Galaxy Photometry

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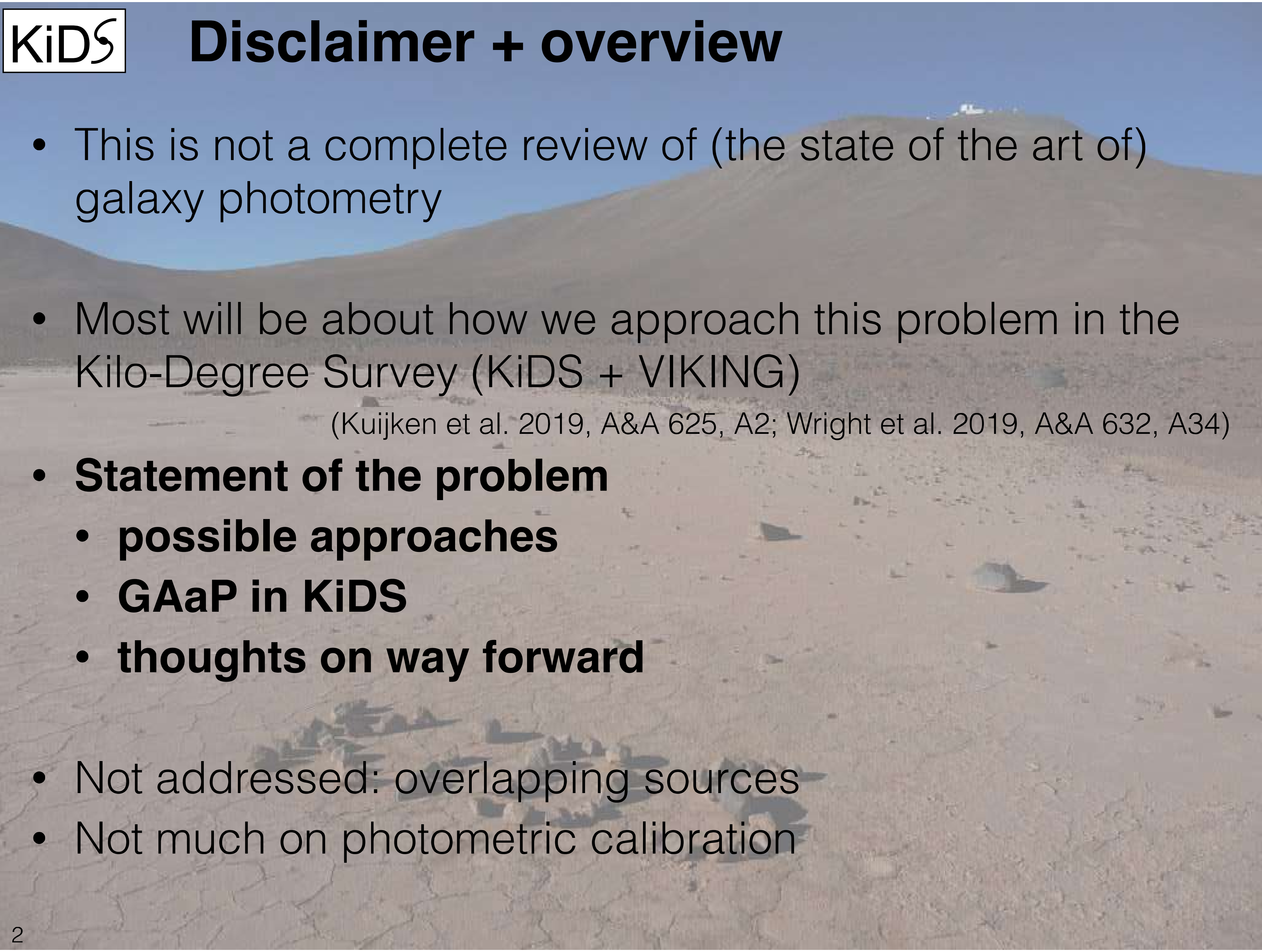
Disclaimer + overview



- This is not a complete review of (the state of the art of) galaxy photometry

- Most will be about how we approach this problem in the Kilo-Degree Survey (KiDS + VIKING)

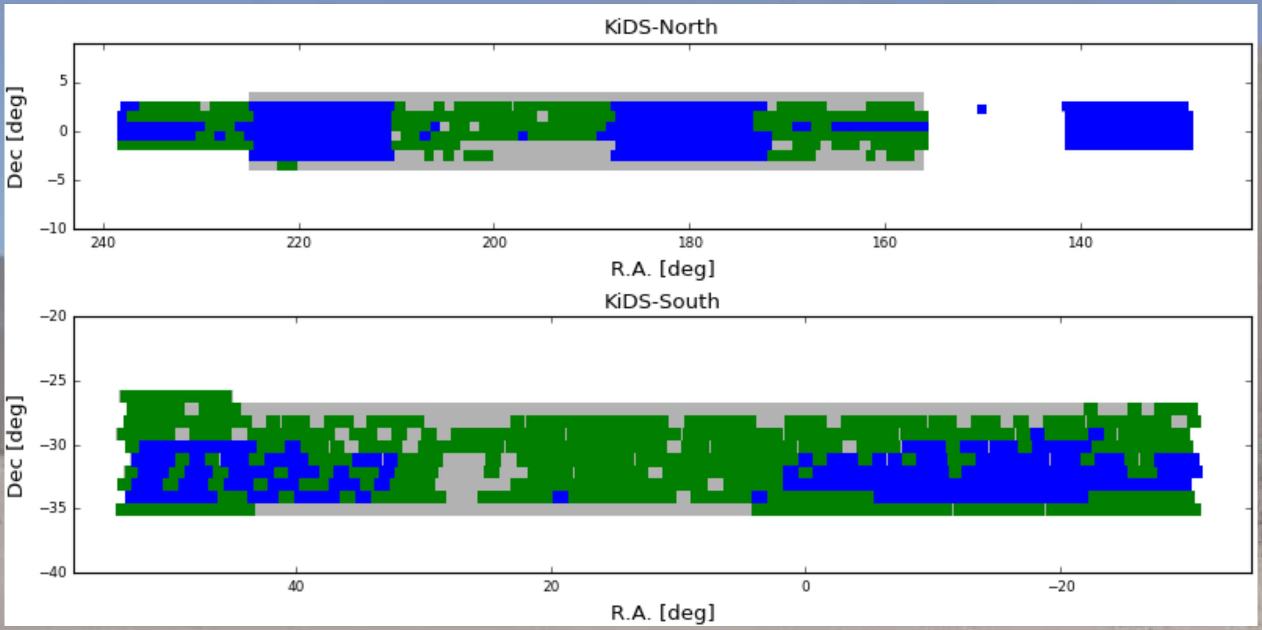
(Kuijken et al. 2019, A&A 625, A2; Wright et al. 2019, A&A 632, A34)

- **Statement of the problem**
  - **possible approaches**
  - **GAaP in KiDS**
  - **thoughts on way forward**

- Not addressed: overlapping sources
- Not much on photometric calibration

KiDS

The Kilo-Degree Survey: basic stats



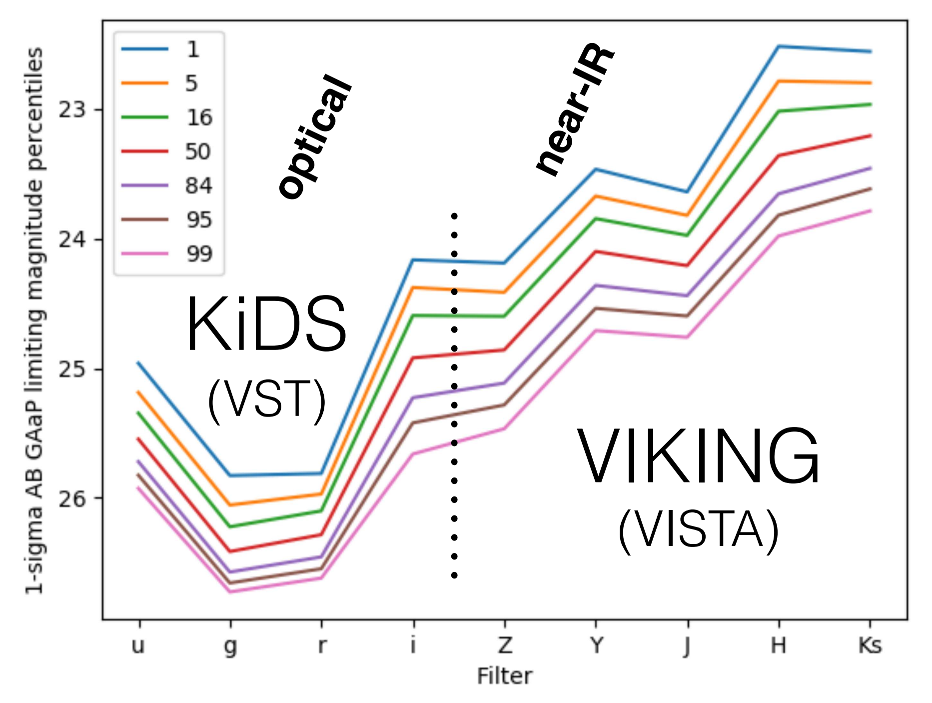
DR3 **DR4**
15M. **33M.**

Final area **1350 deg²**

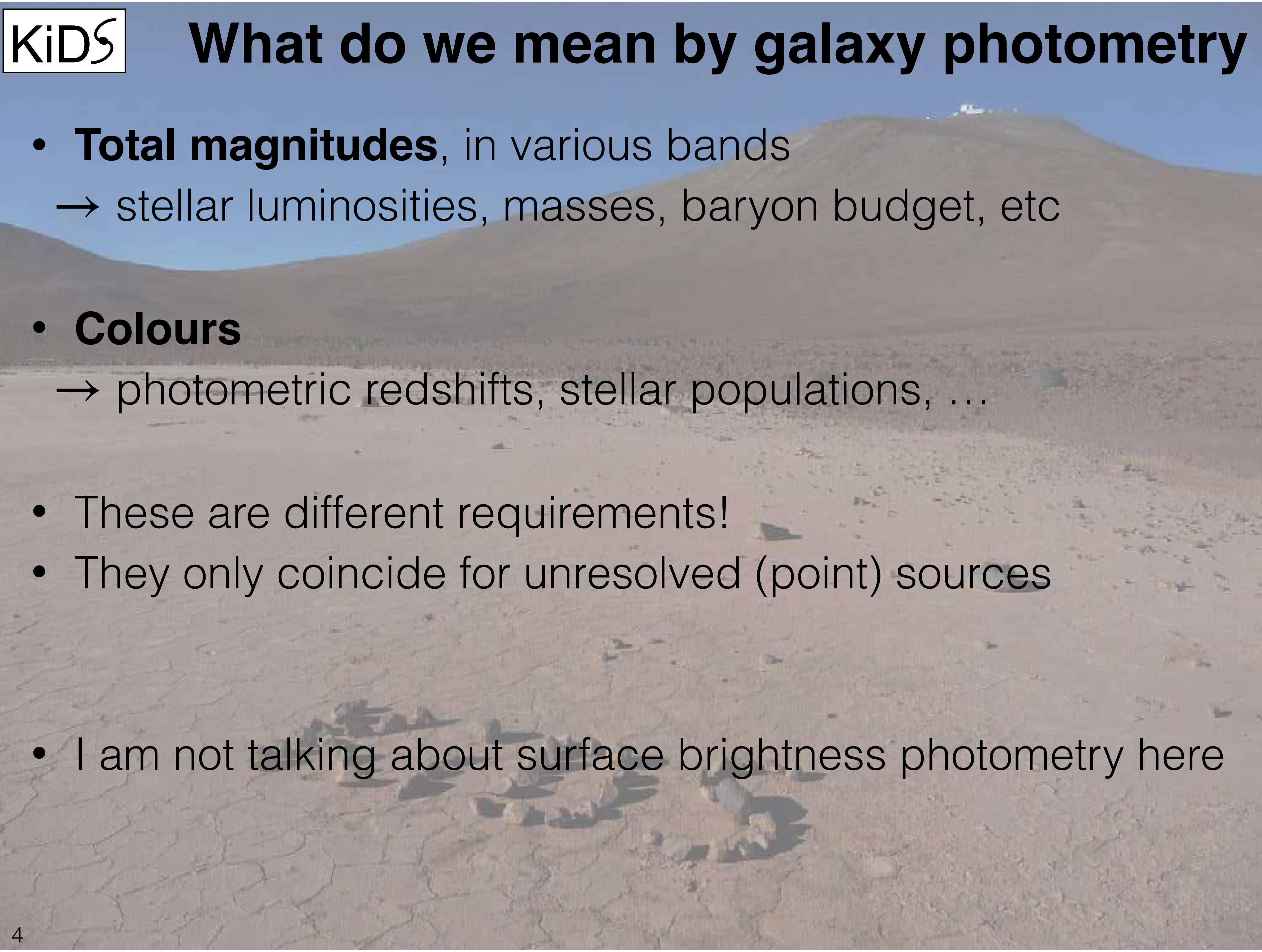
Lensing images (r):

Seeing **0.7”**
Depth **25ᵐ** (5σ AB)
PSF Ellipticity **0.03**

Colours:
ugriZYJHKₛ



What do we mean by galaxy photometry



- **Total magnitudes**, in various bands

  → stellar luminosities, masses, baryon budget, etc

- **Colours**

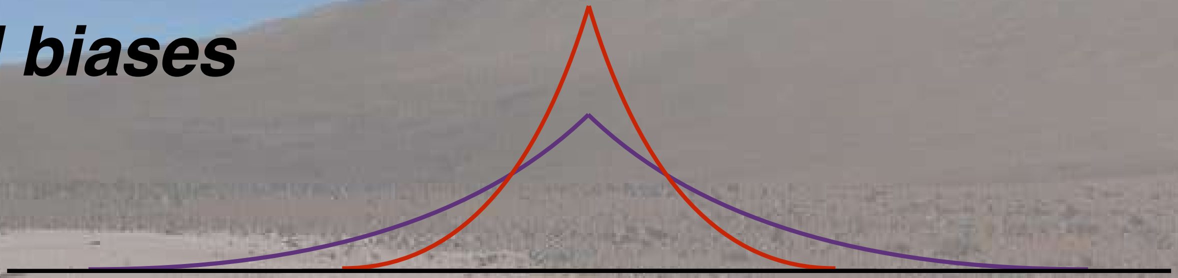
  → photometric redshifts, stellar populations, …

- These are different requirements!
- They only coincide for unresolved (point) sources

- I am not talking about surface brightness photometry here

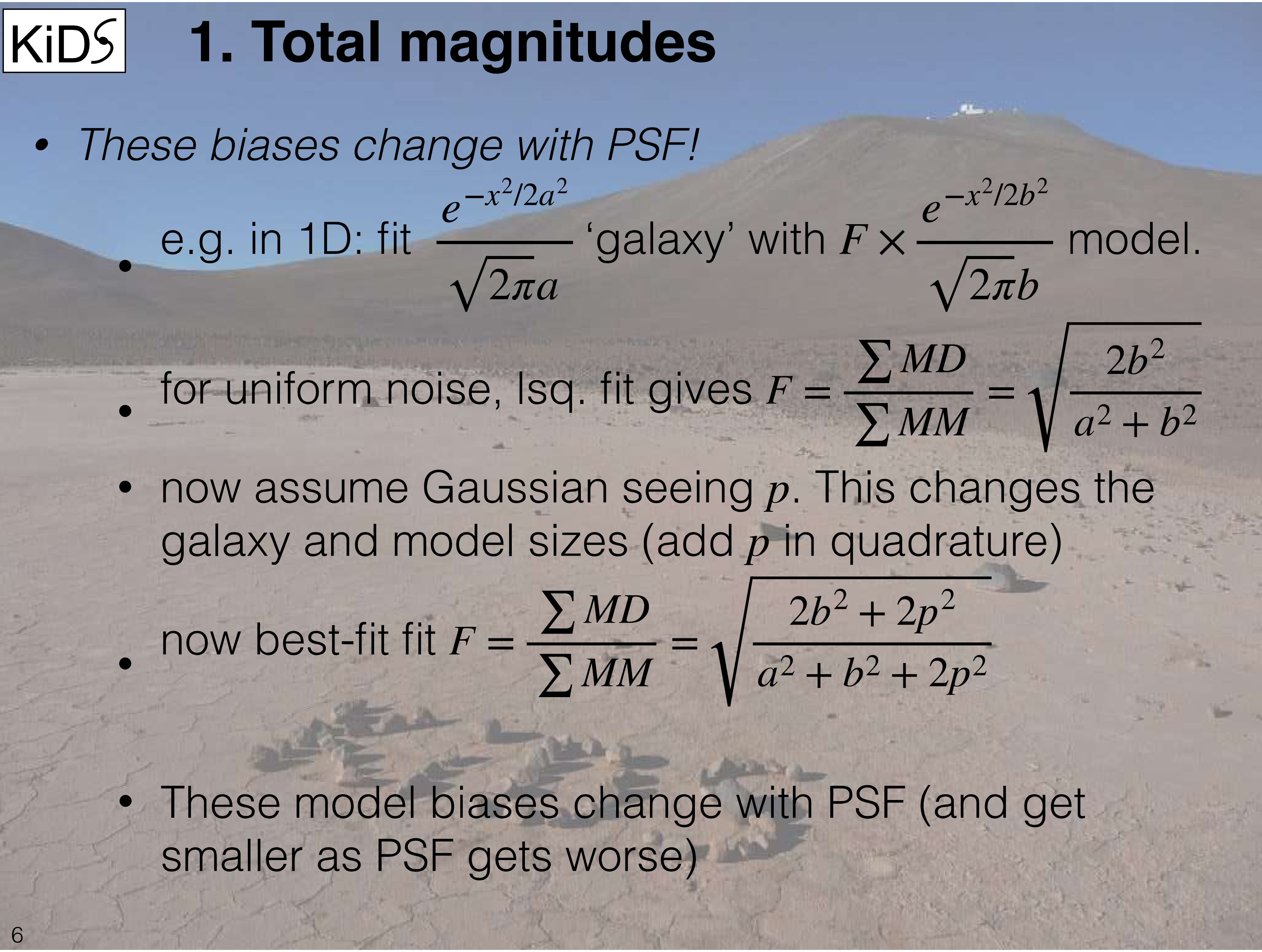
1. Total magnitudes

- Galaxies have no sharp edges
- Need a model to fit wings as they disappear below the noise
  → ***model biases***



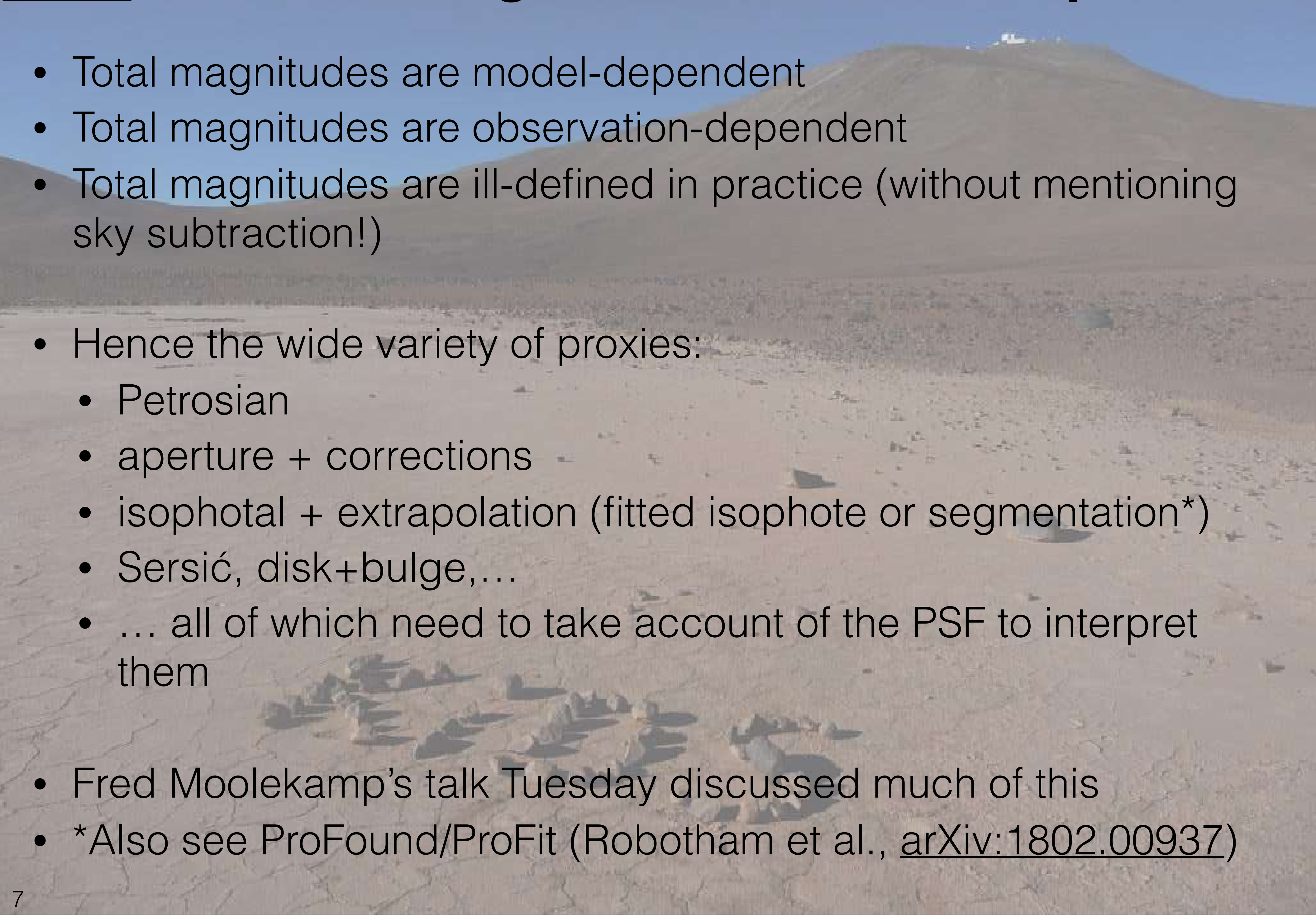
- e.g. in 1D: fit flux=1 $\frac{e^{-|x|/a}}{2a}$ ‘galaxy’ with $F \times \frac{e^{-|x|/b}}{2b}$ model
  - assume uniform noise: lsq. fit gives $F = \frac{\sum MD}{\sum MM} = \frac{2b}{a+b}$
    - model too wide ($b > a$): F overestimated (due to under-constrained wings). Up to factor 2!
    - model too narrow ($b < a$): F underestimated up to arbitrary factor!

1. Total magnitudes



- *These biases change with PSF!*
  - e.g. in 1D: fit $\frac{e^{-x^2/2a^2}}{\sqrt{2\pi}a}$ 'galaxy' with $F \times \frac{e^{-x^2/2b^2}}{\sqrt{2\pi}b}$ model.
  - for uniform noise, lsq. fit gives $F = \frac{\sum MD}{\sum MM} = \sqrt{\frac{2b^2}{a^2+b^2}}$
  - now assume Gaussian seeing p. This changes the galaxy and model sizes (add p in quadrature)
  - now best-fit fit $F = \frac{\sum MD}{\sum MM} = \sqrt{\frac{2b^2+2p^2}{a^2+b^2+2p^2}}$
  - These model biases change with PSF (and get smaller as PSF gets worse)

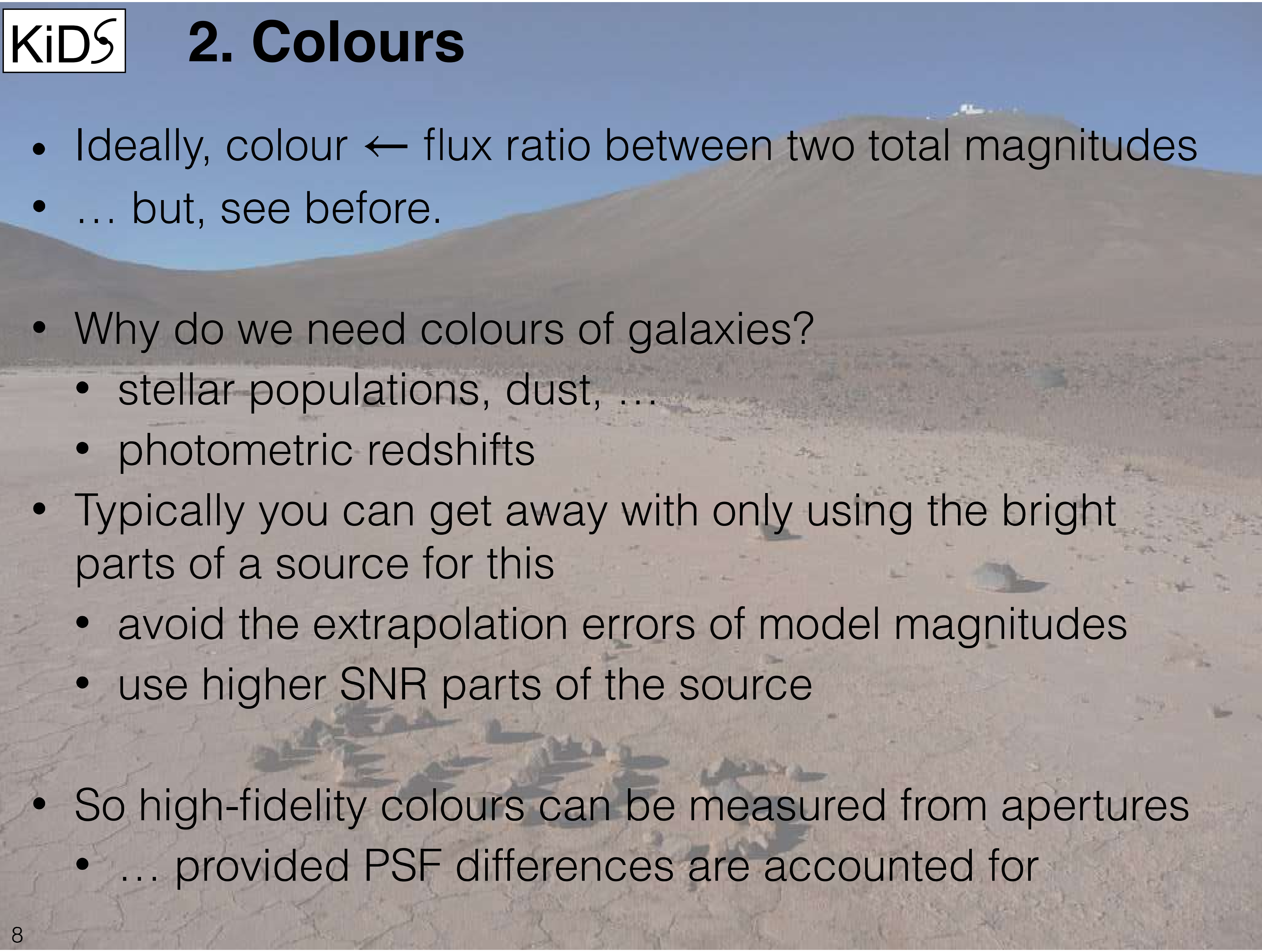
1. Total magnitudes are hard/impossible



- Total magnitudes are model-dependent
- Total magnitudes are observation-dependent
- Total magnitudes are ill-defined in practice (without mentioning sky subtraction!)

- Hence the wide variety of proxies:
  - Petrosian
  - aperture + corrections
  - isophotal + extrapolation (fitted isophote or segmentation*)
  - Sersić, disk+bulge,…
  - … all of which need to take account of the PSF to interpret them

- Fred Moolekamp's talk Tuesday discussed much of this
- *Also see ProFound/ProFit (Robotham et al., arXiv:1802.00937)



2. Colours

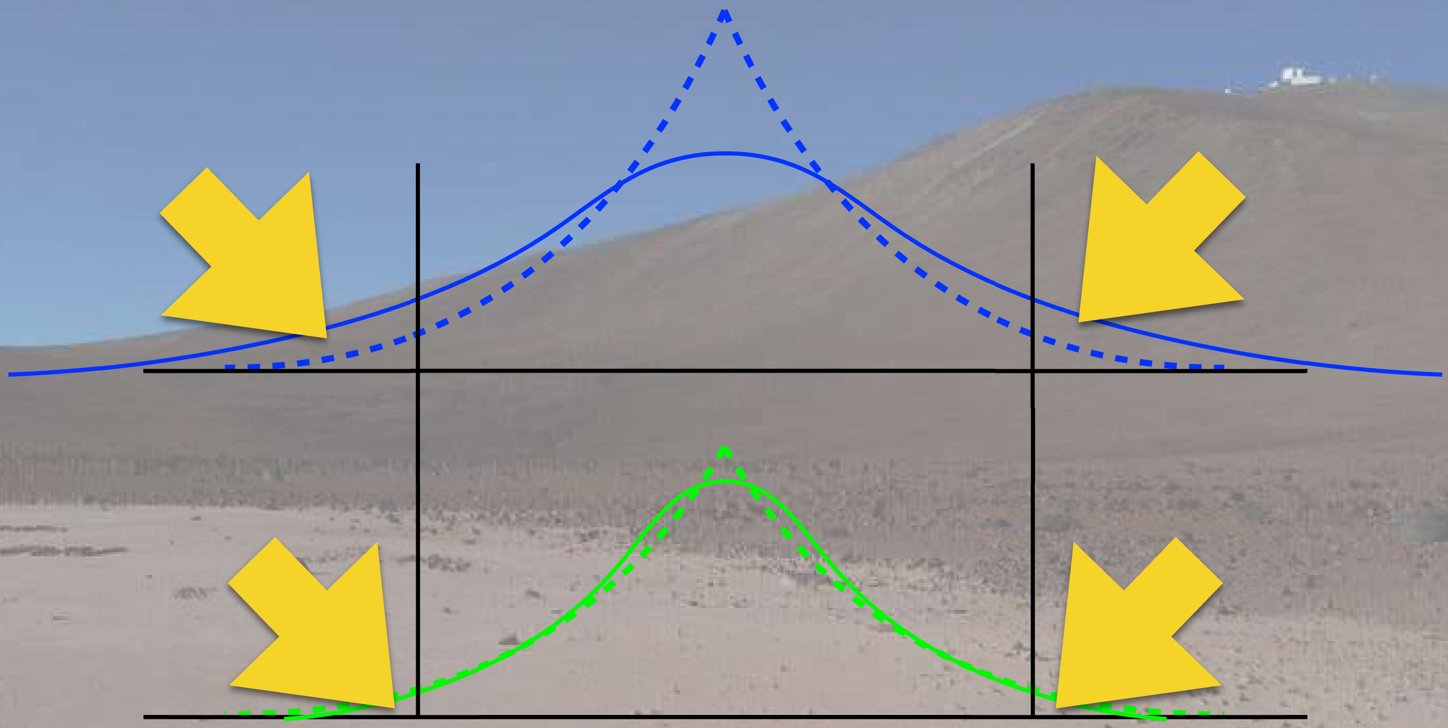
- Ideally, colour ← flux ratio between two total magnitudes
- … but, see before.

- Why do we need colours of galaxies?
  - stellar populations, dust, …
  - photometric redshifts
- Typically you can get away with only using the bright parts of a source for this
  - avoid the extrapolation errors of model magnitudes
  - use higher SNR parts of the source

- So high-fidelity colours can be measured from apertures
  - … provided PSF differences are accounted for

KiDS

2. Colours



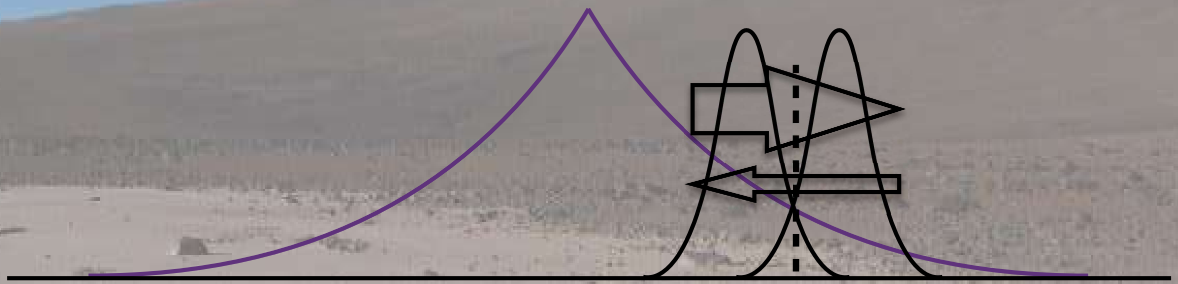
- fraction of flux missed is different:

  ⇒ same aperture on different-seeing data is meaningless unless aperture includes all the flux

- BAD. You need to allow for seeing differences

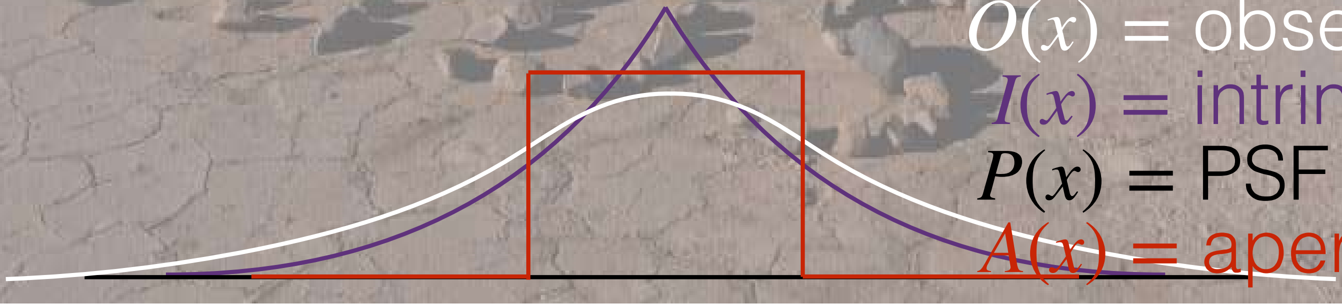
Colours and apertures

- The PSF scatters photons in the source
- Unequal fractions scatter into, and out of, any aperture



- Fraction depends on galaxy surface brightness profile, and on seeing, and on aperture
- What do you actually measure with aperture photometry?

$$F_{\mathrm{Ap}} = \int O(x)A(x)dx = \int (I \otimes P)(x)A(x)dx$$



$O(x)$ = observed image

$I(x)$ = intrinsic image

$P(x)$ = PSF

$A(x)$ = aperture function

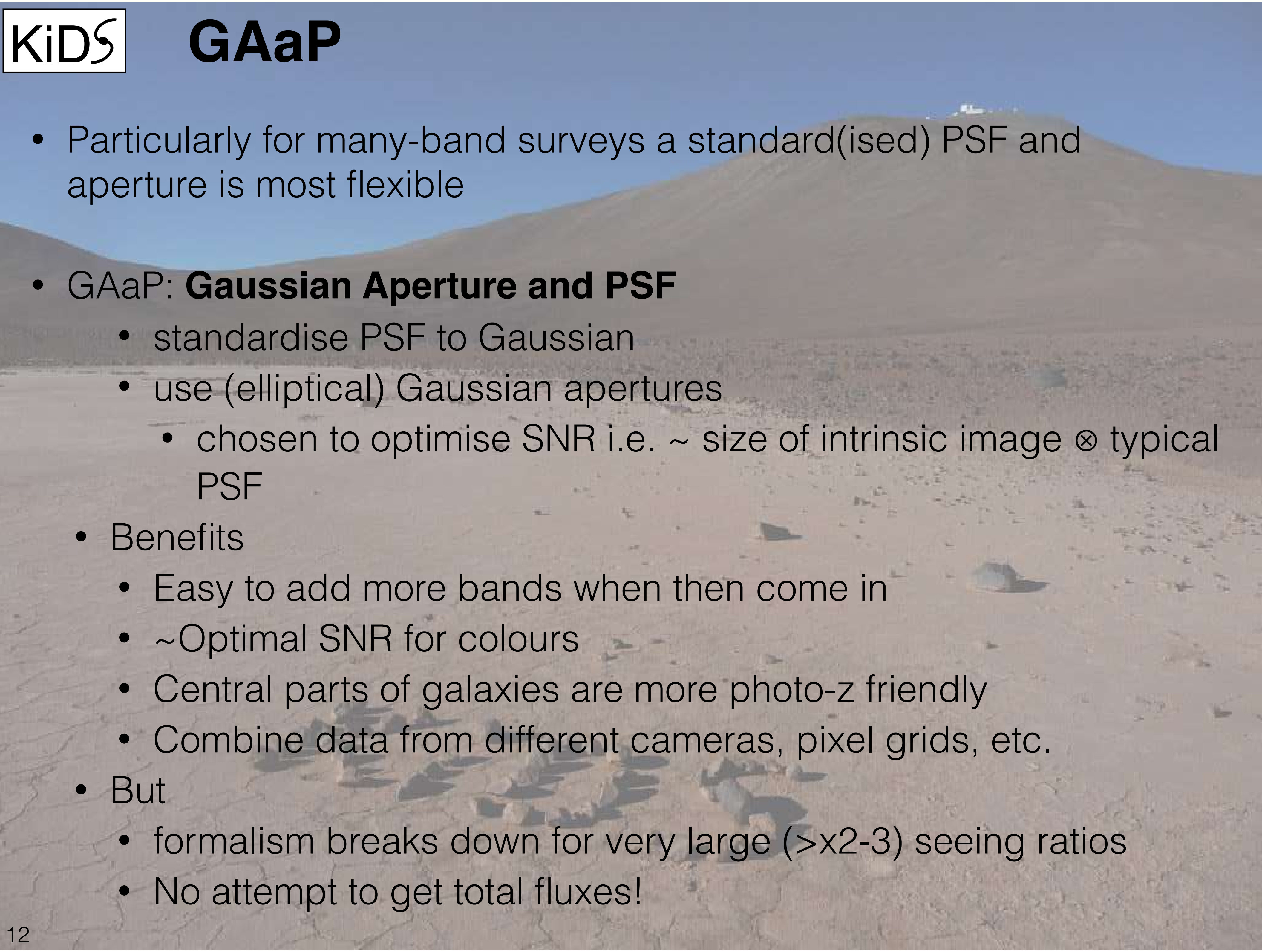
$$F_{\mathrm{Ap}} = \int O(x)A(x)dx = \int (I \otimes P) \times A\, dx$$

- Swap the convolution and the product:

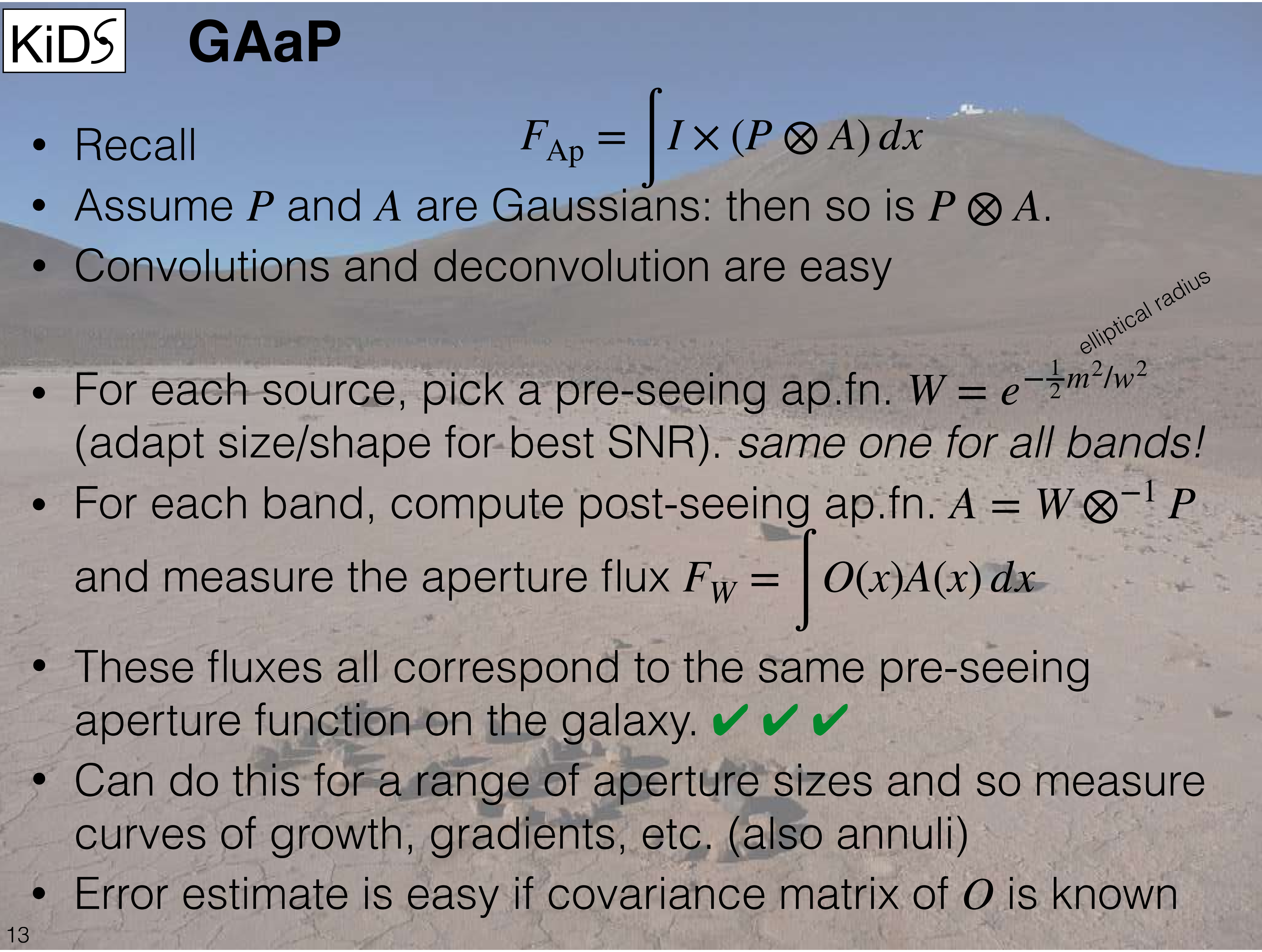
$$F_{\mathrm{Ap}} = \int O(x)A(x)dx = \int I \times (P \otimes A)\, dx$$

- so F_{Ap} = ap.phot. on *Intrinsic* $I(x)$, with aperture $A \otimes P$
  - as long as this convolved aperture is the same, you are comparing apples to apples and can measure useful colours
- Various approaches:
  1. when comparing 2 images, convolve each image with the other's PSF and use matched apertures
  2. degrade seeing of best image to worst
     - approximately or carefully (see DIP talks yesterday)
  3. standardise PSF and aperture and control aperture on *intrinsic* image $A \otimes P$.

GAaP



- Particularly for many-band surveys a standard(ised) PSF and aperture is most flexible
- GAaP: **Gaussian Aperture and PSF**
    - standardise PSF to Gaussian
    - use (elliptical) Gaussian apertures
        - chosen to optimise SNR i.e. ~ size of intrinsic image ⊗ typical PSF
  - Benefits
    - Easy to add more bands when then come in
    - ~Optimal SNR for colours
    - Central parts of galaxies are more photo-z friendly
    - Combine data from different cameras, pixel grids, etc.
  - But
    - formalism breaks down for very large (>x2-3) seeing ratios
    - No attempt to get total fluxes!



GAaP

- Recall $F_{\mathrm{Ap}} = \int I \times (P \otimes A)\, dx$
- Assume P and A are Gaussians: then so is $P \otimes A$.
- Convolutions and deconvolution are easy

elliptical radius

- For each source, pick a pre-seeing ap.fn. $W = e^{-\frac{1}{2}m^2/w^2}$ (adapt size/shape for best SNR). *same one for all bands!*
- For each band, compute post-seeing ap.fn. $A = W \otimes^{-1} P$ and measure the aperture flux $F_W = \int O(x)A(x)\, dx$
- These fluxes all correspond to the same pre-seeing aperture function on the galaxy. ✔ ✔ ✔
- Can do this for a range of aperture sizes and so measure curves of growth, gradients, etc. (also annuli)
- Error estimate is easy if covariance matrix of O is known

But…

- The PSF is not Gaussian
- Make it so

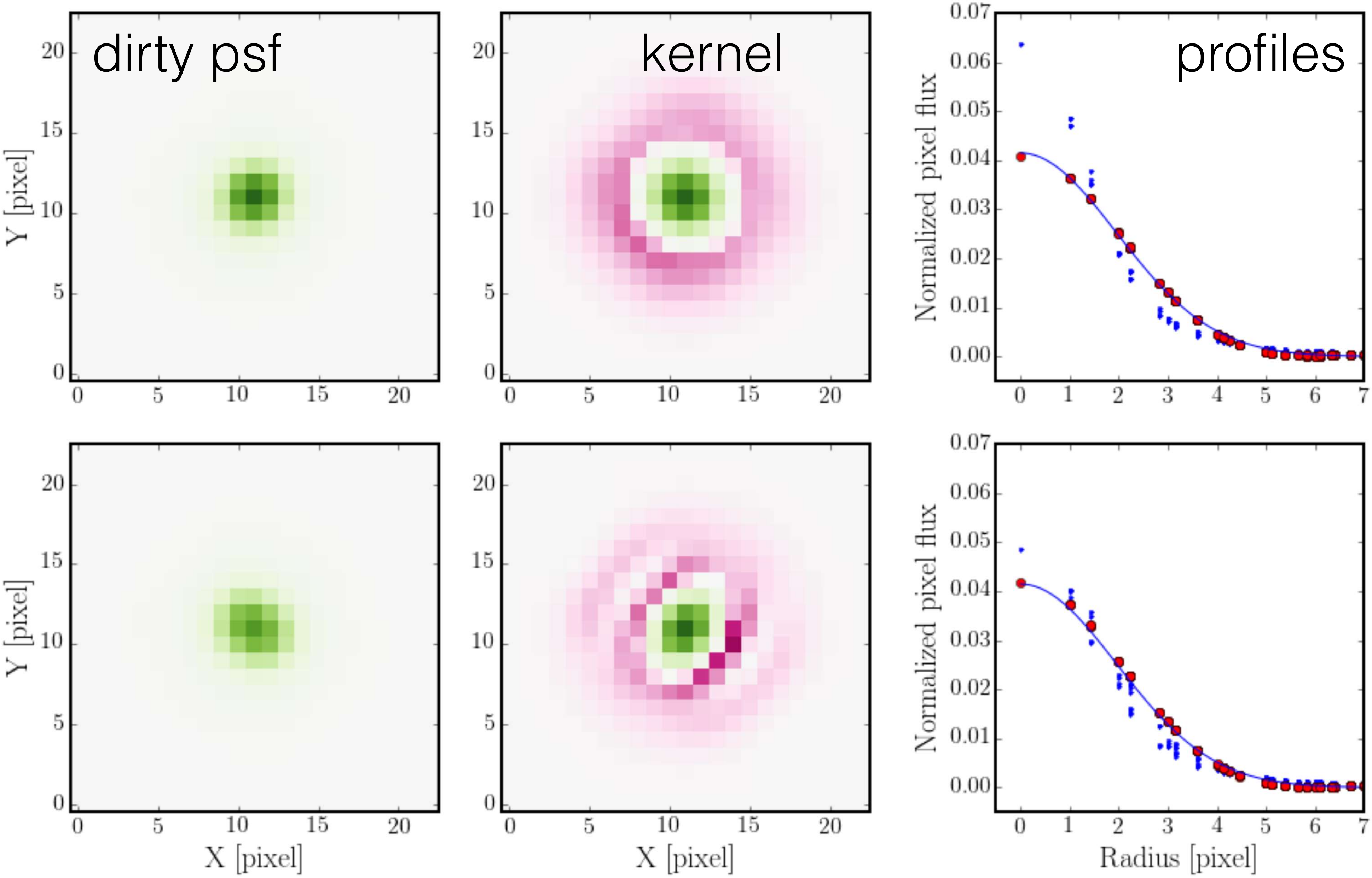
PSF model and Gaussianisation

- *This is a key step*
- Current implementation
  - find all (~1000) stars, deduce seeing, set target PSF size
    - set target Gaussian PSF core ~ 1.2x wider than original
    - star by star, find optimal Gaussianization kernel
      - use overconstrained double shapelet model

$$\sum_{i,j=0}^{i+j\leq 8} k_{ij} H_i(x/\beta) H_j(y/\beta) e^{-r^2/2\beta^2} + \sum_{i+j\geq 3}^{i+j\leq 6} K_{ij} H_i(x/B) H_j(y/B) e^{-r^2/2B^2}$$

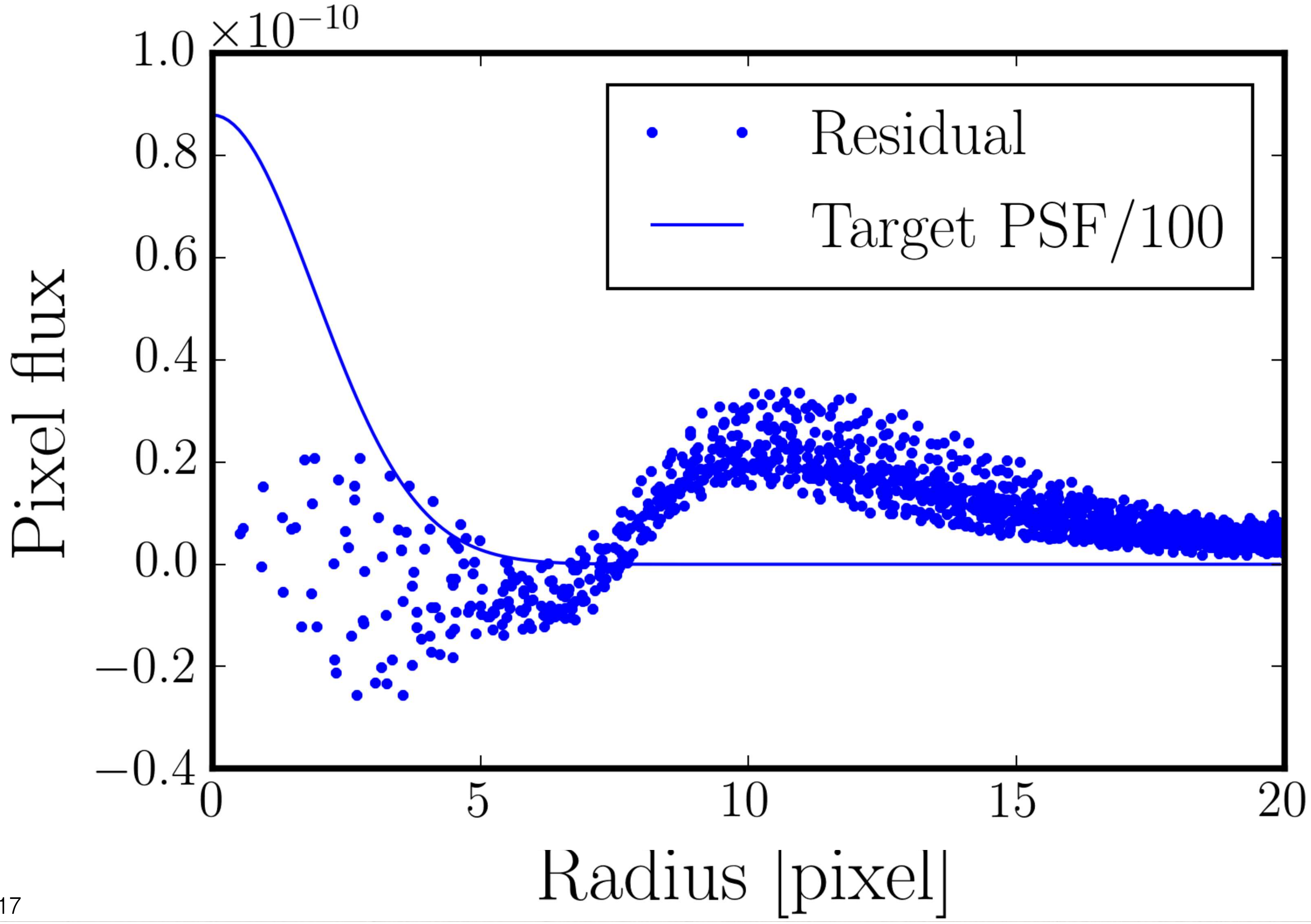
      - fit smooth model to variation of the k_{ij}, K_{ij} coeffs. over the image
  - convolve the (co-added or not) pixels with variable kernel
  - **noise covariances** given by ACF of the kernel (easy in shapelet space)

Example


dirty psf
kernel
profiles
Y [pixel]
X [pixel]
0
5
10
15
20
Normalized pixel flux
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
Radius [pixel]
0
1
2
3
4
5
6
7

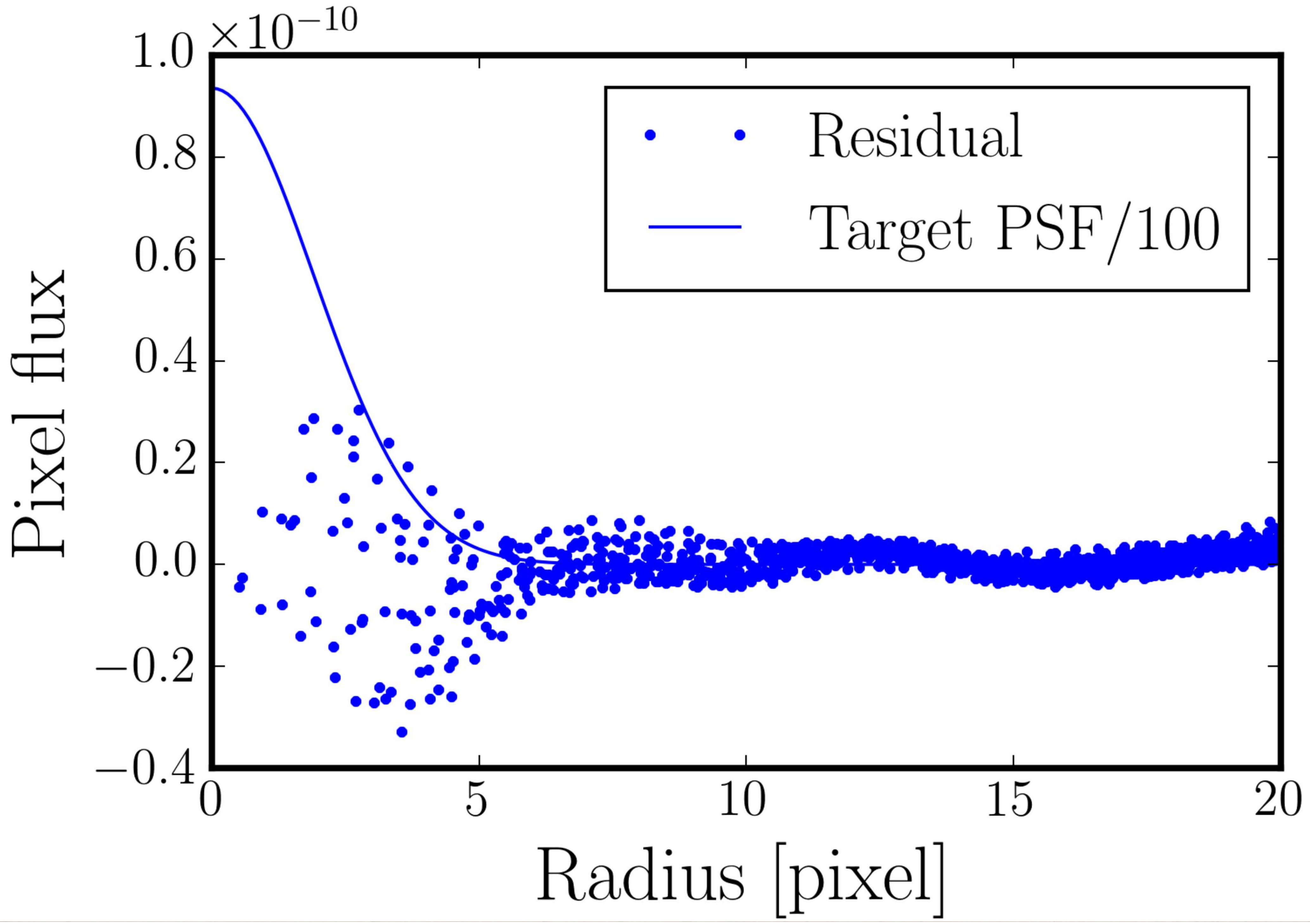
KiDS

psf residual (single shapelet series)



KiDS

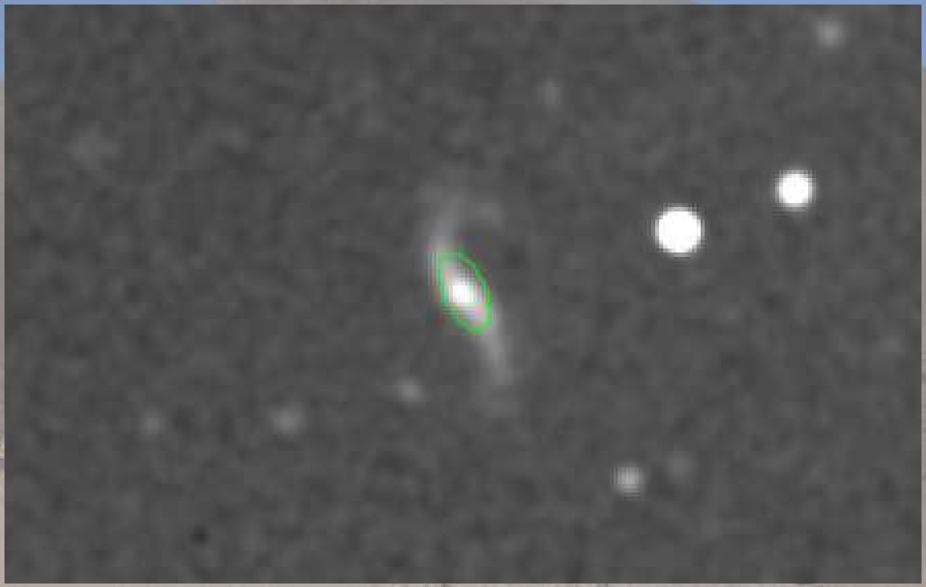
psf residual (double shapelet series)

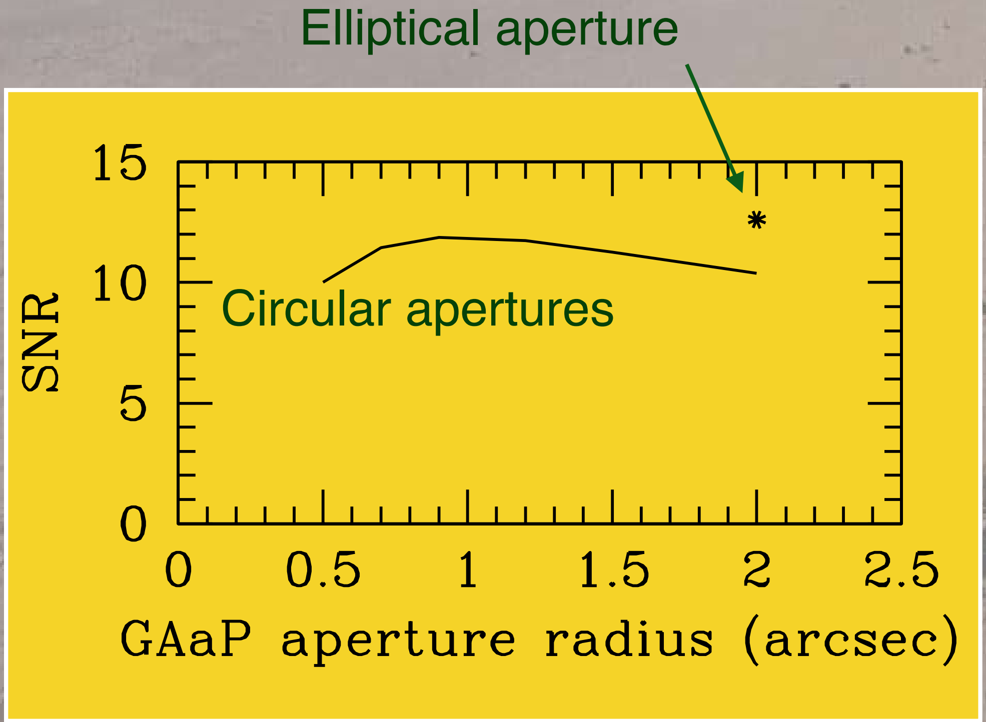


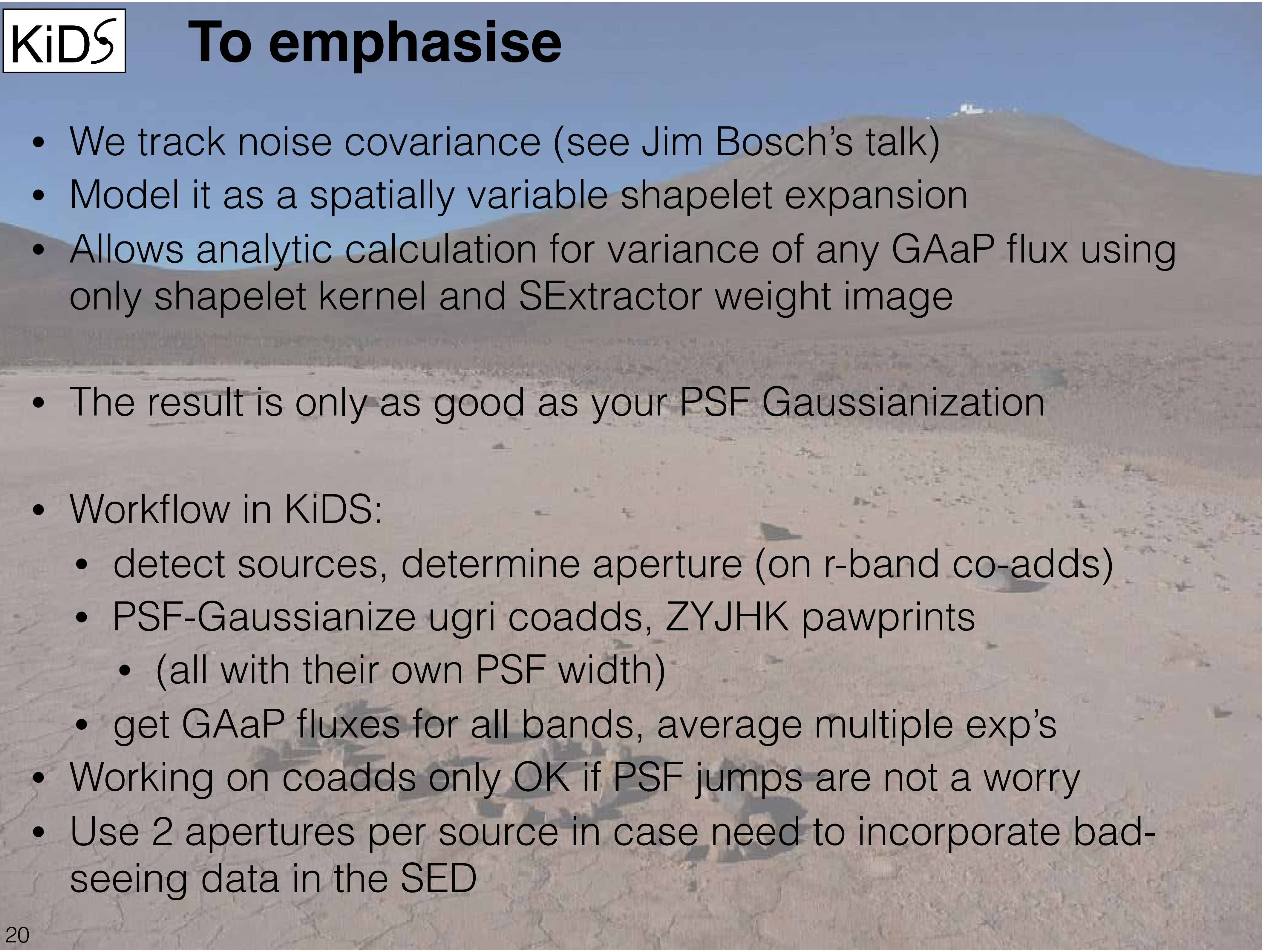
KiDS

Example

- Broad SNR plateau
- gives some dynamic range for seeing differences between bands
- elliptical aperture helps SNR







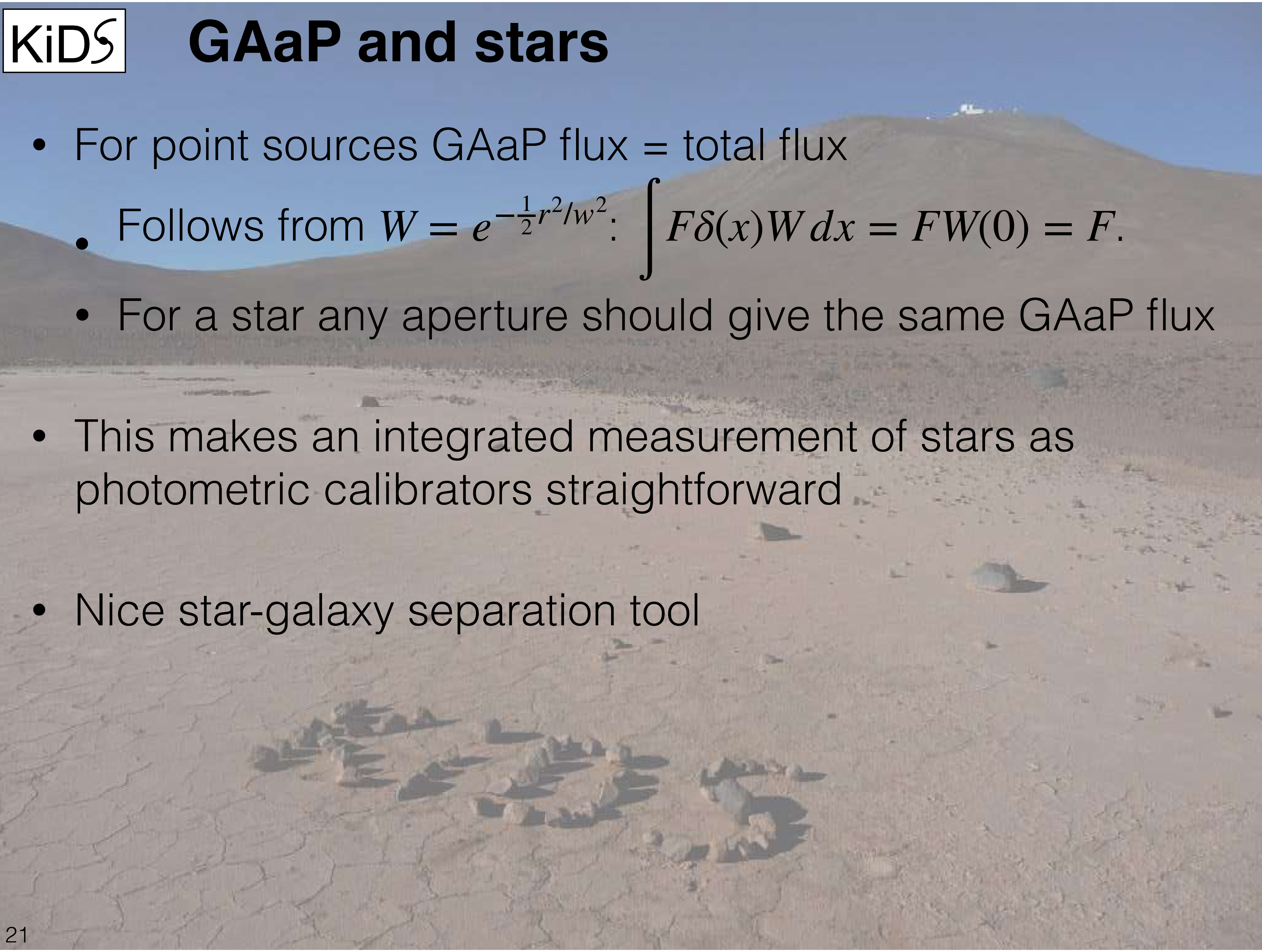
To emphasise

- We track noise covariance (see Jim Bosch's talk)
- Model it as a spatially variable shapelet expansion
- Allows analytic calculation for variance of any GAaP flux using only shapelet kernel and SExtractor weight image

- The result is only as good as your PSF Gaussianization

- Workflow in KiDS:
  - detect sources, determine aperture (on r-band co-adds)
  - PSF-Gaussianize ugri coadds, ZYJHK pawprints
    - (all with their own PSF width)
  - get GAaP fluxes for all bands, average multiple exp's
- Working on coadds only OK if PSF jumps are not a worry
- Use 2 apertures per source in case need to incorporate bad-seeing data in the SED

GAaP and stars



- For point sources GAaP flux = total flux
  - Follows from $W = e^{-\frac{1}{2}r^2/w^2}$: $\int F\delta(x)W\,dx = FW(0) = F$.
  - For a star any aperture should give the same GAaP flux

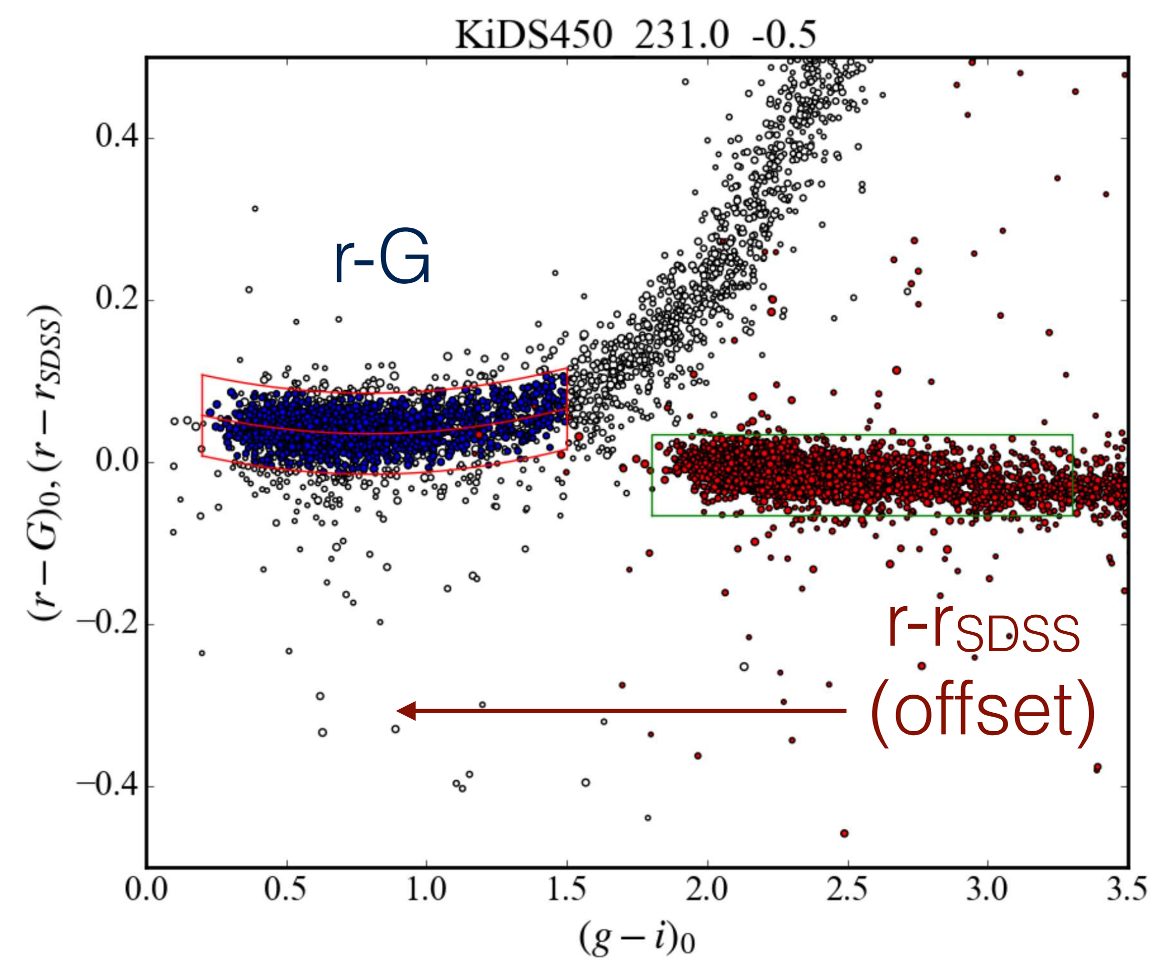
- This makes an integrated measurement of stars as photometric calibrators straightforward

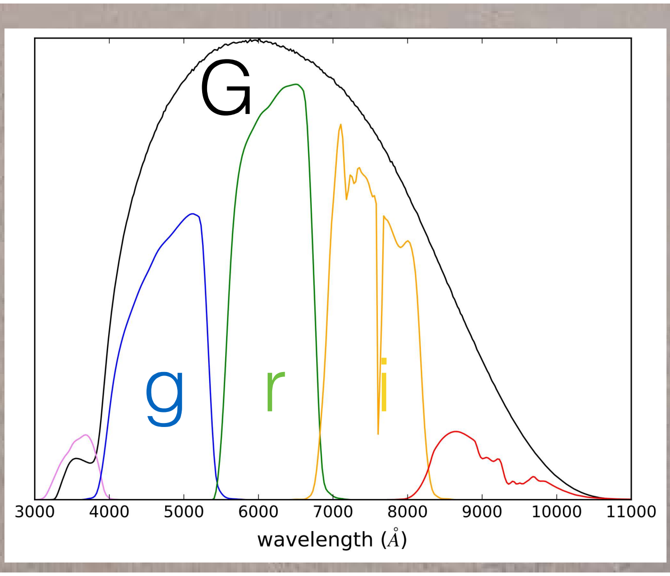
- Nice star-galaxy separation tool

KiDS Photom.cal.

- photometric calibration from stars
  - nightly zeropoint from standard star fields
  - overlap between tiles
  - stellar locus fit (g-r, r-i)
  - r tied to **Gaia** G

  - Will improve further with Gaia DR2 (multi-colour)

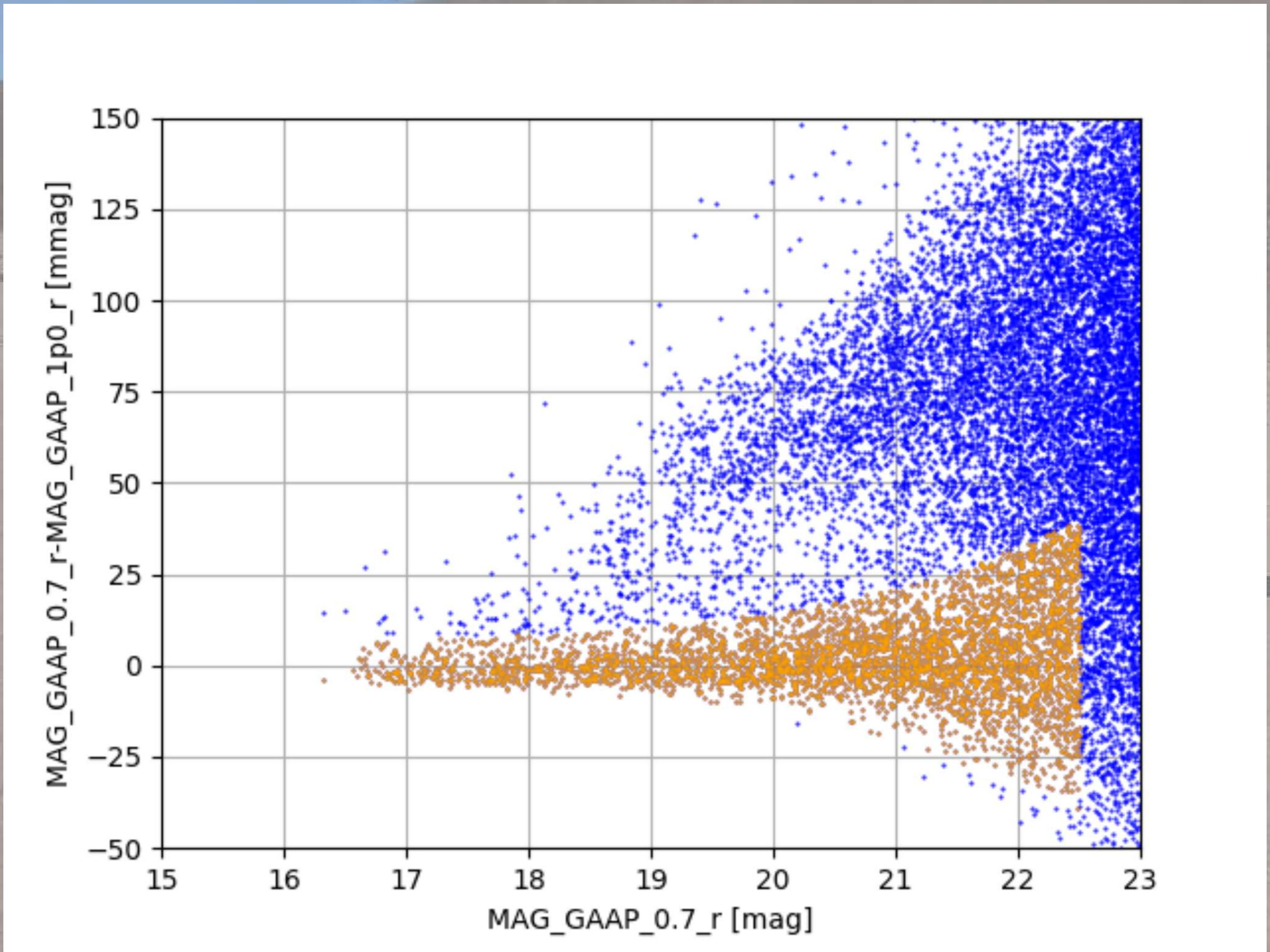




KiDS

Star-galaxy separation

- GAaP curve of ‘growth’: compare σ=0.7” and 1.0”apertures



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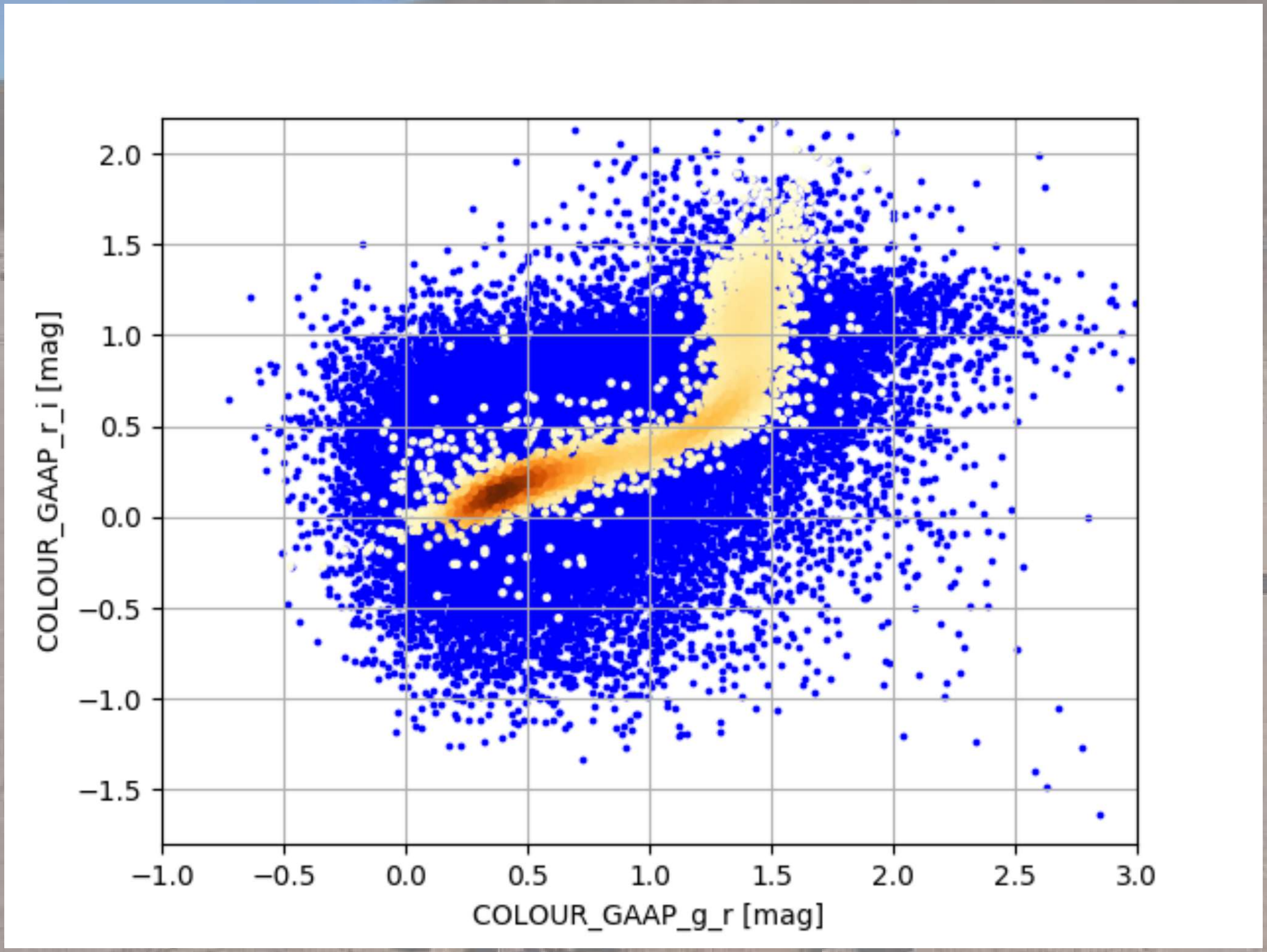


- unresolved sources really are stars

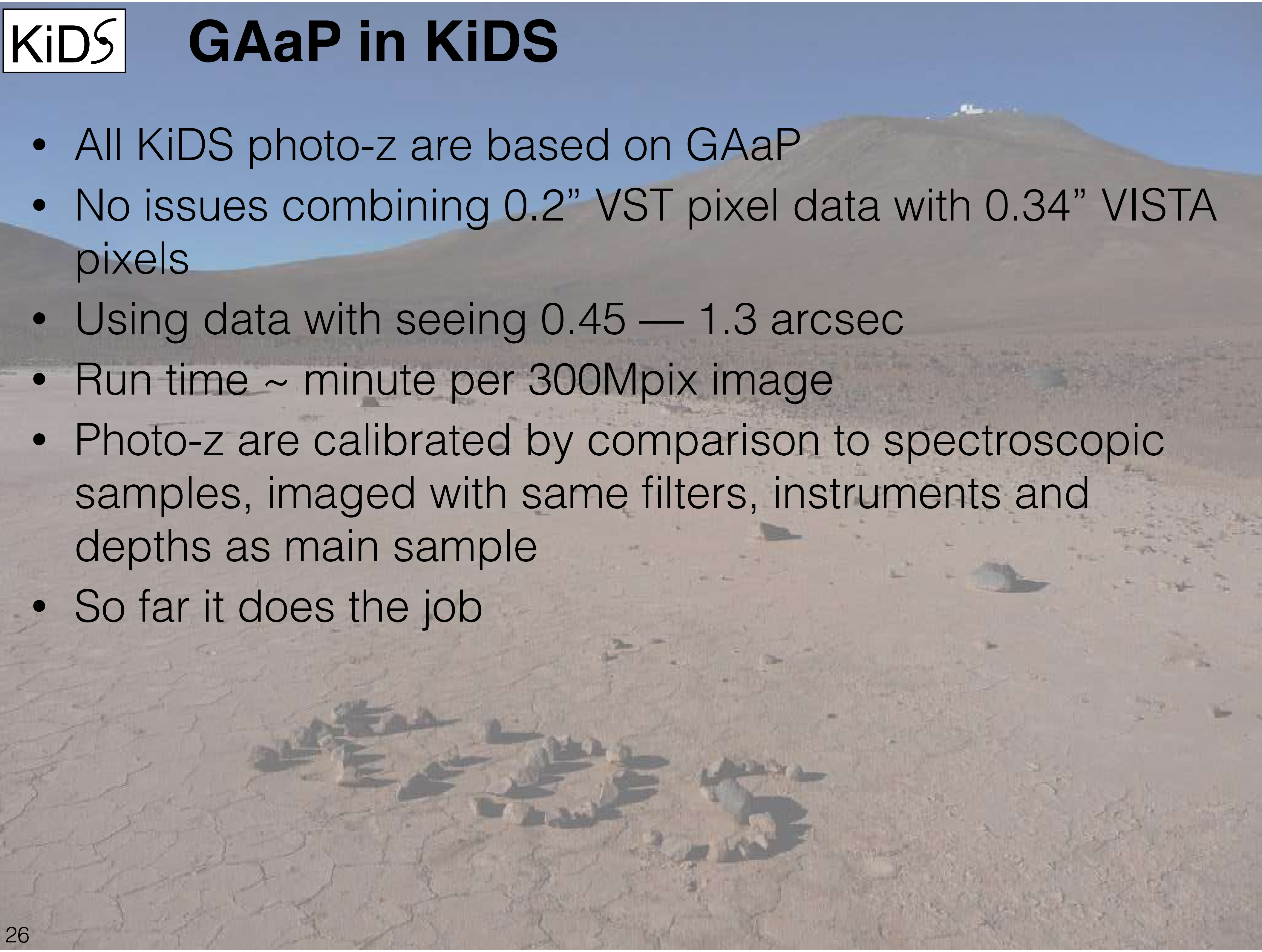
KiDS

Centroid & aperture bias

- Our aperture shape and centre is set by r band detection
  - noise bias (2nd order)
  - for point sources $\sqrt{2}\delta x \sim$ FWHM/SNR
  - Photometry error for point sources $\simeq W_{\rm pre}(\delta x) \simeq e^{-1/{\rm SNR}^2} \simeq 1 - 1/{\rm SNR}^2$

detection SNR

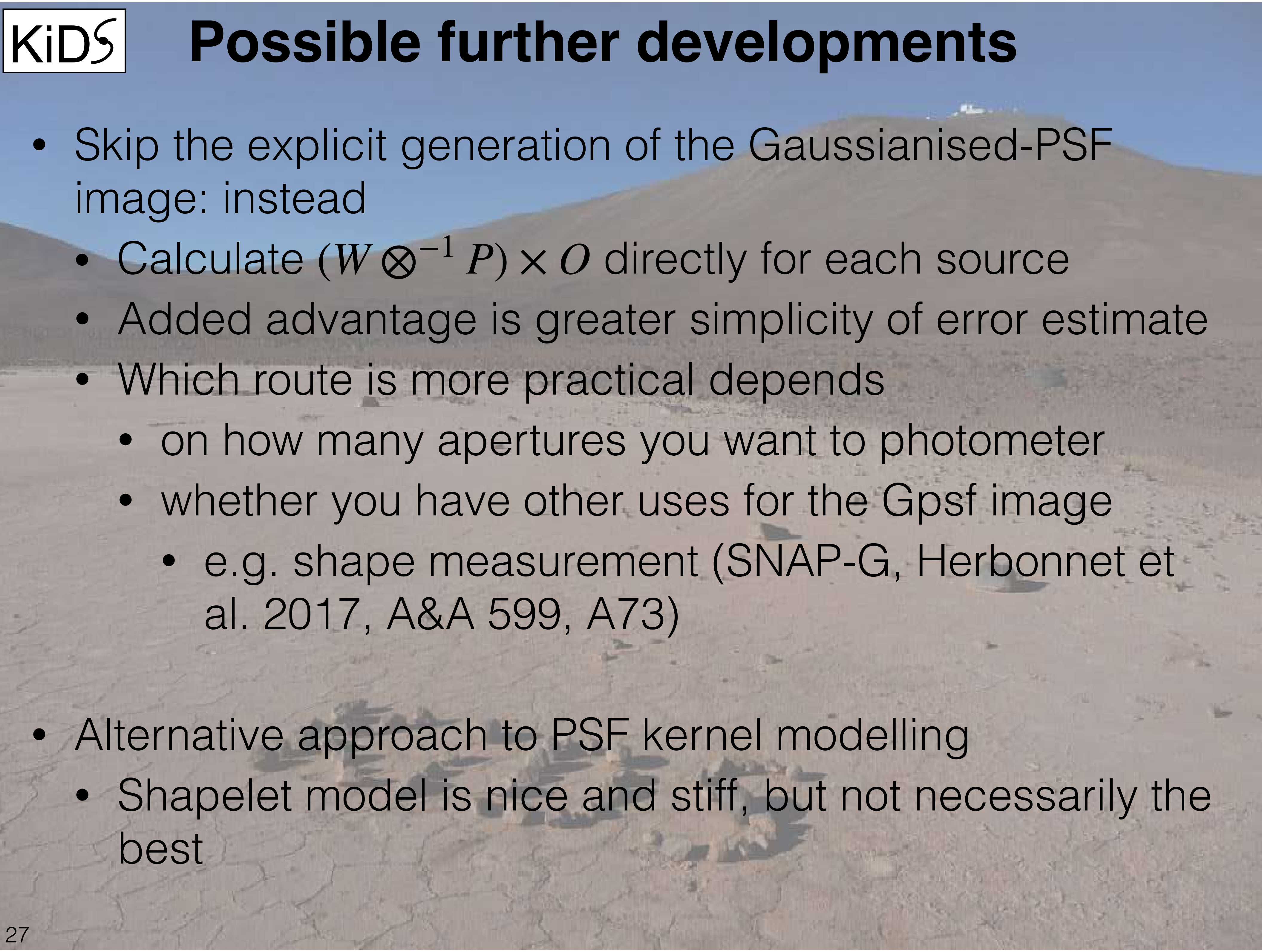
- Important for low-SNR detections



GAaP in KiDS

- All KiDS photo-z are based on GAaP
- No issues combining 0.2” VST pixel data with 0.34” VISTA pixels
- Using data with seeing 0.45 — 1.3 arcsec
- Run time ~ minute per 300Mpix image
- Photo-z are calibrated by comparison to spectroscopic samples, imaged with same filters, instruments and depths as main sample
- So far it does the job

Possible further developments



- Skip the explicit generation of the Gaussianised-PSF image: instead
  - Calculate $(W \otimes^{-1} P) \times O$ directly for each source
  - Added advantage is greater simplicity of error estimate
  - Which route is more practical depends
    - on how many apertures you want to photometer
    - whether you have other uses for the Gpsf image
      - e.g. shape measurement (SNAP-G, Herbonnet et al. 2017, A&A 599, A73)

- Alternative approach to PSF kernel modelling
  - Shapelet model is nice and stiff, but not necessarily the best