ICRAR

International Centre for Radio Astronomy Research

Searching for High Redshift Gravitationally Lensed Galaxies from Radio/Infrared Surveys

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Project Objectives

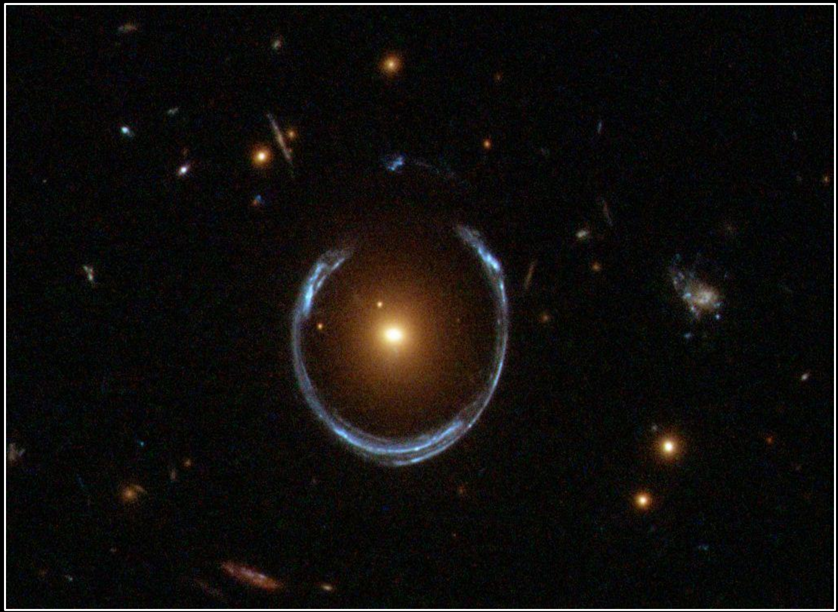


Figure 1: information. (2009). Hubble captures a "lucky" galaxy alignment. Retrieved February 12, 2017, from http://www.spacetelescope.org/images/potw1151a

1. **To develop a model for identifying high redshift strong gravitationally lensed galaxies.**

2. **Search far infrared (FIR) and Radio catalogues for new high redshift gravitationally lensed candidates.**

Galaxy-Galaxy Gravitational Lensing

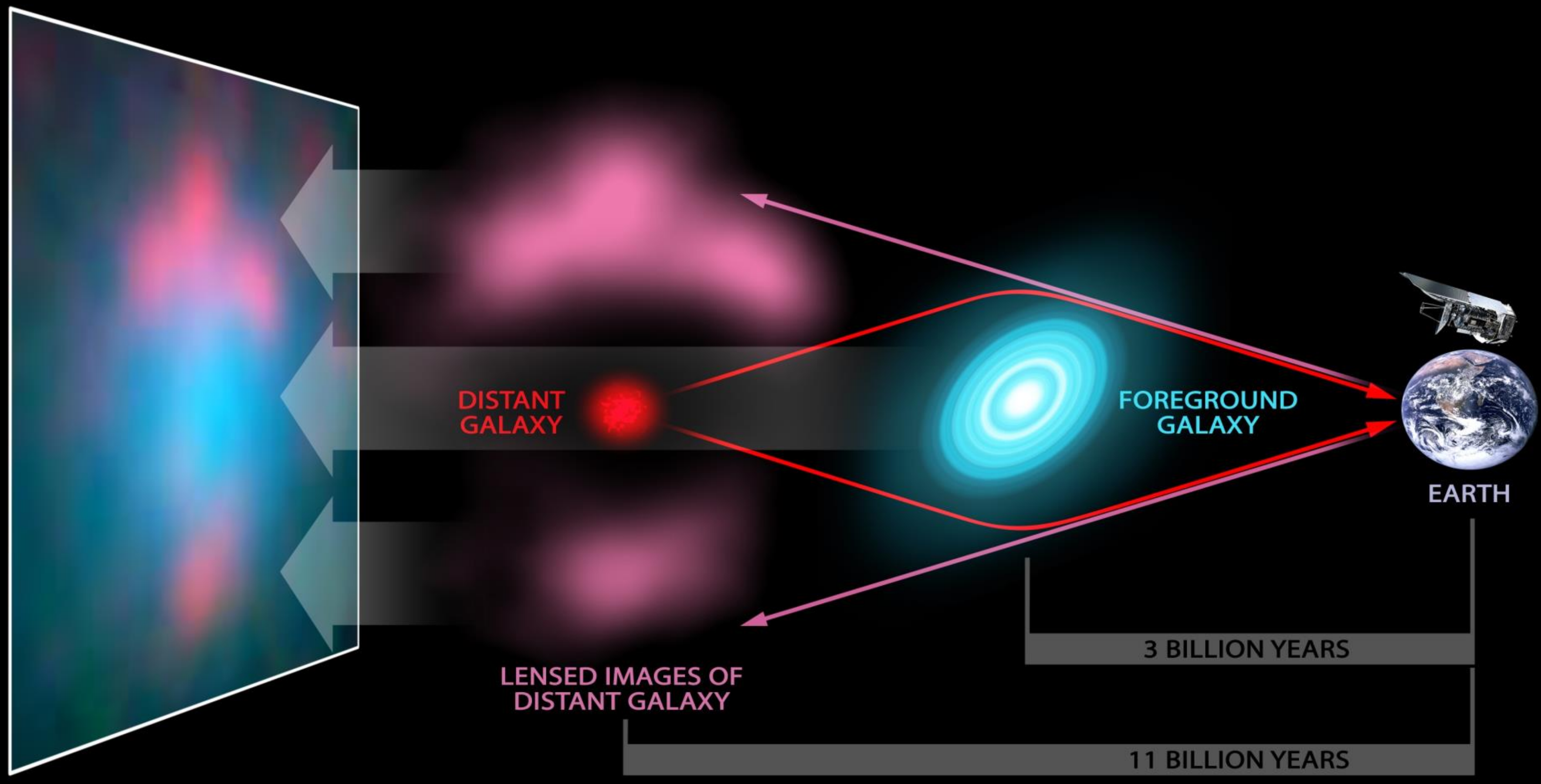


Figure2: Byrd, D. (2015, October 3). Einstein ring helps weigh a black hole. Retrieved February 12, 2017, from EarthSky, http://earthsky.org/space/einstein-ring-helps-weigh-a-black-hole

Strong Gravitational Lensing

- **Increases brightness in some cases up to 20x (Ma et al, 2015).**
- **High redshift lensed galaxies, typically tend to be dusty star forming galaxies (DSFG's) (Wardlow et al 2013).**

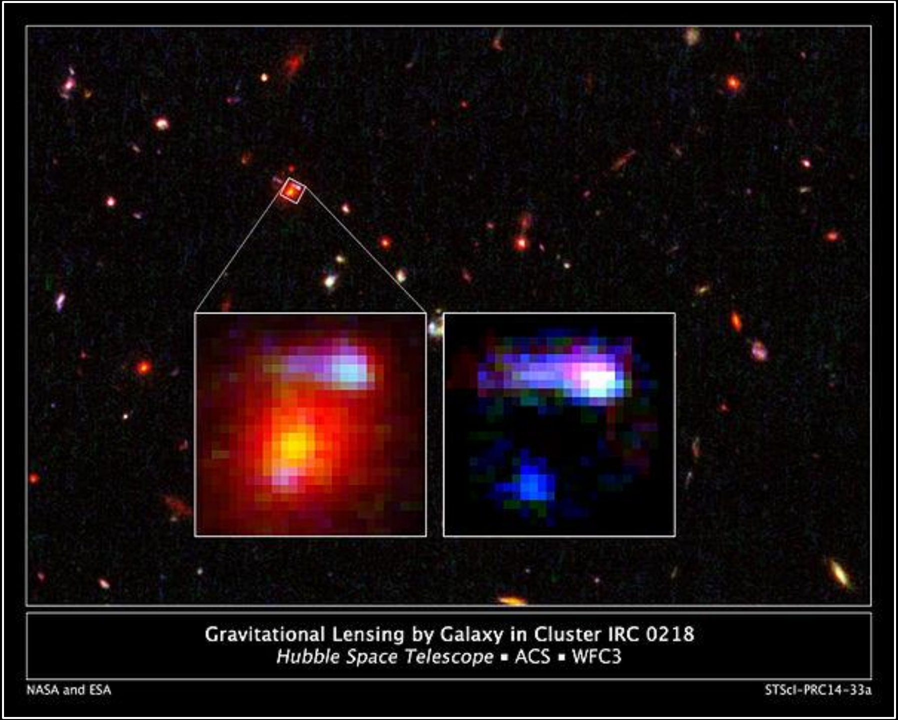


Figure 3: Alexander, S. (2014, July 31). Hubble farthest Lensing galaxy. Retrieved February 12, 2017, from https://www.nasa.gov/press/2014/july/hubble-shows-farthest-lensing-galaxy-yields-clues-to-early-universe/

Dusty Star Forming Galaxies (DSFG's)

Figure 4: Dusty star forming nebula in the Whirlpool galaxy, credit: NASA, ESA, S. Beckwith, and The Hubble Heritage Team

- **z~>2, FIR regime galaxy populations appear to be dominated by DSFG's (Murphy et al. 2009).**
- **DSFG's typically undergoing intense high mass star formation $\sim 8 M_{\odot}$ (Condon et al, 1992).**

Modelling DSFG's as LIRG's

- **DSFG's have star formation rates on the order of $100 \rightarrow 1000 M_{\odot}\,\mathrm{yr}^{-1}$, (Ma et al, 2015).**
- **Luminous infrared galaxies (LIRG's), z < 1, are similar to DSFG's in many ways, but at low redshift.**
- **LIRG's are gas rich galaxies undergoing lots of star formation, $L_{\odot}10^{11} \leq L_{IR} \leq L_{\odot}10^{12}$ (Murphy et al,2009).**
- **LIRG's and ULIRG's were used to model DSFG's.**

LIRG, ULIRG SED Templates

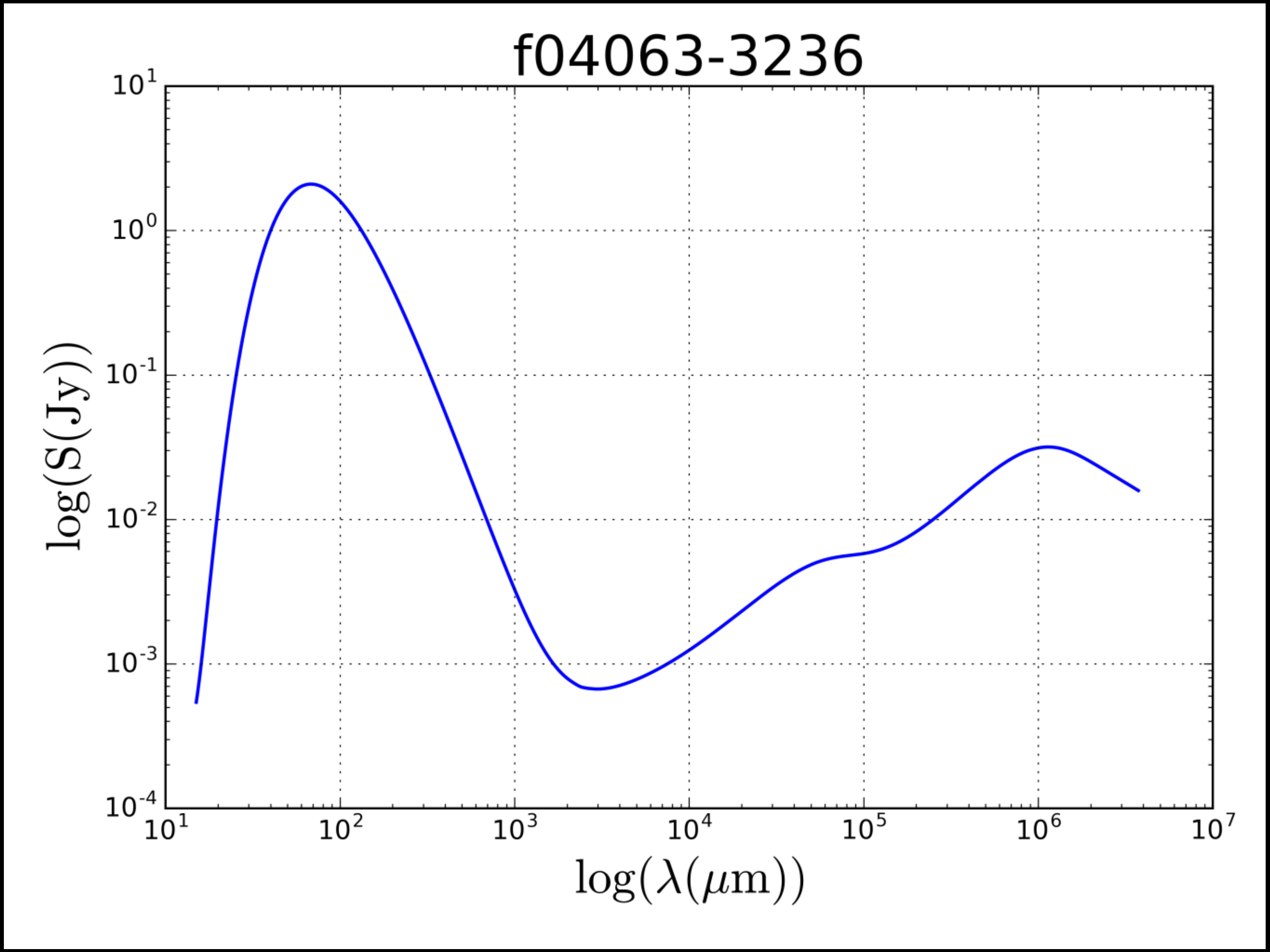


Figure 5: Spectral energy distribution provided by Galvin et al submitted. Log space plot of the flux density in Janksy's v the wavelength in microns.

Modelling the FRC

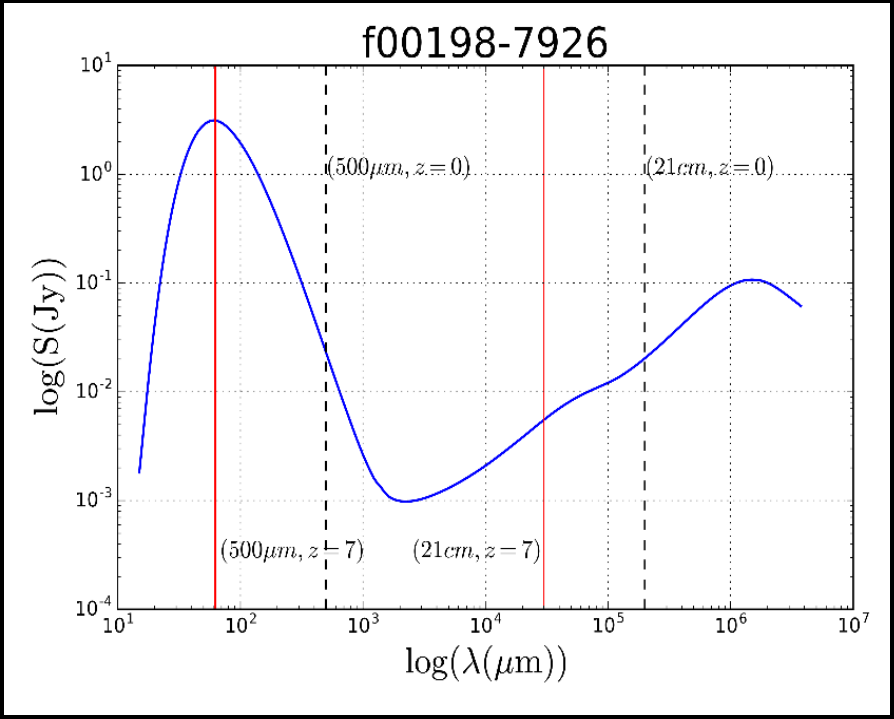


Figure 6: SED template showing the location of the rest frame 500 micron flux and 21 cm flux at z=0 and z=7.

- **FRC can be modelled by taking the ratio of FIR and radio flux measurements.**
- **To model high redshift galaxies, the FRC was shifted incrementally to a redshift of z=7. The evolution with the rest frame was modelled as a function of redshift.**

$$q_{FRC} = \log_{10} S_{FIR} - \log_{10} S_{RADIO}$$

$$q_{FRC} = \log_{10}\left(\frac{S_{FIR}}{S_{RADIO}}\right)$$

Model Final

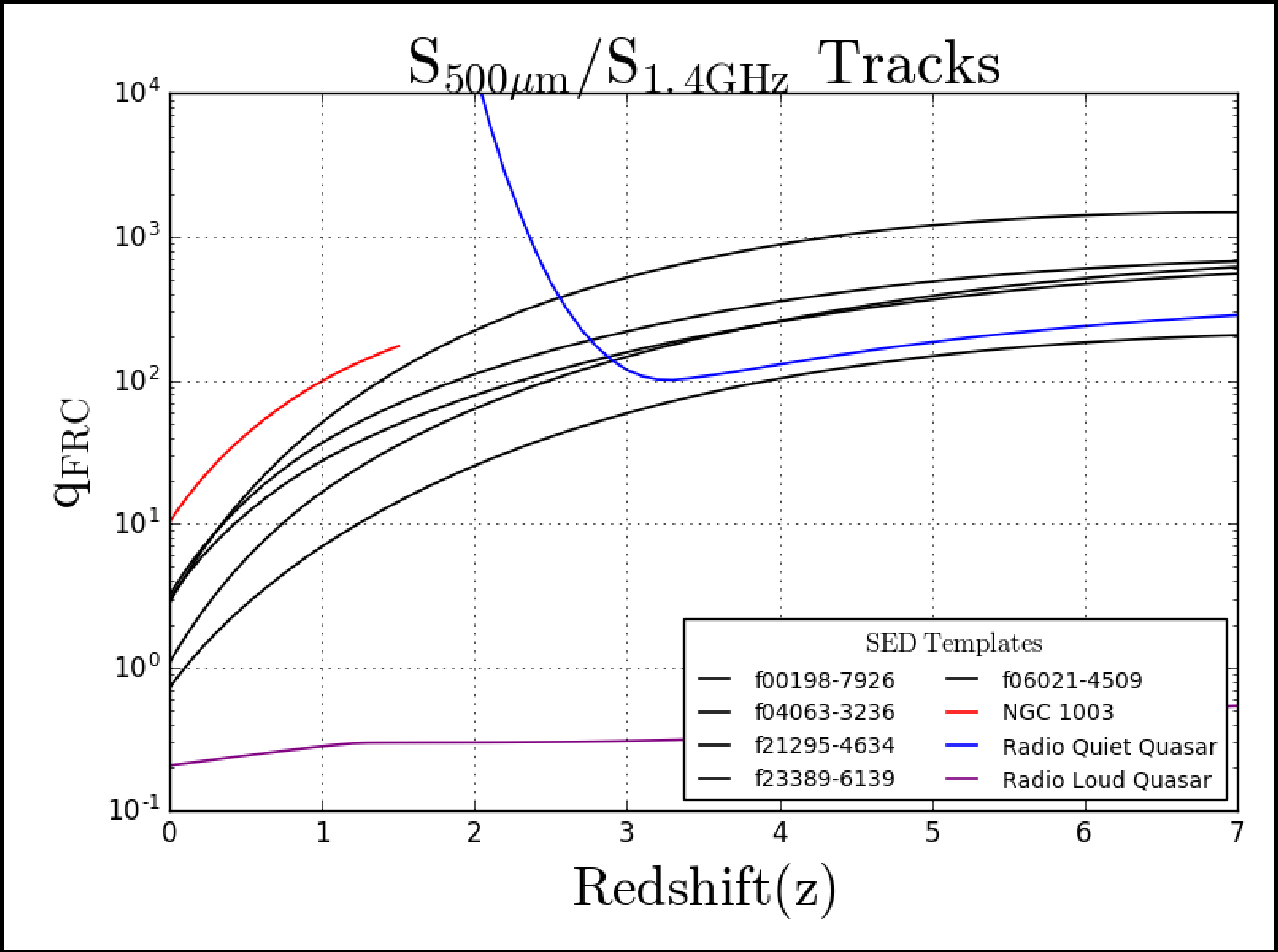


Figure 7: Final model with added low star formation rate SED for NGC 1003 modelling local spirals. And the added Radio Loud and Radio Quiet quasar tracks.

Testing the Model

- **13 known strong galaxy to galaxy gravitationally lensed sources were tested against the model.**

- **7 from (Wardlow et al, 2013), from a wide field survey, with FIR and radio flux data.**

- **6 from SPT (Ma et al, 2015), only FIR data no radio data. Assumed an upper limit radio flux of 2.5mJy.**

Testing the Model

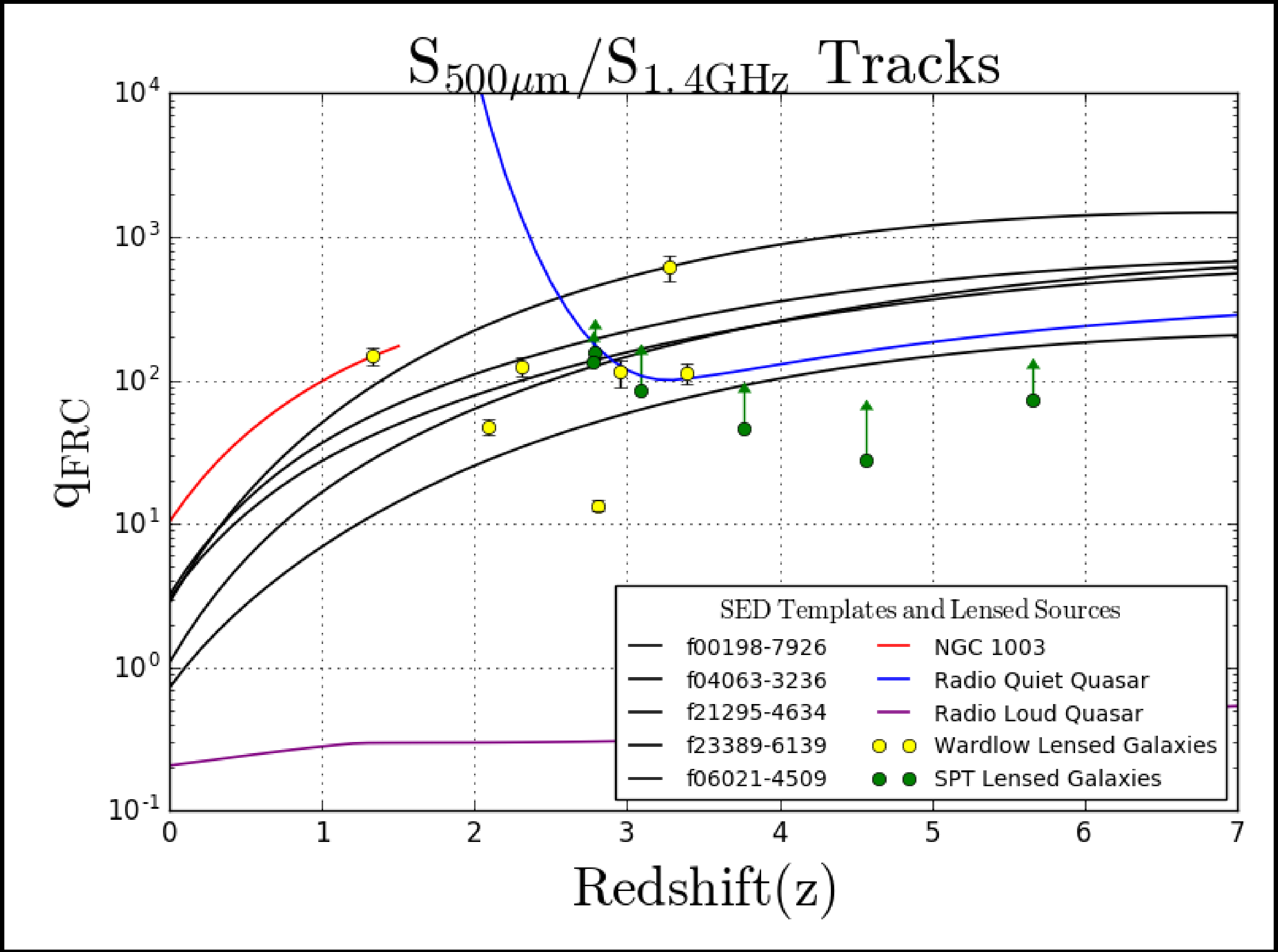


Figure 8: Final model for the 500 micron and 1.4GHz tracks, tested with the 6 Wardlow sources, and the 6 SPT sources. The SPT sources did not have 1.4GHz flux measurements.

Searching for Candidates

- **Cross matched 500 micron Herschel space survey with NVSS/FIRST/COSMOS/ATLAS surveys.**
- **Interested in sources with 500 micron fluxes above 100mJy.**

Figure 9: Herschel Space Observatory retrieved from, http://spaceref.com/missions-and-programs/european-space-agency/herschel/esas-herschel-space-observatory-runs-out-of-helium.html

- **21 candidates with redshift data were identified, 4 of which were already known strong gravitationally lensed galaxies.**

Final Plot

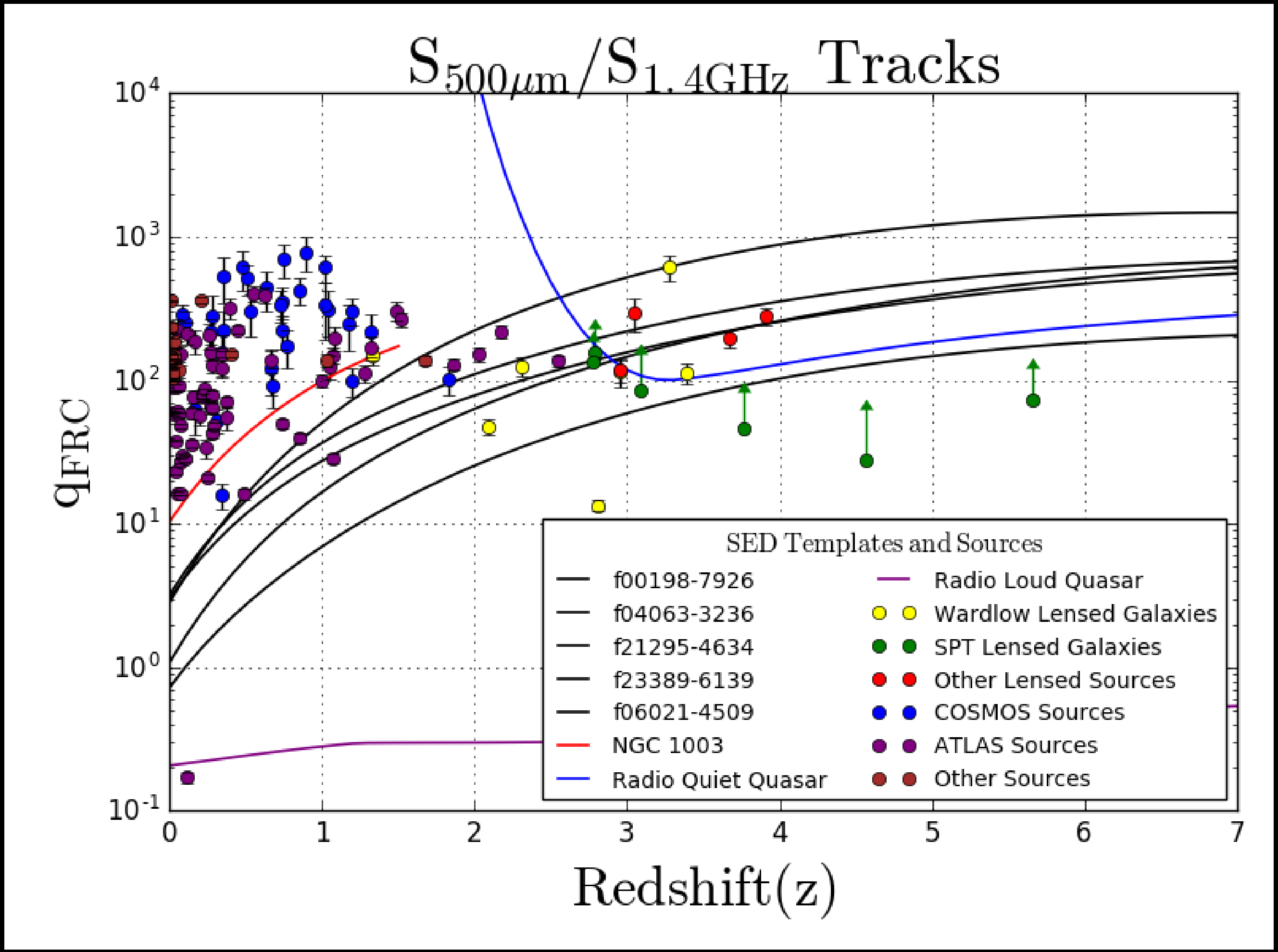


Figure 10: Final model with the candidate COSMOS, ATLAS, and Other sources plotted to determine if there were any potentially lensed candidates.

Conclusion

- **No new lensed sources were found.**
- **The model seems to work for high redshift sources, and all normal type galaxies that are lensed fit the model.**
- **Use different FIR and radio wavelengths to test the model.**
- **Add more local galaxy template tracks.**
- **Potentially adjust for inverse Compton scattering.**

References:

- Wardlow, J., Cooray, A., & De Bernardis, F. (2012). HerMES: CANDIDATE GRAVITATIONALLY LENSED GALAXIES AND LENSING STATISTICS AT SUBMILLIMETER WAVELENGTHS. *The Astrophysical Journal*, *762*(1),
- Wong, K. C., Tran, K.-V. H., Suyu, S. H., Momcheva, I. G., Brammer, G. B., Brodwin, M., … Rudnick, G. H. (2014). DISCOVERY OF A STRONG LENSING GALAXY EMBEDDED IN A CLUSTER AT z = 1.62. *The Astrophysical Journal*, *789*(2), L31. doi:10.1088/2041-8205/789/2/l31
- Ma, J., Gonzalez, A. H., Spilker, J. S., Strandet, M., Ashby, M. L. N., Aravena, M., … Welikala, N. (2015). STELLAR MASSES AND STAR FORMATION RATES OF LENSED, DUSTY, STAR-FORMING GALAXIES FROM THE SPT SURVEY. *The Astrophysical Journal*, *812*(1), 88. doi:10.1088/0004-637x/812/1/88
- Lisenfeld, U. (2015). The far-infrared-radio correlation in galaxies. *Spanish SKA White Book*
- *Condon, J. (1992). Radio Emission From Normal Galaxies. The Astrophysical Journal 30:575-611.*

References:

- Howell, J. H., Armus, L., Mazzarella, J. M., Evans, A. S., Surace, J. A., Sanders, D. B., … Xu, K. (2010). THE GREAT OBSERVATORIES ALL-SKY LIRG SURVEY: COMPARISON OF ULTRAVIOLET AND FAR-INFRARED PROPERTIES. *The Astrophysical Journal*, *715*(1), 572–588. doi:10.1088/0004-637x/715/1/572
- Magnelli, B., Ivison, R. J., Lutz, D., Valtchanov, I., Farrah, D., Berta, S., … Wuyts, S. (2014). The far-infrared/radio correlation and radio spectral index of galaxies in the SFR–M∗plane up toz~2. *Astronomy & Astrophysics*, *573*, A45. doi:10.1051/0004-6361/201424937
- Galvin, T., & Seymour, N. (submitted). The Spectral Energy Distribution of Luminous Infrared Galaxies - Part 1: Modelling the Radio-Continuum. *Royal Astronomy Society*

Suggested Reading and Questions?

- Radio Emission From Normal Galaxies, Condon 1992.
- HerMES: Candidate Gravitationally Lensed Galaxies and Lensing Statistics at Submillimeter Wavelengths, Wardlow et al 2013.
- Characterizing the Radio Continuum Emission From Intense Starburst Galaxies, Galvin et al 2016.
- Stellar Masses and Star Formation Rates of Lensed, Dusty, Star-Forming Galaxies From the SPT Survey, Ma et al 2015.
- The Far-Infrared-Radio Correlation at High Redshifts: Physical Considerations and Prospects for the SKA, Murphy et al 2015.

Future Radio Surveys

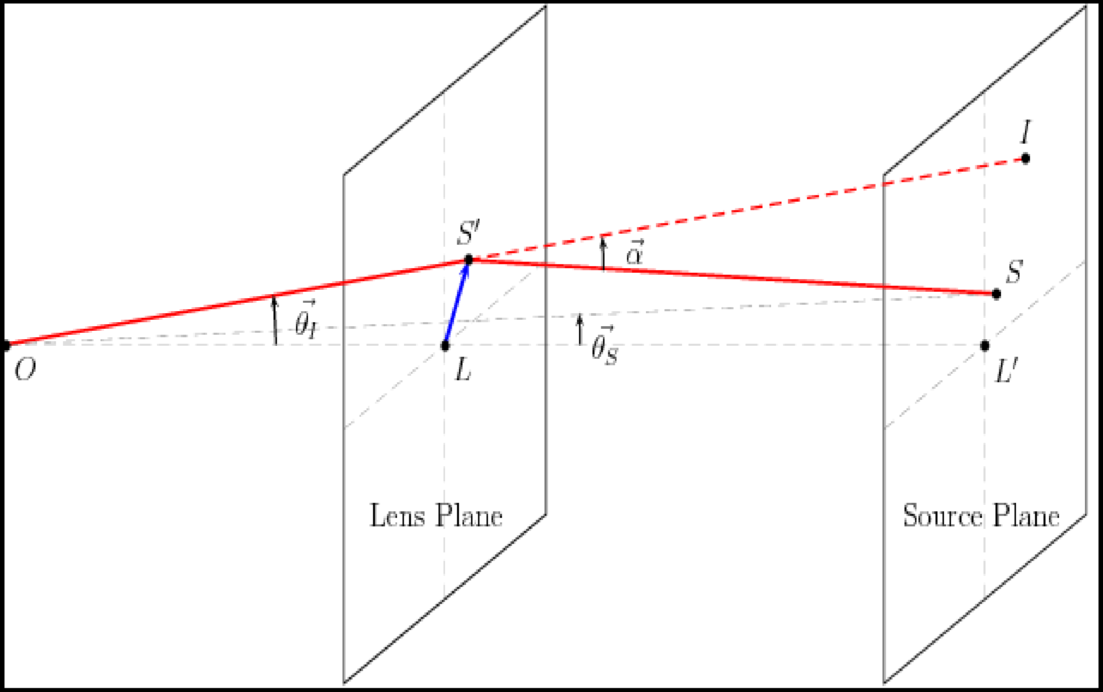
- **SKA will help increase the sensitivity of detections for DSFG's (Murphy et al, 2009).**

- **Deeper resolution will make it possible to detect lensed sources that might not have high radio emission.**

Extra Material

Gravitational Lensing:

- Gravitational lensing bends light around the potential well of some foreground lens (mass distribution). This is analogous to the refraction caused by density differential in glass etc. But unlike glass and other conventional lenses gravity lenses don't have focal points.



- The magnification of the image depends on the angle alpha, other distortions are depend on the lens shape.
- Increase in the angular size of the background source cause an amplification of the brightness of the image due to the conservation of flux.

Adhikari, S. (2009, July 9). Gravitational Lensing REU project. Retrieved February 13, 2017, from https://www.phys.ksu.edu/personal/adhikari/lensingdiagram.html

FRC (Radio Component)

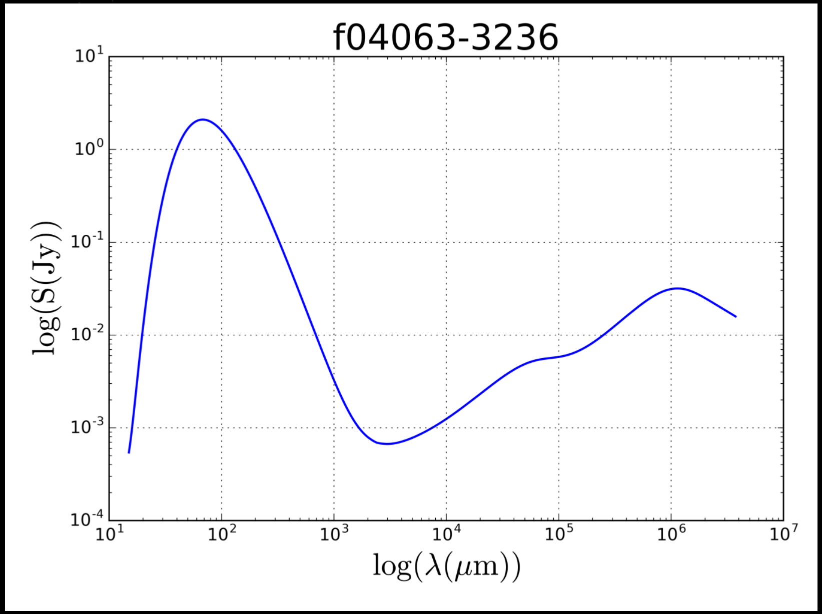
- Thermal radio component from HII regions around high mass young stars, results in both free-free emission and absorption. Given by the power law relationship (Condon et al. 1992):

$$S_{\nu} \propto \nu^{-0,1}$$

- Synchrotron emission from cosmic ray electrons, accelerated by supernovae from high mass young stars, radiate energy via interactions with galactic magnetic fields, proportional to the power law:

$$S_{\nu} \propto \nu^{-0.8}$$

SED Template Model



- **Radio modelled by thermal and synchrotron components of radio power law. Fitted to radio data taken from LIRG's and ULIRG's (Galvin et al, 2016):**

$$S_{Radio}(\nu) = A\left(\frac{\nu}{\nu_o}\right)^{-0,1} + B\left(\frac{\nu}{\nu_o}\right)^{-0,8}$$

- **FIR modelled by a grey body distribution, model was fitted to LIRG and ULIRG data points from observations (Galvin et al submitted):**

$$S_{FIR}(\lambda) = N\left[\left(\frac{60\mu m}{\lambda}\right)^{3+\beta} * \frac{1}{e^{\frac{hc}{\lambda kt}} - 1}\right]$$

Model Tracks

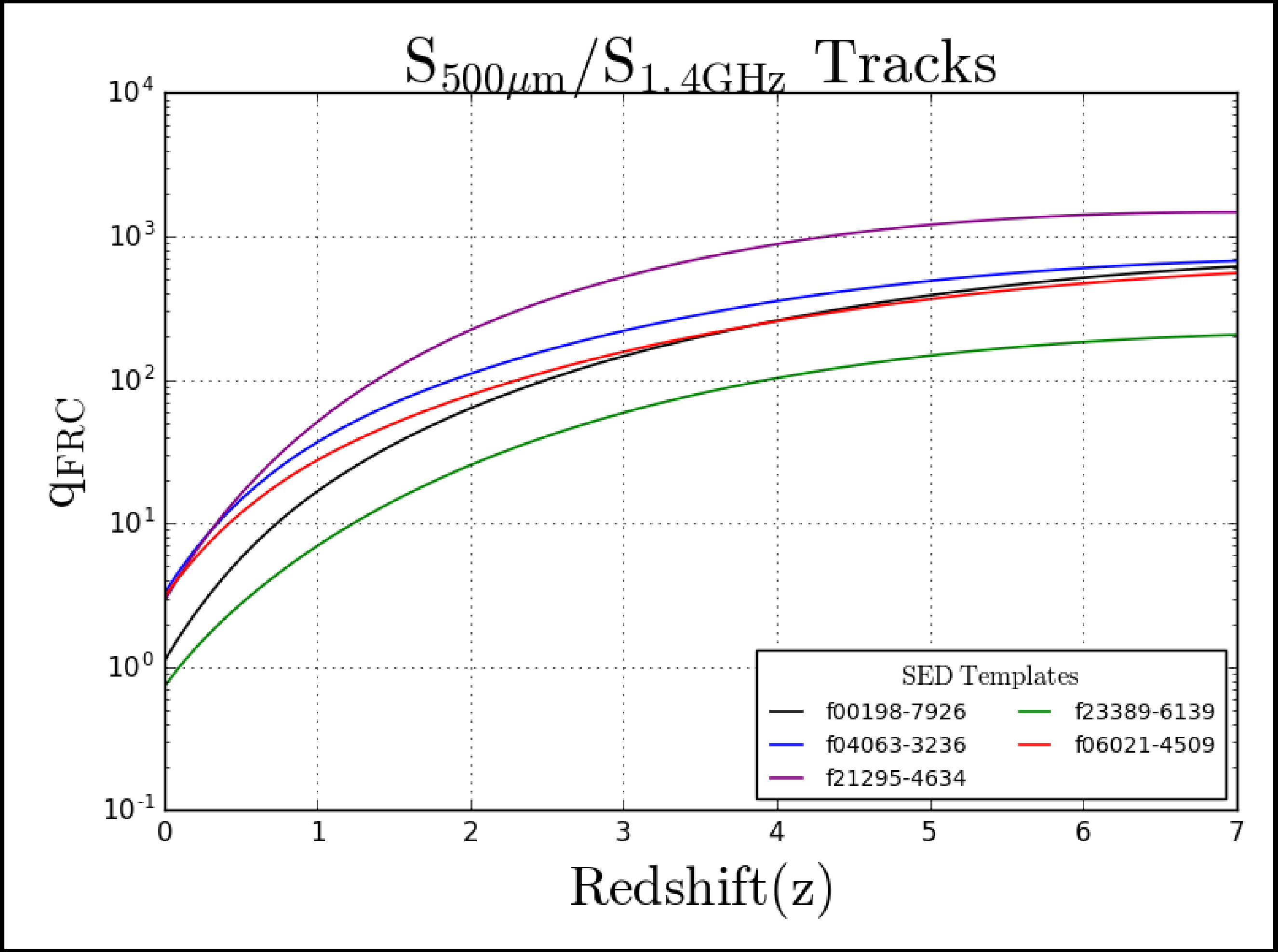


Figure 7: 5 SED templates were retrieved from (Galvin et al, submitted), and were used to model the FRC up to a redshift of z = 7, for the 500 micron FIR regime and the 21cm radio regime.

Herschel/GAMA Model Tracks

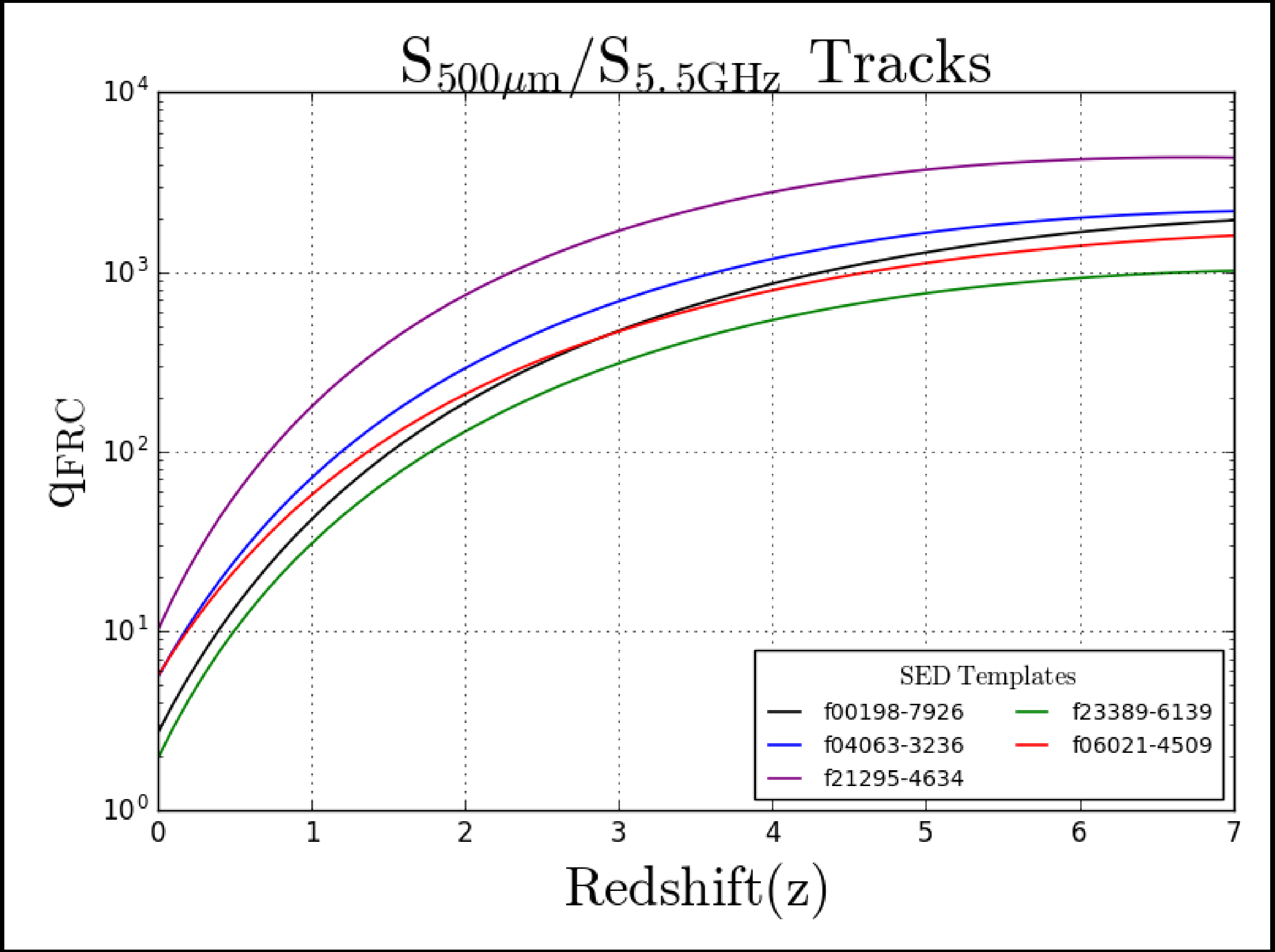


Figure X: Final model with added low star formation rate SED for NGC 1003 modelling local spirals. And the added Radio Loud and Radio Quiet quasar tracks.

Herschel/GAMA Model Tracks

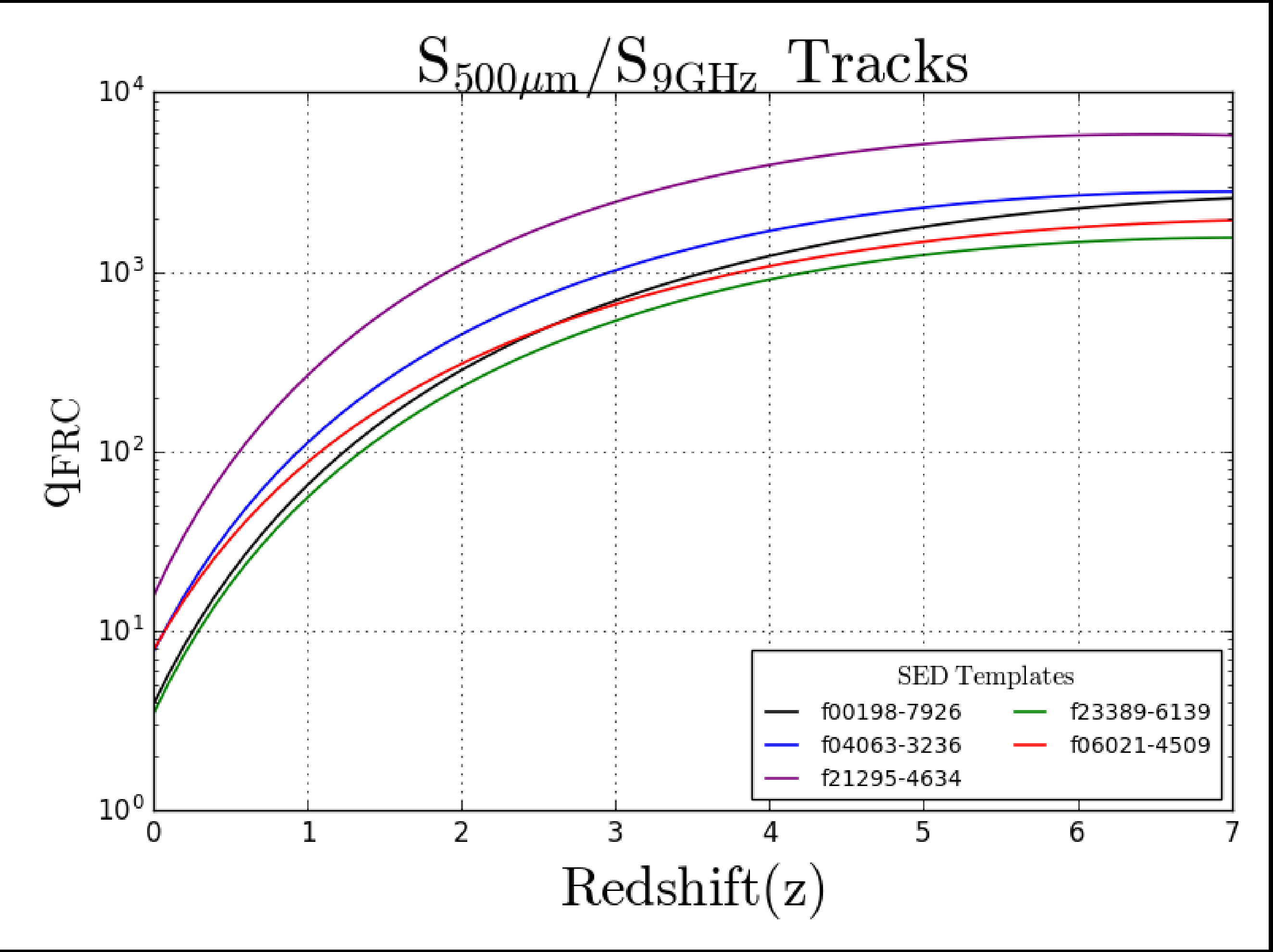


Figure X: Final model with added low star formation rate SED for NGC 1003 modelling local spirals. And the added Radio Loud and Radio Quiet quasar tracks.

SPT/EMU Model Tracks

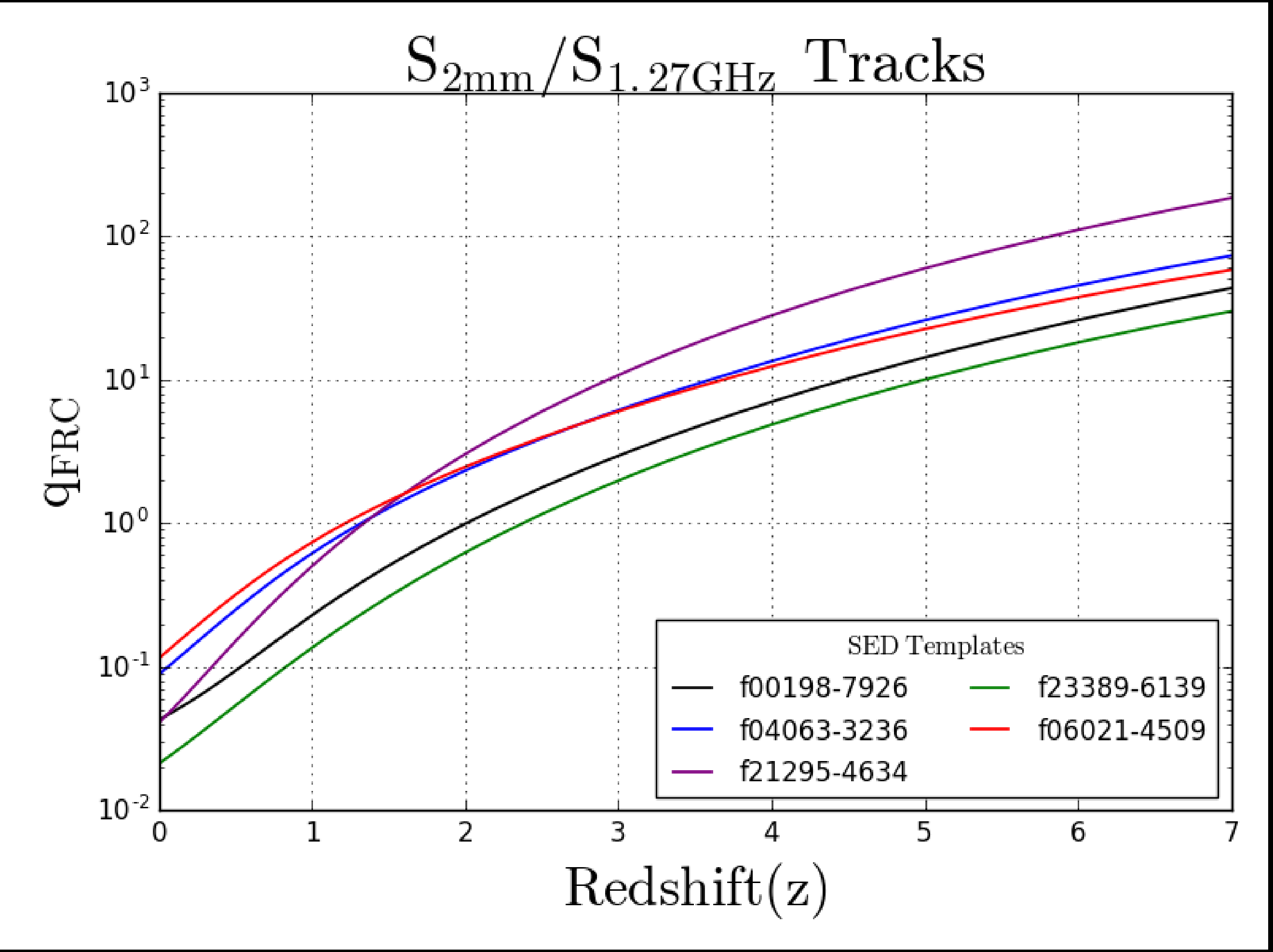


Figure 8: The same 5 templates were used to model the 2mm FIR and 1.27Ghz radio correlation up to a redshift of z = 7.

Distribution of Candidates

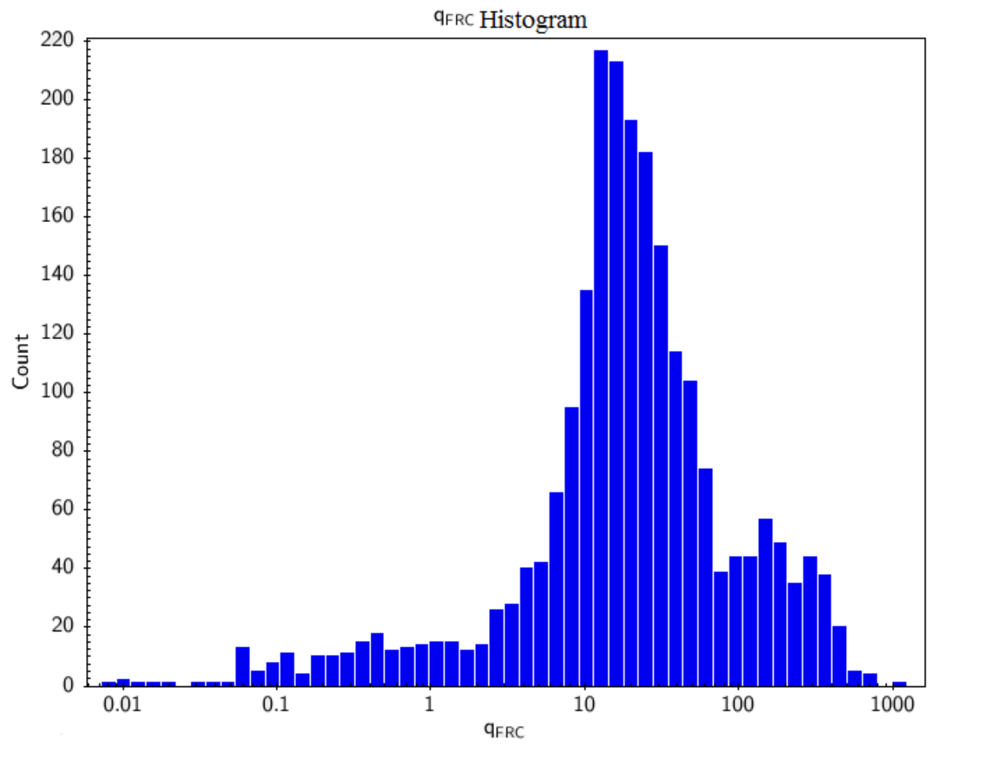


Figure X: Multimodal distribution of the log ratios for the 2000+ candidates found by matching the FIR and radio catalogues. Only interested in sources with ratios of 100 or greater.

The log ratios for the 2286 sources were binned to determine the distribution. Clearly this distribution is multimodal, with there being several distinct populations. With the main population being dominated by local type normal galaxies. The high ratio population being dominated by radio quiet AGN, as well as lensed sources and older local type galaxies.