# McMath-Pierce

## Adaptive Optics Overview

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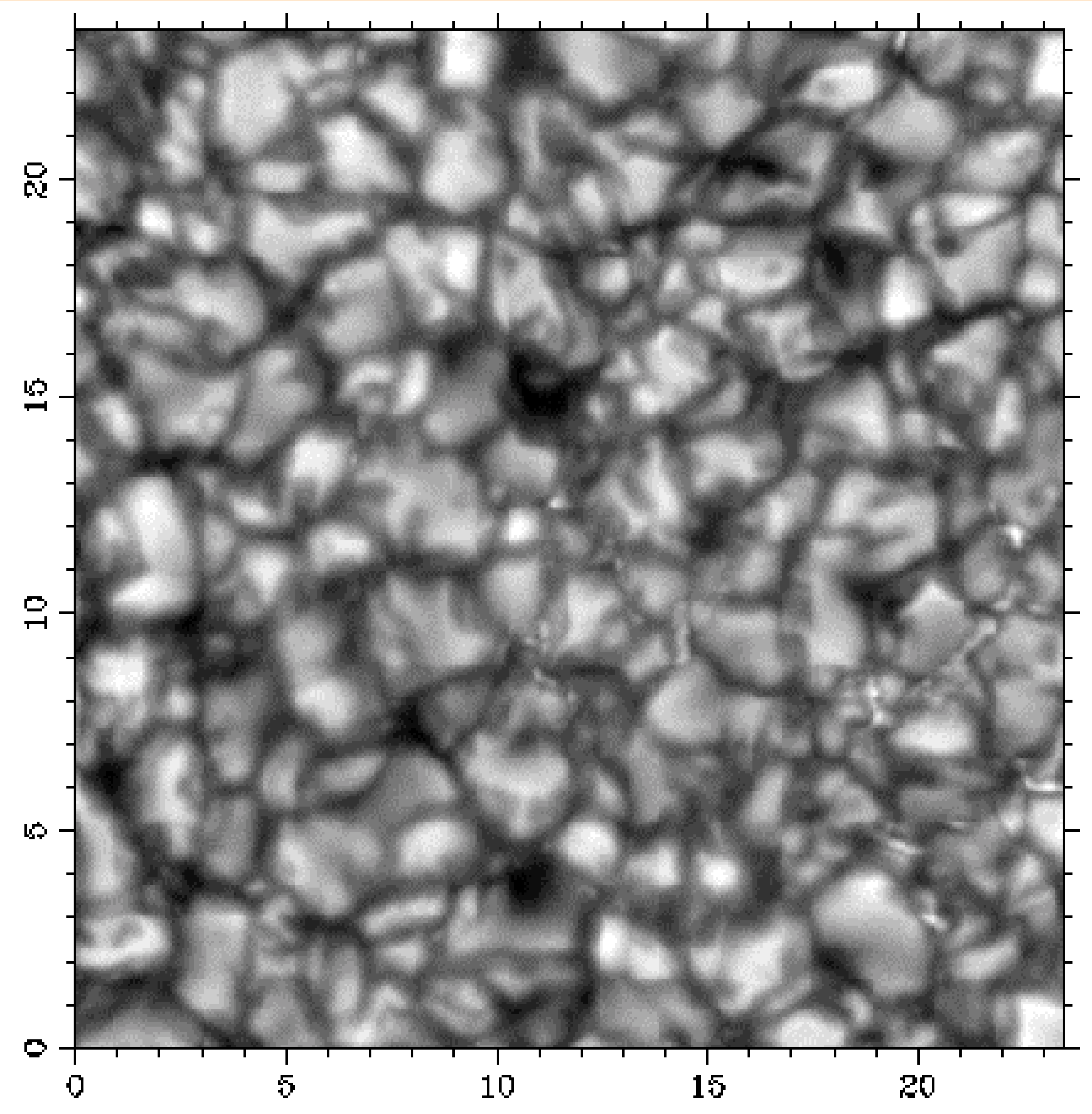
# *Small-Scale Structures on the Sun 1*



arcsec

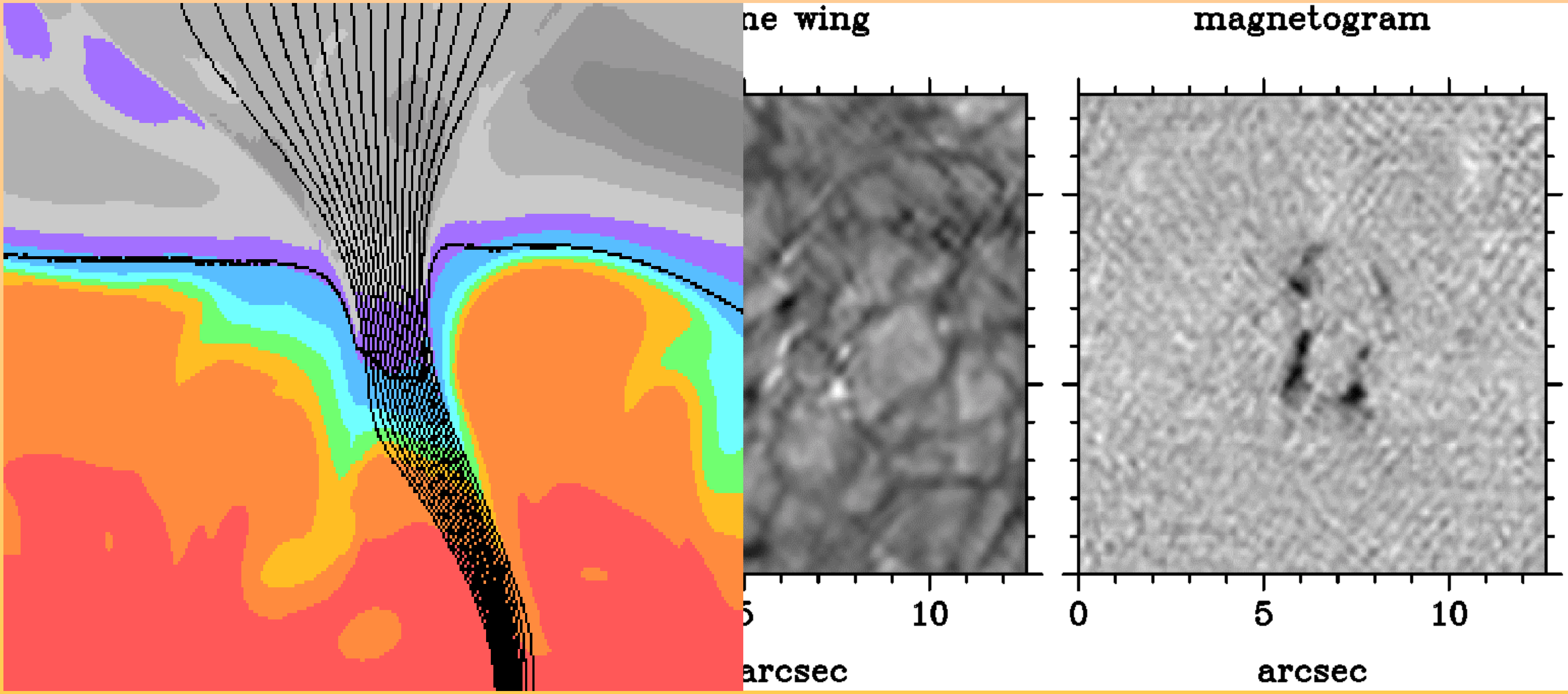
**Important astrophysical scales (pressure scale height in photosphere, photon mean free path in photosphere) are on the order of 0.1 arcsec**

**Convective phenomena at 0.1”:**

- shocks
- vortices
- interaction with magnetic flux
- generation of global 5-minute oscillations

**Diffraction-limited white-light image of solar granulation and small-scale magnetic fields at 600 nm using adaptive optics at the Dunn Solar Telescope and phase-diverse speckle imaging**

# *Small-Scale Structures on the Sun 2*

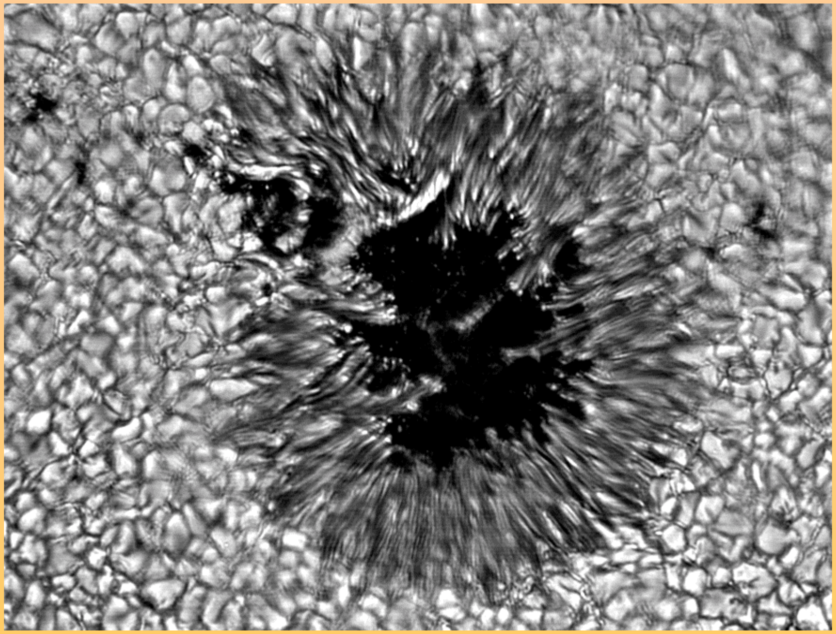


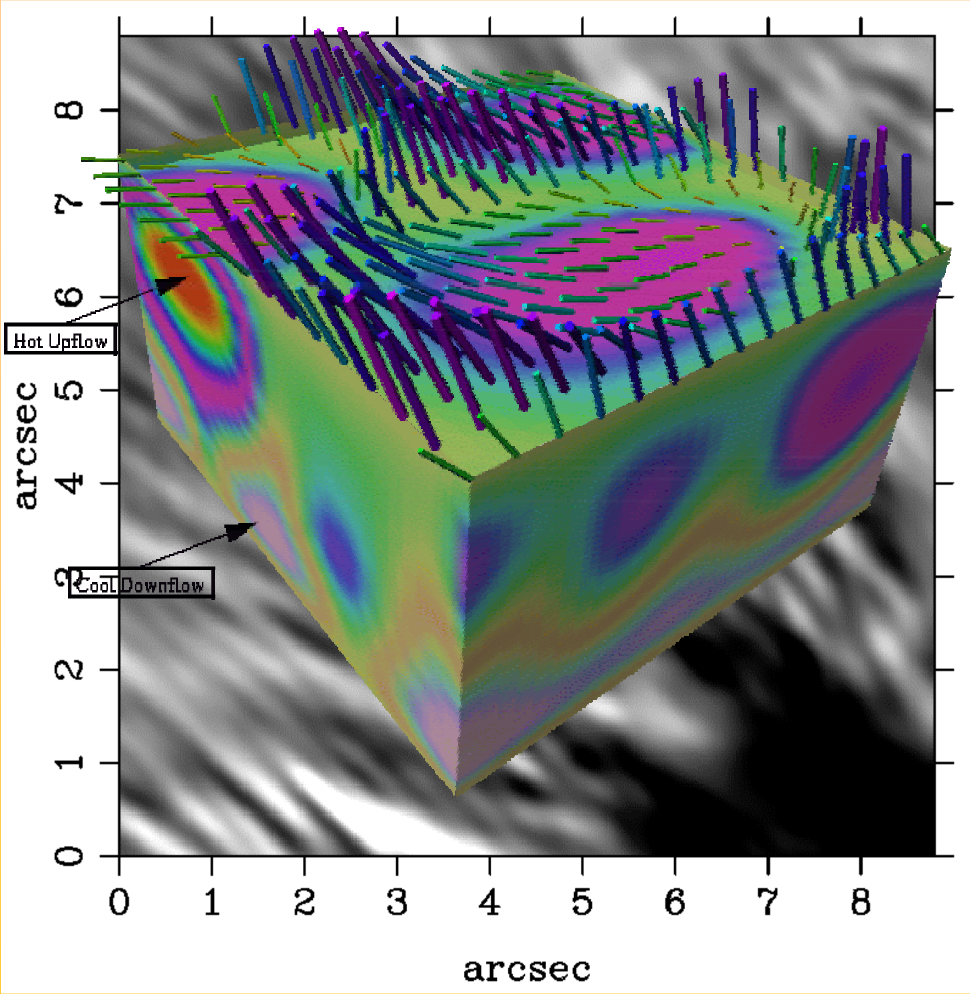
Ohmic diffusion scale length for magnetic field structure is on the order of 0.001”.

Highly concentrated magnetic flux at the spatial limit of current solar telescopes:

- magnetic flux tubes
- building blocks of network and active regions
- most likely channels for transporting energy to upper atmosphere
- affect convection, irradiance, oscillations, solar cycle

# *Small-Scale Structures on the Sun 3*

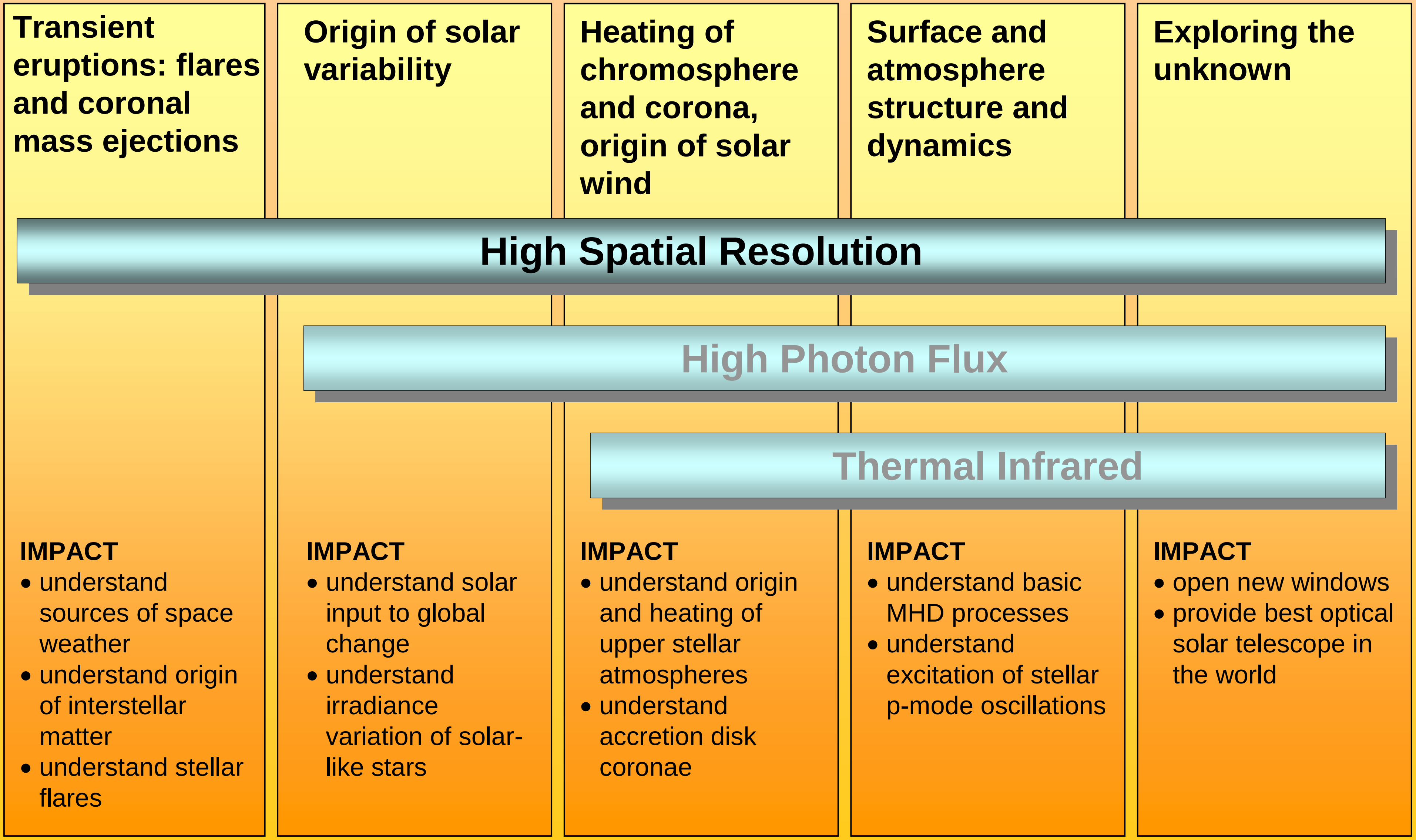




Sunspots

- magneto-convection in umbral dots and penumbral filaments
- combed penumbral fields, Evershed effect
- relevance to other stars with huge spots

# High-Resolution Solar Science



**High Spatial Resolution**

**High Photon Flux**

**Thermal Infrared**

**Transient eruptions: flares and coronal mass ejections**

**IMPACT**

- understand sources of space weather
- understand origin of interstellar matter
- understand stellar flares

**Origin of solar variability**

**IMPACT**

- understand solar input to global change
- understand irradiance variation of solar-like stars

**Heating of chromosphere and corona, origin of solar wind**

**IMPACT**

- understand origin and heating of upper stellar atmospheres
- understand accretion disk coronae

**Surface and atmosphere structure and dynamics**

**IMPACT**

- understand basic MHD processes
- understand excitation of stellar p-mode oscillations

**Exploring the unknown**

**IMPACT**

- open new windows
- provide best optical solar telescope in the world

# Differences to Night-Time Astronomy

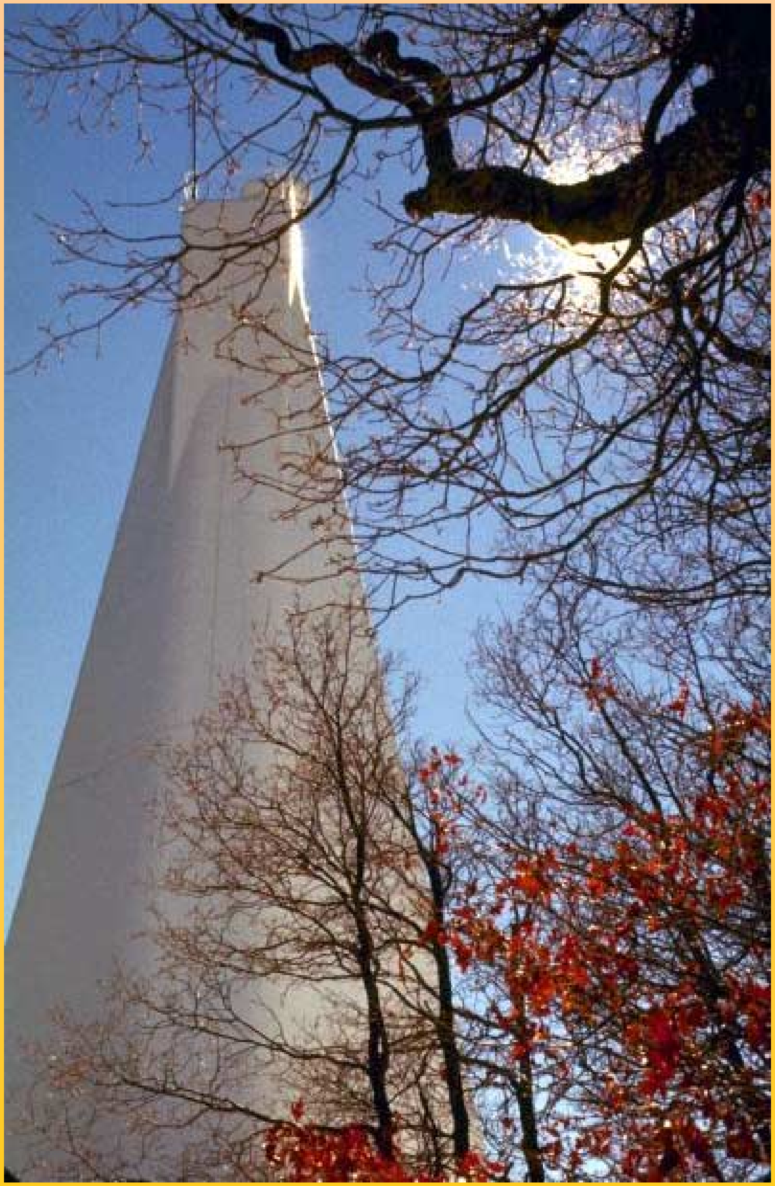
- Extended source that is typically much larger than detector
- No point sources
- Low contrast source, rms intensity of a few percent
- Fast temporal evolution, visible changes within 10 s at 0.1 arcsec resolution

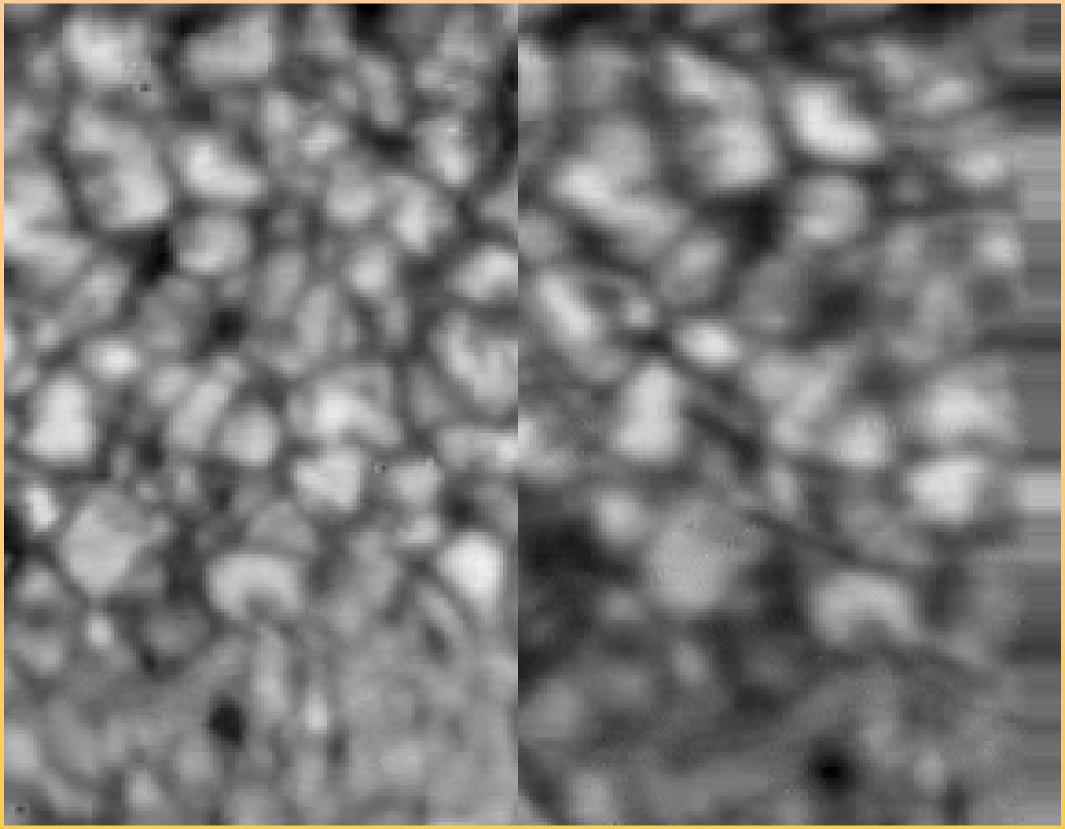
- Worse seeing ($r_0$=10 cm is excellent seeing)
- Small isoplanatic patch size (a few arcsec at most)

- Resolution is so important that visible is used to reduce diffraction
- Still relatively limited telescope apertures (<1.6 m)

- Science requires spectroscopy and often polarimetry

# Low-Order Solar AO (T. Rimmele)

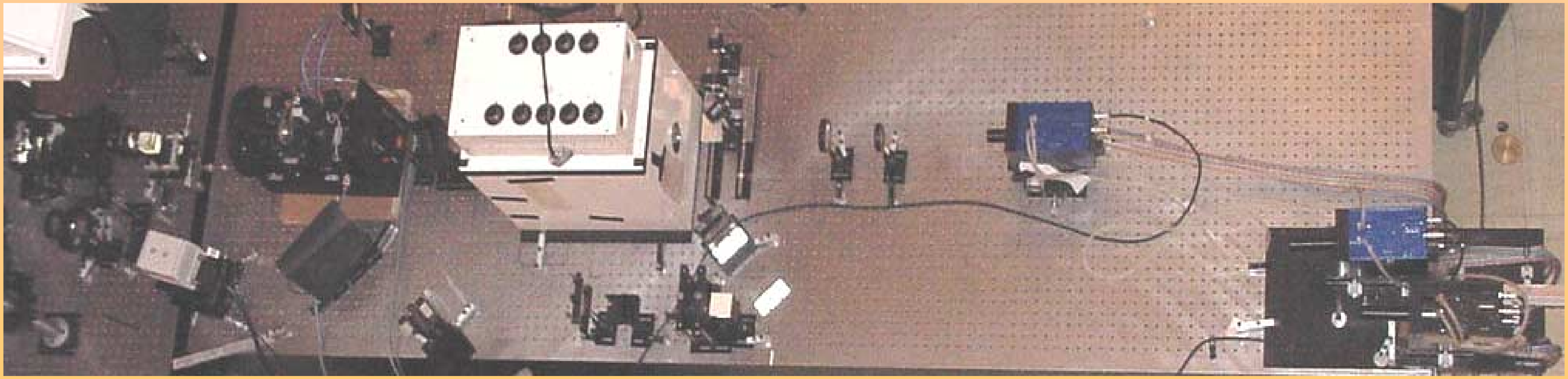


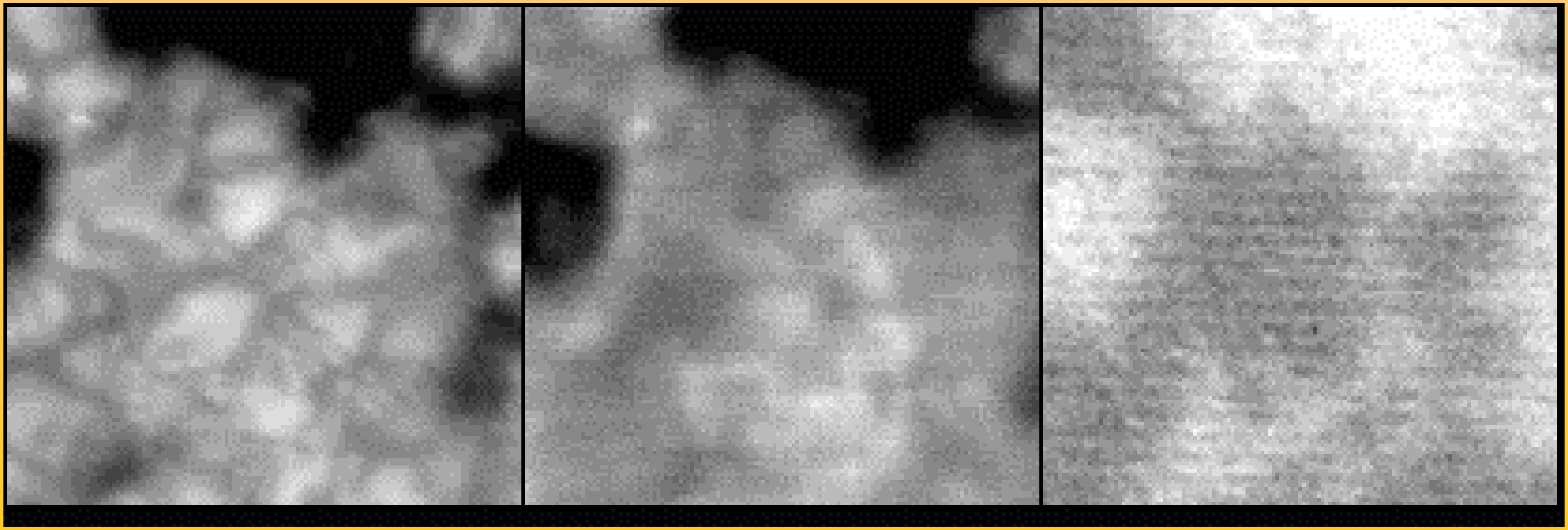


**With AO** **Without AO**

- 76-cm telescope aperture
- median seeing: 7 cm at 600 nm
- 24 subaperture Shack-Hartmann

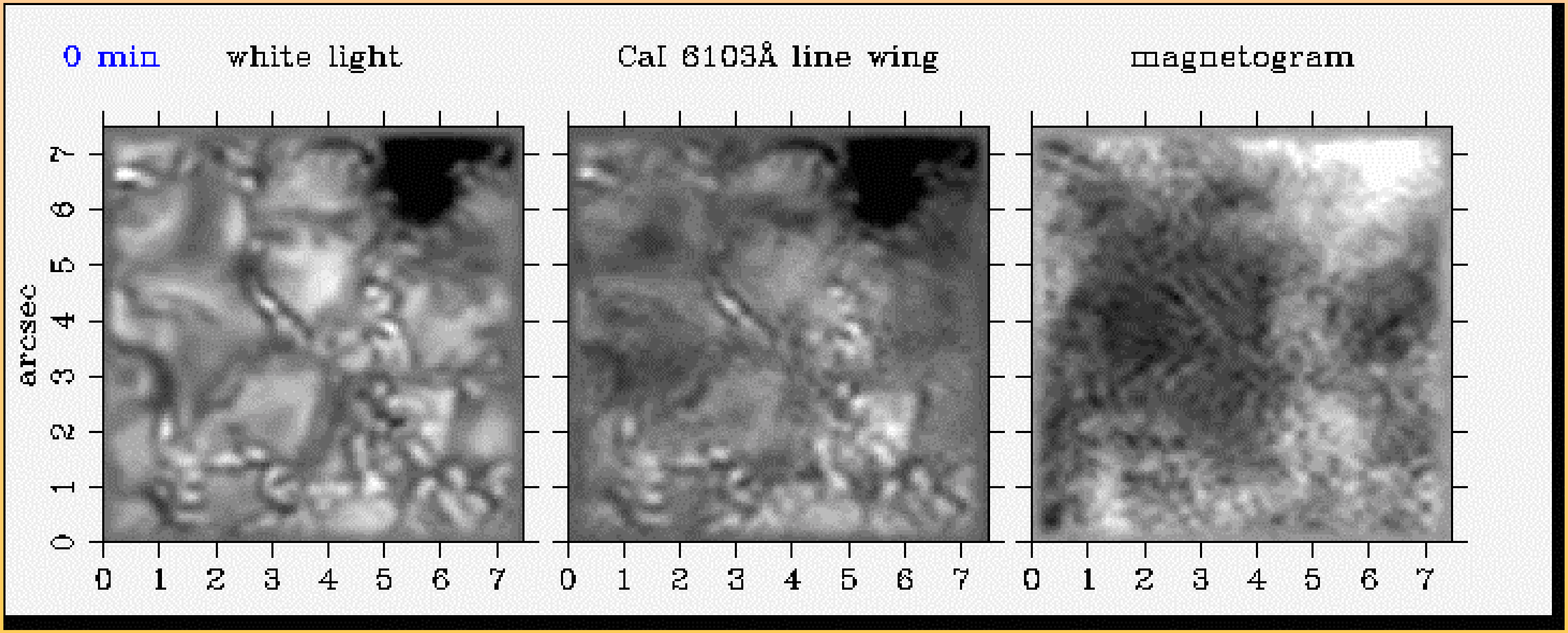
# *Example Optical Setup and Raw Data*





**white light** **line wing intensity** **magnetogram**

# Phase-Diverse Speckle Reconstruction



- Phase-diverse speckle imaging uses pairs of in-focus and out-of-focus images to retrieve object and wavefronts
- Ideally suited to reconstruct partially-corrected images
- Collaboration with Paxman, Seldin, Carrara, and Rimmele

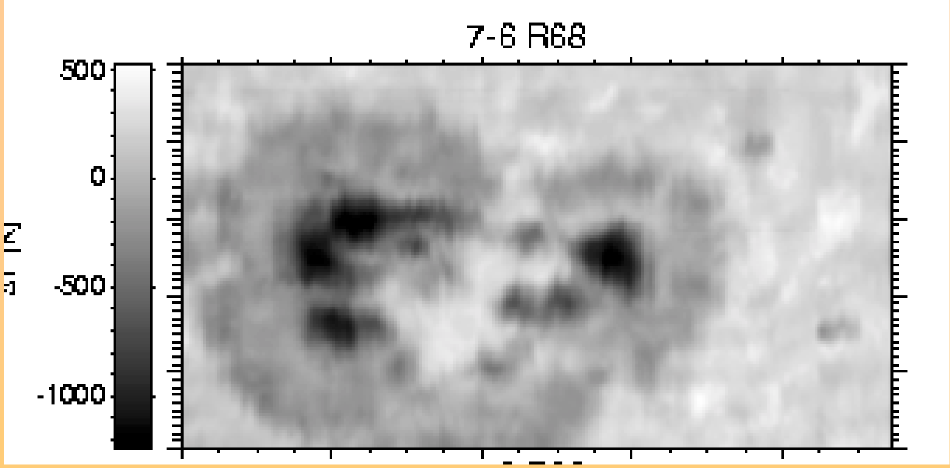
# *The World's Largest Solar Telescope*

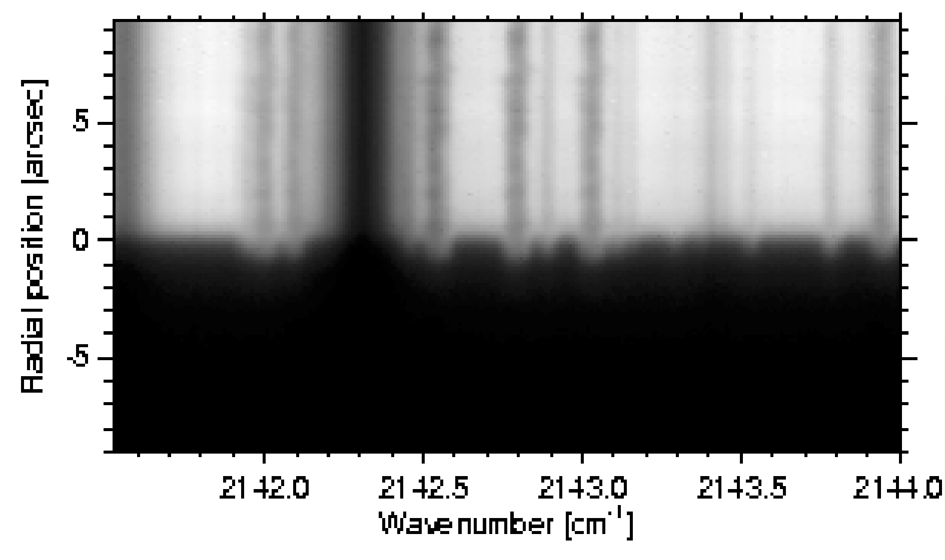
## Infrared Instruments

- 1 to 5 µm imager and polarimeter (1 to 2.3 µm)
- 1.56 µm imaging vector polarimeter
- 0.3 to 12 µm grating spectrograph
- 0.3 to 20 µm FTS
- 6 to 15 µm imager (NASA)
- 12 µm vector polarimeter (NASA)

Adaptive Optics is by far the most important improvement that can be made to infrared observations at the McMath-Pierce

# *Solar Infrared Science 1*

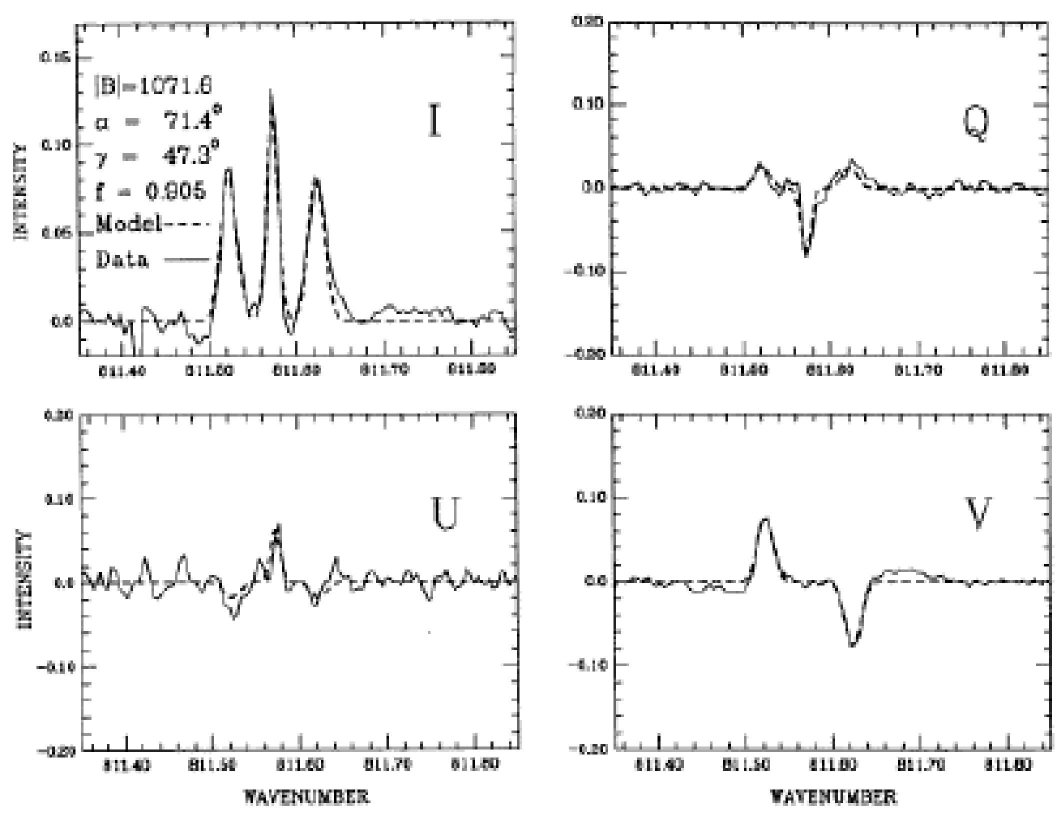




*Data courtesy D. Rabin*

- General infrared advantages:
  - LTE line formation
  - strong *visible* spectral lines formed in upper photosphere and chromosphere are dominated by scattering, NLTE
  - clean way to measure thermodynamics and magnetic fields in higher atmospheric layers
- CO band at 4.8 µm:
  - text-book chromosphere exists almost nowhere on Sun

# *Solar Infrared Science 2*



*Hewagama et al. (1993)*

- MgI at 12 µm:
  - – model-independent vector fields in upper photosphere
  - – more force free in higher layers, better suited for field extrapolation
  - – sensitive to field strengths ~ 100 G
  - – penetration of weak fields into higher layers

# *AO Requirements for 1.5-m Telescope*

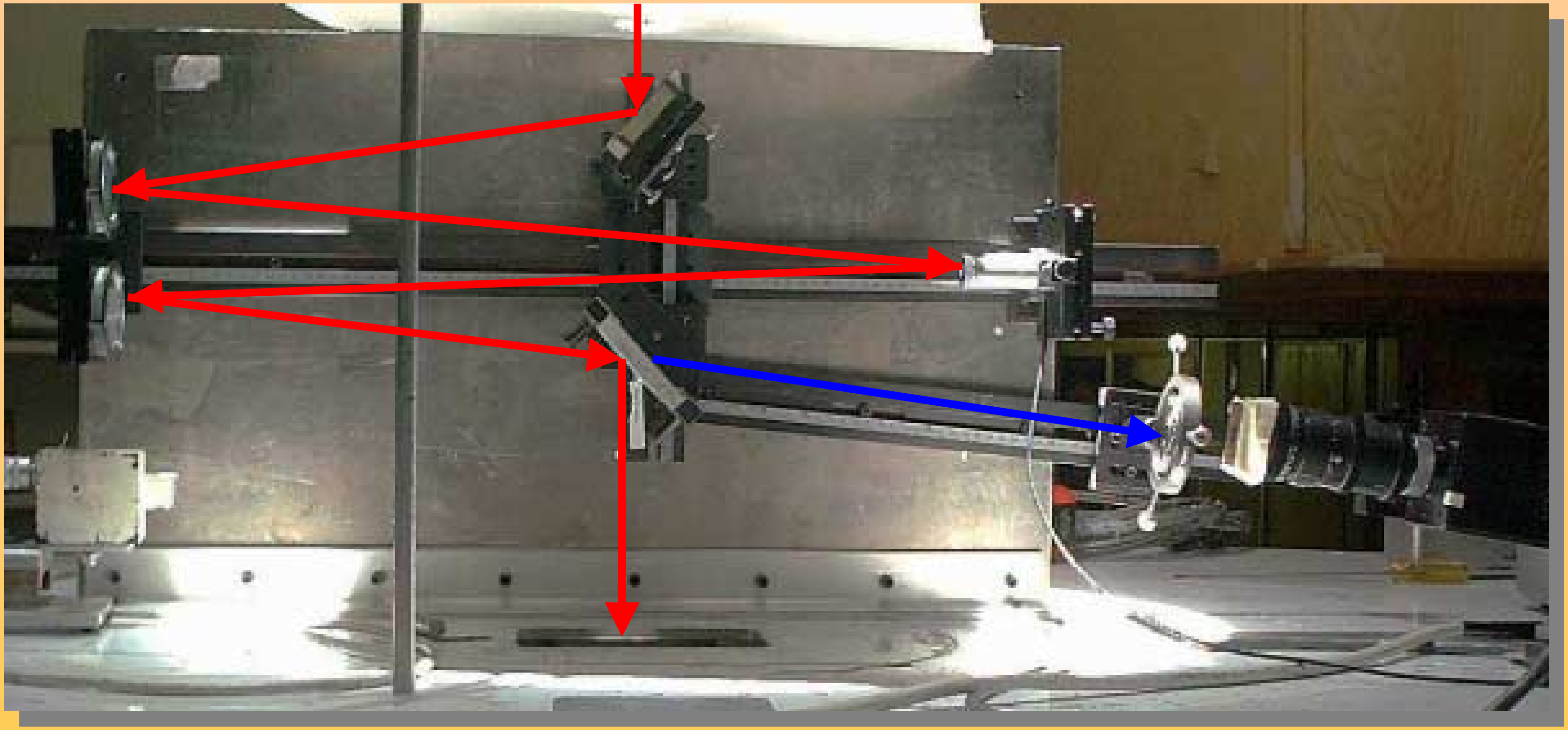
| **wavelength (μm)** | **$r_0$ (cm)** | **actuators** | **bandwidth (Hz)** |
|---|---|---|---|
| 0.5 | 4 | 1100 | 200 |
| 1.5 | 15 | 78 | 50 |
| 2.3 | 25 | 28 | 30 |
| 10.2 | 150 | 2 | 5 |

Tip-tilt is sufficient!

Assumes:

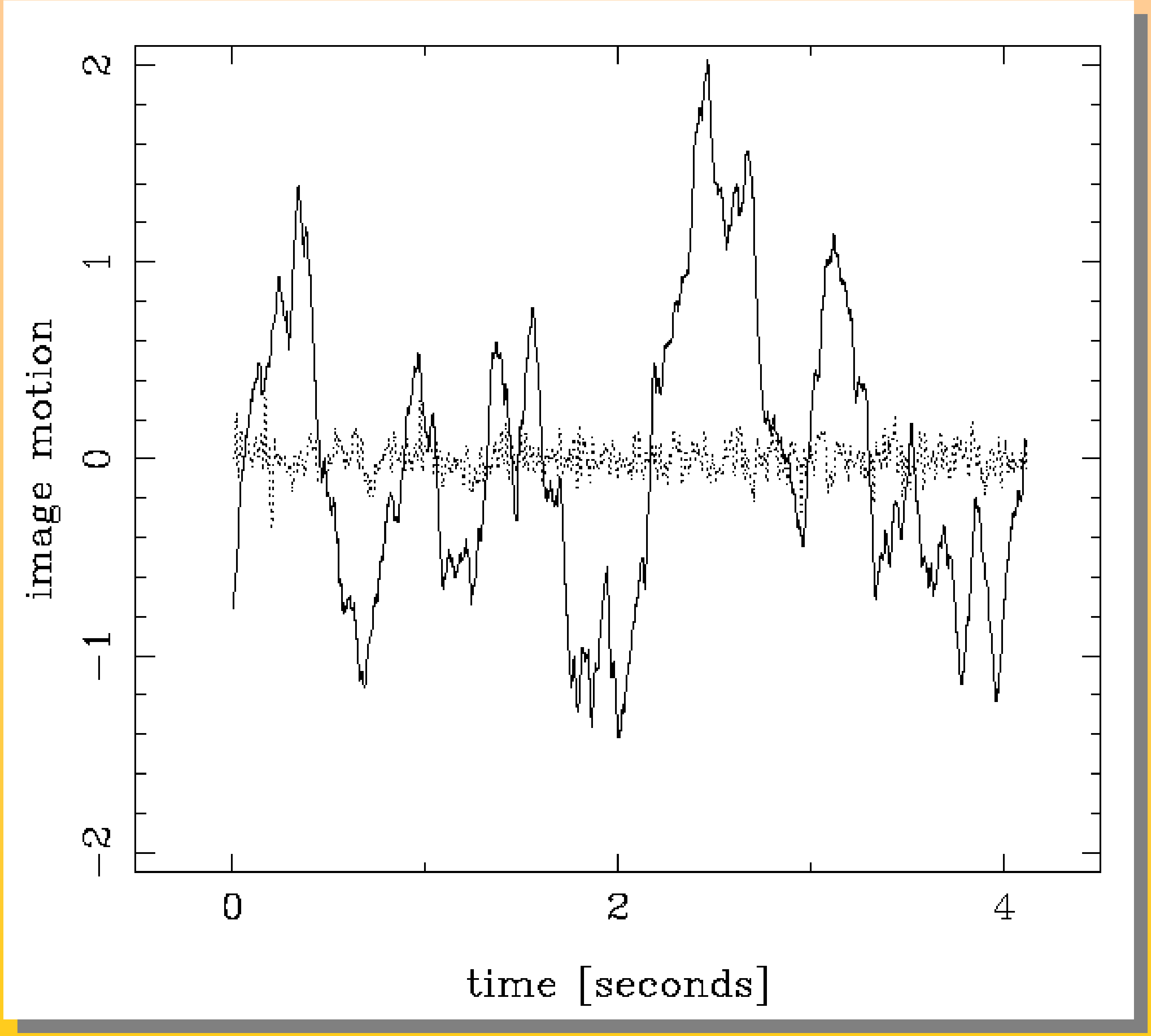
- Kolmogorov statistics
- Single seeing layer with constant wind speed

# Tip-Tilt Correction: Universal Tracker

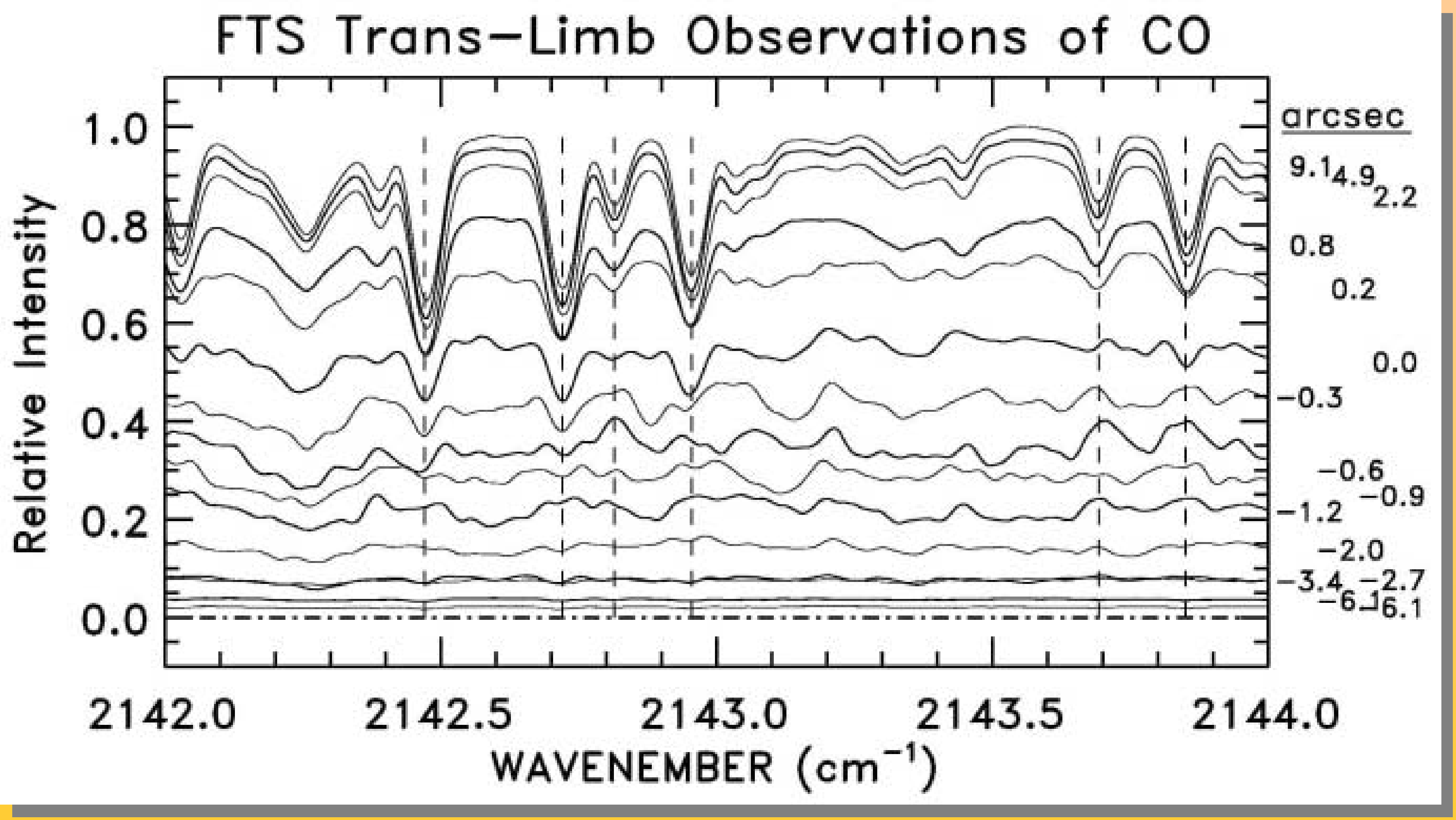


- General-purpose tip-tilt correction with three modes:
  - Digital quad-cell for sunspots
  - Digital limb tracker for various limb position
  - Correlation tracker
- Reference can be moved digitally to scan image across slit
- Current update rate is 500 Hz, corrects to about 50 Hz
- Used for scientific observations by users since April 1, 2002

# Limb-Tracking Performance

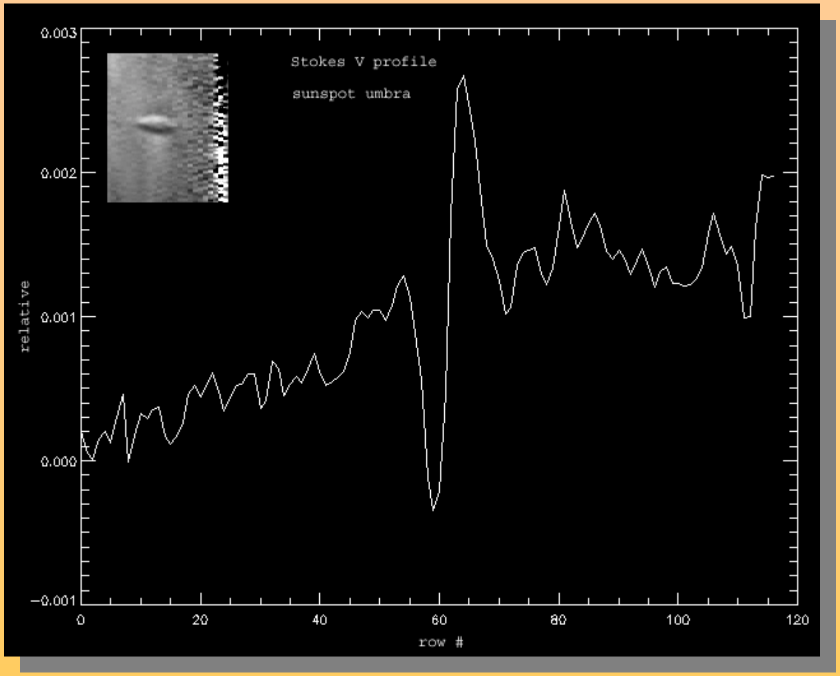


# Universal Tracker Science 1



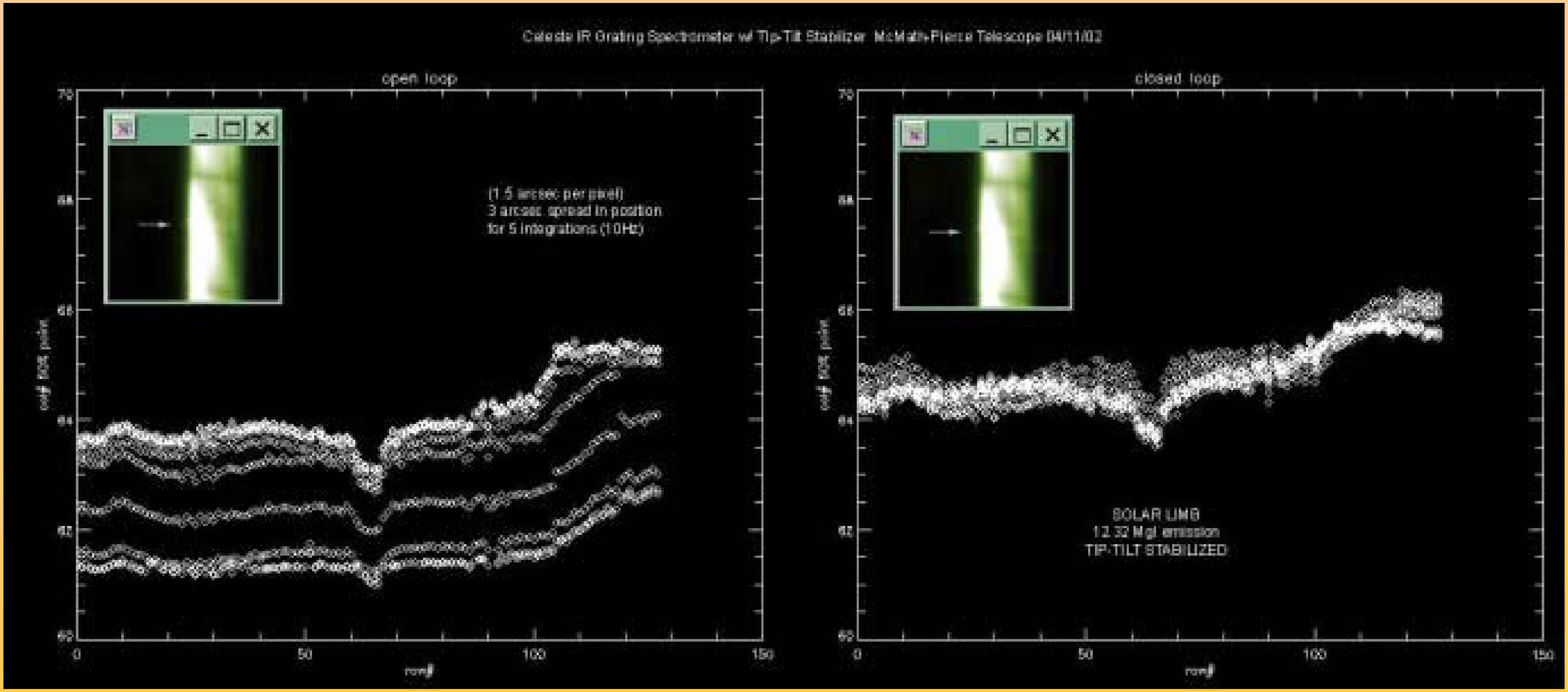
- First FTS observations of CO limb emission at 4.8 µm
- Observations and figure courtesy Tom Ayres

# Universal Tracker Science 2



- NASA Goddard thermal infrared spectrograph and polarimeter (Celeste) combined with tip-tilt system
- Observations and pictures courtesy George McCabe

# Universal Tracker Science 3



- Limb extension of MgI line at 10Hz with and without tip-tilt stabilization
- Graph shows position of limb as a function of wavelength
- Smaller numbers mean further away from sun center
- Observations and picture courtesy George McCabe

# Low-Cost Approach

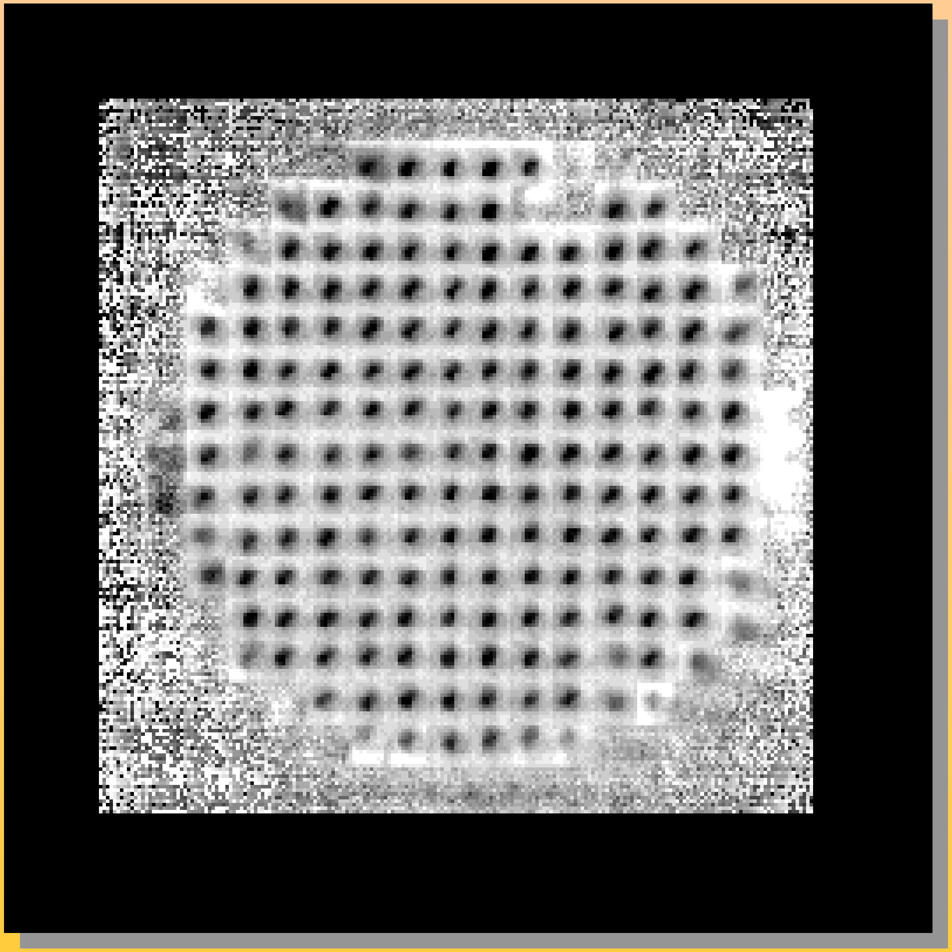
Low-cost, commercial off-the-shelf parts for a complete AO system:

- less than $25k total hardware cost
- all-reflective, gold-coated off-the-shelf optics
- PiezoJena fast tip-tilt stage with large angular range
- Flexible Optics 37-actuators membrane deformable mirror
- DALSA 1kHz frame rate 256 by 256 CCD camera
- Industrial PC with 1 GHz Pentium III processor
- Coreco PC-Dig digital frame grabber

Minimizing labor costs, in particular software effort:

- Linux RedHat 7.1 out of the box
- Open-source drivers for all interfaces

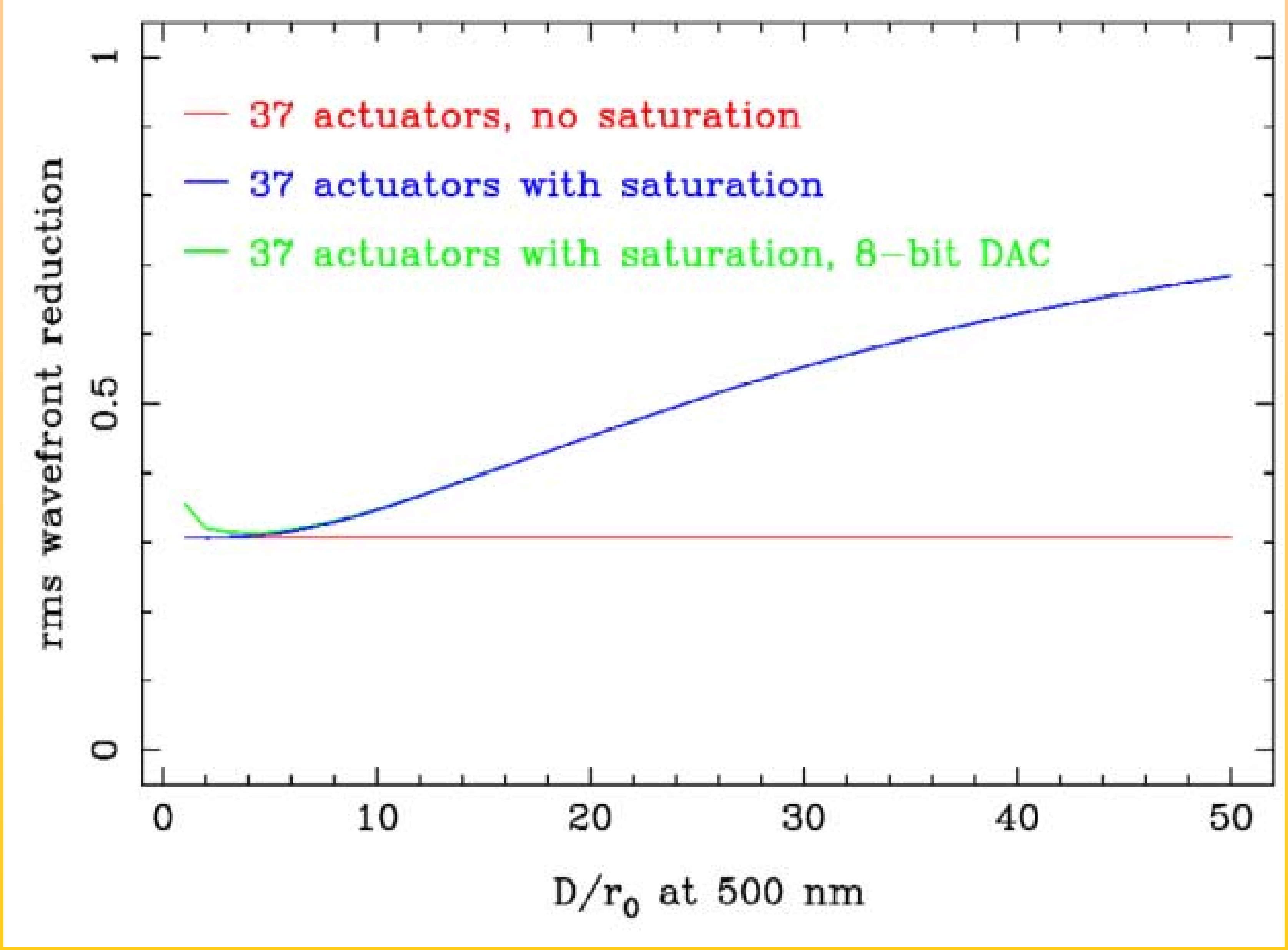
# Shack-Hartmann Wavefront Sensing



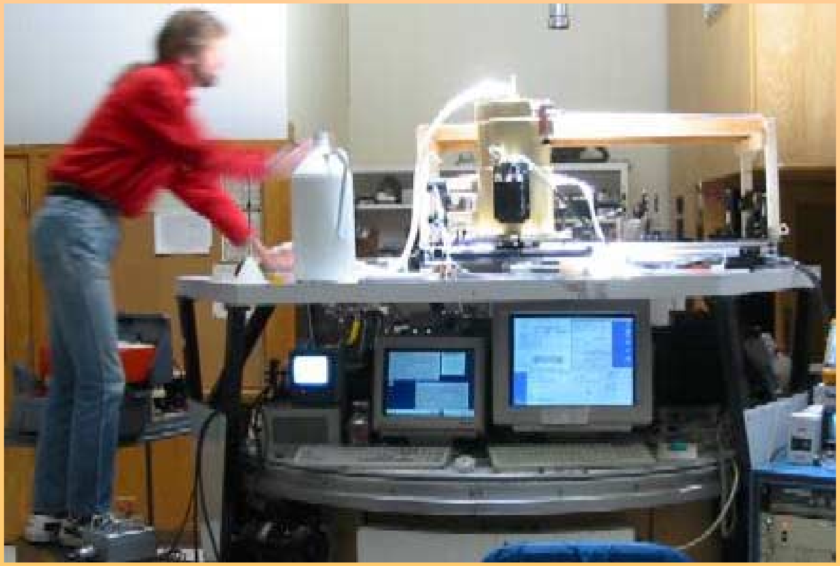
**Prototype wavefront sensor data of sunspot recorded at 500 Hz**

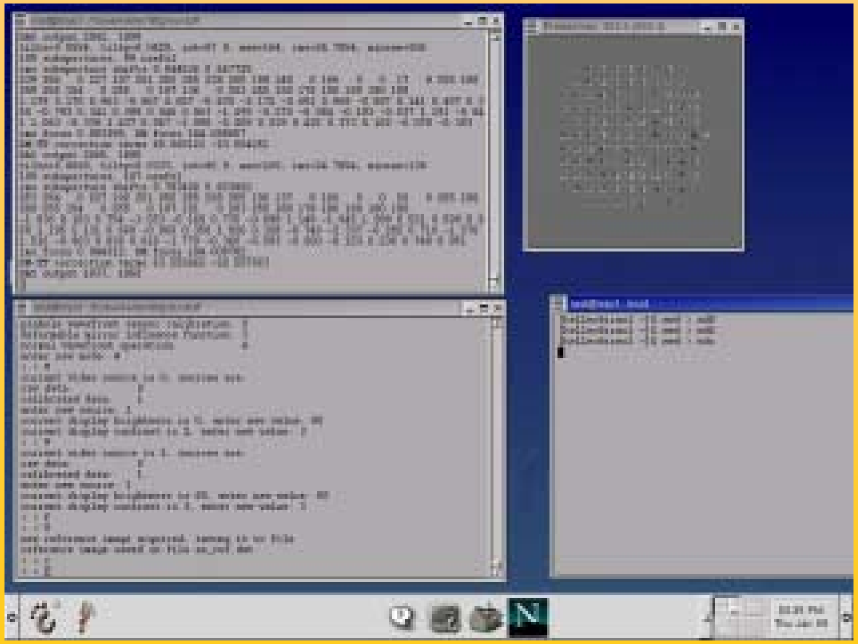
- High-order wavefront sensing at 0.9 µm to use ‘cheap’, fast CCD camera instead of expensive IR camera
- Requires 100 to 200 subapertures to adequately determine wavefront
- This is about 10 times more than any other solar AO system
- Pentium III **`psadbw`** provides wavefront sensing at > 1 kHz with 200 8 by 8 pixel subapertures

# Theoretical Mirror Performance

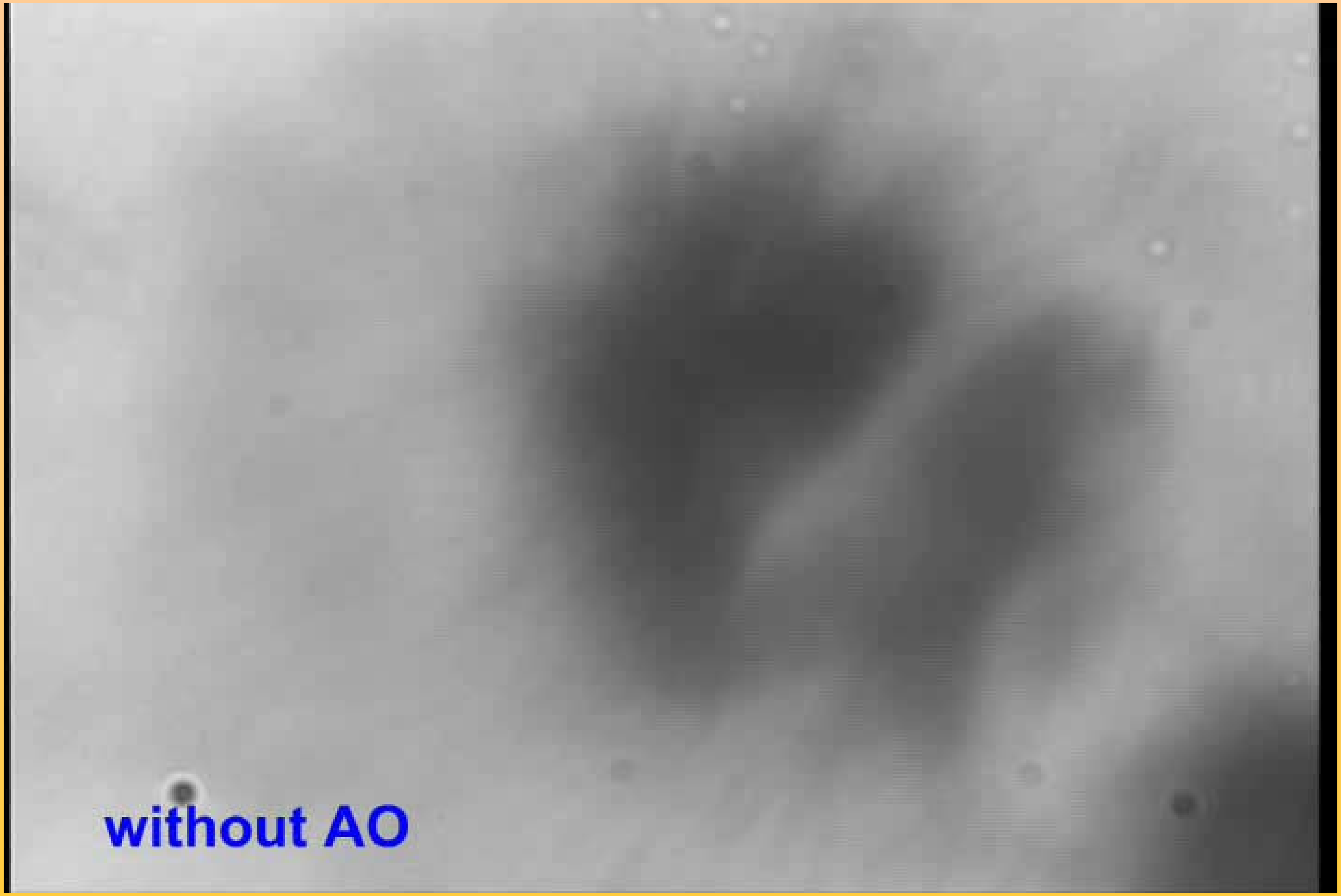


# Prototype AO Setup



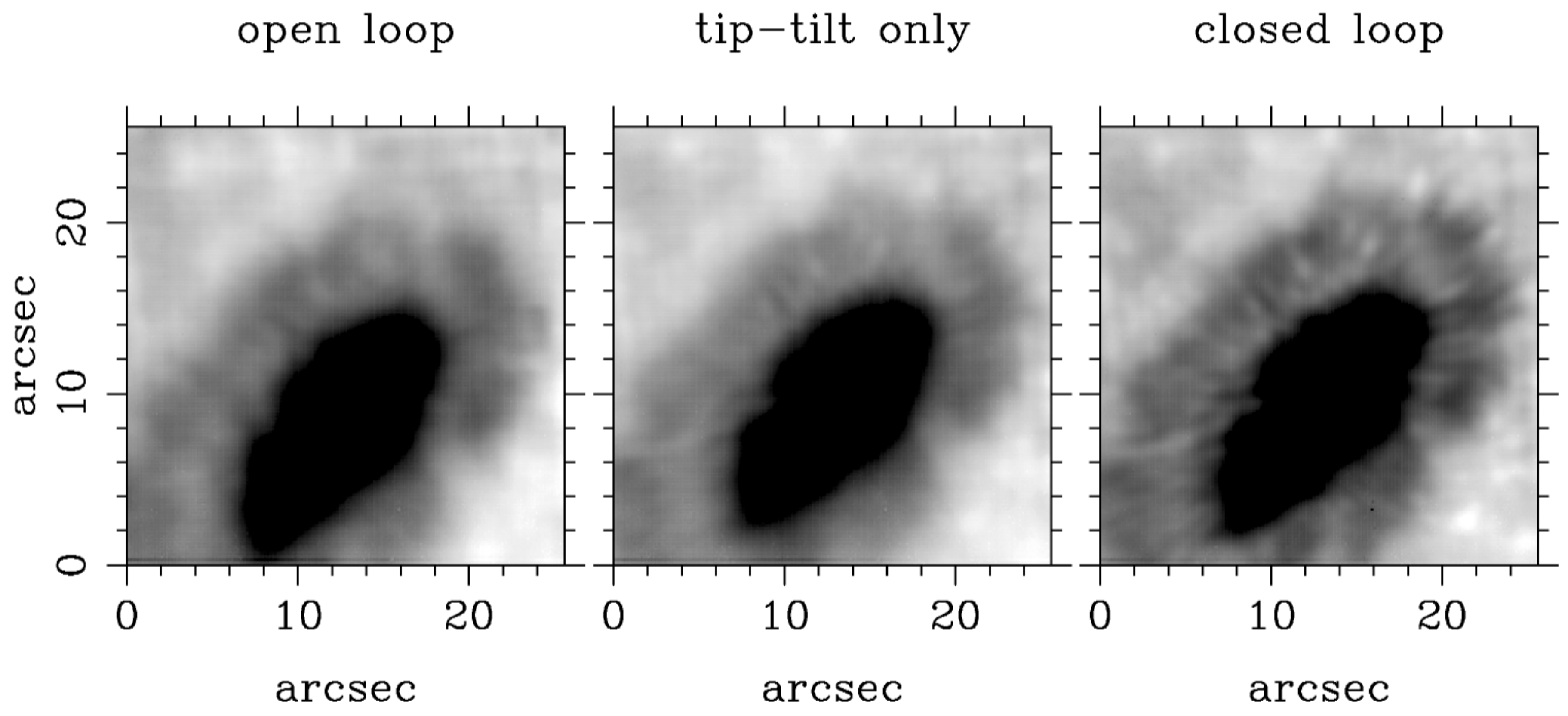


# *July 2, 2002: First Light*



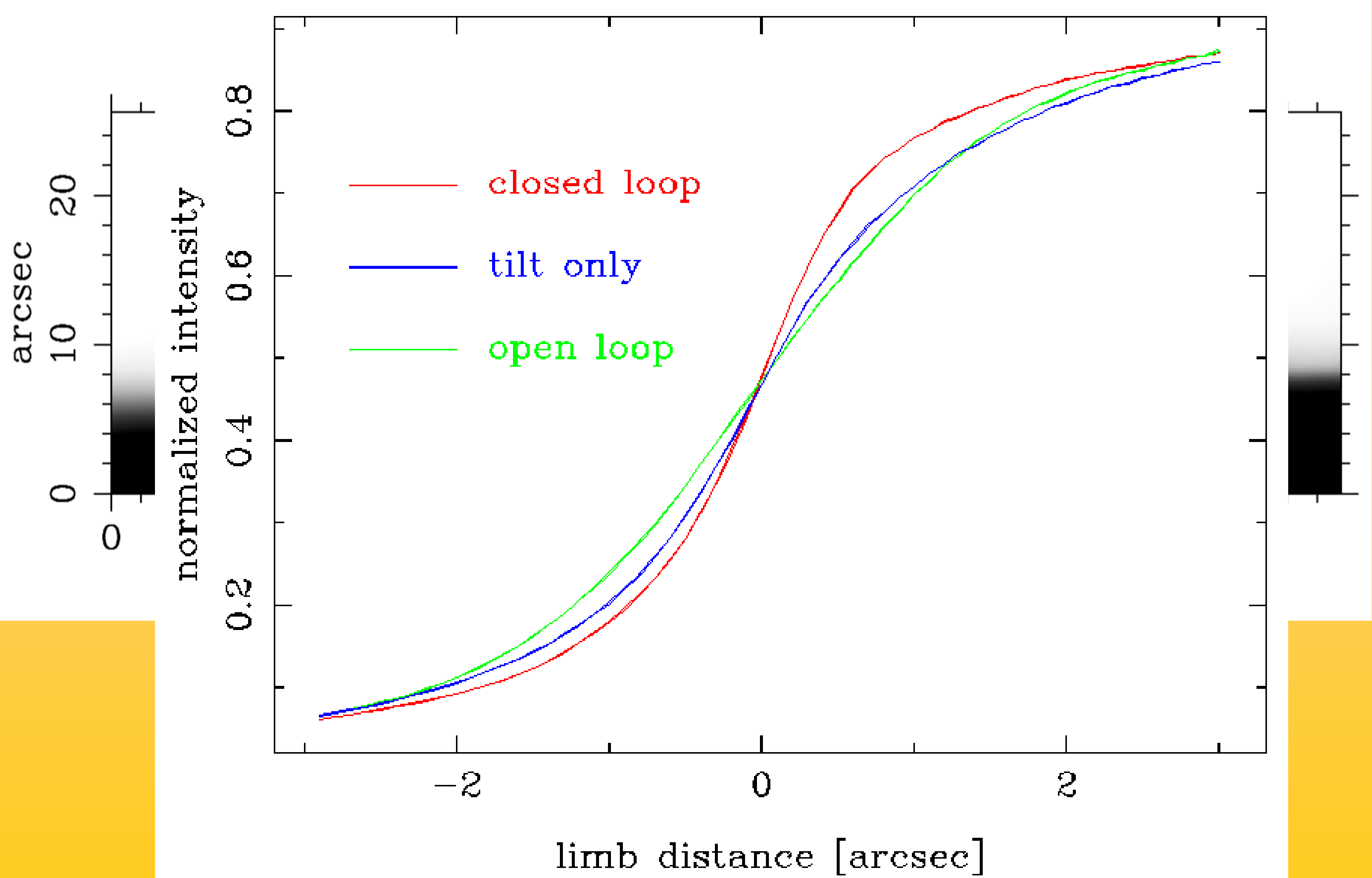
- West Auxiliary telescope, stopped down to 50 cm
- Wavefront sensing at 830 nm, Video ‘science’ camera at 990 nm
- 250 Hz closed-loop update rate, 193 subapertures

# Jan. 22, 2003, First Thermal IR Light



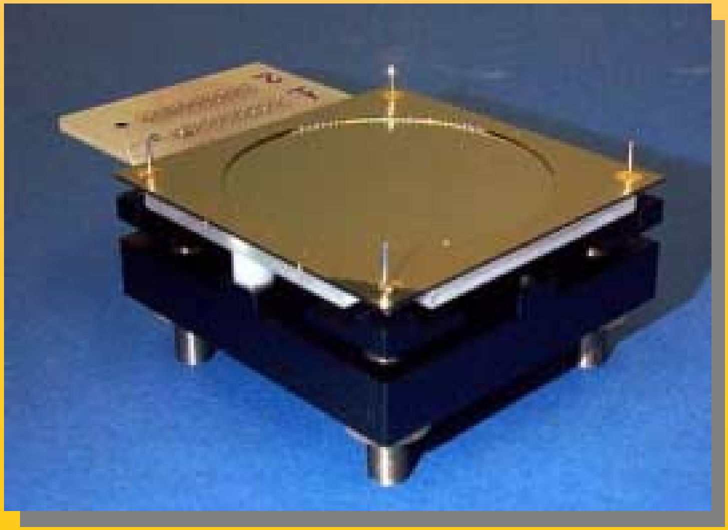
- Median seeing conditions
- 4.8 µm imaging of sunspot close to limb, 0.8 arcsec diffraction limit
- Wavefront sensing at 900 nm
- 955 Hz update rate, 107 subapertures

# *Jan. 22, 2003, First Limb Correction*



# Outlook

- Prototype available on shared risk basis starting now
- User system will be built during the next 12 months
- Linux 2.6 kernel will provide even better real-time behavior
- Simple upgrade: Okotech mirrors available with up to 119 actuators
- Processing architecture scales well:
  - Pentium 4: 3.2 GByte/s, 16 pixels simultaneously!
  - CMOS Cameras with 1280 by 1024 at 485 frames/s (660MB/s)
  - 64-bit, 66MHz PCI bus frame grabbers-> 528 MB/s



| wavelength (μm) | $r_0$ (cm) | actuators | bandwidth (Hz) |
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