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# eXtragalactic Astronomy... the X-games of Adaptive Optics.

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## Abstract

Observing active nuclei, Ultra-Luminous Infrared Galaxies, starburst and merging galaxies, is both a challenge and a requirement for adaptive optics. It is a requirement, because models needed to explain the high infrared flux and the physics of these monsters need constraints that come, in part, from the fine details gleaned on high angular resolution images, and it is a challenge because, being distant, these objects are usually faint in apparent visual magnitude, meaning that the wavefront sensors have to operate in a photon starved regime.

Many observations have been controversial in the past, and it is always difficult to tell an artifact such as astigmatism from an inner bar. The importance of observing the point spread function is therefore even more crucial than on bright objects, as PSF reconstruction methods “à la Véran” break down when the photon noise dominates the statistics of the wave front, or when locking the loop on extended objects.

Yet, while some cases have been controversial, some very clear and profound results have been obtained in the extragalactic domain, such as the detection of host galaxy to quasars and star formation studies. It turns out that the fundamental prerequisite to such success stories is a stable, well understood and well calibrated PSF.

**Keywords:** Adaptive Optics, Extragalactic Astronomy, Observing Techniques

## 1. INTRODUCTION

The X-games are the equivalent of the Olympic Games for eXtreme sports. The categories include such activities as ski-surfing, ice-climbing, aggressive and downhill inline skating or even barefoot jumping! These sports push the limits of people who already enjoy taking risks. This is a very similar situation to extragalactic adaptive optics. The reason for this is because these objects, being distant, are usually faint in apparent visual magnitudes, meaning that the wavefront sensors have to operate in a photon starved regime. However, active nuclei, Ultra-Luminous Infrared Galaxies, starburst and merging galaxies all have very high infrared luminosities, and high angular resolution images are crucial to understanding the physical process that occurs in these monsters, which are amongst the brightest objects in the Universe.

### 1.1. Difficulties of extragalactic adaptive optics

The wavefront sensors, whether they are of Shack-Hartmann or curvature type, have a hard time measuring the wavefront accurately when the reference source is faint and/or extended. This happens at different flux levels and for different reasons in either type, but it is fair to say that Shack Hartman type sensors have a realistic limiting magnitude on the order of 14, while curvature sensors have a limiting magnitude on the order of 16. (This is of course for correction in the near infrared; to be able to correct effectively in the visible, the sub-apertures need to be smaller and the integration times shorter, effectively reducing the limiting magnitude commensurately). The spatial extent of the guide source affects Shack-Hartman sensors differently than curvature sensors. In effect, as the local tilt moves the extended structure across a subaperture, the location of the centroid is a function of what part of the object is currently seen by the field of view of the sensor. This means that the location of the centroid is a function of the location of the centroid! Clearly a non-linear situation... In the case of curvature sensing, the optical gain (i.e. the distance of the intra and extra-focal images from the focal point) can help to alleviate this problem, without solving it; effectively, if the extent of the guide source or size of the structures,  $\theta$  is comparable the size of

sub-apertures  $d$  as seen at the extra focal distance  $l$ , then to avoid non-linear effects and sensitivity reduction, the optical defocus distance  $l$  has to follow the following relationship<sup>24,25</sup>:

$$l \geq \theta \frac{f^2}{d} \quad (1)$$

where  $f$  is the focal distance of the curvature wavefront sensor. The problem is that increasing the extra-focal distance also increases noise propagation and aliasing which both degrade performance. This illustrates the difficulty of wavefront sensors to operate under such conditions.

The effects of guiding on extended objects, even though this has not been studied in detail, are believed to be that some systematic aberrations can be introduced on the deformable mirror. This would then be seen as a structure which is clearly artificial. Chapman *et al.*<sup>1</sup> have noticed in PUEO images an astigmatic (cross-like) structure on approximately 30% of the galaxies they observed. The level and spatial extent of these cross-like structures varies, but as we shall see in section 5.1, this can be quite crucial. It is not clear yet to what extent these artifacts can be introduced, why (i.e. by which mechanisms) and at what level, but it is worth remembering that these *can* exist.

## 1.2. Point Spread Functions

In cases where artifacts are a real possibility, obtaining a point spread function should help to avoid controversies, but there is a further difficulty which is linked to the fact that it is very difficult to obtain a good estimate of the PSF when working in low flux conditions on extended sources. It is so rare that there actually is a point source in the field of the source of interest (but if there is, the problem is solved!) that we assume that we have to go and obtain an image of an unresolved star. What needs to be matched? Is it the flux level? The amount of noise on the centroids (this may not be the same if the guide source is extended)? Or both? Furthermore, in the case of gain optimization (whether modal or zonal), the gains of the galaxy need to be retained. Different AO systems do not have provisions for all these factors, so choosing a reference star is often a subjective and approximate matter.

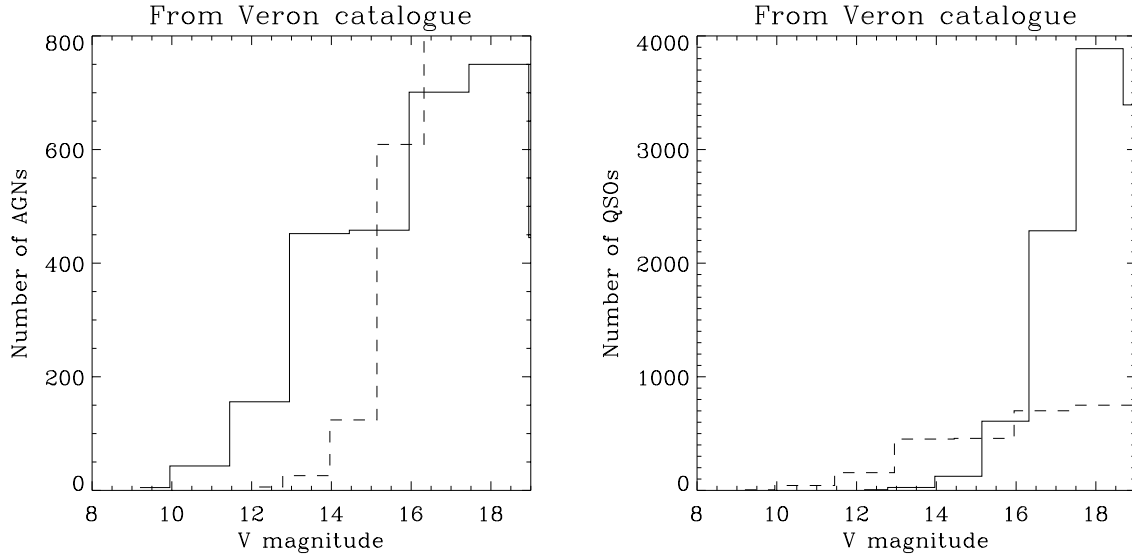
What then of “Véran” methods, i.e. obtaining the Point Spread Function from wavefront sensor measurements and deformable mirror commands? As pointed in section 1.1, the loop is usually working in extreme noise conditions, and this means that it is very difficult to determine what the exact amount of (turbulent) signal is present in the noise. As a matter of fact, this algorithm has a tendency to underestimate the seeing and overestimate the image quality as magnitude of the guide star increases. Luckily, the limits of validity of this algorithm are well known, so we should not be tempted to use it in inappropriate cases.

Still the difficulty of obtaining PSF remains, and deconvolution becomes more uncertain, if we cannot even trust our system’s optical response. In the case where we are observing extended, resolved sources, it might be argued that deconvolution is even of little relevance. However, deconvolution also helps to remove noise in a very efficient way, and as long as it is used in a reasonable way (i.e. the structures could be seen before deconvolution and are merely enhanced by the deconvolution process), it is a powerful technique. As a matter of fact, more and more astronomers now decide to show both the raw *and* deconvolved image and let everyone else make up their mind.

## 2. MUCH ADO ABOUT NOTHING?

How many targets are there that can really be observed with adaptive optics? After all, if we are going to spend time developing AO systems that work on such faint objects, techniques to reduce the data and make models to explain these sometimes uncertain observations, are there at least enough galaxies to justify such an effort? Of course, the answer to how many there actually are is non definitive but may include such factors as

- the magnitude of the galaxy (if it serves as a guide source) or
- the distance of the guide star to the galaxy and the isoplanatic patch size,
- the resolution needed to answer the particular questions concerning each object, and at what wavelength,
- the category of objects, or the type of science,
- etc...



**Figure 1.** Left, full line: Number of AGNs as a function of their V magnitude. Dotted line, number of QSOs. Right, Full line Number of QSO's as a function of their V magnitude. Dotted line: number of AGNs. A few more magnitudes and the extraordinary world of quasars will open itself to us!

However starting from the Véron–Cetty&Véron catalogue<sup>30</sup>, we can find the number of active galaxies and quasars as a function of magnitude; this is displayed in figure 1. Even though the catalogue might not be complete, there is a total of 3154 AGN's and 11124 Quasars in it so this can give an idea of the proportions of observable objects. As these curves show, on the AGN side, we have access to the first few hundred brightest galaxies (not all of them interesting or even observable at each telescope). On the QSO side, we are on the brink of a huge sample, and future developments such as Laser Guide Stars or advanced curvature systems may open this realm that is of yet only barely explored.

### 3. WHAT KIND OF SCIENCE?

The types of galaxies that can be (and indeed have been) observed with adaptive optics can be split up in the following categories\*:

**Normal galaxies** The best studied normal galaxy is Andromeda, Messier 31. Because it is so close to us, individual stars can be observed in the very nuclear region, and spectro-imaging of this region with the OASIS instrument at CFHT was used to study the proper motions of these stars.

**Active galaxies** This category describes the objects where there is an excess luminosity that cannot be explained simply by stellar emission. Therefore, Seyfert nuclei (which are believed to host a black hole in their center), starburst galaxies (where interaction and/or mergers produce huge star forming complexes, that use up the available gas within the galaxy in time scales ten to a hundred times faster than normal galaxies) and Ultra-Luminous Infrared Galaxies (which are believed to be quasars in formation, or super-starbursters) are all part of this category.

**Quasars** This category is concerned with more distant objects (even though there is no clear distinction between QSO's and active galaxies as a function of redshift), which appear point-like. Are these part of star-forming galaxies, or young and ravenous black holes in the center of Seyfert nuclei? These are questions where increased resolution and dynamic range may provide answers.

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\*even though such distinctions are somewhat arbitrary and in many cases more than one type is at play.

**Faint Primordial galaxies** According to Larkin *et al.*<sup>16</sup> (and references therein), there are some  $2 \times 10^5$  galaxies per square degree with  $m_K < 24$ . Even with a detection limit of  $m_K = 20$ , this number only decreases to  $2 \times 10^4$  per square degree. This means that within 20 arcseconds of any star bright enough to lock an AO loop on, there are on average 2 galaxies brighter than K=20 mag and 20 galaxies brighter than 24th magnitude. Imaging of these faint galaxies allows to study early galaxy formation and evolution. (The strategy adopted by Larkin *et al.*<sup>16</sup> is to perform deep preliminary infrared survey around bright (<12 mag) stars to find potential candidates and then observe these with adaptive optics.)

While a few cases are controversial, some very clear and profound results have been obtained in each of these categories and I will illustrate this with a few highlights of extra-galactic adaptive optics.

## 4. NORMAL GALAXIES

The nucleus of Messier 31 is double (with a separation of  $0.5''$ ), and while the fainter of the two nuclei is at the dynamic center of the galaxy, the origin and composition of the brighter one is still unclear. Messier 31 was observed by Davidge *et al.*<sup>4</sup> and a stellar population study was conducted. The infrared colors of both nuclei are very similar and a comparison with HST images of similar resolution reveals that the colors of the two nuclei are very similar to those of the bulge of the galaxy. This would indicate that both nuclei are of dynamical origin and not that the brighter nucleus was accreted as has been previously suggested.<sup>17</sup>

## 5. ACTIVE GALAXIES

### 5.1. NGC 1068

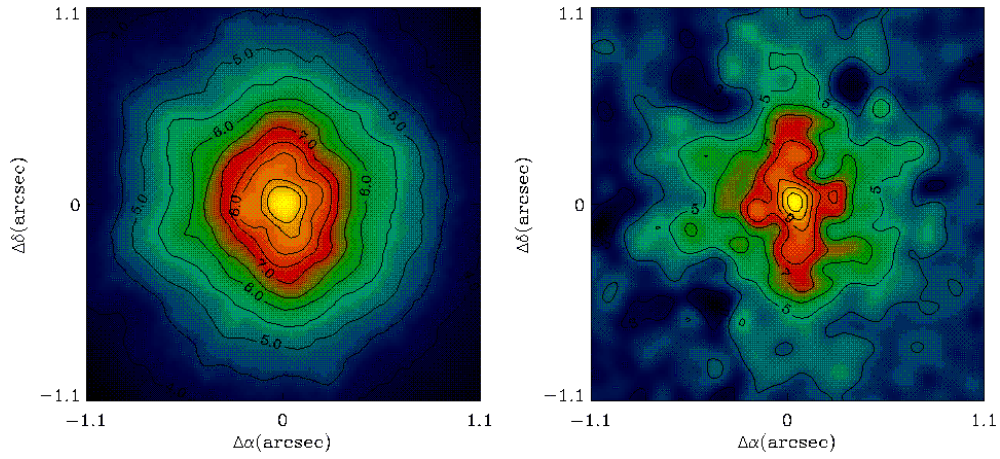
NGC 1068 is the archetypal controversy in the field of adaptive optics. Being the closest active galaxy to us, it has been intensely studied to try to understand the processes that take place in the Narrow Line Region (NLR), where the effects of the central black hole are felt only indirectly. Some images have been obtained by the Hubble Space Telescope, but the infrared and visible images are simply too different to be compared due to large amounts of extinction; in fact, precise astrometry is sorely needed to be able to register the different wavelength ranges without having to rely on apparently common features. The NICMOS images (now in the public domain) do not have long enough integration times (and do not have enough resolution) to probe the structures with which we are concerned. Speckle imaging from Keck<sup>31</sup> and from the SAO (Zelenchuk) 6 meter telescope<sup>32</sup> do not reveal these structures either<sup>†</sup>, but this should come as no surprise because speckle interferometry provides less sensitivity and dynamic range, which is exactly the point that prompted the development of adaptive optics in the first place.

The first observations from ADONIS were very inconclusive (Marco *et al.*, 1997)<sup>18</sup>, partly due to the poor quality of the correction ( $\text{FWHM} \simeq 0.5''$ ). Further observations with PUEO at CFHT (Rouan *et al.*, 1998)<sup>22</sup> reveal a “cross” structure as shown in figure 2, which is interpreted as the molecular torus of the unified model for active galactic nuclei, along the East–West axis, and micro–spiral arms along a North–South axis. At the same time, Chapman *et al.*<sup>1</sup> warned that such cross–like structures had been seen on a large fraction of their AGN sample and could therefore be artifacts. Further observations with ADONIS<sup>19</sup> in the thermal infrared in L and M bands probed the cooler dust, and the results are shown in figure 3. These images are quite consistent with the PUEO images in the sense that the colder dust of the molecular torus has a larger spatial extent than the hotter dust that is closer to the nucleus.

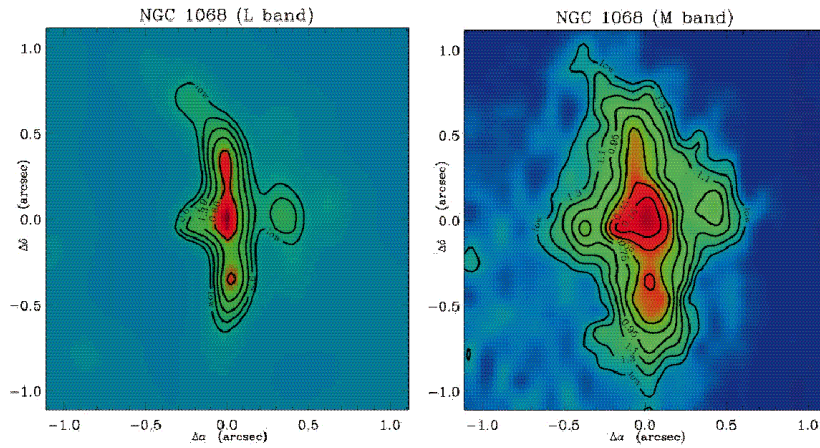
During the second engineering run of the Keck Adaptive Optics System, NGC 1068 was observed as it was setting (i.e. at fairly large airmass). As this was the second engineering run, some details were not quite ironed out and the rotation of the image is undetermined due to an uncertainty in the position rotator. However, by rotating the image to what seems to be the correct orientation (from the angle of the field rotator), we obtain figure 4. These images<sup>21</sup> were certainly not obtained in the best observing conditions, so NGC 1068 was re–observed later that year. By using the image rotator in an active way, it was hoped that the structures of the galaxy would move with the image rotator, while the structures of the artifacts would remain stationary with respect to the optical bench and the detector. Unfortunately this test was inconclusive because of poor seeing, leading to degraded resolution and therefore being unable to even detect the cross structure.

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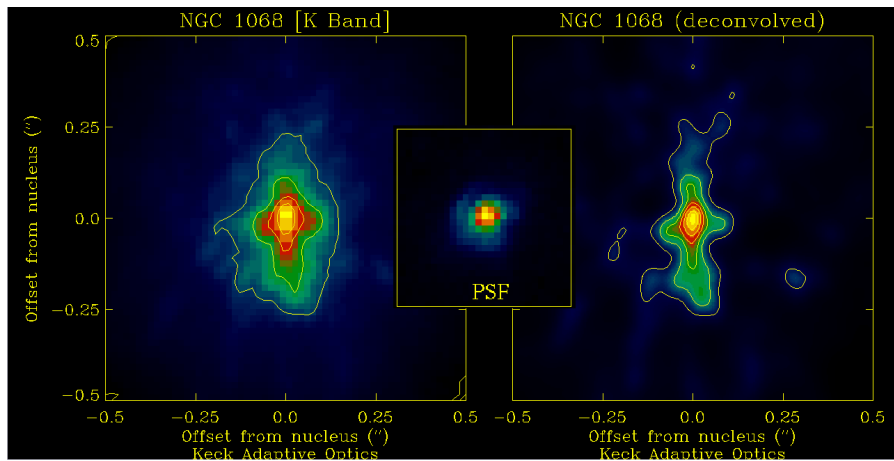
<sup>†</sup>The Zelenchuk images are in the visible domain, so it is not surprising that they are very different to the AO images presented here. However the Keck images in K band show a striking centro–symmetry, which is hard to reconcile with the images shown on figure 4.



**Figure 2.** Left: K band Image of NGC 1068 obtained with PUEO at CFHT (log scale). Right: Deconvolved image.



**Figure 3.** Left: L band image of NGC 1068 obtained with ADONIS at ESO. Right: M band image



**Figure 4.** Left: K band image of NGC 1068 obtained with the Keck Adaptive Optics system. Right: Same image deconvolved by the PSF in the central panel. Note the field is half of the above and there is an uncertainty in the orientation of the frames.

The evidence for the molecular torus and spiral structure seems to be fairly large, yet these results are still considered controversial. This can be attributed to two facts. The first one is that these observations are stretching the limits of adaptive optics systems in more than one way (faint *and* extended guide star). The second one is that once a subject is deemed controversial it (rightfully) requires a large amount of evidence to prove it. However multi-telescope and multi-wavelengths results *that are in agreement* seem to constitute more than just circumstantial evidence...

## 5.2. NGC 7469

In contrast, NGC 7469 is a Seyfert galaxy where things are much simpler and all the observations at various wavelengths, from various telescopes and with different techniques – speckle<sup>7</sup>, ADONIS, PUEO<sup>13</sup>, Keck<sup>21</sup>, HST (see figure 5) – agree with each other: there is no controversy on this object! The structures are seen with more or less contrast depending on the instrument and the telescope, but the presence of a very pointlike source in the visible to guide on (the Seyfert 1 nucleus) and the presence of an unresolved source in the infrared image (the nucleus, again) allows a high degree of confidence in the images. And on top of this, there is an extremely interesting structure around the nucleus, a circumnuclear starburst ring. The presence of this ring was known well before adaptive optics observations, but adaptive optics allowed us to probe the morphology of a starburst. For instance, it was found that the ring was actually tightly wound spiral arms, with a higher concentration of hot spots at a given distance from the nucleus (pointing to a dynamical process such as a resonance) as shown in figure 6. Furthermore, the starburst activity is not homogeneous at all but rather clumped in hot spots that are believed to be young clusters of very hot bright stars, as can be seen from figure 7.

We can actually even go a little further in the analysis of these image if we are looking for an inner bar, as is suspected by dynamical models<sup>†</sup>. The PUEO images (figure 6) show an elongation along a P.A. of approximately 45 and 225 degrees, which can be also seen on the HST image, while the HST image shows a bright source very close to the nucleus at a P.A. of 30 degrees that we do not see in the AO observations (presumably due to the broader PSF wings). Using the colors (such as the [V-K] index) of the star clusters and putting some upper limit on the source see on the HST image, we should be able to determine the source of the HST bright spot (Lai *et al.*, in preparation).<sup>13</sup>

## 5.3. Starbursts, ULIRGs

Ultra Luminous Infrared galaxies are thought to be starburst galaxies, or at least at the heart of most ULIRGs there is some starburst activity. However, the source of the huge luminosities that these galaxies exhibit ( $L > 10^{12}L_{\odot}$ ) is yet unclear; furthermore, most of this luminosity is in the far infrared, because whatever is at the heart of these monsters is hidden, sometimes through hundreds of magnitudes of absorption! It is therefore very difficult to pierce through the veil of dust.

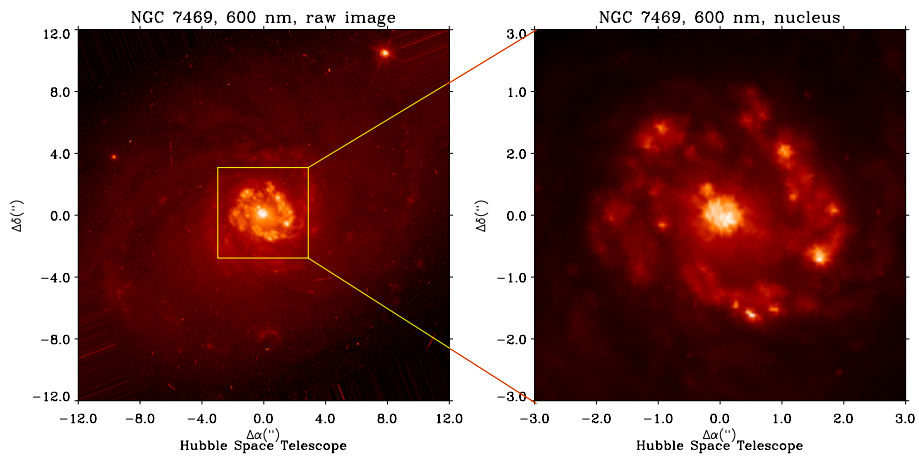
The commonly accepted idea is that at the heart of ULIRGs are quasars in formation. However a very strong starburst may accompany this event and may even dominate; the two examples given below show two extreme and opposite cases.

### 5.3.1. Arp 299

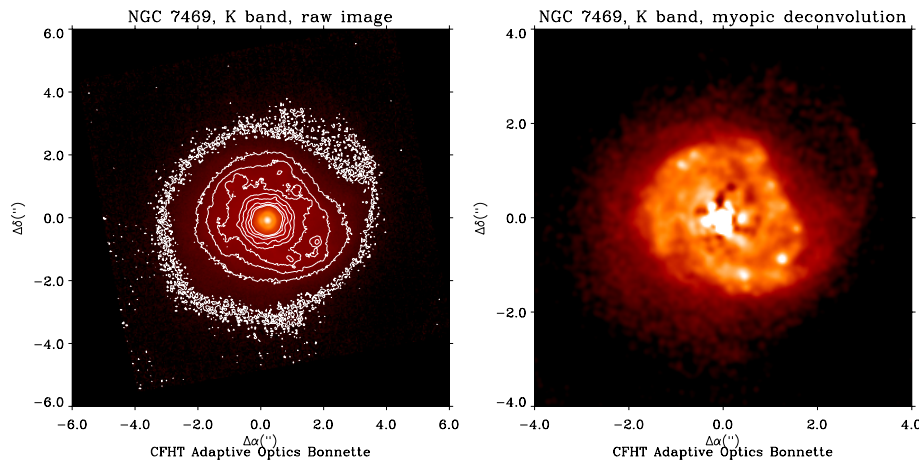
Adaptive Optics observations (Lai *et al.*, 1999)<sup>12</sup> have shown that the source of luminosity of this merging galaxy, which has an infrared luminosity  $L_{IR} \simeq 8 \times 10^{11}L_{\odot}$  is purely of starburst origin, i.e. there is no Seyfert-like activity in any of the components of this galaxy. There are two striking features that are noteworthy. On the one hand it is possible to produce such huge luminosities *without* having to invoke a black hole or a Seyfert nucleus. On the other hand, these observations show star clusters that are brighter than anything we know (i.e. with absolute magnitudes on the order of -21! and unresolved with a linear resolution of 40 pc). We are not let off the hook that easily, as to try to explain ULIRGs without resorting to black holes, we have to invoke “ultra-clusters” of stars...

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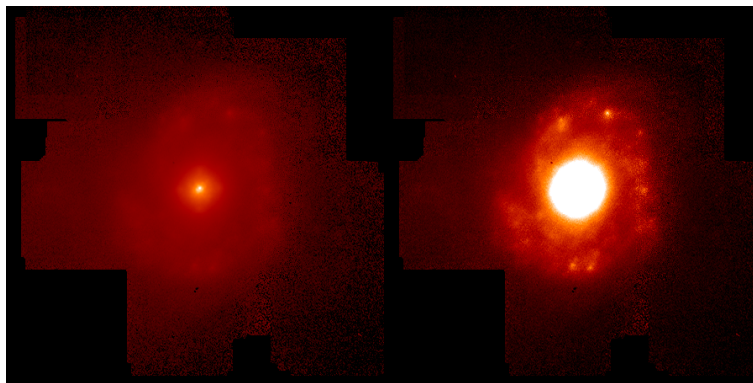
<sup>†</sup>This inner bar allows to dissipate angular momentum because the non-axisymmetric potential that it generates can produce torques that drive the gas onto the nucleus of the galaxy.



**Figure 5.** Left, K band Image of NGC 7469 obtained with HST (from the public domain). Right: zoom on the starburst ring. This image is included for comparison. When there is little absorption, the situation is greatly simplified.



**Figure 6.** Left: Raw K band Image of NGC 7469 obtained with PUEO at CFHT. Right: Deconvolved image of the same. The myopic deconvolution produces less structure around the very pointlike nucleus, but it is unclear which ones are real.

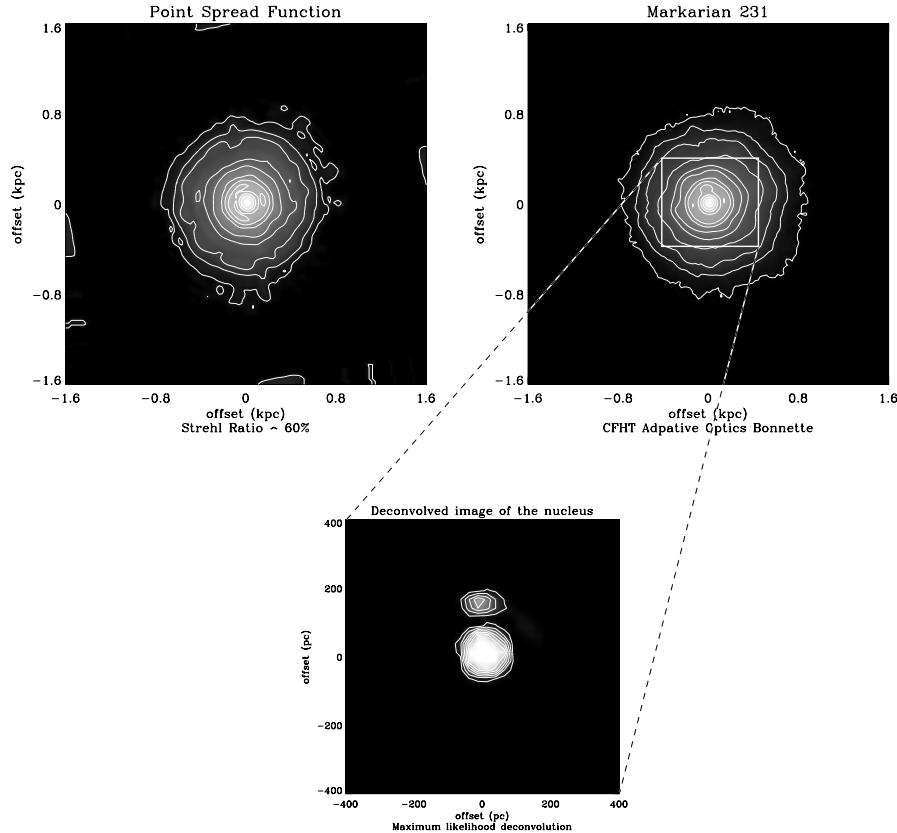


**Figure 7.** H band image of NGC 7469 obtained with the Keck Adaptive Optics System. Left, log scale. Right, linear scale with cuts to enhance the starburst ring. Note the field rotation is not standard, but it is very clear which way it should be rotated to be consistent with the two figures above.



### 5.3.2. Mrk 231

Markarian 231 is the brightest (bolometrically speaking) galaxy in the local universe (i.e. with  $z < 0.1$ ). It shows very different features than Arp 299 as it has a very peaked and point-like nucleus, with a FWHM of  $0.11''$  corresponding to 50 pc on the galaxy, (Lai *et al.*, 1998)<sup>11</sup>, reminiscent of a QSO. Furthermore, the [J-H] and [H-K] are in good agreement with an almost unreddened quasar. As this is the result of an advanced merger (Sanders *et al.*, 1988)<sup>26</sup>, we cannot help but wonder whether we are seeing two different stages of a unique process, i.e. the merging of two galaxies giving rise to an active nucleus, whether it be a QSO or a Seyfert nucleus.



**Figure 8.** Top left: PSF, reconstructed from Wave front sensor, square root scale, Strehl ratio = 60%! Top right: Markarian 231, same scale. Bottom panel, result of the deconvolution, showing the second component,  $0.14''$  North of the nucleus.

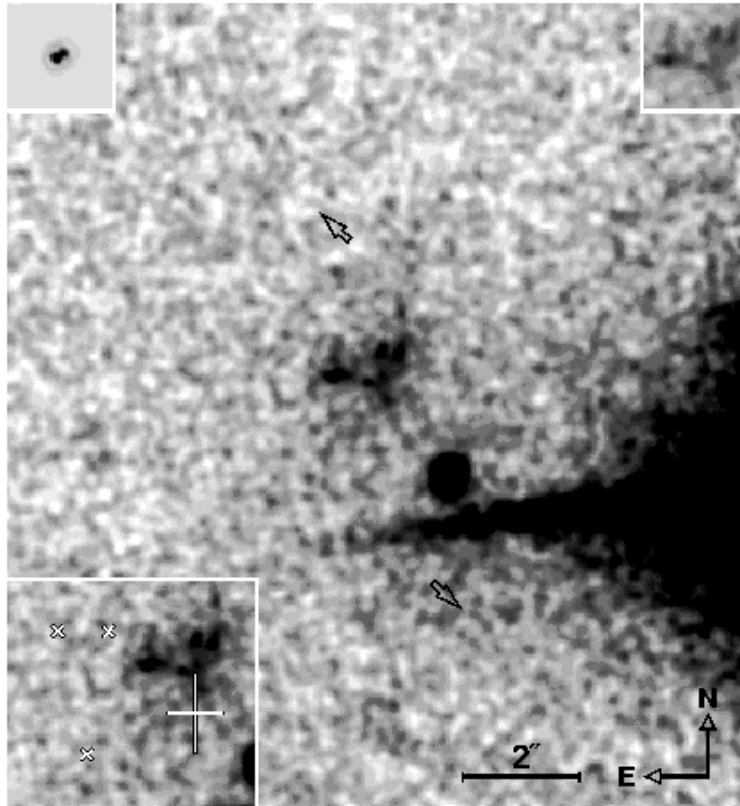
A much fainter source is also detected  $0.14''$  North of the nucleus (figure 8), which coincides with the location of a hot molecular gas cloud seen by Krabbe *et al.*<sup>10</sup> in non-AO corrected spectro-imaging mode, and with the extension of the compact radio source that coincides with Mrk 231 (Neff & Ulvestad, 1988)<sup>20</sup>. This source is most likely associated with a starburst event, and we can wonder whether this starburst is the result of its proximity to such a bright active source, or the remanent of the cloud that nurtured it...?

## 6. QUASARS

The goals of observing quasars with high angular resolution is to find out to what extent they are quasi-stellar. Therefore detecting the (relatively) low surface brightness host galaxy, jets or tails, or any structure that might show some interaction of the quasar with its environment can provide helpful hints to see and understand what a quasar is and how it is formed.

There are two ways to go about observing quasars. One can either study quasars that are bright enough to lock the adaptive optics loop on the quasar itself or by locking the loop on a bright star nearby. The latter method is

powerful as it opens up many more targets than what is currently accessible according to figure 1. Examples of this are the numerous quasars observed by the "Canadian Connection"<sup>3,8,27,9</sup>. To pick but one, QSO 0104+022 (Hutchings *et al.*, 1999)<sup>9</sup> is a remarkable example due to its redshift,  $z = 4.16$ ! However  $0.17''$  resolution is achieved due to a guide star with  $m_V = 13.8$ , located  $17''$  to the south (the galaxy itself has an  $m_v$  of 19.7). Interestingly, the quasar seems to be resolved as it has an East–West elongation. There are also two much fainter sources equidistant from the quasar to the West and South West that may be related to it.

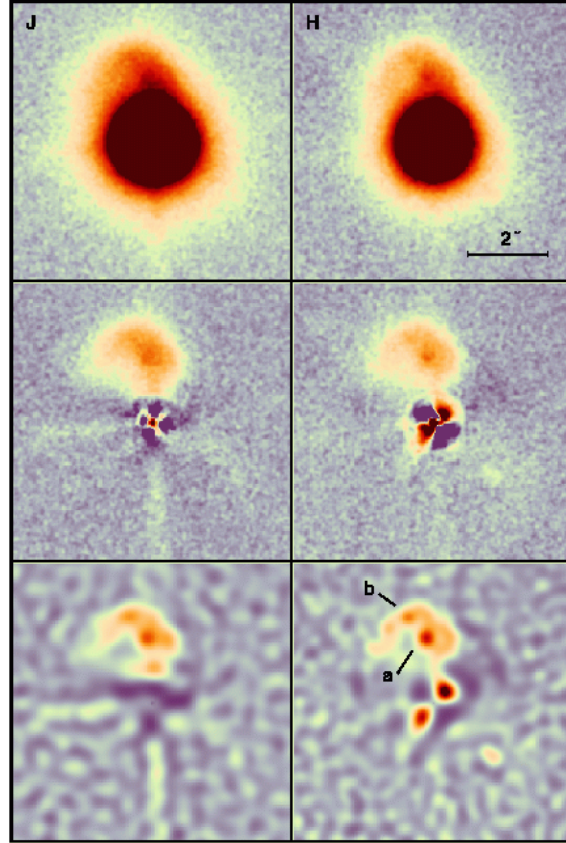


**Figure 9.** Image of the 3C294 quasar next to the  $V=12$  guide star, as seen by Hokupa'a on CFHT.<sup>29</sup> The bright spot seen by the diffraction spike (just South of 3C294) is a ghost of the guide star. The inset on the top left shows the guide star which is in fact double. The inset on the top right shows 3C294 with a different color stretch. The inset on the bottom left shows the location (and  $2\sigma$ ) of the radio source (as shown by the large cross). On the main image the two arrows show the location of the radio hot spots seen on 6 cm VLA maps.

Another example of a close guide star is the  $z=1.79$  radio source 3C294 (Stockton et al, 1999, figure 9)<sup>29</sup>, which has a  $m_V = 12$  star less than  $10''$  to the west. Of course, previously, such a star would have been a hindrance because of the scattered light, but now it allows for efficient adaptive optics.

These spectacular images are used by the author to depict the following view of what a high redshift quasar might look like: the quasar nucleus is hidden from our line of sight by some disk or toroidal structure that allows light out in a bi-conical structure. It therefore illuminates (via scattering), the direct environment of the quasar, that falls within the cone that is not obscured. This vision then is very similar to that which we have of Seyfert galaxies where some of them are seen in direct line of sight (Seyfert 1) and others have their nucleus hidden from the line of sight (Seyfert2) but Broad Line emission is still detected in polarized (i.e. scattered) light.

An example of a QSO that is used as its own reference source is PG 1700+518 (Stockton et al, 1998)<sup>28</sup>. The problem with such observations is that there are few targets available and the few that are need the most sensitive wavefront sensors available, namely curvature sensors. The FWHM on these observations are  $0.32''$  and  $0.28''$  in J and H band respectively, while the seeing at those same wavelengths was  $0.8''$  and  $0.7''$ . This is remarkable inasmuch



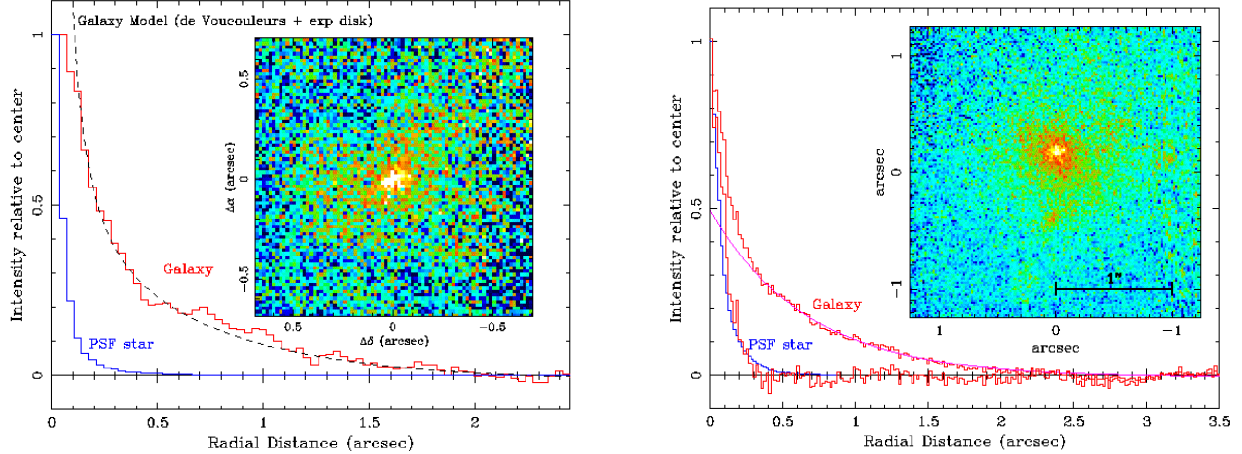
**Figure 10.** Images of PG1700+518. Left column: J band, right column: H band. Top row: raw data, middle row: artificial PSF subtracted, lower row: deconvolved with same artificial PSF. Note that in this case, deconvolving does not reproduce or enhance residual artifacts such as trefoil or astigmatism due to positivity constraints.

as the quasar (i.e the guide star) is a magnitude 15.5! The authors obtained an artificial PSF by removing the northern extension of the quasar and then fitting elliptical isophotes to determine the spatial structure of the PSF, accepting the fact that any elliptical structure of the QSO would be lost. The central row of figure 10 shows the result of the subtraction of the artificial PSF to the quasar. It bears remarkable resemblance to the artifacts reported by Chapman *et al*<sup>1</sup>, yet it is also remarkable that deconvolving the images (as opposed to subtracting the PSF) does not reproduce the artificial trefoil or astigmatic feature seen on the J and H band respectively; this is partly due to the positivity constraint of maximum likelihood algorithms (figure 10, lower row).

## 7. FAINT PRIMORDIAL GALAXIES

James Larkin and collaborators,<sup>16</sup> report on the observations made with the Keck Adaptive Optics System of the highest resolution infrared images of faint galaxies, including the faintest galaxy observed with a high order AO system... The trick? It comes from the fact that the density of galaxies is high when these are faint. For example, there are on average two galaxies brighter than  $K=20$  magnitude within a  $20''$  radius of anywhere in the sky, namely around a guide star bright enough to lock the AO loop on. This program therefore required some pre-AO observing runs which were conducted with the Keck Telescope and the NIRC infrared camera: 25 stars with V magnitudes between 8 and 12 and their surrounding fields were observed. More than 200 galaxies with  $K < 21.5$  were detected, and selected as possible candidates. Many of the fields also had fainter stars at distances from the guide star similar to that of the galaxy, thereby providing an excellent estimate of isoplanatic effects on the PSF.

Figure 11 shows two examples of such primordial galaxies observed with the Keck Adaptive Optics System. On the left is shown PPM 127095-7+17 (the name refers to ProPer Motion designation of the guide star augmented



**Figure 11.** Example of faint galaxies observed at proximity of bright guide stars. Left: PPM127095-7+17, the faintest galaxy ever imaged with a high order AO system (H=19), with a resolution of 50 milli-arcseconds. Right: PPM114182+5+24. Because of its confirmed redshift ( $z = 0.37 \pm 0.05$ ), it is possible to perform some more quantitative estimates of star formation and density of star-forming regions.

by the offsets in arcseconds to the galaxy), with a resolution of 50 milli-arcseconds. With a pixel scale of 17 mas, the signal to noise is modest on this H=19 integrated magnitude galaxy. However on the right, we see the galaxy PPM114182+5+24, which is somewhat brighter (H=17.3). The resolution is not as good as on the previous object but still remarkable (0.1") in absolute. Spiral arms and a particularly bright knot can actually be distinguished on this image. Because the redshift of this object is known ( $z = 0.37 \pm 0.05$ ), and the photometry can be estimated, some remarkable features are found. First, the disk of this galaxy is very bright – at least two magnitudes per unit area brighter than the Milky Way. Second, the core of the galaxy, which is unresolved, has a magnitude of 20 (which corresponds to an absolute magnitude of -22.0), which could be explained by a nuclear starburst. Finally, the knot that is seen 0.6 arcseconds to the south of the galaxy has an absolute H magnitude of  $M_H = -19.8$  which is greater than the brightest knots found in interacting galaxies, but is comparable to that of the “ultra-clusters” found in Arp 299 (Lai *et al.*, 1999)<sup>12</sup>.

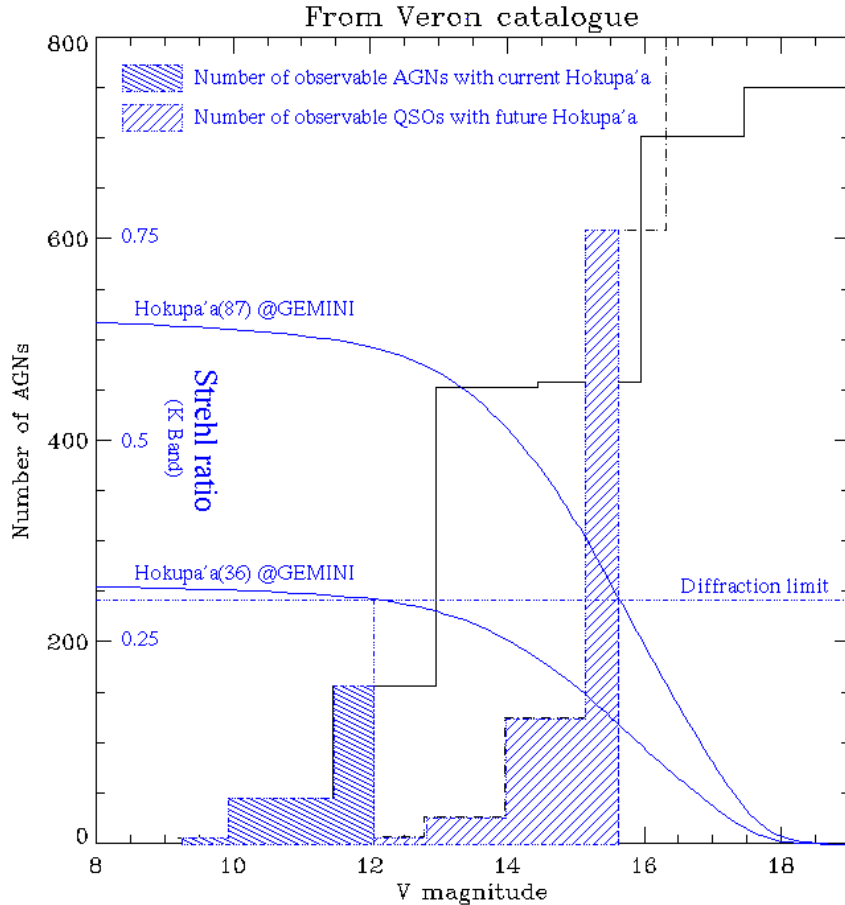
## 8. CONCLUSIONS

Having broadly reviewed some remarkable results in extragalactic adaptive optics (without even attempting to be exhaustive), there are some conclusions to be drawn:

- Even though the field is relatively new, diverse observations of very varied objects have been successfully performed, spanning many magnitudes, and many redshifts, which seems to indicate that a lot remains to be done, even with the current technology.
- We have powerful tools at hand, and the more we use them, the more we’ll come to understand and trust them. This, of course, applies to adaptive optics systems, but also to post-processing techniques such as deconvolution. If we know the AO system’s response to a point source, then we can trust the extragalactic images that much more. Even though “Véran” type algorithms break down at faint magnitudes, they provide valuable information in many cases, and a breakthrough for Shack–Hartman systems<sup>§</sup> will undoubtedly help cases where good correction is achieved, whether it be on the galaxy itself, a nearby star or even a laser guide star.
- When access to different telescopes (with different AO systems) is possible, the possibility of artifacts diminishes greatly if the structures remain. Of course, the possibility of finding the same artifact on different telescopes, at different wavelength, with different AO systems *exists*, but this is part of risk that comes with pushing the limits of a system.

<sup>§</sup>where the problem is much more complicated due to read noise which propagates on centroids in a non-linear fashion.

But the situation is not as dangerous, limited or exclusive as it may seem, because we are on the verge of many new possibilities that will increase the number of objects that we have access to in a near future. There is a lot of hope from the Laser Guide Star (LGS), and even though it does not provide complete sky coverage (a guide star will still be needed for Tip-Tilt sensing), the limiting magnitude of the latter is expected to reach up to magnitude 19. Systems with already operational LGS warn that they are not the panacea, but instead come with their own very special needs and care. Expectations have become much more realistic in the last few years as to what will actually be possible in terms of performance, with systems such as Keck AO LGS or Altair. Still, the increase in sky coverage will benefit all fields, but none more than the extragalactic domain.



**Figure 12.** Same as figure 1, but with Strehl ratio plots as a function of magnitude for K band. The lower curve shows the current Hokupa'a on Gemini (with 36 degrees of freedom), while the upper curve shows expected performance for the 85 DoF Hokupa'a. The hatched areas show the number of AGNs and QSOs observable with each system at a resolution equal to the diffraction limit.

Very promising developments are also expected from higher order curvature systems such as Hokupa'a on Gemini with 85 degrees of freedom. The advantage of such systems is that the Strehl ratio as a function of magnitude curve is the same for a 13 electrode system on a 3.6 meter telescope, or a 36 electrode system on a 3.6 or 8 meter telescope, or an 85 electrode system on a 8 meter telescope, simply scaled by a factor proportional to the fitting error (i.e. a function of  $D/r_0$ ); it is therefore not a function of magnitude<sup>23</sup>. Of course, a Strehl ratio of 30% in H band on a 3.6 meter telescope does not produce the same resolution as the same Strehl ratio on an 8 meter telescope. And, let's face it, to astronomers, what matters more than Strehl ratio is resolution.... Overlaying Strehl ratio plots for Hokupa'a to figure 1 produces figure 12. What is striking is that by increasing the number of degrees of freedom from 36 to 85, even though the limiting magnitude has not changed, the number of AGNs observable with a resolution equal to the diffraction limit has more than quadrupled, and the number of QSOs observable with a resolution equal

to the diffraction limit is greater than the number of previously observable AGNs!

In terms of science, developments in infrared instrumentation will also allow to study the physics of galaxies, through spectroscopy. The first spectrum of an AO corrected galaxy (NGC 4151) was recently obtained with NIRSPEC on Keck AO<sup>14,33</sup>. Further developments in the field of Near infrared integral field spectroscopy<sup>2,15,5</sup> are bound to further our understanding of the physics of these monsters.

Finally, worth mentioning are the longer term developments expected for adaptive optics, namely Multi-conjugate Adaptive Optics<sup>6</sup>. The great advantage is that the performance will not depend on the magnitude of guide stars or isoplanatic angles. The sky coverage factor will probably allow to explore most, if not all, objects, with diffraction limited resolutions AND a good estimate of the PSF!

But while we wait for these wonders, let us push the limits of the systems that we have at hand, let us be bold and intrepid, let us take risks... eXtreme astronomy is not for the faint-hearted.

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