Optimal Photometry of Faint Galaxies

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Collaborator:

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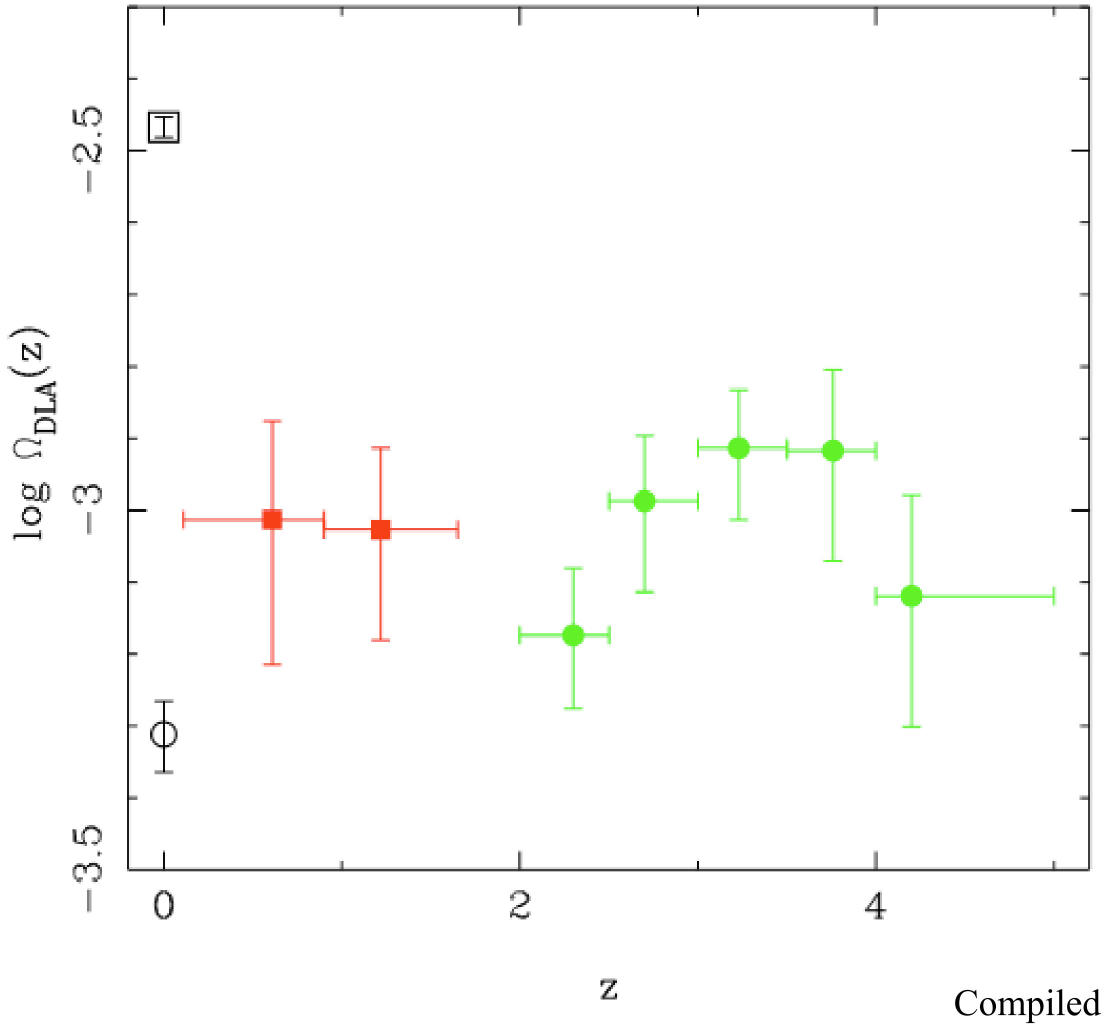
Outline

- scientific motivation
- data
- photometric redshift technique
- optimal photometry and photometric redshifts of faint galaxies

Cosmic chemical evolution

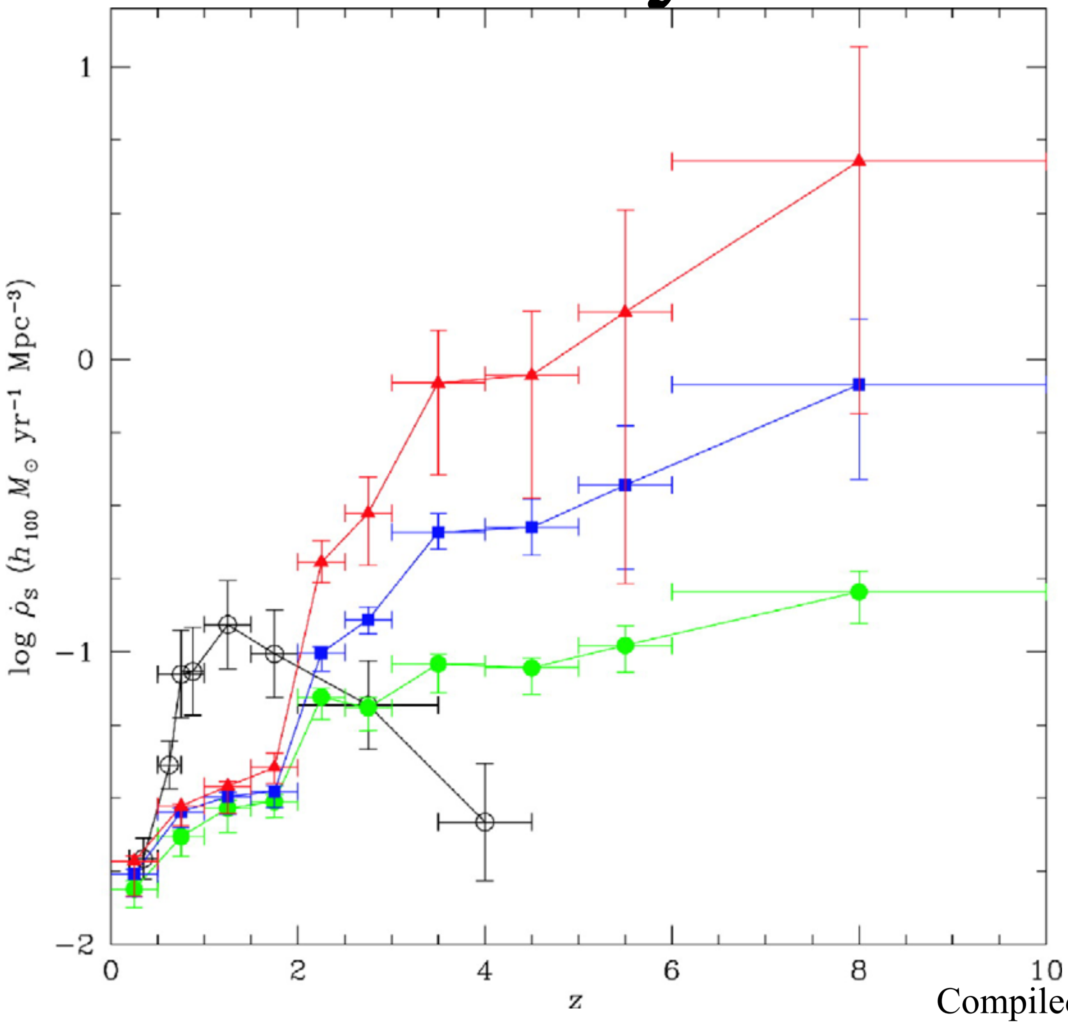
- We are interested in the quantities of cosmic chemical evolution…
  - Ω_g (damped Lyα absorbers)
  - ψ (rest-frame ultraviolet, Hα emission)
  - Z (damped Lyα absorbers)
  - Ω_s (rest-frame near-infrared emission)
- …which are the quantities of galactic chemical evolution averaged over cosmic volumes

Comoving mass density of gas



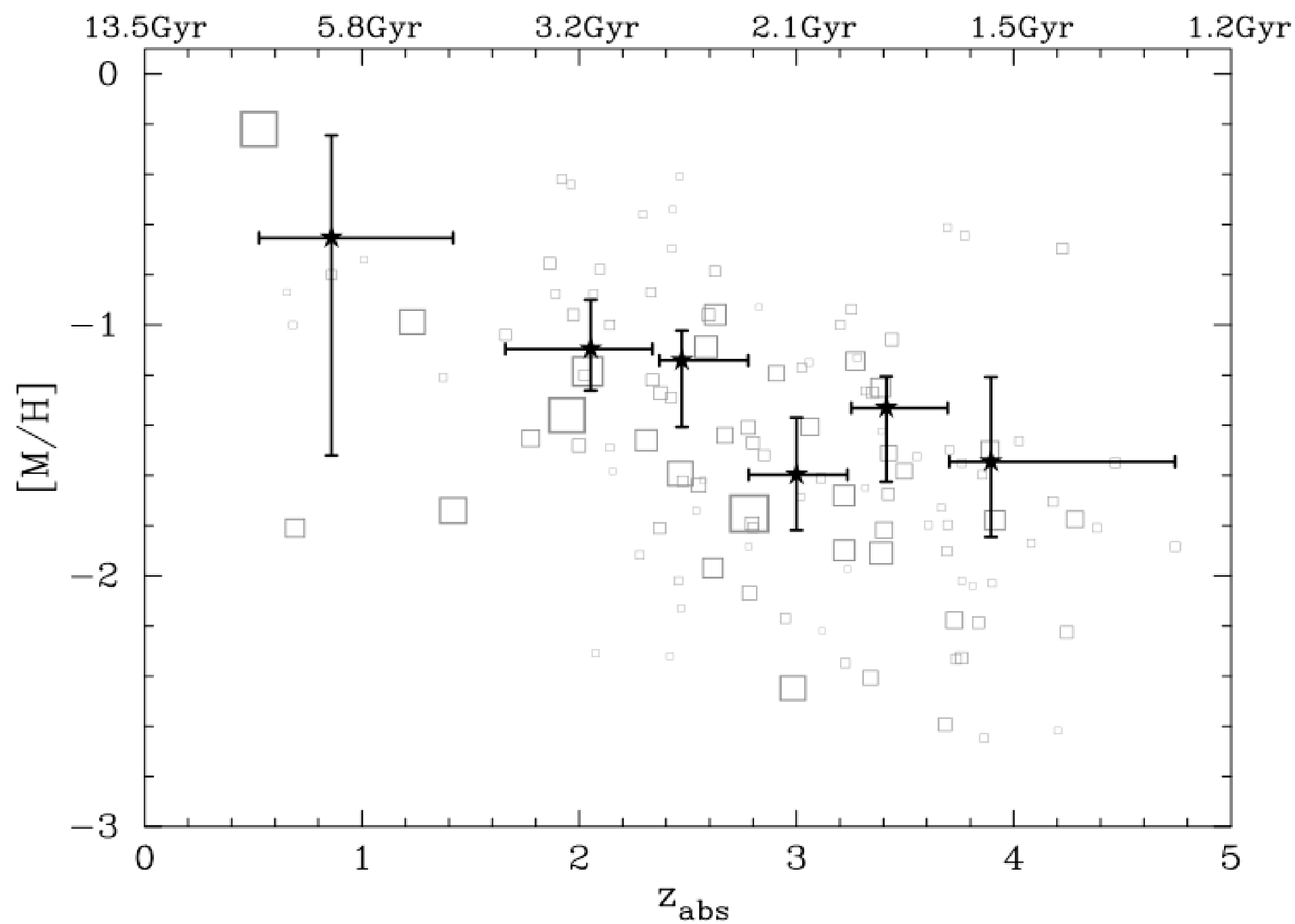
Compiled by Rao et al. 2005

Comoving star formation rate density



Compiled by Lanzetta et al. 2003

Cosmic metallicity



Compiled by Prochaska et al. 2004

Outstanding issues

- very limited statistics
- cosmic variance
- selection biases
  - damped Lyα absorbers: obscuration by dust of QSOs behind high-column-density absorbers
  - ultraviolet emission: dust extinction, cosmological surface brightness dimming

Equations of cosmic chemical evolution

$$\frac{d\Omega_s}{dt} = (1 - R)\psi$$

$$\frac{d\Omega_g}{dt} = -(1 - R)\psi + \phi$$

$$\Omega_g \frac{dZ}{dt} = y(1 - R)\psi - \phi Z$$

Comoving mass density of stars

- existing surveys target very large numbers of galaxies (statistics) across many fields (cosmic variance)
- measurement is based upon rest-frame near-infrared emission (dust extinction)
- *objective: determine the comoving mass density of stars versus cosmic epoch with the accuracy needed to obtain a statistically meaningful time derivative*

Our program

- measure optimal photometry (at observed-frame near-ultraviolet through mid-infrared wavelengths) and photometric redshifts of faint galaxies in GOODS and SWIRE surveys
- use rest-frame near-infrared luminosities and rest-frame optical and near-infrared colors to estimate stellar mass densities
- construct comoving mass density of stars versus cosmic epoch

GOODS survey

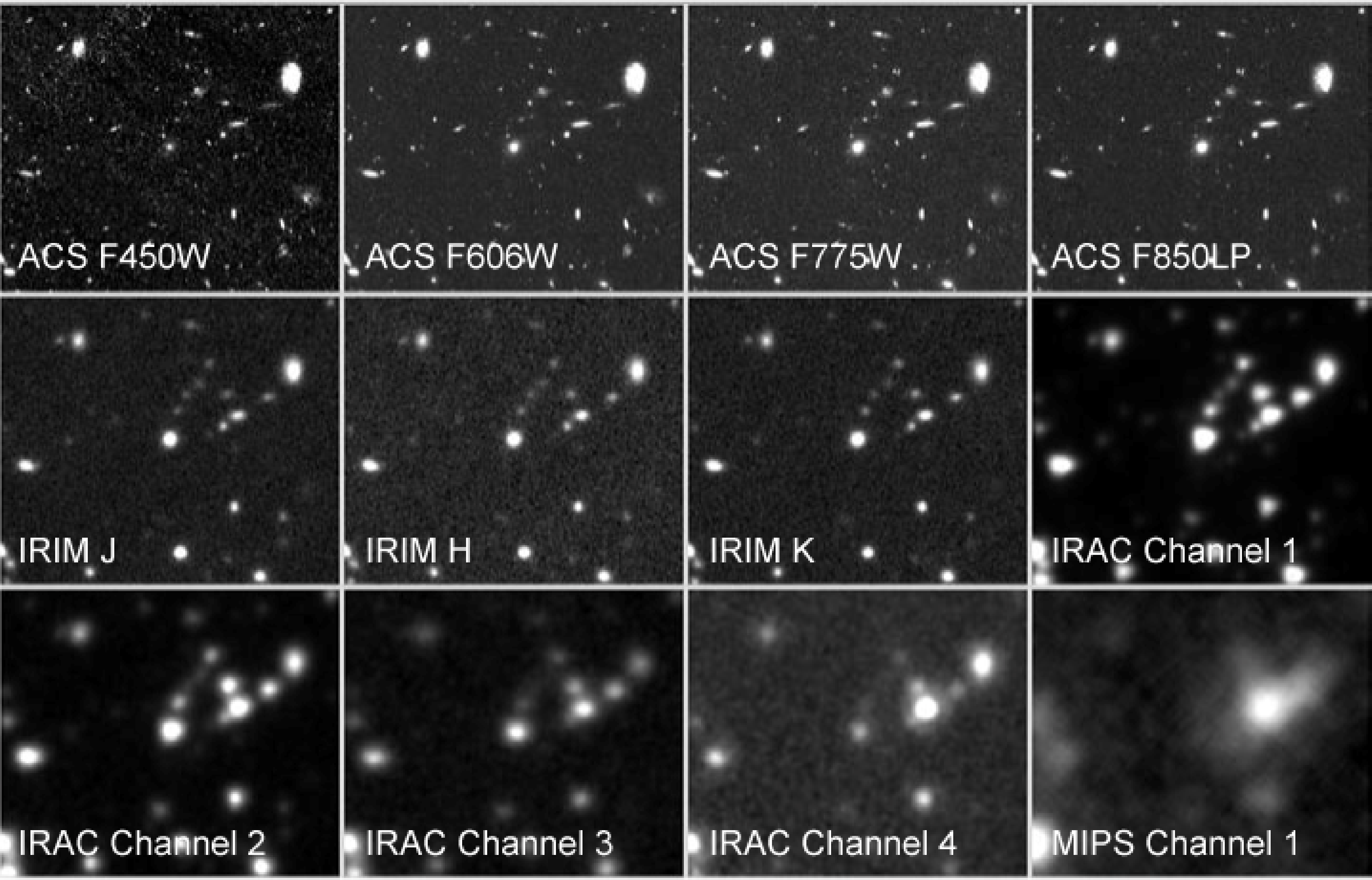
- two fields spanning 320 arcmin^2
- Spitzer IRAC images at 3.6, 4.5, 5.8, and 8.0 μm and MIPS images at 24 μm
- HST and ground-based images at observed-frame optical and near-infrared wavelengths
- roughly 10,000 IRAC images and 10,000 MIPS images
- roughly 200,000 galaxies at $z \approx 0 - 6$

SWIRE survey

- six fields spanning 49 deg^2
- Spitzer IRAC images at 3.6, 4.5, 5.8, and 8.0 μm and MIPS images at 24, 70, and 160 μm
- ground-based images at observed-frame optical wavelengths
- roughly 100,000 IRAC images and 500,000 MIPS images
- roughly 8,000,000 galaxies at $z \approx 0 - 2$

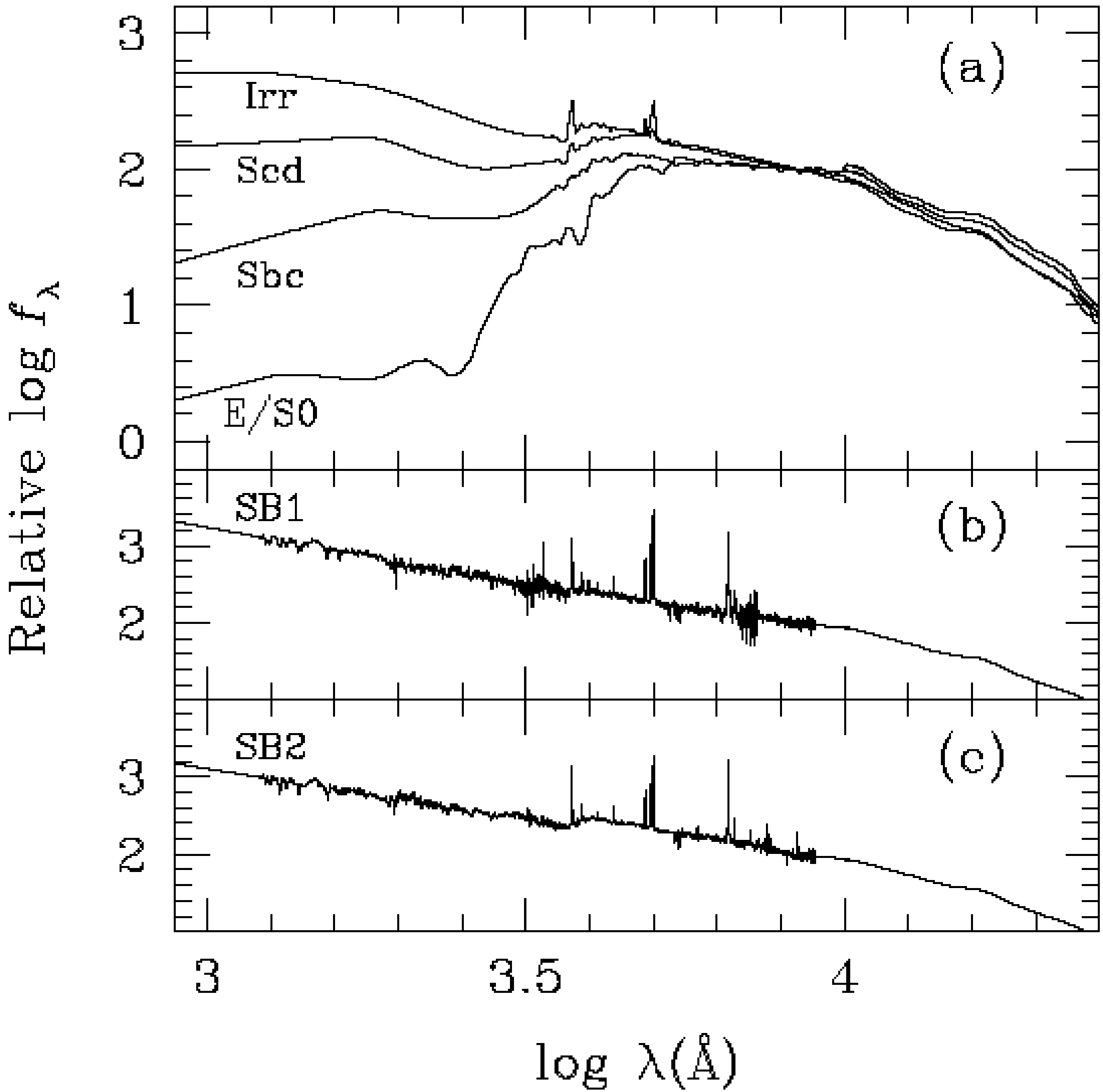
Why the measurement is difficult

- characteristic scale of high-redshift galaxies: 0.1 arcsec
- characteristic scale of Spitzer PSF: 2.5 arcsec (or larger at longer wavelengths)
- Spitzer images are undersampled
- almost all galaxies overlap other galaxies
- how to measure faint galaxies that overlap bright galaxies?

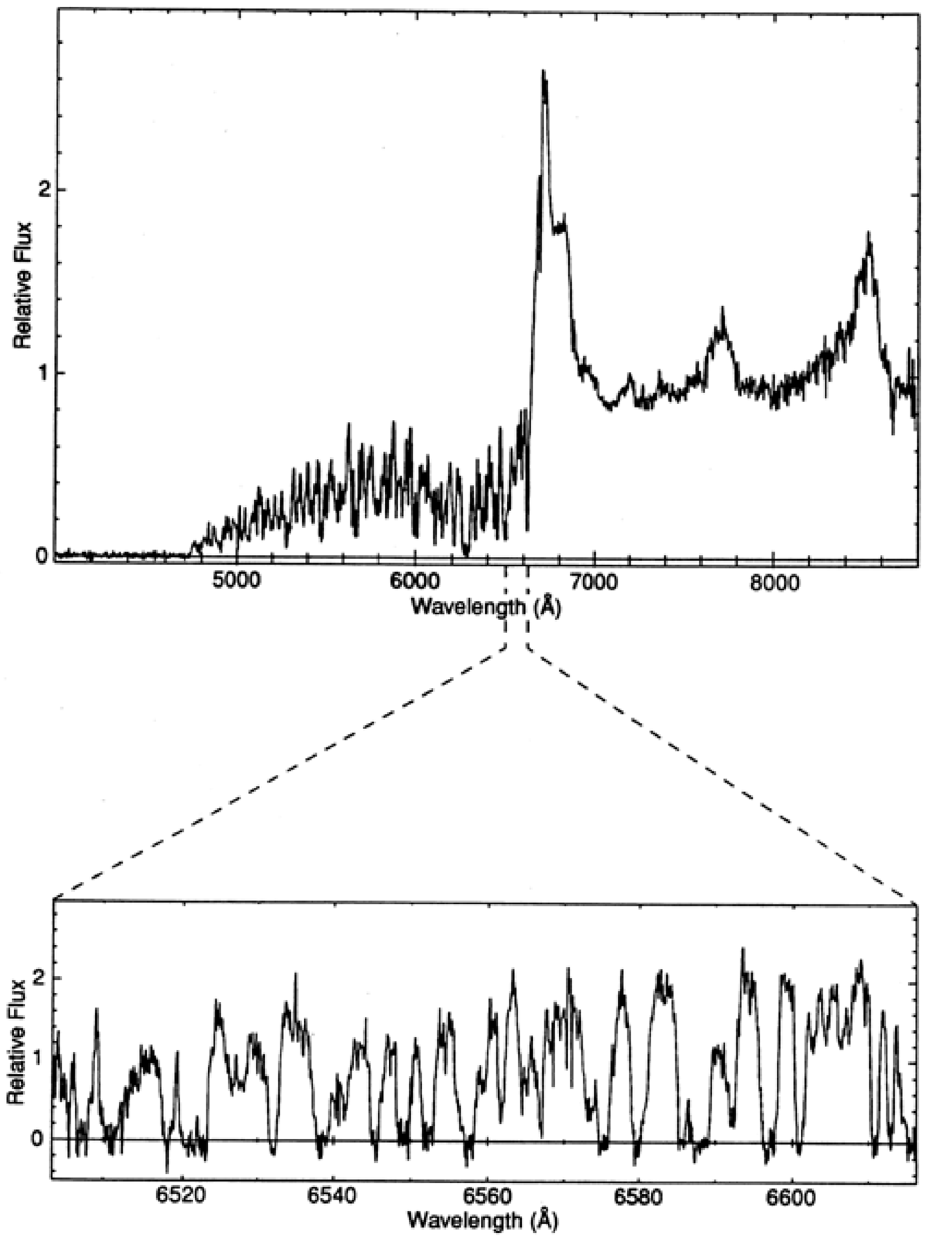

ACS F450W
ACS F606W
ACS F775W
ACS F850LP
IRIM J
IRIM H
IRIM K
IRAC Channel 1
IRAC Channel 2
IRAC Channel 3
IRAC Channel 4
MIPS Channel 1

Photometric redshift technique

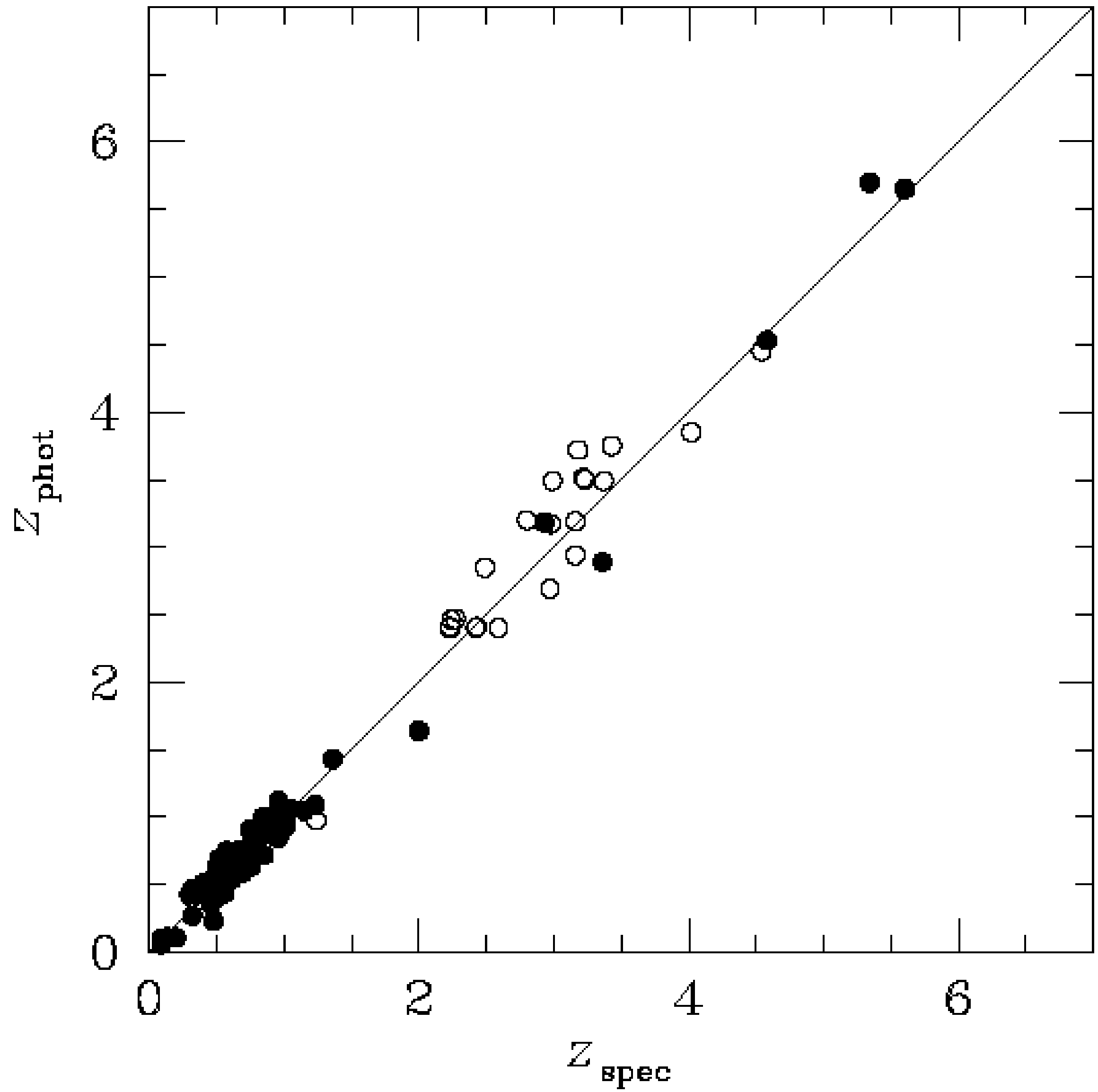
- Determine redshifts by comparing measured and modeled broad-band photometry
- Six galaxy spectrophotometric templates
- Effects of intrinsic (Lyman limit) and intervening (Lyman-alpha forest and Lyman limit) absorption
- Redshift likelihood functions
- Demonstrated accurate ($\Delta z / (1 + z) < 6\%$) and reliable (no outliers) at redshifts $z = 0$ through 6



Relative log f_λ
log λ(Å)
(a)
Irr
Scd
Sbc
E/S0
(b)
SB1
(c)
SB2
3
2
1
0
3.5
4



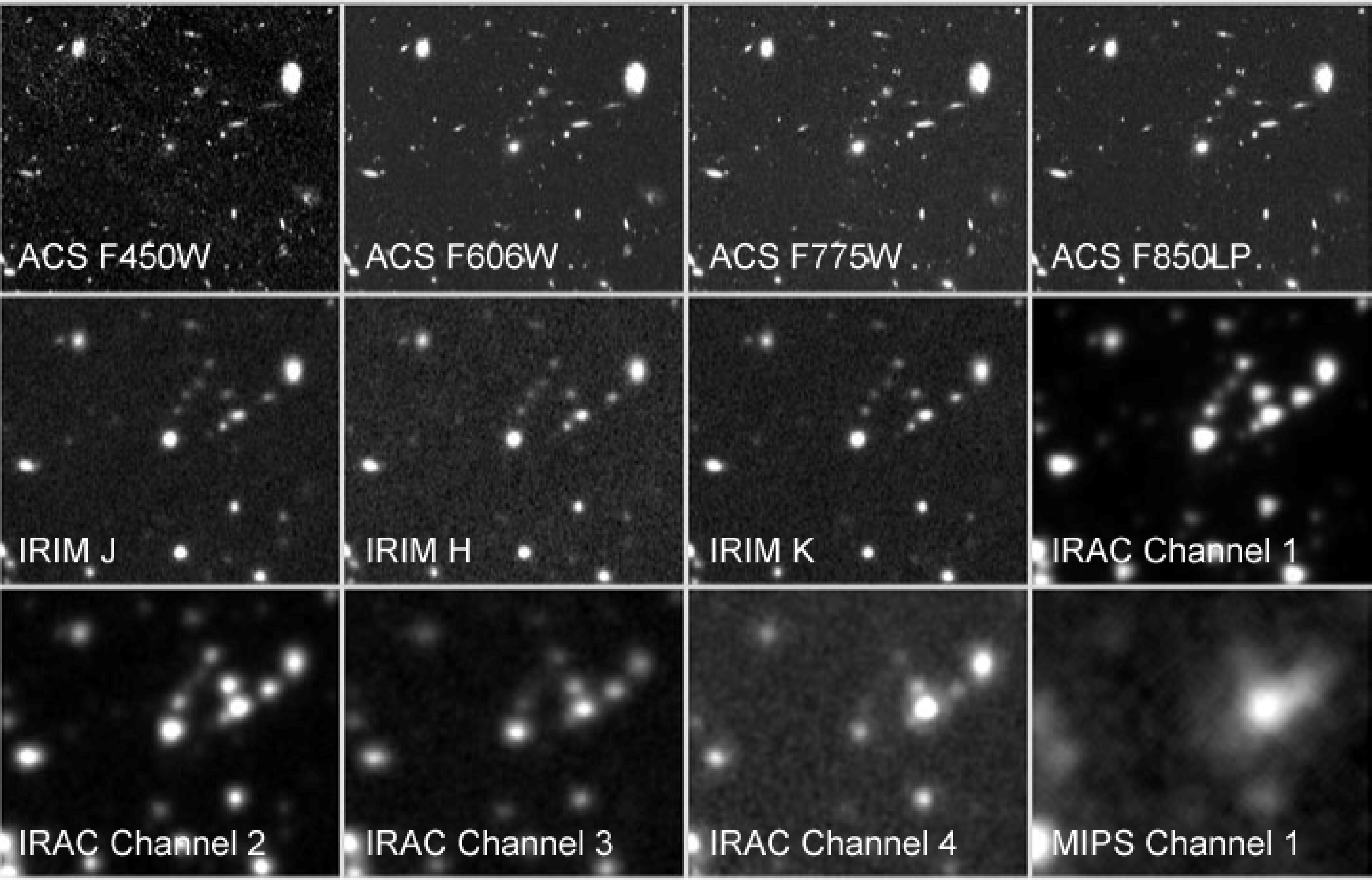
Relative Flux
0
1
2
5000
6000
7000
8000
Wavelength (Å)
Relative Flux
0
1
2
6520
6540
6560
6580
6600
Wavelength (Å)



0
2
4
6
z_phot
z_spec

“Redshift spatial profile fitting” technique

- “deconvolve” a sequence of “source” images (typically higher-resolution images at optical wavelengths) to obtain photometric redshifts and spatial models of galaxies
- use spatial models to fit for energy fluxes in a sequence of “target” images (typically lower-resolution images at near- or mid-infrared wavelengths)

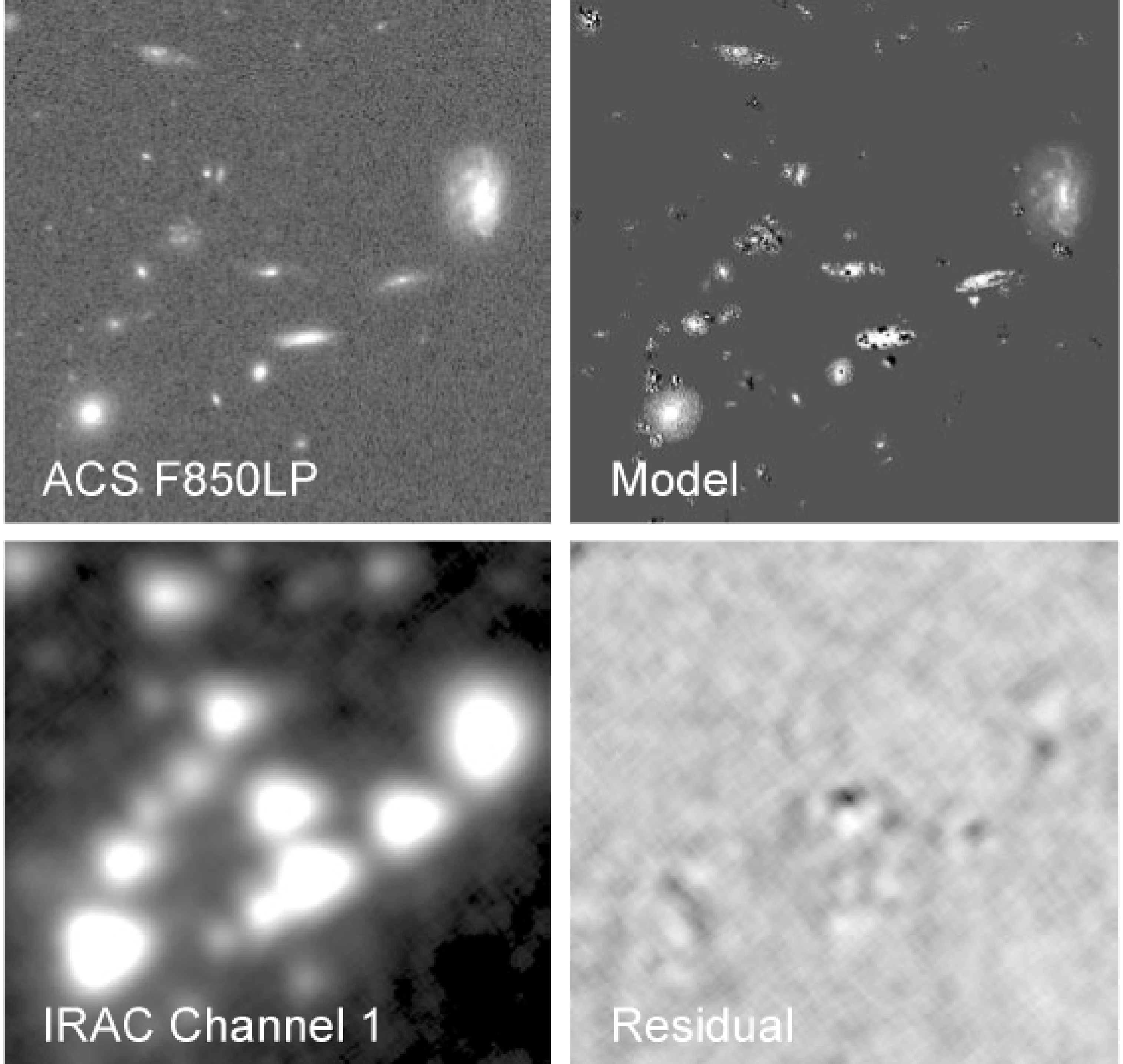

ACS F450W
ACS F606W
ACS F775W
ACS F850LP
IRIM J
IRIM H
IRIM K
IRAC Channel 1
IRAC Channel 2
IRAC Channel 3
IRAC Channel 4
MIPS Channel 1

“Deconvolving” source images

- build one spatial model image on a fine pixel scale
- relate spatial model image to each data image via geometric transformation, convolution, and scaling by spectral templates on a galaxy-by-galaxy basis
- simultaneously determine spatial models and photometric redshifts

Fitting target images

- do not “add” target images (undersampling, correlated noise)
- instead, relate spatial model image to each data image via geometric transformation, convolution, and scaling by unknown energy flux on a galaxy-by-galaxy basis
- determine energy fluxes



ACS F850LP
Model
IRAC Channel 1
Residual

Computational requirement

- each step of “deconvolving” or fitting requires transformation and convolution of the spatial model image to each data image
- registration of each data image must be fitted for as part of the process
- since there are a lot of data images, this is computationally very expensive

Computer setup

- 50 Xeon 3.06 GHz processors (donated by Intel Corporation)
- 20 cluster nodes, four workstations, one file server
- two Itanium 1.4 GHz processors (donated by Ion Computers)
- one database server
- 2 TB disk storage, 10 TB local disk caches
- custom job control and database software

What is needed to measure faint galaxies in deep Spitzer images

- accurate image alignment
  - geometric distortion, registration
  - better than 0.01 pixel
- accurate spatial models
  - deconvolution of source images
  - convolution of target images
- "color segmentation"
  - segment galaxy profiles by color

Part I:

To measure photometry of faint galaxies:

1. Construct profiles (models) of all galaxies using source images (e.g. ACS)

2. Use models to simultaneously solve for best-fit photometry of all galaxies in target images (e.g. SST IRAC, MIPS)

z Spatial Profile Fitting Technique

For source images in bandpasses β:

$$D^{\beta} = T(F^{\beta} \cdot M) \otimes P^{\beta} + \text{noise}$$

(D data, F template, $T(F \cdot M)$ transformed scaled model, P psf)

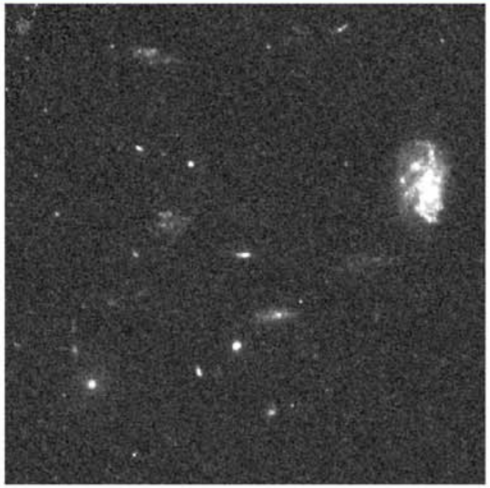
and:

$$\chi^2 = \sum \left(\frac{T(F^{\beta} \cdot M) \otimes P^{\beta} - D^{\beta}}{\sigma^{\beta}} \right)^2$$

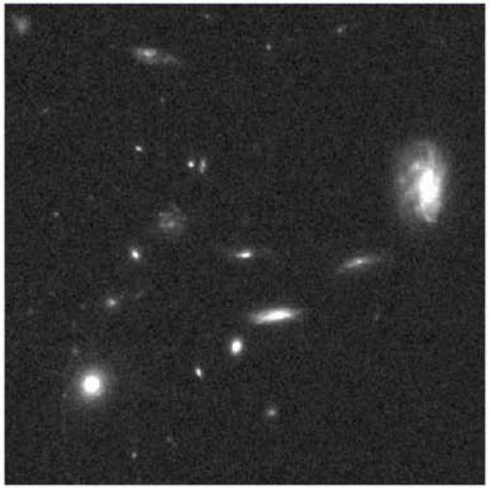
Solve $\nabla \chi^2 = 0$ across all bandpasses for:

- pixels of M on model grid
- Per-galaxy spectral templates F of model
- transformation T of model to each image

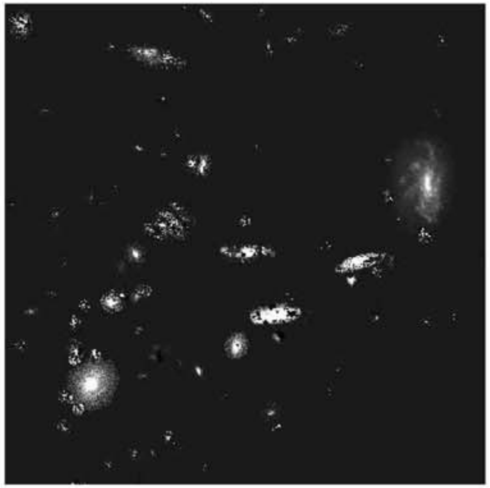
Example: Source Images



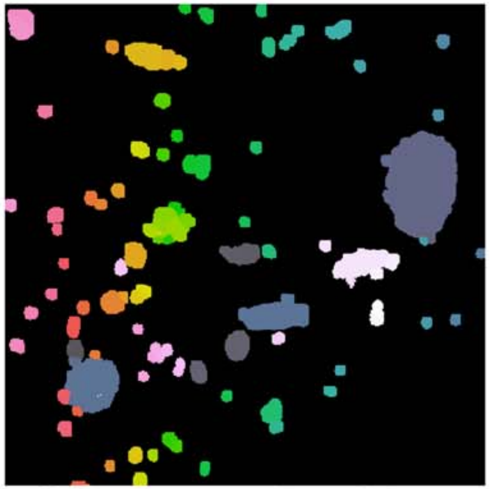
F450W Data



F850LP Data



Model



Segmentation Map

z Spatial Profile Fitting Technique

For target images in a single bandpass γ:

$$D^\gamma = T(f^\gamma \cdot \overline{M}) \otimes P^\gamma \text{ + noise}$$

(f per-galaxy photometry, $T(\overline{M})$ transformed normalized model)

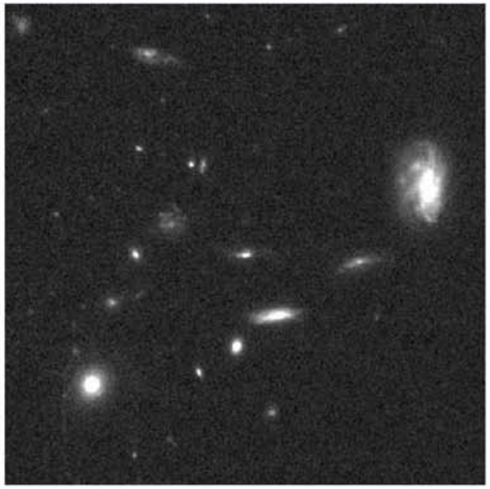
and:

$$\chi^2 = \sum \left(\frac{f^\gamma \cdot T(\overline{M}) \otimes P^\gamma - D^\gamma}{\sigma^\gamma} \right)^2$$

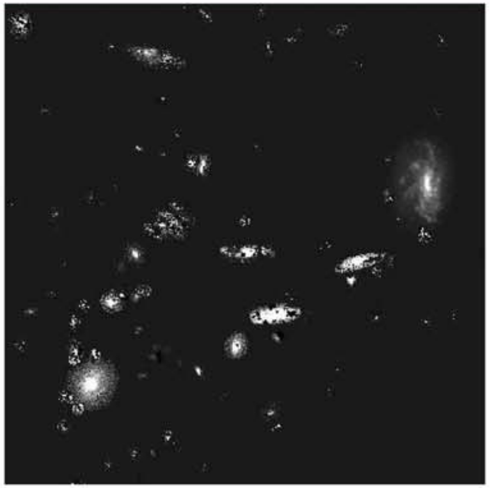
Given model M, solve $\nabla \chi^2 = 0$ for:

- Per-galaxy fluxes f
- transformation T of model to each image

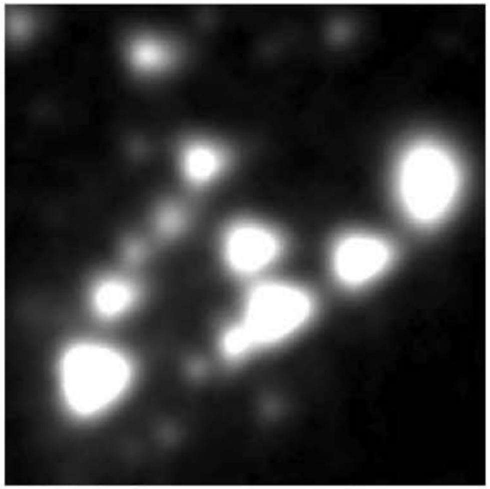
Example: Target Images



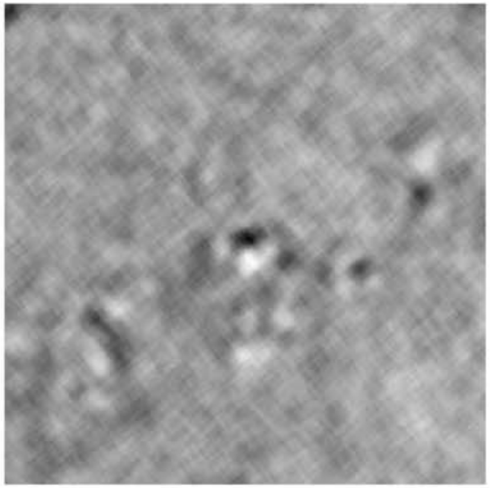
F850LP Data



Model

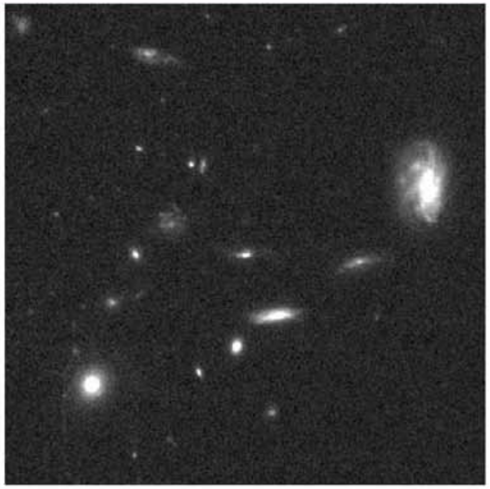


IRAC 3.6 μm Data

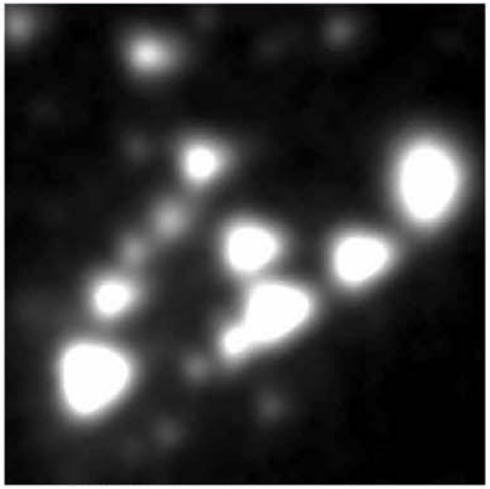


Residual

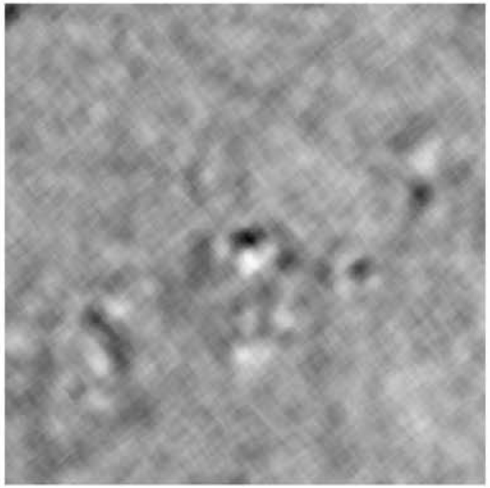
Problem: Target Image Residuals



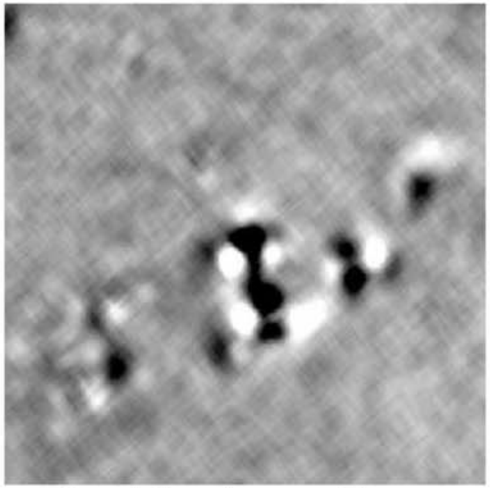
F850LP Data



IRAC 3.6 μm Data

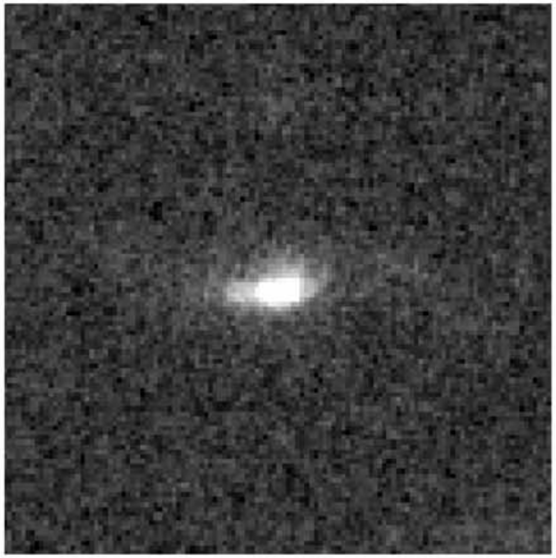


Residual

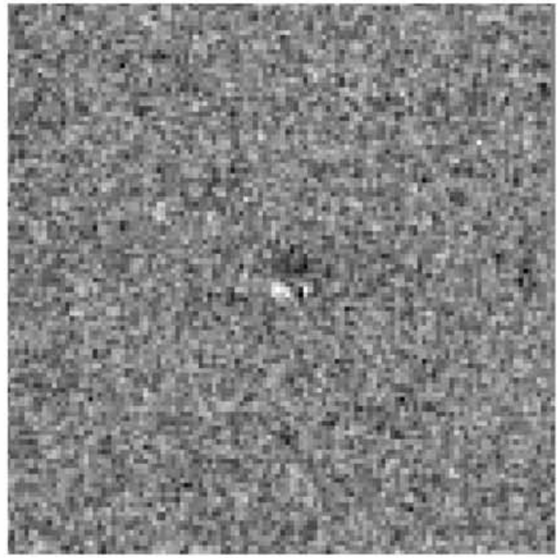


Residual per Eqns

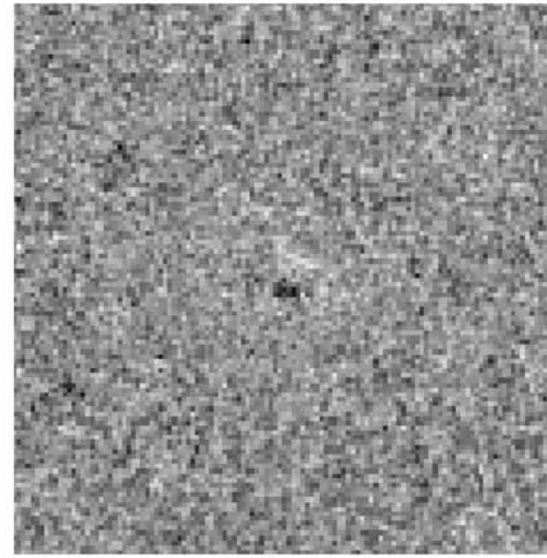
Problem: Color Variations



F850LP data



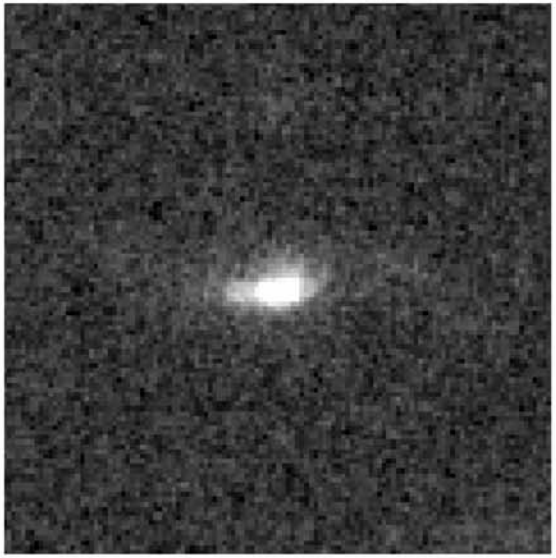
F850LP residual



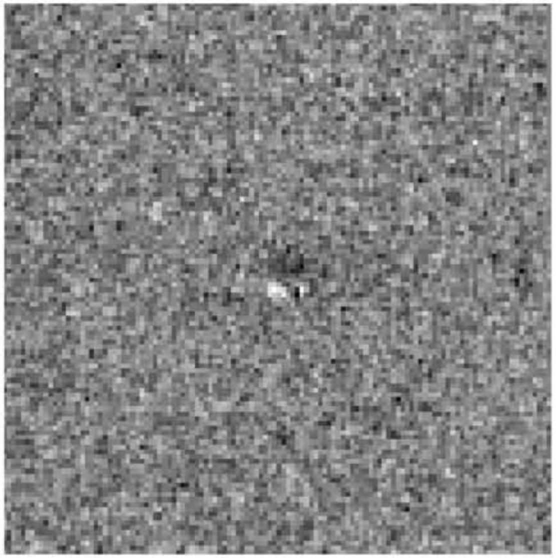
F450W residual

Problem: Galaxy profile changes with wavelength

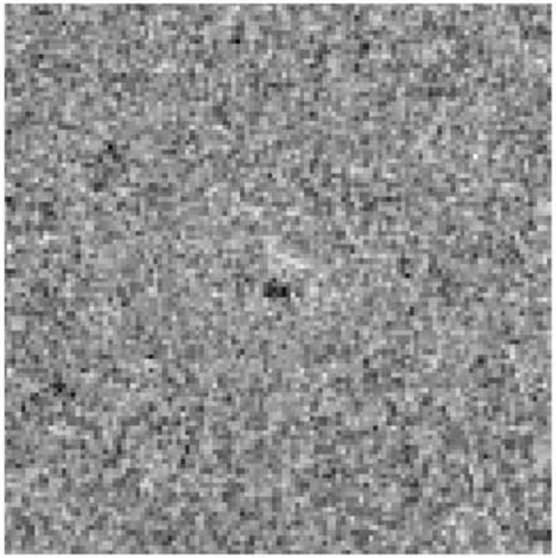
Solution: Color Segmentation



F850LP data



F850LP residual



F450W residual

Problem: Galaxy profile changes with wavelength

Solution: Segment models into color components

Color Segmentation

Recall, for source images:

$$D^\beta = T(F^\beta \cdot M) \otimes P^\beta \qquad (\beta \equiv \text{bandpass})$$

and:

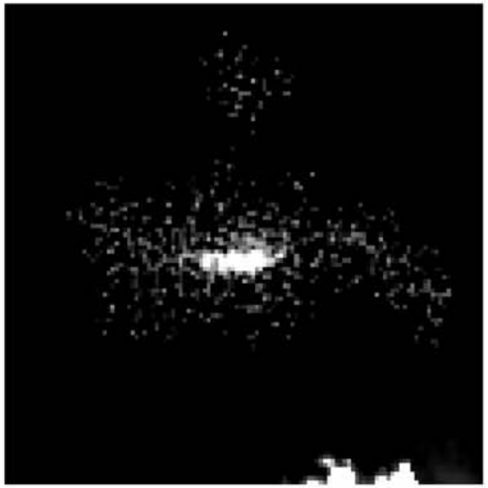
$$\chi^2 = \sum \left(\frac{T(F^\beta \cdot M) \otimes P^\beta - D^\beta}{\sigma^\beta} \right)^2$$

Solve $\nabla \chi^2 = 0$ for pixels of M on model grid

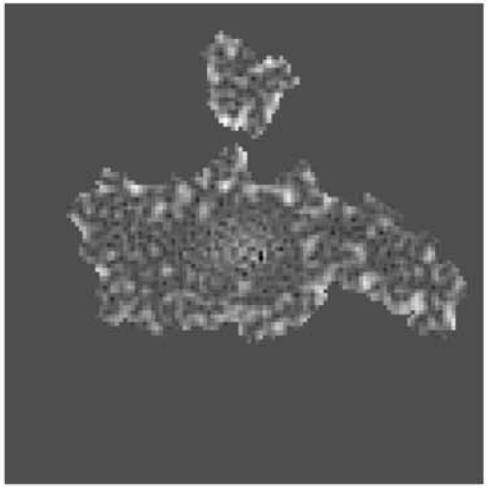
$\Rightarrow$ at minimum, $\nabla \chi^2 = 0$, but $\nabla \chi^2_\beta \neq 0$

$$F^\beta \cdot M \Rightarrow F_1^\beta \cdot M_1 + F_2^\beta \cdot M_2 + \ldots$$

An Example

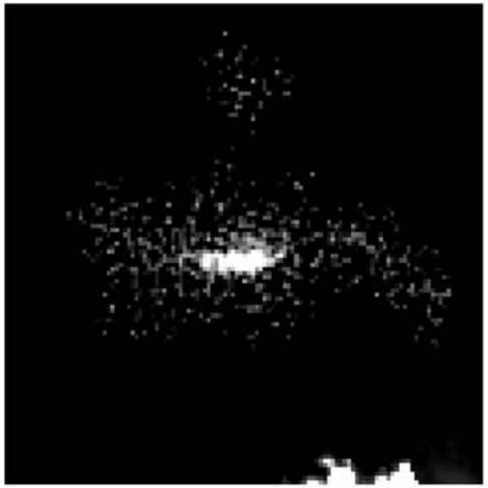


Model

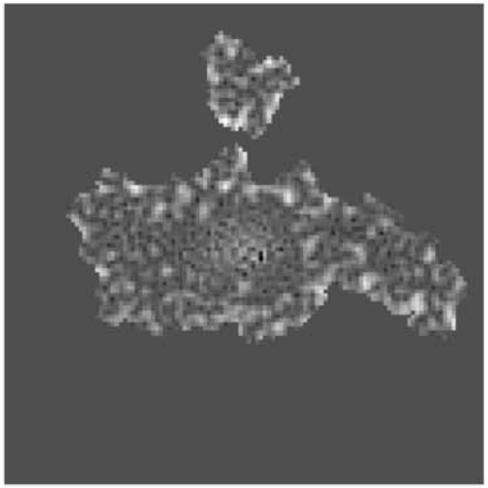


Model gradient

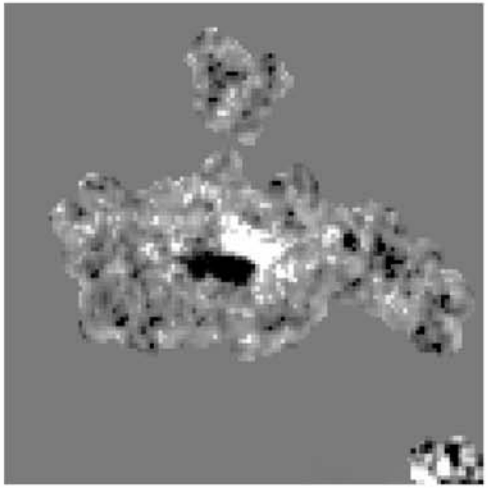
An Example



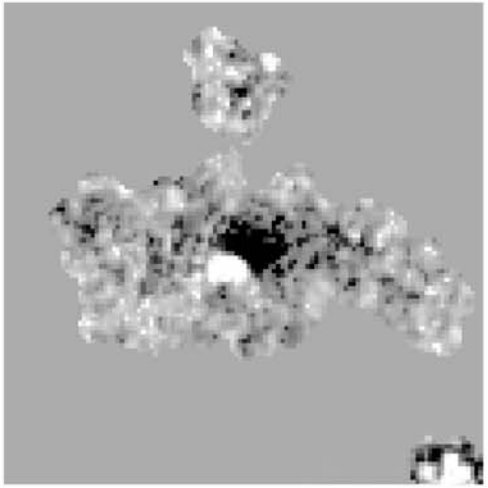
Model



Model gradient

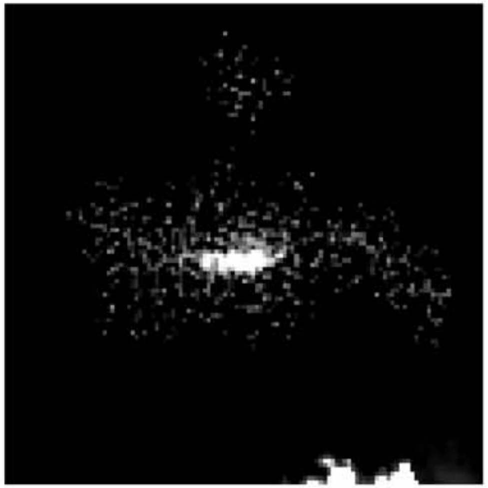


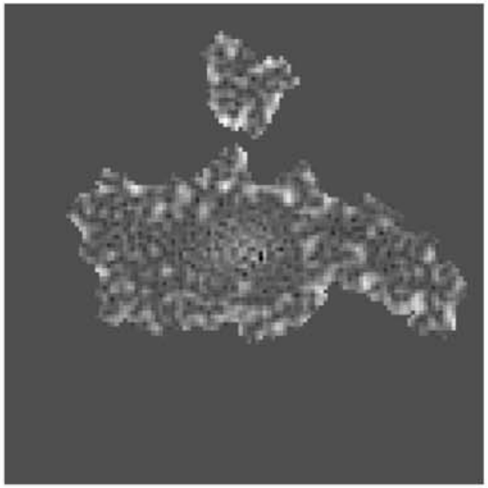
Gradient in F450W

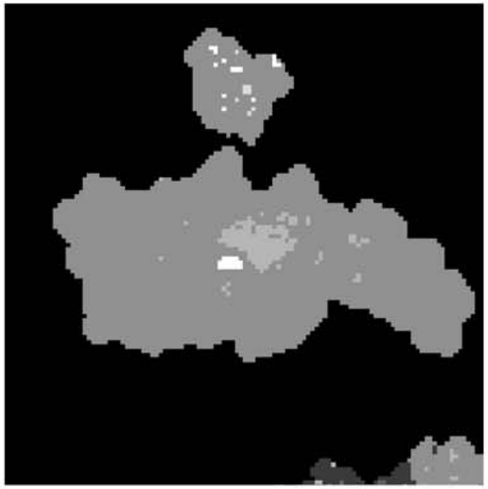


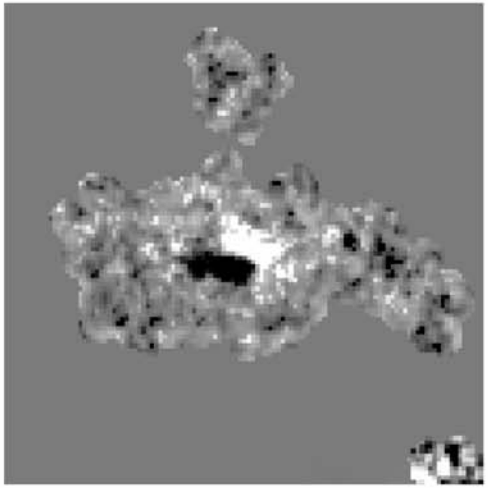
Gradient in F850LP

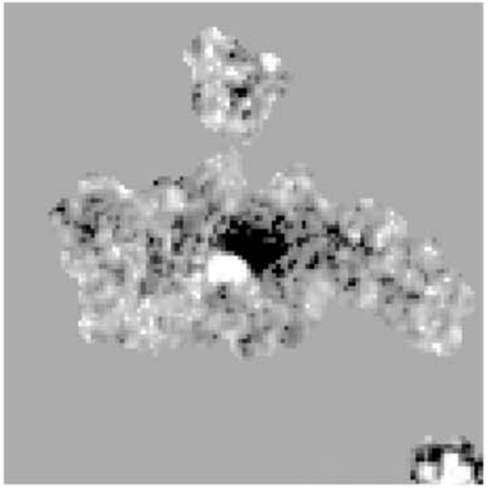
An Example


Model


Model gradient

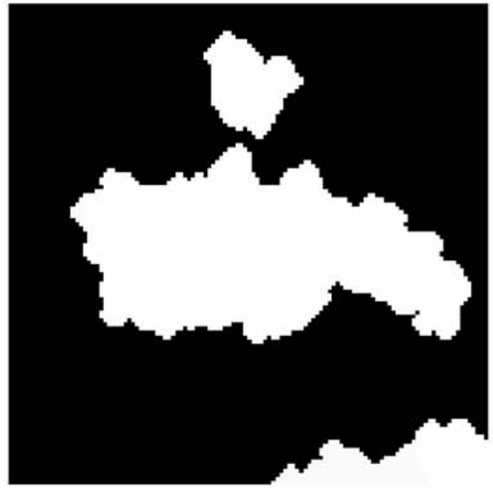

Segmentation


Gradient in F450W

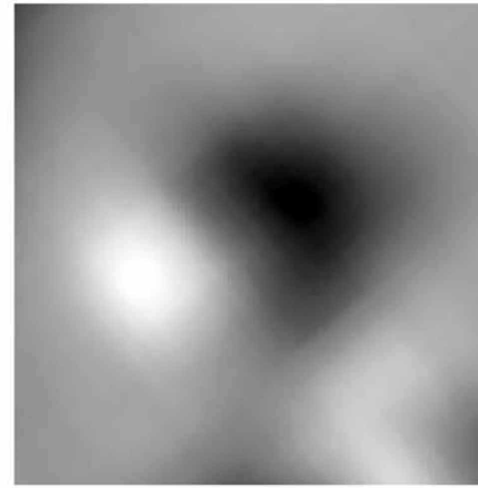

Gradient in F850LP

An example: Spitzer

SST 3.6 μm Data

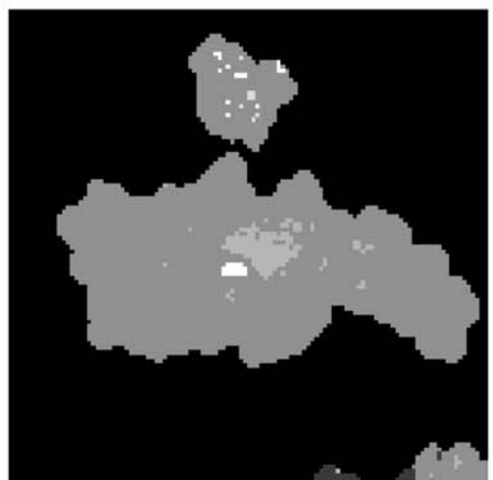


Segmentation Map



SST 3.6 μm Residual

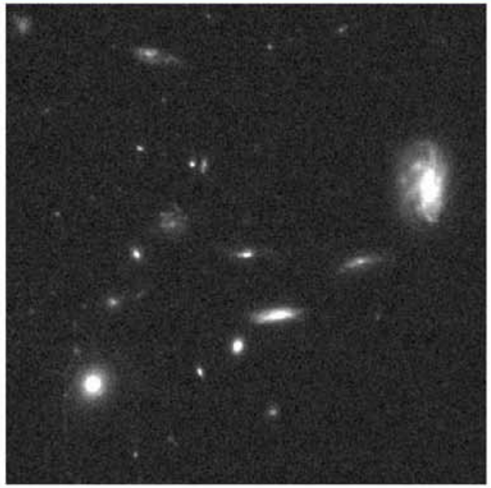
SST 3.6 μm Data



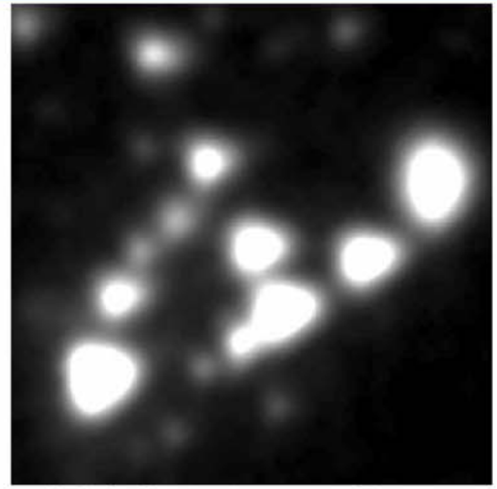
Type Map

SST 3.6 μm Residual

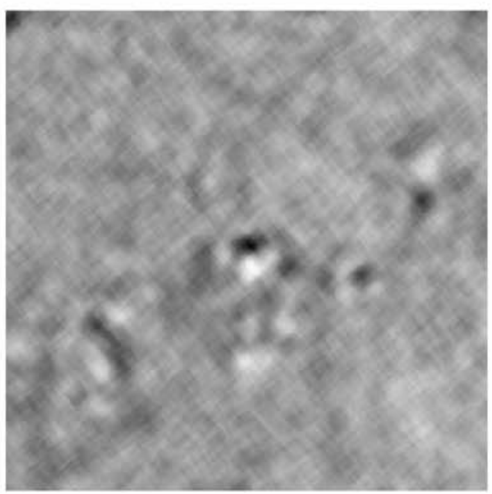
Spitzer PSF Determination



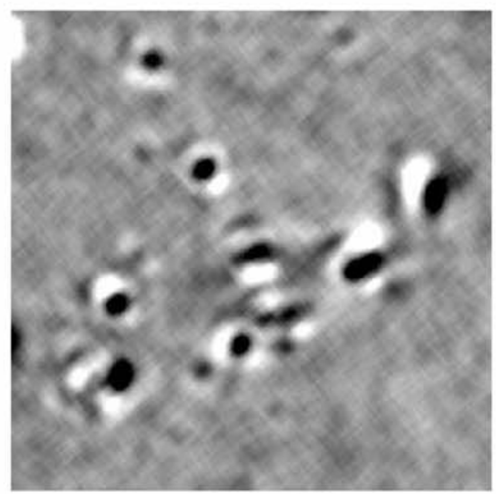
F850LP Data



IRAC 3.6 μm Data



Residual



Residual w/ SST PSF

PSF Fitting

Recall, once again, for source images:

$$D^{\beta} = T(F^{\beta} \cdot M) \otimes P^{\beta} \qquad (\beta \equiv \text{bandpass})$$

and:

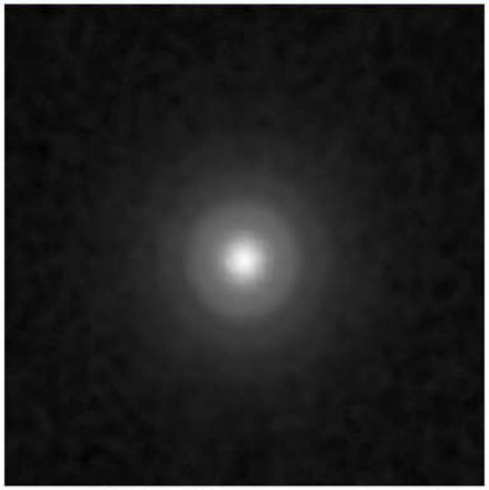
$$\chi^2 = \sum \left(\frac{T(F^{\beta} \cdot M) \otimes P^{\beta} - D^{\beta}}{\sigma^{\beta}} \right)^2$$

Given model M, solve $\nabla \chi^2 = 0$ for:

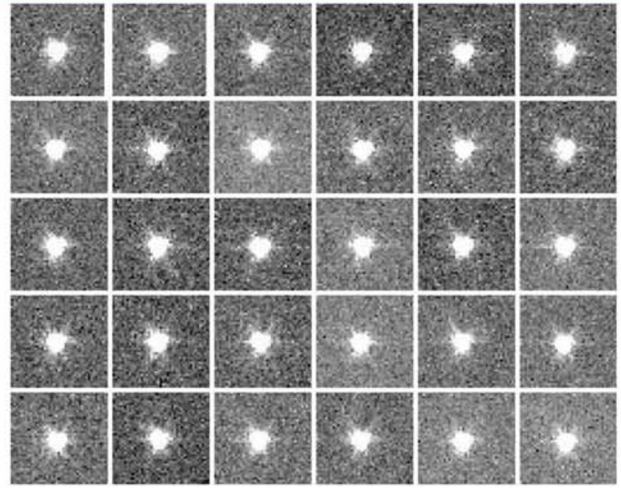
- pixels of P on PSF grid
- transformation T of model to each image

⇒ Use IRAC PSF calibration data (BD+67 1044)

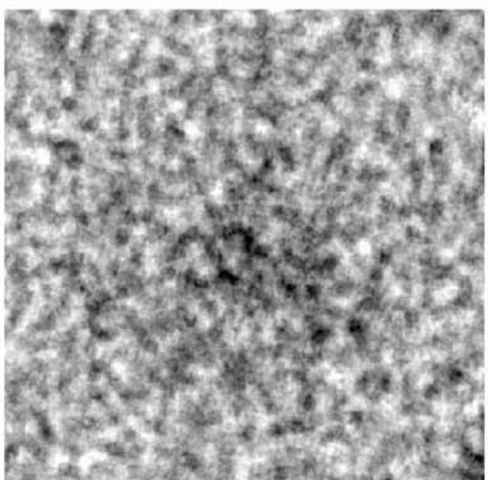
Spitzer PSF Determination



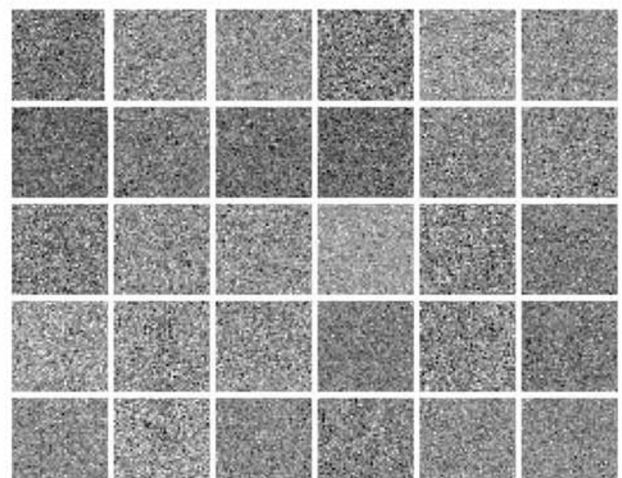
IRAC 3.6 μm Data



Data Mosaic



Residual



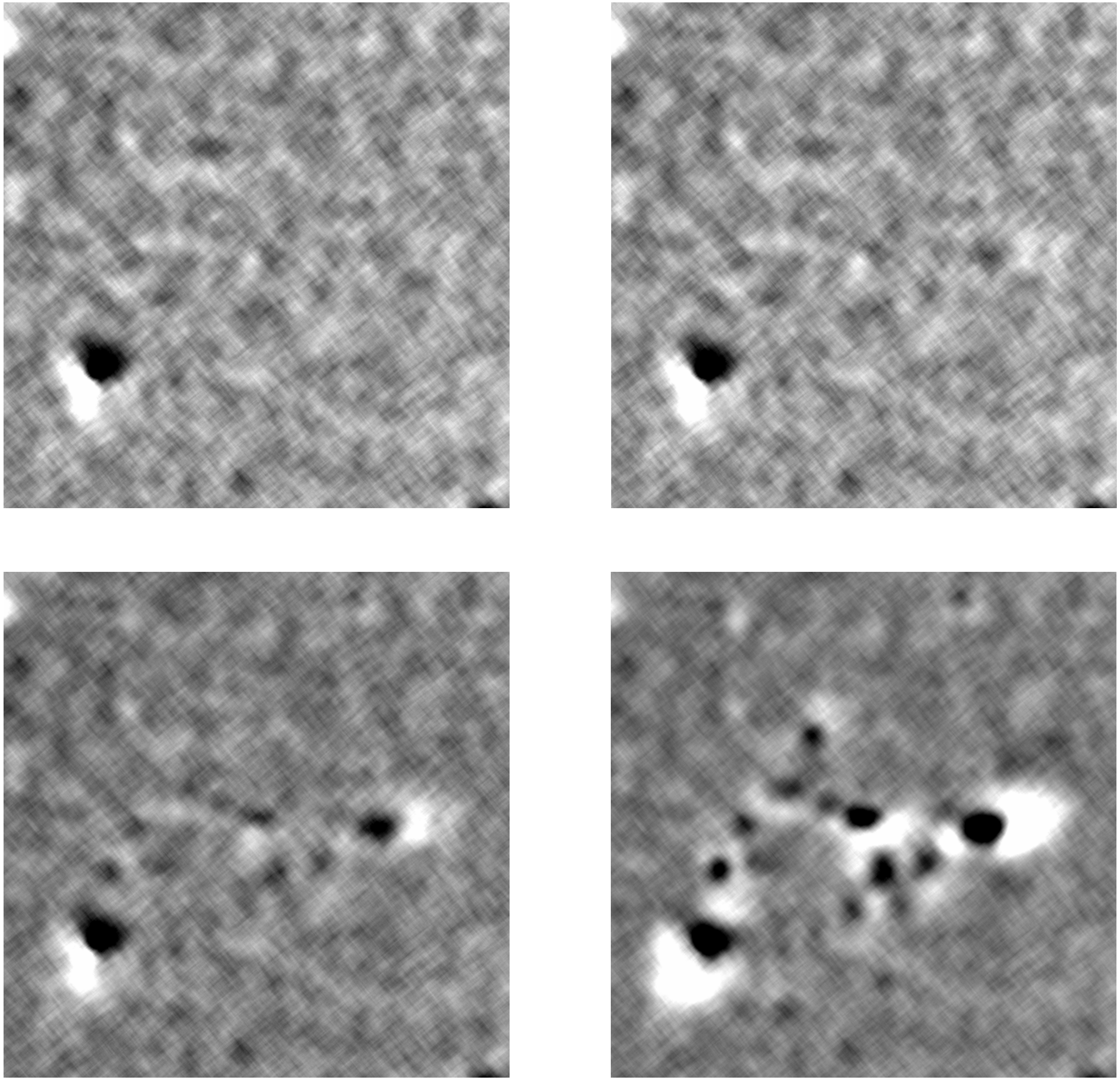
Residual Mosaic

Image alignment

- Geometric distortion and registration—how to calibrate?
- S/N = 500 for a typical SST "pixel"
- Required image alignment accuracy better than 0.01 pixel
- *More or less solved*

Noise in source images

- S/N = 500 for a typical SST pixel
- S/N = 200 over a comparable region of sky for ACS
- *noise in source images is the limiting systematic effect in measuring SST images*
- *SST images cannot be measured to within noise given current ACS images*



Summary

- We believe that faint galaxies can be measured in deep Spitzer images only with...
- ...accurate spatial models (alignment, deconvolution and convolution, color segmentation)...
- ...and computational expense