Lecture 15

How to be a Savvy User and Consumer of AO

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How to be a savvy user and consumer of AO systems? Topics

- What kinds of astronomy are helped by AO?
- For users of astronomical AO:
  - How to plan your observations
  - What questions to ask when you get to the telescope
  - Observing procedures
- For critical readers of AO papers in journals:
  - How to assess the reality of AO results reported in the literature
  - Which data should you take seriously?
  - What are "danger signs" that should make you doubtful?

What kinds of observations will be helped by AO? (Part 1)

- <u>See details</u> that were not previously present
  - Qualitative: can make new morphological statements
    - Examples: this galaxy has a double nucleus, Titan's clouds have re-formed in southern hemisphere, …
  - Quantitative: need to know Point Spread Function; need to understand PSF error bars
    - New methods called "PSF Reconstruction" do a pretty good job
    - Based on wavefront sensor measurements and commands sent to DM (AO Telemetry stream)

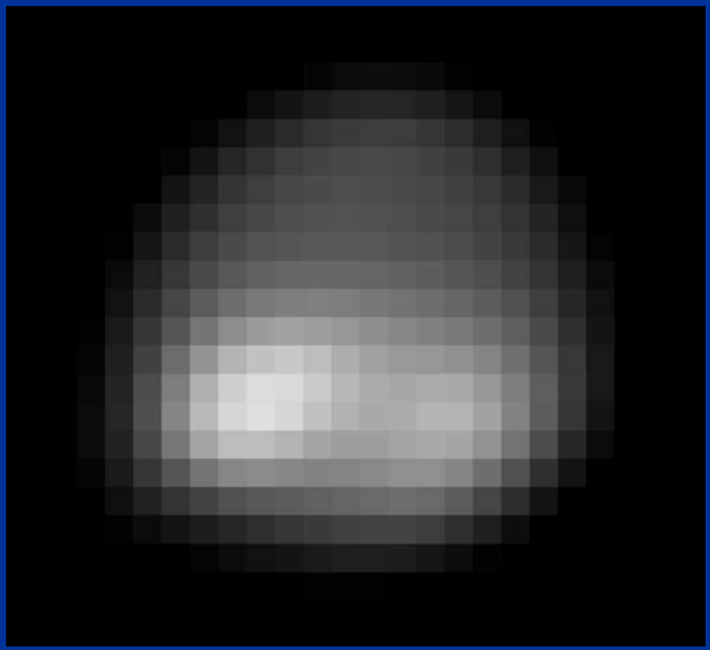
What kinds of observations will be helped by AO? (Part 2)

- Detect fainter objects/features
  - Works for point sources
  - But: IR AO systems may inject more thermal background, because of many mirror surfaces (unless you use an adaptive secondary!)
  - In astronomy, faint extended objects can actually be harder to see with AO. Limiting factor is sky background or thermal background, and AO doesn't improve this for extended objects.
  - For a point source with a diffraction limited core, integration time to reach a given SNR scales as D^{-4} where D is telescope diameter
  - If fully seeing limited, integration time scales as D^{-2}

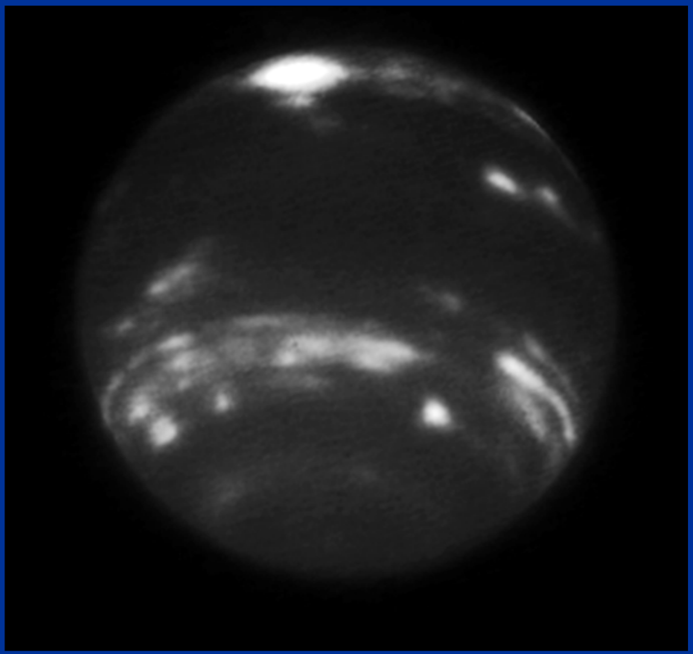
What kinds of observations will be helped by AO? (2)

- AO increases image contrast:
  - Increased Strehl ratio ⇒ sharper edges, brighter features (if they are close to diffraction limit)
  - Detecting faint things close to bright things:
    - companions to bright stars
    - host galaxies of quasars
    - stellar and protoplanetary disks
  - Caution: Contrast improvement may not be helped by AO for extended features, unless they have structure at λ / D
- AO permits more precise astrometry
  - Can measure position of a point source more accurately if a) it is smaller, and b) it is brighter
  - But need other stars in the field to create a reference frame

See new details and structure



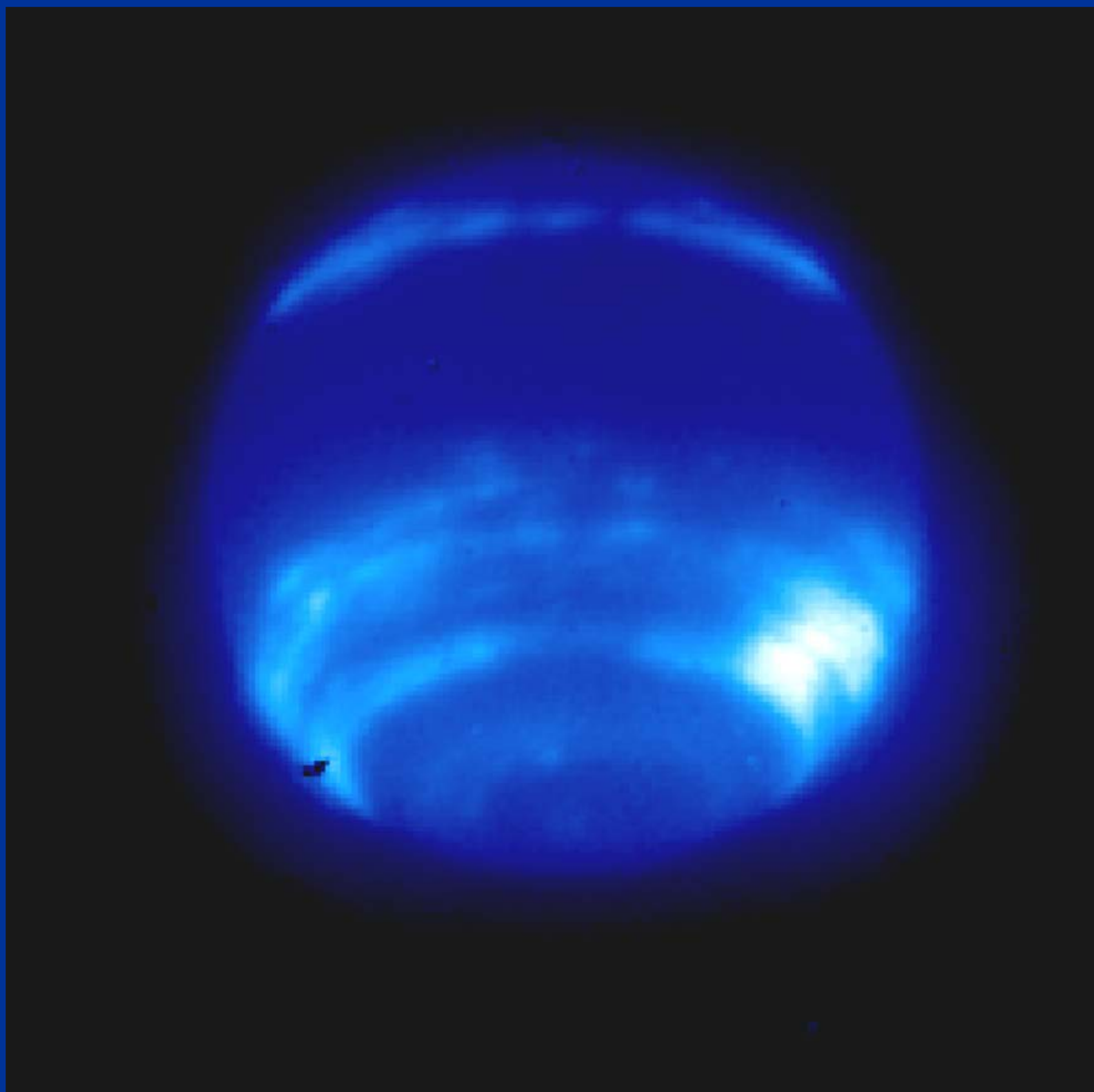
Neptune, Keck, no AO



Neptune, Keck, AO

- Structure is dramatically clearer
- Must take care in measuring quantitative brightness of features
  - AO PSF “spills” light from bright features into fainter areas
  - PSF Reconstruction can help

Spilling of light, Neptune bright clouds



- Light from bright compact cloud region “spills” over limb, and into nearby dark areas
- How do you tell what the “real” intensity is, in a dark region?

Will I detect fainter objects with AO? (1)

- **Assume a point source under sky-background-limited conditions.** Total flux from object is F_{obj} (ergs/cm^2 or watts/m^2).
- Generally choose size of pixel such that two pixels sample a typical point-source diameter. So within the area of the PSF, $n_{pix} \sim 4$
- The area of the PSF on the sky is ~ $(2\lambda/D)^2$ for AO, but is ~ $(2\lambda/r_0)^2$ without AO
- So if all else is the same, the sky background B^{sky} within the PSF of a point source is $(D/r_0)^2$ larger for the no-AO case

$$SNR_{AO} = \frac{Strehl \times F_{obj} T'_{AO} t_{\text{int}}}{\sqrt{n_{pix} B^{sky}_{AO} T'_{AO} t}}$$

$$(T'_{AO} = \text{trans. (tel. + AO + instr.)}$$

$$SNR_{see} = \frac{F_{obj} T'_{NoAO} t_{\text{int}}}{\sqrt{n_{pix} B^{sky}_{NoAO} T'_{NoAO} t}}$$

$$(T'_{NoAO} = \text{trans. (tel. + instr.)}$$

$$B^{sky}_{NoAO} \approx \left(\frac{D}{r_0}\right)^2 \times B^{sky}_{AO}$$

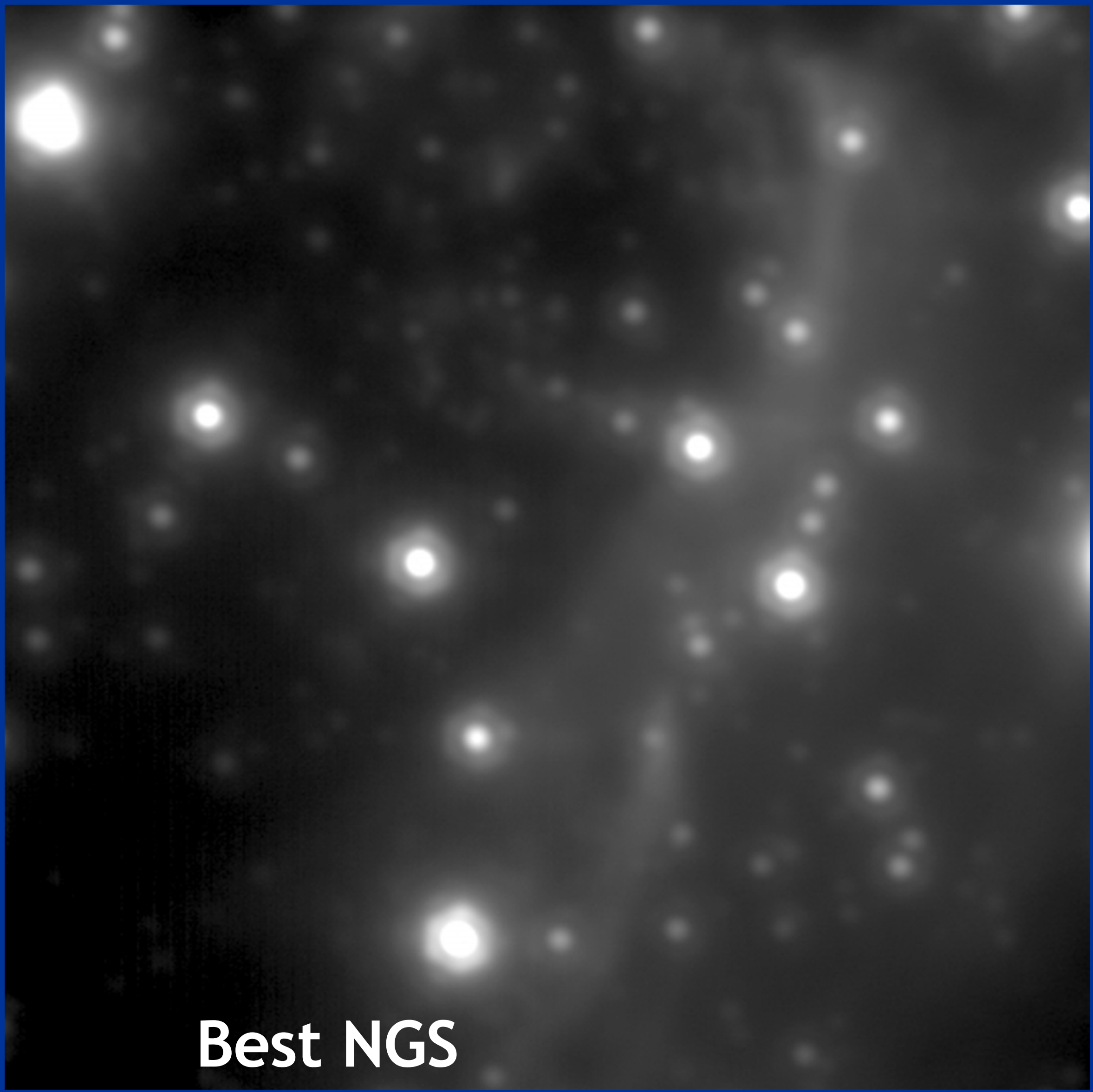
Will I detect fainter objects with AO? (2)

- Lick AO (λ = 1.65 microns):
  S = 0.4
  D = 3 m
  r_0 = 0.6 m
  T'_{ao} / T'_{noao} = 0.5
- At 1.65 microns, the sky background per arc sec is the same with and without AO, so

$$\frac{SNR_{AO}}{SNR_{seeing}} = Strehl \times \sqrt{\frac{B_{AO}^{sky} T'_{AO} n_{pix}^{no-AO}}{B_{no-AO}^{sky} T'_{noAO} n_{pix}^{AO}}} \cong Strehl \left(\frac{D}{r_o} \right) \sqrt{\frac{T'_{AO}}{T'_{noAO}}} \cong 3.5 \times Strehl$$

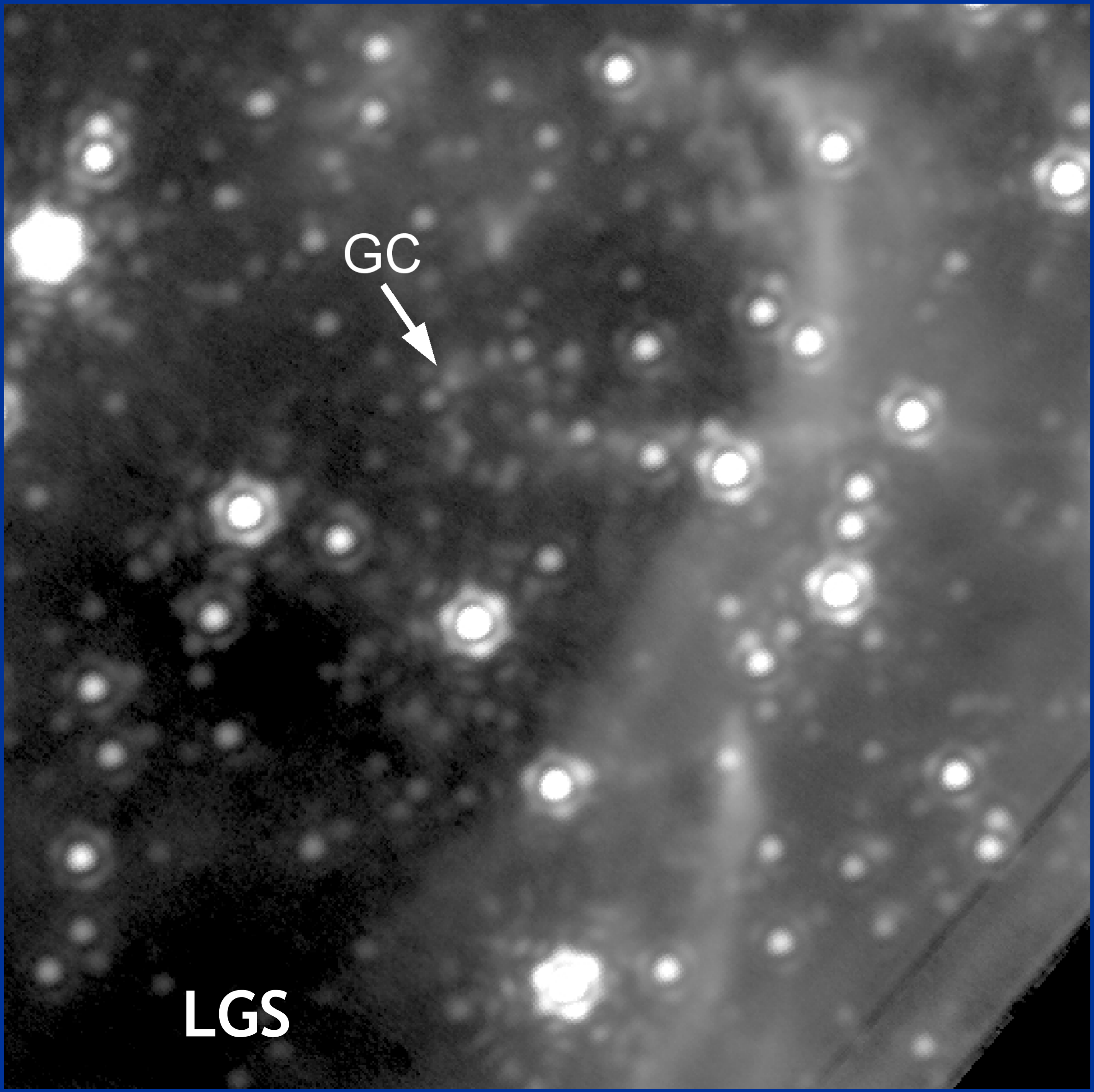
- Only for Strehl > 0.3 does AO give sensitivity advantage even for point sources

Galactic Center: NGS to LGS AO



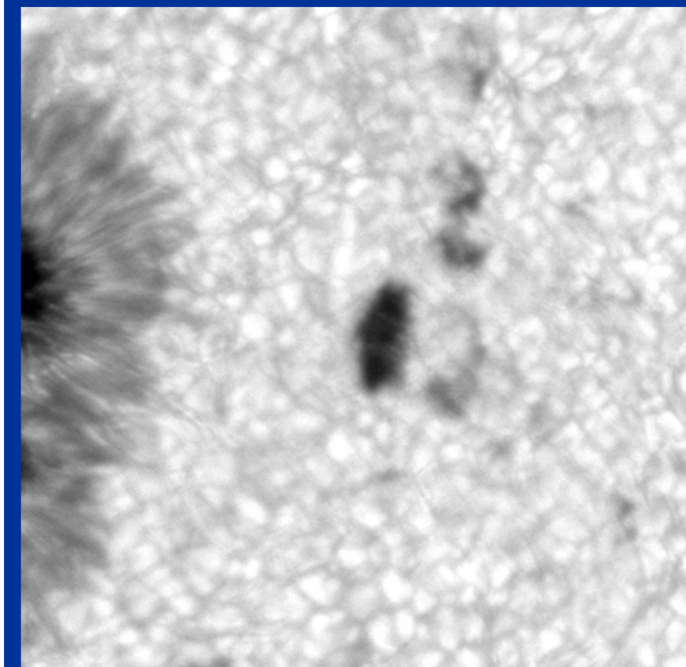
Credit:
Andrea
Ghez's group
at UCLA

Galactic Center: NGS to LGS AO

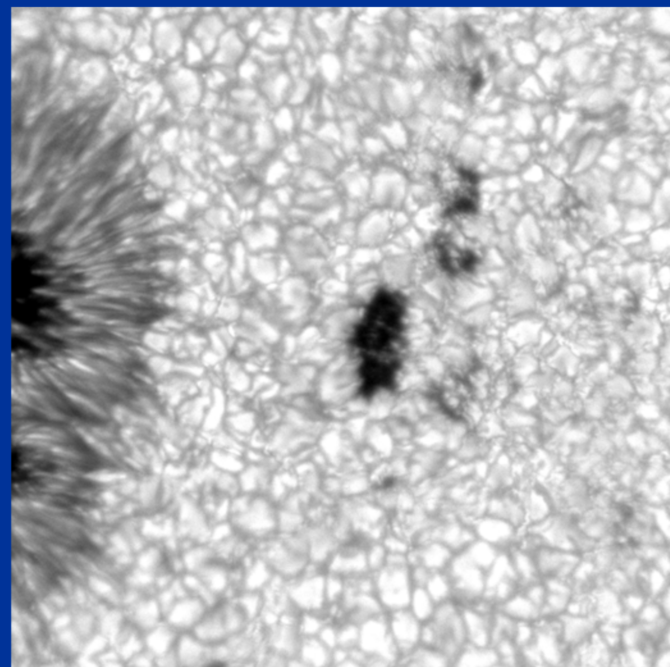


Detect many more point sources (stars) with good LGS AO correction (higher Strehl)

AO yields higher contrast, for small features



AO off

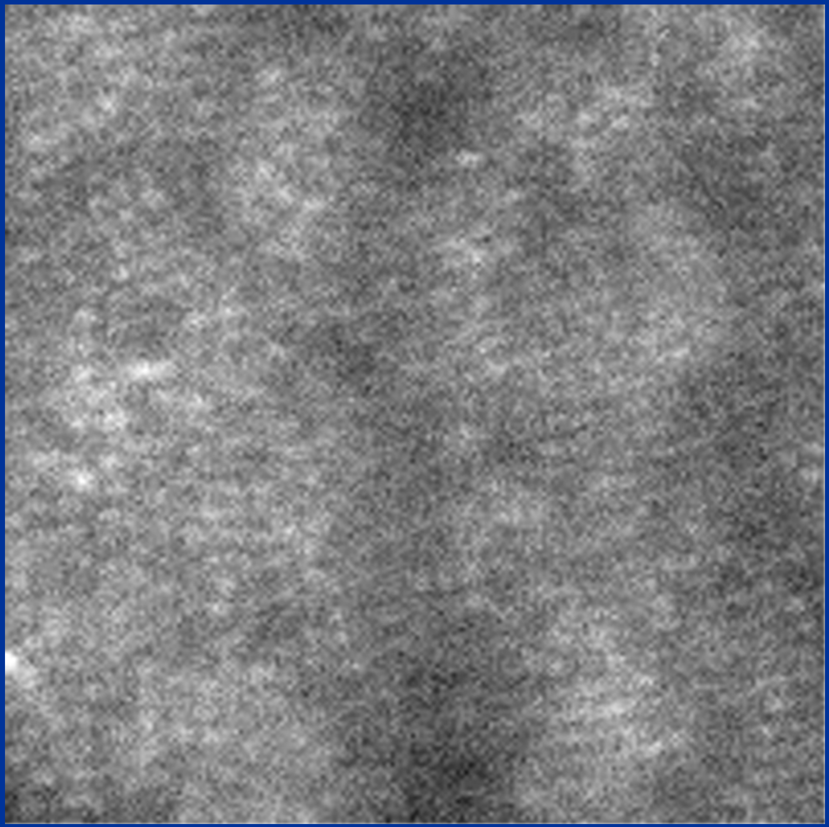


AO off

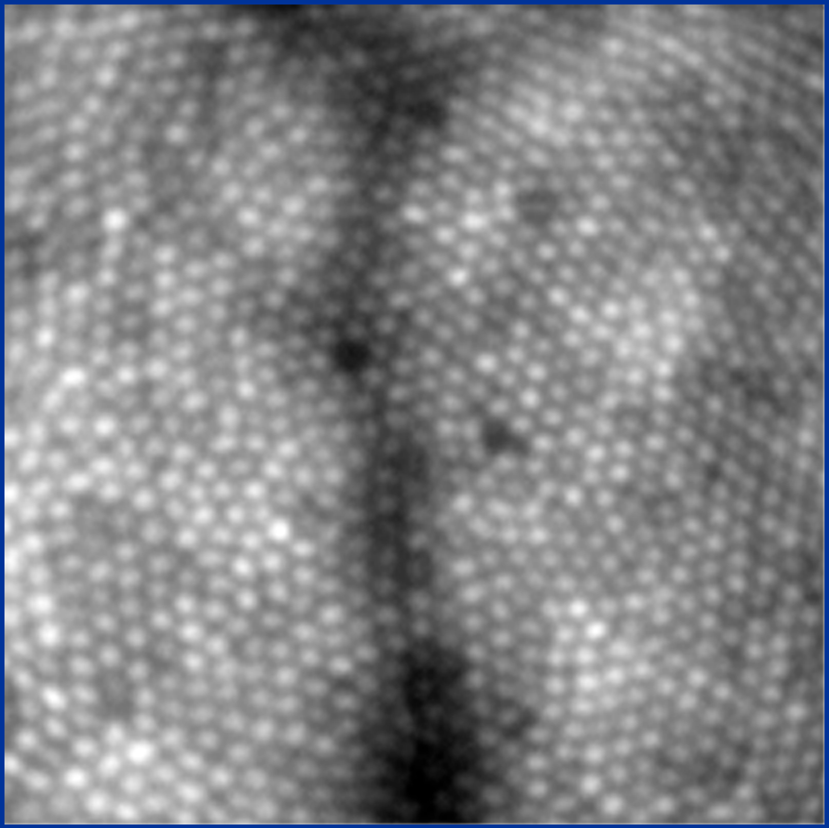
- T. Rimmele
- AO for imaging surface of Sun
- Higher contrast on bright granules, dark regions in between where B field is emerging from sub-surface

Example of higher contrast: vision science images of human retina

- Austin Roorda and David Williams

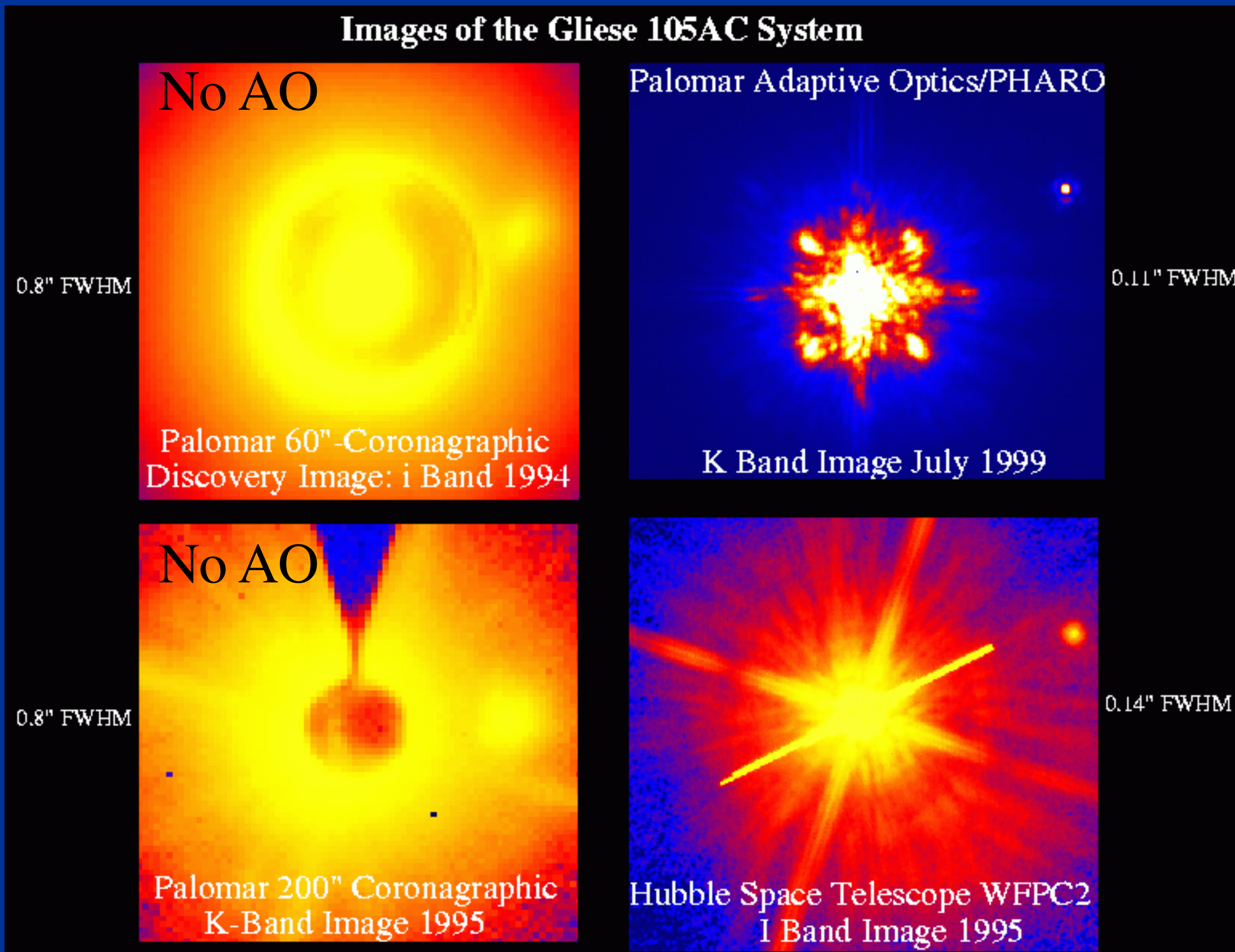


Without AO



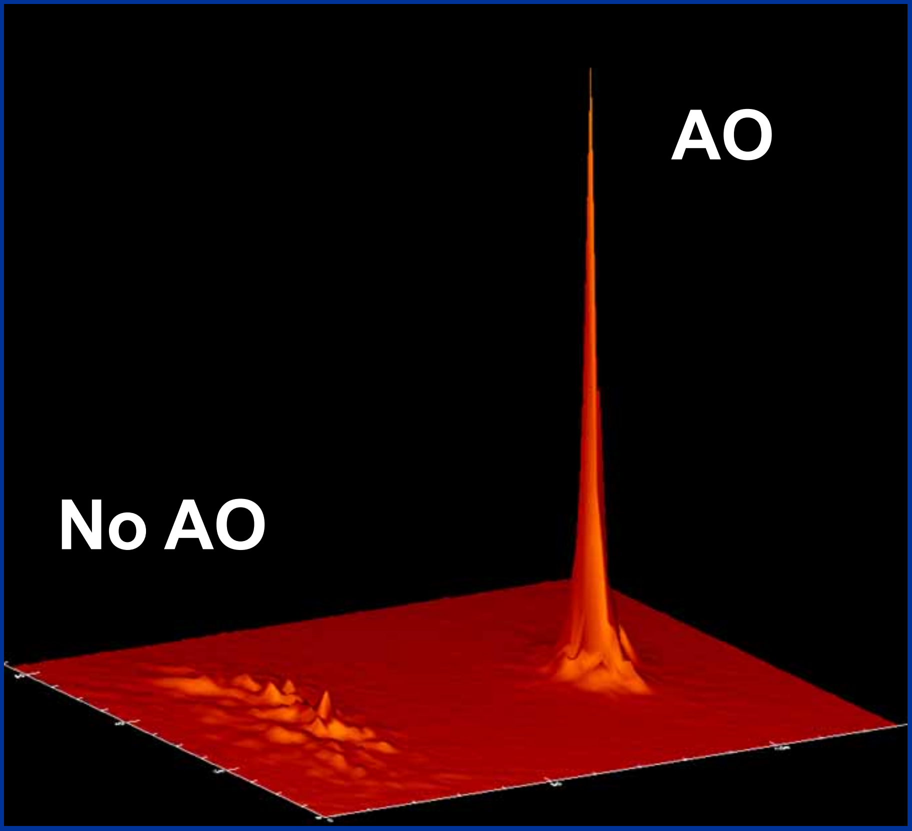
With AO: resolve individual cones

AO yields better contrast for faint objects next to bright objects



AO can permit more accurate astrometry (precise position measurement)

- For a point source, accuracy of centroid measurement increases with intensity, decreases with image size
- AO helps both of these
- But: to do relative astrometry, need stars with known positions in FOV. AO field is small.



Binary stars are perfect for relative astrometry

Questions? Discussion?

How to plan observations ahead of time

- First requirement: understand what Strehl ratio you will need for your science project to succeed
- Estimate exposure time needed to achieve good SNR
  - Some AO systems have exposure time calculators
  - Or check with folks who have observed in the past
- Refer to web pages to see what brightness guide star, at what distance, at what zenith angle, you will need
- Check AO system web page for maximum offset between science target and guide star
- Search star catalogues to find guide stars

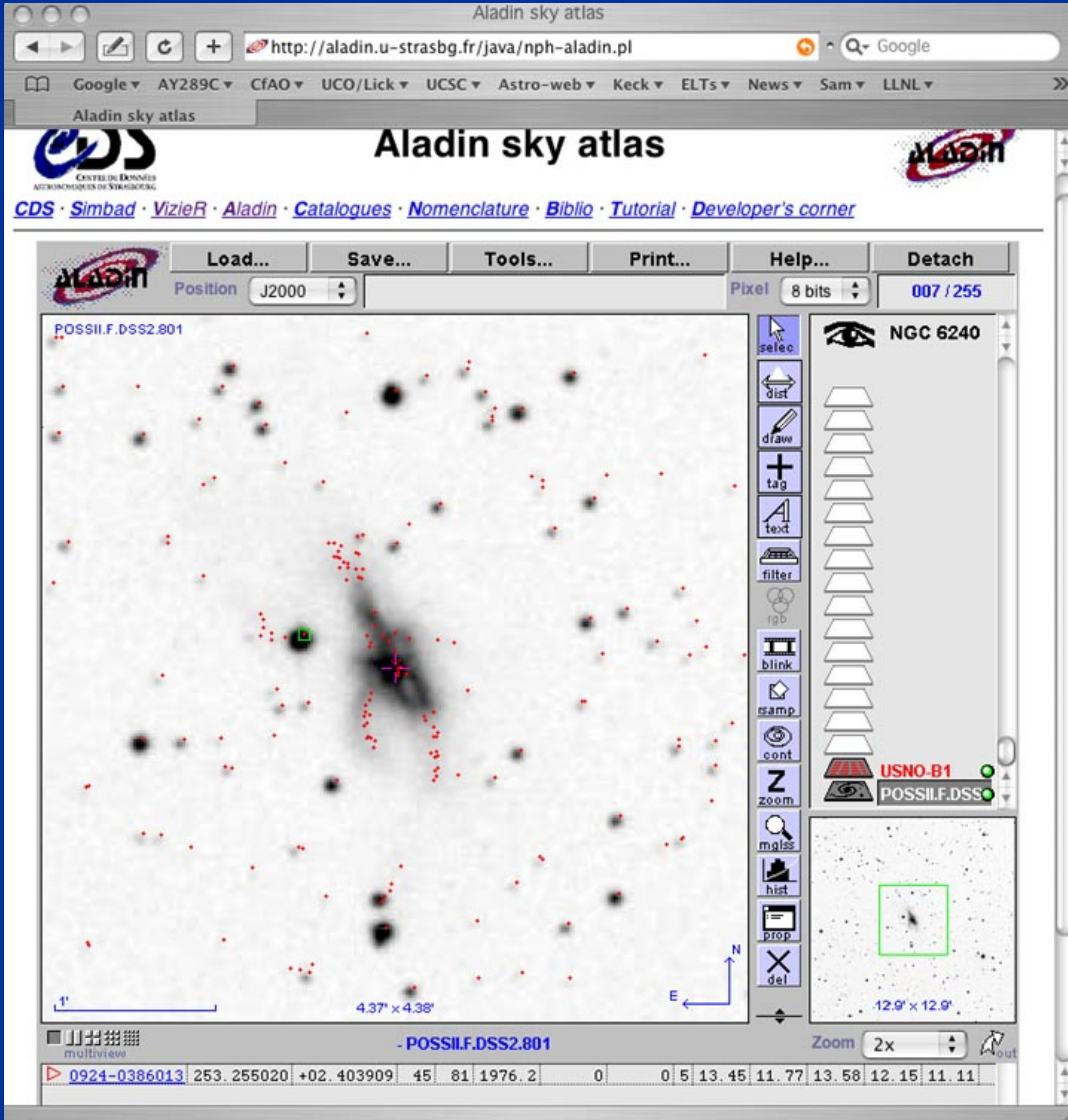
Star catalogs for guide star search

(After B. MacIntosh)

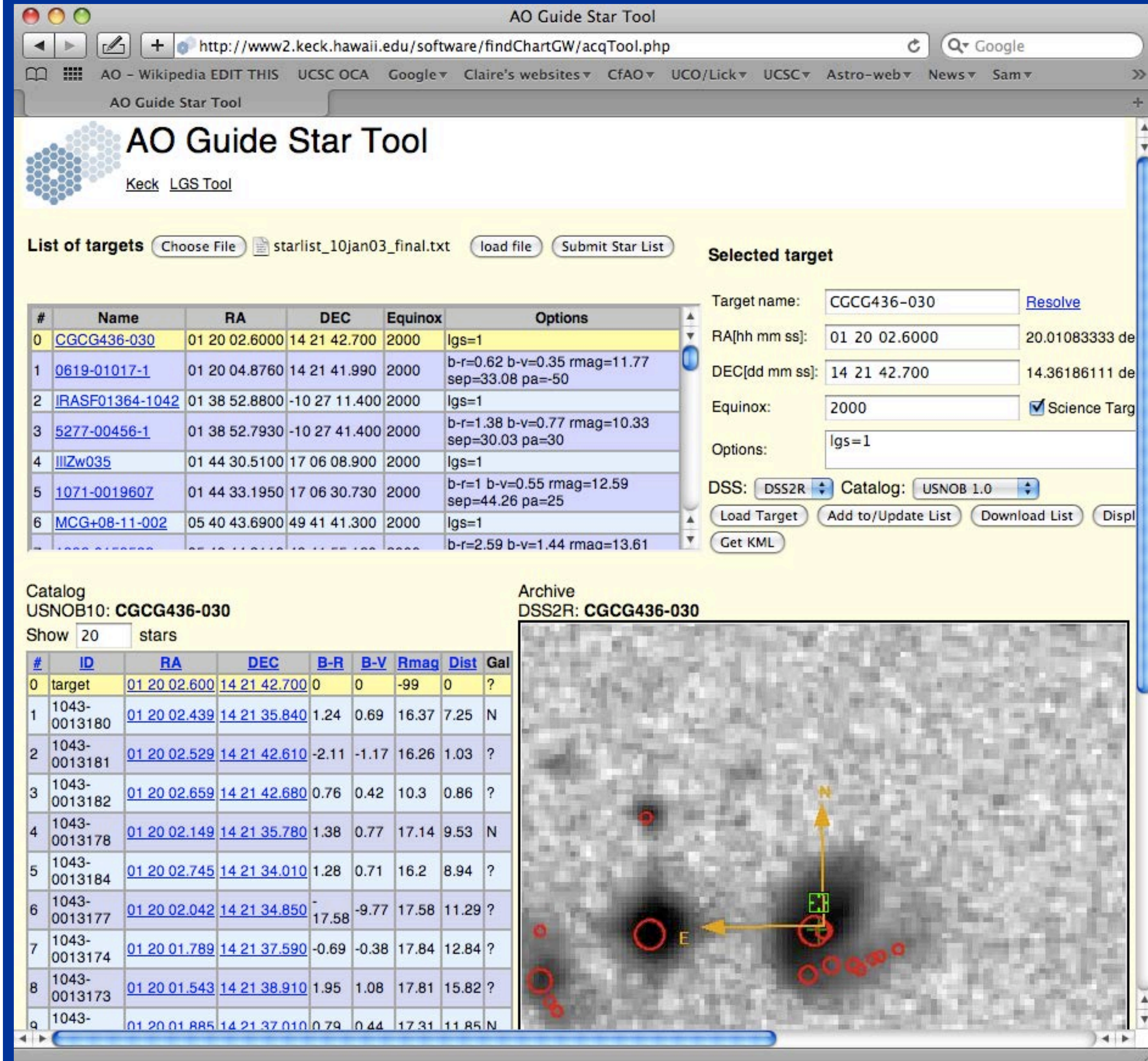
Catalog	Mag Limit	Spectral info?	Notes
GAIA	G=21	Colors	Outstanding positions; excellent web interface
Hipparcos	9	Colors	Good accuracy, catalogue available as IDL file
Tycho 2	11-12	Colors	Accurate
HST Guide Star	15	None	Unreliable (but good near bright stars)
USNO B1.0	20	Colors	Incomplete near bright stars, funky close to big galaxies

Finding a guide star: Tools

- VizieR   http://vizier.u-strasbg.fr/viz-bin/VizieR
  - Has the ability to do constrained searches - limited in position, magnitude, etc. - from a list of input targets
- Aladin (one of Vizier's capabilities)
  - https://aladin.u-strasbg.fr/
  - Can overplot a Digital Sky Survey image of your target with all the stars it can find from the catalogue of choice. Very useful for finding guide stars.



- Aladin and USNO B1 catalog: virtues and pitfalls
- Great user interface, many surveys
- But gets confused near galaxies, nebulosity
- Check out potential guide stars by eye!



Some observatories have their own online guide star tools

Other questions to address prior to observing with AO system

- PSF calibrations
  - What is my PSF star calibration strategy?
  - Can I do PSF reconstruction?
  - What is the impact of anisoplanatism?

- Observing time
  - Calculate exposure times needed for good SNR
  - Have I accurately estimated AO's overhead (wasted time)?

- Calibration and flat-fielding issues
  - How will I calibrate the sky fluxes (offset skies, dithering, other?)
  - How will I calibrate detector response variations?
  - How will I calibrate photometry (brightness measurement)?
    - Usually observe photometric standard stars
    - How often? In what sequence?

"PSF stars"

- Before, after, and sometimes intermingled with observing science target, observe "PSF star"
- Constraints:
  - If science target is offset in angle from guide star, can find PSF star pair with similar relative offset
  - Should be at ~ same zenith angle as science target (but typically an hour or two earlier or later)
  - PSF star should produce same number of wavefront sensor counts as guide star for your science target.
- In practice it's hard to meet all these conditions
- With LGS, I typically end up using the tip-tilt star as PSF

catserver.ing.iac.es/aotools/pairfind.html

UCSC OCA | Google | Claire's websites | AY 289 2011 | CfAO | UCO/Lick | UCSC | Astro-web | Other Bookmarks

AO PSF pair finder

Target coordinates	RA (J2000) [ ] DEC (J2000) [ ] Coordinate system [sexagesimal]
Sky search radius	[2.0] degrees
V magnitude limit	PSF star: [16.0] Guide star: [13.0]
Guide star distance	[ ] arc seconds
Distance tolerance	[ ] arc seconds
Position Angle	[ ] degrees E of N
PA tolerance	[ ] degrees

☐ Plain text output   SEARCH   Reset Form   *Help...*

http://www.ster.kuleuven.be/~roy/ao/pairfind.html

Sometimes you find creative endeavors on the web (!)

Adaptive Optics System User's Manual: AO Song

http://mthamilton.ucolick.org/techdocs/instruments/AO/ao_song.html

UCSC OCA | Google | iGoogle | Astro 289C | Claire's websites | CfAO | UCO/Lick | UCSC | Astro-web | Keck | ELTs
AY18 | OSIRIS | Videoconf | Mergers & BHS | Renewable energy | SC house | Meet-O-Matic | AODP Roadmap | SPIE Marseille

User's Guide to the Adaptive Optics System

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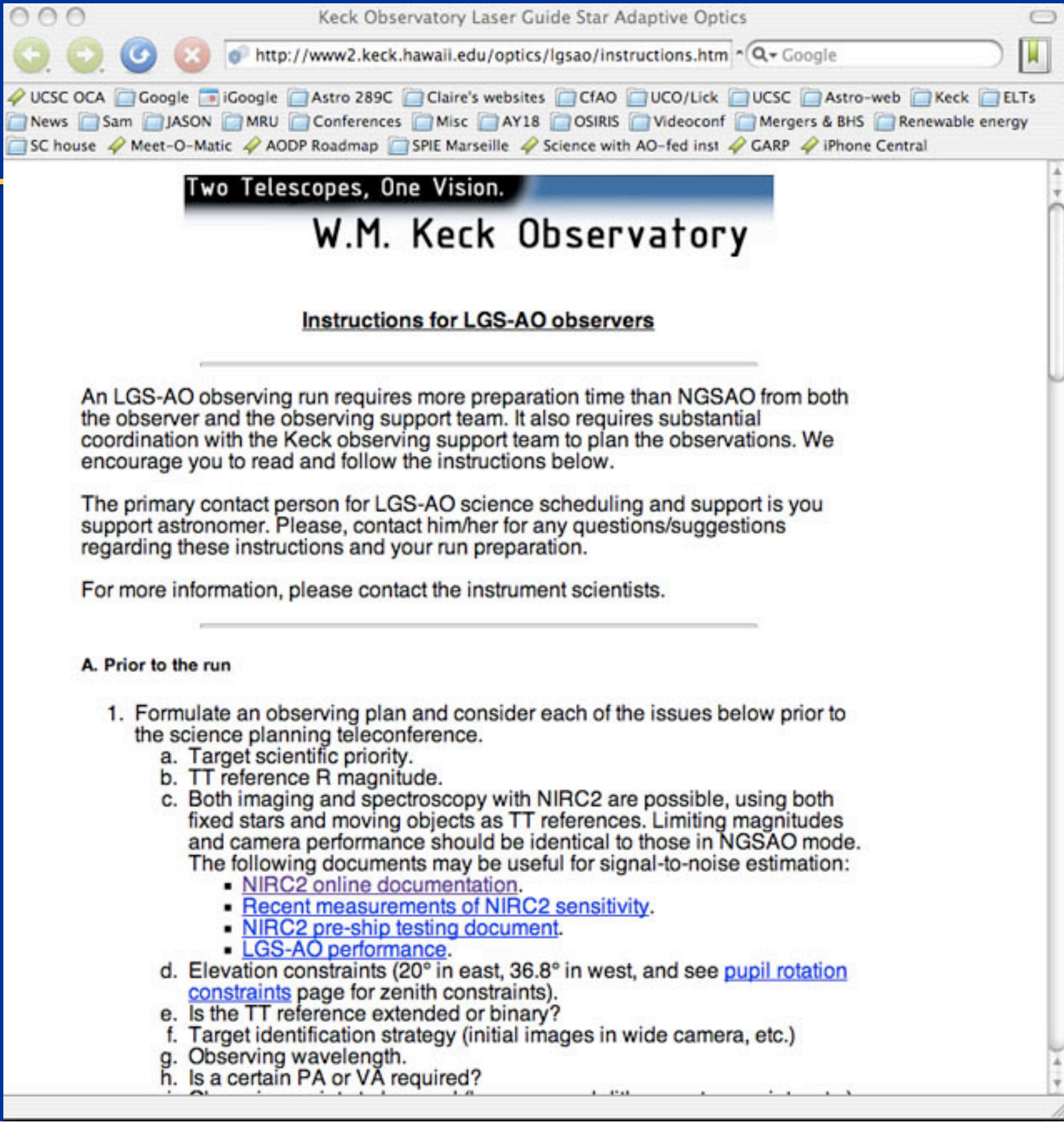
AO Song

The following is a spoof, written by Elinor Gates, of the Banana Boat song (July 2003).

Adaptive Optics Song **to the tune of Banana Boat**	**Lyrics for the Banana Boat version** **by Harry Belafonte**
A-O, A-A-A-O Daylight come and me wanna go home. A-O, A-A-A-O Daylight come and me wanna go home.	Day-o, day-ay-ay-o Daylight come and me wan' go home Day-o, day-ay-ay-o Daylight come and me wan' go home
Work all night on closing the loop Daylight come and me wanna go home. Track the Strehl till de morning come. Daylight come and me wanna go home. A-O, A-A-A-O Daylight come and me wanna go home. A-O, A-A-A-O Daylight come and me wanna go home.	Work all night on a drink of rum Daylight come and me wan' go home Stack banana till de morning come Daylight come and me wan' go home Day-o, day-ay-ay-o Daylight come and me wan' go home Day-o, day-ay-ay-o Daylight come and me wan' go home
Come, Mister 'stronomer, tally me R-nought Daylight come and me wanna go home. Come, Mister 'stronomer, tally me R-nought Daylight come and me wanna go home. A-O, A-A-A-O Daylight come and me wanna go home. A-O, A-A-A-O Daylight come and me wanna go home.	Come, Mister tally man, tally me banana Daylight come and me wan' go home Come, Mister tally man, tally me banana Daylight come and me wan' go home Day-o, day-ay-ay-o Daylight come and me wan' go home Day-o, day-ay-ay-o Daylight come and me wan' go home
Shoot Eight Watt, Nine Watt, Ten Watt Laser Daylight come and me wanna go home Shoot Eight Watt, Nine Watt, Ten Watt Laser Daylight come and me wanna go home	Lift six foot, seven foot, eight foot bunch Daylight come and me wan' go home Lift six foot, seven foot, eight foot bunch Daylight come and me wan' go home
Beautiful laser target star Daylight come and me wanna go home	Beautiful bunch of ripe banana Daylight come and me wan' go home
Laser spotters watching for airplanes Daylight come and me wanna go home	Hide the deadly black tarantula Daylight come and me wan' go home

Laser guide star observing requires more preparation

- US observatories have to submit target list to US Space Command (satellite avoidance) in advance
  - Not good form to destroy the detector on a billion dollar satellite
- Specific formats required
- Check web pages for instructions



Keck Observatory Laser Guide Star Adaptive Optics

http://www2.keck.hawaii.edu/optics/lgsao/instructions.htm

Two Telescopes, One Vision.

W.M. Keck Observatory

Instructions for LGS-AO observers

An LGS-AO observing run requires more preparation time than NGSAO from both the observer and the observing support team. It also requires substantial coordination with the Keck observing support team to plan the observations. We encourage you to read and follow the instructions below.

The primary contact person for LGS-AO science scheduling and support is you support astronomer. Please, contact him/her for any questions/suggestions regarding these instructions and your run preparation.

For more information, please contact the instrument scientists.

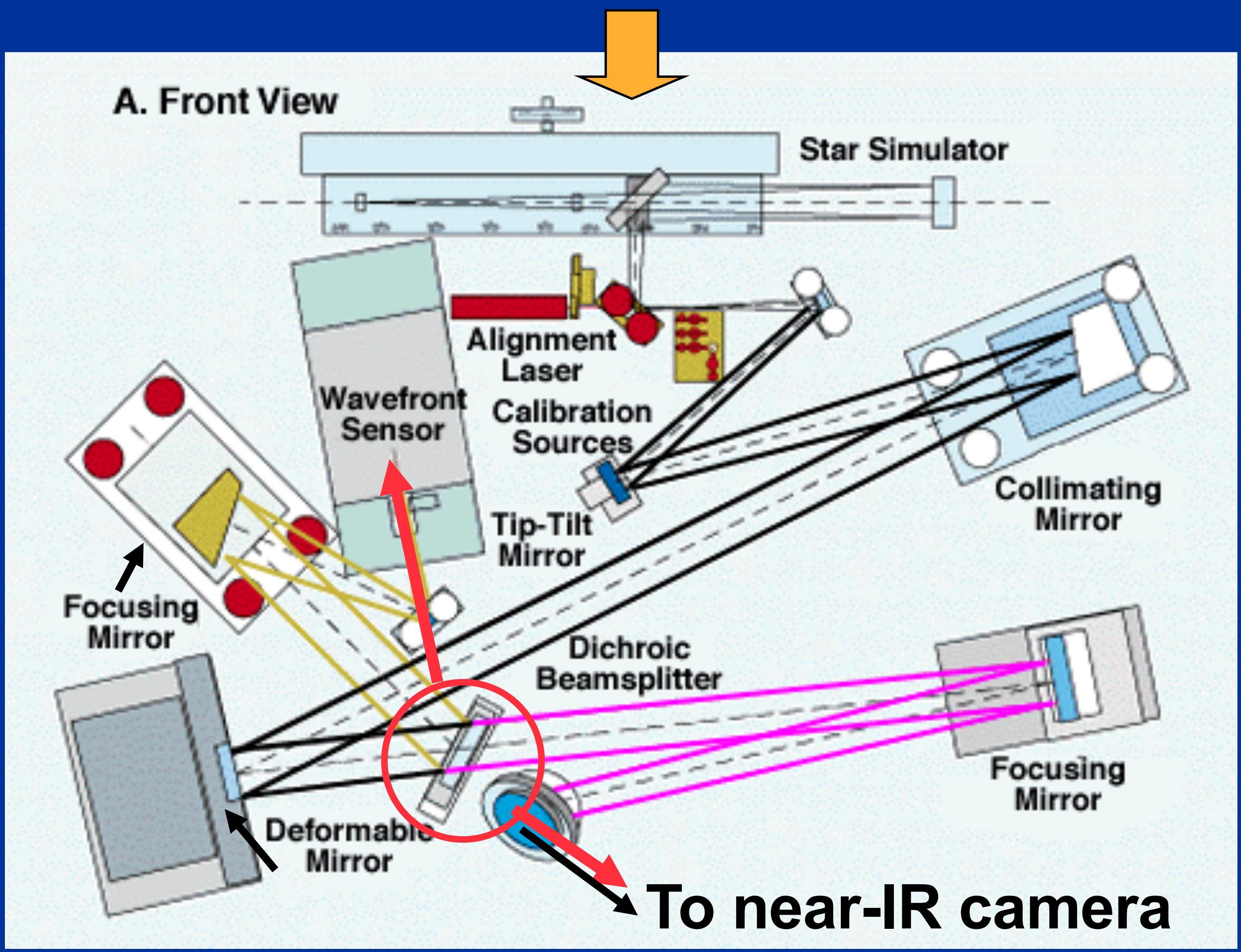
A. Prior to the run

1. Formulate an observing plan and consider each of the issues below prior to the science planning teleconference.
   a. Target scientific priority.
   b. TT reference R magnitude.
   c. Both imaging and spectroscopy with NIRC2 are possible, using both fixed stars and moving objects as TT references. Limiting magnitudes and camera performance should be identical to those in NGSAO mode. The following documents may be useful for signal-to-noise estimation:
      - NIRC2 online documentation.
      - Recent measurements of NIRC2 sensitivity.
      - NIRC2 pre-ship testing document.
      - LGS-AO performance.
   d. Elevation constraints (20° in east, 36.8° in west, and see pupil rotation constraints page for zenith constraints).
   e. Is the TT reference extended or binary?
   f. Target identification strategy (initial images in wide camera, etc.)
   g. Observing wavelength.
   h. Is a certain PA or VA required?

Questions to ask when you get to the telescope

- If possible, come a day early and watch the previous night's observers use the AO system
- Ask for a "lesson" in how to control the AO system from the instrument interface
- Typically the AO system is calibrated each afternoon
  - Observatory staff will use an internal light source to measure non-common-path errors every day (before observing)
  - Instructive to watch this process if you've never seen it before

Why we must calibrate for non-common-path errors



Schematic of Lick AO system (one generation ago)

Overview of the calibration process (usually done by staff in afternoon)

- Method varies from one AO system to another
- Close dome, lights out, flatten the deformable mirror
- Turn on internal light source (e.g. optical fiber with diode or laser light)
  - Record centroid positions on wavefront sensor
  - Record image of internal reference on camera
- Adjust deformable mirror shape until image of internal reference has highest Strehl ratio
  - Can do this one mode at a time (automated)
  - Or Gertschberg-Saxton phase retrieval method
- Record new positions of centroids on wavefront sensor. These will be the "reference centroids" to which AO loop will control.

AO tuning for your guide star

- Wavefront sensor camera frame-rate and AO control loop gain optimized for your guide star
  - For fainter guide stars, want slower frame rate
  - With Shack-Hartmann WFS, typically need 100-200 counts per subaperture per wavefront sensor frame, for good performance
  - For fainter stars, use lower control loop gain (lower bandwidth)
- AO operator will take a sky background measurement for the wavefront sensor
  - Subtracted from each wavefront sensor frame
- Based on number of wavefront sensor counts, AO operator will run a program to optimize the AO system performance (trade frame rate against counts on wavefront sensor)
- Then offset from PSF star's guide star to the real guide star, turn on AO system, take images or spectra

Re-tuning the AO system during the night

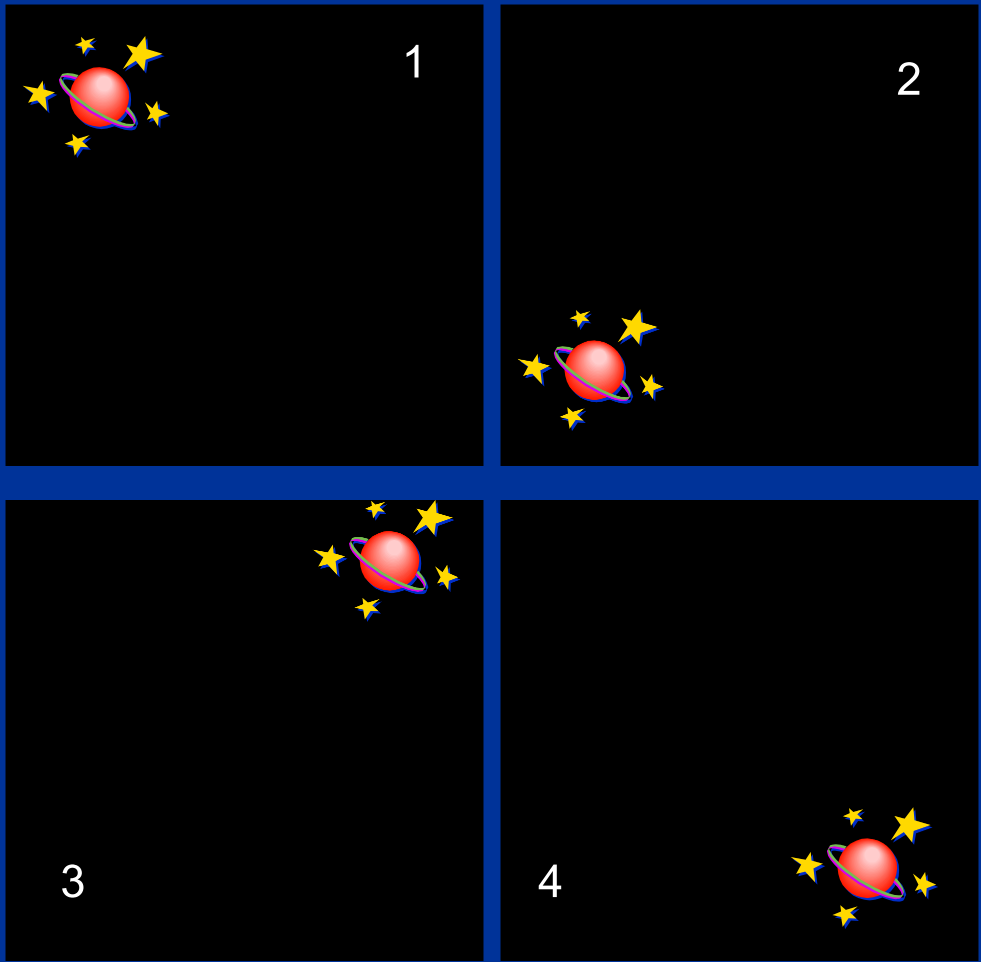
- When does operator re-tune AO system?
  - At each new telescope pointing
  - When background changes (clouds, moon)
  - When flexure changes (after slew, long integrations)
  - Whenever observer requests an updated tune-up
- I usually keep an eye on the number of wavefront sensor counts per subaperture
  - When it drops considerably below its original value, ask for a re-tuning

Other observing procedures are same as for any infra-red observations (1)

- Take sky backgrounds
  - Necessary in IR: science target can be dimmer than the sky background!
  - Can nod to sky so that your science target is entirely off the detector, or
  - If your science target is small enough, can get sky bkgnd just from dithering target on detector
- Observe photometric standard stars several times during the night (if needed)

Other observing procedures are same as for any infra-red observations (2)

- Dithering and nodding:
- IR array non-uniformity requires sky measurement and subtraction
- To obtain a sky subtraction, usually need a multiposition dither (1-2-3-4 etc.)
  - If your science target is big, good to get a separate sky frame too



5 (sky)

Questions? Discussion?

How to assess the reality of AO results reported in the literature

- Which data should you take seriously?
- What are “danger signs” that should make you doubtful?

Taking data seriously: Three big issues

1. Strehl ratio and variability

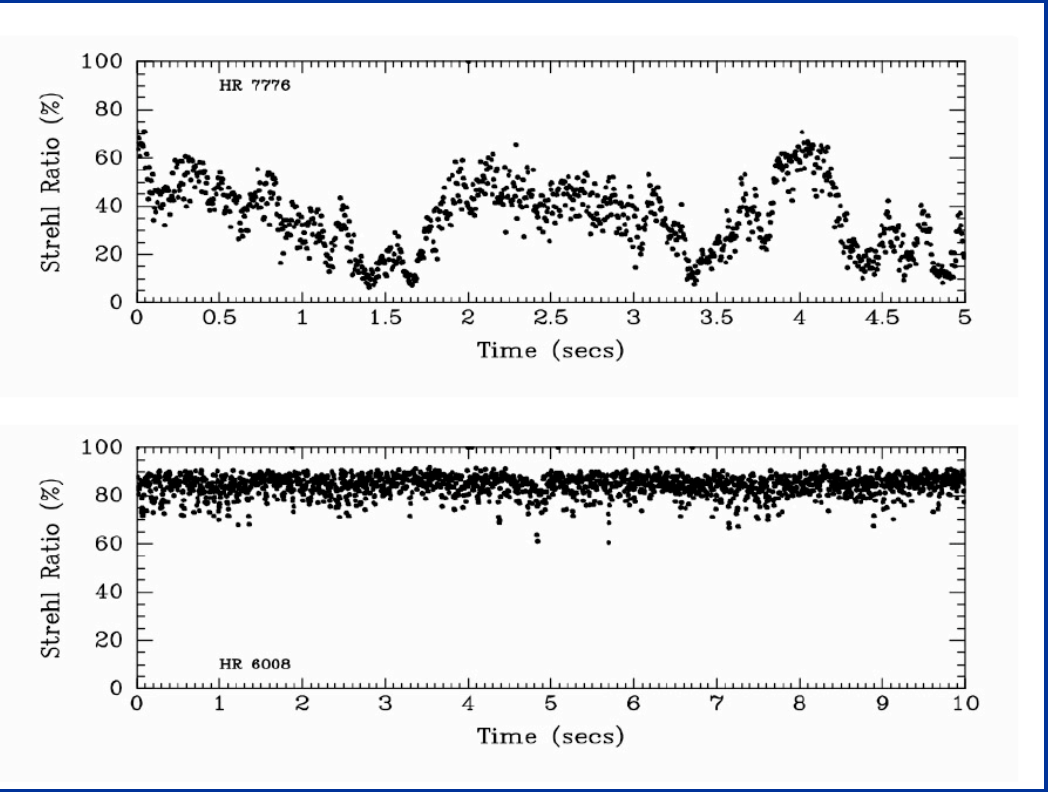
2. Effect of using a non-point-source as a guide star or tip-tilt star

3. Signal to noise ratio

Taking data seriously: Three big issues

1) Strehl:
   - Don't trust low-Strehl results
   - How low is low? My rule of thumb: "low" is S < 10%
   - Problems: unstable photometry, variable PSFs

Higher Strehl ratios are more stable



Credit: J. Christou et al.

Big issues, continued

2) Finite-size object used as “guide star”
   - Frequently produces artifacts on point spread function
   - Sometimes get “double-star” PSF
   - Look for independent measurement of PSF if possible

   - Also there can be issues with using finite-sized object as tip-tilt star
     » Most important example: using bright nucleus of a galaxy as the tip-tilt reference
     » The more point-like it is, the better
     » No firm rules here about what to do - try it!

Big issues, continued

3) Signal to noise ratio of AO image or spectrum
   - Rules of thumb (Hardy):
     - » SNR needed to recognize an object in a noisy background: SNR > 5
     - » SNR needed for spectroscopy is much larger: people use numbers like 20, 50, 100 per resolution element (depends on the application)

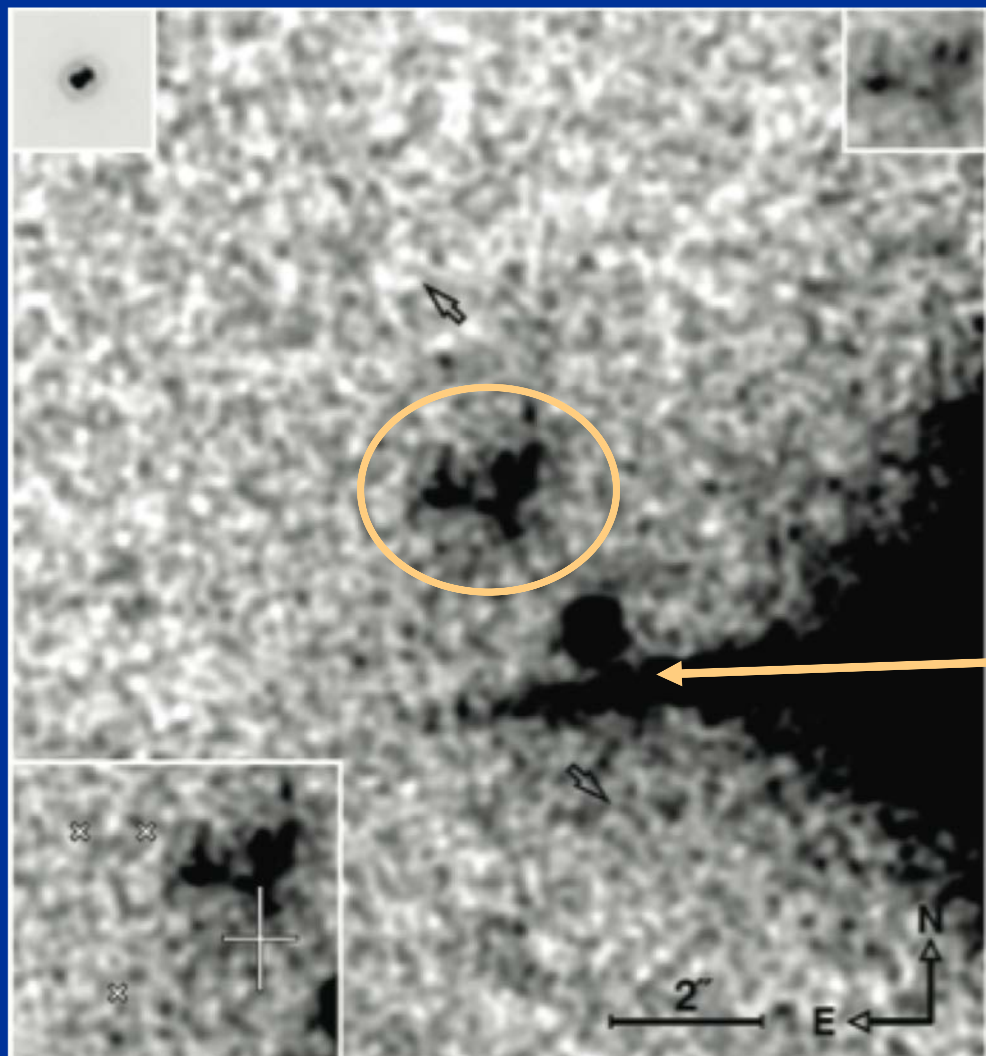
Be sure to look carefully at section of published paper where SNR is discussed.

- If it isn't discussed, try to estimate it yourself.

“Journal of Irreproducible Results ”

- Danger signs:
- Low Strehl ratios (e.g. 5% - 15%)
- Use of an extended source as a “natural guide star”
  - Can give PSFs that are double, or that have several lumps
- Use of a “guide star” that IS a point source, but that is embedded in a fuzzy region
  - Also can give odd PSFs
- Look for repeatable independent measurements of PSF

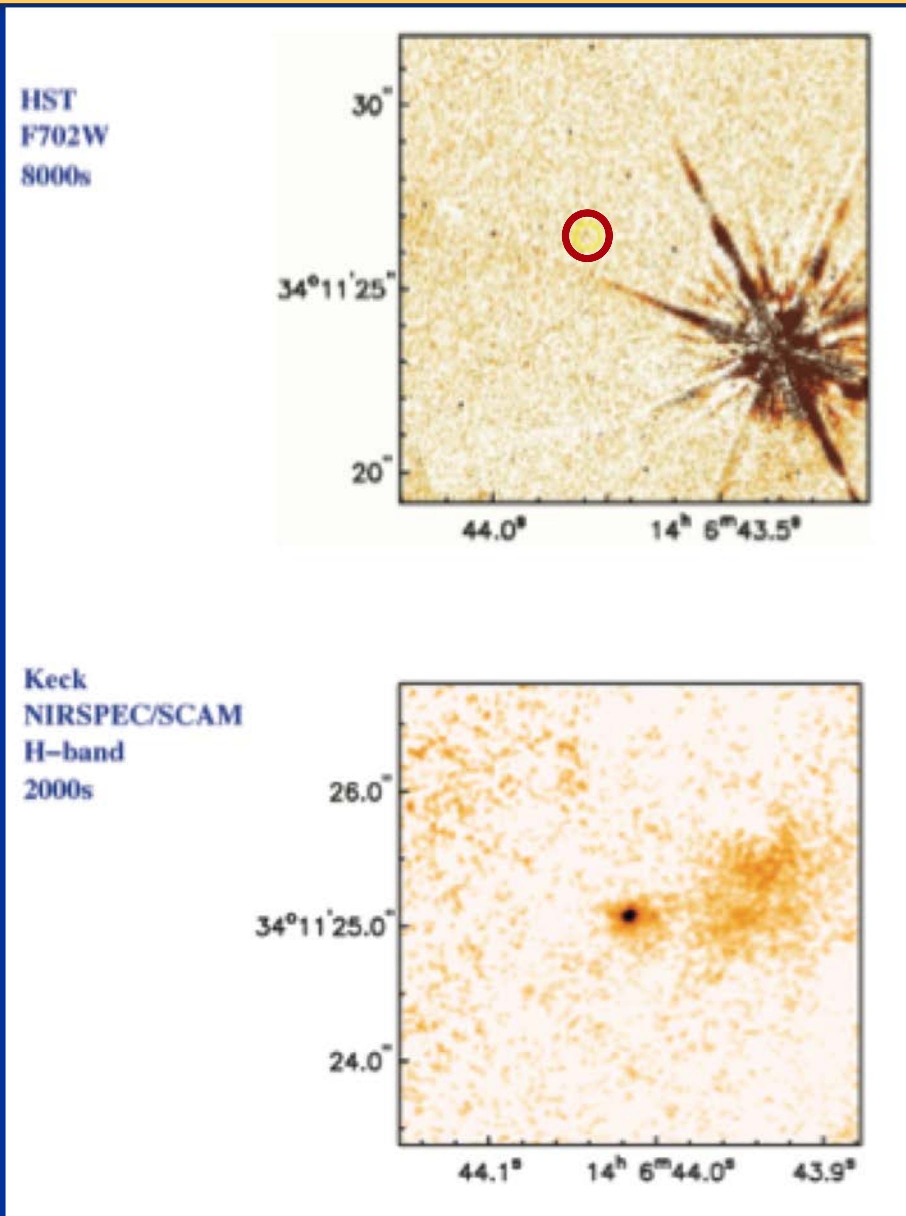
Radio galaxy 3C294 seen with early UH AO system



Diffraction spike from guide star (a double star?)

Stockton et al.
UH AO System
CFHT Telescope

3C294 images from Hubble, Keck AO

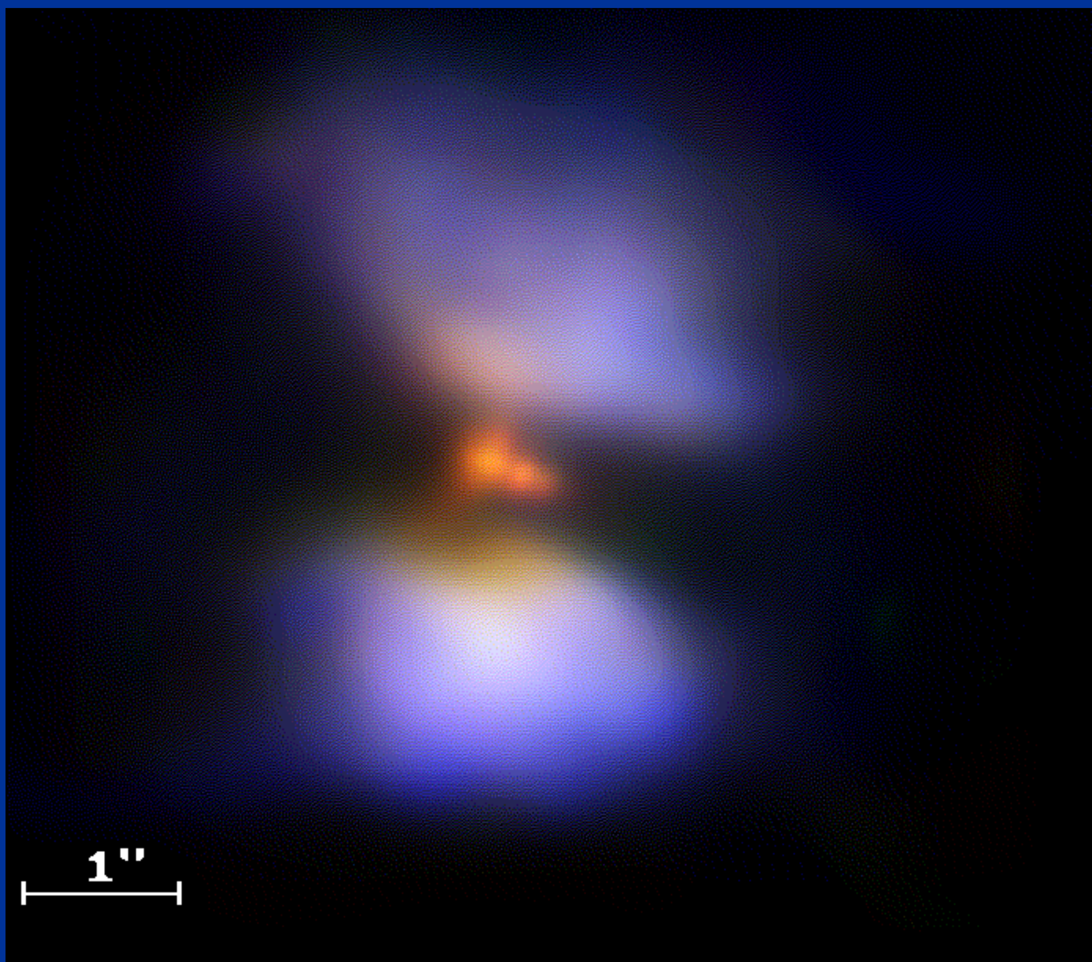


Hubble (0.7 micron)

Keck AO (1.6 microns): Bright point-like core, plus fuzz on right

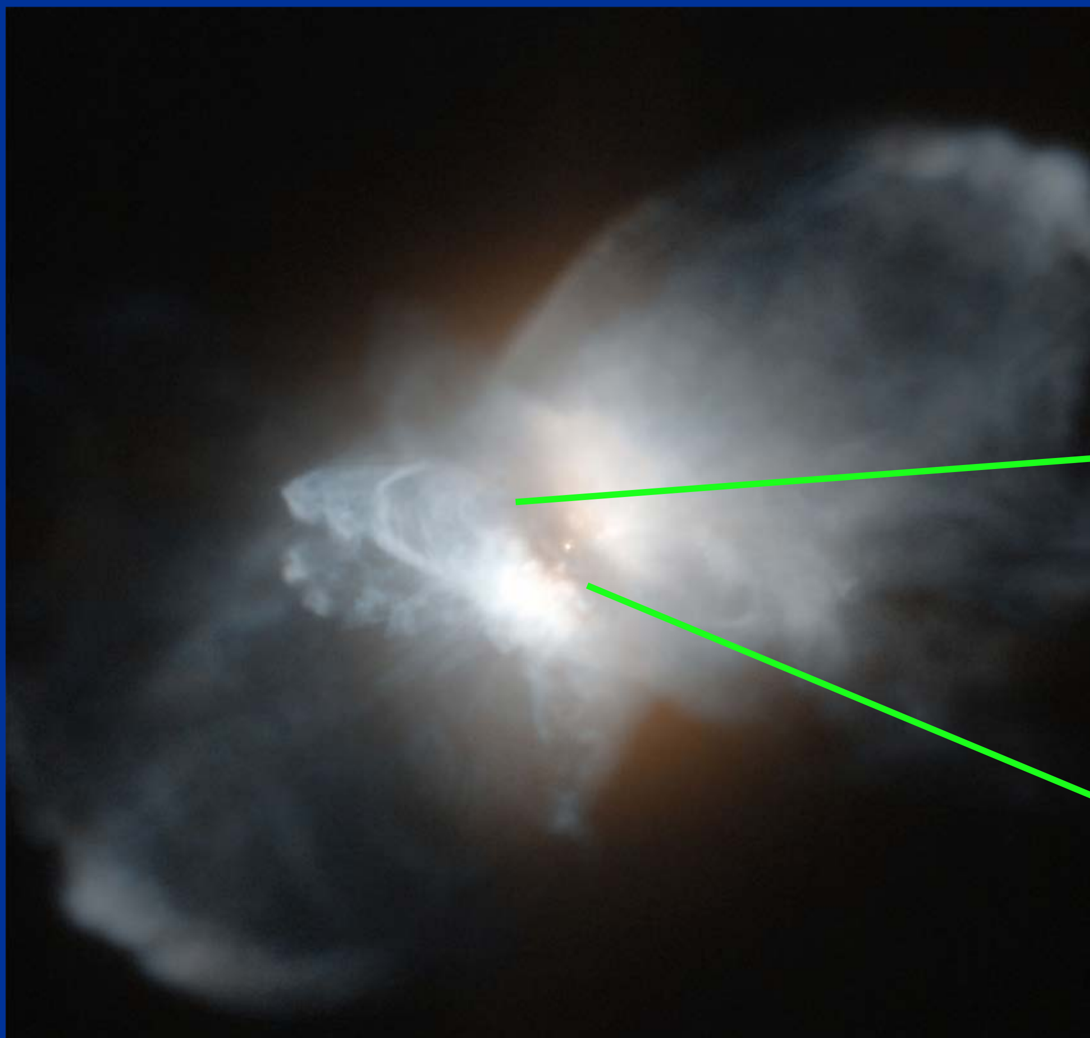
From Wim de Vries. LLNL

Example of dangers from extended guide star: Frosty Leo nebula



- UH AO system
- Closed AO loop on one of the big blue blobs
- Concluded central star is double
- Not confirmed by subsequent observations

Hubble image of Frosty Leo



Visible light

Nice diffraction rings around a single star:

Conclusions

- AO systems can yield flakey results if:
  - Guide star is extended, or too faint
  - Strehl is too low or too variable
- Need good signal to noise (but that is no different from "regular" observations)
- Need thoughtful preparation before an observing run
- But…. RESULT CAN BE WORTH THE TROUBLE!