# MIRC Observations of the O-star Triple Sigma Orionis

Gail Schaefer
Doug Gies
John Monnier
Nils Turner

New Title:

Do NPOI and CHARA Orbits Agree?

.... stay tuned....

# Sigma Orionis

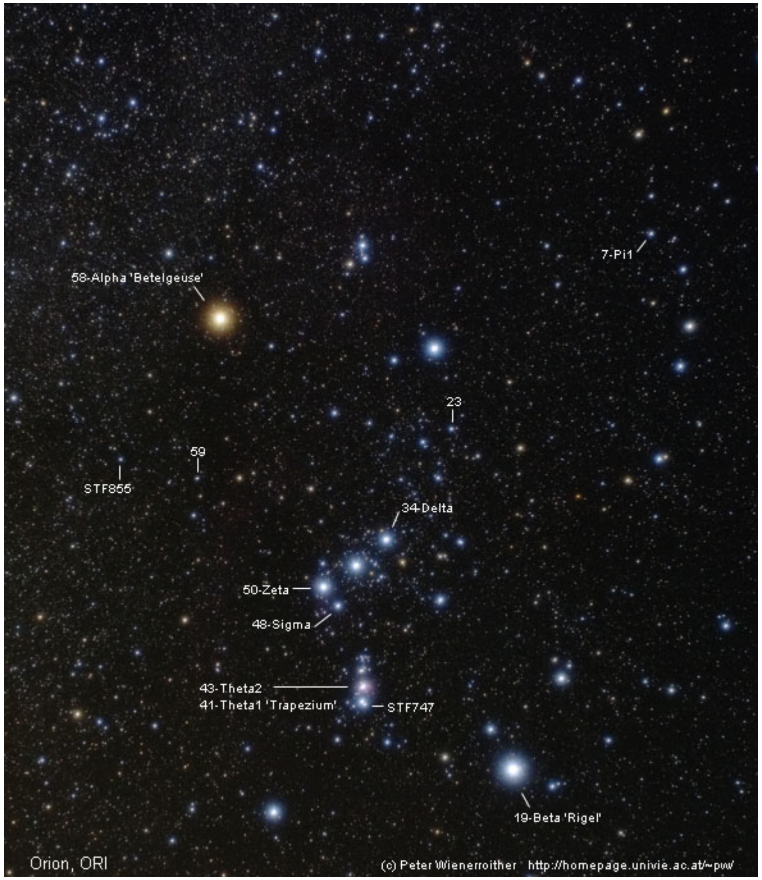
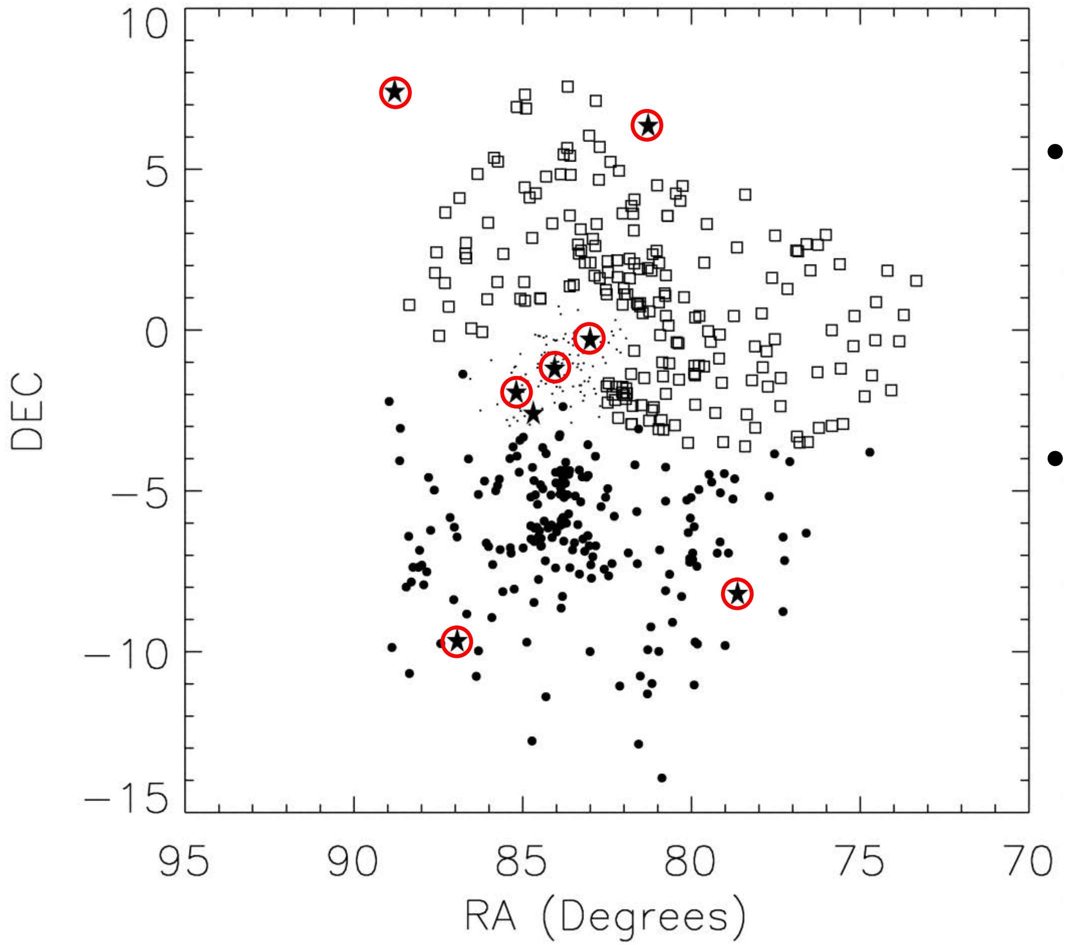



Image credit:
Peter Wienerroither

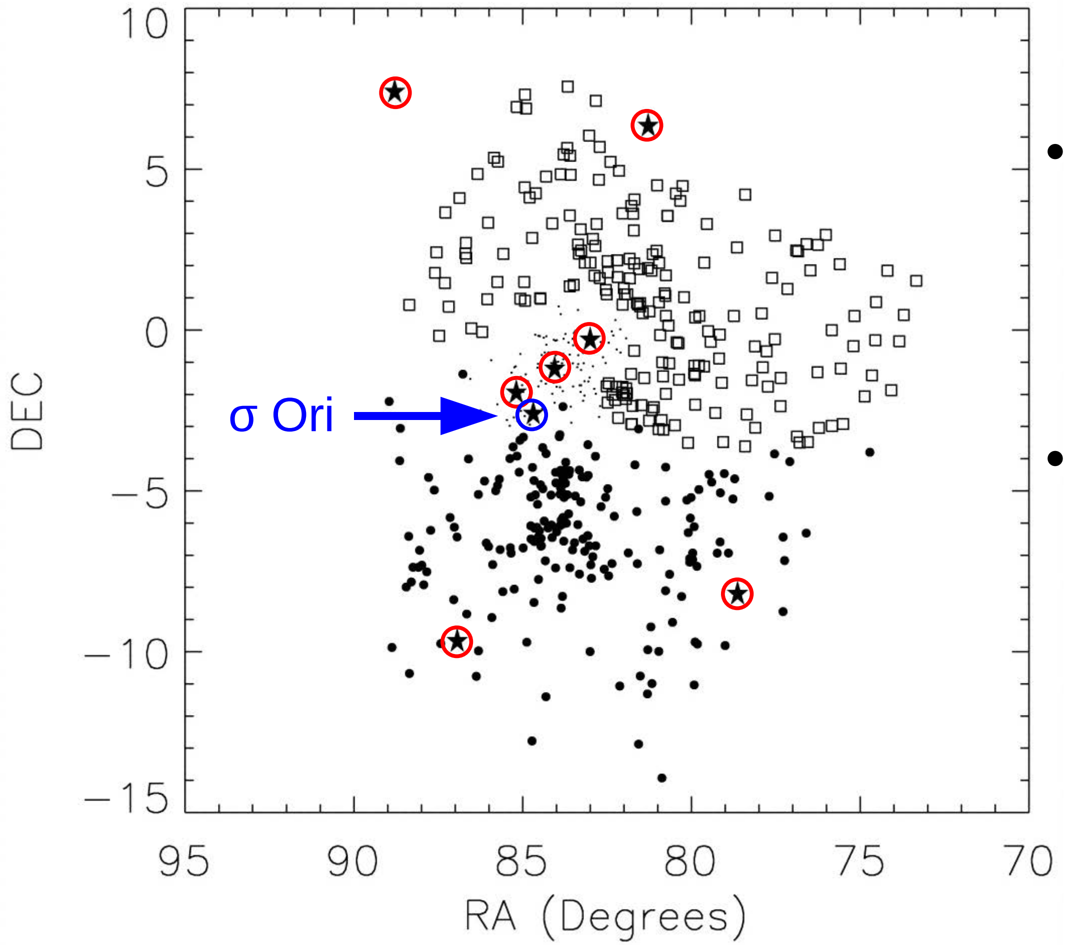
# Orion OB1 Association




- Members of Orion OB1 sub-associations as defined by Brown et al. (2004)
- Mainly OB stars plotted with a few AF stars

Sherry et al. 2004

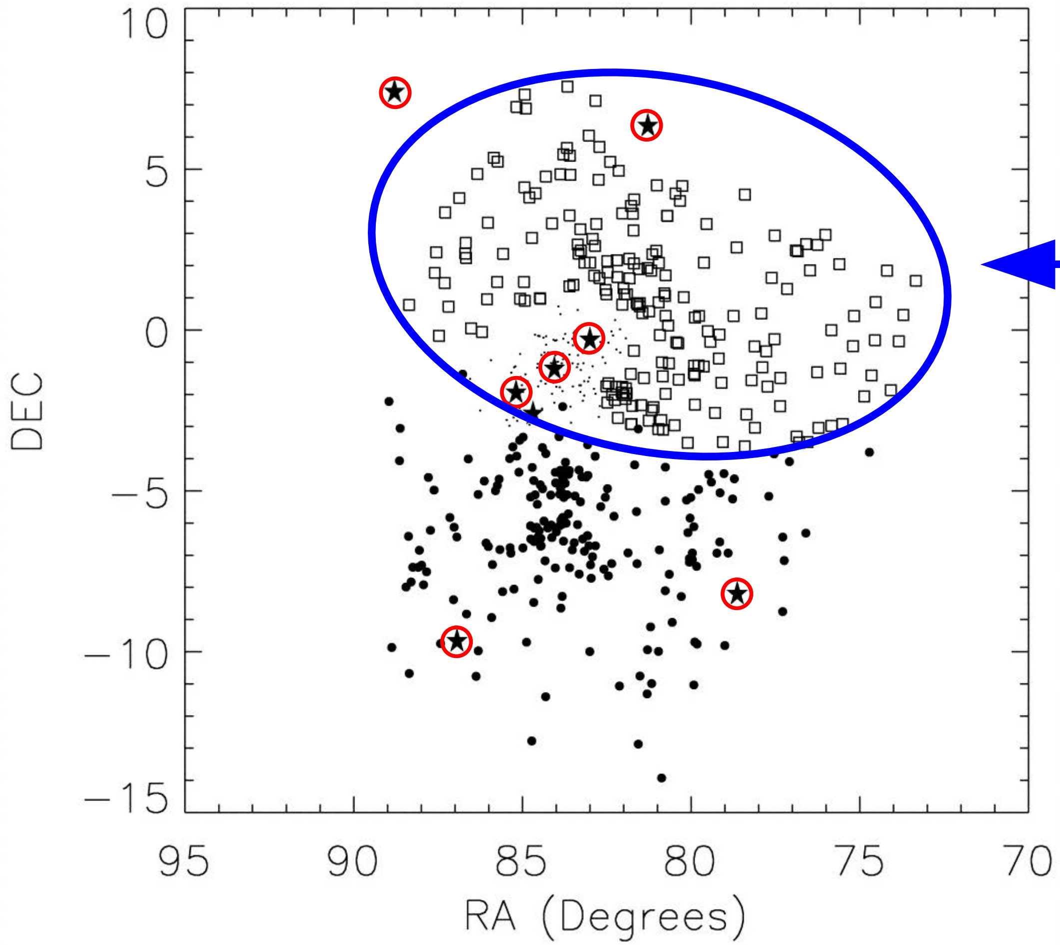
# Orion OB1 Association




- Members of Orion OB1 sub-associations as defined by Brown et al. (2004)
- Mainly OB stars plotted with a few AF stars

Sherry et al. 2004

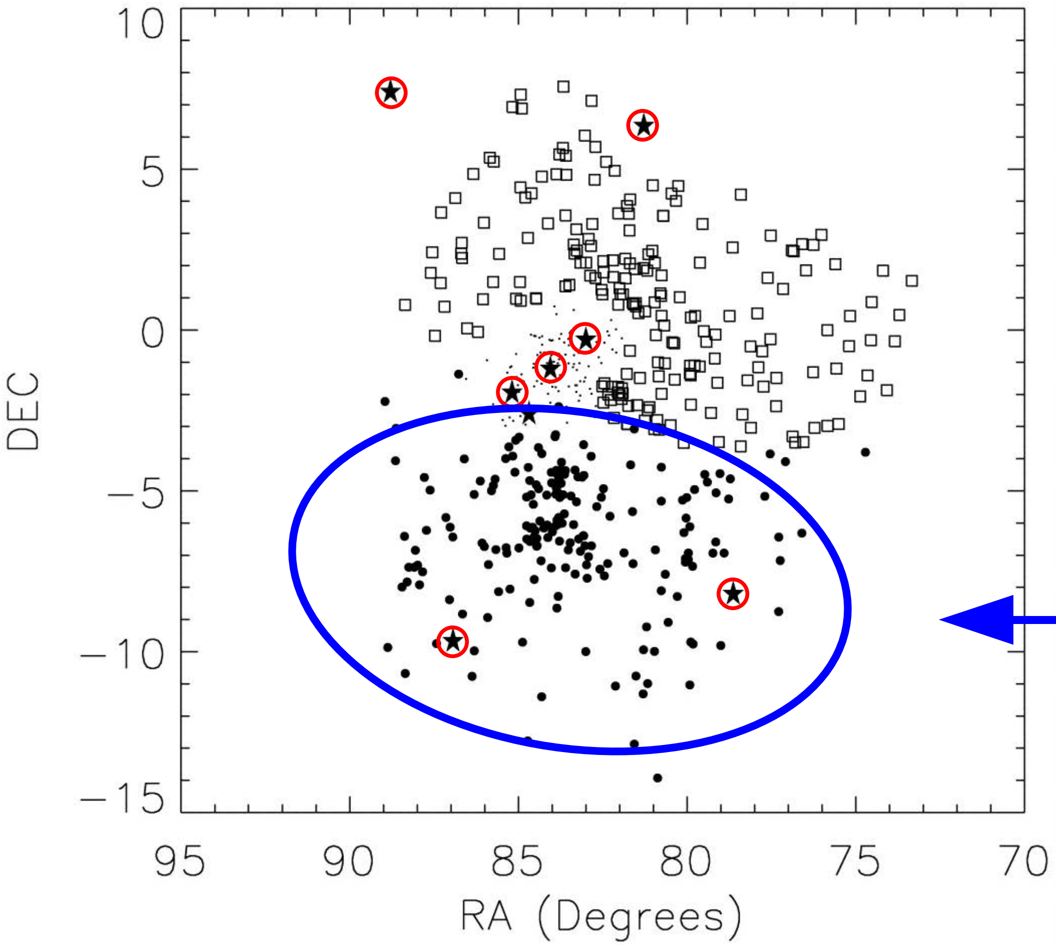
# Orion OB1 Associations




Orion OB1a
(open squares)
~ 10 Myr old

Sherry et al. 2004

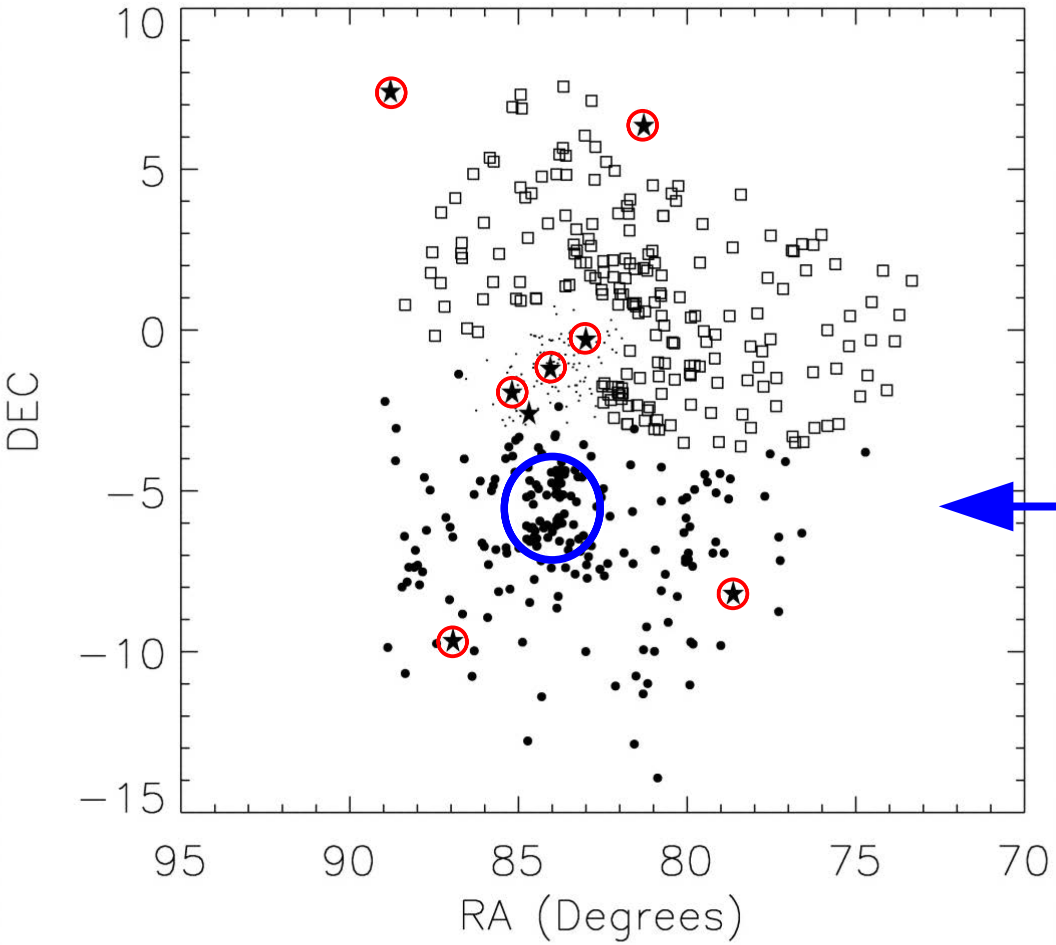
# Orion OB1 Associations




Orion OB1c
(filled circles)

Sherry et al. 2004

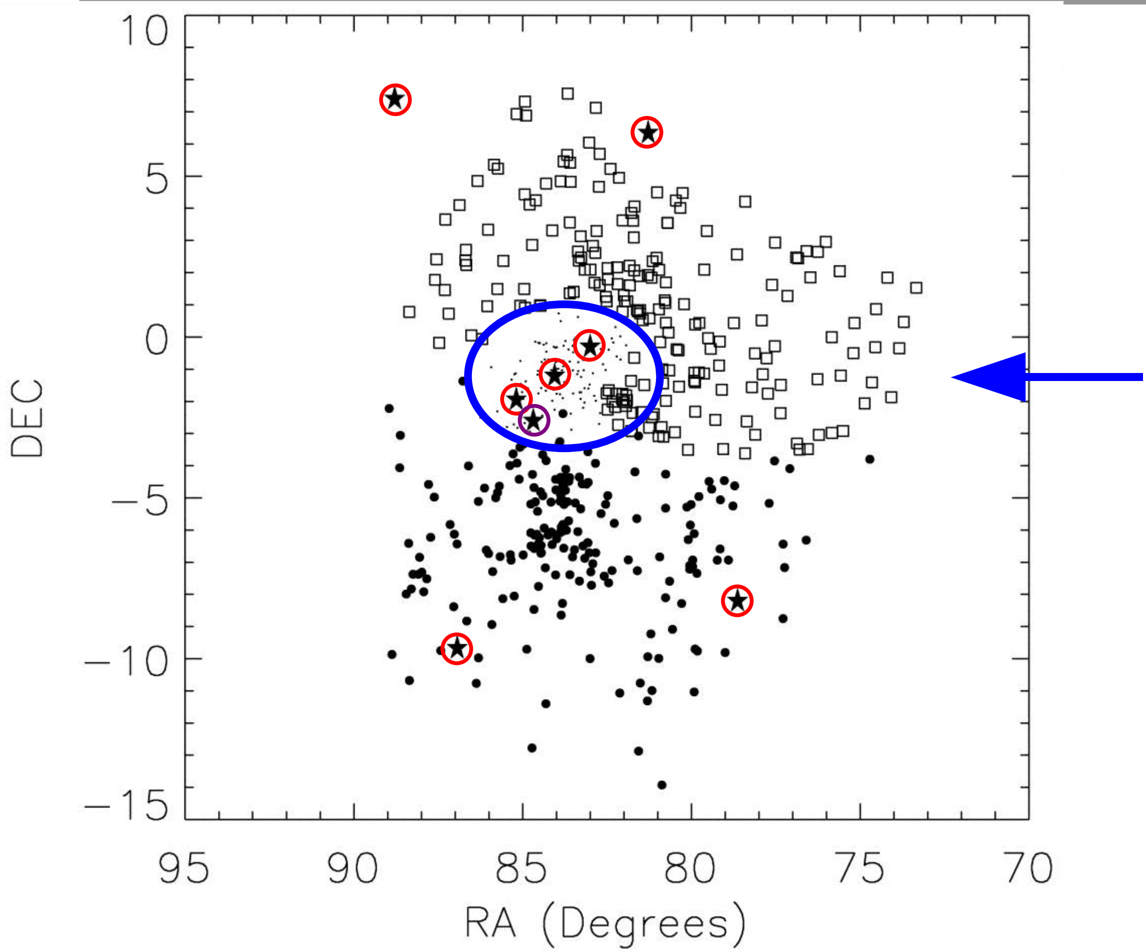
# Orion OB1 Associations




Orion Nebula Cluster
~ 1 Myr

Sherry et al. 2004

# Orion OB1 Associations




Orion OB1b
(small dots)
~ 2-3 Myr

Sherry et al. 2004

# Sigma Orionis

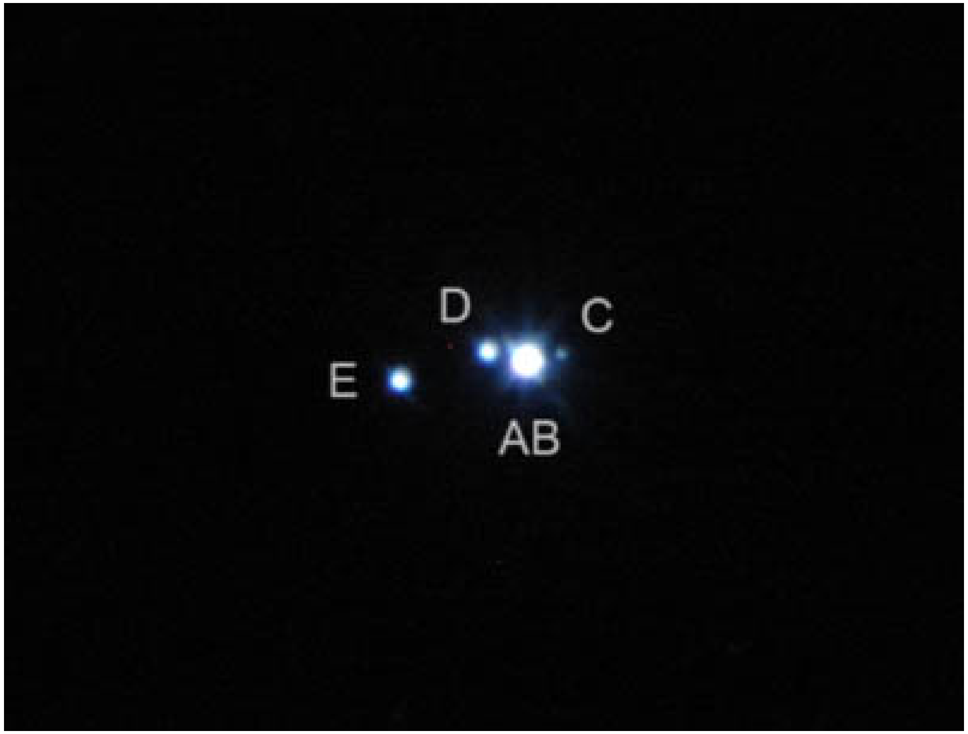



Image credit:
http://astronomy.kez.nu

σ Ori A - 09.5V (Aa+Ab)
σ Ori B - B0.5V (0.26")
σ Ori C - A2V
σ Ori D - B2V
σ Ori E - B2Vpe

# Sigma Ori Cluster

- Unbound cluster of a few hundred young stars centered on the multiple system σ Ori

# Sigma Ori Cluster

- Unbound cluster of a few hundred young stars centered on the multiple system σ Ori
- Clustering of 15 B stars identified - Garrison (1967)

# Sigma Ori Cluster

- Unbound cluster of a few hundred young stars centered on the multiple system σ Ori
- Clustering of 15 B stars identified - Garrison (1967)
- Walter et al. (1997)
  - Identified ~100 low mass pre-main sequence stars based on X-ray emission and spectroscopic Li abundances

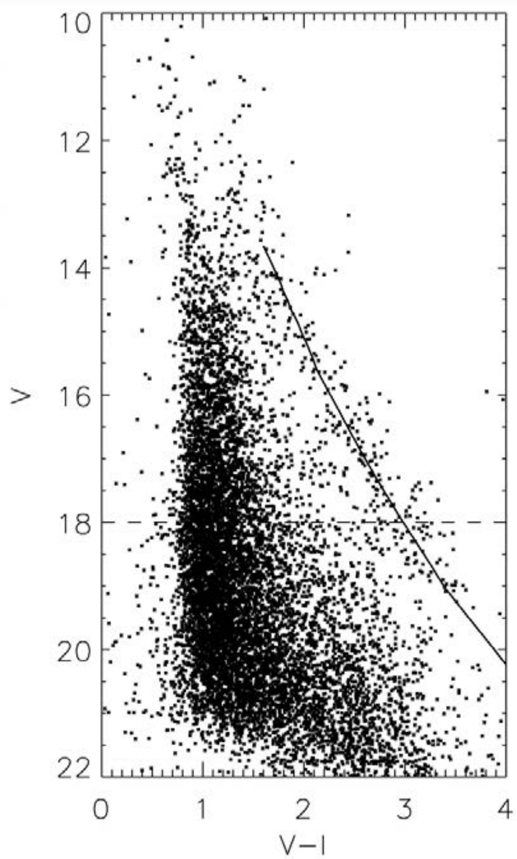
# Sigma Ori Cluster

- Unbound cluster of a few hundred young stars centered on the multiple system σ Ori
- Clustering of 15 B stars identified - Garrison (1967)
- Walter et al. (1997)
  - Identified ~100 low mass pre-main sequence stars based on X-ray emission and spectroscopic Li abundances
- Age ~ 2.5 Myr (Sherry et al. 2004)

# Sigma Ori Cluster

- Unbound cluster of a few hundred young stars centered on the multiple system σ Ori
- Clustering of 15 B stars identified - Garrison (1967)
- Walter et al. (1997)
  - Identified ~100 low mass pre-main sequence stars based on X-ray emission and spectroscopic Li abundances
- Age ~ 2.5 Myr
- Cluster radius: 3 - 5 pc

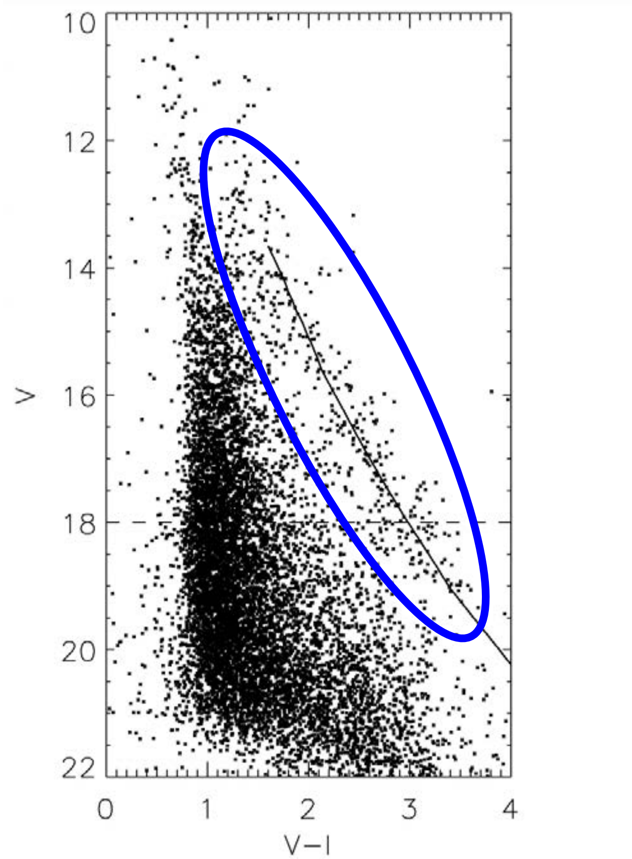
# Low-Mass Stars in Sigma Ori Cluster




Photometric identification of low-mass stars

Sherry et al. 2004

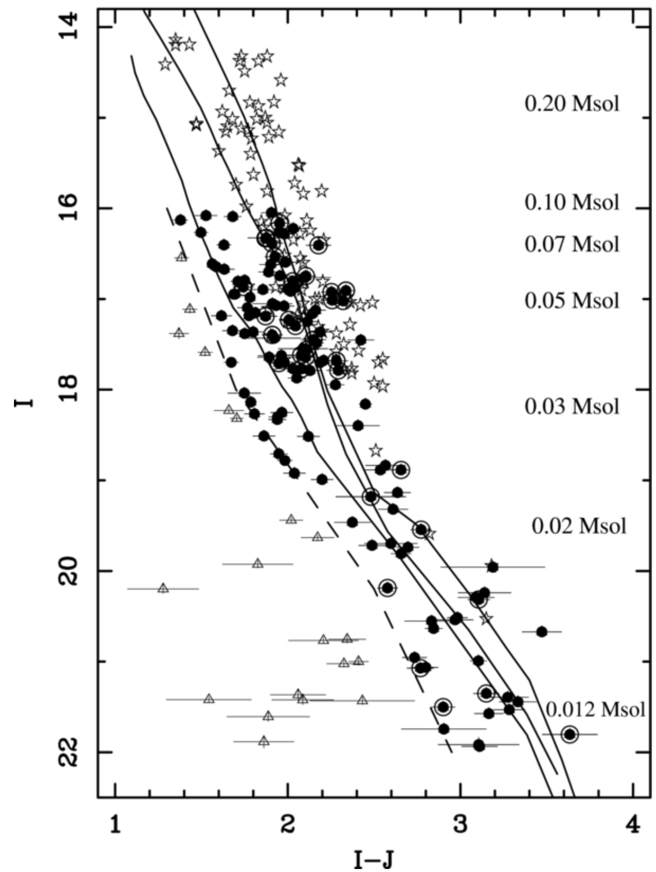
# Low-Mass Stars in Sigma Ori Cluster




Photometric identification of low-mass stars

Sherry et al. 2004

# Substellar Population in Sigma Ori Cluster




Bejar et al. 2011

# Distance to σ Ori Cluster

- Roughly half of the stars have lost their protoplanetary disks

# Distance to σ Ori Cluster

- Roughly half of the stars have lost their protoplanetary disks
- Large population of brown dwarfs

# Distance to σ Ori Cluster

- Roughly half of the stars have lost their protoplanetary disks
- Large population of brown dwarfs
- More accurate age provides tighter constraint on disk lifetimes and time available for planet formation

# Distance to σ Ori Cluster

- Roughly half of the stars have lost their protoplanetary disks
- Large population of brown dwarfs
- More accurate age provides tighter constraint on disk lifetimes and time available for planet formation
- Distance remains biggest uncertainty in the age of the cluster

# Distance to σ Ori Cluster

- Hipparcos parallax to sigma Ori A-B
  - 350 pc (+160/-80) (Perryman et al. 1997)

# Distance to σ Ori Cluster

- Hipparcos parallax to sigma Ori A-B
  - 350 pc (+160/-80) (Perryman et al. 1997)
- Hipparcos distance to Orion OB1b Association
  - 473 ± 33 pc (Hernandez et al. 2005)
  - Orion OB1b extends 30-40 pc across sky

# Distance to σ Ori Cluster

- Hipparcos parallax to sigma Ori A-B
  - 350 pc (+160/-80) (Perryman et al. 1997)
- Hipparcos distance to Orion OB1b Association
  - 473 ± 33 pc (Hernandez et al. 2005)
  - Orion OB1b extends 30-40 pc across sky
- Main sequence fitting of 9 B-stars
  - 2.5 Myr - main sequence turn off late B, early A
  - 420 ± 30 pc (Sherry et al. 2008)

# Formation and Evolution of Massive Stars

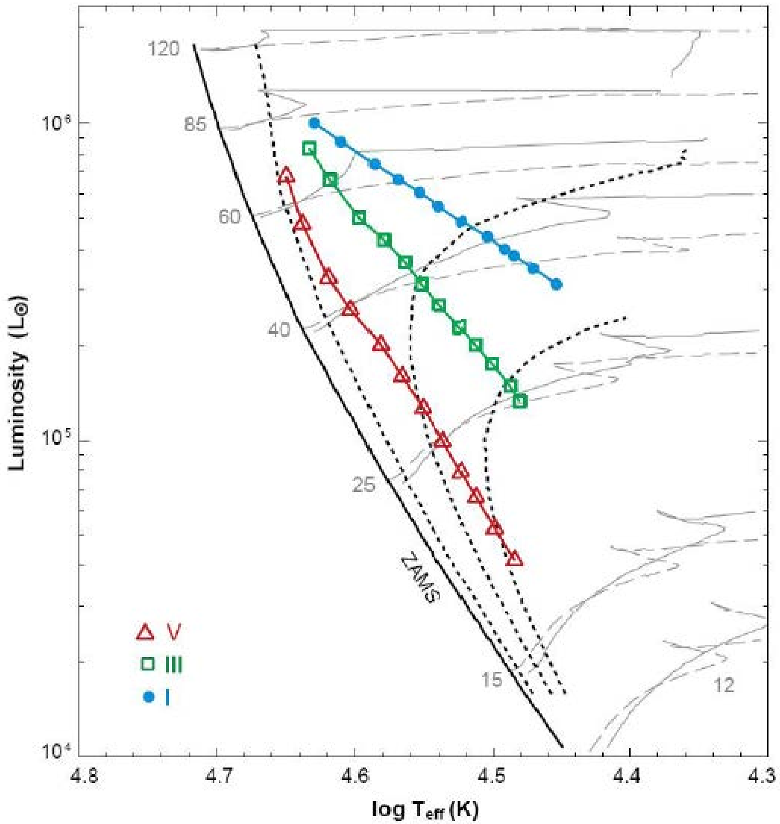
- Stellar mass defines the evolution of a star over time

# Formation and Evolution of Massive Stars

- Stellar mass defines the evolution of a star over time

Zinnecker & Yorke 2007

Evolutionary tracks from Menet & Maeder (2003)

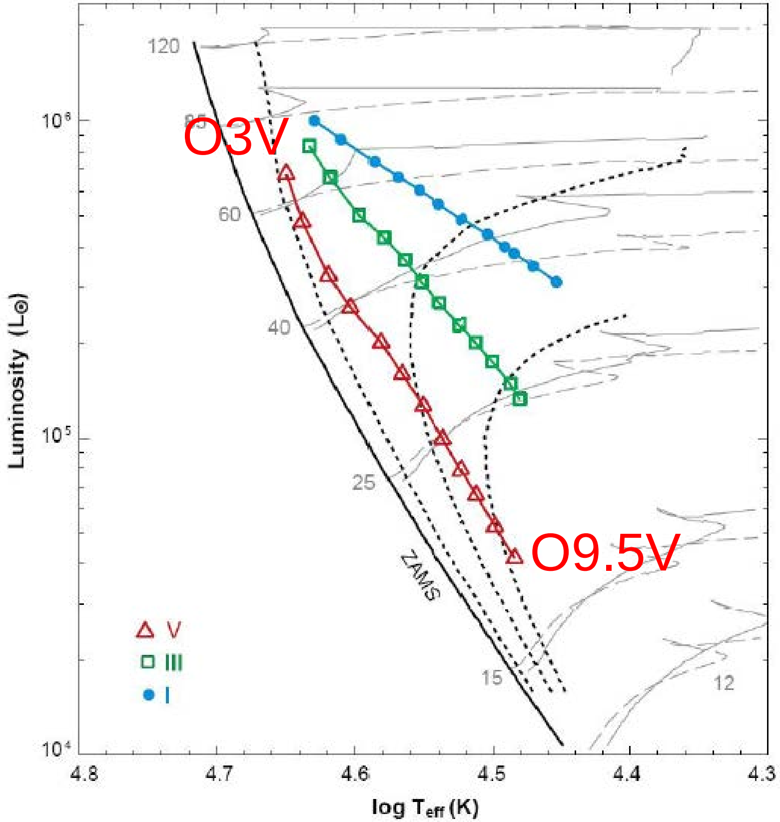


# Formation and Evolution of Massive Stars

- Stellar mass defines the evolution of a star over time

Zinnecker & Yorke 2007

Evolutionary tracks from Menet & Maeder (2003)

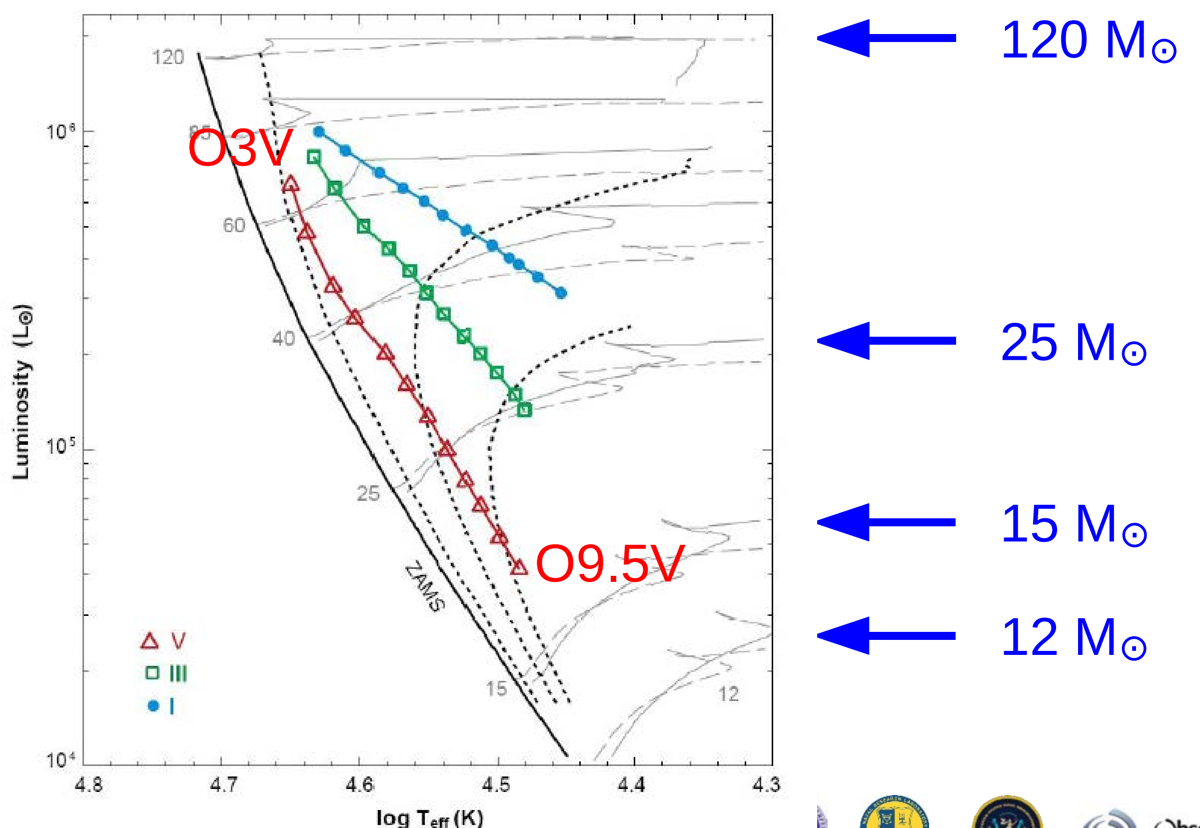


# Formation and Evolution of Massive Stars

- Stellar mass defines the evolution of a star over time

Zinnecker & Yorke 2007

Evolutionary tracks from Menet & Maeder (2003)

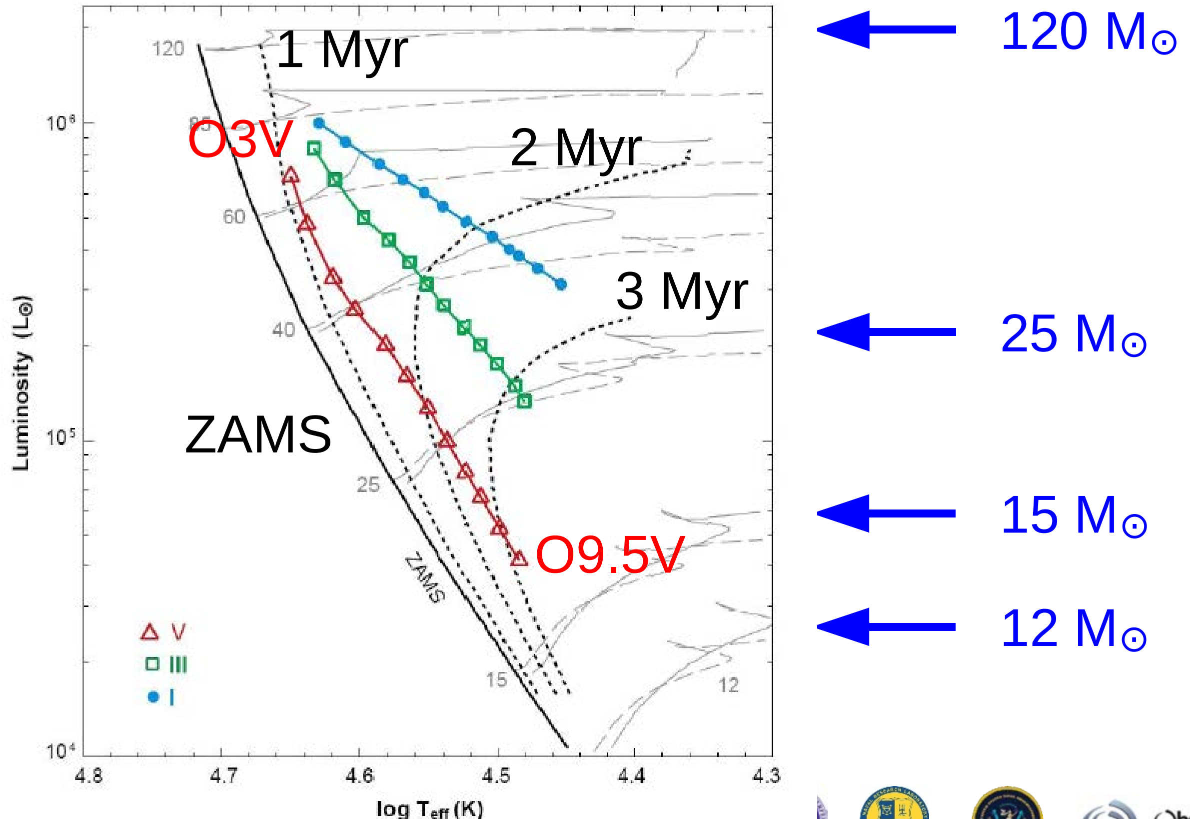


# Formation and Evolution of Massive Stars

- Stellar mass defines the evolution of a star over time

Zinnecker & Yorke 2007

Evolutionary tracks from Menet & Maeder (2003)



# Formation and Evolution of Massive Stars

- Stellar mass defines the evolution of a star over time
- Formation of massive stars not well understood
  - Large distances, high extinction, and short time scales of critical evolutionary phases

# Formation and Evolution of Massive Stars

- Stellar mass defines the evolution of a star over time
- Formation of massive stars not well understood
  - Large distances, high extinction, and short time scales of critical evolutionary phases
- Massive stars have an important impact on star forming regions and galactic evolution
  - production of heavy elements and enrichment of ISM
  - UV radiation, winds, outflows, SN explosions

# Massive Binary Stars

- Binary companions common among O-stars
  - 59% (Mason et al. 1998)

# Massive Binary Stars

- Binary companions common among O-stars
  - 59%  (Mason et al. 1998)
- If the visual orbit of a double-lined spectroscopic binary is resolved, then we know:
  - Masses and Distance!

# Massive Binary Stars

- Binary companions common among O-stars
  - 59% (Mason et al. 1998)
- If the visual orbit of a double-lined spectroscopic binary is resolved, then we know:
  - Masses and Distance!
- Sigma Orionis Aa-Ab ------------ B

# Massive Binary Stars

- Binary companions common among O-stars
  - 59% (Mason et al. 1998)
- If the visual orbit of a double-lined spectroscopic binary is resolved, then we know:
  - Masses and Distance!
- Sigma Orionis Aa-Ab ------------ B
- Masses of three O-B stars and distance to the Sigma Orionis Cluster

# Sigma Orionis

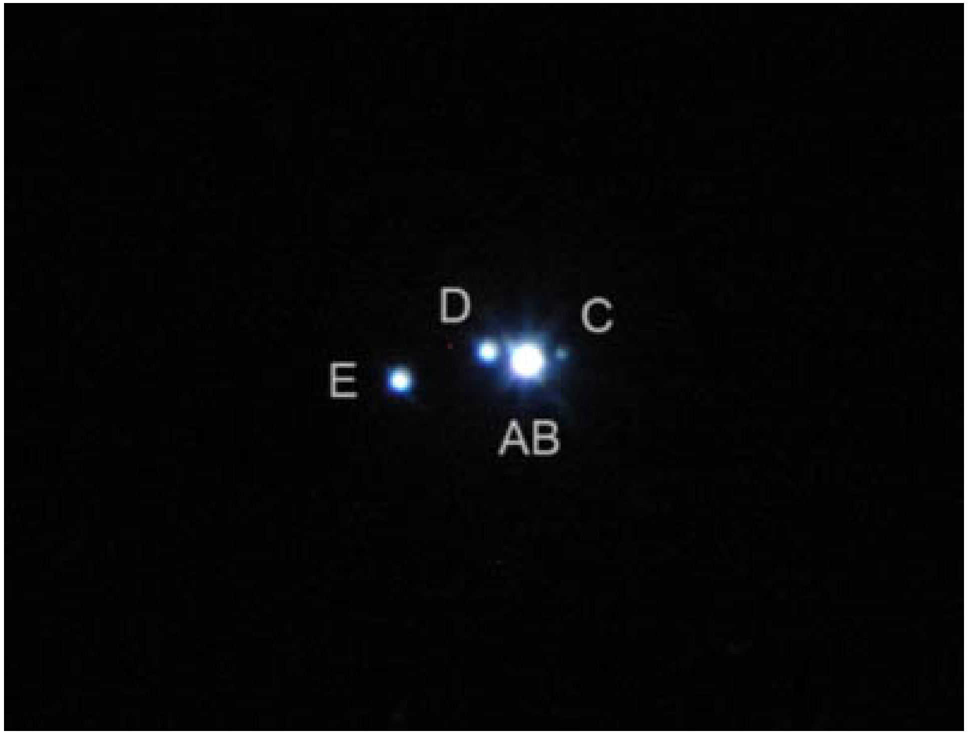
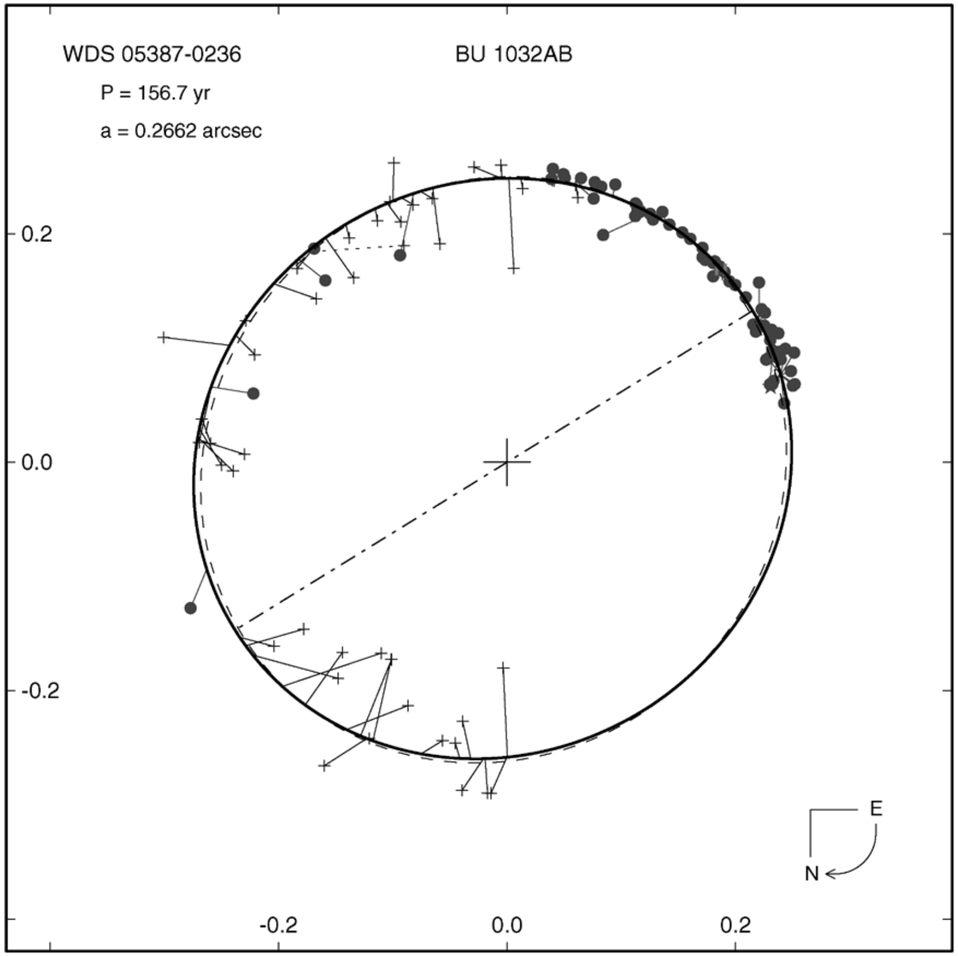



Image credit:
http://astronomy.kez.nu

σ Ori A - 09.5V (Aa+Ab)
σ Ori B - B0.5V (0.26")
σ Ori C - A2V
σ Ori D - B2V
σ Ori E - B2Vpe

# Visual Orbit of Sigma Ori A-B



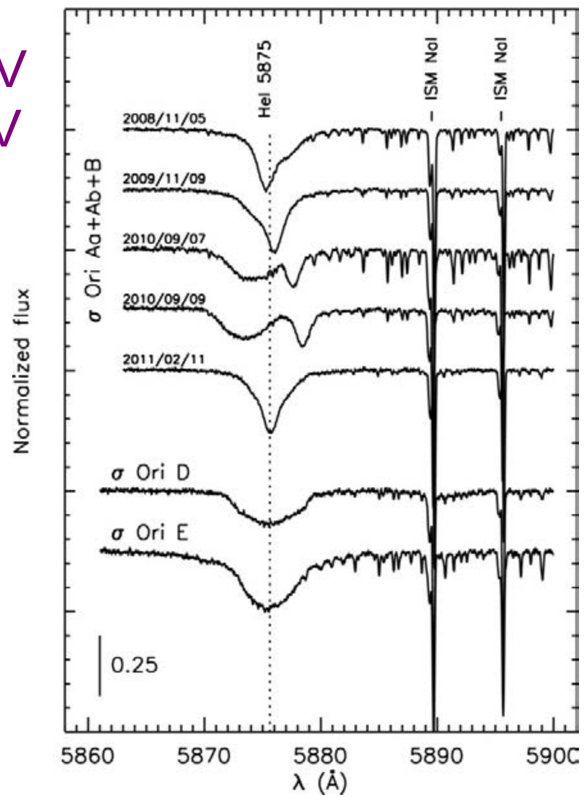

Turner et al. 2008

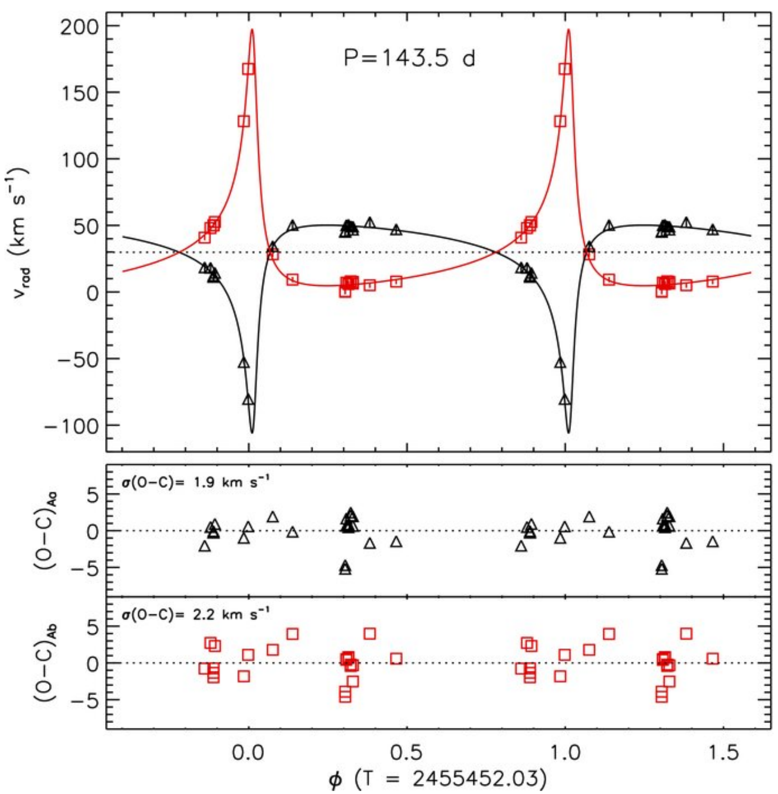
Orbit fit to speckle, AO, and visual measurements

P = 156.7 yr
e = 0.0515
a = 266.2 mas
i = 159.7°

# SB2 Orbit of Sigma Ori Aa-Ab

O9.5V
B0.5V



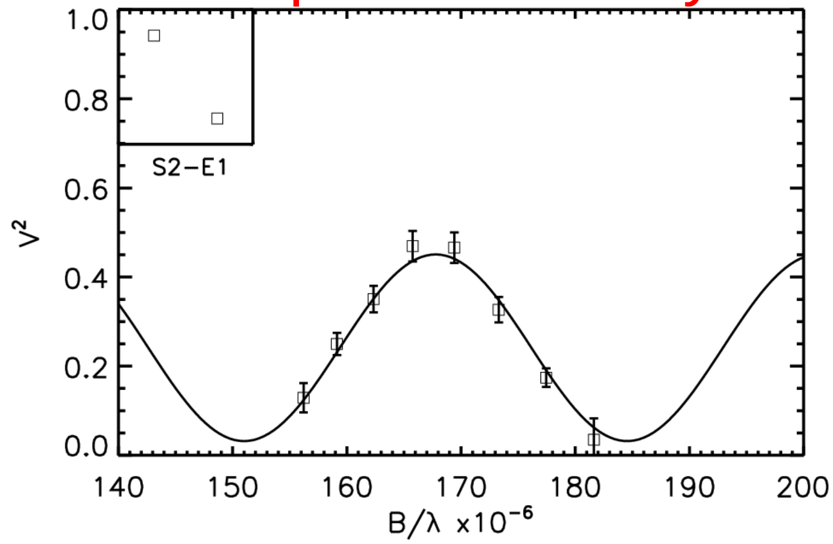

P=143.5 d
e=0.783

$M_{Ab}/M_{Ba}$ = 0.81

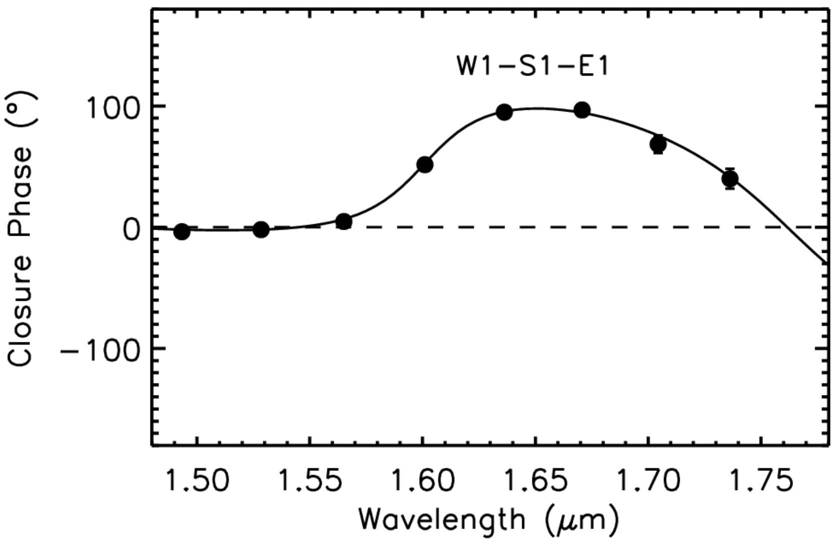
Simon-Diaz et al. 2011

# Examples of MIRC Visibilities and Closure Phases

Squared Visibility

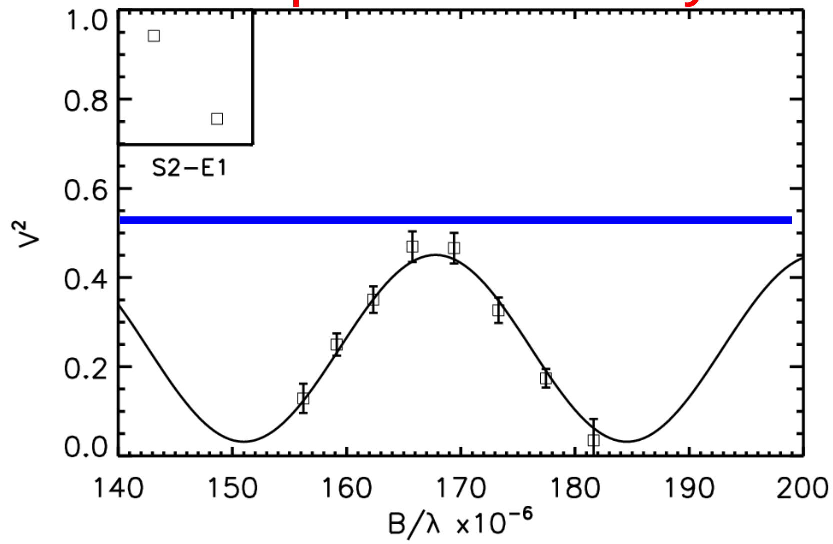



Closure Phase

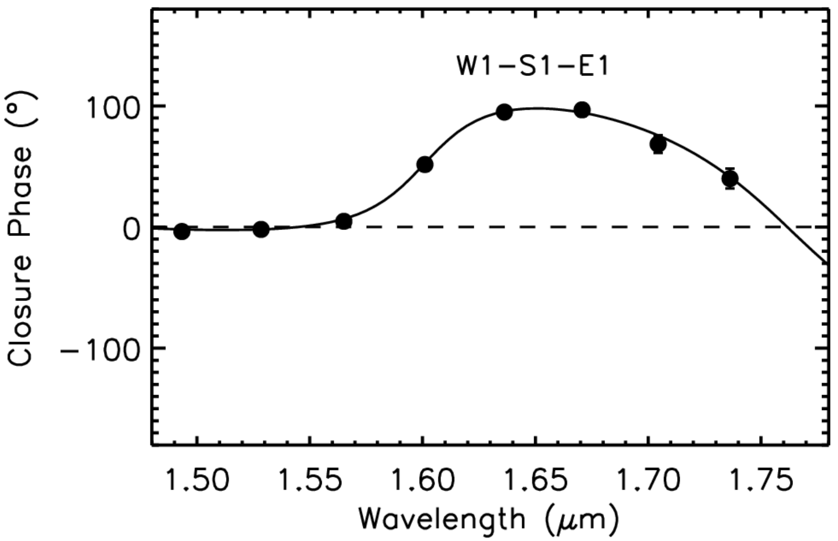


# Examples of MIRC Visibilities and Closure Phases

## Squared Visibility

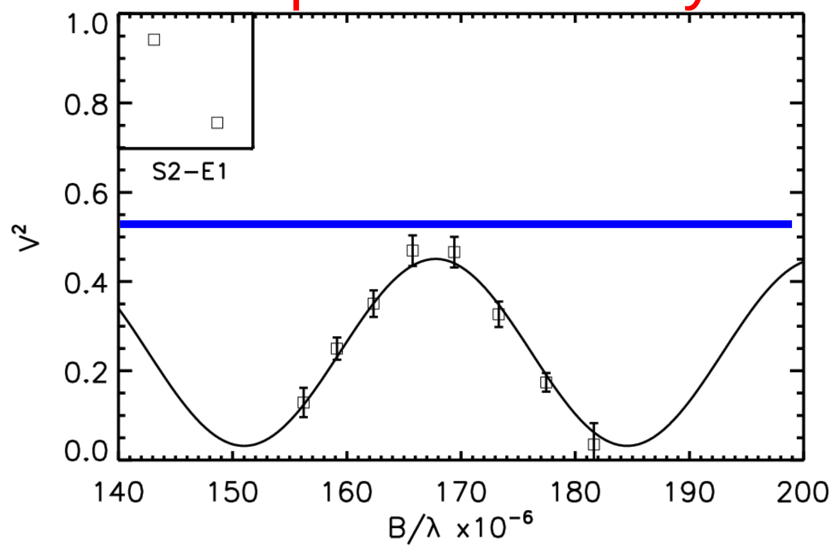



## Closure Phase

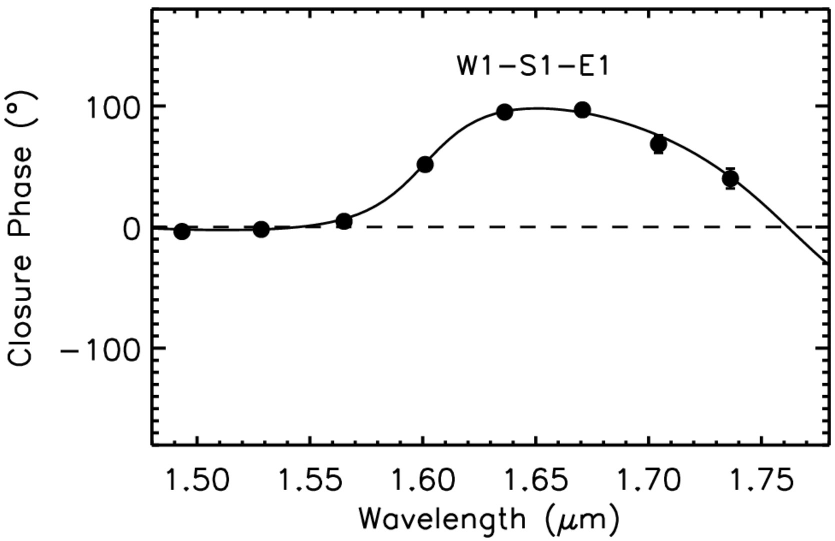


# Examples of MIRC Visibilities and Closure Phases

Squared Visibility




Closure Phase

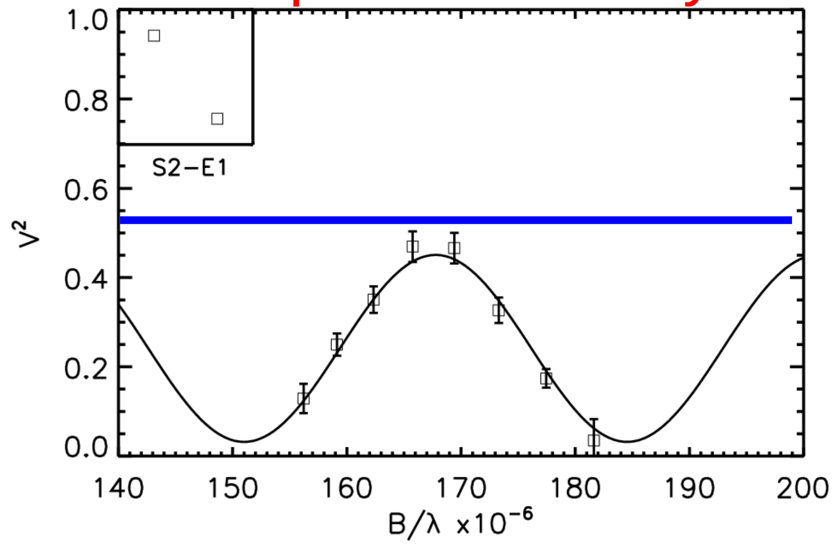



Incoherent light from the wide component B

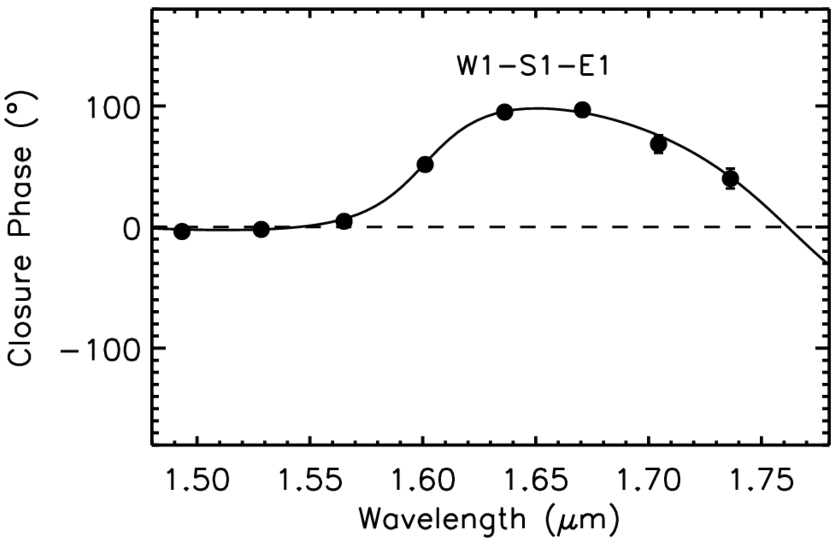
- contributes 29% of total light

# Examples of MIRC Visibilities and Closure Phases

Squared Visibility




Closure Phase



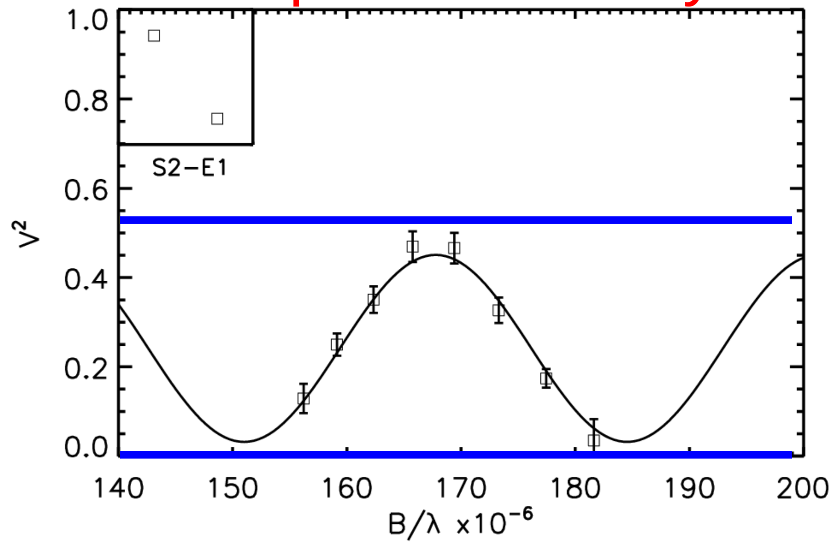

Incoherent light from the wide component B

- contributes 29% of total light

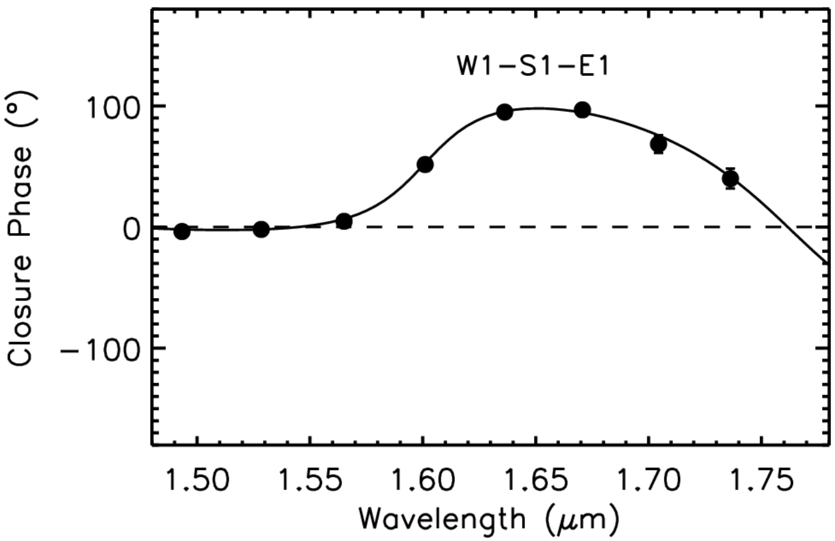
Separation = 7.28 mas, PA = 193.1°

# Examples of MIRC Visibilities and Closure Phases

Squared Visibility




Closure Phase



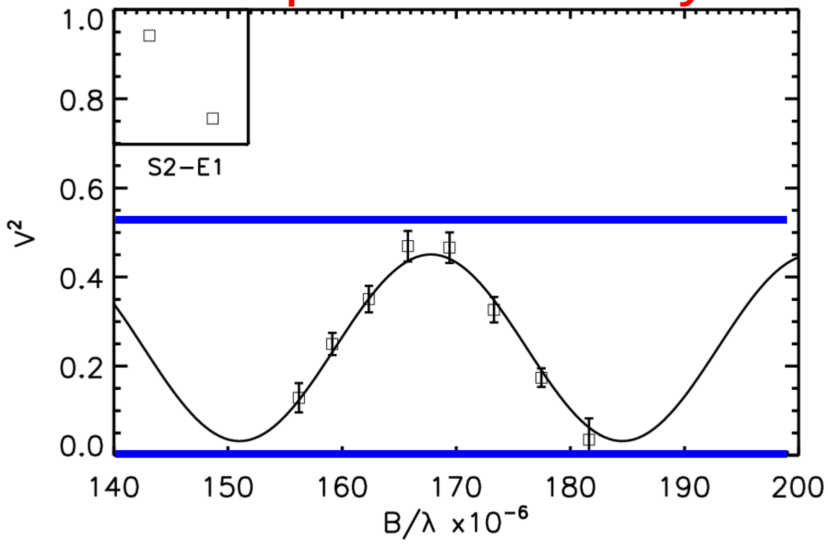

Incoherent light from the wide component B

- contributes 29% of total light

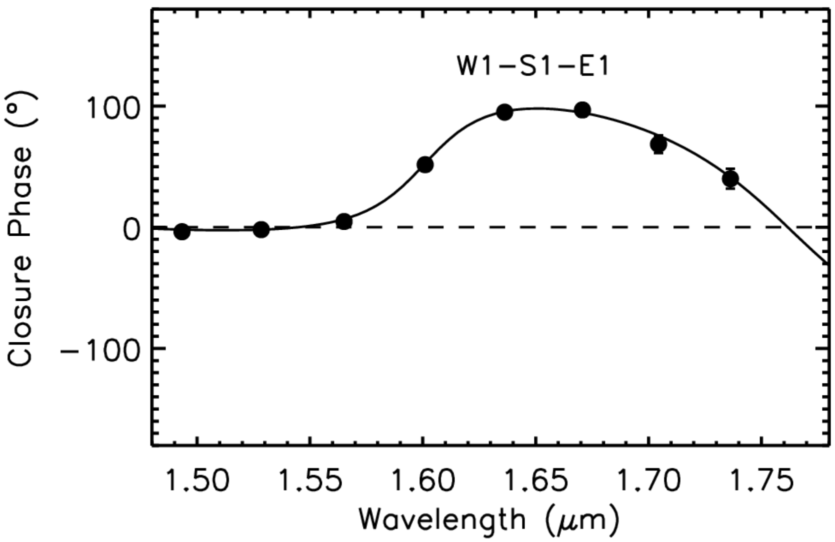
Separation = 7.28 mas, PA = 193.1°

# Examples of MIRC Visibilities and Closure Phases

Squared Visibility




Closure Phase



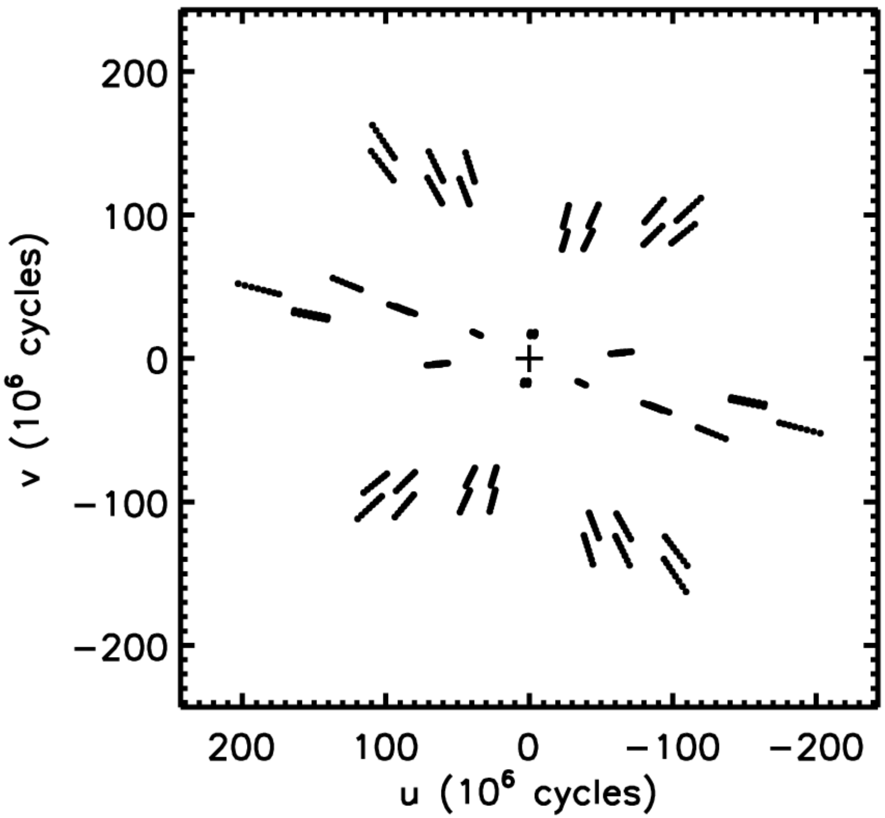

Incoherent light from the wide component B

- contributes 29% of total light

Separation = 7.28 mas, PA = 193.1°

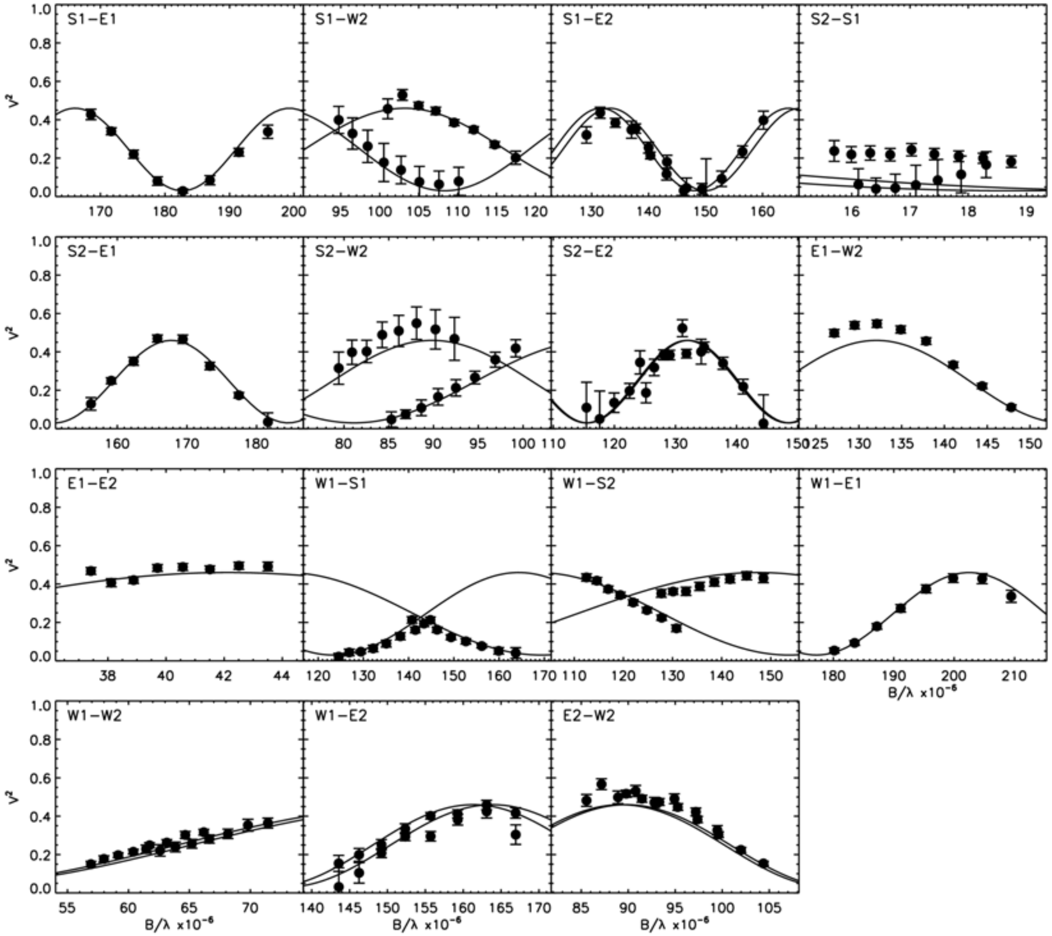
Flux ratio Ab/Aa = 0.60

# uv Coverage - MIRC 6T

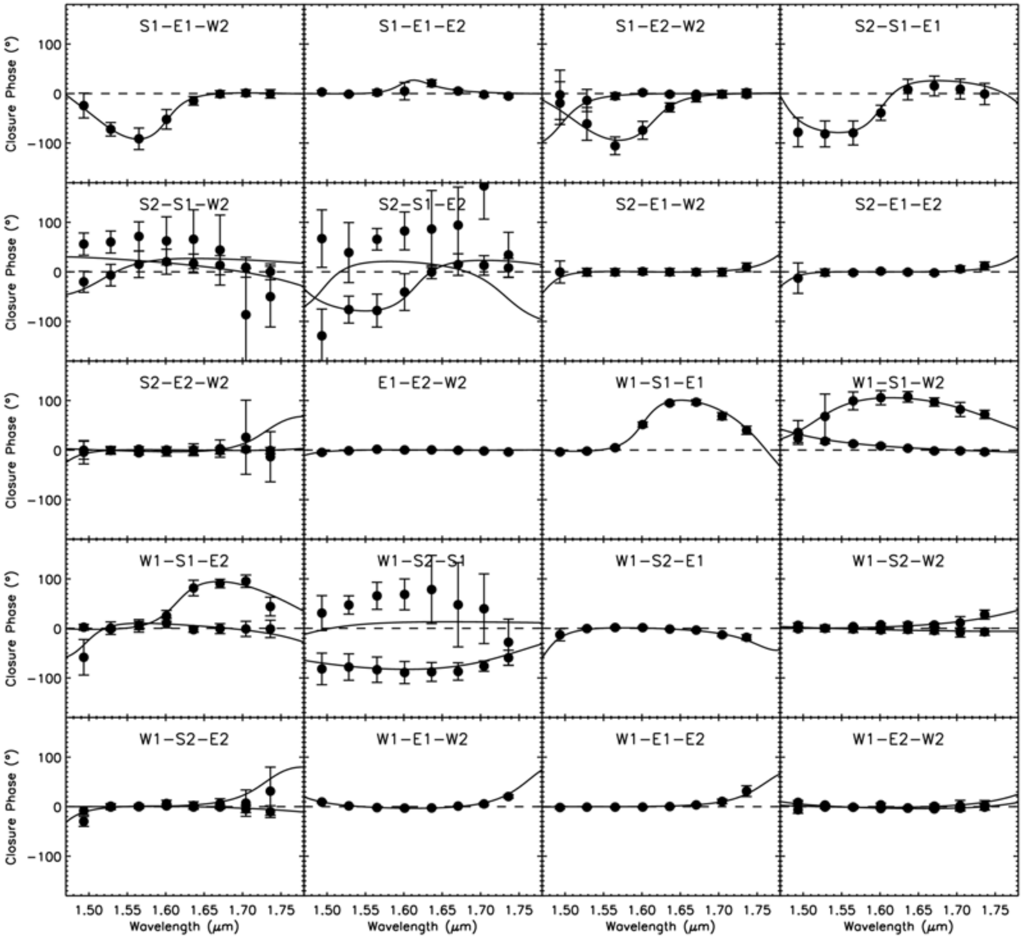



UT 2011Sep29

# Visibilities - UT 2011Sep29

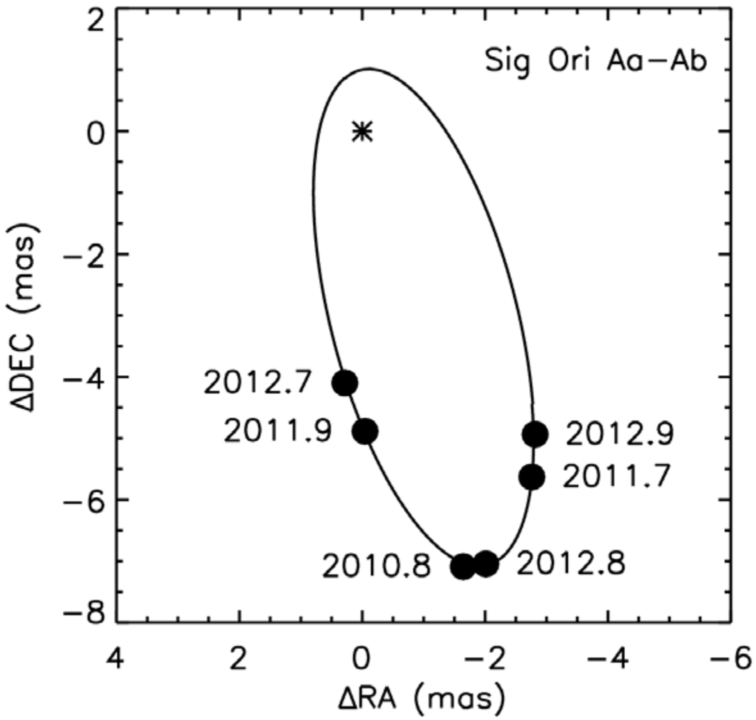


# Closure Phases - UT 2011Sep29

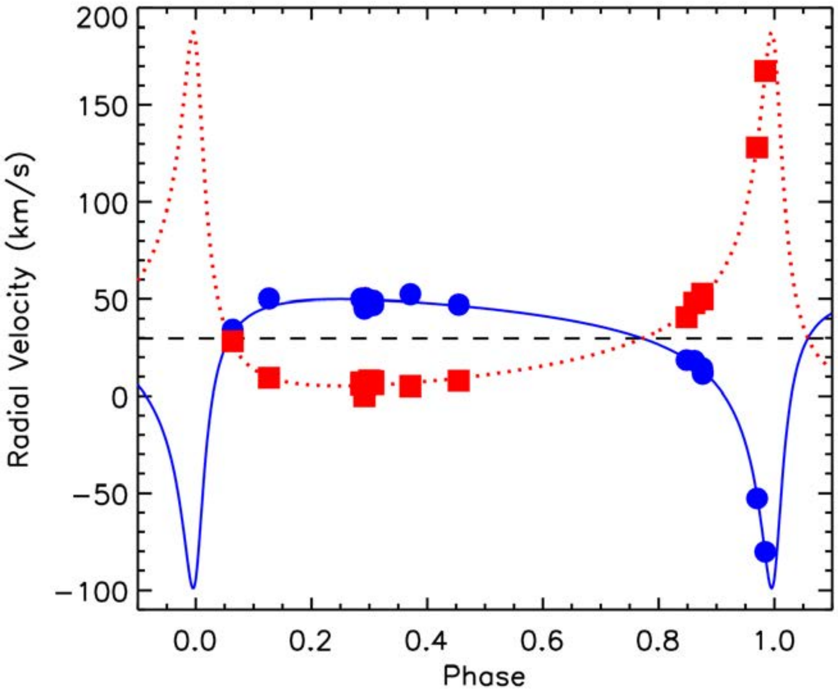


# Orbit of Sigma Ori Aa-Ab

Visual Orbit from MIRC

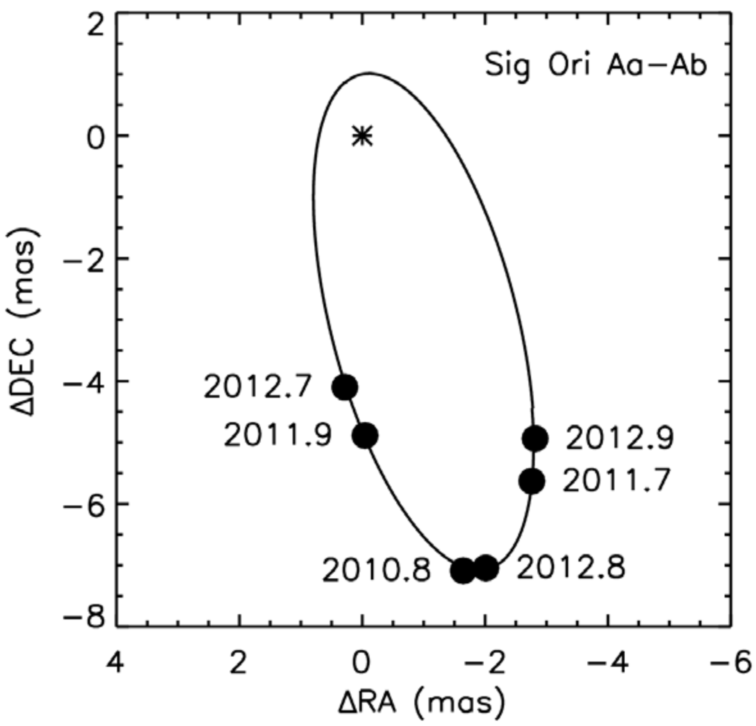



RV from Simon-Diaz et al. 2011




Simultaneous fit to visual orbit and SB2 radial velocities

# Orbit of Sigma Ori Aa-Ab




Orbital Parameters:

$P = 143.25 \pm 0.06$ days

$e = 0.778 \pm 0.004$

$a = 4.30 \pm 0.02$ mas

$i = 57.0° \pm 0.8°$

$K_{Aa} = 74.5 \pm 1.9$ km/s

$K_{Ab} = 91.3 \pm 2.1$ km/s

Masses and distance:

$M_{Aa} = 15.6 \pm 0.9\ M_{\odot}$

$M_{Ab} = 12.8 \pm 0.7\ M_{\odot}$

$d = 380.4 \pm 2.6$ pc

# Comparison of NPOI and CHARA:

Orbital Parameters:

$P = 143.25 \pm 0.06$ days

$e = 0.778 \pm 0.004$

$a = 4.30 \pm 0.02$ mas

$i = 57.0° \pm 0.8°$

$K_{Aa} = 74.5 \pm 1.9$ km/s

$K_{Ab} = 91.3 \pm 2.1$ km/s

NPOI:

Masses and distance:

$M_{Aa} = 15.6 \pm 0.9\ M_{\odot}$

$M_{Ab} = 12.8 \pm 0.7\ M_{\odot}$

$d = 380.4 \pm 2.6$ pc

# Comparison of NPOI and CHARA:

| Orbital Parameters: | NPOI: |
|---|---|
| P = 143.25 ± 0.06 days | P = 143.22 days |
| e = 0.778 ± 0.004 | |
| a = 4.30 ± 0.02 mas | a = 4.3 mas |
| i = 57.0° ± 0.8° | i = 56.3° |
| $K_{Aa}$ = 74.5 ± 1.9 km/s | |
| $K_{Ab}$ = 91.3 ± 2.1 km/s | |

| Masses and distance: | |
|---|---|
| $M_{Aa}$ = 15.6 ± 0.9 $M_\odot$ | $M_{Aa}$ = 16.9 $M_\odot$ |
| $M_{Ab}$ = 12.8 ± 0.7 $M_\odot$ | $M_{Ab}$ = 12.4 $M_\odot$ |
| d = 380.4 ± 2.6 pc | d = 385 pc |

# Comparison of NPOI and CHARA:

| Orbital Parameters: | | NPOI: |
|---|---|---|
| $P = 143.25 \pm 0.06$ days | → | $P = 143.22$ days |
| $e = 0.778 \pm 0.004$ | | |
| $a = 4.30 \pm 0.02$ mas | → | $a = 4.3$ mas |
| $i = 57.0° \pm 0.8°$ | → | $i = 56.3°$ |
| $K_{Aa} = 74.5 \pm 1.9$ km/s | | |
| $K_{Ab} = 91.3 \pm 2.1$ km/s | | |
| **Masses and distance:** | | |
| $M_{Aa} = 15.6 \pm 0.9\ M_\odot$ | → | $M_{Aa} = 16.9\ M_\odot$ |
| $M_{Ab} = 12.8 \pm 0.7\ M_\odot$ | → | $M_{Ab} = 12.4\ M_\odot$ |
| $d = 380.4 \pm 2.6$ pc | → | $d = 385$ pc |

Possible differences

- C. Hummel - better RV coverage of SB2 orbit during periastron
- C. Hummel - more VB points that get slightly to periastron

# Masses of Sigma Ori Aa, Ab, B

Visual and spectroscopic orbit of Aa-Ab:

P = 143 days
a = 4.3 mas

$M_{Aa} = 15.6 \pm 0.9\ M_\odot$
$M_{Ab} = 12.8 \pm 0.7\ M_\odot$
$d = 380.4 \pm 2.6$ pc

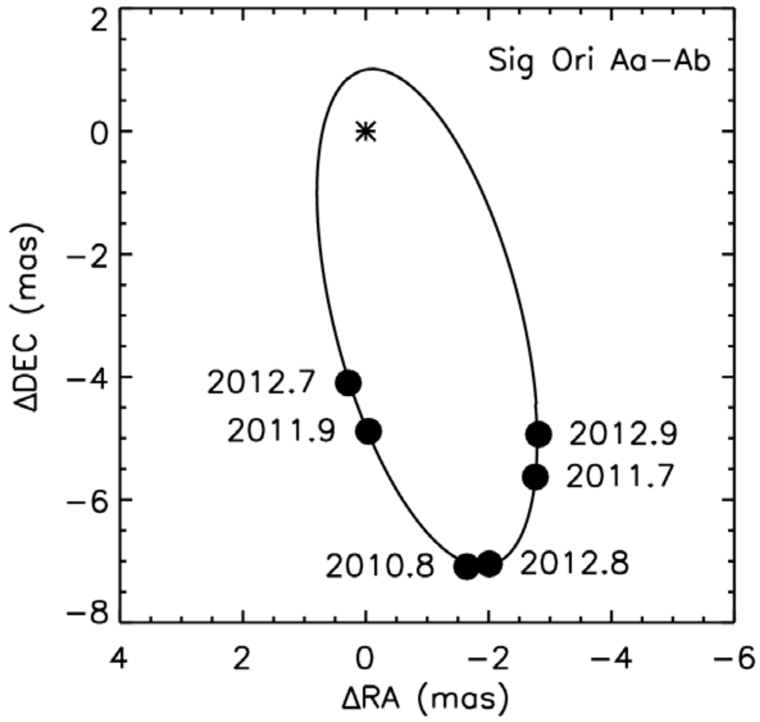
Visual orbit A-B (Turner et al. 2008):

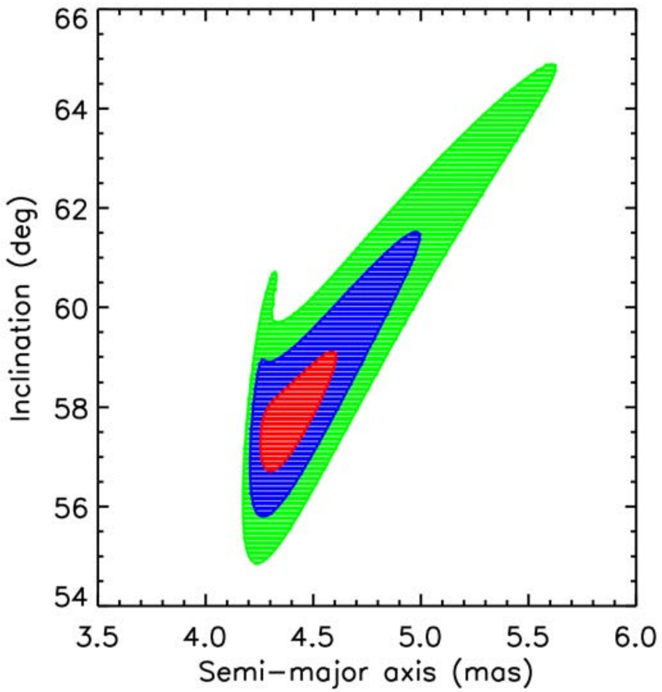
P = 157 years
a = 266 mas

$M_{Aa} + M_{Ab} + M_B = a^3/P^2 = 42.3 \pm 3.2\ M_\odot$

$M_B = 13.9 \pm 3.4\ M_\odot$

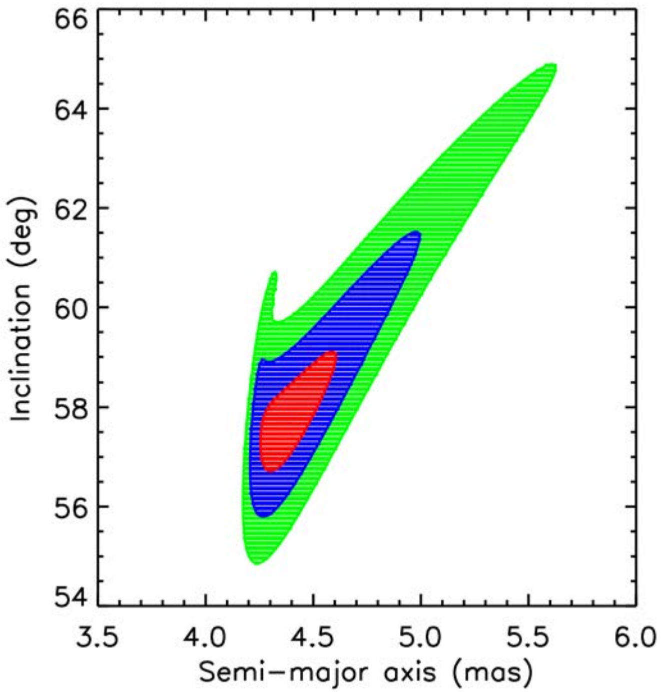
# $\chi^2$ Confidence Intervals



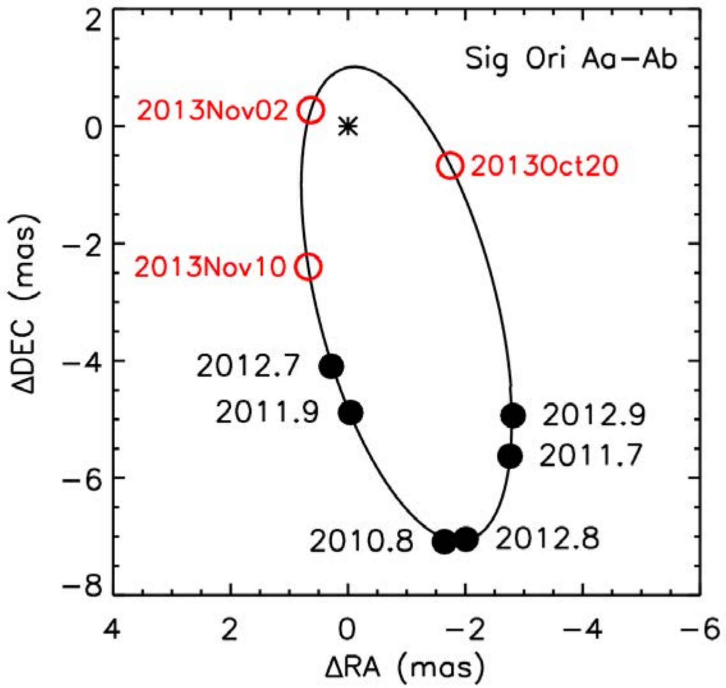



# $\chi^2$ Confidence Intervals

- Strong correlation between inclination and semi-major axis
- 3-σ confidence intervals cover range:
  - $M_{Aa}$: 6 - 18 $M_\odot$
  - $M_{Ab}$: 5 - 15 $M_\odot$



# Periastron Passage - 2013 Nov 1




Requested 3 observations with MIRC in 2013Nov to get good coverage as sig Ori Aa-Ab goes through periastron.

# Summary

- Using MIRC, we spatially resolved the orbit of sigma Ori Aa-Ab
- Combined with the SB2 radial velocities and the visual orbit of A-B, we determined the masses of all 3 components in sigma Ori Aa, Ab, B
  - O9.5V - B0.5V
- Obtain precise distance to sigma Ori Cluster
- Expect to improve and finalize results by mapping the orbit through periastron passage in 2013