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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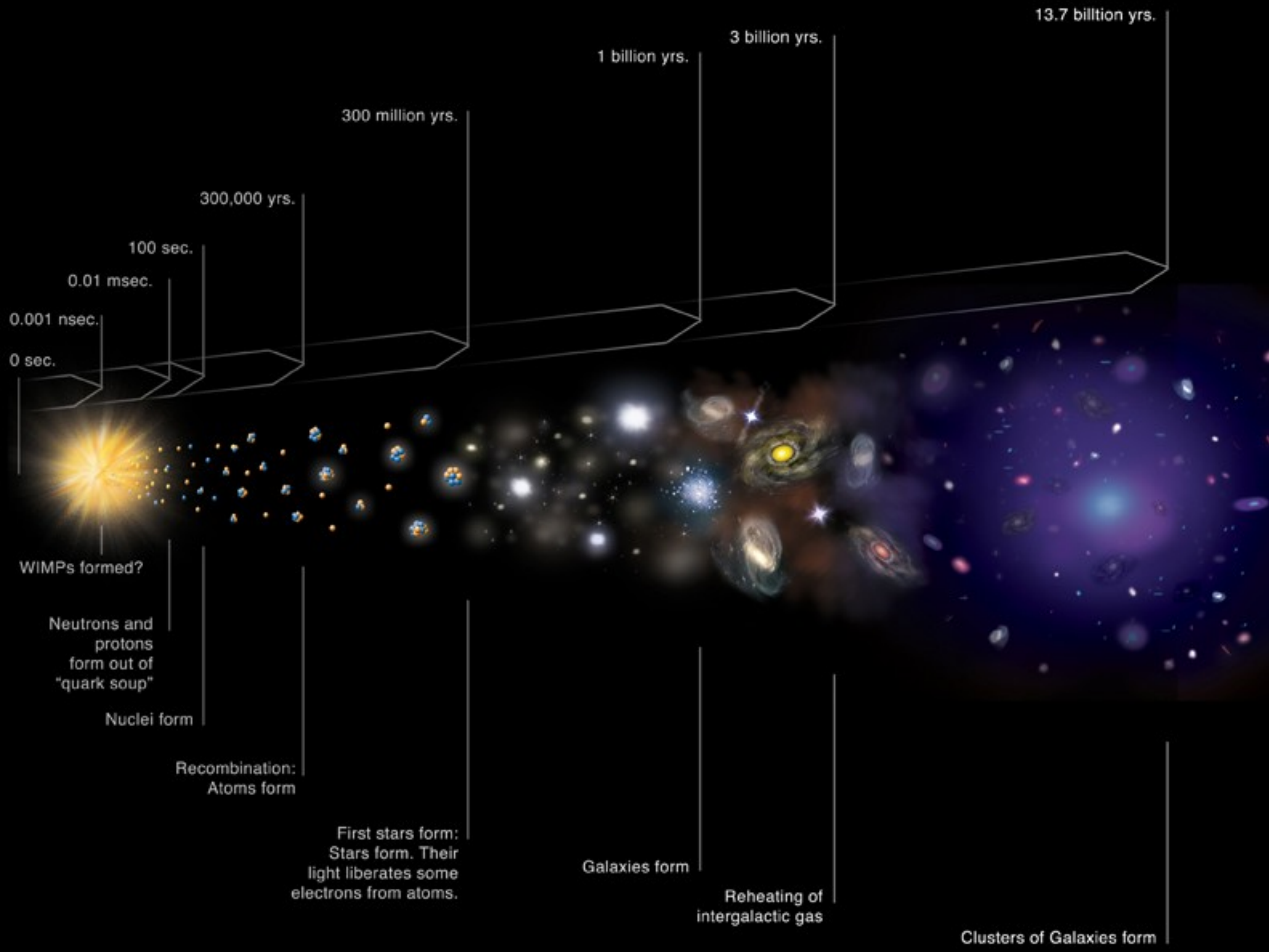
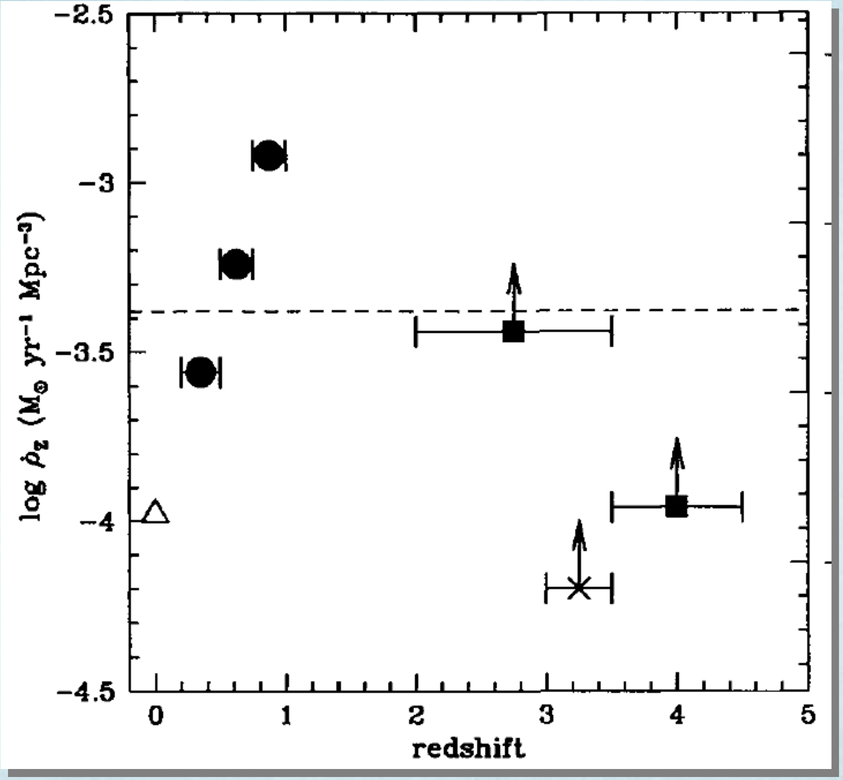

13.7 billtion yrs.
3 billion yrs.
1 billion yrs.
300 million yrs.
300,000 yrs.
100 sec.
0.01 msec.
0.001 nsec.
0 sec.
WIMPs formed?
Neutrons and protons form out of "quark soup"
Nuclei form
Recombination: Atoms form
First stars form: Stars form. Their light liberates some electrons from atoms.
Galaxies form
Reheating of intergalactic gas
Clusters of Galaxies form

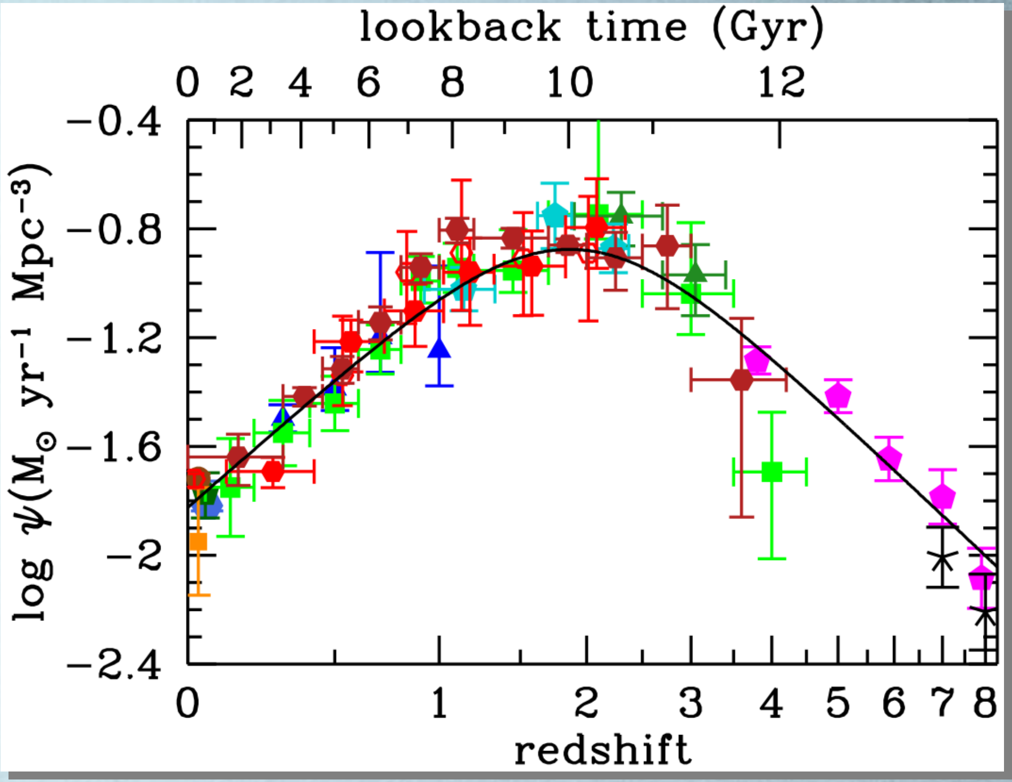
Outline

- 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
  - **Constraints on GSMD**
- Results and future work
  - Future work with the catalog
  - Subsample of WoDrops
- Conclusions

Cosmic Star Formation History



Madau et al. 1996



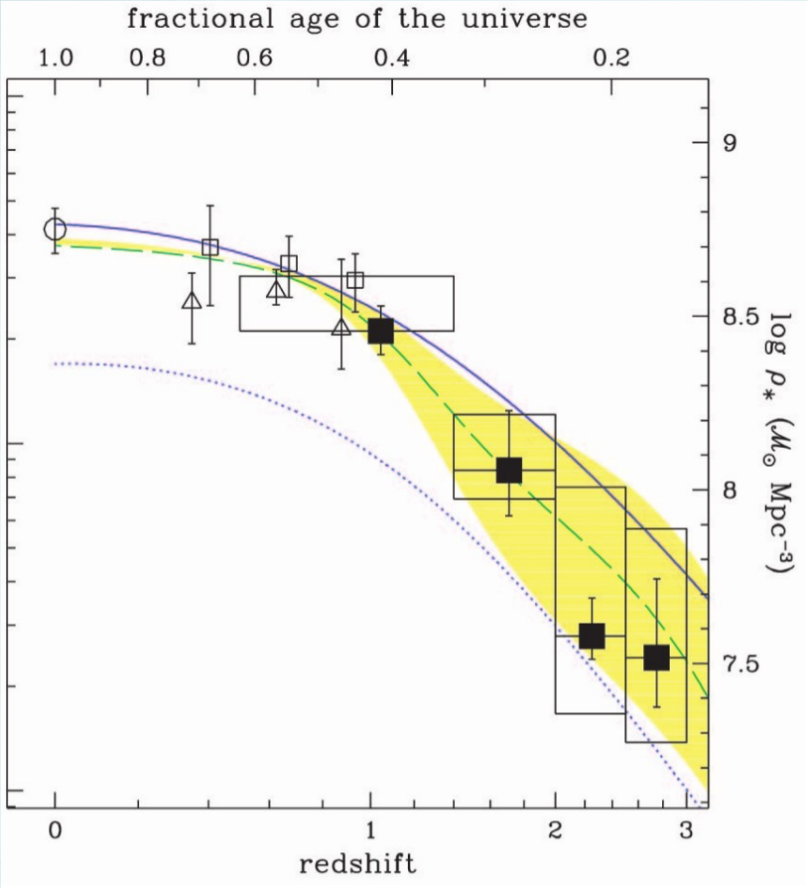
Madau & Dickinson, 2014

True first version of CSFH plot with only 7 data points

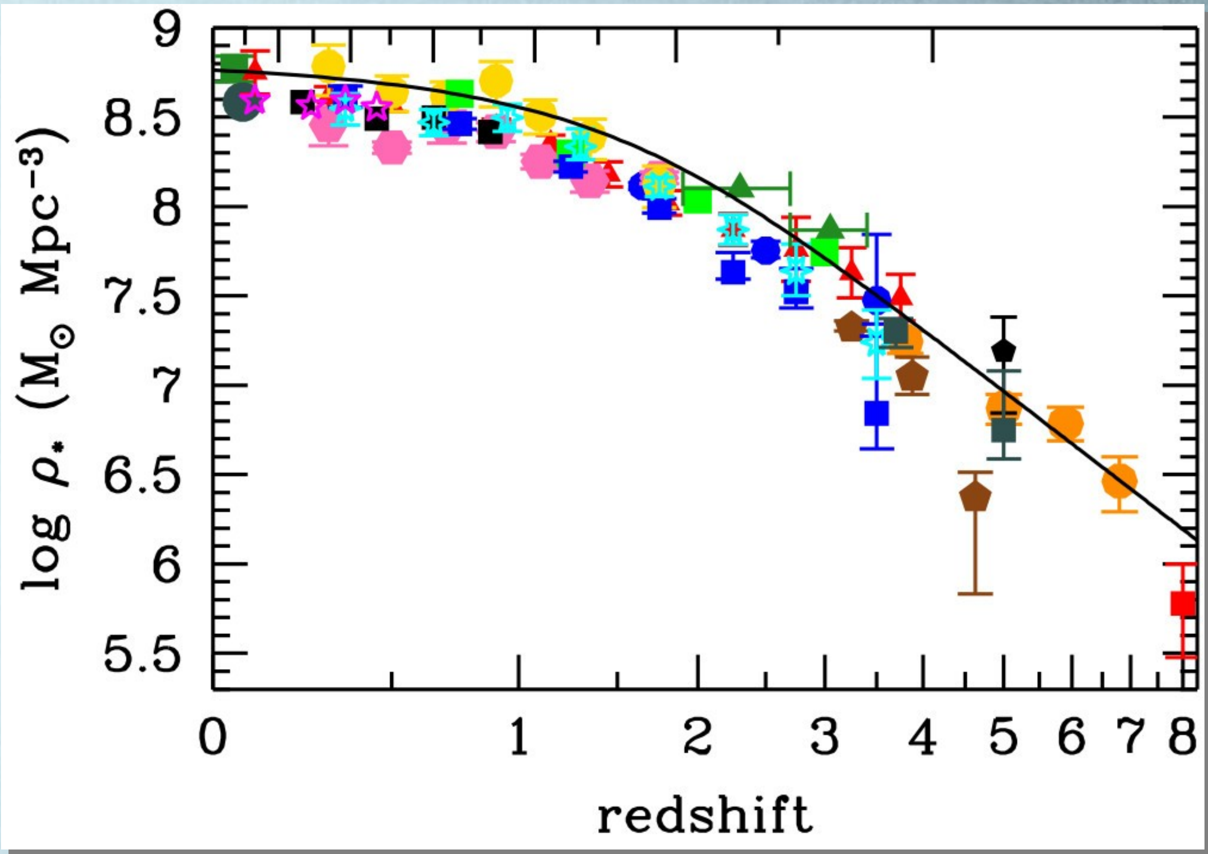
The solid curve shows the total GSFRD from various FUV and IR rest-frame measurements

Evolution of our knowledge about CSFH over the last 20 years

Global Stellar Mass Density



Dickinson et al. 2003

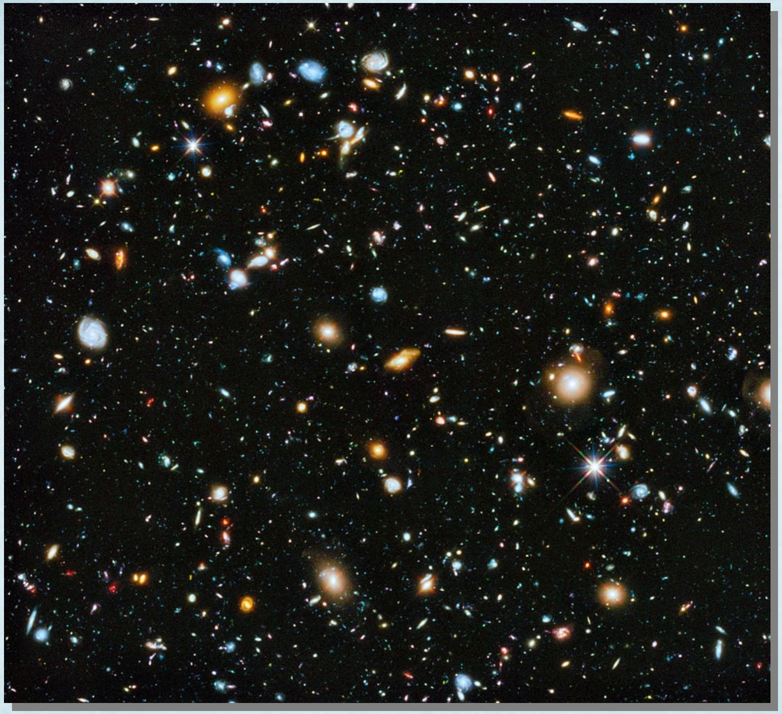


Madau & Dickinson. 2014

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

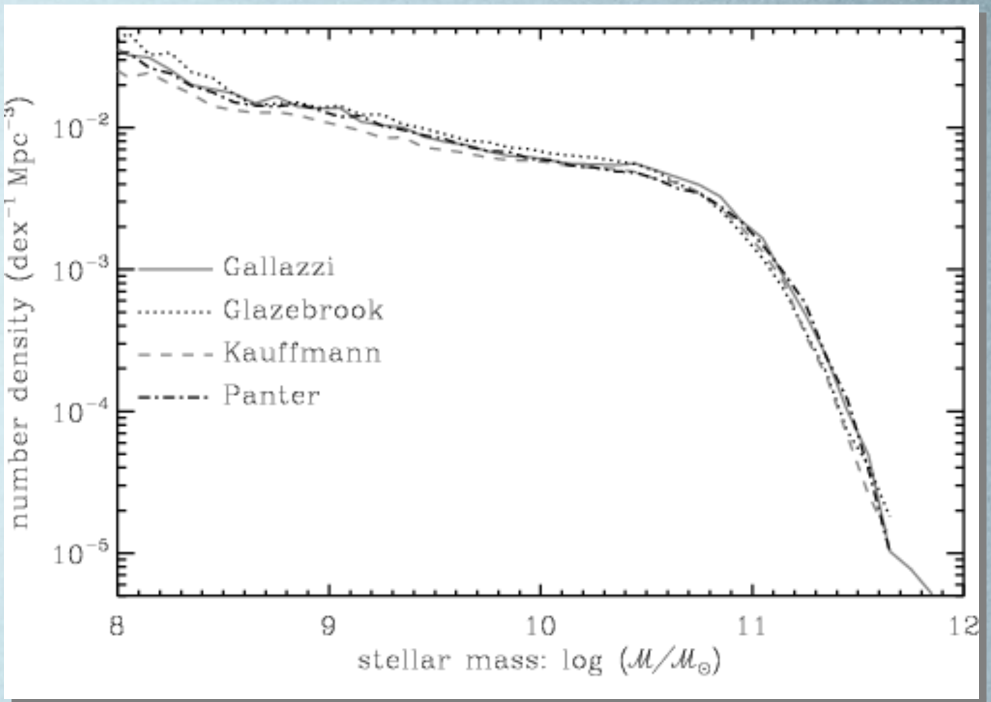
Our goal is to contribute to the plot of GSMD at 0<z<0.8 with robust data that will constraint all future models of galaxy evolution at higher redshifts

Measuring z & mass from light I.



HUDF – 10,000 galaxies in only 3 arcmin FOV

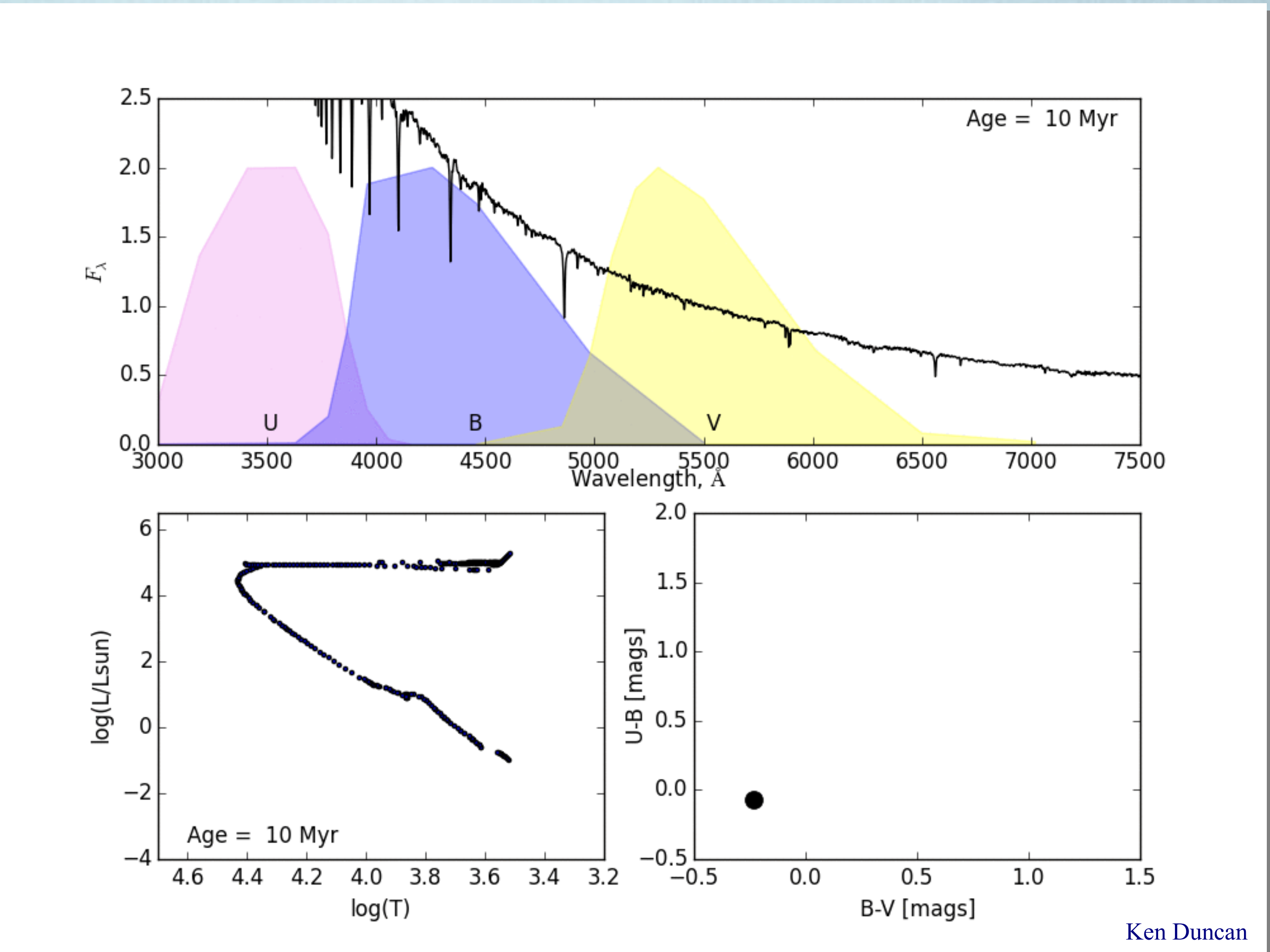
?



Stellar mass function – number density of galaxies of given mass

How do we go from observations to physical parameters?

Measuring *z* & mass from light II. SED fitting



"Color" is the difference of magnitudes in two bands, it is proportional to the ratio of fluxes

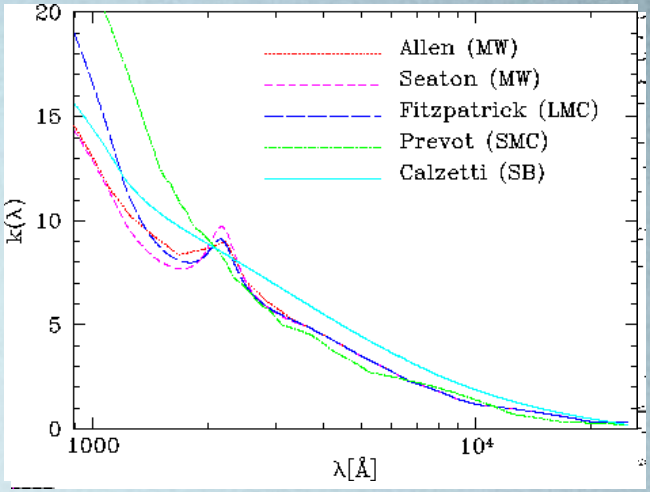
M=-2.5log(Flux)

We use stellar population synthesis (SPS) modeling to study how the spectra, masses 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.

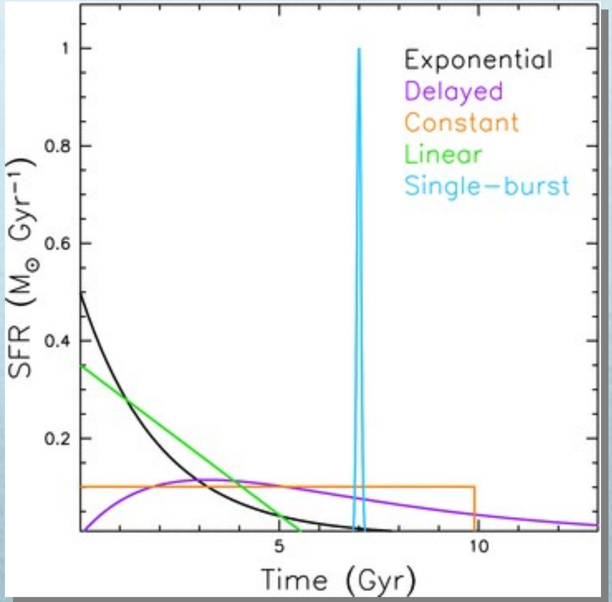
Measuring *z* & mass from light II. SED fitting

The whole process is very model-dependent:

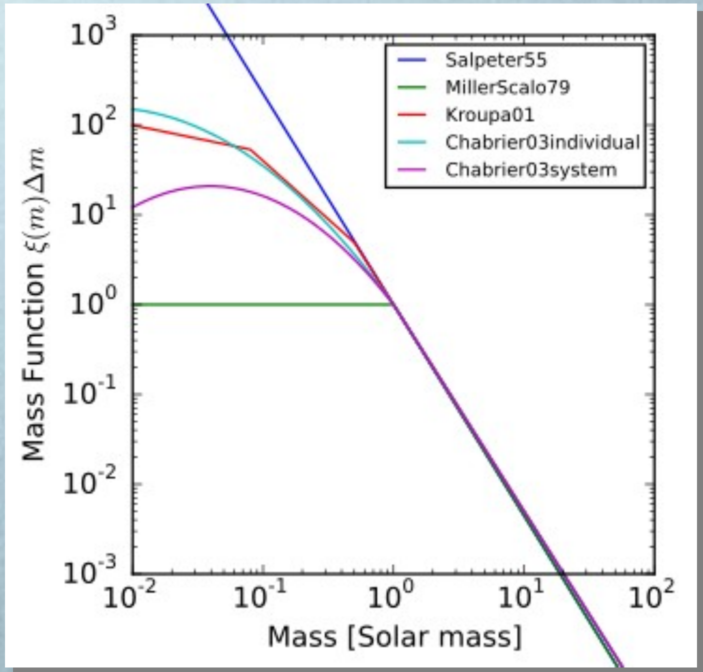
- What SFH we assign to galaxies?
- What was the initial mass function (IMF)?
- What law describes attenuation best?
- What metallicities should be assumed?
- Proper choice of SED fitting code is also important
- **But any model is useless if fluxes are not consistent – this is our main priority in the project**



Extinction curves for different laws

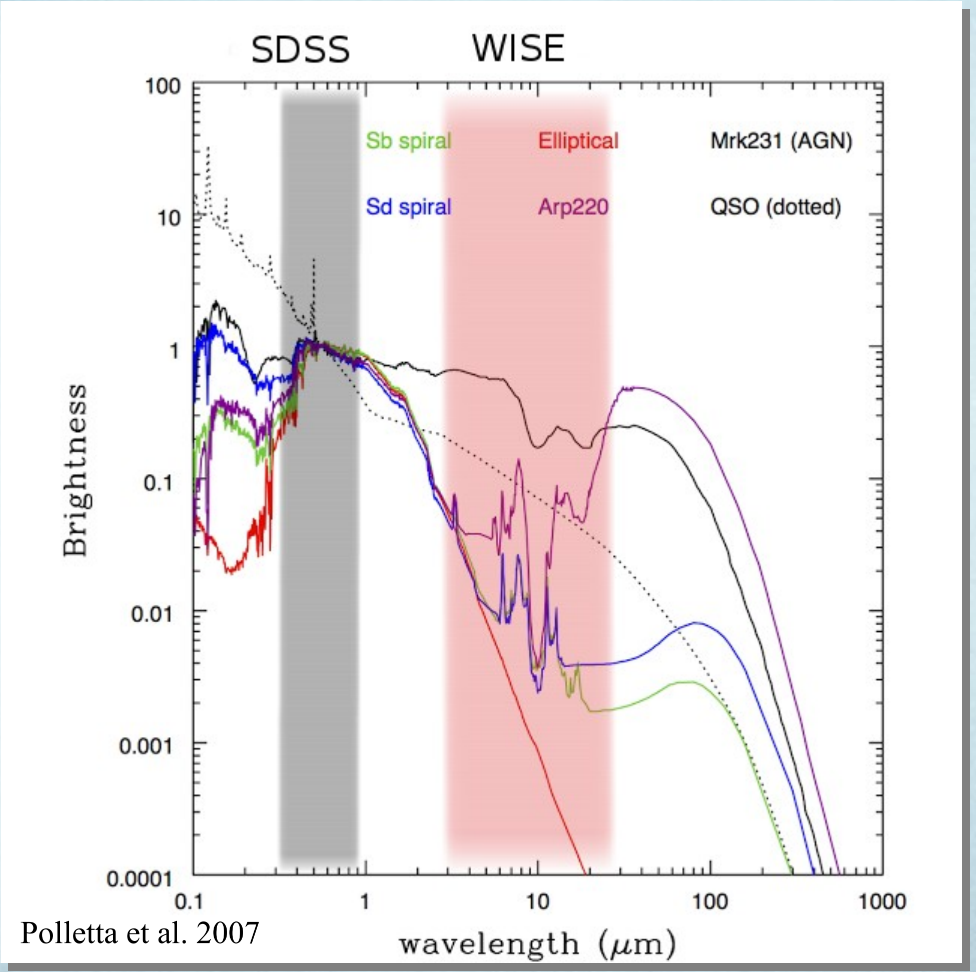


Different star formation histories (SFH)



Various initial mass functions

Measuring *z* & mass from light III. Degeneracy and low-mass stars

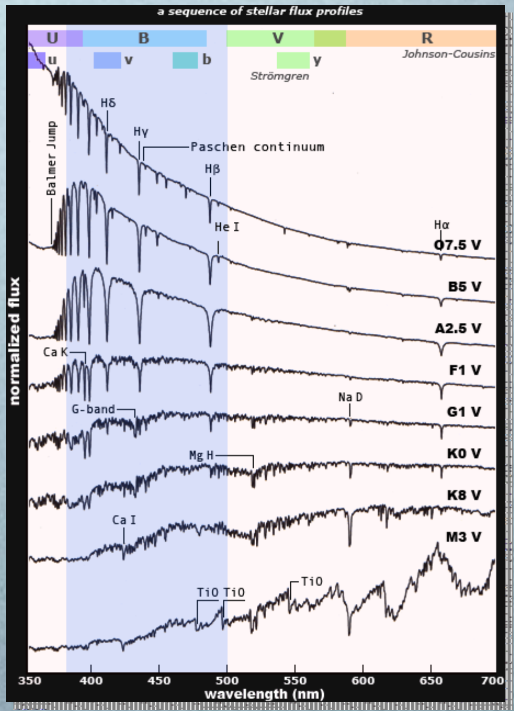


Polletta et al. 2007

Degeneracy of dust vs. age:

- Galaxy with red SED can be dusty
- May have a very old stellar population
- Or both
- High metallicity effectively absorb UV

Another issue - low-mass stars are cool, red and contribute most to the total stellar mass budget of the galaxy.
Near-IR data are needed to account for them



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  - *Lilly-Madau diagram, CSFH, GSMD*
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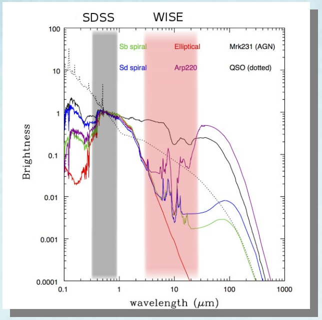
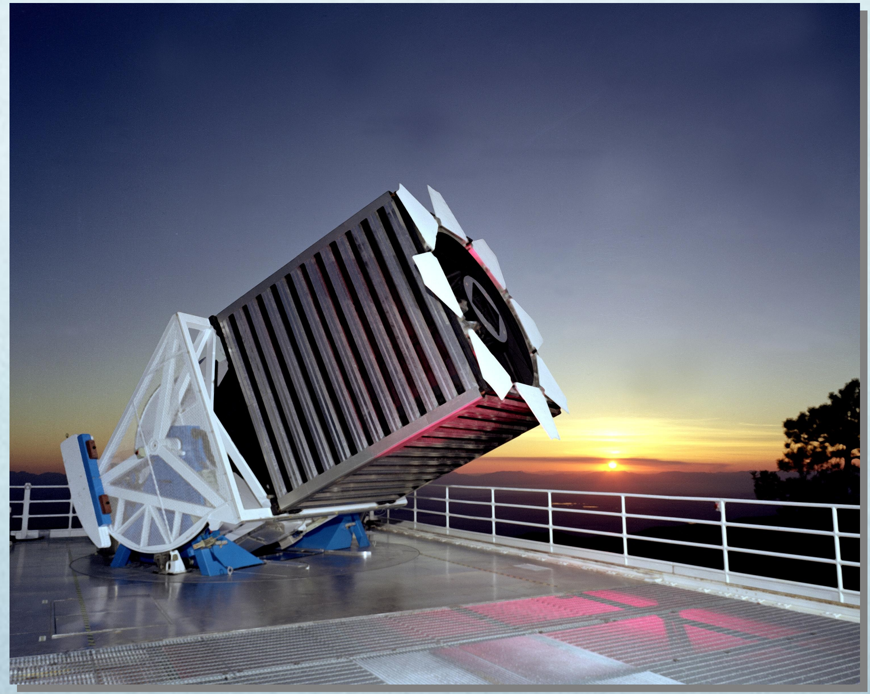
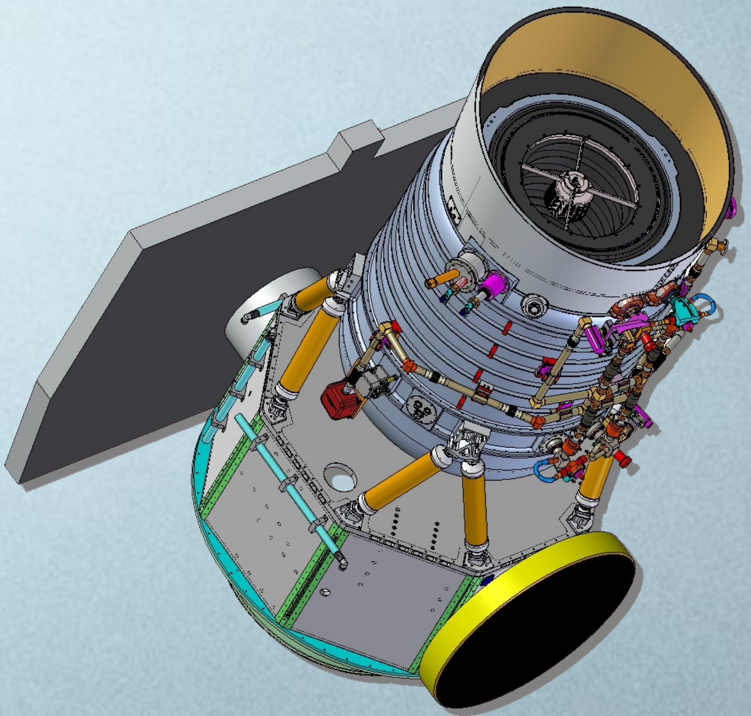
Facility and data I. SDSS and WISE

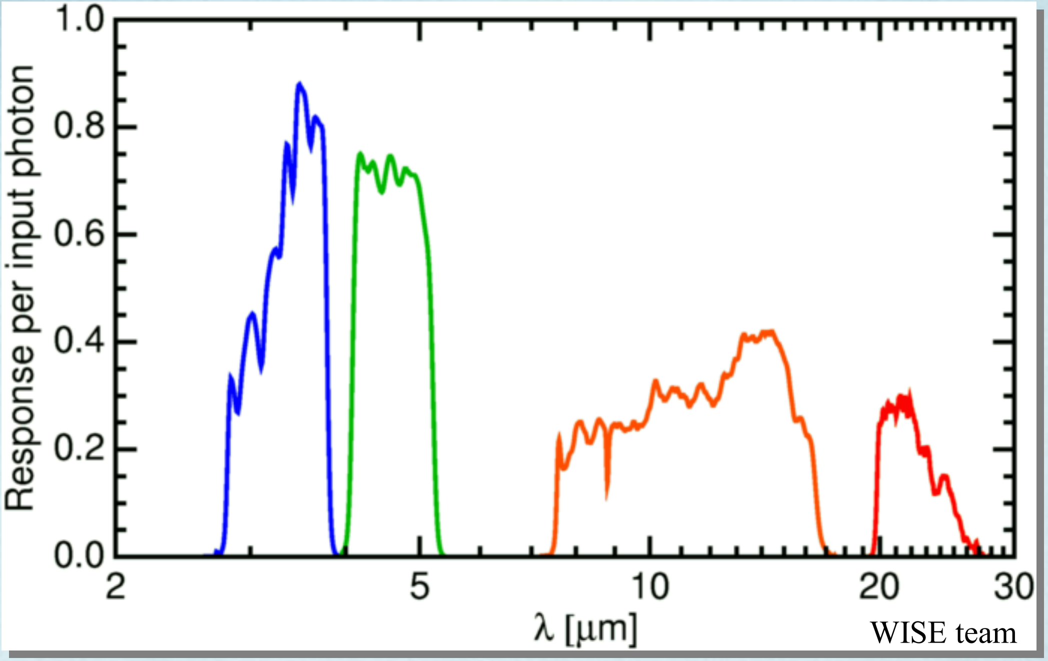


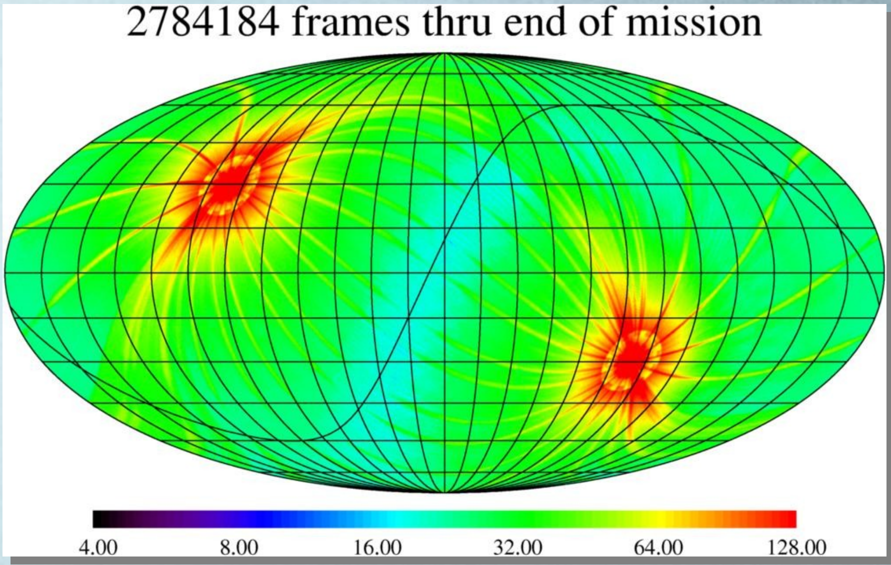




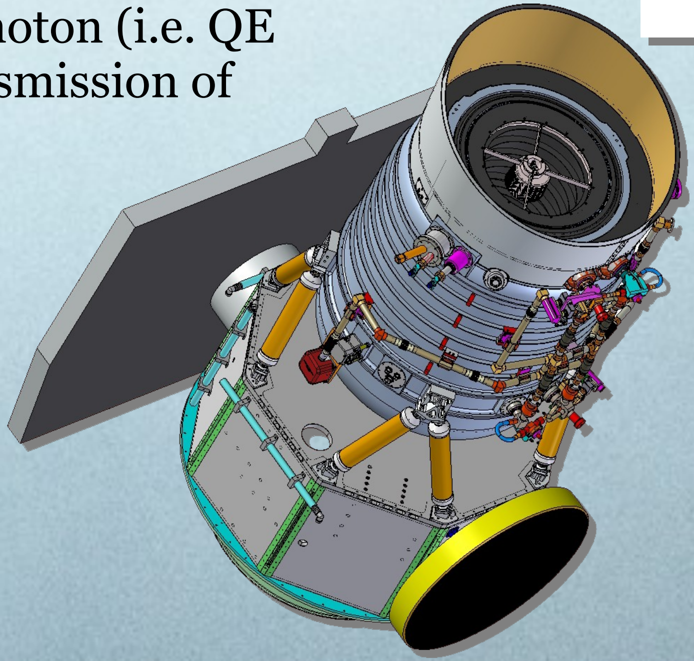
We need a synergy of optical and near-IR data from as deep and as wide-field data samples as possible

Facility and data II. WISE



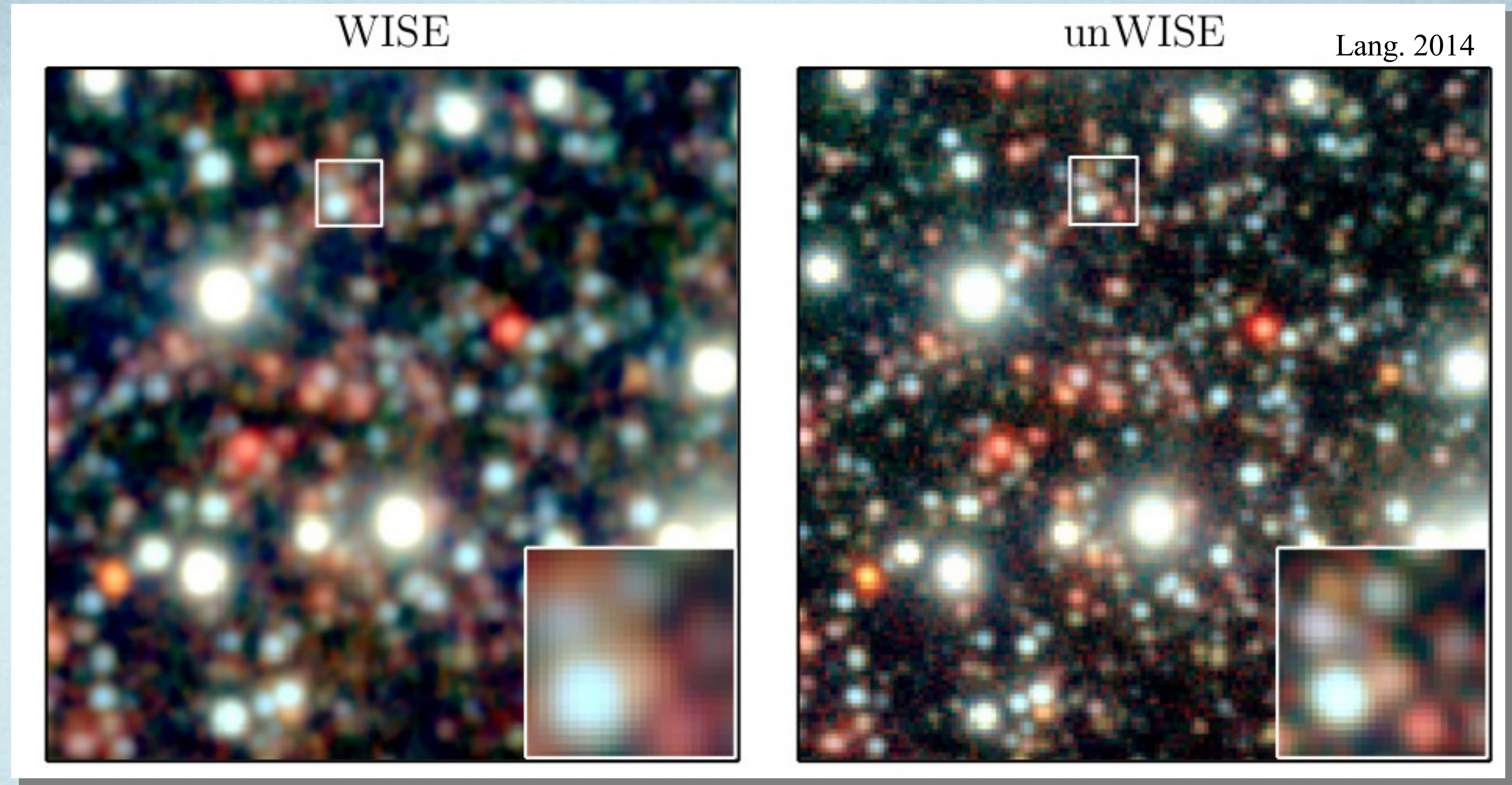


WISE response per photon (i.e. QE of CCD times the transmission of the optics and filters).



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

Facility and data II. Not WISE — unWISE



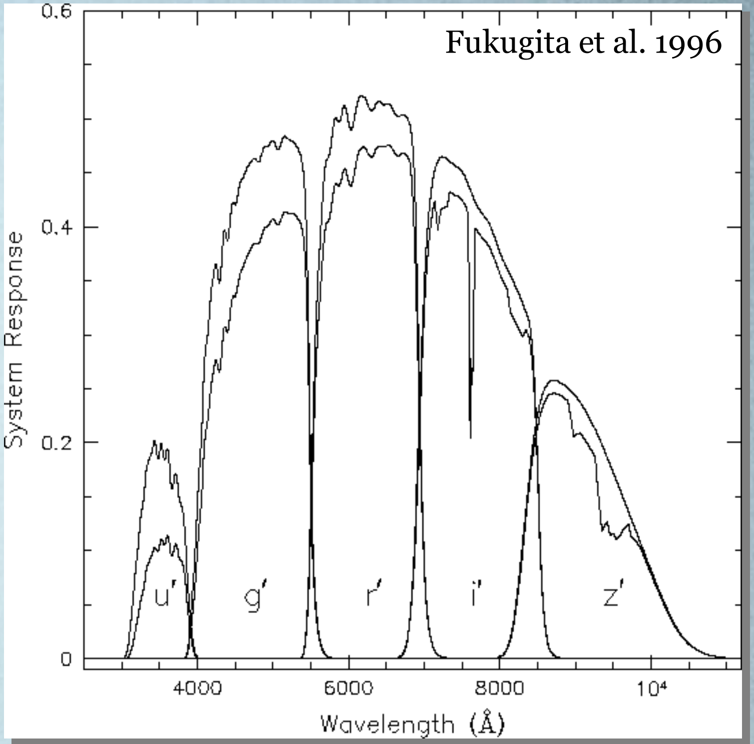
The 7' × 7' co-add tile of the north ecliptic pole, three-band composites (w1, w2, w3).

Left: AllWISE Release Atlas Image (1.375 “/pix)
Right: unWISE co-add with restored intrinsic resolution (2.75 “/pix)

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)			

Facility and data III. SDSS

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

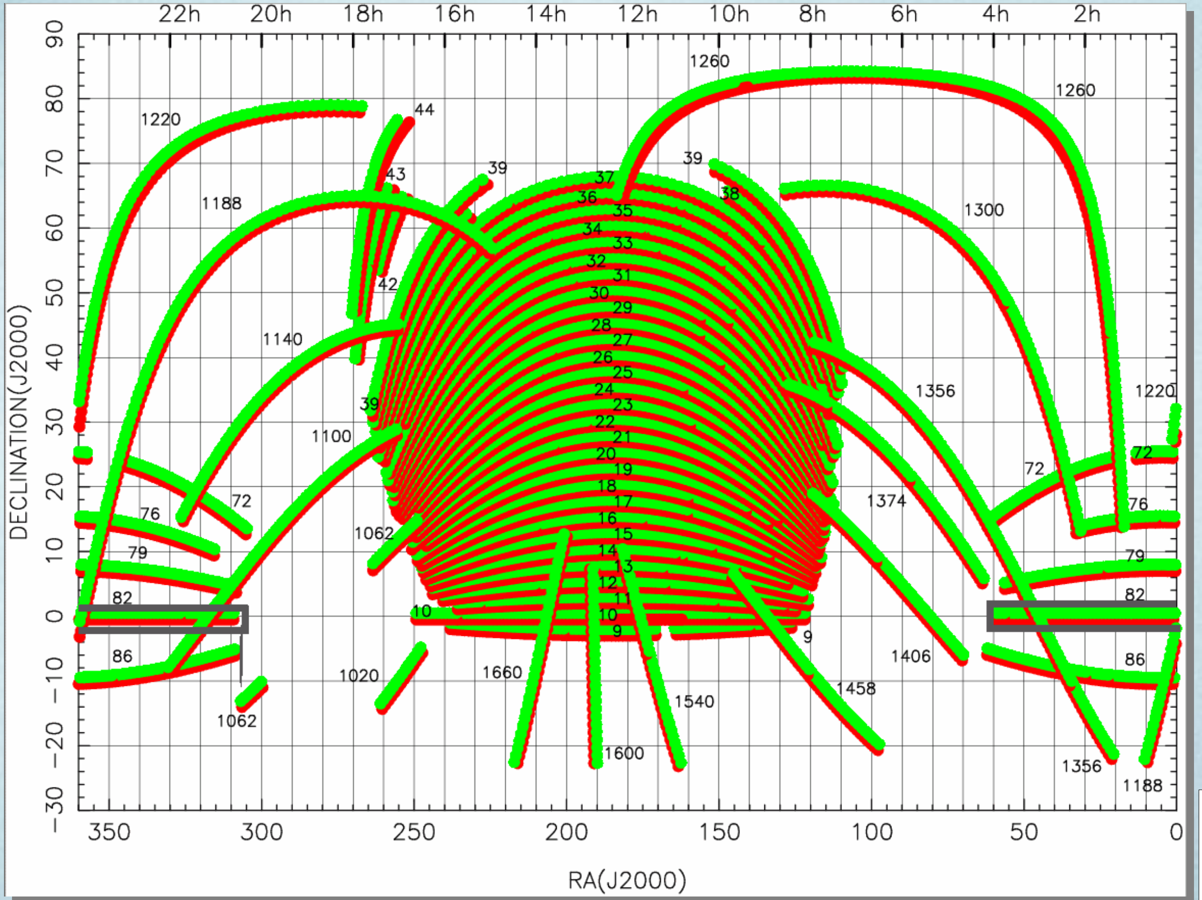


The SDSS system response curves. The curves represent expected total QE of the CCD plus telescope optics.

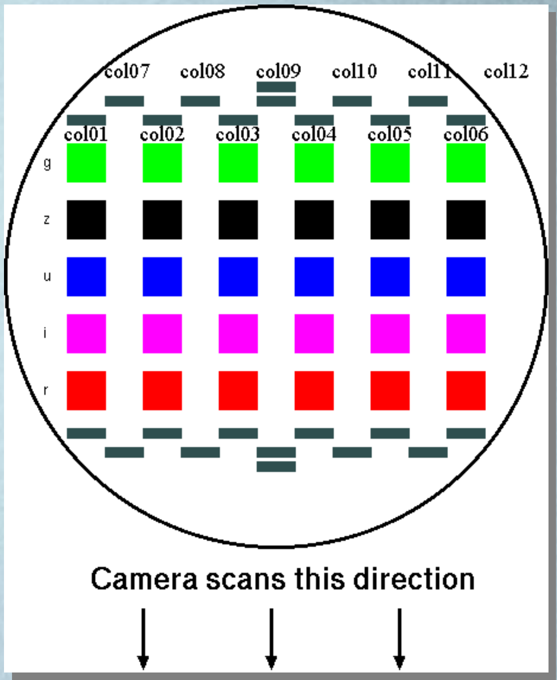
Band	Central wavelength, Å	Limiting magnitude at 95% completeness
u	3551	22.0 AB
g	4686	22.2 AB
r	6165	22.2 AB
i	7481	21.3 AB
z	8931	20.5 AB

Nominal depth of SDSS can only detect "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 III. SDSS Stripe 82

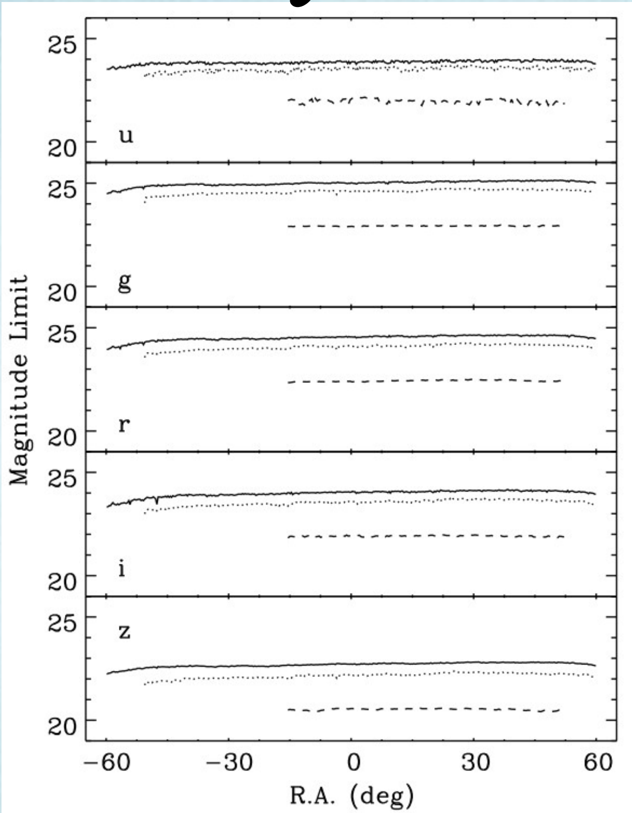


Full SDSS Footprint (10 400 square degrees) with Stripe labels including Stripe 82.

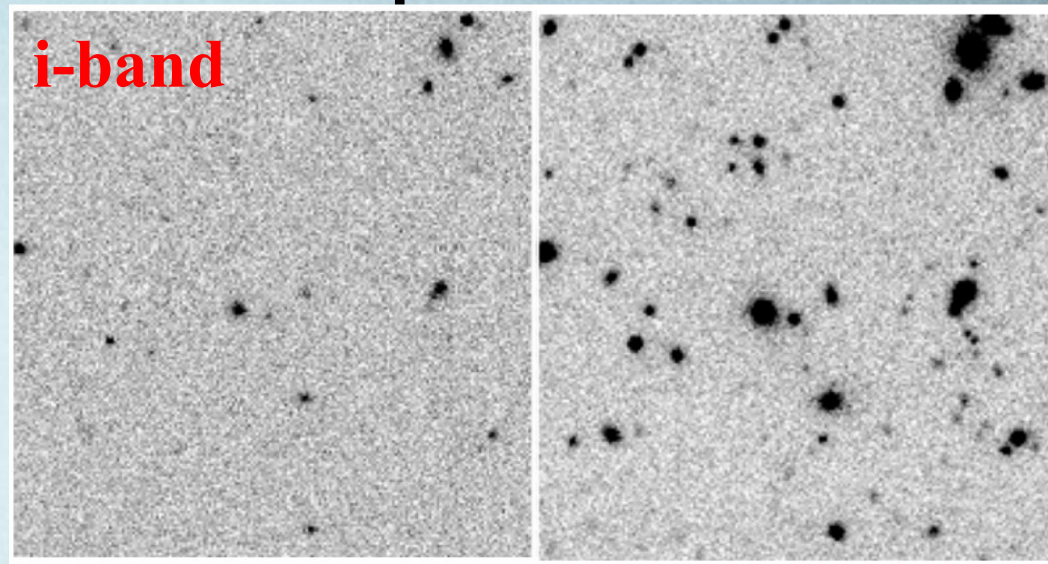


- PSF FWHM, r-band - 1.3 arcsec
- Pixel scale - 0.396 arcsec
- Exposure time per band - 53.9 sec
- Time between observations of each band - 71.72 sec (in *riuzg* order)
- Global astrometric precision - 0.1” rms

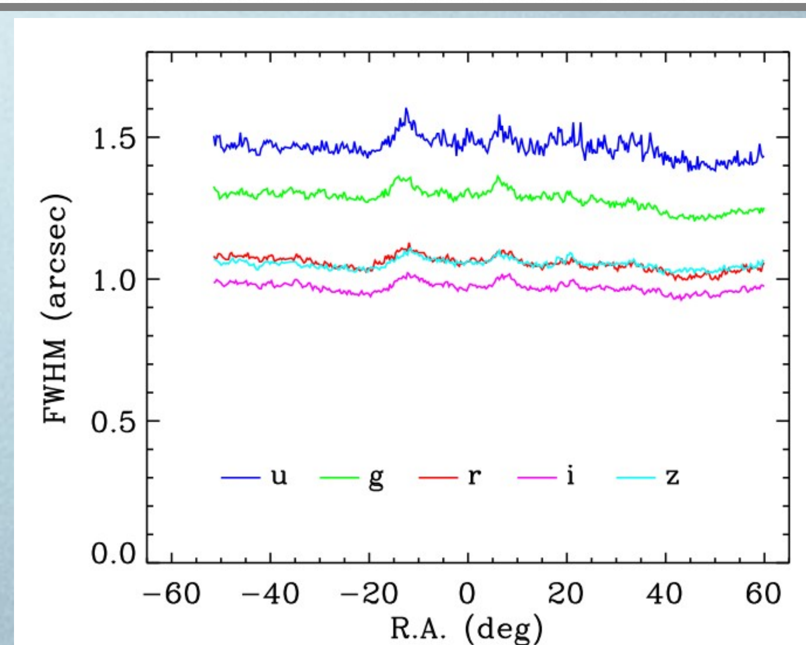
Facility and data III.Stripe 82 co-adds



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



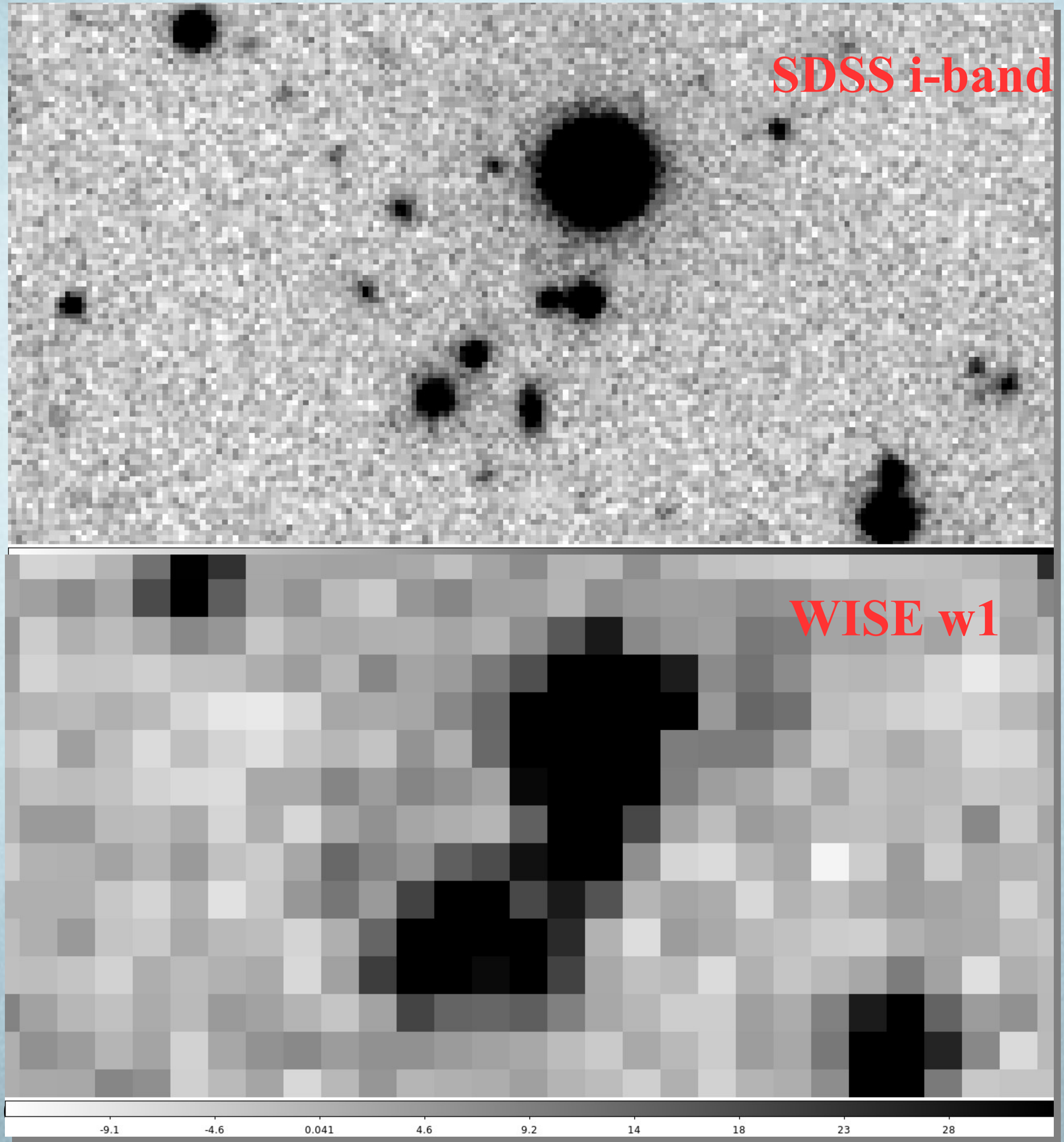
Jiang et al. 2014



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)				

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

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

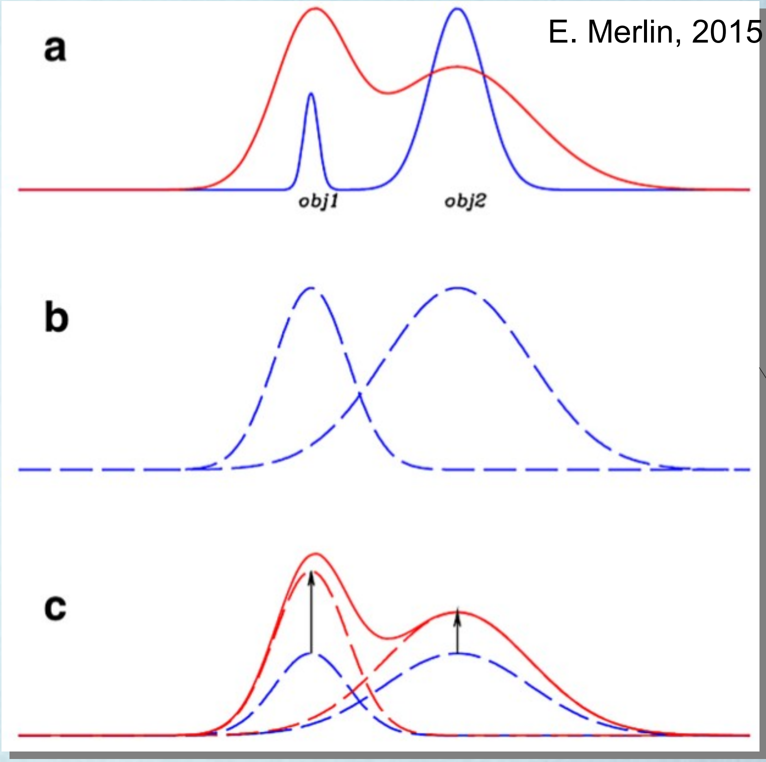


Critical factor is consistent photometry. It is challenging because the spatial resolutions of WISE is 5-6x worse than that of the SDSS.

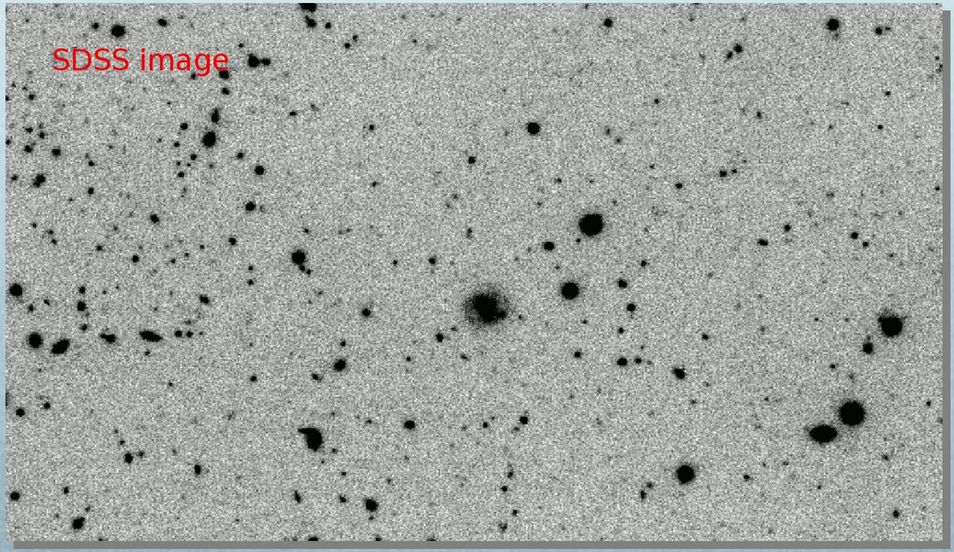
Objects detected in WISE suffer from the blending problem.

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 I. Near-IR - Template fitting

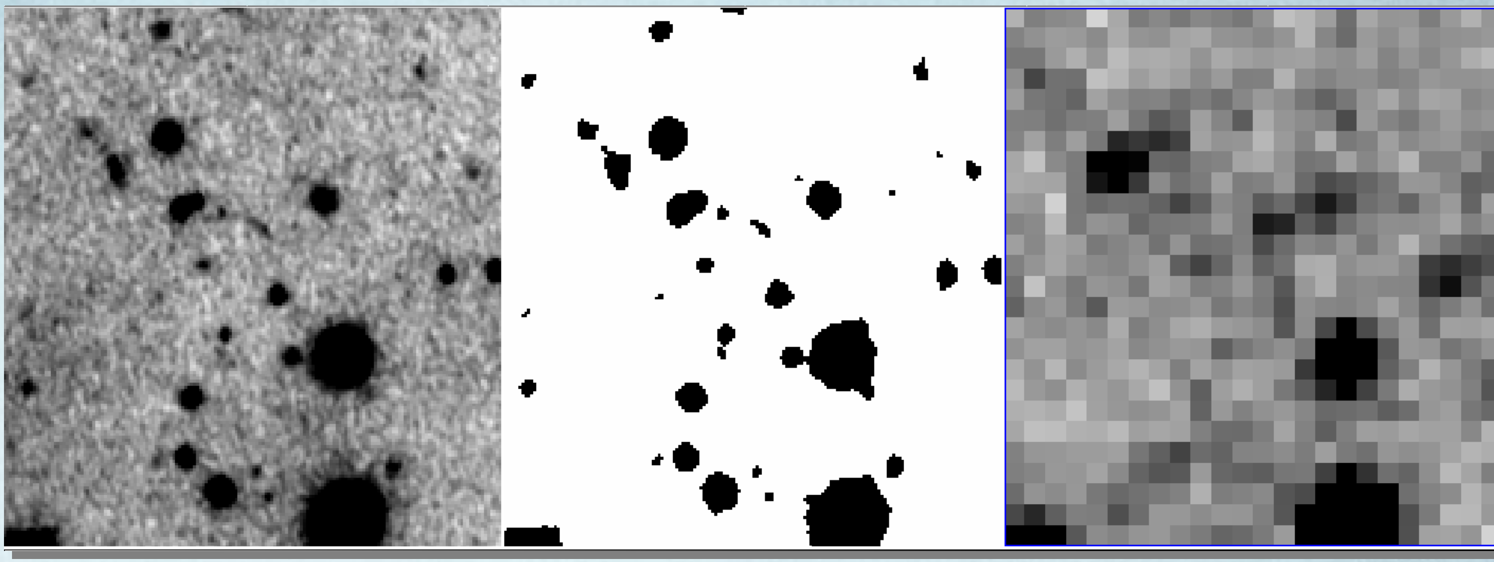


Residual images

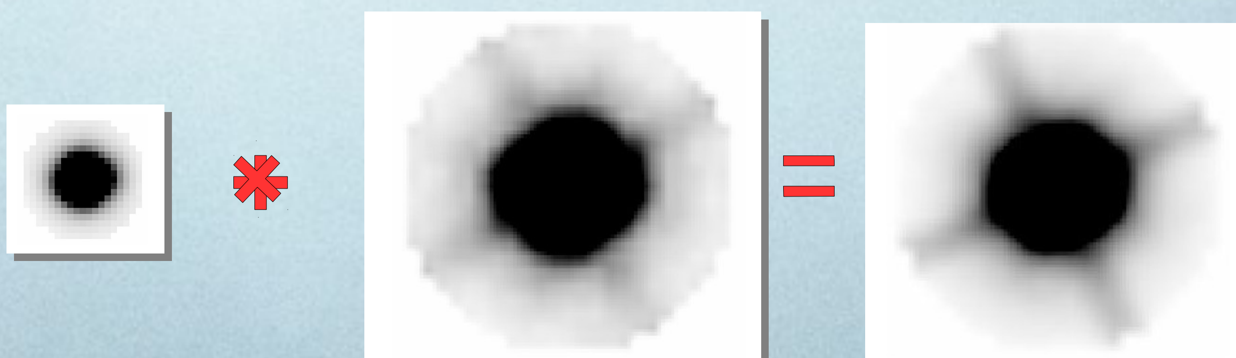


Catalog with **26,585,000 sources** (galaxies, stars, QSO) with consistent fluxes and associated flux errors in 7 bands

Catalog I. Near-IR - Template fitting



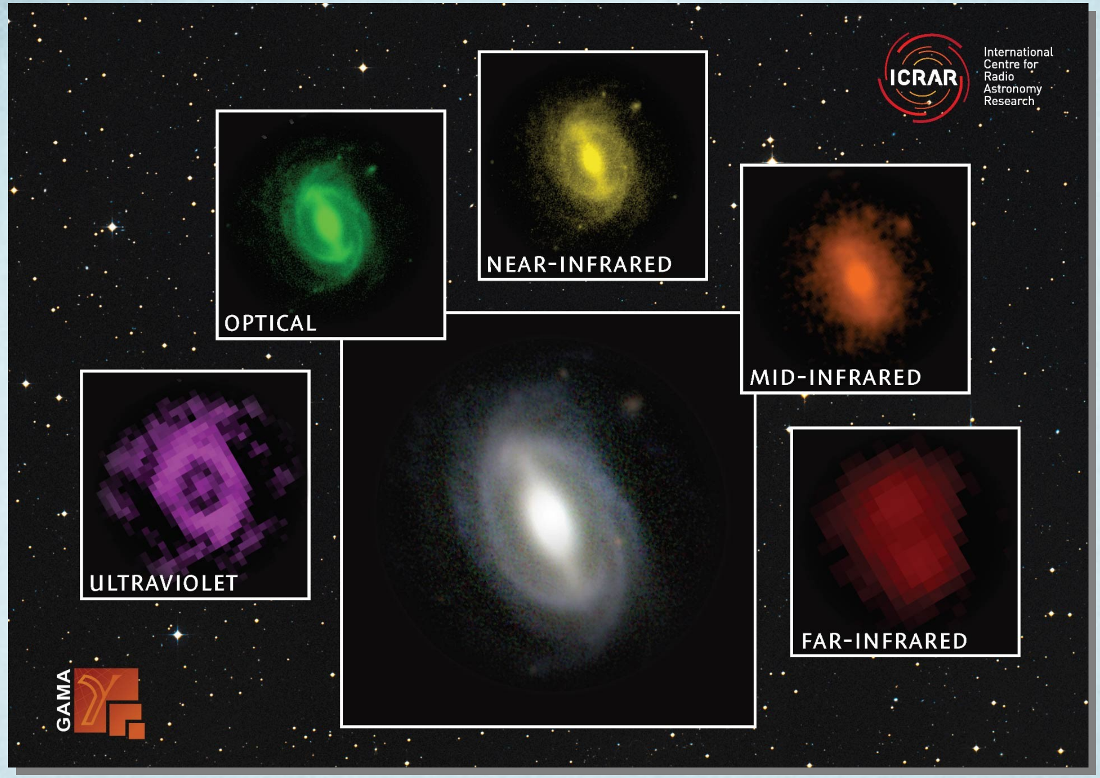
SDSS high-res image SDSS segmentation map unWISE w1-band

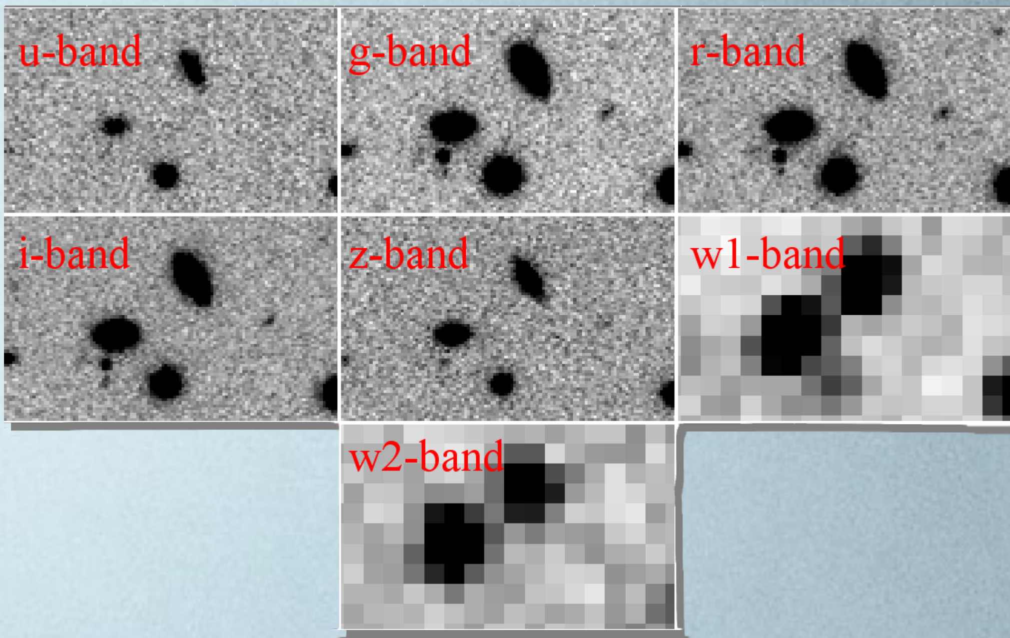


High-res PSF Low-res PSF Kernel

Because I know PSF of both high-res and low-res images, sources do not have to be point-like neither in high-res, nor in low-res images to be successfully subtracted

Catalog I. Near-IR - Assumption

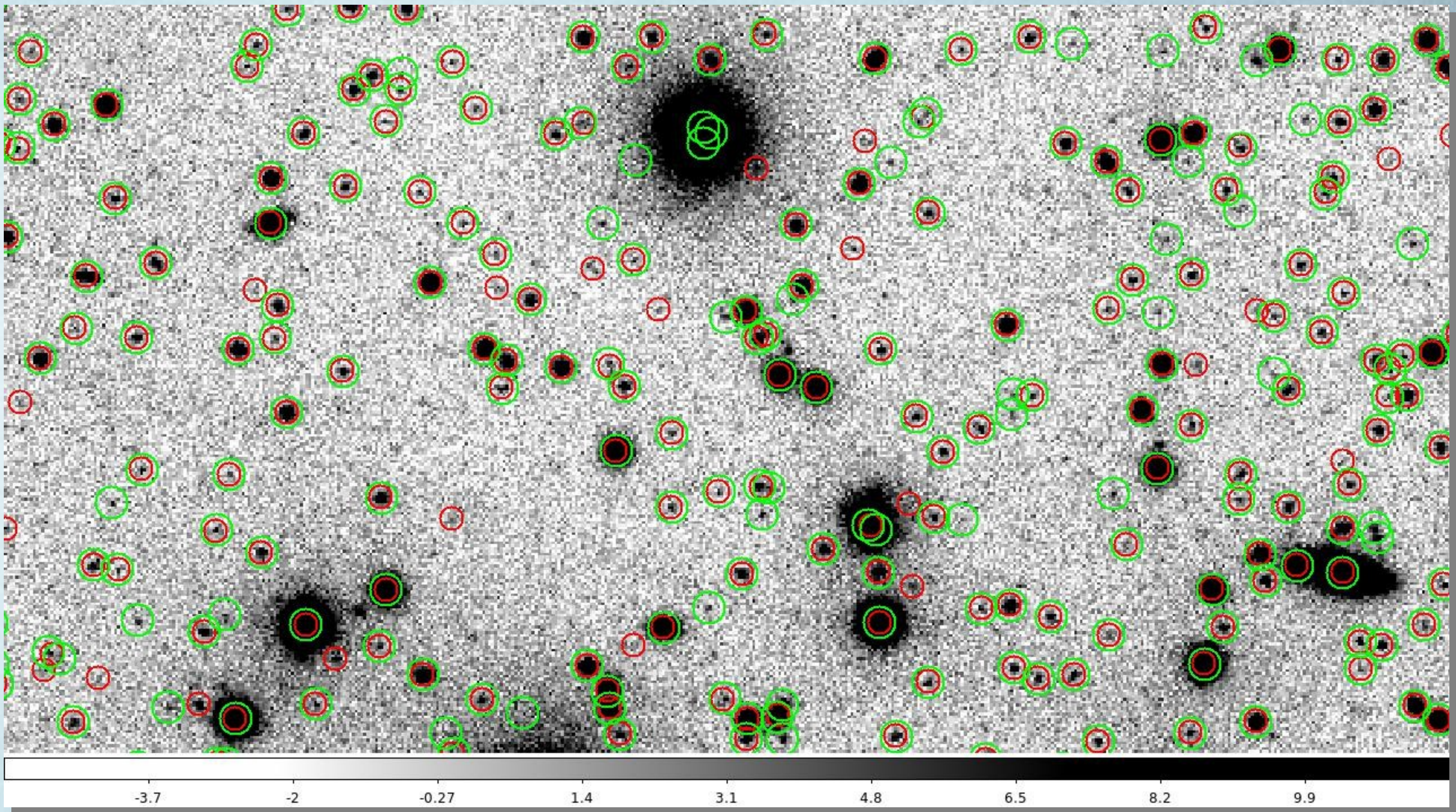




“Template fitting” technique suggests that galaxy's morphology is the same in high-res and low-res images. Generally speaking, this is not correct.

But angular size of regular (60kpc in diameter) galaxy at z=0.7 is only 8 pix

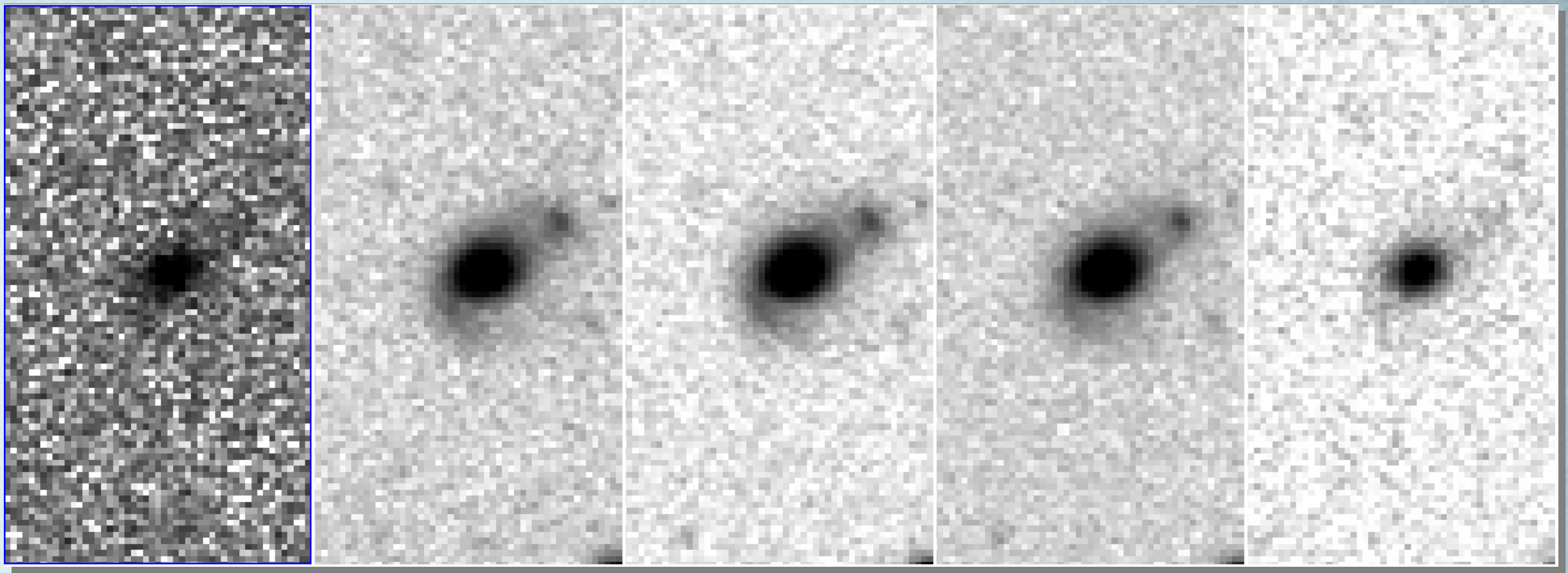
Catalog II. Optical. Why do we need it?



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

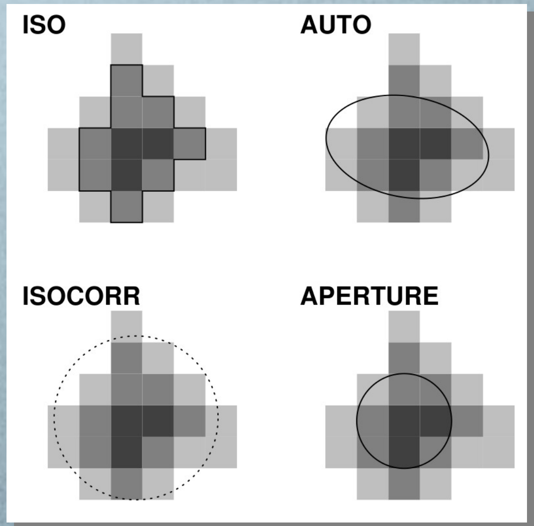
Why do we need to construct our own catalog?
1) Original catalog has to high detection threshold — lots of sources are rejected
2) Catalog is not cleaned out — multiple detections around saturated areas.

Catalog II. Optical

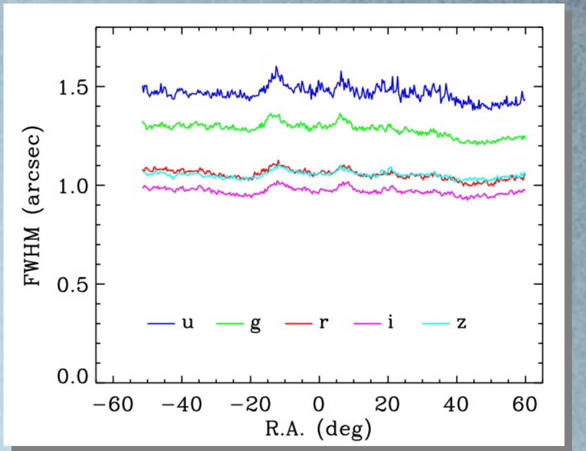


It is not trivial to extract consistent flux even in SDSS bands due to different FWHM, sensitivity and seeing. Source detection in each individual band does not include same fraction of the light from a given source in all bands.

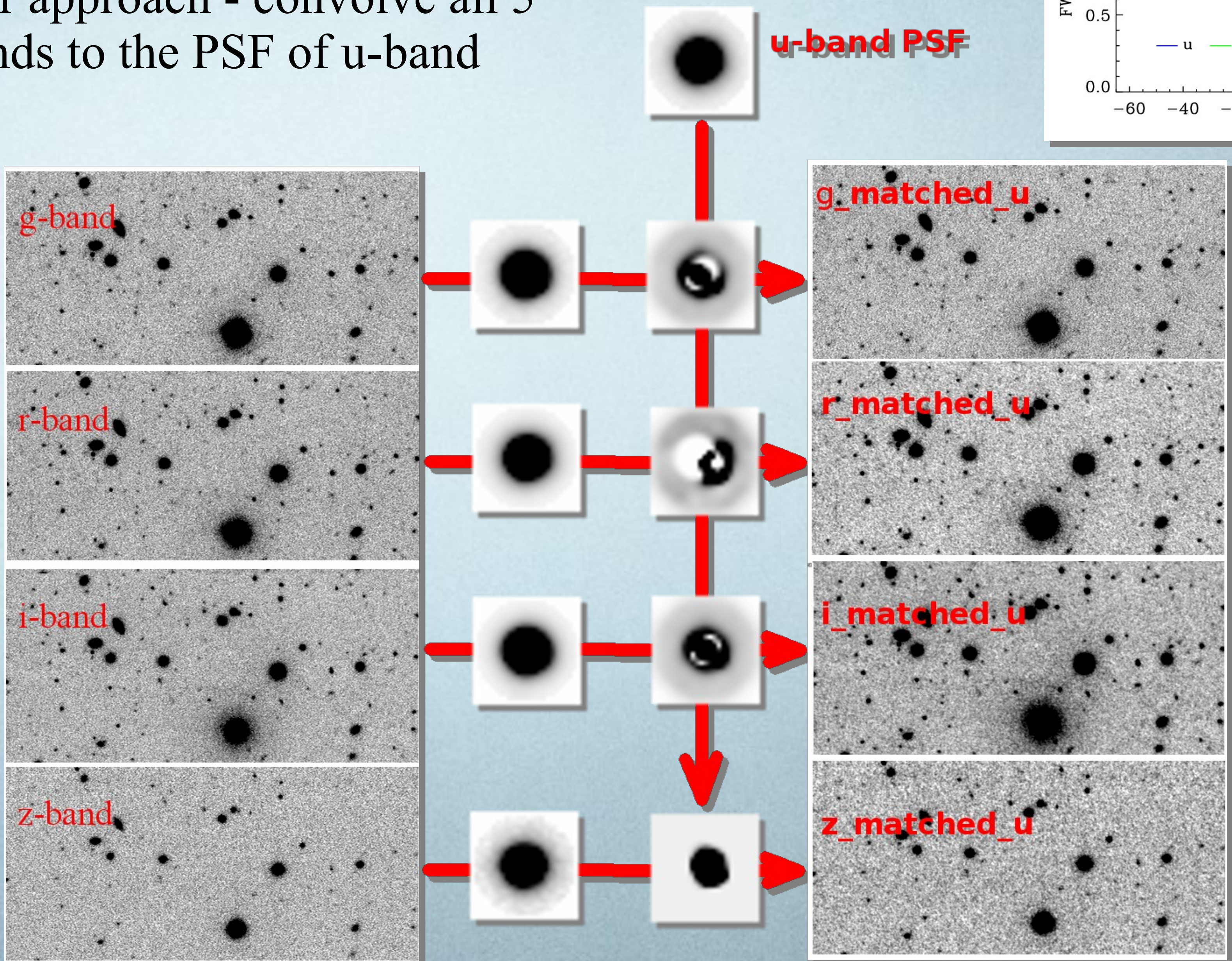
Different possible apertures in SExtractor:



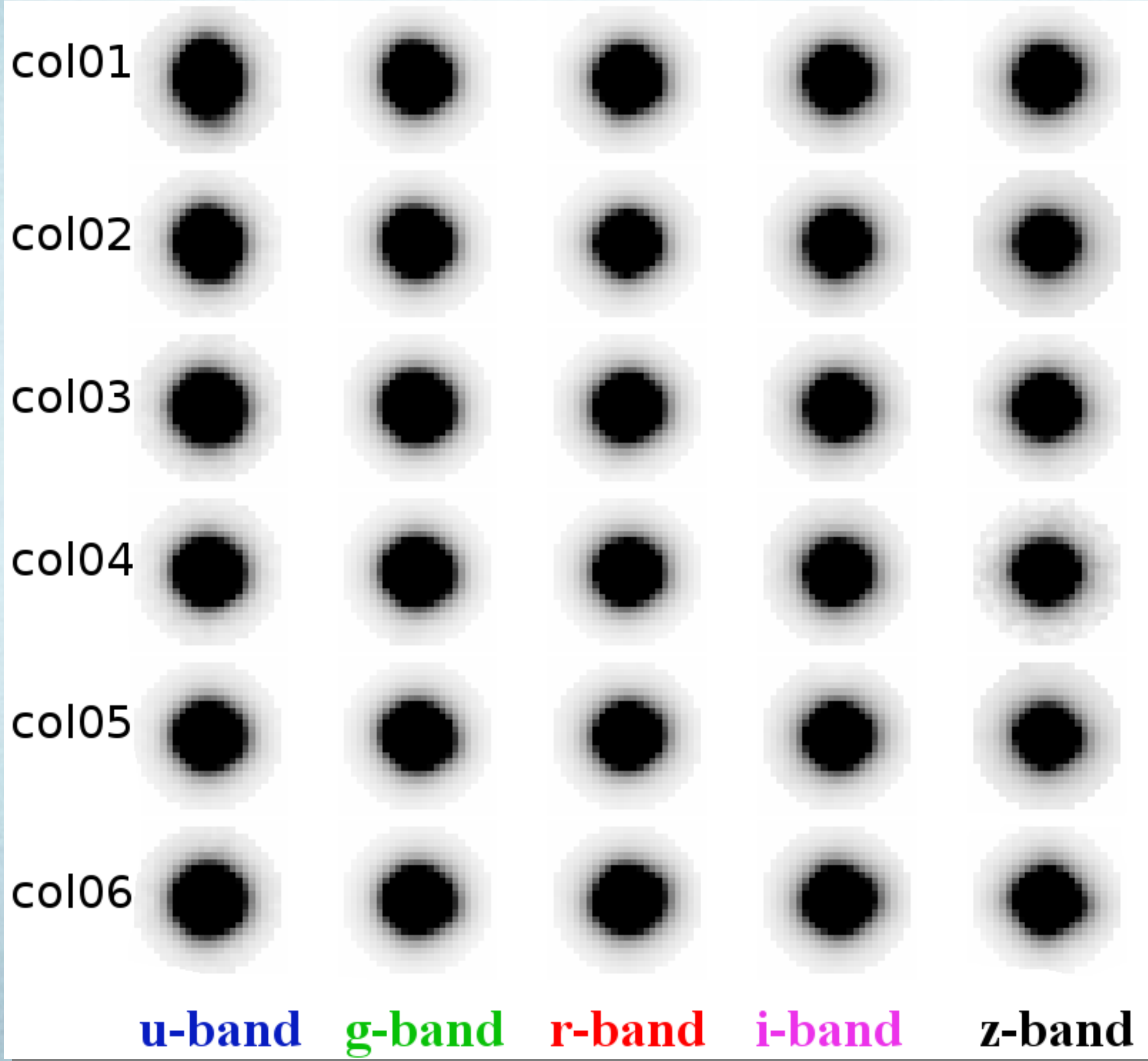
Catalog II. Optical - FWHM

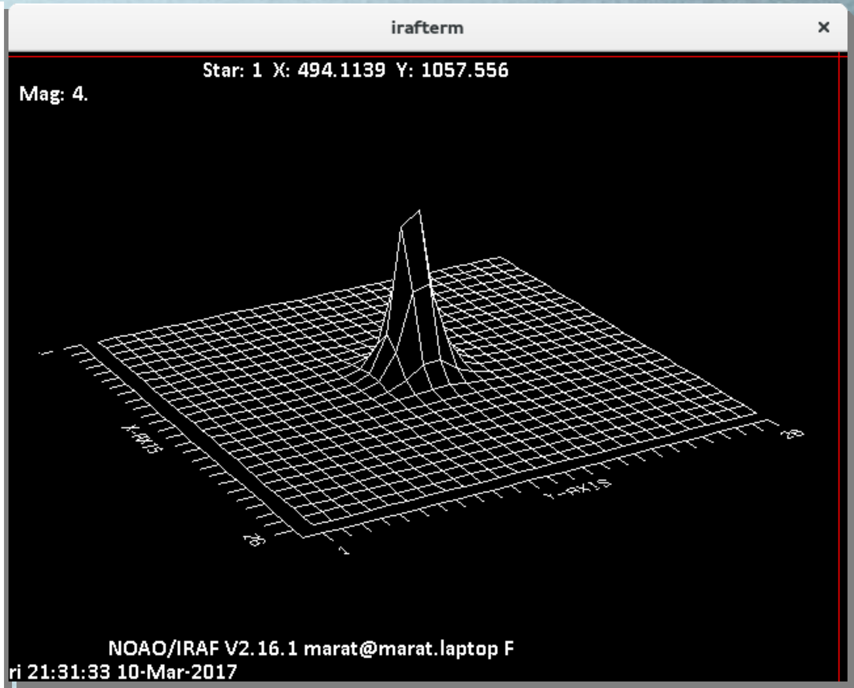


Our approach - convolve all 5 bands to the PSF of u-band



Catalog II. Optical - PSF

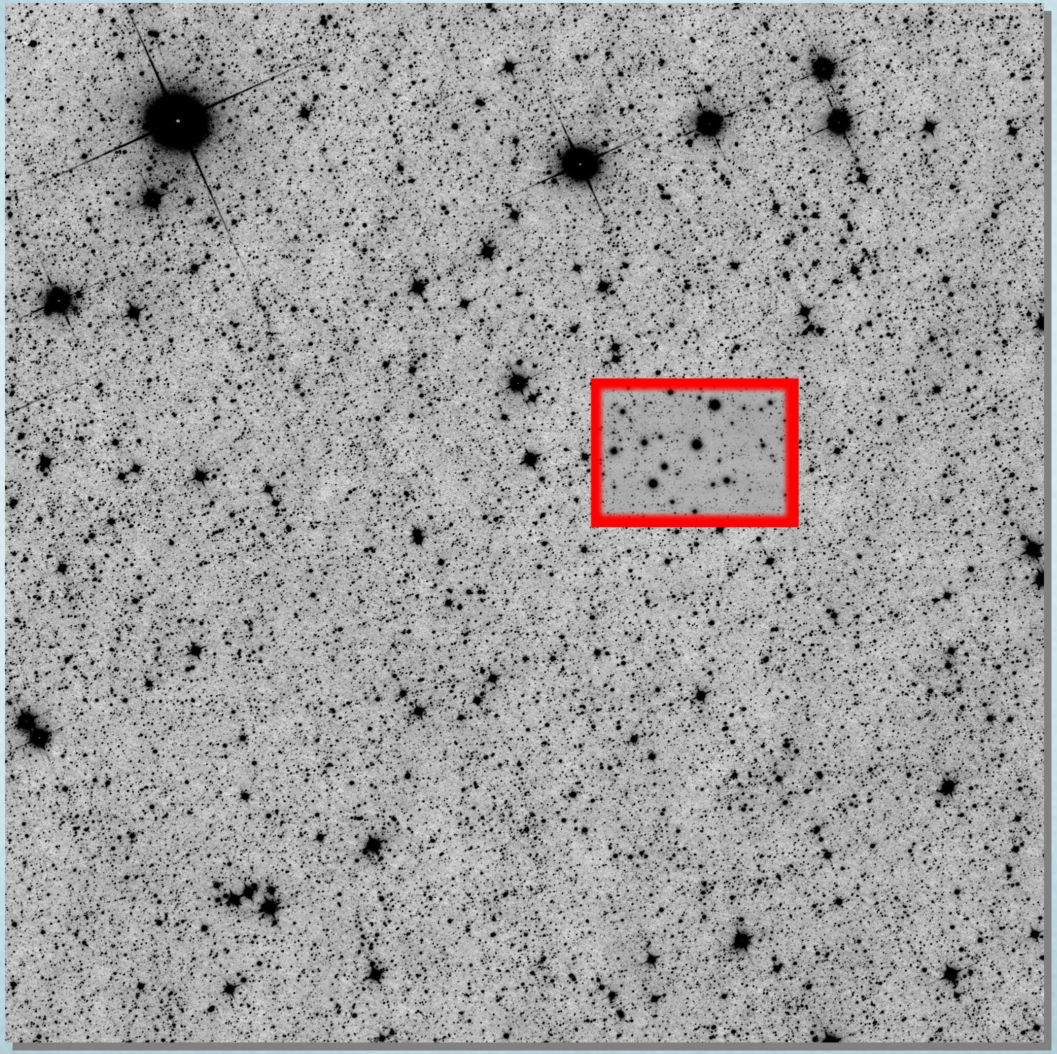




- We need PSF for every SDSS image – 28,000 PSFs
- Each PSF is constructed using ~100 stars
- Each PSF needs to be visually inspected

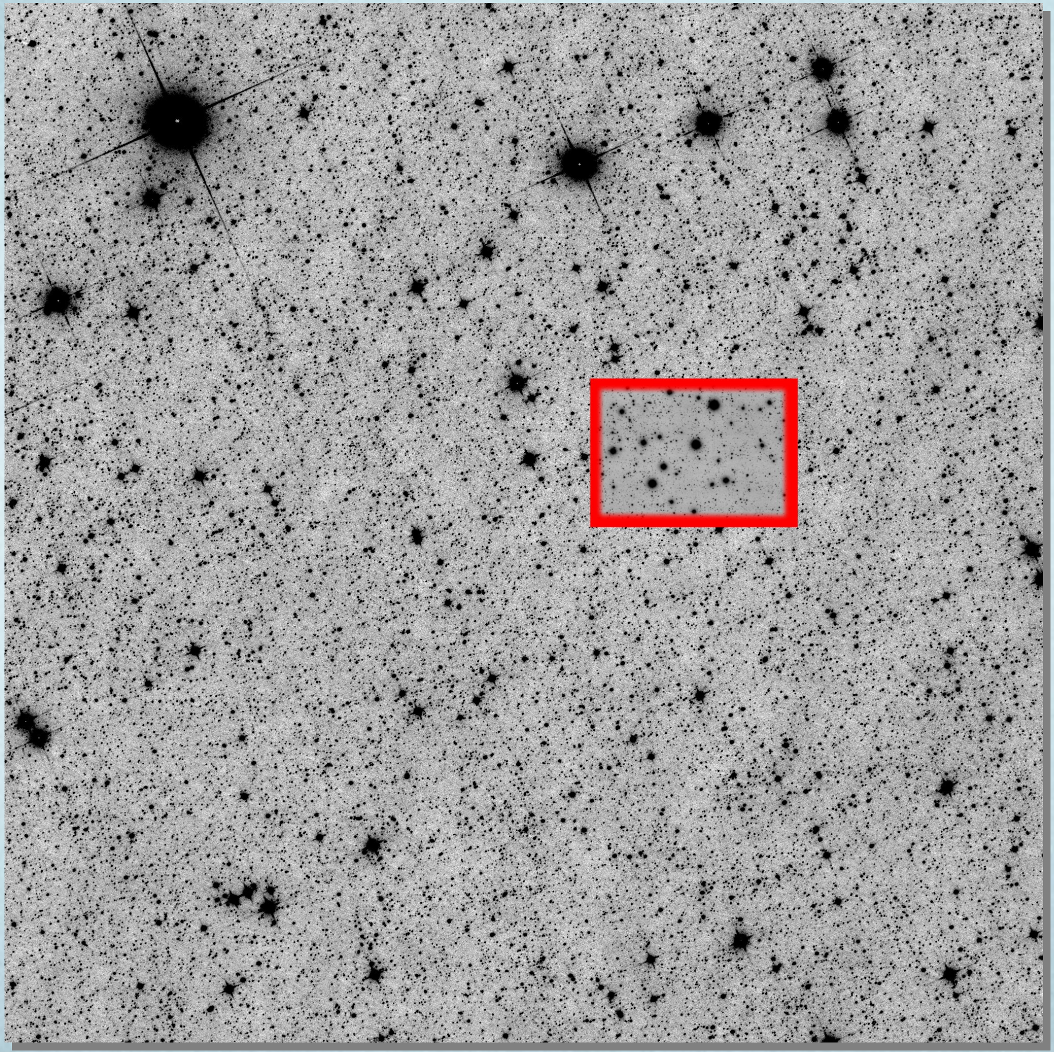
By far ***the most*** time-consuming part of the project...

Catalog IV. Multiband - almost complete

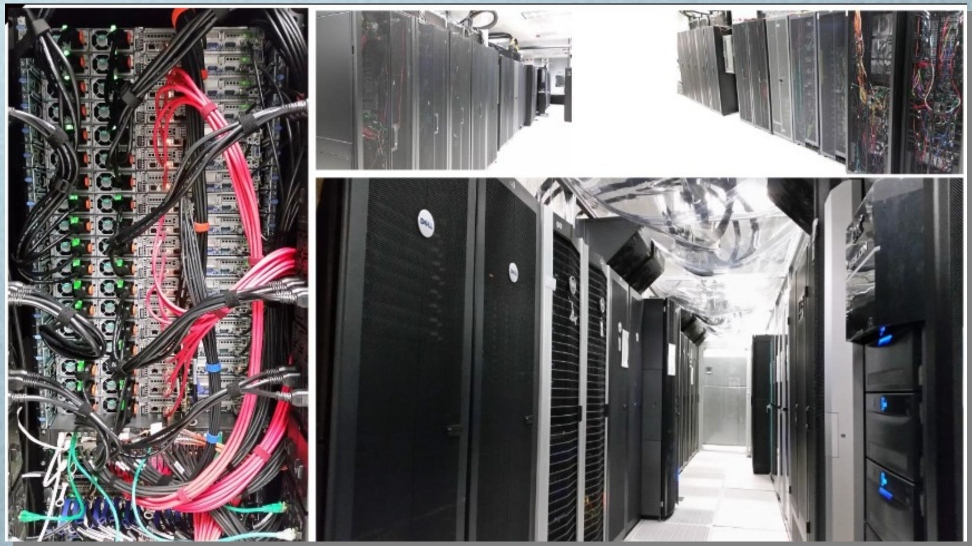


- Once all PSF were constructed we extracted fluxes in all 5 bands using r-band as detection image
- Source is added to catalog if it is detected in r-band with SNR>5
- We use position, morphology and flux of the source in r-band to perform template fitting on near-IR bands

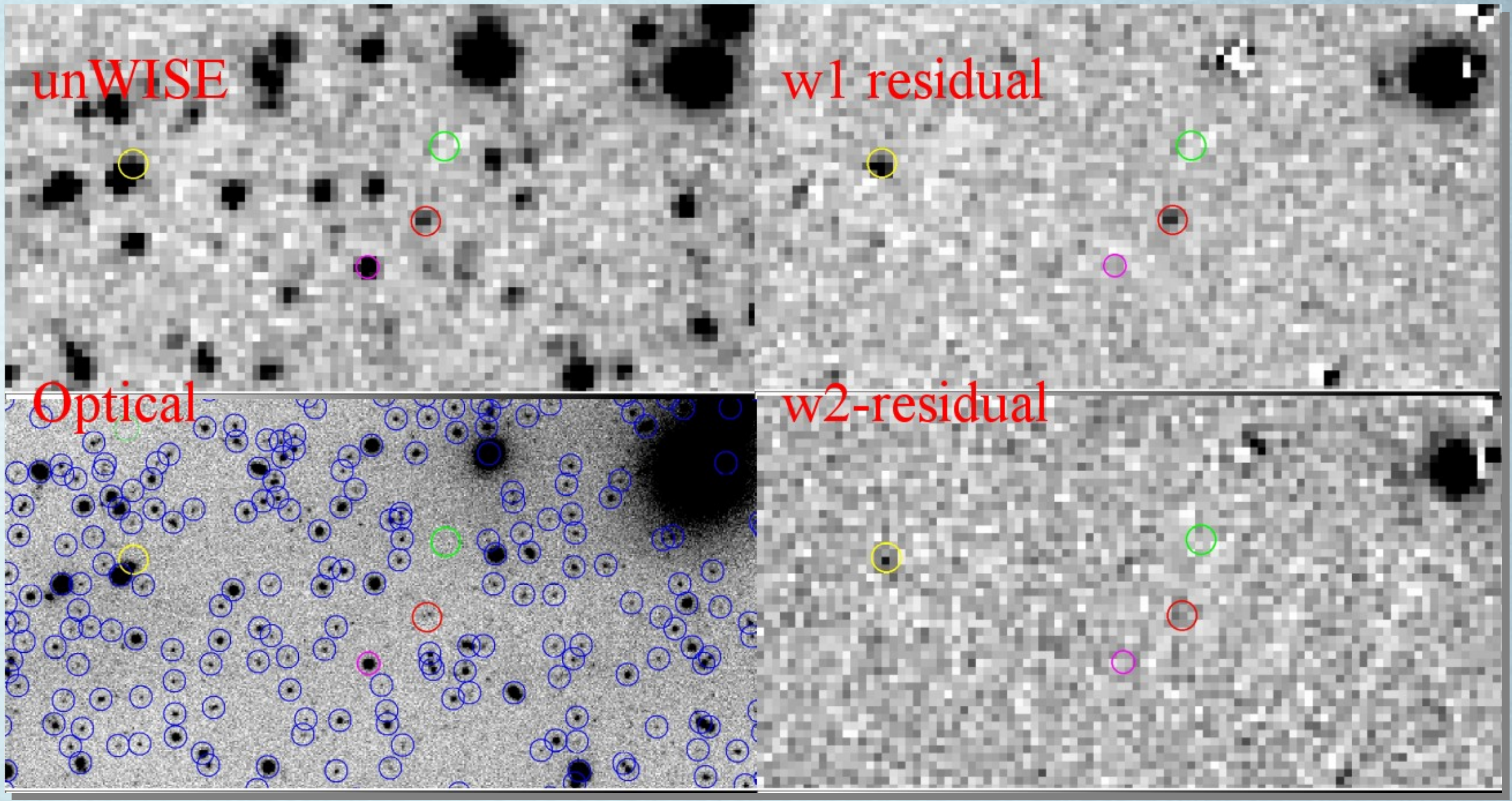
Catalog IV. Multiband - almost complete



- 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

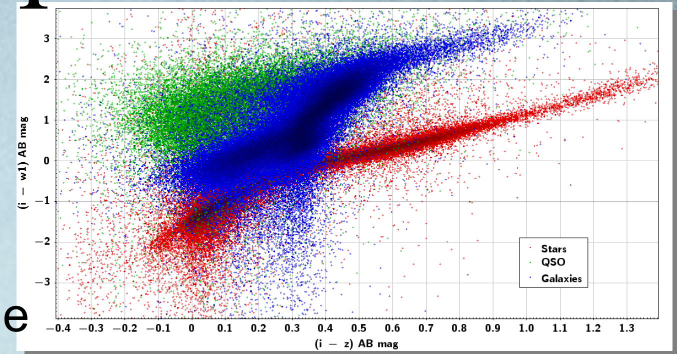


Catalog IV. Multiband - complete



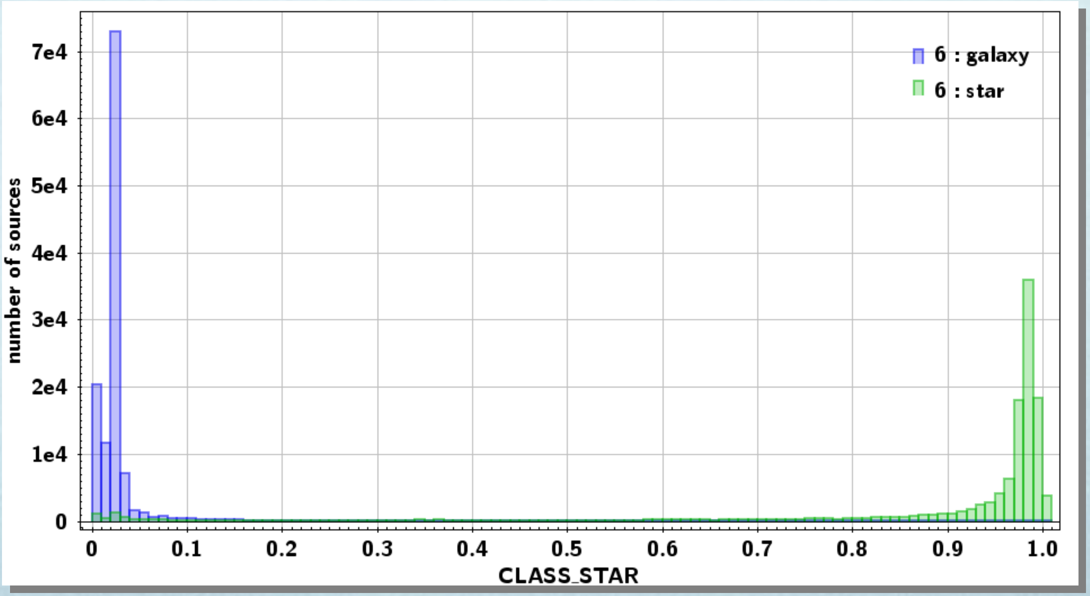
- Pixel values of "cleaned out" sources in near-IR are stored to the output catalogs.
- We match optical and near-IR catalogs by the source number and validate combined catalogs
- ***Construction of a set of 26,585,000 sources with robust fluxes in 7 bands is complete***

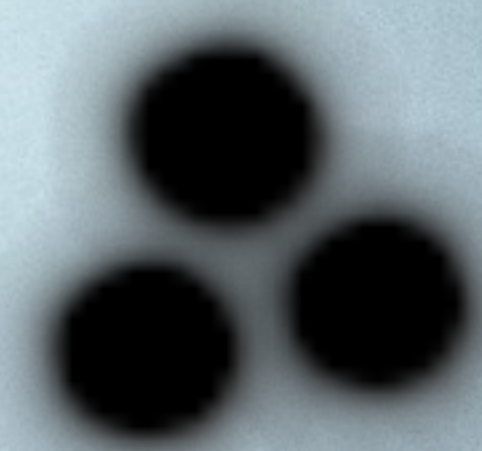
Catalog V. Star-galaxy separation



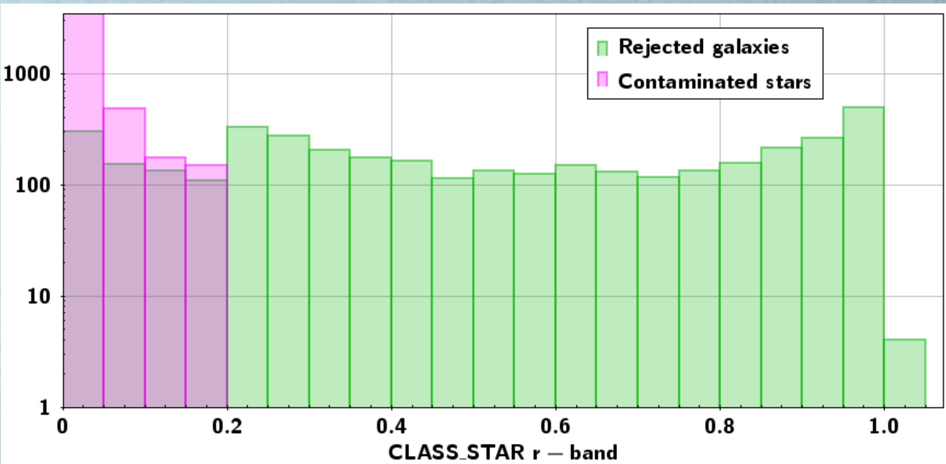
Default configuration file for SExtractor 2.8.6
#------------------------ Star/Galaxy Separation ----------------------------

SEEING_FWHM 1.1 # stellar FWHM in arcsec
STARNNW_NAME default.nnw # Neural-Network_Weight table

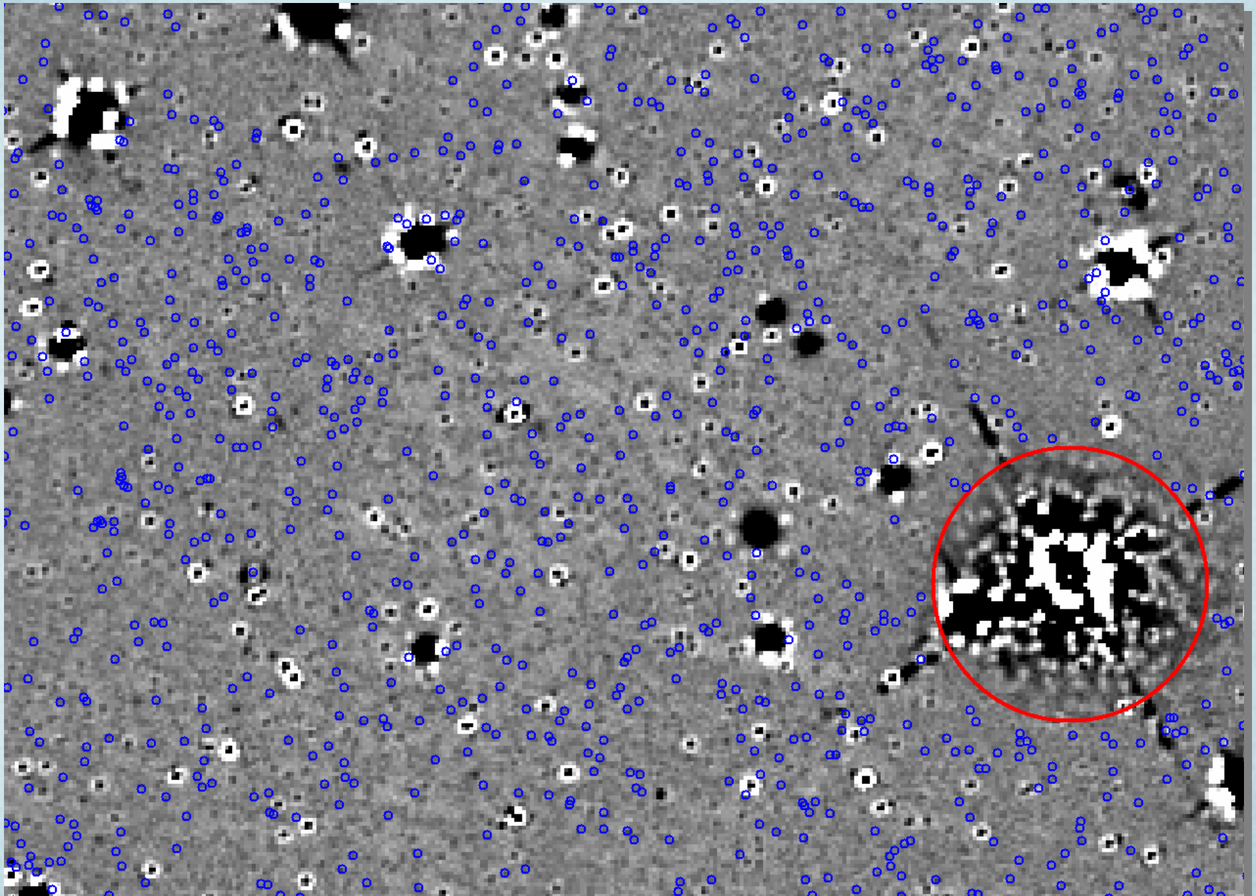




9,340,700 Galaxies with ~2% contamination by stars and QSO



Catalog V. Mask bright/saturated objects

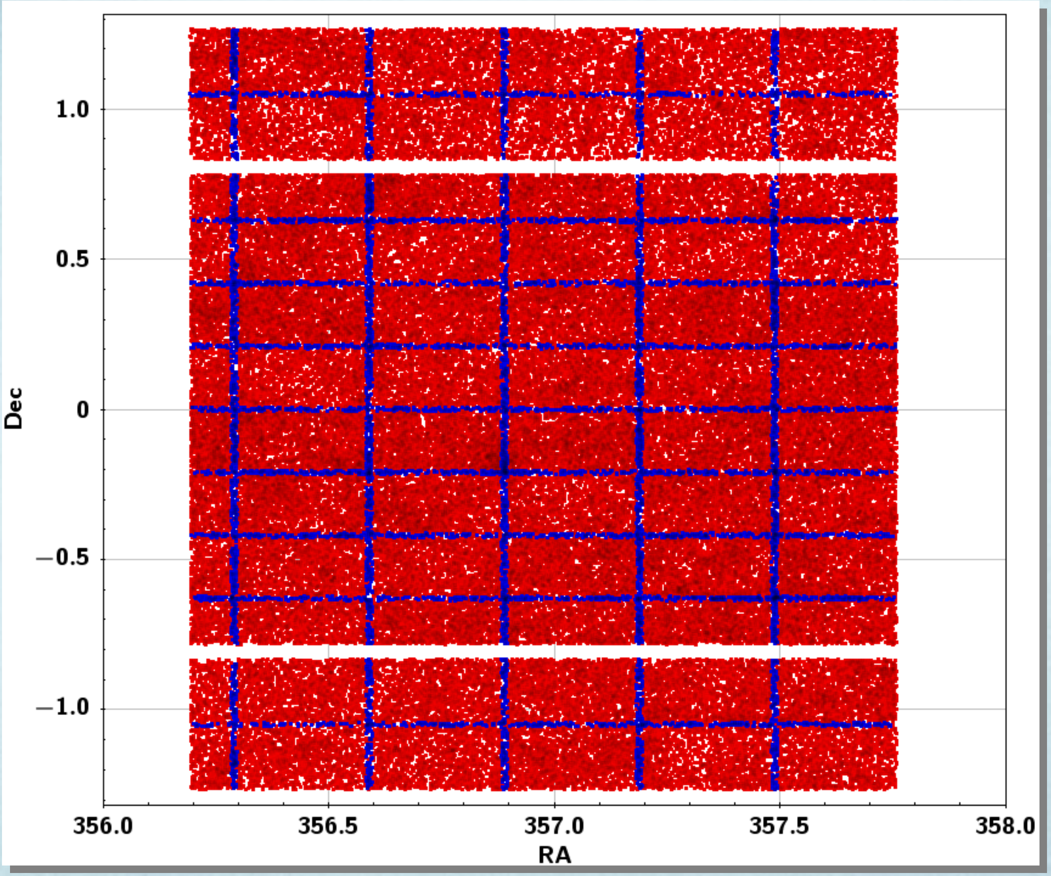


- Smithsonian astrophysical observatory star catalog
- Bright IR Star Compilation (BSIRC) – IPAC team
- 300 regions added after visual inspection
- In total - 700 masked regions in Stripe 82 with angular radii up to 500”

Final numbers before we start SED fitting:

- Total area – 288.212 $\deg^2$
- Total number of galaxies – 9,294,705, largest catalog with robust fluxes in optical and near-IR bands

Catalog V. Remove duplicate sources



Final numbers before we start SED fitting for mass estimation:

- Total area – 288.212 deg²
- 2,305,280 point-like stars selected
- 33,800 PSF constructed
- 66,700 CPU hours of TPHOT run
- 741 cups of coffee drunk

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

This catalog creates a solid basis for the future study of the galaxy evolution. Now we can present some *preliminary* results

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*
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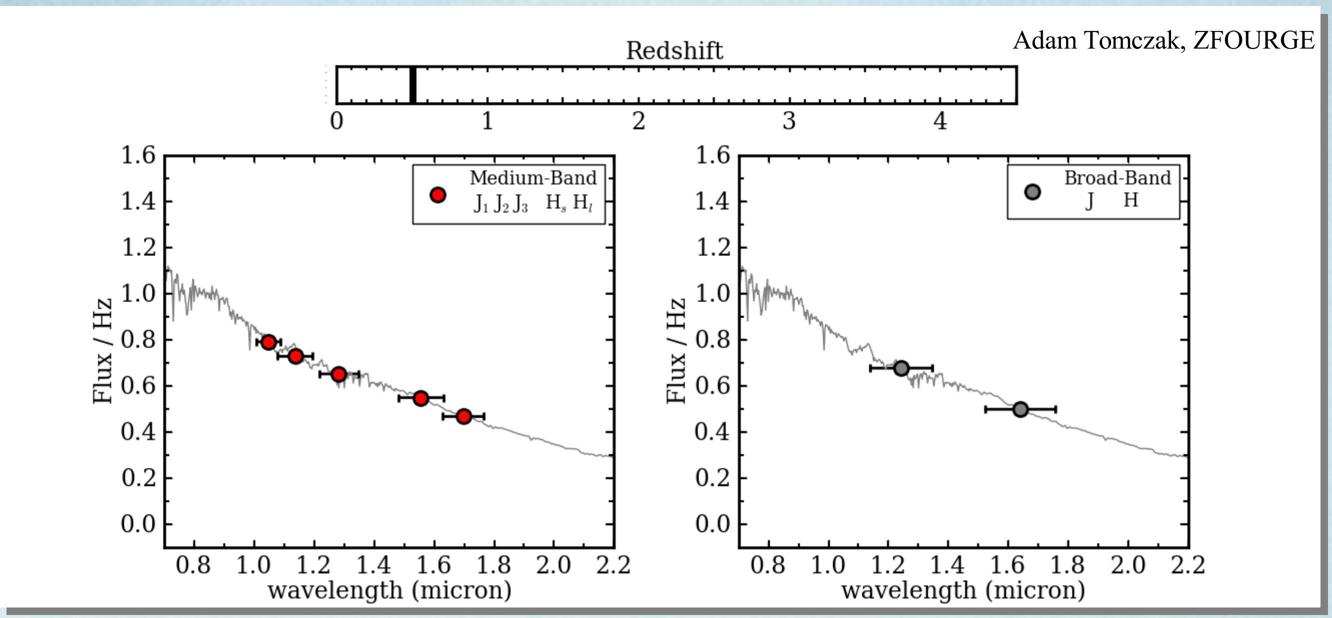
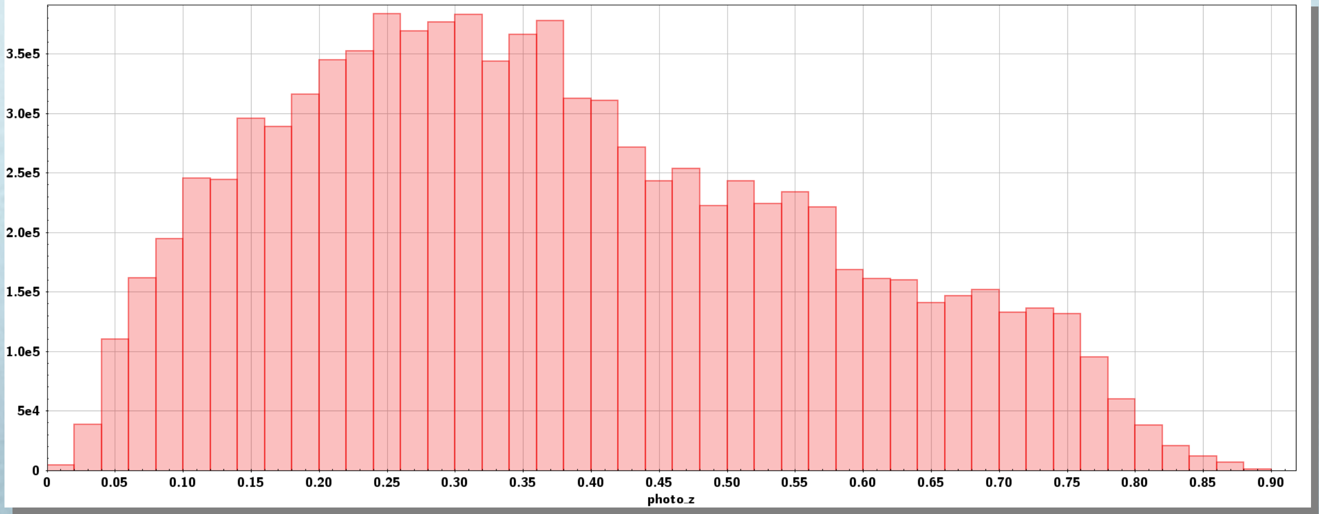
  - SED fitting
  - Calibration and validation of the catalog
  - **Constraints on GSMD**
- Results and future work
  - Future work with the catalog
  - Subsample of WoDrops
- Conclusions

SED fitting I. Photometric redshifts

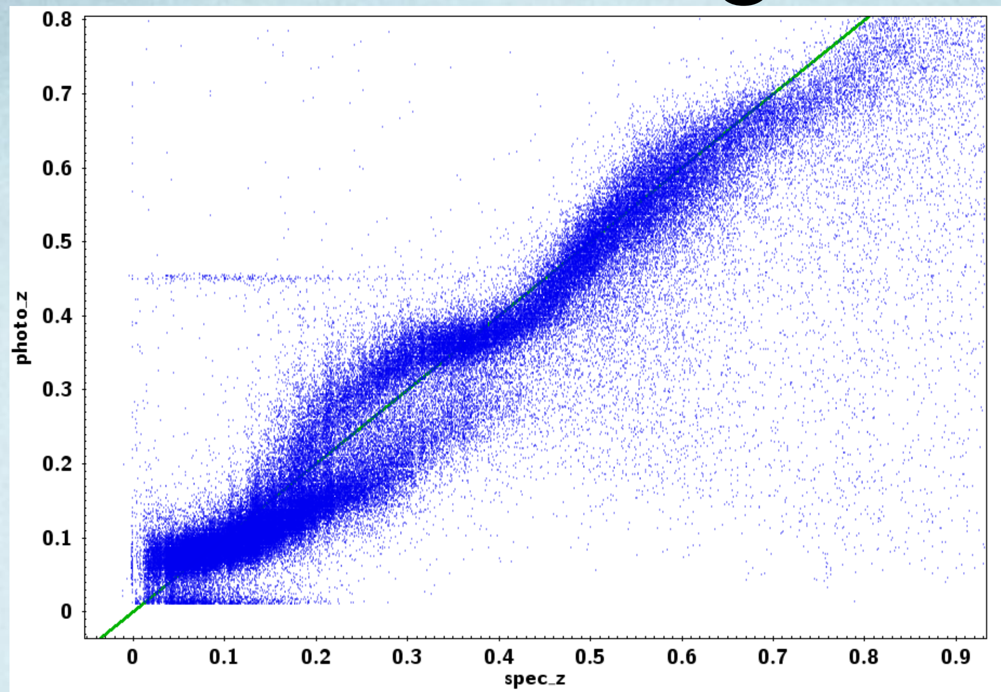




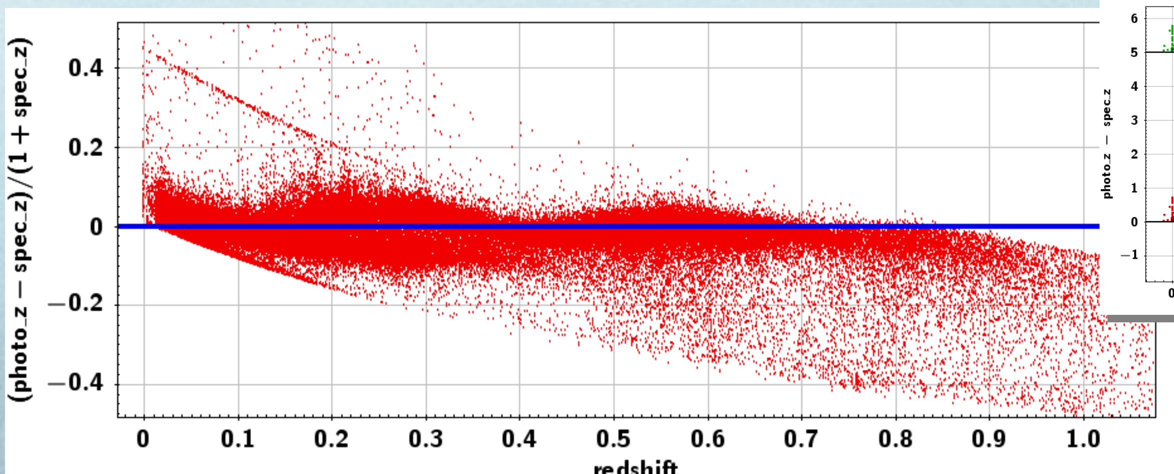
Histogram of photometric redshifts calculated with EAZY

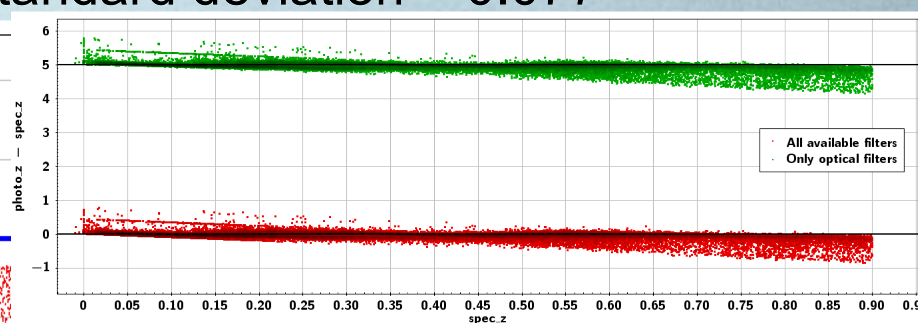
- Using small sub sample of the catalog we tested different SED fitting codes and parameters.
- We decided to utilize SED fitting code EAZY (Brammer et al. 2008) – that computes photometric redshift extremely fast.
- Another SED fitting code, FAST (Kriek et al. 2009) was used later on to calculate stellar mass

SED fitting I. Photometric redshifts



- Range in redshift for which we can get reasonable data was estimated from comparison to the “golden standard” - SDSS DR14 spectroscopic data
- Galaxies in general follow 1:1 line up to z~0.7
- Large scatter and trends needs more thoughtful analysis, several most obvious reasons were already discarded
- Mean value (spec_z-phot_z)=0.02
- Standard deviation = 0.077



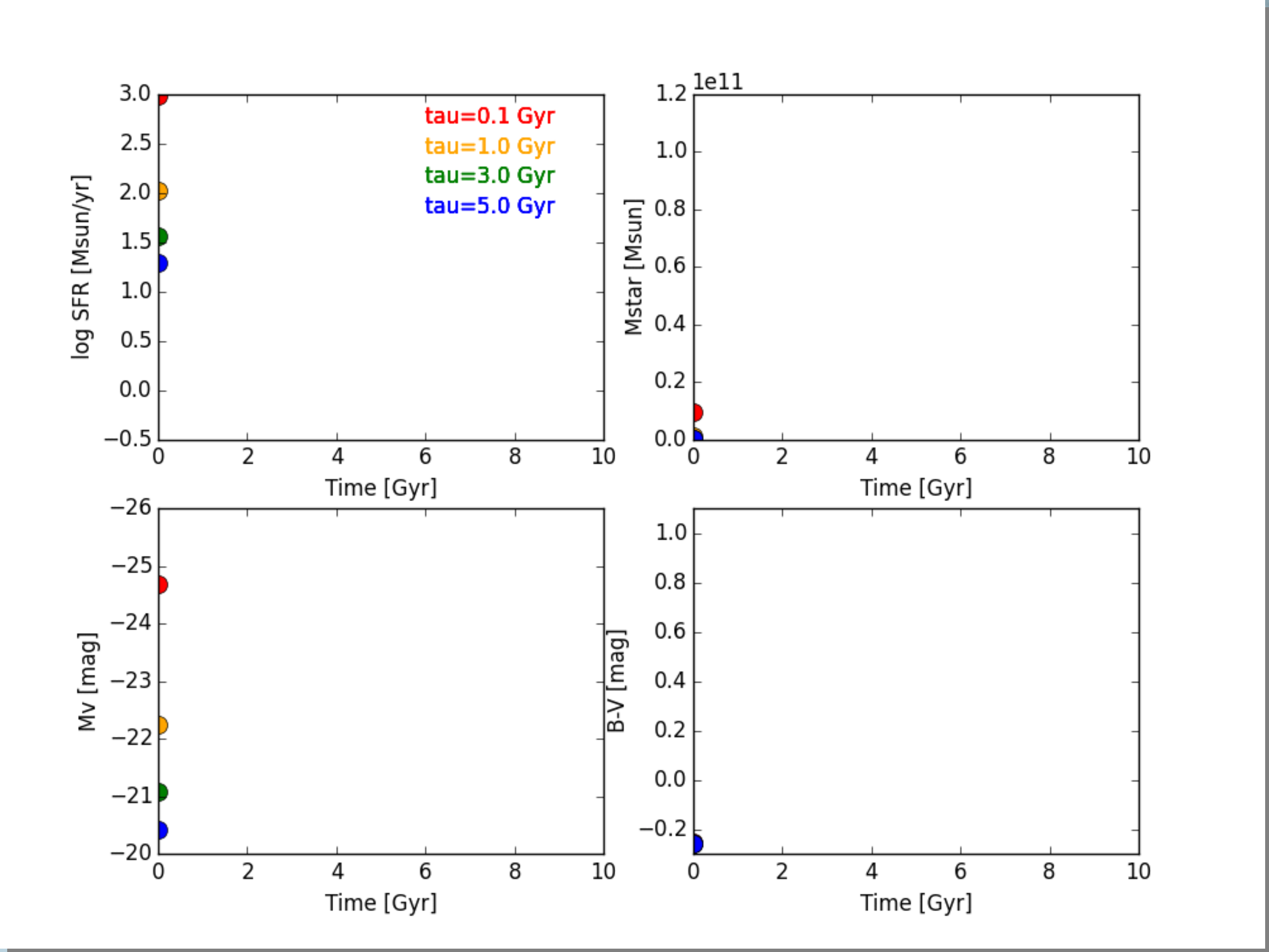


Photometric redshift estimation tests with and without near-IR bands

SED fitting II. Models for mass estimation

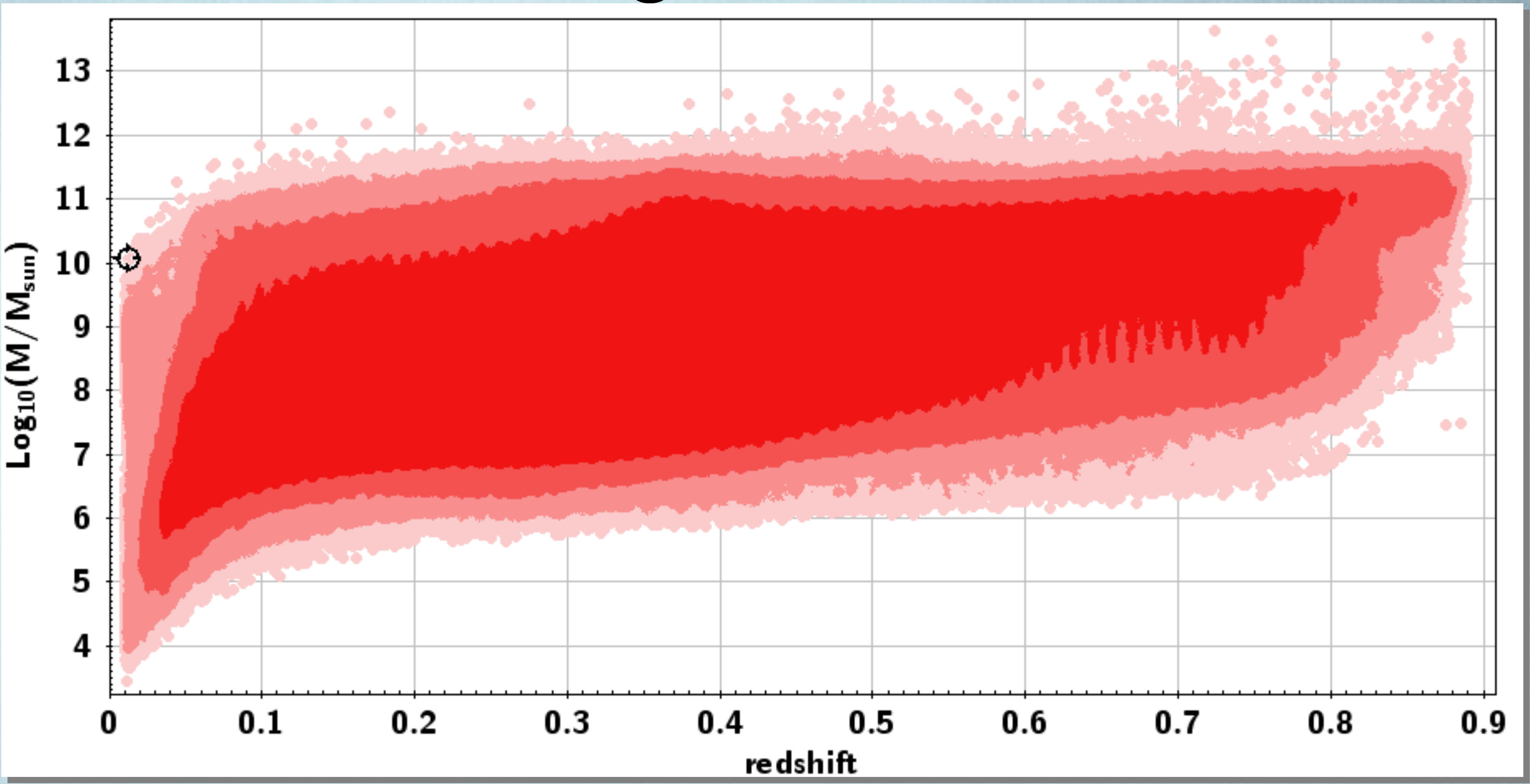
- Mass estimation is model-dependent, ***no golden standard*** to verify our parameters.
- We used FAST code with Bruzual&Charlot'03 stellar population synthesis models
- Chabrier IMF, Calzetti attenuation law, solar metallicity
- We only implemented single stellar population with exponentially declining star formation history with varying tau:

SFR(t) ~ e^(-t/tau)



Animation shows evolution of galaxy in SFR, mass, magnitude and color with exponentially declining star formation rates for 4 different free parameters “tau”.

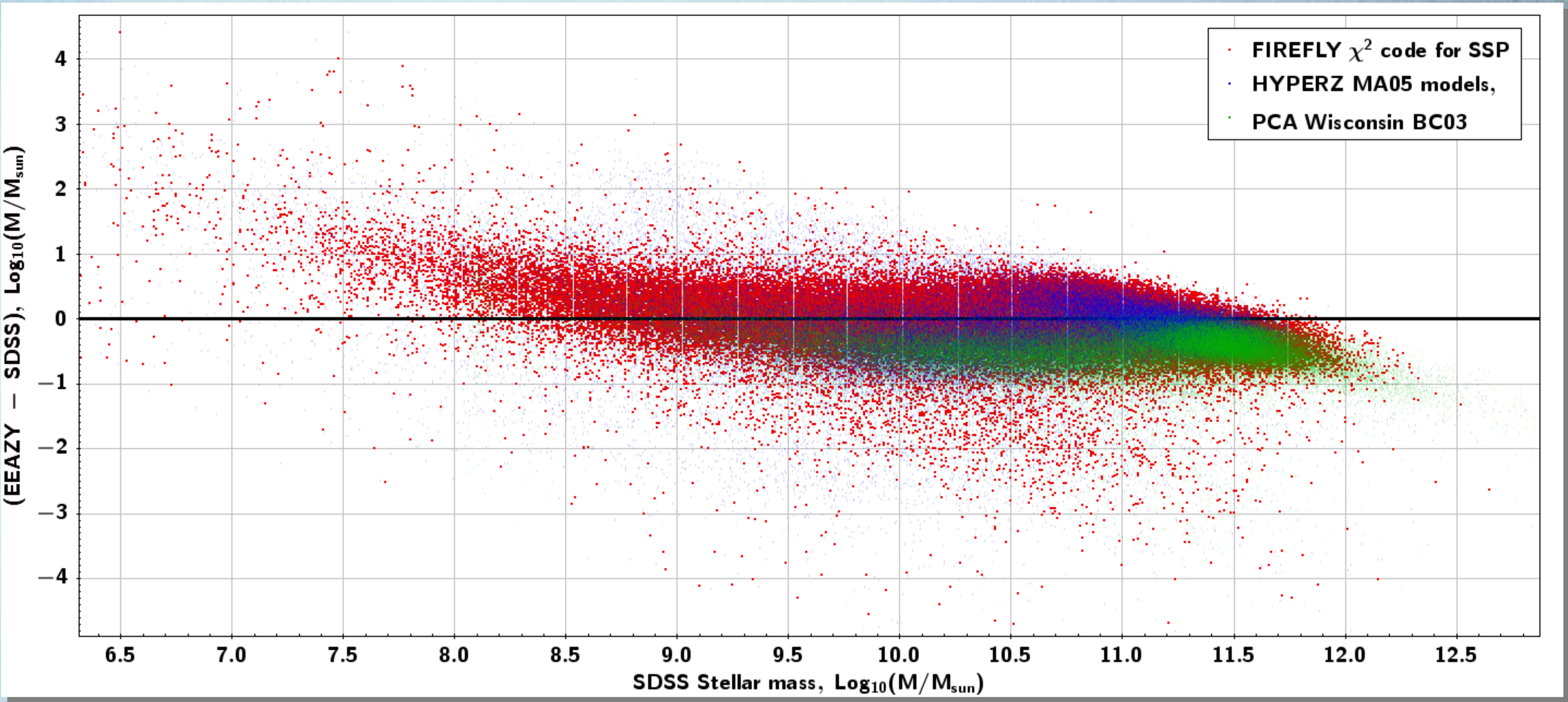
SED fitting III. Stellar masses



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

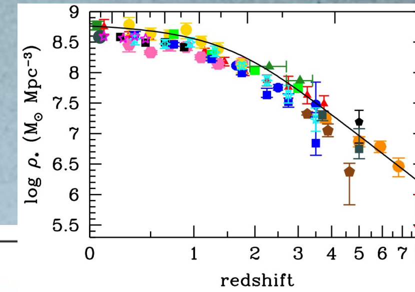
Can you find our Milky Way?

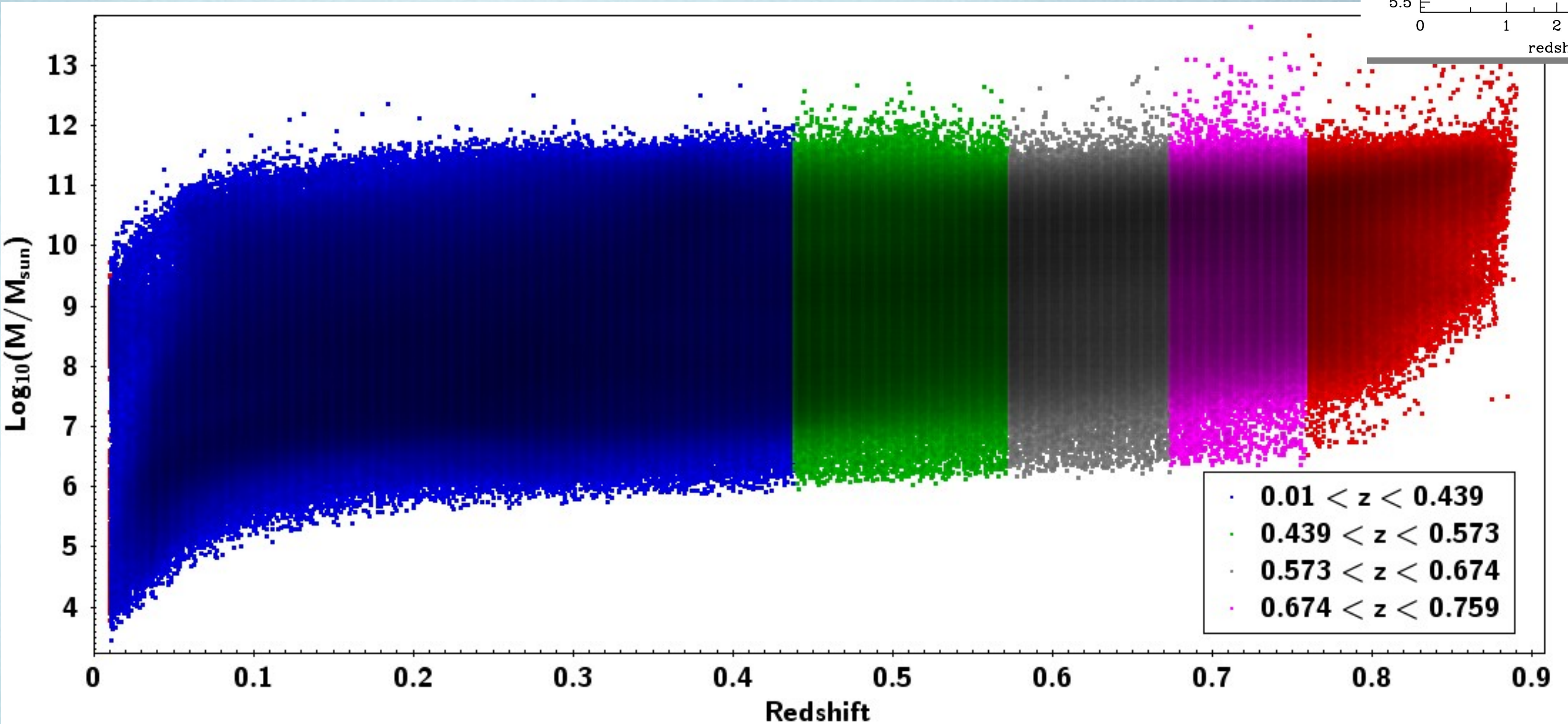
SED fitting III. Compare stellar masses



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

GSMD I. Redshift binning

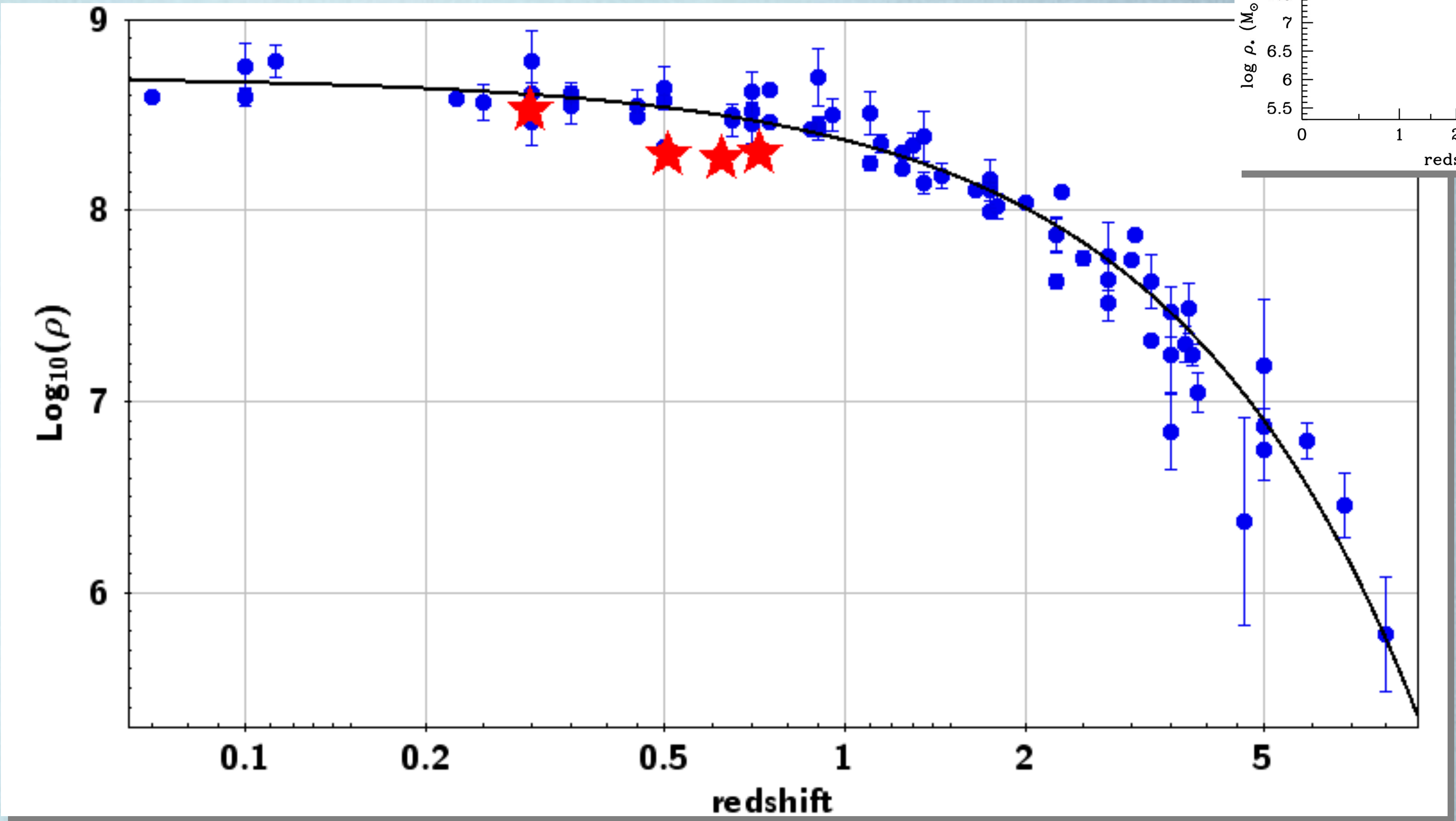


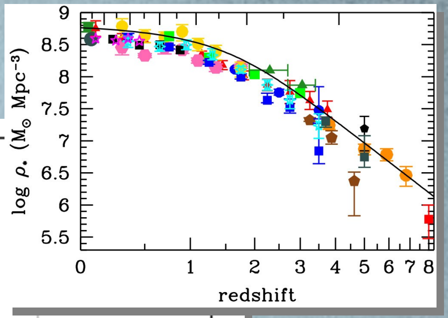


We take 4 comoving volume bins of equal size– 20 Gpc^3.
Red points – sample is highly incomplete and will bias our estimates.

#	redshift interval	mean redshift	# of galaxies per bin	fraction of galaxies per bin
1	$0.010 < z > 0.439$	0.296	6,065,140	0.65
2	$0.439 < z < 0.573$	0.506	1,588,509	0.17
3	$0.573 < z < 0.674$	0.623	812,562	0.09
4	$0.674 < z < 0.759$	0.716	585,009	0.06

GSMD II. Our results

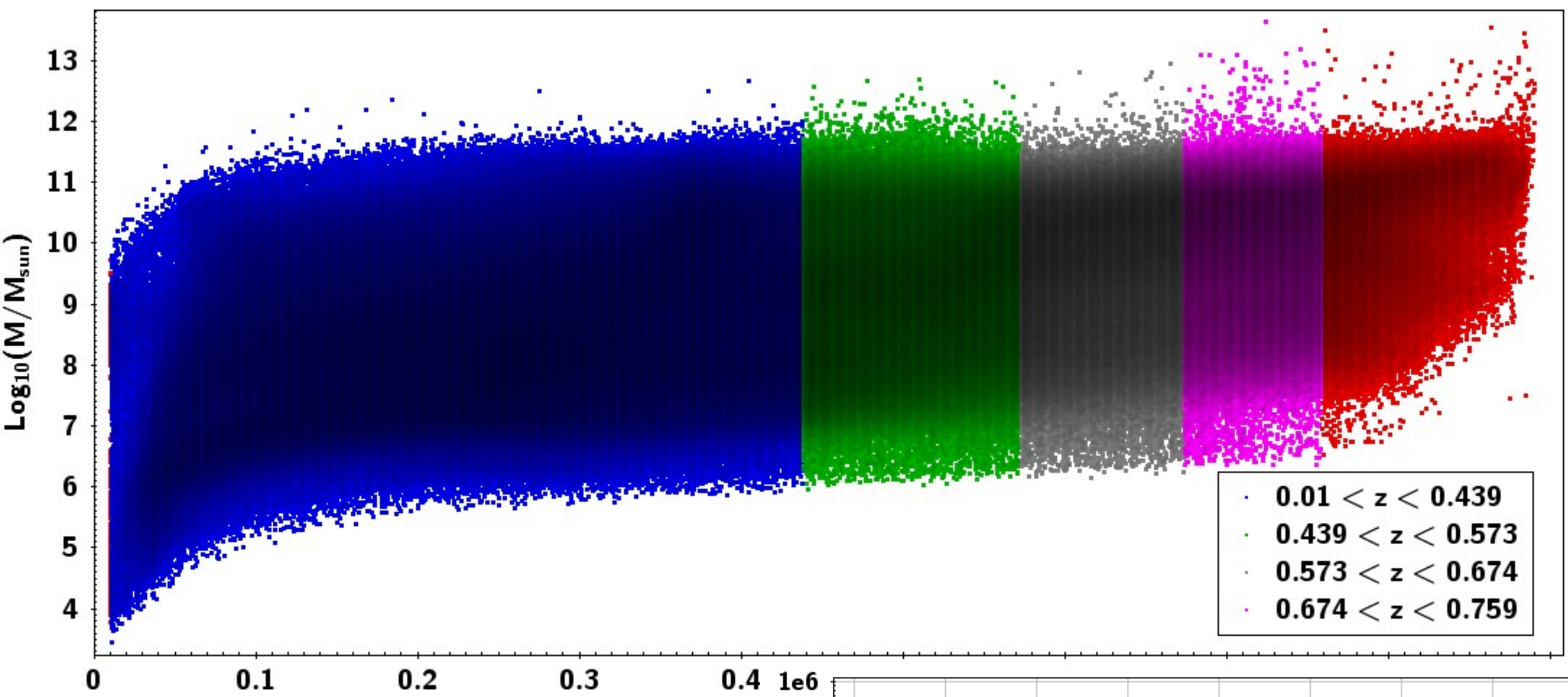


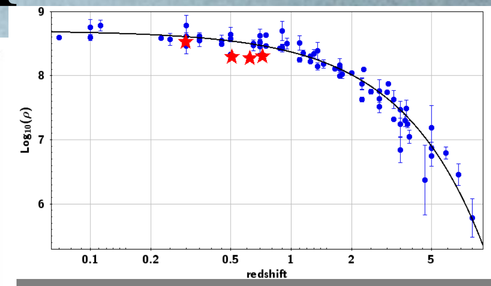


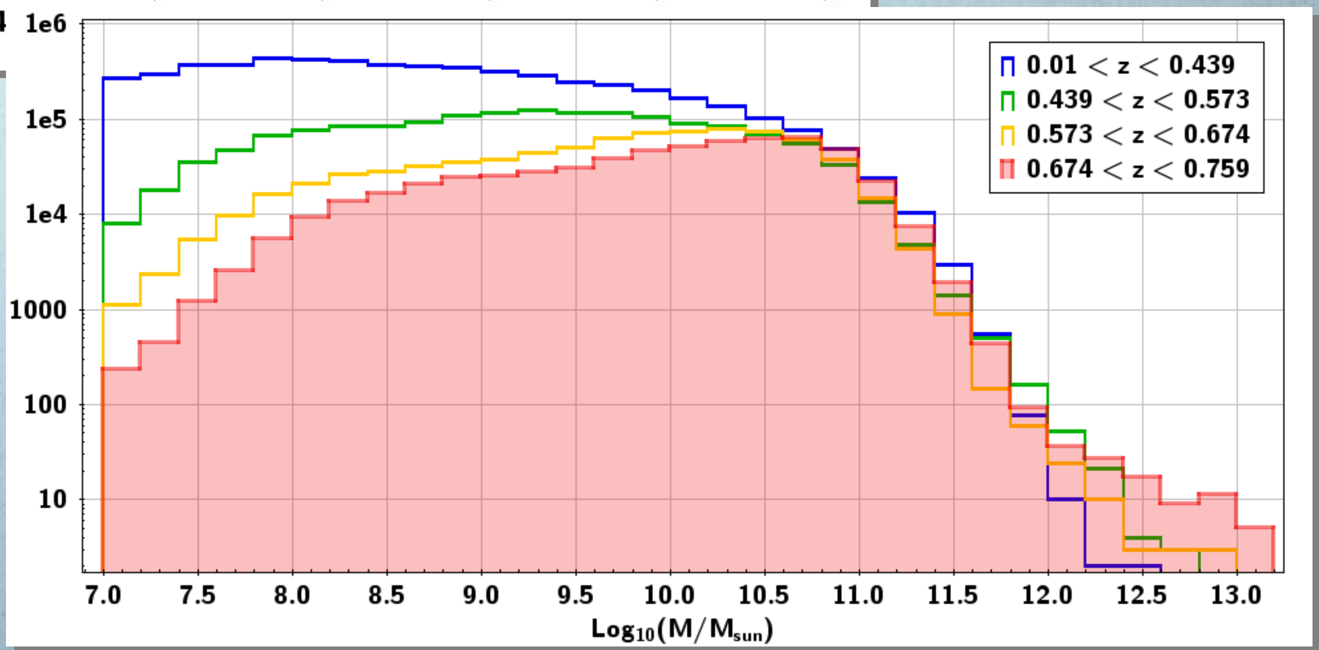
Global stellar mass density – evolution of the stellar mass in a given volume bin in time

#	redshift interval	light-trvel time interval	total mass	$Log_{10}(\rho)$ Salpeter IMF
	z	Gyr	$M_\odot$	$Log_{10}(M_\odot/Mpc^3)$
1	$0.010< z <0.439$	0.139-4.589	$2.785 \cdot 10^{16}$	8.514
2	$0.439< z <0.573$	4.589-5.537	$1.671 \cdot 10^{16}$	8.292
3	$0.573< z <0.674$	5.537-6.154	$1.569 \cdot 10^{16}$	8.265
4	$0.674< z <0.759$	6.154-6.619	$1.718 \cdot 10^{16}$	8.304

GSMD III. A few words about completeness

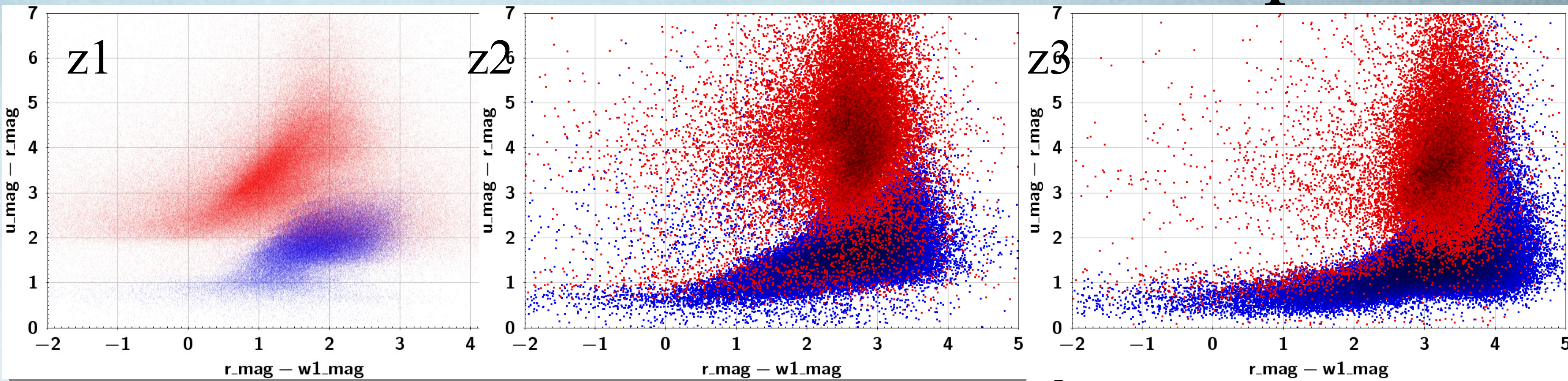


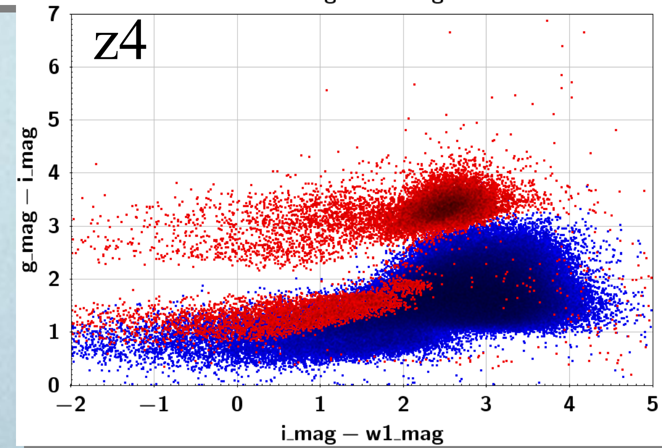




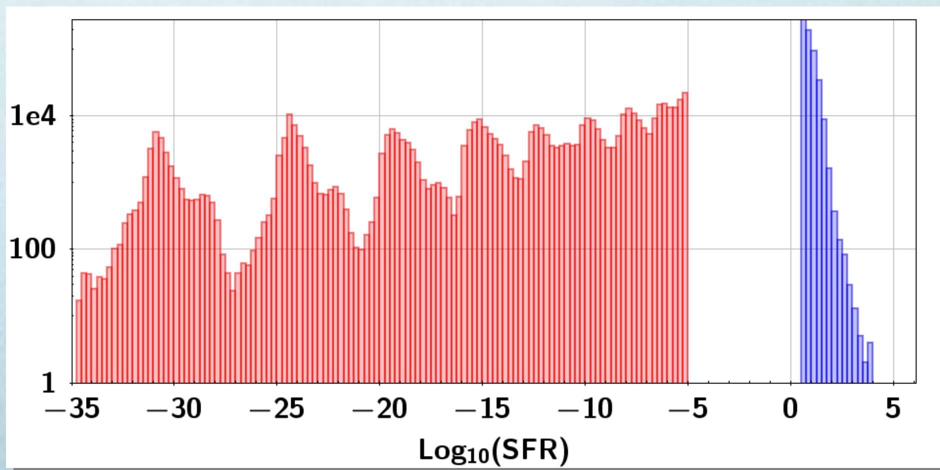
We are incomplete in the low-mass region, this still needs to be corrected

GSMD III. Blue cloud and red sequence





Observed bi-modality between late-type (spiral) and early type (elliptical) galaxies in different redshift bins

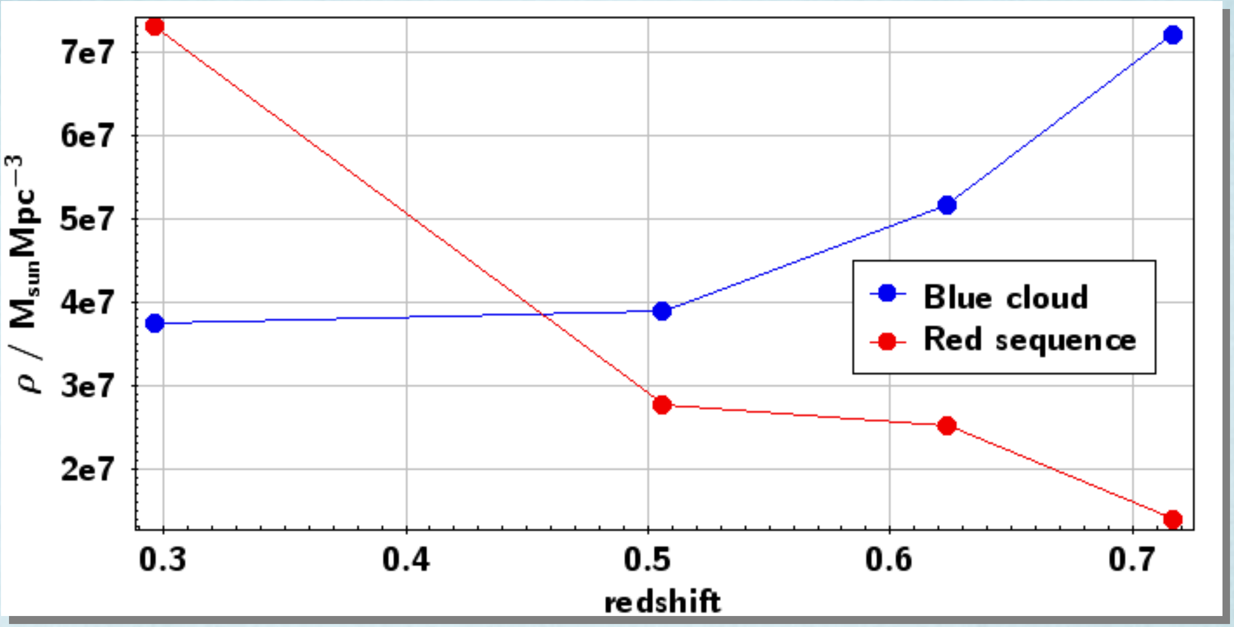


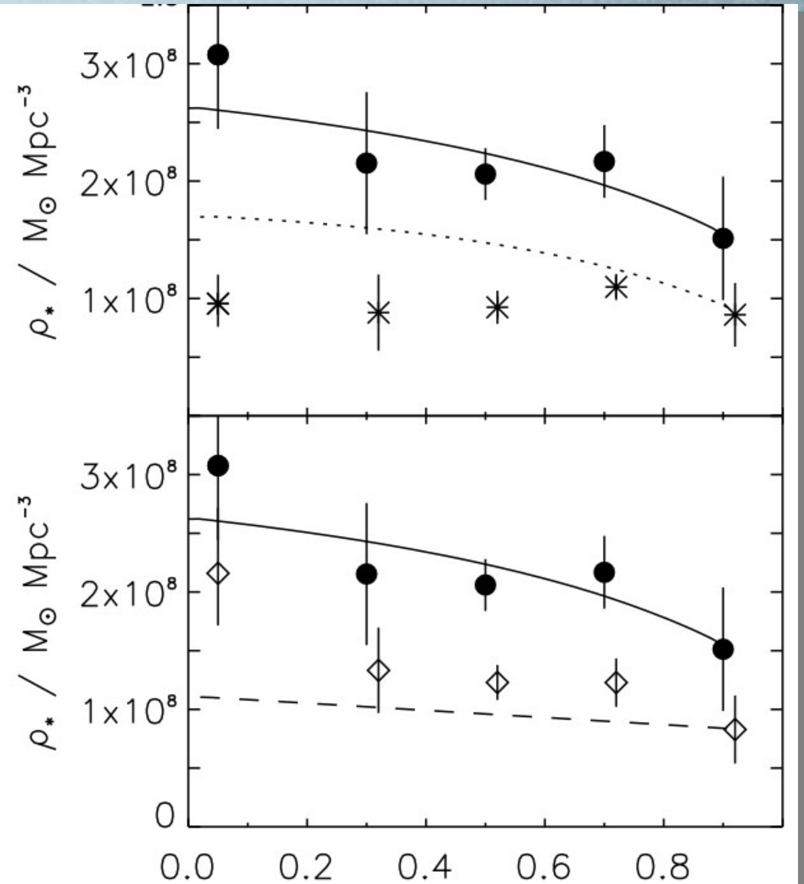
	λ, nm @z=0	Color @z=0	λ, nm @z=0.7	Color @z=0.7
u-band	355.1	NUV	603.7	orange
g-band	468.6	blue	778.6	red/IR
z-band	893.1	near-IR	1518.3	IR

Colors are not in the rest frame

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

GSMD III. Blue cloud and red sequence





Bell et al. 2007

"Blue, star-forming galaxies are shutting off their star formation on global scales and are fading onto the red sequence."

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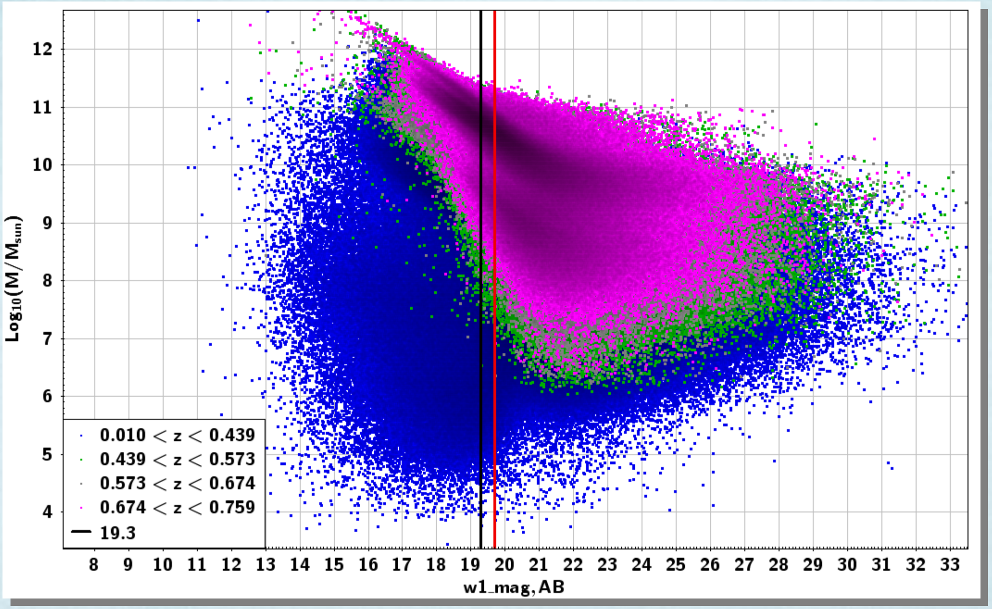
Future work and conclusions I.

Moving deeper

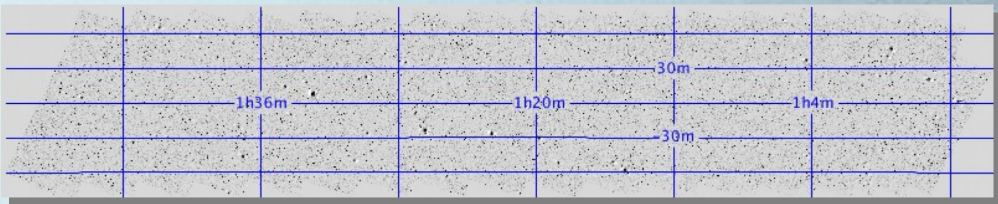


As of now 53% of the sources fall below 3σ detection limit in w1. New data were released 2 months ago – NEOWISER. Limiting mag is 0.38 deeper. And not just deeper – artifacts and transients are removed after stacking images taken at different time. Detection is now more robust.

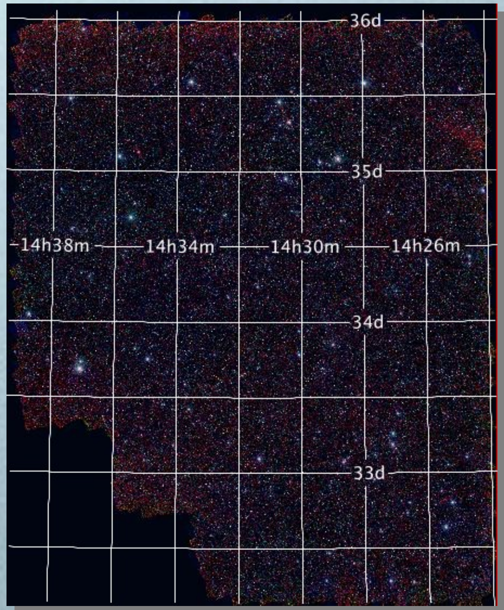
It should not take long to make 480 new PSFs and run the computational cluster all over.

Moving on

Spitzer telescope has 2 imaging instruments: IRAC (3.6μm, 4.5μm, 5.8 μm, 8 μm) and MIPS (24μm, 70 μm, 160 μm)



Images in SHELA region are 80% complete to 22.0 AB mag



The Spitzer Deep, Wide-Field Survey (SDWFS) is complete to 22.56 AB mag

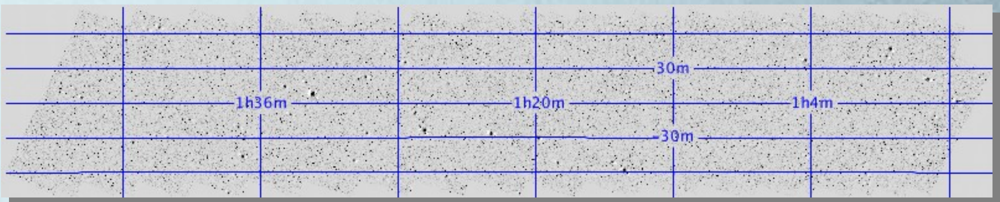
Future work and conclusions I.

Moving wider

- Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) for wide-field imaging
- 1.8 meter telescope,1.4 Gpx camera, 7 deg² FOV
- Filters g, r, i, z, y with 3σ limit 23.8, 23.7, 23.6, 22.8 and 21.8
- Observes ¾ of the sky (all you can get from Hawaii)

Moving on

Spitzer telescope has 2 imaging instruments: IRAC (3.6μm, 4.5μm, 5.8 μm, 8 μm) and MIPS (24μm, 70 μm, 160 μm)



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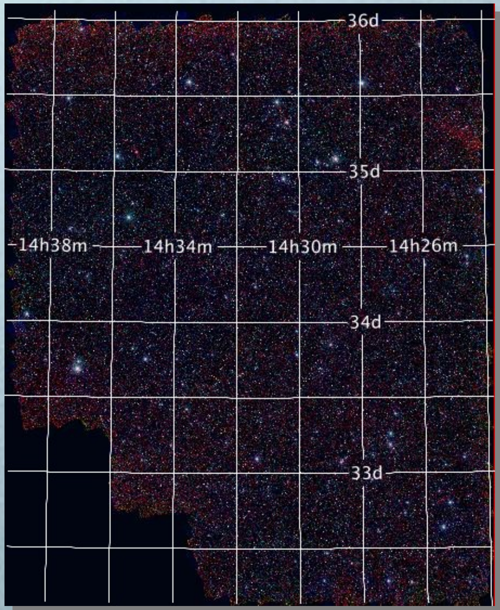

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Future work and conclusions I.

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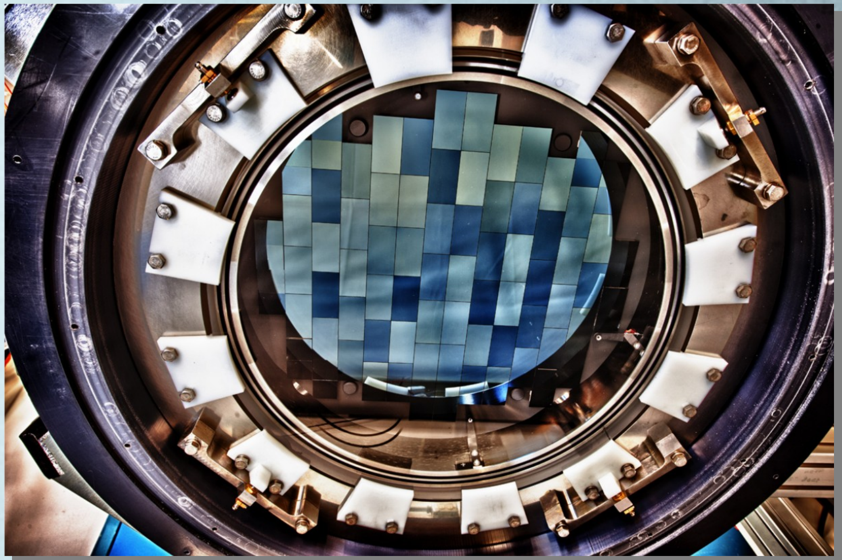
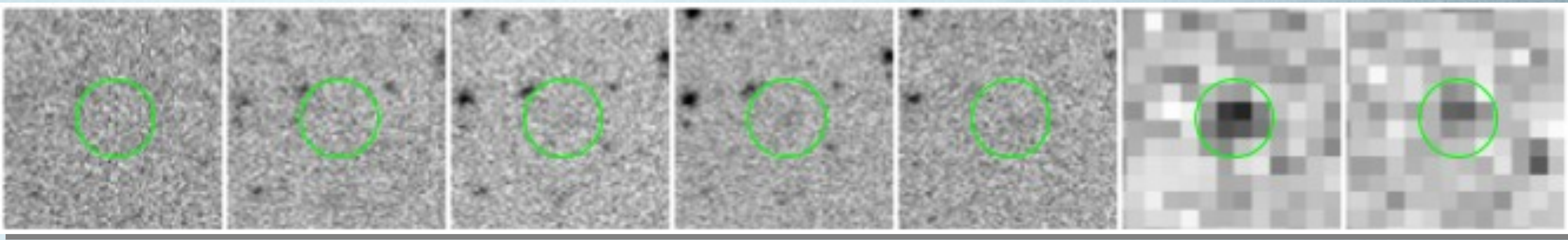
Moving deeper



- Dark Energy Survey (DES)
- 4-m Victor M. Blanco Telescope, 3.8 deg^2 FOV
- Filters g, r, i, z, y with 24 AB mag limit in i-band
- 5000 deg^2 in the southern sky

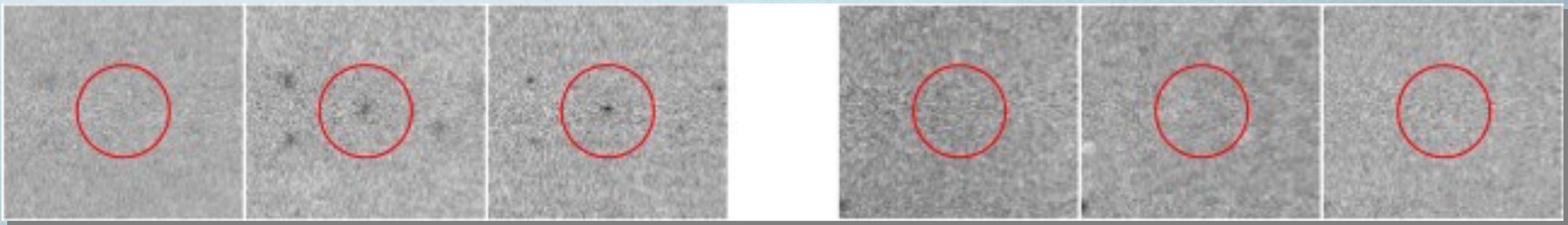
Future work and conclusions II. WoDrops

Example of WoDrop in Stripe 82



u g r i z w1 w2

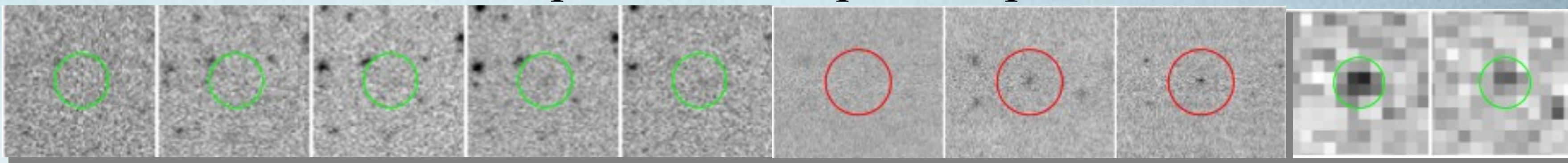
Follow up observations of two selected WoDrops with WHIRC

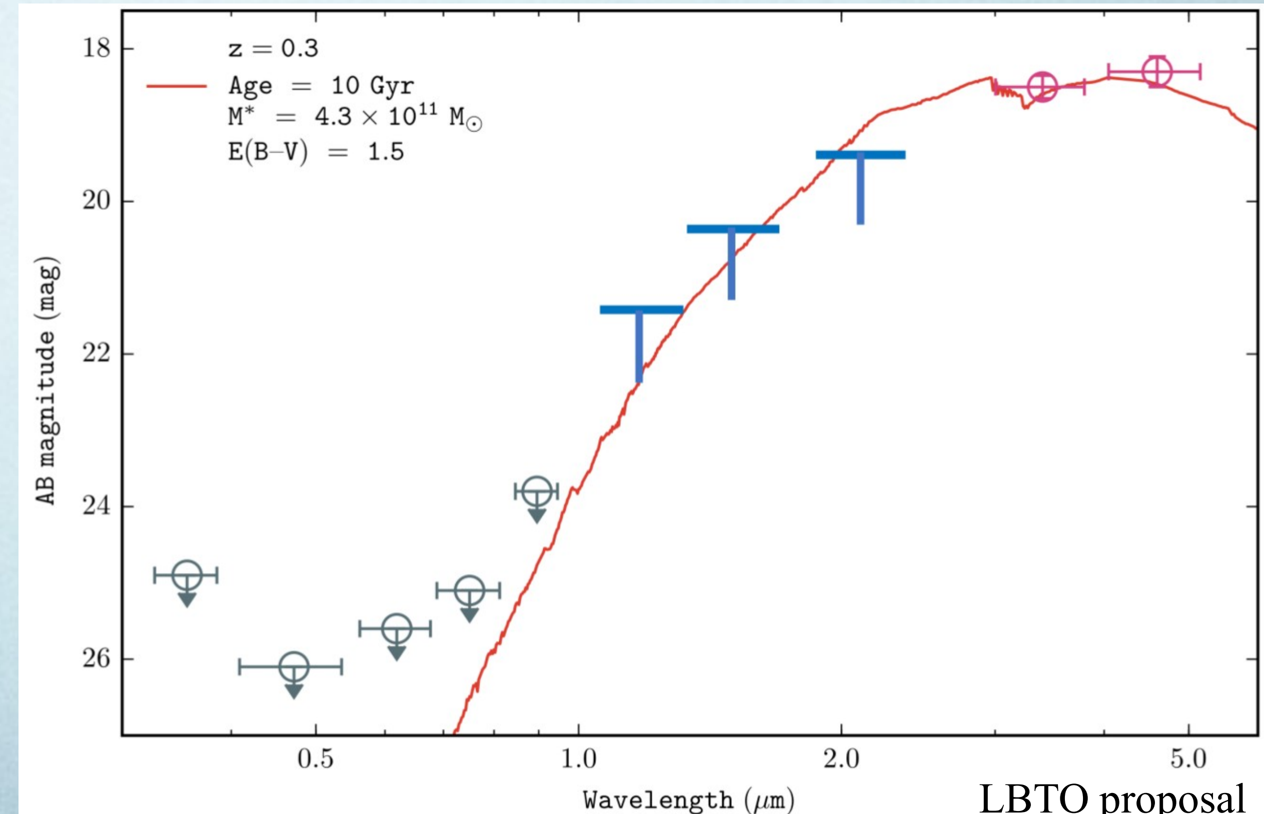


J H Ks J H Ks

Future work and conclusions II. WoDrops

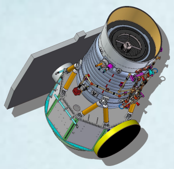
Example of WoDrop in Stripe 82

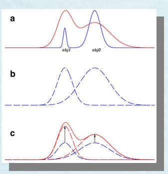


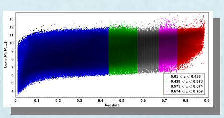


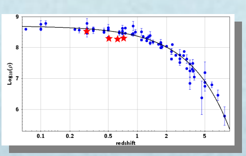
Such galaxies must be at low redshift (z < 0.5), and their dominant population should be high-mass (~10^11 Msun), maximally-old and with very large amount of dust extinction (E(B-V)> 1.0 mag). 5-σ limits of WIYN/WHIRC observations are indicated by blue symbols

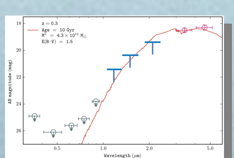
Summary











- 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 field 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 fluxes and colors in optical and near-IR, which has much worse resolution and suffers blending
- 7-band photometry broke color degeneracy and allowed us to derive robust redshifts, masses and mass densities
- We constructed GSMD up to z~0.8 that is 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