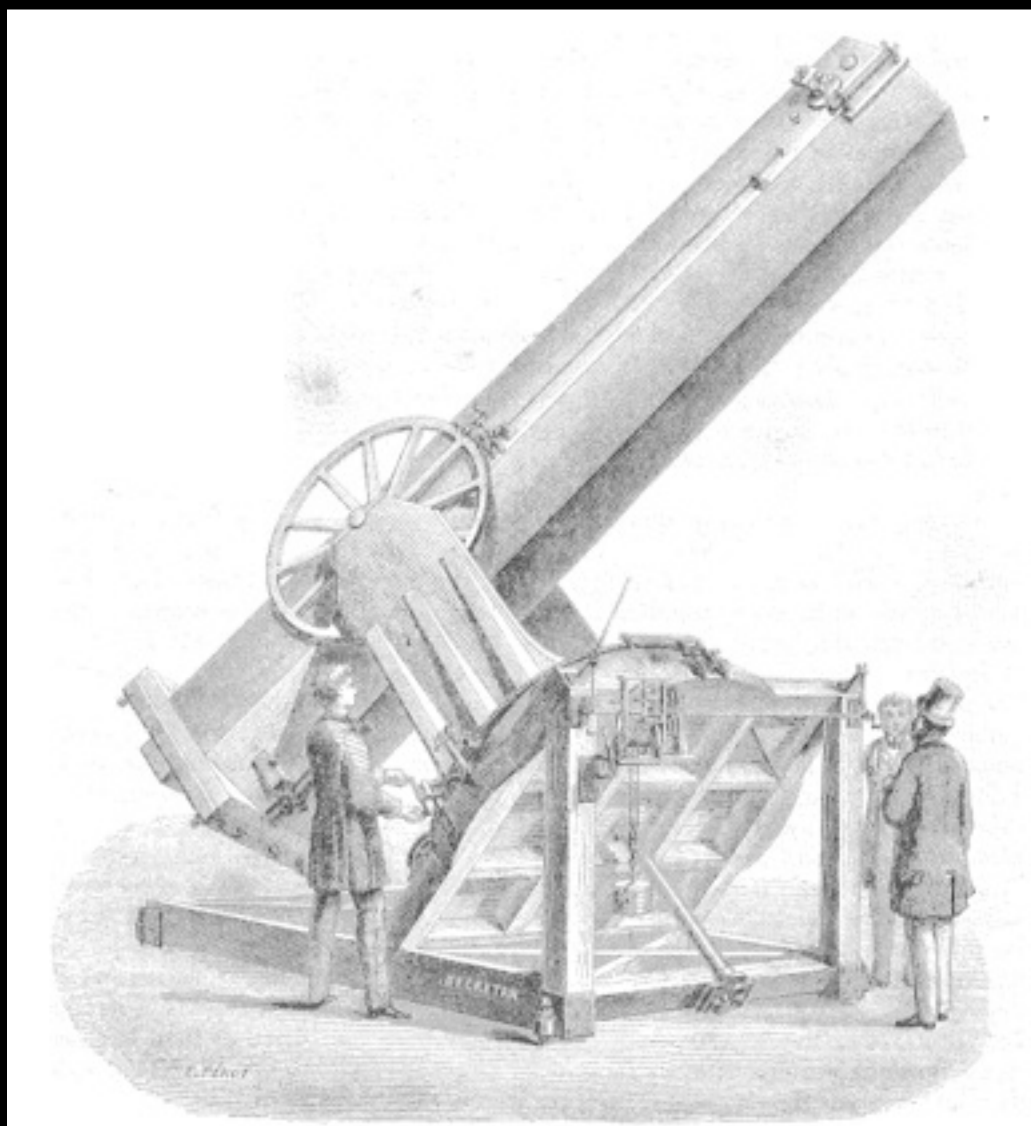
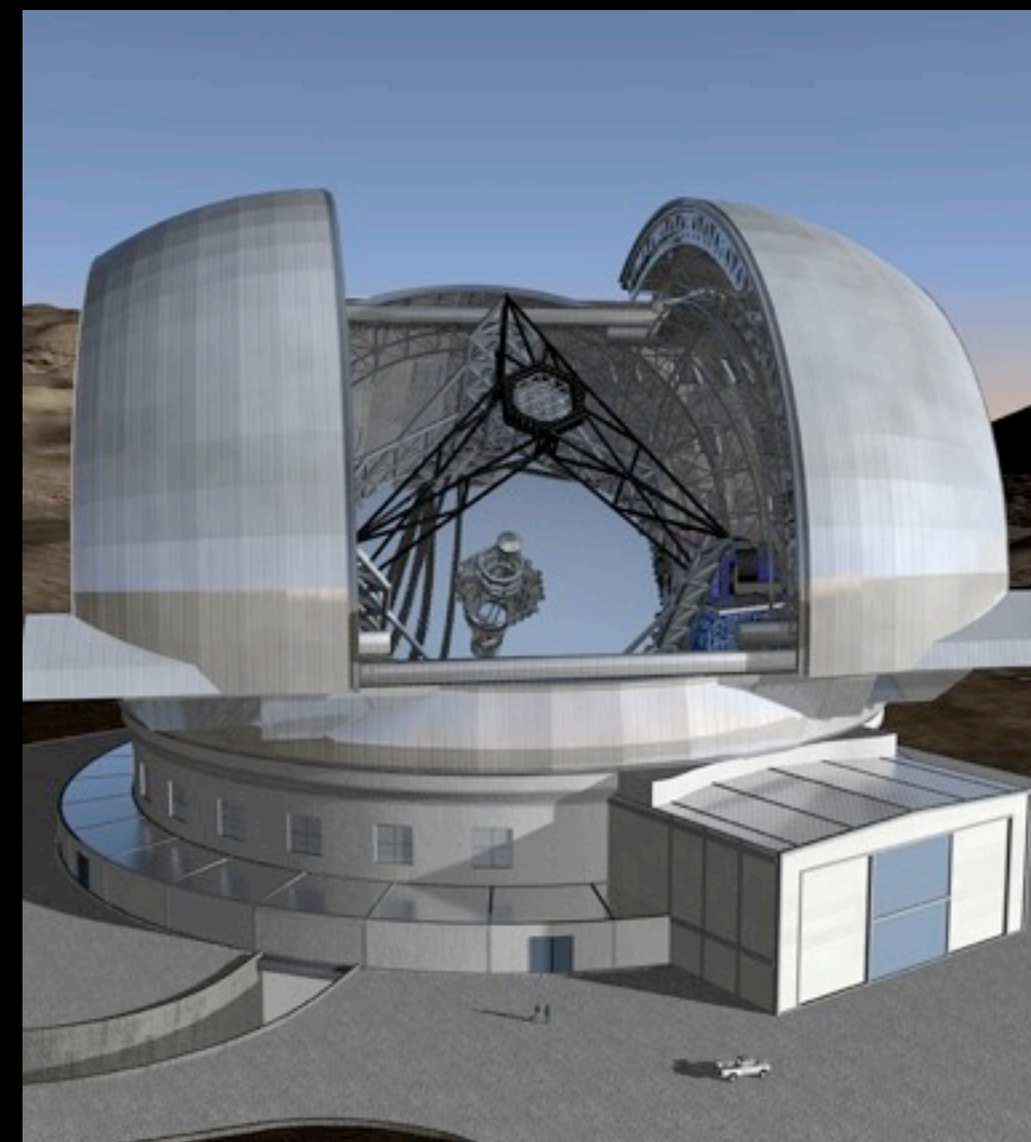
Single-telescope interferometry



Le grand télescope Foucault, de l'Observatoire de Marseille.

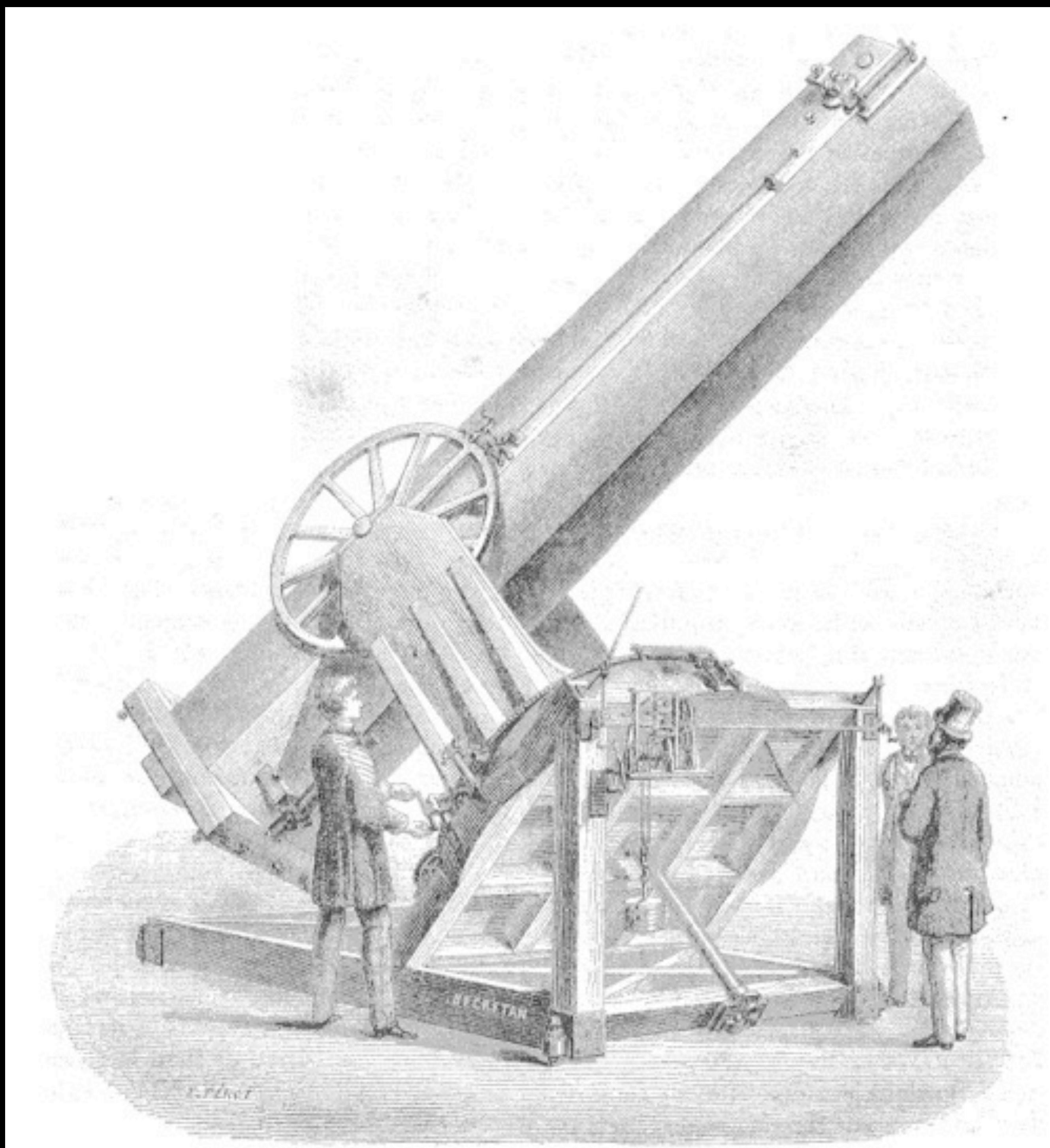
?



Frantz Martinache, Laboratoire Lagrange, OCA

Marseille, 1873

Marseille, 1873

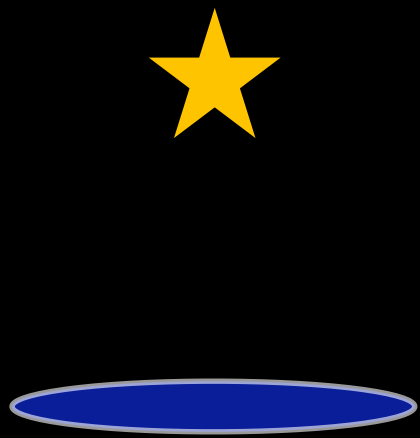


Le grand télescope Foucault, de l'Observatoire de Marseille.

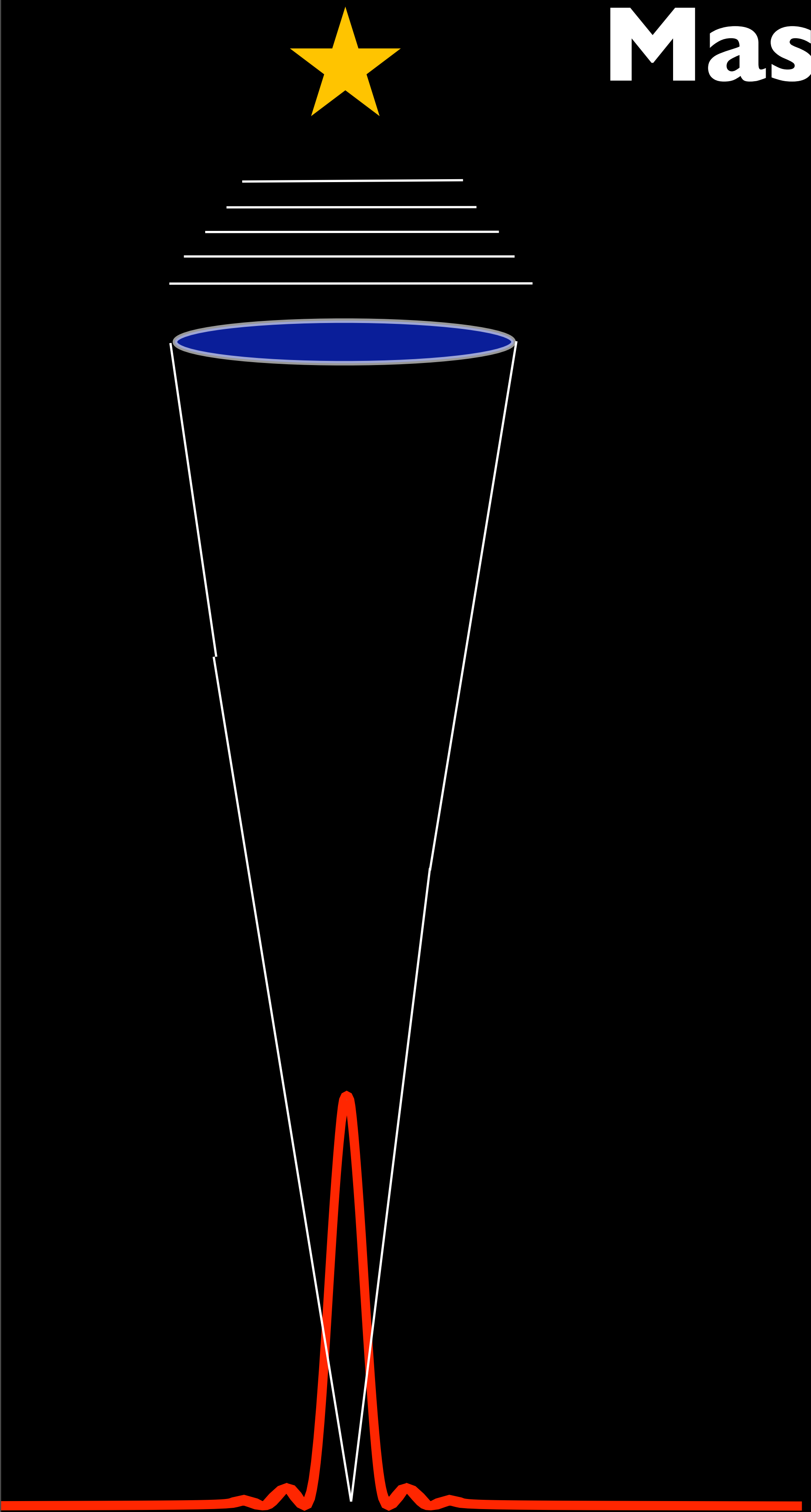
"Le grand télescope Foucault de l'Observatoire de Marseille"

Why would you want to mask what was then the best telescope available?

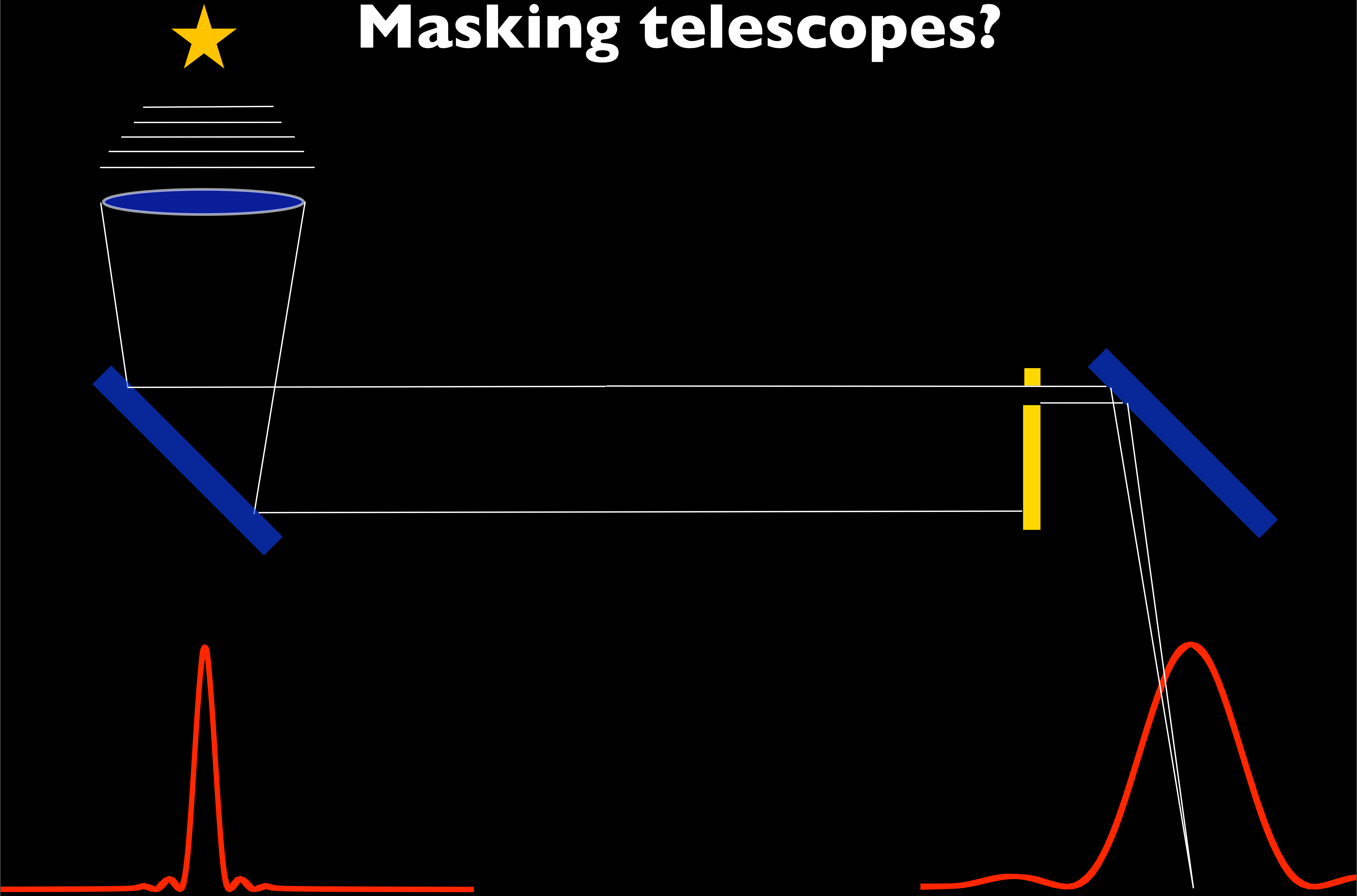
Masking telescopes?



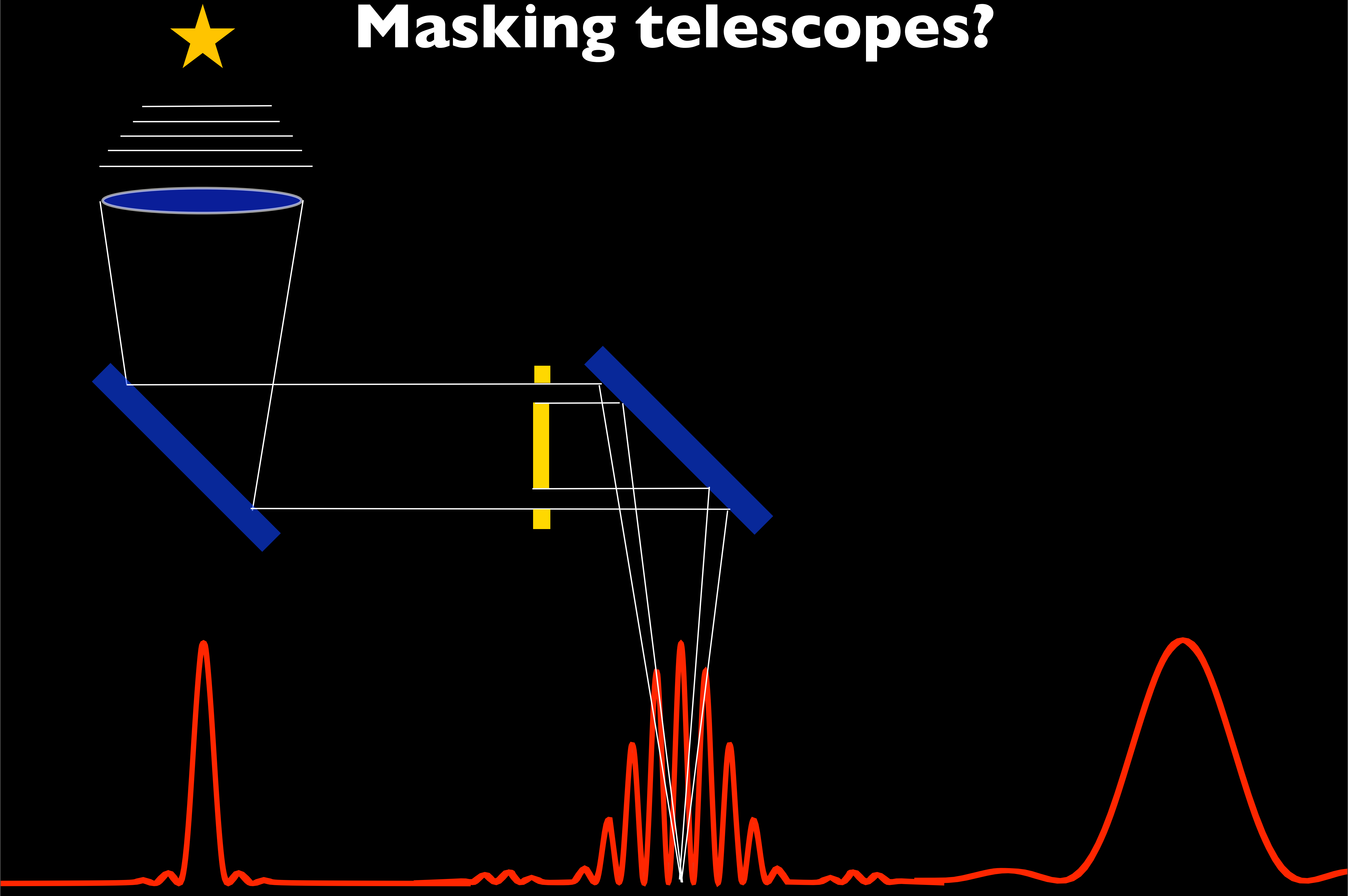
Masking telescopes?



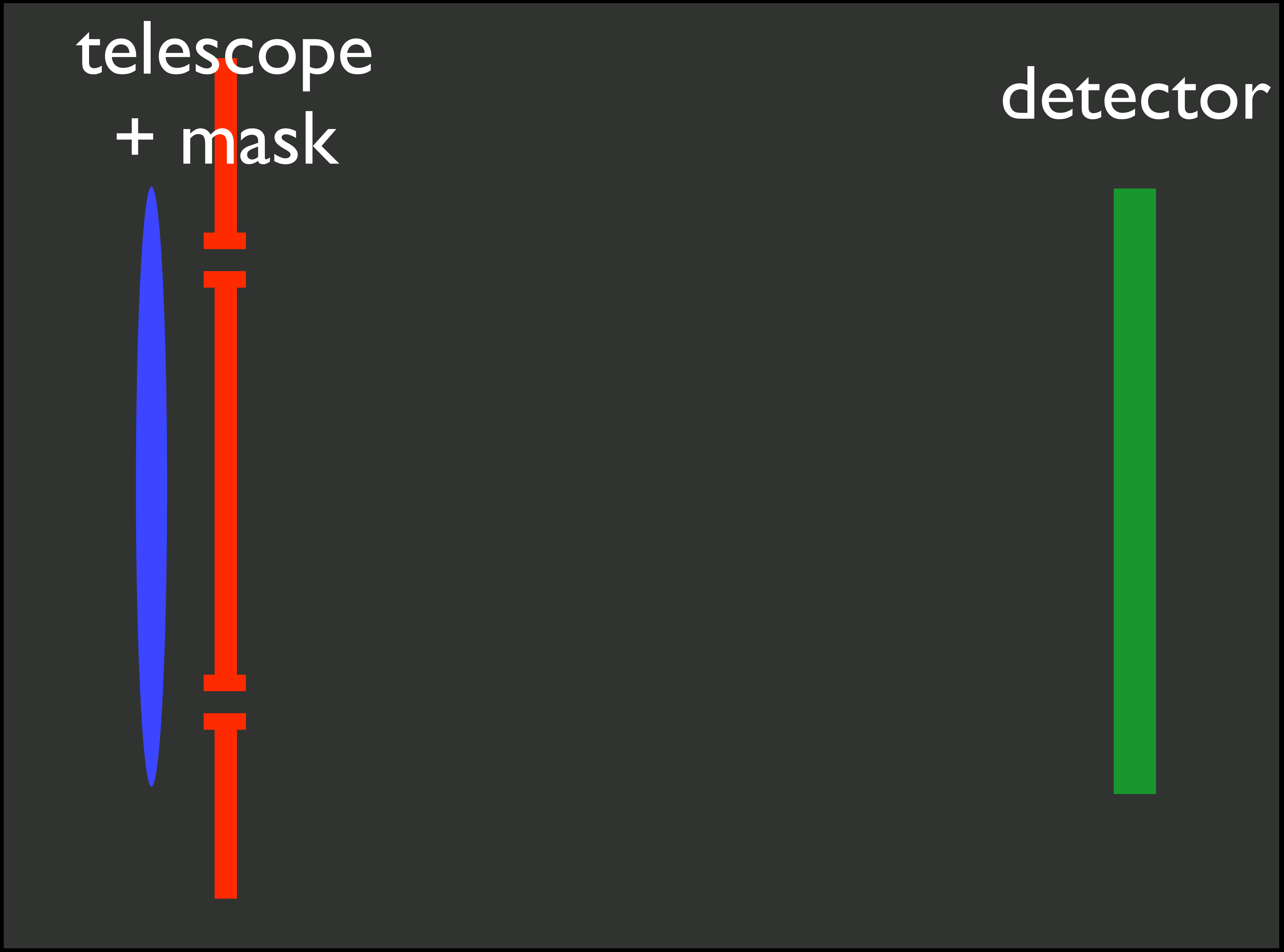
Masking telescopes?



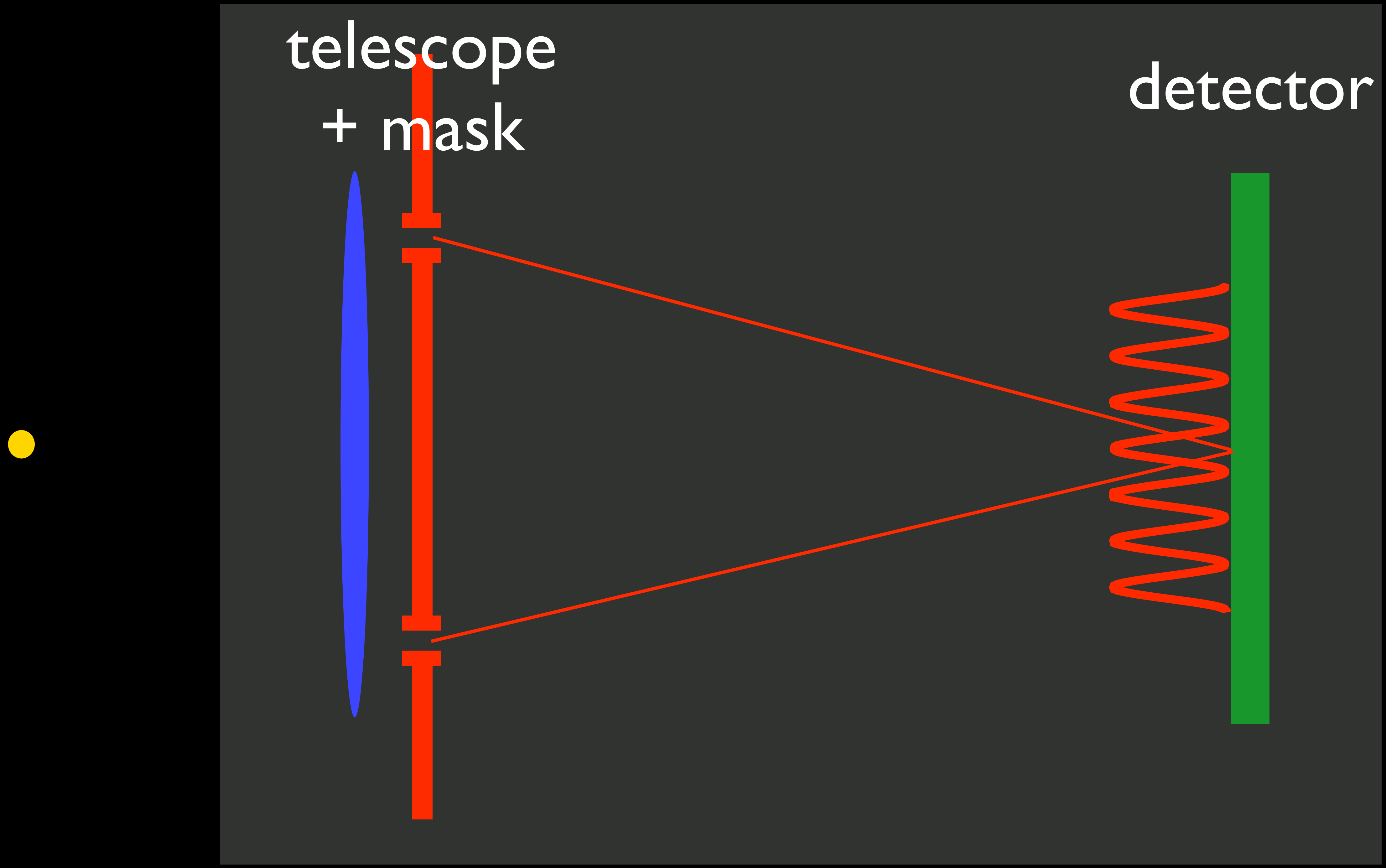
Masking telescopes?



Measuring fringe visibility



Measuring fringe visibility

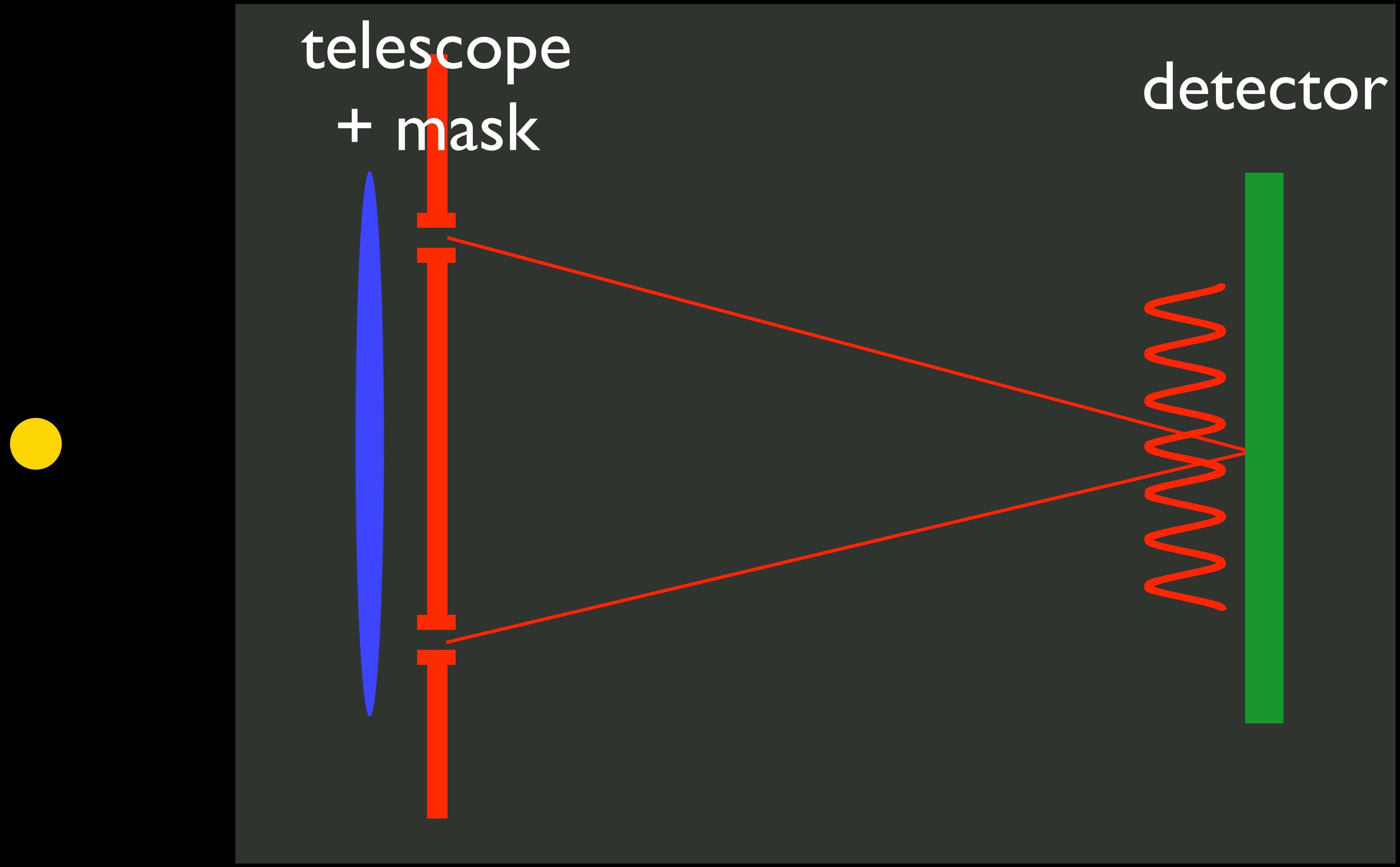


visibility:

$V = (I_{max} - I_{min})/(I_{max} + I_{min})$

$V = 1$

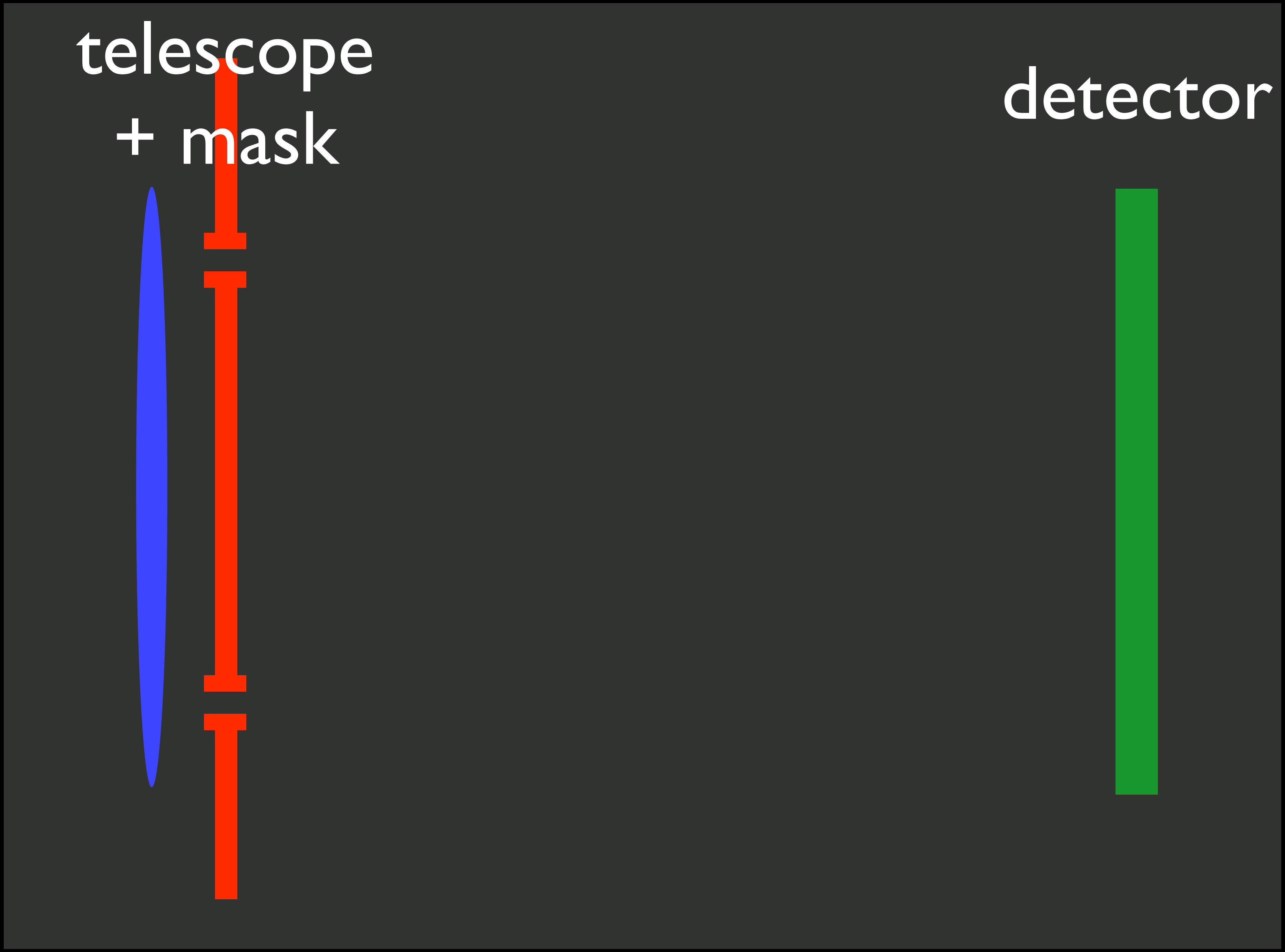
Measuring fringe visibility



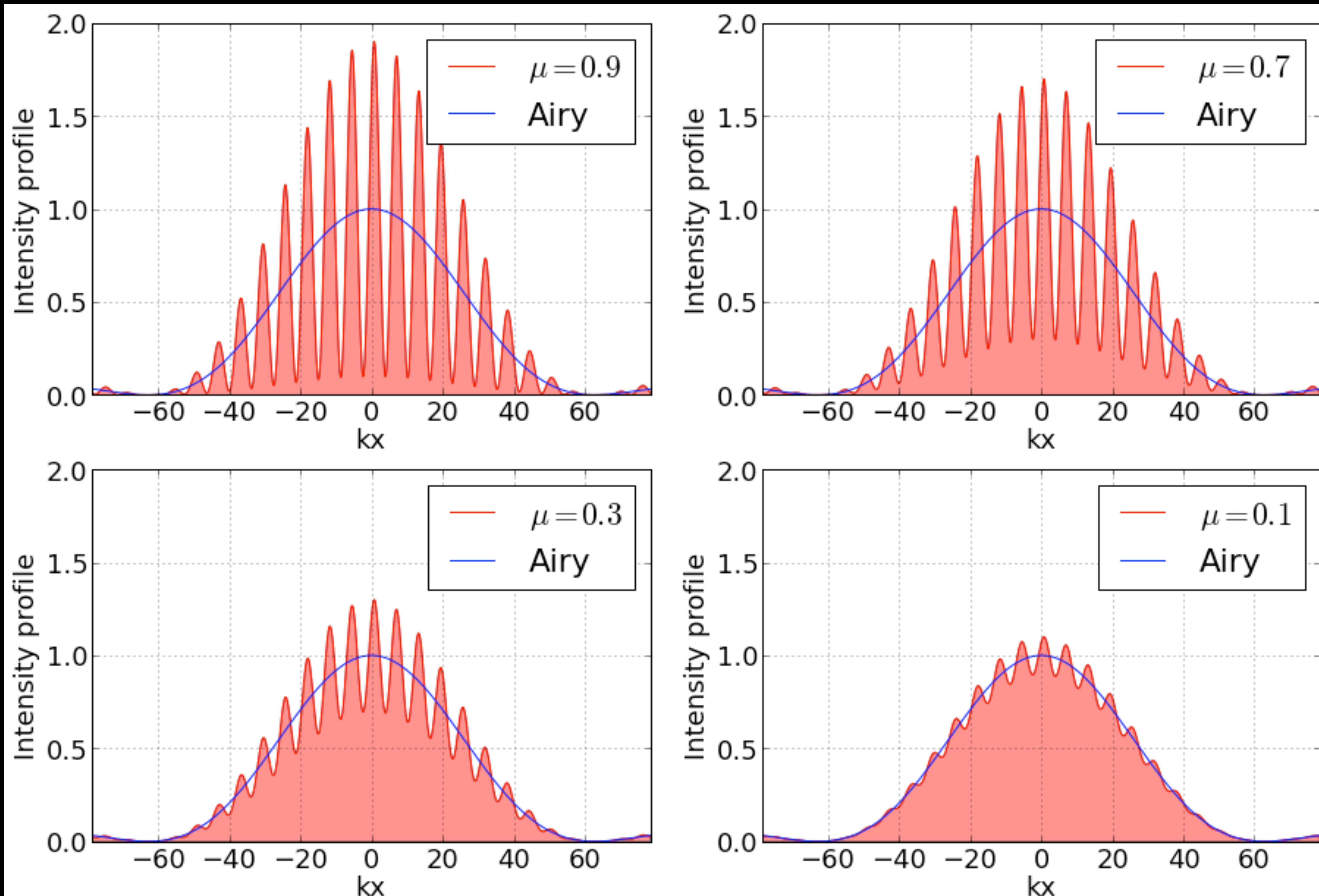
visibility:

$V = (I_{max}-I_{min})/(I_{max}+I_{min})$ $\quad 0 < V < 1$

Measuring fringe visibility

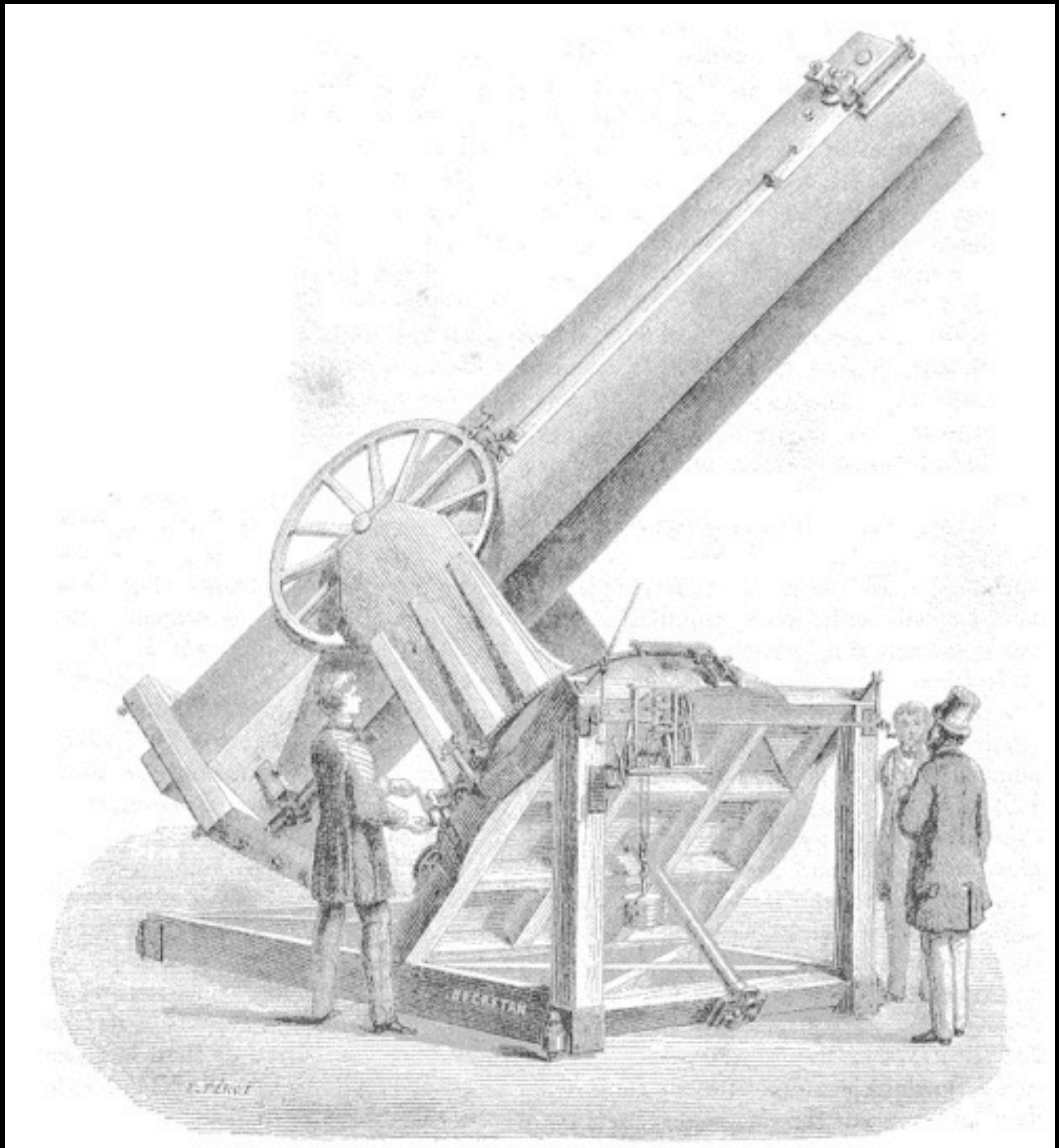


Fringe visibility



Marseille, 1873

Marseille, 1873



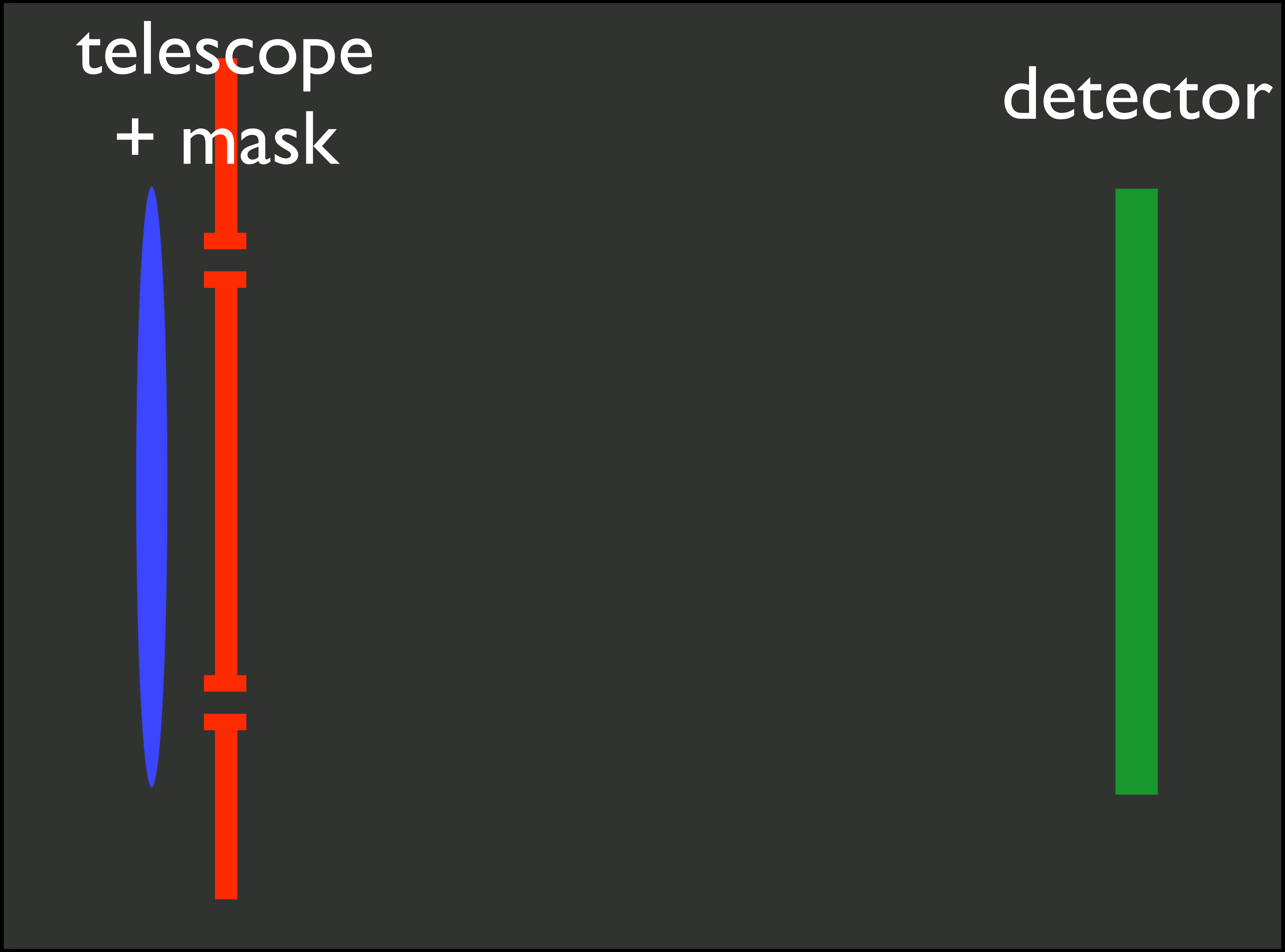
Le grand télescope Foucault, de l'Observatoire de Marseille.

Edouard Stephan attempts the first stellar diameter measurement.

With a maximum baseline of 65 cm, he concludes about the diameter of stars

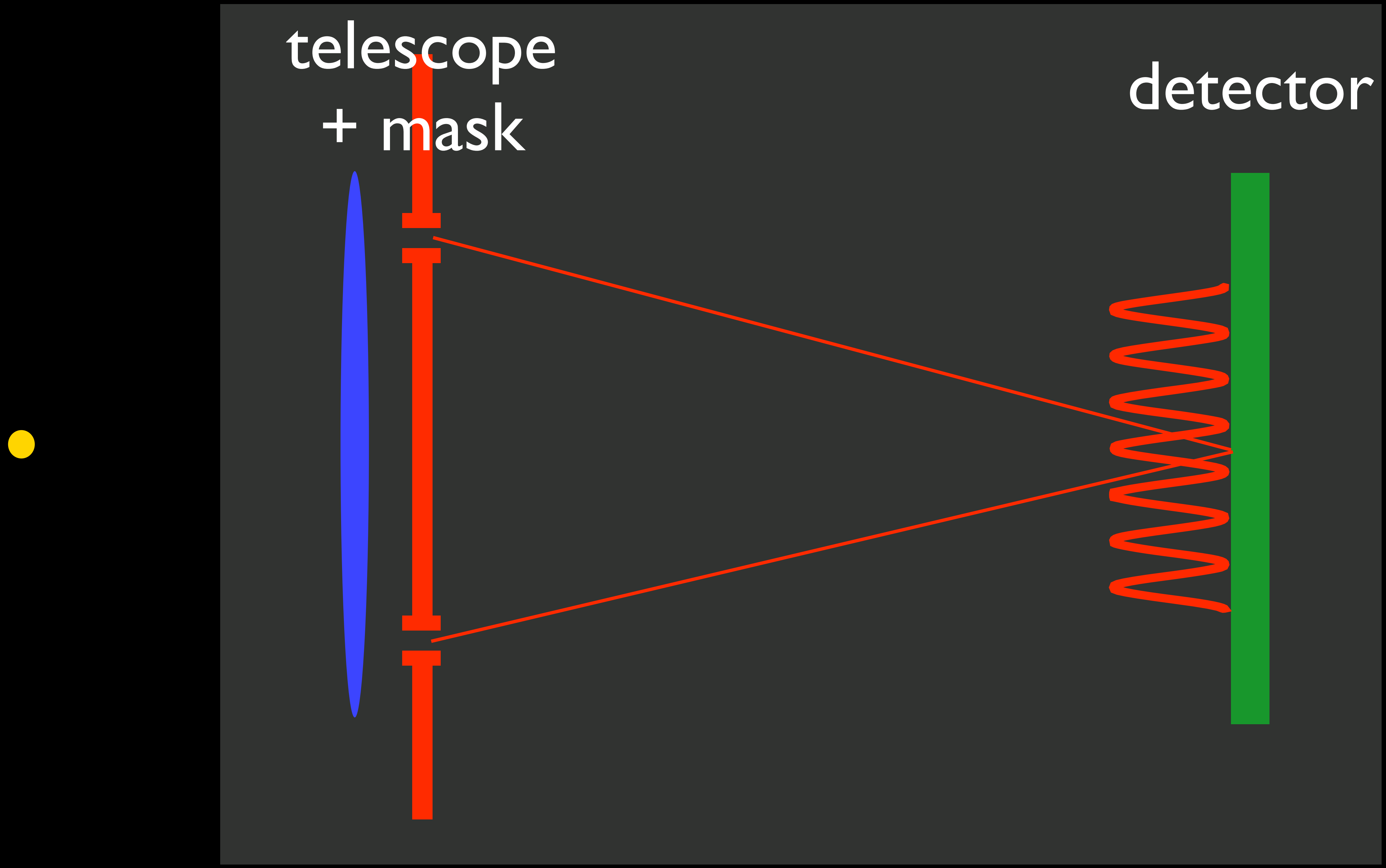
$\varnothing_\star < 0.158''$

Measure complex visibility



visibility:　　　　phase:

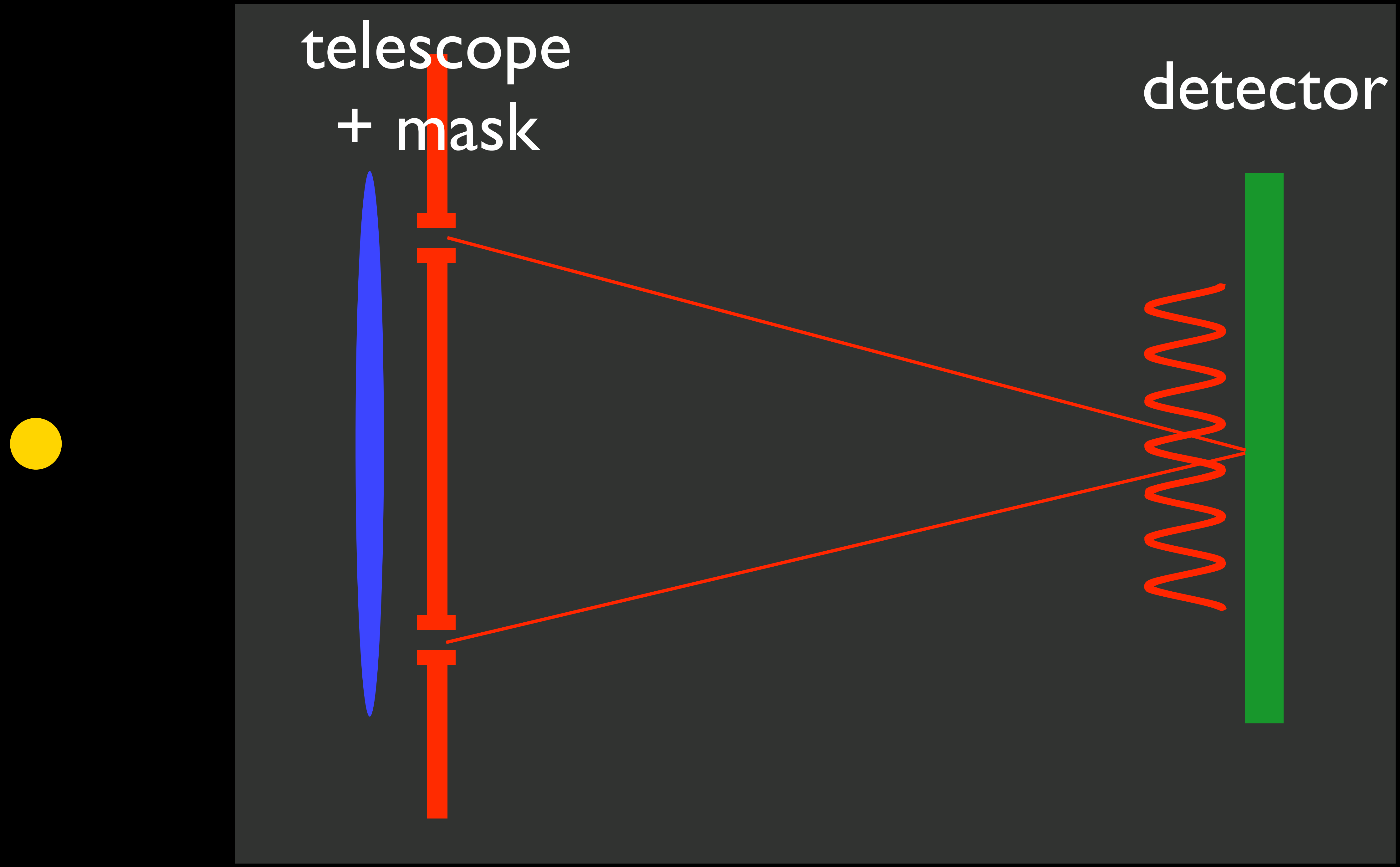
Measure complex visibility



visibility: $V = 1$

phase: $\Phi = 0$

Measure complex visibility



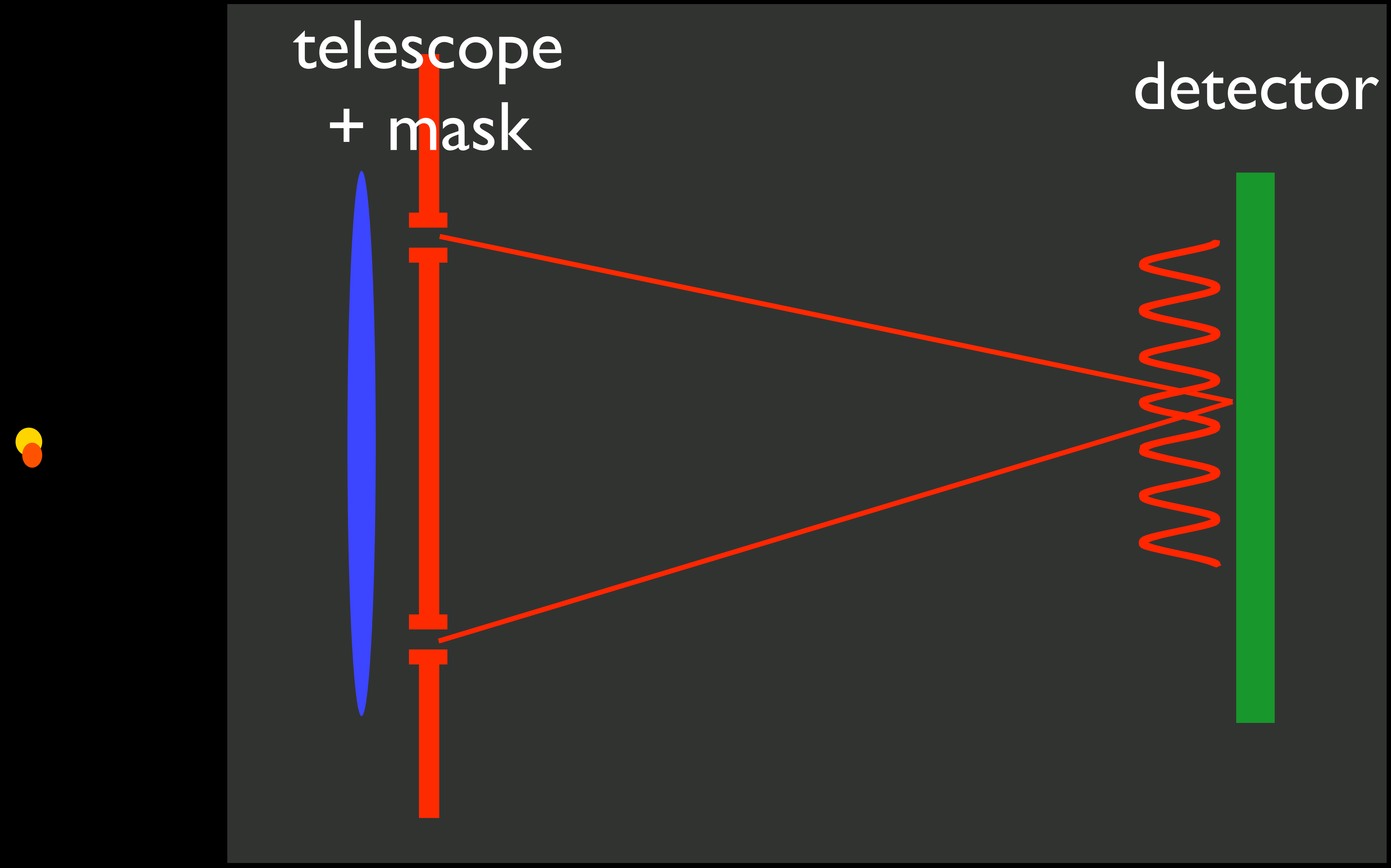
visibility:

$0 < V < 1$

phase:

$\Phi = 0$

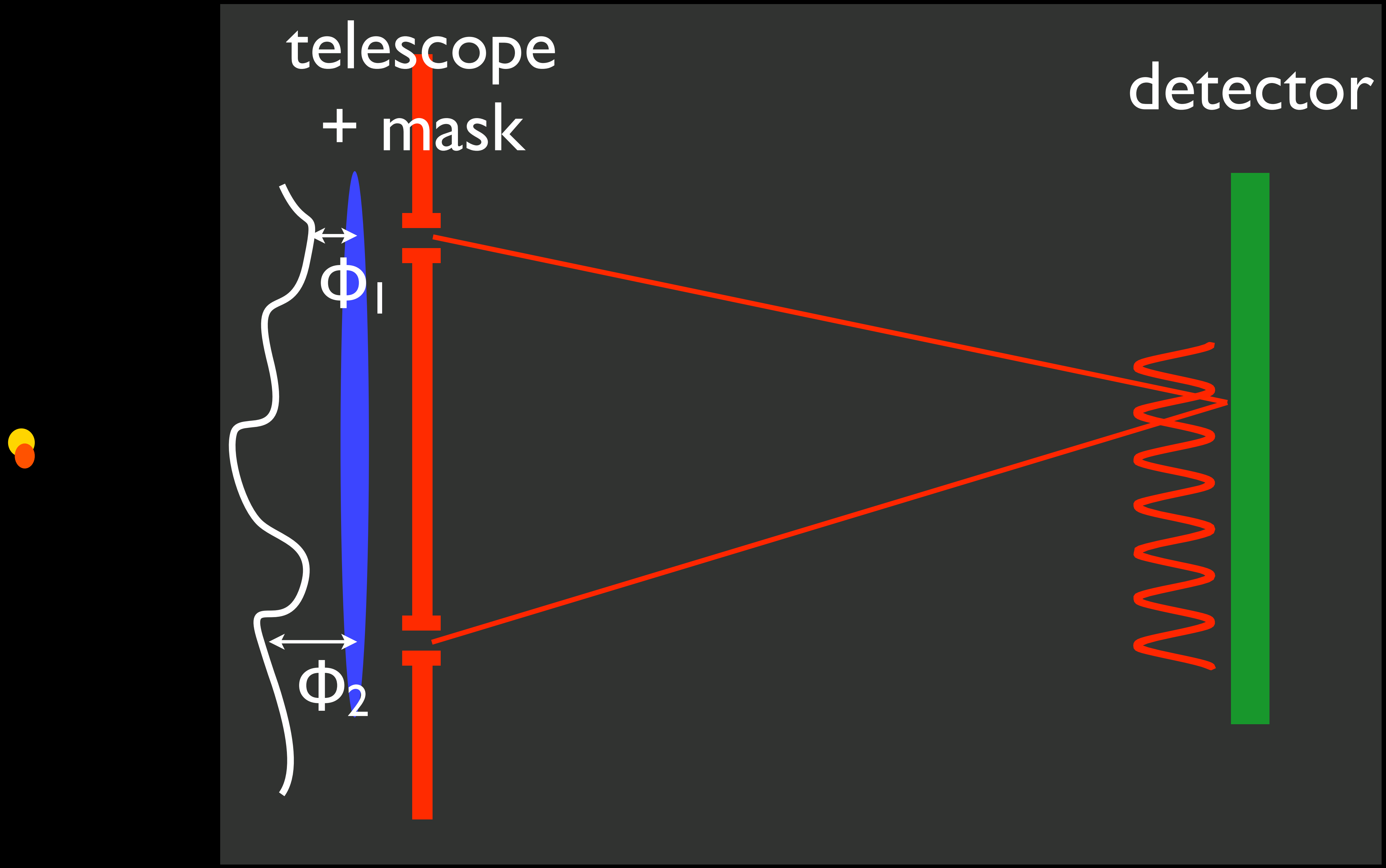
Measure complex visibility



visibility:
$0 < V < 1$

phase:
$\Phi = \Phi_0$

Measure complex visibility



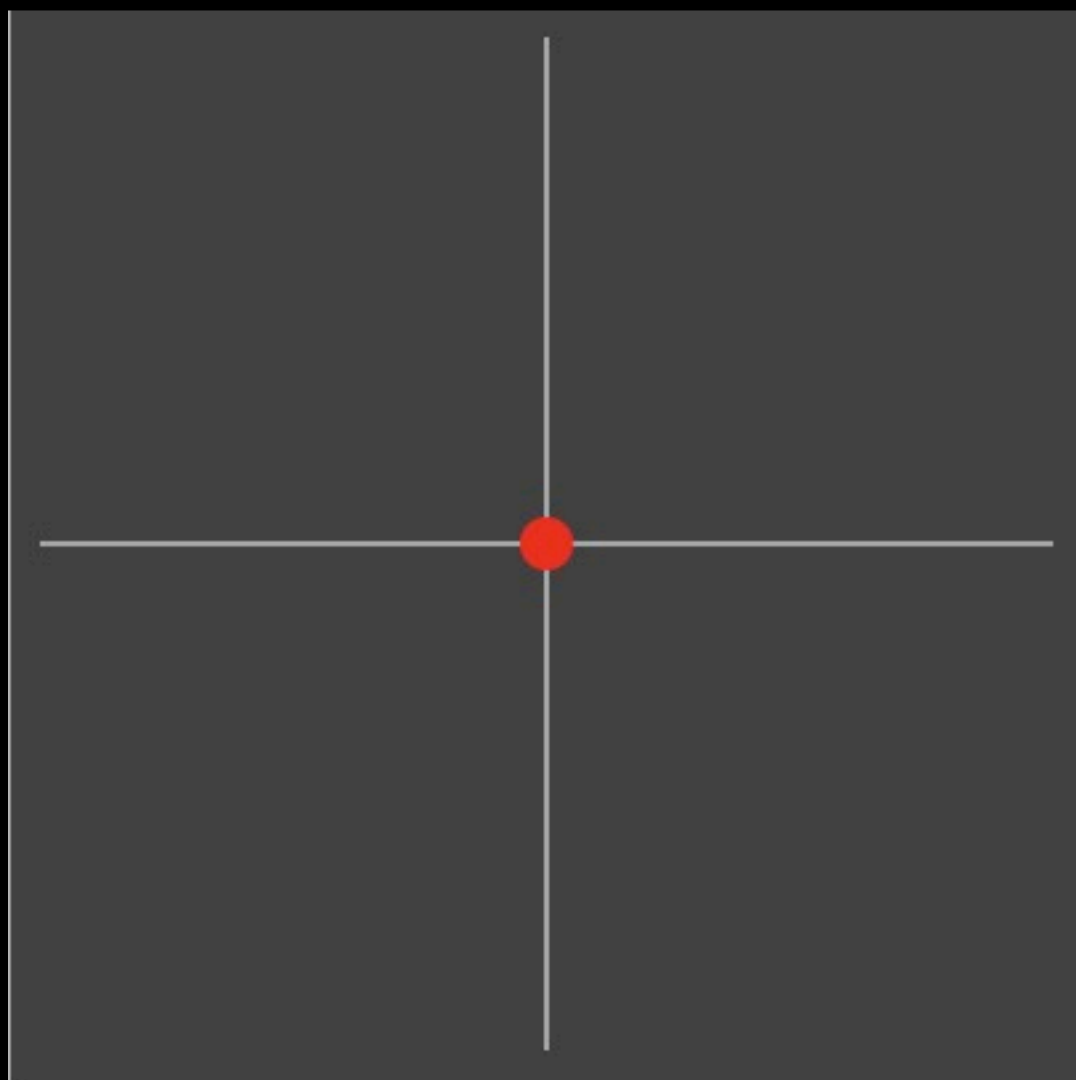
visibility:

$0 < V < 1$

phase:

$\Phi = \Phi_0 + (\Phi_1 - \Phi_2)$

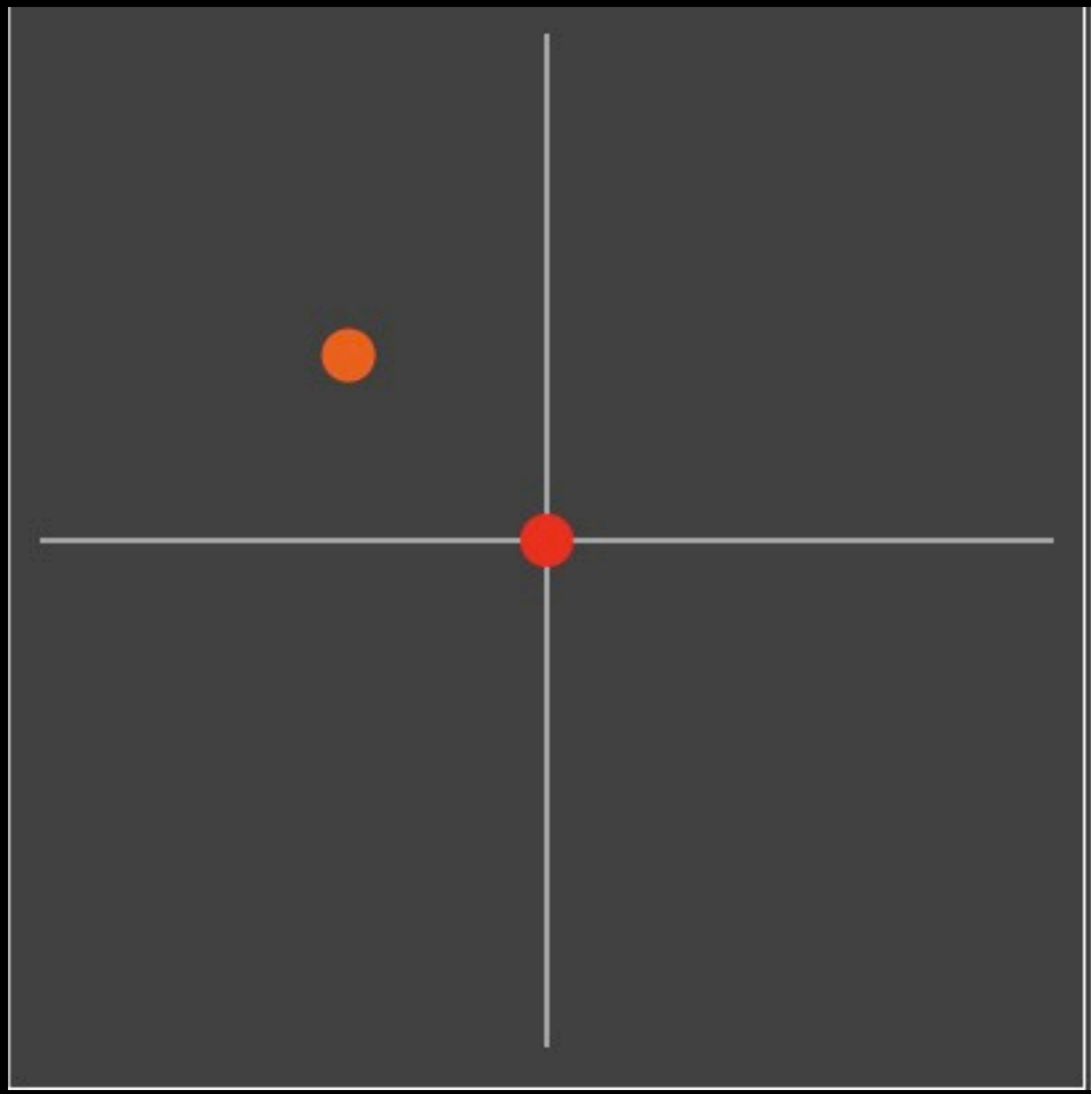
More than two apertures?



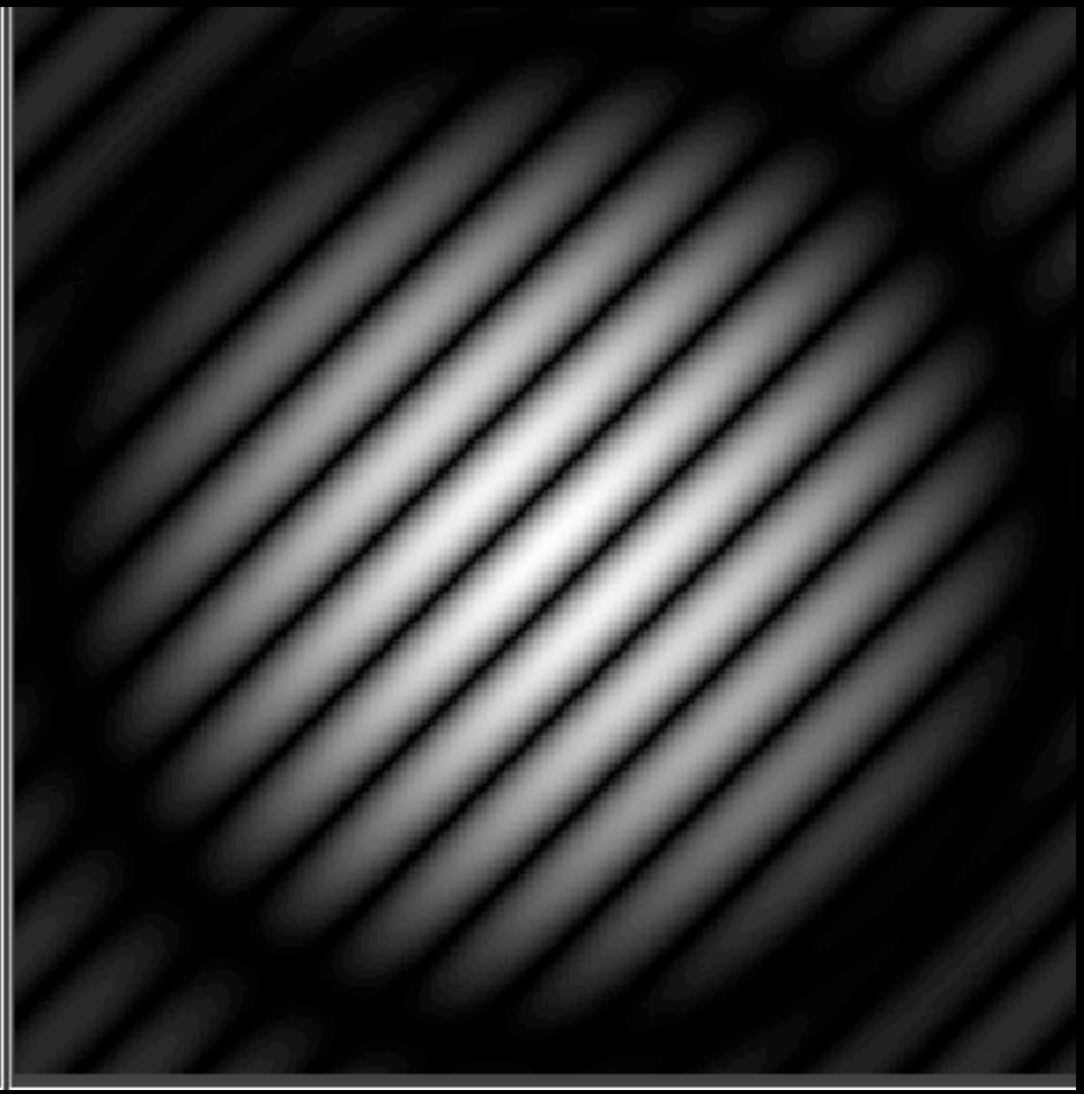
pupil

interferogram

More than two apertures?

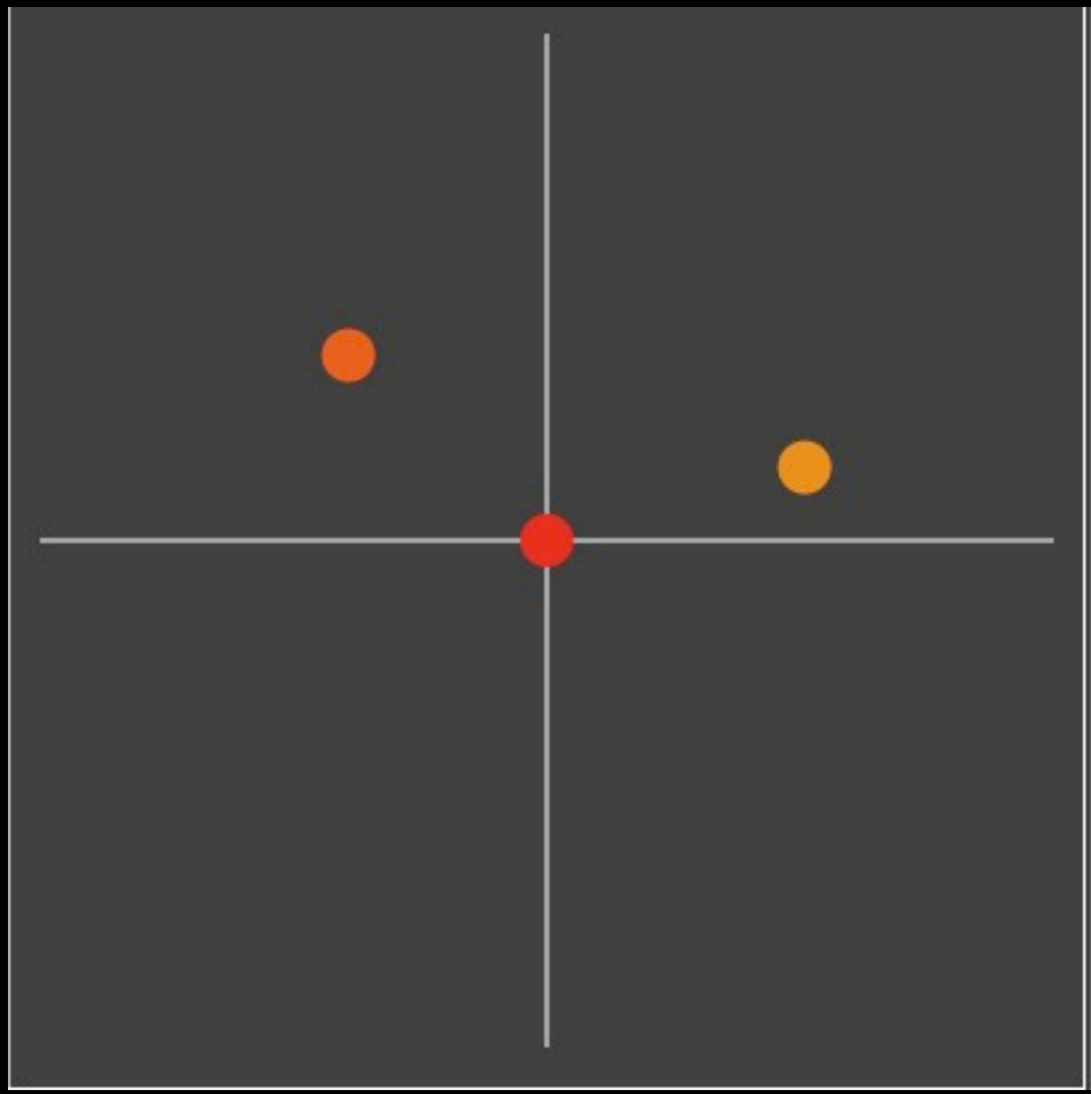


pupil

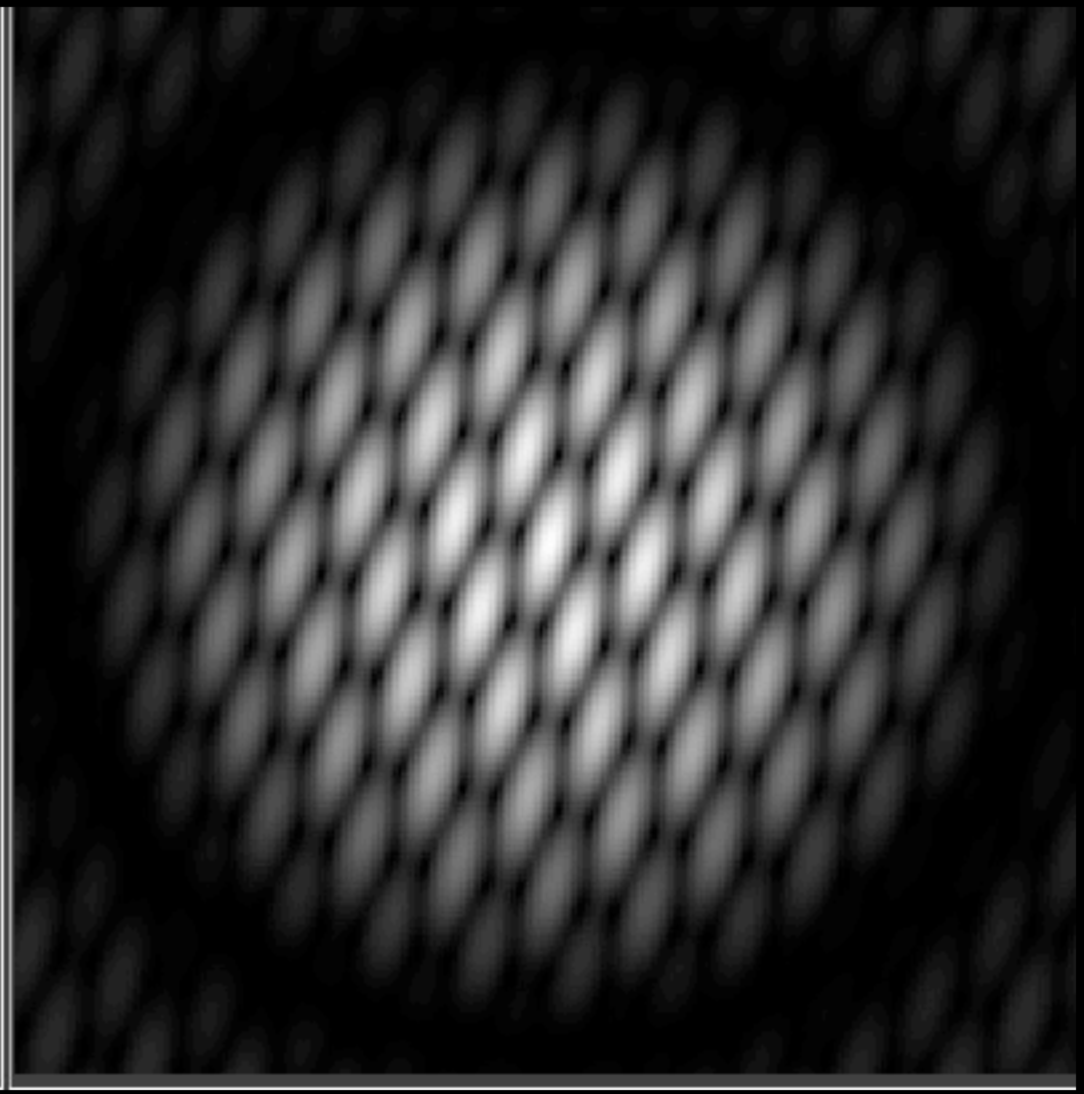


interferogram

More than two apertures?

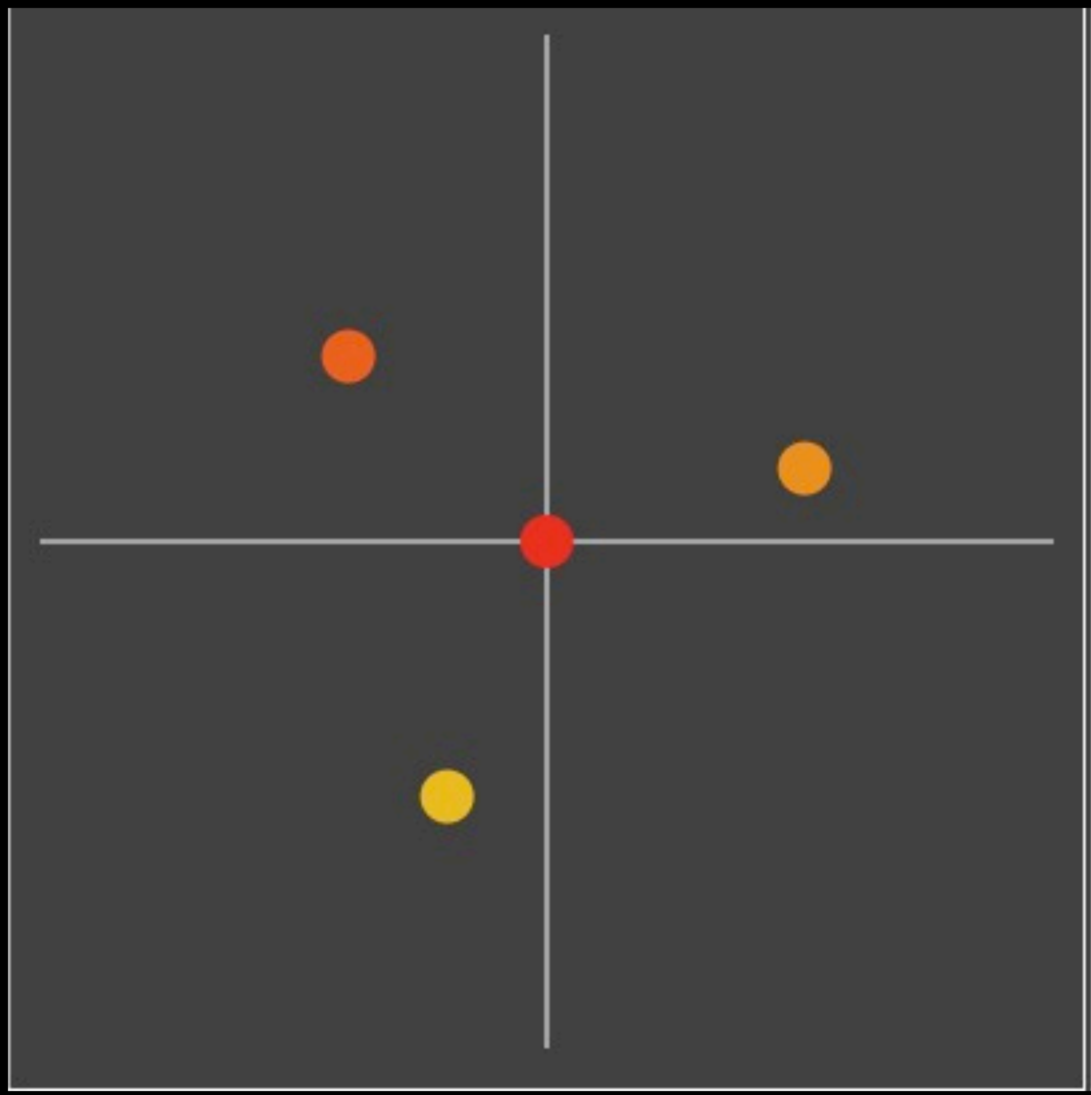


pupil

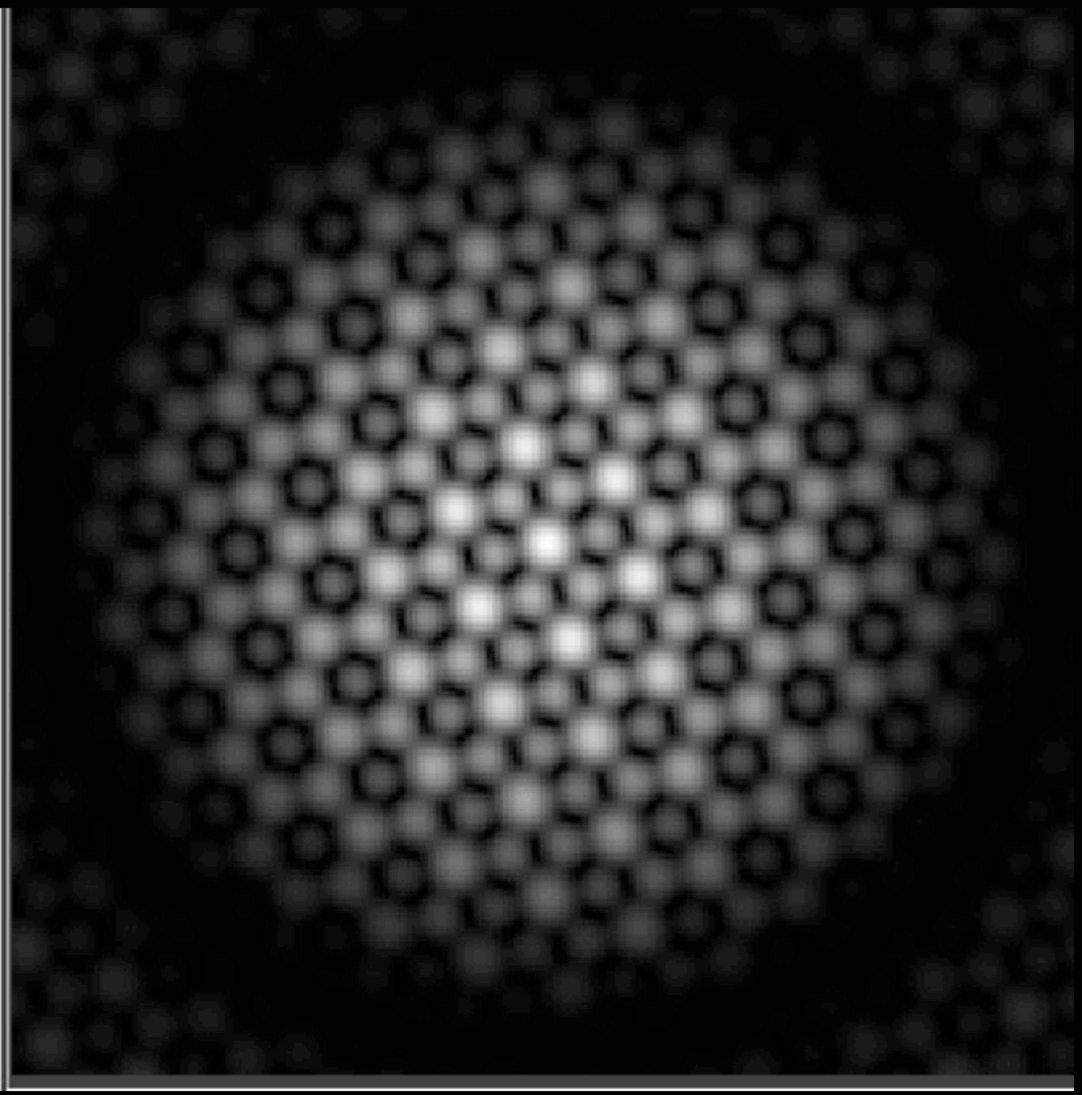


interferogram

More than two apertures?

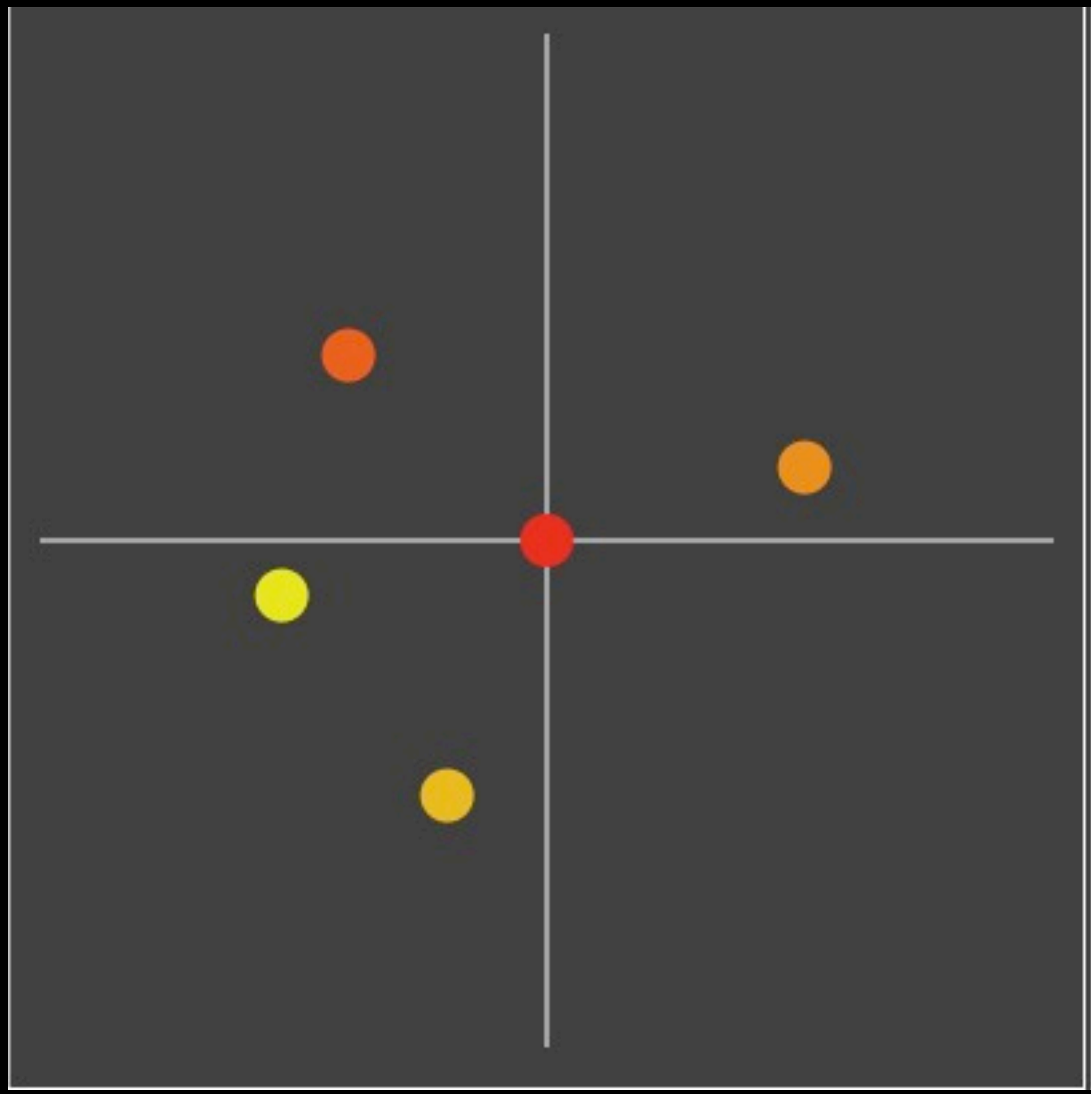


pupil

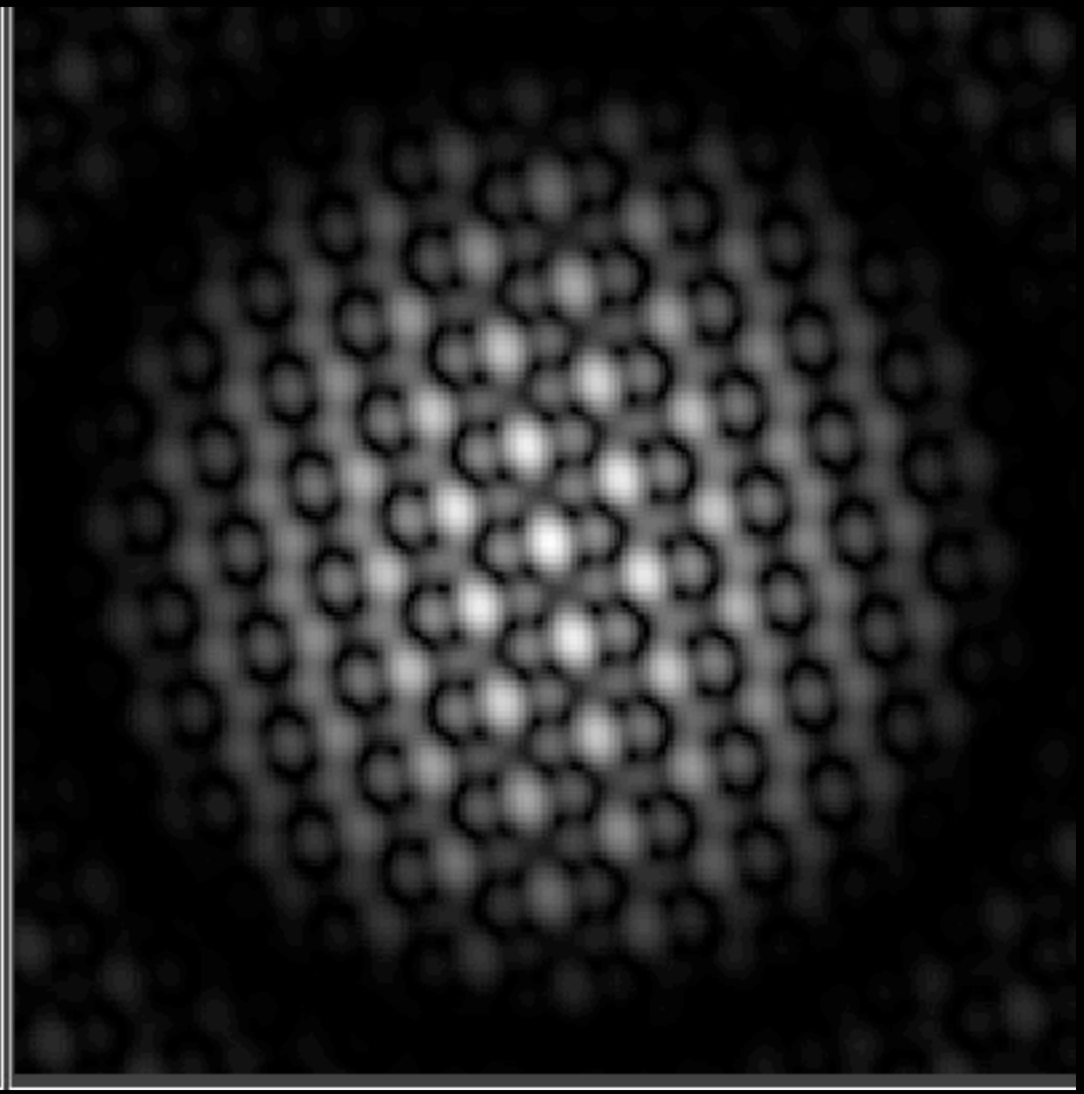


interferogram

More than two apertures?

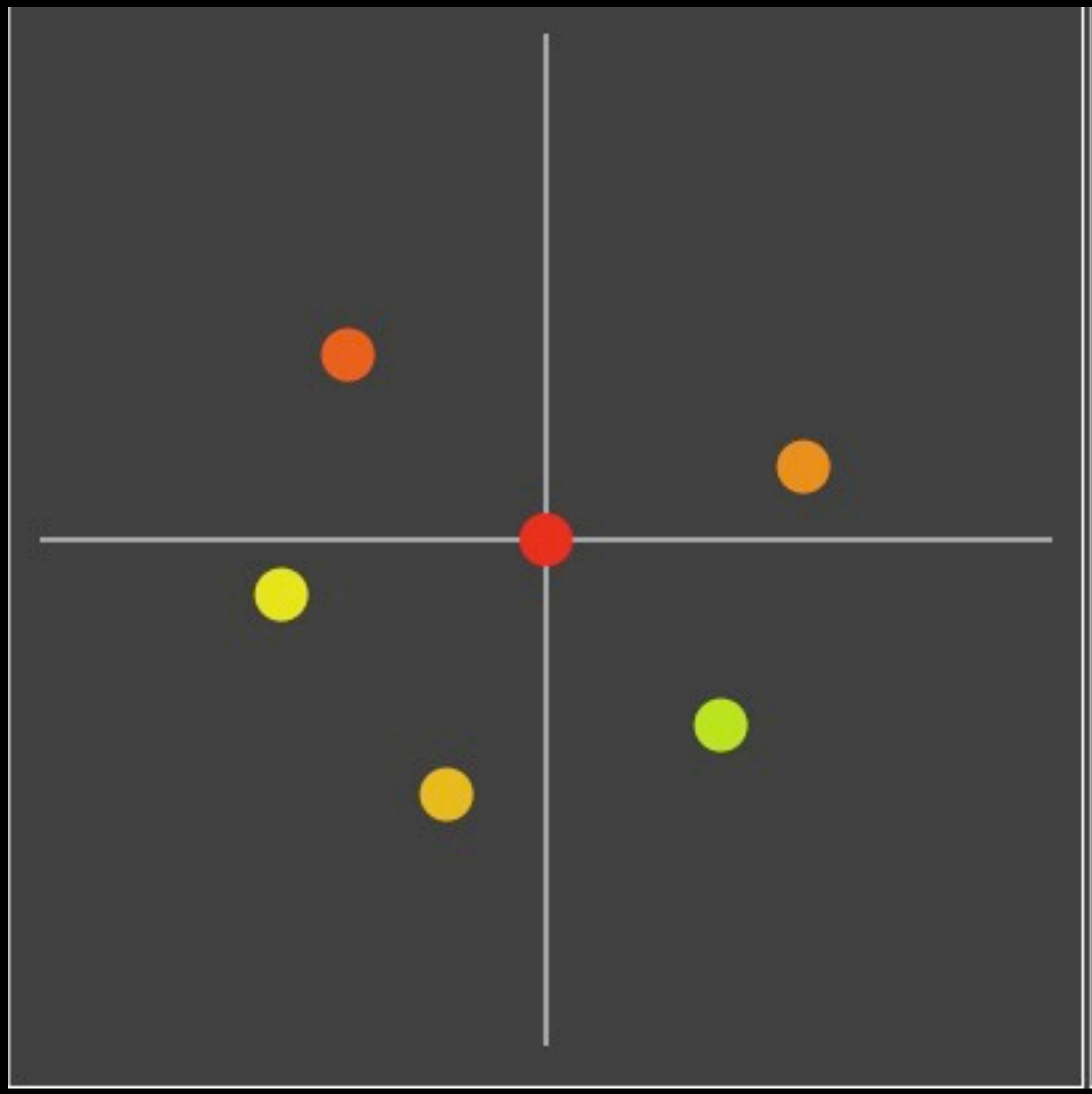


pupil

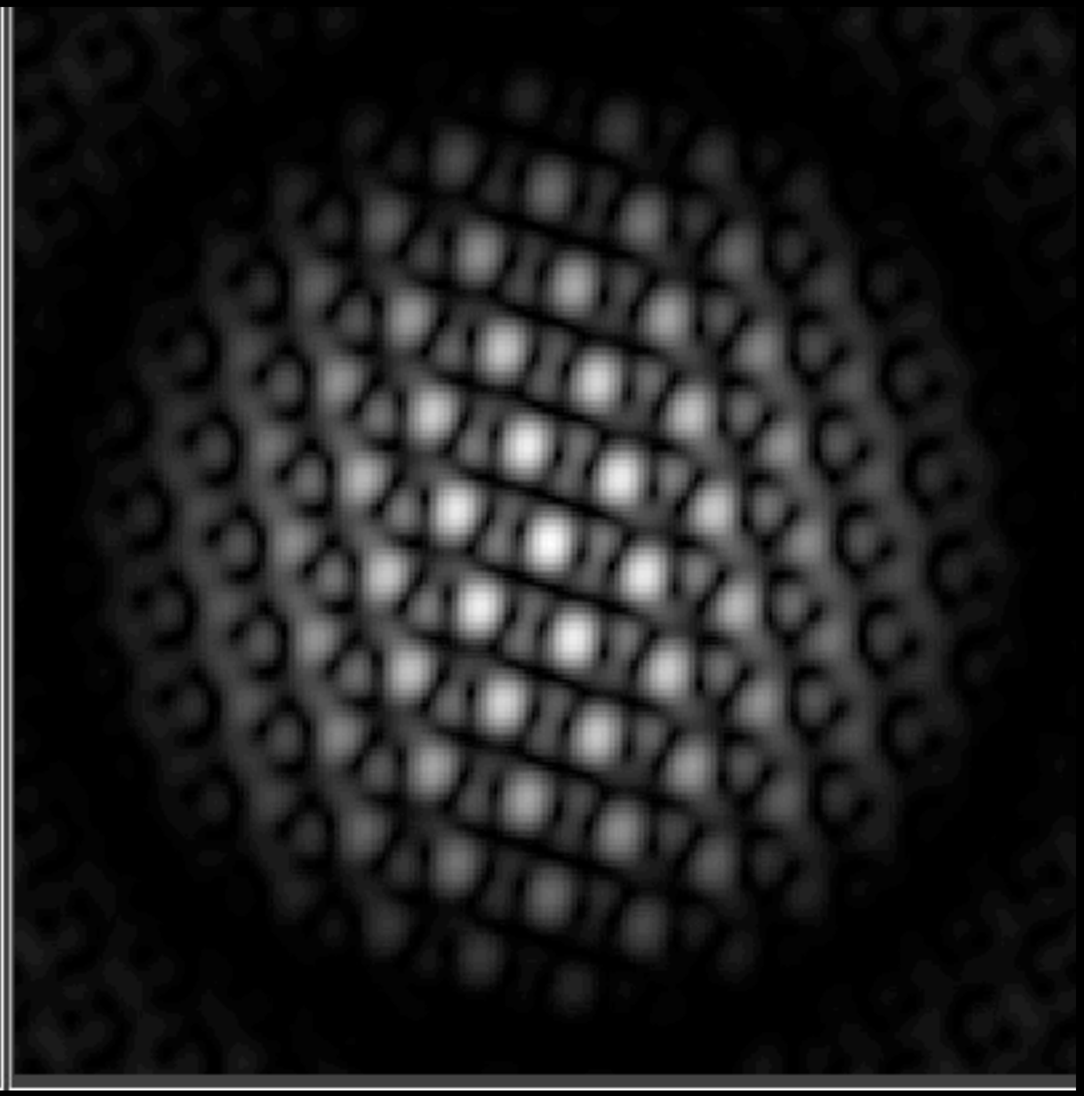


interferogram

More than two apertures?

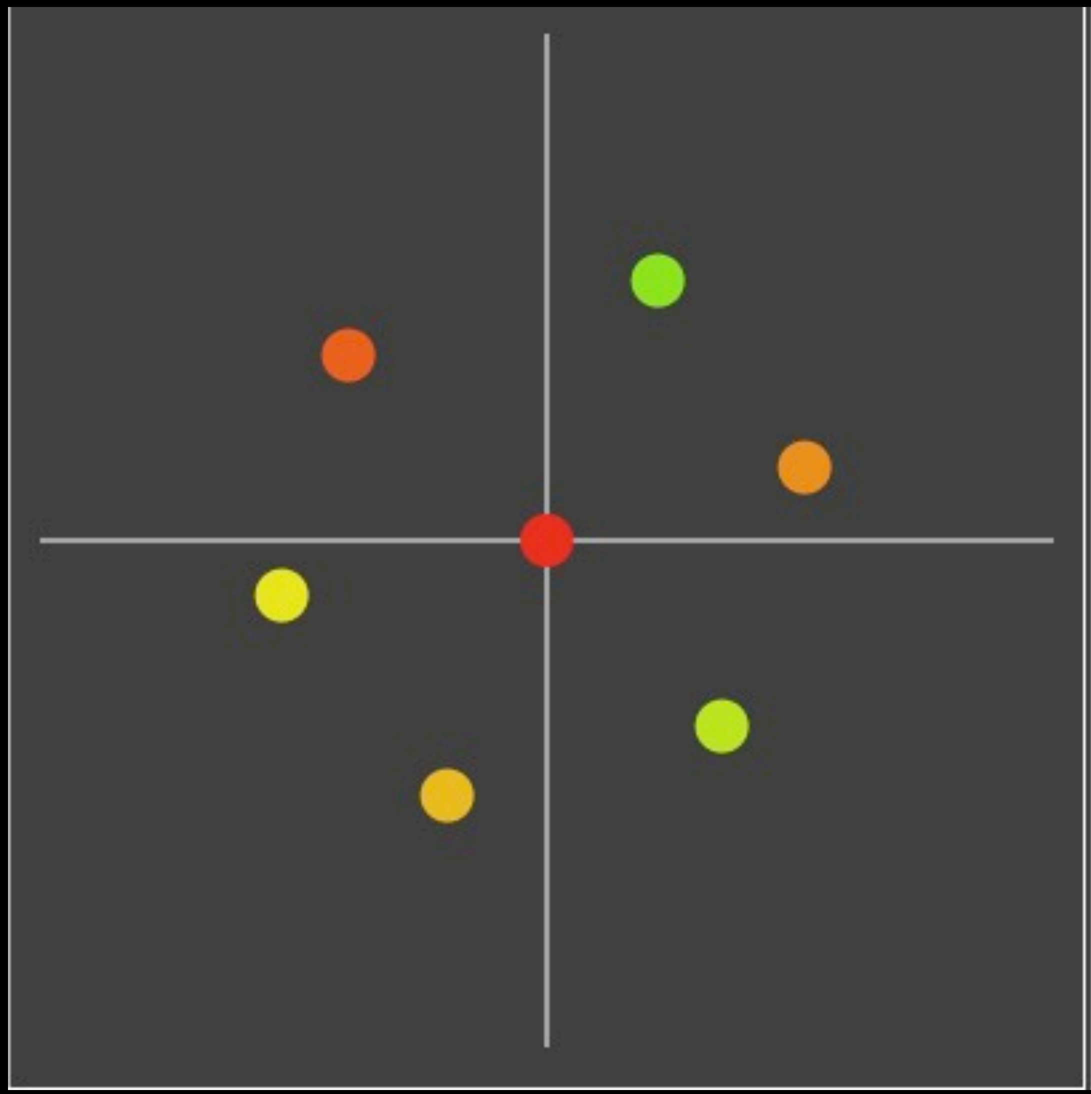


pupil

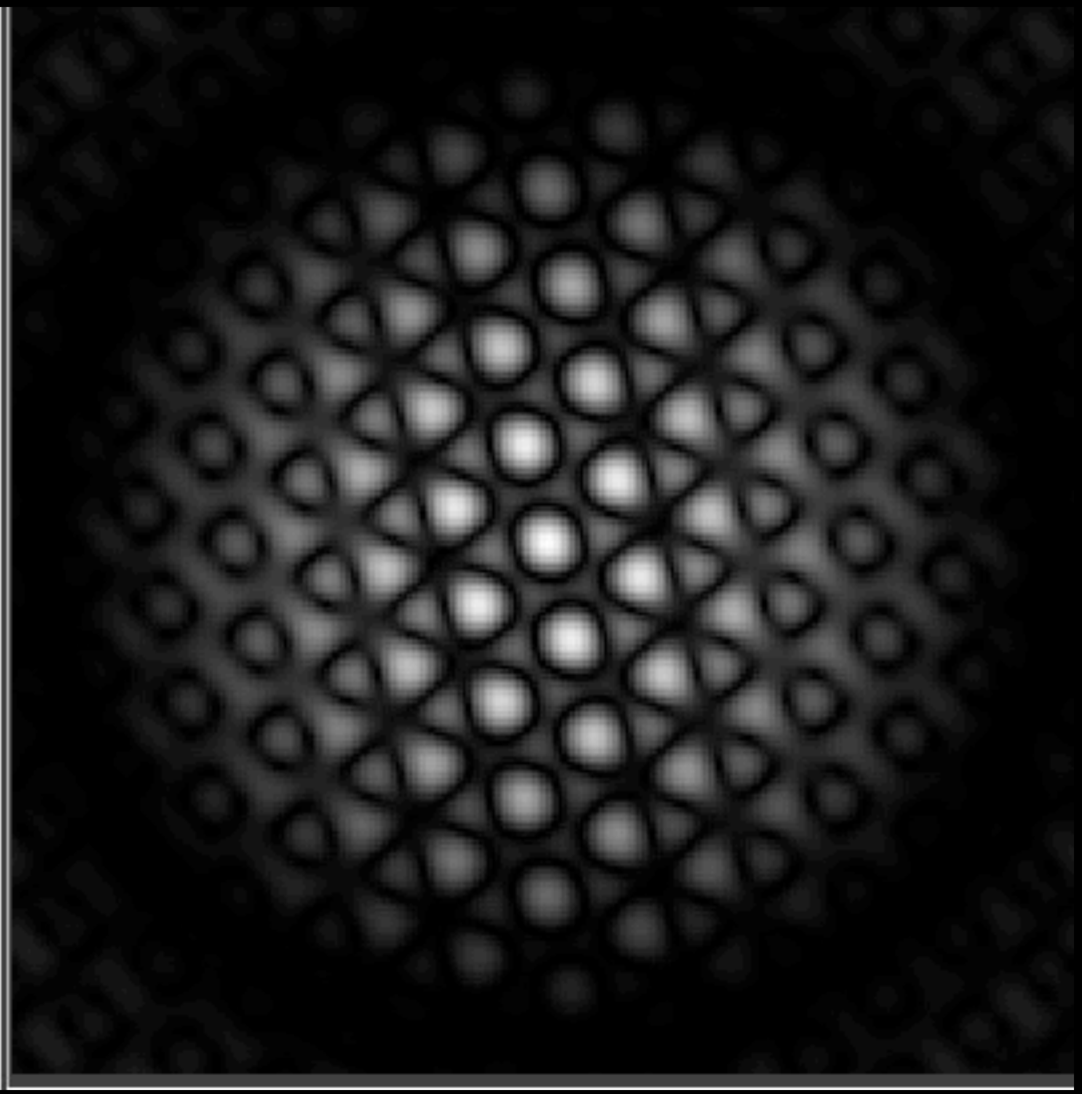


interferogram

More than two apertures?

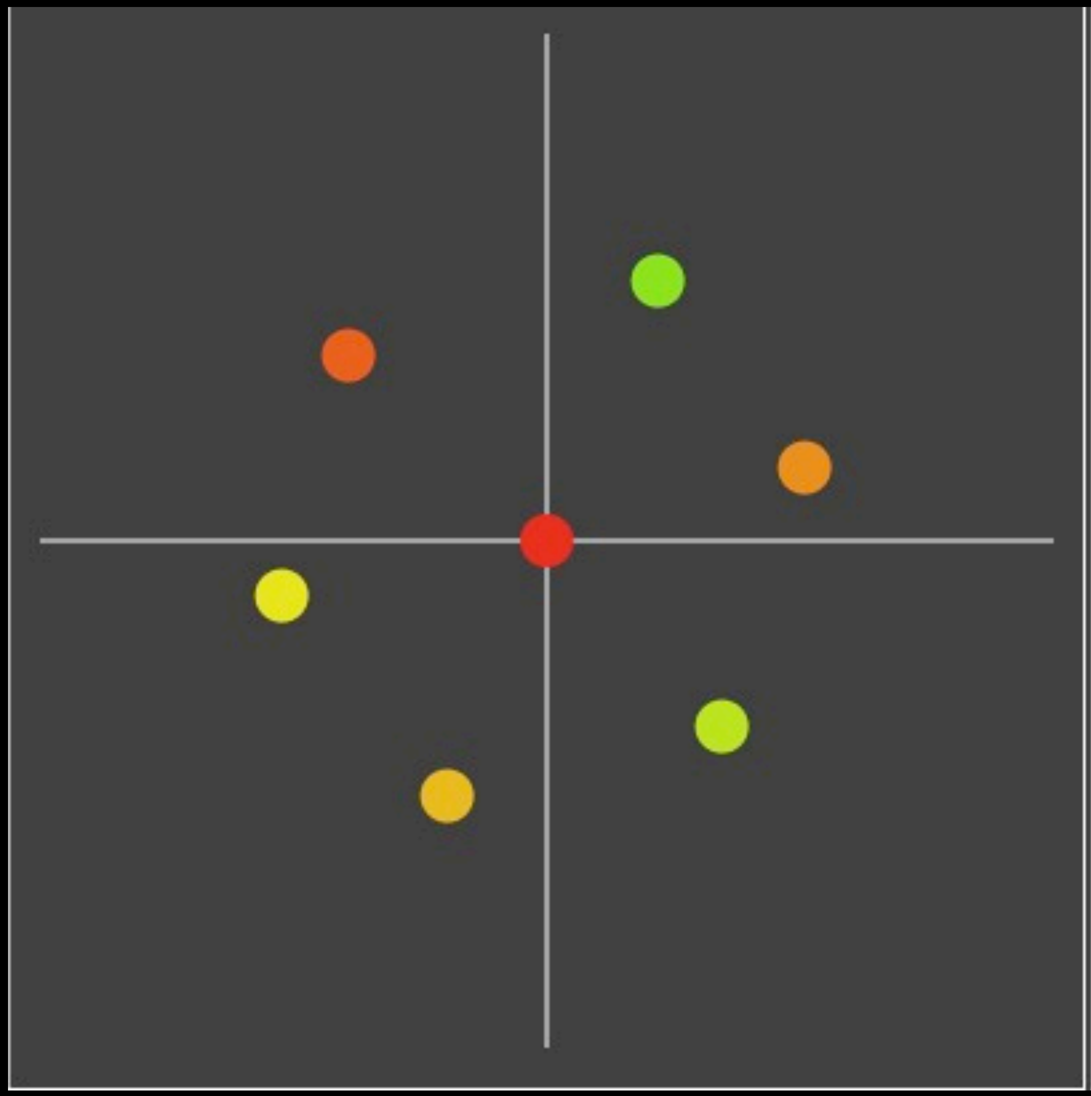


pupil

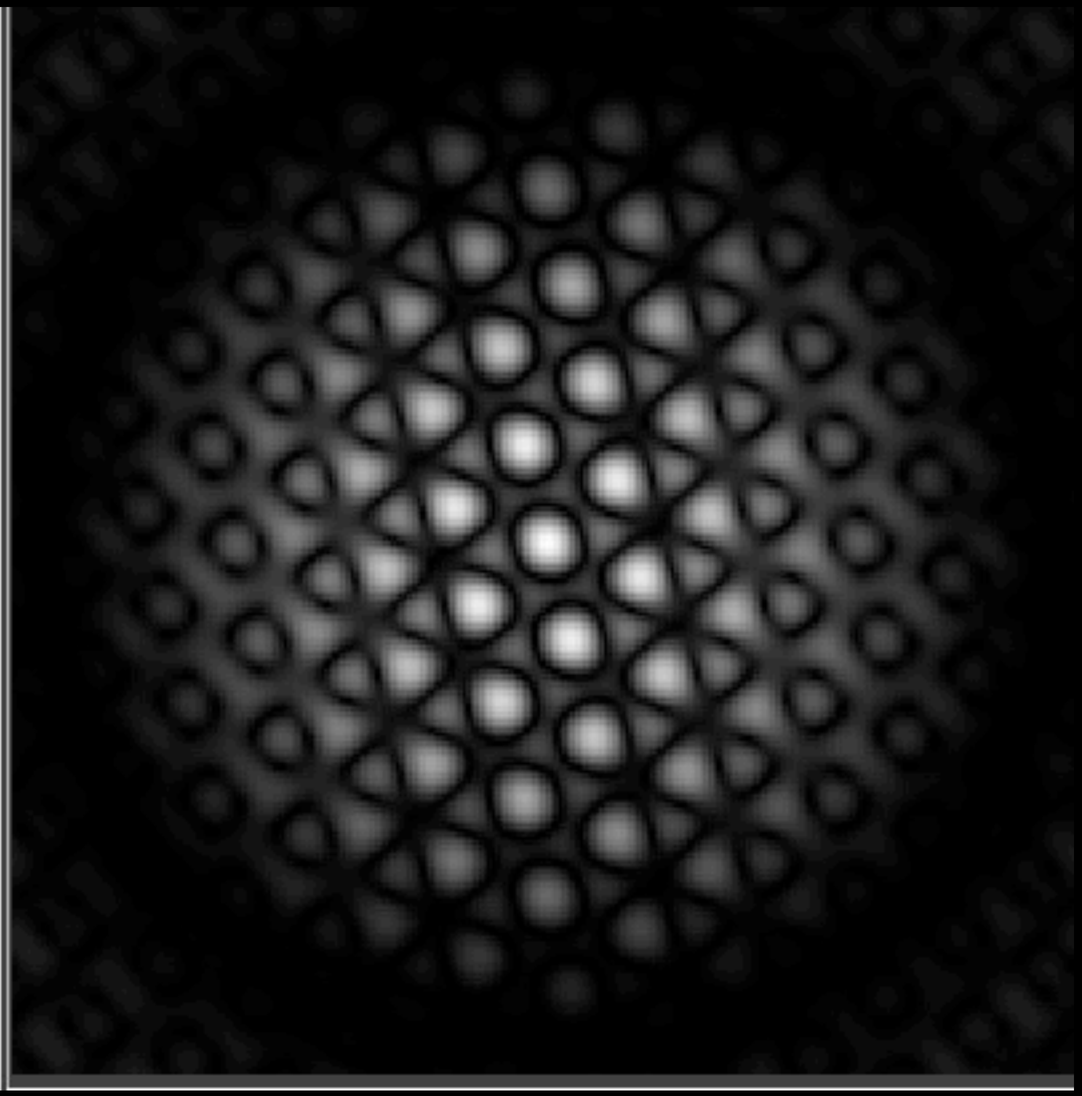


interferogram

More than two apertures?



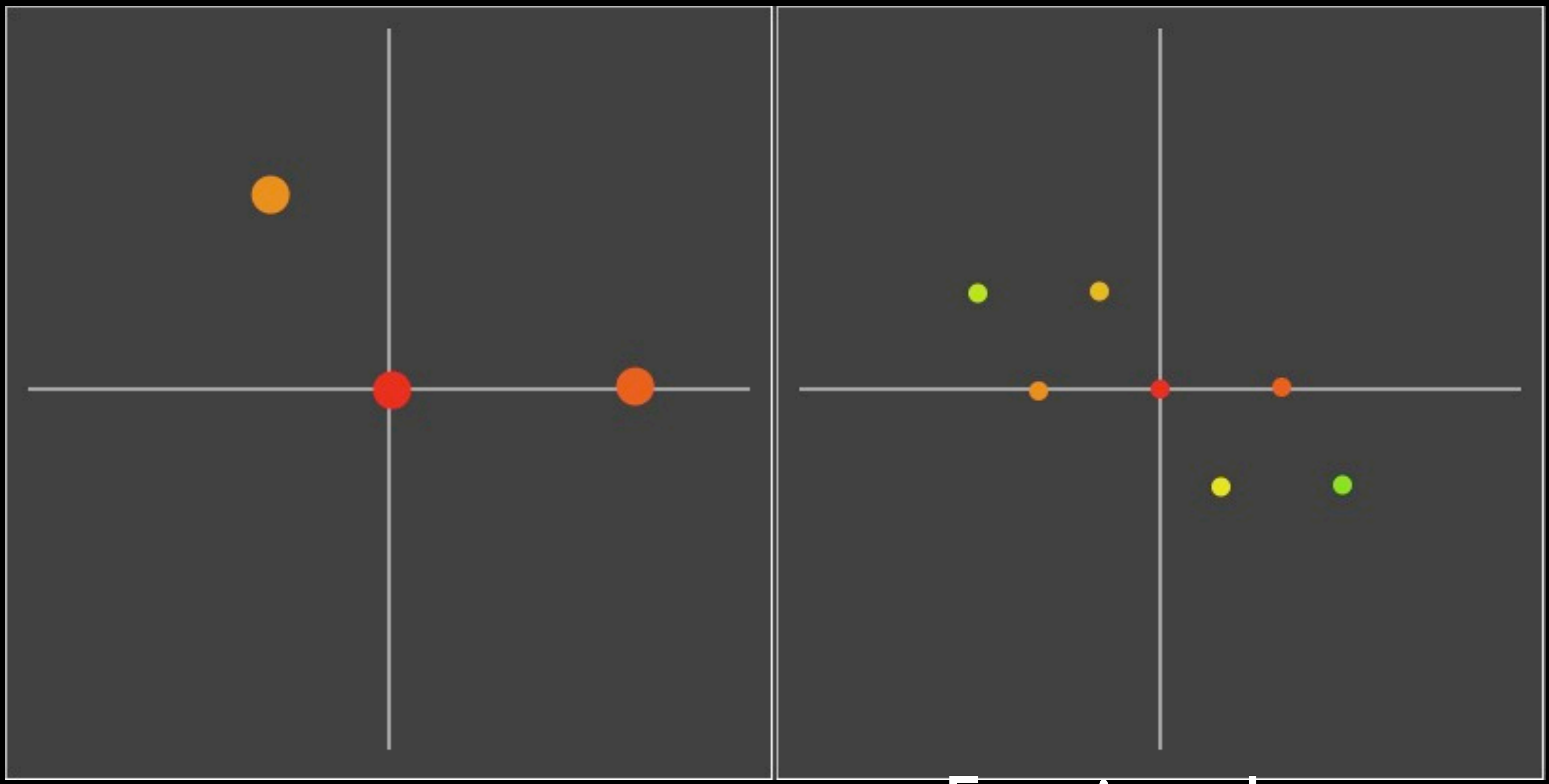
pupil



interferogram

interpretation is a bit harder... but in the Fourier space...

Analysis in the Fourier plane

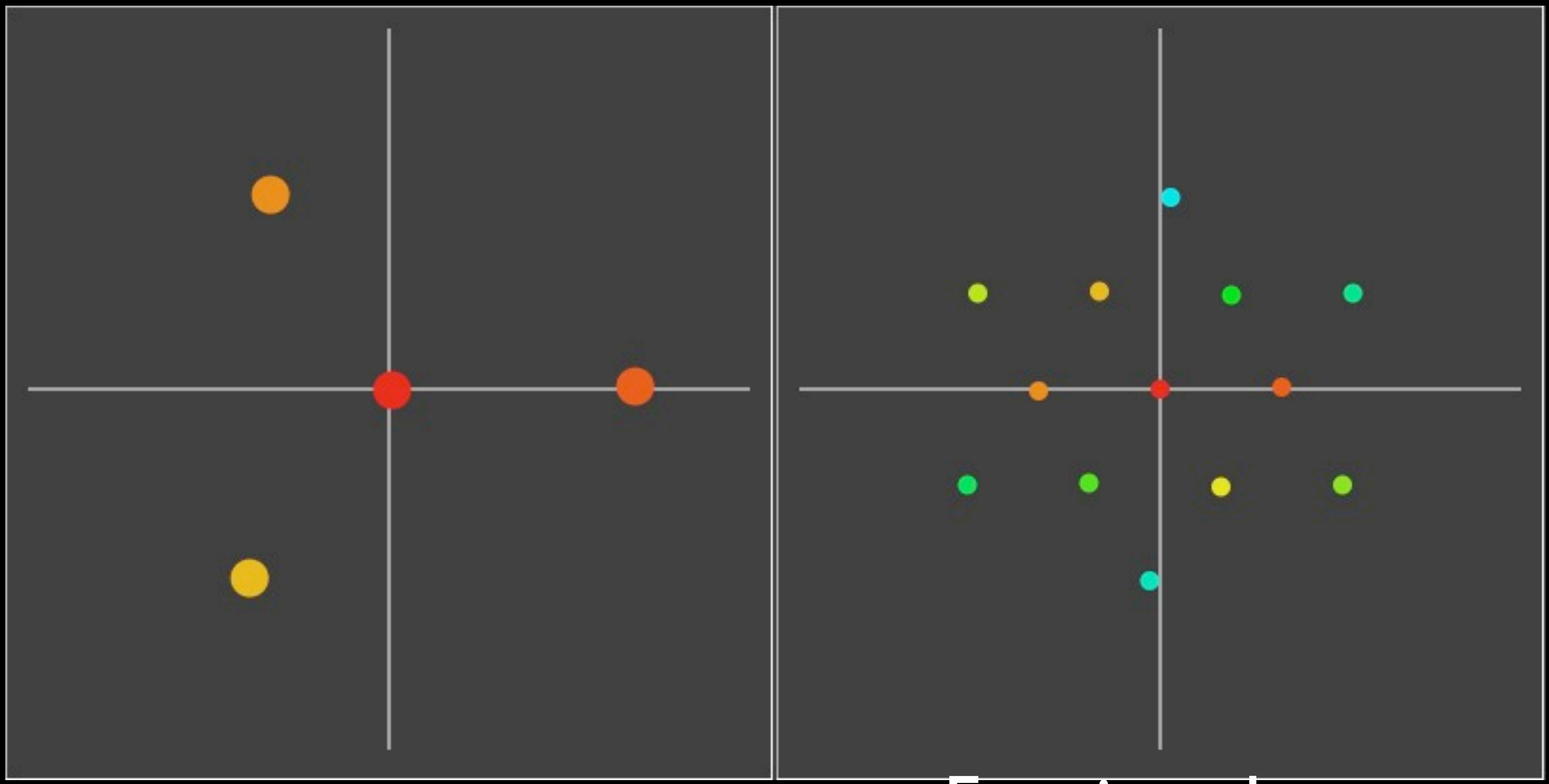


pupil

Fourier plane
(uv-plane)

At each uv-point, one **visibility** + one **phase**

Analysis in the Fourier plane



pupil

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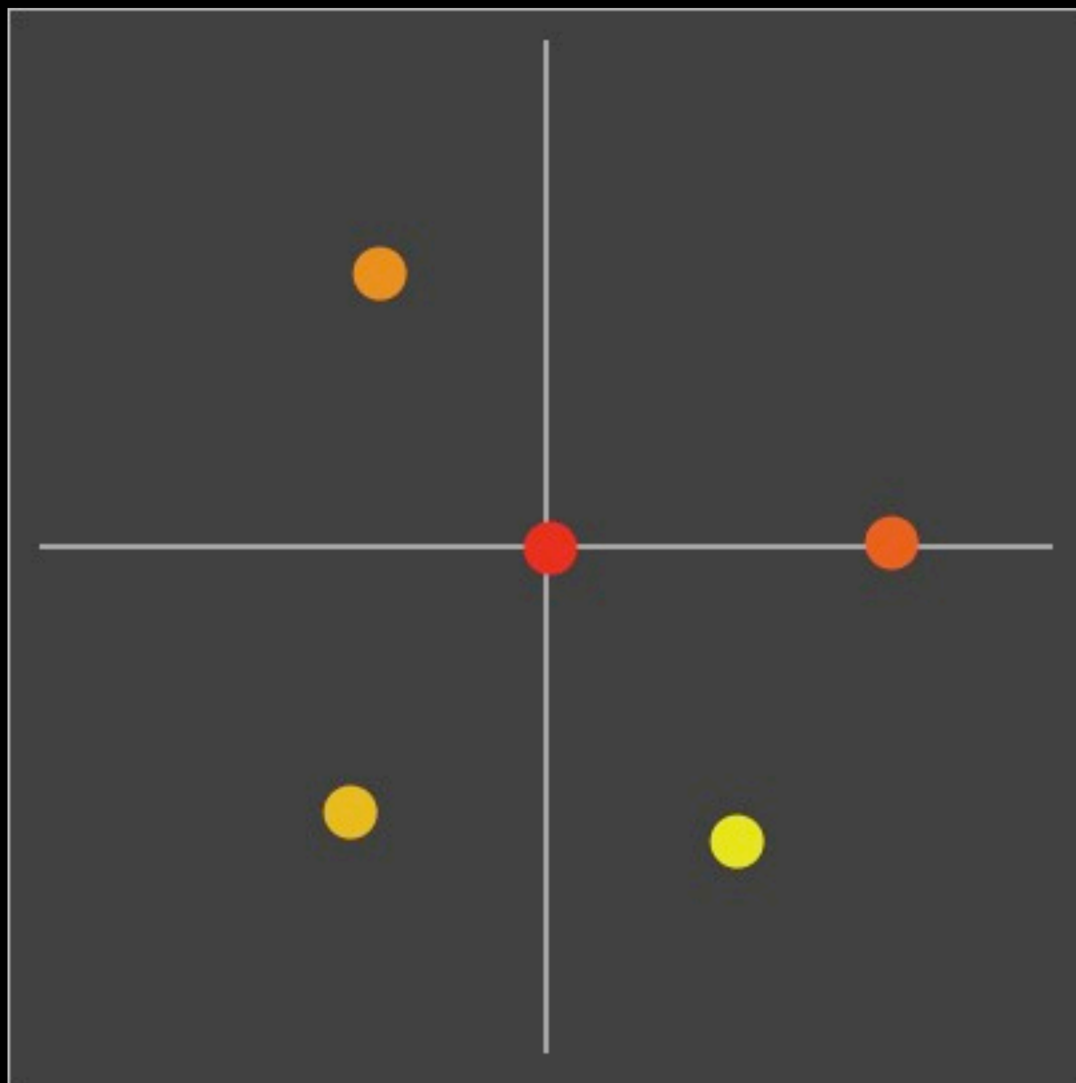
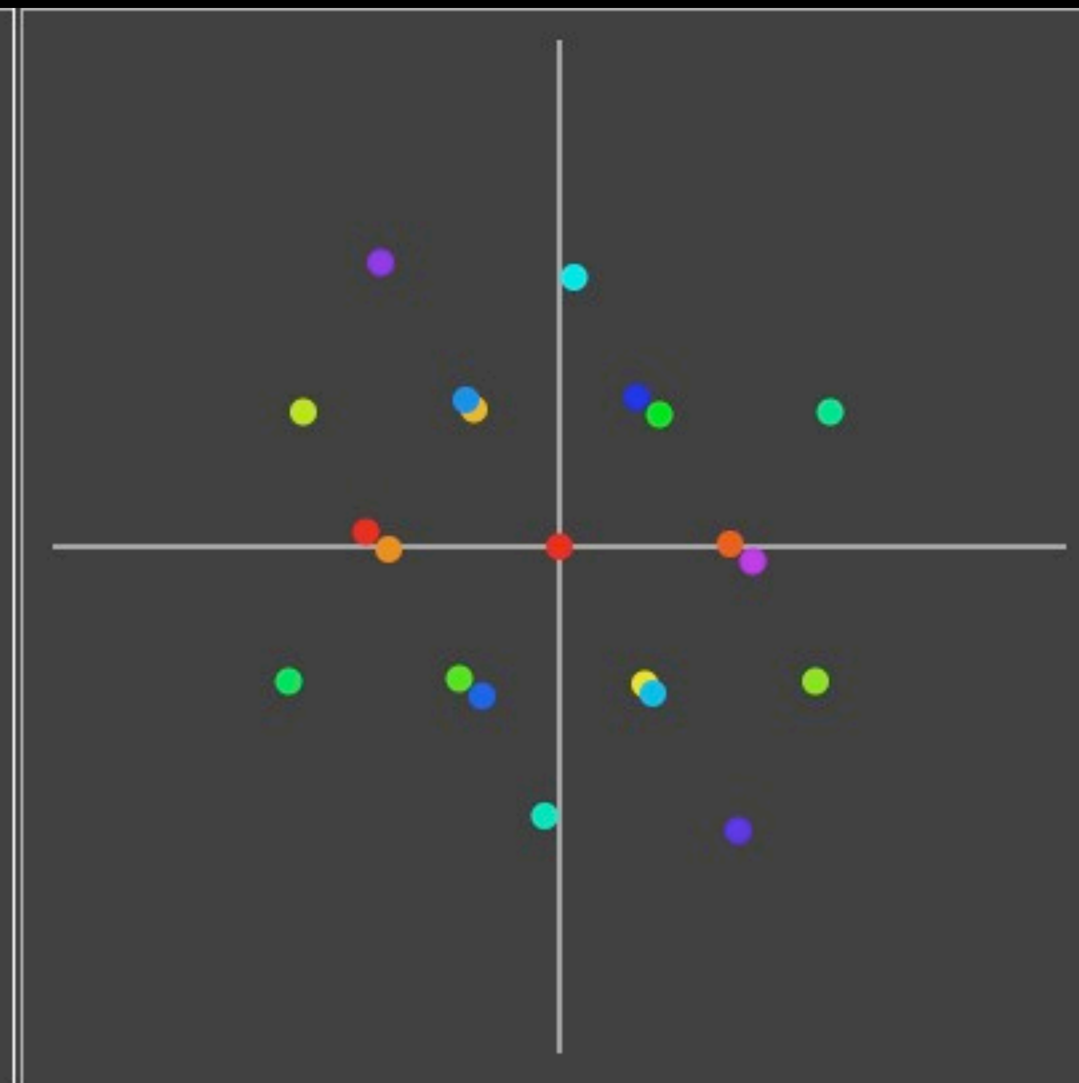
Analysis in the Fourier plane



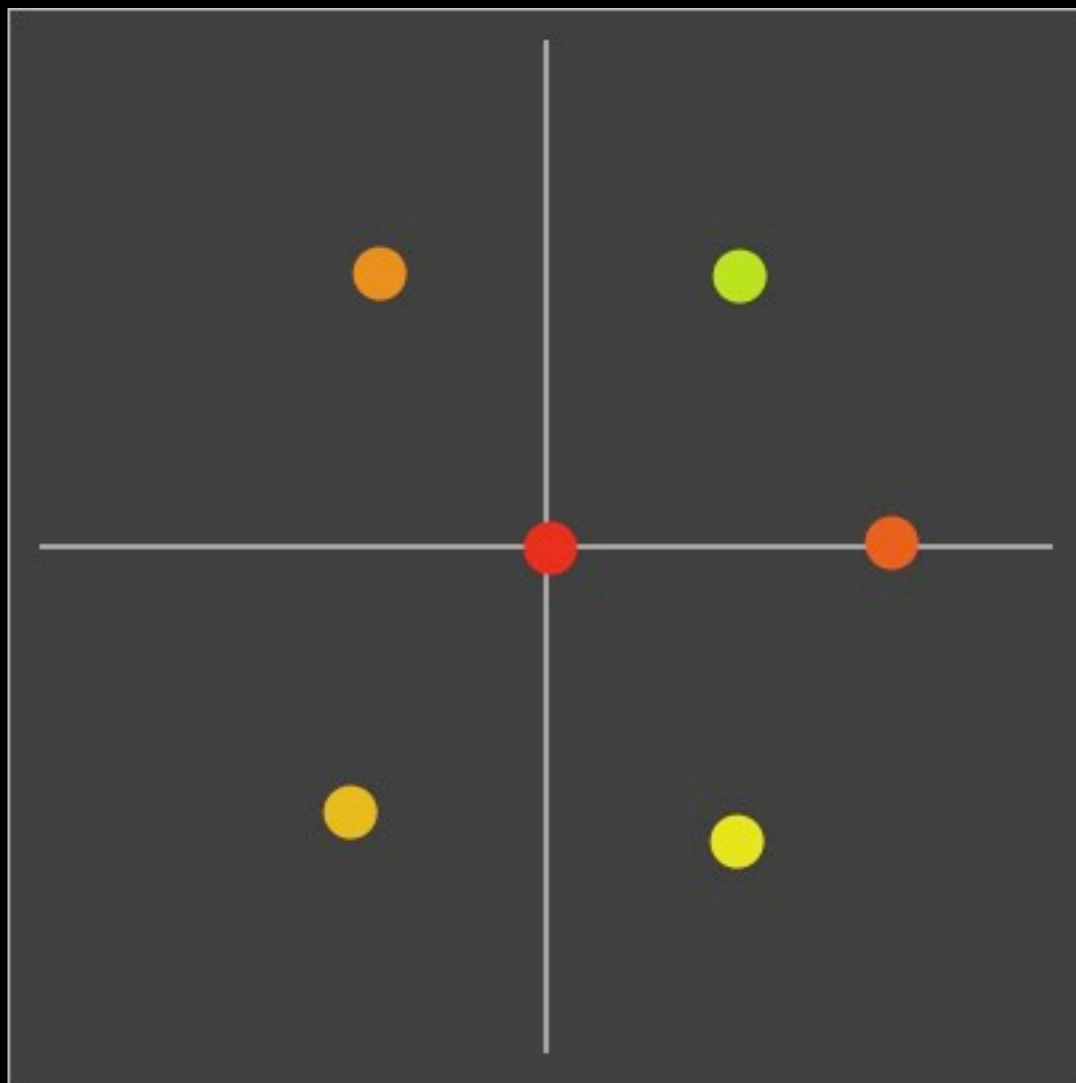
pupil



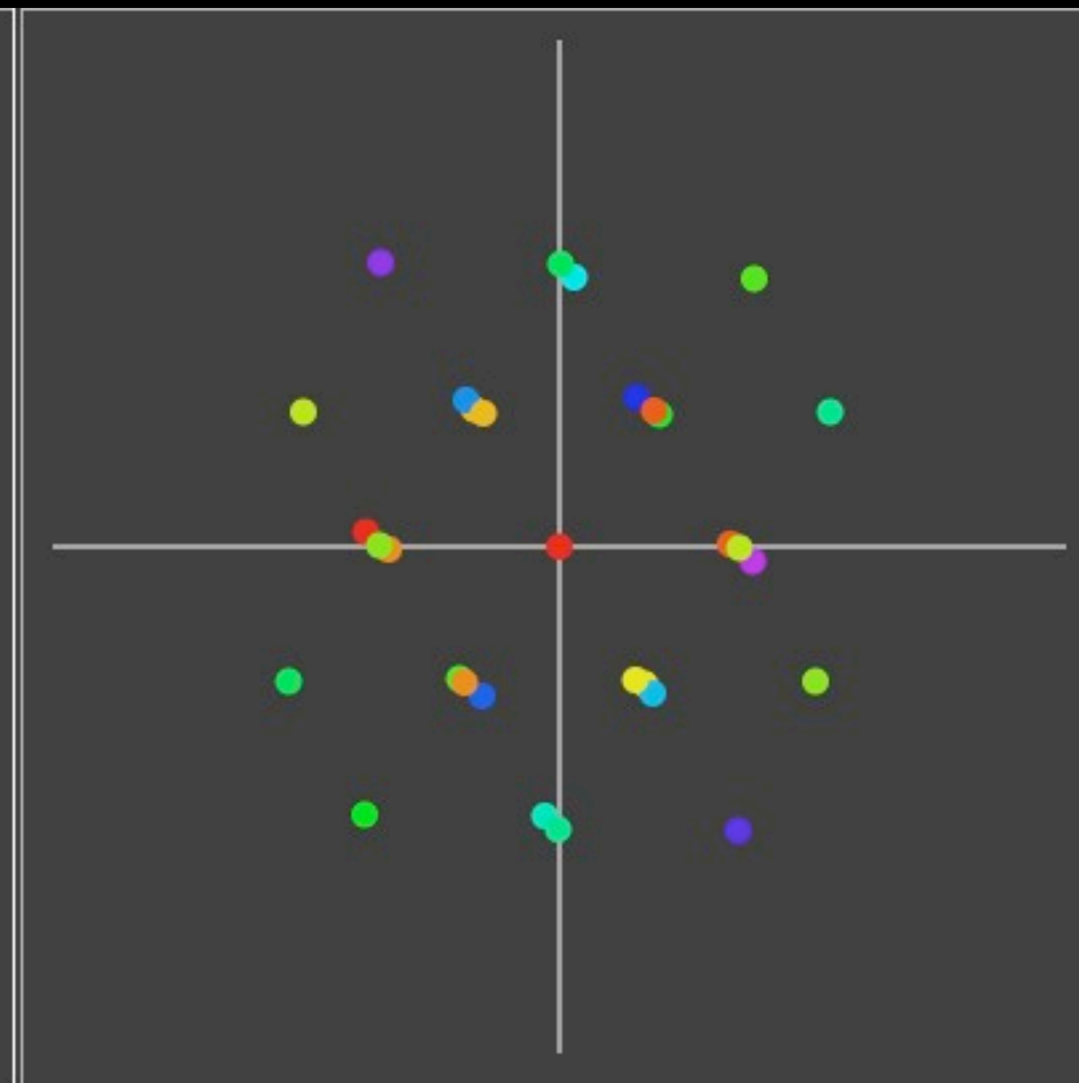
Fourier plane
(uv-plane)

At each uv-point, one **visibility** + one **phase**

Analysis in the Fourier plane



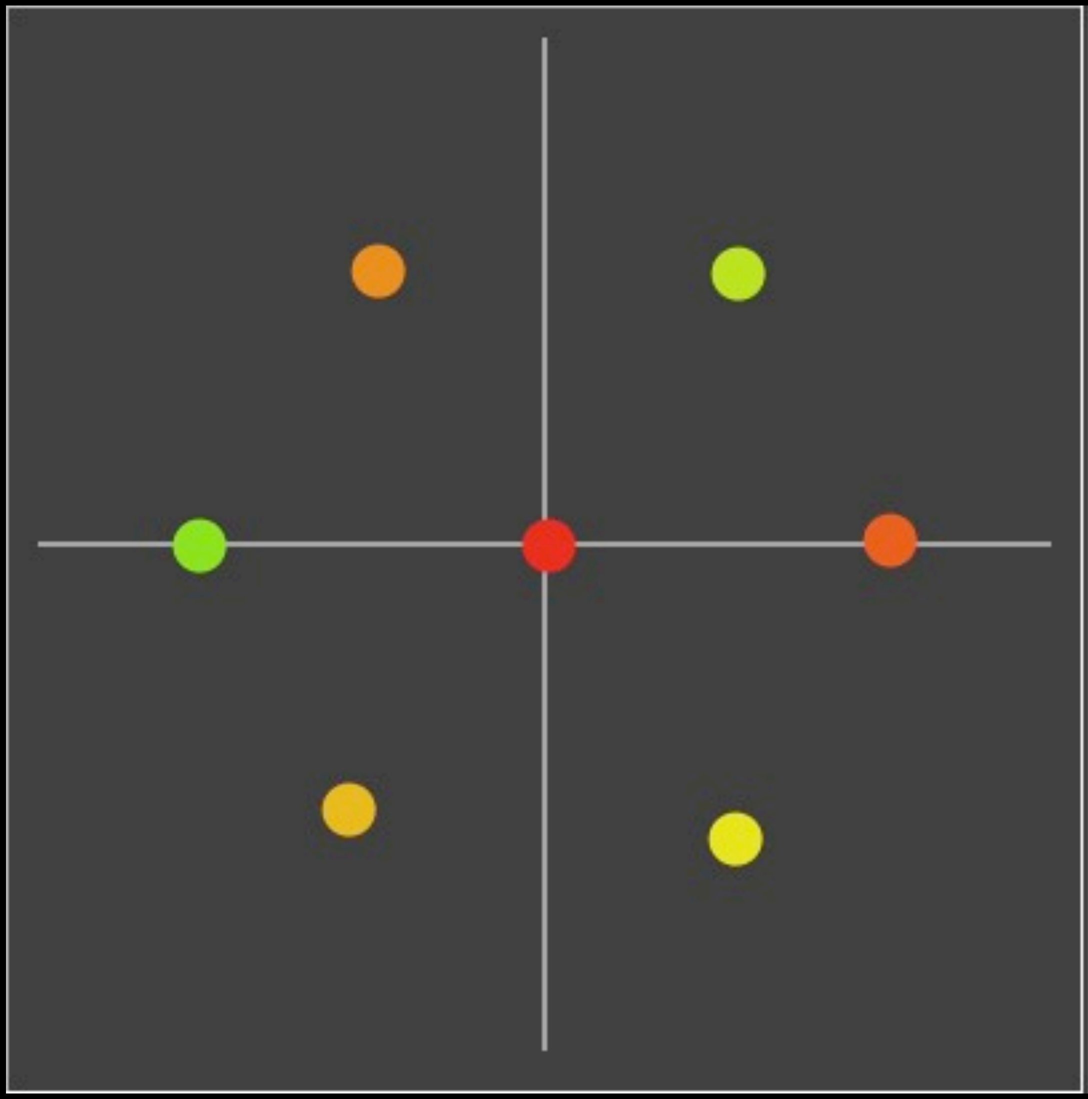
pupil



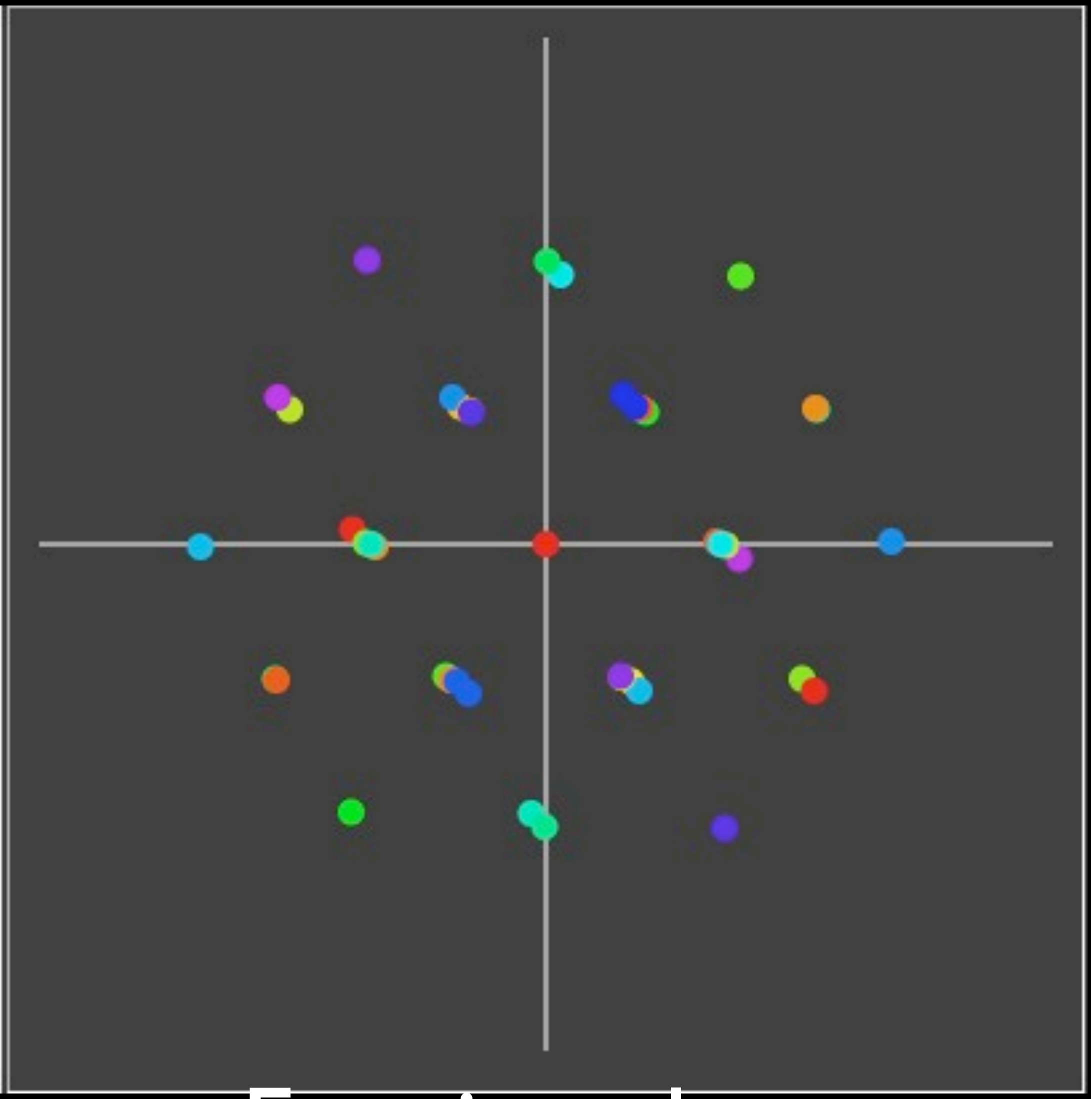
Fourier plane
(uv-plane)

At each uv-point, one **visibility** + one **phase**

Analysis in the Fourier plane



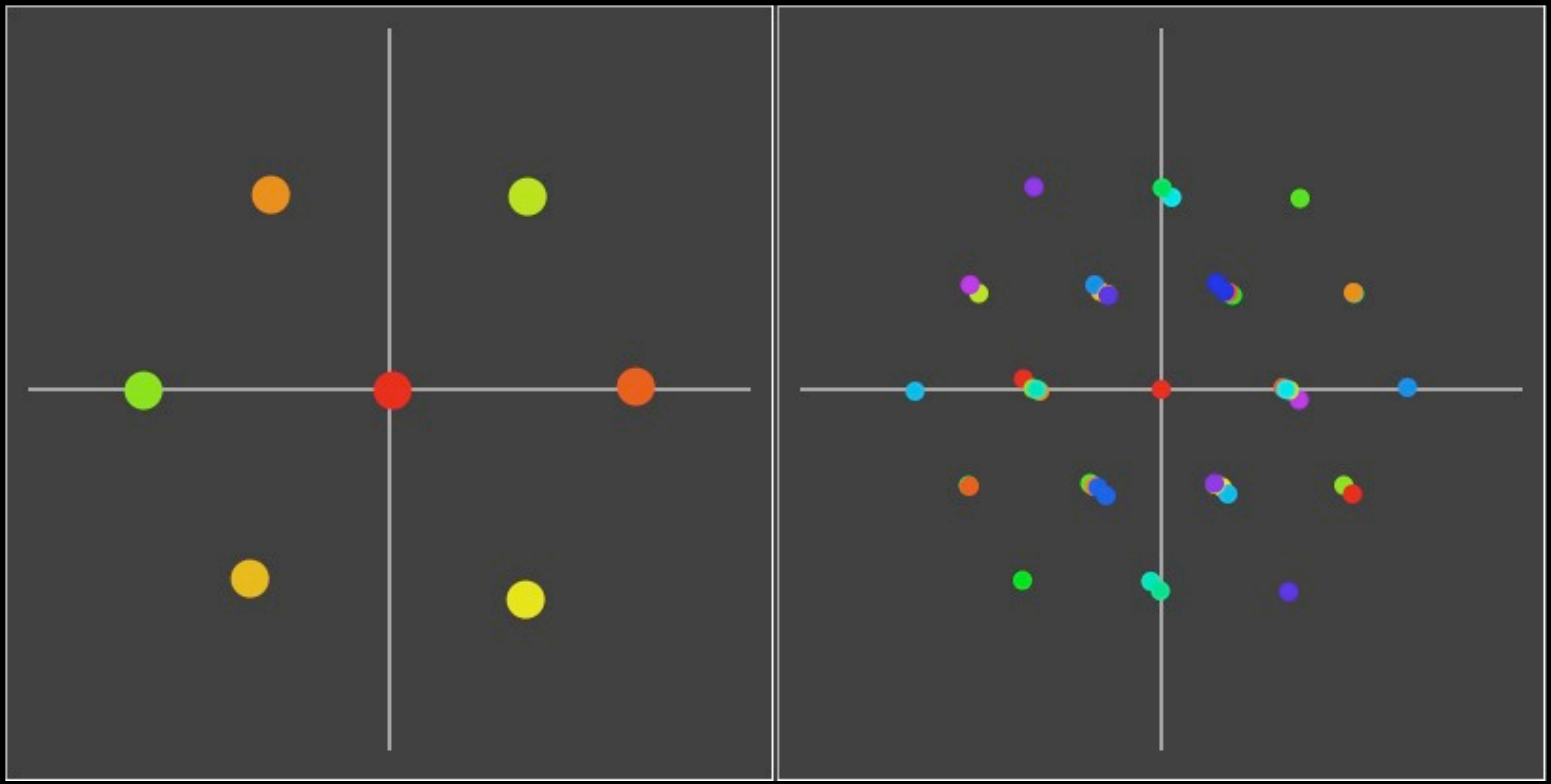
pupil



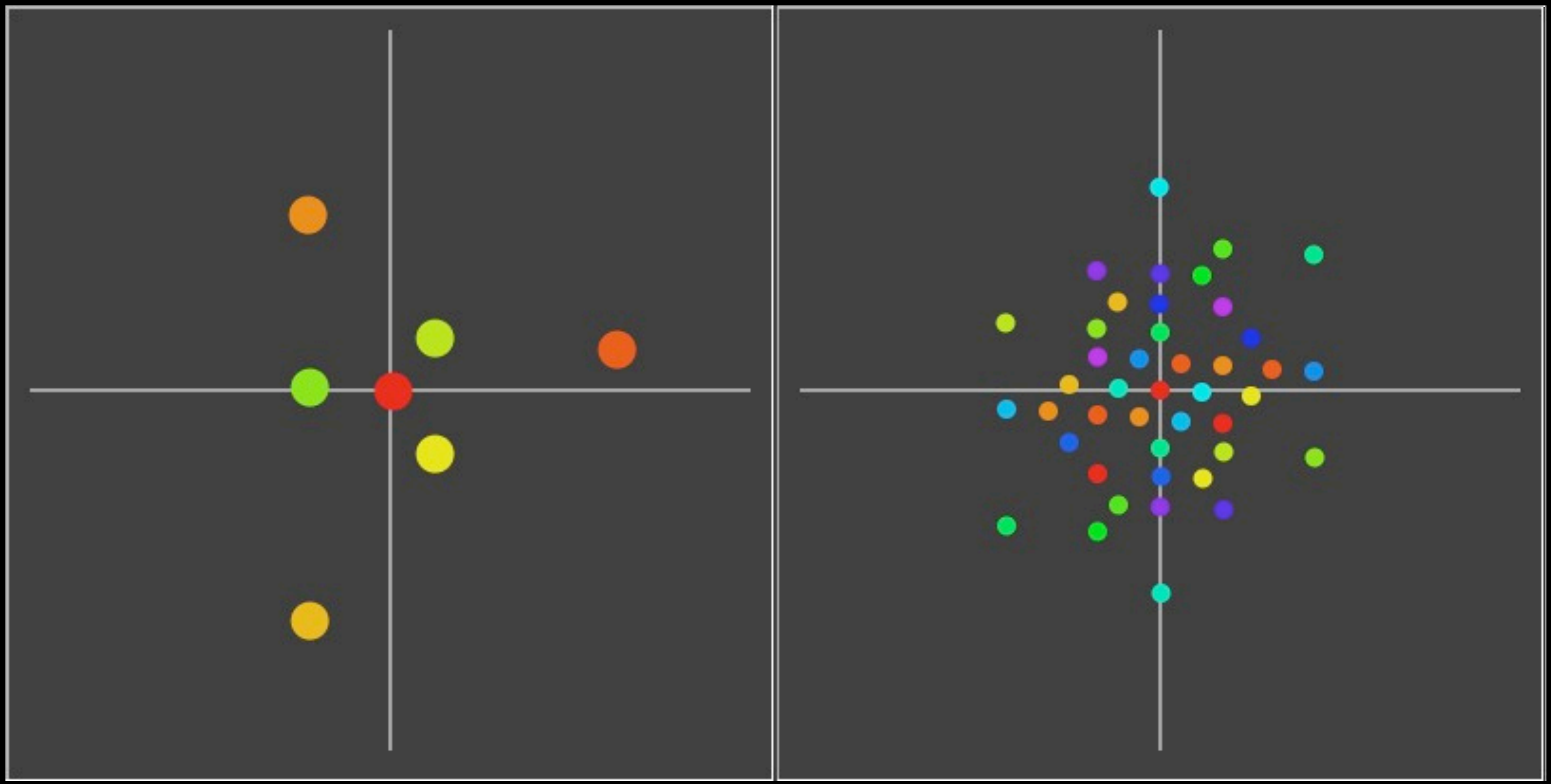
Fourier plane
(uv-plane)

At each uv-point, one **visibility** + one **phase**

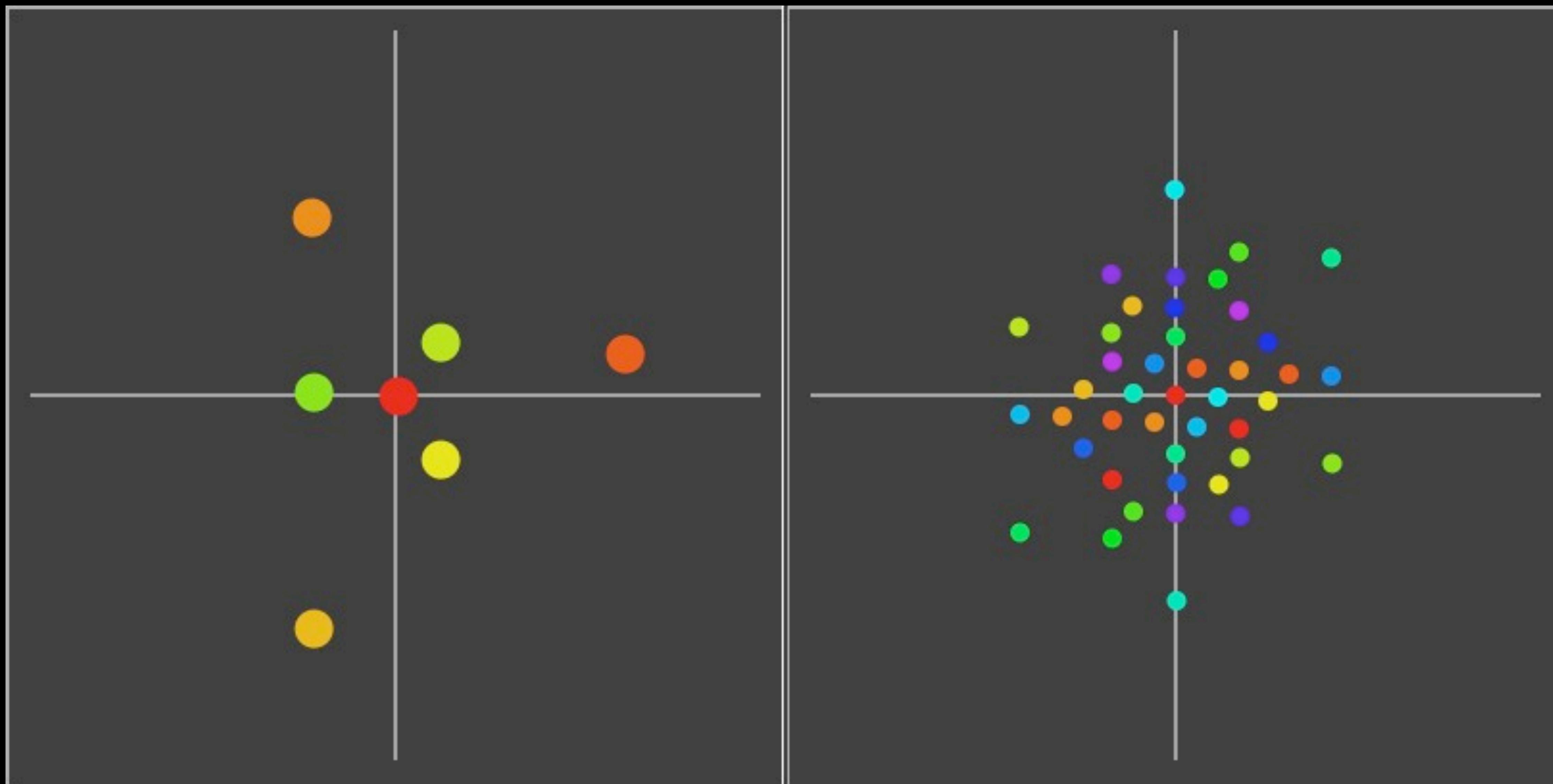
The mask geometry matters



The mask geometry matters

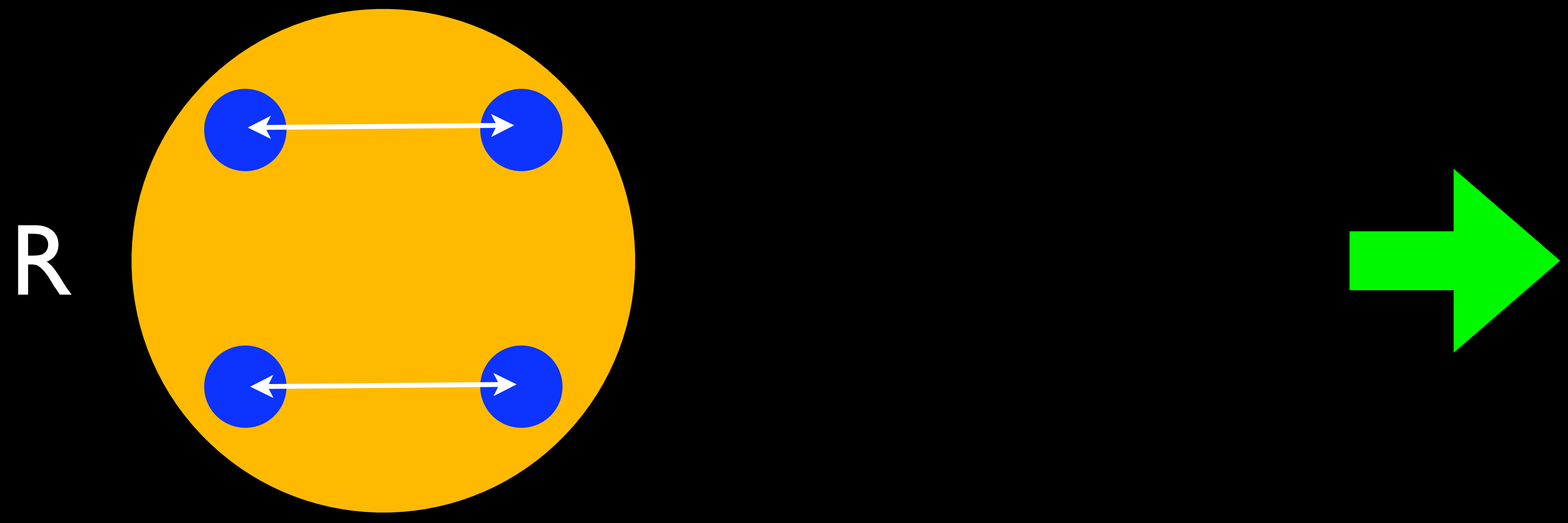


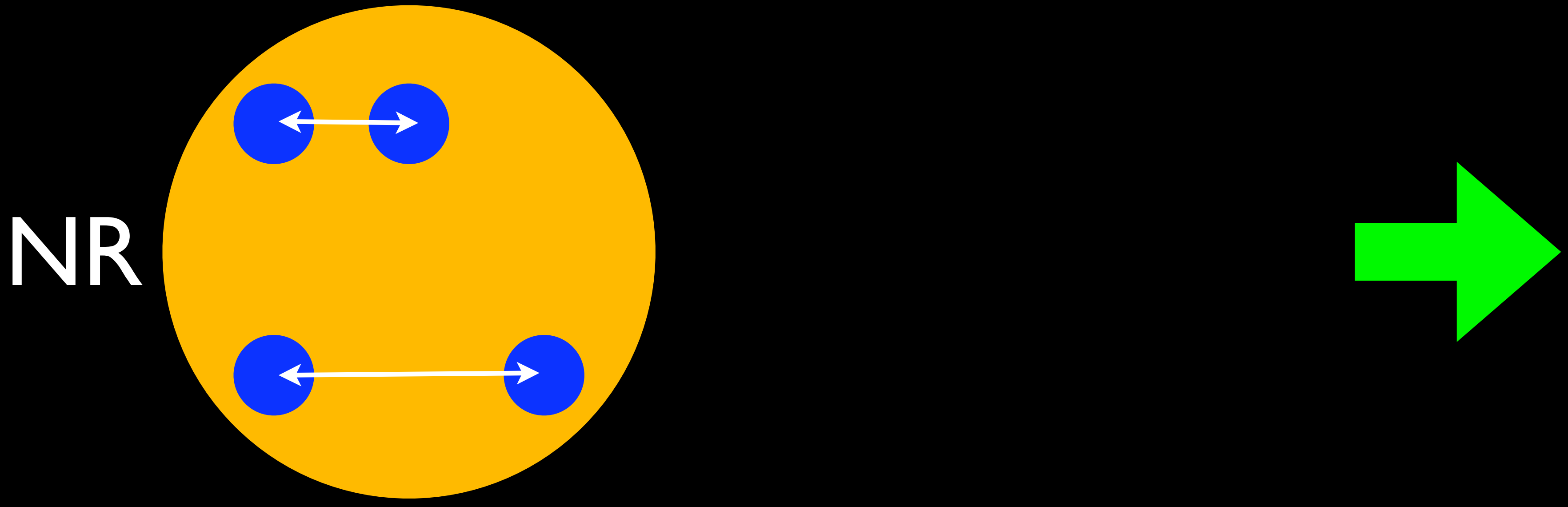
The mask geometry matters



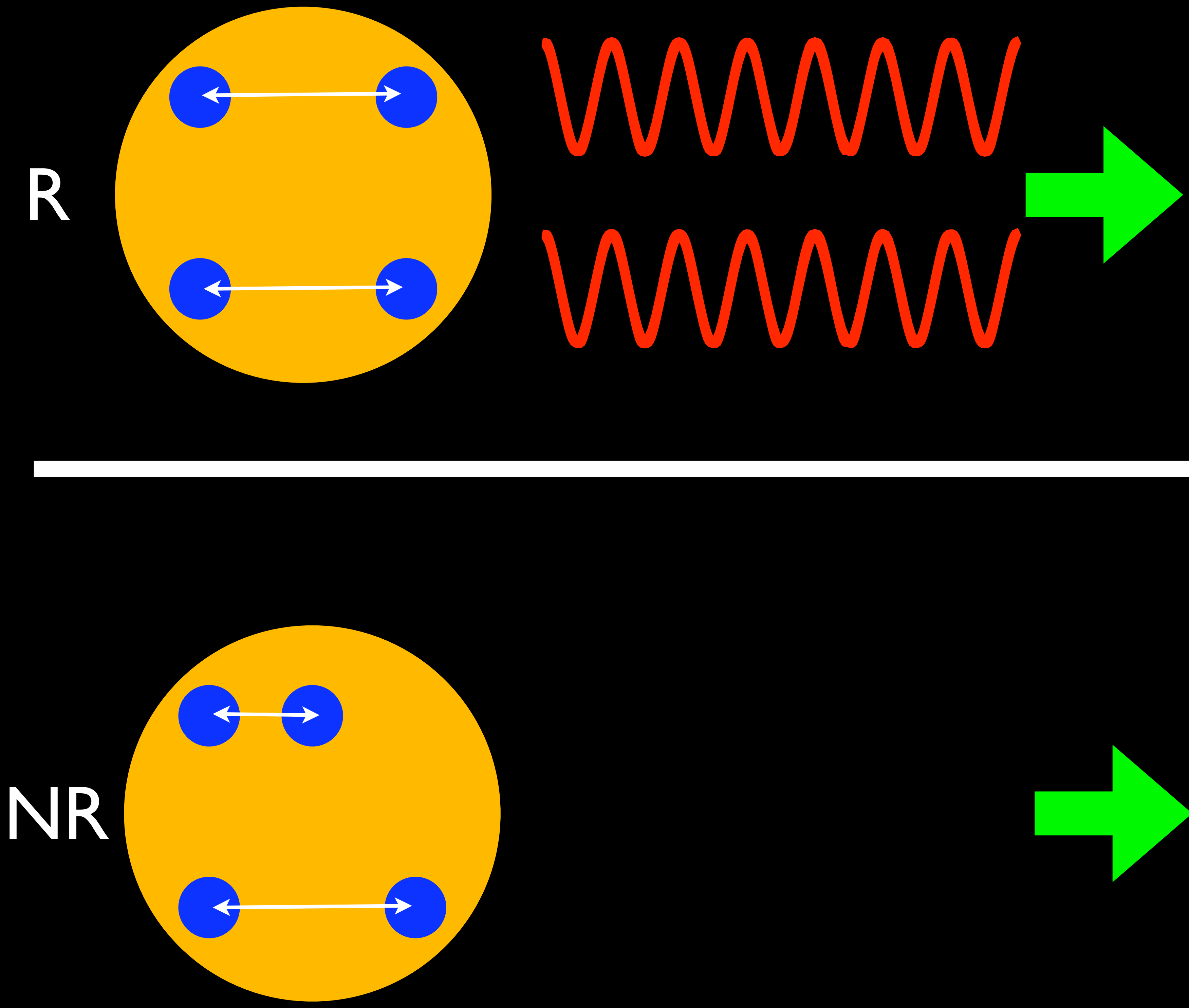
same number of apertures...
but more uv coverage (21 points instead of 9)

Redundancy

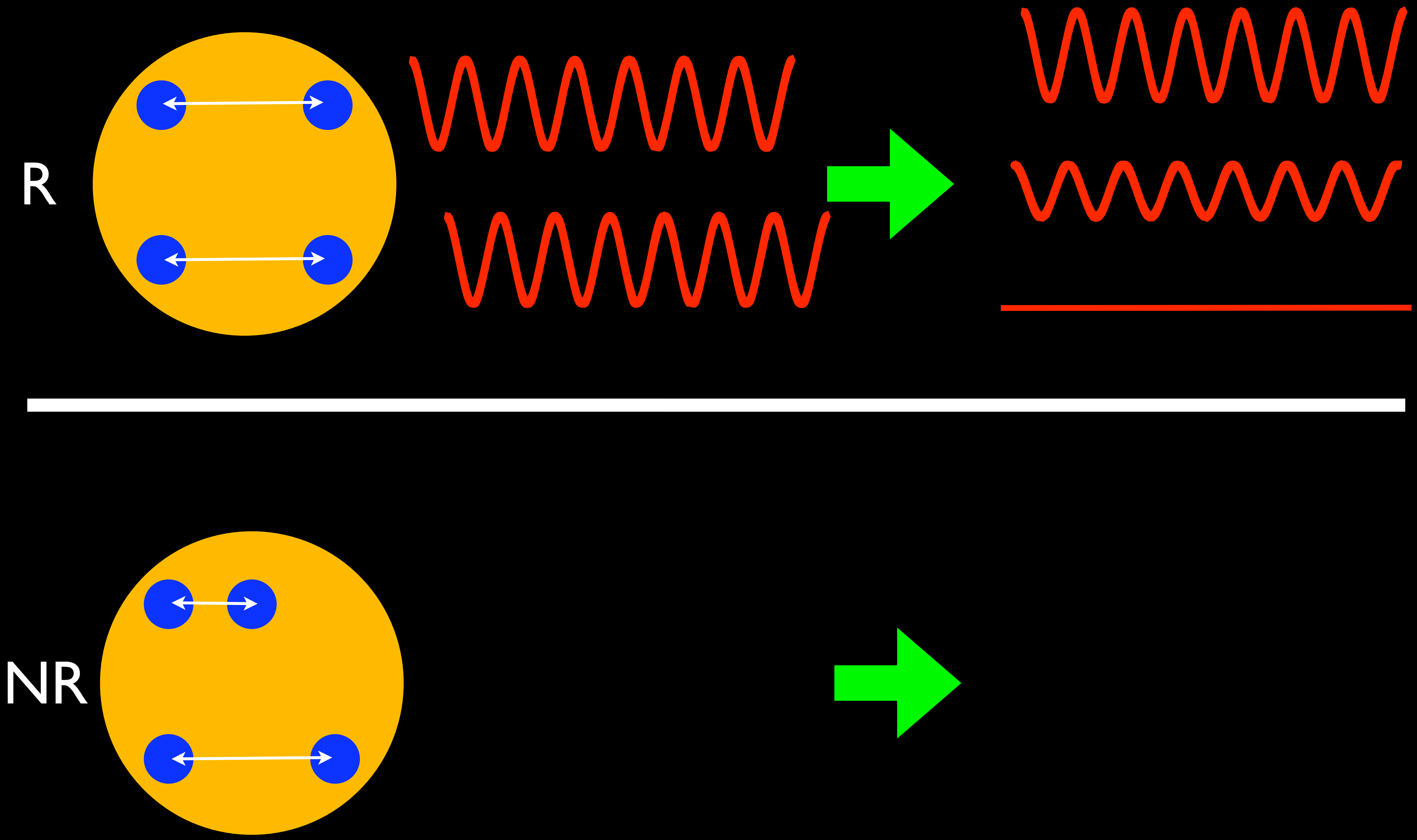




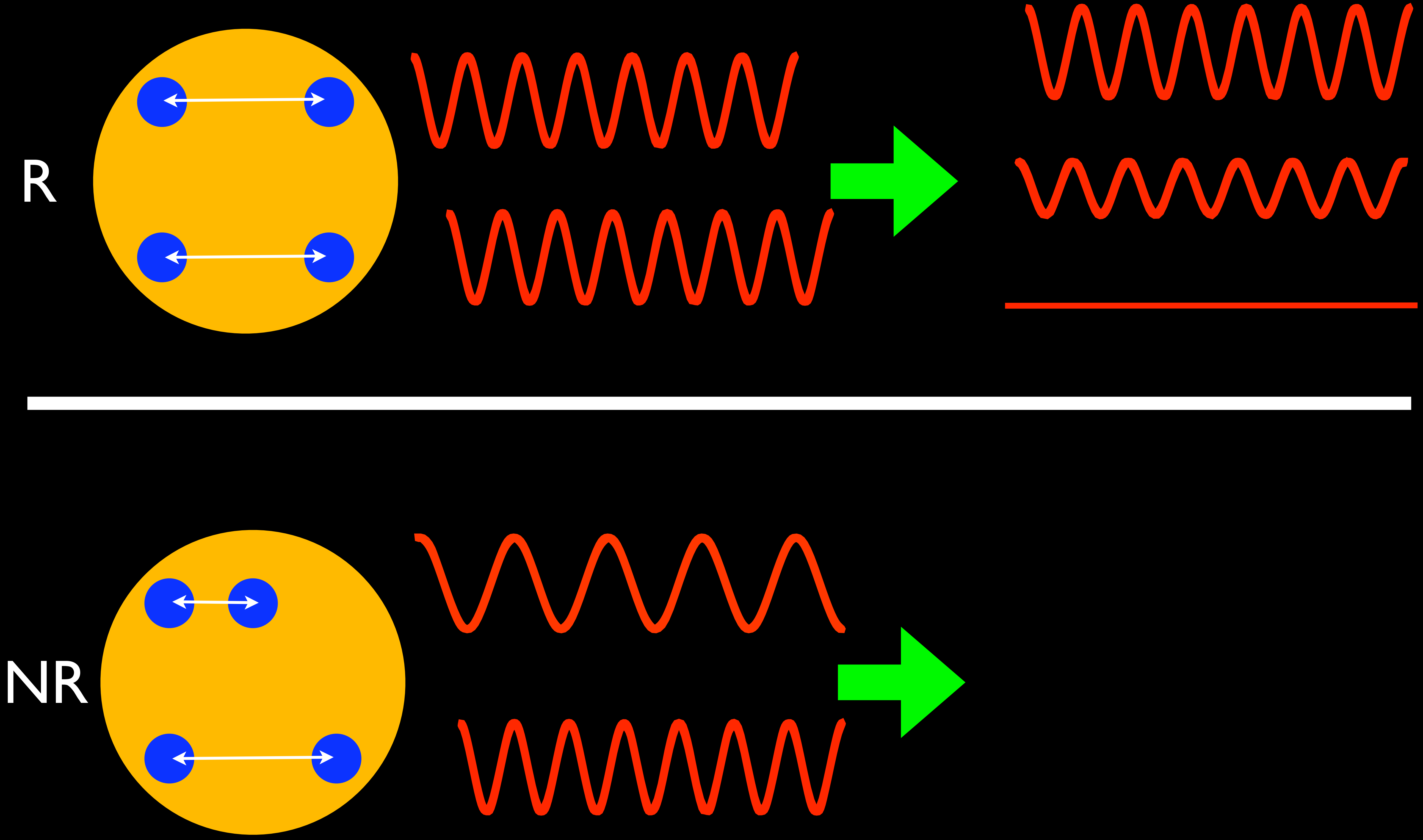
Redundancy



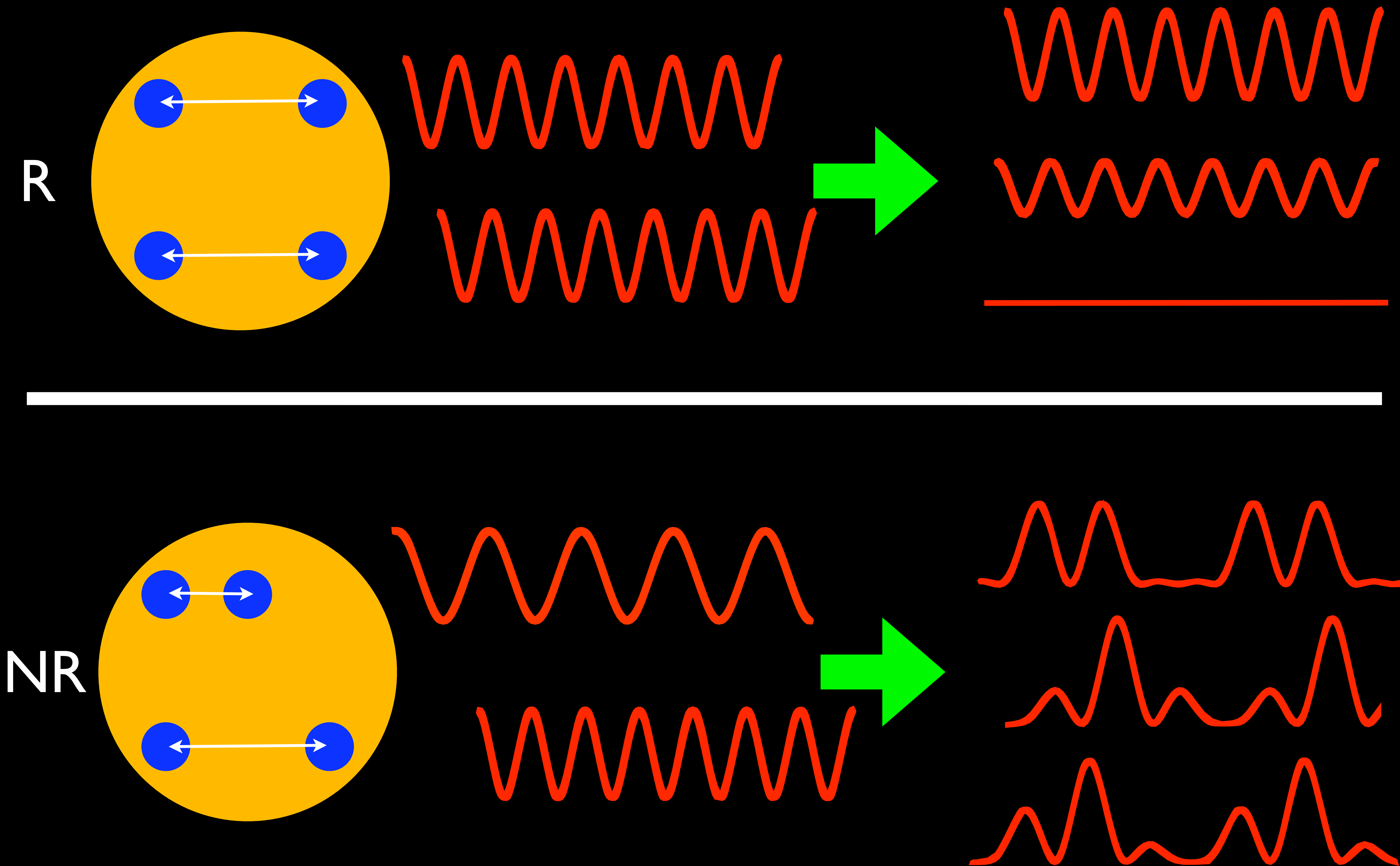
Redundancy



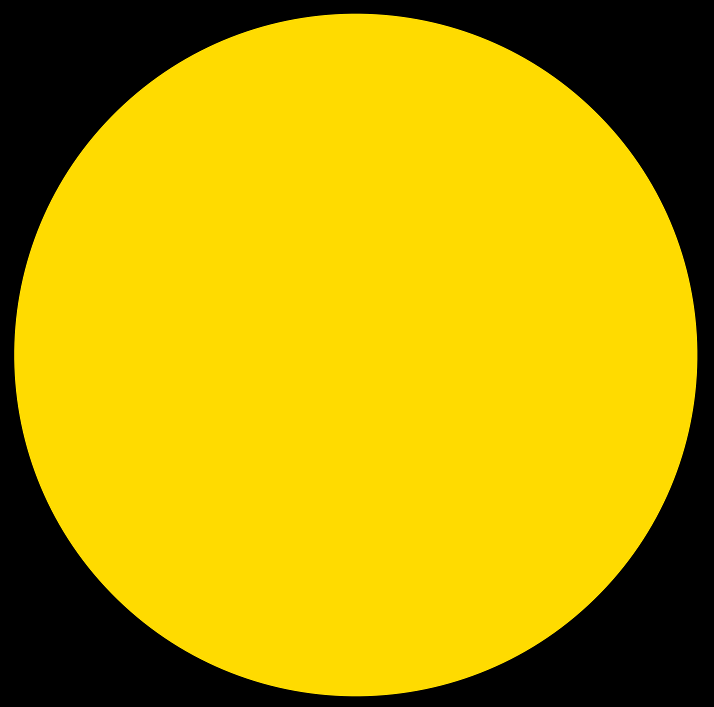
Redundancy



Redundancy



And a full aperture...



And a full aperture...

is very, very,

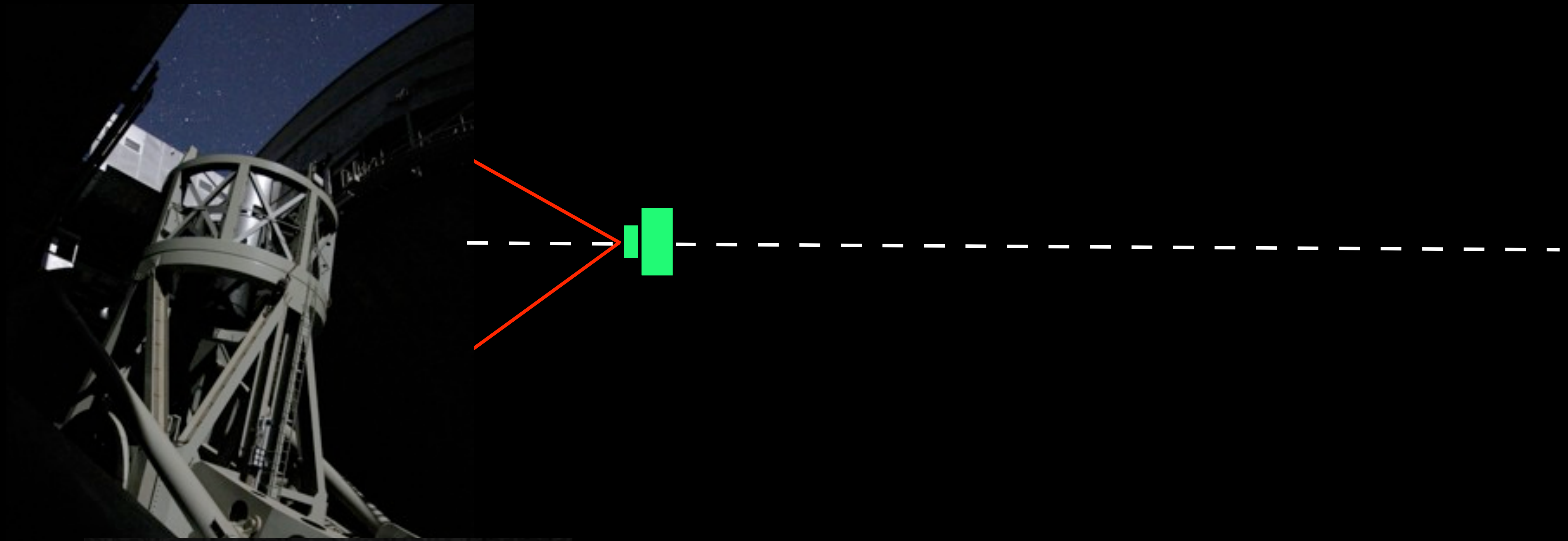
very, very,

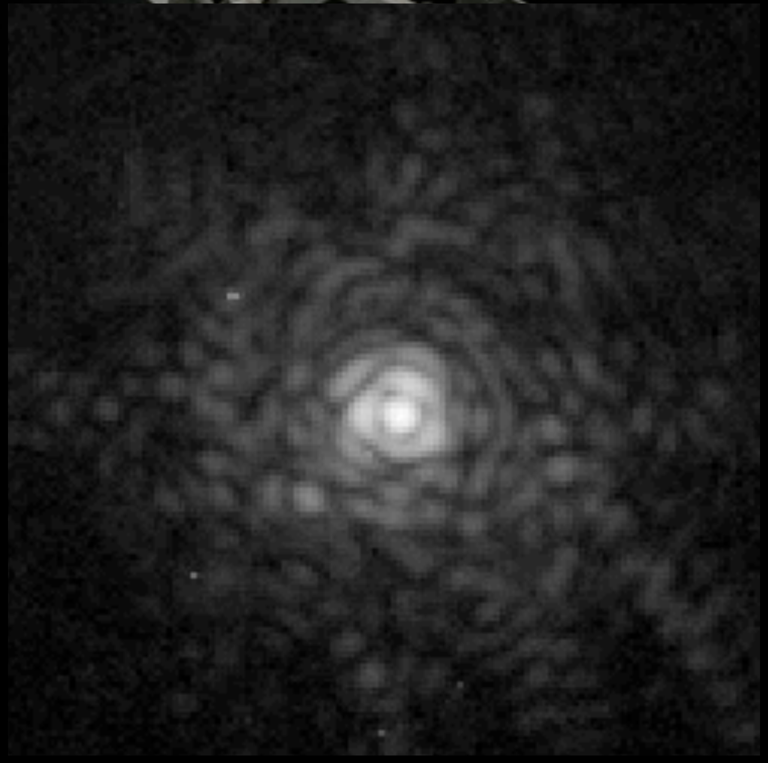
very redundant

Atmosphere affects the phases
Redundancy destroys the amplitudes

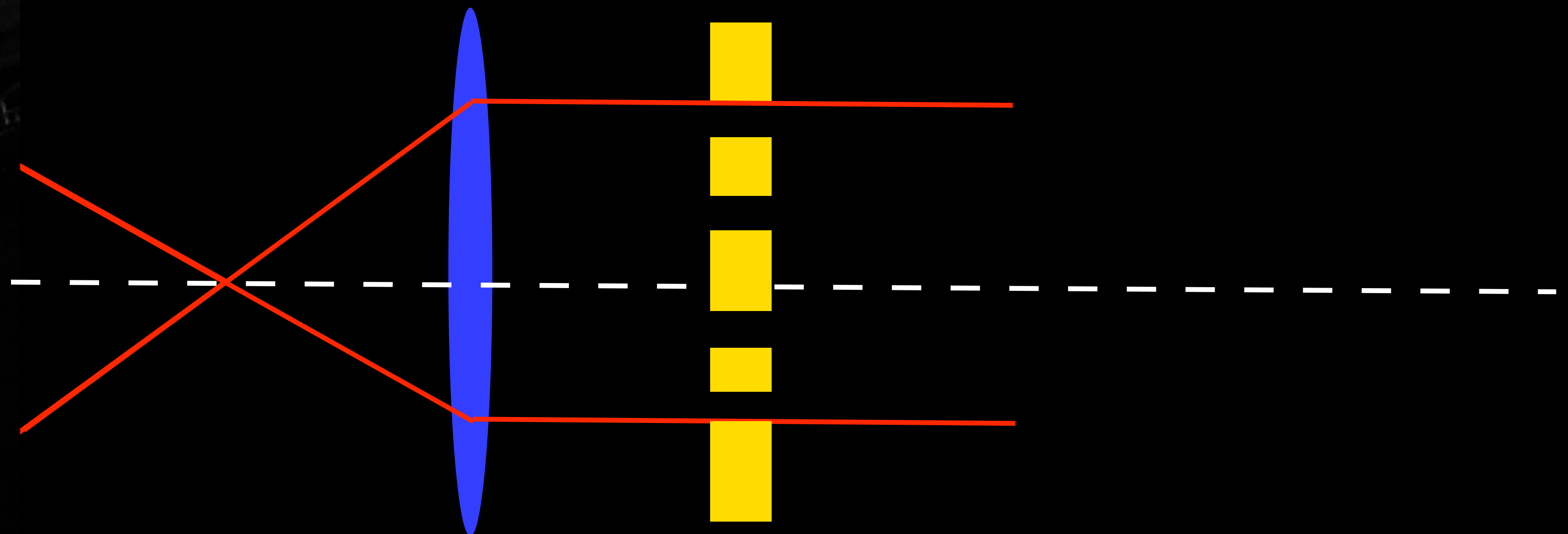
Non-redundant masking

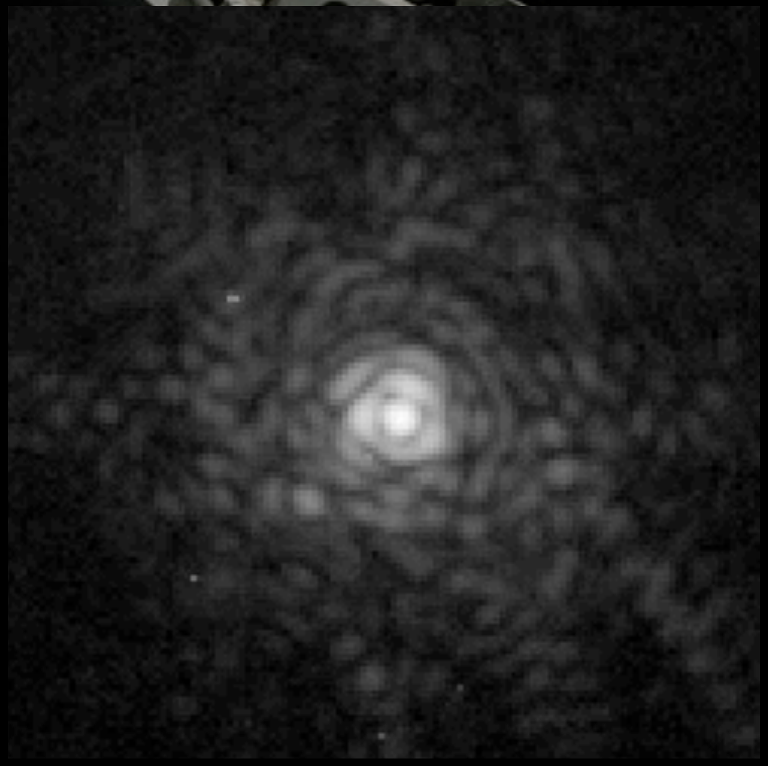
Non-redundant masking

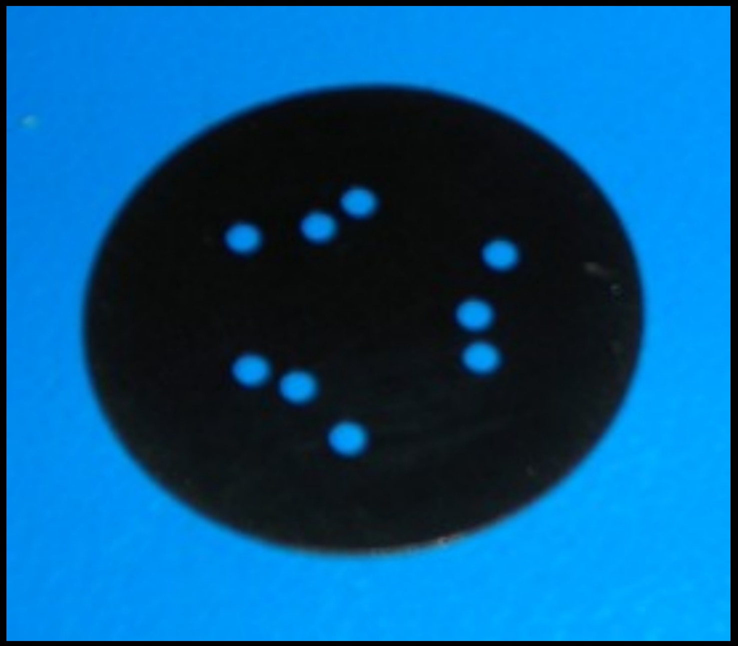




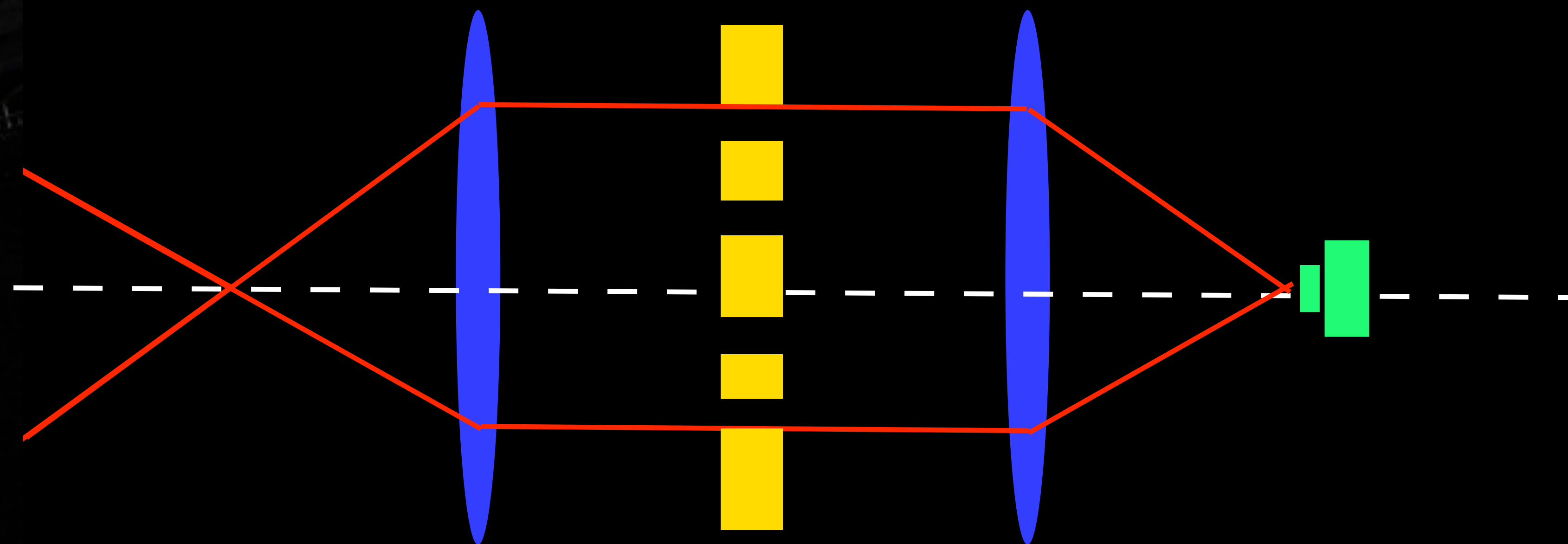
Non-redundant masking

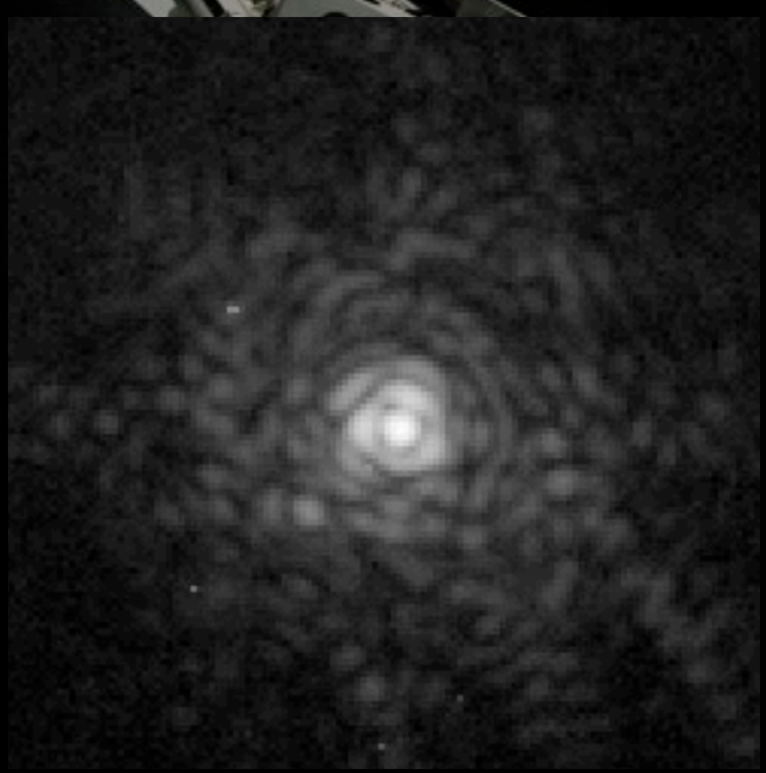


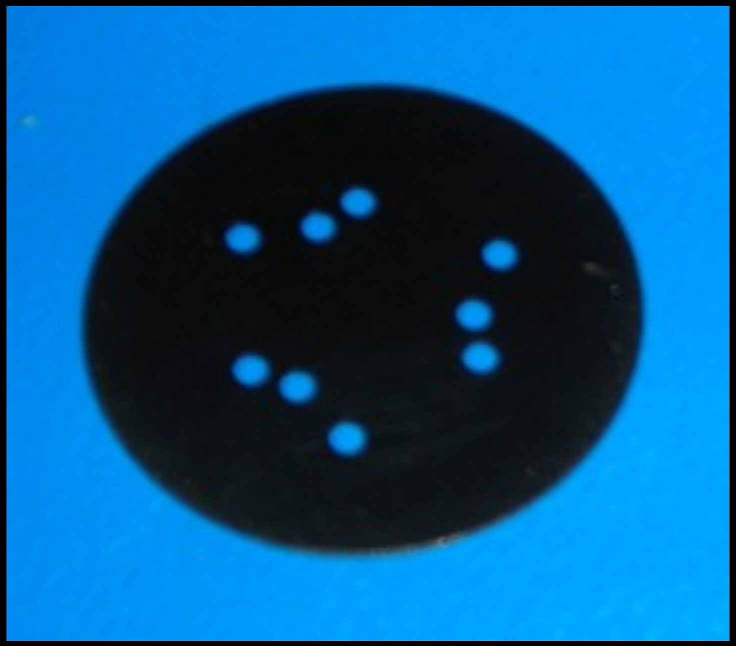


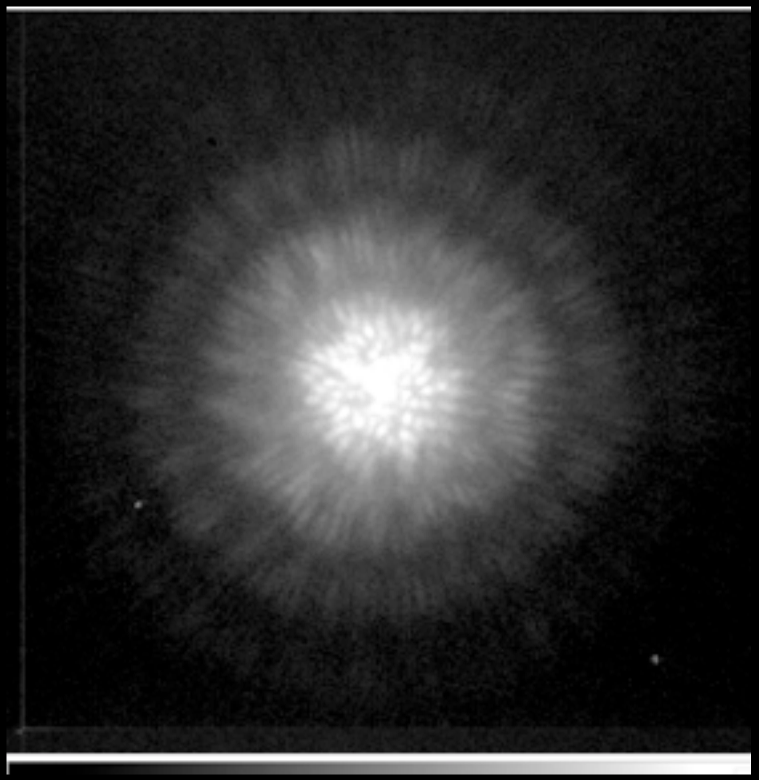


Non-redundant masking



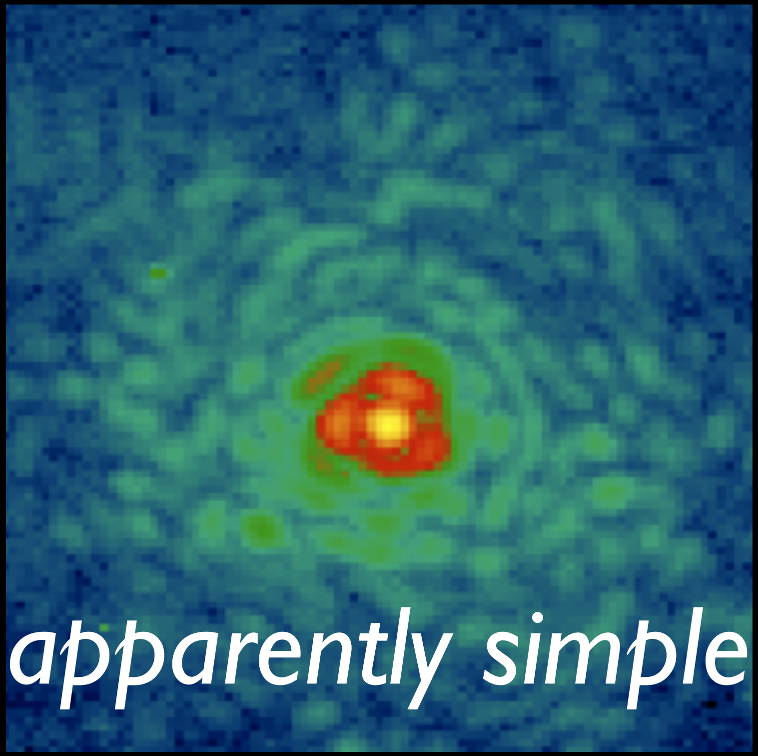


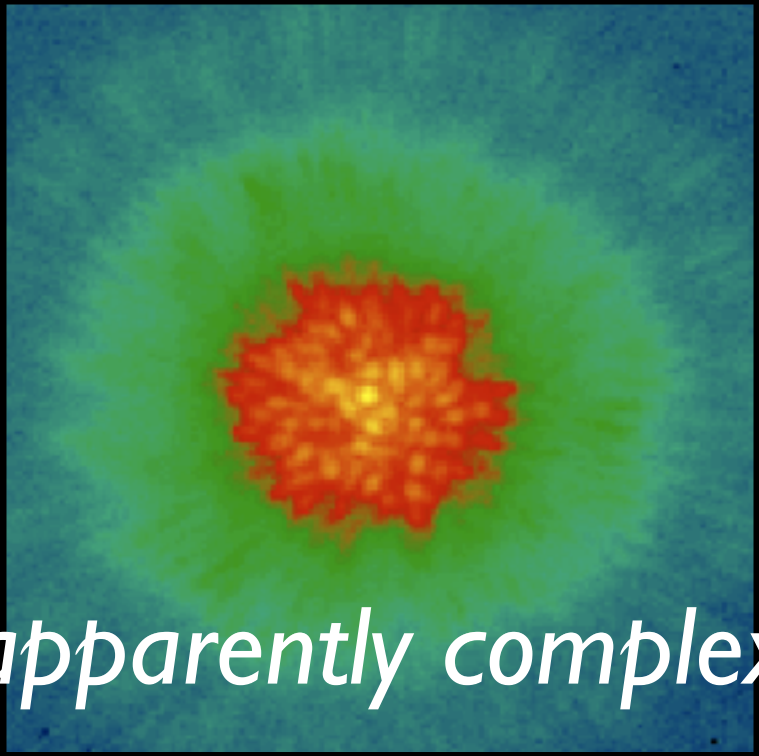




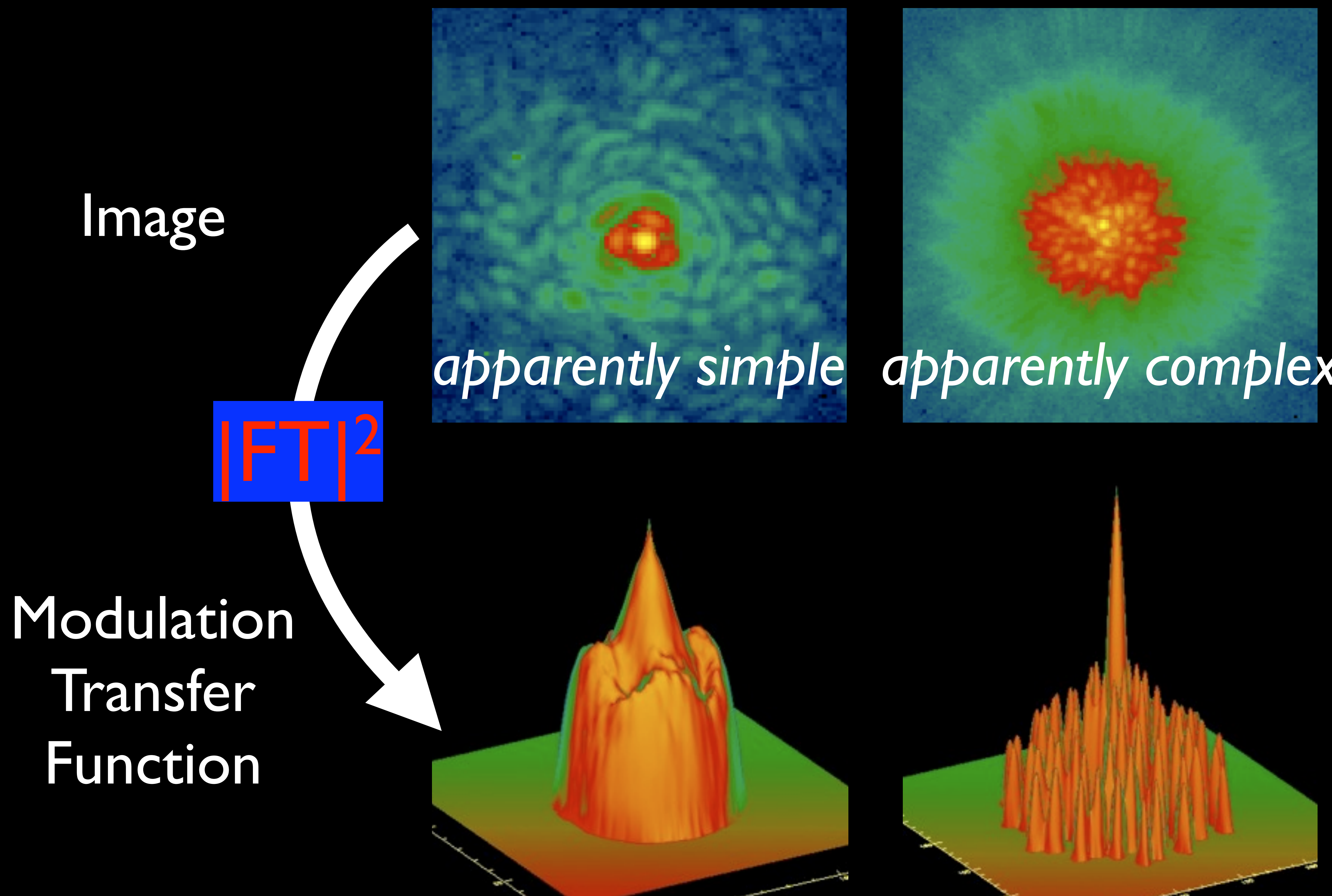
Toward an easier problem

Image

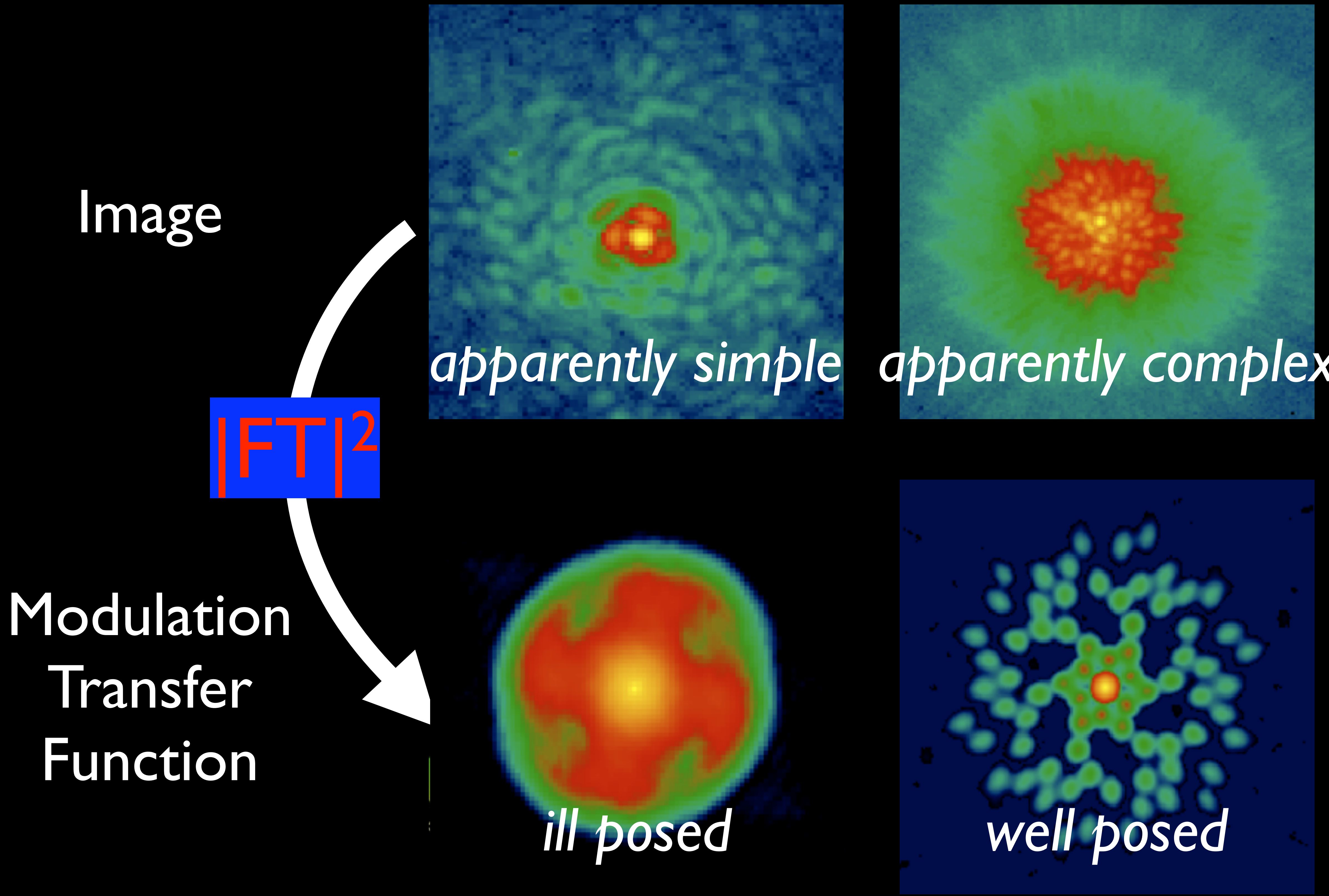




Toward an easier problem

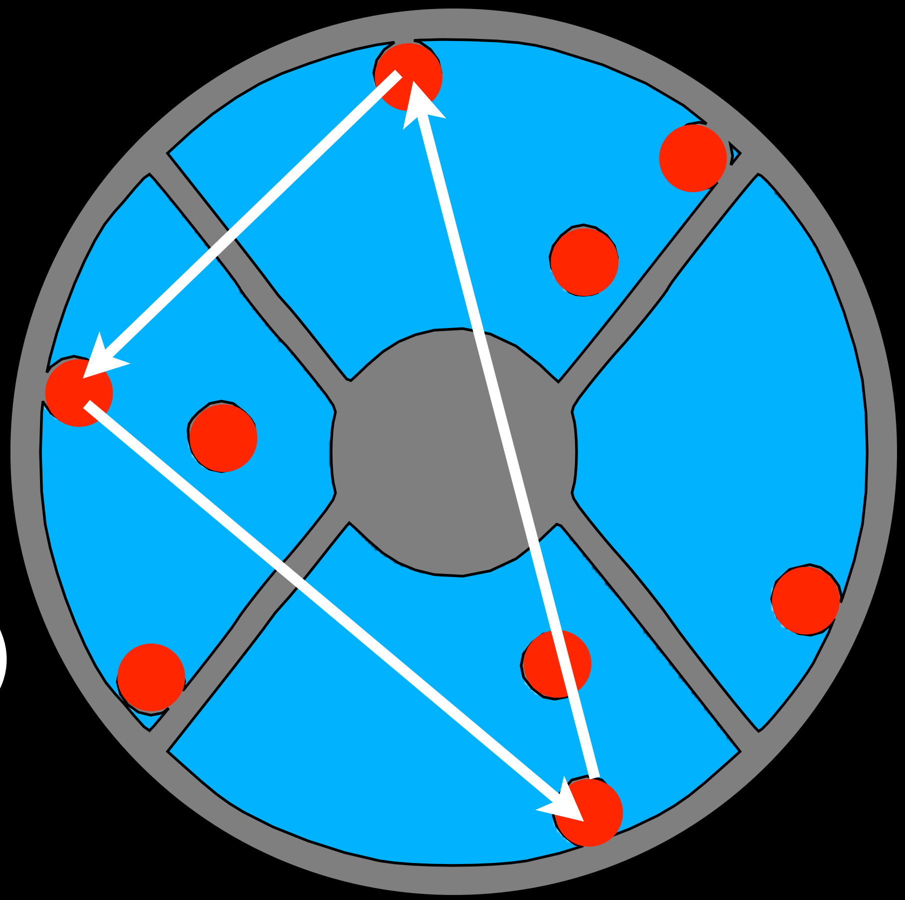


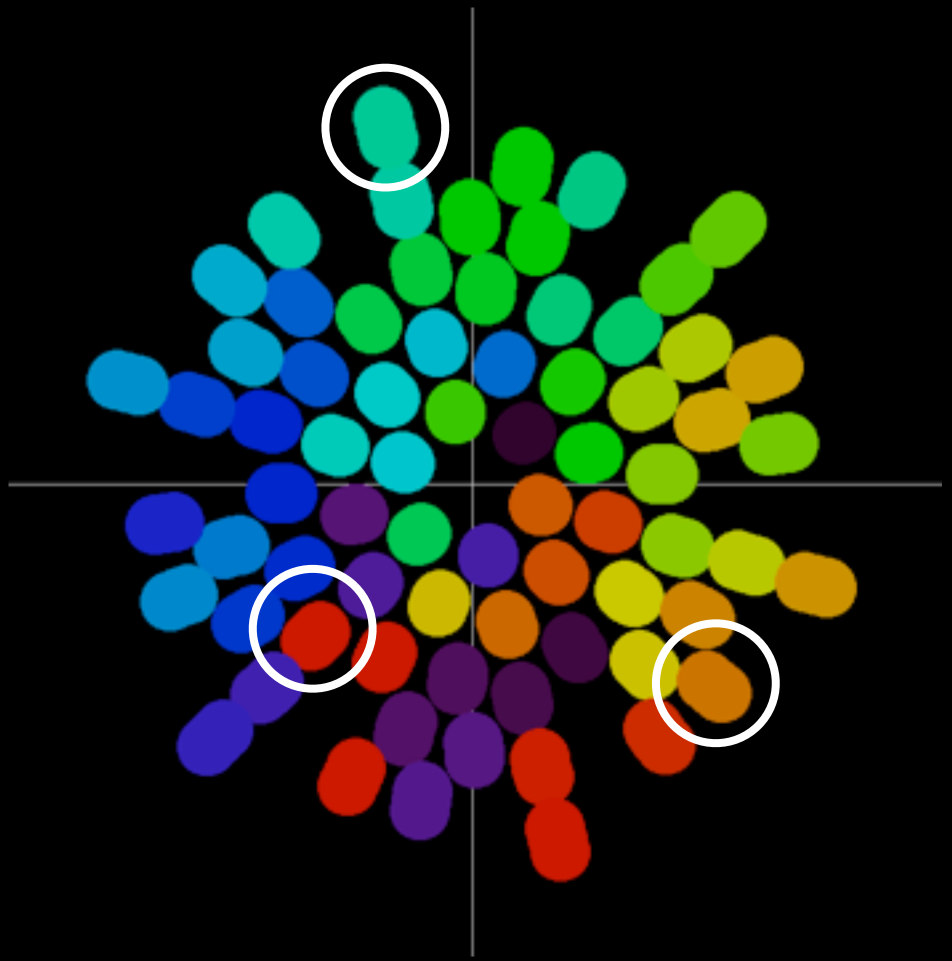
Toward an easier problem



To take advantage of self-calibration

9-hole mask
36 visibilities
84 triangles
(28 independent)





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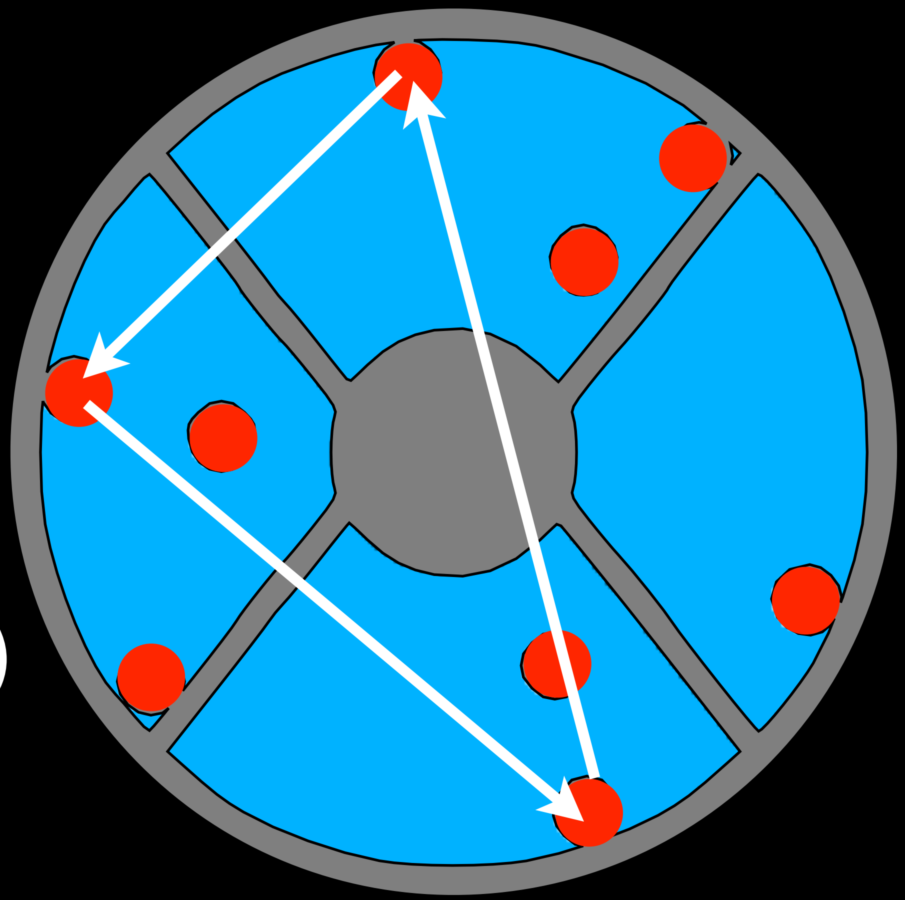
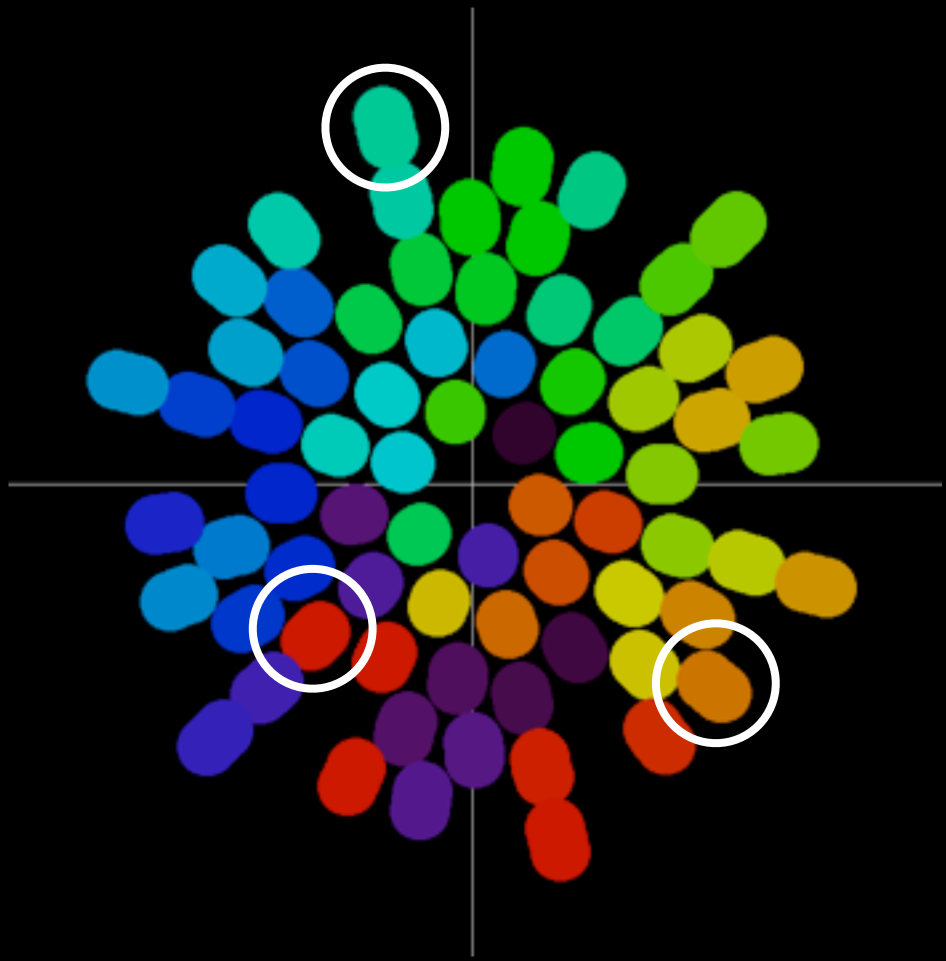




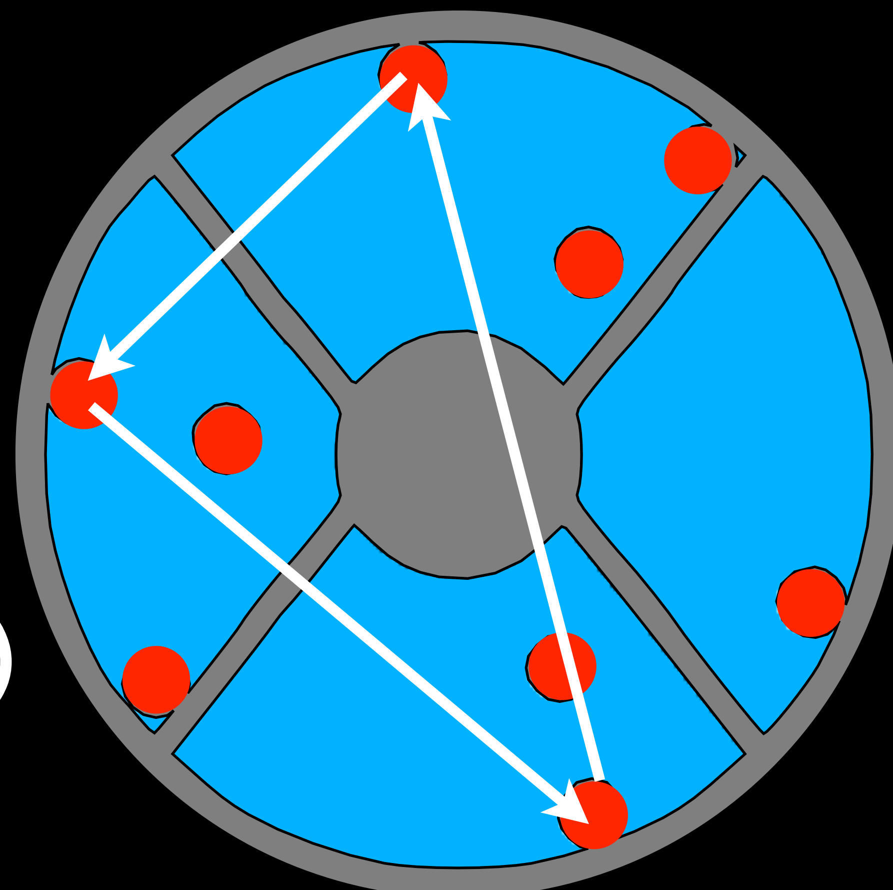
$\Phi(1\text{-}2) = \Phi(1\text{-}2)_0 + (\Phi_1\text{-}\Phi_2)$

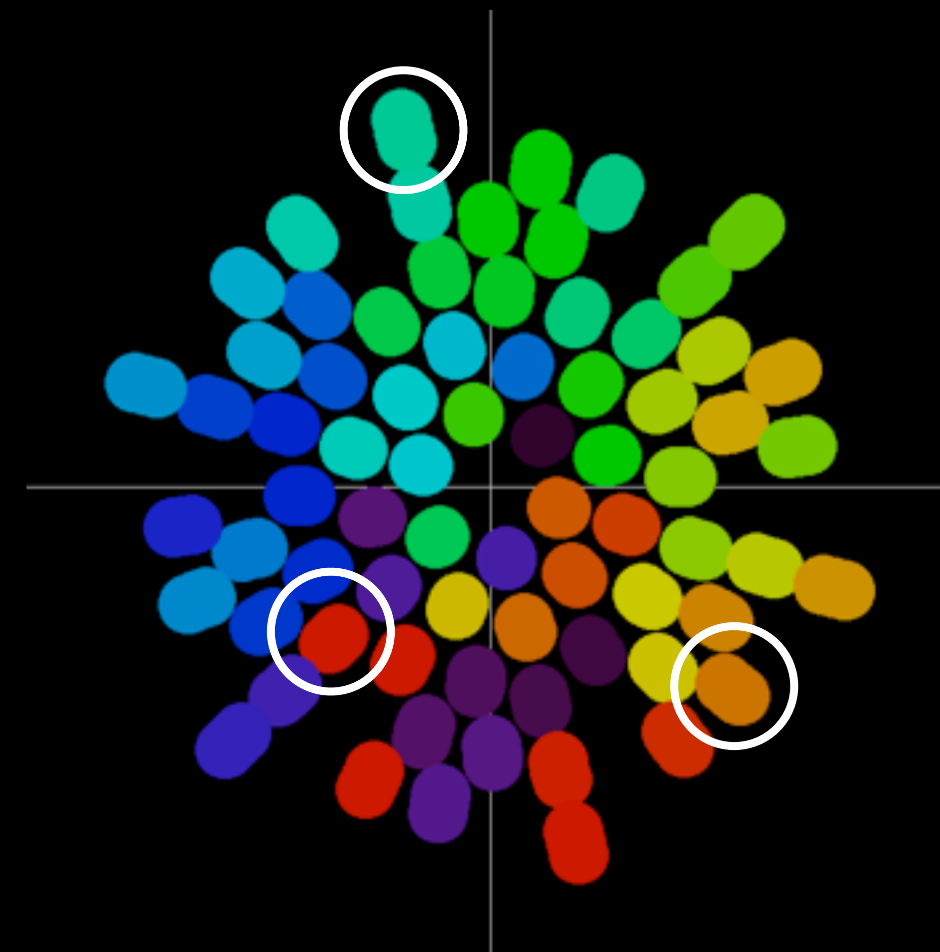
$\Phi(2\text{-}3) = \Phi(2\text{-}3)_0 + (\Phi_2\text{-}\Phi_3)$

$\Phi(3\text{-}1) = \Phi(3\text{-}1)_0 + (\Phi_3\text{-}\Phi_1)$

To take advantage of self-calibration

9-hole mask
36 visibilities
84 triangles
(28 independent)



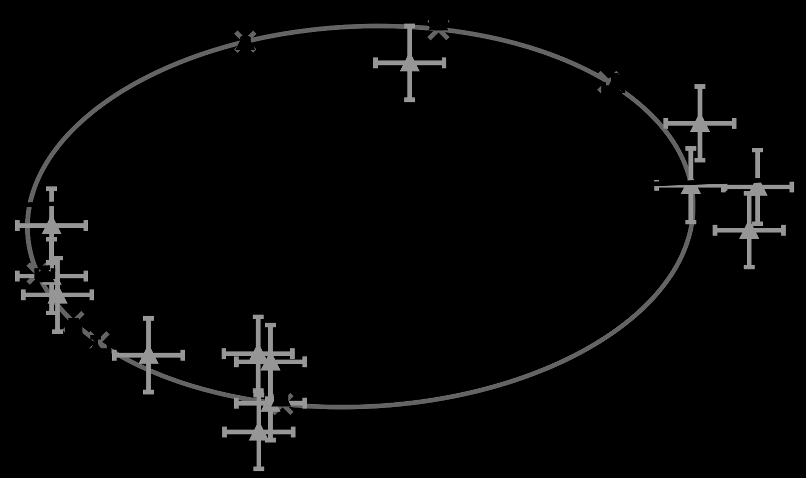


$$\Phi(1\text{-}2) = \Phi(1\text{-}2)_0 + \cancel{(\Phi_1 - \Phi_2)}$$
$$\Phi(2\text{-}3) = \Phi(2\text{-}3)_0 + \cancel{(\Phi_2 - \Phi_3)}$$
$$\Phi(3\text{-}1) = \Phi(3\text{-}1)_0 + \cancel{(\Phi_3 - \Phi_1)}$$

An ideal observable:
the closure-phase!

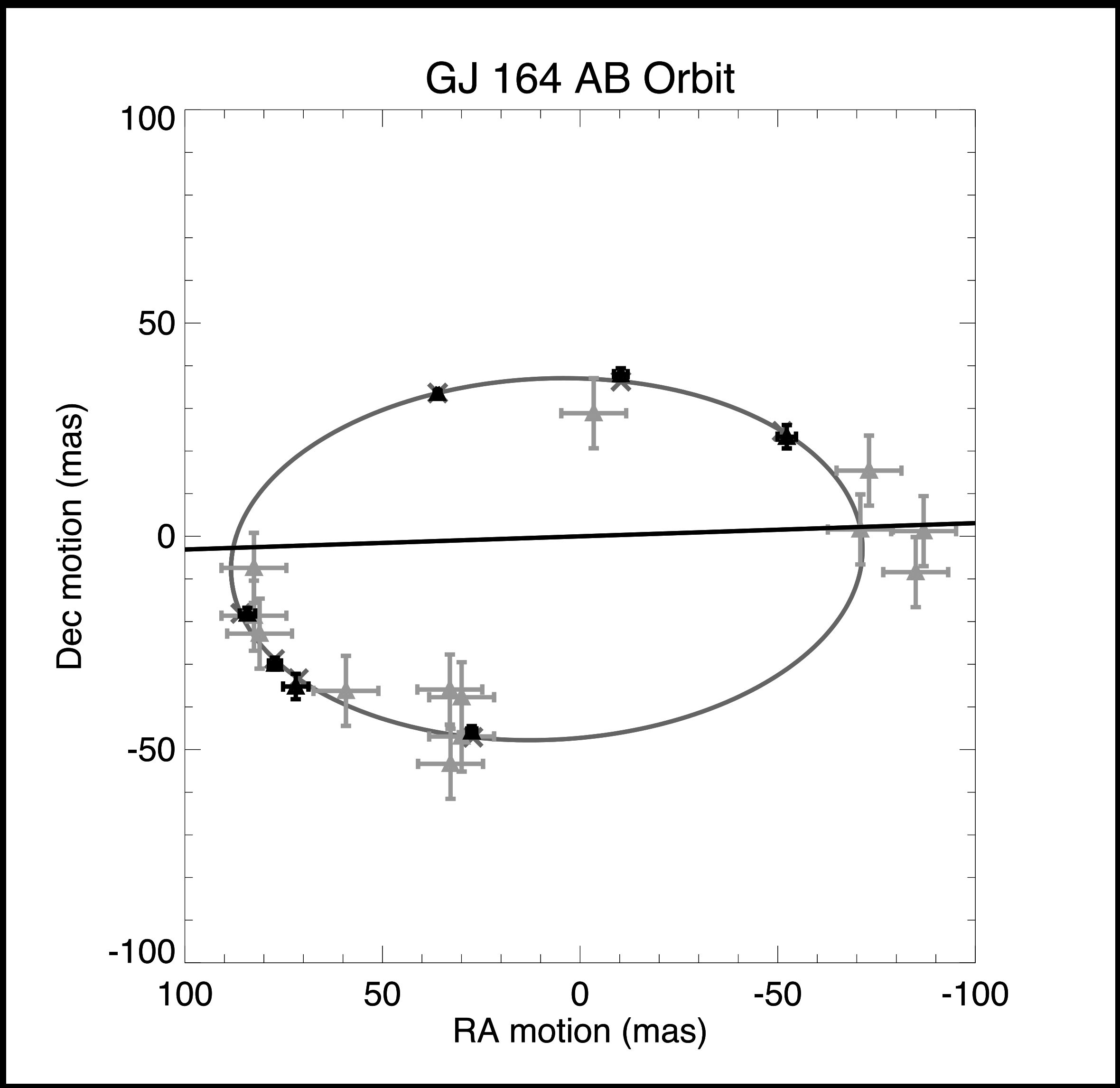
Jennison, 1958, MNRAS, 118, 276

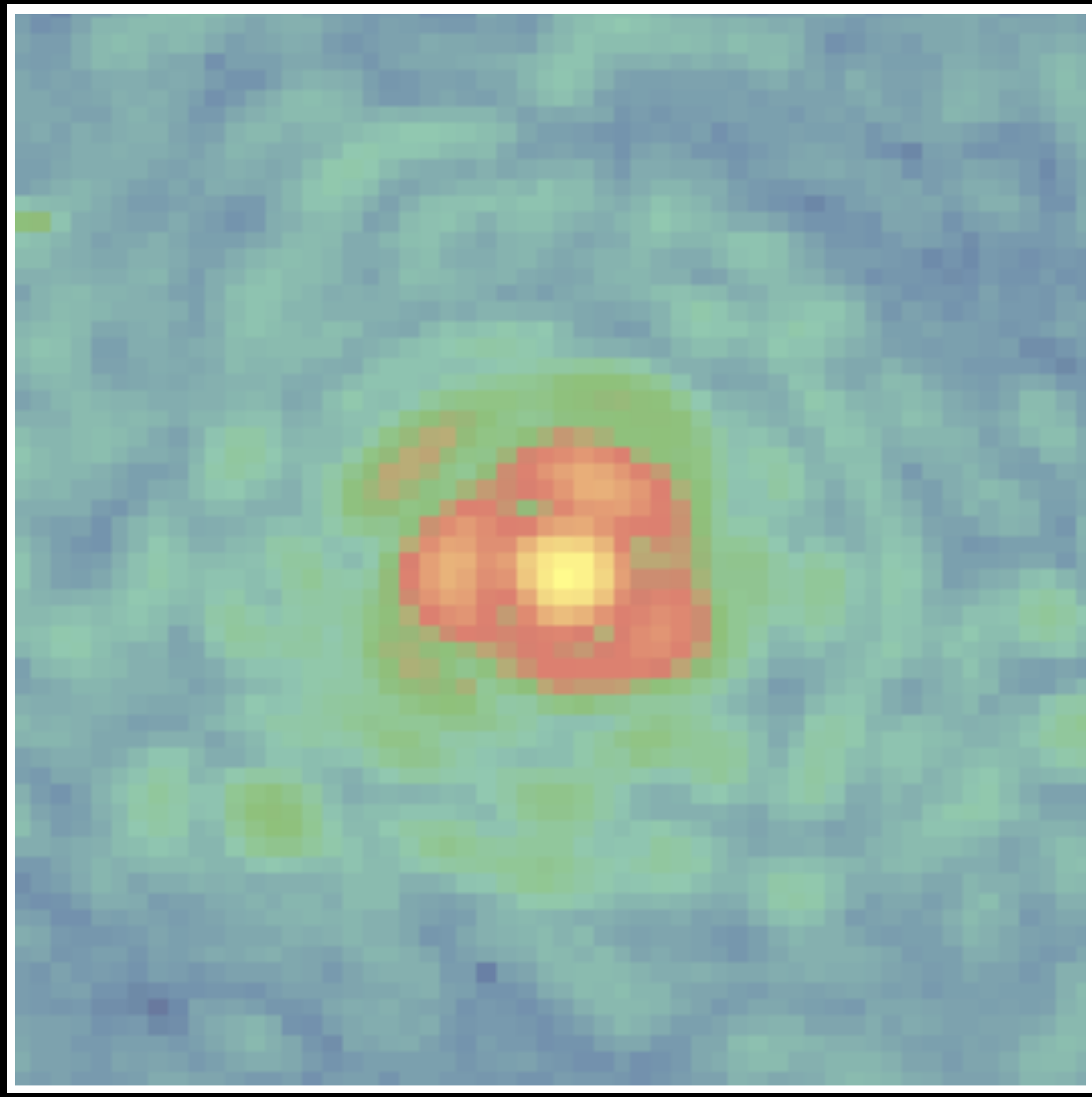
Super-resolution with closure-phase



Martinache et al, 2009, ApJ, 695, 1183

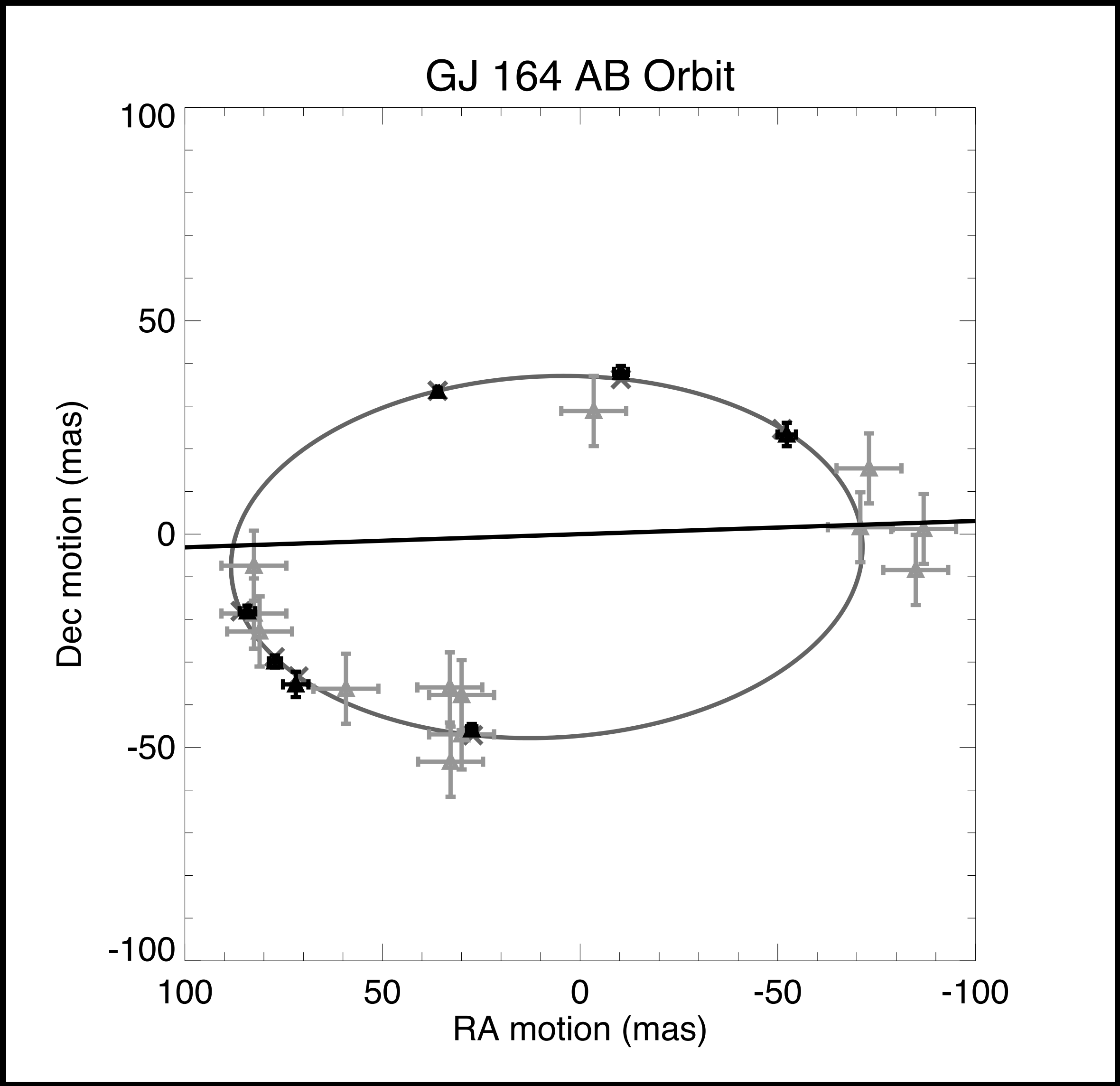
Super-resolution with closure-phase

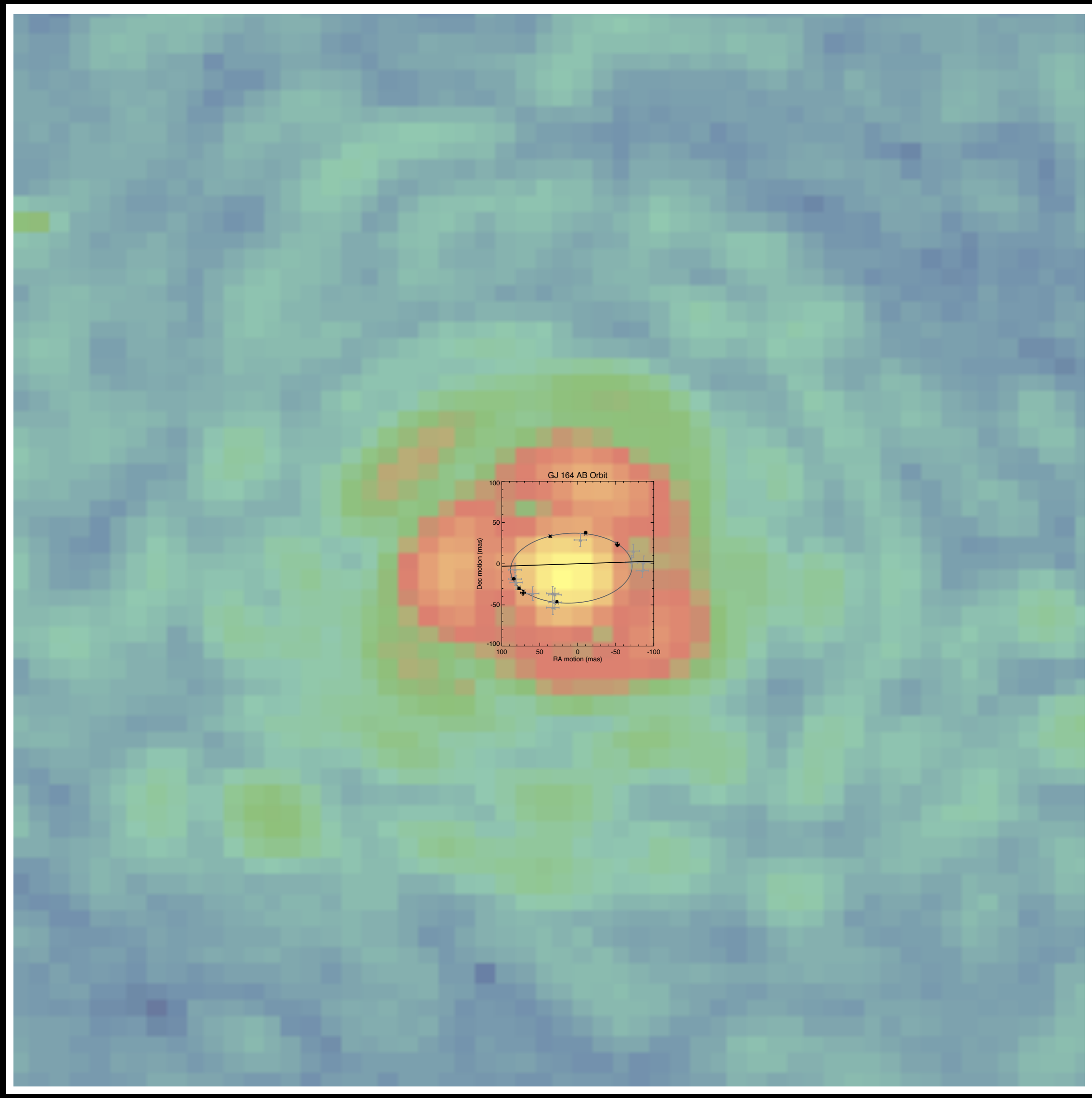




Martinache et al, 2009, ApJ, 695, 1183

Super-resolution with closure-phase





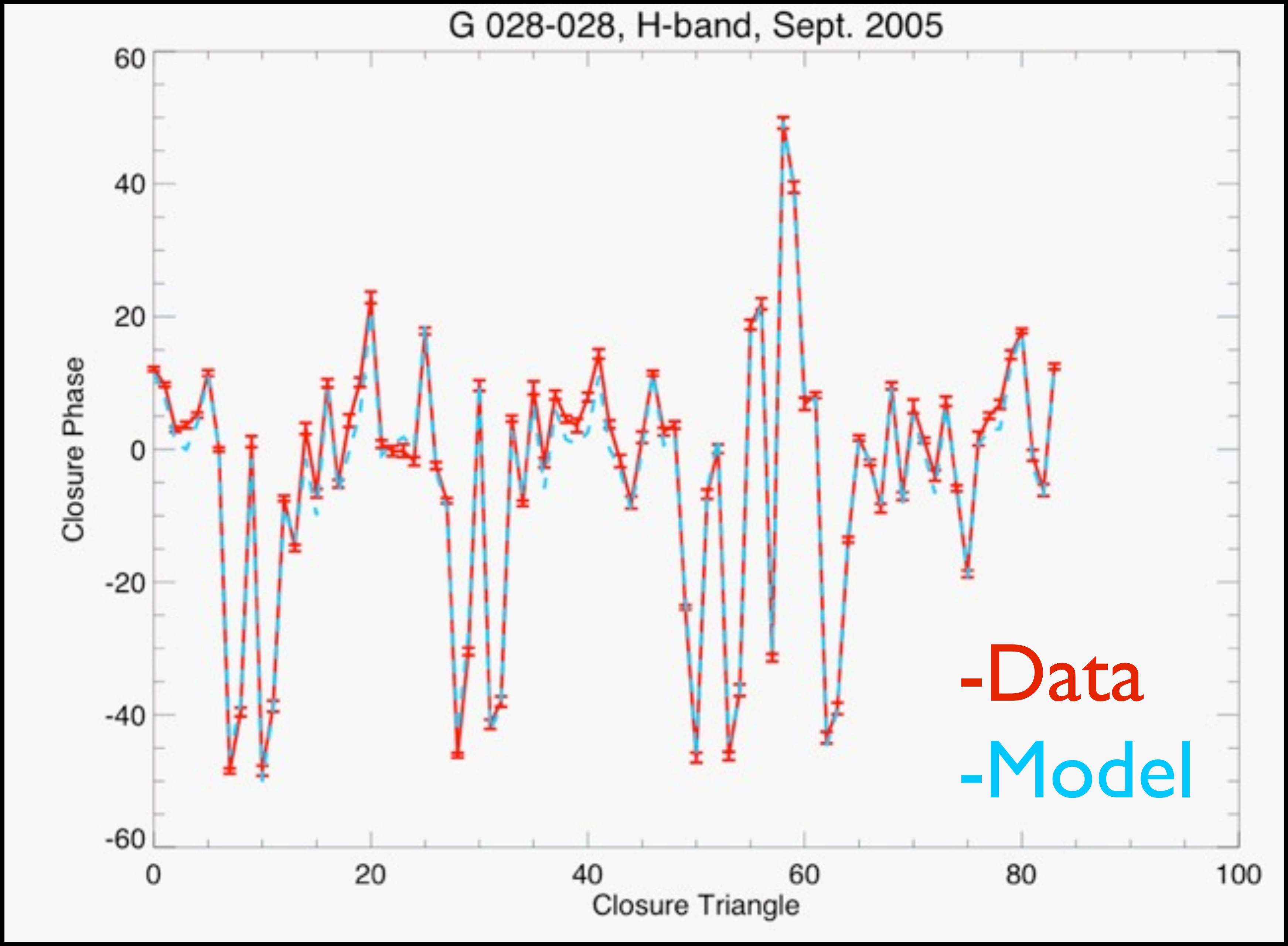
GJ 164 AB
M_1 = 0.247 +/- 0.019 M_S
M_2 = 0.096 +/- 0.008 M_S

Martinache et al, 2009, ApJ, 695, 1183

Good for faint companions

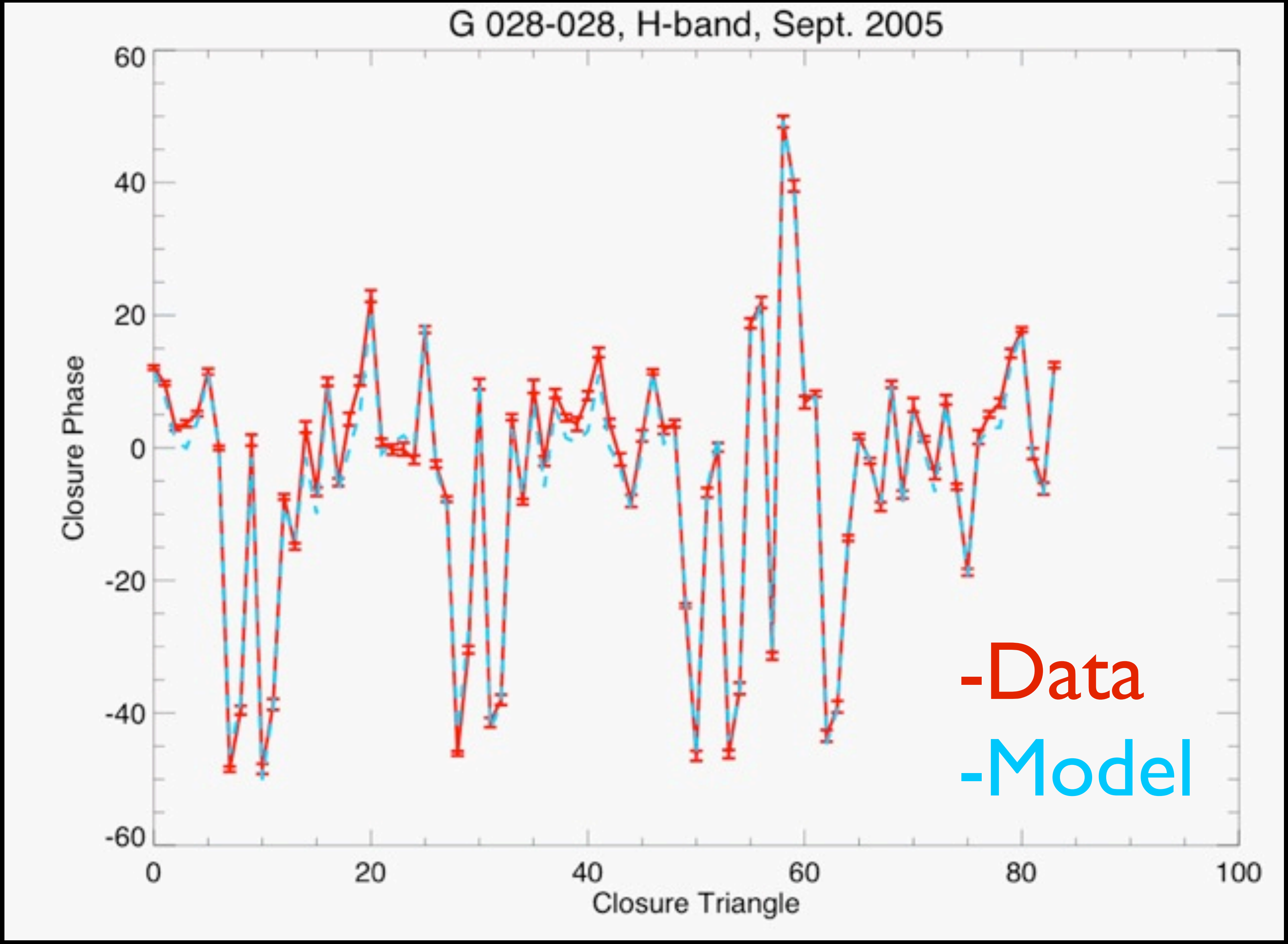
40 % strehl
0.3 deg scatter
stability ~ $\lambda/1000$
all passive !

Good for faint companions



40 % strehl
0.3 deg scatter
stability ~ λ/1000
all passive !

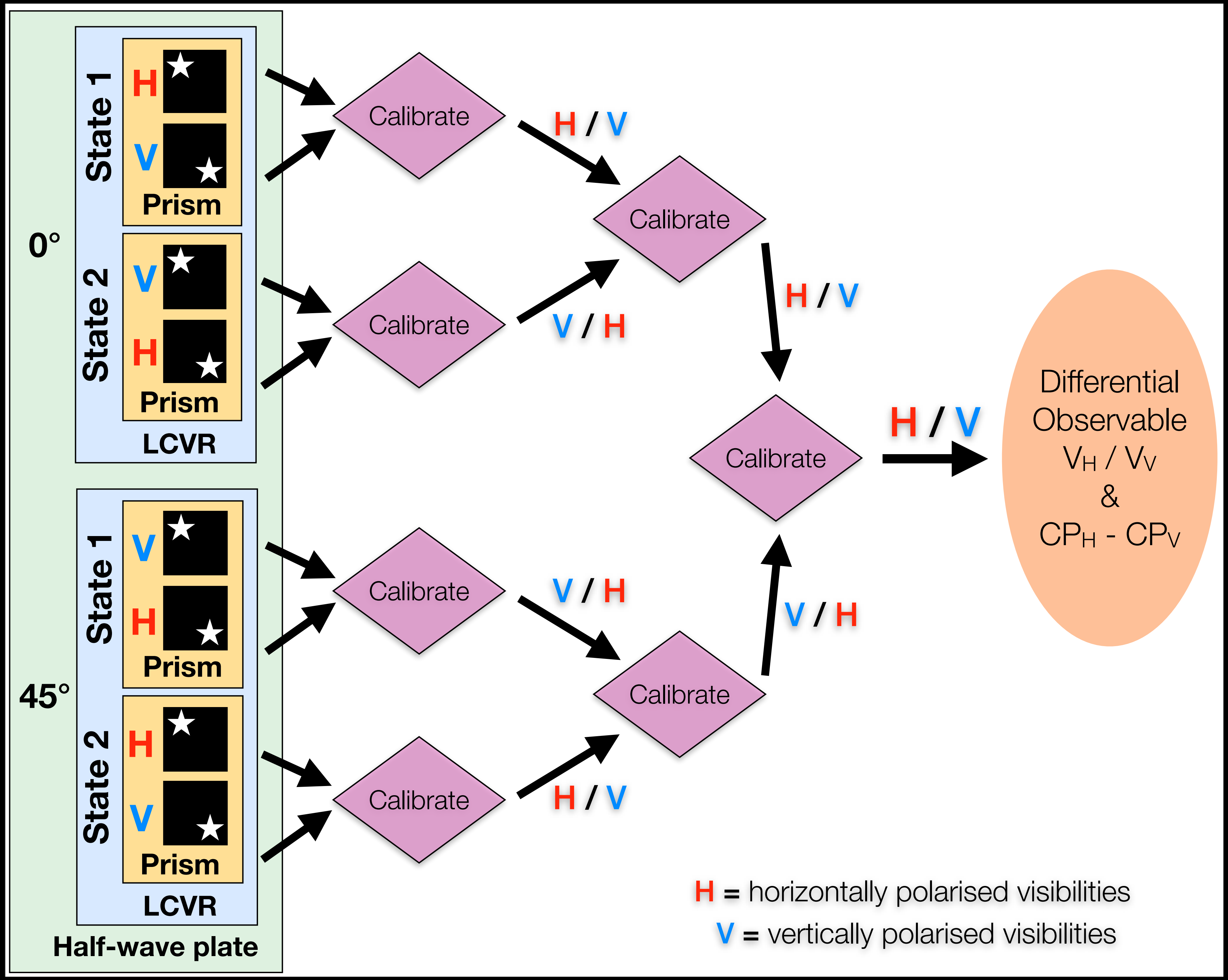
Good for faint companions



40 % strehl
0.3 deg scatter
stability ~ λ/1000
all passive !

Understand your errors: **statistical** and **systematic**

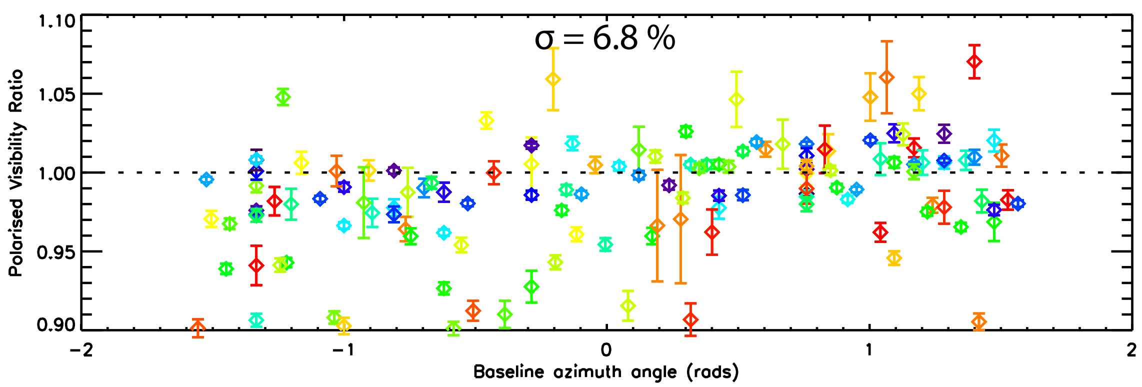
Calibrate, calibrate, calibrate!



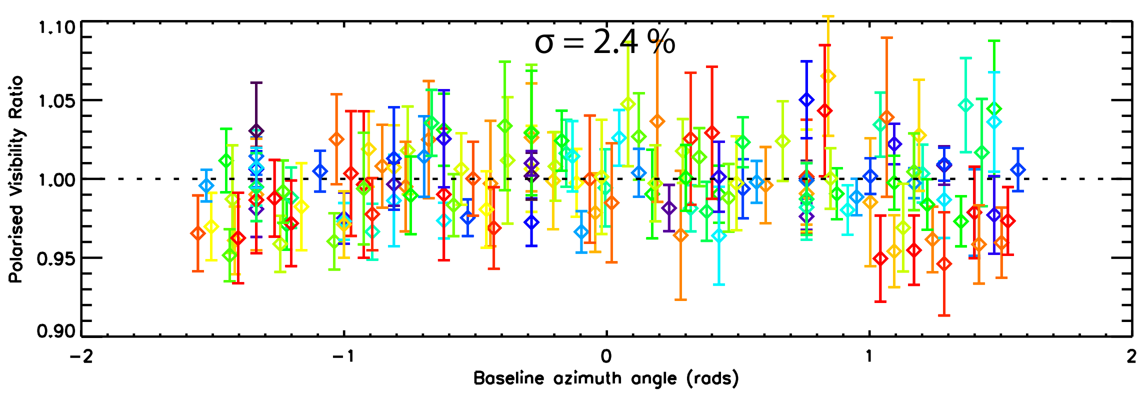
VAMPIRES

Norris et al, 2015, MNRAS, 447, 2894

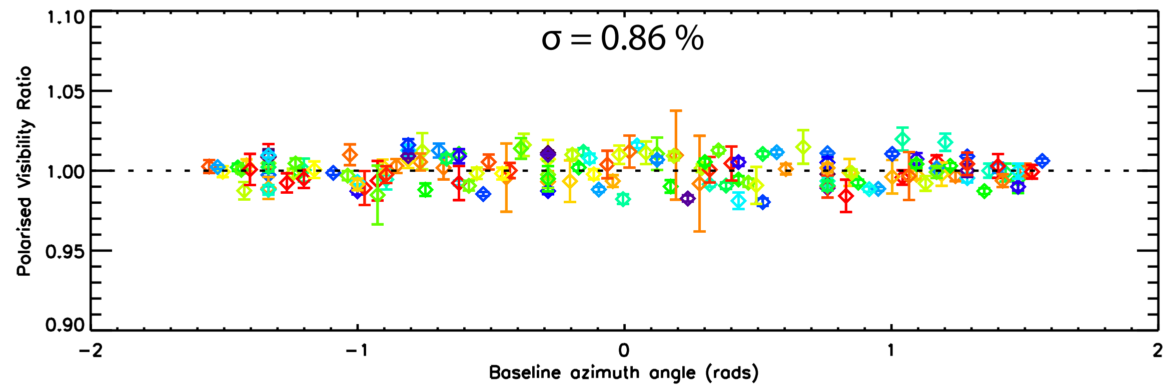
Differential interfero-polarimetry



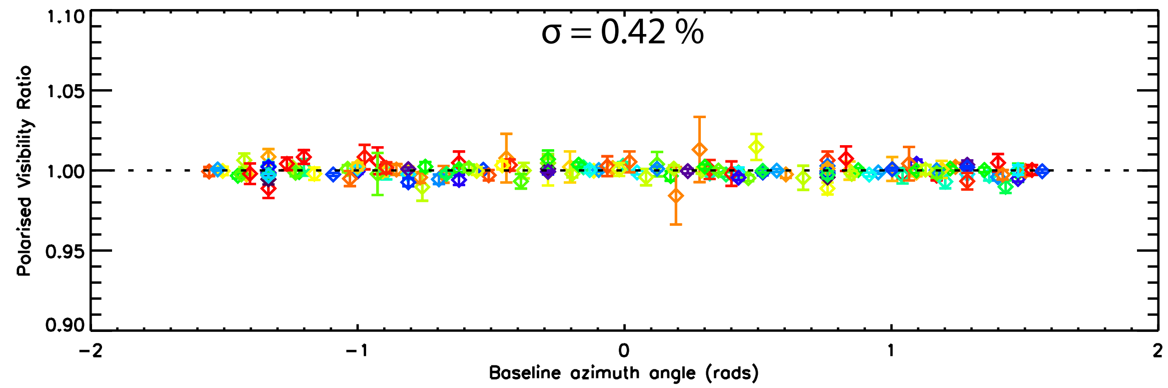
a) 1 tier - Wollaston prism only. No temporal variation leads to small error bars, but strong systematic errors (from non-common path) dominate.



b) 1 tier - LCVR only. No non-common path error, and the mean is ~ 1.0. However since switching is slower than seeing temporal errors lead to large error bars.



c) 2 tiers - Wollaston + LCVR. The Wollaston and LCVR cancel each others errors. Systematic errors are still visible.

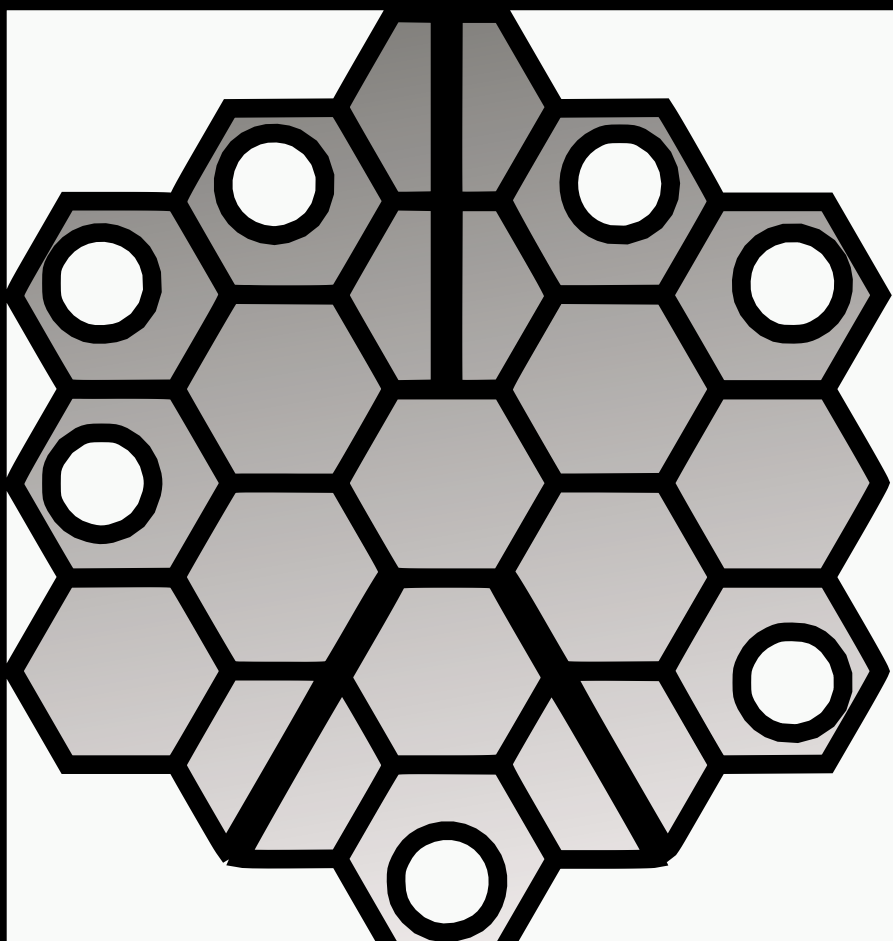


d) 3 tiers - Wollaston + LCVR + HWP. The HWP cancels out static systematic errors (such as those arising from instrumental effects). Here precision is limited by random error; additional integration time would improve precision further.

VAMPIRES

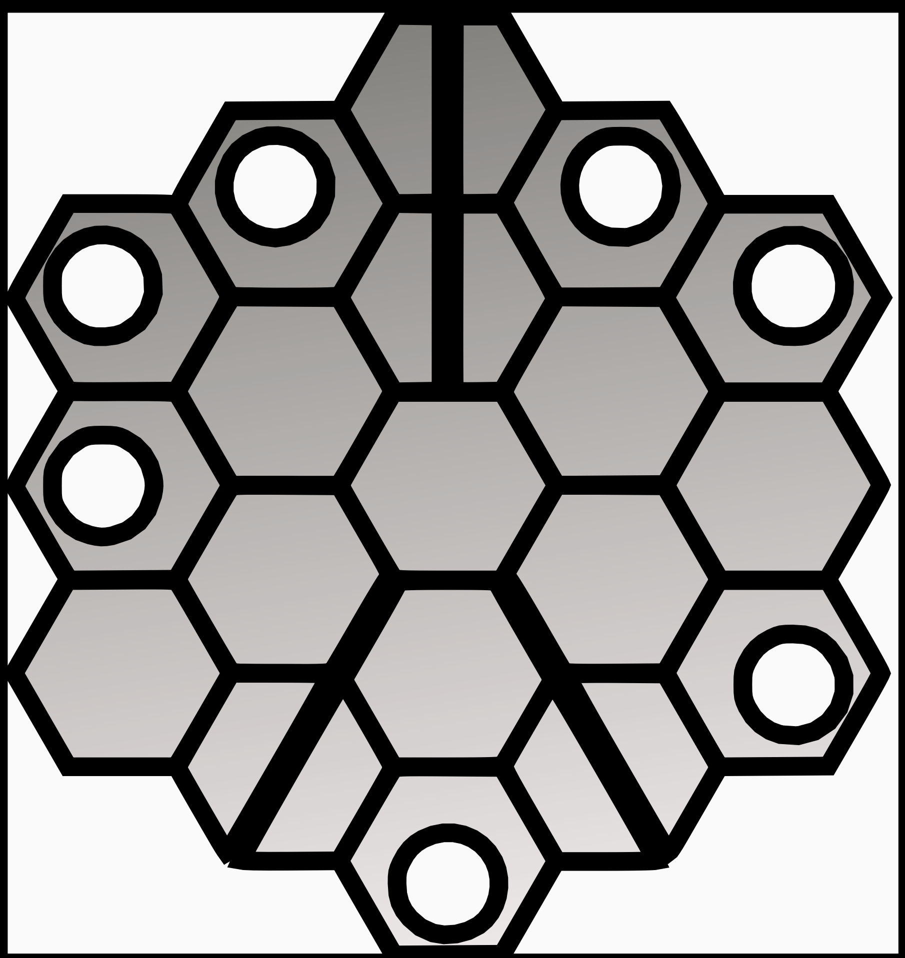
Norris et al, 2015, MNRAS, 447, 2894

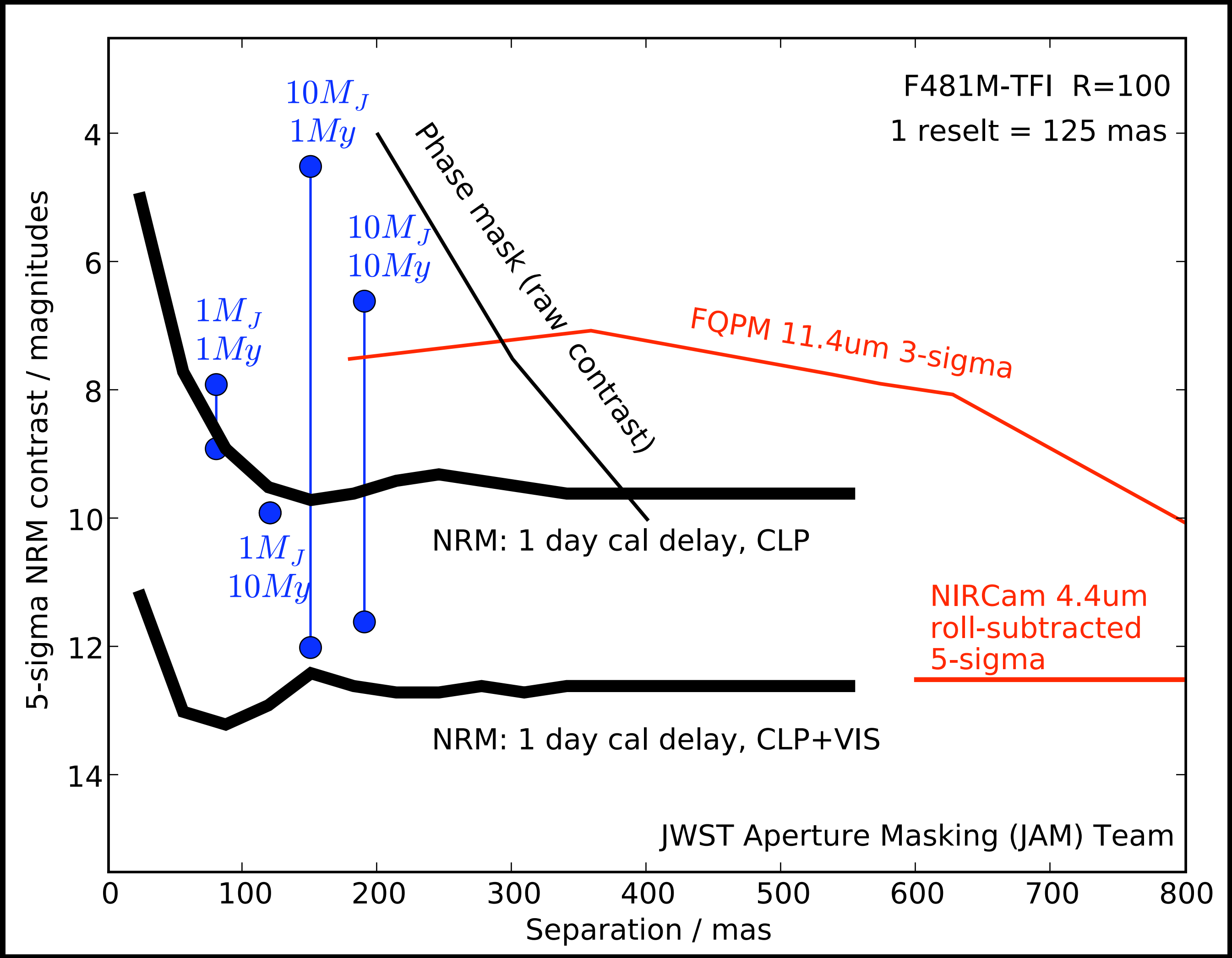
The self-calibration properties of closure phase make NRM "bullet-proof"



NRM onboard JWST in the NIRISS instrument.

The self-calibration properties of closure phase make NRM "bullet-proof"

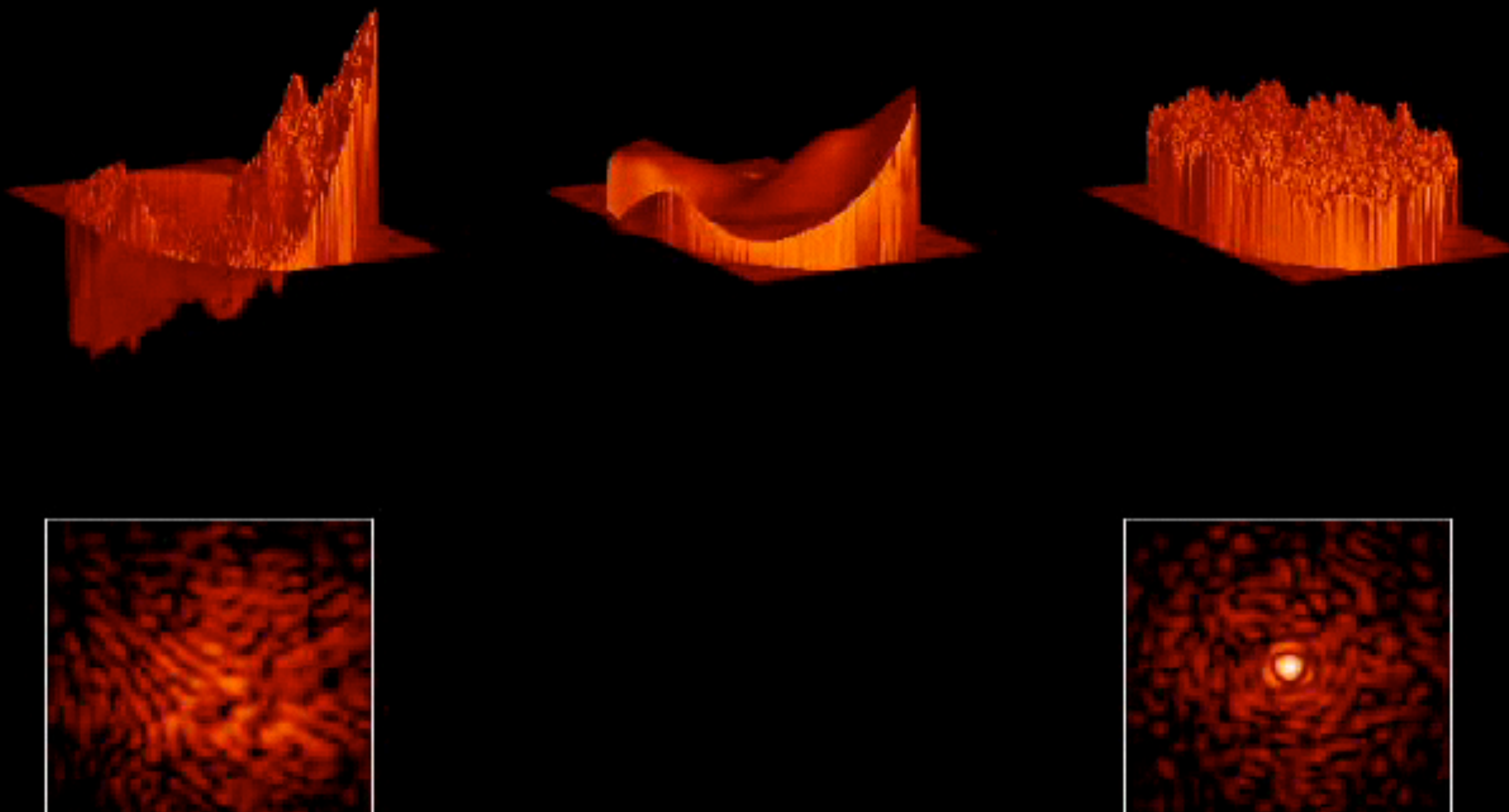




NRM onboard JWST in the NIRISS instrument.

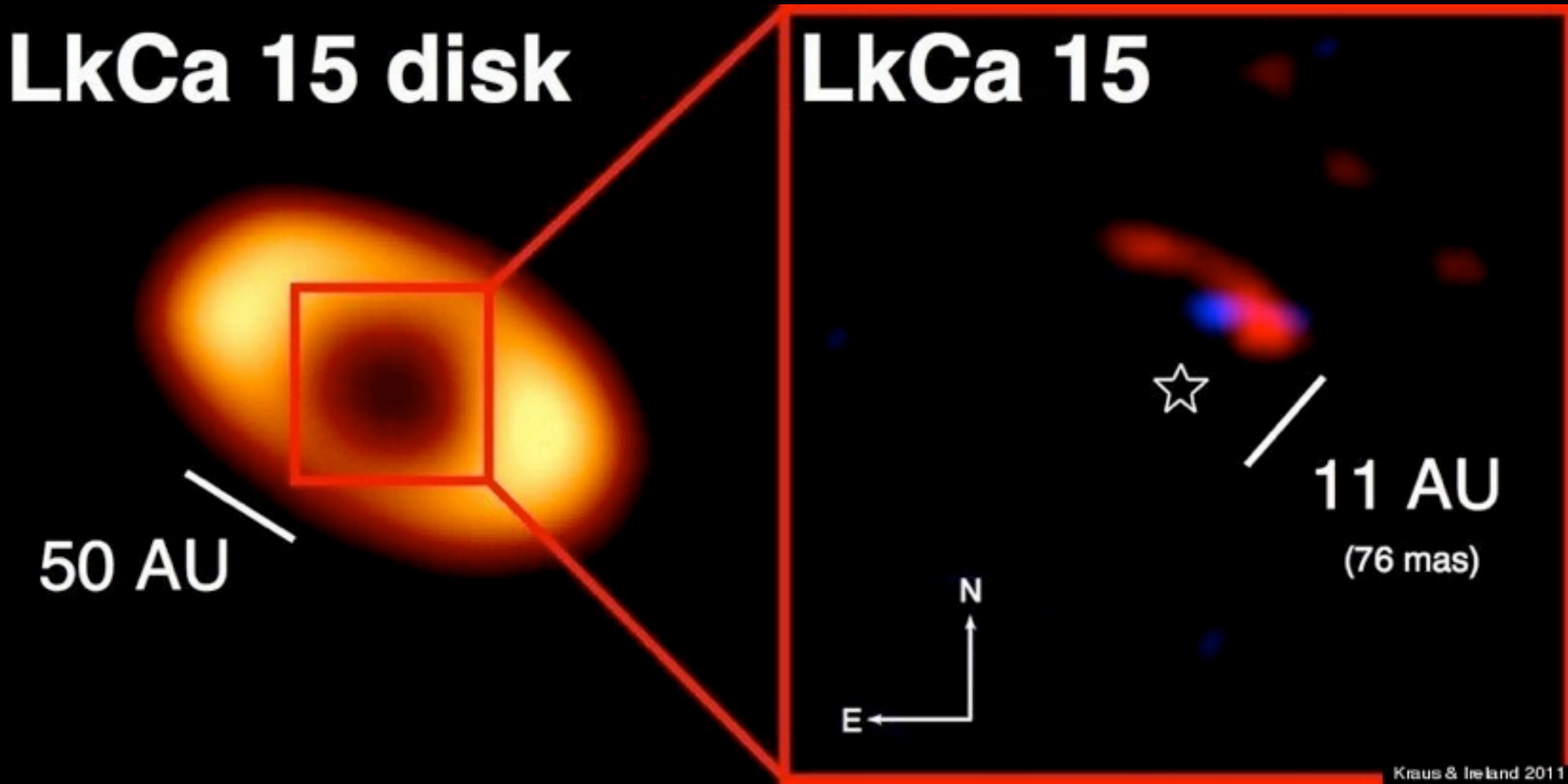
Sivaramakrishnan et al, Astro2010T, 40

A game changer: AO



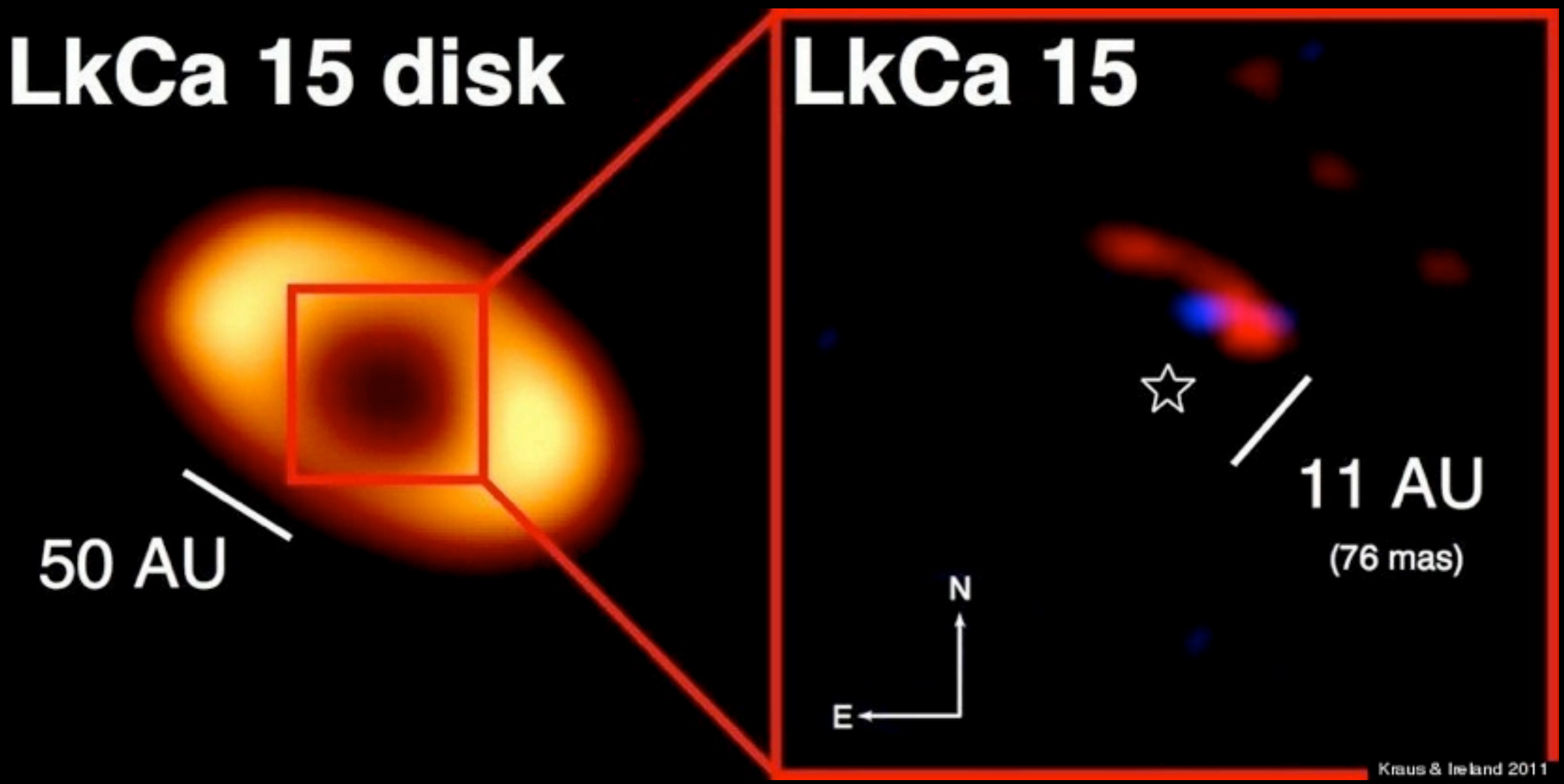
credit: Pr. James Lloyd

closure-phase planet direct detection



Transition-disk host star in
Taurus association (150 pc)
Companion detected @ 11 AU

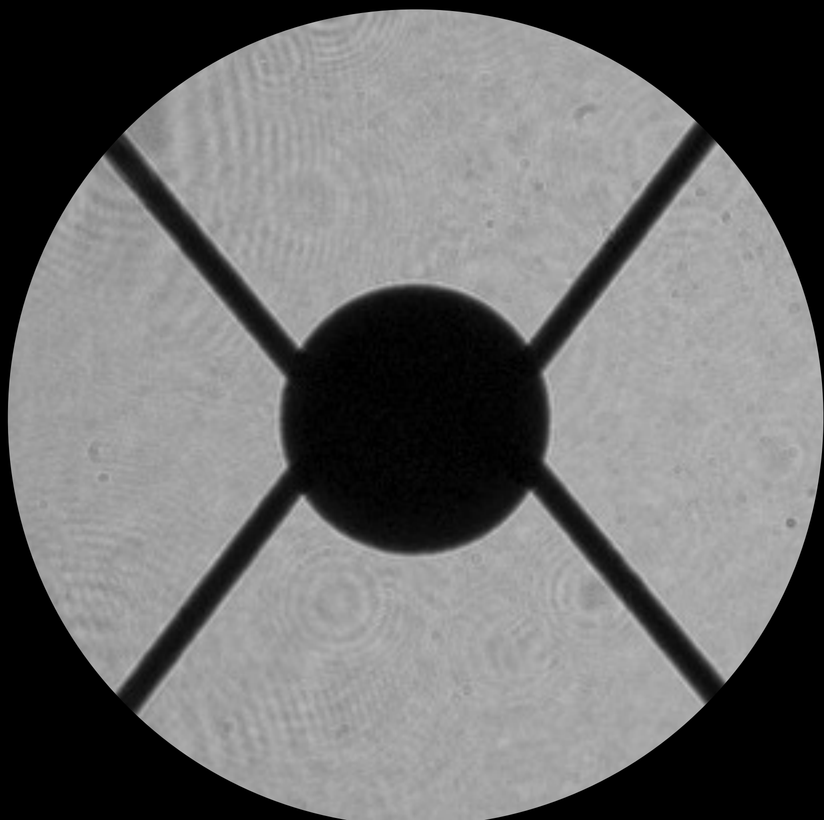
closure-phase planet direct detection



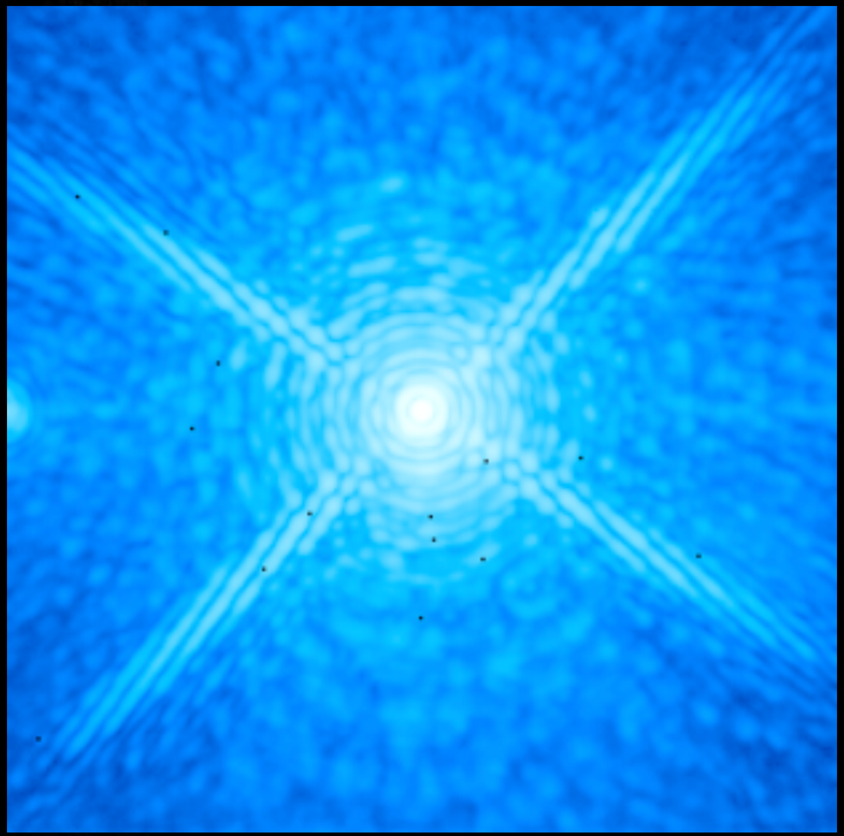
Transition-disk host star in Taurus association (150 pc)
Companion detected @ 11 AU

Kraus & Ireland, 2012, ApJ, 745, 5

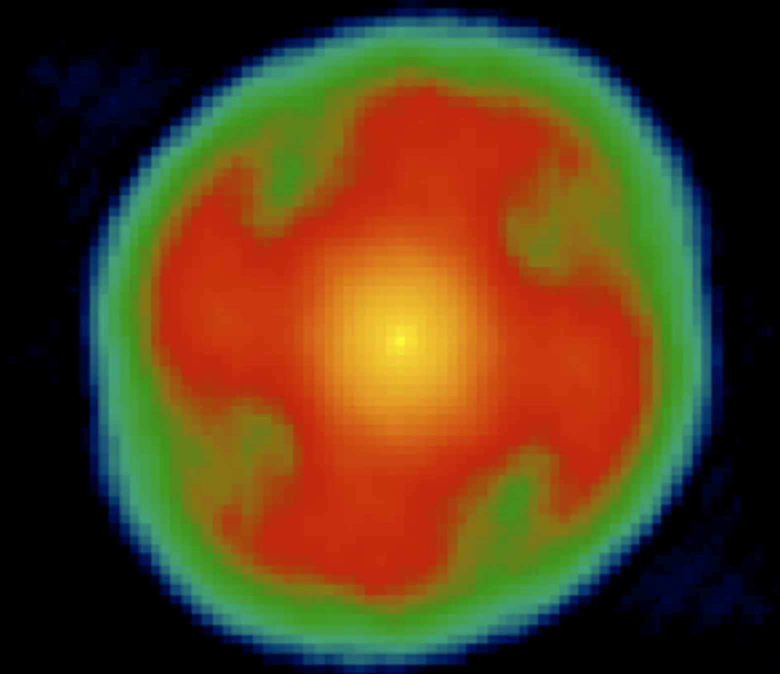
If only one didn't have to mask...



pupil

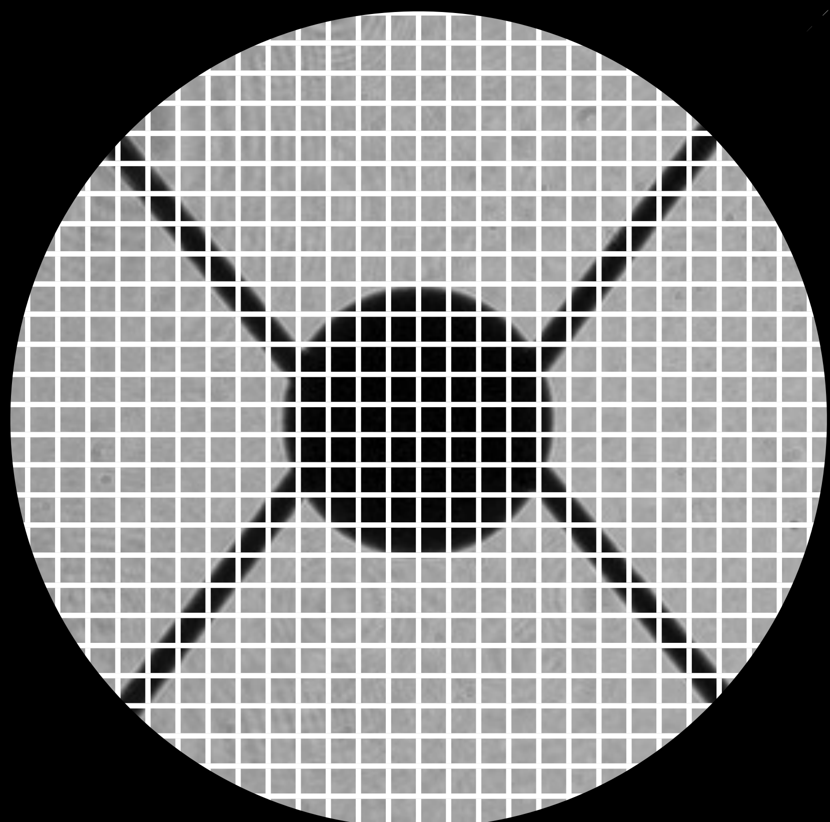


~~interferogram~~
image

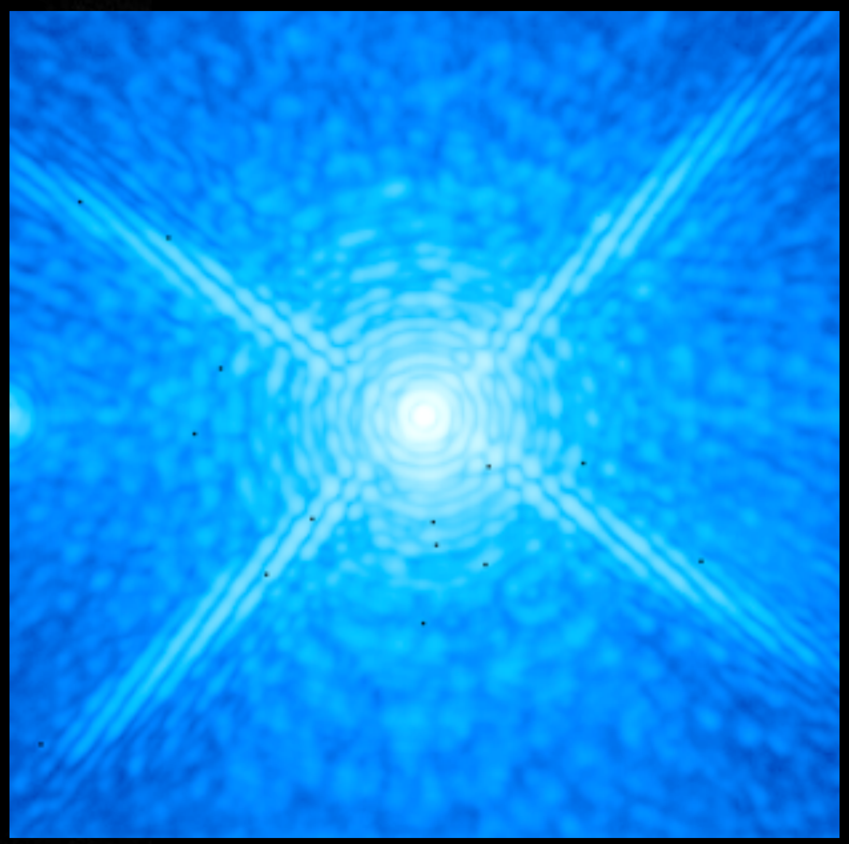


uv-plane

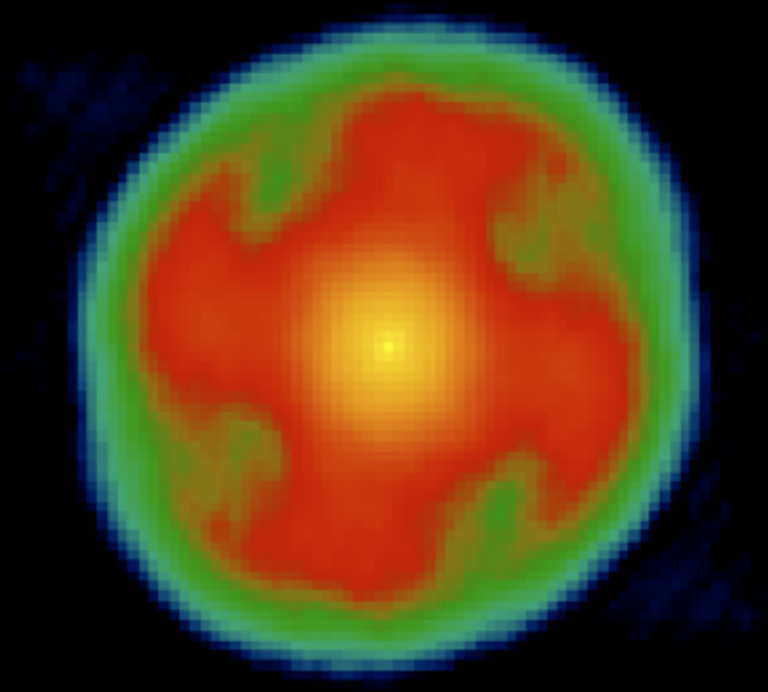
If only one didn't have to mask...



pupil



~~interferogram~~
image

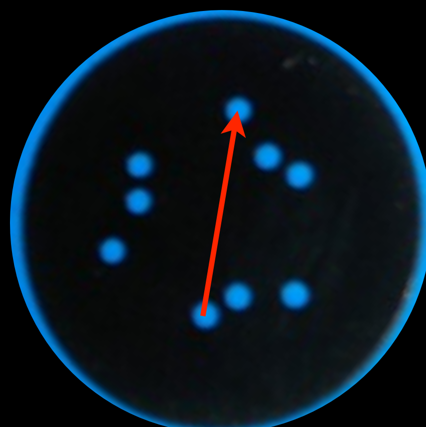


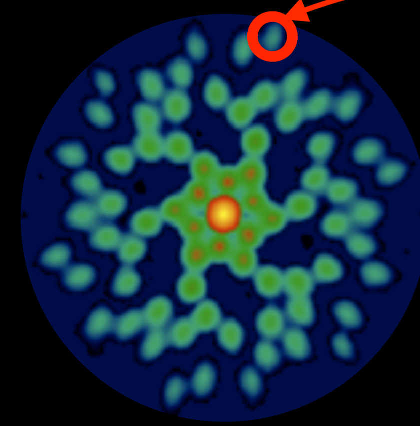
uv-plane

Telescopes apertures are redundant

with AO, the phase can be linearized

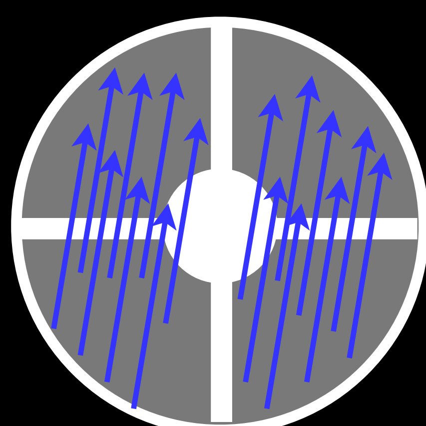
non-redondant

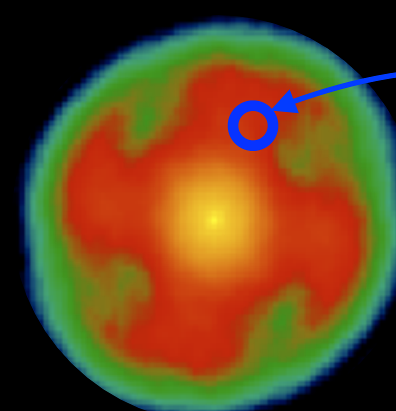




$\Phi_j = \Phi_{0j} + 1\ \Delta\varphi$

full aperture

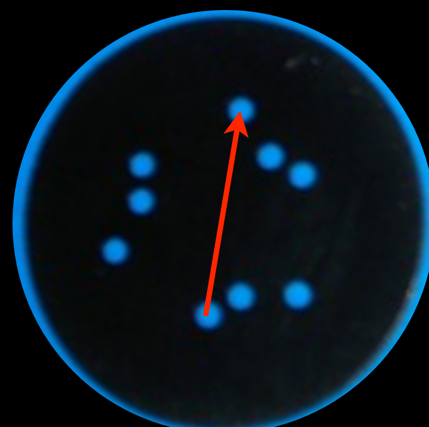


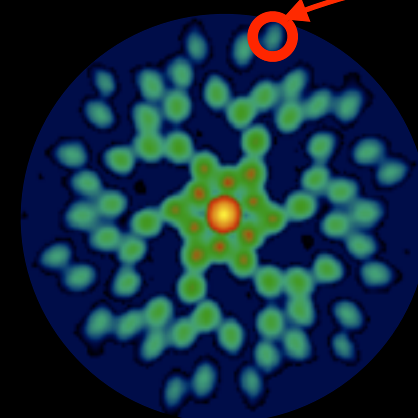


$\Phi_j = \Phi_{0j} + \mathrm{Arg}(\Sigma e^{j\ \Delta\varphi i})$

with AO, the phase can be linearized

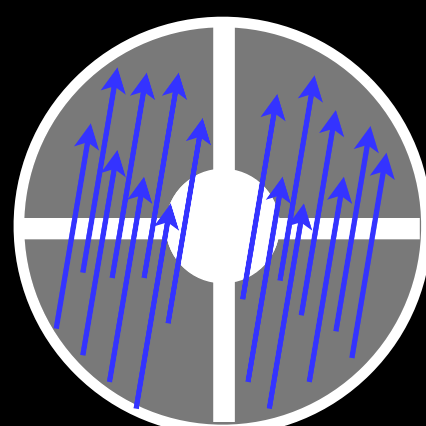
non-redondant

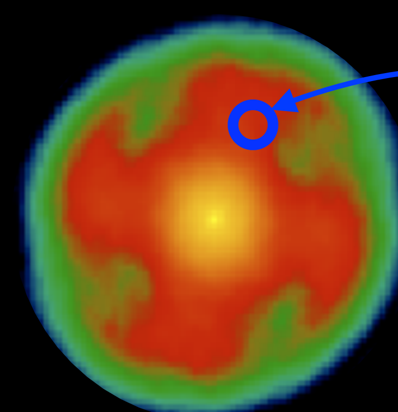




$$\Phi_j = \Phi_{0j} + 1\ \Delta\varphi$$

full aperture

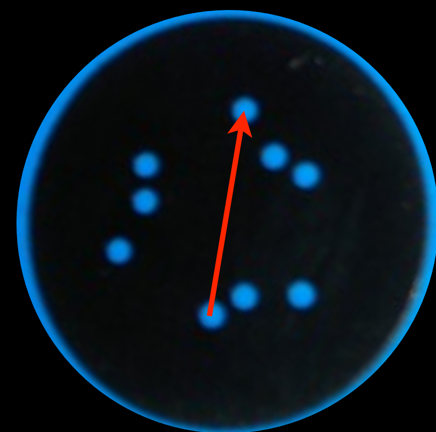


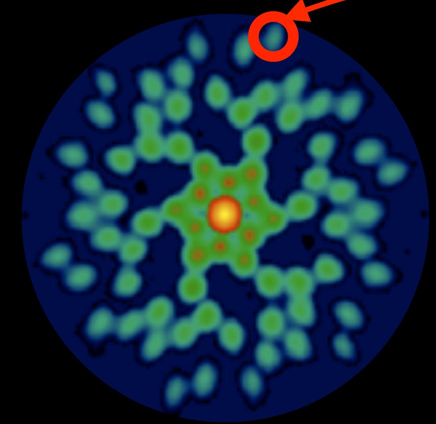


$$\Phi_j = \Phi_{0j} + \mathrm{Arg}(\Sigma e^{j\ \Delta\varphi i})$$

with AO, the phase can be linearized

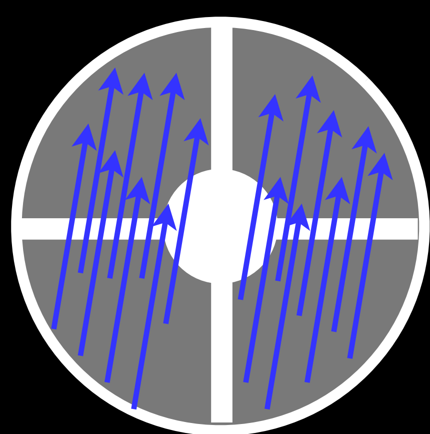
non-redondant

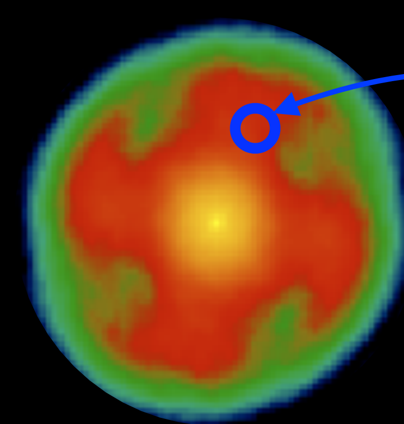




$$\Phi_j = \Phi_{0j} + 1\ \Delta\varphi$$

full aperture

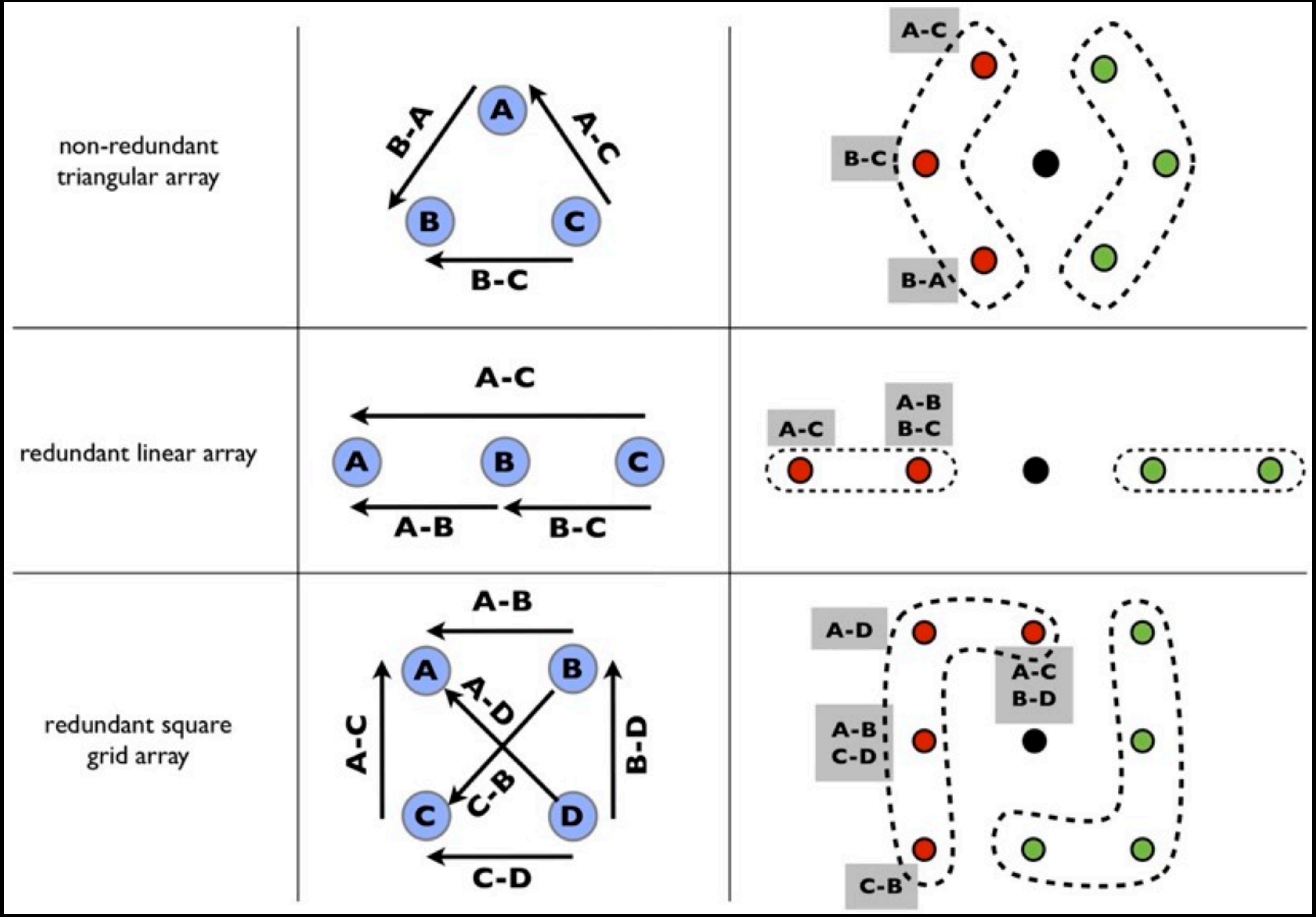




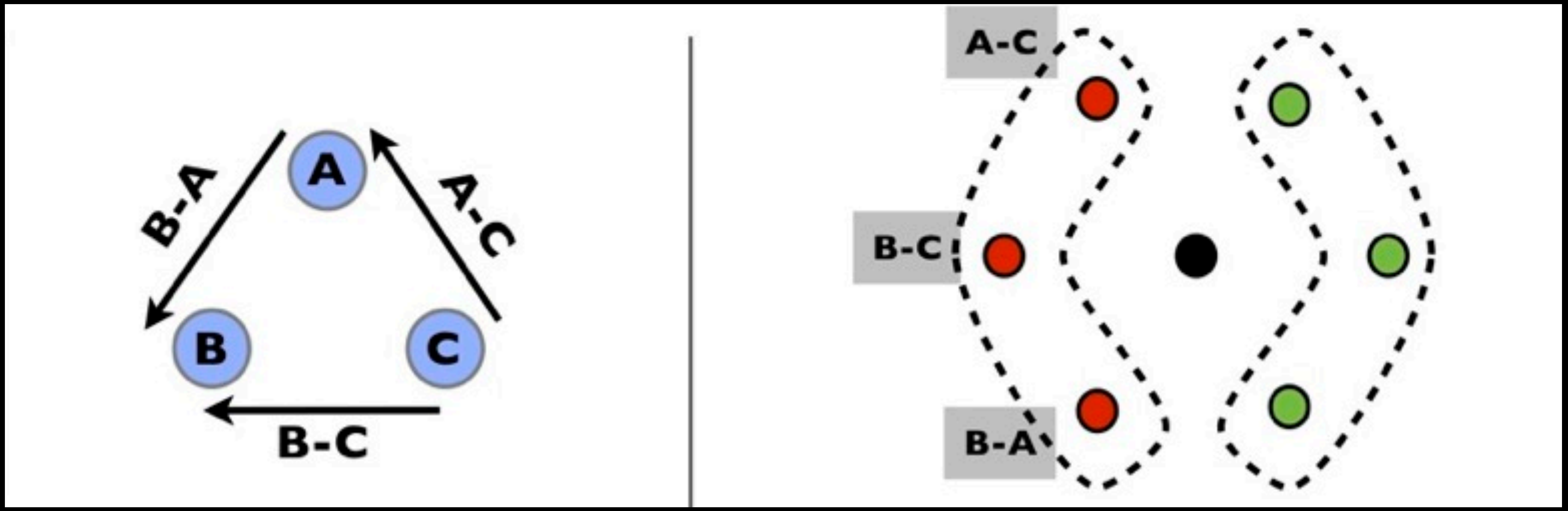
$$\Phi_j = \Phi_{0j} + \mathrm{Arg}(\Sigma e^{j\ \Delta\varphi i})$$

$$\Phi_j = \Phi_{0j} + 1/n_j\ \Sigma_i\ \Delta\varphi i$$

the 3 basic configurations



1. the easy non-redundant one



$$\Phi^{BC} = \Phi^{BC}_0 + (\varphi_B - \varphi_C)$$
$$\Phi^{AC} = \Phi^{AC}_0 + (\varphi_A - \varphi_C)$$
$$\Phi^{BA} = \Phi^{BA}_0 + (\varphi_B - \varphi_A)$$

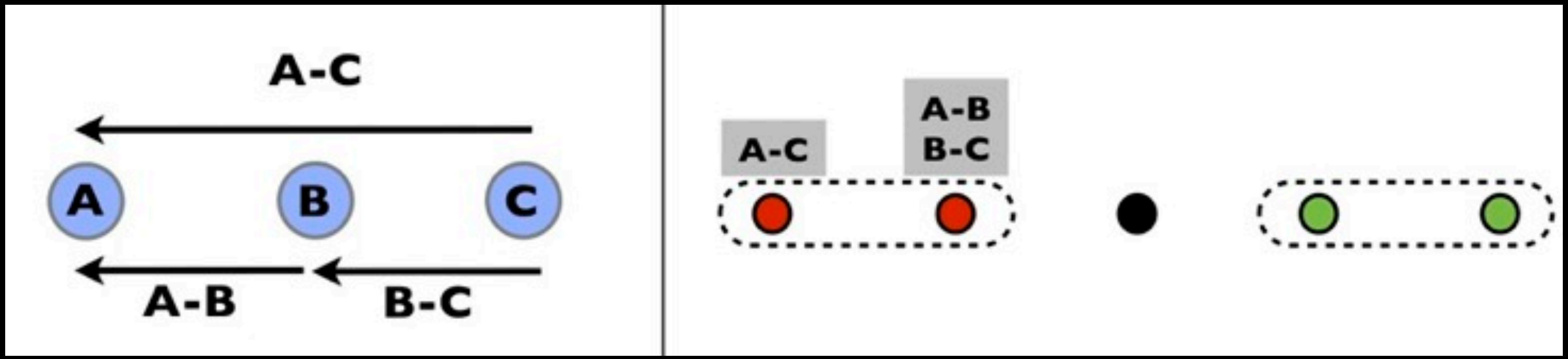
$\Rightarrow$

$$\Phi = \Phi_0 + \mathbf{A}\,\varphi$$

$$\mathbf{A} = \begin{bmatrix} 0 & 1 & -1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{bmatrix}$$

$\mathbf{K} = [1, 1, 1]$ verifies $\mathbf{K} \cdot \mathbf{A} = 0$: the closure phase

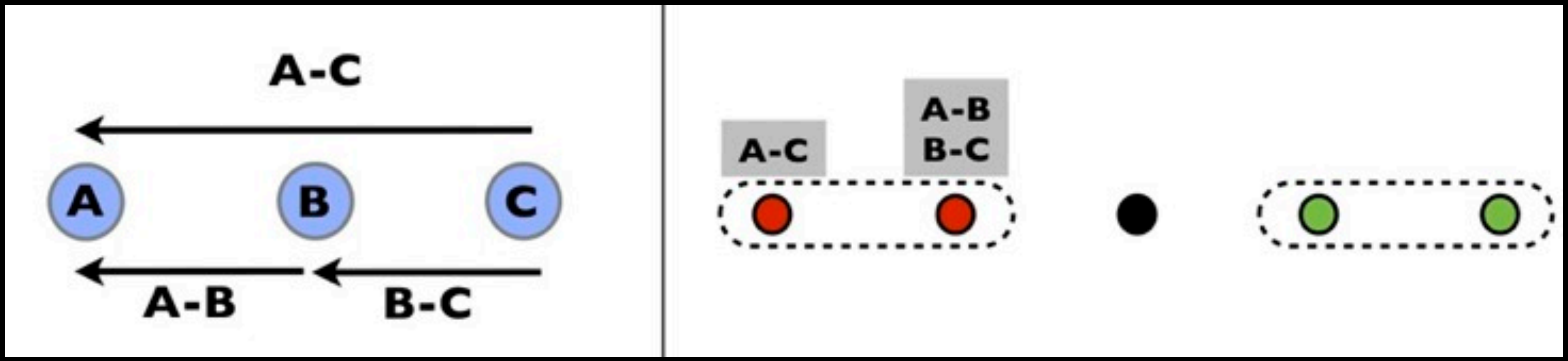
2. the first redundant case



$\Phi^{AC} = \Phi^{AC}{}_0 + (\varphi_A - \varphi_C)$

$\Phi' = \mathrm{Arg}[\exp i(\Phi'_0 + (\varphi_A - \varphi_B)) + \exp i(\Phi'_0 + (\varphi_B - \varphi_C))]$

2. the first redundant case



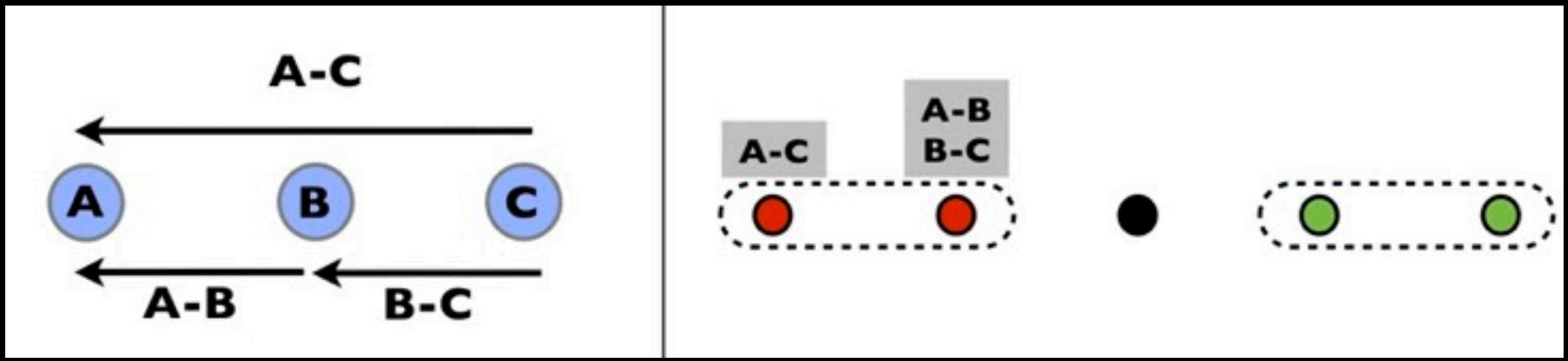
$$\Phi = \Phi_0 + \mathbf{R}^{-1}\,\mathbf{A}\,\varphi$$

$$\Phi^{AC} = \Phi^{AC}{}_0 + (\varphi_A - \varphi_C)$$

$$\Phi' = \Phi'_0 + \tfrac{1}{2}(\varphi_A - \varphi_C)$$

$$\Rightarrow \quad \mathbf{R}^{-1} = \begin{bmatrix} 1 & 0 \\ 0 & \tfrac{1}{2} \end{bmatrix} \qquad \mathbf{A} = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 0 & -1 \end{bmatrix}$$

2. the first redundant case



$$\Phi = \Phi_0 + \mathbf{R^{-1}}\,\mathbf{A}\,\varphi$$

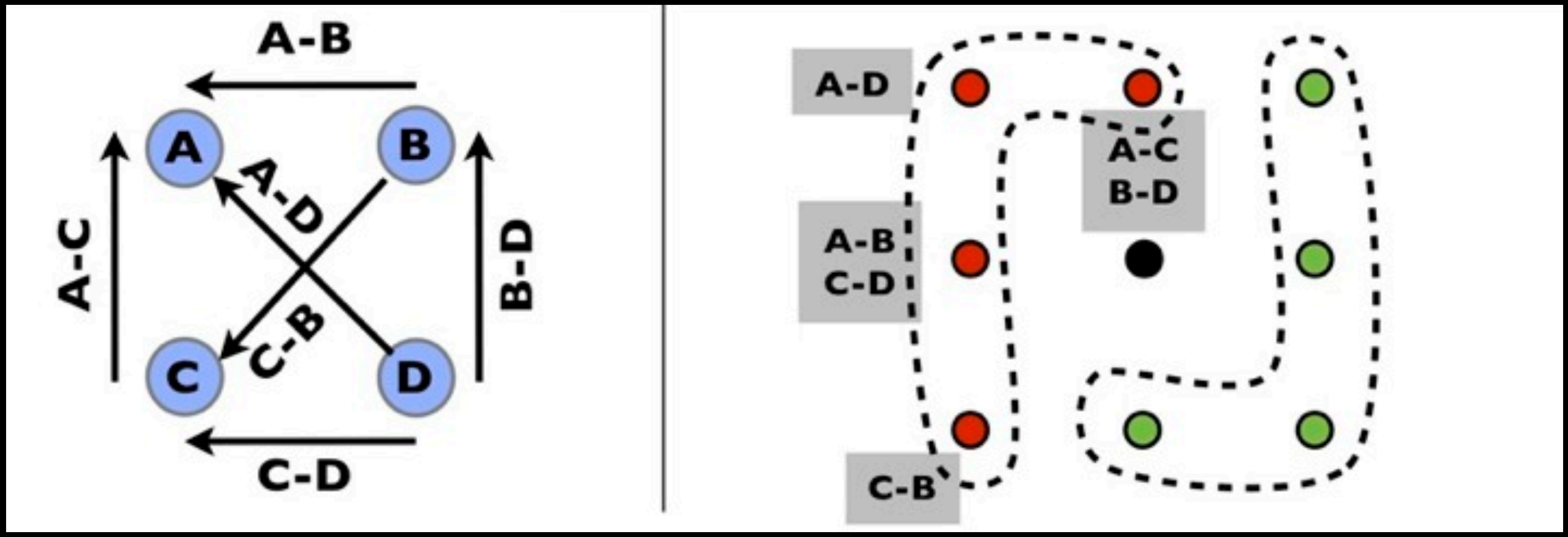
$$\Phi^{AC} = \Phi^{AC}{}_0 + (\varphi_A - \varphi_C)$$

$$\Phi' = \Phi'_0 + ½\,(\varphi_A - \varphi_C)$$

$$\mathbf{R^{-1}} = \begin{bmatrix} 1 & 0 \\ 0 & ½ \end{bmatrix} \qquad \mathbf{A} = \begin{bmatrix} 1 & 0 & -1 \\ 1 & 0 & -1 \end{bmatrix}$$

K = [1, -2] verifies **K R^{-1}A** = 0: the **kernel-phase**

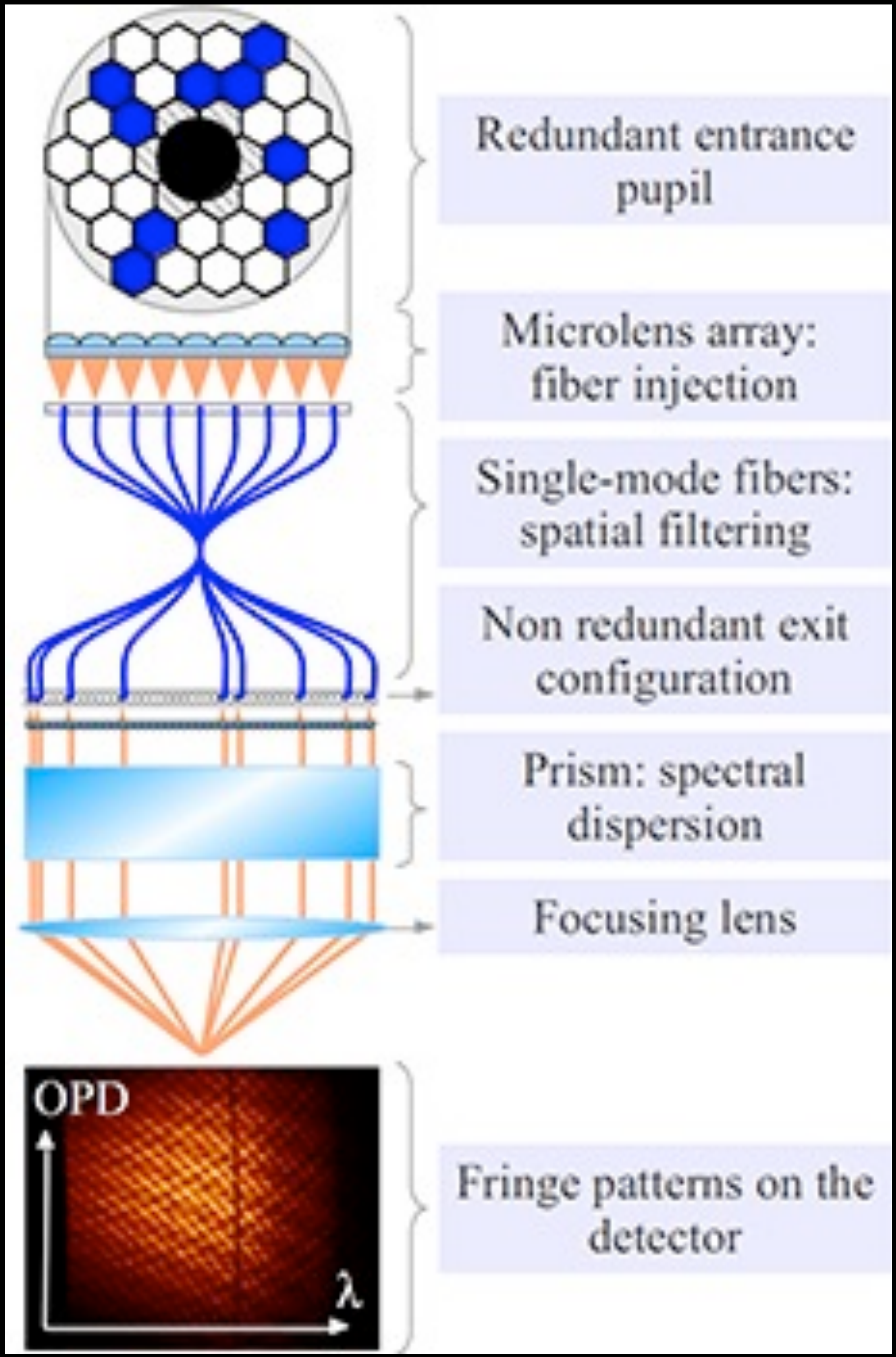
3. the real first case



$$\mathbf{R}^{-1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \tfrac{1}{2} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & \tfrac{1}{2} \end{bmatrix} \qquad \mathbf{A} = \begin{bmatrix} 1 & 0 & 0 & -1 \\ 1 & -1 & 1 & -1 \\ 0 & -1 & 1 & 0 \\ 1 & 1 & -1 & -1 \end{bmatrix} \qquad \mathbf{K} = \begin{bmatrix} 1 & -2 & 1 & 0 \\ 1 & 0 & -1 & -2 \end{bmatrix}$$

You can extract self-calibrating observables from redundant apertures

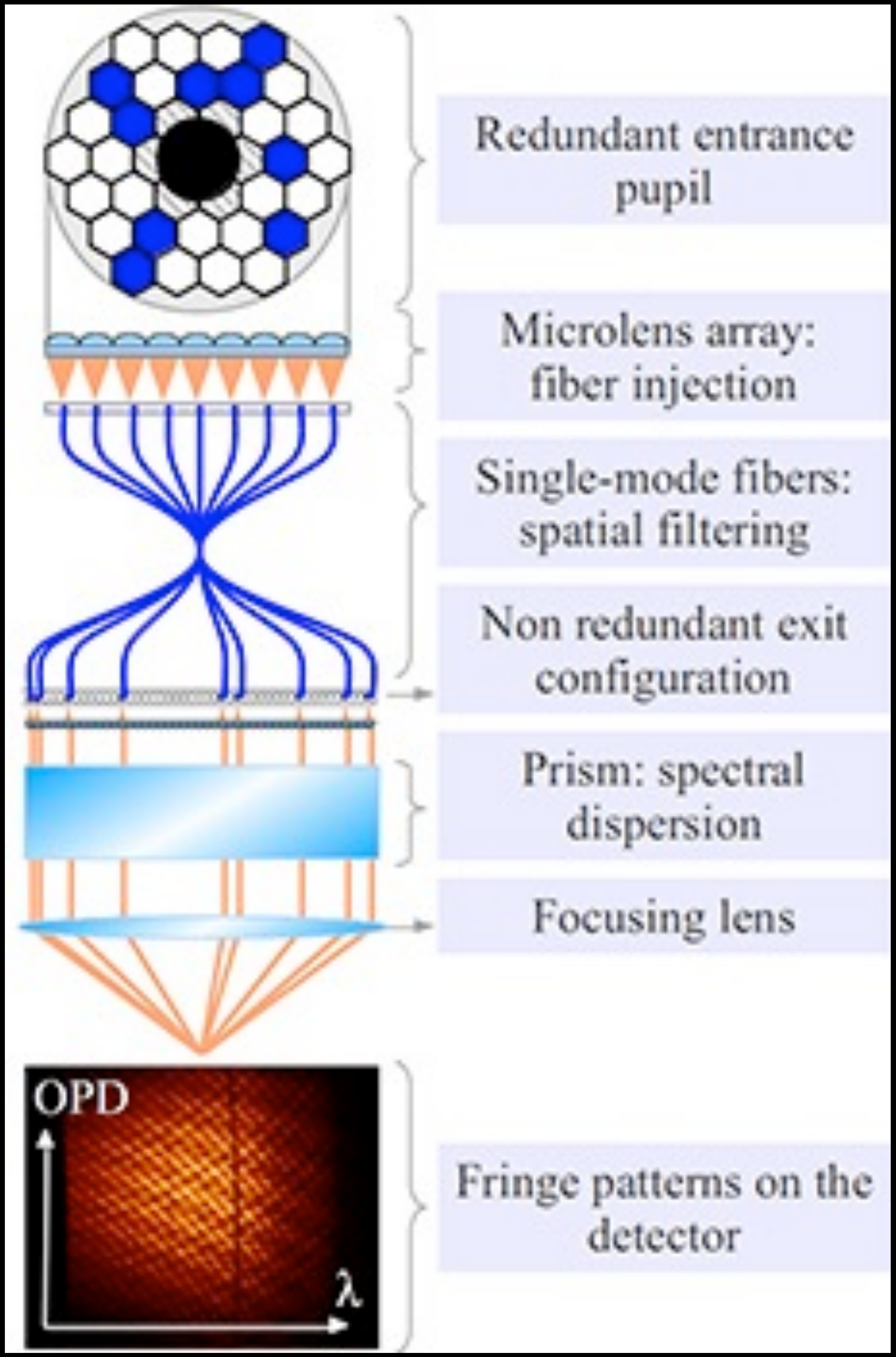
This is of some consequence...



<u>FIRST</u>:
- 36-beam combiner
- fiber remapping
- spatial filtering

Perrin et al, 2006

This is of some consequence...

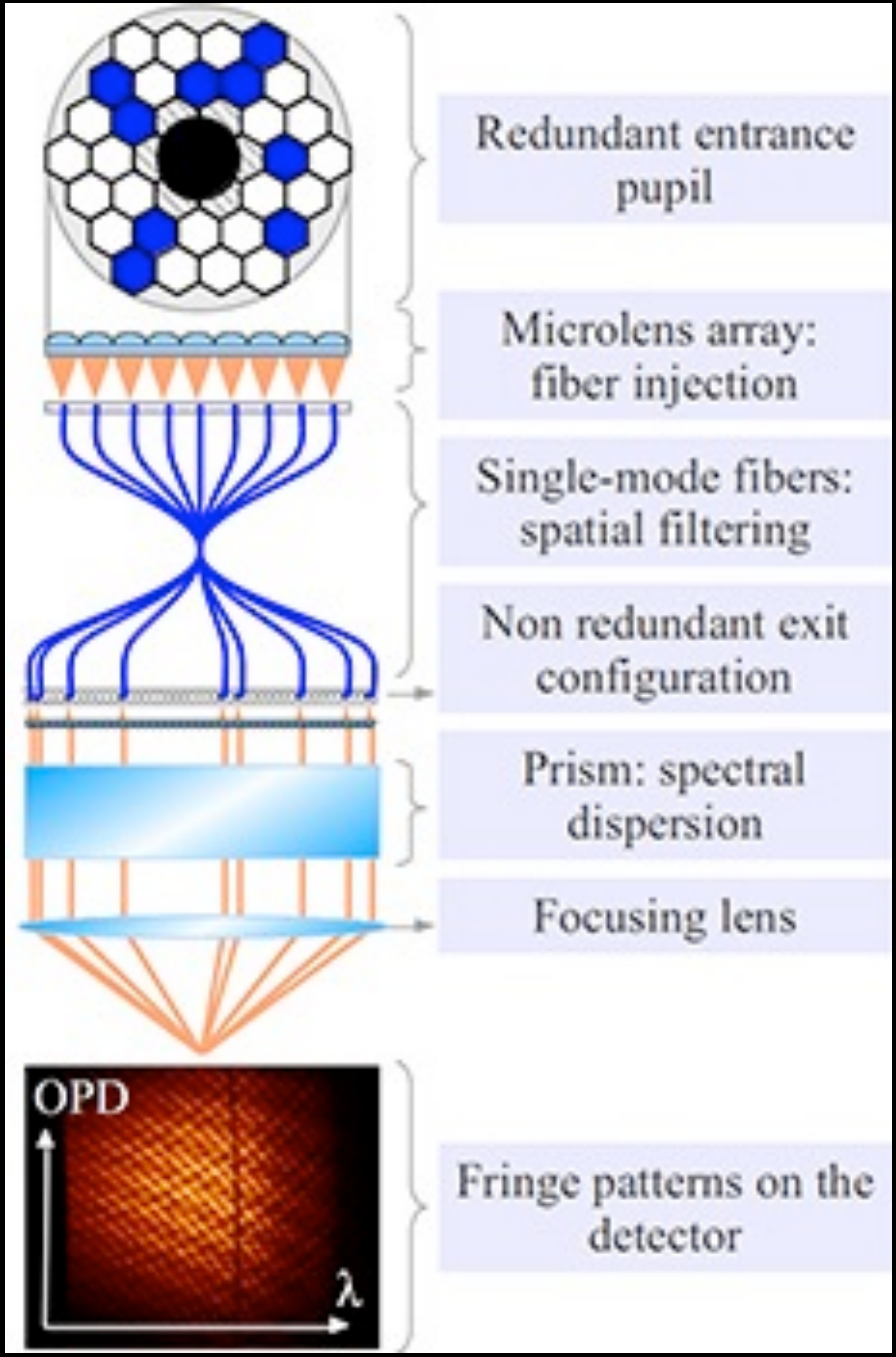


FIRST:
- 36-beam combiner
- fiber remapping
- spatial filtering

With AO, redundancy is a false problem

Perrin et al, 2006

This is of some consequence...

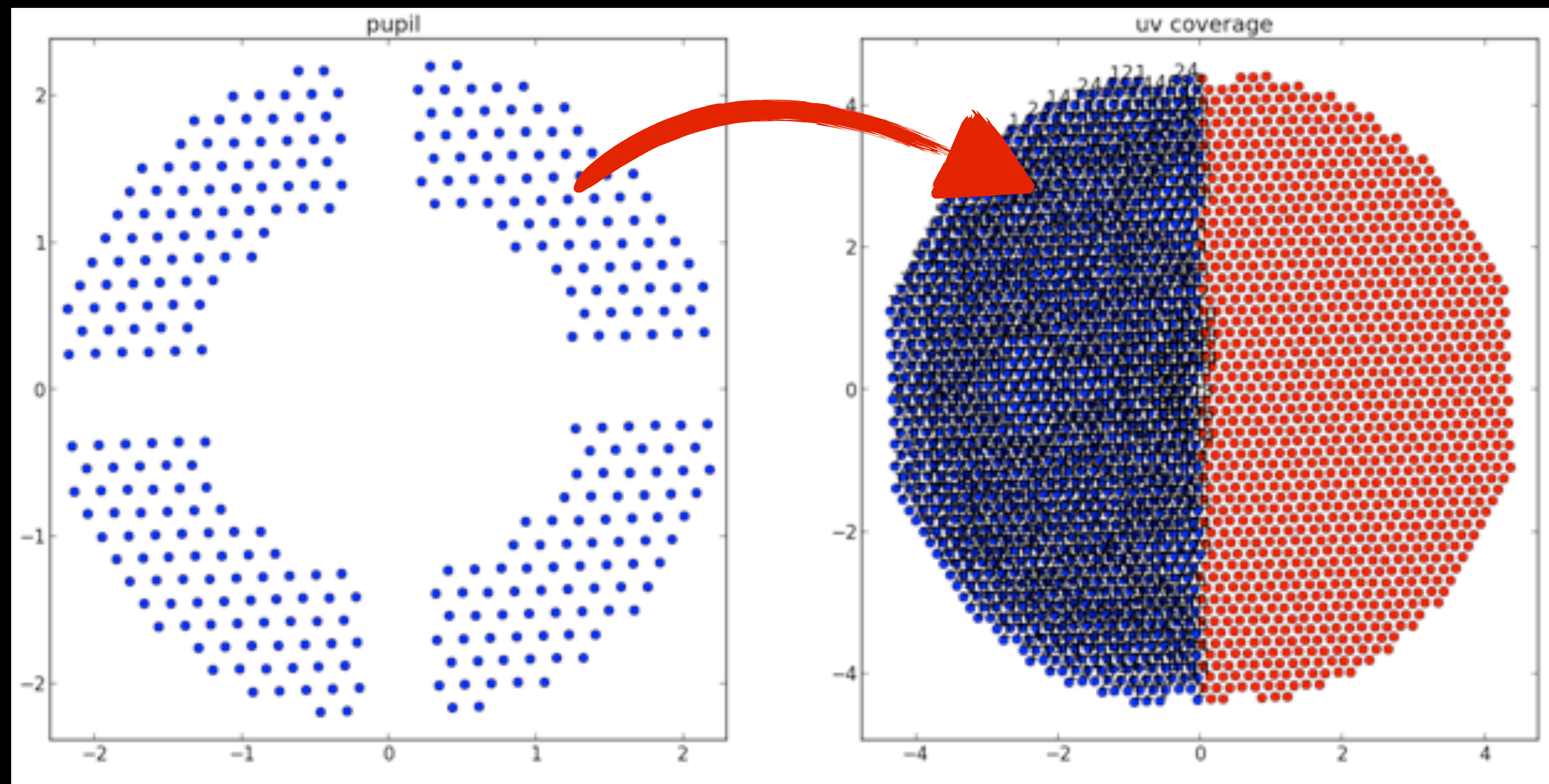


FIRST:
- 36-beam combiner
- fiber remapping
- spatial filtering

With AO, redundancy is a false problem

Perrin et al, 2006

For a complex array... use a computer



$$[\Phi] = [\Phi_0] + [A'] \times [\varphi]$$

measured unknown known unknown

Kernel-phase

Find **K** so that **K**x**A** = 0, but how?

Use the Singular Value Decomposition (SVD) of A:

$$\mathbf{A} = \mathbf{U}\,\Sigma\,\mathbf{V}^{\mathbf{T}}$$

Rows of **K** form a basis for the left null space of **A**
These new closure relations are called kernel-phases

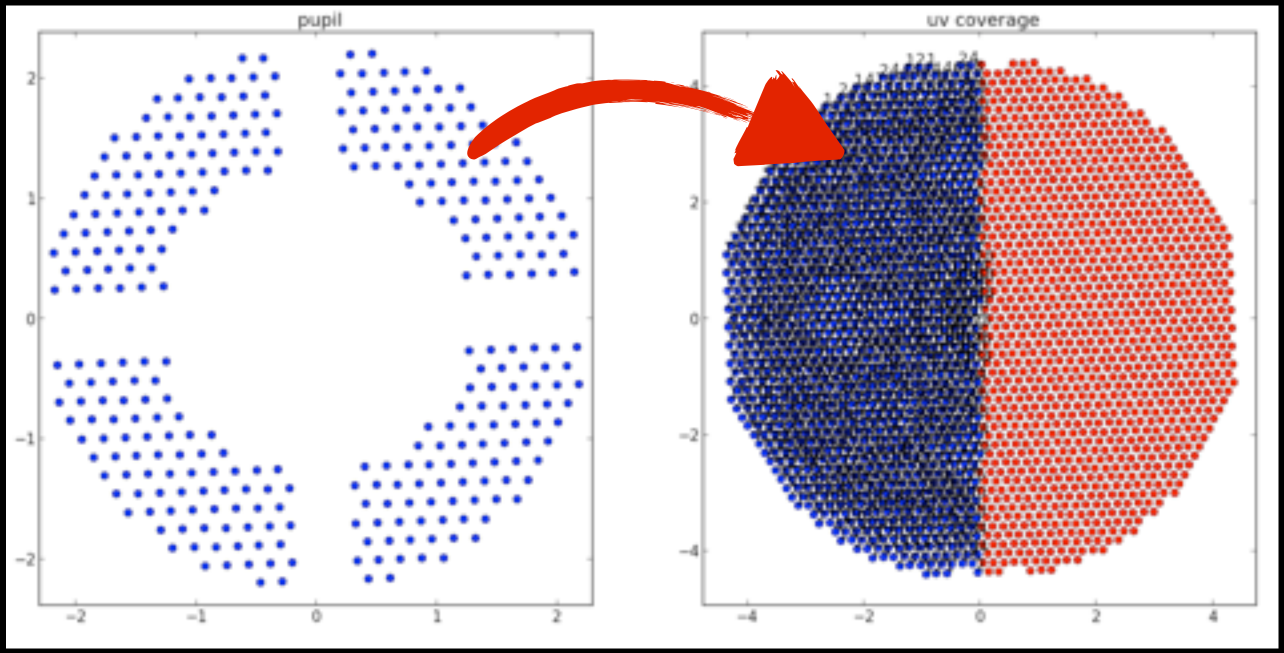
Martinache, 2010, ApJ, 724, 464

Data analysis

http://code.google.com/p/pysco/

Data analysis

1. Build a instrument model => A
2. Find the Kernel of A: K



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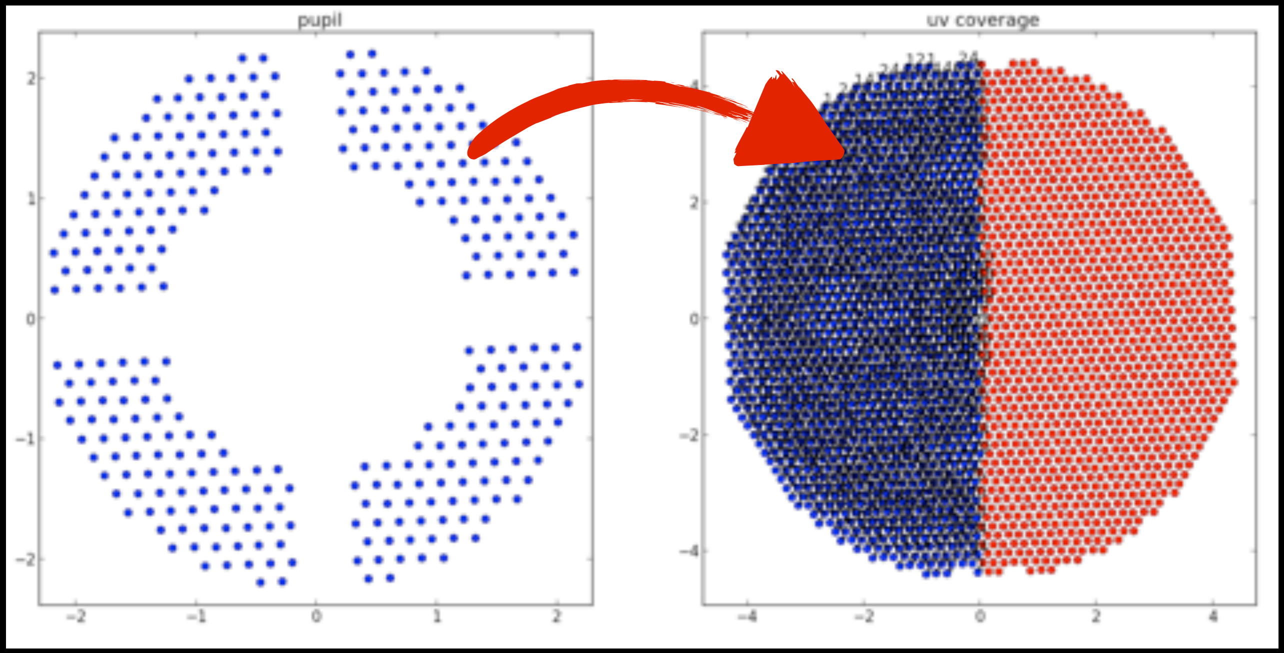
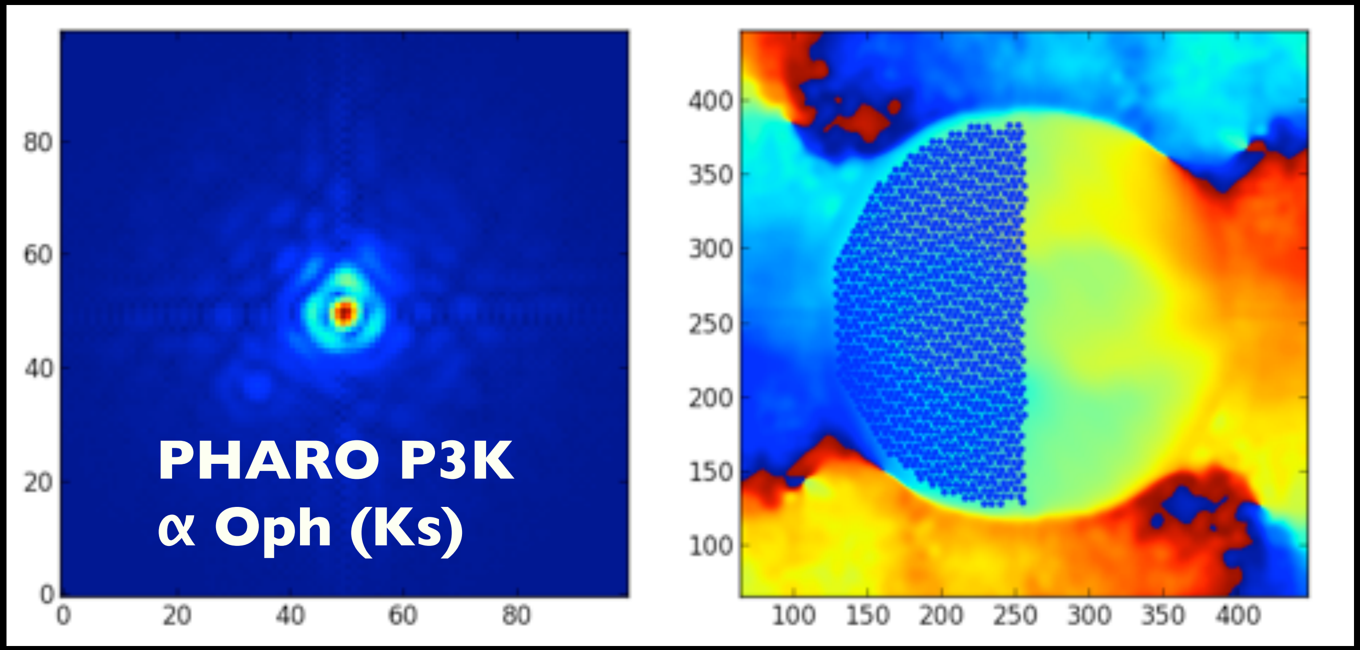


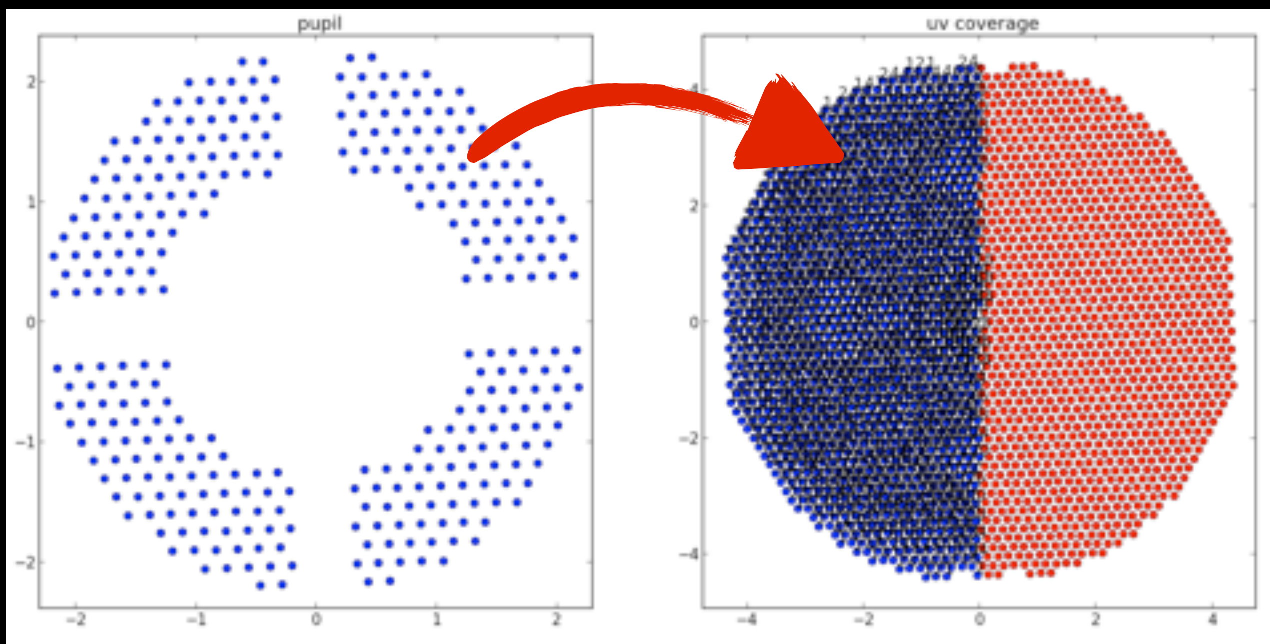
3. Fourier Transform each image
4. Extract phase ϕ



http://code.google.com/p/pysco/

Data analysis

1. Build a instrument model => A
2. Find the Kernel of A: K



3. Fourier Transform each image
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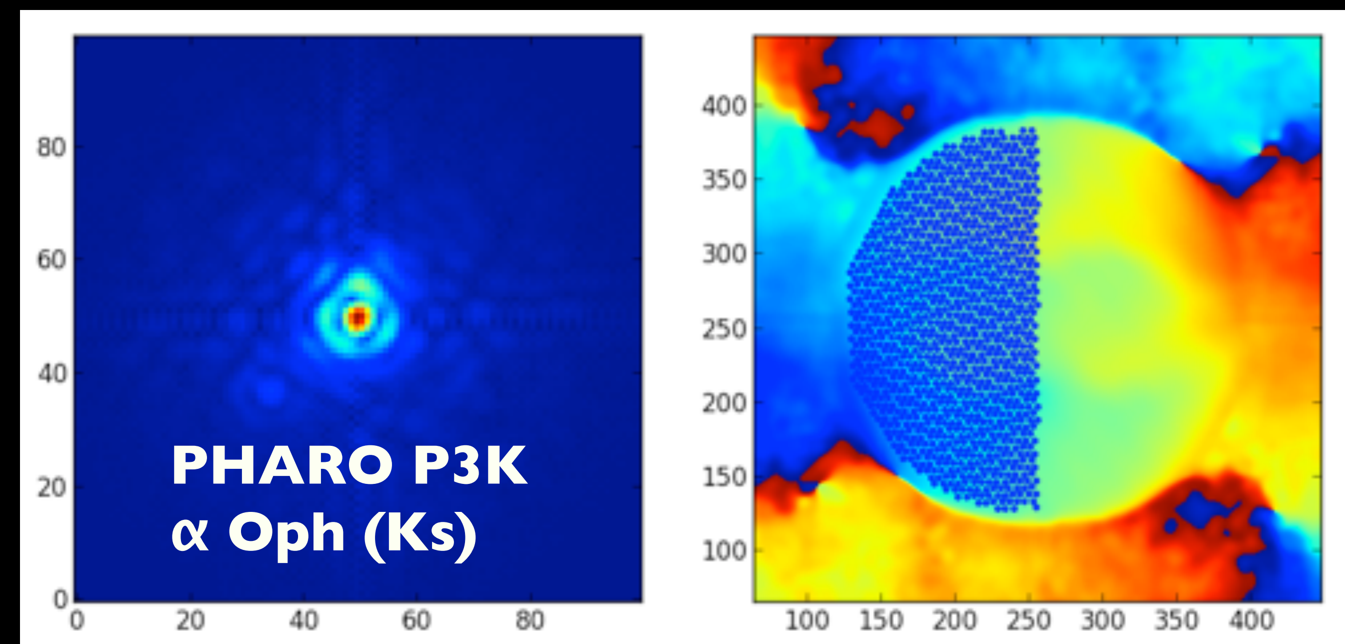
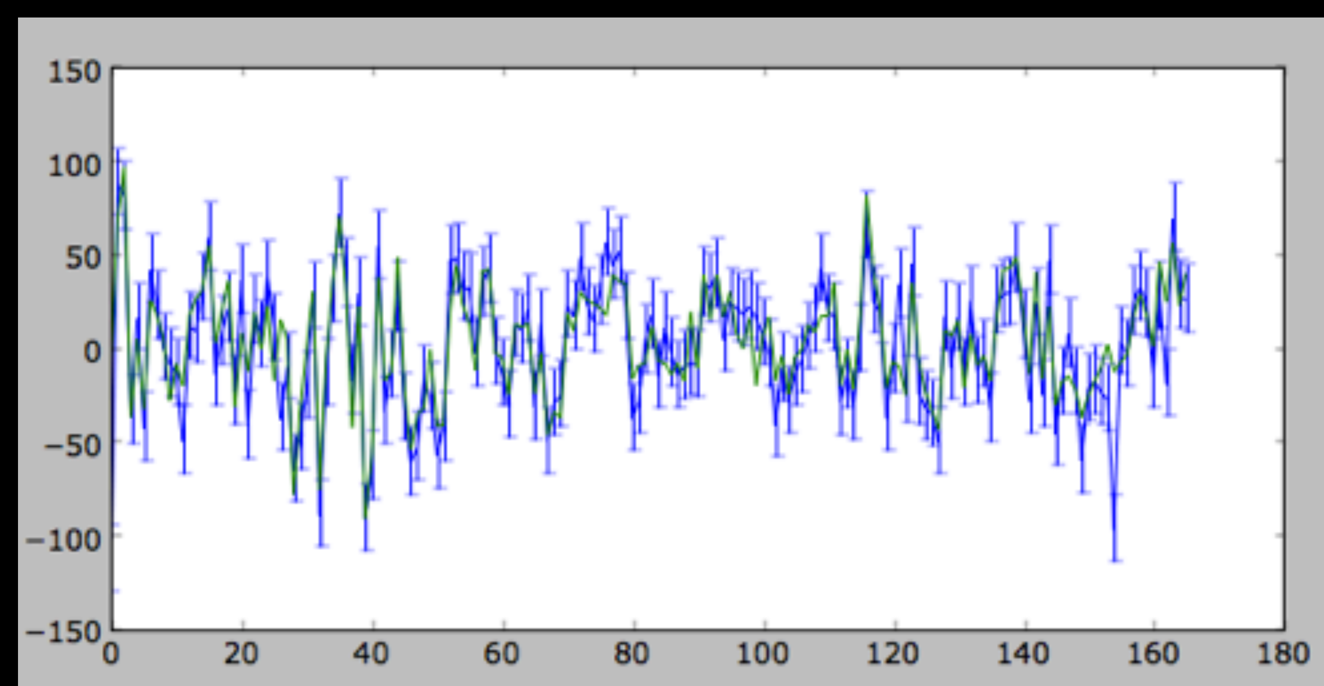


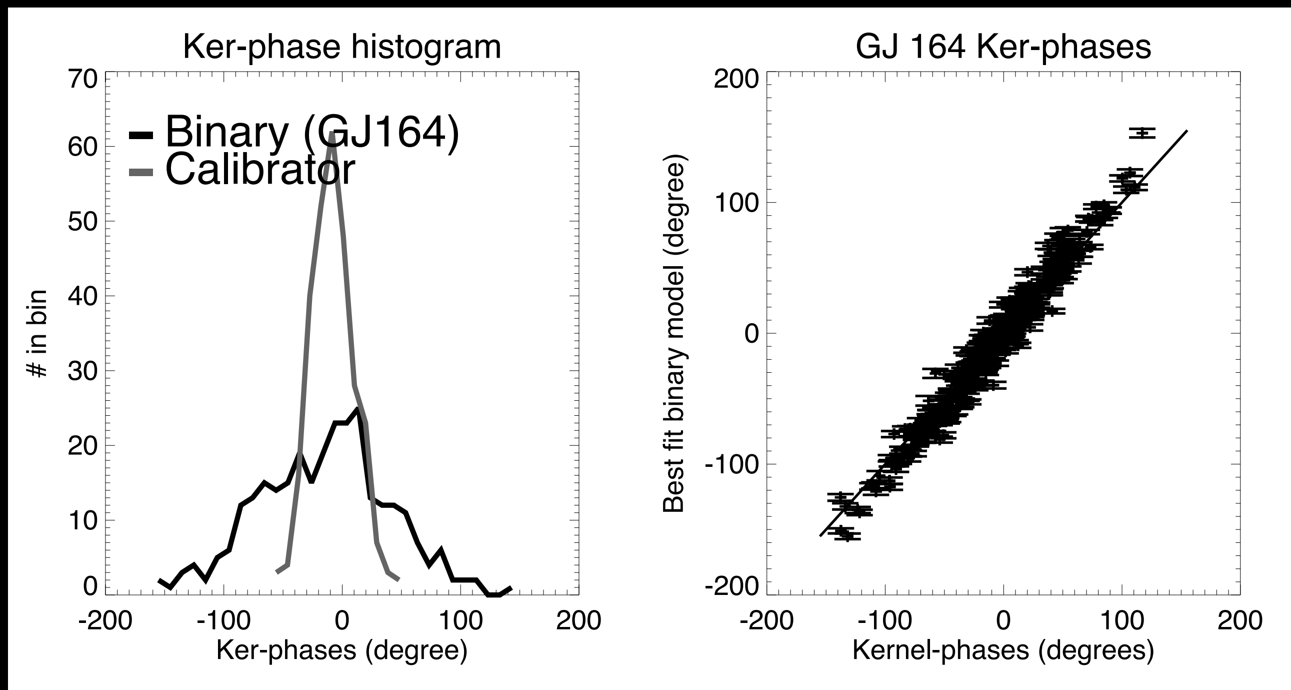
5. Multiply K ϕ: you are done!

<u>Additionally</u>:
- statistics
- model the data (e.g. binary)
- determine contrast limits



http://code.google.com/p/pysco/

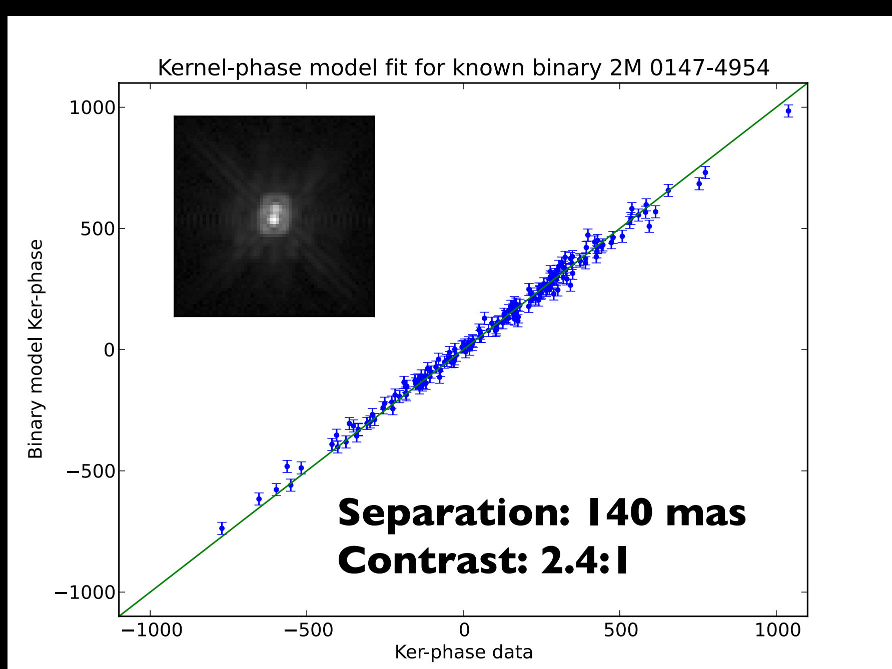
Kernel-phase in space

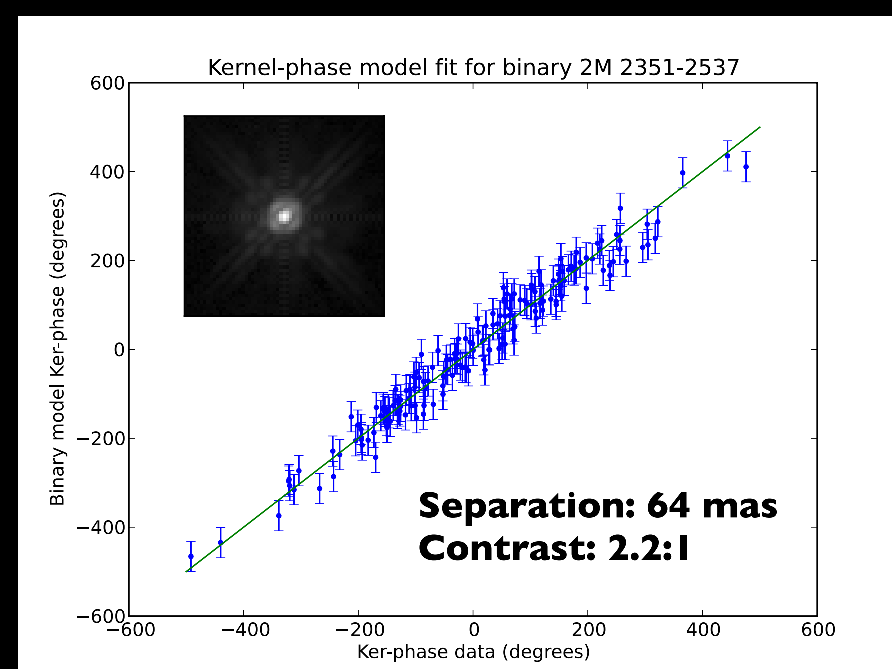


Data @ 1.9 μm (λ/D=150 mas)

A ~10:1 contrast companion to a nearby M-dwarf identified with **milli-arc-second precision** at **0.5 λ/D**

Martinache, 2010, ApJ, 724, 464





Original survey:
Reid et al, 2006, 2008

Revisit ~ 80 brown dwarfs observed with HST/NIC1 in the F110W and F170M filters

- Doubled the fraction of known L-dwarf binary systems
- Improved astrometry x10

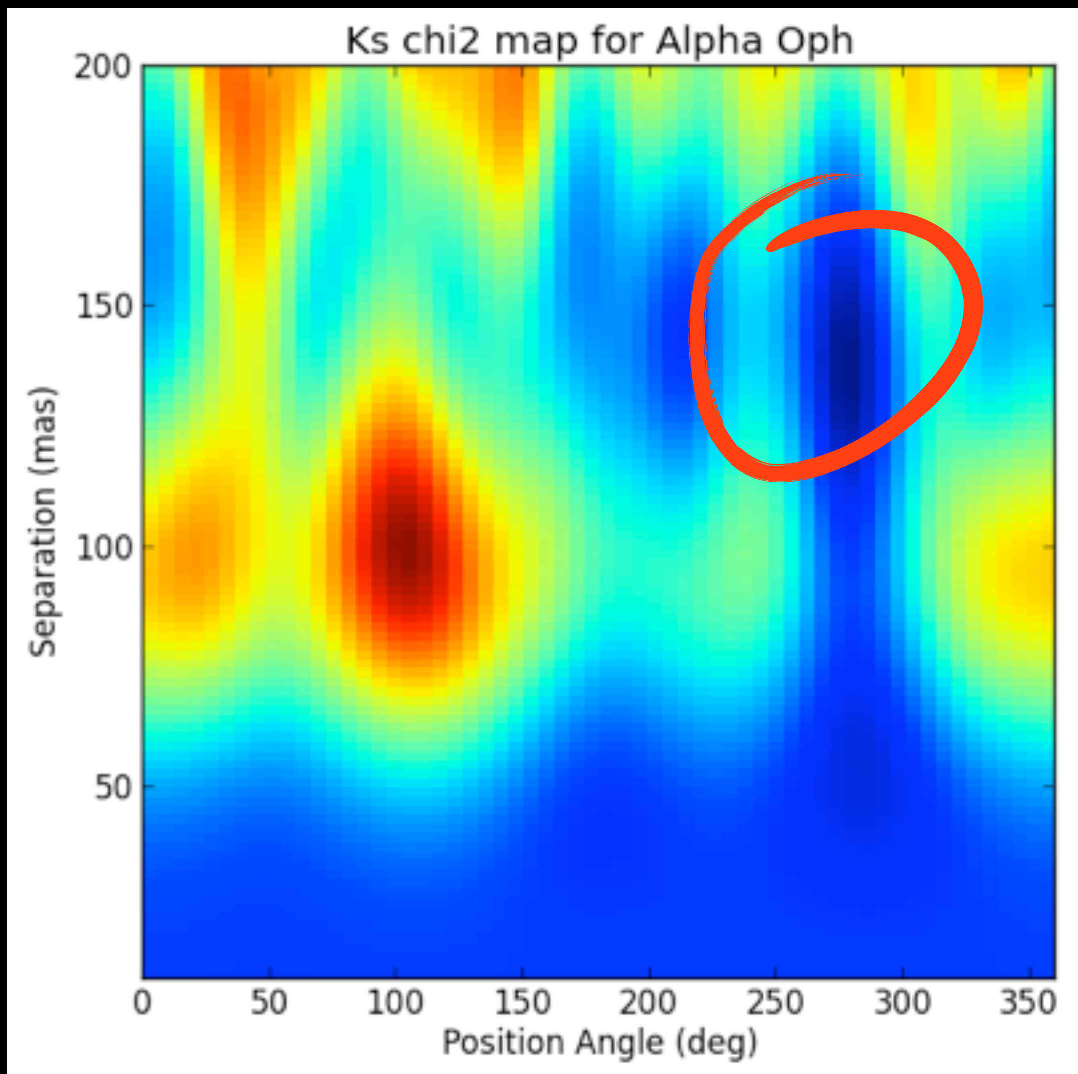
Grant HST-AR-12849.01-A

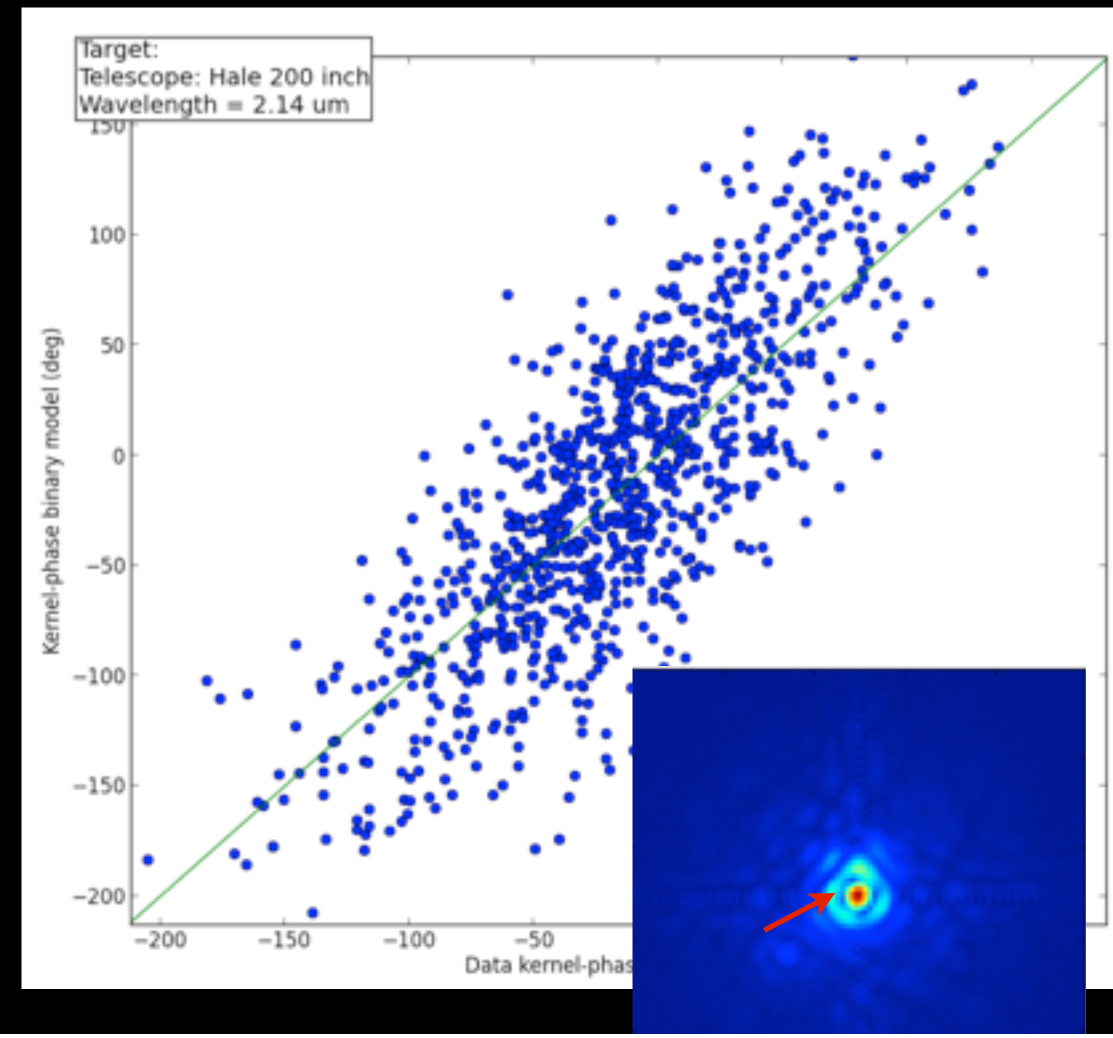
Pope et al, 2013, ApJ, 767, 110

Kernel-phase on ground based AO

Pope et al, 2015, in prep

Kernel-phase on ground based AO

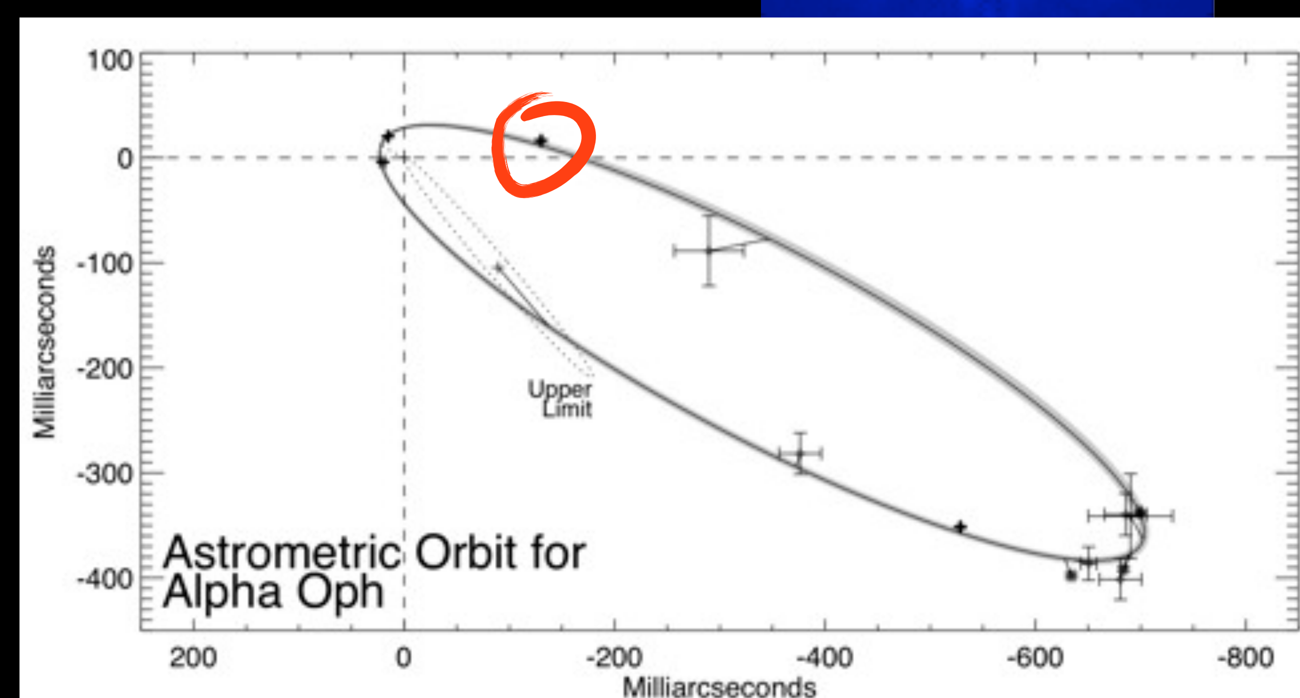




- Separation: 131.4 +/- 0.9 mas
- Position Angle: 86.0 +/- 0.2 deg
- Contrast: 19.7 +/- 0.4

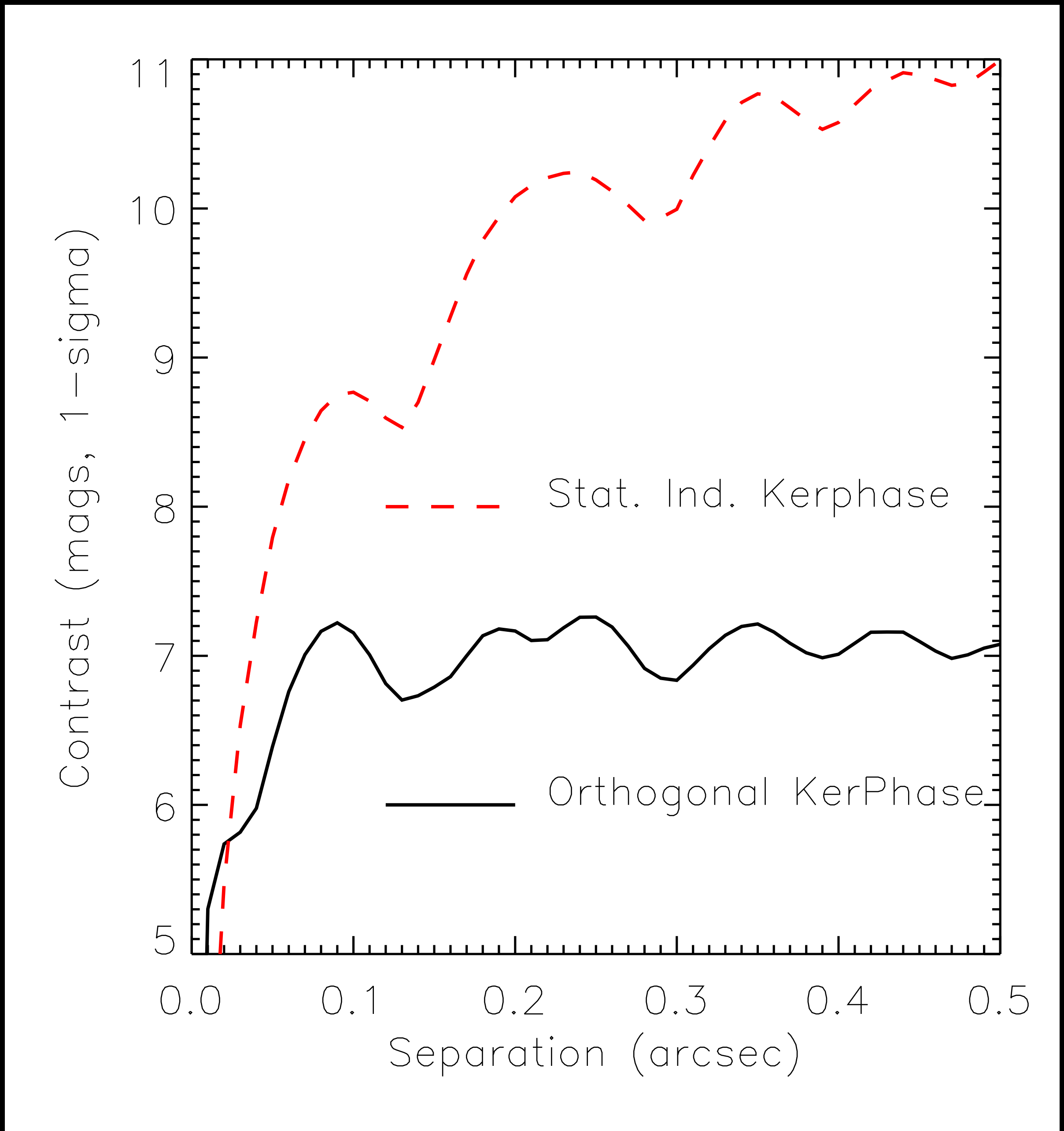
Data, courtesy of S. Hinkley

Pope et al, 2015, in prep



Hinkley et al, 2011, ApJ, 726, 104

Better than the kernel-phase...



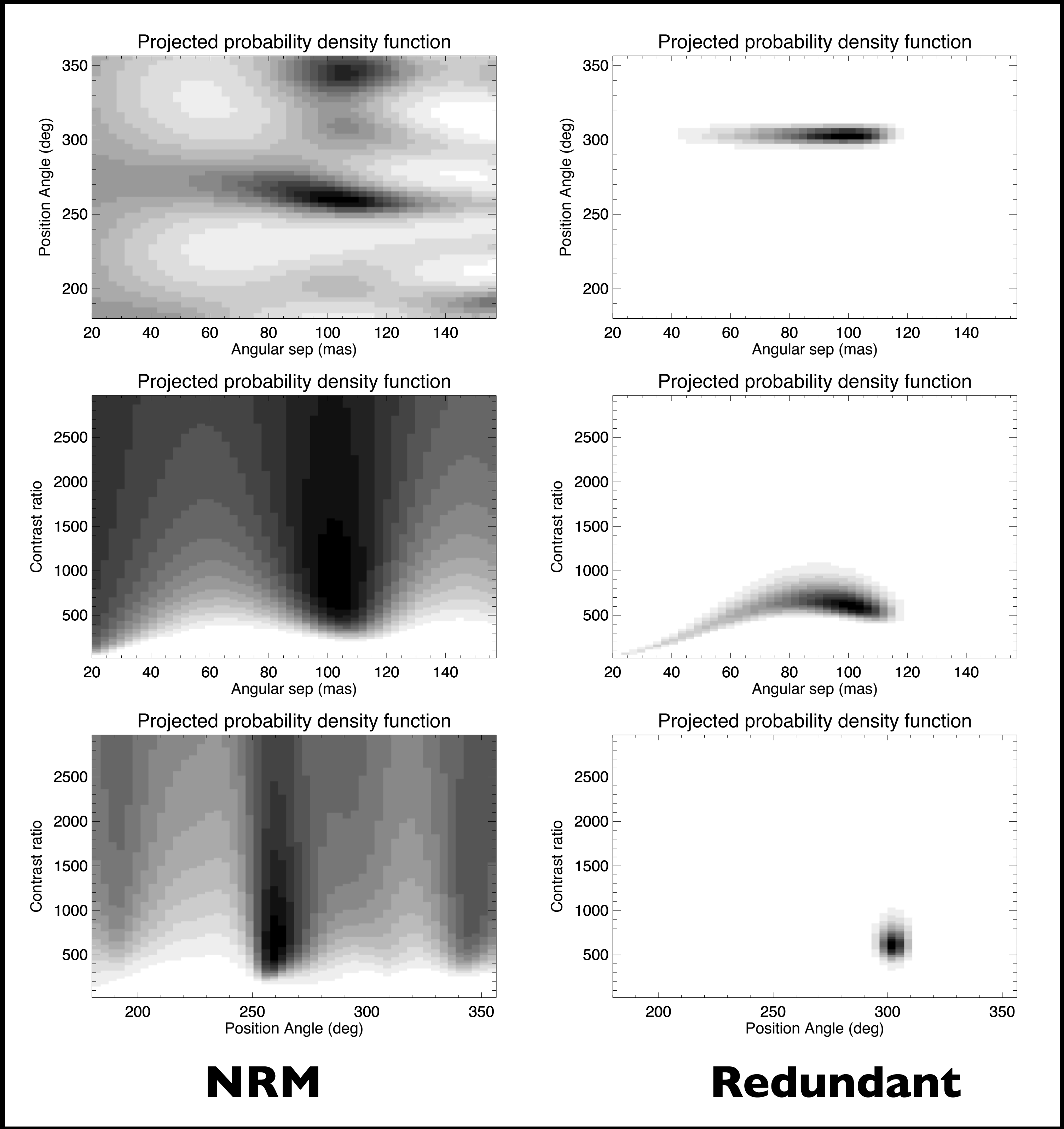
... are the statistically independent kernel-phases!

$$\theta = \mathbf{S.K.}\phi$$

Ireland, 2013, MNRAS, 433, 1718

Requires empirical covariance matrices
Part of a new file exchange standard?

Redundant is good for high contrast



Simulations for Palomar Hale Telescope PHARO full H-band filter

Strehl: 80 %
Δmag ~ 7 @ 1.5 λ/D
Calibrated closure- and kernel-phases

Better performance of redundant array over NRM for high contrast binary detection.

Initial assumptions revised

Linear approximation relies on small phase errors

Ongoing extensive simulations suggest kernel-phase on highly redundant aperture is surprisingly robust.

	B	C	D	E	F	G	H	I	J	K	L	M
30	Hexagonal	ann_hex15	78	378	339	258.4 (27.31)	21.1 (9.15)	0.463		47.0 (7.38)	250.9 (30.59)	162.3 (18
31	Hexagonal	ann_hex15_w05	48	378	354	152.3 (17.61)	1.0 (0.0)	0.783		26.1 (4.42)	138.0 (13.16)	77.0 (12
32		golay9	9	36	28	38.7 (2.84)	1.0 (0.0)	0.839		5.8 (0.0)	10.5 (0.99)	10.7 (2
33	hases)					41.6 (2.92)				48.8 (4.18)	50.6 (4.45)	39.8 (3
34												
35												
36						**Unwrapping off, no low freqs**		**Kernel phases mean STE (degrees)**				
37	Hexagonal	full_hex15	199	378	279	2390.3 (232.92)	2497.2 (829.78)	0.060		1369.9 (146.51)	2606.9 (236.4)	2282.0 (228
38	Hexagonal	ann_hex15	78	378	339	1090.9 (101.93)	423.1 (82.32)	0.113		389.7 (41.32)	1128.3 (113.88)	738.2 (70
39	Hexagonal	ann_hex15_w05	48	378	354	574.4 (43.15)	106.5 (30.67)	0.214		77.4 (12.26)	582.7 (56.53)	277.3 (22
40		golay9	9	36	28	263.9 (16.33)	81.9 (7.55)	0.131		11.1 (0.0)	49.1 (4.15)	28.6 (4
41	hases)					258.5 (12.89)				315.2 (17.1)	332.7 (27.84)	256.1 (14
42												
43												
44						**Unwrapping off, no low freqs**		**Kernel phases mean STE (degrees)**				
45	Hexagonal	full_hex15	199	378	279	8771.0 (866.51)	12000.0 (0.0)	0.019		7633.7 (803.44)	9122.4 (867.86)	8373.9 (892
46	Hexagonal	ann_hex15	78	378	339	2959.7 (311.48)	3042.9 (833.78)	0.042		2855.7 (279.82)	2907.7 (303.09)	2891.1 (297
47	Hexagonal	ann_hex15_w05	48	378	354	1302.6 (98.27)	614.4 (227.31)	0.097		1019.8 (78.13)	1256.8 (106.3)	1281.8 (110
48		golay9	9	36	28	1118.2 (93.88)	1500.8 (137.97)	0.031		353.5 (30.06)	1271.5 (93.69)	451.8 (24
49	hases)					1117.4 (91.18)				1266.7 (117.26)	1226.7 (106.74)	1103.5 (70
50												
51												
52						**Unwrapping off, no low freqs**		**Kernel phases mean STE (degrees)**				
53	Hexagonal	full_hex15	199	378	279	29032.4 (2887.38)	60000.0 (0.0)	0.007		23625.8 (2416.89)	28447.8 (2872.13)	27539.8 (2827
54	Hexagonal	ann_hex15	78	378	339	7815.5 (746.96)	19985.6 (6036.75)	0.017		7074.4 (710.34)	7265.1 (715.55)	7480.7 (700
55	Hexagonal	ann_hex15_w05	48	378	354	3181.9 (257.52)	3558.4 (1326.78)	0.041		2936.5 (255.59)	2961.4 (268.7)	3060.9 (251
56		golay9	9	36	28	4549.0 (567.43)	22009.5 (4197.5)	0.008		4036.9 (553.65)	3953.2 (566.54)	4392.3 (642
57	hases)					4489.0 (489.42)				4236.3 (460.92)	4357.9 (501.39)	4525.2 (627
58												
59												
60						**Unwrapping off, no low freqs**		**Kernel phases mean STE (degrees)**				
61	Hexagonal	full_hex15	199	378	279	66290.3 (6418.11)	120000.0 (0.0)	0.003		53702.4 (5750.76)	65668.3 (6231.02)	62210.4 (673
62	Hexagonal	ann_hex15	78	378	339	16961.7 (1602.45)	94086.3 (24825.23)	0.008		15897.5 (1687.9)	16171.1 (1669.26)	16784.8 (169
63	Hexagonal	ann_hex15_w05	48	378	354	6903.4 (554.81)	17871.1 (6679.32)	0.019		6626.6 (507.53)	6726.1 (545.03)	6850.5 (604
64		golay9	9	36	28	10548.3 (1482.8)	30000.0 (0.0)	0.003		9682.9 (1253.02)	9714.3 (1173.27)	10689.0 (156
65	hases)					10670.2 (1501.84)				10322.8 (1365.58)	10090.1 (1486.06)	10690.0 (141

Latyshev, et al, 2015, in prep

Extensions are possible:

Original linearization for small instrumental phase:

$\Phi_j = \Phi_{0j} + \mathrm{Arg}(\Sigma e^{j\,\Delta\varphi i})$ $\Rightarrow$ $\Phi_j = \Phi_{0j} + 1/n_j\ \Sigma_i\ \Delta\varphi i$

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alternate linearization scheme:

$$\Phi_j(\lambda) = \Phi_{0j}(\lambda) + \mathrm{Arg}(\Sigma \exp(i2\pi\delta/\lambda))$$

$$\mathrm{Arg}\,(\gamma_j(\lambda_1)\times \gamma^*_j(\lambda_2)) = \Delta\Phi_0(\lambda_1,\lambda_2) + 1/n\, \Sigma\, [2\pi\delta_j/\Lambda_0]$$

The same model holds for differential phase

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Original linearization for small instrumental phase:

$$\Phi_j = \Phi_{0j} + \mathrm{Arg}(\Sigma e^{j\,\Delta\varphi i}) \quad \Rightarrow \quad \Phi_j = \Phi_{0j} + 1/n_j\, \Sigma_i\, \Delta\varphi i$$

Work in progress

alternate lineari[...] scheme:

$\Phi_j(\lambda)=$ [...] $\mathrm{Arg}(\Sigma\, \exp(i2\pi\delta/\lambda))$

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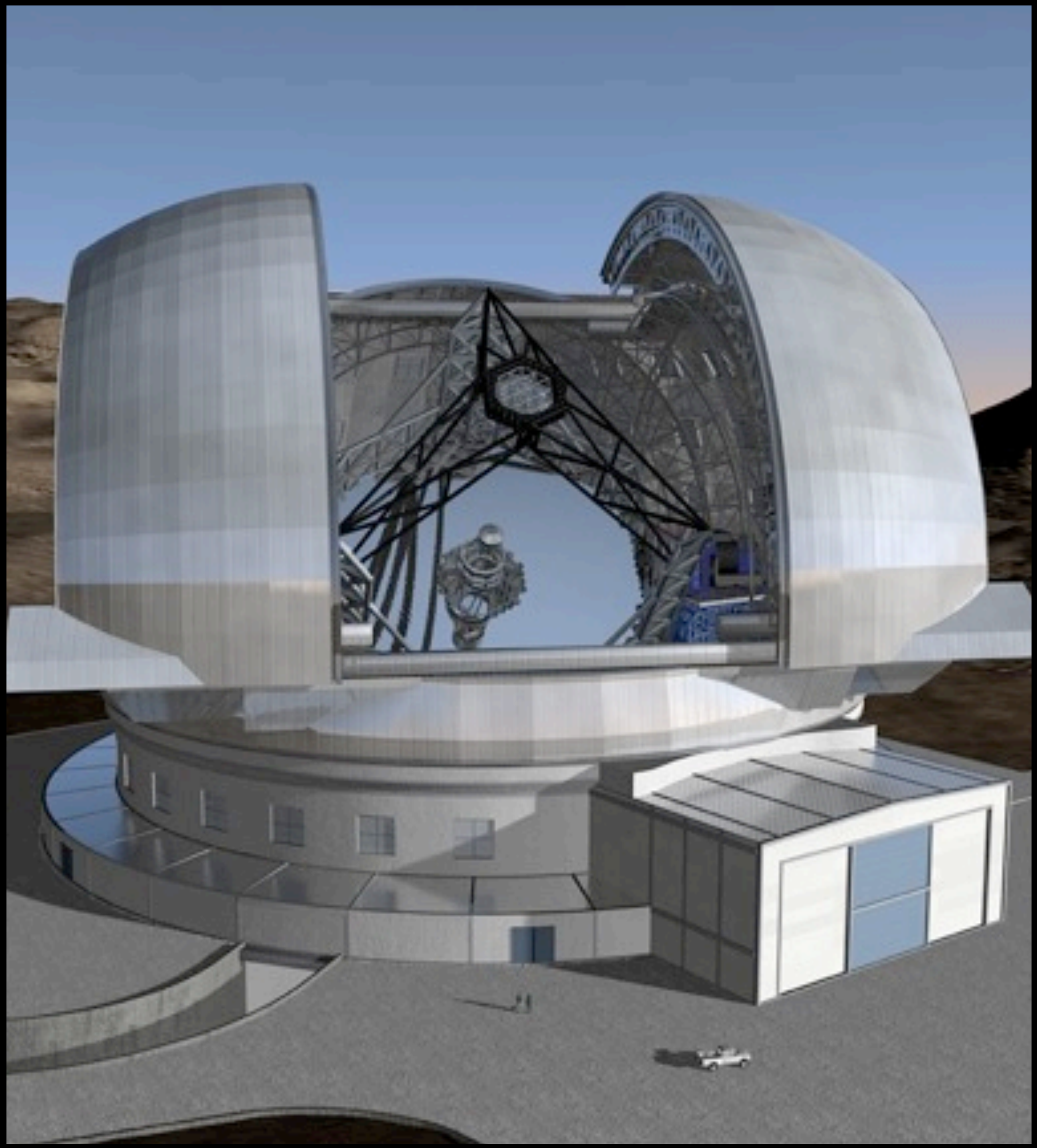
The same model holds for differential phase

Single-telescope interferometry

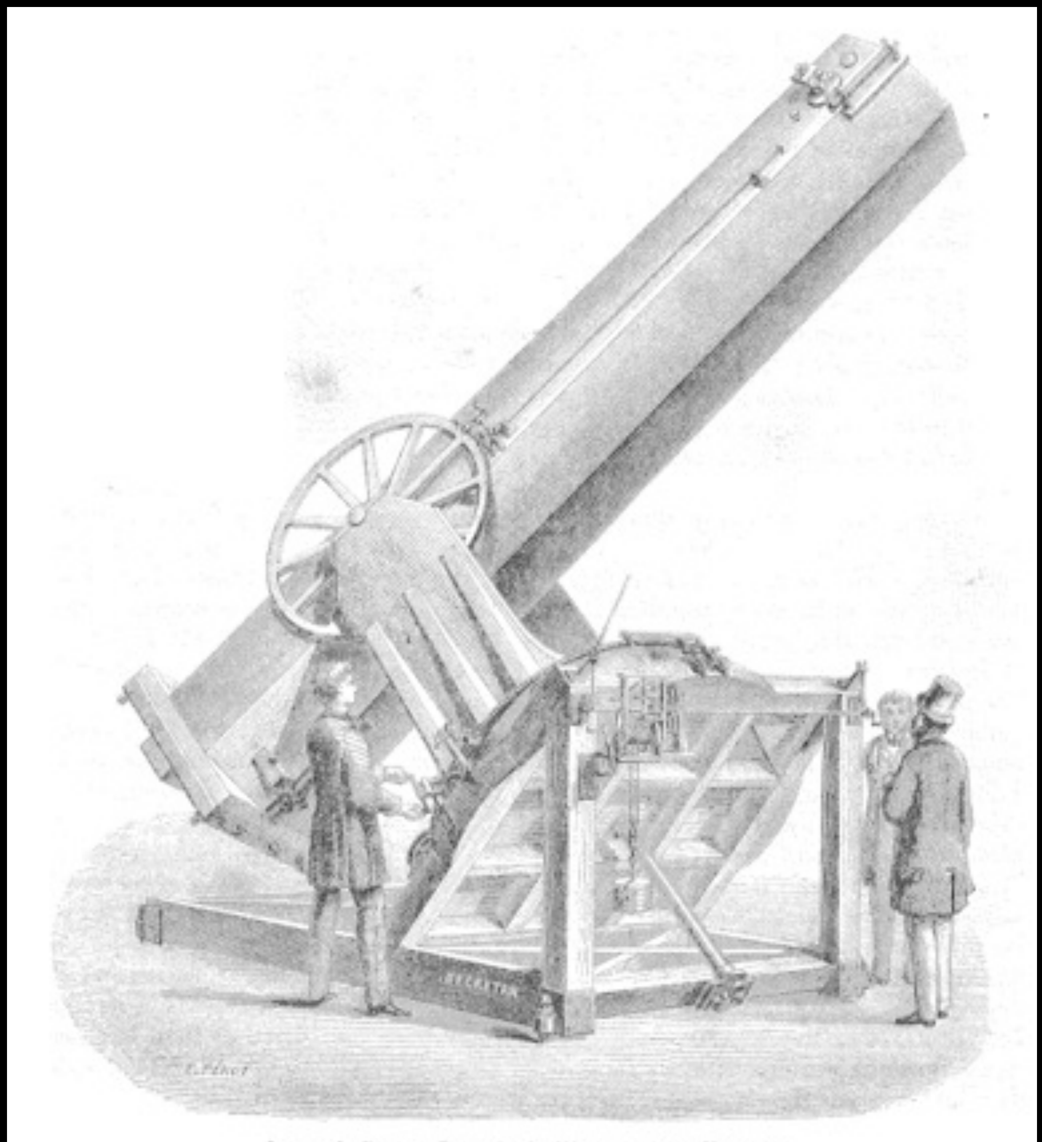
?



Frantz Martinache, Laboratoire Lagrange, OCA

LAGRANGE

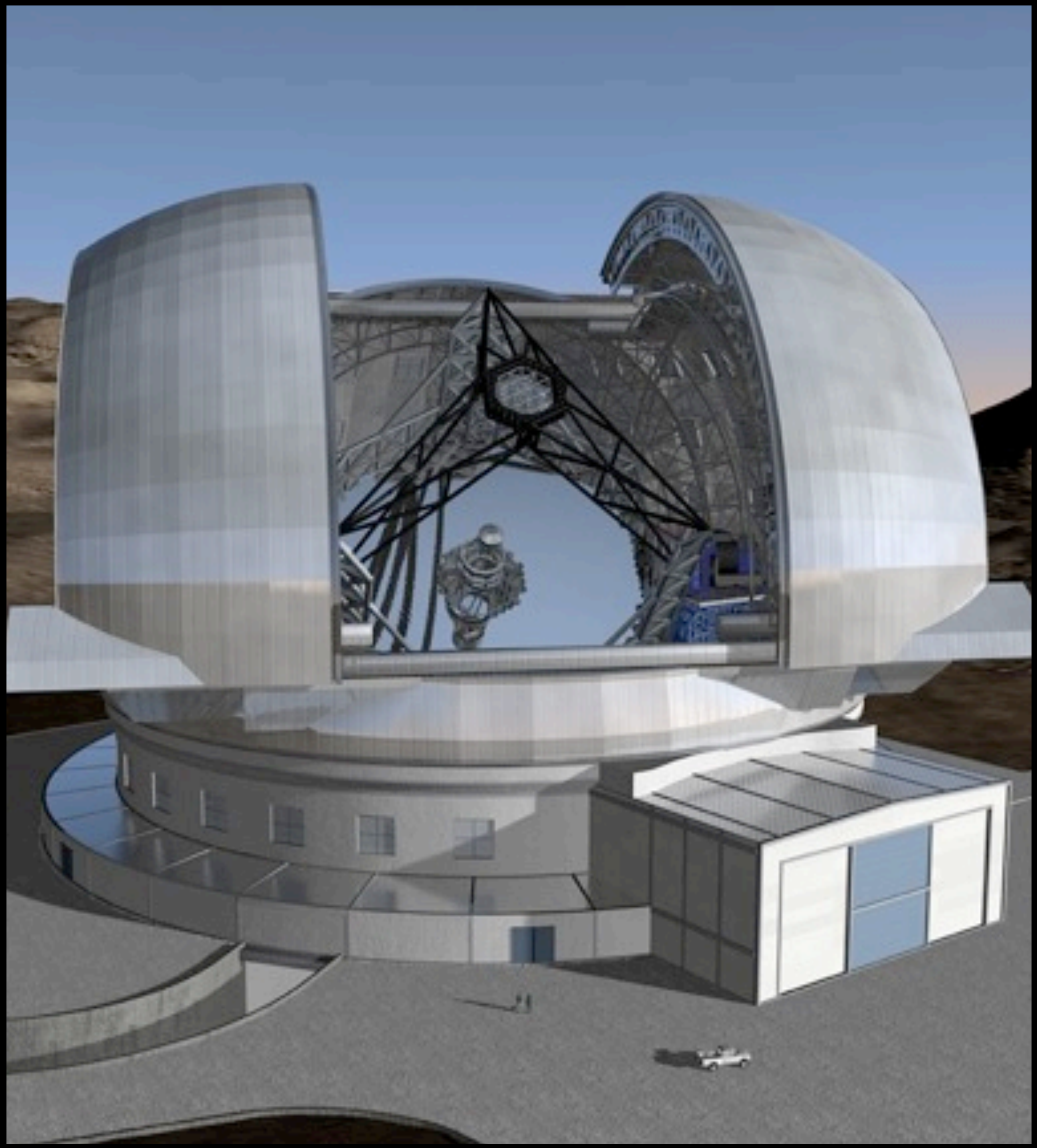
Single-telescope interferometry



Le grand télescope Foucault, de l'Observatoire de Marseille.

?

→



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$$\Phi = \Phi_0 + A.\varphi$$

It is all about exploiting the properties of A

Martinache, 2010, ApJ, 724, 464

Martinache, 2013, PASP, 125, 422

$$\phi = \phi_o + A.\varphi$$

$$K\,\phi = K\,\phi o + K \cancel{A}\,\varphi$$

$$K\,\phi = K\,\phi o$$

(*kernel-phase*)

$$\varphi = A^{-1}\,.\,(\phi - \phi_o)$$

(*eigen-phase*)

It is all about exploiting the properties of A

Martinache, 2010, ApJ, 724, 464

Martinache, 2013, PASP, 125, 422