A novel, nearly model-free sky-subtraction algorithm for the LSST pipeline

Update on LSST:UK Work Package 3.7

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Low-surface-brightness science with LSST

- LSB science includes everything from dwarf galaxies to Galactic cirrus
- Theoretical 10-year depth in surface brightness: 30.3 mag/arcsec^2 in g-band (3σ 10" x 10")
- Should this be achieved, will produce, for the first time, statistically robust samples of:
  - Dwarf galaxies (very low-masses nearby, plus high-redshift dwarfs at lower mass limits than previously achievable)
  - 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

- Last year, injected ~1000 models into LSST pipeline just prior to 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 (small objects *gain* small amounts of flux)
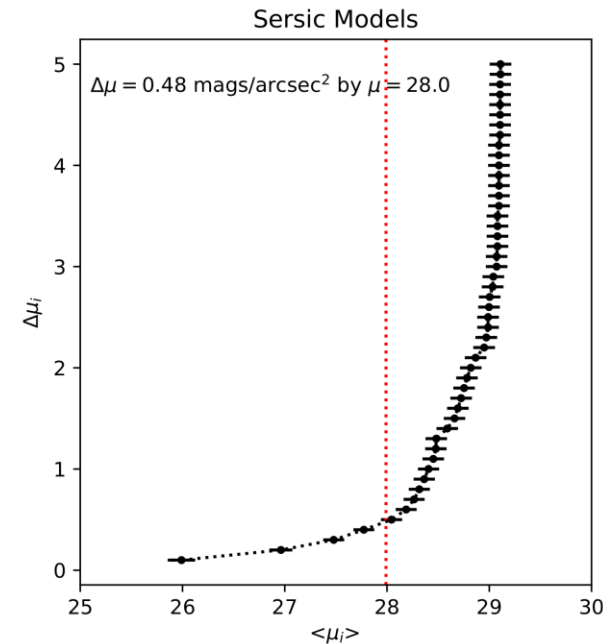
Left: experiment showing amount of over-subtraction in model galaxies vs. isophotal surface brightness

Right: example of injected model post-sky-subtraction. Note dark over-subtraction ring.
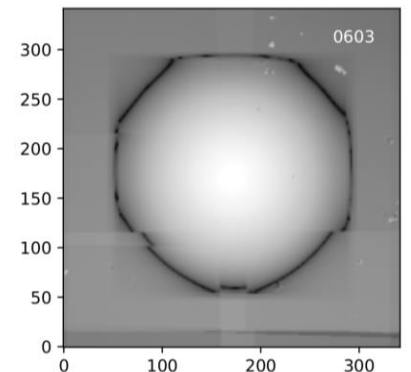
Two potential simple fixes (1)

- Mask flux to deeper levels, and use low-order polynomial to fit unmasked pixels

- Tests on synthetic images show that if masks are deep enough, risk of over-fitting (below) is strongly mitigated (right)
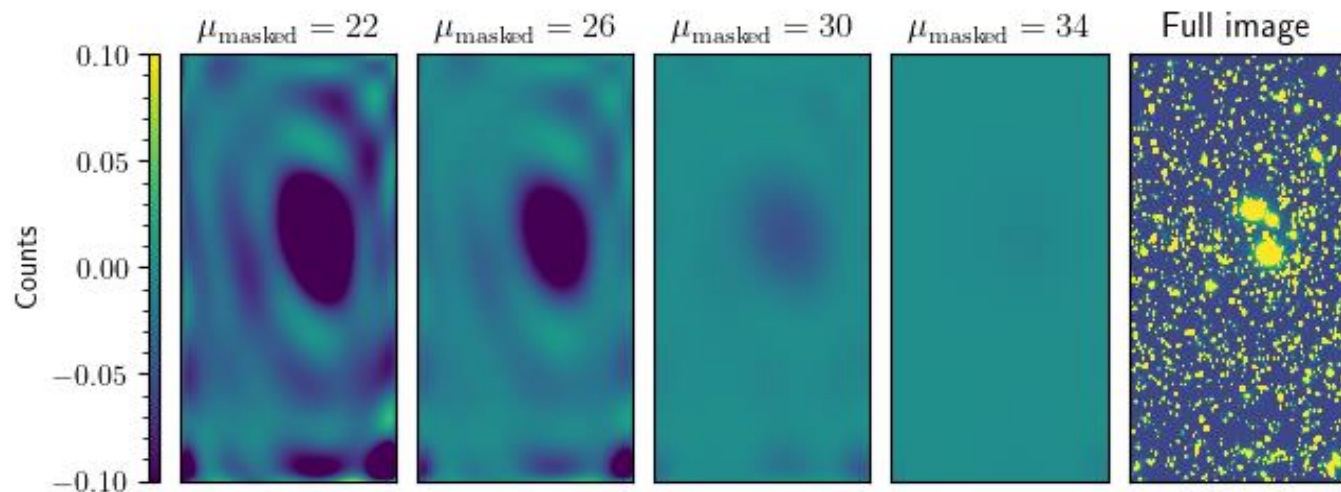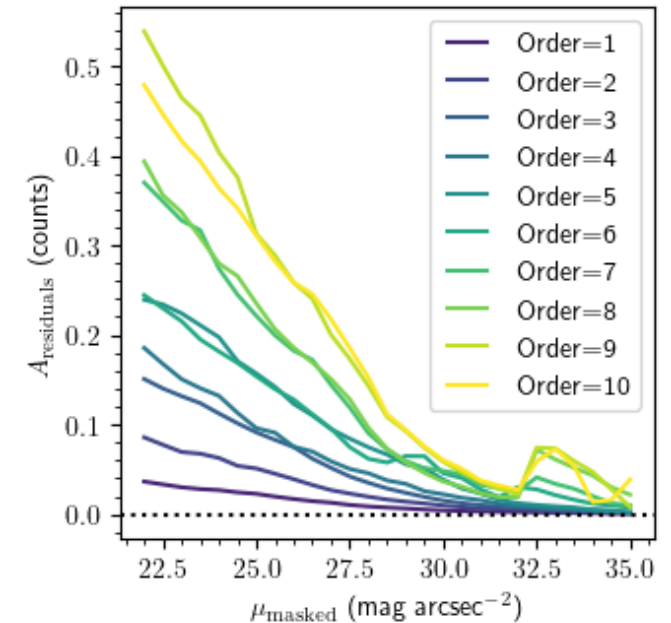
- CAVEAT: fails in extremely crowded fields, or when large, bright objects fill whole frame
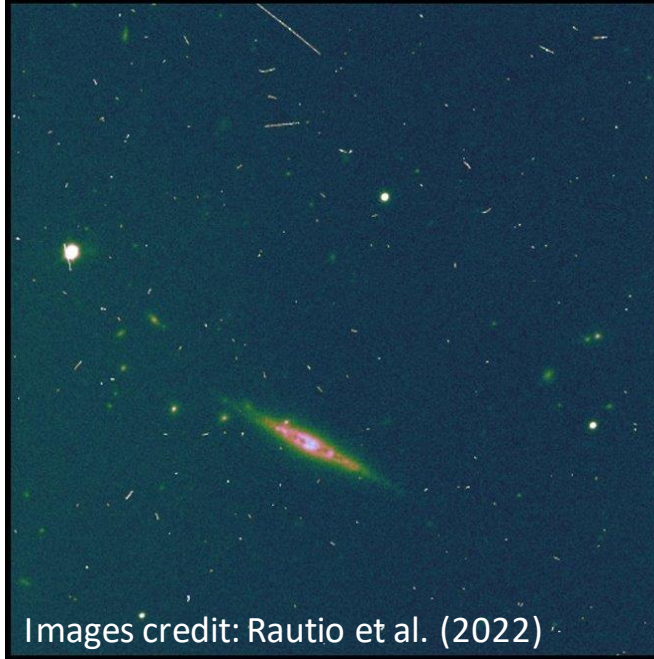
Two potential simple fixes (2)

- 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

- Sky image contains noise (bottom right), which is added to frames on sky-subtraction
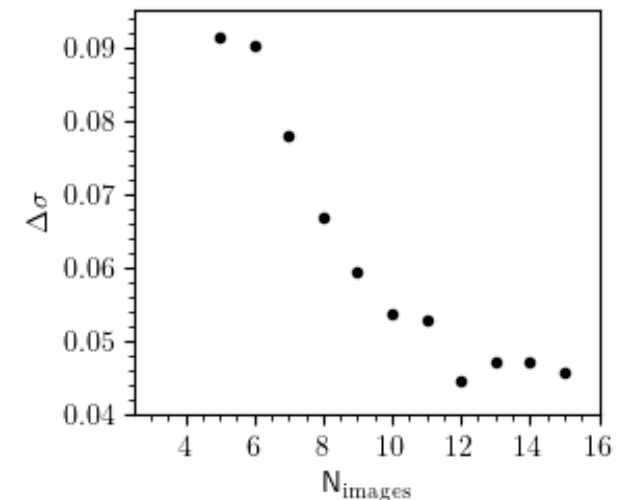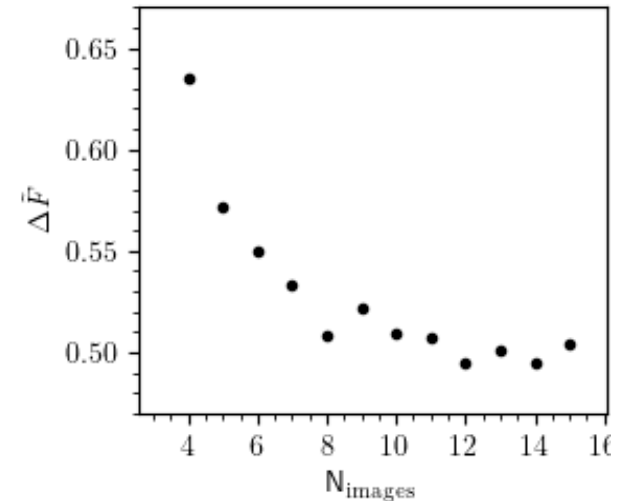
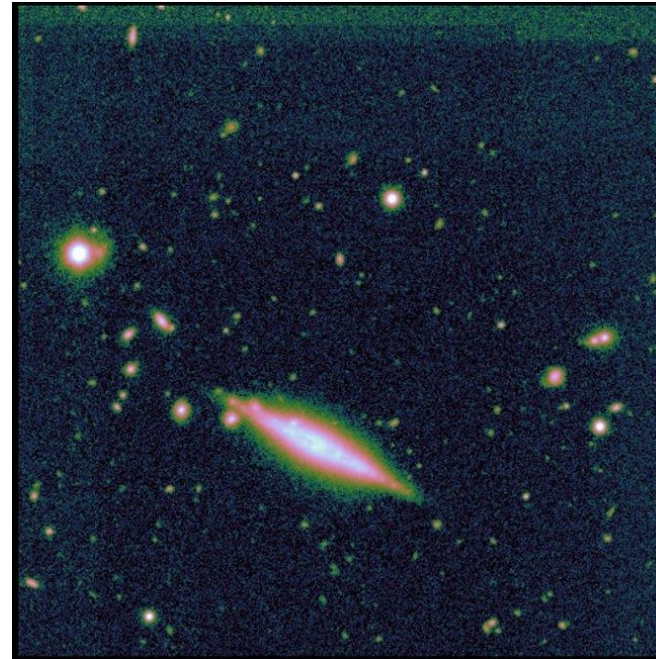# Novel method for cleanup

Single exposure, with sky   Preliminary sky-subtracted coadd   Noisy isolated sky map


Images credit: Rautio et al. (2022)

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- 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

- ## Reducing noise on coadd-subtracted frames
  - Subtracting coadd from individual exposure yields image w/high Gaussian noise
  - Standard (fast!) noise reduction techniques (binning, Gaussian smoothing) imprint noise pattern on binning/smoothing scale
  - Can fit sky image as polynomial, but undesirable

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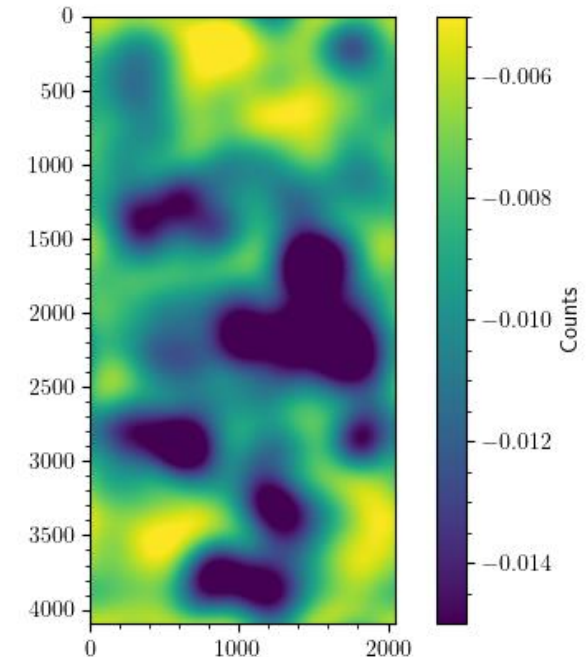
Example noise pattern imprinted on images due to noise reduction strategy (here, binning and Gaussian smoothing)

Potential workaround—fixing bad frames

- 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

Summary

- LSB science composes a large fraction of LSST's potential discovery space, if it is preserved
- As of last year, pipeline was removing large fractions of LSB flux through over-subtraction of sky
- Two potential easy solutions:
  - Better masking and simpler fits to unmasked pixels
    - Fails in very crowded regions (masks too deep, no sky to fit)
  - 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 isolate 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
  - Slight improvement doing this over simply removing bad frames—LSB flux preserved, depth improves, and point-source depth benefits from all exposures. Everybody wins.