Exploring alternative sky-subtraction algorithms for the LSST pipeline

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LSST:UK project work package

with support from the Rubin Data Management Team

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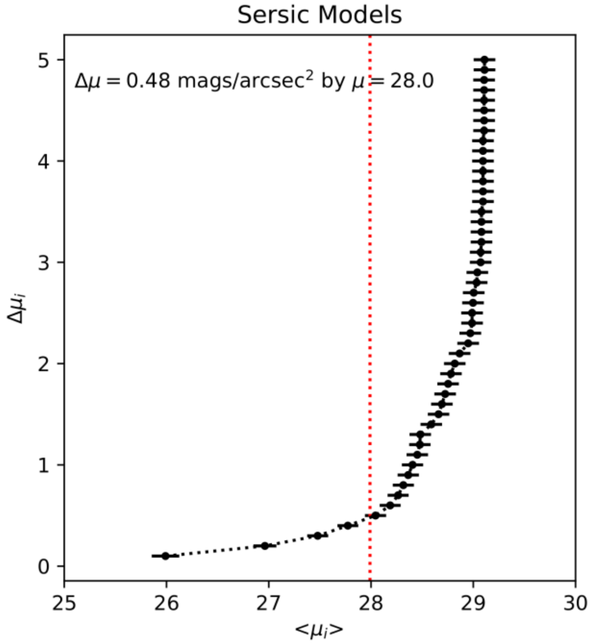
Low-surface-brightness science with LSST

- Theoretical 10-year depth in surface brightness: 30.3 mag/arcsec^2 in *g*-band (3σ 10" x 10")
- Should this be achieved, LSST will produce, for the first time, statistically robust samples of:
  - Dwarf galaxies (very low-masses nearby, plus high-redshift dwarfs at higher masses)
  - Tidal streams (including around dwarf satellites)
  - Intracluster/intragroup light (ICL/IGL)
  - Etc.
- **The LSB regime composes a large fraction of LSST's potential discovery space**

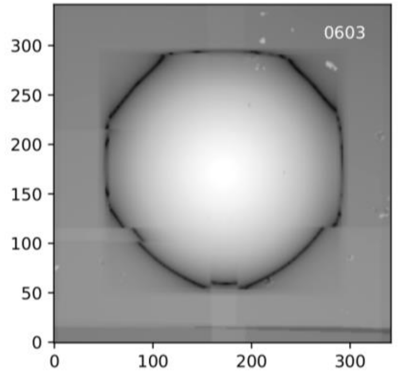
Tucana B, an ultrafaint dwarf recently discovered by Sand et al. (2022)

LSST pipeline sky subtraction testing

- Last year, injected ~1000 models into LSST pipeline just prior to full-focal-plane sky-subtraction
- Post-SS, on average, models lose significant relative flux below ~26 mag/arcsec^2, leading to sometimes large total magnitude changes
- Worse for large, diffuse objects like ICL (though almost everything is affected)
- **Began exploring potential solutions**



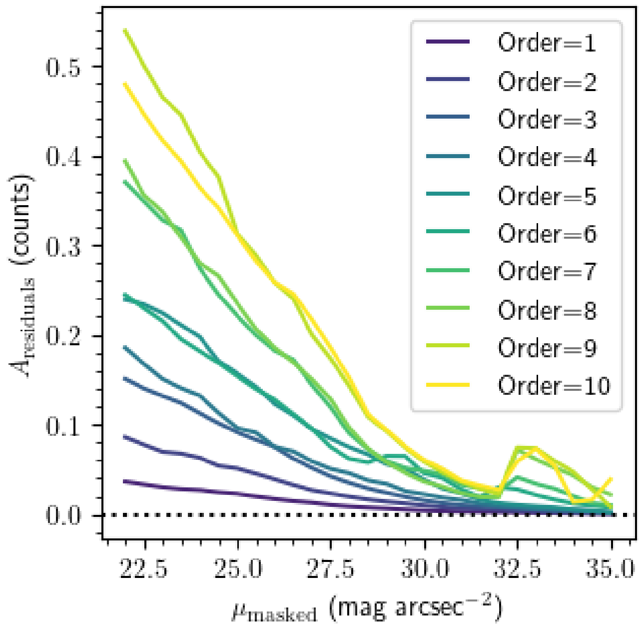
Left: experiment showing amount of over-subtraction in model galaxies vs. isophotal surface brightness

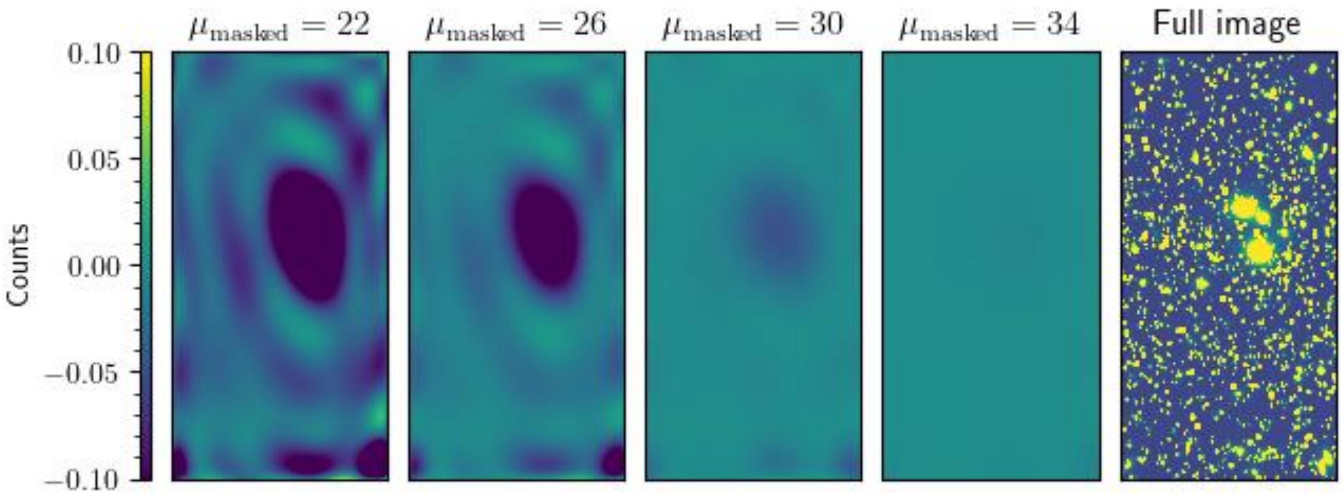


Right: example of injected model post-sky-subtraction. Note dark over-subtraction ring.

Two potential simple fixes (1)

- Mask flux to deeper levels, and use low-order polynomial to fit unmasked pixels
- Tests on synthetic images (bottom, right) show that over-fitting risk is substantially reduced by doing this

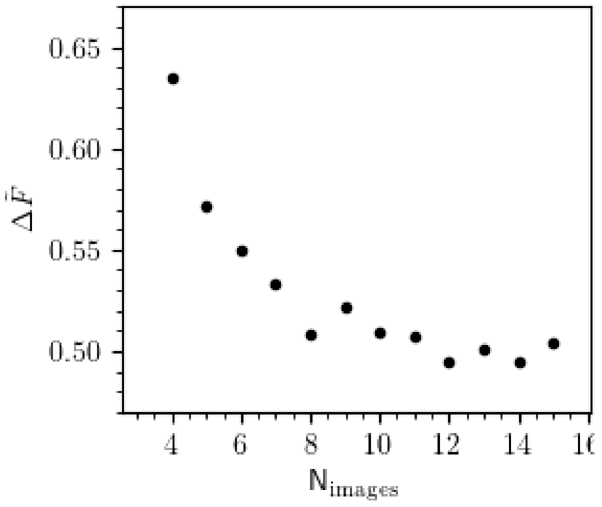




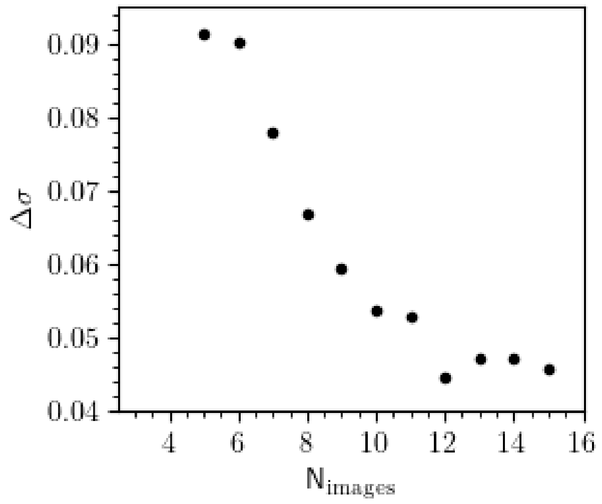
- CAVEAT: fails in extremely crowded fields, or when large, bright objects fill whole frame

Two potential simple fixes (2)

- Combine 8—12 frames (right) taken close in sky and in time to make local average sky
- Akin to chop and nod strategy for NIR, so should work as long as sky is stable across combined frames

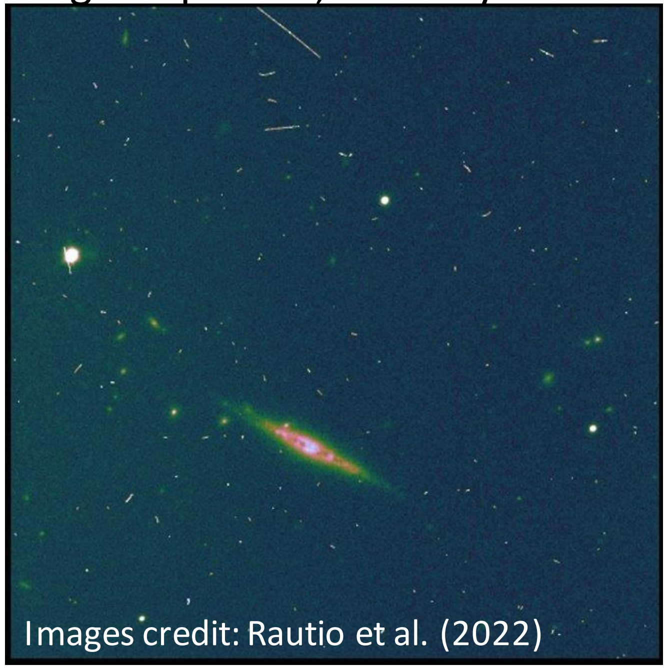


- CAVEATS: diffuse light always incurs a pedestal flux level in final averaged sky (top right), which requires masking to estimate and remove
  - Not a critical flaw (see previous slide)
- Strong reliance on dither pattern + cadence
- Sky image contains noise (bottom right), which is added to frames on sky-subtraction



Novel method for cleanup

Single exposure, with sky



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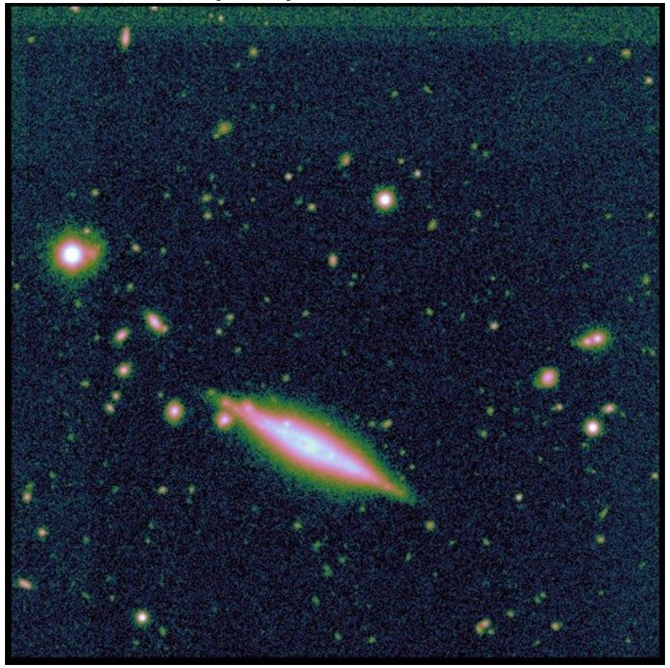
Preliminary sky-subtracted coadd



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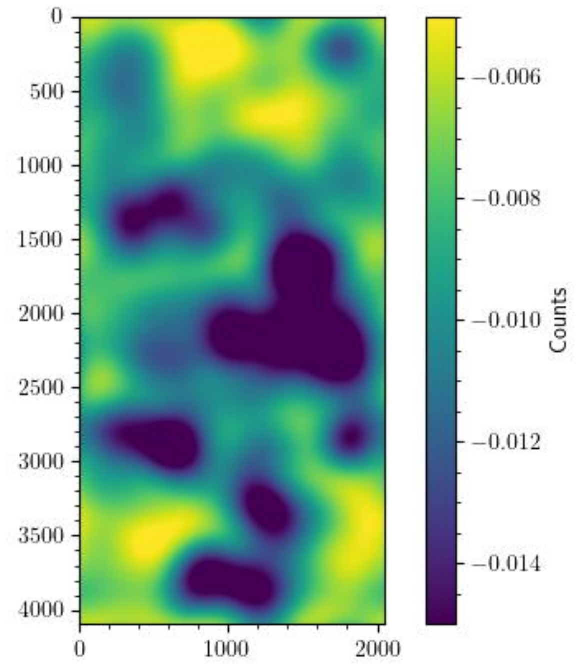
Noisy isolated sky map

- Create initial sky-subtracted coadd
- Align, flux-scale (PSF-match), and subtract from individual frame to isolate sky
- Process sky image to reduce noise/remove artifacts, and subtract from frame

Caveats to new method

- High noise on coadd-subtracted frames
  - Standard (fast!) noise reduction techniques (binning, Gaussian smoothing) imprint noise pattern on binning/smoothing scale
  - Can fit sky image as polynomial to avoid this, but less desirable (prefer model-free)
- Minimal improvement over initial coadd
  - If first coadd *isn't* already good, will imprint large-scale patterns on backgrounds upon sky-subtraction
  - If first coadd *is* already good, second coadd shows minimal improvement over first most of the time
    - Partly related to above point about noise
  - Time needed to produce second coadd not justified?



Example noise pattern imprinted on images due to noise reduction strategy (here, binning and Gaussian smoothing)

Potential fix—don't use full image set

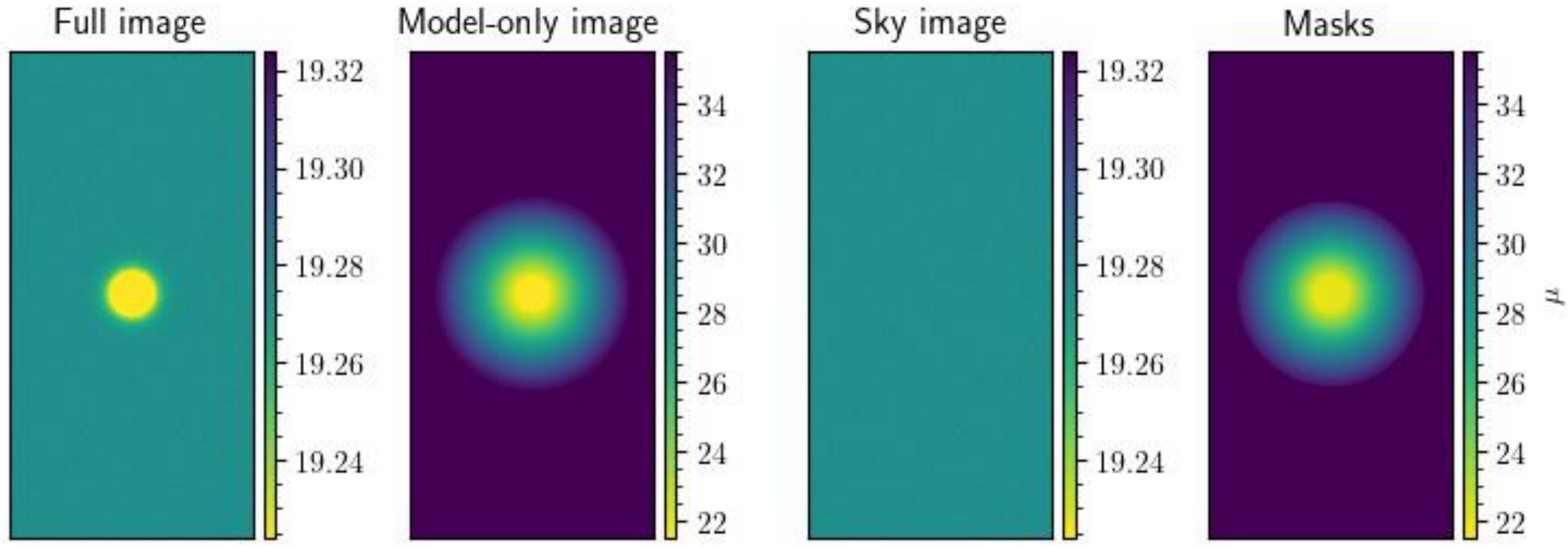
- Create a "good sky" preliminary coadd, using only "best" 20%—30% of exposures for observing run for a given part of the sky
  - "Best": TBD, but maybe low airmass, dark conditions, good seeing (photometric)
- Use this coadd to correct only exposures taken under "bad" conditions
  - "Bad": strong moonlight, scattered light from planets, city glow, etc.
- Standard LSB strategy is to throw away "bad" frames—this strategy would allow one to keep them, improving point-source depth in LSB-friendly coadd
  - Preliminary experiment w/synthetic images found that limiting surface brightness in coadd improves slightly more by fixing bad frames over removing them
  - Clean backgrounds + best point-source depth; everybody wins

Summary

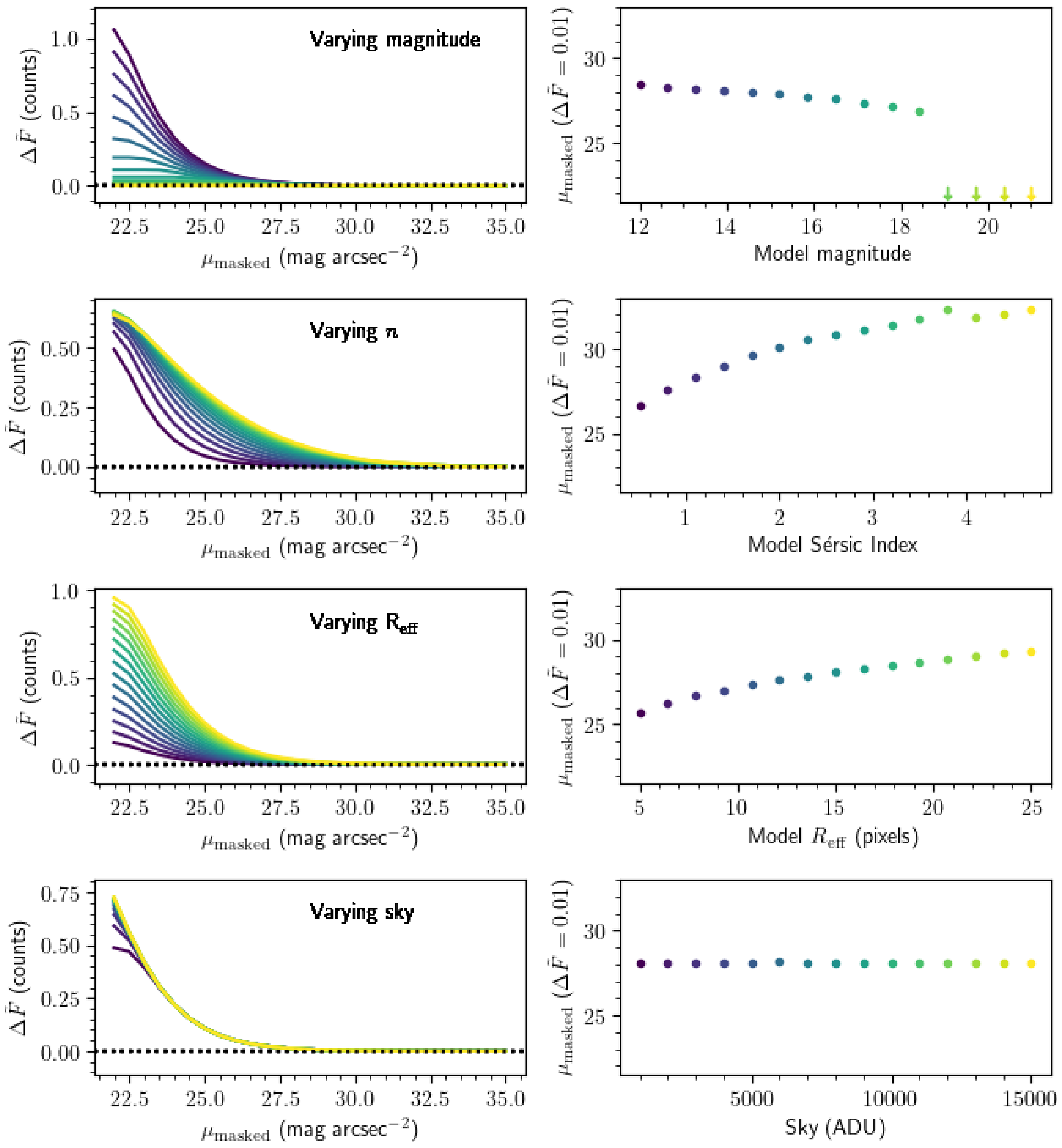
- LSB science composes a large fraction of LSST's potential discovery space, if LSB flux is preserved
- As of last year, pipeline was removing LSB flux through over-subtraction of sky
- Two potential simple solutions:
  - Better masking and simpler fits to unmasked pixels
    - Fails in very crowded regions (need unmasked, uncontaminated pixels to fit a sky model)
  - Combine dithered exposures taken close on sky and in time
    - Assumes stable sky, creates pedestal level from smoothed LSB flux that must be removed, adds noise
- Novel method: use preliminary coadd to isolate sky on individual exposures
  - Reducing noise in isolated sky images problematic, and testing found only small gains over initial coadd—hard to justify added time required
  - Potential workaround: make preliminary coadd using only a subset of images w/clean skies, and use this to correct only images w/bad skies
    - Equal (better?) improvement in SB depth doing this as by removing bad frames—LSB flux preserved, depth improves, and point-source depth maintained, pleasing everyone

Extra discussion stuff follows…

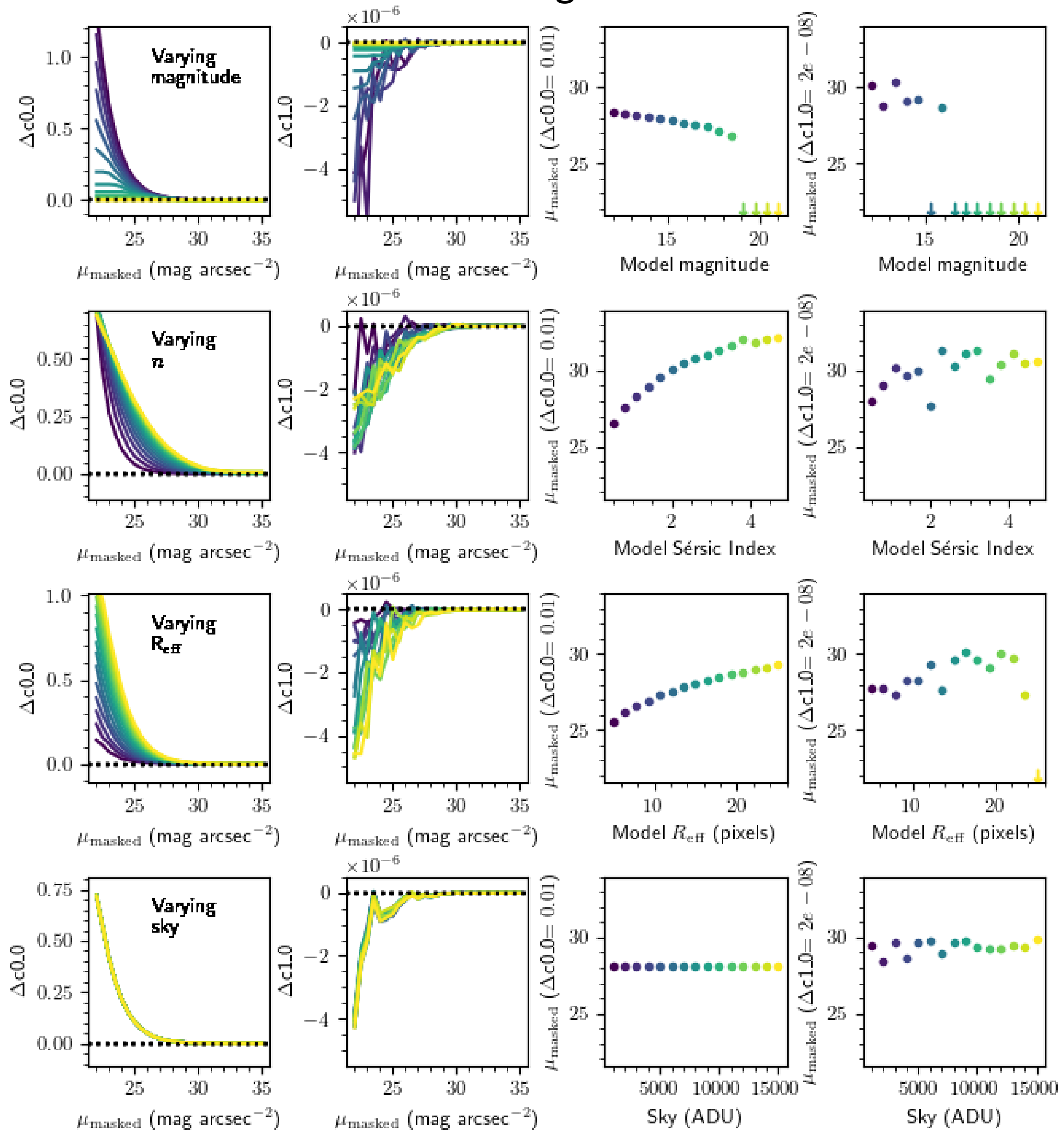
Single model tests



Median robustness to masking

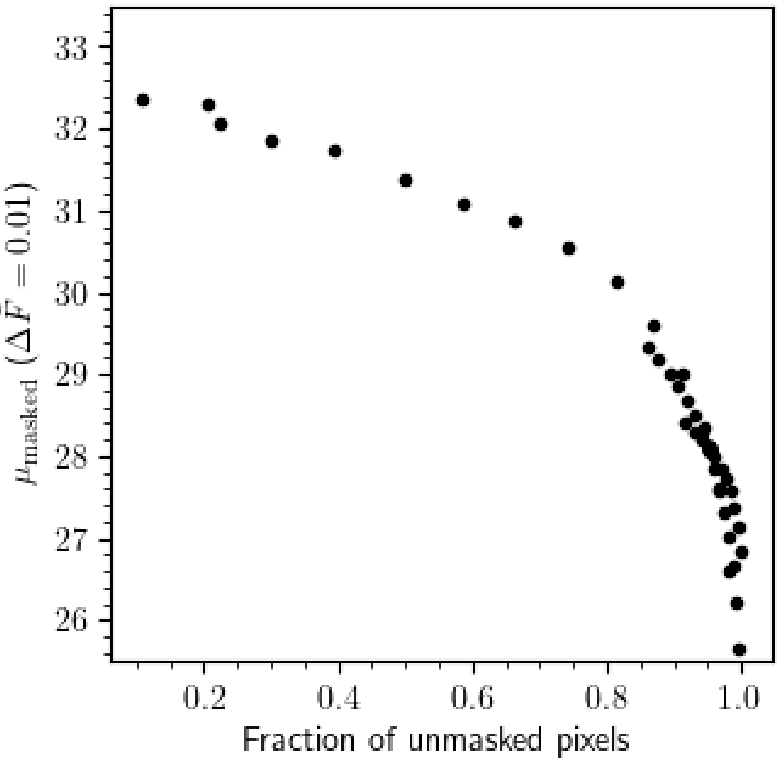


Plane fit robustness to masking

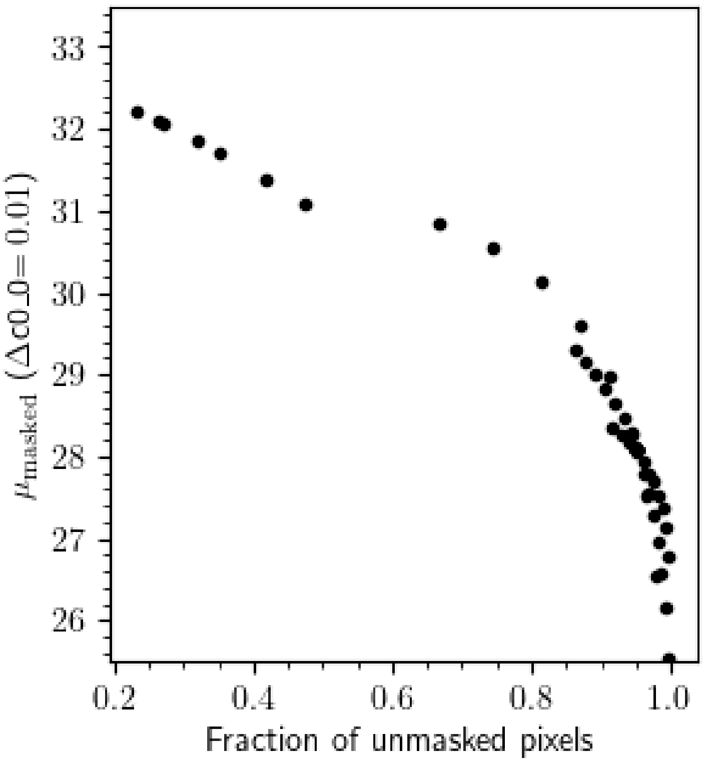


Convergence to true sky vs. Fraction of unmasked pixels

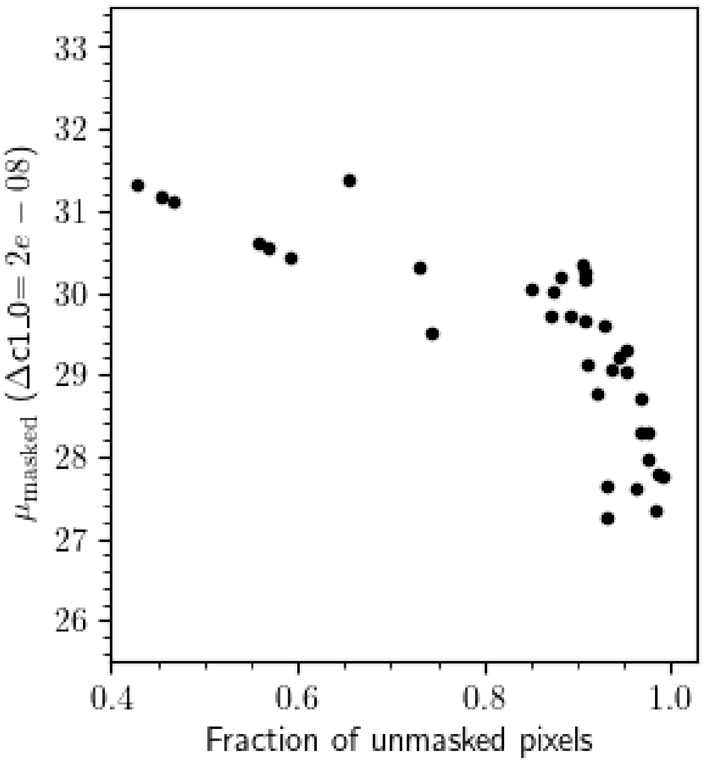
Median



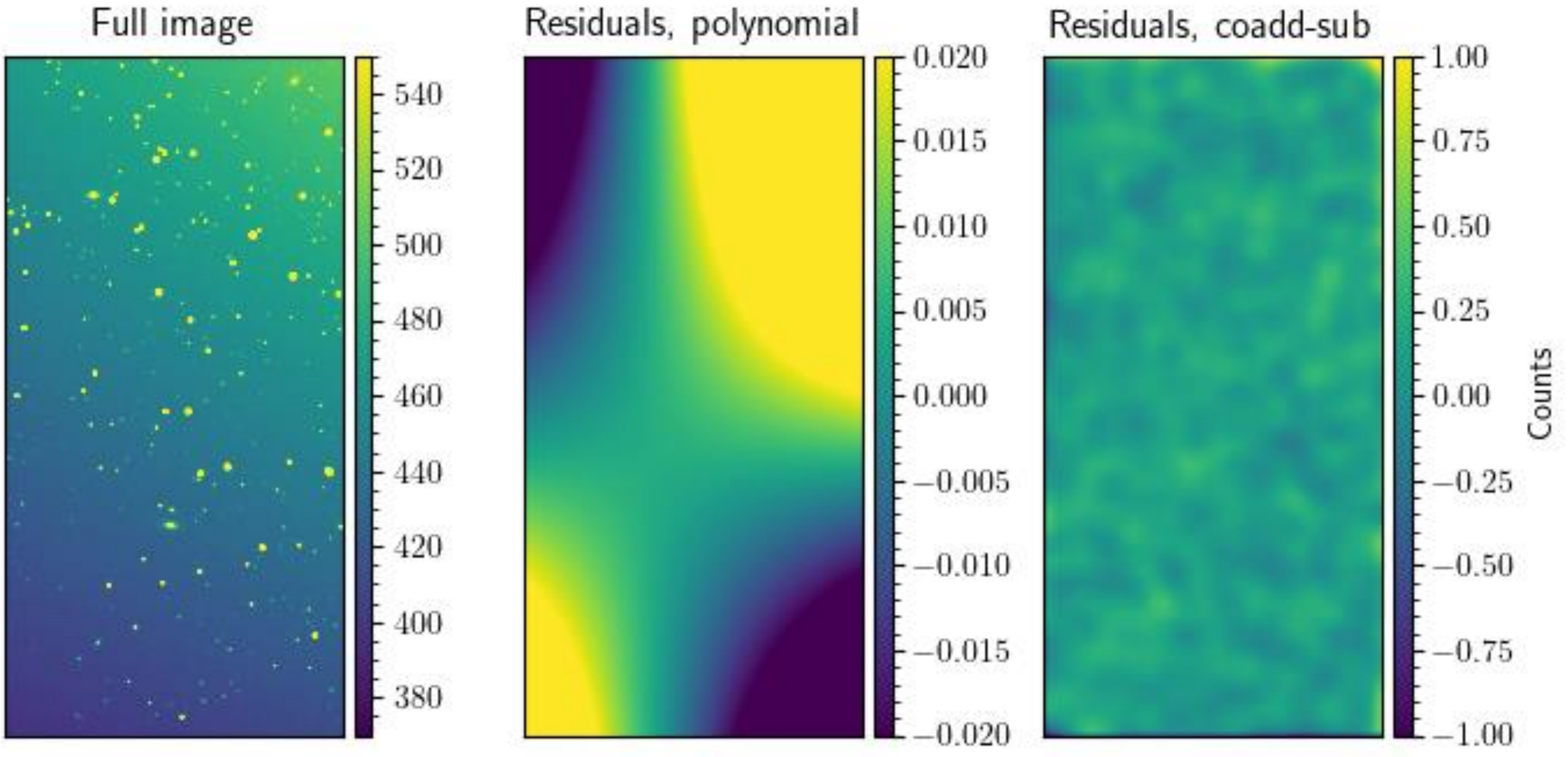
Plane fit 0th order term



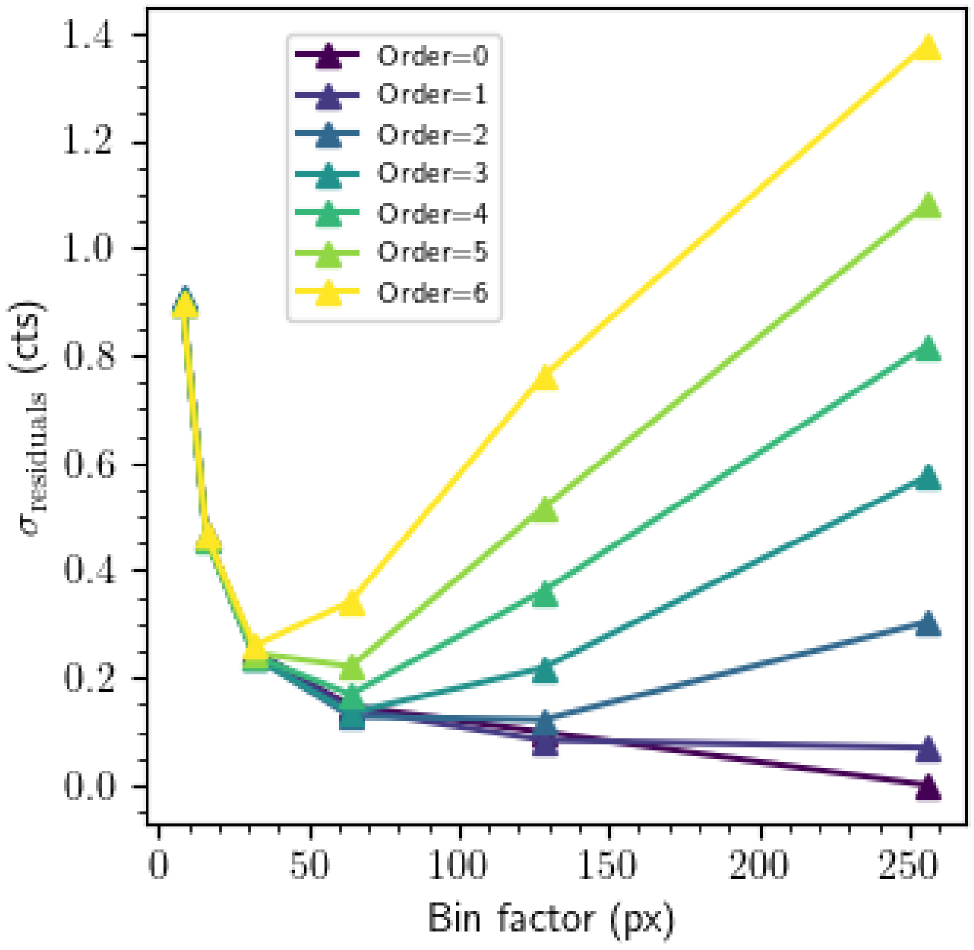
Plane fit 1st order term

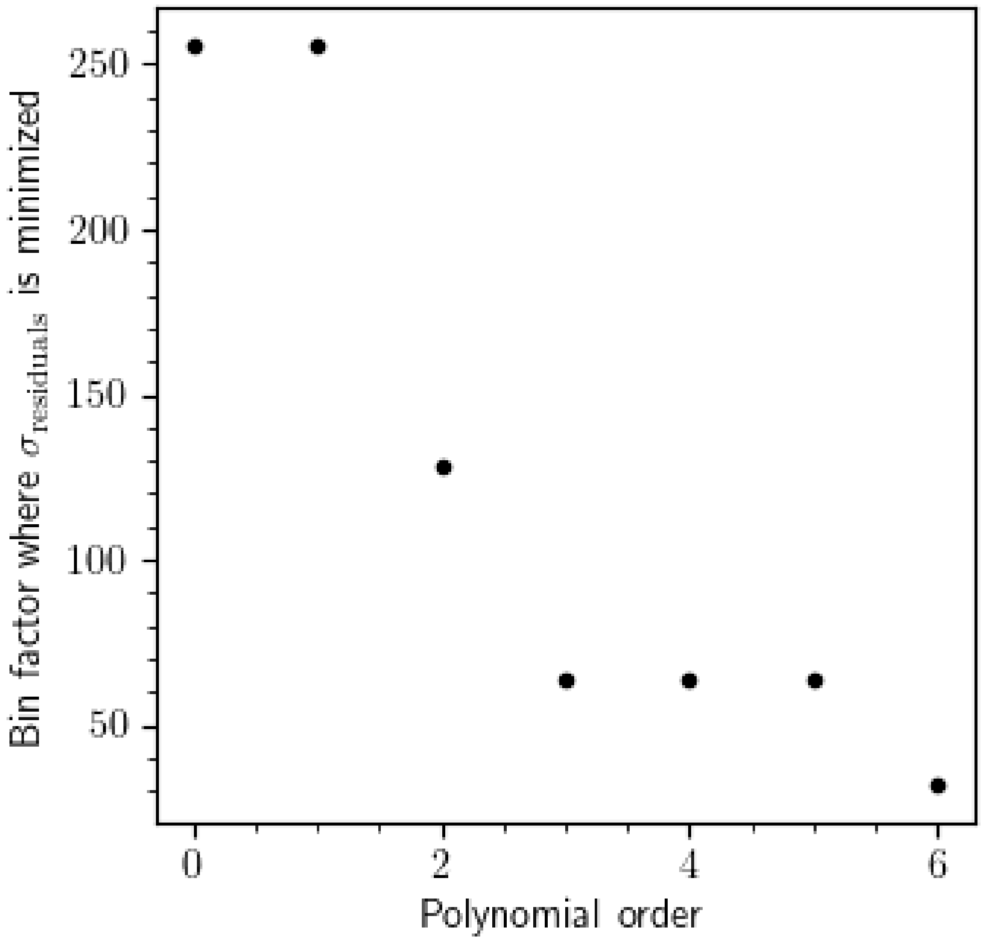


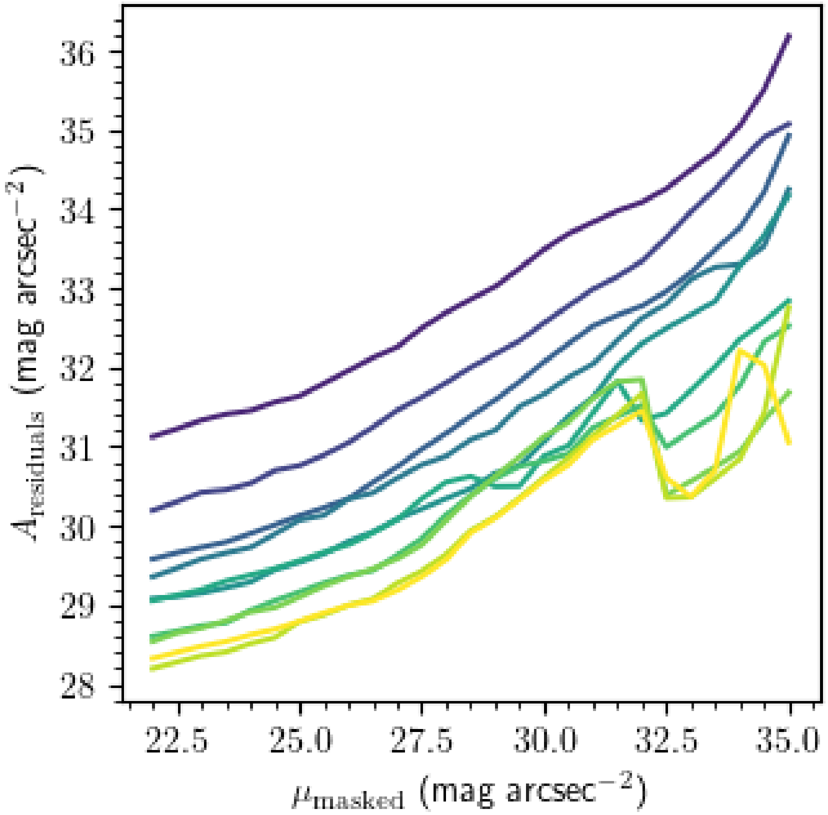
Sky-sub residuals comparison



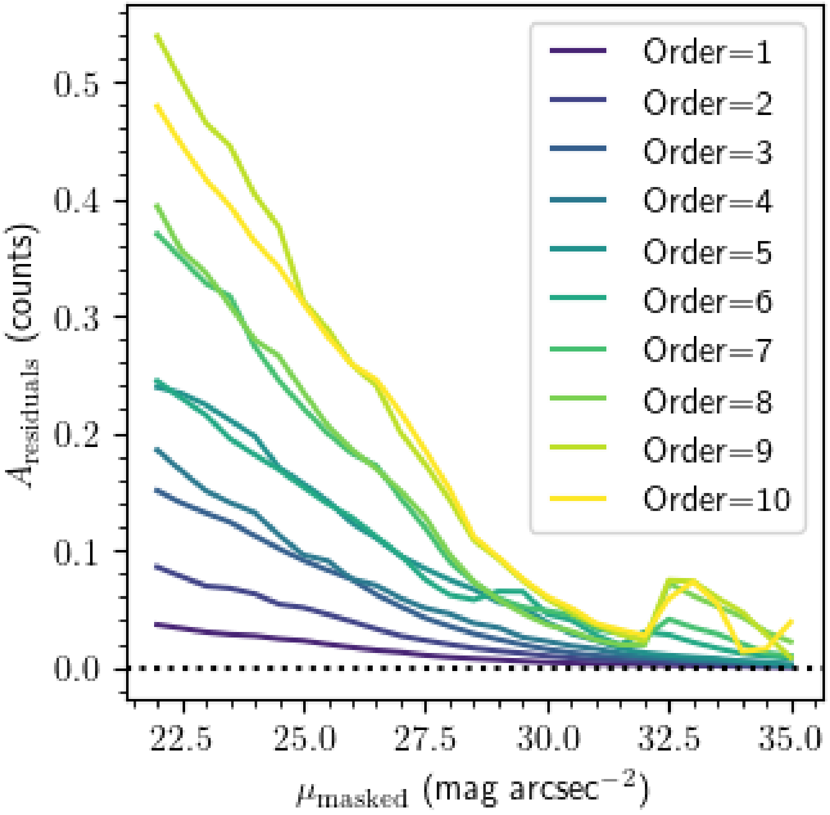
Noise reduction for model polynomial skies as a function of bin size







$A_{\rm residuals}$ (mag arcsec^{-2})
$\mu_{\rm masked}$ (mag arcsec^{-2})



$A_{\rm residuals}$ (counts)
$\mu_{\rm masked}$ (mag arcsec^{-2})
Order=1
Order=2
Order=3
Order=4
Order=5
Order=6
Order=7
Order=8
Order=9
Order=10

Sky recovery using scattered light model