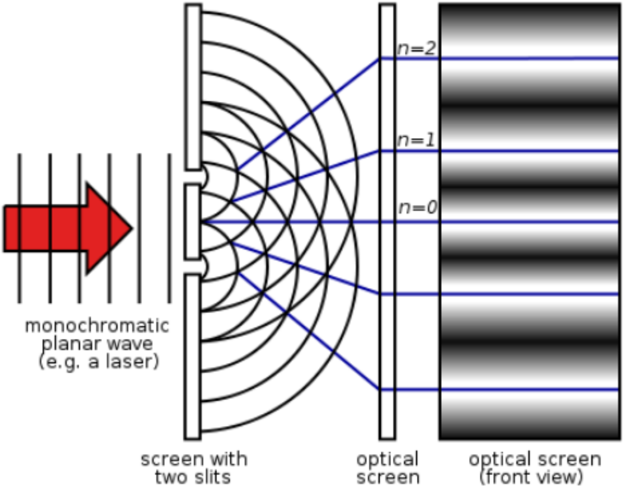
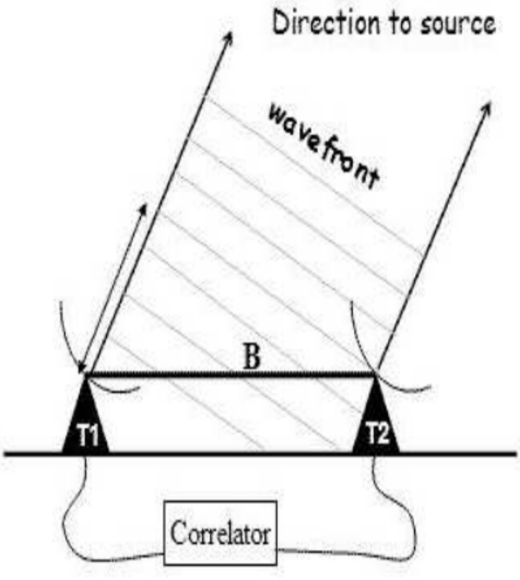
"Deep Images of the Galactic Center with GRAVITY"
GRAVITY Collaboration (2021)

20.04.2023

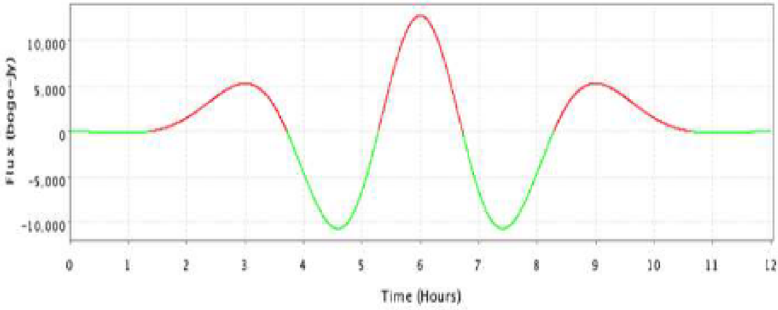
Interferometry - Young's experiment



Interferometry



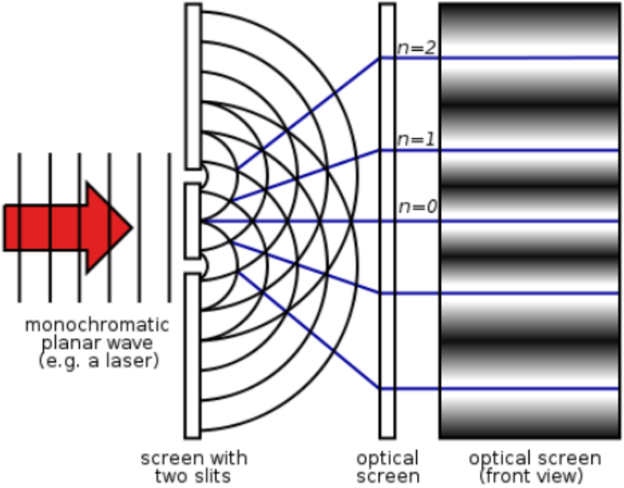
Interferometer output

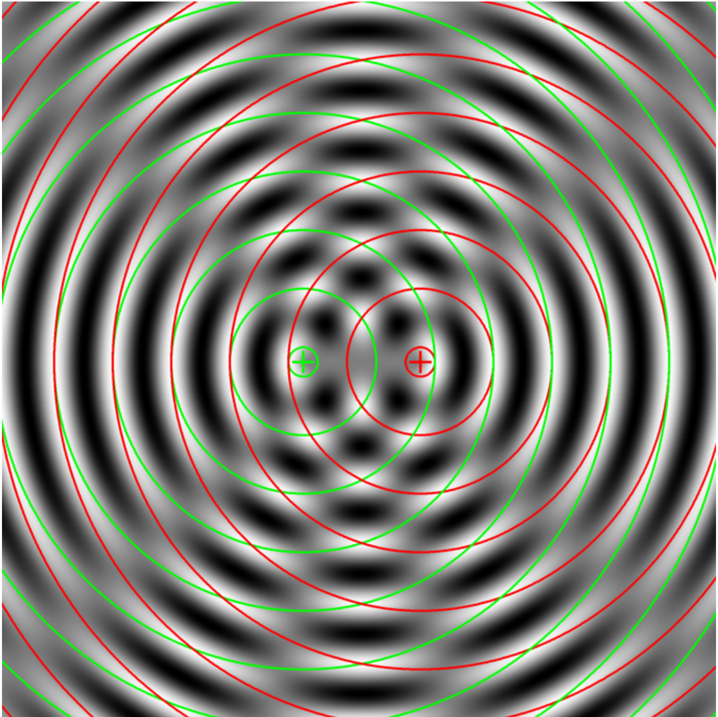


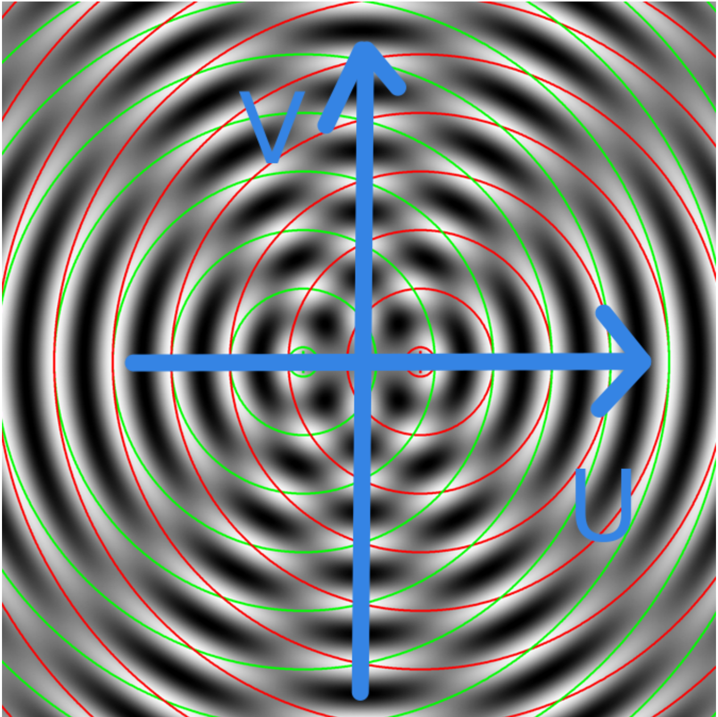
We use two independent correlators (beam combiners) and define the Complex Visibility -> V(u,v)

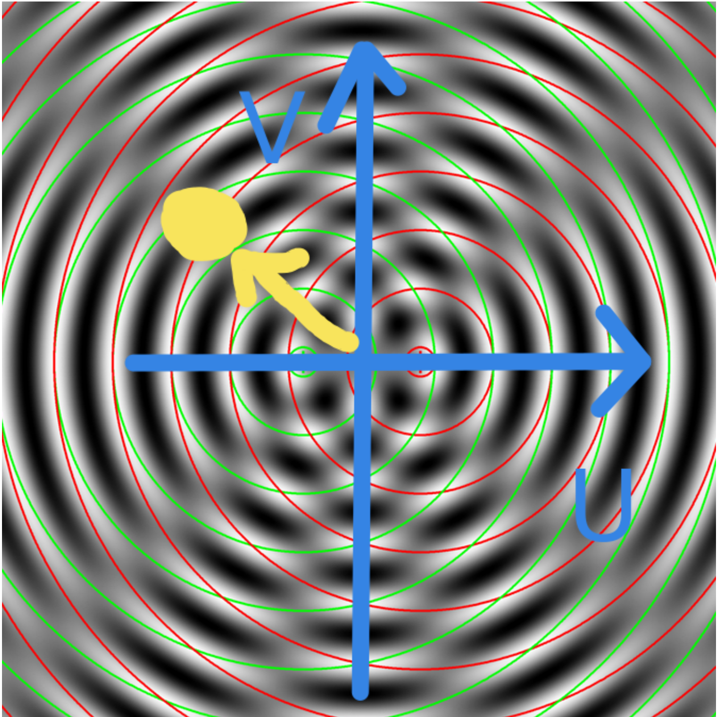
real and imaginary parts -> information about the amplitude and phase

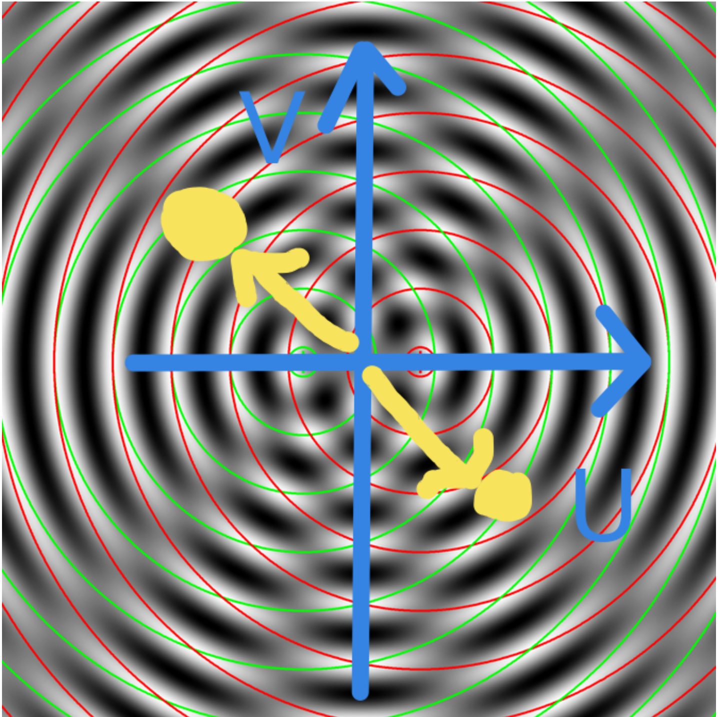
u,v - E-W and N-S spatial frequencies [wavelengths]


n=2
n=1
n=0
monochromatic
planar wave
(e.g. a laser)
screen with
two slits
optical
screen
optical screen
(front view)




V
U


V
U


V
U

We have the Complex Visibility V(u,v) - how do we obtain the image?

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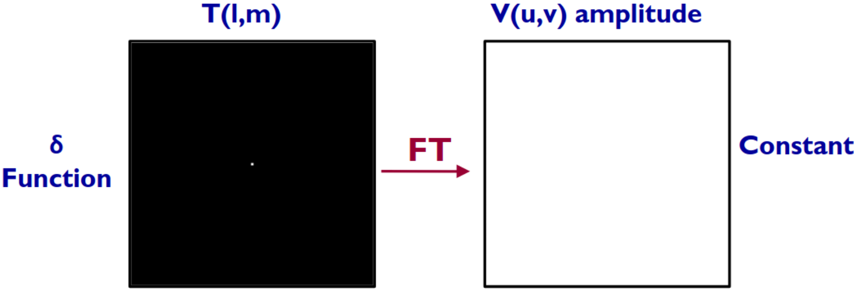
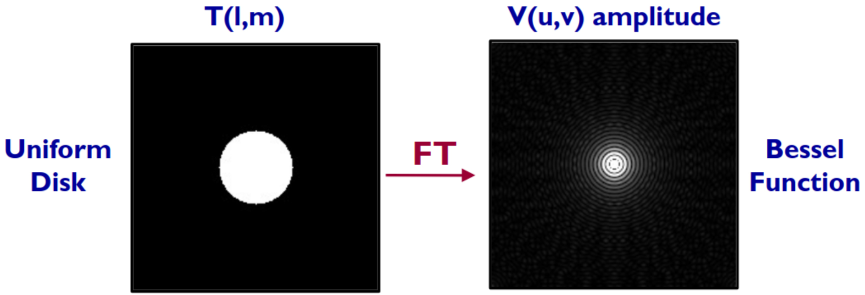
From the Citter-Zernike theorem: V(u,v) is a 2D Fourier transform of the image:

$T(l,m)=F^{-1}[V(u,v)]$ - the sky brightness distribution

where l and m are E-W and N-S angles in the tangent plane [radians]



Source: Meredith MacGregor



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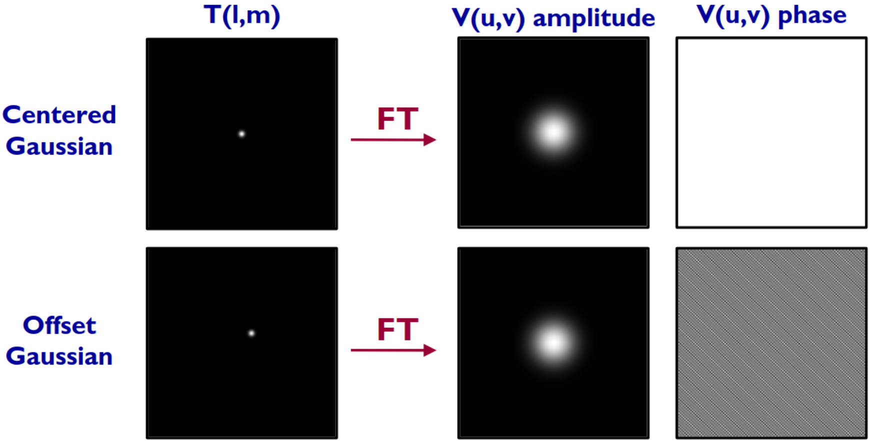

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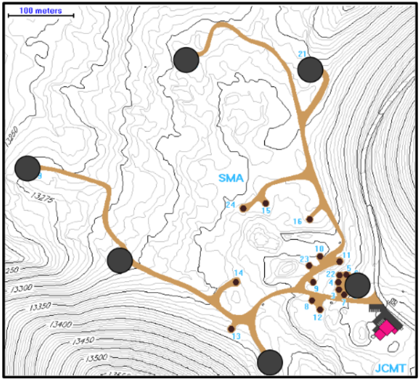

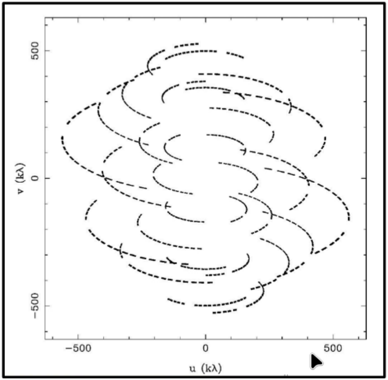

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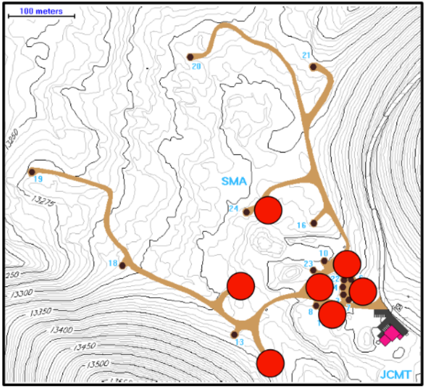

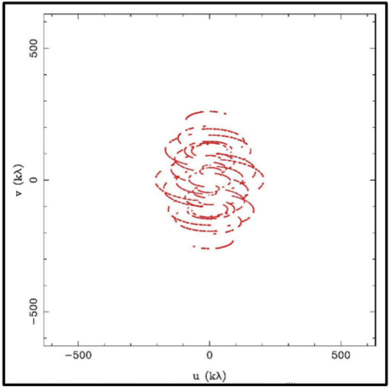

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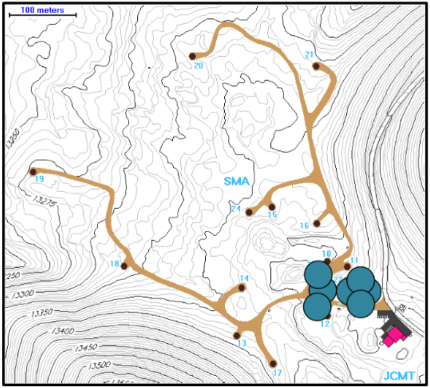

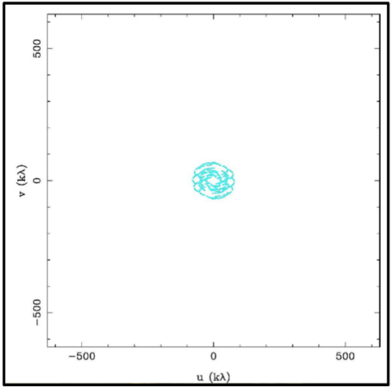

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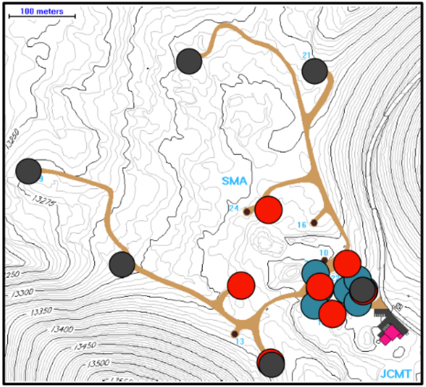

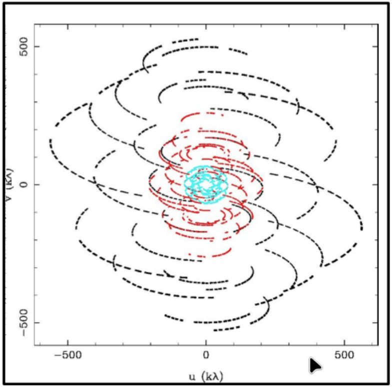

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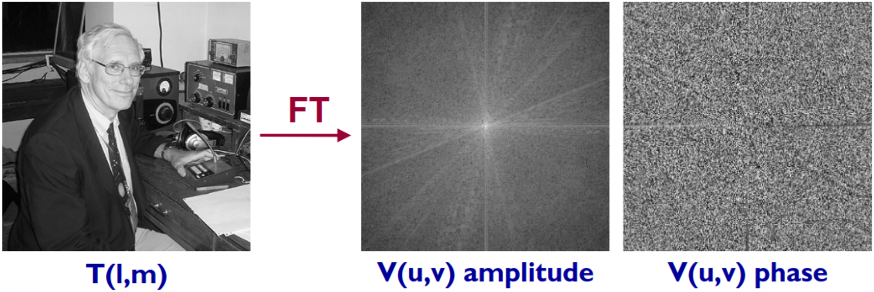

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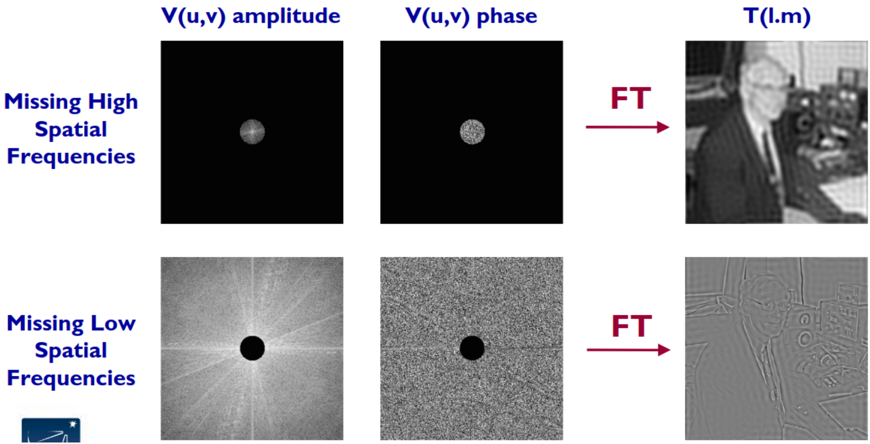

Source: Meredith MacGregor

Astronomy & Astrophysics manuscript no. aa42459
December 15, 2021

Deep Images of the Galactic Center with GRAVITY

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(Affiliations can be found after the references)

December 15, 2021

GRAVITY - testing general relativity by measuring the orbits of stars passing near the central BH

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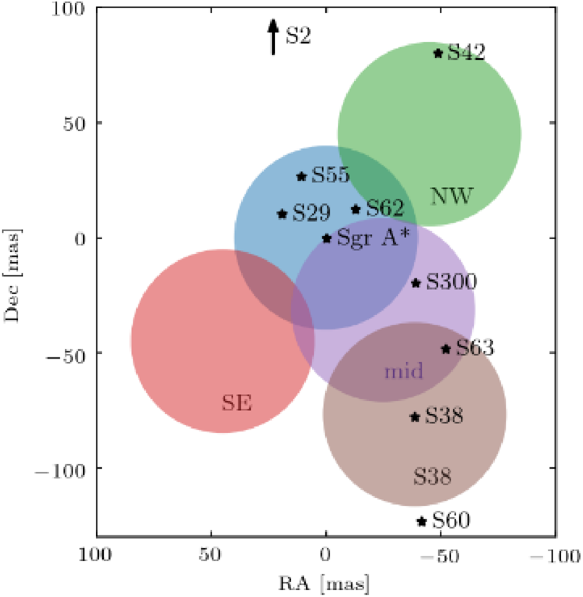
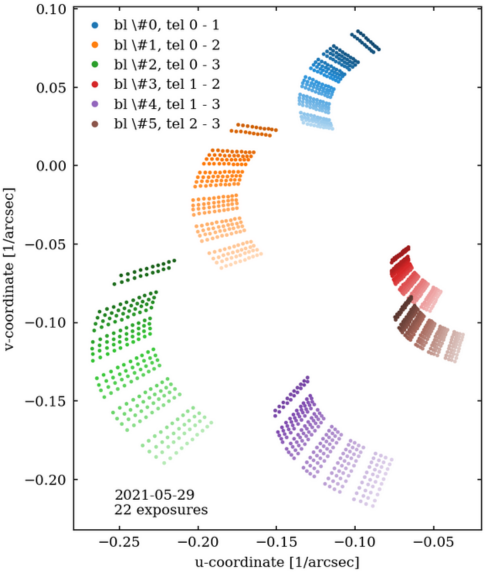
Solution -> search for fainter stars

VLTI GRAVITY observations



VLTI GRAVITY observations



Model fitting is a powerful method to extract the desired information, but we do not know where the stars may be present

Common solution: the CLEAN algorithm

CLEAN views the image as a collection of point sources, whose signal it subtracts iteratively from the measured coherent flux until only the noise is left.

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Problem: CLEAN depends on the linearity and invertibility of the Fourier transform - this is not true for the GRAVITY observations due to the instrumental effects

Solution: Bayesian forward modeling -> non-linear and non-invertible terms can be handled straightforwardly

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= new code -> GRAVITY-RESOLVE (G^R)

Prior model for the Galactic Center

- The position of Sgr A follows a Gaussian distribution with user defined mean and variance

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- 256^2 pixels - limit imposed by the angular resolution
- All pixels in the image are statistically independent
- Vast majority of pixels will be dark.

Image priors

$$\mathcal{P}\left(I_{\rm Img}\right) = \prod_{i}^{N_{\rm pix}} \frac{q^{\alpha}}{\Gamma(\alpha)} I_{\rm Img}(i)^{-\alpha-1} \exp\left[\frac{-q}{I_{\rm Img}(i)}\right]. \qquad (2)$$

i - pixels in the image
Γ - Gamma function
q and α - user defined variables, set to reflect the fact that max(I)=1 and the image may contain 1 star to the order of magnitude

Gamma prior is conjugate to Poisson likelihood

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- Some known stars separately added by adding a prior on their expected positions -> helps convergence

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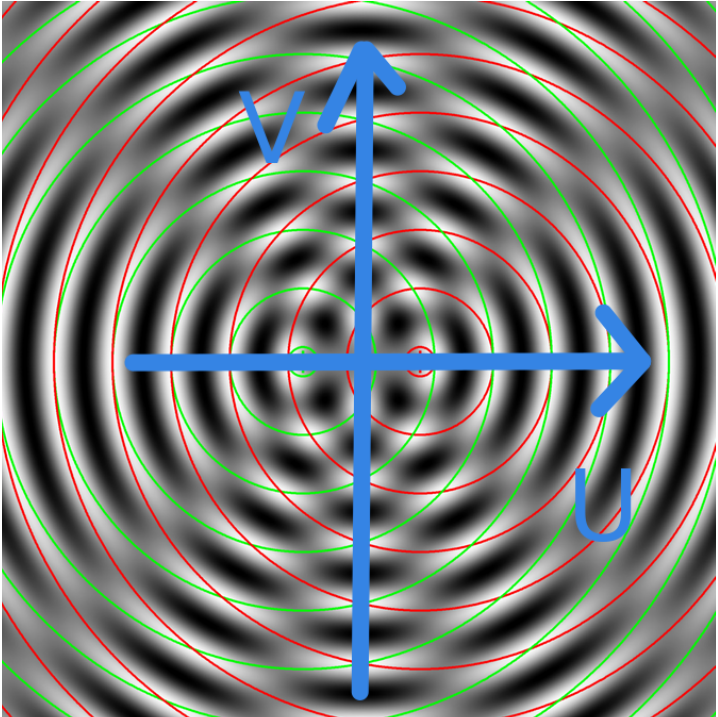
- Some known stars separately added by adding a prior on their expected positions -> helps convergence
- Spectral distribution of Sgr A is approximated with two powerlaws

Response function

- Fiber damping
- Optical aberrations
- Bandwidth smearing


V
U

Self calibration

Fixes time-variable instrumental effects (e.g. atmospheric conditions)

Self calibration by using closure phases formed over a triangle of telescopes

$$\phi_{i,j,k} = \arg\left(v_{i,j}\, v_{j,k}\, v_{k,i}\right) ,$$

Thanks to this we can estimate errors

Number of dimensions

$$
\begin{aligned}
d = 256^2 & \quad \text{image of faint sources} \\
+ 2 \times N_{\text{exp}} & \quad \text{Sgr A* light curves} \\
+ 2 & \quad \text{Sgr A* position} \\
+ 3 \times N_{\text{PS}} & \quad \text{point sources position and flux} \\
+ 6 \times N_{\text{exp}} & \quad \text{amplitude self-calibration} \\
+ 2 & \quad \text{spectral indices} \\
\sim 7 \times 10^4 \, . &
\end{aligned}
$$

A high number of dimensions -> very expensive calculation of posterior

Solution: Metric Gaussian Variational Inference

Covariance measured using the Fisher information metric

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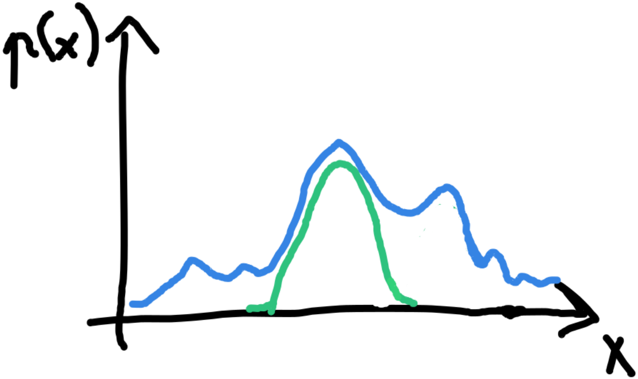
Fisher information metric = a covariance of gradient of the probability function as function of random variables


p(x)
x

Multivariate Gaussian distribution

$$\mathcal{G}\left(\xi \middle| \bar{\xi}, \Xi\right)$$

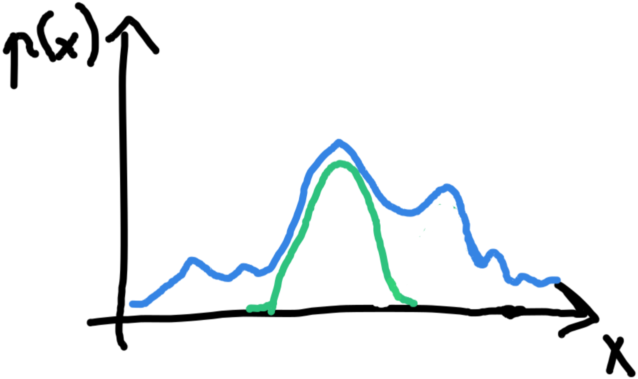
ξ - standardized coordinates for each degree of freedom - prior is given by a unit Gaussian with zero mean
Ξ - covariance - first estimated using the Fisher metric

The real mean $\bar{\xi}$ and covariance Ξ are found interatively

How well our posterior surrogate fits the real posterior?

Kullback-Leibler divergence

$$\mathrm{D}_{KL}(\mathrm{P}||\mathrm{Q}) = \int_x p(x) * \log(p(x)/q(x))\mathrm{d}x$$



p(x)
x

$$\bar{\xi}_{i+1} = \min_{\bar{\xi}} \int \mathrm{d}\xi \, \mathcal{G}\left(\xi | \bar{\xi}, \Xi_i\right) \ln\left[\frac{\mathcal{G}\left(\xi | \bar{\xi}, \Xi_i\right)}{\mathcal{P}\left(\xi | d\right)}\right] .$$

How do we calculate this if we don't know the real posterior?

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

$$\mathcal{P}(I \mid d) \propto \mathcal{P}(d \mid I)\, \mathcal{P}(I)$$

The evidence term (marginal) P(d) incomputable, but luckily it is invariant

$$\bar{\xi}_{i+1} = \min_{\bar{\xi}} \int \mathrm{d}\xi \, \mathcal{G}\left(\xi | \bar{\xi}, \Xi_i\right) \ln \left[\frac{\mathcal{G}\left(\xi | \bar{\xi}, \Xi_i\right)}{\mathcal{P}\left(\xi | d\right)} \right] .$$

We switch between estimating $\bar{\xi}$ using the Kullback-Leibler divergence and covariance Ξ using the Fisher metric

$$\bar{\xi}_{i+1} = \min_{\bar{\xi}} \int \mathrm{d}\xi \, \mathcal{G}\left(\xi | \bar{\xi}, \Xi_i\right) \ln\left[\frac{\mathcal{G}\left(\xi | \bar{\xi}, \Xi_i\right)}{\mathcal{P}\left(\xi | \boldsymbol{d}\right)}\right].$$

This integral is calculated by calculating a mean of random sample from the approximate posterior distribution

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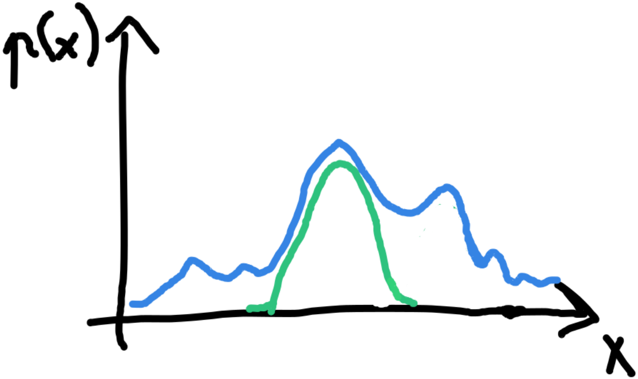
This integral is calculated by calculating a mean of random sample from the approximate posterior distribution-> we can sample multi-modal posterior distributions and avoid problems with the convergence by switching the seed

They calculated ten independent imaging runs -> good enough to capture the dominant modes of the posterior, but not enough to estimate the relative weights reliably

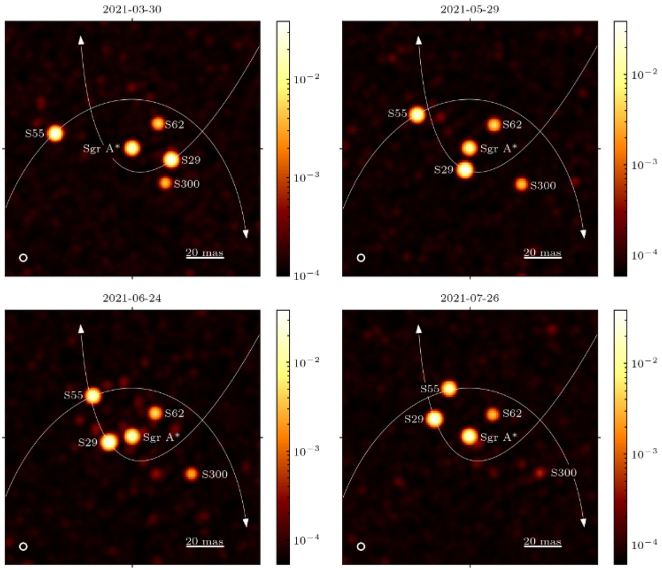
Instead, consistency between different paintings was used as a sanity check

The sensitivity and selection of arbitrary parameters tested on a mock data set

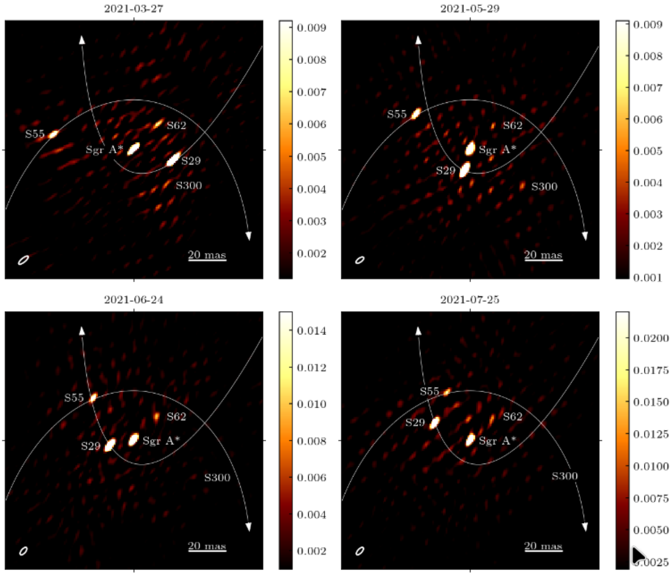


p(x)
x

Results


2021-03-30
S55
Sgr A*
S62
S29
S300
20 mas
2021-05-29
2021-06-24
2021-07-26
10^{-2}
10^{-3}
10^{-4}

Results from the CLEAN algorithm



GRAVITY-RESOLVE (G^R) has a problem with fast moving sources

In GRAVITY-RESOLVE (G^R) error bars had to be scaled by hand and by trial-and-error