Science Opportunities with the CHARA Array

CHARA interferometry, coupled with additional data (spectra, photometry, etc.), enable precise measures of stellar properties

Science Opportunities with the CHARA Array

Important to know!

1. At 331-m

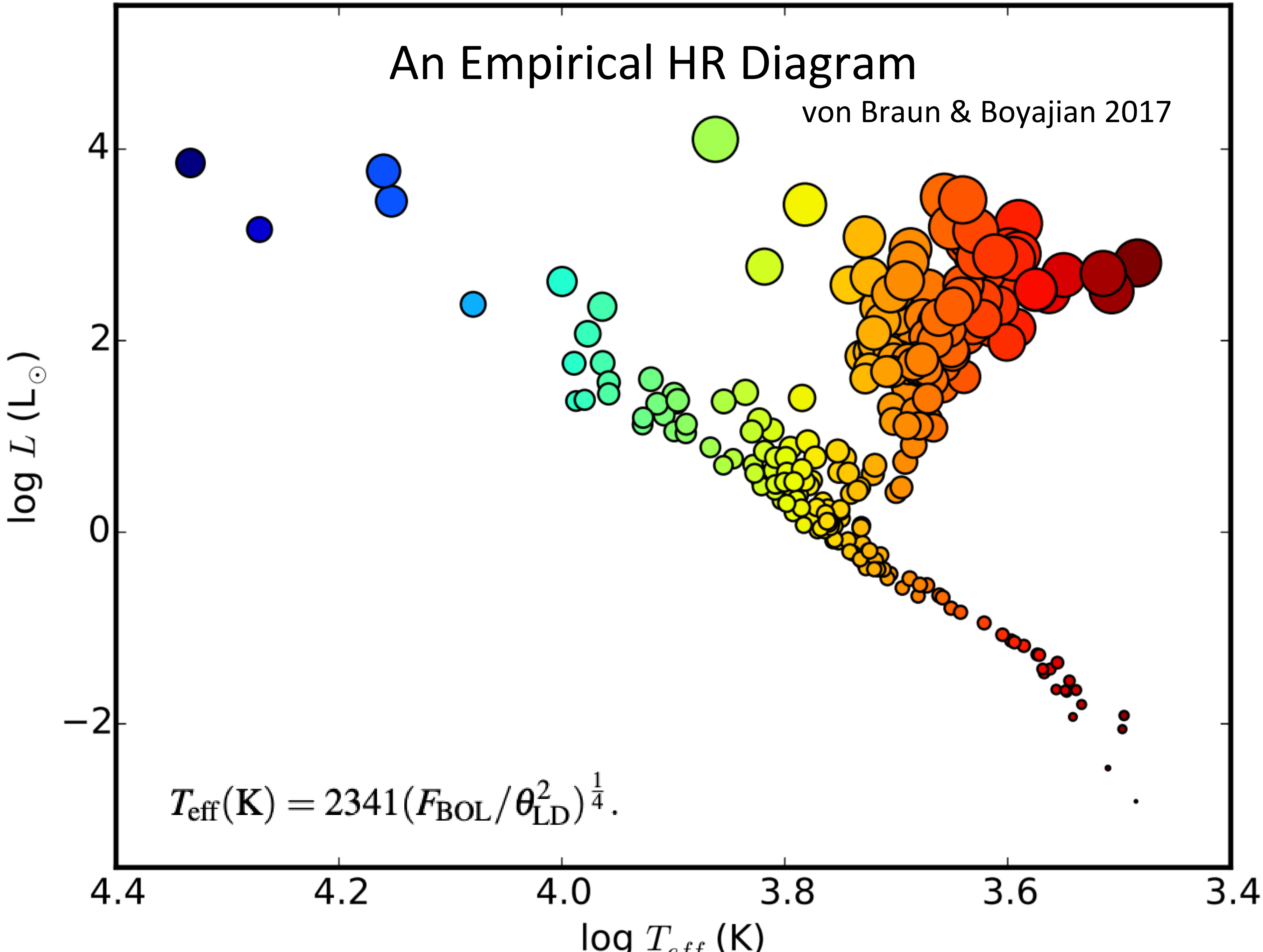
   θres = 0.66 mas (at K)

   θres = 0.48 mas (at H)

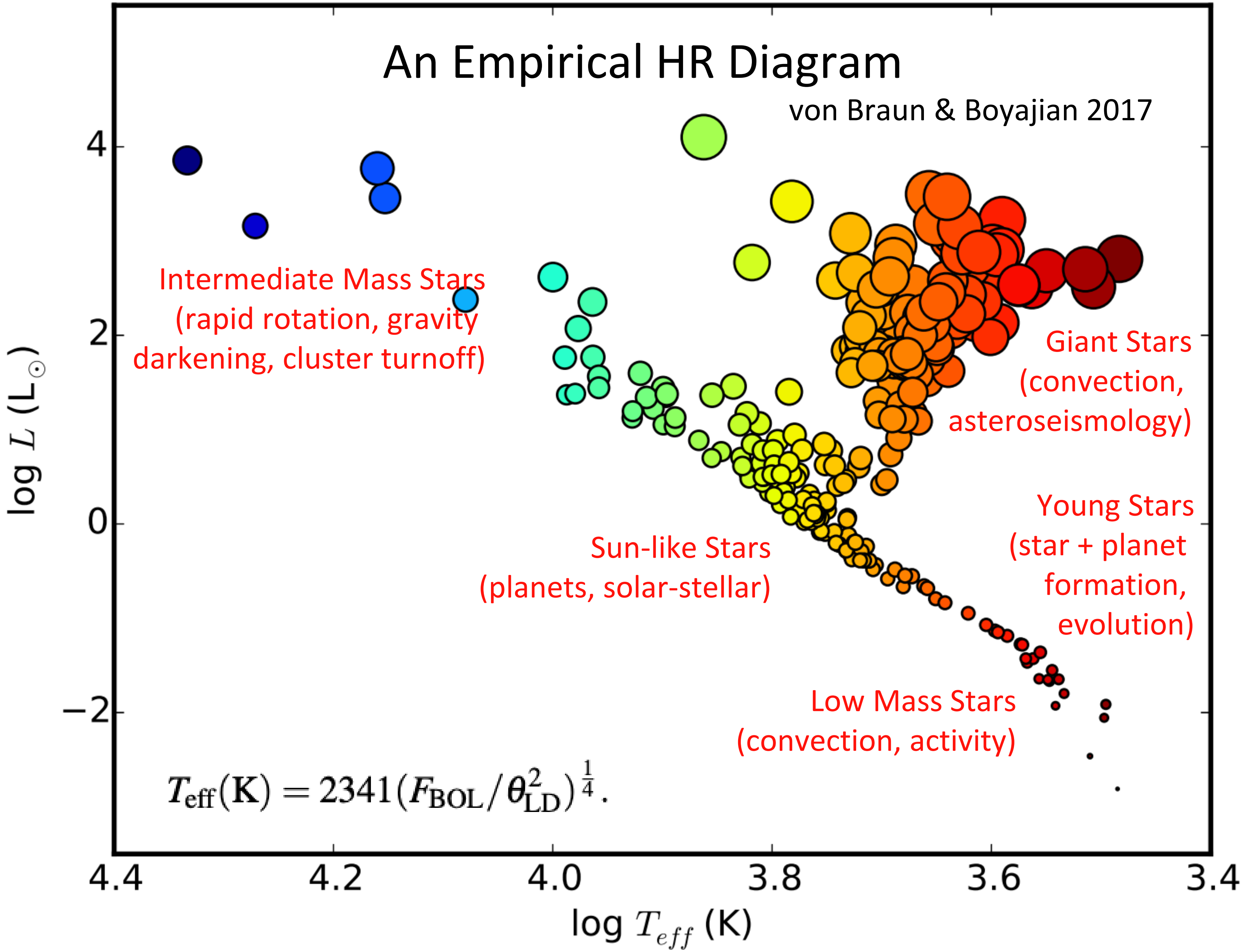
   θres = 0.20 mas (at R)

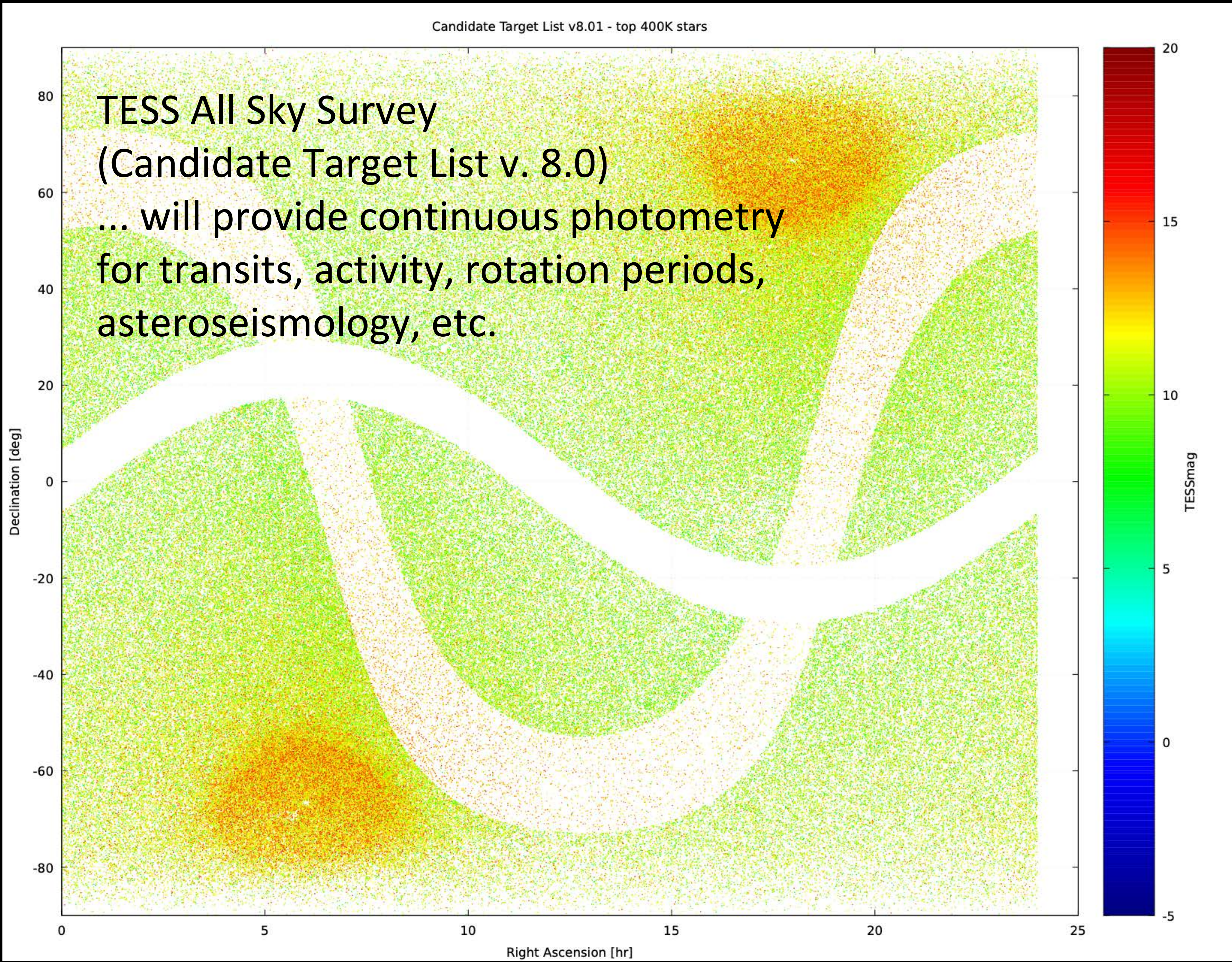
   formally $0.5\ \lambda / B$

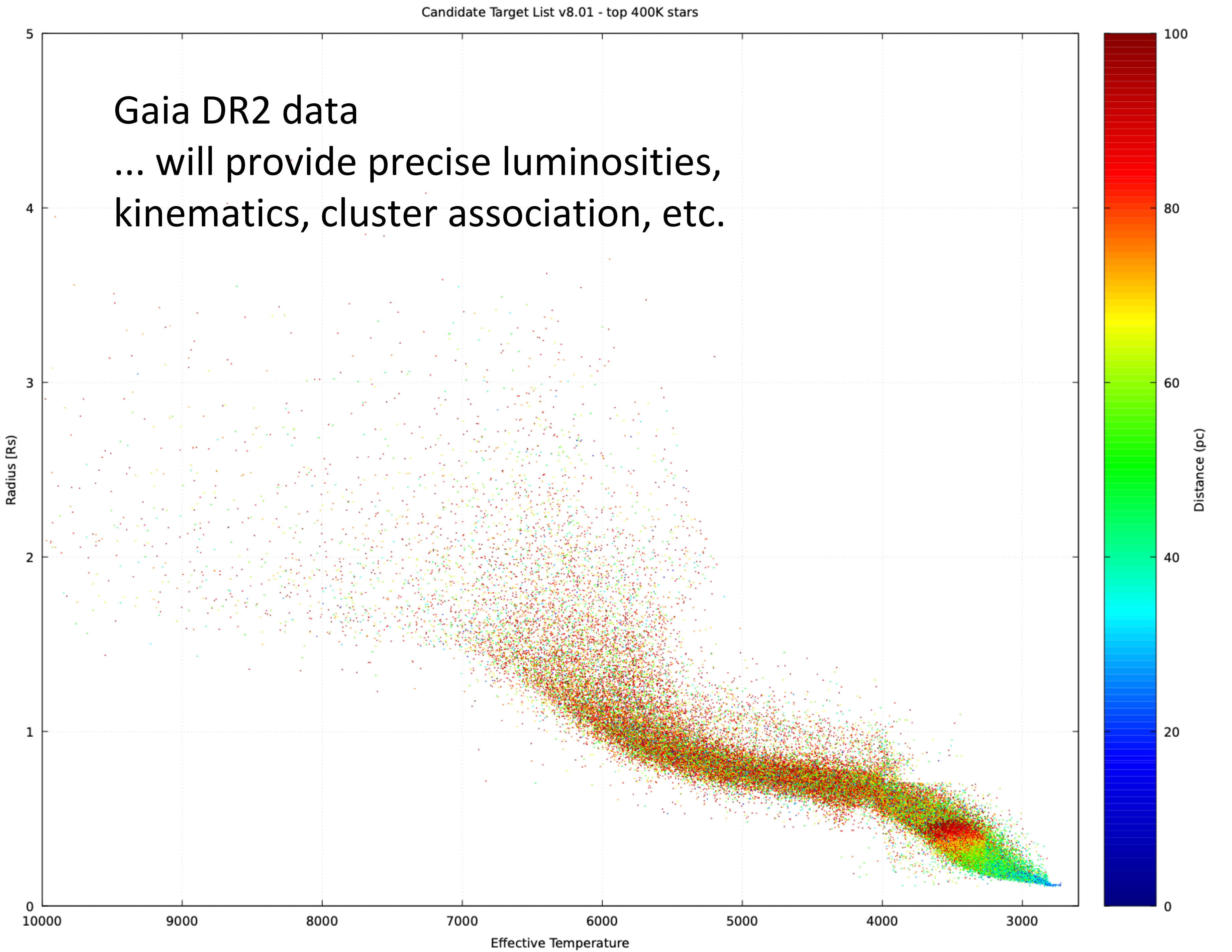
2. Sun at 10 pc has θdiam = 0.9 mas

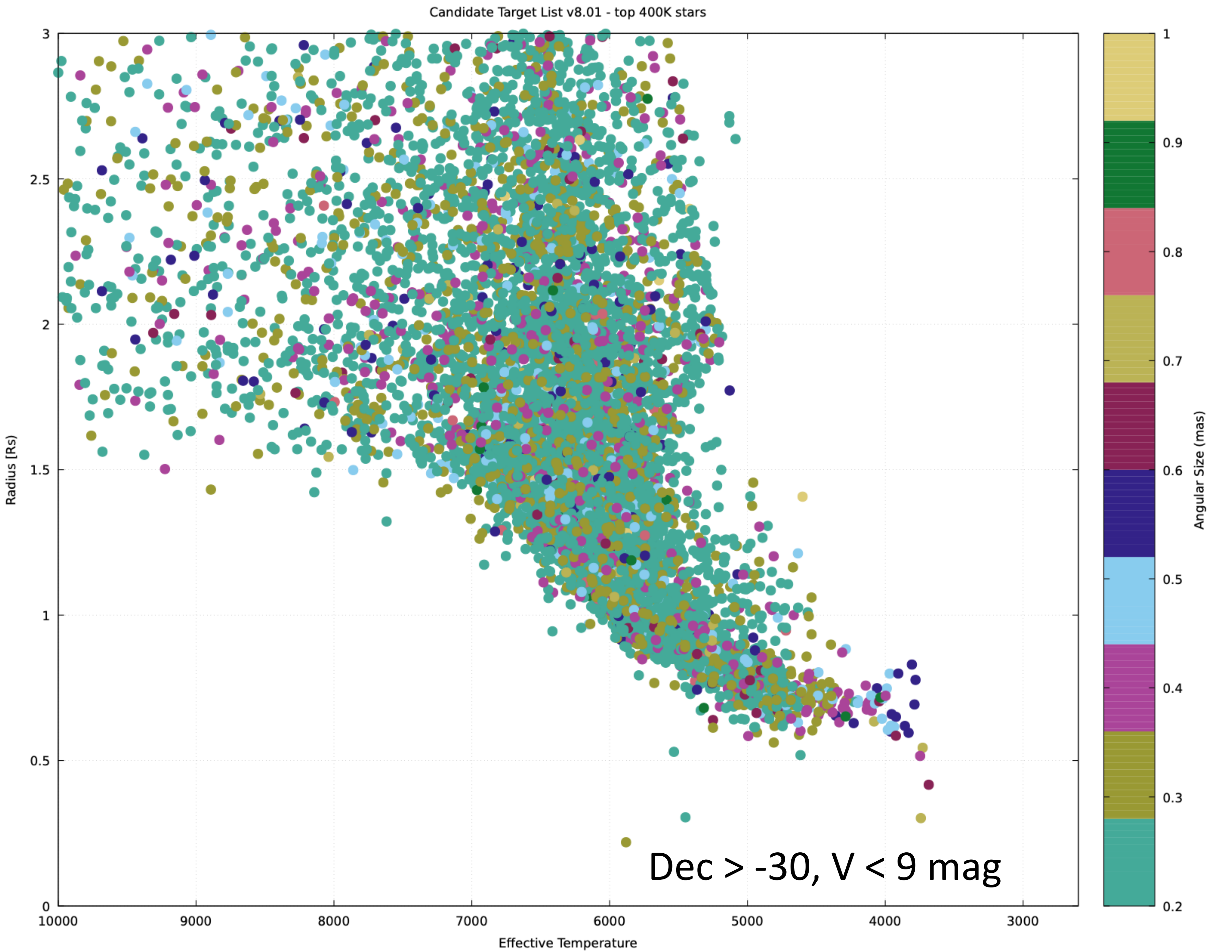


An Empirical HR Diagram
von Braun & Boyajian 2017
$T_{\rm eff}(\mathrm{K}) = 2341(F_{\rm BOL}/\theta_{\rm LD}^2)^{\frac{1}{4}}.$
log L ($L_\odot$)
log T_{eff} (K)
4
2
0
−2
4.4
4.2
4.0
3.8
3.6
3.4

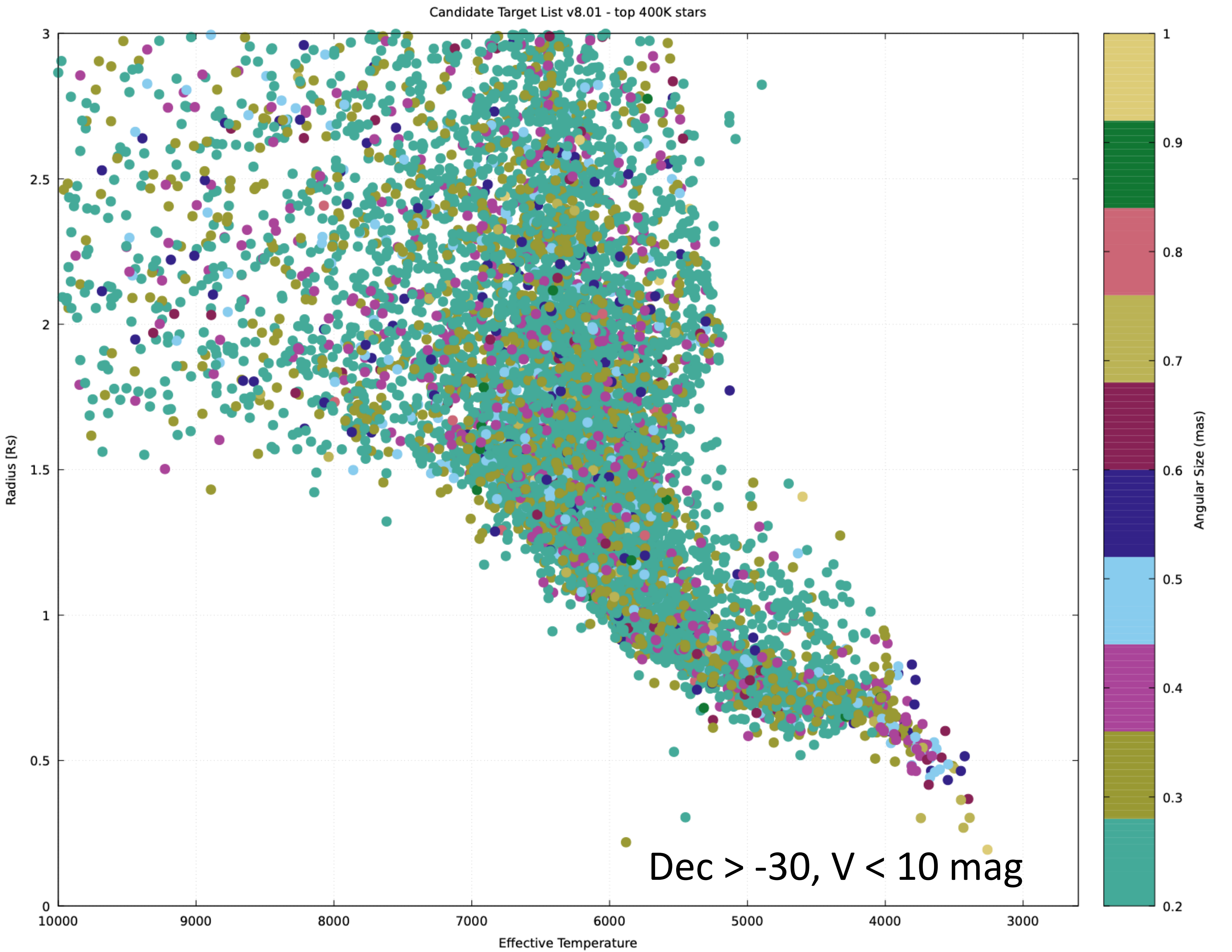

An Empirical HR Diagram
von Braun & Boyajian 2017
Intermediate Mass Stars
(rapid rotation, gravity
darkening, cluster turnoff)
Giant Stars
(convection,
asteroseismology)
Young Stars
(star + planet
formation,
evolution)
Sun-like Stars
(planets, solar-stellar)
Low Mass Stars
(convection, activity)
$T_{\rm eff}({\rm K}) = 2341(F_{\rm BOL}/\theta^2_{\rm LD})^{\frac{1}{4}}.$
log L ($L_\odot$)
log T_{eff} (K)
4.4
4.2
4.0
3.8
3.6
3.4
4
2
0
−2


Candidate Target List v8.01 - top 400K stars
TESS All Sky Survey
(Candidate Target List v. 8.0)
... will provide continuous photometry
for transits, activity, rotation periods,
asteroseismology, etc.
Declination [deg]
Right Ascension [hr]
TESSmag
80
60
40
20
0
-20
-40
-60
-80
0
5
10
15
20
25
20
15
10
5
0
-5

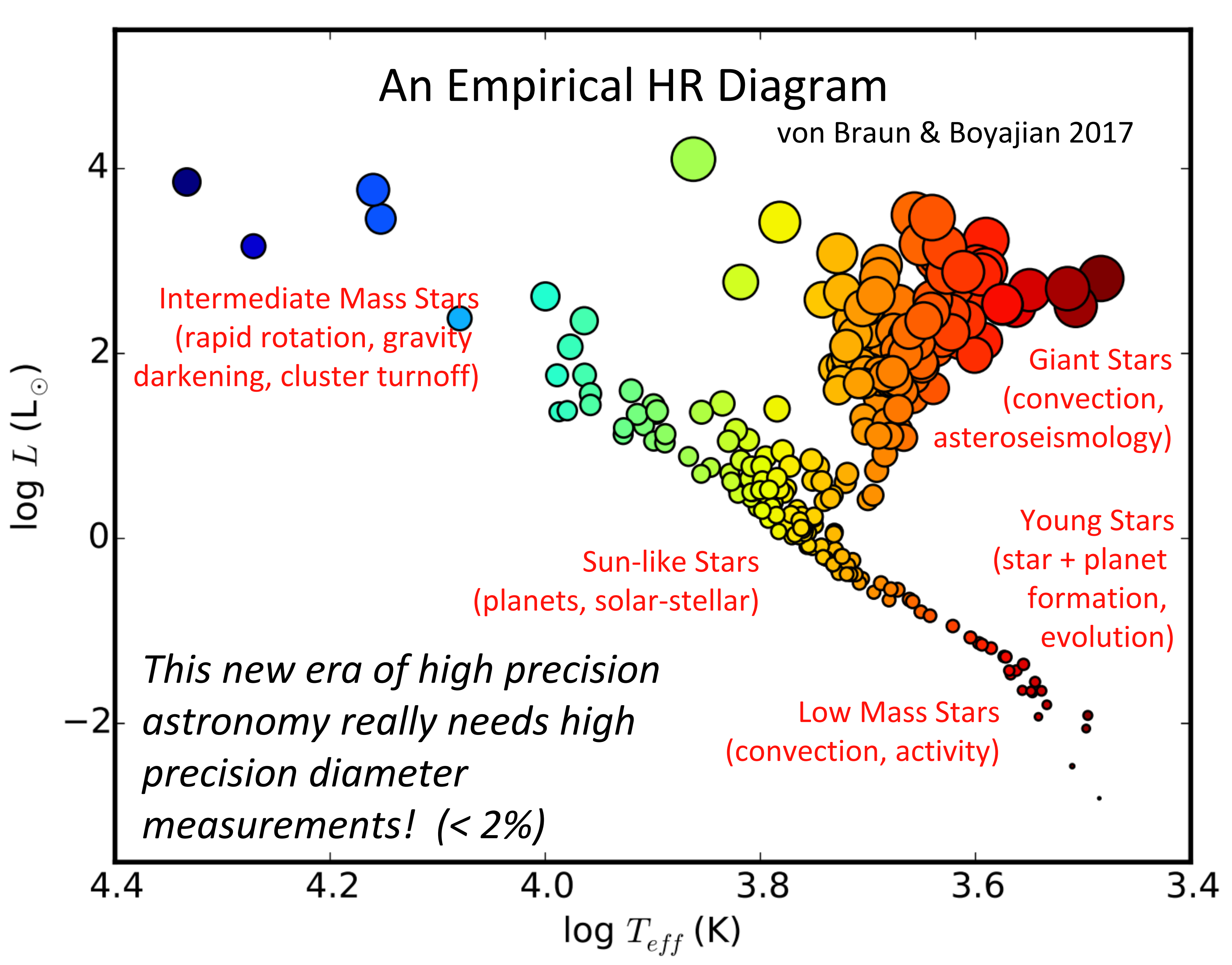

Candidate Target List v8.01 - top 400K stars
Gaia DR2 data
... will provide precise luminosities,
kinematics, cluster association, etc.
Radius [Rs]
Effective Temperature
Distance (pc)
0
1
2
3
4
5
10000
9000
8000
7000
6000
5000
4000
3000
0
20
40
60
80
100



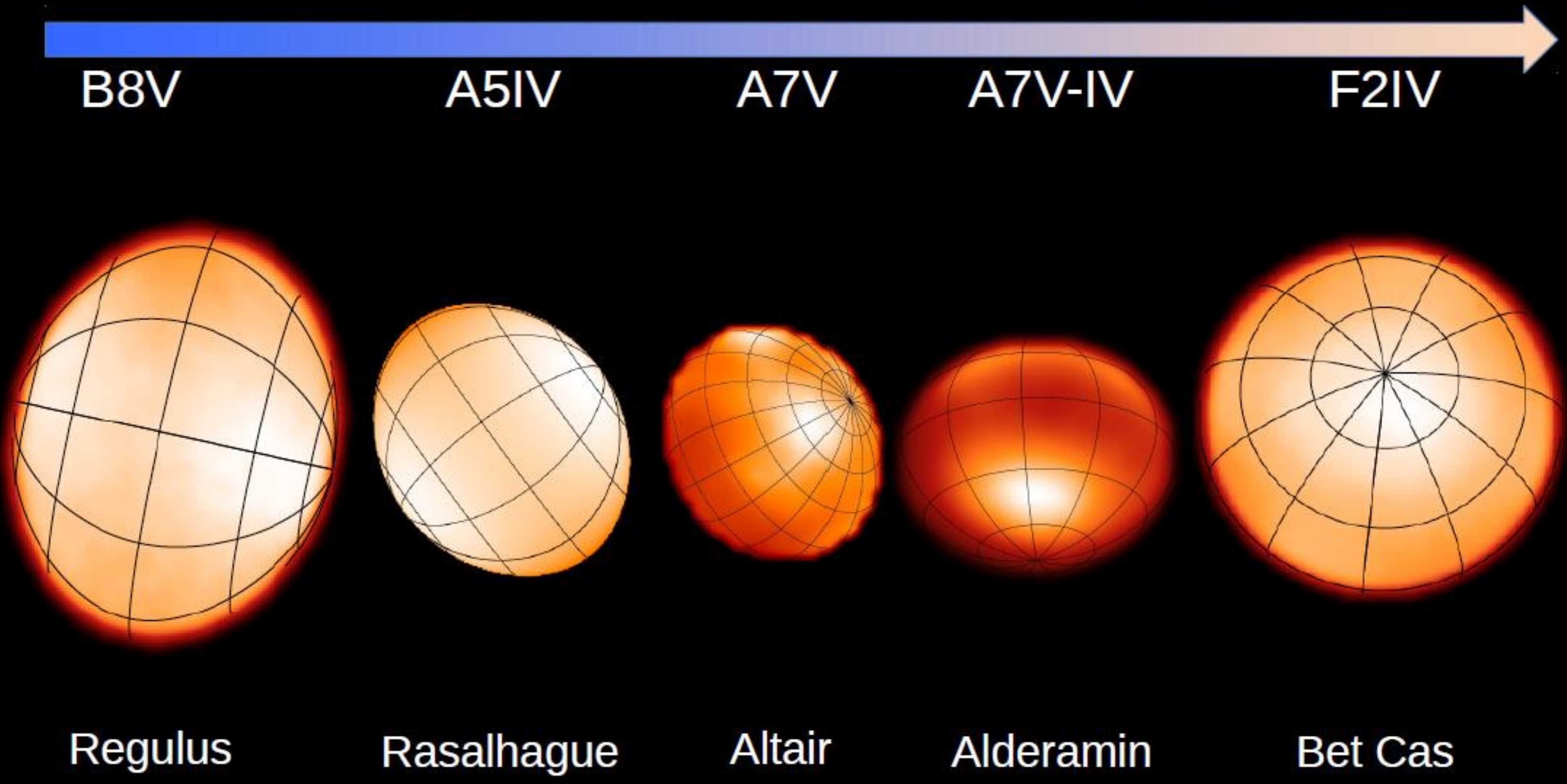
Candidate Target List v8.01 - top 400K stars
Radius [Rs]
Effective Temperature
Angular Size (mas)
10000
9000
8000
7000
6000
5000
4000
3000
0
0.5
1
1.5
2
2.5
3
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Dec > -30, V < 9 mag



Candidate Target List v8.01 - top 400K stars
Radius [Rs]
Effective Temperature
Angular Size (mas)
0
0.5
1
1.5
2
2.5
3
10000
9000
8000
7000
6000
5000
4000
3000
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Dec > -30, V < 10 mag


An Empirical HR Diagram
von Braun & Boyajian 2017
Intermediate Mass Stars
(rapid rotation, gravity
darkening, cluster turnoff)
Giant Stars
(convection,
asteroseismology)
Young Stars
(star + planet
formation,
evolution)
Sun-like Stars
(planets, solar-stellar)
Low Mass Stars
(convection, activity)
This new era of high precision
astronomy really needs high
precision diameter
measurements! (< 2%)
log L ($L_\odot$)
log T_{eff} (K)
4
2
0
−2
4.4
4.2
4.0
3.8
3.6
3.4

Rapidly Rotating Stars



Jeremy Jones, CHARA Data Scientist

Why Rapid Rotators?

And What Counts as a Rapid Rotator?

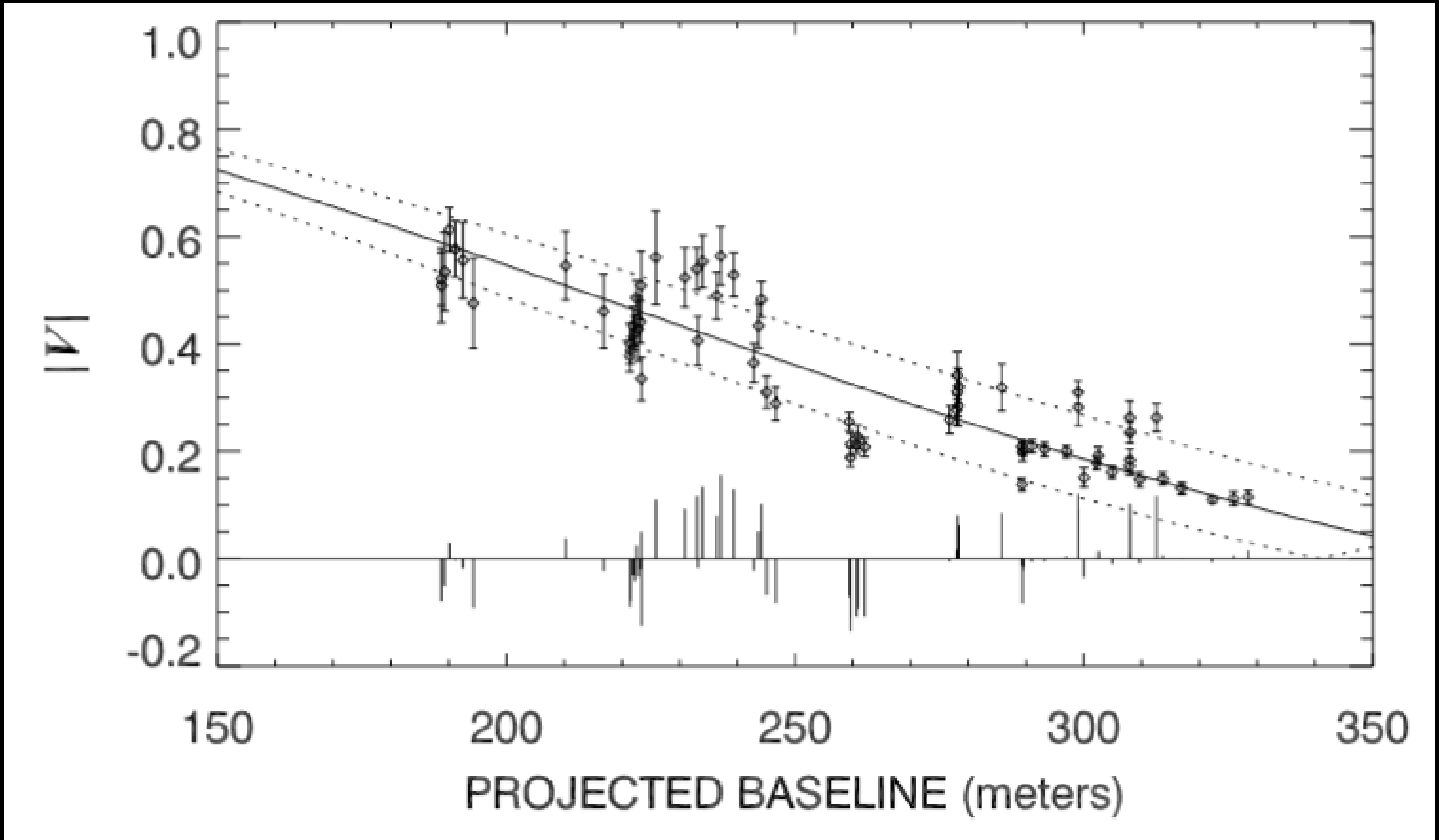
Alderamin
(Zhao et al. 2009)

- Stars with vsini > 100 km/s
- Typically early-type stars
- Rotation causes oblateness
- Oblateness causes temp. differential
- Interferometry can distinguish v from i in vsini
- Interesting physics:
  - Diffusion vs. rotational mixing (no convection)
  - Evolves differently from slowly rotating stars
  - Inclination affects apparent lum/temp
  - Defining temp. differential (gravity darkening)

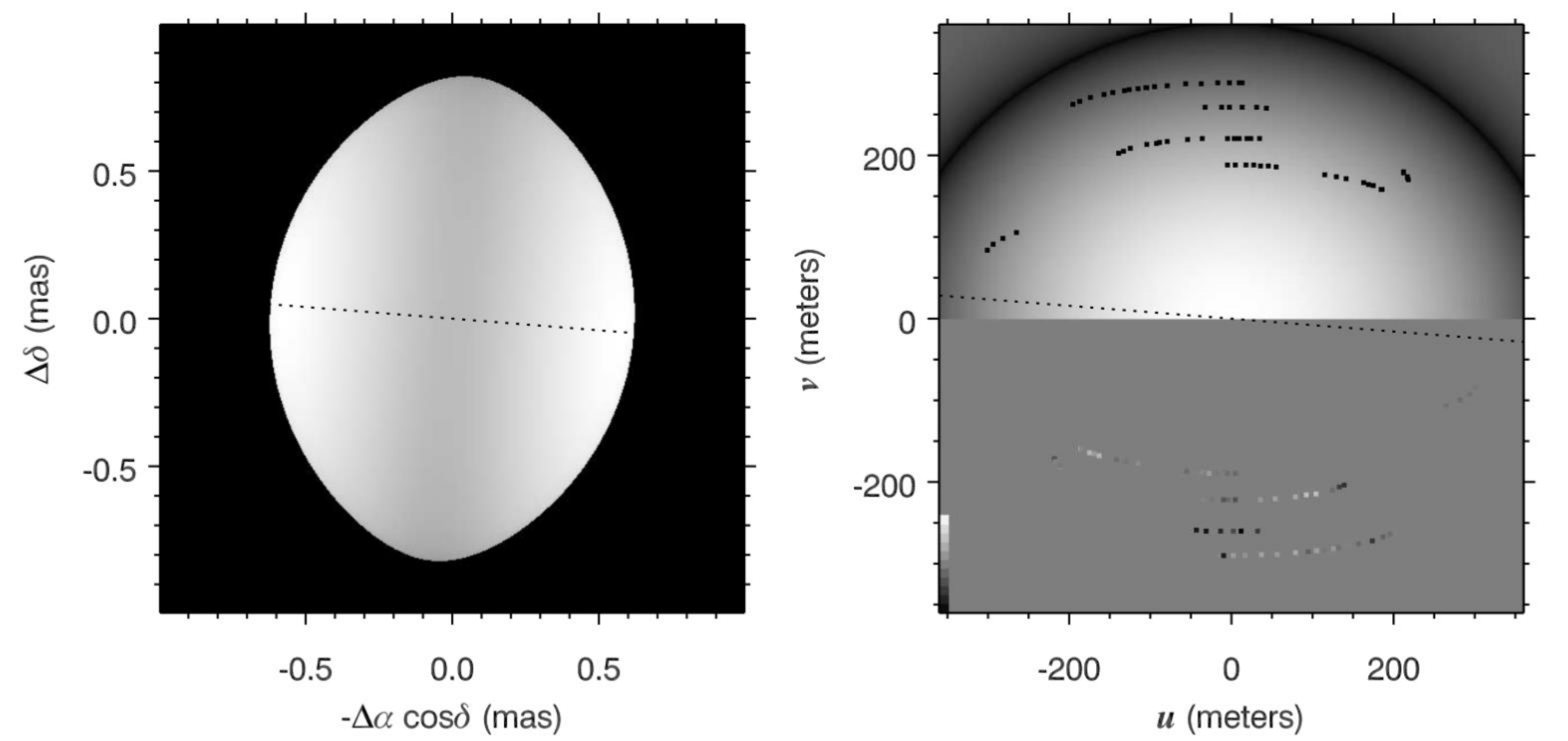
The Early Work

Paper 1 – McAlister et al. 2005

Regulus

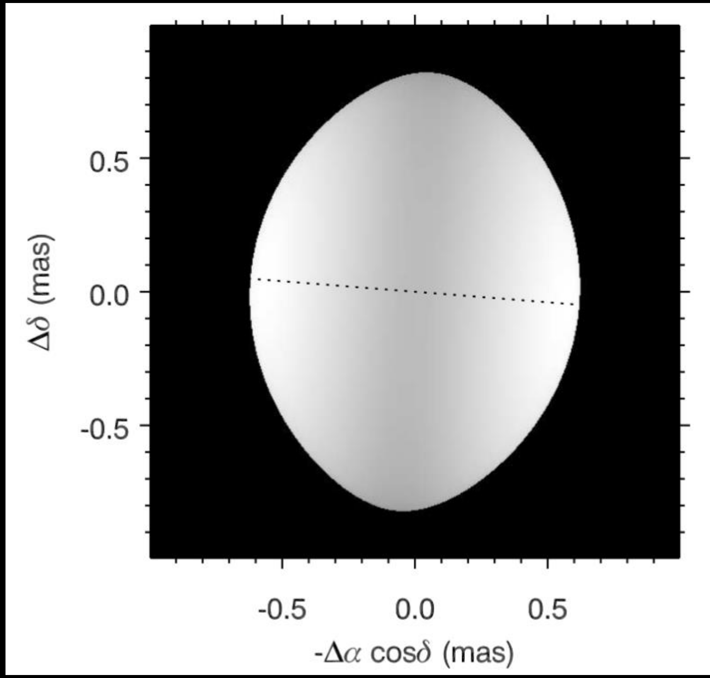


The Early Work
Paper 1 – McAlister et al. 2005
Regulus



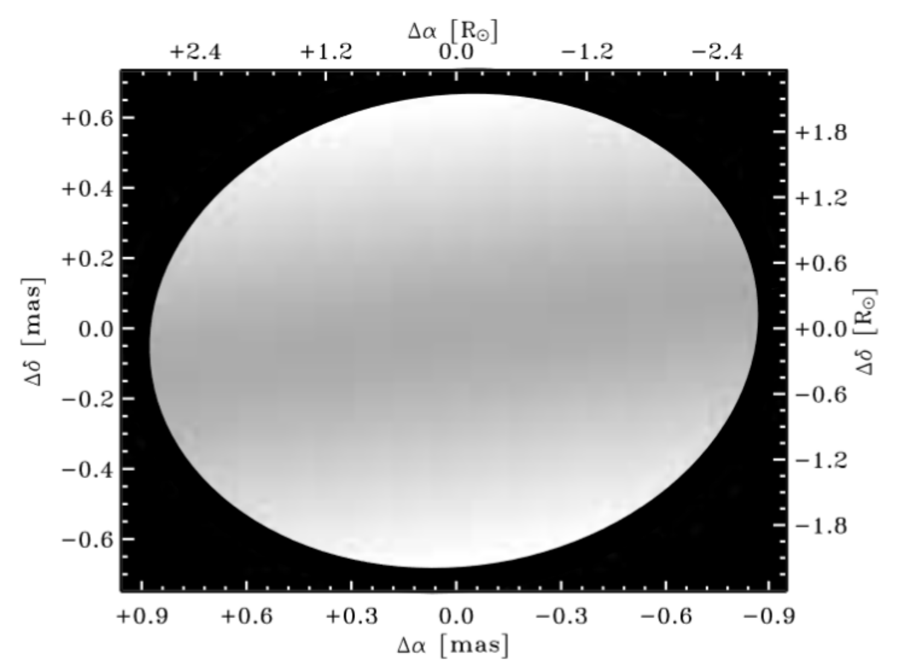
The Early Work

Paper I



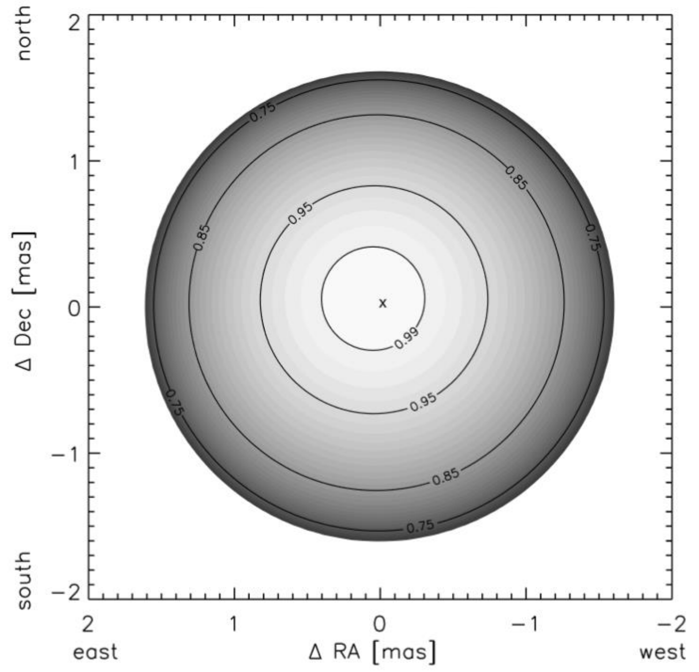
Regulus
(McAlister et al. 2005)

Paper III



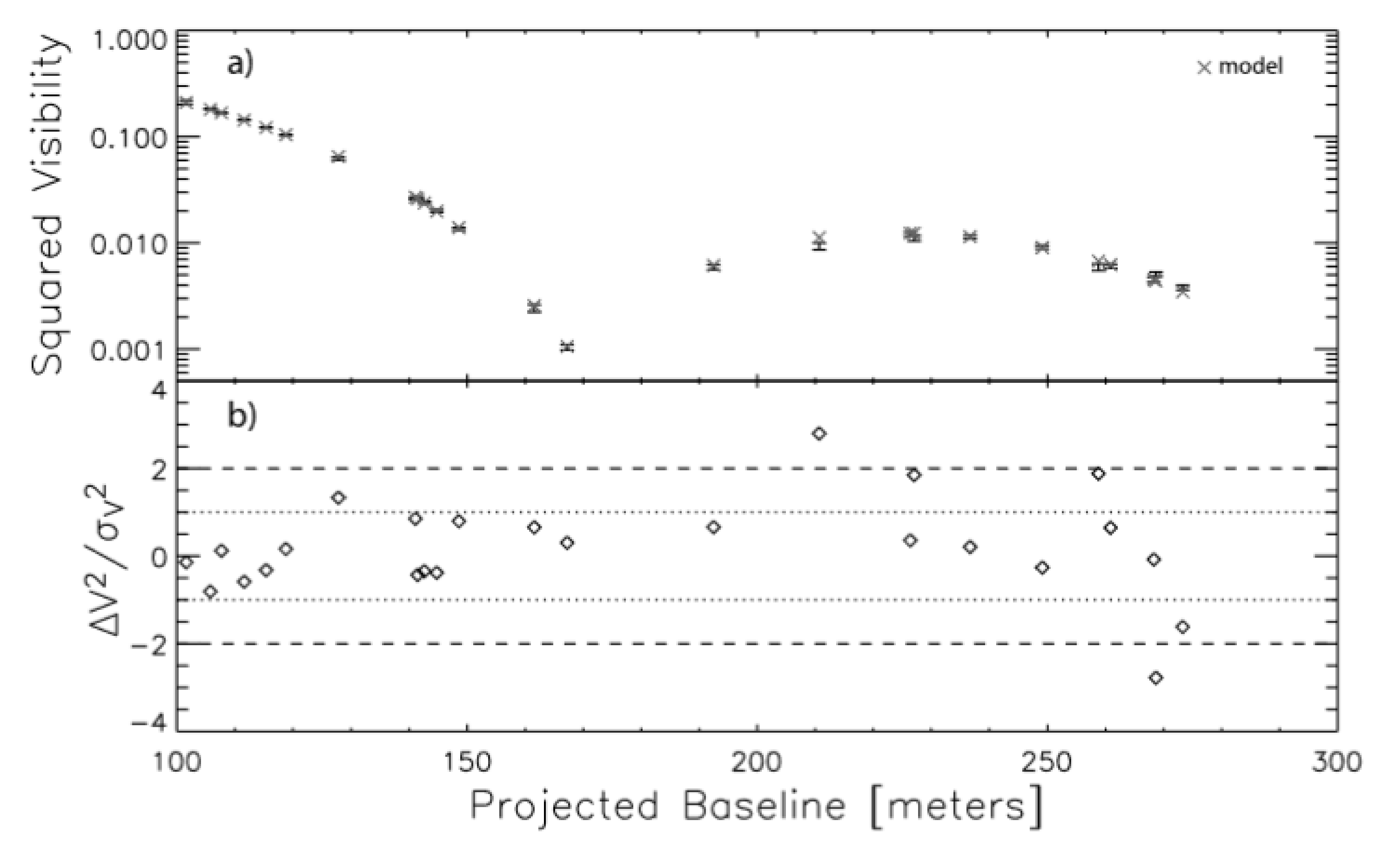
Alderamin
(van Belle et al. 2006)

Paper VII
(using Fluor)



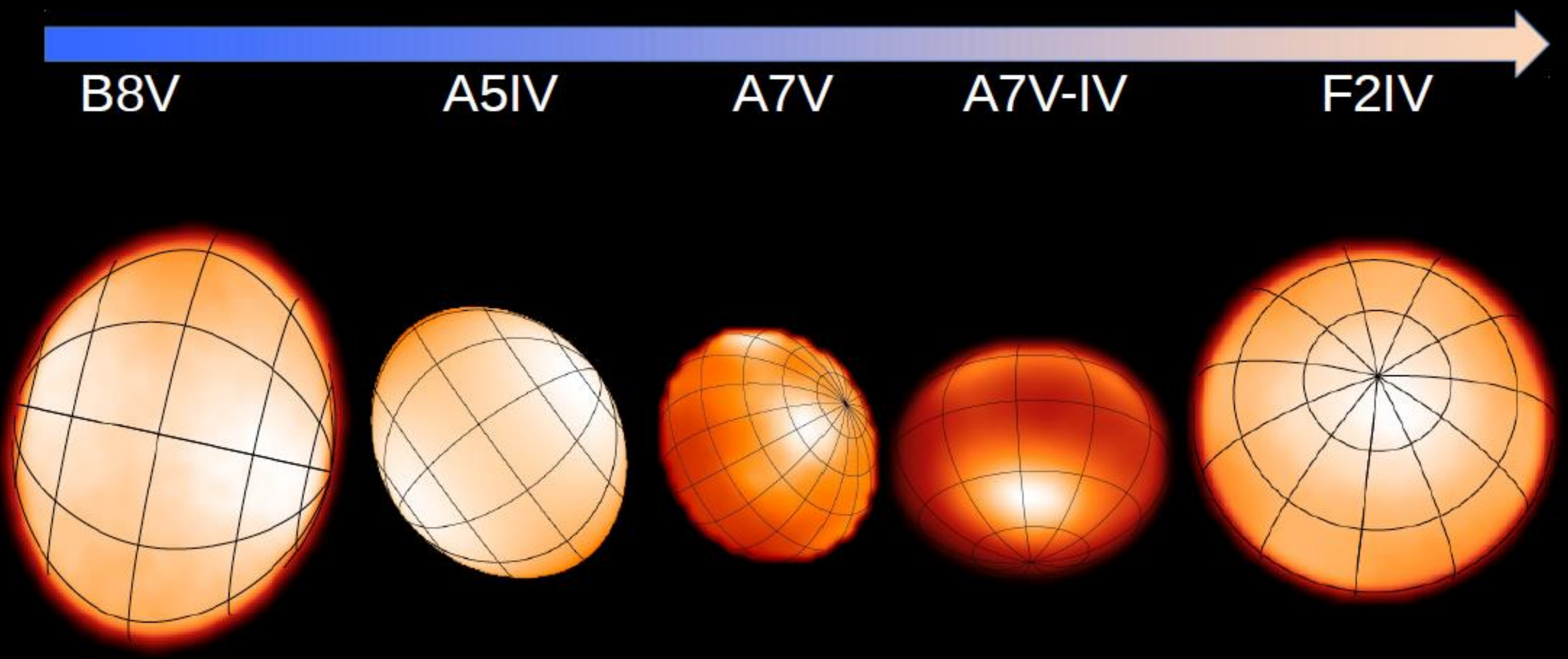
Vega
(Aufdenberg et al. 2006)

The Early Work
Vega



(Aufdenberg et al. 2006)

MIRC Work – 4T days



Regulus (Che et al. 2011)

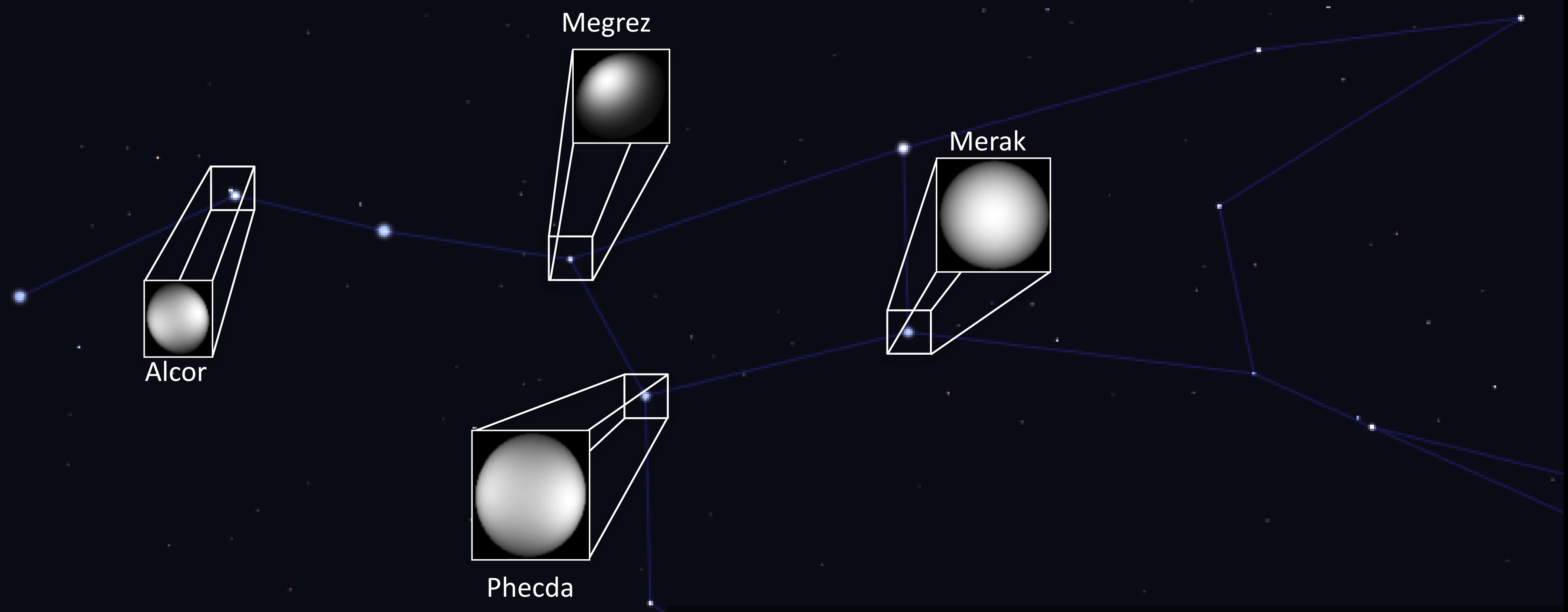
Rasalhague (Zhao et al. 2009)

Altair (Monnier et al. 2007)

Alderamin (Zhao et al. 2009)

Bet Cas (Che et al. 2011)

My Work – Ursa Major Moving Group

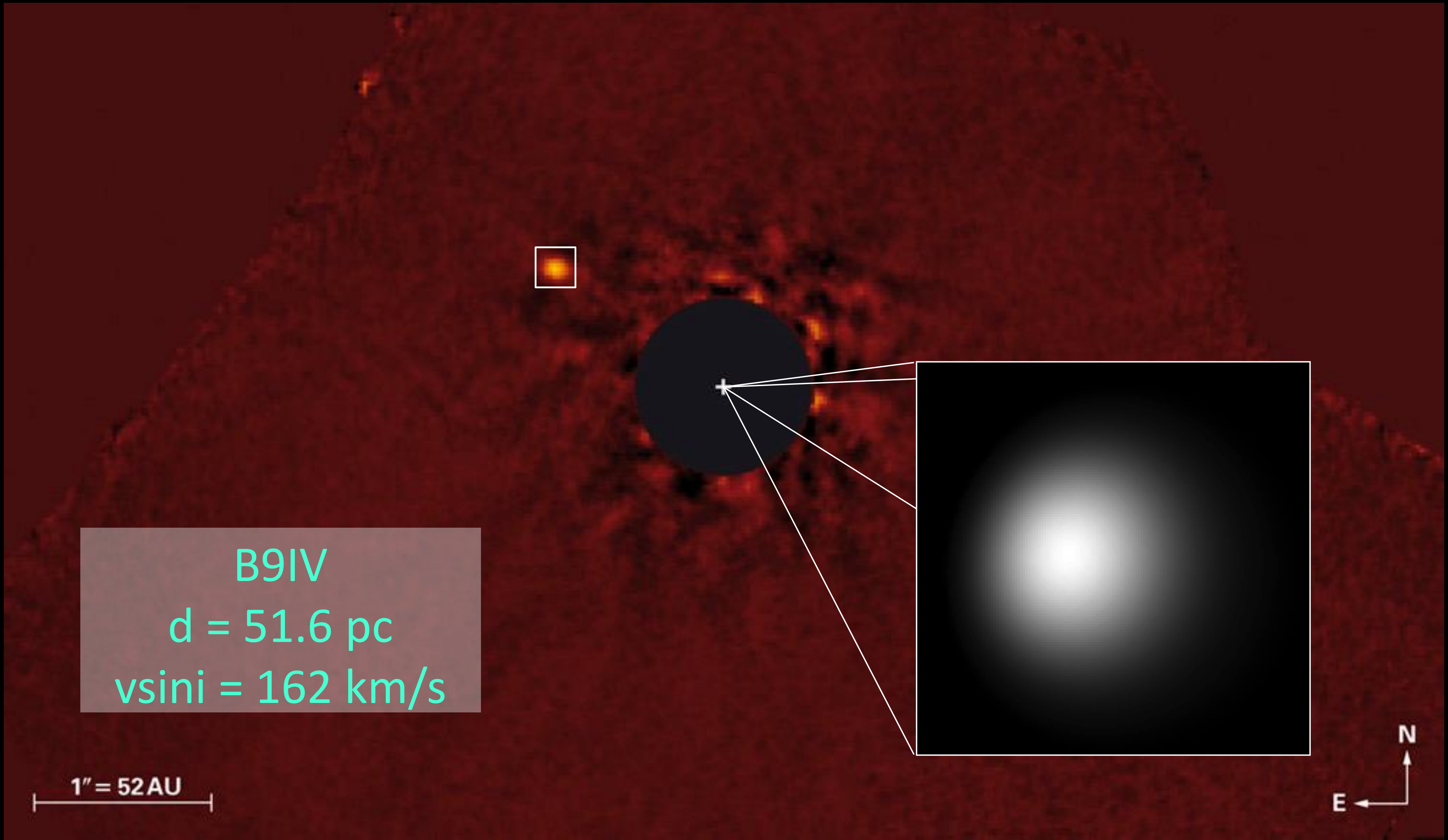


UMa Work

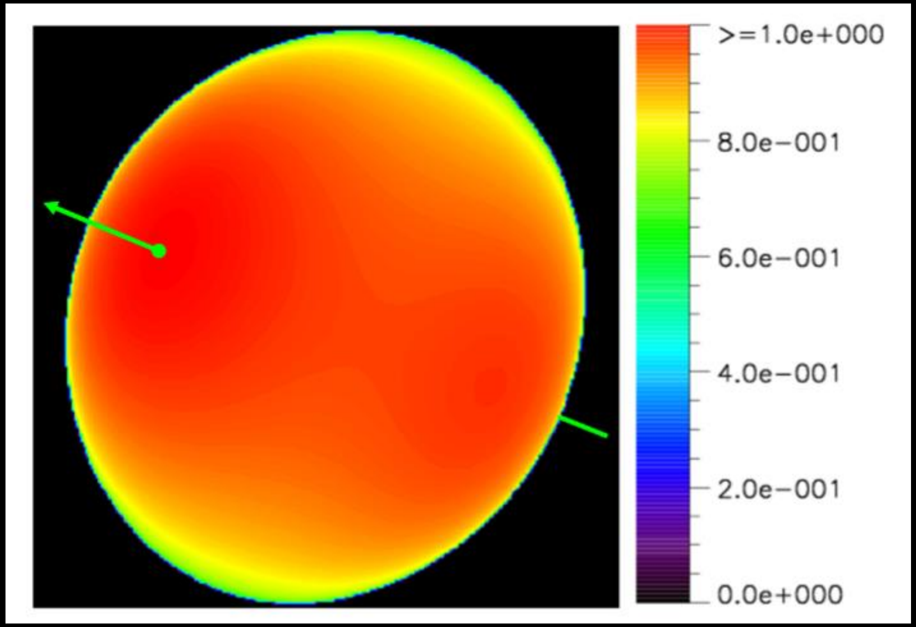
- Simultaneous Photometry/Visibility Model Fitting
  - All visibilities on the 1st lobe

Jones et al. (2015)

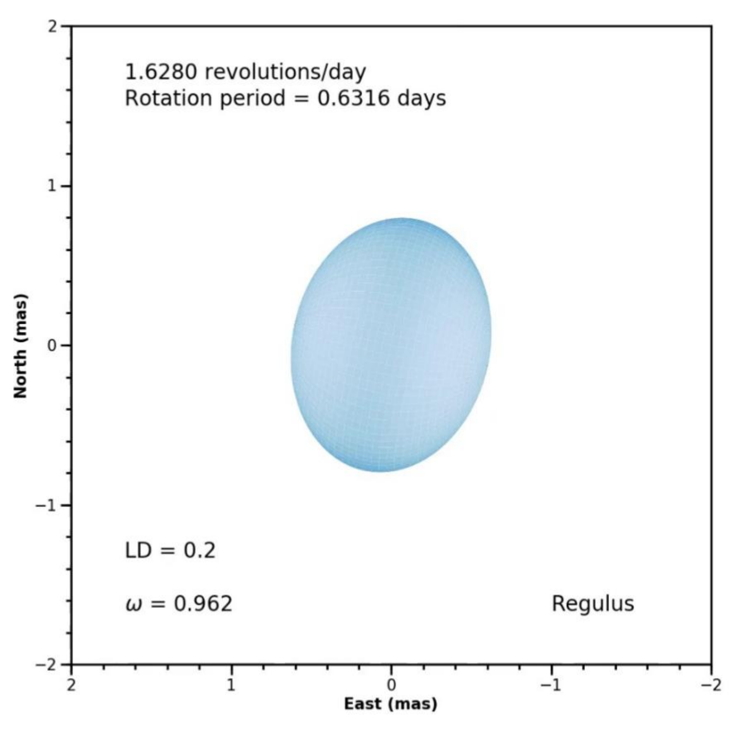
My Work – kappa Andromedae

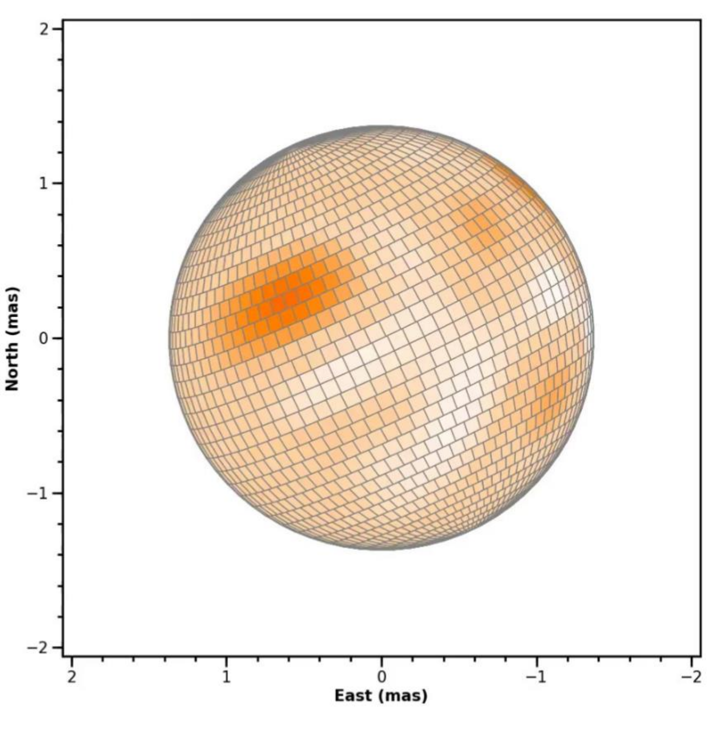


Recent and Upcoming Work



delta Persei
(Challouf et al. 2017)





The ROTIR Code
(Baron et al.)

Why Rapid Rotators?

Alderamin
(Zhao et al. 2009)

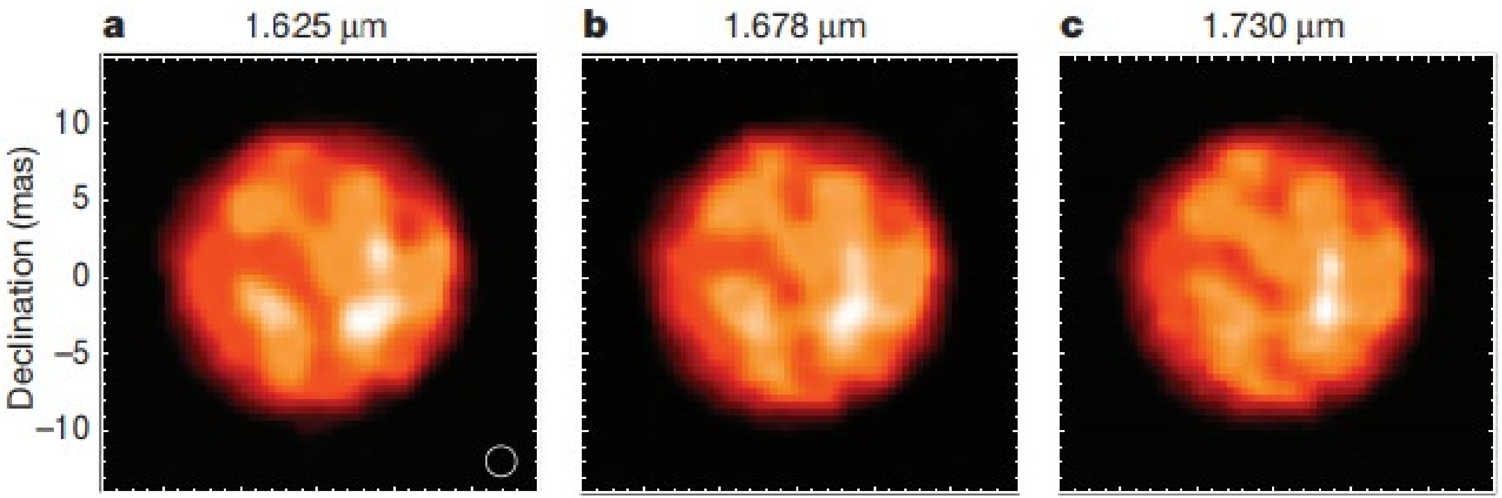
- Rotation causes oblateness
- Oblateness causes temp. differential
- Interferometry can distinguish v from i in vsini
- Interesting physics:
  - Diffusion vs. rotational mixing (no convection)
  - Evolves differently from slowly rotating stars
  - Inclination affects apparent lum/temp

Beyond Snapshot Imaging

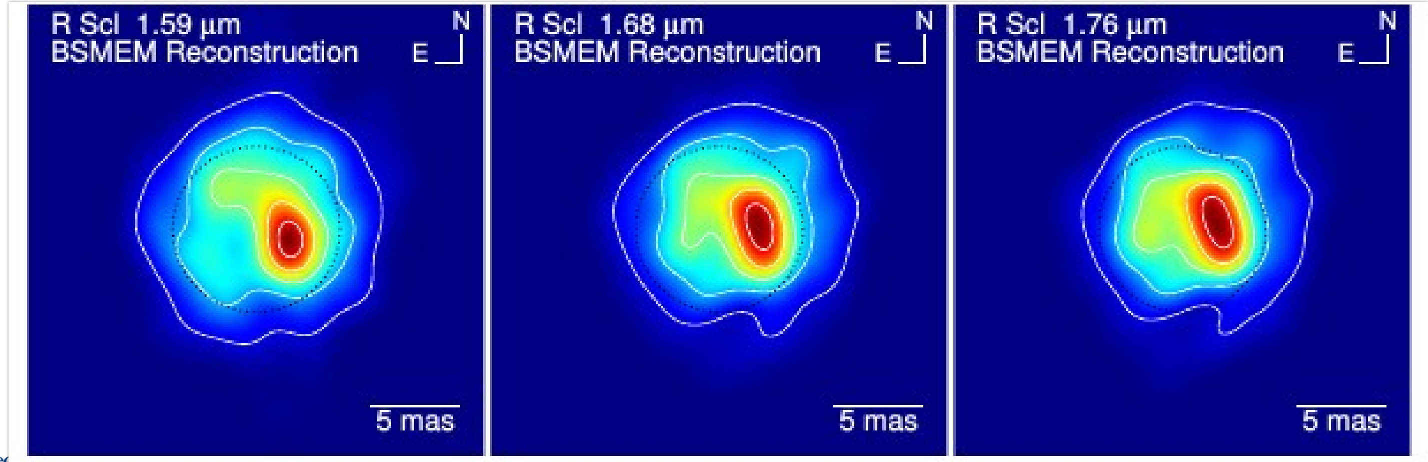
Advanced image reconstruction

- Polychromatic & Dynamical imaging
- Model-fitting + imaging
- Imaging on Spheroids

Polychromatic Imaging



Paladini, C., et al, Nature 2018

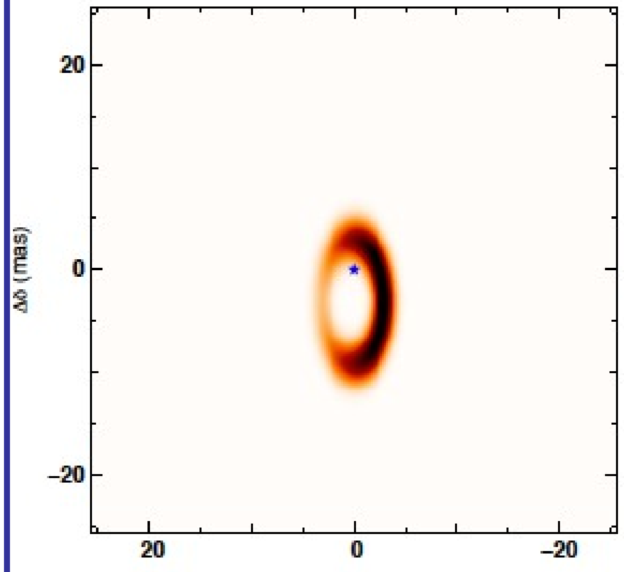


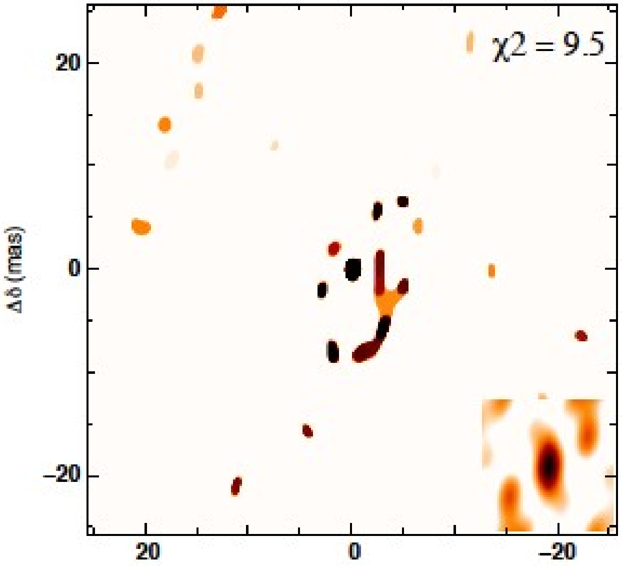
Wittkowski et al., A&A 606, L1, 2017

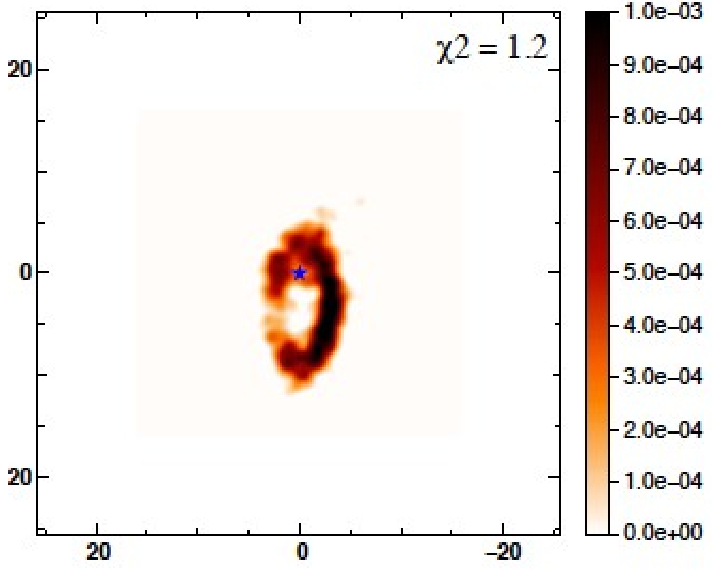
Model-fitting + Imaging

- SPARCO: the stellar central source is analytically modeled while its environment is imaged; both presumed to follow chromatic power laws

Model Image | Grey image reconstruction | SPARCO reconstruction

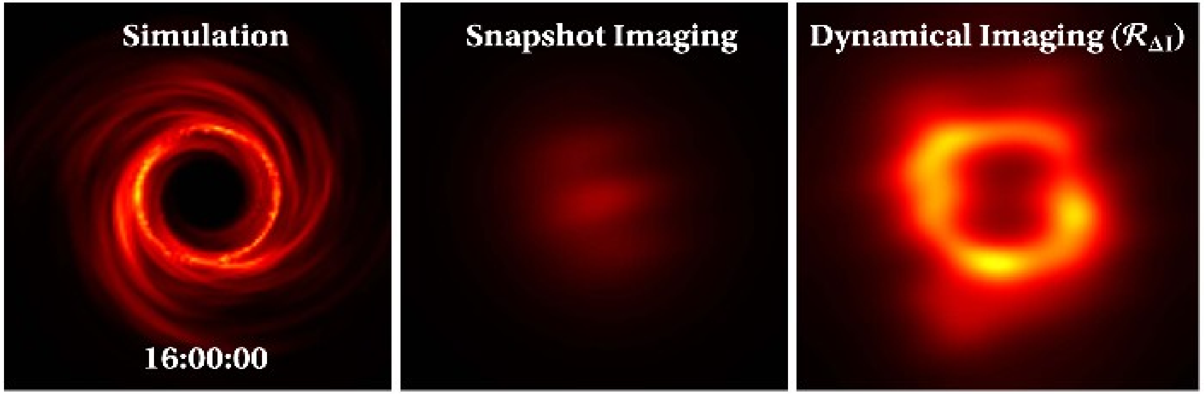




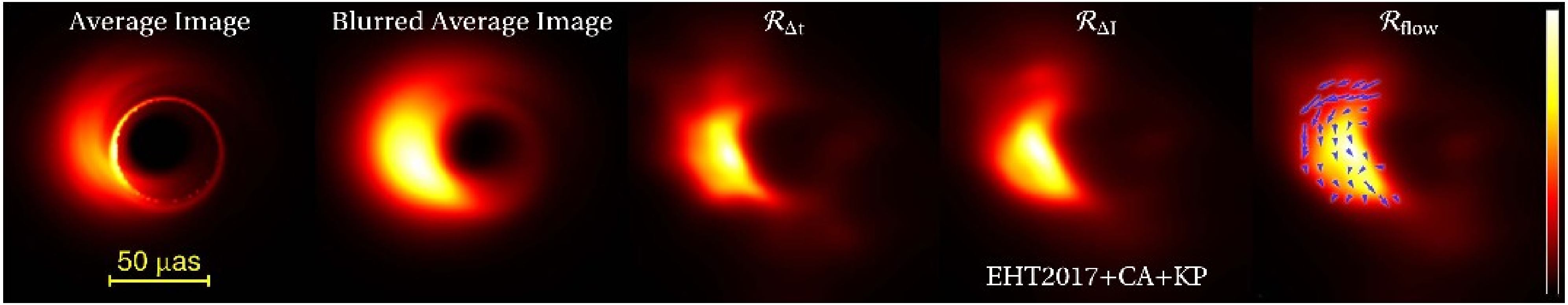


Kluska et al., 2014 - A&A 564, A80

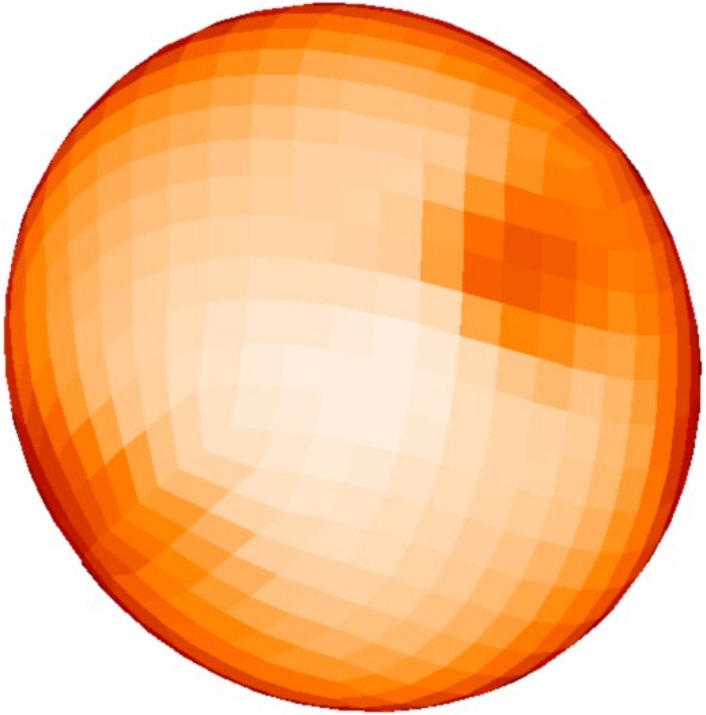
Dynamical Imaging



Johnson et al., 2017 – ApJ 850:172



Imaging on Spheroids

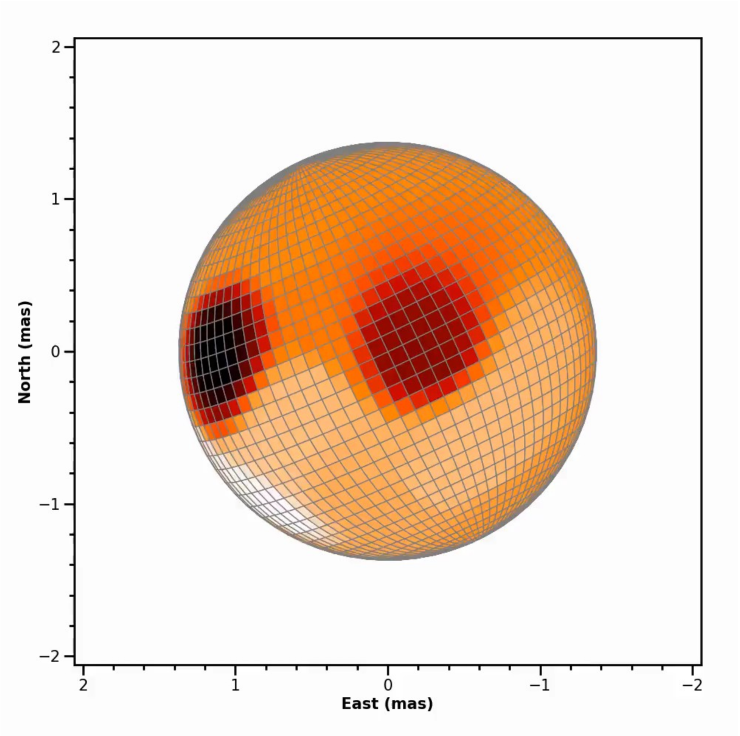


SURFING reconstruction of zet And
Roettenbacher et al., *Nature*, 2016

SURFING

Affine-invariant code developed by John Monnier

Imaging on Spheroids



ROTIR reconstruction of lam And
Martinez at al., in prep., 2020

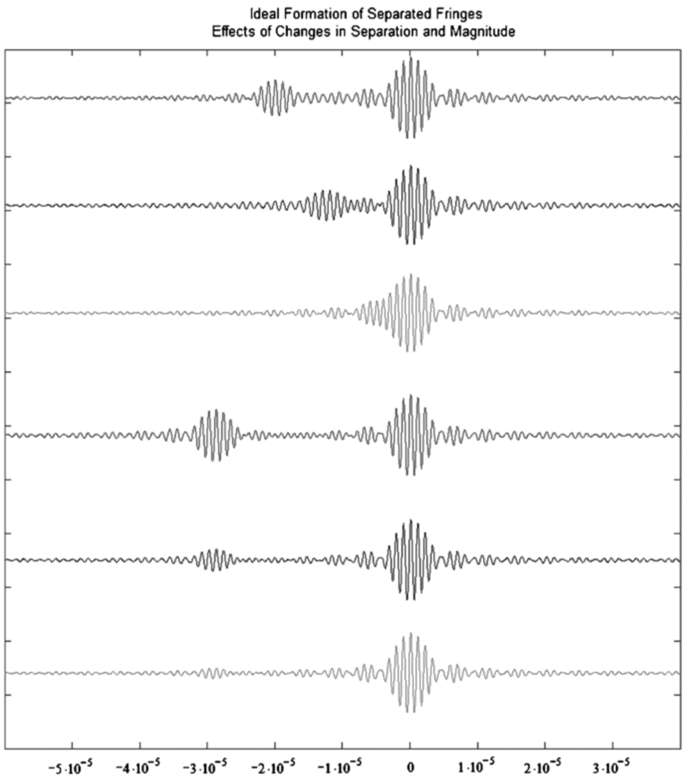
ROTIR

Gradient-based code developed by Baron & Martinez

Imaging on Roche lobes, rapid rotators, binaries

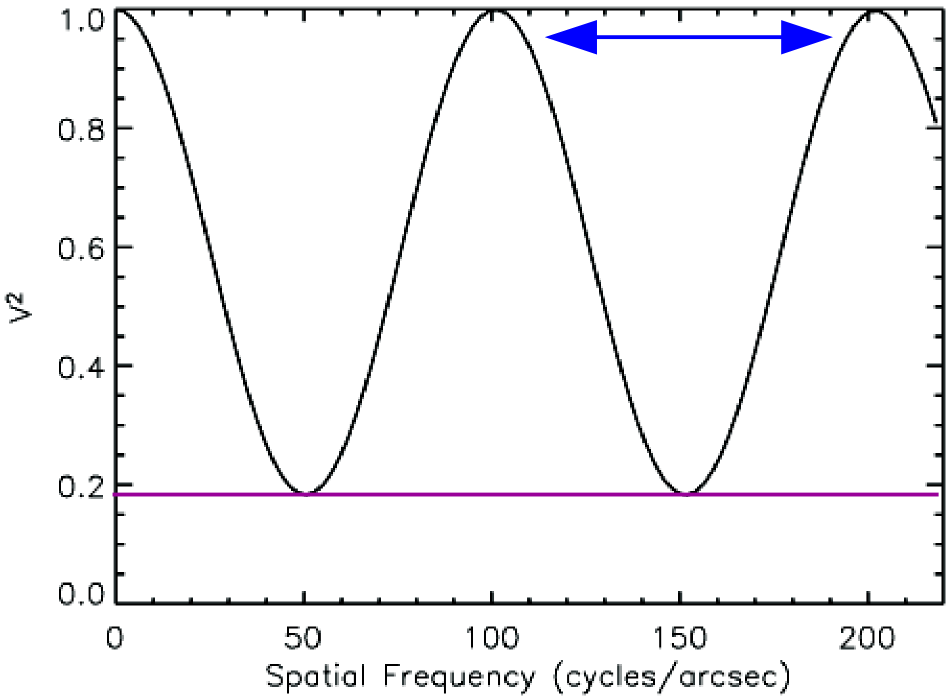
Binary Stars

Separated Fringe Packet Binaries



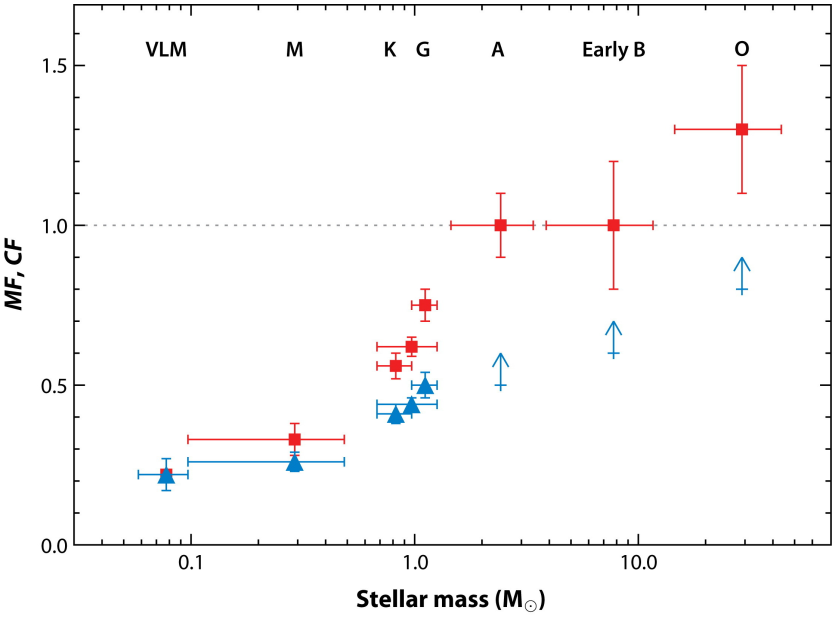
Farrington et al. (2010)

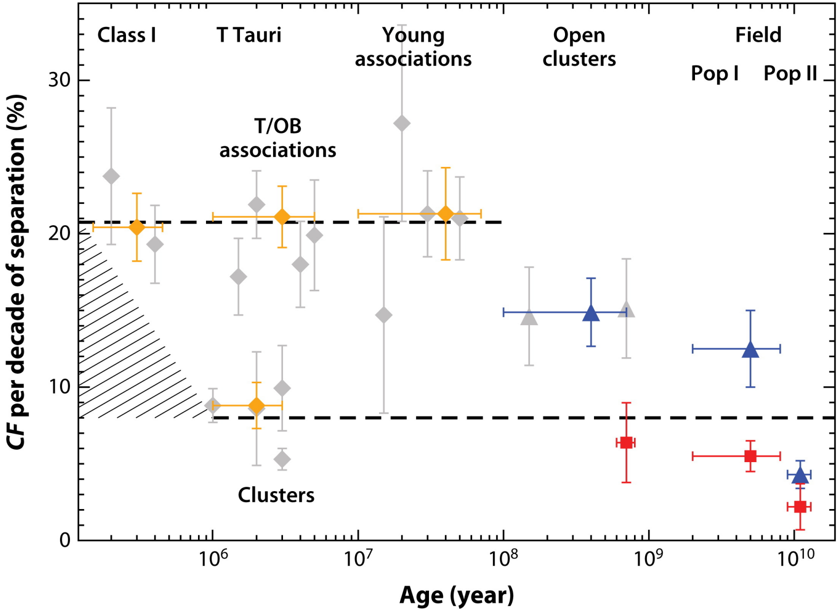
Visibility Modulation Binaries



- Fringe packets for the two components overlap
- Visibility amplitude and closure phase vary periodically
- Separation between peaks
  - binary separation
- Minimum in visibility curve
  - flux ratio

Binary Frequency

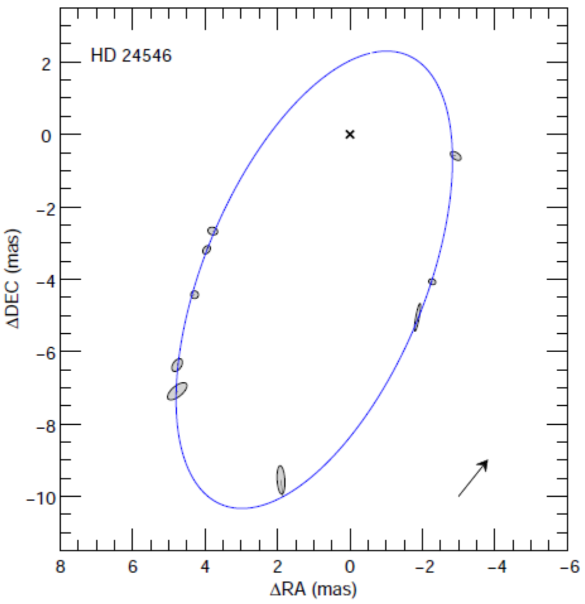


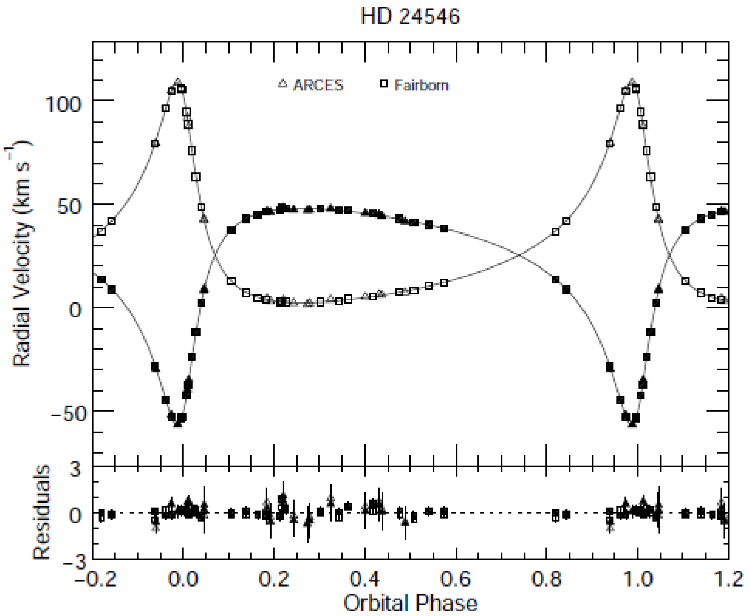


Duchene & Kraus (2013)

CHARA Multiplicity Surveys:
Solar-type stars (Raghavan et al. 2010); Massive O-stars (Lanthermann et al., in prep)

Dynamical Masses





Lester et al. (2020)

- Visual + spectroscopic orbits
- Dynamical Masses
- Orbital Parallax
- 1% precision
- Calibration of stellar evolutionary models
- Mass-radius and mass-luminosity relationships

O-Star Triple: Sigma Orionis Aa,Ab-B

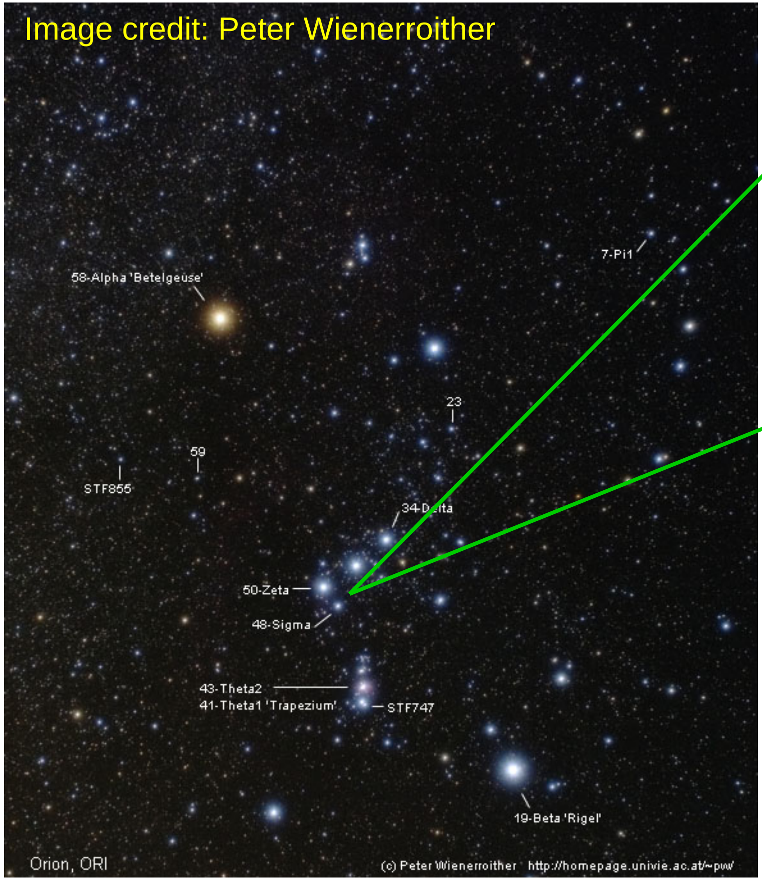
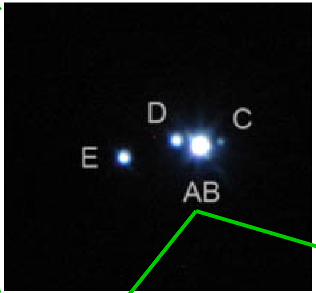
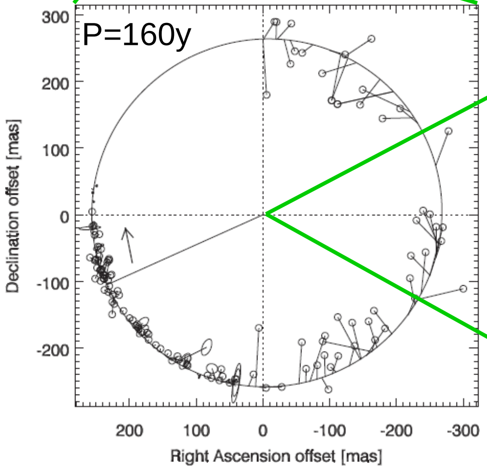


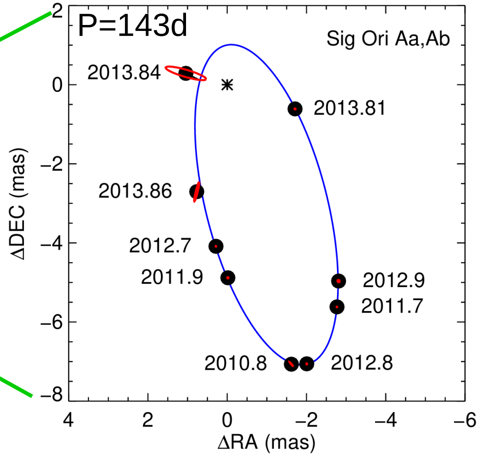
Image: http://astronomy.kez.nu



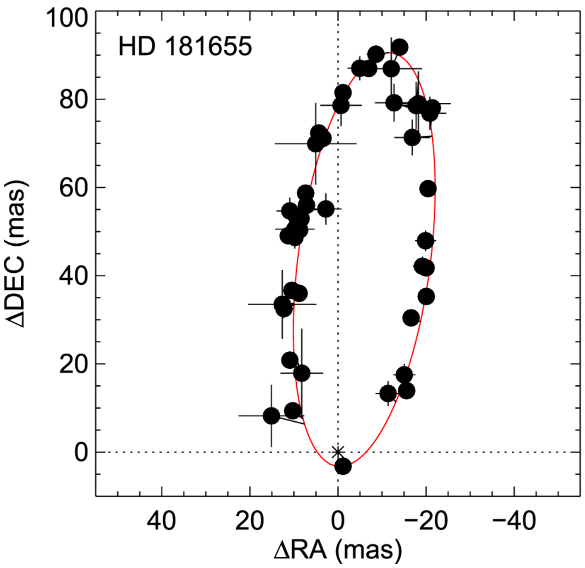


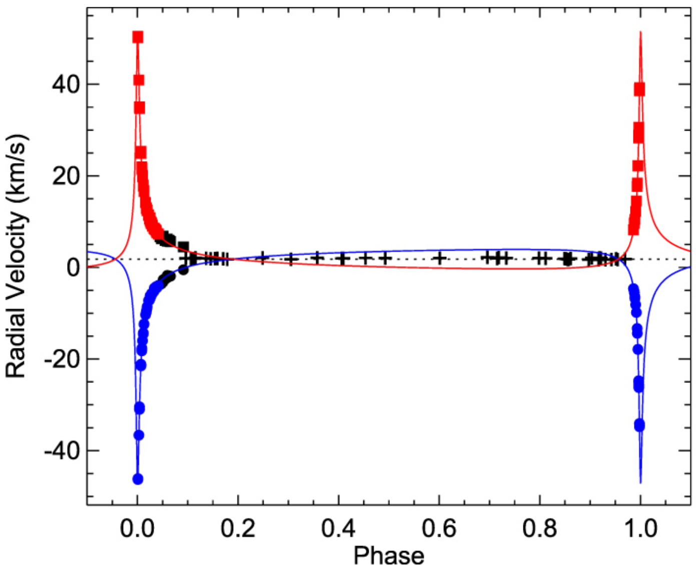
- Dynamical masses of three O-stars
- Precise distance to the sigma Orionis cluster
- Orbits are not coplanar

Schaefer et al. (2016)



Discovery of High Eccentricity Binary

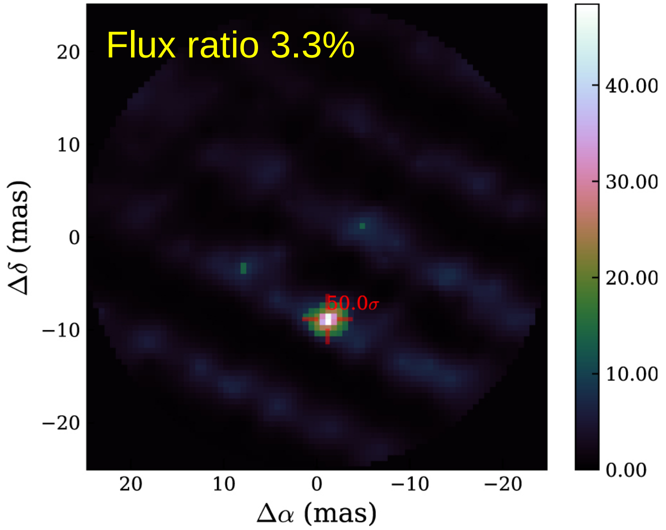


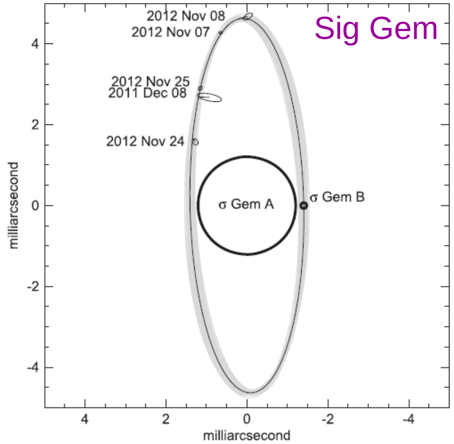


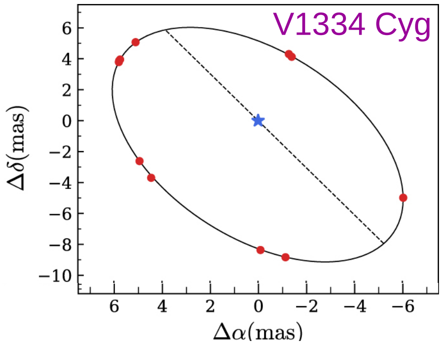
- Pair of G-dwarfs in very eccentric orbit
- P = 332 days, e=0.93
- Tertiary M-star might be responsible for driving eccentricity through the Kozai-Lidov mechanism

Farrington et al. (2018)

High Contrast Companions



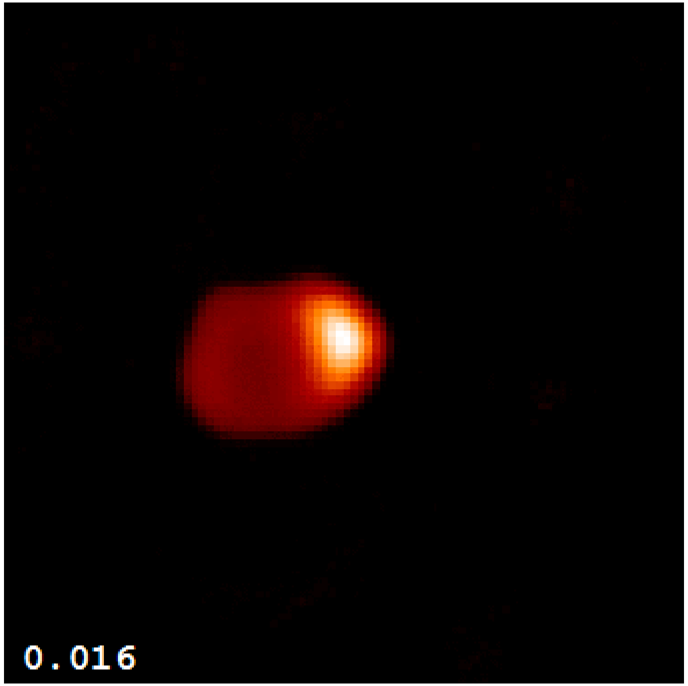




Roettenbacher et al. (2015a, 2015b)
Gallenne et al. (2015, 2018)

- High contrast: MIRC/MIRC-X
  - Separations 0.5 - 50 mas
  - ΔH < 6 mag
- RS CVn: spotted active star
  - Evolved primary and subgiant/dwarf companion
- Cepheids
  - Calibration of the Leavitt Period-Luminosity Law

Mass Transfer

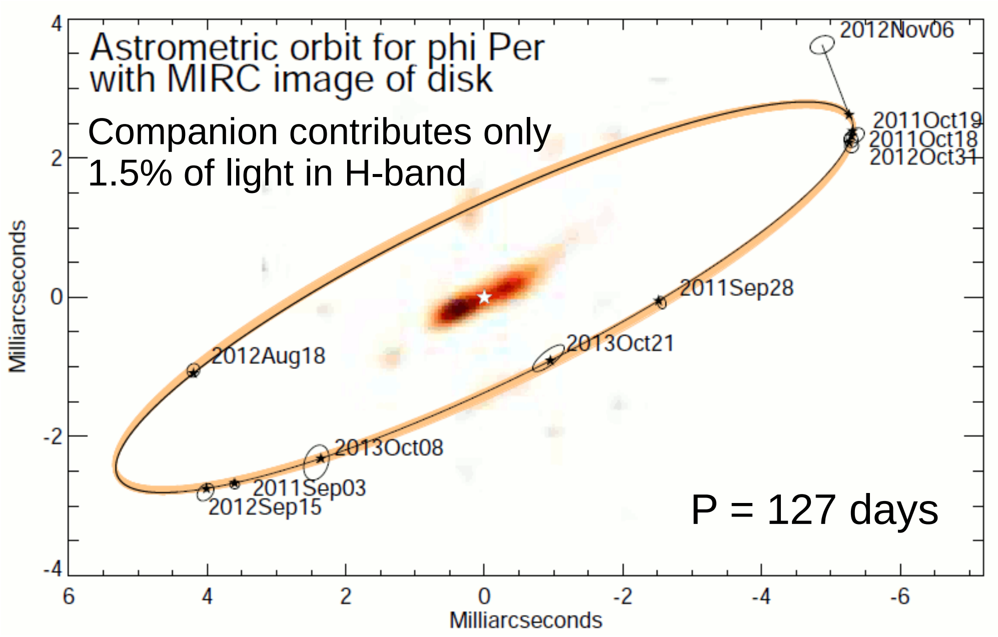


- Mass transfer in interacting binaries
- Tidal distortion of mass donor – Roche lobe filling
- Thick disk around mass gainer

Beta Lyrae: P=13d, a=0.87 mas
Zhao et al. (2008)

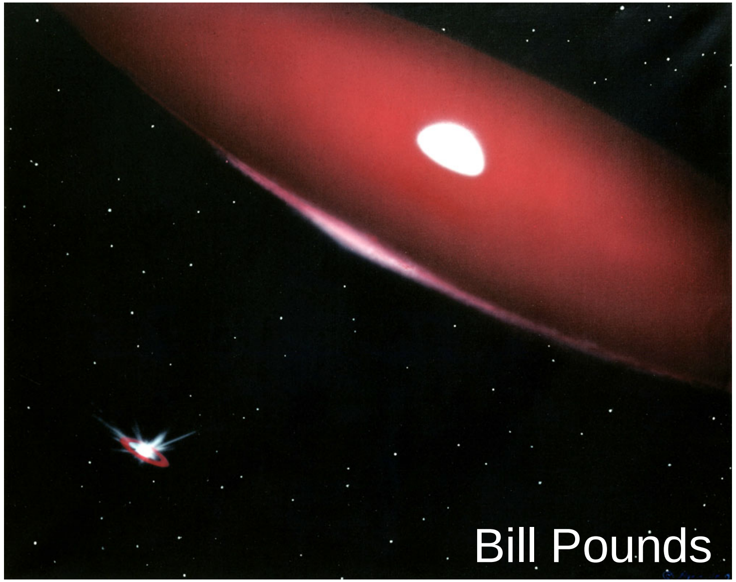
Algol: P=2.9d, a=2.2 mas
Baron et al. (2012)

Binarity in Be Stars

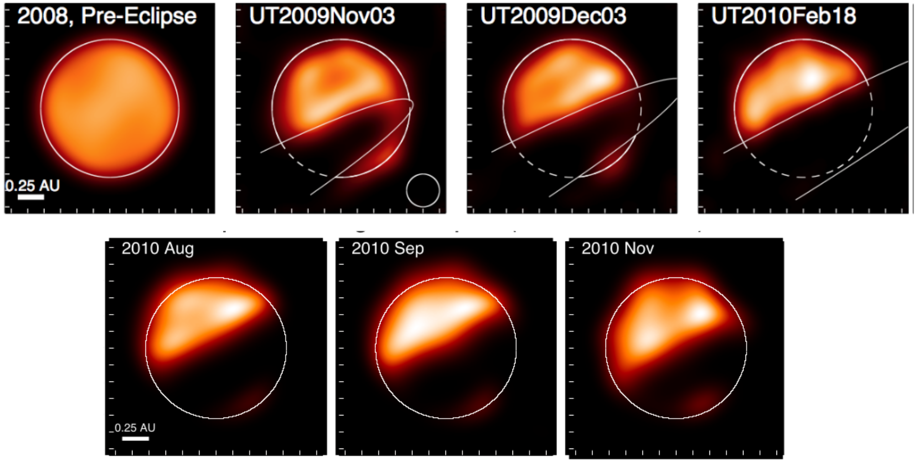


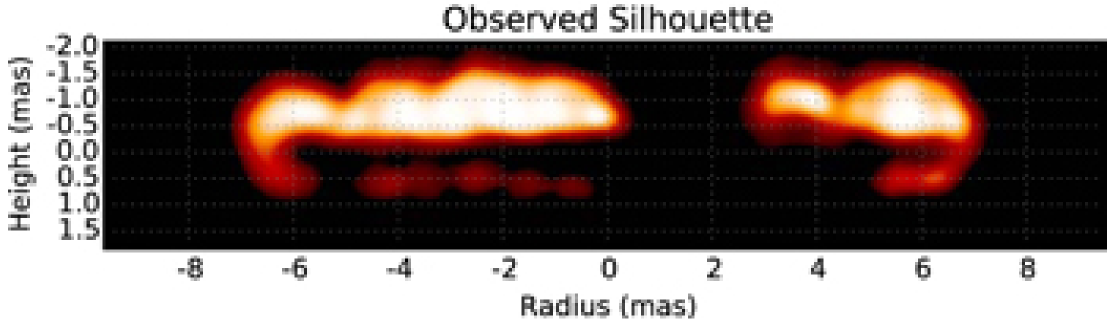
Mourard et al. (2016)

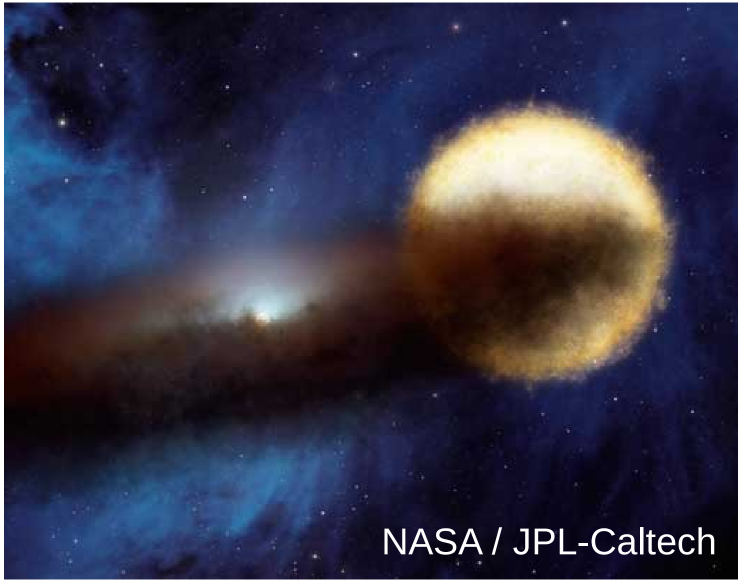
- Spun up Be star orbiting stripped down remnant companion (neutron star, white dwarf, helium star)



Transiting Disk: Epsilon Aurigae

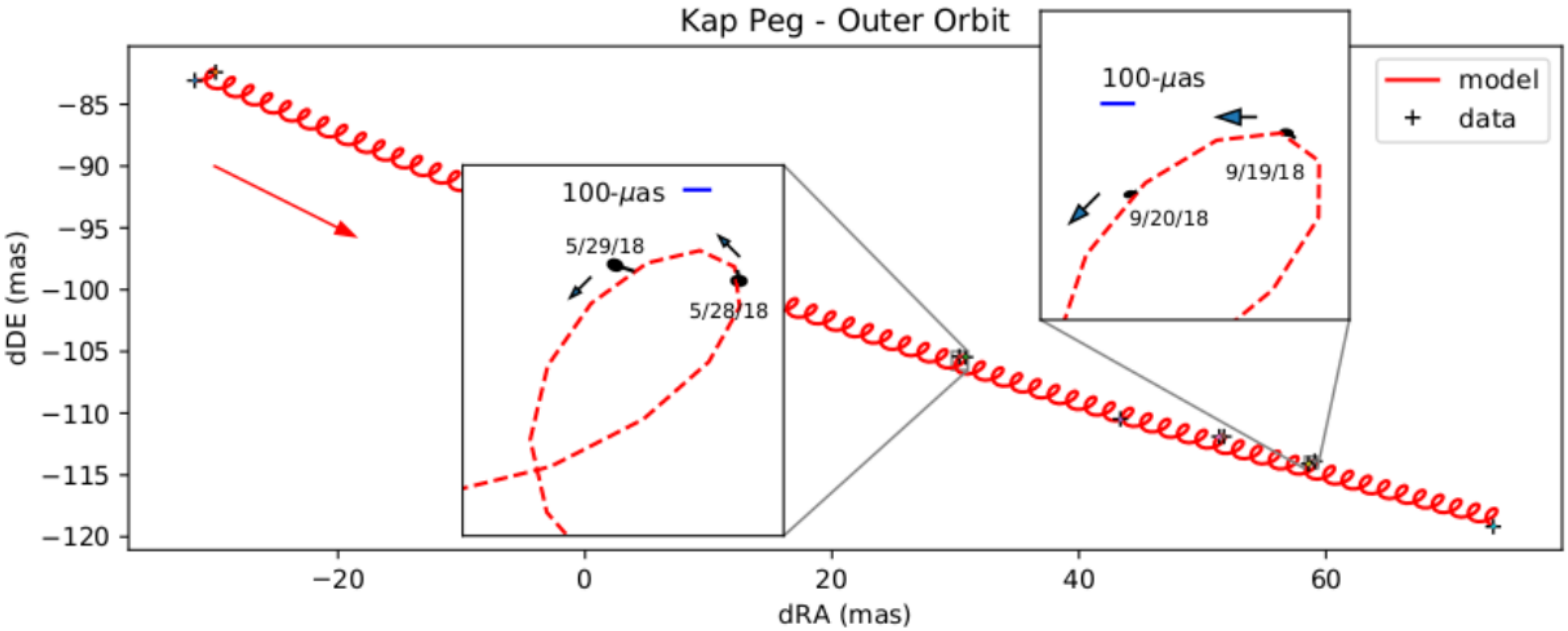






Kloppenborg et al. (2010, 2015)

Planet Detection in Binary Systems: Astrometric Wobble

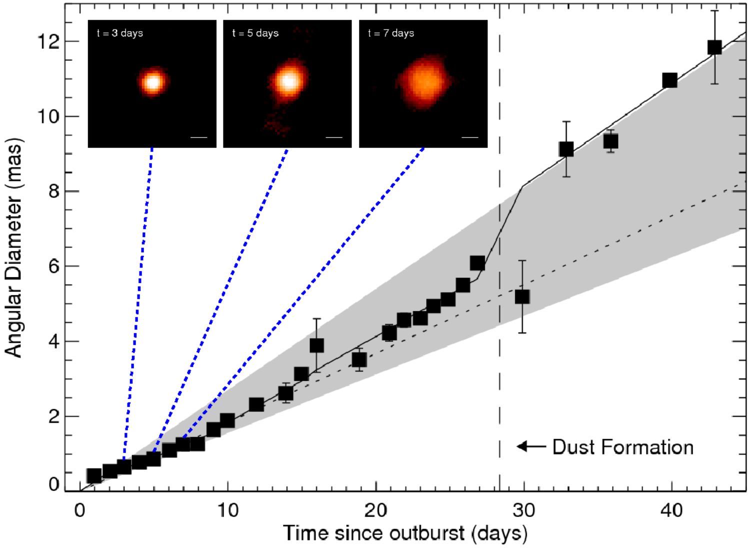


Gardner et al. (2018, in prep)

Transient Events

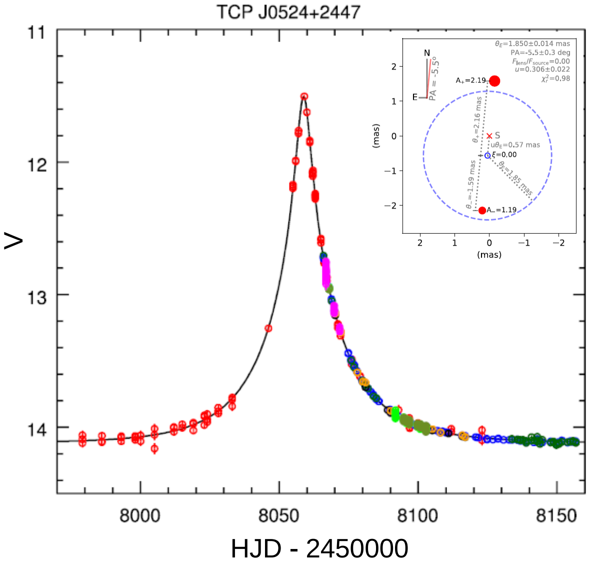
Transient Events

Nova Explosions:
Angular expansion



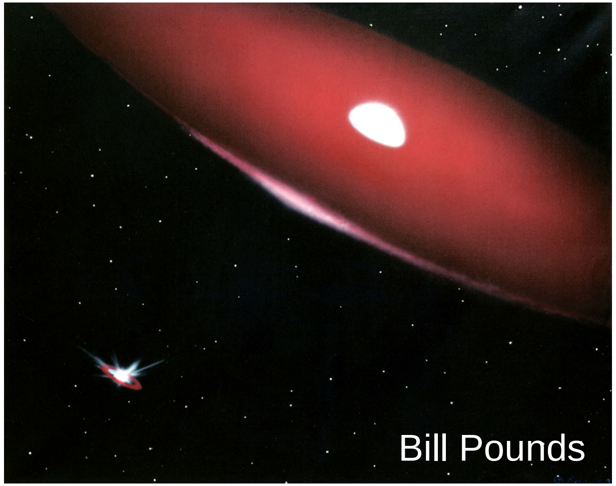
Schaefer et al. (2014)

Gravitational Microlensing:
Resolve lensed image



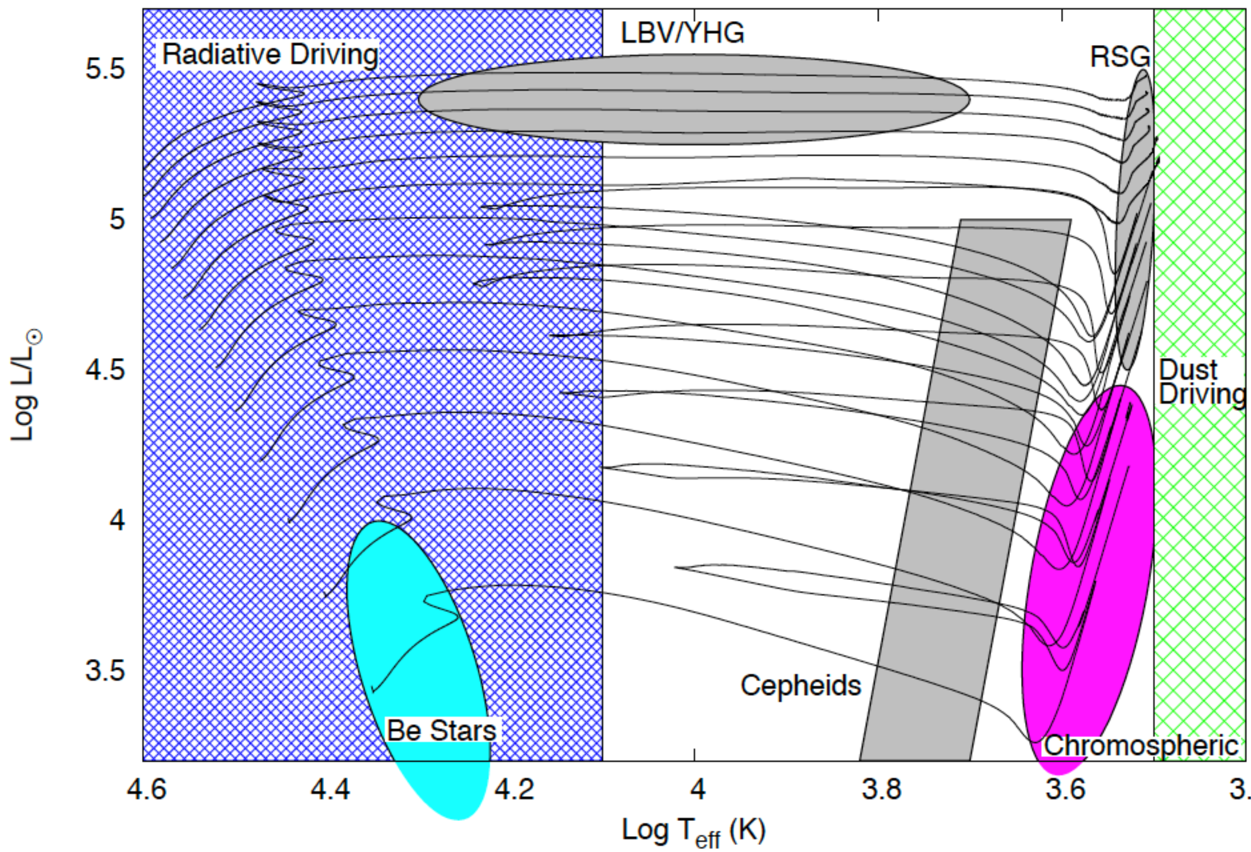
Dong et al. (2014)

Outbursting Be Star:
Formation of Disk



Klement et al. (in prep)

Stellar mass loss: high luminosity



Neilson (2013, arXiv:1309.4115)

Massive star winds

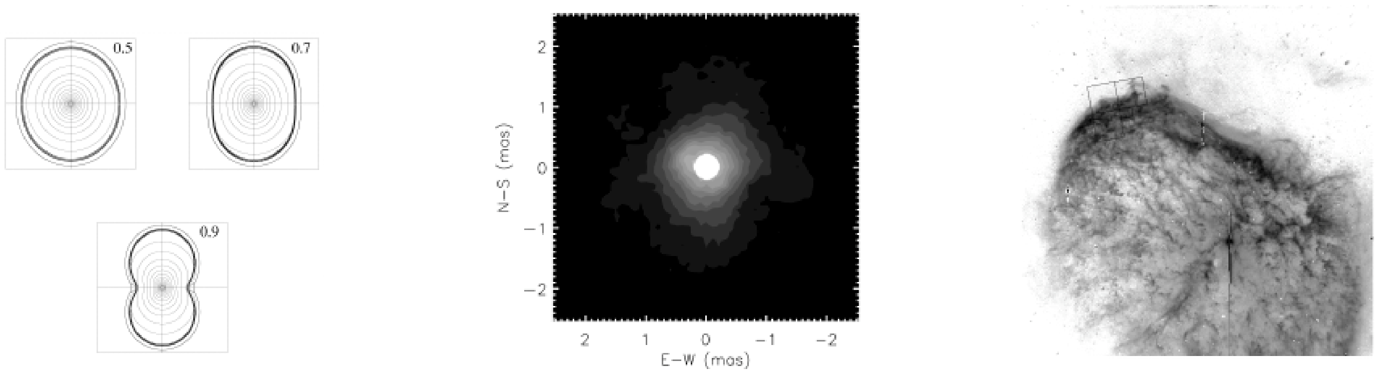


FIG. 1 – Left: Isodensity contours for winds of rotating stars (Dwarkadas & Owocki 2002). Middle: P Cygni (Richardson et al. 2013). Right: Nebula around WR 136 (Moore et al. 2000).

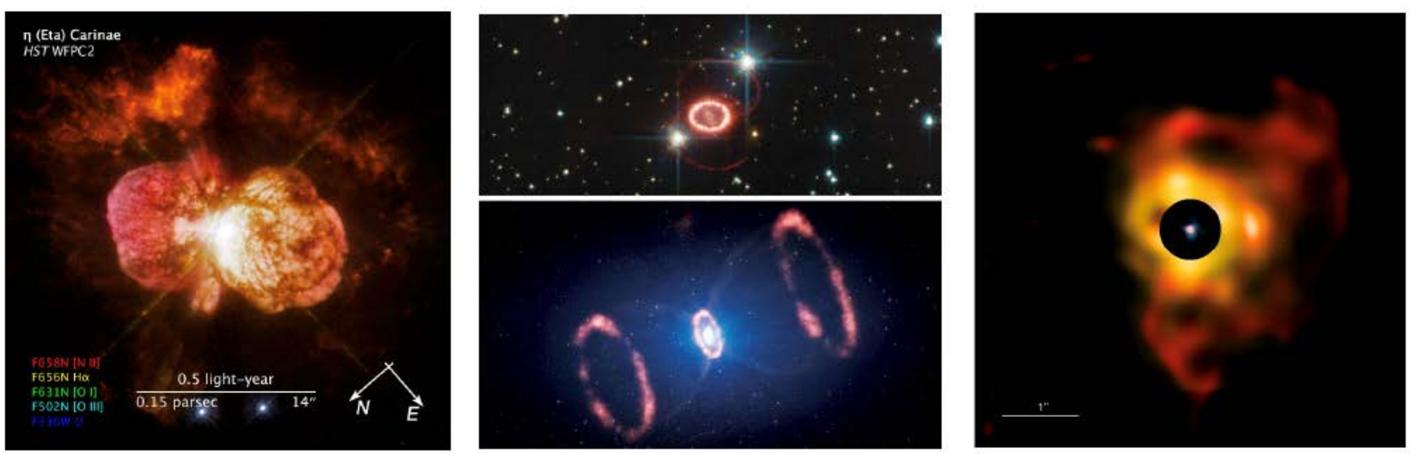


FIG. 2 – η Carinae (NASA, ESA); SN1987A (NASA, ESA); Betelgeuse (Kervella et al. 2011).

Be star disks

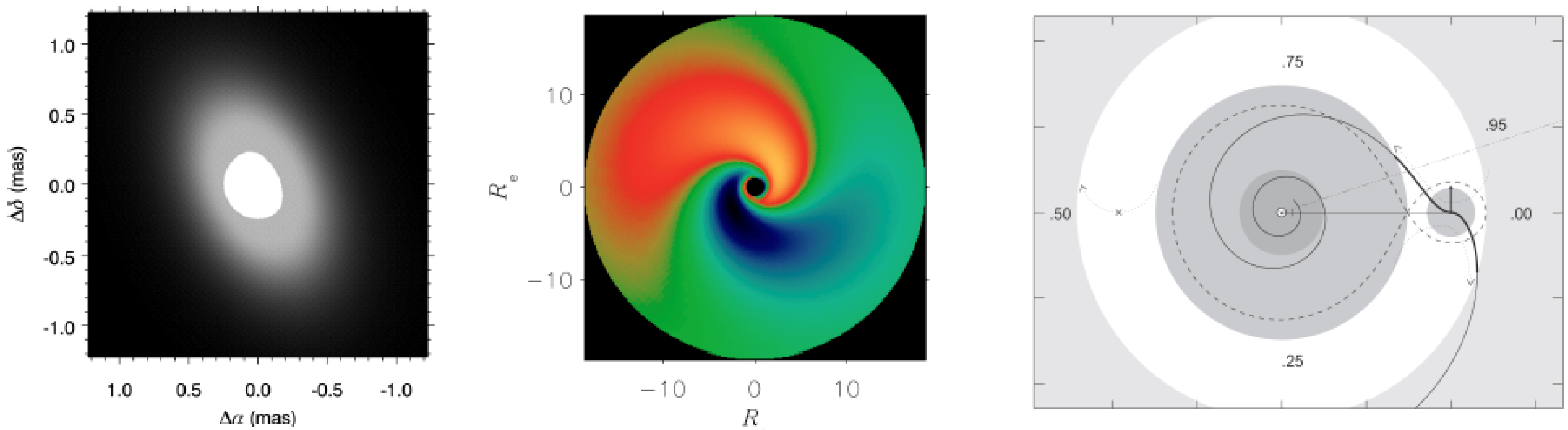
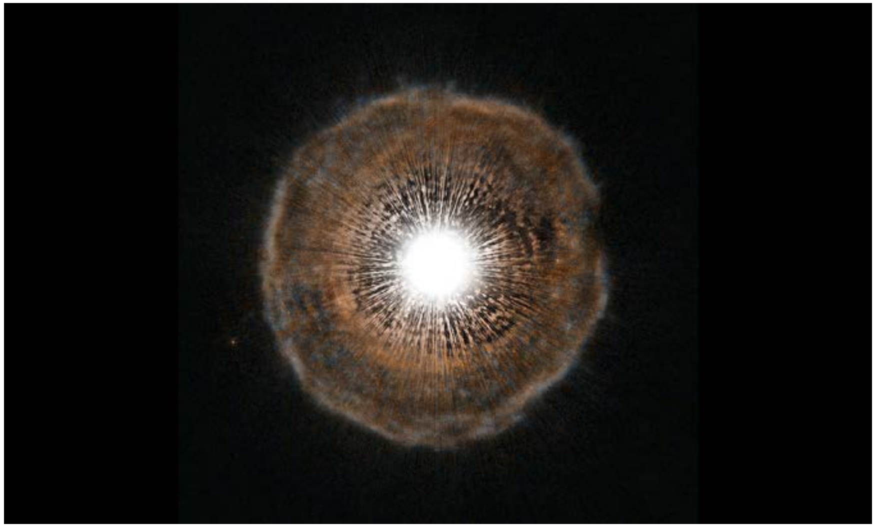
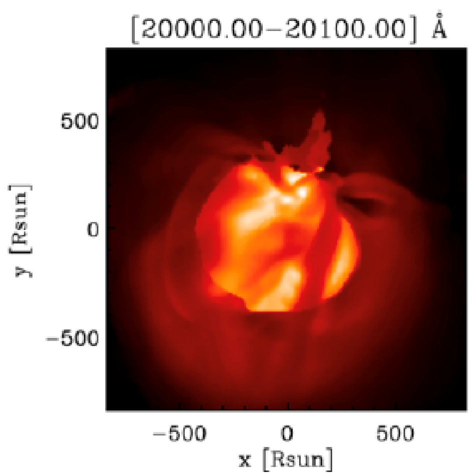


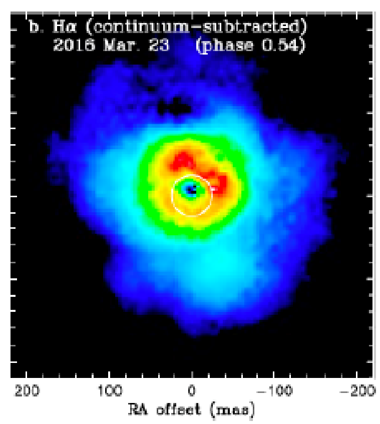
FIG. 3 – Models of the disk of γ Cas (Gies et al. 2007); the one-armed spiral density wave of ζ Tau (Carciofi et al. 2009); a gap created by the companion of HR 2142 (Peters et al. 2016).

Asymptotic Giant Branch & RSGs



Hubble Space Telescope image of the AGB star U Cam [ESA/Hubble]





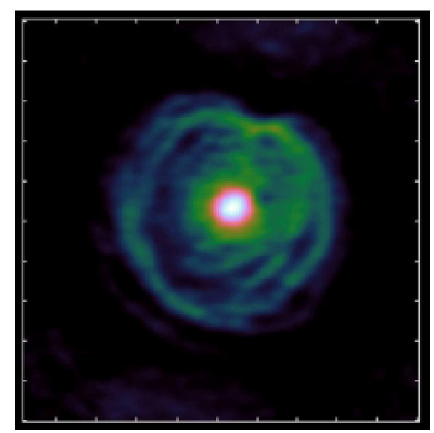


FIG. 4 – 3D model of intensity in a water vapor band (Wittkowski et al. 2016); clumpy dust emission around W Hya (Ohnaka et al. 2017); ALMA ^{12}CO map of OH30.1-0.7 (Decin et al. 2019).

Binary stars

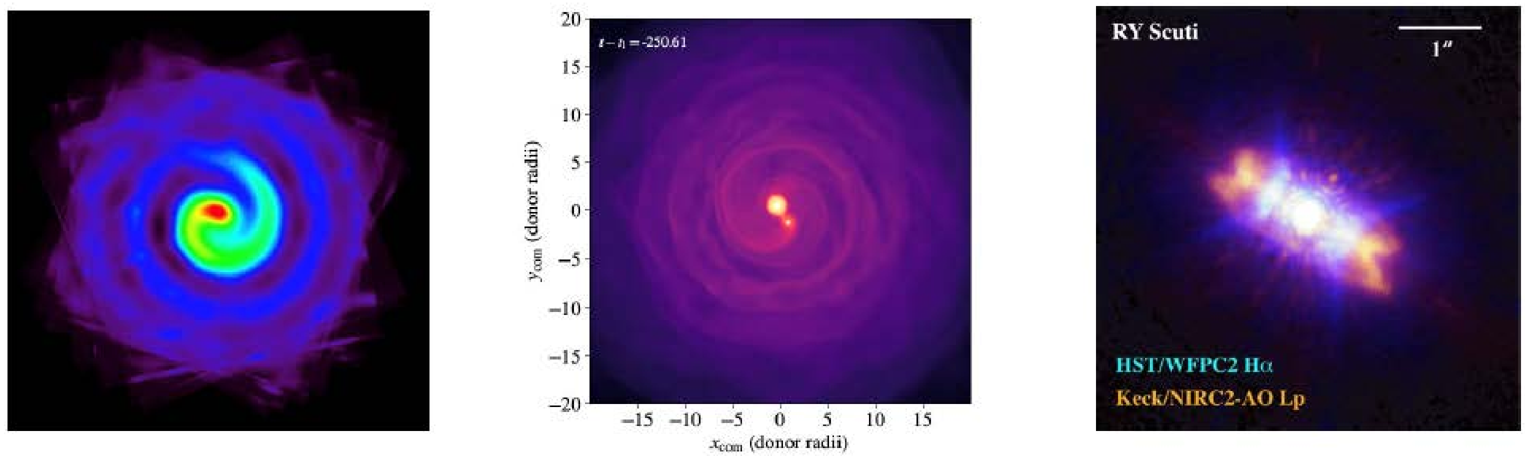


FIG. 5 – The dust pinwheel formed by wind-wind collision in WR104 (Tuthill et al. 2008); model RLOF and circumbinary disk (MacLeod et al. 2018); double-torus of RY Scuti (Smith et al. 2011).

Astro2020 Science White Papers

- AGN (Kishimoto) 2019BAAS...51c.156K
- Asteroseismology (Huber) 2019BAAS...51c.488H
- Binaries (Schaefer) 2019BAAS...51c.483S
- Evolved stars (Ridgway) 2019BAAS...51c.332R
- Exoplanets (Monnier) 2019BAAS...51c.514M
- Mass loss (Gies) 2019BAAS...51c.171G
- Pulsators (Creech-Eakman) 2019BAAS...51c.196C
- Transients (Schaefer) 2019BAAS...51c.502S
- YSOs (Monnier) 2019BAAS...51c.498M (Isella) 2019BAAS...51c.174I
- Imaging (Roettenbacher) 2019BAAS...51c.181R
- Radii (van Belle) 2019BAAS...51c.381V

Observing requests

- Next opportunity: 2021A Semester (March-July)
- Proposals due October 1, 2020
- CHARA Collaboration
  http://www.chara.gsu.edu/observers/applying-for-chara-time
- NSF’s NOIRLab (everyone else)
  http://ast.noao.edu/observing/call-for-proposals-2020b

Thank you!

- Fabien Baron
- Tyler Gardner
- Daniel Huber
- Jeremy Jones
- Robert Klement
- Katie Lester
- Arturo Martinez
- Gail Schaefer
- Theo ten Brummelaar
- Russel White
- CHARA staff
- CHARA collaboration

http://www.chara.gsu.edu/workshops/chara-summer-seminar-2020