by Roberto Abraham, Karl Glazebrook, and Pat McCarthy

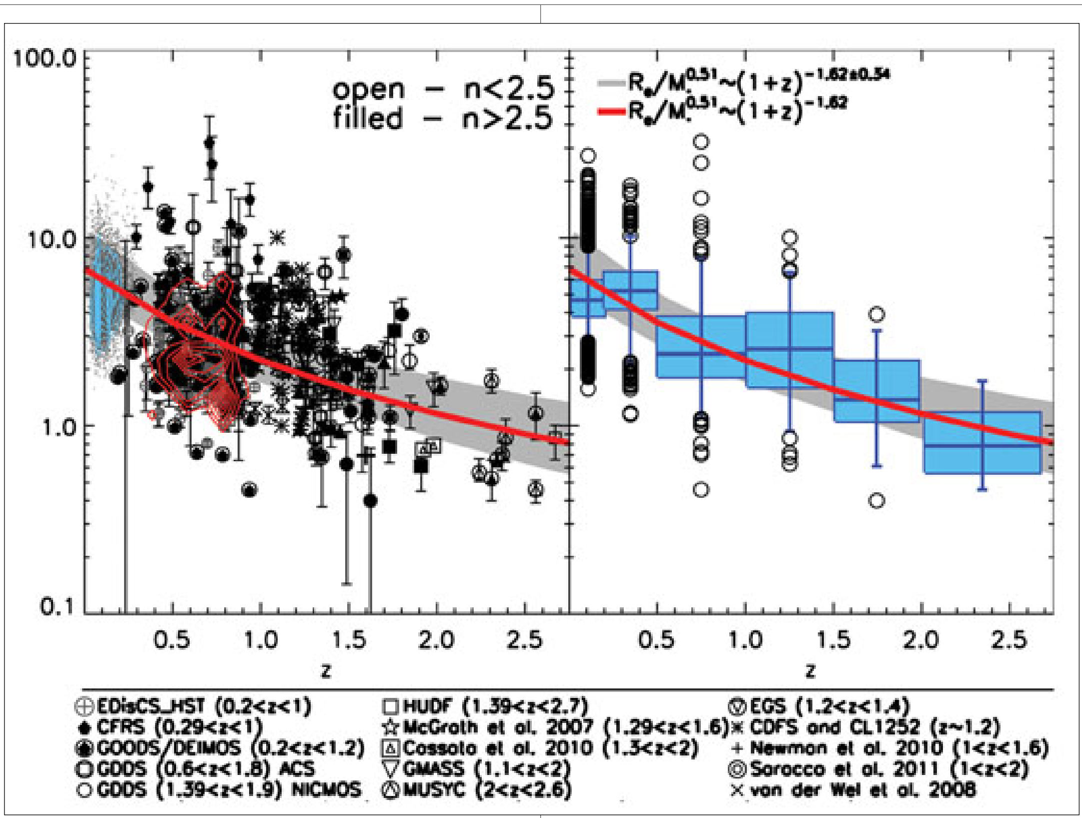
The Gemini Deep Deep Survey: *The Impact Continues*

After more than nine years and 13 scientific papers, the Gemini Deep Deep Survey (GDDS) continues its legacy of scientific impact in new and surprising ways. In this article, the three Co-PI's share the latest results from the GDDS data set, shedding light on the intriguing ultra-compact, massive, high-redshift galaxy population and the identification of a 2-5-micron, near-infrared excess that could be the start of an exciting new field — extragalactic planet formation.

If anybody had told us (the authors) nine years ago that the Gemini Deep Deep Survey (GDDS) observations (obtained in 2003) would still be leading to papers in 2012, we'd have said they were crazy. Yet, here we are. In this article we focus on a pair of results emerging recently from GDDS data, developed over several papers over the last few years (Chevance *et al.*, 2012; Damjanov *et al.*, 2011; and Mentuch *et al.*, 2009). These concern the intriguing "ultra-compact," massive, high-redshift galaxy population, and the nature of a curious near-infrared (NIR) excess seen in our star-forming sample. We will consider these in turn.

Models of galaxy formation fall into two main categories: monolithic collapse and hierarchical merging. In the monolithic view, large galaxies formed all at once through the rapid gravitational collapse of a large gas cloud. In the hierarchical scheme, small galaxies merged gradually over time to create larger, more massive, systems. The discovery of a puzzling new population of compact (half-light sizes less than one kiloparsec (3,260 light-years), massive galaxies, existing at an epoch when the universe was not more than one-third of its current age, poses severe challenges for both models.

Figure 1.
Size growth of quiescent galaxies (normalized to fixed stellar mass) from 17 surveys (including GDDS), plotted as a function of redshift (bottom axis) and time (top axis). The left-hand panel shows data for individual galaxies, while the right panel shows a "box and whiskers" plot summarizing the data in quantiles. The red line and the gray shaded area in both panels show the best fit to the median redshift points and the ±1σ errors of the best relation. Figure taken from Damjanov et al., *2011.*



Cimatti *et al.* first reported a handful of these objects in 2004. Later work by many groups (including GDDS) has confirmed the basic result. Our latest analyses focus on charting the growth in their typical sizes (Damjanov *et al.*, 2011), while asking a more basic question: "just what are these things?" (Chevance *et al.*, 2012).

New Results

In the Damjanov *et al.* paper, we synthesize results from 17 spectroscopic surveys observed at similar spatial resolution, augmented by new measurements for GDDS galaxies. By combining many separate surveys, we were able to grow our sample to a respectable size; ours contains structural data for 465 red galaxies in the redshift range $0.2 < z < 2.7$.

The main result shows that size evolution of passively-evolving compact red galaxies over this redshift range is gradual and continuous (Figure 1). We found no evidence for an end or change to the process around $z = 1$, as has been hinted at by some surveys that analyze subsets of the data in isolation. Furthermore, the size growth appears to be independent of stellar mass, with the mass-normalized, half-light radius scaling with redshift as $R_e \, (1 + z)^{(-1.62 \ +/-0.34)}$.

Why are these results important? First, they confirm that the size growth in massive galaxies is large, something like a factor of 3 out to $z = 1$; this was already fairly clear before our work. Arguably more interesting is our conclusion that the growth appears smooth (at least on average), and that it does not end at around $z \sim 1$, as suggested by some earlier surveys of strongly star-forming blue galaxies.

A Bad Assumption?

Unfortunately, our results do not provide a response to the basic question we really wanted answered: namely, why are these massive galaxies growing in size? In fact, in the most recent GDDS paper (led by student Melanie Chevance and Toronto postdoc Anne-Marie Weijmans) related to this question, we seemed to have muddied the waters a little, albeit in an interesting way, with the second recent GDDS paper (Chevance *et al.*, 2012).

Until recently, we assumed that these ultra-compact objects are early-type galaxies — elliptical systems, shrunken in size by a factor of three, while retaining their overall mass. This seemed like a fairly safe assumption, and in some ways likely, because elliptical galaxies are not only pretty massive, as the objects seen seem, but also appear structureless, as do ellipticals.

However, there are growing indications that this may actually be a bad assumption — after all, the galaxies are so compact that even if they harbored lots of interesting substructure, we would not resolve it with the Hubble Space Telescope (HST). This is a nice argument, by the way, for imaging these objects with Gemini's new Multi-Conjugate Adaptive Optics system.

Furtheremore, recent deep, high-resolution images taken with the HST's Wide Field Camera 3 and Near-Infrared Camera 2 have shown, based on observed ellipticities and Sersic profile fits, that some of these compact, high-redshift galaxies may contain disks. Indeed, based on a sample of 14 quiescent, ultra-compact galaxies, van der Wel *et al.* (2011) claim that disks dominate the majority of these systems.

To investigate this claim, we compared the ellipticity distribution of 31 carefully selected quiescent, ultra-compact galaxies to a set of mass-selected ellipticity and Sersic index distributions (obtained from 2D structural fits to ~ 40,000 nearby galaxies from the Sloan Digital Sky Survey). A Kolmogorov-Smirnov test shows that the distribution of ellipticities for the high-redshift galaxies is consistent with the ellipticity distribution of a similarly chosen sample of massive early-type galaxies.

However the distribution of Sersic indices for the high-redshift sample is inconsistent with that of local early-type galaxies, and instead resembles that of local disk-dominated populations. In other words, while the ellipticities argue for these compact galaxies being early-type systems, their profiles argue for them being disks (Figure 2).

The correct conclusion, then, seems to be that nothing works. The mismatch between the properties of high-redshift compact galaxies and those of putative local analogs leads us to conclude that the basic structures of ultra-compact galaxies probably do not closely resemble those of any single local galaxy population. Any galaxy population analog to the high-redshift compact galaxies that exists at the current ep-

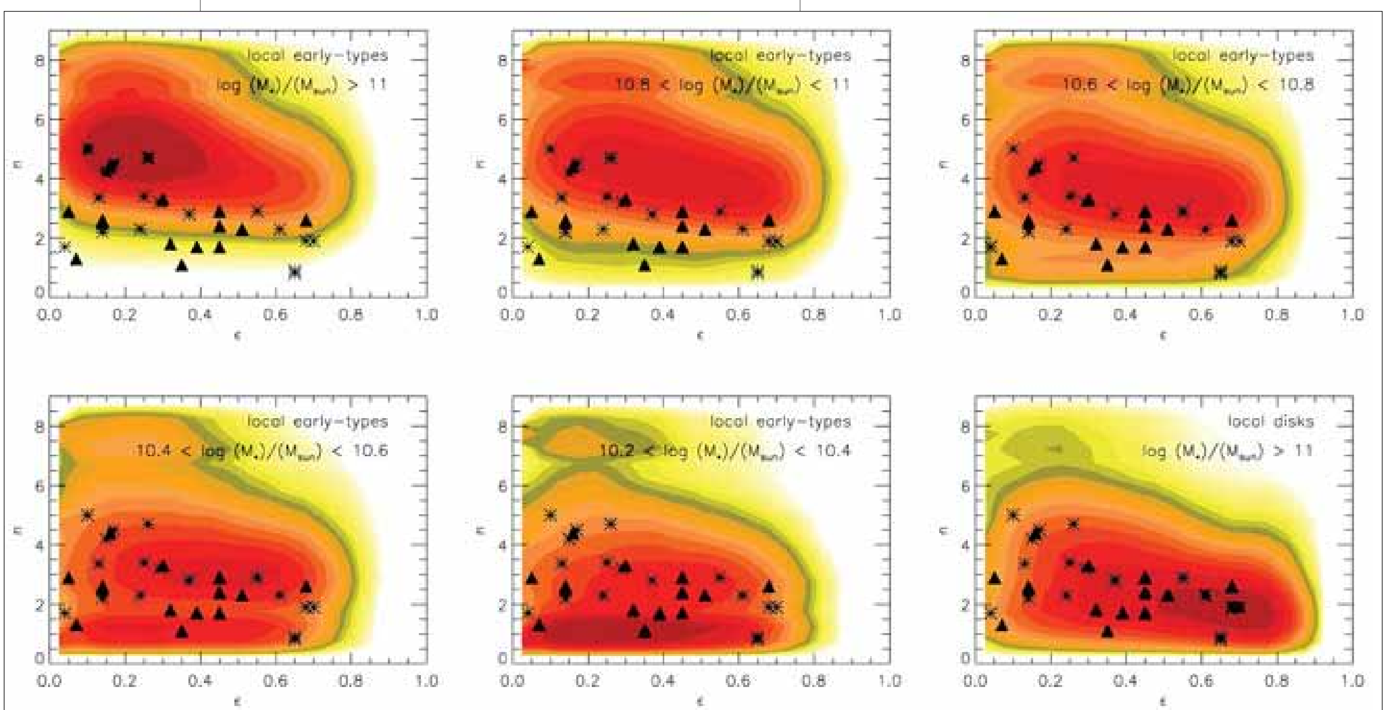


Figure 2.
A comparison of ellipticity and Sersic index distributions from local early-type galaxies (contours) with those of the high-redshift massive compact galaxies published in van der Wel et al. *(2011, black filled triangles) and Damjanov* et al. *(2011, black stars). Contours are normalized and smoothed, increasing in number density from yellow to red in logarithmic steps. Different panels show changing mass ranges for the local early-type galaxy sample, denoted in the upper right corner or each panel. The last panel (lower right) shows the distribution for local massive disk-dominated galaxies. Figure taken from Chevance* et al.*, 2012.*

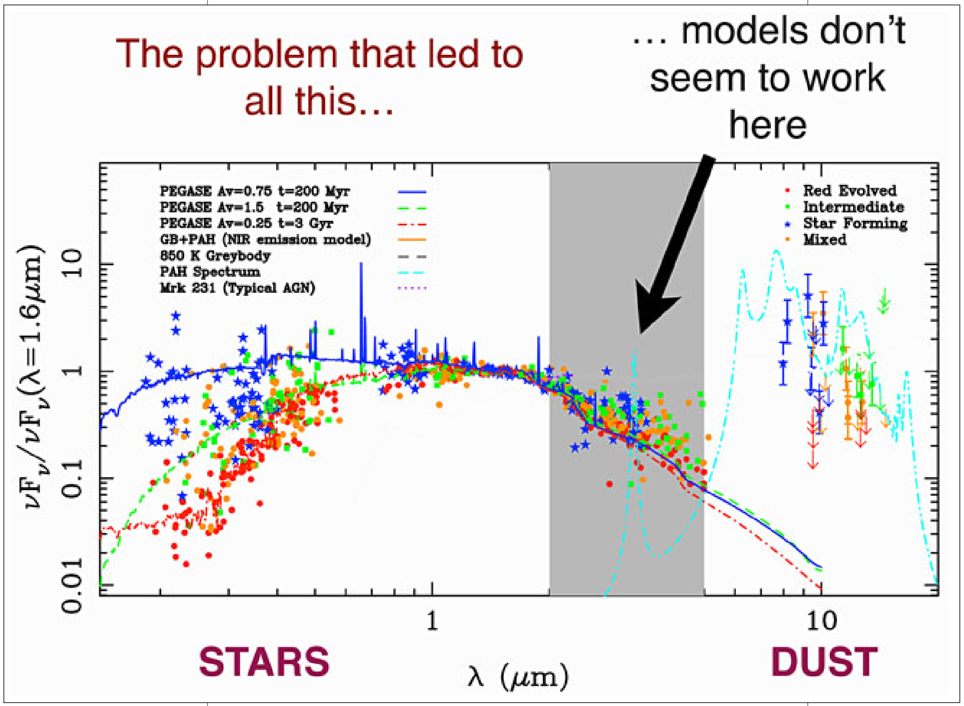


Figure 3.
The case for hot (~ 1000 K) dust or PAH continuum emission in GDDS galaxies, based on multi-wavelength rest-frame photometry for 88 GDDS galaxies. See Mentuch et al. *(2009), from which this figure is taken, for details. Observations from the Gemini Deep Deep Survey nearly always show a disagreement between pure-stellar models and observations at 2-5 μm. As shown in the next figure, adding an 850 K greybody+PAH line emission fit data well. Is this related to star formation, and if so, how?*

och is either a mix of different types of galaxies, or possibly a unique class of objects.

Extragalactic Circumstellar Disks?

Shifting gears completely, another relatively recent result from the GDDS, and presented in a paper led by Erin Mentuch in 2009, focuses on the blue star-forming galaxies in the GDDS. Of course, we originally set out to target a totally different (quiescent) population of galaxies: the so-called red and dead galaxies. But since these systems are fairly rare, and, since one has to fill up gaps in Gemini Multi-Object Spectrograph masks with something, we also targeted bluer objects when redder ones were unavailable. As it turned out, the survey did some of its most interesting work on these "runt" galaxies.

Detailed modeling of the Spitzer colors of these objects (Figure 3) shows clear evidence for a near-infrared excess at around 3 microns, which, at the redshifts of these galaxies, is seen in the Infrared Array Camera (IRAC) [5.8]-micron and [8.0]-micron bands. In a nice surprise, Mentuch *et al.* modeled this excess as an additional Spectral Energy Distribution (SED) component consisting of a modified 850 K greybody, augmented with a mid-infrared, polycyclic aromatic hydrocarbon emission template spectrum, as suggested by da Cunha *et al.* (2008). The luminosity of the excess SED component correlates with the star-formation rate of the galaxy, so the excess shows some promise as an extinction-free star formation tracer.

HST imaging data hint that the excess correlates with star-formation activity and morphology. But the main interest of the excess lies in the interpretation of its origin. The five best candidates for the excess emission are: (1) active galactic nuclei (AGN); (2) the high-redshift counterpart to the interstellar cirrus emission seen in our own galaxy, (3) reflection nebulae; (4) post-asymptotic giant branch (AGB) stars/planetary nebulae; and (5) proto-stellar/proto-planetary disks in massive star-forming regions.

Mentuch *et al.* (2009) come down firmly in favor of the last candidate, in effect attributing the excess light to the collective emission from the thousands of flared circumstellar disks around massive stars in galaxies at high redshifts. We can largely rule out AGN on the basis of IRAC color-color diagrams for the galaxies. Cirrus, reflection nebulae, and post-AGB stars can be ruled out on the basis of simple scaling relations, which show the predicted contributions from these objects are more than an order of magnitude too low to explain the excess. So, in a sense, circumstellar disks are the only candidate that remains standing after we eliminate the others.

Figure 4 shows that a simple flared disk model does a surprisingly credible job of explaining the excess emission. With essentially no "tuning," the simple model goes straight through the data points. We conclude that

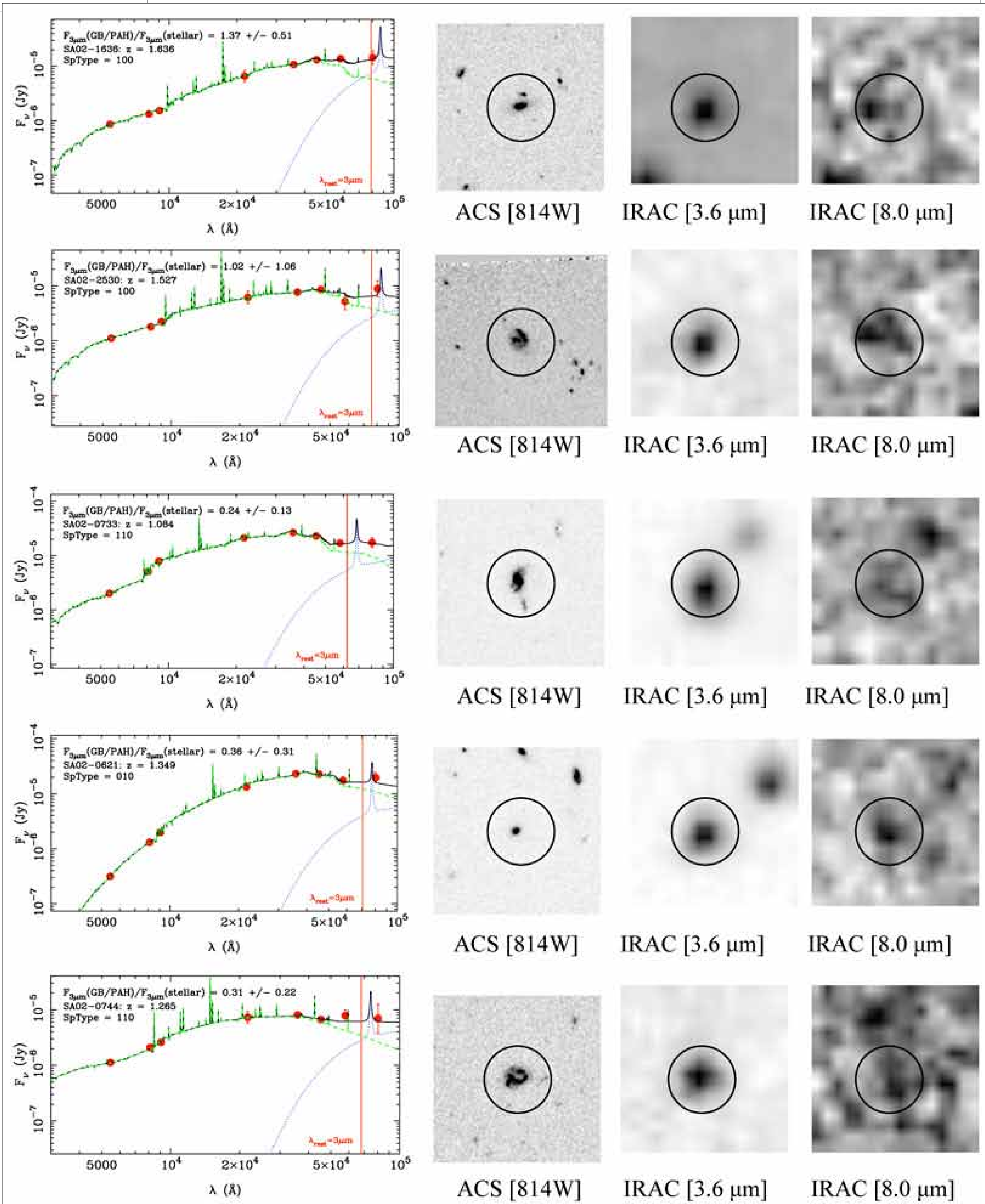


Figure 4. *Fits to rest-frame photometry for individual GDDS galaxies. A hot greybody + PAH model (the dashed blue line) is seen to do an excellent job of boosting the flux from starlight at rest wavelengths around 3 μm in order to fit the data. Mentuch* et al. *(2009) shows how such a model is consistent with emission from a hot circumstellar torus around massive young stars.*

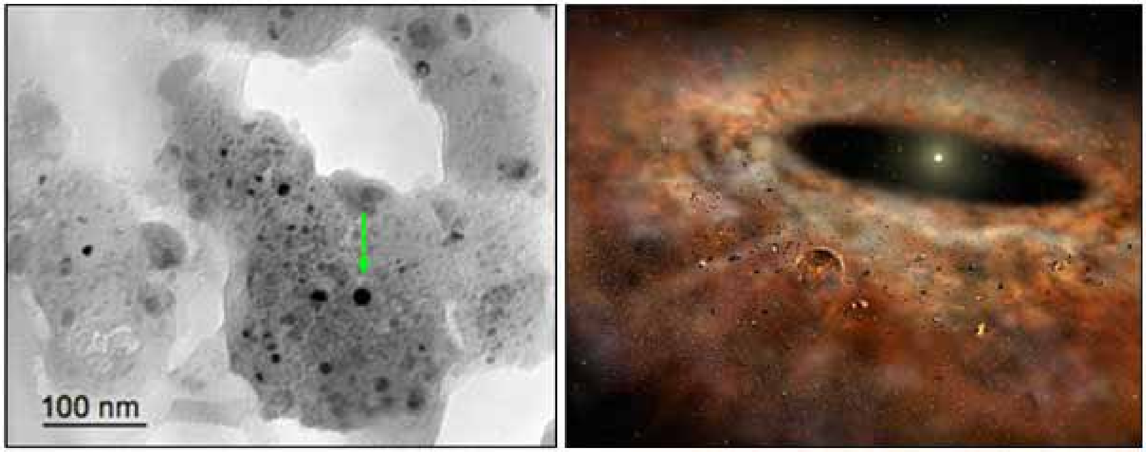


Figure 5. *Evidence for a hot toroidal phase in the early circumstellar envelope of our own Solar System (right) has emerged from data from the Stardust probe (left), which showed crystalline silicates that were likely annealed at temperatures around ~ 1000 K. Abraham and collaborators [no relation to the first author] described a scenario for such annealing in a 2009* Nature *paper.*

Gemini Observatory/ AURA artwork by Lynette Cook.

the most likely explanation for the 2-5-micron excess seen in Figure 3 is the contribution from thousands of flared circumstellar disks around massive young stellar objects seen in the integrated light of these high-redshift galaxies.

Dawn of a New Era?

It seems natural to suppose that the presence of circumstellar disks around massive stars at high redshifts would also imply the presence of disks around less massive stars. Of course, we would also expect planets to form around these less massive systems. Therefore this 2-5-micron excess might present us with an opportunity to probe the formation of planets (as seen in their total integrated light) at cosmic epochs even before our own Solar System formed (Figure 5).

This is a very indirect argument of course, but it's a rather intriguing possibility. Perhaps the most interesting follow-up measurement from a cosmological standpoint would be the measurement of something like the cosmic evolution of the volume-averaged planet formation rate density. Could this be the dawn of a new subject area in astrophysics: the study of extragalactic planet formation?

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