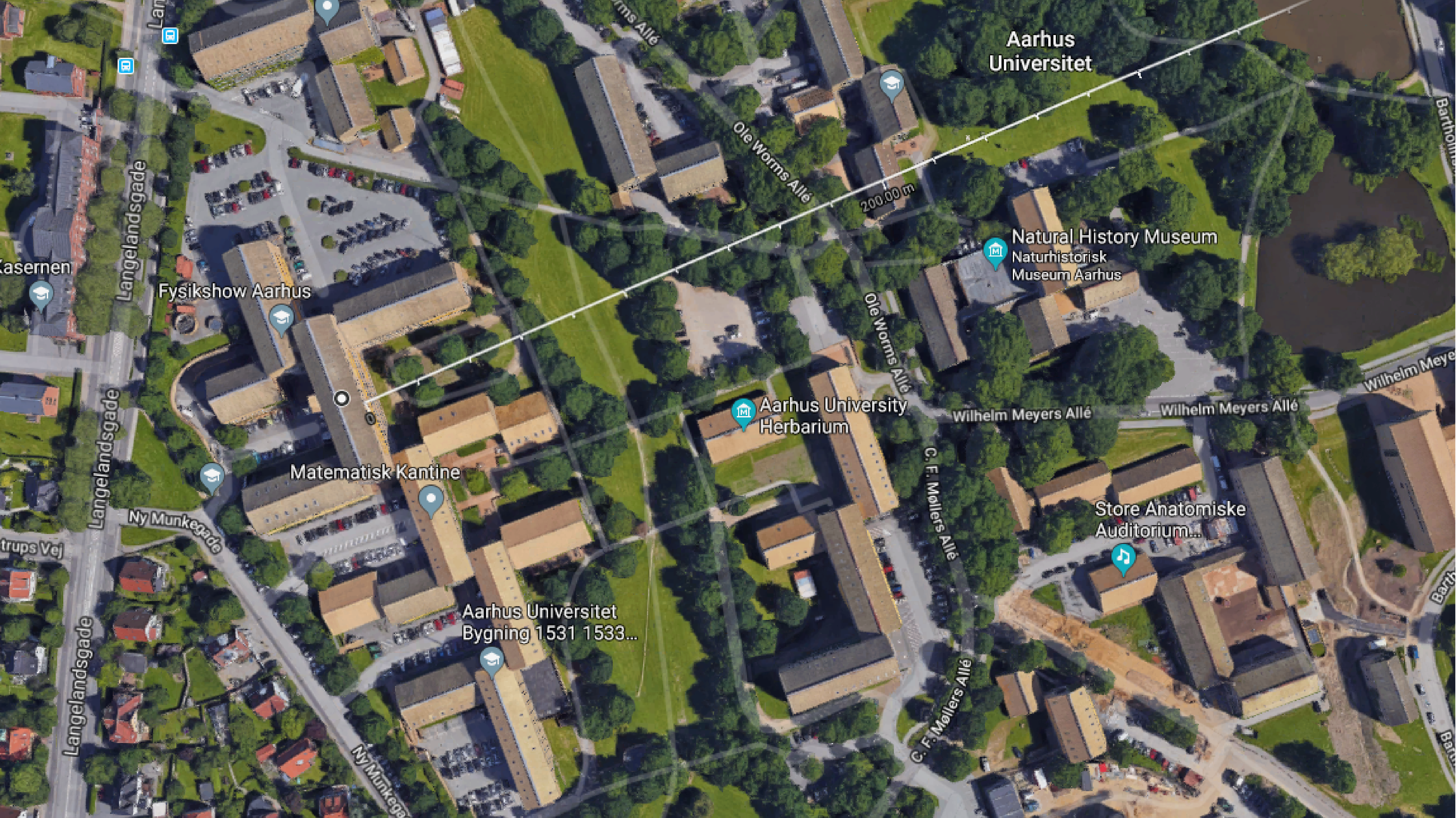
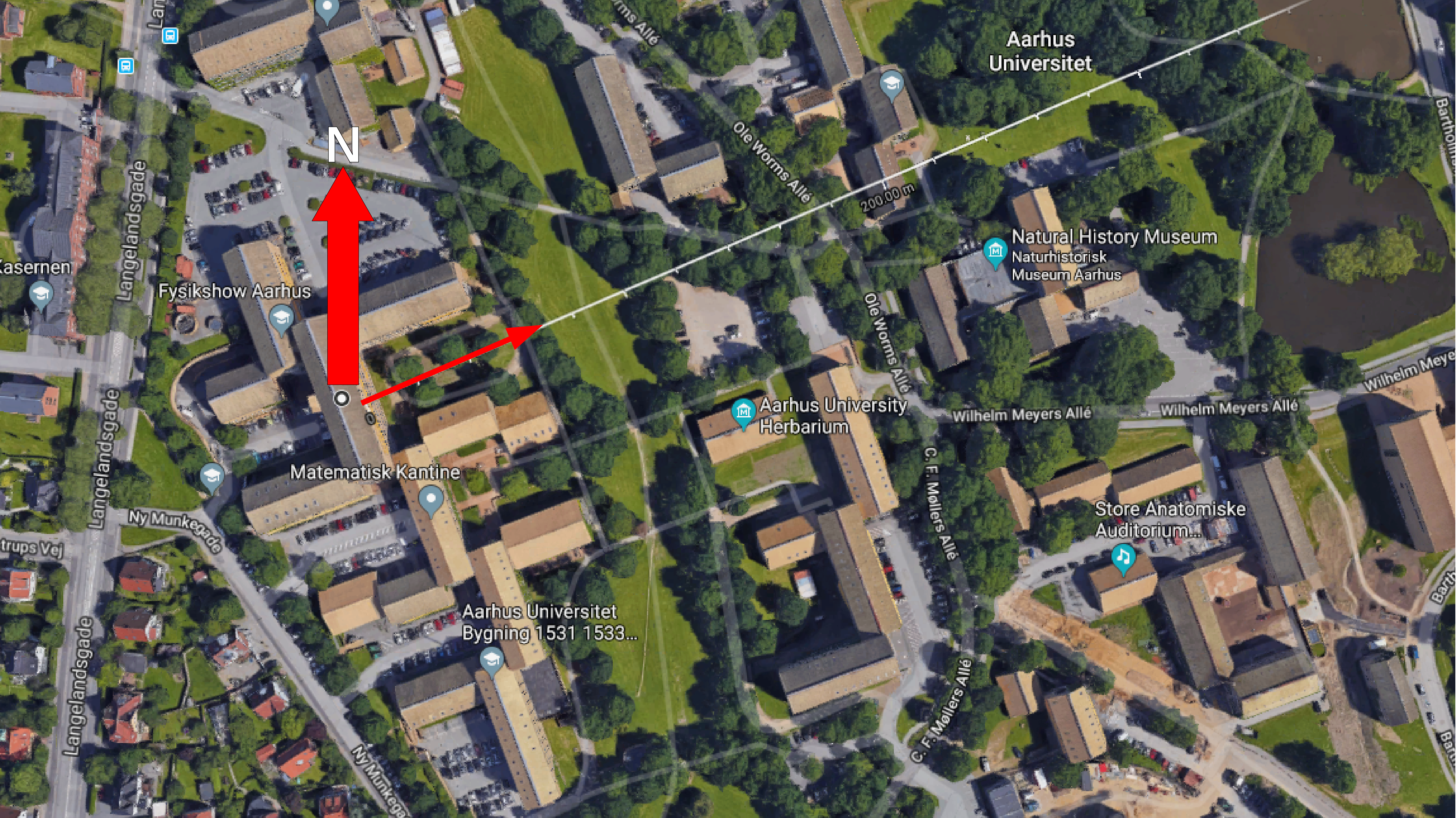
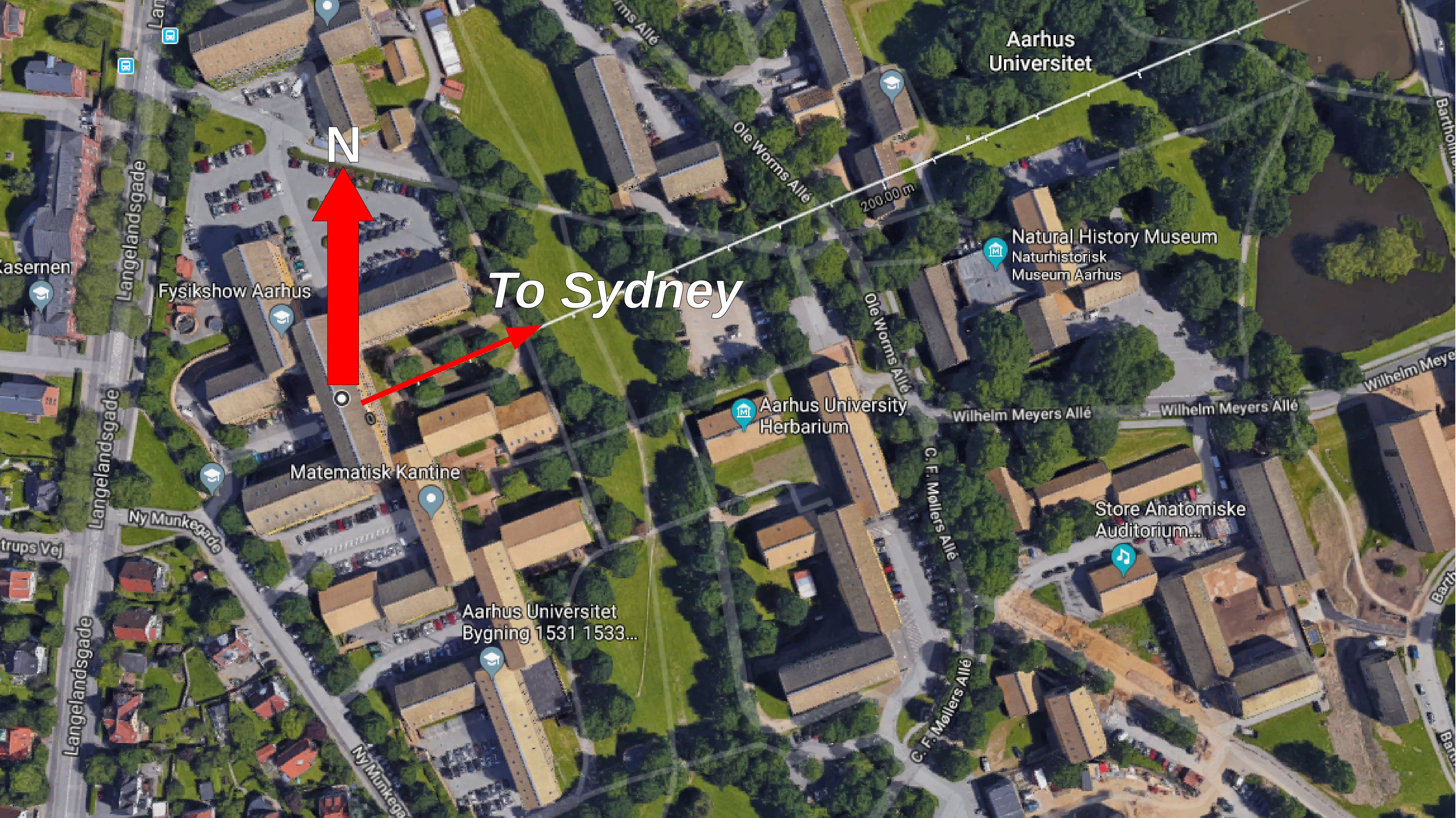
Interferometry and Asteroseismology

Tim White
Stellar Astrophysics Centre, Aarhus University

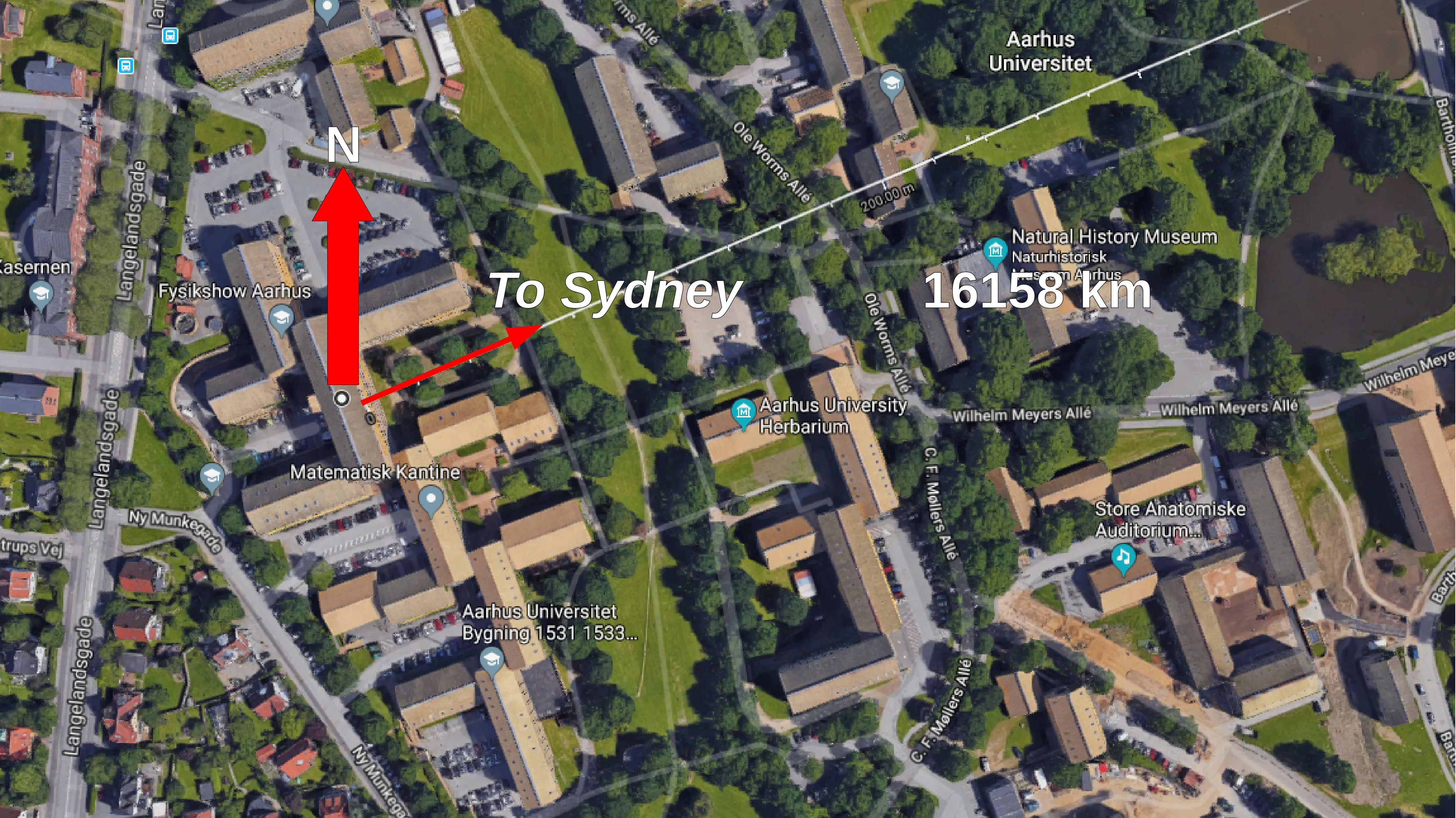

Aarhus Universitet
200.00 m
Ole Worms Allé
Natural History Museum
Naturhistorisk
Museum Aarhus
Fysikshow Aarhus
Langelandsgade
Aarhus University
Herbarium
Wilhelm Meyers Allé
Wilhelm Meyers Allé
Matematisk Kantine
C. F. Møllers Allé
Store Anatomiske
Auditorium...
Ny Munkegade
Aarhus Universitet
Bygning 1531 1533...



N
Aarhus Universitet
200.00 m
Natural History Museum
Naturhistorisk Museum Aarhus
Fysikshow Aarhus
Kasernen
Langelandsgade
Ole Worms Allé
Aarhus University Herbarium
Wilhelm Meyers Allé
Matematisk Kantine
C. F. Møllers Allé
Store Anatomiske Auditorium...
Ny Munkegade
Aarhus Universitet Bygning 1531 1533...



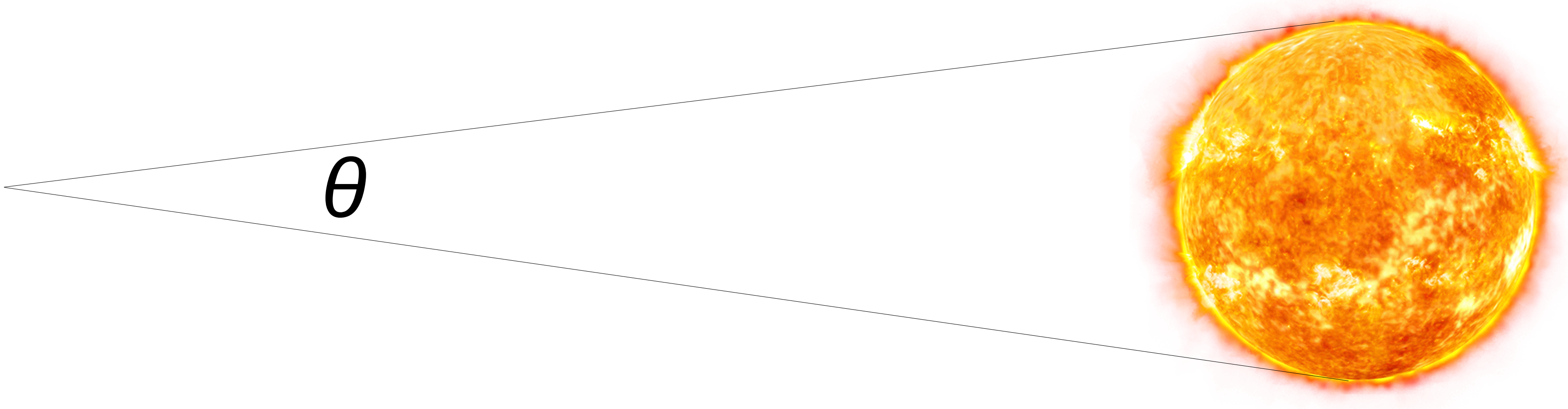
N
To Sydney
Aarhus Universitet
200.00 m
Natural History Museum
Naturhistorisk Museum Aarhus
Fysikshow Aarhus
Matematisk Kantine
Aarhus University Herbarium
Aarhus Universitet Bygning 1531 1533...
Store Anatomiske Auditorium...
Ole Worms Allé
Wilhelm Meyers Allé
C. F. Møllers Allé
Langelandsgade
Ny Munkegade


N
To Sydney
16158 km
200.00 m
Aarhus Universitet
Natural History Museum
Naturhistorisk
Fysikshow Aarhus
Matematisk Kantine
Aarhus University Herbarium
Store Anatomiske Auditorium...
Aarhus Universitet Bygning 1531 1533...
Ole Worms Allé
Wilhelm Meyers Allé
C. F. Møllers Allé
Langelandsgade
Ny Munkegade


N
To Canberra
16156 km
200.00 m
400.00 m
Aarhus Universitet
Natural History Museum
Naturhistorisk
Fysikshow Aarhus
Matematisk Kantine
Aarhus University Herbarium
Store Anatomiske Auditorium...
Aarhus Universitet Bygning 1531 1533...
Langelandsgade
Ny Munkegade
Ole Worms Allé
Wilhelm Meyers Allé
C. F. Møllers Allé

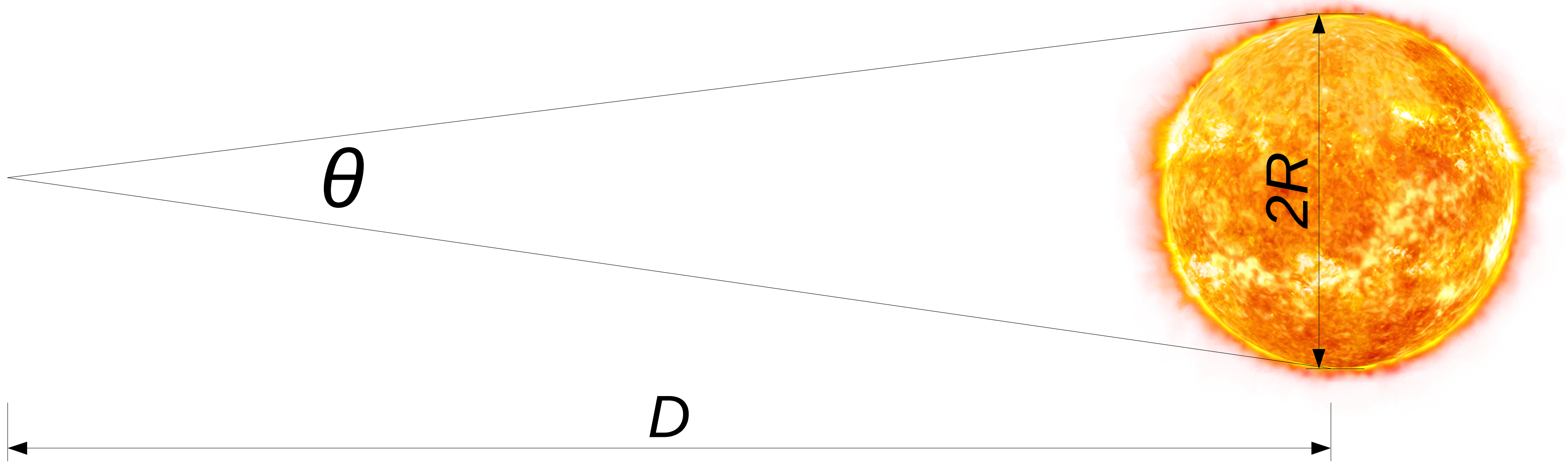
Precise measurements of angles and distances are really useful.

Angular diameter



Angular diameter

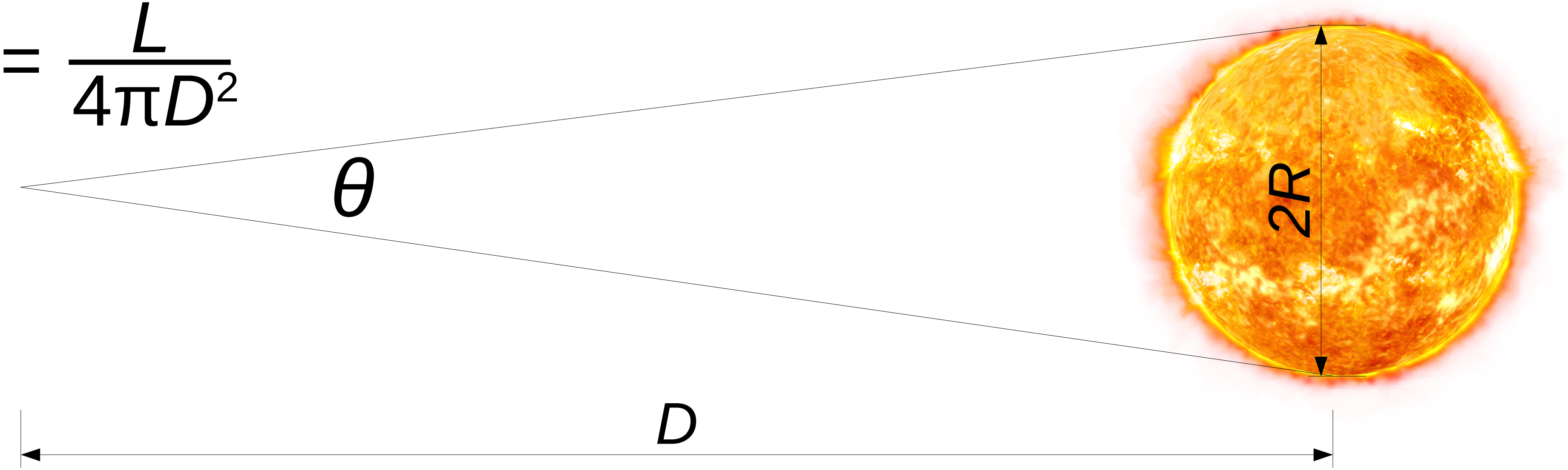
$$R = \tfrac{1}{2}\theta D$$



Angular diameter

$$R = \tfrac{1}{2}\theta D$$

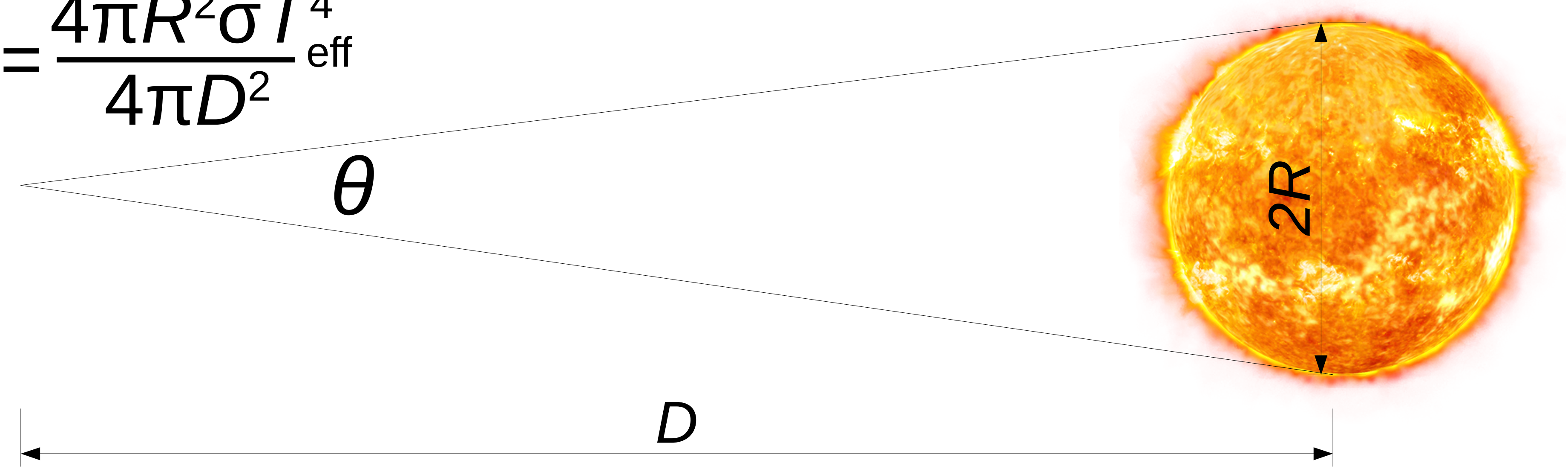
$$f_{\mathrm{bol}} = \frac{L}{4\pi D^2}$$



Angular diameter

$$R = \tfrac{1}{2}\theta D$$

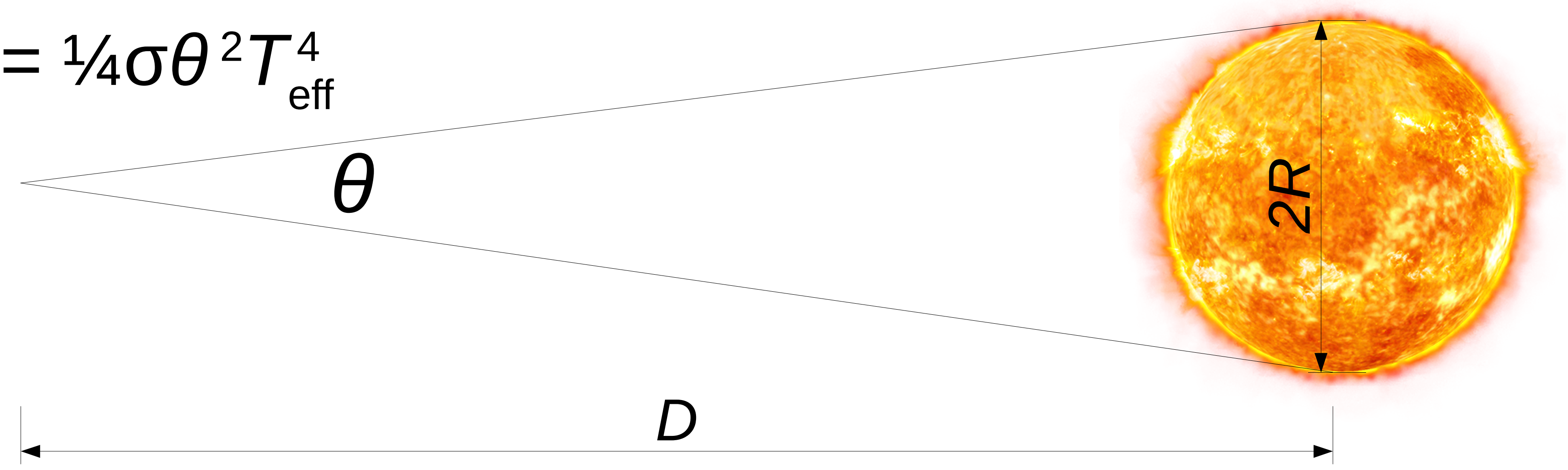
$$f_{\mathrm{bol}} = \frac{4\pi R^2 \sigma T_{\mathrm{eff}}^4}{4\pi D^2}$$

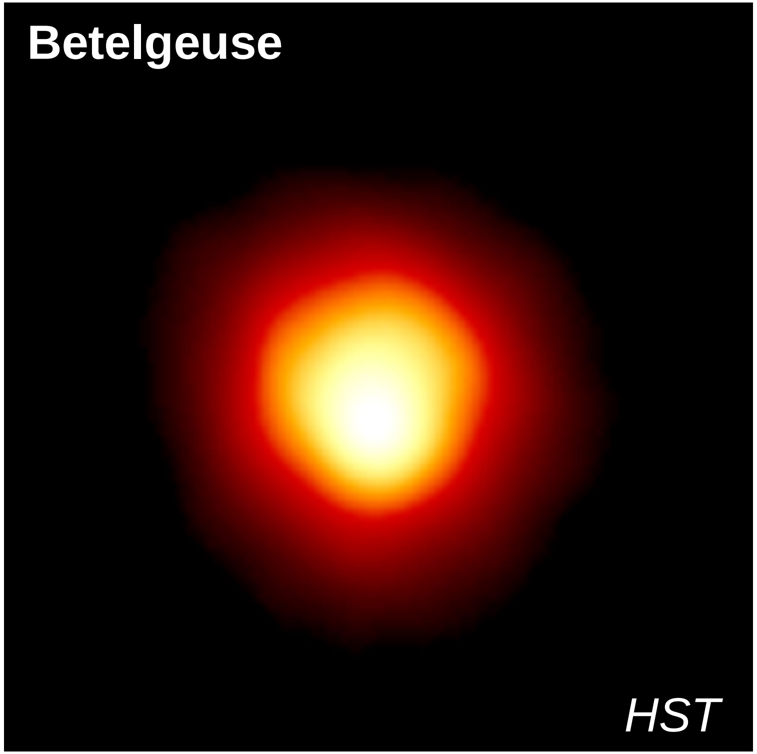


Angular diameter

$$R = \tfrac{1}{2}\theta D$$

$$f_{\text{bol}} = \tfrac{1}{4}\sigma\theta^{2}T_{\text{eff}}^{4}$$

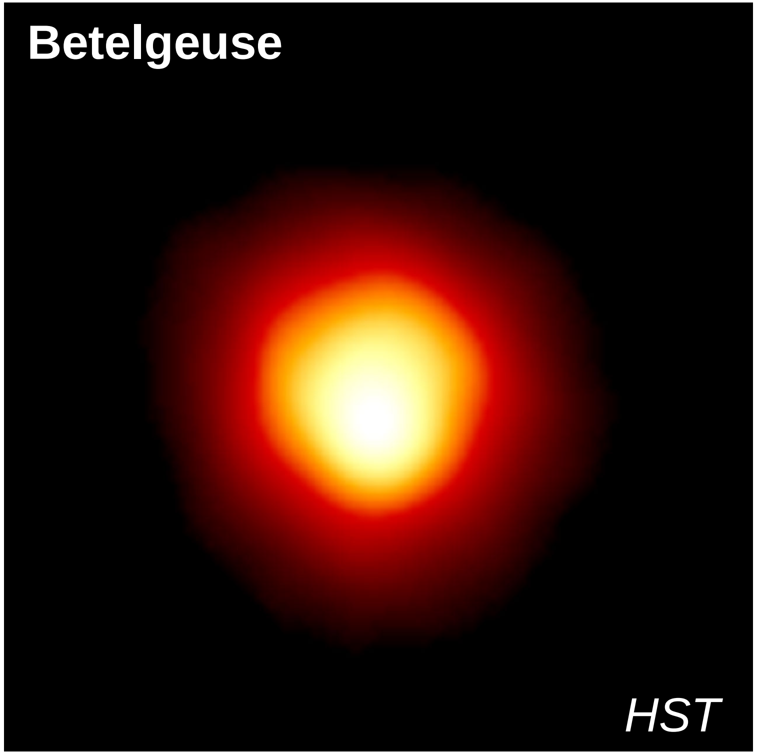




Gilliland & Dupree (1996)

The Sun: ~32 arcmin

Betelgeuse: 125 mas (UV)
55 mas (optical)



Gilliland & Dupree (1996)

The Sun: ~32 arcmin

Betelgeuse: 125 mas (UV)
55 mas (optical)

α Cen A: 8.5 mas

α Cen B: 6.0 mas

The Sun: ~32 arcmin

Betelgeuse: 125 mas (UV)
55 mas (optical)

α Cen A: 8.5 mas

α Cen B: 6.0 mas

The Sun: ~32 arcmin

Betelgeuse: 125 mas (UV)
55 mas (optical)

α Cen A: 8.5 mas

α Cen B: 6.0 mas

20 kr. coin in Aarhus: 1.5 mas

The Sun: ~32 arcmin

Betelgeuse: 125 mas (UV)
55 mas (optical)

α Cen A: 8.5 mas

α Cen B: 6.0 mas

20 kr. coin in Aarhus: 1.5 mas

θ Cyg: 0.75 mas

The Sun: ~32 arcmin

Betelgeuse: 125 mas (UV)
55 mas (optical)

α Cen A: 8.5 mas

α Cen B: 6.0 mas

20 kr. coin in Aarhus: 1.5 mas

θ Cyg: 0.75 mas

The Sun: ~32 arcmin

Betelgeuse: 125 mas (UV)
55 mas (optical)

α Cen A: 8.5 mas

α Cen B: 6.0 mas

20 kr. coin in Aarhus: 1.5 mas

θ Cyg: 0.75 mas

50c coin in Sydney: 0.35 mas

The Sun: ~32 arcmin

Betelgeuse: 125 mas (UV)
55 mas (optical)

α Cen A: 8.5 mas

α Cen B: 6.0 mas

20 kr. coin in Aarhus: 1.5 mas

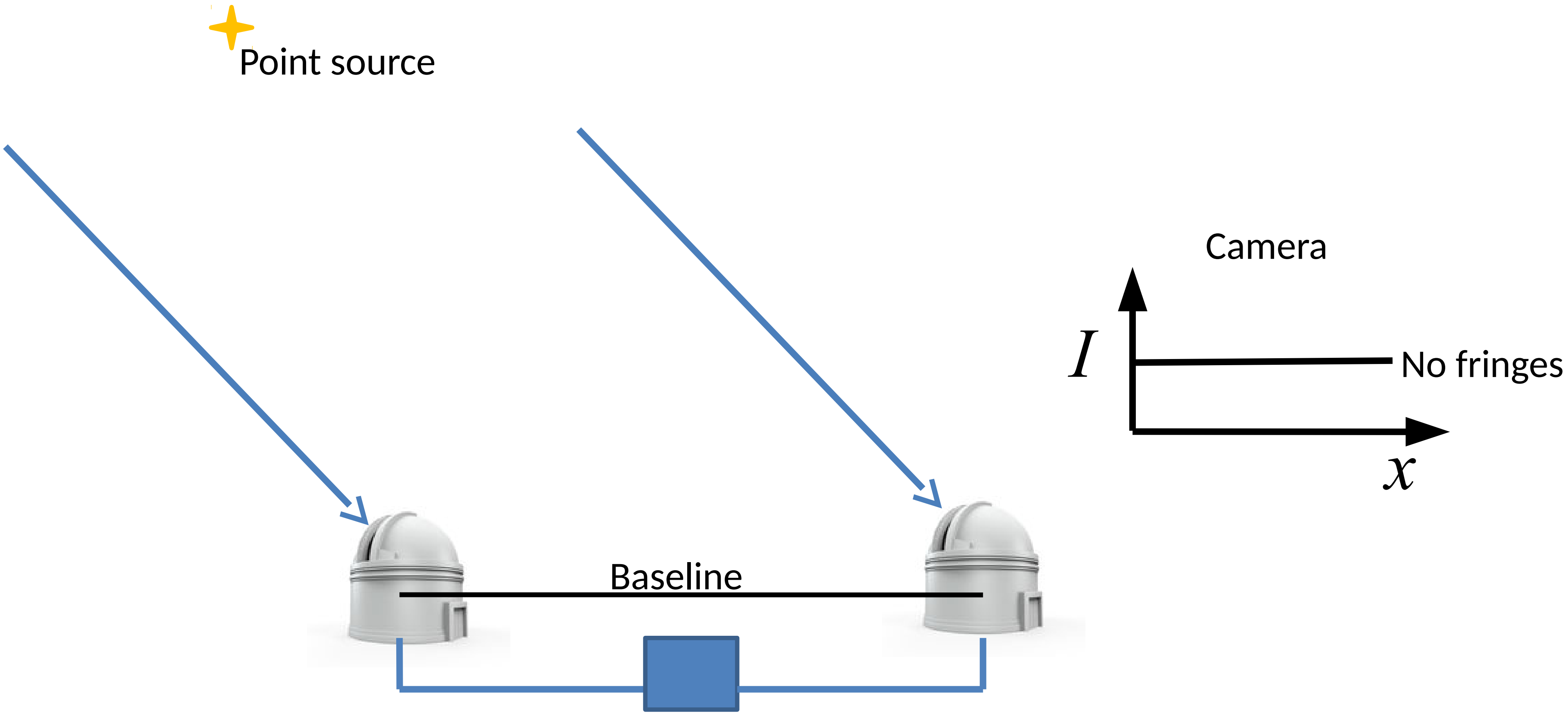
θ Cyg: 0.75 mas

50c coin in Sydney: 0.35 mas

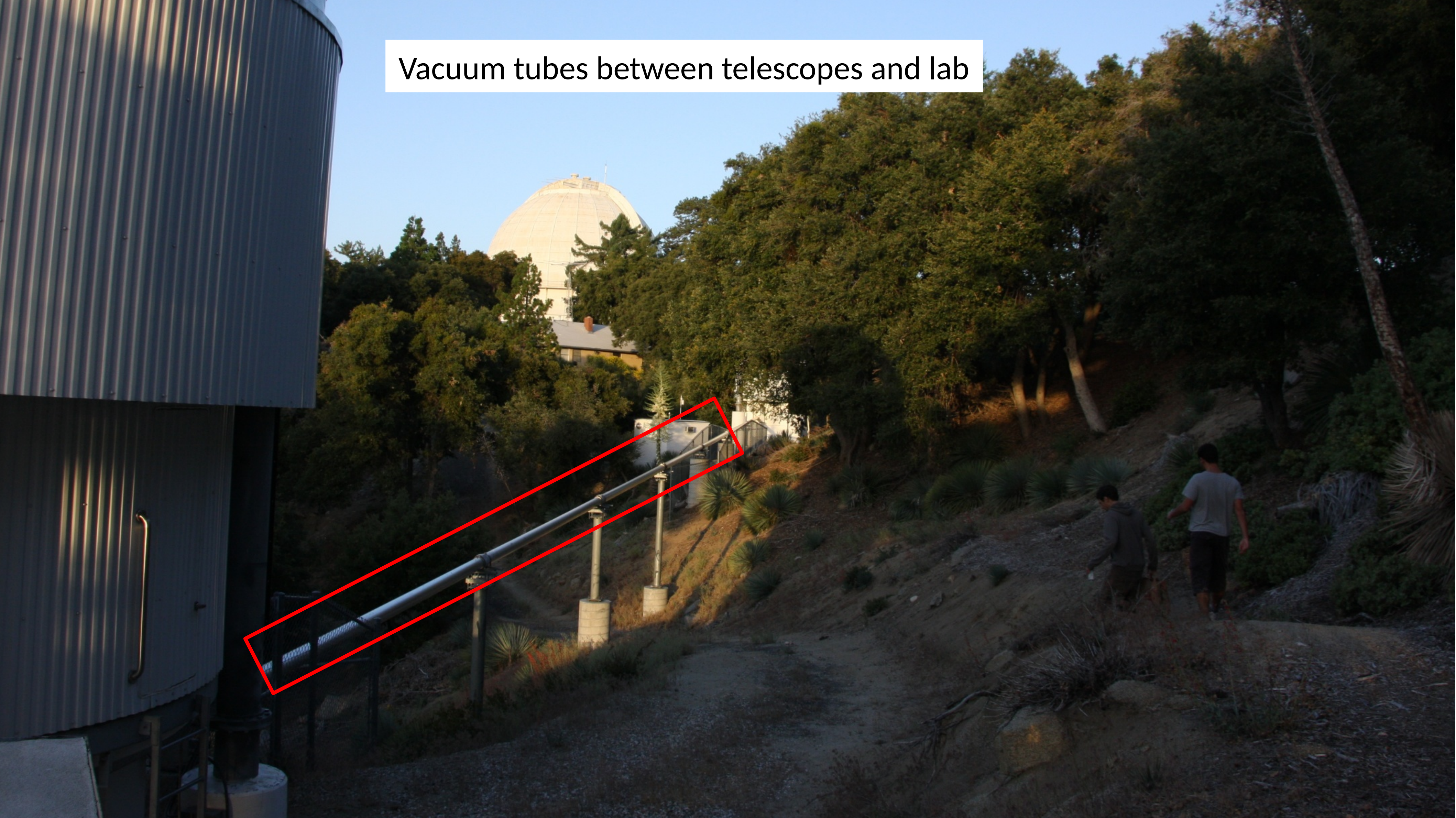
HD 140283: 0.32 mas

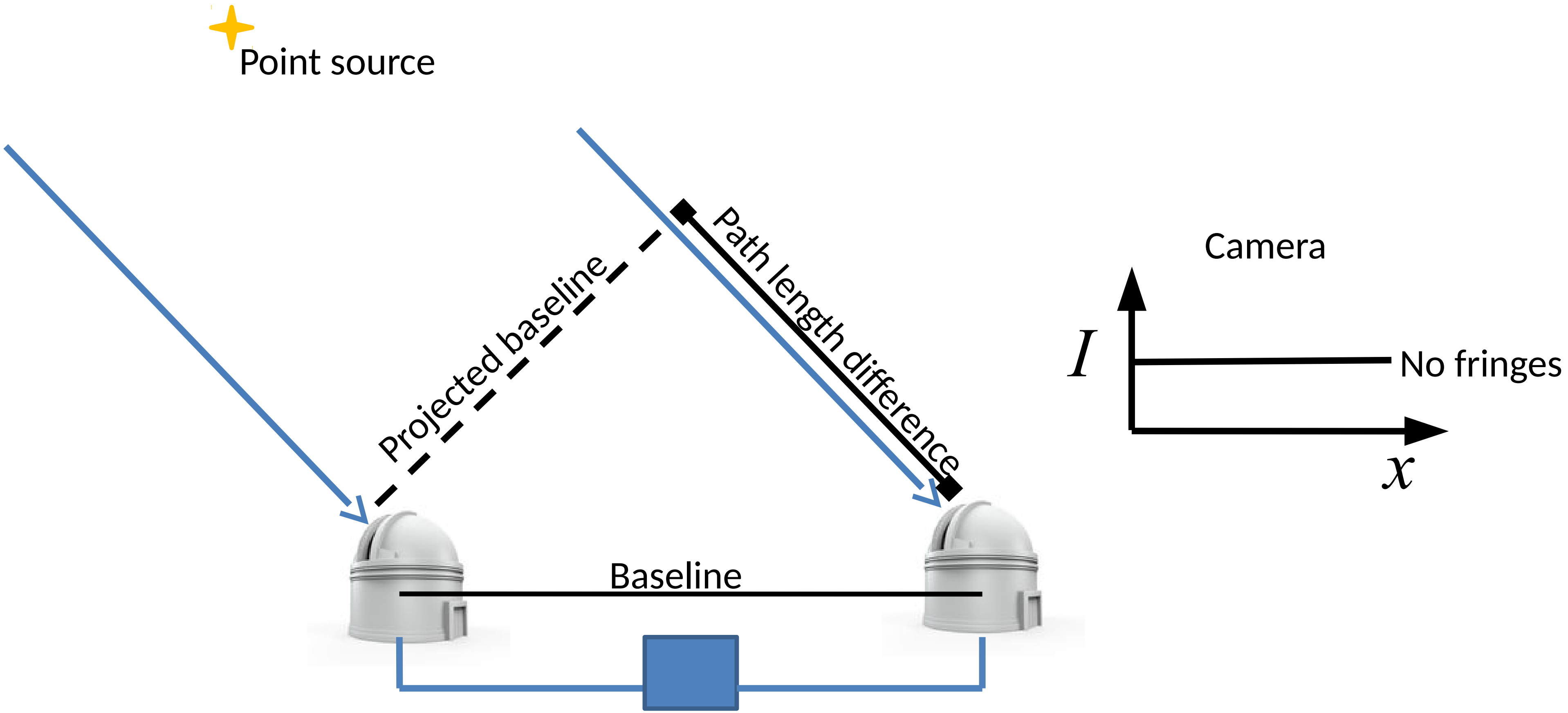

S1
S2
W2
W1
E2
E1
100 m


W2
W1
E2
100 m
E1

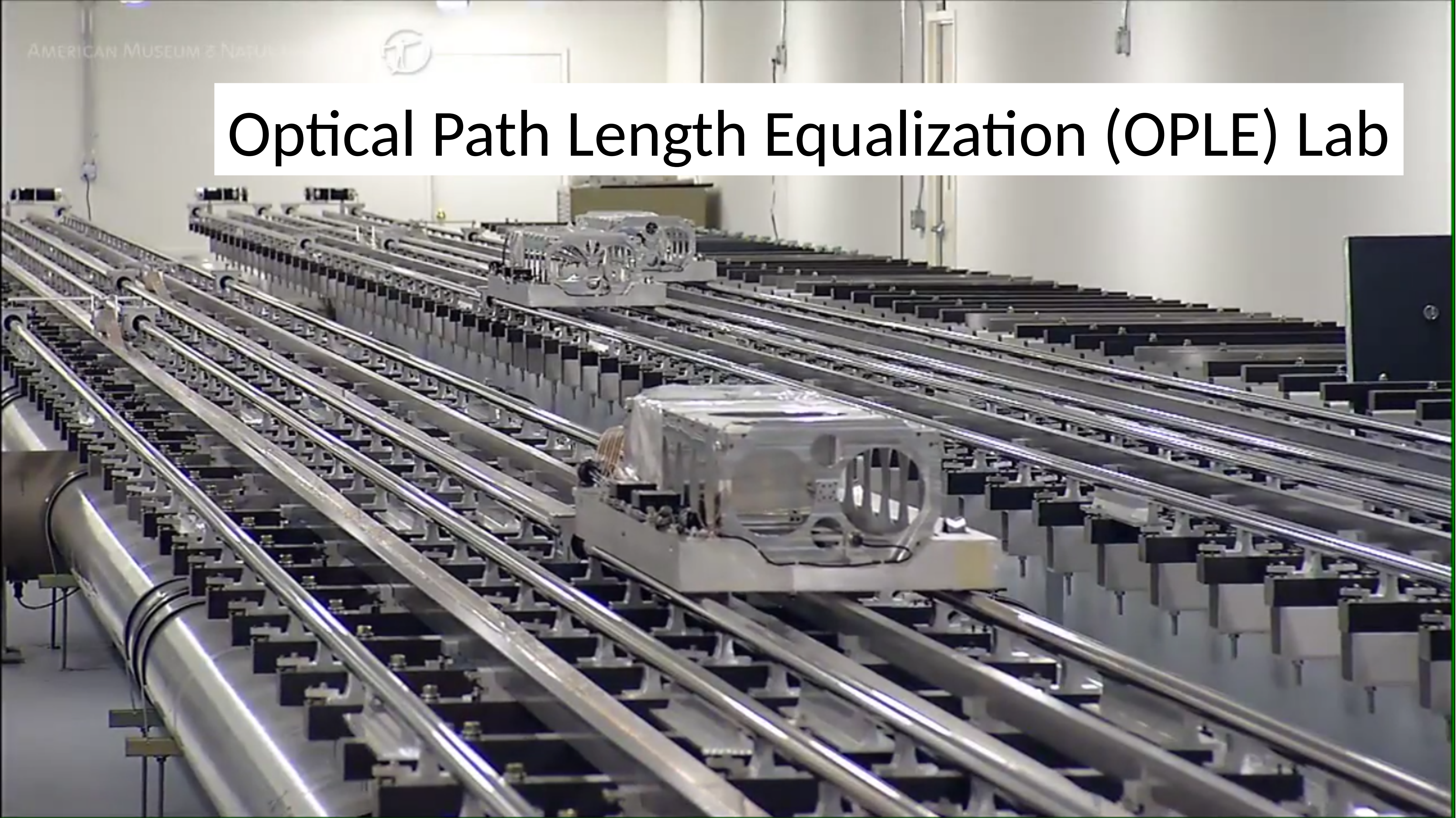

Point source
Camera
I
No fringes
x
Baseline

Vacuum tubes between telescopes and lab

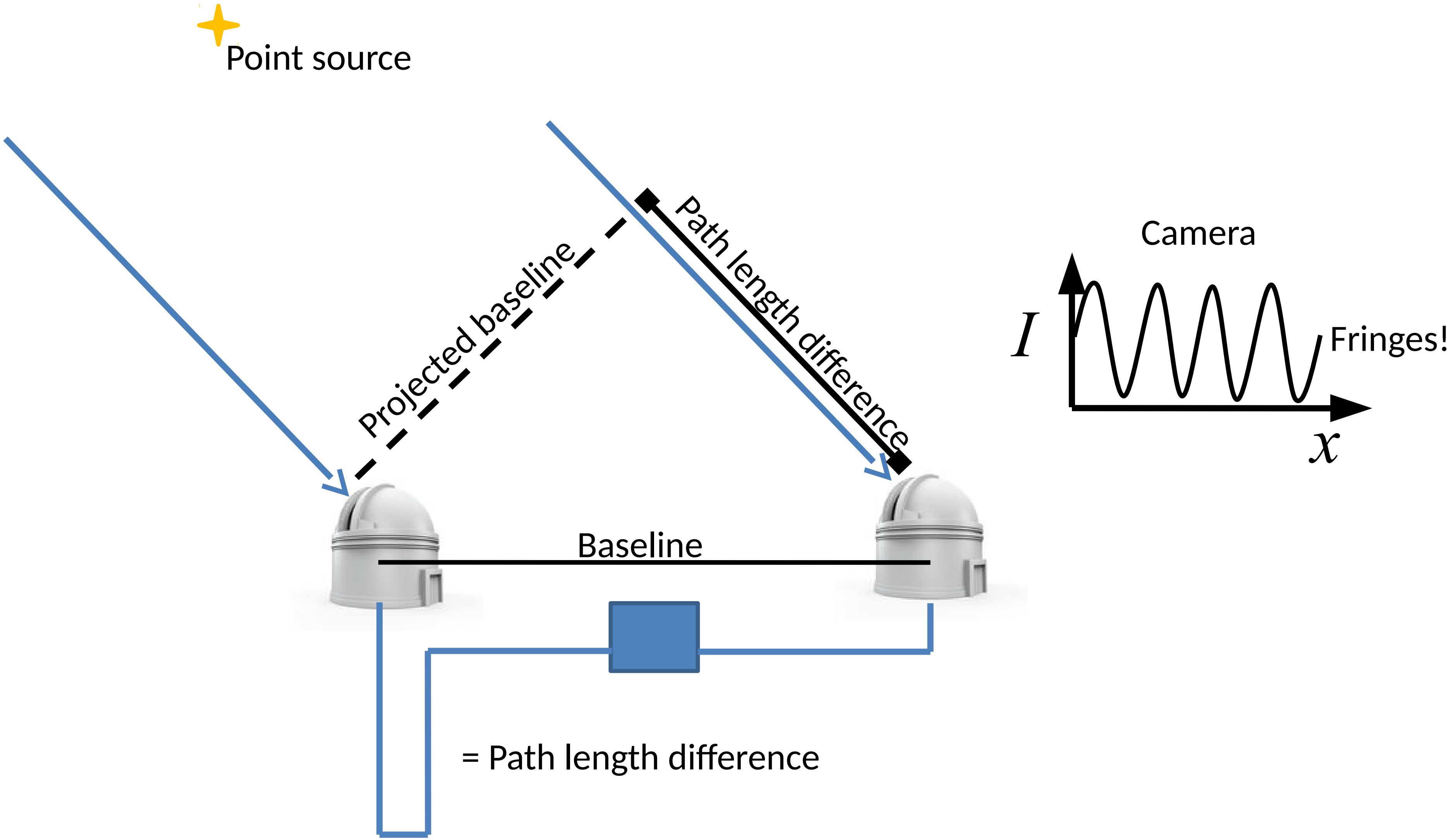



Point source
Projected baseline
Path length difference
Baseline
Camera
I
No fringes
x

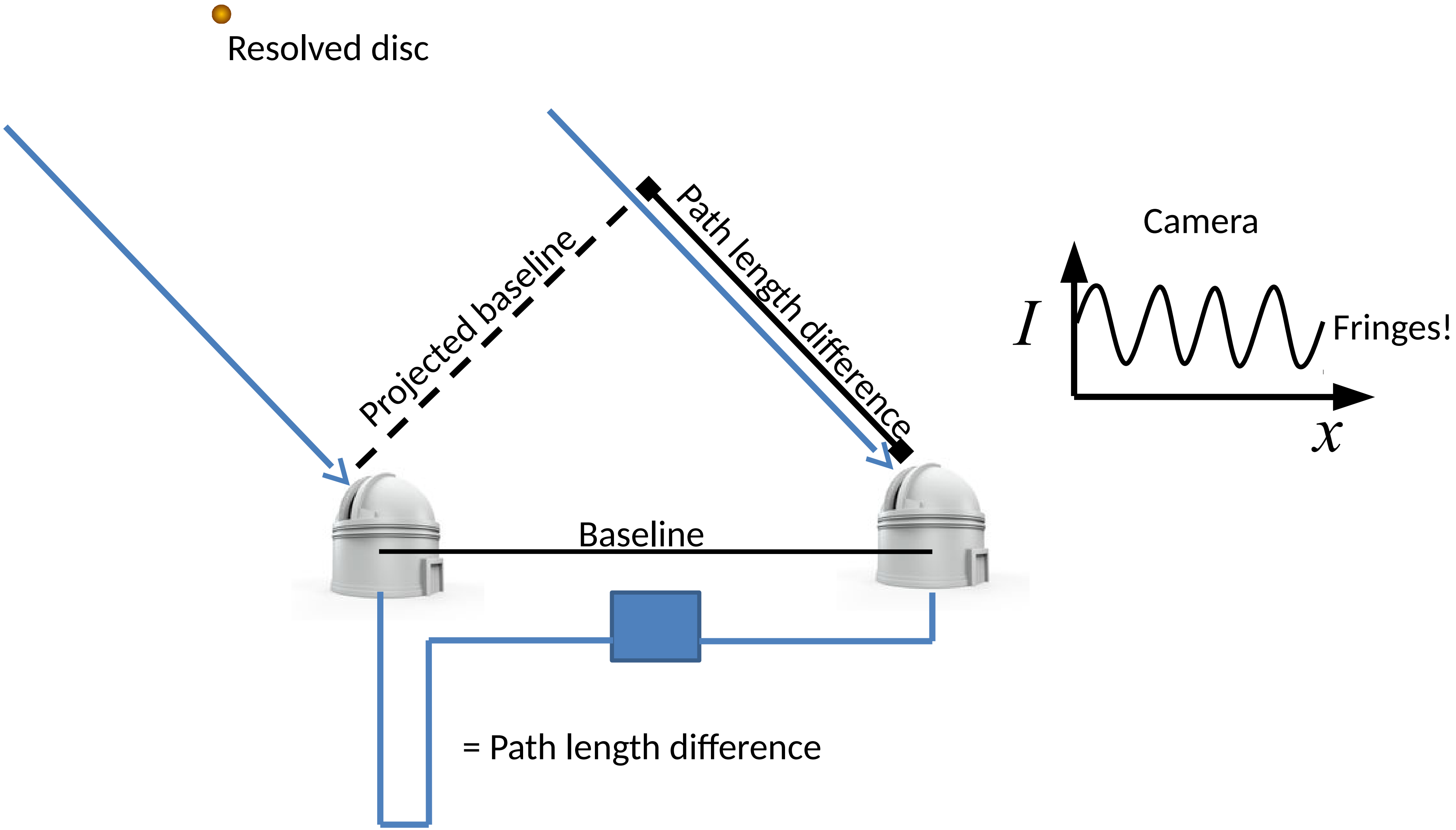
Optical Path Length Equalization (OPLE) Lab

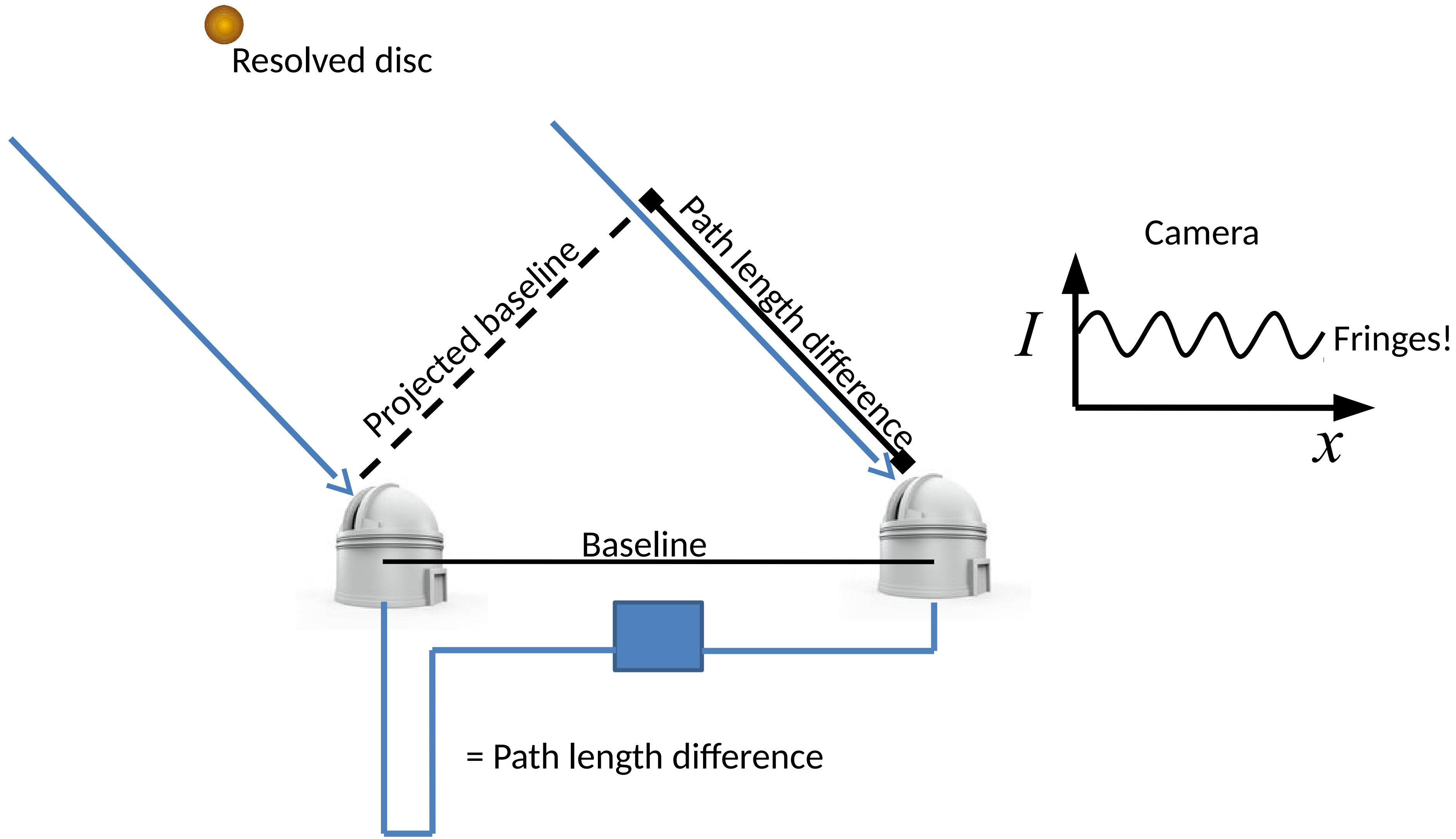


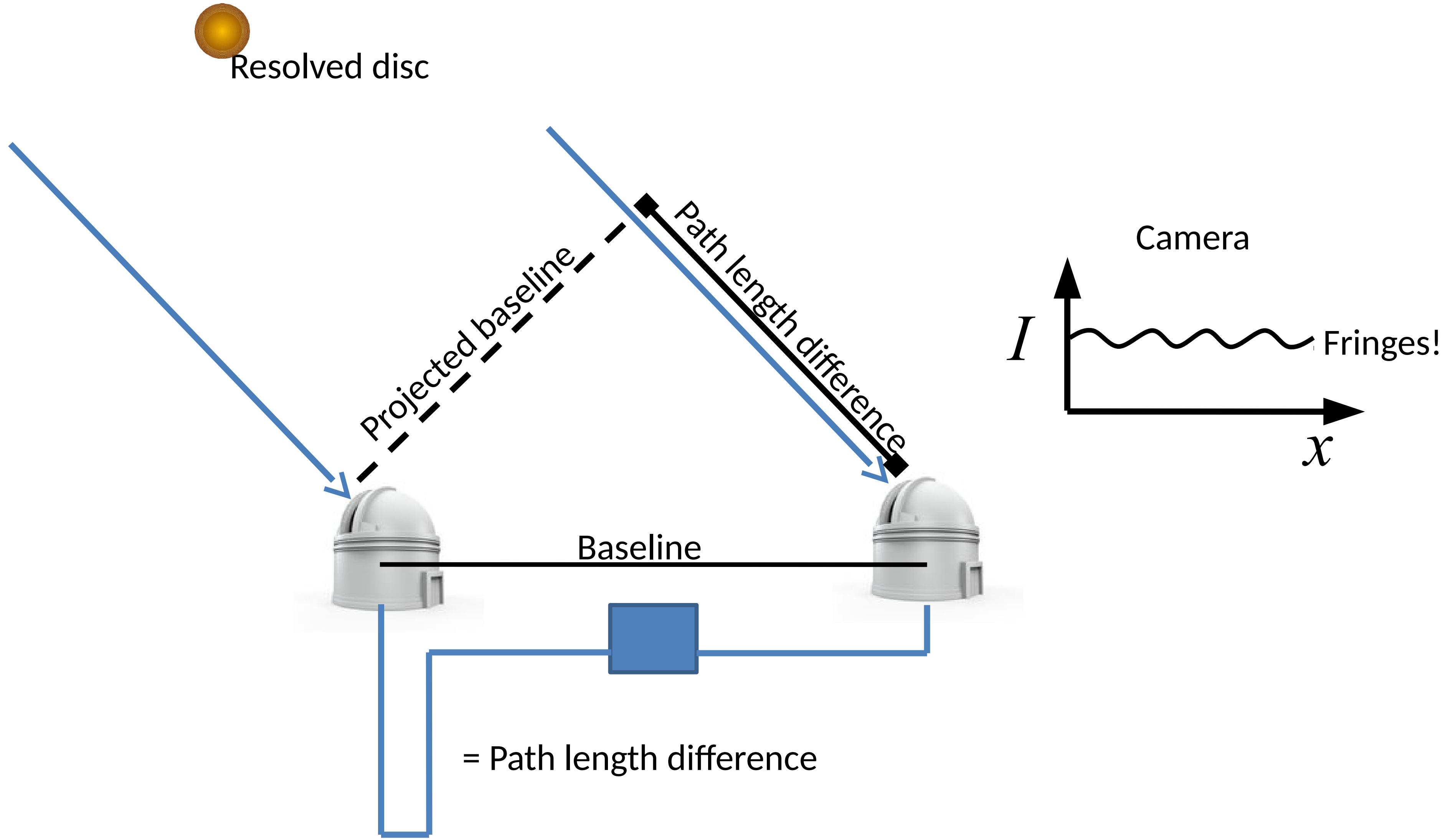
PAVO – one of several beam combiners

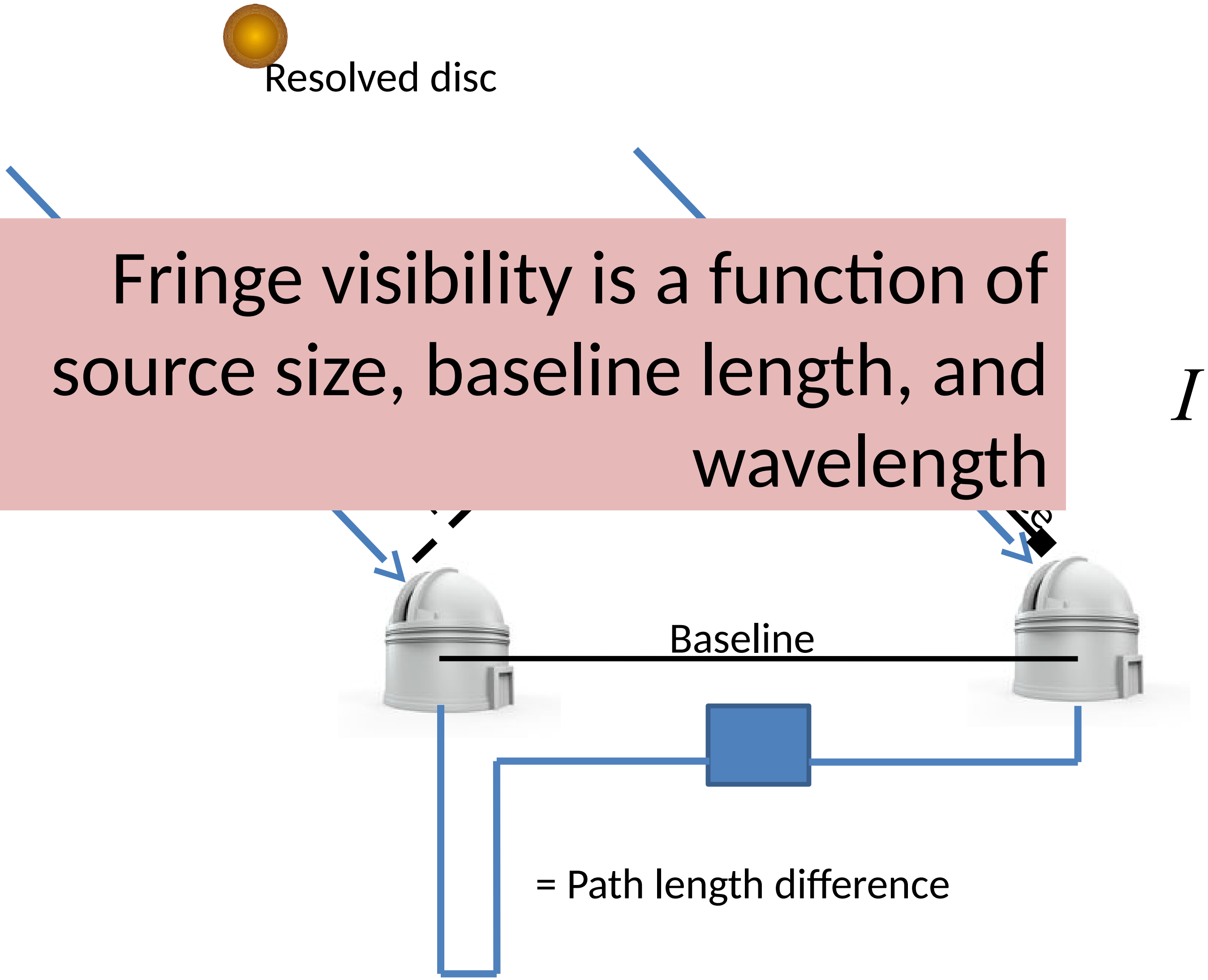


Point source
Projected baseline
Path length difference
Camera
I
Fringes!
x
Baseline
= Path length difference

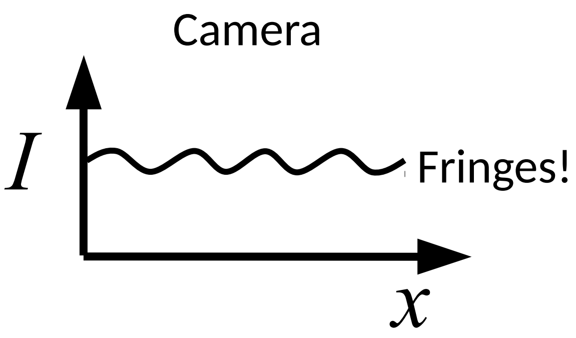

Resolved disc
Projected baseline
Path length difference
Camera
I
Fringes!
x
Baseline
= Path length difference


Resolved disc
Projected baseline
Path length difference
Camera
I
Fringes!
x
Baseline
= Path length difference

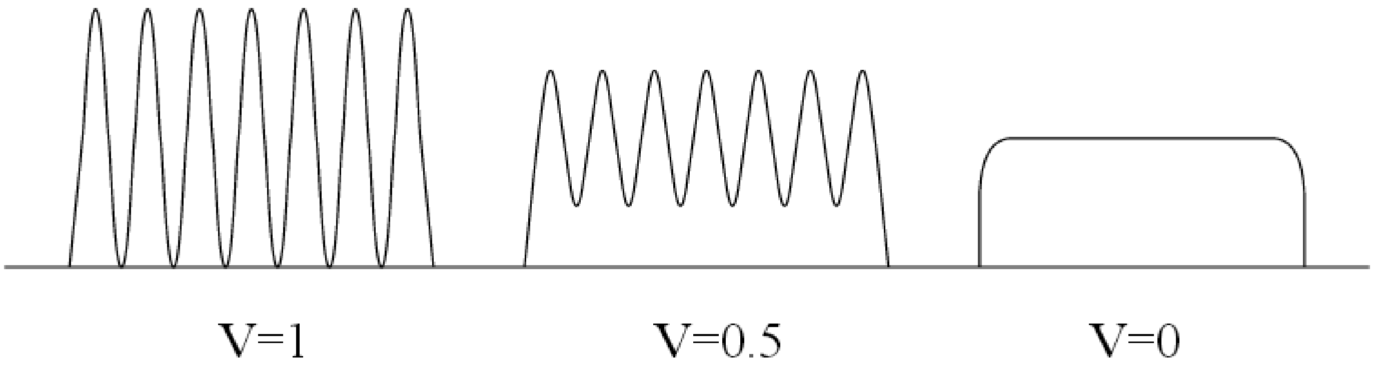

Resolved disc
Projected baseline
Path length difference
Camera
I
Fringes!
x
Baseline
= Path length difference

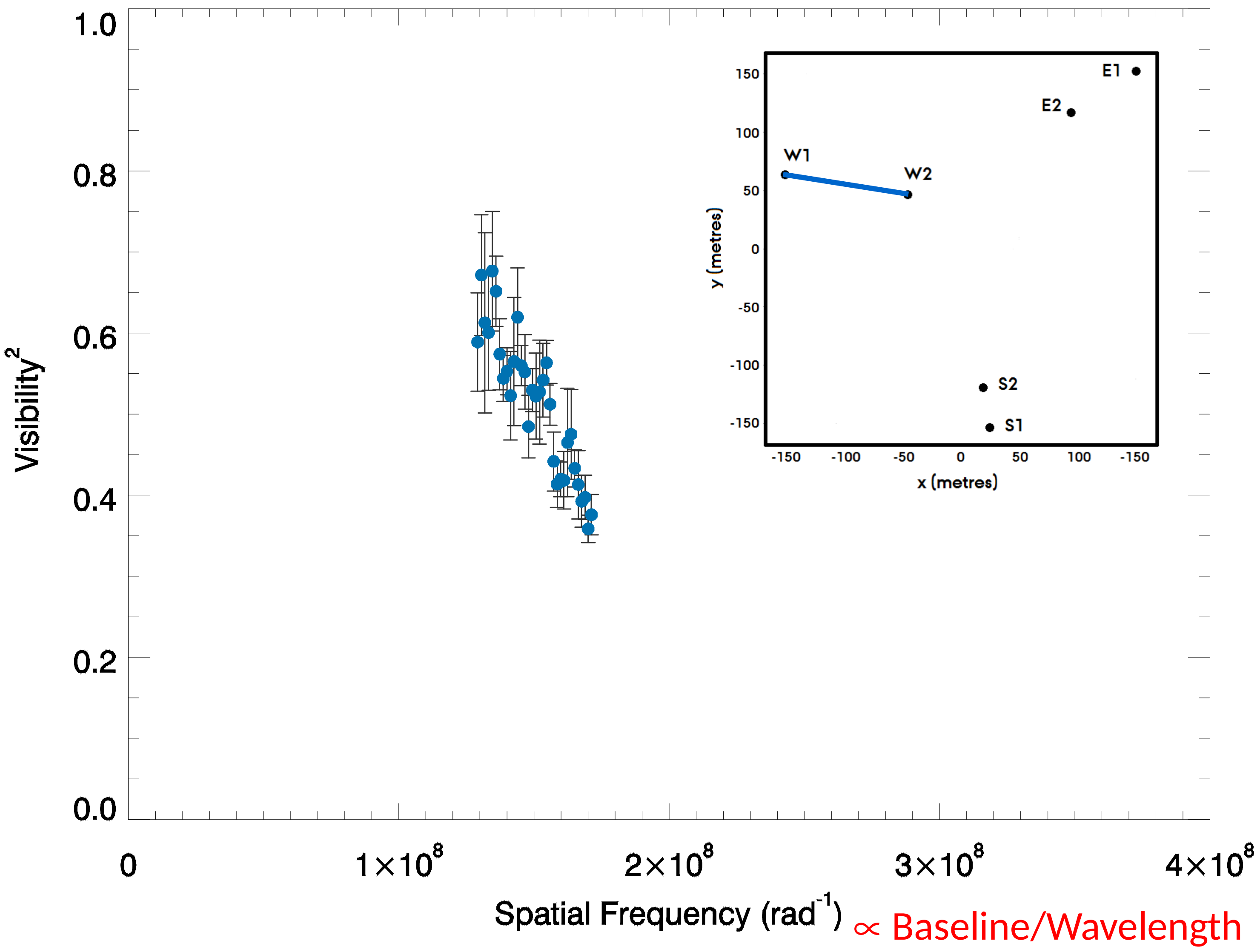


Fringe visibility is a function of source size, baseline length, and wavelength

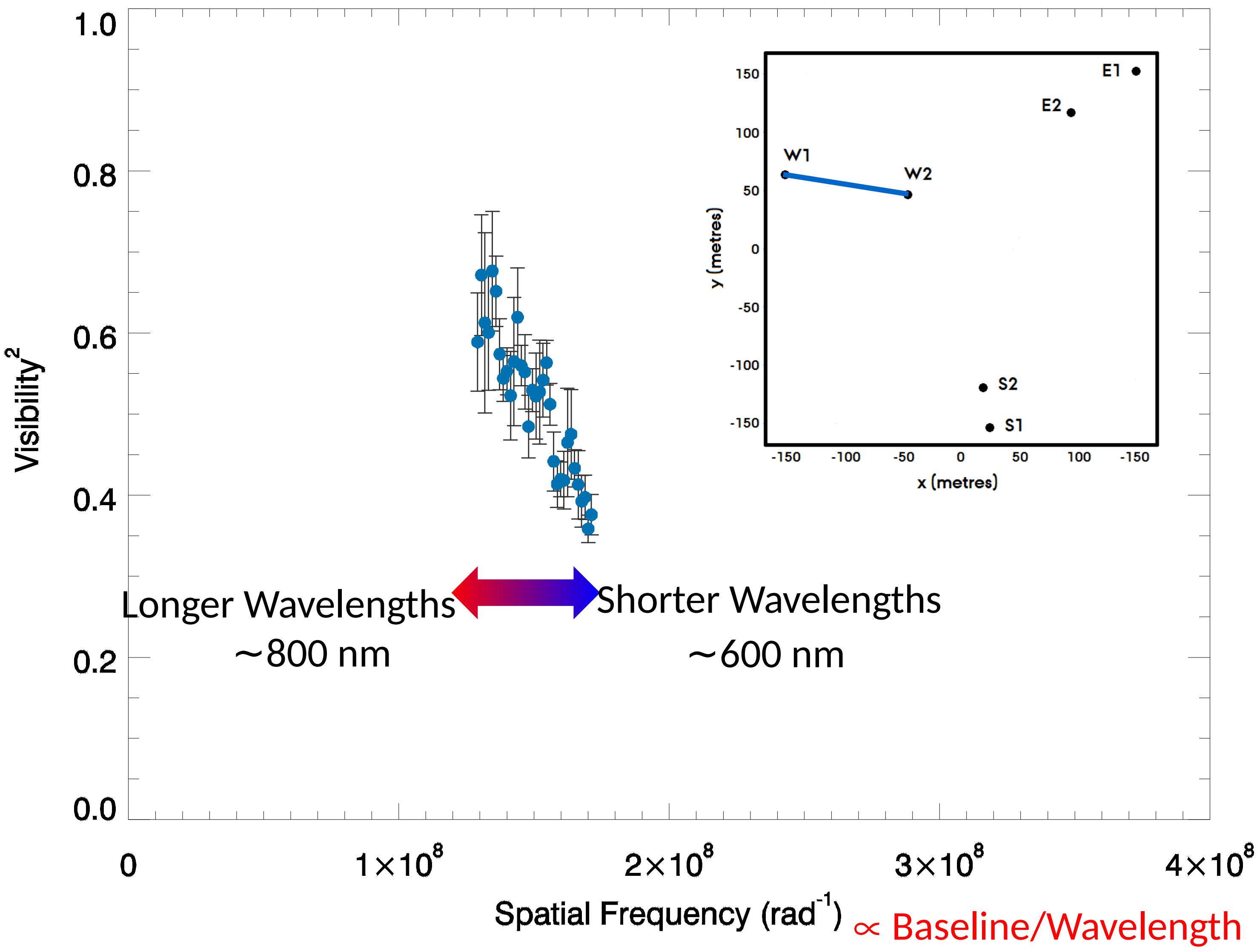


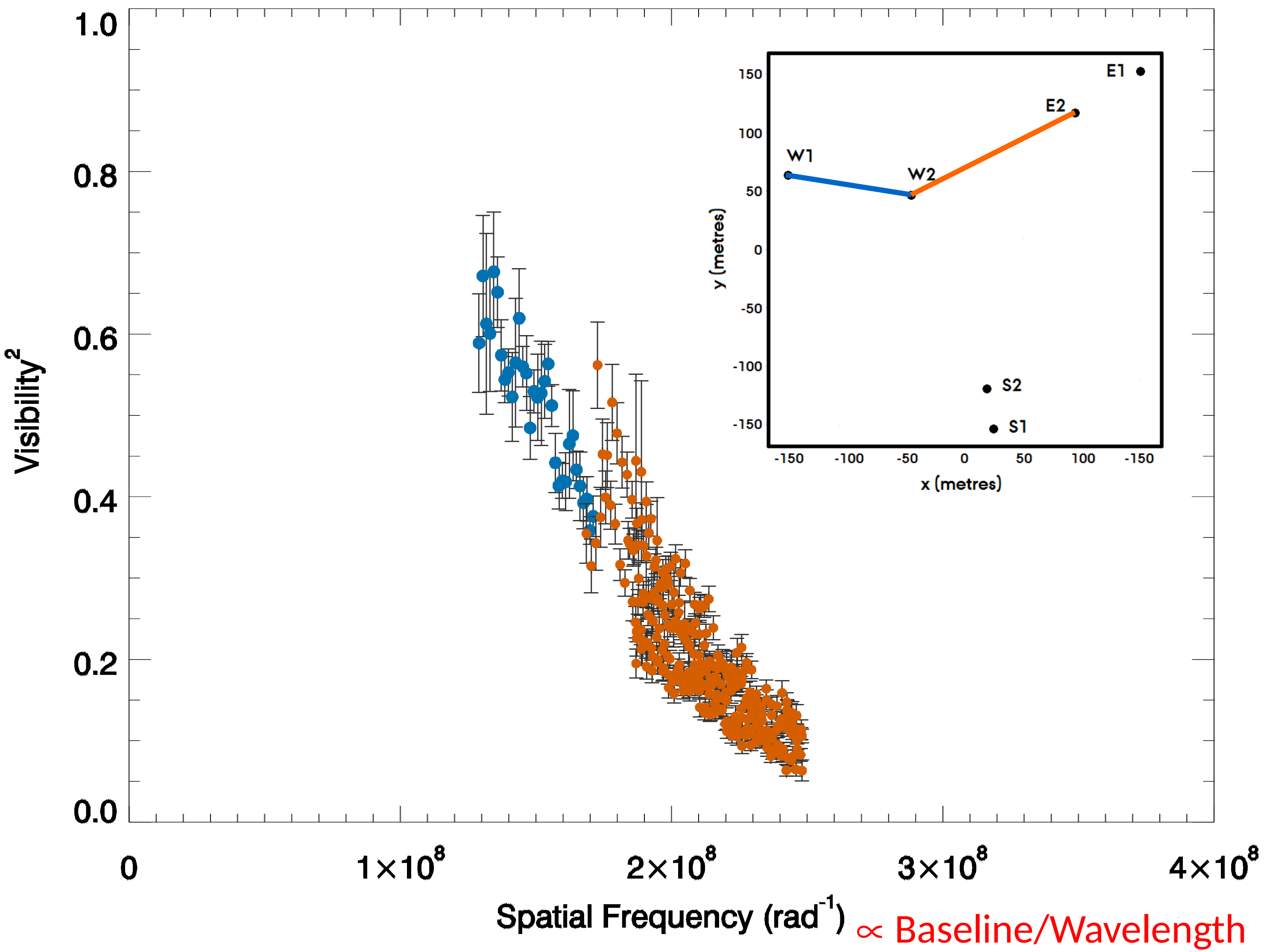
Fringe Visibility



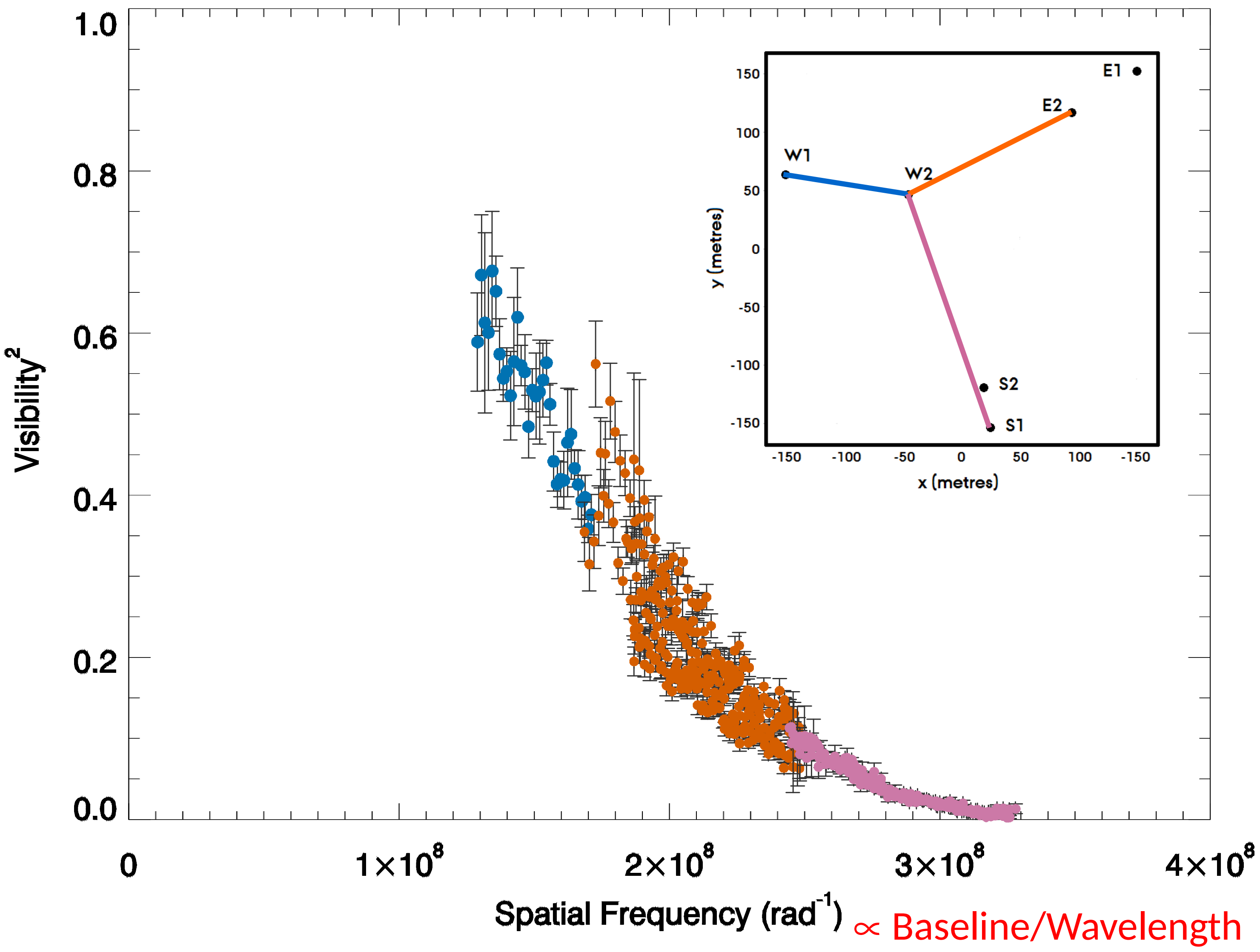


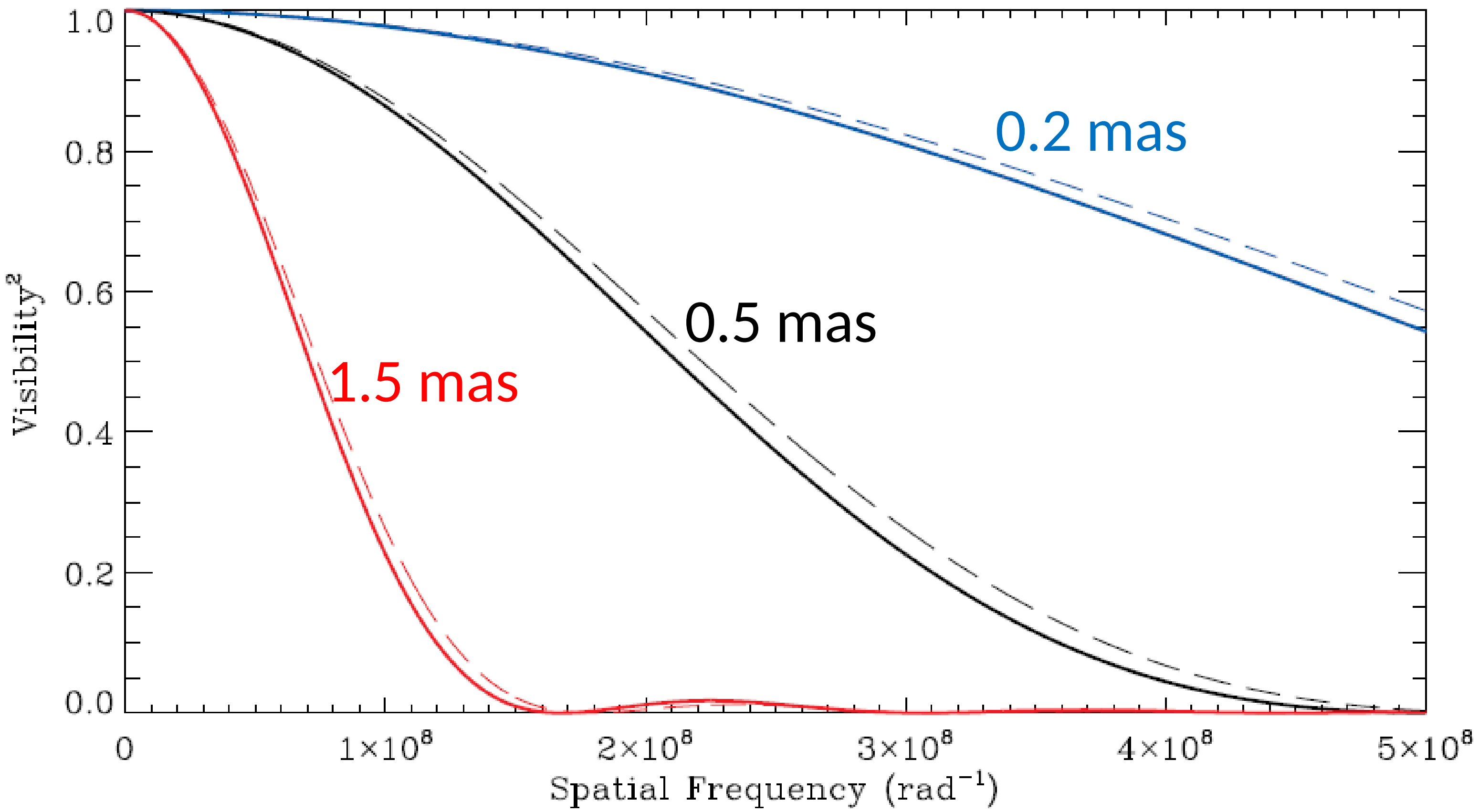
Visibility^2
1.0
0.8
0.6
0.4
0.2
0.0
0
1×10^8
2×10^8
3×10^8
4×10^8
Spatial Frequency (rad^{-1})
∝ Baseline/Wavelength
y (metres)
x (metres)
150
100
50
0
-50
-100
-150
-150
-100
-50
0
50
100
-150
E1
E2
W1
W2
S2
S1


1.0
0.8
0.6
0.4
0.2
0.0
Visibility^2
0
1×10^8
2×10^8
3×10^8
4×10^8
Spatial Frequency (rad^{-1})
∝ Baseline/Wavelength
Longer Wavelengths
~800 nm
Shorter Wavelengths
~600 nm
E1
E2
W1
W2
S2
S1
150
100
50
0
-50
-100
-150
y (metres)
-150
-100
-50
0
50
100
-150
x (metres)



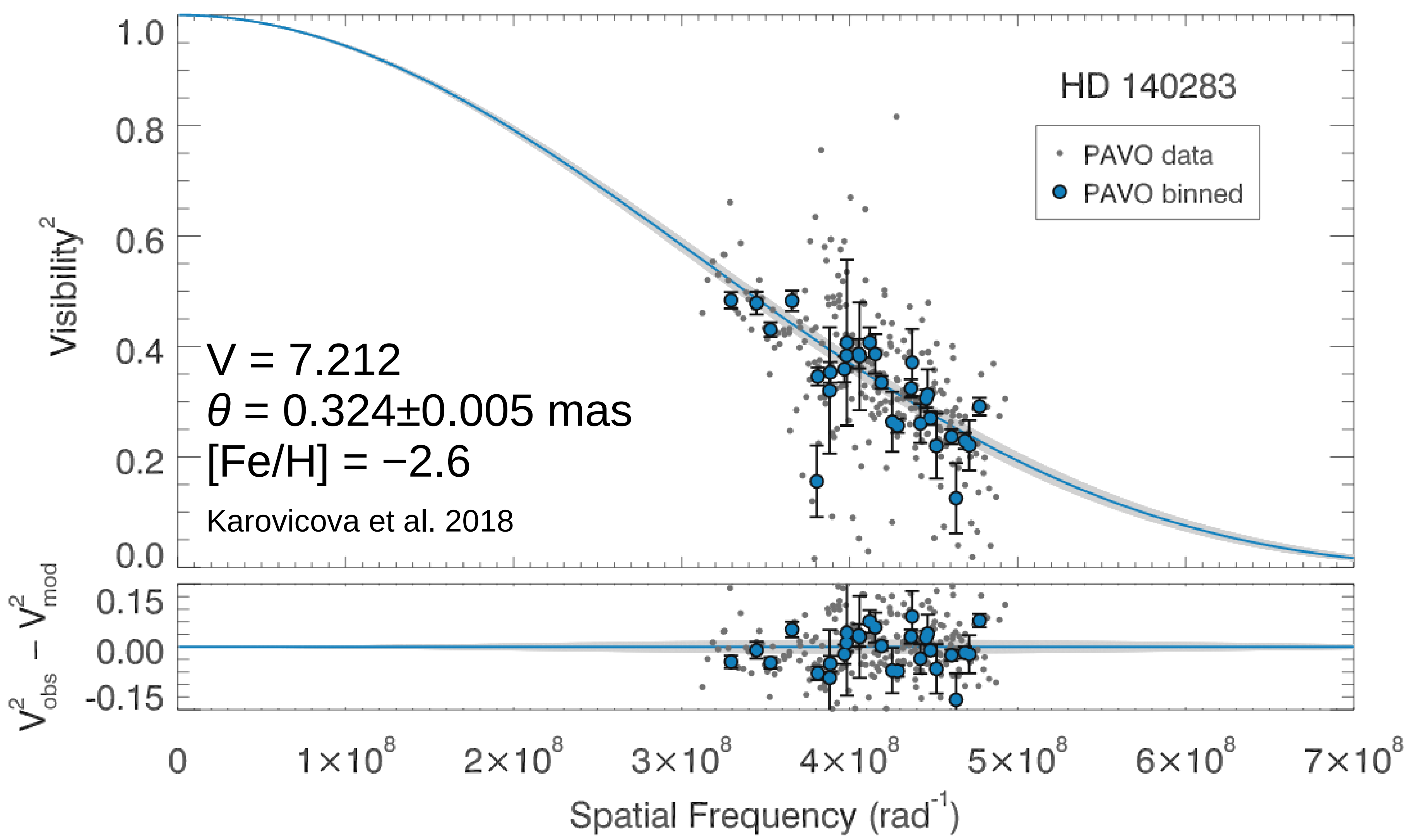
∝ Baseline/Wavelength


1.0
0.8
0.6
0.4
0.2
0.0
Visibility2
0
1×108
2×108
3×108
4×108
Spatial Frequency (rad-1)
E1
E2
W1
W2
S2
S1
150
100
50
0
-50
-100
-150
y (metres)
-150
-100
-50
0
50
100
-150
x (metres)
∝ Baseline/Wavelength

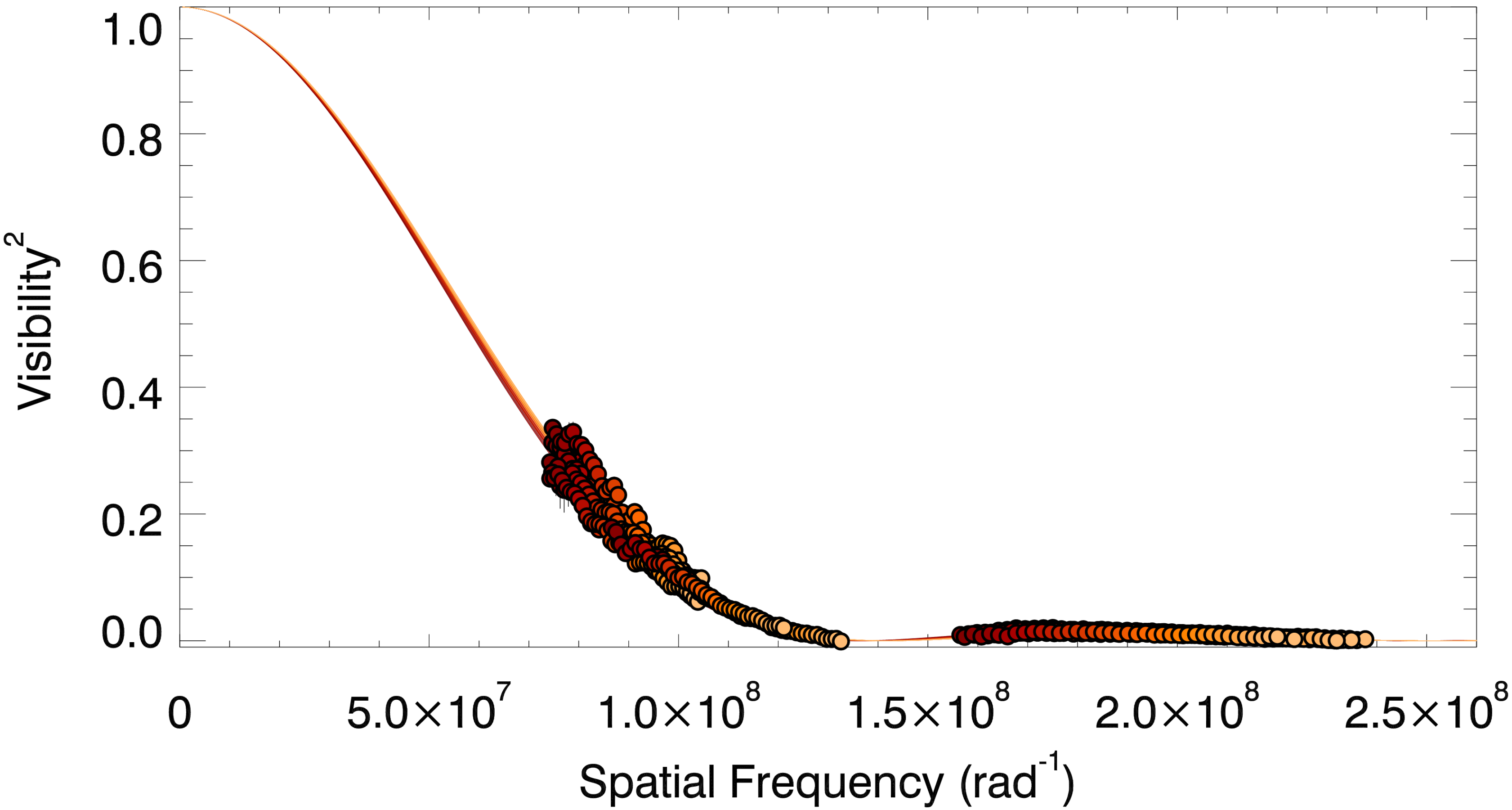

0.2 mas
0.5 mas
1.5 mas
Visibility²
1.0
0.8
0.6
0.4
0.2
0.0
0
1×10⁸
2×10⁸
3×10⁸
4×10⁸
5×10⁸
Spatial Frequency (rad⁻¹)

CHARA instruments

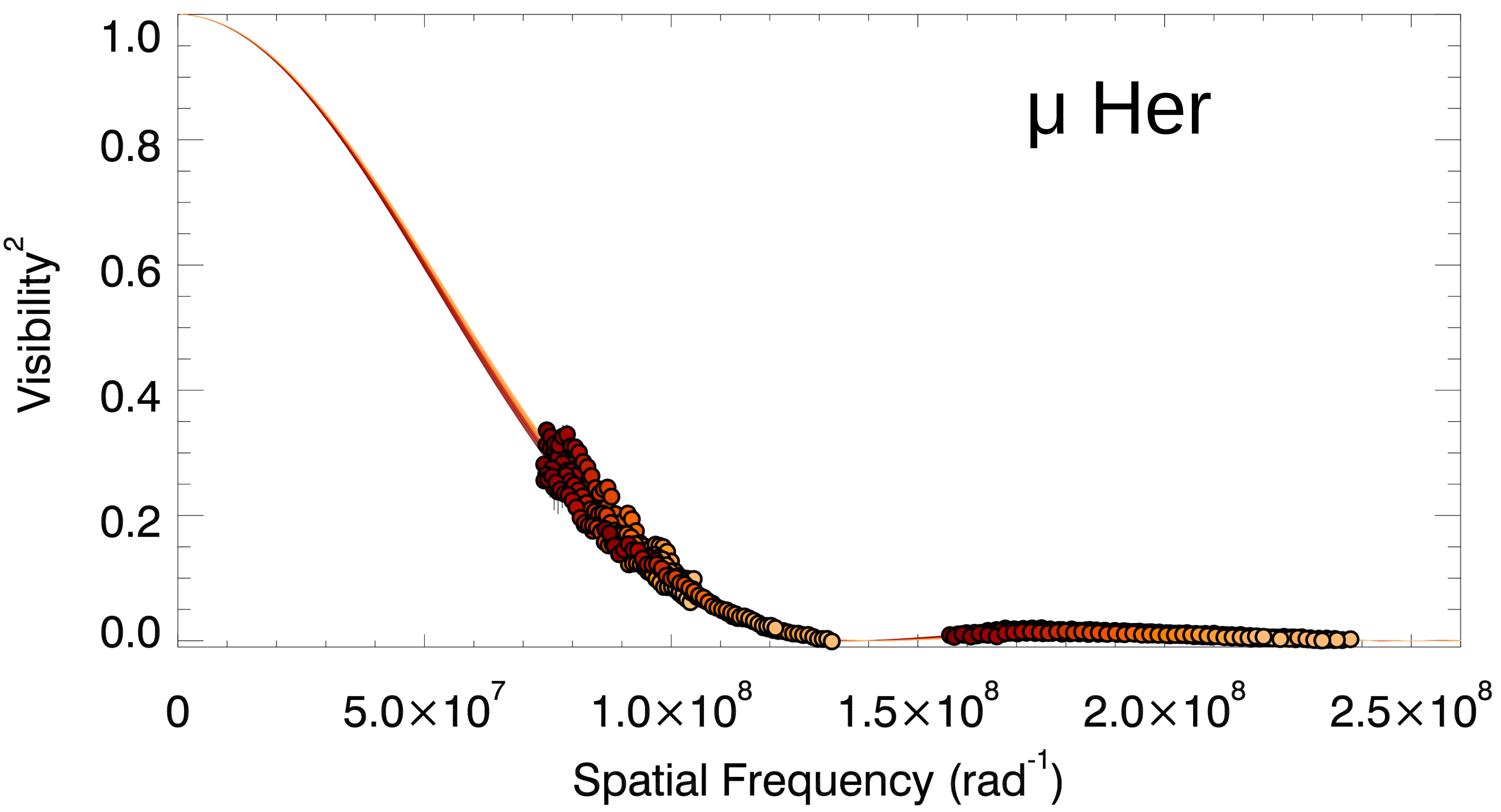
Instrument	Telescopes	Band(s)	Limiting Magnitude	Spectral Resolution
CLASSIC	2	H (1.6µm) K (2.2µm)	8.5	Broadband
CLIMB	3	H, K	7.0	Broadband
JouFLU	2	K	5.0	Broadband
MIRC	6	H	6.0	40
PAVO	2	630-900 nm	8.0	30
VEGA	3	480-850 nm	5.0 (high) / 7.5 (low)	30000, 6000

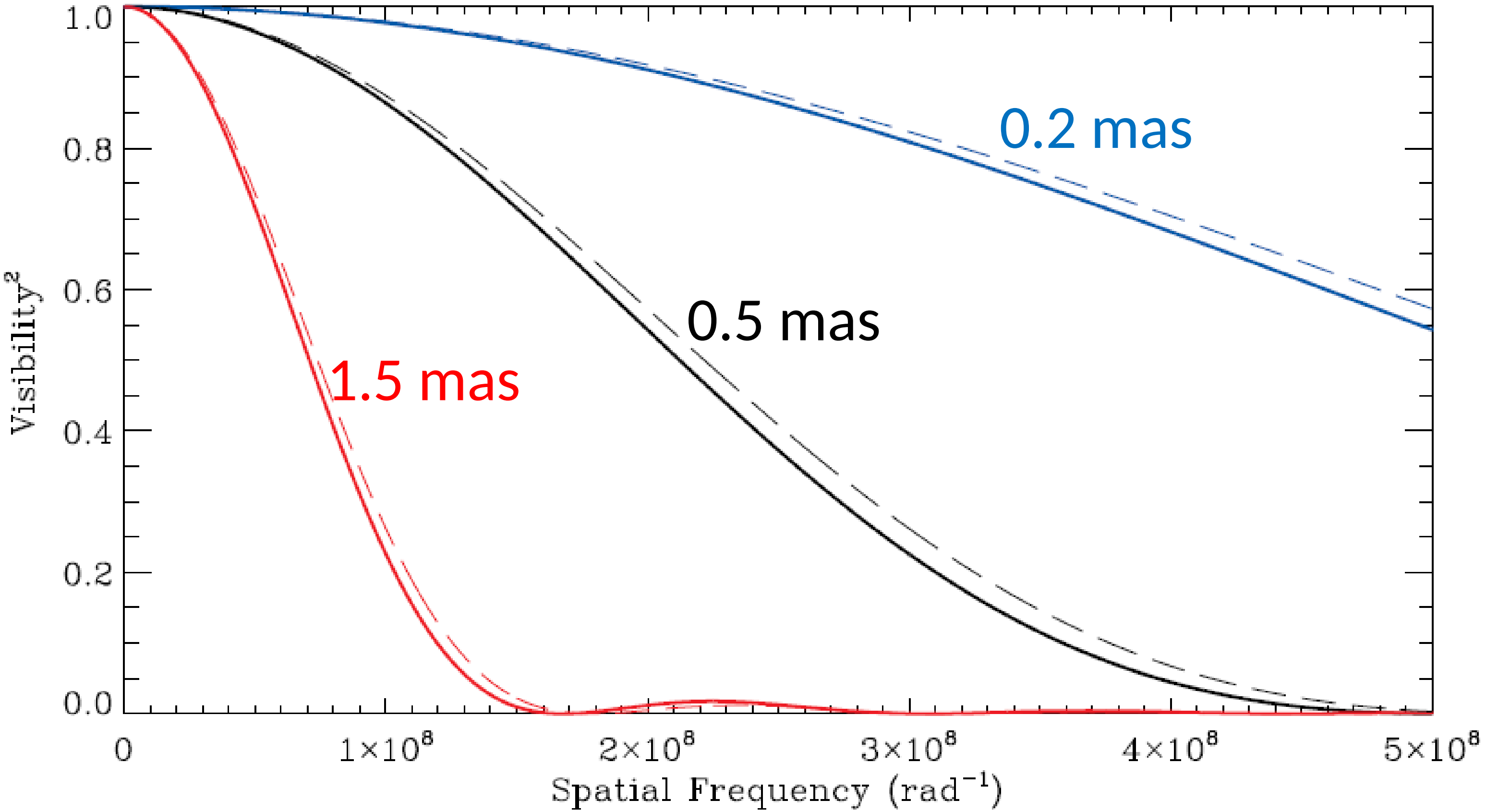


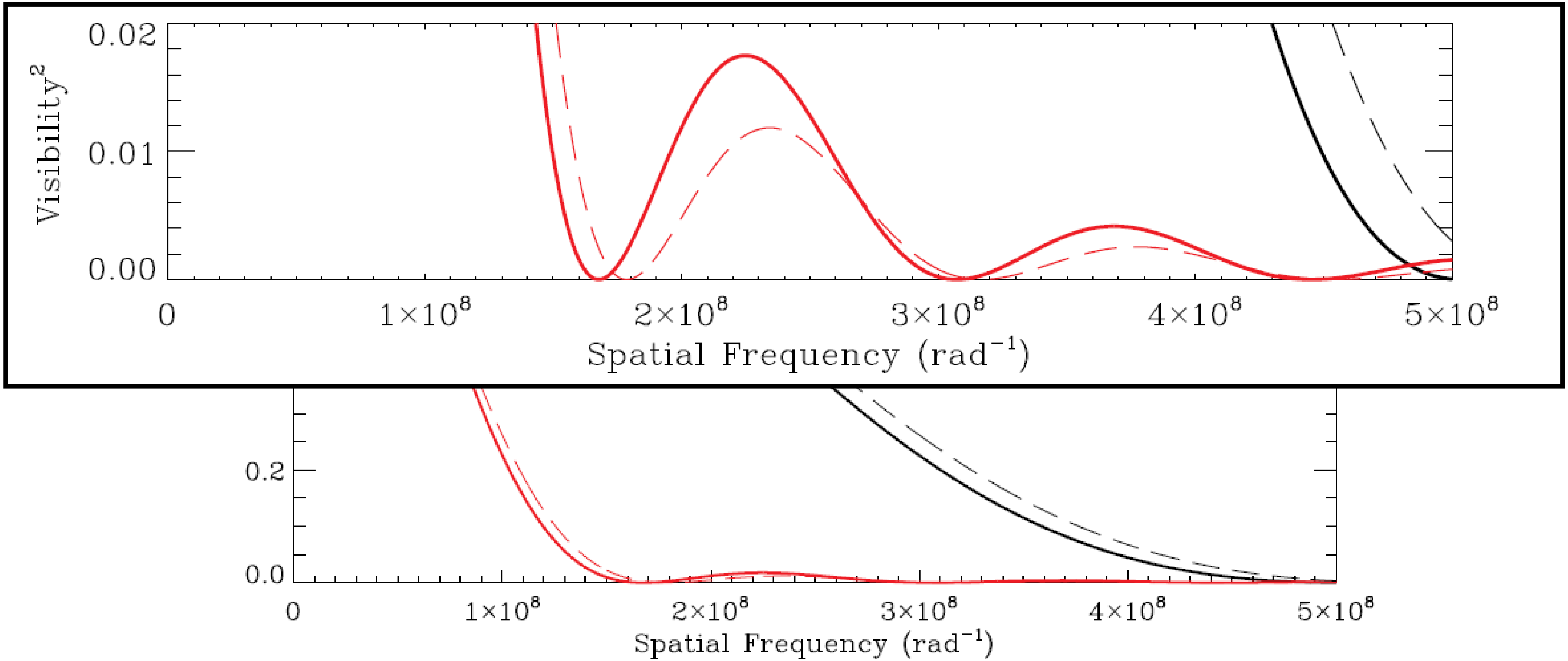
HD 140283
PAVO data
PAVO binned
V = 7.212
θ = 0.324±0.005 mas
[Fe/H] = −2.6
Karovicova et al. 2018
Visibility²
V²obs − V²mod
Spatial Frequency (rad⁻¹)
0
1×10⁸
2×10⁸
3×10⁸
4×10⁸
5×10⁸
6×10⁸
7×10⁸
1.0
0.8
0.6
0.4
0.2
0.0
0.15
0.00
-0.15



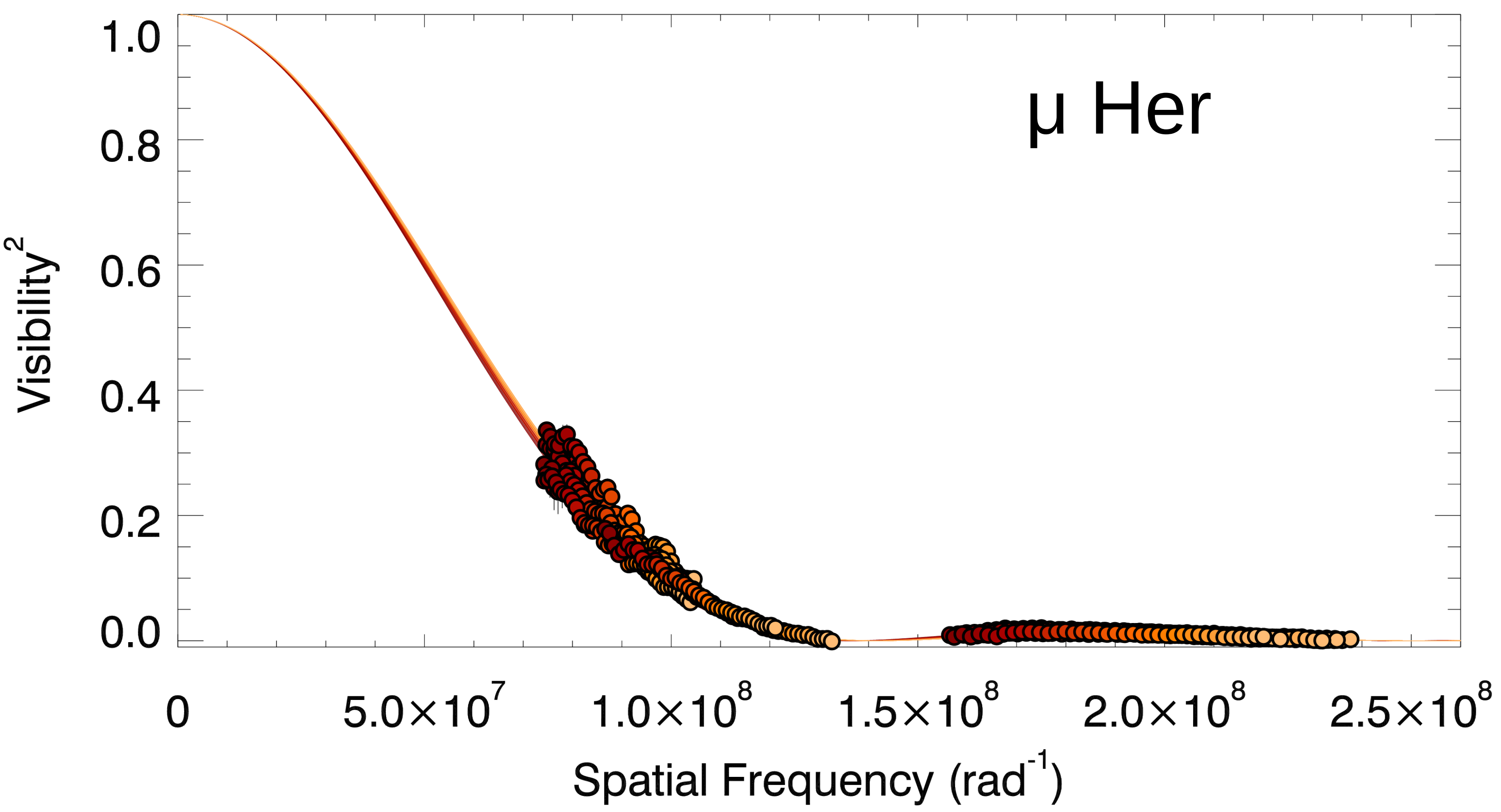
Visibility^2
1.0
0.8
0.6
0.4
0.2
0.0
0
5.0×10^7
1.0×10^8
1.5×10^8
2.0×10^8
2.5×10^8
Spatial Frequency (rad^{-1})


μ Her
Visibility^2
1.0
0.8
0.6
0.4
0.2
0.0
0
5.0×10^7
1.0×10^8
1.5×10^8
2.0×10^8
2.5×10^8
Spatial Frequency (rad^{-1})

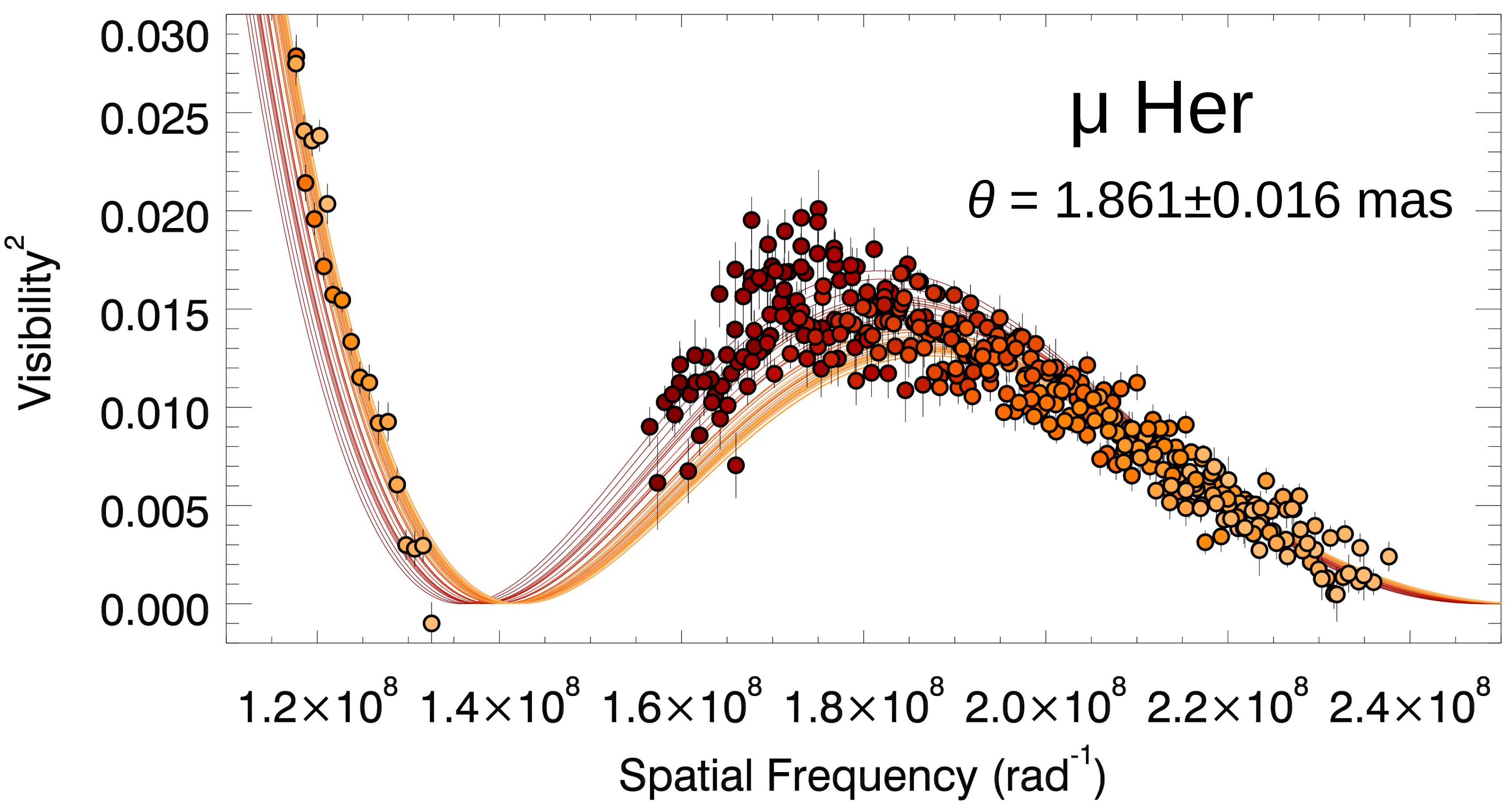

0.2 mas
0.5 mas
1.5 mas
Visibility^2
1.0
0.8
0.6
0.4
0.2
0.0
0
1×10^8
2×10^8
3×10^8
4×10^8
5×10^8
Spatial Frequency (rad^{-1})

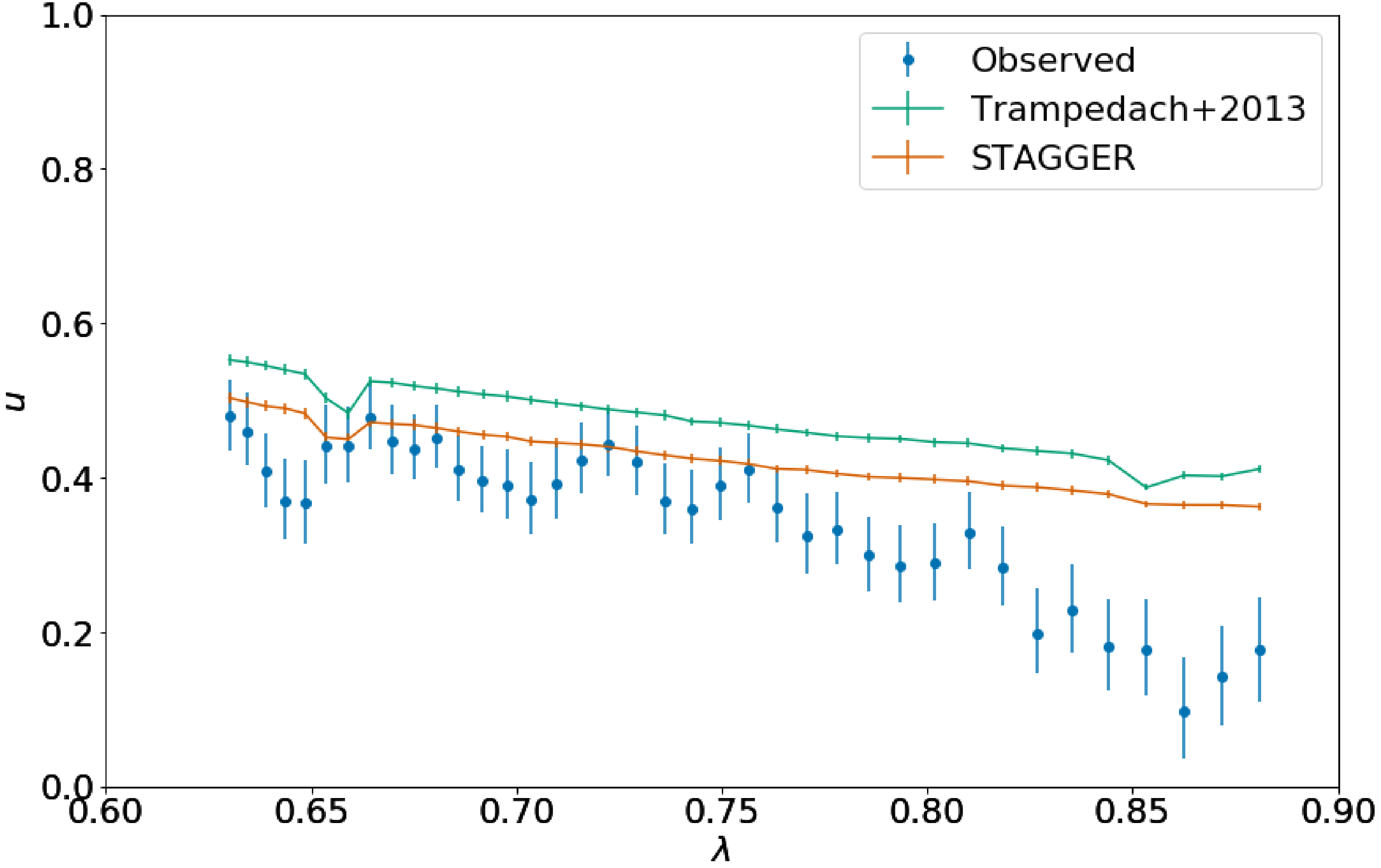


Visibility^2
0.02
0.01
0.00
0
1×10^8
2×10^8
3×10^8
4×10^8
5×10^8
Spatial Frequency (rad^{-1})
0.2
0.0
0
1×10^8
2×10^8
3×10^8
4×10^8
5×10^8
Spatial Frequency (rad^{-1})

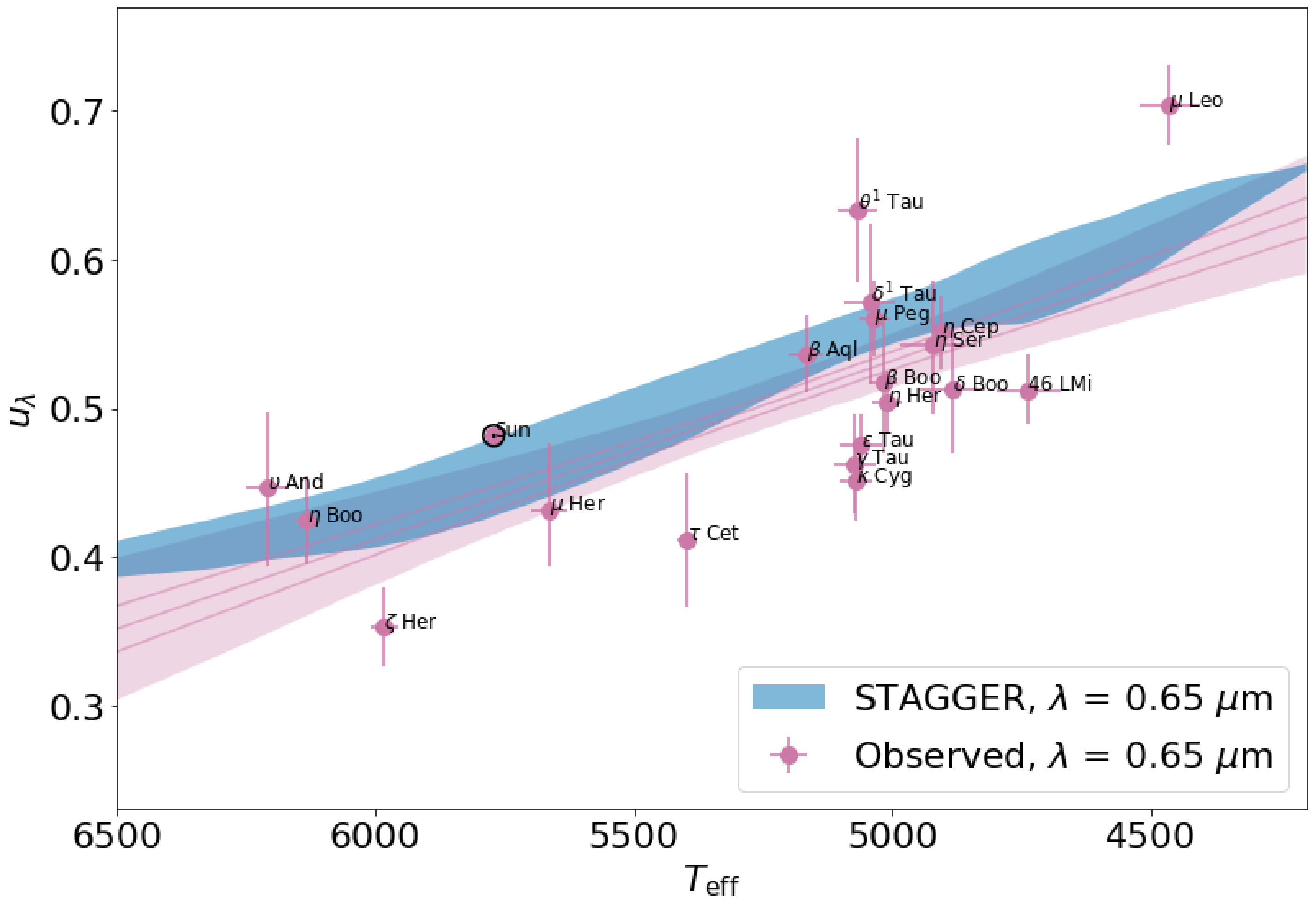


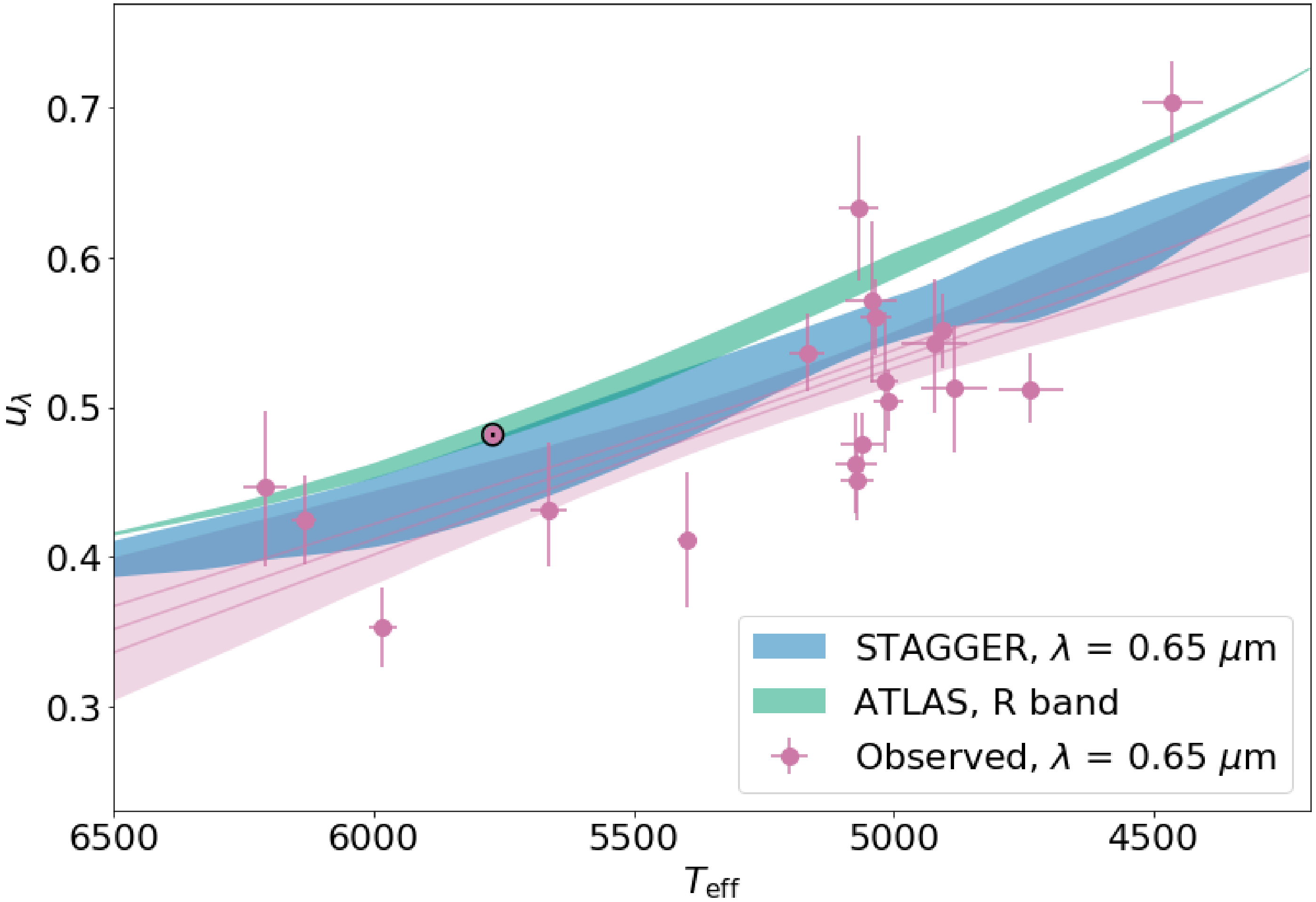
μ Her
Visibility^2
1.0
0.8
0.6
0.4
0.2
0.0
0
5.0×10^7
1.0×10^8
1.5×10^8
2.0×10^8
2.5×10^8
Spatial Frequency (rad^{-1})


μ Her
θ = 1.861±0.016 mas
Visibility²
0.030
0.025
0.020
0.015
0.010
0.005
0.000
1.2×10⁸
1.4×10⁸
1.6×10⁸
1.8×10⁸
2.0×10⁸
2.2×10⁸
2.4×10⁸
Spatial Frequency (rad⁻¹)

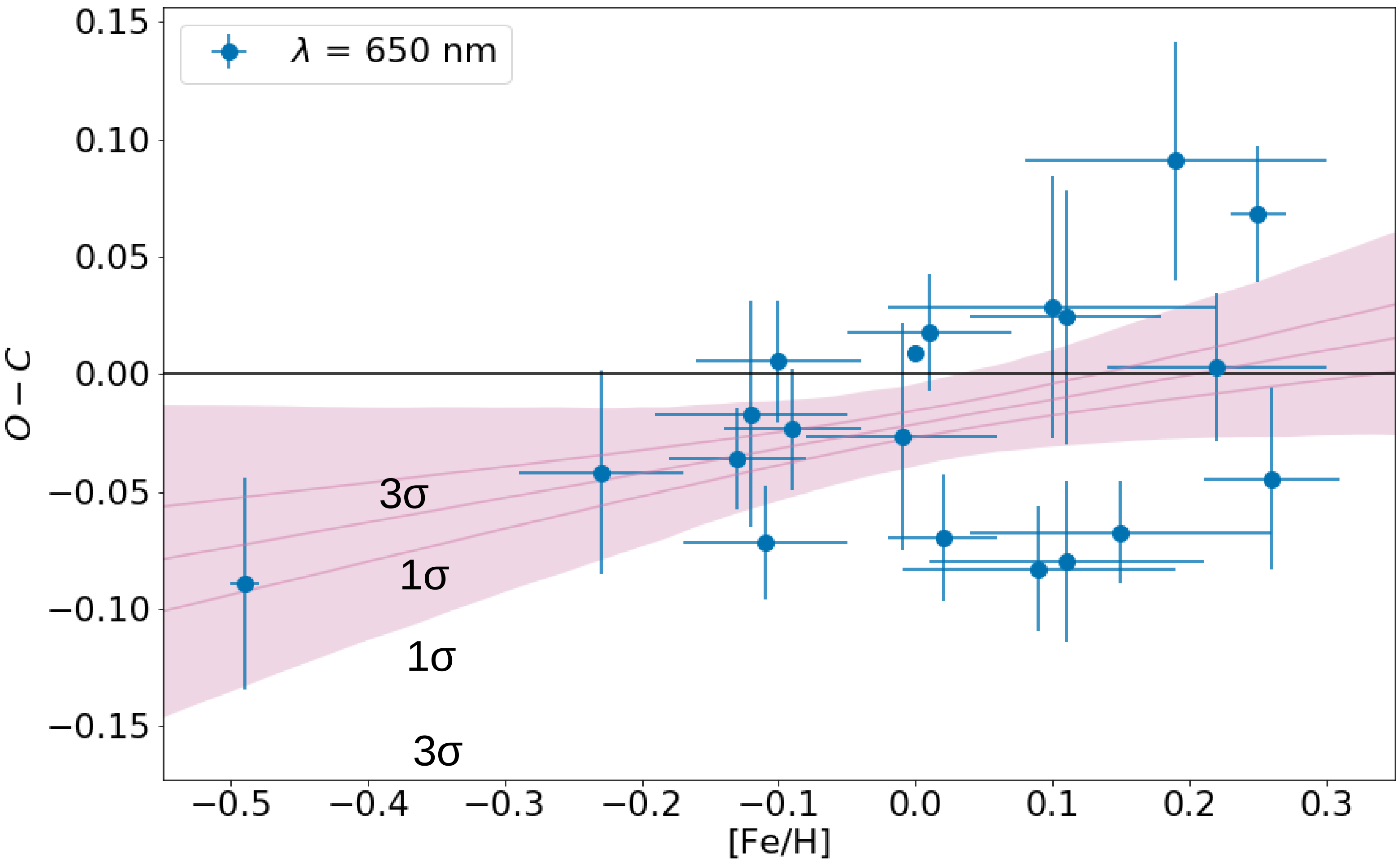


Observed
Trampedach+2013
STAGGER
u
λ
1.0
0.8
0.6
0.4
0.2
0.0
0.60
0.65
0.70
0.75
0.80
0.85
0.90

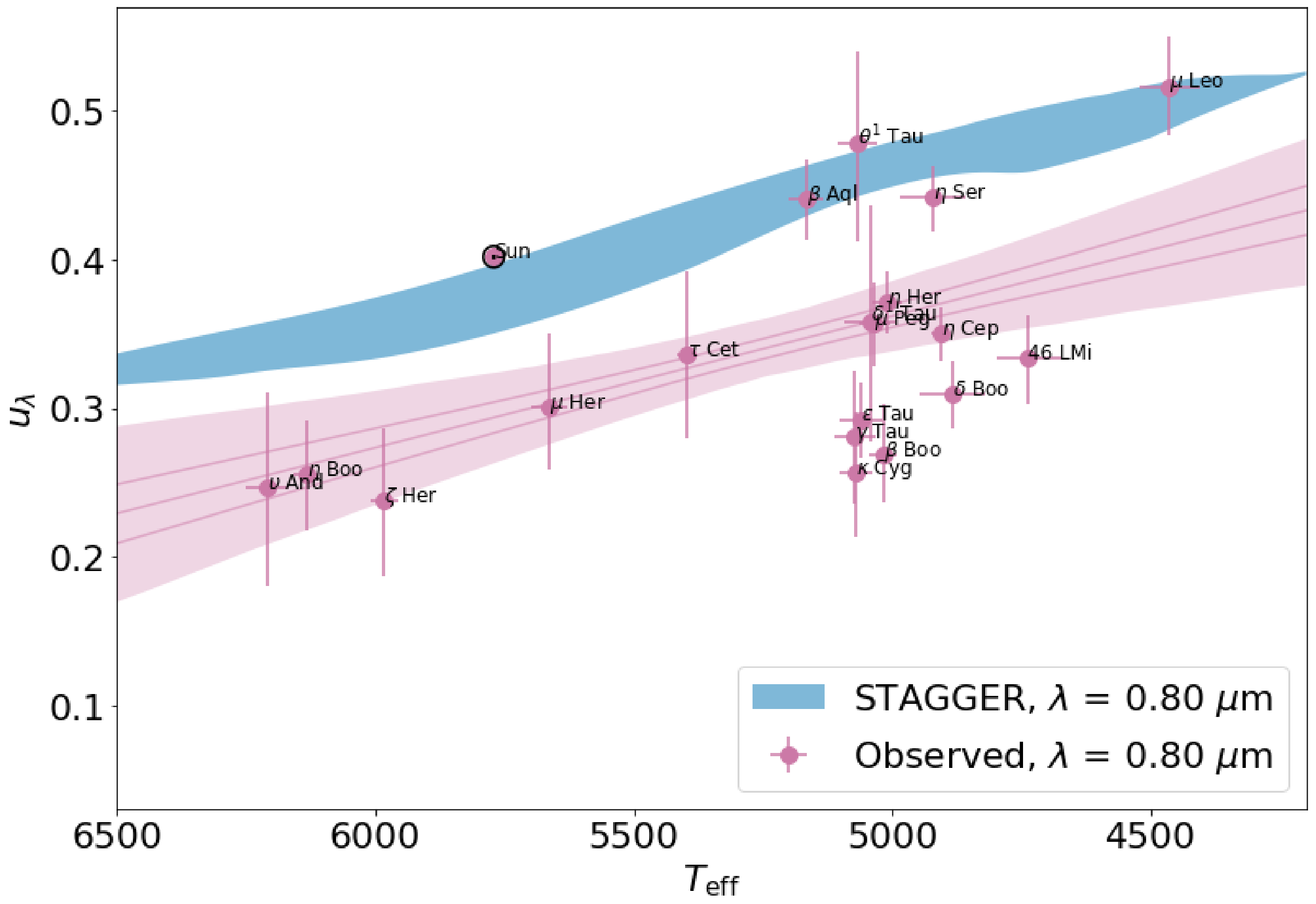

0.7
0.6
0.5
0.4
0.3
u_λ
6500
6000
5500
5000
4500
$T_{\rm eff}$
μ Leo
θ1 Tau
δ1 Tau
μ Peg
η Cep
η Ser
β Aql
β Boo
η Her
δ Boo
46 LMi
Sun
ε Tau
γ Tau
κ Cyg
υ And
η Boo
μ Her
τ Cet
ζ Her
STAGGER, λ = 0.65 μm
Observed, λ = 0.65 μm



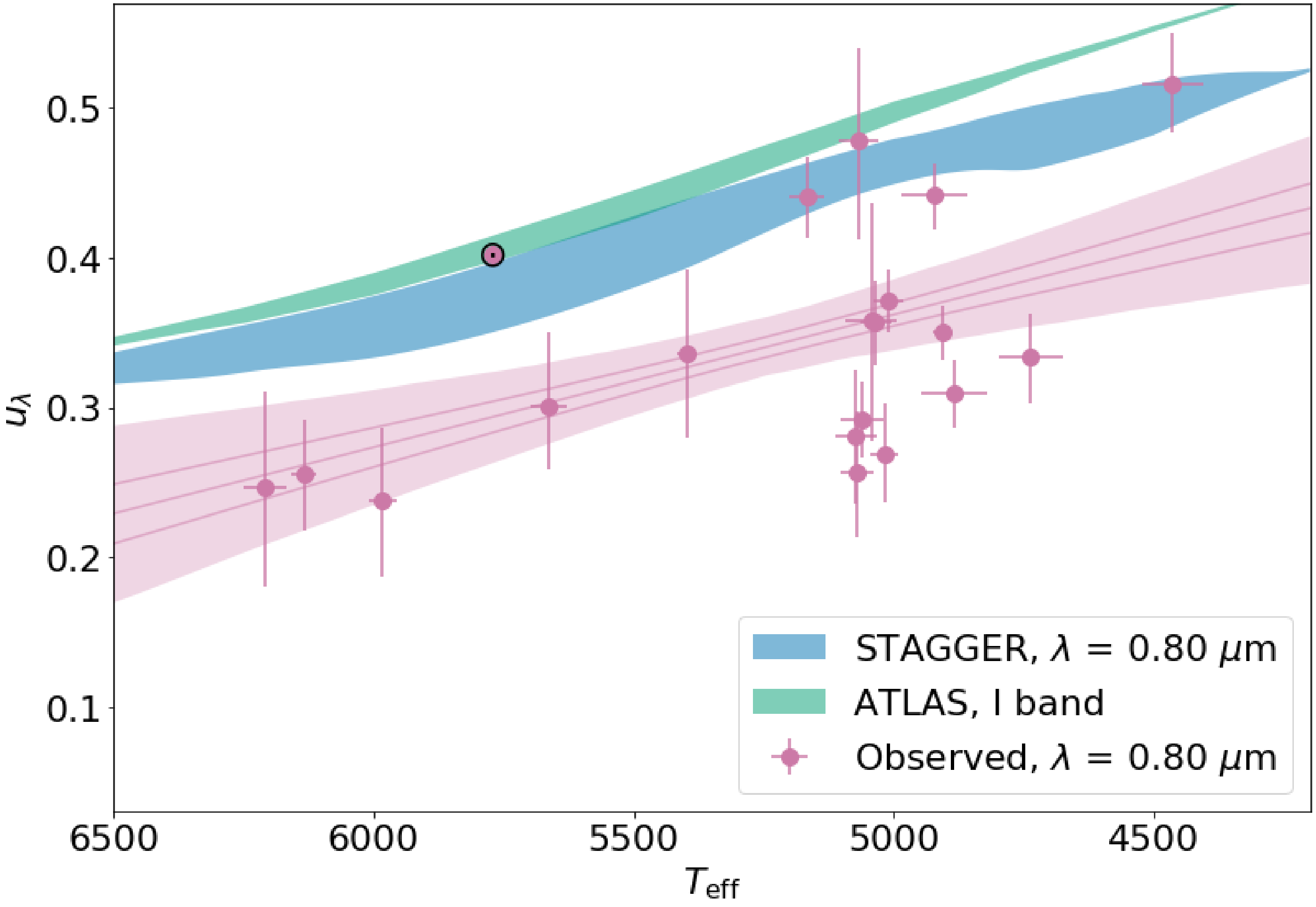
0.7
0.6
0.5
0.4
0.3
u_λ
6500
6000
5500
5000
4500
$T_{\rm eff}$
STAGGER, λ = 0.65 μm
ATLAS, R band
Observed, λ = 0.65 μm



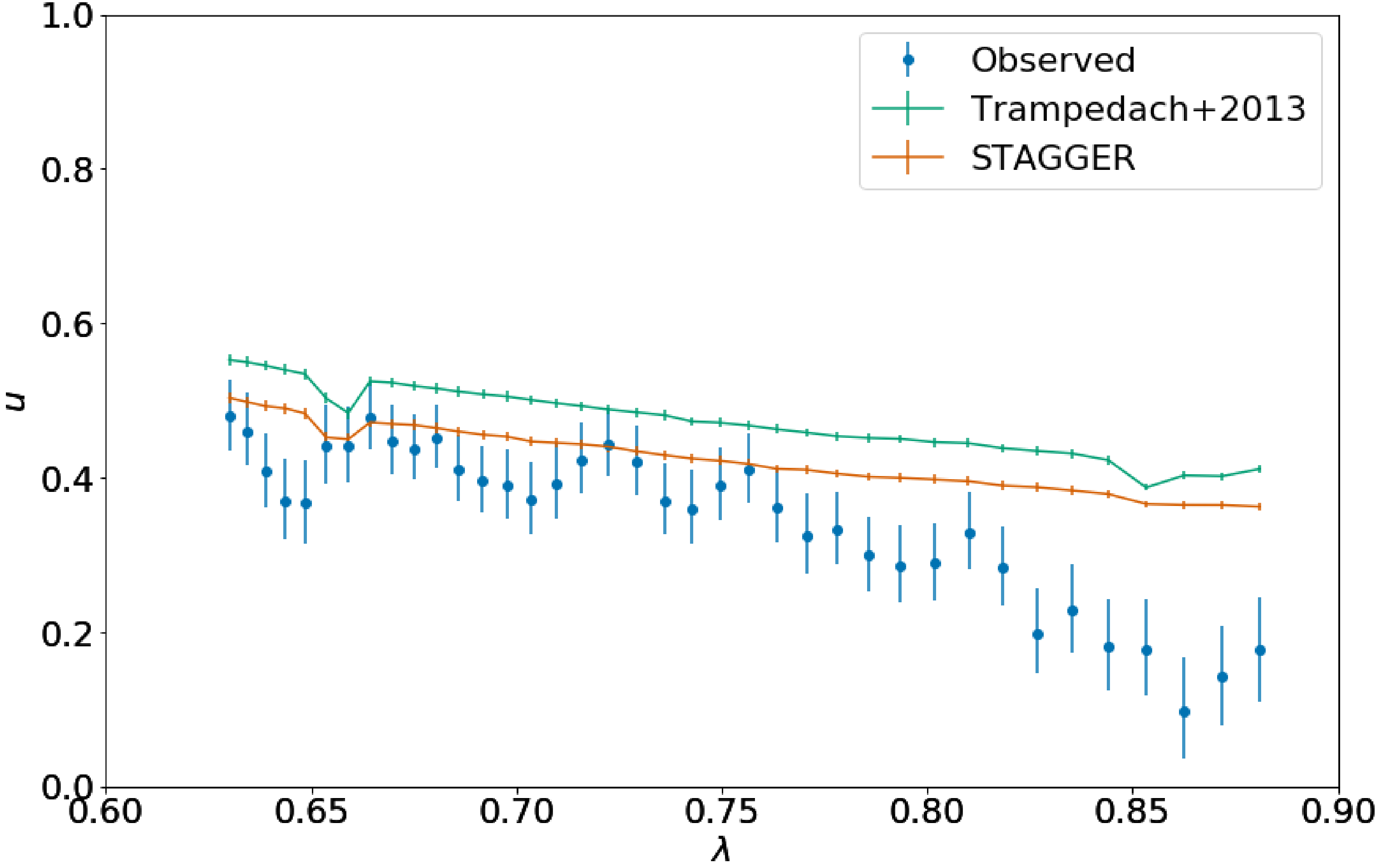
λ = 650 nm
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
O − C
3σ
1σ
1σ
3σ
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
[Fe/H]



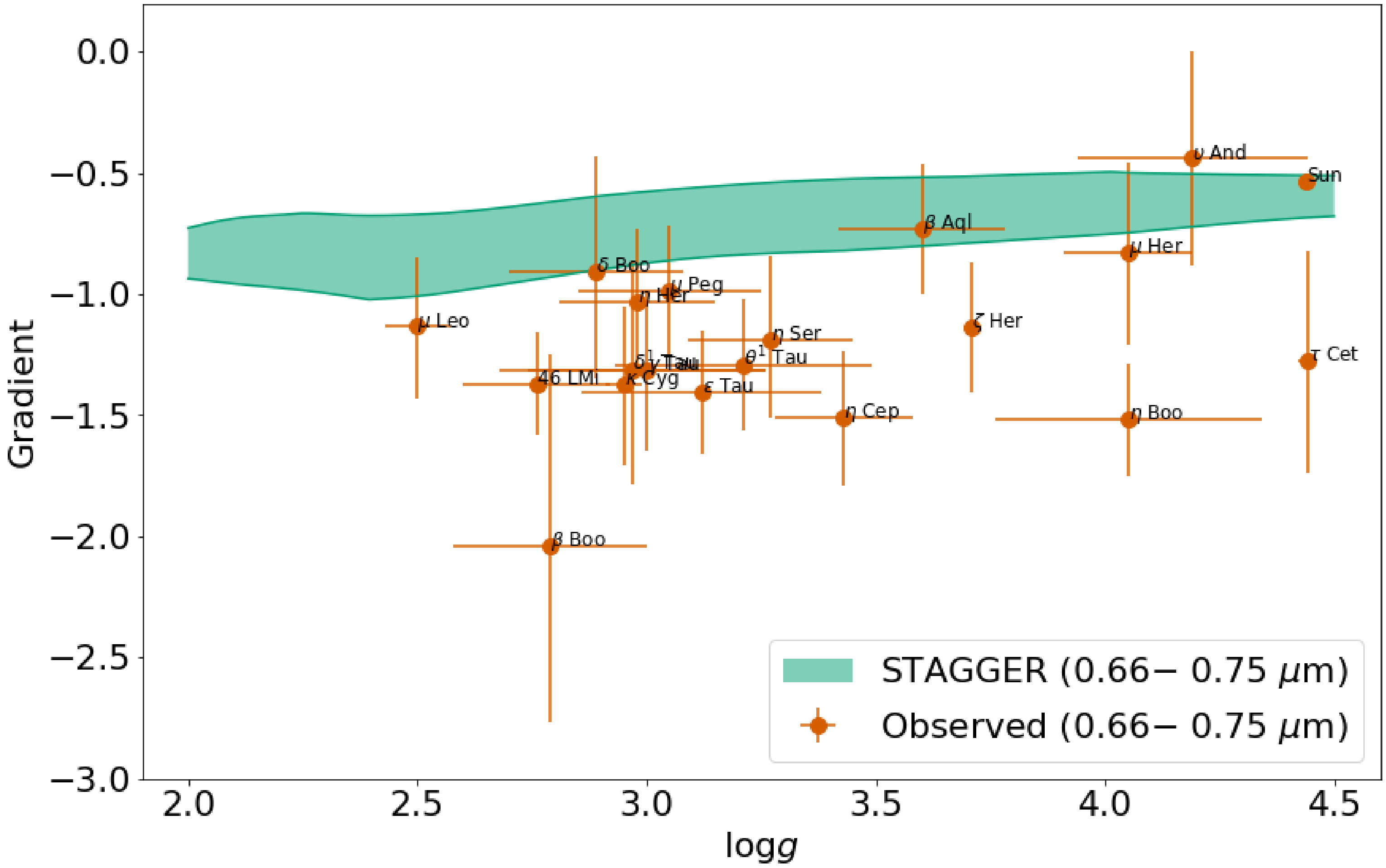
0.5
0.4
0.3
0.2
0.1
u_λ
6500
6000
5500
5000
4500
$T_{\rm eff}$
μ Leo
θ^1 Tau
β Aql
η Ser
Sun
η Her
μ Peg
η Cep
46 LMi
τ Cet
δ Boo
μ Her
ϵ Tau
γ Tau
β Boo
κ Cyg
η Boo
υ And
ζ Her
STAGGER, λ = 0.80 μm
Observed, λ = 0.80 μm



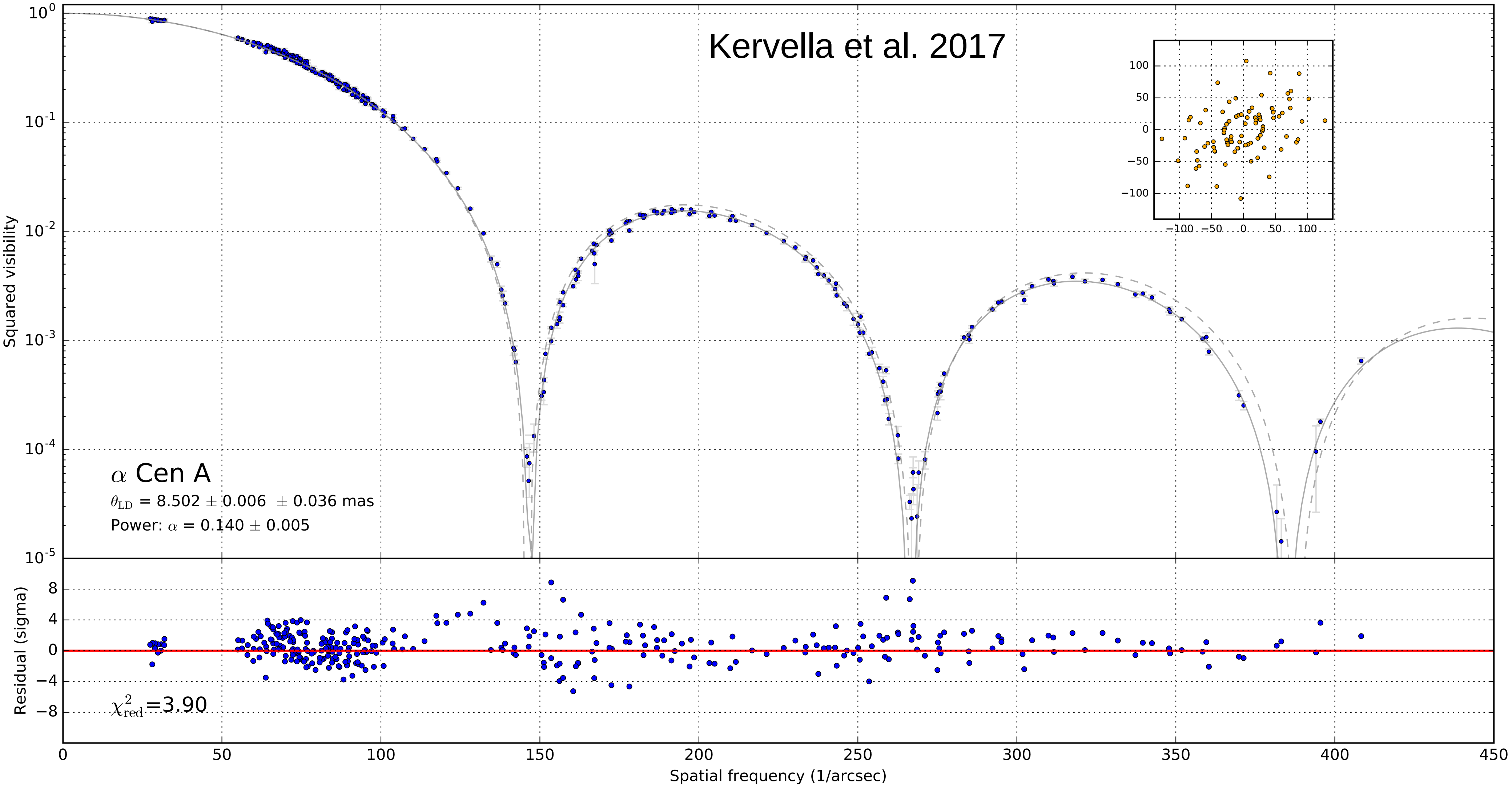
0.5
0.4
0.3
0.2
0.1
u_λ
6500
6000
5500
5000
4500
$T_{\rm eff}$
STAGGER, λ = 0.80 μm
ATLAS, I band
Observed, λ = 0.80 μm

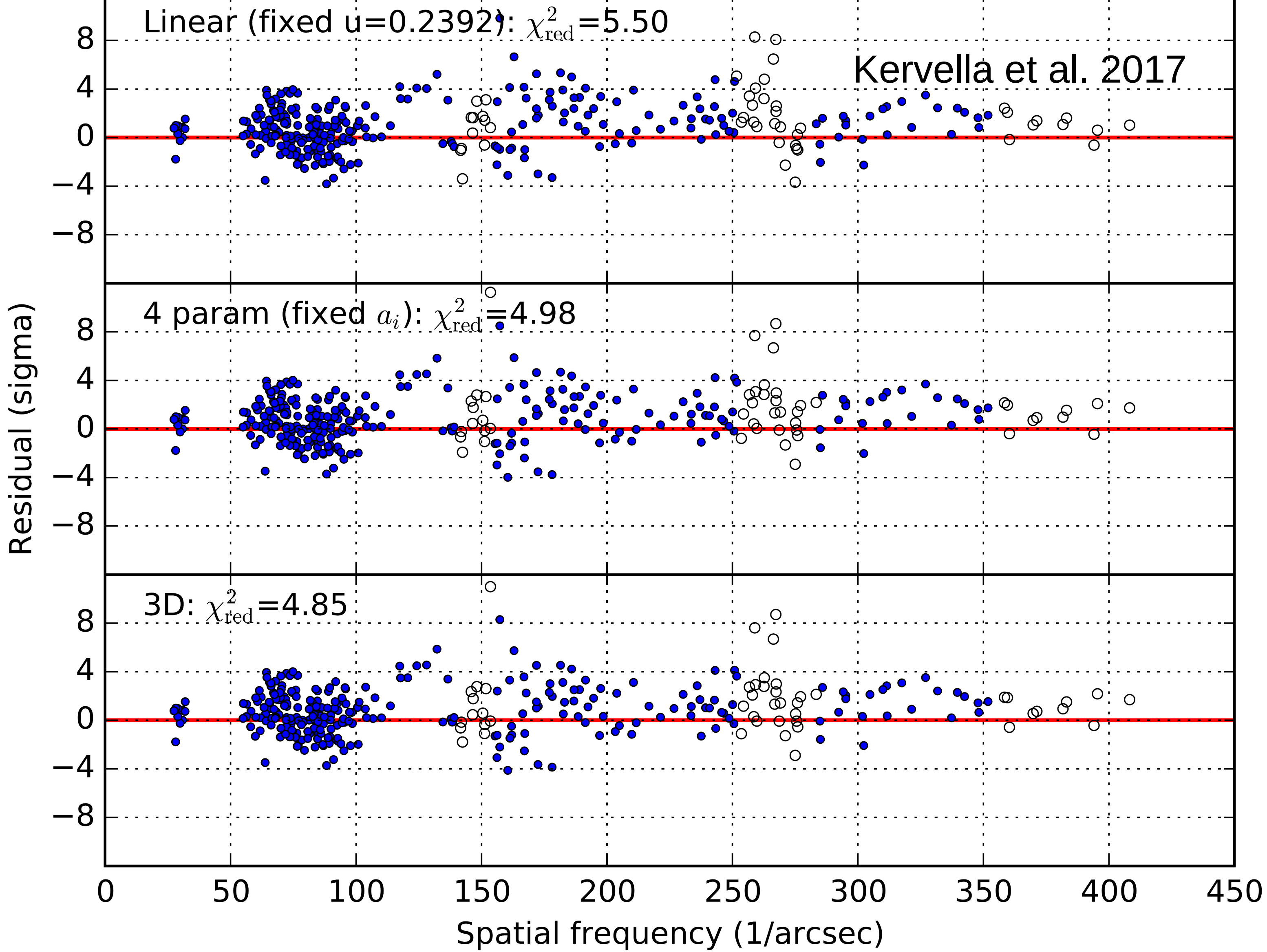


Observed
Trampedach+2013
STAGGER
u
λ
0.0
0.2
0.4
0.6
0.8
1.0
0.60
0.65
0.70
0.75
0.80
0.85
0.90



Gradient
log g
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
2.0
2.5
3.0
3.5
4.0
4.5
υ And
Sun
β Aql
υ Her
δ Boo
μ Peg
η Her
μ Leo
ζ Her
η Ser
θ¹ Tau
τ Cet
46 LMi
κ Cyg
ϵ Tau
η Cep
η Boo
β Boo
STAGGER (0.66− 0.75 μm)
Observed (0.66− 0.75 μm)


Kervella et al. 2017
α Cen A
θ_{LD} = 8.502 ± 0.006 ± 0.036 mas
Power: α = 0.140 ± 0.005
χ^2_{red}=3.90
Squared visibility
Residual (sigma)
Spatial frequency (1/arcsec)



Linear (fixed u=0.2392): $\chi^2_{\rm red}$=5.50
Kervella et al. 2017
4 param (fixed a_i): $\chi^2_{\rm red}$=4.98
3D: $\chi^2_{\rm red}$=4.85
Residual (sigma)
Spatial frequency (1/arcsec)

Effective Temperatures

$$T_{\rm eff} = \left(\frac{4F_{\rm bol}}{\sigma\theta^2}\right)^{1/4}$$

Bolometric fluxes – μ Her

Reference	f_{bol}
Mozurkewich et al. 2003	1.25 nW m^{-2}
Boyajian et al. 2013	(116.4000 ± 0.1240) x 10^{-8} erg s^{-1} cm^{-2}
Baines et al. 2014	(102.0 ± 0.2) x 10^{-8} erg s^{-1} cm^{-2}
Swihart et al. 2017	(118.700 ± 1.974) x 10^{5} W m^{-2}
Freund et al. 2018	1.31 x 10^{6} fW m^{-2}

Bolometric fluxes – μ Her

Reference	f_{bol} (nW m^{-2})
Mozurkewich et al. 2003	1.25
Boyajian et al. 2013	1.1640 ± 0.0012
Baines et al. 2014	1.020 ± 0.002
Swihart et al. 2017	$(1.187 \pm 0.020) \times 10^{16}$
Freund et al. 2018	1.31

VizieR

start AladinLite

J/AJ/153/16/table3	Calibrator stars catalog for interferometers (Swihart+, 2017) Angular diameters for 1523 calibrator stars estimated from the sedFit fitting routine *(1510 rows)*

Post annotation about this record
Find more around this position in : *Aladin Image* *VizieR* *Simbad* *CDS Portal* table view

Name	**HD161797**		HD catalog identifier (meta.id;meta.table)
Vmag	**3.42**	mag	V band magnitude, SIMBAD/GCPD (phot.mag;em.opt.V)
Fbol	**118.700**	10+5W/m2	Bolometric flux, 10+8 erg/cm2/s (phot.flux.bol)
e_Fbol	**1.974**	10+5W/m2	Uncertainty in fbol (stat.error)

Table 3
Angular Diameters for 1510 Calibrator Stars Estimated from the *sedFit* Fitting Routine along with the χ^2_{red} as a Q

HD#	V (mag)	$f_{bol} \pm \sigma$ ($\times 10^{-8}$ erg cm^{-2} s^{-1})	$A_V \pm \sigma$ (mag)	# of Phot. Pts	$\theta_{SED} \pm \sigma$ (mas)
HD87	5.51	18.900 ± 1.041	0.023 ± 0.046	17	0.893 ± 0.061
HD144	5.59	25.890 ± 0.436	0.205 ± 0.020	13	0.227 ± 0.041
HD360	5.99	15.830 ± 2.135	0.236 ± 0.078	10	0.896 ± 0.094

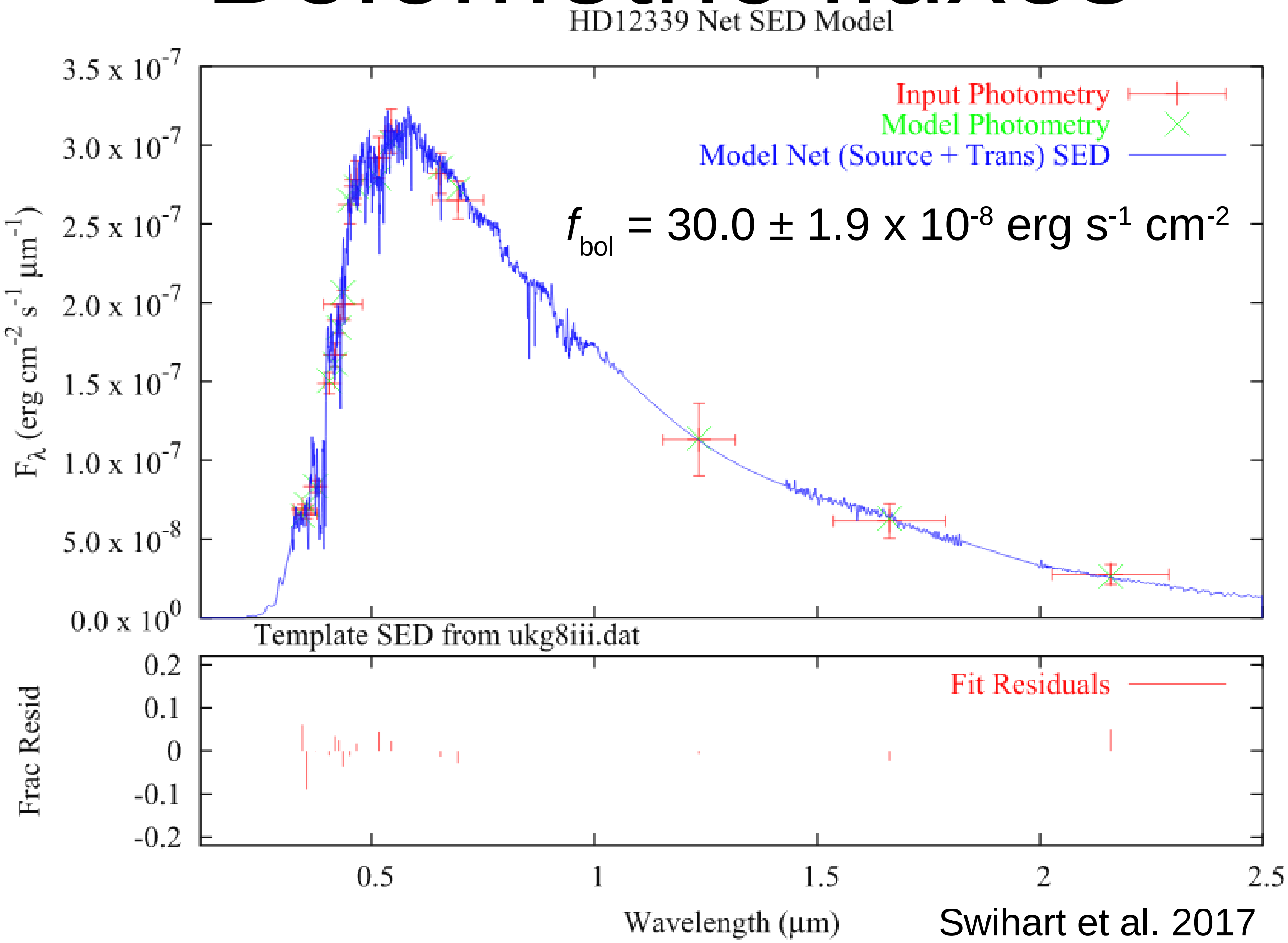
Bolometric fluxes – μ Her

Reference	f_{bol} (nW m^{-2})
Mozurkewich et al. 2003	1.25
Boyajian et al. 2013	1.1640 ± 0.0012
Baines et al. 2014	1.020 ± 0.002
Swihart et al. 2017	1.187 ± 0.020
Freund et al. 2018	1.31

Bolometric fluxes – μ Her

Reference	f_{bol} (nW m^{-2})	T_{eff} (K)
Mozurkewich et al. 2003	1.25 (± 5% ?)	5736 ± 77
Boyajian et al. 2013	1.1640 ± 0.0012	5636 ± 25
Baines et al. 2014	1.020 ± 0.002	5453 ± 24
Swihart et al. 2017	1.187 ± 0.020	5663 ± 34
Freund et al. 2018	1.31 (± 5% ?)	5803 ± 77

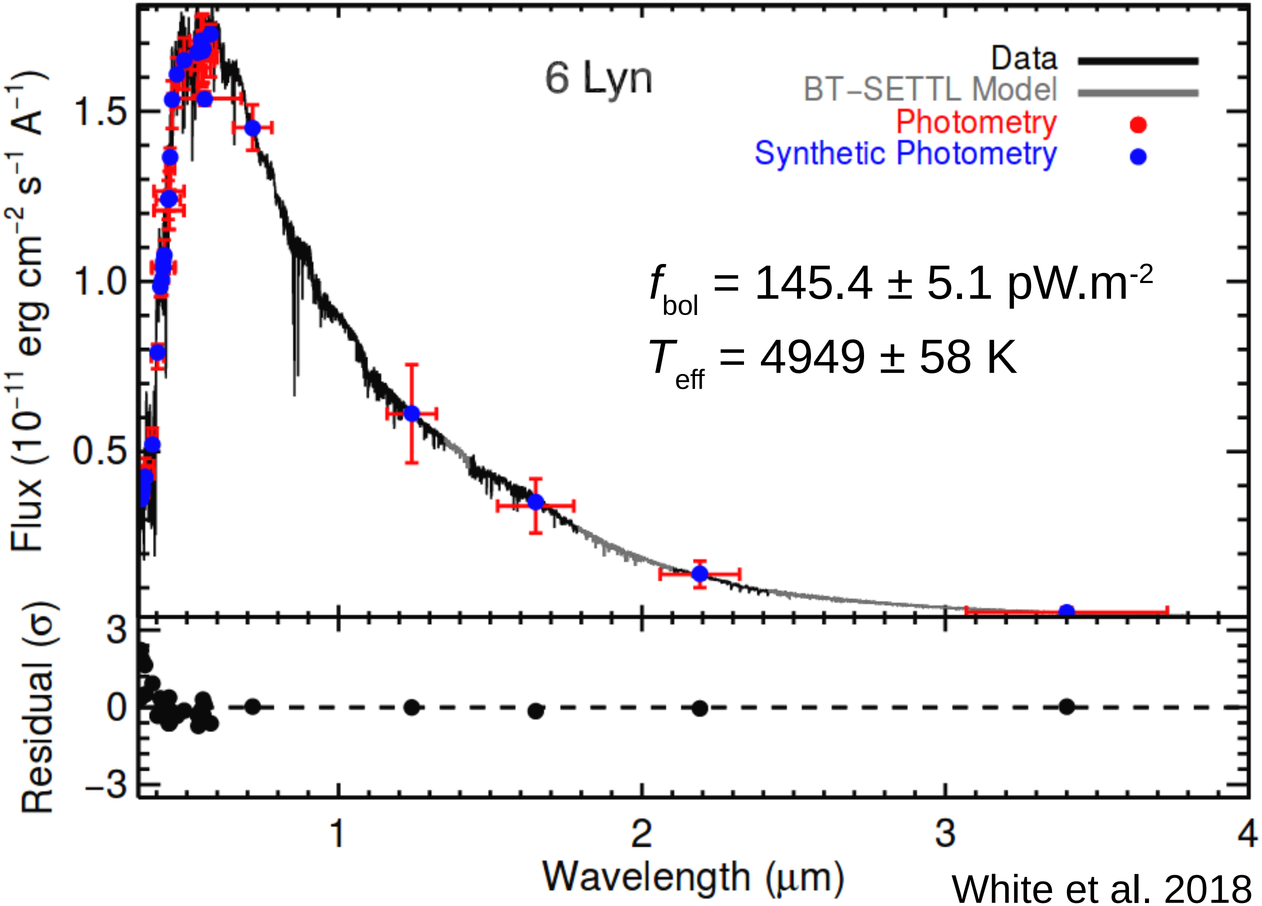
Bolometric fluxes



$f_{bol} = 30.0 \pm 1.9 \times 10^{-8}$ erg s^{-1} cm^{-2}

Swihart et al. 2017

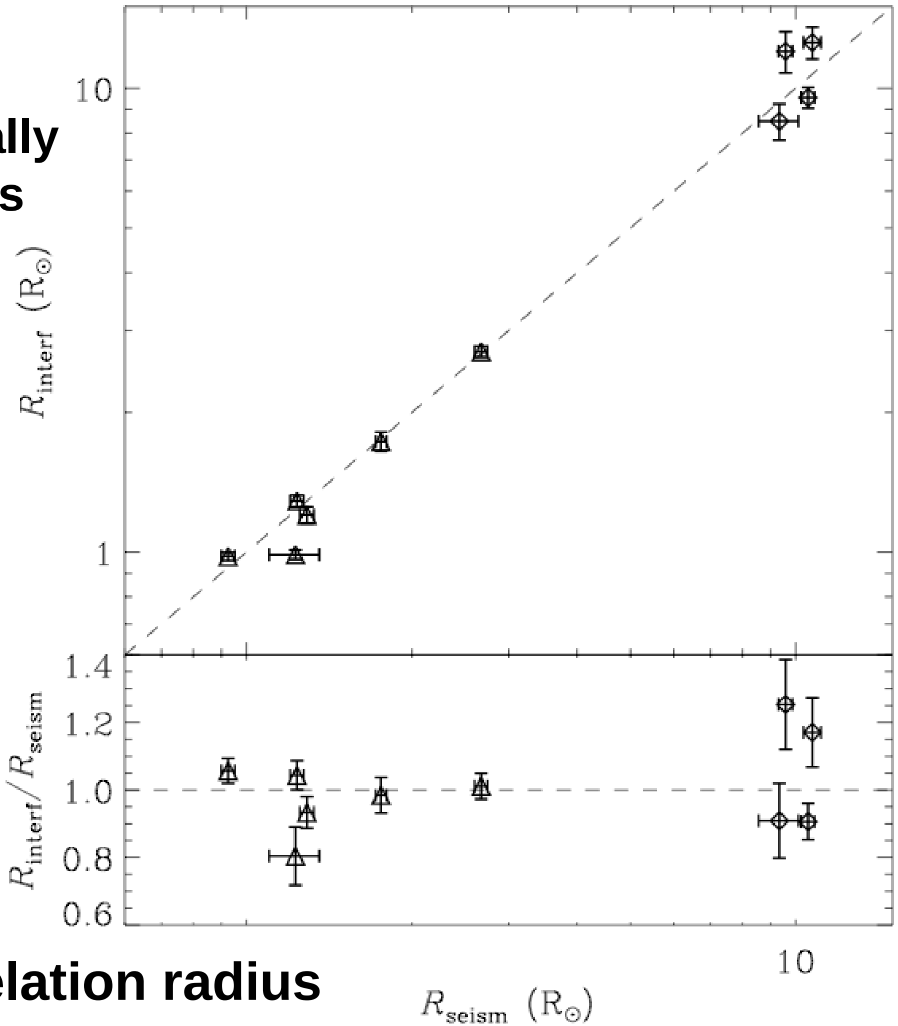
Bolometric fluxes



White et al. 2018

Asteroseismic vs Interferometric Radii

Interferometrically measured radius

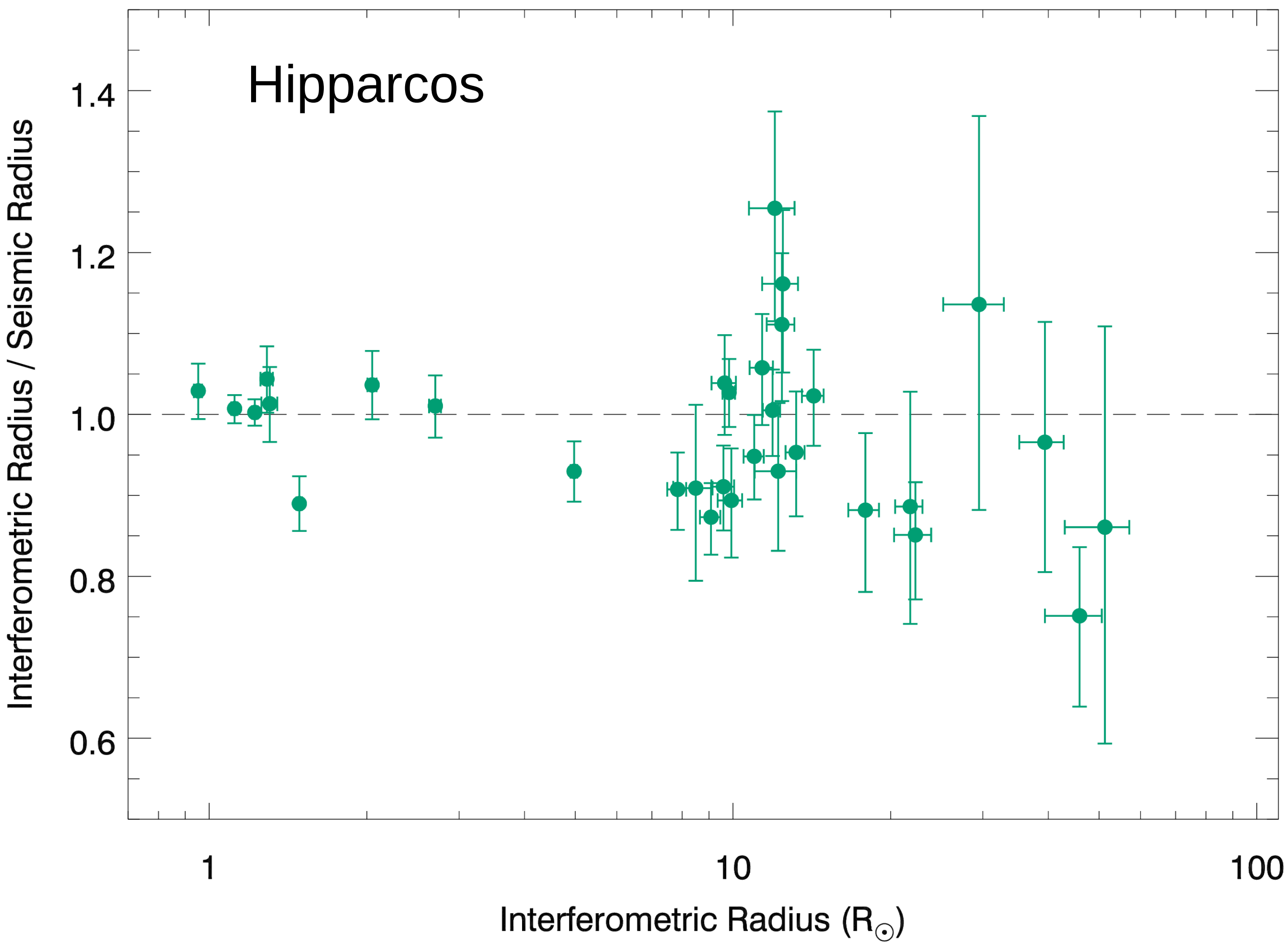


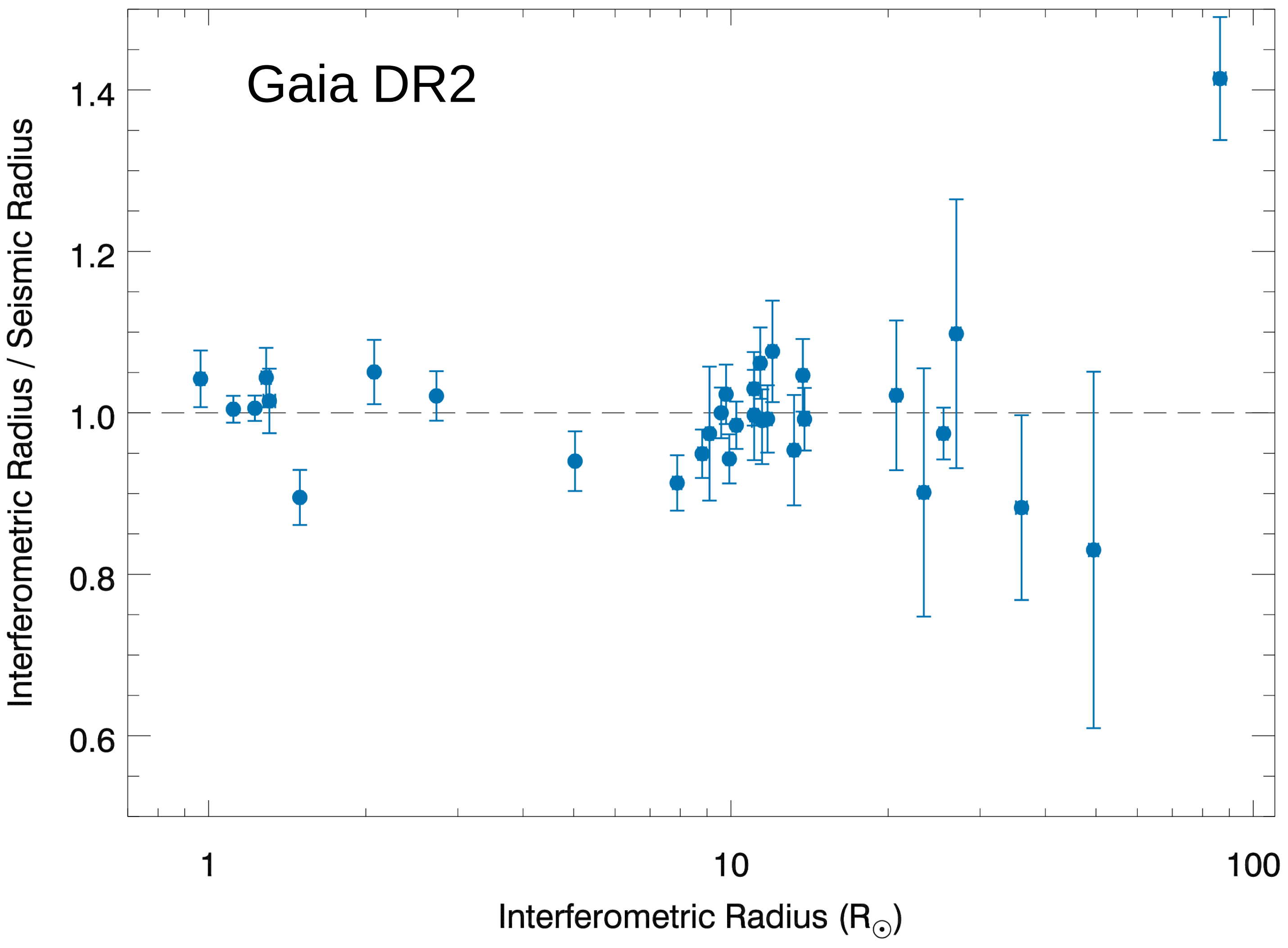
Scaling relation radius

First results for CoRoT & *Kepler* stars

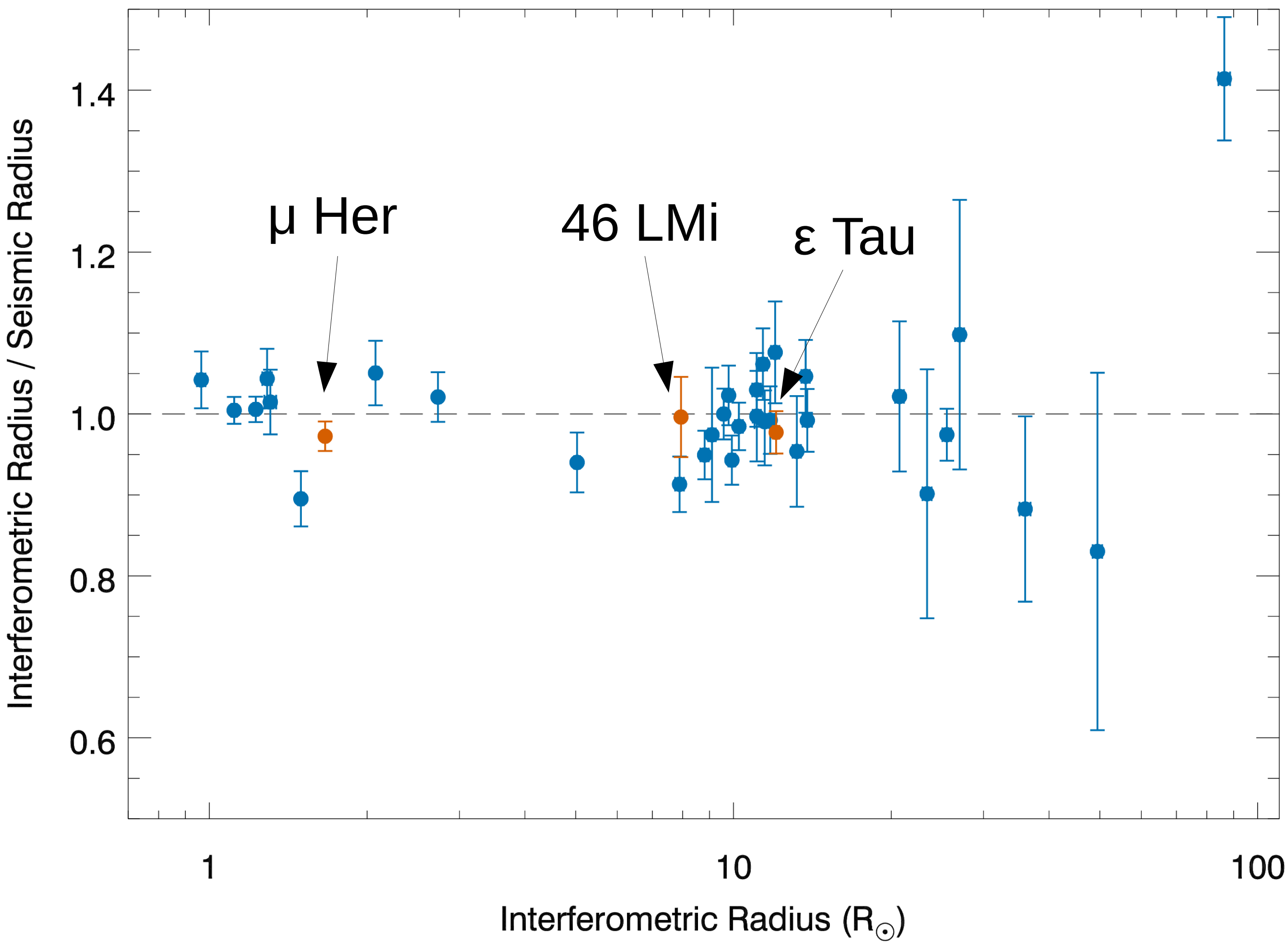
$$\frac{R}{R_\odot} \approx \left(\frac{\nu_{\rm max}}{\nu_{\rm max,\odot}}\right)\left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-2}\left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{\frac{1}{2}}$$

Huber et al. 2012

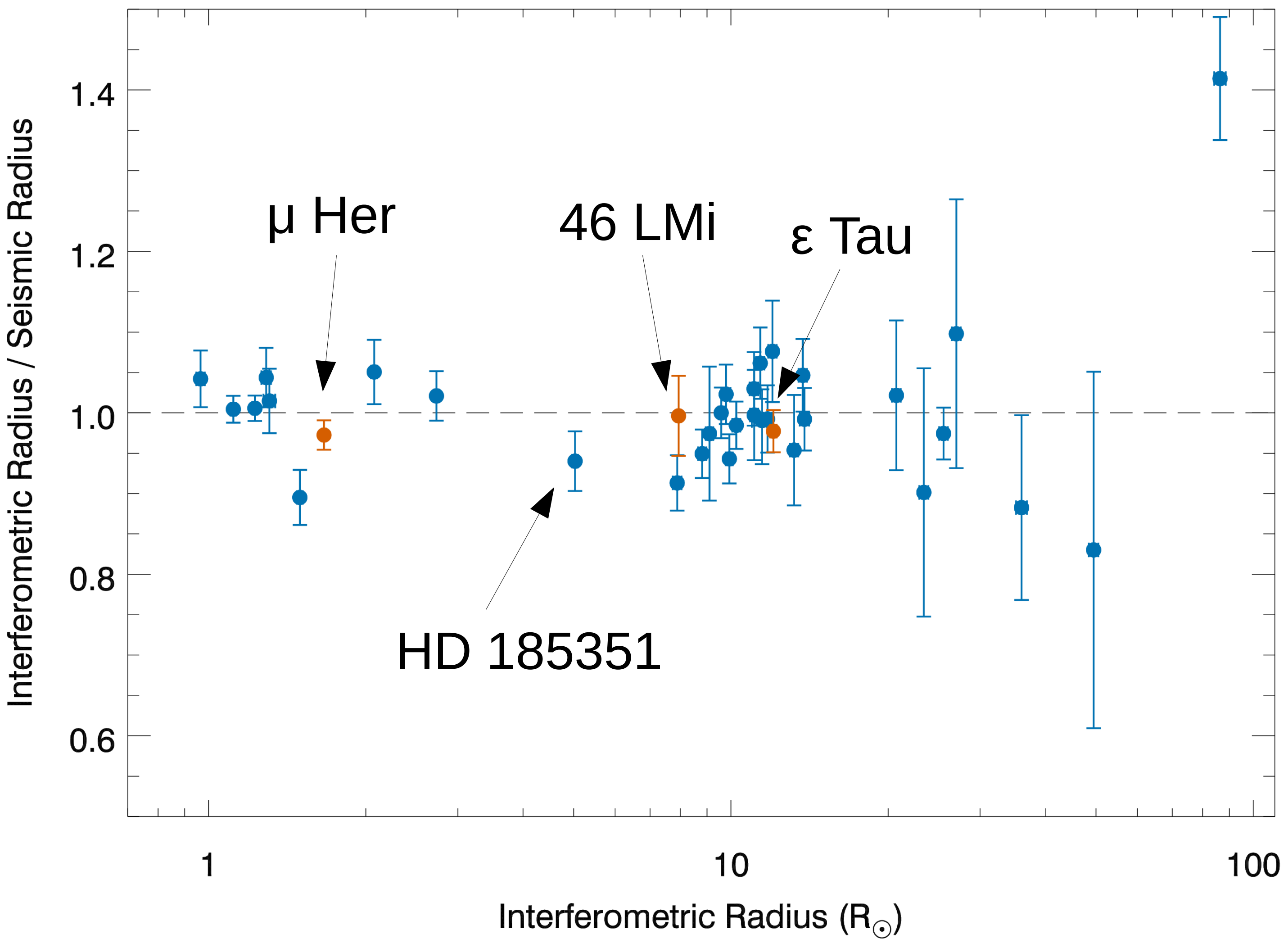

Hipparcos
1.4
1.2
1.0
0.8
0.6
Interferometric Radius / Seismic Radius
1
10
100
Interferometric Radius ($R_\odot$)



Gaia DR2
1.4
1.2
1.0
0.8
0.6
Interferometric Radius / Seismic Radius
1
10
100
Interferometric Radius ($R_\odot$)

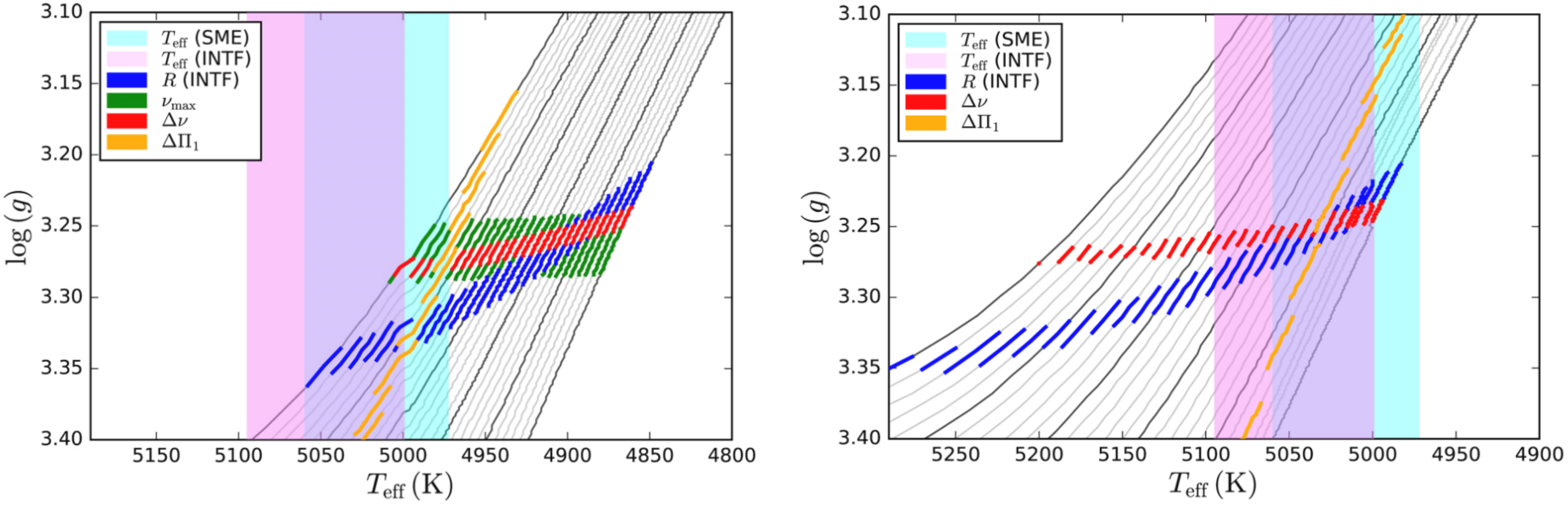


μ Her
46 LMi
ε Tau
1.4
1.2
1.0
0.8
0.6
1
10
100
Interferometric Radius / Seismic Radius
Interferometric Radius ($R_\odot$)

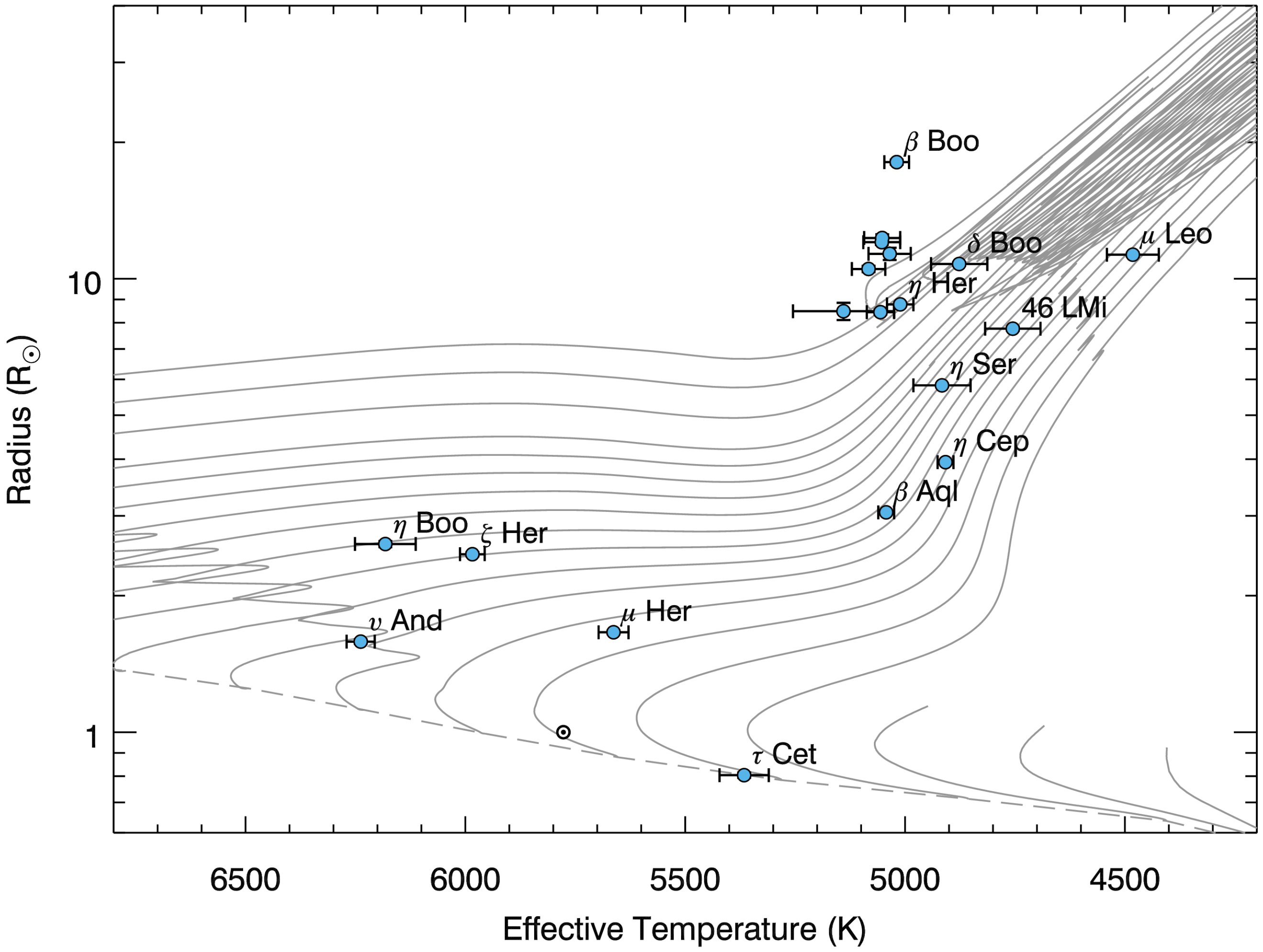


μ Her
46 LMi
ε Tau
HD 185351
1.4
1.2
1.0
0.8
0.6
1
10
100
Interferometric Radius / Seismic Radius
Interferometric Radius ($R_\odot$)

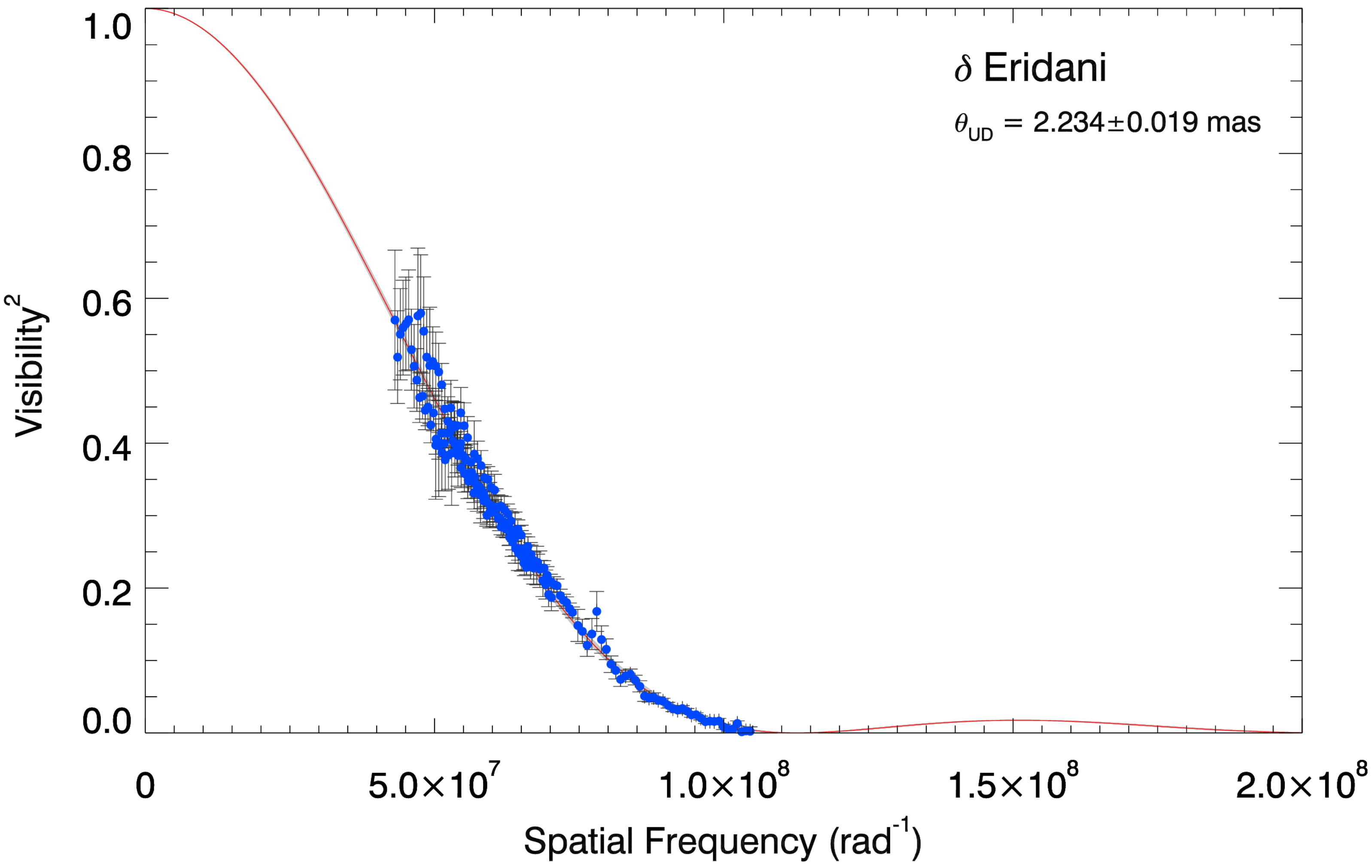
HD 185351



Hjørringgaard et al. 2017



β Boo
δ Boo
μ Leo
η Her
46 LMi
η Ser
η Cep
β Aql
η Boo
ζ Her
υ And
μ Her
τ Cet
10
1
Radius (R☉)
6500
6000
5500
5000
4500
Effective Temperature (K)



δ Eridani
θUD = 2.234±0.019 mas
Visibility2
1.0
0.8
0.6
0.4
0.2
0.0
0
5.0×107
1.0×108
1.5×108
2.0×108
Spatial Frequency (rad-1)

Summary

- The best SONG targets also make the best targets for interferometry
- We need to be aware of possible systematic errors
- With nearby bright stars we can measure limb darkening and test model atmospheres
- There will be great opportunities to take advantage of the combination of asteroseismology and interferometry to test and refine stellar models, particularly as the network expands and more stars can receive a μ Her-like treatment.