1 Scientific Context:

Context — A comprehensive study of the physical properties of low-z ultra-luminous infrared galaxies (ULIRGs; $L_{IR} \geq 10^{12} L_{\odot}$), specifically their interstellar medium (ISM), is critical to understanding the evolution of $> L_{*}$ galaxies and active galactic nuclei (AGN) across cosmic time. ULIRGs at low redshifts are central to this endeavor, as they establish a baseline from which to measure evolution with redshift in the ULIRG population.
Aims, Methods & Anticipated results — We propose FIFI-LS observations of the far-IR (FIR) fine structure lines of 11 ULIRGs with $S_{60\mu m} \gtrsim 2$ Jy at $0.01 < z < 0.13$ selected by *IRAS*, primarily targeting the [OIII]52 and [NIII]57 μm lines, which are *only* accessible by FIFI-LS. The proposed observations will provide comprehensive diagnostics of the physical conditions of the ISM such as the gas density, radiation field intensity and hardness, and metallicity that is much less susceptible to extinction than traditionally used UV/optical transitions. We will be able to apply the best FIR metallicity diagnostic, ([OIII]52+2.2[OIII]88)/[NIII]57, *for the first time*, which photoionization models have shown to break the density degeneracy and reduces the scatter of the correlation to within 0.2 dex. The unprecedentedly reliable metallicity measurements will address whether ULIRGs lie below the mass-metallicity relation of star-forming galaxies as previously thought based on optical metallicity diagnostics.
Synergies — Along with archival *Herschel*/PACS+SPIRE observations, we will be able to test all the line-ratio diagnostics by comparing to models (e.g. CLOUDY) and identify the best pairs to optimize future observations with ALMA for high-z analogs. This program also has implications for the Origins Space Telescope science objectives.

2 Scientific Justification:

ULIRGs are a cosmologically important population whose nature changes substantially with redshift. At $z < 0.3$, ULIRGs are rare, with less than one per $\sim$ hundred square degrees, and are invariably mergers between approximately equal mass galaxies (e.g. Clements et al. 1996; Farrah et al. 2001; Veilleux et al. 2002, 2006). Evidence suggests that their IR emission arises mainly from high rates of star formation (Genzel et al 1998; Franceschini et al. 2003; Wang et al. 2011), though on the order of half of them also contain an AGN (e.g. Rigopoulou et al. 1999; Vega et al. 2008; Nardini & Risaliti 2011). The AGN in ULIRGs may become more important with increasing IR luminosity and advancing merger stage, and sometimes initiate powerful outflows. The number of ULIRGs rises rapidly and reaches a density of several hundred per square degree at $z \gtrsim 1$. High-redshift ULIRGs have a lower merger fraction, wider range in dust temperatures and spectral energy distribution (SED) shapes, and a greater star formation efficiency compared to local ULIRGs (e.g. Kartaltepe et al. 2010; Magdis et al. 2010; Sajina et al. 2012; Geach et al. 2013). Studying low-z ULIRGs is crucial to understanding the stellar history and super massive black hole mass assembly in $\gtrsim L_{*}$ galaxies as they lay the foundation for measuring evolution over cosmic time.

ULIRGs have been found to lie below the well-established mass-metallicity relation based on their metallicities inferred from optical lines (e.g. Caputi et al. 2008; Pupke et al. 2008;

Kilerci Eser et al. 2014). The observed offset from the mass-metallicity relation could have at least two explanations (Herrera-Camus et al. 2018b). First, as shown by theoretical models and numerical simulations (e.g., Naab et al. 2006; Montuori et al. 2010; Rupke et al. 2010; Torrey et al. 2012), tidal forces acting in merging/interacting galaxies drive low-metallicity gas from the outskirts toward the central active star-forming regions; hence the observed nuclear metallicity under-abundances and shallower metallicity gradients (e.g. Rupke et al. 2008; Kewley et al. 2010; Kilerci Eser et al. 2014). Second, the low gas metallicity inferred from the optical nebular lines may not be representative of the metallicity of the heavily obscured bulk of the gas in ULIRGs. This hypothesis is supported by the large dust masses found in ULIRGs and the $\sim$3$\times$, solar neon abundance found in the average spectrum of 27 PAH-dominated ULIRGs (Veilleux et al. 2009b; Verma et al. 2003), which are incompatible with the low metallicities inferred from the optical lines (e.g. Santini et al. 2010). But these measurements are subject to uncertainties, and an independent, reliable, and extinction insensitive determination of the metallicity is required to validate one of the two possible scenarios.

The FIR fine-structure lines of C, N, and O offer a powerful tool to characterize the ISM of local and high-z galaxies, including radiation fields, gas densities, temperatures, and metal abundances that are much less susceptible to extinction than UV and optical transitions (e.g. Kaufman 2006; Fischer et al. 2014). For local galaxies, the FIR lines are not accessible by ground-based facilities. The *Herschel Space Observatory* with its instruments PACS and SPIRE offers significantly improved sensitivity and resolution over previous space-based facilities. The *Herschel* ULIRG Survey (HERUS; Farrah et al. 2013) and the Survey with *Herschel* of the ISM in Nearby INfrared Galaxies (SHINING Strum et al. 2011; Herrera-Camus et al. 2018a,b; overlapping with ULIRGs in the GOALS sample Díaz-Santos et al. 2017) assembled PACS and SPIRE observations of 43 (nearly all) ULIRGs at $z < 0.27$ drawn from the *IRAS* PSC-z survey (Saunders et al. 2000), with a 60μm flux density greater than $\sim$ 1.7 Jy, and made detailed diagnostics of the FIR fine structure lines possible (Farrah et al. 2013; Pereira et al. 2017; Herrera-Camus et al. 2018a). All objects have been spectroscopically confirmed with high-resolution optical observations and observed with *Spitzer* IRS for mid-IR lines and PAH features (Armus et al. 2007; Farrah et al. 2007; Desai et al. 2007). UV/optical line diagnostics have been established and used for decades but are subject to dust extinction (e.g. Liu et al. 2006; Nagao et al. 2011; Béthemin et al. 2016). The FIR line diagnostics are advantageous in this regard, but validating and applying those diagnostics and how they compare to optical ones are still ongoing research, and we need a sample with a full set of lines to accomplish that. Although HERUS, SHINING, and GOALS surveys already represent the best explored samples so far with some FIR lines observed such as [OI]63 and [CII]158 μm, none of the objects have the full set of lines simultaneously observed, missing critical lines [OIII]52, [NIII]57, [OIII]88, and/or [NII]122. A number of important diagnostics cannot be done due to the lack of these lines (discussion below). SOFIA/FIFI-LS offers the unique blue channel to cover the [OIII]52 and [NIII]57 lines. This will be the first sample with a full set of mid-IR to FIR lines that enable unprecedented detailed and reliable diagnostics and lay the foundation for high-z object observations with ALMA and NOEMA in the near future.

In this pilot program, we have selected 11 ULIRGs in the HERUS, SHINING, and GOALS ULIRG samples to complete line observations especially [OIII]52 and [NIII]57 μm. We propose to perform the following diagnostic analyses, which can be only accomplished on our ULIRG sample with a full set of critical FIR lines. We will also compare the line maps traced by different transitions.

Gas density and radiation field intensity: The ratio of the fine-structure transitions from the same ion but with different critical densities allows the determination of the emitting gas density (e.g. Draine 2011). We will use the [OIII]52/[OIII]88 and [NII]122/[NII]205 ratios to constrain the gas density. For a given density, the scatter of these ratios due to variations of the ionization parameter and gas metallicity is only 10-20 per cent (Pereira-Santaella et al. 2017). If an estimate of the metallicity is available, it is possible to use the [N II]122/[N III]57 μm and [O III]88/[N II]122 μm ratios to constrain the ionization parameter (Pereira-Santaella et al. 2017). The [O III]88/[N II]122 μm line ratio provides a sensitive probe of the UV field hardness and has the advantage of being practically insensitive to the gas density (e.g., Rubin 1985; Ferkinhoff et al. 2011). Rather than considering each line ratio, more can be learned by examining the line ratios with PDR modeling and CLOUDY photoionization modeling (which can include both PDR and H II regions) (Nagao et al. 2011; Pereira-Santaella et al. 2017; Wardlow et al. 2017). Given the full set of lines, we will be able to constrain the gas density and FUV radiation field strength etc. with least uncertainties. We will also be able to test which combination of line ratios gives the best results in the circumstances of limited available lines to help prepare high-z observations.

Extinction insensitive metallicity: The individual line ratios [O III]52/[N III]57 and [O III]88/[N III]57 have been identified as FIR metallicity tracers (e.g. Liu et al. 2011; Nagao et al. 2011), although they are strongly dependent on the gas density. However, for a fixed metallicity, the density dependence of the [O III]52/[N III]57 μm ratio is opposite to that of the [O III]88/[N III]57 μm ratio. Based on this effect (i.e. breaking the density degeneracy) and photoionization models, Pereira-Santaella et al. (2017; see also Nagao et al. 2011) show that the combined ratio of ([O III]52+2.2[O III]88)/[NIII]57 is an excellent tracer of the gas metallicity and reduces the scatter of the correlation to within 0.2 dex (Figure 1). Pereira-Santaella et al. (2017) use the [O III]52/[N III]57 ratio for the HERUS ULIRGs and the [O III]88/[N III]57 ratio for the SHINING ULIRGs, and find their metallicities and the mass-metallicity relation are consistent with previous work using optical metallicity diagnostics. Herrera-Camus et al. (2018a) revisited the mass-metallicity relation for the SHINING (U)LIRGs with metallicities constrained from the [O III]88/[N III]57 ratio. They show, however, that (U)LIRGs tend to lie below the mass-metallicity for star-forming galaxies, but the offset is smaller than previously thought from studies based on optical-based metallicities (Figure 1; e.g., Rupke et al. 2008). The combined line-ratio diagnostic will be applicable, for the first time, to our proposed ULIRG sample. We will also perform multi-wavelength SED modeling to derive their stellar masses for all the sources in a consistent manner. **The proposed observations will improve the metallicity measurements and allow us to draw definite conclusions on whether the optical-based metallicities are underestimated thus cannot represent the ULIRG sample.**

There are still a great number of *IRAS*-detected (U)LIRGs (Kim & Sanders 1998) that were under-explored, and SOFIA/FIFI-LS, with its unique capabilities, will be able to increase the low-z ULIRG sample with a full set of critical FIR line observations by a factor of 2-3.

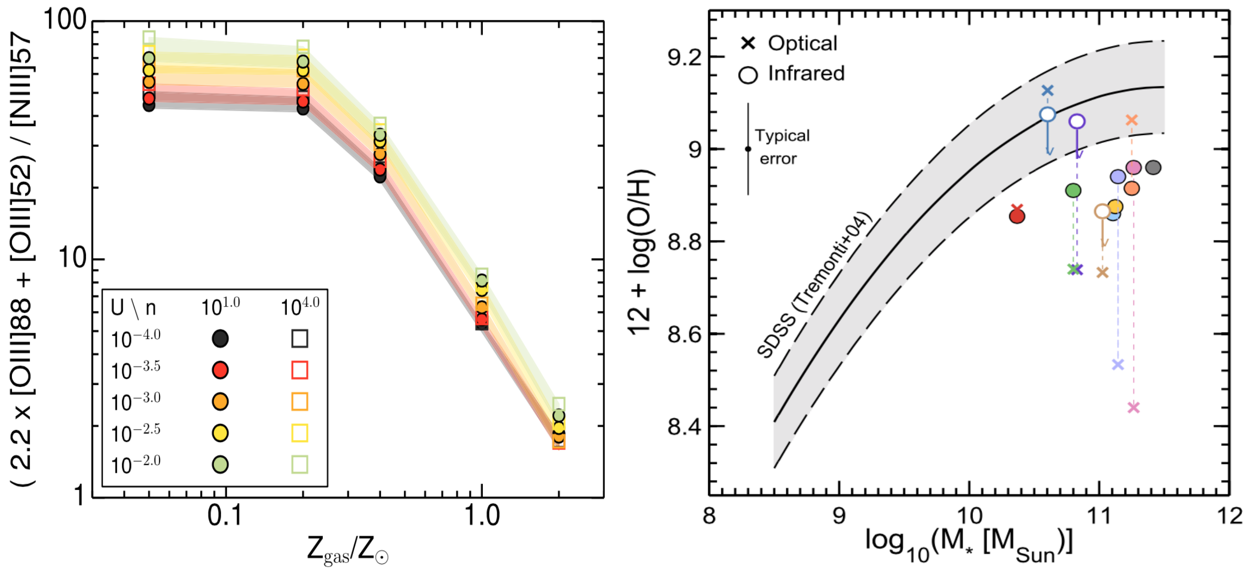

Figure 1: (Left) Combined (2.2×[O III]88+[O III]52)/[NIII]57 μm emission line ratio as a function of the gas-phase metallicity based on the photoionization models by Pereira-Santaella et al. (2017; see also Figure 5). No sources yet have measurements with *Herschel* providing all three lines. SOFIA/FIFI-LS will fill this gap and allow us to apply this diagnostic for the first time. The models are grouped by their ionization parameter and the shaded area is given by the density dependence. (Right) Mass-metallicity relation observed in local galaxies (Tremonti et al. 2004) and (U)LIRGs whose metallicities are measured using optical-based (crosses; Tremonti et al. 2004; Rupke et al. 2008; Hou et al. 2009) and IR-based (circles; Herrera-Camus et al. 2018a) methods. These results suggest that (U)LIRGs tend to have lower oxygen abundances compared to star-forming galaxies of the same stellar mass, but shows that this offset is smaller than previously thought from studies based on optical-based metallicities (e.g. Rupke et al. 2008).

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3 Feasibility:

The proposed targets are drawn from the HERUS (Farrah et al. 2013), SHINING (Herrera-Camus+2018a), and GOALS (Diaz-Santos et al. 2017) ULIRG samples. Some FIR lines (e.g. [OI]63, [OI]145, [CII]158 μm) were observed with *Herschel* but most of the sources do NOT have observations of the critical diagnostic lines [OIII]52 and [NIII]57, and some also lack [OIII]88, and/or [NII]122 μm. We have selected 11 ULIRGs at $0.01 < z < 0.13$ that are accessible by SOFIA/FIFI-LS in reasonably good transmission windows. Completing these line observations will allow us to perform comprehensive diagnostics including the fundamental mass-metallicity relation, and also prepare us for high-z object observations with ALMA. Table 1 lists the source information. We propose to observe the lines that do not have any measurements yet (marked with 'N').

Table 1: The proposed ULIRG sample drawn from the HERUS (Farrah et al. 2013), SHINING (Herrera-Camus et al. 2018a), and COALS (Díaz-Santos et al. 2017) surveys and their properties. $S_{60\mu m}$ is the *IRAS* 60 μm flux density (Sanders et al. 2003). L_{IR} is the total 8-1000 μm IR luminosity. We list the known [O I]63 μm line fluxes for reference. The last three columns indicate whether the target also has [OIII]52, [NIII]57, [OIII]88, and/or [NII]122 μm line measurements from *Herschel* with 'Y' or not with 'N'.

Source ID	z	$S_{60\mu m}$ (Jy)	$log(L_{IR})$ $log(L_\odot)$	[O I] 63μm 10^{-16}Wm^{-2}	[O III] 52μm	[N III] 57μm	[O III] 88μm	[N II] 122μm
IRAS F08572+3915	0.0584	7.30	12.04	1.07 ± 0.17	N	Y	Y	Y
IRAS F09111-1007	0.0541	6.75	12.00	1.50 ± 0.15	N	N	N	N
IRAS F09320+6134	0.0394	11.68	12.00	3.14 ± 0.19	N	Y	Y	Y
IRAS 10565+2448	0.0430	12.10	12.28	6.74 ± 0.07	N	Y	Y	Y
IRAS 12112+0305	0.0730	8.18	12.48	0.80 ± 0.10	N	Y	Y	Y
Mrk 273	0.0378	22.51	12.10	8.06 ± 0.55	N	Y	Y	Y
IRAS 14348-1447	0.0830	6.82	12.60	1.92 ± 0.19	N	N	Y	Y
IRAS 15206+3342	0.1244	1.52	12.07	1.71 ± 0.05	N	N	N	N
IRAS 15250+3609	0.0552	7.10	12.00	0.83 ±0.17	N	N	Y	Y
Arp 220	0.0181	104.09	12.20	10.0 ±1.50	N	N	N	Y
IRAS 17208-0014	0.0430	34.79	12.68	9.00± 1.00	N	Y	Y	Y

Expected line fluxes: Since the [OI]63 μm line has been detected in all of the sources, we estimate the [O III]52μm line flux based on the observed [OI]63 μm line flux and assume a flux ratio of [OIII]52/[OI]63 $\sim$ 0.6. Most of the observations in the literature are consistent with this ratio (e.g. Farrah et al 2013). The [NIII]57/[OI]63 line ratios are more scattered and we assume a ratio of 0.13 as a conservative estimate. We list the estimated [OIII]52 μm line fluxes per pixel in Table 2 for references.

Required S/N and exposure time: We request a S/N of at least 5 for all the lines. We estimate the exposure time using the SOFIA Instrument Time Estimator (SITE) and employ the default Observatory Altitude, Water Vapor Overburden, and Telescope elevation on SITE. We use the Symmetric Chop mode with one tuning at the blue channel for [OIII]52 or [NIII]57 and one tuning at the red channel for [NII]122 in most cases. For three sources, the [OIII]88 μm line unfortunately falls in bad transmission windows so we do not attempt [OIII]88 observations. The on-source integration as well as the total time including the overheads for each target are listed in Table 2. **We request a total of 16.22 hours to complete this program.**

Analysis plan:

UCI graduate student Amy Ralston will perform the data reduction and analysis for this program. She will also conduct a combined project of FIR lines using the SOFIA data and *Herschel*/PACS+SPIRE spectroscopic data, which will become her thesis. PI Jingzhe Ma will mentor the student with data reduction and analysis, as well as interpretation of the results. UCI Admin PI Cooray will be responsible for the overall outcome of this program, mentoring and supervising research work. If selected, all the funds for this program will be used at UCI in support of the graduate student and partial funding for the postdoc PI. We expect at least two publications out of this data. One will be focused on reporting the SOFIA/FIFI-LS results, and another one will be on the combined analysis with *Herschel* spectroscopy.

Table 2: Estimated line fluxes per pixel and requested exposure times.

Source ID	R.A. (J2000)	Dec. (J2000)	Estimated [O III]52μm line flux (W m^{-2})	Exp. Time (s) (on source/total)
IRAS F08572+3915	09:00:25.3	+39:03:54.4	6.0×10^{-17}	1020/3020
IRAS F09111-1007	09:13:38.8	-10:19:19.9	8.0×10^{-17}	3900/11000
IRAS F09320+6134	09:35:51.6	+61:21:11.4	4.2×10^{-16}	180/780
IRAS 10565+2448	10:59:18.1	+24:32:34.4	4.1×10^{-16}	120/620
IRAS 12112+0305	12:13:46.0	+02:48:38.0	4.8×10^{-17}	1500/4300
Mrk 273	13:44:42.1	+55:53:12.6	4.8×10^{-16}	240/940
IRAS 14348-1447	14:37:38.4	-15:00:20.0	1.4×10^{-16}	3120/8920
IRAS 15206+3342	15:22:38.0	+33:31:35.8	1.0×10^{-16}	4080/11480
IRAS 15250+3609	15:26:59.4	+35:58:37.5	5.0×10^{-17}	5160/14360
Arp 220	15:34:57.2	+23:30:11.3	6.0×10^{-16}	660/2360
IRAS 17208-0014	17:23:21.9	-00:17:00.9	1.9×10^{-16}	120/620

We request a total of 16.22 hours to complete this program.

4 Proposing Team:

PI Jingzhe Ma (UCI postdoc; CV attached below) led the Cycle 5 (PID 05_0087) SOFIA/HAWC+ data analysis and has published a paper in ApJ entitled "SOFIA/HAWC+ detection of a gravitationally lensed starburst galaxy at $z = 1.03$". She has extensive experience with multi-wavelength characterization of high-z ultra-luminous infrared galaxies or dusty star-forming galaxies. She has also done a lot of work on deriving physical conditions and chemical abundances of the ISM and CGM in metal absorption line systems, including Cloudy photoionization modeling. She will assist with the line diagnostics and multi-wavelength characterization of ULIRGs.

Admin PI Asantha Cooray was the US or NASA PI of H-ATLAS and was a primary member of the HerMES team. He co-chairs OST Science and Technology Definition Team (STDT). He coordinated some of the lensed source identification that was led at UCI and led several follow-up programs with *Spitzer*, *Hubble*, *Herschel*, Keck. He was also the PI of the Cycle 5 (PID 05_0087) SOFIA/HAWC+ program of gravitationally lensed starburst galaxies.

Co-I Julie Wardlow (Lancaster University, UK) has extensive experience with *Herschel*/PACS+SPIRE spectroscopy and FIR line analyses, and will assist with the interpretation of the FIFI-LS data.

Co-I Hooshang Nayyeri (UCI postdoc) has extensive experience with *HST*, *Spitzer*, Keck, and *Herschel* data and will assist with the multi-wavelength studies of ULIRGs.

5 Thesis-Enabling Program

Co-I Amy Ralston is a first-year graduate student in Prof. Cooray's group (Admin PI) at UCI, who will use the proposed SOFIA data as the key component of her thesis on "Far-infrared line diagnostics of ultra-luminous infrared galaxies near and far". Amy is currently working on FIR line diagnostics of ULIRGs based on *Herschel*/PACS+SPIRE data. She will lead the reduction and analysis of the FIFI-LS data. She will also perform a combined FIR line analysis of the SOFIA/FIFI-LS data with the *Herschel*/PACS+SPIRE data. Amy is expected to publish at least two papers out of the SOFIA data: one will be focused on reporting the SOFIA/FIFI-LS results, and another one will be on the combined analysis with *Herschel* spectroscopy. Amy is expected to finish her thesis work in the next three years and graduate in 2023 or 2024.

Jingzhe Ma

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Irvine, CA 92697 Phone: (213)245-9687 — http://www.jingzhema.com

EMPLOYMENT AND EDUCATION

Postdoc research associate, University of California, Irvine Sept 2017 - present

- Project: "*Herschel*-selected dusty star-forming galaxies" with Asantha Cooray

PhD in Astronomy, University of Florida Aug 2012 - Aug 2017

- Thesis Topic: "The Formation and Evolution of High-redshift Dusty Galaxies"

TELESCOPE EXPERIENCE

SOFIA/HAWC+, *HST*, *Spitzer*, *Herschel*, Keck, ALMA, NOEMA, *Chandra*, MMT, Lick

FIRST-AUTHOR PUBLICATIONS

9. "*Spitzer* catalog of *Herschel*-selected ultrared dusty, star-forming galaxies", **Ma, J.** et al. 2019, ApJS, in press
8. "SOFIA/HAWC+ detection of a gravitationally lensed starburst galaxy at z = 1.03", **Ma, J.** et al. 2018, ApJ, 864, 60
7. "Revealing the host galaxy of a quasar 2175 Å dust absorber at z=2.12", **Ma, J.** et al. 2018, ApJL, 857, L12
6. "Quasar 2175 Å dust absorbers II: Correlation analysis and relationship with other absorption line systems", **Ma, J.** et al. 2017, MNRAS, 474, 4870
5. "Quasar 2175 Å dust absorbers I: metallicity, depletion pattern, and kinematics", **Ma, J.** et al. 2017, MNRAS, 472, 2196
4. "SPT0346-52: Negligible AGN Activity in a Compact, Hyper-starburst Galaxy at z = 5.7", **Ma, J.** et al. 2016, ApJ, 832, 114
3. "Stellar Masses and Star Formation Rates of Lensed, Dusty, Star-forming Galaxies from the SPT Survey", **Ma, J.** et al. 2015, ApJ, 812, 88
2. "Cold gas and a Milky Way-type 2175-Å bump in a metal-rich and highly depleted absorption system", **Ma, J.** et al. 2015, MNRAS, 454, 1751
1. "Probing the dynamics of dark energy with novel parametrizations", **Ma, J.** & Zhang, X. 2011, Physics Letters B, 699, 233

SELECTED PRESS RELEASES

SOFIA Newsletter: "A Gravitationally Lensed Starburst Galaxy at High Redshift"
Chandra Press Office: "Super starburst galaxy found one billion years after the Big Bang"

SELECTED HONORS, AWARDS & GRANTS

- Rodger Doxsey Travel Prize (Dissertation award), 229th AAS meeting — Jan, 2017
- HST Cycle 23 GO-14200 (**PI**) $49303 — 2016 - 2018
- Spitzer Cycle 10 (10094) & HST Cycle 21 GO-13614 (co-I) $41504 — 2014 - 2017