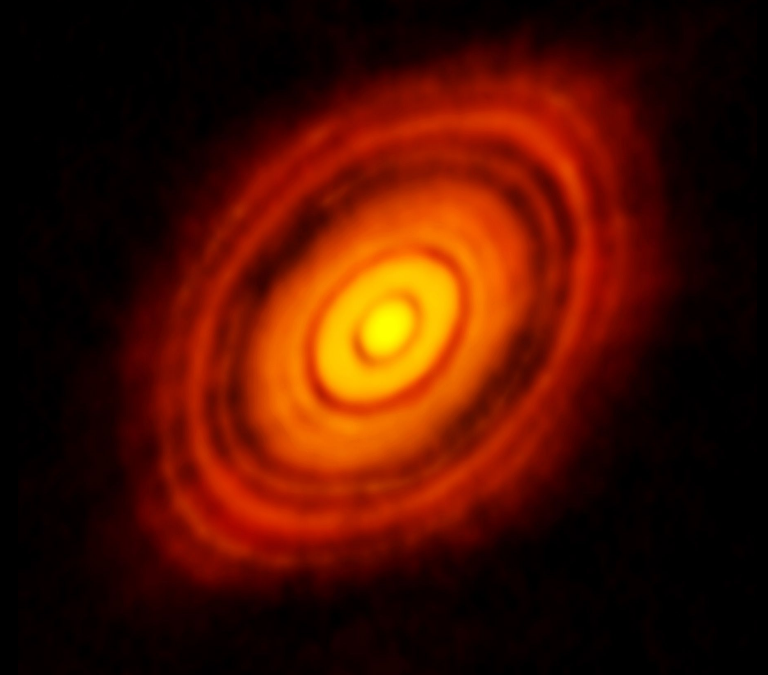
Interferometry

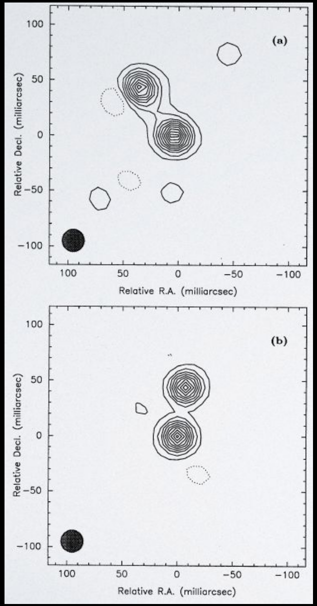
MPAGS Astrophysical Techniques



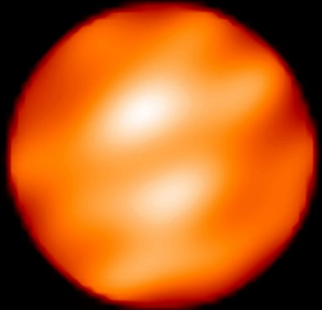
Tim Pearce

Combining light from different paths to resolve tiny differences

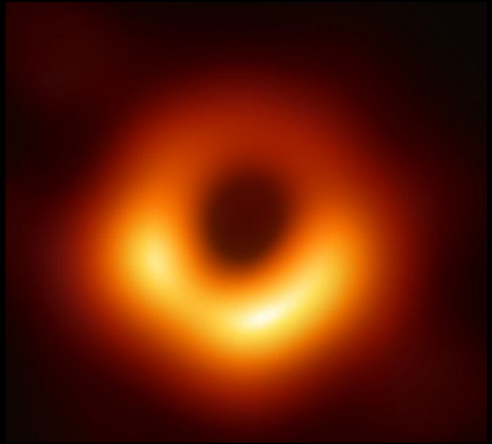
What can we do with interferometry?



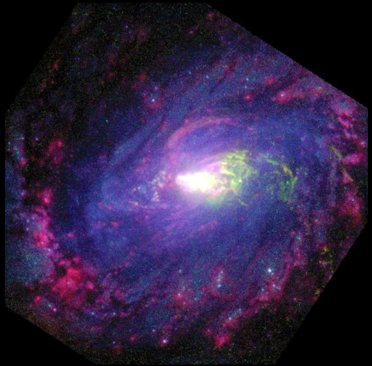
Binary stars
(Baldwin et al. 1996)



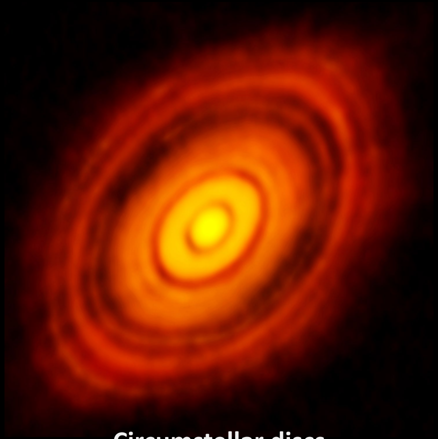
Star surfaces
(Haubois et al. 2009)



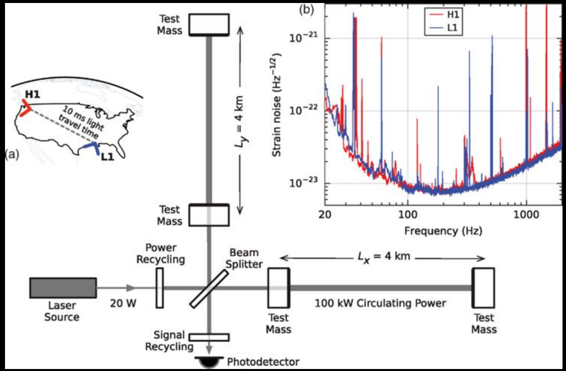
Black-hole discs
(Event Horizon Telescope Collab. 2019)



Galaxy structures
(Jaffe et al. 2004)

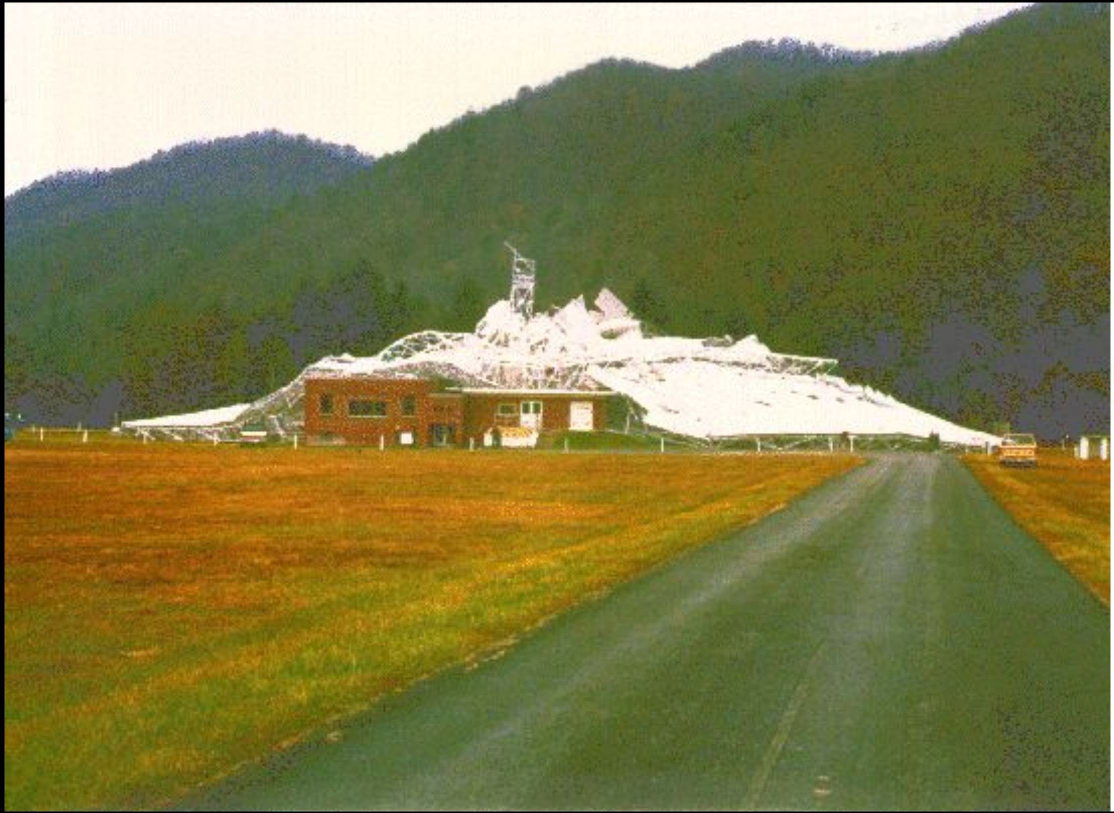


Circumstellar discs
(ALMA Partnership 2015)



Gravitational waves
(Abbott et al. 2016)

Why do interferometry?



America's most powerful radio telescope IS . . .

ZAPPED!

. . . by hostile space aliens!

THE Green Bank radio telescope in West Virginia after the alien attack. At left is how it looked after construction.

BEFORE ▲ AFTER ▶

Space aliens zapped the enormous radio telescope at Green Bank, W. Va., with a powerful laser to keep scientists from monitoring their activities in the northern hemisphere!

By RAGAN DUNN

That's the claim of Swiss astronomer Peter Voisard, who says the destruction of the 300-foot instrument on November 15 qualifies as the boldest act of extraterrestrial aggression in the history of the world.

"We know that extraterrestrials have shot down planes and abducted people but this is the first time they have been brazen enough to destroy a government research facility," the expert told newsmen in Geneva. "The Americans must have been learning too much about them," he continued. "There is no other rational explanation for such a strike as this. In some circles, it might be considered an act of war."

Dr. Voisard's report sent shockwaves throughout the world's scientific community. But the handful of men who can talk about the Green Bank disaster with authority refused to describe the incident as anything more than "a mystery."

There is no doubt that the instrument — which could detect objects almost two-thirds of the way to the edge of the visible universe — was essential to monitoring extraterrestrial activity in the northern skies.

And its devastation by a destructive beam stands as compelling proof that it was zapped by extraterrestrials who wanted to mask their activity from mankind, Dr. Voisard said.

"Any other explanation defies logic," he continued. "The telescope had been in operation since 1962 and was solid as a rock.

"Suddenly it collapses in the dead of night. What are we supposed to think? That the telescope just fell apart?"

French radio astronomer Marc Kraemer was inclined to agree with Dr. Voisard but warned against jumping to conclusions.

"I firmly believe that we can prove extraterrestrials toppled the telescope at Green Bank," he said. "But let's wait until all the evidence is in.

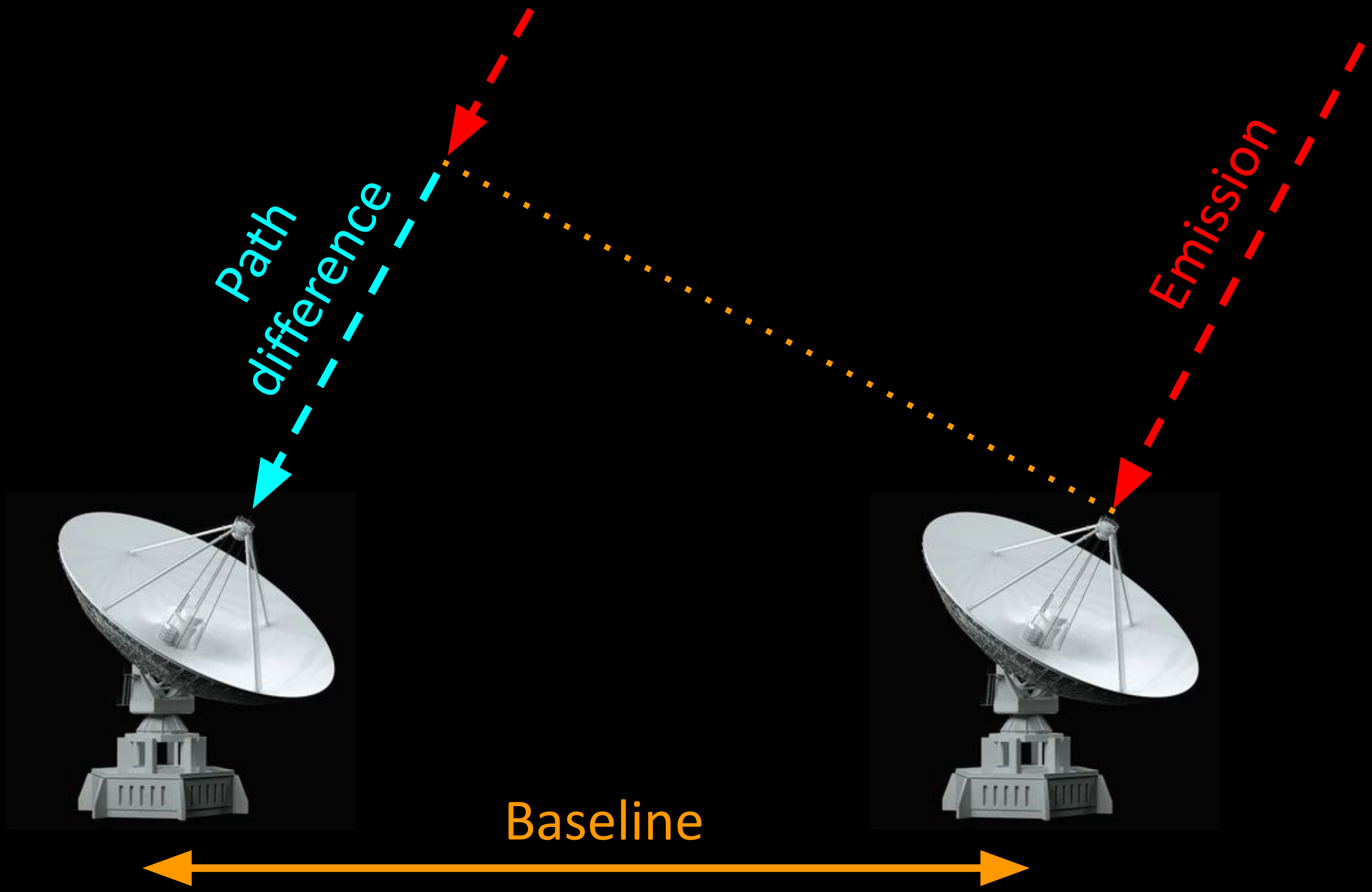
"Then we can take whatever steps are necessary to prevent things like this from happening in the future."

⇒ We can only build dishes so big

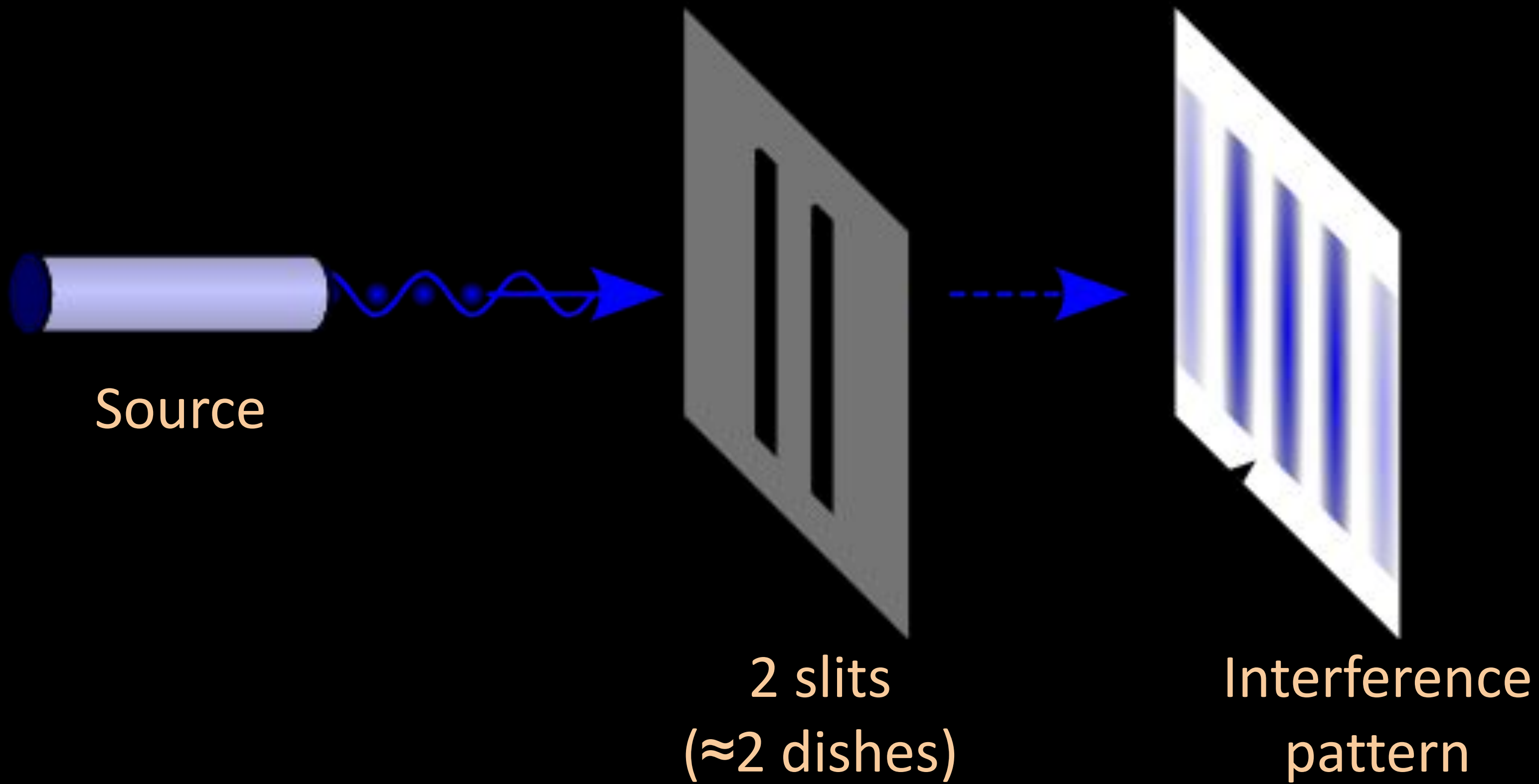
Interferometer: combining dishes together

Jansky Very Large Array, USA

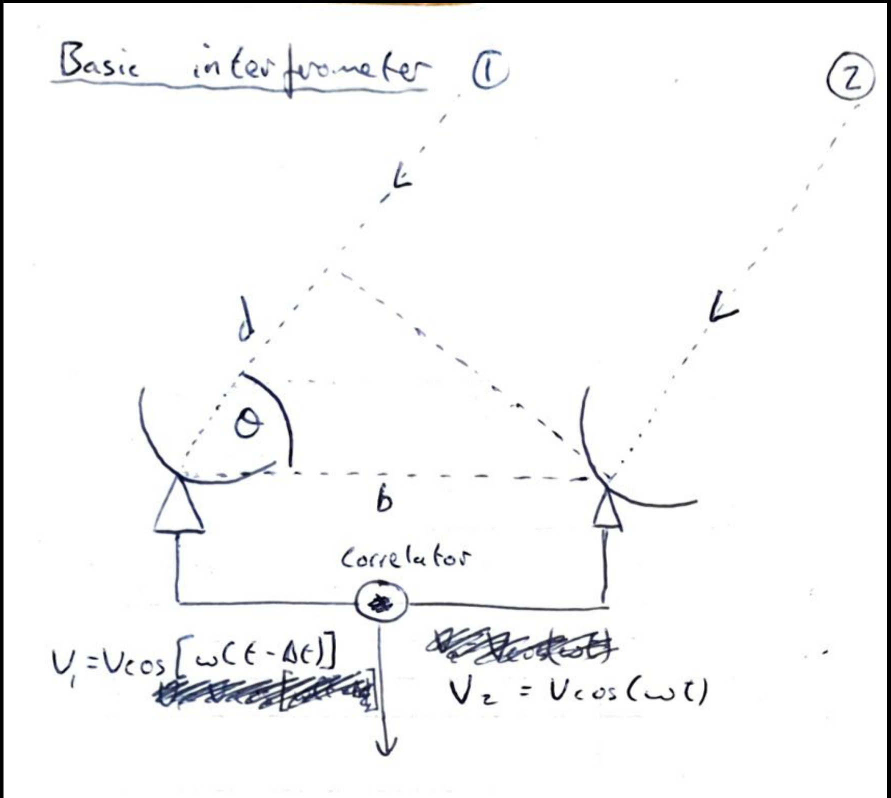
Roughly how it works



Similar to Young's double-slit experiment



Derivation of basic interferometer response



Incoming wave: $V\cos(\omega t)$

Path difference: $d = b\cos\theta$

Extra travel time for wave 1: $\Delta t = \frac{d}{c} = \frac{b\cos\theta}{c}$

So when wave 1 hits detector:

$$V_1 = V\cos[\omega(t - \Delta t)]$$

Correlator:

1. Multiplies signals:

$$V_1V_2 = \frac{V^2}{2}\left[\cos(2\omega t - \omega\Delta t) + \cos(\omega\Delta t)\right]$$

(from trig. identity)

$$\cos x\cos y = \left[\cos(x+y) + \cos(x-y)\right]\frac{1}{2}$$

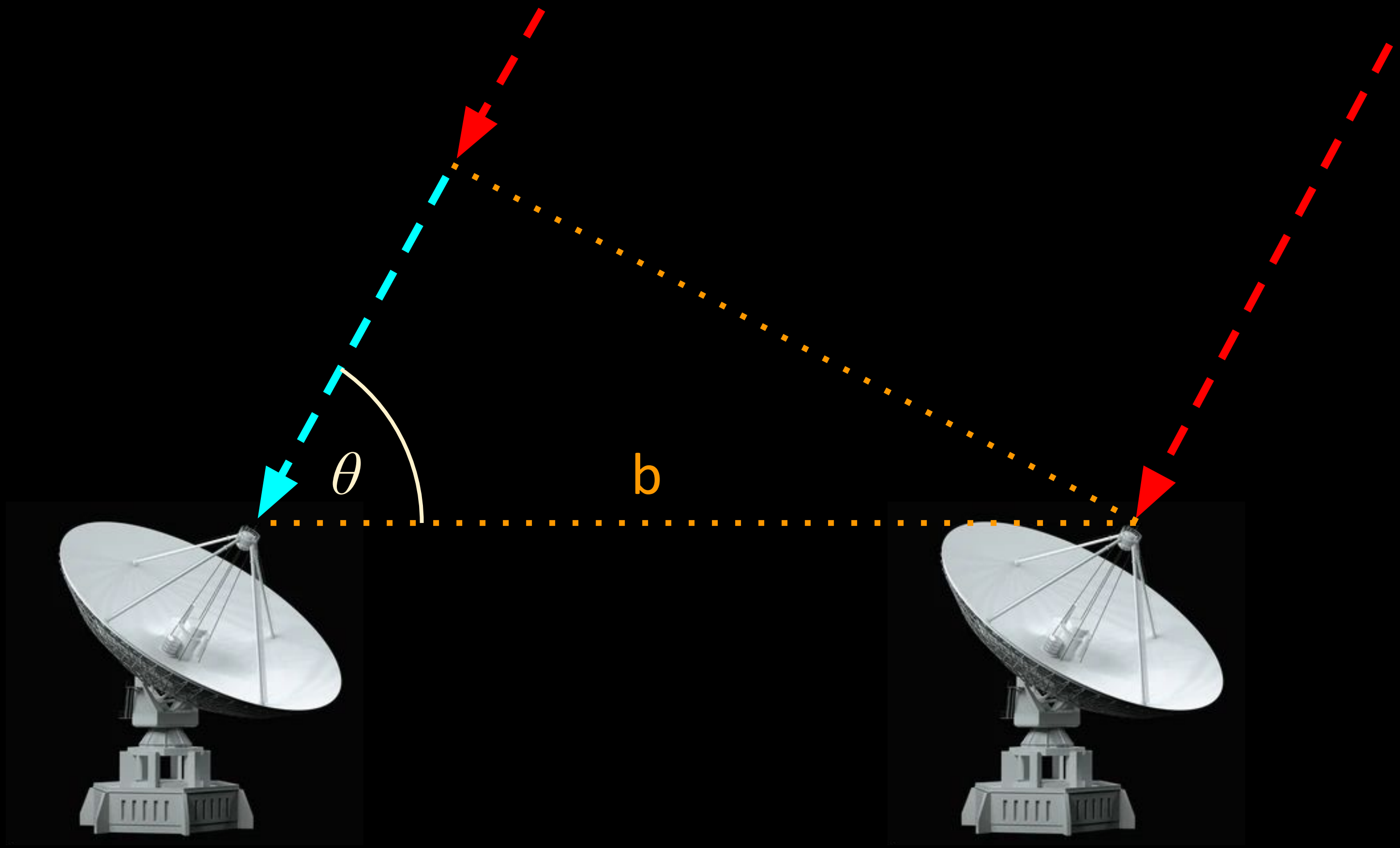
2. Time-averages ~~a~~ over time $\gg (2\omega)^{-1}$ to remove high-freq. ~~response~~ term $\cos(2\omega t - \omega\Delta t)$ output!

$$\Rightarrow \boxed{R = \langle V_1V_2\rangle = \frac{V^2}{2}\cos(\omega\Delta t)}$$

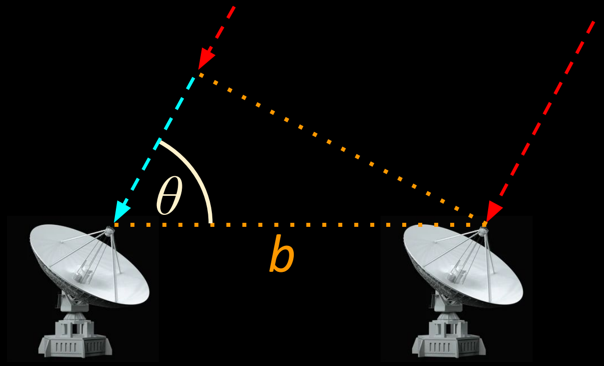
$$\Delta t = \frac{b\cos\theta}{c}$$

Interference

Function of θ
-> interference on sky


θ
b

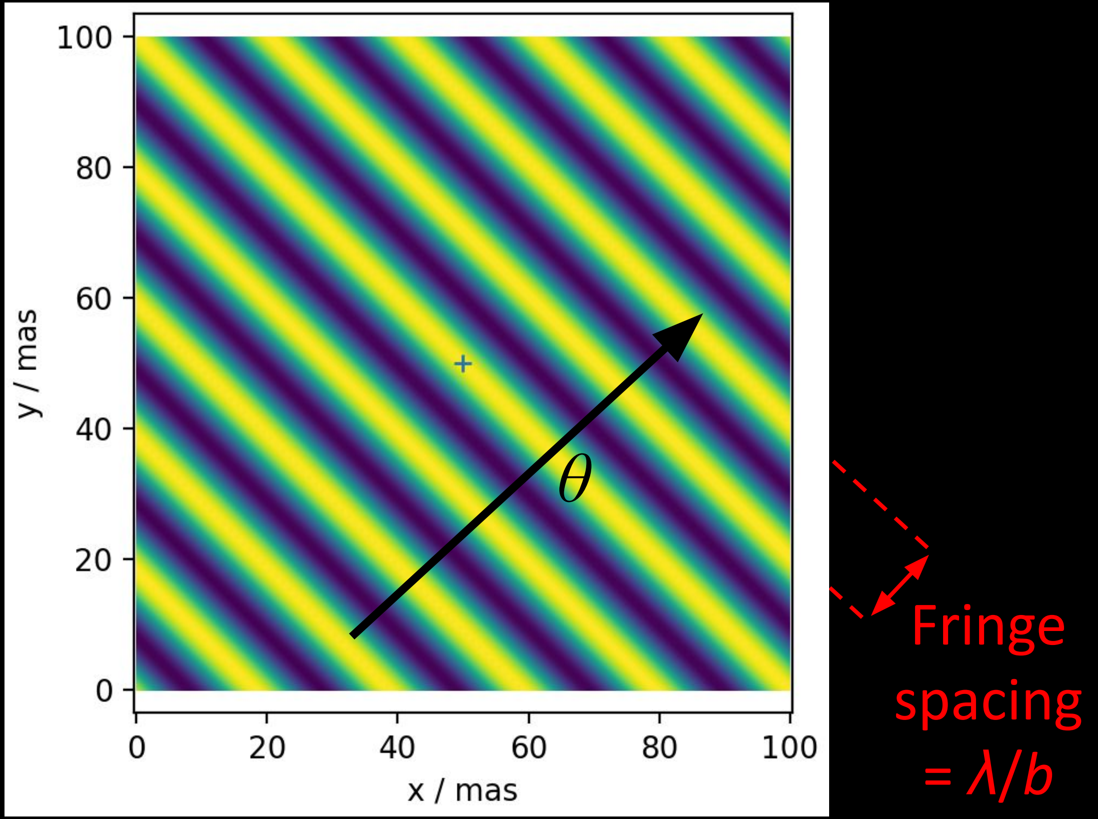
Sensitivity fringes



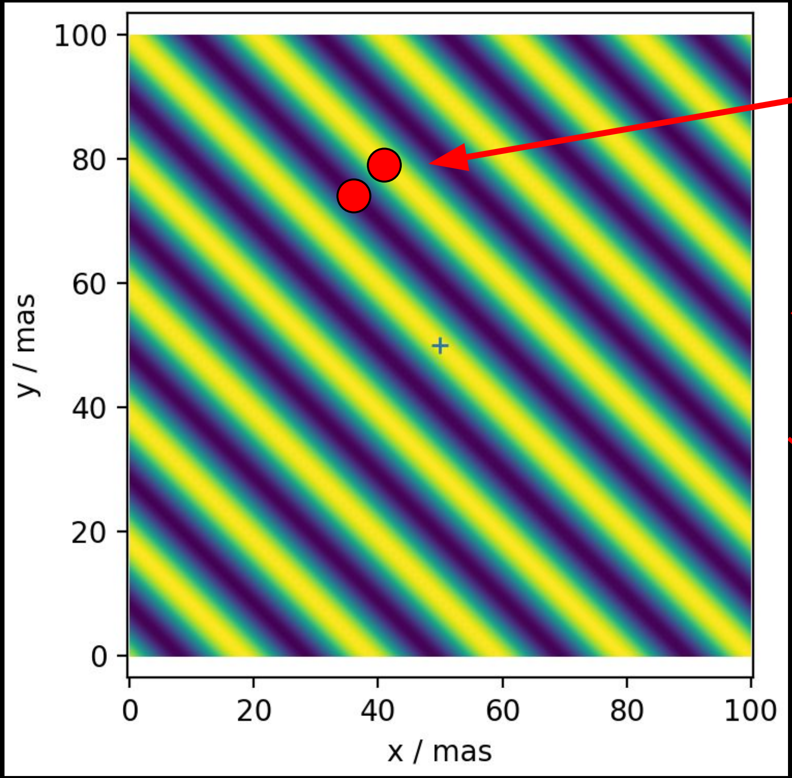
$$R = \frac{V^2}{2}\cos(\omega\Delta t)$$

$$\Delta t = \frac{b}{c}\cos(\theta)$$

Colour = correlator response *R*



Resolution



'Resolved':
$\Delta\theta \geq \lambda/(2b)$

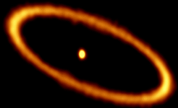
Fringe spacing = λ/b

Signal = sum of (sky image x fringe pattern)

$$R = \int I(x, y)\cos(\omega\Delta t)\mathrm{d}\Omega$$

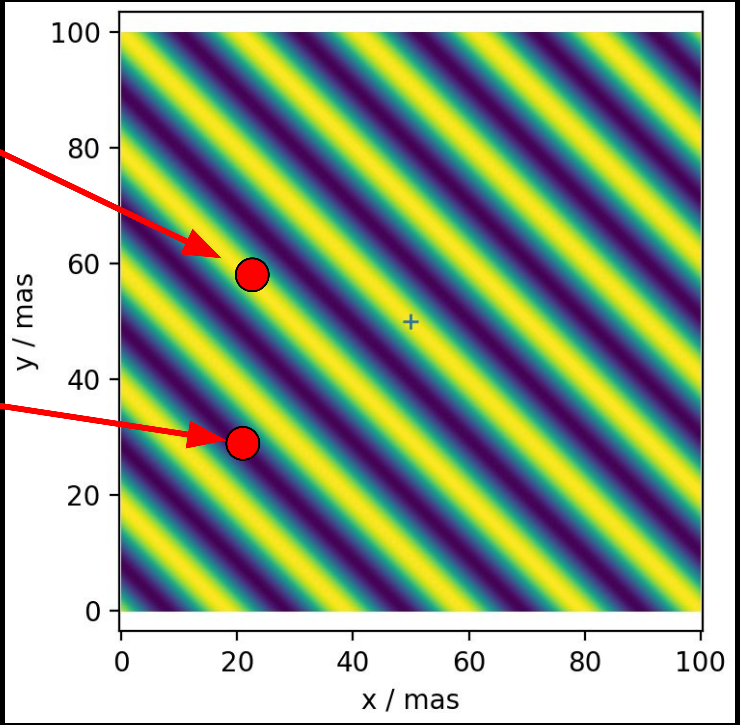
Integral over field of view

$I(x, y)$



Point source at fringe max.: δR_1=1

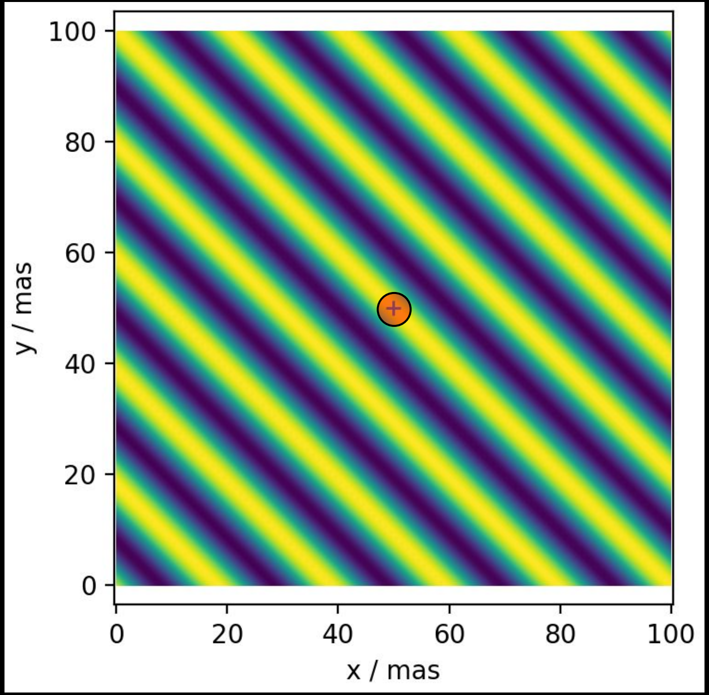
Point source at fringe min.: δR_2=-1



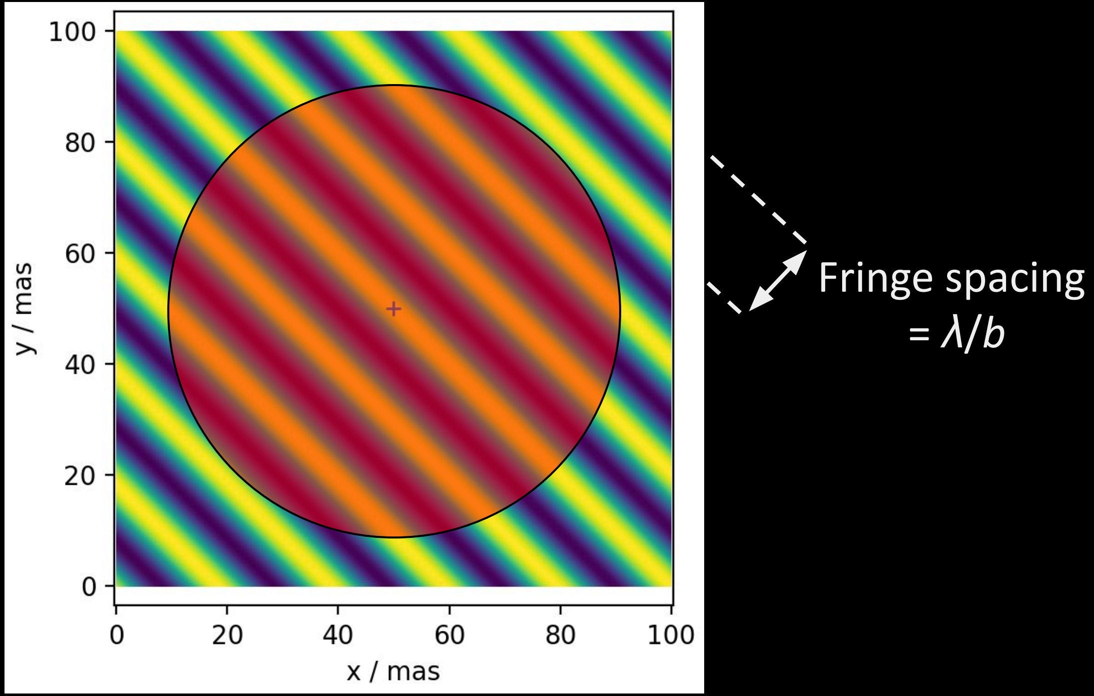
$R = \Sigma\delta R_i = 1 - 1 = 0$

Resolving out extended flux

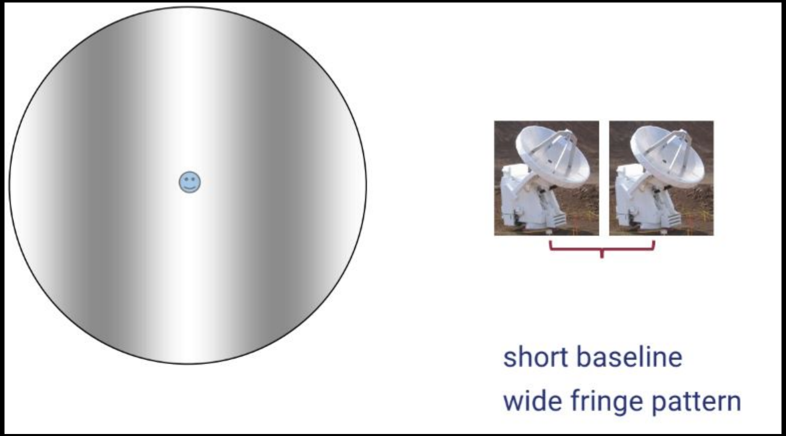
Small source: signal ≠ 0

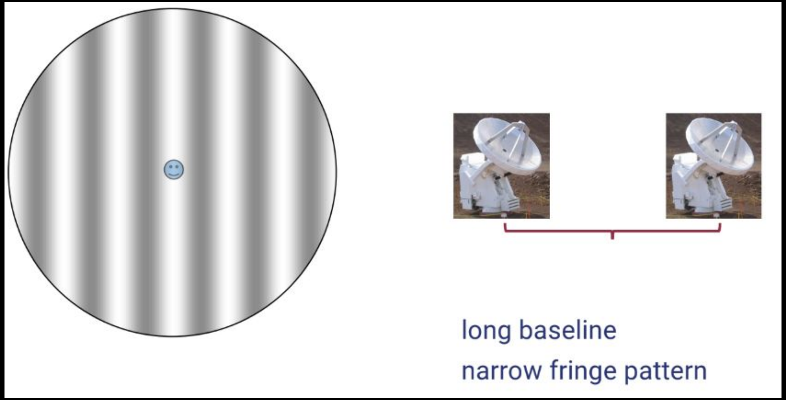


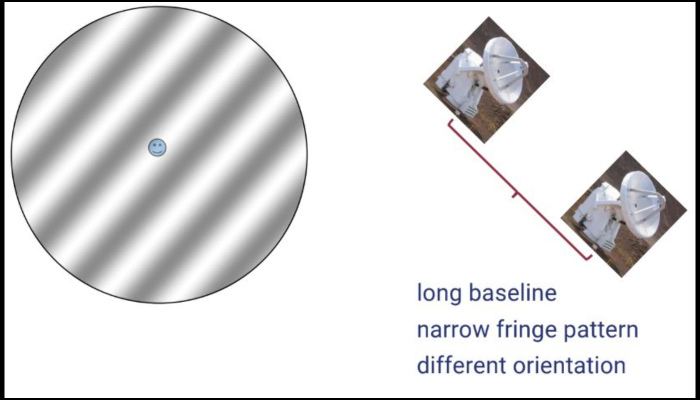
Large source: signal ≈ 0



⇒ Detecting big things requires small baselines (b), and *vice versa*

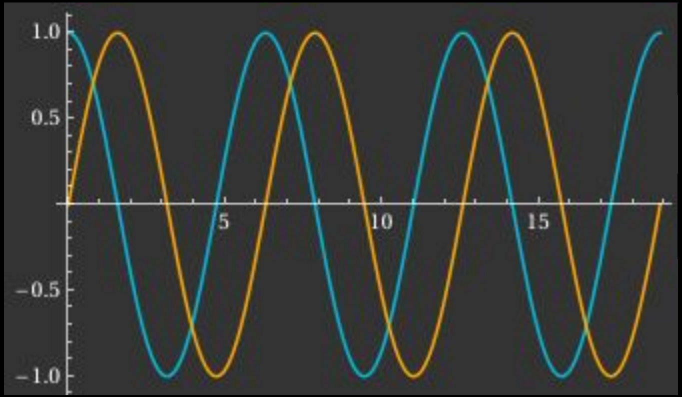






Images courtesy of David Wilner

Complex visibility



$$R_c = \int I(x,y)\cos(\omega\Delta t)d\Omega$$

$$R_s = \int I(x,y)\sin(\omega\Delta t)d\Omega$$

Cosine correlator only sensitive to even components of extended source

Add second correlator with 90° phase shift ⇒ sine

Complex visibility: $V = R_c - i\,R_s = Ae^{-i\phi}$

Amplitude: $A = \sqrt{R_c^2 + R_s^2}$

Phase: $\phi = \arctan(R_s/R_c)$

Fourier Transforms

Complex visibility:

$$V = R_C - i\,R_S = Ae^{-i\phi}$$

where

$$R_C = \int I(x,y)\cos(\omega\Delta t)\mathrm{d}\Omega$$

$$R_S = \int I(x,y)\sin(\omega\Delta t)\mathrm{d}\Omega$$

The complex visibility is a Fourier Transform

$$V(u,v) = \int\int I(x,y)e^{-2\pi i(ux+vy)}\mathrm{dxdy}$$

u, v are spatial frequencies corresponding to *x, y* dimensions:

$$(u,v) = \boldsymbol{b}/\lambda$$ (***b*** is baseline vector)

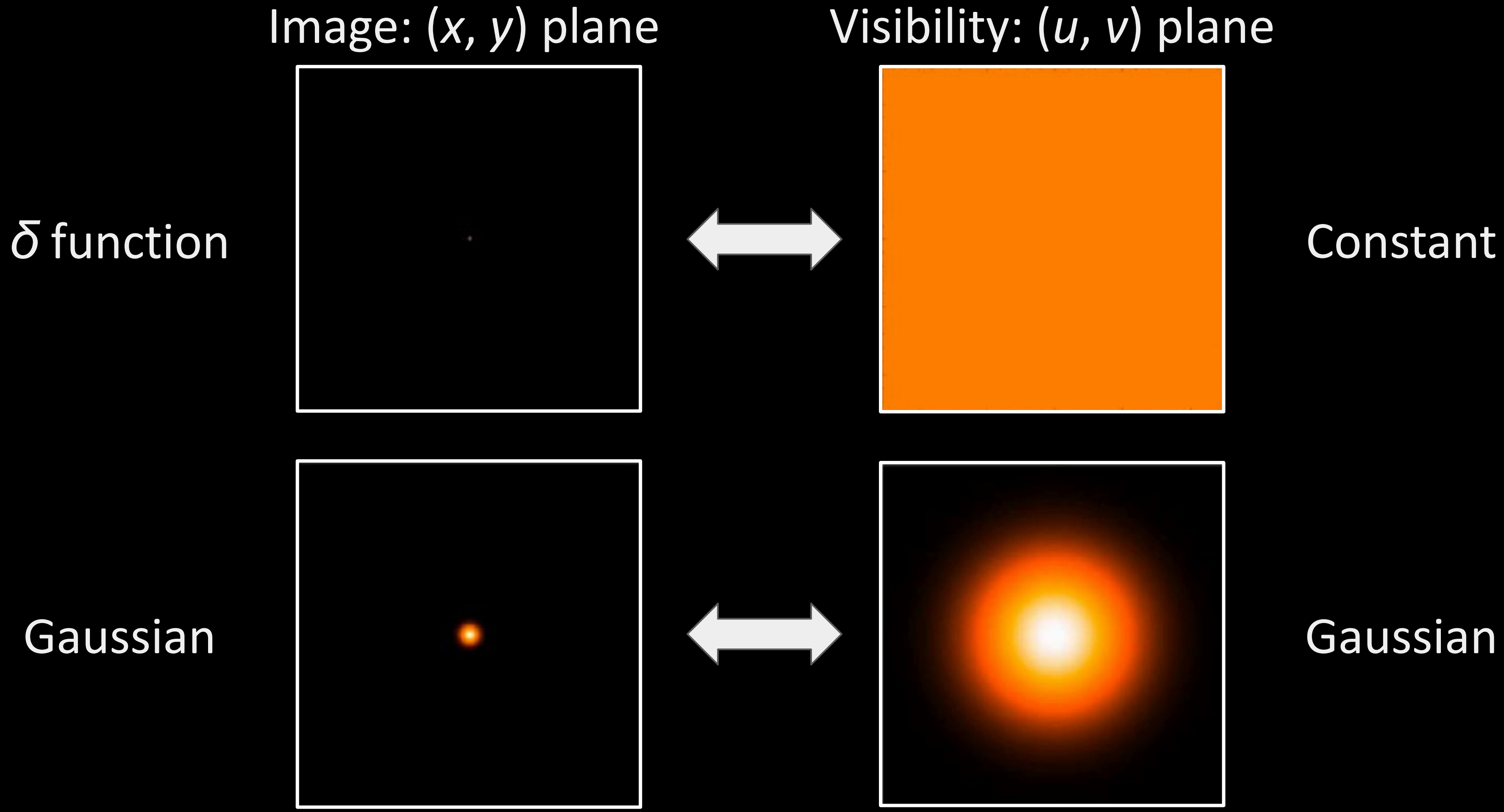
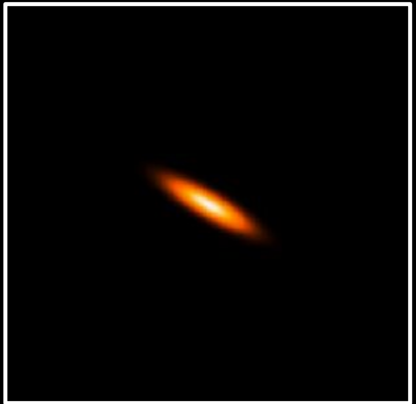


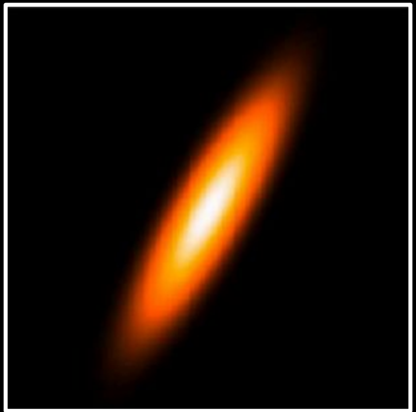
Image: (x, y) plane
Visibility: (u, v) plane
δ function
Constant
Gaussian
Gaussian

Image: (x, y) plane

Visibility: (u, v) plane

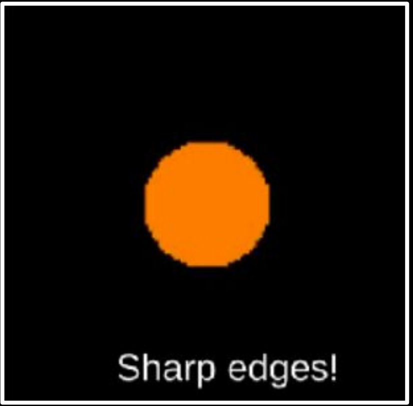
Elliptical Gaussian

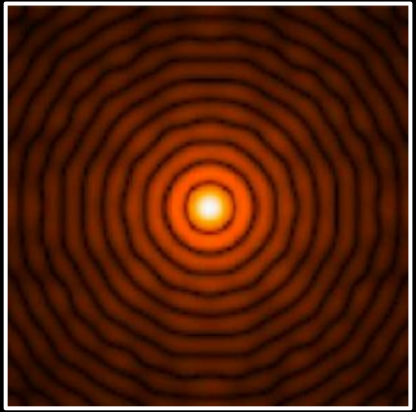




Elliptical Gaussian

Disc





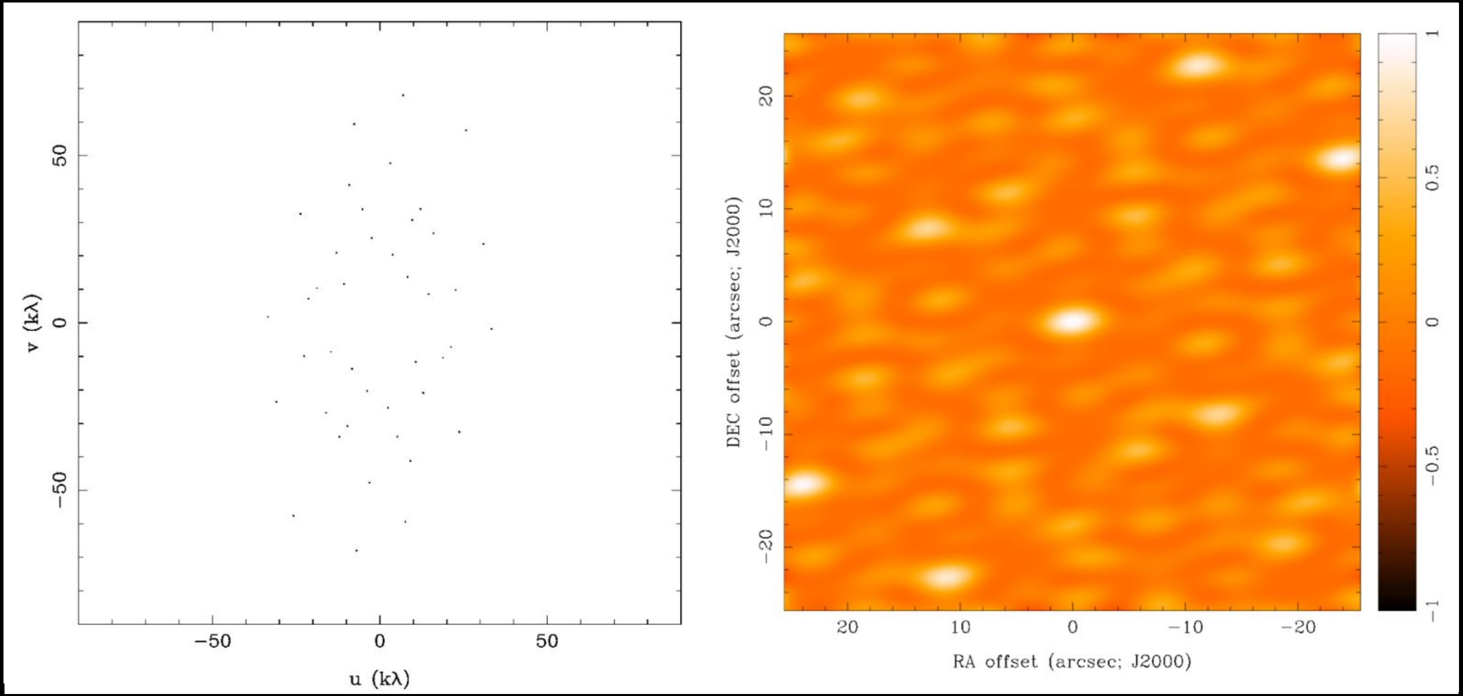
Bessel

Multiple baselines

Each baseline is a pair of points on the *u*, *v* plane




7 dishes = 21 baselines



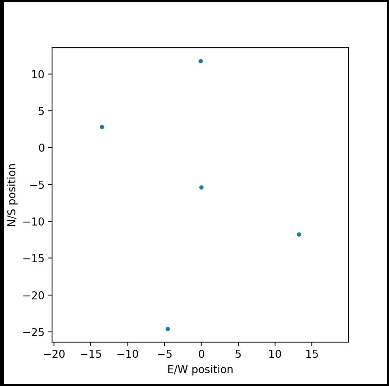


Goal: populate *u*, *v* plane with as many baselines as possible

Images courtesy of David Wilner

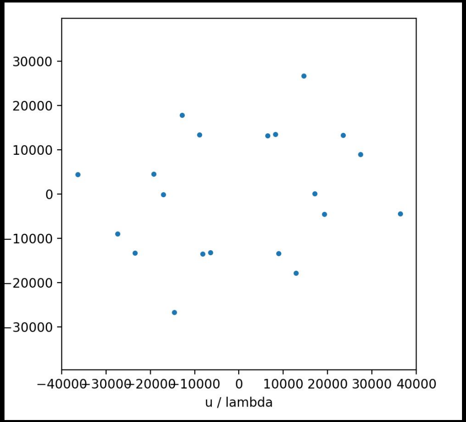
Sky rotation

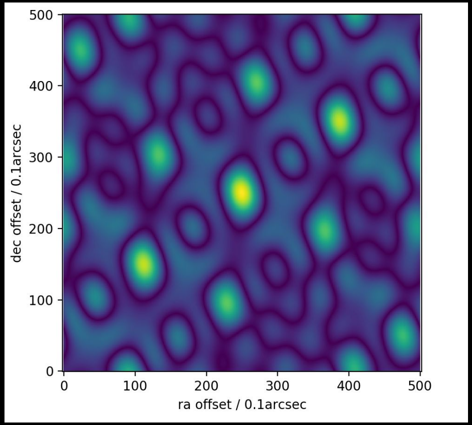
5 dishes



No sky rotation

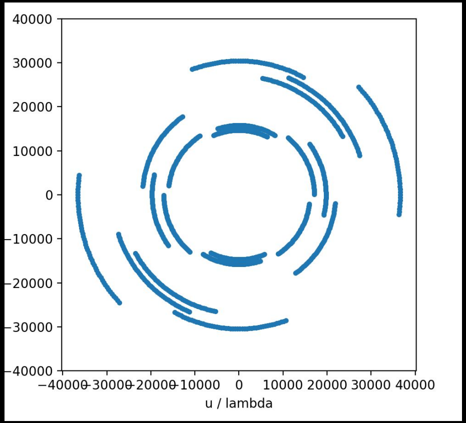
With sky rotation

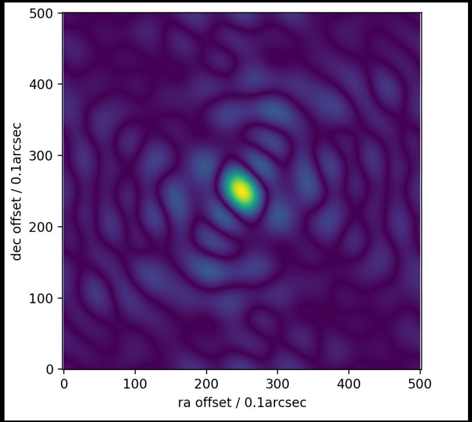




Baselines

Fringes





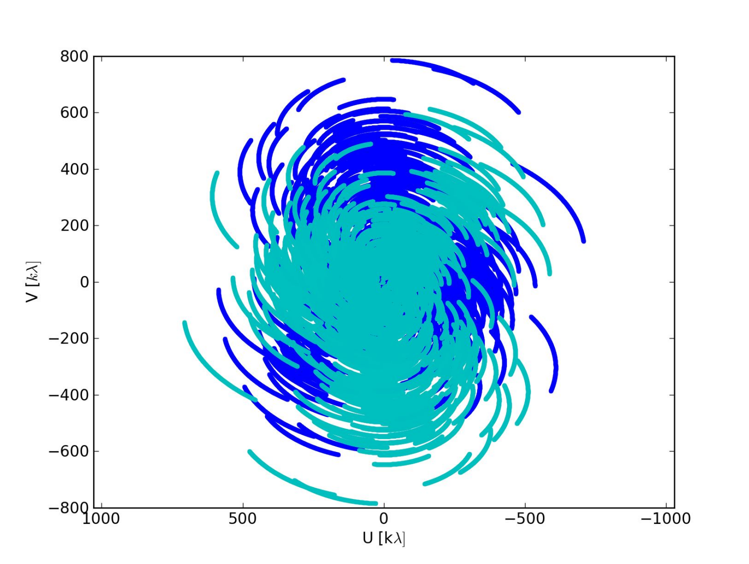
Images courtesy of Grant Kennedy

Sky rotation

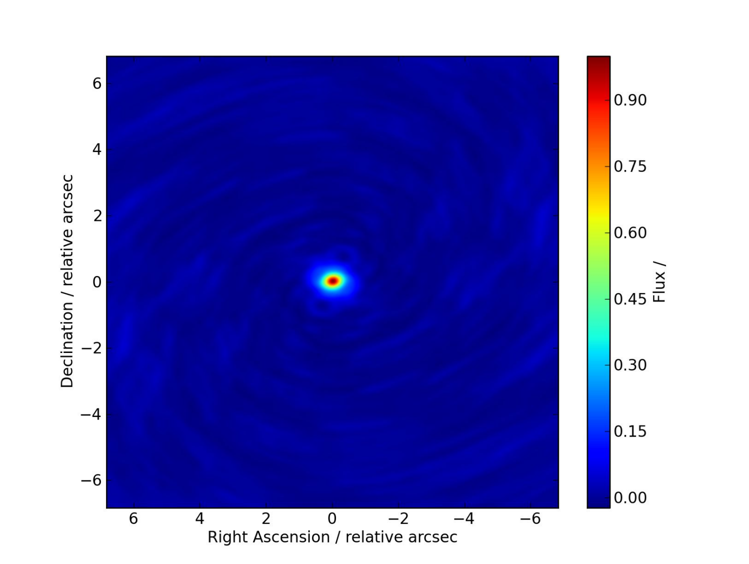
Real example: ALMA

2.5 km max baseline, 3hour integration, 43 antennas

Baselines: (u, v) plane



Fringes: (x, y) plane



Images courtesy of Grant Kennedy

Dirty beam

Conventional imaging:

$$I(x, y) \otimes \mathrm{PSF}(x, y) = \mathrm{O}(x, y)$$

Reality

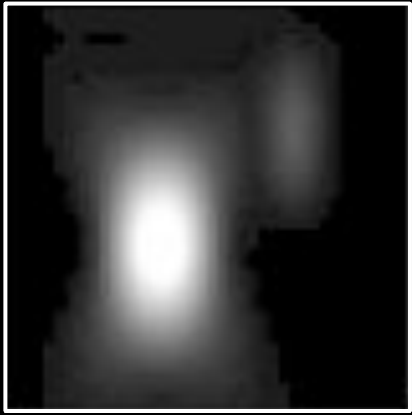
$\otimes$

Convolve

Point-spread function

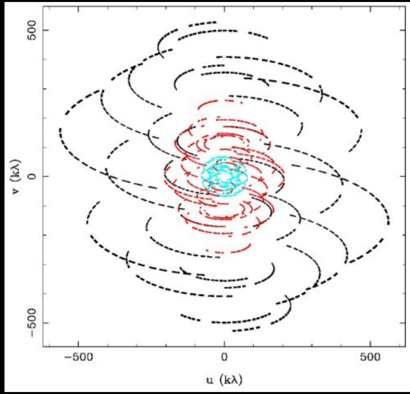
=

Image



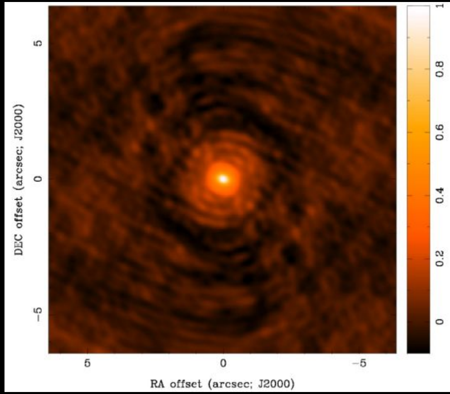
Similar in interferometry:

Baselines



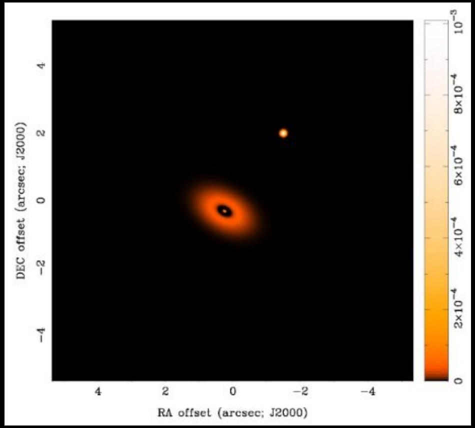
Fourier transform

‘Dirty beam’ (~PSF)

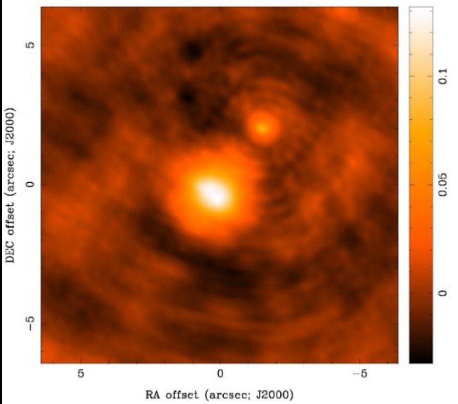


Convolve with

Reality



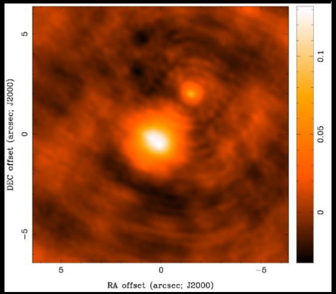
‘Dirty image’



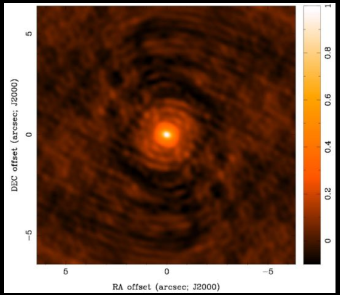
Images courtesy of David Wilner

CLEAN algorithm (rough):

Dirty image



Dirty beam



Get dirty image and make dirty beam

Loop:

Find peak of dirty image

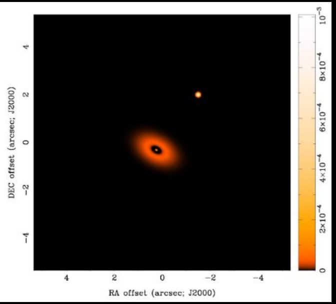
Subtract fraction of dirty beam centered at peak

Add subtracted peak to sky model (and clean component list)

If peak of residual dirty image < stopping threshold:

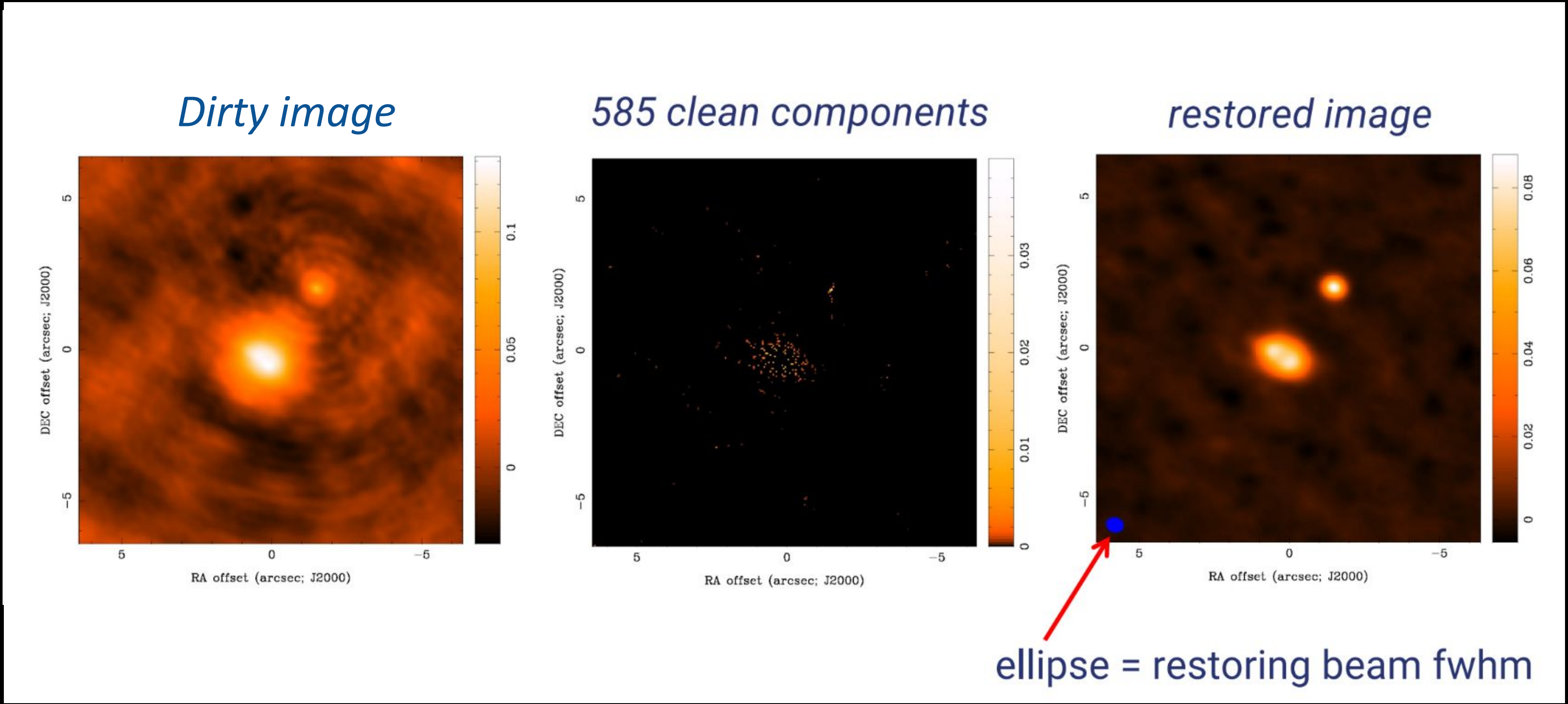
break

Reality



Images courtesy of David Wilner

CLEAN algorithm (rough):



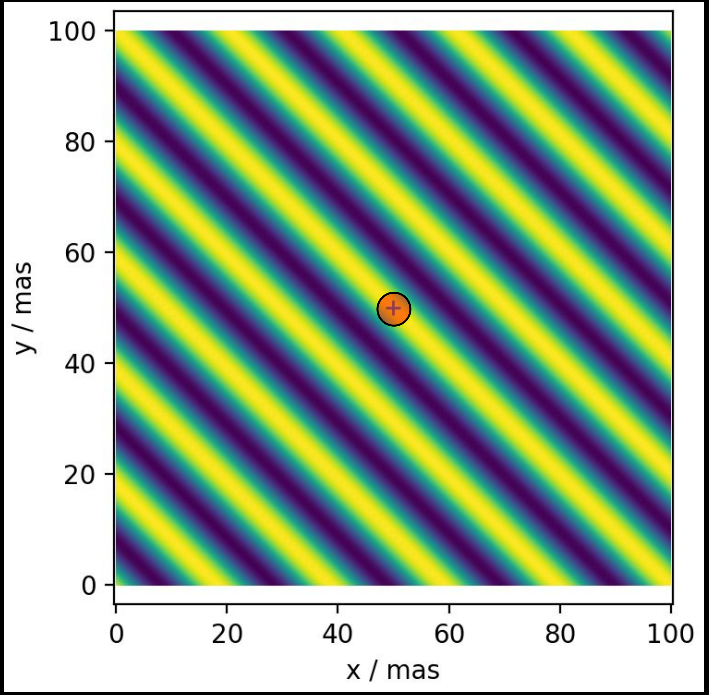
Images courtesy of David Wilner

Vevox

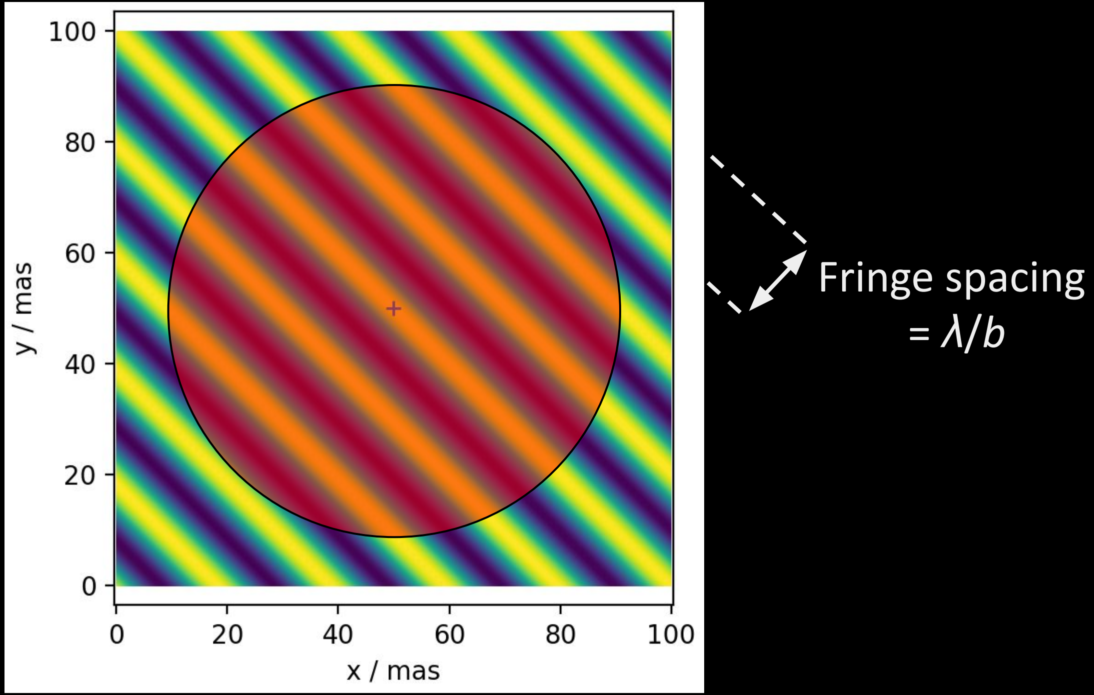
Other techniques

Resolving out extended flux

Small source: signal ≠ 0



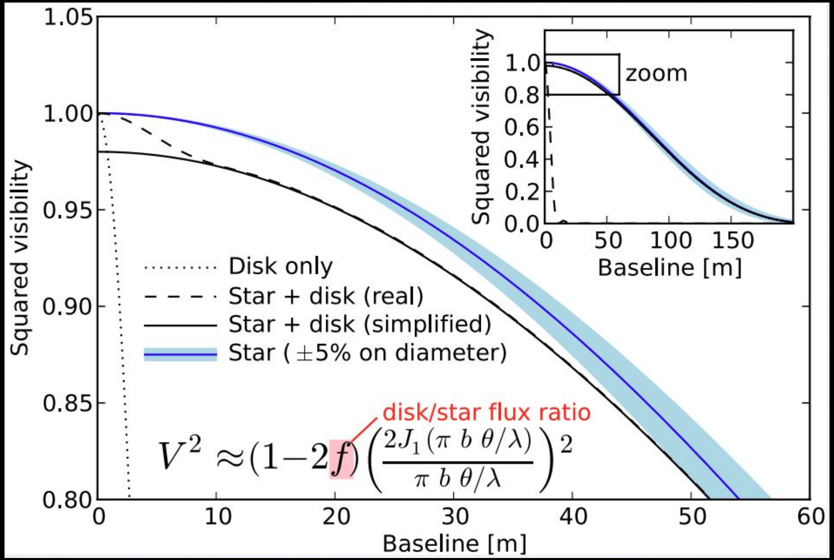
Large source: signal ≈ 0

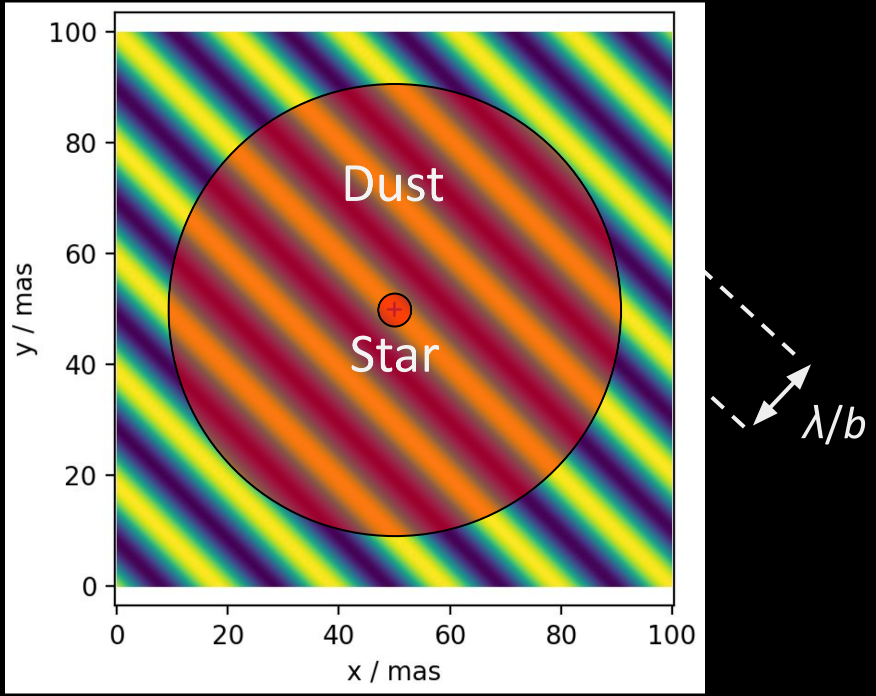


⇒ Detecting big things requires small baselines (*b*), and *vice versa*

Resolving out extended flux

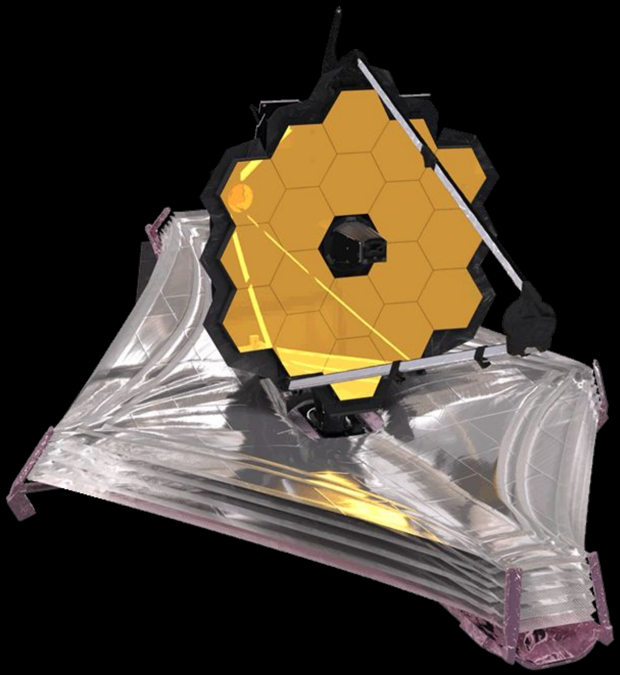
Example: hot dust

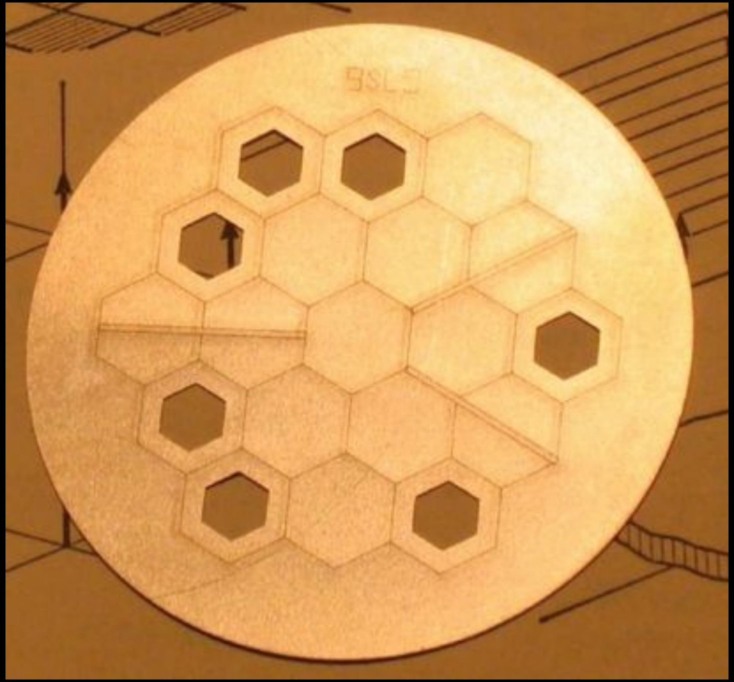




Ertel et al. (2014)

Sparse-aperture masking



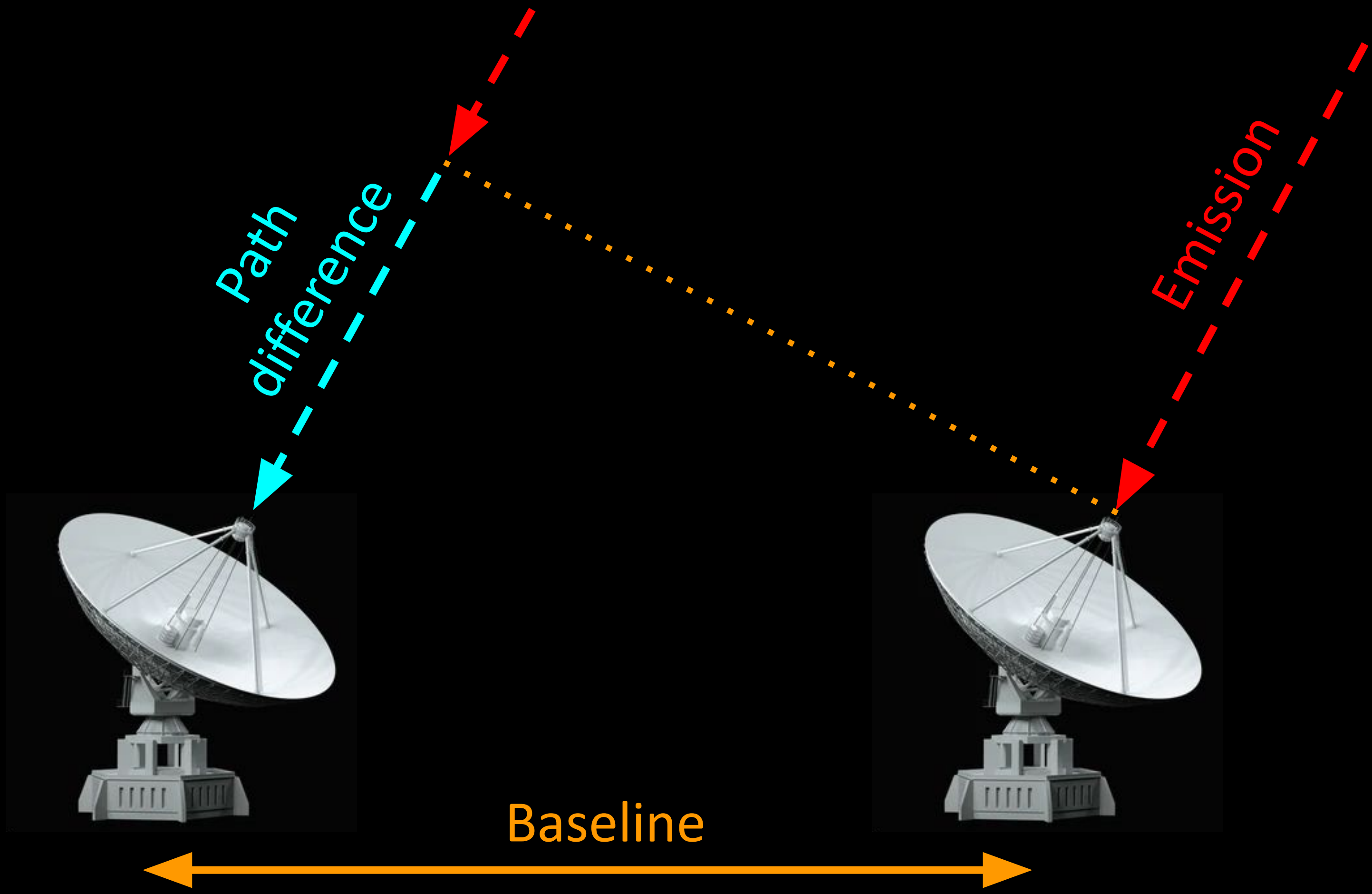


Higher resolution: 0.5 λ/b (interferometry) vs. 1.22 λ/D (imaging)

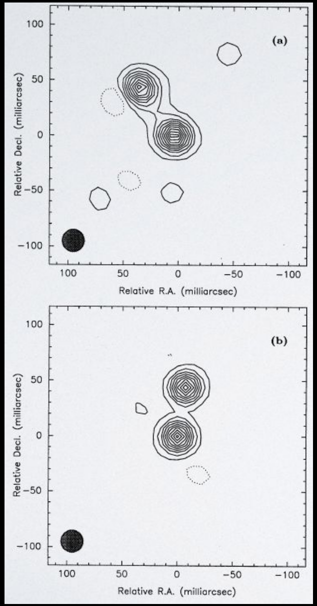
Comes at the expense of light-gathering power

Summary

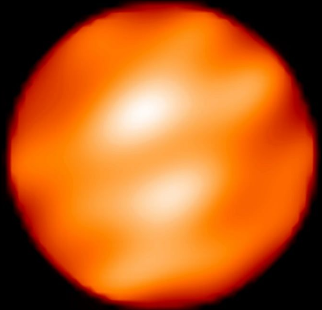
Roughly how it works

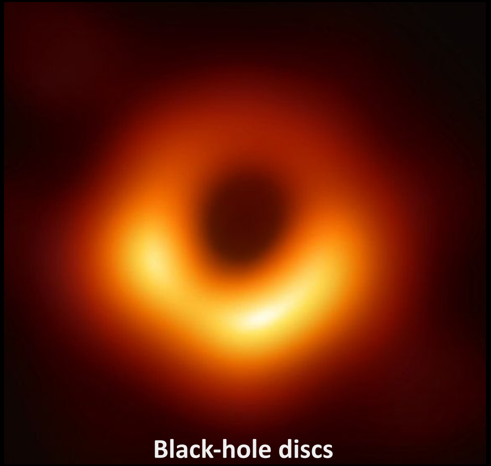


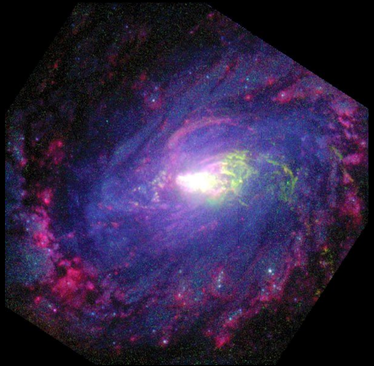
What can we do with interferometry?

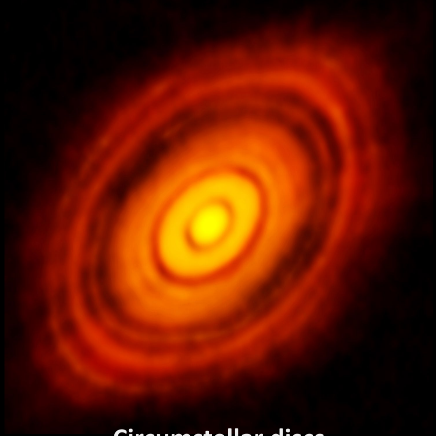


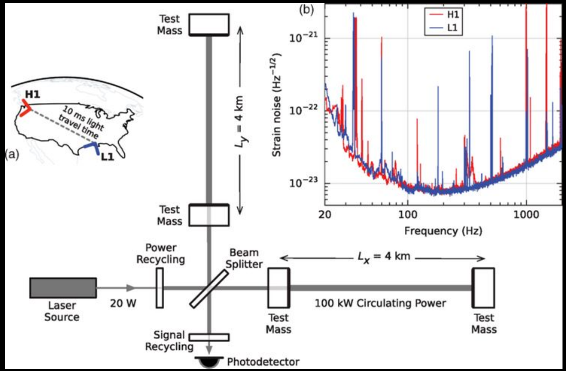
Binary stars
(Baldwin et al. 1996)


Star surfaces
(Haubois et al. 2009)


Black-hole discs
(Event Horizon Telescope Collab. 2019)


Galaxy structures
(Jaffe et al. 2004)

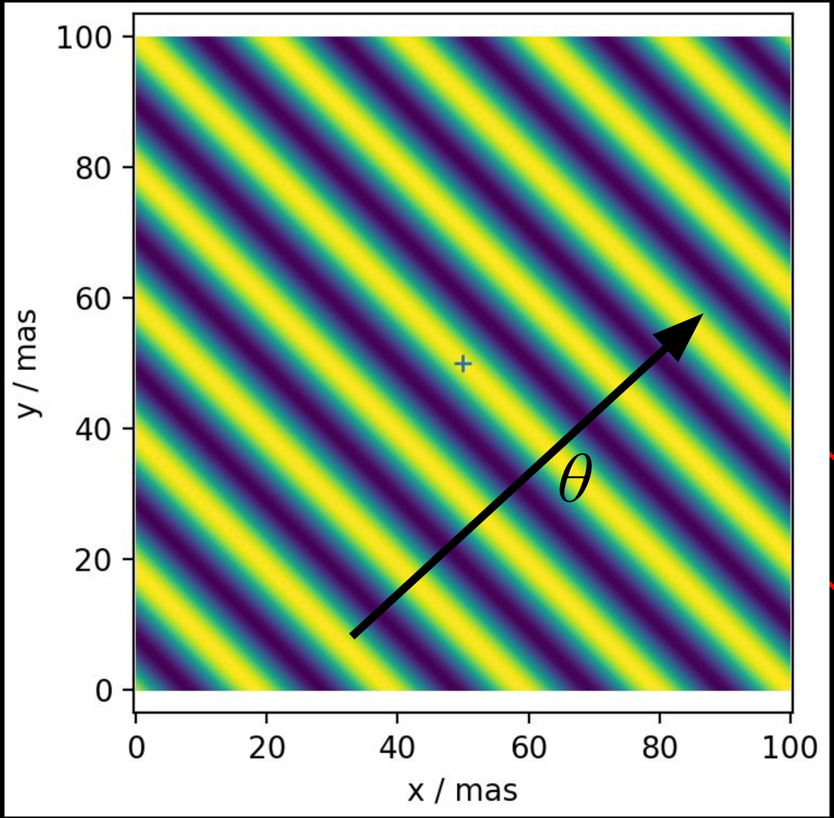

Circumstellar discs
(ALMA Partnership 2015)



Gravitational waves
(Abbott et al. 2016)

Sensitivity fringes

Colour = correlator response *R*



$$R = \frac{V^2}{2}\cos(\omega\Delta t)$$

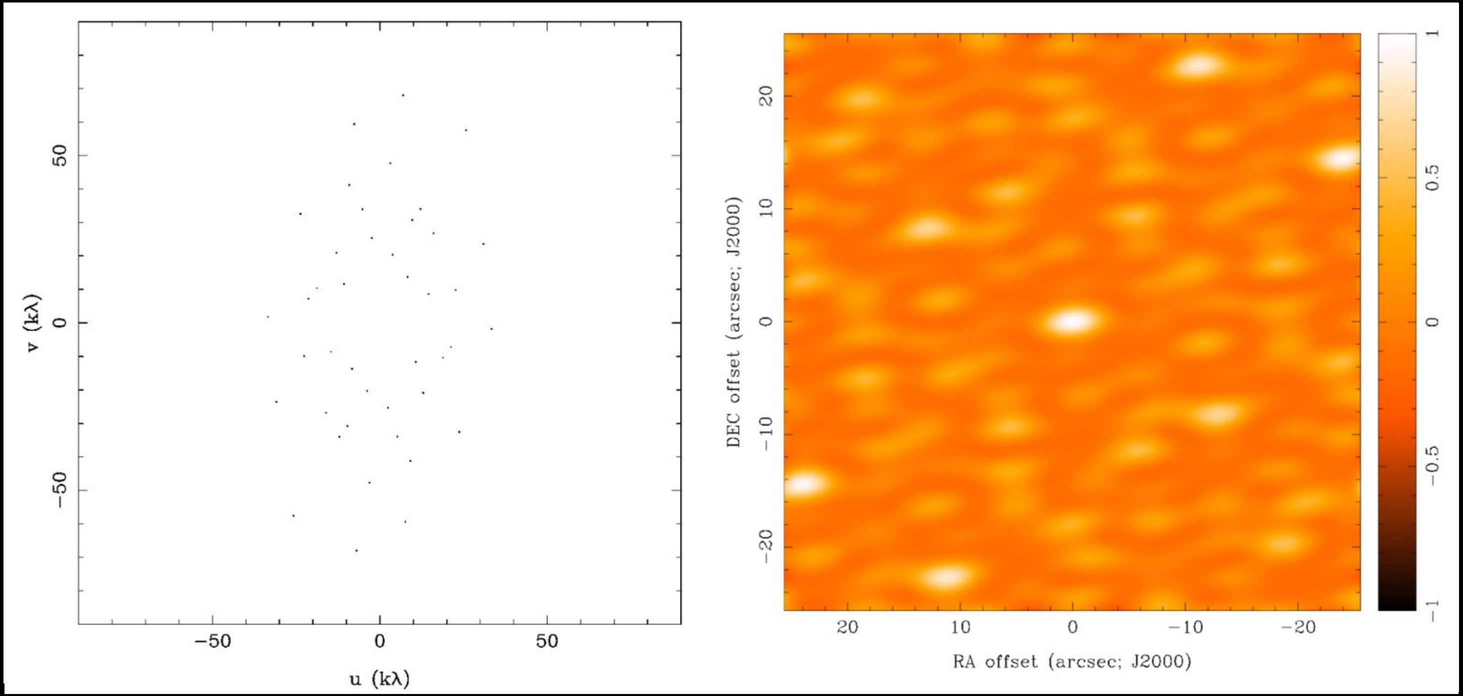
$$\Delta t = \frac{b}{c}\cos(\theta)$$

Fringe spacing = λ/b

Each baseline is a pair of points on the *u*, *v* plane




7 dishes = 21 baselines



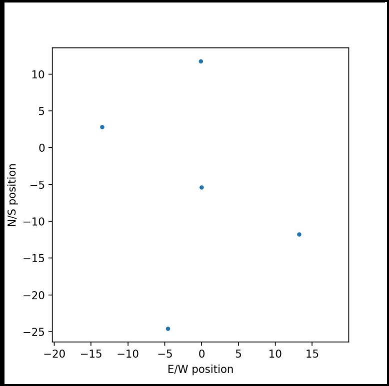


Goal: populate *u*, *v* plane with as many baselines as possible

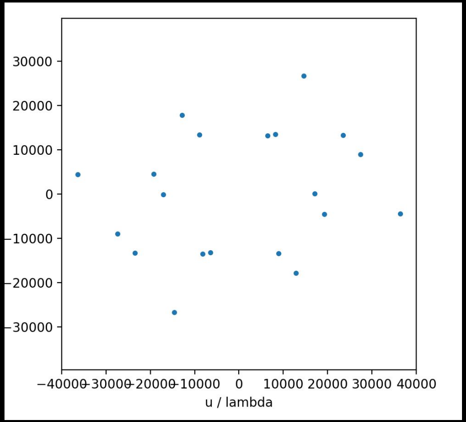
Images courtesy of David Wilner

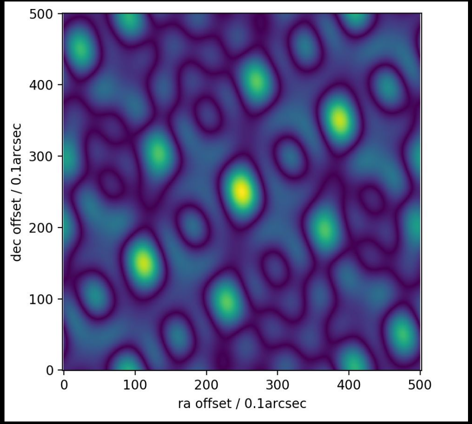
Sky rotation

5 dishes



No sky rotation

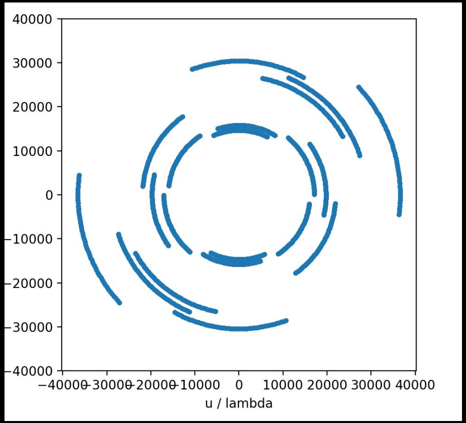


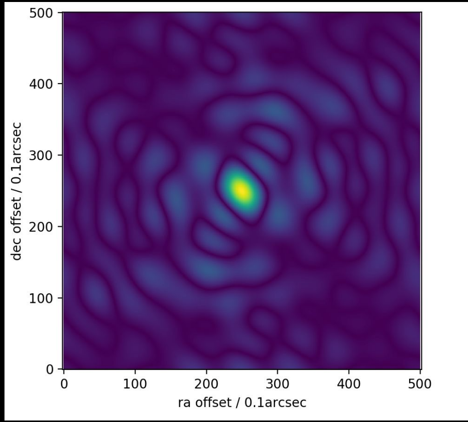


Baselines

Fringes

With sky rotation

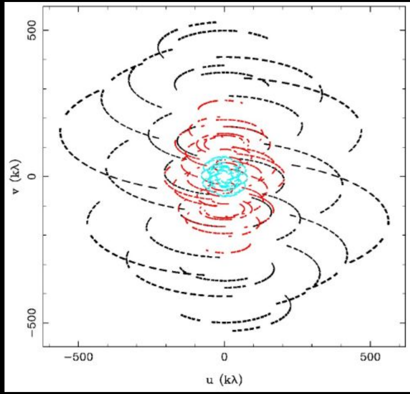




Images courtesy of Grant Kennedy

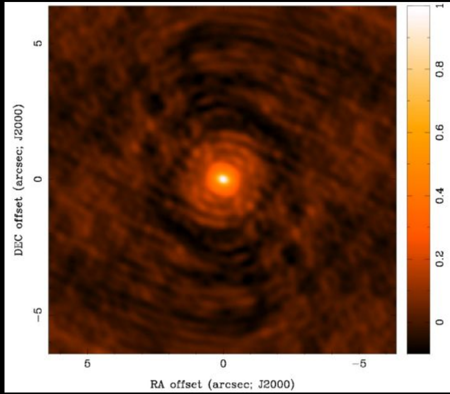
Dirty beam + dirty image

Baselines



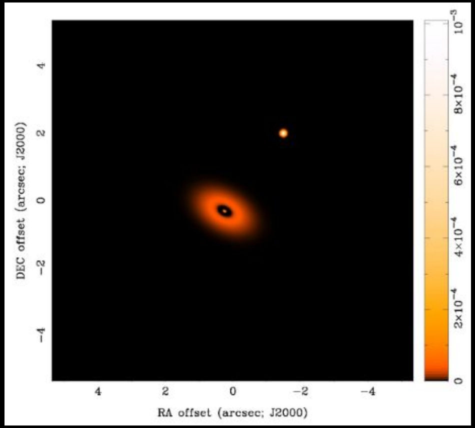
Fourier transform

'Dirty beam' (~PSF)

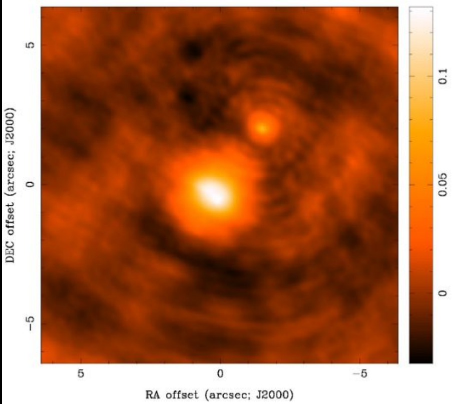


Convolve

Reality



'Dirty image'



Images courtesy of David Wilner

Course assessment

Due Wed 26 Nov