Adaptive Optics: Observations & Prospects for AGN Studies

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- **Adaptive Optics Concepts & Techniques**
- **QSOs at Low and High Redshift**
- The Galactic Center
- Nearby AGN
- Future Perspectives

1. Adaptive Optics: Concepts & Techniques

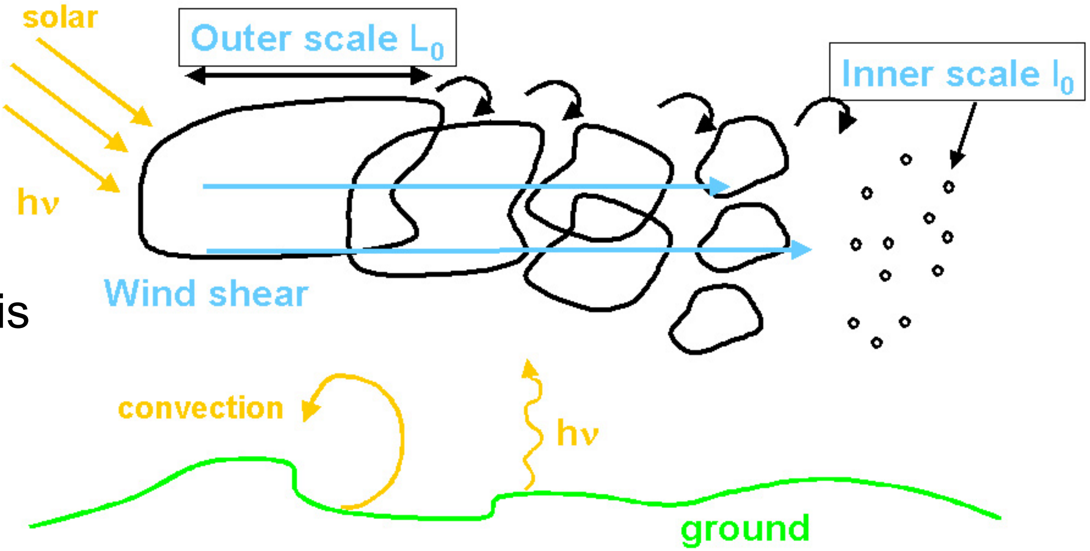
Beckers 1993: ARA&A 31, 13
Hardy 1998: Adaptive Optics for Astronomical Telescopes
Kasper 2000: PhD thesis on AO control systems
Egner 2007: PhD thesis on C_N^2 & MCAO at the LBT
also
Sterne & Weltraum articles 1994 (Hippler, Kasper, Davies, Ragazzoni)
Hippler & Davies 2009? Principles & Applications of AO in Astronomy

- Atmospheric Turbulence & its Impact on Observations
- Measuring & Correcting Wavefront Aberrations
- Limitations of Adaptive Optics & How to Avoid them
- Realistic Expectations

Atmospheric Turbulence

quantified using the structure function

$$D(r) = \left\langle \left(f(r') - f(r'+r) \right)^2 \right\rangle$$



for Kolmogorov statistics, the refractive index structure function is

$$D_n(r) = C_N^2 r^{2/3}$$

for a wavefront propagating through the atmosphere, the phase structure function is

$$D_\phi(r) = 2.91 \left(\frac{2\pi}{\lambda} \right)^2 (\sec\zeta) r^{5/3} \int_0^\infty C_N^2 \, dh$$

van Karman model includes inner (~1cm) & outer (~30m) scales

Atmospheric Turbulence

C_N^2 is refractive index structure constant.

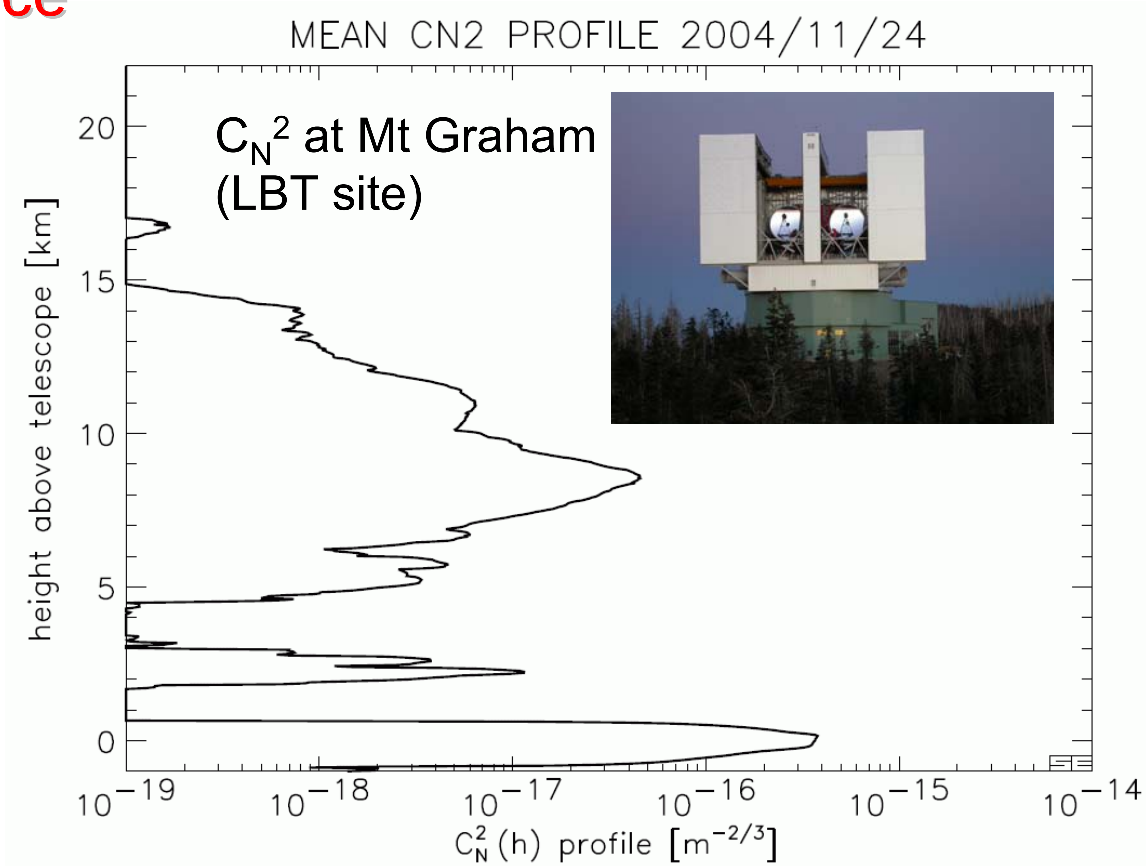
The integral of C_N^2 is Fried's parameter

$$r_0 \propto \left(\int_0^\infty C_N^2 \, dh \right)^{-3/5}$$

and variance of wavefront aberrations is just

$$\sigma^2 = 1.030 \left(\frac{D}{r_0} \right)^{5/3}$$

Turbulence limits the resolution of a telescope to λ/r_0 instead of λ/D.



Everything depends on C_N^2

coherence length r_0

where $$r_0 = 0.185\lambda^{6/5}(\sec\zeta)^{3/5}\left(\int_0^\infty C_N^2 dh\right)^{-3/5}$$

coherence timescale $\tau_0 = 0.314 r_0 / V_{wind}$

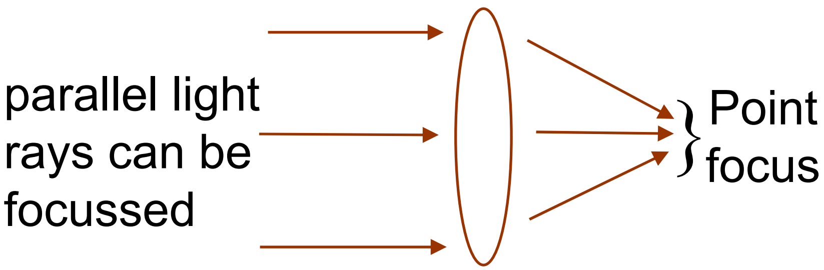
where $$V_{wind} = \left[\int_0^\infty C_N^2 v^{5/3} dh \Big/ \int_0^\infty C_N^2 dh\right]^{3/5}$$

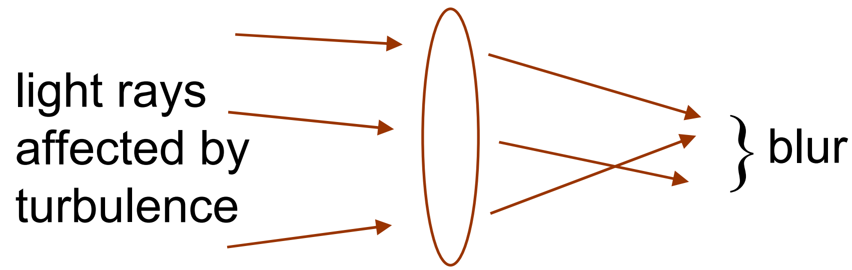
assumes Taylor's frozen flow hypothesis

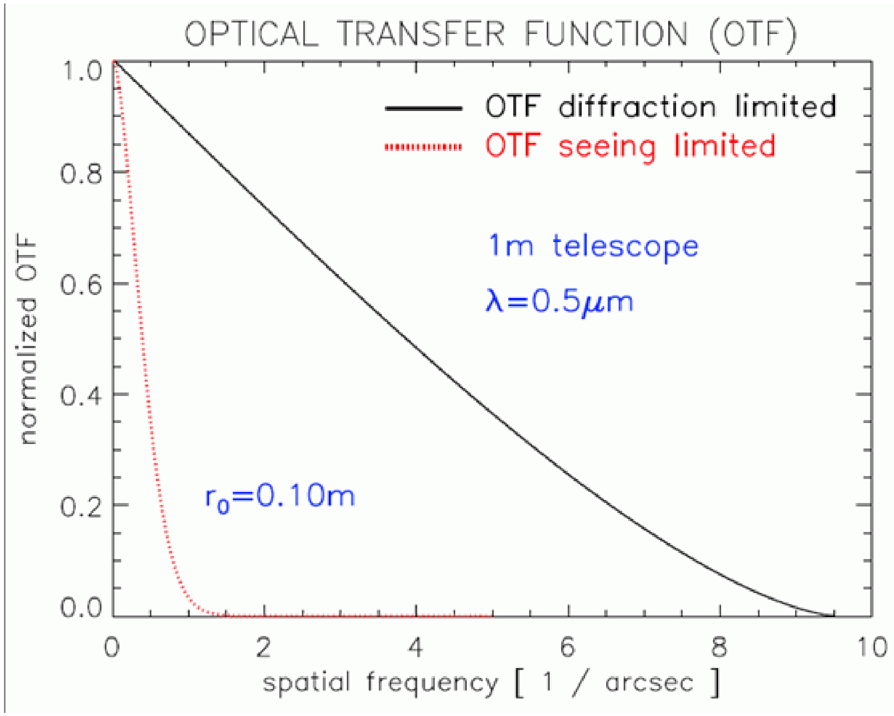
isoplanatic angle $\theta_0 = 0.314 r_0 / H$

where $$H = \sec\zeta \left[\int_0^\infty C_N^2 h^{5/3} dh \Big/ \int_0^\infty C_N^2 dh\right]^{3/5}$$

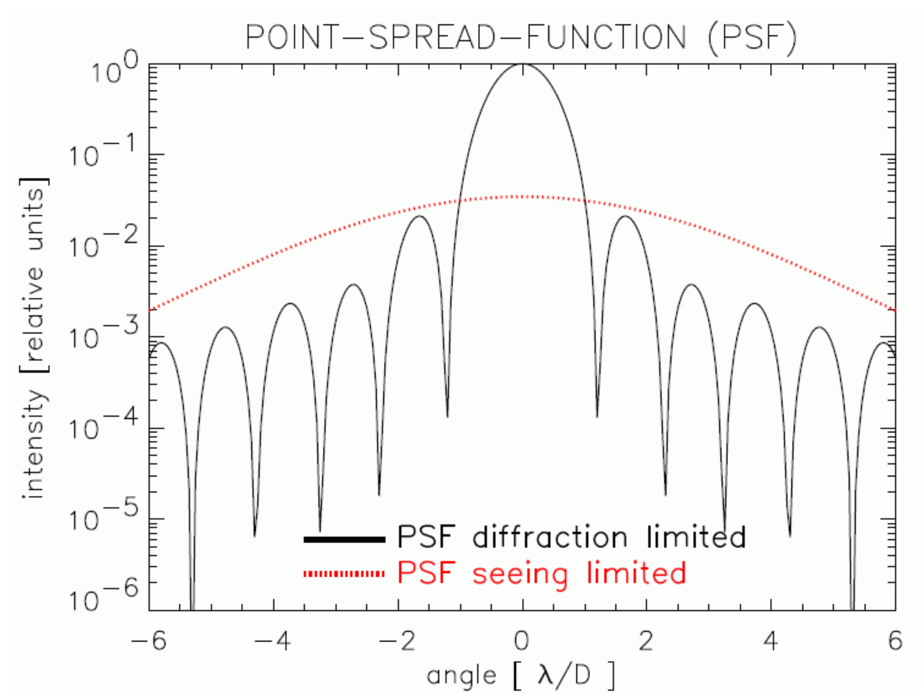
Impact of a Perturbed Wavefront





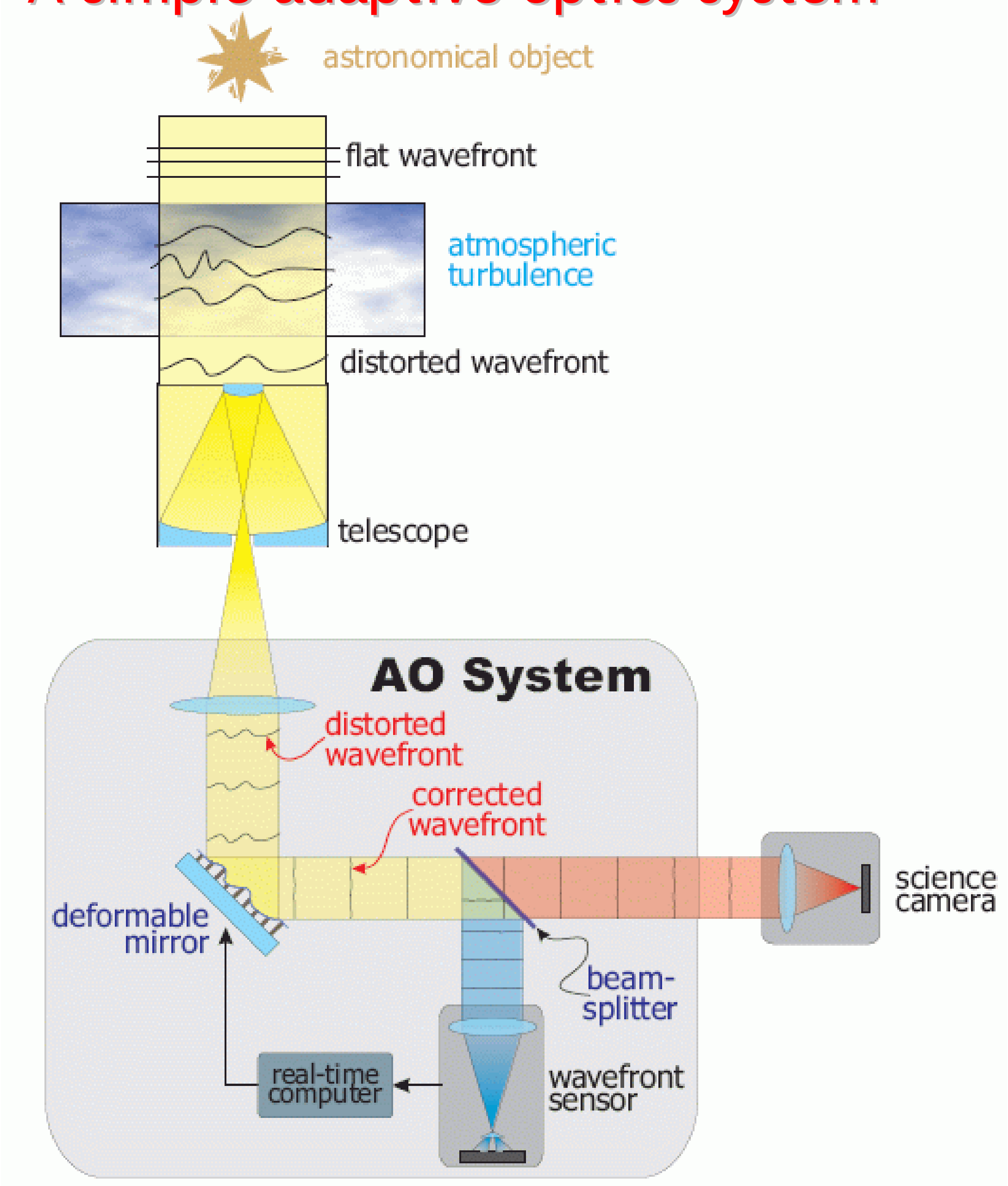


how well spatial frequencies are transferred through the optical system



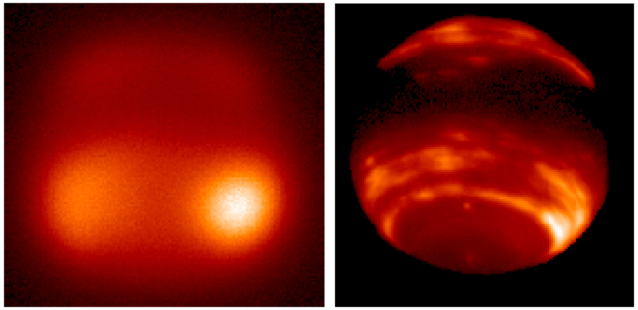
resulting shape of a point source

A simple adaptive optics system

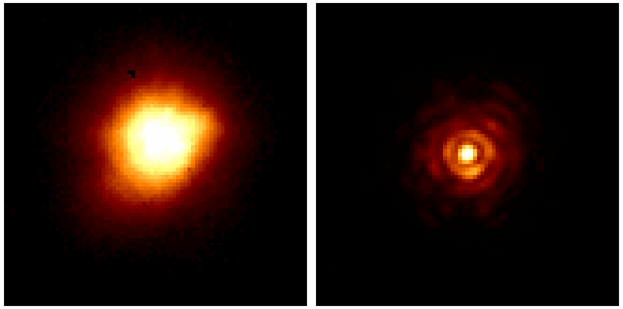


open & closed loop images

Neptune (Keck, NGS)

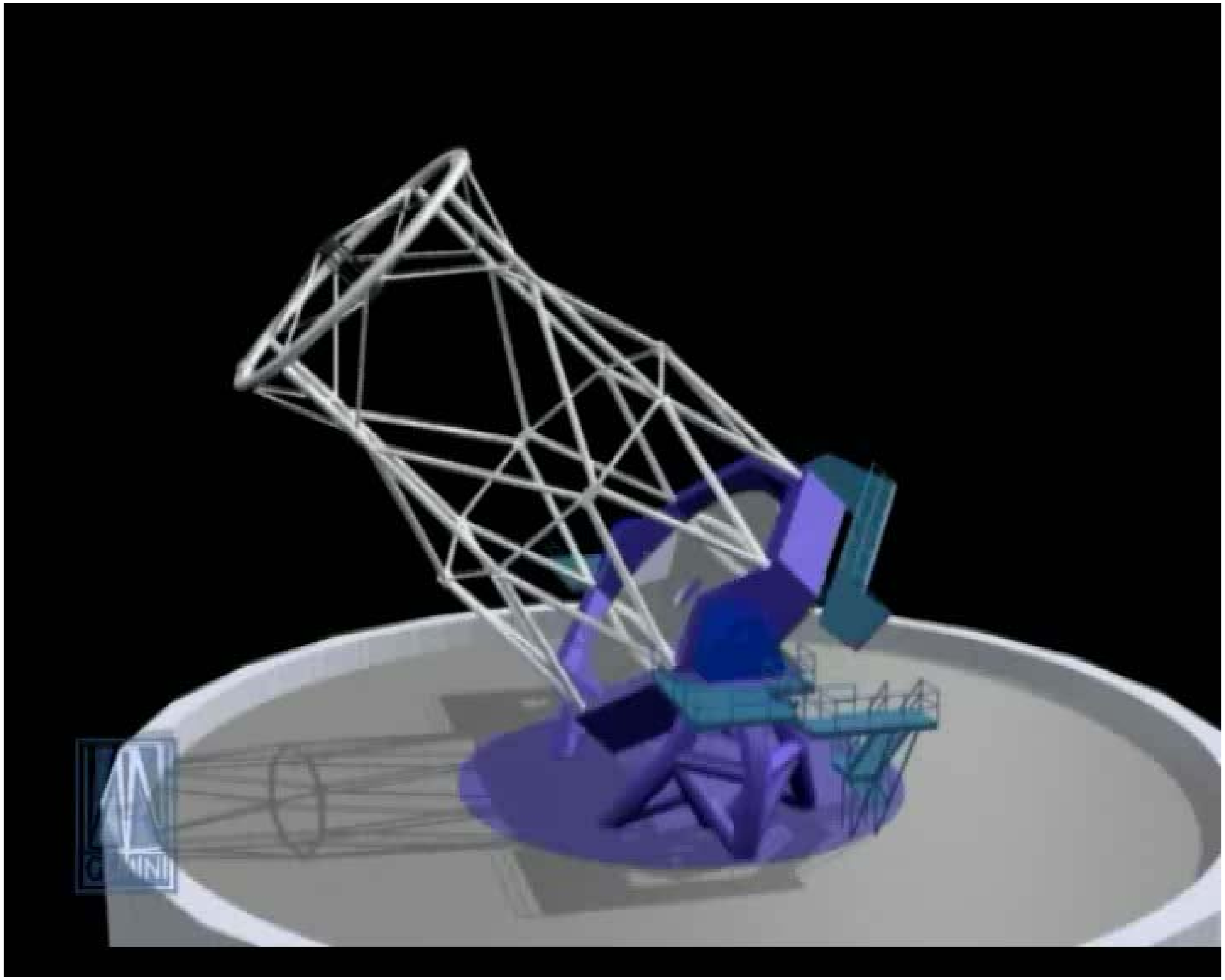


star (Calar Alto, LGS)



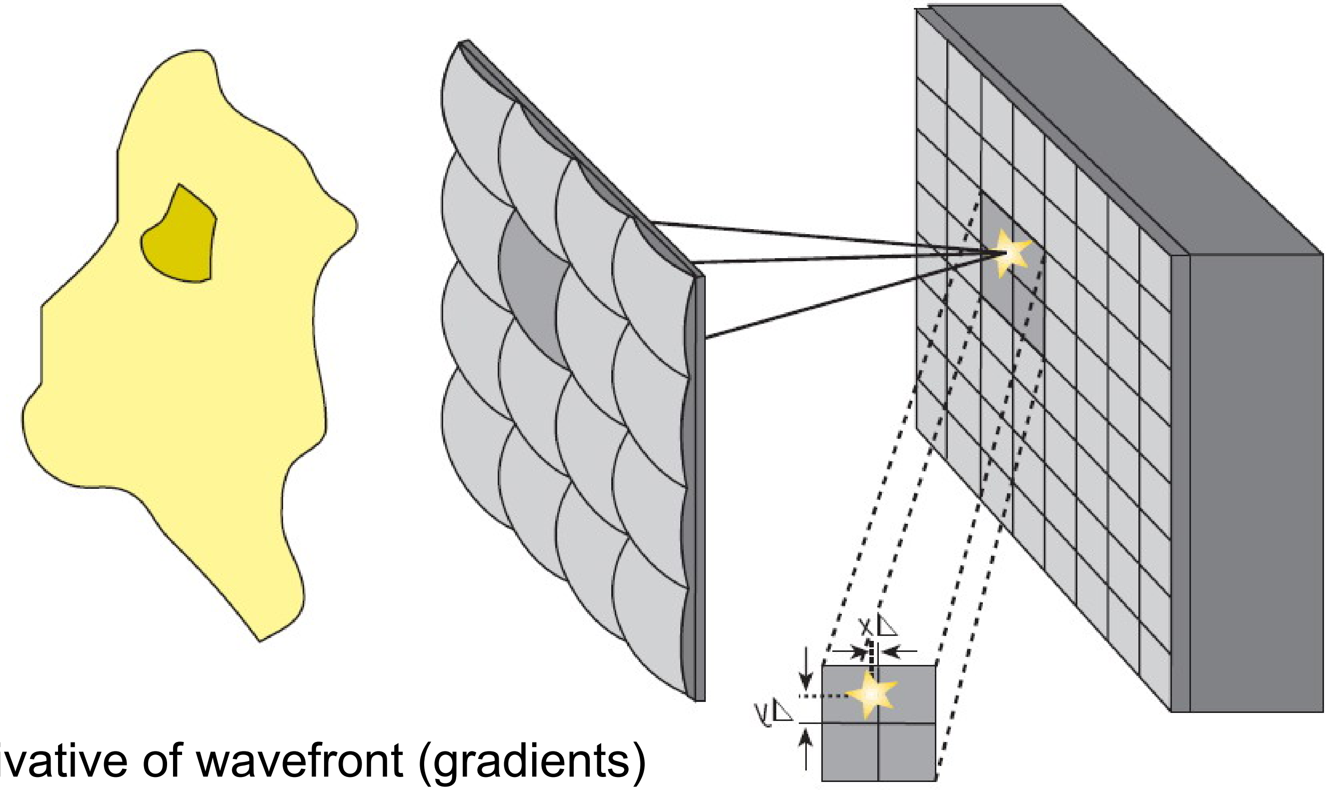
A simple adaptive optics system

Cartoon of adaptive optics (Gemini Observatory)



Shack Hartmann Sensor

(developed in 1900 by J.Hartmann)



Measures first derivative of wavefront (gradients)

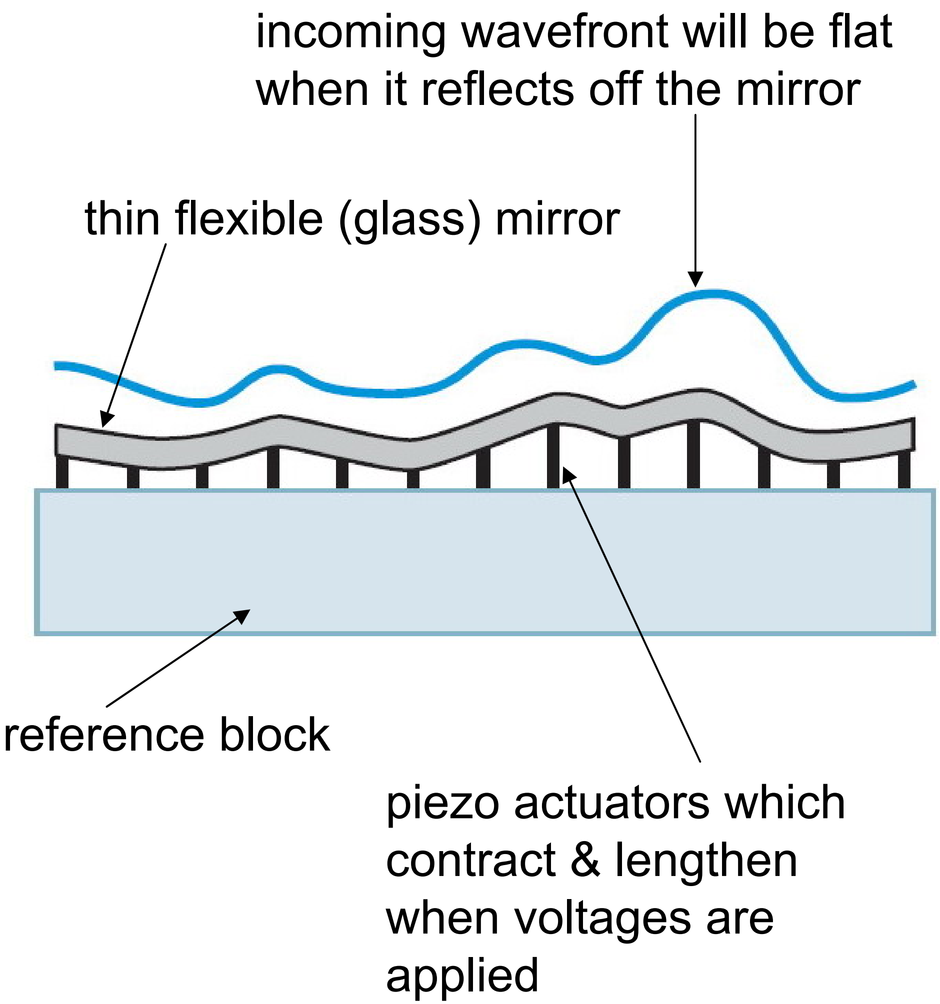
Displacement of spots is proportional to the wavefront tilt

Many algorithms possible for centroiding

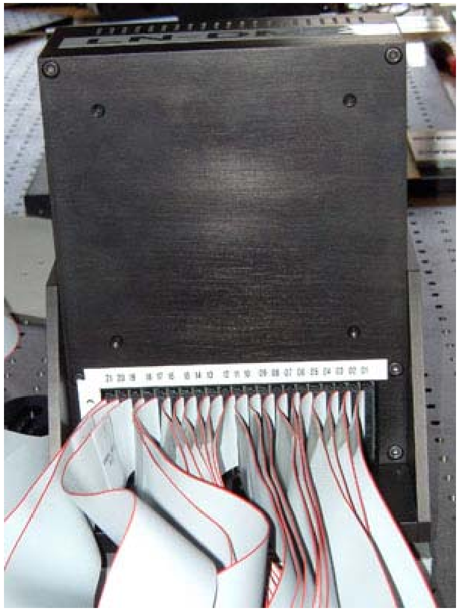
Easy to extend to very high order systems

Divides pupil into subapertures

Piezo Actuator Mirrors

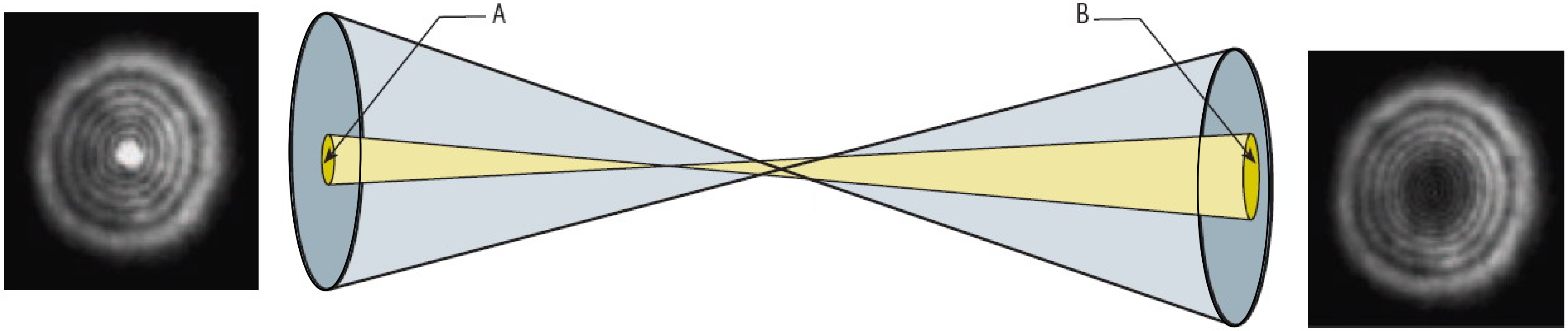


349 actuator DM



wiring on back side

Curvature Sensor (developed in 1994 by F.Roddier)



Measures second derivative of wavefront (curvature)

Can apply measurements almost directly to bimorph mirror

Does not divide pupil

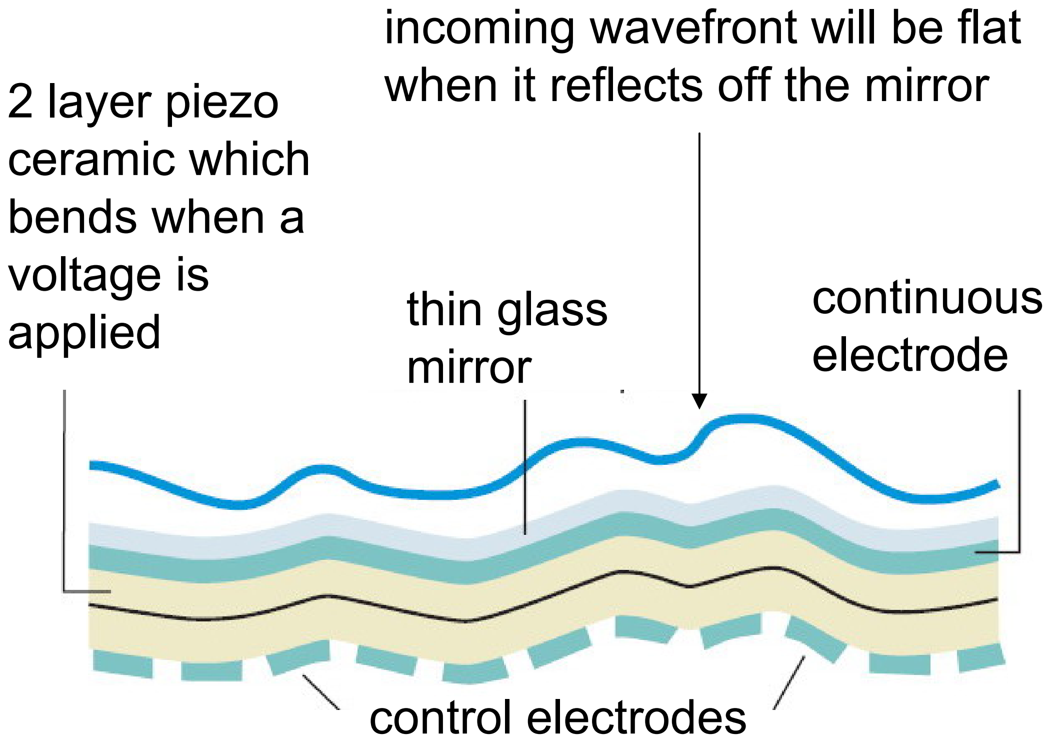
Gain adjustable online (by changing how afocal the two reference images are)

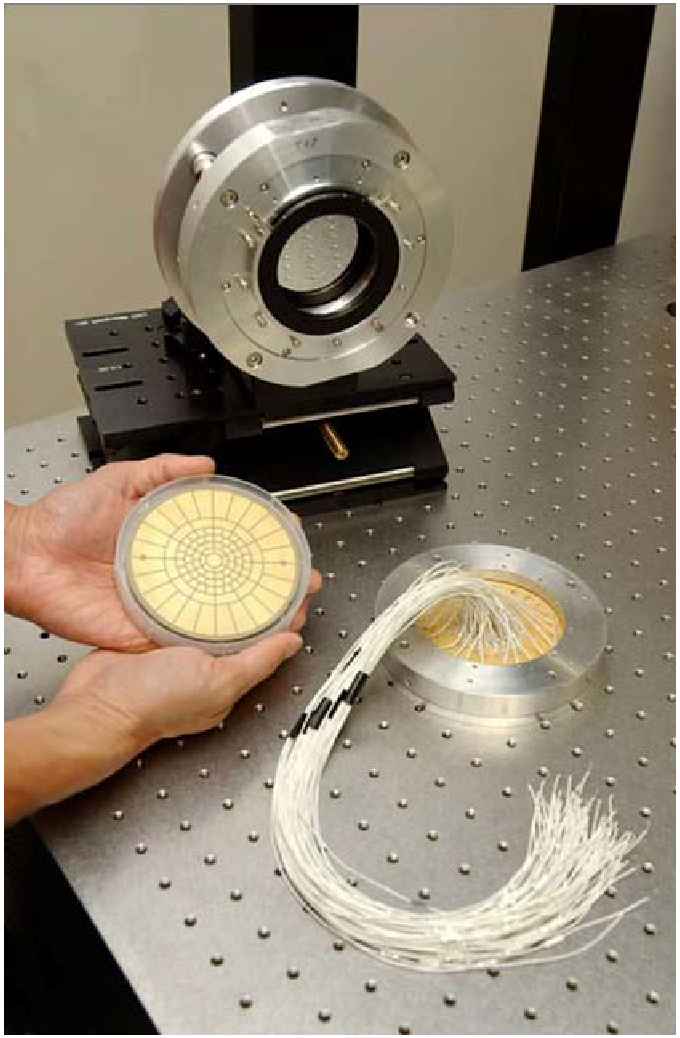
Usually used with APDs

Hard to make high-order systems

Similar to phase retrieval (used to derive HST’s aberrations) & phase diversity

Bimorph Mirrors



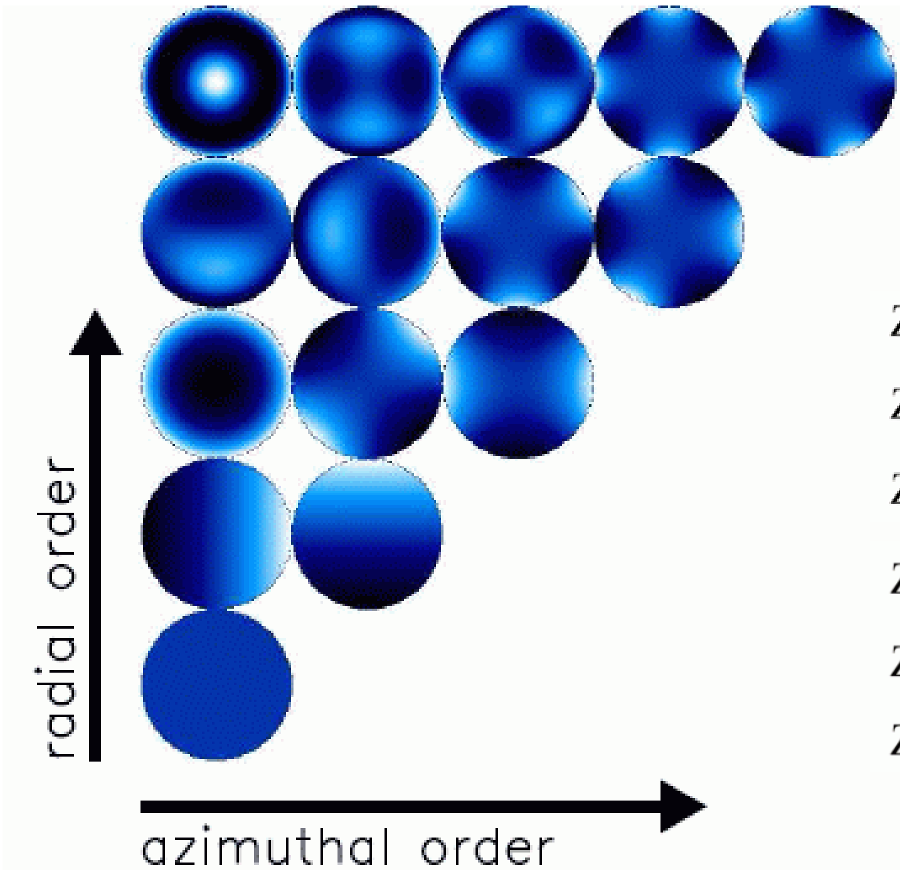


bimorph mirror for Gemini, showing the zones

Modal Decomposition

Most common & simplest for a circular aperture are Zernike modes.

For an annular aperture, Karhunen-Loève modes are better.



coma & trefoil

$Z_{2,0} = \sqrt{3}\,(2r^2 - 1)$ — focus

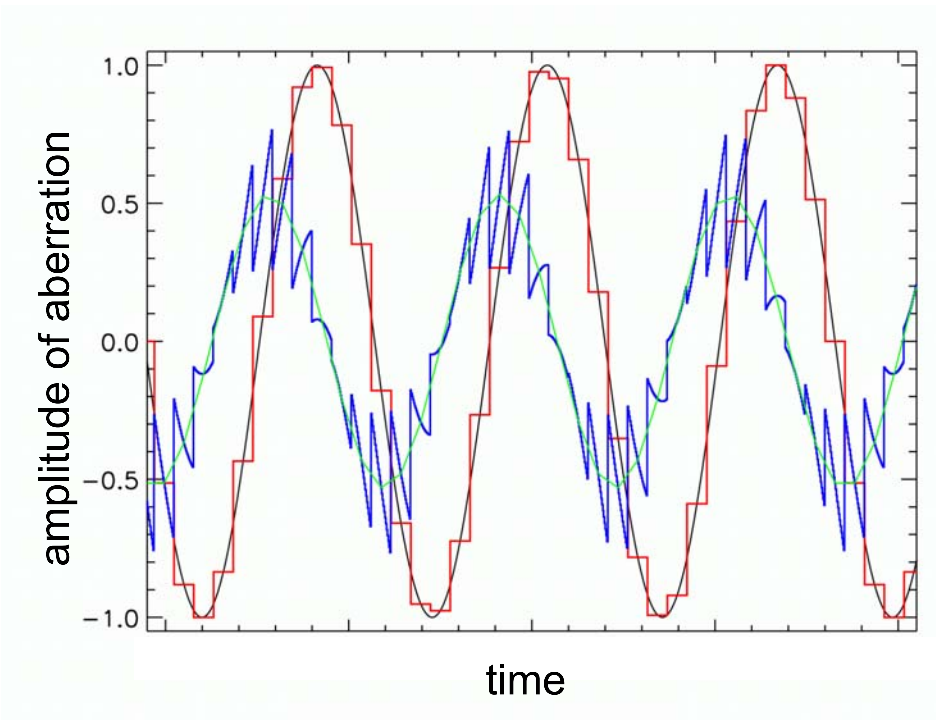
$Z_{2,-2} = \sqrt{6}\,r^2 \sin 2\theta$
$Z_{2,2} = \sqrt{6}\,r^2 \cos 2\theta$ — astigmatism

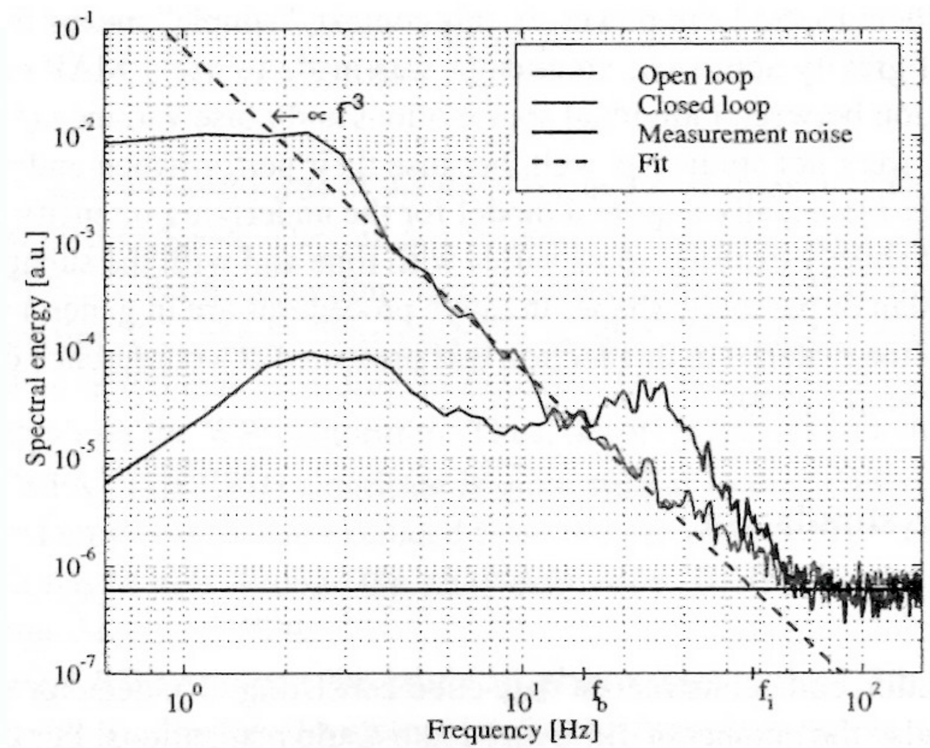
$Z_{1,-1} = 2\,r \sin\theta$
$Z_{1,1} = 2\,r \cos\theta$ — tip/tilt

$Z_{0,0} = 1$ — piston

A few things to bear in mind

- AO works better at longer wavelengths (dependence of r_0 on $\lambda^{6/5}$)
  e.g. consider a phase change of 250nm with respect to 500nm optical light and 2.2µm near infrared light. So at longer wavelengths, coherence length is greater & timescales are longer
- One can measure in optical & correct in infrared (absolute phase change is same)
- AO systems have to run fast (bandwidth ~1/10 of the frame rate)
  prediction would be great…





Residual Wavefront Variance & Strehl Ratio

coherence length

$$\sigma^2_{fitting} \sim 0.2944\, j^{-\sqrt{3}/2} \left(D/r_0\right)^{5/3}$$

for large j (number of Zernike modes)

coherence timescale

$$\sigma^2_{timedelay} = \left(\tau/\tau_0\right)^{5/3}$$

isoplanatic angle

$$\sigma^2_{angle} = \left(\theta/\theta_0\right)^{5/3}$$

total wavefront variance

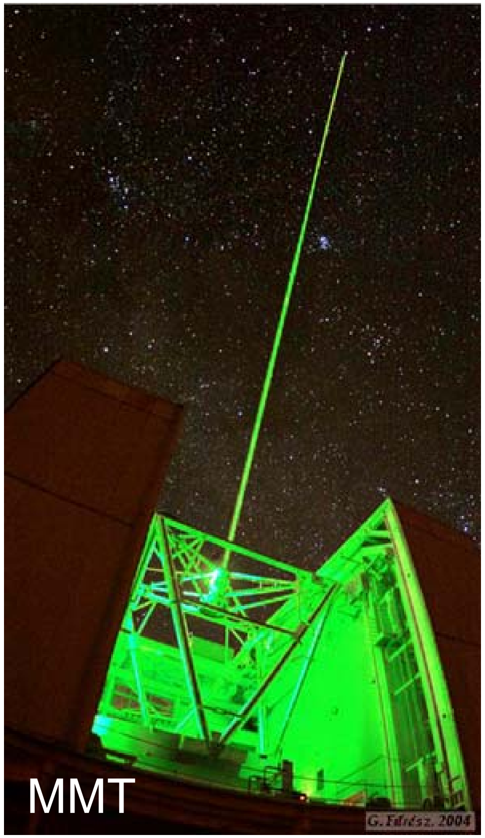
$$\sigma^2_{total} = \sigma^2_{fitting} + \sigma^2_{angle} + \sigma^2_{timedelay} + \sigma^2_{noise} + \ldots$$

Strehl ratio

$$SR \sim \exp\left(-\sigma^2\right)$$

ratio of peak intensity to that for a perfect optical system

Sodium & Rayleigh Laser Guide Stars

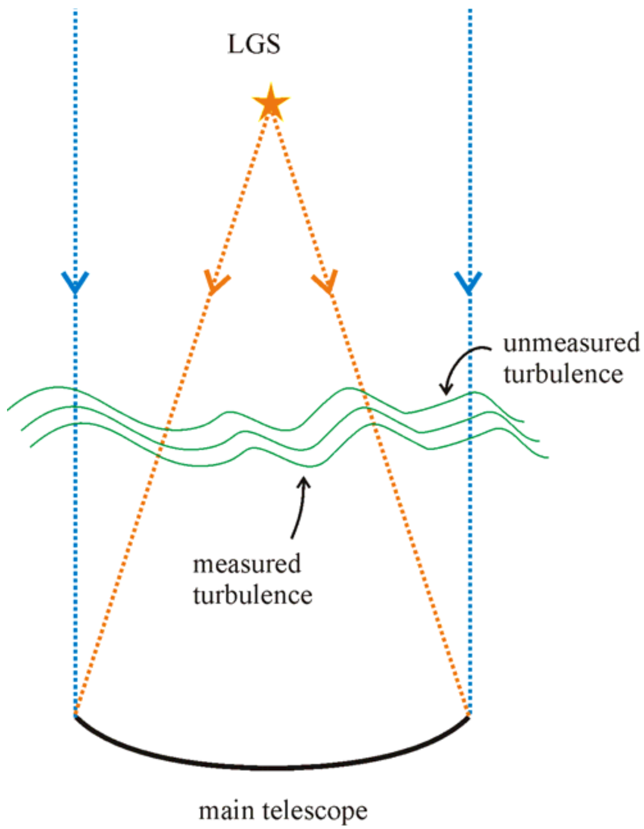


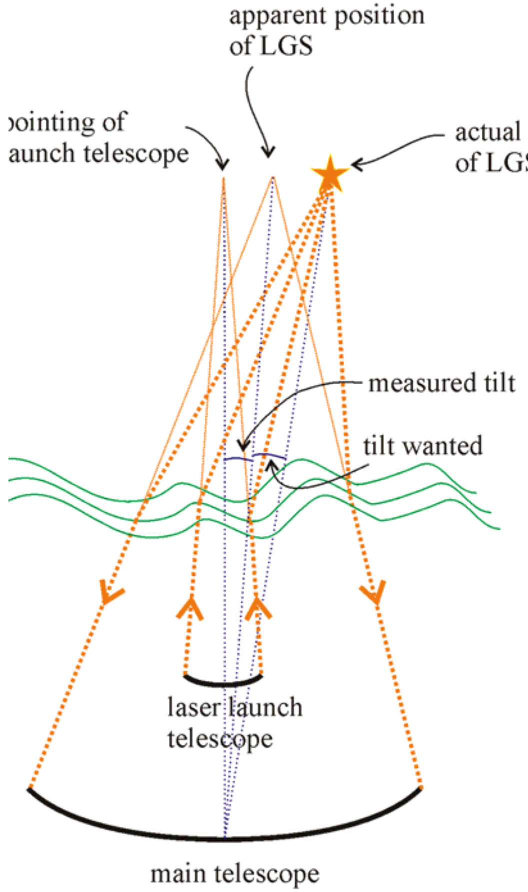
sky coverage few % with NGS but ~50% with LGS
(most coverage in galactic plane; almost none at galactic pole)

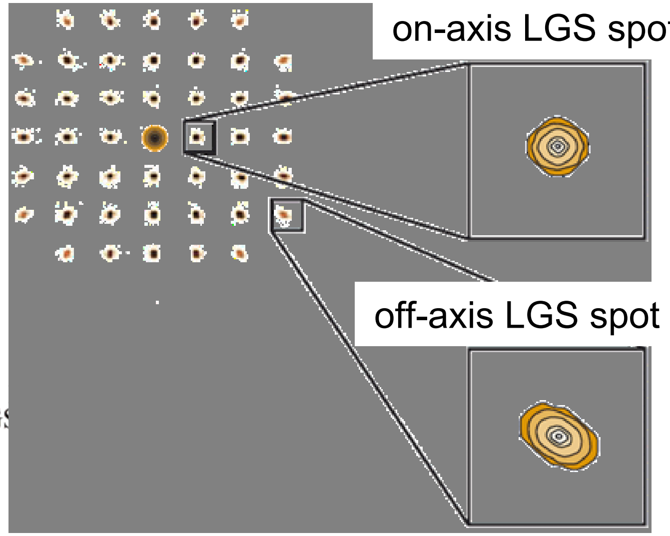
Starfire Optical Range, Calar Alto, Lick, MMT, Keck, VLT, Subaru, Gemini North, WHT, Palomar 200”, Mt Wilson 100”, (LBT, Gemini South)

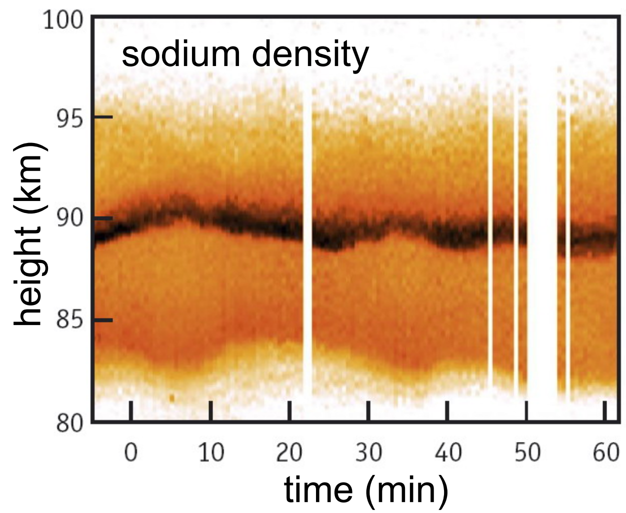
A few issues with Laser Guide Stars

1. laser technology
2. elongation of spot due to finite thickness of layer
3. variations in height of sodium layer
4. cone effect
5. need for tip-tilt star



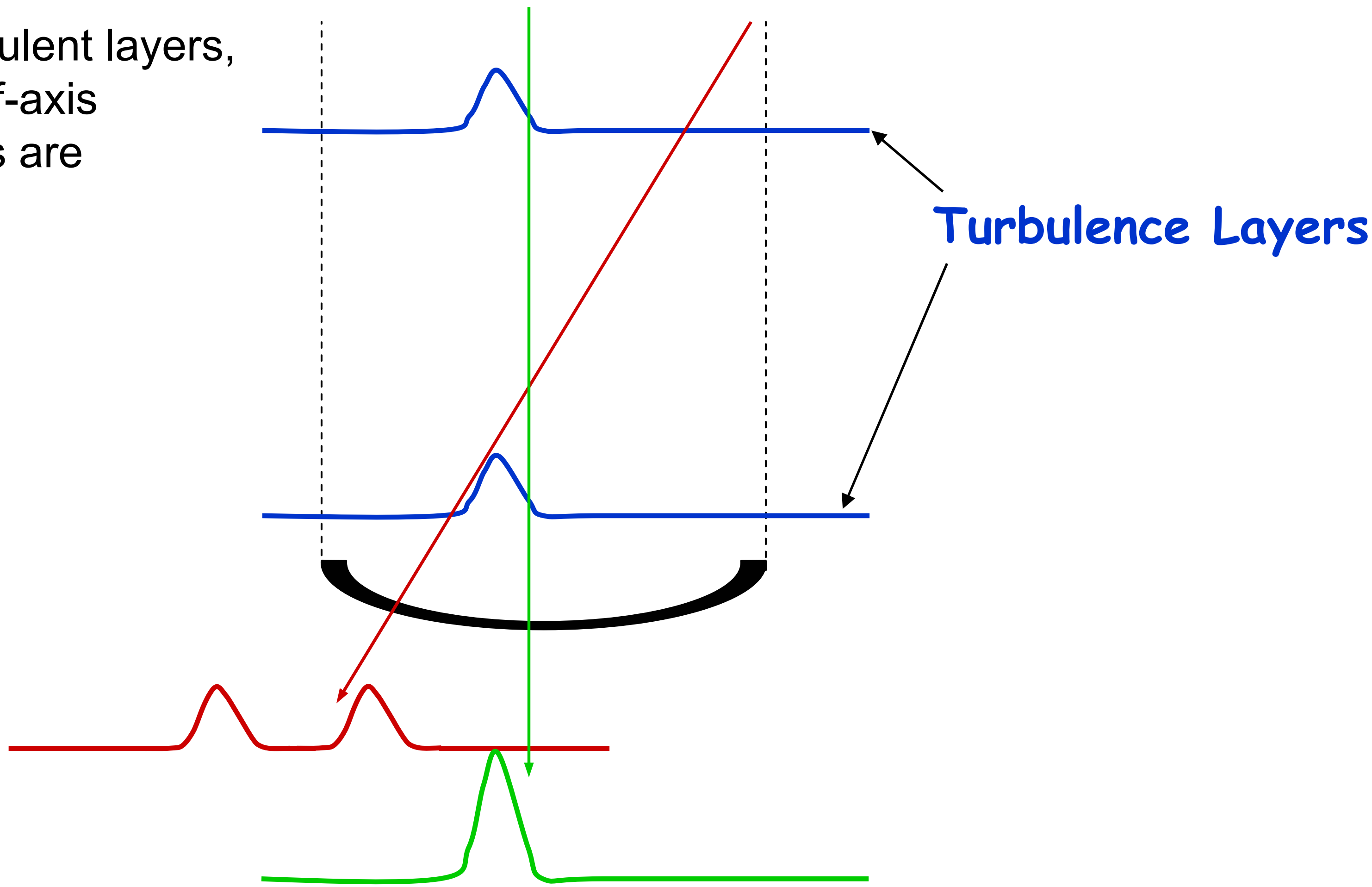






Multiple Layers of Turbulence

with 2 turbulent layers, on- and off-axis wavefronts are different

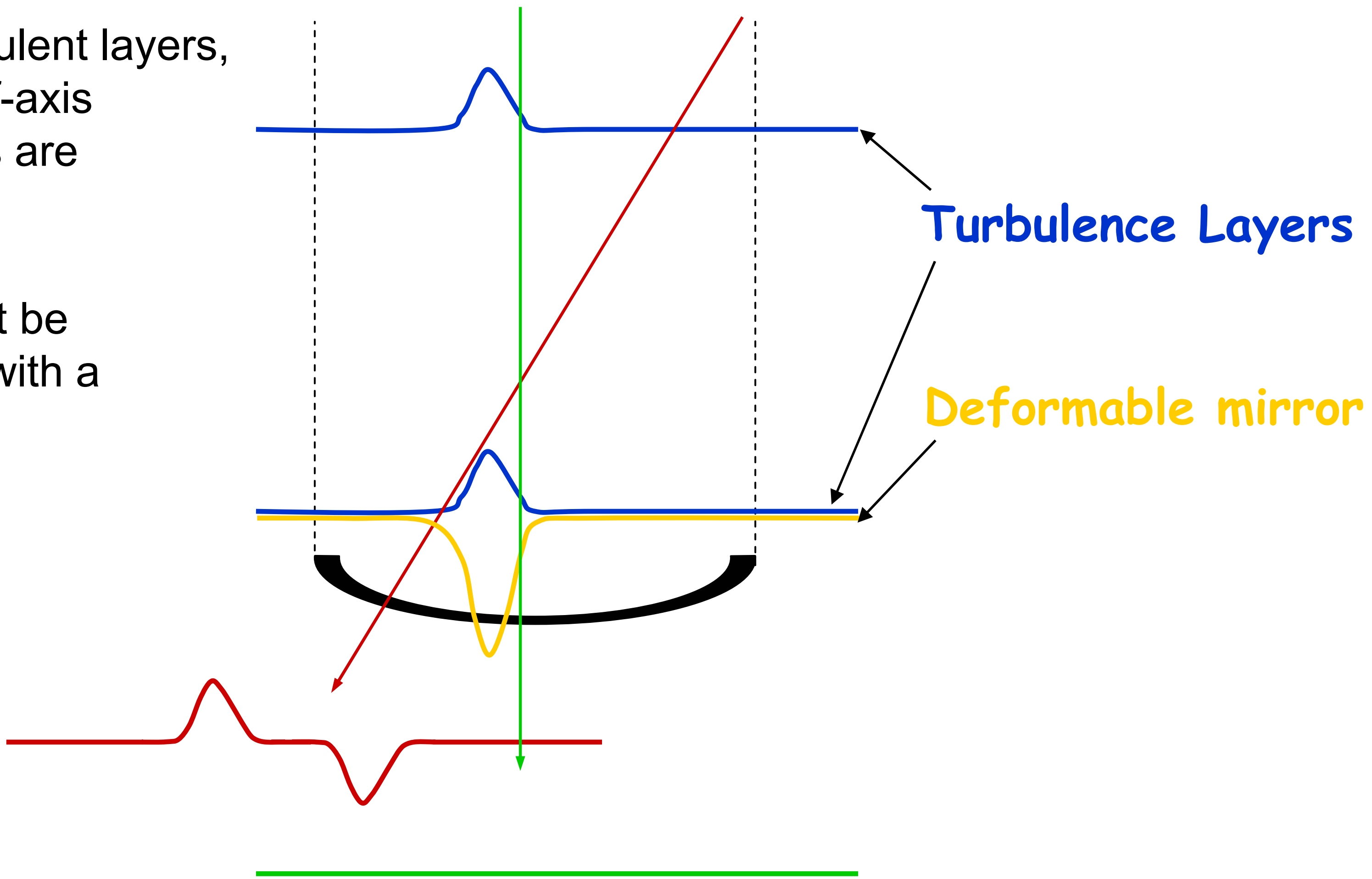


adapted from Rigaut 2000

Multiple Layers of Turbulence

with 2 turbulent layers, on- and off-axis wavefronts are different

and cannot be corrected with a single DM



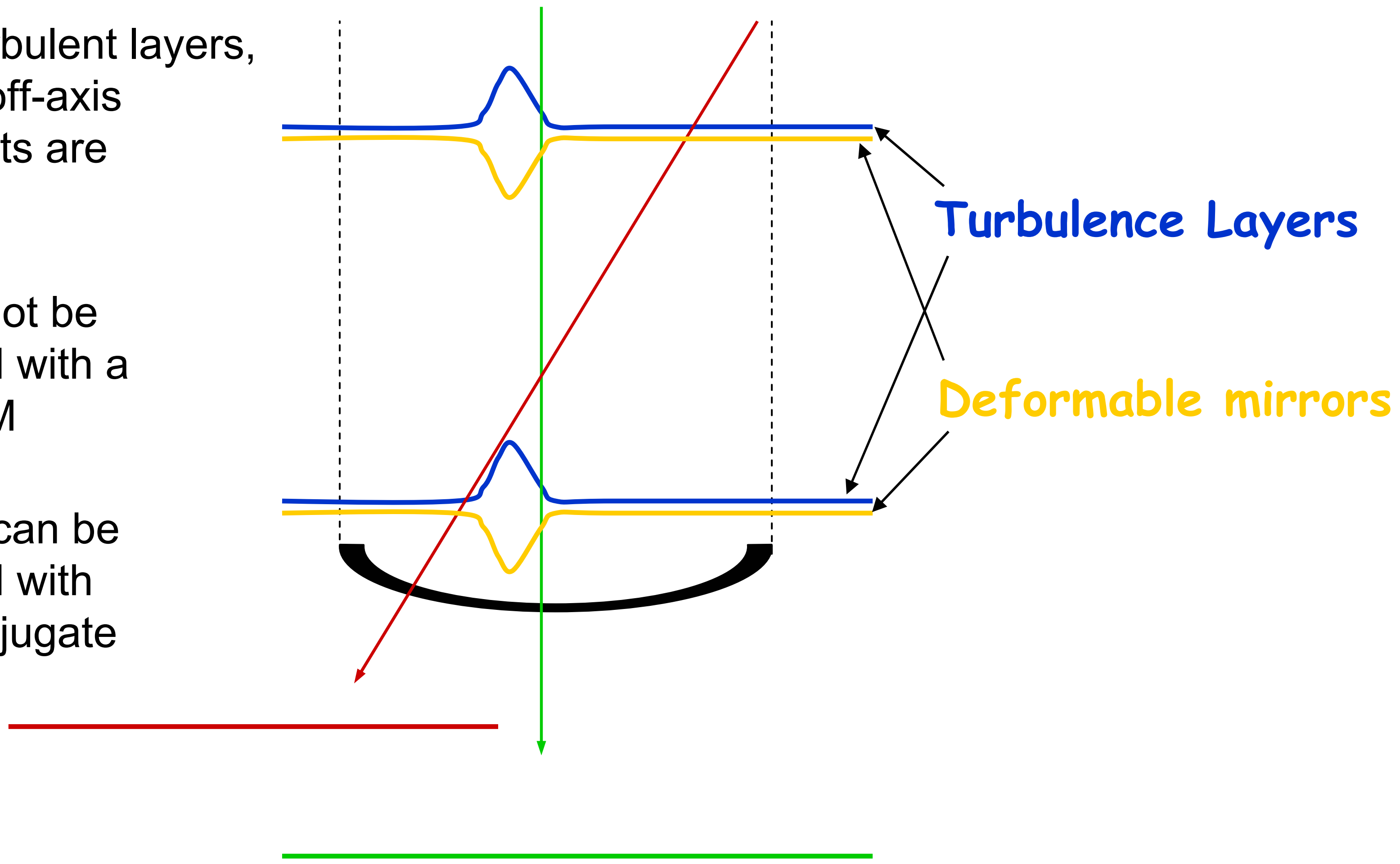
adapted from Rigaut 2000

Multiple Layers of Turbulence

with 2 turbulent layers, on- and off-axis wavefronts are different

and cannot be corrected with a single DM

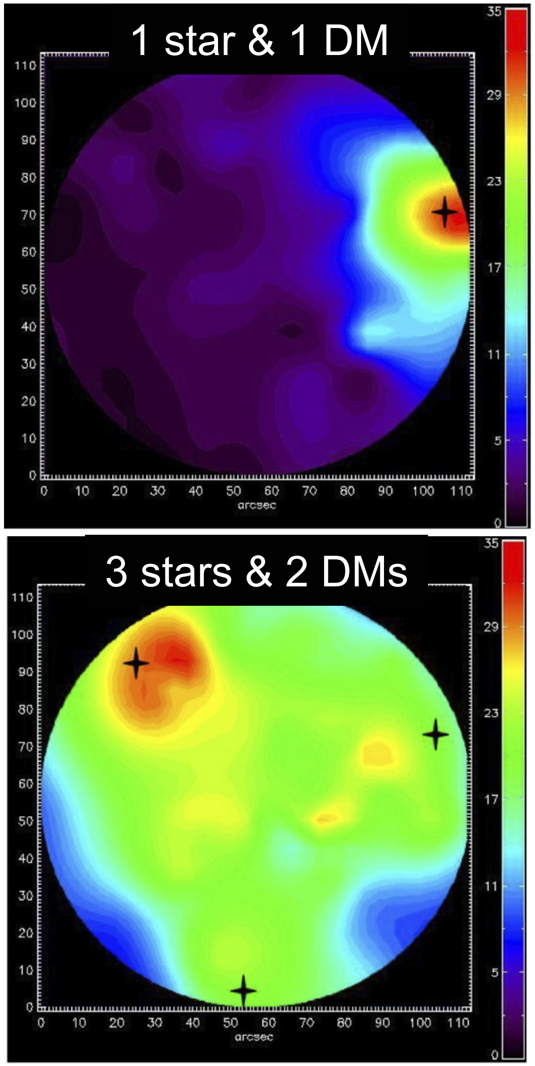
but they can be corrected with multi-conjugate DMs

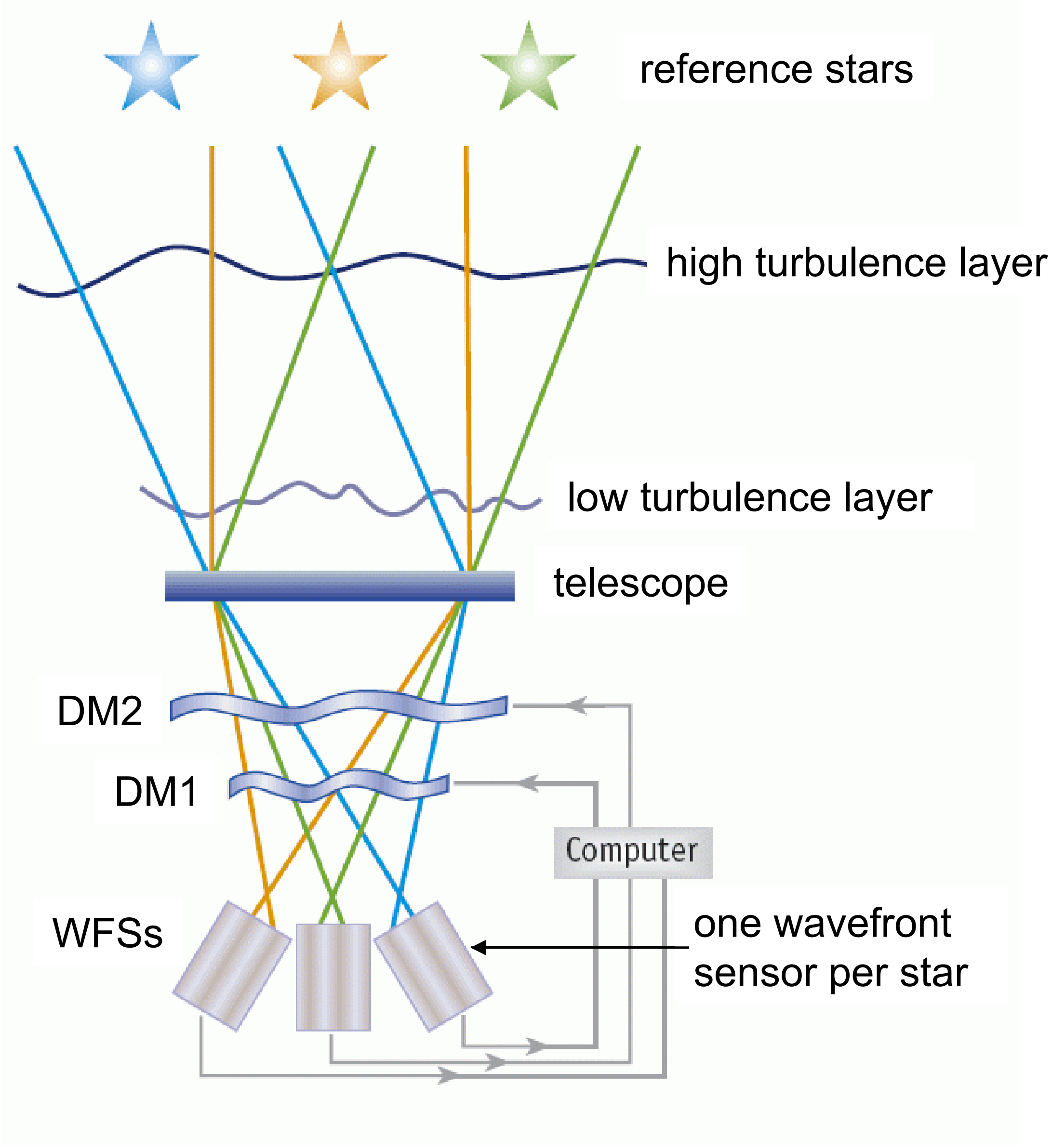


adapted from Rigaut 2000

MultiConjugate Adaptive Optics

MAD strehl maps





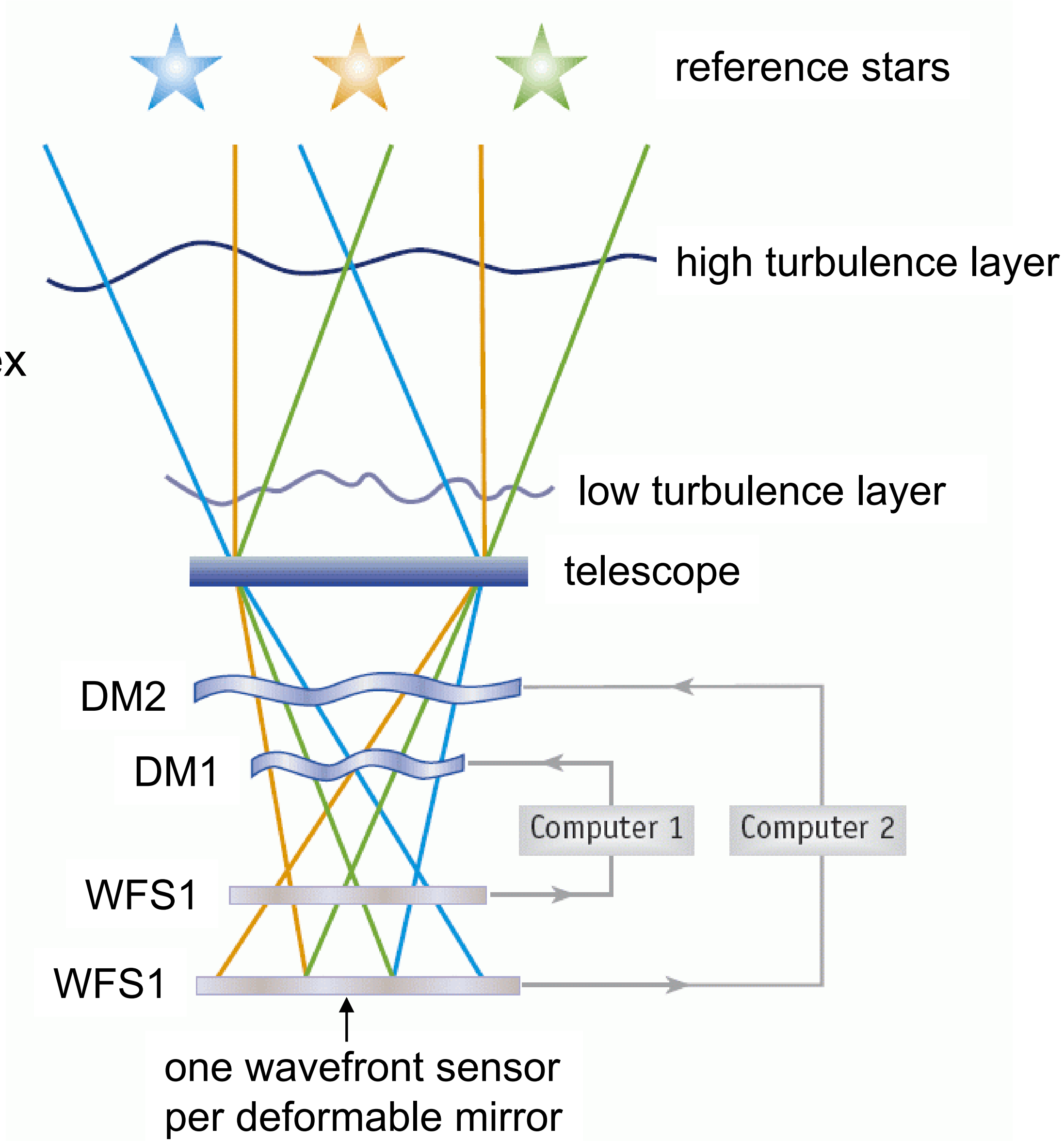
MultiConjugate Adaptive Optics

Classical MCAO needs multiple guide stars (e.g. Gemini South MCAO needs 5 LGS & 3 NGS).

This is computationally complex

Instead, one can use the layer oriented approach, with LGS or NGS.

LINC-NIRVANA on the LBT uses pyramid sensors to co-add the light from many faint stars on the detector; but note that the strehl ratio is expected to be limited & vary a bit over the field



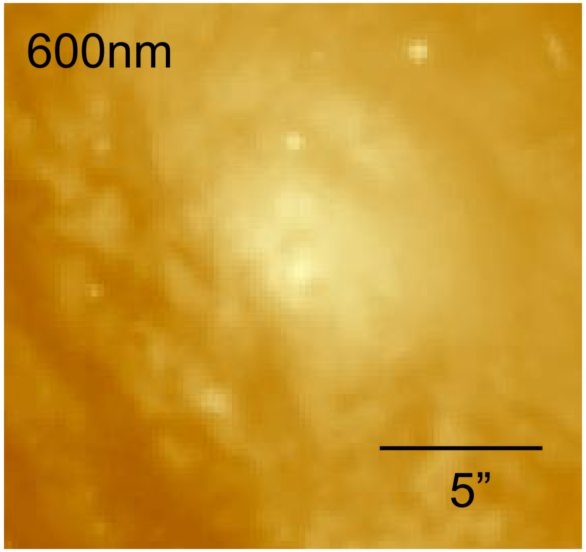
Realistic Expectations

Extreme AO (e.g. “planet finders”) aims for >90% strehl at K… but with bright stars

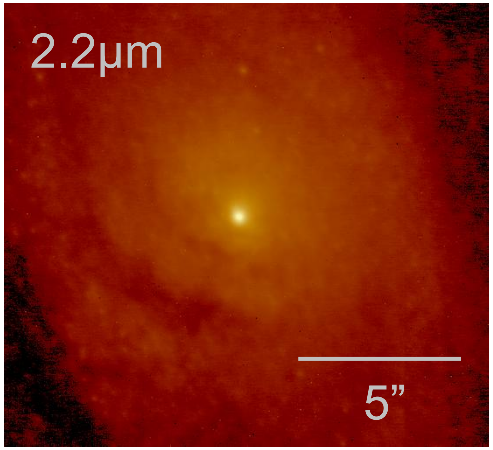
AGN are not particularly bright (fainter than typical limit of R~15mag), and tend to be fuzzy with a relatively bright background.
Off-axis correction is usually not an option.
LGS performance can vary from 0.1” resolution to ~20% Strehl at K.

One can do much better than the seeing limit, but don’t expect perfect performance every time; and beware of spatial & temporal variations

Circinus Galaxy



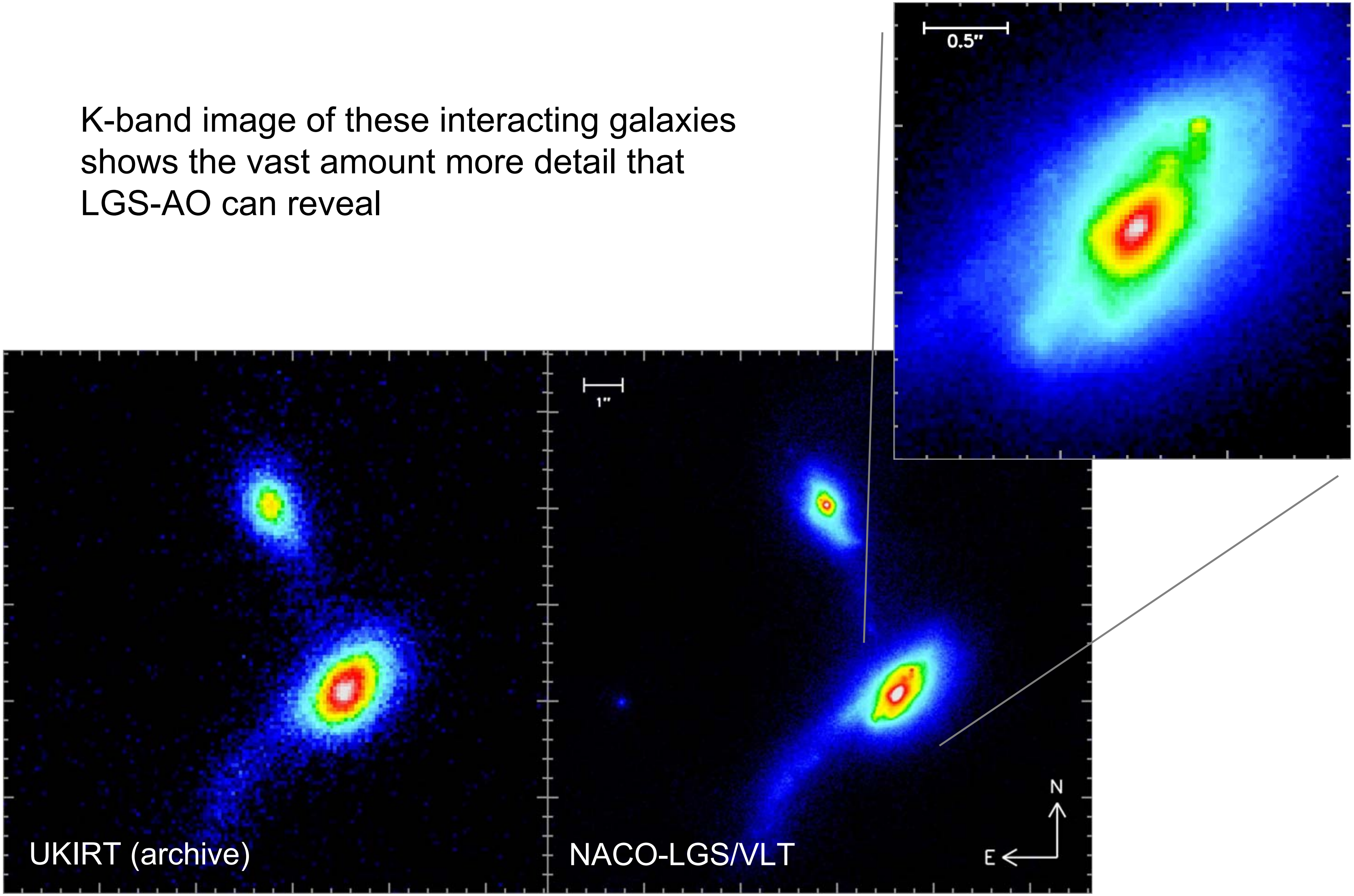
no bright point source for AO reference; and bright background.



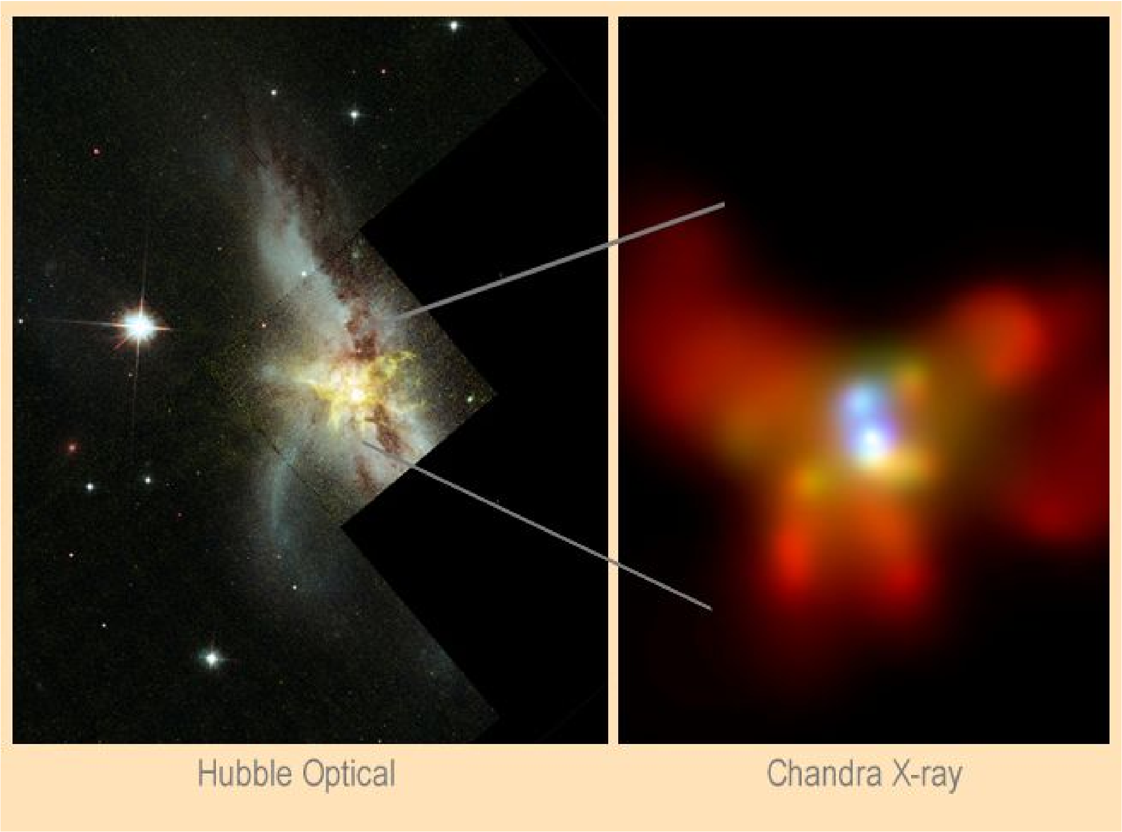
with an IR-WFS (i.e. NACO)

Examples of LGS-AO: interacting galaxies IRAS 09061-1248

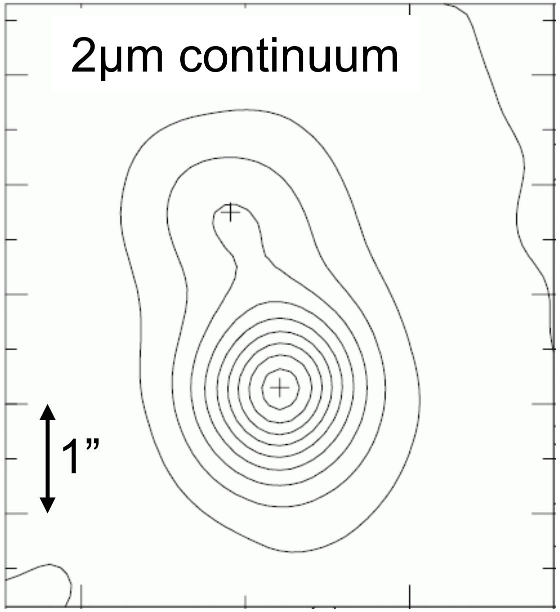
K-band image of these interacting galaxies shows the vast amount more detail that LGS-AO can reveal



Examples of LGS-AO: prototypical merger NGC6240

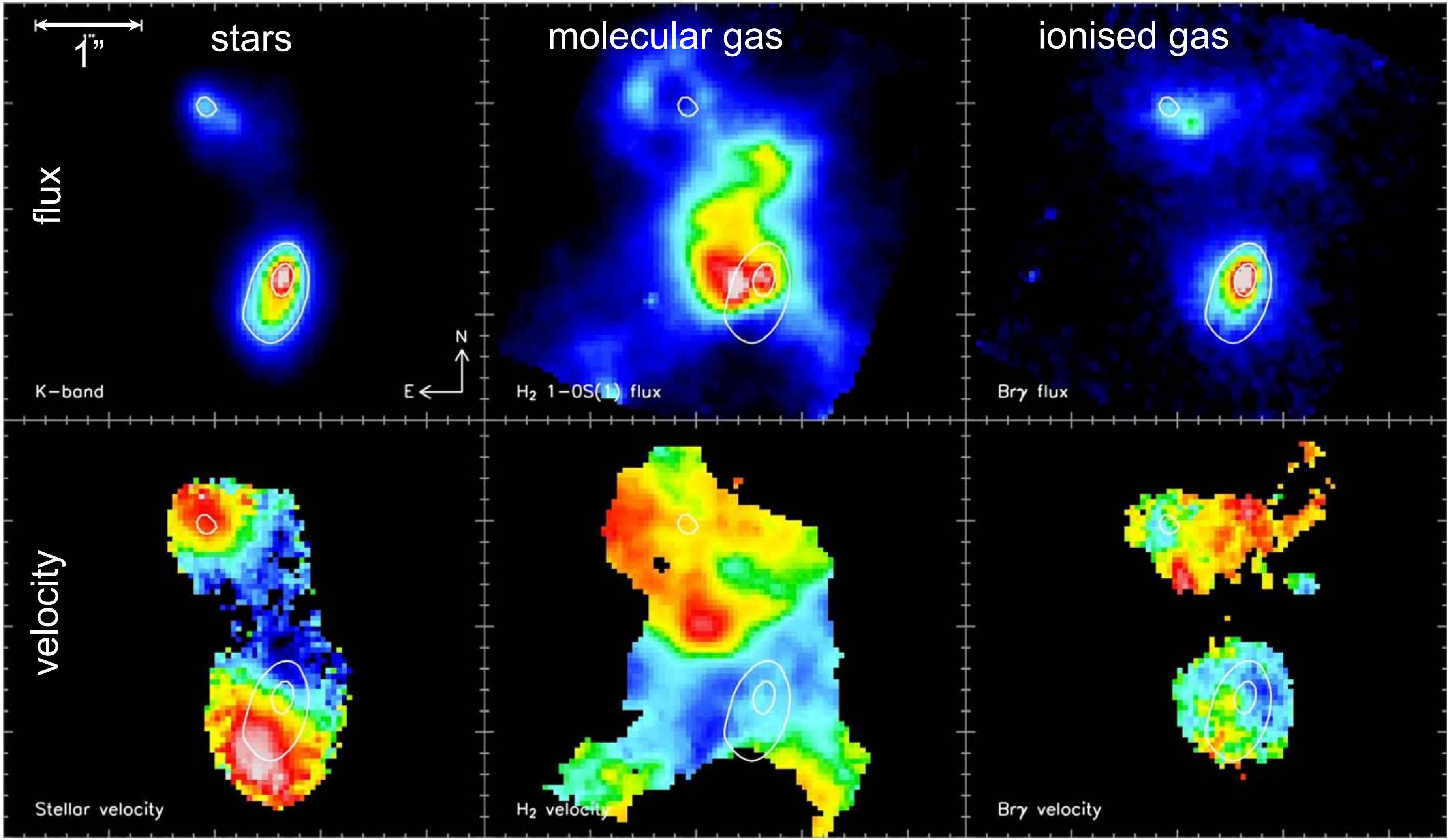


Komossa et al. 2003

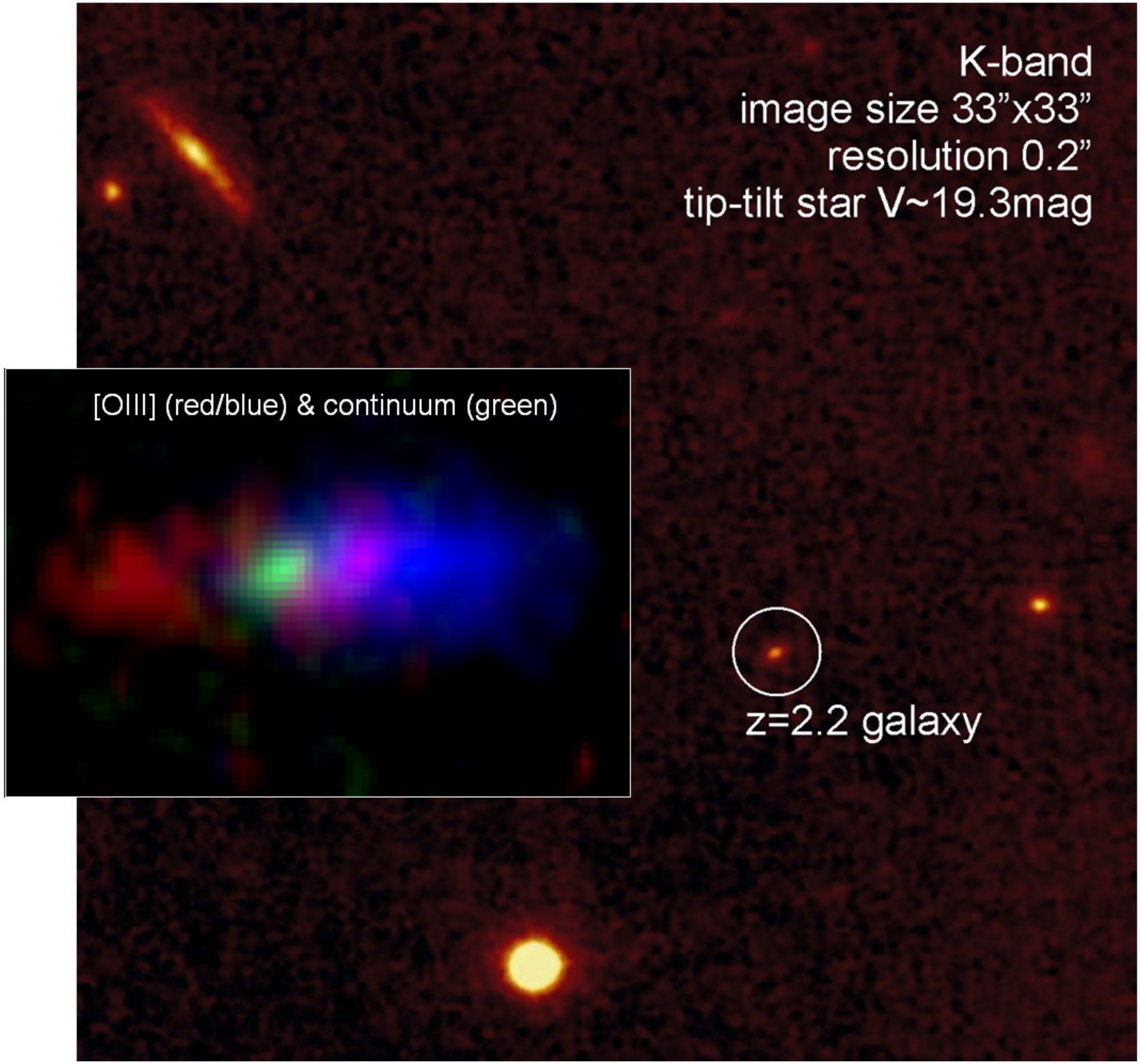


Tecza et al. 2000

Examples of LGS-AO: prototypical merger NGC6240



Examples of LGS-AO: high redshift galaxies



2. QSOs at High & Low Redshift

main references:

New Astronomy Reviews, vol. 50, 2006 (editors: P. Barthel & D. Sanders):
Workshop – "QSO Host Galaxies: Evolution and Environments"

Astrophysics Update, vol. 2, 2006 (editor: J. Mason)
Chapter 6 – "Quasars and Their Host Galaxies" (M. Lacy)

various AO papers on QSO host galaxies, 1998-2006

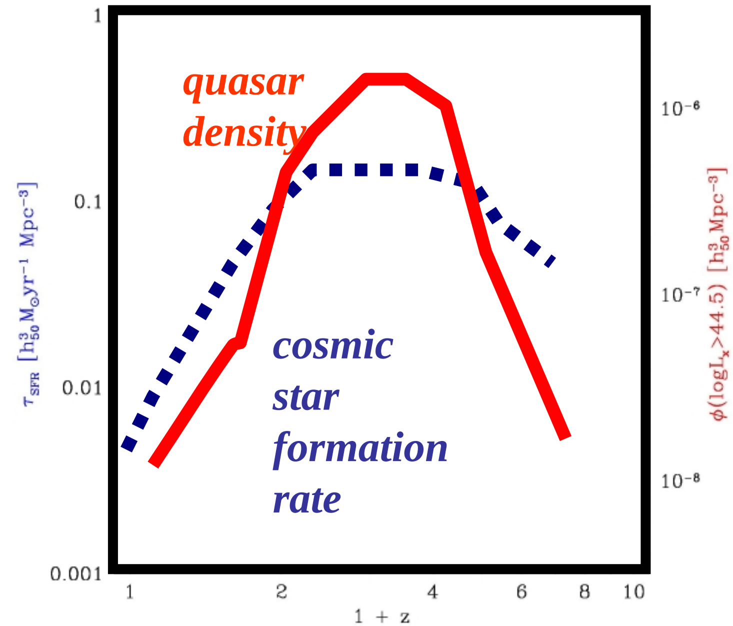
- *How AO can help with QSO research*
- *Host galaxy characterisation*
- *Stellar Populations in QSO Hosts*
- *Evolutionary Scenarios*

What can we learn from QSO host galaxies?

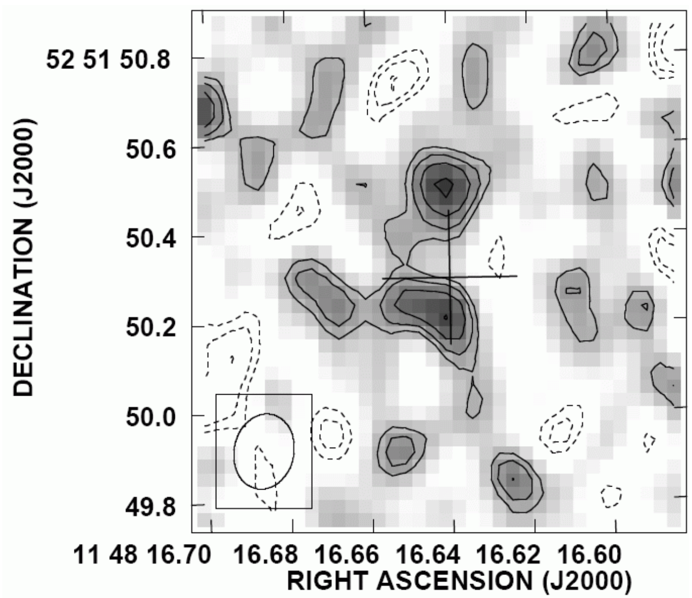
link between BH & galaxy evolution

understand M-σ relation by studying of co-evolution of QSOs & their host galaxies; at a time when BHs are actively accreting

To do this, we can look locally at relic population (eg SDSS) or at high redshifts where the action is taking place



J1148+5251 @ z=6.4
QSO with M_{BH} = 1-5×$10^9 M_{sun}$
M-σ implies M_{bulge}~$10^{12} M_{sun}$
M_{dyn} from CO(3-2) ~5×$10^{10} M_{sun}$
BHs assembled before stellar bulges?



(Fan 06, Walter+ 04)

How can we study high-z QSOs & their host galaxies?

Black Hole Mass M_{BH} from proxy indicators such as line width & optical continuum luminosity (Verstergaard 2004):

$$\log M_{BH}/M_{sun} = 6.7 + 0.7\log\left(\left[\frac{FWHM(H\beta)}{1000km/s}\right]^2\left[\frac{\lambda L_\lambda(5100\mathrm{A})}{10^{44}erg/s}\right]^{0.7}\right)$$

based on relation for R_{BLR} (Kaspi et al. 2000) & virial mass: $M \propto \sigma^2 R$

Eddington rate L_{bol}/L_{Edd} where $L_{Edd}(erg/s) = 1.3\times10^{38} M_{BH}/M_{sun}$
by combining this with QSO luminosity

Host galaxy: minimise flux & PSF size of QSO with respect to host galaxy

Minimising QSO flux & size wrt Host Galaxy

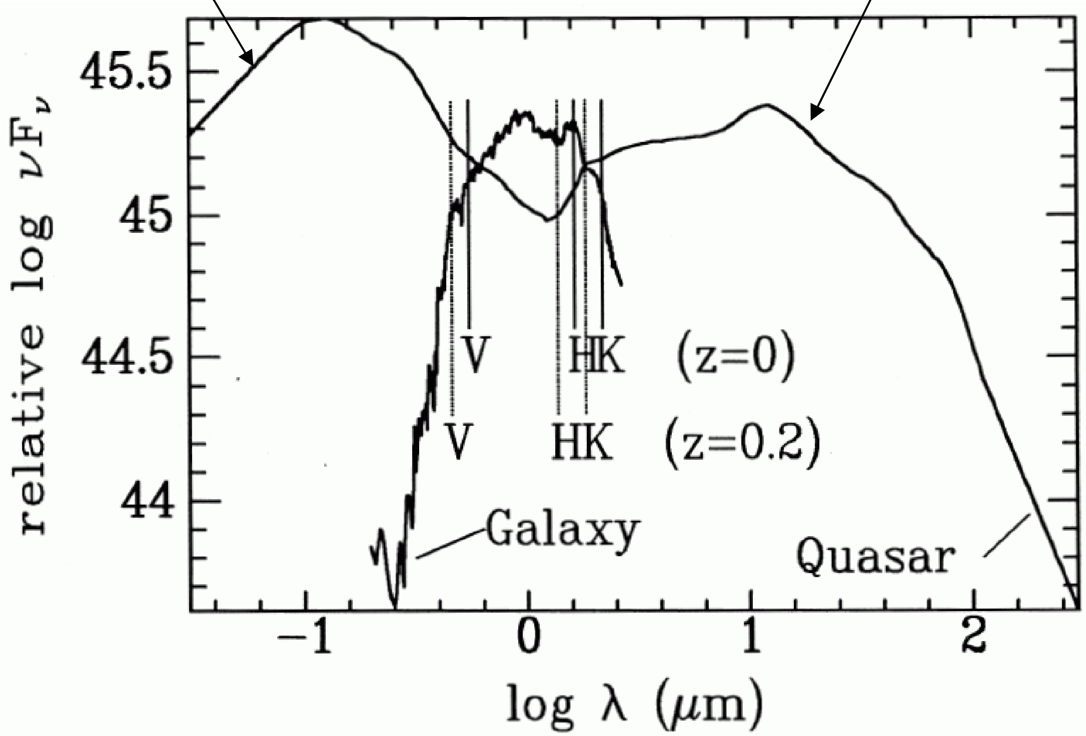
PSF characterisation, spatial resolution, & signal-to-noise are important:

- HST+NICMOS (but limited resolution & field of view)
- ground-based 8-m with AO: high resolution, long integrations, large surveys

Observe in the near-infrared: best contrast, less reddening than optical, & for high redshift galaxies less bias towards only recent star formation

thermal emission from accretion disk at 10^4-10^5K

reprocessed emission from dust at 100-1000K



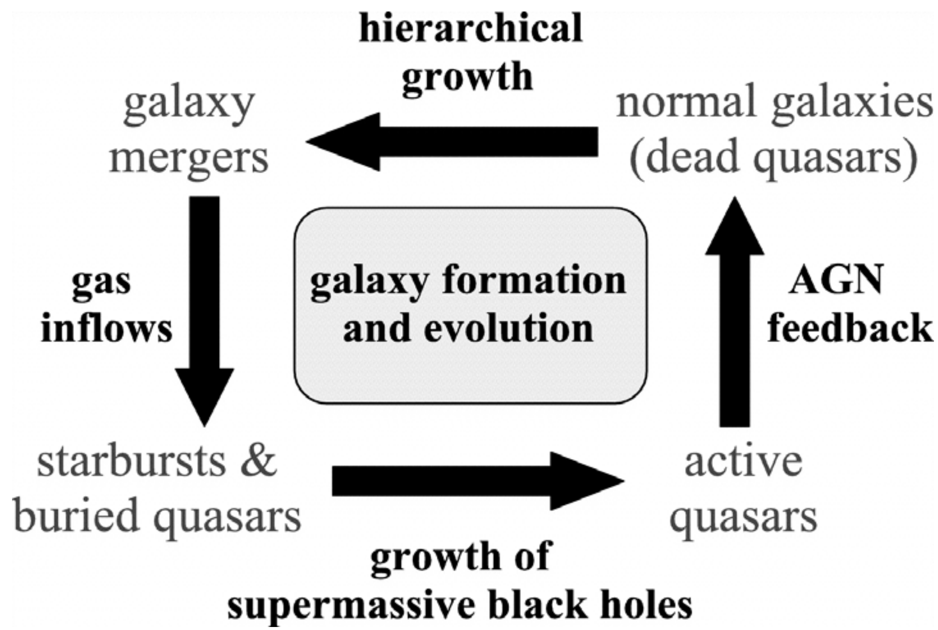
typical QSO & galaxy SEDs (arbitrary normalisation; QSO is usually much brighter than galaxy)

McLeod & Rieke 1995

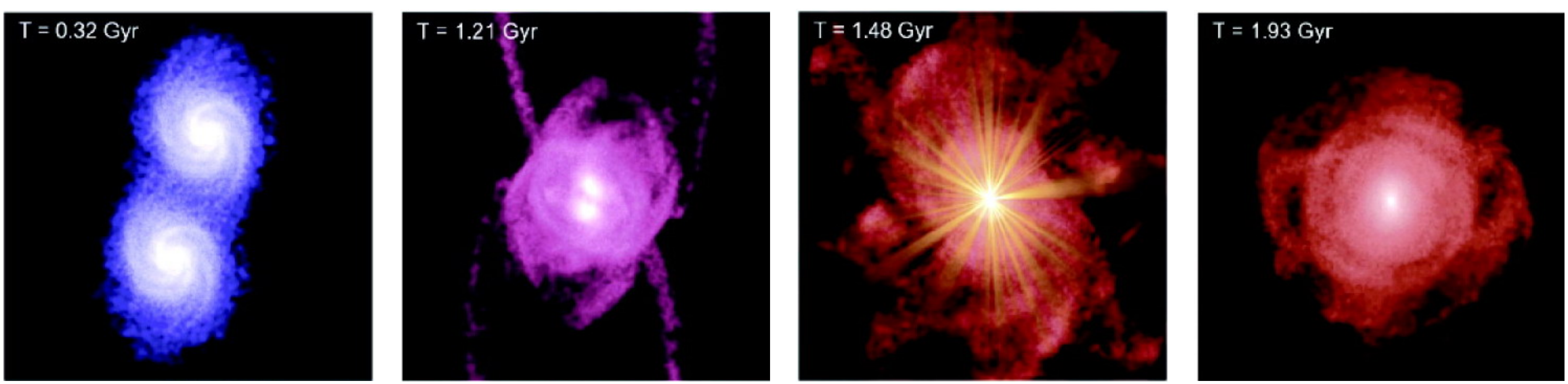
Are QSOs formed by Merging Galaxies?

Sanders et al. 1988 & many others:

- ULIRG formed by merger of gas rich spiral galaxies
- gas falls to centre, fuelling starburst & AGN
- dust is cleared by radiation pressure & supernovae, creating optical QSO
- QSO fades, leaving an old elliptical remnant



Hopkins et al. 2006

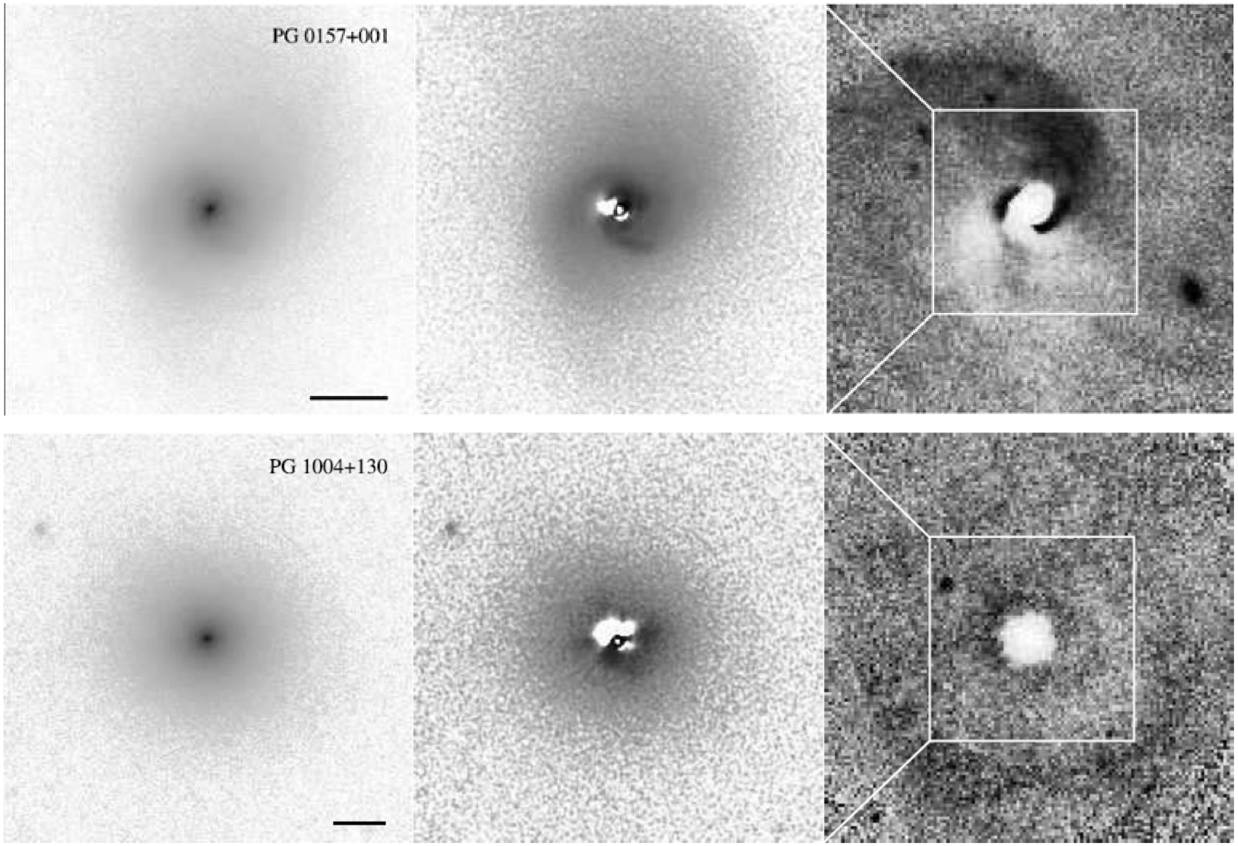


QSO Host Galaxies at Low Redshift

Largest & most successful AO survey: 32 QSOs at z<0.3, with dynamic range >10^4
Guyon et al. 06 (Hokupa'a on Gemini, & Subaru)

Images fit using: $$\chi^2 = \sum \left\{ \left[image - (pointsource + host) \otimes PSF \right] / \sigma^2 \right\}$$

host has 4 parameters for bulge & 4 for disk: brightness, size, axis ratio, orientation

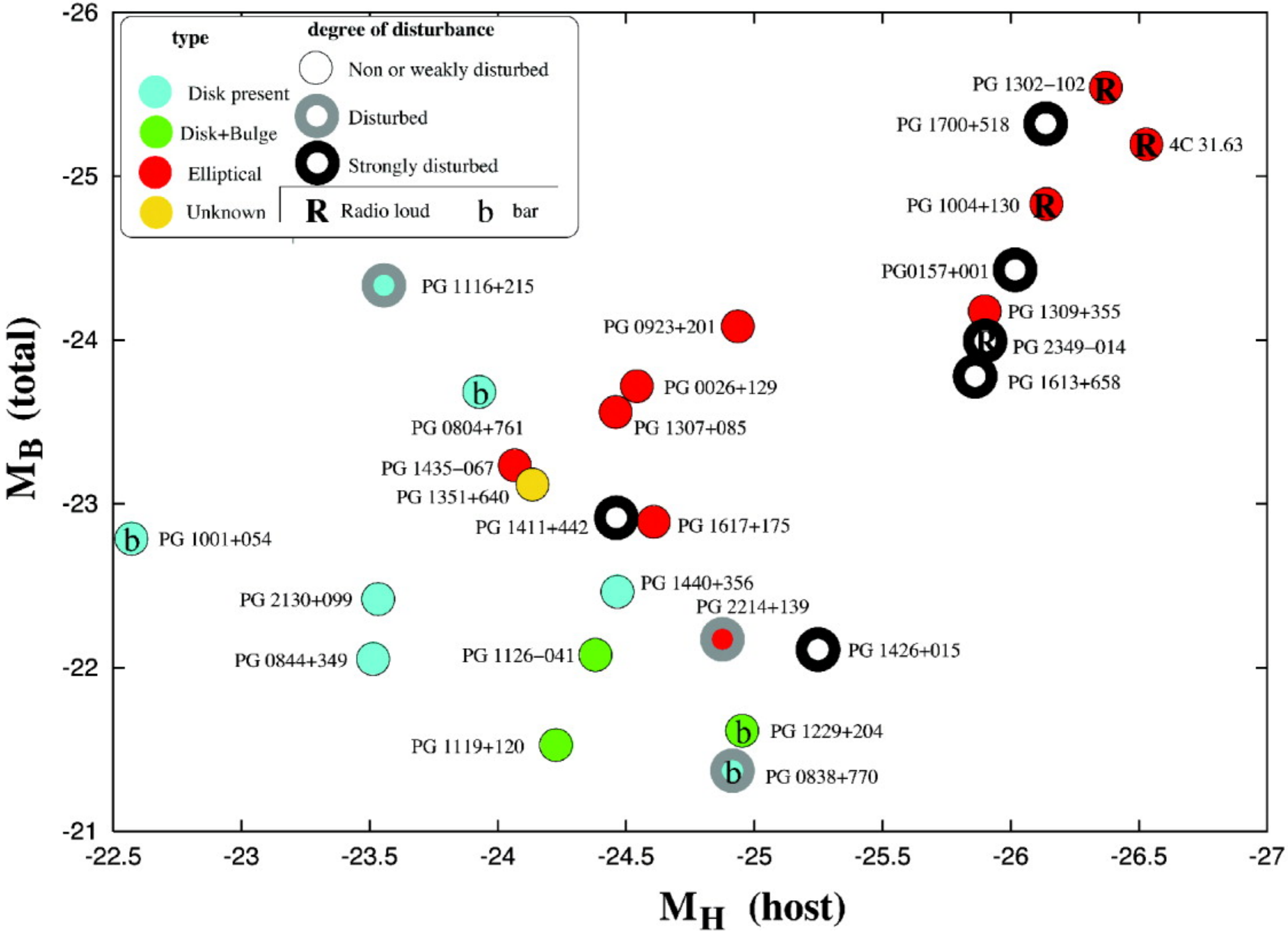


residuals are tidal tails rather than spiral arms

bulge fits better than disk, & lack of residuals suggests this is an elliptical

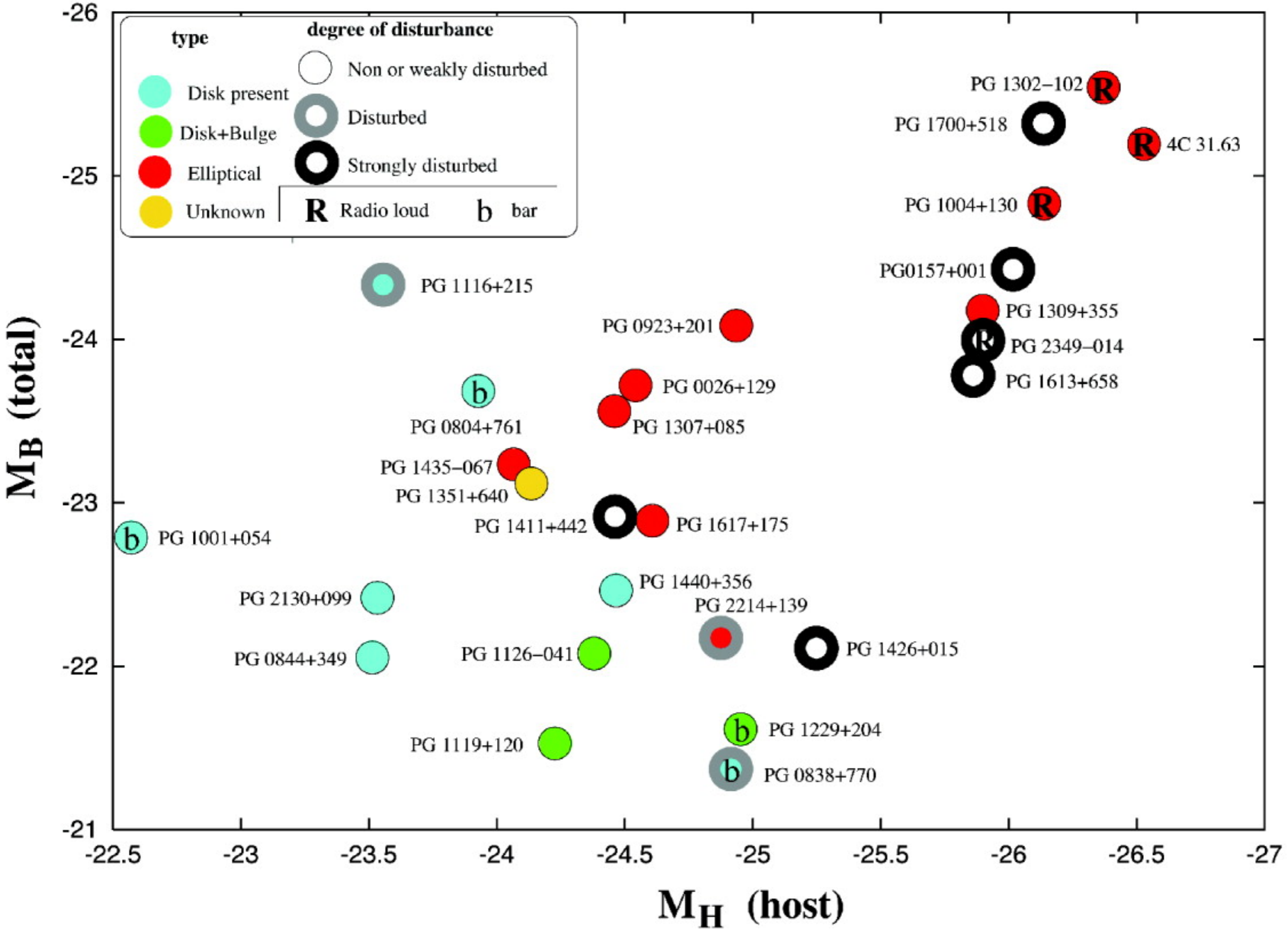
QSO Host Galaxies at Low Redshift

1. lower luminosity hosts are mostly disks; higher luminosity hosts are mostly ellipticals (i.e. end point of major merger), but with a significant fraction of disturbed morphologies



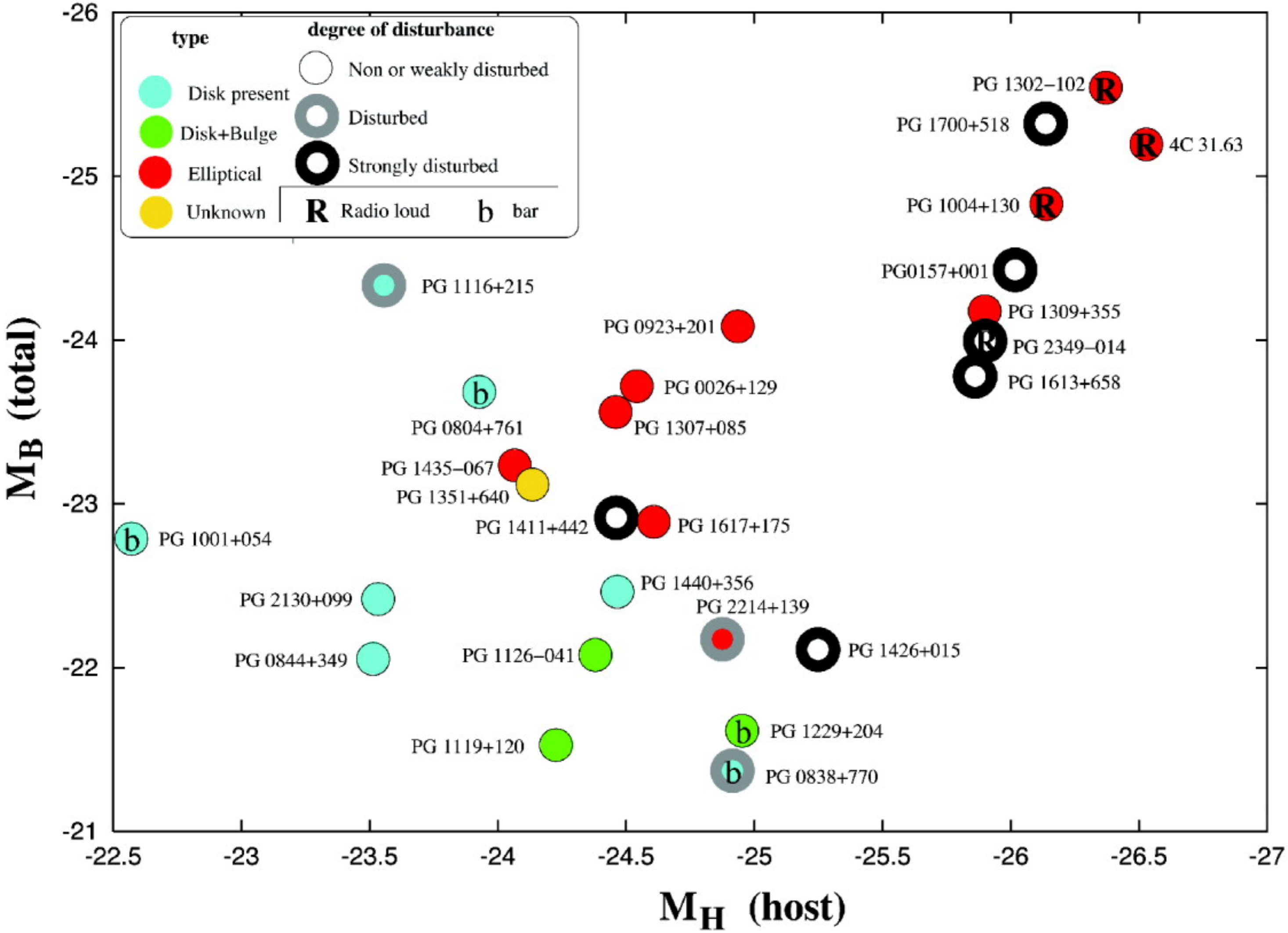
QSO Host Galaxies at Low Redshift

2. disky hosts do not harbour really luminous QSOs, which are found in strongly disturbed hosts or ellipticals. Perhaps luminous QSOs *only* arise from really major mergers which destroy the disk



QSO Host Galaxies at Low Redshift

3. Radio Loud QSOs (only ~15% of total, typical fraction) are only found in most luminous hosts (is this suggesting that RQ/RL correlates with BH size, or perhaps BH spin?)



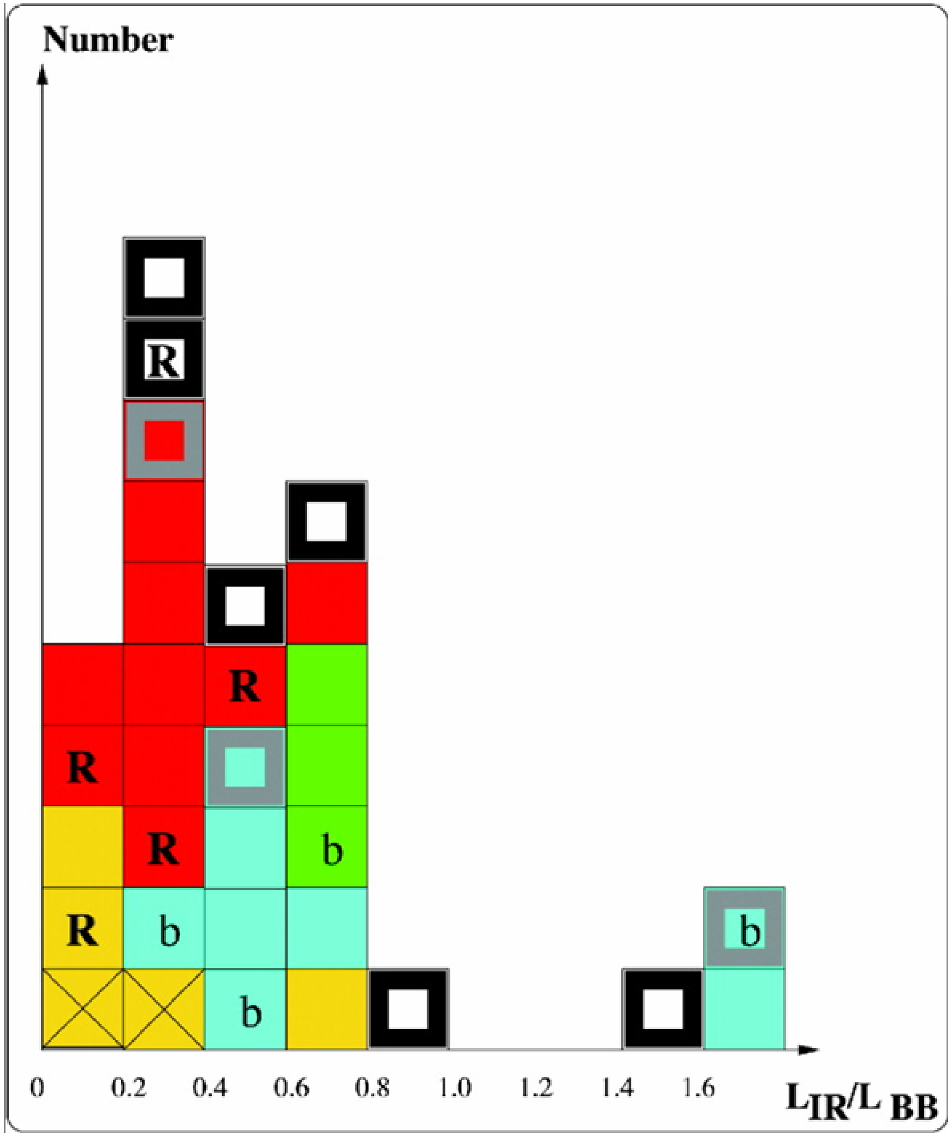
QSO Host Galaxies at Low Redshift

L_{IR} is reprocessed emission –
i.e. amount of dust coverage

L_{BB} is big blue bump of QSO –
i.e. amount of direct emission

elliptical hosts (harbouring the most luminous QSOs) have lowest ratio of L_{IR}/L_{BB}, i.e. least dust

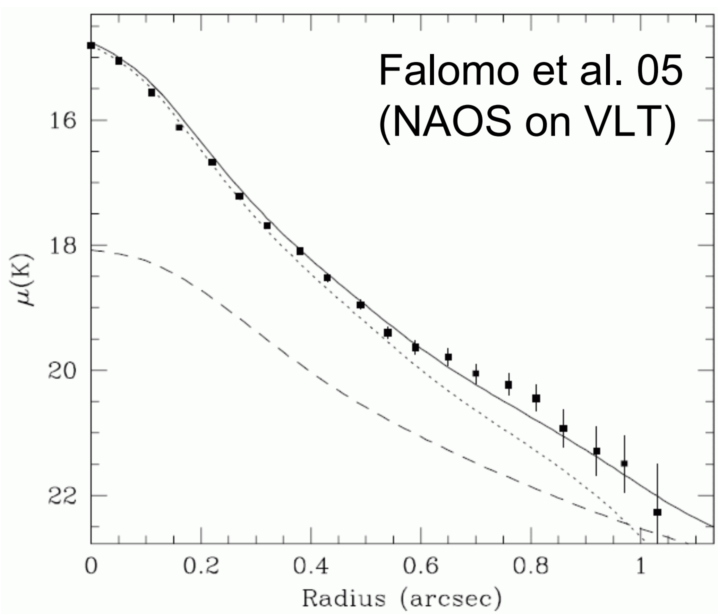
disky hosts (& also disturbed systems) have higher L_{IR}/L_{BB} and hence more dust



Detecting Host Galaxies at High Redshift

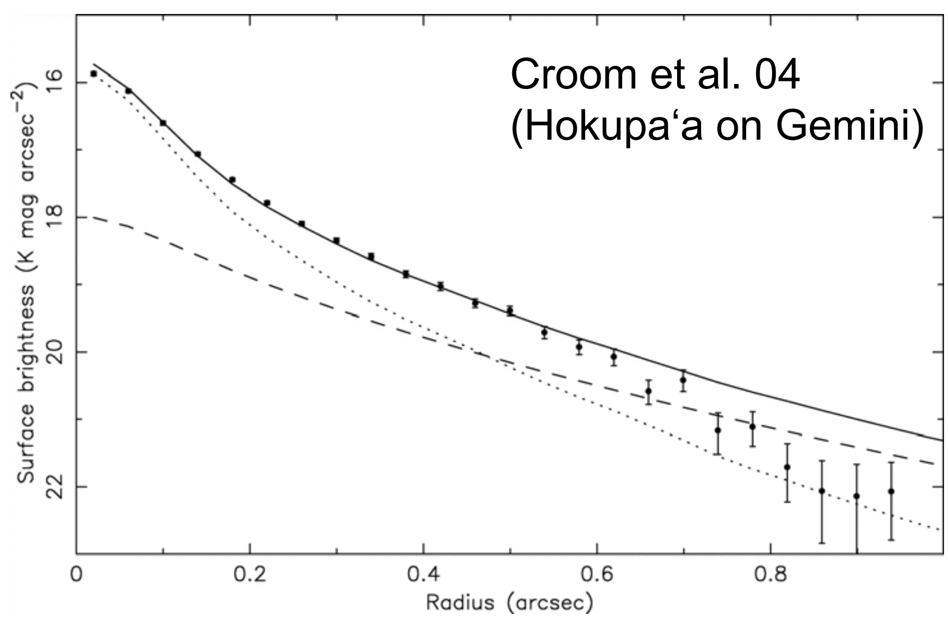
- QSO is more luminous than host, particularly with $(1+z)^{-4}$ surface brightness dimming
- HST WFPC2: luminous QSOs have Elliptical hosts (but due to bias toward RLQs?)
- At high z, issue is to detect the host, and estimate its size/magnitude
- Early AO studies were struggling to simply detect the host at z=1-4
- At z>2, even recent studies need to assume a galaxy profile rather than derive it
- Non detections can be useful – puts limits on maximum luminosity of host galaxy.

PKS 0113-283 at z=2.6



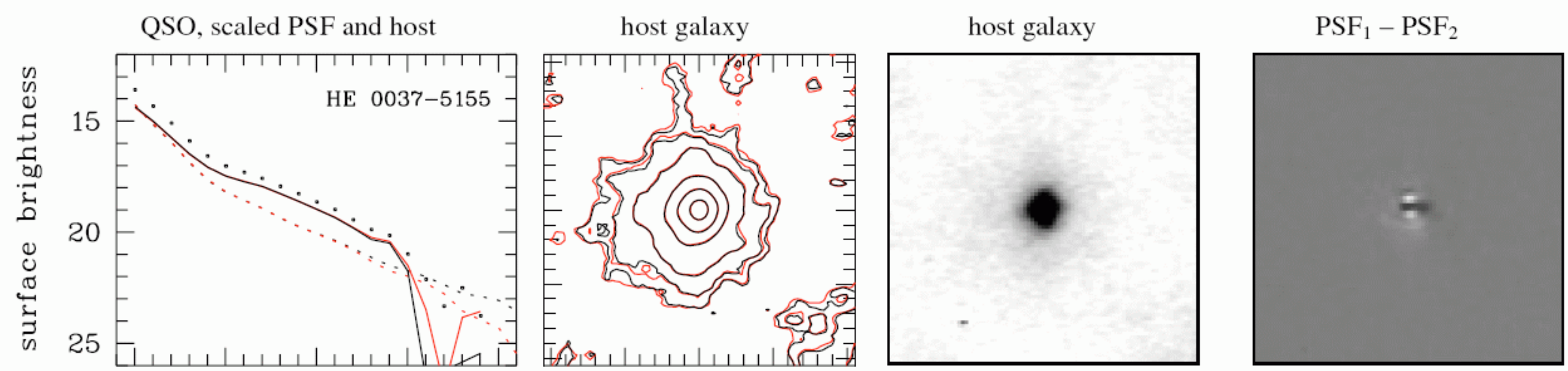
1 of 3 hosts detected

2QZ J133311.4+001949 at z=1.9



1 of 9 hosts detected

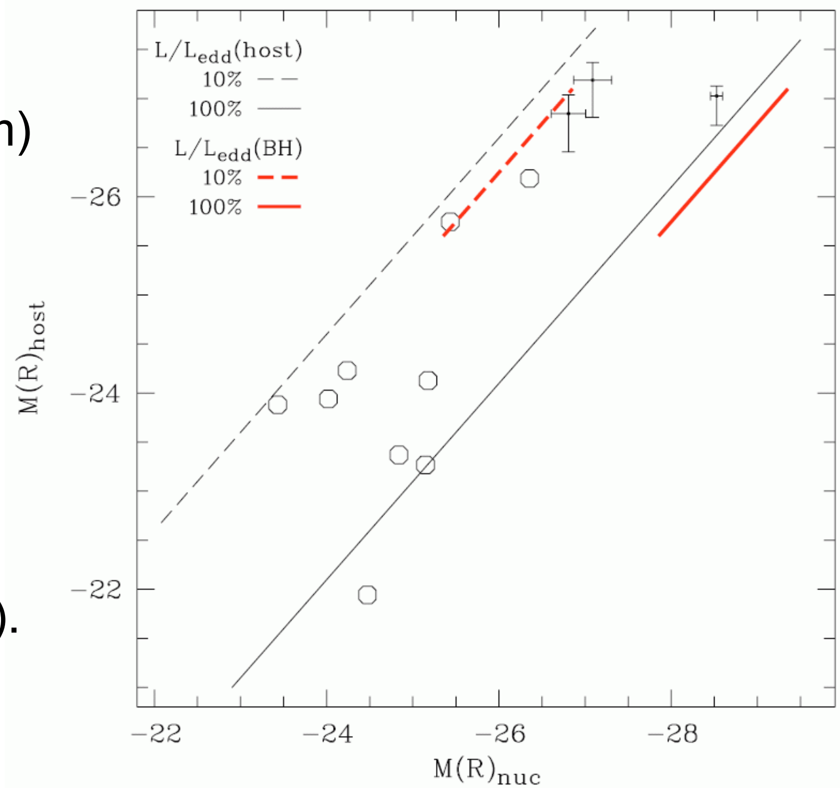
Detecting Host Galaxies at High Redshift



dotted line: total; red/black dashed: PSFs; solid: residuals

Kuhlbrodt et al. 05 (ADONIS on ESO 3.6m)

- detected hosts in all 3 QSOs at z~2.2
- hosts are rather luminous, especially for their size – but not unexpectedly given QSO/host luminosity relation
- magnitude-size relation implies lower mass/light ratio & hence younger population: ~100Myr (then would fade onto the usual relation by low z).

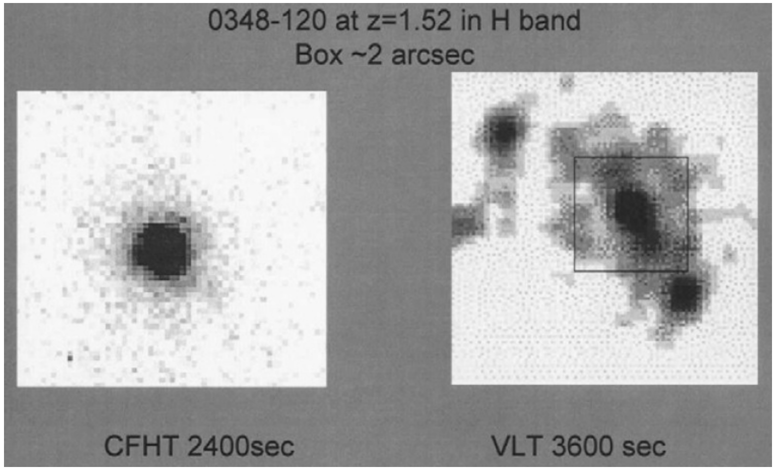


Are elliptical hosts really elliptical?

Hutchings 2006 (Pueo on CFHT; Gemini):

"claims that all hosts at z>2 are elliptical are suspicious"

- observations strongly affected by dynamic range
- bright inner bulges easily seen & resolved at 0.1" scales
- faint extended parts (perhaps showing signs of merging) are harder to see

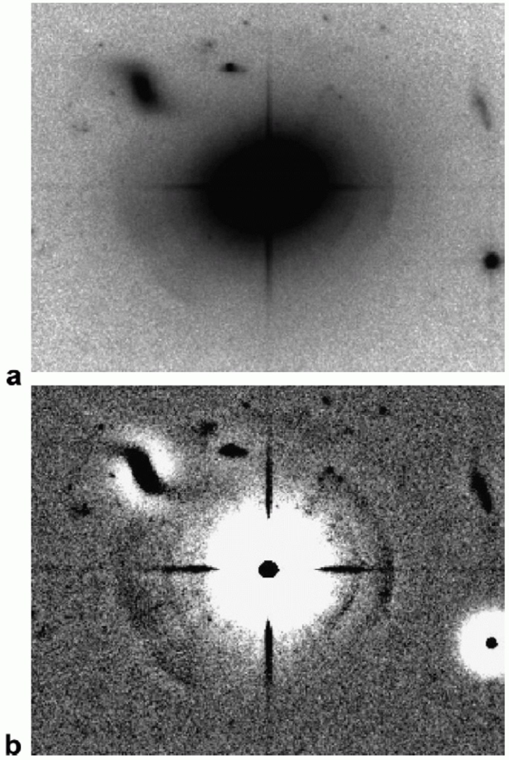


Marquez et al. 2001 (Pueo on CFHT):

- detected hosts in 11/12 QSOs at z<0.6
- elliptical hosts were always fit as ellipticals
- disk hosts were sometimes fit better as ellipticals if the QSO was bright

Canalizo et al. 2006 (HST/ACS):

deep imaging of MC2 1625+119 at z~0.2 shows that even elliptical hosts have shell structure, and so perhaps formed ~1Gyr in past.



How old are the stars in QSO hosts?

very old:
Dunlop et al. 03: carefully selected sample of luminous QSOs, find host galaxies are all quiescent ellipticals, perhaps with old populations.

Nolan et al. 01: spectroscopy found evolved stellar populations with ages ~10Gyr & only a small amount of recent star formation.

not so old:
Kauffman et al. 03: luminous QSO hosts have evolved populations, but colours are bluer than typical ellipticals, implying a significant starburst in the last 1-2Gyrs.

Canalizo & Stockton 01: spectroscopy found evidence for recent star formation in the last ~100Myr in QSOs with far-infrared excess

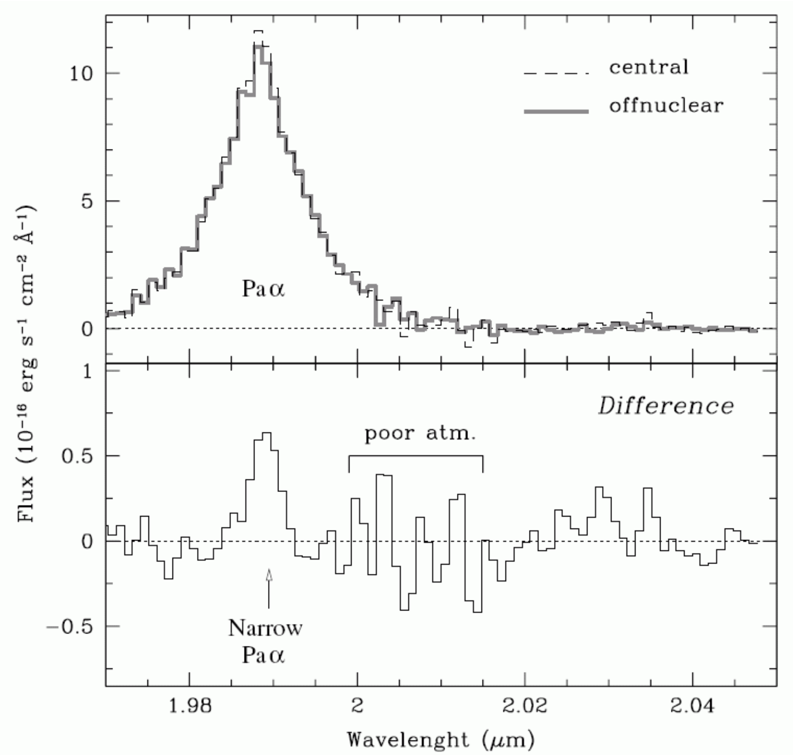
Canalizo et al. 05: spectroscopy of QSOs in Dunlop's sample revealed for 13/14, a component comprising stars formed in the last 0.6-2.2Gyr making up >10% of the host's mass

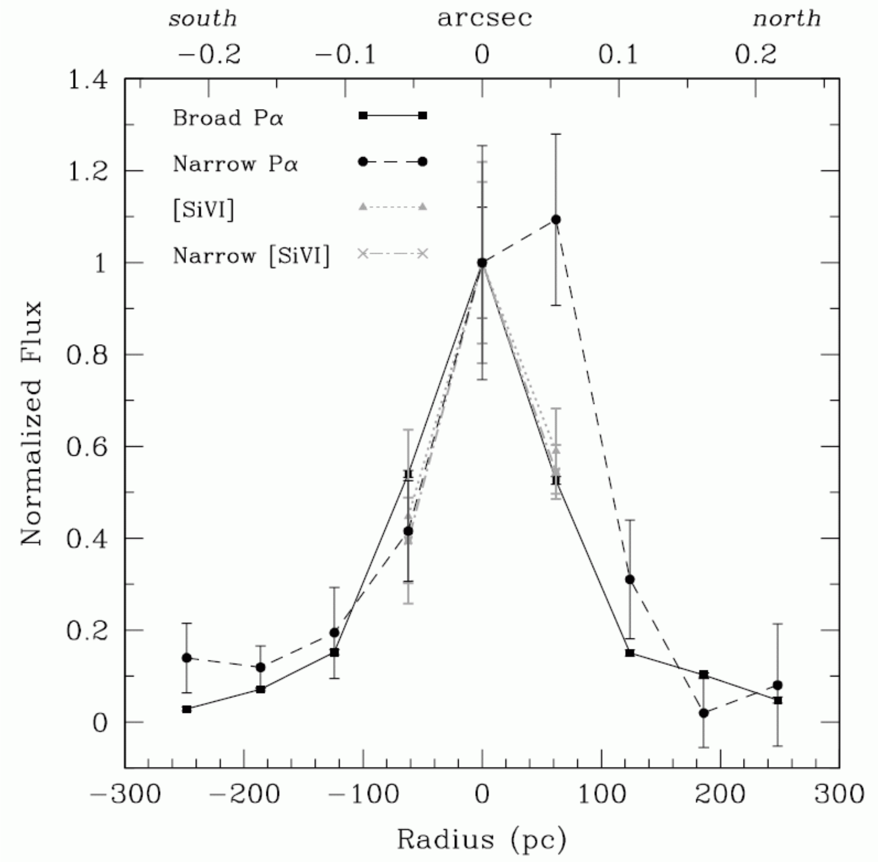
Is there recent star formation & is it linked to QSO activity?
need to find really young stars, close to nucleus … i.e. use adaptive optics

Are there Young Stars in the Centres of QSO hosts?

Cresci et al. 2004 (NACO on VLT):

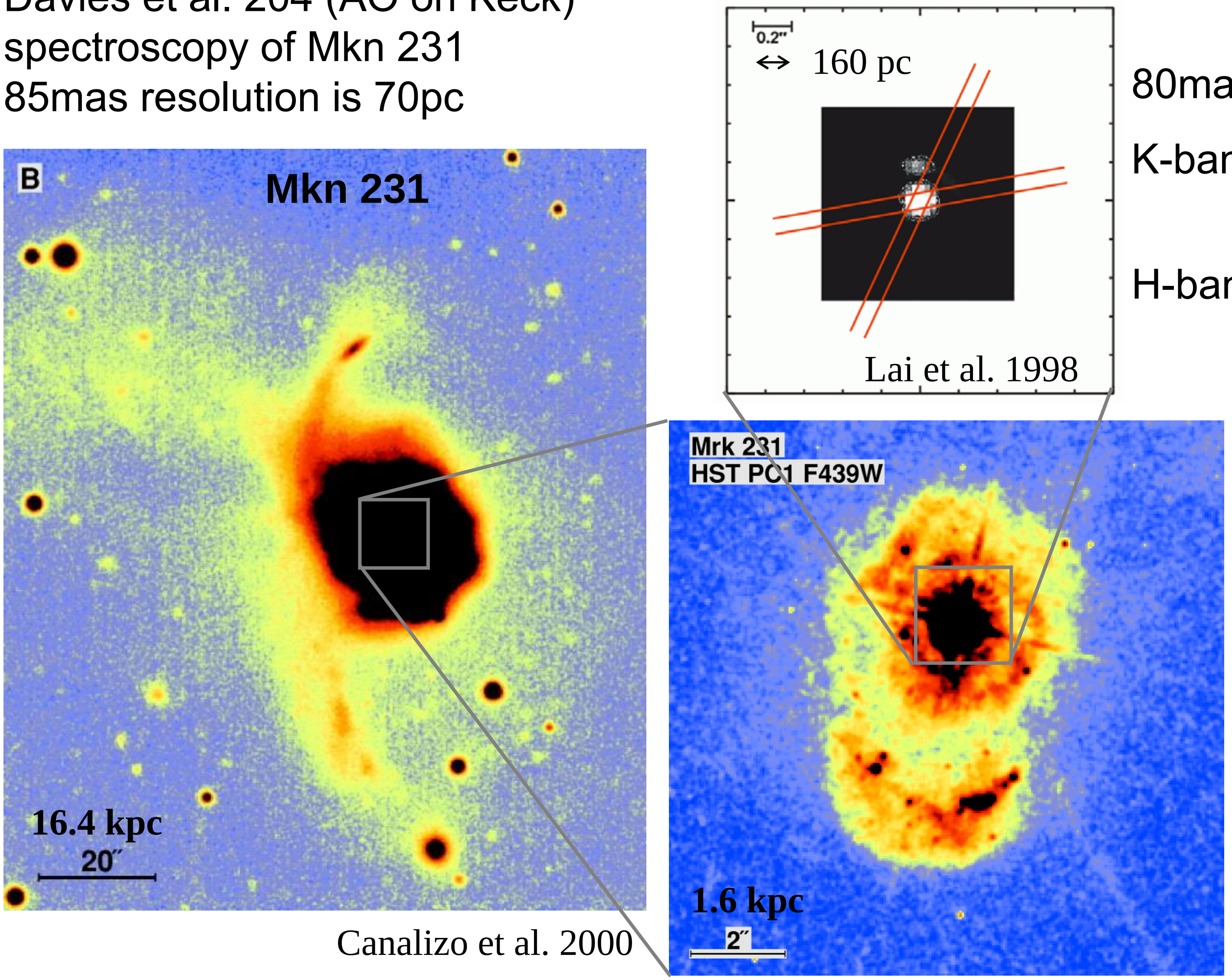
- AO spectroscopy of z~0.06 QSOs.
- PG1126-041: spatially resolved narrow Paα, which is stronger wrt [SiVI] than expected. So attributed to star formation within a few ×100pc of nucleus.
- SFR of ~13M_{sun}/yr can account for a large fraction of L_{IR} – i.e. nuclear star formation within a few ×100pc is as energetically important as the QSO





Are there Young Stars in the Centres of QSO hosts?

Davies et al. 204 (AO on Keck)
spectroscopy of Mkn 231
85mas resolution is 70pc

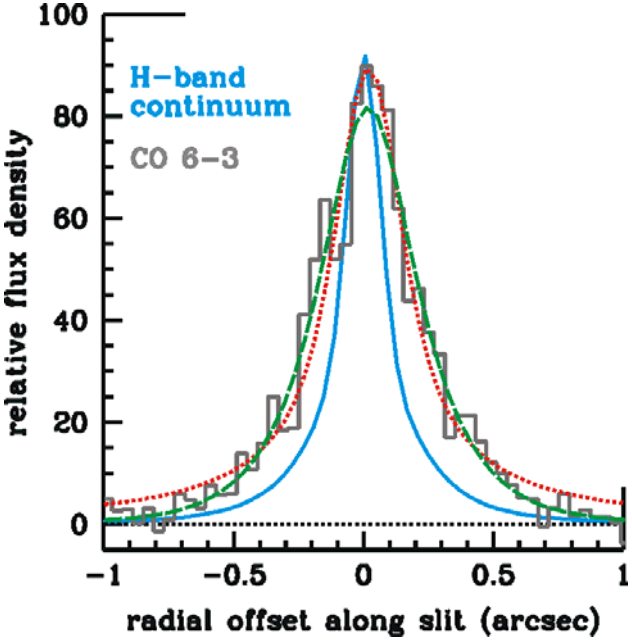


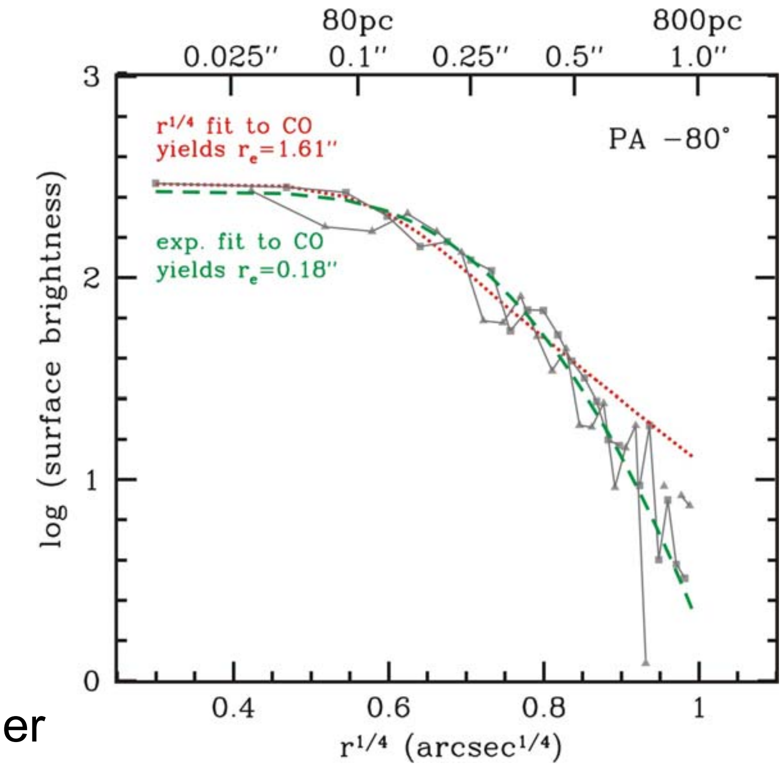
80mas slits

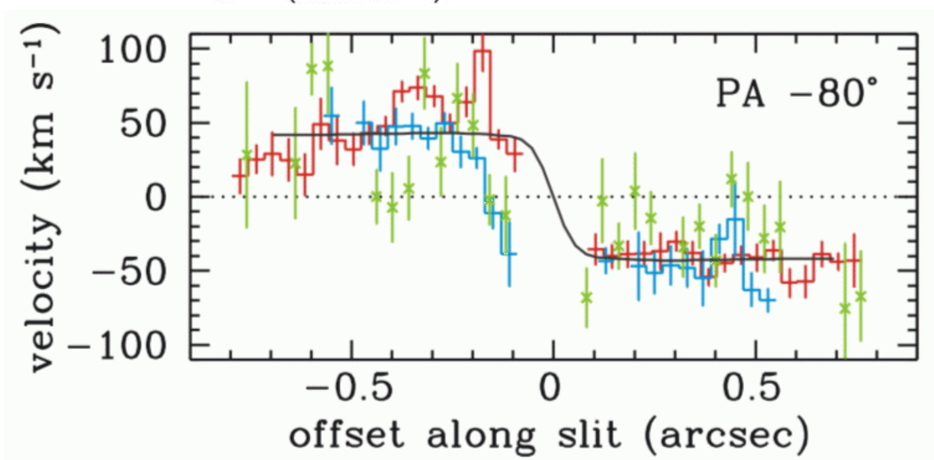
K-band: R~2500
H_2 1-0 S(1)

H-band: R~1800
CO6-3, [FeII]

Are there Young Stars in the Centres of QSO hosts?







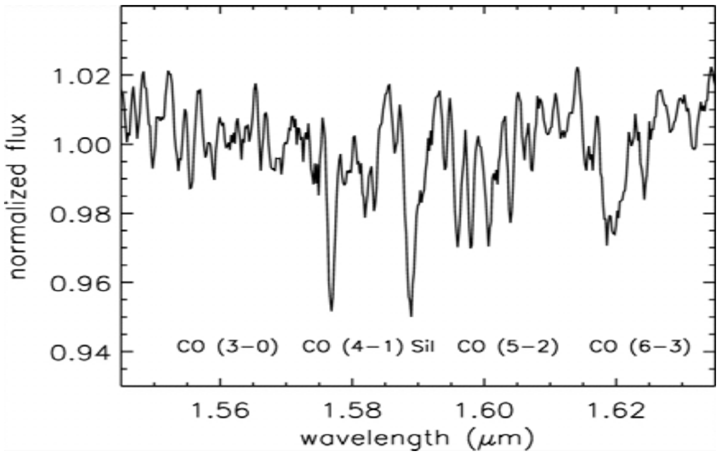
- profile of stellar light follows disk rather than bulge profile
- stellar & gas kinematics can be modelled as nearly face on rotating disk
- dynamical mass & stellar luminosity gives M/L and hence an age – no more than ~100Myr in central kpc
- SFR ~ 50-100M_{sun}/yr
- star formation contributes 1/3 of L_{bol}

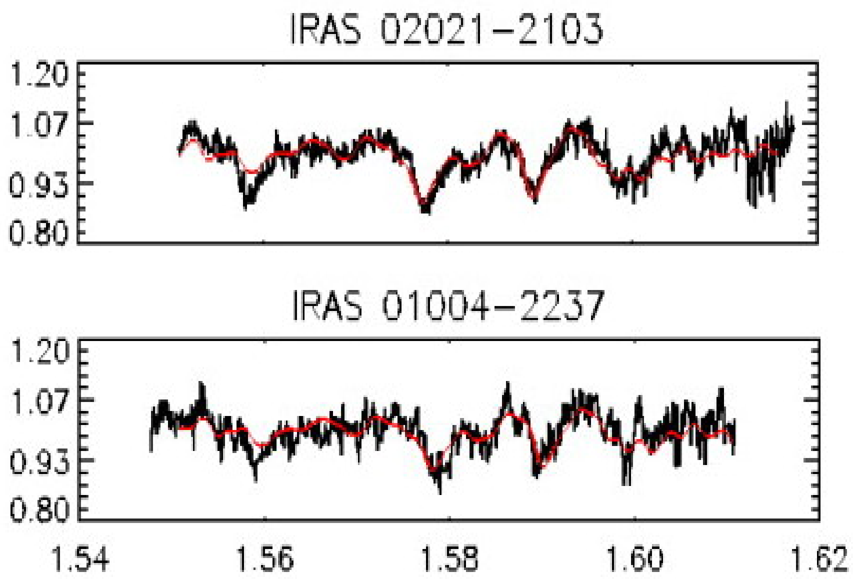
Stellar Kinematics of ULIRGs & QSO hosts

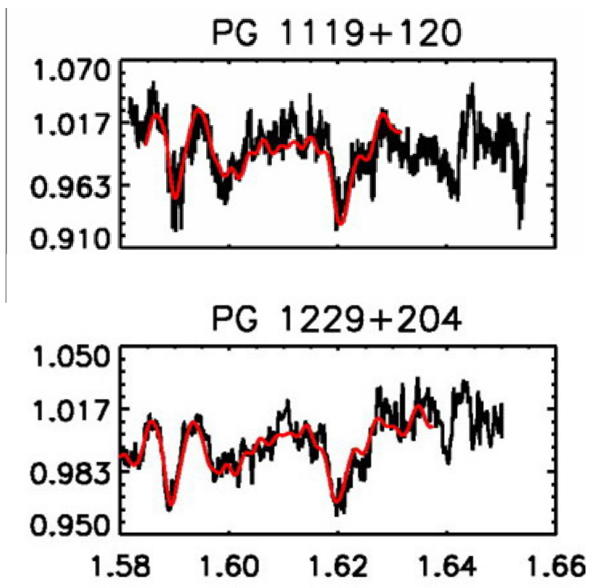
Dasyra et al. 06a, 06b, 07

- template spectrum convolved to match profiles of ULIRGs & QSOs
- this is *really* hard & AO would certainly help
- σ_* in merged ULIRGs ~ 161km/s
- σ_* in QSOs ~ 186km/s

template spectrum showing main absorption features

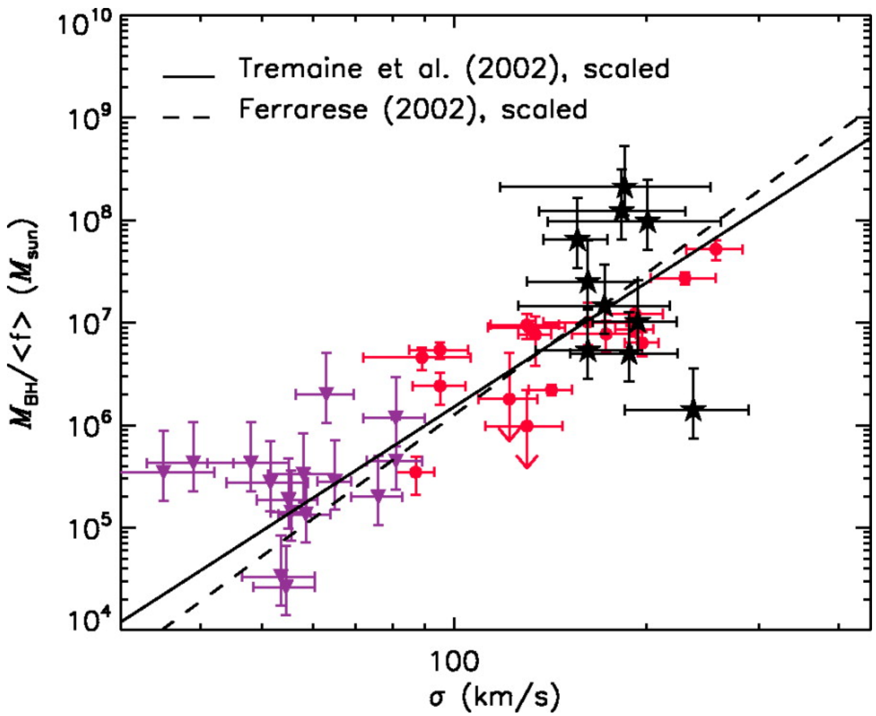


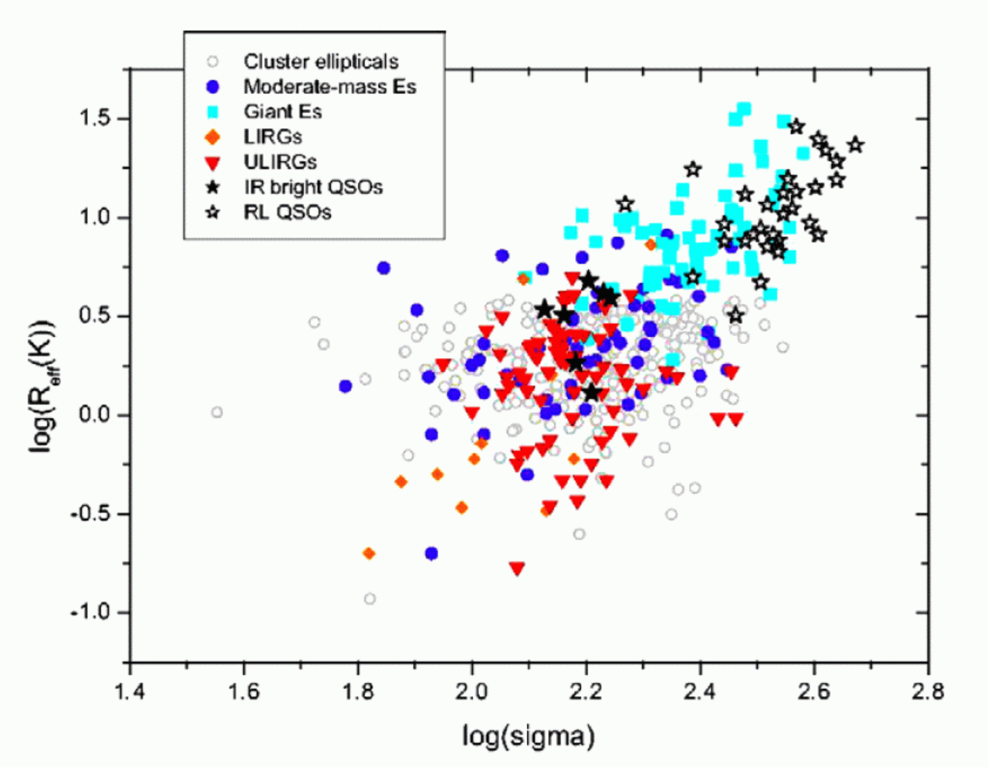




Stellar Kinematics of ULIRGs & QSO hosts

- σ_* & M_{BH} (line & continuum scaling relations) measurements are independent: can plot points on M-σ relation & test its validity for QSOs
- σ_* & R_e (HST images): can plot on fundamental plane, with ULIRGs. Similarity of kinematics & locations in fundamental plane makes it plausible that at least some QSOs and ULIRGs are just different phases of an evolutionary path; but also perhaps there are 2 types of QSOs





Summary & Outlook for tomorrow's lecture

- Adaptive Optics Concepts & Techniques
  - Atmospheric Turbulence & its Impact on Observations
  - Measuring & Correcting Wavefront Aberrations
  - Limitations of Adaptive Optics & How to Avoid them
  - Realistic Expections
- QSOs at High & Low Redshift
  - How AO can help with QSO research
  - Host galaxy characterisation
  - Stellar populations in host galaxy
  - Evolutionary Scenario
- The Galactic Center
- Nearby AGN
- Future Perspectives