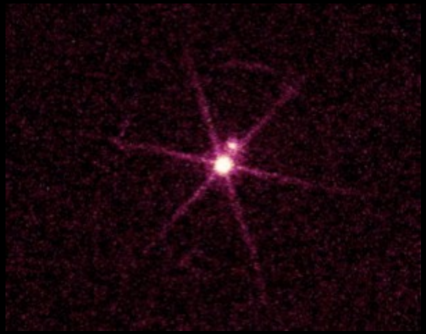
# A basic introduction to optical interferometry

Henri Boffin

## Visual Binary

Mizar A & B

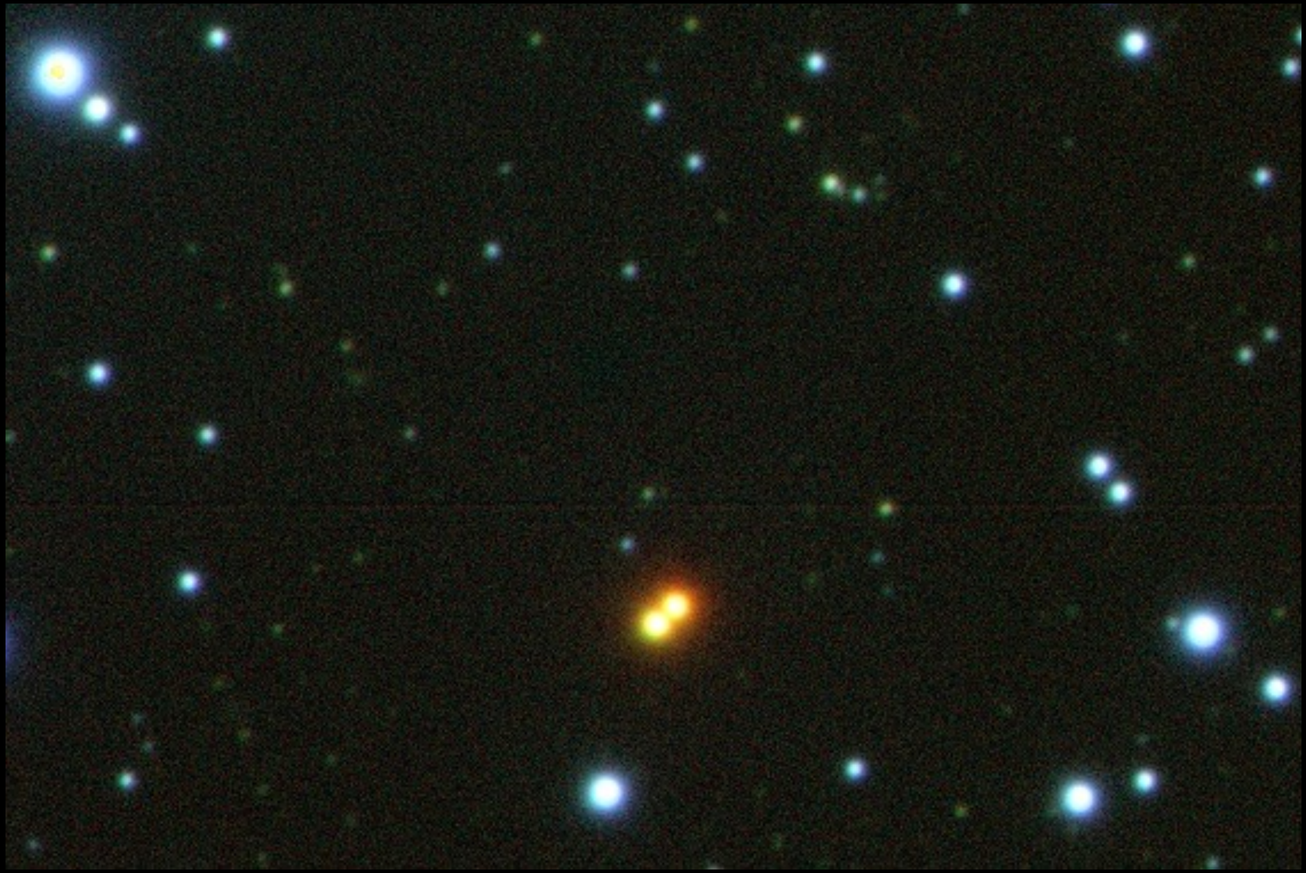


SiriusA & B

Both stars in the binary system can be spatially resolved

seeing limited → separation ~ 0.3” or more

# A close example



Boffin+ 13 FORS2

Luhman 16 AB

2 brown dwarfs

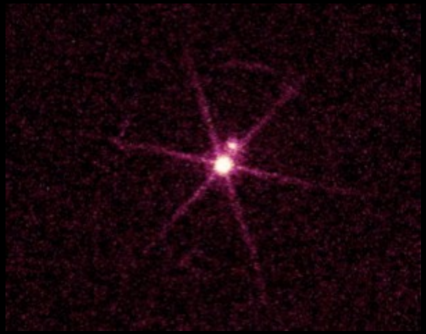
Separation 1.5”

Distance 2 pc

→ 3 AU separation

# Visual Binary

Mizar A & B



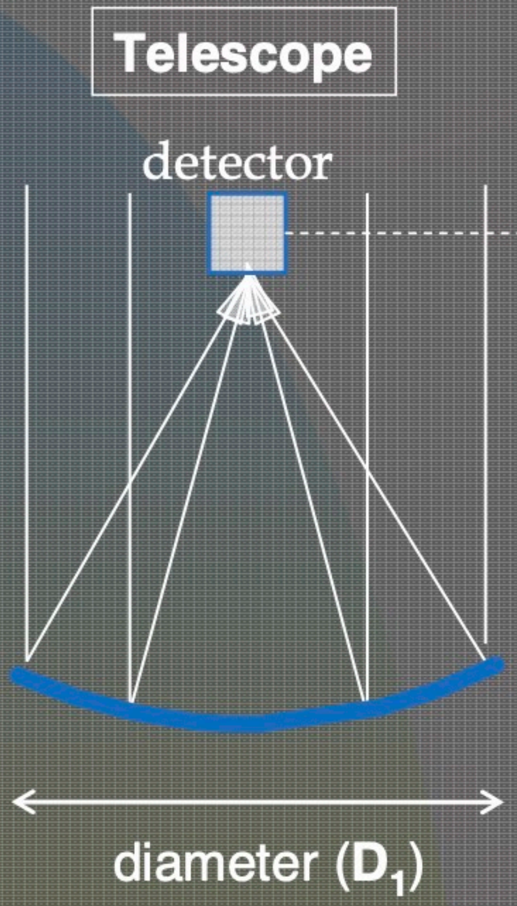
SiriusA & B

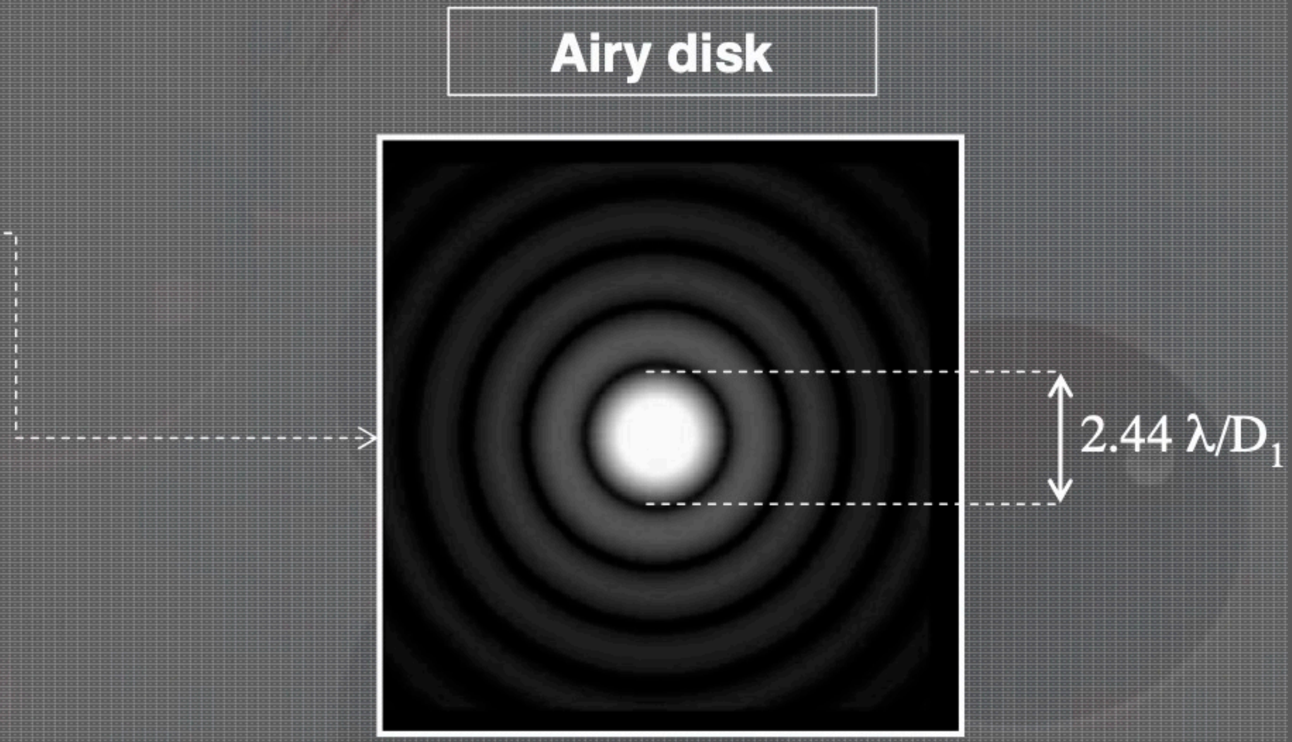
Both stars in the binary system can be spatially resolved

seeing limited → separation ~ 0.3” or more

HST and AO on ground → ~ 0.05”

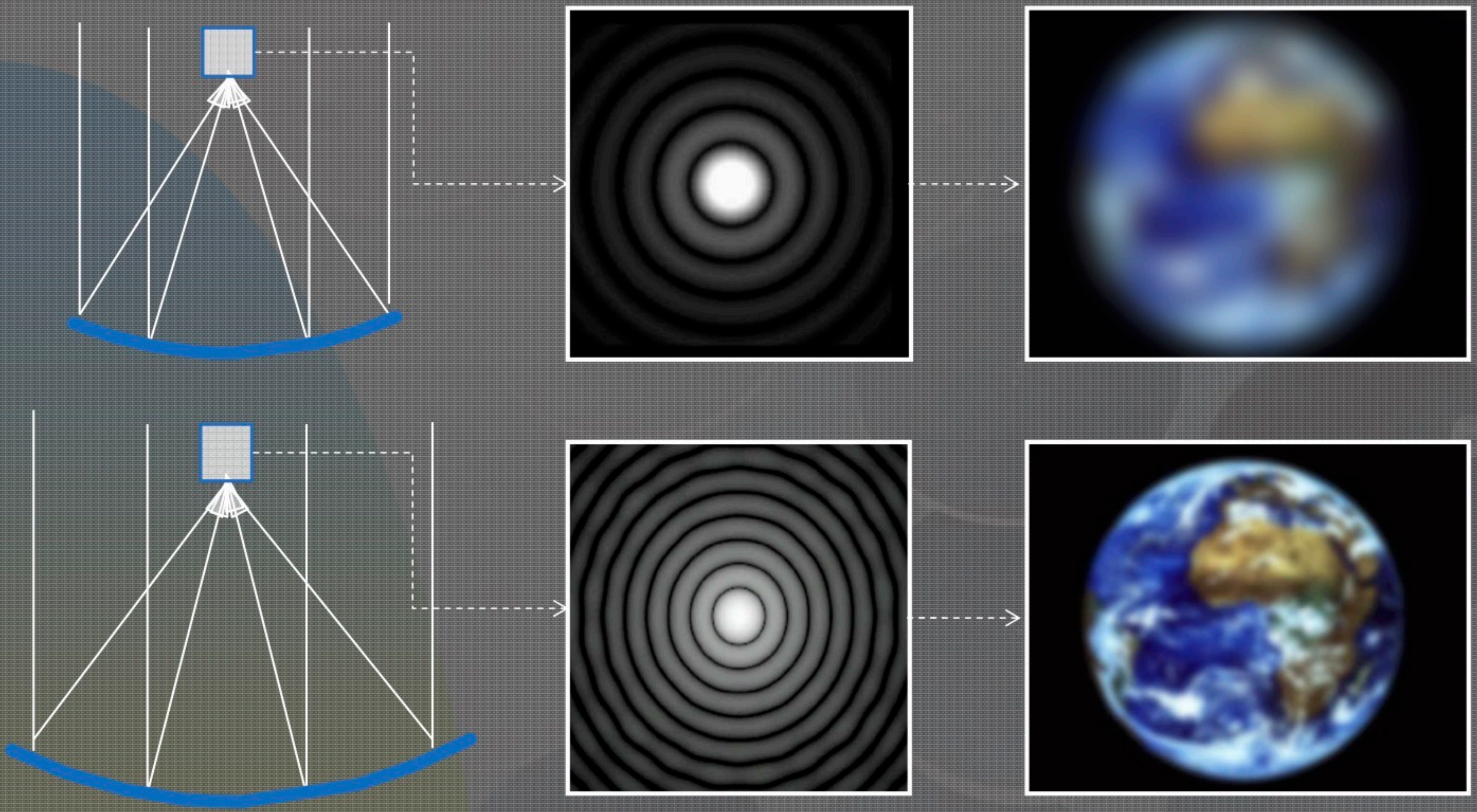
Diffraction limit of VLT: $1.22\lambda/D = 0.017''$ (=17mas) for a D=8m telescope in the visible ($\lambda$=550nm)



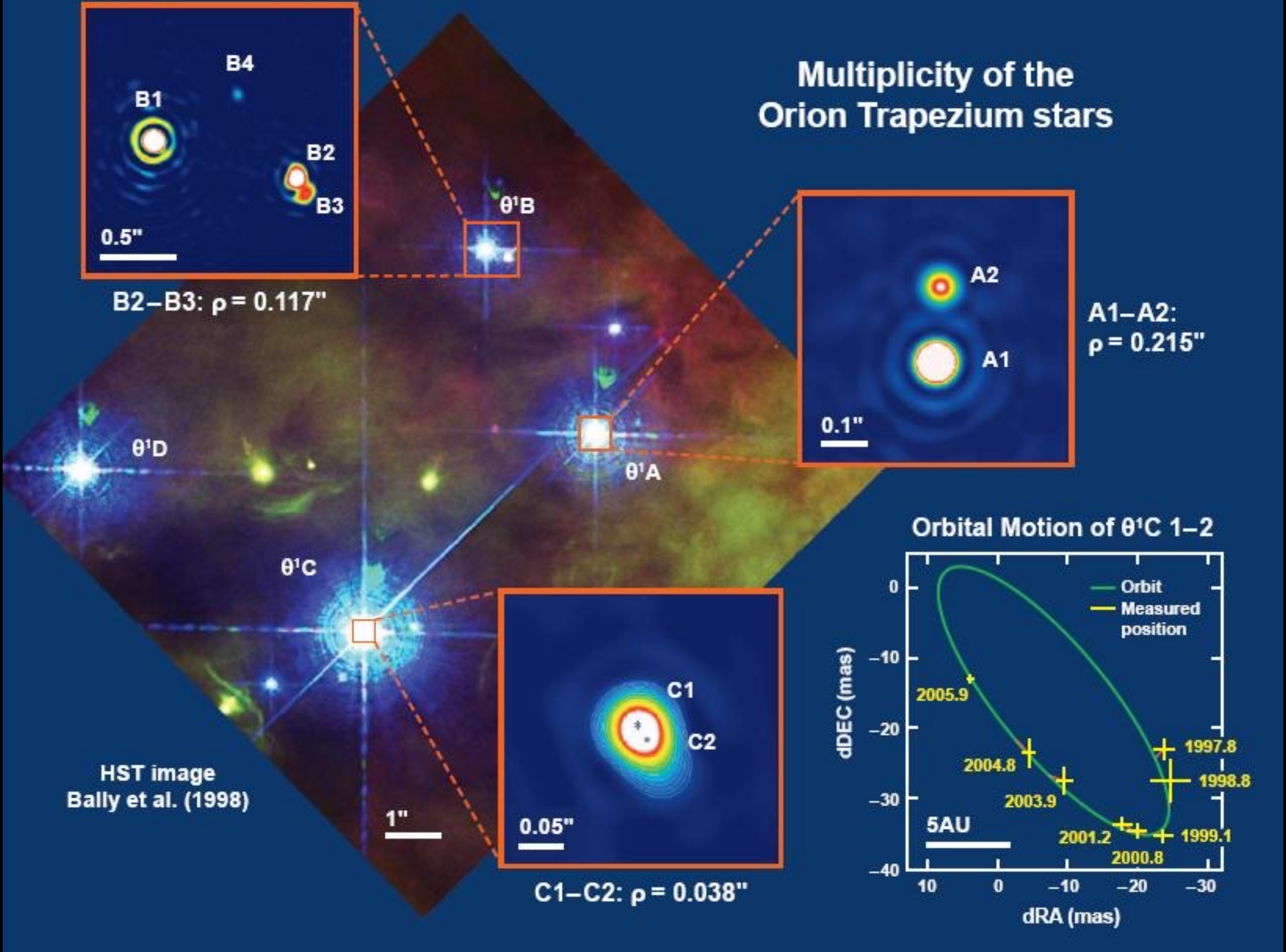

- The image of a star is like a dot!

c/o Denis Defrère



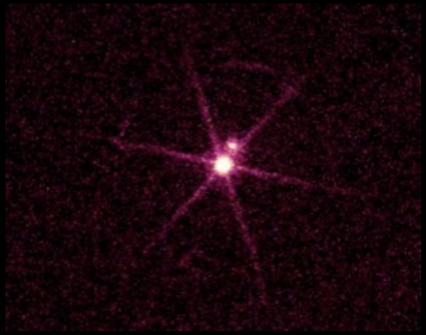
- Need for very large telescopes !!!

# Multiplicity of the Orion Trapezium stars



## Visual Binary

Mizar A & B



SiriusA & B

Both stars in the binary system can be spatially resolved

seeing limited → separation ~ 0.3” or more

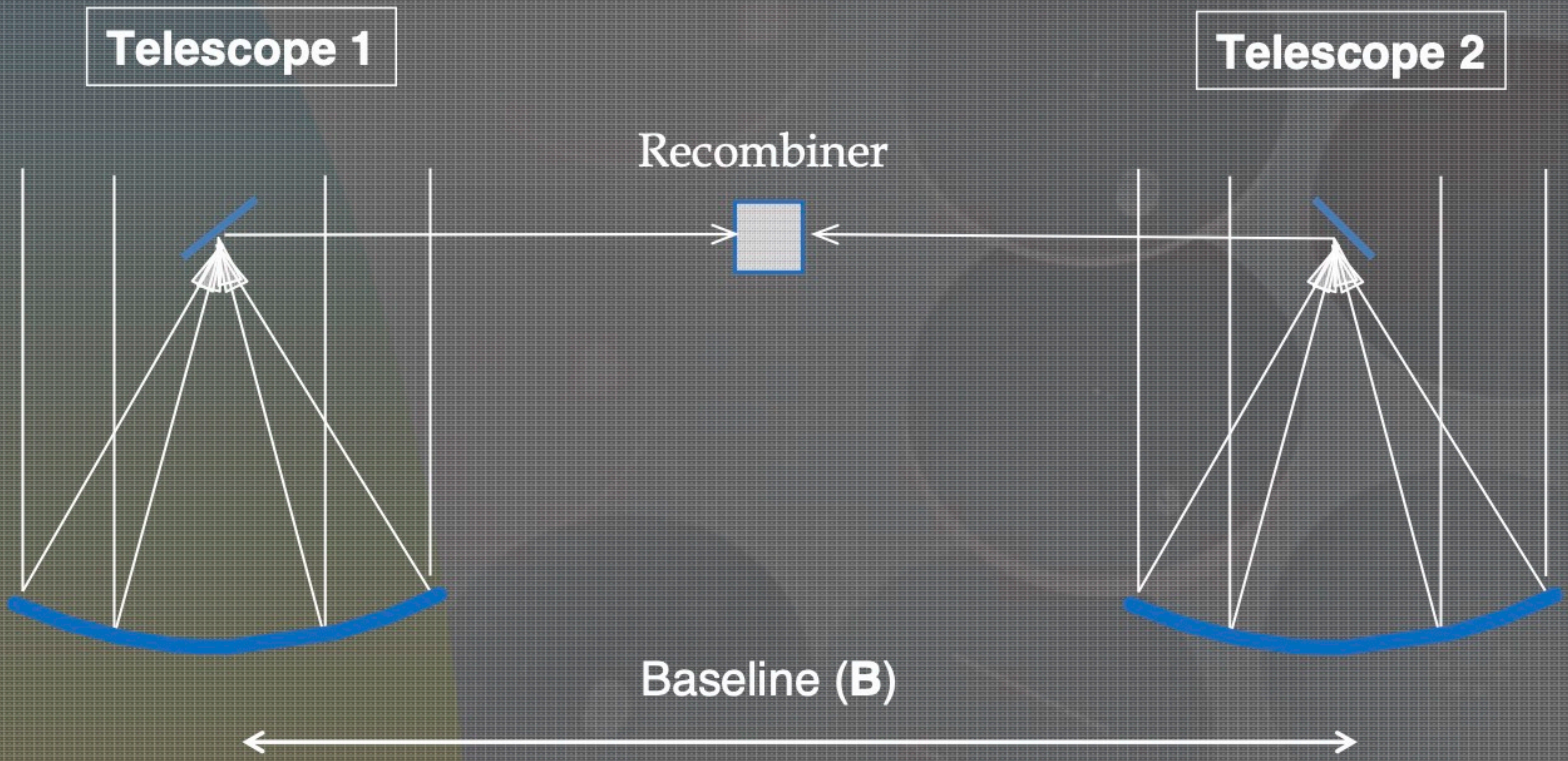
HST and AO on ground → ~ 0.05”

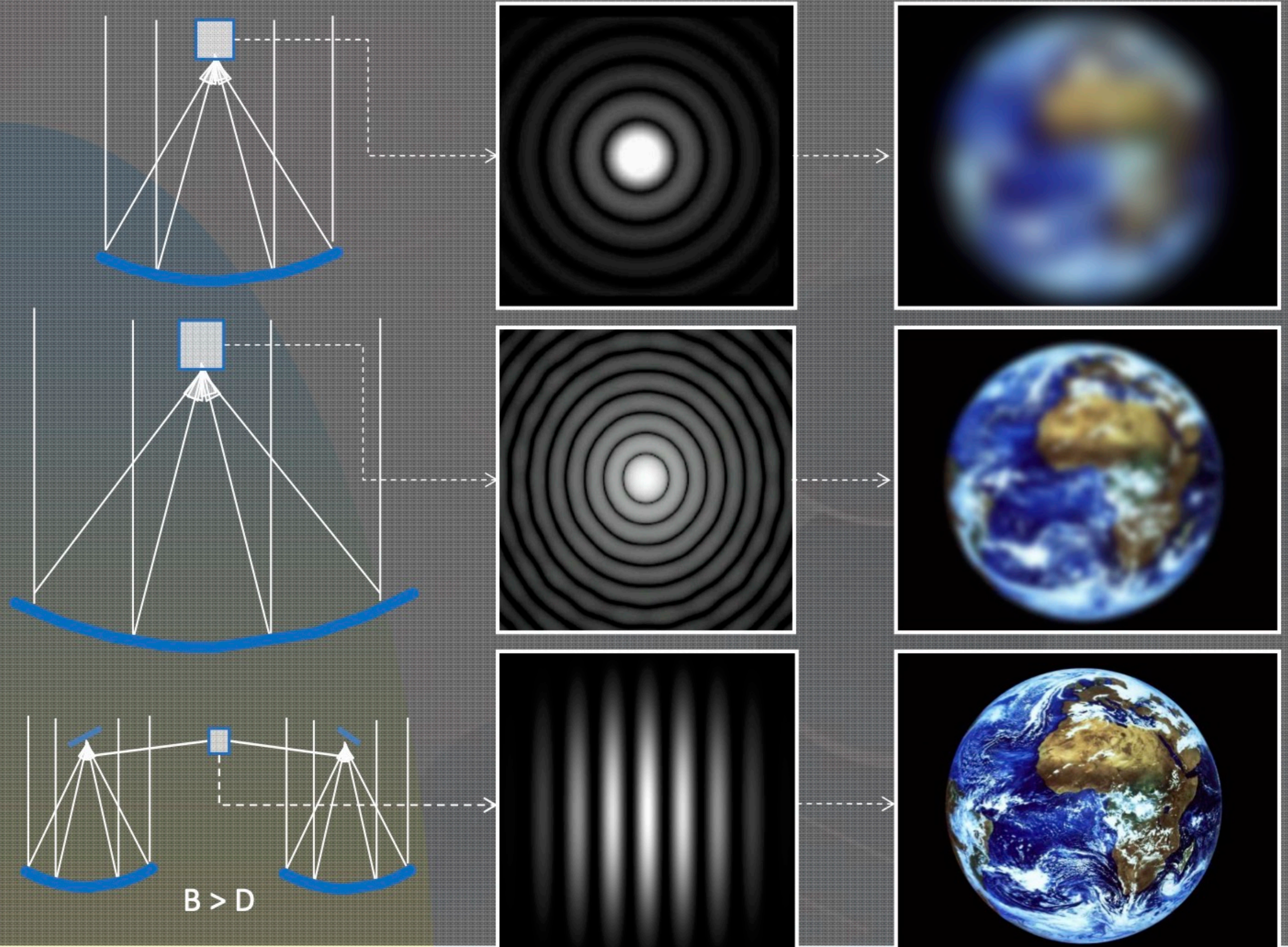
To resolve smaller objects: interferometry!

→ a few 0.001” (mas)

- H. Fizeau and E. Stephan (1868-1870):

  "In terms of angular resolution, two small apertures distant of B are equivalent to a single large aperture of diameter B"




B > D

# Some orders of magnitude

$1.22\lambda/D = 0.017''$ (=17mas) for an D=8m telescope in the visible ($\lambda$=550nm)

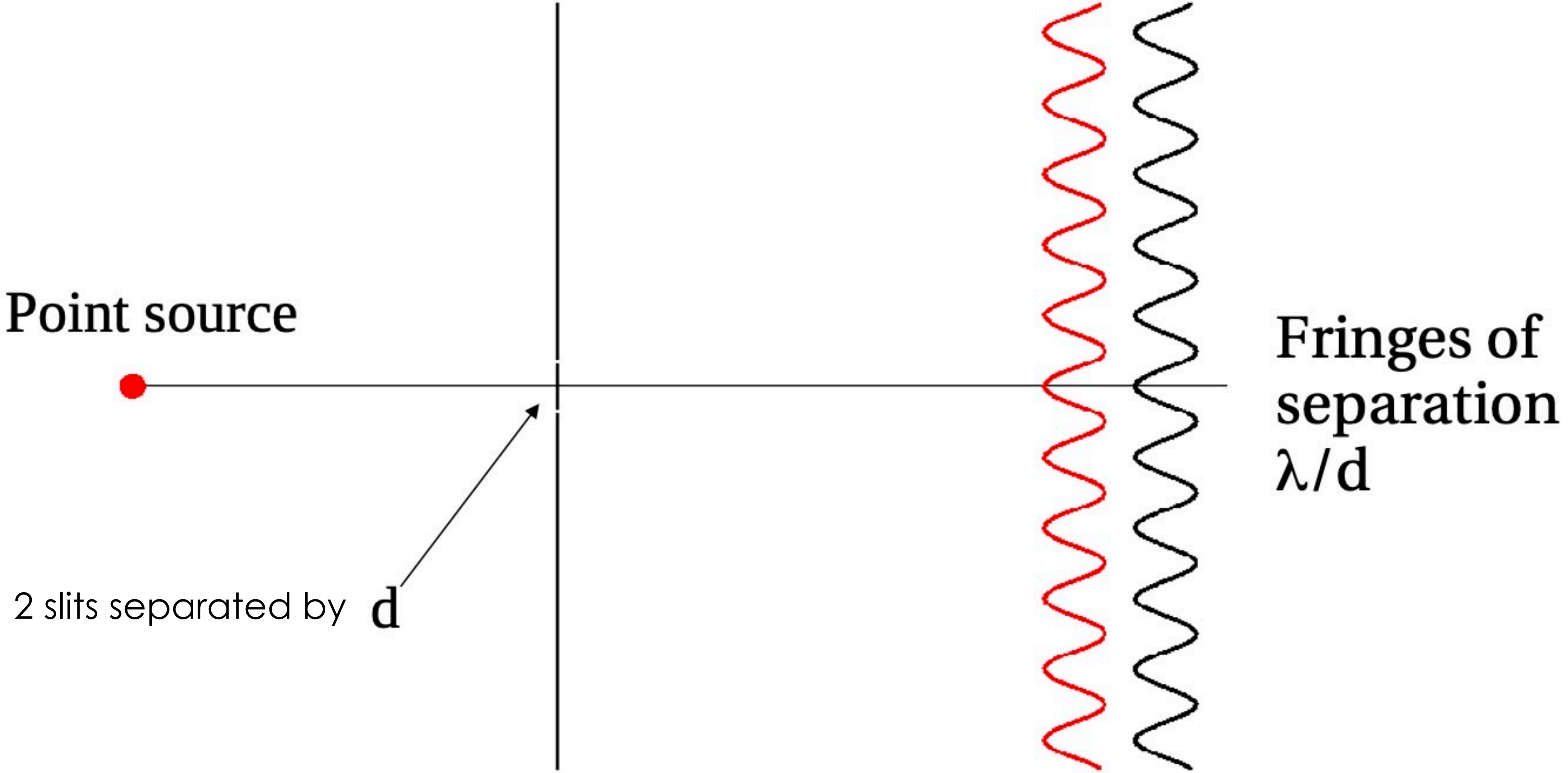
1 arcsec = 1 astronomical unit ($150\times10^6$km) seen from a distance of 1 parsec (~3.26 light years)

From the closest star (proxima Cen, d=1.3pc): the Sun appears 0.007”=7mas

Closest star forming regions at d ≈ 140pc:
1” is 140 au ≈ 3x Pluto’s orbit
0.017” is 2.4 au ≈ asteroid belt
1 mas is 0.14 au ≈ within Mercury orbit

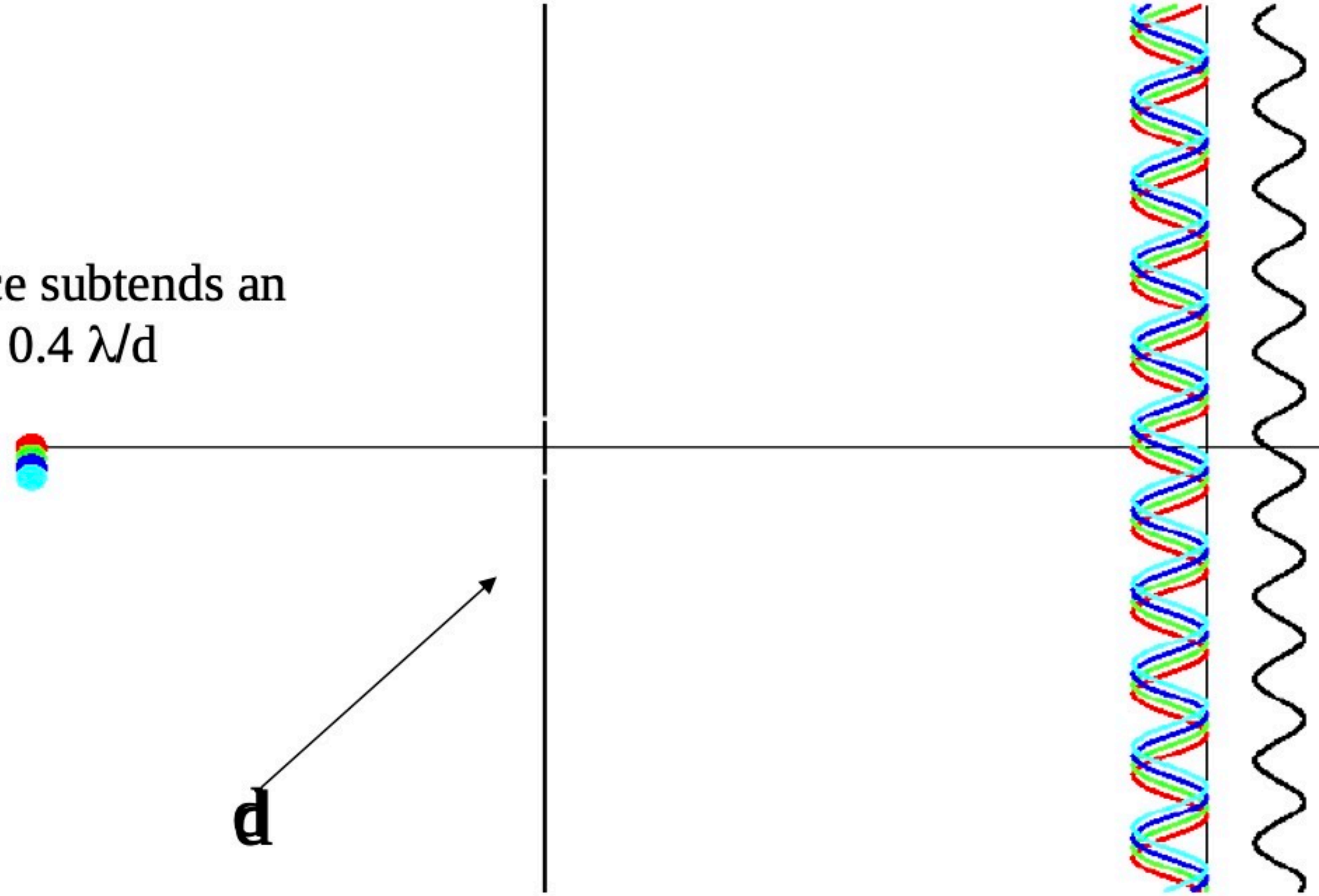
At 1 kpc, 1 mas is 1 au → ideal for binary stars

# Young's slits revisited



# Larger source

Source subtends an angle 0.4 λ/d

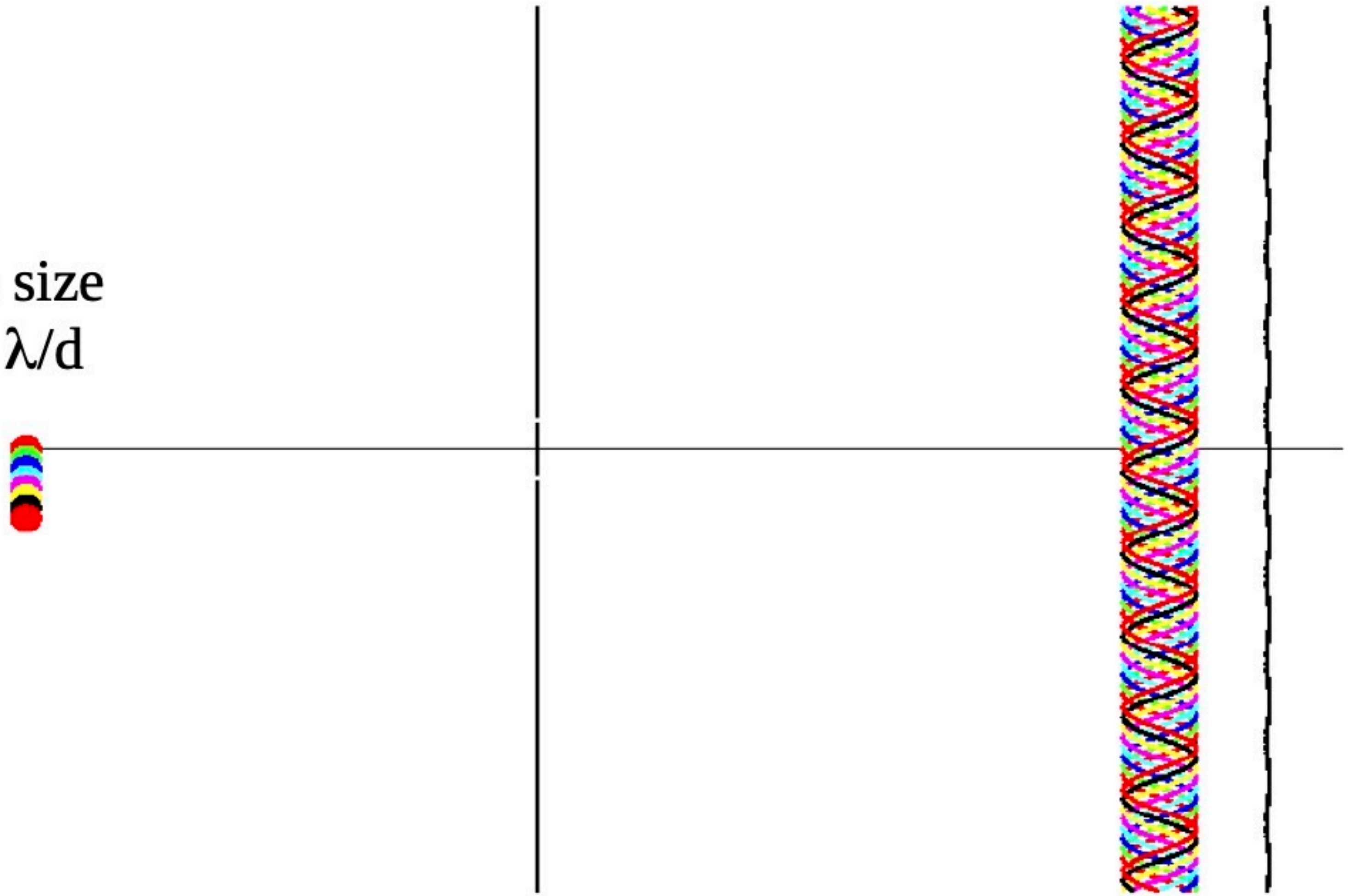



Fringes move by 0.4 λ/d. Incoherent sources -> add intensities, fringes start to add out destructively

Define |fringe visibility| as ($I_{max}$-$I_{min}$)/($I_{max}$+$I_{min}$)

# Still larger source

Source size
gets to λ/d



No fringes remain (cancellation). Little fringing seen for larger sources than λ/d either.

Credit: ESO

# Fringe visibility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- The fringes' amplitude and phase is called the **complex visibility**
- Baseline vector $\vec{B} = (u, v)$ [same unit as λ]
- Pointing vector $\vec{s} = (x, y)$ [in rad]
- The complex visibility is the normalized Fourier transform of the image I(x,y):

$$V(u, v, \lambda) = \frac{\iint I(x, y) e^{-2\pi i (xu + yv)/\lambda} dx dy}{\iint I(x, y) dx dy}$$

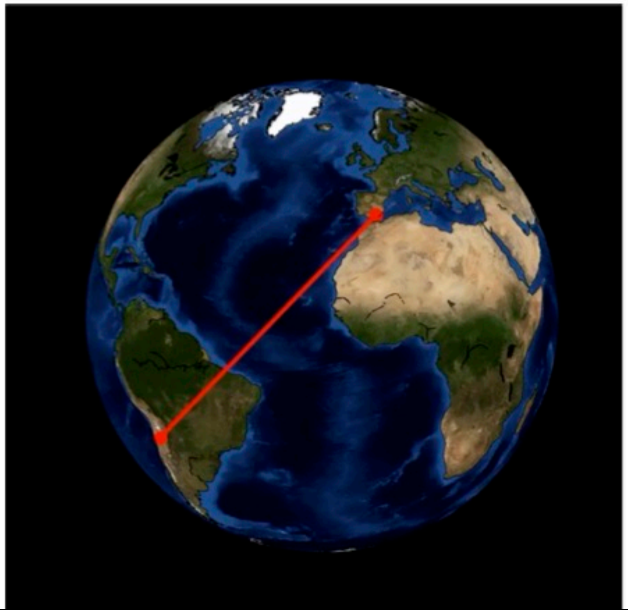
*[Van Cittert – Zernike Theorem]*

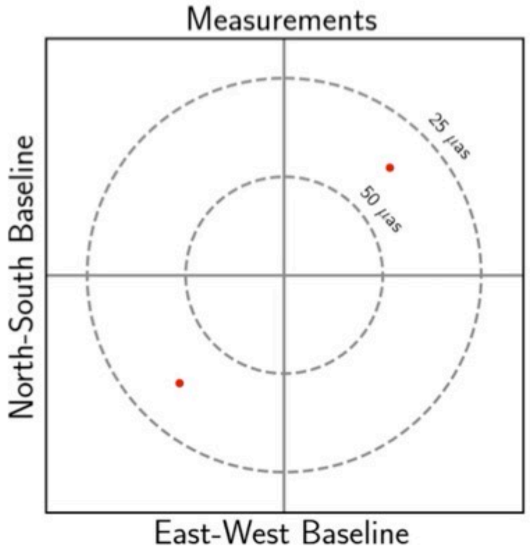
A. Mérand

x, y: components of the source    u, v: projection vector of the telescopes

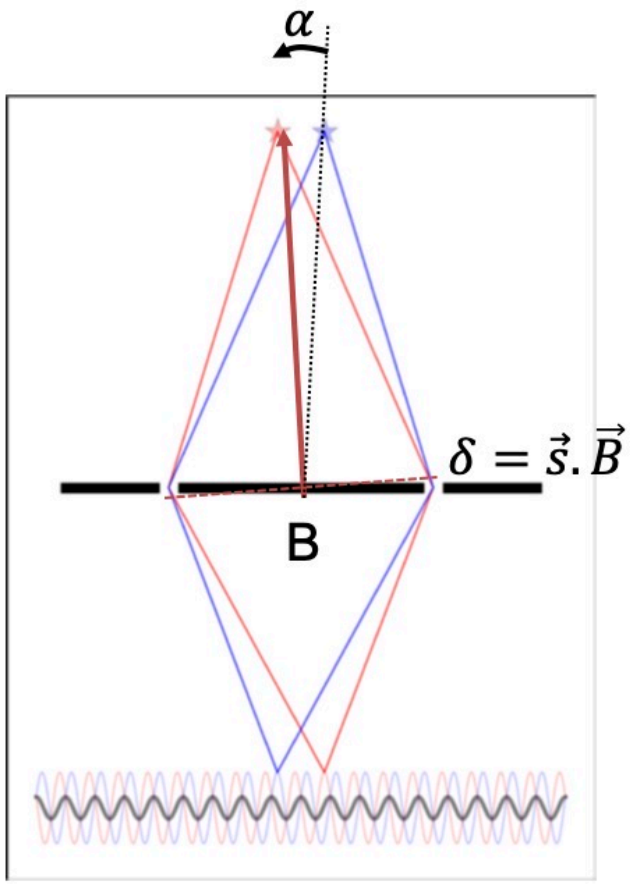
# Single baseline gives very limited information

- Binaries separated by $\alpha$, $2\alpha$, $3\alpha$, … have same fringe pattern for a given B
- Image is 2D and baseline is 1D









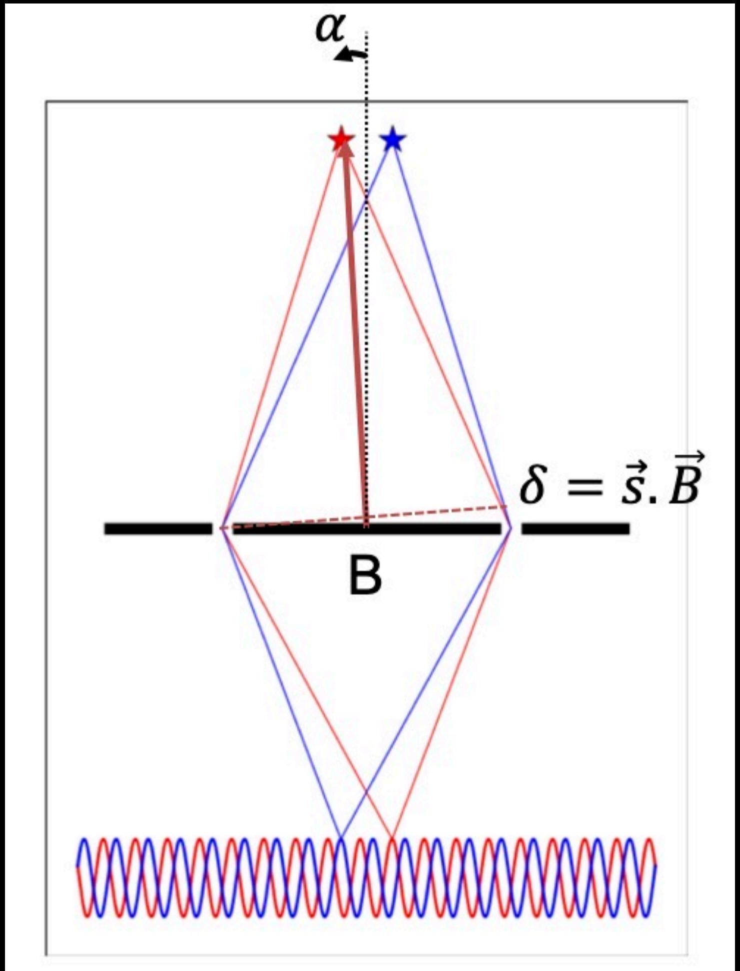


A. Mérand

The complex visibility is defined by

**Amplitude** → generally use the intensity $\simeq$ Visibility$^2$

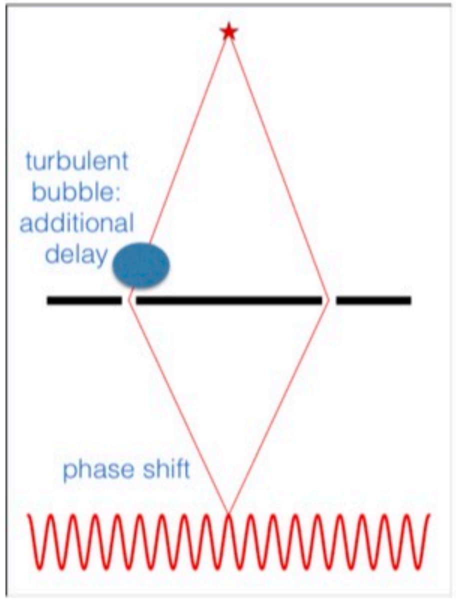
**Phase** → this cannot be used on its own, generally

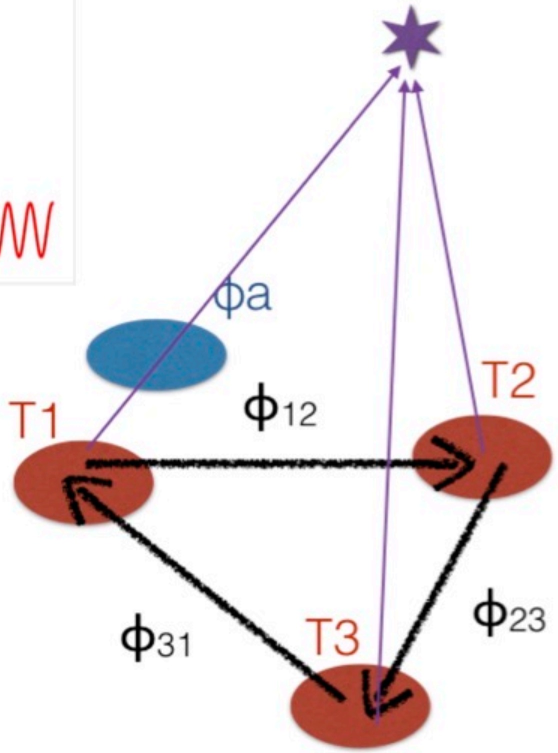


# Recover the phase information

- The atmosphere induces phase jitter >> $2\pi$
- Sum of phases in a triangle are immune to the turbulence: closure phase

$$\begin{aligned} CP &= (\phi_{12}+\varphi_a) + \phi_{23} + (\phi_{31}-\varphi_a) \\ &= \phi_{12} + \phi_{23} + \phi_{31} \end{aligned}$$

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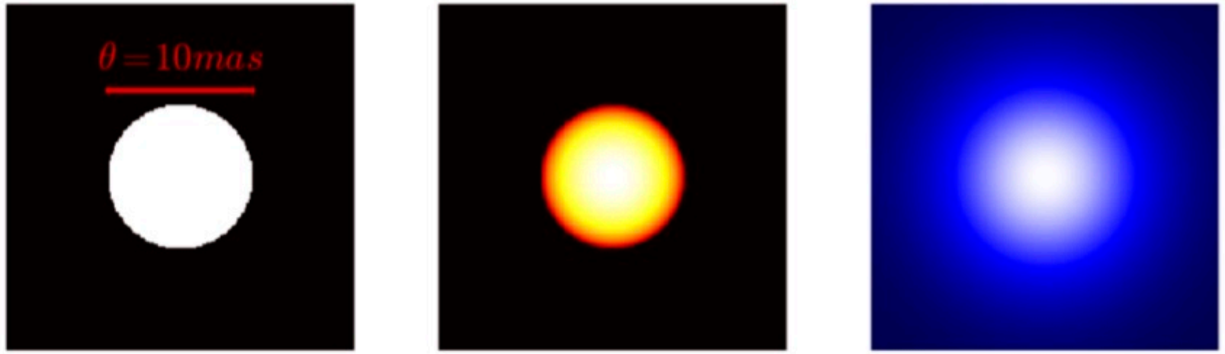
# Centro-symmetric images

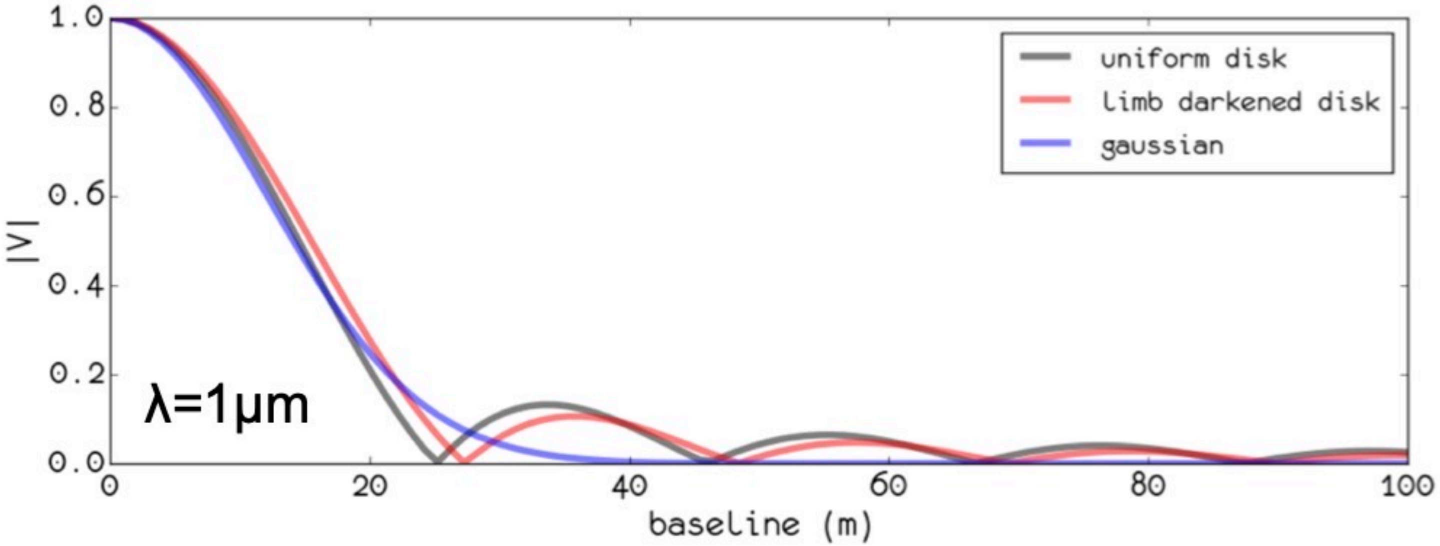
For a centro-symmetric image, Fourier transform becomes an Hankel transform:

$$V(B,\lambda) = \frac{\int I(r,\lambda) J_0(rB/\lambda) r dr}{\int I(r,\lambda) dr}$$

Case for a uniform disk:

$$V_{\mathrm{UD}} = 2\frac{J_1(x=\pi B\theta/\lambda)}{x}$$

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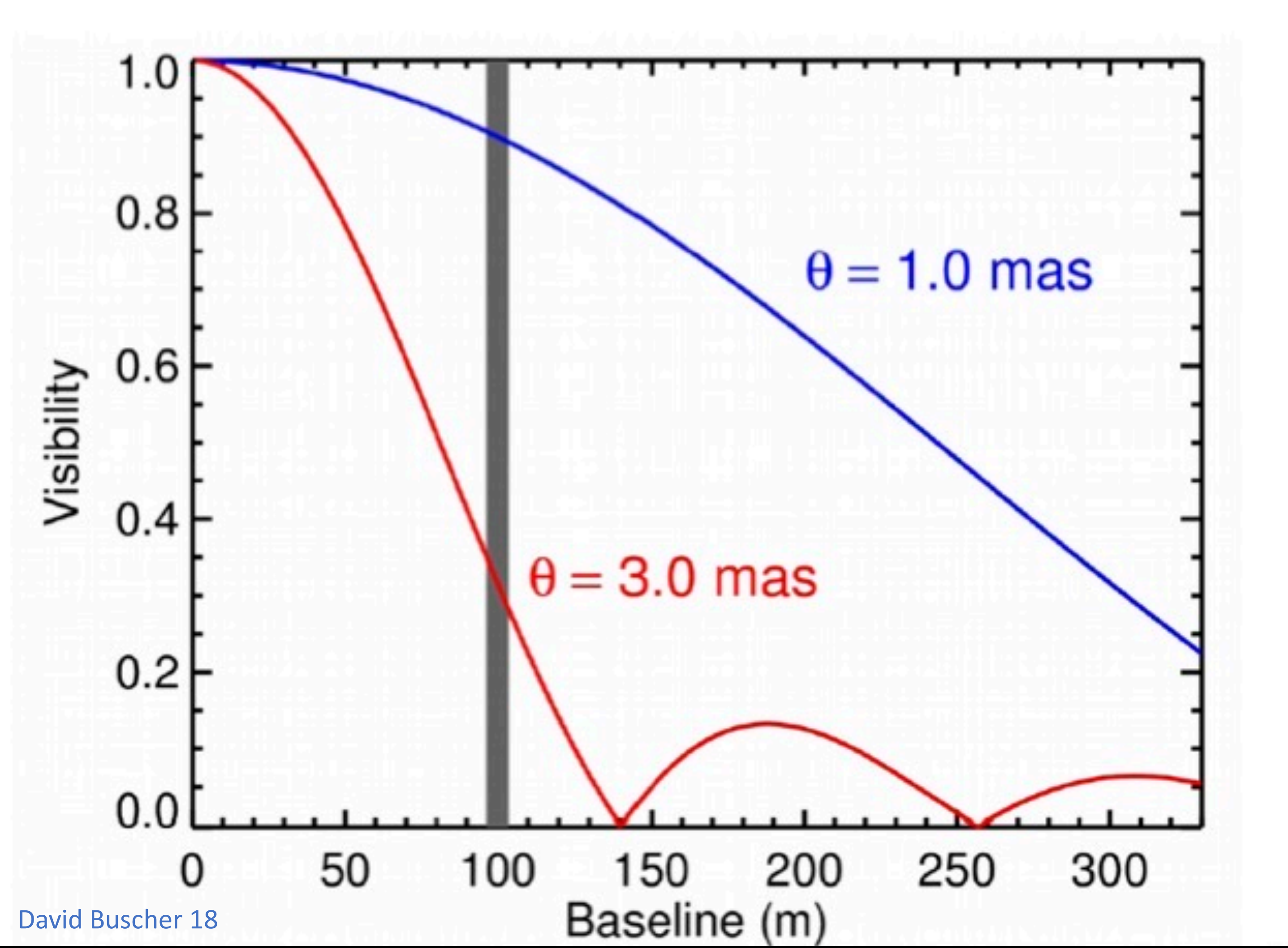
# Uniform disc

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## In a nutshell

**Visibility** = “contrast” of the fringes

→ Tells about the size of an object

- → The smaller the visibility, the larger the object

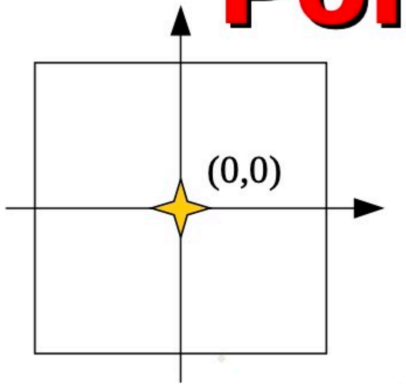
**Closure Phase**

→ Tells about the shape and orientation of an object

Observations are done in the **u-v plane**: the more baselines, the better the resulting fit/image

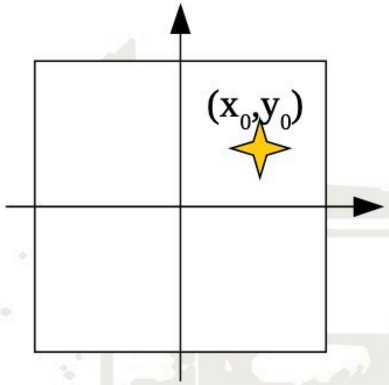
# Point source function

**Use: Multiple stars**



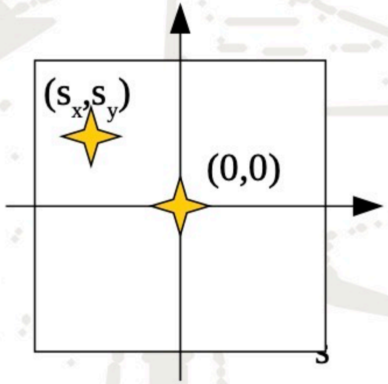

### *Centered source*

$$I(x,y) = \delta(x,y) \Rightarrow V(u,v) = 1$$




### *Off-axis source*

$$I(x,y) = \delta(x-x_0)\delta(y-y_0) \Rightarrow V(u,v) = \exp[-2i\pi(x_0u + y_0v)]$$

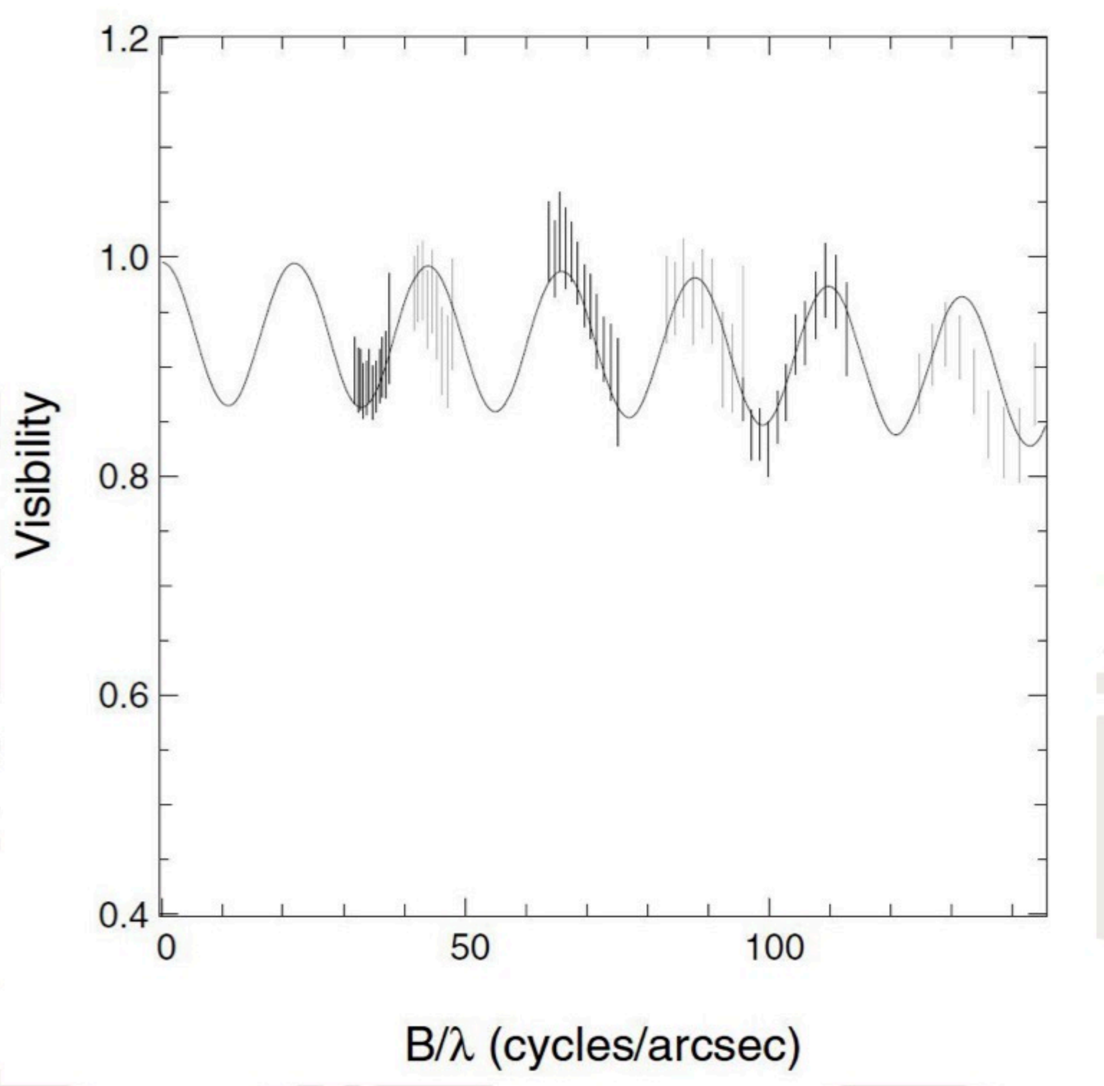



### *Binary system*

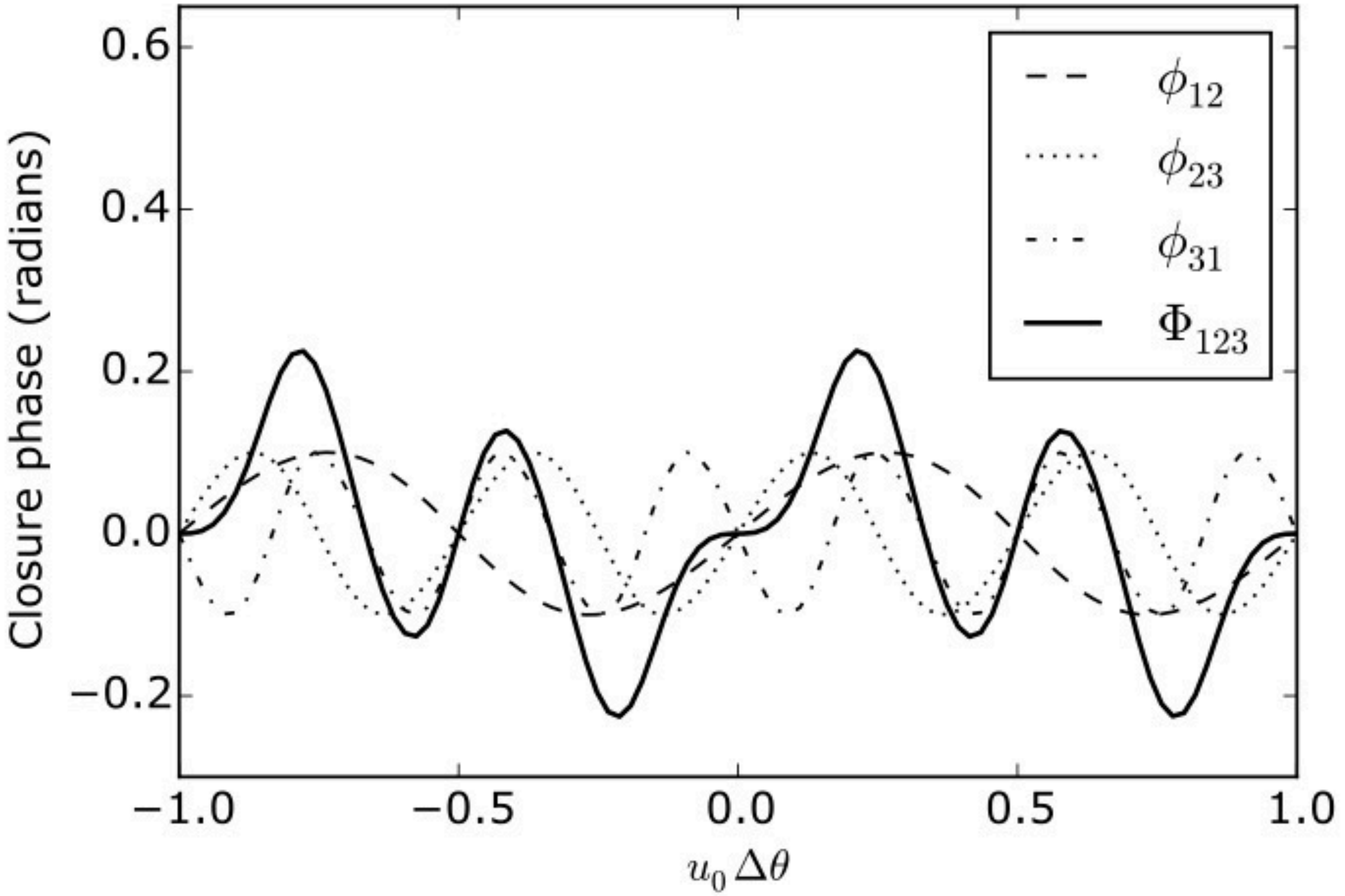
$$A\delta(x,y) + B\delta(x-sx, y-sy) \text{ with } s = \sqrt{sx^2+sy^2}$$

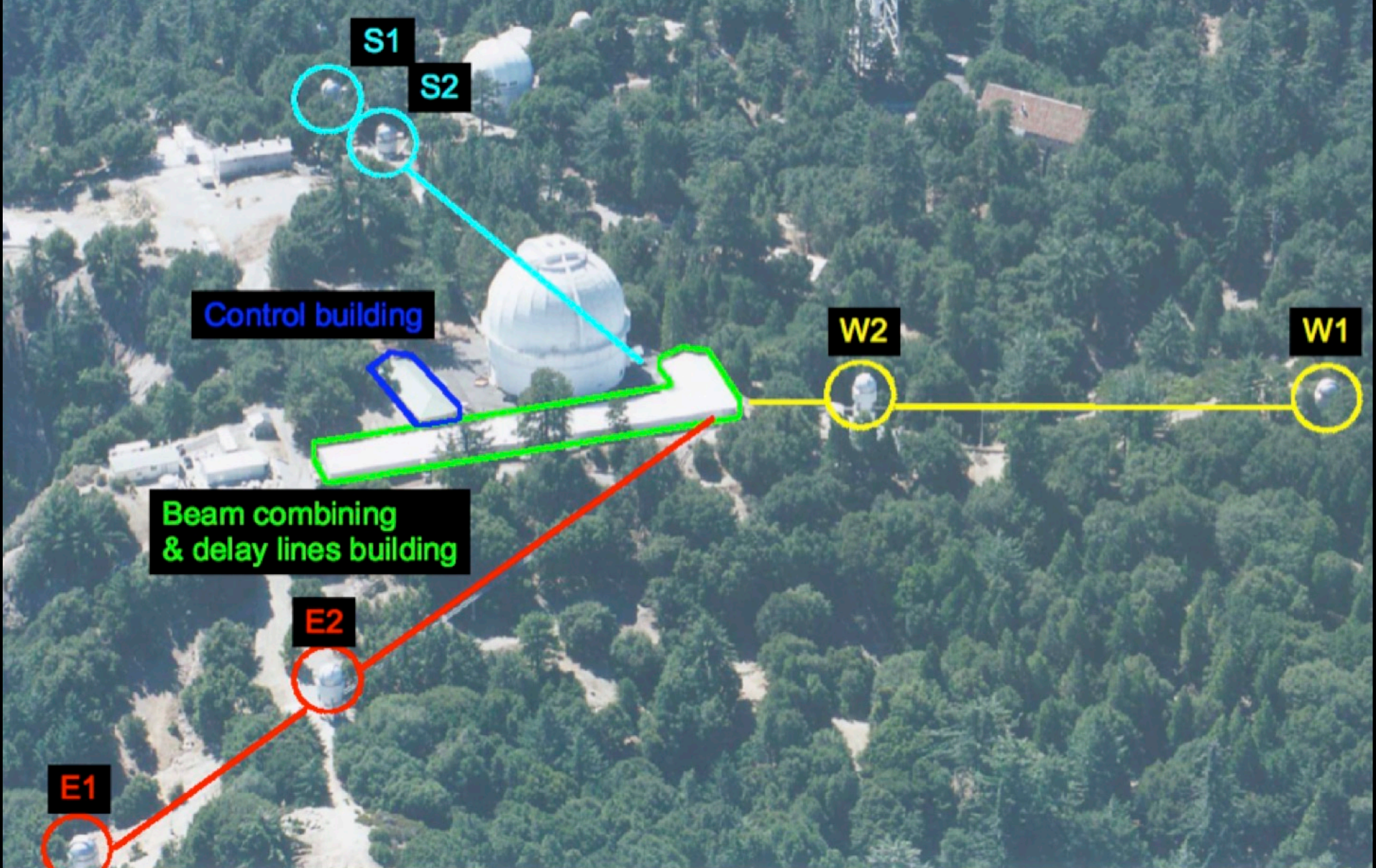
$$\Rightarrow \begin{aligned} \mathrm{V(u,v)} &= \sqrt{\frac{1+r_{ab}^2+2r_{ab}\cos 2\pi \vec{L_b}\vec{s}/\lambda}{1+r_{ab}^2}} \\ \text{with } \mathrm{r}_{ab} &= \mathrm{A/B} \\ \text{with } \vec{L}_b &= \text{Baseline vector} \end{aligned}$$

Binary star visibility curve as a function of baseline



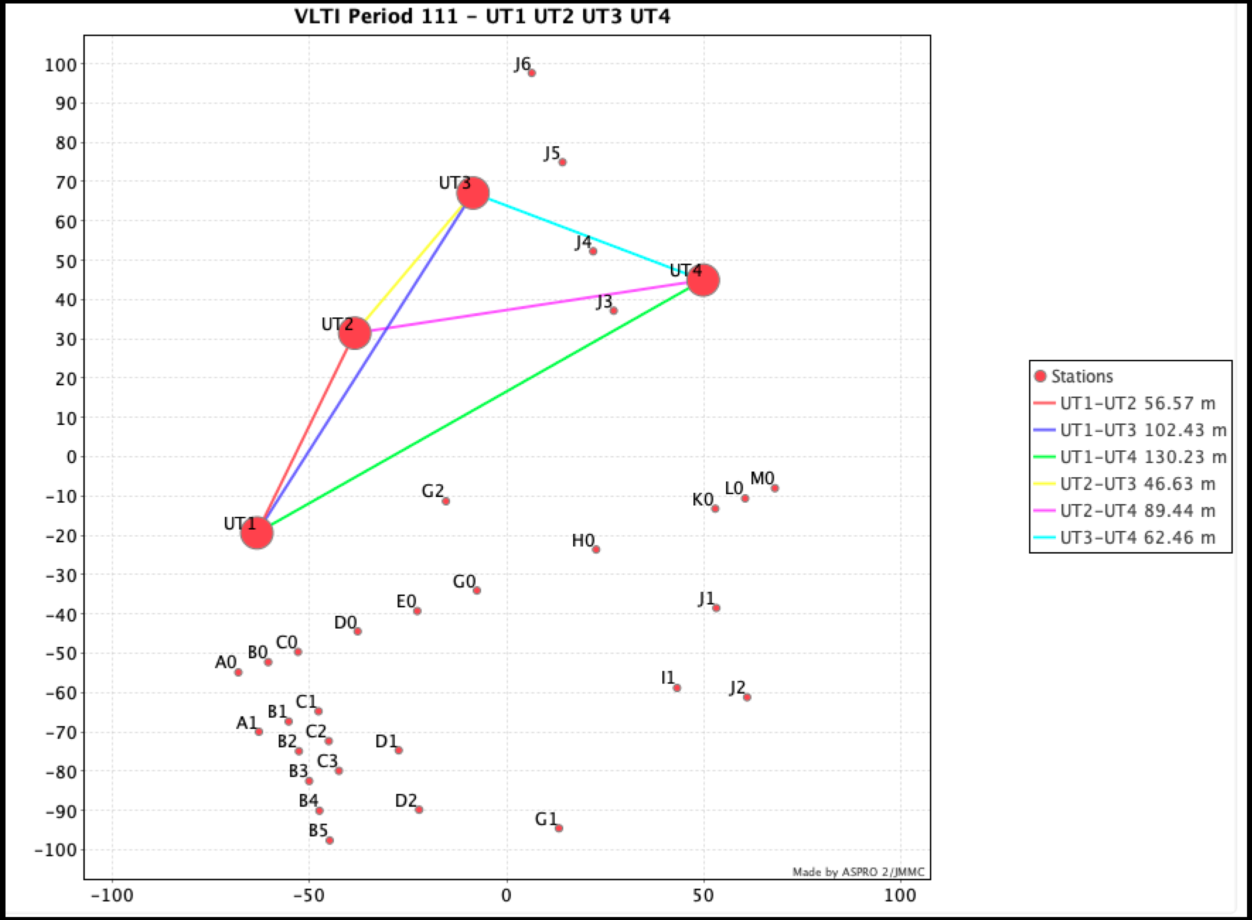
# Binary star example



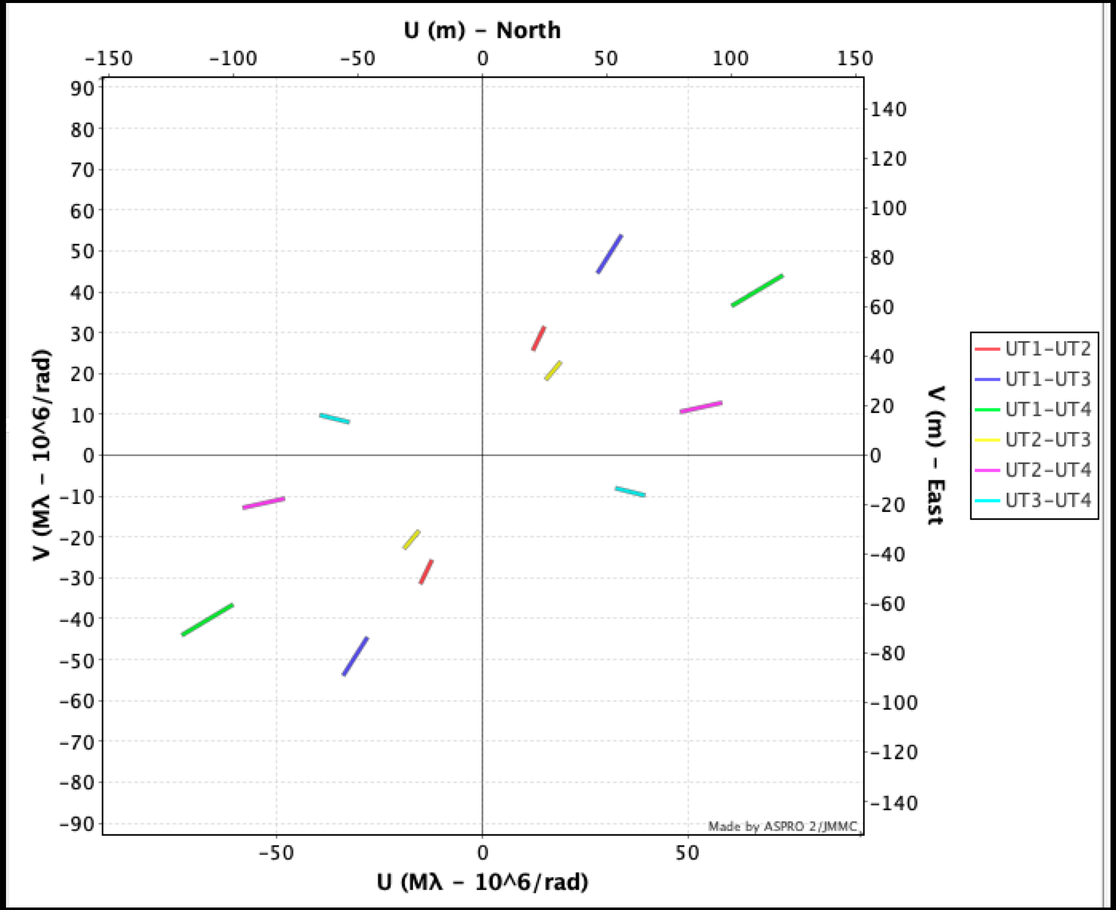

S1
S2
Control building
W2
W1
Beam combining
& delay lines building
E2
E1

B ~ 140m
λ ~ 2.2μm
λ/B ~ 3mas

# VLTI – The UTs



VLTI Period 111 - UT1 UT2 UT3 UT4
Stations
UT1-UT2 56.57 m
UT1-UT3 102.43 m
UT1-UT4 130.23 m
UT2-UT3 46.63 m
UT2-UT4 89.44 m
UT3-UT4 62.46 m
Made by ASPRO 2/JMMC

U (m) - North
V (m) - East
V (Mλ - 10^6/rad)
U (Mλ - 10^6/rad)
UT1-UT2
UT1-UT3
UT1-UT4
UT2-UT3
UT2-UT4
UT3-UT4
Made by ASPRO 2/JMMC

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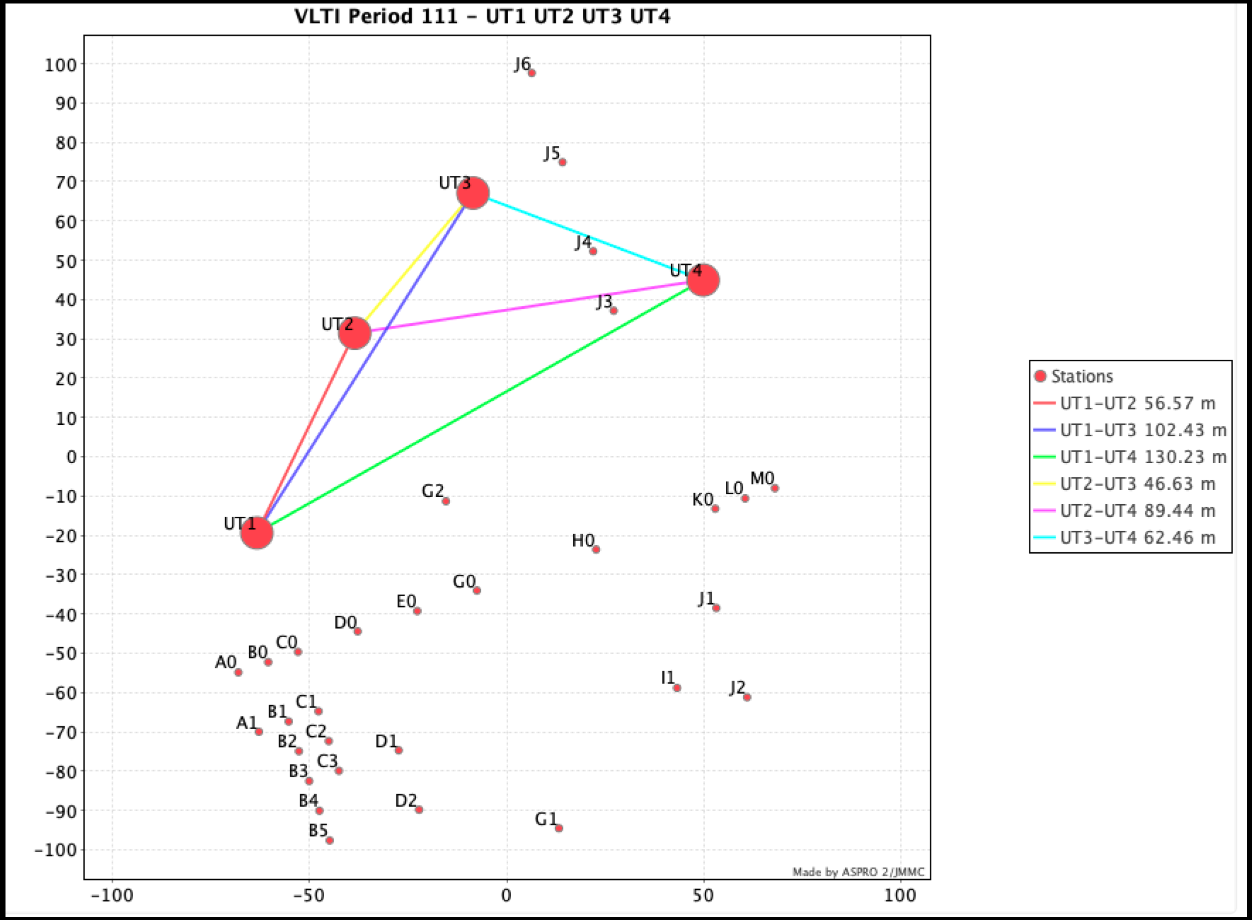

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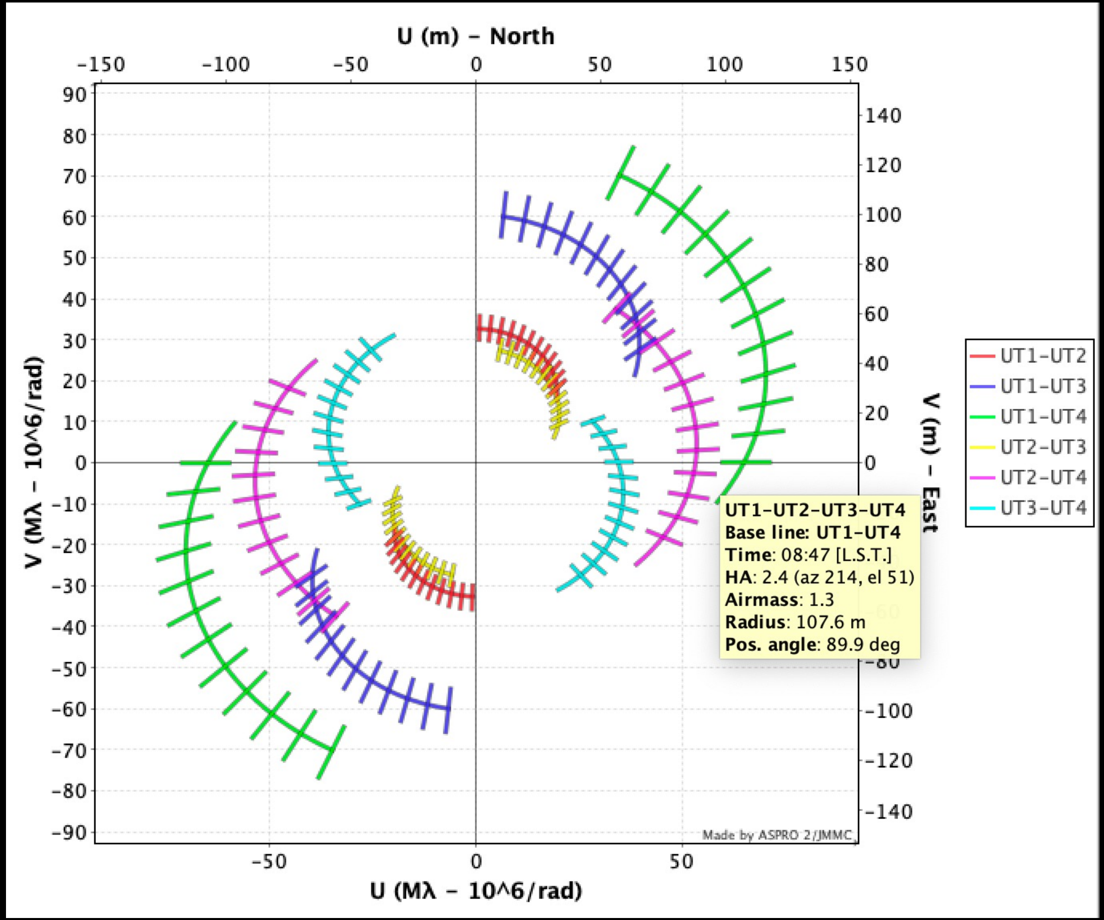
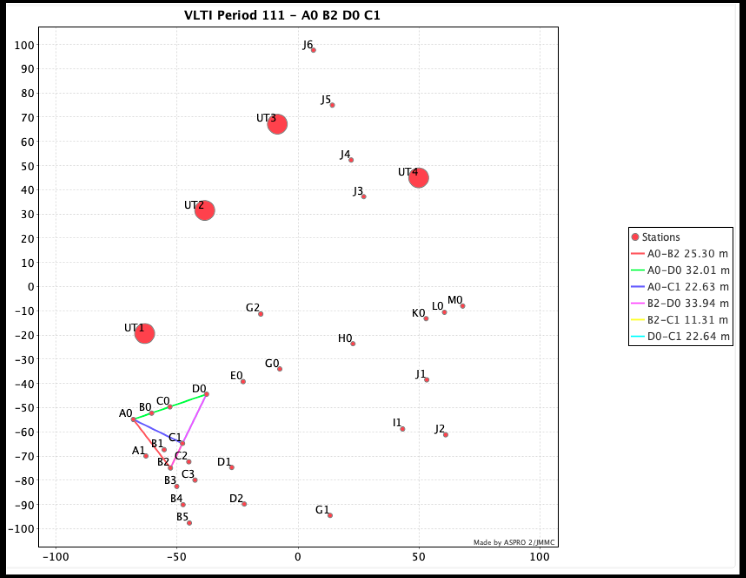
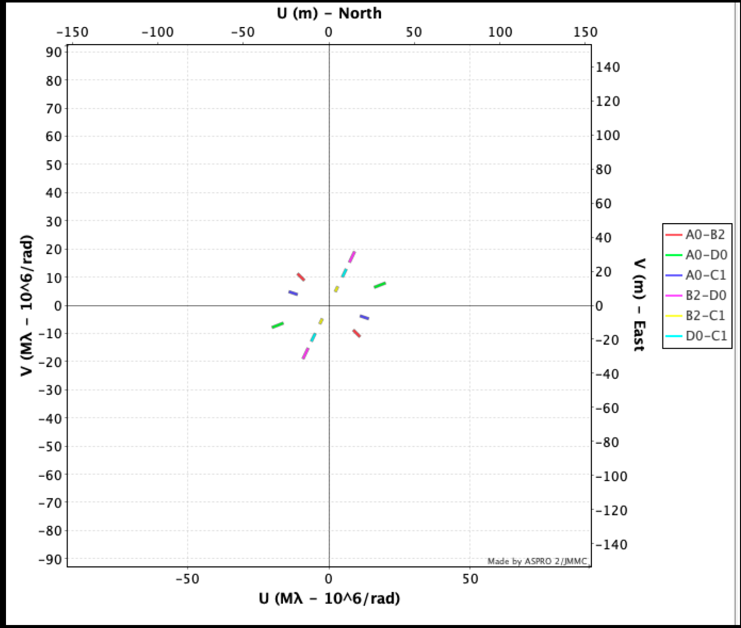


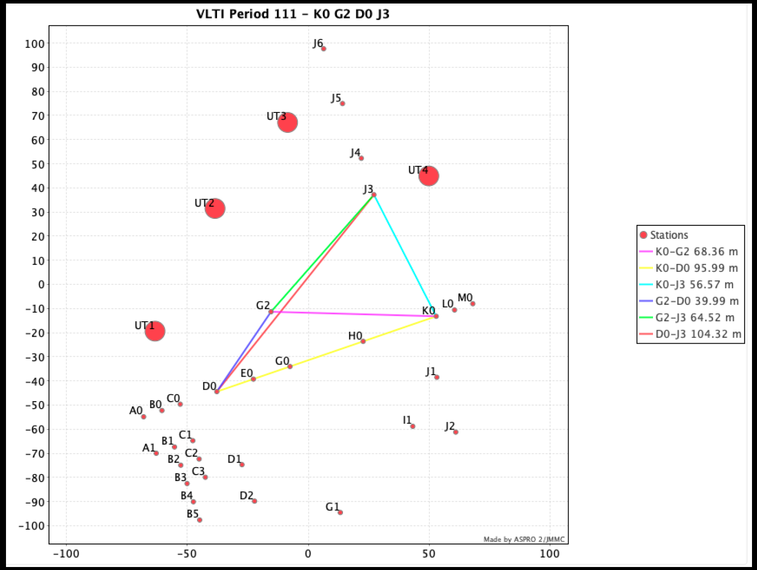
U (m) – North
V (m) – East
U (Mλ – 10^6/rad)
V (Mλ – 10^6/rad)
UT1-UT2
UT1-UT3
UT1-UT4
UT2-UT3
UT2-UT4
UT3-UT4
UT1-UT2-UT3-UT4
Base line: UT1-UT4
Time: 08:47 [L.S.T.]
HA: 2.4 (az 214, el 51)
Airmass: 1.3
Radius: 107.6 m
Pos. angle: 89.9 deg
Made by ASPRO 2/JMMC

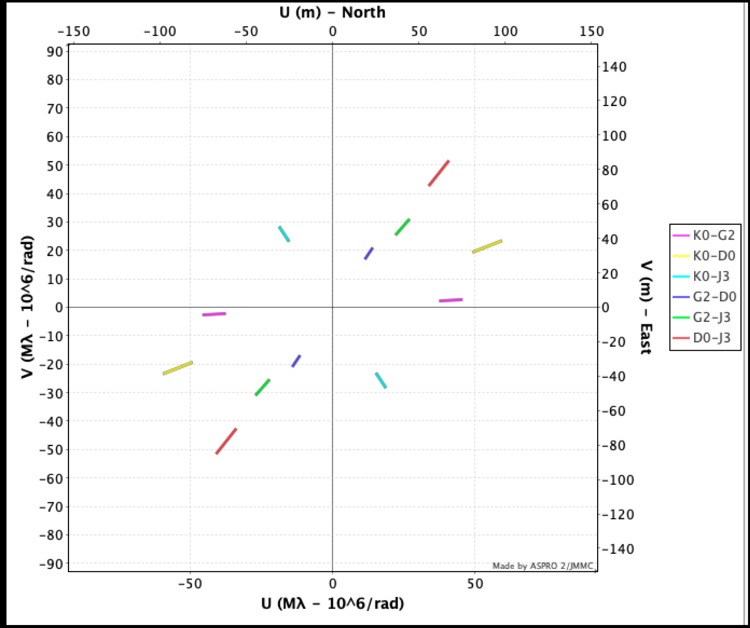
# ATs: Small configuration



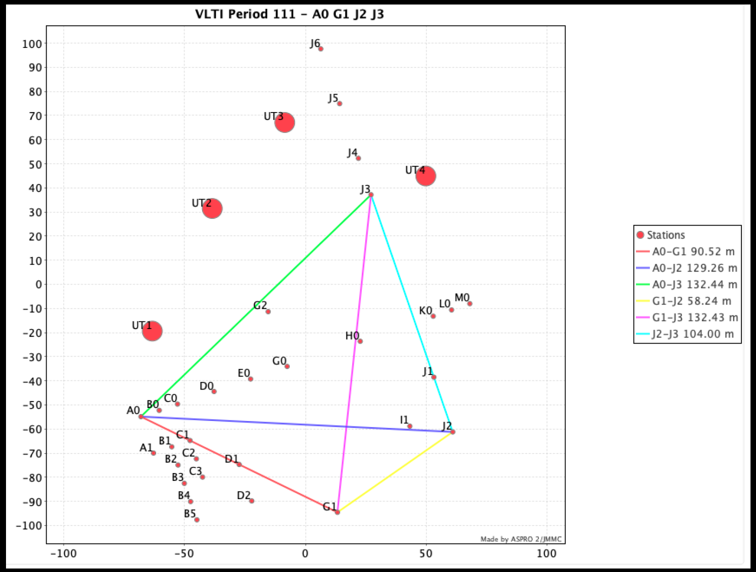



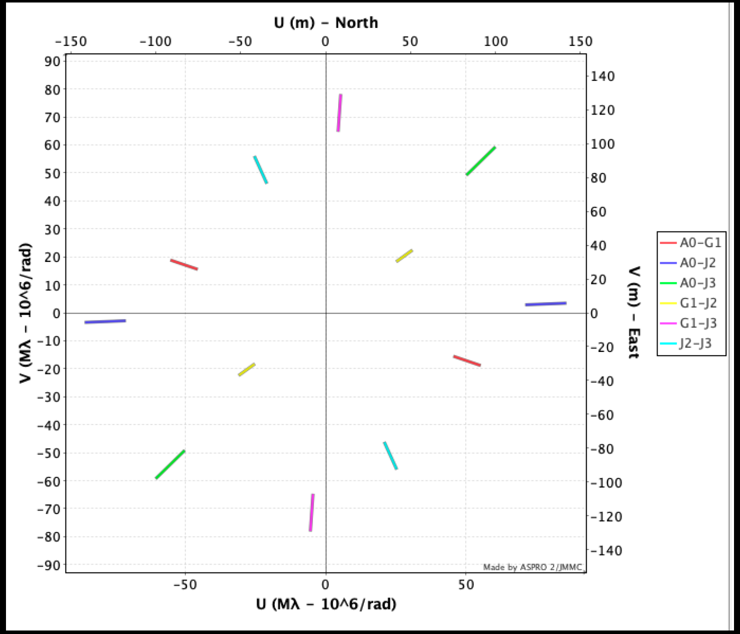

# Intermediate configuration



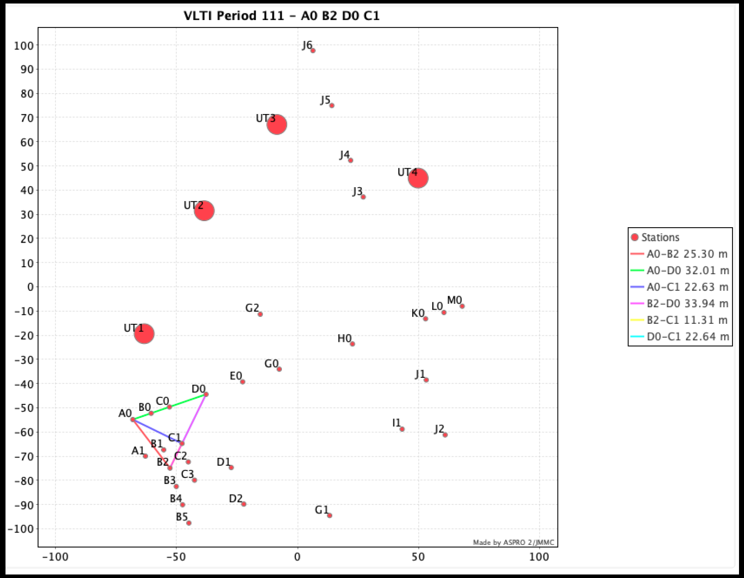



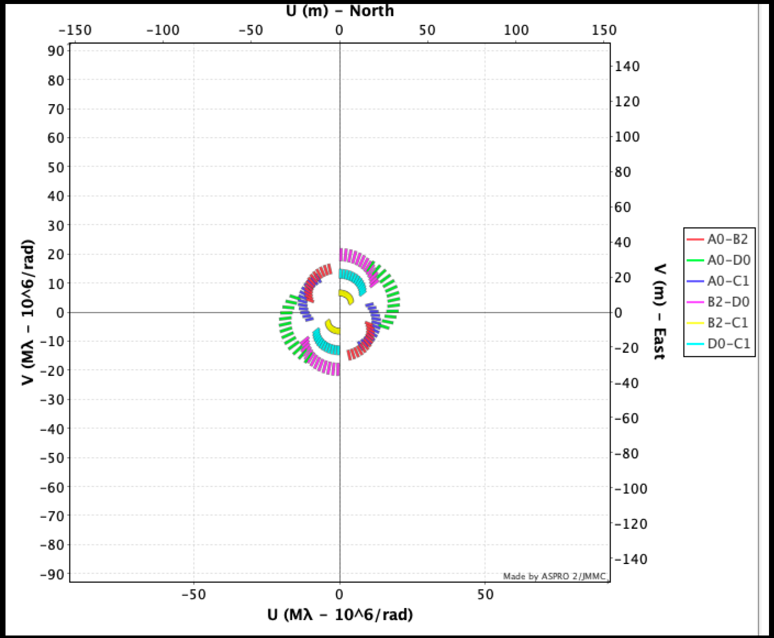

# Large configuration



# Small configuration

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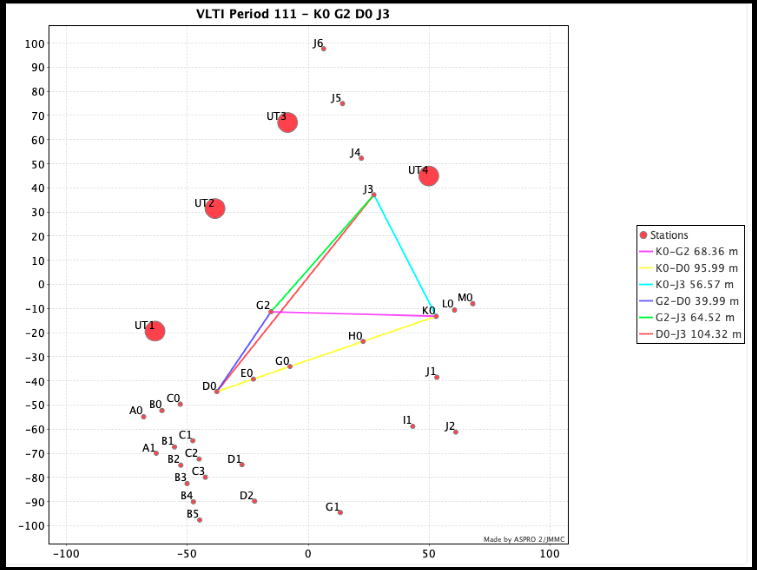


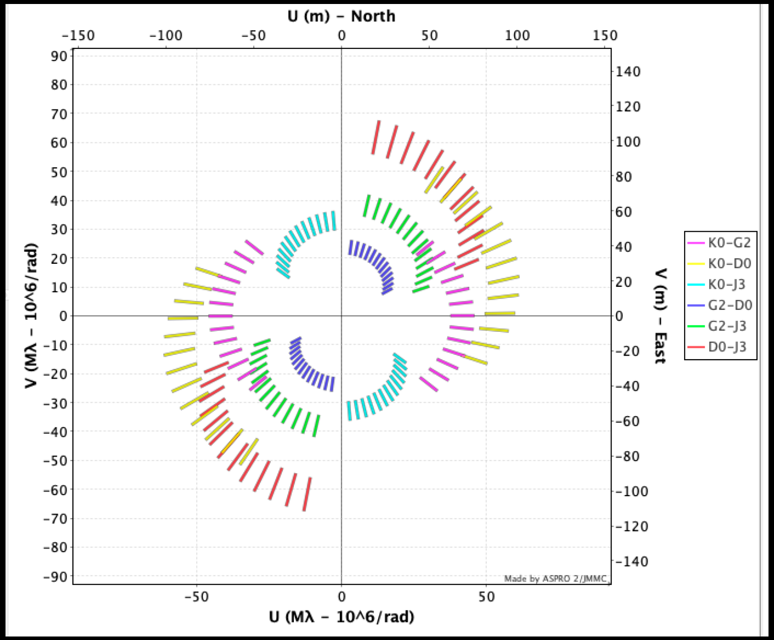


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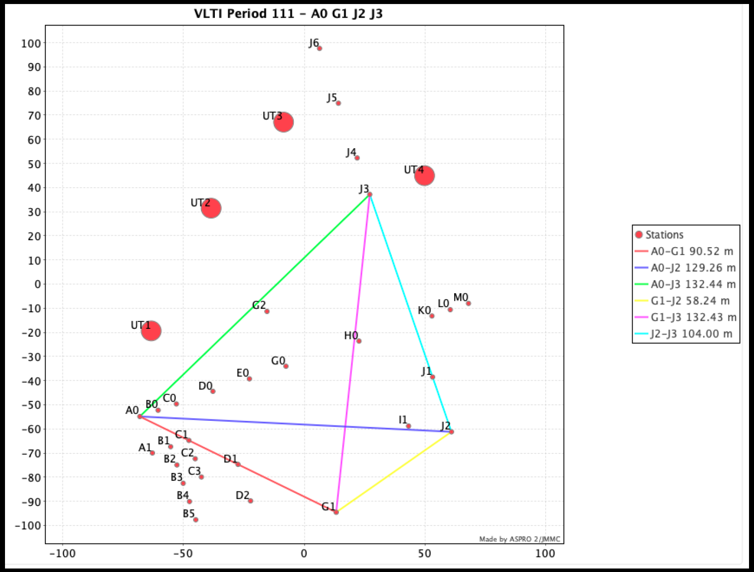
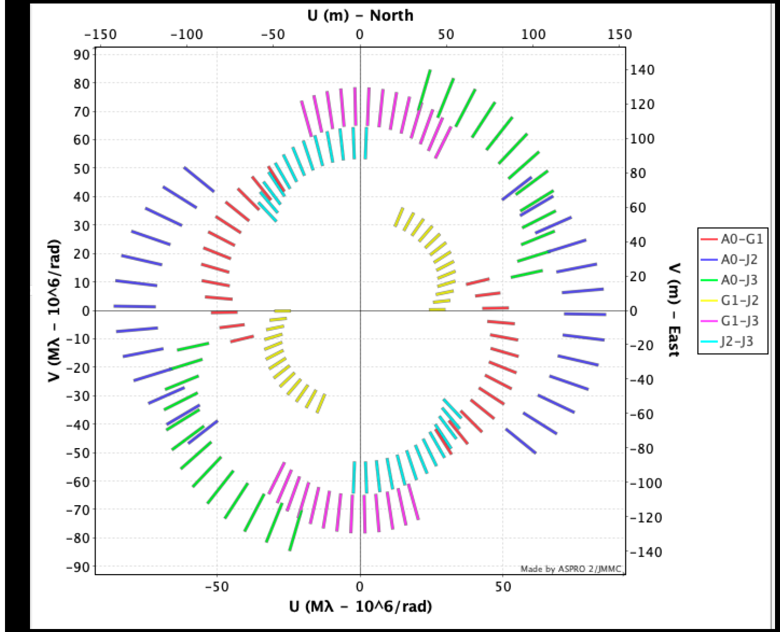
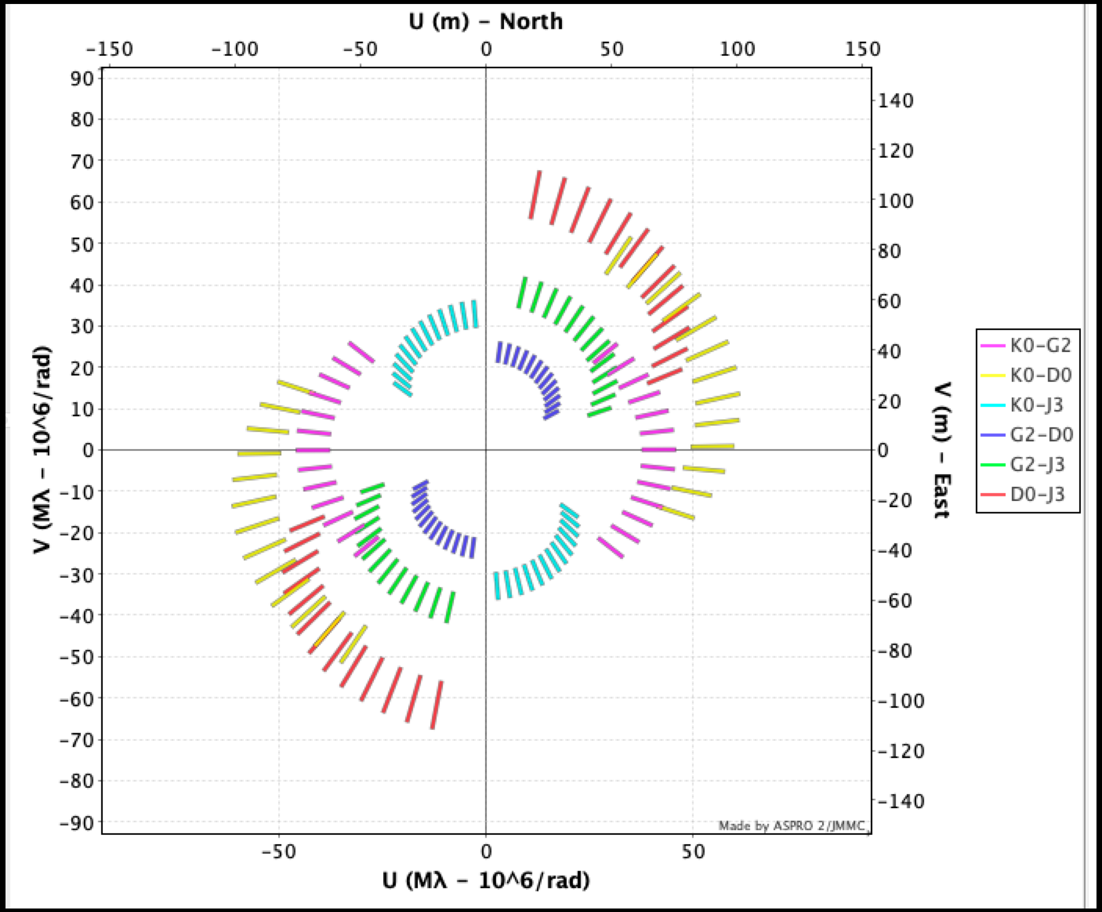
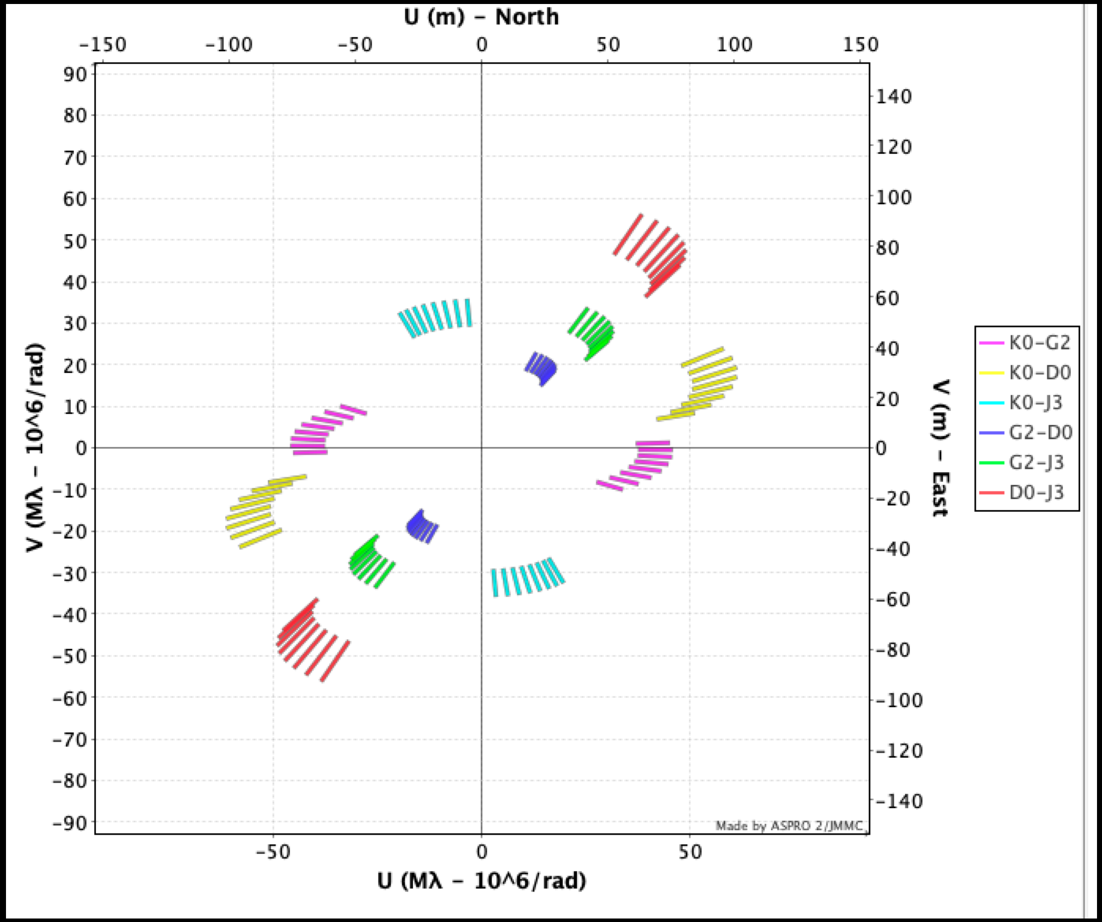


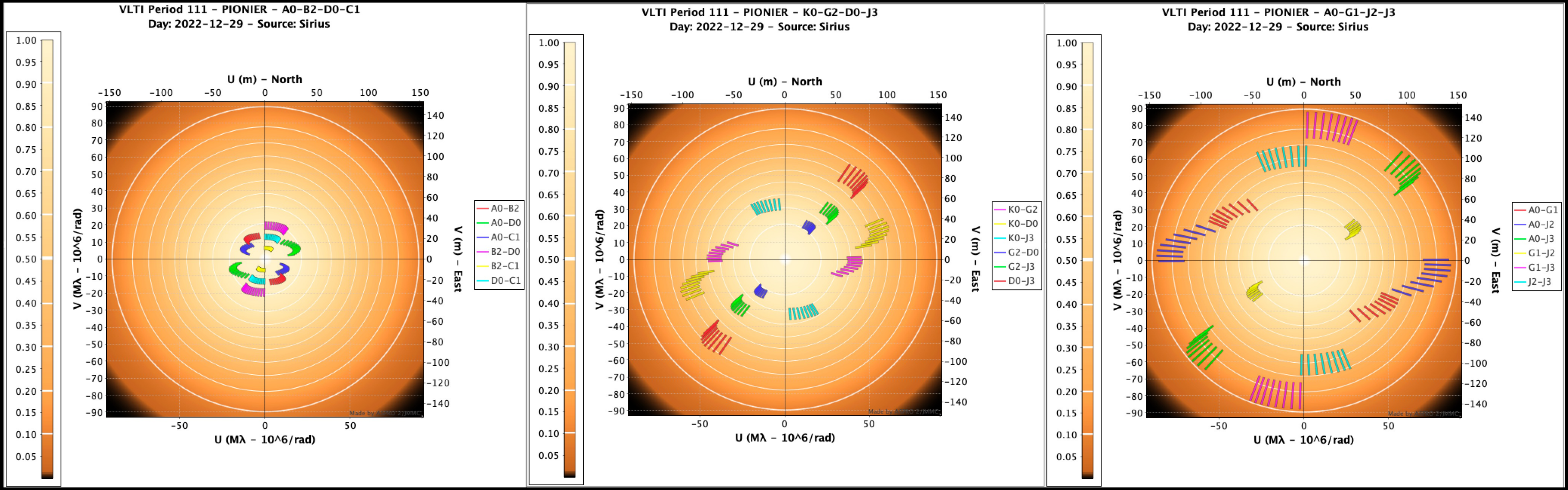
Declination: :  -52 degrees

Declination:  -16 degrees



# A disc of 2 mas diameter



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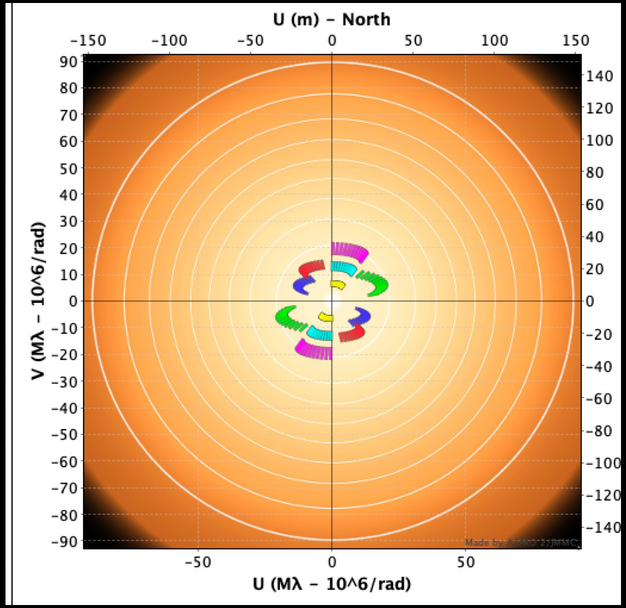
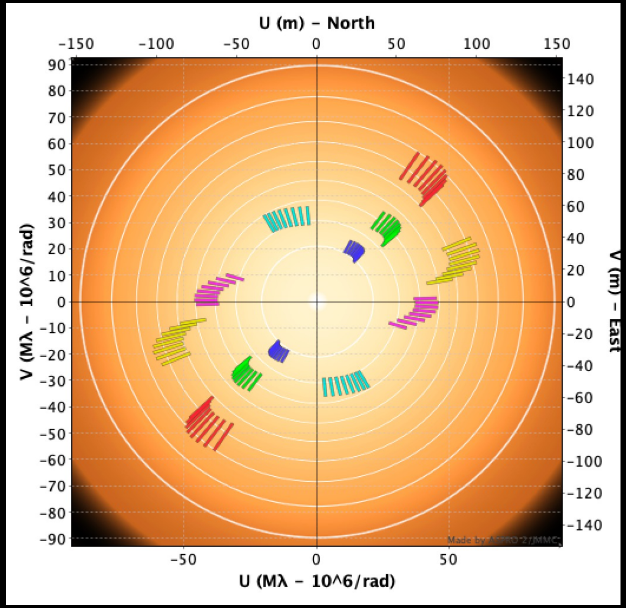
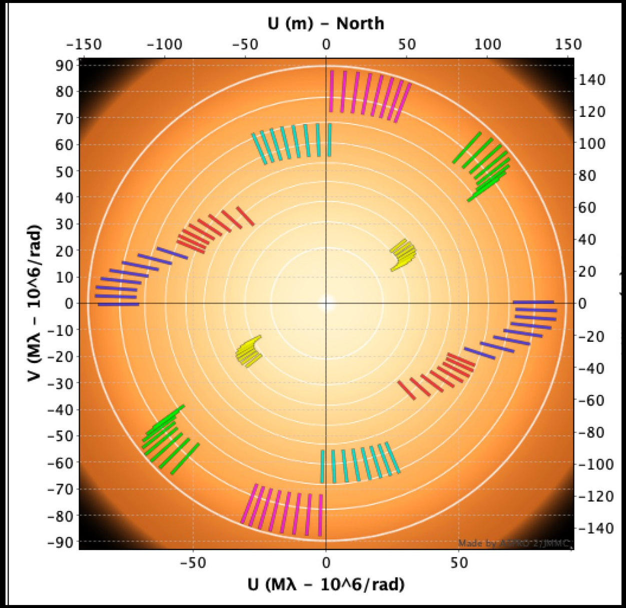
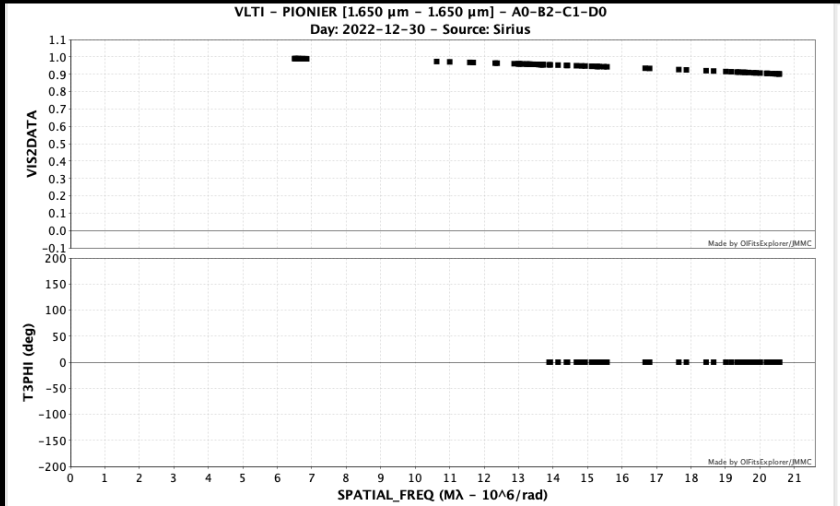
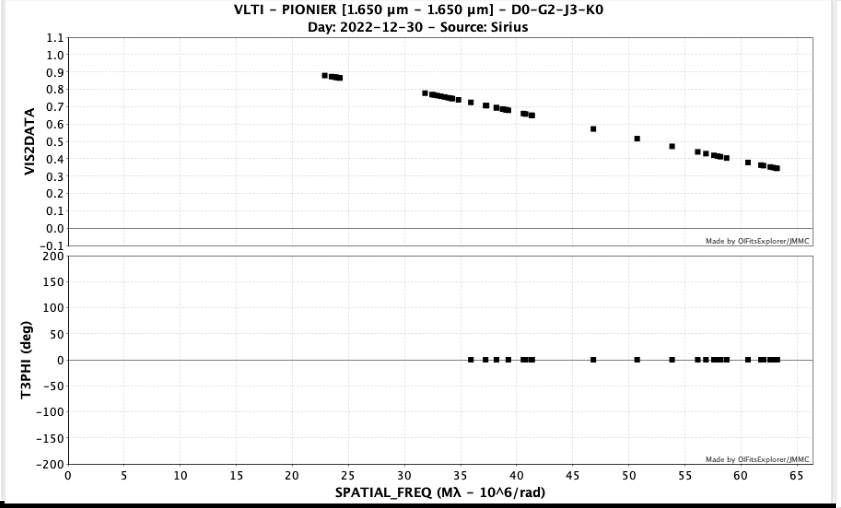
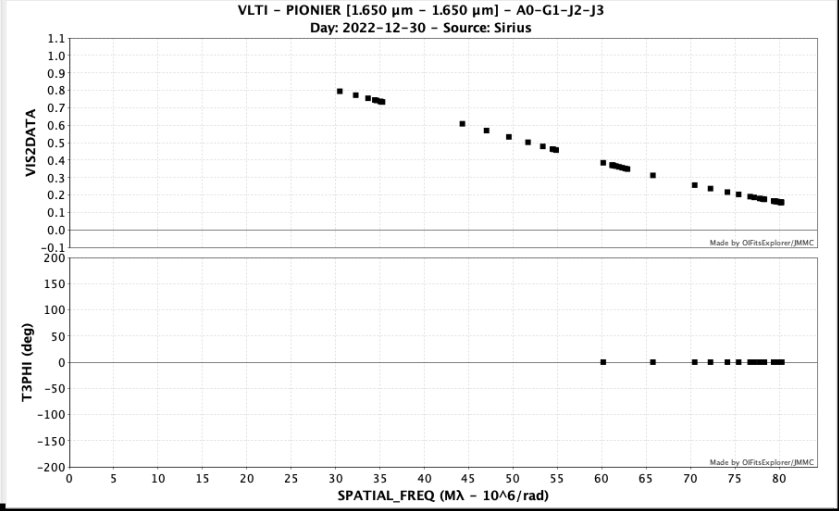


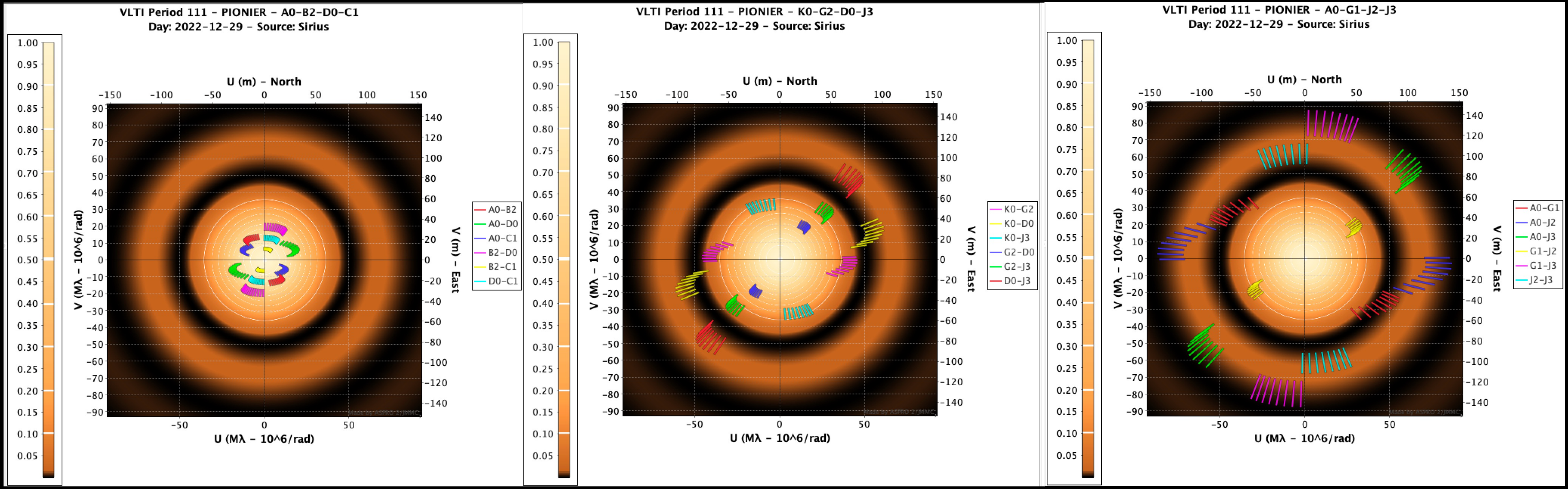



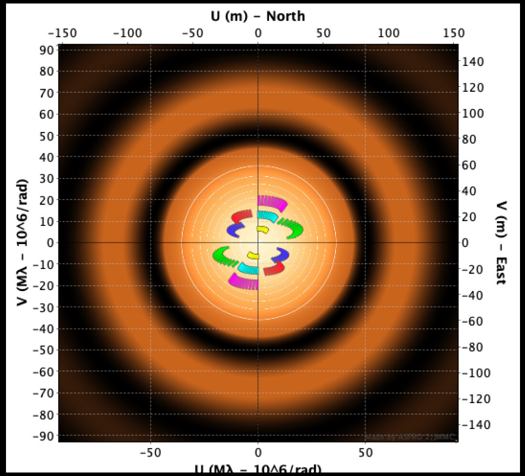



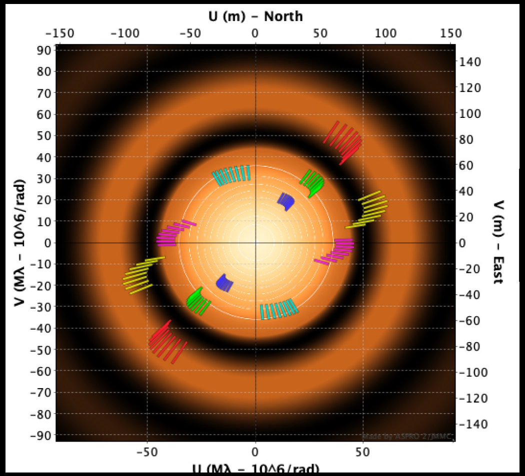



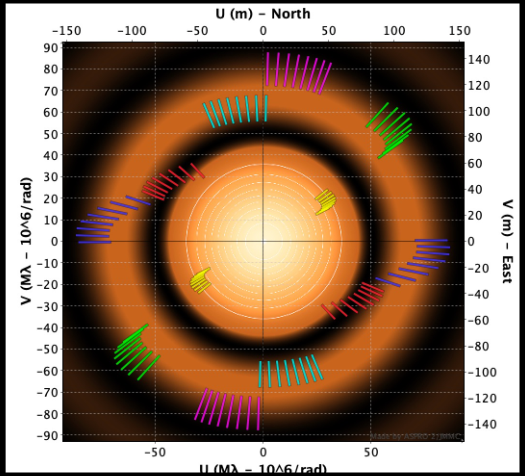
# A disc of 5 mas diameter

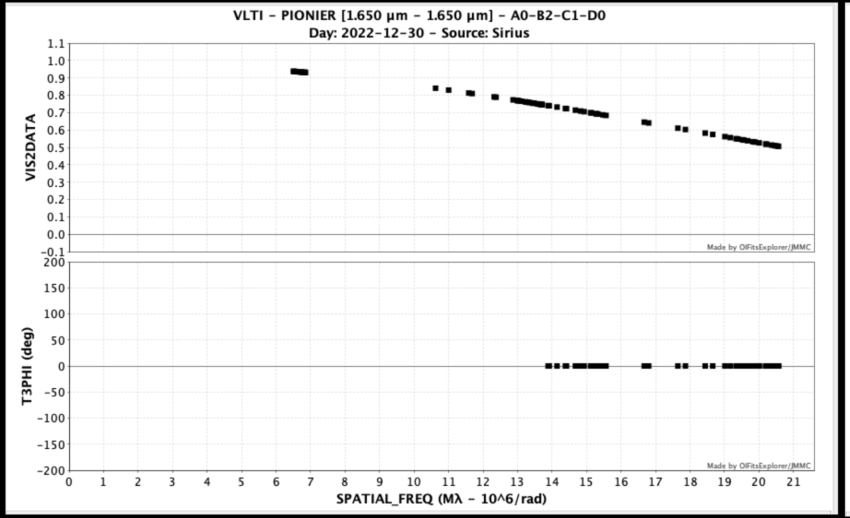


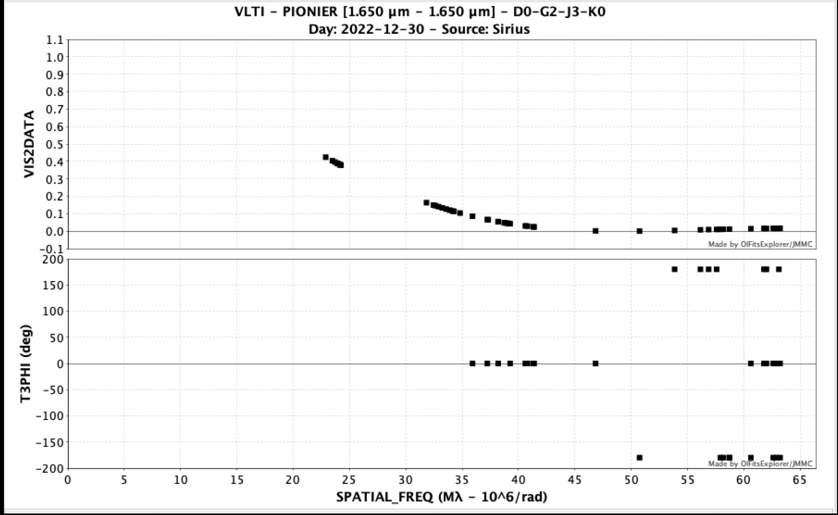
# A disc of 5 mas diameter

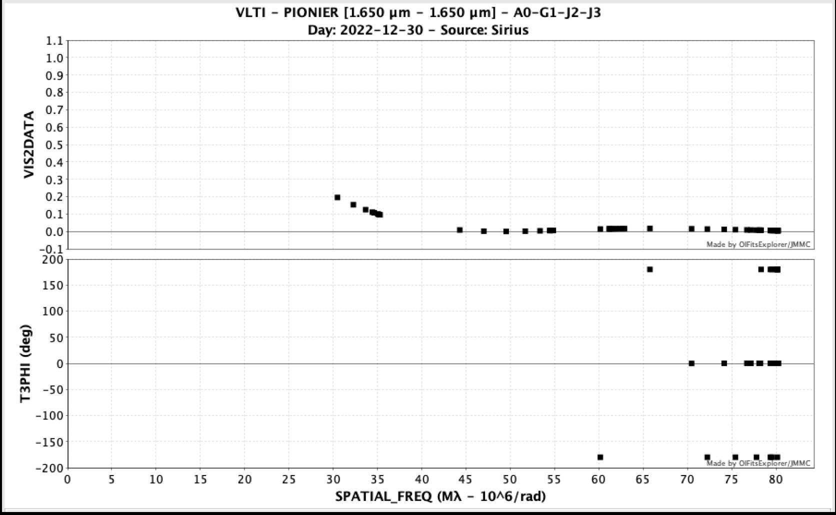


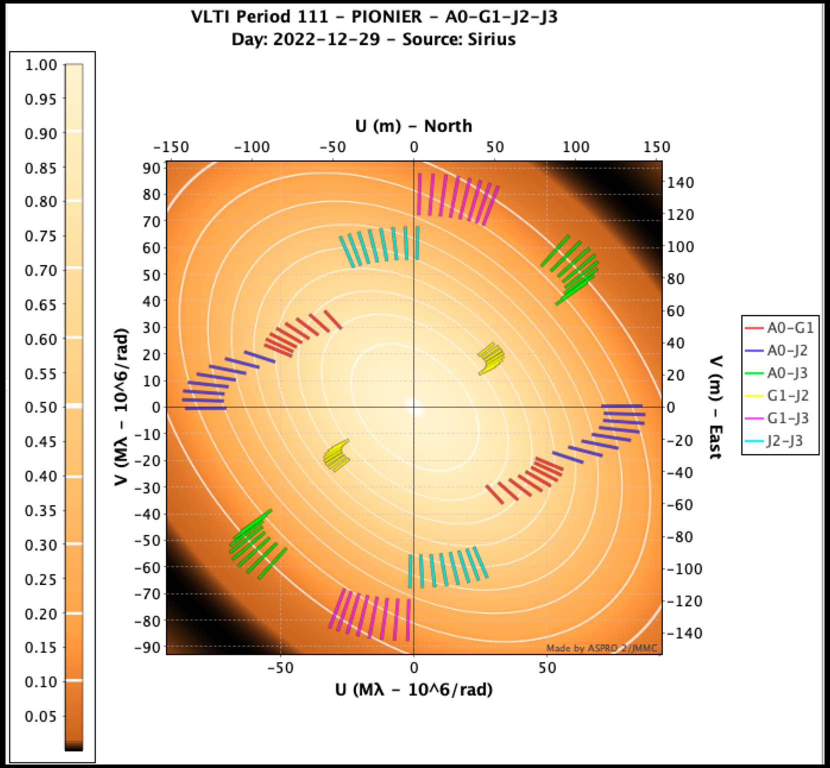



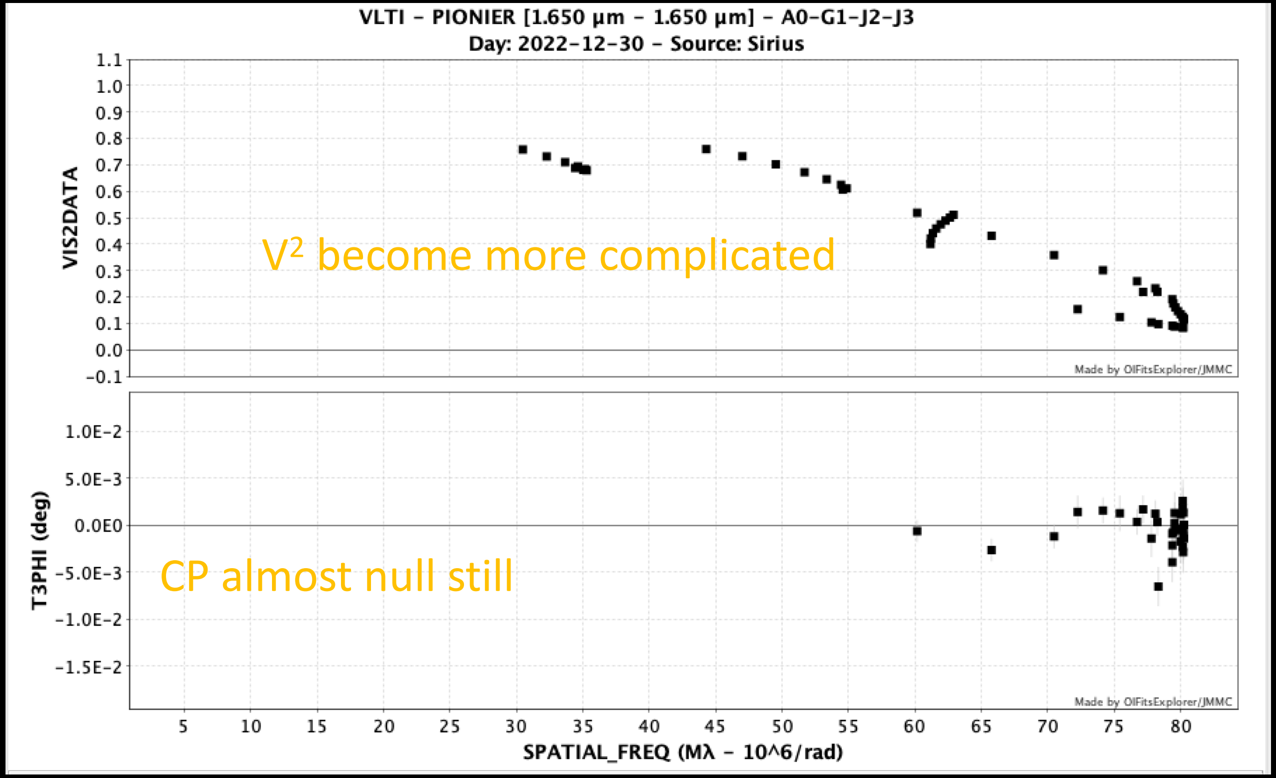



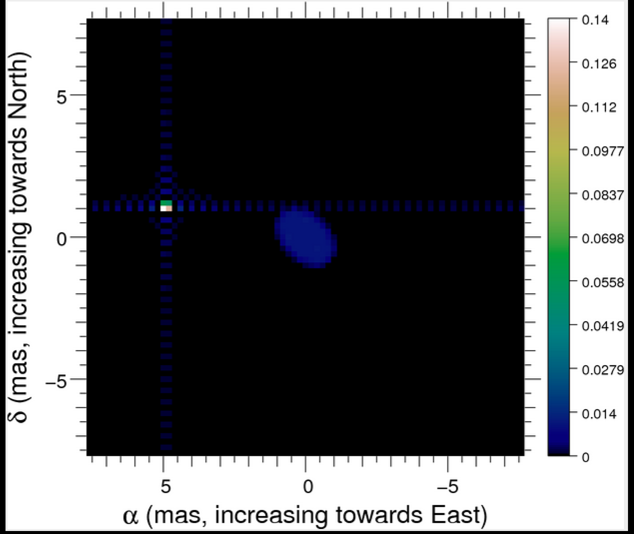



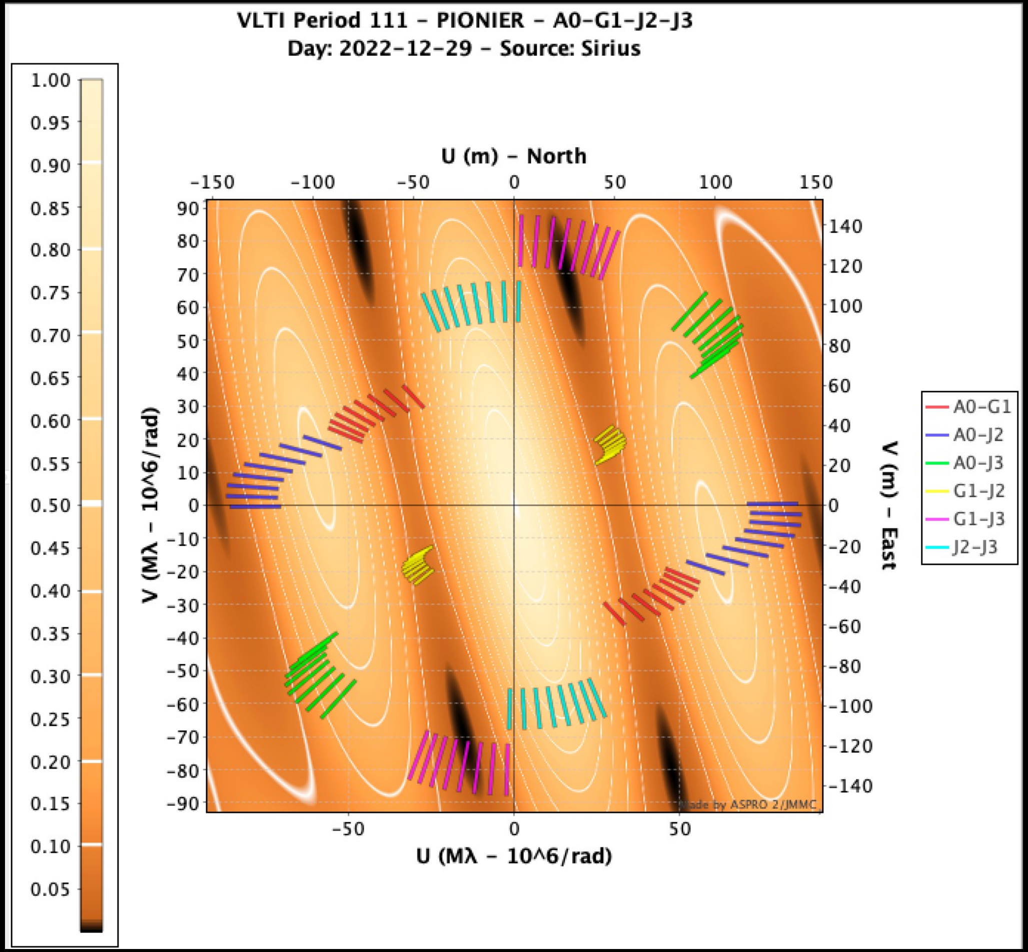
# Elongated disc

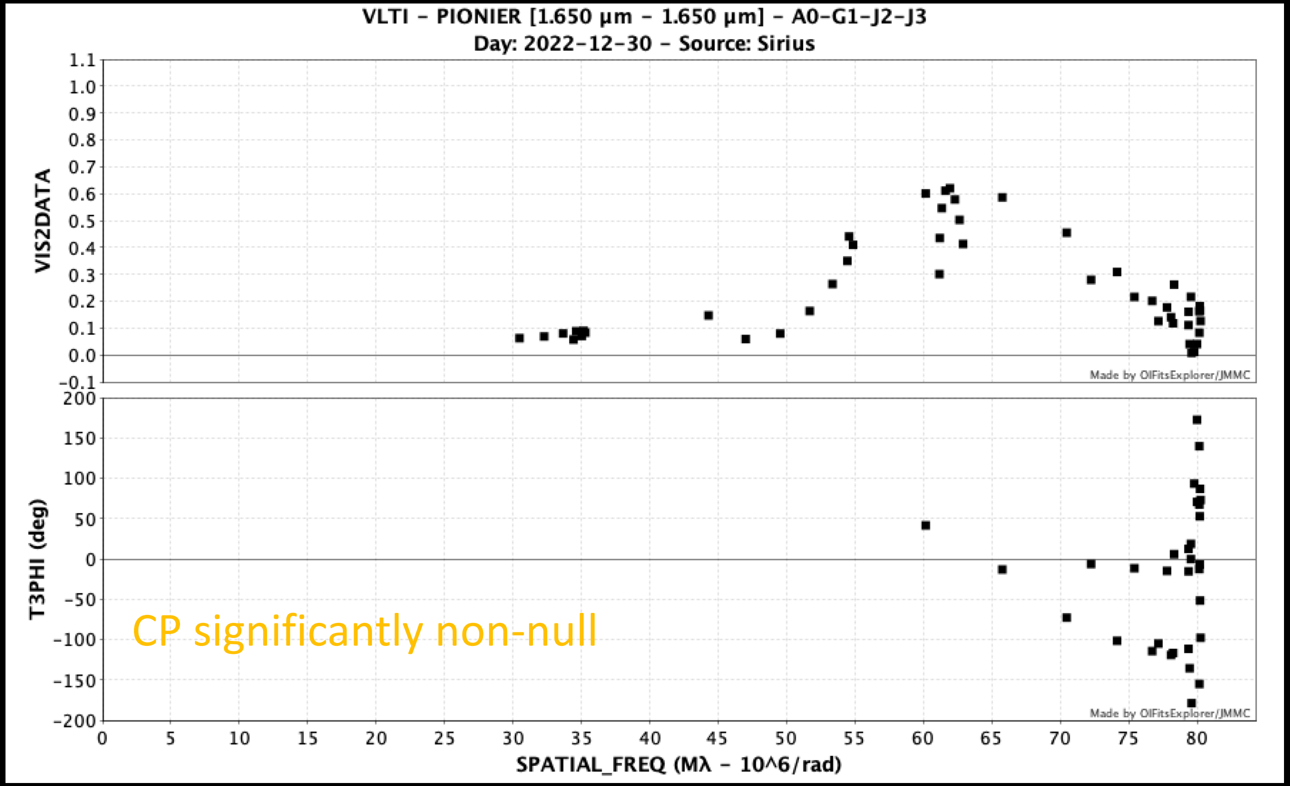


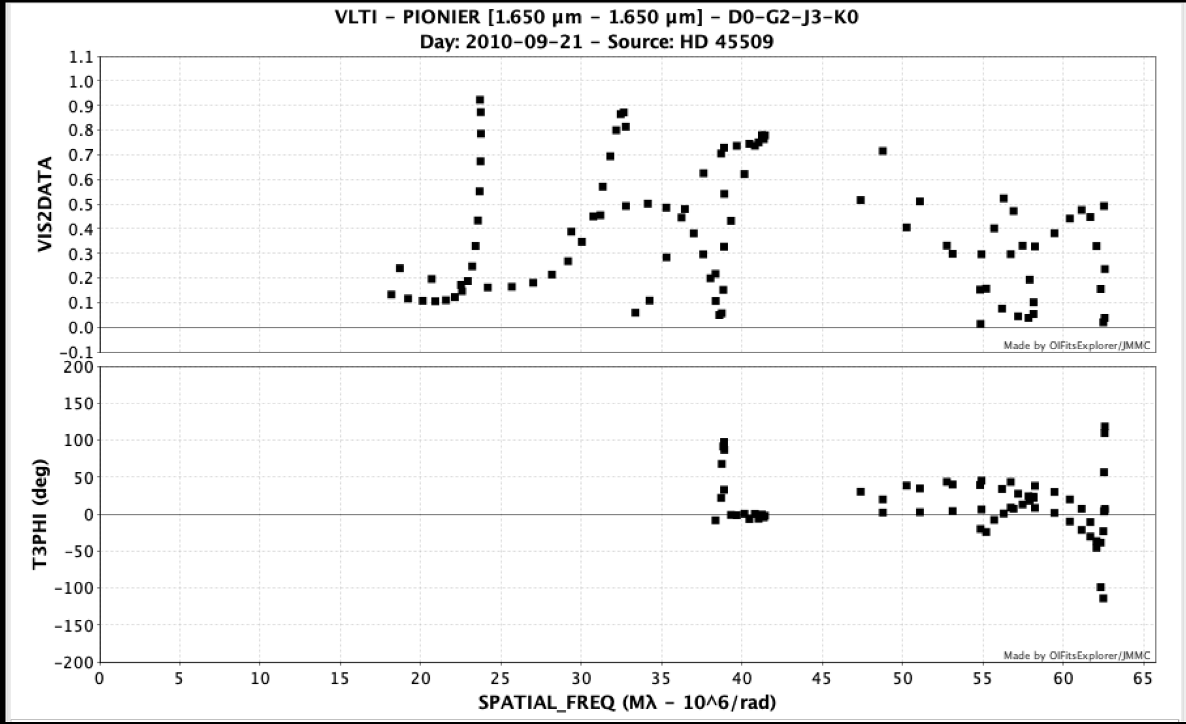
# An elongated disc with a companion

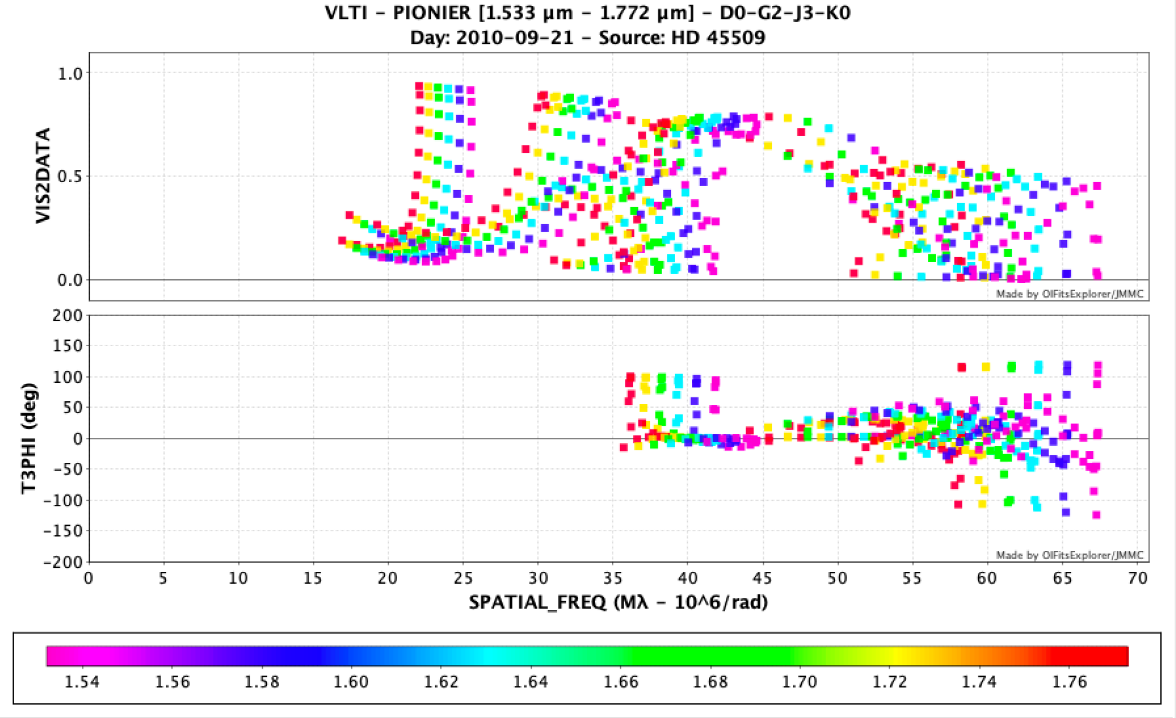


# Importance of spectral information




Spatial frequencies are measured in units of wavelengths
→ more points if spectral channel are available

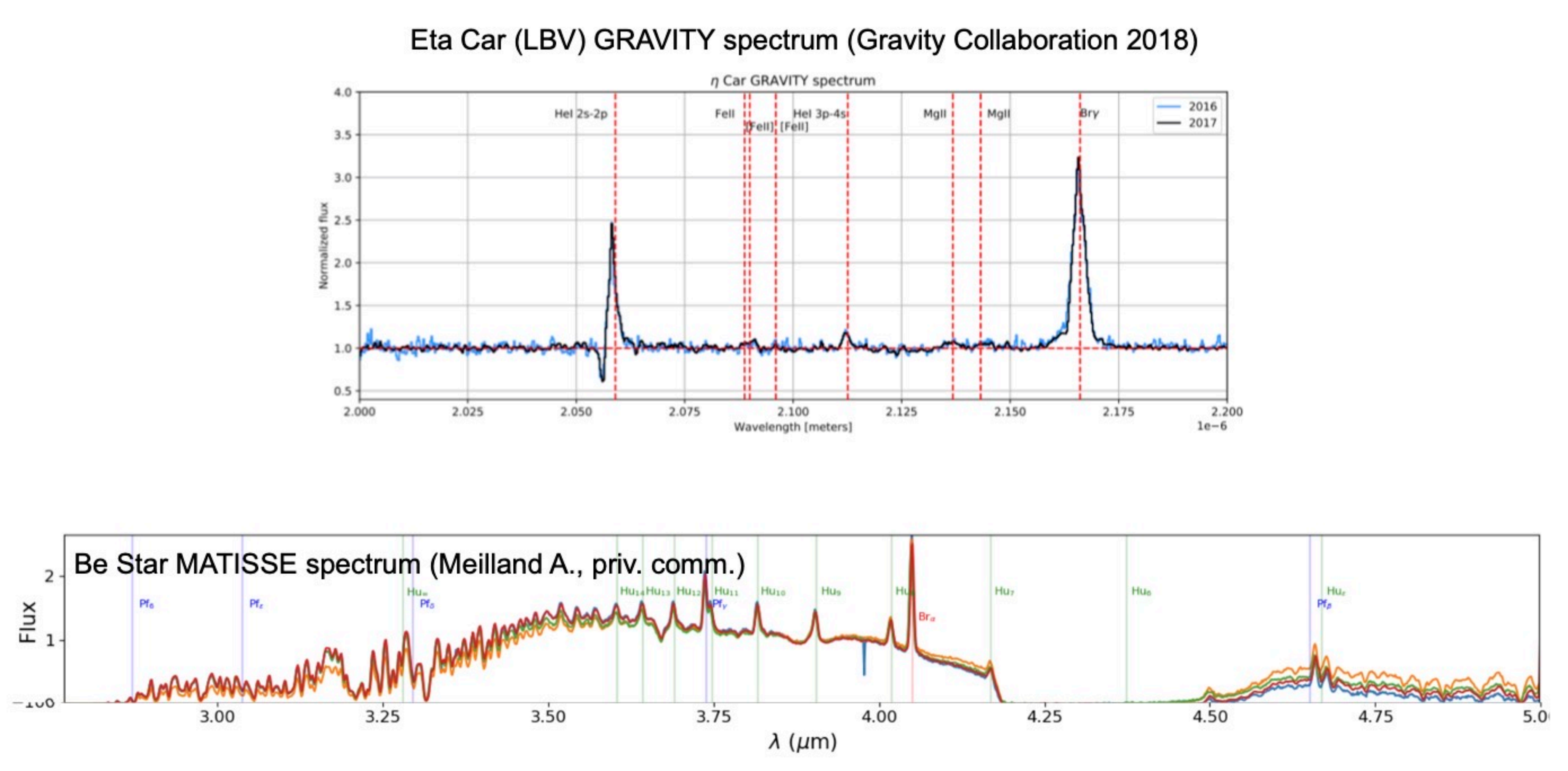
VLTI Instruments


- PIONIER
  H band ($\lambda \approx 1.6\mu m$), $R \approx 50$

- GRAVITY
  K band ($\lambda \approx 2.2\mu m$), $R \approx 20$, 500 and 4000

- MATISSE
  L,M,N bands ($\lambda \approx 3$ to $12\mu m$), $R \approx 30$, 500, 1000 and 3500

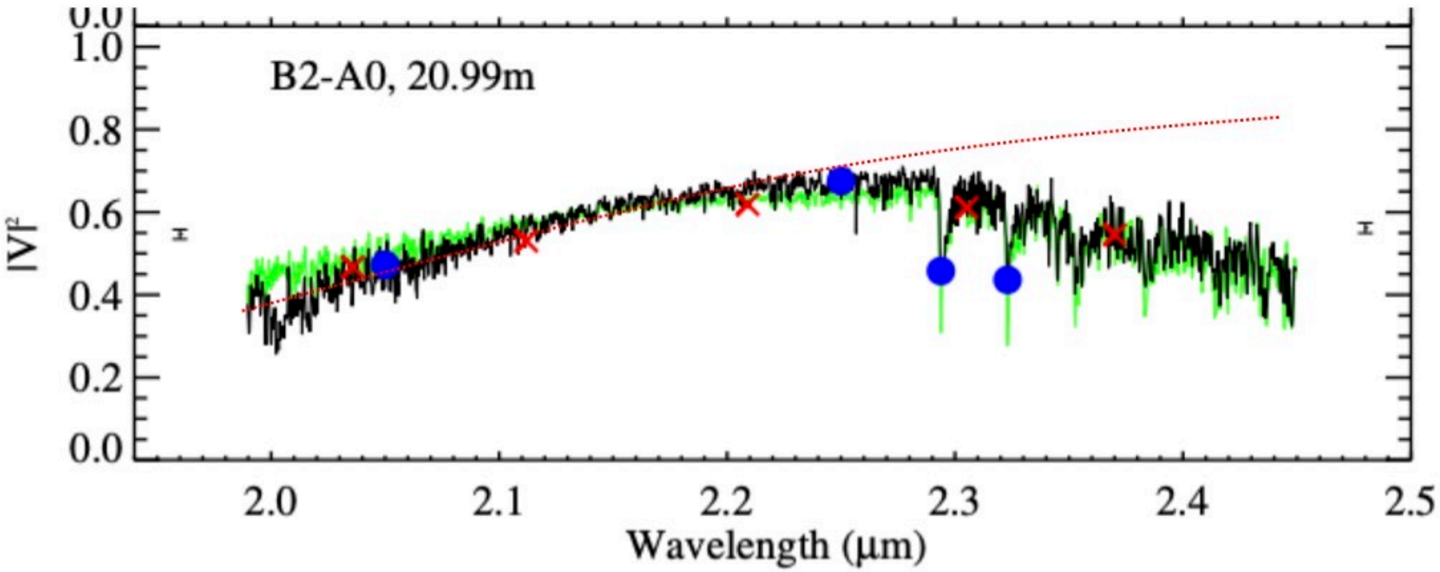
# Spectral capabilities



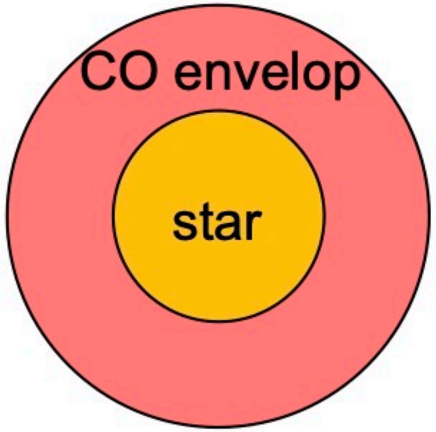

A. Mérand

# Differential visibilities

CO lines in Mira-type star (Wittkowski+ 2018)

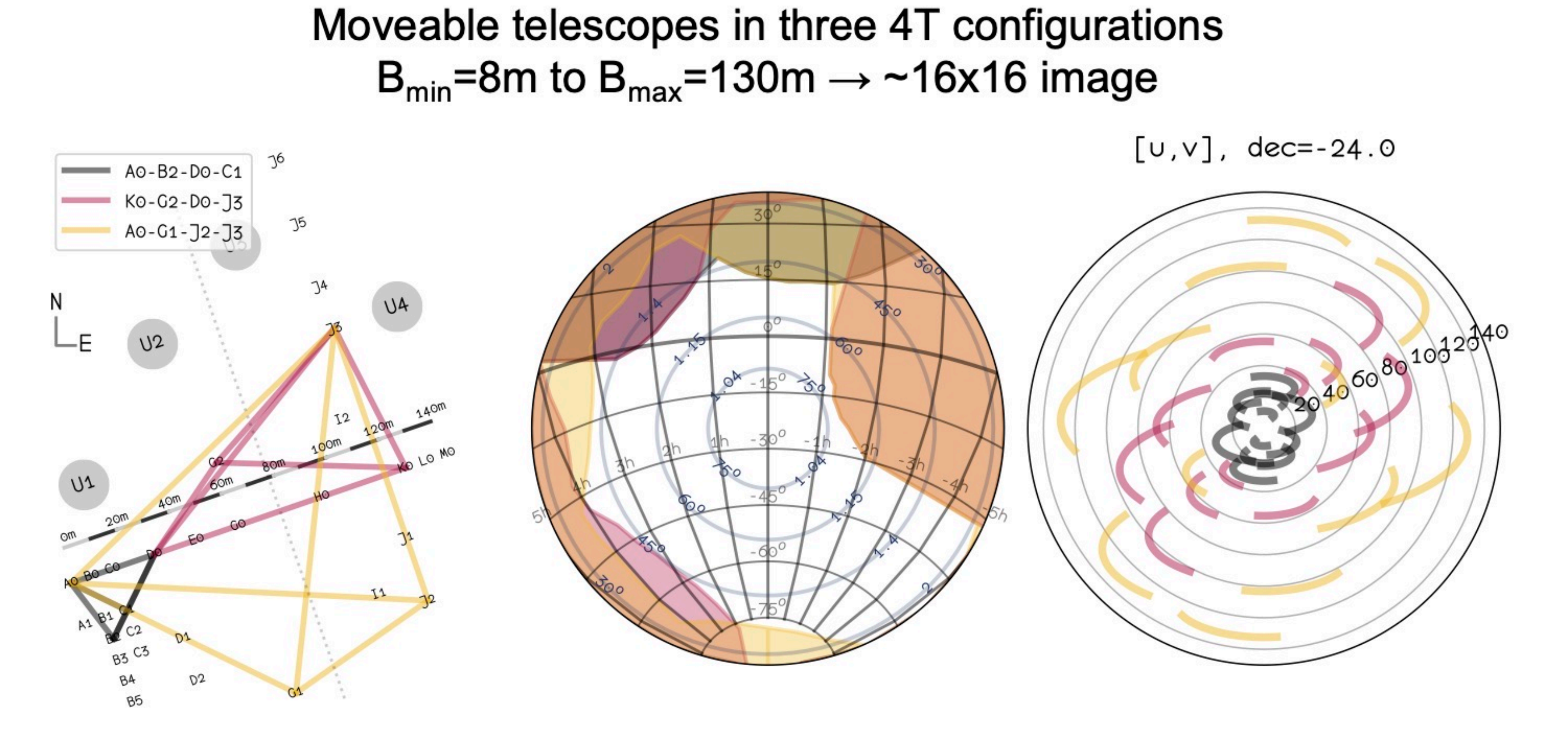



Visibility drops in a line → object is larger



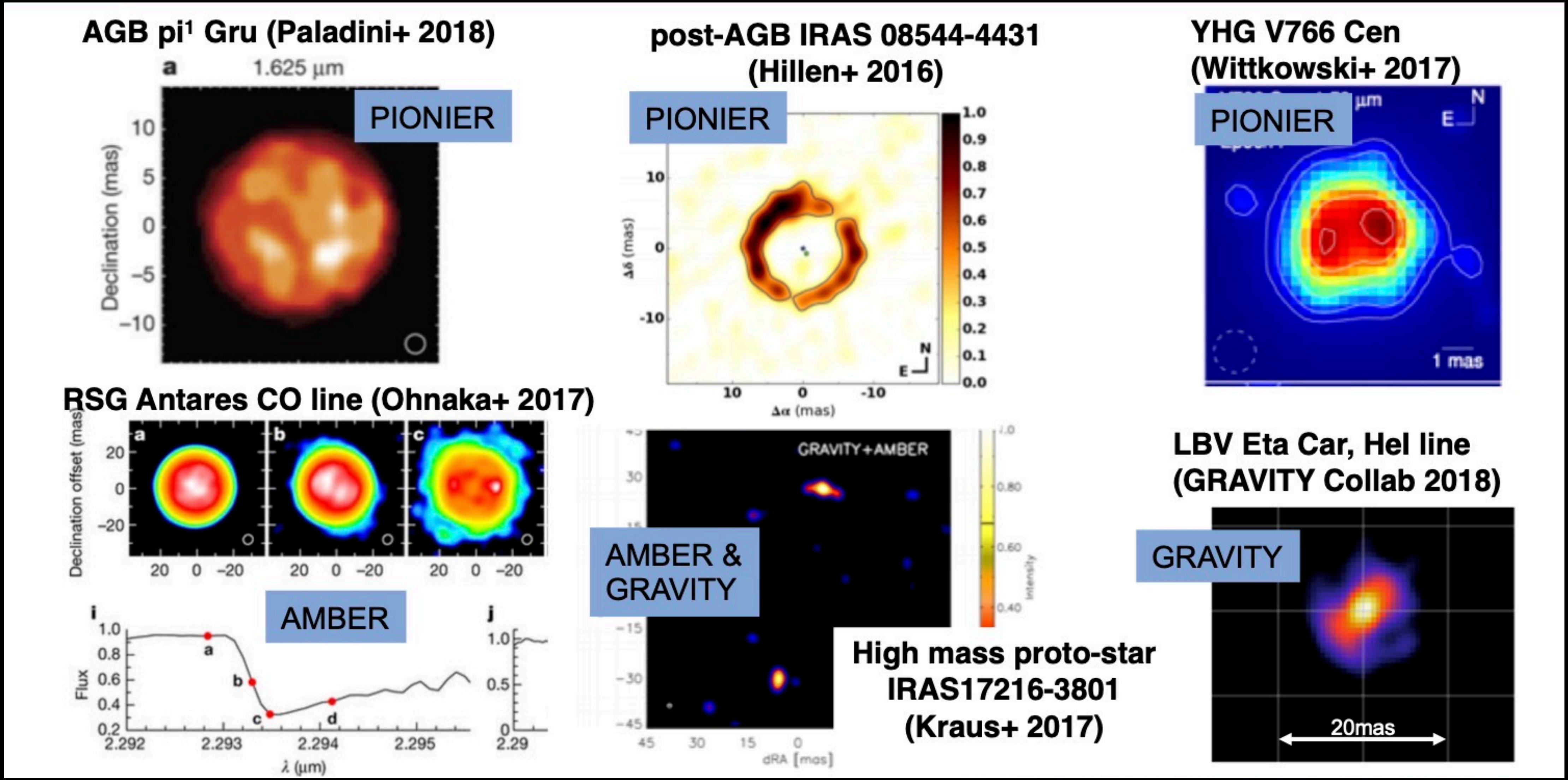

A. Mérand

# Imaging at VLTI




A. Mérand

# Some VLTI images

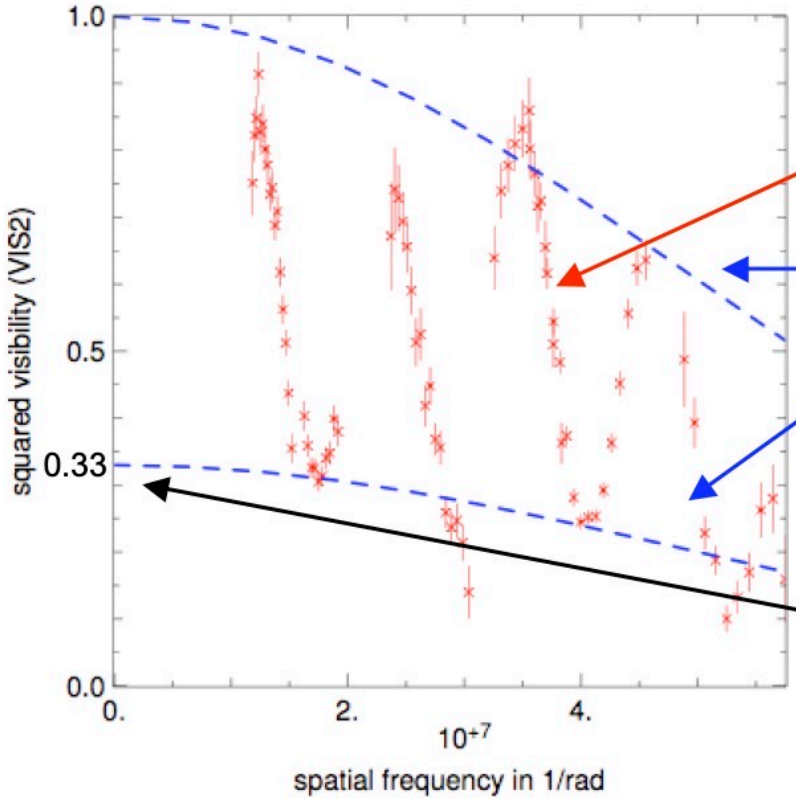



A. Mérand

In most cases, we do not have enough data points to cover the (u,v) plane and we cannot invert the data to get meaningful data

→ Make fit of models instead

# Observe your data!




$$V^2_{\min} = 0.33 \Rightarrow r = 0.27$$

Modulation = binary (or >2 components)

Attenuation = components resolved

binary convolved by an extended function

$\Downarrow$

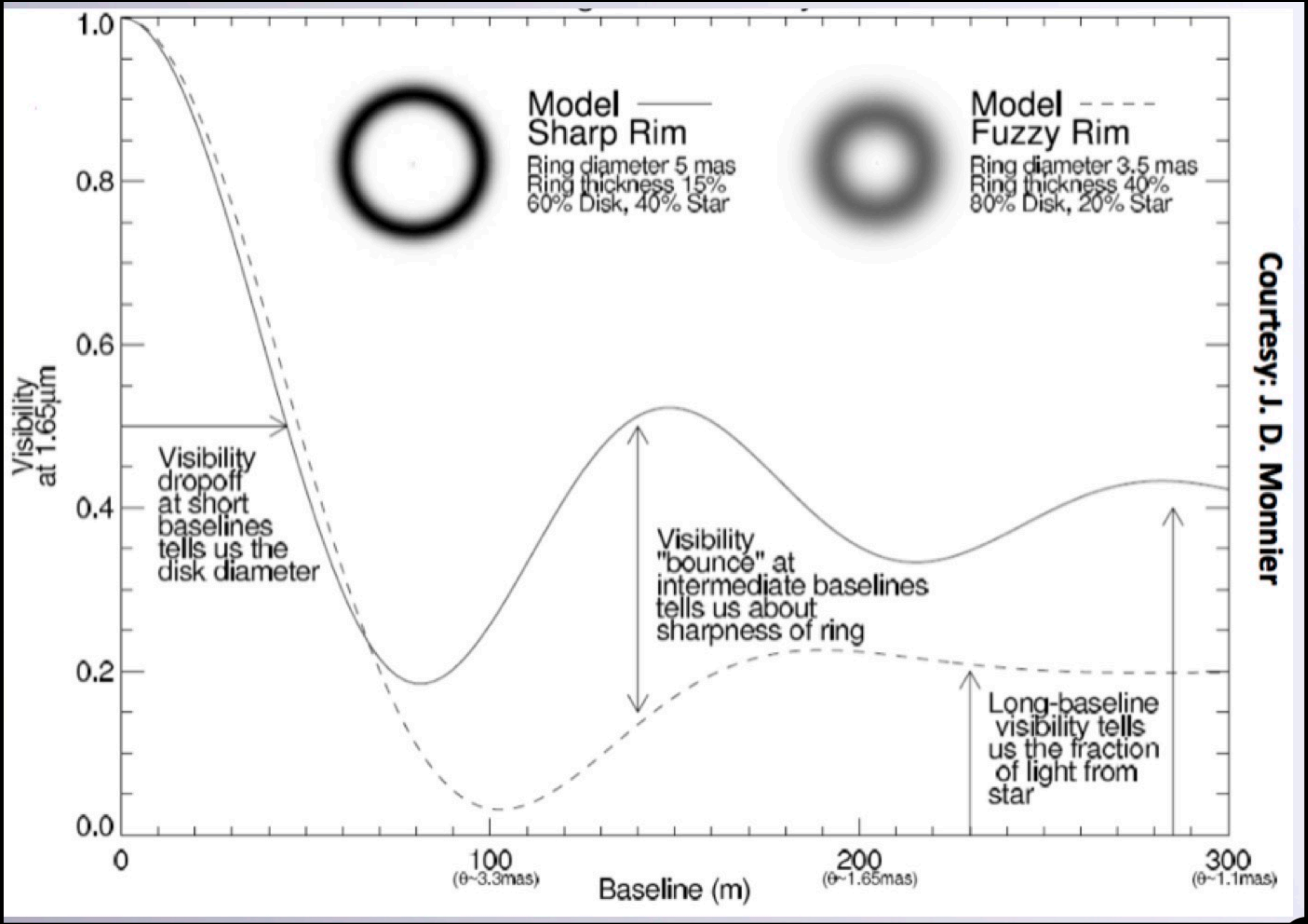
Fourier transform multiplied by a window

Minimum of modulation gives intensity ratio of the components:

$$r = \frac{1 - \sqrt{V^2_{\min}}}{1 + \sqrt{V^2_{\min}}}$$

*— Starting from a good first guess may be decisive —*

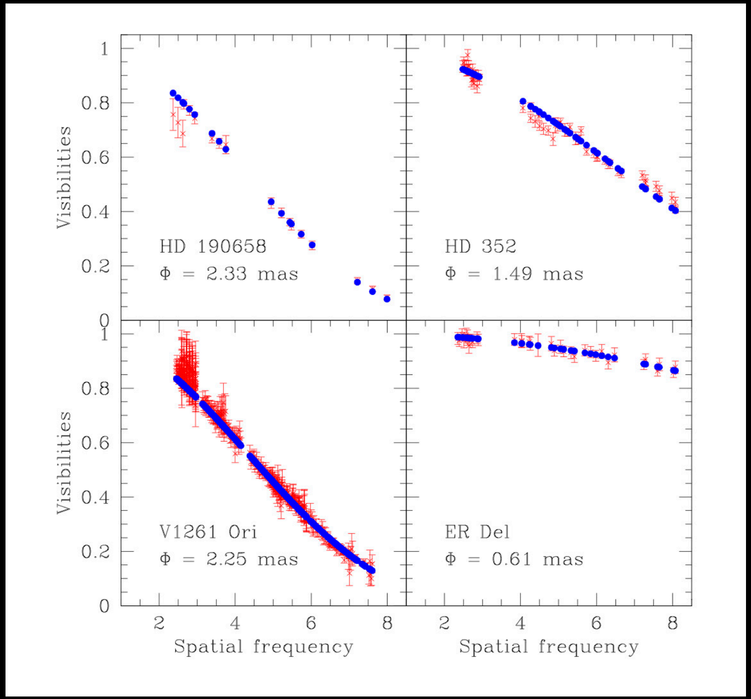
M. Tallon & I. Tallon-Bosc 10



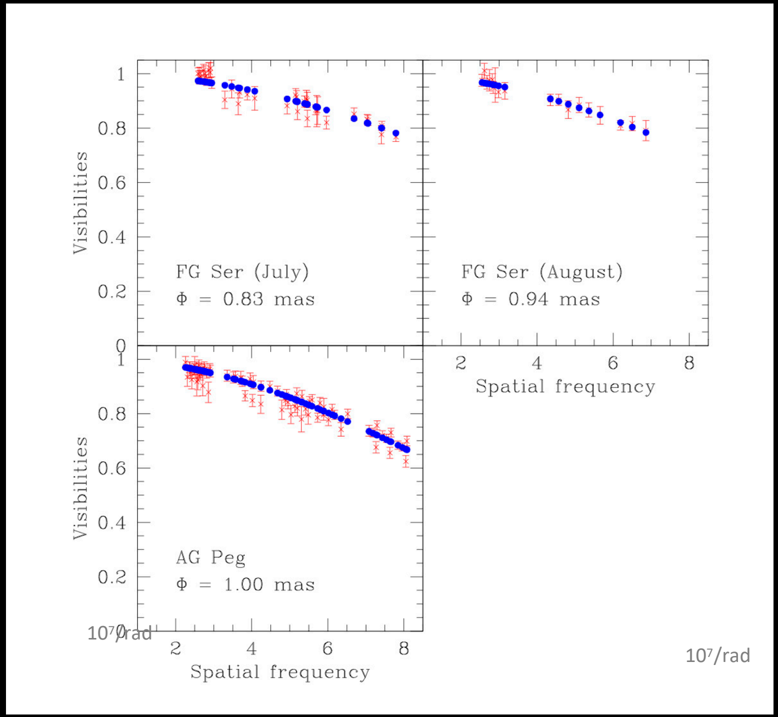

R. Milan-Gabet

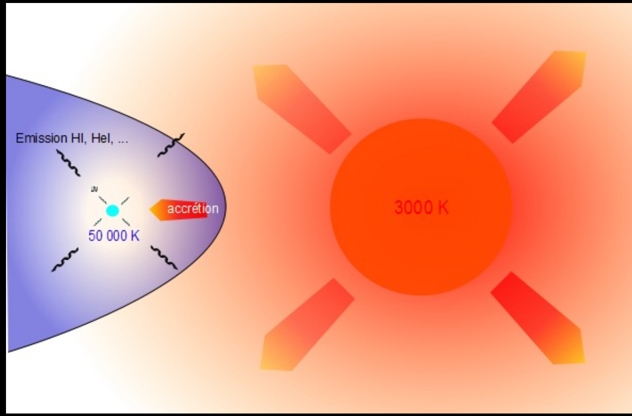
# **Symbiotic stars** observed with PIONIER: Visibilities

V2




V2



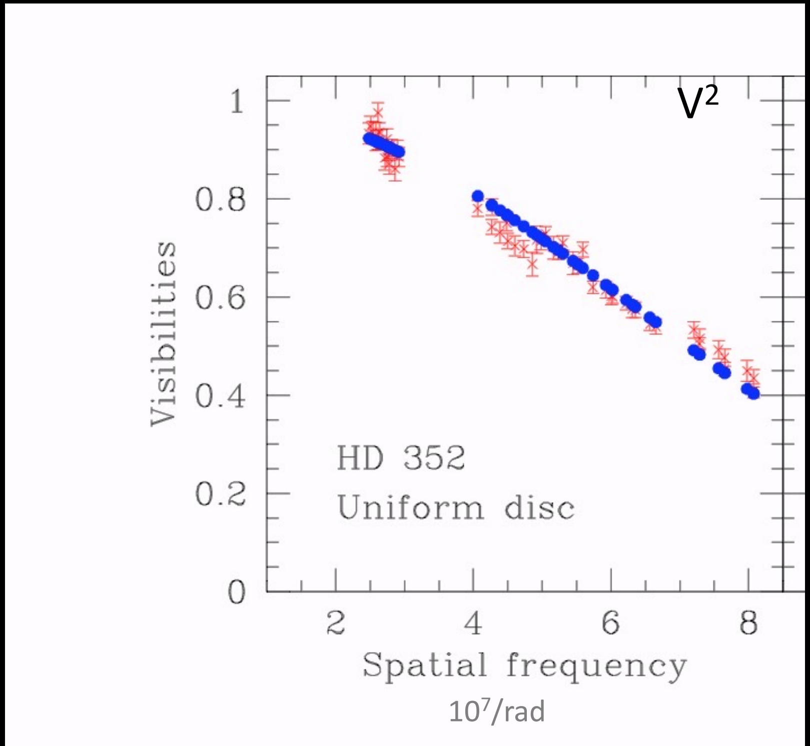




Can generally be fitted with a simple uniform disc

→ Get the diameter of the stars
→ Can compare with their Roche lobe radius

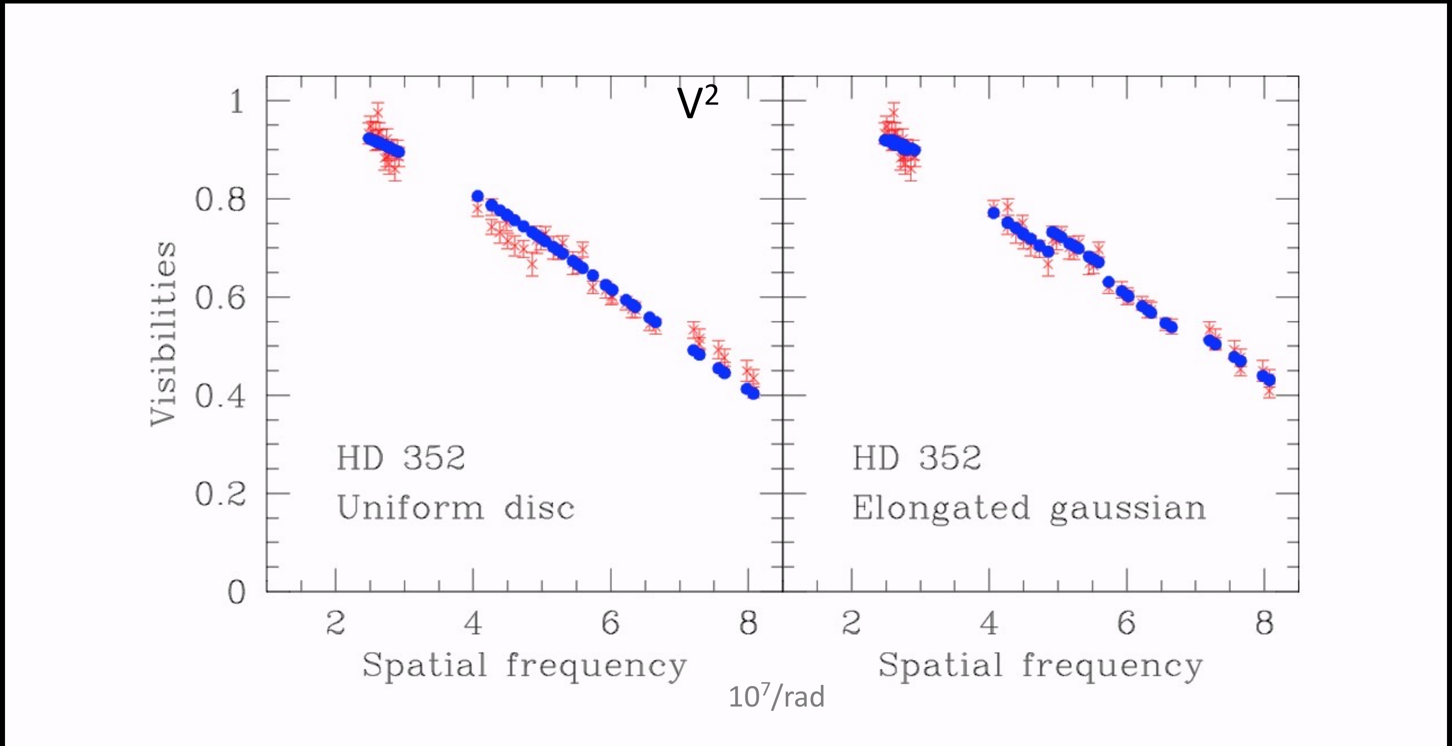
Boffin+ 14

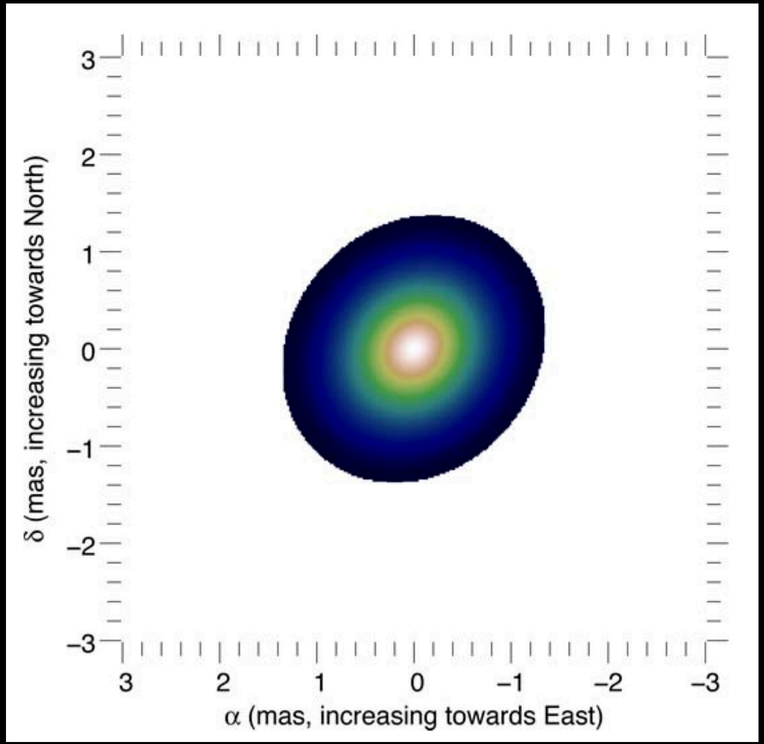
# HD 352 - Elongated




Boffin+ 14

# HD 352 - Elongated



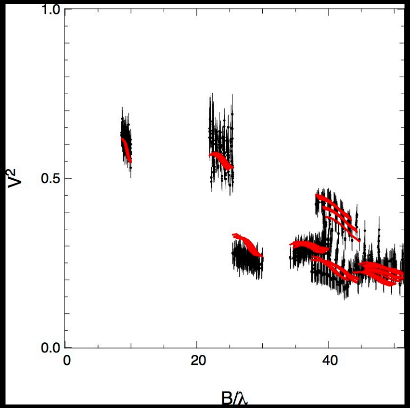




Elongation ratio: 1.16
1.38 x 1.6 mas

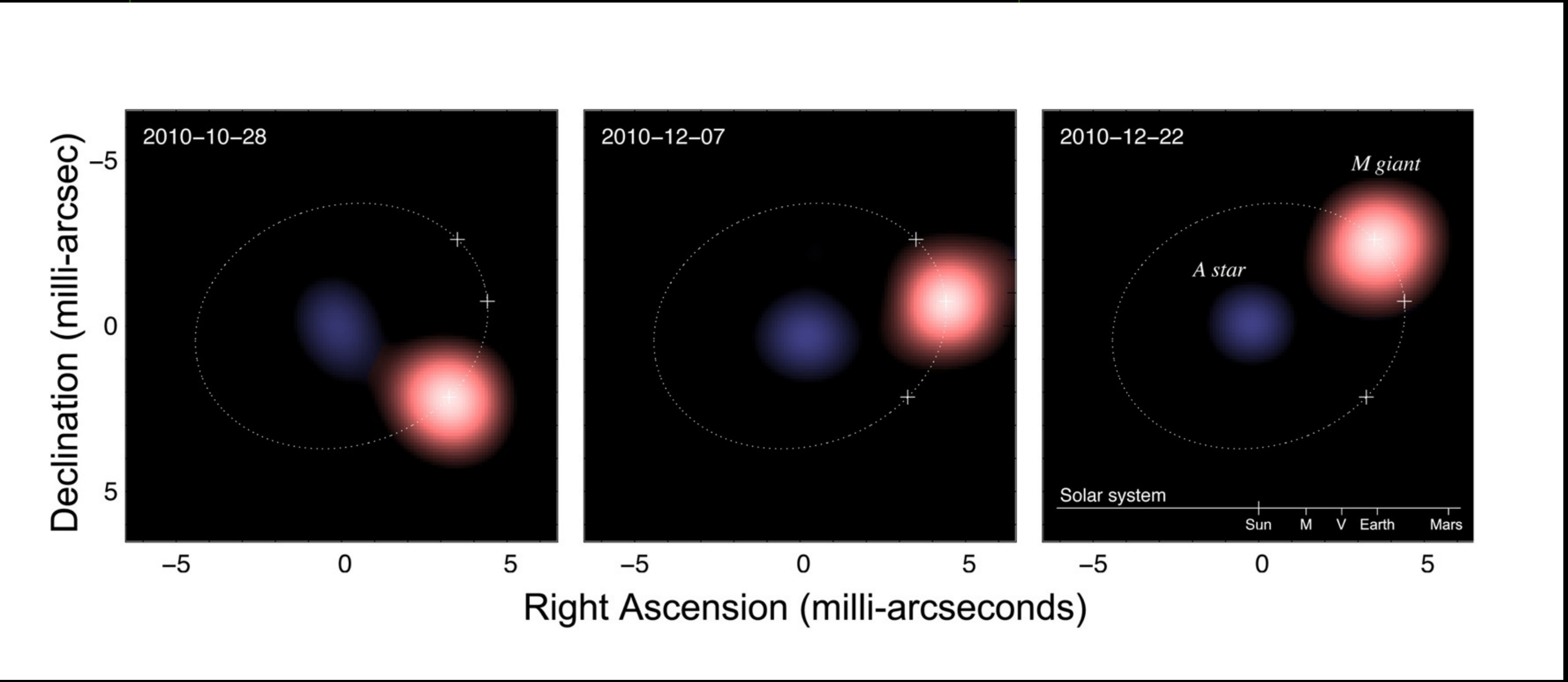
→ Tidal deformation?

Boffin+ 14

# Image Reconstruction

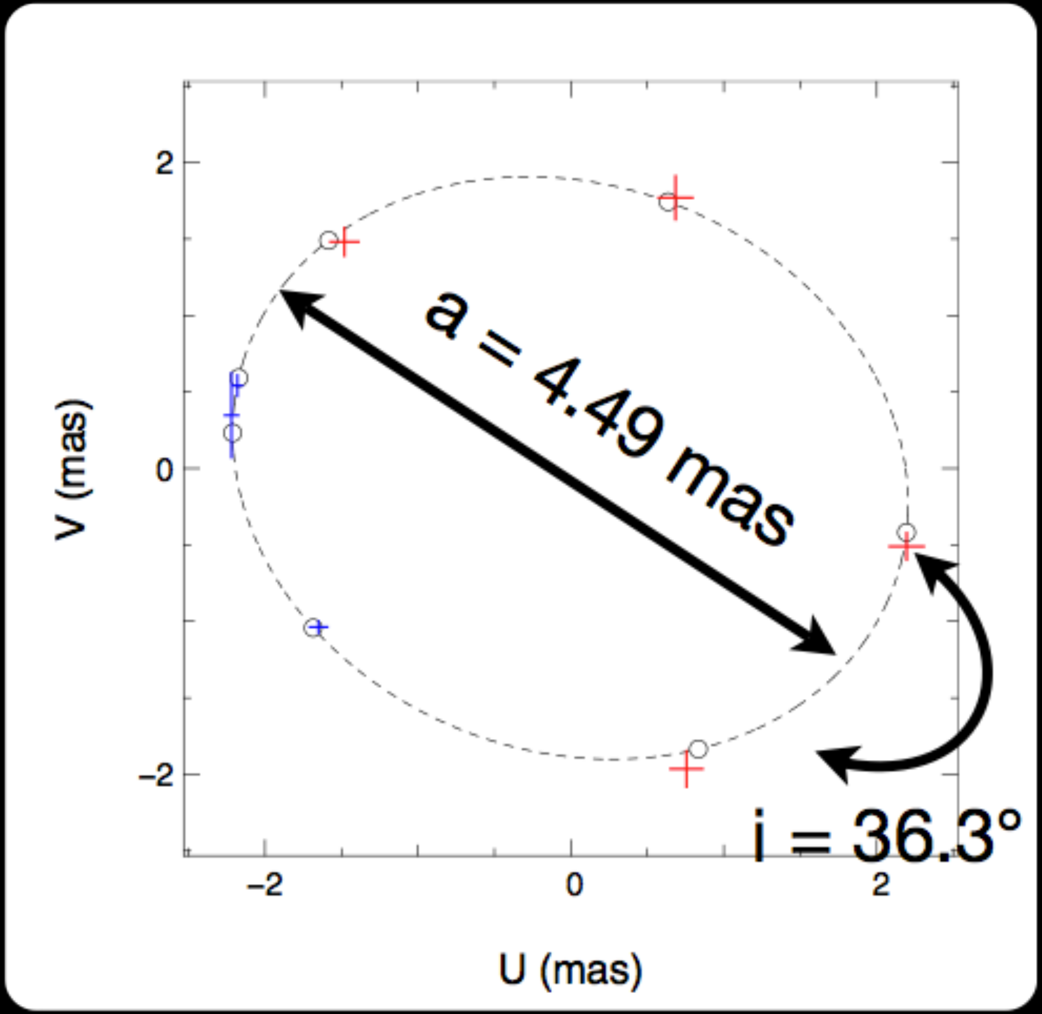



PIONIER data - 2 month-span




Blind, Boffin, Berger+ 11

# Orbit




Blind, Boffin, Berger+ 11

Visual orbit + distance → total mass

Spectroscopic orbit → mass ratio

→ Get the masses of both stars!

## Type of Data: OIFITS file

VLTI instruments → pipeline → get reduced data:

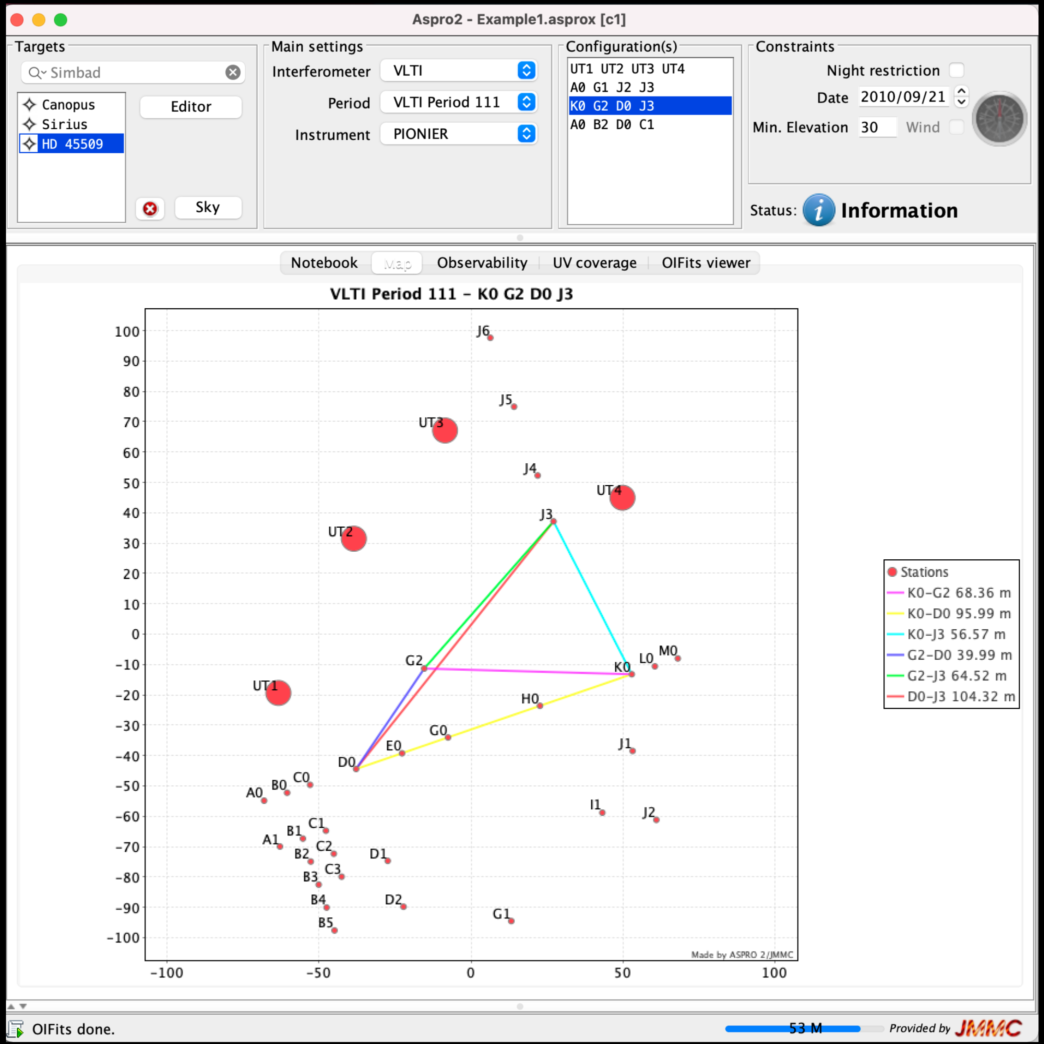
PIONI.2019-07-30T07-32-59.267_oidataCalibrated.fits

OIFITS – specific FITS format for interferometry

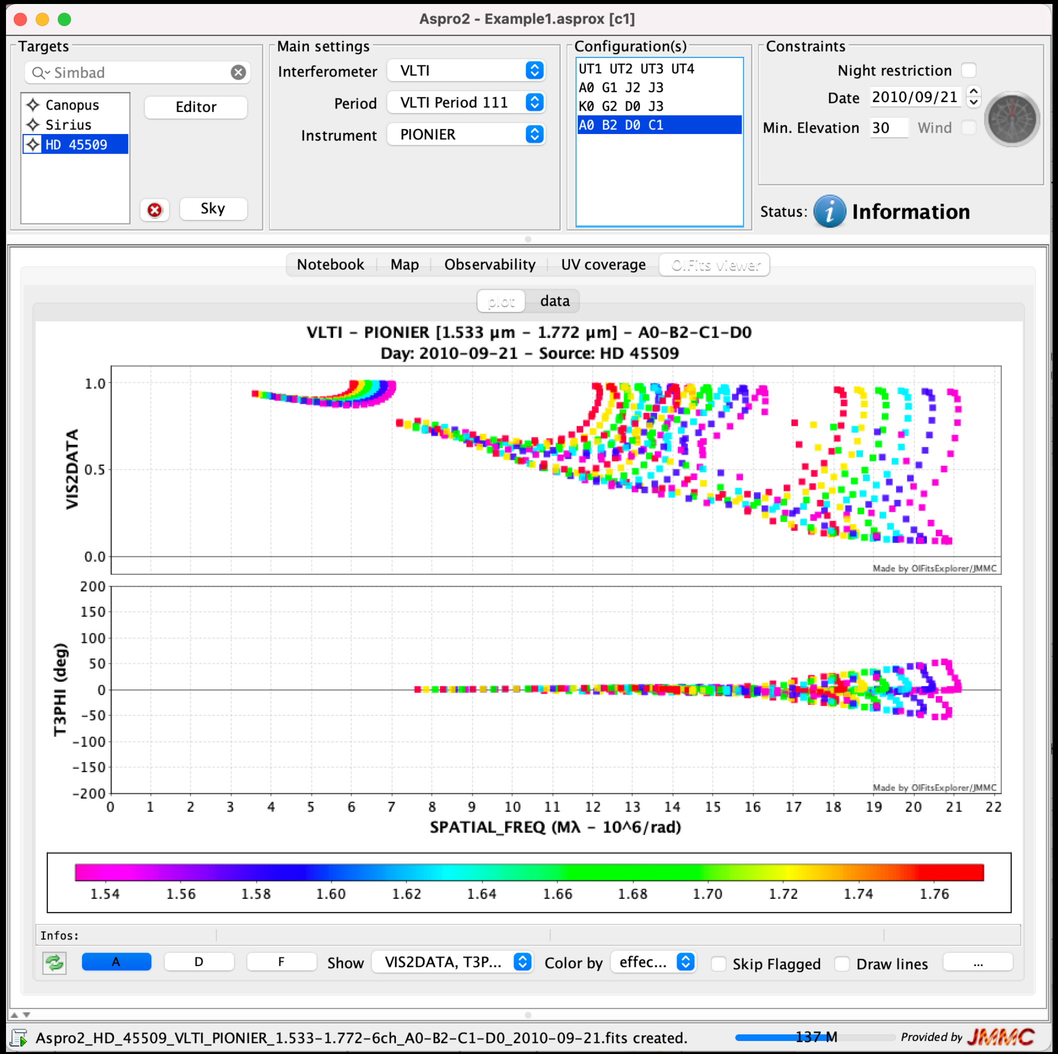
- Squared visibilities (VIS2)
- Complex visibilities (VISAMP, VISPHI)
- Bispectrum (T3AMP, T3PHI)

We typically only use VIS2 and T3PHI

# ASPRO



Aspro2 - Example1.asprox [c1]
Targets
Simbad
Canopus
Sirius
HD 45509
Editor
Sky
Main settings
Interferometer VLTI
Period VLTI Period 111
Instrument PIONIER
Configuration(s)
UT1 UT2 UT3 UT4
A0 G1 J2 J3
K0 G2 D0 J3
A0 B2 D0 C1
Constraints
Night restriction
Date 2010/09/21
Min. Elevation 30
Wind
Status: Information
Notebook
Map
Observability
UV coverage
OIFits viewer
VLTI Period 111 – K0 G2 D0 J3
Stations
K0-G2 68.36 m
K0-D0 95.99 m
K0-J3 56.57 m
G2-D0 39.99 m
G2-J3 64.52 m
D0-J3 104.32 m
Made by ASPRO 2/JMMC
OIFits done.
53 M
Provided by JMMC

Aspro2 - Example1.asprox [c1]
Targets
Simbad
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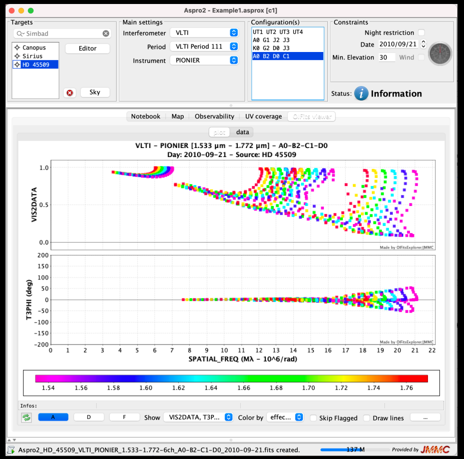
Editor
Sky
Main settings
Interferometer VLTI
Period VLTI Period 111
Instrument PIONIER
Configuration(s)
UT1 UT2 UT3 UT4
A0 G1 J2 J3
K0 G2 D0 J3
A0 B2 D0 C1
Constraints
Night restriction
Date 2010/09/21
Min. Elevation 30
Wind
Status: Information
Notebook
Map
Observability
UV coverage
OIFits viewer
plot
data
VLTI – PIONIER [1.533 µm – 1.772 µm] – A0-B2-C1-D0
Day: 2010-09-21 – Source: HD 45509
VIS2DATA
T3PHI (deg)
SPATIAL_FREQ (Mλ – 10^6/rad)
Made by OIFitsExplorer/JMMC
Infos:
Show VIS2DATA, T3P...
Color by effec...
Skip Flagged
Draw lines
Aspro2_HD_45509_VLTI_PIONIER_1.533-1.772-6ch_A0-B2-C1-D0_2010-09-21.fits created.
137 M
Provided by JMMC

# ASPRO




helps you to prepare observations on various optical interferometers

**Interferometer sketch:** display base lines of the selected configuration(s)

**Observability plot:** represents time intervals when the source can be observed

**UV Coverage plot:** shows projected base lines on the UV plan and an image of the source model to see the UV coverage of the source

**OIFits viewer:** provides several OIFits data plots (square visibility and closure phase vs spatial frequency ...) including error bars and spectral dispersion

**Target editor:** show complete target information, edit missing target magnitudes and associate calibrators to your science targets

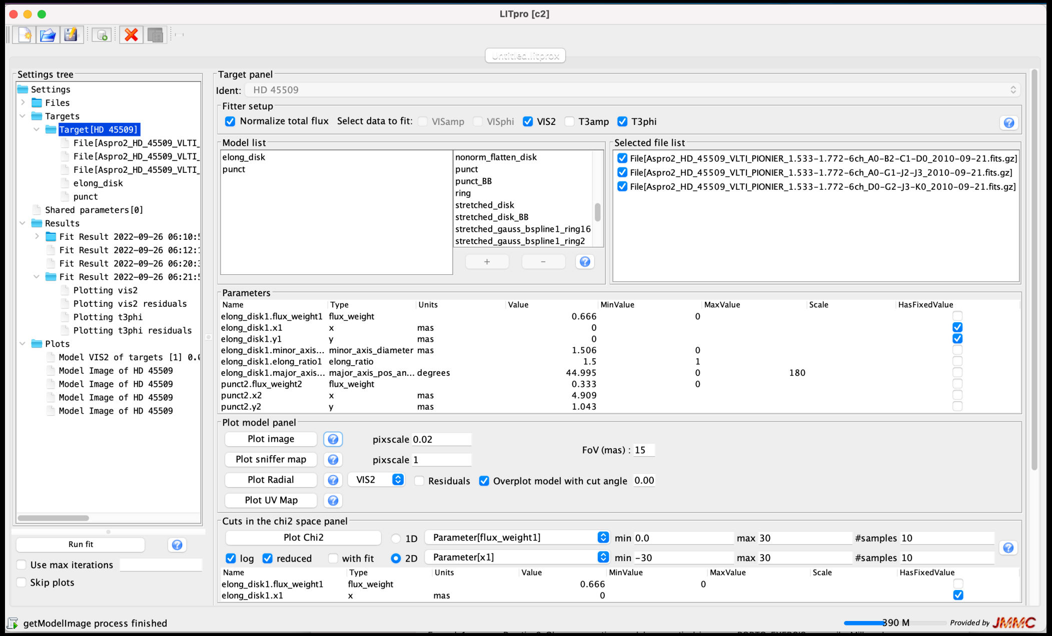
**Model editor:** each source can have its own object model composed of several elementary models (punct, disk, ring, gaussian, limb darkened disk ...) or an user-defined model (FITS image)

**Observing Blocks can be generated**

**OIFits file generation** with error and noise modelling

# LITpro: Lyon Interferometric Tool prototype

- Parametric model fitting software for interferometry
- Complementary to image reconstruction
  - Sparse (u,v) coverage
  - Model fitting extracts measured quantities



Let’s do some hands-on!