The Dusty Co-evolution of Black Holes and Galaxies: A Science Case for a Large Far-IR Space Telescope

A whitepaper written in response to the COPAG call for large astrophysics missions to be studied by NASA prior to the 2020 Decadal Survey

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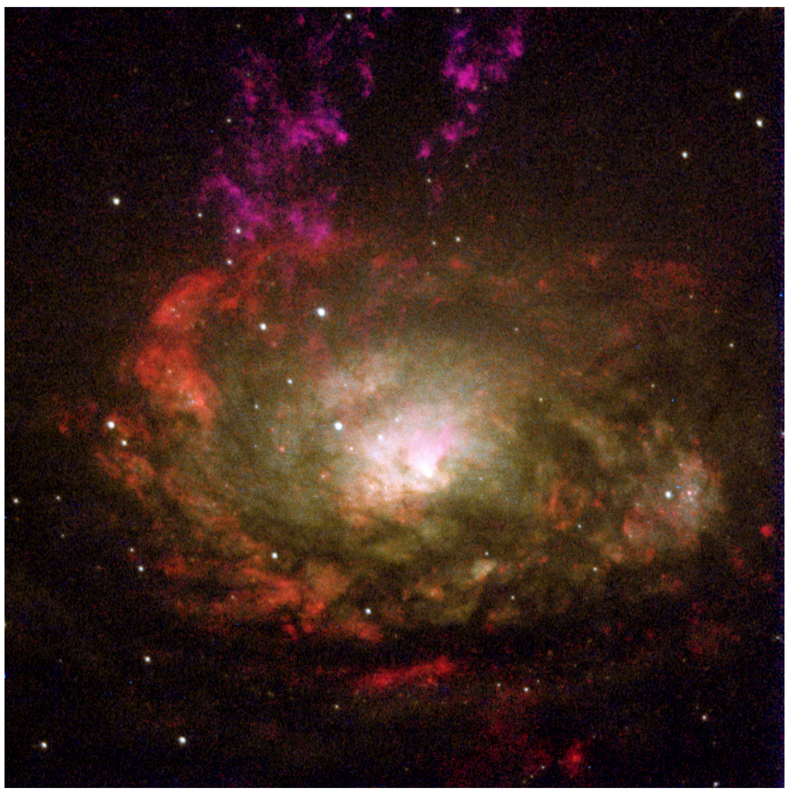


***Cover Image**: Hubble Space Telescope of the nearby Circinus galaxy. The dusty center shows evidence for a massive black hole, a powerful starburst, and outflows of hot gas.*

Background & Key Questions

In order to obtain a comprehensive picture of galaxy evolution, we need to accurately measure the growing population of stars and super-massive black holes in galactic dark matter halos. This evolution is determined by a complex interplay of physical processes (gravity, gas heating and cooling, star formation, black hole fueling, and feedback from star formation and AGN) that couple on scales ranging from < 1pc to tens of Mpc.

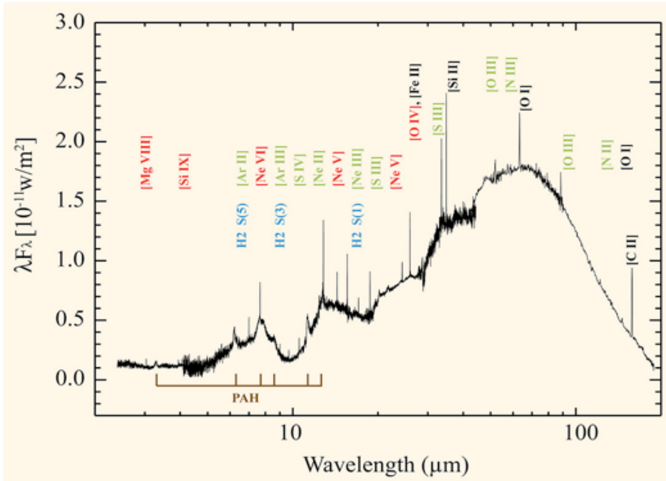
One of the most striking results to appear in the last decade has been the discovery that the mass of the central black hole and the stellar bulge in galaxies are correlated [11,17]. The idea that galaxies spend most of their lives on a star formation vs. stellar mass "main sequence" [48] further suggests that star formation and black hole accretion are intimately linked. Understanding how this relationship is built over time drives a great deal of observational and theoretical astrophysics, providing considerable motivation for the next generation of ground and space-based observatories. Despite the success of cosmological simulations that model the hierarchical growth of galaxies [7, 34, 35], and observations suggesting that periods of significant AGN accretion occur during episodes of enhanced nuclear star-formation [6, 9, 23], a number of critical questions still remain, such as: **When do the first heavy elements appear, and how does the chemical history of the Universe regulate the collapse of the first stars and the build-up of galaxies? How and when do the first black holes form and how does the black hole – bulge mass relation evolve with redshift for galaxies on and off the star forming main sequence? How and when does feedback from stellar winds, supernovae and AGN regulate star formation and the growth of galaxies?**

Although we have broadly measured the evolution of the bolometric luminosity density to z~3, the relative contribution of AGN and star formation at early epochs is quite uncertain. To piece together a complete picture of the co-evolution of galaxies and black holes requires the ability to make extremely sensitive infrared measurements of the most obscured regions at the centers of faint, distant galaxies.

The Need for Background-Limited FIR Spectroscopy

More than half of all the light emitted from stars is absorbed by dust and re-emitted in the infrared [8]. While traditional UV and optical diagnostics can be severely hampered by dust attenuation, FIR spectroscopy provides a direct measure of the basic physical properties (density, temperature, pressure, kinematics) of the ionized ($T\sim10^4$ K), the neutral atomic, and the warm (T~100-500 K) molecular gas in obscured galaxies. **It is the only part of the electromagnetic spectrum that gives a complete picture of all phases of the interstellar medium, from atoms to complex organic molecules.** The infrared is rich in fine-structure lines of Oxygen, Carbon, Nitrogen, Neon, Sulfur and Silicon covering a wide range in ionization potential, as well as molecular hydrogen and dust (Polycyclic Aromatic Hydrocarbons - PAHs). Together, these features constrain the strength and hardness of the interstellar radiation field [18, 3, 20]. This is extremely relevant since z~3, UV-selected galaxies seem to have starbursts with harder radiation fields, higher ionization potentials and/or different abundances than those at z~0 [50]. The FIR lines can be used to trace molecular outflows [37, 38] and infer the size of the starburst [39], and mid-J transitions of CO can distinguish starburst from AGN heating of the molecular gas [4, 30, 40, 41]. A FIR spectroscopic survey of high-redshift galaxies can solidly establish the history of early chemical enrichment, the rise of metals, and the presence of organic molecules.

With ISO, Spitzer and Herschel we have studied large samples of dusty galaxies in the local Universe [5, 2, 9, 42, 45, 46], identified PAHs in the most luminous galaxies out to z~4 [24, 19, 43] and detected the populations responsible for the bulk of the FIR background at z~1 [16]. However, our knowledge of how AGN and galaxies grow together, and the role of feedback in rapidly evolving, dusty galaxies at z >2-3 is extremely limited.



Infrared spectrum of the Circinus galaxy showing a strong dust continuum studded with features from small grains, ions, and warm molecular gas [21].

In order to produce a complete census of AGN and chart the growth of super-massive black holes and stellar mass in dusty galaxies across a significant fraction of the age of the Universe, a broadband, FIR spectrometer capable of reaching the natural astrophysical background over the ~30-300µm range is required. FIR cooling lines in z~2 IR galaxies should have fluxes ~10^{-19} Wm^{-2}. The rest-frame MIR lines will be 5-10x fainter. JWST will provide our first glimpse of the earliest galaxies, yet most of the mid-infrared diagnostic lines will pass out of the observable range of the JWST spectrographs by z~2. ALMA is already detecting z >5-6 galaxies [31, 44, 47, 49], yet it operates in limited atmospheric windows, and cannot access the rest-frame MIR spectral features. In particular, we require: **(1)** sensitivity of ~$1x10^{-20}$ Wm^{-2} in an hour to detect normal dusty galaxies at z > 2 and luminous galaxies at z > 4, **(2)** broad spectral coverage from ~30-300 µm to cover the key redshifted MIR and FIR lines, **(3)** a spectral resolving power of R > 100 to separate individual atomic features from dust emission and absorption, and **(4)** spectral multiplexing to place 10-100 beams on the sky and allow for significant samples to be built up rapidly. The required sensitivity and wavelength coverage is impossible to reach from the ground, but could be achieved with a large, actively cooled telescope in space.

CALISTO, a cold T~4K, 5m class telescope which has been put forward for the FIR Surveyor concept (see Bradford et al. whitepaper), is the only mission currently envisioned for the next decade capable of achieving the goals outlined above. Through FIR spectra of thousands of distant galaxies, CALISTO will allow us to map out the history of galactic chemical enrichment, accurately estimate the bolometric fraction contributed by AGN and starbursts in even the most obscured sources, and trace AGN and stellar feedback via IR absorption and emission features providing a complete census of the buildup of galaxies and black holes over the past 10 Gyr.

References

[1] Alexander, D.M., et al. 2008, AJ, 135, 1968 ● [2] Armus, L. et al. 2007 ApJ, 656, 148 ● [3] Brauher, J.R., Dale, D.A., and Helou, G. 2008 ApJS, 178, 280 ● [4] Bradford, C.M. et al. 2003 ApJ, 586, 891 ● [5] Brandl, B.R. et al. 2006 ApJ, 653, 1129 ● [6] Daddi, E. et al. 2007, ApJ, 670, 156 ● [7] Vogelsberger, M., et al. 2014 Nature, 509, 177 ● [8] Elbaz, D., & Cesarsky, C. 2003 Science, 300, 270 ● [9] Farrah, D. et al. 2007, ApJ, 667, 149 ● [10] Ferrarese, L. & Merritt, D. 2000, ApJ, 539, 9L ● [11] Gebhardt, K., et al. 2000 ApJ, 539, 13L ● [12] Gonzalez-Alfonso, E., et al. 2004 ApJ, 613, 247 ● [13] Hopkins, P.F., et al. 2008, ApJS, 175, 390 ● [14] Huang, J.-S., et al. 2007, ApJ, 660, 69L ● [15] Lutz, D. et al. 2001, A&A, 378, 70L ● [16] Magnelli, B., et al. 2013, A&A, 553, 132 ● [17] Magorrian, J. et al. 1998, AJ, 115, 2285 ● [18] Malhotra, S., et al. 2001 ApJ, 561, 766 ● [19] Menendez-Delmestre, K. et al. 2007, ApJ, 655, 65L ● [20] Luhman, M.L., et al. 1998 ApJ, 499, 799L ● [21] Moorwood, A.F.M. 1999 ASPC, 177, 141 ● [22] Ogle, P., et al. 2007 ApJ, 668, 707 ● [23] Papovich, C., et al. 2007, ApJ, 668, 45 ● [24] Pope, A. et al. 2008, ApJ, 675, 1171 ● [25] Robertson, B., et al. 2006, ApJ, 645, 986 ● [26] Santoro, F. & Shull, J.M. 2006, ApJ, 643, 26 ● [27] Soifer, B.T., et al. 1984, ApJ, 283, L1 ● [28] Springel, V. & Hernquist, L. 2005, ApJ, 622, L9 ● [29] Walter, F., et al. 2009, Nature, 457, 699 ● [30] Weiß, A. et al. 2007, A&A, 467, 955 ● [31] Willott, C.J., et al. 2015, arXiv:1504.05875 ● [32] Yan, L. et al. 2005, ApJ, 628, 604 ● [33] Yu, Q. & Tremaine, S. 2002, MNRAS, 335, 96 ● [34] Hopkins, P.F., et al. 2014 MNRAS, 445, 581 ● [35] Schaye, J., et al. 2015, MNRAS, 446, 521 ● [36] Sturm, E., et al. 2010, A&A, 518, L36 ● [37] Sturm, E., et al. 2011, ApJ, 733, L16 ● [38] Veilleux, S., et al. 2013, ApJ, 776, 27 ● [39] Diaz-Santos, et al. 2013, ApJ, 774, 68 ● [40] van der Werf, P., et al. 2010, A&A, 518, L42 ● [41] Rosenberg, M.J.F., et al. 2015, ApJ, 801, 72 ● [42] Stierwalt, S., et al. 2013, ApJS, 206, 1 ● [43] Riechers, D.A., et al. 2014, ApJ, 786, 31 ● [44] Riechers, D.A., et al. 2014, ApJ, 796, 84 ● [45] Sturm, E., et al. 2000, A&A, 358, 451 ● [46] Genzel, R., et al. 1998, ApJ, 498, 579 ● [47] Capak, P. et al. 2015, Nature, in press ● [48] Elbaz, D., et al. 2011, A&A, 533, A119 ● [49] Maiolino, R., et al. 2015, MNRAS submitted ● [50] Steidel, C.C., et al. 2015, ApJ, 795, 165