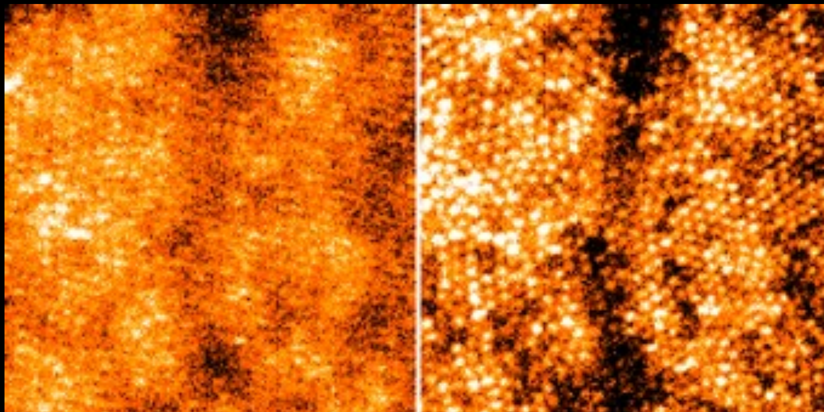
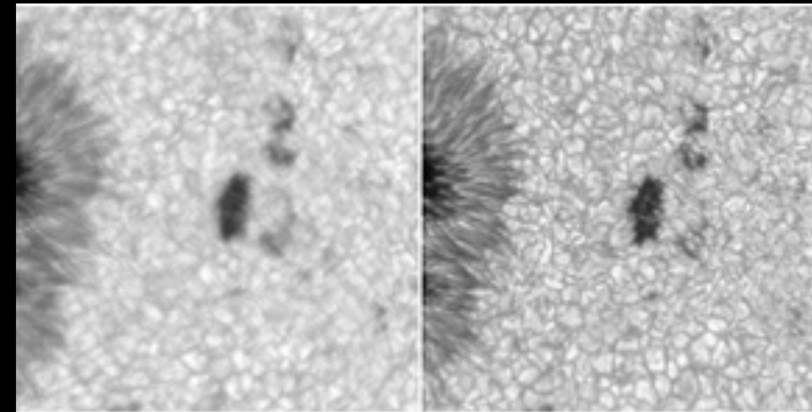
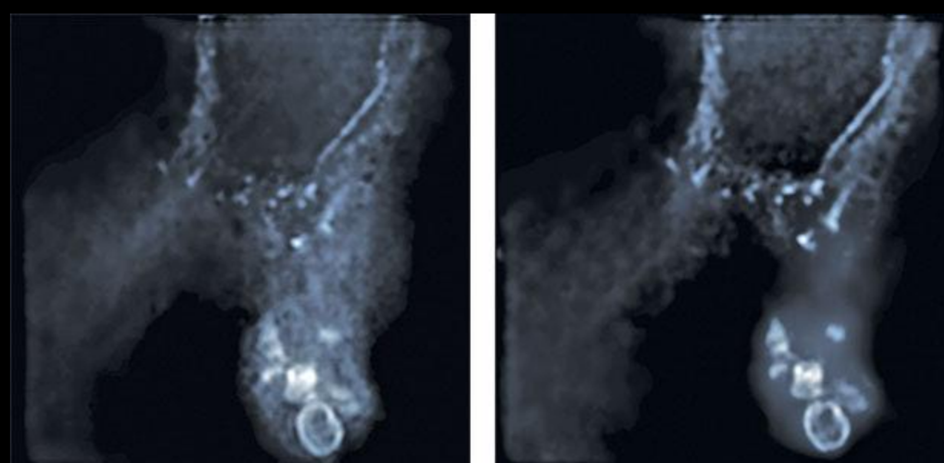




Adaptive Optics

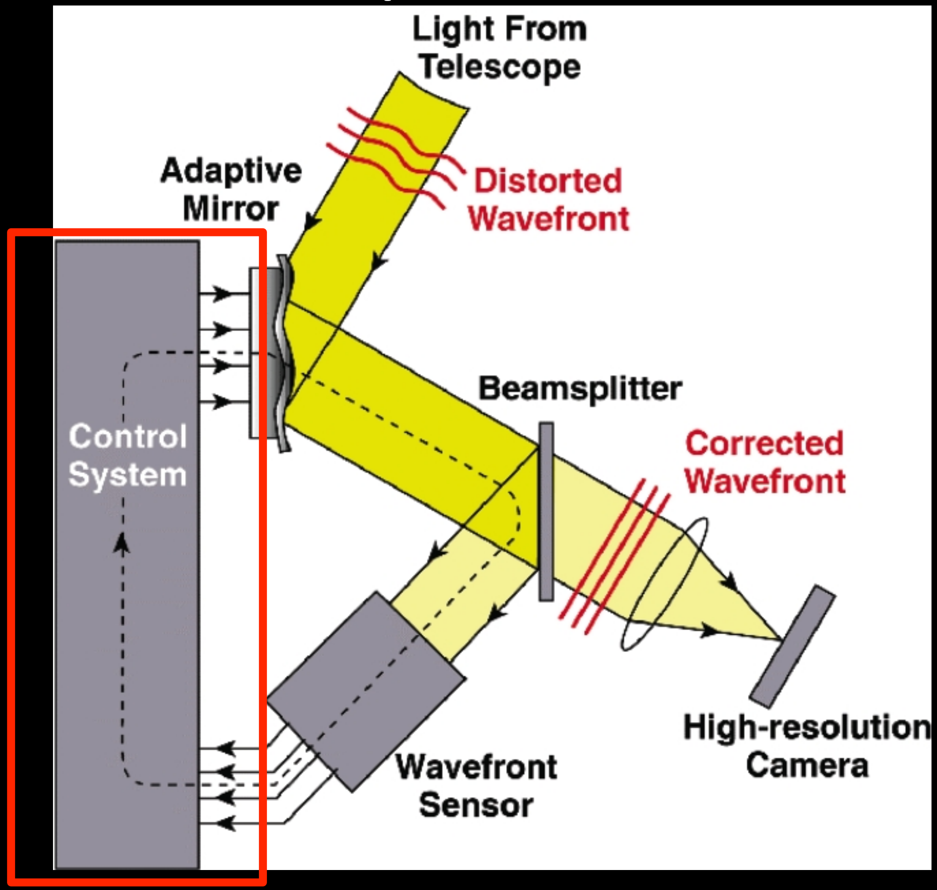
Special Topic in Astrophysics

ASTRON 250 - Fall 2013



AO control: what is it?

- Not the most iconic part of an AO system, but arguably the most important!

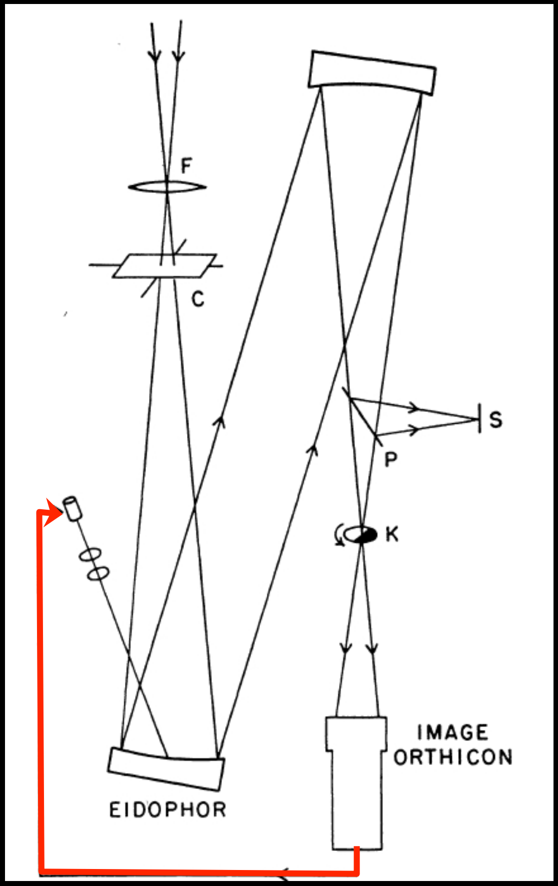


AO control: defining the problem

- Input = WFS measurements
- Output = DM commands
- How to go from A to Z while ensuring
  - Efficiency
  - Reliability
  - Stability
  - Optimal (minimum?) phase residuals
- Take into account response-to-command and previous position (relative command)

“Direct” WFS-DM link

- Reduce the intermediate steps and pieces of hardware to the bare minimum
- Babcock’s idea had no computer!
  - Direct e^- detection/transport
- Limitations:
  - 1:1 mapping of WFS and DM
  - No stability control
  - Sensitivity to WFS noise



Babcock (1953)

A simple matrix representation

- Act on each actuator & record the effect on WFS
  - This is the poke matrix, the inverse of which is the control matrix
  - No explicit reconstruction of the phase needed
- It is often more convenient to first reconstruct the wavefront from the WFS and then determine the appropriate DM commands
  − More operations to effectuate
  \+ Quality check possible in intermediate step

A simple matrix representation

- In general, matrix is rectangular and cannot be inverted directly (over-constraining needed)
  - Pseudo-inverse
  - Least square approach
  - Singular value decomposition (avoid singularities)
  - Sparse matrix techniques (faster computation)
  - Fourier transform reconstructor (better behavior, natural filtering)

A simple matrix representation

- Computing cost of matrix approach can be high/prohibitive, depending on situations
  - Can be problematic even for slow operations
    - Vector-matrix mult. is $O(n^2)$, but $O(n \log n)$ is possible
    - Memory requirements could be challenging for $n \approx 10^4$
- Matrix inversion can be performed ahead of time to save computing time, but control scheme is then fixed by design
  - No ability to adjust to situations

More advanced control methods

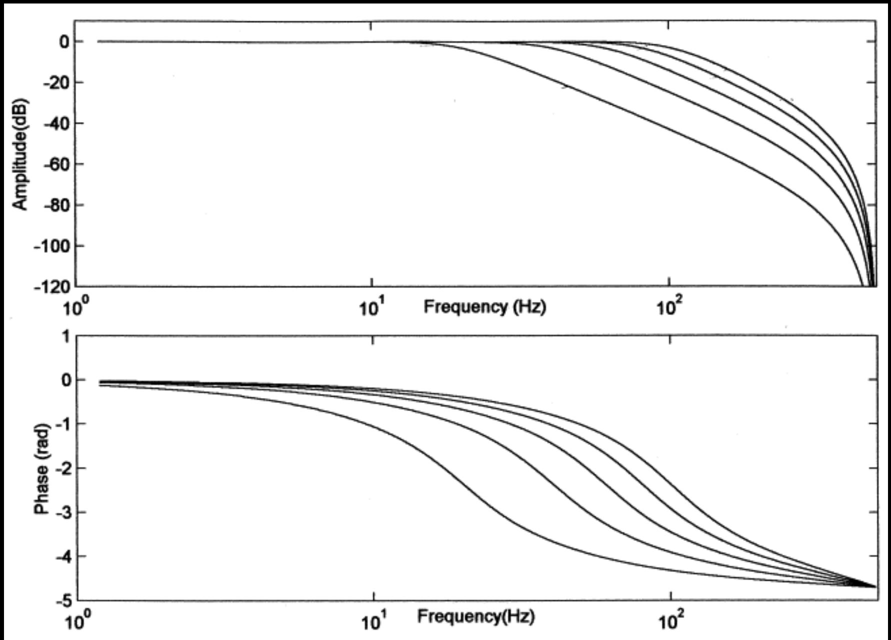
- It is useful to include prior knowledge about noise and/or wavefront corrugation in reconstruction step
  - Informed reconstruction (e.g., Kolmogorov spectrum)
- Ability to adjust control scheme regularly can improve efficiency/stability
  - variable gain in control loop
  - aberration-dependent control algorithm

AO control: key factors (I)

- Time (frequency) response of DM
  - Correction is delayed relative to sensing

Bode plots

- Bode plots represent the temporal transfer function of a system
  - Max temporal frequency ("bandwidth")
  - Frequencies at risk of overshooting

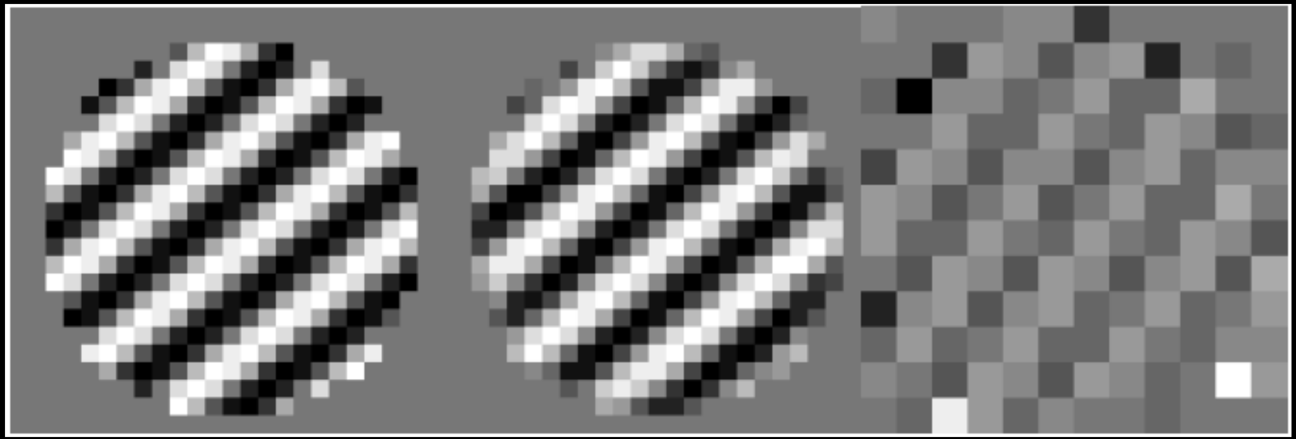


AO control: key factors (II)

- Time (frequency) response of DM
  - Correction is delayed relative to sensing
- Spatial sampling of DM and WFS
  - Cannot sense and/correct high spatial frequency modes (aliasing)
  - Blind/null/“phantom” modes

Aliasing

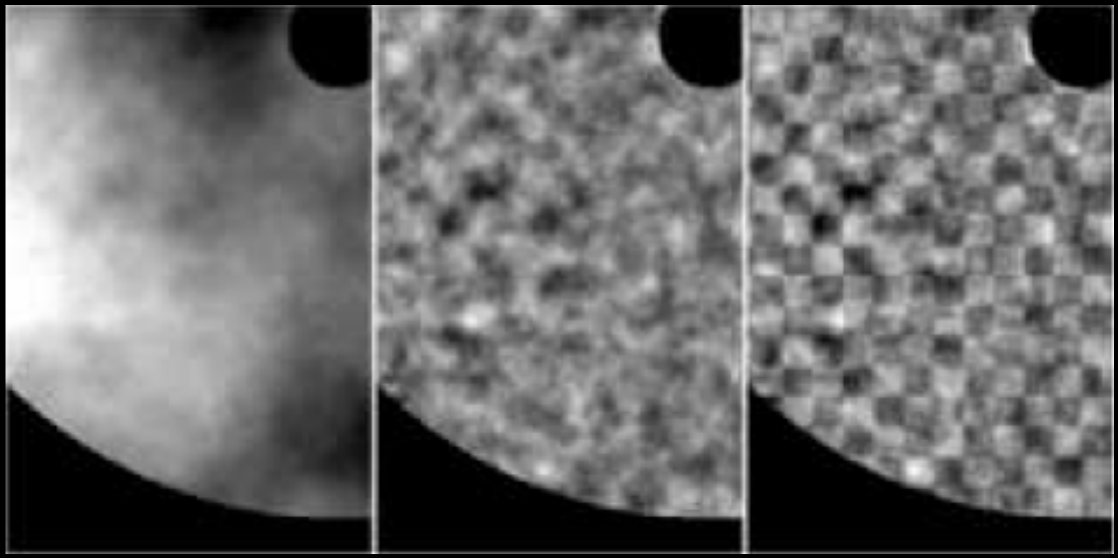
- If WFS more densely sampled than DM, some high-frequency modes can be sensed but not corrected for
  - Aliasing with lower-order modes

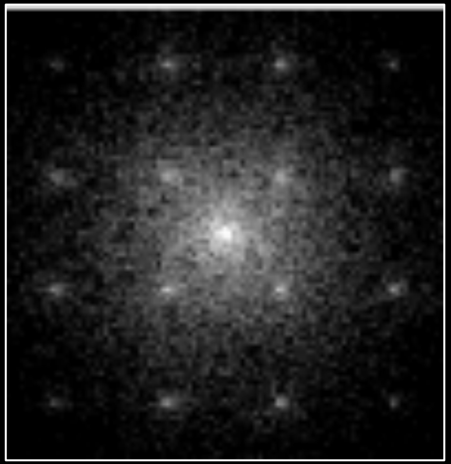


Evans et al. (2009)

Blind modes

- Depending on WFS geometry, even some low-order modes can be “invisible”
  - Global piston (don’t care in most cases…)
  - “waffle” for a S-H WFS (flat slope within aperture)





Makidon et al. (2005)

AO control: key factors (III)

- Time (frequency) response of DM
  - Correction is delayed relative to sensing
- Spatial sampling of DM and WFS
  - Cannot sense and/correct high spatial frequency modes (aliasing)
  - Blind/null/“phantom” modes
- Gain factors for DM commands
  - Trade-off between rapid correction and risk of overshoot/instability

DM gain

- High gain = immediate and large movement
  - Risk of overshooting and ringing
  - Memory loss of previous state(s), possibly oscillating around stable position
- Low gain = moving only a little
  - Slow to get to the correct position (N iterations)
  - May never be in the right state
- A tricky compromise that may not be constant

(Some) Complicating factors

- WFS noise and its propagation
  - Need to estimate noise and its statistical properties
- Influence function of DM
  - Limits ability to produce high-order correction
- Perturbations from different sources
  - Telescope wind shaking, AO bench vibrations
- Discretization of analogic commands
  - Limited precisions in correction

AO error budget: how well do we do?

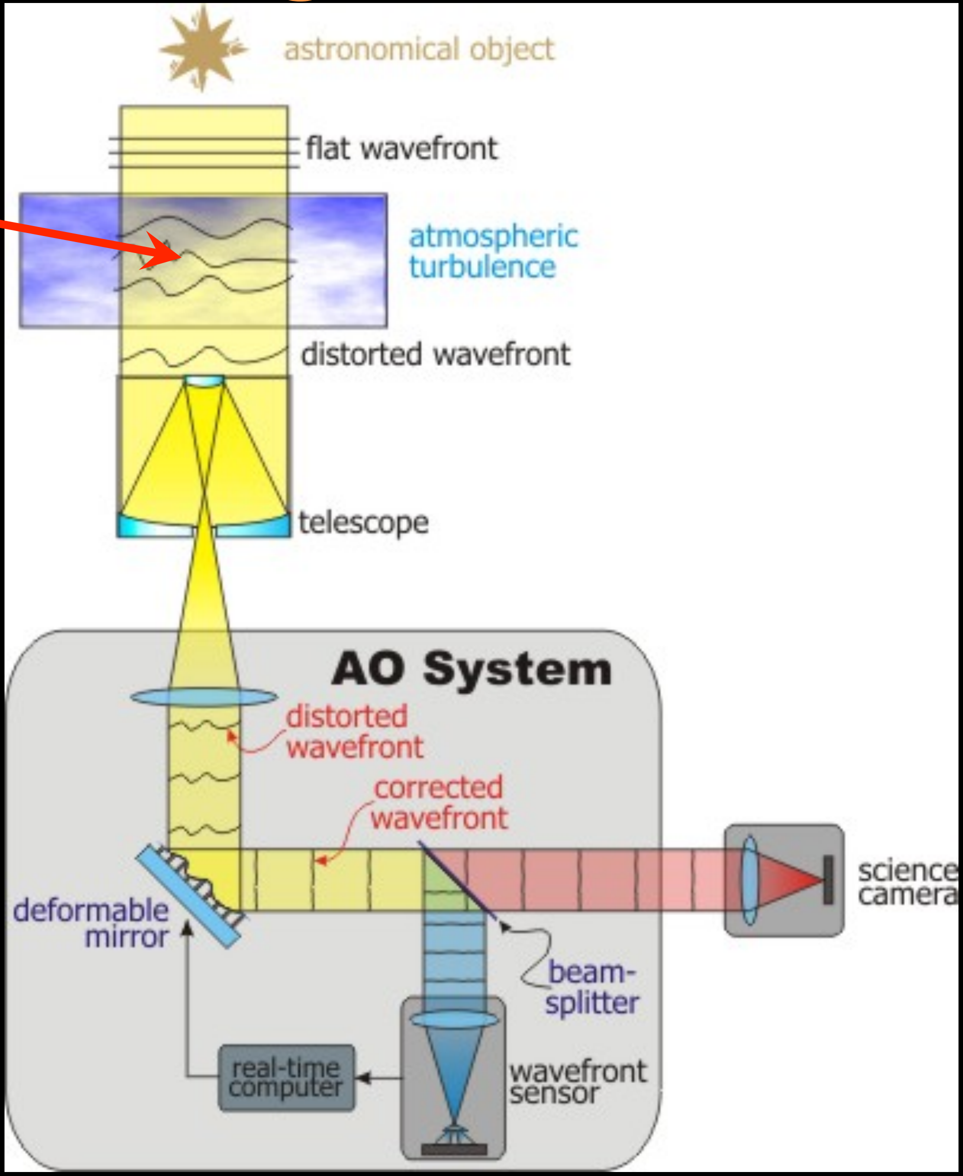
- The smaller the residual wavefront fluctuations, the better the image quality
- Usually measured with Strehl ratio
  - $SR = \exp -\sigma_{\varphi}^2 \,.\, \exp -\sigma_{I}^2$ (Maréchal approx.)
- In practice, phase fluctuations dominate (and may be the only one we can correct)
- Other possible metrics, such as contrast at a given position, or FWHM

AO error budget

Scintillation

$$\sigma_I^2 \approx [\sqrt{(\lambda H)} / r_0]^{5/3}$$

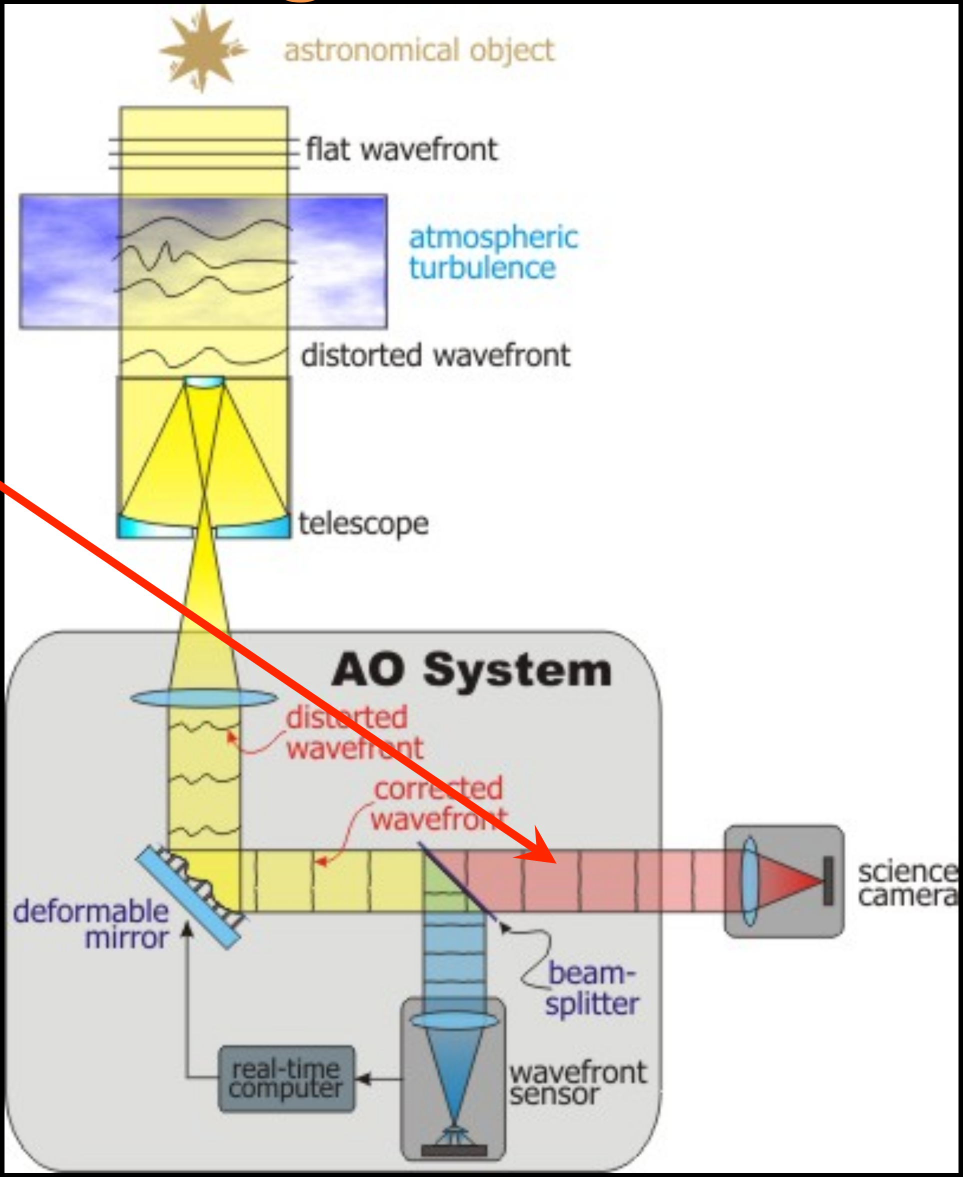
(Kolmogorov turb.)
Negligible!



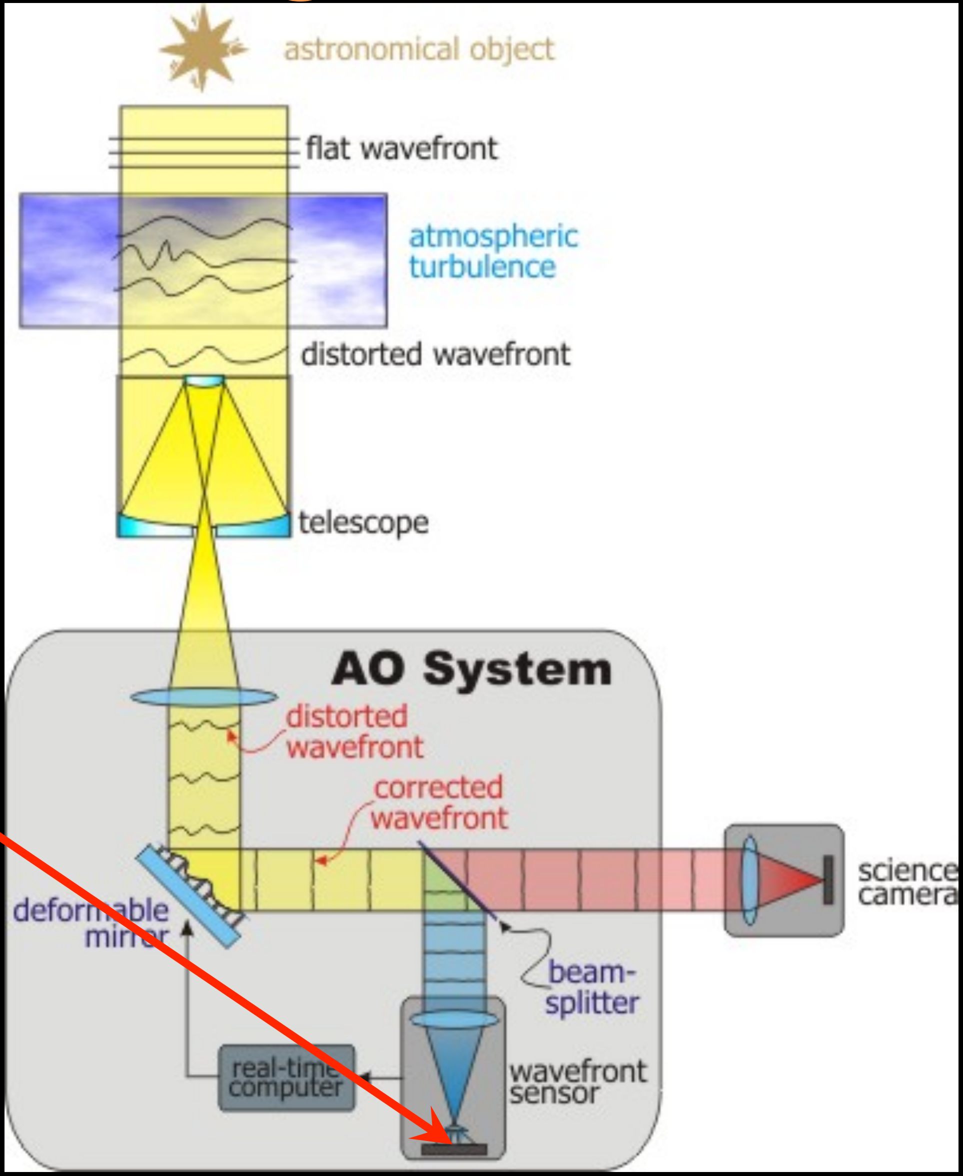
AO error budget

Non-common path errors

Can be estimated from calibration data acquisition (sharpening; also addresses static aberrations)



AO error budget



WFS errors

Photon/detector noise,
propagated through control loop;
extraneous light;
possibly spatially-dependent

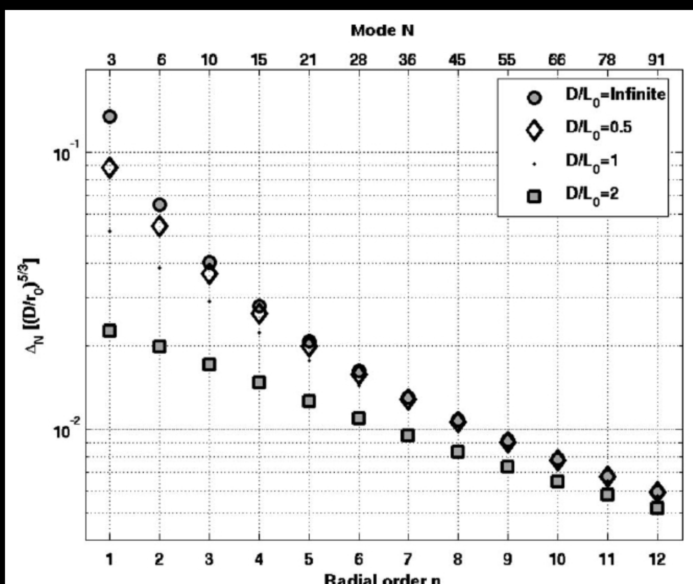
AO error budget

Reconstruction errors

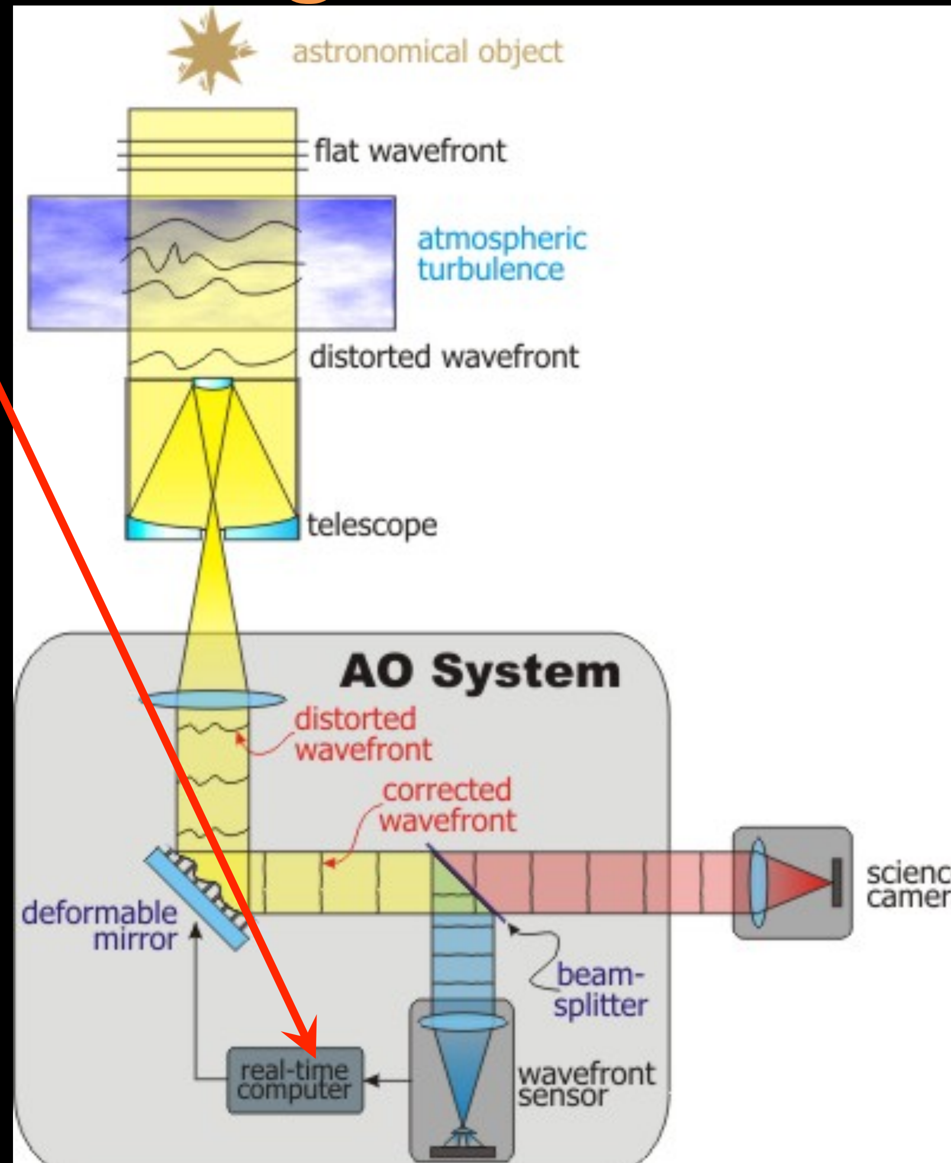
Number of corrected modes

$\sigma_{\varphi}^{2} \approx N_{m}^{\sqrt{3}/2}(D / r_{0})^{5/3}$

Aliasing, blind modes



Conan (2008)

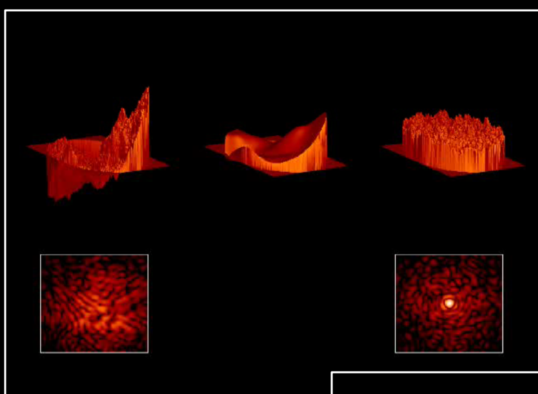


AO error budget

Fitting errors

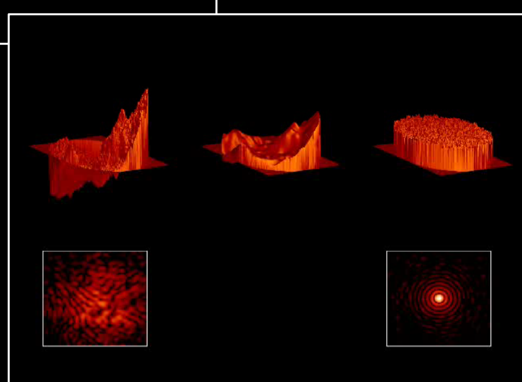
Ability of DM to match corrugated wavefront

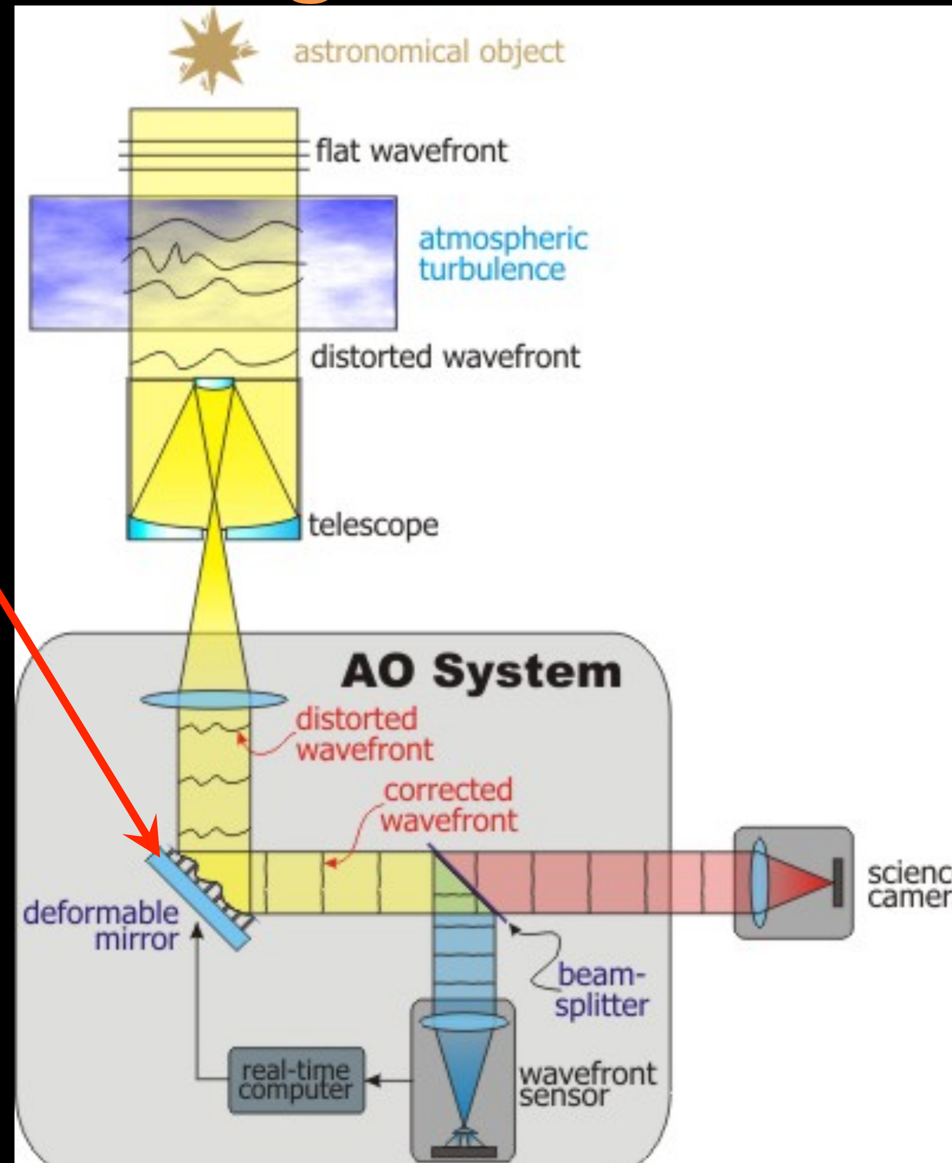
$\sigma_\varphi^{\,2} \approx (r_S / r_0)^{5/3}$



Regular AO

Extreme AO





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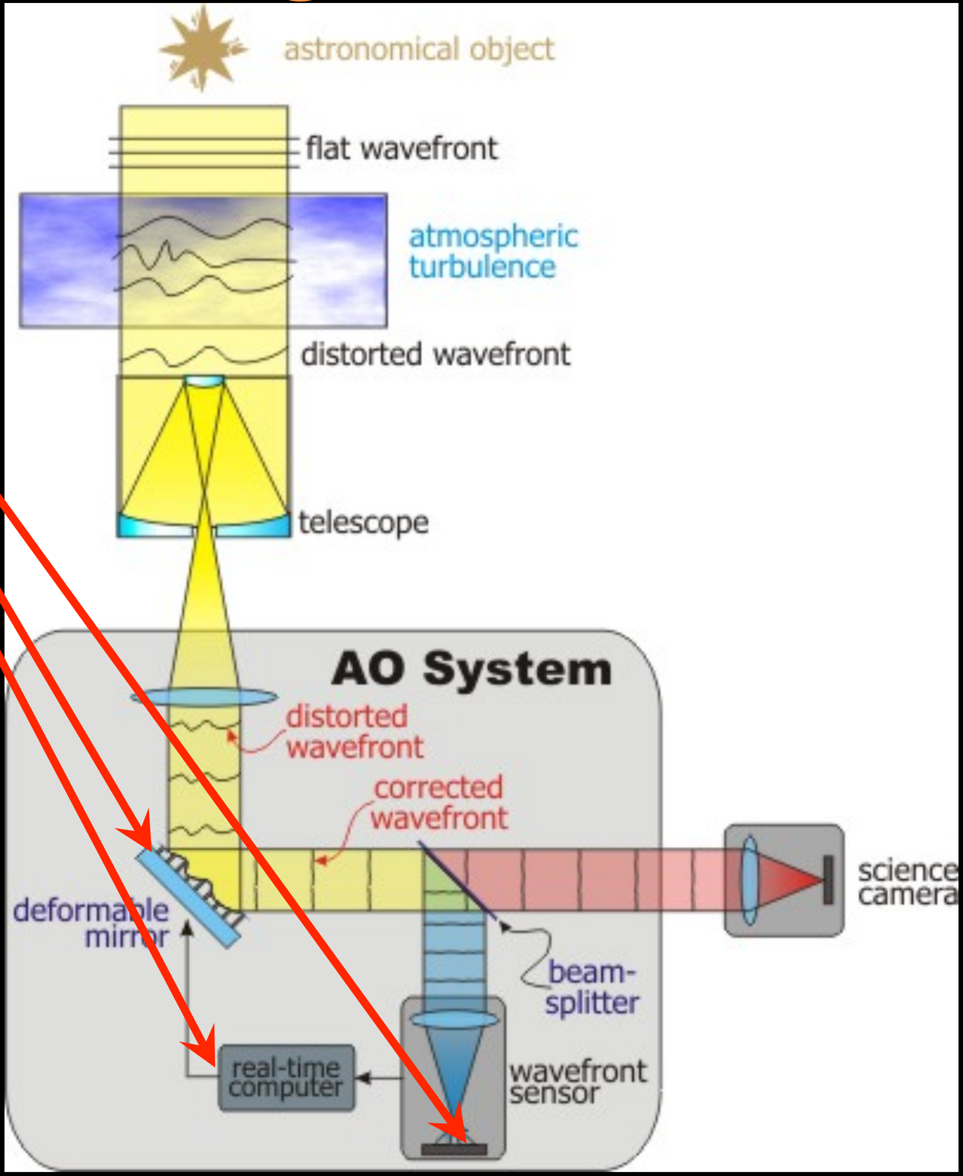
AO error budget

Bandwidth errors

AO loop is constantly late relative to turbulence

$$\sigma_{\varphi}^{2} \approx (f_{Greenwood} / f_{band})^{5/3}$$

where $f_{Greenwood} \approx v_{wind}/r_0$

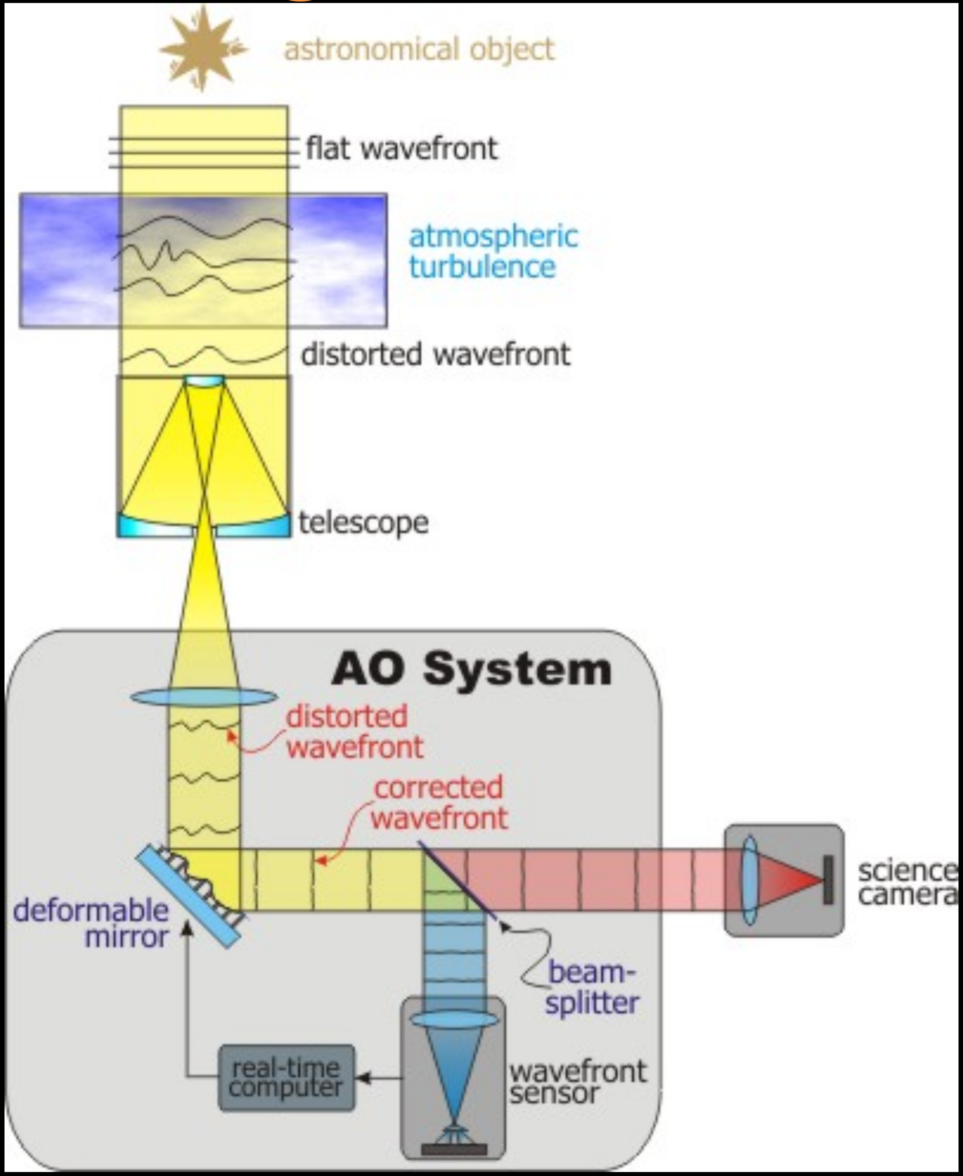


AO error budget

Many other sources of errors

- DM influence function
- WFS sampling errors
- Averaging within subapertures
- Anisoplanatism $\sigma_\varphi^2 \approx (\theta / \theta_0)^{5/3}$

- Discretization of control signal
- Electronic noises
- Dynamic calibration errors
- Interactions between DMs
- Extraneous modes (vibrations)



Next week readings

- AO for observing the Sun
  - von der Lühne (1985)
  - Rimmele (2000)
- AO for retinal imaging (A. Roorda's visit)