Synergy of the SDSS and the WISE in the Stripe 82: physical properties of 15 million galaxies

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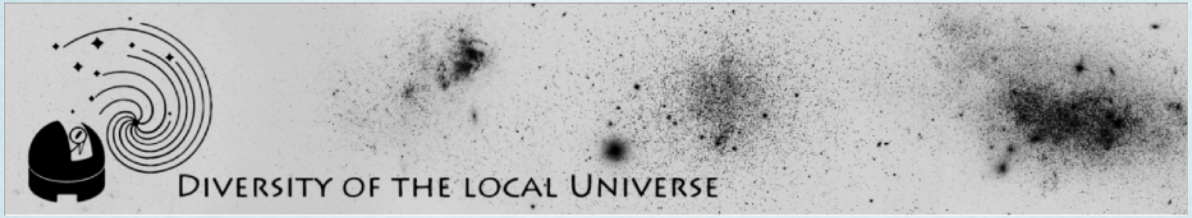
in collaboration with: Haojing Yan and Jiasheng Huang

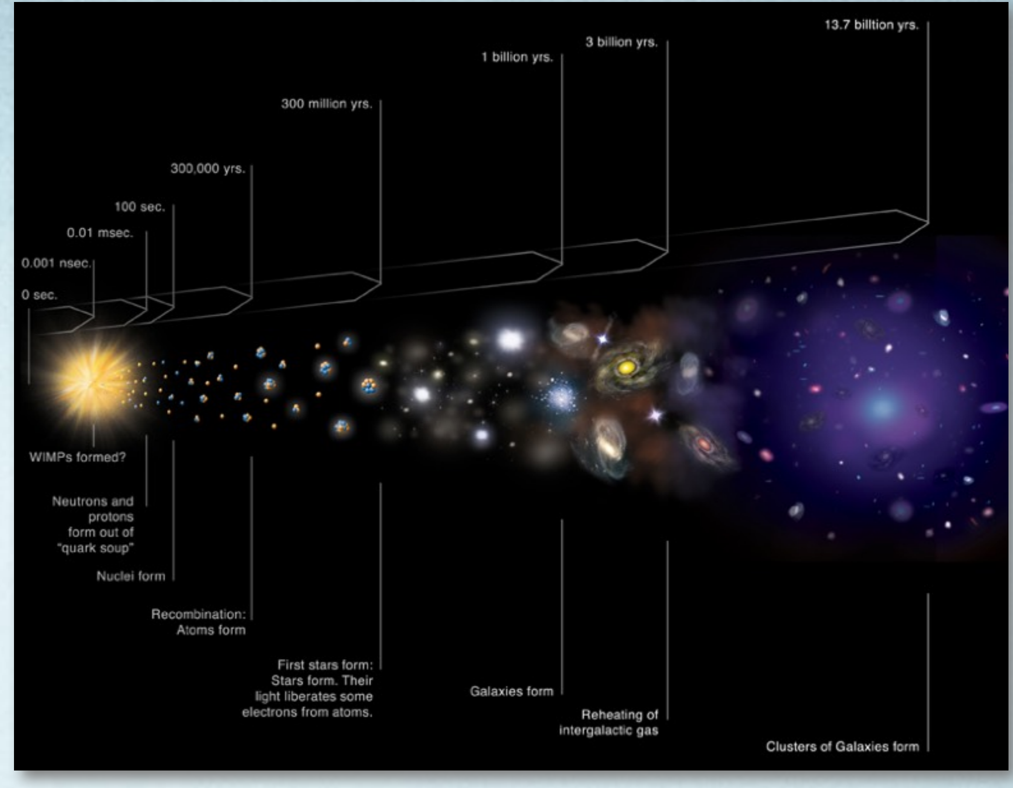
1 October, 2019



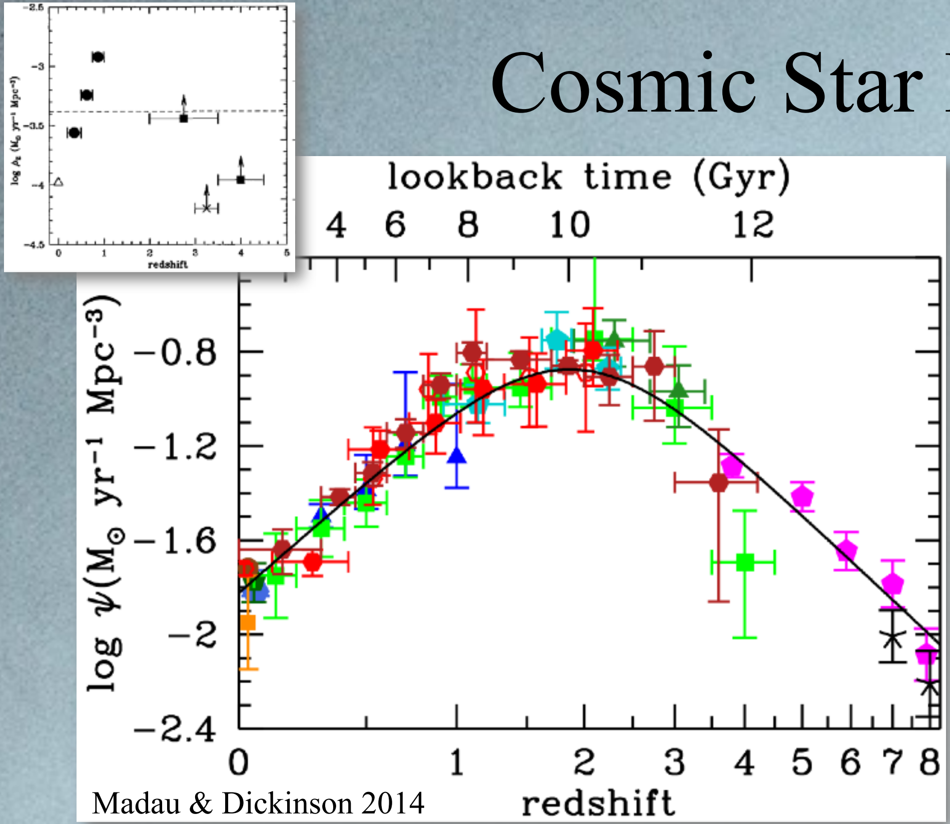
Special Astrophysical Observatory, Russia

Outline

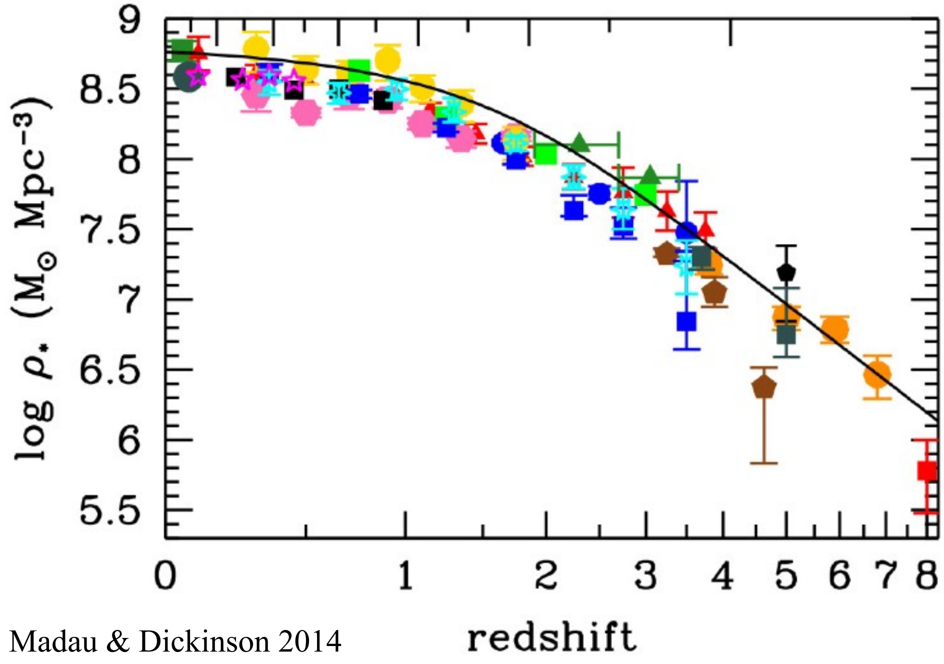
- Context — evolution of galaxies over the cosmic time:
  - Lilly-Madau diagram, Cosmic Star Formation History (CSFH) and Global Stellar Mass Density (GSMD)
  - Stellar mass of galaxies: data we need and problems we have
- Sample — wide field optical and near-IR surveys:
  - **Unique approach — "template fitting" to obtain consistent flux measurements**
  - Construction of the largest optical and near-IR catalog of its kind
- Redshift and mass estimates:
  - SED fitting vs neural network
  - Constraints on GSMD
- Another result:
  - Subsample of WoDrops



Cosmic Star Formation History



Madau & Dickinson 2014

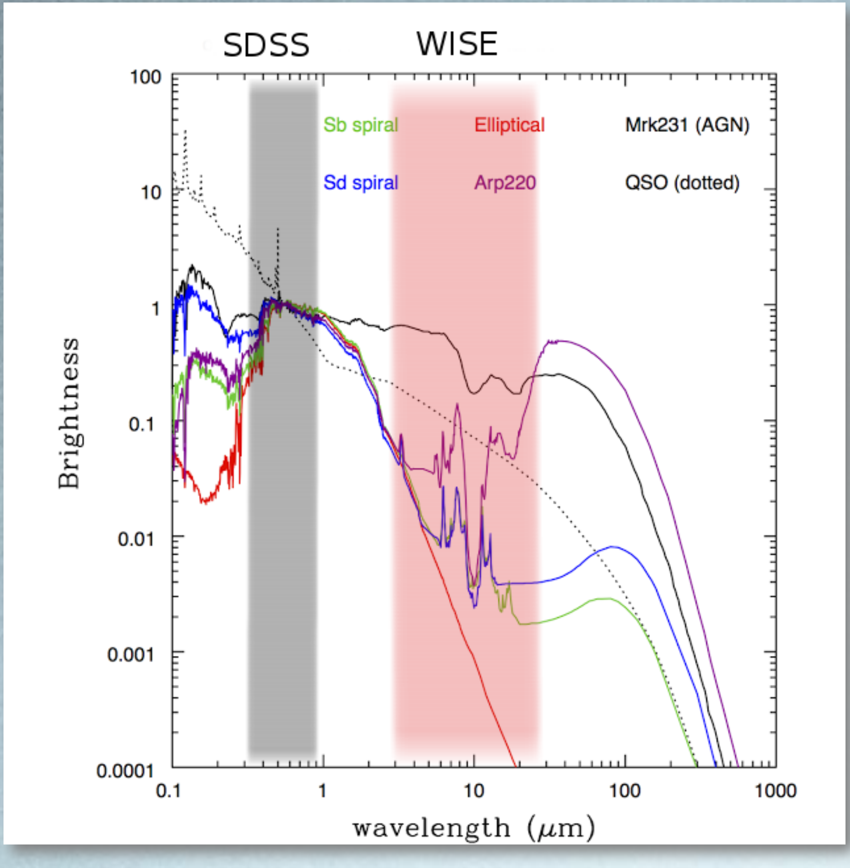


Madau & Dickinson 2014

GSMD traces the same physical processes as GSFRD (because integral of SFR over time gives mass) but from a different angle, and thus provides an independent venue to investigate the evolution of the Universe

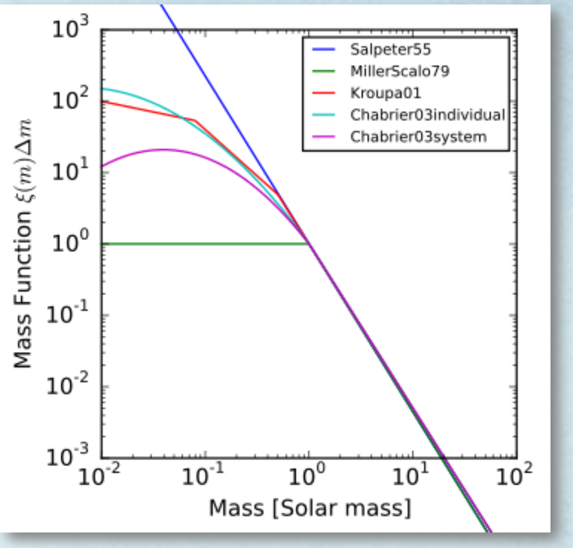
Our goal is to contribute to the study of GSMD up to z~0.85 in a unique way so that we can provide strong constraints to galaxy evolutionary models

Synergy of optical and near-IR



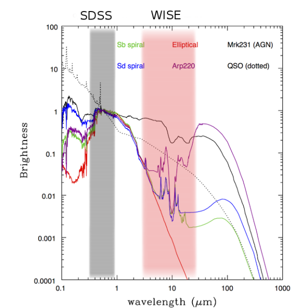
Degeneracy of dust vs. age:

- Galaxy with red SED can be dusty
- May have a very old (red) stellar population
- ISM with high metallicity effectively absorbs UV

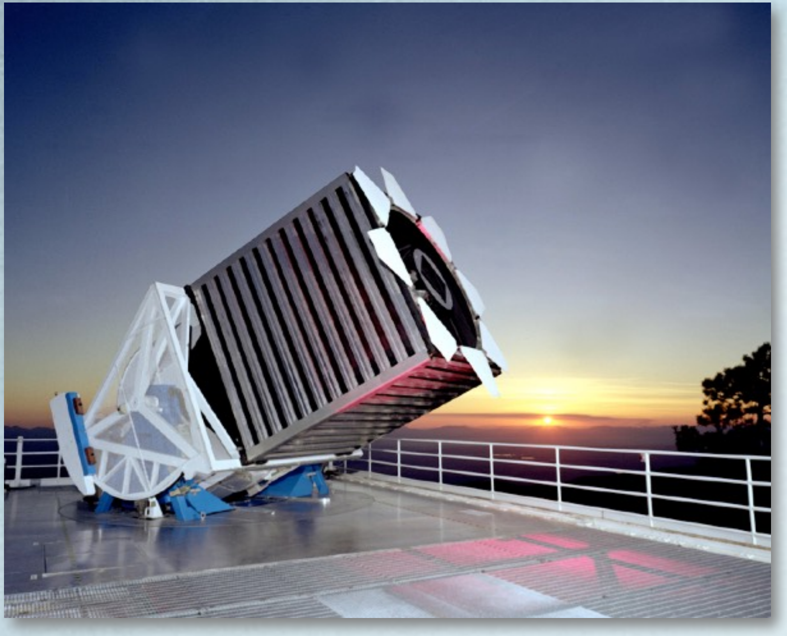


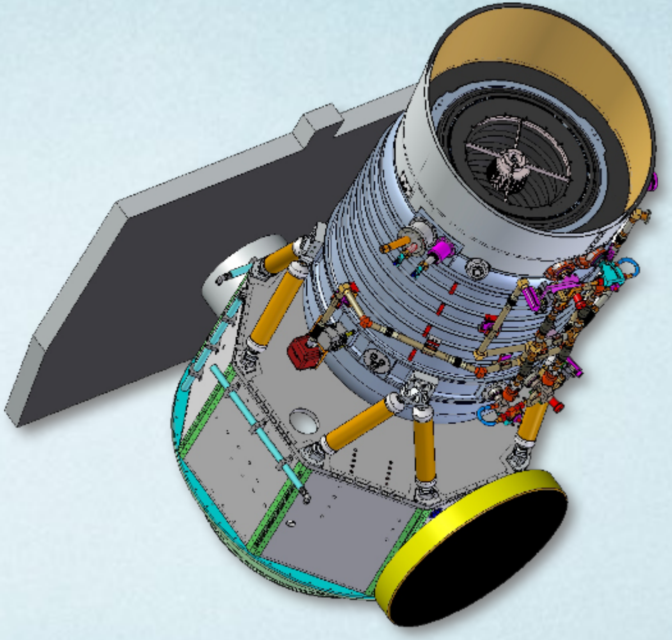
Low-mass stars are cool, red and (no matter what IMF you choose) contribute most to the total stellar mass budget of the galaxy. Near-IR data are needed to account for them!

Facility and data I. SDSS and WISE

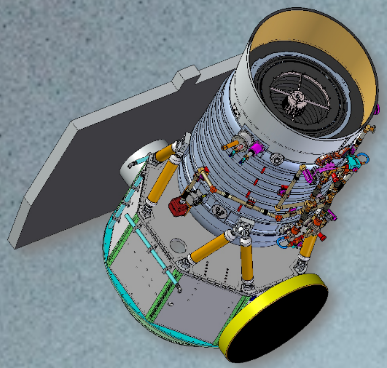


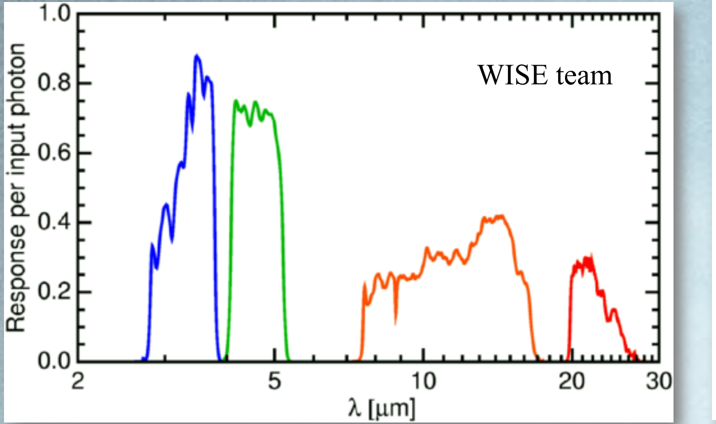
We need a synergy of optical and near-IR data from as deep and as wide-field data samples as possible



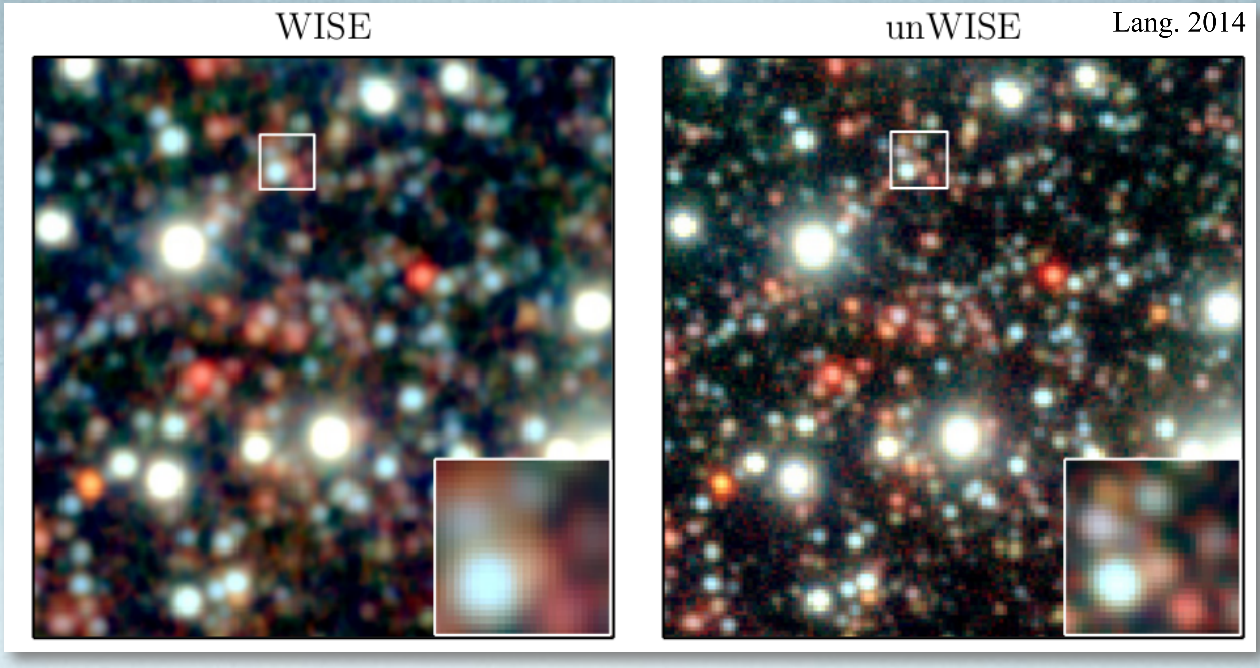


Facility and data II. Not WISE - unWISE





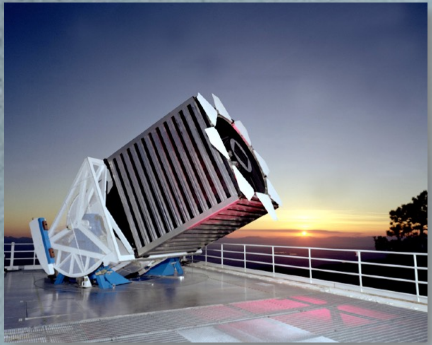
Band	w1	w2	w3	w4
Central λ,μm	3.4	4.6	12	22
Mag_{lim} (5 σ), AB	19.53	18.94	16.49	14.62
Flux limit, mJy	0.068	0.098	0.86	5.4
FWHM, asec	6.1	6.4	6.5	12.0
Pixel size	2.75 "/pix (restored in unWISE)			



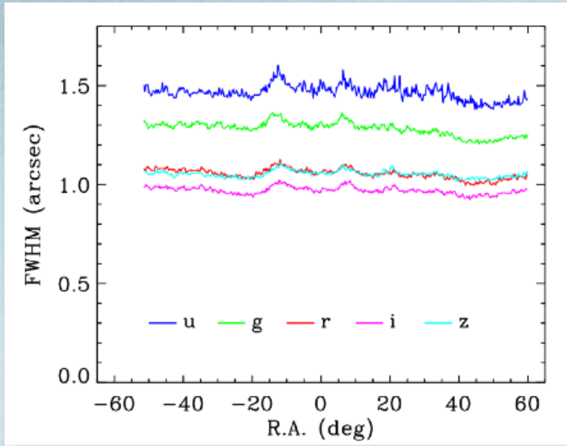
Lang. 2014

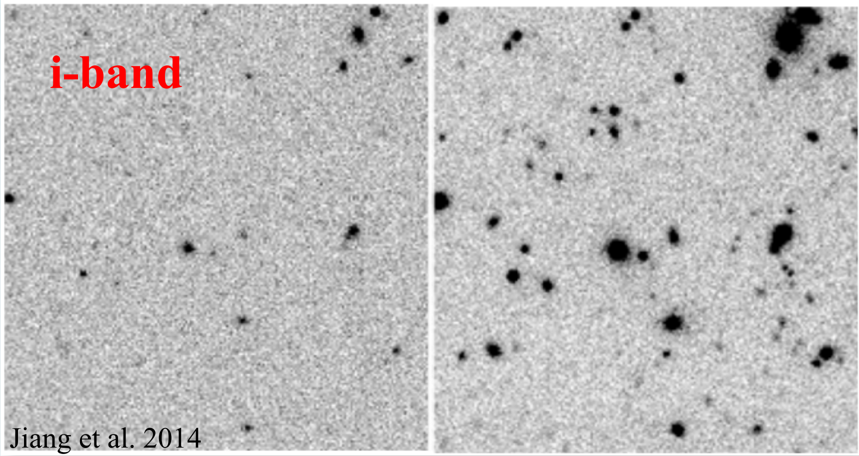
The 7’×7’ co-add tile of the north ecliptic pole, three-band composites (W1, W2, W3). Left: AllWISE Release Atlas Image (1.375”/pix). Right: unWISE co-add with restored intrinsic resolution (2.75”/pix)

Facility and data III. Co-adds in SDSS Stripe 82

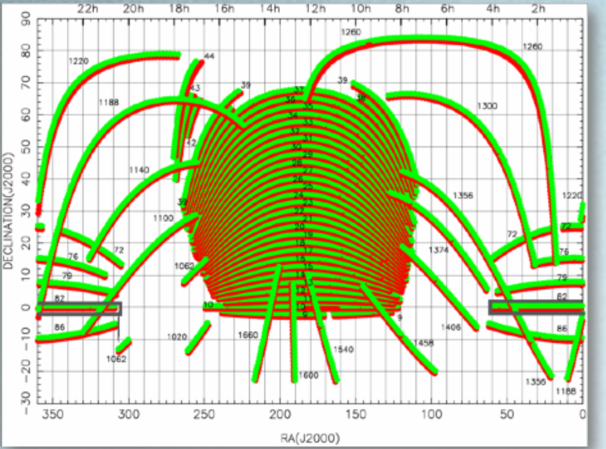


Nominal depth of SDSS (single-pass image) can only detect "normal" galaxies up to $z<0.4$. Stripe 82 (~300 deg^2) was used for calibration and has up to 90 images per pointing. Co-adds are produced by several teams (e.g. Annis et al. 2011, Huff et al. 2014)





Jiang et al. 2014



Full SDSS Footprint (10,400 deg^2) with Stripe labels including Stripe 82.

Jiang et al. co-adds' PSF FWHM is ~1.0" in the *riz* bands, and ~1.3–1.5" in *ug* bands

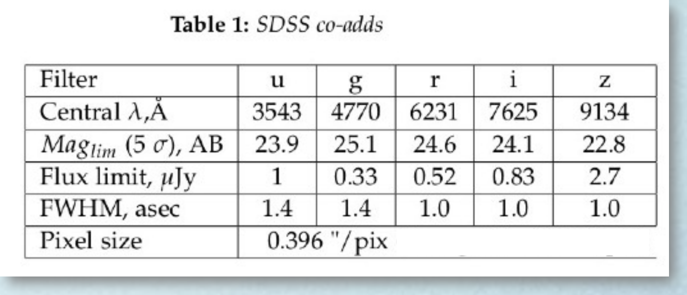
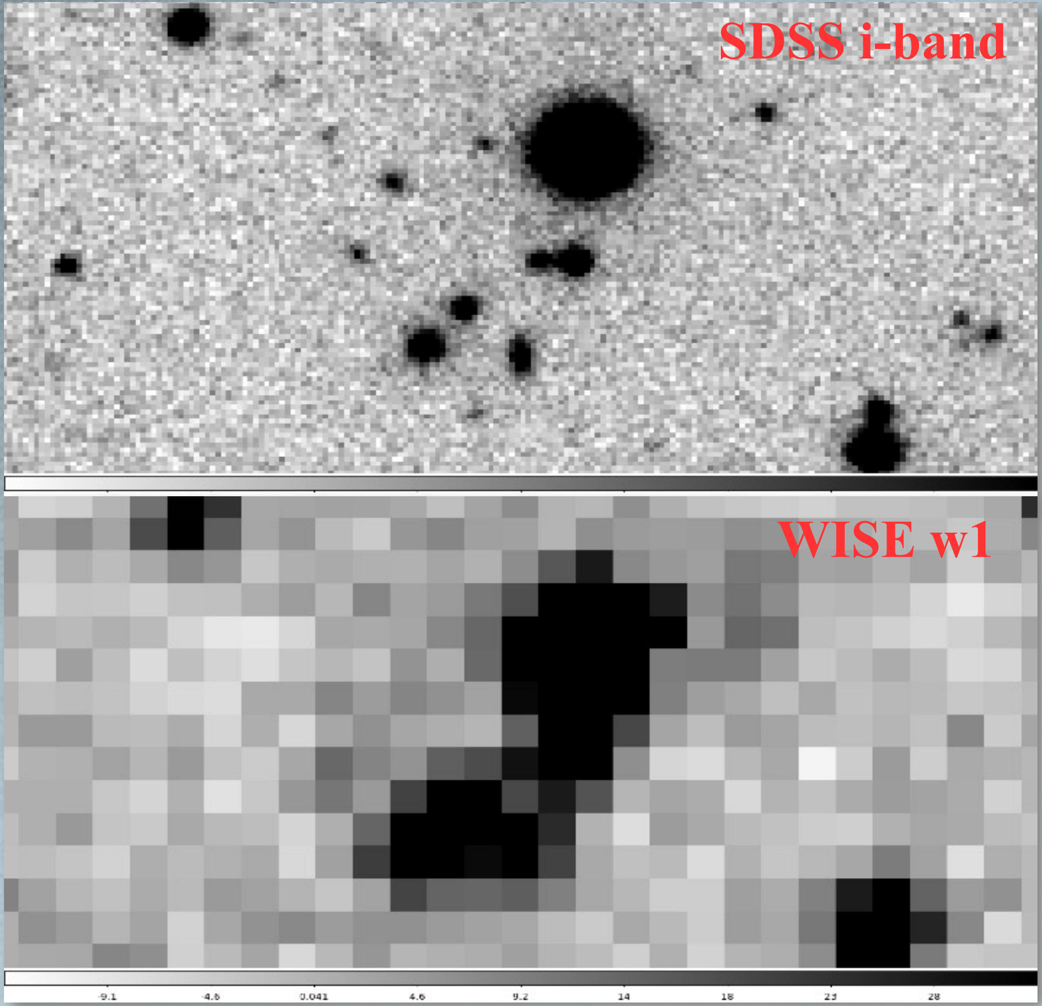


Table 1: *SDSS co-adds*

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				

Catalog I. Optical and near-IR – is there a problem?

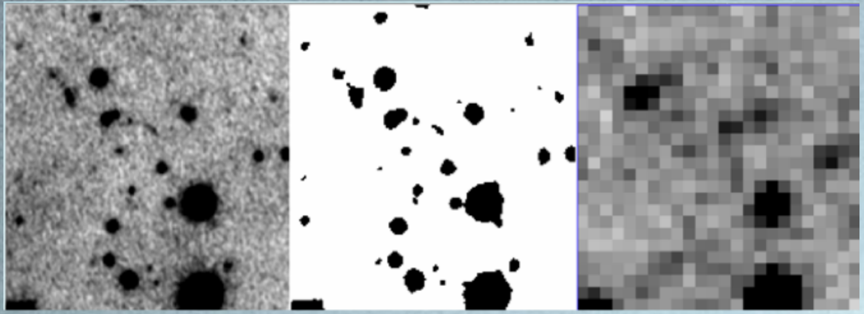


Critical factor is consistent photometry. It is challenging because the spatial resolutions of WISE is ~7 times worse than that of the SDSS

Objects detected in WISE suffer from the blending problem

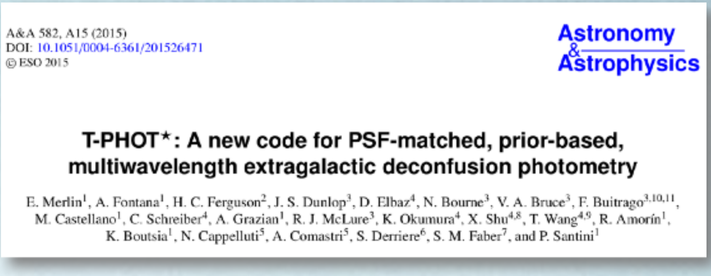
Photometric apertures appropriate for the WISE images cannot guarantee the same fraction of light being included comparing to SDSS. Such a systematic offset, which is different for every galaxy, can severely skew our results

Catalog II. “Template fitting” technique



High-res Segmentation map Low-res

T-PHOT is a publicly available software package that is aimed at extracting accurate photometry from low-resolution images using high-resolution image as a prior



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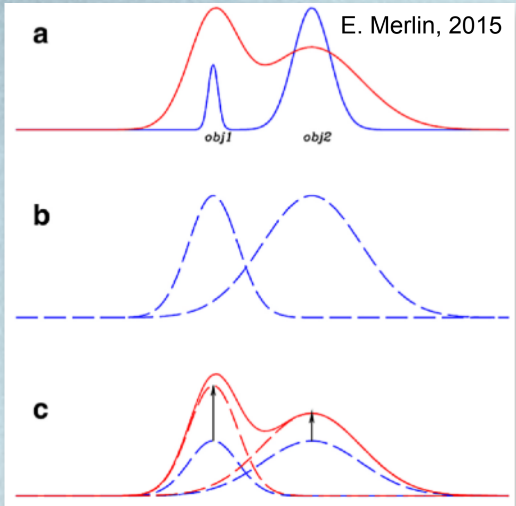
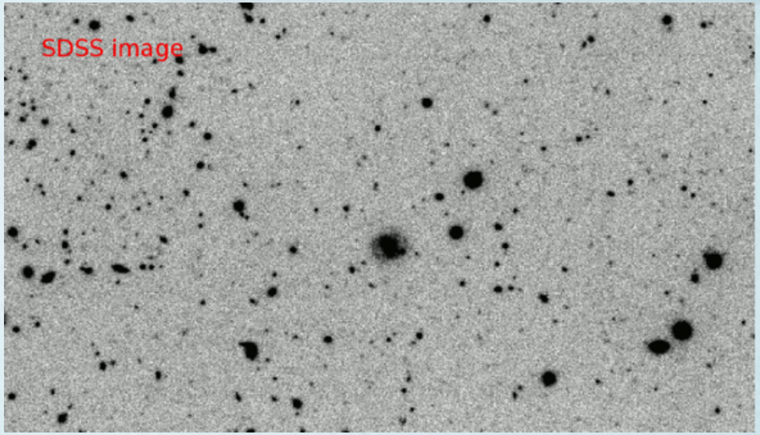
Astronomy & Astrophysics

T-PHOT★: A new code for PSF-matched, prior-based, multiwavelength extragalactic deconfusion photometry

E. Merlin[1], A. Fontana[1], H. C. Ferguson[2], J. S. Dunlop[3], D. Elbaz[4], N. Bourne[3], V. A. Bruce[3], F. Buitrago[3,10,11], M. Castellano[1], C. Schreiber[4], A. Grazian[1], R. J. McLure[3], K. Okumura[4], X. Shu[4,8], T. Wang[4,9], R. Amorín[1], K. Boutsia[1], N. Cappelluti[5], A. Comastri[5], S. Derriere[6], S. M. Faber[7], and P. Santini[1]

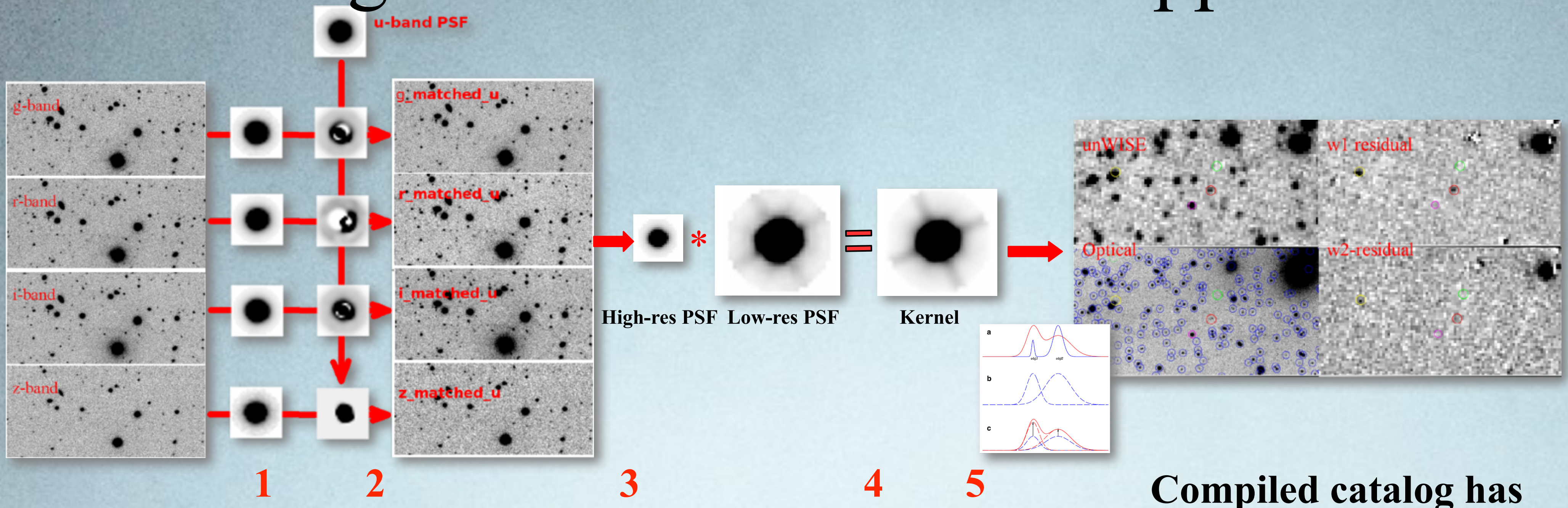


Schematic T-PHOT algorithm



Residual images and a catalog with consistent fluxes and associated flux errors in W1 and W2

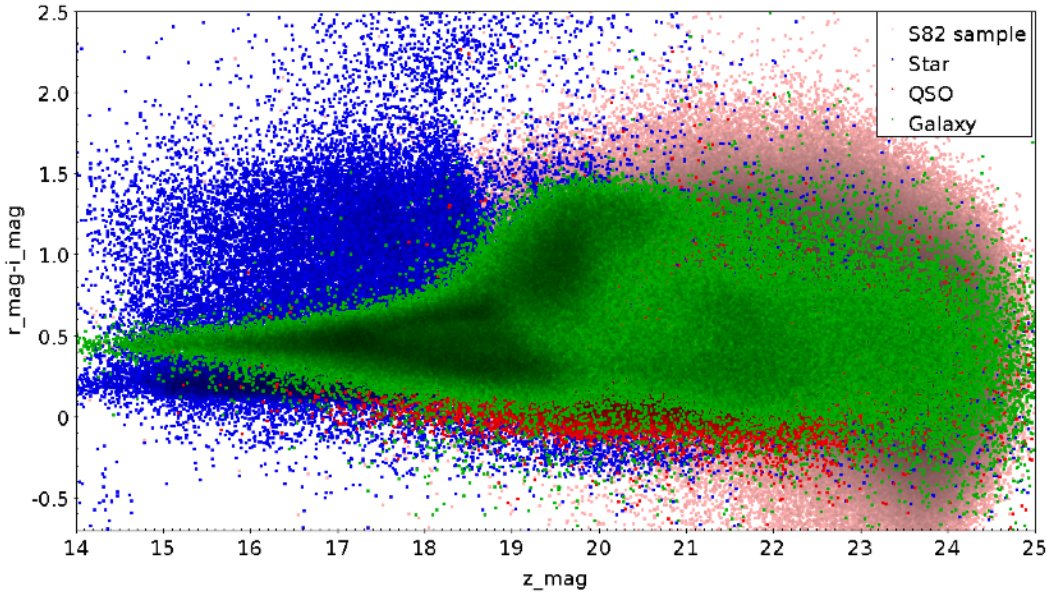
Catalog III. Flow chart of our approach

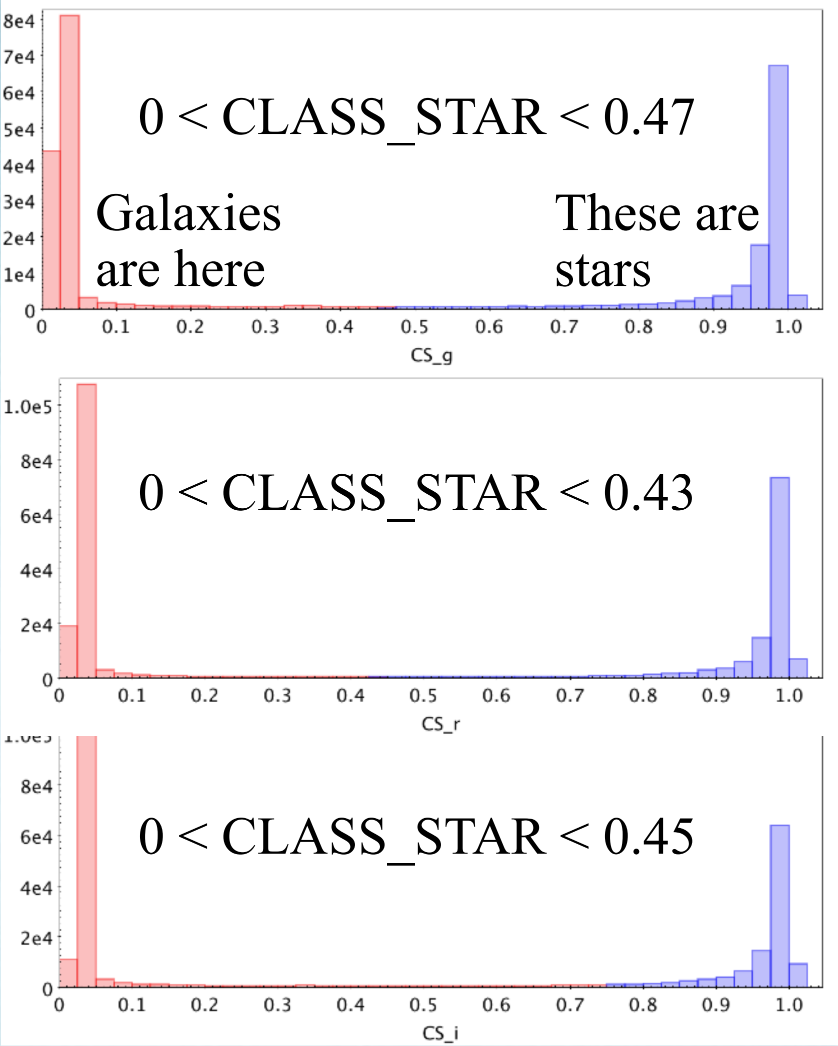


1. Construct PSF per every image in each optical band (*ugriz*) = 28,000 PSFs.
The most time-consuming stage of the project!
2. Convolve optical bands to the PSF of u-band
3. Construct PSF for the r-band matched to the u-band
4. Create a kernel using high-res and low-res PSFs
5. Run T-PHOT on 5556 pairs of images (high-res and low-res)

Compiled catalog has 27,552,100 sources (galaxies, stars, QSO) with robust fluxes in 7 bands

Catalog IV. Star-galaxy separation





0 < CLASS_STAR < 0.47

Galaxies are here

These are stars

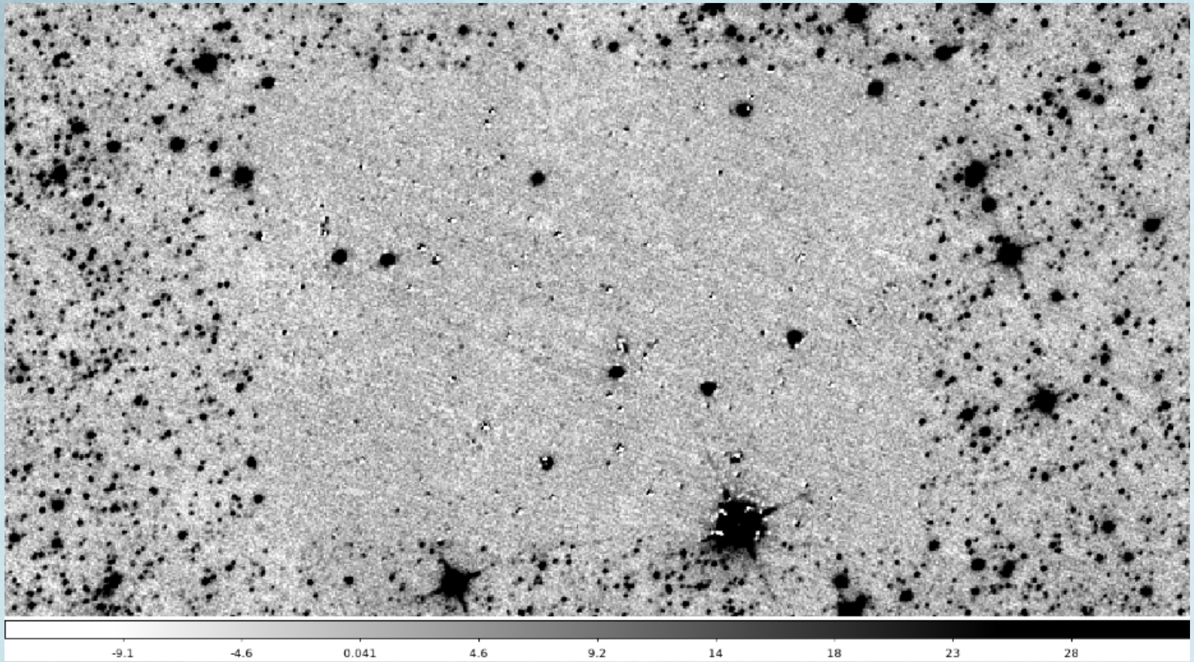
0 < CLASS_STAR < 0.43

0 < CLASS_STAR < 0.45

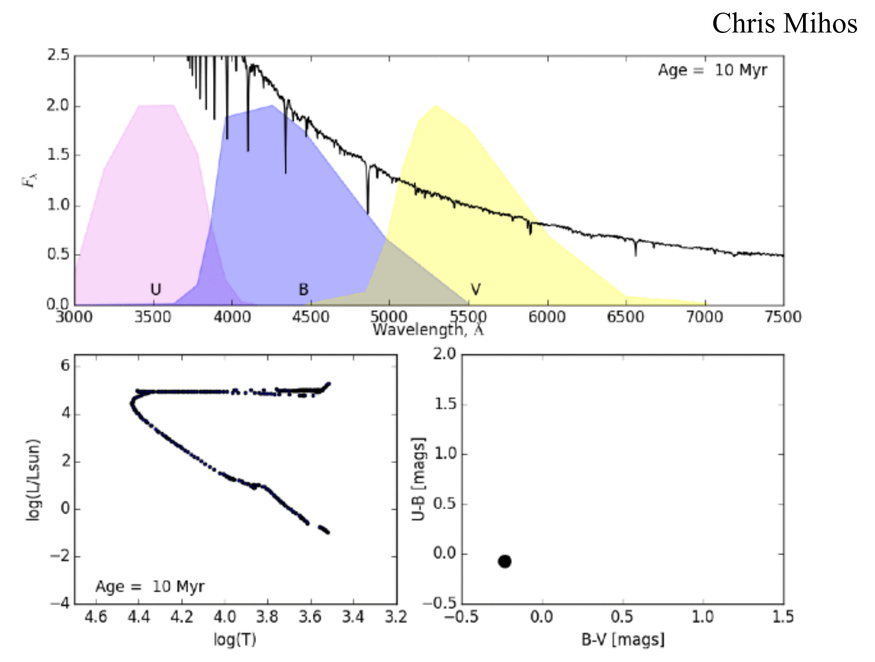
- Separation is performed based on the SExtractor “Stellarity index”
- Include FWHM to prevent misclassification
- We already have PSFs (and thus know FWHM) for every SDSS image in all 5 bands;
- Combination of CLASS_STAR in *gri*-bands shows the best performance

Some numbers before we start SED fitting:

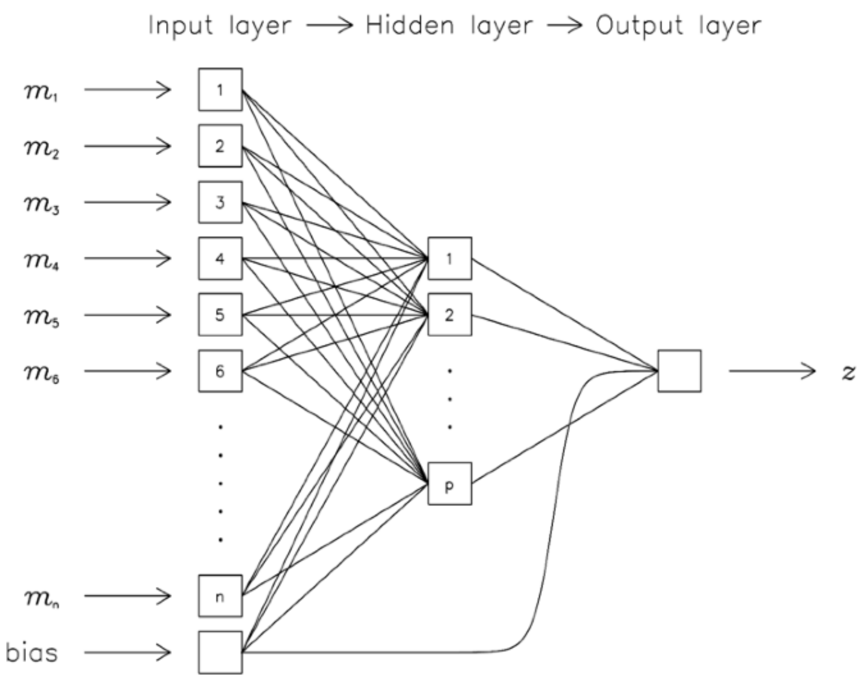
- Total area (after masking) – 288.212 deg^2
- Total number of galaxies – 14,419,000 (10,404,000 with S/N > 5 in *gri*)
- QSO and stars contamination ~2% based on spectroscopic identification
- 24% and 12% of galaxies have S/N > 3 in W1 and W2, respectively



Photometric redshift: SED fitting vs neural network

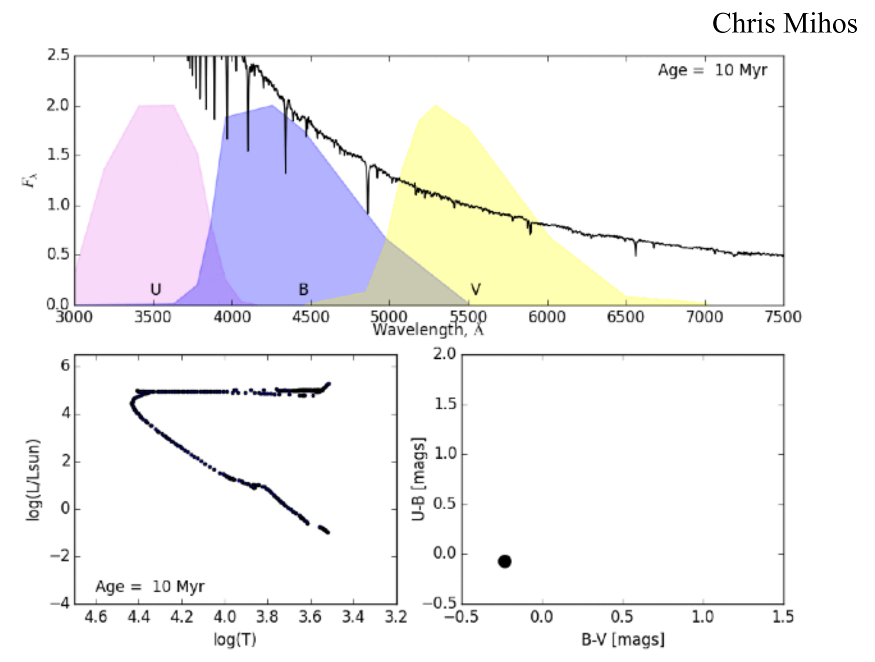


Chris Mihos



- SED fitting relies on a set of galactic templates, either empirical or synthetic. During the fitting templates are modified to simulate change in redshift, extinction, age, etc. The best fit template defines the properties of the galaxy
- Neural network approach relies on the training set of galaxies for which the redshift is known (usually from external spectroscopic survey). Program “learns” that each redshift value has some particular combination of input nodes (e.g. magnitude or colours)

Photometric redshift: SED fitting vs neural network


Chris Mihos

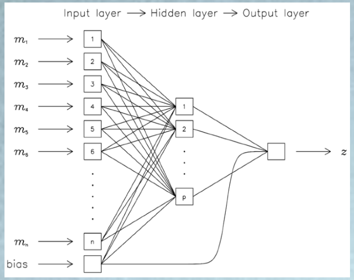
Cons:

- Model-dependent:
  - What SFH we assign to galaxies?
  - What was the initial mass function (IMF)?
  - What law describes attenuation best?
  - What metallicity should be assumed?
- Different set of templates give different z_{phot}
- Fails at $z>0.8$ for our set of filters

Pros:

- Output SED is built for each source - the quality of the fit can be tested
- No need for the training set - more robust at fainter magnitudes

Photometric redshift: SED fitting vs neural network

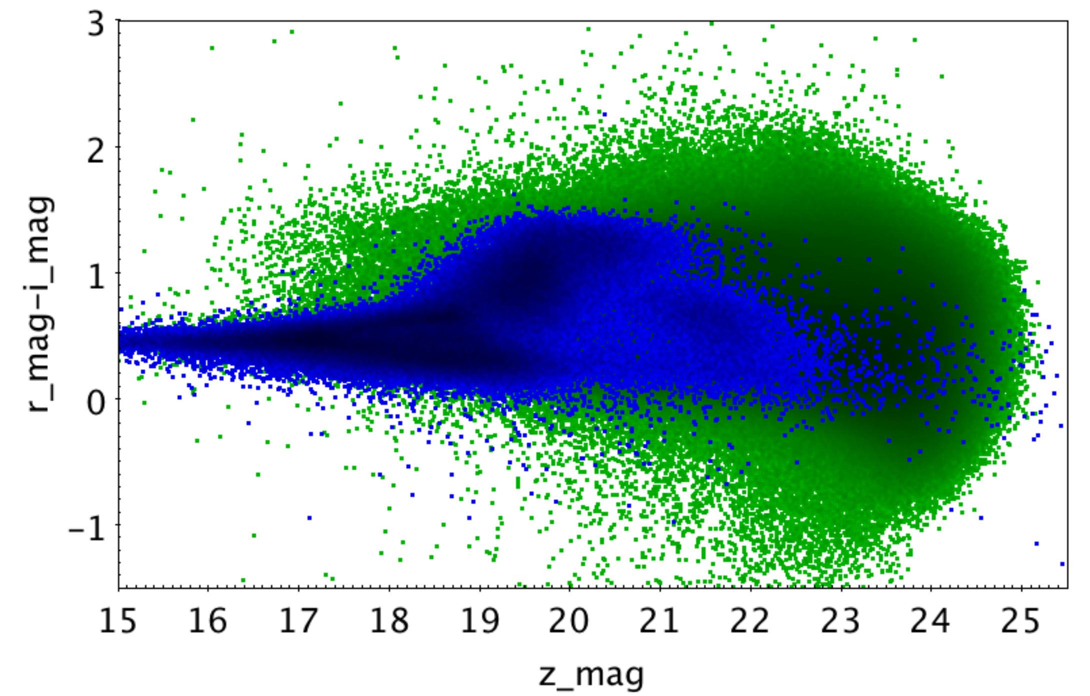


Cons:

- "You can only train what you know" - Jiasheng Huang
- No way to check the quality of the fit

Pros:

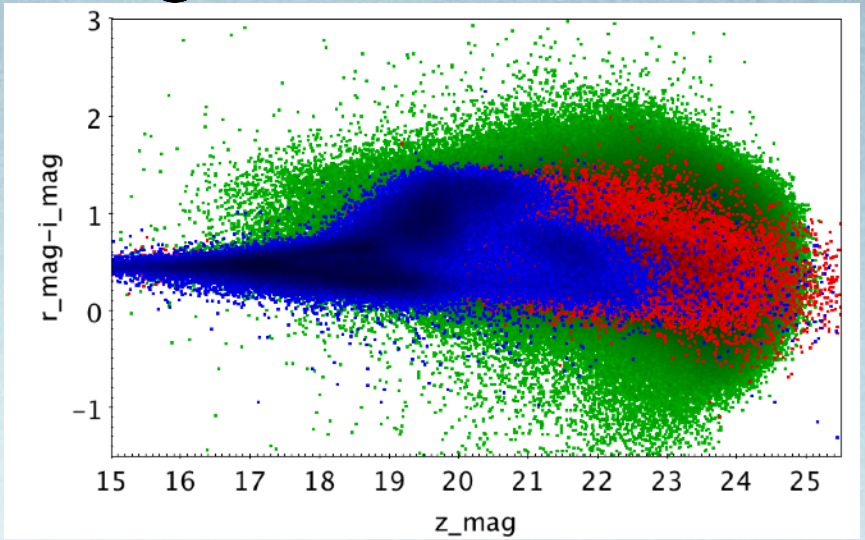
- Extremely fast (~1 hr)
- Works to higher redshift limits (z~1)
- Mixed input data (magnitudes and colours)



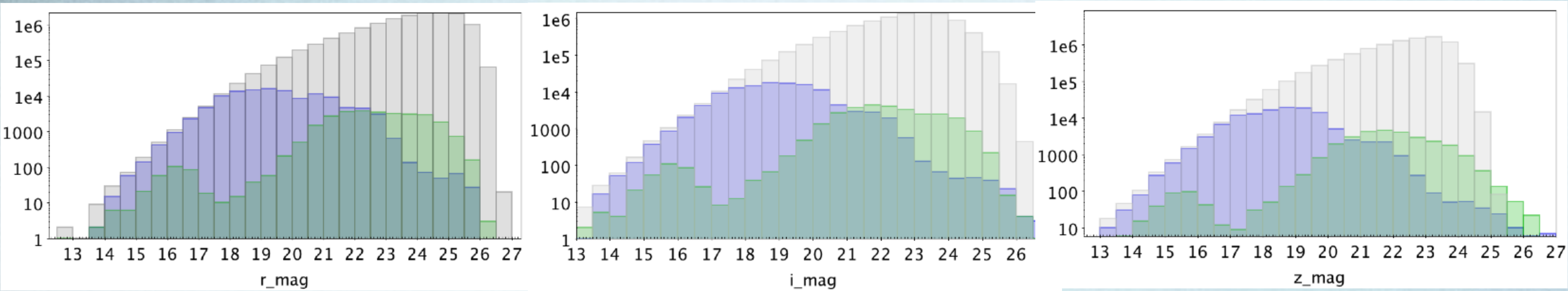
Photometric catalog (green) and SDSS DR14 sources with known spec_z (blue)

Photometric redshift: SED fitting and neural network

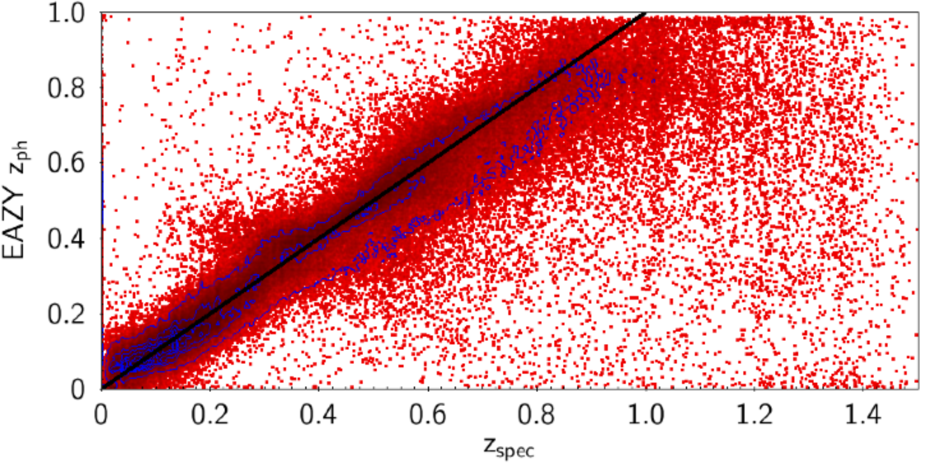
- We opt to derive photometric redshifts using both methods
- In addition to the SDSS spectroscopic data we use DEEP2, WiggleZ, VVDS, VIPERS and 6df data:
  - Fill in colour-mag plane and makes ANNz more robust
  - Put better constraints on the z_{max} for the SED fitting



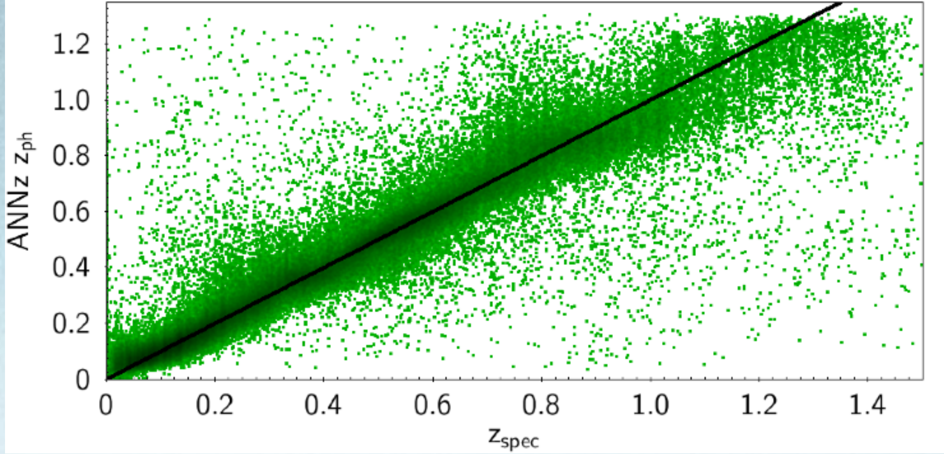
Photometric catalog (green), SDSS DR14 spec_z catalog (blue) and 4 auxiliary catalogs with spec_z (red)



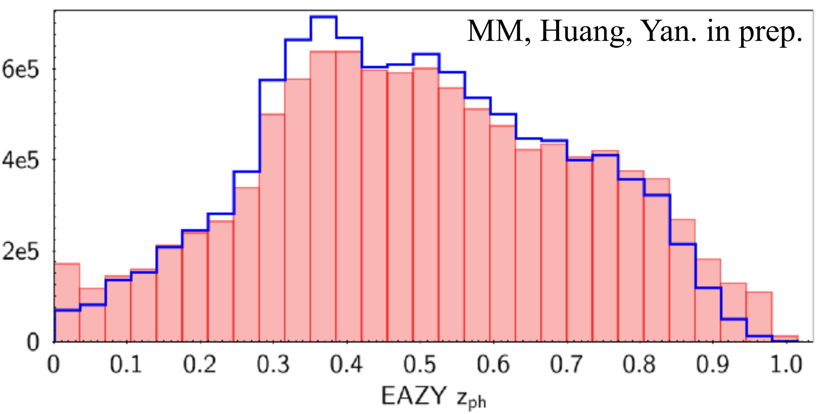
Photometric redshift: SED fitting and neural network



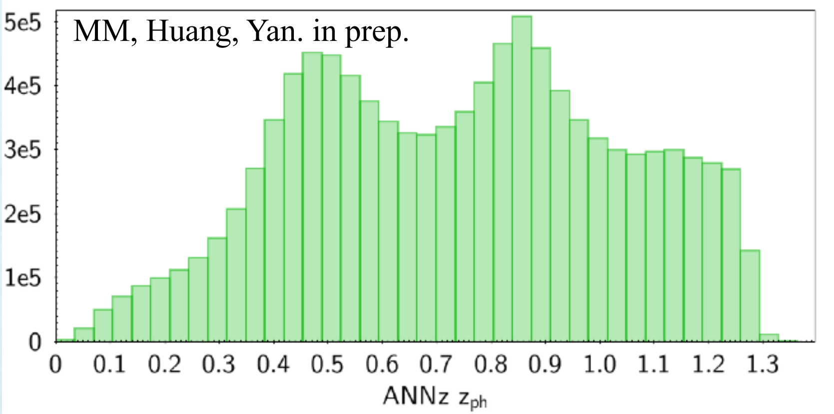
SED fitting with EAZY (Brammer et al. 2008)



Neural Network code ANNz (Collister & Lahav, 2004)

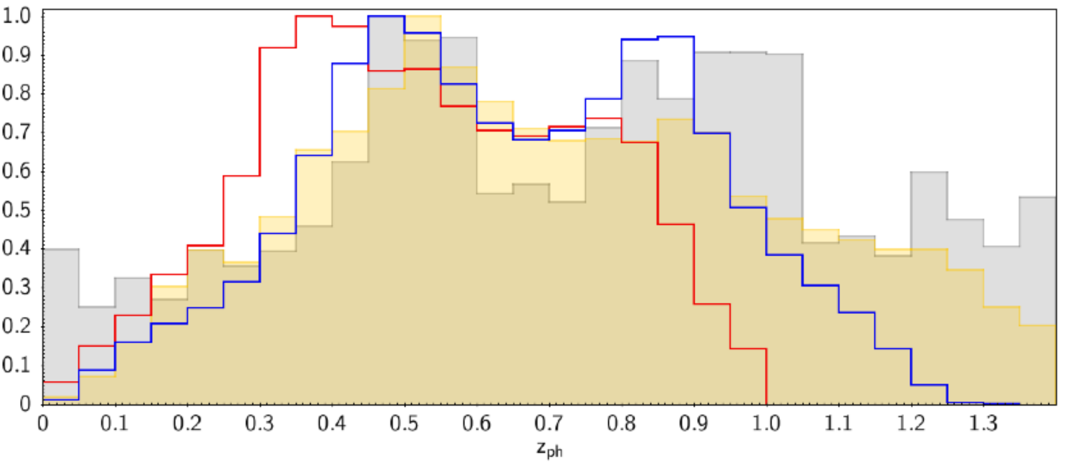


MM, Huang, Yan. in prep.

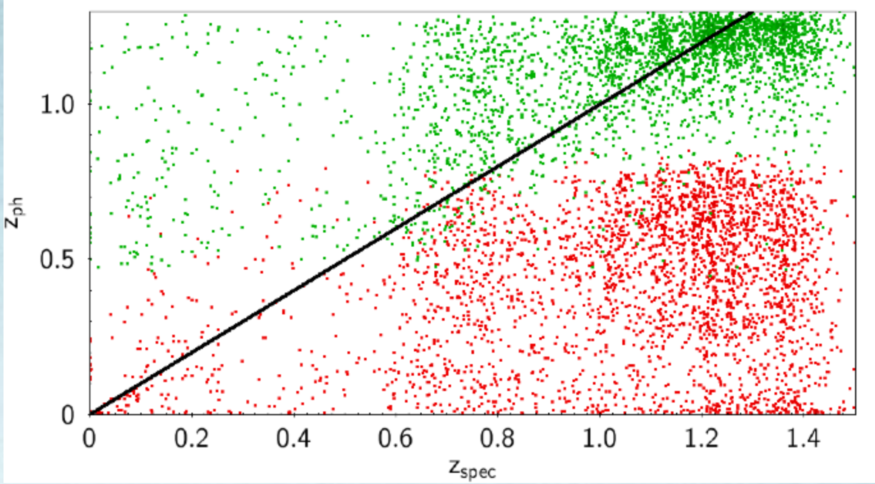


MM, Huang, Yan. in prep.

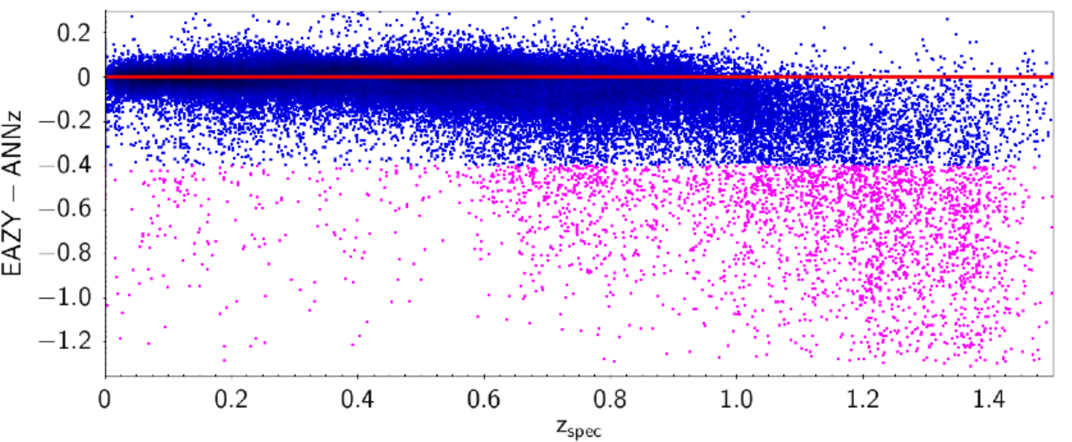
Photometric redshift: high-z contamination



Redshift distribution: CANDELS (yellow), CFHTLS (grey), EAZY corr (red) ANNz corr (blue)

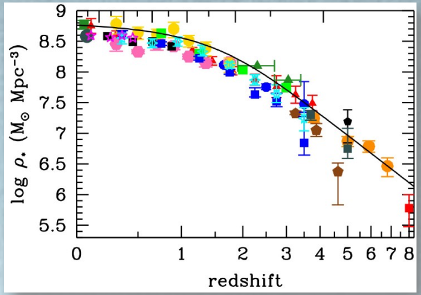


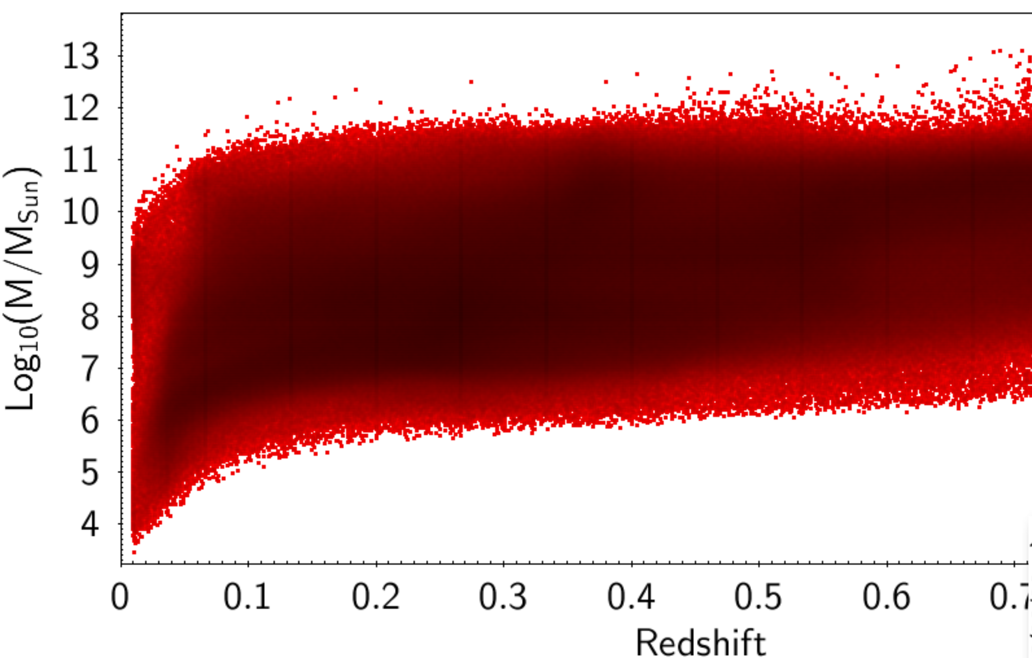
EAZY (red) and ANNz (green) sources rejected with criteria "EAZY - ANNz > -0.4". Most of them are high-z sources and very few had correct z_{phot}



After rejection of high-z sources our catalog has 8.5 million sources

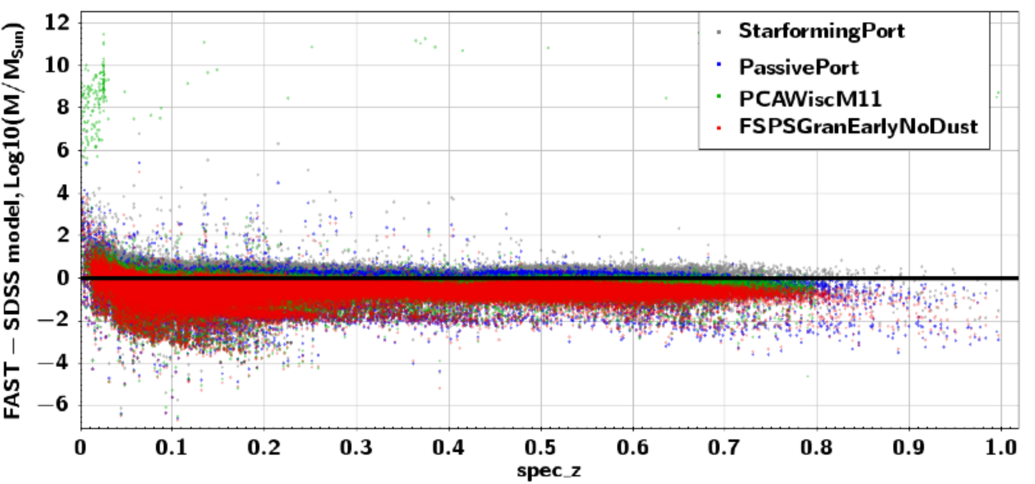
GSMD I. (Preliminary) stellar masses



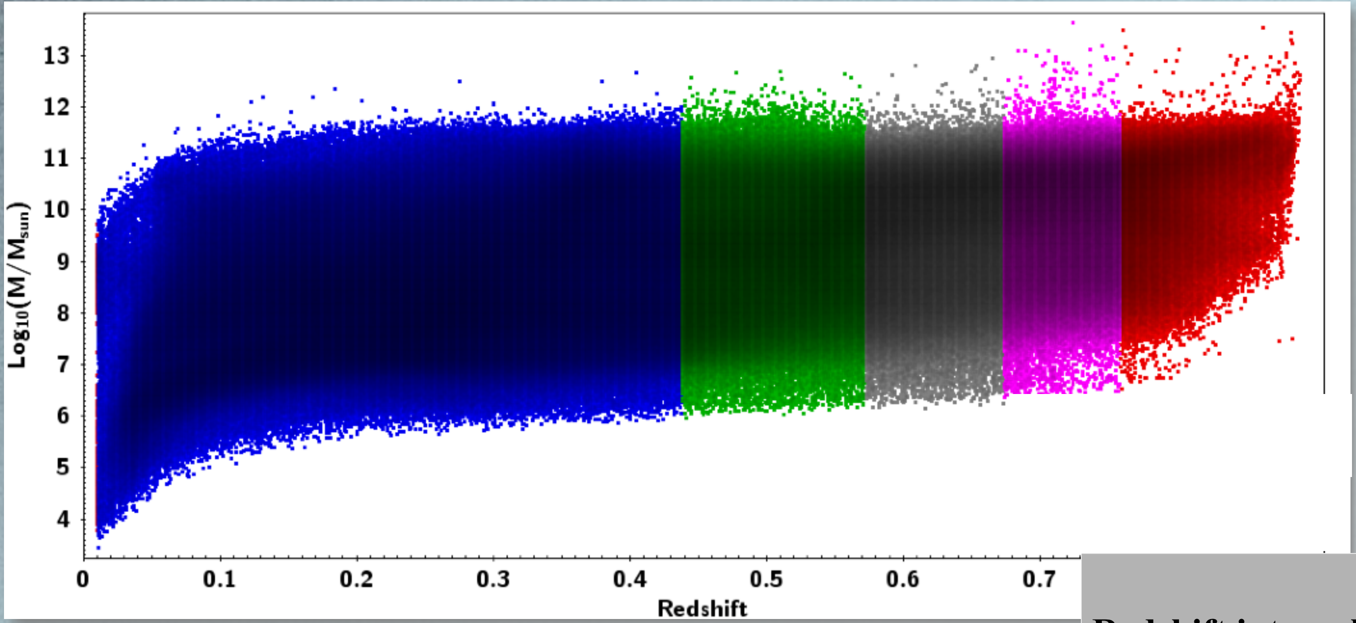


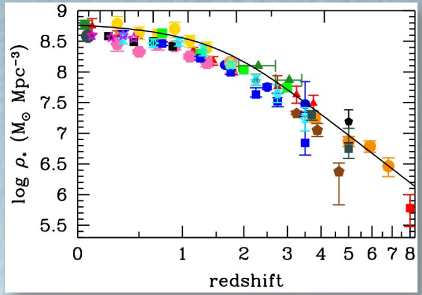
SED fitting done with the FAST code (Kriek et al. 2009)

Testing our results against publicly available SDSS data:



GSMD I. (Preliminary) stellar masses



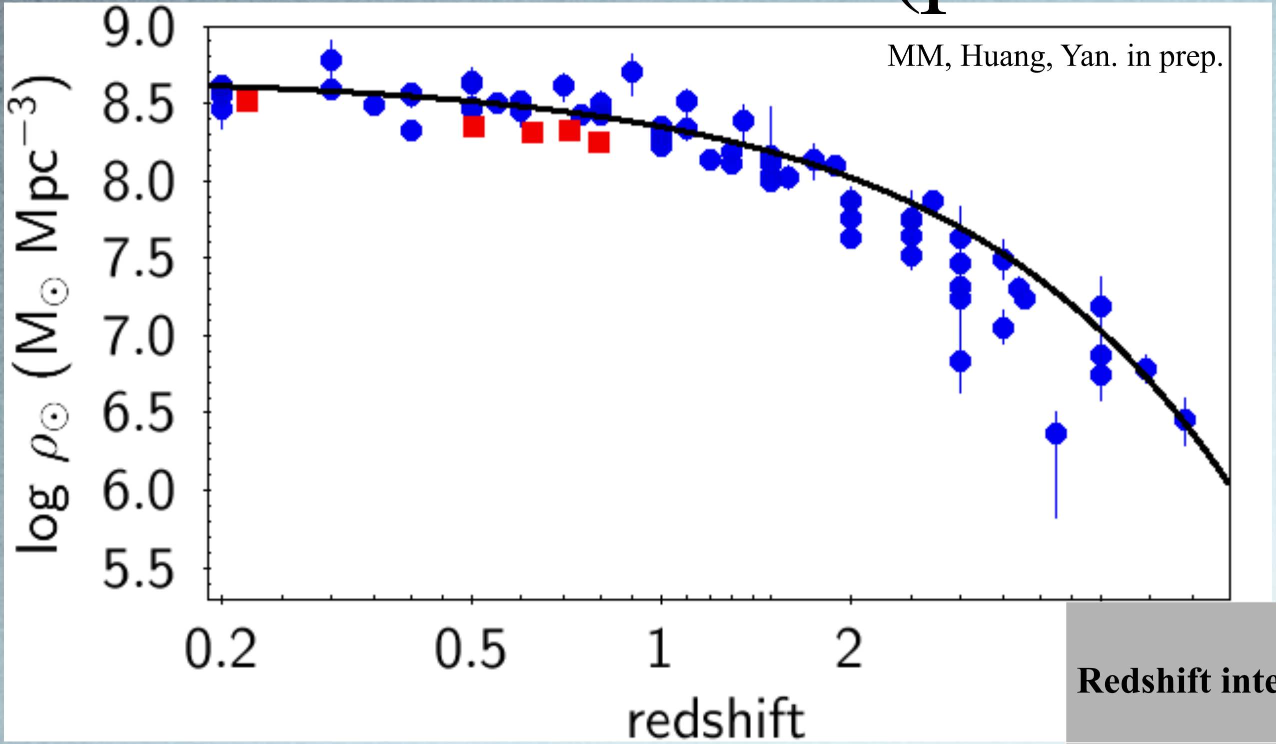


SED fitting done with the FAST code (Kriek et al. 2009)

Five comoving volume bins of equal size – 20 Gpc^3

Redshift interval	Mean redshift	Fraction of galaxies per bin	Stellar mass density (BC03), Log(M/Mpc^3)
0.010 < z < 0.439	0.22	0.403	8.52
0.439 < z < 0.573	0.506	0.208	8.35
0.573 < z < 0.674	0.623	0.125	8.31
0.647 < z < 0.759	0.716	0.097	8.32
0.759 < z < 0.834	0.795	0.083	8.25

GSMD II. Our (preliminary) results



MM, Huang, Yan. in prep.

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

Data points from Madau & Dickinson’14 (blue) are in a relatively good agreement with our derived SMD (red)

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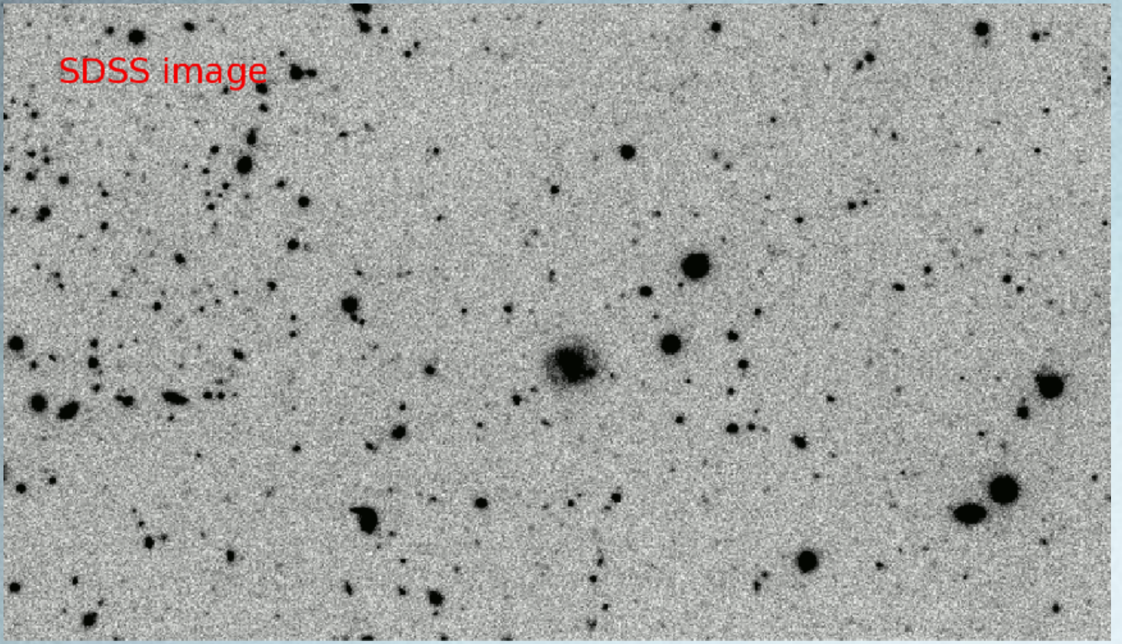
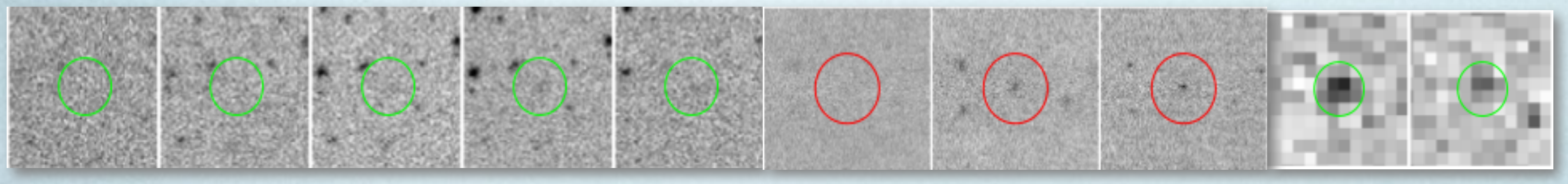
Subsample of WISE optical Dropouts - “WoDrops”



13,600 sources with non-detection in optical and 3σ detection in W1/W2

About quarter of them are visually confirmed in our pilot study

What are they?
The only known color resemblance to the WoDrops are the Spitzer IRAC-selected Extremely Red Objects (IERO; Yan et al. 2004);
A fraction of WoDrops have existing IRAC data from SHELA and SpIES, and their IRAC photometry are consistent with the WISE ones.

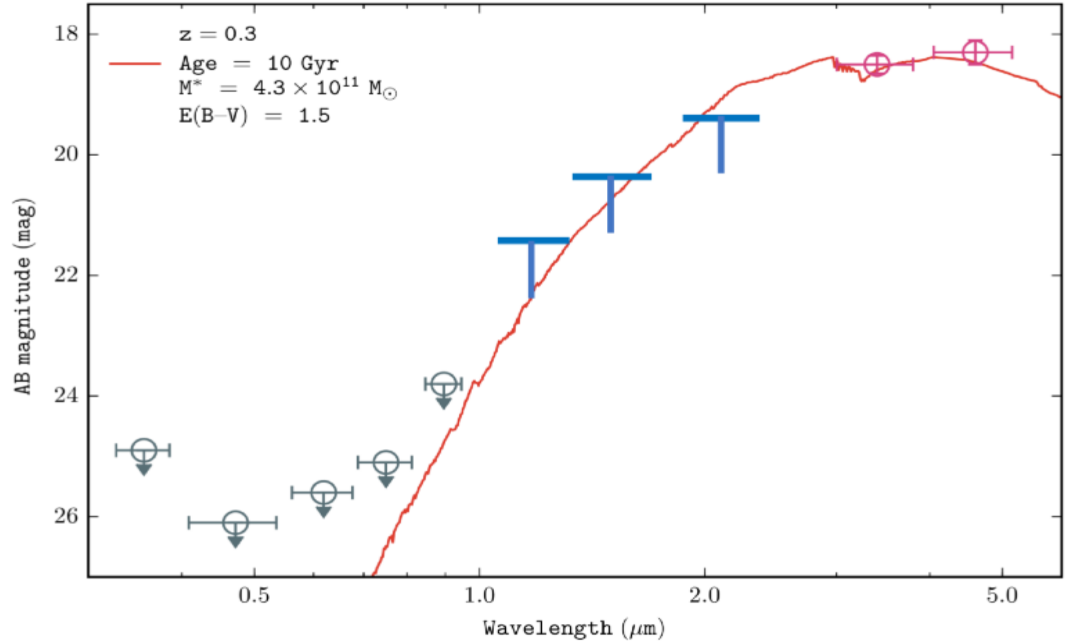


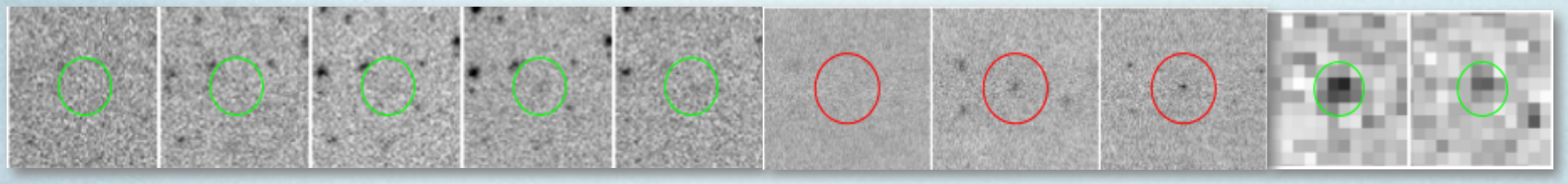
Subsample of “WoDrops”

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

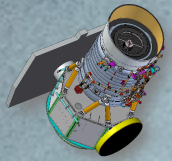
- 5 sources were observed at WIYN/WHIRC to AB 19.5–21.5 mag in KsHJ

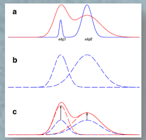
- Just 2 weeks ago 21 sources were observed at P200/WIRC to AB 22.0 mag in Ks

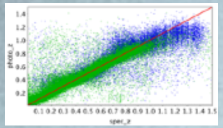


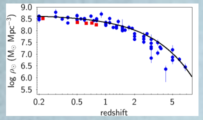


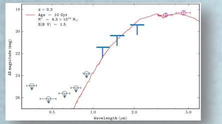
Summary











- We want to study evolution of galaxies over the last 7 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 14 million of galaxies
- “Template fitting” technique was used to derive consistent fluxes and colours 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 using SED fitting (EAZY) and neural network (ANNz) techniques
- Our preliminary GSMD values up to z~0.85 are consistent with results of other groups and will place strict constraints on the lower limit of the SMD
- An interesting sub-sample of sources, “WoDrops” was discovered. After pilot observations at WIYN/WHIRC and P200/WIRC its nature is still a mystery and requires follow-up observations