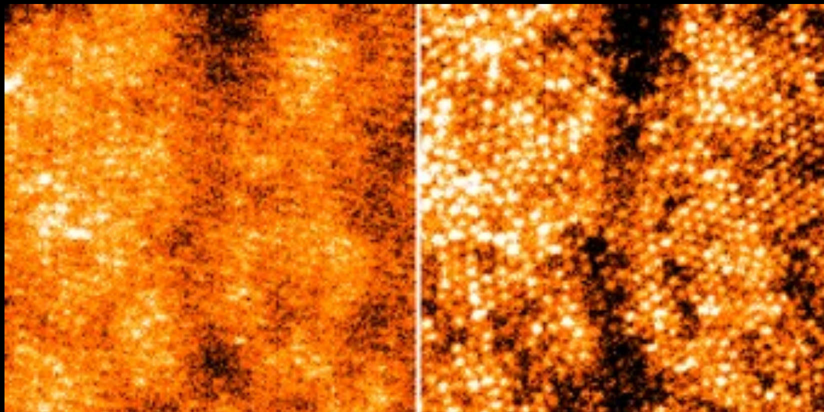
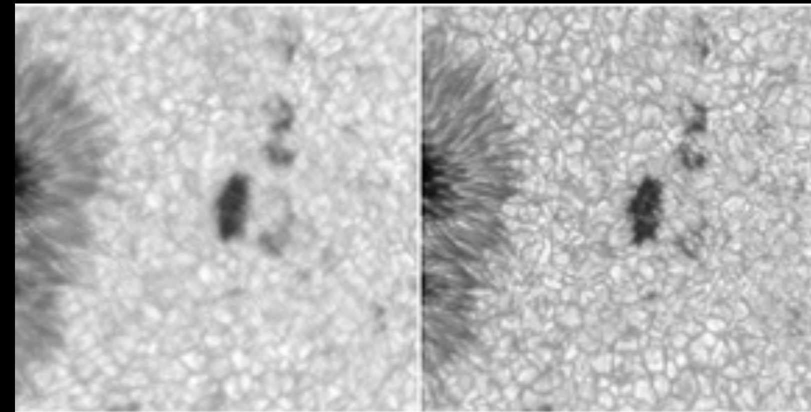
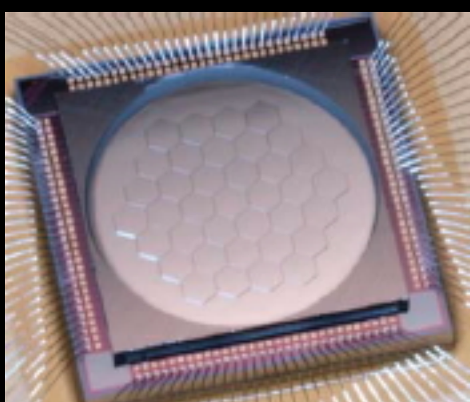


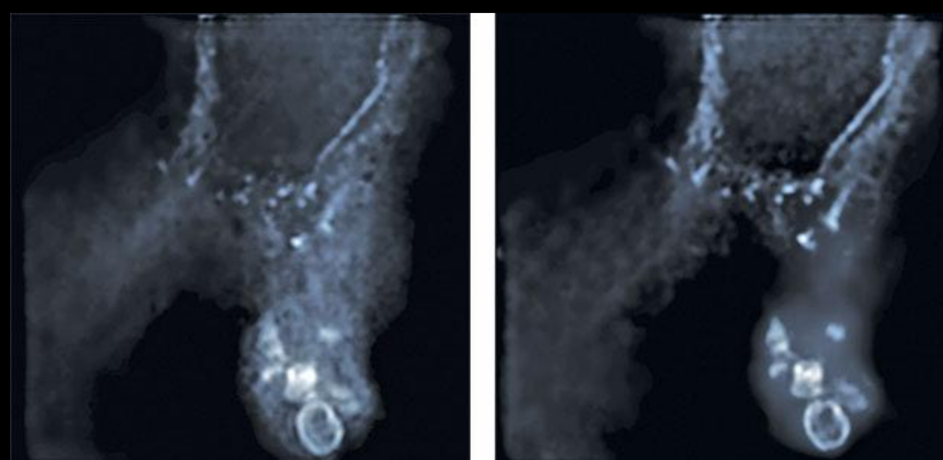


Adaptive Optics

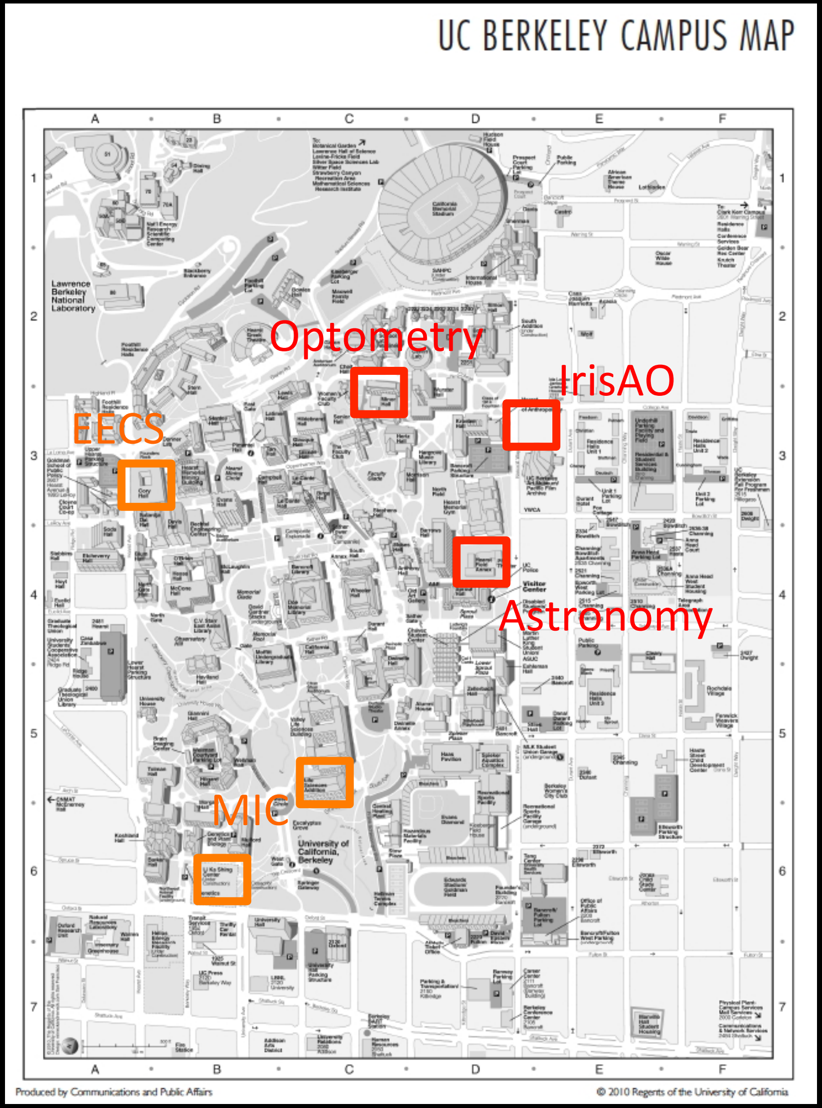
Special Topic in Astrophysics

ASTRON 250 - Fall 2013





World-wide topic, local expertise



Class practical aspects

- Syllabus
- Grading
  - Class participation
  - Final project & paper
- Content: readings & in-class discussions
- "Electronic" materials:
  - bDrive for sharing readings
  - Class website for lecture slides

Class final project

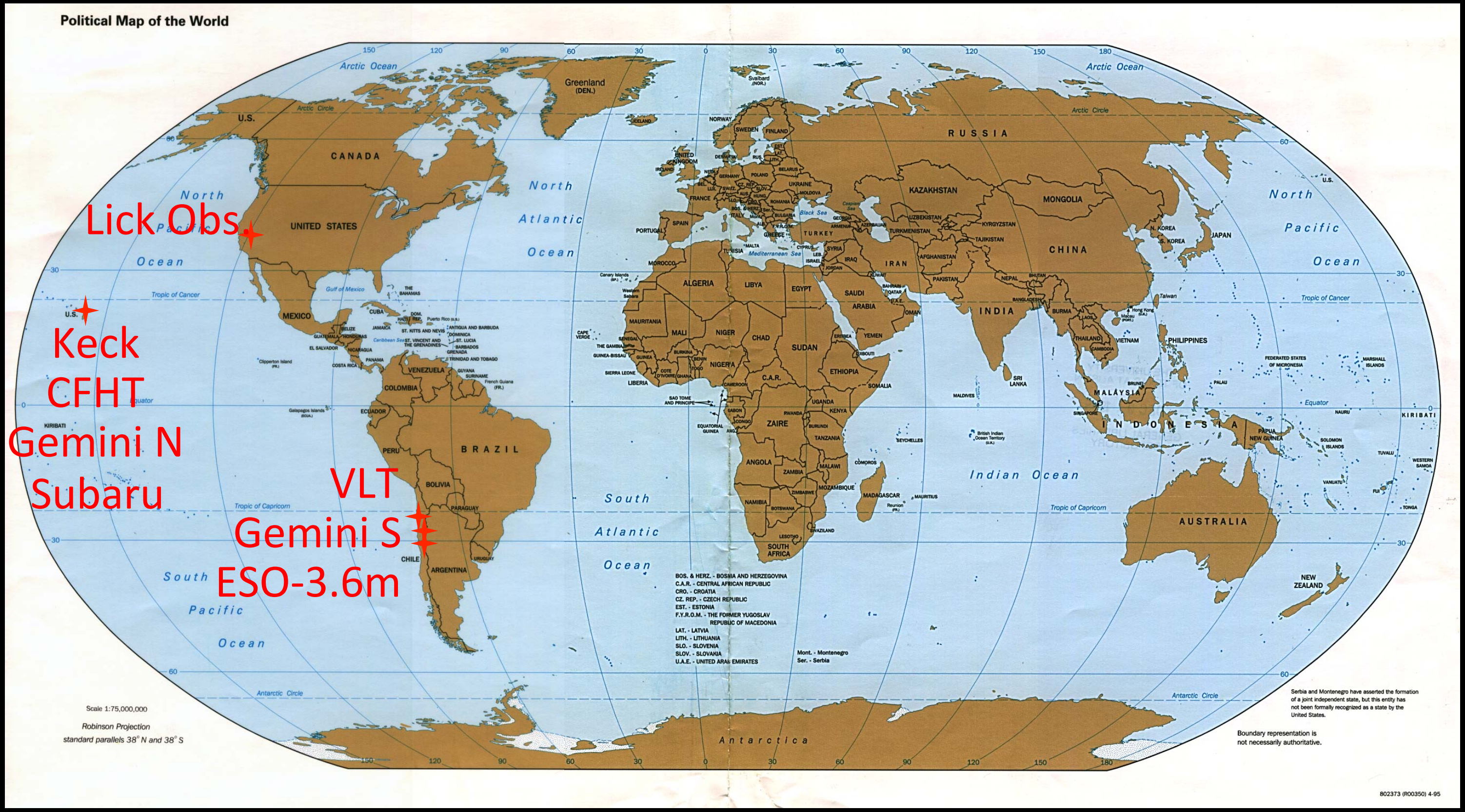
- Design an AO-related project (implementation not required!)
  - A science question that can be addressed with a particular type of AO
  - A new piece of hardware/control
- Detail the key requirements and how they fit in the framework discussed in class
- Final paper + presentation

External resources

- Key readings
  - *Principles of AO*, R. Tyson [Eng.]
  - *AO in astronomy*, F. Roddier ed. [Phy./Ast.]
  - *AO for astronomical telescopes*, J. Hardy [Phy./Ast.]
  - *AO for biological imaging*, J. Kubby ed. [e-book]
  - Many research articles (back to the source!)
- Websites
  - UC *Center for AO* (CfAO) cfao.ucolick.org
  - Many more…

Who are we?

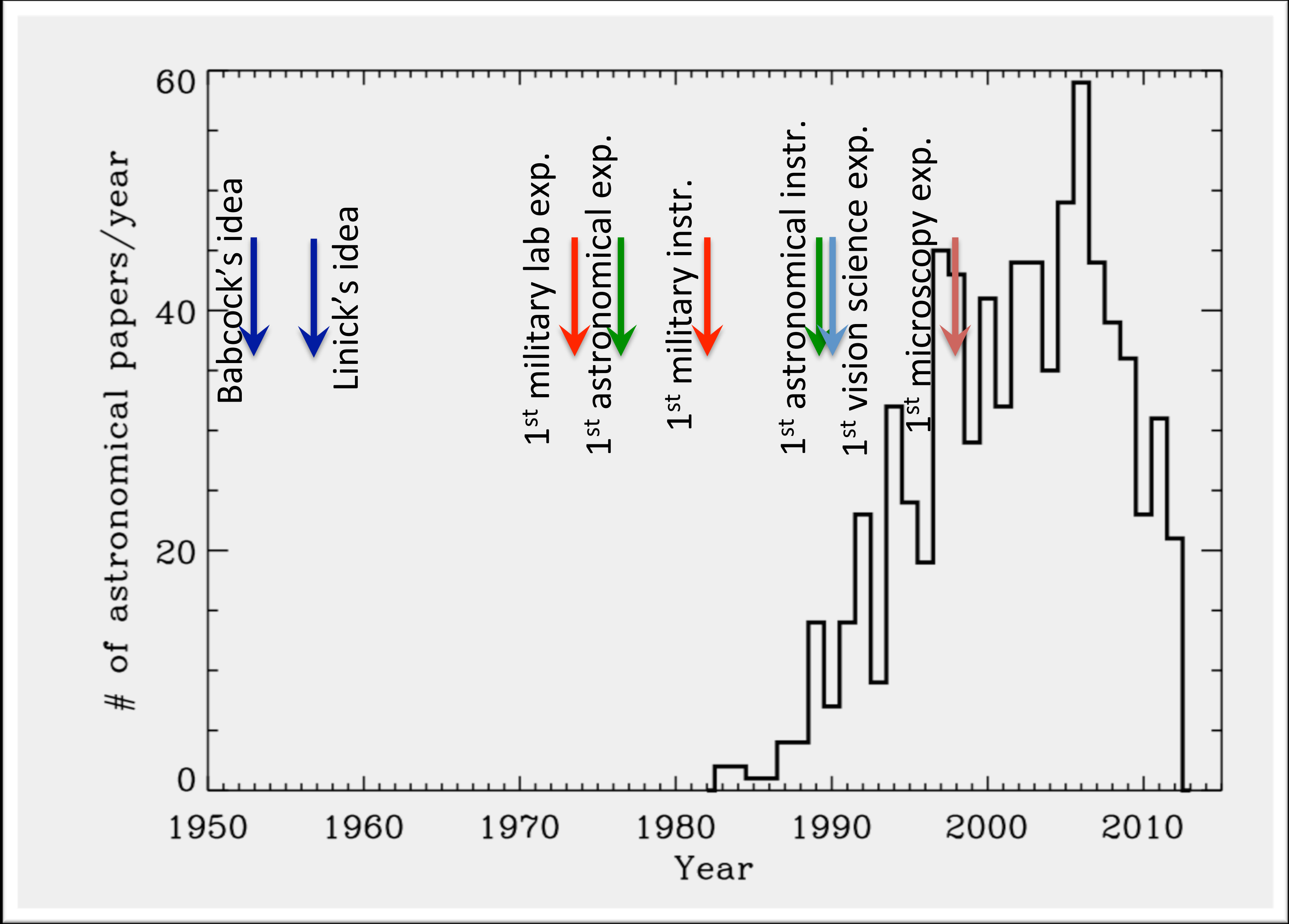
- What's your background?
- What do you expect/hope to learn from it?



An AO timeline

- When was the
  - idea of AO first proposed?
  - the first on-sky military demonstration?
  - the first on-sky astronomical demonstration?
  - the first full-scale astronomical instrument?
  - the first vision science demonstration?
  - the first microscopy AO demonstration?

An AO timeline

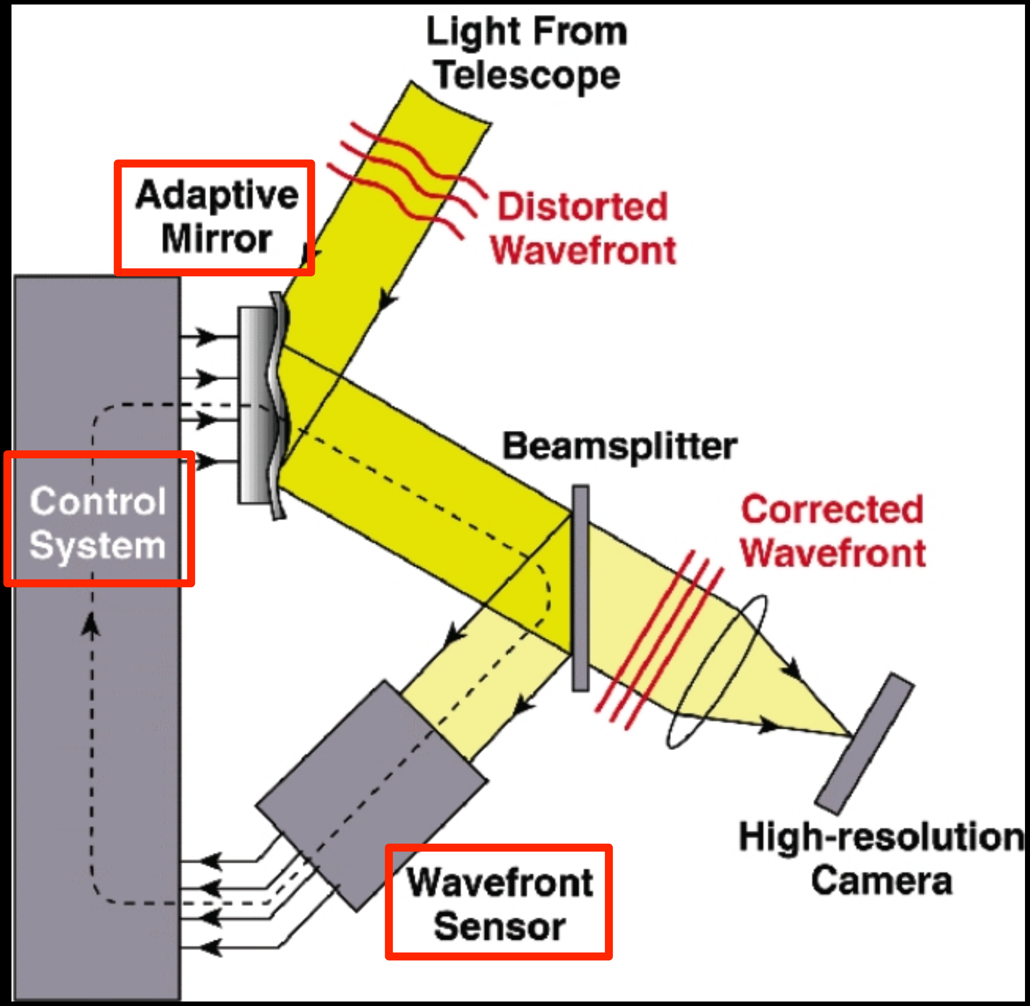


What do you know about AO?

What the class will cover

- Image formation, effect of aberrations
- Principles and history of AO
- Key building blocks of an AO system
- Applications of AO
- Considerations to design an AO system
- Advanced AO systems
- Doing the "best" science with AO
- …

AO: the basic concept



Basic goal: correct for optical aberrations

High-resolution imaging

Image quality boosting

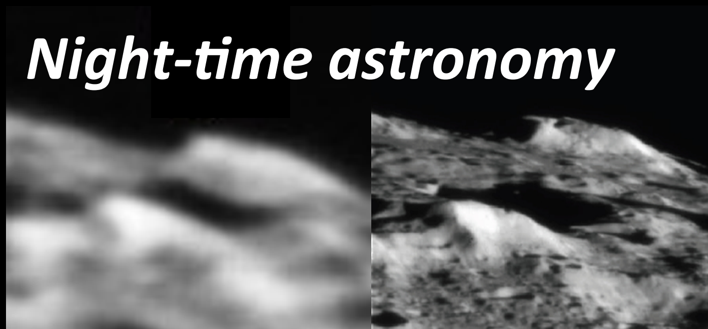
Beam control/quality

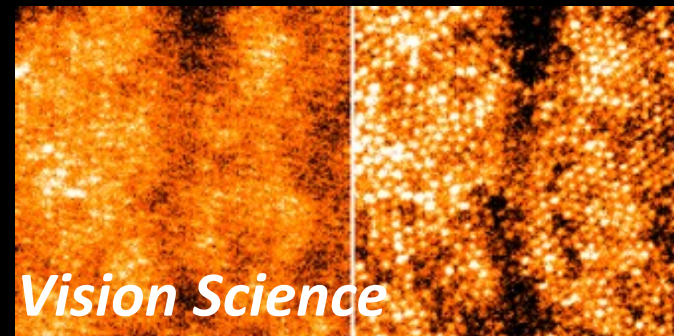
Active *vs* adaptive optics

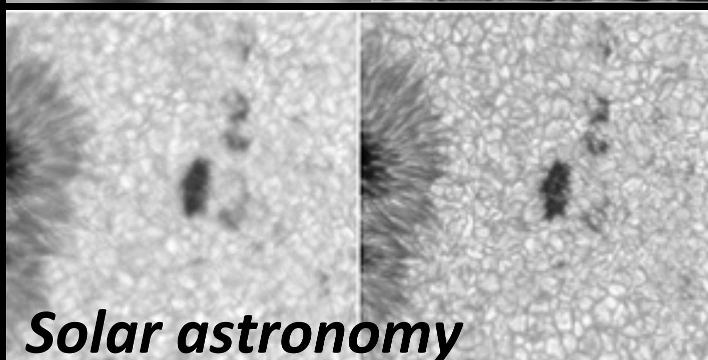
- Exact terminology is field-dependent
- Active optics
  - moving elements can be (predictively) adapted to correct for aberrations
    - e.g, thermal deformations, gravity-induced flexures
- Adaptive optics
  - Measurement-based correction, in “closed loop”
    - Continuous feedback
  - “fast” correction (~kHz *vs* ~Hz in astronomy)

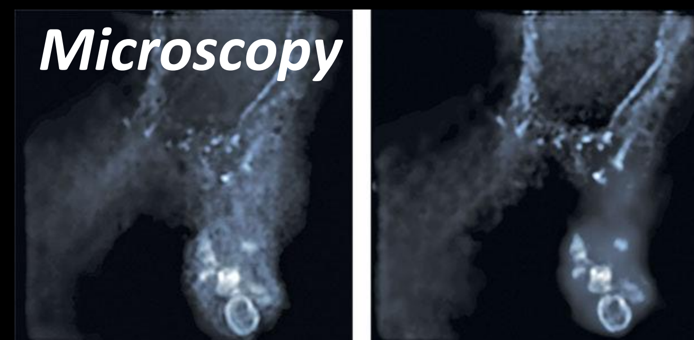
Fiber coupling with adaptive optics for free-space optical communication

AO in a variety of fields









Low-noise adaptive optics for gravitational wave interferometers

Adaptive Optics for High-Peak-Power Lasers – An Optical Adaptive Closed-Loop Used for High-Energy Short-Pulse Laser Facilities: Laser Wave-Front Correction and Focal-Spot Shaping

Microelectronics and Microsystems

Optical Military Systems

Adaptive Optical Systems

What is resolution? Image/beam quality?

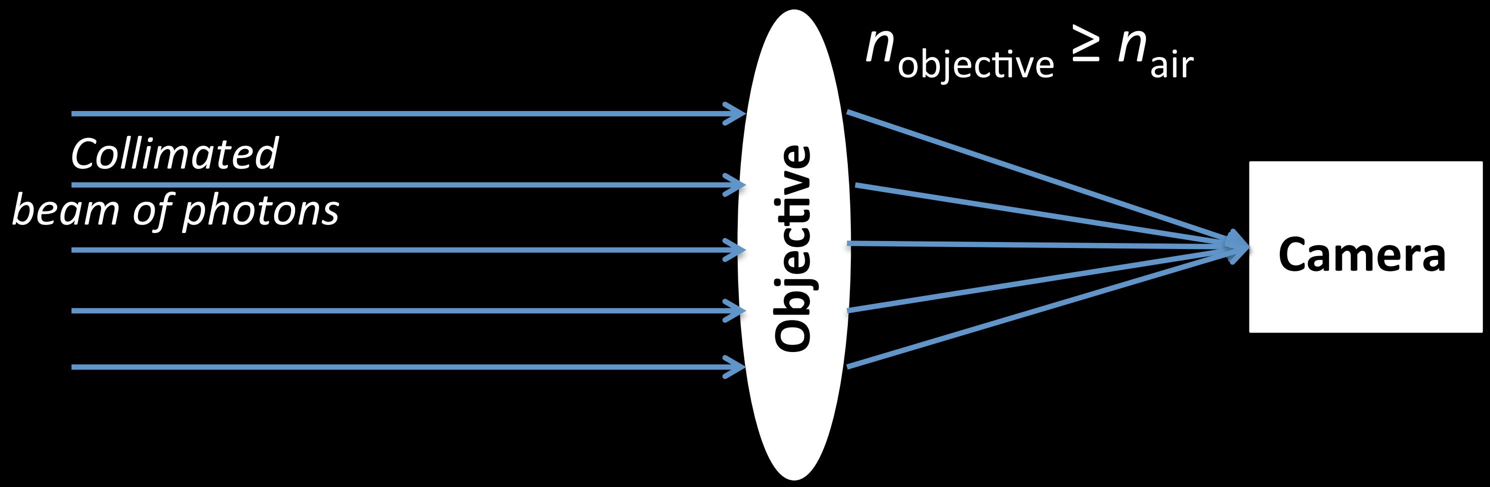
- What metric(s) to use to measure improvement in image resolution and/or quality?

The dual nature of light

- Light can be described
  - as an ensemble of particles (photons)
  - as an ensemble of energy-carrying waves
- Neither is a perfect description; it depends on the situation
  - Photo-electric effect: photons
  - Diffraction, interferences: waves
- Both approaches are generally needed

Image formation: geometric optics

- Photon paths = light “rays”
- The objective focuses all rays onto a single spot on the camera
  - typically using refraction (Snell’s law)

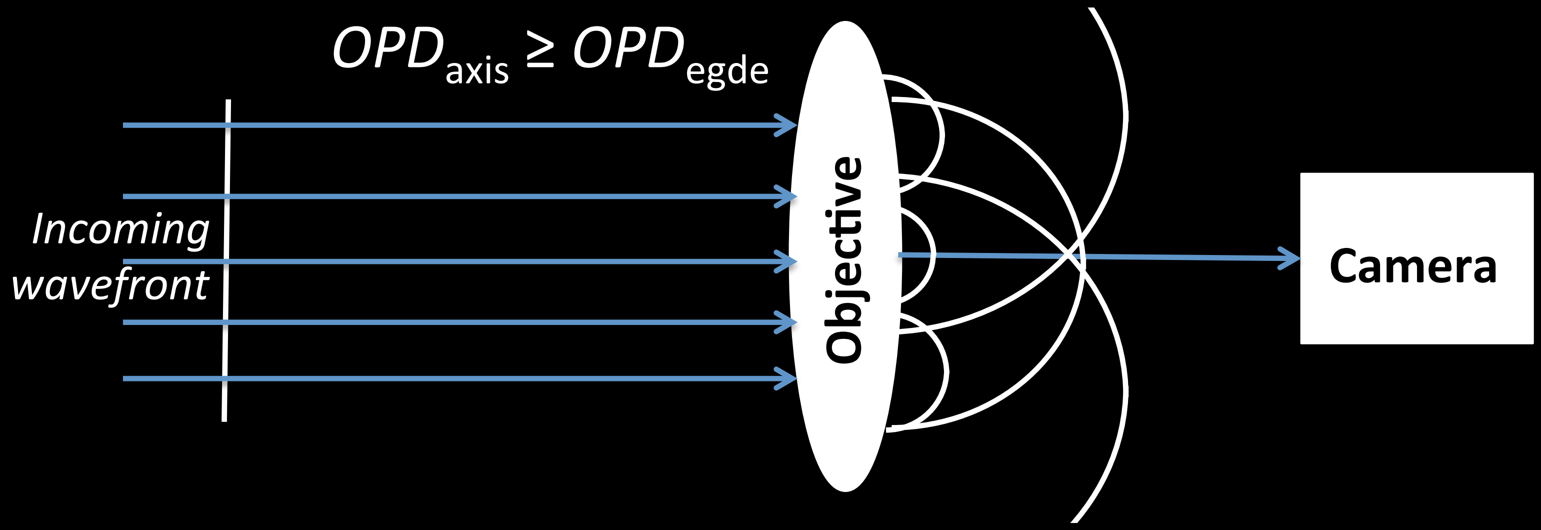


Diffraction limit: geometric optics

- How well collimated is the focus? How small is the resulting image?
- Heisenberg's uncertainty principle: $\Delta x\, \Delta p \approx \hbar$
  - Photon pass through a diameter D
  - Hence $\Delta p \approx \hbar / D$
  - For a photon $p = h\nu / c = h / \lambda$
  - Thus $\Delta p / p \approx \Delta \Theta \approx \lambda / D$
- Image spot has a finite size, on the order of λ / D

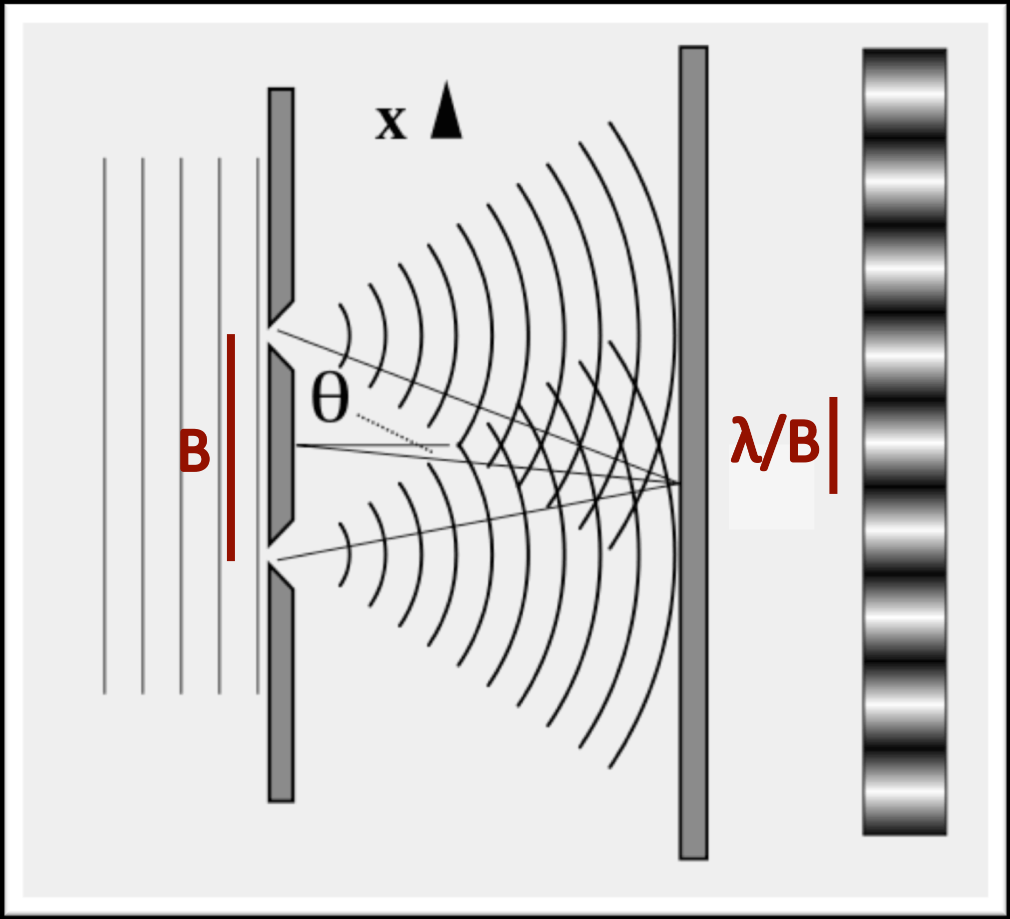
Image formation: wave optics

- Huygens' principle: each point of a wavefront is the source of a new spherical wavefront
- Those wavefronts interfere constructively all together in a single point: the focal point



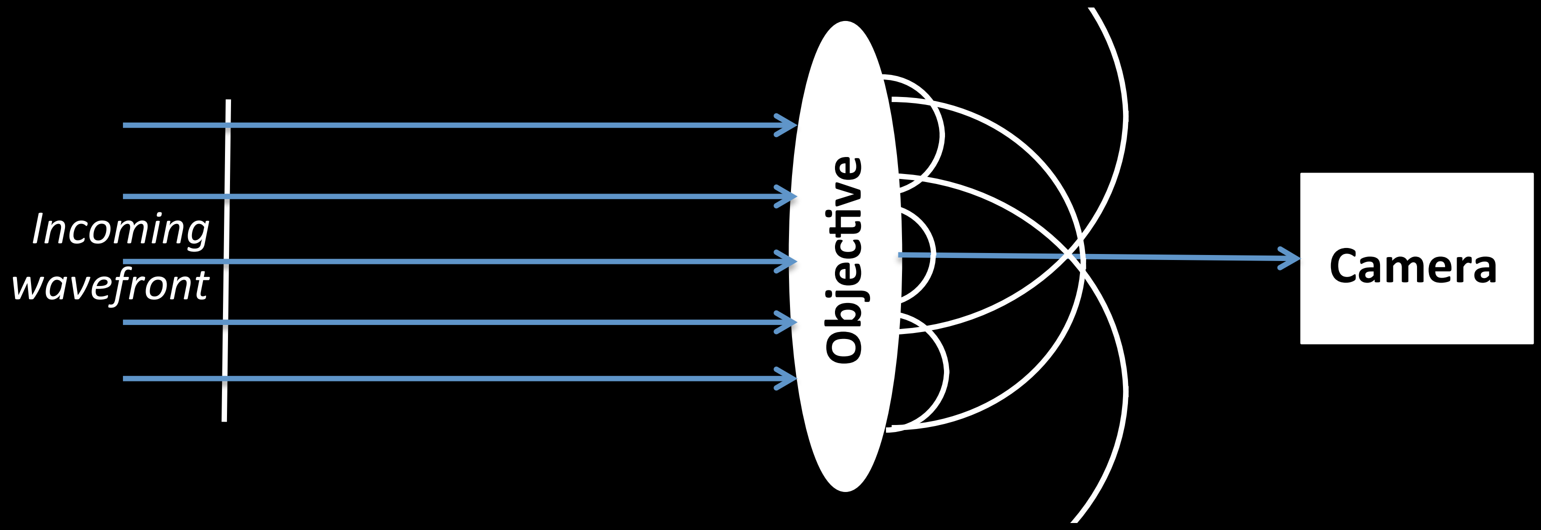
Diffraction limit: wave optics

- Intermediate step: Young's slit experiment



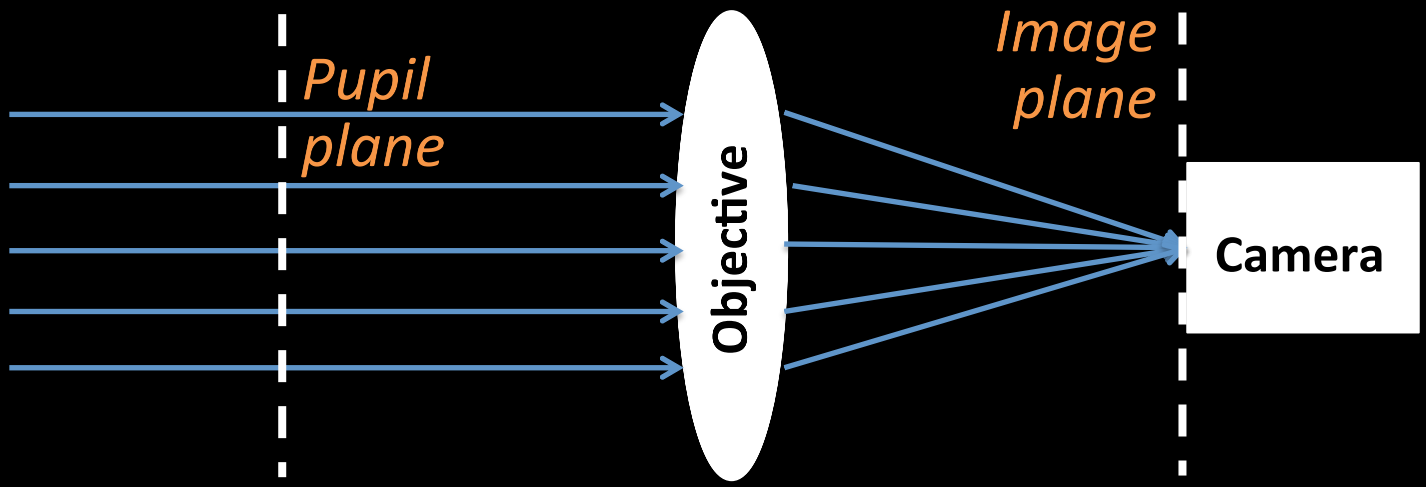
Diffraction limit: wave optics

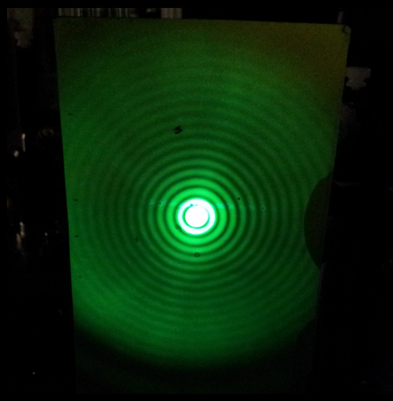
- Objective = a broad range of "baselines"
  - Longest one is the diameter *D*
  - Thus, the shortest fringe spacing is $\Delta\Theta \approx \lambda/D$
- Image spot has a finite size, on the order of λ/D



Pupil/image plane connection

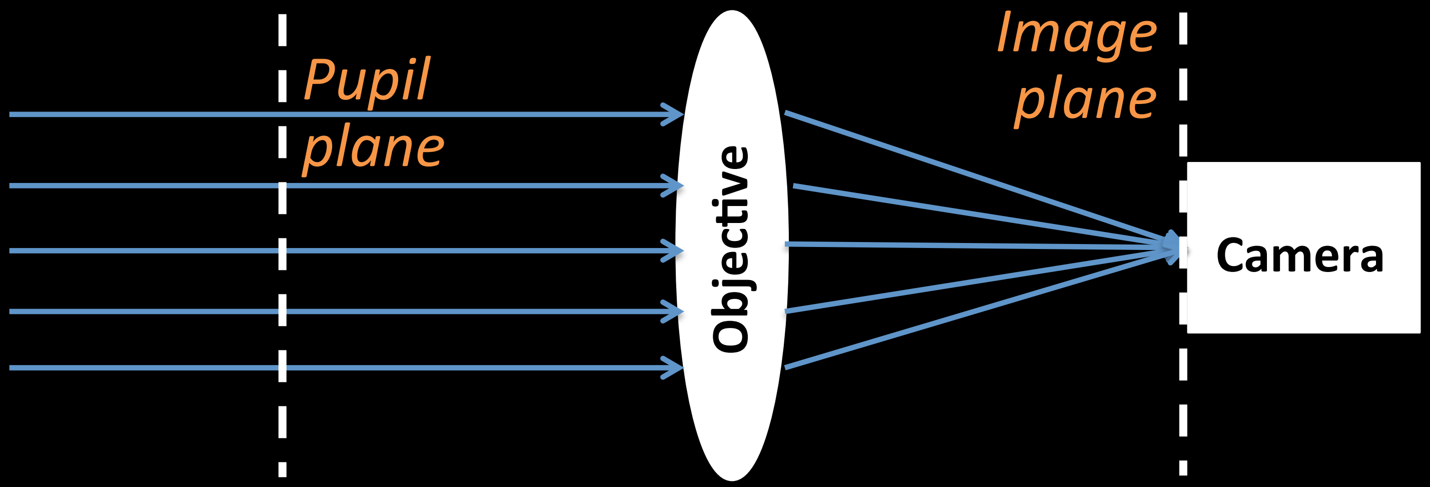
- The relationship between the E/B fields in the pupil and image planes is a Fourier transform
- Finite diameter pupil → Airy function = $[J_1(x)/x]^2$
  - FWHM = 1.02 λ/D; first dark ring at $1.22\ \lambda/D$
  - Also applies along *z* axis for source not at infinity





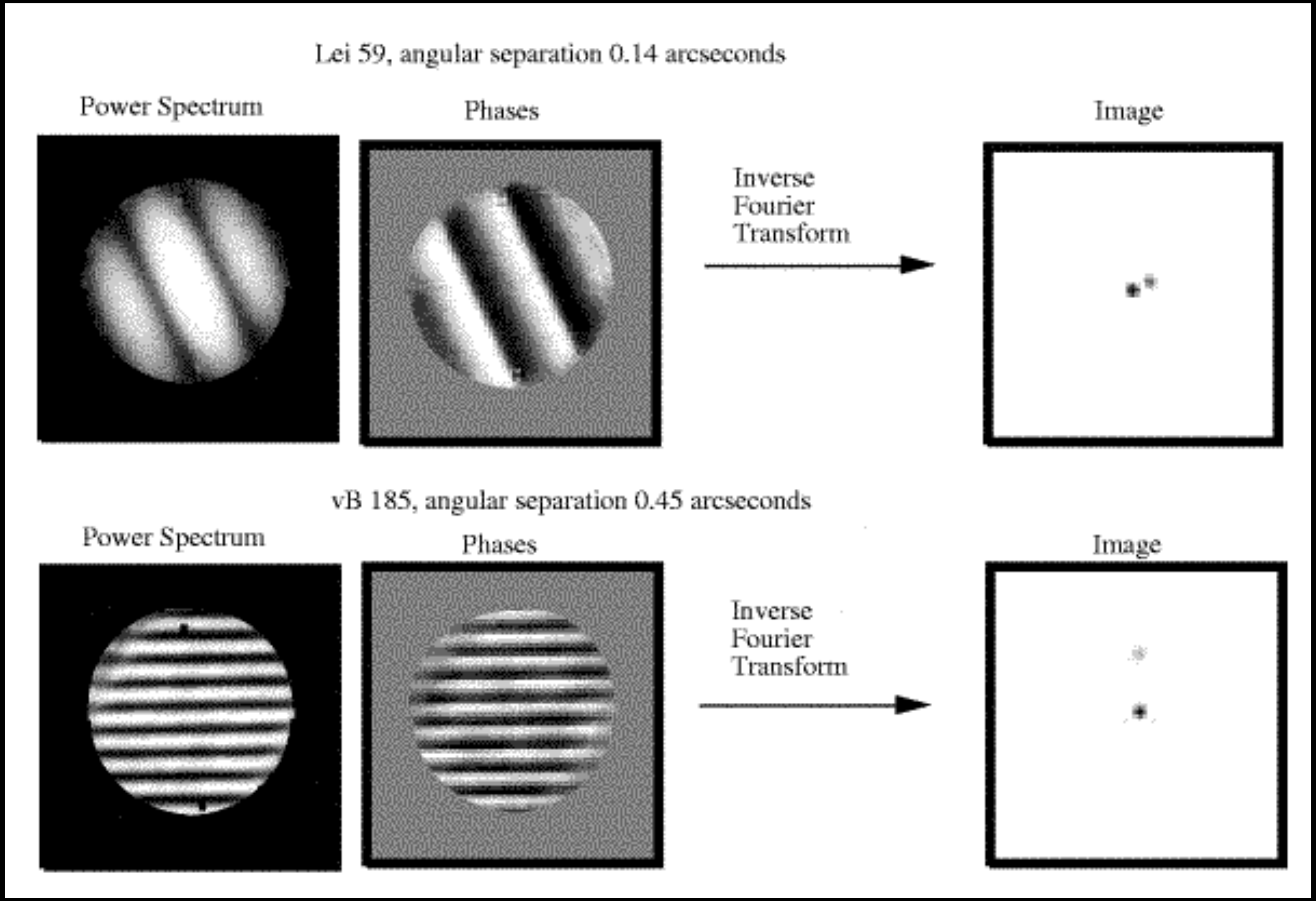
Pupil/image plane connection

- The relationship between the E/B fields in the pupil and image planes is a Fourier transform
  - Angular/linear dimensions (*Θ,φ/x,y*) in image plane
  - Spatial frequencies (*u,v*) in pupil plane
  - Think about Young's slit experiment…



Pupil/image plane connection

- Example for a binary stellar system

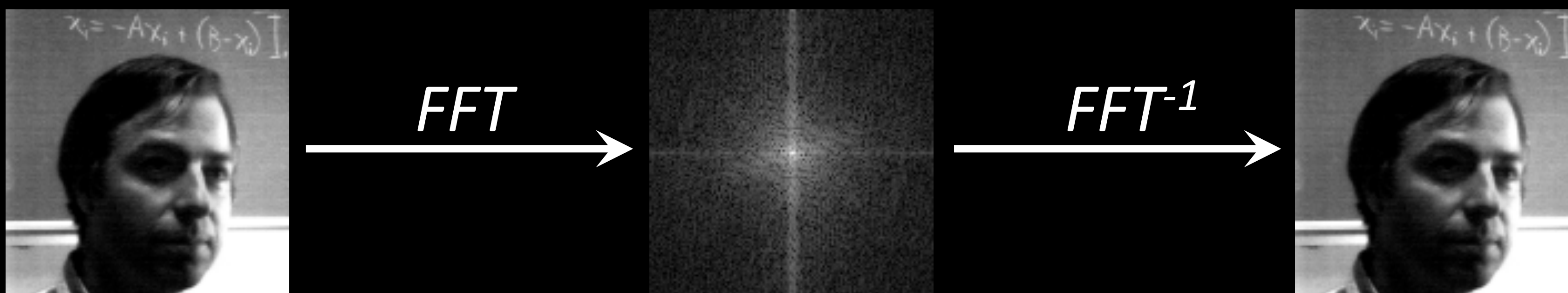


Pupil plane

Image plane

Pupil/image plane connection

- Example for a complex image

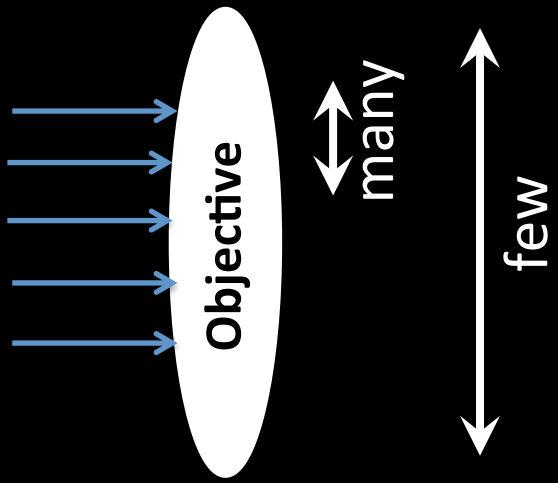


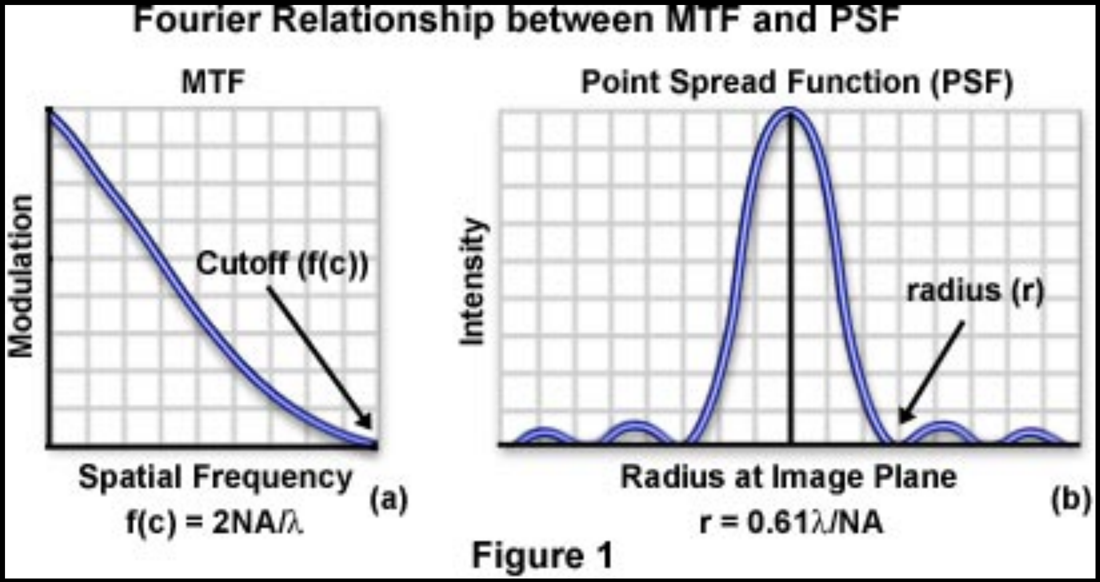
Optical system: PSF and OTF

- Any optical system can be described by the way it affects light propagating through it
- In the image domain, this is described by the Point Spread Function
  - *Img(x,y) = Obj(x,y)⊗PSF(x,y)*
- In the Fourier (pupil) domain, this is described by the Optical Transfer Function
  - *[FFT(Img)](u,v) = [FFT(Obj)](u,v) × OTF(u,v)*
- *PSF(x,y) = FFT[OTF(u,v)]*

OTF = transmission of information in the Fourier domain

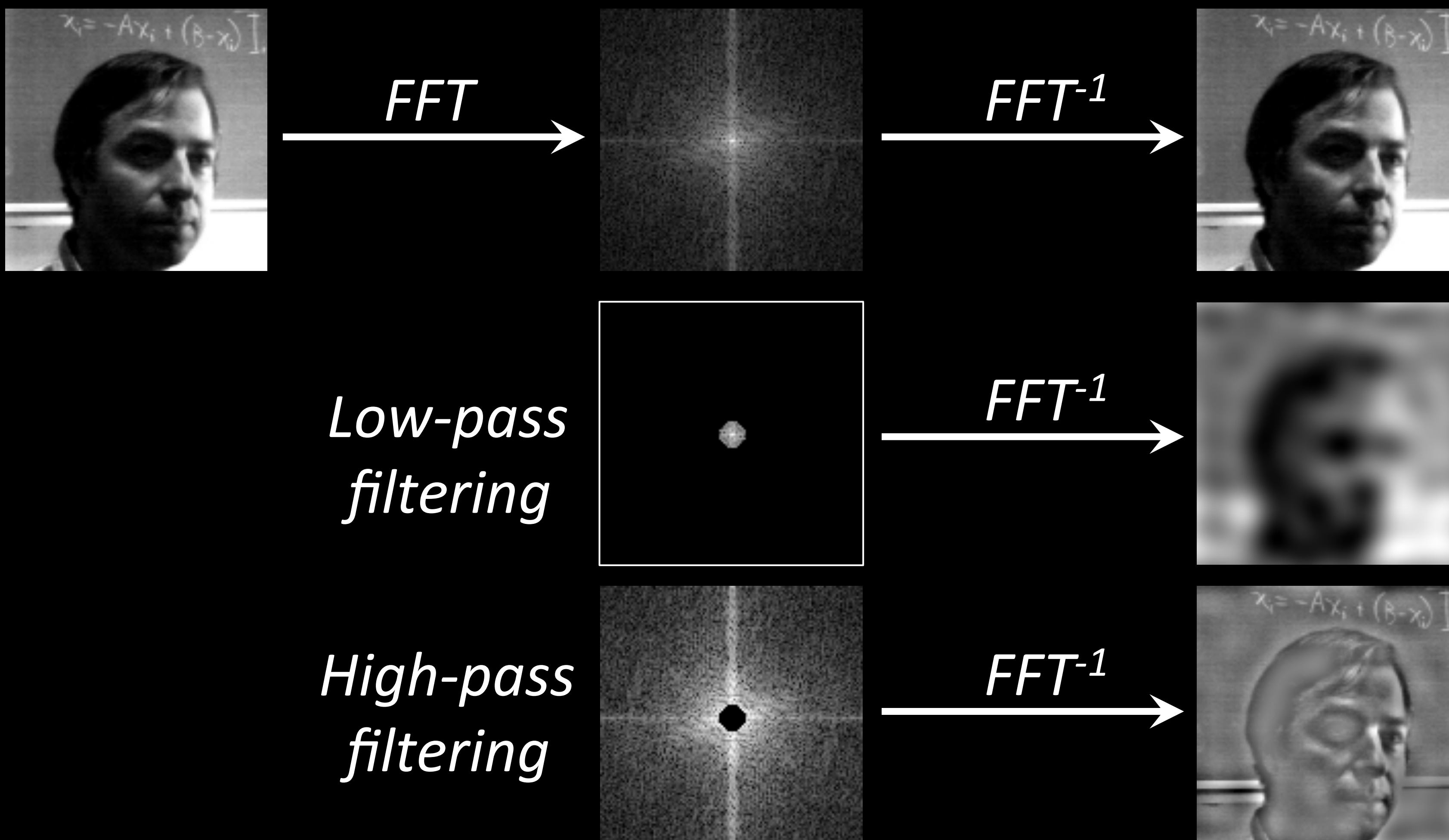
- OTF = auto-correlation of entrance pupil
- How many pairs of "elements" exist in the pupil to transfer information on a given scale?





Pupil/image plane connection

- Example for a complex image



Properties of OTF

- OTF is a complex function: amplitude and phase
  - If aperture is centro-symmetric, OTF is a real function
  - MTF = Modulus Transfer Function
- Characterize not only imaging instrument but everything from the light source to the detector
  - $OTF_{total} = \Pi \; OTF_{sources}$
- Knowing/understanding/controlling the OTF of a system is key to achieve diffraction limit