Image reduction using *The Tractor*; and the Legacy Surveys

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University of Toronto

Euclid Calibration Workshop / 2016-09-22

Astronomical image reduction

Astronomical image reduction

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ExpGalaxy at RaDecPos: RA, Dec = (241.40283, 8.63426) with NanoMaggies: g=23.4, r=21.3, z=20.1 and E
PointSource at RaDecPos: RA, Dec = (241.40487, 8.63815) with NanoMaggies: g=23.6, r=24.5, z=21.7
PointSource at RaDecPos: RA, Dec = (241.40324, 8.62651) with NanoMaggies: g=14.4, r=13.9, z=13.8
PointSource at RaDecPos: RA, Dec = (241.40213, 8.62382) with NanoMaggies: g=16.6, r=16.2, z=16
PointSource at RaDecPos: RA, Dec = (241.40507, 8.62800) with NanoMaggies: g=27.8, r=22.2, z=21.1
PointSource at RaDecPos: RA, Dec = (241.40913, 8.62305) with NanoMaggies: g=18.3, r=16.9, z=16
PointSource at RaDecPos: RA, Dec = (241.40734, 8.62209) with NanoMaggies: g=26.5, r=22.2, z=21.9
FixedCompositeGalaxy at RaDecPos: RA, Dec = (241.43068, 8.62910) with NanoMaggies: g=18.9, r=17.8, z
PointSource at RaDecPos: RA, Dec = (241.43154, 8.63251) with NanoMaggies: g=21.7, r=21.4, z=22.4
FixedCompositeGalaxy at RaDecPos: RA, Dec = (241.42616, 8.63367) with NanoMaggies: g=20.5, r=18.9, z
PointSource at RaDecPos: RA, Dec = (241.40536, 8.64217) with NanoMaggies: g=21.8, r=20.2, z=19.1
PointSource at RaDecPos: RA, Dec = (241.40477, 8.64181) with NanoMaggies: g=22.2, r=20.7, z=19.5
PointSource at RaDecPos: RA, Dec = (241.42465, 8.62741) with NanoMaggies: g=20.7, r=20.3, z=19.9
PointSource at RaDecPos: RA, Dec = (241.42507, 8.62513) with NanoMaggies: g=24.1, r=21.4, z=20.7
PointSource at RaDecPos: RA, Dec = (241.41836, 8.63195) with NanoMaggies: g=22.4, r=20.9, z=19.9
FixedCompositeGalaxy at RaDecPos: RA, Dec = (241.42272, 8.64120) with NanoMaggies: g=20.6, r=19.9, z
FixedCompositeGalaxy at RaDecPos: RA, Dec = (241.42276, 8.62457) with NanoMaggies: g=21.5, r=20.1, z
PointSource at RaDecPos: RA, Dec = (241.43404, 8.62773) with NanoMaggies: g=21.9, r=20.6, z=18.7
FixedCompositeGalaxy at RaDecPos: RA, Dec = (241.43345, 8.61975) with NanoMaggies: g=21.8, r=20.8, z
PointSource at RaDecPos: RA, Dec = (241.40560, 8.63421) with NanoMaggies: g=23.7, r=22.2, z=21.3
PointSource at RaDecPos: RA, Dec = (241.41174, 8.62798) with NanoMaggies: g=23.5, r=22.2, z=21.5
PointSource at RaDecPos: RA, Dec = (241.41362, 8.63167) with NanoMaggies: g=23.7, r=22.5, z=20.8
PointSource at RaDecPos: RA, Dec = (241.41552, 8.63480) with NanoMaggies: g=22.9, r=21.4, z=19.9
PointSource at RaDecPos: RA, Dec = (241.41910, 8.64038) with NanoMaggies: g=23, r=21.9, z=19.7
PointSource at RaDecPos: RA, Dec = (241.41619, 8.62815) with NanoMaggies: g=23.2, r=22.3, z=(flux -0
DevGalaxy at RaDecPos: RA, Dec = (241.41651, 8.62424) with NanoMaggies: g=23.2, r=22, z=20.9 and Ell
PointSource at RaDecPos: RA, Dec = (241.42234, 8.62769) with NanoMaggies: g=23, r=21.7, z=20.1
ExpGalaxy at RaDecPos: RA, Dec = (241.42484, 8.63754) with NanoMaggies: g=22.8, r=22.3, z=21.8 and E
ExpGalaxy at RaDecPos: RA, Dec = (241.42847, 8.62040) with NanoMaggies: g=21.9, r=21.7, z=20.6 and E
PointSource at RaDecPos: RA, Dec = (241.43236, 8.62368) with NanoMaggies: g=23.2, r=22.5, z=21.3
PointSource at RaDecPos: RA, Dec = (241.43837, 8.63847) with NanoMaggies: g=23, r=21.8, z=20.8
FixedCompositeGalaxy at RaDecPos: RA, Dec = (241.40960, 8.63108) with NanoMaggies: g=(flux -0.224),
PointSource at RaDecPos: RA, Dec = (241.43644, 8.63866) with NanoMaggies: g=25.5, r=23.7, z=21.3
```

Conclusions

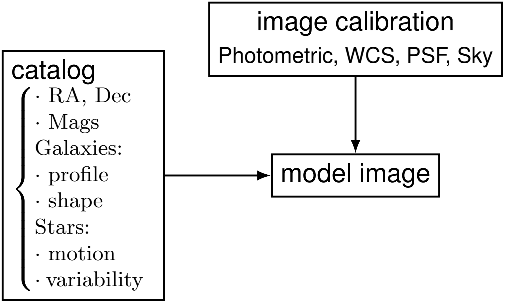
Take-away messages:

- Forward modeling is a clean way of getting *all* the information out of images from diverse instruments (no PSF homogenization; no resampling; no coadds)
- Consider forced photometry for Euclid: VIS detects and measures all the objects; this makes EXT/MER photometry easier!

Second-order:

- the Tractor is a code that can do these things
- We're using the Tractor at scale in the Legacy Surveys (DECaLS, MzLS)
- Can re-fit calibration parameters
- Can use sampling to characterize covariances

the Tractor – forward modeling for images



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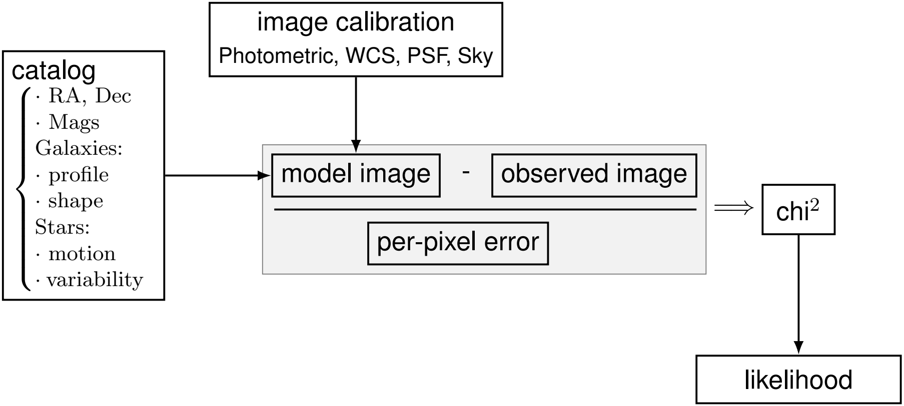
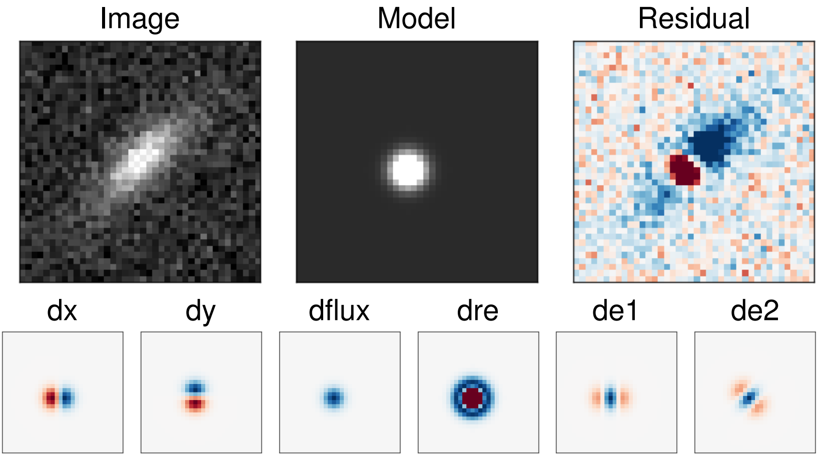
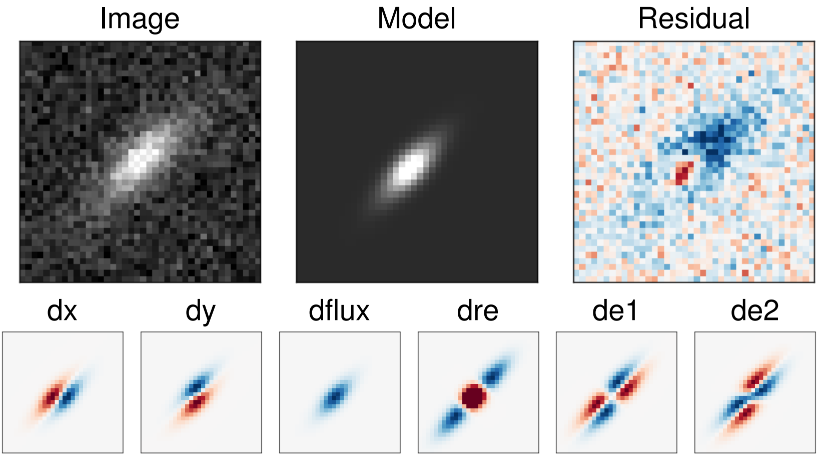


Example: Galaxy fitting



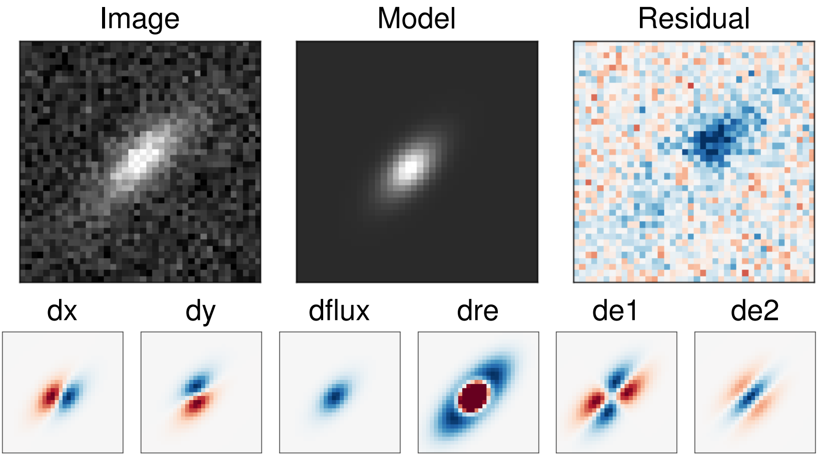
ExpGalaxy at pixel (18.00, 18.00) with Flux: 500
shape EllipseE: re=1, e1=0, e2=0

Example: Galaxy fitting



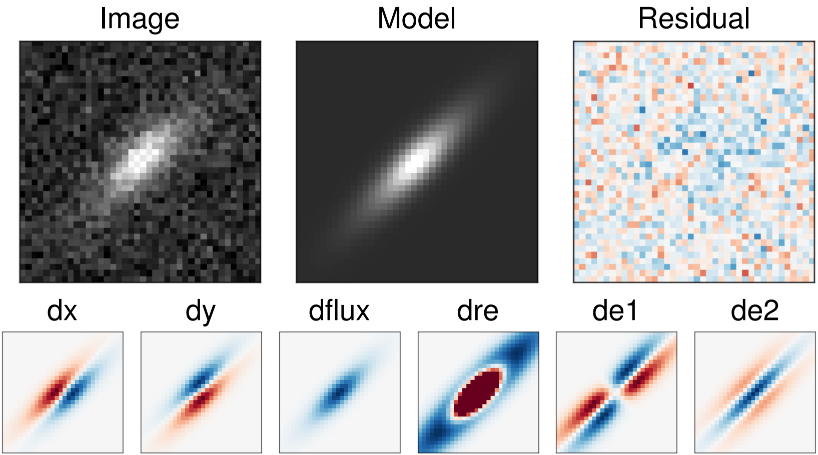
ExpGalaxy at pixel (18.30, 18.30) with Flux: 432.5
shape EllipseE: re=3.74, e1=0.07, e2=0.98

Example: Galaxy fitting



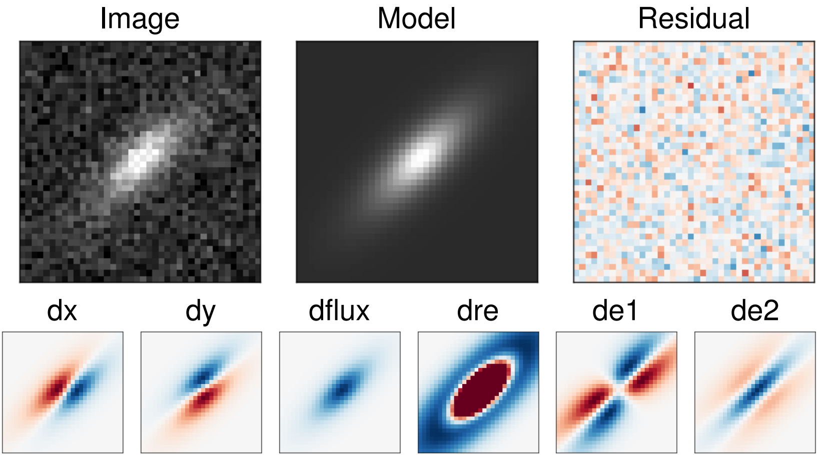
ExpGalaxy at pixel (18.33, 18.32) with Flux: 441.7
shape EllipseE: re=3.85, e1=0.03, e2=0.46

Example: Galaxy fitting



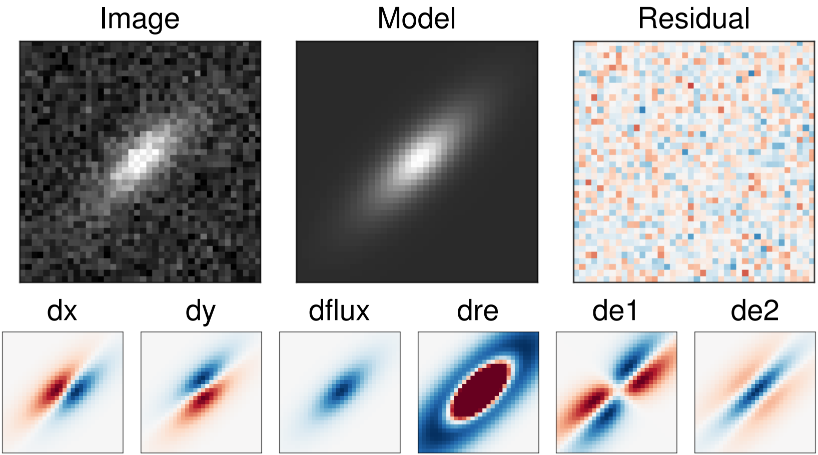
ExpGalaxy at pixel (19.27, 19.29) with Flux: 837.4
shape EllipseE: re=8.16, e1=0.002, e2=0.70

Example: Galaxy fitting



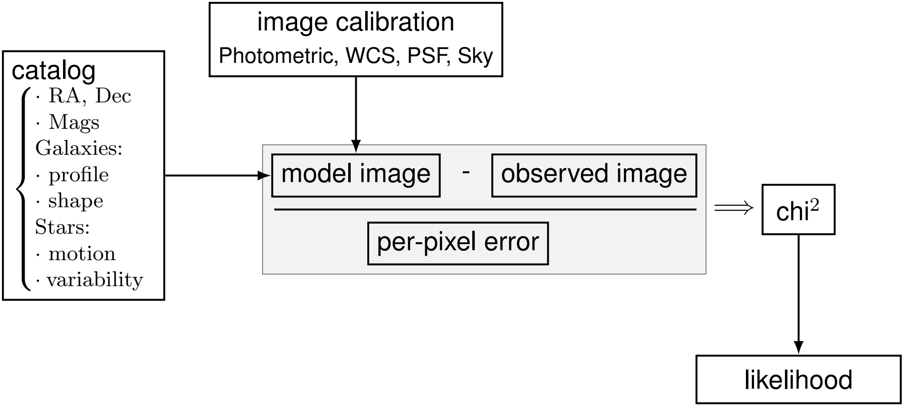
ExpGalaxy at pixel (20.12, 20.06) with Flux: 1094.5
shape EllipseE: re=8.89, e1=-0.013, e2=0.54

Example: Galaxy fitting



ExpGalaxy at pixel (19.91, 19.85) with Flux: 1082.7
shape EllipseE: re=8.92, e1=-0.018, e2=0.54

the Tractor – forward modeling for images



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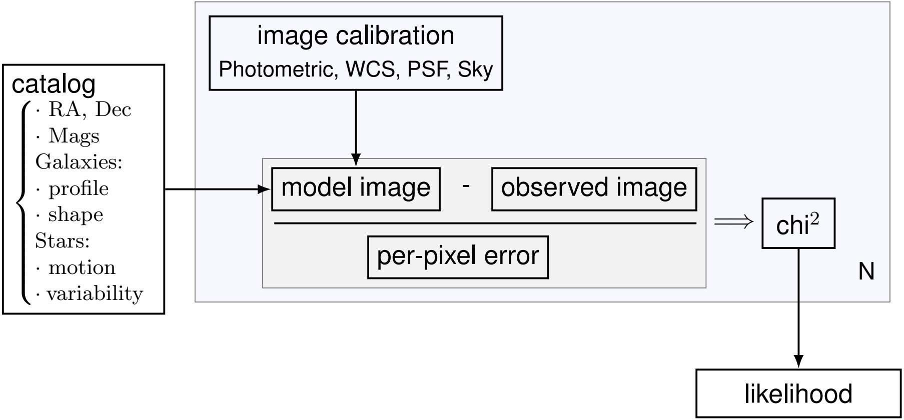
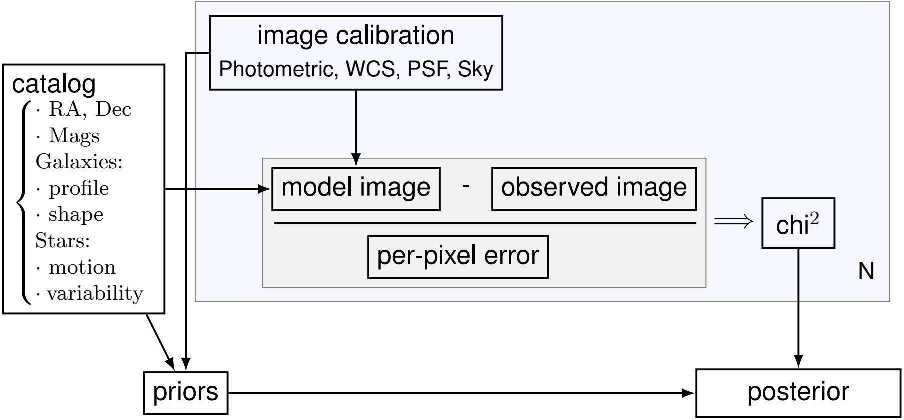
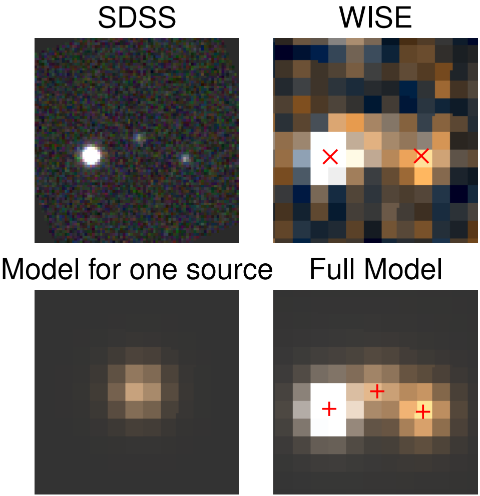


the Tractor – forward modeling for images

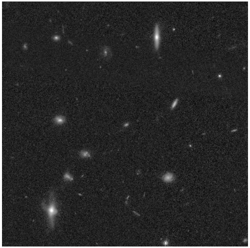


Example: Forced photometry



Example: Forced photometry for Euclid

“VIS” (from ACS F814W)

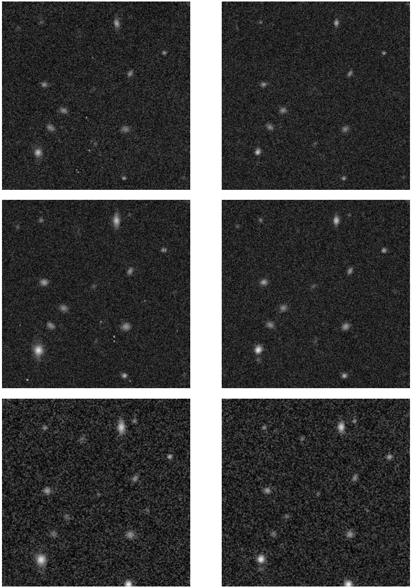


Data Model

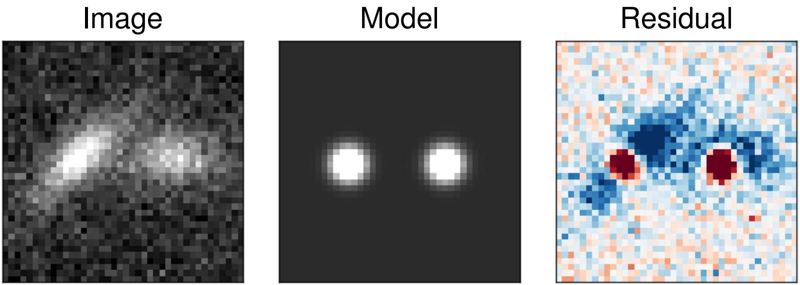
CFHT g

CFHT r

DECam z



Example: Two galaxy fitting



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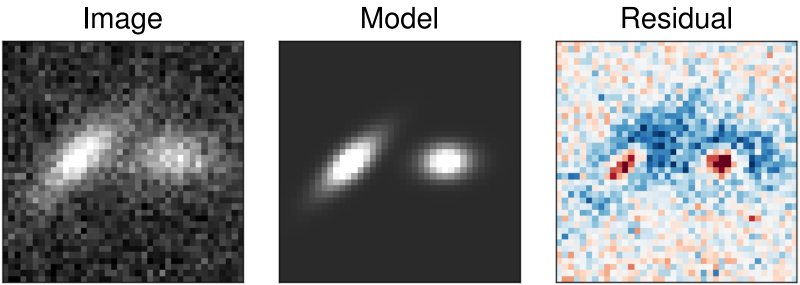
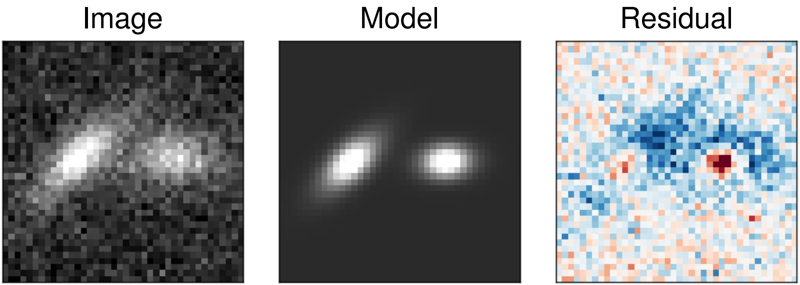
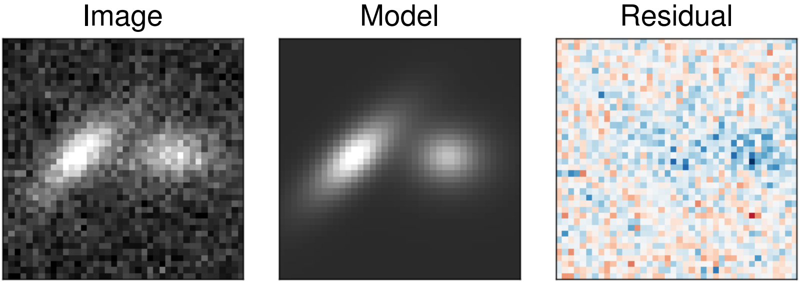


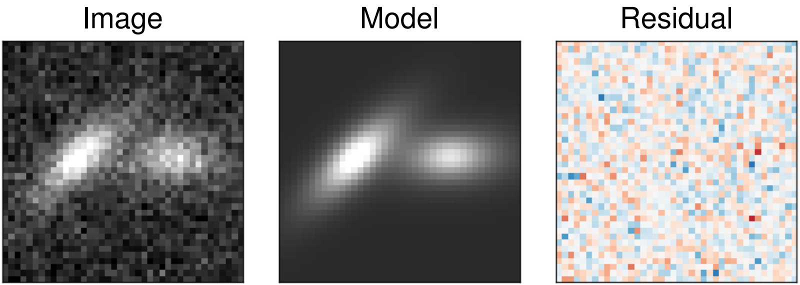
Example: Two galaxy fitting



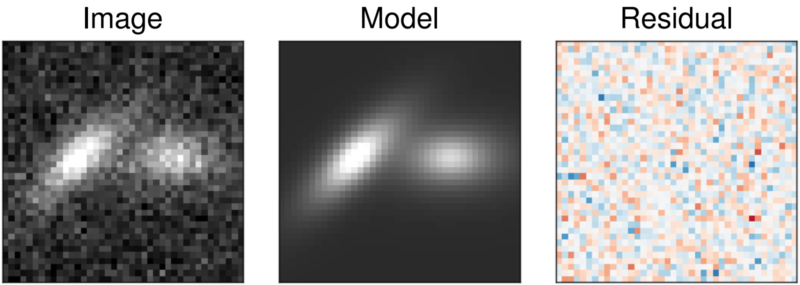
Example: Two galaxy fitting



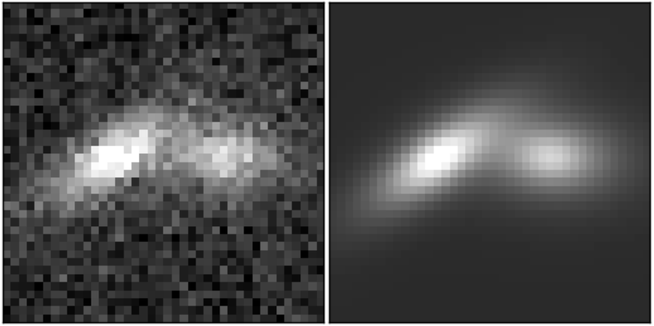
Example: Two galaxy fitting



Example: Two galaxy fitting

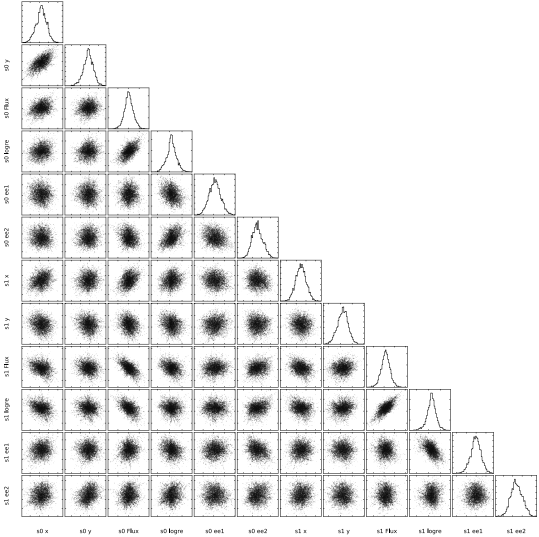


Example: Two galaxy sampling

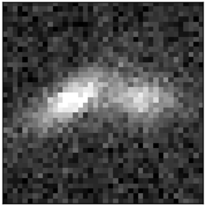


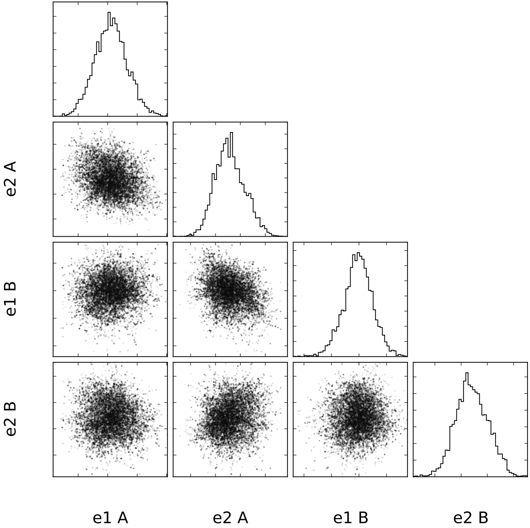
skip

Example: Two galaxy sampling

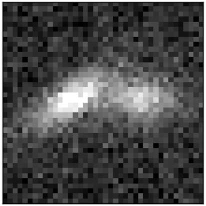


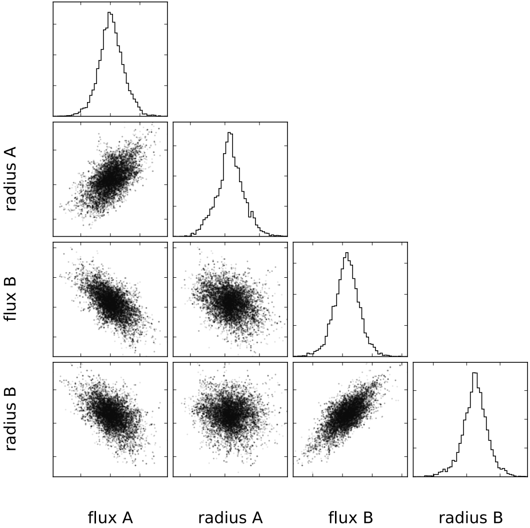
Example: Two galaxy sampling





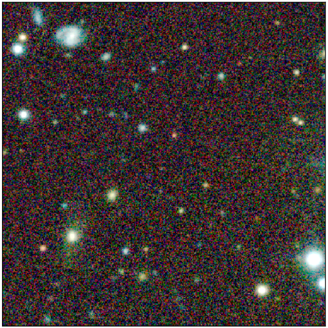
Example: Two galaxy sampling

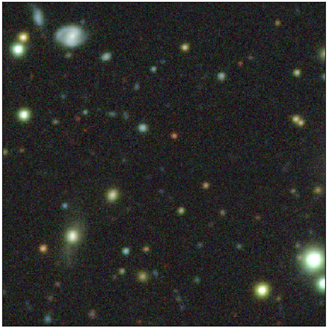




the Legacy Survey family (*legacysurvey.org*)

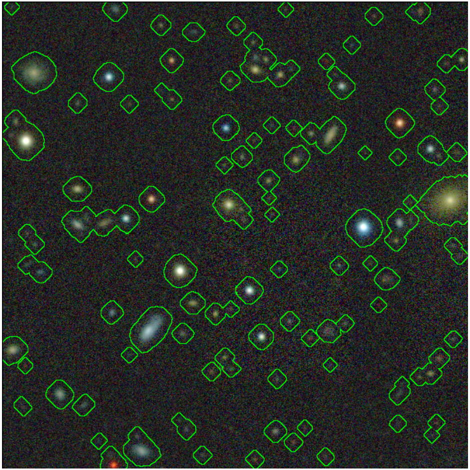
- Public imaging surveys, g, r, z, WISE, for DESI targeting ($g \sim 24.7, r \sim 23.9, z \sim 23$)
- All raw data immediately public; reduced $\sim$semi-annually
- Code: *github.com/legacysurvey*, Viewer *legacysurvey.org/viewer*
- Equatorial sky: DECam (Blanco 4 m)
- Northern sky: Mosaic (Mayall 4 m) $+$ 90-Prime (Bok 2.3 m)


SDSS

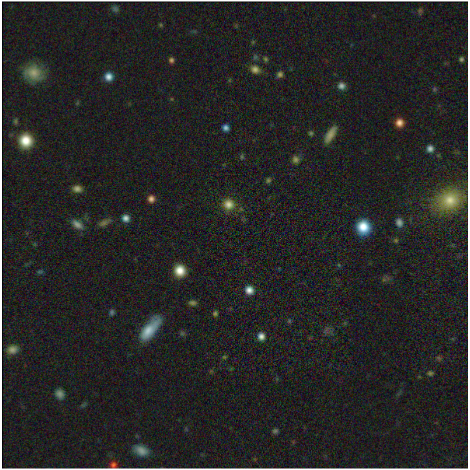

DECaLS

Applying the Tractor to DECaLS data

Blobs



DECam Coadd



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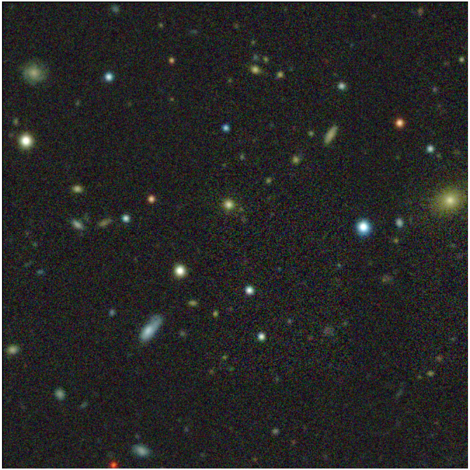
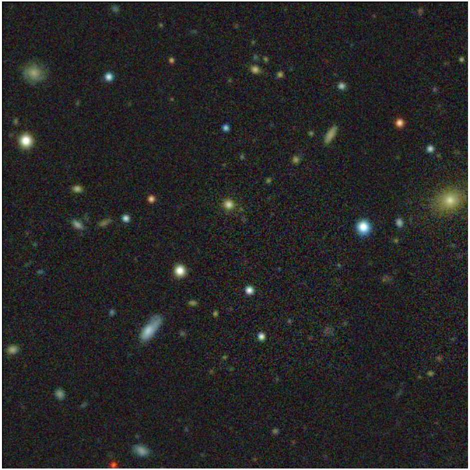
DECam Coadd

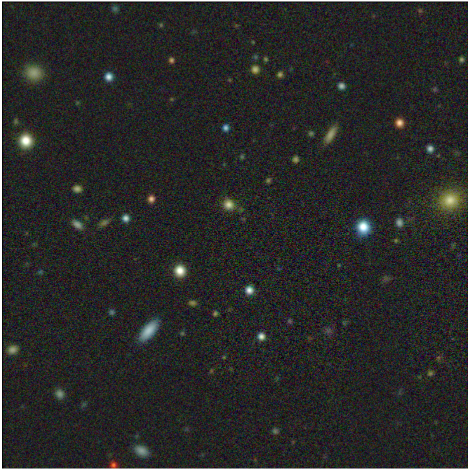


DECam Coadd



Applying the Tractor to DECaLS data

Model + Noise



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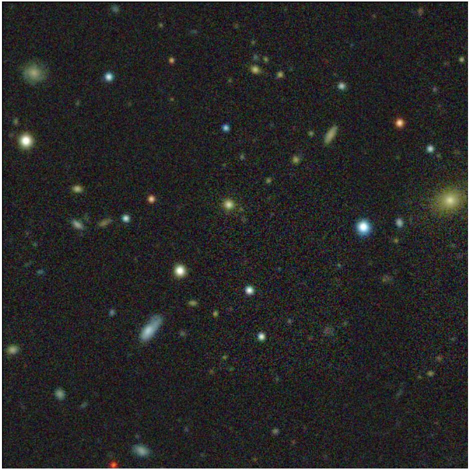
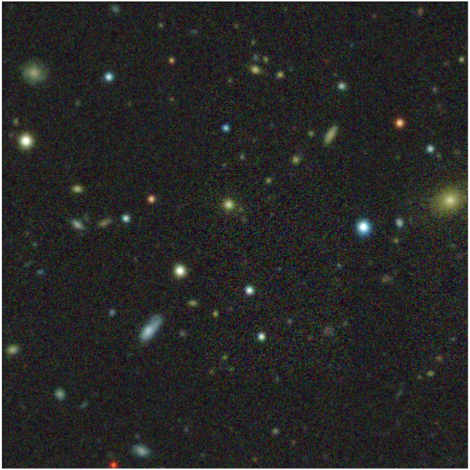


Applying the Tractor to DECaLS data

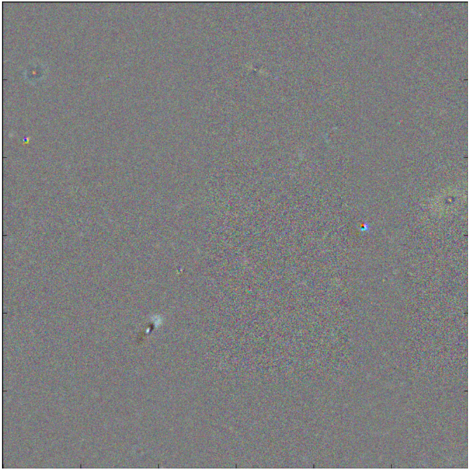
Model

DECam Coadd

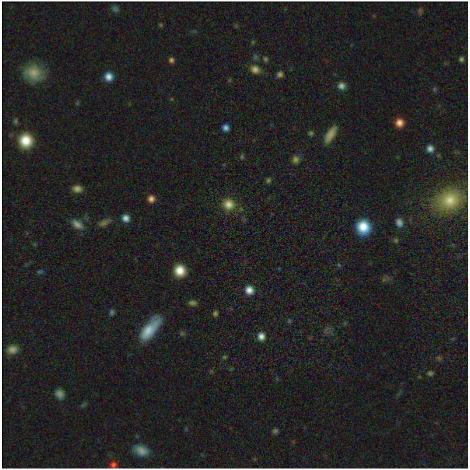


Applying the Tractor to DECaLS data

Residuals

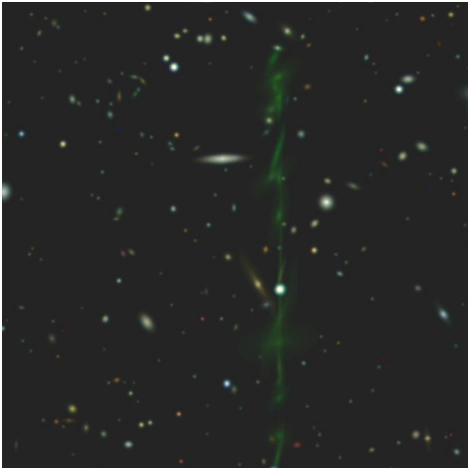


DECam Coadd

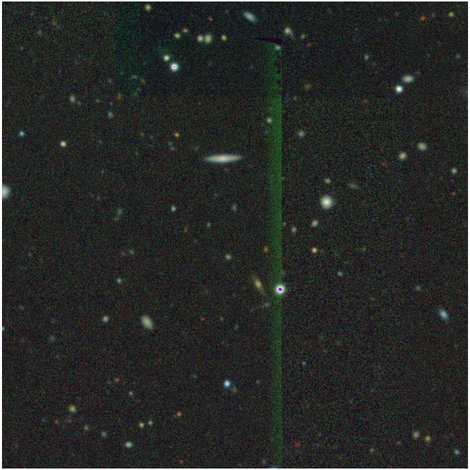


Applying the Tractor to DECaLS data

Model

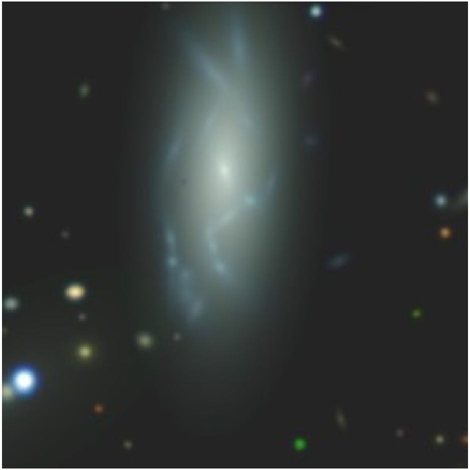


DECam Coadd

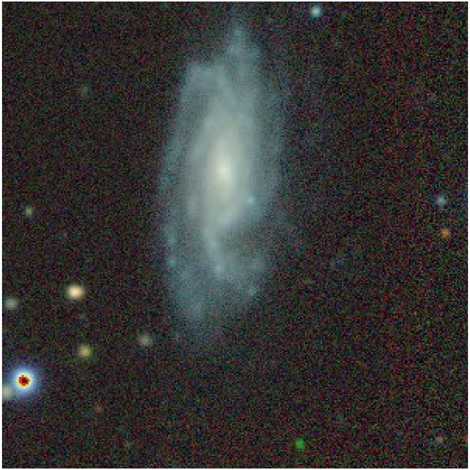


Applying the Tractor to DECaLS data

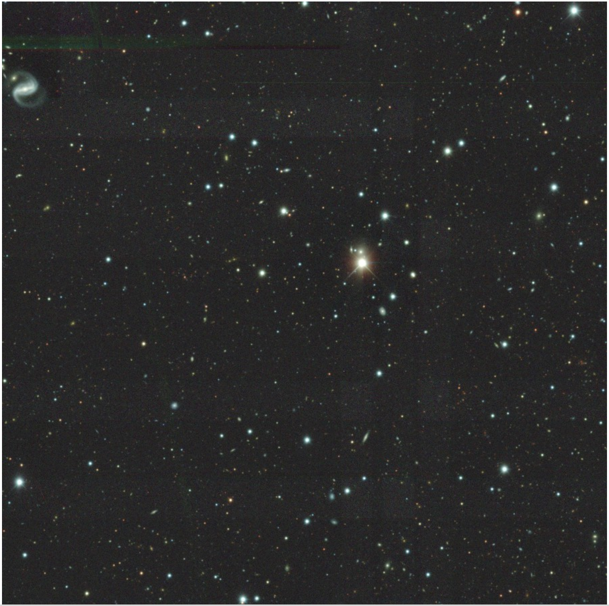
Model



DECam Coadd



Applying the Tractor to DECaLS data



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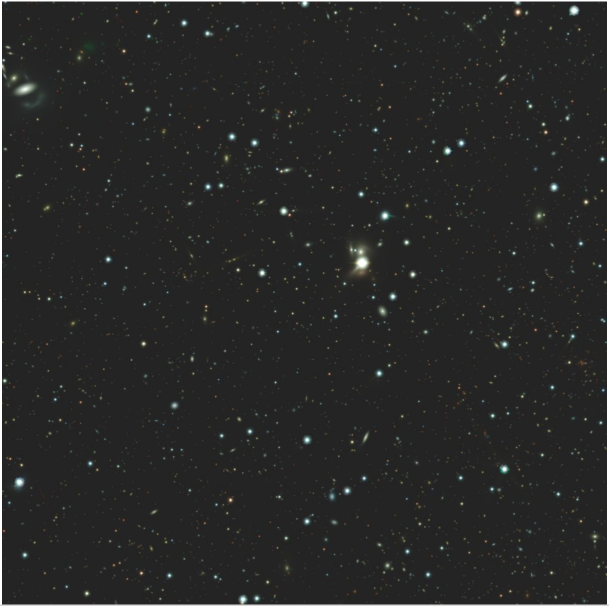

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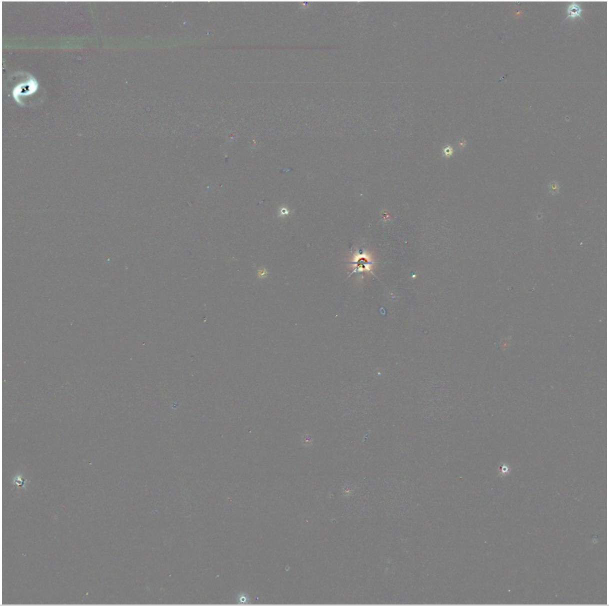
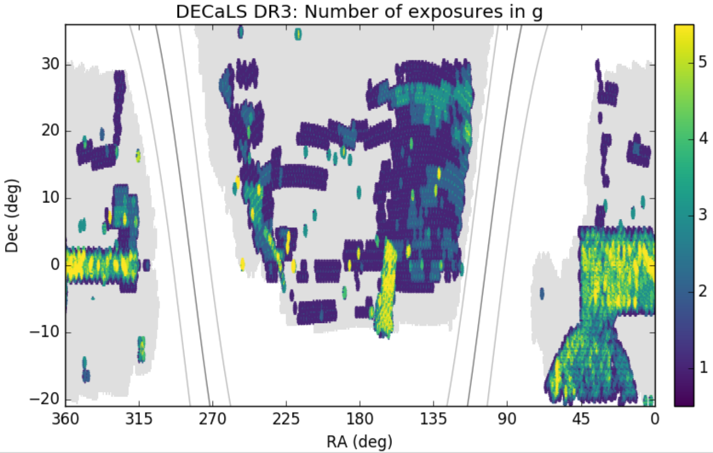


DECaLS: Data Release 3

- Released September 2016
- Processing all our data AND all public DECam data
- 4200 sq. deg with g, r, z coverage ($\sim$ 500 million sources)



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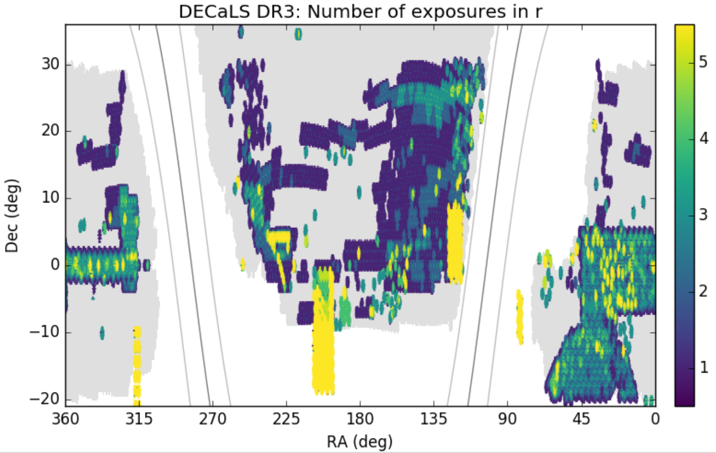

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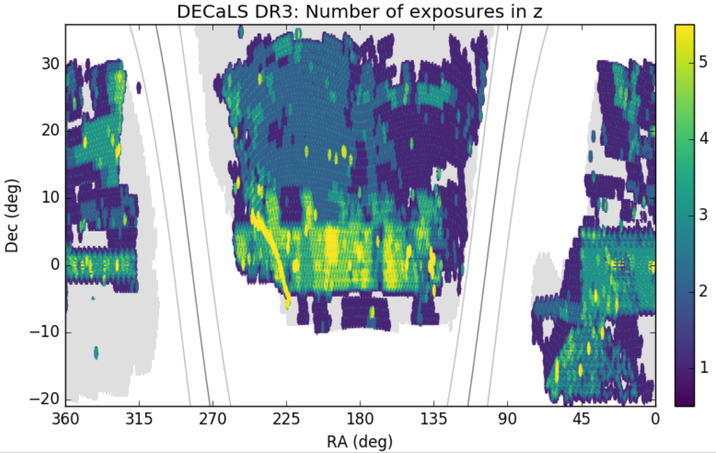

Conclusions

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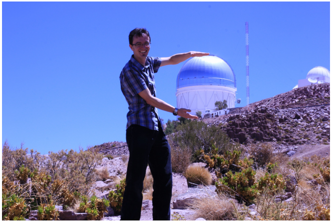
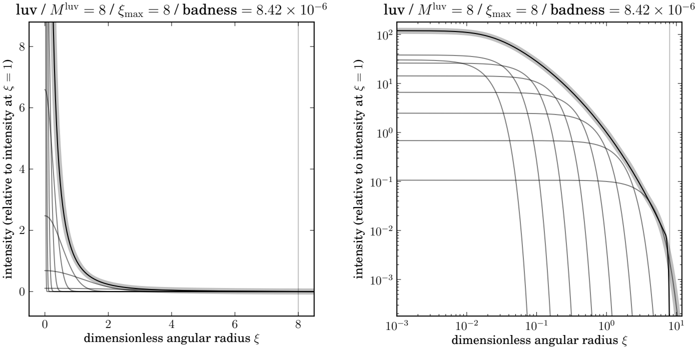
Thanks!



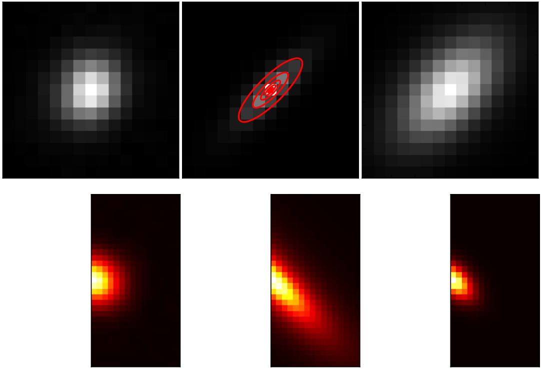
Tricks

- central operation: render pixel models & derivatives
- galaxies: convolution of galaxy profile by PSF
  (can't do naive convolution)
- we use two tricks, both using Mixtures of Gaussians
  approximations of galaxy profiles ($G_s(r) \propto e^{-kr^{1/s}}$)



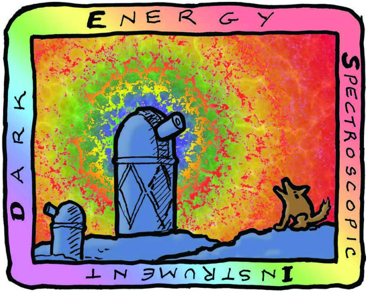
Convolution Trick #2

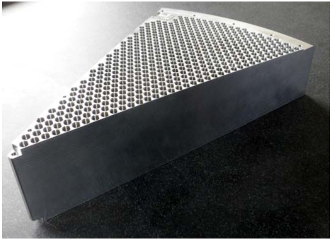
- pixelized PSF model; take Fourier transform
- Gaussians have analytic Fourier transforms; $F(g) = G$
- evaluate $F(\mathrm{galaxy})$ directly
- multiply and Inverse FFT to get the convolved profile



Dark Energy Spectroscopic Instrument (DESI)

- 5000-fiber spectrograph, 3° FOV, on the 4-m Mayall
- On-sky 2018, 5-year survey. 9k to 14k sq deg
  - 4M Luminous Red Galaxies (LRGs), $z \in [0.4, 1]$
  - 18M Emission Line Galaxies (ELGs), $z \in [0.6, 1.6]$
  - 2M tracer QSOs, $z < 2.1$ plus 0.7M Ly-α QSOs, $z > 2.1$

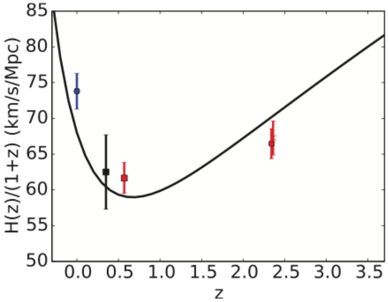




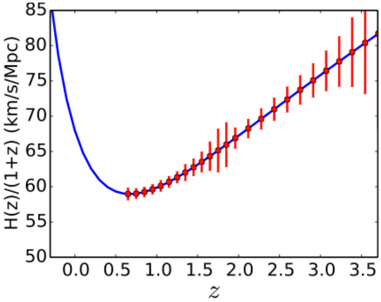
Dark Energy Spectroscopic Instrument (DESI)

BAO in many redshift slices to nail down the growth history

Before DESI

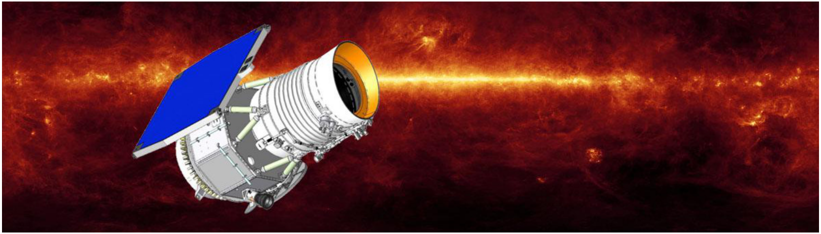


DESI

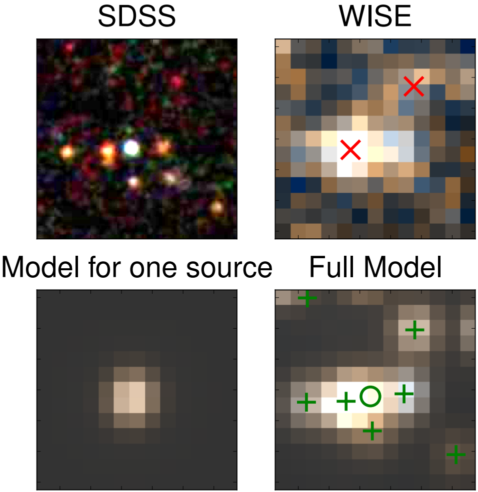


WISE Satellite

- Wide-field Infrared Survey Explorer
- Mid-infrared: W1 (3.4μ), W2 (4.6μ), W3 (12μ), W4 (22μ)
- Primary survey: 2010-2011; reactivated for more in 2014!
- W1/W2 — median of 33 exposures all-sky
- Scans from Ecliptic pole-to-pole — $5{,}000$ exposures at the poles
- Pixel scale: 2.75 arcsec/pixel: (7 times bigger than SDSS)



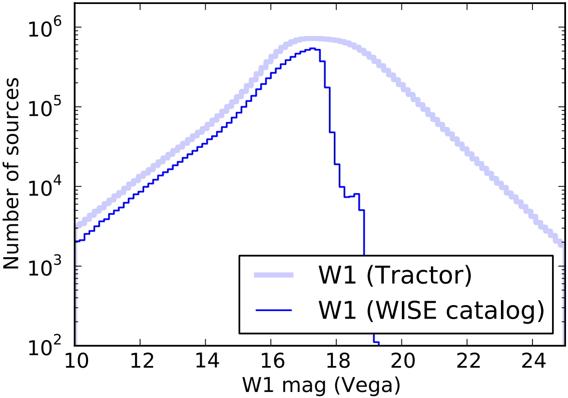
WISE photometry



(Targeted in BOSS W3 ancillary; quasar at $z = 2.71$)

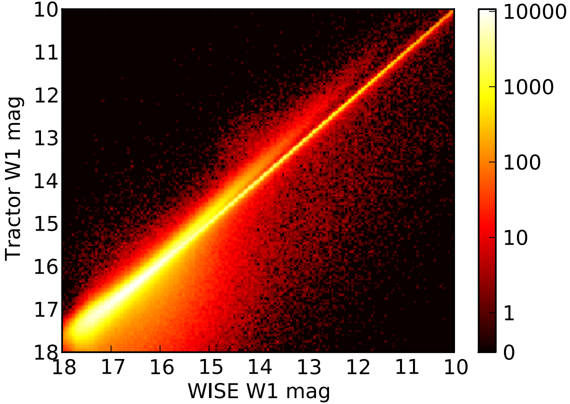
WISE Tractor photometry: depth

We measure sources below the WISE catalog 5-sigma threshold



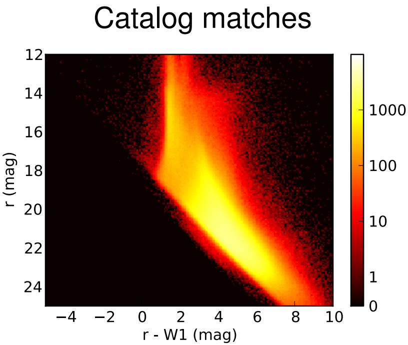
WISE Tractor photometry: accuracy

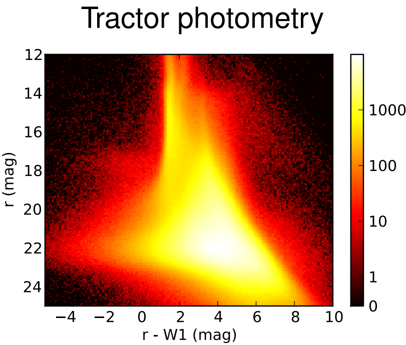
The Tractor measurements are consistent with the WISE catalog



WISE Tractor photometry: depth

The Tractor measurements of faint objects make sense astrophysically





Multi-Band (SED-matched) Detection

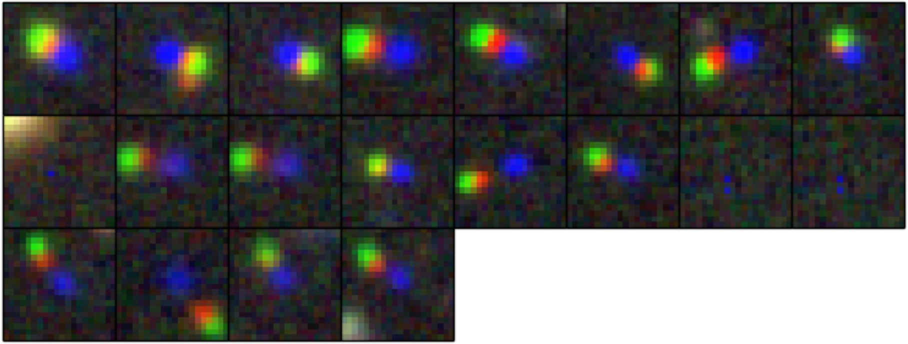
- Example: g,r,i measurements

- Assume flat SED ("Vega"); estimate r flux
- g flux is an estimate of r flux; $\hat{r}_g = g$
- i flux is an estimate of r flux; $\hat{r}_i = i$
- Three predictions of r flux, with Gaussian errors
- $\rightarrow$ inverse-variance weighting

- Assume red spectrum (colors $g - r = r - i = 1$):
- g flux is an estimate of r flux; $\hat{r}_g = g * 2.5$
  (with variance 2.5^2 larger)
- i flux is an estimate of r flux; $\hat{r}_i = i/2.5$
  (with variance 2.5^2 smaller)

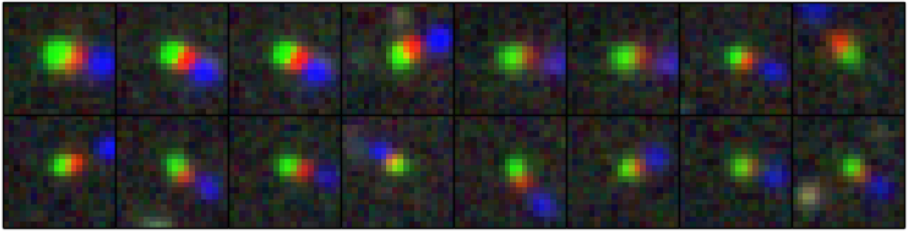
SED-matched detection

Detections strongest in g-only



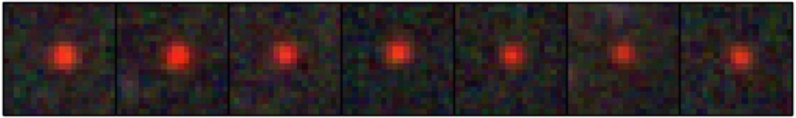
SED-matched detection

Detections strongest in r-only



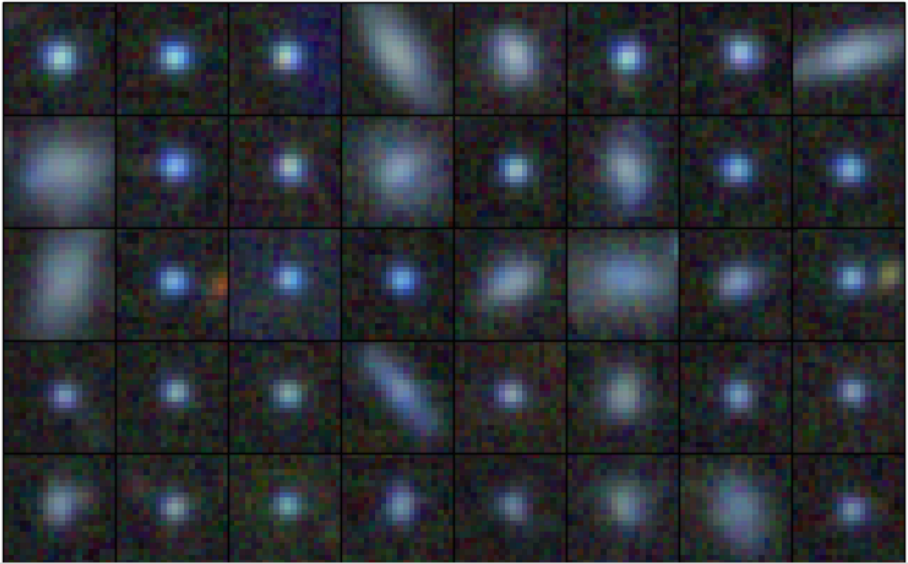
SED-matched detection

Detections strongest in i-only

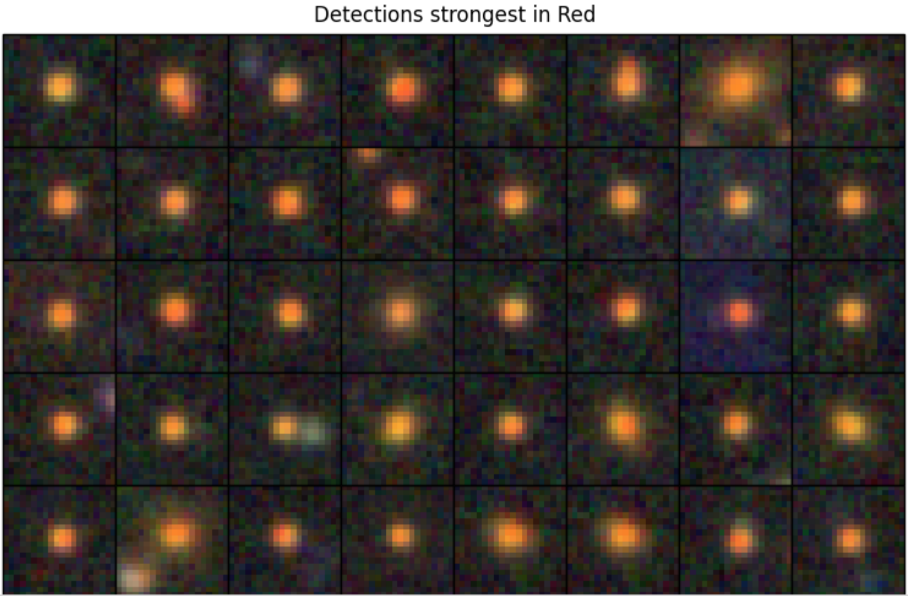


SED-matched detection

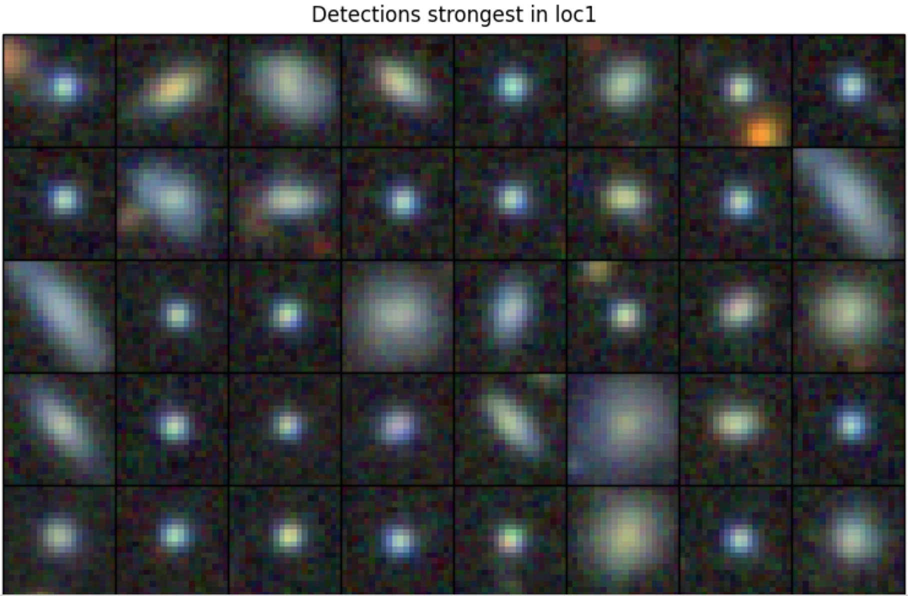
Detections strongest in Flat



SED-matched detection

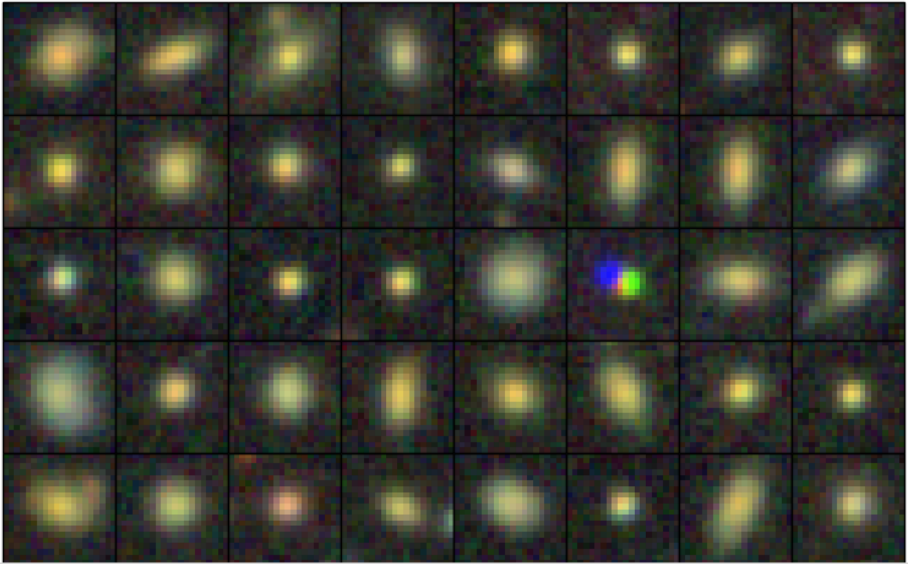


SED-matched detection

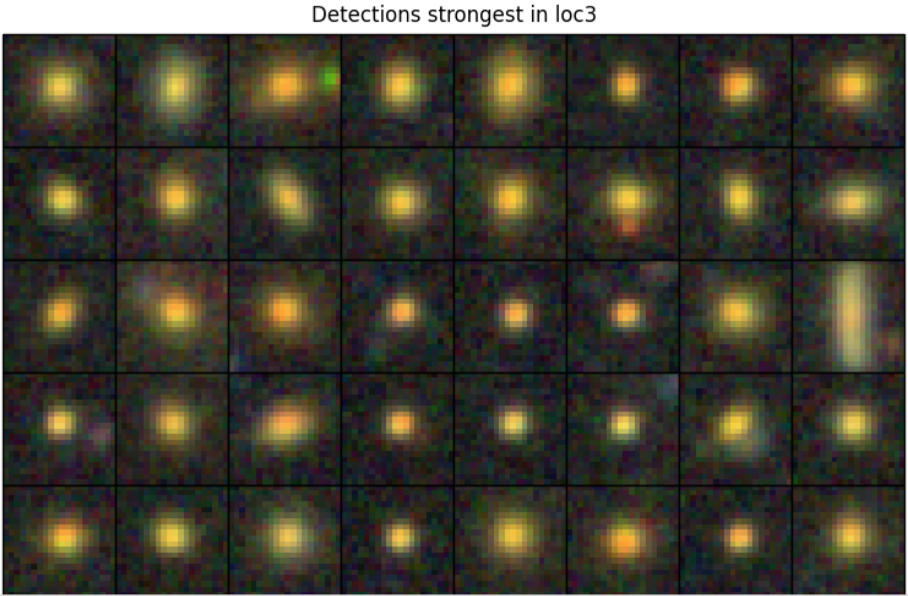


SED-matched detection

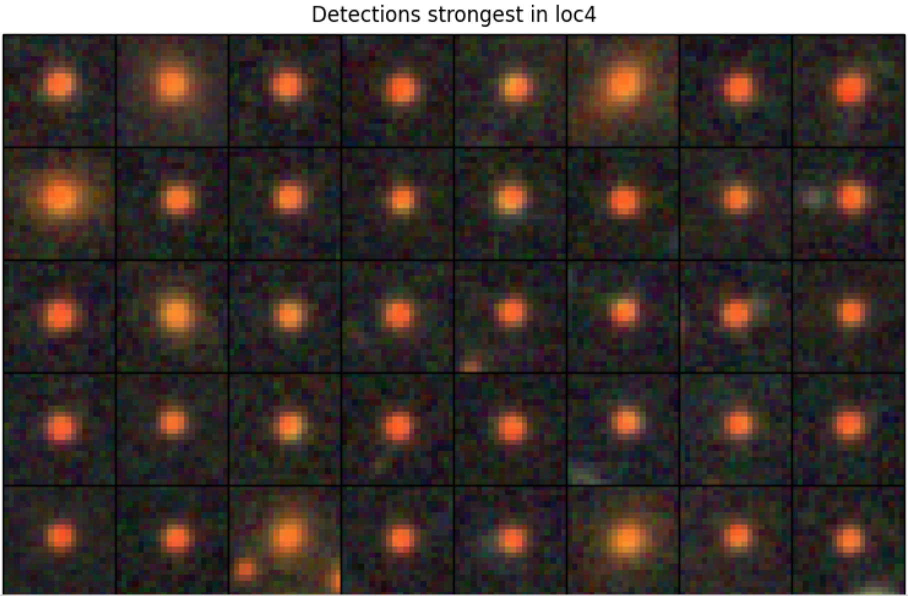
Detections strongest in loc2



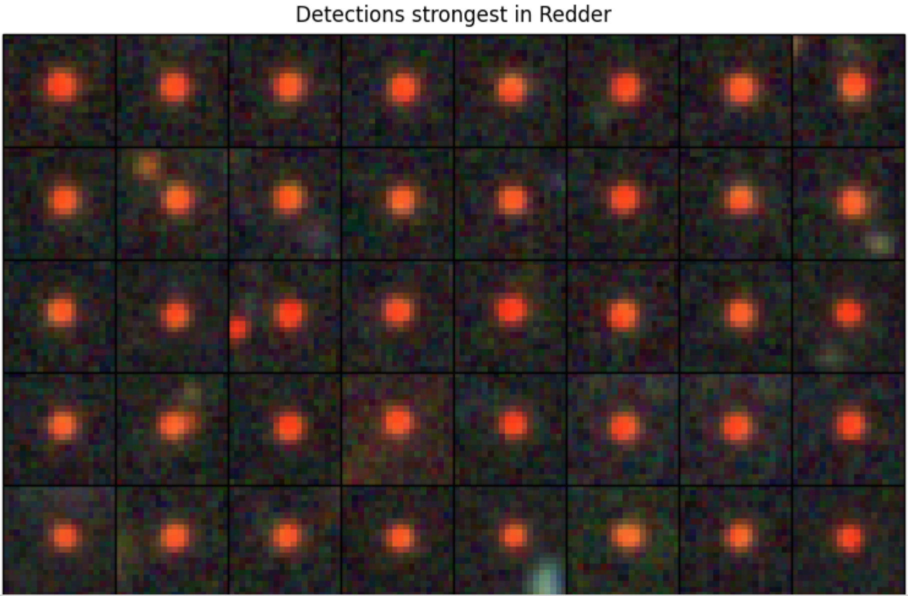
SED-matched detection



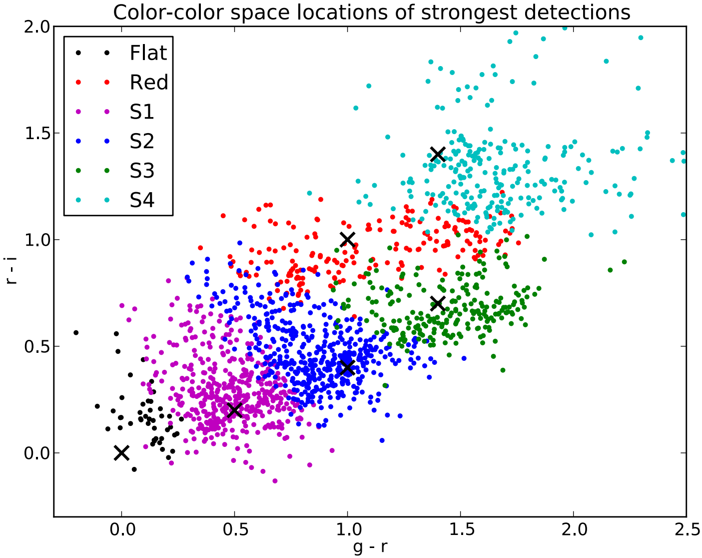
SED-matched detection



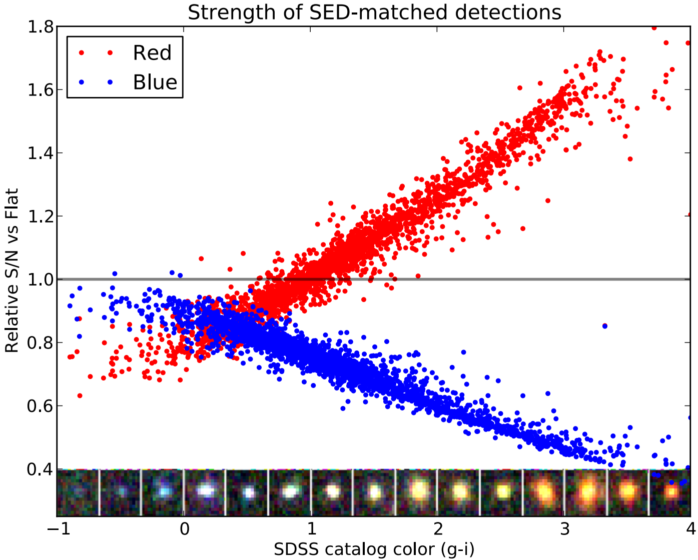
SED-matched detection



SED-matched detection



SED-matched detection



SED-matched detection