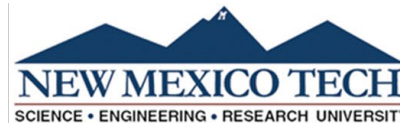


Overview of the Design and Scientific Goals for the MROI

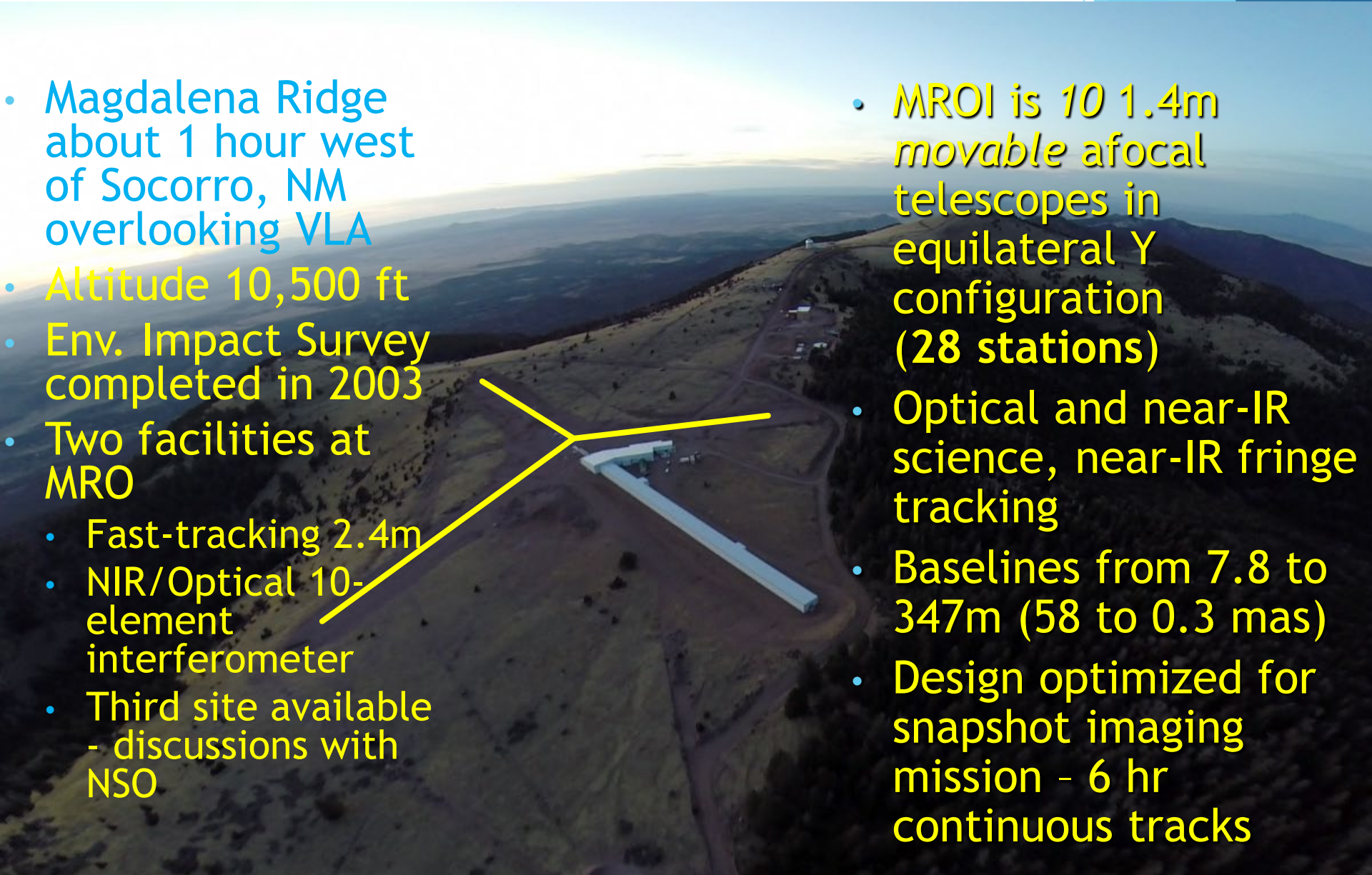
M. J. Creech-Eakman

On behalf of

the NM Tech and Cambridge MROI team members

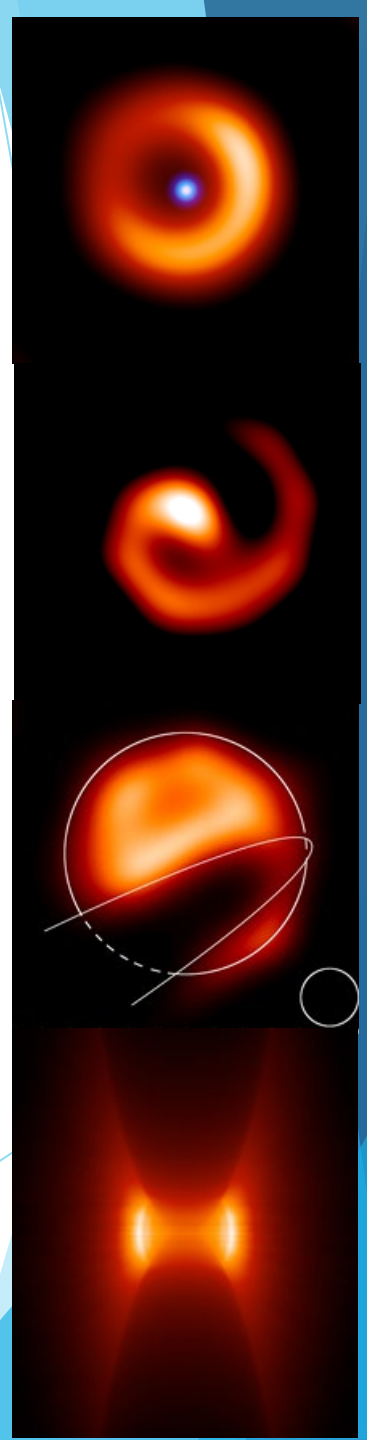


Overview of the Observatory

- 
- Magdalena Ridge about 1 hour west of Socorro, NM overlooking VLA
 - Altitude 10,500 ft
 - Env. Impact Survey completed in 2003
 - Two facilities at MRO
 - Fast-tracking 2.4m
 - NIR/Optical 10-element interferometer
 - Third site available - discussions with NSO
 - MROI is 10 1.4m *movable* afocal telescopes in equilateral Y configuration (28 stations)
 - Optical and near-IR science, near-IR fringe tracking
 - Baselines from 7.8 to 347m (58 to 0.3 mas)
 - Design optimized for snapshot imaging mission - 6 hr continuous tracks

MROI Key Science Mission

- Star and planet formation:
 - Protostellar accretion, imaging of dust disks, disk clearing as evidence for planet formation.
 - Emission line imaging of jets, outflows and magnetically channeled accretion.
 - Detection of sub-stellar companions.
- Stellar accretion, mass loss and B fields/circulation:
 - Convection, mass loss and mass transfer in single and multi-star systems.
 - Bipolarity and collimation of circumstellar material, wind and shock geometries, interacting binary systems.
 - Pulsations in Cepheids, Miras, RV Tauris, etc.
 - Star spots, oblateness, asymmetric properties.
- Active Galactic Nuclei:
 - Verification/investigation of the unified model.
 - Determination of nature of nuclear/extra-nuclear starbursts.
 - $H = 14$ gives >100 targets.



Flow Down for Requirements

- Telescope diameter of 1.4 m
 - H magnitude = 14th for group delay tracking limit
- Spatial scales of 0.3 to 58 mas
 - Baselines from 7.8 to 347 m (for 0.6-2.4 microns)
- Moderate-to-high spectral resolutions
 - Separate fringe tracking and science cameras
- High throughput to achieve sensitivity limit
 - Fifteen reflections from primary to detectors (13% throughput)
 - Optimized coatings (polarization, phase, reflectivity) for 0.6-2.4 microns
- Large number of telescopes rapidly combined/movable
 - Optimized for model-independent imaging



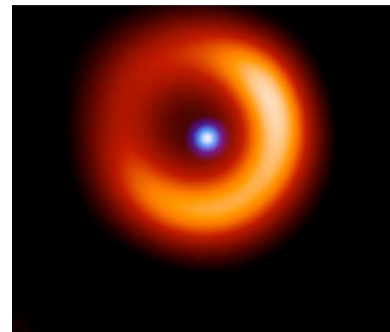
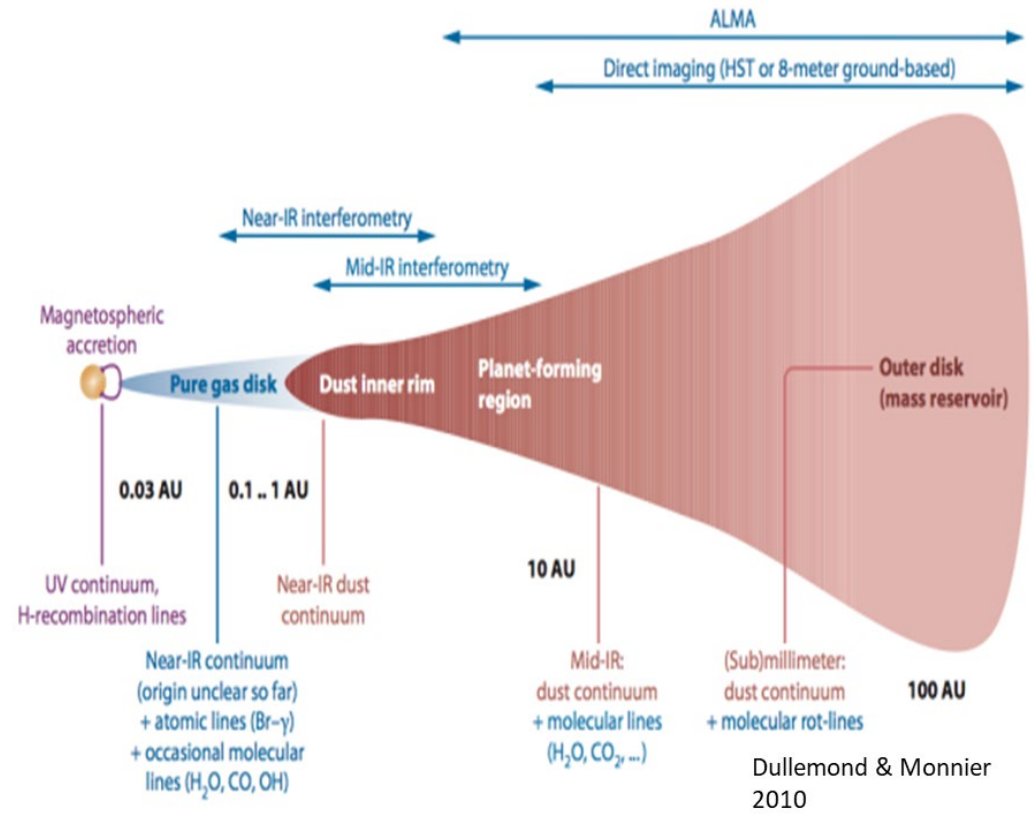
Photo T. Eakman, Array layout: A. Olivares

Try to apply lessons learned from other interferometric facilities whenever possible.

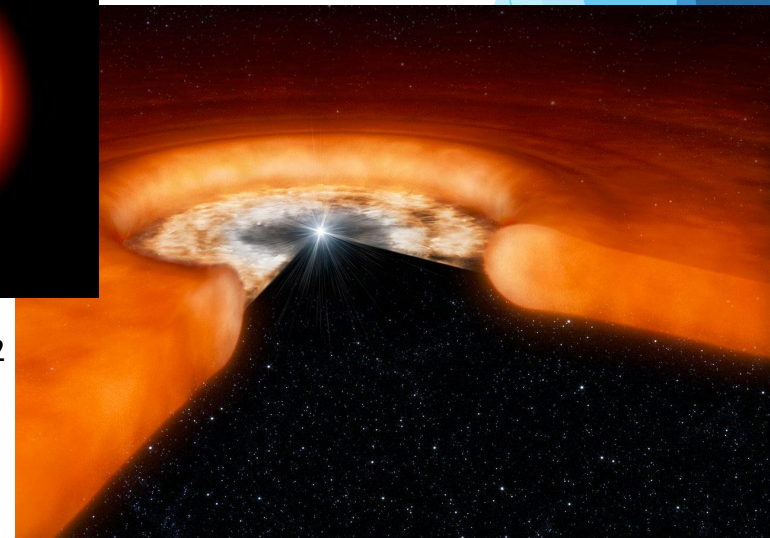
Team has experience with hardware at: COAST, SUSI, KI, CHARA, NPOI and PTI

YSO Disks

- ▶ Disks have openings close to protostar which scale with luminosity
- ▶ Evidence of puffed up inner disk walls and flaring
- ▶ Disk geometries and clearings can be identified from infrared imaging with infrared interferometry within a few AU
- ▶ Strongly complementary with ALMA/NGVLA interferometric and JWST imaging
- ▶ Excited magnetic reconnection lines from disk onto the protostar may be identified in future



Tuthill et al. 2002

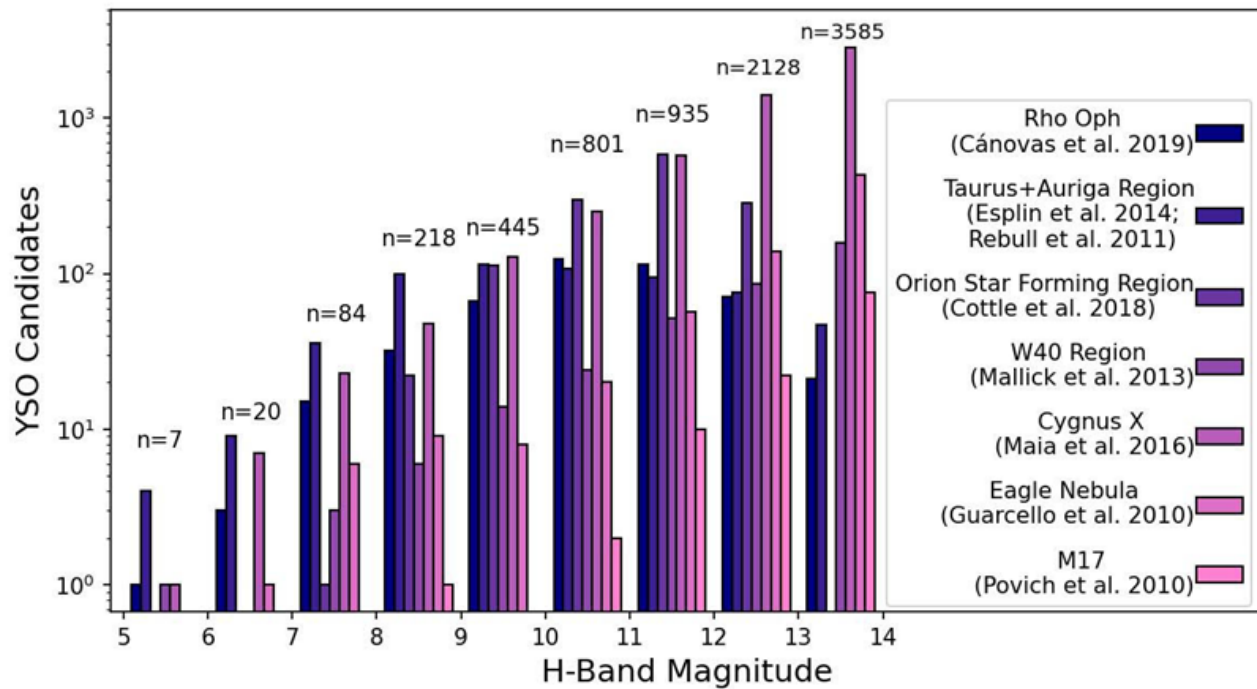


YSOs with MROI

Scoured series of catalogs with opt/IR magnitudes for NSF MSRI-1 of 7 nearest star-forming regions, 30° above horizon for MROI (TMC, Ori, W40, etc)

Using 14th H/K fringe-tracking and 17th at V for tip-tilt limit

Redness of targets is a challenge; off-source tracking may help



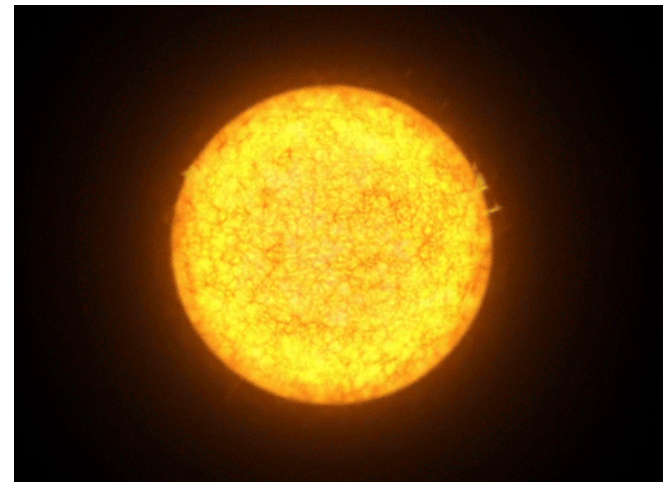
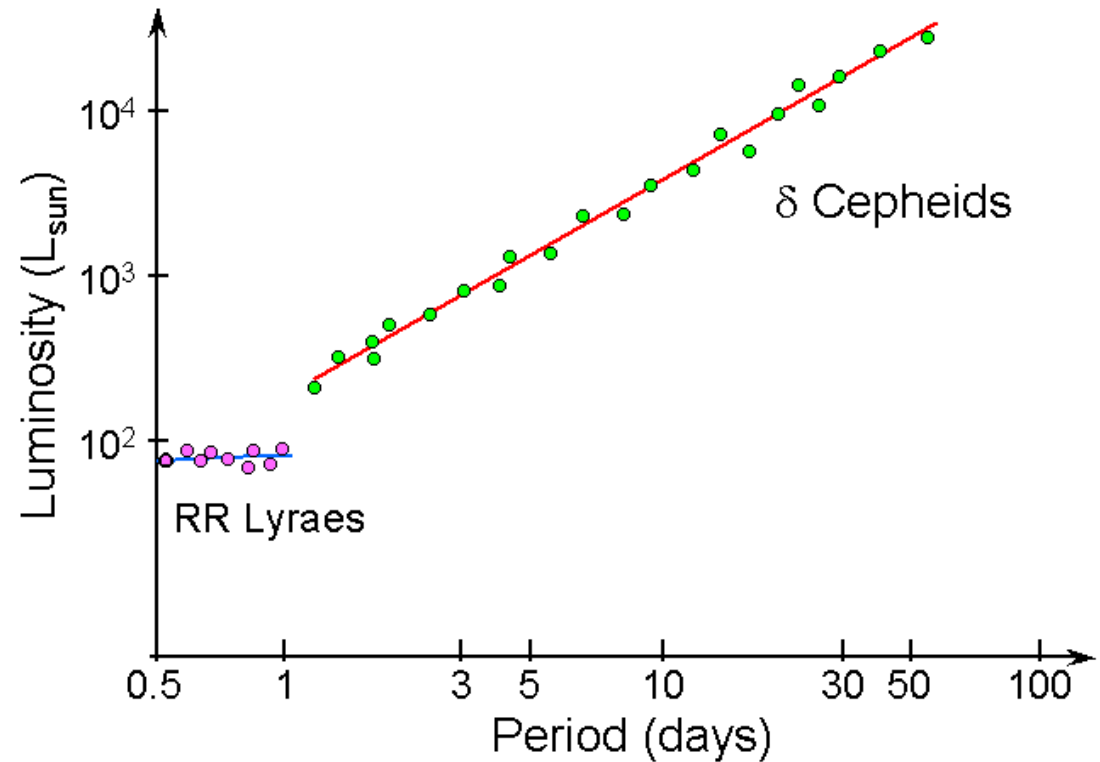
Stellar Physics - Outstanding Questions

- ▶ Mass Loss
 - ▶ Smooth, episodic, clumpy
 - ▶ Driven by B fields, spectral lines or winds
- ▶ Convection/Spots
 - ▶ Sizes, lifetimes, migration, coverage of cells
- ▶ Pulsation
 - ▶ Radial/non-radial, modes, kappa/gravity driven
- ▶ Binarity
 - ▶ Interactions with other member, disk
 - ▶ Mass-transfer process, emission lines, B fields
- ▶ Triple/Hierarchical systems
 - ▶ Like/unlike binaries, angular momentum alignment
- ▶ Rotation, Meridional Circulation, Limb-darkening, many others

Pulsation of Cepheids

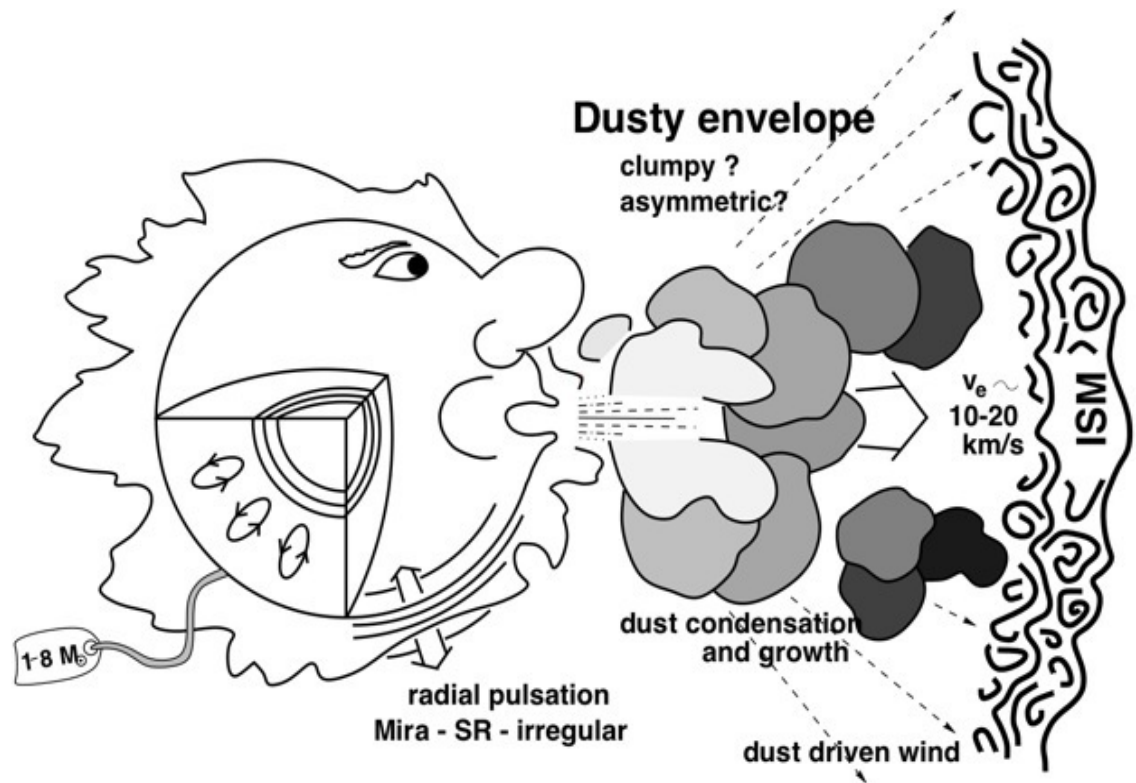
- Cepheids and other intrinsic pulsators have a Period-Luminosity relationship
- This fact renders them as Standard Candles to determine independent distances
- Much of our understanding of the size and expansion rate of the galaxy depends on this being correct
- **211 galactic Cepheids brighter than $V=14$ at min light**

Period-Luminosity Relationship



AGB Stars

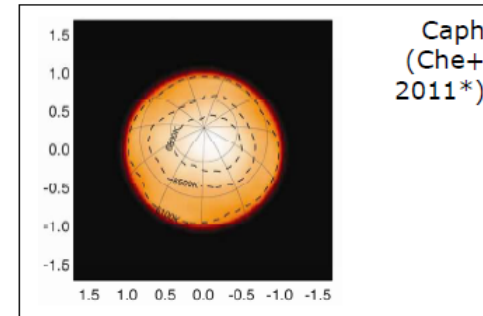
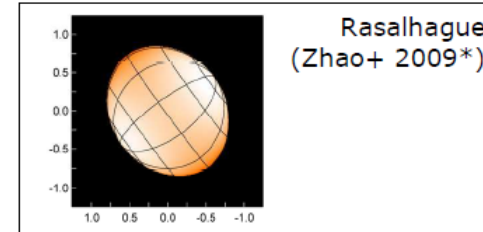
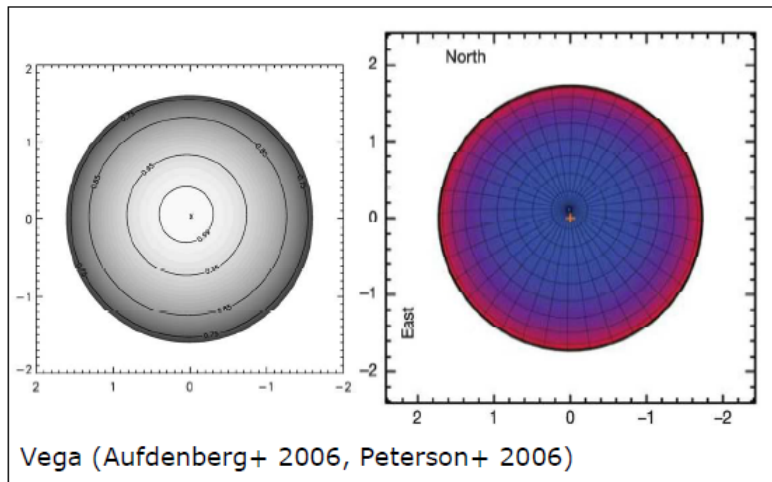
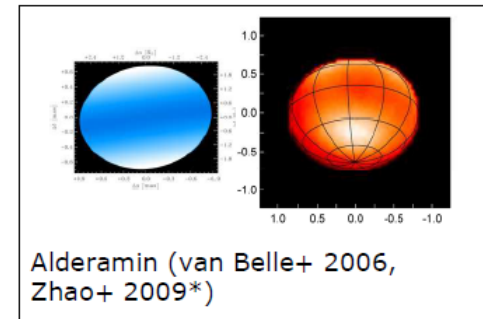
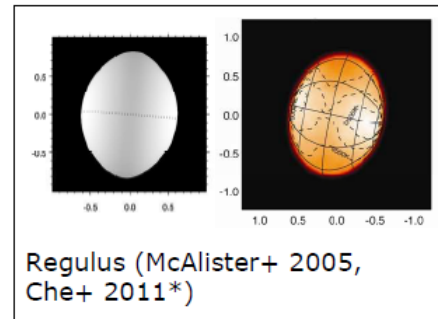
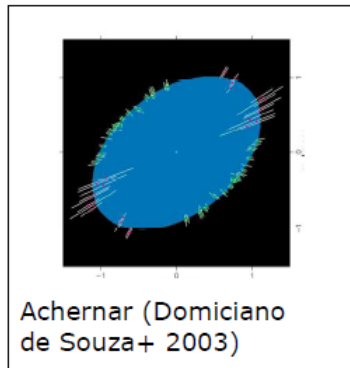
- ▶ Complicated cool stars - pulsate, molecule and dust production, clumpy/episodic mass loss, return the majority of the material to the galaxy
- ▶ Many interferometers image these - recent results on W Hyd - Mira variable using multiwavelength approaches
- ▶ 409 AGBs brighter than $V_{\text{max}} = 12$ in galaxy (delta mag V-K can be very large)



M. Marengo CfA website

Rapid Rotators

- ▶ Some stars rotate close to break-up speeds
- ▶ Gravity-darkening at limb - Von Zeipel effect
- ▶ Opens up questions about circulation and interplay with convection
- ▶ **Hundreds of targets for MROI**



WRs accessible to MROI

- ▶ Questions include: binarity fractions, dust formation, co-rotating regions, chemical differences

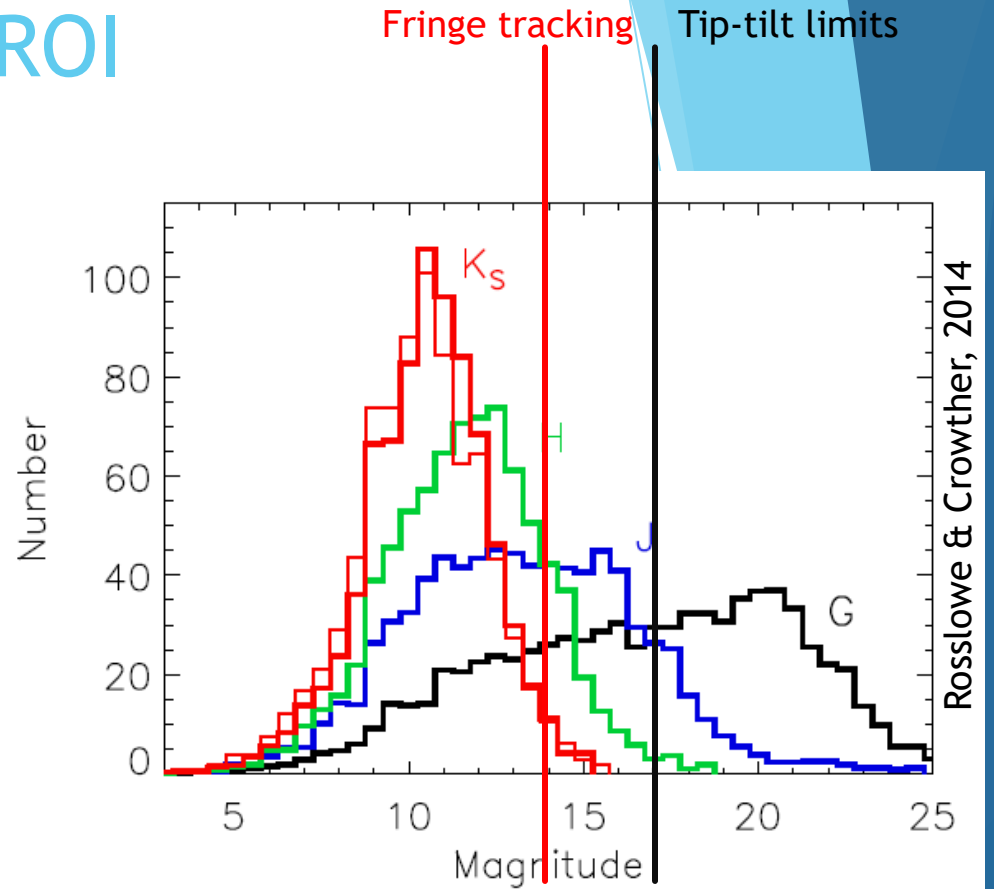
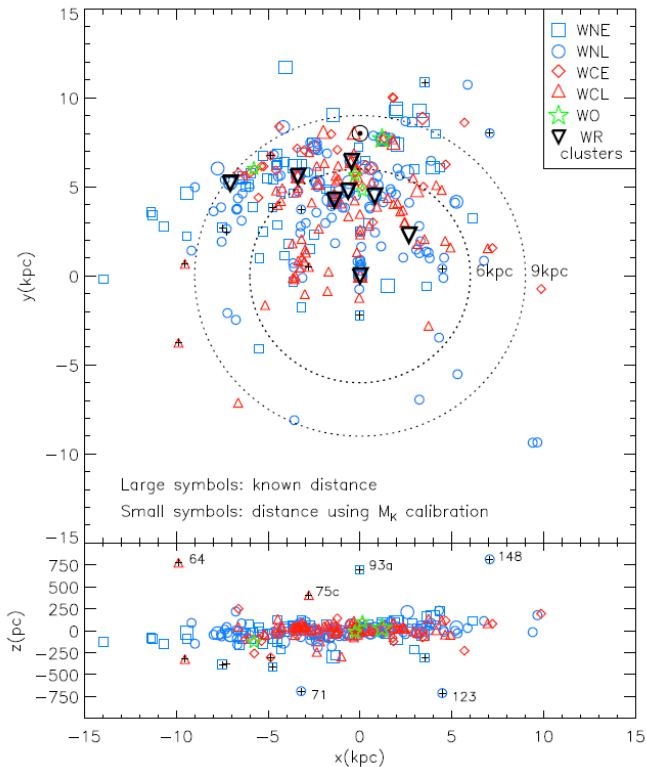
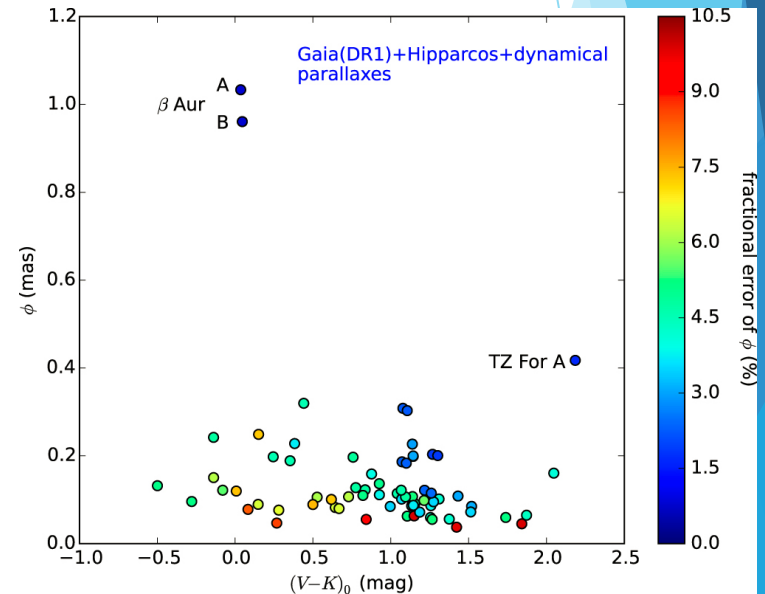


Figure 12. Histogram of 2MASS JHK_S and G-band (*Gaia*) magnitudes predicted for our preferred model Galactic WR star population. Each distribution shown is an average over 10 model repetitions. Two K_S -band distributions are plotted, the thin (red) line represents a model population where 28% of WC stars are dust forming (WC8d/9d, $M_{K_S} = -6.95$, Table 5). All thick lines represent populations consisting of WN and non-dusty WC stars.

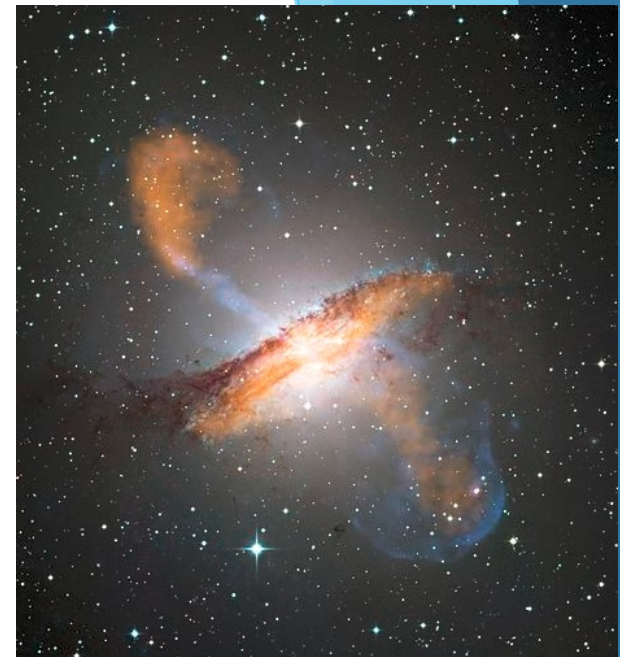
Eclipsing or Interacting Binaries

- ▶ Many binary stars are close enough to transfer mass - changing the evolution of both members in the pair
- ▶ These systems have very short orbital periods
- ▶ Eclipsing systems provide more constraints - e.g. geometry and radius
- ▶ Surface brightness relations used for most stars are based on eclipsing binaries - limited by knowledge of diameters and distances
- ▶ **74 Cataclysmic Variables and hundreds of eclipsing systems in reach at MROI**

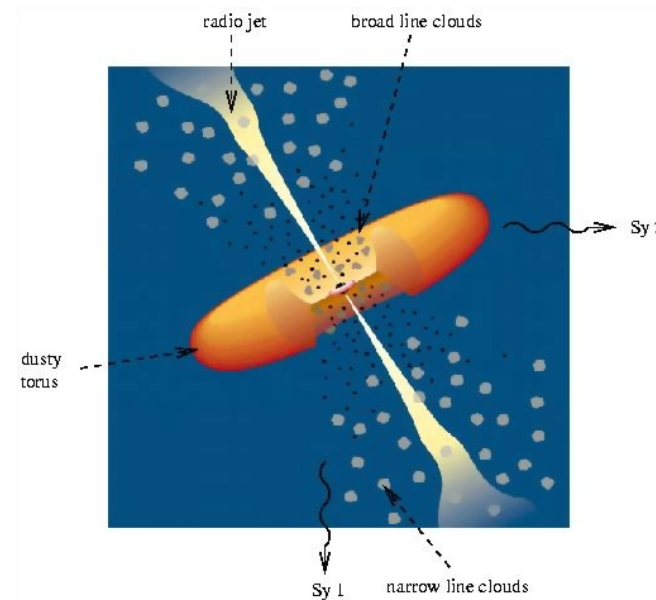


Active Galactic Nucleus - AGN

- ▶ At the hearts of most galaxies is a supermassive blackhole
- ▶ If the blackhole is actively accreting matter it will produce an electromagnetic spectrum that is “non-stellar” at multiple wavelengths
- ▶ We call galaxies that are doing this “Active Galaxies”
- ▶ The region immediately around these central blackholes likely have special physical features that are of interest to astrophysicists

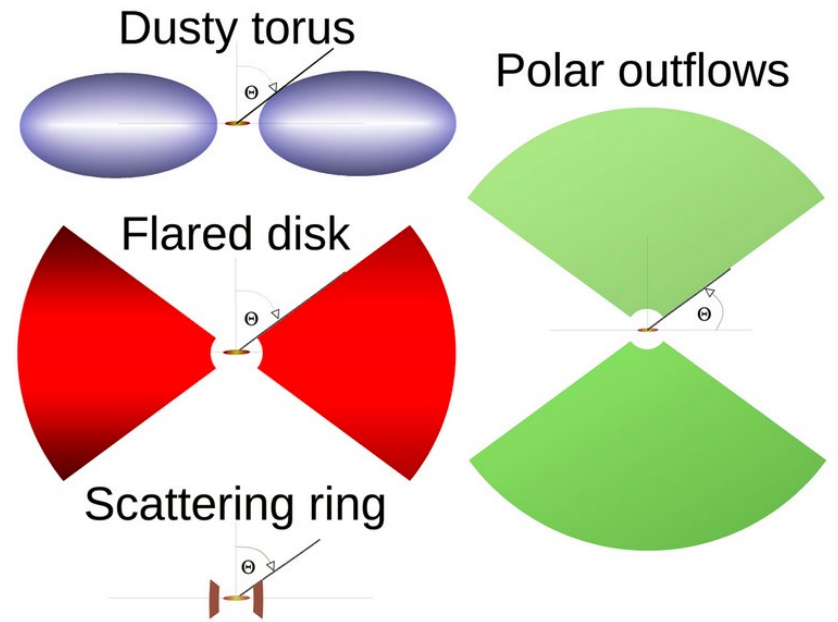


ESA/NASA Composite Image Centaurus A

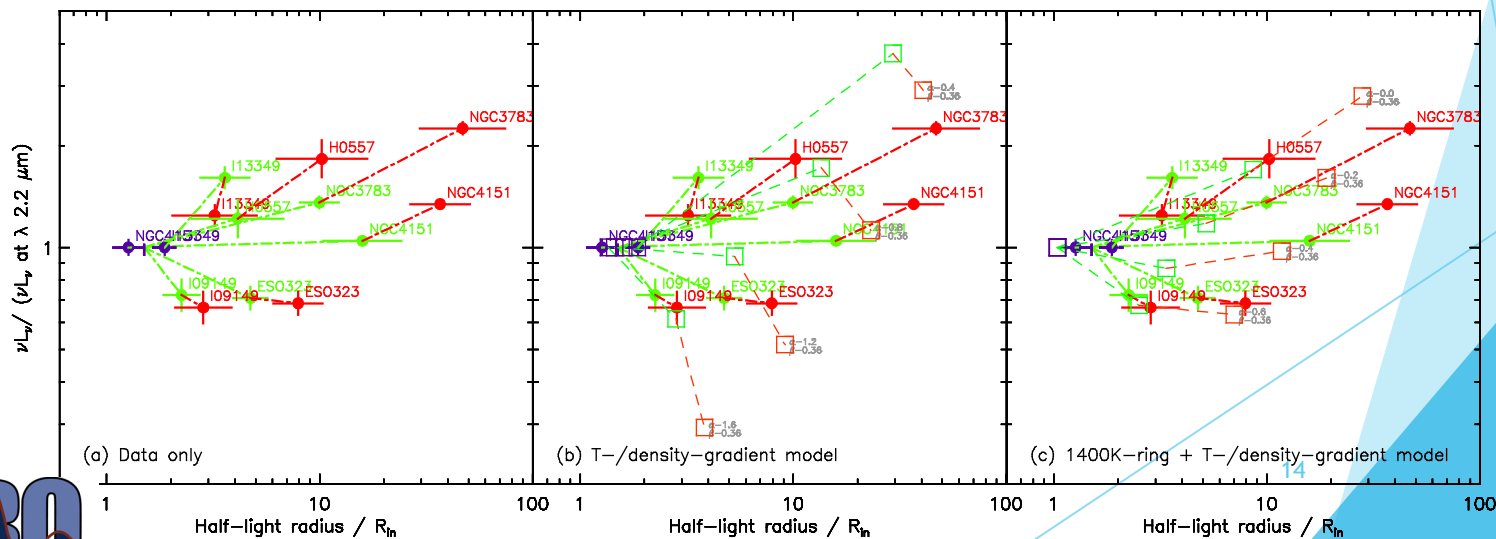


Type 1 or 2, other?

- ▶ Depending on the orientation between us and the AGN, we may preferentially “see” different features - most of these measures are indirect as we cannot actually resolve the structures with conventional methods
- ▶ The size of the blackhole is expected to scale with the luminosity of the galaxy it is in
- ▶ Today only ~10 AGN can be observed with optical interferometry to get a more direct measure of the AGN and its surroundings



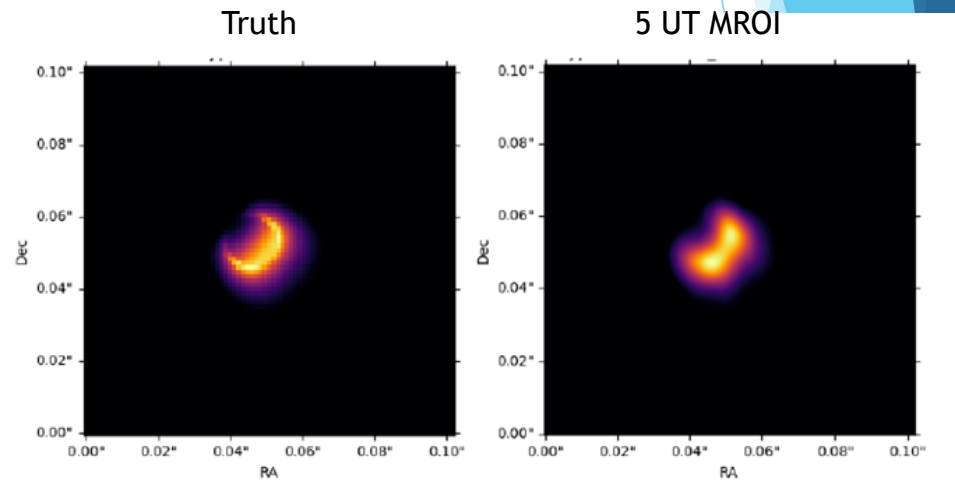
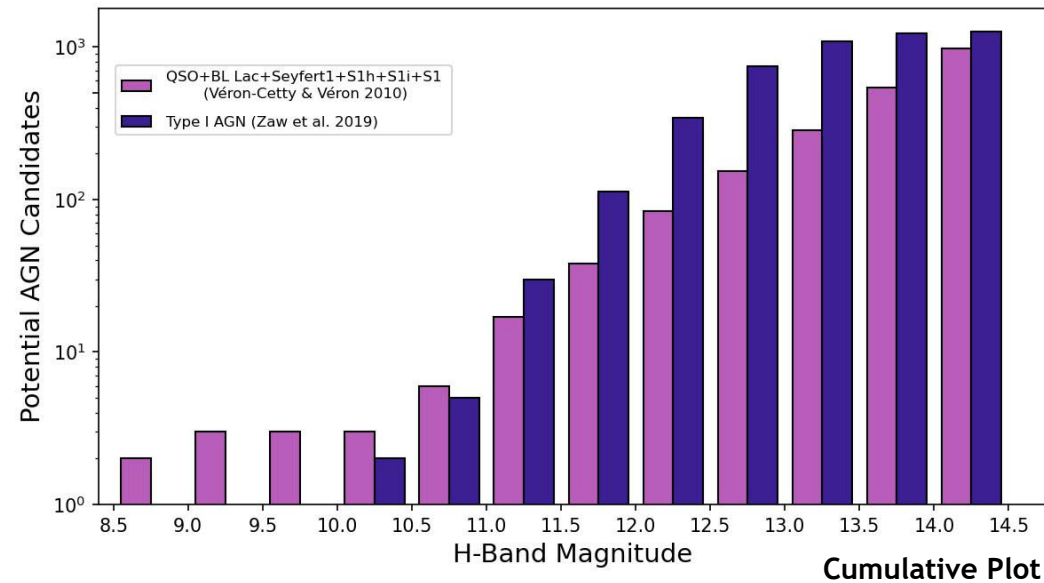
Rojas Lobos et al. 2018



Kishimoto et al. 2011

AGN with MROI

- ▶ Scoured catalogs for AGN central magnitudes
- ▶ Difficult to get core fluxes in quiescence vs. outburst with conventional telescopes
- ▶ Using same limits (FT, T/T and Dec) we have tried to quantify AGNs we might access
- ▶ MROI can begin to make contribution with just 5 UTs on the array

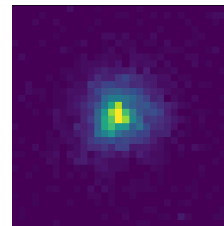


Two MROI configurations of 5-Telescope array on Seyfert 2 (Nikutta et al. 2021)

Fringes and AFRL Demos

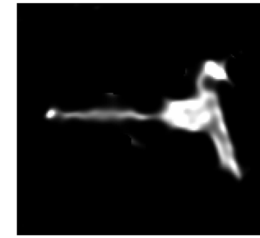
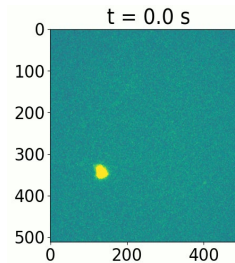
Fast tip-tilt tracking

- ▶ Proof of sensitivity and closure phase for AFRL with 1st 3 telescopes
- ▶ SSA mission to assist with imaging, calibration and nearby object discrimination
- ▶ Tracked (with FTTs) dozens of GEOs and attempted fringe tracking
- ▶ 7 telescopes needed to make useful images for SSA

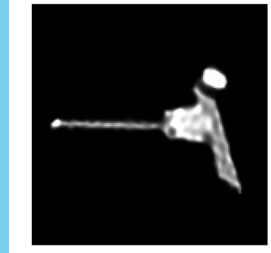


Eutelsat 117

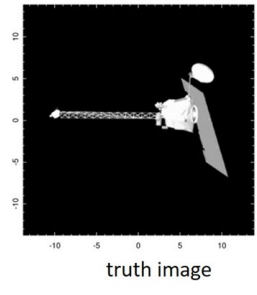
Tracking a GEO with a UT



7 telescopes

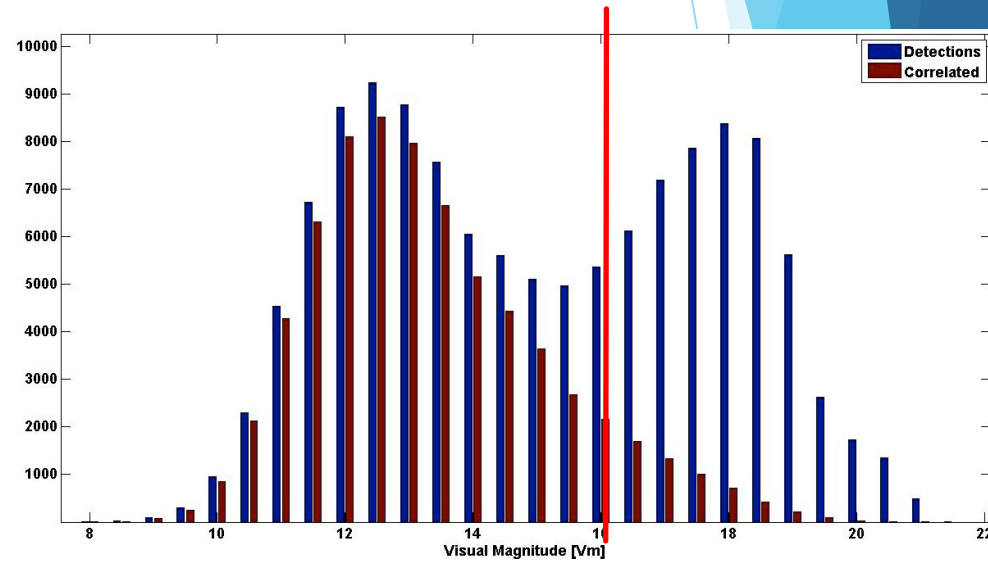


10 telescopes



truth image

Young et al. (2016)

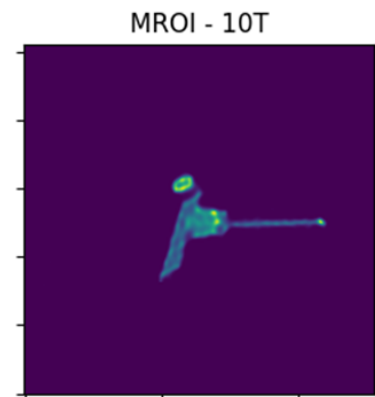
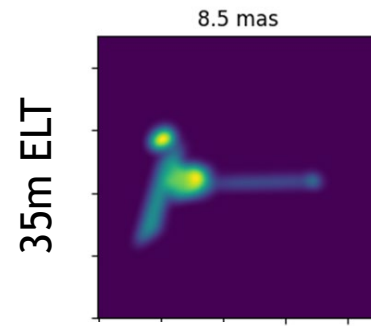
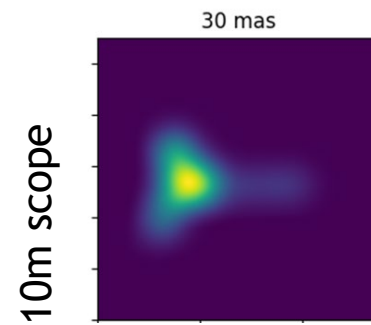
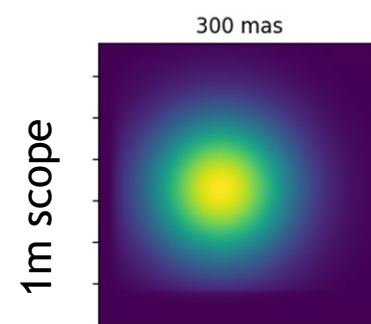


From MIT Lincoln Lab work with SST (not classified)
MROI limit in red - V-K ~2 for GEOs

Funding Needs

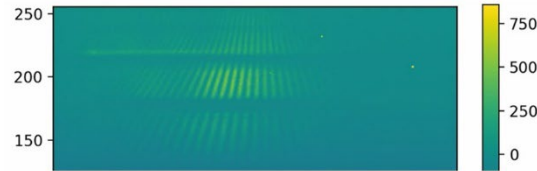


- Current facility and infrastructure \$100M+ on mountain; completed ~\$240M
- Funding via AFRL under CA with university for \$30M through late '26
 - \$18.7M appropriated to date
- Important cost points:
 - \$2M/yr for staffing/ops today
 - ~\$9M per beamline for hardware
 - NSF 5UT system + arms: ~\$30M + 3 yrs
 - 10UT complete system: ~\$140M + 7 yrs to finish
 - Operating costs: ~\$4-5M/yr
 - Business model: State of NM,
 - NSF, NASA, DoD, collaborators, private funds, endowment



Anticipated Upgrades coming soon

- Closing the loop with Delay Lines for real-time, fainter, fringe tracking
- Daytime cooling of telescopes
- Automated (ML) alignment of mirrors in beamtrain
- SAPHIRA detector read-noise optimization
- Installing first Atmospheric Dispersion Correctors (18mo+)
- Installing ICoNN Fringe Tracker (18mo+)
- 3rd Telescope and Beamline (2+ years)



Potential Early 2 & 3 Telescope MROI Science Projects

▶ Two telescopes:

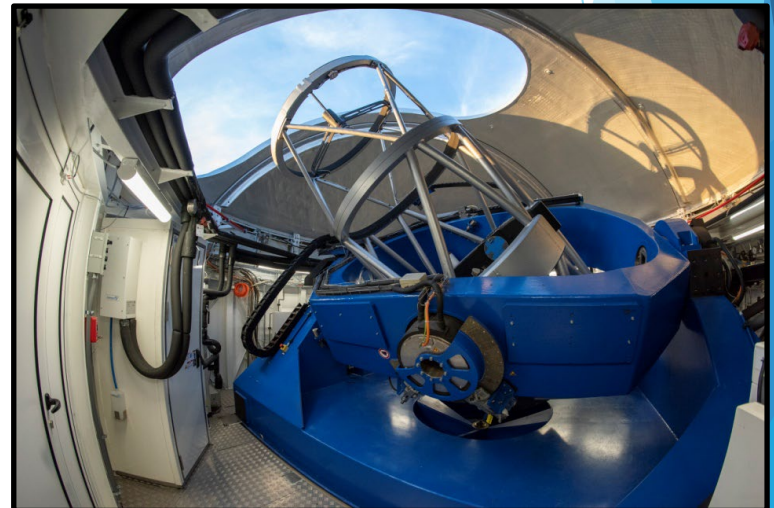
Assume deeper magnitudes

- ▶ Binarity in faint systems - several different applications
- ▶ AGN reverberation mapping
- ▶ Diameters/limb-darkening of faint dwarfs/exoplanet host stars
- ▶ Stellar pulsations

▶ Three telescopes:

Assume closure phase capability

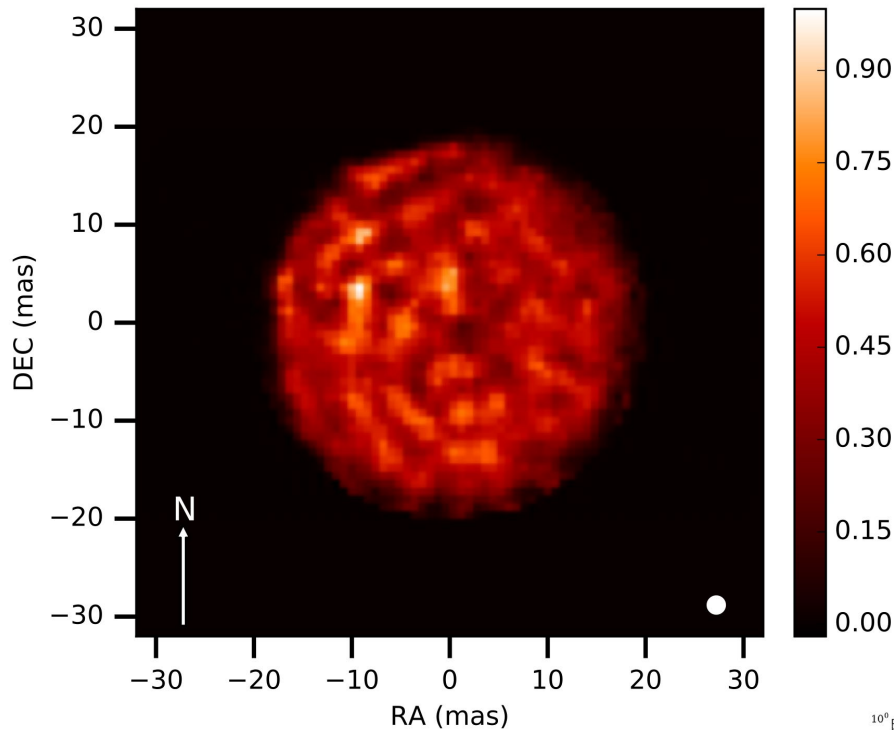
- ▶ CVs/Novae in active phases
- ▶ Stellar rotational elongation
- ▶ Non-radial stellar pulsations
- ▶ YSO disks/openings



Photos C. Gino

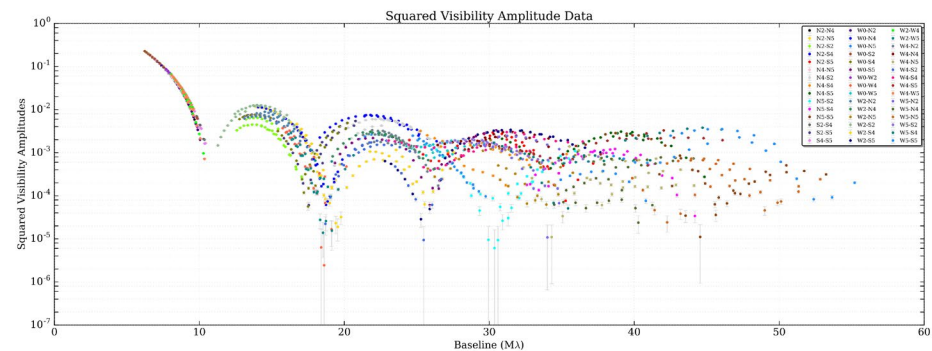
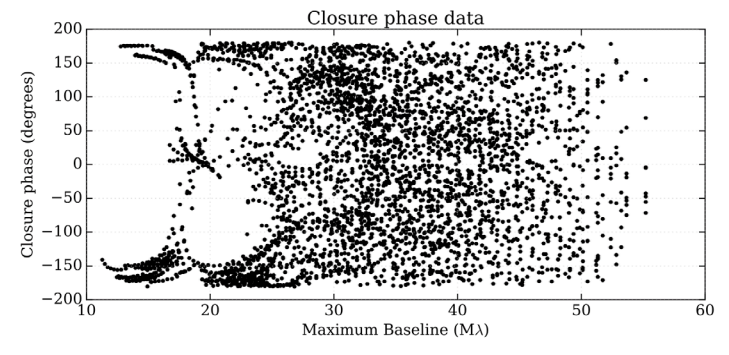
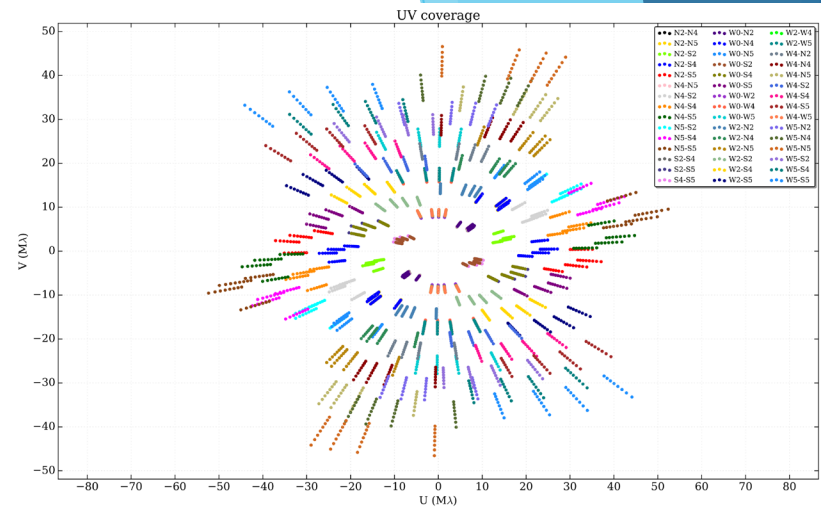
CHARA-MROI Science Meeting

The True Promise of MROI



*One night of MROI
10-telescope data.*

Courtesy of Ryan Norris, collaborating with F. Baron and J. Young

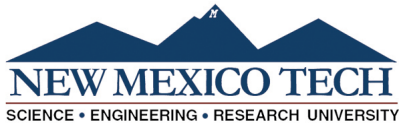


Thank you for your attention!

Our team:

- ▶ At NMT/MROI: J. Altamirano, W. Cook, M. J. Creech-Eakman, C. Eakman, A. Farris, E. Floyd, D. Frothingham, J. Giron, M. Giron, C. Greiner, A. Haque, J. Hernandez, A. Jorgensen, J. Luis, J. C. Mason, R. Norris, A. Olivares, S. Orizaga, G. Owens, S. Rochelle, V. D. Romero, C. Salcido, R. Santoro, I. Schofield
- ▶ At Cambridge: C. Haniff, D. Buscher, J. P. Barrios, A. Esmailzadeh, M. Fisher, S. Murphy, E. B. Seneta, J. Young, D. Wilson

Special thanks to Dana Baylis-Aguirre for NSF plots!



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