Robust measurements of galaxy morphology with LSST

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How do galaxies evolve?

star-forming

disk-dominated

star formation

quenching mechanism = ????

morphology

quiescent

bulge-dominated

How do galaxies evolve?

star-forming

disk-dominated

gas: hydrodynamics
star formation

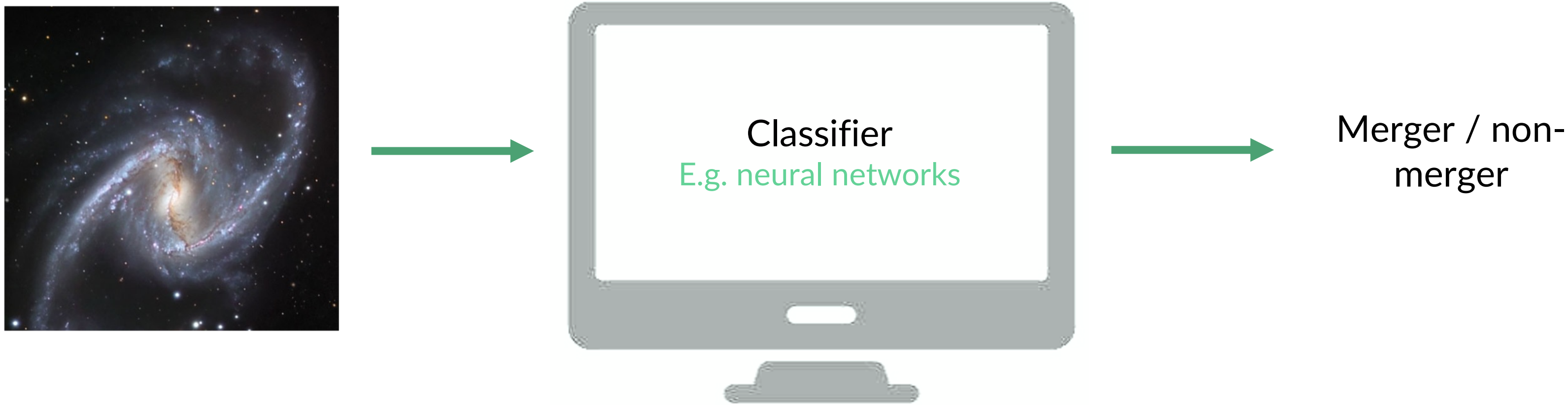
quenching mechanism = ????

morphology
stars: gravity

quiescent

bulge-dominated

Why quantitative morphology?



Why quantitative morphology?

Quantitative measurements
CAS, Gini, M20, ...

Disk / bulge strength
C, Sersic n, B/T

Tidal features
As, outer A

Internal disturbances (e.g. dust lanes)
A + As in different bands

Different merger stages
A, As, G/M20

Why quantitative morphology?

Quantitative measurements
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Internal disturbances (e.g. dust lanes)
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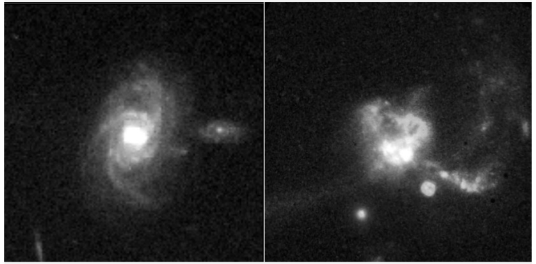
Different merger stages
A, As, G/M20

\+ *Continuous* distributions let us study galaxy structure as a *function* of their environment/physical properties/etc

Disturbance



Asymmetry

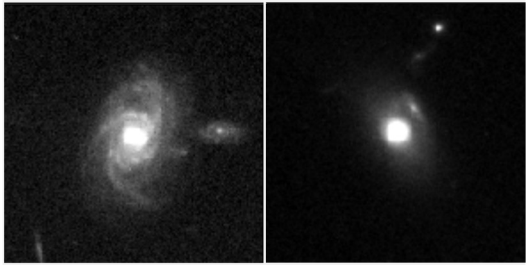
Shape asymmetry

G/M_{20} disturbance

Shape asymmetry

Residual Flux Fraction [RFF]

Bulge strength



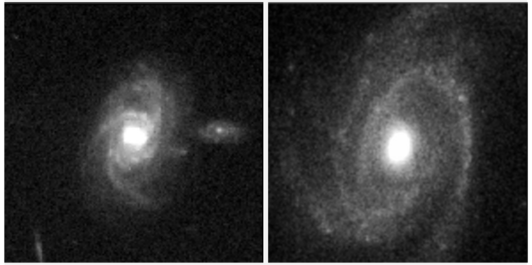
Concentration

G/M_{20} bulge strength

Sérsic index

Bulge-to-disk ratio [B/T]

Size



Petrosian radius

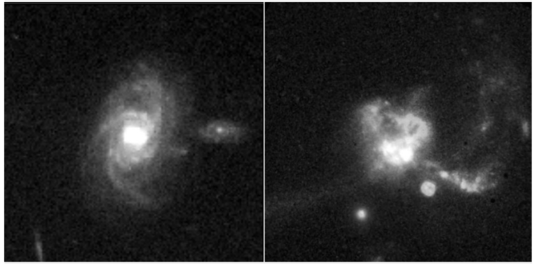
Compactness

Sérsic radius

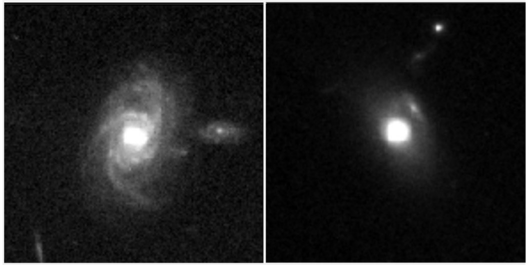
Non parametric

Model dependent

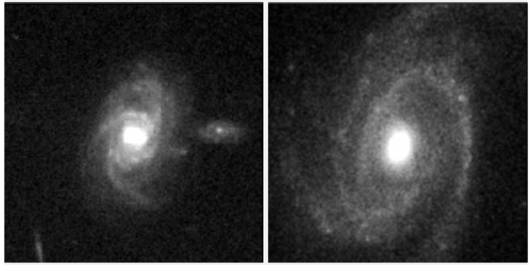
Disturbance



Bulge strength



Size



Non parametric

Asymn

Shape

G/M_{20}

Shape asymmetry

us

A million definitions + implementations
Inconsistent measurements across different studies!

Model dependent

Residual Flux Fraction [RFF]

Sérsic index

Bulge-to-disk ratio [B/T]

Sérsic radius

Case study: asymmetry

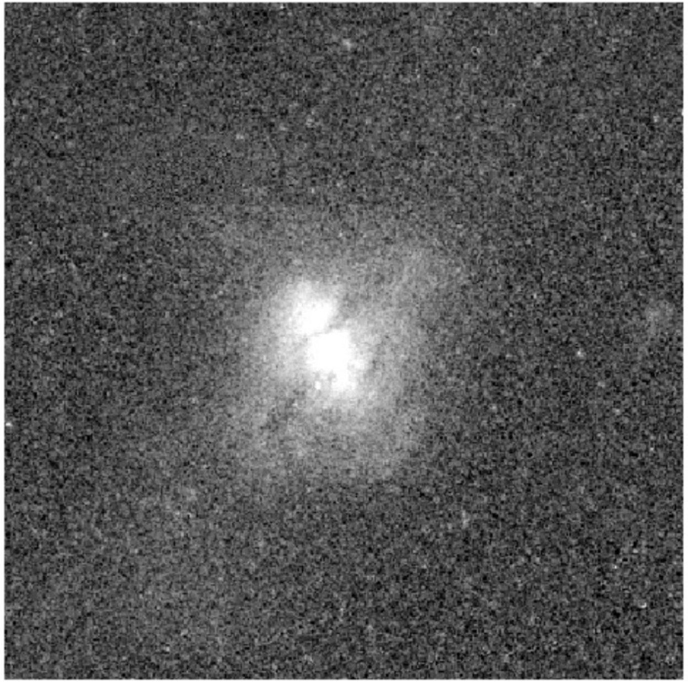
Conselice et al. (2003)

image rotated image

$$A = \frac{\sum |f - f^{180}| - N\langle A_{bg} \rangle}{\sum |f|}$$

background asymmetry

Important in detecting mergers, dust lanes, etc...



What’s up with asymmetry?

Conselice et al. (2003)

image rotated image

$$A = \frac{\sum |f - f^{180}| - N\langle A_{bg} \rangle}{\sum |f|}$$

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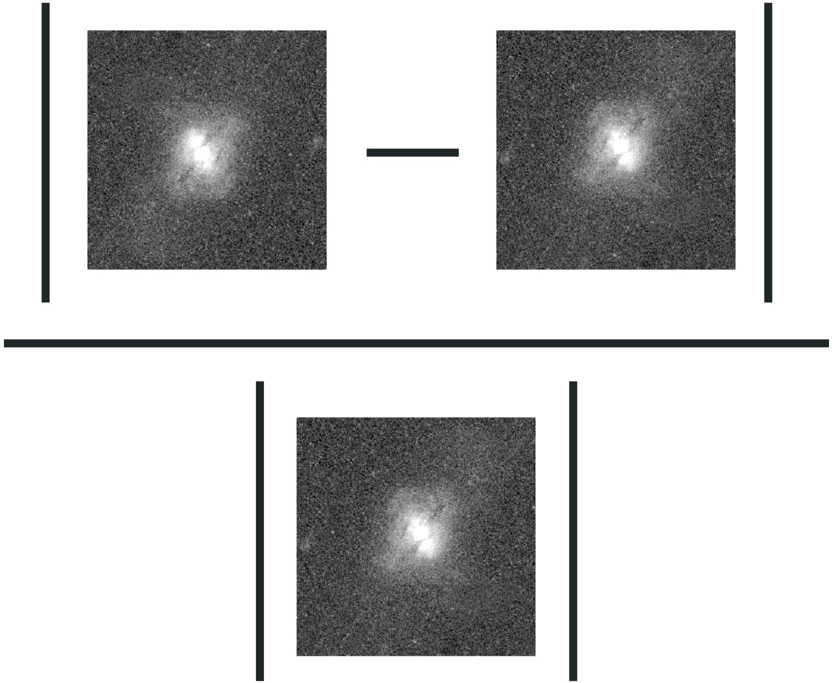

What's up with asymmetry?

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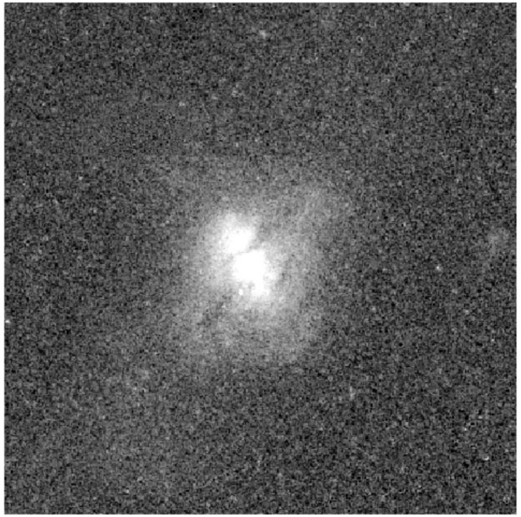
HST *R*-band



A = 0.35

SDSS *r*-band

A = 0.11

What’s up with asymmetry?

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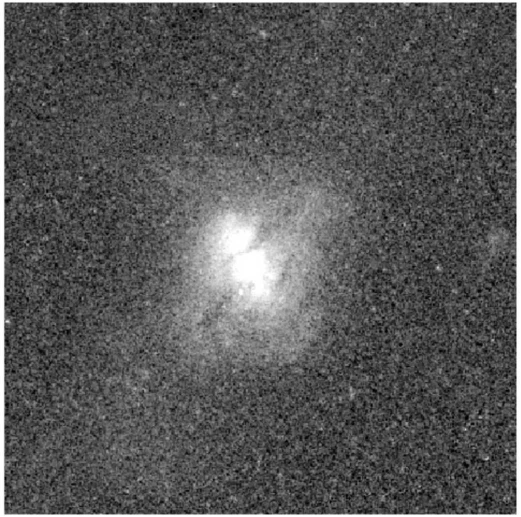

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LSST imaging will still have high seeing (~0.5 of SDSS) and a *variable* image depth across the survey lifetime!

What's up with asymmetry?

Conselice et al. (2003)

image rotated image

$$A = \frac{\sum |f - f^{180}| - N\langle A_{bg} \rangle}{\sum |f|}$$

background asymmetry

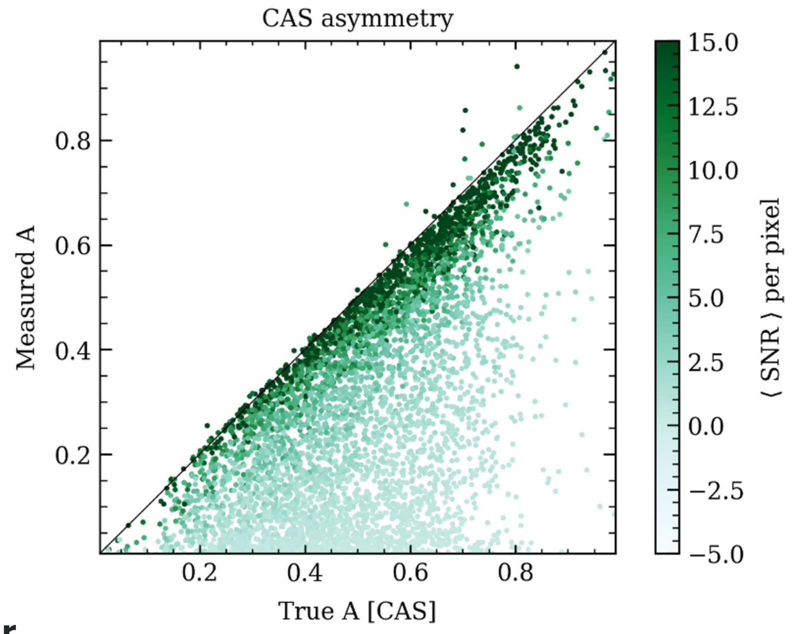
Only tested statistically in a few studies

Lotz et al. 2004, Thorp et al. 2021

Depends strongly on noise & resolution

But how much? And why?

We need to understand these measurements better before we commit to measuring them for 10^6 galaxies



Asymmetry *squared*

image rotated image

$$A = \frac{\sum |f - f^{180}| - N\langle A_{bg} \rangle}{\sum |f|}$$

background asymmetry

$$A = \frac{\sum (f - f^{180})^2 - N\langle A_{bg}^2 \rangle}{\sum f^2 - N\langle f_{bg}^2 \rangle}$$

background flux correction

Better normalization

Normalization used to include a non-zero noise contribution, making asymmetry aperture size-dependent

Better behaviour with noisy images

Gaussian noise completely decoupled from the source asymmetry

Asymmetry *squared: why?*

$$\underbrace{f}_{\text{image}} = \underbrace{\lambda}_{\text{PSF}} * \underbrace{f_s}_{\text{source}} + \underbrace{\sigma}_{\text{noise}}$$

Source image

An observation is made from a source image by convolving it with a PSF and adding noise.

Asymmetry *squared: why?*

source

$$f = \lambda * f_s + \sigma$$

PSF noise

CAS asymmetry:

$$|f - f^{180}| = |\lambda * (f_s - f_s^{180}) + (\sigma - \sigma^{180})|$$

$$\neq |\lambda * (f_s - f_s^{180})| + |\sigma - \sigma^{180}|$$

Background contribution is **not** separable

Source image

An observation is made from a source image by convolving it with a PSF and adding noise.

CAS asymmetry

Absolute value calculation does not allow you to separate the noise term and recover the real asymmetry

Asymmetry *squared: why?*

$$\underset{\text{PSF}}{f = \lambda} * \overset{\text{source}}{f_s} + \underset{\text{noise}}{\sigma}$$

CAS asymmetry:

$$A = \frac{\sum |\overset{\text{image}}{f} - \overset{\text{rotated image}}{f^{180}}| - N\langle A_{bg} \rangle}{\sum |f|}$$

background asymmetry

this term doesn't do much good...

Source image

An observation is made from a source image by convolving it with a PSF and adding noise.

CAS asymmetry

Absolute value calculation does not allow you to separate the noise term and recover the real asymmetry

Asymmetry *squared: why?*

$$\underbrace{f}_{} = \underbrace{\lambda}_{\text{PSF}} * \overbrace{f_s}^{\text{source}} + \underbrace{\sigma}_{\text{noise}}$$

Squared asymmetry:

$$(f - f^{180})^2 = \lambda^2 * (f_s - f_s^{180})^2 + (\sigma - \sigma^{180})^2 +$$

$$2(\sigma - \sigma^{180}) \times \lambda * (f_s - f_s^{180})$$

This term is 0 when the image is background-subtracted!

The background term is **separable**

Source image

An observation is made from a source image by convolving it with a PSF and adding noise.

Better behaviour with noisy images

Gaussian noise completely decoupled from the source asymmetry

Asymmetry *squared: why?*

$$\underbrace{f}_{} = \underset{\text{PSF}}{\lambda} * \overset{\text{source}}{f_s} + \underset{\text{noise}}{\sigma}$$

Squared asymmetry:

$$A = \frac{\sum (f - f^{180})^2 - N\langle A_{bg}^2 \rangle}{\sum f^2 - N\langle f_{bg}^2 \rangle}$$

This term recovers source asymmetry!

Source image

An observation is made from a source image by convolving it with a PSF and adding noise.

Better behaviour with noisy images

Gaussian noise completely decoupled from the source asymmetry

Asymmetry *squared*

image rotated image

$$A = \frac{\sum |f - f^{180}| - N\langle A_{bg}\rangle}{\sum |f|}$$

background asymmetry

$$A = \frac{\sum (f - f^{180})^2 - N\langle A_{bg}^2\rangle}{\sum f^2 - N\langle f_{bg}^2\rangle}$$

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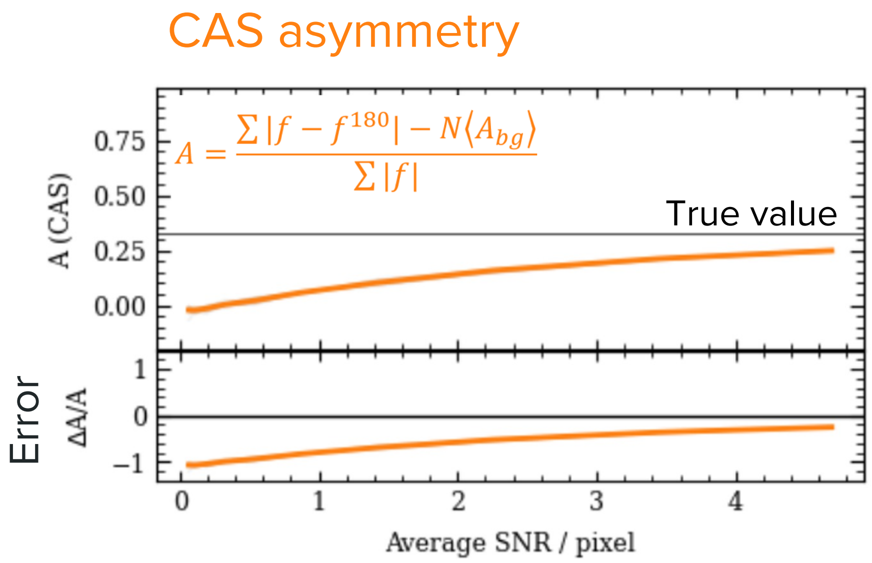
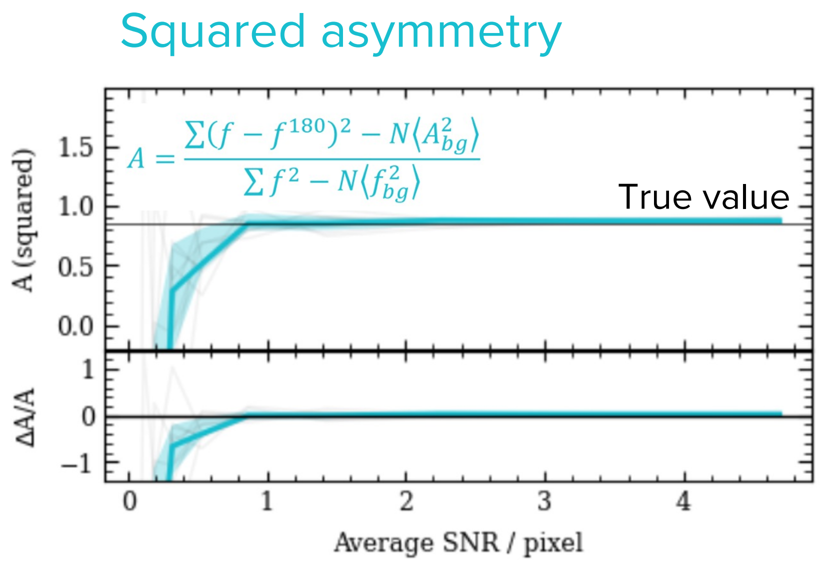
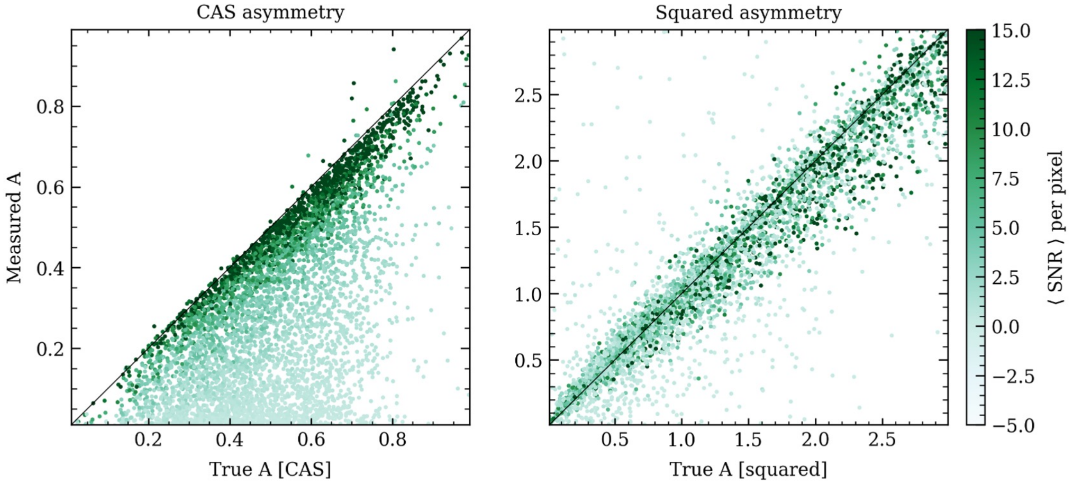
Asymmetry *squared*





Asymmetry *squared*

$$A = \frac{\sum (f - f^{180})^2 - N\langle A_{bg}^2 \rangle}{\sum f^2 - N\langle f_{bg}^2 \rangle}$$



Better normalization

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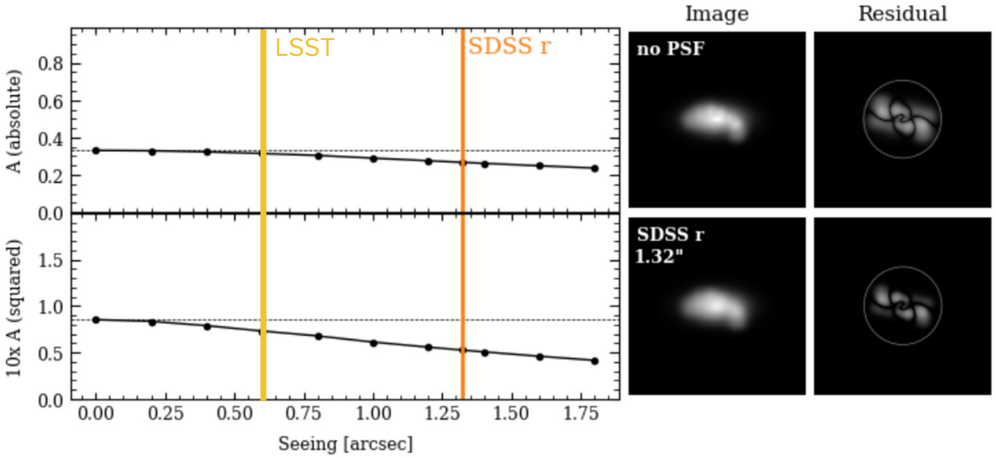
Better behaviour with noisy images

Gaussian noise completely decoupled from the source asymmetry

Asymmetry *squared: PSF*

$$A = \frac{\sum(f - f^{180})^2 - N\langle A_{bg}^2\rangle}{\sum f^2 - N\langle f_{bg}^2\rangle}$$



Worse at very low SNR

background flux normalization makes the denominator ~0 when background flux dominates

Worse behaviour with PSF

flux^2 responds strongly to re-distribution of flux via seeing

Fourier

Asymmetry *squared*

$$\underbrace{f}_{} = \underbrace{\lambda}_{\text{PSF}} * \overbrace{f_s}^{\text{source}} + \underbrace{\sigma}_{\text{noise}}$$

Fourier facts

1. Power ($\sum f^2$) in image space and image space are the same

2. Convolution in Fourier space is multiplication ⇒ separable

Fourier

Asymmetry *squared*

1 $A^2(\text{source}) = A^2(\mathcal{F}[\text{source}])$

$$\underbrace{f = \overbrace{\lambda}^{}}_{} \underset{\text{PSF}}{\lambda} * \overset{\text{source}}{f_s} + \underset{\text{noise}}{\sigma}$$

Fourier facts

1. Power ($\sum f^2$) in image space and image space are the same

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Fourier

Asymmetry *squared*

1. $A^2(\text{source}) = A^2(\mathcal{F}[\text{source}])$

2. $\mathcal{F}[\text{source}] = H \times \mathcal{F}[\text{image}]$

$$H = \frac{1 + \text{SNR}^{-2}}{\lambda^2 + \text{SNR}^{-2}}$$

PSF signal-to-noise

$$\underset{}{f} = \underbrace{\lambda}_{\text{PSF}} * \overset{\text{source}}{f_s} + \underbrace{\sigma}_{\text{noise}}$$

Fourier facts

1. Power ($\sum f^2$) in image space and image space are the same

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Fourier

Asymmetry *squared*

1. $$A^2(\text{source}) = A^2(\mathcal{F}[\text{source}])$$

2. $$\mathcal{F}[\text{source}] = H \times \mathcal{F}[\text{image}]$$

The rest of the calculation as usual, but in Fourier space!

$$A = \frac{\sum (f - f^{180})^2 - N\langle A_{bg}^2 \rangle}{\sum f^2 - N\langle f_{bg}^2 \rangle}$$

Better normalization

Normalization used to include a non-zero noise contribution, making asymmetry aperture size-dependent

Corrects for noise

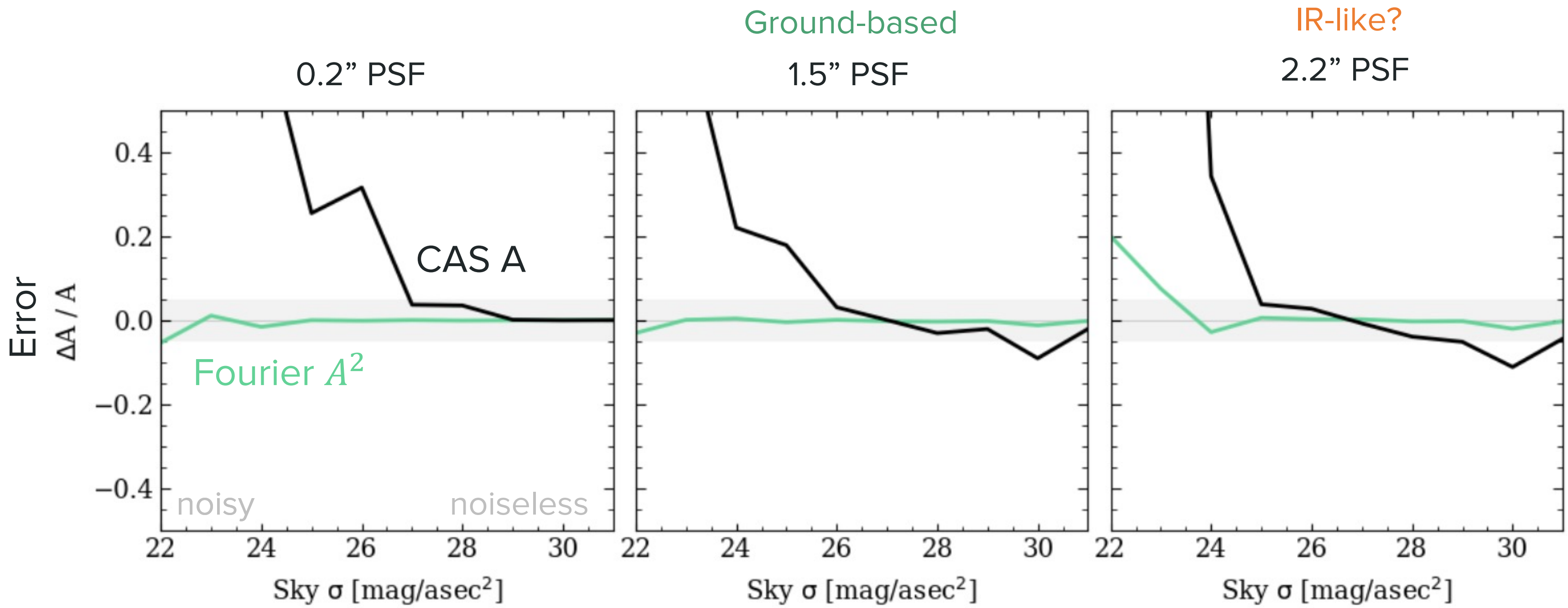
Gaussian noise completely decoupled from the source asymmetry

Corrects for PSF

In Fourier space, PSF can be decoupled. We calculate A in Fourier space -
no deconvolution!

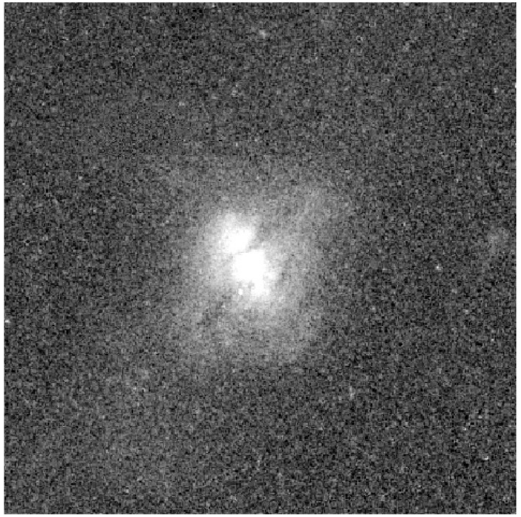
Fourier

Asymmetry *squared*



Still work in progress, but...

HST *R*-band



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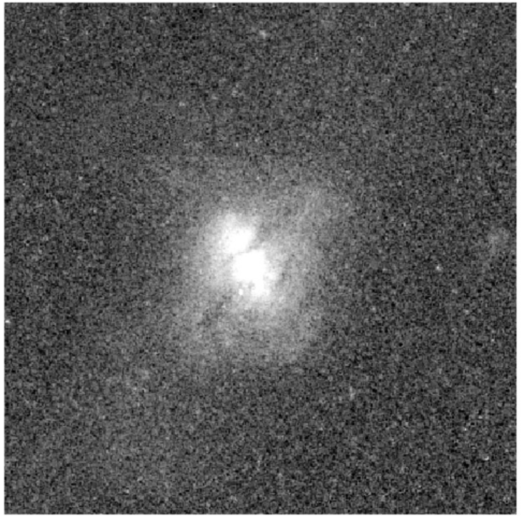


A = 0.35

$\mathcal{F}[A^2]$ = **1.61**

SDSS *r*-band

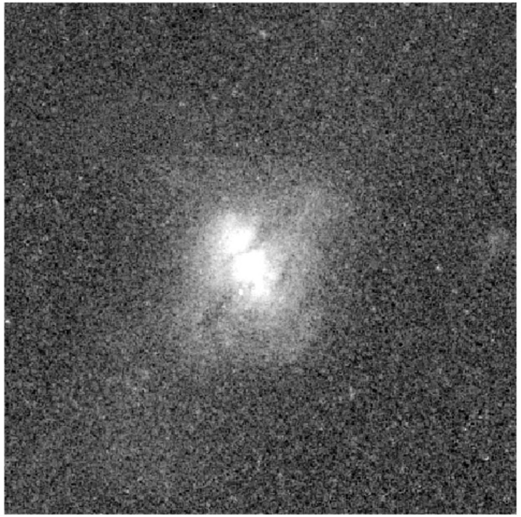
A = 0.11

$\mathcal{F}[A^2]$ = **1.29**

Deconvolved

Still work in progress, but...

HST *R*-band



A = 0.35

$\mathcal{F}[A^2]$ = **1.61**

SDSS *r*-band

A = 0.11

$\mathcal{F}[A^2]$ = **1.29**

Deconvolved

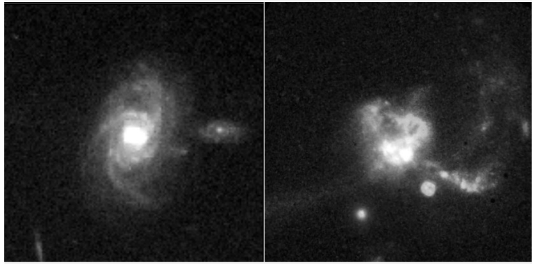
70% error

20% error

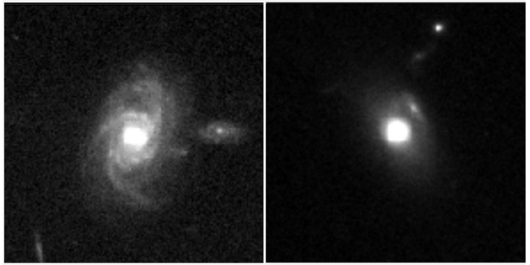
almost

So asymmetry is great again, what next?

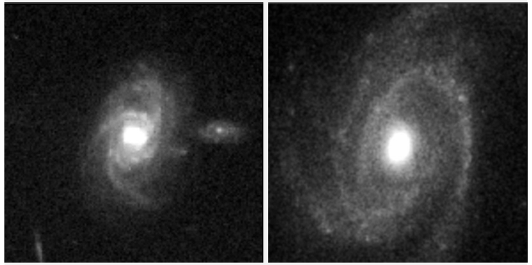
Disturbance



Bulge strength



Size



Non parametric

- Disturbance: **Asymmetry**; Shape asymmetry; G/M_{20}; Shape
- Bulge strength: Concentration; G/M_{20} bulge strength
- Size: Petrosian radius; Compactness

Model dependent

- Disturbance: Residual Flux Fraction [RFF]
- Bulge strength: Sérsic index; Bulge-to-disk ratio [B/T]

Gotta test ‘em all!

Long overdue – stay tuned ☺

Quantitative morphology with ML

Faster and **even more robust!**

Quantitative measurements
CAS, Gini, M20, ...
+ neural network

Disk / bulge strength
C, Sersic n, B/T

Tidal features
As, outer A

Internal disturbances (e.g. dust lanes)
A + As in different bands

Different merger stages
A, As, G/M20

Work plan

1. Statistically test common morphology measurements. Long overdue!
    - Evaluate response to noise + seeing
    - See if improvements can be made to algorithms
    - Edit **statmorph** (open-source morphology code)

2. Train a neural network to *quickly* measure their *traditional* values
   Easy to use by community right away after the initial data release

3. Train a neural network to *robustly* measure *intrinsic* values
   These values should be consistent across all data releases

Thank you!