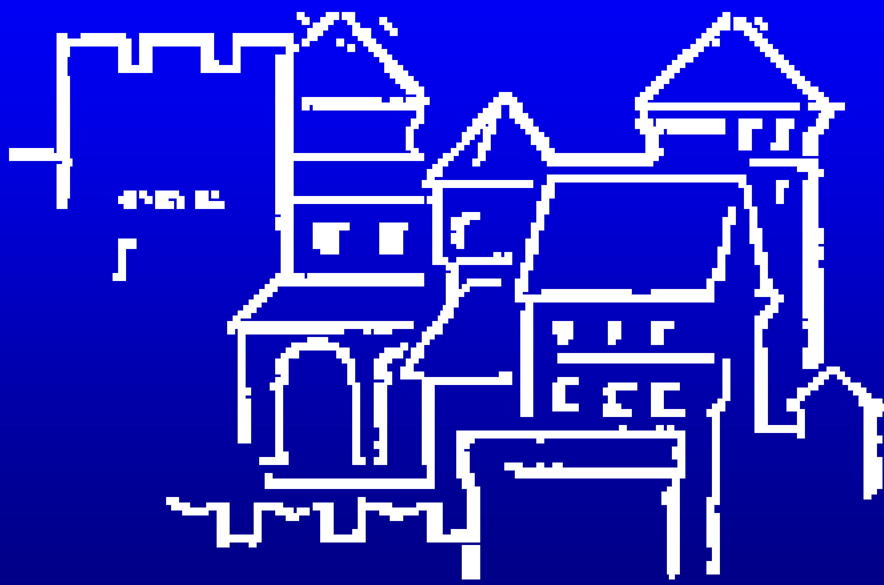
Co-Phasing Segmented Optics: from LBT to ELT?

<u>or:</u> Using multiple sub-aperture AO loops to increase feasibility, distribute risk of failure, and eliminate single-item show-stoppers



ELT – *complexity*

opto-mechanical design of ELTs pushes the limit for several parts of the system(*):

- moving high mass with great precision in open environment:
  14,400 tons (~25 × A380) @ 1 arcsec (2.4 mm on Ø=100 m track)
  → specification can be relaxed using **active & adaptive optics** ✓
- flexure of telescope structure due to changing wind load and gravity
  secondary mirror ~100 m in front of primary; elevation down to 30°
  → multi mirror design + **active & adaptive optics** ✓
- large surfaces with optical quality:
  6,000 m² (~soccer field) @ λ/10 ~ 20 nm (visible)
  → segmented optics (>3000 segs.) using **active & adaptive optics** ✓

⇒ active & adaptive optics are key elements of ELT design !!!

(*) numbers according to OWL phase A study

ELT – *'active' optics*

two categories of active, *i.e. 'deformable'* optics:

- **active optics** ≤ 10 Hz
  obtain first order alignment of segmented mirrors
  based on non-wavefront-sensing detectors, i.e. position sensors
  remove flexure effects due to changing gravity vector and wind load
  → remaining wavefront errors corrected by adaptive optics ✓
- **adaptive optics** ~ 100 Hz
  wavefront sensors, e.g. Shack-Hartmann, curvature, pyramid ?
  wavefront reconstruction computers ?
  wavefront correcting optics, i.e. deformable mirrors ?

⇒ adaptive optics recognised as most daring challenge !!!

ELT – *adaptive optics*

wavefront sensing:

- diffraction limited PSF from NIR to visible
  → atmospheric turbulence cells to be corrected Ø = 1.0m – 0.1m
  → number of sub-apertures 8,000 – 600,000
- number of pixels per sub-aperture depending on WFS technology from 2×2 (pyramid) to 3×3 (Shack-Hartmann)
- megapixel camera with framerate ≥ 100 Hz to sense wavefront over full aperture
  → not very likely within next decade

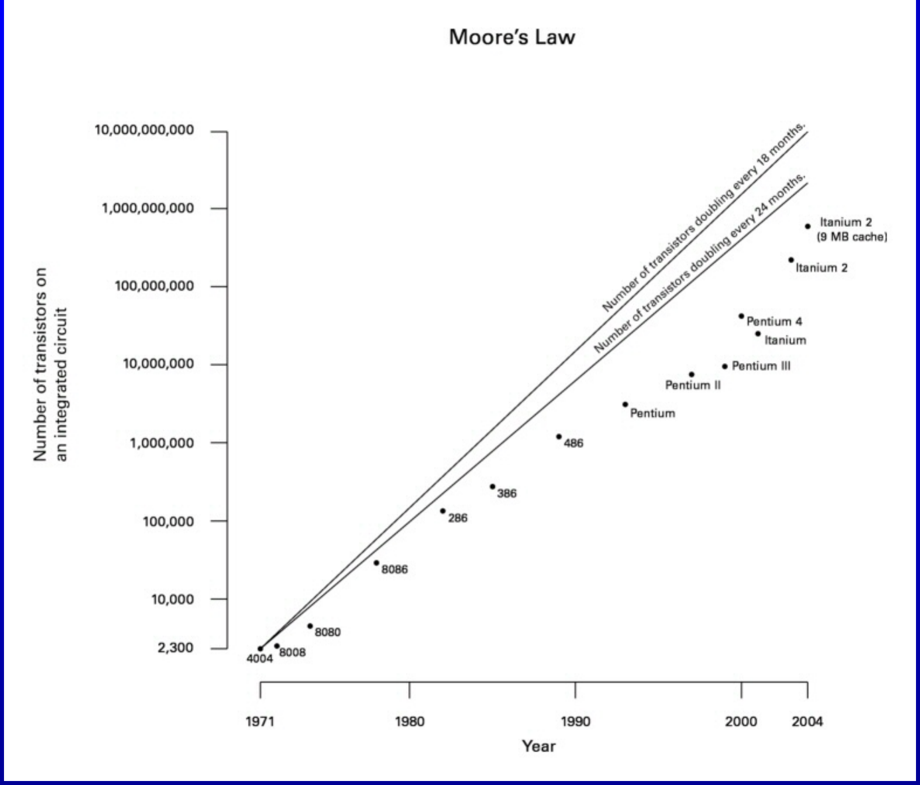
→ splitting image on several smaller detector arrays
"smart fast camera" – still up to 35 detectors of 256×256 pixel ✓

⇒ **to sample full aperture (Shack-Hartmann, pyramid, ...), signal will have to be obtained on sub-apertures**

ELT – *adaptive optics*

wavefront reconstruction:

- since 2002 NAOS @ VLT:
  NIR diffraction limited PSF
  up to 144 sub-apertures sensed
- number of sub-apertures has to be increased:
  → ~ 100× due to aperture size
  → ~ 10× due to wavelength
- computing load scales linear with number of sub-apertures
- Moore's law predicts ~ 32× within one decade



⇒ **full high order reconstruction of wavefront over full aperture very challenging within next decade** **?**

ELT – *adaptive optics*

wavefront correction, i.e. deformable mirrors:

- correction bandwidth ~ kHz
  $\rightarrow$ thickness of mirror skin ~ few mm
- one actuator per (scaled down) turbulence cell
- min. actuator spacing limited by technical feasibility ~ few mm
- 10cm turbulence cell + 100m telescope + 2mm actuator spacing
  $\rightarrow$ deformable mirror with Ø ~ 2m and ~ 600.000 actuators

$\Rightarrow$ **manufacturing and reliable operation of (single) deformable mirror seems most challenging for successful AO**

Is is realistic that such devices can be built within next decade? **?**

ELT – *adaptive optics*

summary of current baseline AO concept

advantages:

- current AO concept designed to deliver best possible PSF (i.e. image quality) limited only by telescope mechanics/structure

disadvantages:

- current AO concept represents a single-point of failure item, nevertheless several sub-systems are based on uncertainties
- WFS: number of sub-apertures by far exceeds detector sizes
- WFR: computing power presumably only available via clustering
- WFC: large size DM with densely spaced high number of actuators

Is current AO concept feasible within next decade ?

segmented DM ?

No new idea in OWL design: option of using segmented M6 already mentioned in Phase A study as possibility for first AO implementation

benefits:

- smaller devices easier to manufacture, assemble & handle (cost!) (maybe the only ones feasible at all within next decade)
- serialisation of DM segments (cost + possibility of spare units!)
- option to split up single but complex full-aperture AO system into several individual, identical, smaller sub-aperture AO systems with additional master AO loop (i.e. ***LBT / LINC-NIRVANA style AO***)
- reduces/spreads load of single wavefront reconstruction computer

$\Rightarrow$ **segmented DM eliminates single-point-of-failure item & allows to spread system load in exchange with different AO concept**

segmented DM ?

disadvantages:

- artifacts of segmentation will be present even in optimum PSF
- performance of non-circular shapes of deformable mirrors unclear
- sub-aperture AOs need additional master AO loop for coherent combination (i.e. co-phasing) of full aperture wavefront
  $\rightarrow$ goal is diffraction limited PSF of *full* aperture of telescope
- multiple AO loops to close instead of a single one
- multiple devices $\rightarrow$ multiple points of failure

$\Rightarrow$ **segmented DM reduces maximum achievable PSF quality; sub-aperture AO (may) lead to nested AO loops**

only a fantasy ?

Is using segmented (i.e. individual) DMs, independent sub-aperture AO systems, and a master co-phasing AO system an unrealistic option for an astronomical telescope?

NO !

minimum number of deformable mirrors:

2

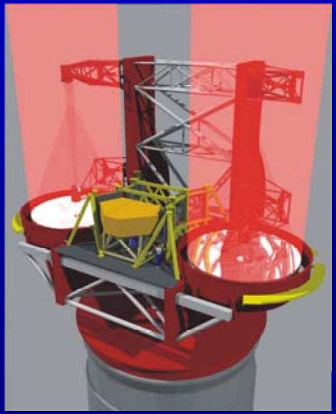
minimum number of sub-aperture AO systems:

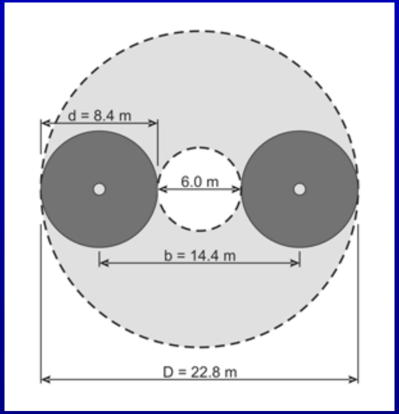
2

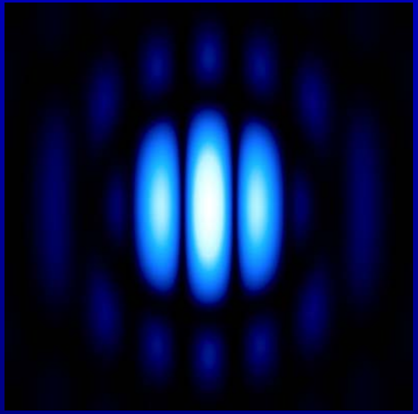
LINC - NIRVANA at the LBT

LBT/LN – *AO system*

- not a real ELT but a *binocular* telescope
  → two identical but still individual 8m telescope
- two identical but individually operating sets of adaptive optics
  → two adaptive secondaries (Ø ~ 0.9m, 672 actuators each)
  → two sets of wavefront sensing systems (pyramid based)
  ⇒ two diffraction limited 8m wavefronts
- achieve diffraction limit comparable to 23m telescope
  → coherent combination of diffraction limited single-eye wavefronts
  ⇒ master AO loop



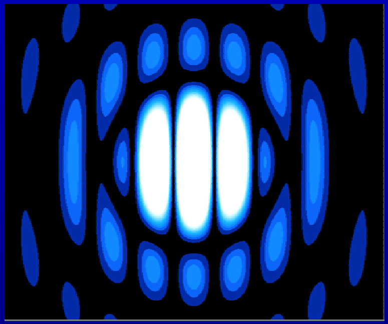




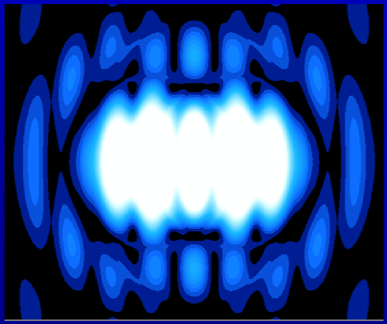
LN – *co-phasing*

- master AO for co-phasing of diffraction limited 8m wavefronts
  → Fringe and Flexure Tracking System (FFTS)
- FFTS aligns optical axes of single-eye telescopes and removes pistonic wavefront differences
  → correction of instrument/telescope flexure at sub-Hz rate
  → correction of instrumental and atmoshperic OPD at ~10–100 Hz

analysis of single-eye Airy rings
→ alignment signal



no misaligment



1.0 R_{Airy} misalignment

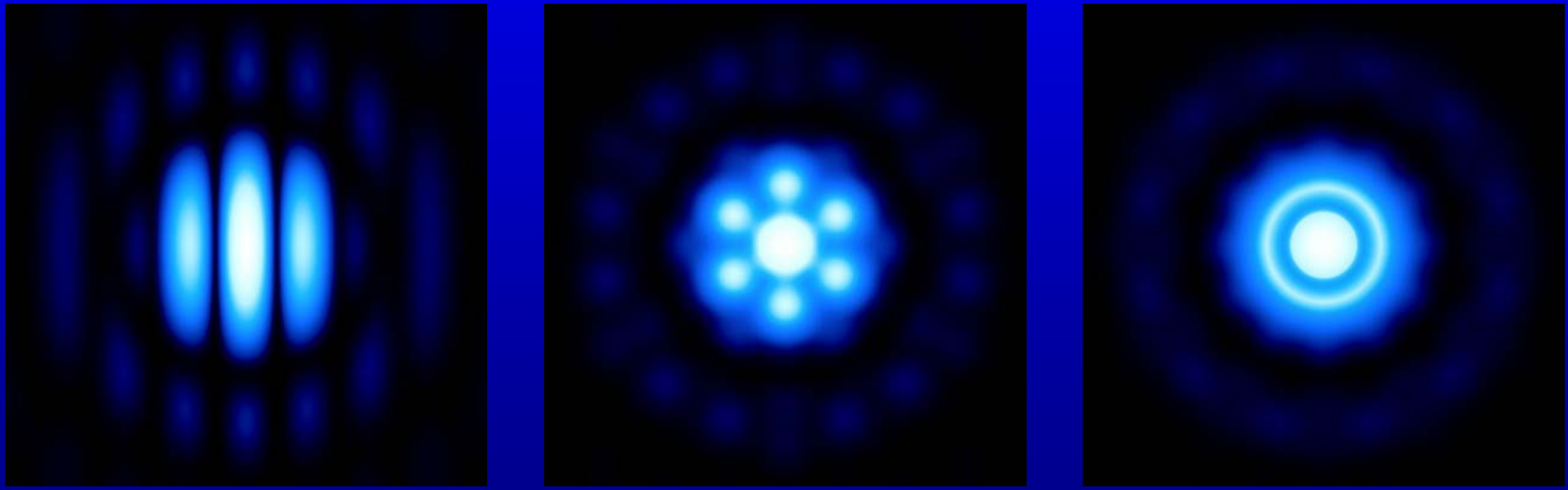
analysis of fringe pattern
→ OPD between telescopes

zero OPD

0.33 π OPD

LN – *image reconstruction*

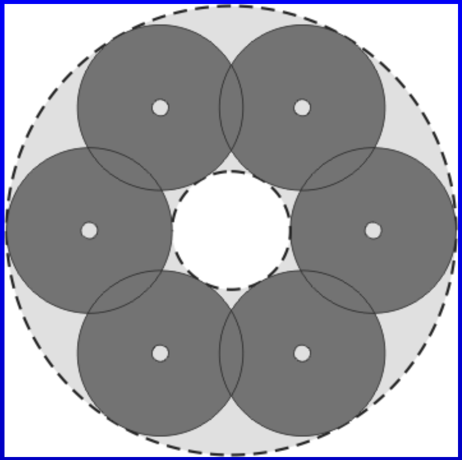
- diffraction limited PSF of LBT is not circular symmetric:
  angular resolution || baseline → 8m Airy distribution
  angular resolution ⊥ baseline → 14.4m fringe pattern
- exposures at different baseline orientations allow to reconstruct full two-dimensional angular resolution at data reduction

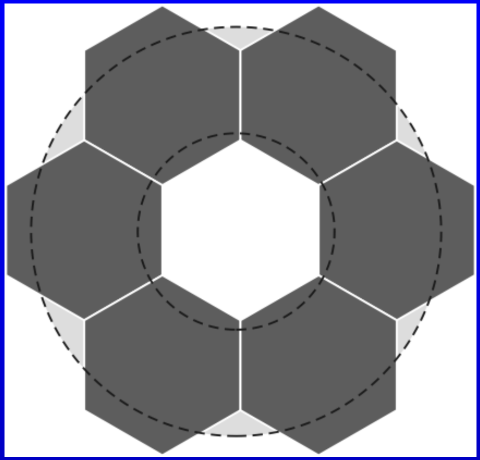


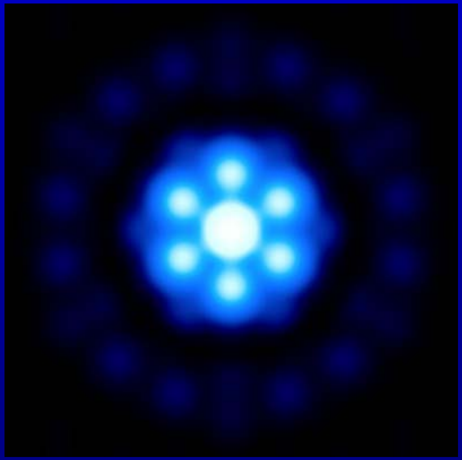
orientation 0 deg   orientation 0+60+120 deg   0+30+60+90+120+150 deg

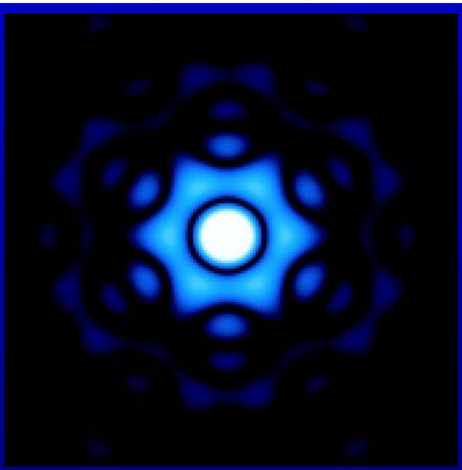
from LBT to ELT

LBT configuration at 0 + 60 + 120 deg	OWL configuration with segmented DM
mirror Ø 8m	mirror Ø 100m
aperture Ø 23m	aperture Ø 100m
DM Ø 90cm	DM Ø ~1m









ELT – *AO configuration*

proposal for alternative AO configuration for ELTs like OWL:

- 6 × Ø ~ 1m deformable mirrors (approx. LBT size)
  → 1,600 – 160,000 actuators each
- 6 × independent single-eye AO loops

⇒ 6 × Ø ~ 40m single-eye diffraction limited telescopes

- 1 × master AO loop for alignment and co-phasing of single-eyes
  → e.g. pyramid based WFS with low number of sub-apertures
  → determined corrections may be communicated as 'presets' to single-eye AO systems

⇒ **diffraction limited point spread function of Ø = 100m aperture**

summary

single full-aperture AO system with unsegmented DM:

- may be system of choice when aiming at best-possible PSF
- is hard at or even beyond technical limits at wavefront sensing, wavefront reconstruction and especially wavefront correction
  $\rightarrow$ segmentation/split of system perhaps unavoidable

multiple sub-aperture AO systems with master AO and segmented DM:

- individual sub-systems become more feasible (i.e. less complex) with increasing segmentation
- may introduce other areas of complexity with nested AO loops (i.e. master AO loop)
- may be only way to realise ELT AO systems (e.g. DM fabrication)