Bar Classification based on the Potential Map

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1. Introduction

- Roughly 60% of disk galaxies in the local universe.
- Bars play significant roles in the secular evolution.
  - Drive gas and stars into the center of galaxies (Roberts+1979; Athanassoula 1992; Sellwood & Wilkinson 1993; Ann & Thakur 2005)
  - Increase the central star formation & central mass concentration (Heckman 1980; Martin 1995; Ellison+2011; Oh+2012; Pfenniger & Norman 1990; Ann & Lee 2000; Athanassoula 2002)
  - Build up bulge-like structures, pseudobulges & peanut-shaped bulges (Kormendy 1982; Li & Shen 2015; Li+2015)
- Bars may govern spiral arms, rings & central dust structures.
  - Strong bars prefer stronger spiral arms, smaller rings, and straighter dust lanes (Peeples & Martini 2006; Buta+2009; Salo+2010; Knapen+2002; Comeron+2010; Kim+2012; Athanassoula 1992; Knapen+2002)

1. Introduction

- Bar strength, length, and pattern speed
  - Bar ellipticity (Martinet & Friedli 1997; Aguerri 1999, 2009; Abraham & Merrifield 2000; Marinova & Jogee 2007)
  - Normalized Fourier amplitude (Ohta+1990; Aguerri+2000; Athanassoula & Misiriotis 2002)

$$A_2 = \max\left(\frac{\sqrt{a_2^2 + b_2^2}}{a_0}\right)$$

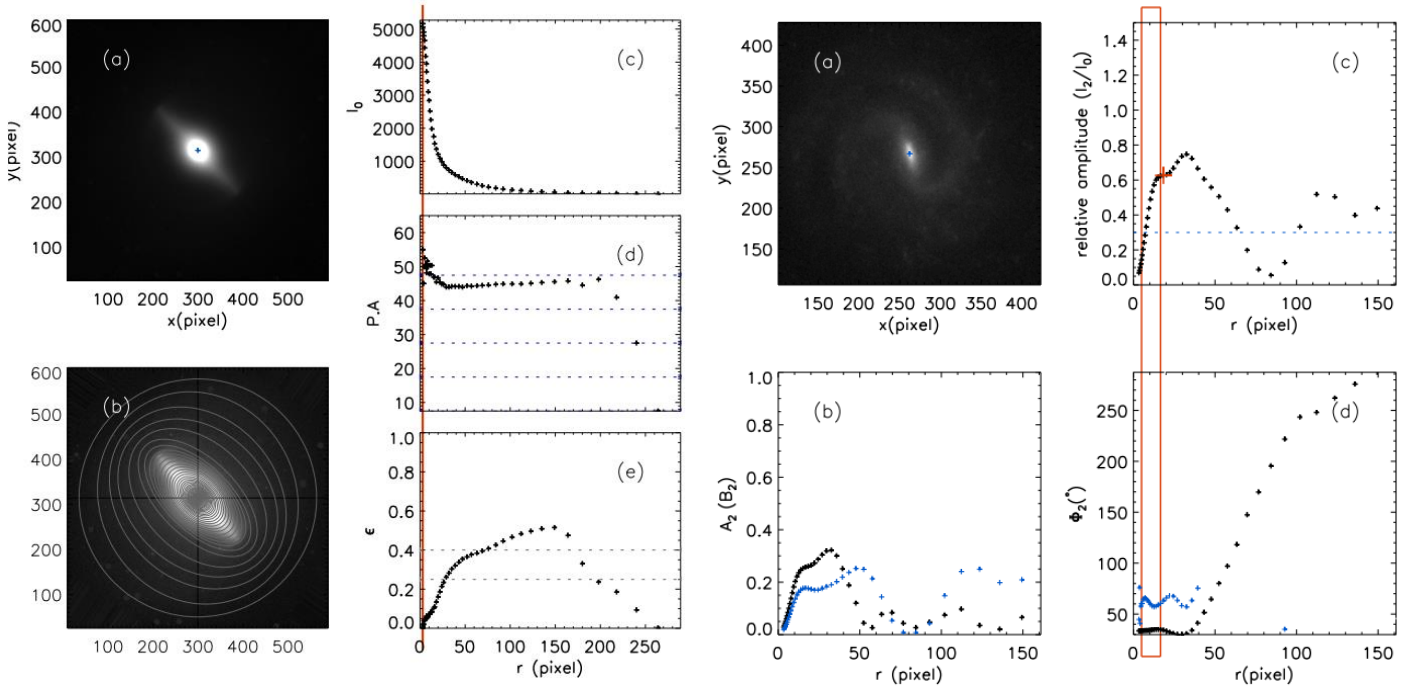
  - Transverse-to-radial force ratio (Combes & Sanders 1981; Buta & Block 2001; Laurikainen & Salo 2002; Diaz-Garcia+ 2016)

$$Q_{\rm T}(r) \equiv \frac{F_{\rm T}^{\rm max}(r)}{\langle F_{\rm R}(r)\rangle}$$

    - Most promising way to evaluate the bar strength
    - Tightly correlated to the kinematic bar strength from spectroscopy (Seidel+2015)

1. Introduction

- Bar Classification
  - Bar ellipticity vs. Normalized Fourier amplitude



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- High bar fraction in late-type spirals vs. In early-type spirals

2. Transverse-to-radial Force ratio

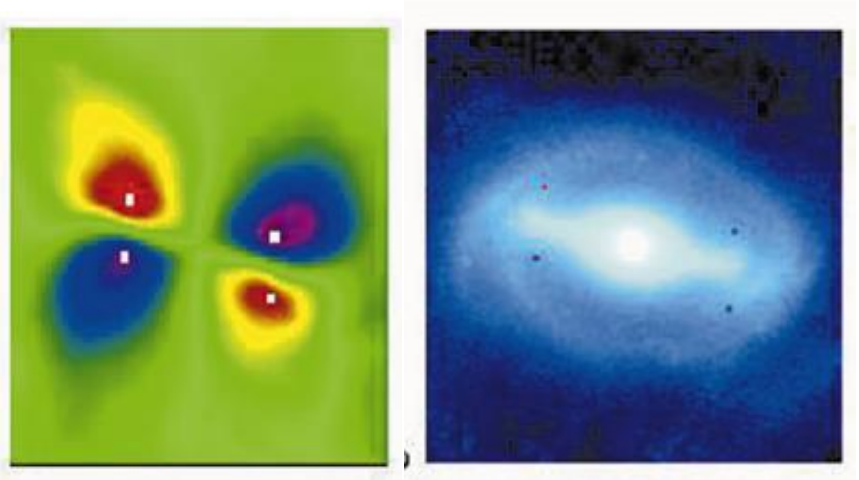
1. Bar Strength (Combes & Sanders 1981)

$$Q_{\rm T}(r,\phi) = \frac{\max(|F_{\rm T}(r,\phi)|)}{\langle |F_{\rm R}(r)| \rangle} \qquad \max(|F_{\rm T}(r,\phi)|) = \frac{1}{r}\frac{\partial \Phi(r,\phi)}{\partial \phi}$$

$$\langle F_{\rm R}(r) \rangle = \left(\frac{d\Phi_0}{dr}\right)$$

2. Force ratio map (Buta & Block 2001)

$$Q_{\rm T}(i,j) = \frac{F_T(i,j)}{\langle F_R(i,j) \rangle}$$



"Butterfly pattern"

Bar strength: $Q_b = \sum_{i=1}^{4} Q_{bi}/4$

2. Transverse-to-radial Force ratio

- Assumption: constant M/L ratio in the disk (Quillen et al. 1994)
- Calculation of potential
  1. Expand i-band deprojected images with four times area
  2. Calculate potential by solving Poisson equation using FFT

$$\Phi(x) = -G \int \frac{\rho(x')d^3x'}{|x - x'|}$$

$$\Phi(x, y, z = 0) = -G \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \sum(x', y')g(x - x', y - y')dx'dy'$$

  3. Consider the mass density in the vertical direction by convolving the image with the exponential model

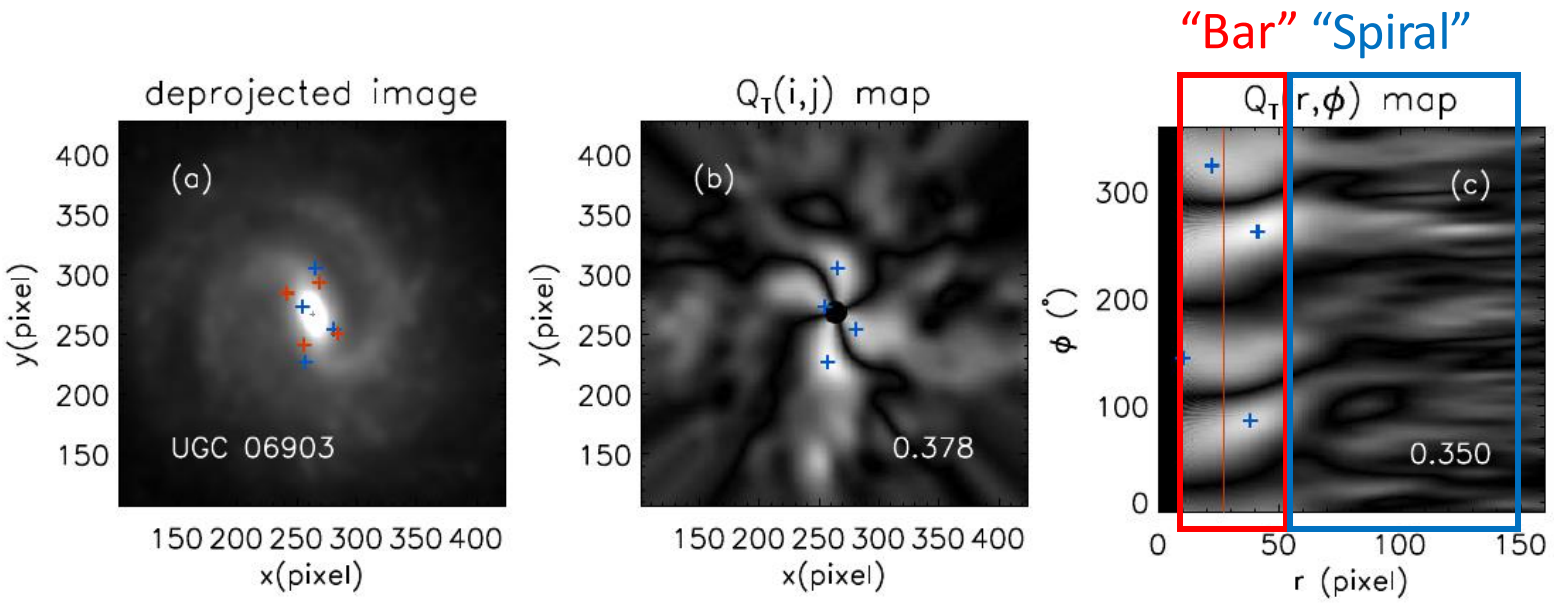
$$g(r) = \int_{-\infty}^{\infty} \frac{\rho_z(z)}{\sqrt{r^2 + z^2}} dz$$

$$\rho_z(z) = \frac{1}{2h_z} exp(-|\frac{z}{h_z}|)$$

- h_r/h_z=4 for T ≤ 1
- h_r/h_z=5 for 2 ≤ T ≤ 4
- h_r/h_z= for T ≥ 5 (Laurikainen+2004)

3. New Classification Method

1) Force ratio map in the Polar coordinate



- Simplify the complex butterfly pattern
- Good to disentangle a bar region from a bulge and spiral arms

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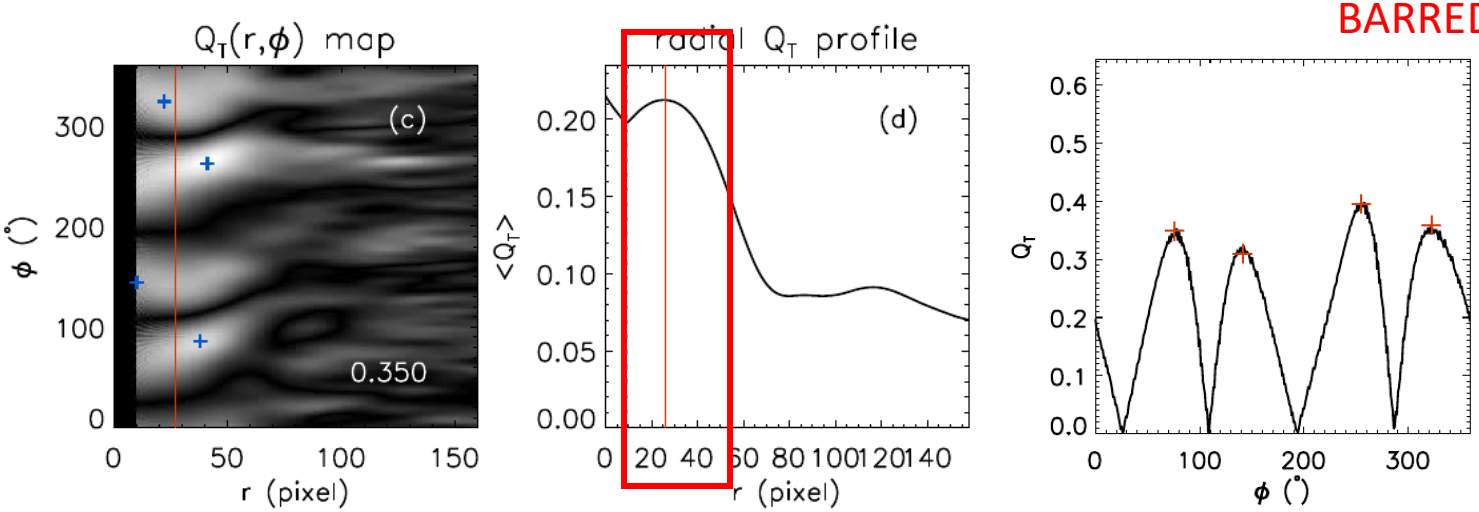
3. New Classification Method

1) Force ratio map in the Polar coordinate

4 peaks + Q_b > 0.15 :
BARRED Galaxy



"r_{Qb}"

Force ratio map (r, Φ) — Radial Qt profile — Cross-section at r_{Qb}

$$\langle Q_{\rm T}\rangle(r) = \frac{1}{2\pi}\int_0^{2\pi} Q_{\rm T}(r,\phi)d\phi$$

Bar Strength $$Q_{\rm b} \equiv \frac{1}{m}\sum_{i=1}^{m} Q_{{\rm T}i}$$

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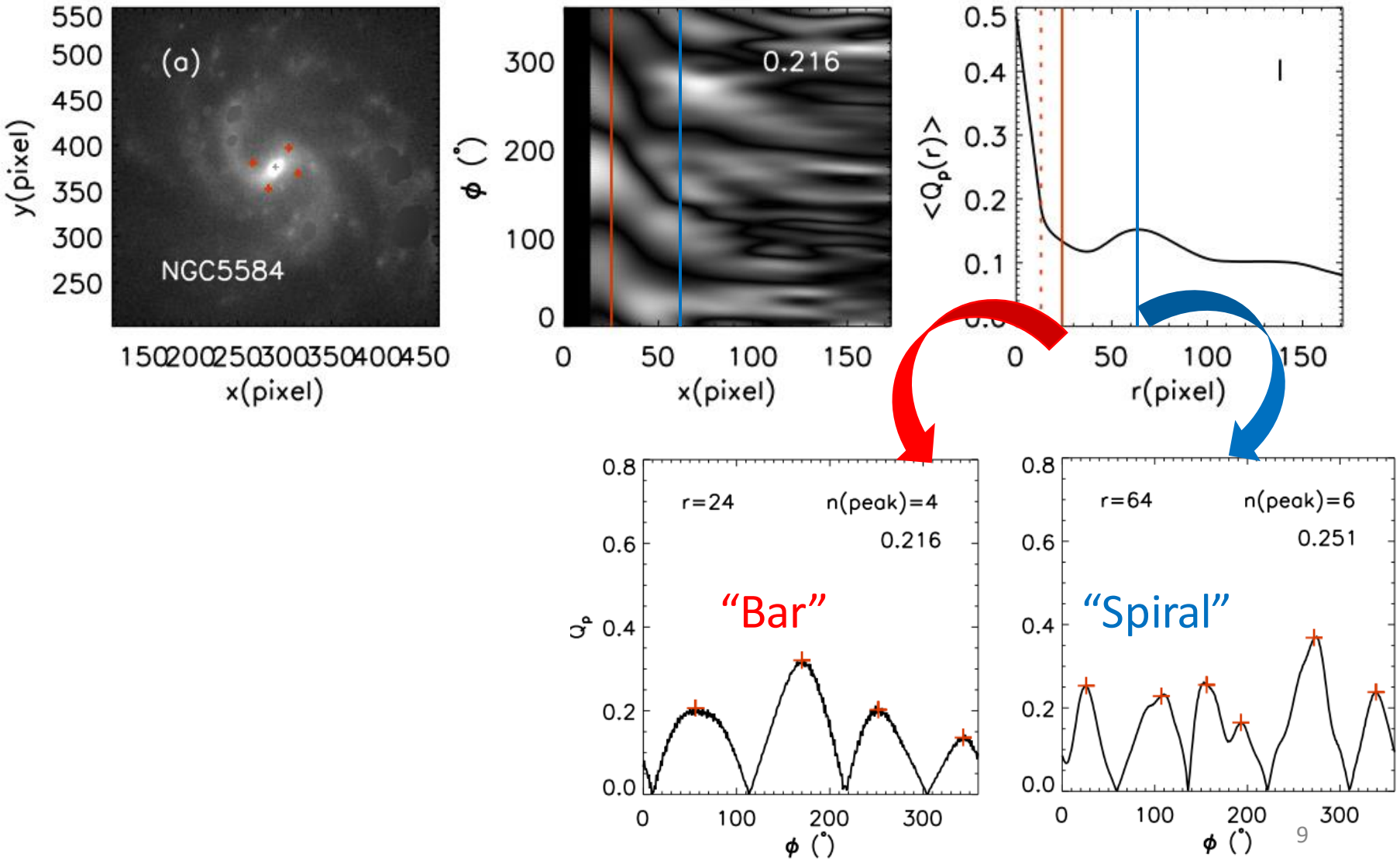
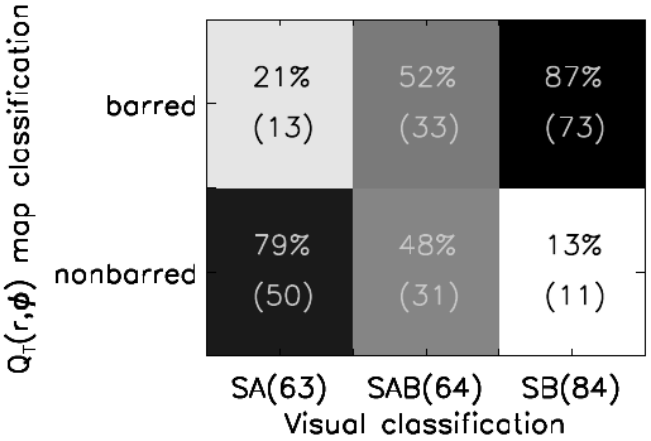
3. New Classification Method

1) Force ratio map in the Polar coordinate



3. Classification

2) Comparison with visual inspection



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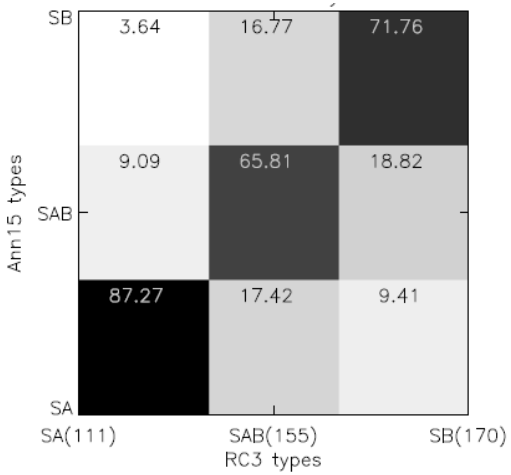
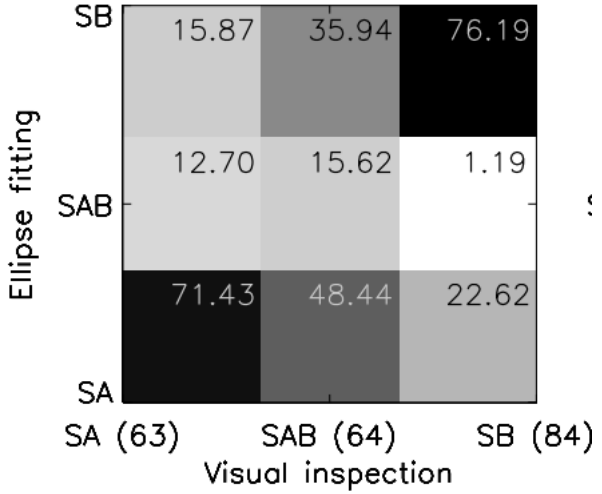
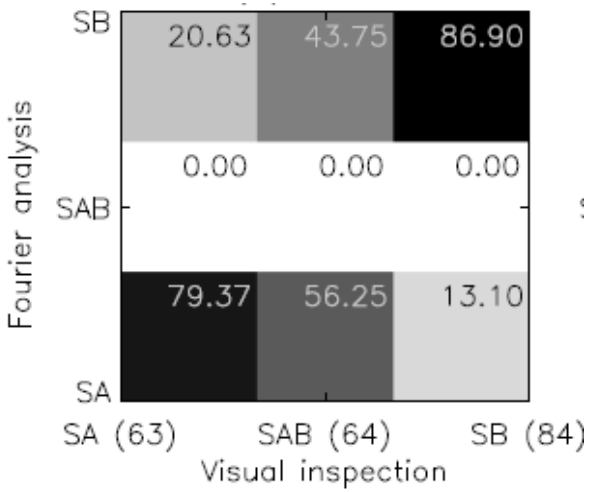
Visual inspection



Ellipse fitting method



Fourier analysis



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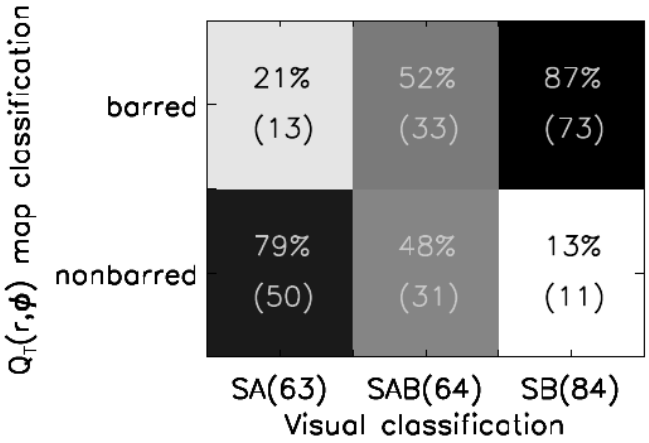
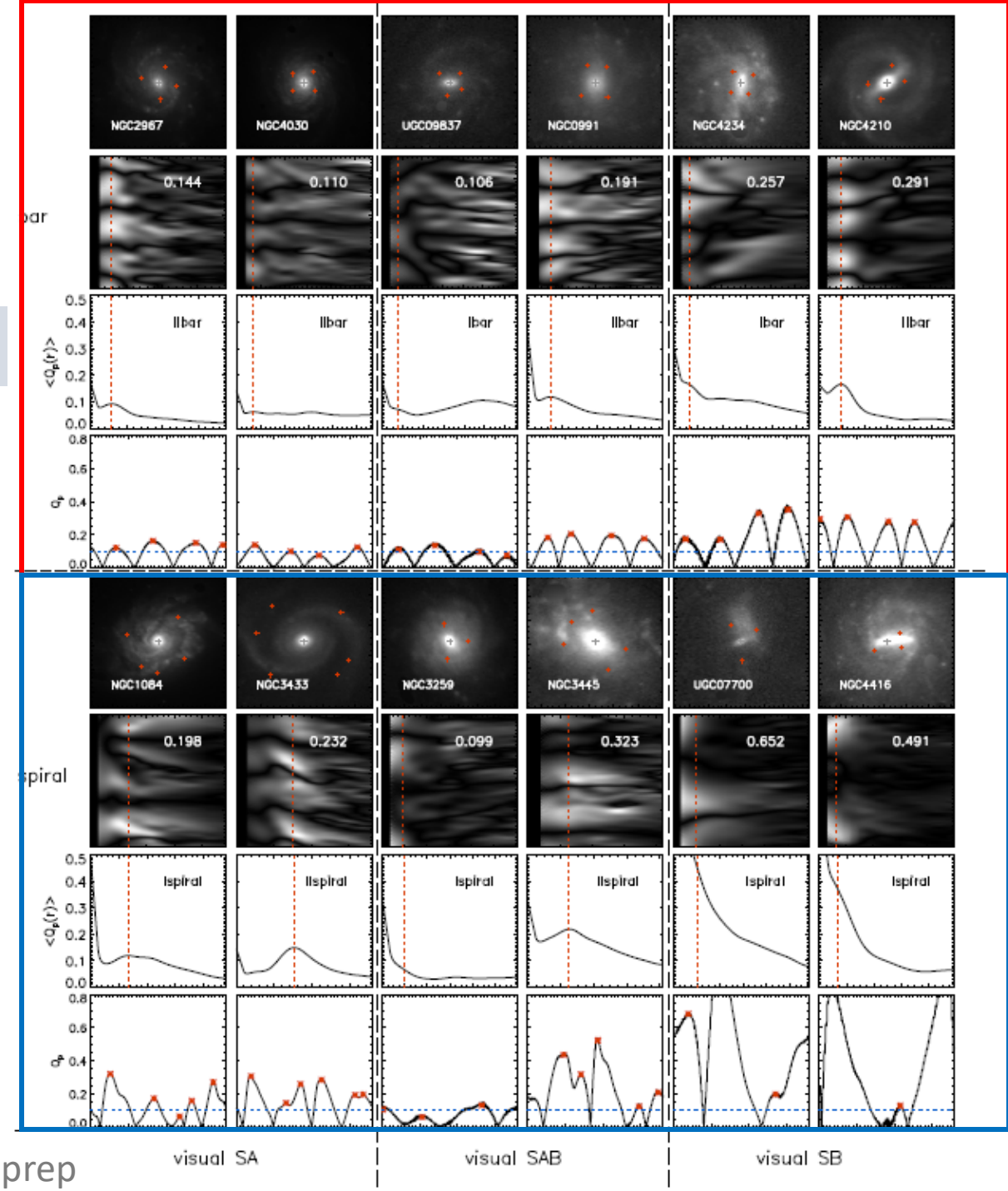
3. Classification

Bar fraction: 56%





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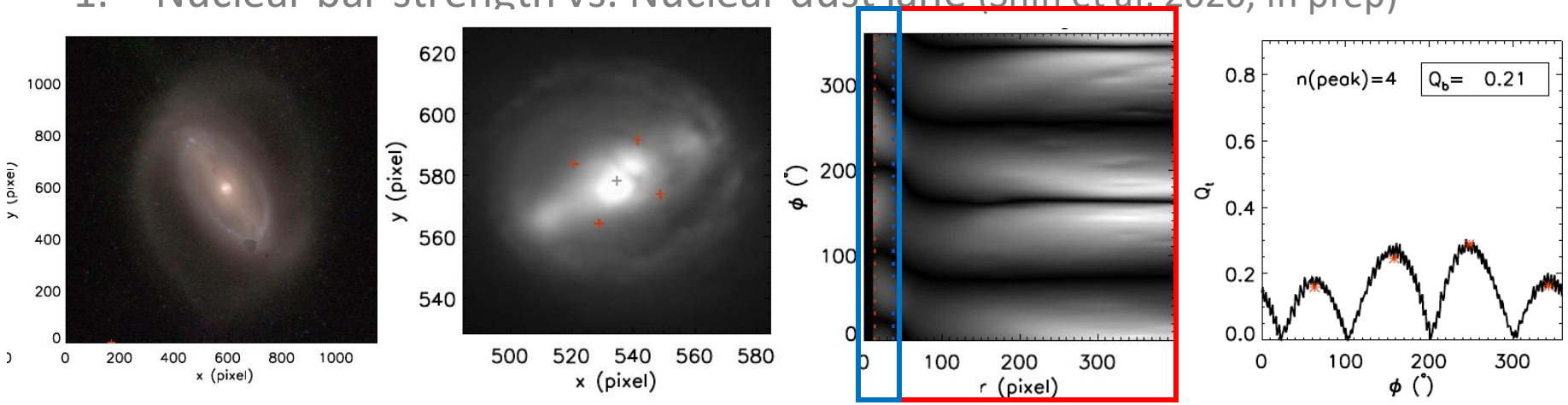
4. Calculation of Bar strength

1. Nuclear bar strength vs. Nuclear dust lane (Shin et al. 2020, in prep)



2. Bar strength evolution (Kim et al. 2020, in prep)