Synergy of Wide-field Infrared Survey Explorer (WISE) and the Sloan Digital Sky Survey in Stripe 82

Ph.D. Thesis Defense

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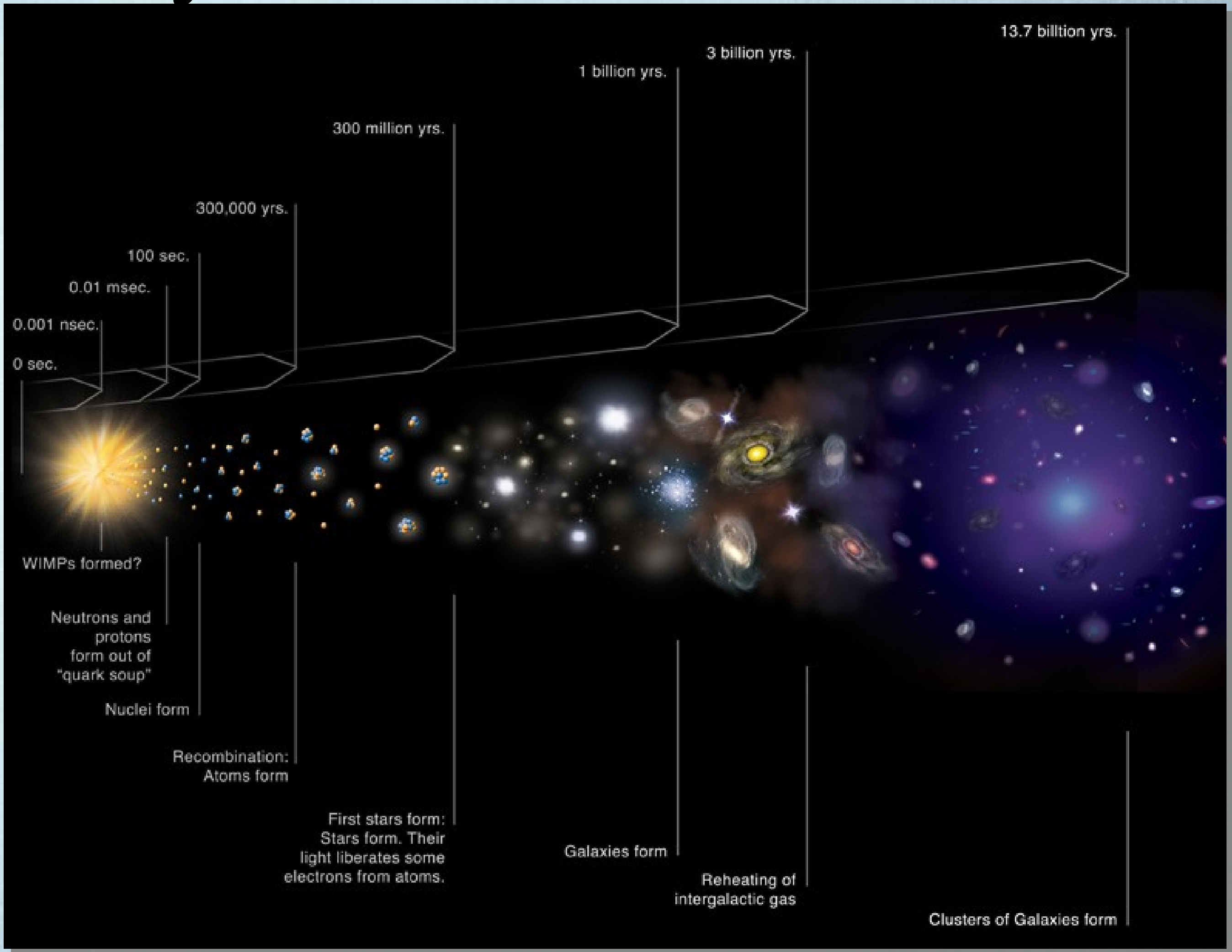
Outline

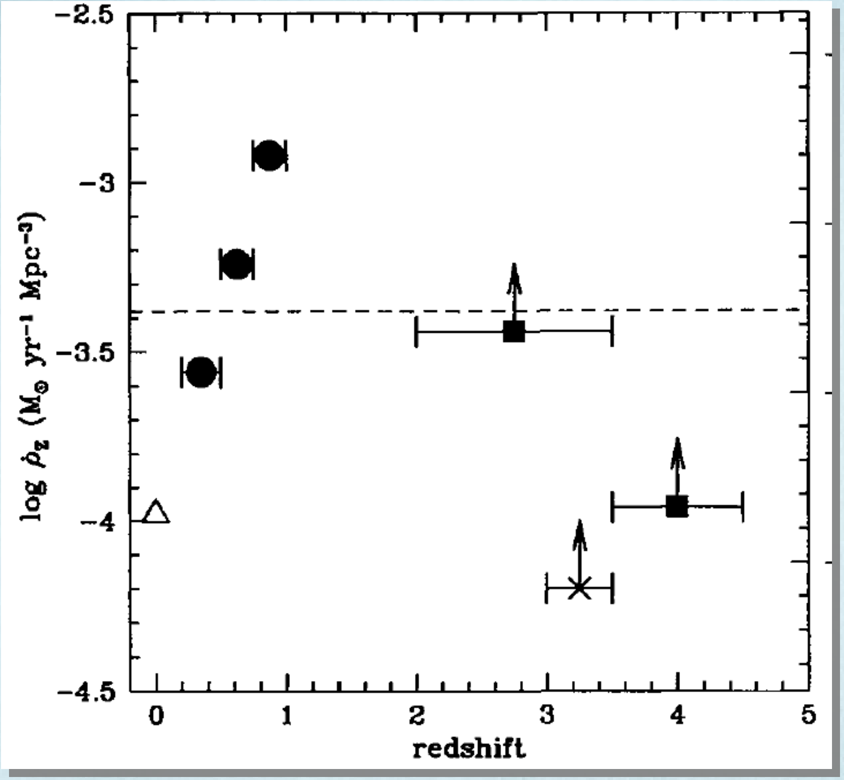
- Context — evolution of galaxies over Cosmic time:
  - Lilly-Madau diagram, CSFH, GSMD
- Stellar masses of galaxies:
  - From photometry to SED fitting
  - from SED fitting to redshift and mass
- Sample — wide field optical and near-IR surveys
  - Construction of the largest optical+near-IR catalog
  - Unique approach — template fitting with consistent flux for near-IR data
- Mass and redshift estimation
  - SED fitting
  - Calibration and validation of the catalog
- Results and future work
  - Constraints on GSMD
  - Future work with the catalog
  - Subsample WoDrops
- Conclusions

Galaxy formation and evolution

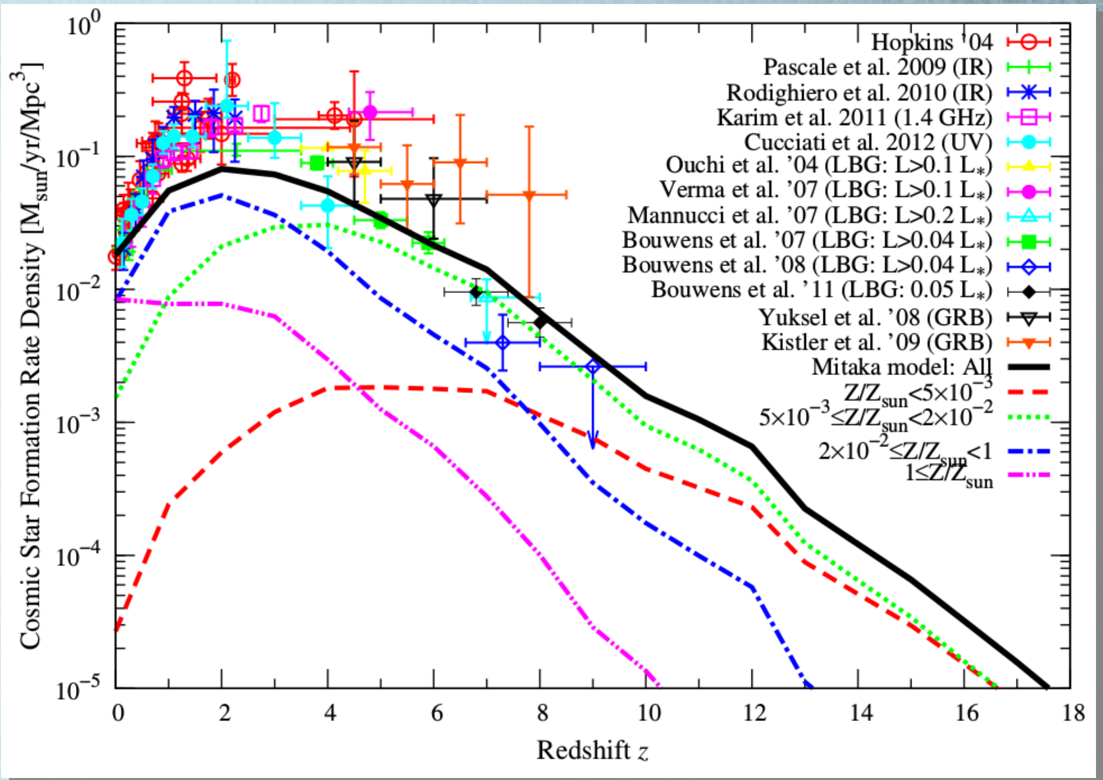


Stellar population is different in different galaxies and it evolves with time. A key aspect in studying galaxy formation and evolution is to understand how their stellar populations evolve in time.

Cosmic Star Formation History



Madau et al. 1996



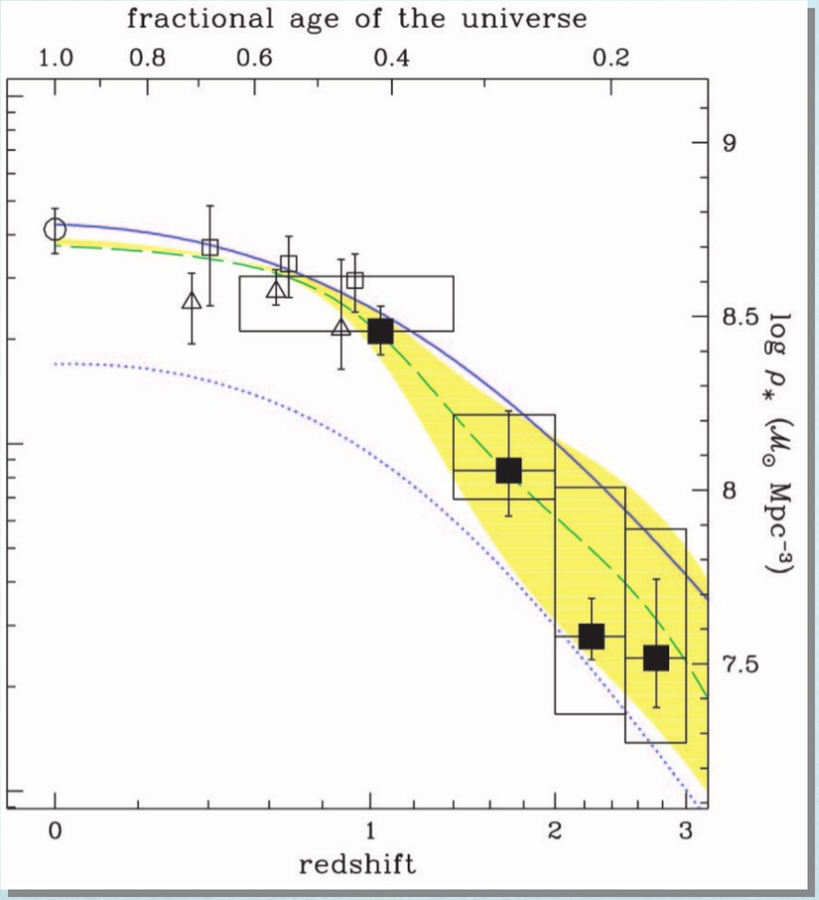
Inoue et al. 2013

True first version of CSFH plot with only 7 data points

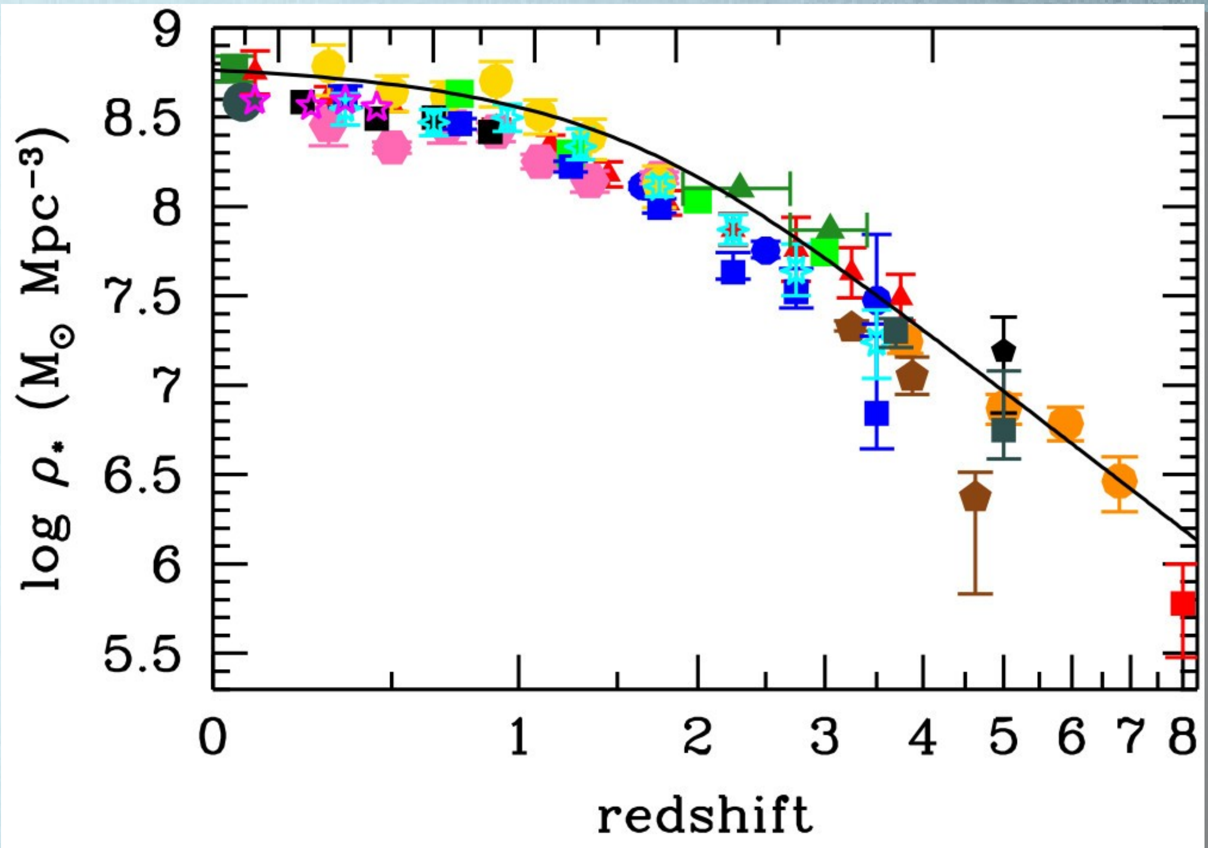
The solid curve shows the total CSFRD, other curves show the fractional contributions from stars with different metallicities

Evolution of our knowledge about CSFH over last 25 years

Global Stellar Mass Density



Dickinson et al. 2003

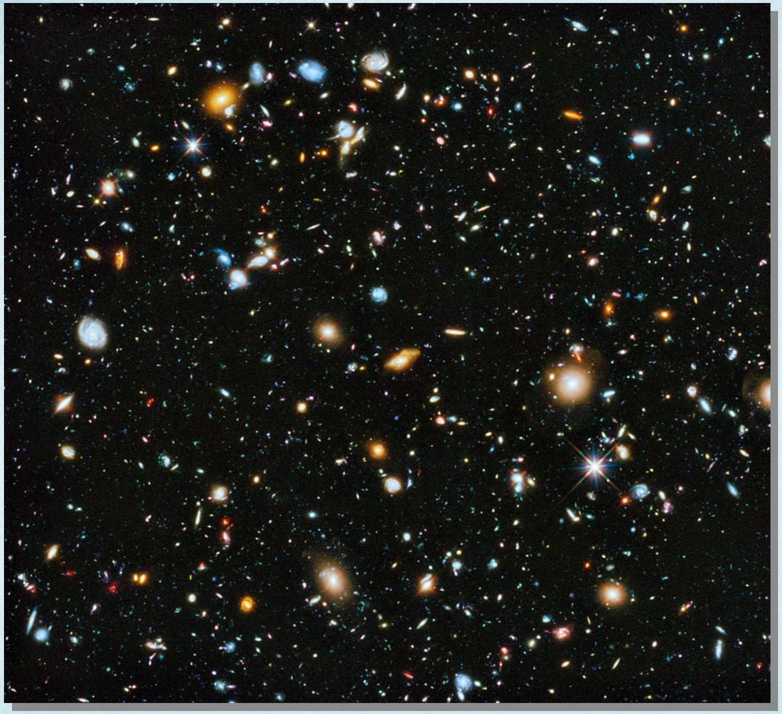


Madau & Dickinson. 2014

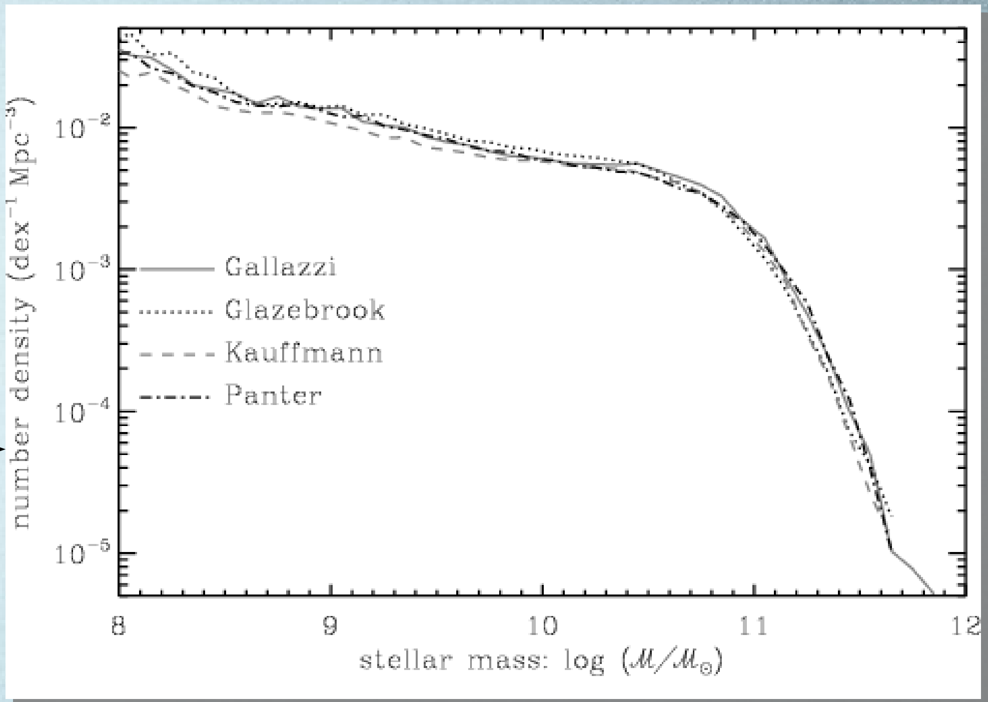
GSMD traces the same physical processes (integral of SFR over time gives mass), but is subjected to different systematic uncertainties and thus is a wonderful probe of the evolution of the Universe

Our goal is to contribute to the plot of GSMD at $0<z<0.8$ with robust data that will constraint all future models of galaxy evolution at higher redshifts

Measuring mass from light I.

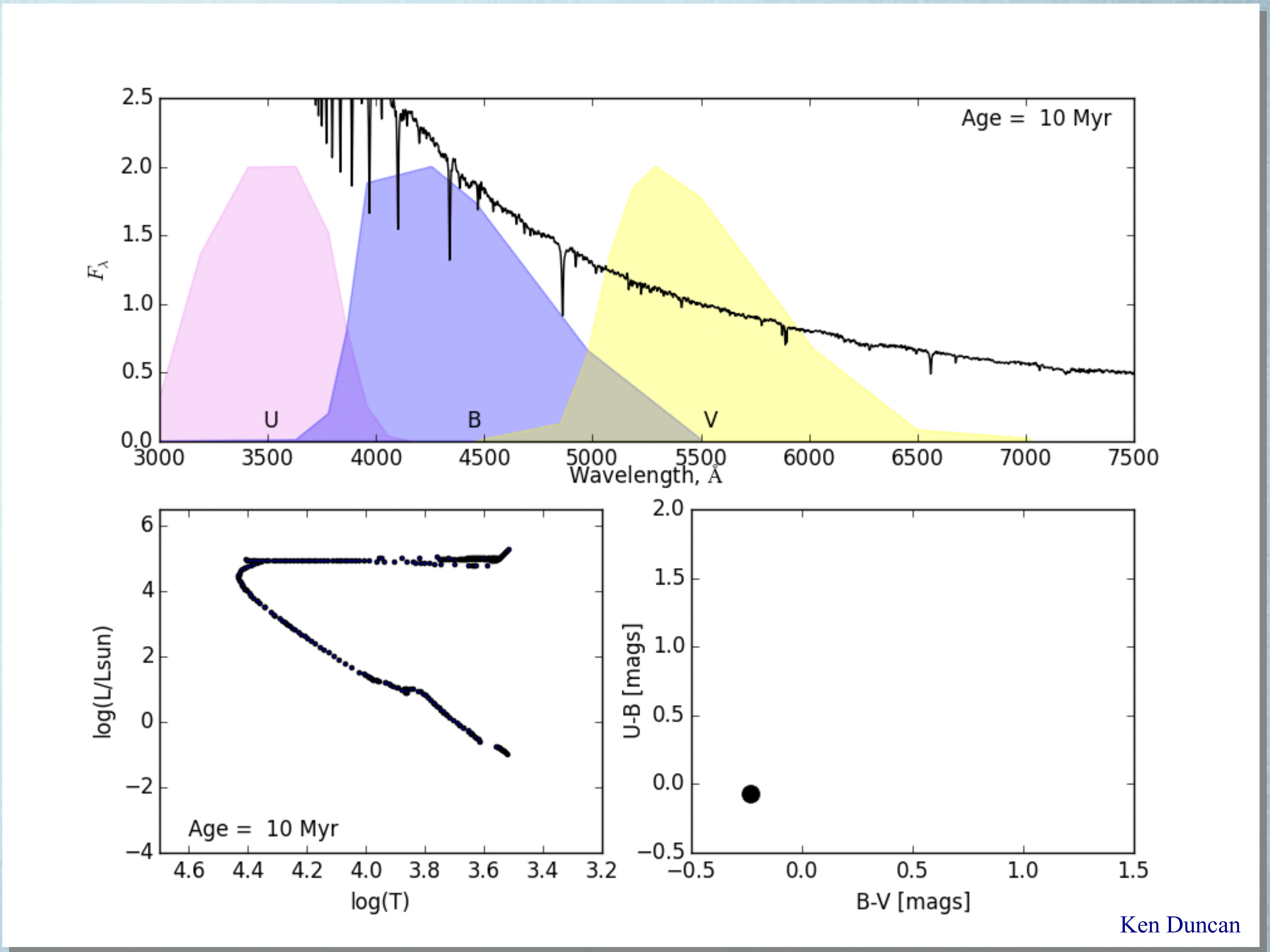


?



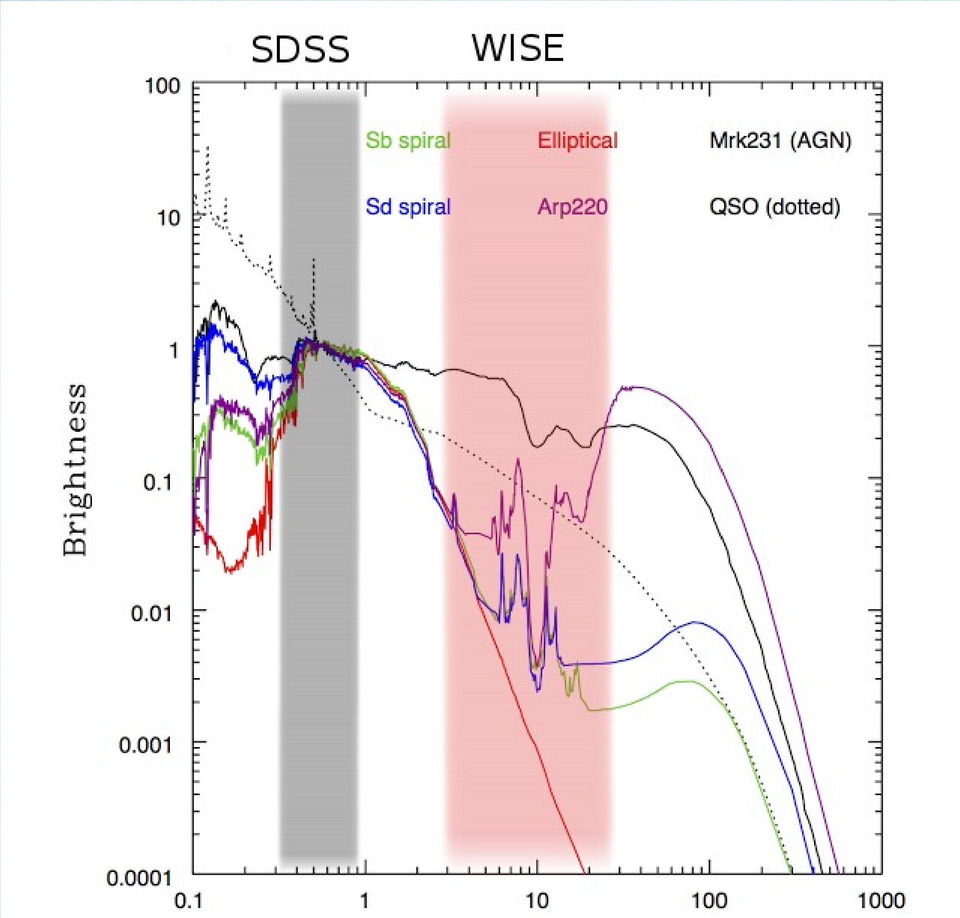
How do we go from observations to physical parameters?

Measuring mass from light II. SED fitting



For the large sample of galaxies we only can study their stellar populations using integrated colors. We use stellar population synthesis (SPS) modeling to study how the spectra and colors of a population of stars evolve with time, under different input star formation histories. On this animation an evolving population of stars is formed in a single burst of star formation.

Measuring mass from light III. Degeneracy and low-mass stars



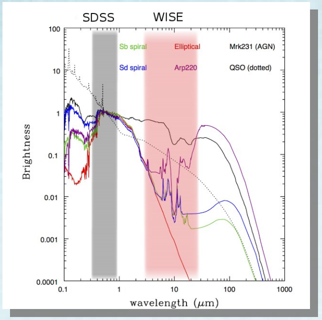
Polletta et al. 2007

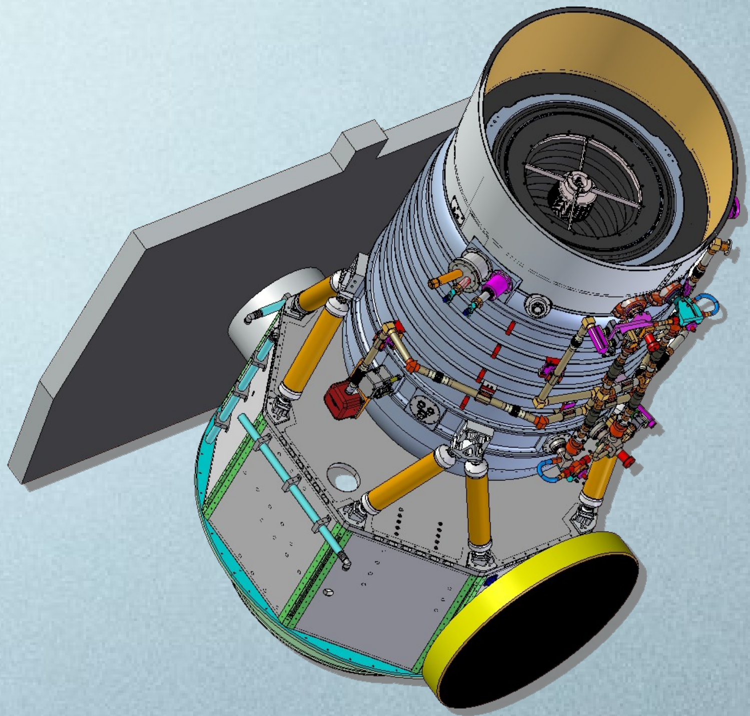
Spectral energy distributions for typical galaxies - old elliptical galaxy, spiral galaxies, AGN, QSO, and star-bursting galaxy Arp 220. Flux is scaled to unity in optical.

Degeneracy of dust vs. age:
Galaxy with red SED can be dusty,
or have a very old stellar population,
or both,
or have high metallicity (effective UV absorption)

Low-mass stars are intrinsically red and contribute most to the total stellar mass budget of the galaxy. Near-IR data are needed to account for them

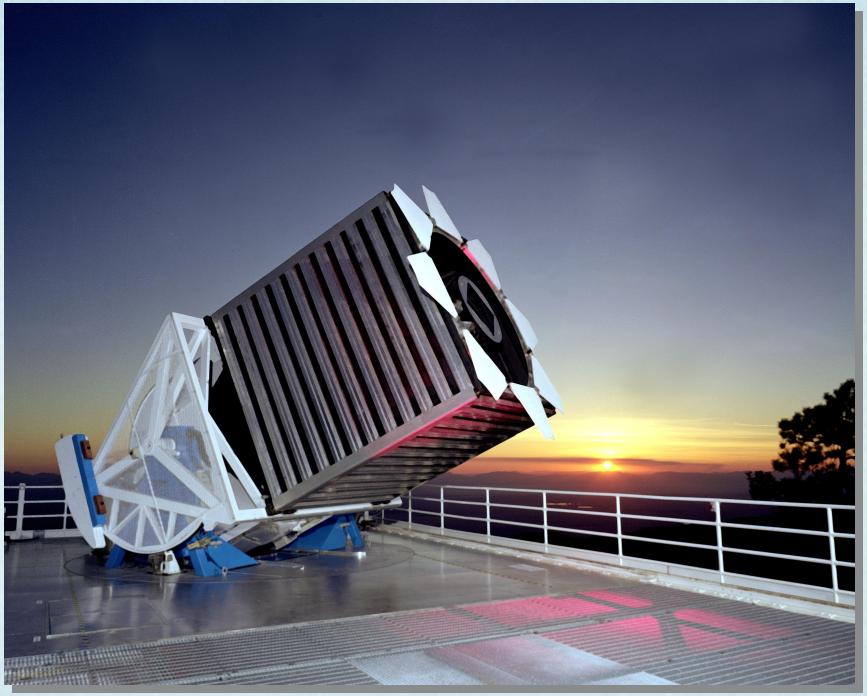
Facility and data I. SDSS and WISE



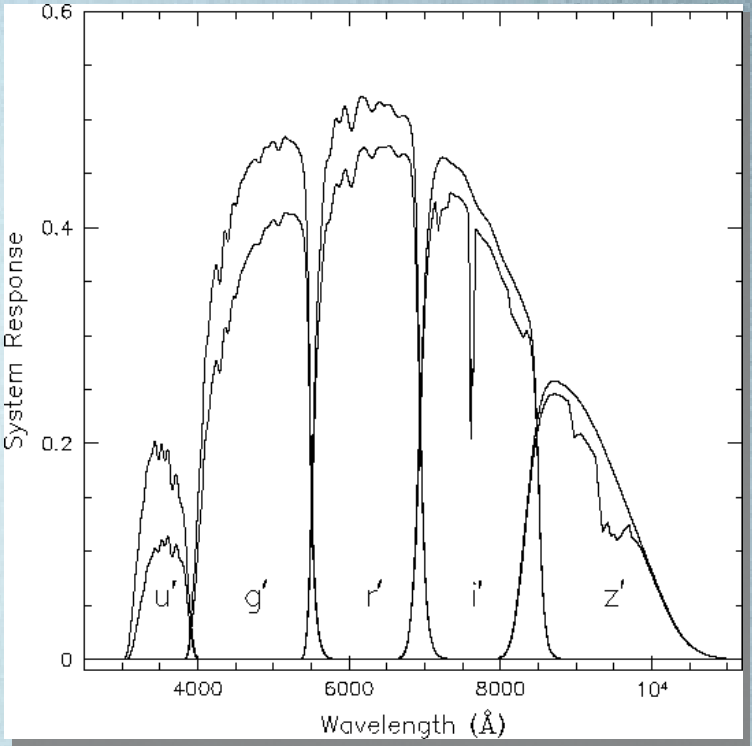


We need a synergy of optical and near-IR data from as deep and as wide-field data as possible

Facility and data II. SDSS



Credits: Frieman



Credits: Fukugita et al. 1996

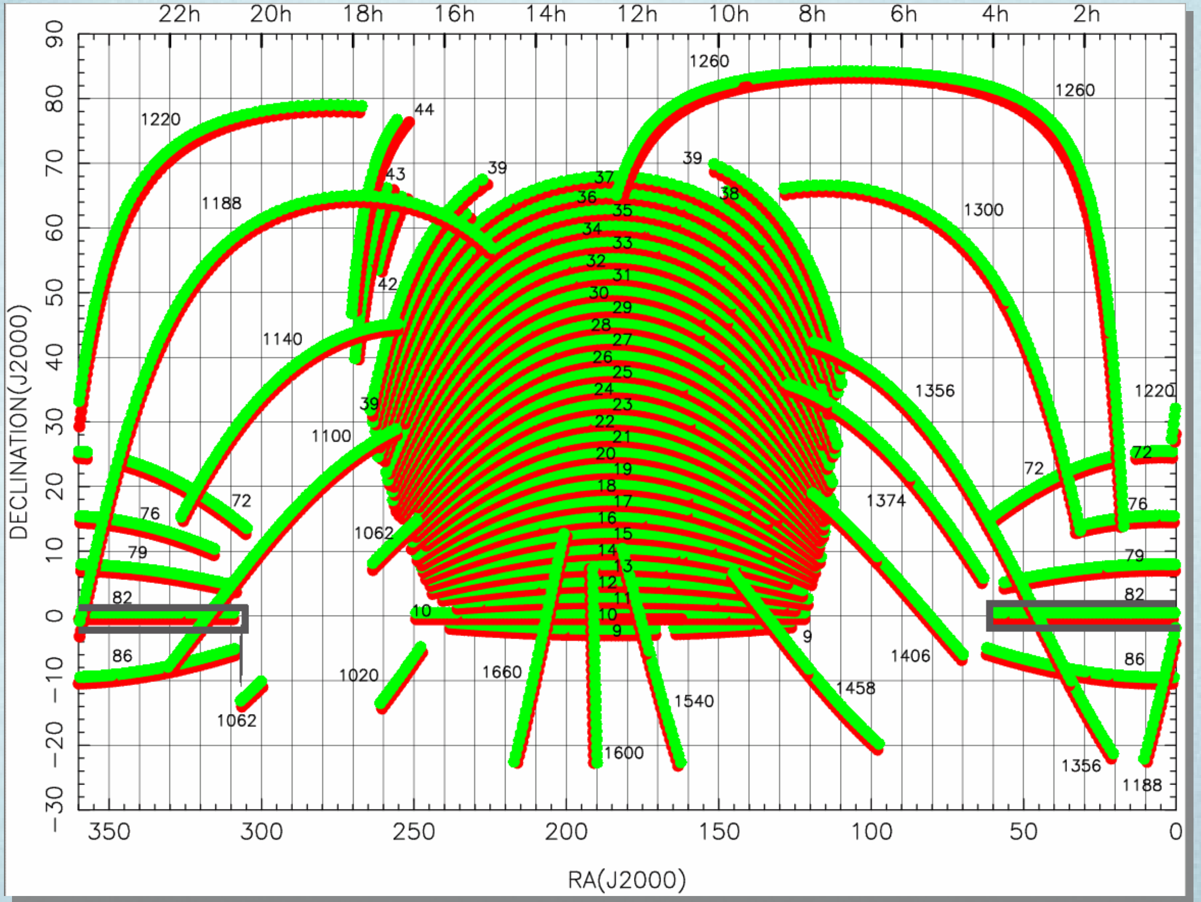
SDSS — multi-filter 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico, United States.

The SDSS system response curves. The responses are shown without atmospheric extinction (upper curves) and with modified extinction at 1.2 airmasses (lower curves). The curves represent expected total QE of the CCD plus telescope optics.

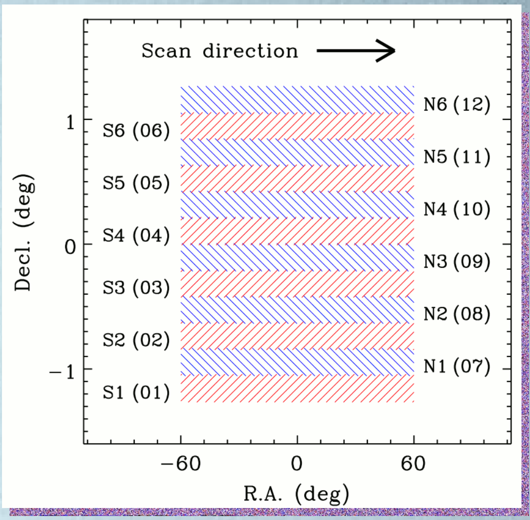
SDSS, is mostly useful for "normal" galaxies up to z<0.4. (Some particular types of objects though, such as quasars, can be probed to higher redshifts).

Facility and data II. SDSS Stripe 82

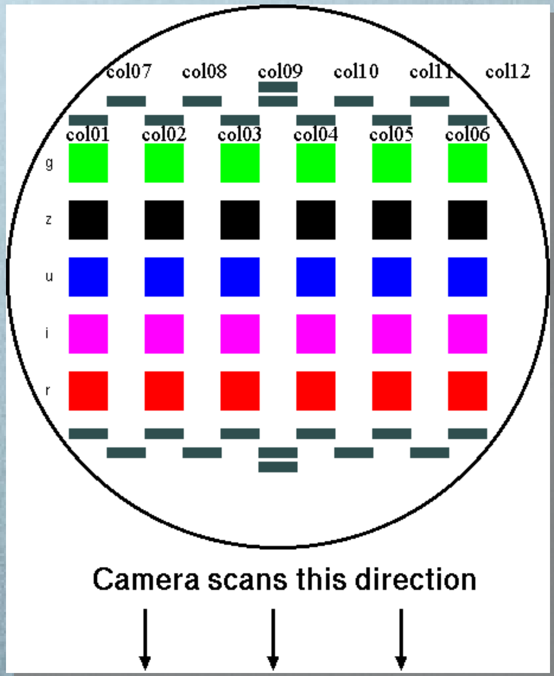
Credits: Jiang et al. 2014



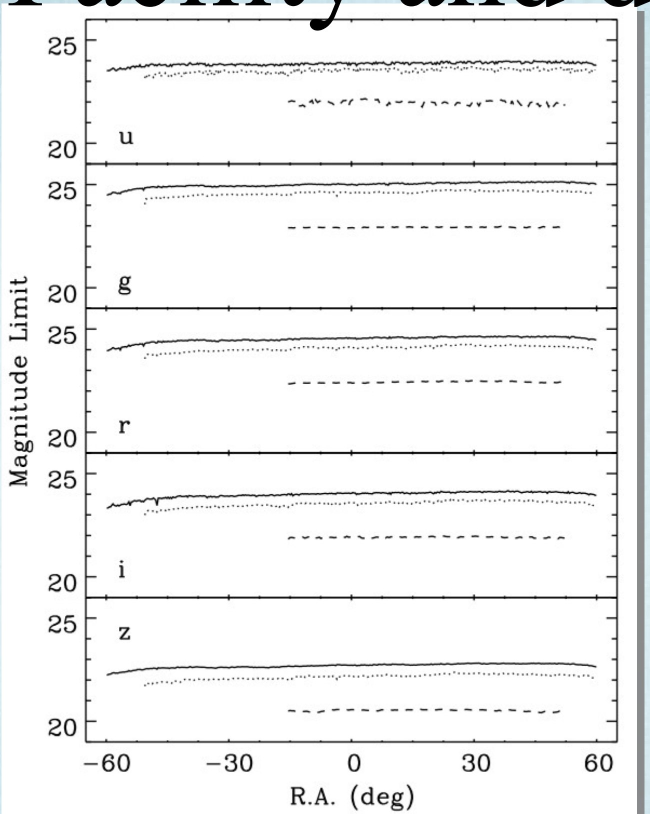
Full SDSS Footprint (10 400 square degrees) with Stripe labels including Stripe 82.



Layout of SDSS Stripe 82. It is used for calibrations and has been extensively scanned for 70-90 times.

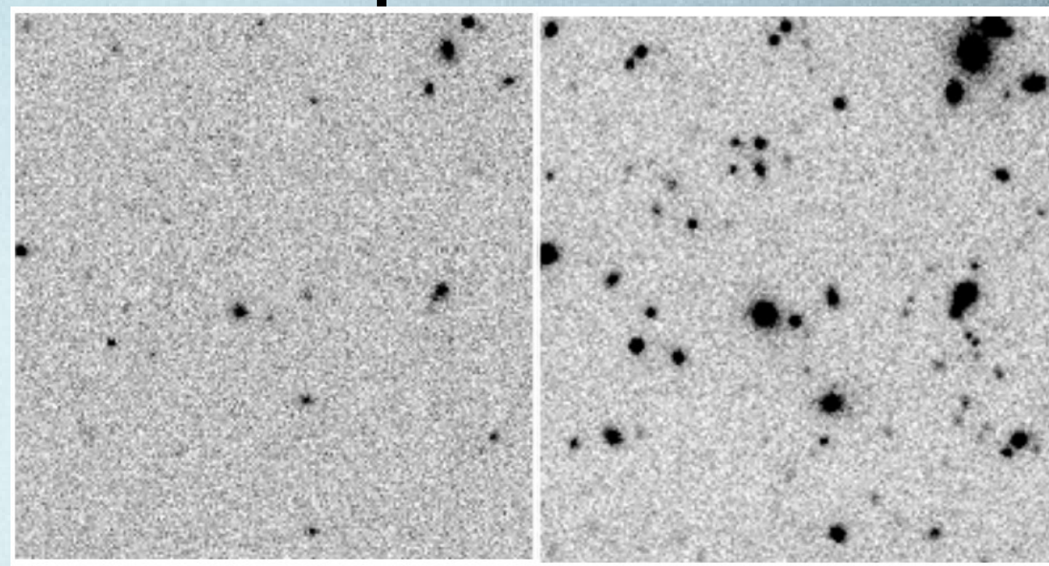


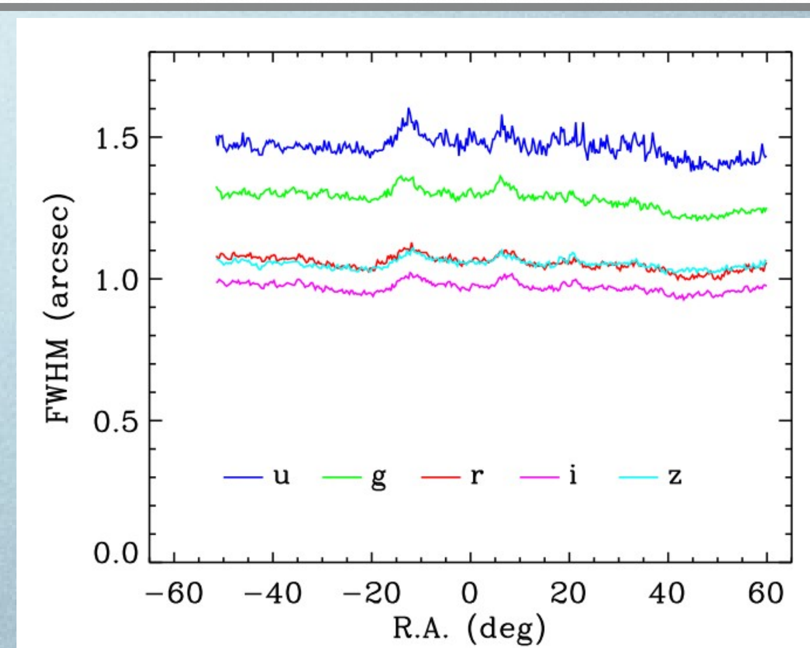
Facility and data II.Stripe 82 co-adds



5σ detection limits of the aperture (1".6) magnitudes for point sources

All credits: Jiang et al. 2014



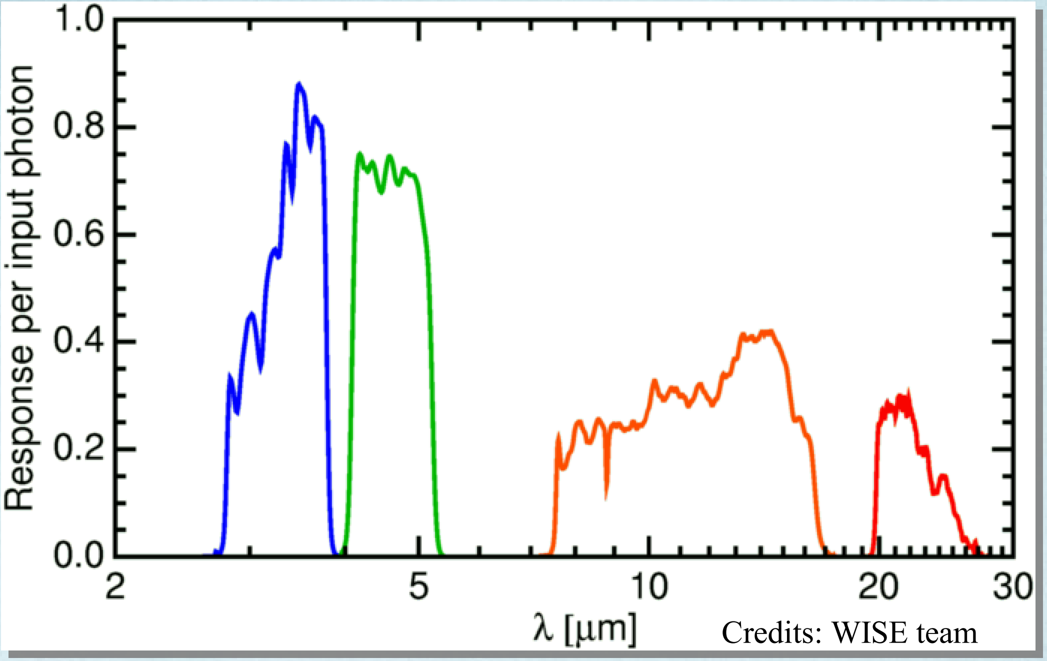


The co-adds PSF FWHM in the *riz* bands is roughly 1".0, and is about 1".3–1".5 in *ug* bands

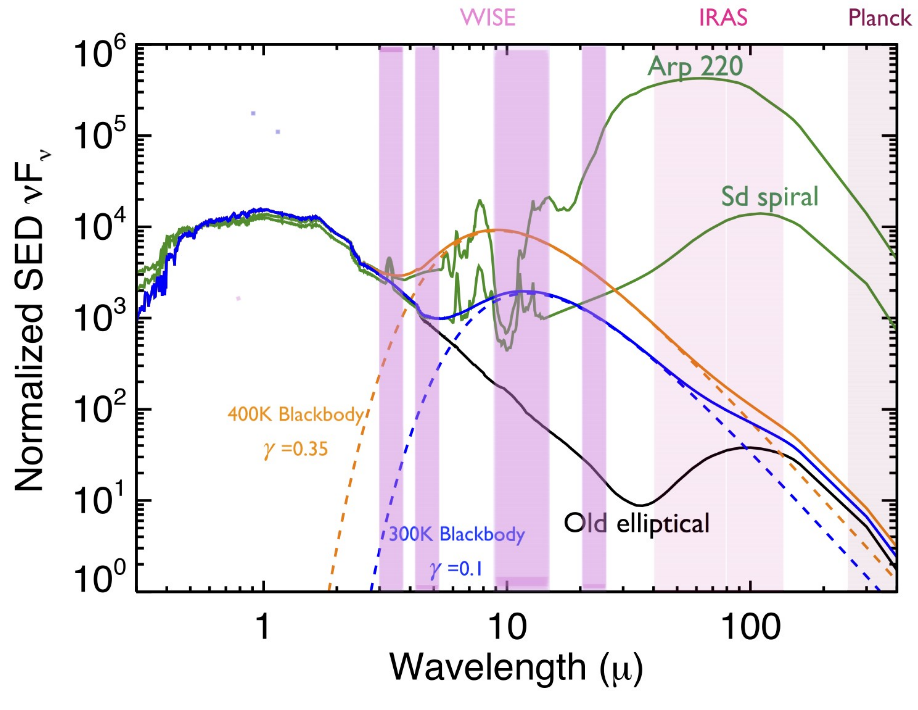
Table 1: *SDSS co-adds*

Filter	u	g	r	i	z
Central λ,Å	3543	4770	6231	7625	9134
Mag_{lim} (5 σ), AB	23.9	25.1	24.6	24.1	22.8
Flux limit, μJy	1	0.33	0.52	0.83	2.7
FWHM, asec	1.4	1.4	1.0	1.0	1.0
Pixel size	0.396 "/pix (changed to 0.55 "/pix)				

Facility and data III. WISE



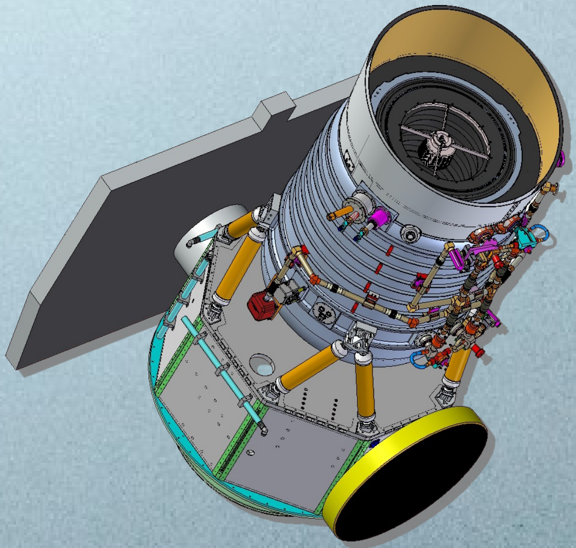
Credits: Jason Wright



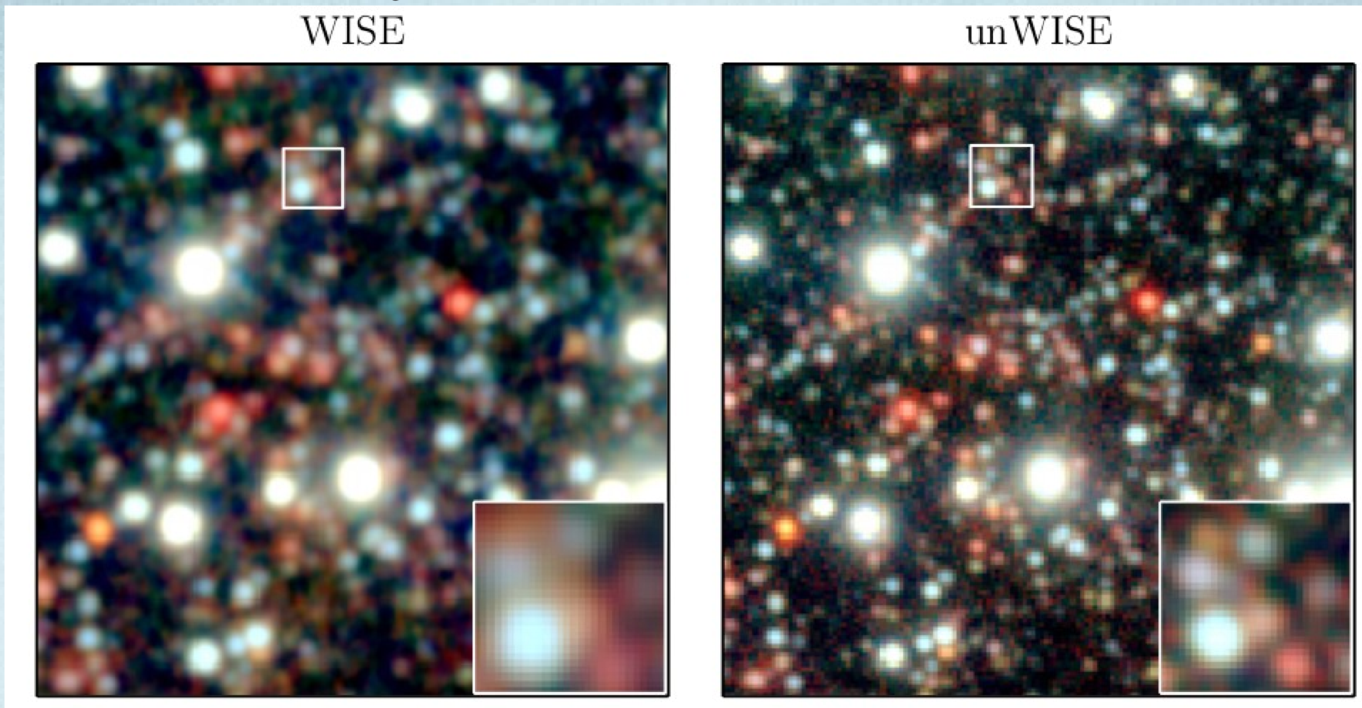
WISE response per photon (i.e. QE of CCD times the transmission of the optics and filters).

SEDs for the typical old elliptical, spiral galalxies, and Arp 220.

Other near-IR surveys are not suitable for our purposes:
- 2MASS has low sensitivity;
- Spitzer does not cover sufficient area where we have deep optical data.



Facility and data III. Not WISE — unWISE



The 7' × 7' coadd tile of the north ecliptic pole, three-band composites (w1, w2, w3).

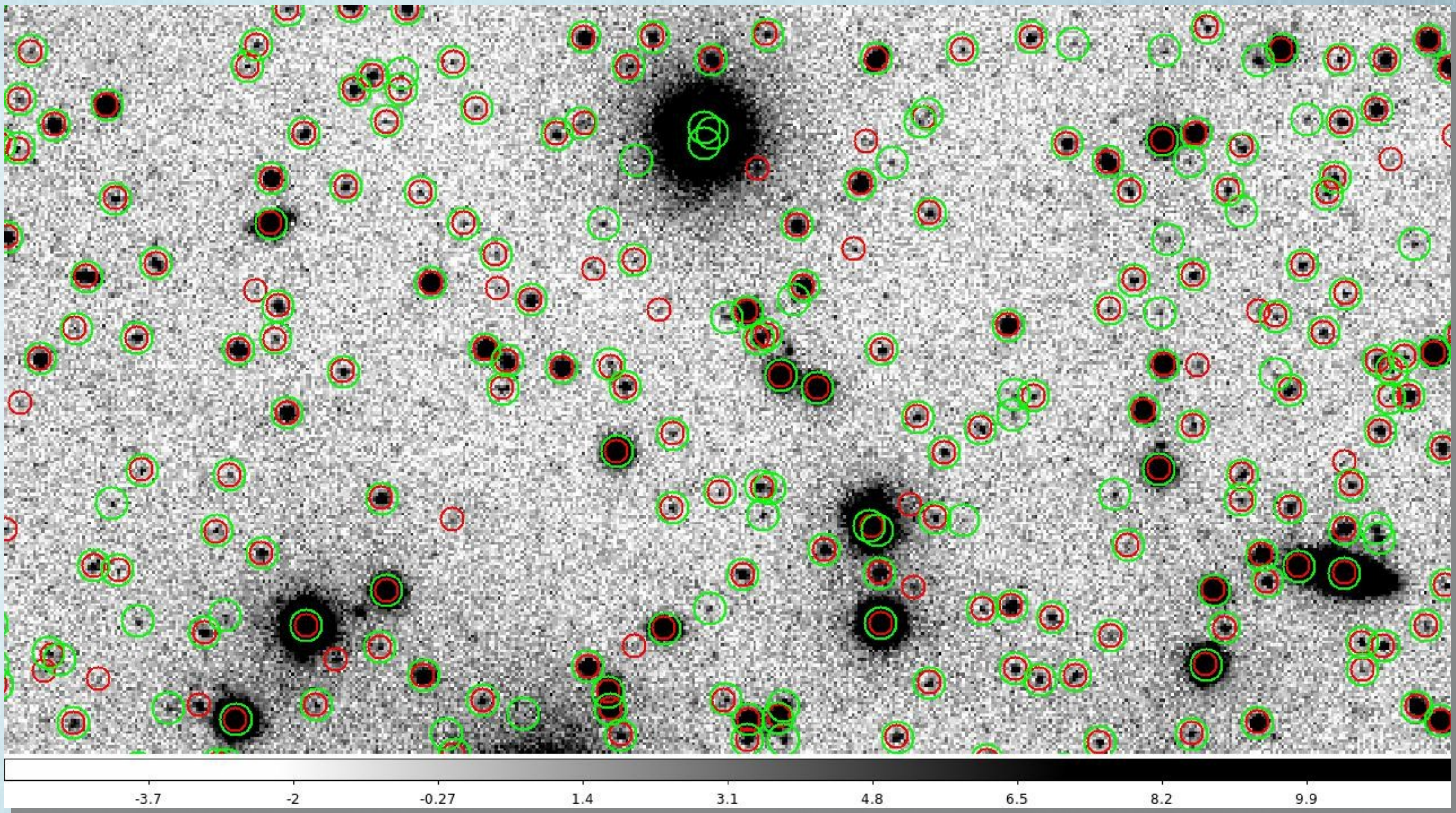
Credits: Lang. 2014

Left: AllWISE Release Atlas Image
Right: unWISE coadd with restored intrinsic resolution

Table 2: *unWISE co-adds (only bands w1 and w2 are used in the current work)*

Band	w1	w2	w3	w4
Central λ,μm	3.4	4.6	12	22
Mag_{lim} (5 σ), AB	19.53	18.94	16.49	14.62
Flux limit, mJy	0.068	0.098	0.86	5.4
FWHM, asec	6.1	6.4	6.5	12.0
Pixel size	2.75 "/pix (restored in unWISE)			

Catalog I. Why do we need it?



Catalog from Jiang et al — green circles; our catalog — red circles.

Why do we need to construct our own catalog?

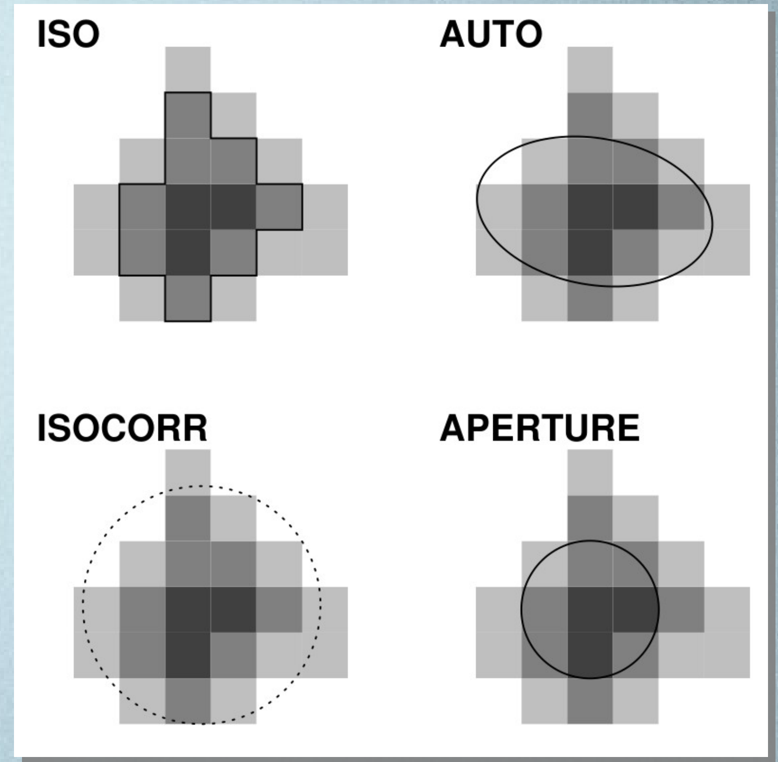
1) Original catalog has to high detection threshold — lots of sources are rejected

2) Catalog is not cleaned out — multiple detections around saturated areas.

We run Sextractor on Jiang's images and got more than 22 million sources detected in ~300 square degrees.

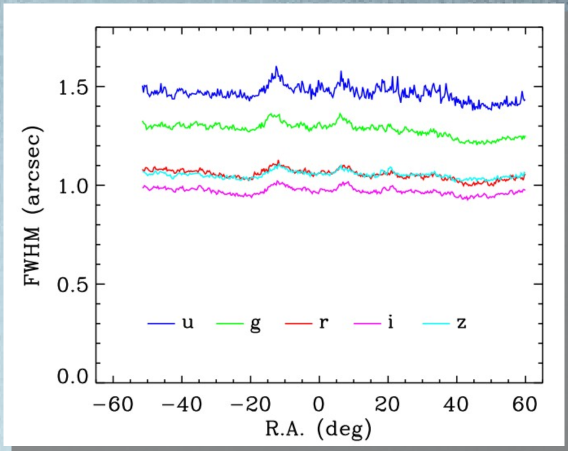
Catalog II. Optical

Show same object in 5 optical bands to see that it is not trivial to extract flux even in SDSS.

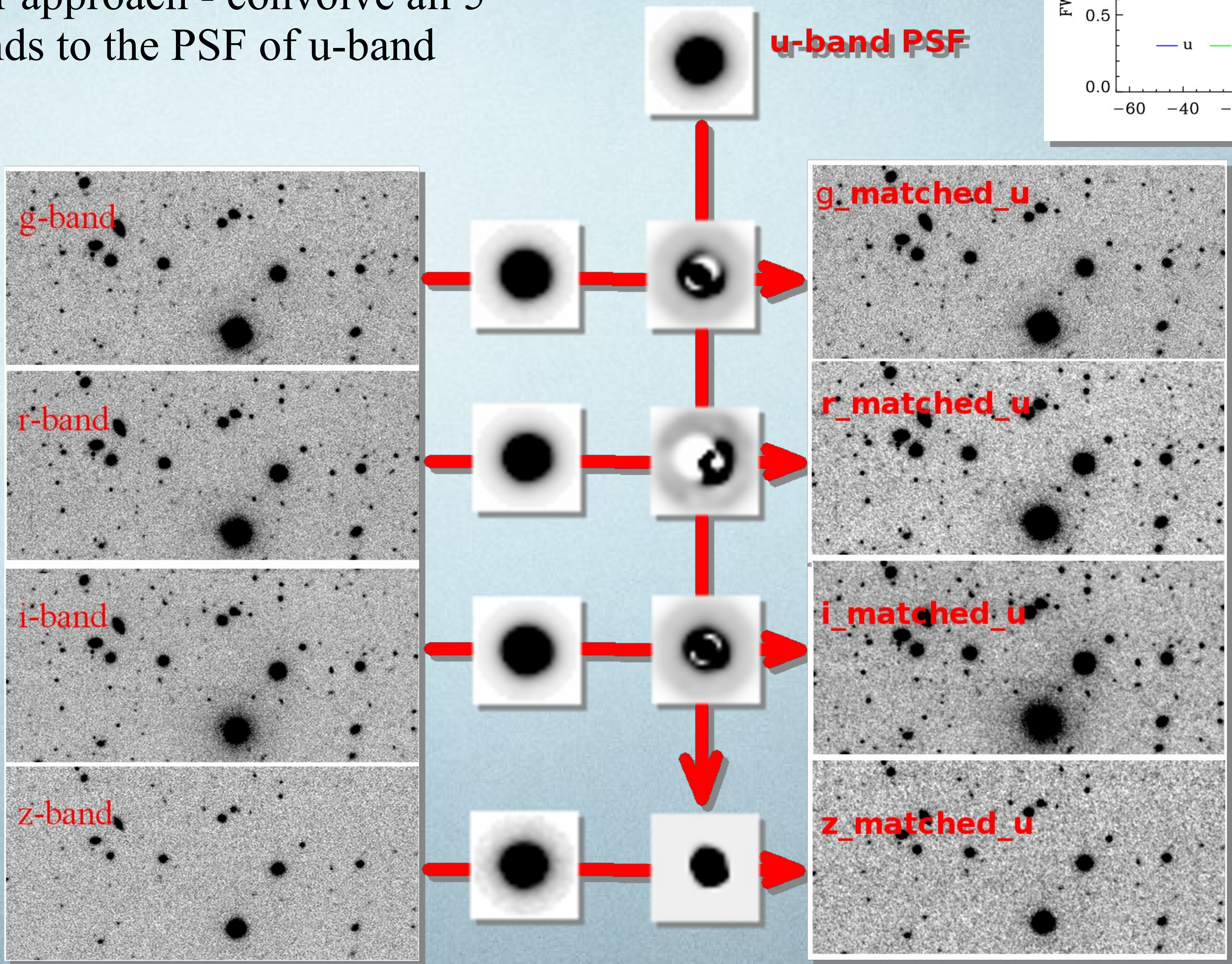


Different possible apertures in SExtractor

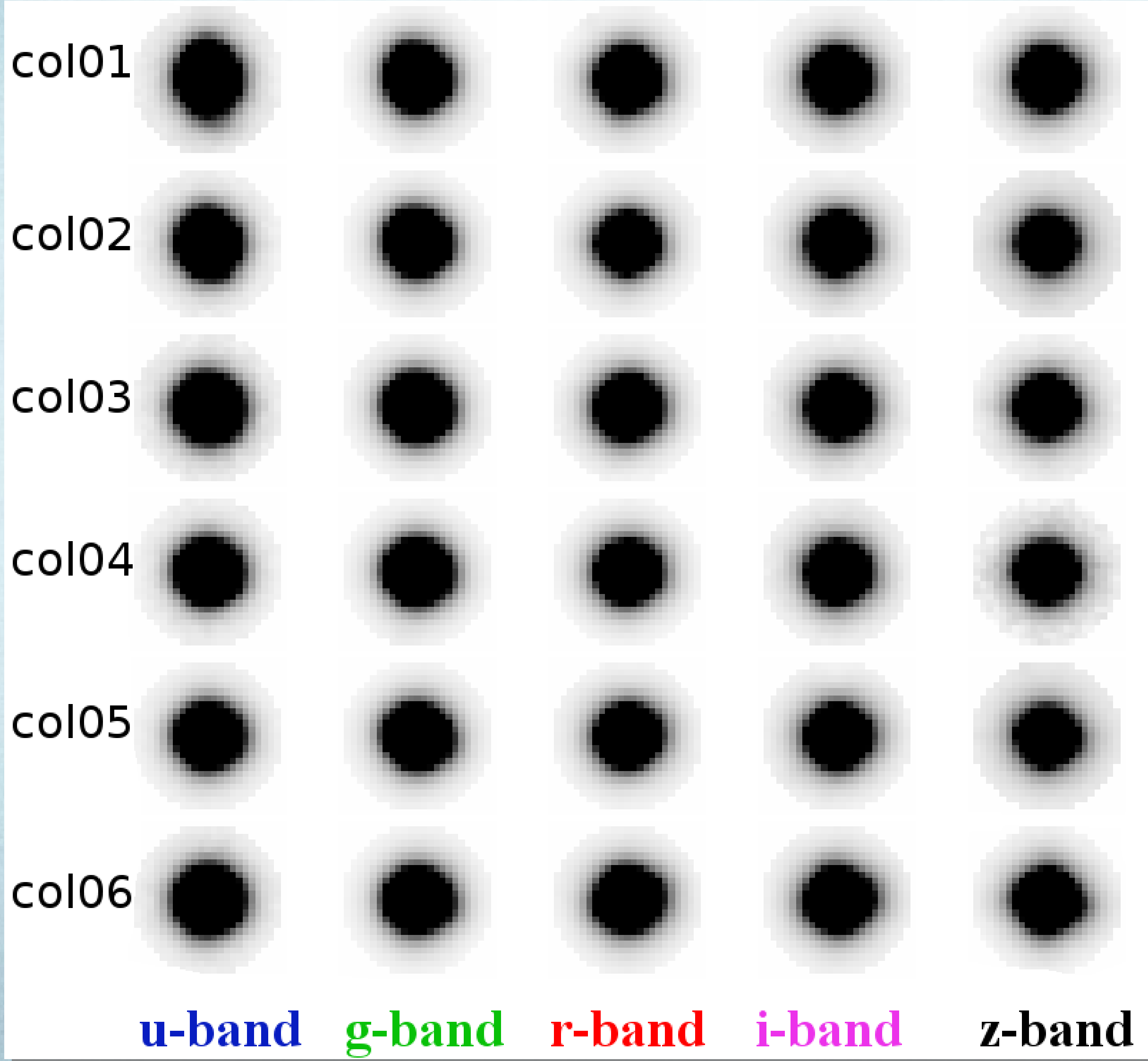
Catalog II. Optical - FWHM

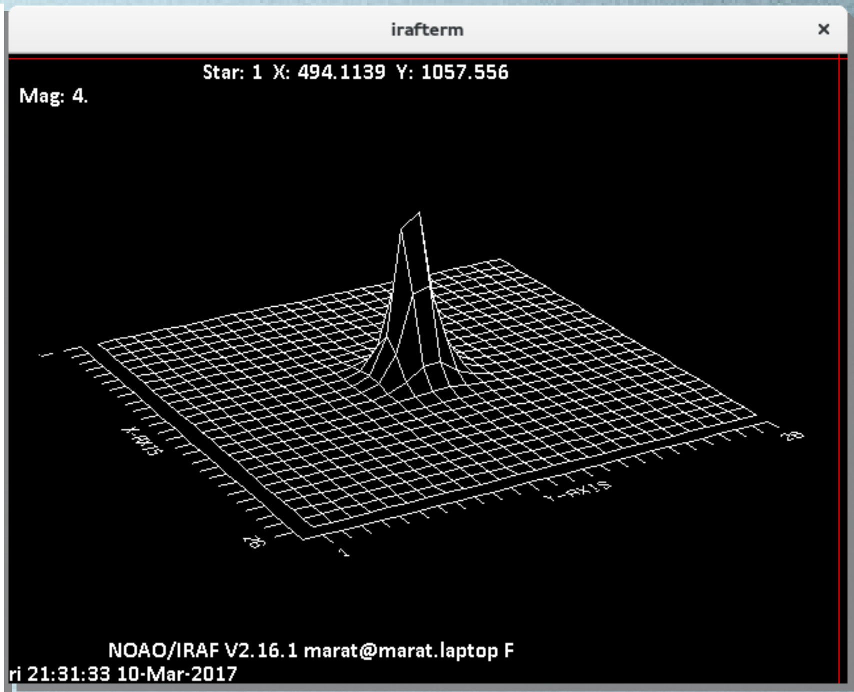


Our approach - convolve all 5 bands to the PSF of u-band



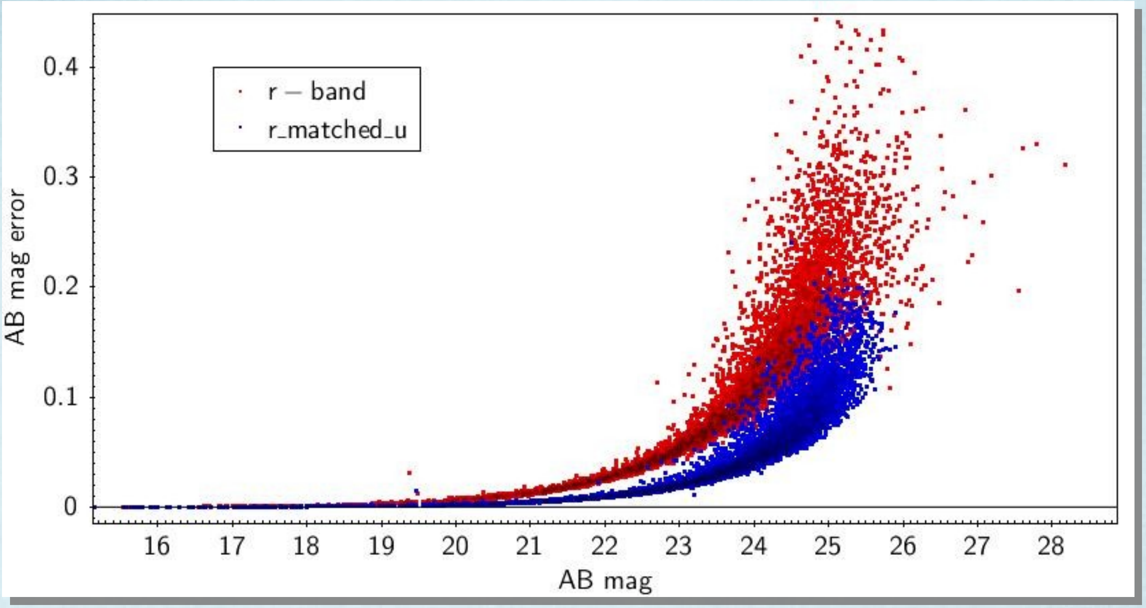
Catalog II. Optical - PSF

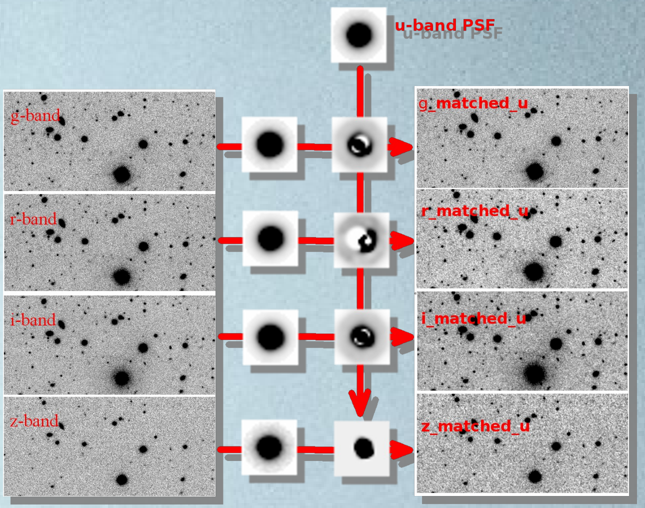


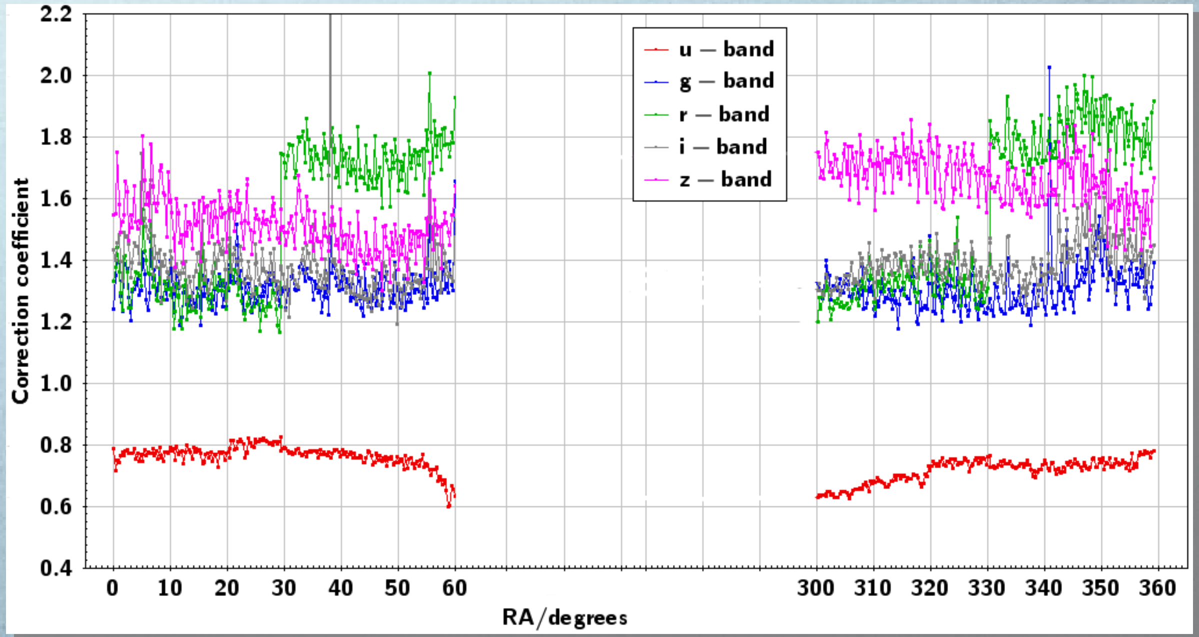


We need PSF for every SDSS image – 28,000 PSFs

Catalog II. Optical – error correction



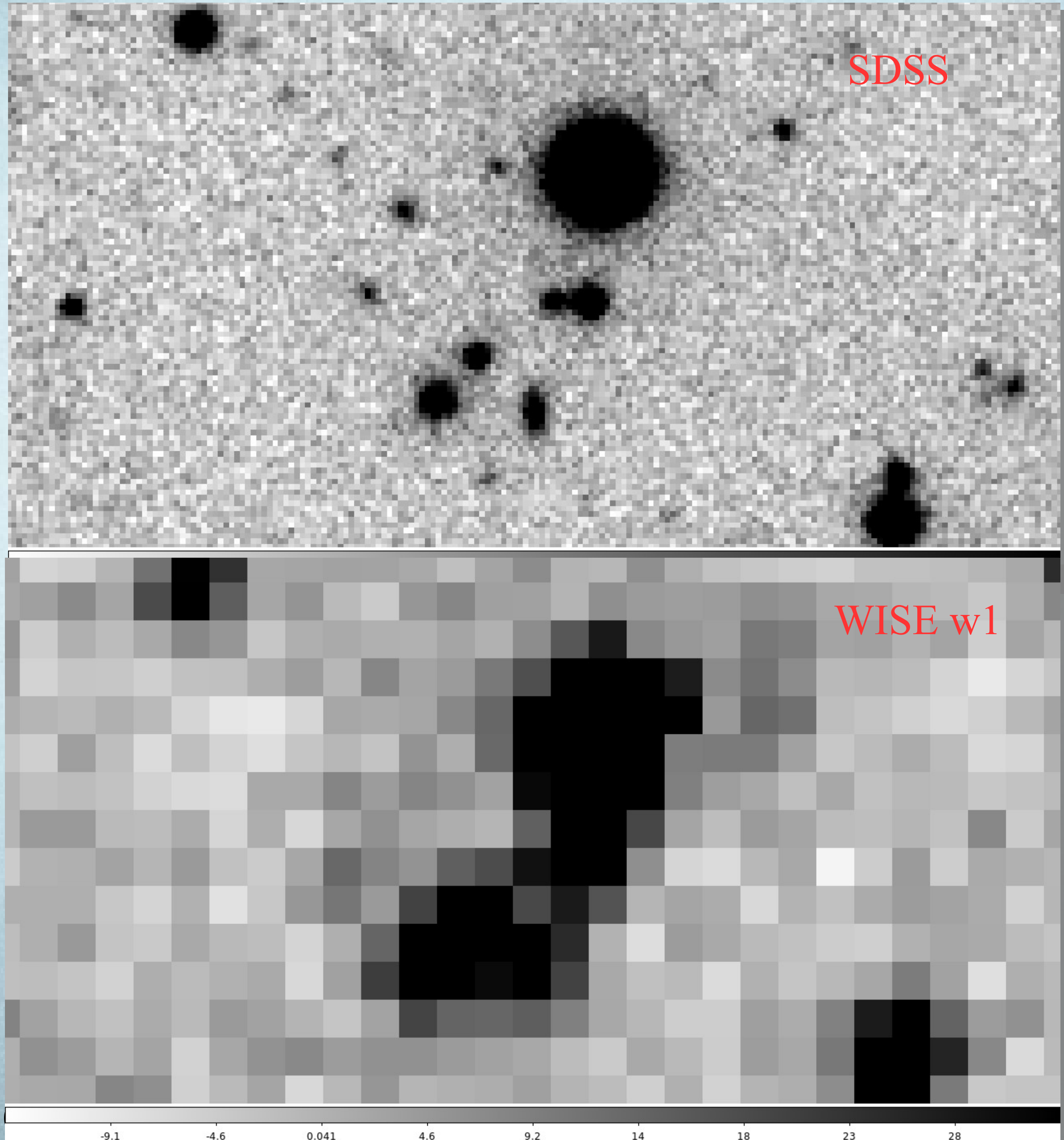




Catalog II. Optical catalog

We run SExtractor in dual mode – using r_matched_u band as detection.
This constrain astrometry and we have a base catalog – sources is counted if it is in r-band

Catalog III. Near-IR - what is the problem?

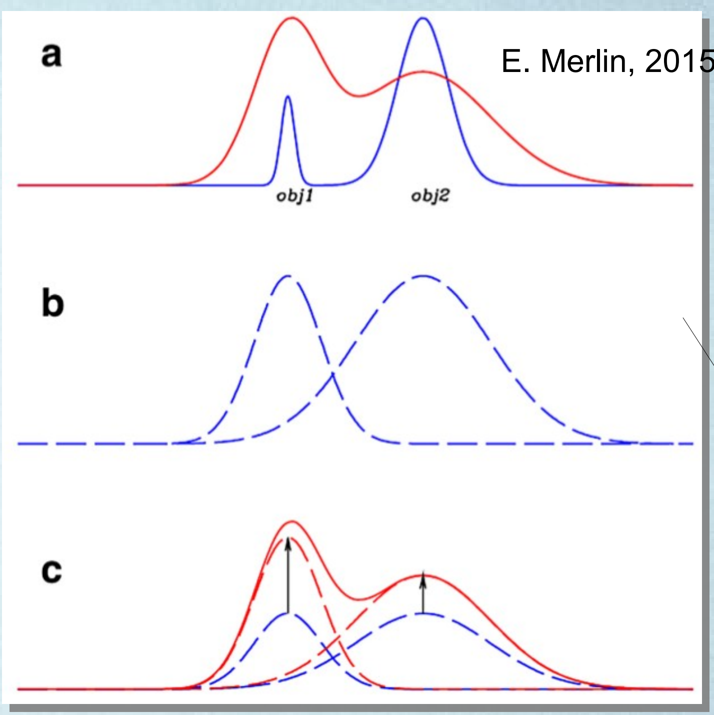


Critical factor is consistent photometry. It is challenging because the spatial resolutions of WISE is 5-6x worse than that of the SDSS.

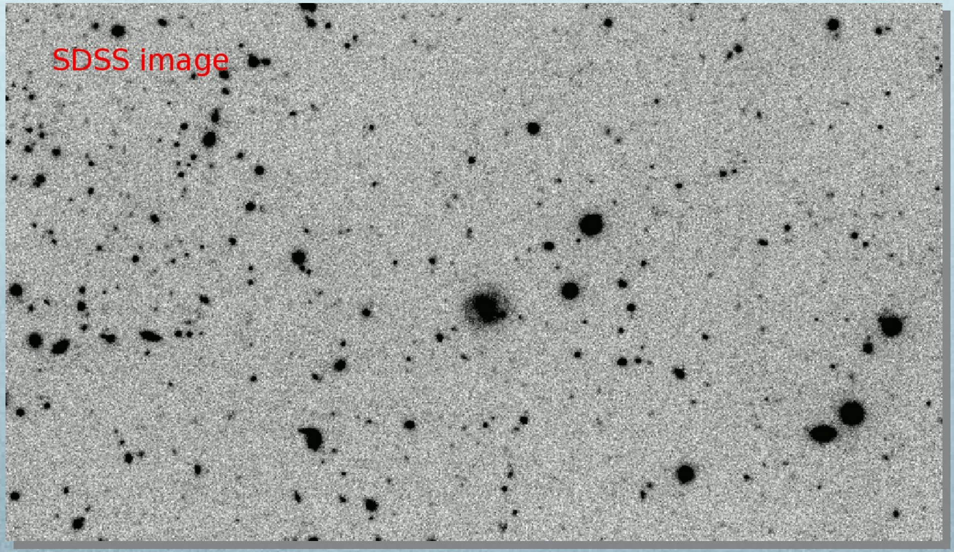
Objects detected in WISE suffer from the blending problem.

Photometric apertures appropriate for the WISE images cannot guarantee the same fraction of light being included comparing to SDSS. Such a systematic offset, which is different for every galaxy, can severely skew the SED fitting.

Catalog III. Near-IR - Template fitting

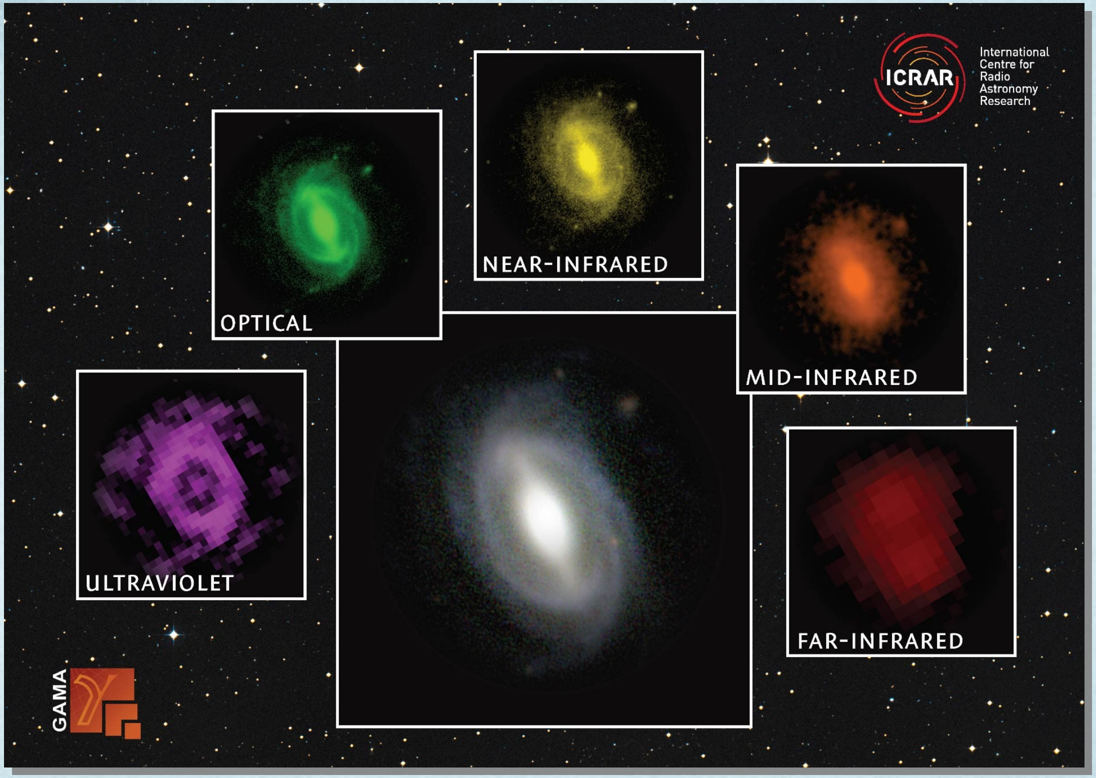


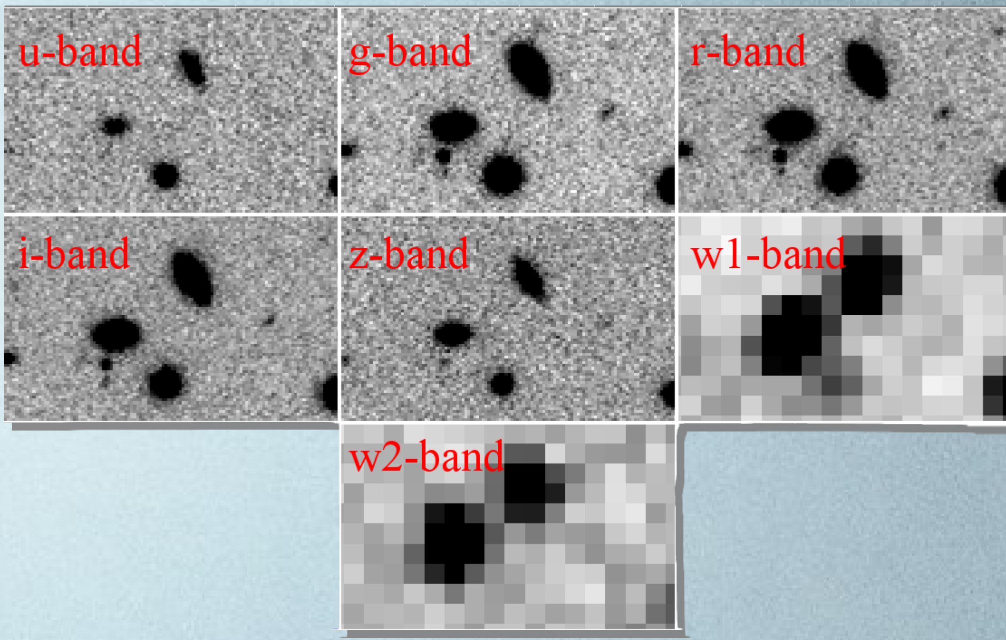
Residual images



Catalog with consistent fluxes and associated flux errors in 7 bands for 26,585,000 sources (galaxies, stars, QSO)

Catalog III. Near-IR - Assumption

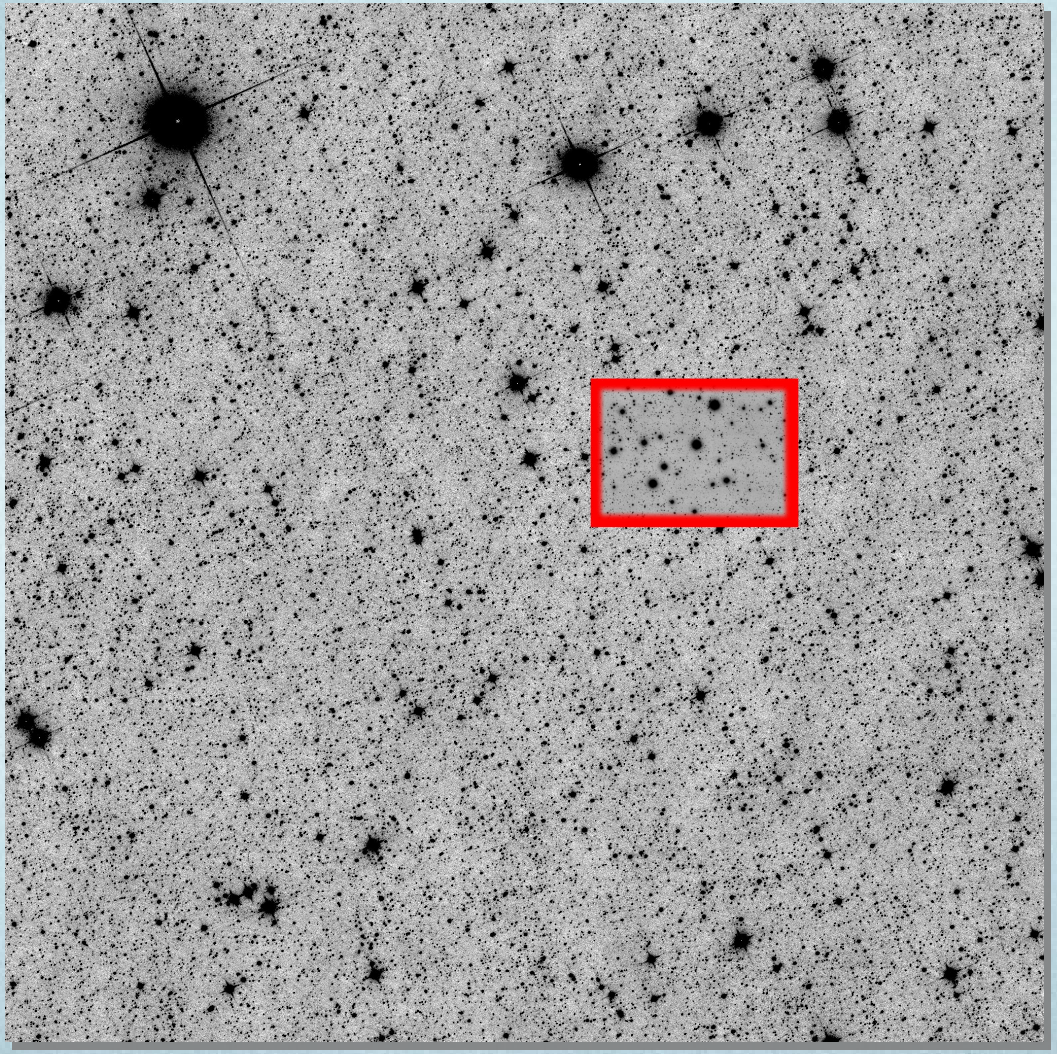




“Template fitting” technique suggests that galaxy's morphology is the same in high-res and low-res images. Generally speaking, this is not correct, and we approach this issue from 2 sides:

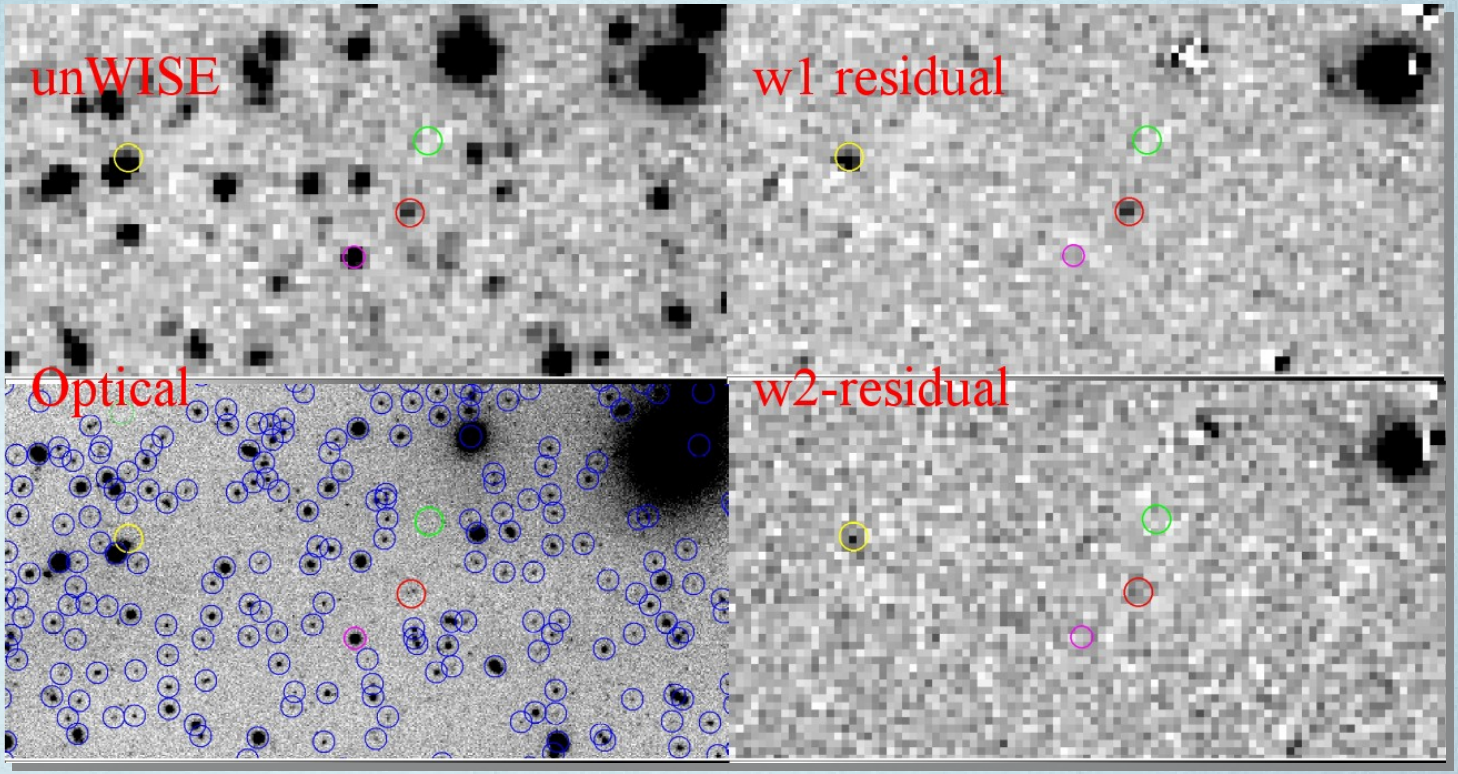
1. given the angular size of the vast majority of the sources this should not be a big concern.
2. r-band (high-res image) is a red filter, should not be any extreme variations.

Catalog IV. Multiband - almost complete



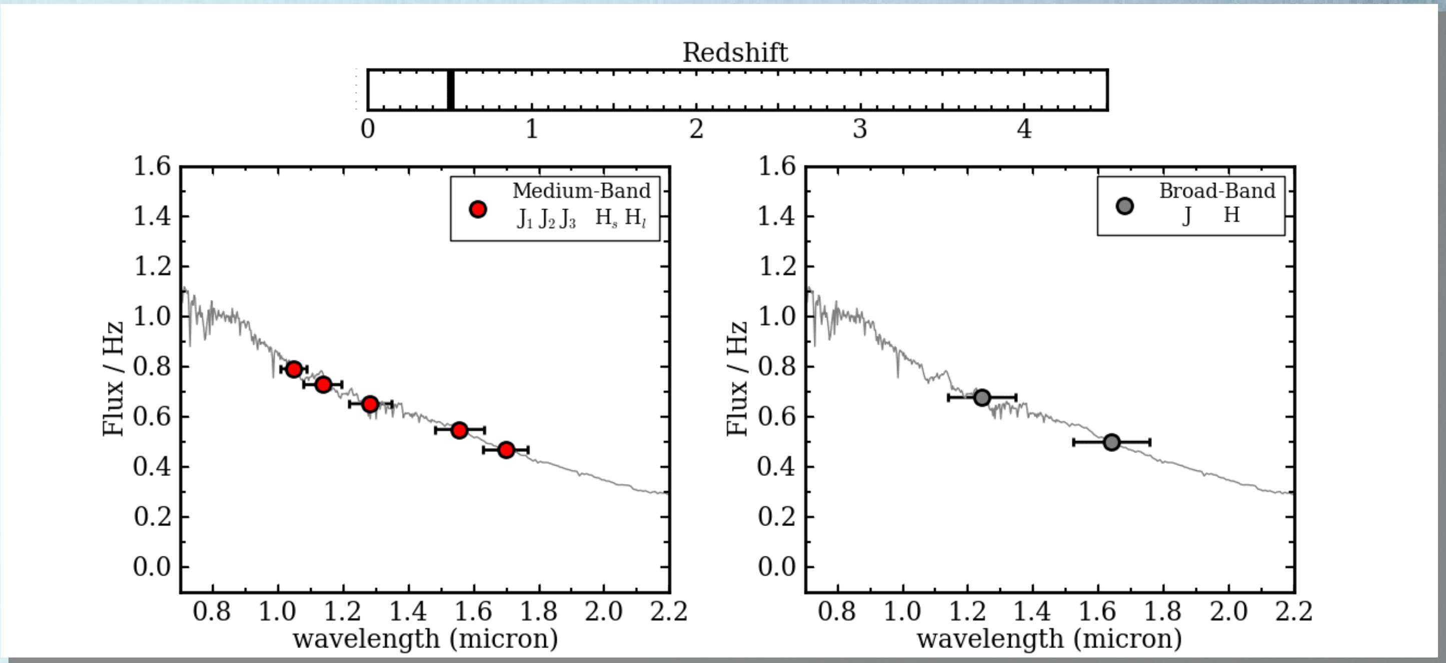
- It takes ~4 hours of CPU time to process one image as small as 253 sq.arcmin in one band (w1 or w2)
- There are 5556 images per band
- We use MU Lewis computational cluster to speed up my graduation
- High-Performance Computing is a shared cluster accessible to researchers at the University of Missouri

Catalog IV. Multiband - complete

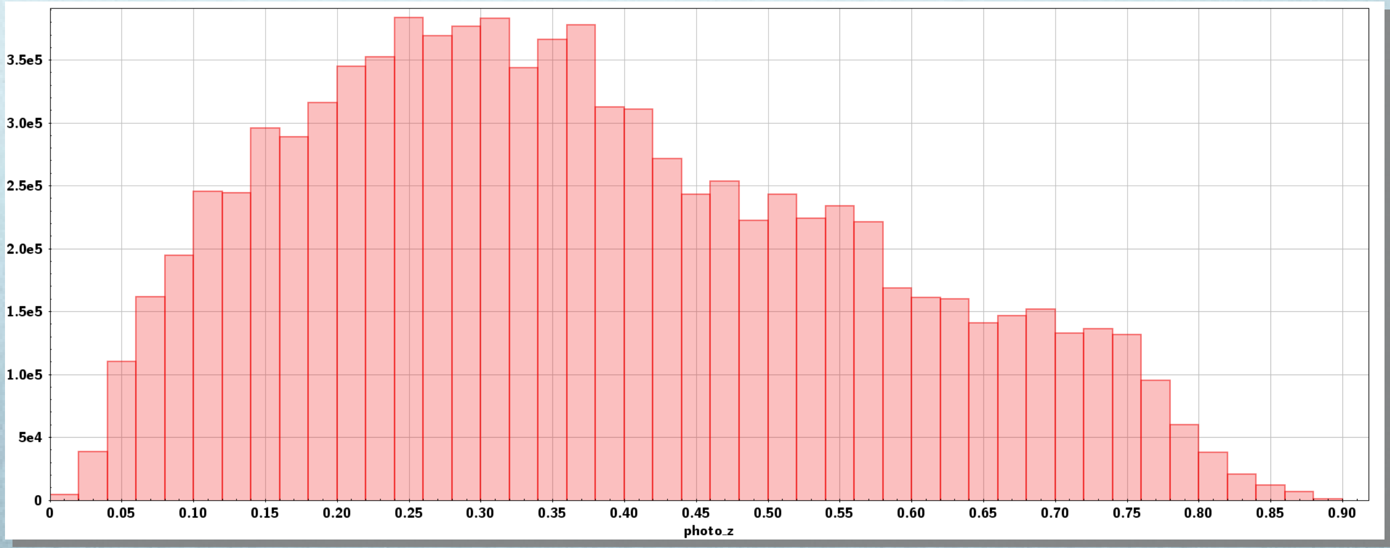


- Pixel values of "cleaned out" sources are stored in output catalogs.
- We match optical and near-IR catalogs by the source number
- Construction of a set of 26,585,000 sources with robust fluxes in 7 bands is complete
  - Not every source necessarily has fluxes in all bands

SED fitting I. Photometric redshifts



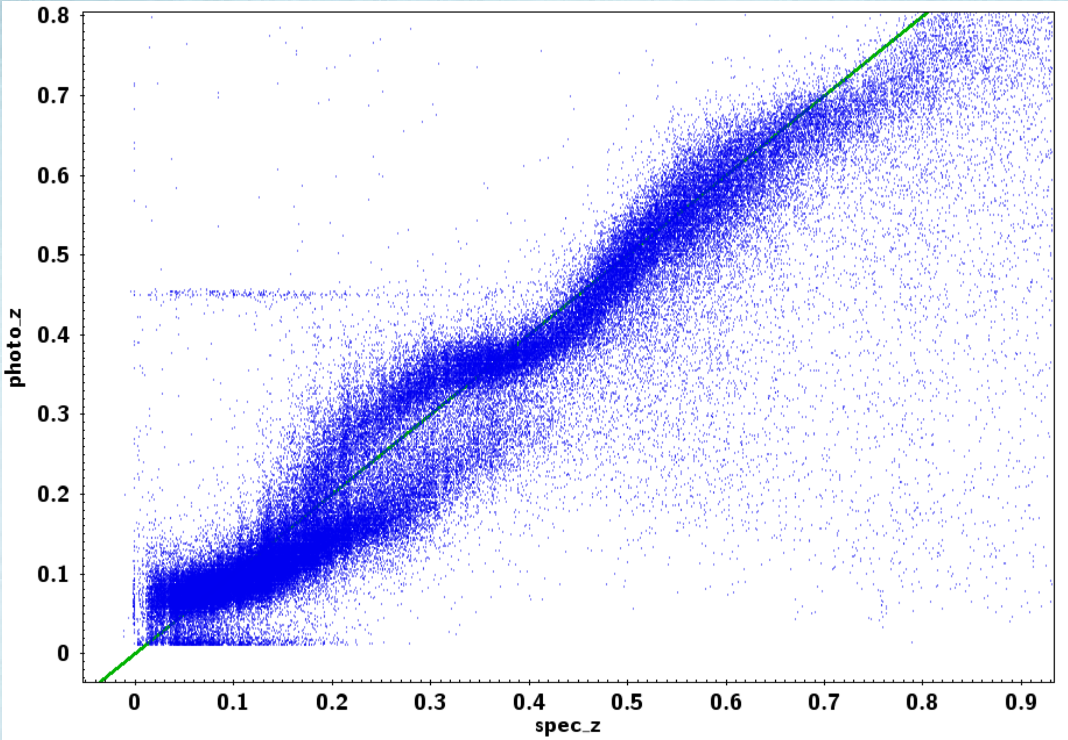
Adam Tomczak, ZFOURGE



Histogram of photometric redshifts

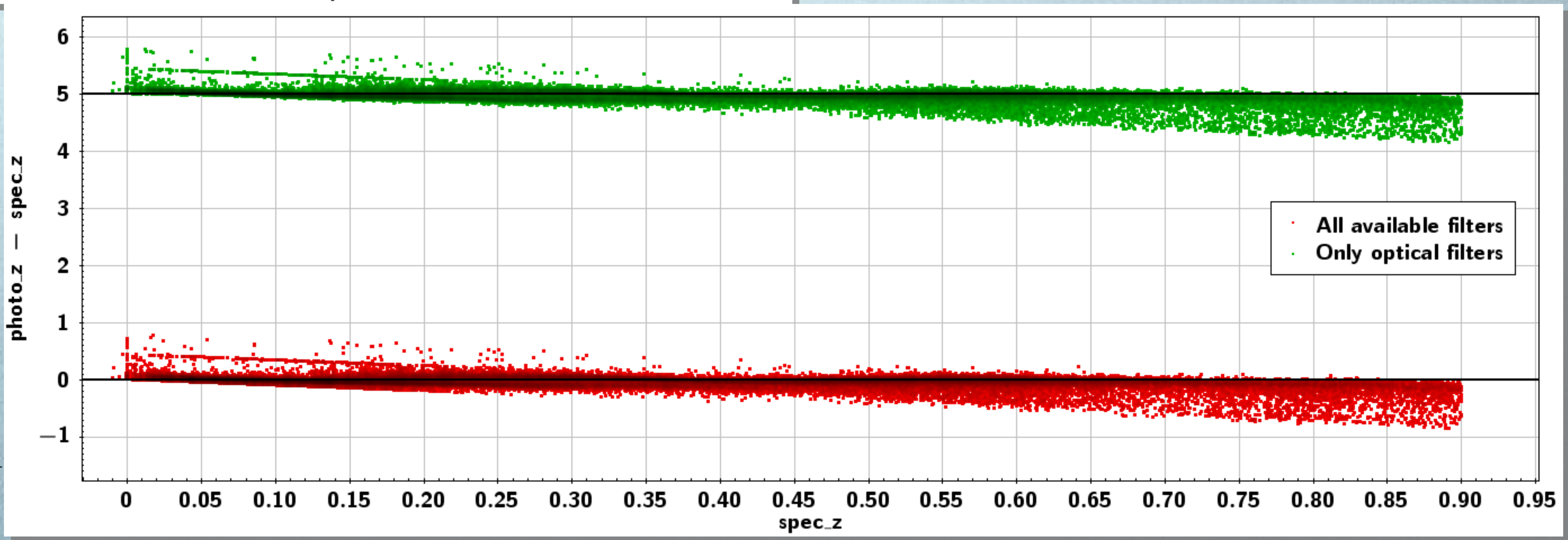
Spectroscopic redshift is a golden standard – we can test and tune our parameters against the true solution.

SED fitting I. Photometric redshifts

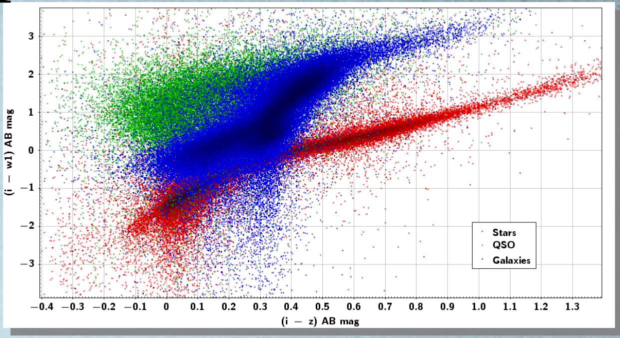


EAZY (Brammer, van Dokkum & Coppy. 2008) – SED fitting code that computes photometric redshift extremely fast.

Control sample – 270,000 SDSS DR14 galaxies with spec_z

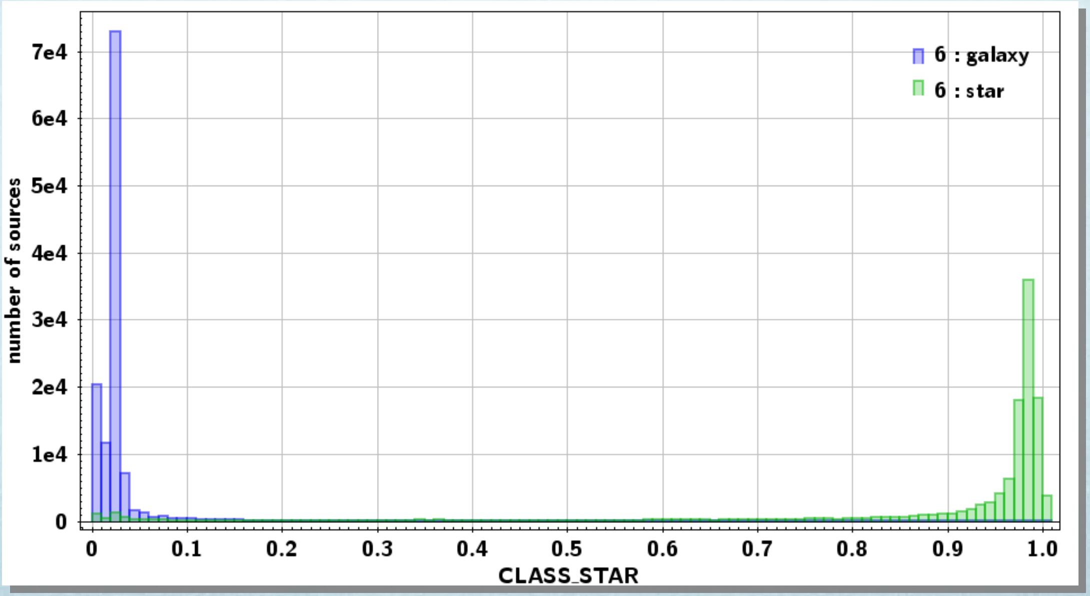


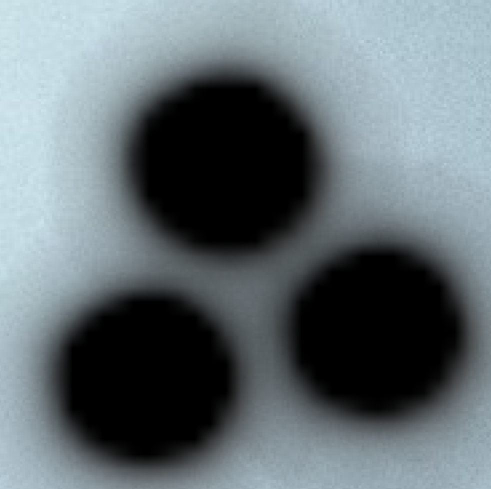
Catalog V (!) Star-galaxy separation



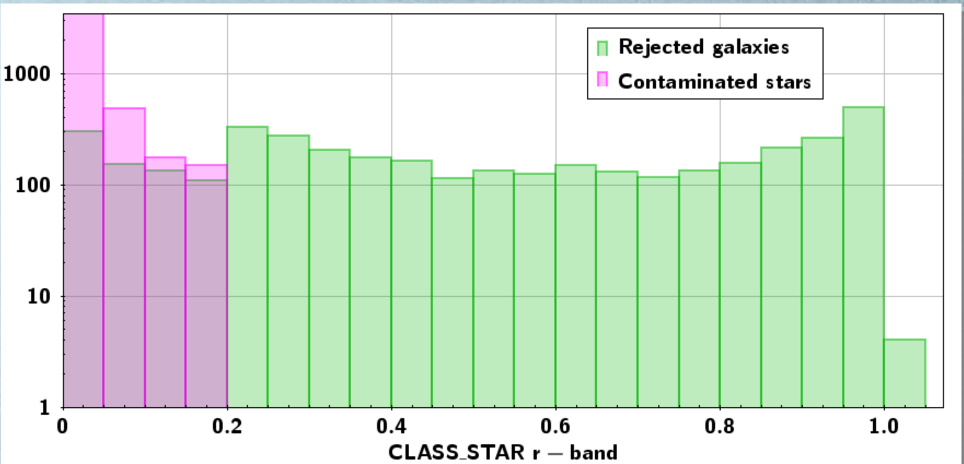
Default configuration file for SExtractor 2.8.6
#------------------------ Star/Galaxy Separation ---------------------------

SEEING_FWHM 1.5 # stellar FWHM in arcsec
STARNNW_NAME default.nnw # Neural-Network_Weight table

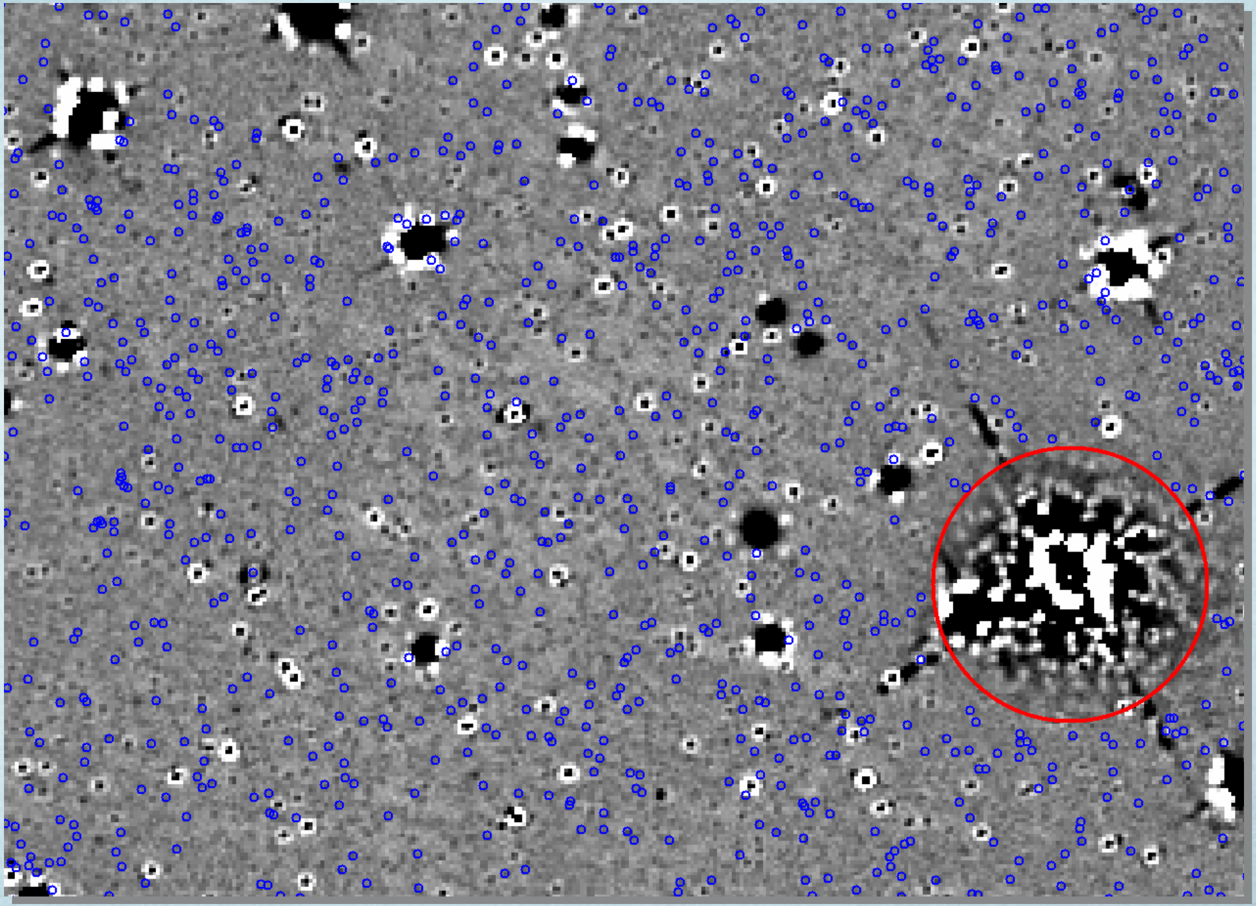




9,340,700 Galaxies with ~2% contamination by stars and QSO



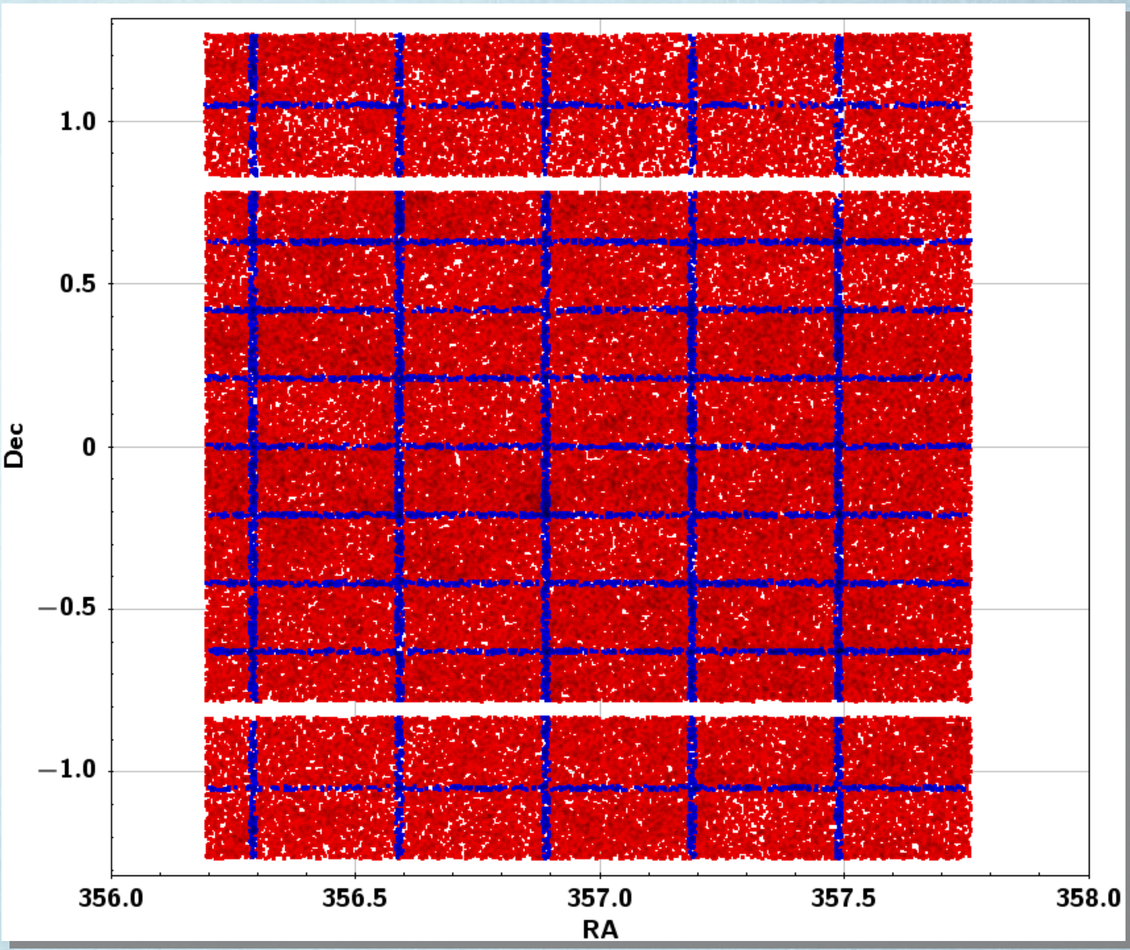
Catalog V. Masking bright/saturated objects



700 masked regions in Stripe 82:
* Smithsonian astrophysical observatory star catalog
* Bright IR Star Compilation (BSIRC) R. Tam and C. Xu - IPAC
* 300 regions added after visual inspection

Final numbers before we start SED fitting:
* Total area – 288.212 deg^2
* Total number of galaxies – 9,294,705

Catalog V. Remove duplicate sources



Final numbers before we start SED fitting for mass estimation:

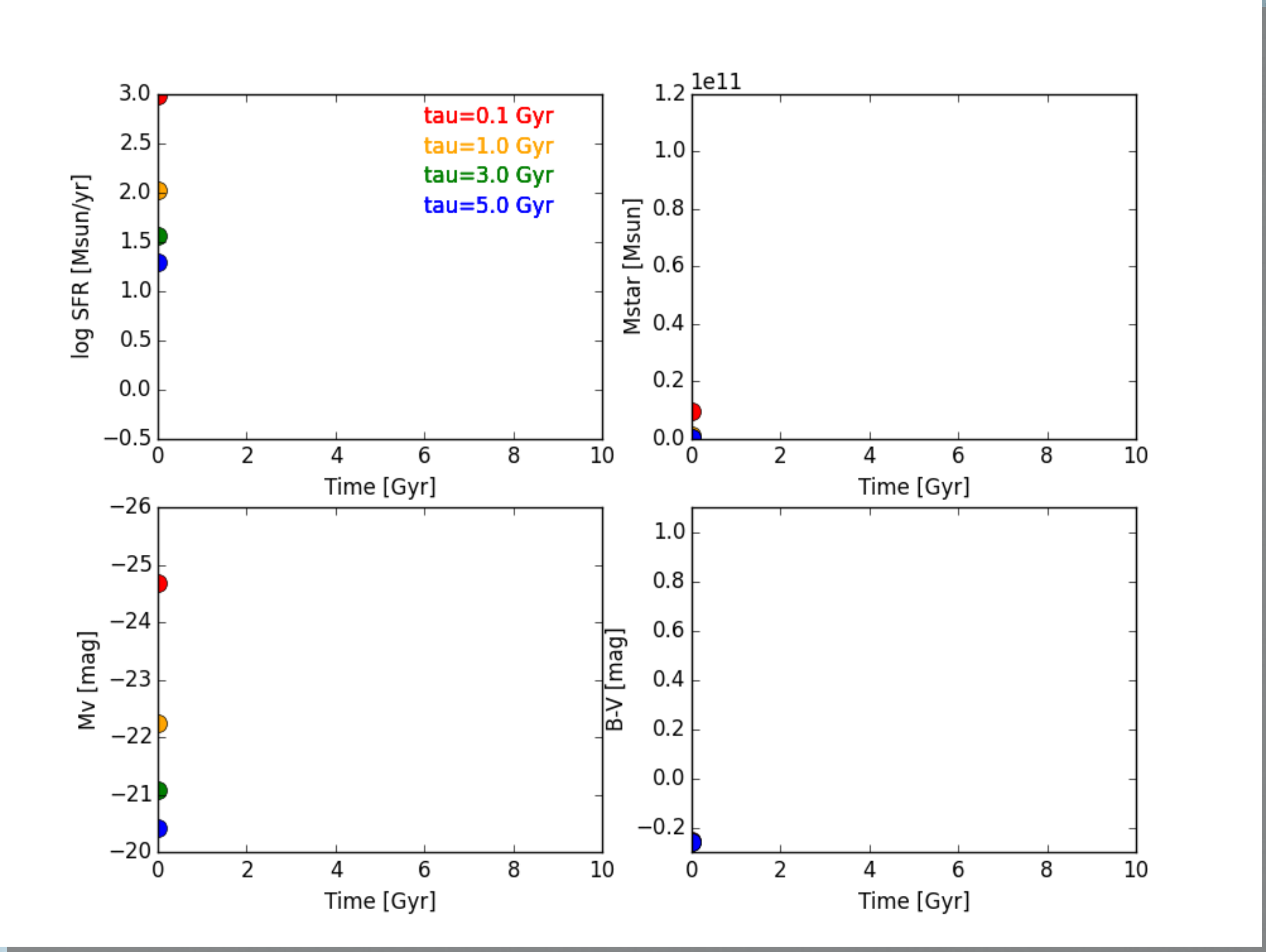
* Total area – 288.212 deg^2

* Total number of ***galaxies*** – 9,061,068 – largest sample of galaxies with consistent fluxes in optical and near-IR

Back to SED fitting II. Models for mass estimation

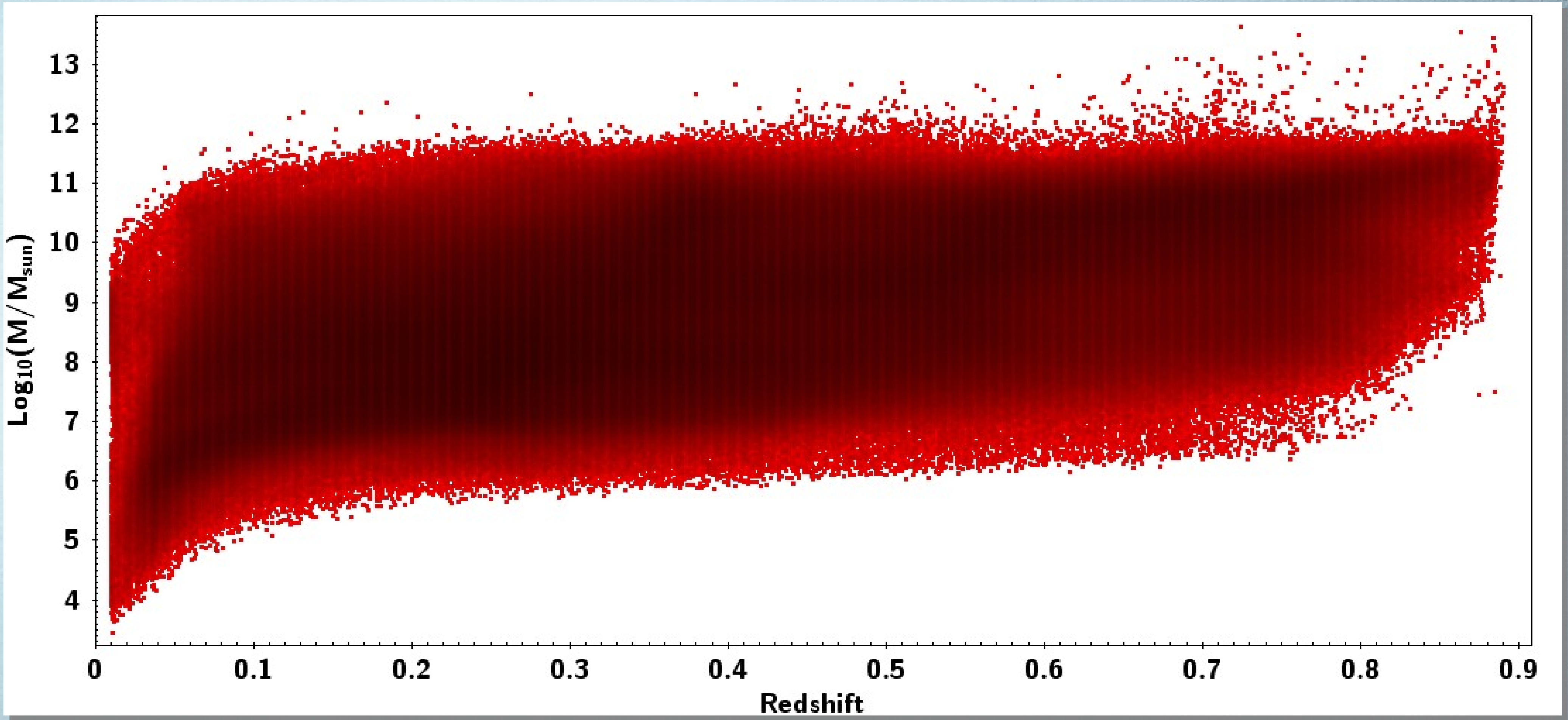
Describe our set of models:

BC03
Chabrier IMF
Calzetti attenuation law
Exponentially declining SSP
Solar metallicity



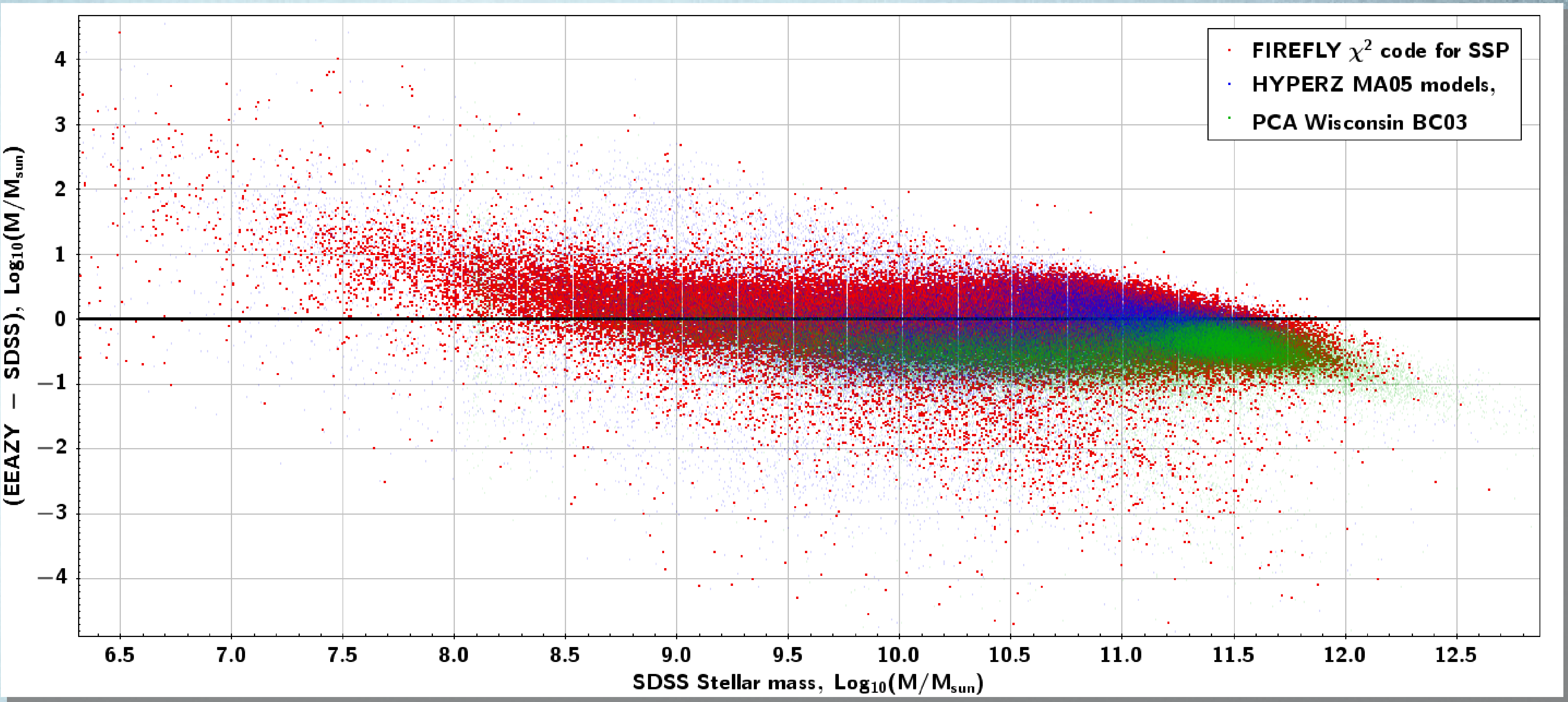
One of the parameterization of star formation history would be an exponentially declining star formation rate, with different timescales: SFR(t) ~ e-(t/tau) where tau is left as a free parameter. Animation shows galaxies with four different star formation histories (different tau) that evolve differently in SFR, mass, magnitude and color

SED fitting III. Stellar masses



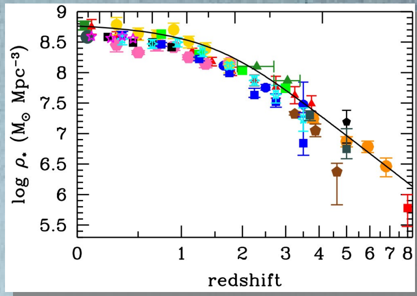
Stellar masses for the whole sample of galaxies. We constrained redshift range, but not the mass. Normal stellar mass range for galaxies is 7 < Log10(M/Msun) < 12

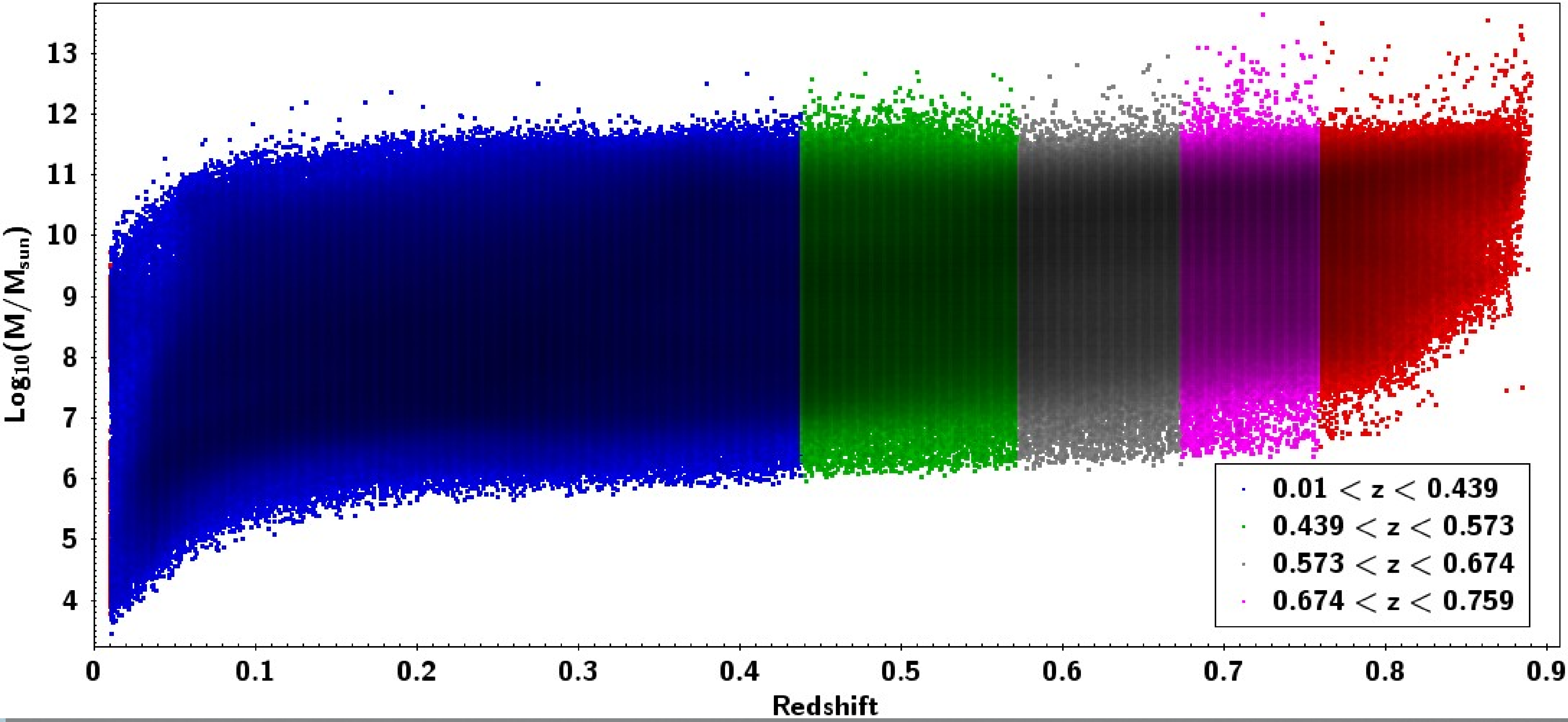
SED fitting III. Compare stellar masses



Comparing our data to other group's estimates. No golden standard here – stellar mass is model dependent

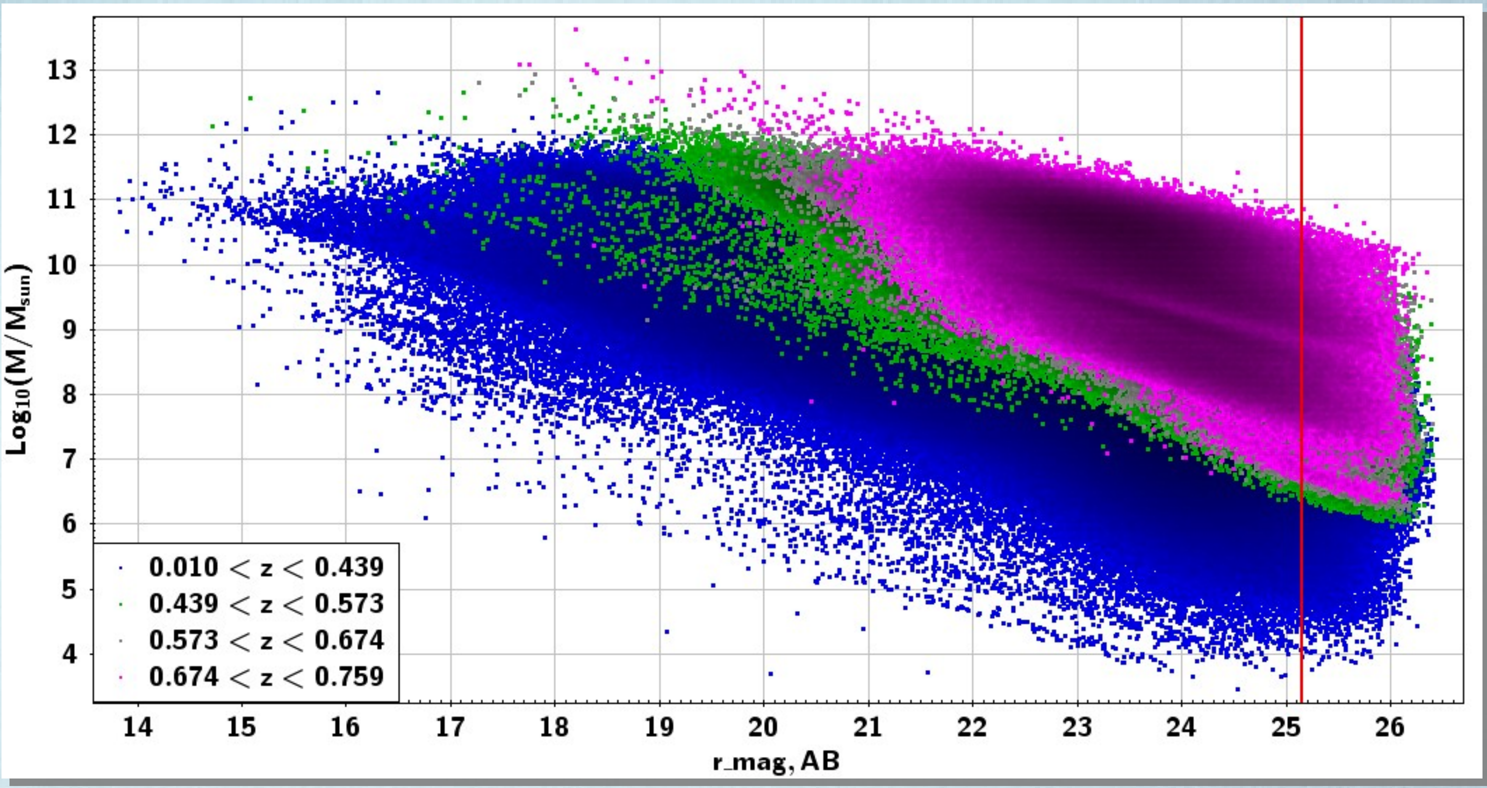
GSMD I. Redshift binning



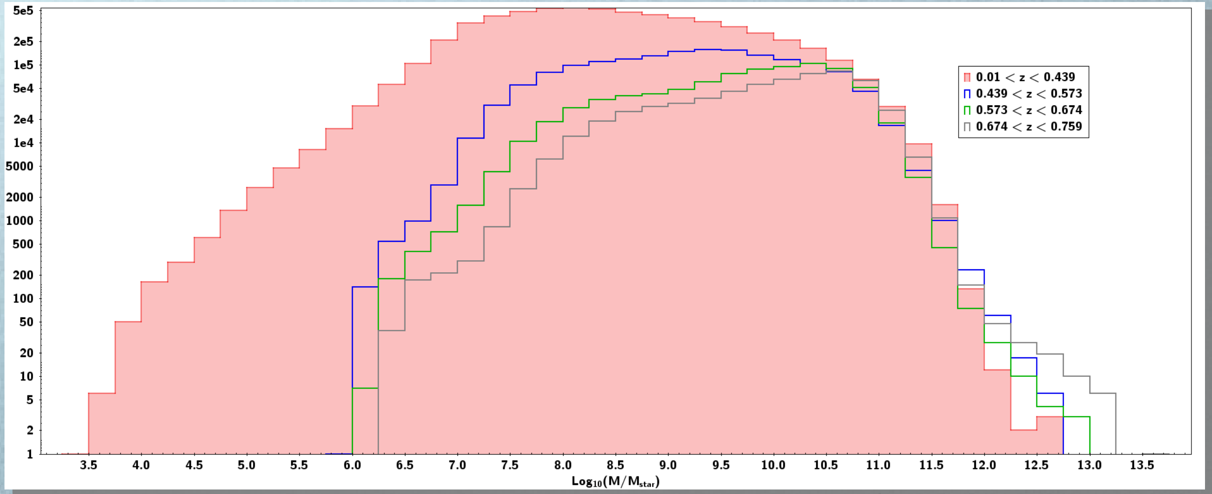


We take equal size comoving volume – 20 Gpc^3.
Red points – sample is highly incomplete and will bias our estimates.

GSMD I. A few words about mass



Red line – 5 sigma detection limit in r-band. We have a lot of sources beyond it – not necessarily wrong, because it may be well detected in other bands. We don't see lot of nonphysical masses at these magnitudes



GSMD II. Our results

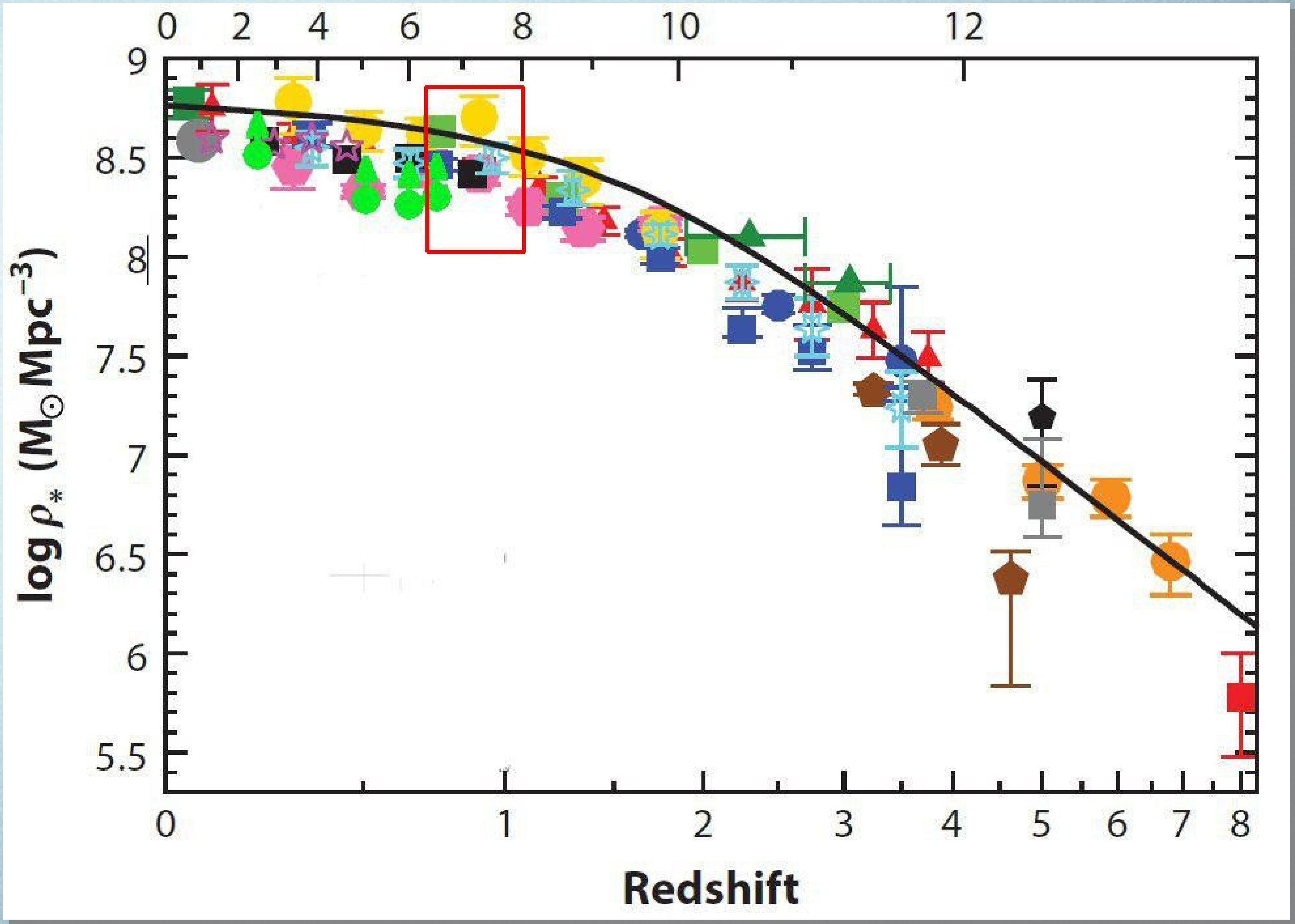
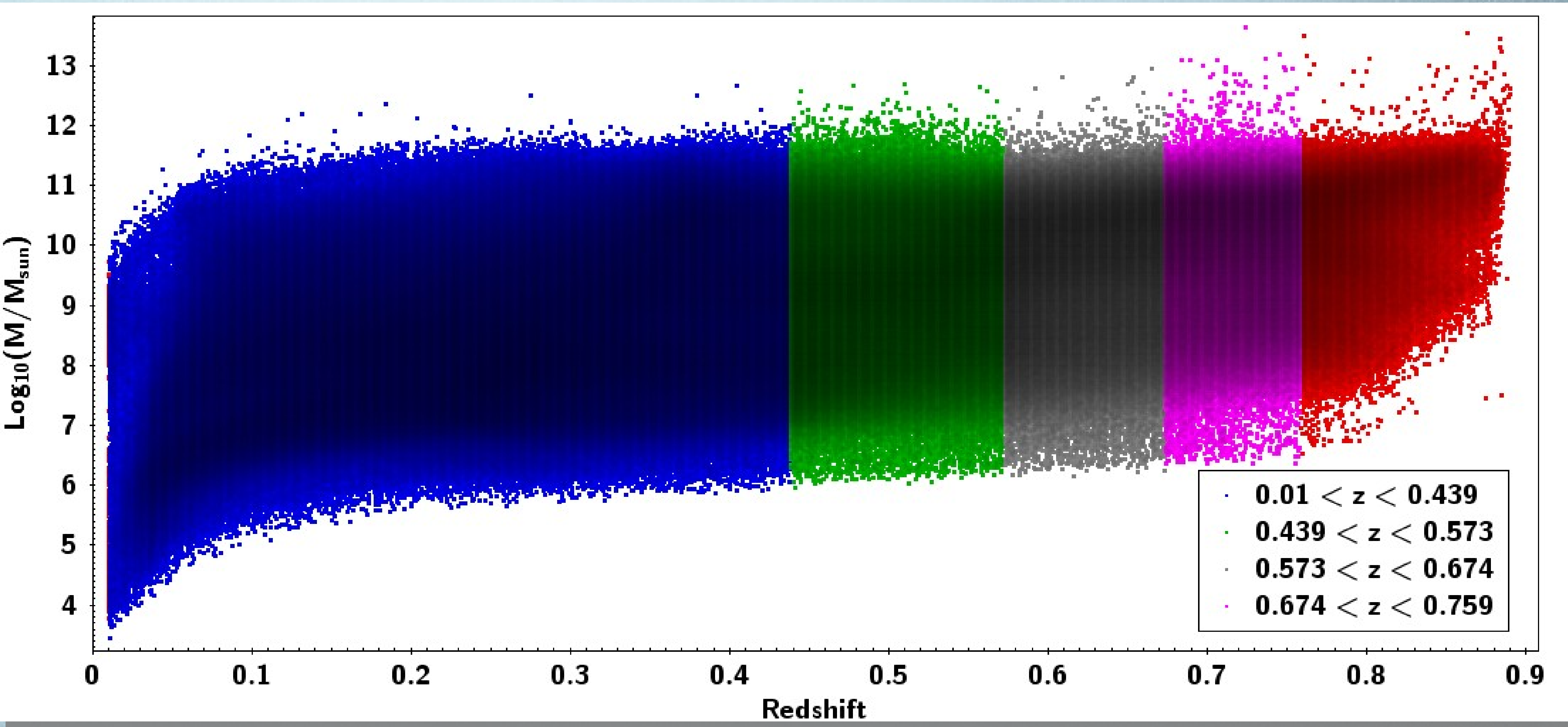


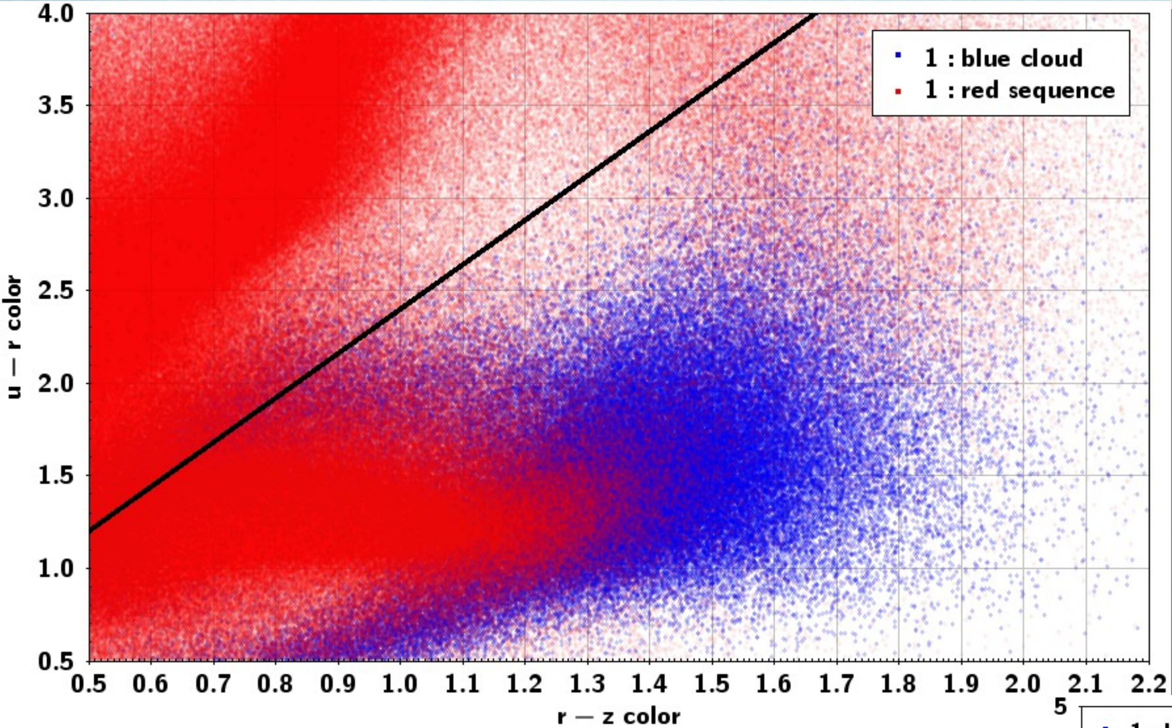
Table with my values for density from the thesis, explain why we only have low-limits and the “wiggle” around z~0.7.

GSMD III. A few words about completeness



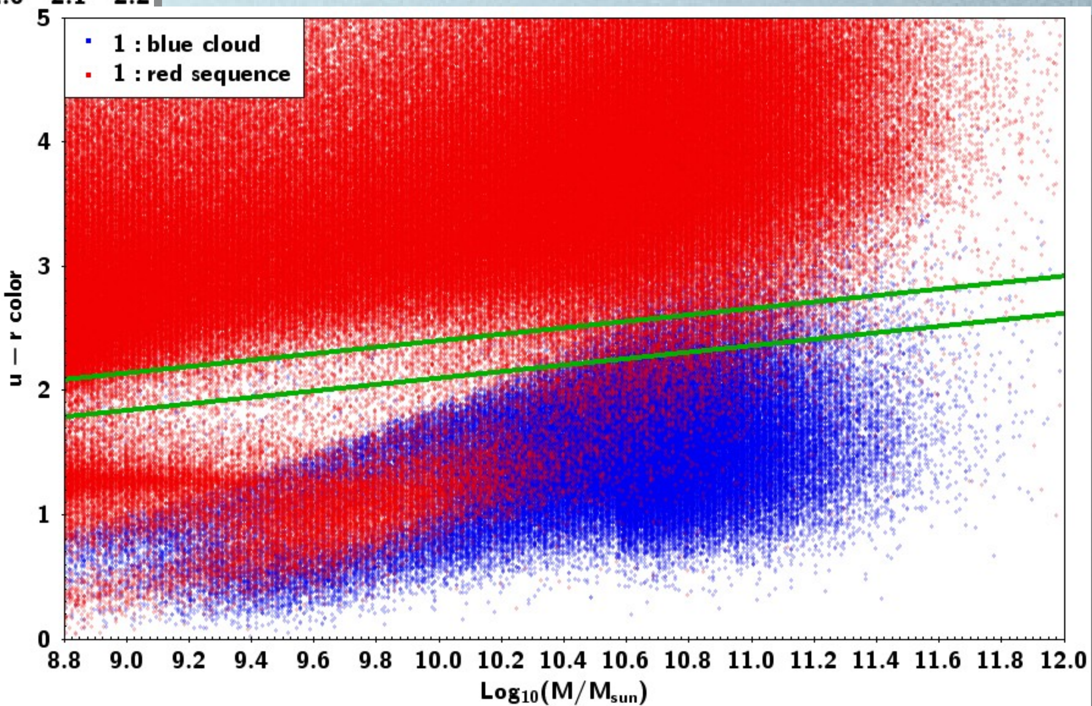
We are incomplete in the low-mass region, this needs to be corrected (somehow)

GSMD III. Blue cloud and red sequence



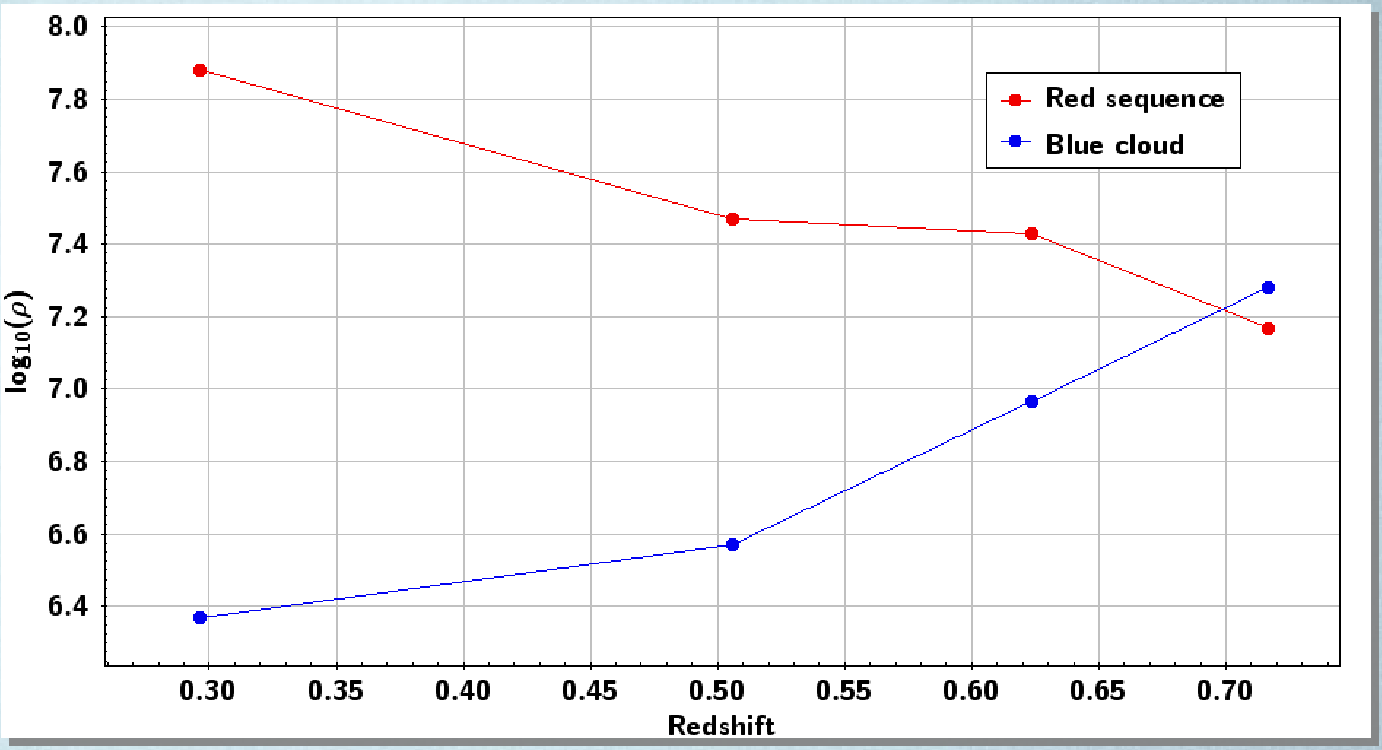
$$\lambda_{observed} = (1+z)\cdot\lambda_{emitted}$$

	λ, nm @z=0	Color @z=0	λ, nm @z=0.7	Color @z=0.7
u-band	355.1	UV	603.7	orange
g-band	468.6	blue	778.6	red/IR
z-band	893.1	near-IR	1518.3	IR



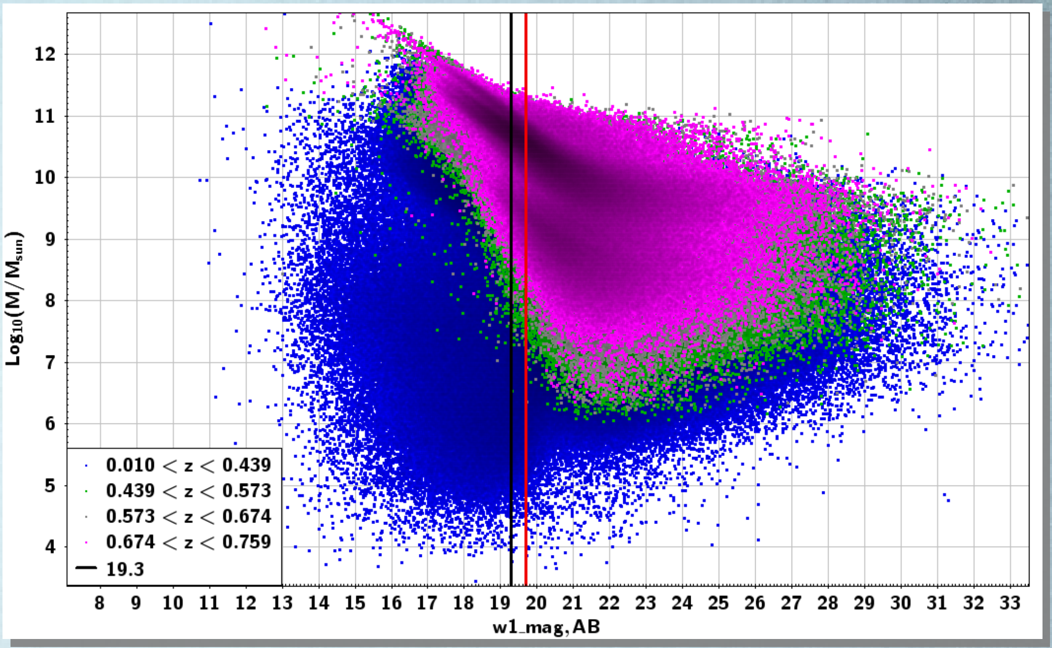
Colors are not in the rest frame, so for higher redshift it is not giving the bimodal picture

GSMD III. Blue cloud and red sequence



I want to plot "stellar mass vs redshift" for 2 subsamples – red and blue galaxies (as in Bell 2003) and see if I can reproduce his conclusions – all SFG tend to have the same SMD over Cosmic time, while passive galaxies have increasing SMD due to the migration of quenched galalxies to that region.

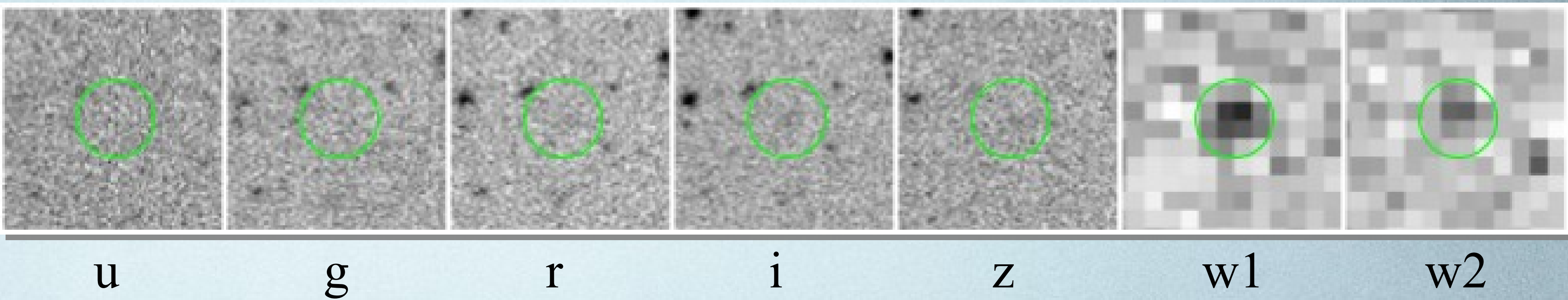
Conclusions and future work I.



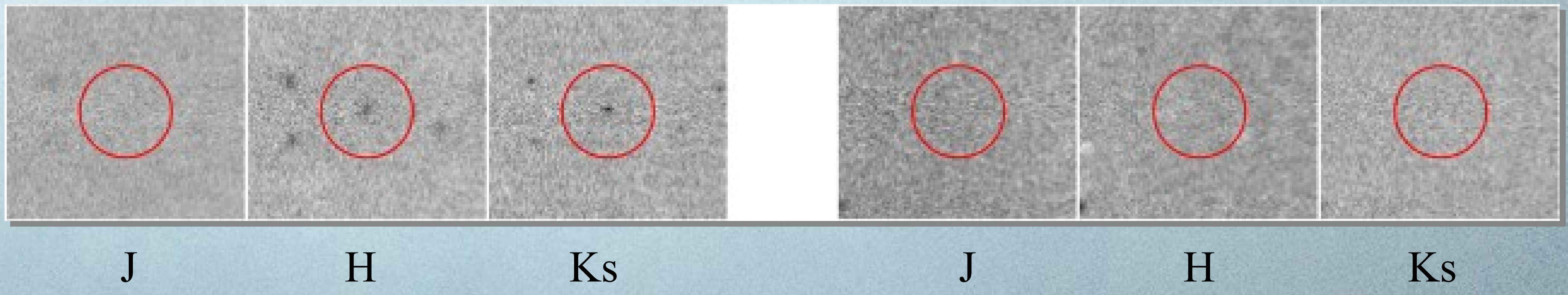
As of now 53% of my sources fall below w1-band 3 sigma detection limit. New release of WISE w1 and w2 data has been released 2 months ago – NeoWISER. Limiting mag will be 0.38 deeper and this will put another 5% of the sources above the detection limit. New data are not just deeper – by stacking images from so many years Meisner et al. Got rid of lots of artifacts and transients – detection is now more robust. It will not take long to make 480 new PSFs and run the computational cluster all over.

Conclusions and future work II. WoDrops

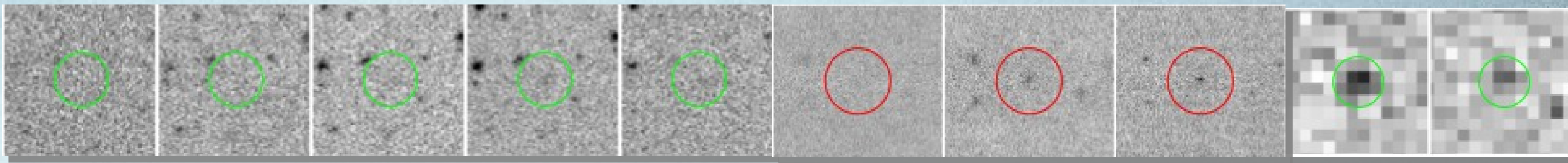
Example of WoDrop in Stripe 82

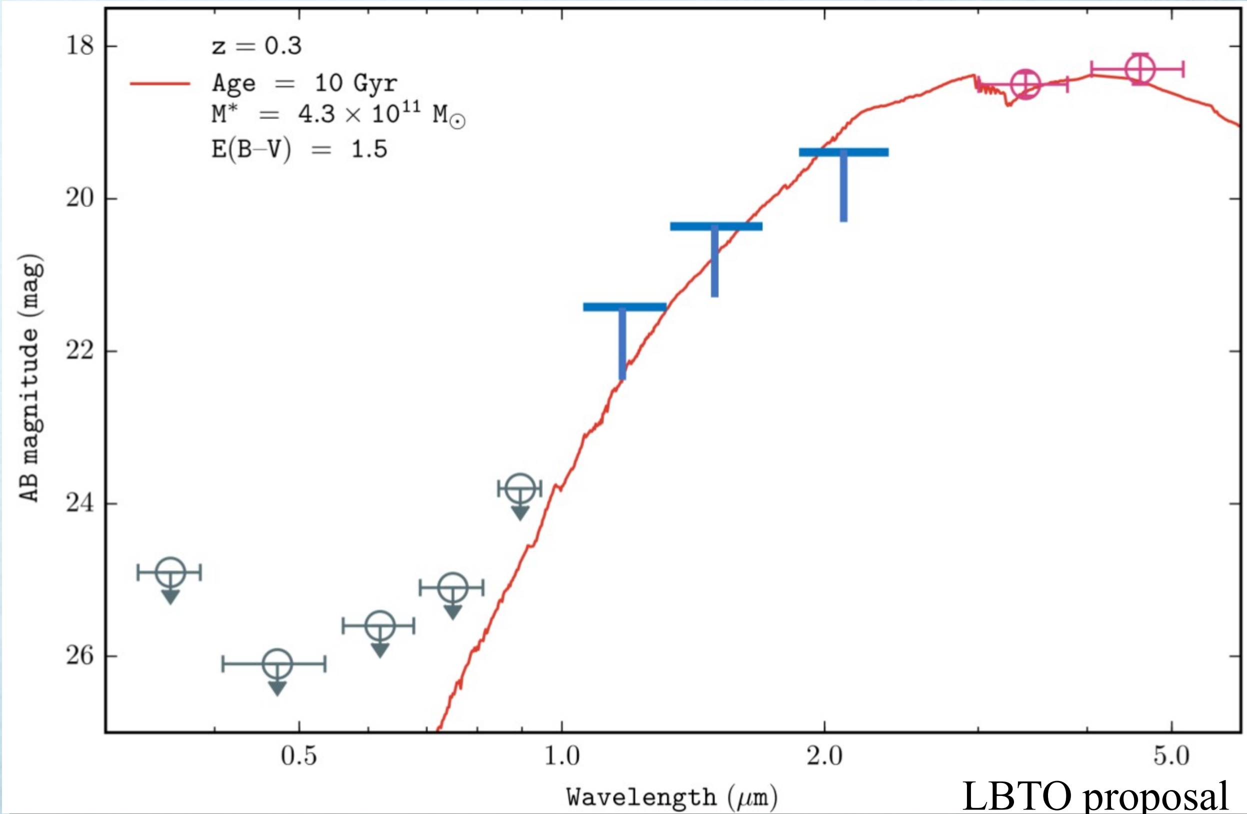


Follow up observations of two selected WoDrops with WHIRC



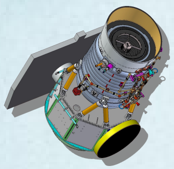
Conclusions and future work II. WoDrops



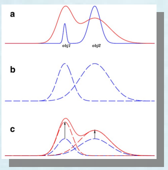


Conclusions and future work III.

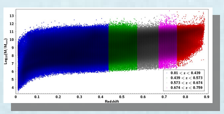
- We studied galaxy evolution over last 6 Gyr through the growth of the stellar mass density



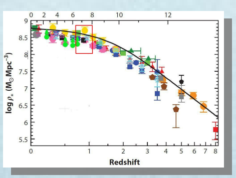
- We used deep optical data in SDSS Stripe 82 and near-IR images from WISE to construct the largest to date photometric catalog – over 9 million of galaxies



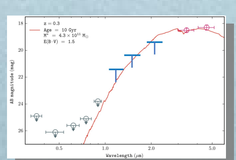
- “Template fitting” technique was used to derive consistent flux and colors in optical and IR, which has much worse resolution and suffers blending



- 7-band photometry broke color degeneracy and allowed us to derive robust masses and mass densities



- We constructed GSMD up to z~0.8 that are consistent with results of other groups and place strict constraints on the lower limit of the SMD
- We plan to continue this project with deeper near-IR data



- An interesting sub sample of sources, “WoDrops” was discovered. Its nature is still a mystery and requires follow-up observations
- This thesis will be presented at AAS meeting in Denver, June 2018