Astronomical Catalogs for Locating Gravitational-wave Events

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LIGO SURF 2016

- ❖ Skymap Viewer
- ❖ Galaxy Stellar Mass Estimation
  - Method 1: B Mag (blue light)
  - Method 2: W1-W2 method (MIR)
  - Method 3: Evolutionary Population Synthesis and SED fitting (red light)
  - Comparison between catalogs
- ❖ Galaxy Cluster Stellar Mass Estimation
  - Method 1: Using cluster richness (optical)
  - Method 2: Using total luminosity (X-Ray)
  - Method 3: Using Sunyaev–Zel'dovich Effect (G lensing)
- ❖ Metallicity Estimation
  - Metallicity from SED fitting
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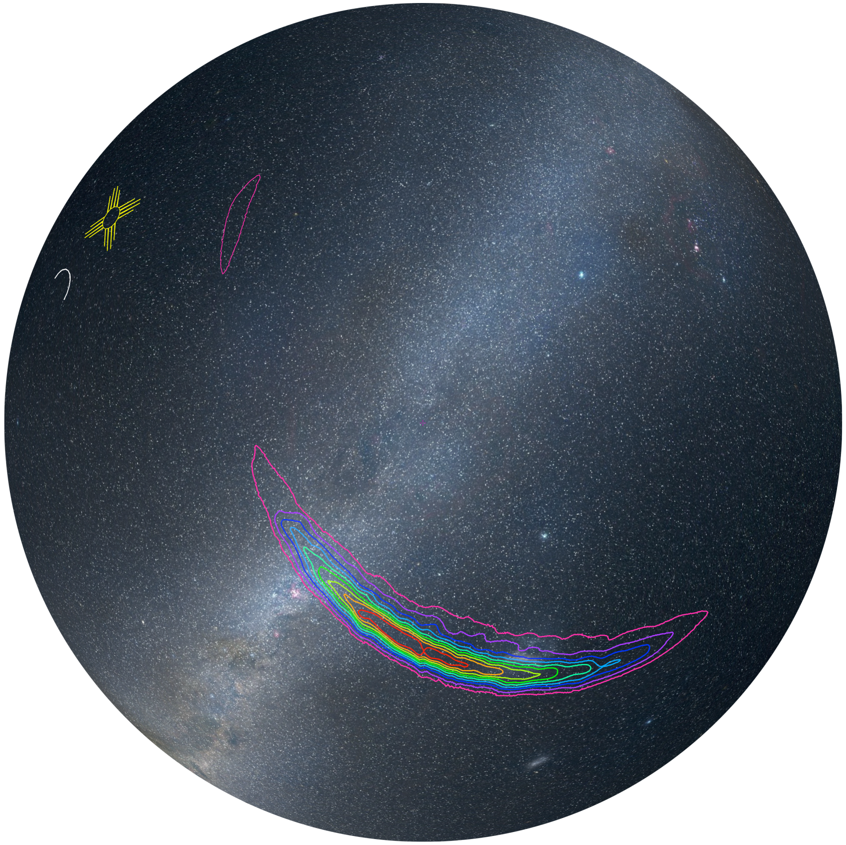
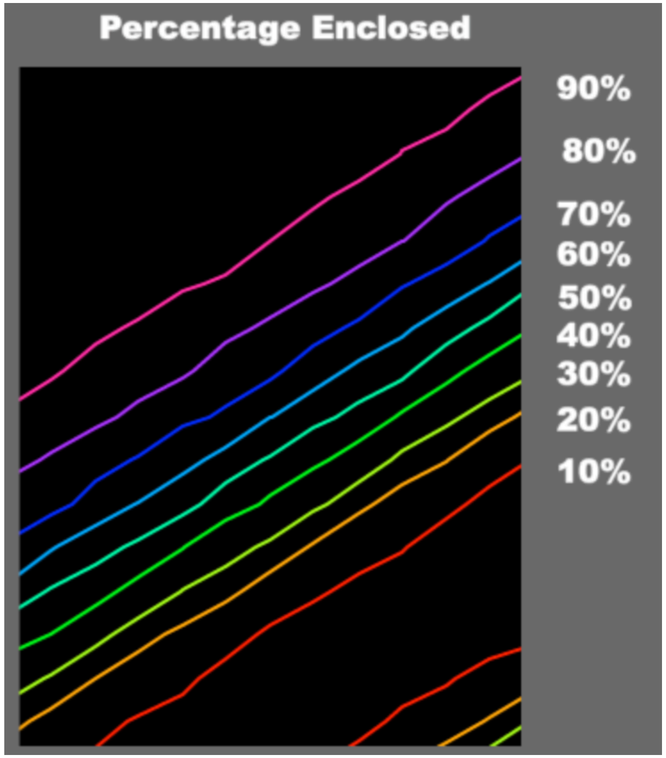
- ❖ Future Work
- ❖ Summary

❖ Skymap Viewer

- Skymap Viewer is an interactive, web-based tool to display a sky map along with a host of relevant information for follow-up observers.
- The sky map is shown as a contour plot, each color-coded line enclosing a given percentage of the total probability.



GW150914



❖ Skymap Viewer

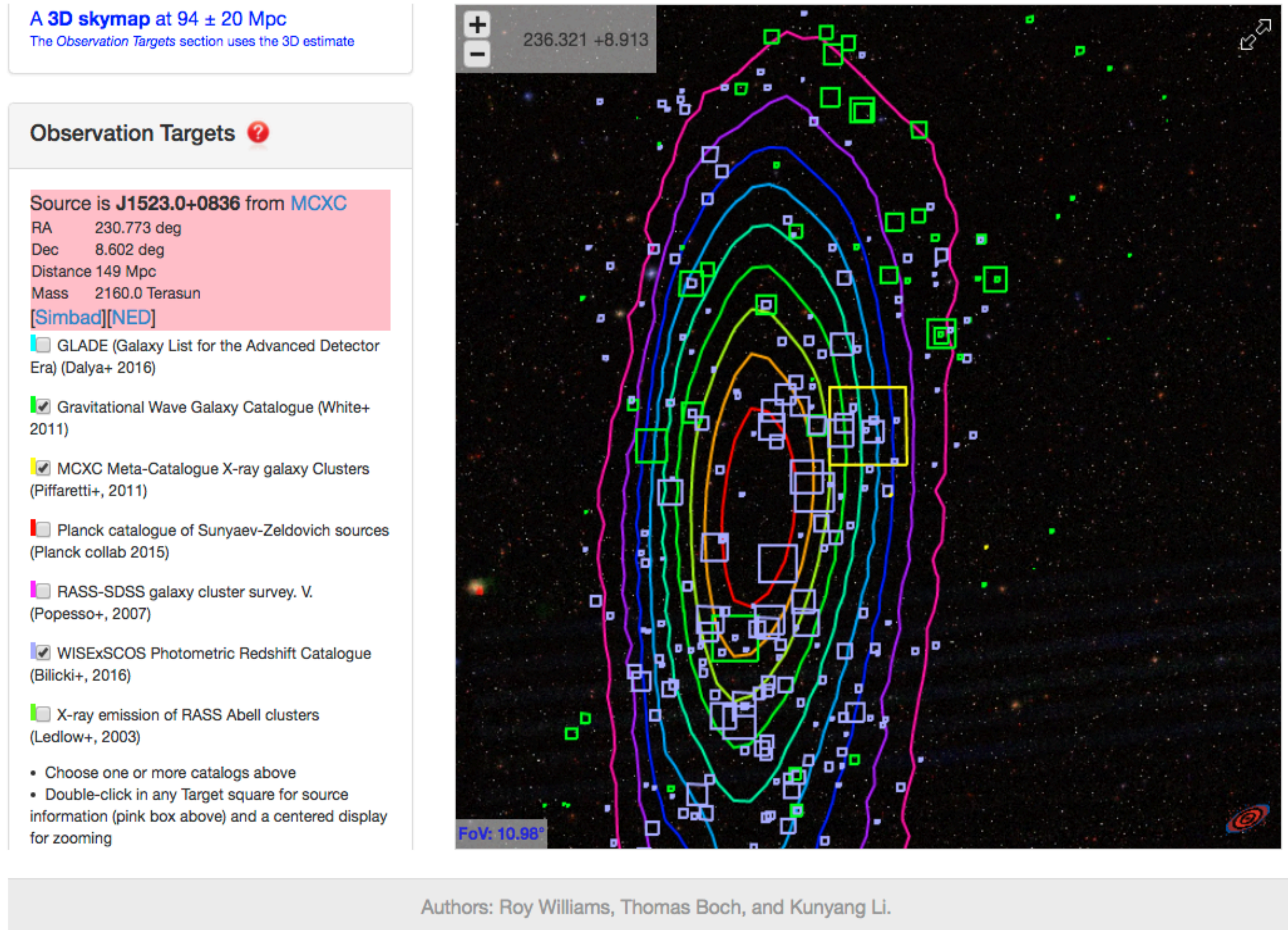
FOV=15d

catalogs checked:

- GWGC (OPT)
- 2MASS-GLADE
- WISExSCOS galaxies
- Planck (SZ)
- RASS-SDSS (X-Ray)
- RASS-Abell
- MCXC galaxy clusters

area of each square is prop. to **MASS * 3D prob density**

double-click in square for pink info and centering



Skymap Viewer coming soon to https://losc.ligo.org/s/skymapViewer/ (R.Williams, T.Boch, K.Li)

FOV=0.5d

keep zooming

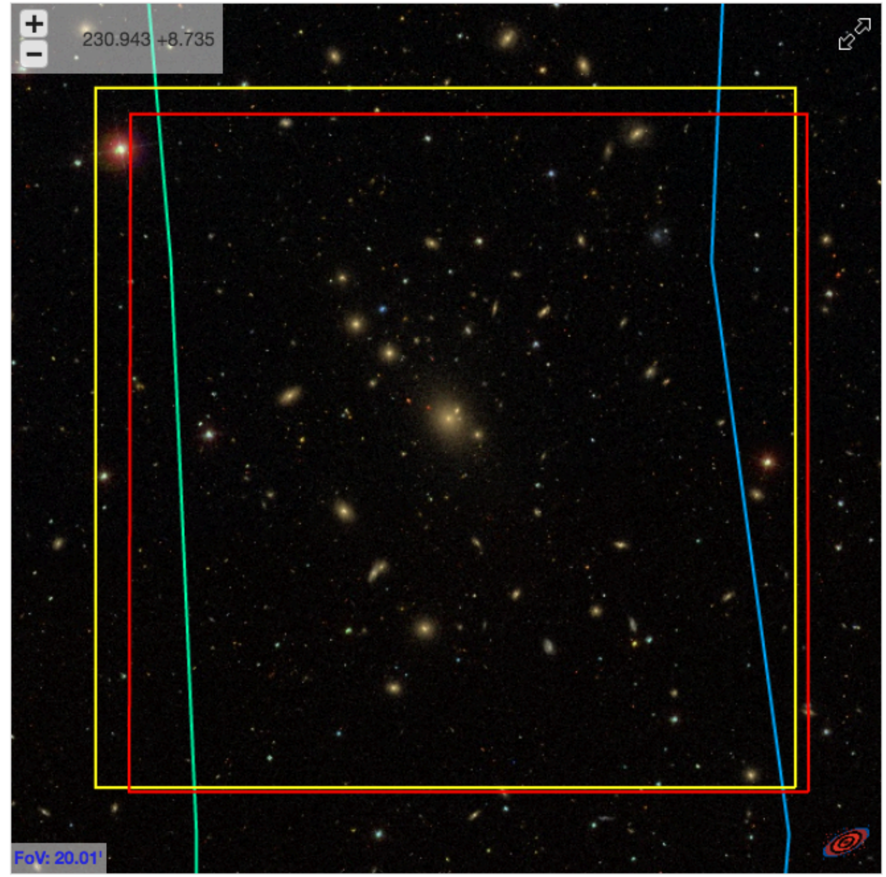
here is prime observational target Abell 2063

Source is **J1523.0+0836** from MCXC
RA 230.773 deg
Dec 8.602 deg
Distance 149 Mpc
Mass 2160.0 Terasun
[Simbad][NED]

- [ ] GLADE (Galaxy List for the Advanced Detector Era) (Dalya+ 2016)
- [x] Gravitational Wave Galaxy Catalogue (White+ 2011)
- [x] MCXC Meta-Catalogue X-ray galaxy Clusters (Piffaretti+, 2011)
- [x] Planck catalogue of Sunyaev-Zeldovich sources (Planck collab 2015)
- [ ] RASS-SDSS galaxy cluster survey. V. (Popesso+, 2007)
- [ ] WISExSCOS Photometric Redshift Catalogue (Bilicki+, 2016)
- [ ] X-ray emission of RASS Abell clusters (Ledlow+, 2003)

- Choose one or more catalogs above
- Double-click in any Target square for source information (pink box above) and a centered display for zooming
- Make Target squares smaller larger
- Observation priorities as a table

Zoomable Multiwavelength Sky



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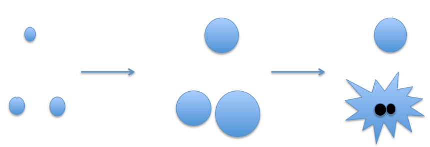
❖ Mass as Priors

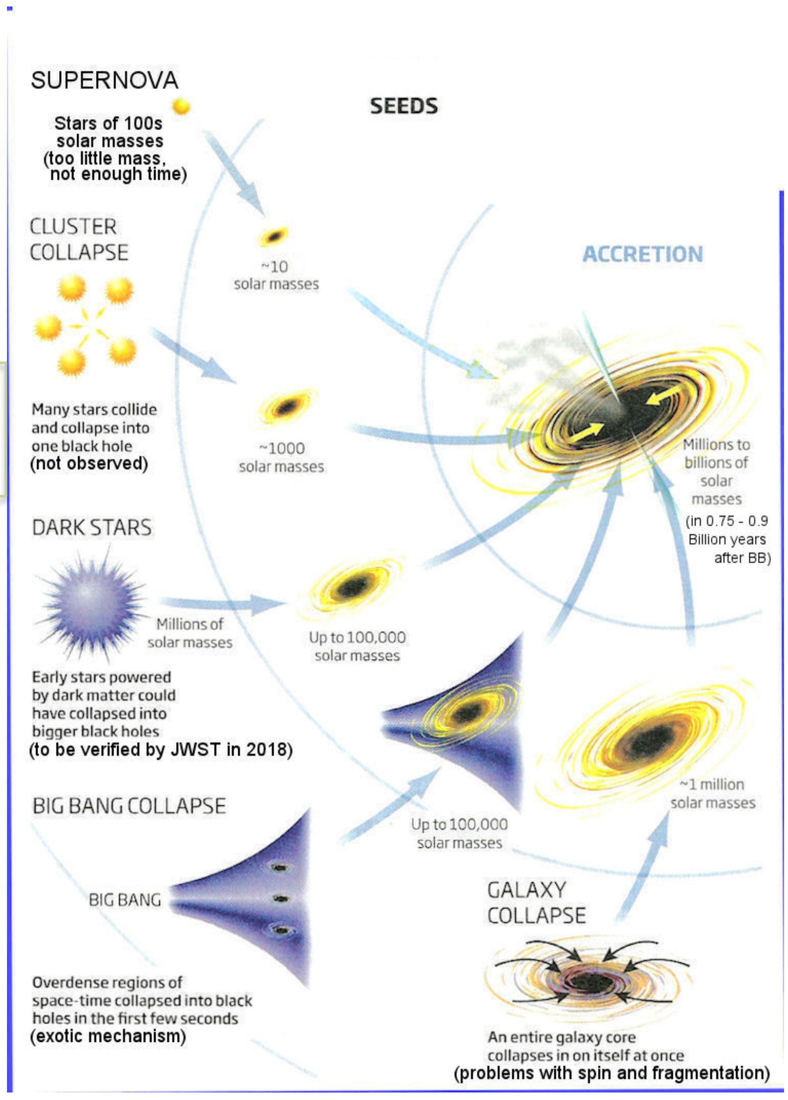
Probability = <u>MASS</u> * 3D prob density (GW signal)

- Number of GCs (Dynamical interaction) ∝ galaxy stellar mass
- DM (Primordial BHs) ∝ galaxy stellar mass

<u>Low Metallicity</u> (only required by massive BBHs)

- Pop III stars
- BBHs in hierarchal three-body system
- Rotational mixing





❖ Galaxy Stellar Mass Estimation

➢ Method 1: Using B band photometry data to estimate galaxy stellar mass:

Assumption: all stars in galaxies have the same mass-to-light ratio of the Sun

Input: apparent B band magnitude, redshift (z)

$$M_g \cong L_B * \frac{M_\odot}{L_{B\odot}}$$

$Output: galaxy\ stellar\ mass\ M_g$

➢ Method 2: Using W1-W2 band photometry data:

The W1 band (3.4 μm) of WISE survey is dominated by the light from old stars and can be used as an effective measure of stellar mass (Jarrett et al. 2013).

$Input: W1, W2, redshift$

$$\log\left(\frac{M_{stellar}}{L_{W1}}\right) = -1.96(W_1 - W_2) - 0.03$$

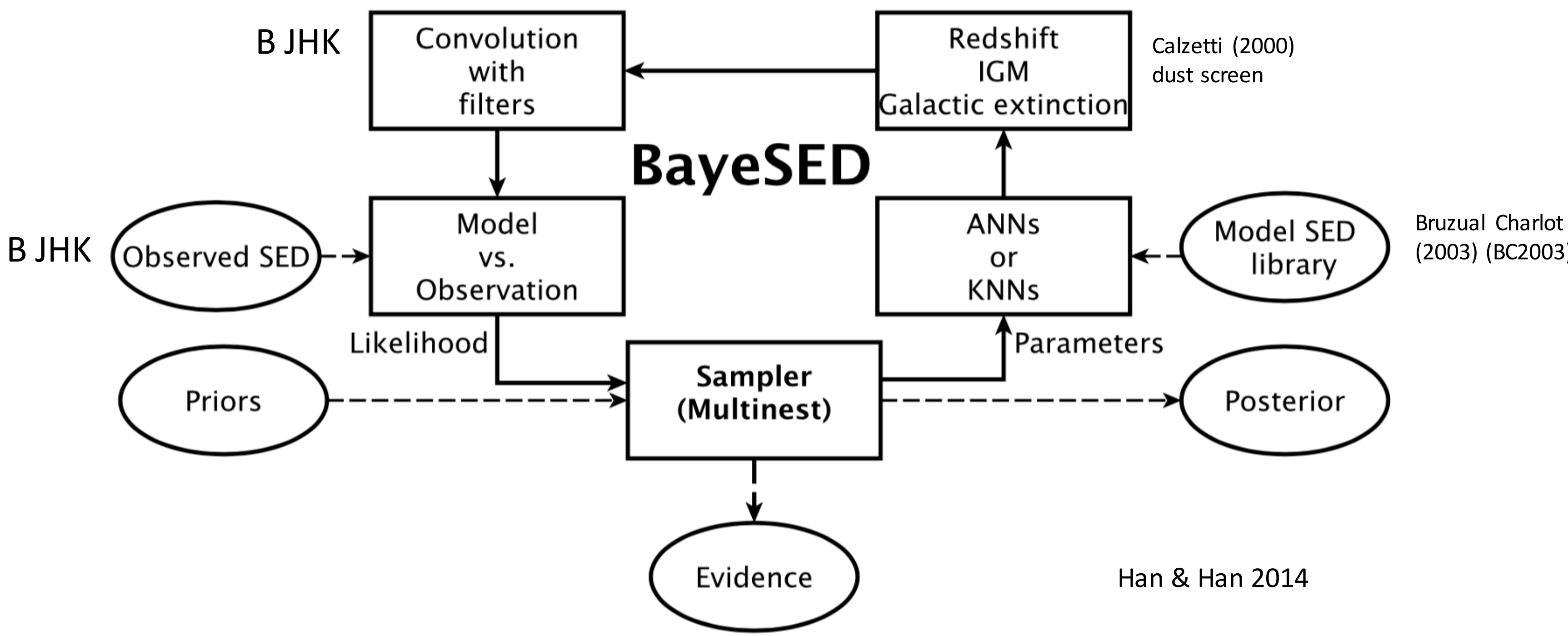
$Output: galaxy\ stellar\ mass\ M_{stellar}$

❖ Galaxy Stellar Mass Estimation

➢ Method 3: Evolutionary Population Synthesis and SED fitting (BayeSED)

BayeSED code algorithm flow chart:

BayeSED: A general approach to fitting the SED of galaxies

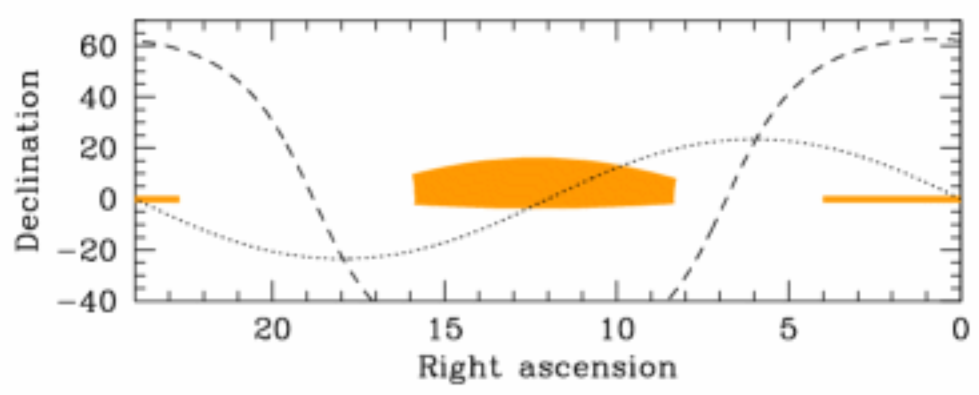


- Input B JHK photometry data (broad band SEDs), redshift
- Output include galaxy stellar mass, metallicity, etc.

❖ Stellar mass comparison between galaxy catalogs

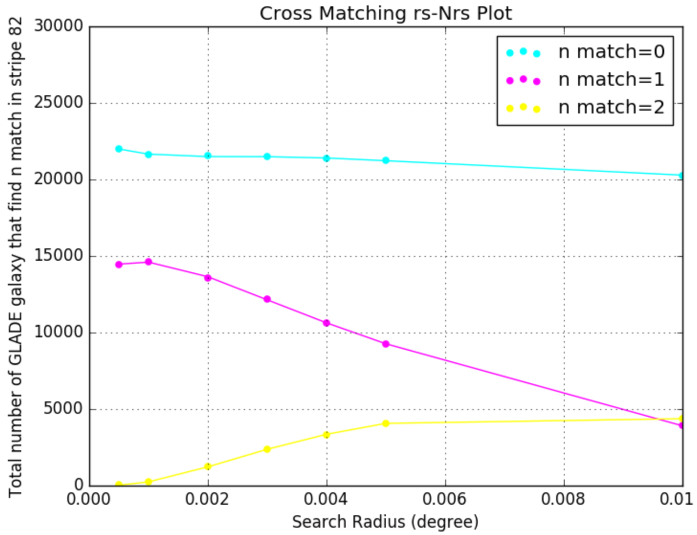
➢ Stripe 82-Massive Galaxy Catalog (S82-MGC)

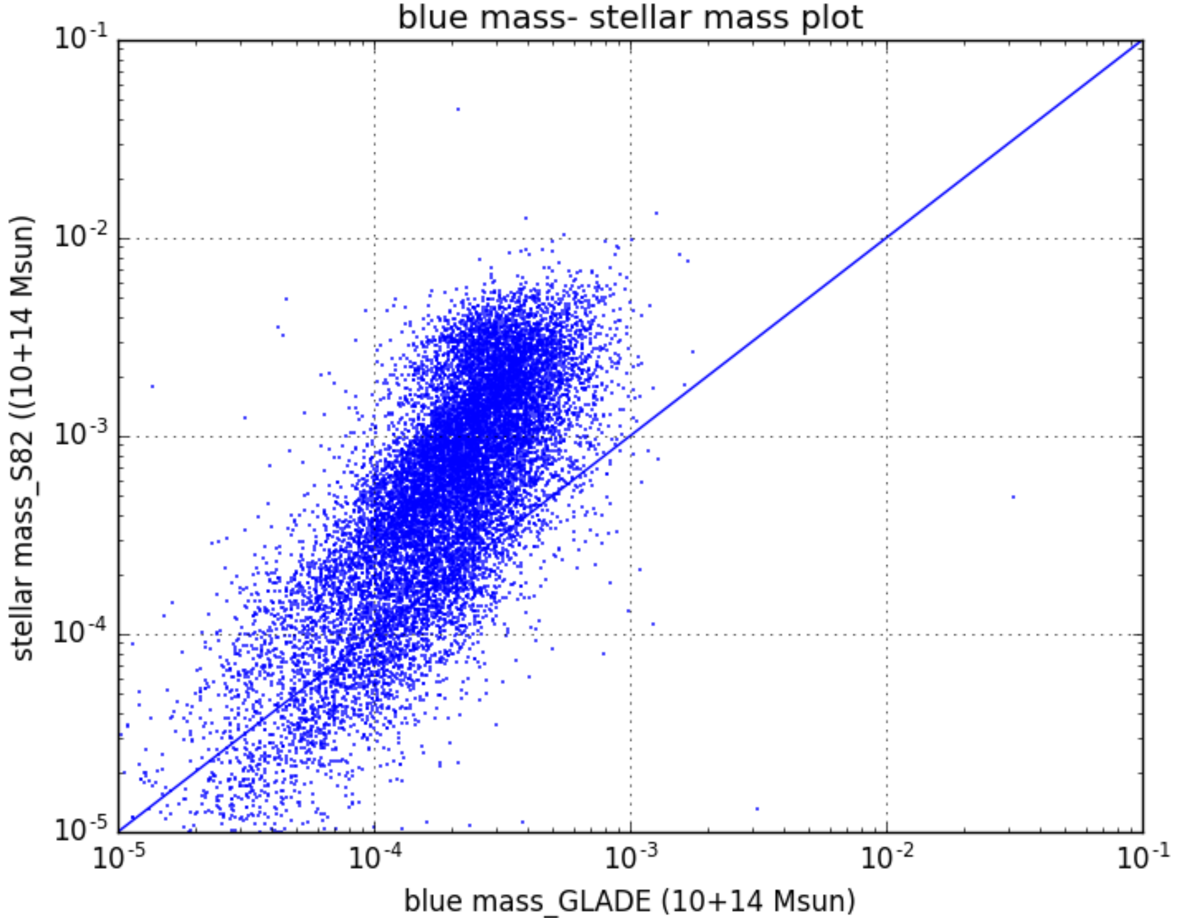
- S82-MGC is a part of the SDSS that was covered many times
- 2 magnitudes deeper than the SDSS survey
- Relatively precise stellar mass estimated by Bayesian SED fitting between Y JHK photometry from the UKIDSS Large Area Survey (LAS) and FSPS models (FSPS: Flexible Stellar Population Synthesis Conroy et al. 2010)
- Covers only a small area: ~250 $degree^2$,
- Can be used to compare mass estimated by different methods



❖ Stellar mass comparison between galaxy catalogs

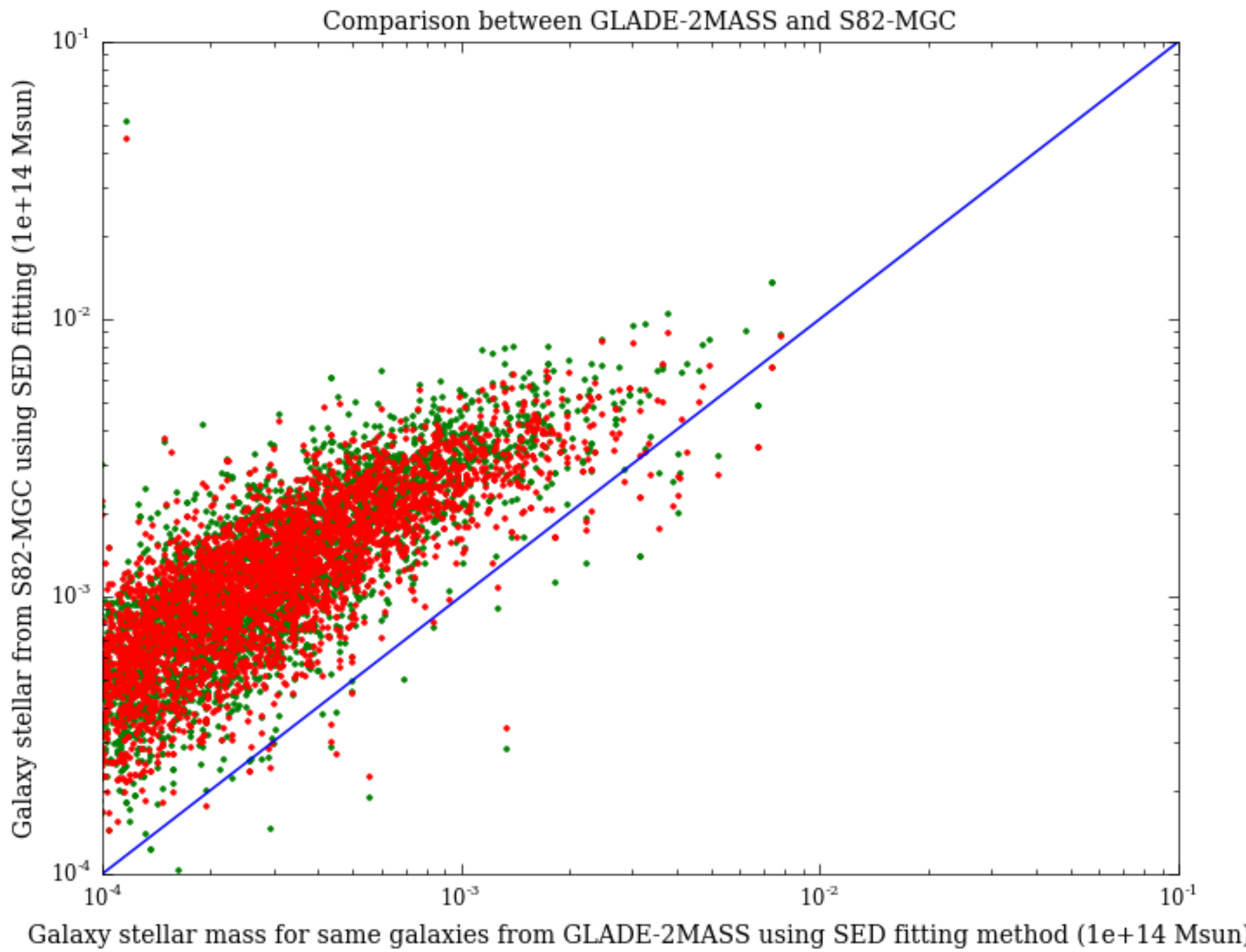
- ➢ Comparison between GLADE (B mag method) and S82-MGC
- Cross-matching GLADE and S82-MGC using best search radius (~0.01 deg)
- Compare stellar mass of the same group of galaxies (14,878) estimated by applying B mag method and SED fitting method to data from two catalog.
- Mass estimation using B mag method is smaller by ~1 mag due to heavy dust attenuation in blue band





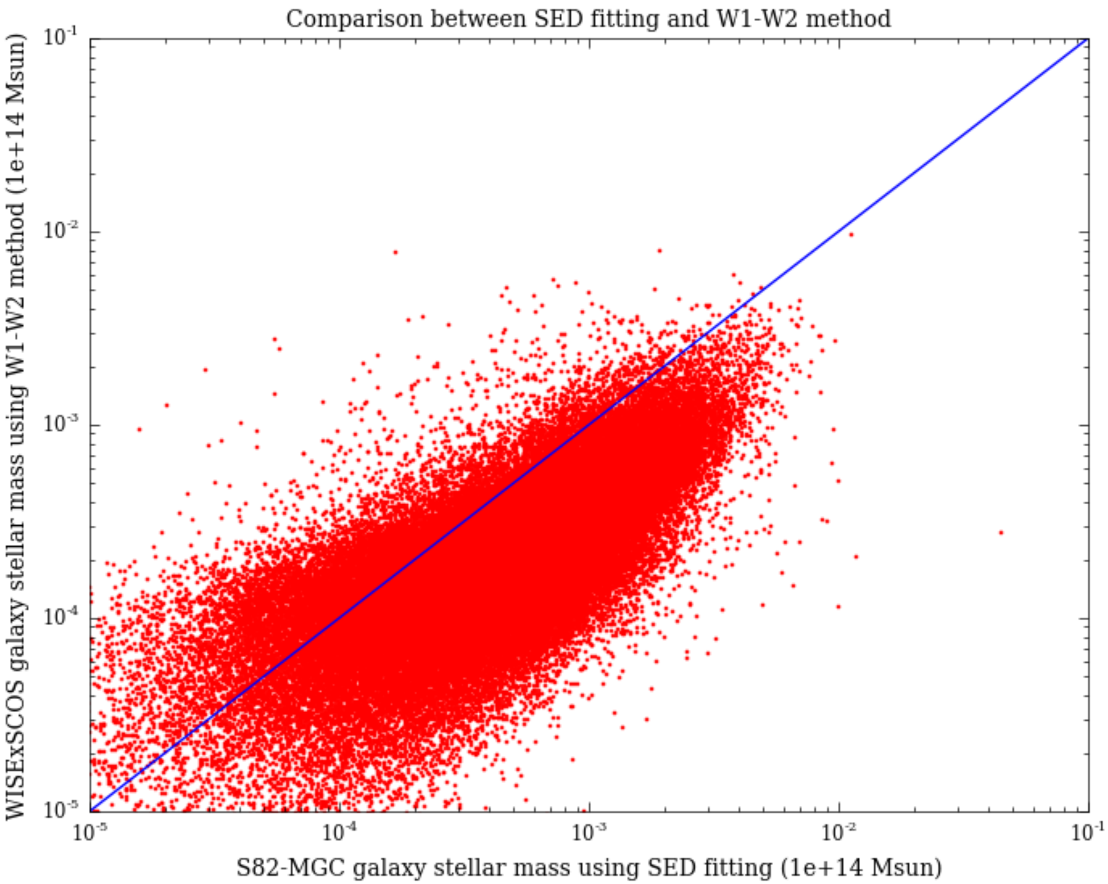
❖ Stellar mass comparison between galaxy catalogs

- ➢ Comparison between GLADE-2MASS (SED fitting method) and S82-MGC
- Cross-matching GLADE-2MASS and S82-MGC using best search radius (0.0005 deg)
- Mass estimation is ~ 0.5 mag smaller than expected: lack of photometry data in optical and NIR band (VRIY)



❖ Stellar mass comparison between galaxy catalogs

- ➢ Comparison between WISExSCOS (W1-W2 method) and S82-MGC
- Cross-matching WISExSCOS and S82-MGC using best search radius (~0.01 deg)
- Compare stellar mass of the same group of galaxies (74,403) estimated by using W1-W2 method and SED fitting method
- Mass estimation agree with expectation



❖ Galaxy Cluster Stellar Mass Estimation

- ➢ Method 1: Using galaxy richness of a cluster(Optical)
- Estimate galaxy cluster mass using the stacked velocity dispersion- richness relation derived from MacBCG catalog data (Koester et al. 2007) and Virial theorem

$Input: dynamical\ radius, richness$

$$\ln \sigma(N_{200}) = (5.52 \pm 0.04) + (0.31 \pm 0.01)\ln(N_{200})$$

$$M_{200} = \frac{5R_{200} * \sigma(N_{200})^2}{G} \text{ (Virial theorem)}$$

$Output: galaxy\ cluster\ mass$

- Estimate galaxy cluster mass using the central halo mass-richness relation (Sheldon et al. 2007) derived by applying cross-correlation cluster lensing method on SDSS II data

$Input: richness$

$$M200|20 = (8.8 \pm 0.4 \pm 1.1)\times 10^{13} h^{-1} M_{\odot}$$

$$\alpha = 1.28 \pm 0.04$$

$$M200(N200) = M200|20 * \left(\frac{N200}{20}\right)^{\alpha}$$

$Output: galaxy\ cluster\ mass$

❖ Galaxy Cluster Stellar Mass Estimation

- Method 2: Using total luminosity (X-Ray)
- X-Ray observation: no cluster richness valid
- Mass estimation from L500 (the approximate total luminosity) using the L-M relation given in Arnaud et al. (2010)

$Input: total\ luminosity\ (L_{500})$

$$h(z)^{-7/3} \frac{L_{500}}{10^{44}} \frac{erg}{s} = C \left(\frac{M_{500}}{3\times10^{14} M_{\odot}} \right)^{\alpha}$$

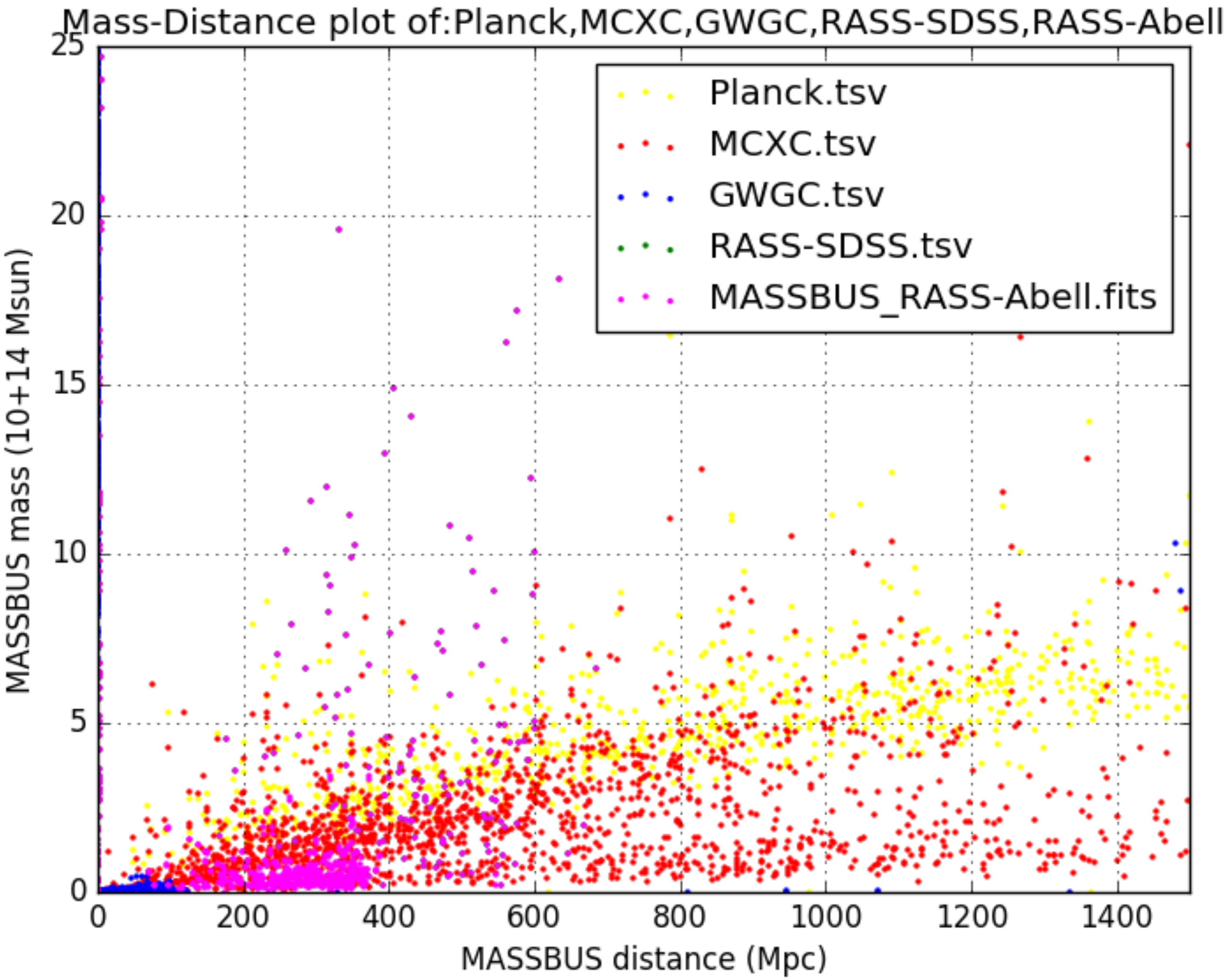
$$\log(C) = 0.274$$

$$\alpha = 1.64$$

$Output: cluster\ mass\ (M_{500})$

- Method 3: Using Sunyaev–Zel'dovich Effect (gravitational lensing)
- Planck catalog (439) : cluster mass provided by using gravitational lensing (von der Linden et al. 2014b; Hoekstra et al. 2015)

❖ Mass-distance distribution plot of 5 catalogs in Skymap Viewer



❖ Metallicity Estimation

- For all GLADE-2MASS galaxies, metallicities are estimated together with stellar mass using the BayeSED.
- Metallicities of WISExSCOS galaxies, on the other hand, are derived from stellar mass using the empirical mass-metallicity relation:

Assumption: metallicity of a galaxy is uniform and equals to the mean metallicity of the star forming gas in the galaxy.

$Input: galaxy\ mass\ (M_{gal}), redshift\ (z)$

$$\log\left(\frac{Z_{gas}}{Z_{Sun}}\right) = 0.35\left[\log(M_{gal}) - 10\right] + 0.93e^{-0.43z} - 1.05$$

$Output: galaxy\ metallicity\ (Z_{gas})$

The mass-metallicity relation comes from high-resolution cosmological simulation suite *FIRE* , and it agrees with both gas and stellar metallicity measurements observed at low redshifts for $10^4 < M_{gal} < 10^{11}\, M_{\odot}$,as well as the data at higher redshifts.

❖ Future Work

- More catalogs (PanSTAR, etc.)
- Improve the accuracy in stellar mass estimation
- Add metallicity and SFR to each galaxy
- Better localization from GW network (HLVIK) will make Skymap Viewer more helpful

❖ Summary

- Mass and distance estimations for 7 catalogs
- Observation priority is constructed by stellar mass * skymap
- Testing different stellar mass estimation by cross-matching with S82-MGC (SDSS)

Thank you!

Dr. Roy Williams

Dr. George Djorgovski

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An Extended List of Galaxies for Gravitational-Wave Searches in the Advanced Detector Era. 2016. url: http://aquarius.elte.hu/glade/GLADE Documentation 1.3.pdf
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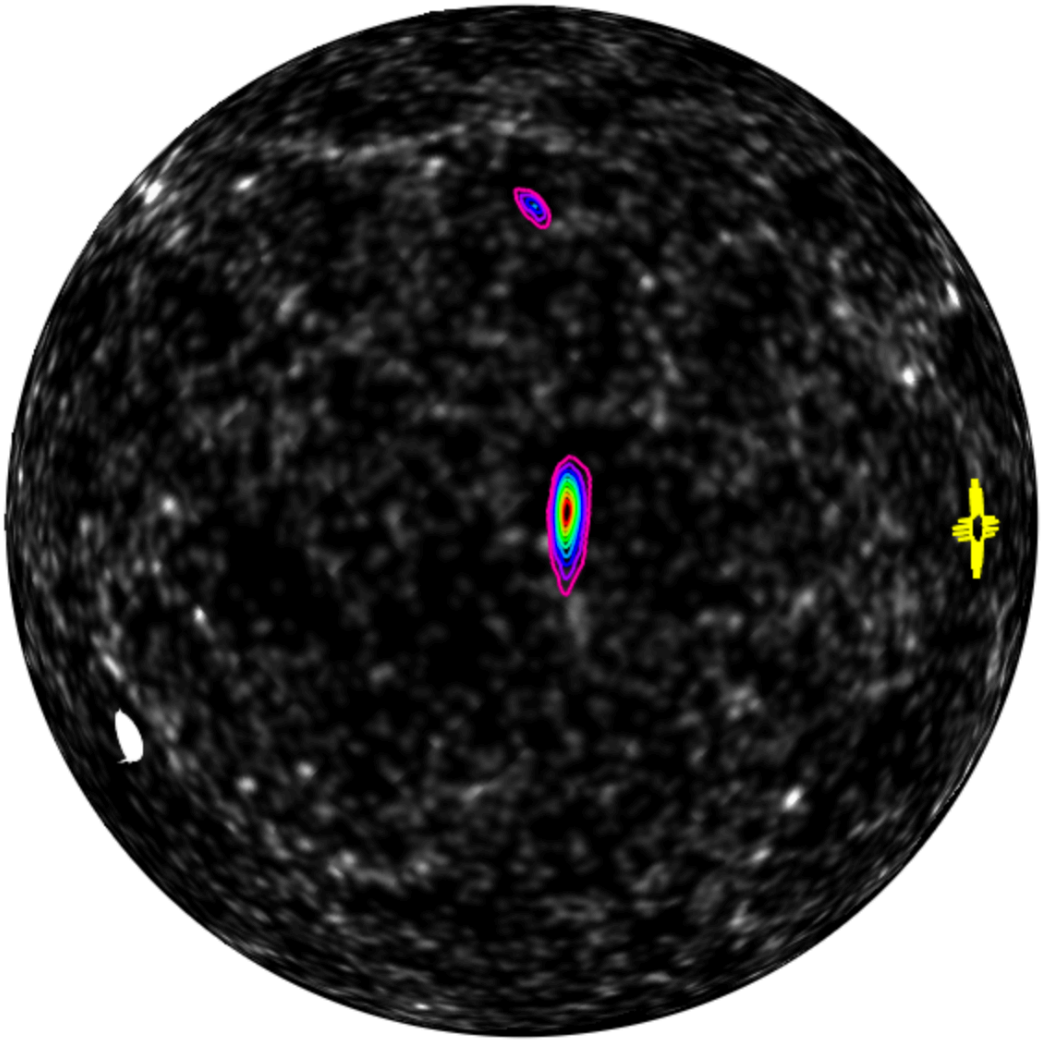
❖ Extra Slids

simulated HLV skymap from First2Years

contours are deciles of probability

many backgrounds, here shown 2MASS galaxy density*

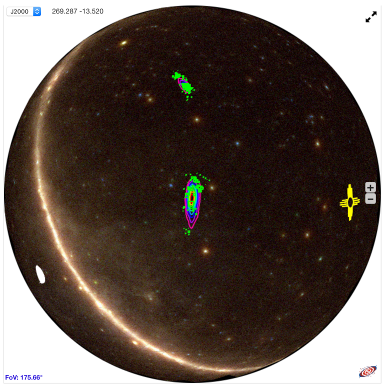
* density of 2MASS galaxies 85 to 128 Mpc
Antolini+Heyl 1602:07710



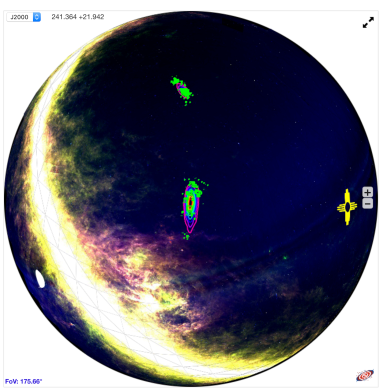
Skymap Viewer coming soon to
https://losc.ligo.org/s/skymapViewer/
(R.Williams, T.Boch, K.Li)

❖ Skymap Viewer

- AladinLite enables drill-down from whole-sky to arc-second resolution, including image surveys from radio to gamma-ray wavelengths.
- Visualize arbitrary astronomical catalogs in terms of observation priority , which combines knowledge from the gravitational wave detection (the sky map), with known astrophysical objects (i.e. galaxies and galaxy clusters).

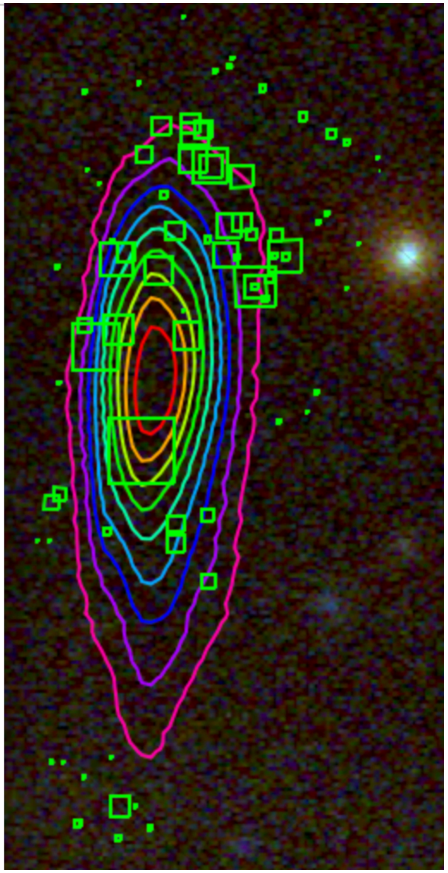


Fermi (Gama-Ray)



IRAS (IR)

Name	RA	Dec	Dist	Prior	Catalog
IC4567	234.305	43.298	81.61	1	Gravitat
UGC09959	234.782	43.865	81.33	0.847	Gravitat
PGC055257	232.545	5.838	93.36	0.7886	Gravitat
IC4564	234.113	43.519	80.67	0.7725	Gravitat
IC4566	234.176	43.539	80.1	0.7711	Gravitat
IC4562	233.988	43.493	80.62	0.7225	Gravitat
IC4565	234.147	43.425	82.22	0.5618	Gravitat
UGC09905	233.679	8.334	83.36	0.5475	Gravitat
UGC09812	229.778	9.798	90.87	0.4828	Gravitat
PGC055781	235.177	43.751	85.51	0.4419	Gravitat
NGC5926	230.854	12.715	86.74	0.4099	Gravitat
PGC055363	233.161	10.453	85.28	0.3995	Gravitat
UGC09794	229.045	10.51	90.72	0.3929	Gravitat
SDSSJ153232.46	233.135	8.765	93.93	0.3433	Gravitat
IC1118	231.248	13.445	94.22	0.3301	Gravitat
PGC055042	231.286	12.883	98.42	0.3243	Gravitat
PGC1350230	231.456	8.611	85.83	0.3232	Gravitat
IC4562A	234.012	43.503	81.61	0.323	Gravitat
PGC1375780	232.146	10.181	93.21	0.3213	Gravitat
2MASXJ15433659	235.902	43.98	86.19	0.31	Gravitat
PGC054822	230.403	11.257	90.15	0.2874	Gravitat
PGC054844	230.486	10.568	90.21	0.2847	Gravitat
PGC054946	230.842	12.693	91.54	0.2811	Gravitat
NGC5947	232.652	42.717	84.35	0.2697	Gravitat
PGC054675	229.778	9.775	90.56	0.2631	Gravitat
PGC054729	230.072	12.455	93	0.261	Gravitat
PGC2231045	234.843	43.866	81.71	0.2487	Gravitat
PGC055349	233.077	-2.822	97.86	0.2414	Gravitat
PGC091459	233.653	43.039	87.28	0.2393	Gravitat
UGC09890	233.136	41.98	85.56	0.2372	Gravitat
UGC10070	237.803	47.255	84.86	0.2361	Gravitat
PGC055051	231.339	13.73	93.37	0.2337	Gravitat



❖ Galaxy Stellar Mass Estimation

➢ Method 1: Using B band photometry data to estimate galaxy stellar mass:

Assumption: all stars in galaxies have the same mass-to-light ratio of the Sun

Input: apparent B band magnitude, redshift (z)

$$m_B - M_B = 5\log(d) - 5$$

$$L_B = \frac{L_{B\odot}}{10^{0.4(M_B - M_{B\odot})}}$$

$$M_g \cong L_B * \frac{M_\odot}{L_{B\odot}}$$

$M_{B\odot}$=5.48 mag (absolute magnitude of the Sun in B band)

$L_{B\odot}=\frac{3\times10^{33} erg}{s}$ (B band luminosity of the Sun)

$M_\odot=1.989\times10^{30} kg$ (mass of the Sun)

$Output: galaxy\ stellar\ mass\ M_g$

❖ Galaxy Stellar Mass Estimation

➢ Method 3: Using W1-W2 band photometry data

The W1 band ($3.4\ \mu m$) of WISE survey is dominated by the light from old stars and can be used as an effective measure of stellar mass (Jarrett et al. 2013).

$Input: W1, W2, redshift$

$$\log\left(\frac{M_{stellar}}{L_{W1}}\right) = -1.96(W_1 - W_2) - 0.03$$
$$L_{W1}(L_{\odot}) = 10^{-0.4(M - M_{Sun})}$$

-$M_{Sun} = 3.24$

-$M: W_1\ band\ absolute\ magnitude$

-$W_1 - W_2: rest\ frame\ color$

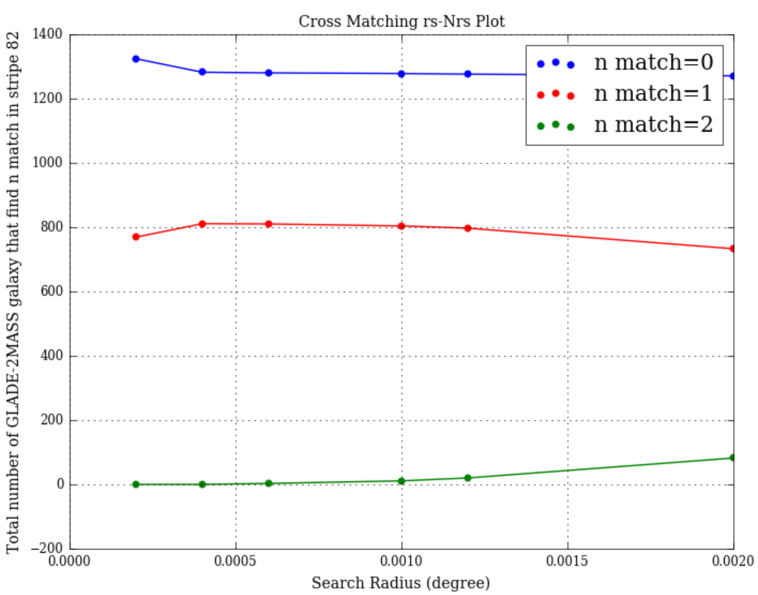
$Output: galaxy\ stellar\ mass\ M_{stellar}$

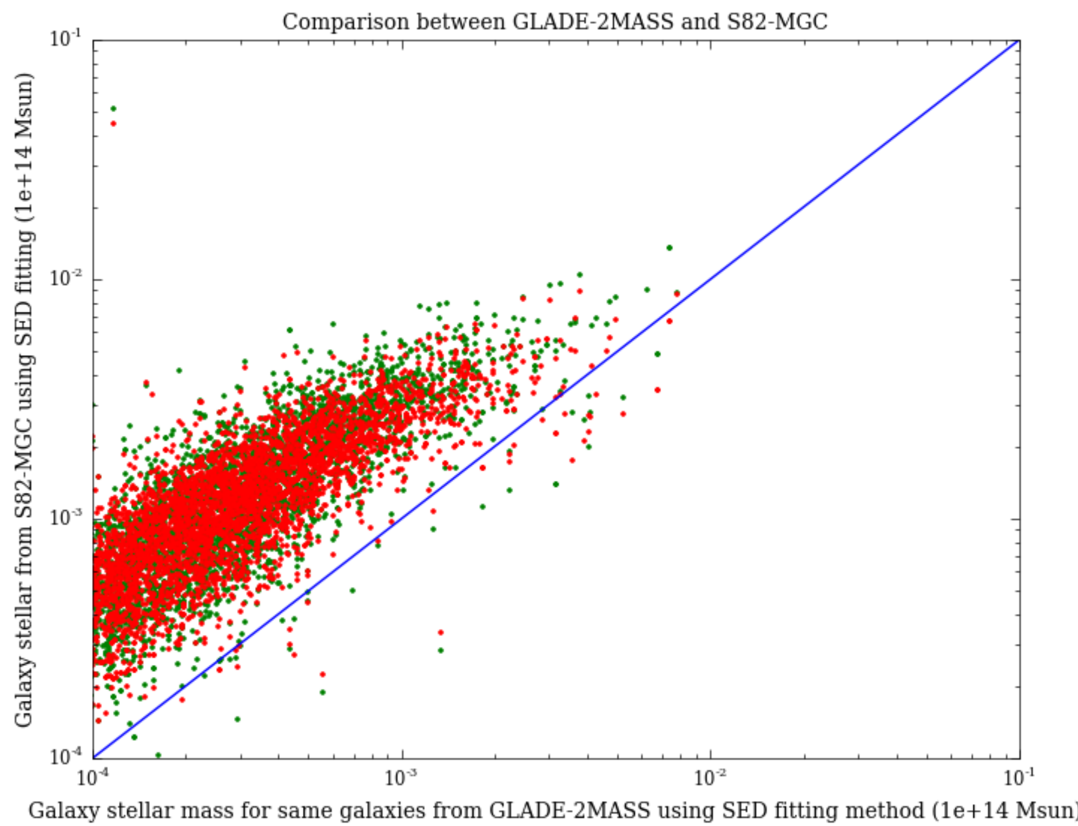
❖ Galaxy Stellar Mass Estimation

- GLADE-2MASS catalog (548,876 galaxys): B, J, H, K band magnitude and redshift
- Evolutionary population synthesis model library: Bruzual Charlot (2003) (BC2003)
- IMF (Initial Mass Function) adopted: Chabrier (2003)
- SFHs (Star Formation History) of galaxies: $SFR \propto e^{t/\tau}$
  - t : the time since the start of star formation
  - τ : the e-folding star formation timescale
- Dust attenuation:
  - A uniform dust screen
  - Dust extinction law adopted: Calzetti et al. (2000)
- BC2003 parameter grid:
  - $\log\left(\frac{\tau}{yr}\right) \in [6.5, 11], step\ size = 0.1\ yr$
  - $\log\left(\frac{t}{yr}\right) \in [7.0, 10.1], step\ size = 0.05\ yr$
  - $Av \in [0, 4], step\ size = 0.2$
  - Metallicity $\in \{0.004, 0.008, 0.02, 0.05\}$
- 243,434 model SEDs in the library, which we used to compare with observed galaxy SEDs in GLADE-2MASS.

❖ Stellar mass comparison between galaxy catalogs

- ➢ Comparison between GLADE-2MASS (SED fitting method) and S82-MGC
- Cross-matching GLADE-2MASS and S82-MGC using best search radius (0.0005 deg)
- Compare stellar mass of the same group of galaxies both estimated by using SED fitting but using different data from two catalogs.

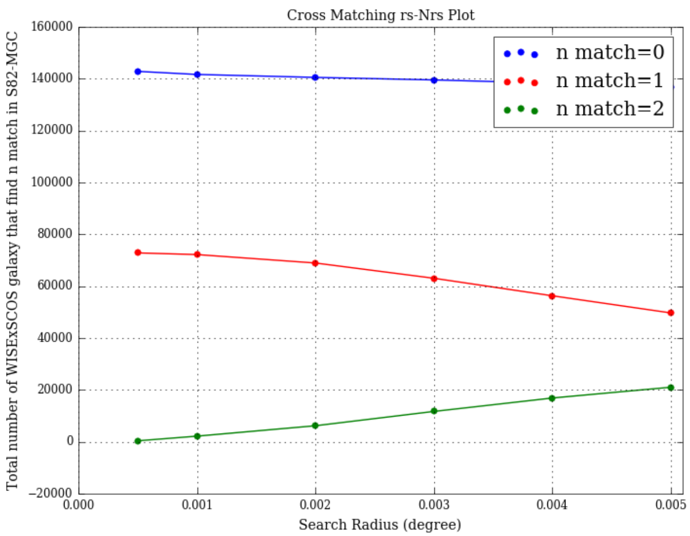


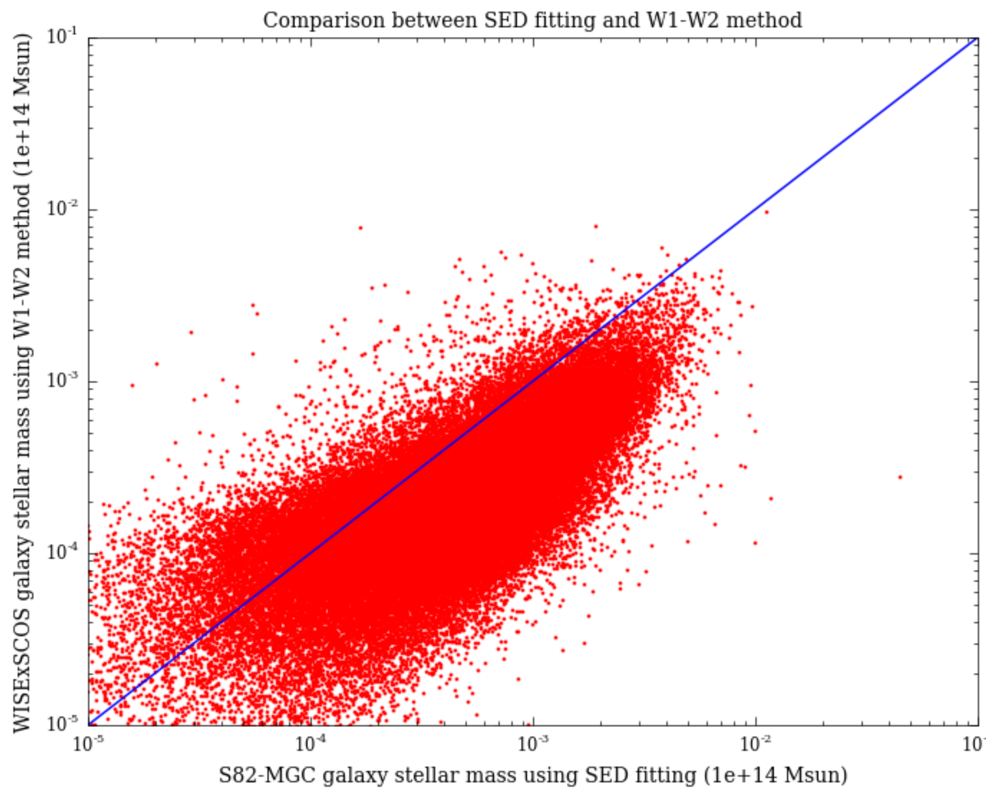


❖ Stellar mass comparison between galaxy catalogs

➢ Comparison between WISExSCOS (W1-W2 method) and S82-MGC

- Cross-matching WISExSCOS and S82-MGC using best search radius (~0.01 deg)
- Compare stellar mass of the same group of galaxies (74,403) estimated by using W1-W2 method and SED fitting method





❖ Galaxy Cluster Stellar Mass Estimation

- Method 1: Using galaxy richness of a cluster(Optical)
- Estimate galaxy cluster mass using the stacked velocity dispersion- richness relation derived from MacBCG catalog data (Koester et al. 2007)

$Input: R_{200}, N_{200}$

-R_{200}: $the\ radius\ inside\ which\ the\ average\ density\ is\ 200 * critical\ density(z)$

-N_{200} : $the\ number\ of\ galaxies\ enclosed\ by\ the R_{200}\ circle$

$$\ln \sigma(N_{200}) = (5.52 \pm 0.04) + (0.31 \pm 0.01)\ln(N_{200})$$

$$M_{200} = \frac{5R_{200} * \sigma(N_{200})^2}{G}$$ (Virial theorem)

-$\sigma(N_{200})$: $the\ stacked\ velocity\ dispersion\ at\ R_{200}\ (dynamical\ cluster\ radius)$

$Output: galaxy\ cluster\ mass$

❖ Metallicity Estimation

- For all GLADE-2MASS galaxies, metallicities are estimated together with stellar mass using the BayeSED.
- Metallicities of WISExSCOS galaxies, on the other hand, are derived from stellar mass using the empirical mass-metallicity relation:

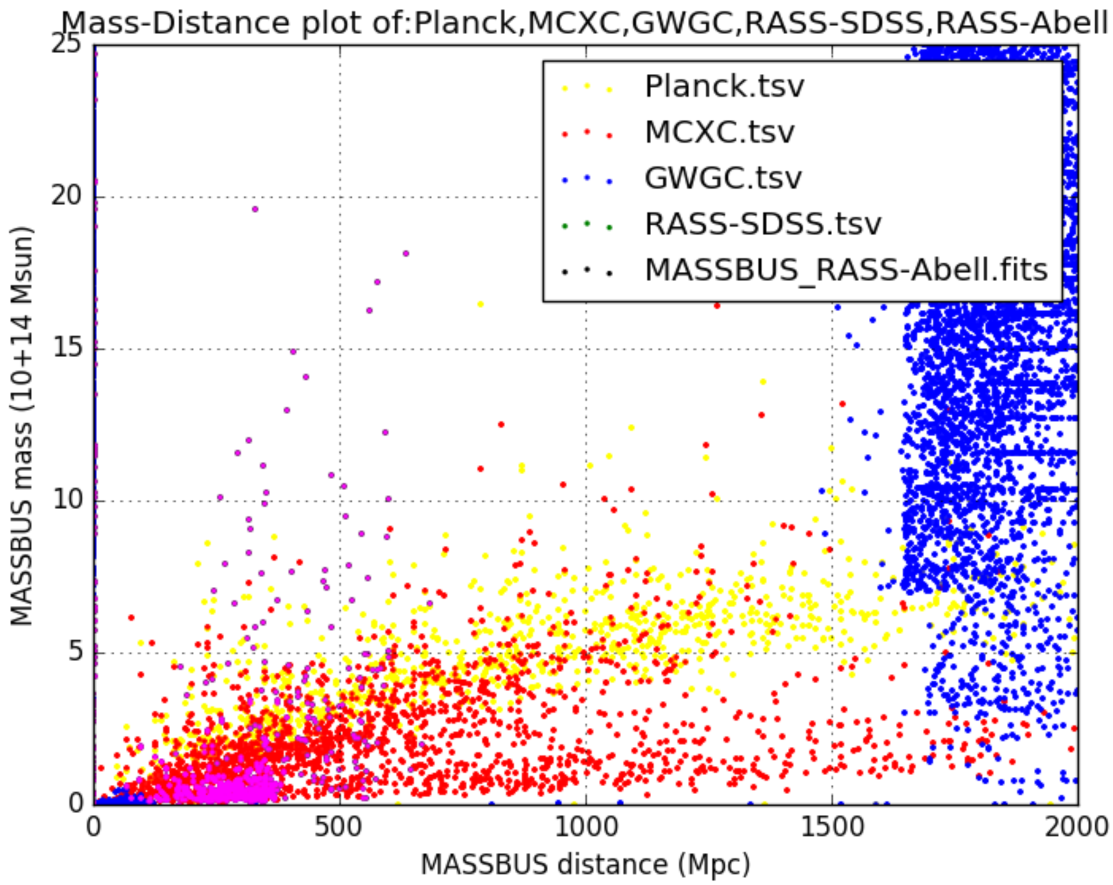
Assumption: metallicity of a galaxy is uniform and equals to the mean metallicity of the star forming gas in the galaxy.

$Input: galaxy\ mass\ (M_{gal}), redshift\ (z)$

$$\log\left(\frac{Z_{gas}}{Z_{Sun}}\right) = 0.35\left[\log\left(M_{gal}\right) - 10\right] + 0.93e^{-0.43z} - 1.05$$

$Output: galaxy\ metallicity\ (Z_{gas})$

The mass-metallicity relation comes from high-resolution cosmological simulation suite *FIRE* , and it agrees with both gas and stellar metallicity measurements observed at low redshifts for $10^4 < M_{gal} < 10^{11}\,M_{\odot}$,as well as the data at higher redshifts.


Mass-Distance plot of:Planck,MCXC,GWGC,RASS-SDSS,RASS-Abell
Planck.tsv
MCXC.tsv
GWGC.tsv
RASS-SDSS.tsv
MASSBUS_RASS-Abell.fits
MASSBUS mass (10+14 Msun)
MASSBUS distance (Mpc)
0
5
10
15
20
25
0
500
1000
1500
2000