DISCLAIMER: This is a working document. Its purpose is to establish the framework for the Science Cases for KPAO, given the expected performance, and to elicit a response, in the form of ideas, comments, suggestions or contributions from the targeted user community (and to widen that community, if possible). Therefore, the scope of the document is quite broad and its style quite rough and even speculative at times. When higher quality and more specific documents (e.g. a glossy science summary aimed at securing funding) will be required, they can be assembled from information extracted from this repository.

1. Introduction
The W.M. Keck Observatory opened the way with adaptive optics (AO) for the class of very large telescopes (8-10m). The first such Natural Guide Star (NGS) system saw its “first light” on the Keck II telescope in February 1999. Six years of development and operations have highlighted some limitations of first generation concepts and early technology, but operations and astrophysical returns have increased both in efficiency, quality and amount (a total of 68 refereed science papers have been published using Keck AO as of May, 2005, including four interferometer science papers that required AO on both Keck telescopes). The Keck II Laser Guide Star (LGS) facility, another first on 8-10m telescopes, is again opening the way for this powerful technique on very large telescopes.

While competing observatories are actively pursuing new concepts in adaptive optics technology, often with a very specific science case, the KPAO project goal is to pave the way with second generation general-purpose adaptive optics for the 8-10m class of telescopes, focusing on image quality and sky coverage.

1.1 General concepts of second generation adaptive optics.
From a deliverable (user) standpoint (that is if a user wants to observe a certain object), the most important parameters of an adaptive optics system can be identified as:
• Guide Star magnitude (sky coverage/image quality trade-off)
• Image quality (optimal wavelength/sky coverage trade-off)
• Corrected Field of View (FoV) (increases sky coverage but requires different conceptual approaches).

† Chris Neyman, Ralf Flicker, Antonin Bouchez, Sam Kim.
‡ Mike Brown, Andrea Ghez, James Larkin, Mike Liu, Claire Max, David Le Mignant, Peter Wizinowich.
The guide star magnitude depends on the technology used (sensitivity to read noise, etc.) and the size of the subapertures. For a given system, the guide star magnitude determines the sky coverage and the achievable image quality. The promise of LGS is to increase (shift) the sensitivity of a given AO system with respect to NGS by (roughly) \((D/d)^2\) (where \(D\) is the telescope diameter and \(d\) is the subaperture size; e.g. Keck, \(D=10m\), \(d=0.56m\), so 6 magnitudes fainter). The sky coverage increases accordingly (and therefore not to 100% due to the tilt indeterminacy problem), while providing a slightly poorer intrinsic image quality (maximum Strehl ratio is reduced by focal anisoplanatism and LGS measurement error).

The image quality on the other hand, is a function of (the technology used and) the number of degrees of freedom (or the inverse of the subaperture size), and unless a laser guide star is used, it determines the limiting magnitude and hence the sky coverage. In the case of a laser guide star system, this is intimately tied to the power of the laser (and the LGS image size), since, due to the shape of the power spectrum of atmospheric fluctuations (most of the turbulence induced phase variance is in the low spatial frequencies), it is more detrimental to have a high order system that is photon starved rather than a low order system with good SNR (this can be improved with read-noise-less detectors and modal control). Therefore the image quality is ultimately defined by the available laser power. Image quality also determines the dynamic range achievable by an AO system or a coronograph fed by one. Furthermore, it also determines the optimal wavelength at which diffraction limit is still achieved (or at which the gain in Strehl ratio is maximized, see Roddier, 1998).

All the methods proposed to modify (increase) the corrected Field of View (whether it is at the expense of image quality – GLAO, or without Laser Guide Star(s), such as altitude mirror conjugation, or with a constellation of Laser Guide Star for conventional MCAO) are a high price to pay for somewhat specific science cases and rely on new (and sometimes untested) technology and appear to be still in their infancy. Furthermore in sparsely populated regions of the sky, the multiplex gain provided by increasing the corrected field of view is not necessarily equal to the increase in corrected surface, but rather to the number of sources per isoplanatic patch.
Figure 1: The Galactic Center. This early Keck LGS AO wide field image is 80" wide (the field of MCAO) and combines images at 2.1 and 3.8 mm. This 2x2 mosaic was obtained by positioning the LGS at the center of each field.

Given that the guide star magnitude is determined almost exclusively by the imaging wavelength, irrespective of what AO system is being considered (there needs to be at the very least one photon per $r_0$ and per coherence time – both of which are chromatic), current forefront AO research has focused on the other two parameters, image quality and field of view. Specific astrophysical problems delineate two extremes in terms of requirements. On the one hand, there is a push for the highest image quality possible at the expense of corrected FoV and Guide Star magnitude. This is mostly driven by extra-solar planet direct detection (i.e. imaging) and includes projects like XAOPI, ExAOC, and VLTPF. In this case, a NGS is still required because of focal anisoplanatism, and the field of view is not as much of a concern as the dynamic range achievable within 2" of the guide star. On the other hand, there is the MCAO class of systems, where the corrected FoV and sky coverage is increased with the use of multiple Laser Guide Stars, and consequently a slight drop in image quality. For the field of star formation and evolution in our galaxy and in others, which is the main science driver for MCAO, a constant PSF over a large corrected field of view is of prime importance, since it is needed to resolve individual stars and measure their magnitudes, colors and position to a high accuracy.

Some history of drawbacks (may be limitations is a better word) of existing, (“first generation”) AO systems.
Advances both at technological and conceptual level. (Emphasis on LGS. Could potentially point out that impact of LGS AO at Keck, with respect to NGS, will be of the same order of magnitude as the impact of KPAO with respect to LGS AO)

At the conceptual level, KPAO would focus on excellent image quality in the near-infrared (which implies a very stable image) with almost complete sky coverage. Note that there is no stringent requirement on the corrected field of view, because it is assumed the objects of interest will not be star fields specifically and the isoplanatic patch size is sufficient to study individual astrophysical objects at high resolution. A side product of a high Strehl ratio in the infrared is the ability to observe at high resolution in the visible (albeit at lower Strehl ratio). An important aspect of KPAO is a good knowledge of the delivered PSF for photometric and deconvolution purposes.

1.2 What is KPAO and what is not?
Similarities with TMT AO requirements, differences with MCAO.
General use concept drives some general requirements, Strehl, stability, sky coverage, emissivity, polarization, etc. In turn, these requirements drive possible astrophysical science.

In theory, the following chart represents the model for a particular science case driven instrument. The science case drives the requirements and provides input to the performance analysis which may also drive the requirements. Finally, the requirements are measured up against feasibility. Not shown in the chart is the feedback from the feasibility to the science case; this indicates what science may actually be feasible instead of wanted and it has to be evaluated if this science case is still sufficiently strong to warrant the instrument.

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<tr>
<th>Science Cases</th>
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<th>Requirements</th>
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<tr>
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<td>Feasibility</td>
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In the case of KPAO, a major difference is that it is a general use instrument, not driven by a single science case, but instead aimed at providing the best overall performance within a certain feasibility budget. In such a case, the chart would look something like this:

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Since there is not one single science case, but rather a plethora of community driven astrophysical problems, there is much more interplay between the various elements of the chart. The feasibility is really the ultimate limitation, so it affects both the requirements and the performance analysis, although the latter obviously feeds back into the feasibility. The science cases depend on the performance analysis to a certain extent, and may drive
parts of the requirements. Finally, once the requirements have been established from the science cases and the performance analysis, the feasibility can be re-evaluated.

All this is to say that the science cases presented in this document are neither exhaustive nor fully developed, but are meant to illustrate the potential of an instrument such as KPAO. Here, we present an overview of the fields where a second generation AO system may contribute, but the actual astrophysical science that will eventually be done with the instrument will be community driven and is surely well beyond the scope of this document.

2. Possible back end instruments

2.1 Near IR imager

KPAO’s major difference with existing AO is the Strehl ratio. This has an impact on the dynamic range of the images (lower read noise detectors?) and can benefit any form of coronographs. Being critically sampled is crucial and with 120nm rms error, the Strehl ratio will be 0.89 at K band, 0.81 at H band and 0.70 at J band (see Figure 2: Predicted KPAO Strehl for different rms wavefront error goals.). Assuming a NIR imager extends down to 1 micron, then the required pixel size will be 10mas, with a field of view of 42” for current large format detectors. This is perfectly adequate as larger fields will be dominated by anisoplanatism. Requirements on the science camera are also more stringent at higher Strehl ratio.

![KPAO Strehl vs. rms wavefront error](image)

Figure 2: Predicted KPAO Strehl for different rms wavefront error goals.
2.2 Near IR spectrograph or Integral Field Spectrograph.
OSIRIS will likely be the first instrument to be used with KPAO. While the gain in Strehl affects the sensitivity (and hence the inverse of the exposure time) in the read noise limited case linearly, the cross talk of adjacent pixels is reduced. [May be James to add something?]

2.3 Visible imager
Also see 3. Of particular importance…

With a rms phase error of 120nm, it is possible to obtain the diffraction limit of the telescope down to the R band (750 nm), with a spatial resolution of 15mas. Detailed simulations will provide the effective resolution at Hα, but with a Strehl ratio of 0.27, we can expect a resolution <0.02”. The high angular resolution comes at the expense of Strehl stability, but this will not be worse than current observations in the J band.

Visible AO on a 10 meter telescope will open three distinct and exciting science applications. First, there is of course, the increased resolution. Second, there is the sensitivity increase on unresolved objects and finally, the study of scattered light and polarization, which increases at shorter wavelength. Any of these will have an effect on possible instruments. The increased resolution will require adequate sampling. The increased sensitivity may have an effect on exposure times (and very importantly on the observing time efficiency) required to get a given SNR. Finally, the polarimetry, which will be very important for studies of disk and dust in scattered light, will have repercussions on the optical design (the polarimeter unit should be at the entrance of the AO system to reduce the effect of instrumental polarization).

Emissivity requirement relaxed and tip–tilt in the IR? Beamsplitter requirements. Polarization requirements. Impact on requirements.

2.4 Visible spectrograph or integral field spectrograph
This area needs input from potential users and spectroscopy experts.
All else being equal, Spectrograph resolution proportional to $D/r_0$

On the one hand a long slit spectrograph with a 0.03” slit at Hα can be used for high spectral resolution.
On the other hand, integral field spectroscopy with lower spectral resolution will provide the advantage of ???

Exposure time calculator to quantify improved performance.

3. Of particular importance…
Metric for PSF stability, speckle distribution, super-speckles control and suppression
Thermal IR: 120nm rms phase produces a Strehl ratio of 95% at 3.5μm and 97.6% at 4.8μm. This is well within the range of extreme AO for planet hunts. Contrast also gets much more manageable at 5μm.
The visible applications may be the strongest selling point for KPAO, because there is a “hard” limit at 120nm rms, which produces diffraction limited images in the red part of the visible spectrum. The cone effect on an 8 meter telescope with a single laser guide star produces 125nm of error. So an AO system with comparable performance (e.g., Subaru C188 has 145nm fitting error - in 0.6” seeing - $S_R=23\%, S_H=72\%, S_K=84\%$) would have to have this error added quadratically (so Subaru’s C188 residual phase due to fitting and cone effect errors would be 190nm r.m.s. – $S_R=8\%, S_H=57\%, S_K=75\%$). So it is quite clear that in LGS mode, only a system using multiple guide stars, such as KPAO will be able to provide diffraction-limited imaging in the visible.

By going to the visible domain, Keck’s 10 meter aperture will provide the highest possible (filled pupil imaging) resolution achievable from the ground or from space. The large aperture, coupled with the gain in sensitivity to point sources will be very useful when looking for very distant quasars. Finally, the polarimetry of disks and young stellar objects at such high resolution in the visible will allow the study of gaps and warps of such disks at unprecedented level, providing observational constraints to planet formation models. This is an intelligent way in which Keck can contribute to direct detection planet searches without directly competing with either Gemini or ESO.

The three main areas astrophysical areas thus identified are 1) highest possible imaging resolution from ground or space (with innumerable applications, from planets to stellar properties in globular clusters or nearby galaxies to morphology of distant galaxies) 2) an increase in sensitivity to point sources that will allow searches for the most distant quasars, and finally 3) polarimetric studies of disks and YSOs to look for tracers of planet formation. In the visible domain, the gain in sensitivity will actually be greatest on very faint objects. Indeed, the signal to noise ratio is given by

$$S/N = \frac{F_{obj}}{\sqrt{F_{obj} + N_{pix} (F_{sky} + \sigma_{CCD})^2}}$$

where $F_{obj}$ is the total flux from the object, $N_{pix}$ is the number of pixels covered by the object (the size of the photometric aperture), $F_{sky}$ is the sky flux per pixel and $\sigma_{CCD}$ is the read noise of the detector (which is usually smaller than the sky background). Irrespective of the exact number and assuming that everything else is constant (i.e. same number of pixels in aperture, same object flux, same read noise), we can see that reducing the size of the pixels reduces $F_{sky}$ in proportion to the area, as long as $F_{sky}$ is the dominant source of noise. The sky background in $V$ band is approximately $22\text{mag/}^2$ ; if the pixels are 10mas then objects brighter than 32 magnitudes/pixel will be sky background limited. Therefore the gain in sensitivity to point sources with respect to seeing will be proportional to $1/\left(\frac{r_0}{D}\right)^2$ or simply $D/r_0$. However, this assumes perfect correction and only $S$ of the flux is actually coherent (in other words 1-$S$ of the flux is scattered over the halo and does not contribute to the signal in $F_{obj}$). Therefore in the case of background limited observations, the gain in sensitivity with respect to seeing limited observing is $S \times D/r_0$, (for a Nyquist sampled pixel size). So for example with typical values ($D = 10\text{m}$, $\text{seeing}_{0.5\mu\text{m}} = 0.65''$), KPAO would provide a gain in sensitivity of
• At 2.2µm with respect to seeing: 9.5 (Nyquist sampled in each case)
• At 2.2µm with respect to KeckAO: 1.5 (same pixel scale, Strehl improvement)
• At 0.75µm with respect to seeing: 11.6 (Nyquist sampled in each case)
• At 0.75µm with respect to KeckAO: 7.5 (assuming $S_{\text{KeckAO}}(0.75\mu m) \sim 4\%$)

Finally it should be noted that Keck’s highly structured PSF (with a lot of coherence and energy in the wings) will make any high dynamic range imaging very difficult. The need to develop some way to reconstruct the exact (as opposed to statistical) PSF would be crucial for such applications; this is far from trivial as it will require taking pupil rotation (with respect to field, sky and DM/sensor) into account. Alternately, these diffraction effects could be suppressed or at least reduced, although no single method is very simple. Therefore, by concentrating in a domain of application where the Strehl improvement is greatest (but not the Strehl itself), these structures are not that important. Long exposure times (and the consequent pupil rotation) in the visible will allow averaging out a lot of the residual speckles and diffractive effects. As long as the MTF does not go to zero until the cut-off spatial frequency, information can be retrieved even with a limited knowledge of the PSF.

One of the consequences of focusing the Science cases in the visible is that it affects the requirements of the KPAO instrument. In essence, it increases the need for as small as possible residual wavefront error: To be diffraction limited ($S \sim 0.3$, $\sigma^{2}_\phi \sim 1\text{ rad}^2$), the rms wavefront error as a function of wavelength has to be smaller than $\lambda/2\pi$.

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<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>450</th>
<th>500</th>
<th>550</th>
<th>600</th>
<th>650</th>
<th>700</th>
<th>750</th>
<th>800</th>
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<tbody>
<tr>
<td>Residual phase error requirement (nm rms)</td>
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<td>80</td>
<td>88</td>
<td>95</td>
<td>103</td>
<td>111</td>
<td>120</td>
<td>127</td>
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**4. Planetary Science**

DISCLAIMER: KPAO has very solid and enticing science cases in the planetary sciences. Beyond the traditional list of solar system objects that will be within the observational range of the AO system, this section would be better served by some specific atmospheric, volcanic or chemical problem that could specifically be addressed by ground based diffraction limited imaging and monitoring with a 10 meter telescope. Input from the appropriate communities is therefore solicited.

Some words as to the success of AO in solar system studies, including spectacular results on Titan and Io. Limitations? How to overcome…? What about spectroscopy (and at which wavelength range)? Also what about polarimetry, since such a large fraction of the light in the solar system is reflected or scattered from the sun?

**4.1 Venus and Mars**

Ground based observing allows long-term monitoring (much harder from space which provides snapshots). Venus and Mars have been out of reach of existing AO systems because they are too large and too bright to allow guiding. Numerous attempts to observe
Mars while guiding the AO system on Phobos have been performed (Pueo, Palomar, Keck) but have yet to succeed. A LGS could be used if a proper filter could be used to block the light of the planet from the wavefront sensor. Tip-tilt could then be done on appulses of bright stars.

In the visible domain, the spatial resolution of KPAO could be as low as 15 mas, providing a linear resolution of 7.5 km and 5.7 km on Venus and Mars at maximum elongation and opposition, respectively.

Example of comparative atmospheric studies enabled by KPAO: Venus rotates extremely slowly, Venus’s day is 243 earth days. And because of the constant surface temp from equator to poles, at first it was thought that the winds would be fairly slow. On the earth, winds at low latitudes move more slowly than its rotation whereas those at higher latitudes exceed the speed of the surface - i.e. superrotating. The atmosphere of Venus superrotates at all latitudes and at all heights from close to the surface to at least 90 kms above the surface. The winds attain their peak velocity near the cloud tops where they blow 100m/s, about 60 times as fast as the rotation of the underlying surface.

Even now, planetary scientists do not fully understand why the entire lower atmosphere of Venus superrotates. The large fraction of solar energy that is absorbed high in the atmosphere, near the tops of the clouds, probably contributes to the brisk winds. The high-altitude heating of the atmosphere may set up a circulation system that is much less influenced by frictional interaction with the surface than is the case on the earth. Thus the atmosphere of Venus might be highly susceptible to the formation of eddies that can efficiently transport angular momentum. Such eddies could counteract the ability of that Hadley circulation to prevent superrotation at low latitudes. Images from the pioneer orbiter provide evidence of small-scale eddy-like variations in the winds.

Source: Monash University research brochure.

Monitoring of the upper atmosphere for the formation of eddies from ground based observing.

Mars’ meteorology is exotic, and many phenomena can be studied with ground based monitoring capabilities. For example, the dust activity seen on many Hubble Space Telescope images during the Pathfinder landing or the global dust storms at the time of the Mars Global Surveyor provided many insights into where and how dust was being raised, and how planet-wide series of events triggered storms that eventually reached global scales.

4.2 Titan

4.3 Io
4.4 Neptune, Uranus

4.5 Pluto & Charon: global changes
The smaller icy solar system objects lie outside the range of current AO systems. Pluto is the prototype object, and it has a size of 0.1”. PSF will need to be highly stable for reliable mapping during a planetary rotation. In K band, there are 2.2 resolution elements across the disk of Pluto. In R band, there will be 38 independent points of measure on the surface. This will be complementary to the HST UV maps produced with FOC. Its magnitude between 13 and 15 makes it suitable for tip tilt guiding, and too faint for high dynamic range AO (which has good resolving power in the visible).

4.6 TNOs, Trojans,

4.7 Binarity in Solar System

4.8 Outer Solar System?

5. Stellar and Galactic Astronomy

5.1 Young Stellar Objects, Protoplanetary nebulae, Proplyds, TTauri and Disks. A. Ghez

Circumstellar disks
Study of grain growth. This will need high Strehl ratios over a large wavelength range and polarimetry. Results of current AO system in L’ band (Strehl >80%) illustrates high contrast application.
5.2 Debris Disks around main sequence stars (Beta Pic, Vega)

5.3 Low Mass stars in Binaries and Clusters

Companion searches with current AO systems are limited by residual speckles. A stable and well characterized PSF would allow sufficiently accurate photometry to push the low mass limit in clusters to Jupiter masses and even lower.

Dynamical measurement of low mass binaries will allow the calibration of the pre-main sequence evolutionary tracks.

5.4 Brown Dwarfs and Planets around White Dwarfs / Brown Dwarfs

The most ambitious, but also the most rewarding, goal is the direct detection of planets. While it may not be possible to obtain sufficient contrast in direct imaging, KPAO coupled with a coronographic and/or dual imaging device to reduce scattered light and speckle noise, could be used to search for giant planets around nearby stars.
5.5 Evolved stars, AGB, post-AGB, planetary nebulae
Study of Mass loss.

5.6 Galactic Center. A. Ghez
Dynamical measurement (astrometric and spectroscopic) to search for extended dark matter, Ro and general relativistic effects on orbits.

5.7 Globular Clusters & Galactic populations studies T. Davidge? A Ghez.
Dynamical measurements (astrometric and spectroscopic) to search for intermediate mass black holes.

Photometric measurement to study stellar population (See Davidge work with Pueo). This is a case where KPAO may be better suited than MCAO since photometric accuracy is of paramount importance (one can assume it increases with Strehl ratio), and their average size is much larger than the corrected FoV of both KPAO and MCAO (~10’).

6. Extragalactic Astronomy
[N.B. Most of the text is built around James Larkin’s presentation to the AOWG]

One of the most crucial issues for extragalactic applications of AO is the brightness of the guide star: Very few galaxies have sufficiently bright cores for high-order AO systems: approximately 200 AGNs have a core with V<12 in the Véron-Cetty & Véron catalogue, 1998, while there are >1800 AGNs with that have a core with V<17. Similarly, there are no quasars brighter than V=12 while there are >3000 QSOs with V<17. Therefore, curvature AO systems are currently doing most of the extragalactic science, albeit with limited Strehl, and the associated difficulties that ensue.

Furthermore, only 0.01% of extragalactic objects are near bright foreground stars that would provide a fortuitous beacon for wavefront sensing. Therefore, the use of systems like KPAO, providing high Strehl, high sky coverage through the use of multiple LGS is necessary to provide consistent performance on a variety of sources: First and foremost, a LGS system allows selecting targets based on their physical characteristics, and not by the magnitude of their nuclei. So, rare but important objects, such as Lyman-break galaxies, sub-mm galaxies, and ultra-luminous infrared galaxies can already start to be studied in detail with high angular resolution. The use of multiple laser beacons will also open up the Hubble Deep Fields and the ground based redshift fields; the brightest star within the ultra deep field, for example, has R~15. As the gain in sensitivity (or reciprocal of exposure time) on unresolved point sources on such deep fields is directly proportional to the gain in Strehl ratio, a 10 meter telescope equipped with a system delivering a stable PSF with S>80% in K band will be beneficial to all areas of extragalactic science.

Surface Brightness
The sensitivity increases rapidly with Strehl for point sources, but extended (resolved)
targets gain much less. AO systems produce additional background in the near-IR and reduce throughput further making it difficult to observe faint extended sources. This will have strong constraints on the throughput and emissivity requirements. For example, normal galaxy disks only achieve a maximum surface brightness of K~16 mag/arcsec$^2$ and this fades as $(1+z)^4$. This means all normal disks are fainter than 22.5 mag within 0.05x0.05", although galaxy evolution somewhat improves this effect. Therefore, even just for imaging, observations can take many hours.

Despite the lower throughput and higher emissivity of the current Keck AO system, it is a powerful tool to identify point-like sources within galaxies that have an extended and resolved background. So although the sensitivity to the background itself is reduced with respect to seeing limited observing (with Nyquist sampled pixels in either case), the sensitivity to point sources actually increases in the same way as with any background (such as sky or thermal), in that there is a gain to embedded point sources detection limits which is proportional to $S \times (D/r_0)$.

6.1 AGNs, NLR/Torus/BLR & Jets.
C. Max, J. Larkin

The Narrow Line Region (NLR) and close environment to the molecular torus and Broad Line Region will benefit tremendously from an instrument such as KPAO: the internal structure of all nearby active nuclei is unresolved with one arcsecond resolution. The interaction between the galaxy and its nucleus (reservoir of matter to feed the black hole in and around NLRs, mechanisms responsible for triggering inflow, such as mergers, asymmetric gravitational potential, etc.) are starting to be understood with the use of near infrared spectroscopy AO at Keck (e.g. NGC 7469, Davies, Tacconi & Genzel, 2004, Markarian 231, Davies, Tacconi & Genzel 2004. Note that in all these cases, the structures resulting from the mechanism that “feed the monster” of these nearby active nuclei is indeed unresolved without subarcsecond resolution).

From a morphological standpoint, these studies are always limited by speckle noise. Indeed the constraints are not as stringent as an extreme AO system, but Seyfert1 nuclei or quasars are usually unresolved at 40 mas scales, but residuals of mergers, such as secondary nuclei or disks will only be seen in high contrast (and stable) images; existing data is usually not photon noise limited, but speckle noise limited. The active nucleus of a galaxy is often brighter than the rest of the galaxy, so the contrast in surface brightness can be very large; any structure seen at or below the level of the diffraction pattern will be indistinguishable at first from residual, speckles or artefacts. Furthermore, morphological studies don’t require a fixed contrast level to be useful, but rather sufficient confidence in the data that the 3 dimensional model may be reconstructed from a 2 dimensional observations.

However, a very point-like nucleus that is much brighter than the surrounding galaxy can usually be used for tip-tilt guiding in terms of brightness and proximity to the zone of interest (usually the inner 2” to 10” of the galaxy), but has conventionally been too dim on existing systems to provide enough photons for high order correction.
Coupled with integral field spectroscopy as provided by OSIRIS, this is a powerful tool to study the composition and kinematics of these morphologies. Integral field spectroscopy, whether cross dispersed Fabry-Perot or lenslet array based will allow very accurate narrow line imaging and continuum subtraction. Furthermore, unresolved structures in the continuum can be used to obtain the Point Spread Function. A full spectro-image will also allow one to see which structures are wavelength dependent in position (the location of optical defects due to diffraction is proportional to wavelength).

6.2 ULIRGs, QSO in formation, Starbursts
The goal is to look for systematic signs of mergers such as double nuclei, tidal tails, etc., and to investigate the triggers of star formation. Ideally, we would wish to study the mechanism that regulates starbursts. The study of the stellar populations of starburst systems allows one to retrace the history of the starburst, but the crowding of stars in nearby systems prevents an accurate analysis of stellar populations.

6.3 QSO host galaxies
Contrast and PSF stability. Star formation in QSO host galaxies, young stellar population, role of merger.

6.4 Primordial galaxies
J. Larkin
Allow studies of stellar populations as a controlled function of radius.

6.5 High redshift galaxies
At high redshift, optical spectral lines shift into the infrared where AO correction is best and HST has had limited impact. The “magic” redshift is at approximately 2.3 where, simultaneously:
- Hα & NII are in the K band,
- OIII & Hβ are in the H band,
- OII, 4000 Break in the J band and,
- this is probably the formation epoch of Milky Way-like disks (1” diameter).

6.6 Deep Fields
Exposure time calculator to determine sensitivity

6.7 Gravitational lensing
Most gravitational lenses occur in areas under a couple of arcseconds, and weakly lensed galaxies are elongated by of order an arcsecond.

Gravitational lensing is a perfect tool to study very distant galaxies since their light is amplified. Feeding this light into a spectrograph allows the measurement of the redshift and some of the dynamics, composition and characteristics of early (so-called “dark ages”) galaxies (e.g. arc in Abell 2218 observed by HST and Keck with a redshift between 6.6 and 7.1, and a “magnification” of 25).
But high angular resolution can add a very important component of extragalactic study and analysis. Indeed, by modeling the deflecting gravitational potential, it is possible to disentangle the arc-like structure of the lens to reconstruct the image of the galaxy. This technique has been successfully demonstrated by the Hubble Space Telescope on the image of the galaxy cluster CL1358+62.

![Figure 4: Reconstruction of a galaxy from its lensed image in the Cluster CL1358+62 using a model for the deflecting gravitational field. Left image is 64" a side, top right 10" and reconstructed image is 2".](image)

Many early galaxies have very irregular shapes due to interaction or collisions and unless there is a perfect alignment between the source, the deflecting cluster and the observer, the amplification shows a preferred axis. Resolution is therefore important so that the two-dimensional reconstructed images can be interpreted in terms of morphology. For example in the case of CL1358+62, the gravitational lens measures 8"x1" and the final image has no more than 10 resolution elements across its narrow axis.

A very stable PSF to enable long exposures (these objects are very faint) and a very high image quality is needed.