Tools to study

Morphological Evolution of Galaxies

for $0 < z < 0.5 < 1$

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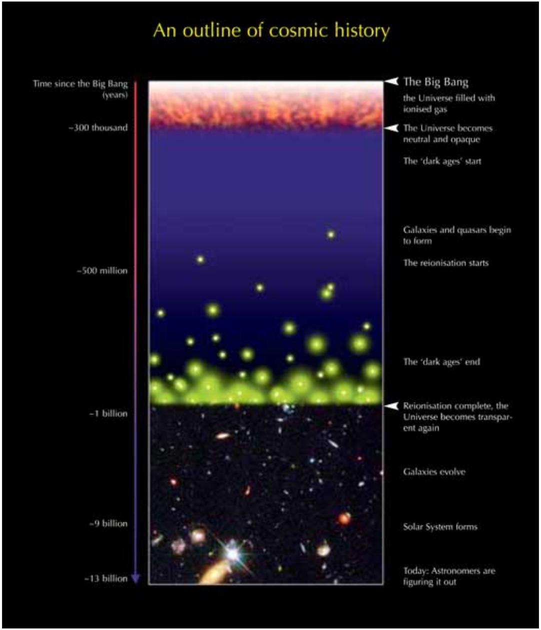

Djorgovski and Digital Media Center, Caltech

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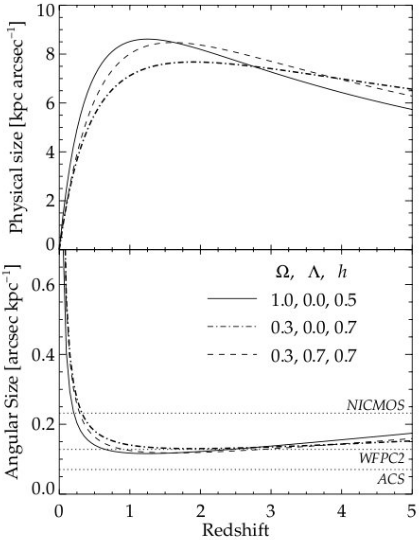
- Galaxy morphology at different environments
- Two-body correlation-function, find clusters, large scale structures
- Galaxy and Universe evolution

What we can



Papovich et al. 2003 ApJ **598** 827P

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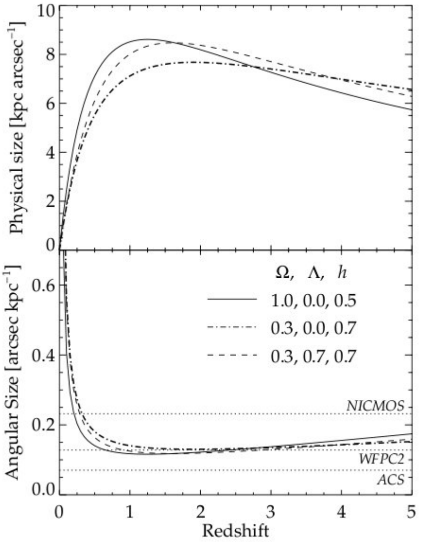

JPAS magnitude limit

$$m_{\mathrm{AB}} < 25 \quad (?)$$

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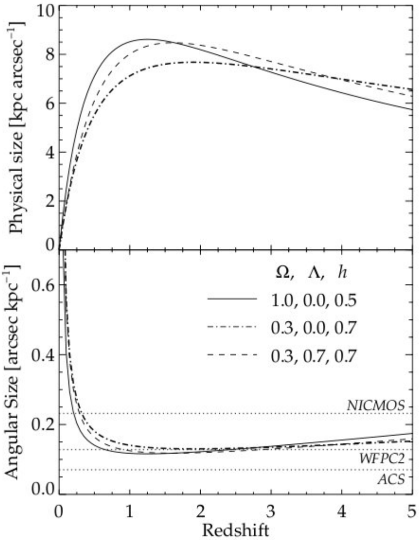

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PSF variation

$$p = p(x, y, \lambda, t) \qquad t = t(T, az, alt)$$

Deconvolution

traditionally in morphology: a sin, immoral, shameful, harmful

Algorithms

- iterative
  - Jansson-Van Cittert
  - Richardson-Lucy (maximum likelihood)
  - Landweber
- non-iterative
  - Wiener (least squares, non-iterative)

most can be combined with **wavelet** transform to remove noise

Deconvolution techniques

– **Wiener deconvolution**

Find a filter g so that the *estimated s*

$$\tilde{s} = g * o \qquad\qquad \hat{\tilde{s}} = \hat{g} . \hat{o}$$

The **Wiener** filter g

$$\hat{g} = \frac{1}{\hat{p}} \left[\frac{|\hat{p}|^2}{|\hat{p}|^2 + \frac{|\hat{n}|^2}{|\hat{s}|^2}} \right]$$

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– **Jansson-Van Cittert**

$$s^{n+1} = s^n + \alpha(o - h * s^n)$$

term proportional do the residual is added.
similar to **Richardson Lucy** or **Landweber**

How to measure morphology

- Standard Bulge-Disk-Halo decomposition
- Image Simulations (shapelets, multi-gaussian fitting, ...)
- Image moments
- Asymmetry indexes

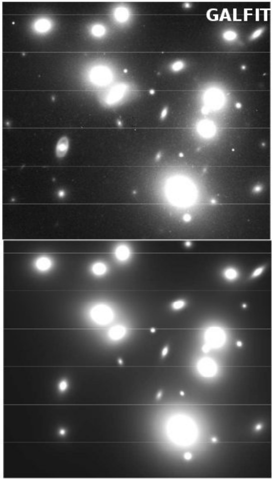
Available Tools

GIM2D – Galaxy Image 2D
Simard et al. 2002, ApJS, **142**, 1

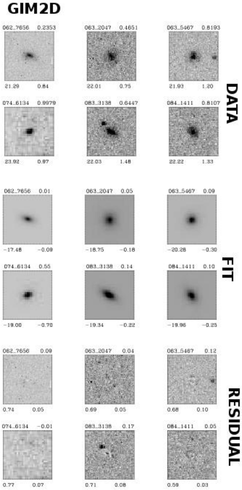
GALFIT
Peng et al. 2002, AJ, **124**, 266

it would be nice to have mock images to play with

Examples



A1689 $z = 0.186$, Pannella (Thesis) 2007



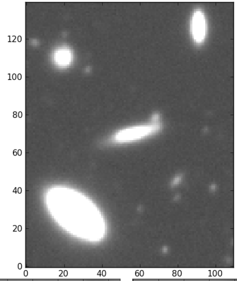
Groth Strip Survey, Simard et al 2002

New Tools

- Discrete Wavelet Transform – DWT
- Image Invariant Moments
- Principal Component Analysis – PCA
- Waveleted Principal Component Analysis – WPCA

Discrete Wavelet Transform

multiscale transform



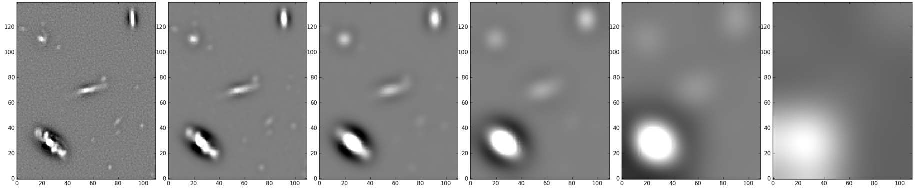


Image Moments

$$M_{pq} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} x^p y^q f(x,y)\, dx\, dy \qquad \rightarrow \text{discrete} \rightarrow \qquad M_{ij} = \sum_x \sum_y x^i y^j I(x,y)$$

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Central Normalized Moments

$$\mu_{pq} = \frac{1}{M_{00}} \sum_x \sum_y (x-\bar{x})^p (y-\bar{y})^q \; I(x,y)$$

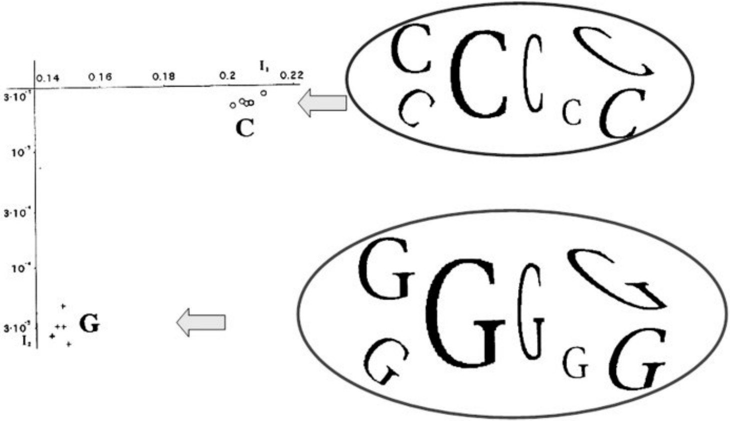
Scale Invariants

$$\eta_{ij} = \frac{\mu_{ij}}{\mu_{00}^{\left(1+\frac{i+j}{2}\right)}}$$

Translation, scale and rotation invariants – Hu (1962) set

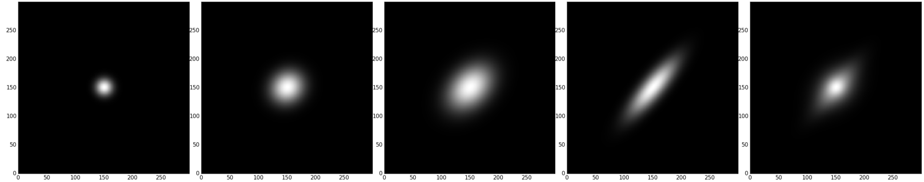
$$I_1 = \eta_{20} + \eta_{02} \tag{1}$$
$$I_2 = (\eta_{20} - \eta_{02})^2 + (2\eta_{11})^2 \tag{2}$$
$$I_3 = (\eta_{30} - 3\eta_{12})^2 + (3\eta_{21} - \eta_{03})^2 \tag{3}$$
$$\ldots \tag{4}$$

Pattern Recognition with Moments



Flusser, Suk, Zitová 2009

Synthetic example



gal1 (6%) gal2 (23%) gal3 (40%) gal4 (31%) gal1234

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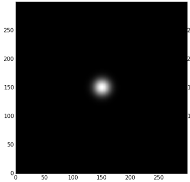

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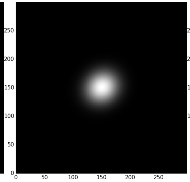
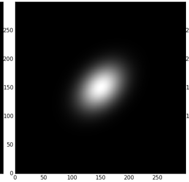
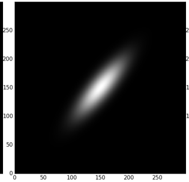


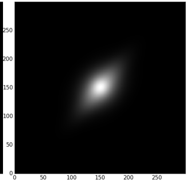
gal2 (23%)



gal3 (40%)



gal4 (31%)



gal1234

model	μ_{00}	μ_{01}	μ_{02}	μ_{10}	μ_{11}	μ_{12}	μ_{20}	μ_{21}	μ_{22}
gal1	1	0	100	0	0	0	100	0	10 000
gal2	1	0	355	0	37	0	368	0	133 800
gal3	1	0	670	0	229	-0.0011	670	-0.001124	55 4900
gal4	1	0	998	0	716	-0.3436	745	-0.2489	1 772 000
gal1234	1	0	662	0	319	-0.1133	587	-0.08201	79 5700

$\mu = 0$ means $\mu < 10^{-10}$

Principal Component Analysis

Write the data in a basis where all the variables are *uncorrelated*[1].

Usual: PCA in spectral direction $\rightarrow$ eigenspectras
useful to compare **common spectral** features between **galaxy pixels**.

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Classification scheme

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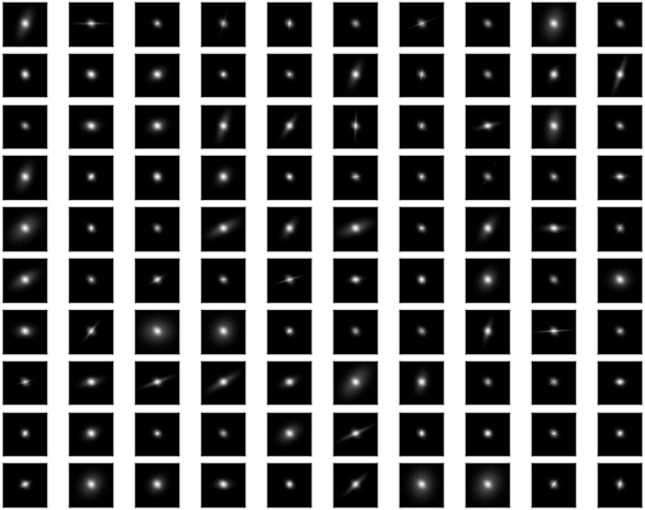
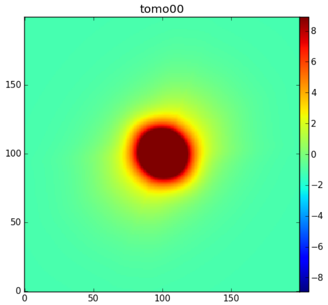
Face recognition: eigenfaces

Principal Component Analysis

Simulated 'galaxies'.
All have a common spherical component)



PCA - eigengalaxies



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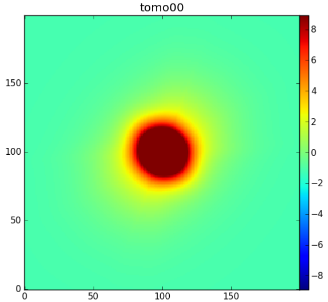
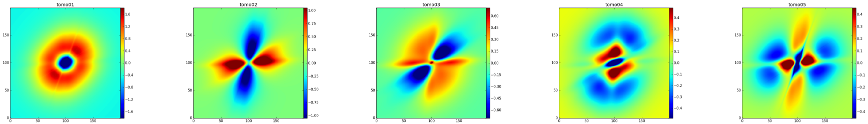
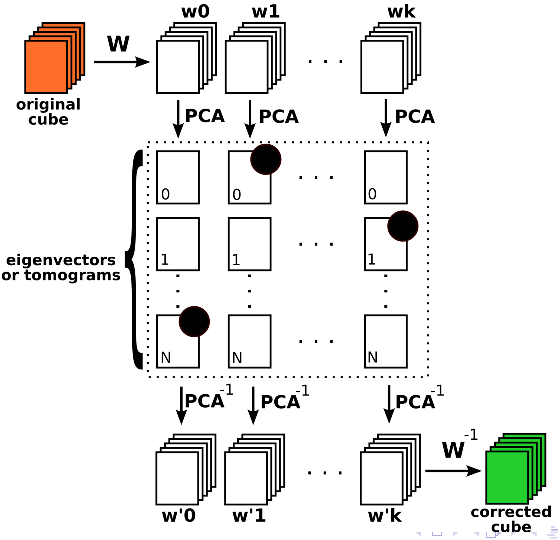




1st: 93% **2nd: 4%** **3rd: 2%** **4th+5th+...:1%**

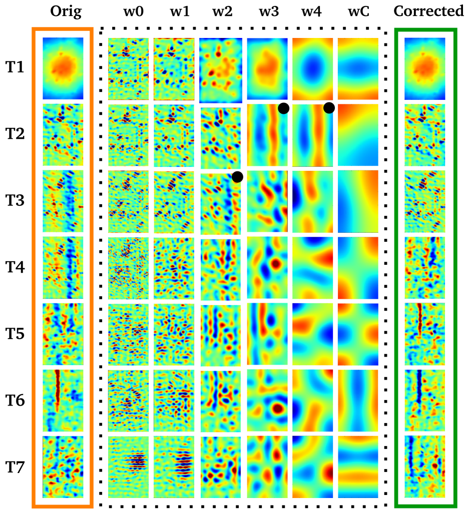
WPCA - removal of instrumental signature

Ferrari et al 2010; Riffel, Riffel, Ferrari & Storchi-Bergmann 2011; Ferrari et al 2012 (in prep)



WPCA NGC 1399

Steiner et al. data - Gemini GMOS



Costs

Linux + Python + Scipy 200x200 pixels image

ACTION	DURATION
$\star$ find object, retrieve data$\star$	1 s
$\star$ deconvolution $\mathcal{F}^{-1}\{\mathcal{F}\}$	1 s
•2D fitting	10 s
$\star$ brightness profile with aberture photometry	1 s
$\star$ fit brightness profile	2 s
$\star$ moments calculation	1/10 s
• wavelet transform (6 scales)	8 s
•PCA (100 images=7s)	1 s

1 CPU	1 million objects
⋆ basic plan	60 days
• premium plan	1 year

300 10^6 objects basic plan $\rightarrow$ 50 years.

JPAS

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20 GPUs 500 cores	1 million objects
⋆ basic plan	3 hours
• premium plan	15 hours

300 10^6 objects basic plan $\rightarrow$ 36 days.

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- Stellar mass, size, and Sérsic index can predict the velocity dispersions in SDSS (Bezanson et al 2011 ApJ **737** 31)

Some Similar Works

- MGC –Millennium Galaxy Catalogue
- COSMOS – Cosmic Evolution Survey
- STAGES – Space Telescope Galaxy Evolution Survey
- SAGE – Surveying the Agents of Galaxy Evolution

Gracias