Instrumental Calibration

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Flux calibration: “Metrology, Meteorology, and Mie Scattering”

Galactic scattering

$$\phi(i,j) = \sum_{sources} \int S(\lambda) A(\lambda) G(\lambda) T(\lambda)\, d\lambda$$

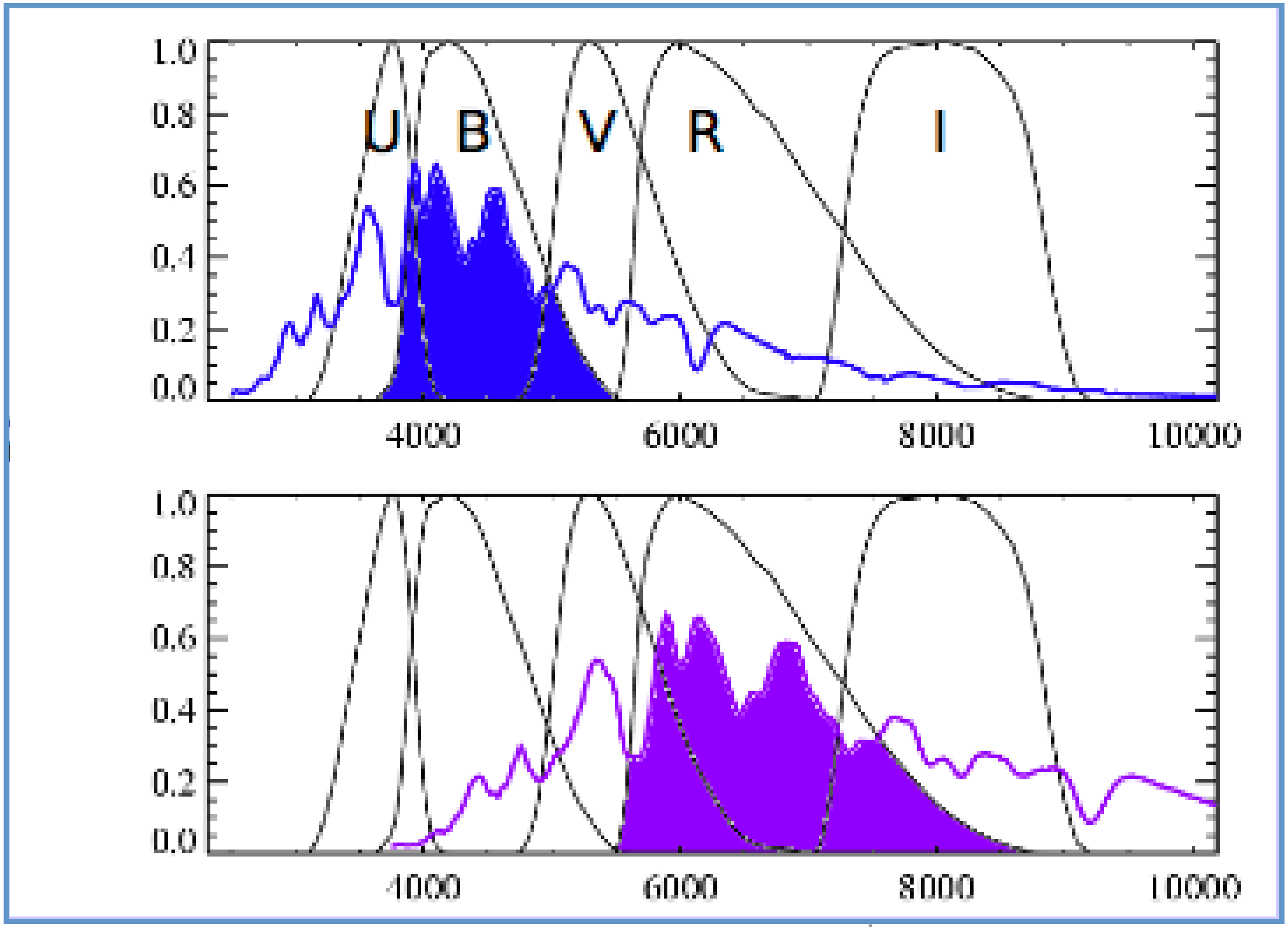
Source Atmosphere Instrumental transmission

Five aspects to the photometry calibration challenge:

1. *Determination of relative instrumental throughput*
2. *Absolute instrumental calibration (I claim this this is far less important for cosmology)*
3. *Determination of atmospheric transmission (dedicated facility for this, Aux Tel)*
4. *Determination of Galactic extinction (most stars lie behind the extinction layers)*
5. *Correction of sensor artifacts (BFE, pixel distortions, crosstalk, overshoot….).*

Historical approach has been to use spectrophotometric sources (known S(λ)) to deduce the instrumental and atmospheric transmission, but this (on its own) is problematic: integral constraints are inadequate, plus we don’t know the source spectra to the requisite precision.

Passbands and System Sensitivity



We should strive to achieve mmag precision in flux determination

Fractional change in SN brightness

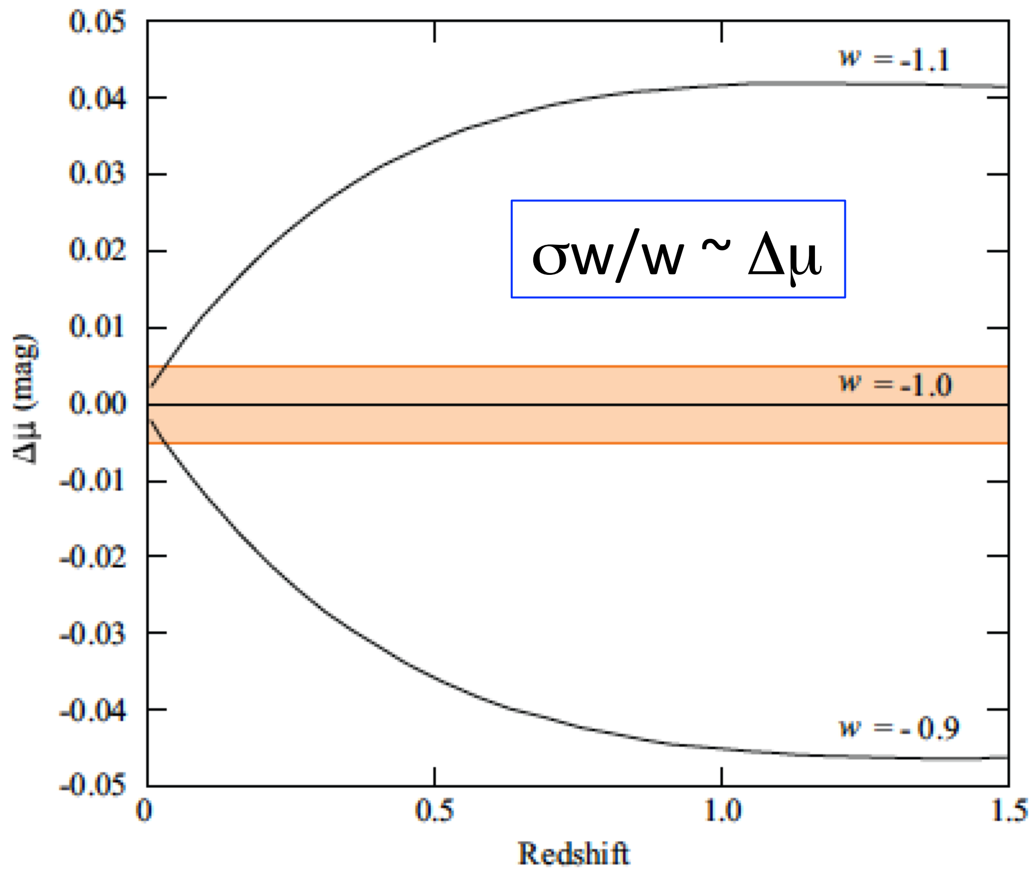


Fig. 2. (color online) Dependence of luminosity distance, in magnitudes, on the equation of state parameter w, vs. redshift. Contemporary observations constrain the equation of state parameter to lie within 10% of $w = -1$ and so achieving substantially better constraints requires sub-percent precision in flux measurements. A magnitude difference of 0.01 corresponds to a 1% flux change. The orange bar represents an uncertainty of 1%.

Precise astronomical flux calibration and its impact on studying the nature of the dark energy, Stubbs & Brown, MPLA **30**, No. 40 (2015)

Doing so requires metrology at the part-per-thousand level

Potential flux standards:

1. Theoretical models of DA white dwarf stars (The CalSpec approach)
2. Well-calibrated detectors (Stubbs & Tonry, 2006)
3. Well-calibrated sources of illumination (pure blackbody…)
4. Statistical aggregate of stellar flux models (SLR-like approach)
5. Calibrated narrowband celestial sources (PNe, emission line galaxies)

Three pathways:

1. Determine $T(\lambda)$ directly, in the dome, using laboratory standards
2. Transfer knowledge of terrestrial standard onto celestial sources (Vega approach)
3. Ab-initio knowledge of celestial SED. DA/Calspec approach.

Any observations of celestial sources for instrumental calibration will require compensation for atmospheric attenuation, which is not yet a solved problem.

THE ASTROPHYSICAL JOURNAL, **197**:593–601, 1975 May 1

A REDISCUSSION OF THE ATMOSPHERIC EXTINCTION AND THE ABSOLUTE SPECTRAL-ENERGY DISTRIBUTION OF VEGA

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ABSTRACT

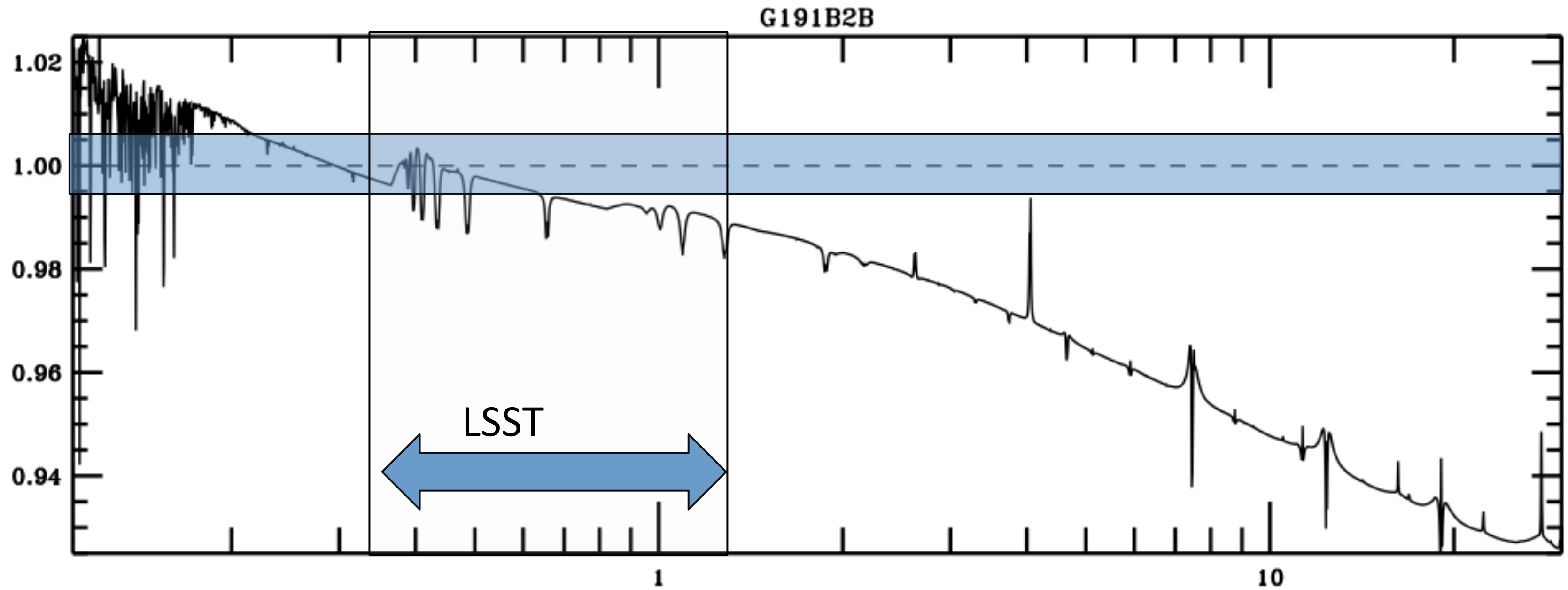
For both the Lick and the Palomar calibrations of the spectral-energy distribution of Vega, the atmospheric extinction was treated incorrectly. We present a model for extinction in the Earth's atmosphere and use this model to calculate corrections to the Lick and Palomar calibrations. We also describe a method that can be used to fabricate mean extinction coefficients for any mountain observatory.

We combine selected portions of the corrected Lick and corrected Palomar calibrations with the new Mount Hopkins calibration to generate an absolute spectral-energy distribution of Vega over the wavelength range 3300–10,800 Å. Until better measurements become available, we recommend the use of this calibration for all practical applications.

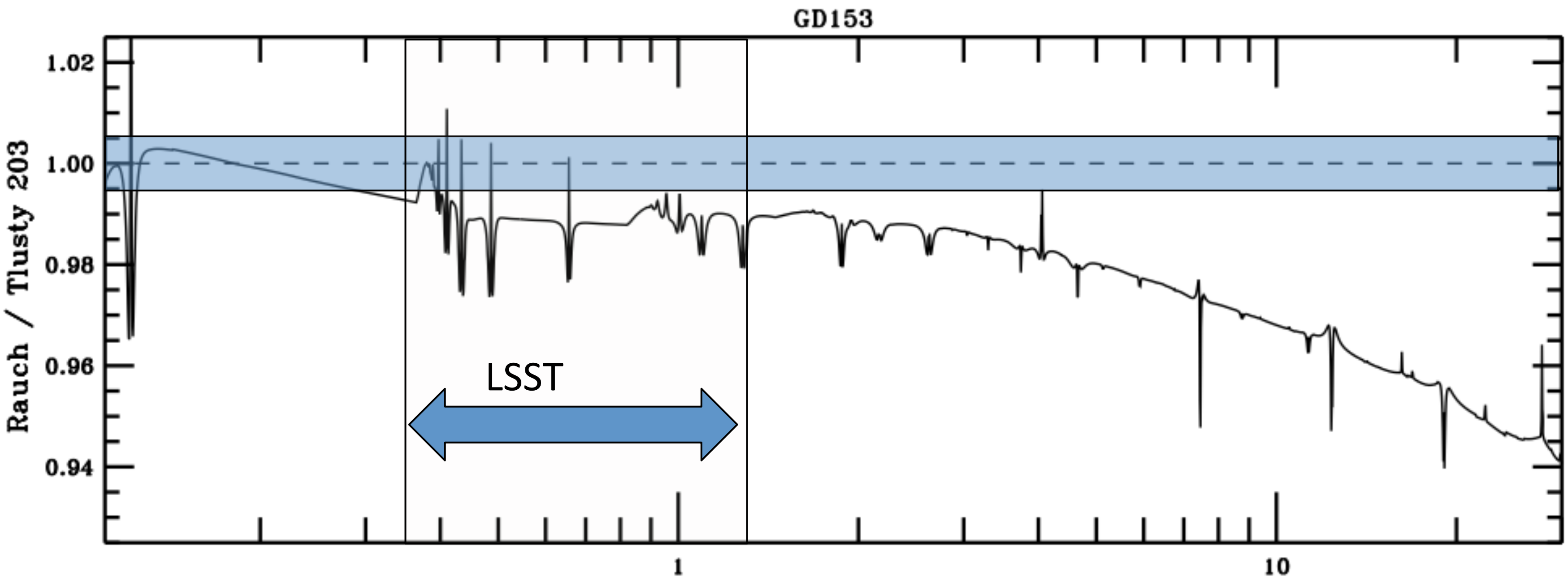
Subject headings: atmospheres, terrestrial — spectrophotometry — stars, individual

water vapor absorption and subtracting the extinction due to Rayleigh scattering and ozone. Both these last two parameters can be calculated with an accuracy of about ± 0.01 mag (air mass)$^{-1}$ for wavelengths between 3300 and 10,800 Å, by using equations (1) and (2). With this procedure, we have analyzed the observed mean extinction coefficients for the Boyden and Le Houga Observatories (Irvine and Peterson 1970), Cerro Tololo Inter-American Observatory (Gutiérrez-Moreno, Moreno, and Stock 1967; Gutiérrez-Moreno and Moreno 1970), Lick Observatory (Hayes 1967, 1970, 1974), Mount Hopkins (Latham and McCargar 1975), and Mount Lemmon (Dunkelman and Scolnik 1959). In each case, α was determined from linear fits on log-log plots of the aerosol extinction versus wavelength. The resulting values for α are given in table 1, along with the observatory, limiting dates, wavelengths covered, and number N of nights reported (except in the case of Cerro Tololo, where N is the number of monthly means). The mean of α for the stellar observations, weighted approximately by the number of nights, is 0.81. We cannot explain why the solar observations at Mount Lemmon and Mount Hopkins give a much larger value of α, and we have arbitrarily adopted $\alpha = 0.8$ as appropriate for nighttime photometric conditions. This value is smaller than those quoted in the literature on atmospheric aerosols, which usually refer to lower altitudes and poorer transparency point blackbody for 3300–10,800 Å. For the platinum blackbody, Oke and Schild adopted a temperature 6 K below the standard freezing point of platinum in order to get agreement with their other sources, thus destroying the value of the platinum blackbody as a fundamental source. Furthermore, they quote an uncertainty of 5 percent, which is two or three times worse than the uncertainties they quote for the lamp and copper blackbody results. Because of these two problems, we have rejected all their platinum blackbody data. Their absolute fluxes for Vega from their lamp and copper blackbodies agree within 0.01 mag at the four shorter overlap wavelengths (6050, 6370, 6800, and 7100 Å), but the lamp data drop off at the two longest wavelengths of the lamp calibration (7550 and 8080 Å) by as much as 0.06 mag. A similar drop-off appears when the Palomar lamp results are compared with the Lick and Mount Hopkins calibrations. Therefore, we have rejected the Palomar lamp data at 7550 and 8080 Å. The Lick calibration was judged to be poorly determined at the extreme wavelengths 3200, 3250, and 10,870 Å, and these points were therefore rejected.

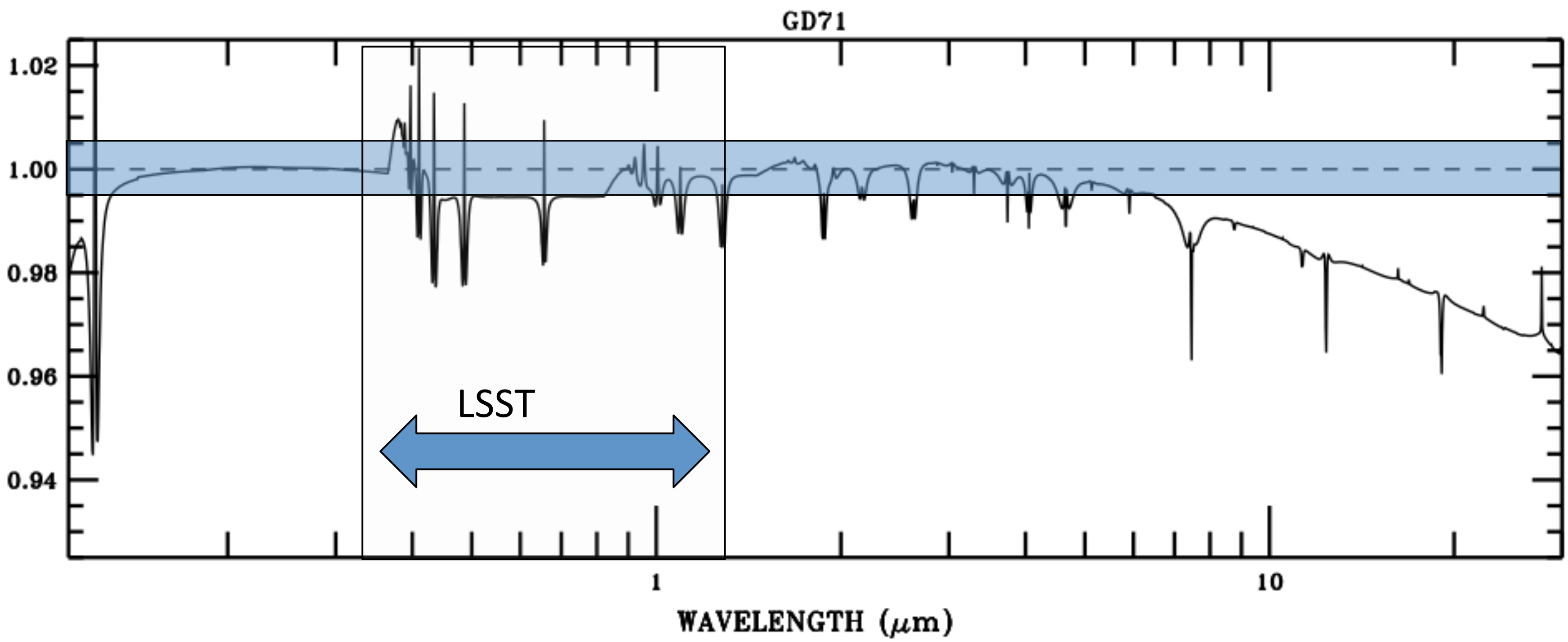
G191B2B- white dwarf with metal pollution



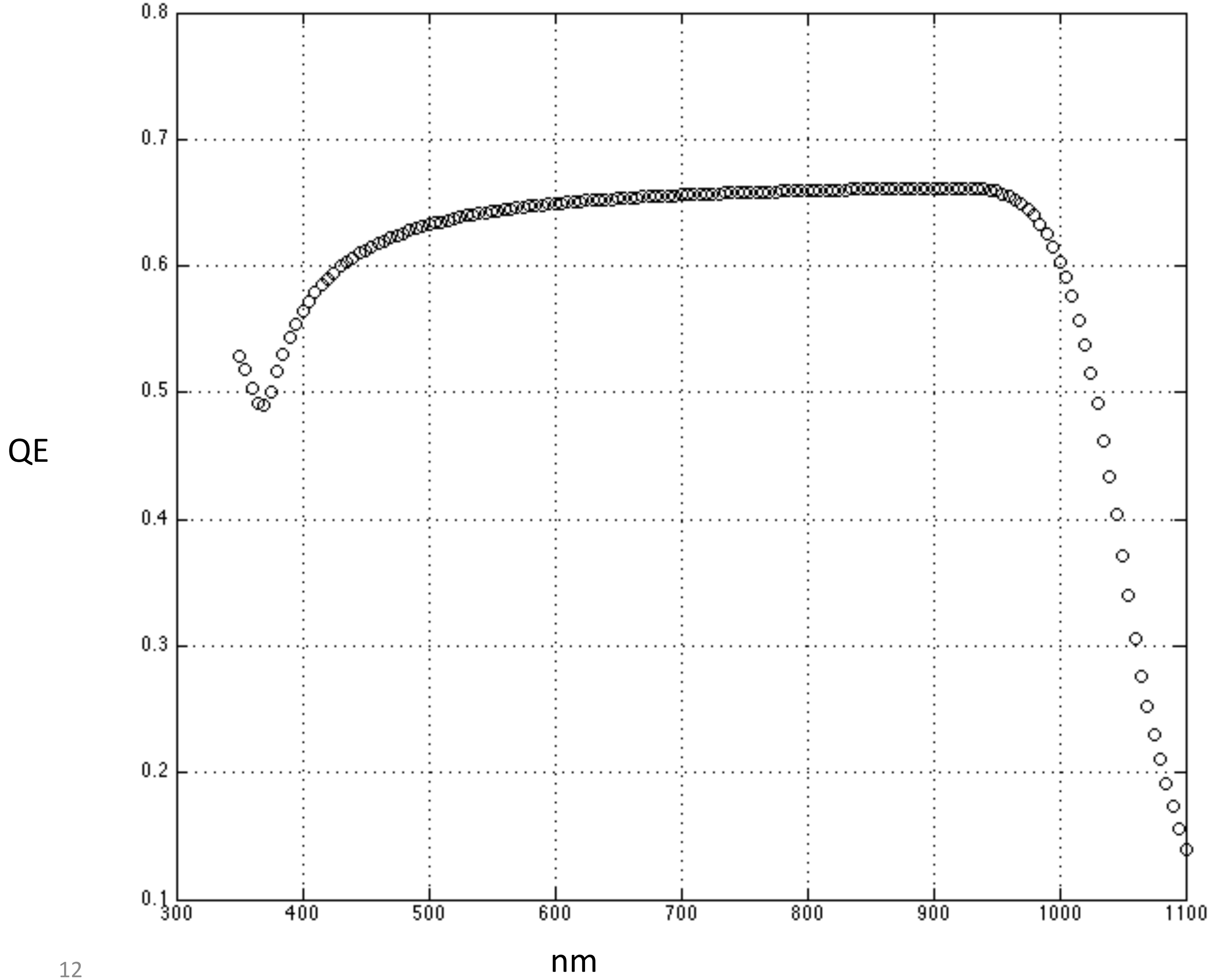
GD153



GD 71



NIST-calibrated Si photodiodes are the *only* relevant standards at 10^{-3} level



From Tonry et al, ApJ **750**, 99 (2012)

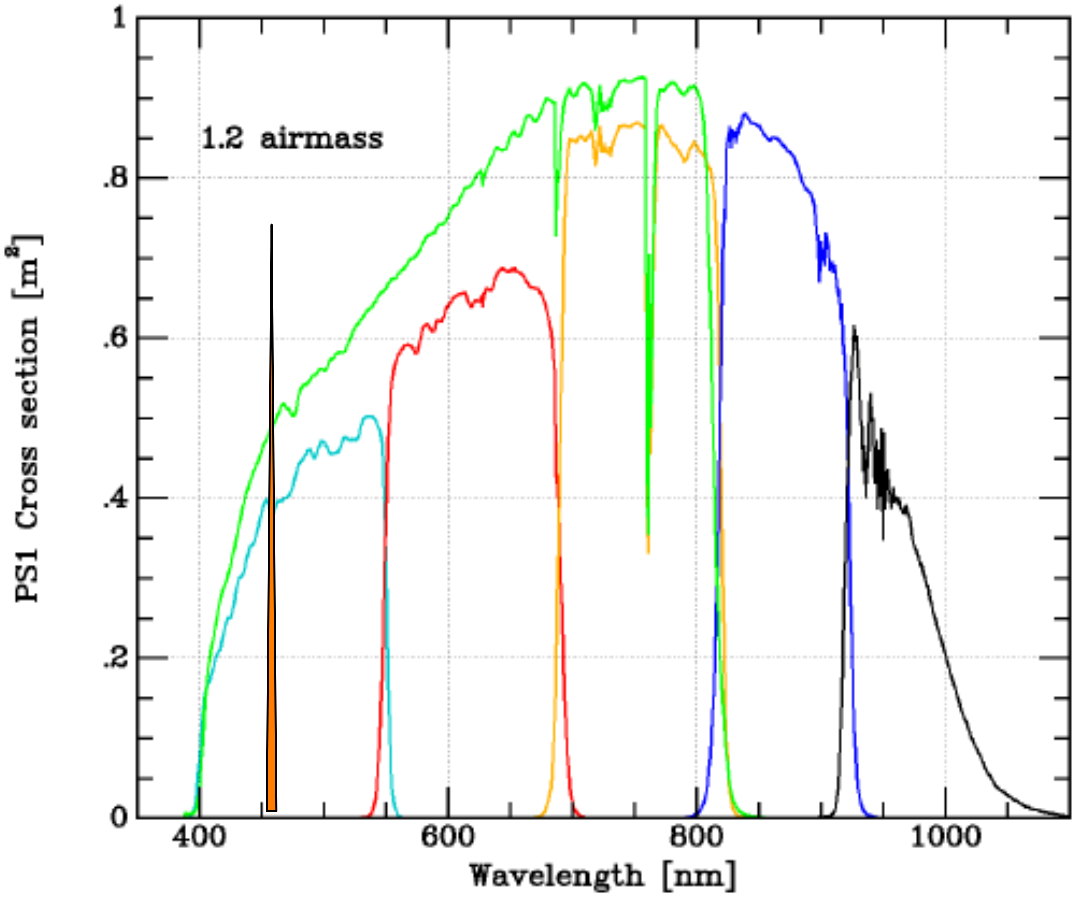
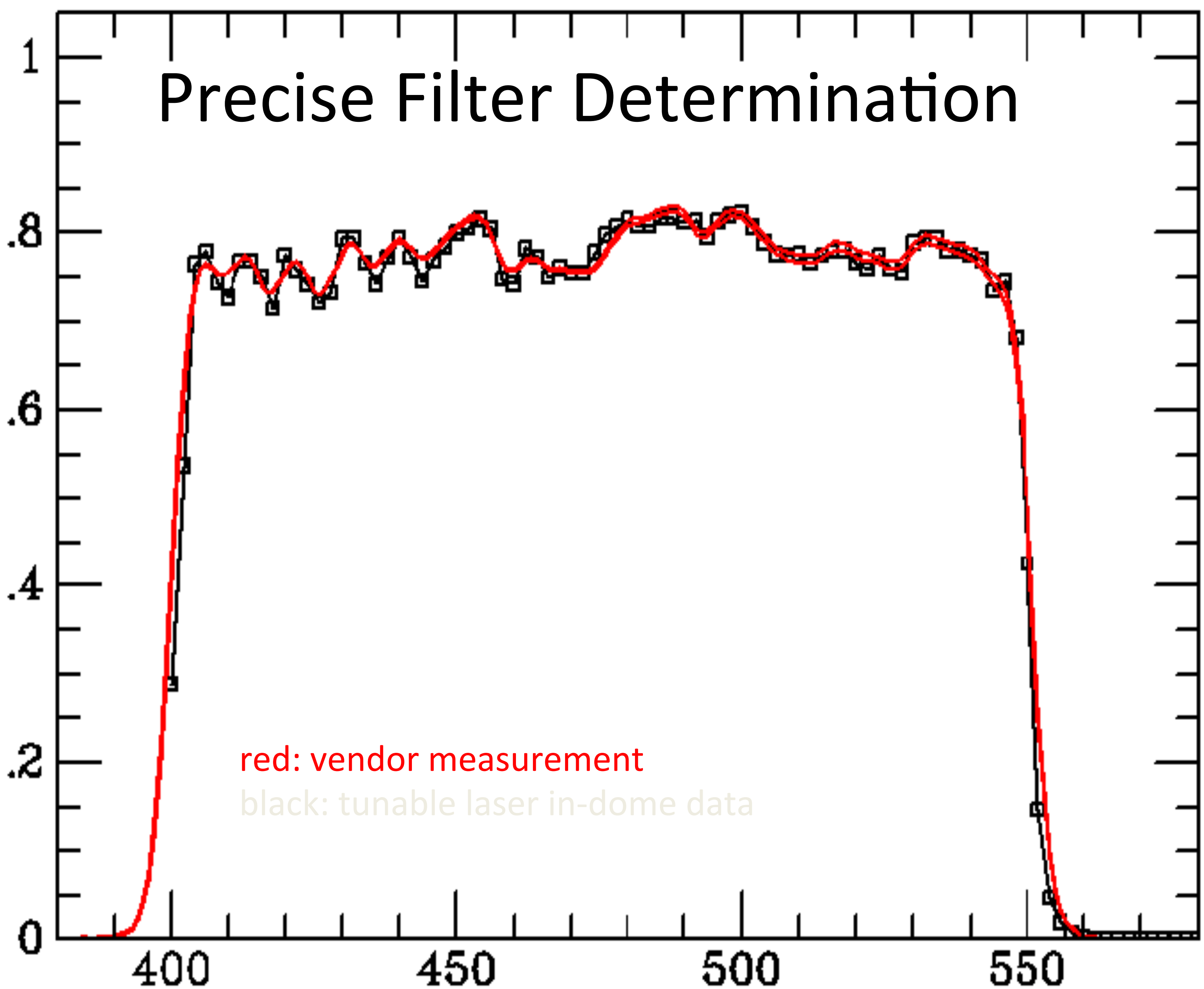
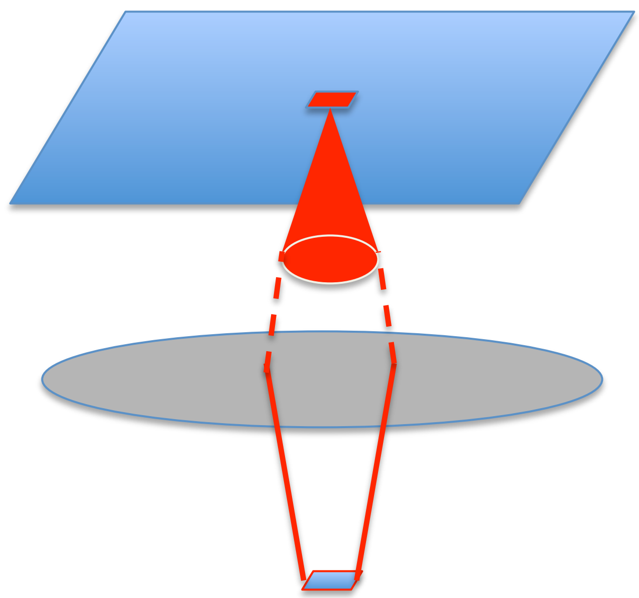


Fig. 4.— The Pan-STARRS1 capture cross section $A(\nu)$ in m^2-e$^-$/photon to produce a detected e^- for an incident photon for the six Pan-STARRS1 bandpasses. This is at the standard airmass of 1.2, with standard PWV of 0.65 cm and aerosol exponent 0.7. Summary properties of each bandpass are found in Table 4.


Precise Filter Determination
red: vendor measurement
black: tunable laser in-dome data
1
.8
.6
.4
.2
0
400
450
500
550

Dome Flats

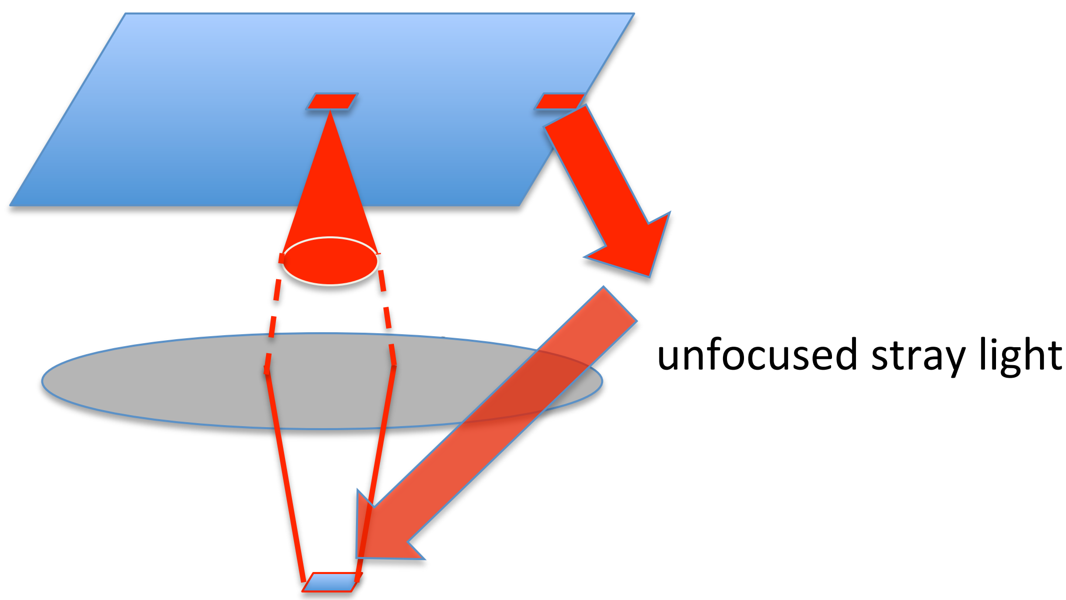
Each element of area dA on dome screen illuminates every pixel so if we're only measuring relative response function of each pixel, uniformity of screen surface brightness is irrelevant. It is important that $I(\theta,\phi)$ be wavelength-independent.



Beware of differences between point source and surface brightness response!

Challenges to Using Dome Flats are well known

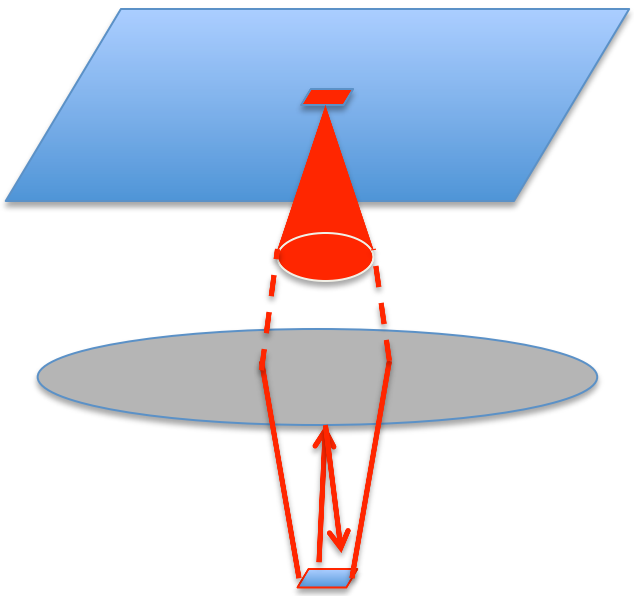
Problem 1: diffuse unfocused light scatters onto the focal plane



Fractional error is ~(stray/focused) surface brightness. Illumination corrections fix this, in the standard processing chain. Dome flats used for high spatial Fourier components, with low order illumination correction.

Challenges to Using Dome Flats are well known

Problem 2: backscatter and ghosting along the optical path



Ghosting light paths, for example reflection from detector scatters from backside of filter.

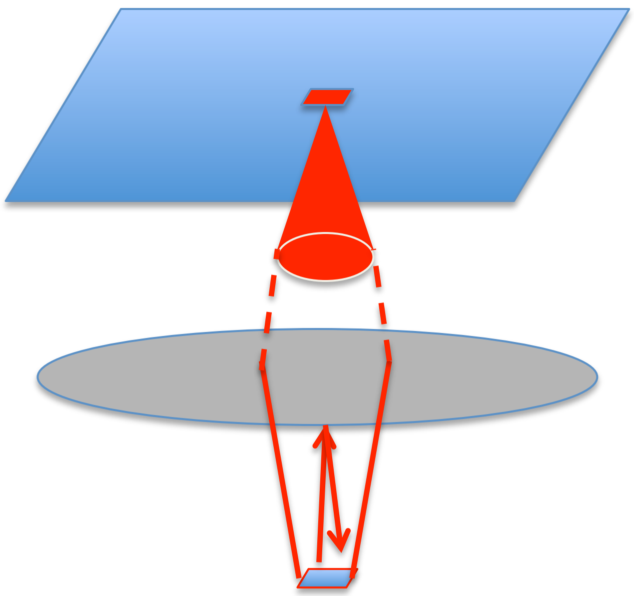
Fractional error in flatfield is ~(ghost/focused) light fraction.

For broadband flatfielding, also taken care of with illumination correction.

But this can have a big systematic effect for monochromatic throughput measurement

Ghosting is especially bad on filter edges, in monochromatic light.

Problem 2: backscatter and ghosting along the optical path



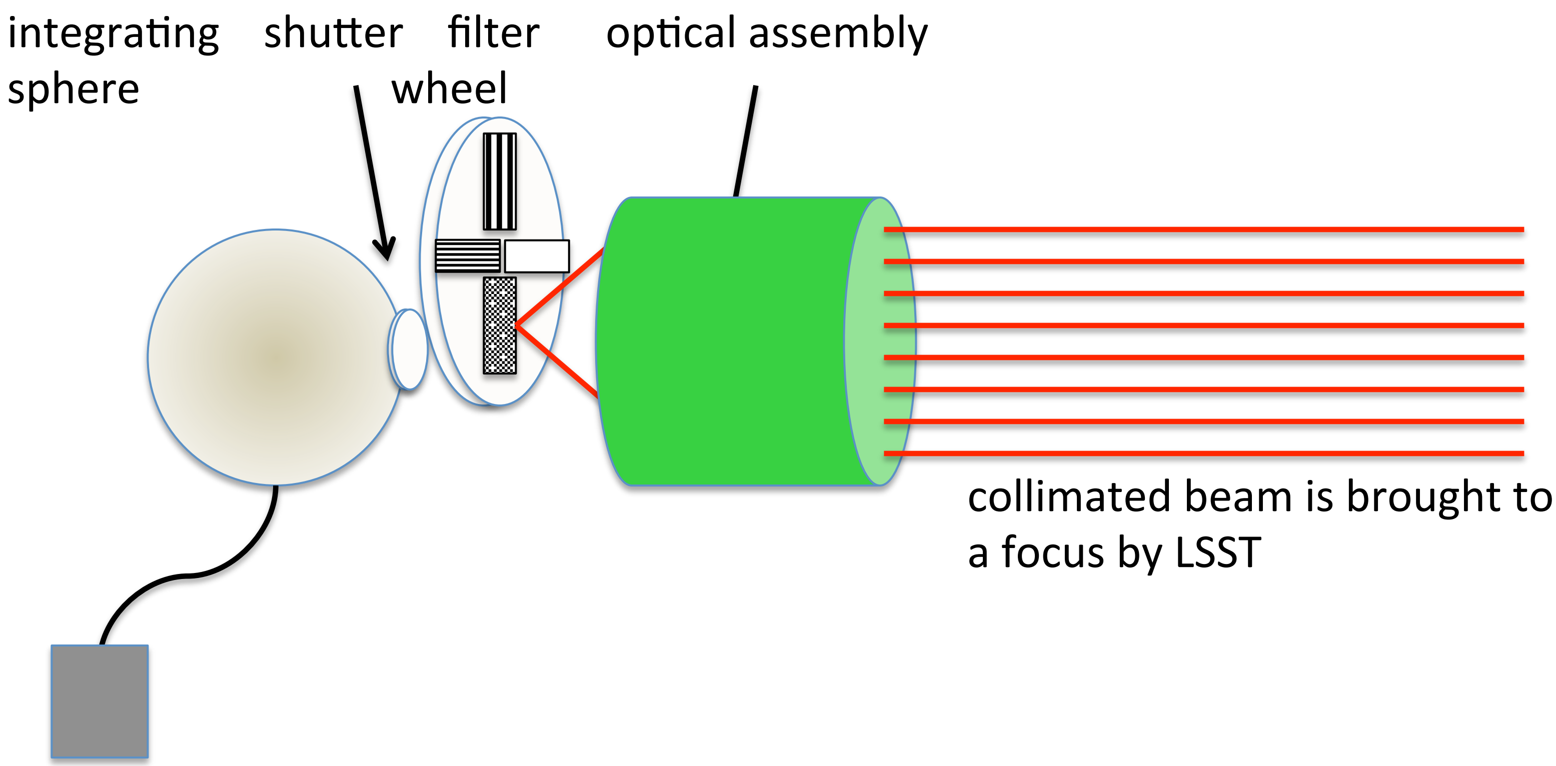
Say we're at the 50% point on filter skirt

Take 80% detector QE

20% of the light scatters off CCDs and then half of that comes back off filter!

So this is a 10% systematic error in throughput, from a non-focusing light path.

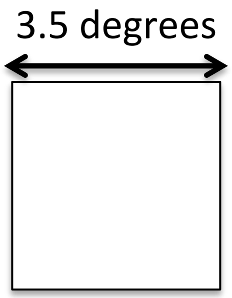
Collimated projector conceptual design



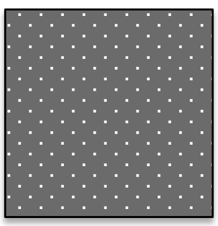
light source, broadband or tunable laser

Spatial mask at CBP focus is re-imaged onto LSST focal plane.

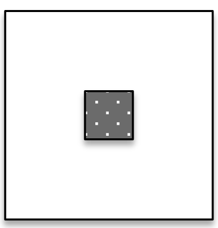
Potential Masks at Focus of Collimator, re-imaged onto LSST focal plane



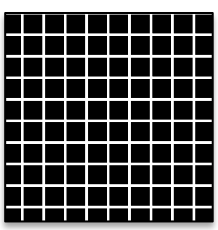
open,
full field illumination



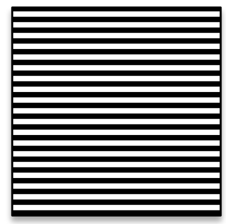
one spot per CCD, for throughput



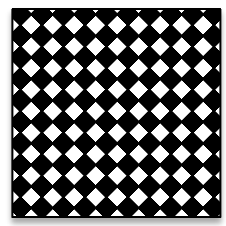
Crosstalk driver
1 spot/amp on 1 chip



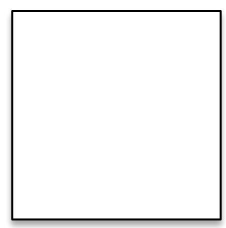
registration pattern



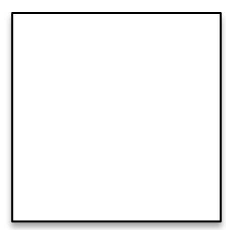
Ronchi grating for gradient flats



shape calibration mask

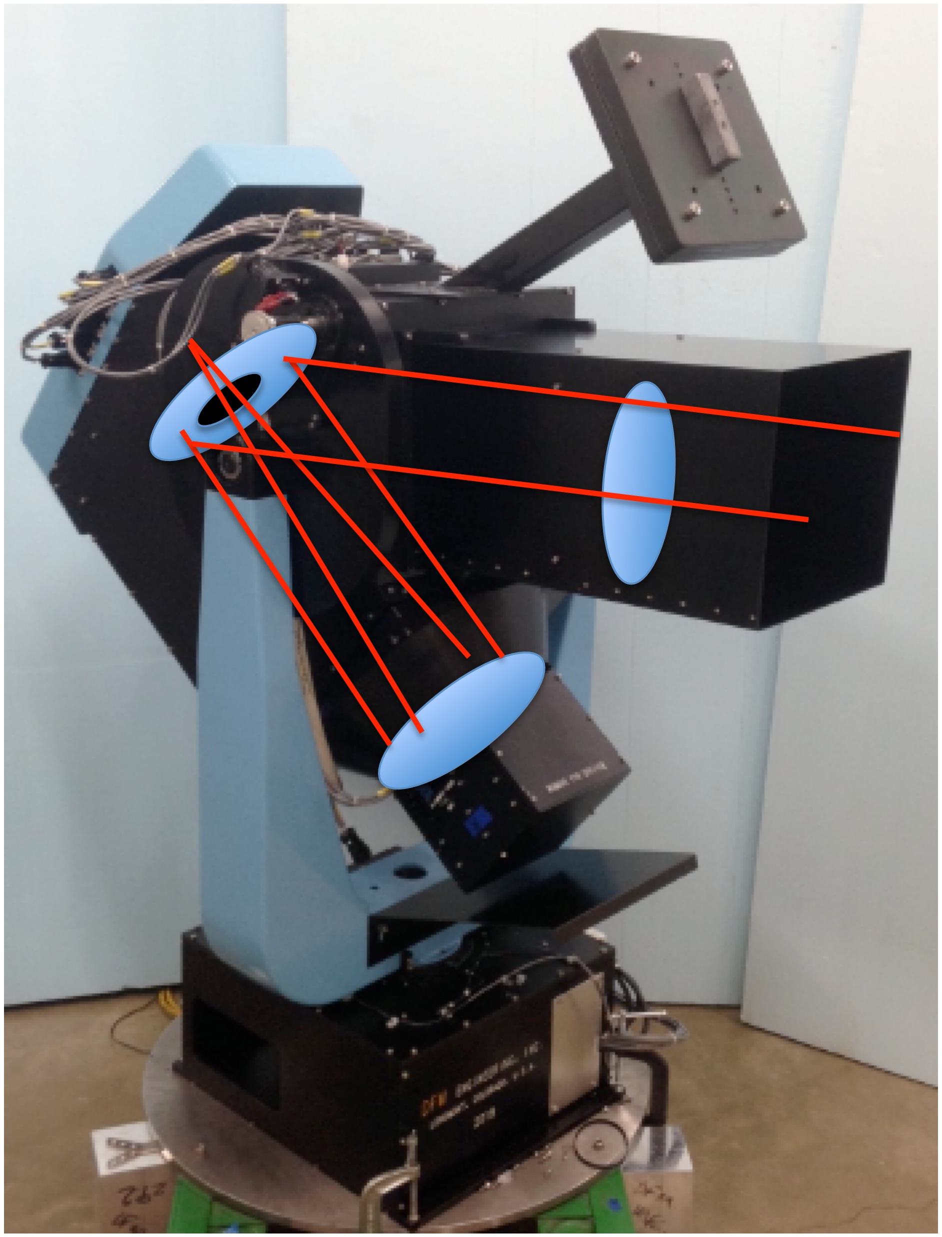


?



?

LSST CBP is a folded Schmidt design, construction completed.



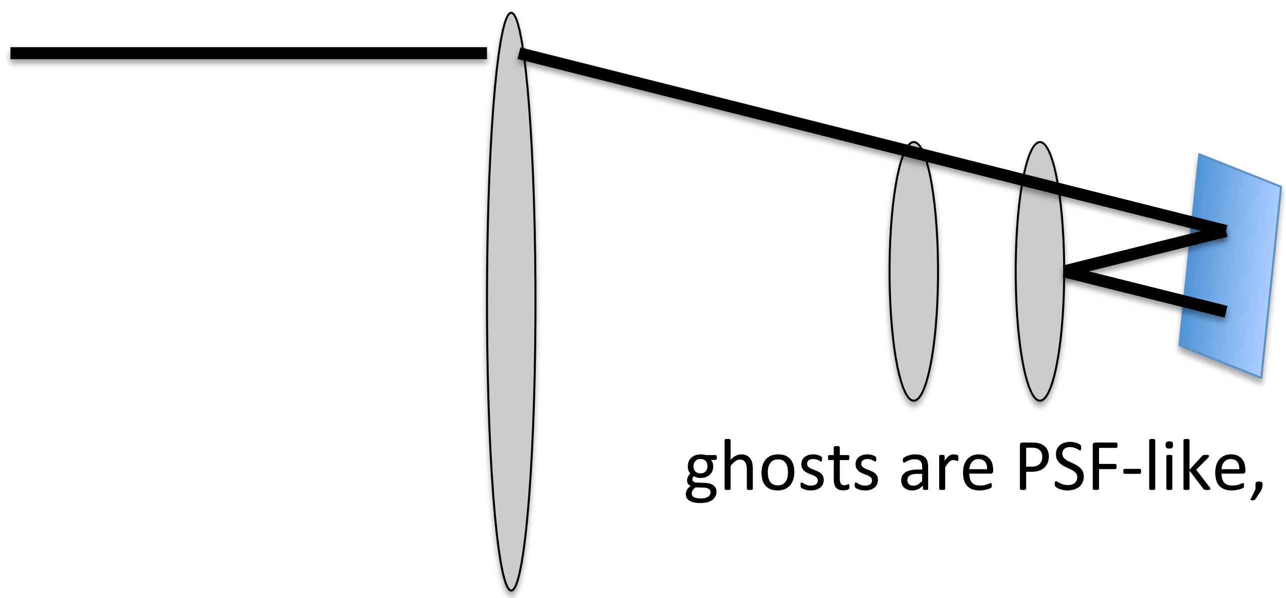
625 mm focal length
120 mm aperture

magnification onto LSST focal plane is
(8.4*1.2)/0.625=16.1

Full-field capability, but not full aperture

Sub-arcsec image

Beams are very small in extent, effective f-number is D_CBP/LSST focal length=f/84.



ghosts are PSF-like, and small!

Implementation of NIST-diode-based flux calibration

All we need to do is measure number of photoelectrons captured in each LSST pixel, relative to flux normalization using NIST photodiode.....

Ideal calibration beam:

- full aperture
- uniform surface brightness
- temporally stable
- monochromatic, tunable
- flat wavefront, adjustable (θ,ϕ).

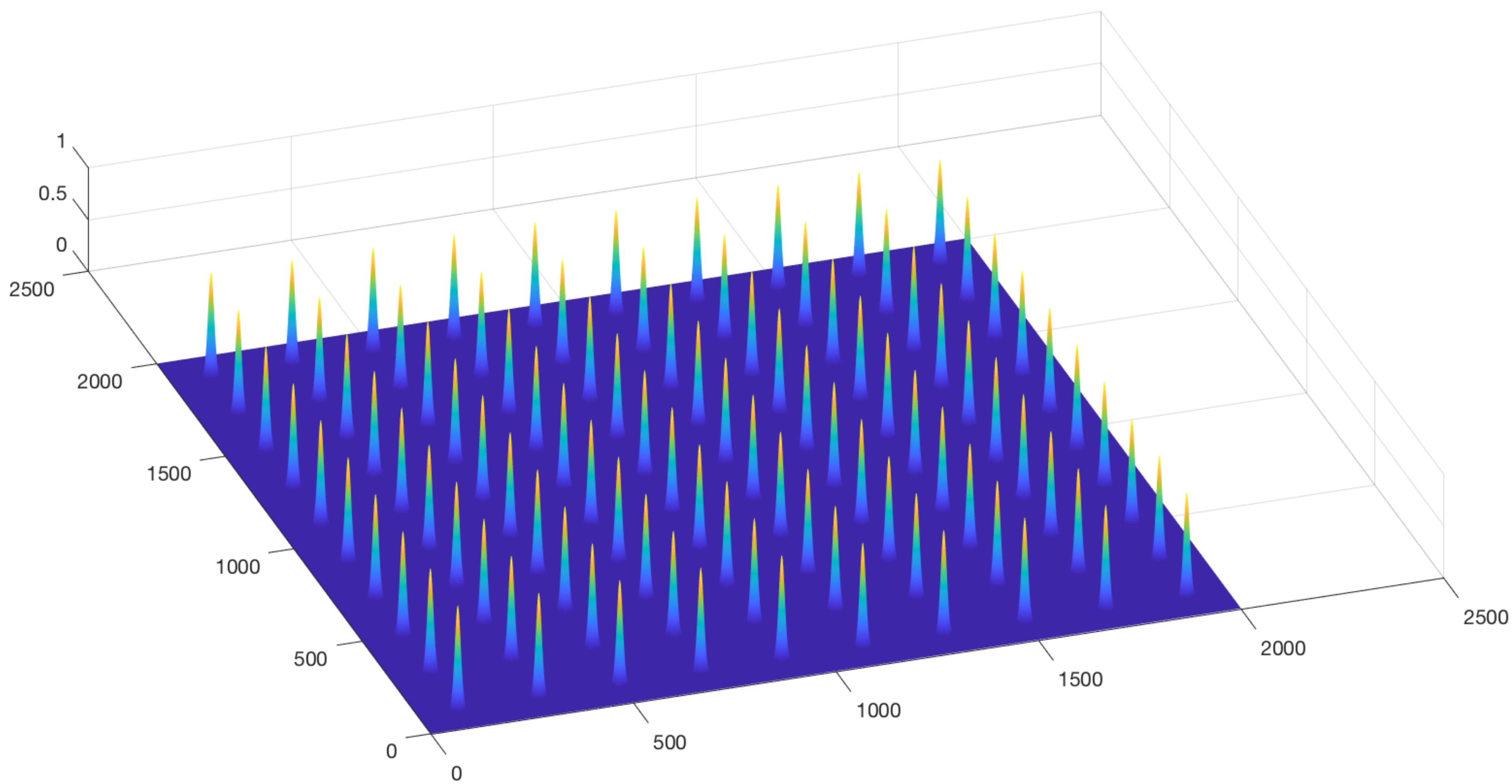
We don't know how to produce that, so we use two light sources in the dome:

	Flat-field screen	**Collimated beam projector**
full-pupil?	Y	N
uniform surface brightness?	N	N*
temporally stable?	N*	N*
monochromatic, tunable?	Y	Y
flat wavefront, adjustable?	N	Y

Utility of Collimated Beam Projector

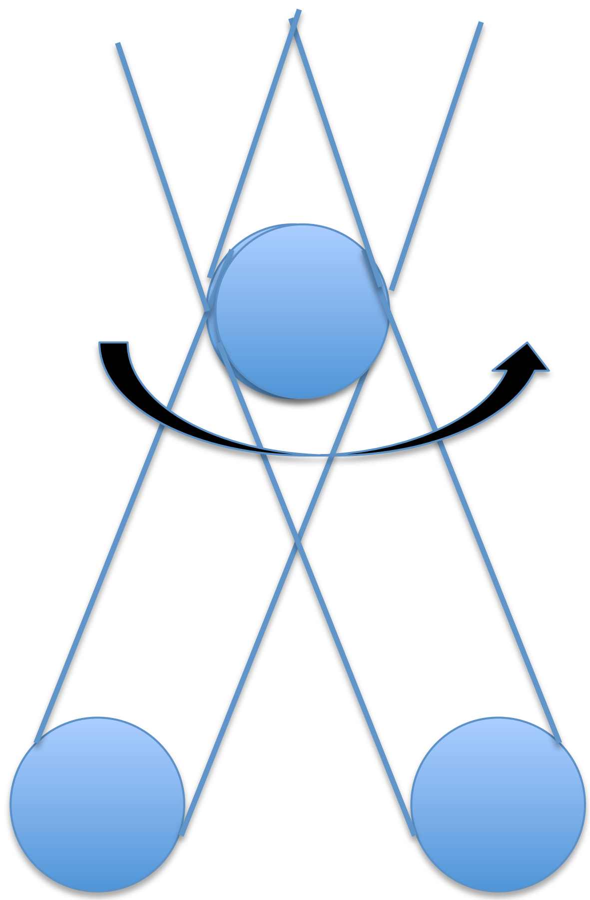
- As long as ghost/stray light is not superimposed on main PSF, can discriminate focusing light path from stray light path.
- This allows for higher precision determination of system throughput than using dome flats alone.
- Ghost reflections can be quantified and monitored over time, and over λ.
  - stability of AR coatings on lenses
  - stability of filter interference coatings
- CBP throughput measurements can be merged with dome flats to get the best of both, we think/hope.
- If run as a reverse-DIMM, we can measure dome & mirror seeing directly.

Relative throughput vs. λ measured at each spot location, for single ray pencil.



LSST focal plane

CBP can pivot about the pupil, to send different pencils down same path

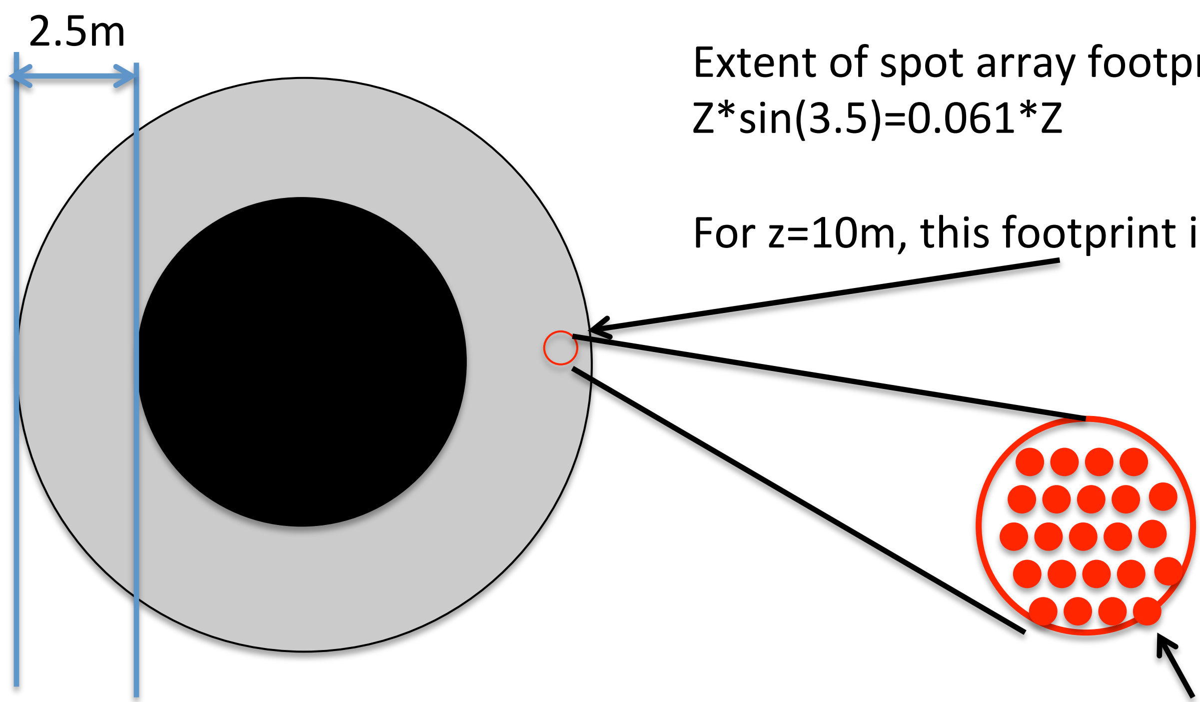


Each pencil beam can be sent through pupil and imaged onto same pixels on detector.

This will allow us to determine relative flux in each pencil beam.

CBP footprint on primary, and measurement plan

- At each fixed pointing, map out throughput for single sub-aperture vs. λ.
- Multiple coordinated pointings, move illumination around on primary, and shift angle of arrival of rays at interference filter, keeping same location on LSST CCDs



Extent of spot array footprint on primary is Z*sin(3.5)=0.061*Z

For z=10m, this footprint is 0.61 m in diameter

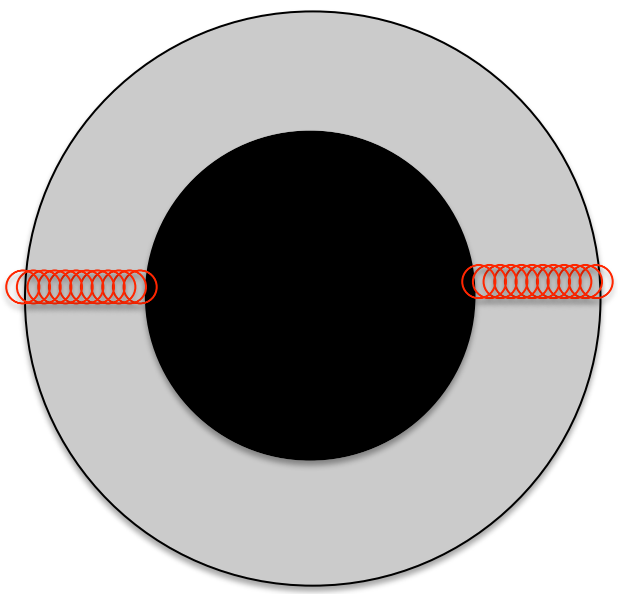
Each collimated pencil is 0.12 m diameter

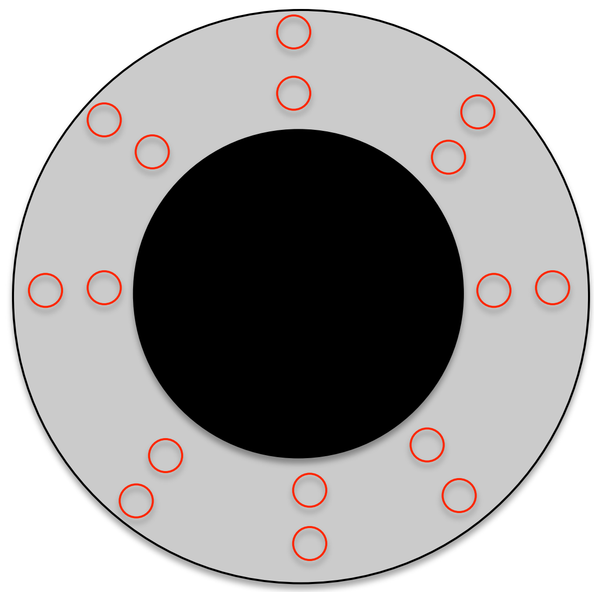
CBP footprint on primary, and measurement plan

- Full-aperture synthesis with 100% coverage across a diameter of primary:
  5m/0.1m = 50 pointings, times 6 filters times 120 wavelengths/filter=36K images
  This is the equivalent of 50 nights of observing.

- This drops a factor of 6 if we take the scans with no filter in the beam, and rely on vendor characterization of filter response.

- Other sampling schemes are also possible, of course

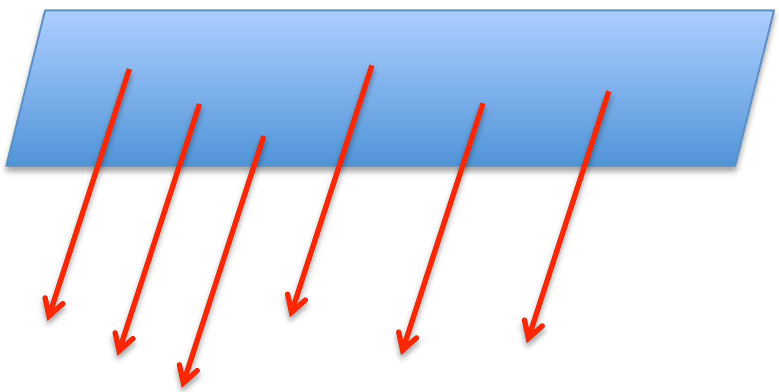




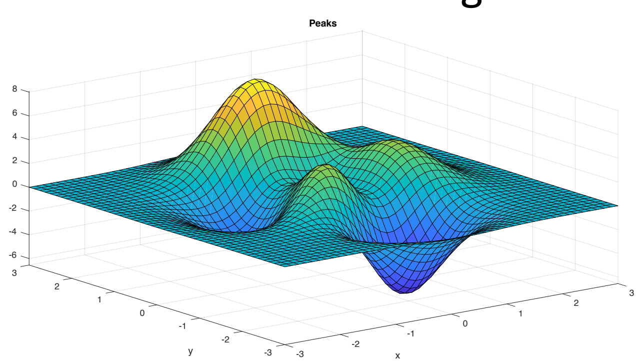
Blended flats

- CBP provides sub-aperture throughput determination at finite number of focal plane locations, with no stray light contamination.
- Dome flats are complementary- full aperture illumination of all pixels.

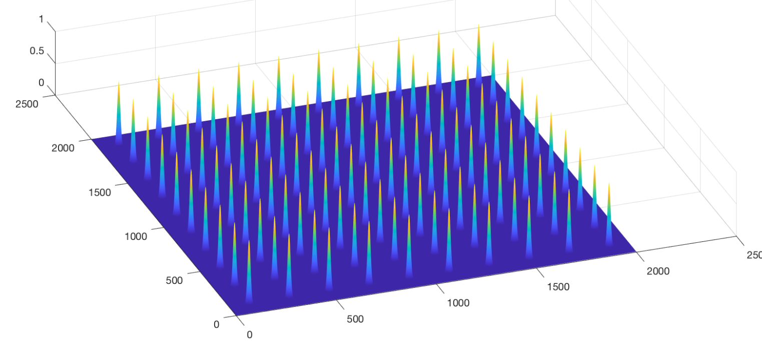
all rays emitted at (θ,ϕ)
land on a given pixel



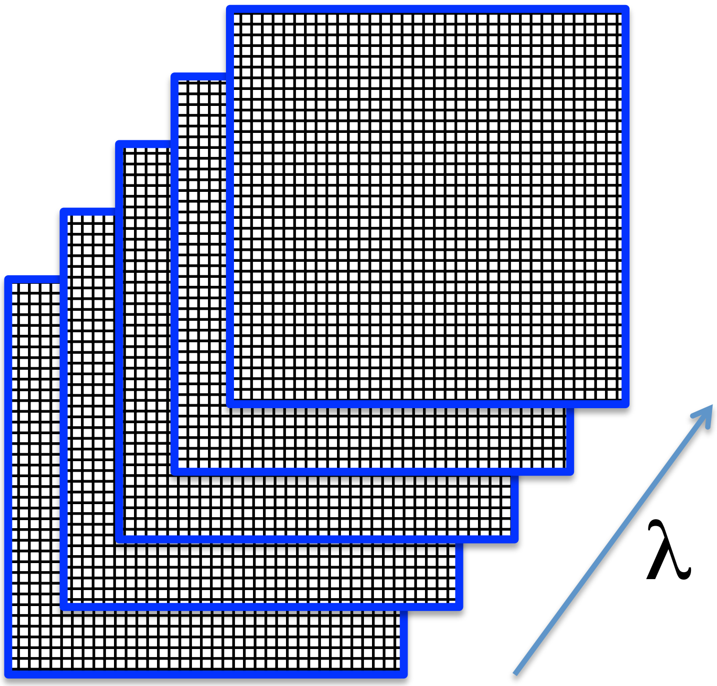
dome flat- surface brightness response



CBP "flat"- PSF response



Data Product

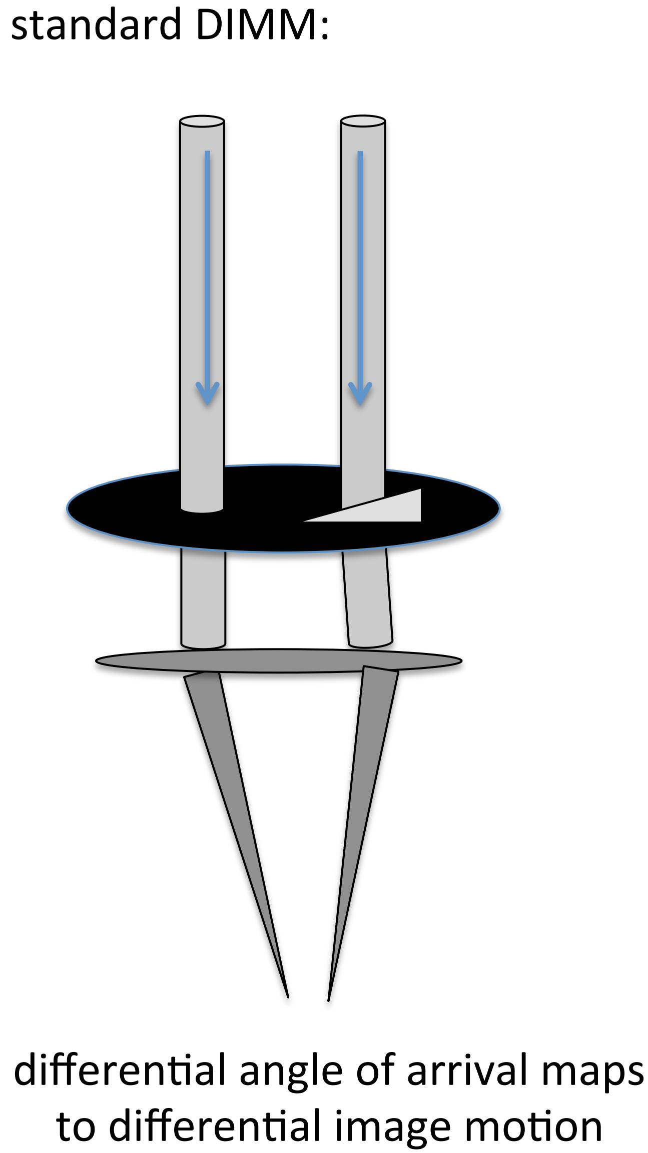


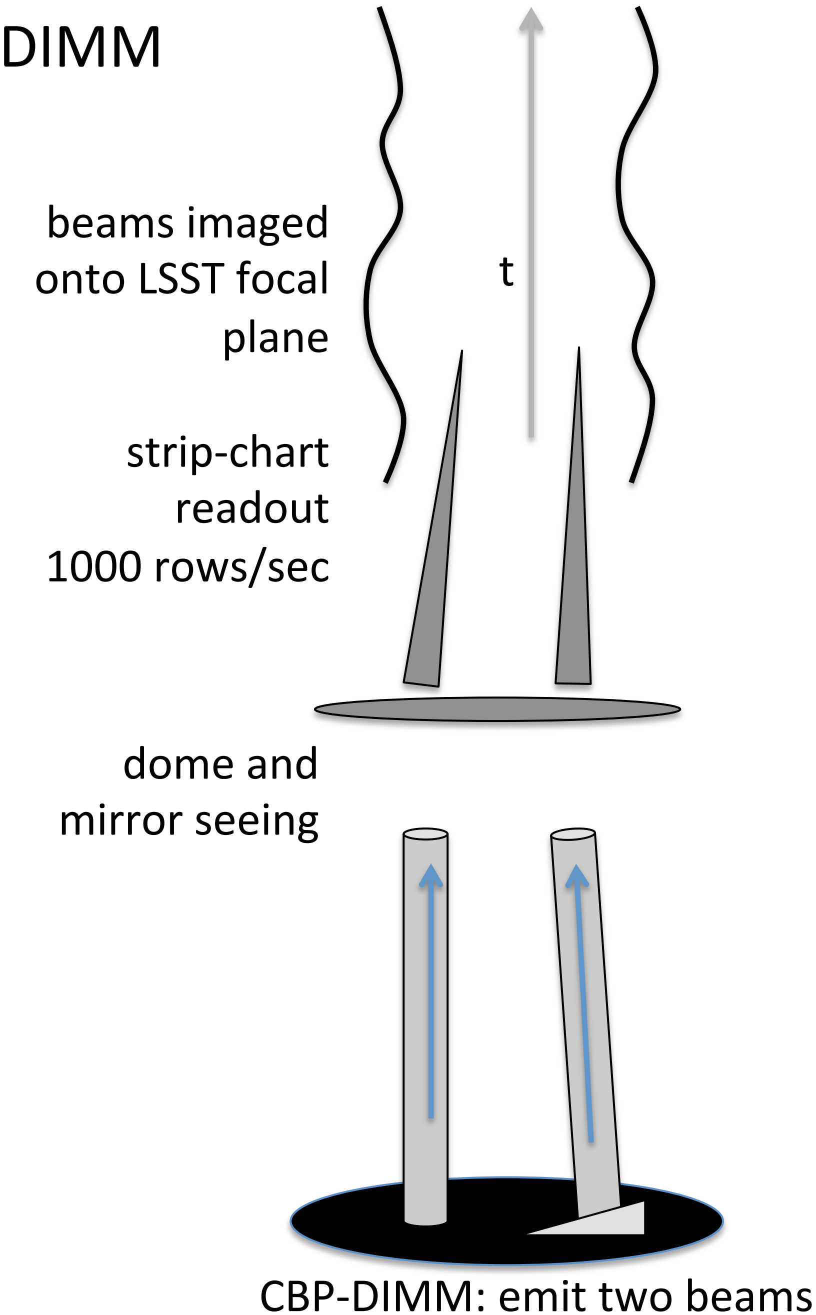
Data cube of relative system throughput

T(I,j,λ)

for each passband, at part-per-thousand precision

CBP dome-DIMM





Potential Topics for DESC-Project collaboration: instrumental throughput

1. Detailed plan for CBP and dome flat data collection
2. Detailed plan for CBP and dome flat data analysis
3. Synthesis of multi-pointing CBP data to produce full-aperture equivalent
4. Optimal combination of CBP and dome flats
5. Achieving throughput determination at higher precision than LSST requirements
6. Absolute calibration of system throughput, overall scale/zeropoint
7. Merging celestial and laboratory calibration results
8. Determination of systematic uncertainty in relative system throughput
9. Exploiting GAIA spectrophotometry
10. Establishing network of emission line spectrophotometric standards
11. …..


I will only use properly calibrated LSST data for cosmology
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