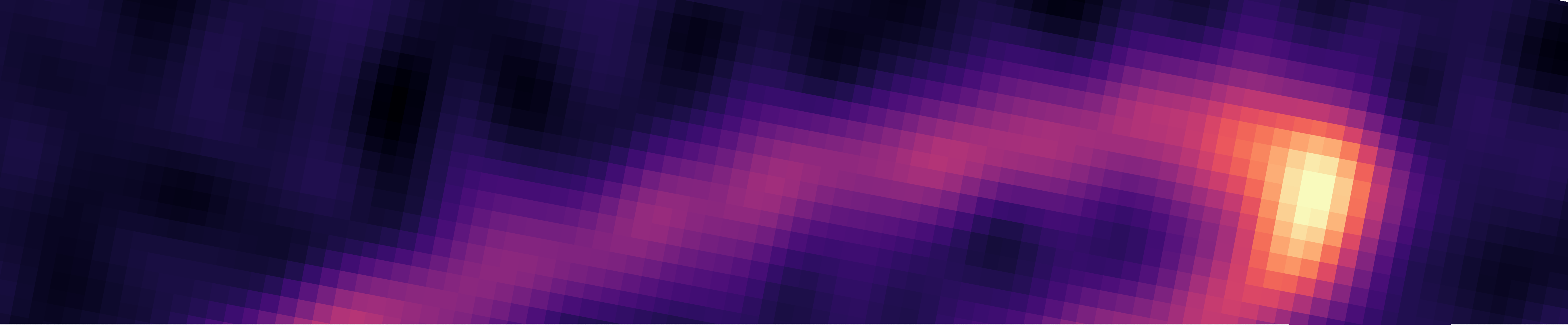


Interferometry

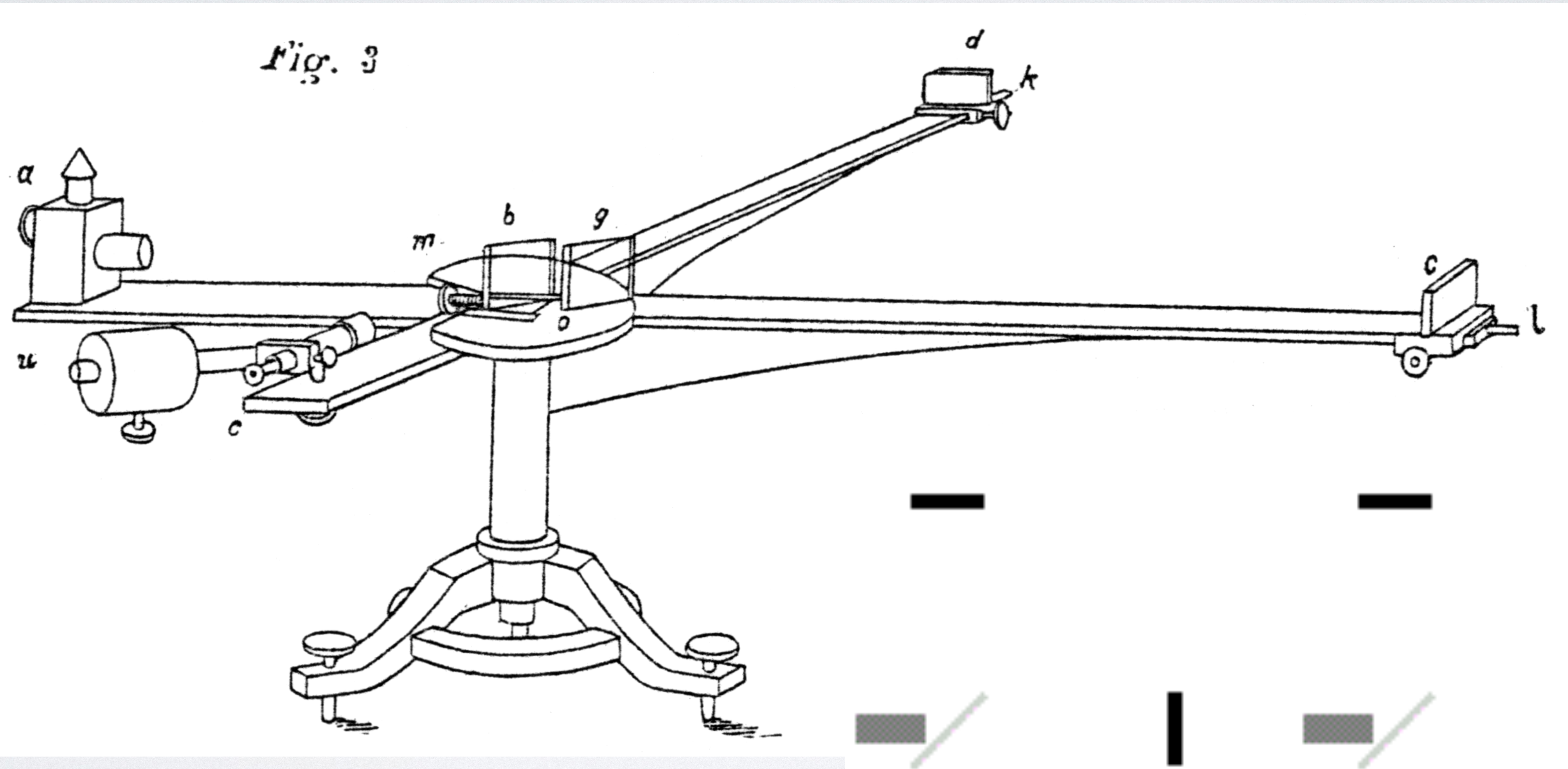
MPAGS Astrophysical Techniques 2021

Grant Kennedy

(this session is being recorded)

Early interferometers

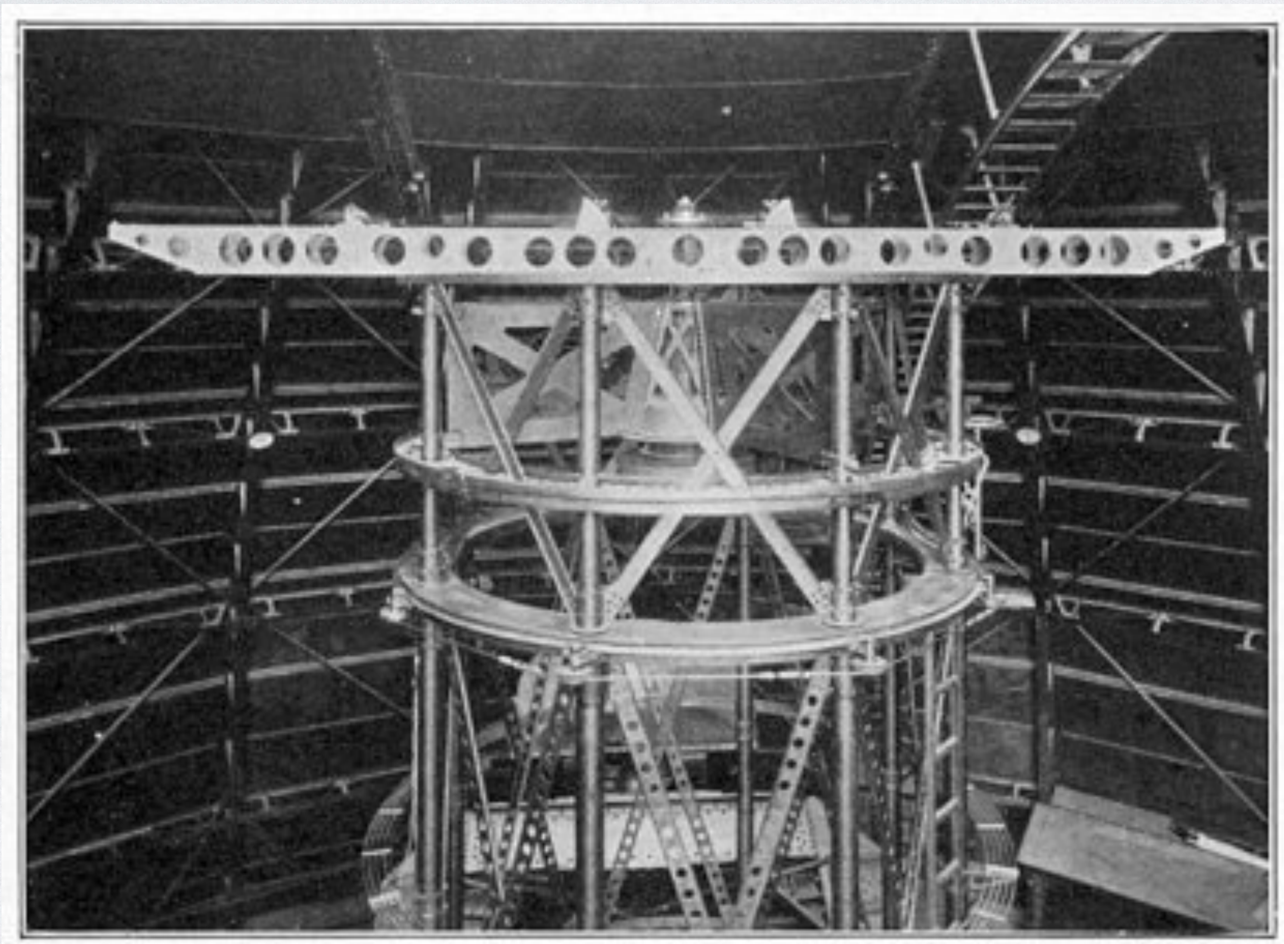
Michelson in 1881

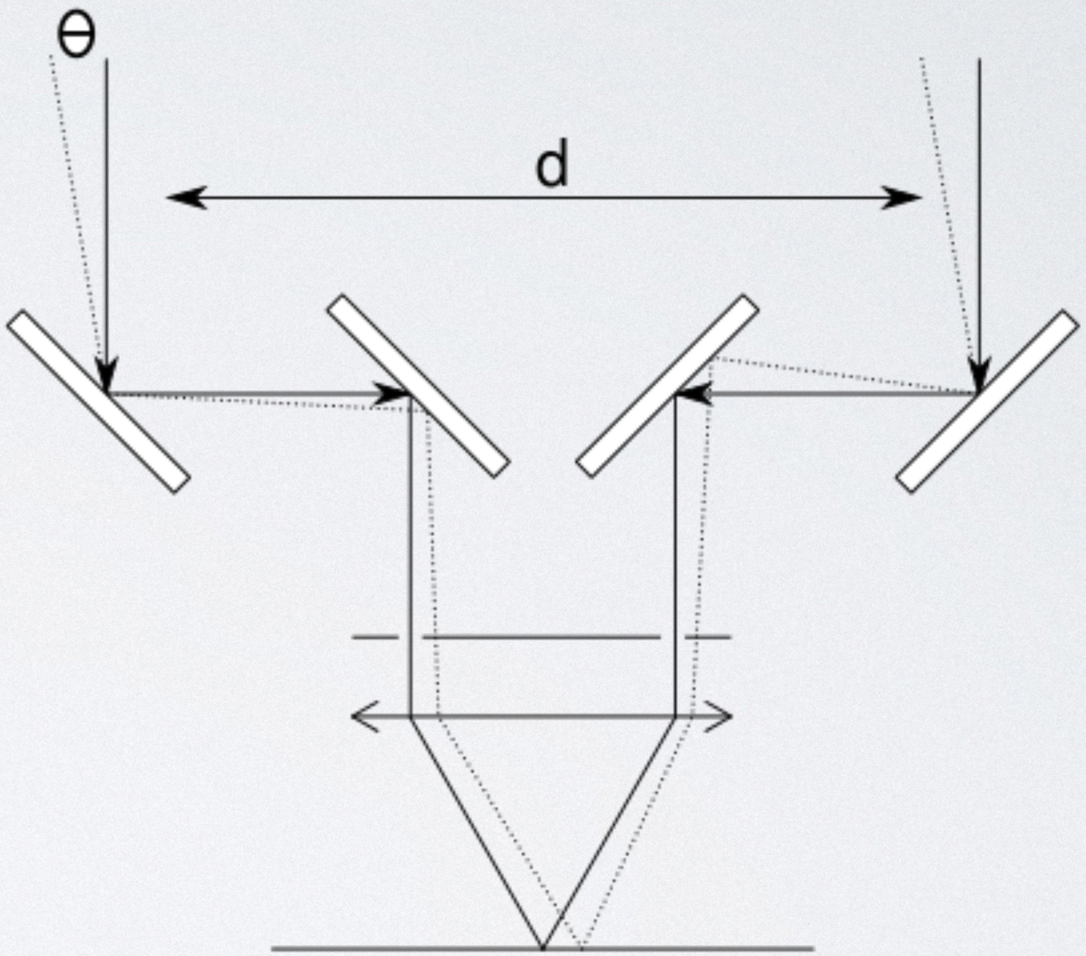


Wikipedia: Michelson Morley experiment

Early interferometers

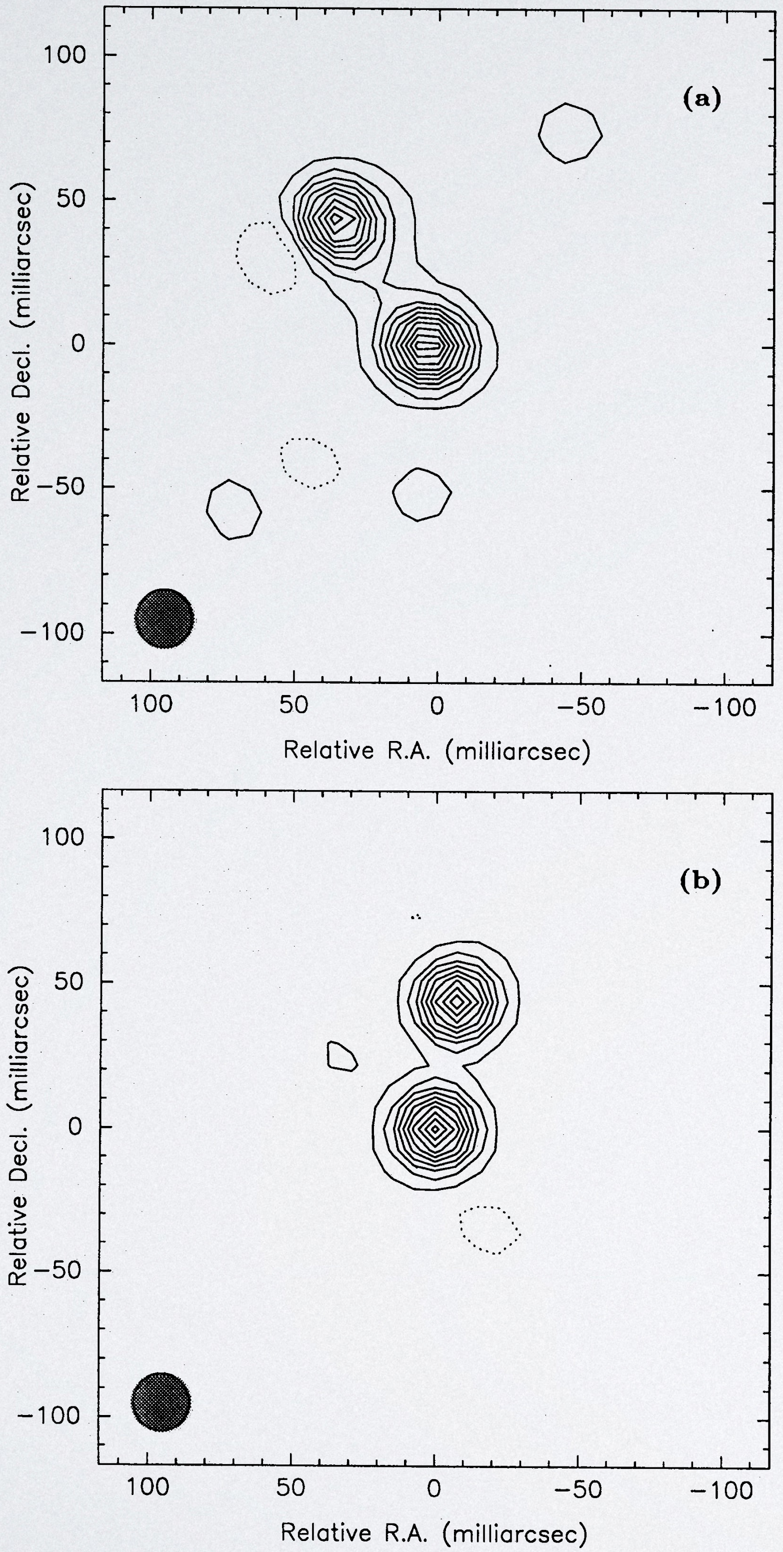
Measurement of the diameter of Betelgeuse (by 'resolving out' the source - see later)





Michelson & Pease 1921

Optical interferometry



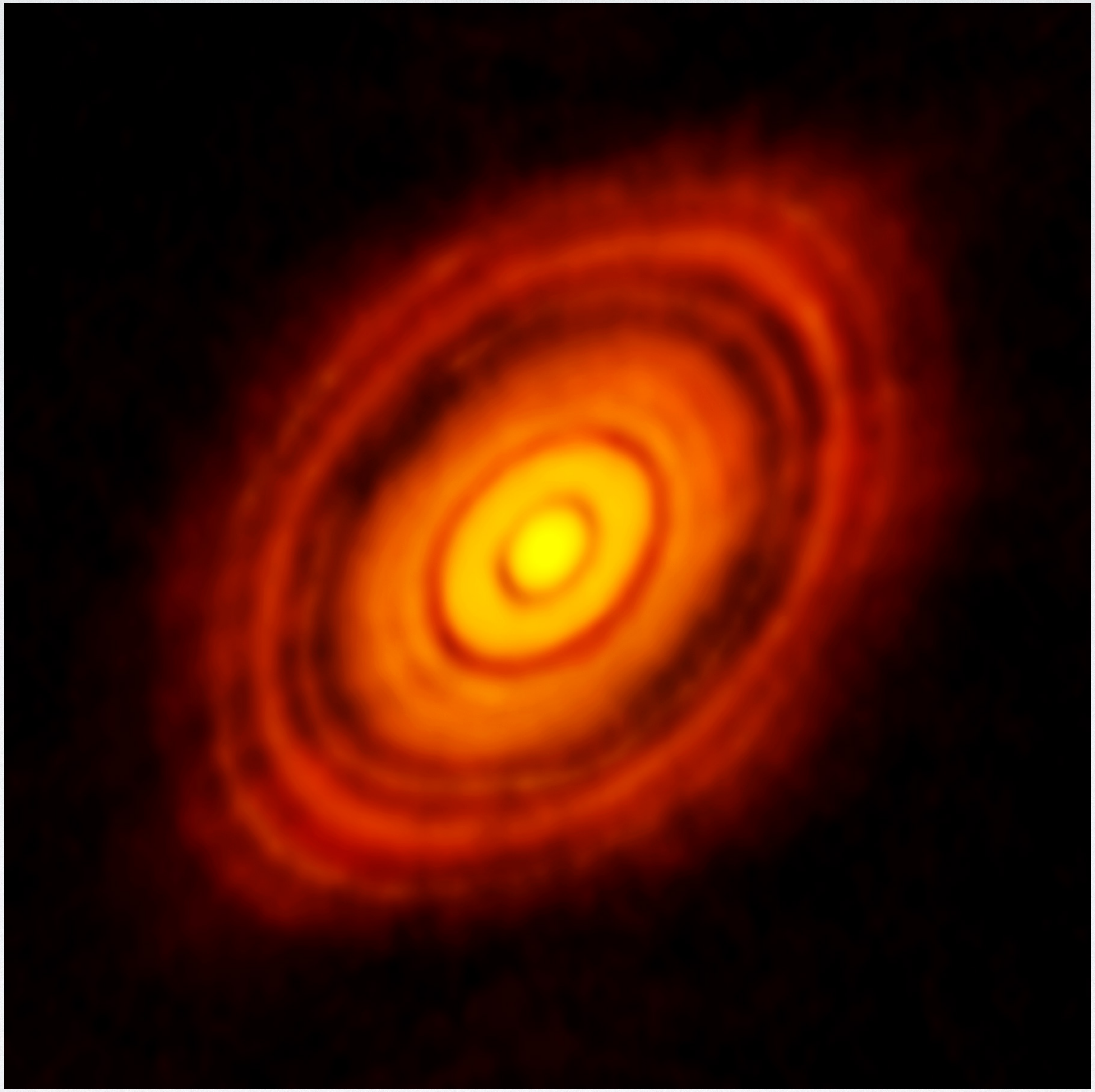
Capella binary at two epochs

Cambridge!

Baldwin et al 1996

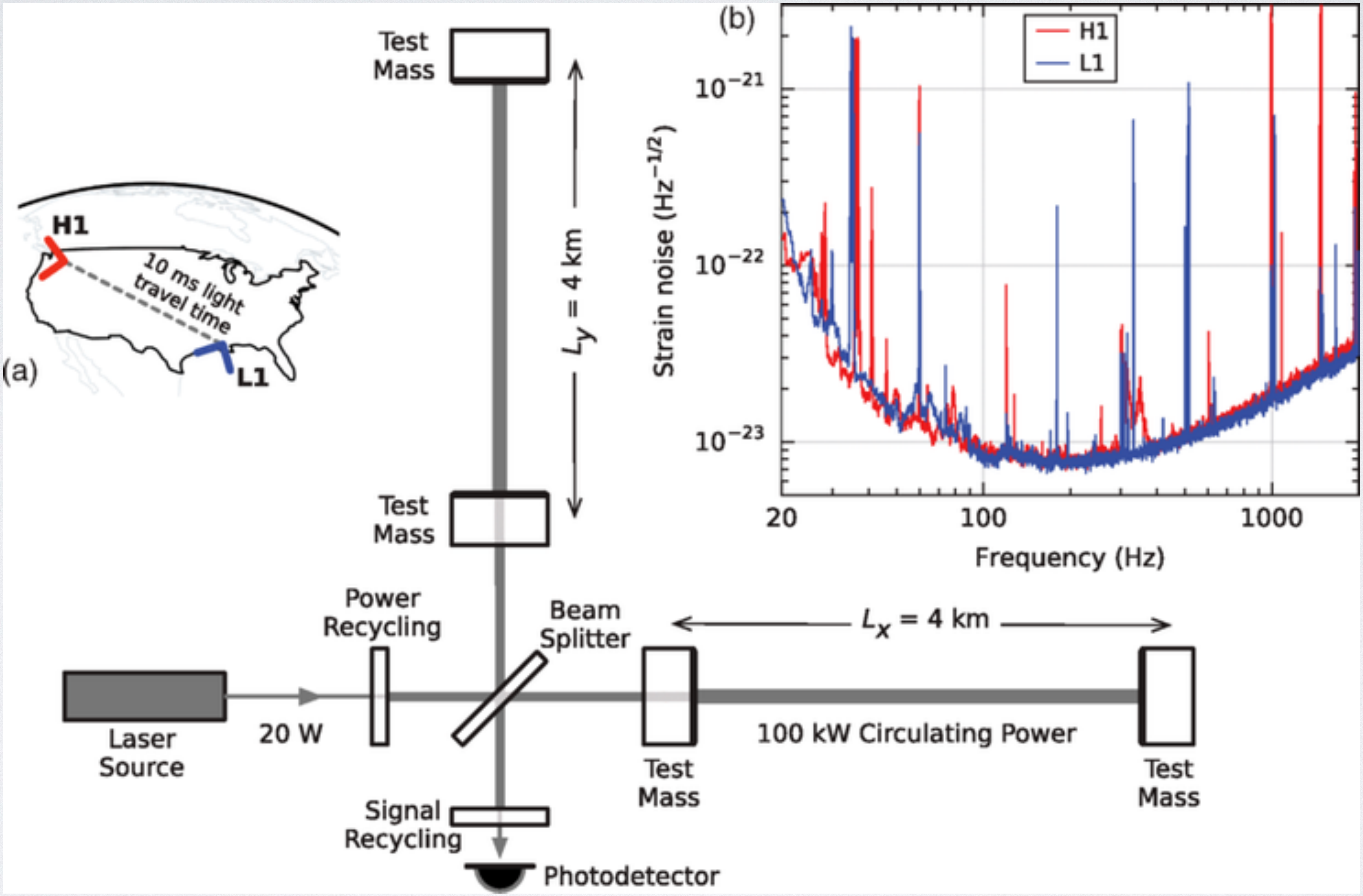
Mid-IR interferometry

Radio interferometry



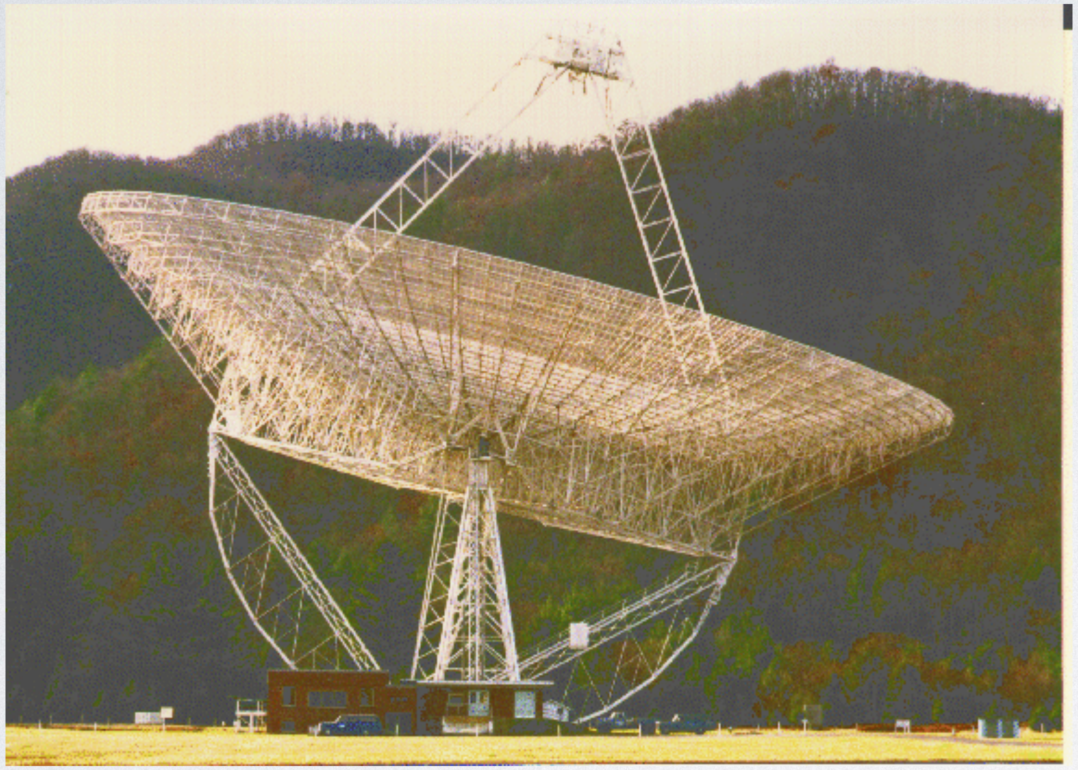
ALMA Partnership 2015

Gravitational waves



Abbott et al 2016

Why do interferometry?



- Resolution $1.22\lambda/D \rightarrow \lambda/(2b)$
- Dishes can only be so big

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!

That's the claim of Swiss astronomer Peter Voisard,

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 mys-

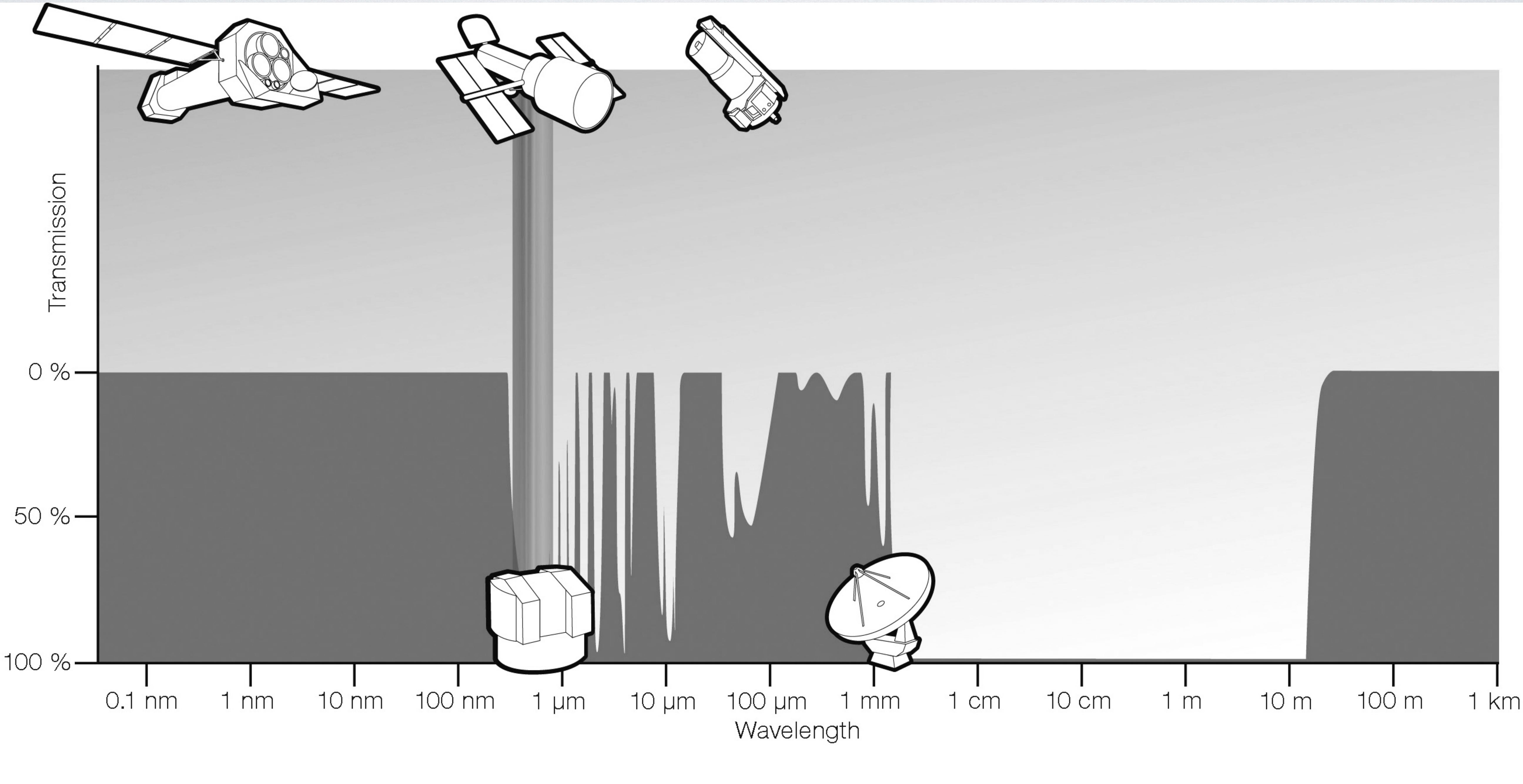
zapped by extraterrestrials who wanted to mask their activity from mankind, Dr. Voisard said.

"Any other explanation defies logic," he continued. "The

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

Windows for astronomy

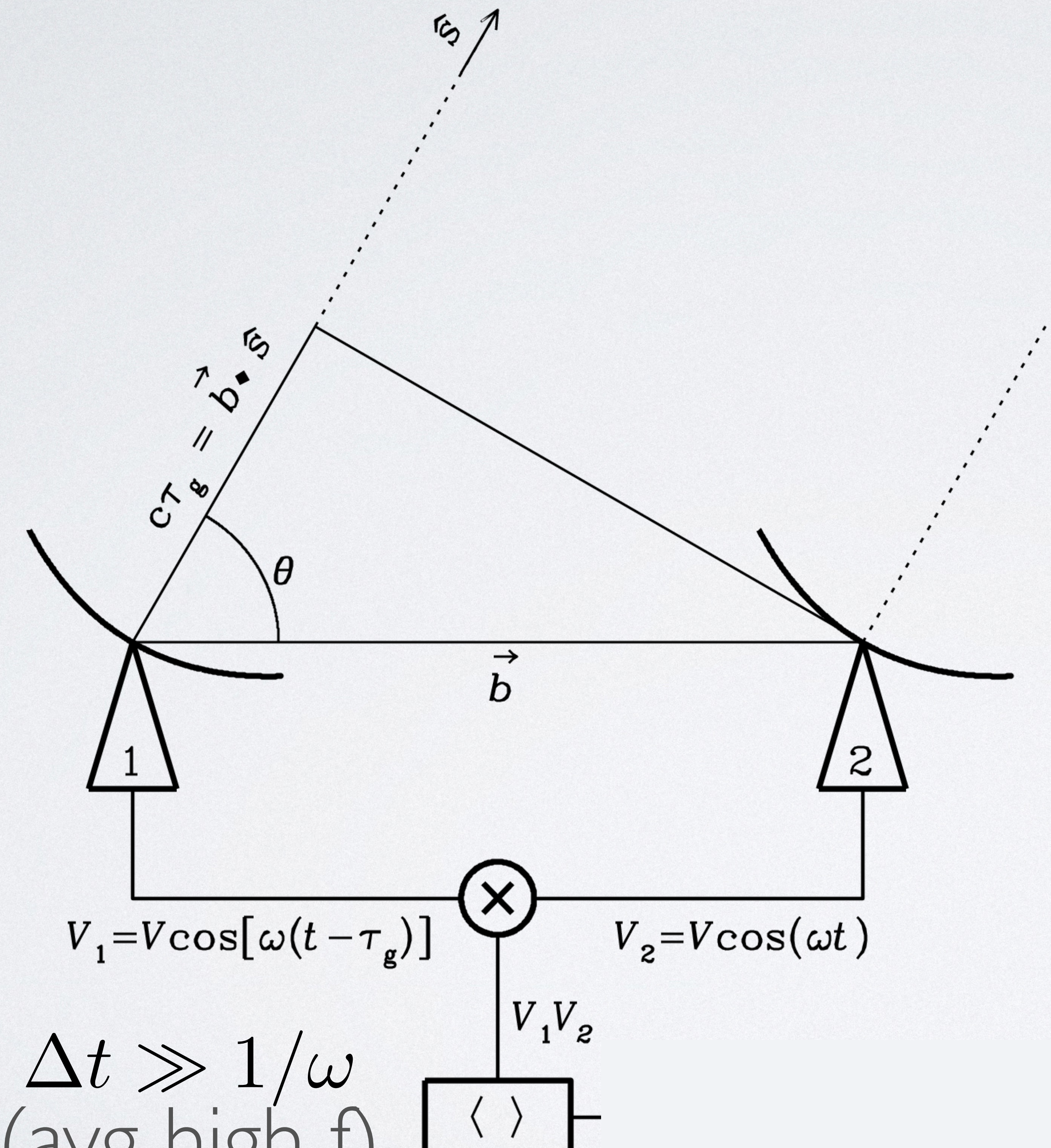


Interferometry

Jansky Very Large Array, New Mexico

Basic interferometer

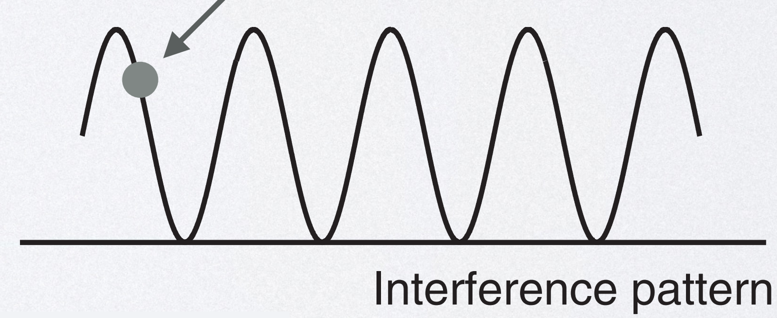
response to a monochromatic source



$$R_C = (V^2/2)\cos(\omega\tau_g)$$

$$= (V^2/2)\cos(2\pi\frac{\mathbf{b}\cdot\hat{\mathbf{s}}}{\lambda})$$

(i.e. a number)



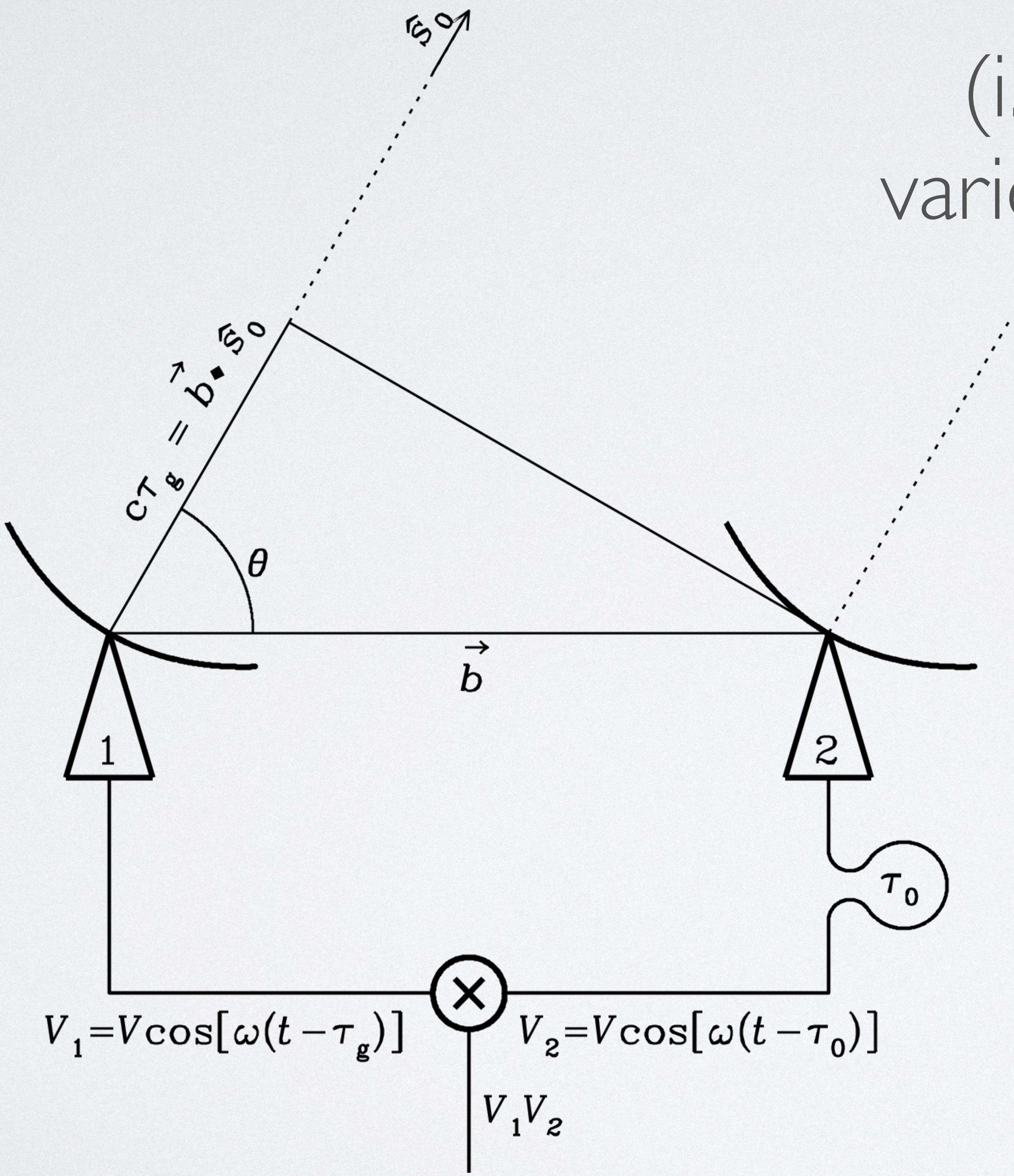
$\Delta t \gg 1/\omega$
(avg high f)

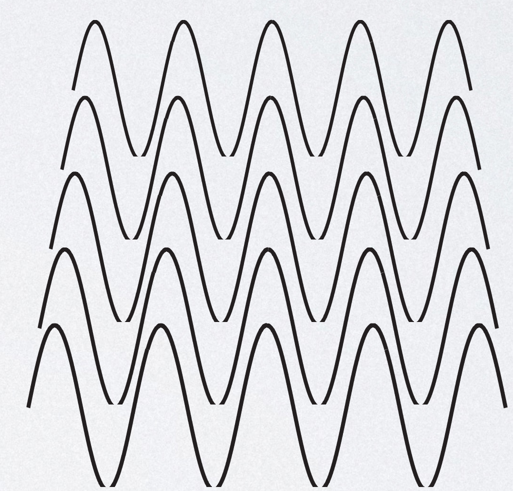
ERA: Fig 3.41

Basic interferometer

finite bandwidth - add delay to “point” phase center

(i.e. fringe spacing varies with frequency)





$$\tau_0 \approx \tau_g$$

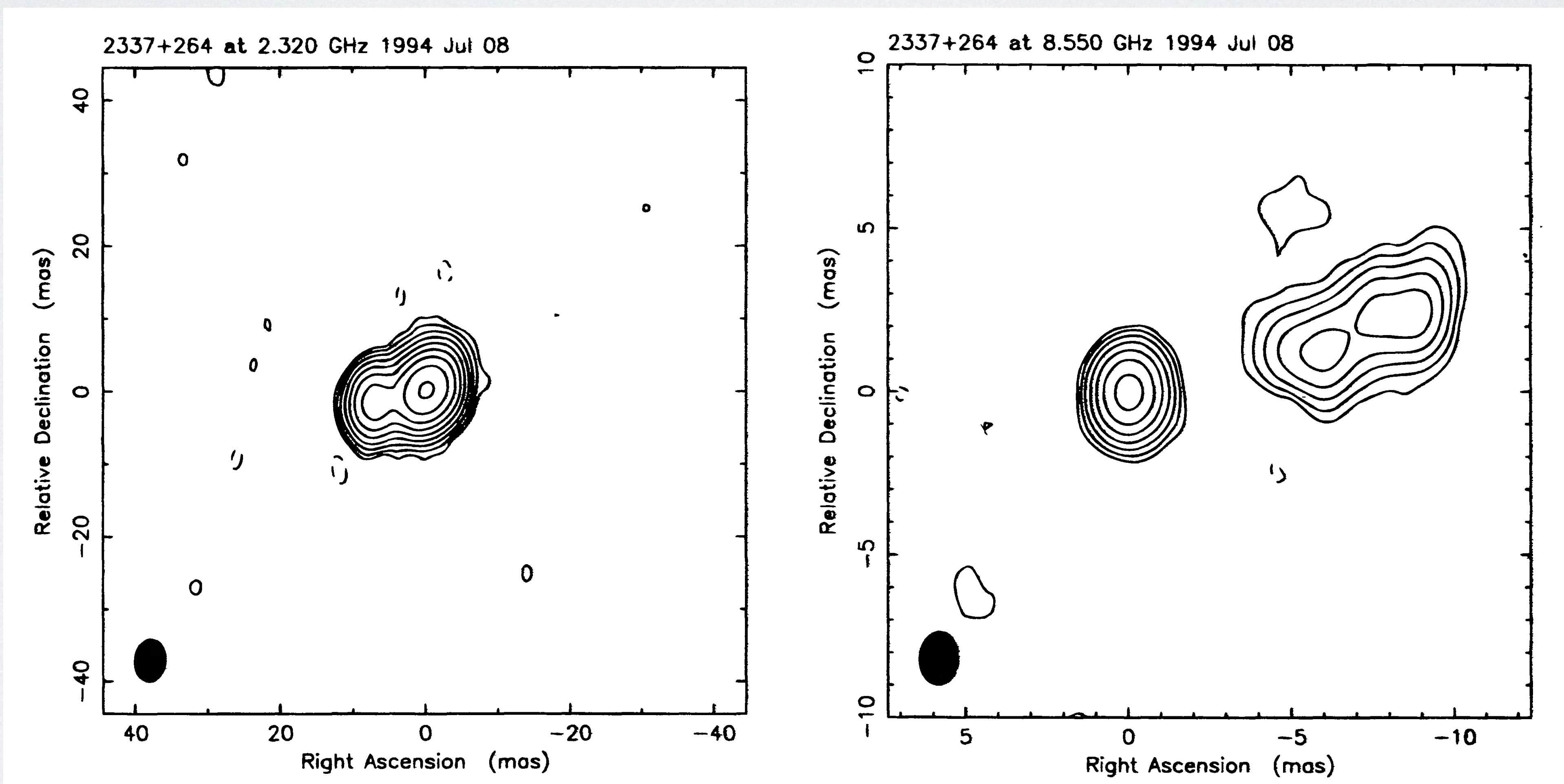
ERA: Fig 3.43

Astrometry

milli-arcsec precision - basis of ICRF

phase ↘

$$\phi = 2\pi \frac{b\cos\theta}{\lambda} \qquad d\phi/d\theta = 2\pi\frac{b\sin\theta}{\lambda} \qquad b\sin\theta \gg \lambda$$

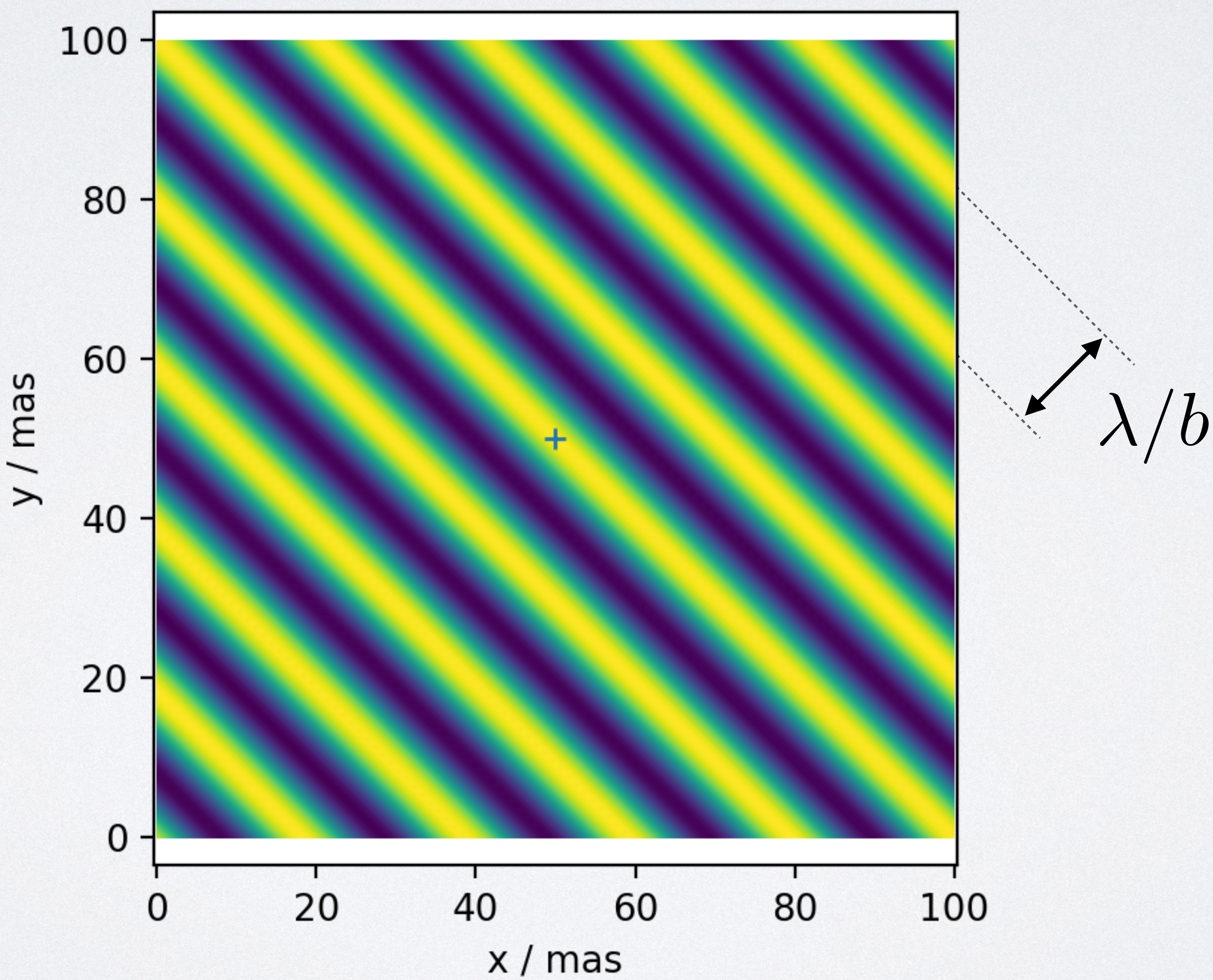


Fey et al 1996

Basic interferometer

signal = sum of (sky image x fringe pattern on sky)

$$R_C = \int I(\mathbf{s}) \cos(2\pi \mathbf{b} \cdot \hat{\mathbf{s}}/\lambda) d\Omega$$ (i.e. a number)

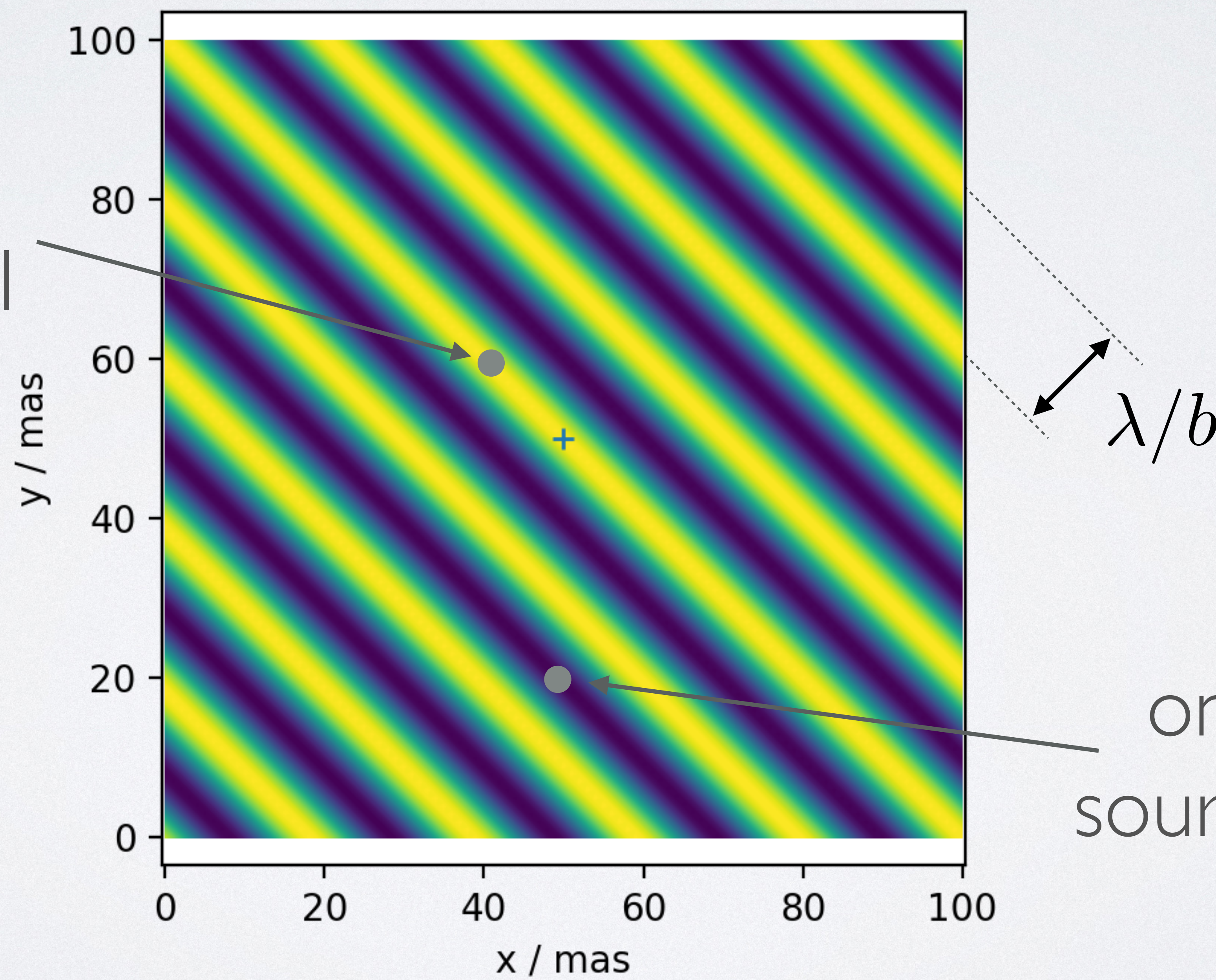


Basic interferometer

signal = sum of (sky image x fringe pattern on sky)

$$R_C = \int I(\mathbf{s}) \cos\left(2\pi \mathbf{b} \cdot \hat{\mathbf{s}}/\lambda\right) d\Omega$$ (i.e. a number)

one point source: R_C=1



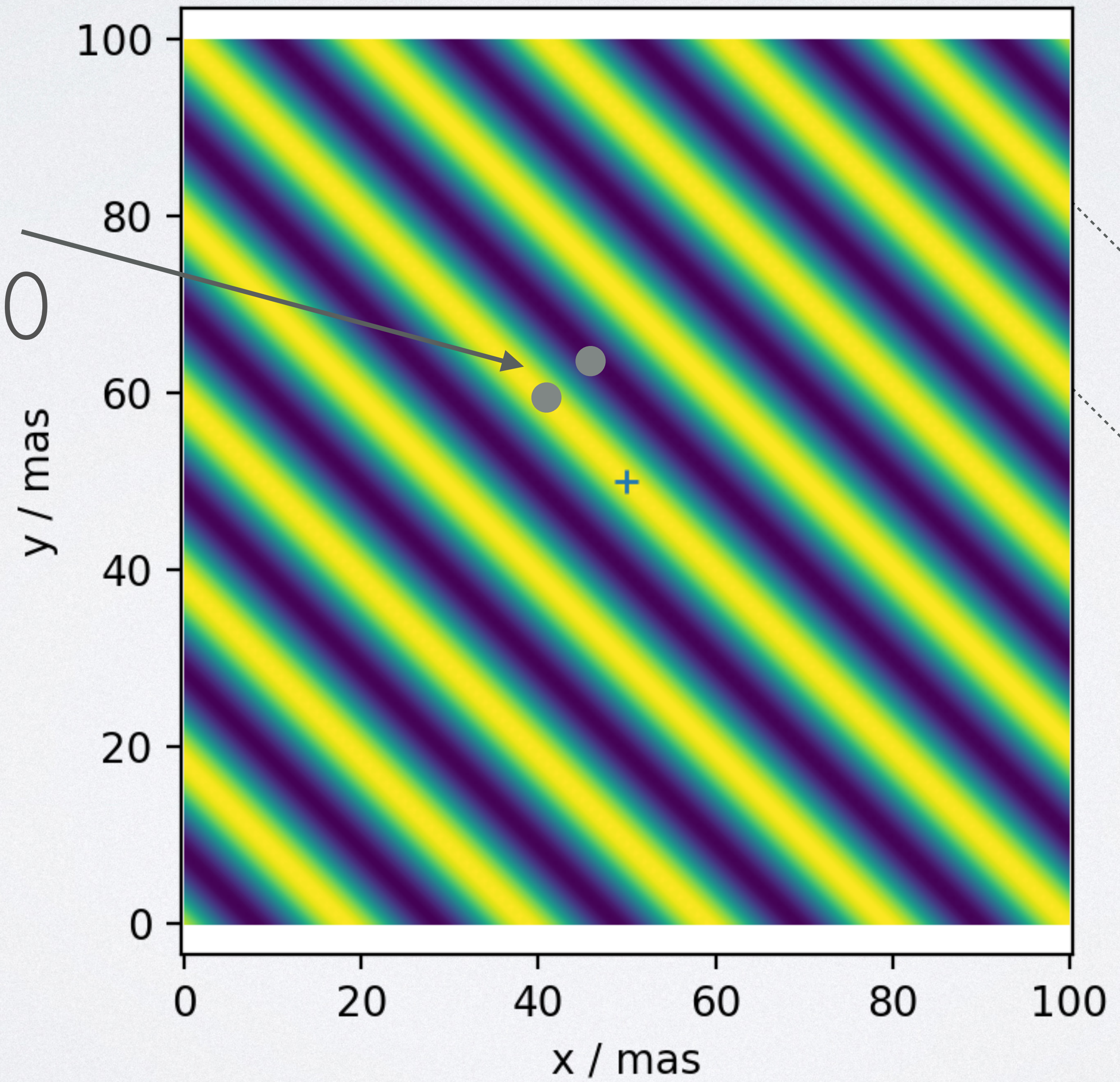
one point source: R_C=-1

Basic interferometer

signal = sum of (sky image x fringe pattern on sky)

$$R_C = \int I(\mathbf{s}) \cos\left(2\pi \mathbf{b} \cdot \hat{\mathbf{s}}/\lambda\right) d\Omega$$ (i.e. a number)

two point sources: R_C=0



λ/b

define "resolved"

$$\Delta\theta = \lambda/(2b)$$

Basic interferometer

but odd component of a signal is invisible:
second correlator with 90deg phase shift

$$R_S = \int I(\mathbf{s}) \sin\left(2\pi \mathbf{b} \cdot \hat{\mathbf{s}}/\lambda\right) d\Omega$$

now define complex visibility

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

$$A = \left(R_C^2 + R_S^2\right)^{1/2}$$

visibility amplitude

$$\phi = \tan^{-1}\left(R_S/R_C\right)$$

visibility phase

Basic interferometer

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

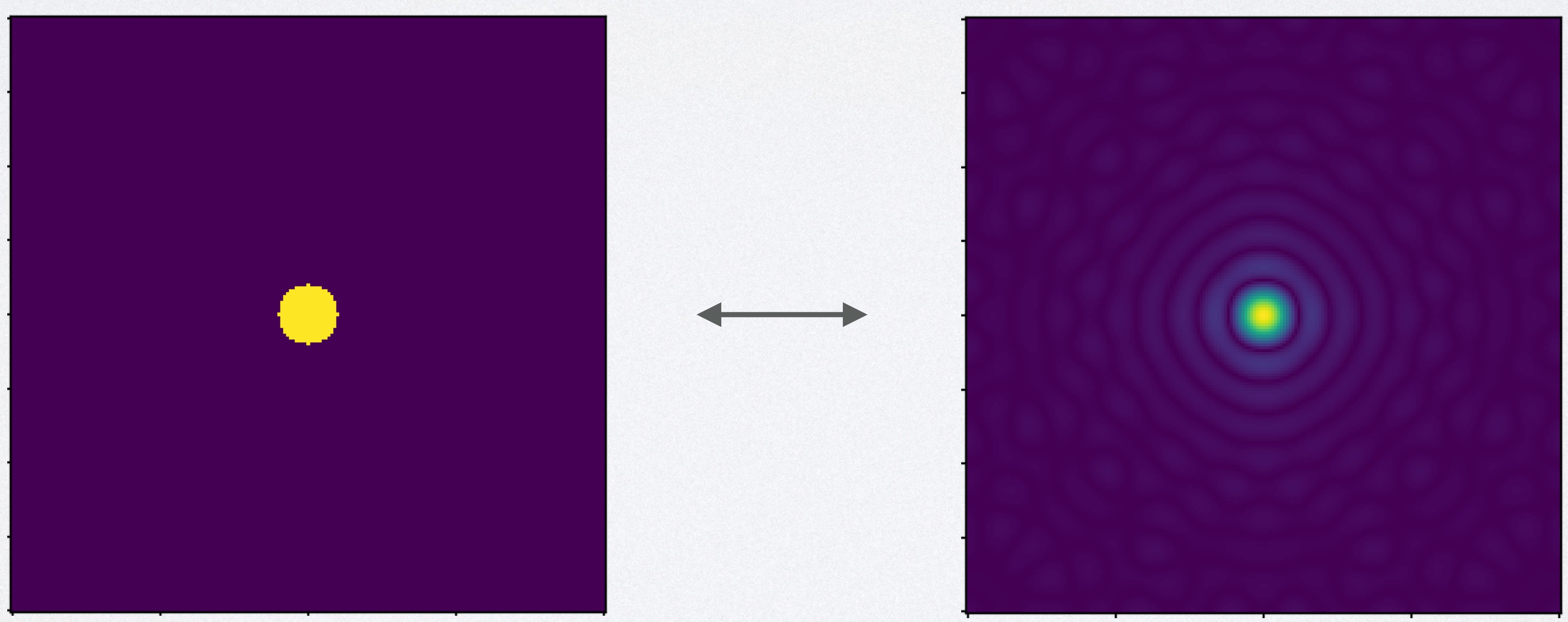
$$V = \int I(\mathbf{s}) \exp\left(-i2\pi \mathbf{b} \cdot \hat{\mathbf{s}}/\lambda\right) d\Omega$$

Van Cittert-Zernike thorem:

Fourier transform of a far source is equal to its complex visibility

image

'uv' plane $u = b/\lambda$

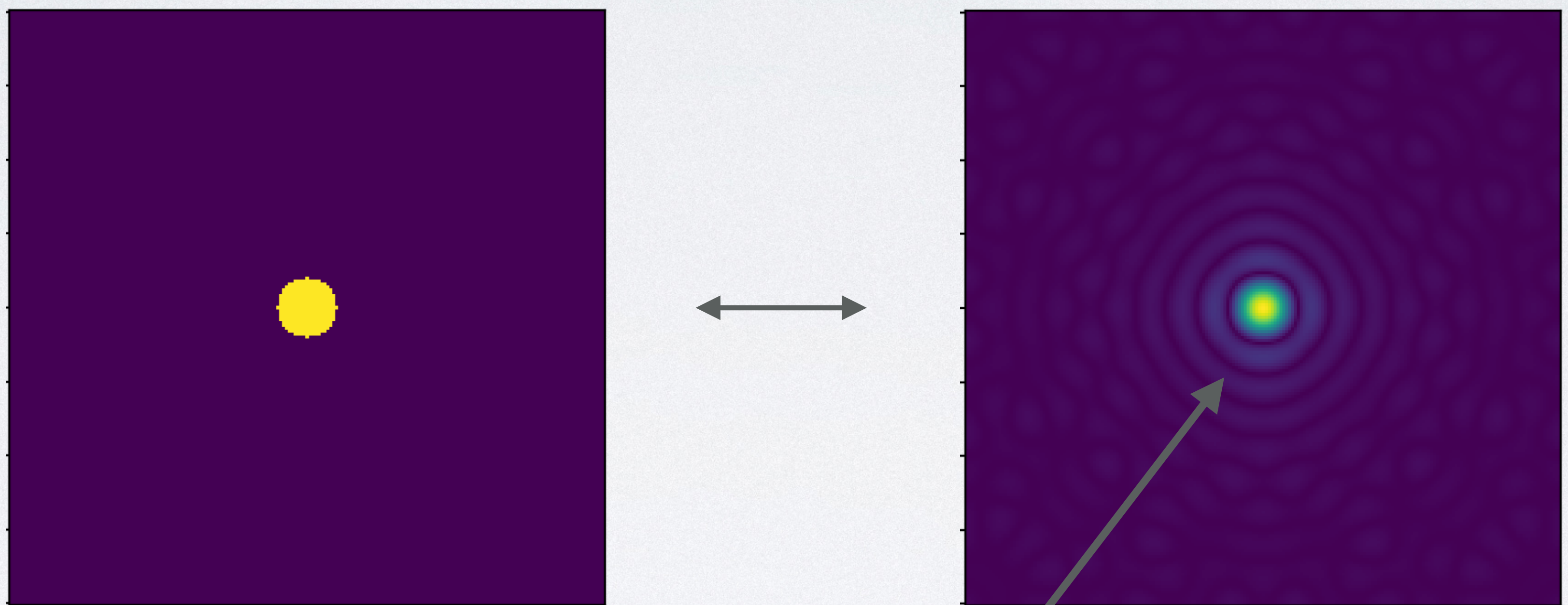


i.e. sample V at a given u,v (which is set by baseline)

Basic interferometer

i.e. sample V at a given u,v (which is set by baseline)

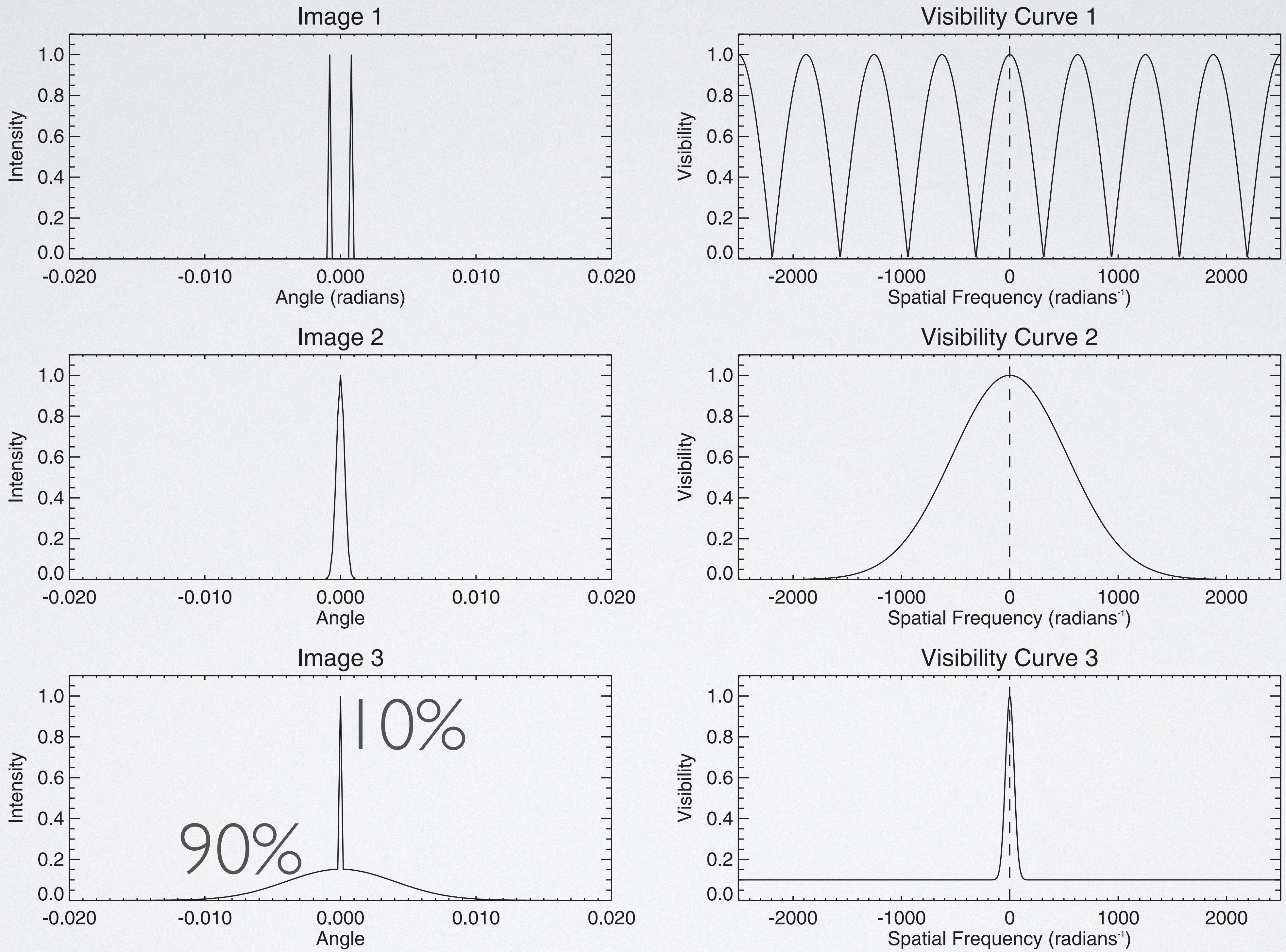
image ‘uv’ plane $u = b/\lambda$



(+ phase)

each point corresponds to a baseline separation and orientation

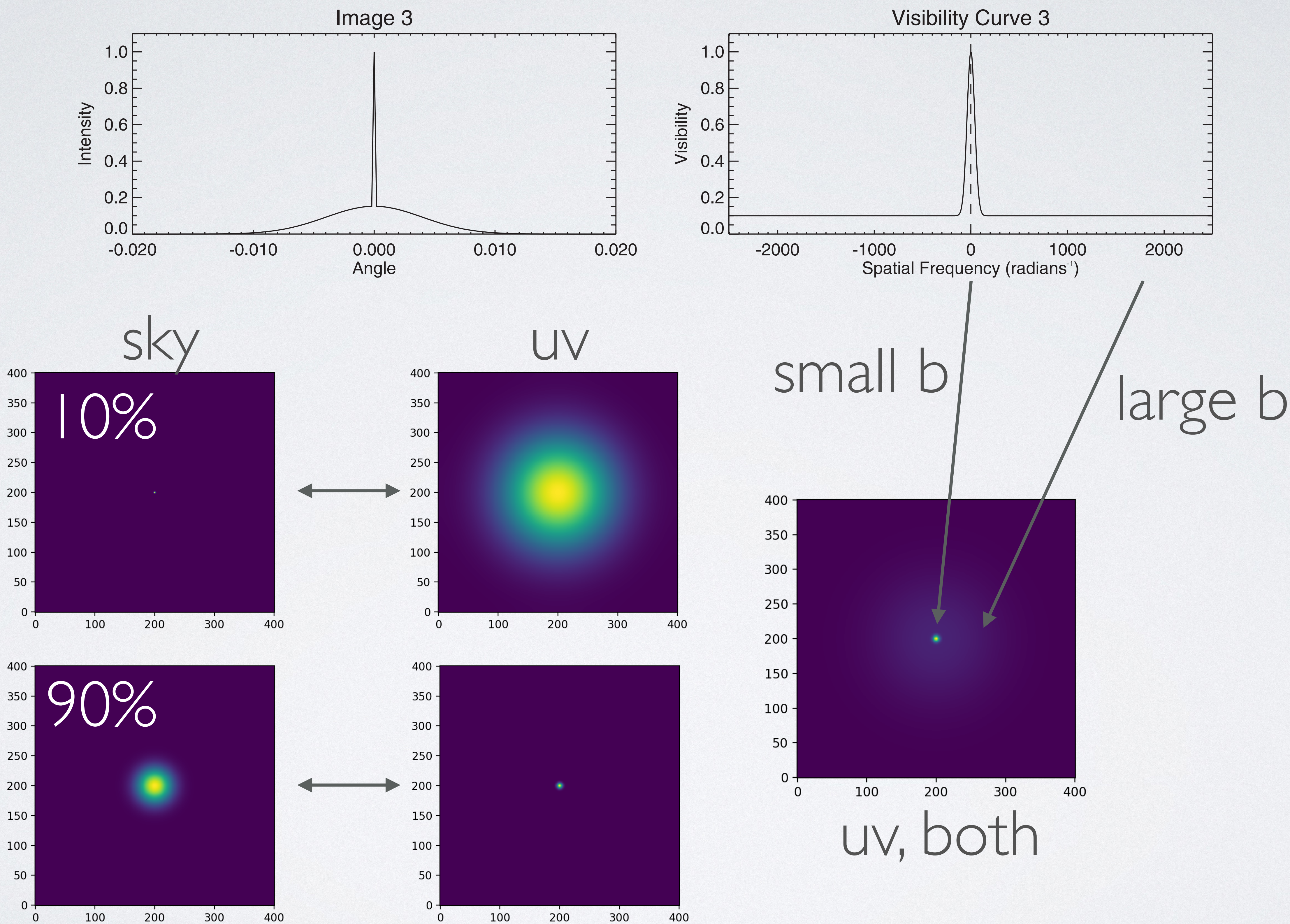
Visibility curves



baseline (b/λ)

Monnier 2003

Resolving out 'extended' flux

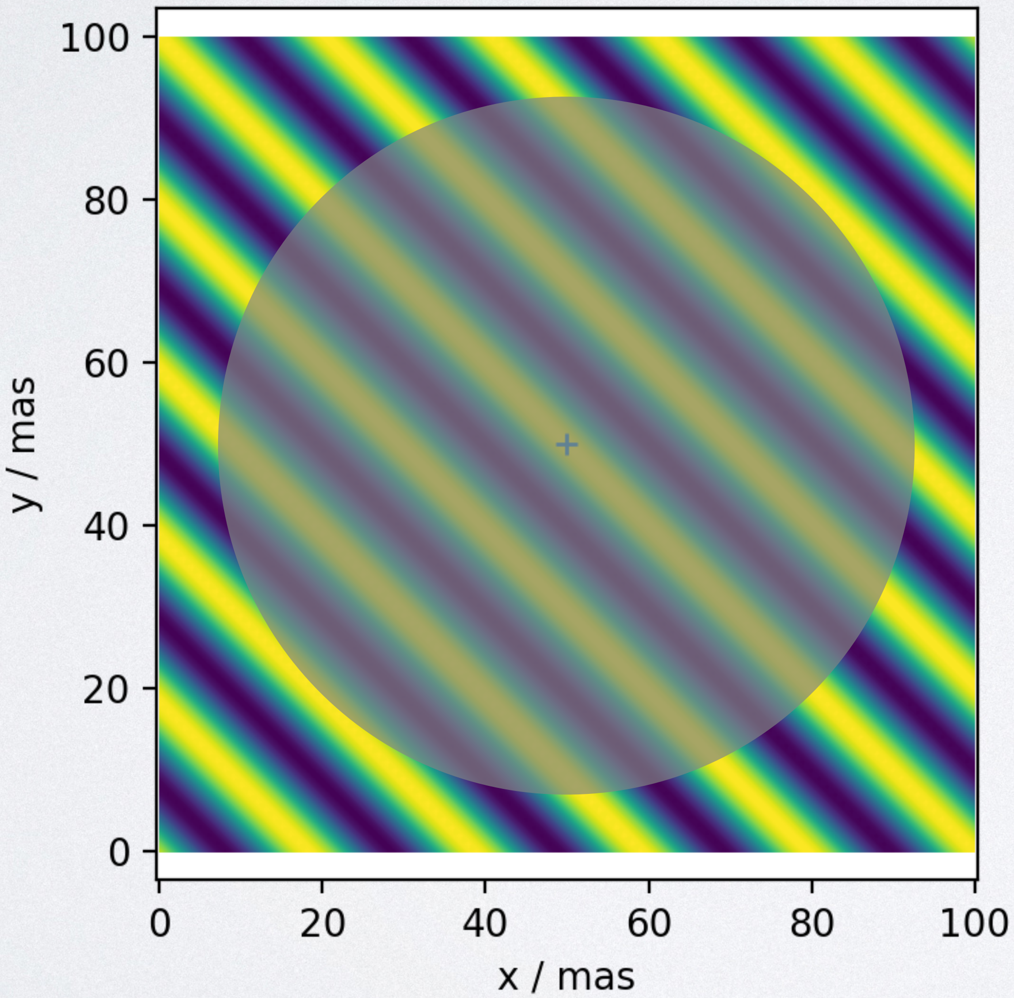


Resolving out 'extended' flux

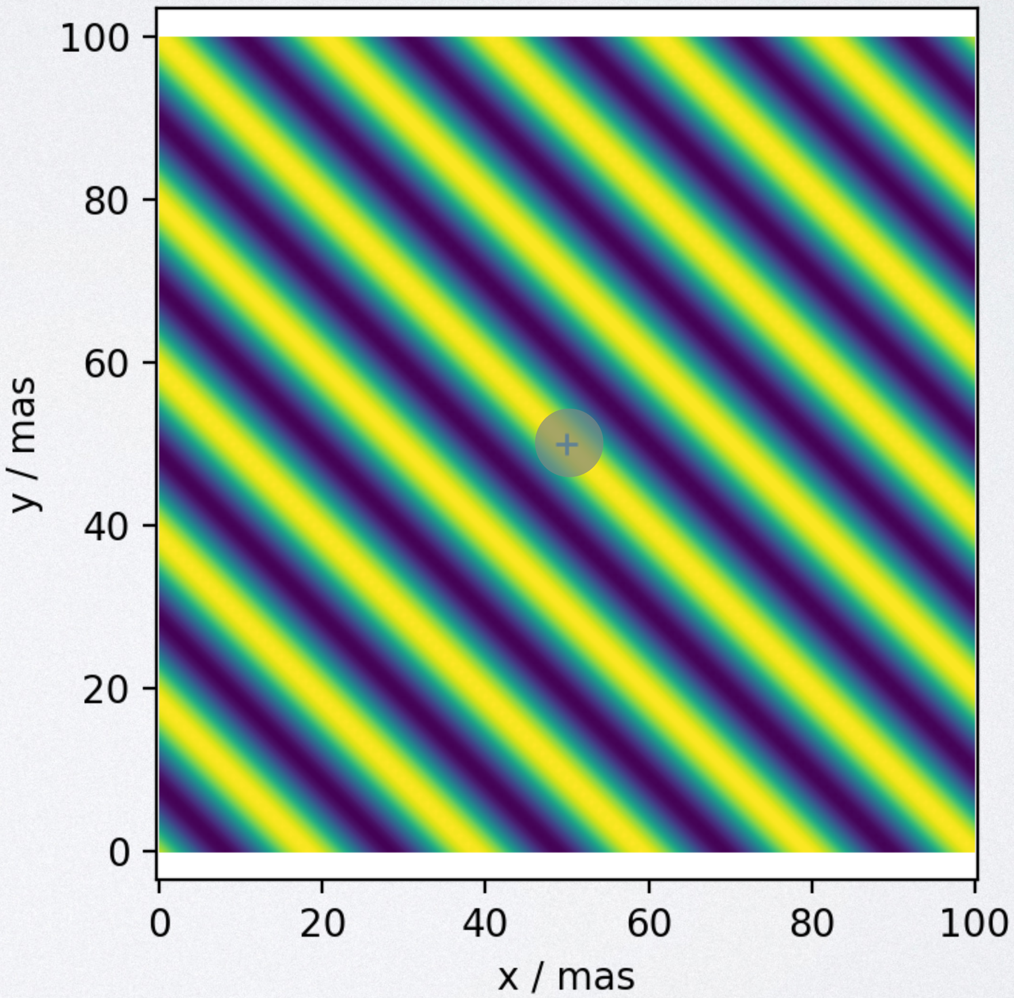
signal = sum of (sky image x fringe pattern on sky)

$$R_C = \int I(\mathbf{s}) \cos\left(2\pi \mathbf{b} \cdot \hat{\mathbf{s}} / \lambda\right) d\Omega$$ (i.e. a number)

$R_C \sim 0$



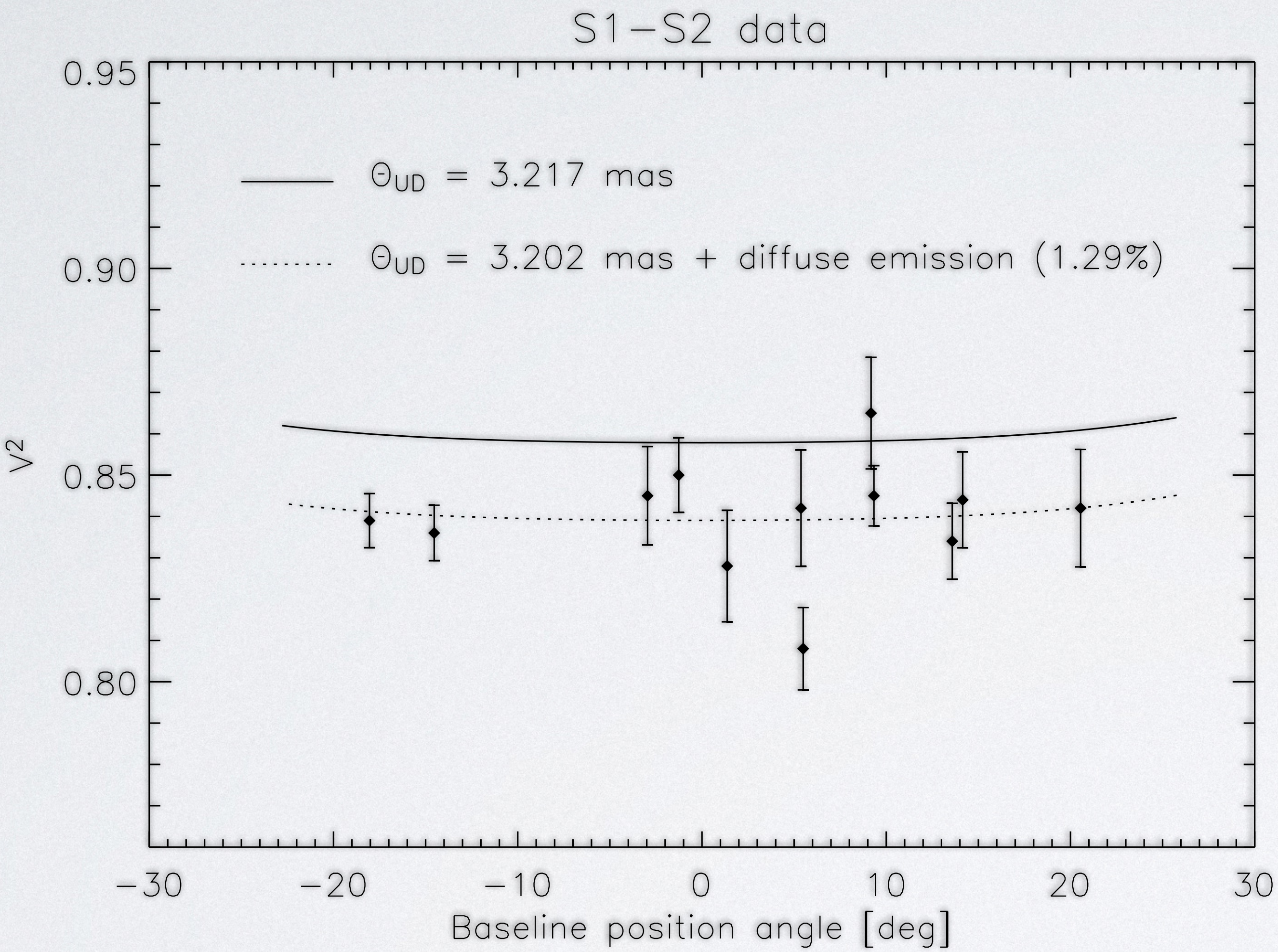
$R_C \sim 0.1$



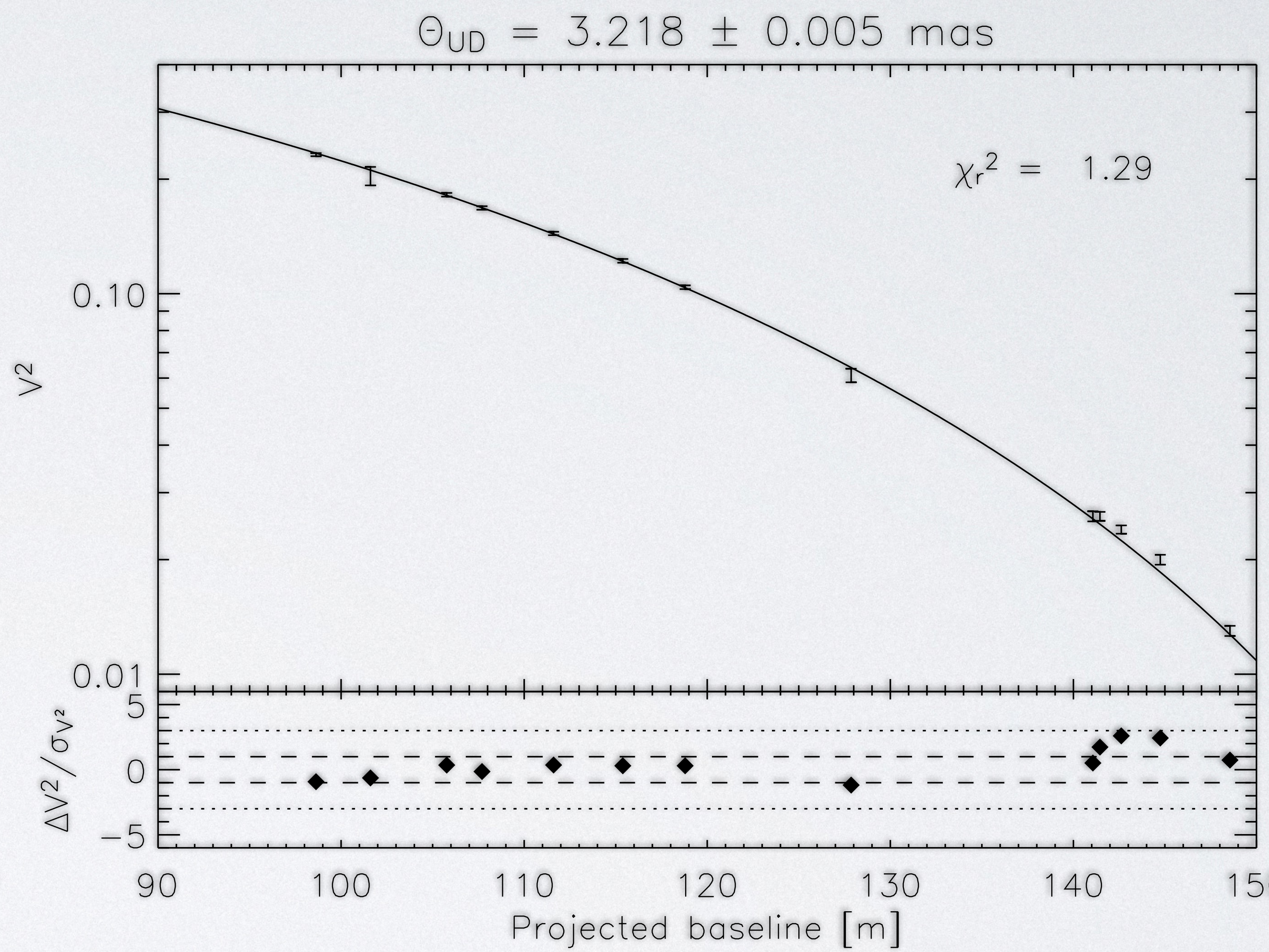
large source - averaging over many fringes

Resolving out 'extended' flux

application to 'exo-Zodi' with CHARA



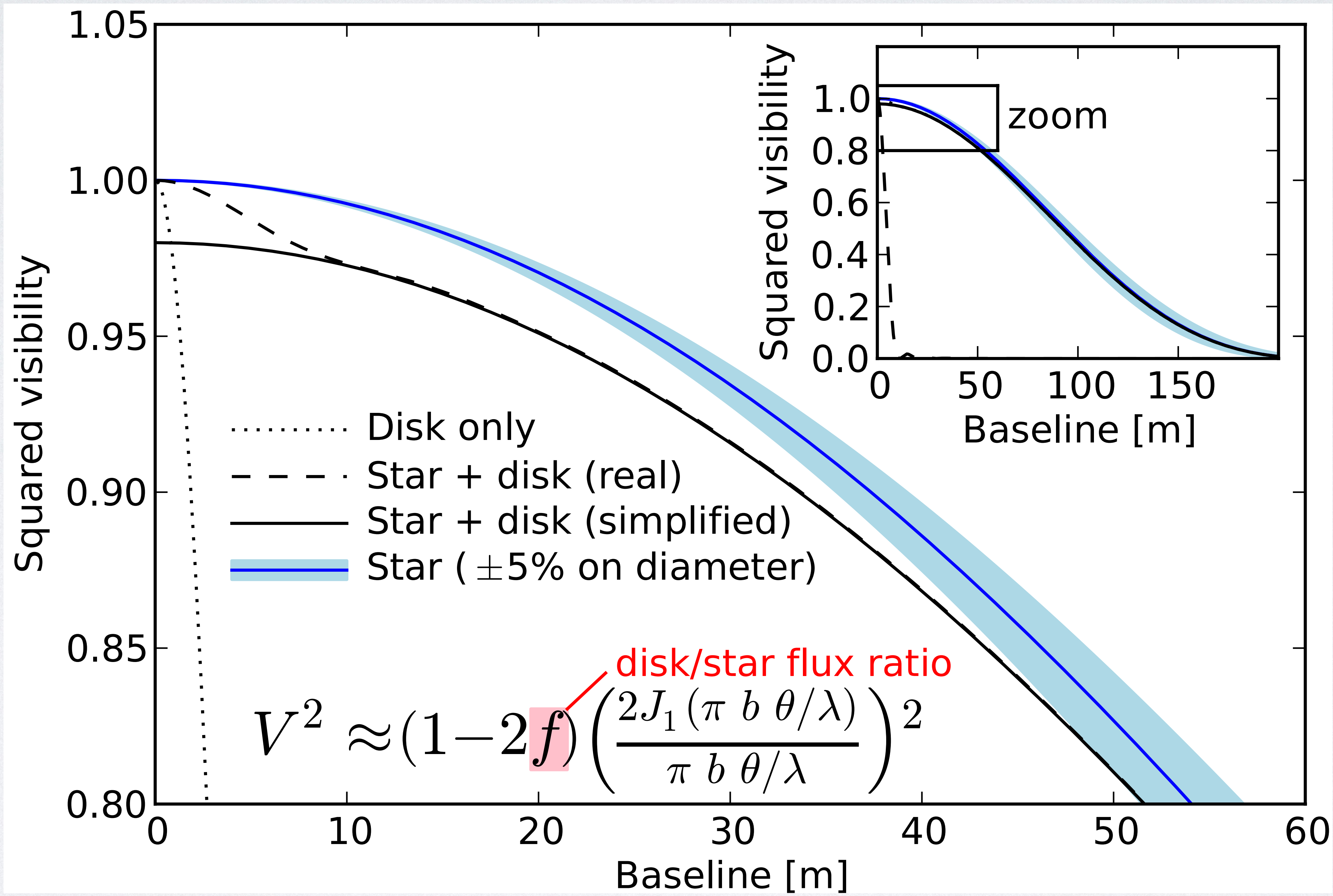
34m baseline



Absil et al 2006

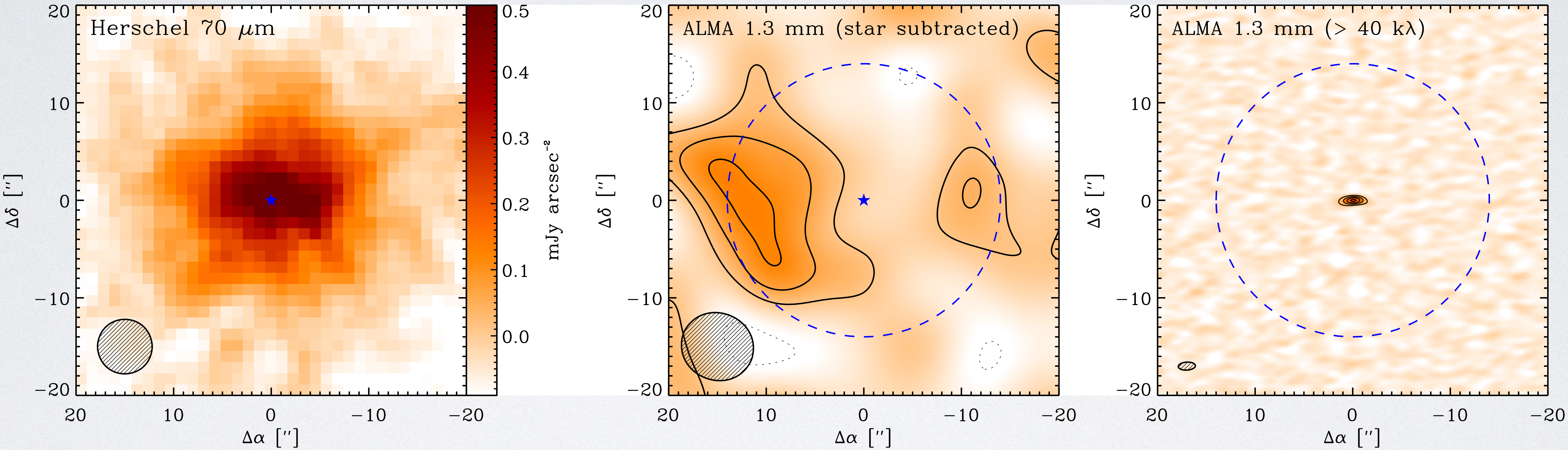
Resolving out 'extended' flux

application to 'exo-Zodi' with CHARA



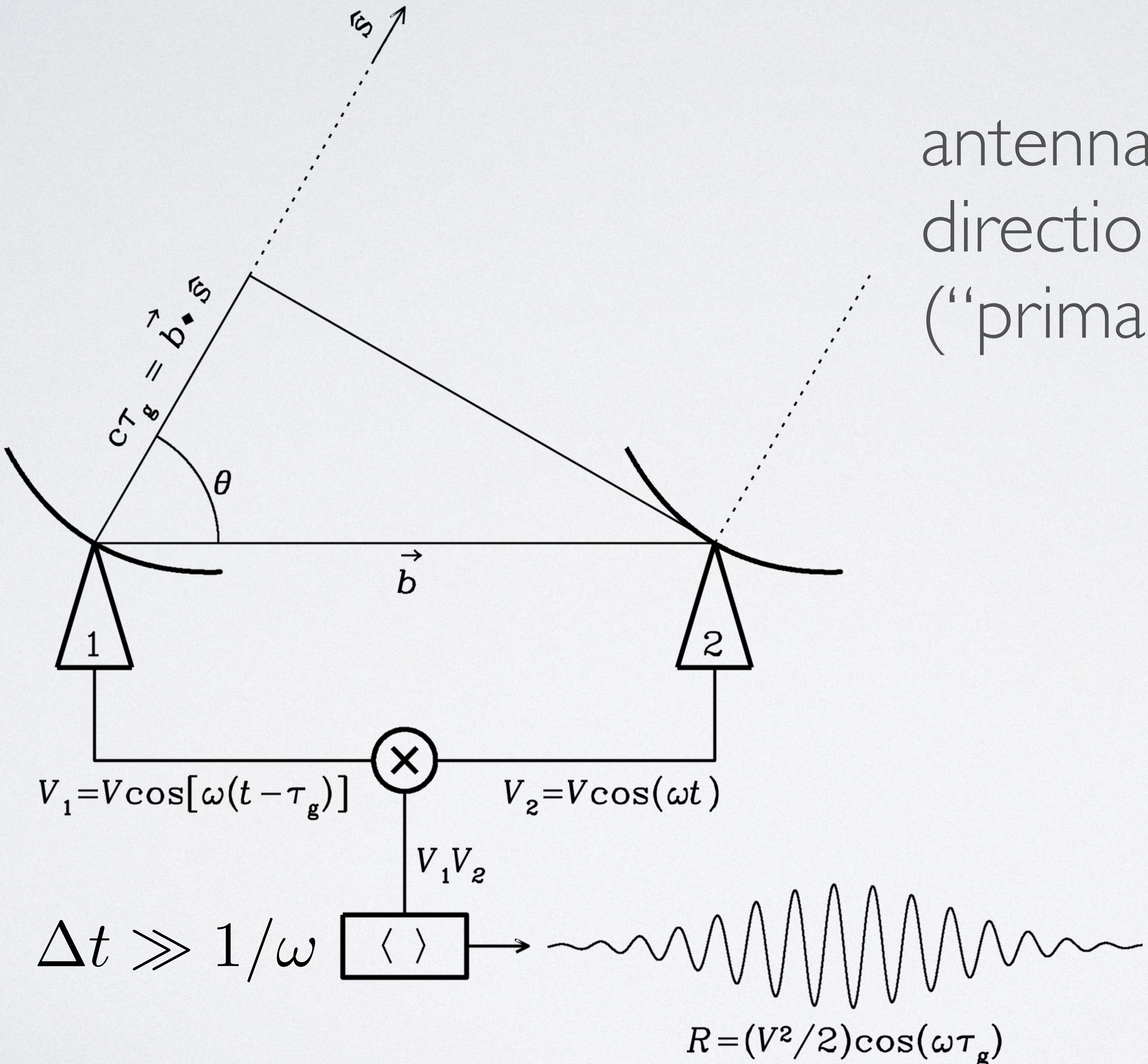
Ertel et al 2014

Resolving out 'extended' flux



MacGregor et al 2016

Basic interferometer



antenna has directional response ("primary beam")

$\Delta t \gg 1/\omega$

'fringe' for source moving past **s**

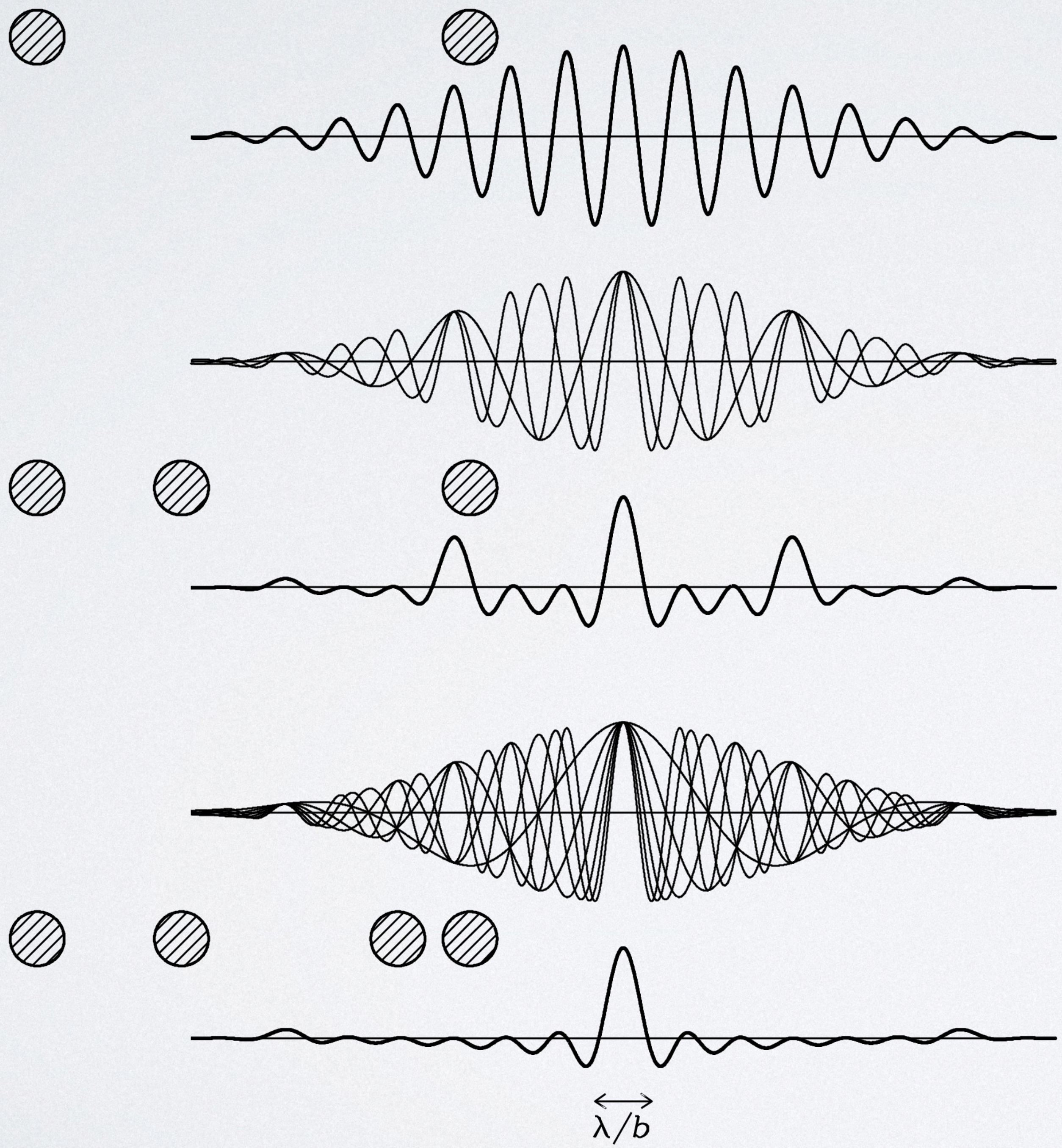
ERA: Fig 3.41

Aperture synthesis

- Two element interferometer - imaging degenerate
- But, N antennas means N(N-1)/2 unique baselines
- Goal: sample visibility at enough u,v points with many small antennas to "synthesise" an aperture of size u_{max}, v_{max}
- Result: response to point source ("dirty beam") is the average of the fringes for all baselines (more baselines, more Gaussian beam).

Multiple baselines

point-source response = synthesised ("dirty") beam



single baseline

three baselines

six baselines

ERA: Fig 3.42

Multiple baselines

what is the dirty beam?

dirty beam → $b(x,y)$

reality → $I(x,y)$

image obtained → $O(x,y)$

$$b(x,y) \otimes I(x,y) = O(x,y)$$

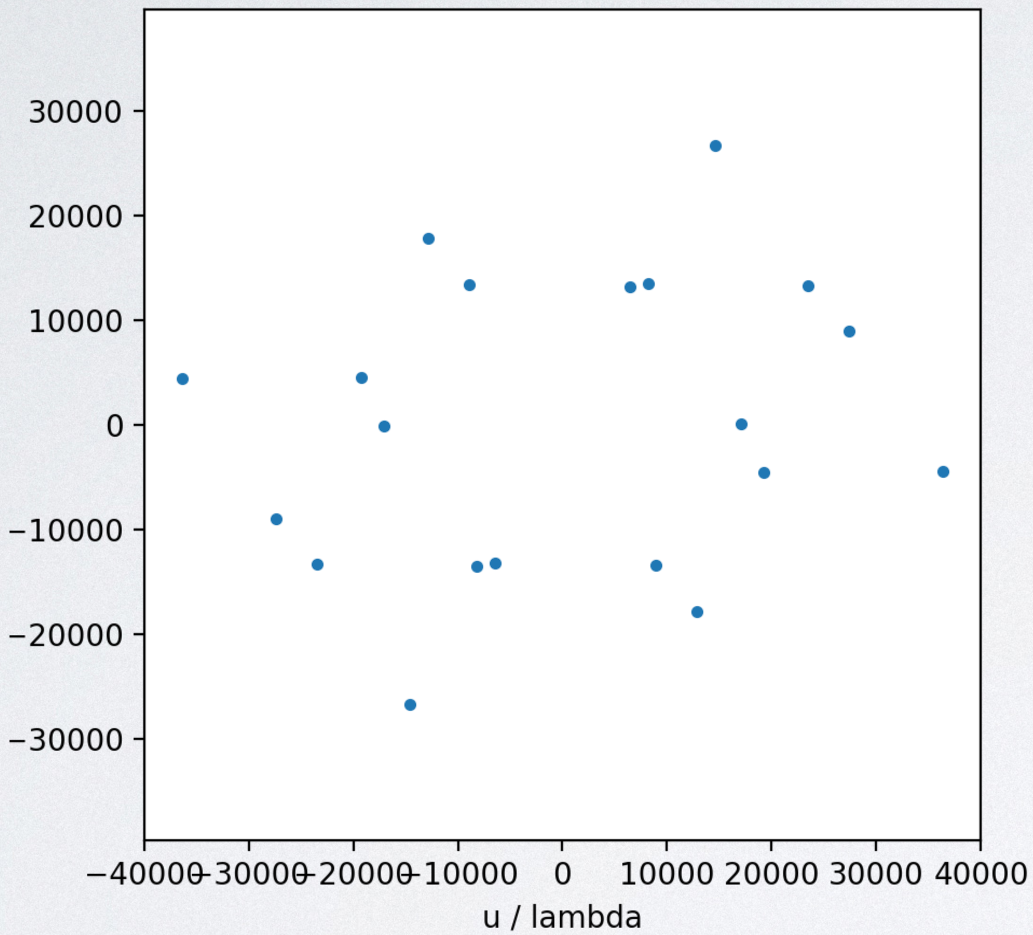
↕ convolution theorem

$$FT^{-1}\{B(u,v)V(u,v)\} = O(x,y)$$

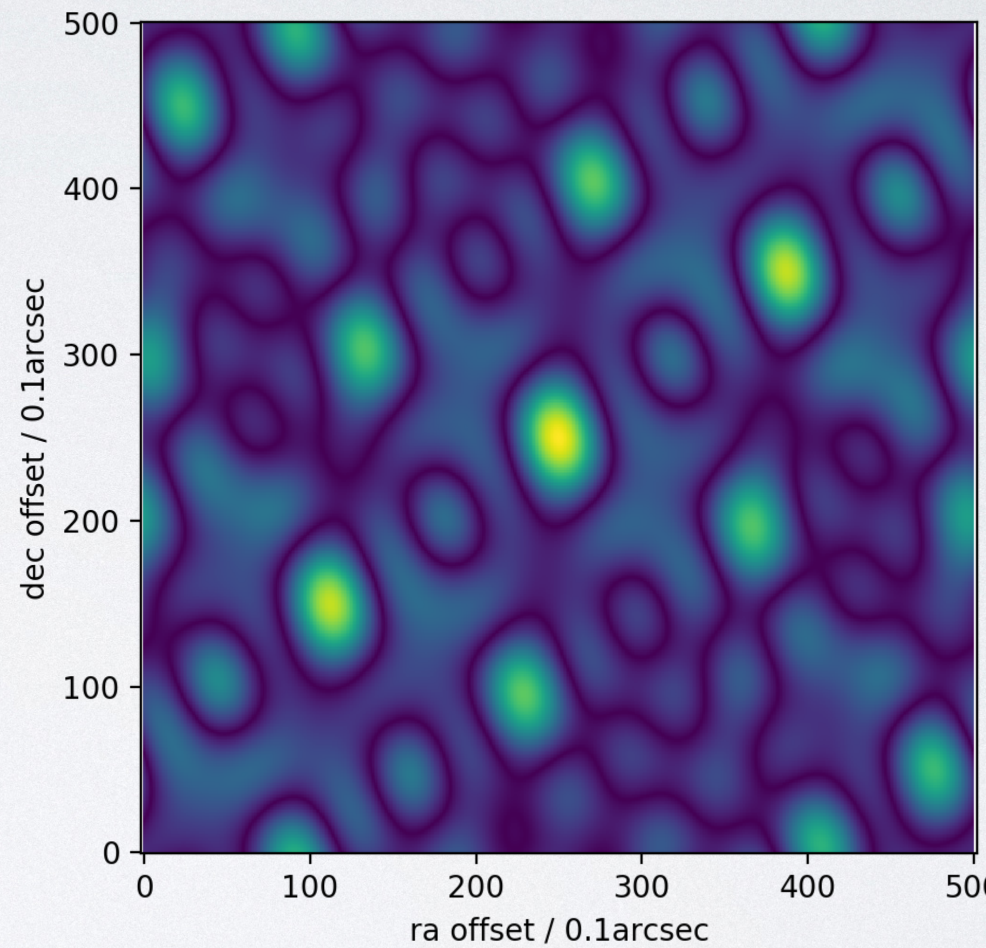
sampled visibilities → $V(u,v)$

Multiple baselines

$$B(u,v) = \Sigma_i(u_i, v_i)$$



$$FT^{-1}\{B(u,v)\} = b(x,y)$$

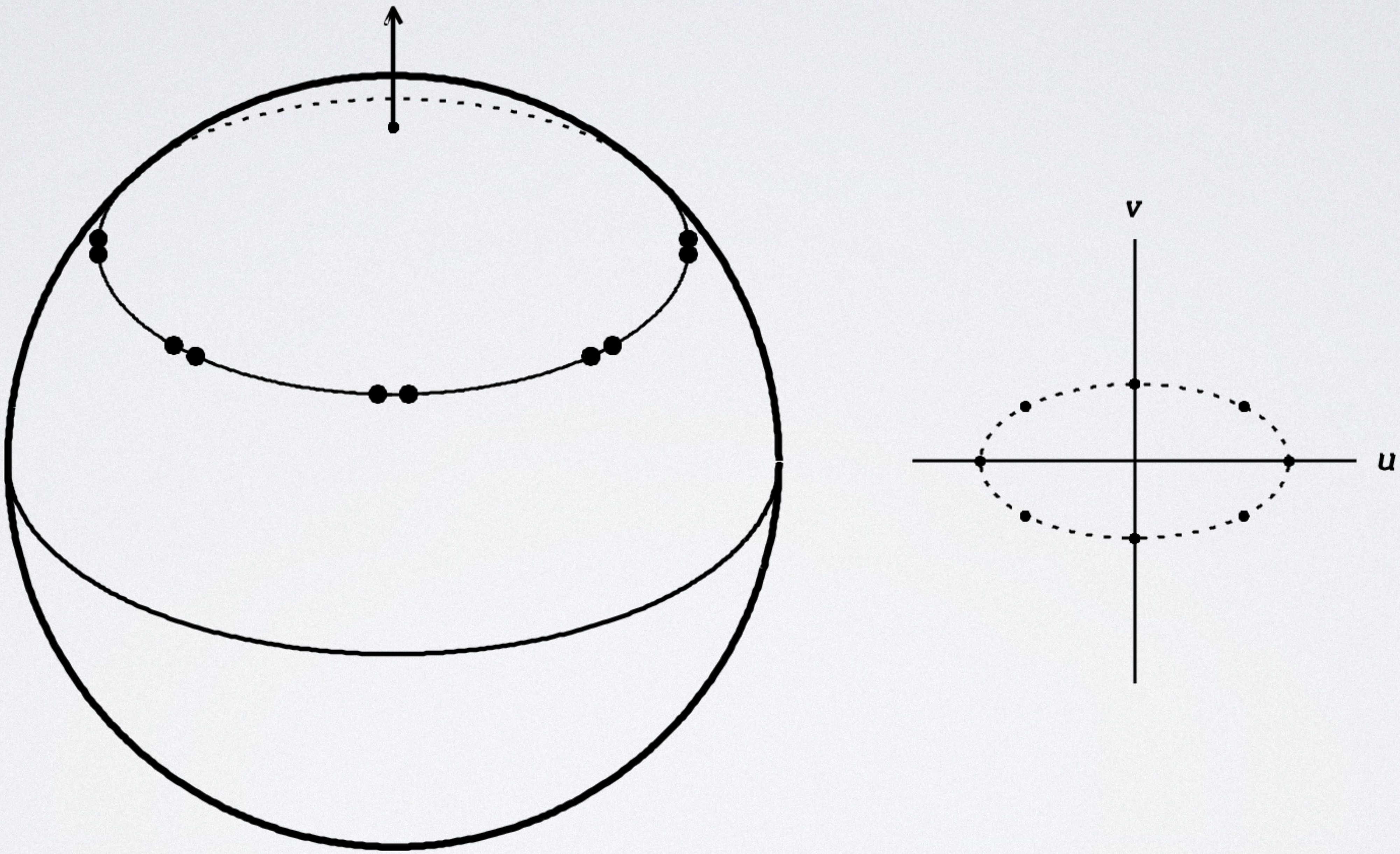


'dirty beam'

i.e. sample all spatial scales,
and FT(constant) = delta function

Aperture synthesis

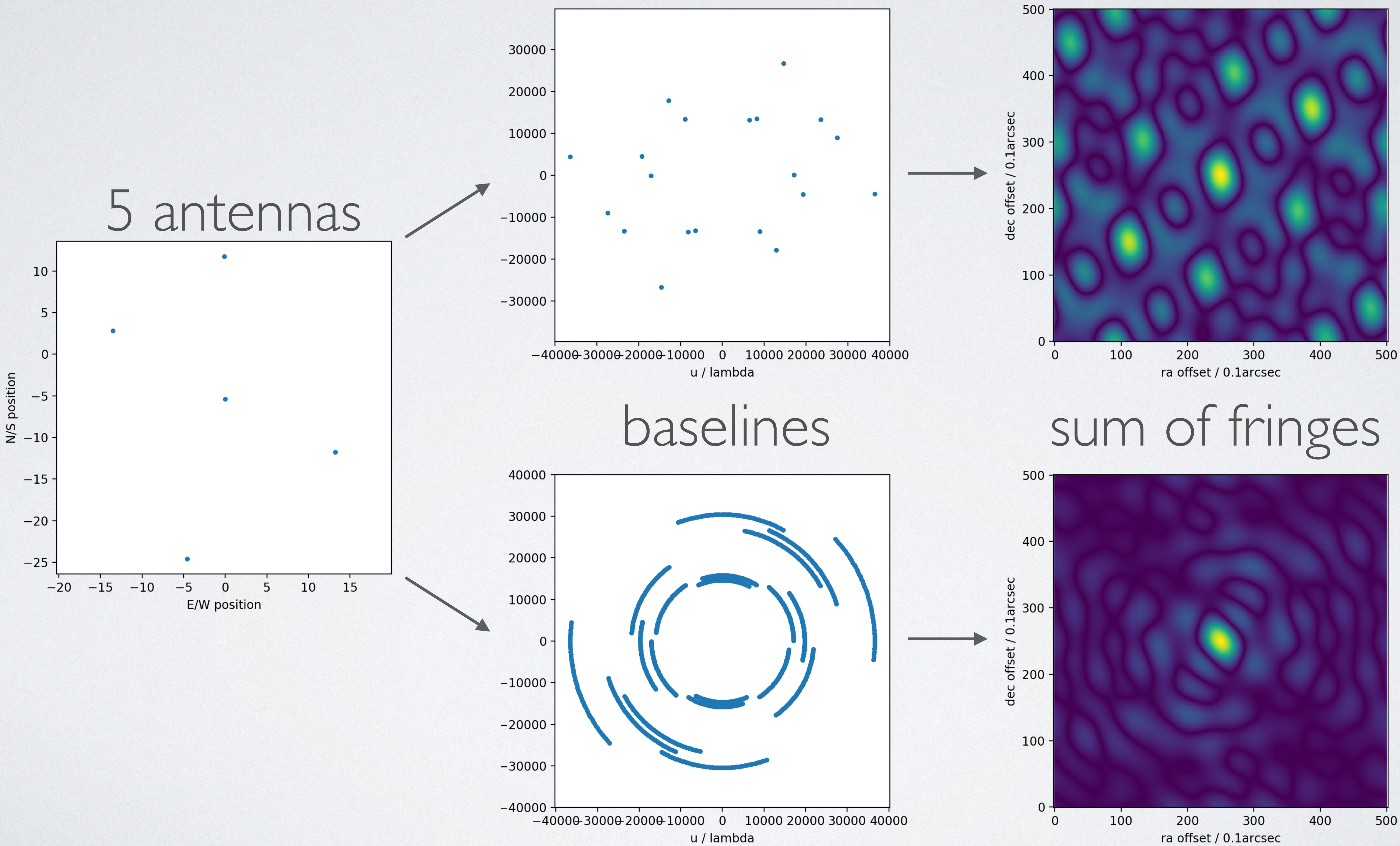
use Earth rotation to fill in uv plane



ERA: Fig 3.44

Aperture synthesis

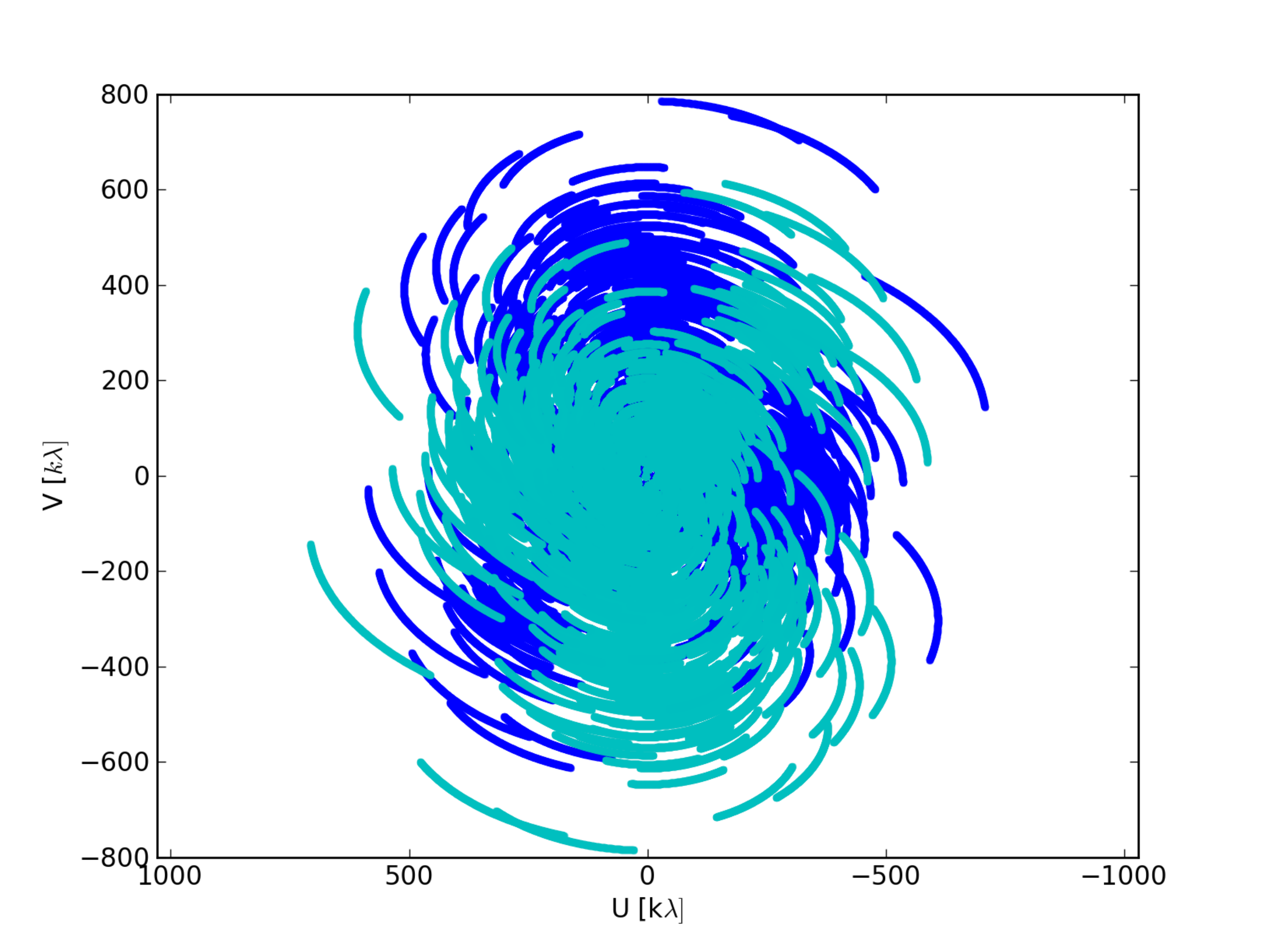
sky rotation makes all the difference

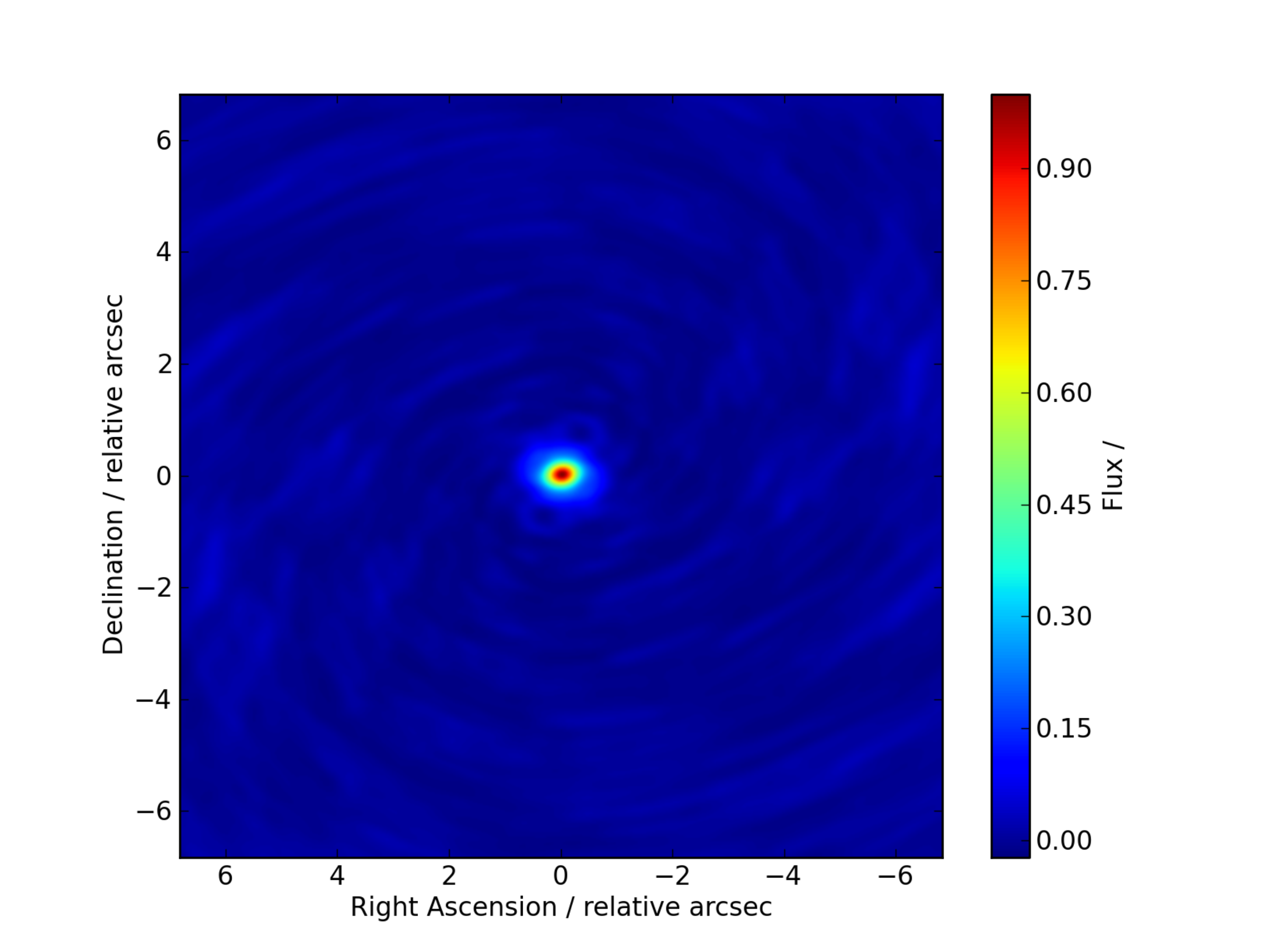


Aperture synthesis

ALMA: 2.5km max baseline, 3h, 43 antennas: 861 baselines

(for ALMA integration time the main consideration)

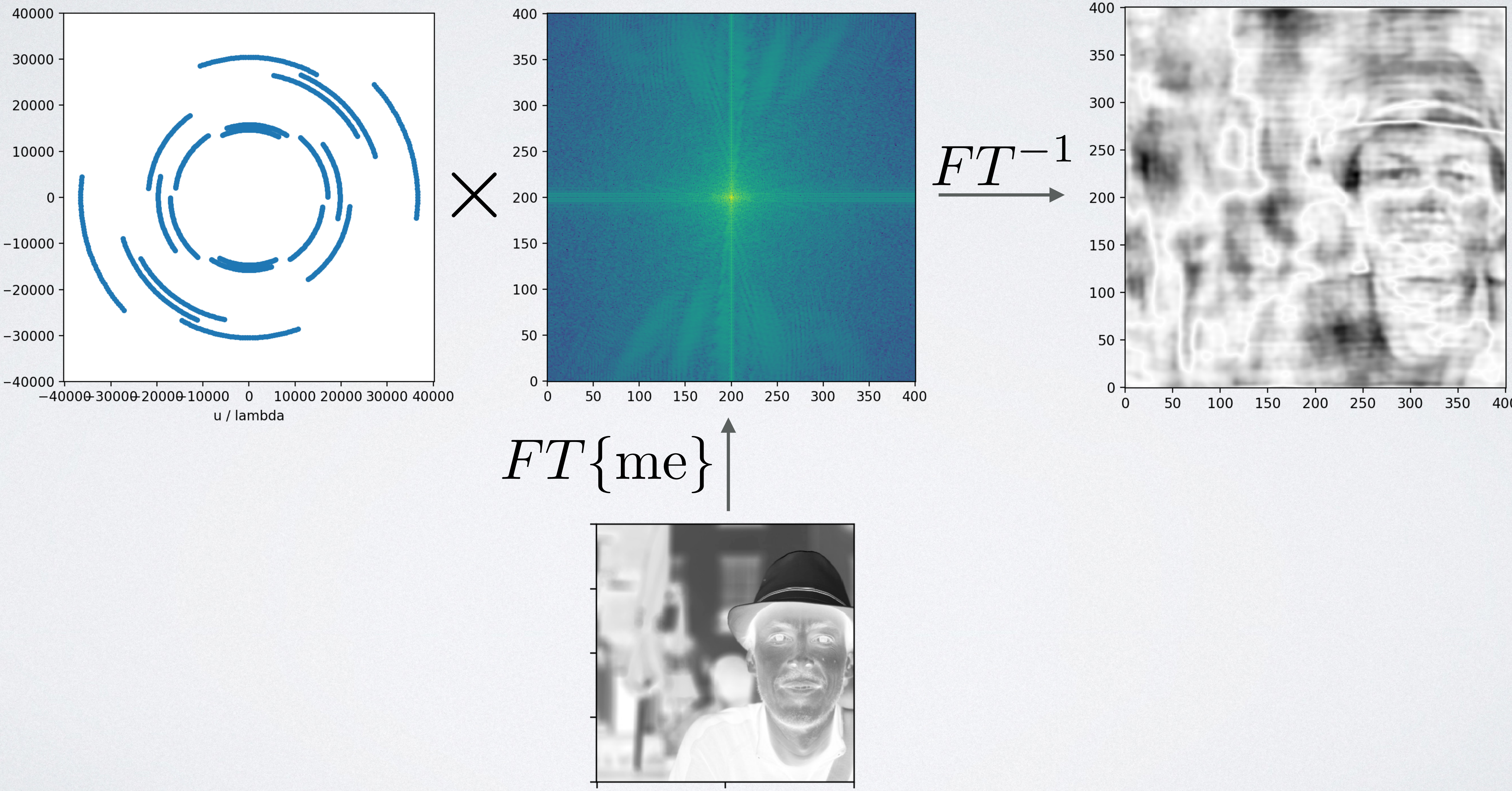




http://almaost.jb.man.ac.uk/

Imaging visibilities

incomplete uv coverage results in spatial filtering



CLEAN

turning visibility data into images

- Initialise residual image to dirty image
- Identify strongest source in residual image
    - subtract fraction of this peak from residual image
    - add it to clean component list
- Repeat until residual image maximum less than some threshold

CLEAN

turning visibility data into images

- Make restored image:
  - make image with all clean components
  - convolve with Gaussian fit to main lobe of dirty beam
  - add residual map

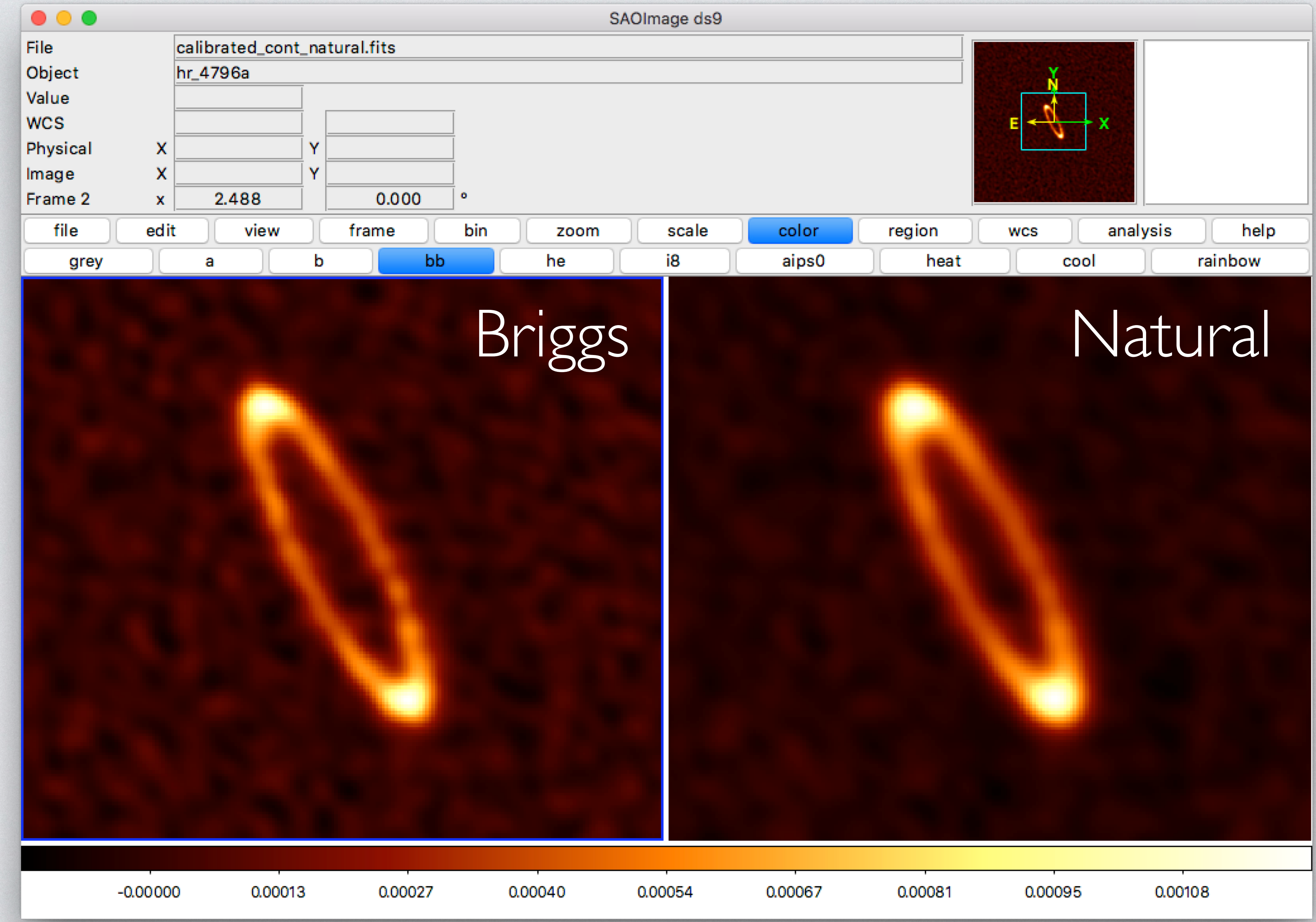
CLEAN

turning visibility data into images

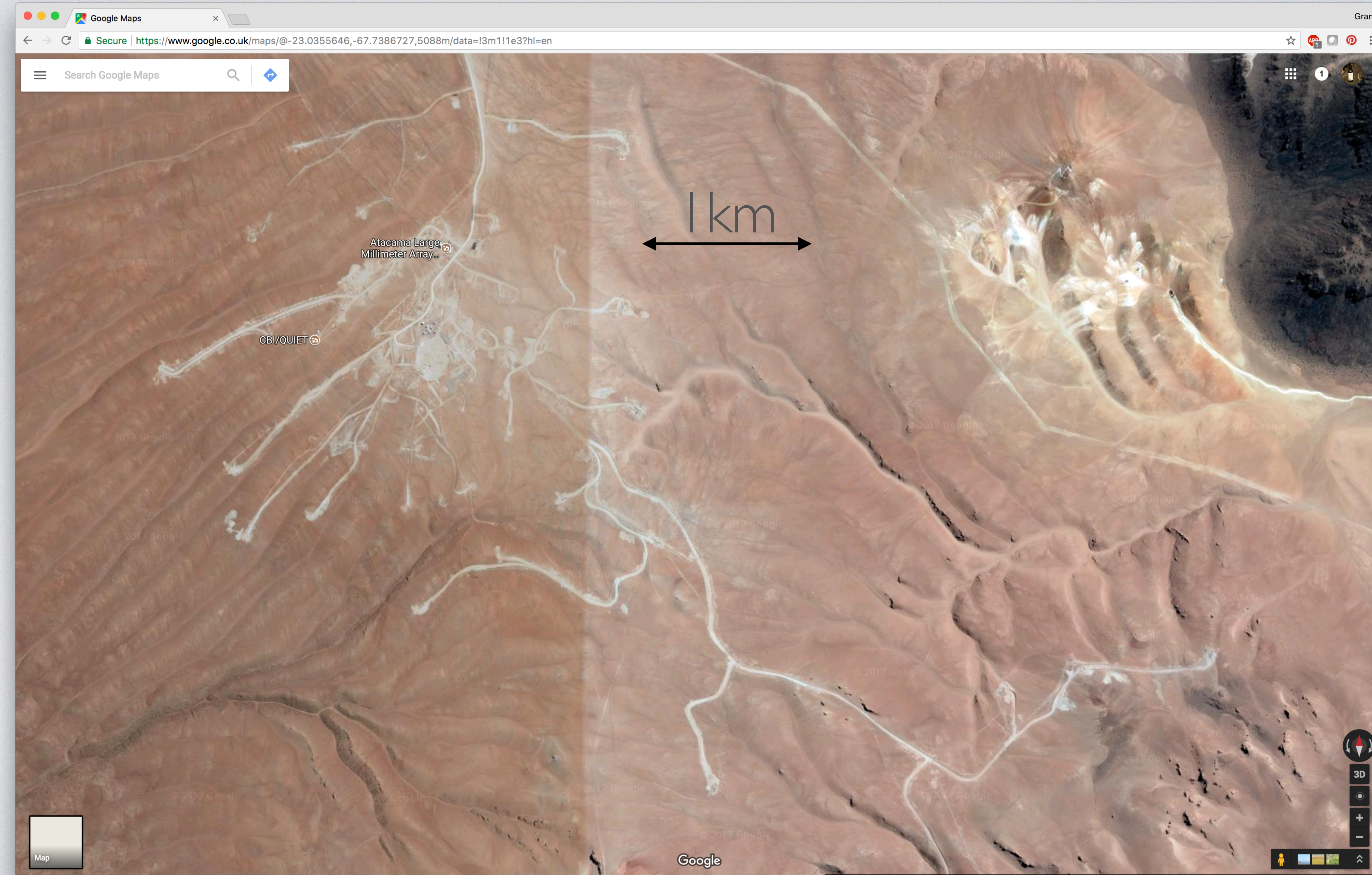
- Main options:
  - Continuum vs. spectral cube
  - Choose how to weight baselines (e.g. ‘natural’)
  - Choose where clean components are (‘mask’)

CLEAN

turning visibility data into images



ALMA


Google Maps
Grant
Secure
https://www.google.co.uk/maps/@-23.0355646,-67.7386727,5088m/data=!3m1!1e3?hl=en
Search Google Maps
1 km
Atacama Large Millimeter Array...
CBI/QUIET
Map
Google
3D
Imagery ©2017 CNES / Airbus, DigitalGlobe, DigitalGlobe, Map data ©2017 Google
United Kingdom
Terms
www.google.com/maps
Send feedback
200 m

ALMA

ALMA

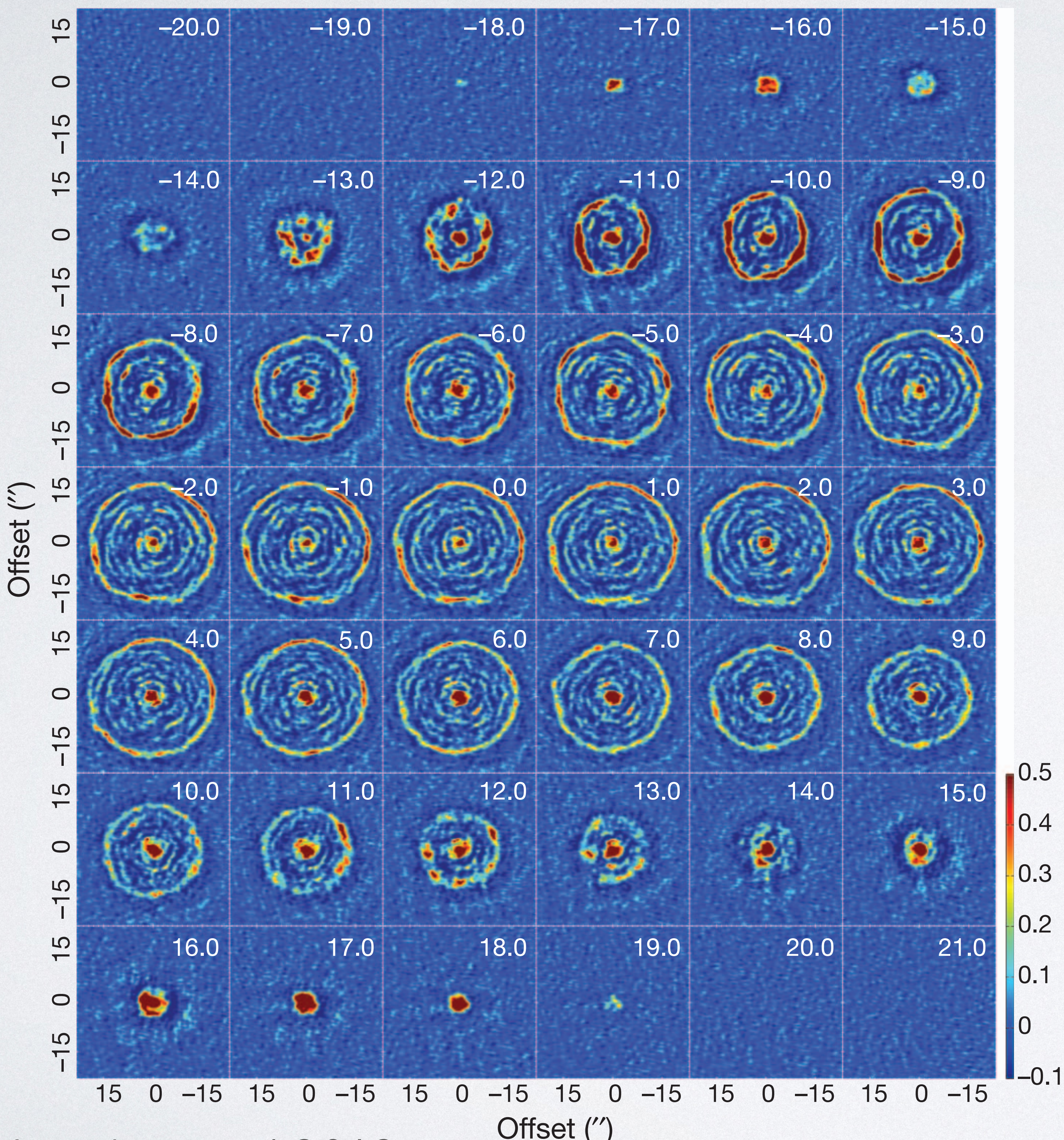
4 x 12m +12 x 7m compact array, the ‘ACA’
acts as a ‘single dish’ to recover large scale structure

Spectral line observations

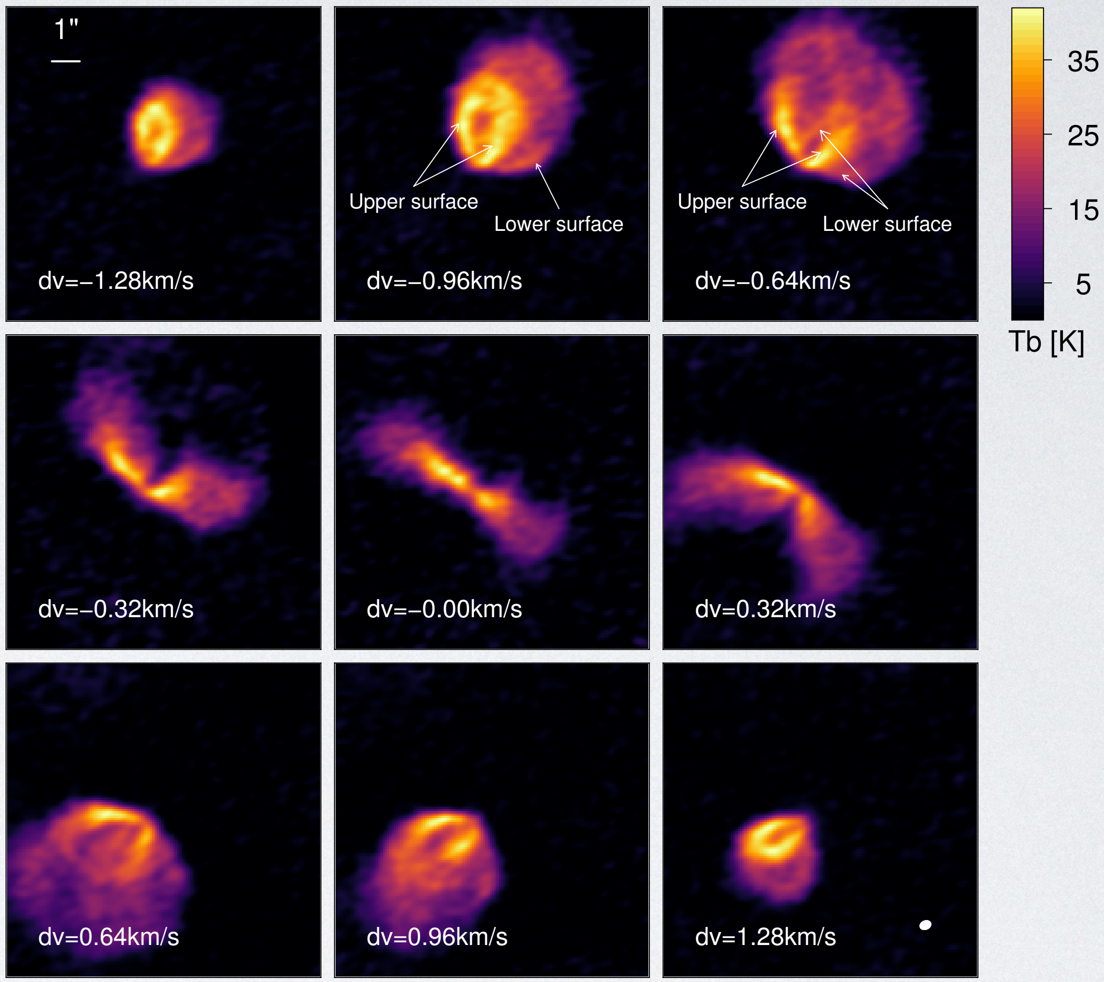
Maercker et al 2012

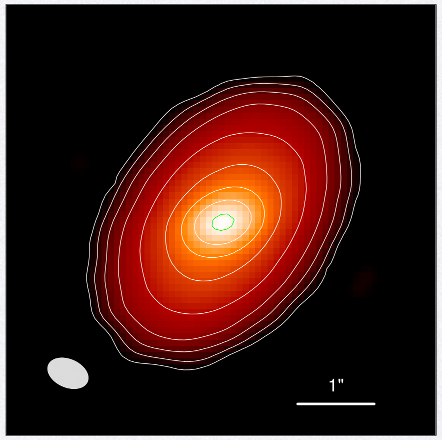
Spectral line observations

different 'slices' through a data cube



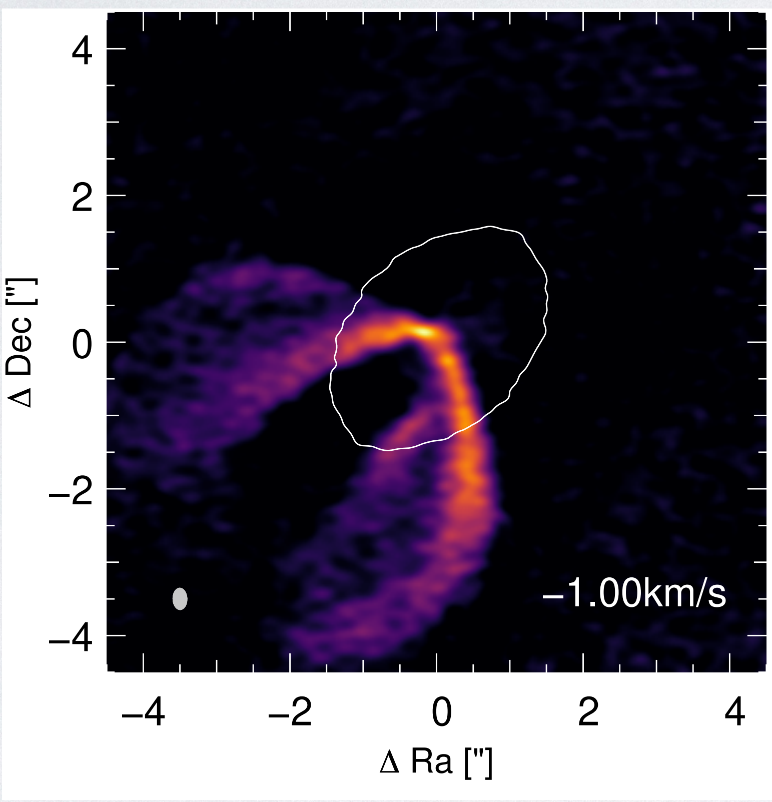
Maercker et al 2012

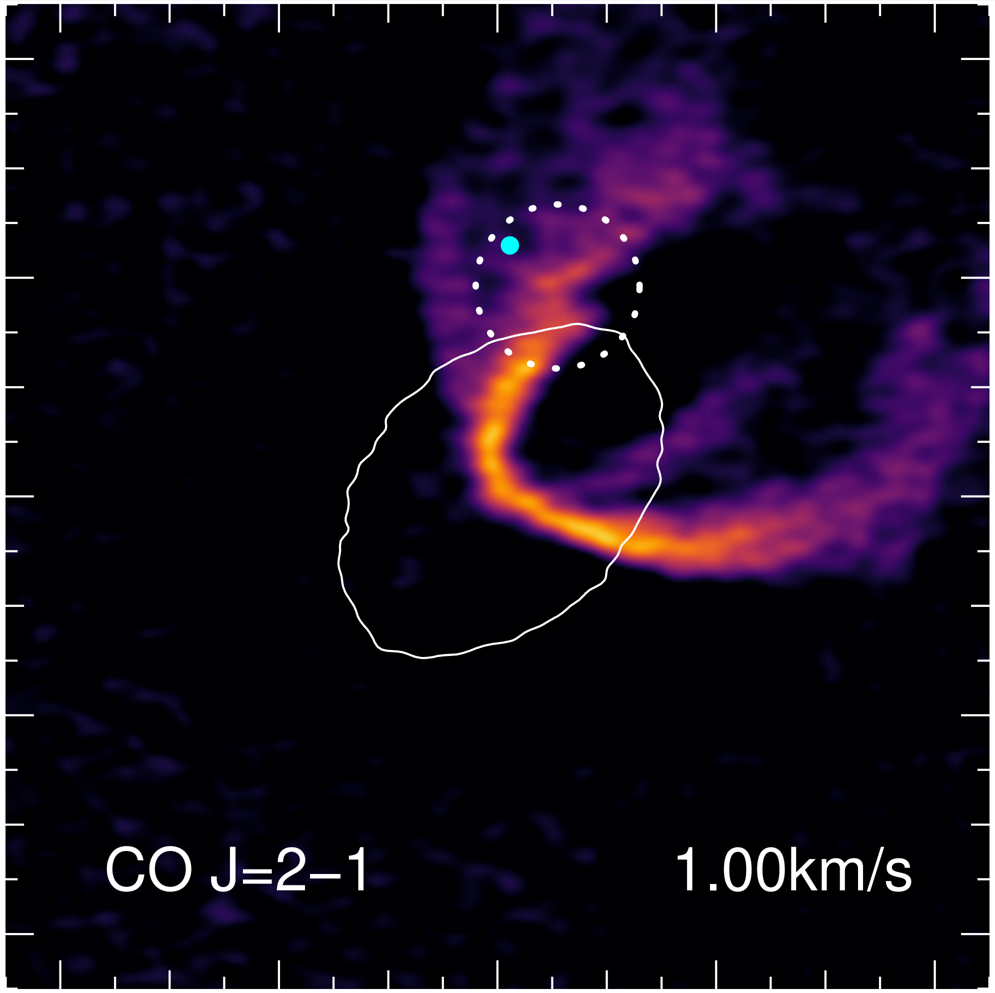


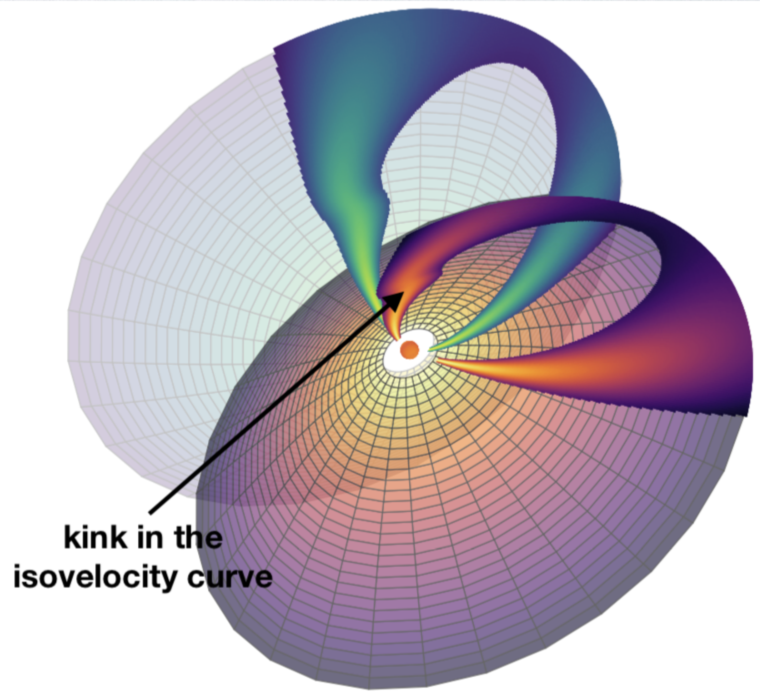


Pinte et al 2017

Spectral line observations



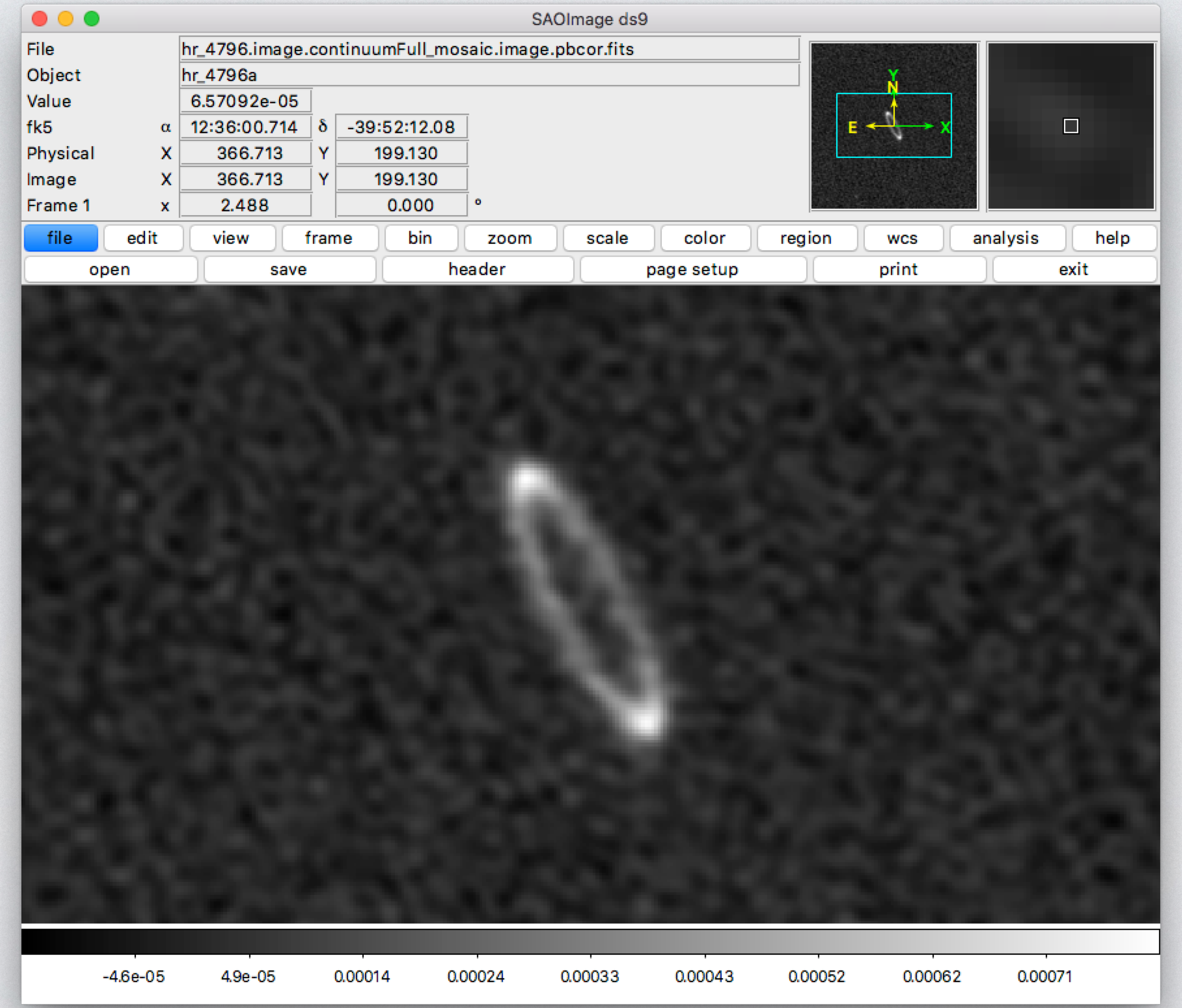




Pinte et al. 2018

ALMA…

…will do a lot of the hard stuff for you



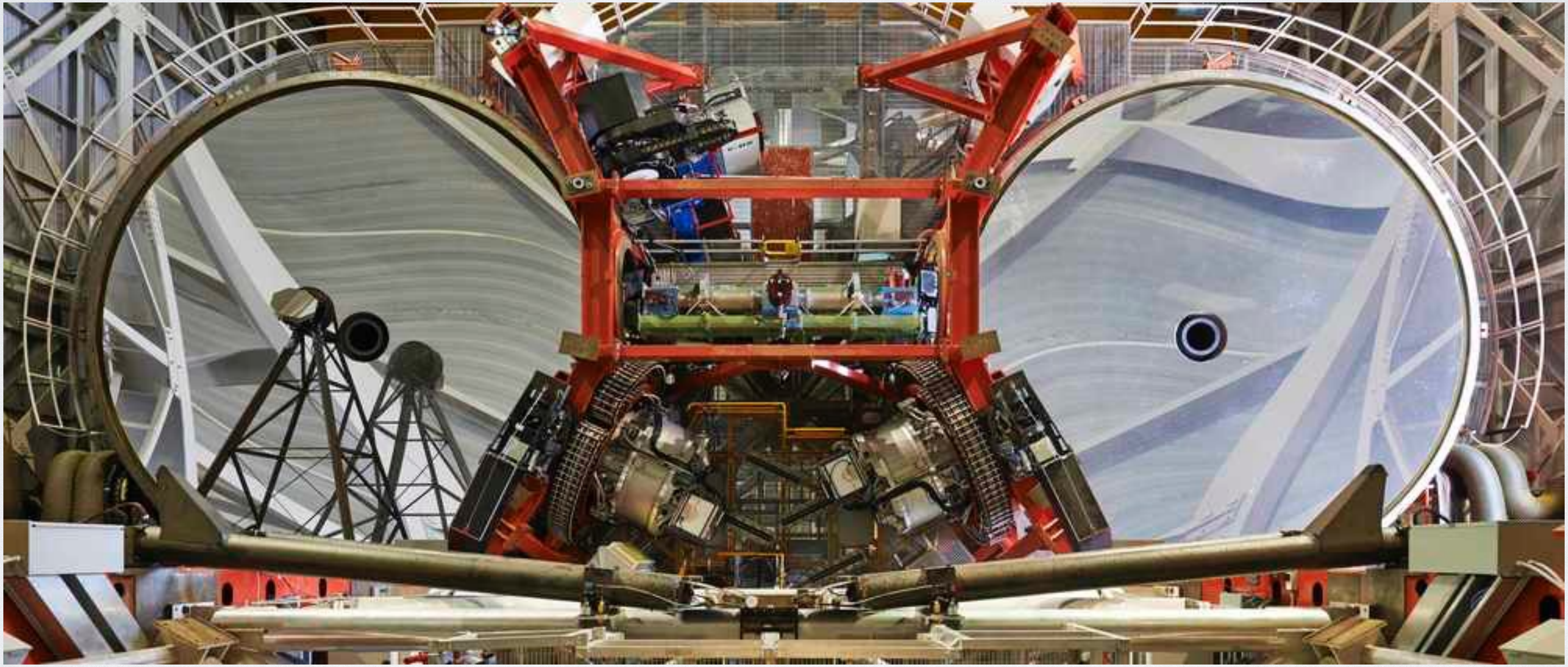
ALMA

…and packages exist to deal with visibility modelling

- Modelling example:
- https://github.com/drgmk/alma/blob/master/examples/vis_model.ipynb

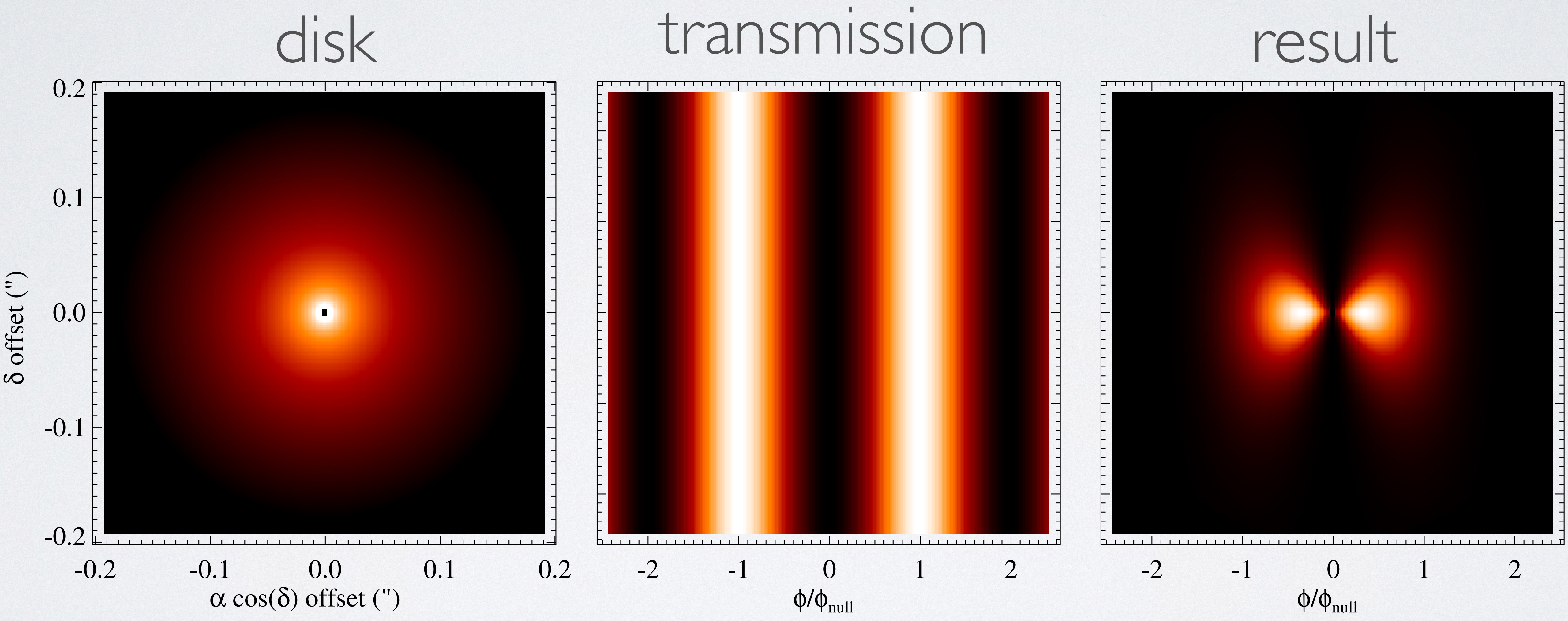
Nulling interferometry

~as before, but 180deg phase shift and no correlator
(i.e. photons on an IR detector)



Nulling interferometry

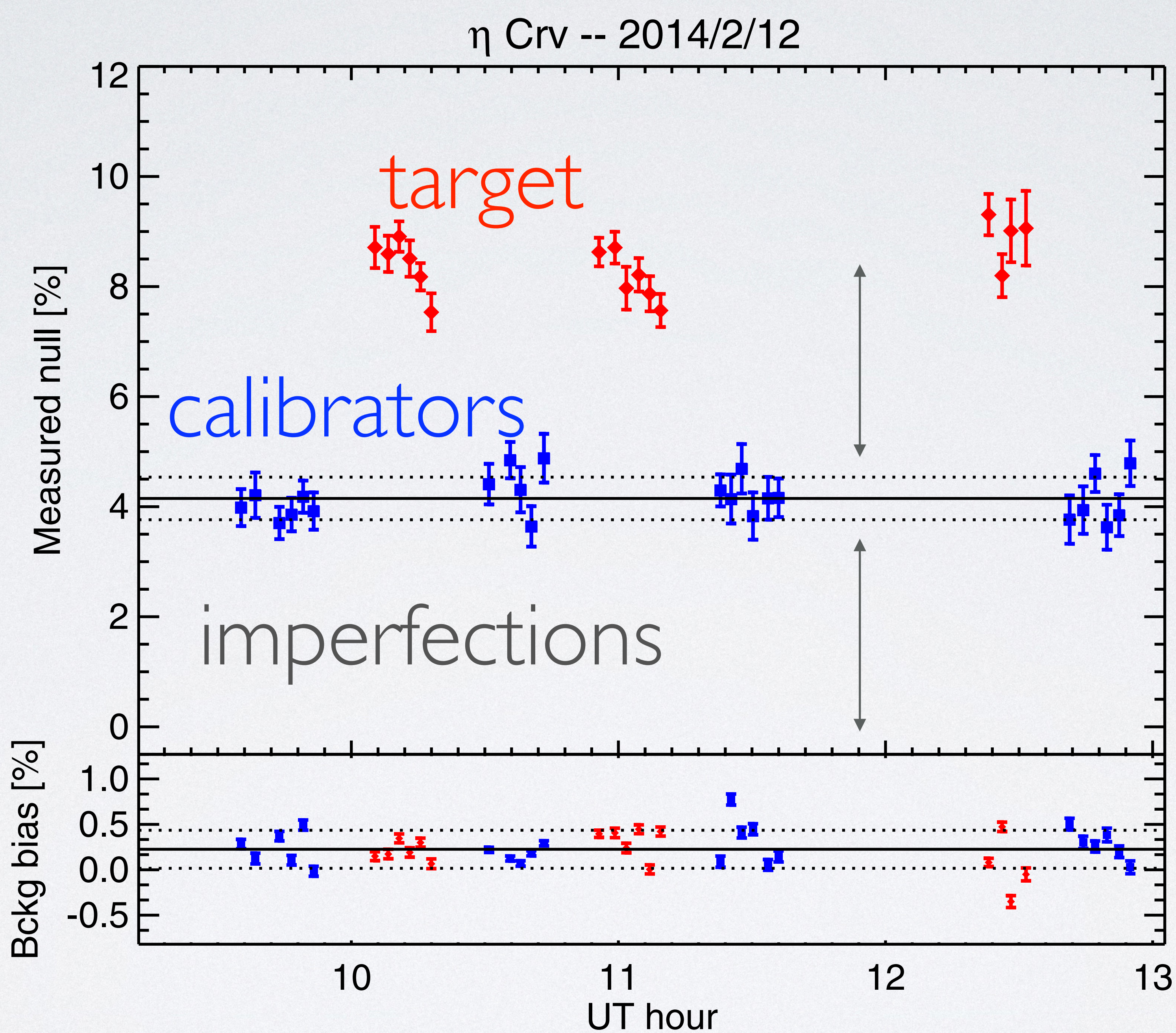
as before, but 180deg phase shift and no correlator (i.e. photons on an IR detector)



Kennedy et al 2015

Defrere et al 2015

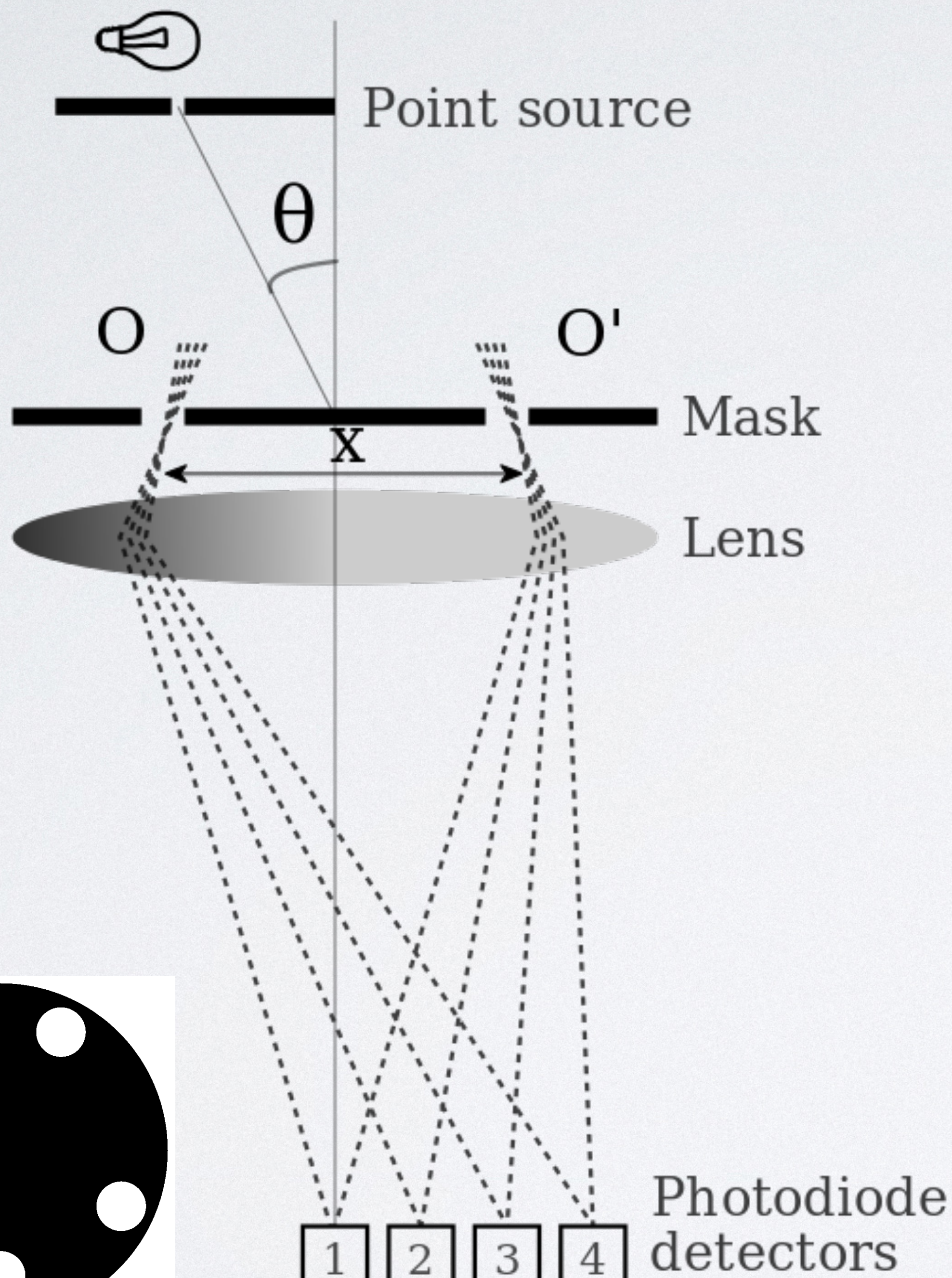
LBTI - early results

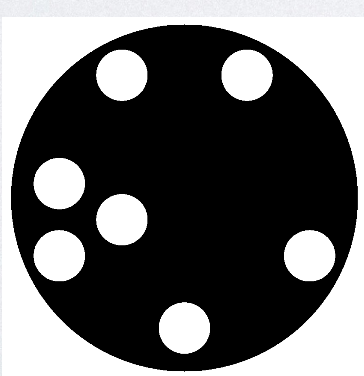


signal =4.4%

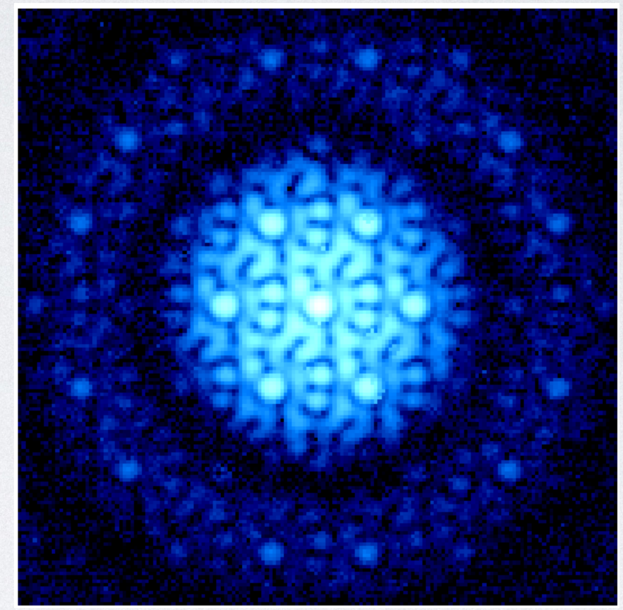
$$\text{signal} = \frac{\text{transmitted disk flux}}{\text{stellar flux}}$$

Sparse Aperture Masking

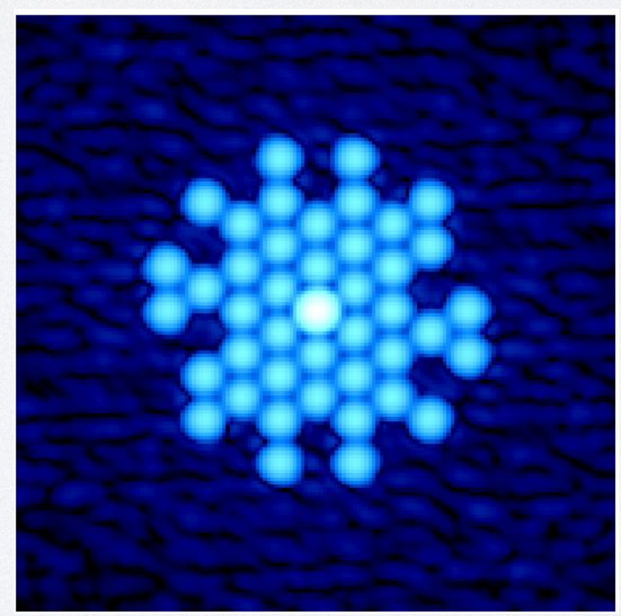




21 unique baselines - ‘sparse’



image



Fourier transform (42 dots)

Cheetham et al 2016

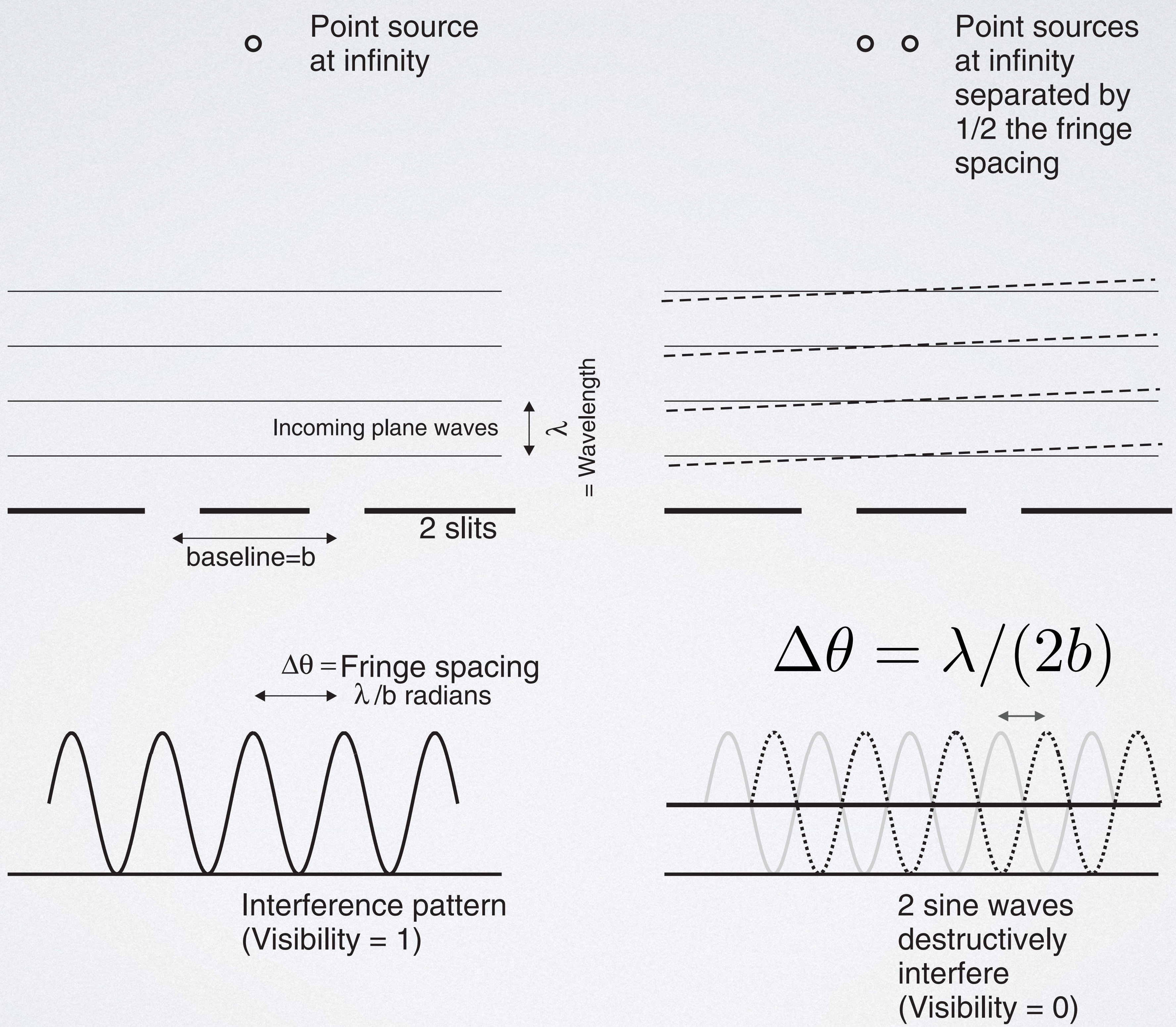
Resources

- http://www.phys.unm.edu/~gbtaylor/astr423/s98book.pdf
- https://science.nrao.edu/opportunities/courses/era/
- John D Monnier, 2003, Rep. Prog. Phys. 66 789
- http://almaost.jb.man.ac.uk/ https://github.com/crpurcell/friendlyVRI
- http://www.jb.man.ac.uk/pynterferometer/index.html
- https://launchpad.net/apsynsim
- https://github.com/griffinfoster/fundamentals_of_interferometry

Summary

- Interferometry is a valuable and flexible tool
- Main concept: interferometer samples *uv* space
- With good *uv* coverage; well-defined beam, images

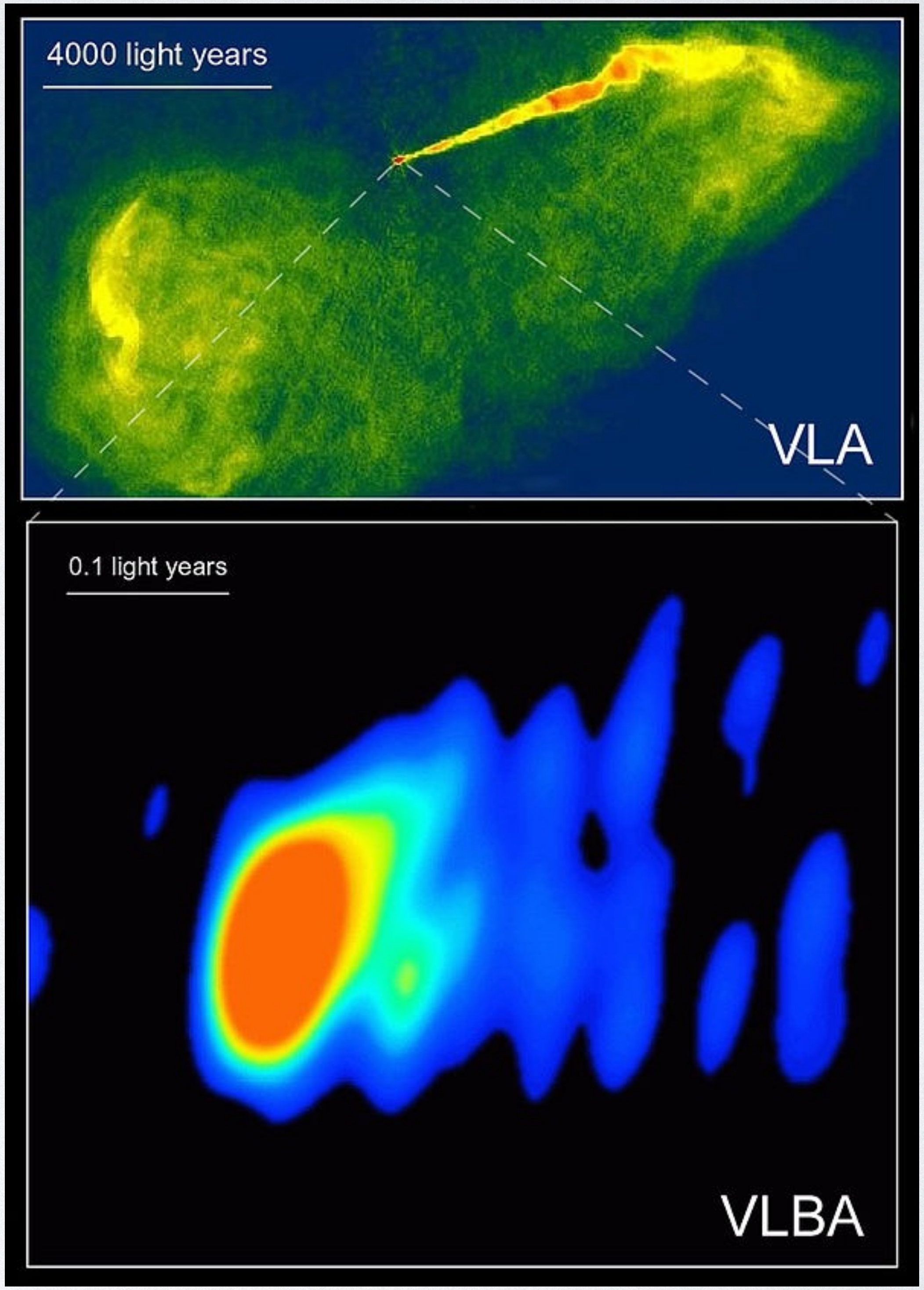
When is a source resolved?



Monnier 2003

Radio astronomy

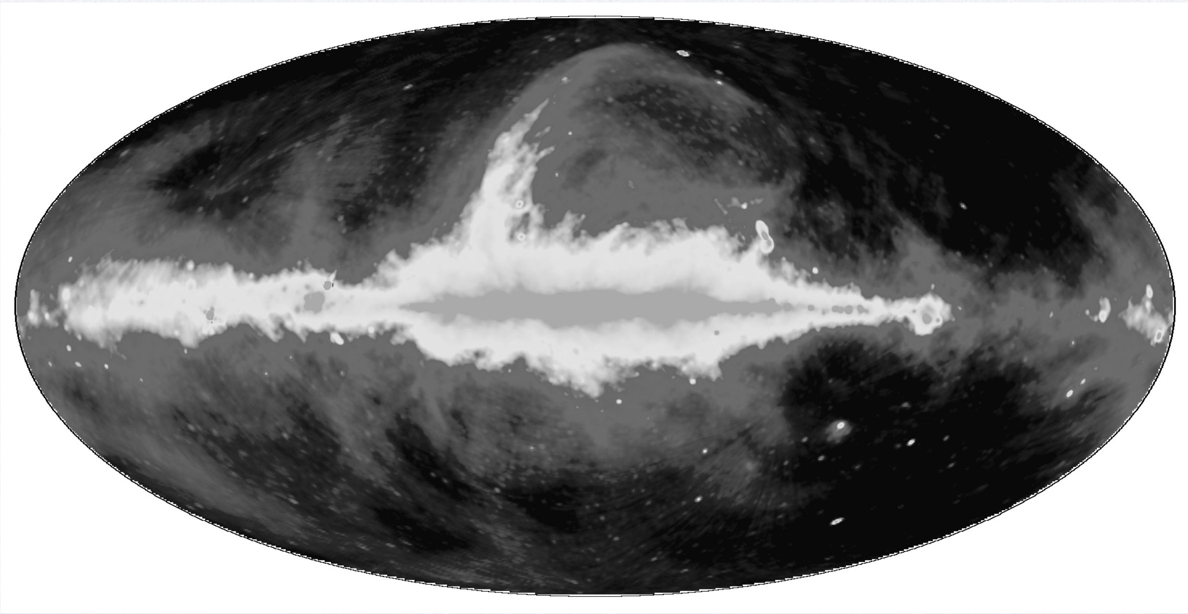
M87



- Dust obscures optical light
- Not all emission is thermal

Radio astronomy

- Interstellar dust smaller than wavelength - e.g. Sgr A*
- Cold emission negligible in optical - e.g. CMB
- Free-free radiation - e.g. (ionised) HII regions
- Spectral lines - e.g. 21cm HI line, CO rotational transitions
- Synchrotron emission - e^- accelerated in SN remnants



sky at 408MHz