Interferometric Science at Lowell Observatory

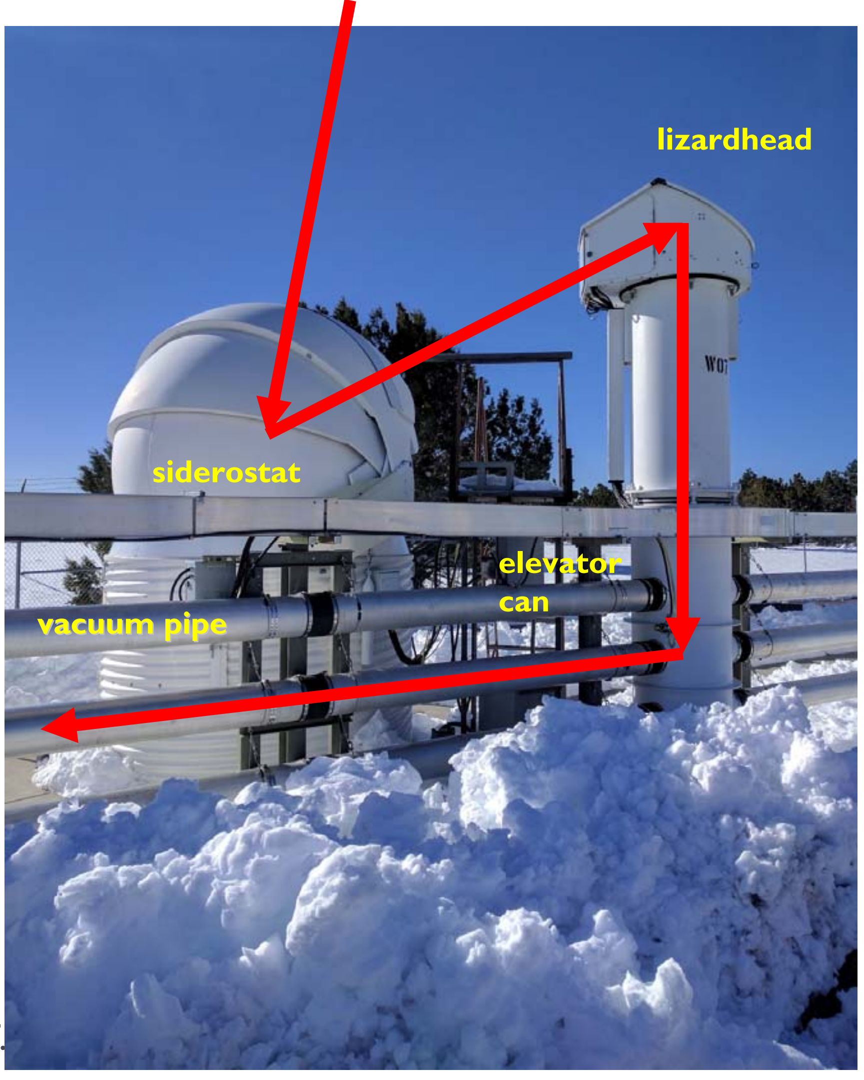
Gerard van Belle (Lowell Observatory)

NPOI Overview

Paul Signac, "Port St. Tropez", 1899

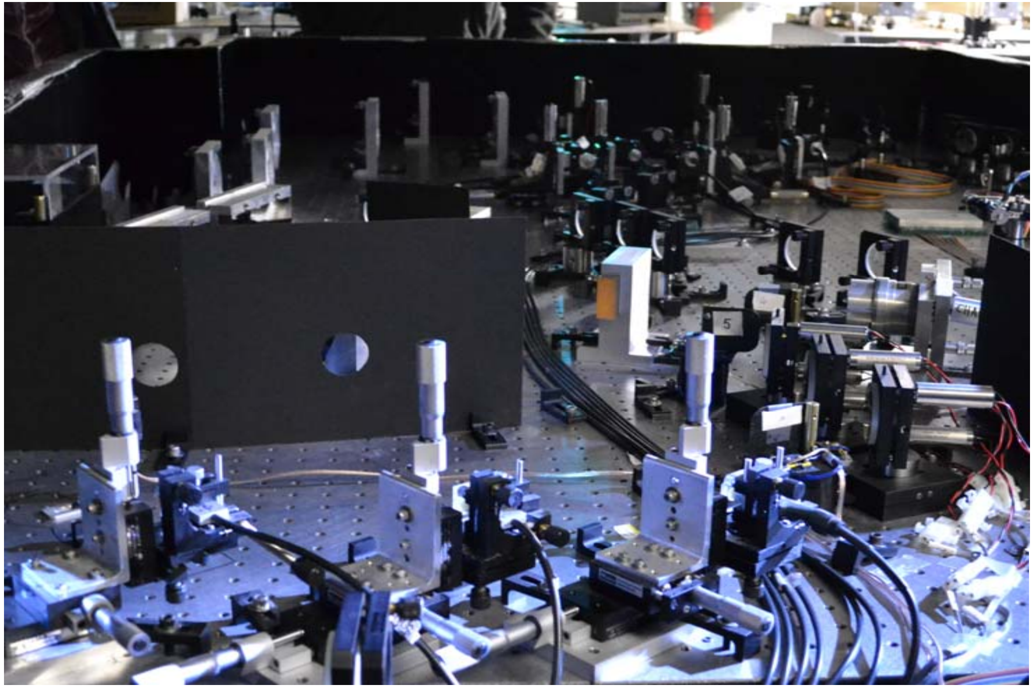
NPOI Basics

- NPOI is collaboration between US Naval Observatory (USNO), Naval Research Lab (NRL) & Lowell Observatory
  - Major funding by Oceanographer of the Navy and Office of Naval Research
  - Additional instrument funding from National Science Foundation
- Currently small (12cm) apertures
- Vacuum feed system
  - Up to 3 beams per arm
  - Combinations of 6 beams selectable at array center
- Significant facility infrastructure investment
  - Elevator cans, lizard heads, vacuum beam pipes, foundations



NPOI Current Performance

- ‘Classic’ Combiner
  - APD-based temporally modulating combiner
  - Spectral resolution: R=40 (16 channels) over 550-850nm
  - Collects *many* N-way permutations
    - 1/3 of data dropped
  - Sensitivity limit of $m_V \approx 6.0$



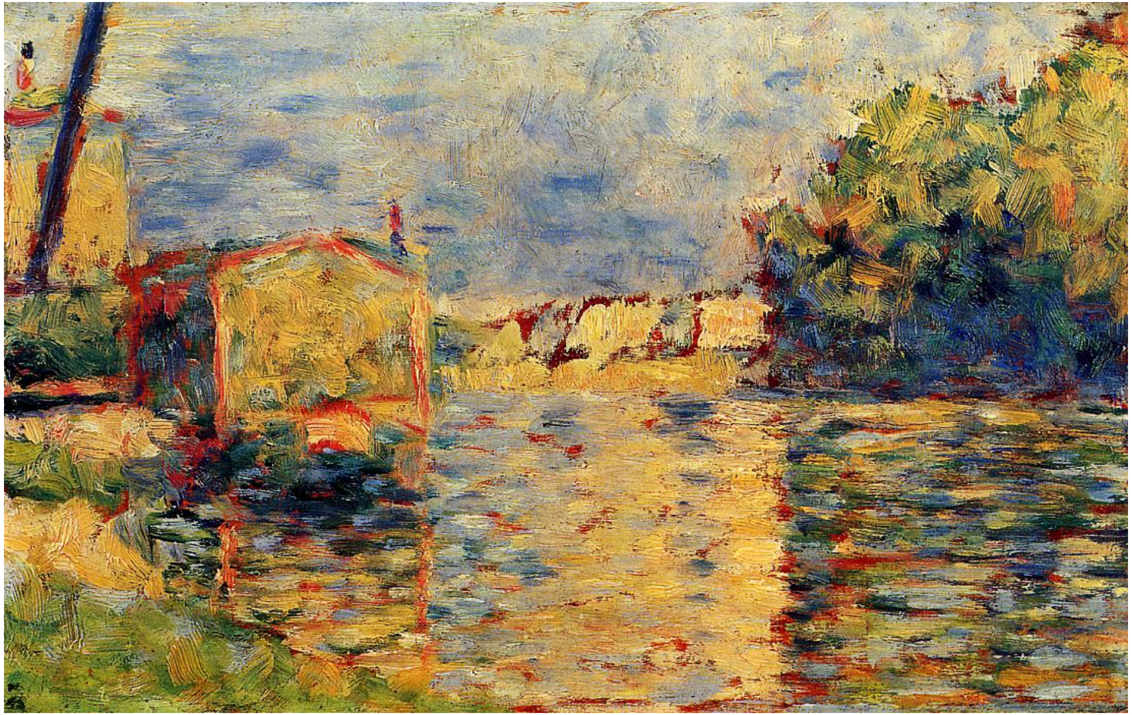
NPOI Current Performance

- VISION
  - EMCCD-based spatially modulating combiner
  - Spectral resolutions: R=200, 1000 over 570-850nm
  - Collects *all* N-way permutations
  - Automatic data pipeline adapted from MIRC
  - Sensitivity limit of $m_V \approx 3$
    - Limited by Andor EMCCD CIC, new NüVü EMCCDs being installed
    - Upgraded tip-tilt tracking to address additional system limits

Large Apertures for NPOI

- New 1.0 m model (CDK1000) from PlaneWave Instruments
  - Robust, turnkey operations
  - CDK700 proven with MINERVA and other projects
  - Coudé train to be added to unmodified telescope
  - Breadboard for AO
- 70× increase in collecting area: Δm of up to +4.5mag

Basic Interferometry Science



Georges Seurat, “Rivers Edge”, 1884

Science Motivation

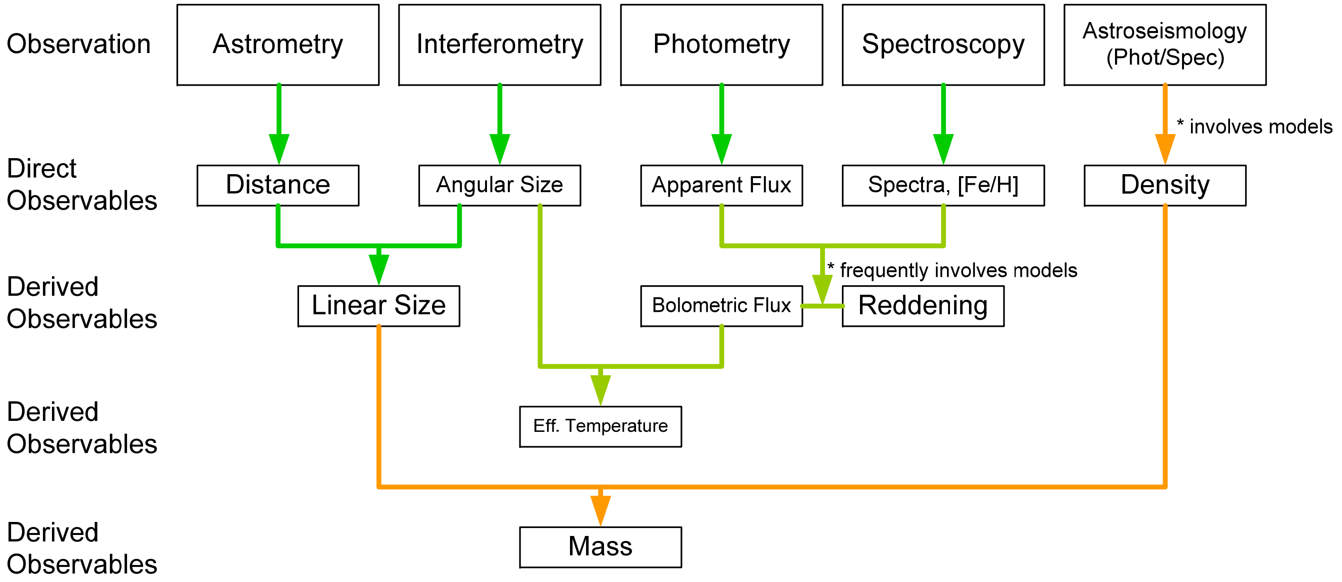
- Stellar Fundamental Parameters
  - Linear radius (R), Effective Temperature (T_{EFF}), Mass (M), multiplicity
- Tight constraints on these values guide stellar modeling
  - Needs? Depends on stars
    - Solar-type: <1% values
    - Early-type, late-type: <5% values
- *Direct* measurement important
  - High spatial resolution observations, *plus* ancillary observations

Angular Sizes: How are they Useful?

- By measuring the contrast of fringes, we *directly* measure the angular size of a star

  - If we know the **distance** to a star, we get its **linear size** (*R*)
  - If we know the **brightness** of a star, we get its **temperature** (*T*)
- Interestingly enough, these fundamental parameters are often very hard to directly measure
- The key here is 'directly'
  - Astronomers often guess their way to *R* and *T*
  - But the guesses needed to be tested

Tree of Fundamental Parameters: Single Stars



Green = Empirical

Red = Contaminated by models

Fundamental Parameters from Angular Sizes

- **Linear Size**

$$\boxed{R = \pi\theta}$$

(the real trick here is determination of π)

- **Effective Temperature** – from *definition* of luminosity

$$\boxed{L = 4\pi\sigma R^2 T_{\mathrm{EFF}}^2}$$

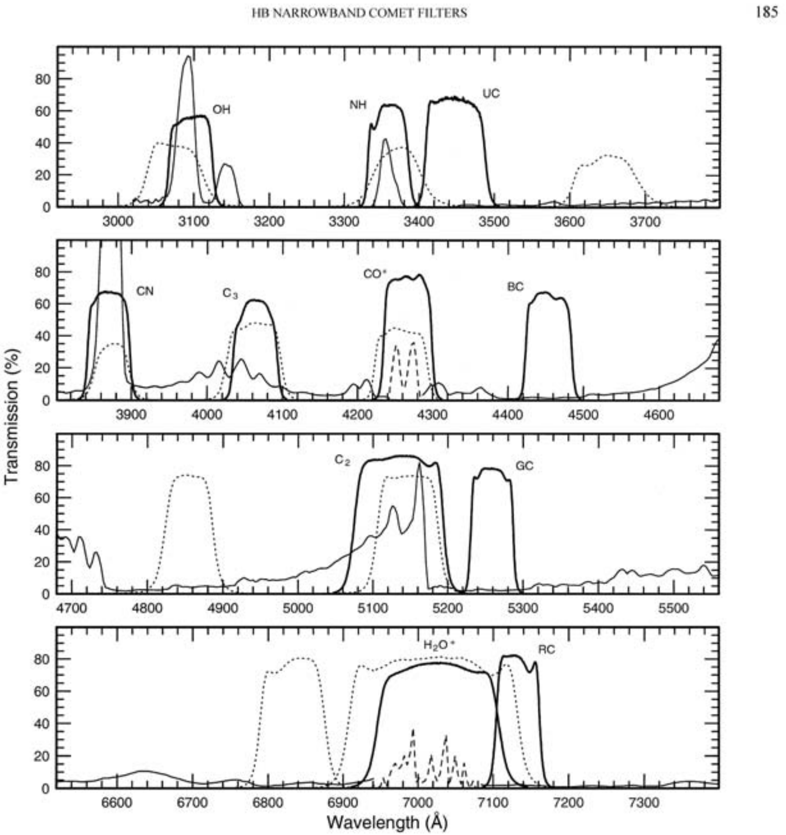
we can divide out distance and get

$$\boxed{T_{\mathrm{EFF}} \propto \left(\frac{F_{\mathrm{BOL}}}{\theta^2}\right)^{1/4}}$$

(the real trick here is determination of F_{BOL})

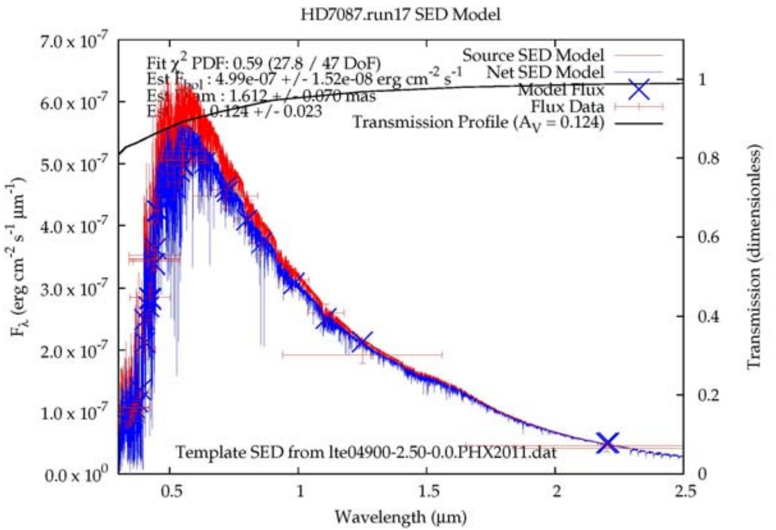
Bolometric Flux Determination

- Convert magnitudes to flux
  - Problem: many photometric zeropoints established to only ~1-3%
- Interesting recalibrations (& techniques) now available
  - E.g. Mann & von Braun

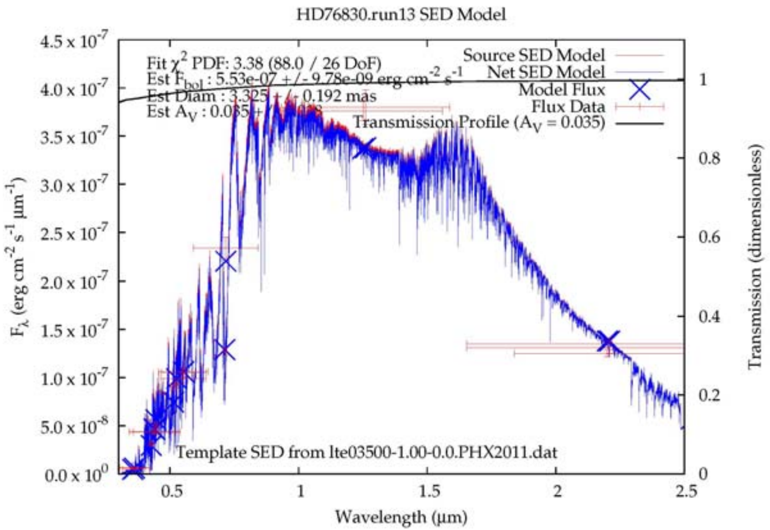


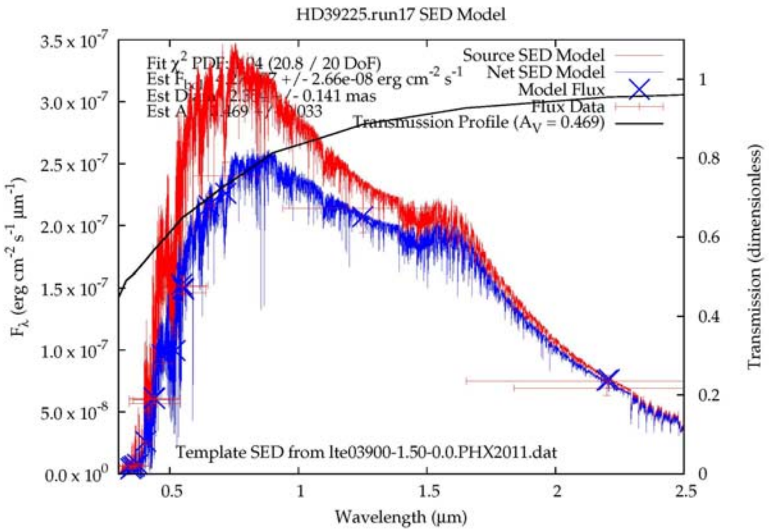
Bolometric Flux Determination

- Interpolate between photometry points by SED fitting
  - Challenge: use models or empirical templates? (i.e. Pickles versus PHOENIX)
  - Solution: grid of PHOENIX fits to Pickles templates
- Have to correct for extinction
  - NB. Convolution of effects interstellar and circumstellar dust
  - Degeneracy between magnitude of extinction and spectral template



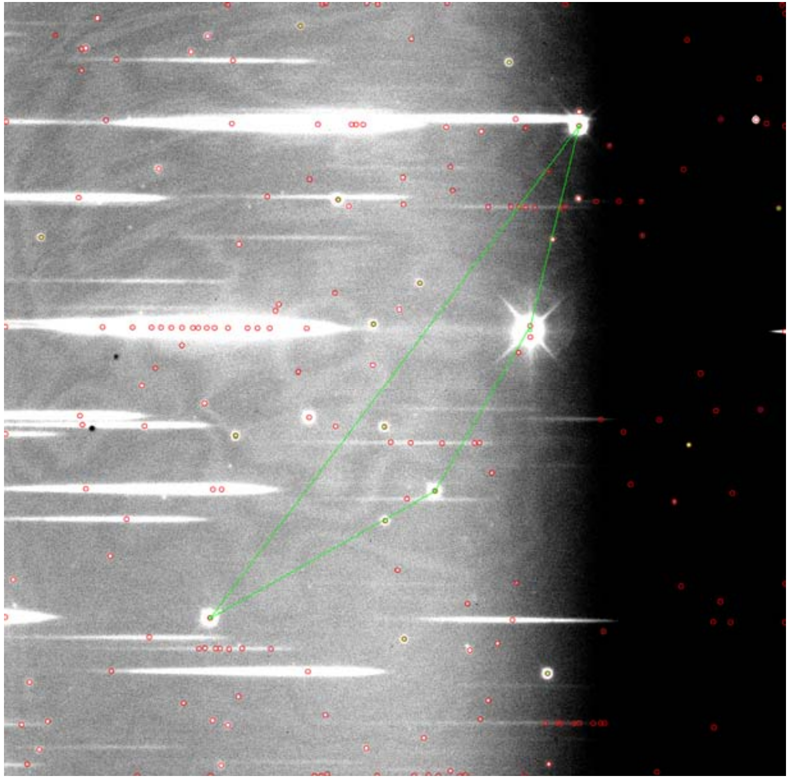
sedFit Examples



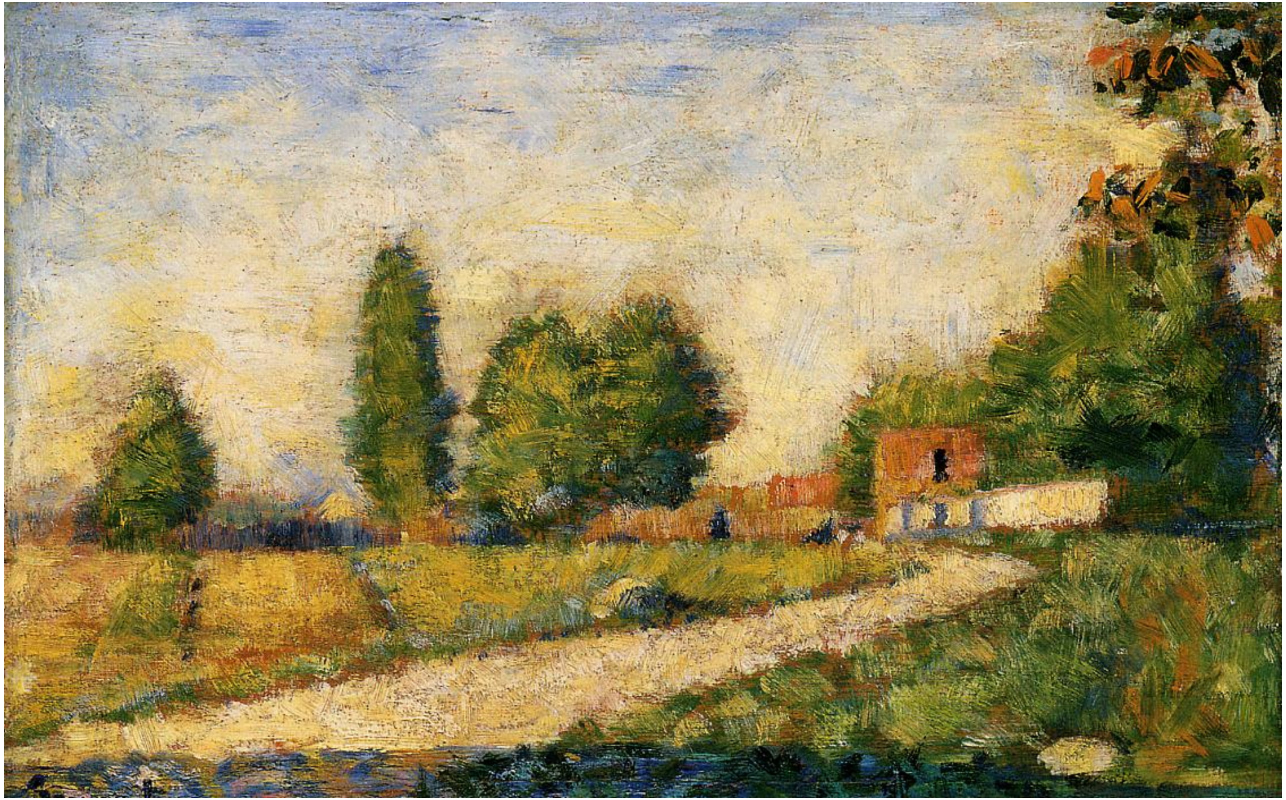


31” Spectrophotometry

- Filter slot in 31” replaced with transmission grating
- Roughly 10 nm pixels across 300-1000nm
  - 700 ‘narrowband photometry’ channels
- Observation sequence now includes HST STIS standards
  - Flux-calibrated spectral library
- Adds ‘stretch/squish’ of spectra due to differential chromatic refraction
  - Depending upon ZA, angle between spectral dispersion & zenith vector
- Code is multi-threaded



Example: Giant Star Survey



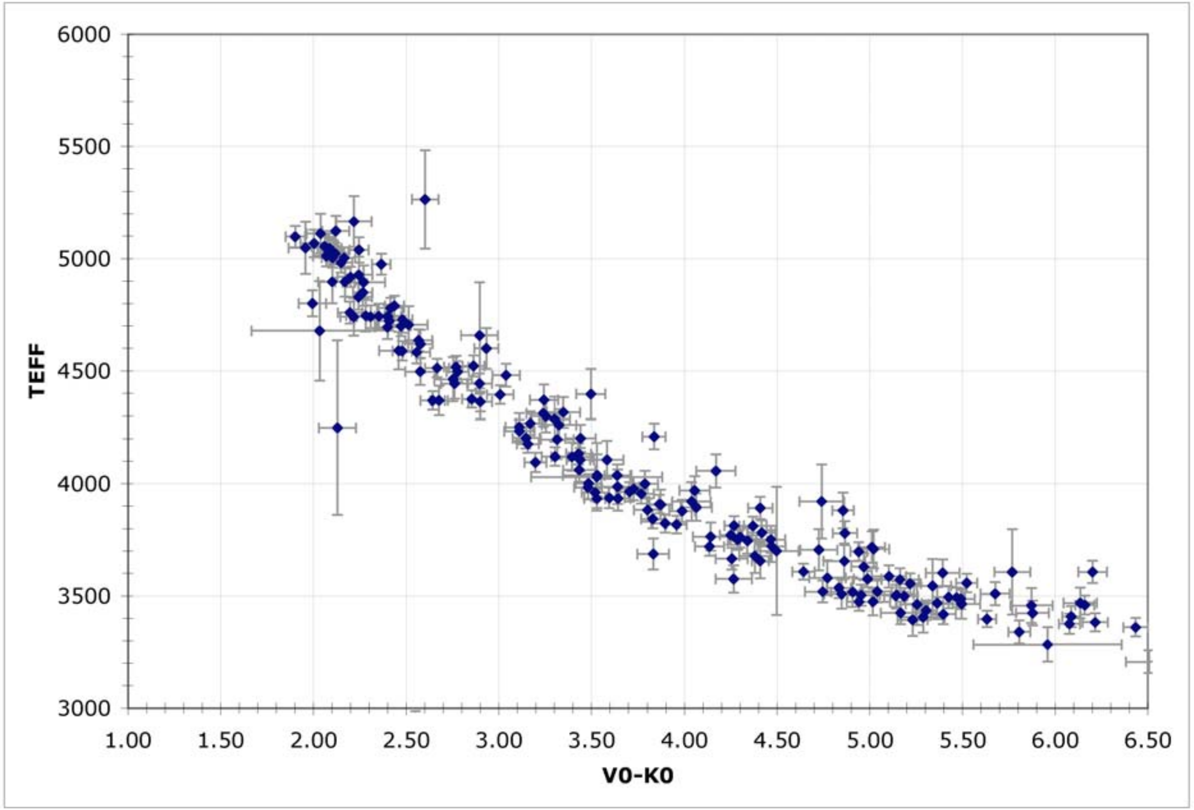
Georges Seurat, "Village Road", 1883

PTI Evolved Star Survey

- Palomar Testbed Interferometer archive
  - Pair-wise 0.5-m on 85m, 109m baselines
  - Resolved objects between 1.5-5.0mas in size
  - m_K < 5.0 (resolved objects tended to be m_K<3.0)
  - Approved as a 'NASA mission' archive
- Extensive survey
  - 1996-2008
  - Over 400+ evolved objects
  - Culled to ~200 'normal' giants
  - Other surveys as well:
    - ~100 variable giants
    - Other objects: carbon stars, supergiants

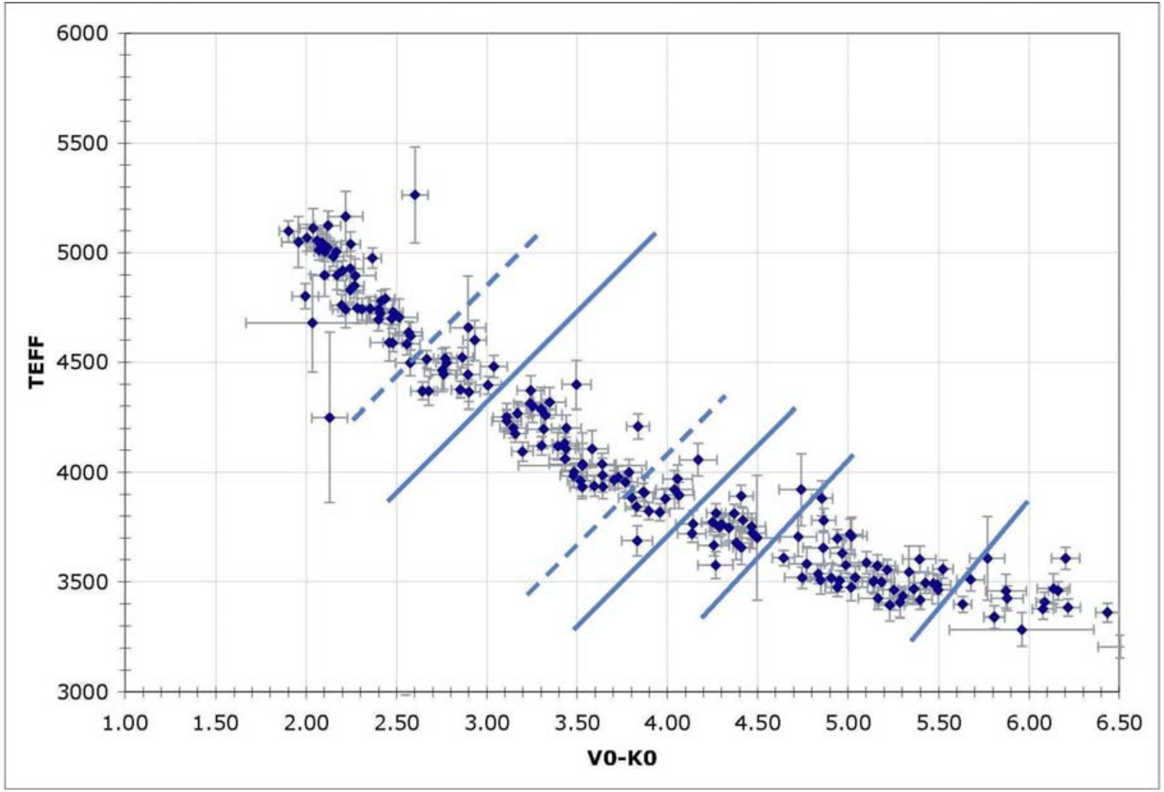
Example Survey Result

- 195 giant stars
- TEFF vs V_0-K_0, in ΔV_0-K_0 0.01 bins:
  - N=4.6 stars/bin
  - ΔT_{EFF}=77K
    - Greater than median error of 52K → intrinsic scatter
- Gaps in sequence?
  - Astrophysical or experimental?

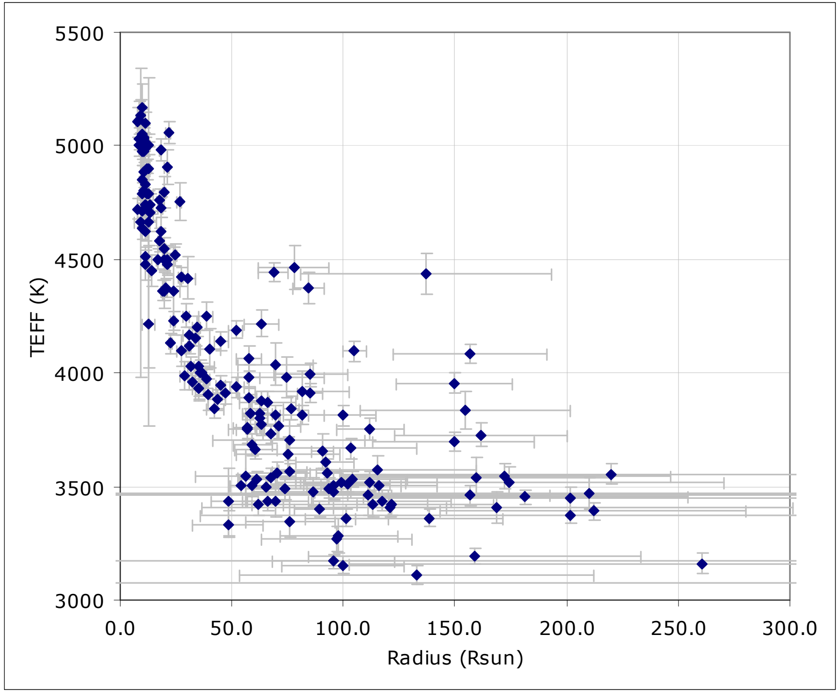


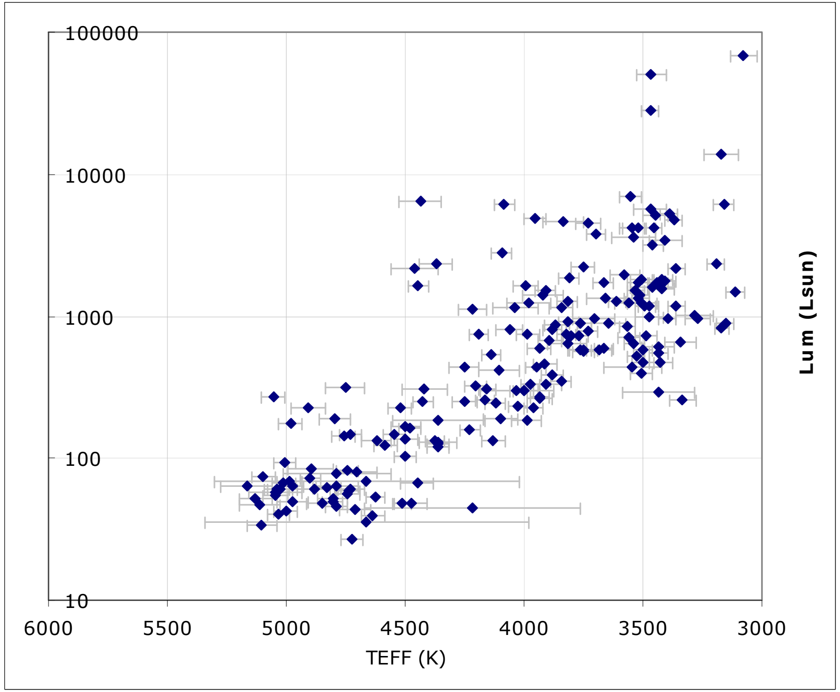
Gap Analysis

- Statistical consult
  - Passes the 'intraocular test'
- Dereddening effect?
  - No, effects persist when correction removed
- Selection effect?
  - Source catalog taken from field stars
  - K- versus M-type giants? Possible
- Shouldn't this be seen in just photometry?
  - Not seen in V-K data of XHIP catalog
  - Diagonal nature of cuts



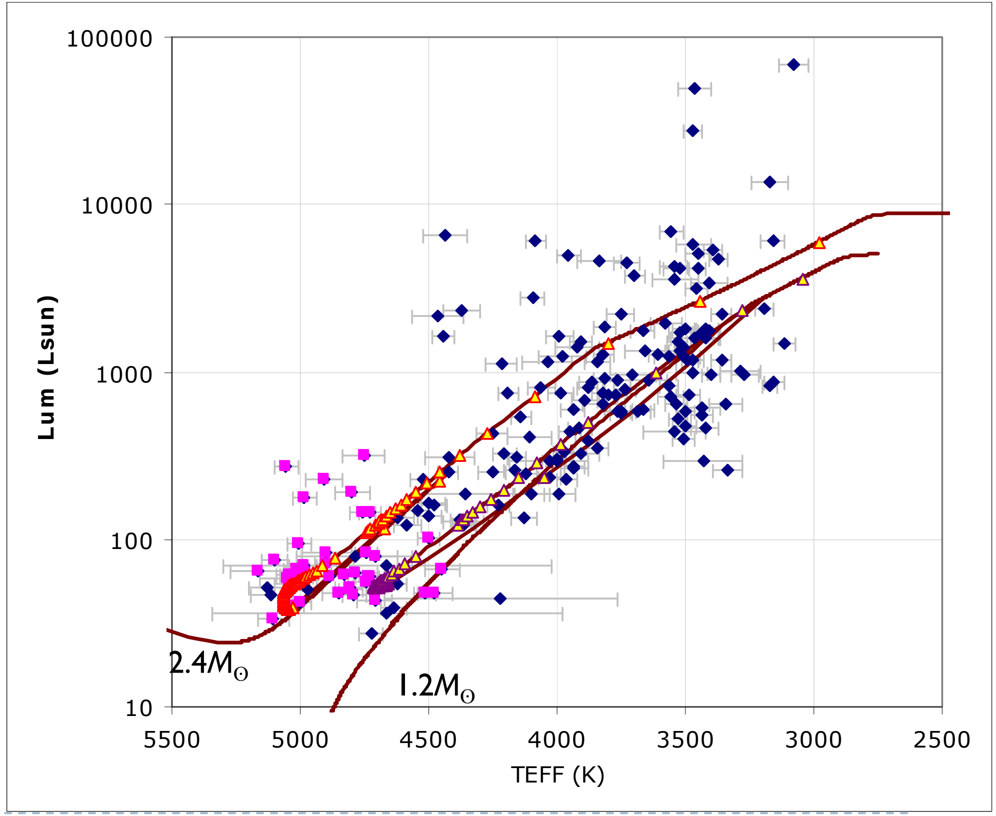
Linear Radius, Luminosity





HR Diagram Features

- Pink points: Cross-ID of stars ID'd as Tycho-2 red clump stars in Gontcharov, 2008
- Stellar evolution tracks from Pietrinferni+ 2008
  - Triangle tick at 100Myr intervals after He flash
  - 1.2 - 2.4$M_\odot$ tracks
    - >75% of asteros. masses of giants in Kepler field of Mosser+ 2012
- Gaia distances – if available – will uncover more 'personality'?

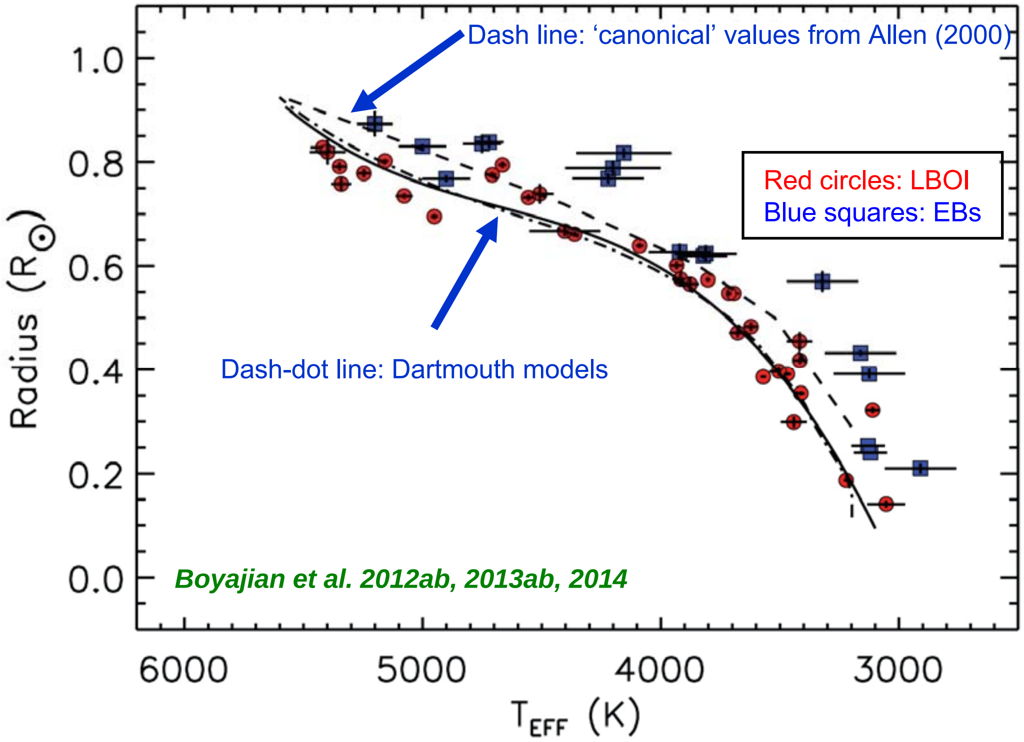


Additional Topics

Georges Seurat, "Seated and Standing Woman", 1884

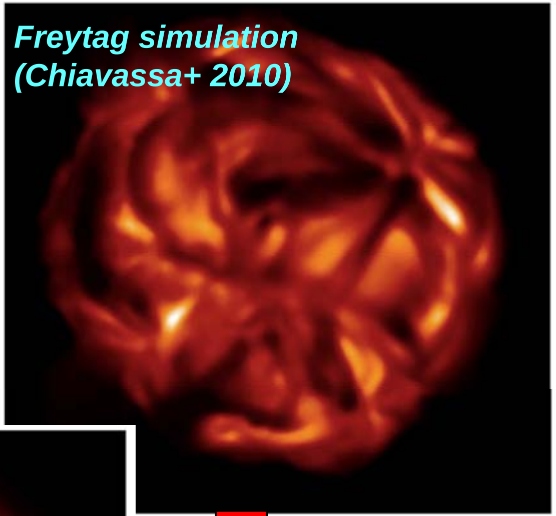
Fundamental Parameters: Low-Mass Stars

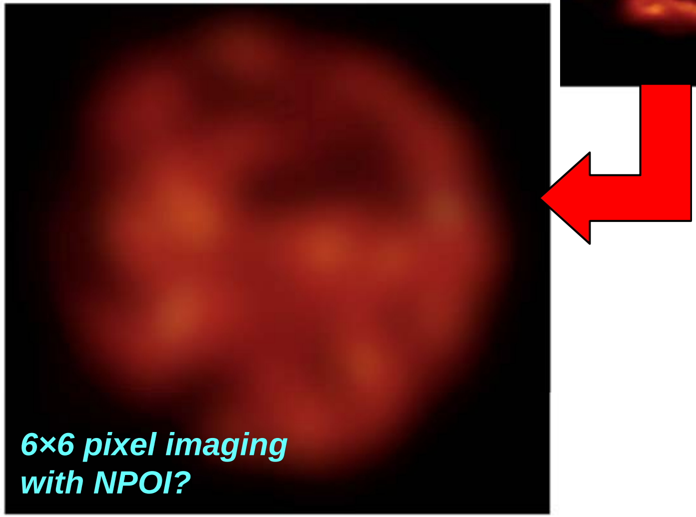
- Models tend to under-predict radius of low-mass MS stars
  - Stars are 'puffed up'
- Onset of convection (~M3) is where problem crops up
- Reflects bias of (current) binary star observations toward short-period systems?
  - Tidal locking driving MHD effects?
- Current studies working at the limit of resolution of CHARA
  - NPOI can improve upon



Stellar Surface Mapping

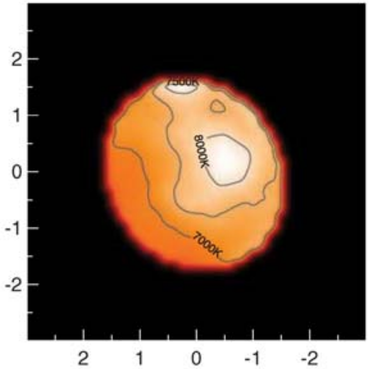
- RSG surfaces are thought to be dominated by large convection cells (Schwarzschild 1975)
- Direct imaging of these features should be possible with New Classic, VISION
  - Time-evolution → movies
- Current leader in the field: CHARA-MIRC

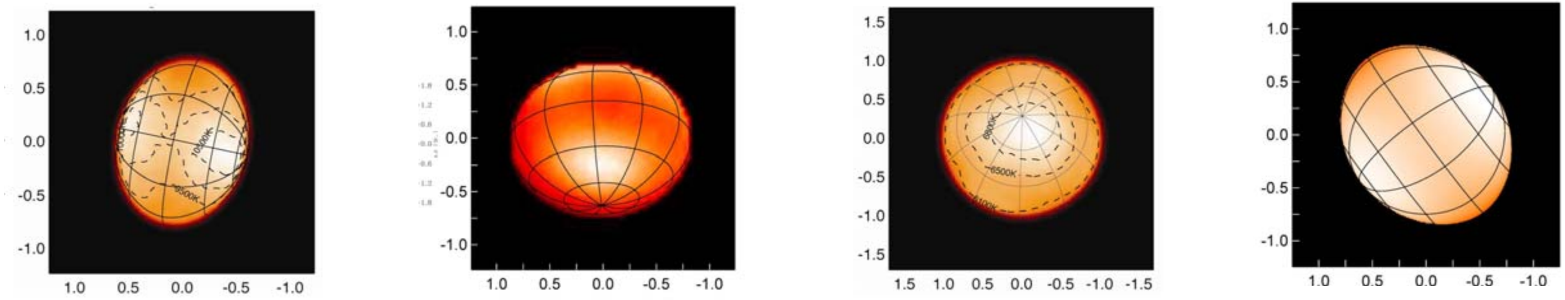




Imaging: Stars are Photogenic

- The past 10 years
  - **Parametric modeling** at first,
  - the **Surface morphology**
  - and nowadays **Direct imaging**
- Already starting to see some surprises
  - Stellar structure not as expected from simple models

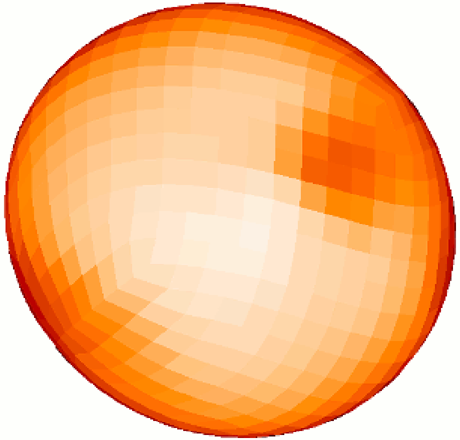


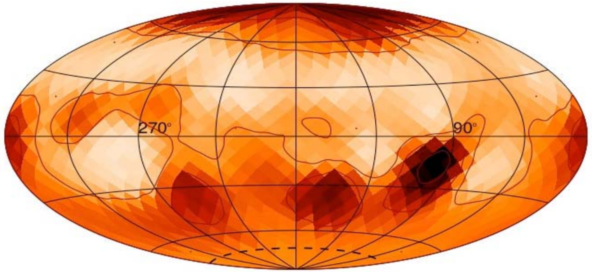


CHARA-MIRC Images of Rapid Rotators

Surface Snapshots → Movies

- zet And
  - 18d rotation period
  - KIII-IIIe; $15 R_{\odot}$ @ 55pc
- Starspots
  - Magnetic field blocks flow of heat
  - Cooler, darker
  - Detected in near-IR: *very* dark spots
- Confirmed by ZDI imaging



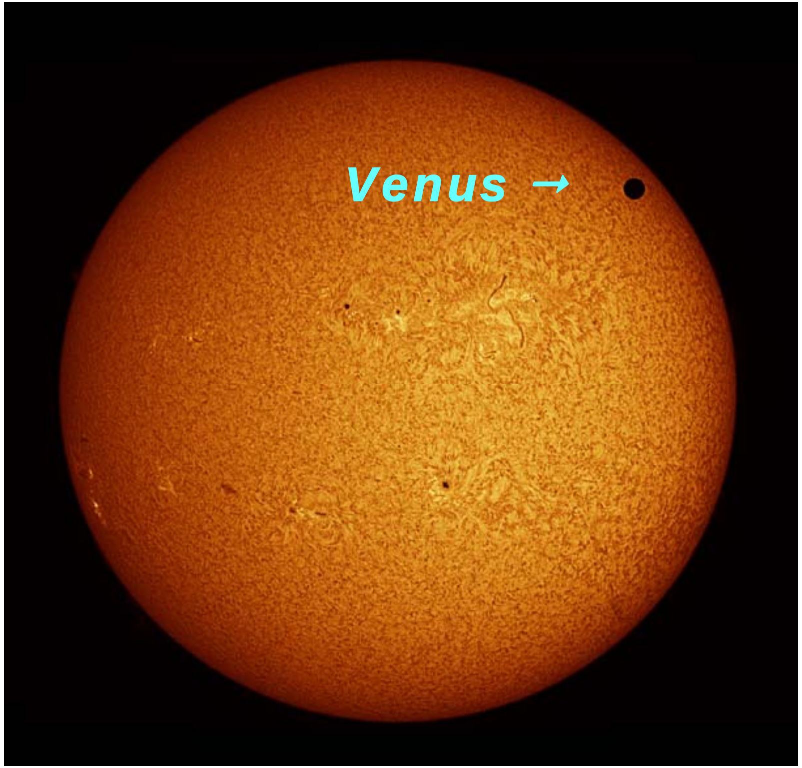


CHARA-MIRC

Roettenbacher et al. 2016

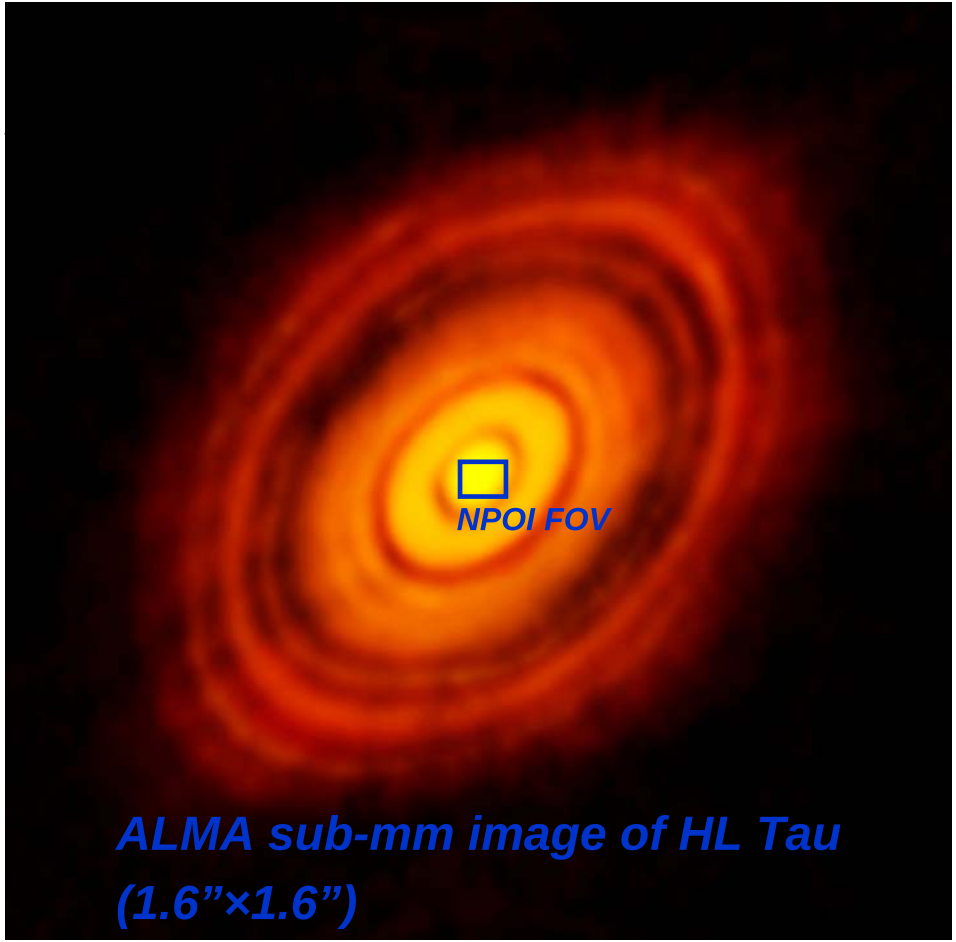
Imaging Exoplanet Transits

- NPOI, other facilities CHARA can observe exoplanet transits
- Planet's shadow is 'perfect' star spot
- Extreme challenge: needs very high signal-to-noise, high angular resolution
- Theory paper published in 2008



Planet Formation

- Unlocking the physical processes of planet formation
- ALMA (sub-mm): cold (~50K) outer regions of gas giants
- NPOI (optical): warm (~300-1000K) inner region of terrestrial planets



Questions?

Georges Seurat, "A Sunday on La Grande Jatte", 1884