# TMT AO Performance

CATAC March 21, 2017

# Outline

1. AO parameters at ORM
   - TMT site testing team: AO parameters at ORM (Schöck presentation)
   - E-ELT site testing team (Vernin et al. 2011)
2. AO science − which parameters matter?
3. Comparison with EELT and LCO

# Summary of Site Parameters

| | | ORM | LCO | SPM | Armazones Mackenna | MK 13N | Honar |
|---|---|---|---|---|---|---|---|
| **Parameter** | Uncertainty | 2250 | 2500 | 2790 | 3114 | 4050 | 5400 |
| Usable time fraction | 0.03 | 0.72 | 0.75 | 0.80 | 0.86 | 0.72 | 0.79 |
| Median seeing (60 m) | 0.05 | 0.55 | 0.50 | 0.57 | 0.50 | 0.50 | 0.51 |
| AO Strehl merit function | 0.03 | 0.93 | 0.92 | 0.81 | 0.92 | 1.00 | 0.87 |
| Isoplanatic angle | 0.2 | 2.33 | 2.05 | 1.99 | 2.05 | 2.55 | 1.78 |
| Atm. coherence time | 0.5 | 6.0 | 5.0 | 5.1 | 5.0 | 7.3 | 5.21 |
| NIR sensitivity (Cohen metric) | 0.03 | 0.80 | 0.76 | 0.90 | 0.86 | 1.00 | 1.19 |
| PWV < 2mm | 0.03 | 0.20 | 0.23 | 0.26 | 0.50 | 0.54 | 0.76 |
| Mean night temperature | 1.0 | 7.6 | 13.0 | 5.4 | 7.5 | 2.3 | -7.3 |

# Adaptive Optics Turbulence Metrics

Form of metric: Strehl$^2$

- with Strehl = exp($-\sigma^2$)
- $\sigma$ : wavefront error (WFE) in radians
  - In principle, this needs to include implementation and NGS controlled low-order modes
  - However, normalizing to the best site is mathematically equivalent to only using the incremental WFE with respect to that site
  - Best site: Maunakea 13N for AO performance, because of low free-atmosphere turbulence strength and large isoplanatic angle
- $\sigma^2 \sim \lambda^{-2}$
  - Need to evaluate this at a variety of wavelengths
  - Using J (1.22 µm), H (1.63 µm), K (2.19 µm)

# Adaptive Optics Turbulence Metrics

Wavefront error is calculated by two methods (but only Method 2 is used in the final results):

1. From measured turbulence parameters:

$$\sigma^2 = \sigma_{fitting}^2 + \sigma_{bandwidth}^2 + \sigma_{isopl}^2$$

- Fitting error: $\sigma_{fitting}^2 \sim r_0^{5/3}$
- Bandwidth error: $\sigma_{bandwidth}^2 \sim \tau_0^{5/3}$
- Isoplanatism error: $\sigma_{isopl}^2 \sim \theta_2^{5/3}$
  - Note that this is $\theta_2$, not $\theta_0$ : taking the 2-DM correction of NFIRAOS into account
  - On-axis results by setting $\sigma_{isopl}^2 = 0$

2. Full NFIRAOS simulations:

- Use $\sigma^2$ from above only to define representative profiles
- Run these profiles through the AO group's MAOS simulations

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AO merit function: $Strehl^2$

- with Strehl = $\exp(-\sigma^2)$
- $\sigma$ : wavefront error (WFE)
- Turbulence contributions: fitting, bandwidth and isoplanatism errors

WFE for all candidate sites from **full end-to-end simulation of NFIRAOS** using measured profiles

More information in the backup slides

# Question: Isoplanatic Angle and Coherence Time

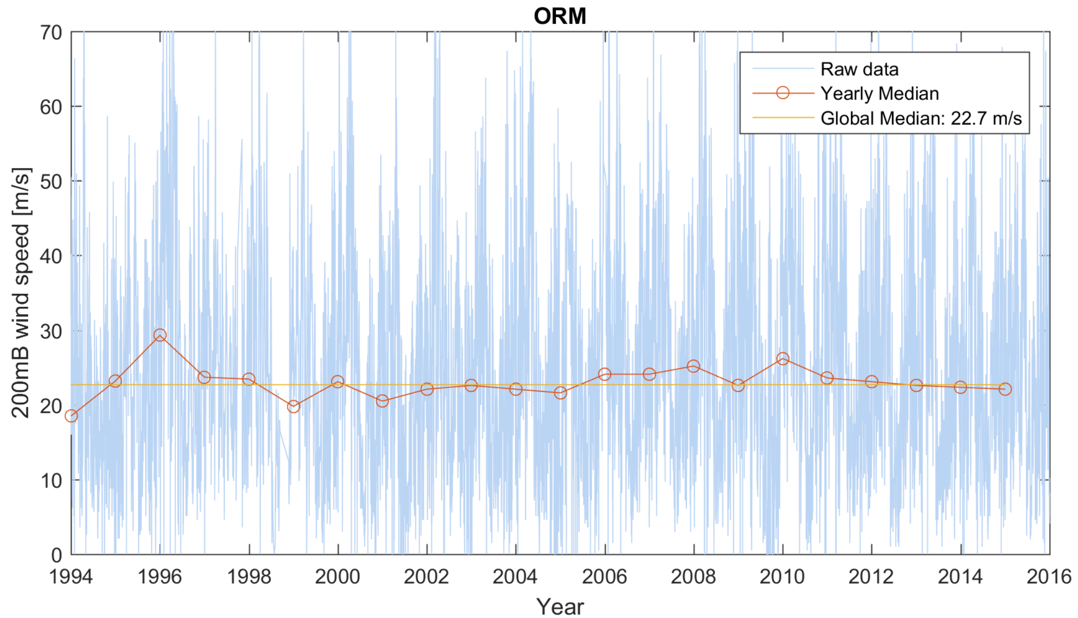
- Isoplanatic angle: SCIDAR provides reliable estimate
  - GL does not matter at all
  - We use MASS-resolution profiles from SCIDARs for comparison with other sites
- There is no question that the coherence time is large at ORM
  - This has been shown over and over again
    - 200 mbar wind speed (see next slide)
    - Weak high-elevation turbulence
    - Consistent with existing measurements
- No time series of $\tau_0$ measurements simultaneous with SCIDAR profiles available
  - Using estimate of average $\tau_0$ for all profiles for AO performance simulations
  - Some uncertainty on exact value, but:
    - Undoubtedly longer than at Chilean sites and probably a bit shorter than Maunakea
    - Sensitivity and "inverse" analyses show that this has a small effect on NFIRAOS performance
    - 6 ms is *likely conservative estimate* compared to other sites

# 200 mbar wind speed

| Site | $V_{200}$ (m s$^{-1}$) Mean | Std. dev. |
|---|---|---|
| ORM | 22.13 | 11.67 |
| La Silla | 33.35 | 12.94 |
| Mauna Kea | 24.33 | 12.30 |
| Paranal | 30.05 | 13.01 |
| San Pedro | 26.55 | 15.39 |

Table 9: Results of $V_{200}$ from NCEP/NCAR reanalysis data (1980–2002) at different astronomical sites (García-Lorenzo et al., 2005).

Published 200 mbar wind speeds

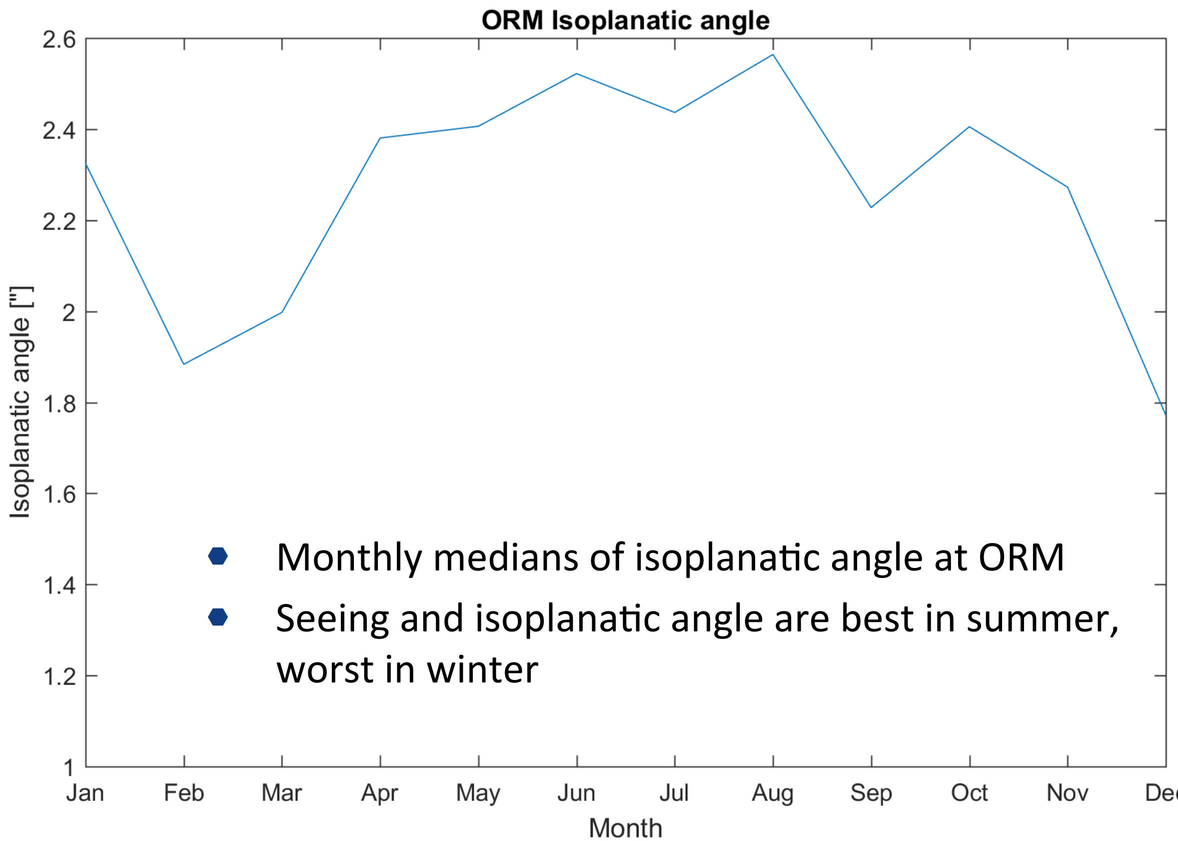



Our own analysis of radiosonde data

Two main conclusions:

- Data published by IAC in agreement with our analysis
  - This is also true for the sites not shown here
- There is no significant trend in the long-term statistics

# Seasonal variation




- Monthly medians of isoplanatic angle at ORM
- Seeing and isoplanatic angle are best in summer, worst in winter

# E-ELT@ORM

- EELT considered ORM. Site characterization work 2005-2009. Vernin et al. (2011)
  - Numbers are in good agreement with TMT numbers. Exception is even higher clear fraction

TABLE 3

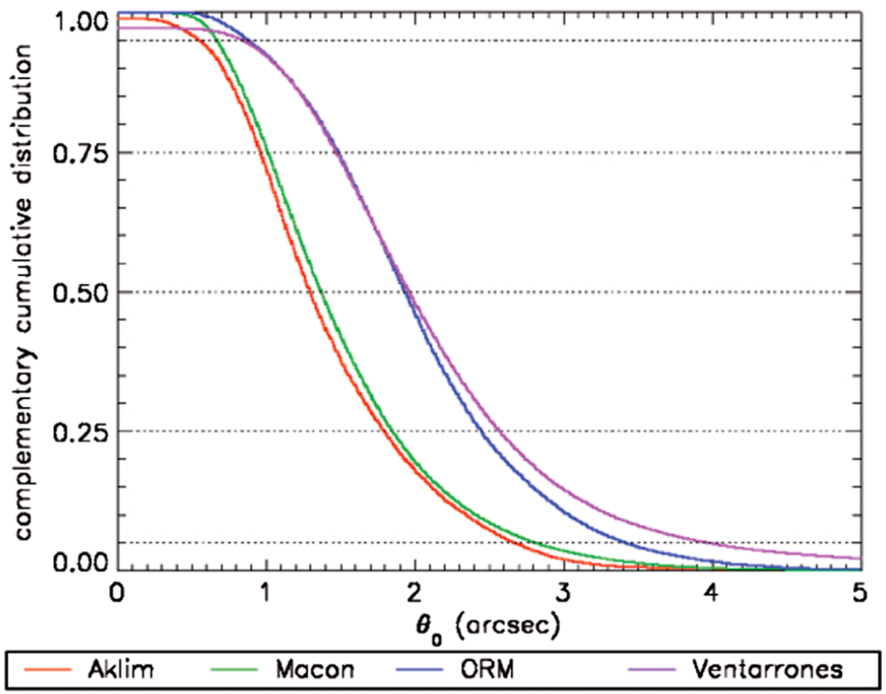
GLOBAL MEDIAN VALUES OBTAINED DURING ELT-DS PERIOD

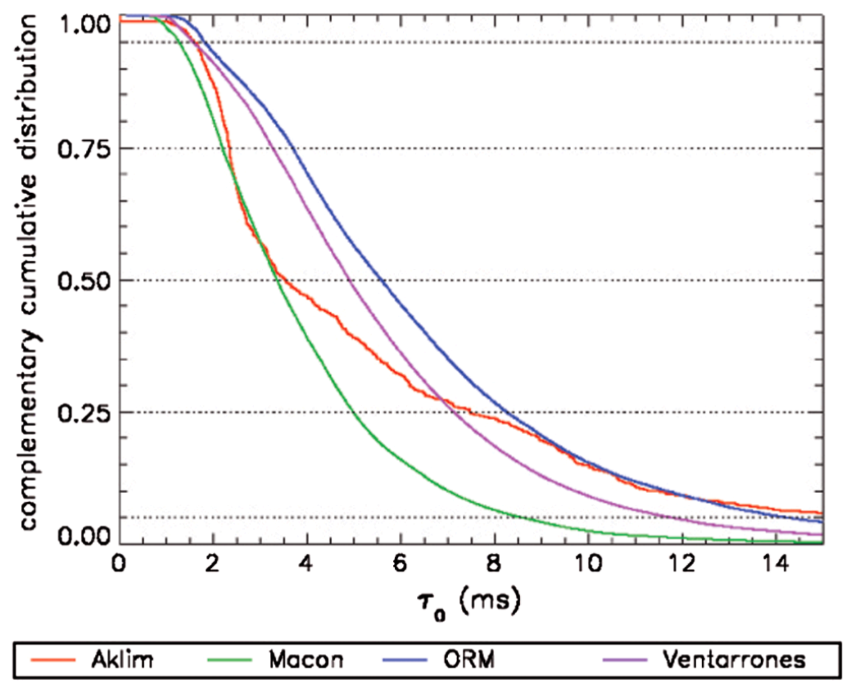
| Parameter | Instrument | Aklim | ORM | Ventarrones | Macon |
|---|---|---|---|---|---|
| Total seeing $\varepsilon$ ($''$) ........................ | DIMM | 1.00 | 0.80 | 0.91 | 0.87 |
| Isoplanatic angle $\theta_0$ ($''$) .................. | MASS | 1.29 | 1.93 | 1.96 | 1.37 |
| Coherence time $\tau_0$ (ms) ................ | MASS/DIMM/NOAA | 3.53 | 5.58 | 4.90 | 3.37 |
| Optical étendue $G_0$ ($m^2$ ms arcsec$^2$) ..... | MASS/DIMM/NOAA | 0.05 | 0.38 | 0.26 | 0.10 |
| Free-atmosphere seeing ($''$) $\varepsilon_{FA}$ ......... | MASS | 0.52 | 0.31 | 0.55 | 0.66 |
| Boundary-layer seeing ($''$) $\varepsilon_{BL}$ .......... | DIMM-MASS | 0.77 | 0.65 | 0.60 | 0.51 |
| Cloud: clear fraction (%) ................ | Satellite | 76 | 84 | 85 | 75 |
| Night temperature at 2 m (°C) .......... | AWS | 12.5 | 7.3 | 10.9 | −0.2 |
| Night relative humidity at 2 m (%) ..... | AWS | 32 | 21 | 14 | 20 |
| Night wind speed at 10 m (m/s) ....... | AWS | 6.2[a] | 8.2 | 5.9 | 11.3 |
| Night pressure at 2 m .................. | AWS | 767.0 | 772.4 | 727.0 | 581.8 |

[a] At Aklim, night wind speed was measured at 2 m.

# E-ELT@ORM

- Distributions of isoplanatic angle and coherence time.  Blue is ORM.  Purple is Ventarrones (near Paranal)




Vernin et al. (2011)

# Summary: AO characteristics

- ORM appears to be a very good site for AO
  - Long $\tau_0$ and $\theta$ make the site stand out; second only to MK
  - Wide-field AO is a strength of the TMT design. The good $\theta$ will be beneficial and TMT could have the best off-axis correction.
- Usable time fraction is ~85% that of Armazones
  - Will need an adaptive queue to make best use of this time.

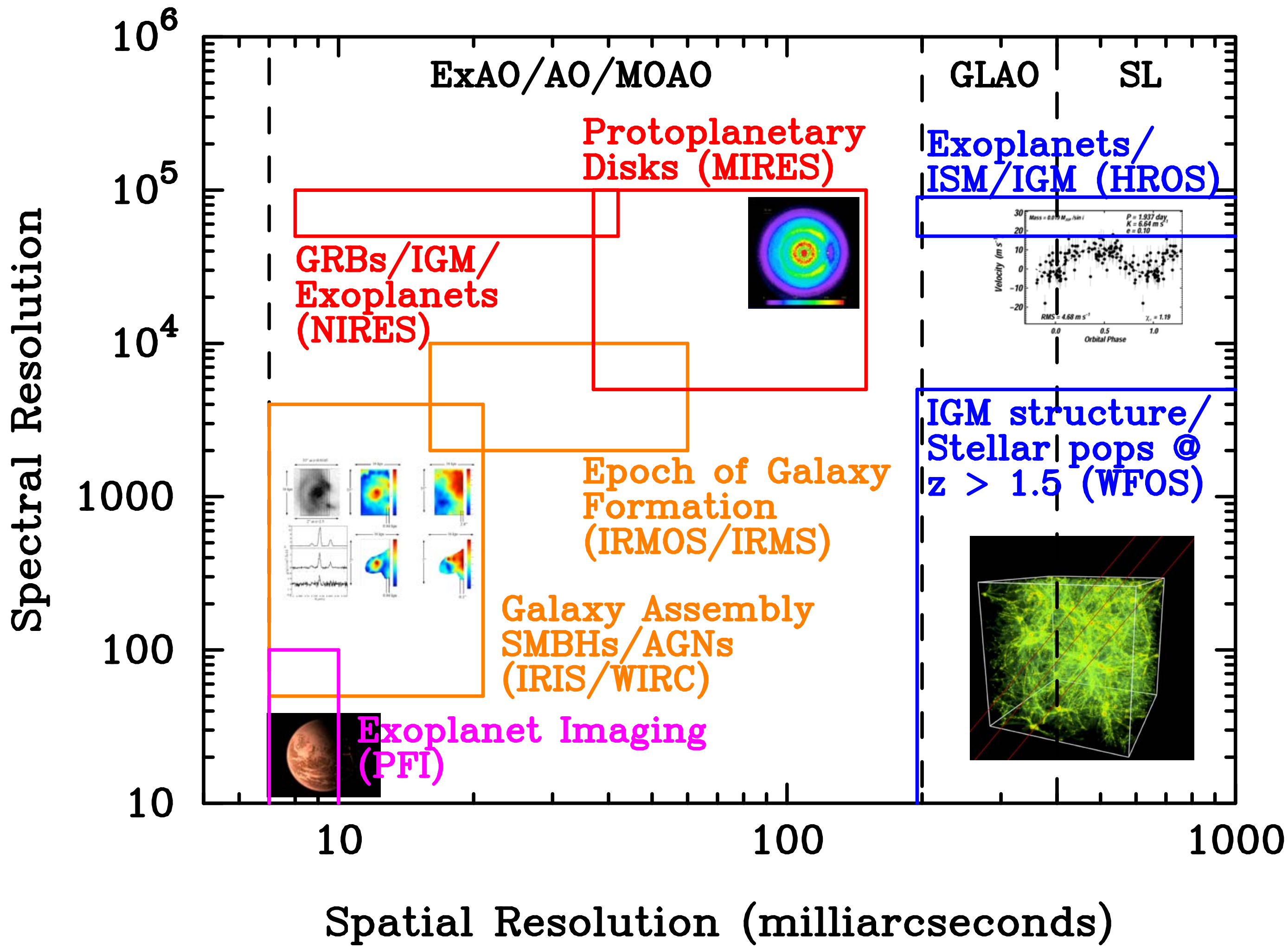
# 2. AO Science @TMT

See Simard's presentation http://ao4elt3.arcetri.astro.it/archive/slides_16445.ppt for lots more detail

# Summary of TMT Science Objectives and Capabilities

| Theme | Science Objectives | Observations | Requirements | Capabilities |
|---|---|---|---|---|
| Cosmology and Fundamental Physics (Dark energy, dark matter, physics of extreme objects, fundamental constants; DSC Section 3) | Mapping distribution of dark matter on large and small scales (CFP-[1,2,3,4], GAN-[3,4], GCT-1)<br>General Relativity in new mass regime◆ (GAN-[4,D], SSE-4)<br>Very precise expansion rate of Universe (CFP-2)<br>Mapping variations in constants over cosmological timescales<br>Physics of extreme objects ◆ (SSE-[2,3,D]) | Proper motions in dwarf galaxies<br>Wide-field optical spectroscopy of $R$ = 24.5 galaxies<br>Microarcsecond astrometry<br>Transient events lasting > 30 days<br>High spectral resolution observations of quasars and GRBs | $\lambda$ = 0.31-0.62μm, 2-2.4μm<br>$R$ = 1000 - 50000<br>Very efficient acquisition<br>0.05 mas astrometry stable over 10 years<br>Field of view > 10′ | SL/WFOS<br>SL/HROS<br>MCAO/IRIS/WIRC<br>MCAO/ NIRES |
| The Early Universe (First objects, IGM at z > 7; DSC Section 4) | Detection of metal-free star formation in First Light objects◆ (GAN-2, GCT-4)<br>Mapping topology of re-ionization (GCT-4)<br>Structure and neutral fraction of IGM at z > 7 (CFP-1, GCT-4) | Multiplexed, spatially-resolved spectroscopy of faint objects<br>High spectral resolution, near-IR spectroscopy | $\lambda$ = 0.8 – 2.5 μm<br>$R$ = 3000 – 30000<br>$F$ = 3 x 10-20 ergs $s^{-1}cm^{-2}Å^{-1}$<br>Exposure times > $15e^3$s | MCAO/ IRMS/IRIS<br>MOAO/ IRMOS<br>MCAO/ NIRES |
| Galaxy formation and the IGM (DSC Section 5) | Baryons at epoch of peak galaxy formation◆ (CFP-1, GAN-1, GCT-[1,2])<br>2D Velocity, SFR, extinction & metallicity maps of galaxies at $z$ = 5-6◆ (CFP-3, GAN-1, GCT-[1,2])<br>IGM properties on physical scales < 300 kpc◆ (GAN-1, GCT-2) | Optical/near-IR multiplexed diagnostic spectroscopy of distant galaxies & AGNs<br>Optical/near-IR multiplexed identification spectroscopy of extremely faint high redshift objects (to R~27)<br>Spatially-resolved spectroscopy | $\lambda$ = 0.31 – 2.5 μm<br>$R$ = 3000-5000, 50000<br>Very efficient acquisition<br>Multiplexing factor > 100 | SL/WFOS<br>SL/HROS<br>MCAO/IRIS/IRMS<br>MOAO/ IRMOS |
| Extragalactic supermassive black holes (DSC Section 6) | Demographics of black holes over new ranges in mass and redshift◆ (GAN-4, GCT-3)<br>Dynamical measurements out to $z$ = 0.4◆ (GAN-4,GCT-[1,3])<br>Scaling relations out to $z$ = 2.5 and masses at z>6◆ (GAN-4, GCT-[1,3]) | Spatially-resolved spectroscopy of galaxy cores | $\lambda$ = 0.8 – 2.5 μm<br>$R$ = 3000-5000<br>Precise positioning | MCAO/IRIS<br>MOAO/ IRMOS |
| Galactic Neighborhood (DSC Section 7) | Abundance of oldest stars in Milky Way (CFP-4, GAN-[2,3], SSE-2)<br>Chemical evolution in Local Group galaxies◆ (GAN-2)<br>Diffusion and mass loss in stars (GAN-1, SSE-1)<br>Resolved stellar populations out to Virgo cluster◆ (GAN-[2,3]) | High spectral resolution optical and near-IR spectroscopy<br>High-precision photometry in crowded fields | $\lambda$ = 0.33-0.9, 1.4-2.4 μm<br>$R$ = 4000, 40000-90000<br>Photometry precision of 0.03 mag at Strehl = 0.6 | SL/HROS<br>MCAO/ NIRES<br>MCAO/IRIS/WIRC<br>SL/WFOS |
| Planetary Systems and Star Formation (physics of star formation,proto-planetary disks, exoplanets; DSC Section 8, Section 9) | Origin of mass in stars (GAN-[1,2], PSF-1)<br>Architecture of planetary systems (PSF-[2,3,D])<br>Deposition of pre-biotic molecules onto protoplanetary surfaces (PSF-2)<br>First direct detection of reflected-light Jovians (PSF-2)<br>Characterization of exo-atmospheres (e.g., oxygen) (PSF-[3,4,D]) | High-precision, crowded field photometry<br>Diffraction-limited, high spectral resolution mid-IR spectroscopy<br>Very high Strehl AO-assisted imaging: precise wavefront control<br>High spectral resolution optical and near-IR spectroscopy | $\lambda$ = 1 – 25 μm<br>$R$ = 4000, 30000-100000<br>Low telescope emissivity<br>Dry site (PWV < 5 mm)<br>Fixed gravity vector and thermal control<br>Very efficient acquisition<br>Contrast ratio of $10^8$–$10^9$ | MCAO/IRIS<br>MIRAO/ MIRES<br>MCAO/ NIRES<br>SL/HROS<br>ExAO/PFI |
| Our Solar System (outer parts, surface physics and atmospheres; (DSC Section 10) | Composition of Kuiper Belt Objects and comets (PSF-2)<br>Monitoring weather, (cryo-) vulcanism and tectonic activity◆ | Spatially resolved spectroscopy of objects in solar system<br>Transient events (hours to years) | $\lambda$ = 1-10 μm<br>$R$ = 1000 – 100000<br>Non-sidereal tracking<br>Fast response time | MCAO/IRIS/WIRC<br>MCAO/ NIRES<br>MIRAO/ MIRES |

# Strong Overlap Between Science and Instrumentation






From Luc Simard: http://ao4elt3.arcetri.astro.it/archive/slides_16445.ppt

# AO science

- Good on-axis performance
  - Key parameter is free atmosphere seeing
  - E.g. Solar system objects, high redshift galaxies, quasars
- Wide field AO
  - Requires good free atmosphere seeing and large isoplanatic angle for consistent Strehl across the corrected FOV
  - E.g. Resolved populations of nearby galaxies, Galactic centre
- Extreme AO (PFI)
  - $\tau_0$ is the most important parameter
  - E.g. Exoplanet imaging

# 3. Comparison with E-ELT

# Comparison with E-ELT

- Sites are comparable for relevant AO parameters, though usable time fraction at ORM is lower.
- AO performance therefore comes down to telescope/enclosure design as well as that of the AO system itself
  - The advertised AO performance of TMT/NFIRAOS and EELT/MAORY are quite different. Advertised Strehl ratios in K are 0.75 (TMT) and 0.3 (EELT).
  - There is a lot more to it than mirror diameter

# The Importance of Adaptive Optics

- Seeing-limited observations and observations of resolved sources

$$Sensitivity \propto \eta D^2 \quad (\sim 14 \times 8\text{m})$$

- Background-limited AO observations of unresolved sources

$$Sensitivity \propto \eta S^2 D^4 \quad (\sim 200 \times 8\text{m})$$

- High-contrast AO observations of unresolved sources

$$Sensitivity \propto \eta \frac{S^2}{1-S} D^4 \quad (\sim 200 \times 8\text{m})$$

$$Sensitivity = 1/\text{time required to reach a given s/n ratio}$$

$$\eta = \text{ throughput}, S = \text{ Strehl ratio}. D = \text{ aperture diameter}$$



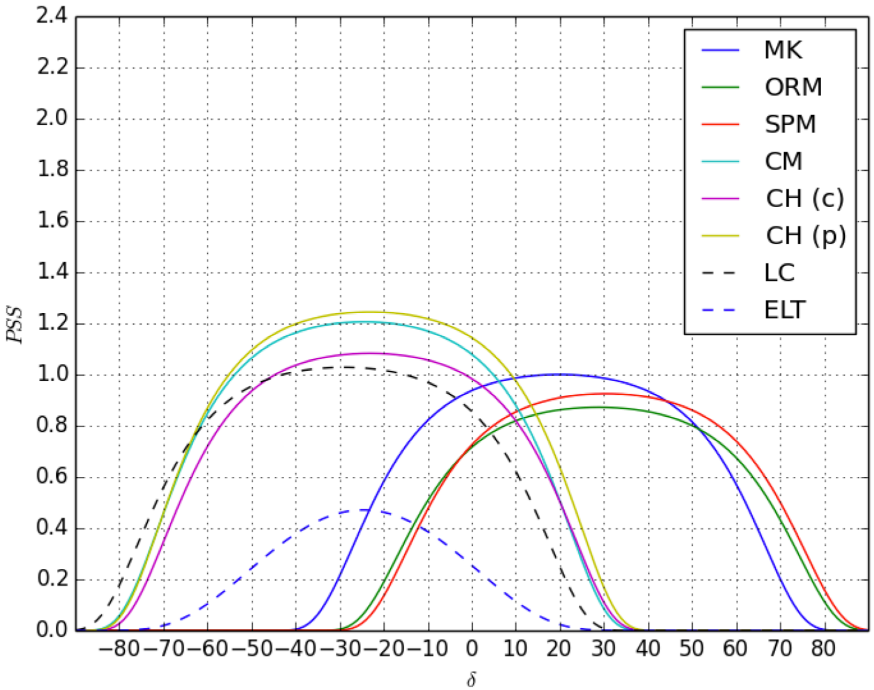
From Luc Simard: http://ao4elt3.arcetri.astro.it/archive/slides_16445.ppt

# Design considerations

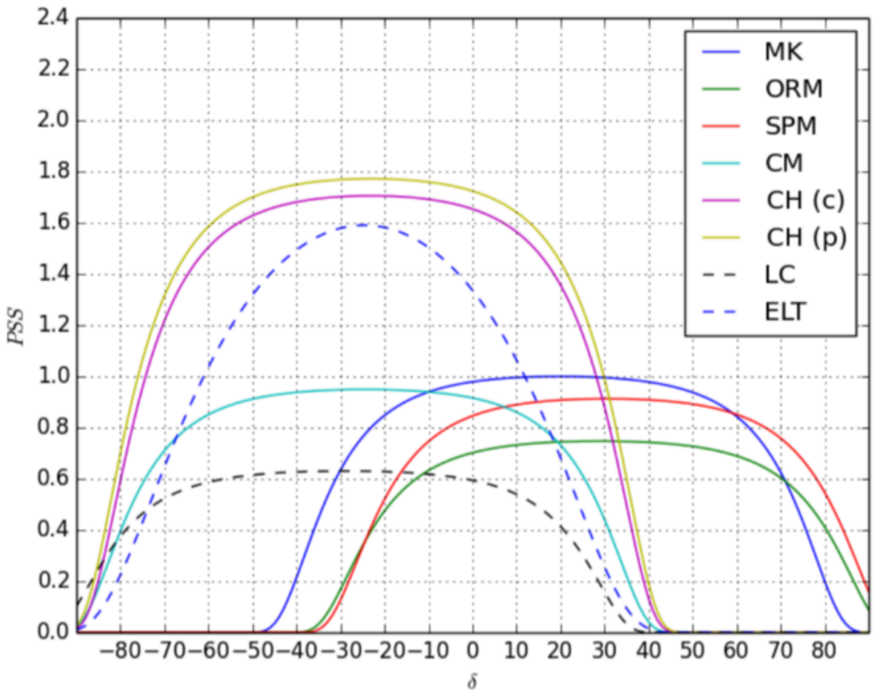
- Both NFIRAOS and MAORY use similar deformable mirror technology and are therefore limited by the same number of actuators.
  - At a fixed number of actuators, the size of a sub-aperture (the unit area over which AO corrections can be sensed and made) will be larger and Strehl performance will be lower.
- Telescope control system can eat up some of your "AO performance capital" to compensate for the floppiness of your telescope structure.
  - This is what the E-ELT designers had to do. The deformable mirror corrections are an integral part of the telescope control system because they had to make the structure "floppy" enough to keep it down to a reasonable mass.
  - The E-ELT cannot simply freeze all of its deformable mirror and operate. The adaptive mirror (M4) in the E-ELT architecture is a single point failure. If it does not work, the whole telescope will not work. The E-ELT will always have to be running adaptively. The TMT telescope structure is stiff enough to avoid this.
- The other "ELT image quality killer" is windshake. An un-shielded ELT will suffer about 800 milli-arcseconds of windshake jitter. The DSL Calotte will be a key ingredient in the TMT performance.

# On-axis AO corrected PSS

J




K




Hickson and Carlberg 2016

# TMT@ORM

- 20% less sensitive than at MK13N for NIR AO observations. Comparable to TMT@LCO
- Outperforms EELT in J, but a factor 2 lower PSS in K.
  - Lower usable time fraction leads to another 20-30% deficit relative to EELT
  - The implementation of the AO system has a large effect
- Conclusion: TMT is likely to be highly competitive for NIR AO observations, even at ORM.