# Stellar Angular Diameters from CHARA & NPOI Data (Plus Some Other Stuff)

Ellyn Baines

Naval Research Laboratory
ellyn.baines@nrl.navy.mil

The CHARA Array:
Hal McAlister, Theo ten Brummelaar, Nils Turner, Judit Sturmann, Laszlo Sturmann, Christopher Farrington, Norm Vargas, + others

Naval Research Laboratory:
Thomas Armstrong
Henrique Schmitt

# Up for discussion:

- HR 8799: final *final* CHARA results

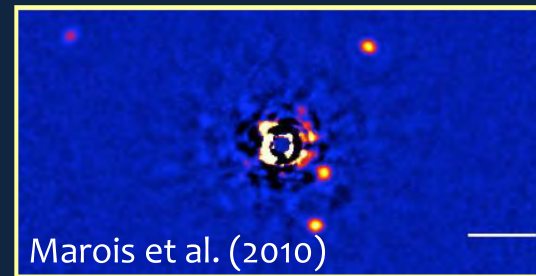
  This time I mean it!

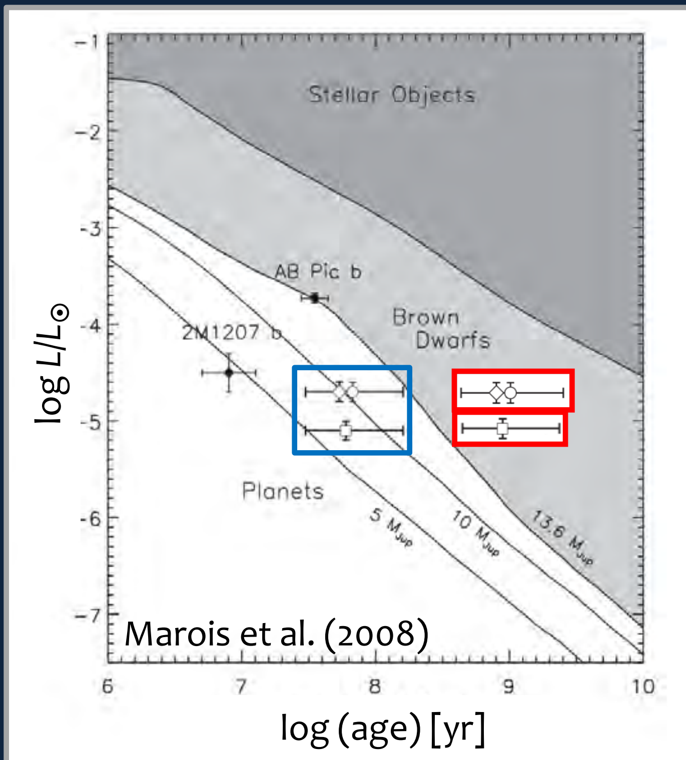
- CHARA target HR 2582

- NPOI targets ε Eri & κ Oph

- Imaging GEOsats with the NPOI

# HR 8799's Close Up

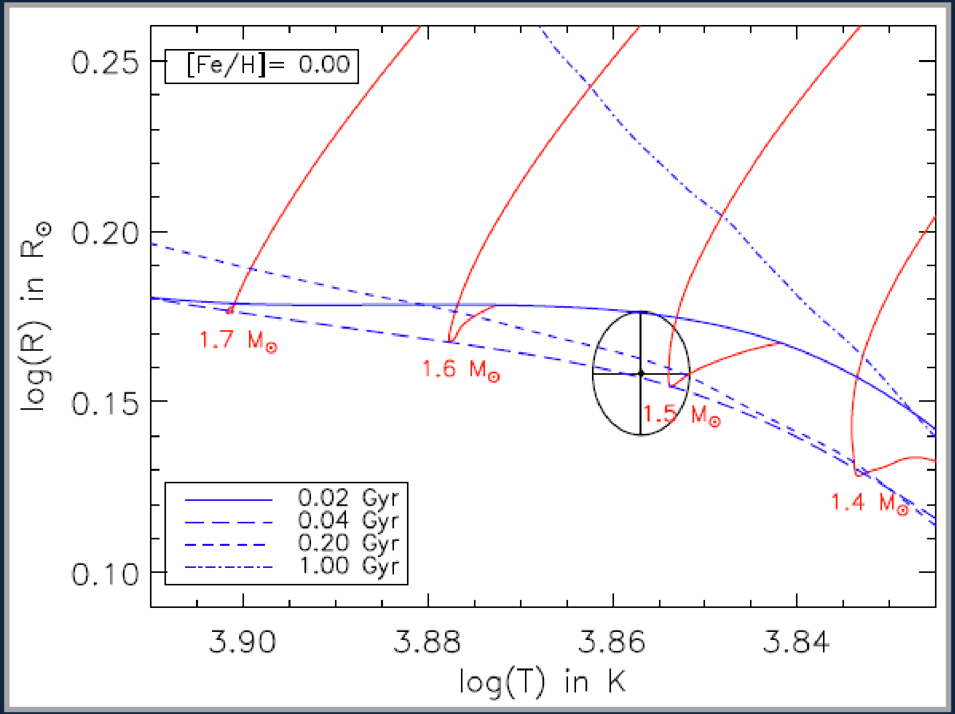


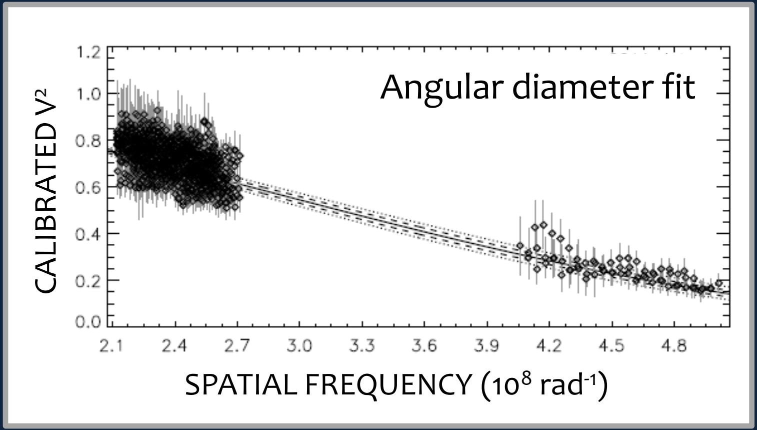




- Companion type? Star's age & [Fe/H]? It's a λ Boo star, so…?
- Observed using the CHARA Array
  - 7 nights, 2010 – 2011
  - 5 calibrators (3 used in the paper)

| Companion location if star is young → exoplanets | Companion location if star is older → brown dwarfs |
|---|---|

# PAVO Results



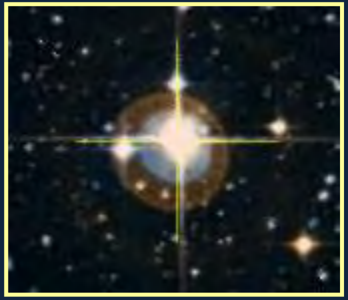

| Parameter | Value |
|---|---|
| $\theta_{LD}$ | $0.342 \pm 0.008$ mas |
| $R$ | $1.44 \pm 0.06\ R_{\odot}$ |
| $T_{eff}$ | $7193 \pm 10$ K |
| $L$ | $5.05 \pm 0.29\ L_{\odot}$ |
| $M_{star}$ | $1.52 \pm 0.03\ M_{\odot}$ |
| Age | $33\ ^{+7}/_{-13.2}$ Myr |
| $M_{star}$ | $1.51 \pm 0.02\ M_{\odot}$ |
| Age | $90\ ^{+381}/_{-50}$ Myr |

If star is contracting onto ZAMS: $M_{star}$ = $1.52 \pm 0.03\ M_{\odot}$, Age = $33\ ^{+7}/_{-13.2}$ Myr

If star is expanding from ZAMS: $M_{star}$ = $1.51 \pm 0.02\ M_{\odot}$, Age = $90\ ^{+381}/_{-50}$ Myr

Our results agree with a young age for the star, so we confirm imaged companions are exoplanets.

# CHARA Target HR 2582



- G6 or K0 III star
- Observed using CoRoT for stellar oscillations

They found some!

- Observed using the CHARA Array in Dec. 2012

# Why it's interesting

- *M*, *R*, and age are challenging because *L* and $T_{eff}$ are poorly constrained.

- HR 2582 appears to be more massive than normal red clump stars → implies rapid evolution

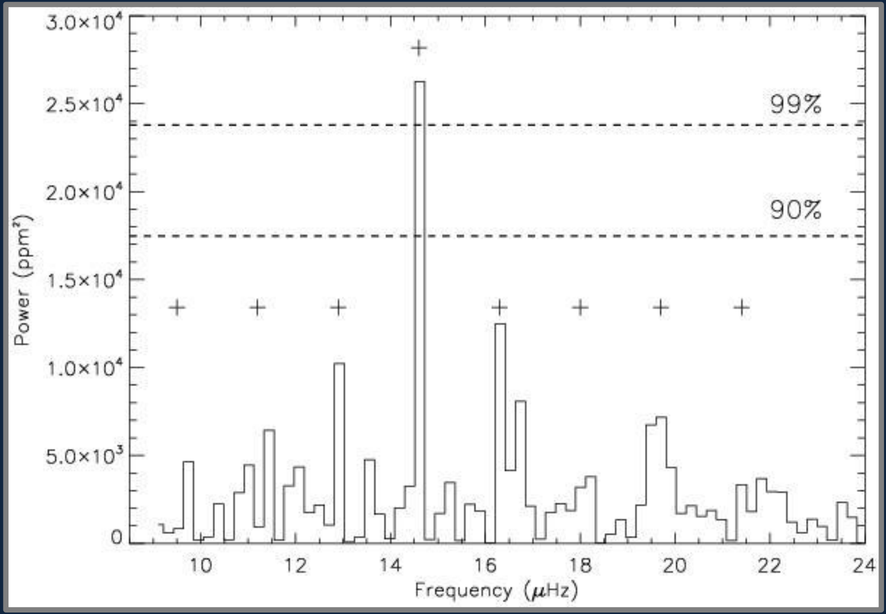
- Unknown if star is:
  - H-shell burning on ascending red giant branch?
  - burning He in a later stage?

# CoRoT Results

- Observed HR 2582 for 55 days (Baudin et al. 2012)
- Used complementary spectroscopic observations to determine:
  - $T_{eff} = 4665 \pm 200$ K
  - $\log g = 1.4 \pm 0.3$ cm s$^{-2}$
  - [Fe/H] = $-0.18 \pm 0.14$
  - $L = 2.70 \pm 0.15\ L_{\odot}$
  - $R \sim 34 \pm 8\ R_{\odot}$

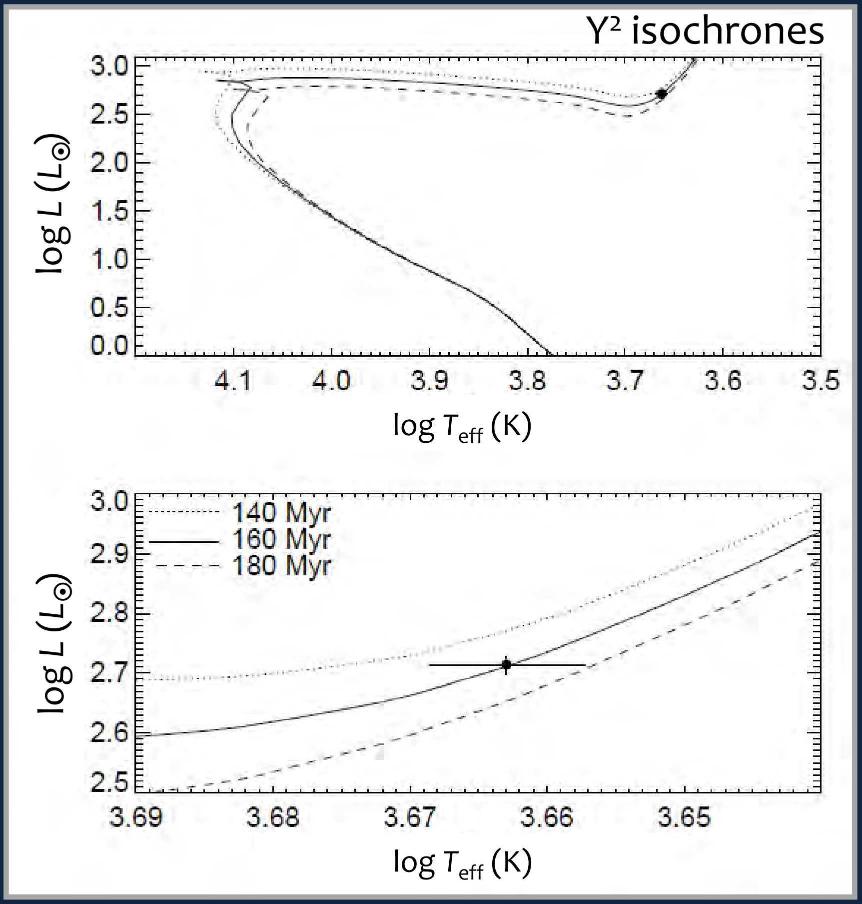
$$\upsilon_{max} \approx \frac{M/M_{Sun}}{\left(R/R_{Sun}\right)^2 \sqrt{T_{eff}/T_{eff,Sun}}}$$

Power density spectrum, $\nu_{max} = 15 \pm 1\ \mu$Hz




$M \sim 5.2 \pm 2.9\ M_{\odot}$

# CHARA Results




| Parameter | Result |
|---|---|
| $\theta$ (mas) | $1.00 \pm 0.02$ |
| $R$ ($R_\odot$) | $35.8 \pm 5.3$ |
| $T_{\mathrm{eff}}$ (K) | $4712 \pm 151$ |
| $M$ ($M_\odot$) | $5.7 \pm 0.5$ |
| Age (Myr) | $160 \pm 20$ |

H-shell burning in 1$^{st}$ ascending branch: 157 Myr

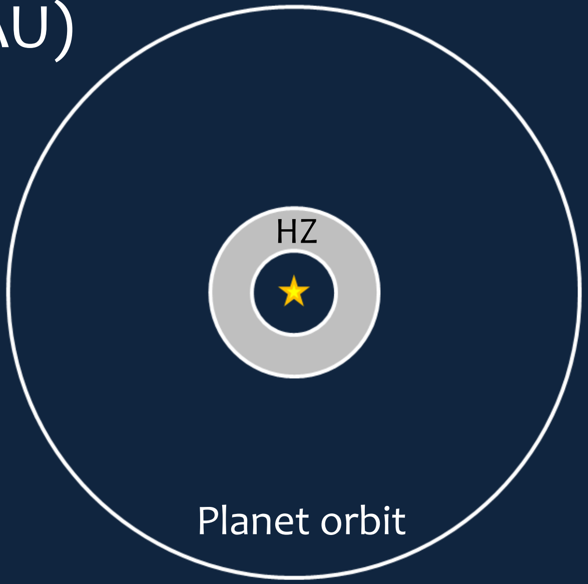
Core He-burning in 1$^{st}$ ascending branch: 163 Myr

Core He-burning in 2$^{nd}$ ascending branch: 180 Myr

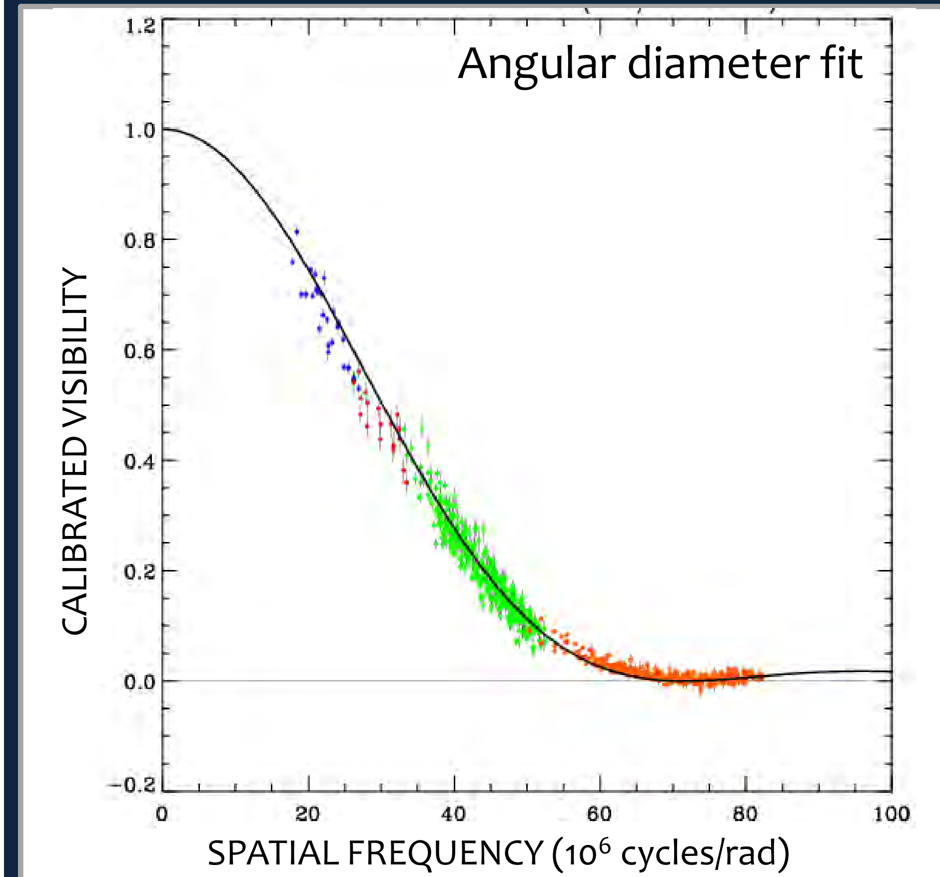
# Exoplanet Host Star ε Eri

- Measured angular diameter
- Calculated $T_{eff}$, $R$, $L$
- Used $T_{eff}$, $R$ with Y² isochrones to estimate $M_{star}$
- Combined $M_{star}$ with $f(m)$ and $i$ to calculate $M_{planet}$
- Used $T_{eff}$ to determine HZ (0.5 to 1.0 AU)

| Parameter | Value |
| --- | --- |
| $\theta_{LD}$ | $2.153 \pm 0.028$ mas |
| $R$ | $0.74 \pm 0.01\ R_\odot$ |
| $T_{eff}$ | $5039 \pm 126$ K |
| $L$ | $0.32 \pm 0.03\ L_\odot$ |
| $M_{star}$ | $0.82 \pm 0.05\ M_\odot$ |
| $M_{planet}$ | $1.55 \pm 0.24\ M_{Jupiter}$ |



# Asteroseismology Target κ Oph




- Observed using NPOI Feb. & March 2013
- Used $\Delta\nu_{max}$ from Stello et al. (2009) to determine mass:

$$\Delta \nu_{\text{max}} = \frac{M\,T^{3.5}}{L}$$

# NPOI Results

This is the only method to measure the mass of a single star.

| Parameter | Value | % err |
|---|---|---|
| $\theta_{LD}$ | $3.68 \pm 0.01$ mas | 0.3 |
| $R$ | $11.1 \pm 0.1\ R_\odot$ | 1 |
| $T_{eff}$ | $4679 \pm 113$ K | 2 |
| $L$ | $53.1 \pm 5.1\ L_\odot$ | 10 |
| $M_{star}$ | $3.9 \pm 0.5\ M_\odot$ | 13 |

There are 7 other targets with stellar oscillation observations and archival NPOI data:

- $1.32 \leq \theta \leq 3.01$ mas; $0.80 \leq R_{star} \leq 9.98\ R_\odot$
- $4863 \leq T_{eff} \leq 6349$ K
- $2.8 \leq M_{star} \leq 4.8\ M_\odot$

# And now for "some other stuff"

# Imaging GEOsats with the NPOI

- Objective:
  - Address space situational awareness needs by using the NPOI to observe geostationary satellites (GEOsats)
  - Build on previous fringe detection of GEOsat by NPOI to create an image
- We want to answer the questions:
  - What is the GEOsat orientation, configuration?
  - Is there major damage to the GEOsat?
  - Are the GEOsats at risk?

# The Challenge

Imaging is difficult because GEOsats are:

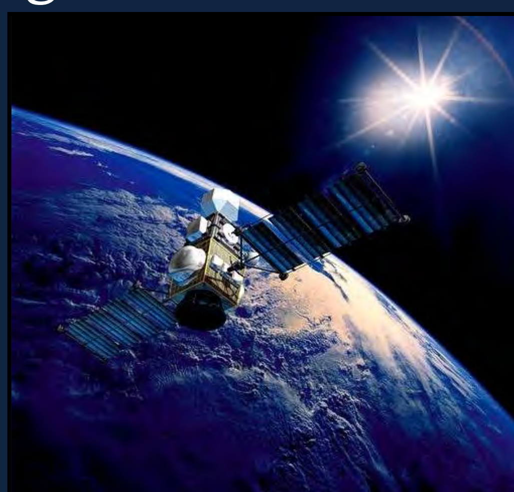
- Complex
- Faint, usually $10^{th}$-$14^{th}$ magnitude
- Small in apparent size
  - ~40,000 km away
  - 2 to 50 m in physical size → 10 to 250 mas in angular size
  - Single telescope would need an aperture of 40-60 m

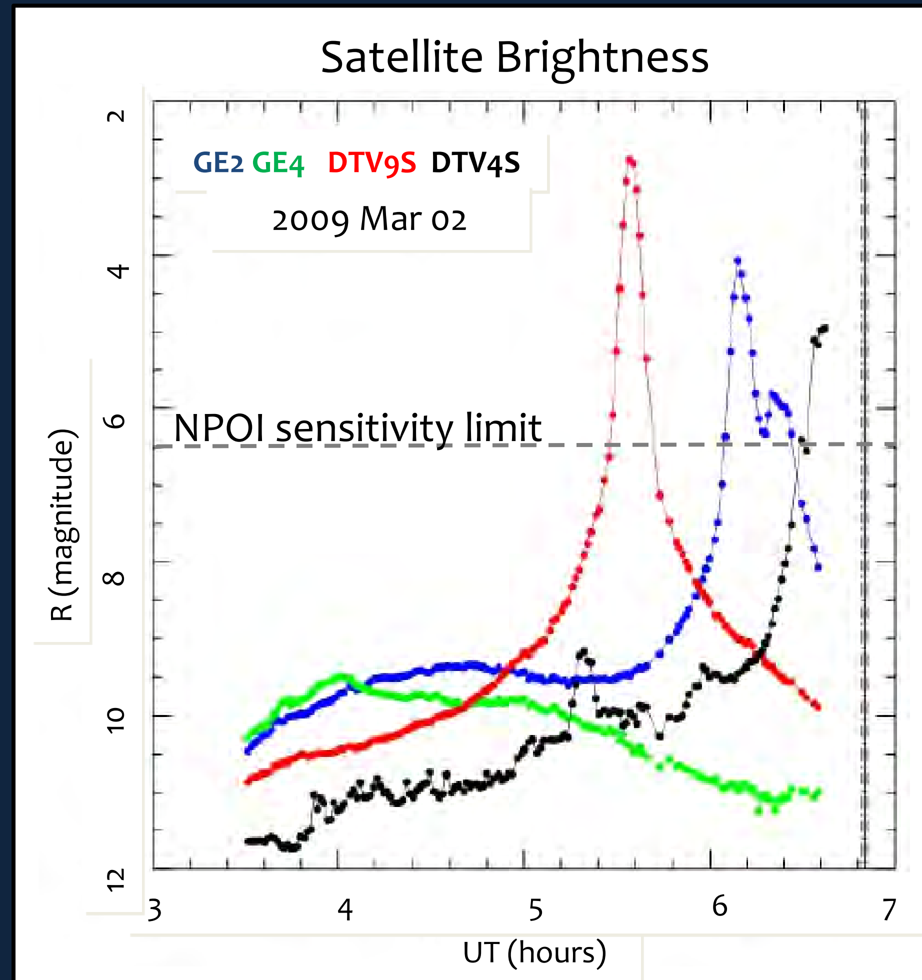
The technology developed to interferometrically image stars is directly applicable to imaging GEOsats.

# NPOI Observations During Glint

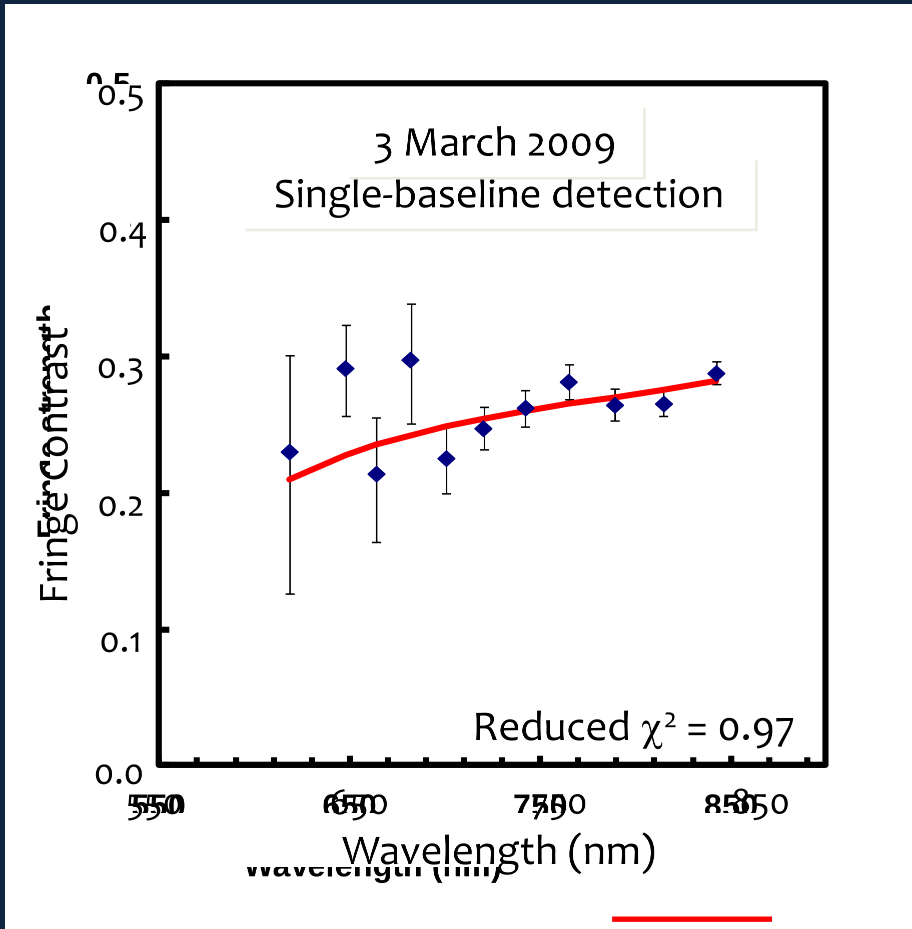
During glint:

- GEOsats brighten from 10-14th magnitude up to 1st
- Occurs twice a year
- Lasts ~10 minutes each night for a week





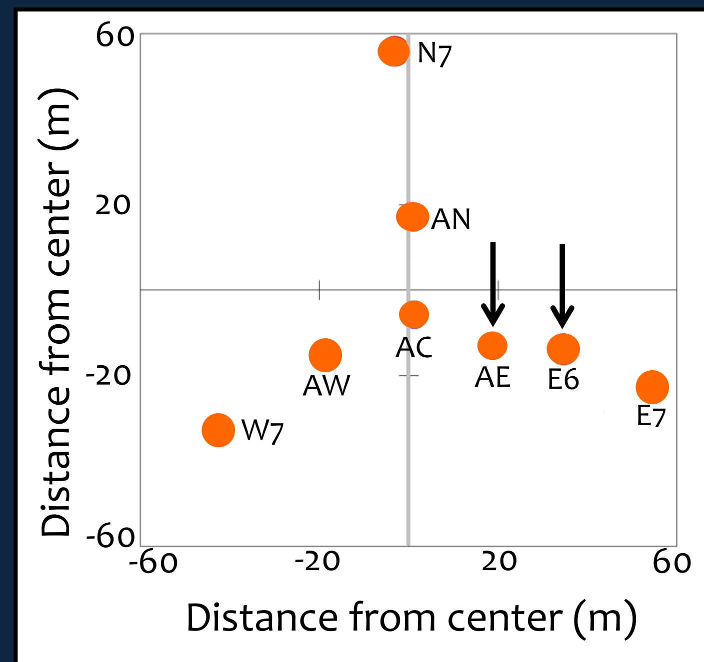
# Previous Detection




- small, bright element (1 m)
- large, diffuse element (≥3 m)

Artist's conception:

NPOI stations used



# Experiment Approach

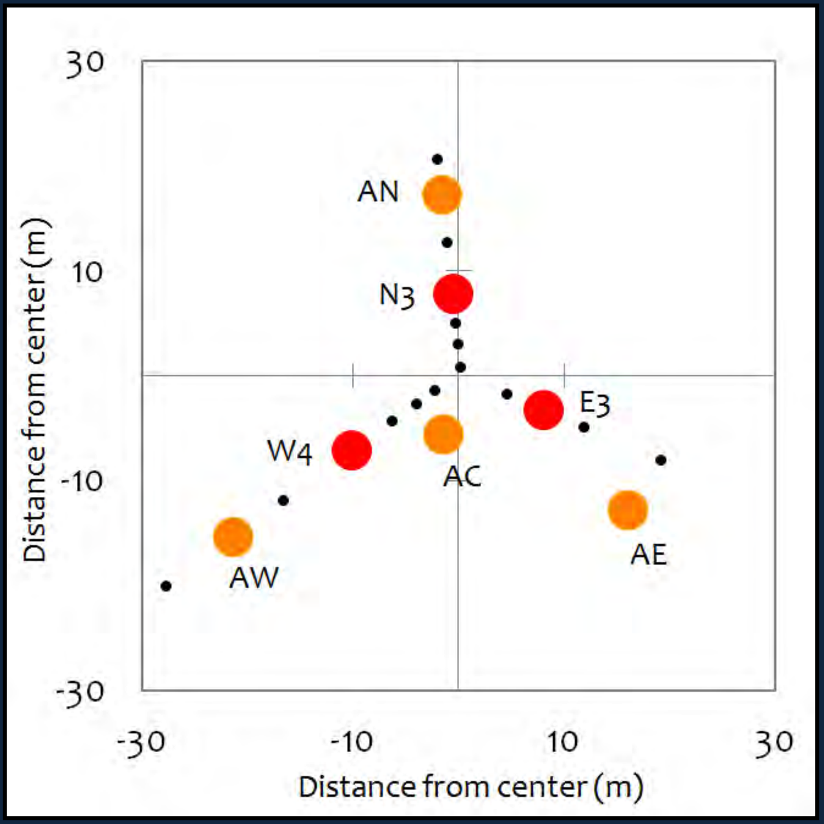
1. Observe GEOsats, including NRL's microsatellite
   – Maneuverable, in sub-GEO track

2. Simulations
   – Develop computer models; learn how much information can be derived from observations

3. Apply observing and data processing techniques
   – Implement multiple baseline measurements
   – Remove atmospheric effects from the data

# Applicable Techniques

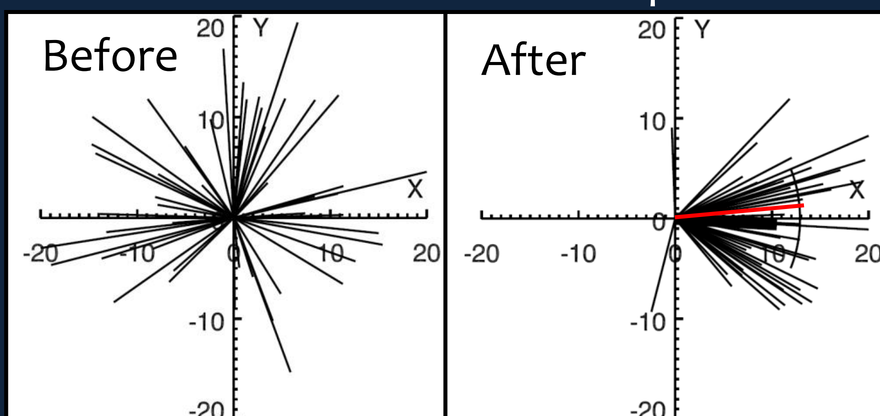
- Baseline bootstrapping
  - Build up to the long *B* in small increments
- Phase closure
  - Remove atmospheric phase effects by summing over a triangle
- Coherent averaging

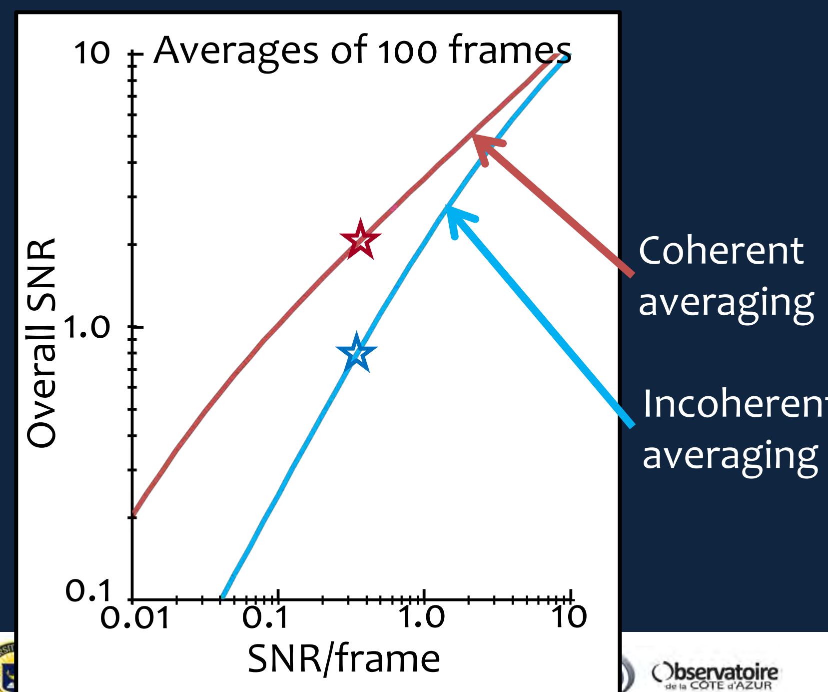


# Coherent Averaging

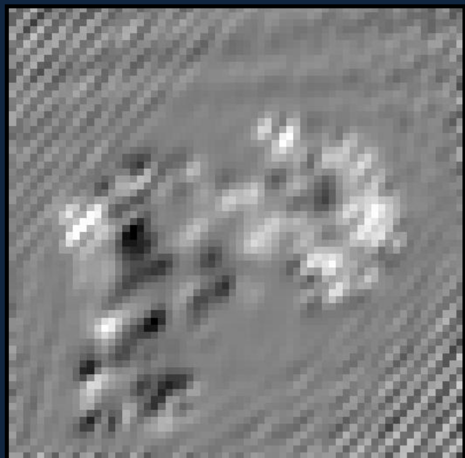
- Ongoing collaboration with A. Jorgensen, New Mexico Tech
- Start with a sequence of fringe measurements
- Fit a function to characterize atmospheric phase effects, compensate, and average
- Result: fringe phase + amplitude with higher SNR

NPOI Observations of ν Oph

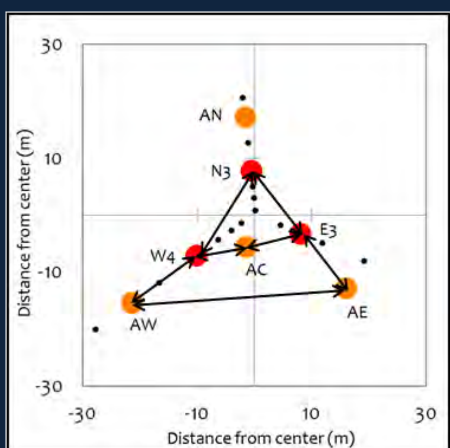


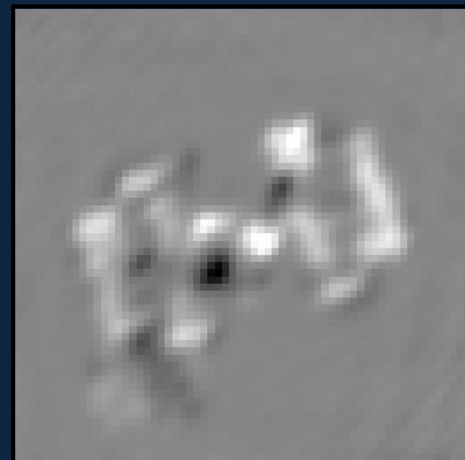



# GEOsat Image Quality

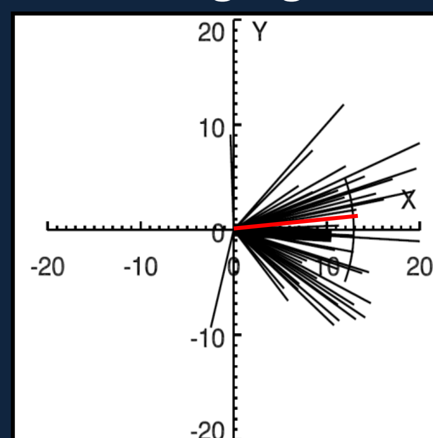


Simulation with realistic noise…



…apply coherent averaging…




…and assume perfect phase closure