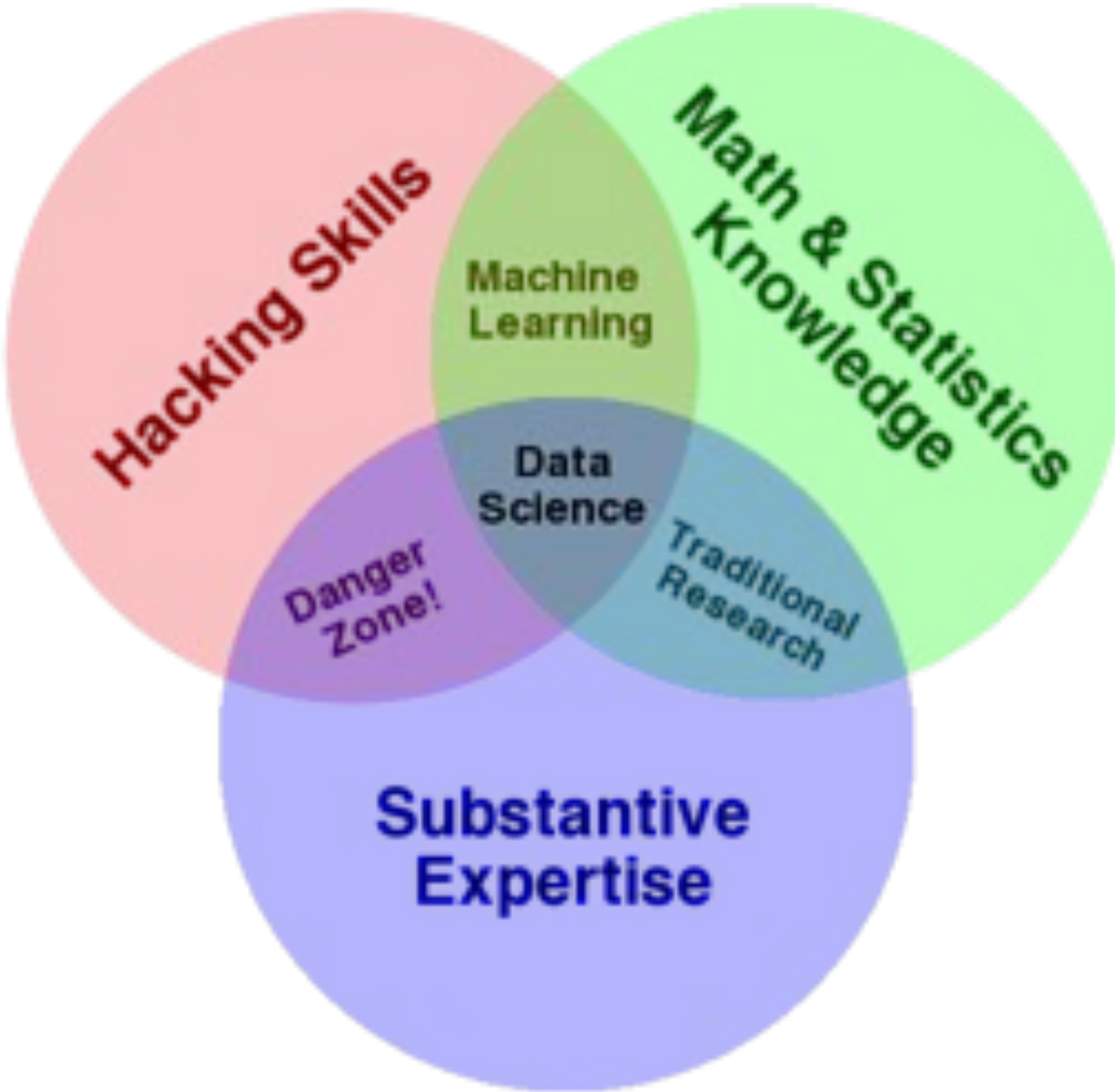
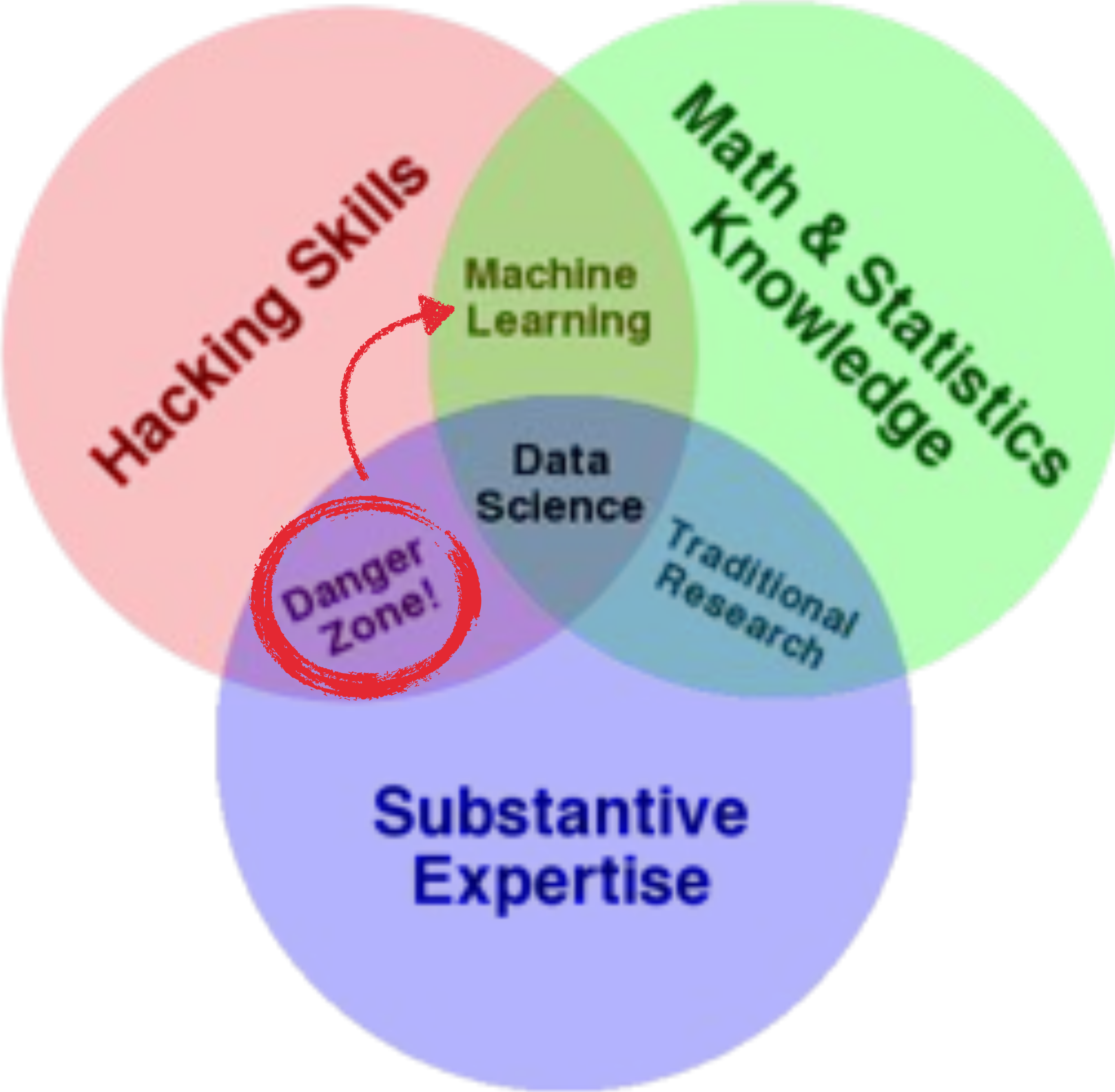
Merging observations across the EM spectrum

Mehmet Alpaslan
Center for Cosmology and Particle Physics, New York University

Friday, January 26th



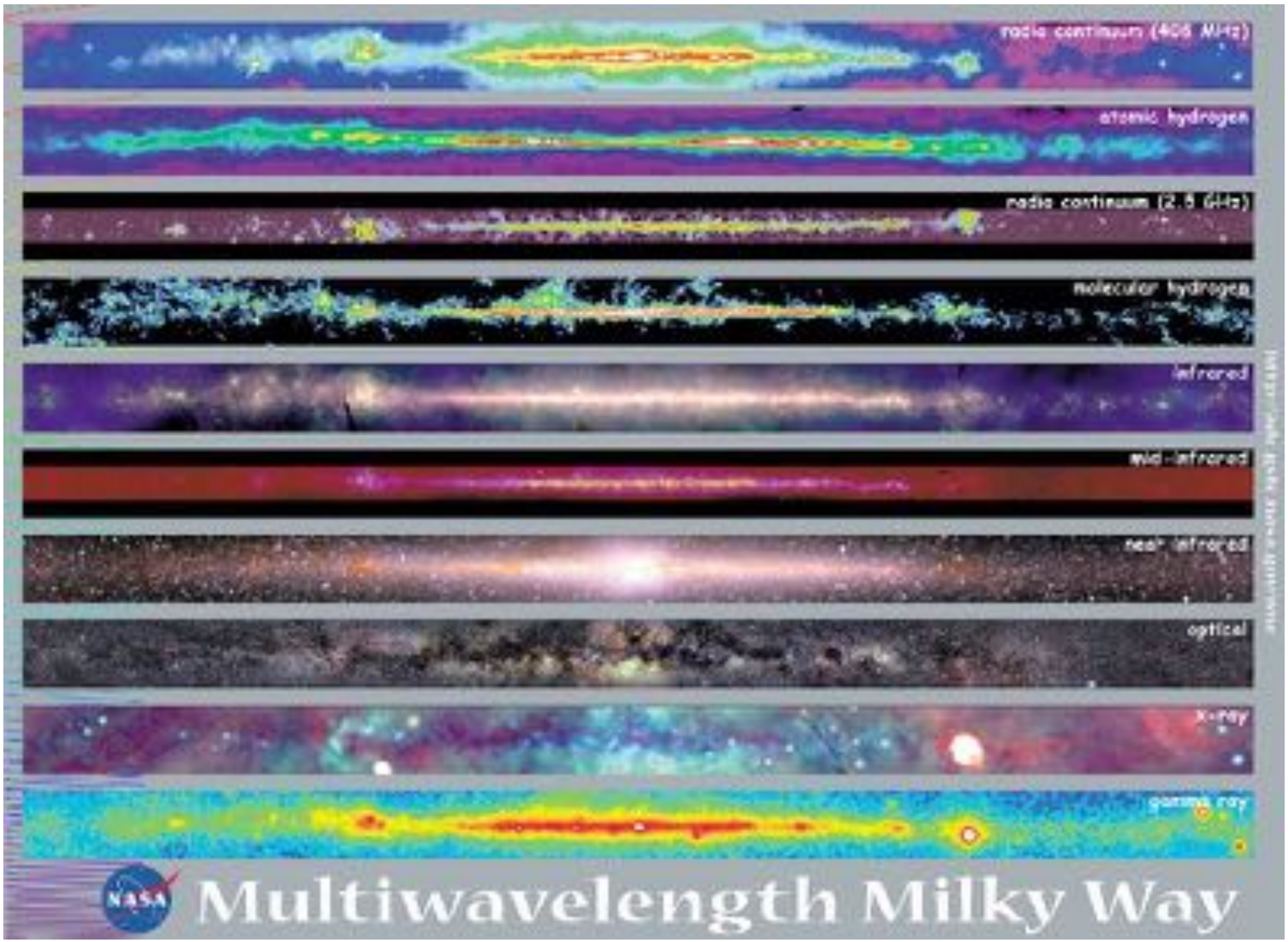
Hacking Skills
Math & Statistics Knowledge
Machine Learning
Data Science
Danger Zone!
Traditional Research
Substantive Expertise


Hacking Skills
Math & Statistics Knowledge
Machine Learning
Data Science
Danger Zone!
Traditional Research
Substantive Expertise

OUTLINE

- Multiwavelength photometry can be hard! Why bother?
- Two primary ways:
- **DIY multiwavelength photometry.**
  - Matched aperture photometry, dealing with survey/instrument/data variability, homogenizing data.
- **Creating multiwavelength databases from existing data.**
  - Magnitude conversions, database queries, software tools.

I'M AN EXTRAGALACTIC ASTRONOMER, SO…



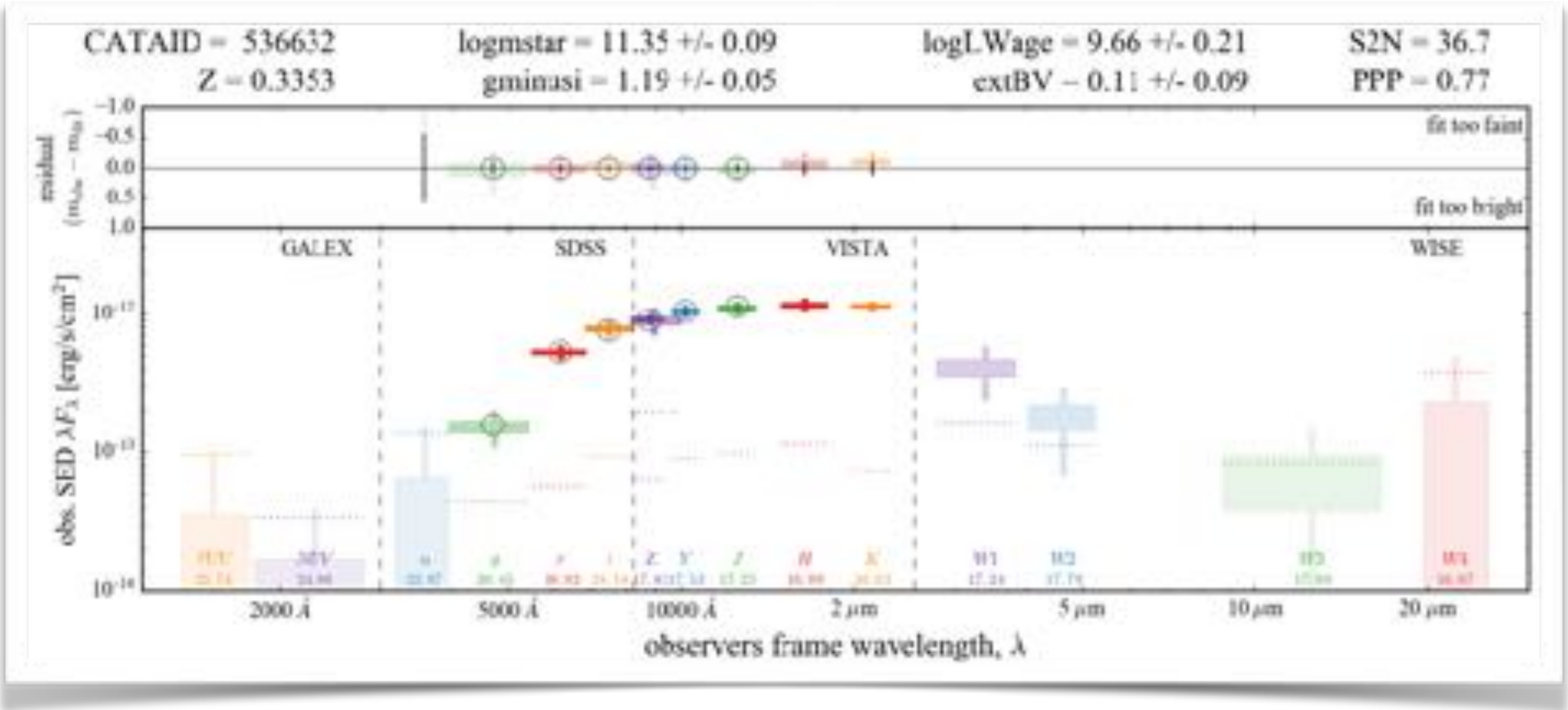
GALAXIES ARE FULL OF PHYSICS!

Type of observation	Wavelength range (nm)	Frequency range (Hz)	Typical sources	Temperature of radiating object (K)	Examples of telescopes
Radio	$> 1 \times 10^{3}$	$< 3 \times 10^{11}$		< 10	VLA, ATCA, ALMA
IR	$10^{3} - 10^{6}$	$3 \times 10^{11} - 4 \times 10^{14}$		$10 - 10^{3}$	SCUBA, Spitzer, Herschel, JWST
Visible	400-700	$4 - 7.5 \times 10^{14}$		$10^{3} - 10^{5}$	VLT, HST
UV	20-400	$7.5 \times 10^{14} - 3 \times 10^{16}$		$10^{5} - 10^{6}$	HST, FUSE
X-ray	0.01-20	$3 \times 10^{16} - 3 \times 10^{19}$		$10^{6} - 10^{8}$	Chandra, XMM
Gamma ray	< 0.01	$> 3 \times 10^{19}$		$> 10^{8}$	Integral, GLASS, HESS

GALAXIES ARE FULL OF PHYSICS!

Type of observation	Wavelength range (nm)	Frequency range (Hz)	Typical sources	Temperature of radiating object (K)	Examples of telescopes
Radio	$> 1 \times 10^3$	$< 3 \times 10^{11}$	ISM, cool gas, electrons	< 10	VLA, ATCA, ALMA
IR	$10^3 - 10^6$	$3 \times 10^{11} - 4 \times 10^{14}$	Cool clouds (dust / gas); planets	$10 - 10^3$	SCUBA, Spitzer, Herschel, JWST
Visible	400-700	$4 - 7.5 \times 10^{14}$	Stellar surfaces	$10^3 - 10^5$	VLT, HST
UV	20-400	$7.5 \times 10^{14} - 3 \times 10^{16}$	SNR remnants; very hot stars	$10^5 - 10^6$	HST, FUSE
X-ray	0.01-20	$3 \times 10^{16} - 3 \times 10^{19}$	SNR remnants, gas in galaxy clusters, stellar coronae	$10^6 - 10^8$	Chandra, XMM
Gamma ray	< 0.01	$> 3 \times 10^{19}$	Hypernovae, BH accretion disks	$> 10^8$	Integral, GLASS, HESS

WHY BOTHER?

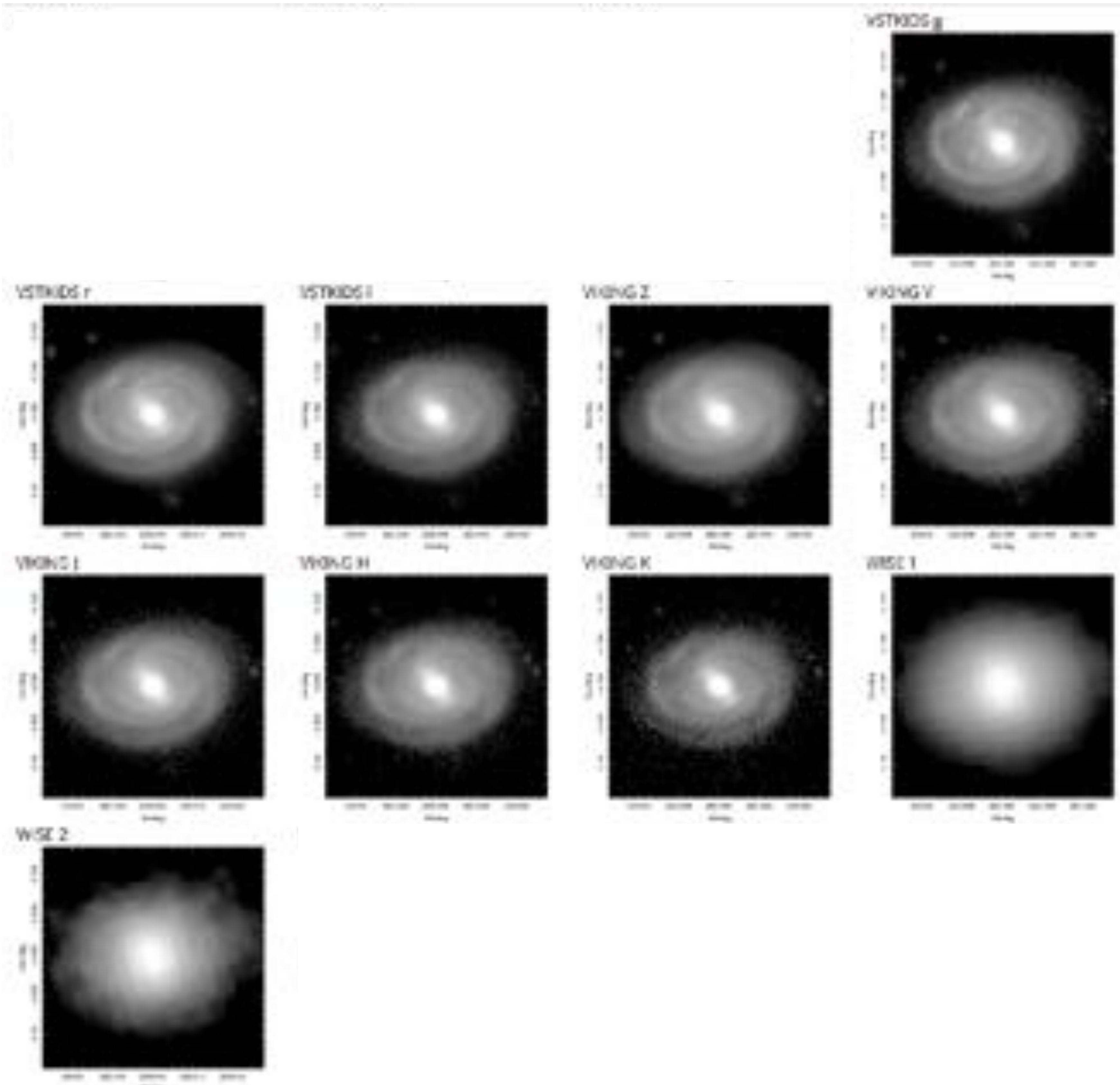


You need as much multiwavelength photometry as possible to fully sample the physics of a galaxy. Stellar mass, dust mass, and star formation rate estimates all greatly benefit from multiwavelength data.

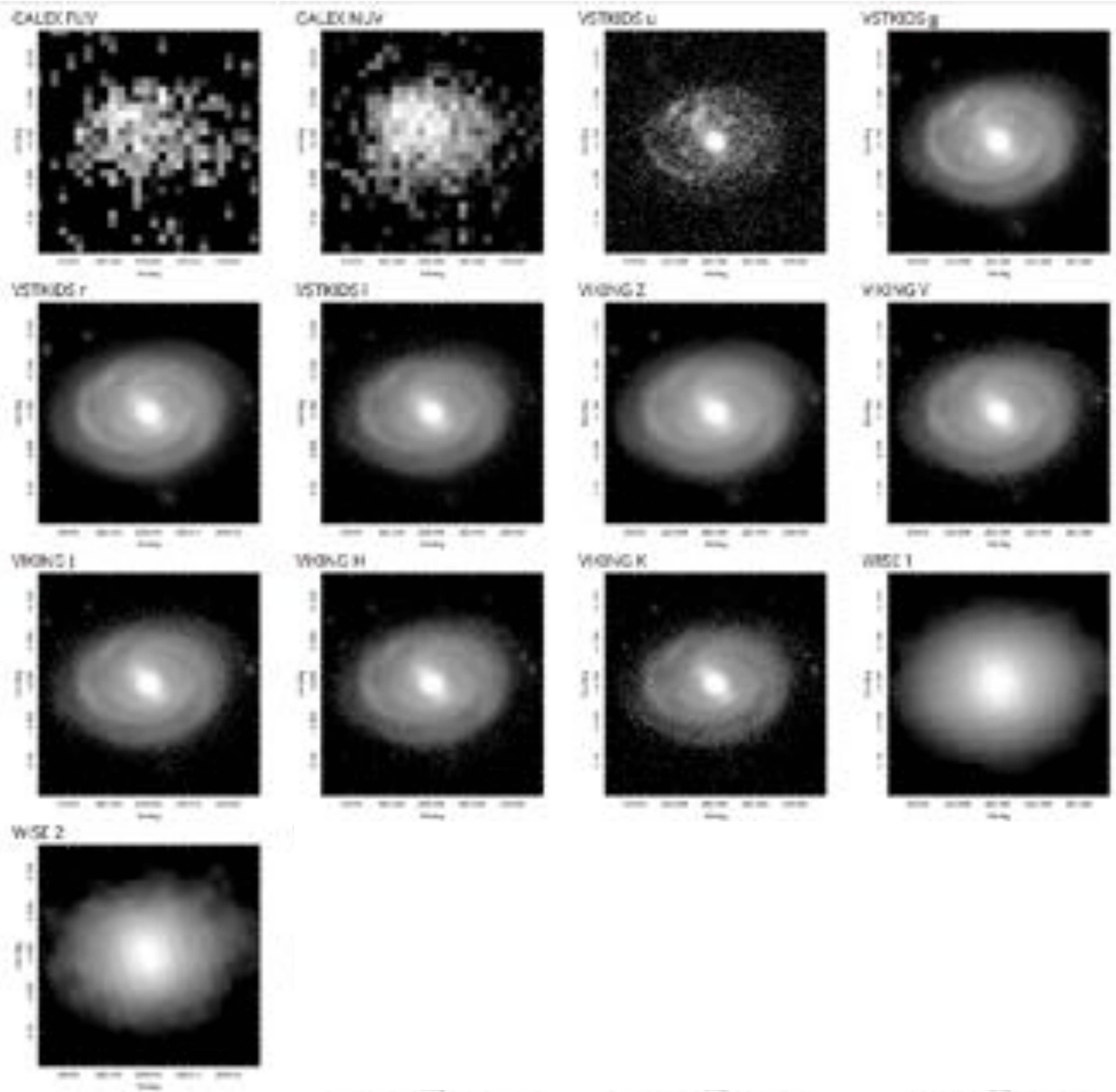
BUT GALAXIES AREN'T EVERYTHING!

- Multiwavelength broadband photometry is also useful in…
  - Assigning spectral types of stars (r - i or z - i colors).
  - Studying globular clusters (age gradients, dynamics, RGB and AGB branch population gradients).
  - Characterizing stellar flares, and studying their frequency as a function of wavelength.
  - Color gradients of star spots correlate with their temperature.
  - Exoplanet transits: multiwavelength photometry makes it possible to study different depths of planetary atmospheres.
- Multiwavelength narrow-band photometry:
  - e.g. chemical studies of the ISM with ALMA.

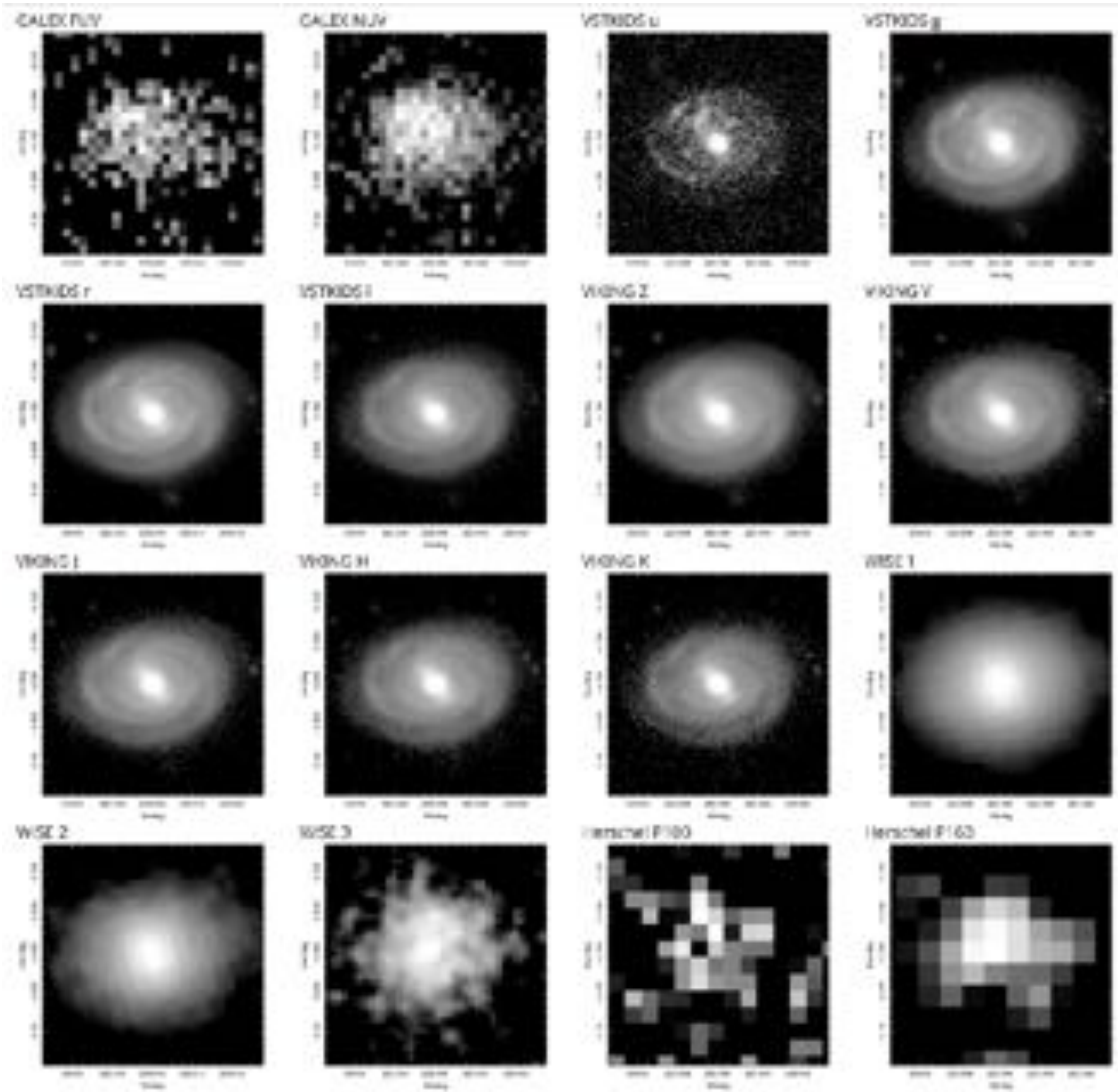
WHY IS IT CHALLENGING?



WHY IS IT CHALLENGING?

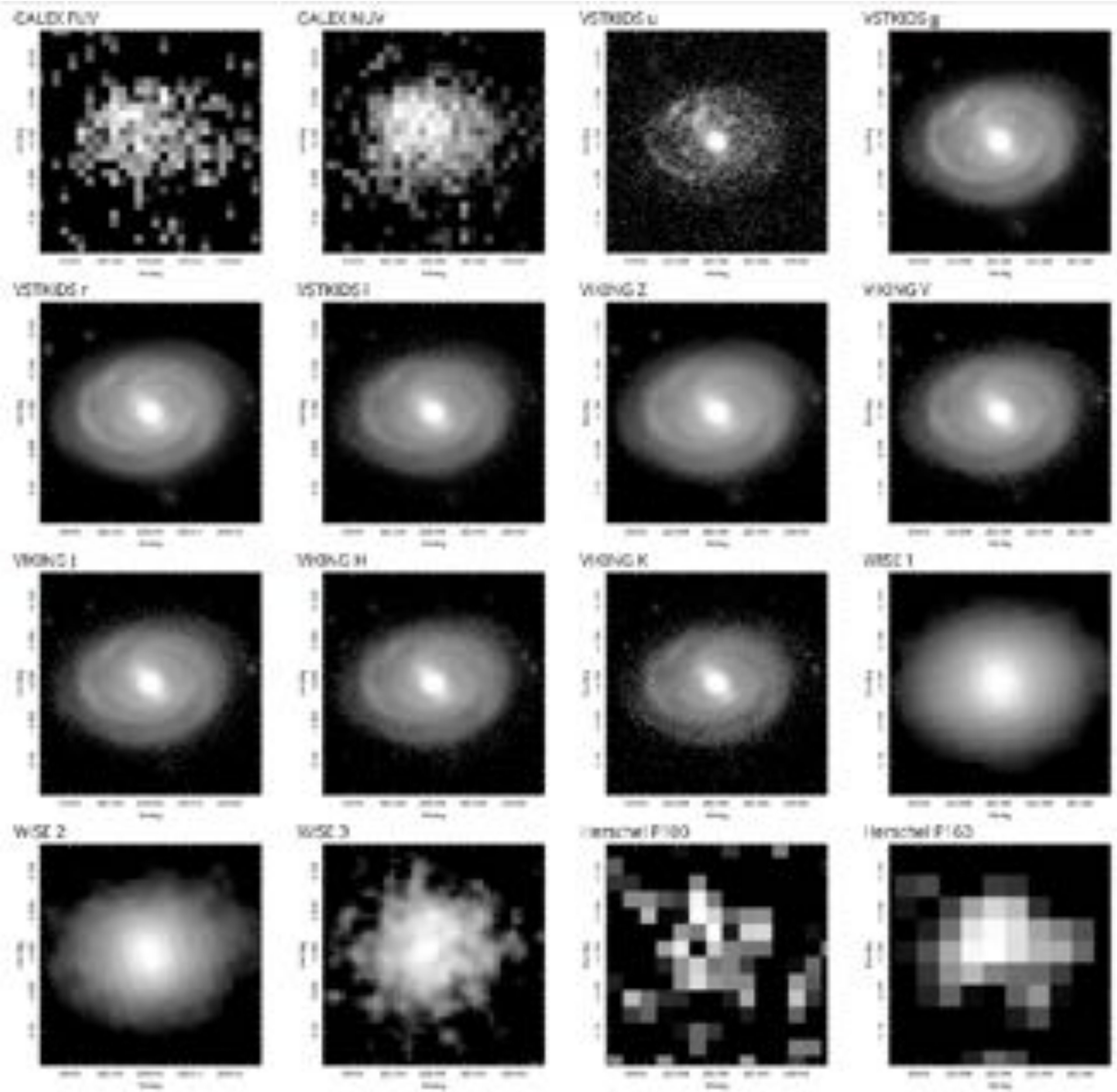


WHY IS IT CHALLENGING?



WHY IS IT CHALLENGING?

WHAT PROBLEMS NEED TO BE ADDRESSED HERE?



Note: SDSS pixel scales should be 0.396.

THINGS TO WORRY ABOUT…

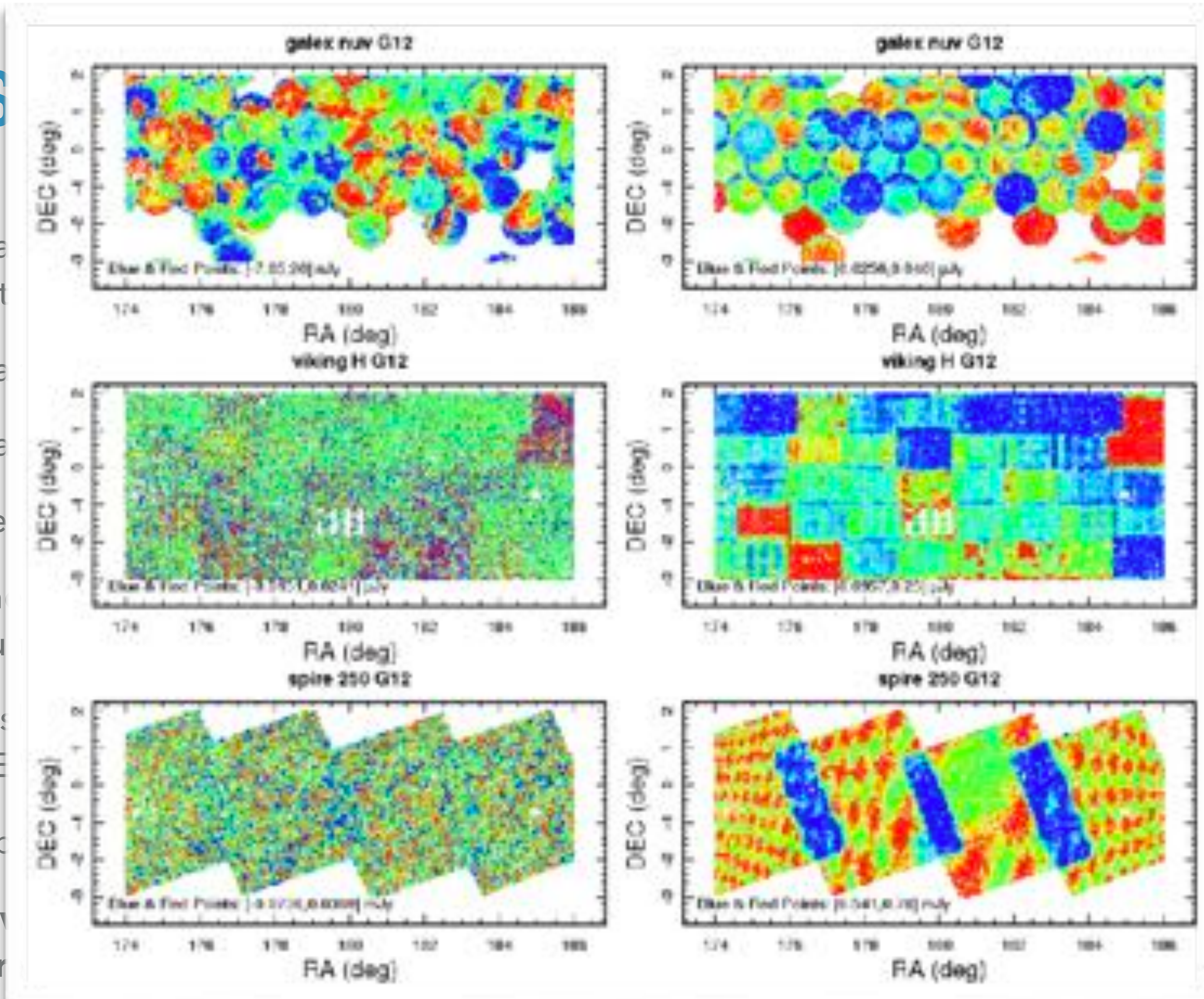
- Variable seeing across different telescopes / instruments.
- Variable optics in different detectors.
- Variable resolution in different instruments.
- Different sensitivity limits.
- Some telescopes are in space; others are ground-based.
- The sky isn't uniformly transparent across the EM spectrum.
- Calibration, zeropoints, etc…
- **Know what you're doing, and don't overdo it!**

Band	Survey/ Facility	Central Wavelength	Pixel Scale (″)	Native (conv.) PSF FWHM (″)
FUV	*GALEX*	1550Å	1.5	4.1
NUV	*GALEX*	2275Å	1.5	5.2
u	SDSS	3540Å	0.339	1.4 (2.0)
g	SDSS	4770Å	0.339	1.4 (2.0)
r	SDSS	6230Å	0.339	1.4 (2.0)
i	SDSS	7630Å	0.339	1.4 (2.0)
z	SDSS	9134Å	0.339	1.4 (2.0)
Z	VIKING	8770Å	0.339	0.9 (2.0)
Y	VIKING	1.020μm	0.339	0.9 (2.0)
J	VIKING	1.252μm	0.339	0.9 (2.0)
H	VIKING	1.645μm	0.339	0.9 (2.0)
K	VIKING	2.147μm	0.339	0.9 (2.0)
W1	*WISE*	3.4μm	1	5.9
W2	*WISE*	4.6μm	1	6.5
W3	*WISE*	12μm	1	7.0
W4	*WISE*	22μm	1	12.4
100	H-ATLAS	100μm	3	9.6
160	H-ATLAS	160μm	4	12.5
250	H-ATLAS	150μm	6	18
350	H-ATLAS	350μm	8	25
500	H-ATLAS	500μm	12	36

Note: SDSS pixel scales should be 0.396.

THINGS

- Varia / inst
- Varia
- Varia
- Diffe
- Som grou
- The the E
- Calib
- **Knov over**



Native (conv.) PSF FWHM (″)
4.1
5.2
1.4 (2.0)
1.4 (2.0)
1.4 (2.0)
1.4 (2.0)
1.4 (2.0)
0.9 (2.0)
0.9 (2.0)
0.9 (2.0)
0.9 (2.0)
0.9 (2.0)
5.9
6.5
7.0
12.4
9.6
12.5
18
25
36

Note: SDSS pixel scales should be 0.396.

THINGS

- Varia / inst
- Varia
- Varia
- Diffe
- Som grou
- The the E
- Calib
- **Kno over**

Native (conv.) PSF FWHM (″)
4.1
5.2
1.4 (2.0)
1.4 (2.0)
1.4 (2.0)
1.4 (2.0)
1.4 (2.0)
0.9 (2.0)
0.9 (2.0)
0.9 (2.0)
0.9 (2.0)
0.9 (2.0)
5.9
6.5
7.0
12.4
9.6
12.5
18
25
36

MULTIWAVELENGTH SURVEYS

- Modern galaxy surveys now produce photometry across multiple bands.
  - e.g. SDSS: *ugriz*; VISTA VIKING: *ZYJHK*.
- The survey I'm involved with, GAMA, brings together photometry from a number of different photometric surveys.
  - Lots of in-house image analysis required to do this, but the end result is a single homogeneous database of photometry in multiple bands.

BASIC PROCEDURE

OBTAIN RAW DATA

PERFORM CALIBRATION

ACCOUNT FOR VARYING SEEING / RESOLUTION

EXTRACT PHOTOMETRY

CREATE DATABASE

MAGNITUDES

THIS IS THE ORIGINAL SLIDE FROM THE TALK — HOWEVER THESE MAGNITUDE CALIBRATIONS ARE NOT GENERALLY HUGELY NECESSARY.

- Given that the raw data is coming from multiple sources, that usually means that it will have been pre-processed by different teams / organizations, etc.
- For example, the zeropoint of an instrument is the magnitude of an object that produces one count per second on that detector.

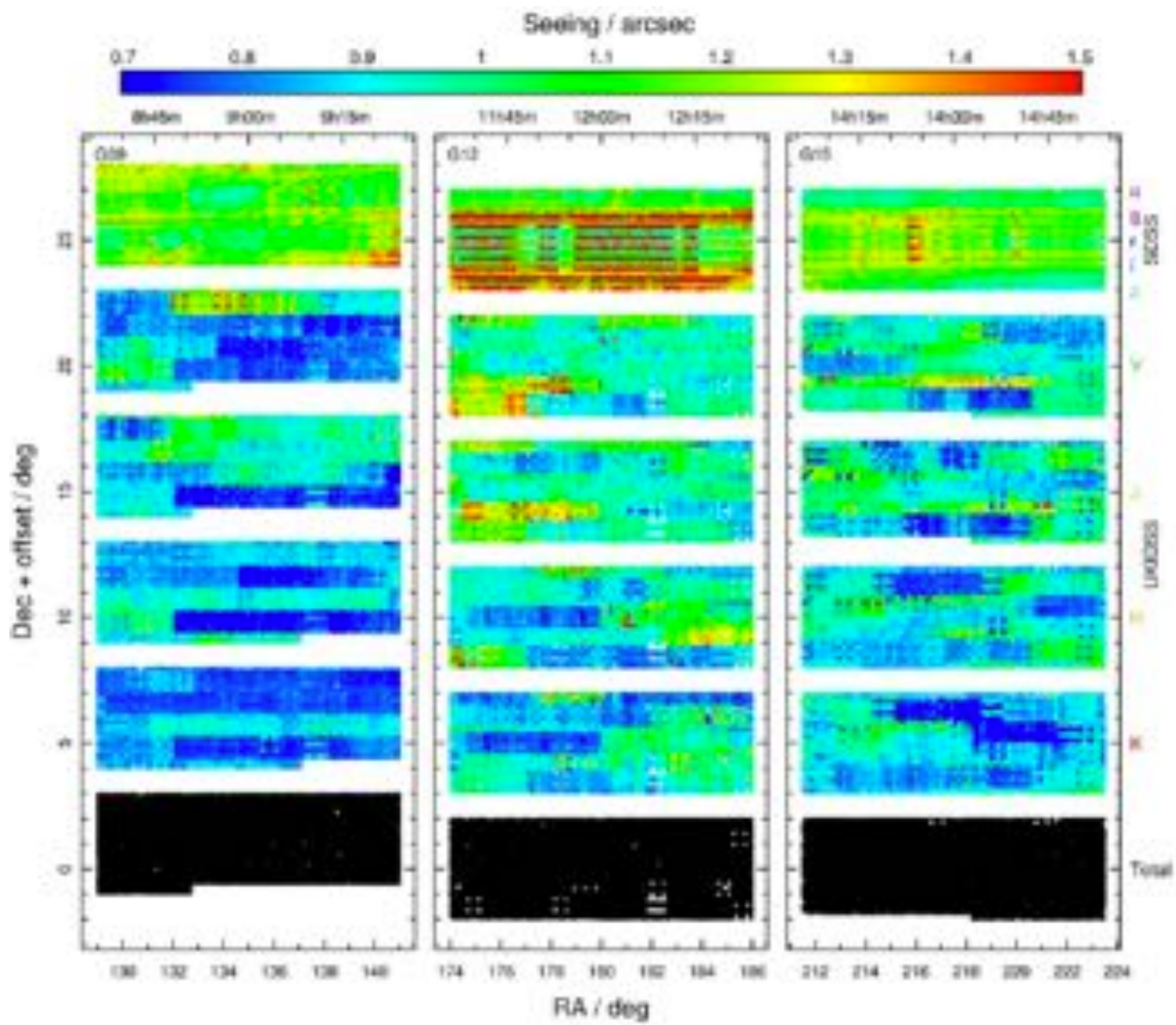
data number, or count

$$m = -2.5 \times \log\left(\mathrm{DN}/\mathrm{EXPTIME}\right) + \mathrm{zp}$$

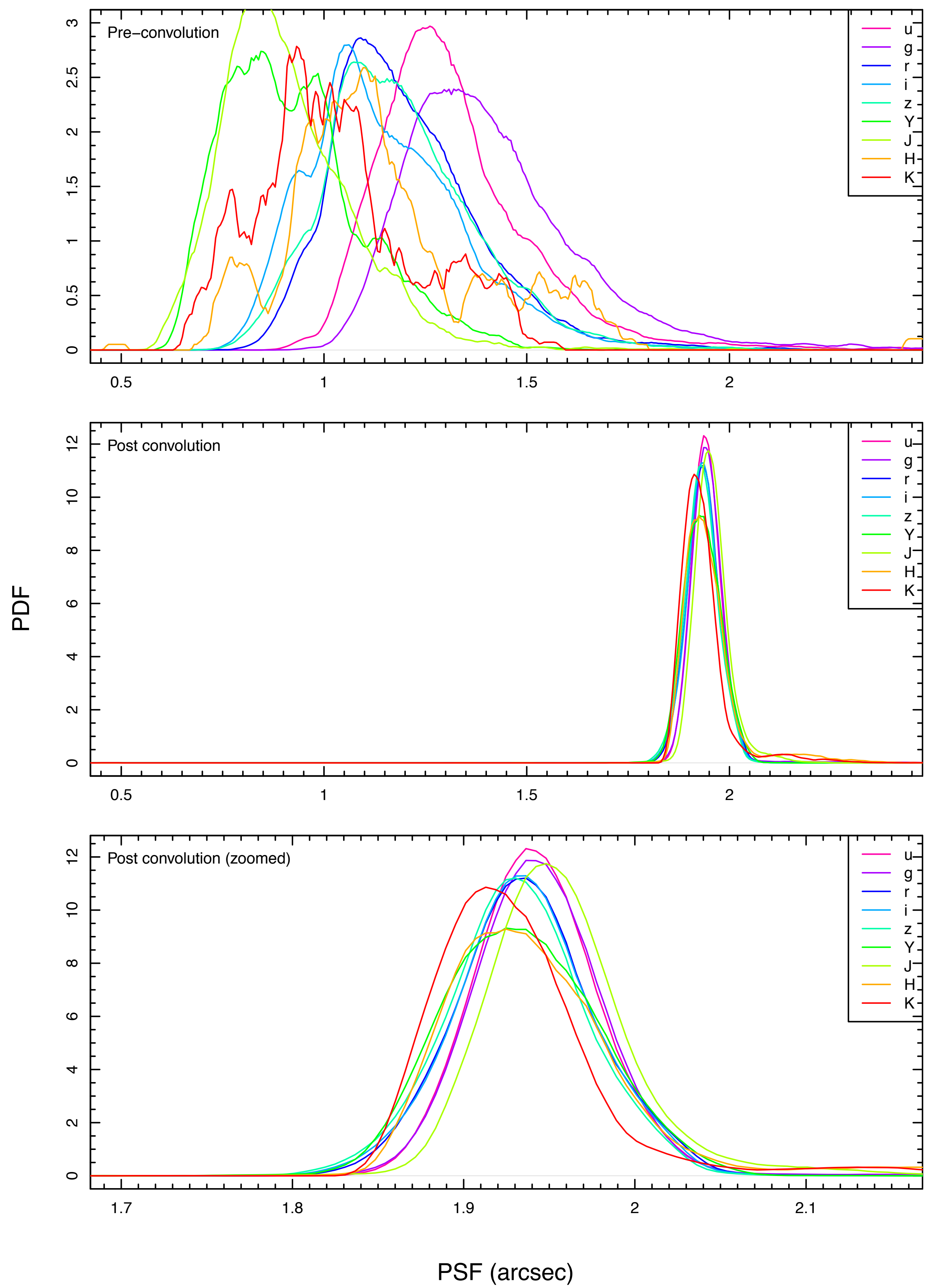
- These all need to be standardized. So do the gains!
- All these corrections can either be applied on a per-magnitude basis to your data, or to the photometric images on which you perform your multiwavelength photometry.

$$10^{-0.4\times(zp_i - zp_f)}$$

SEEING


Seeing / arcsec
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
Dec + offset / deg
RA / deg
SDSS
UKIDSS
Total

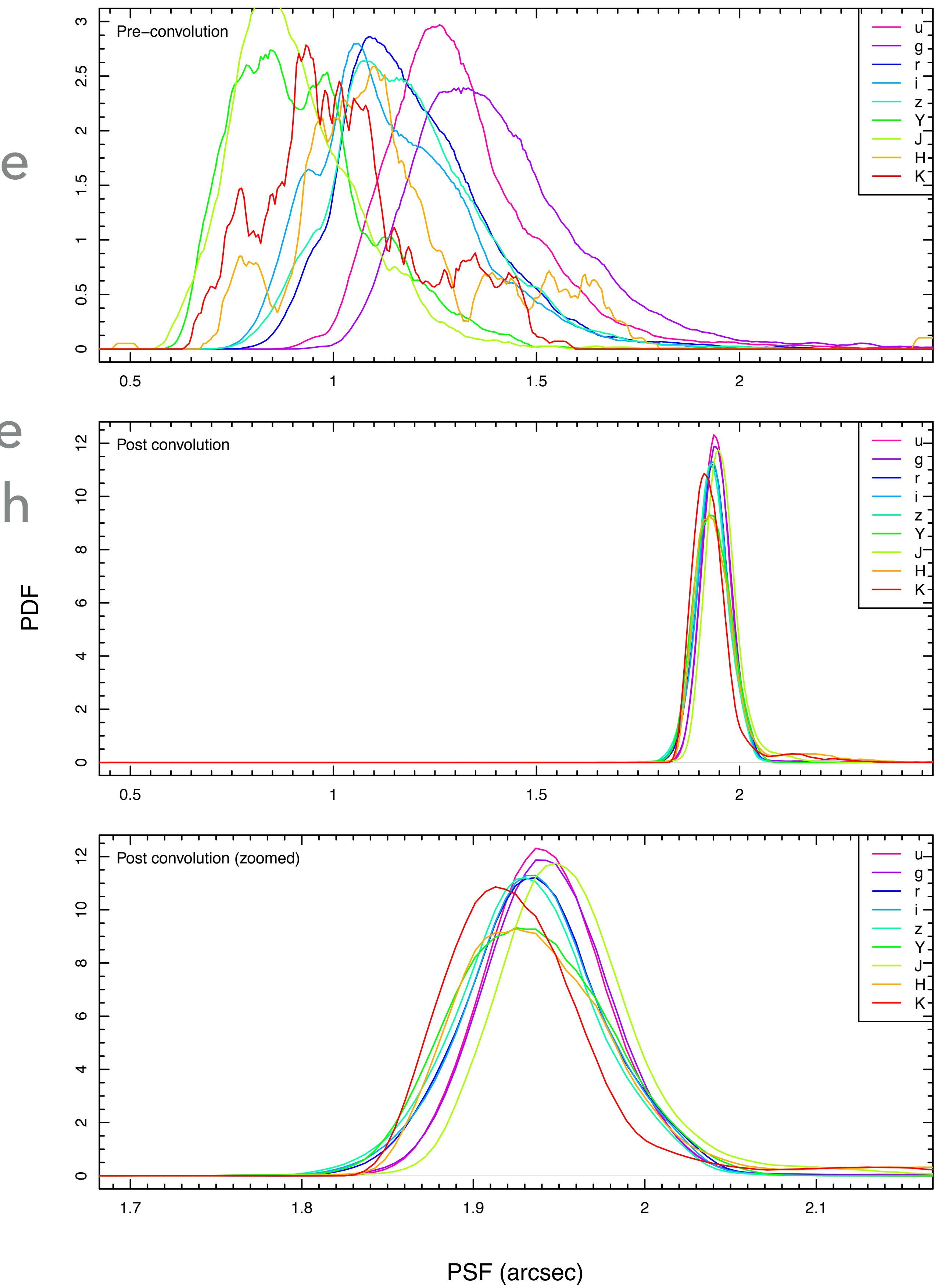
DIY - APERTURE PHOTOMETRY



- Aperture photometry, if performed on images without the same seeing/resolution will be catastrophically wrong.
- One solution to this is to measure the PSF across all the data in each band, then determine a value to degrade everything to.

$$\sigma_{\rm req} = \sqrt{\sigma^2_{\rm final} - \sigma^2_{\rm initial}}$$

Set   Measure

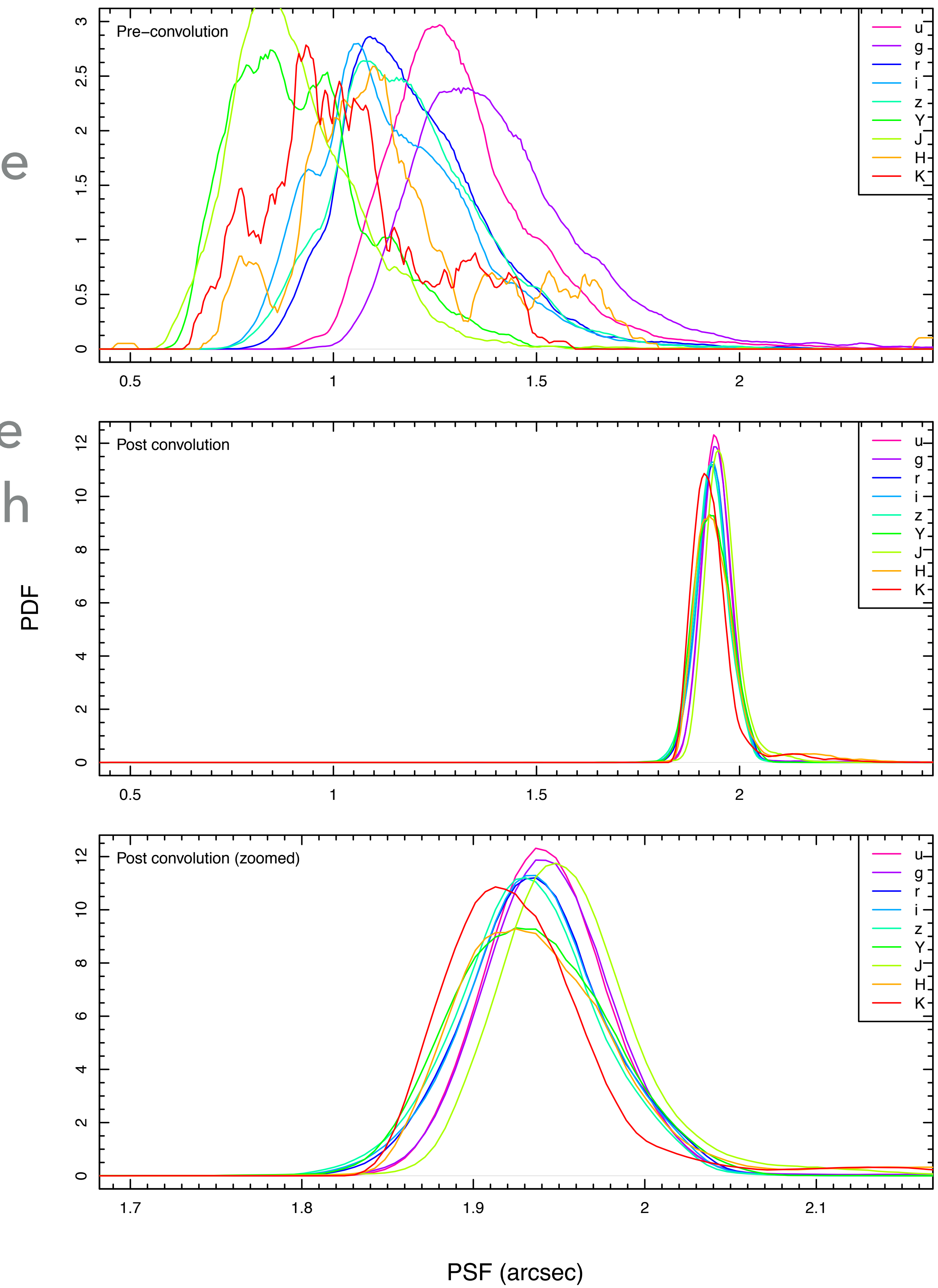


- Aperture photometry, if performed on images without the same seeing/resolution will be catastrophically wrong.
- One solution to this is to measure the PSF across all the data in each band, then determine a value to degrade everything to.

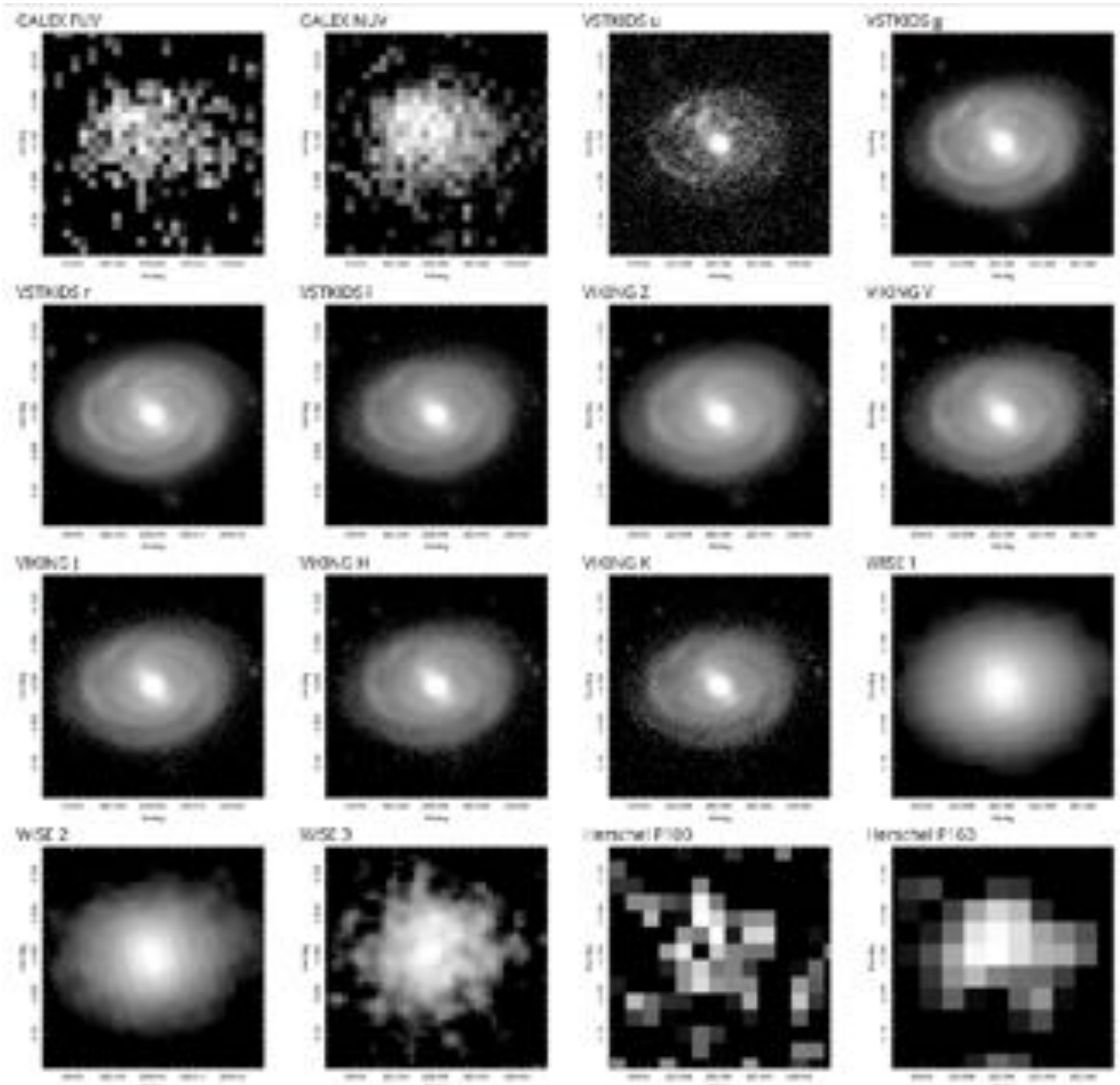
$$\sigma_{\rm req} = \sqrt{\sigma^2_{\rm final} - \sigma^2_{\rm initial}}$$

Set Measure

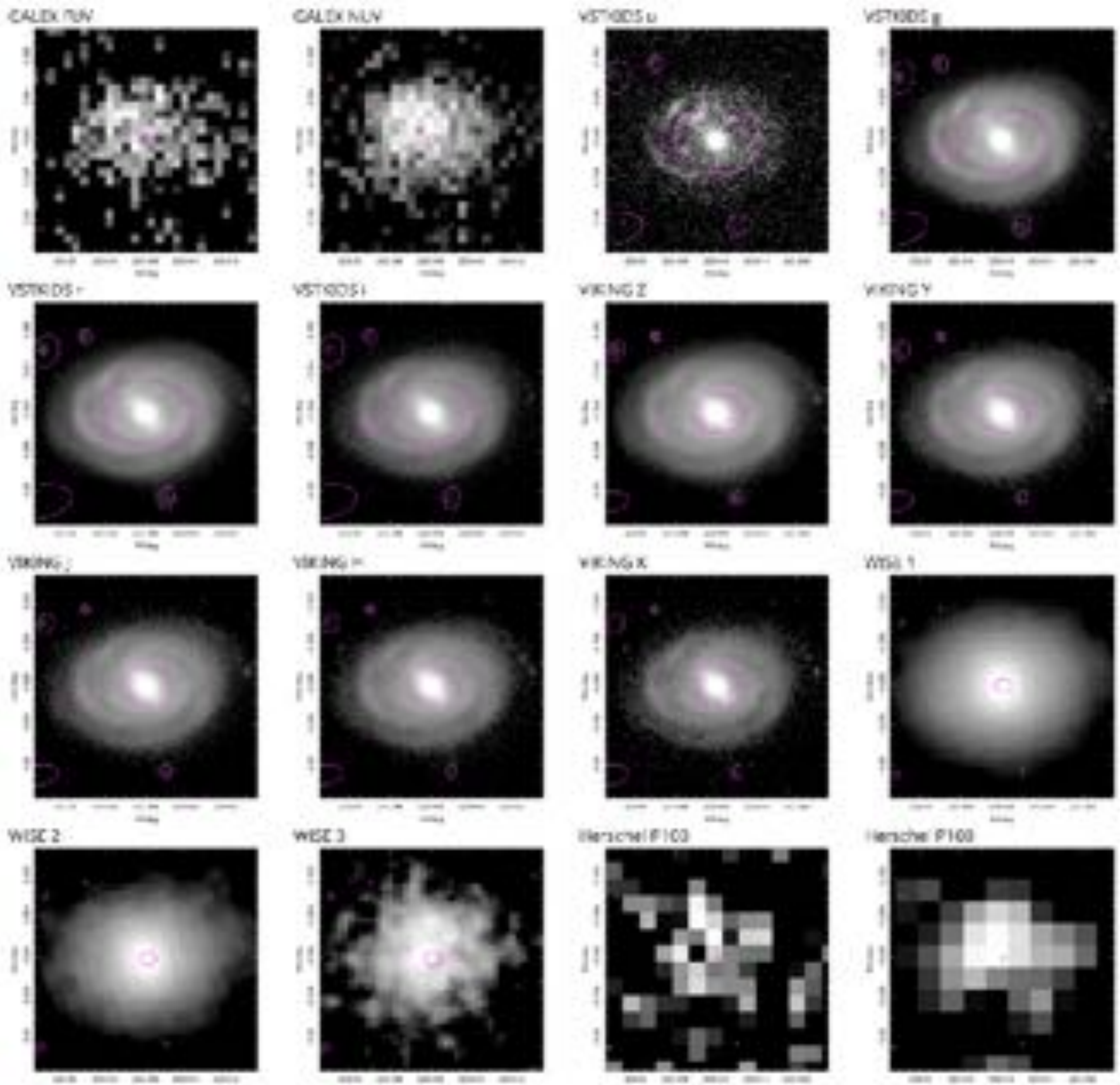
WHAT DRAWBACKS DOES THIS HAVE?

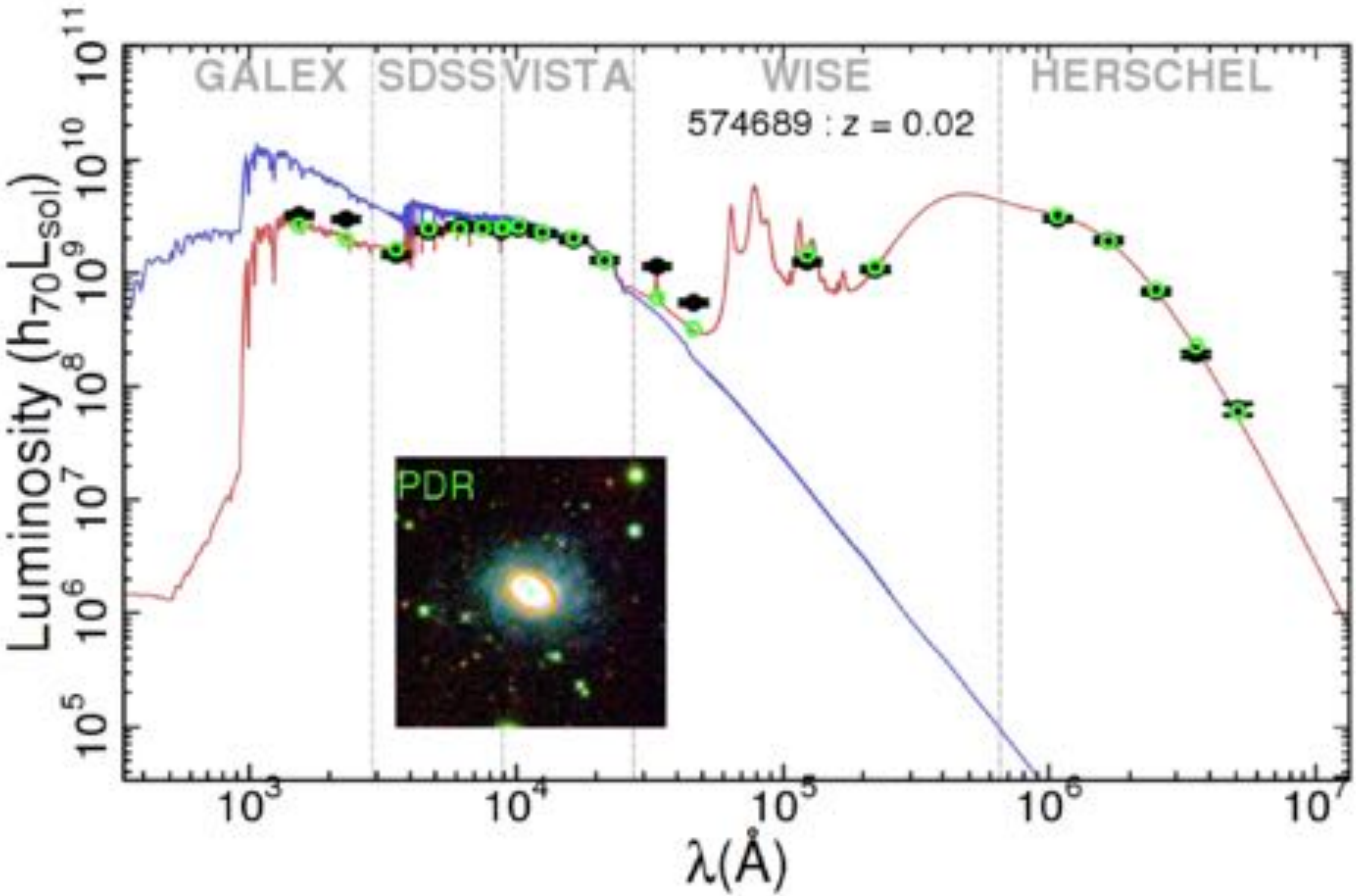


DIY - APERTURE PHOTOMETRY

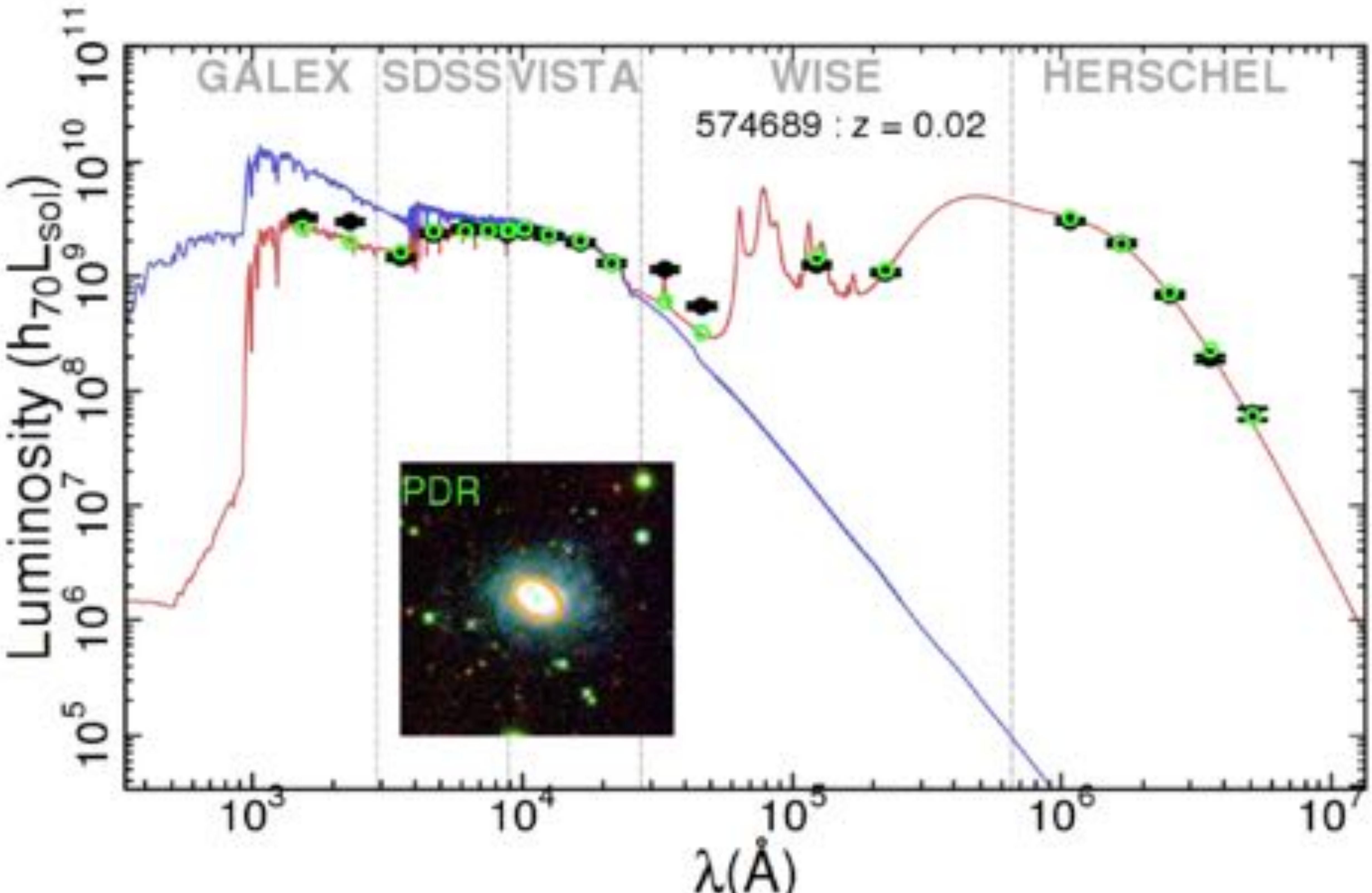


DIY - APERTURE PHOTOMETRY



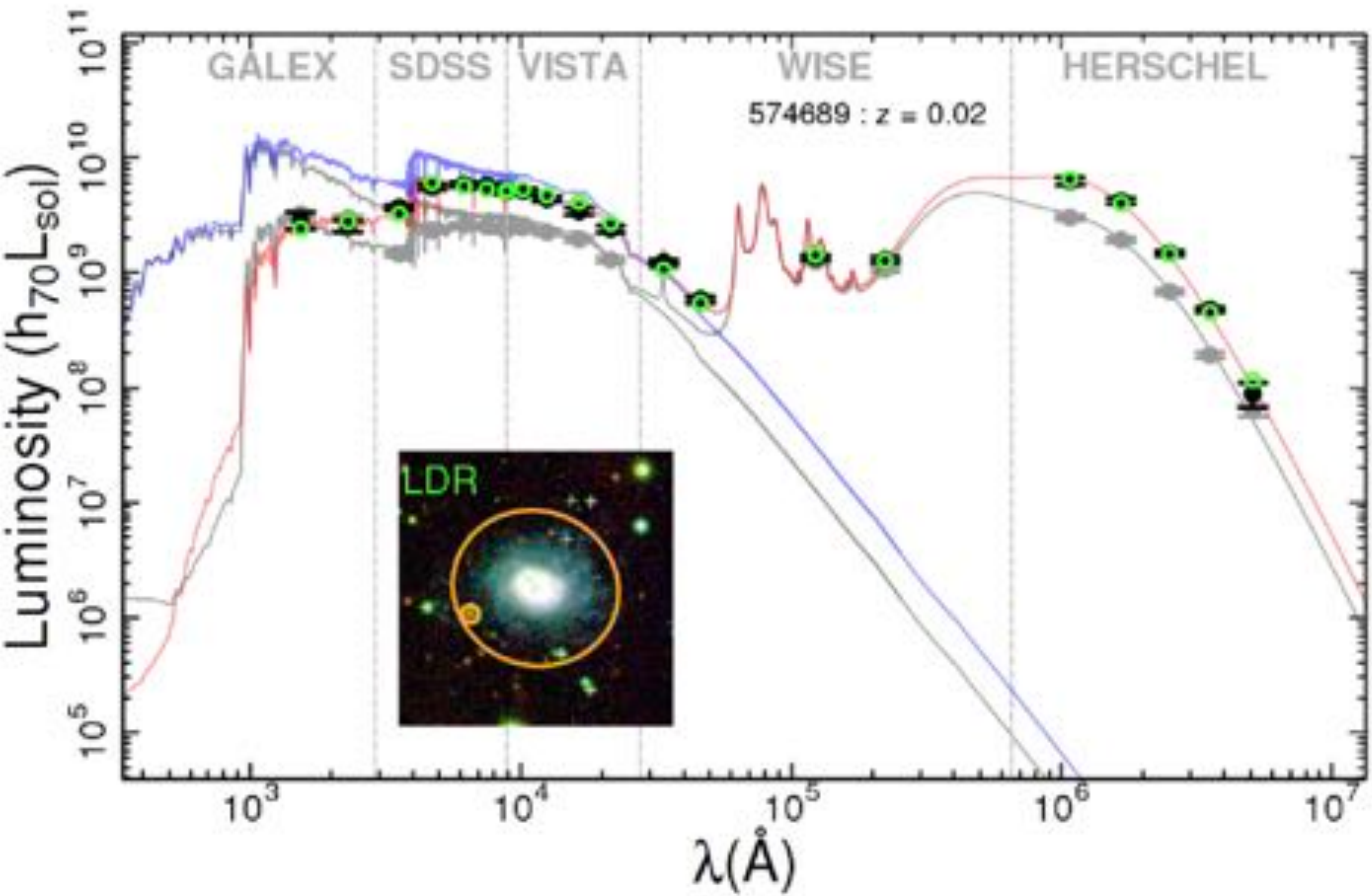

GALEX
SDSS
VISTA
WISE
HERSCHEL
574689 : z = 0.02
PDR
Luminosity ($h_{70}L_{sol}$)
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
λ(Å)

WHY IS THIS A BAD FIT?



IF YOU DON'T WANT TO DEGRADE ALL YOUR IMAGES…

- Flux fitting is an alternative to matched aperture (a.k.a. 'forced flux') photometry.
- Instead of only using degraded images, flux fitting works by taking information from the best quality image and using it to infer the flux from a lower resolution image (e.g. TFIT; Laigler et al. 2007; Mancone et al. 2013).
    - Start with a catalogue of galaxy positions and fluxes from the high resolution image.
    - Degrade that to match the PSF / resolution of the low quality image (e.g. Hubble -> ground-based telescope).
    - Then measure flux in the low-band image modulo some parameters such that a chi-squared fit to the flux in the degraded high-resolution image is minimized.
- Even more sophisticated algorithms are being developed (e.g. Wright et al. 2016).


GALEX
SDSS
VISTA
WISE
HERSCHEL
574689 : z = 0.02
LDR
Luminosity ($h_{70}L_{sol}$)
λ(Å)
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^3
10^4
10^5
10^6
10^7

DATABASES ARE YOUR FRIEND

- You don’t have to conduct a huge multiwavelength survey to obtain multi-band photometry.
  - It’s tricky, but perfectly viable to collate & concatenate photometry from different sources for the astronomical objects you’re interested in studying.
- This is referred to as ‘cross-matching.’
  - As before, the devil is in the details.

BASIC PROCEDURE

GET RAW DATA (CATALOGUES)

CROSS-MATCH

PERFORM CALIBRATION

CREATE DATABASE

DATABASES ARE YOUR FRIEND

- Most photometric surveys will have catalogues you can download, or databases you can query.
- SQL is worth learning, even if just enough to construct some basic queries.

DATABASES ARE YOUR FRIEND

- Most photometric surveys will have catalogues you can download, or databases you can query.

```
SELECT TOP 100
objID, ra ,dec
-- Get the unique object ID and coordinates
FROM
PhotoPrimary
-- From the table containing photometric data
for unique objects
WHERE
ra > 185 and ra < 185.1
AND dec > 15 and dec < 15.1
```

ough to construct

DATABASES ARE YOUR FRIEND

- Most photometric surveys will have catalogues you can download, or databases you can query.

```
SELECT TOP 100
objID, ra ,dec
-- Get the unique object ID and coordinates
FROM
PhotoPrimary
-- From the table containing photometric data
for unique objects
WHERE
ra > 185 and ra < 185.1
AND dec > 15 and dec < 15.1
```

ough to construct

```
SELECT top 100
objid, ra, dec, psfmag_i-extinction_i AS mag_i,
psfmag_r-extinction_r AS mag_r, z
-- In SpecPhoto, "z" is the redshift
FROM SpecPhoto
WHERE
(class = 'QSO')
```

DATA MATCHING

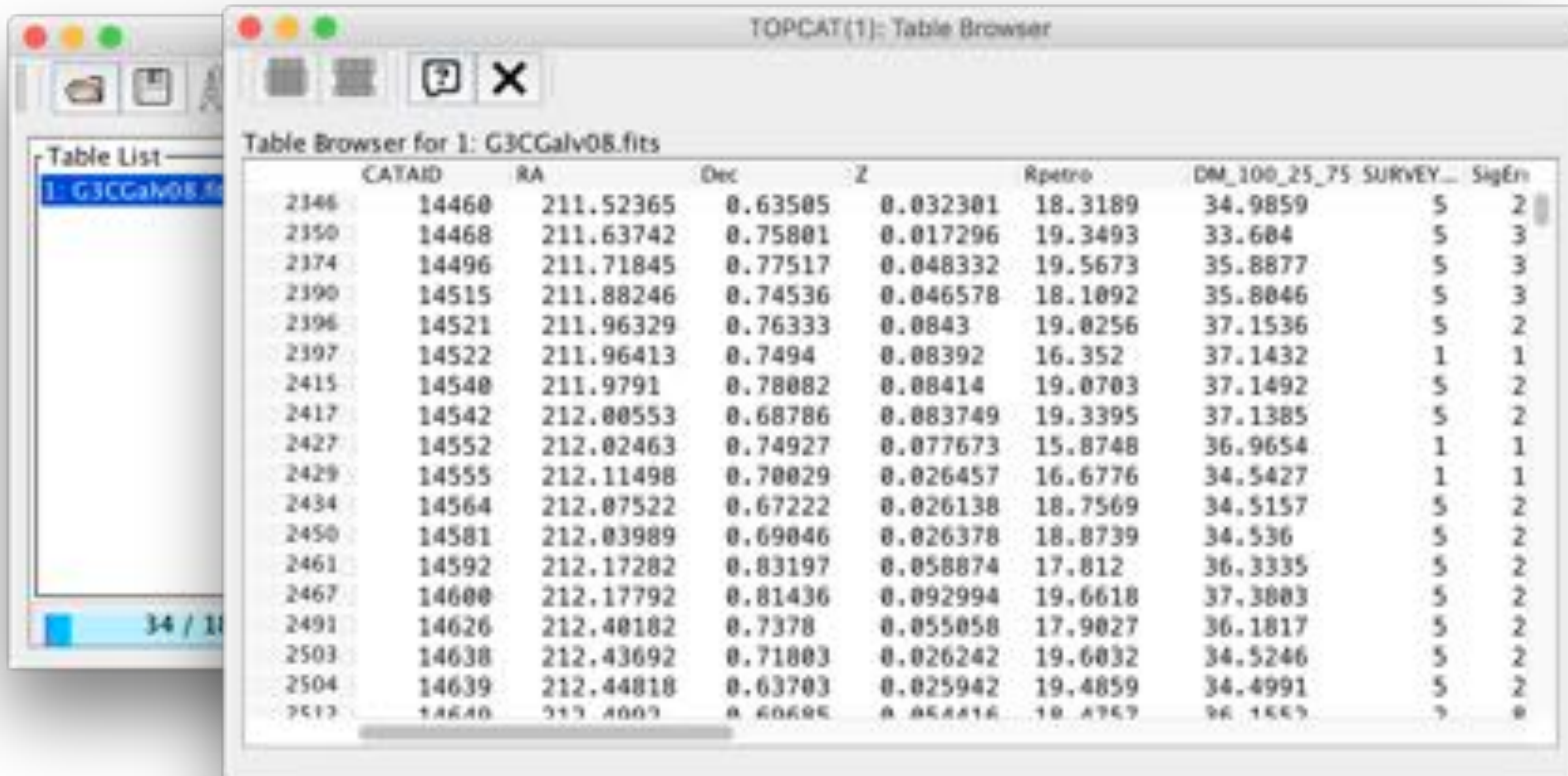
- ID matching:
  - Internally, most photometry (or spectroscopy, or …) databases will have an internal galaxy identifier that is kept constant within a survey.
  - e.g. PhotObjID in SDSS, or SpecObjID when looking at spectra. This can be a 64 bit integer, so be careful!
- Sky matching:
  - Most databases will also provide you the central RA, Dec, and sometimes even redshift of a target. This can be useful when merging photometry from different surveys.
  - However! Make sure you are matching by the correct centroid.
  - Keep track of separations.

DATABASES ARE YOUR FRIEND

- TOPCAT is also your friend.

DATABASES ARE YOUR FRIEND

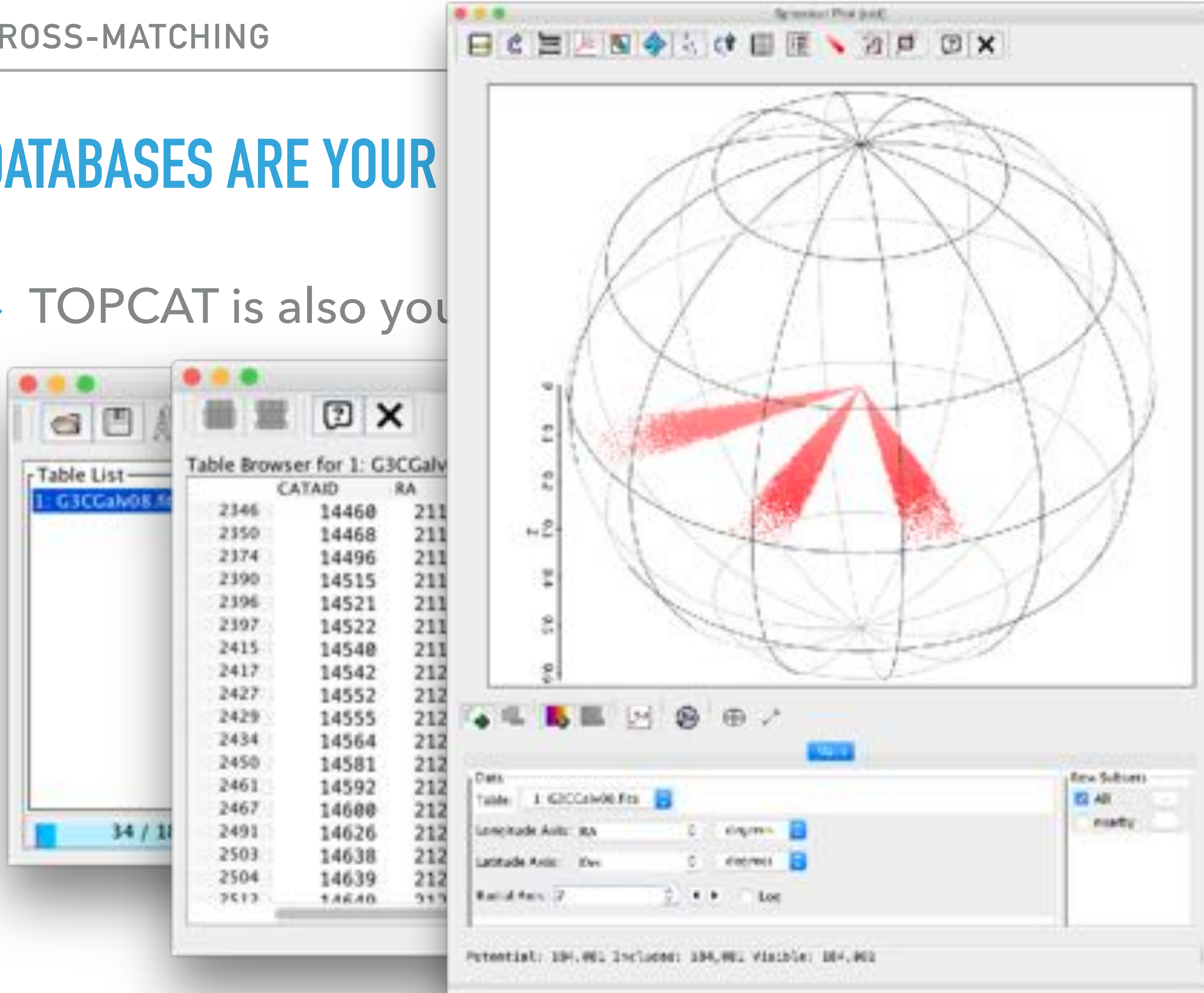
- TOPCAT is also your friend.



	CATAID	RA	Dec	Z	Rpetro	DM_100_25_75	SURVEY...	SigErr
2346	14460	211.52365	0.63505	0.032301	18.3189	34.9859	5	2
2350	14468	211.63742	0.75801	0.017296	19.3493	33.604	5	3
2374	14496	211.71845	0.77517	0.048332	19.5673	35.8877	5	3
2390	14515	211.88246	0.74536	0.046578	18.1092	35.8046	5	3
2396	14521	211.96329	0.76333	0.0843	19.0256	37.1536	5	2
2397	14522	211.96413	0.7494	0.08392	16.352	37.1432	1	1
2415	14540	211.9791	0.78082	0.08414	19.0703	37.1492	5	2
2417	14542	212.00553	0.68786	0.083749	19.3395	37.1385	5	2
2427	14552	212.02463	0.74927	0.077673	15.8748	36.9654	1	1
2429	14555	212.11498	0.70029	0.026457	16.6776	34.5427	1	1
2434	14564	212.07522	0.67222	0.026138	18.7569	34.5157	5	2
2450	14581	212.03989	0.69046	0.026378	18.8739	34.536	5	2
2461	14592	212.17282	0.83197	0.058874	17.812	36.3335	5	2
2467	14600	212.17792	0.81436	0.092994	19.6618	37.3803	5	2
2491	14626	212.40182	0.7378	0.055058	17.9027	36.1817	5	2
2503	14638	212.43692	0.71803	0.026242	19.6032	34.5246	5	2
2504	14639	212.44818	0.63703	0.025942	19.4859	34.4991	5	2

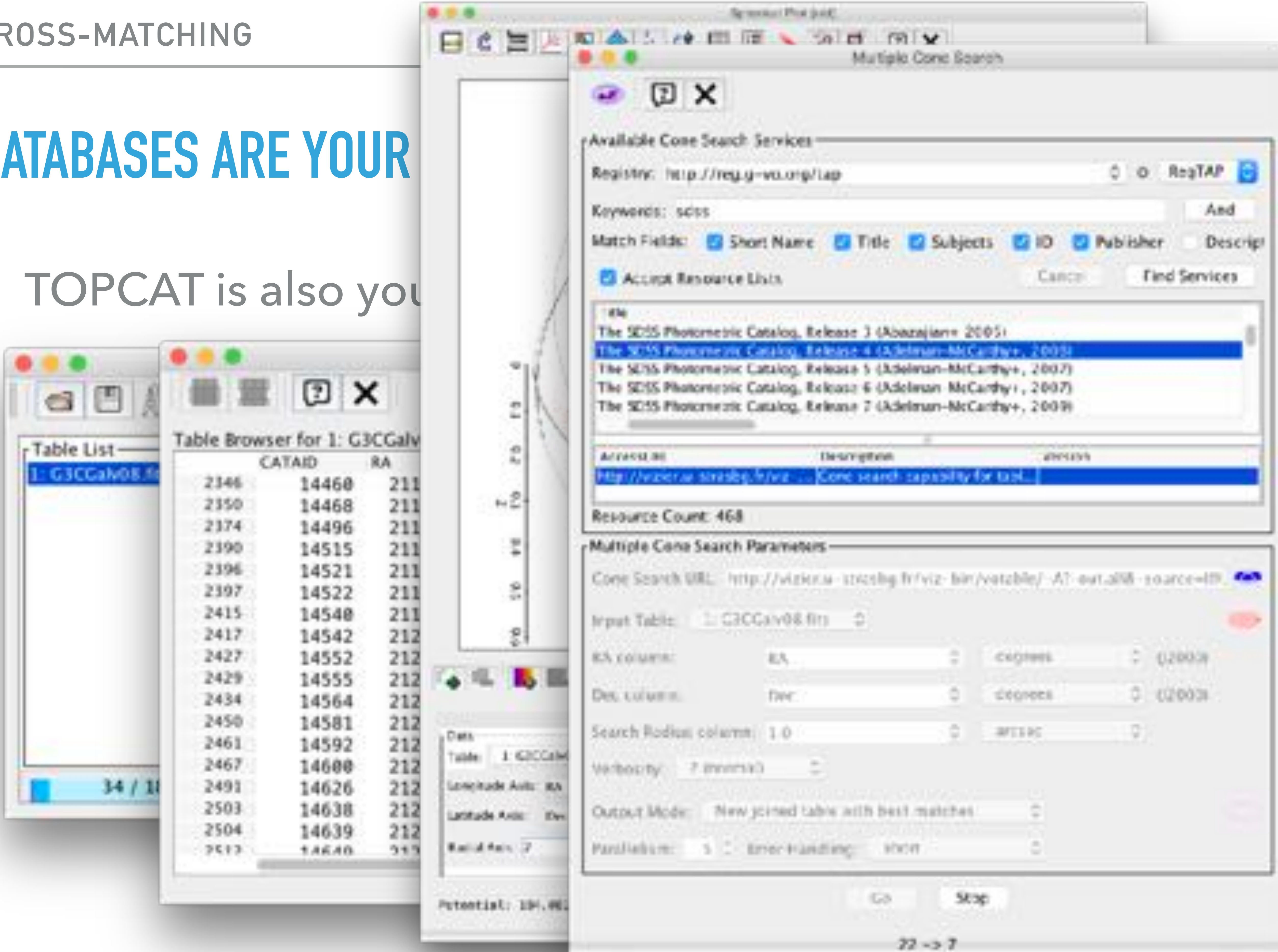
DATABASES ARE YOUR

- TOPCAT is also you



DATABASES ARE YOUR

- TOPCAT is also you



CALIBRATION

- Standard fixes for zeropoint and gain.
- You'll probably also run into different magnitude systems / filters (e.g. *UBVRI* vs *ugriz*).
- Generally speaking, converting between AB and Vega is done as:

$$m_{\mathrm{AB}}(\mathrm{Obj}) = m_{\mathrm{Vega}}(\mathrm{Obj}) + m_{\mathrm{AB}}(\mathrm{Vega})$$

$$\mathrm{Conversion} = m_{\mathrm{AB}}(\mathrm{Vega}) = -2.5\log\left(\frac{\int F_\lambda(\mathrm{Vega})S_\lambda d\lambda}{\int S_\lambda d\lambda}\right) - 48.6$$

  - (For historical reasons, this assumes you're working in cgs.)
- Magnitude conversion tables exist!

MAGNITUDES

- e.g. Blanton 2007:

Band	λ_{eff}	mAB - mVega	MSun(AB)	MSun(Vega)
U	3571	0.79	6.35	5.55
B	4344	-0.09	5.36	5.45
V	5456	0.02	4.80	4.78
R	6442	0.21	4.61	4.41
I	7994	0.45	4.52	4.07
J	12355	0.91	4.56	3.65
H	16458	1.39	4.71	3.32
K_s	21603	1.85	5.14	3.29
u	3546	0.91	6.38	5.47
g	4670	-0.08	5.12	5.20
r	6156	0.16	4.64	4.49
i	7472	0.37	4.53	4.16
z	8917	0.54	4.51	3.97

(You don't need to know these numbers off-hand; just where to find them!)

TO CONCLUDE… (I.E. LEARN FROM MY MISTAKES)

- Know the data well! Always read the manual (or, in this case, database notes).
- Know what photometry you're matching.
    - e.g. some surveys output Kron magnitudes by default, whereas others do Petrosian magnitudes. These are not the same thing!
    - Pay particular attention to what kind of apertures are being used.
- Make sure your cross-matching / data collection routine is reproducible. **Keep careful notes!**
- It isn't easy, but it is worth doing.
- Not only is multiwavelength photometry an excellent way of doing interesting science, but a well prepared, high quality database of multi-band photometry is a useful tool for the whole astronomical community.