From

# Aperture Masking

To

# Kernel-phase

Dr. Jens Kammerer

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From

# Aperture Masking

To

# Kernel-phase

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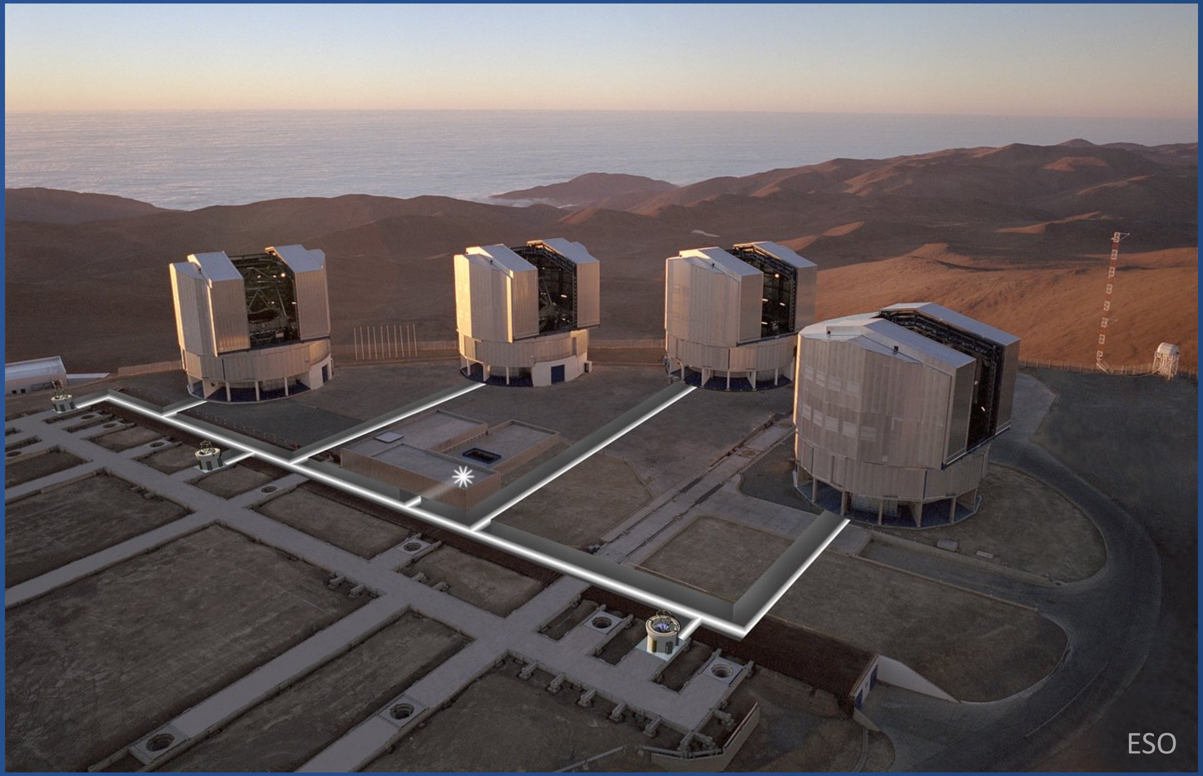
# Radio interferometry

# Optical interferometry



# Astronomical interferometer

Try to define the term "astronomical interferometer" in one sentence!

# Astronomical interferometer

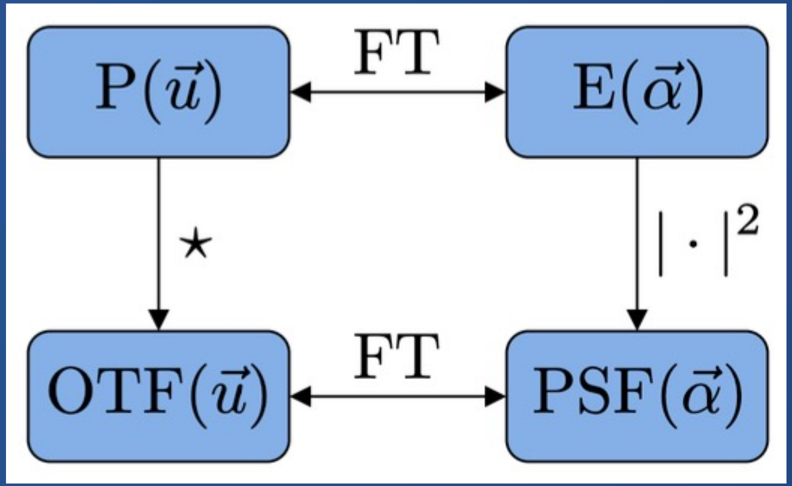
Try to define the term "astronomical interferometer" in one sentence!

An astronomical interferometer is an array of separate telescopes, mirror segments, or radio telescope antennas that work together as a single telescope to provide higher resolution images of astronomical objects such as stars, nebulas and galaxies by means of interferometry.

Wikipedia

# The point-spread function (PSF)

OTF = optical transfer function
PSF = point-spread function

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# The point-spread function (PSF)


NASA

$$\begin{tikzcd} \mathrm{P}(\vec{u}) \arrow[r, leftrightarrow, "\mathrm{FT}"] \arrow[d, "\star"] & \mathrm{E}(\vec{\alpha}) \arrow[d, "|\cdot|^2"] \\ \mathrm{OTF}(\vec{u}) \arrow[r, leftrightarrow, "\mathrm{FT}"] & \mathrm{PSF}(\vec{\alpha}) \end{tikzcd}$$

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OTF = optical transfer function
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Wikipedia

# The point-spread function (PSF)

OTF = optical transfer function
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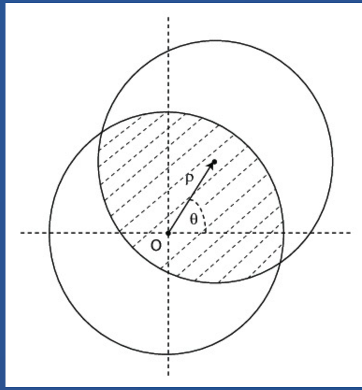
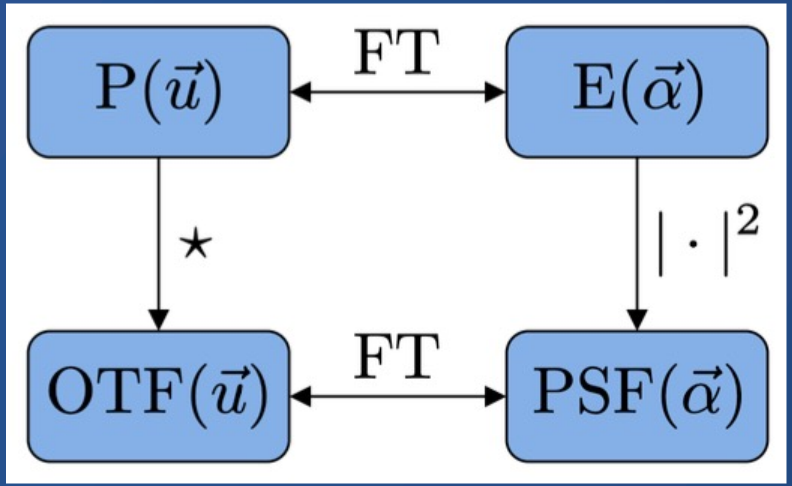
Wiener-Khinchin or auto-correlation theorem




Janssen2011

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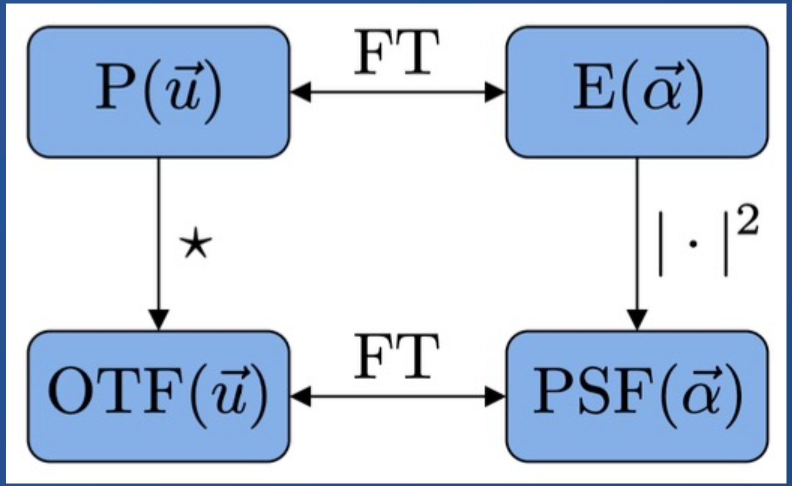


$\star\ \delta(\vec{0})$

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# The point-spread function (PSF)

OTF = optical transfer function
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Wiener-Khinchin or auto-correlation theorem

$$
\begin{tikzcd}
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\mathrm{OTF}(\vec{u}) \arrow[r, leftrightarrow, "\mathrm{FT}"] & \mathrm{PSF}(\vec{\alpha})
\end{tikzcd}
$$

$\widetilde{\delta(\vec{0})}\,\cdot$ OTF

PSF $\star\,\delta(\vec{0})$

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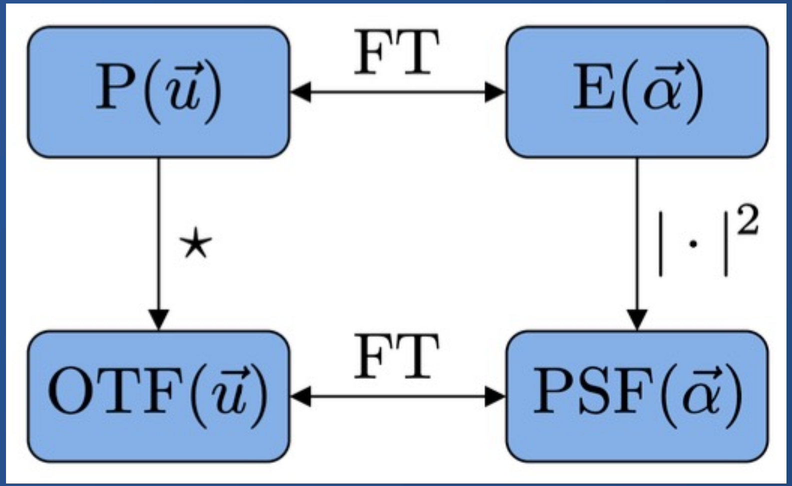
$$\widetilde{\delta(\vec{0})} = 1$$

# The point-spread function (PSF)

Wiener-Khinchin or auto-correlation theorem




$\star\,(\delta(\vec{0}) + \delta(\vec{\alpha}))$

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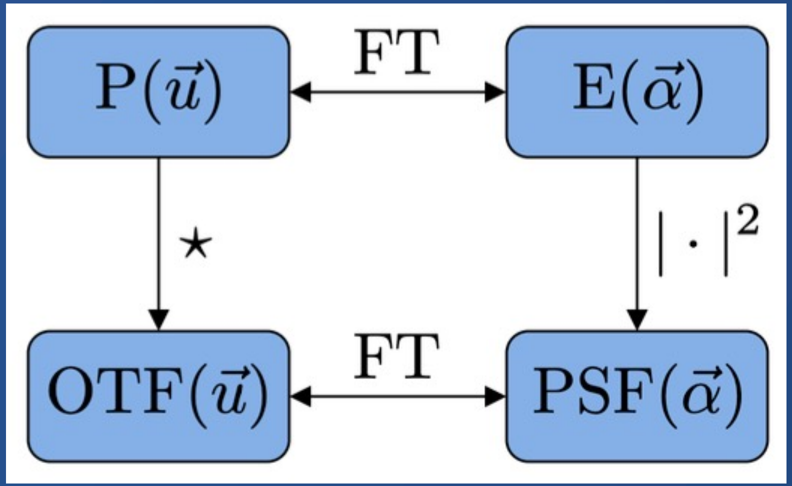
# The point-spread function (PSF)

Wiener-Khinchin or auto-correlation theorem

$$(\delta(\vec{0}) \widetilde{+ c} \cdot \delta(\vec{\alpha})) \cdot$$




$$\star\ (\delta(\vec{0}) + c \cdot \delta(\vec{\alpha}))$$

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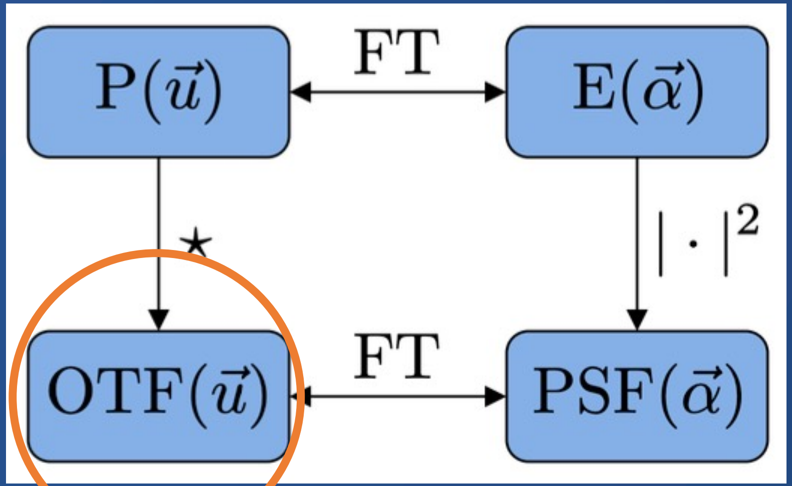
$$(\delta(\vec{0}) \widetilde{+ c} \cdot \delta(\vec{\alpha})) = 1 + c \cdot \exp(-2\pi i \vec{\alpha} \cdot \vec{u})$$

# The point-spread function (PSF)

Wiener-Khinchin or auto-correlation theorem

$\widetilde{\delta(\vec{0})} \cdot$

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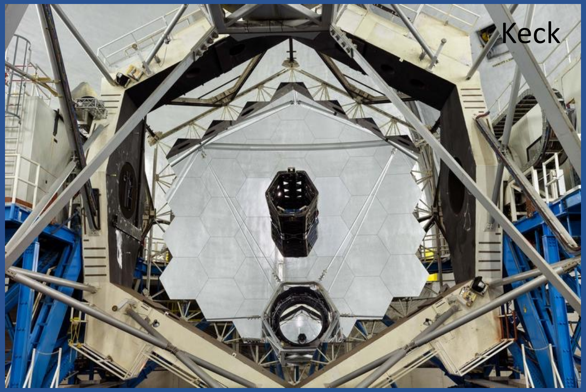
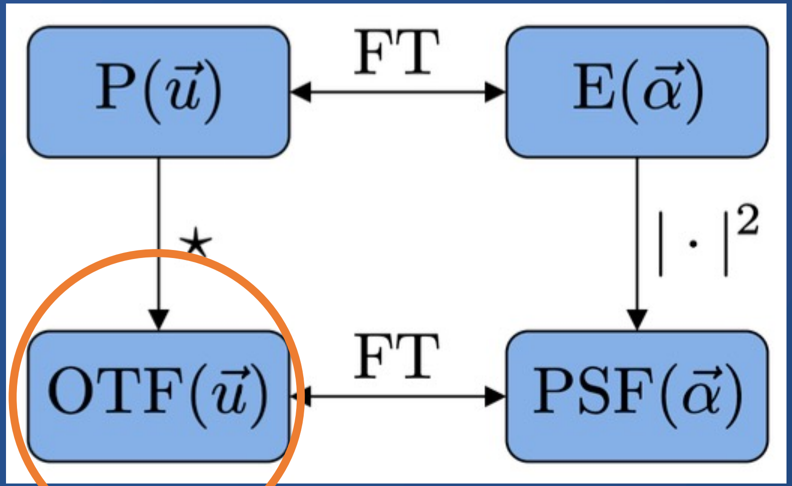



$\widetilde{\delta(\vec{0})} \cdot$




$\star\ \delta(\vec{0})$

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$$\widetilde{\delta(\vec{0})} = 1$$

# Astronomical interferometer

What does an astronomical interferometer measure?

# Astronomical interferometer

What does an astronomical interferometer measure?

$$V(u, v) = \iint A(\alpha, \beta) * F(\alpha, \beta) * \exp(-i2\pi[\alpha u + \beta v]) * d\alpha * d\beta$$

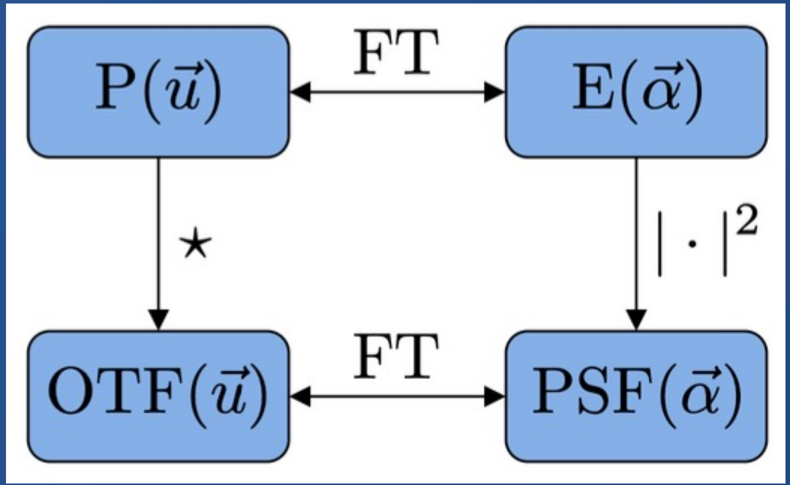
Complex visibility = Fourier transform of object intensity distribution

# The point-spread function (PSF)

Wiener-Khinchin or auto-correlation theorem

Complex visibility!

$$\widetilde{(\delta(\vec{0}) + c \cdot \delta(\vec{\alpha}))} \cdot$$




$$\star\ (\delta(\vec{0}) + c \cdot \delta(\vec{\alpha}))$$

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$$\widetilde{(\delta(\vec{0}) + c \cdot \delta(\vec{\alpha}))} = 1 + c \cdot \exp(-2\pi i \vec{\alpha} \cdot \vec{u})$$

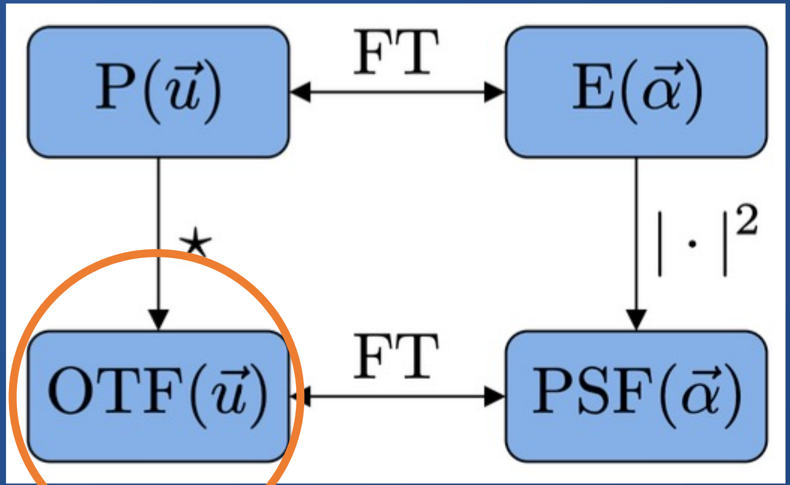
# Astronomical interferometer

So what is the difference between a single-dish telescope and a multi-aperture interferometer?

# The point-spread function (PSF)

Wiener-Khinchin or auto-correlation theorem

Complex visibility!




$\widetilde{(\delta(\vec{0}) + c \cdot \delta(\vec{\alpha}))} \cdot \quad \mathrm{OTF}(\vec{u}) \quad \mathrm{PSF}(\vec{\alpha}) \quad \star\, (\delta(\vec{0}) + c \cdot \delta(\vec{\alpha}))$

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$$\widetilde{(\delta(\vec{0}) + c \cdot \delta(\vec{\alpha}))} = 1 + c \cdot \exp(-2\pi i \vec{\alpha} \cdot \vec{u})$$

# Astronomical interferometer

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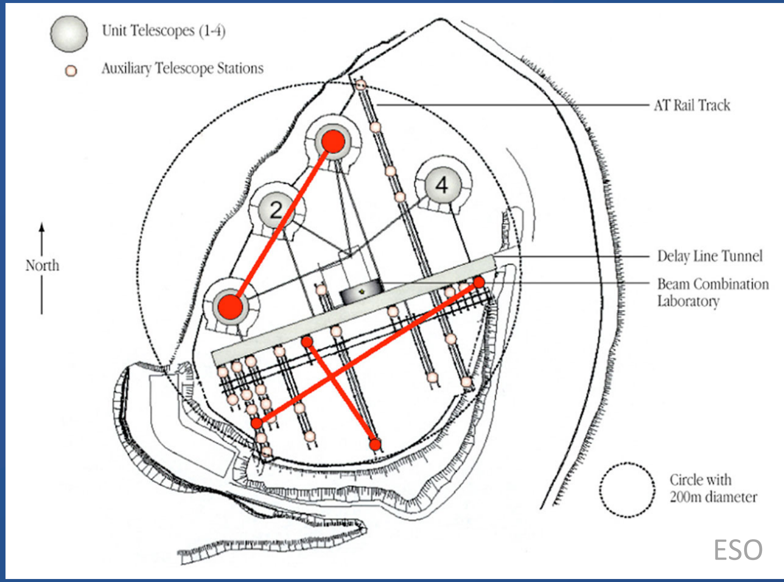


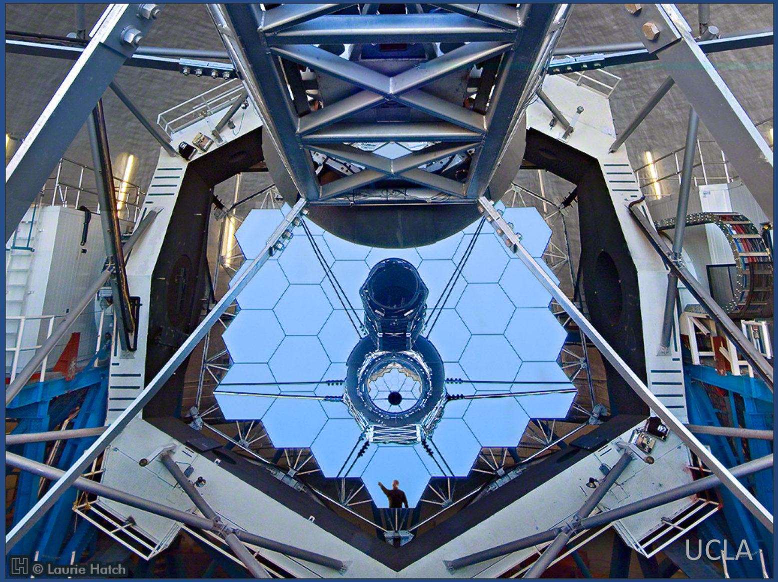


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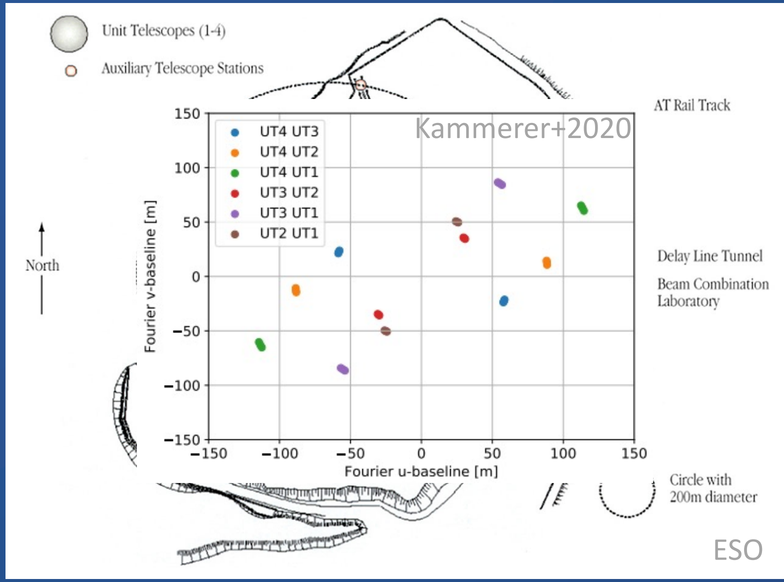
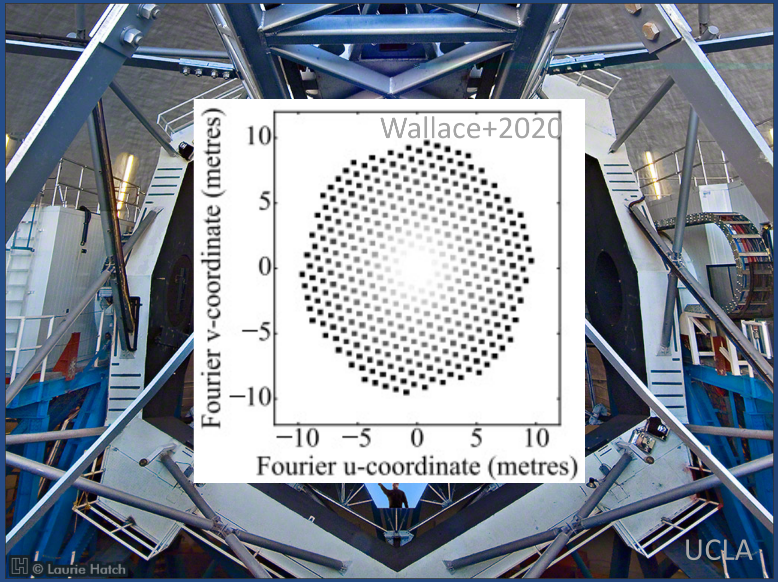
# Astronomical interferometer

So what is the difference between a single-dish telescope and a multi-aperture interferometer?

UV-coverage!

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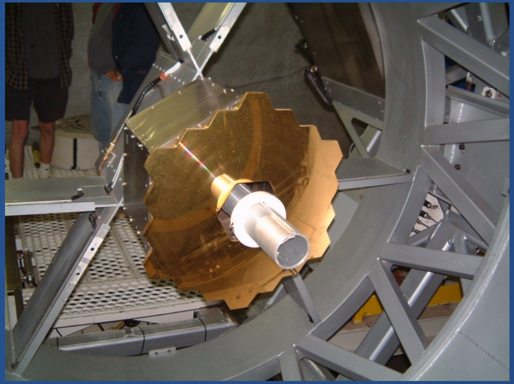
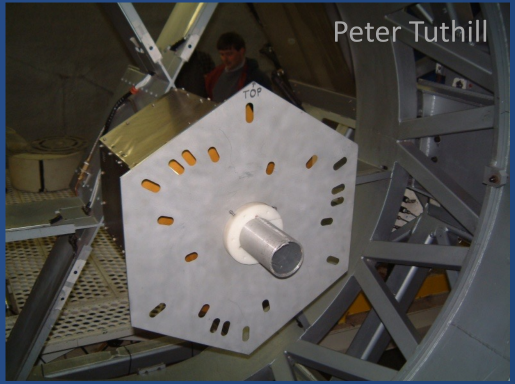
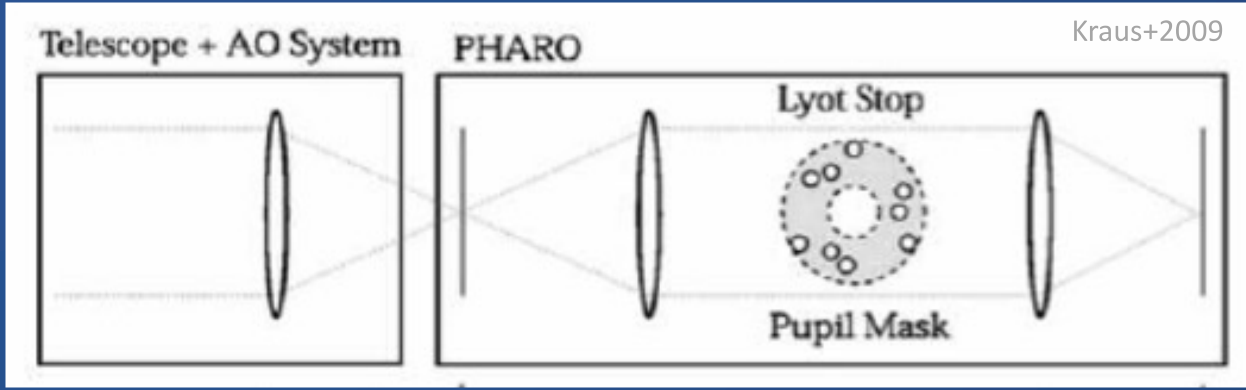
# Aperture masking interferometry (AMI)



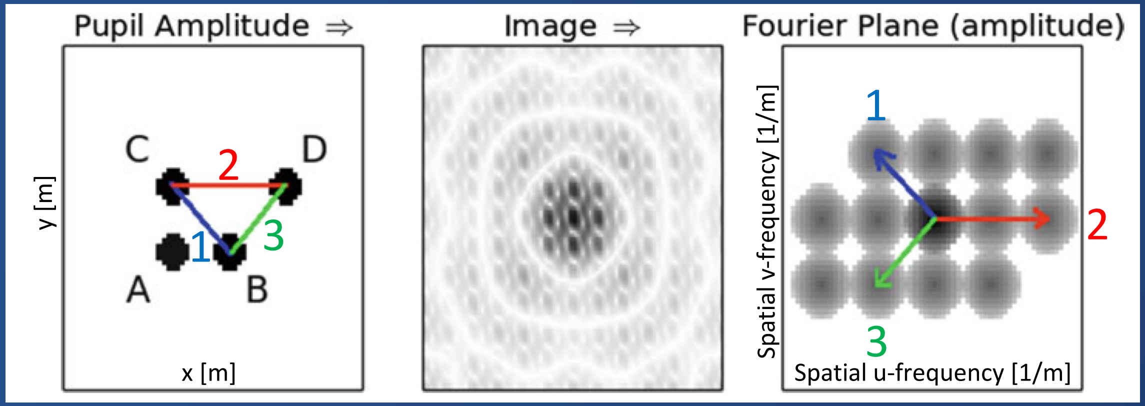



# Aperture masking interferometry (AMI)

- Disclaimer:
  - Interferometers measure visibility amplitudes and closure phases
  - Visibility amplitudes contain information about source radial structure
  - Closure phases contain information about source asymmetries
  - With an aperture mask, both quantities can be measured and are measured
  - However, we will focus on the closure phases in the following, because they contain information about e.g., faint companions or disk structure and are important to achieve high angular resolution

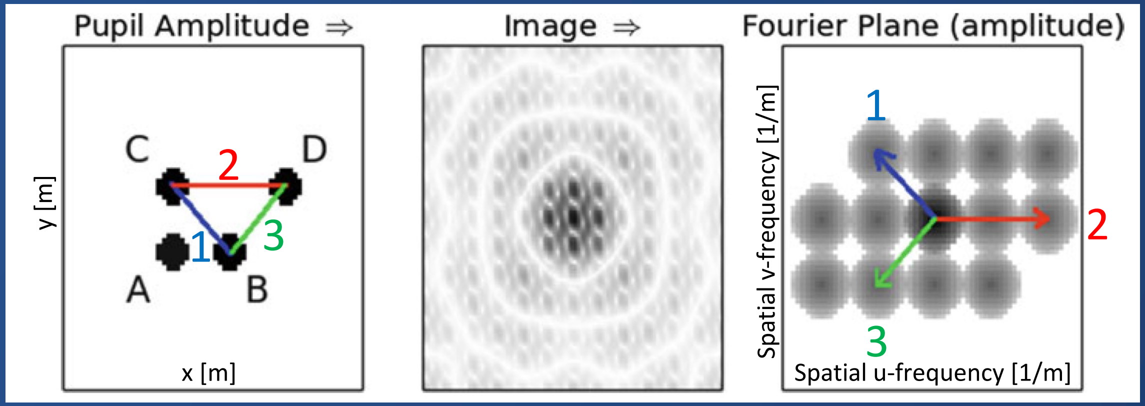
# Aperture masking interferometry (AMI)




Ireland2016

# Aperture masking interferometry (AMI)

- $\phi_1 = \phi_{source,1} + \varphi_C - \varphi_B$
- $\phi_2 = \phi_{source,2} + \varphi_D - \varphi_C$
- $\phi_3 = \phi_{source,3} + \varphi_B - \varphi_D$

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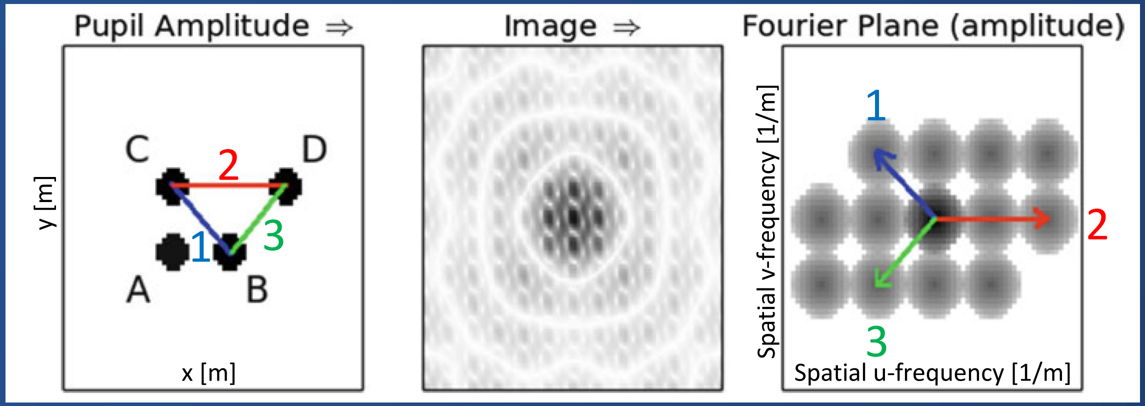



Ireland2016

- Closure phase $\phi_{123} = \phi_1 + \phi_2 + \phi_3 = \phi_{source,1} + \phi_{source,2} + \phi_{source,3}$

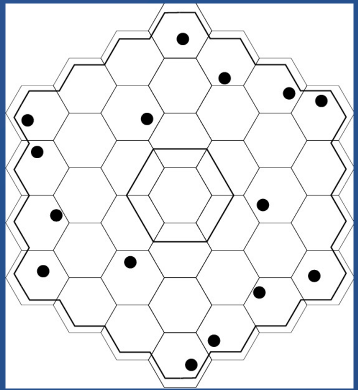
# Aperture masking interferometry (AMI)

Design of aperture masks

# Aperture masking interferometry (AMI)

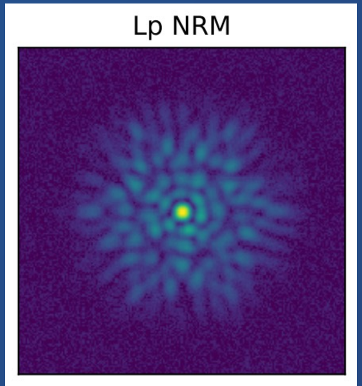
Design of aperture masks

Pupil plane



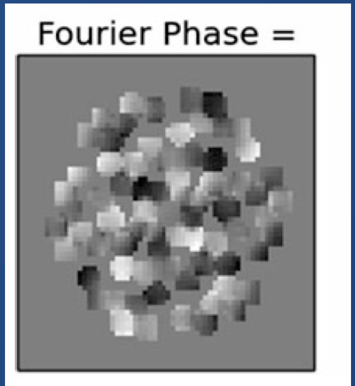
Tuthill2000

Image plane




Sallum&Skemer2019

Fourier plane




Ireland2016

# Aperture masking interferometry (AMI)

Design of aperture masks

$$N_{tria} = \frac{N(N-1)(N-2)}{6}$$

# Aperture masking interferometry (AMI)

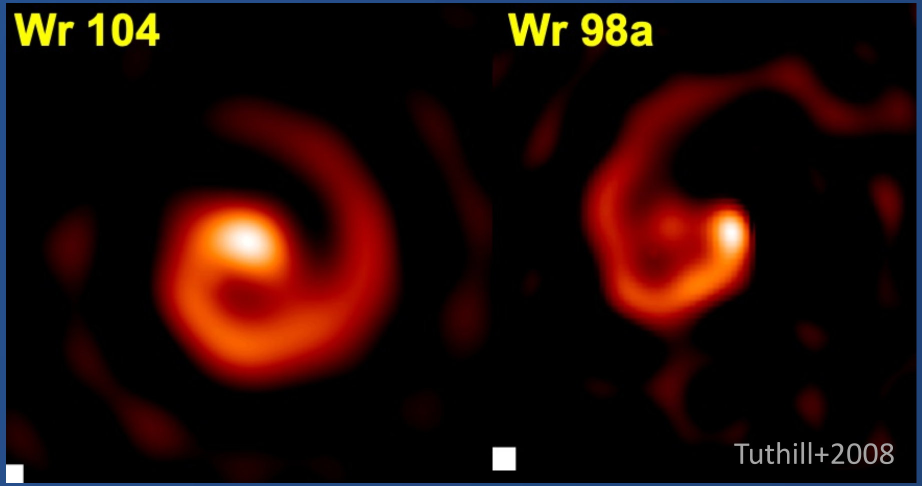
Design of aperture masks

- Apertures should only be so big that the phase perturbation across them can be approximated as linear
- Aperture size determines throughput
- Need to place apertures in such a way that Fourier plane remains non-redundant

# Aperture masking interferometry (AMI)

Image reconstruction using a regularized maximum entropy method


Circumstellar dust disk




Circumbinary rotating nebula

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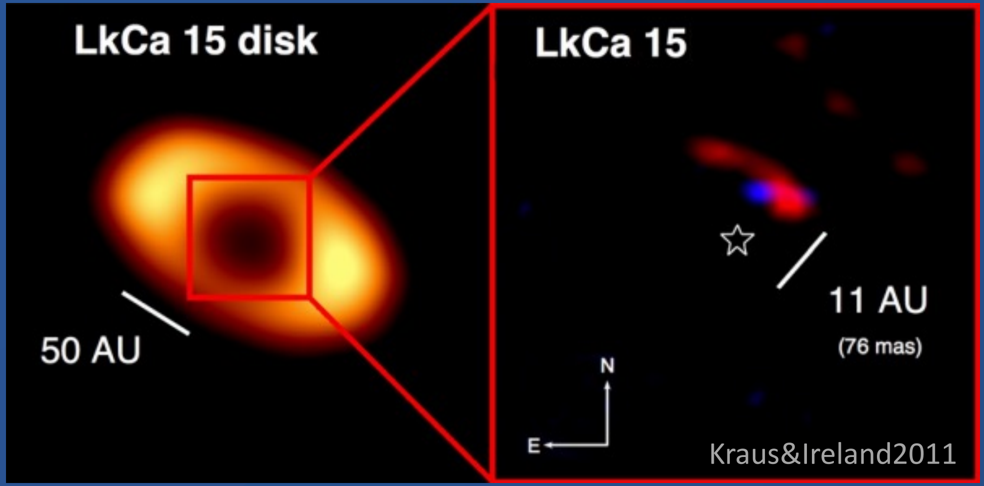
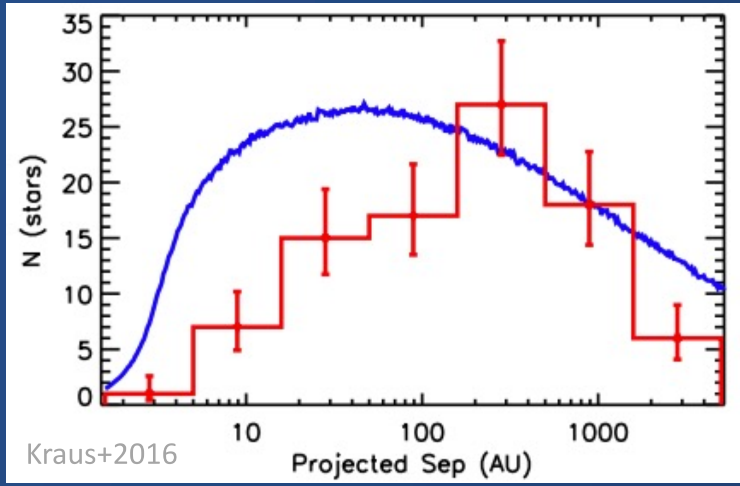
# Aperture masking interferometry (AMI)

Image reconstruction using a regularized maximum entropy method




Planets caught at formation?




Planets around close binaries

# Aperture masking interferometry (AMI)

- $\phi_1 = \phi_{source,1} + \varphi_C - \varphi_B$
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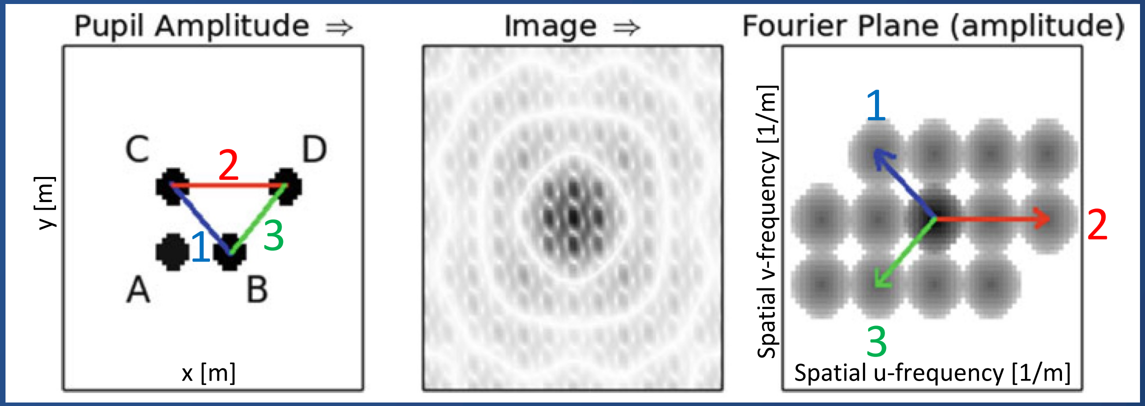
- $\phi_3 = \phi_{source,3} + \varphi_B - \varphi_D$



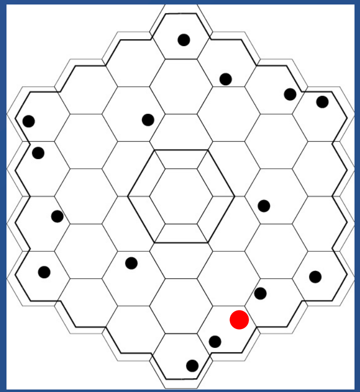

Ireland2016

- Basis of left null space is $\begin{pmatrix}1\\1\\1\end{pmatrix}$, so that $\begin{pmatrix}1\\1\\1\end{pmatrix} \cdot \begin{pmatrix}\phi_1\\\phi_2\\\phi_3\end{pmatrix} = \phi_1 + \phi_2 + \phi_3 = 0$

# Aperture masking interferometry (AMI)

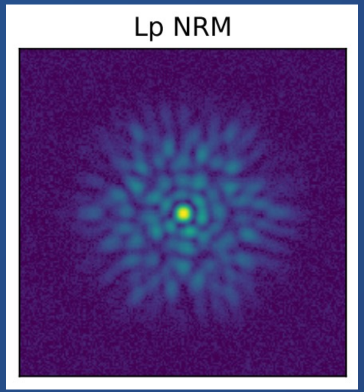
Design of aperture masks

Pupil plane



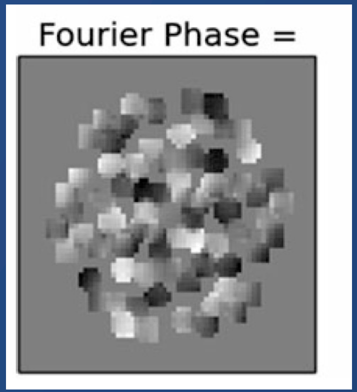
Tuthill2000

Image plane




Sallum&Skemer2019

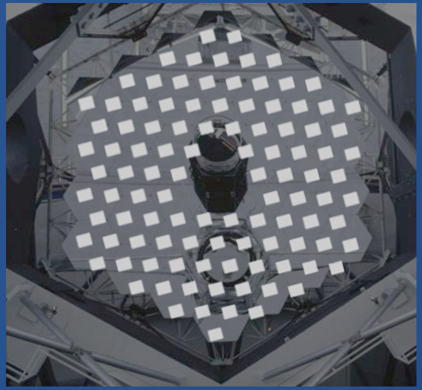
Fourier plane




Ireland2016

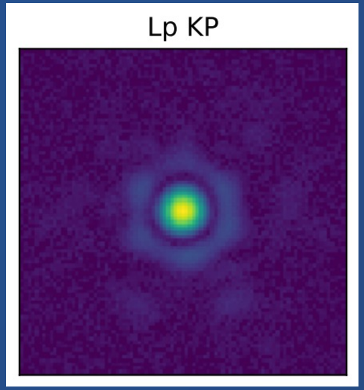
# Kernel-phase interferometry (KPI)

Pupil plane



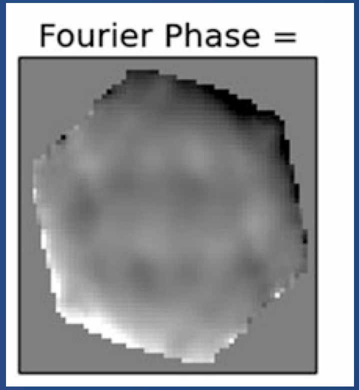
Medium

Image plane




Sallum&Skemer2019

Fourier plane

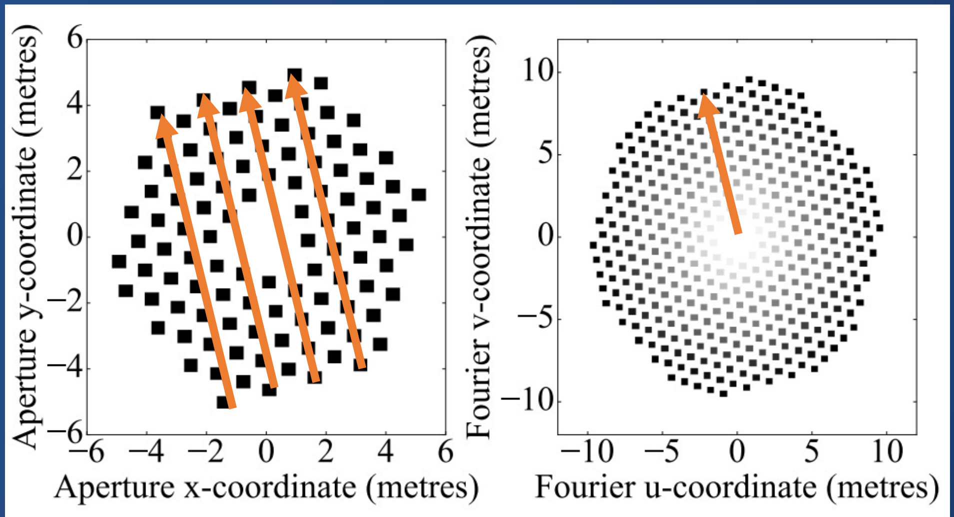



Ireland2016

# Kernel-phase interferometry (KPI)

- $\phi = \phi_{source} + R^{-1} \cdot A \cdot \varphi + \mathcal{O}(\varphi^2)$

Martinache 2010 (ApJ, 724, 464M)




Wallace+2020

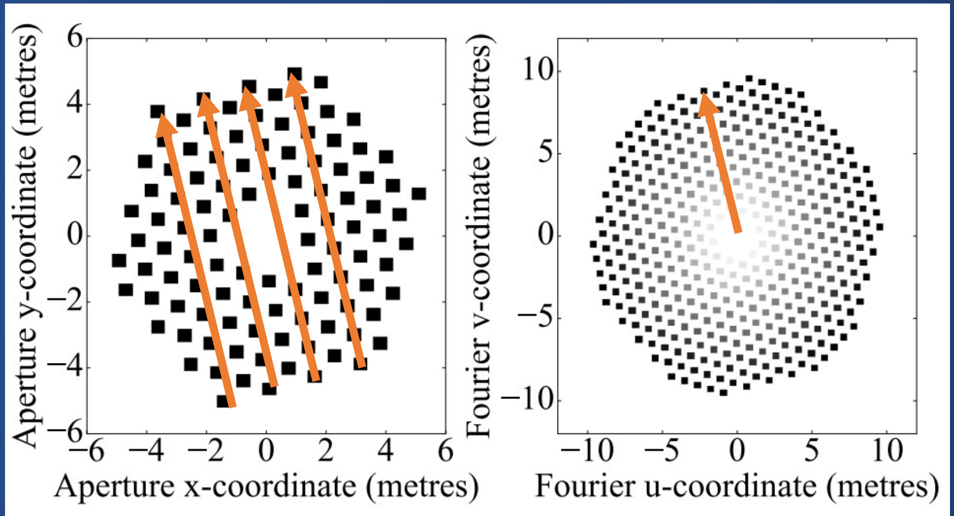
Contributing apertures

- $A = \begin{pmatrix} 1 & -1 & 0 & 0 & -1 & 1 & \cdots \\ 0 & 0 & 1 & -1 & 1 & -1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$

Spatial frequency

# Kernel-phase interferometry (KPI)

- $\phi = \phi_{source} + R^{-1} \cdot A \cdot \varphi + \mathcal{O}(\varphi^2)$
- $R \cdot K \cdot \phi = R \cdot K \cdot \phi_{source} + K \cdot A \cdot \varphi + \mathcal{O}(\varphi^2)$ Martinache 2010 (ApJ, 724, 464M)




Wallace+2020

- $$A = \begin{array}{cc} \text{Contributing apertures} & \\ \begin{pmatrix} 1 & -1 & 0 & 0 & -1 & 1 & \cdots \\ 0 & 0 & 1 & -1 & 1 & -1 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} & \text{Spatial frequency} \end{array}$$

# Kernel-phase interferometry (KPI)

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Contributing apertures

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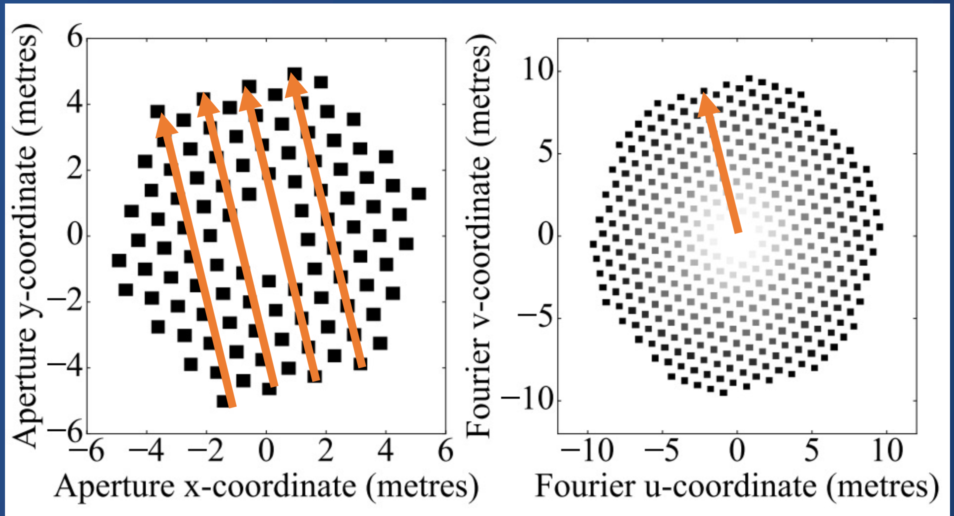


Wallace+2020

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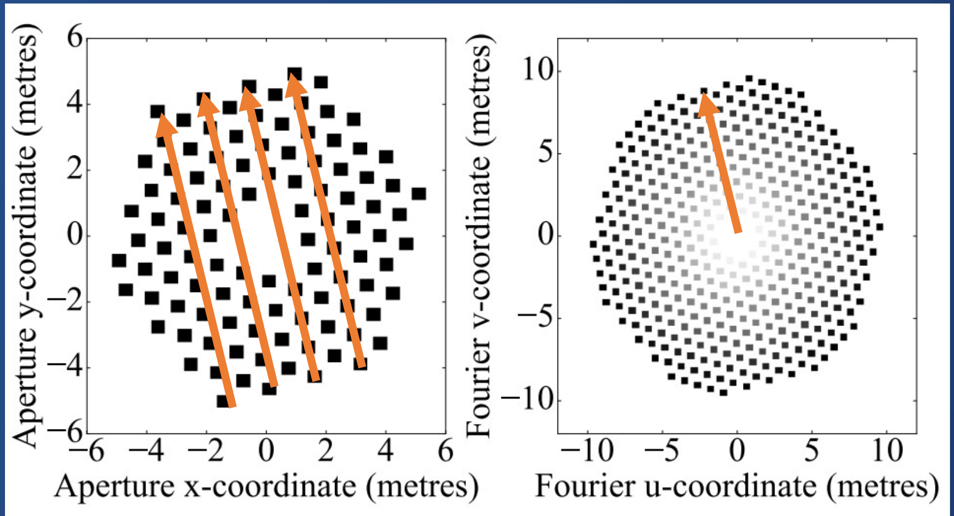
- $R \cdot K \cdot \phi = R \cdot K \cdot \phi_{source} + \mathcal{O}(\varphi^2)$
- In AMI, each Fourier phase $\phi$ can be uniquely associated with a baseline in the pupil plane (that is why AMI is sometimes also called non-redundant masking)
- Now, many baselines contribute to the same Fourier phase $\phi$, we say the pupil is redundant




Wallace+2020

# Kernel-phase interferometry (KPI)

- Since closure- and kernel-phases are linear combinations of Fourier phases, they are also expected to be zero for a PSF reference star
- In practice, there are always some systematic errors causing a non-zero closure- or kernel-phase even for a PSF reference star
- Let’s look at an example!

# Pros & cons

| Kernel-phase | Aperture masking |
| --- | --- |
| • Robust w.r.t. phase errors | • Robust w.r.t. phase errors |
| • High throughput | • Low throughput |
| • Needs high Strehl | • Works with low Strehl |
| • "Normal" image | • Interferogram |

# Pros & cons

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| --- | --- |
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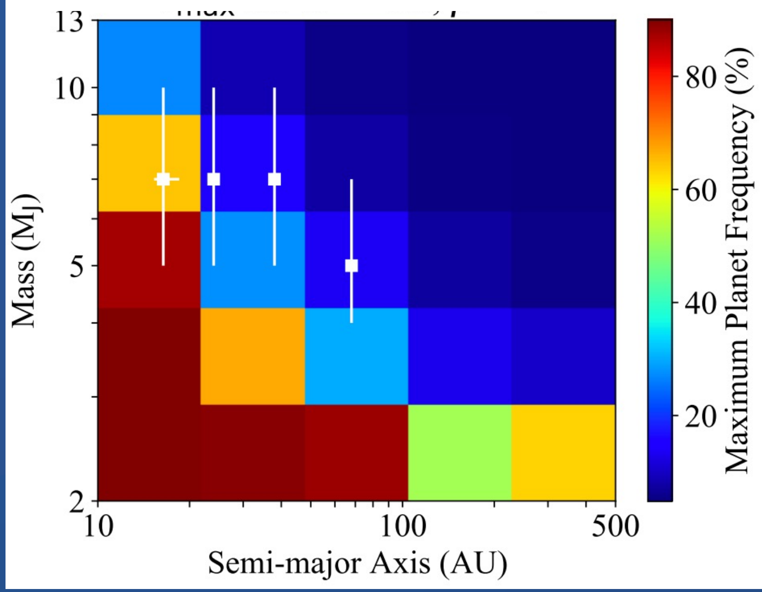
| • “Normal” image | • Interferogram |

Strehl = peak flux/ ideal peak flux

# Kernel-phase interferometry (KPI)

- ~50 very young stars in Taurus (1-2 Myr)

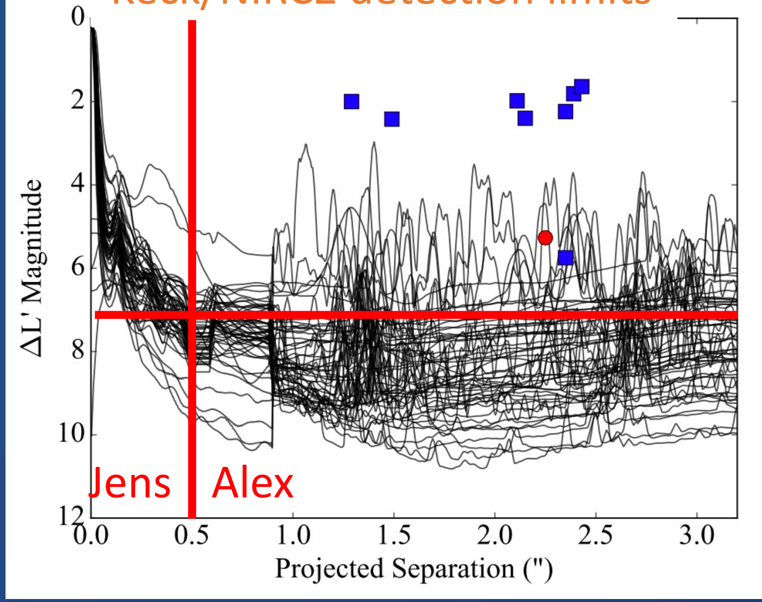
Limits on giant planet frequency

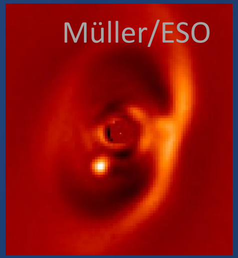



Wallace/Kammerer+2020

Keck/NIRC2 detection limits

PDS 70 b



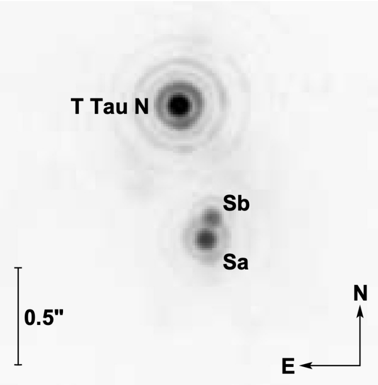




Wallace/Kammerer+2020

# Kernel-phase interferometry (KPI)

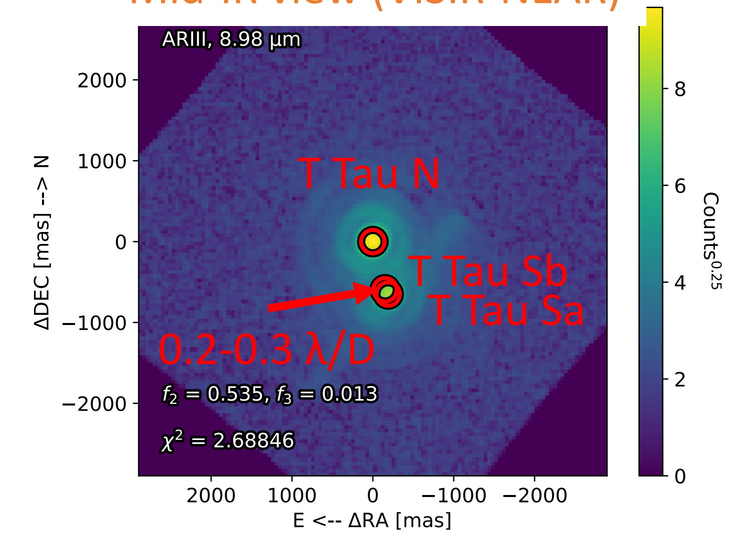
- VISIR-NEAR
  - Mid-IR imaging with ESO's AOF on UT4
  - Strehl close to 100%

Near-IR view (SPHERE)



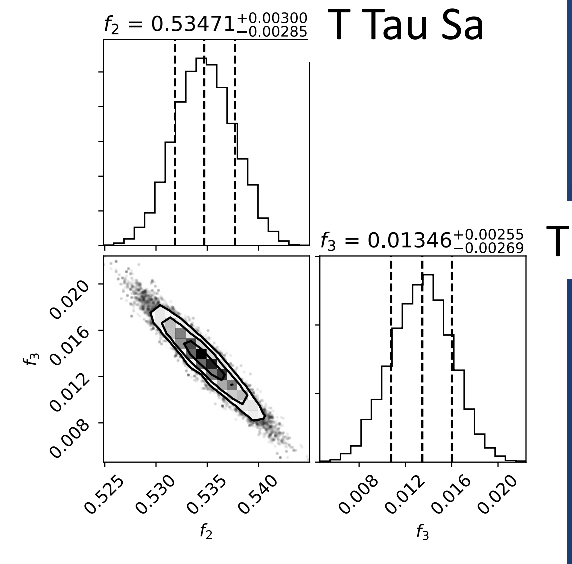

Köhler+2016

Mid-IR view (VISIR-NEAR)




Kammerer+2021a

MCMC fit for companion flux

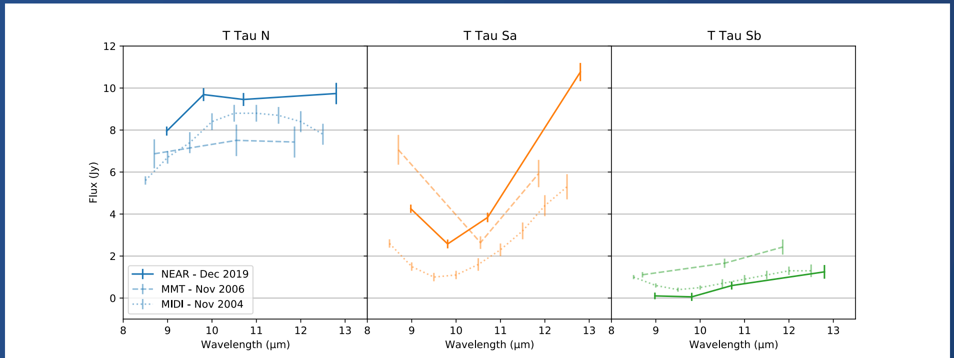



Kammerer+2021a

# Kernel-phase interferometry (KPI)

- Weak silicate emission
- Optically thin at ~10 µm
- ~Face-on disk

e.g. Ghez+1991


Kammerer+2021a

- Excess emission from disk
- Non-edge on disk
- Recent dimming in NIR and MIR by ~2 mag
- Extinction by circumbinary disk

e.g. Duchêne+2005

Köhler&Kubiak2020

- Silicate absorption
- ~Edge-on disk
- Tidally truncated disk due to Sb
- Even edge-on disk should cause emission
- Need circumbinary disk

e.g. van Boekel+2010

# Summary

- Our observable is the **Fourier phase**, which is the phase of the Fourier transform of the image
- We have found **linear combinations of Fourier phases** which are less affected by pupil plane phase noise (e.g., atmospheric turbulence)
- If a sparse **aperture mask** is placed in the beam, each spatial frequency (i.e., Fourier plane coordinate) can be uniquely associated with a baseline in the pupil plane; this means our array is **non-redundant**
- With full pupil **kernel phase**, multiple baselines contribute to the same spatial frequency; this means our array is **redundant**