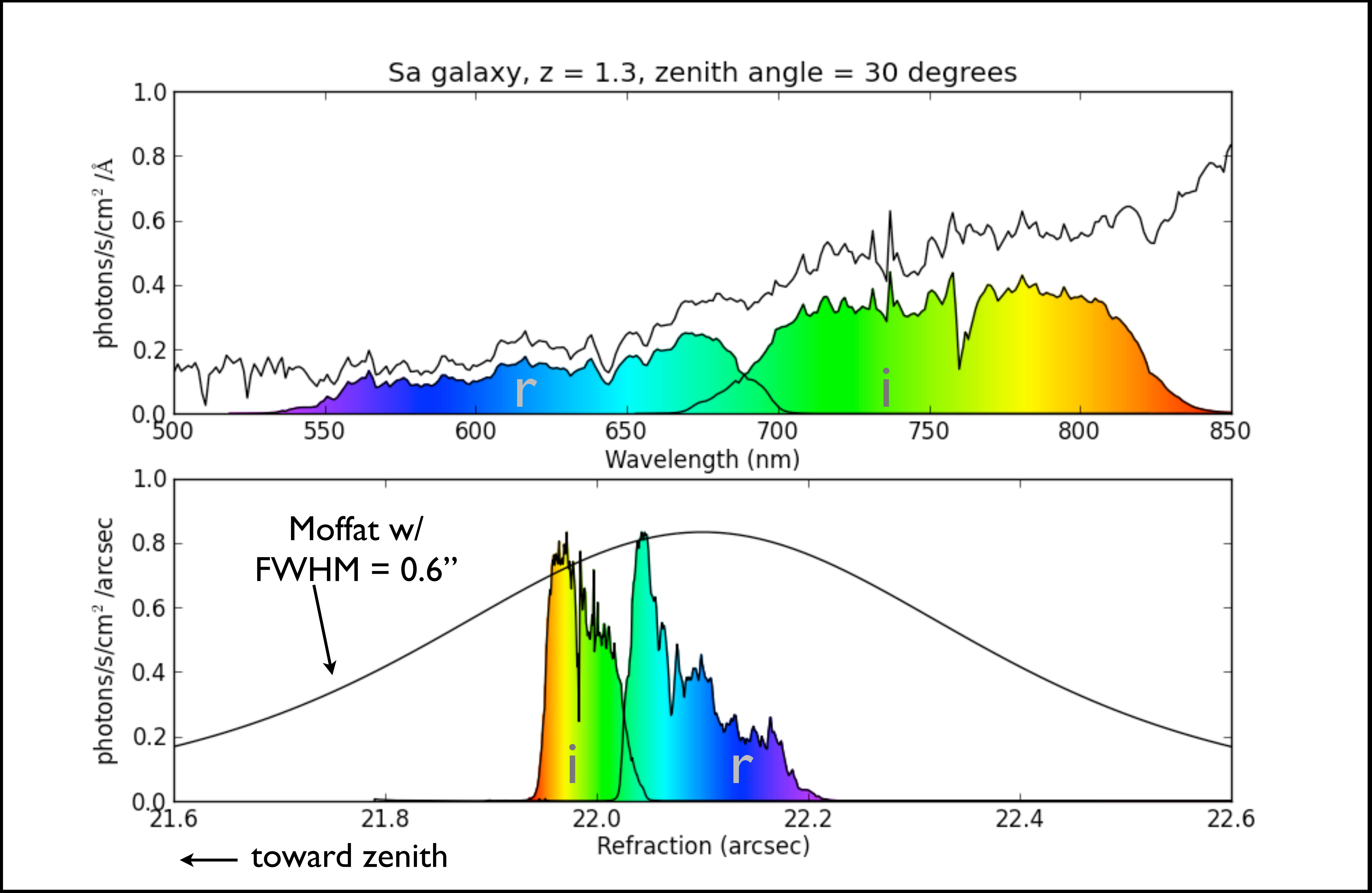


PSF centroid shifts

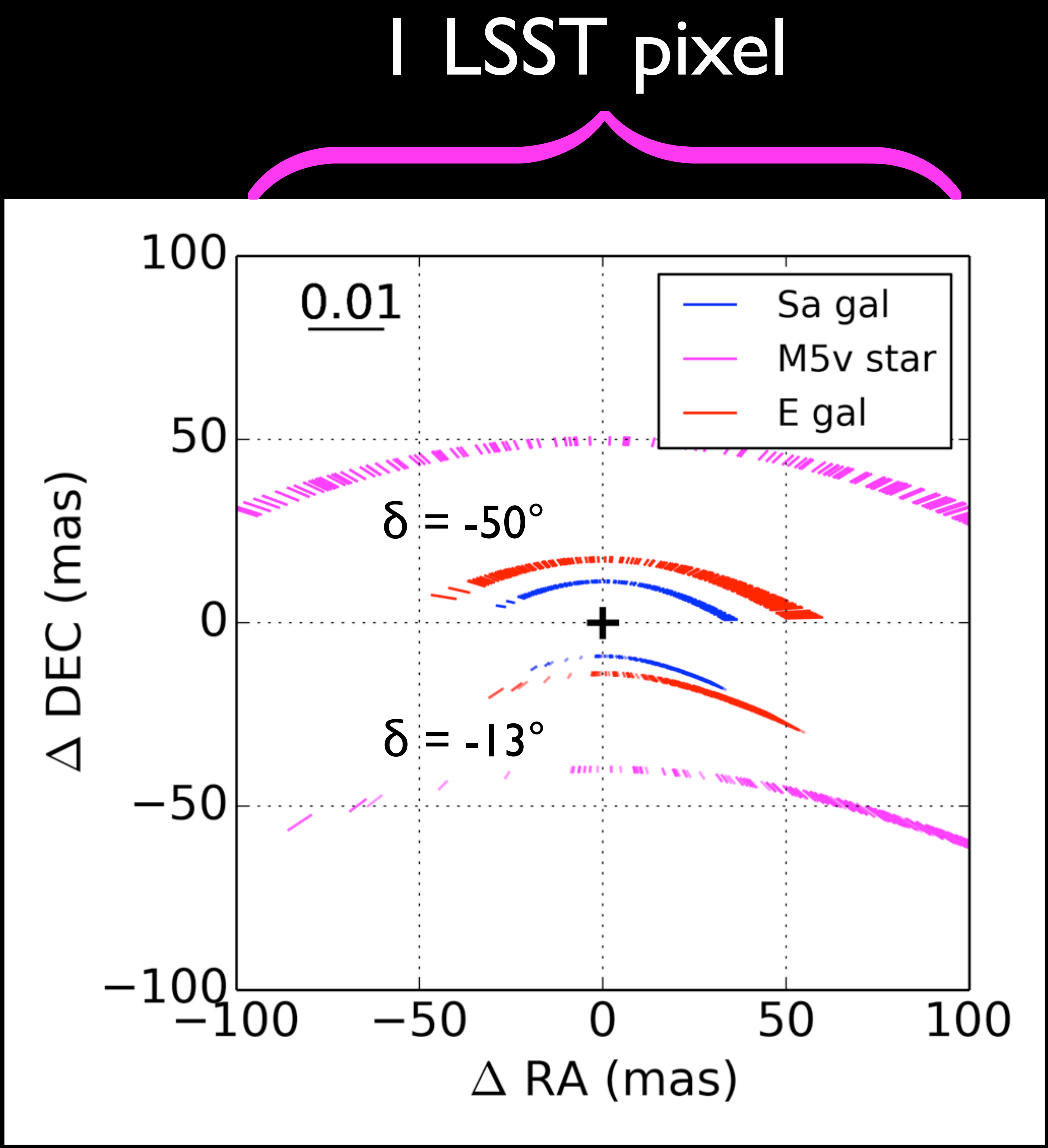
$$\bar{R} = \frac{\int p(\lambda)\, R(\lambda)\, \mathrm{d}\lambda}{\int p(\lambda)\, \mathrm{d}\lambda}$$

Centroid shifts don't directly affect galaxy shapes, but do make registration of multiple exposures tricky.

If images are registered using G5v stars, then centroids of other types of objects shift.

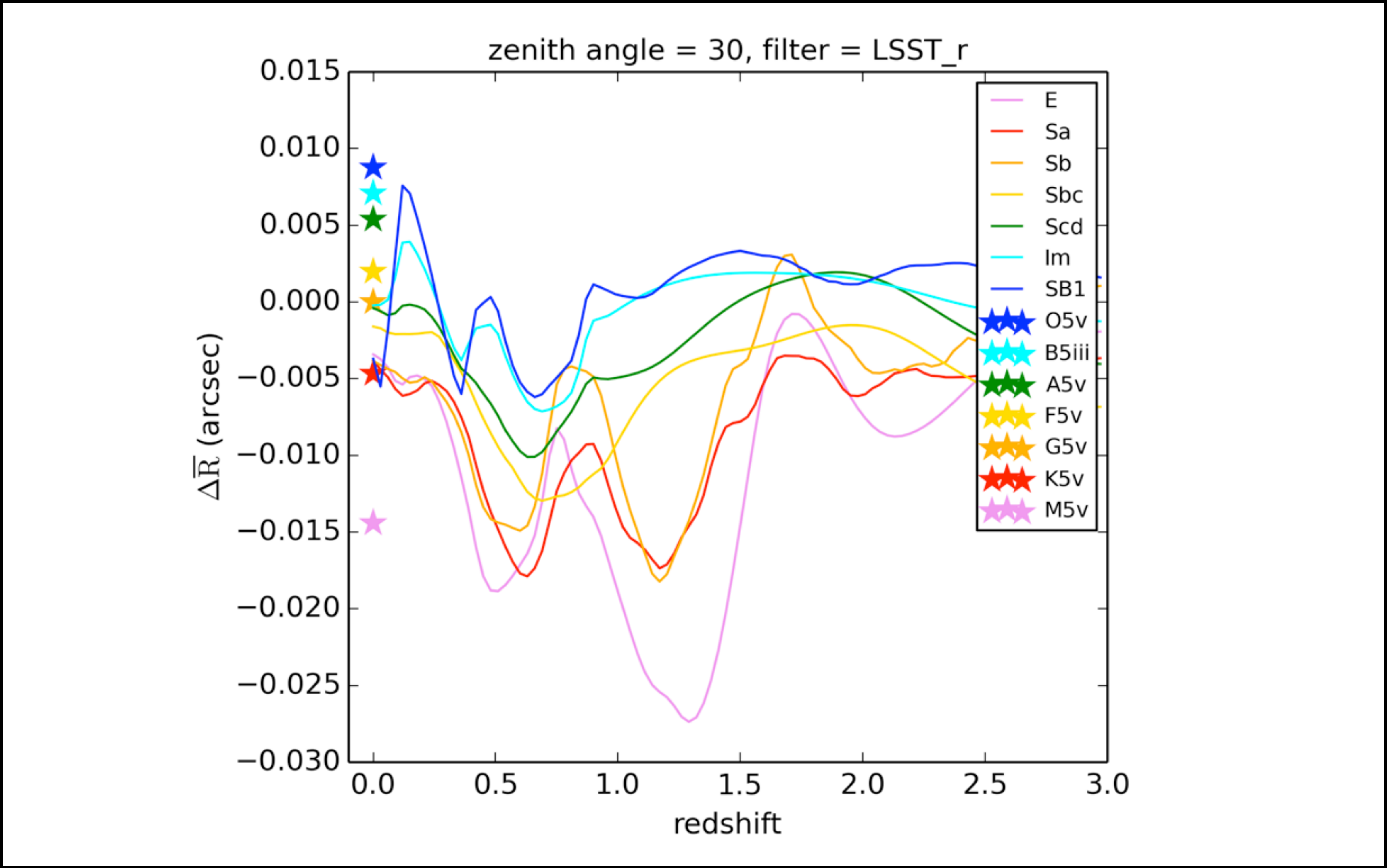
The shift depends on zenith angle and hour angle.

Distribution of zenith and hour angles depends on declination.



Shifts in PSF centroids due to DCR

cf. Plazas & Bernstein 2012



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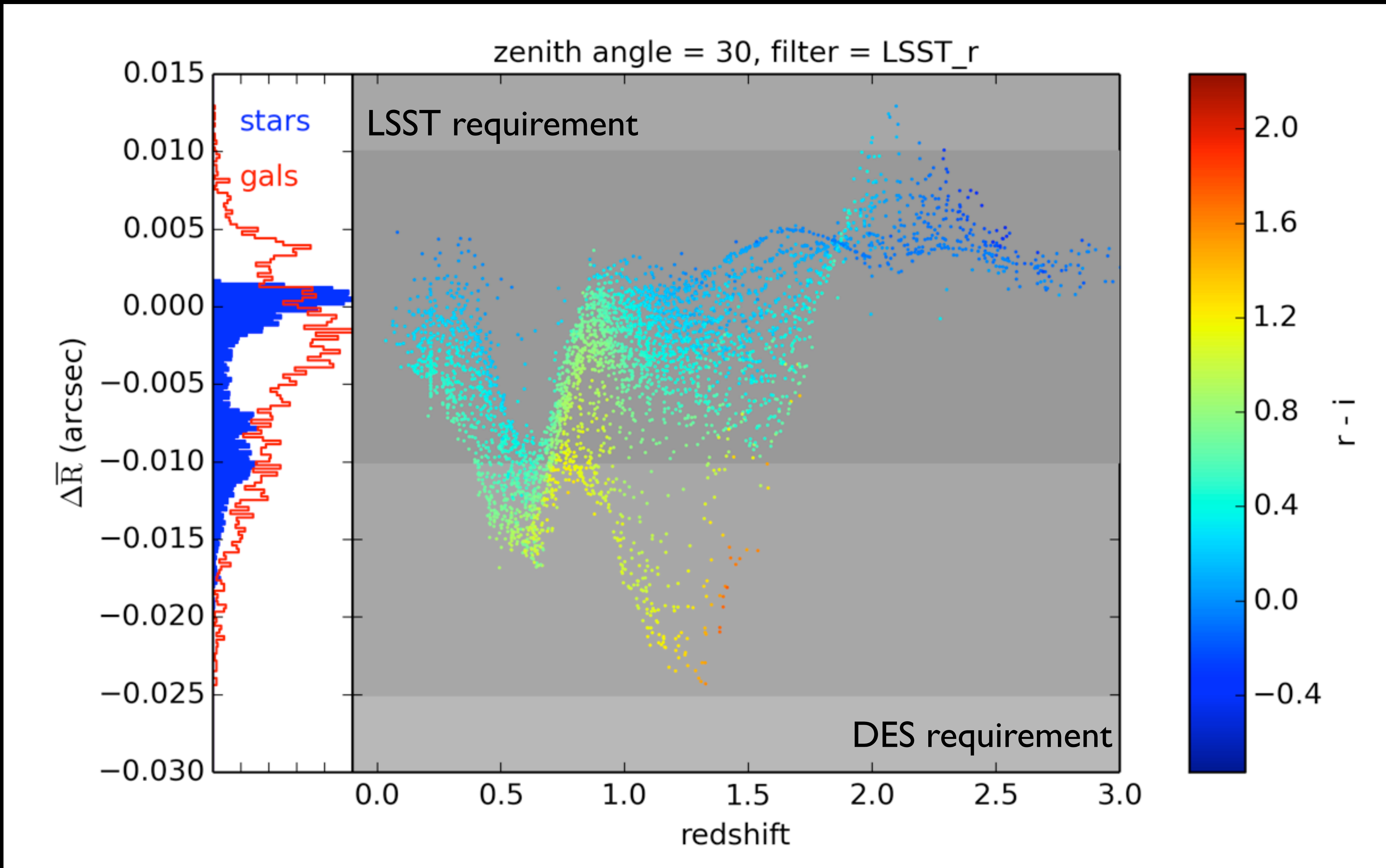

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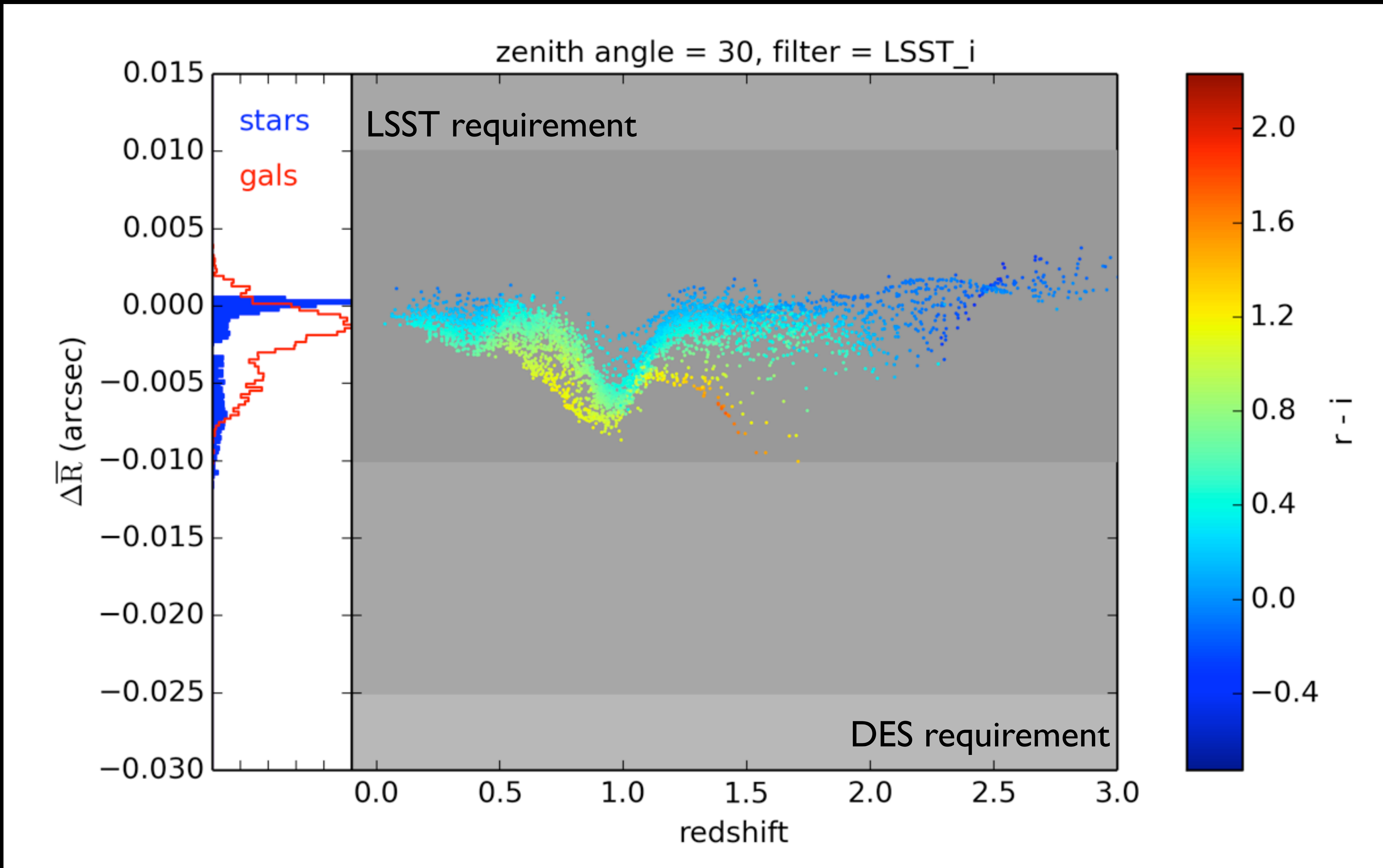
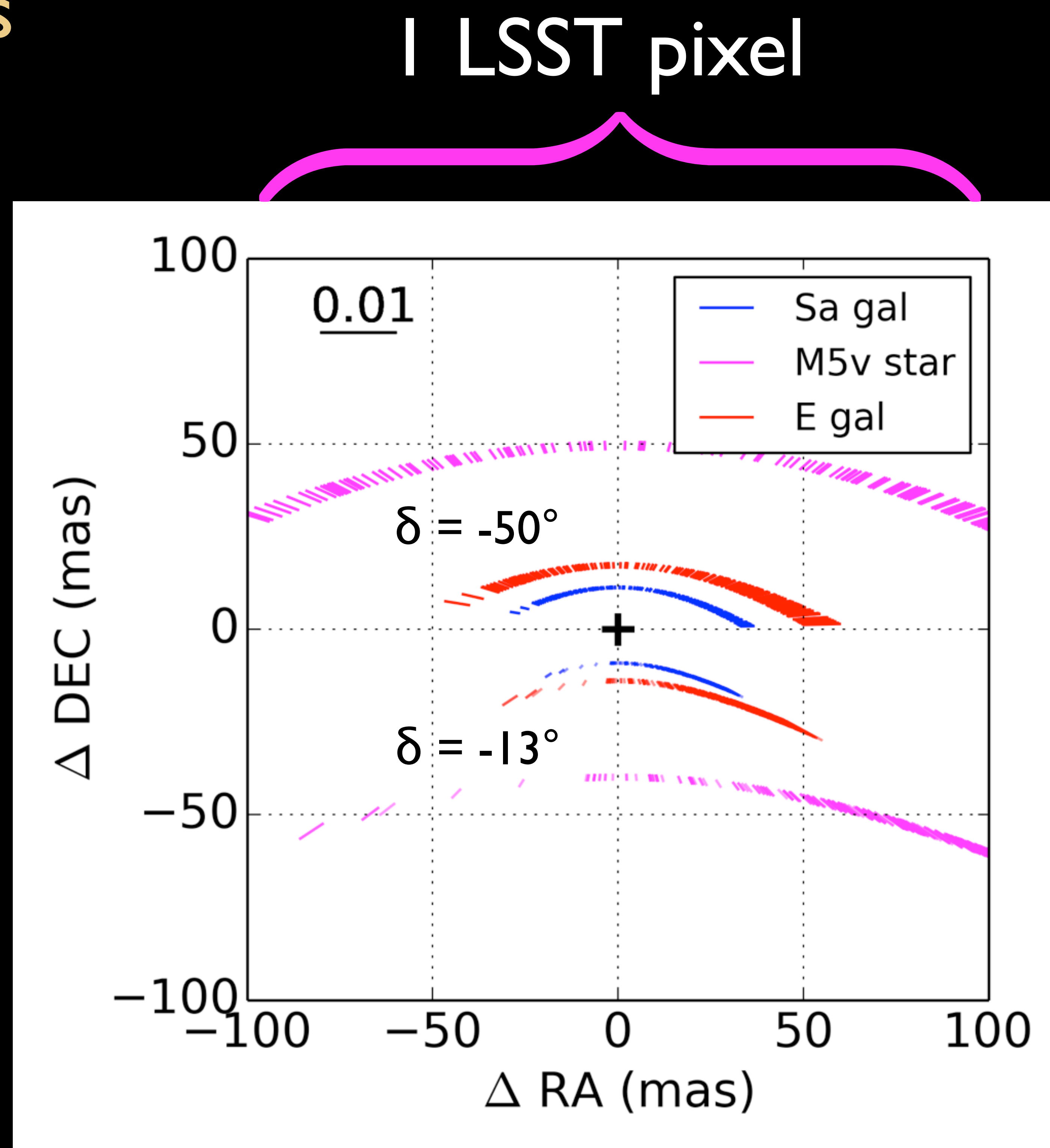


PSF second moment shifts



DCR increases zenith-direction second moments of all objects.

Amount of increase depends on SED.

Amplitudes and directions of relative second moment shifts depend on zenith angle and hour angle.

Distribution of zenith and hour angles depends on declination.

Effect of misestimating the PSF (c.f. Paulin-Henriksson+08)

Ellipticity definition

$$\epsilon_1 = \frac{I_{xx}^{\mathrm{gal}} - I_{yy}^{\mathrm{gal}}}{I_{xx}^{\mathrm{gal}} + I_{yy}^{\mathrm{gal}}}$$

Corrected second moment

$$I^{\mathrm{gal}} = I^{\mathrm{obs}} - I^{\mathrm{psf,g}}$$

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PSF misestimate

$$\Delta I^{\rm psf} = I^{\rm psf,*} - I^{\rm psf,g}$$

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Propagate into ellipticity

$$\epsilon_1 \to \frac{(I_{xx}^{\mathrm{gal}} + \Delta I_{xx}^{\mathrm{psf}}) - (I_{yy}^{\mathrm{gal}} + \Delta I_{yy}^{\mathrm{psf}})}{(I_{xx}^{\mathrm{gal}} + \Delta I_{xx}^{\mathrm{psf}}) + (I_{yy}^{\mathrm{gal}} + \Delta I_{yy}^{\mathrm{psf}})}$$

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Define second-moment radius (squared)

$$r_{\rm gal}^2 = I_{xx}^{\rm gal} + I_{yy}^{\rm gal}$$

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Define second-moment radius (squared)

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Algebra

$$\epsilon_1 \rightarrow \epsilon_1 \left(1 - \frac{\Delta I_{xx}^{\rm psf} + \Delta I_{yy}^{\rm psf}}{r_{\rm gal}^2}\right) + \frac{\Delta I_{xx}^{\rm psf} - \Delta I_{yy}^{\rm psf}}{r_{\rm gal}^2} + \mathcal{O}\left(\Delta I\right)^2$$

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Algebra

$$\epsilon_1 \to \epsilon_1 \left(1 \underbrace{- \frac{\Delta I_{xx}^{\text{psf}} + \Delta I_{yy}^{\text{psf}}}{r_{\text{gal}}^2}}_{\text{m}}\right) + \underbrace{\frac{\Delta I_{xx}^{\text{psf}} - \Delta I_{yy}^{\text{psf}}}{r_{\text{gal}}^2}}_{\text{2c}} + \mathcal{O}\left(\Delta I\right)^2$$

Shear calibration biases

$$\hat{\gamma}_i = \gamma_i(1 + m_i) + c_i$$

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Propagate into ellipticity

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$$\epsilon_2 \rightarrow \epsilon_2 \overbrace{\left(1 - \frac{\Delta I^{\rm psf}_{xx} + \Delta I^{\rm psf}_{yy}}{r^2_{\rm gal}}\right)}^{m} + \overbrace{\frac{2\Delta I^{\rm psf}_{xy}}{r^2_{\rm gal}}}^{2c} + \mathcal{O}\left(\Delta I\right)^2$$

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Algebra

$$\epsilon_1 \to \epsilon_1 \left(1 - \underbrace{\frac{\Delta I_{xx}^{\mathrm{psf}} + \Delta I_{yy}^{\mathrm{psf}}}{r_{\mathrm{gal}}^2}}_{m}\right) + \underbrace{\frac{\Delta I_{xx}^{\mathrm{psf}} - \Delta I_{yy}^{\mathrm{psf}}}{r_{\mathrm{gal}}^2}}_{2c} + \mathcal{O}\left(\Delta I\right)^2$$

$$\epsilon_2 \to \epsilon_2 \left(1 - \overbrace{\frac{\Delta I_{xx}^{\mathrm{psf}} + \Delta I_{yy}^{\mathrm{psf}}}{r_{\mathrm{gal}}^2}}\right) + \overbrace{\frac{2\Delta I_{xy}^{\mathrm{psf}}}{r_{\mathrm{gal}}^2}} + \mathcal{O}\left(\Delta I\right)^2$$

Shear calibration biases

$$\hat{\gamma}_i = \gamma_i(1 + m_i) + c_i$$

generic, but assumes unweighted second moments

Effect of DCR on PSF and inferred galaxy ellipticity

PSF centroid shift

$$\bar{R} = \frac{\int p(\lambda)\, R(\lambda)\, \mathrm{d}\lambda}{\int p(\lambda)\, \mathrm{d}\lambda}$$

PSF second moment shift

$$V = \frac{\int p(\lambda) \left(R(\lambda) - \bar{R}\right)^2 \mathrm{d}\lambda}{\int p(\lambda)\, \mathrm{d}\lambda}$$

Plazas & Bernstein 2012

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Plazas & Bernstein 2012

PSF misestimate for DCR, declare x to be the zenith direction

$$\Delta I_{xx}^{\mathrm{psf,DCR}} = \Delta V \qquad \Delta I_{xy}^{\mathrm{psf,DCR}} = \Delta I_{yy}^{\mathrm{psf,DCR}} = 0$$

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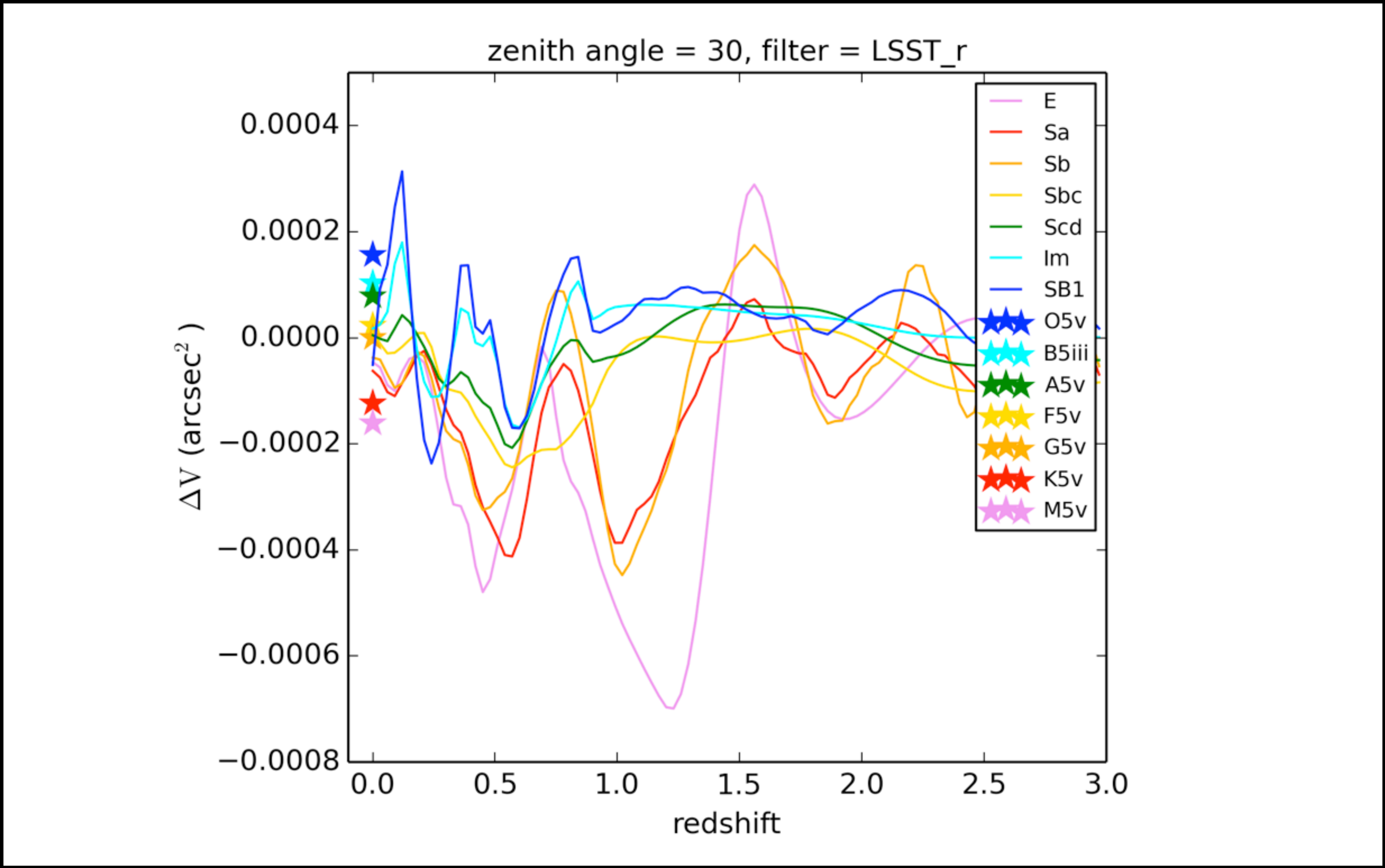
Shear calibration biases for DCR

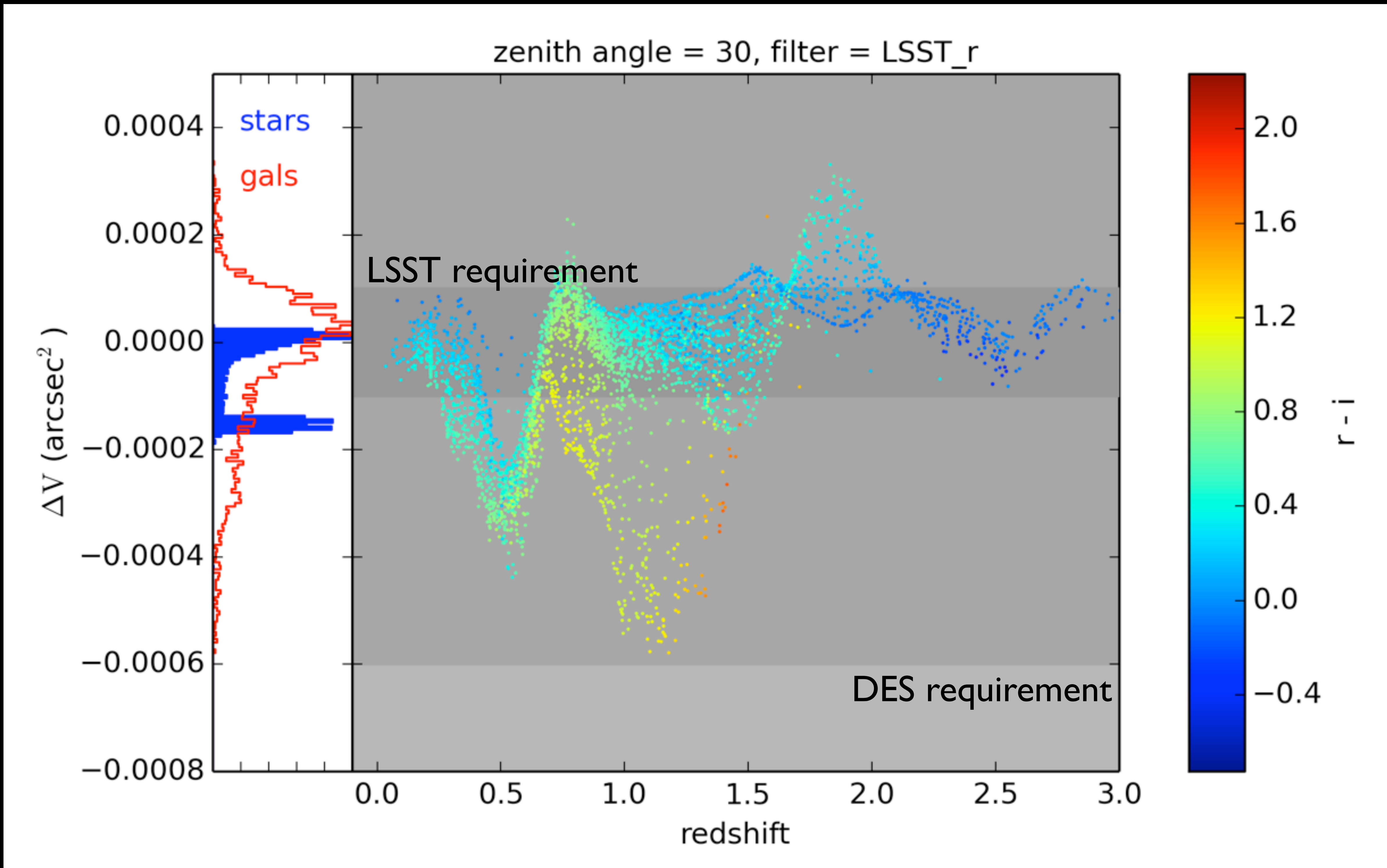
$$m_1^{\mathrm{DCR}} = m_2^{\mathrm{DCR}} = \frac{-\Delta V}{r_{\mathrm{gal}}^2} \qquad c_1^{\mathrm{DCR}} = \frac{\Delta V}{2 r_{\mathrm{gal}}^2} \qquad c_2^{\mathrm{DCR}} = 0$$

Shifts in PSF second moments due to DCR

cf. Plazas & Bernstein 2012



Shifts in PSF second moments due to DCR cf. Plazas & Bernstein 2012



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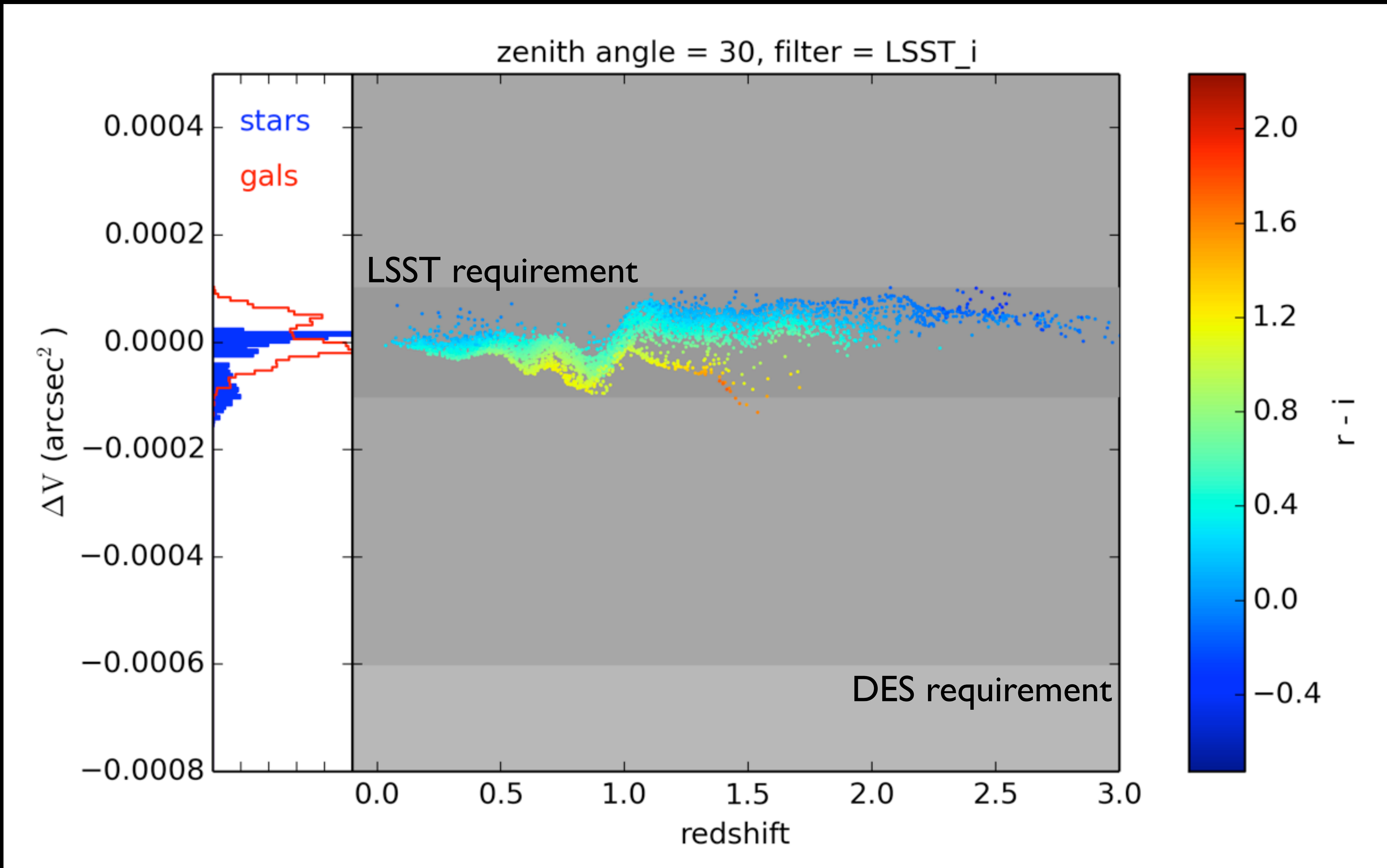
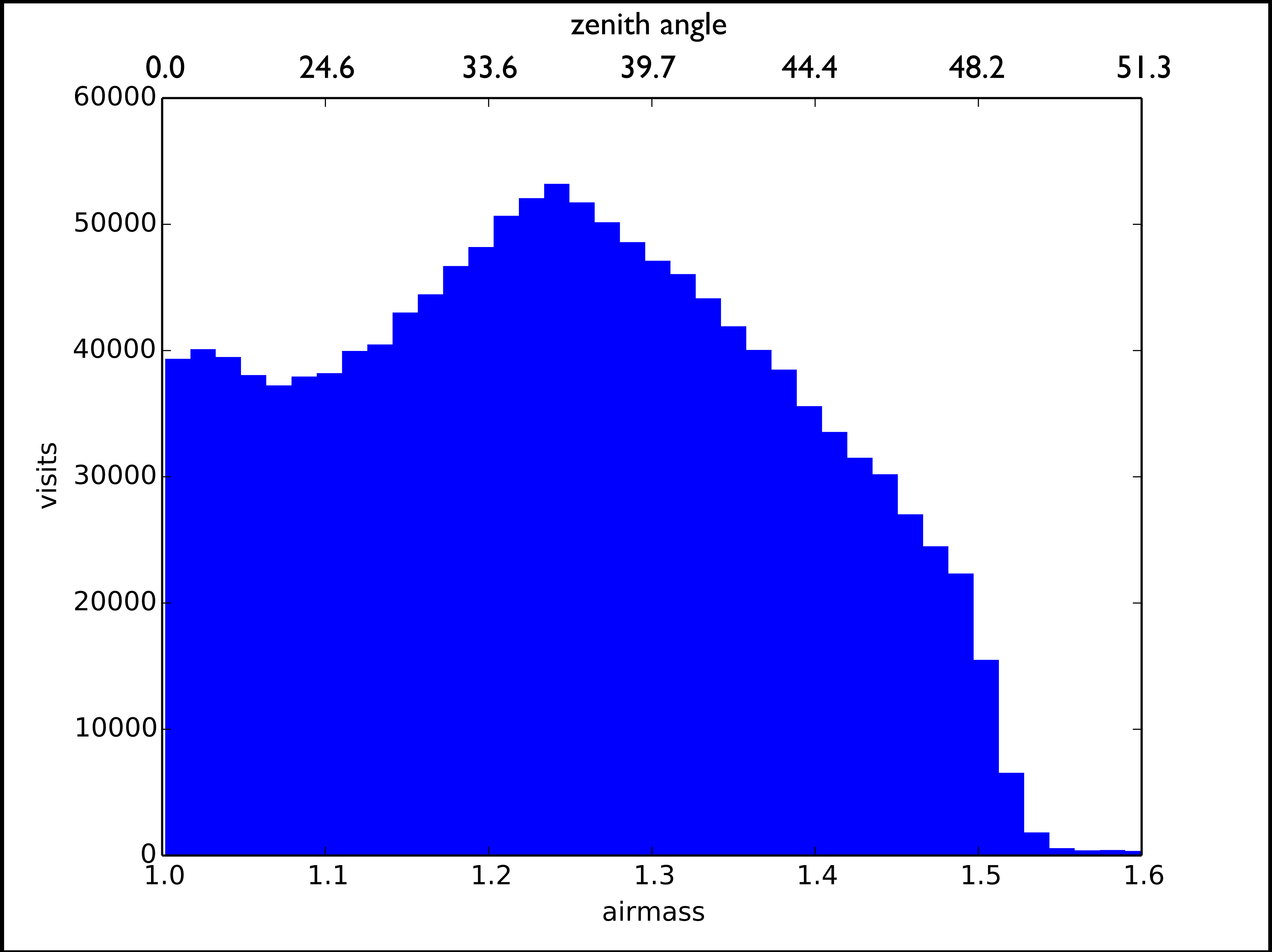


LSST OpSim airmass (zenith angle) distribution

- Operations simulator: simulate observation cadence, weather, incorporate past observing, other priorities
- zenith angle 25th/50th/75th percentiles:
  - 29, 37, 42 degrees
- much ongoing work to optimize survey
- first moment of DCR scales like $\tan(z_a)$
- second moment of DCR scales like $\tan^2(z_a)$

OpSim run 3.61



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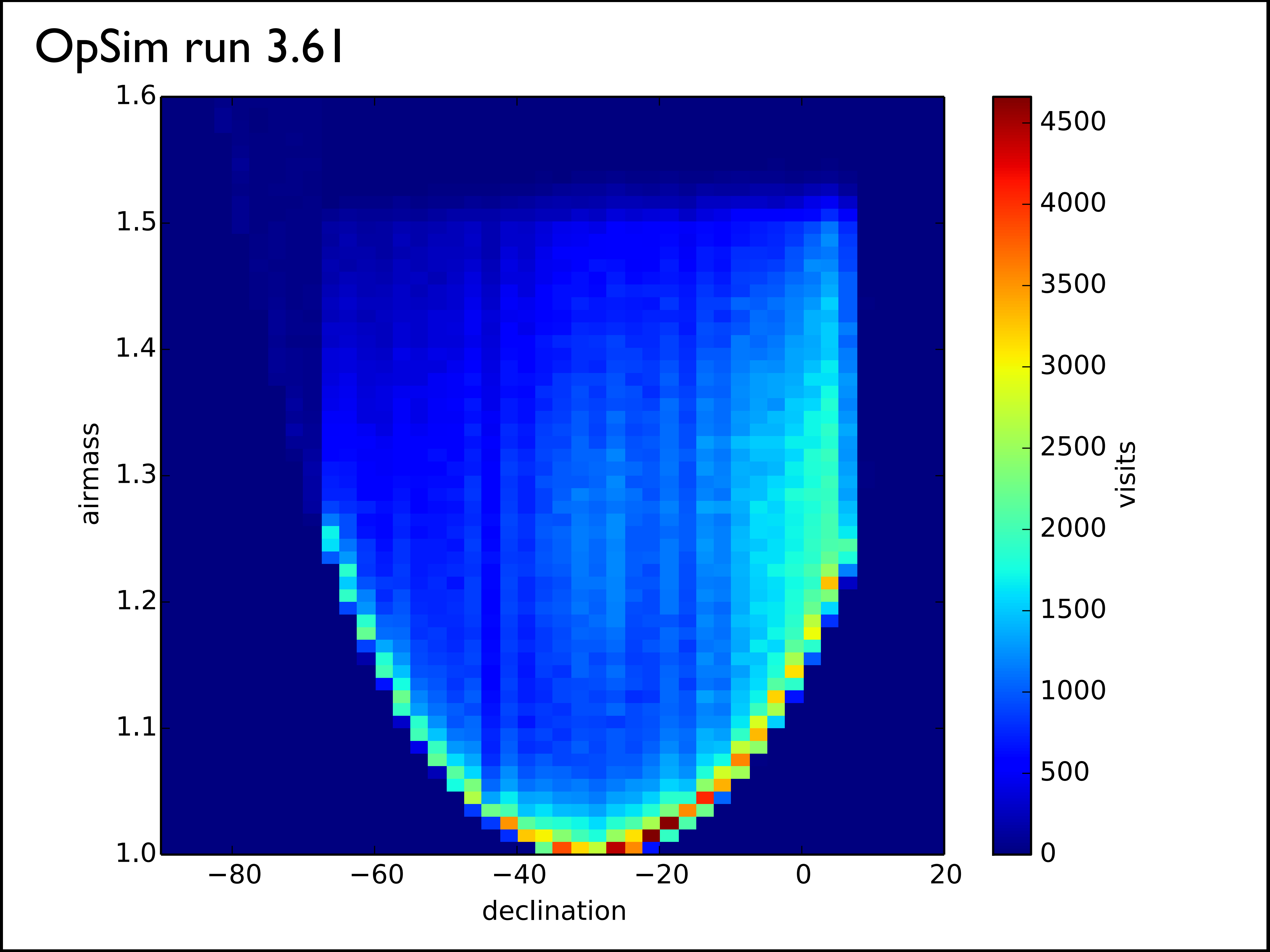
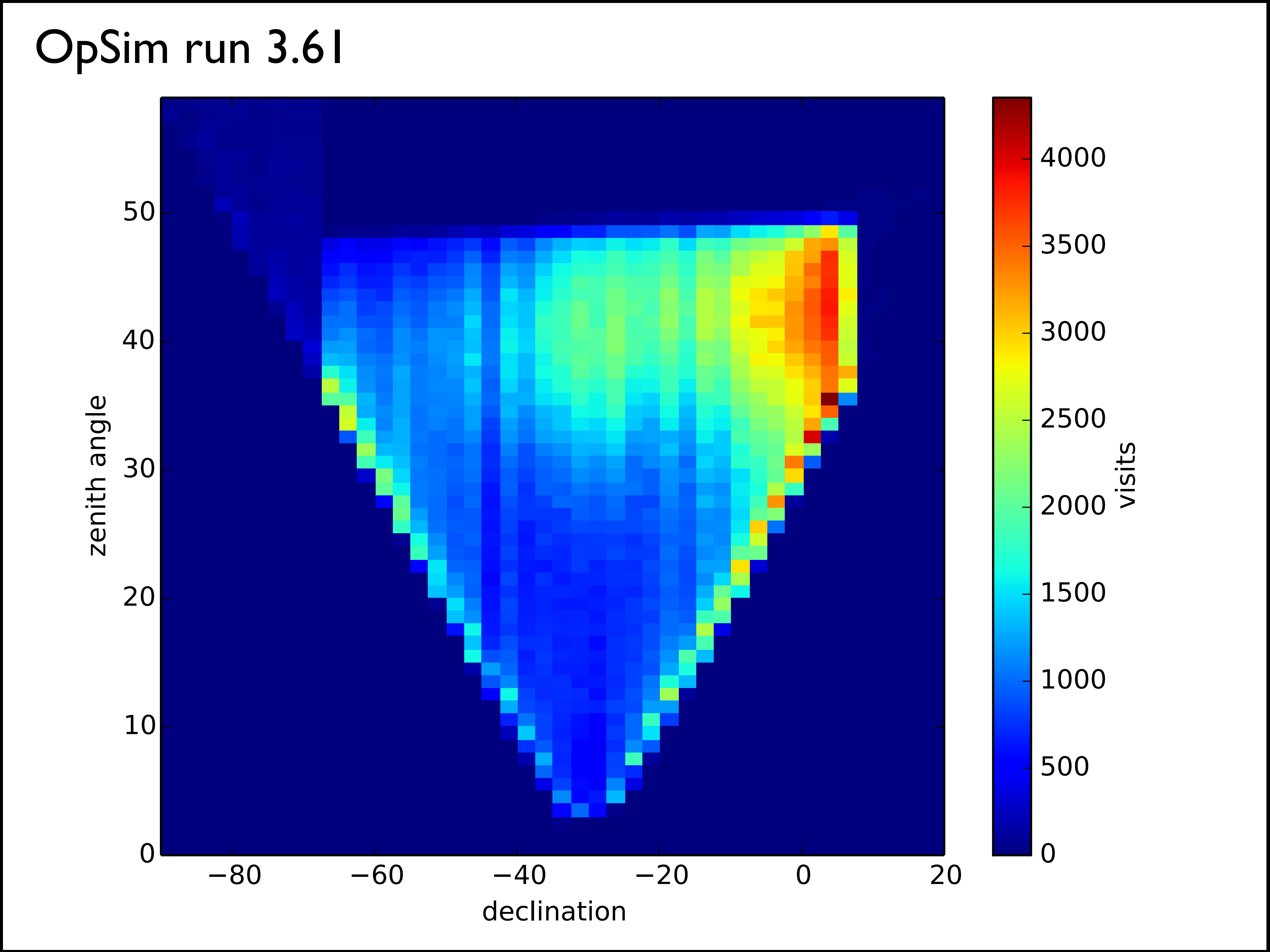


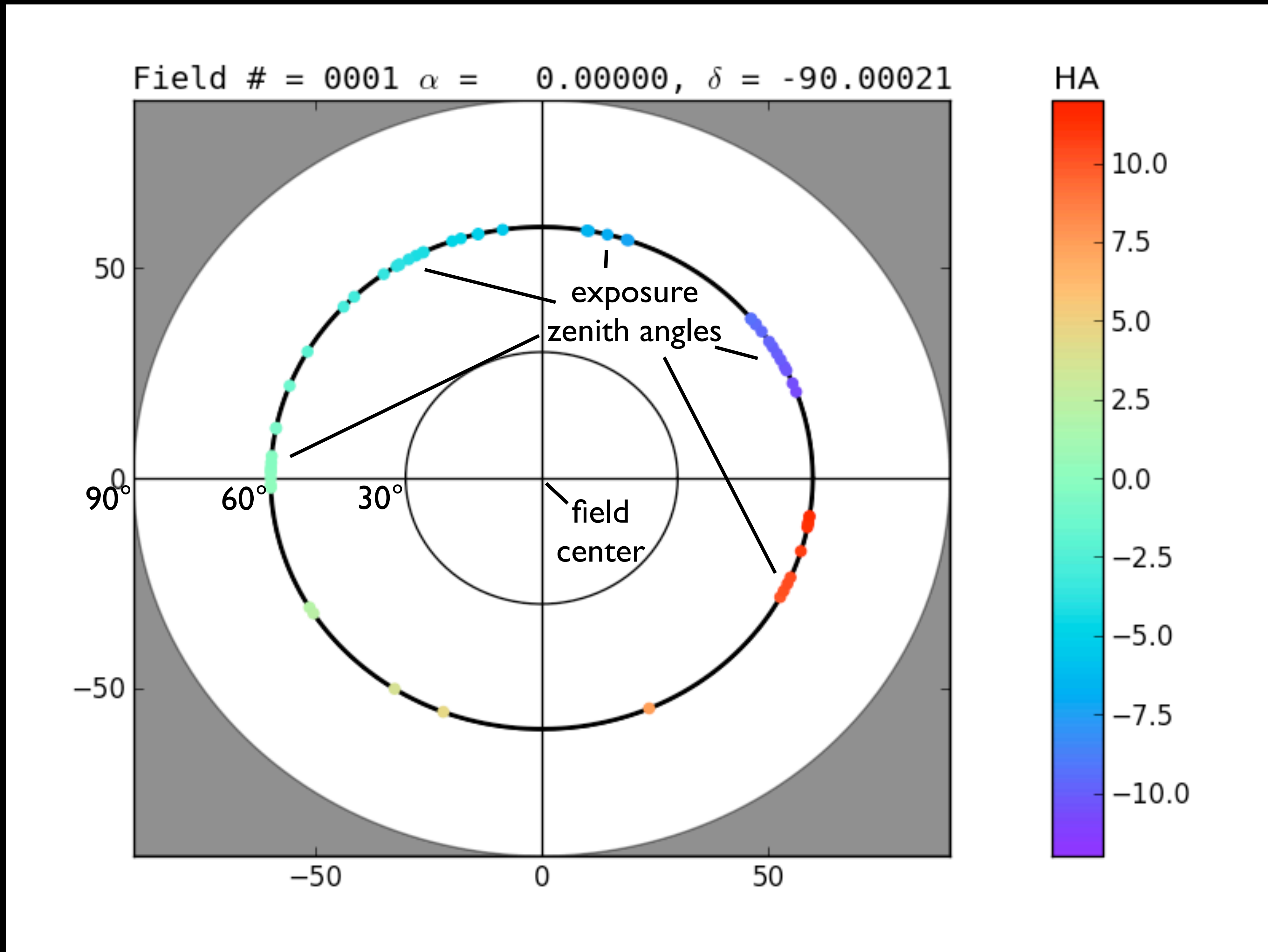
LSST OpSim zenith angle distribution



LSST OpSim zenith and parallactic angle distribution

OpSim run 3.61

Where the zenith is in field coordinates



video available at:
github.com/DarkEnergyScienceCollaboration/chroma/blob/master/bin/opsim/zenith_parallactic.mp4

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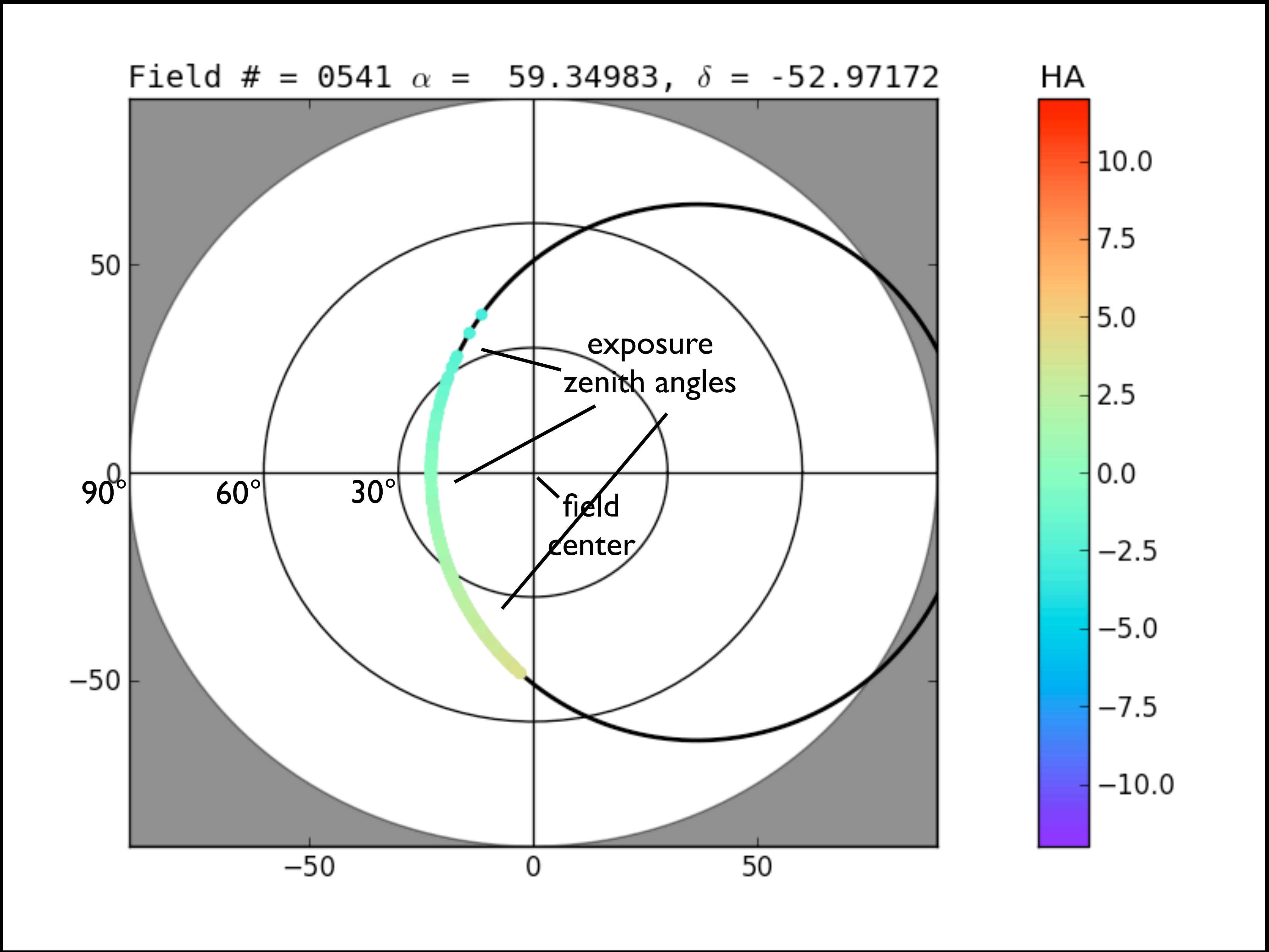

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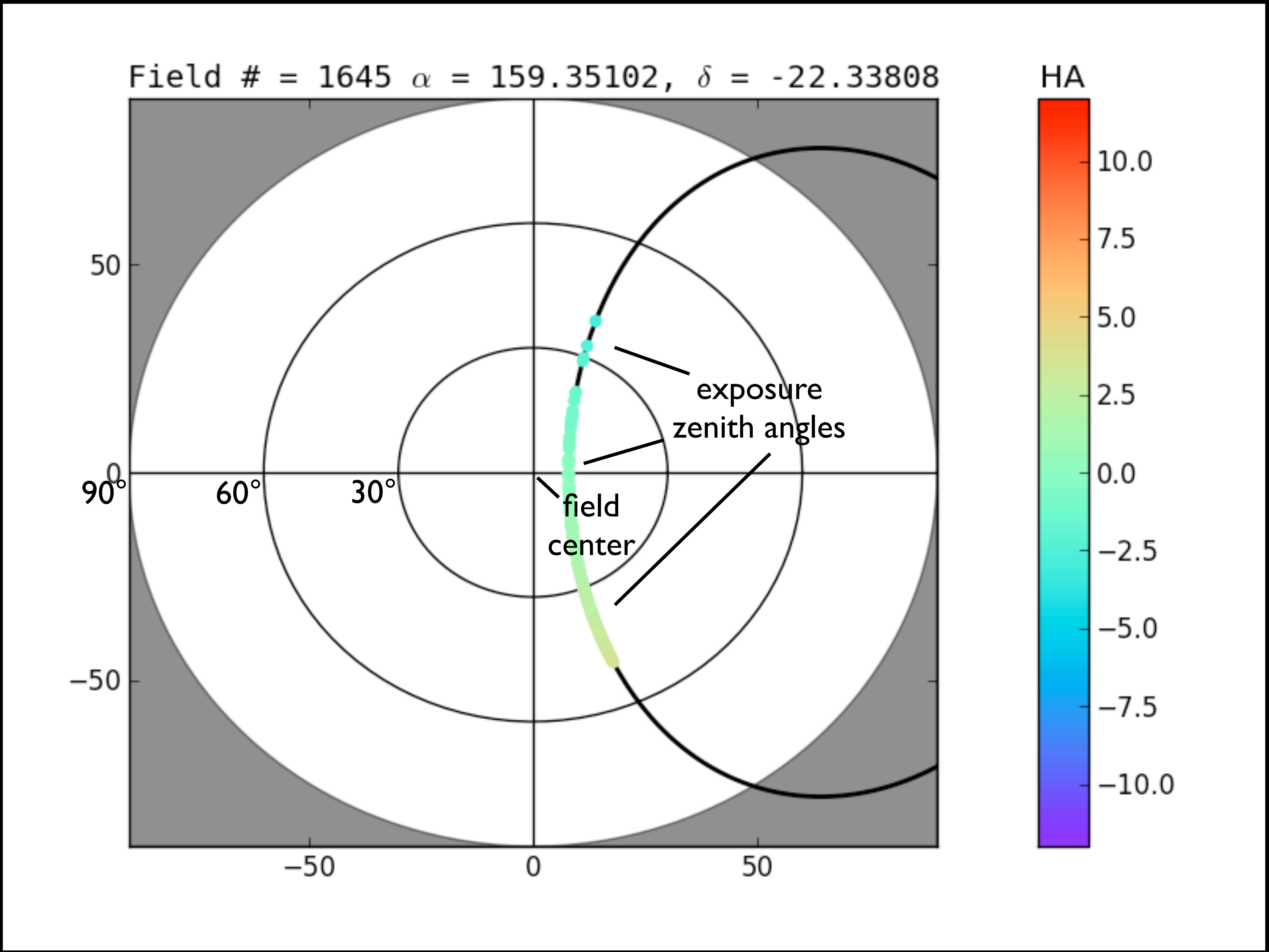

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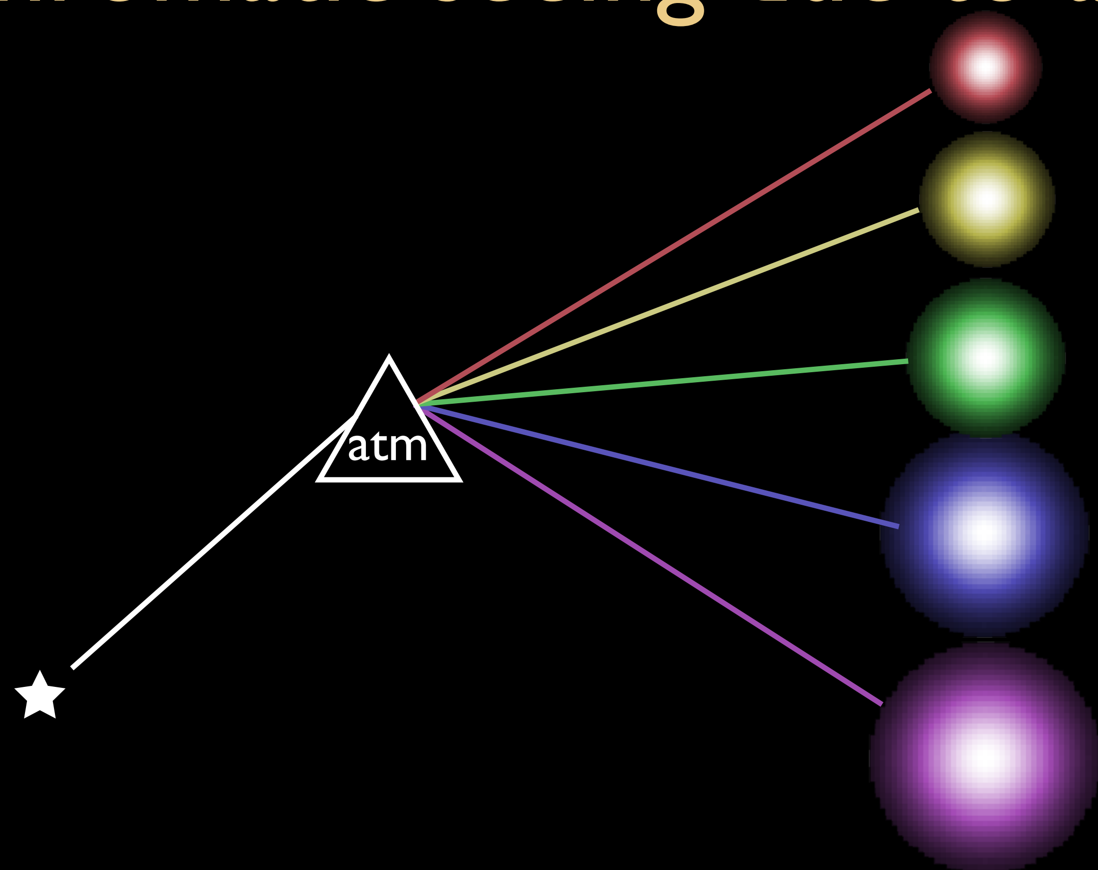
Chromatic seeing due to atmospheric turbulence

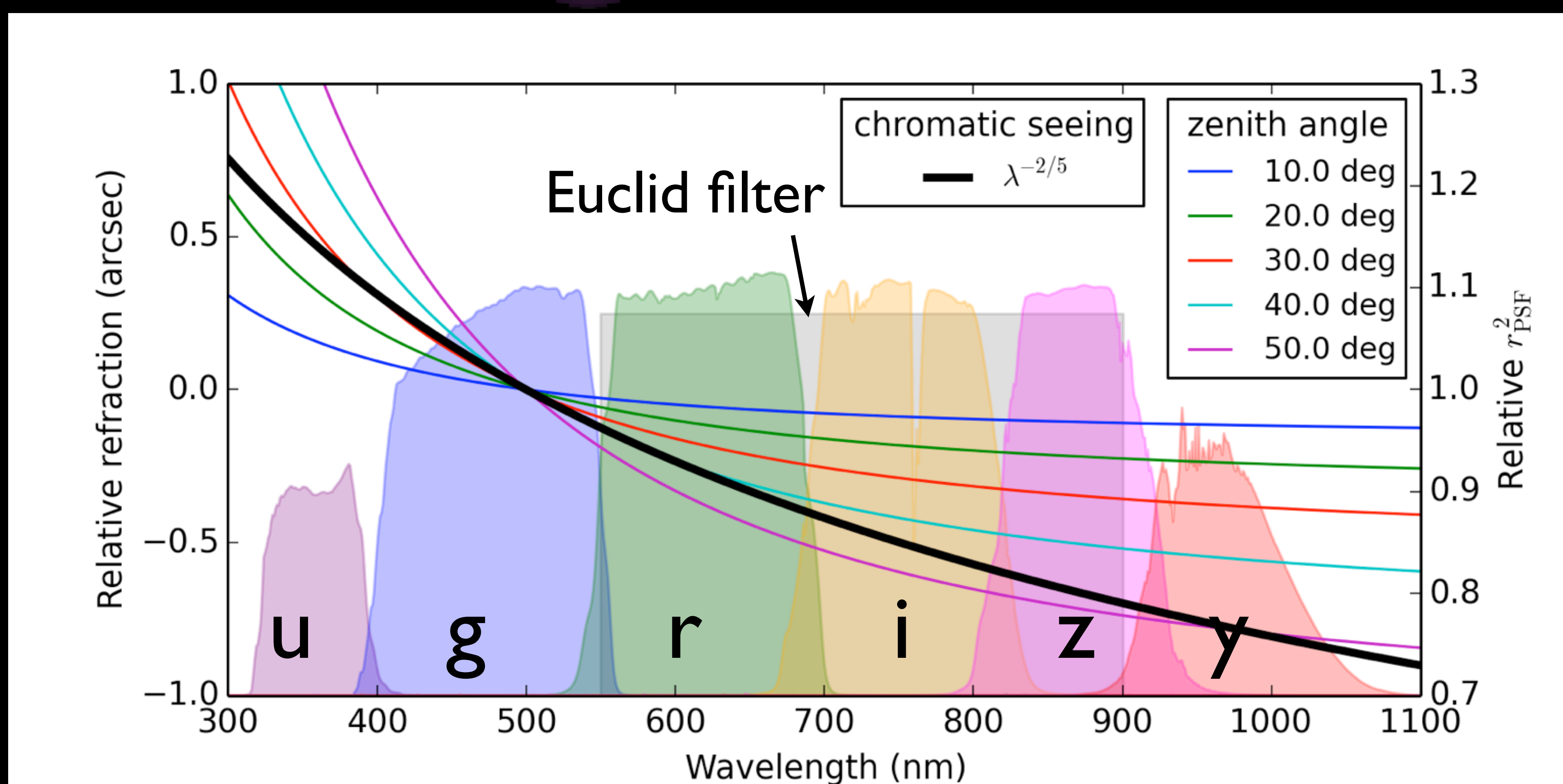


Kolmogorov turbulence predicts that the atmosphere smears out blue photons more than red photons:

$$\mathrm{FWHM} \propto \lambda^{-1/5}$$

Qualitatively similar to diffraction limit:

$$\mathrm{FWHM} \propto \lambda^{+1}$$



Chromatic seeing and effect on inferred galaxy ellipticity

PSF second moments dependence on the SED:

$$I^{\mathrm{psf}} = I^{\mathrm{psf},\lambda_0} \frac{\int p(\lambda)(\lambda/\lambda_0)^{-2/5}\,\mathrm{d}\lambda}{\int p(\lambda)\,\mathrm{d}\lambda}$$

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Shear calibration biases for chromatic seeing:

$$m_1^{\mathrm{seeing}} = m_2^{\mathrm{seeing}} = -\frac{r^2_{\mathrm{psf}}}{r^2_{\mathrm{gal}}}\frac{\Delta r^2_{\mathrm{psf}}}{r^2_{\mathrm{psf}}}$$

$$c_i^{\mathrm{seeing}} = \frac{r^2_{\mathrm{psf}}}{r^2_{\mathrm{gal}}}\frac{\Delta r^2_{\mathrm{psf}}}{r^2_{\mathrm{psf}}}\epsilon_i^{\mathrm{psf}}$$

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Switch exponent to +2 for diffraction limit

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Switch exponent to +2 for diffraction limit

This term is worse for Euclid

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This term is worse for LSST

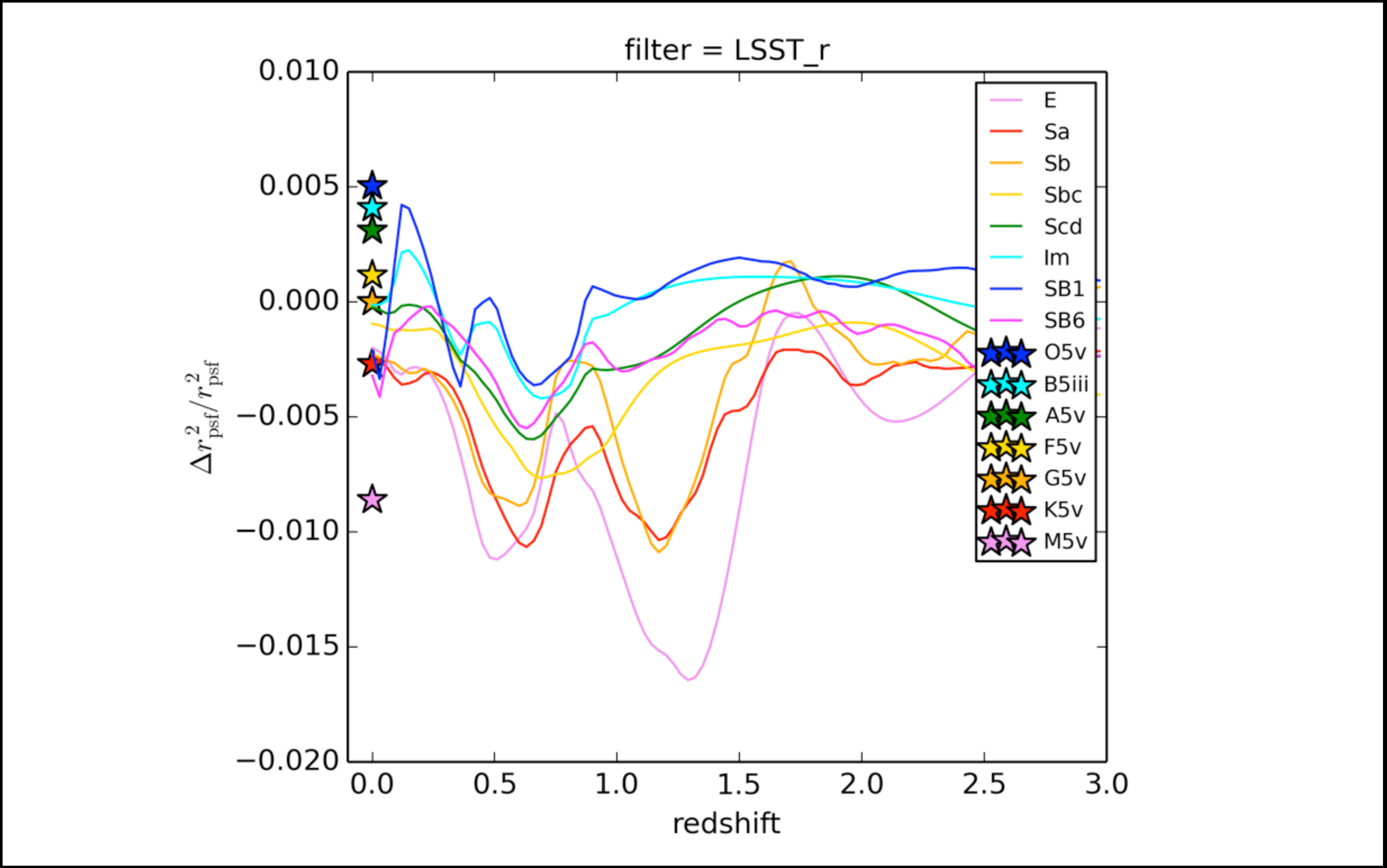
Estimating r^2_{PSF}/r^2_{gal} and LSST requirement on $\Delta r^2_{\rm psf}/r^2_{\rm psf}$

- Want to keep $|m| \lesssim 0.0015$
- Gaussian has 3x smaller r^2 than Moffat of same FWHM
- Half light radius (HLR) underestimates r^2 by factor of ~2-20 for Sersic profiles with n between 1.0 and 4.0
- Caveat: Formula assumes <u>unweighted</u> second moments

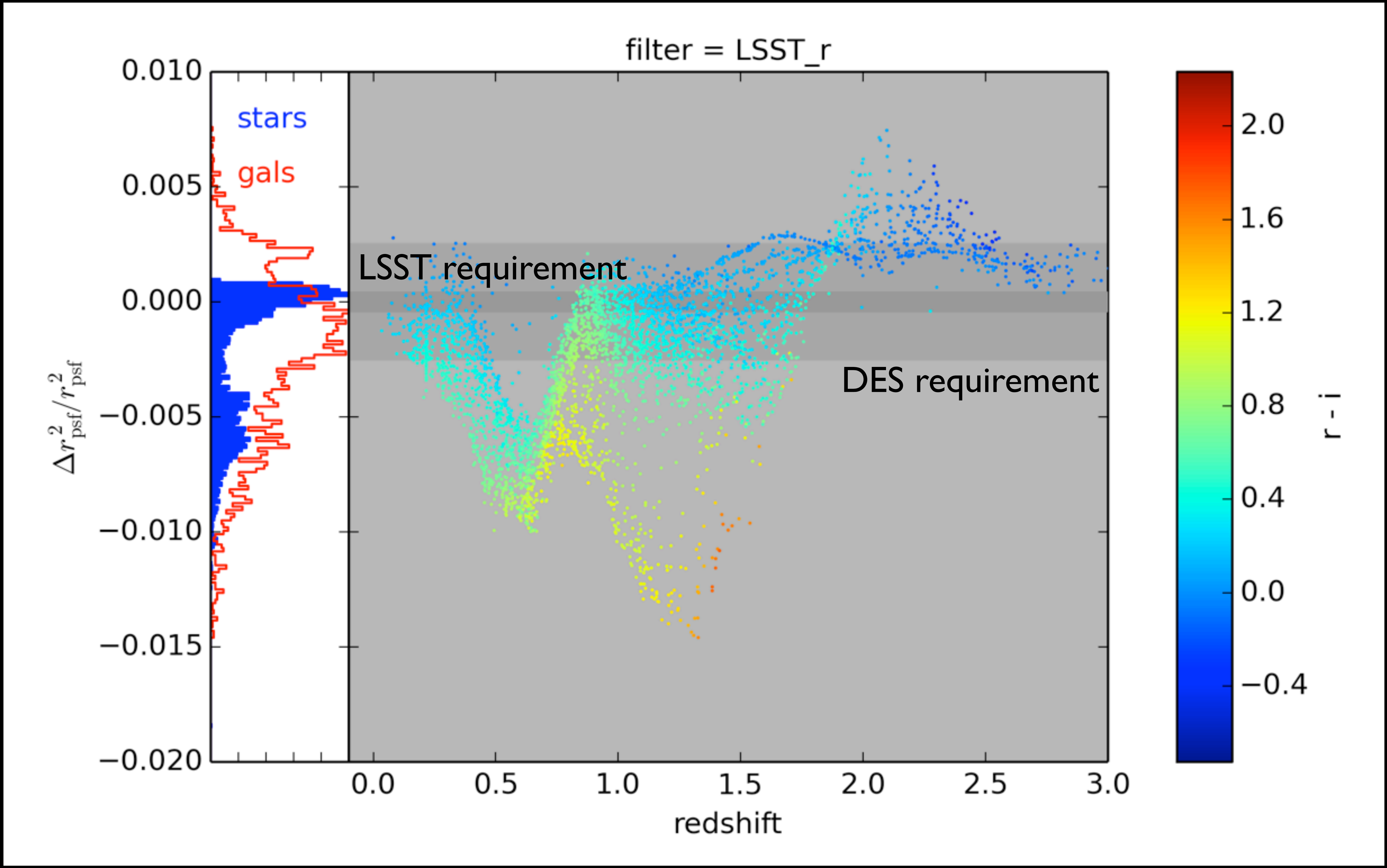
PSF	gal	r^2_{PSF}/r^2_{gal}	$\Delta r^2_{\rm psf}/r^2_{\rm psf}$ requirement
Chang priv. comm. OpSim Gaussian	CatSim Sersic r^2	1.5	10×10^{-4}
Gaussian FWHM=0.7	Jouvel+09 COSMOS <HLR> = 0.27	2.5	6×10^{-4}
Moffat FWHM=0.7	Jouvel+09 COSMOS <HLR> = 0.27	7.5	2×10^{-4}

Wide range of possible estimates

Differences in PSF size due to chromatic seeing



Differences in PSF size due to chromatic seeing



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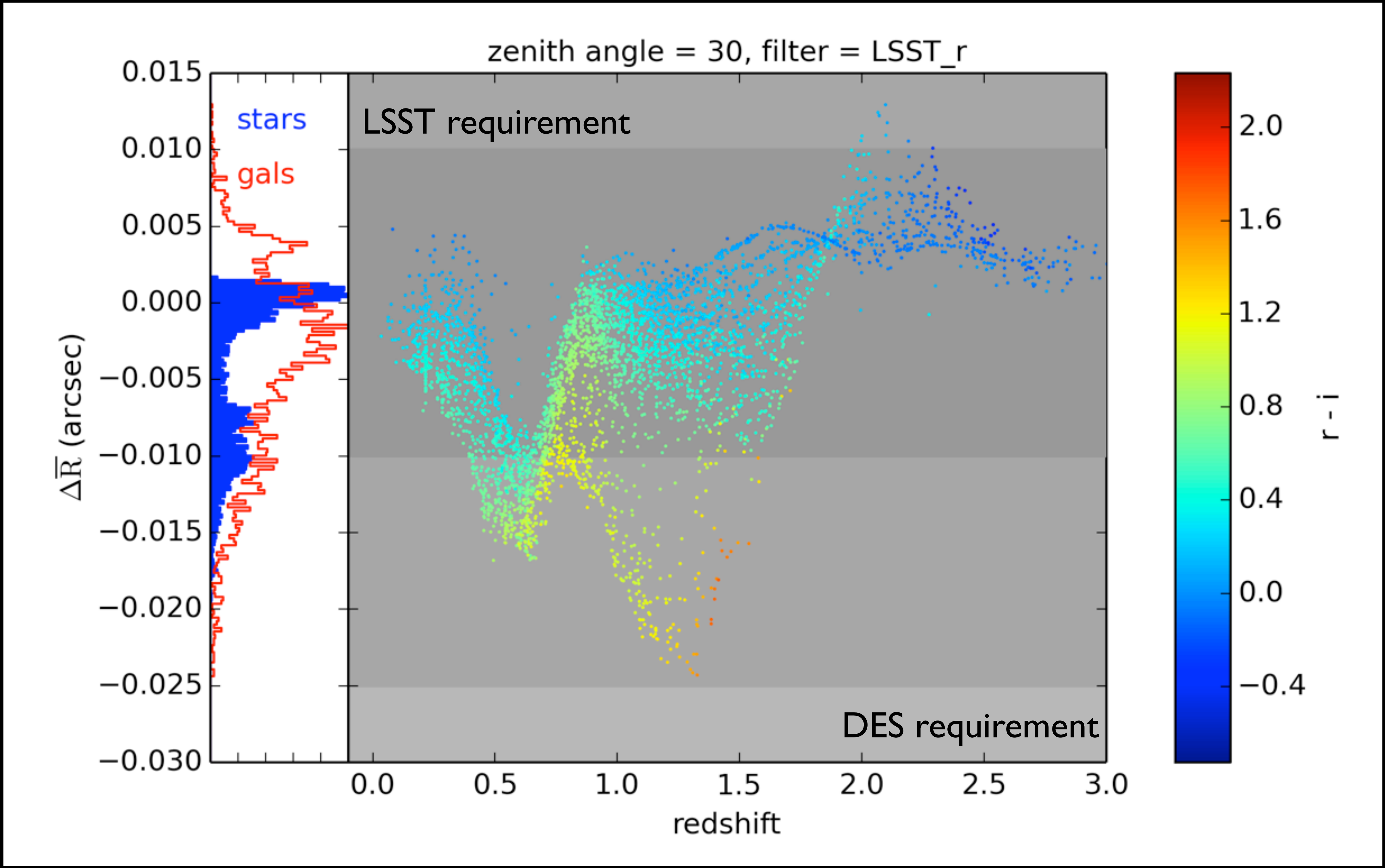

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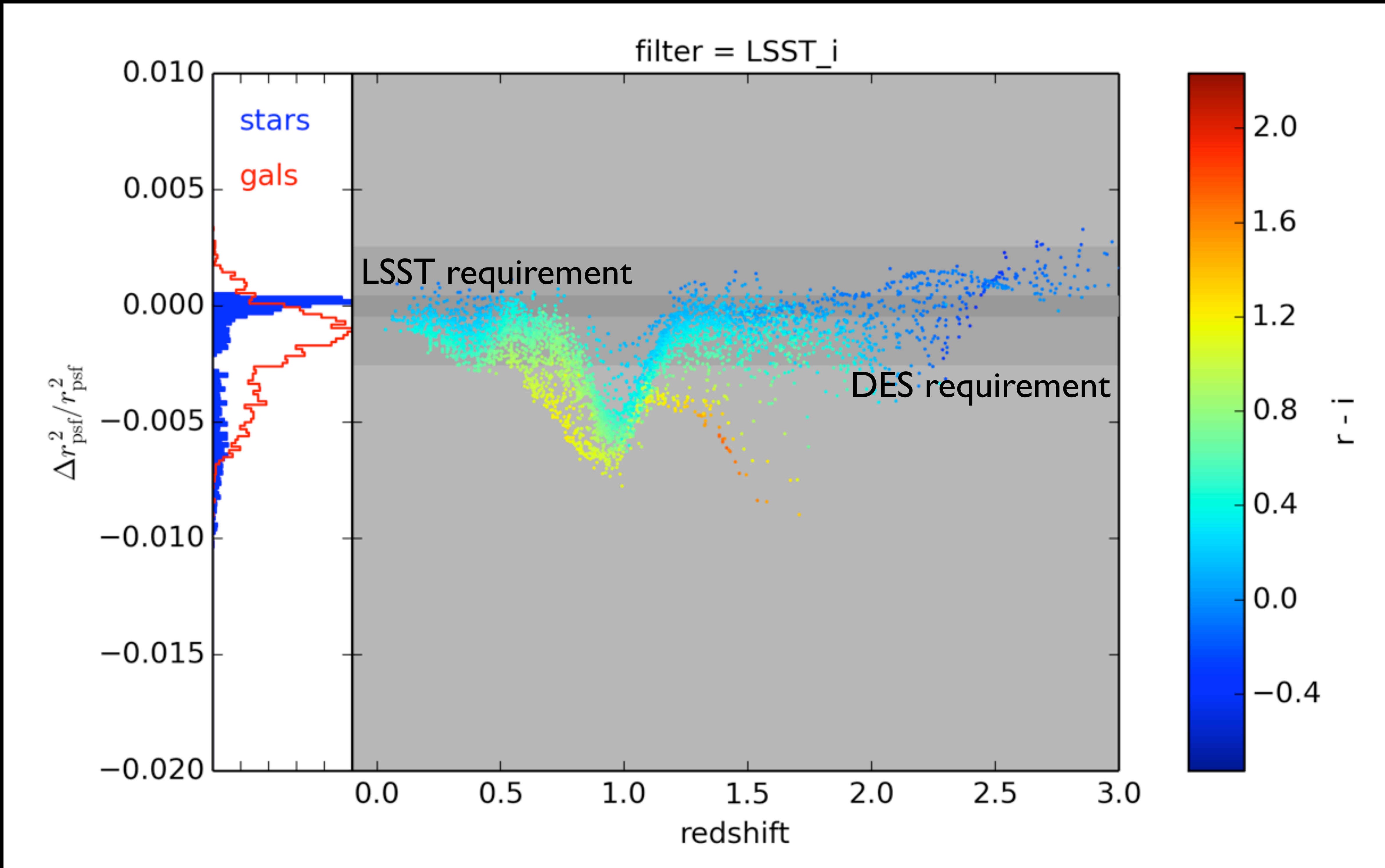
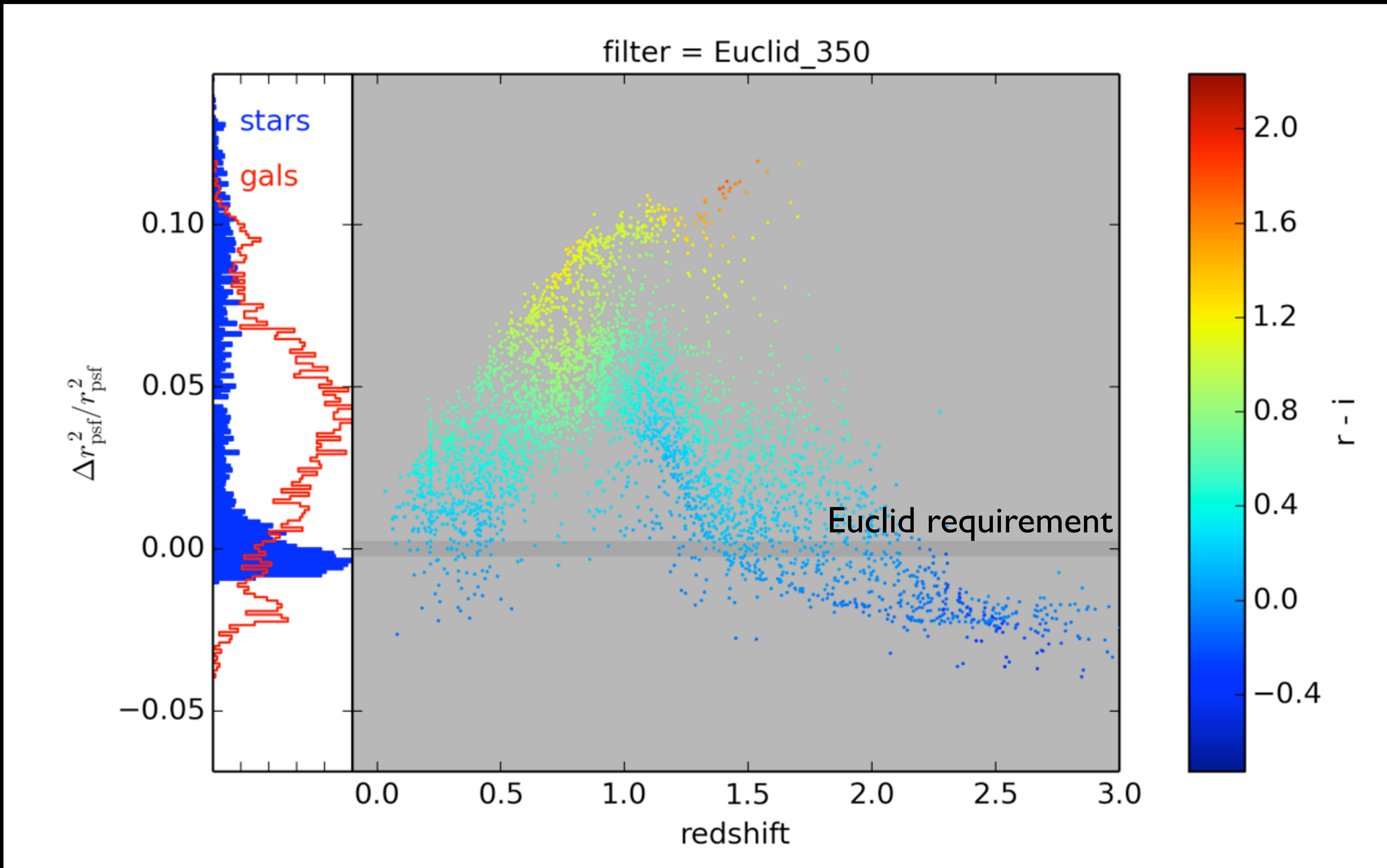
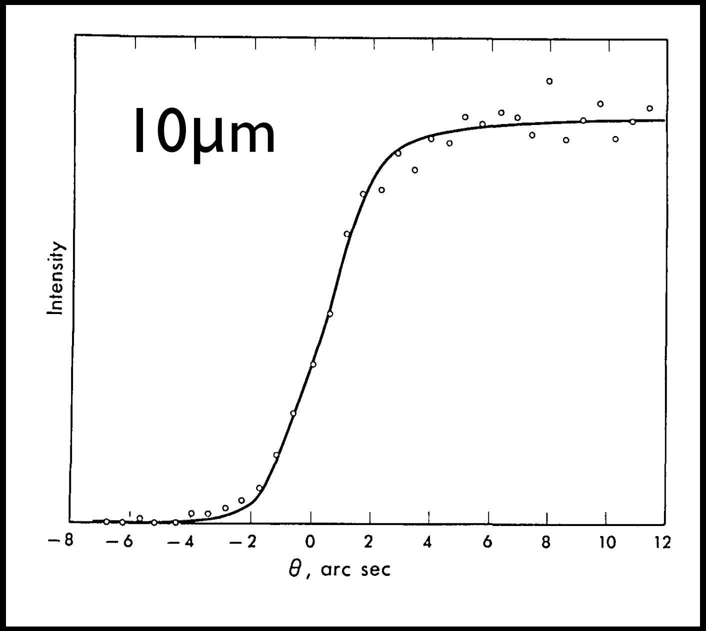


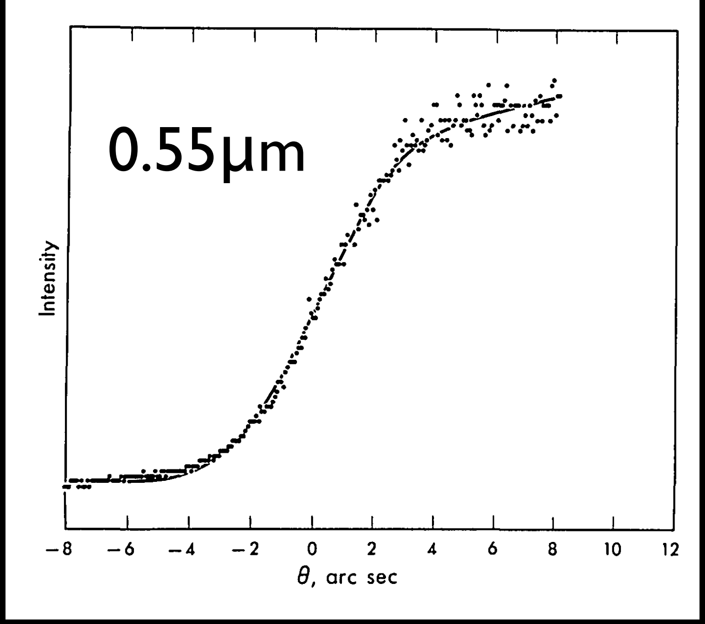
Differences in PSF size for Euclid

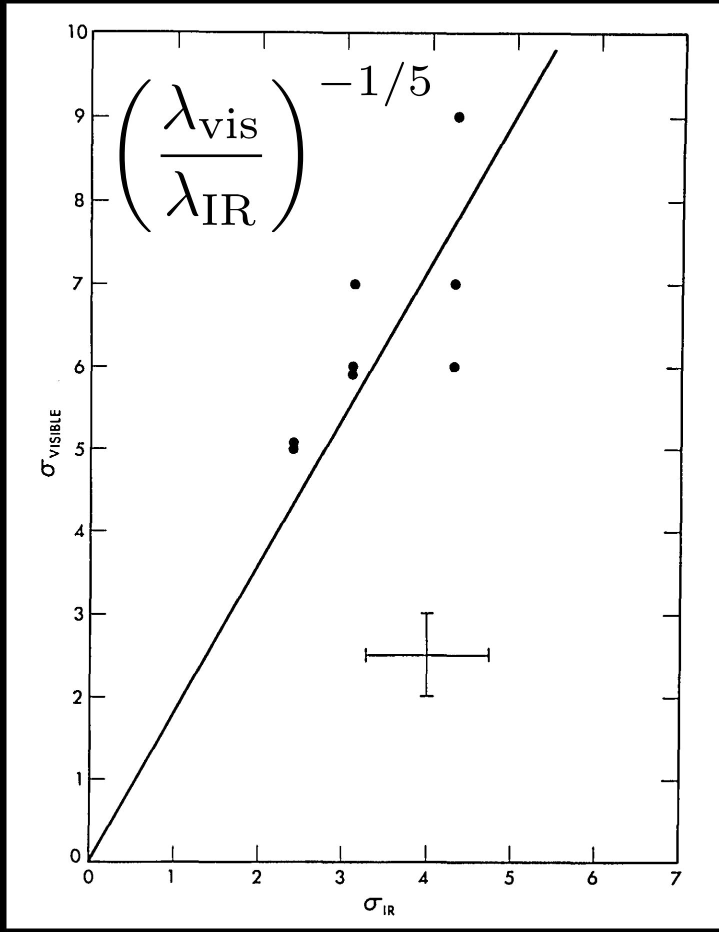


Chromatic seeing in data

Boyd78: solar limb

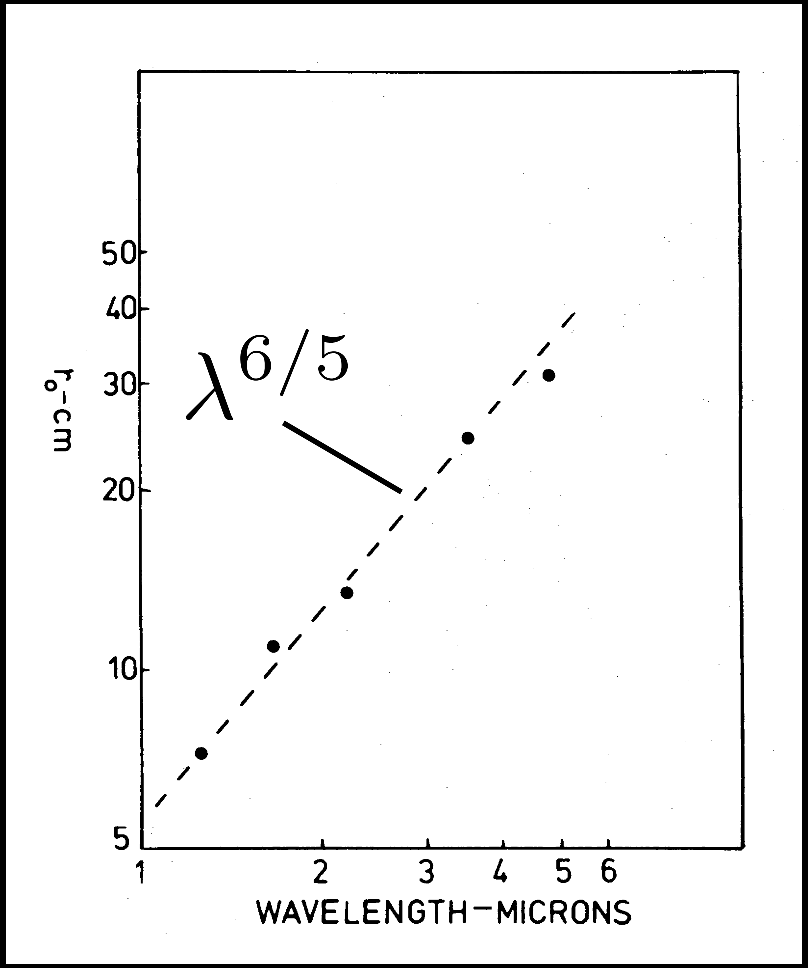






visible wavelength, but done in really poor seeing!

Selby+79: speckle interferometry



IR only, really bad seeing (~5")

Suggestions that power law slope is *not* -1/5

β, the turbulence power spectrum index, predicted to be 5/3

Linfield+01:Palomar testbed interferometer

$$\mathrm{FWHM} \propto \lambda^{1-2/\beta}$$

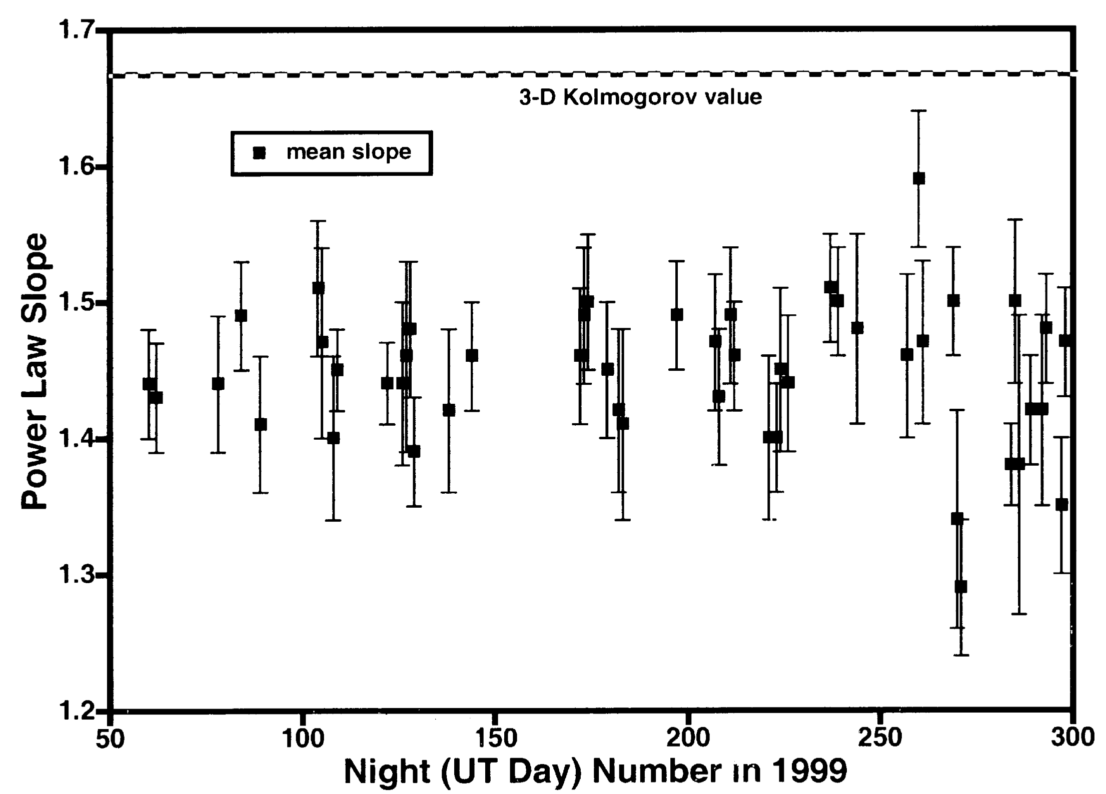
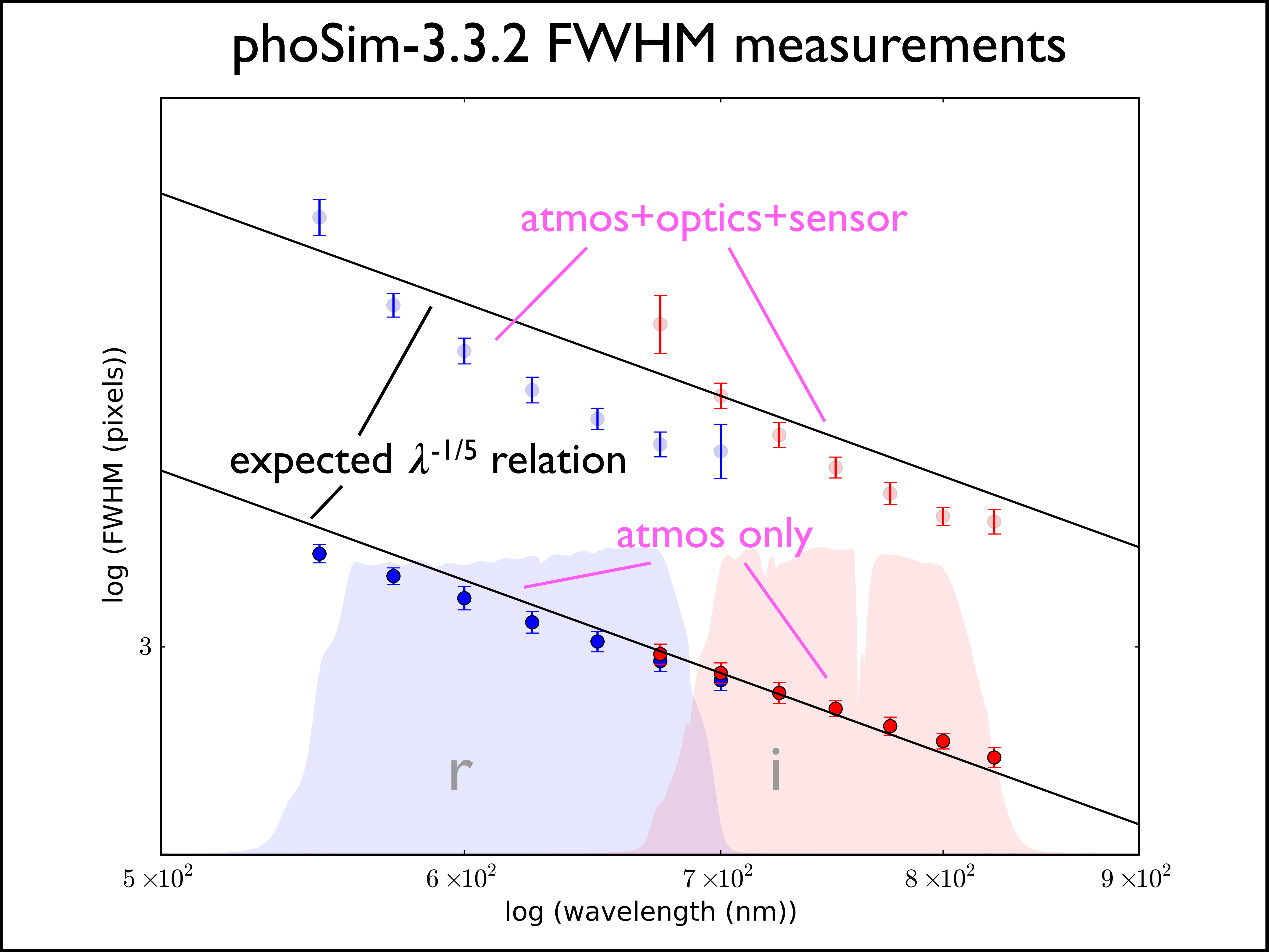


FIG. 5.—Mean value of spectral slope (β) for each night in 1999 with 10 or more scans. The error bars represent the 1 σ scatter about the mean value for that night. [*See the electronic edition of the Journal for a color version of this figure.*]

β	$1-2/\beta$
5/3	-0.2
1.45	-0.4
1.35	-0.5

Similar sub-Kolmogorov slopes found by Bester+92, Buscher+95, Colavita&Lane 2001, Short+03

Additional sources of chromatic PSF size changes



Corrections

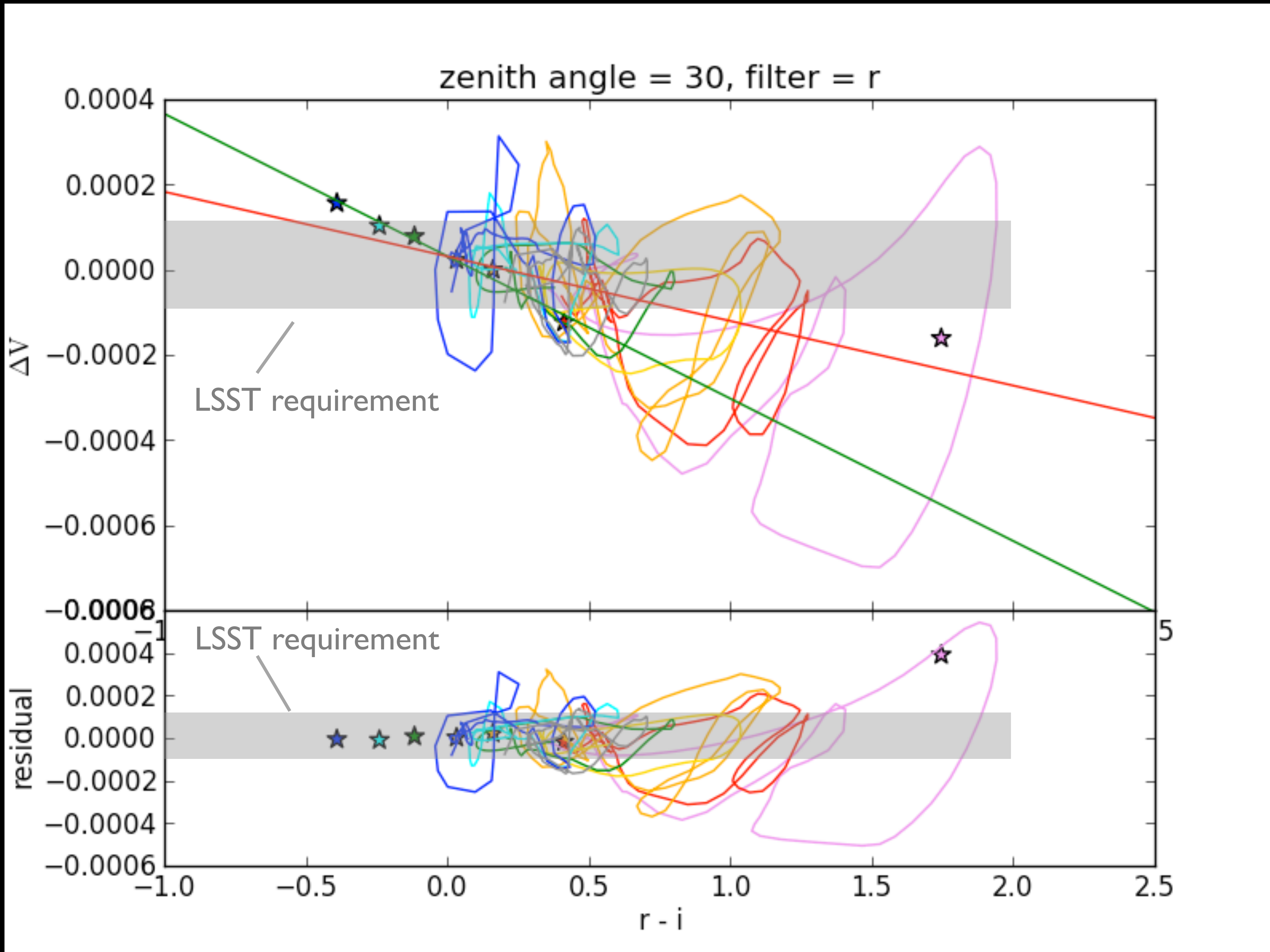
Can de-bias PSF measurements if SEDs are known

Use photometry to constrain SED

- similar to a photometric redshift
- however, no catastrophic outliers!

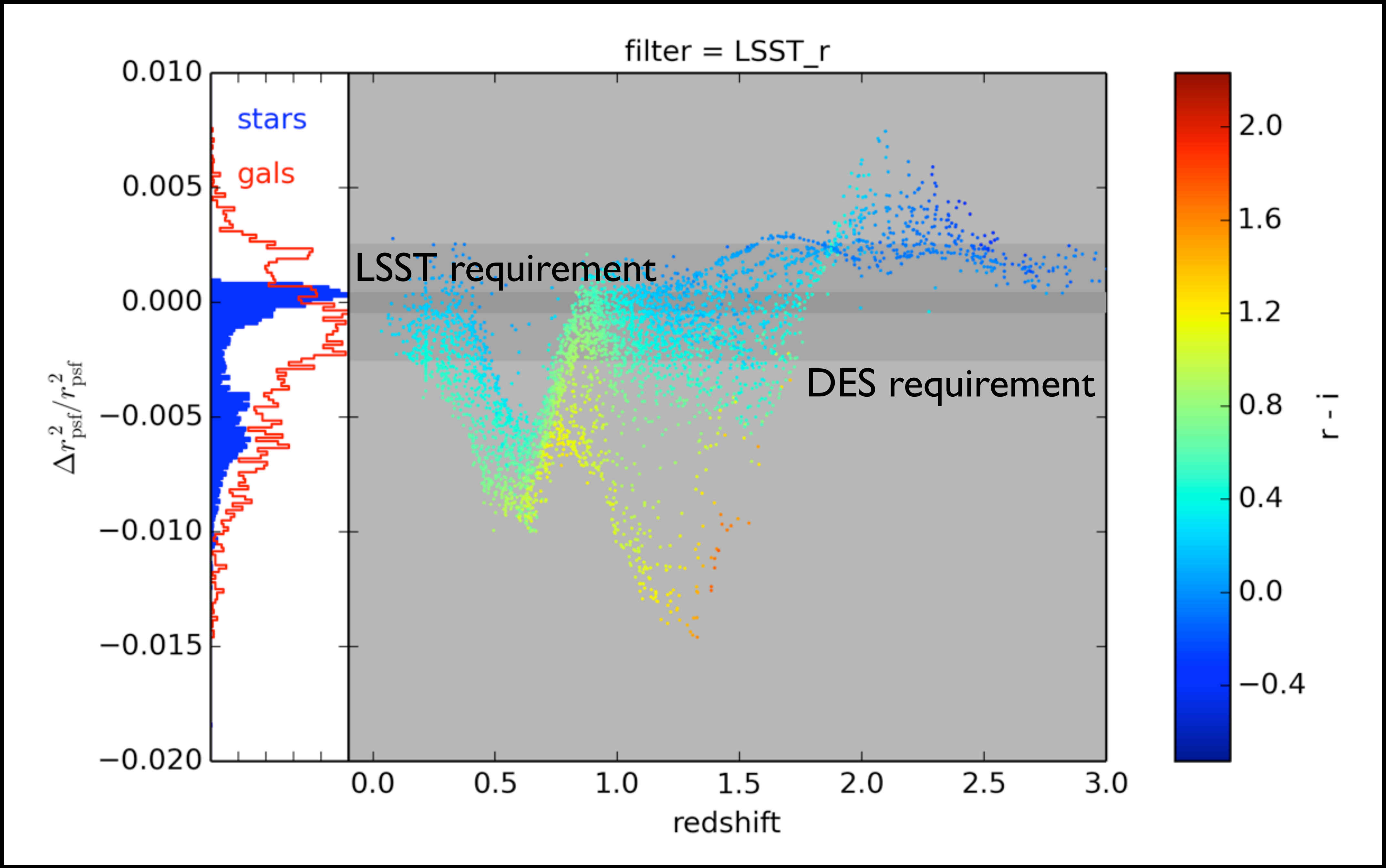
Correct second moment shift using color

cf. Plazas & Bernstein 2012



Correct chromatic biases using machine learning

- Can better constrain SED using all 6 LSST photometry points.
- Train support vector regression algorithm on LSST colors + i-band.



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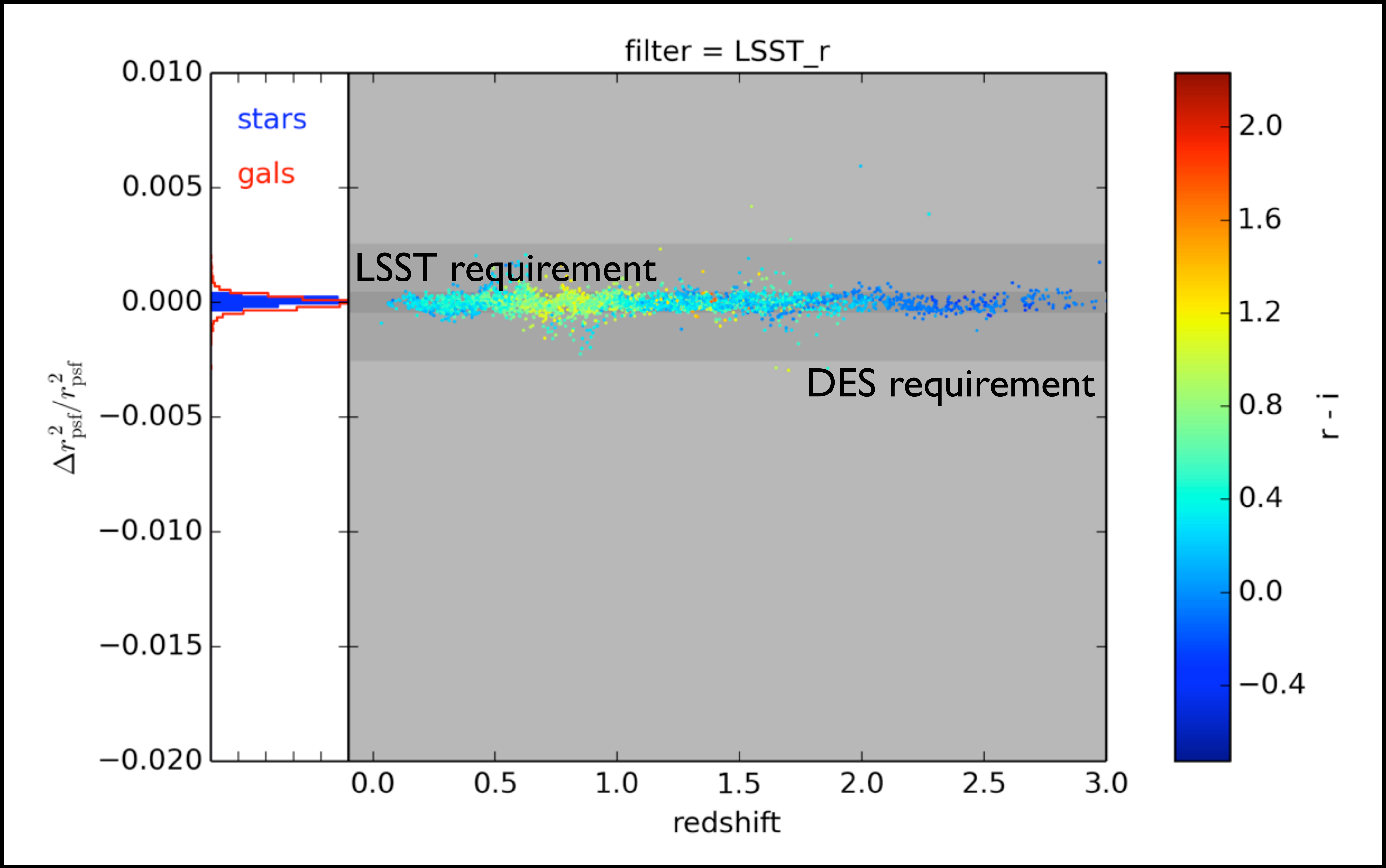
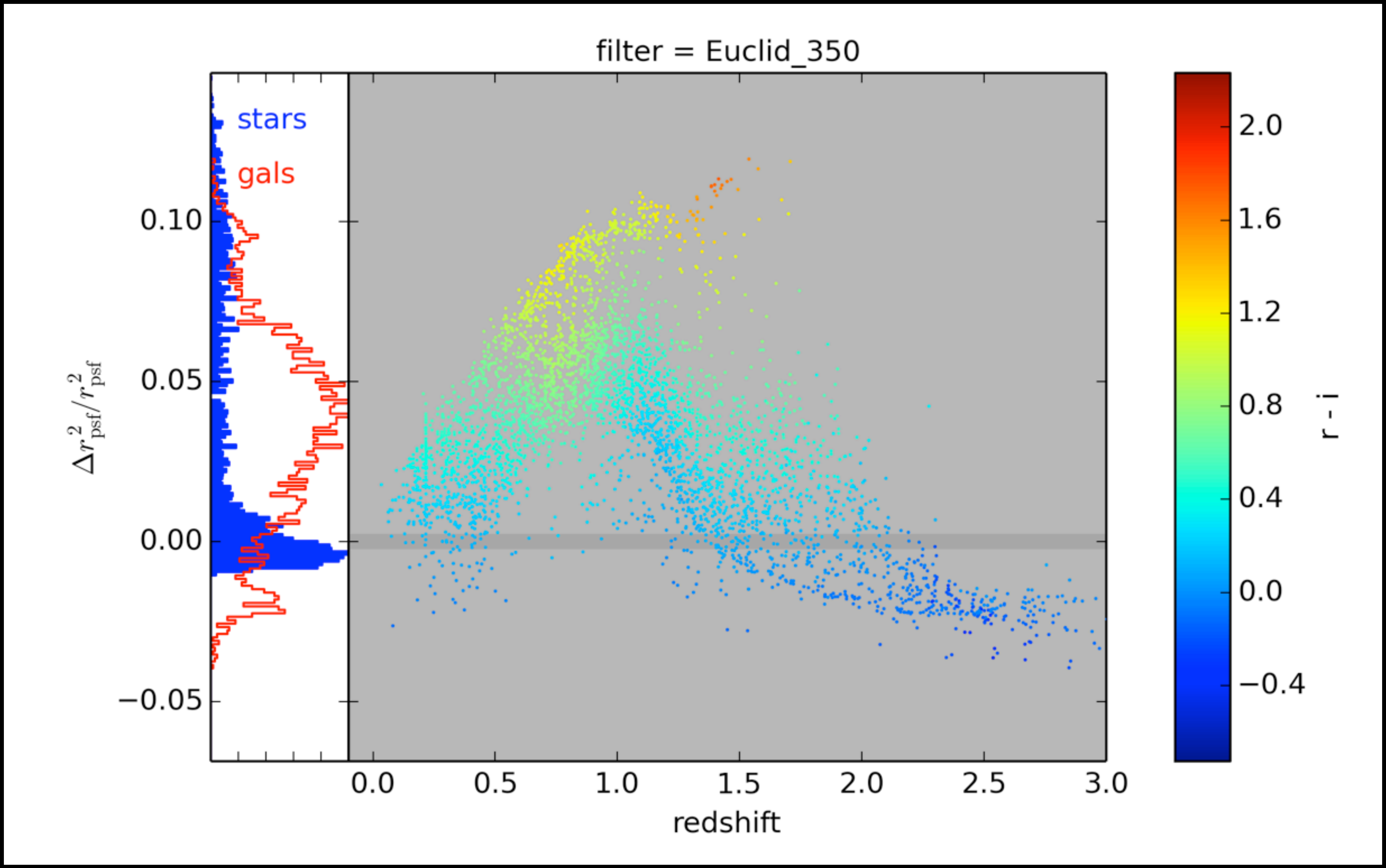


Correct chromatic biases using machine learning

- LSST photometry works really well at constraining Euclid chromatic biases
- LSST sky overlaps proposed Euclid sky by ~5000 square degrees



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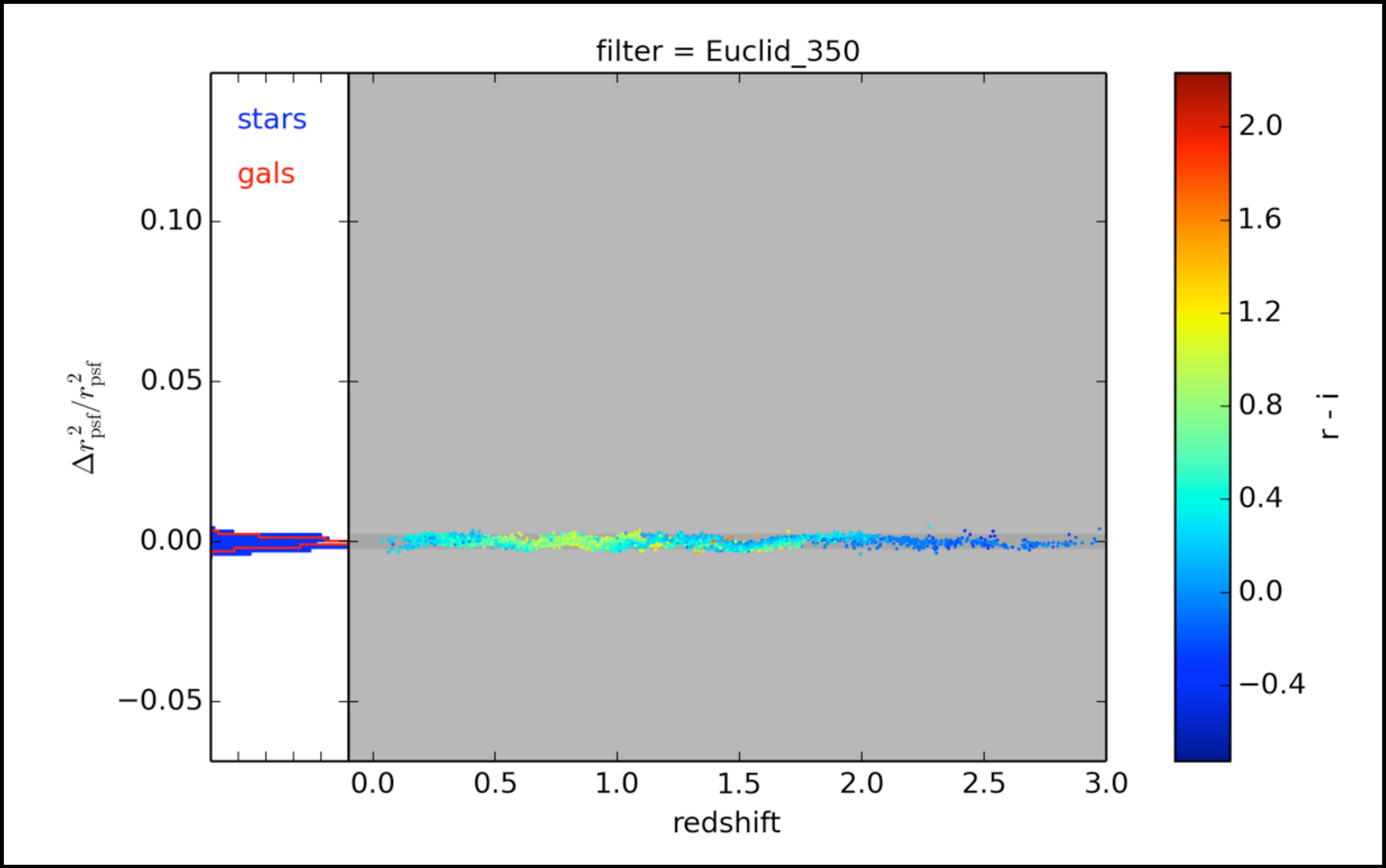
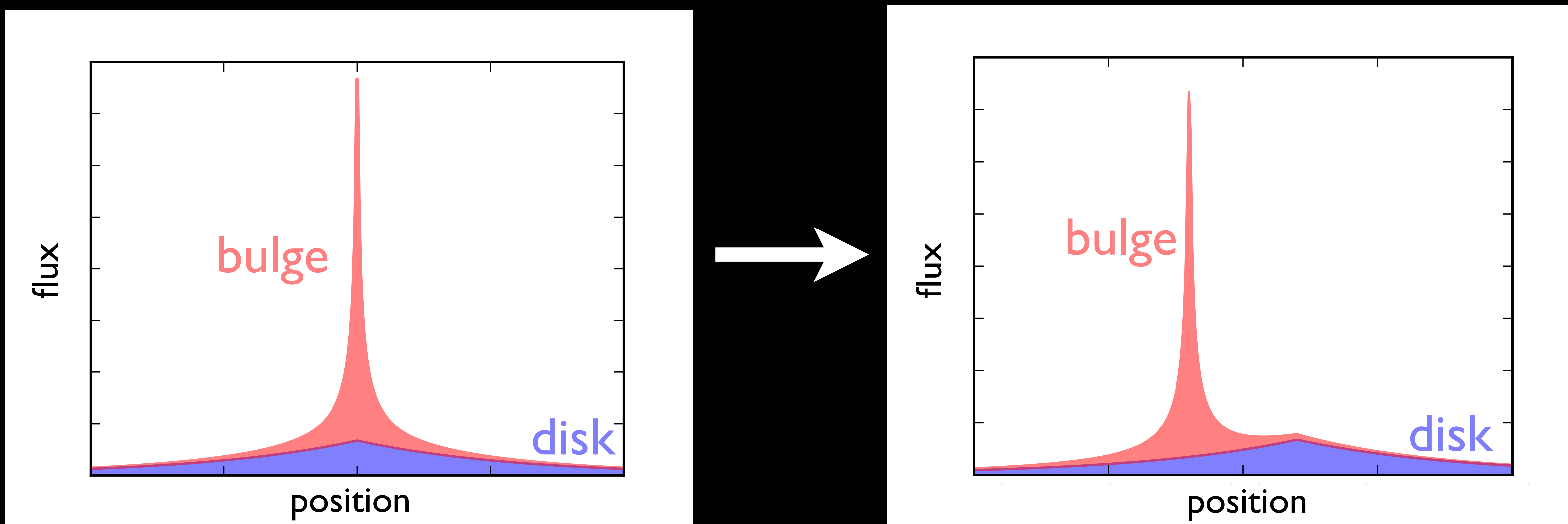
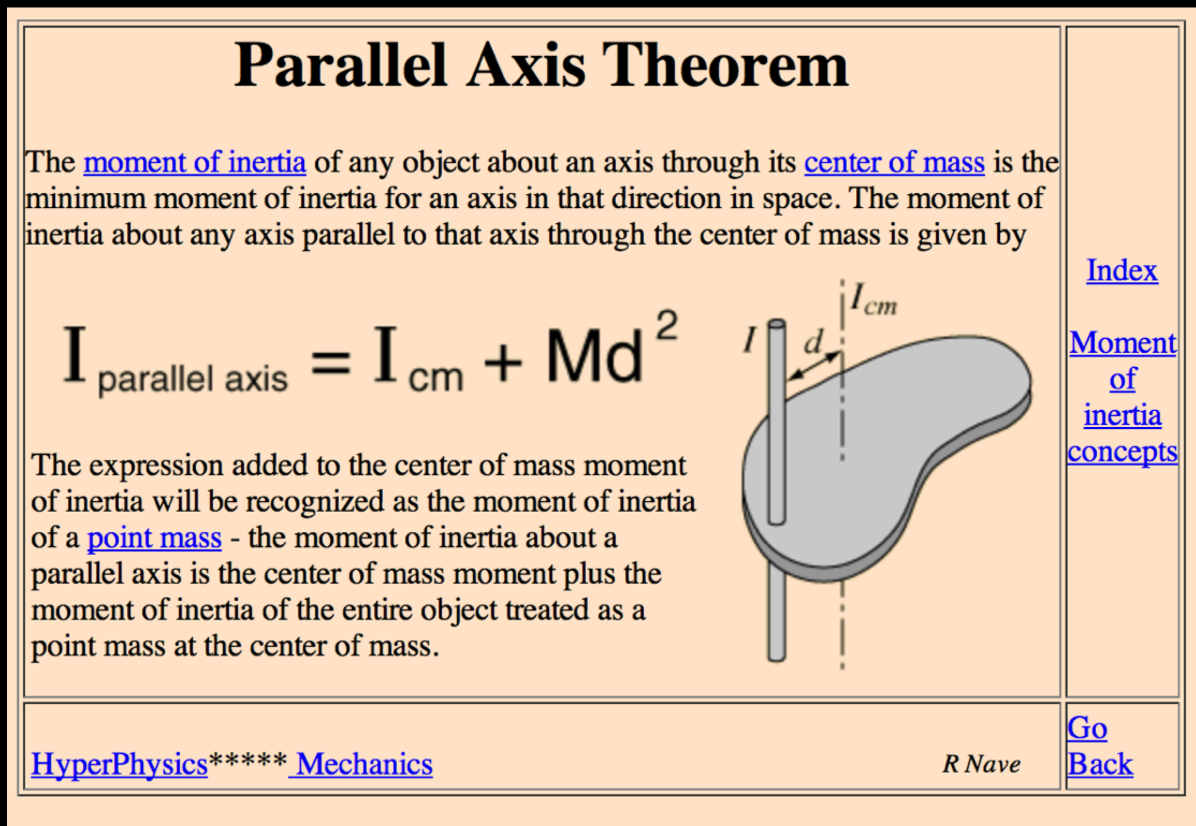


Galaxies with color gradients



- Let's pretend we know the composite bulge+disk SED perfectly. Then two effects are present:
    - bulge and disk separate spatially
    - would like to deconvolve bulge with bulge-PSF, and similarly the disk, but only have access to the composite bulge+disk PSF

Bulge+Disk separation: parallel axis theorem



Parallel Axis Theorem

The moment of inertia of any object about an axis through its center of mass is the minimum moment of inertia for an axis in that direction in space. The moment of inertia about any axis parallel to that axis through the center of mass is given by

$$I_{\text{parallel axis}} = I_{cm} + Md^2$$

The expression added to the center of mass moment of inertia will be recognized as the moment of inertia of a point mass - the moment of inertia about a parallel axis is the center of mass moment plus the moment of inertia of the entire object treated as a point mass at the center of mass.

Index

Moment of inertia concepts

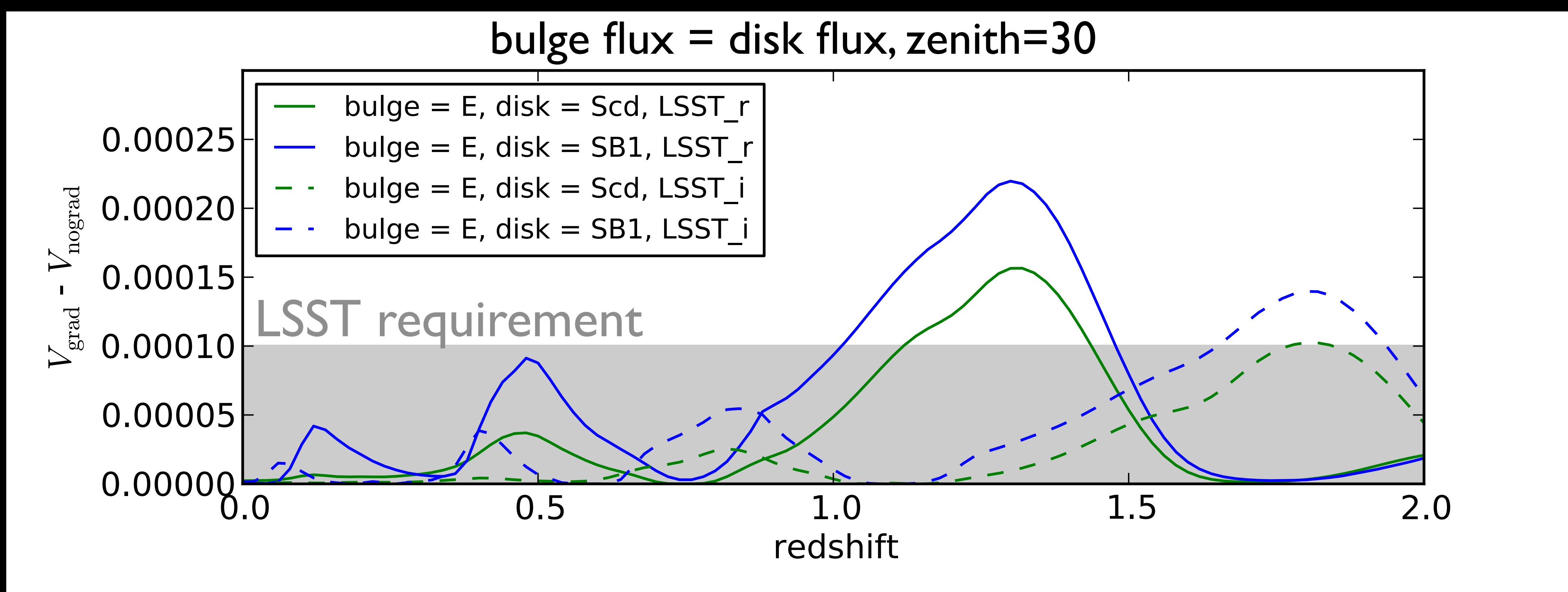
HyperPhysics***** Mechanics

R Nave

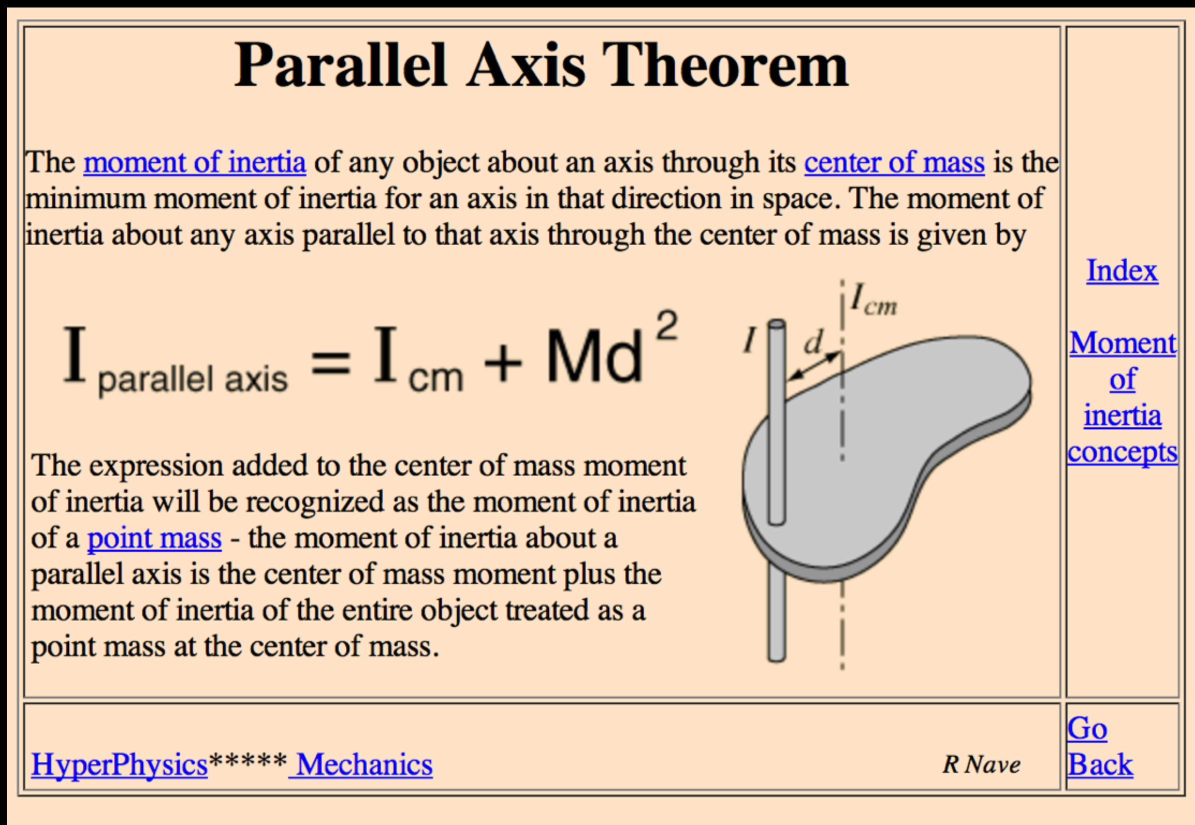
Go Back

$$R_c = f_b R_b + f_d R_d$$

$$V_{\text{grad}} = V_{\text{nograd}} + f_b(R_b - R_c)^2 + f_d(R_d - R_c)^2$$

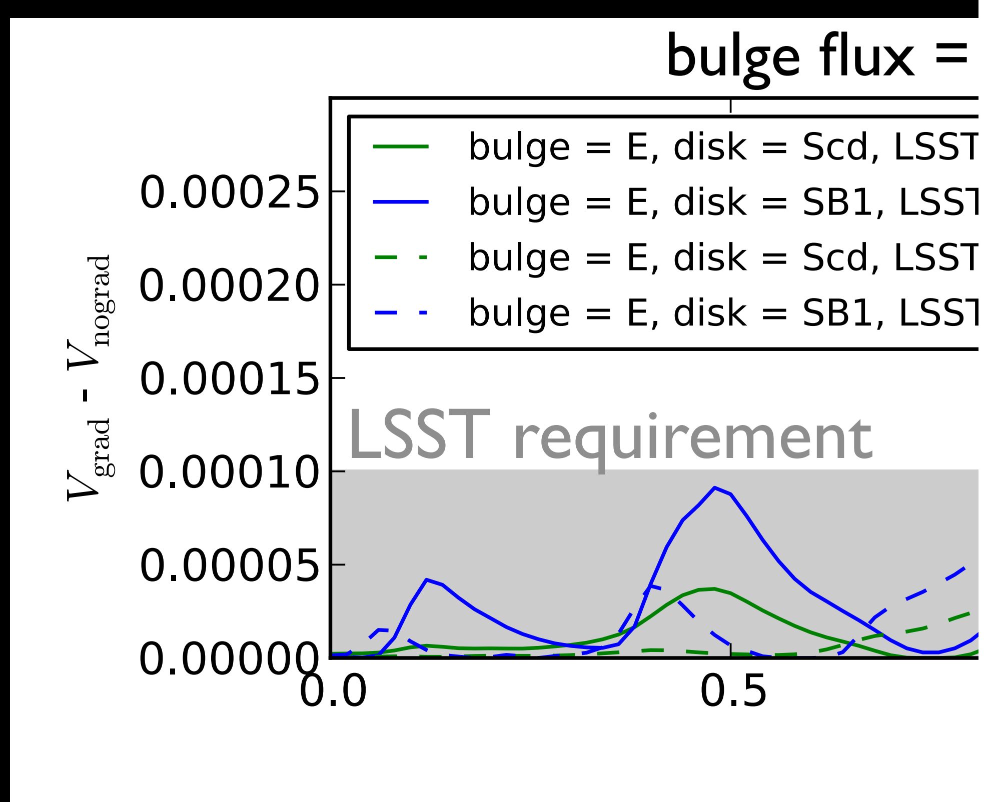


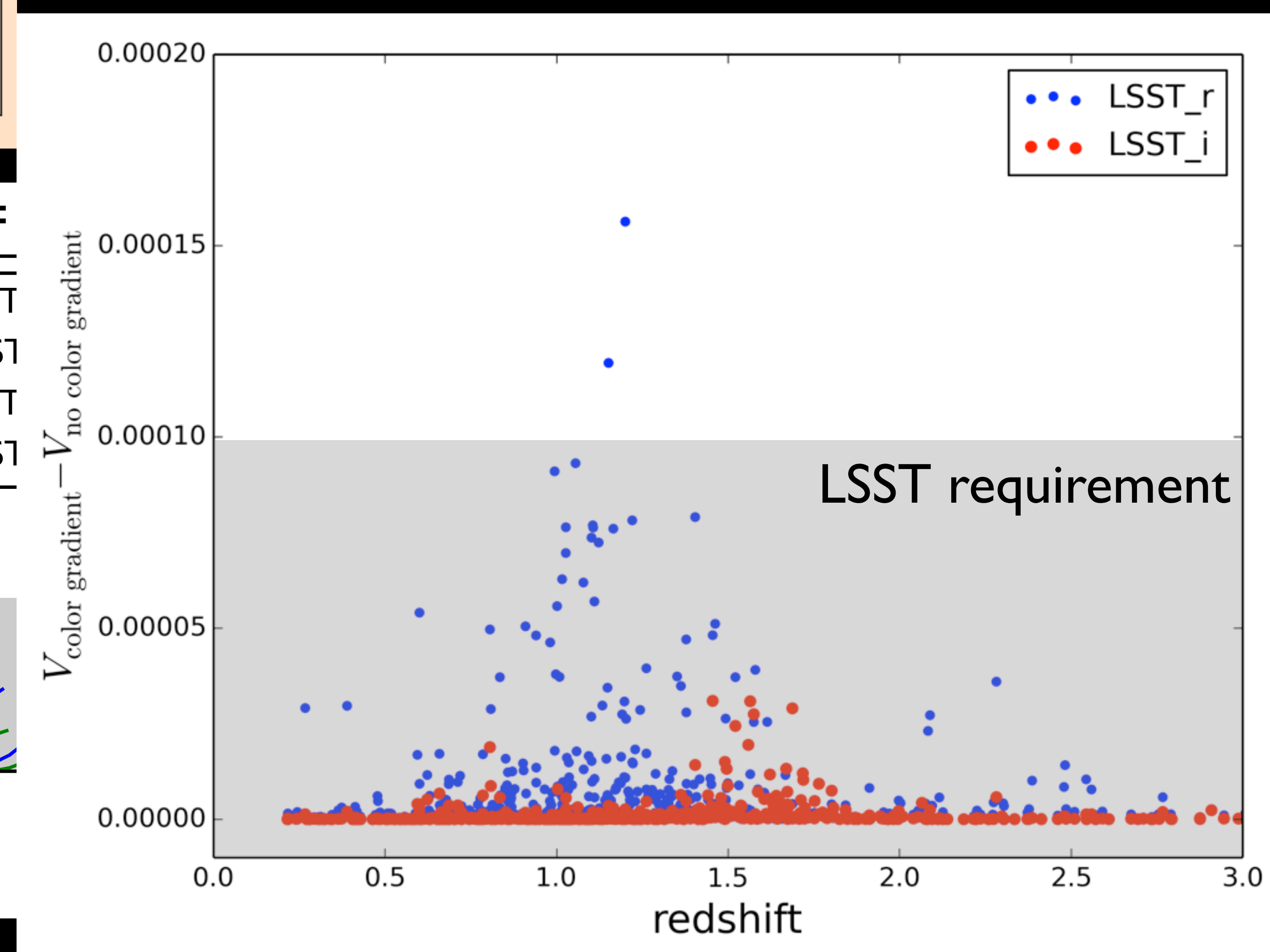
Bulge+Disk separation: parallel axis theorem



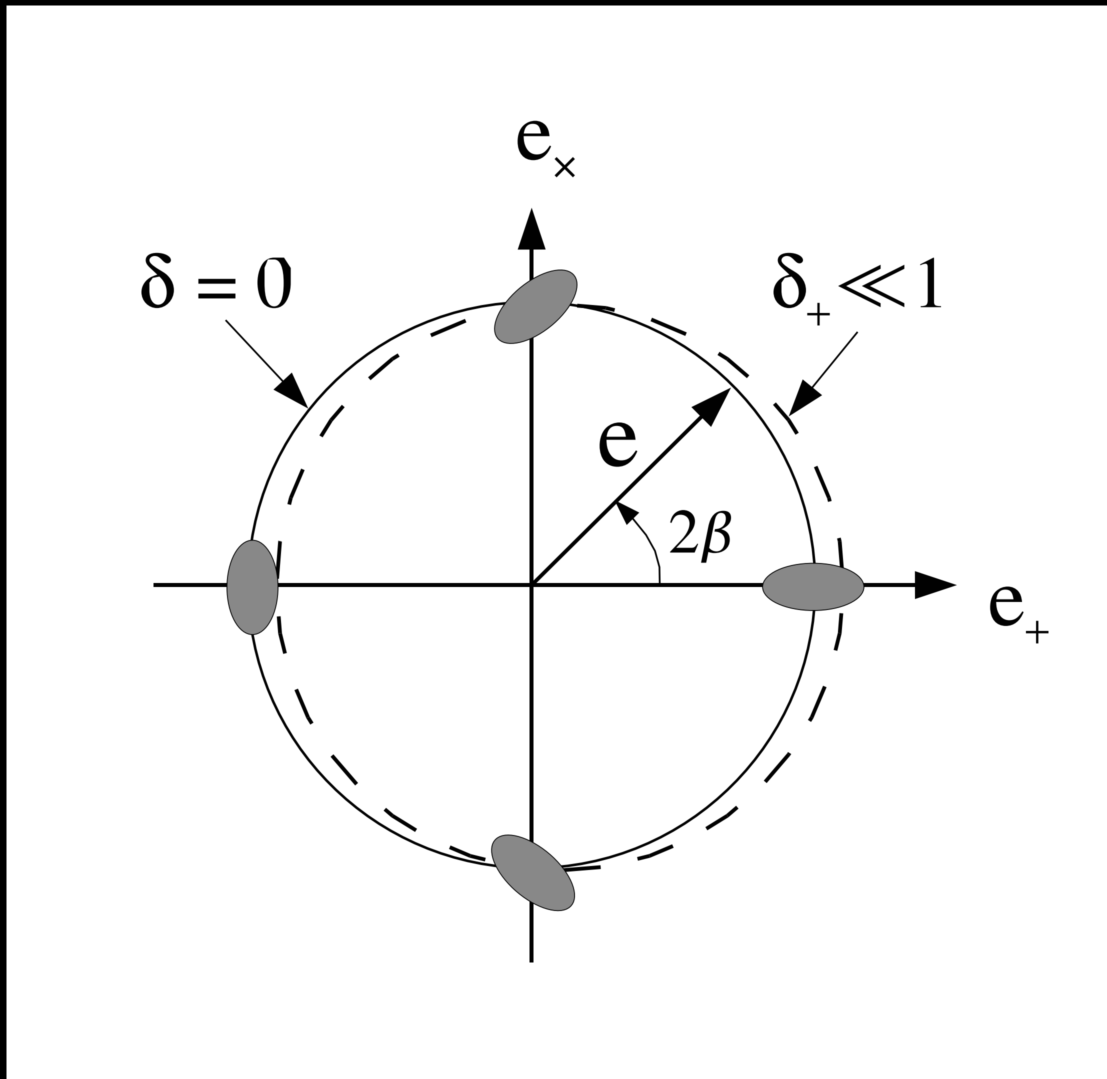
$$R_c = f_b R_b + f_d R_d$$

$$V_{\rm grad} = V_{\rm nograd} + f_b(R_b - R_c)^2 + f_d(R_d - R_c)^2$$





When analytic approaches are unavailable (e.g. color gradients)



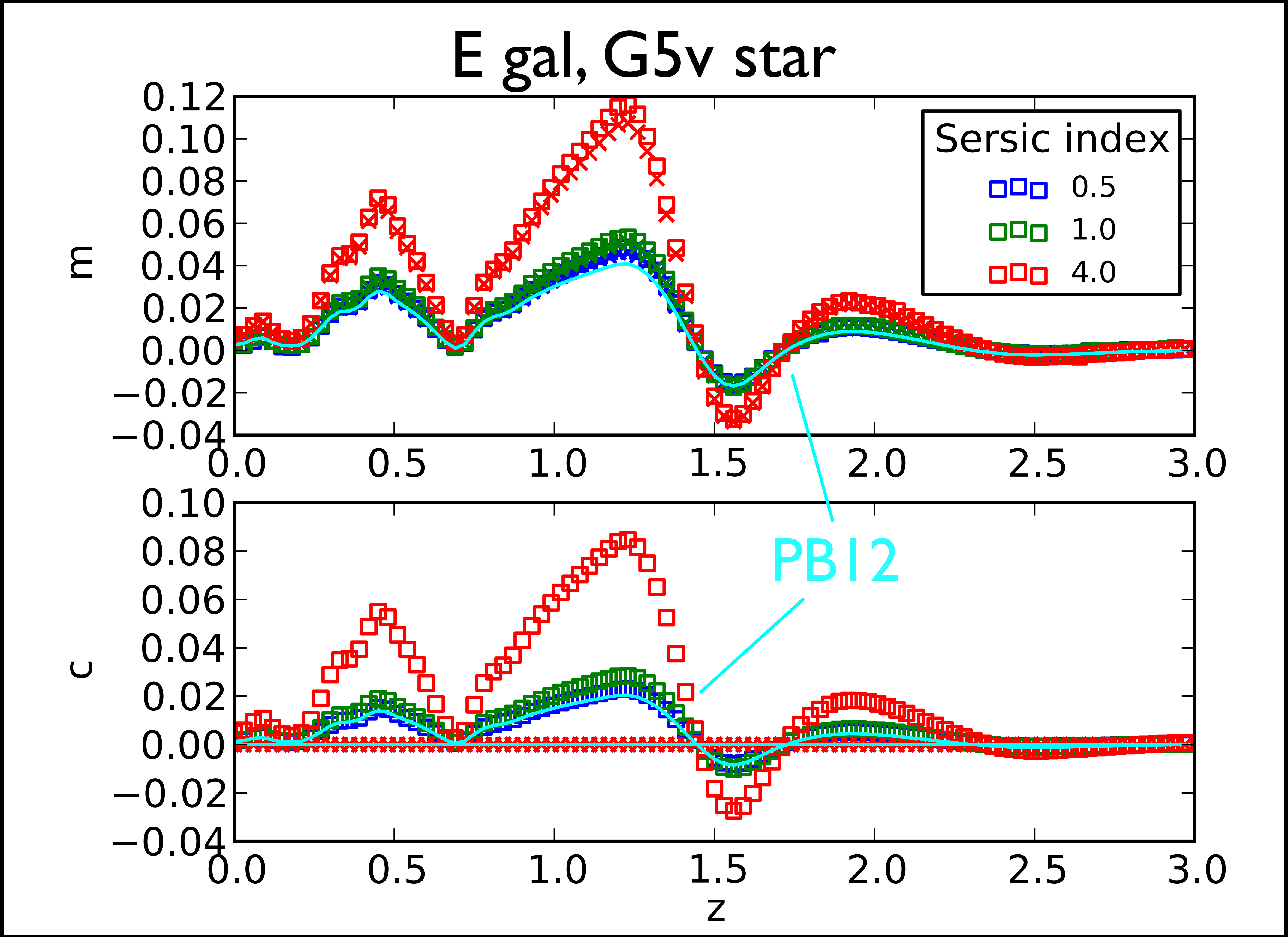
Nakajima & Bernstein 2007

Simulate and use a ring test!

- Simulate ring of galaxy observations using "true" PSF, all sheared same amount
- Measure ellipticities of sheared galaxies using (incorrect) inferred PSF
- Shear estimate is average of reconstructed ellipticities. Ring ensures that average pre-shear ellipticity is 0.
- Repeat for multiple shears and measure calibration parameters:

$$\hat{\gamma} = \gamma^t(1 + m) + c$$

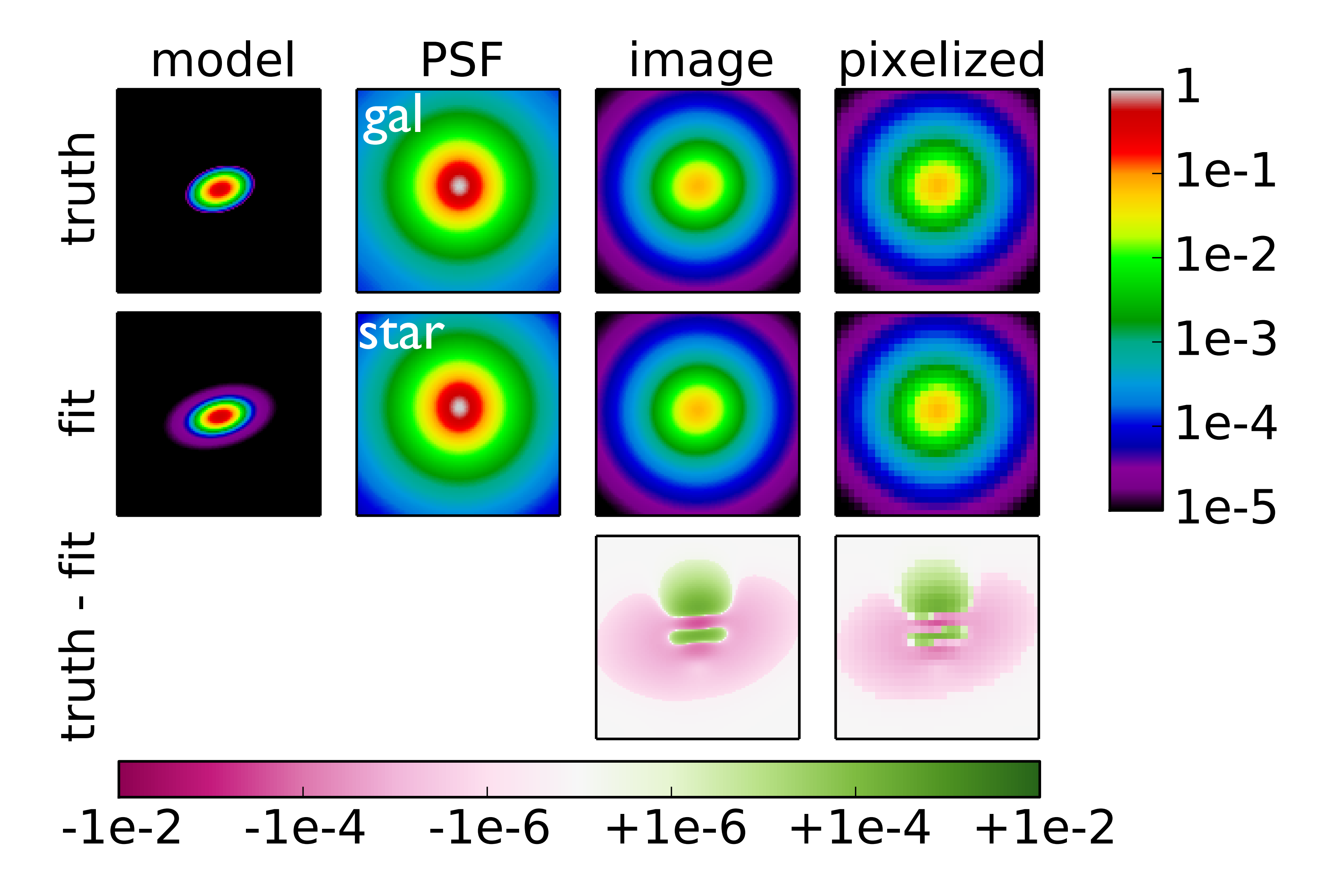
Ring test results for Sersic gals and DCR



Model fitting bias

Gaussian n=0.5

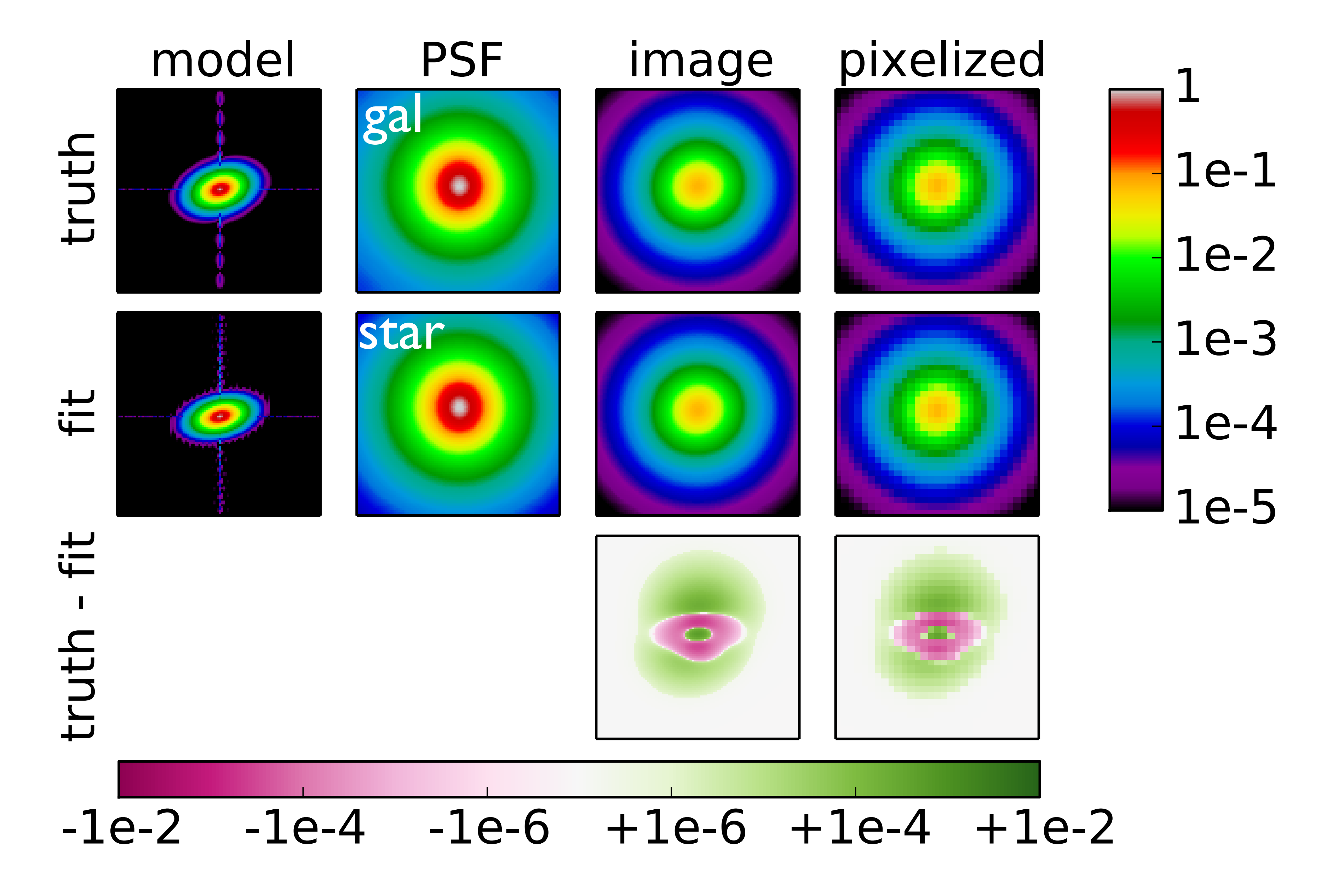
Residuals grow with increasing Sersic index



Bias comes from improper modeling of PSF, not galaxy

Model fitting bias

Exponential n=1.0



Residuals grow with increasing Sersic index

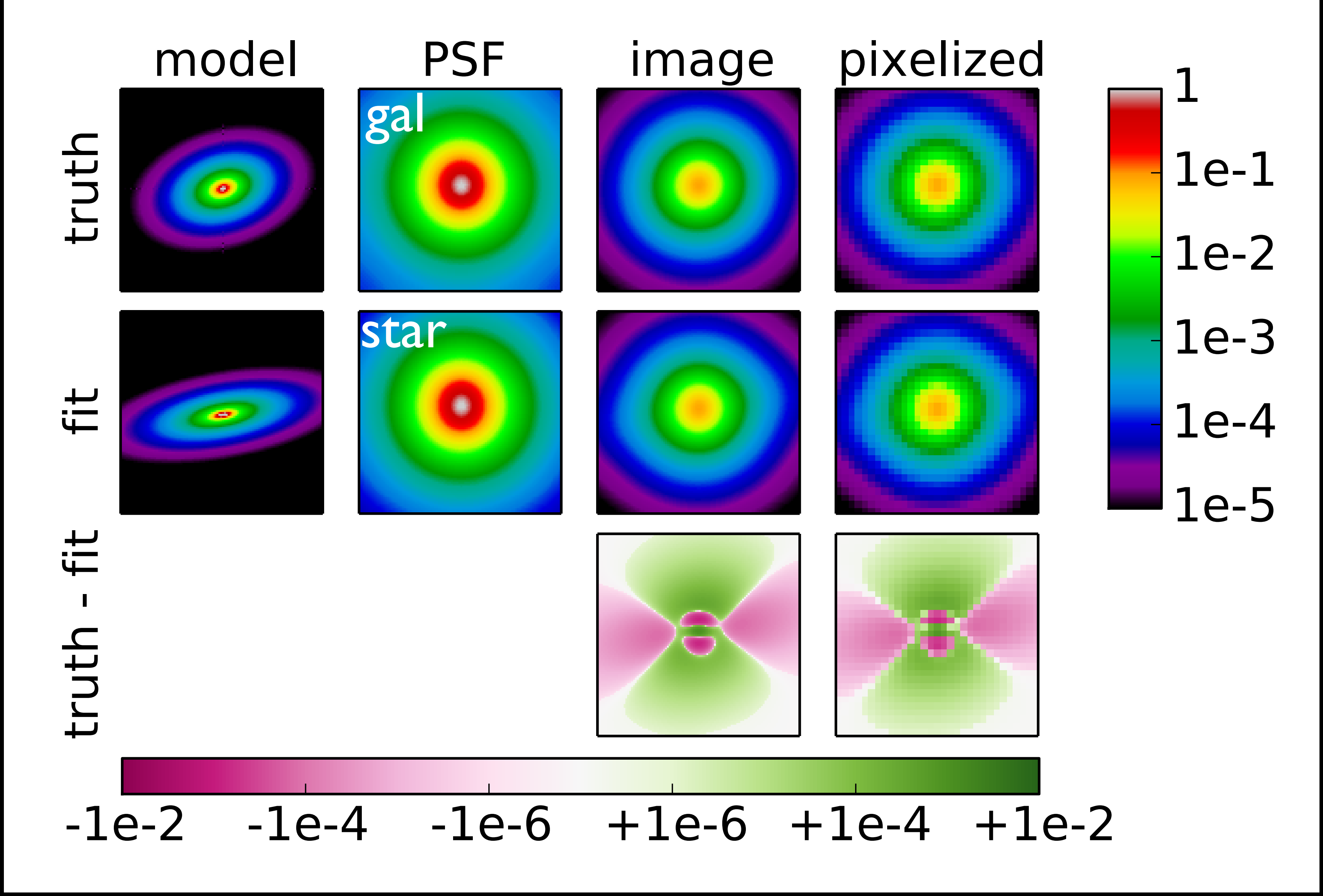
Bias comes from improper modeling of PSF, not galaxy

Model fitting bias

de Vaucouleurs n=4.0

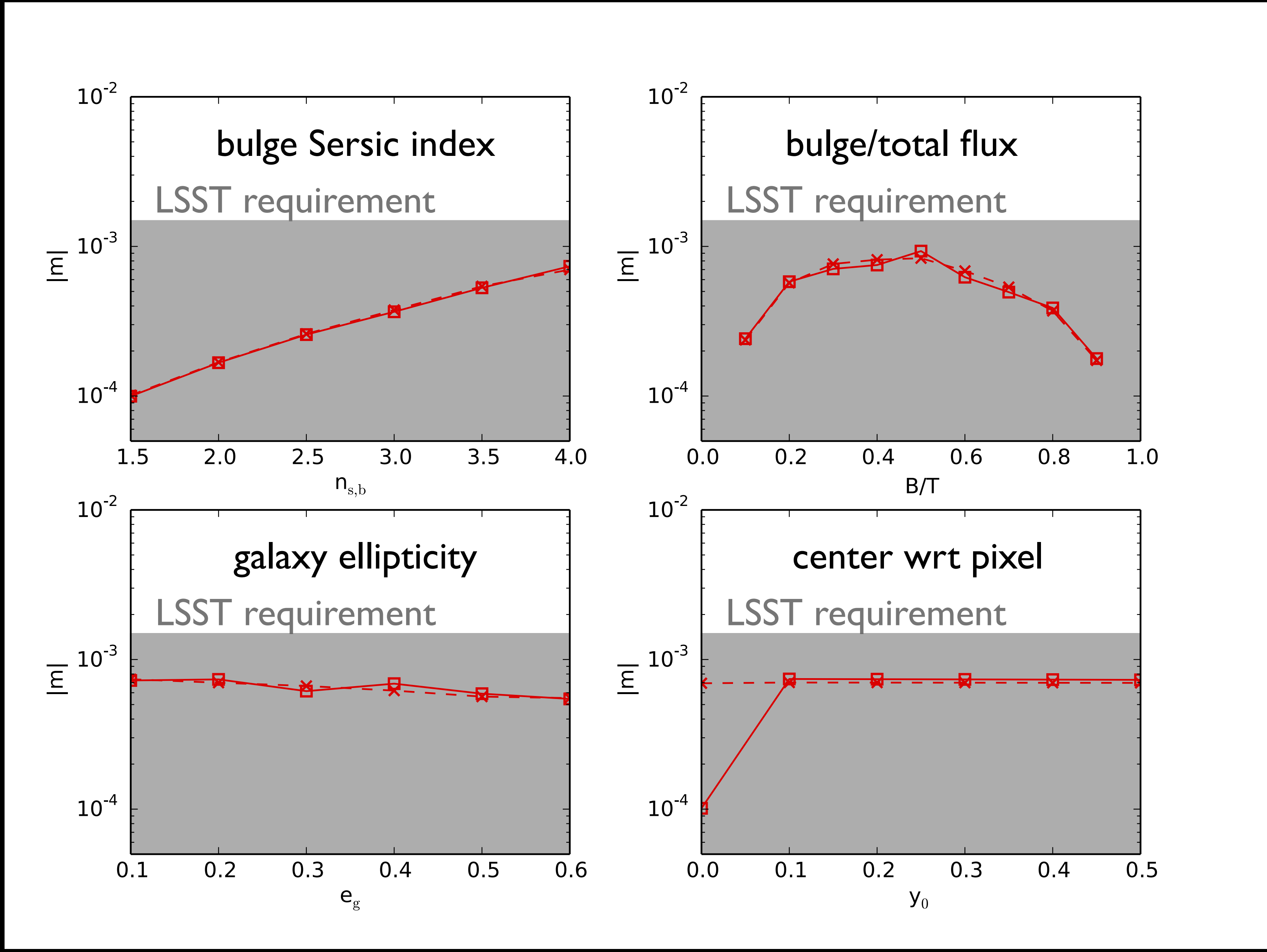
Residuals grow with increasing Sersic index

Bias comes from improper modeling of PSF, not galaxy



Preliminary: toy model not sensitive to color gradients?

- Implement chromatic seeing and DCR with GalSim
- Similar to Voigt+12 study for Euclid
- Fiducial parameters (from Simard +2002 catalog):
    - second-moment radius = 0.27”
    - $r_{e,B}$ / $r_{e,D}$ = 1.1
    - n_B = 4, n_D = 1
    - z = 0.9
    - disk spec = Sbc, bulge spec = E
    - B/T = 0.25
    - $|e_g|$ = 0.2
- sufficient catalog?
- what about realistic galaxies?



Final thoughts

DCR depends on zenith angle and filter, chromatic seeing does not

Orders of magnitude for LSST chromaticity

	DCR (r-band)	DCR (i-band)	seeing
m	$\sim 10^{-2.5}$	$\sim 10^{-3}$	$\sim 10^{-1.5}$
c	$\sim 10^{-3}$	$\sim 10^{-3.5}$	~ 0

What next?

- Chromatic effects in optics and sensors
- Measure effects in real data (stellar FWHM vs color?)
- Galaxy color gradients (especially a realistic catalog)