Telescopes and the Basics of Radio Astronomy

ICRAR/CASS Radio School

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1 Oct 2018

Geraldton, WA


Radio Image of
Ionised Hydrogen in Cyg X
CGPS (Penticton)

WHY?

- National Facilities
  - ✓ Easy for non-experts to use
  - ✗ don’t know what you are doing
- Cross fertilization
- Doing the best science
- Value of radio astronomy

Indirect Imaging Applications

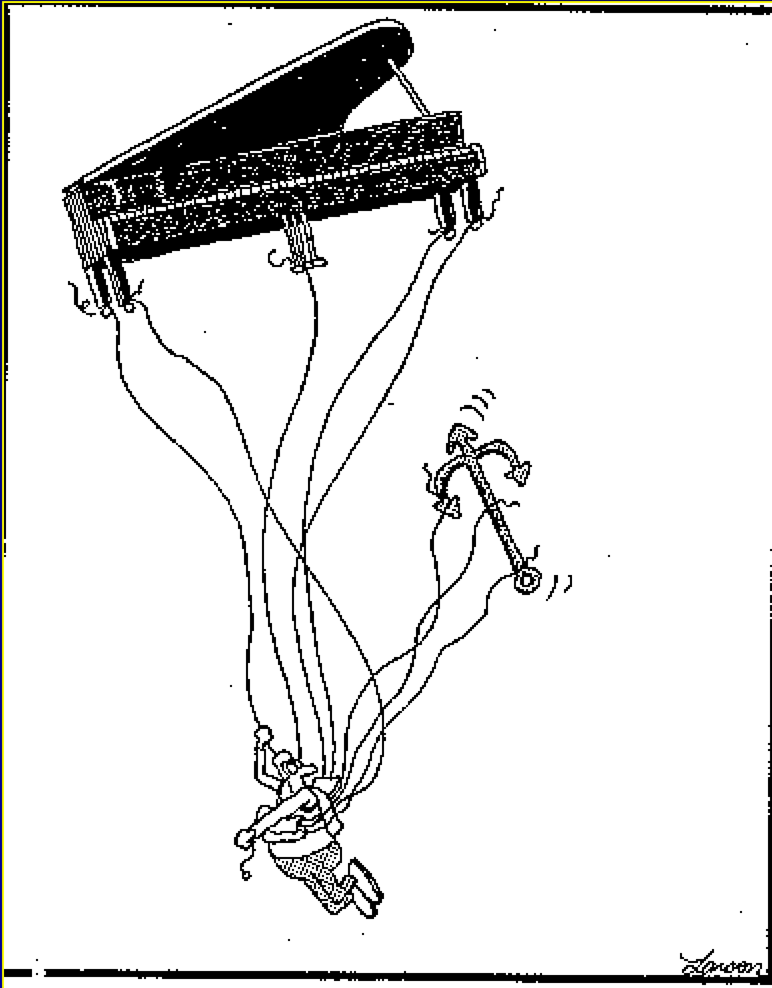
- Interferometry
  - radio, optical, IR, space...
- Fourier synthesis
  - measure Fourier components and make images
  - Earth rotation, SAR, X-ray crystallography, ….
- Axial tomography (CAT)
  - NMR, Ultrasound, PET, X-ray tomography
- Seismology
- Fourier filtering, pattern recognition
- Adaptive optics, speckle

Doing the best science

- The telescope as an analytic tool
  - how to use it
  - integrity of results
- Making discoveries
  - Most discoveries are driven by instrumental developments
  - recognising the unexpected phenomenon
  - discriminate against errors
- Instrumental or Astronomical specialization?

HOW ?

- Don’t Panic!
  – Many entrance levels



Murray didn't feel the first pangs of real panic until he pulled the emergency cord.

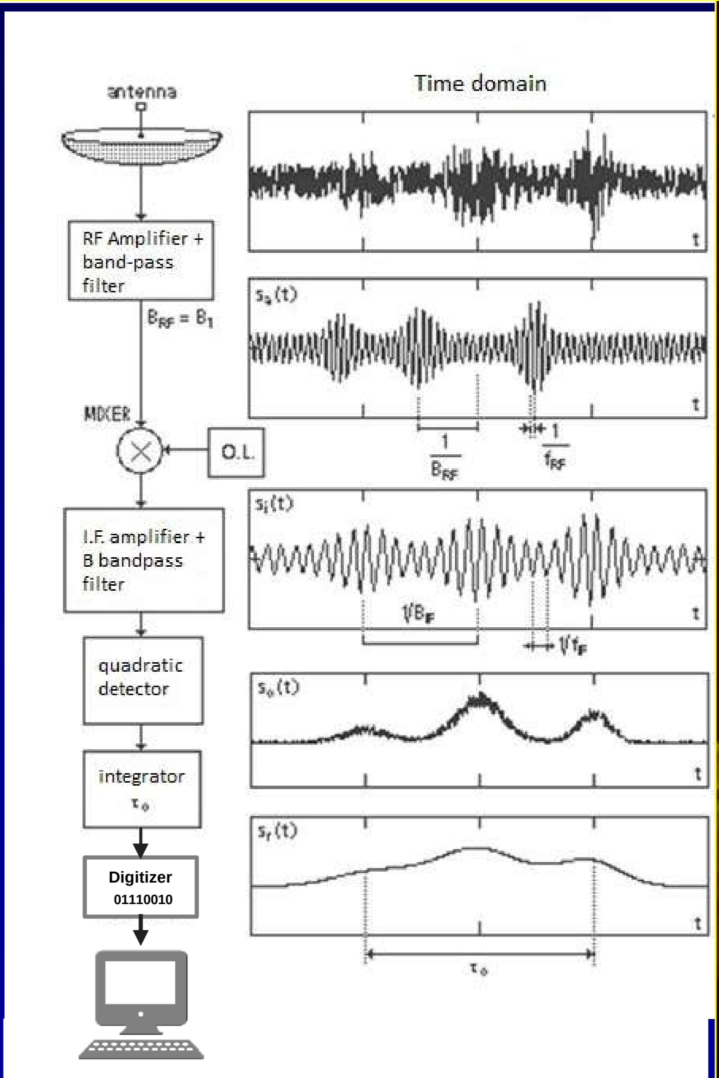
Basic concepts

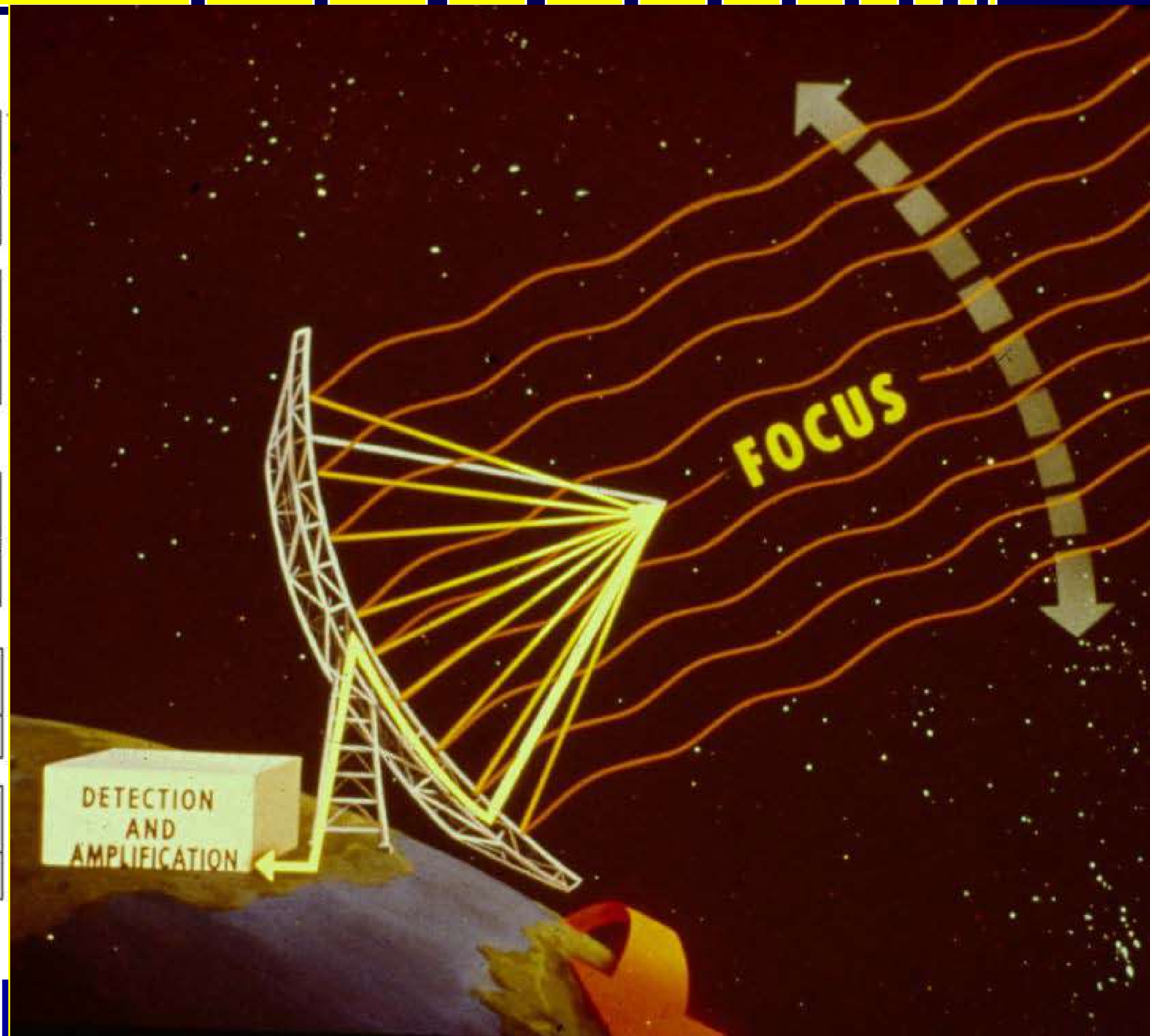
- Importance of analogies for physical insight
- Different ways to look at a synthesis telescope
  - Engineers model
    - Telescope beam patterns…
  - Physicist electromagnetic wave model
    - Sampling the spatial coherence function
    - Barry Clark *Synthesis Imaging chapter1*
    - Born & Wolf *Physical Optics*
  - Quantum model
    - Radhakrishnan *Synthesis Imaging last chapter*

References

- Essential Radio Astronomy
  - a complete one semester course, J.J. Condon and S.M. Ransom
  - *www.cv.nrao.edu/course/astr534/ERA.shtml*
  - **David Wilner, ANITA lectures, Swinburne, 2015**
- Thompson, A.R., Moran, J.M. & Swensen, G.W. **2017**, "Interferometry and Synthesis in Radio Astronomy" **3rd** edition (Wiley-VCH)
- NRAO Synthesis Imaging workshop proceedings
  - Perley, R.A., Schwab, F.R., Bridle, A.H., eds. 1989, ASP Conf. Series 6, "Synthesis Imaging in Radio Astronomy" (San Francisco: ASP)
  - *www.aoc.nrao.edu/events/synthesis*
- IRAM Interferometry School proceedings
  - *www.iram.fr/IRAM/FR/IS/IS2008/archive.html*
- Ekers & Wilson, *Radio Telescopes,* in *Planets, Stars and Stellar Systems*, Springer, 2013

Detecting Signals from Radio Telescopes

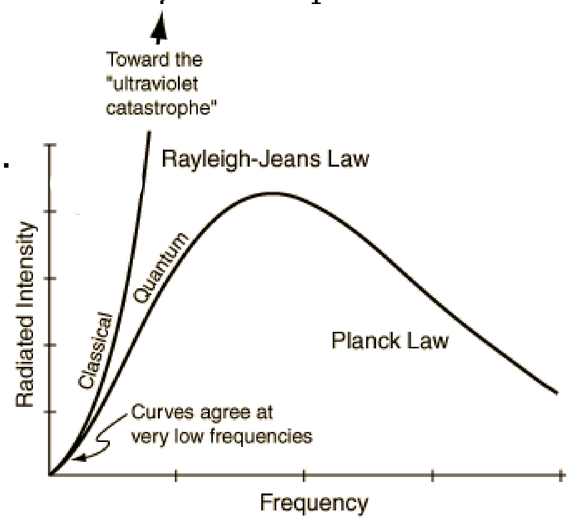




Planck's Law
Rayleigh-Jeans approximation

The spectral distribution of the radiation of a black body in thermodynamic equilibrium is given by the Planck law:

$$\boxed{B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}} \;.$$



If $h\nu \ll kT$, the *Rayleigh-Jeans Law* is obtained:

$$\boxed{B_{\mathrm{RJ}}(\nu, T) = \frac{2\nu^2}{c^2}kT} \;.$$

In the Rayleigh-Jeans relation, the brightness and the thermodynamic temperatures of black body emitters are strictly proportional (➋ 8.3). This feature is useful, so the normal expression of brightness of an extended source is *brightness temperature* T_{B}:

$$T_{\mathrm{B}} = \frac{c^2}{2k}\frac{1}{\nu^2}I_\nu = \frac{\lambda^2}{2k}I_\nu\,. \tag{8.4}$$

If I_ν is emitted by a black body and $h\nu \ll kT$, then (➋ 8.4) gives the thermodynamic temperature of the source, a value that is independent of ν. If other processes are responsible for the emission of the radiation (e.g., synchrotron, free-free, or broadband dust emission), T_{B}

Radhakrishnan "noise"
ASPC 180 671, 1999

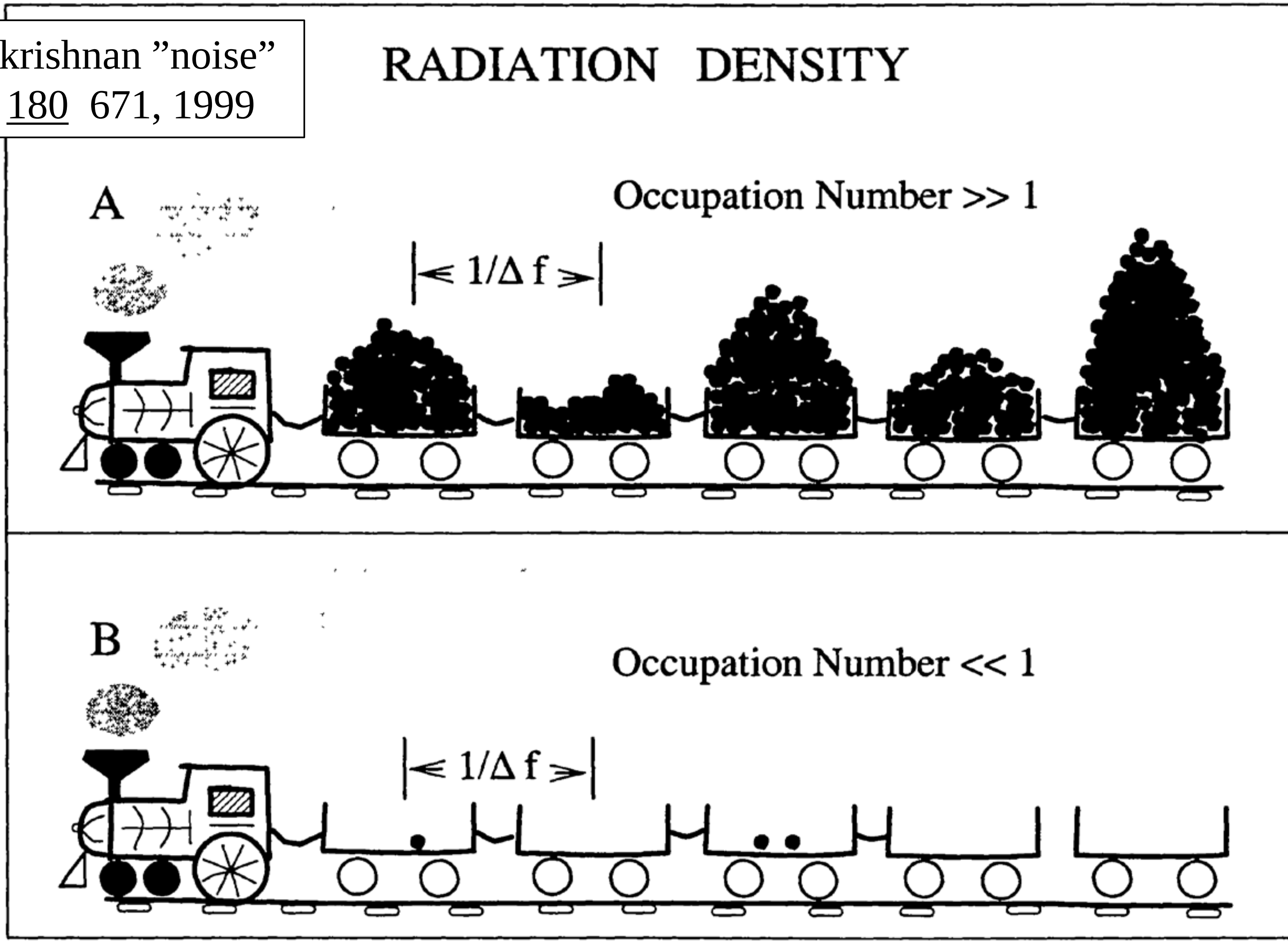


Figure 33–1. Boxcar representation for a stream of radiation. Each boxcar is a sample and corresponds to the reciprocal of the bandwidth, the rate at which new information arrives. A) The high density case where there is an enormous number of photons in each sample and substantial variation from sample to sample. B) The very low density case when the number of photons is minute compared to the number of samples.

Resolving Power

- Angular resolution = wavelength/aperture

	Light	Radio
Wavelength	**0.00005cm**	**21cm**
Aperture	**10cm**	**10km**
Resolution	**0.00005/10 rad = 1" arc**	**$21/10^6$ rad = 4" arc**

Imaging at Radio Wavelengths

- Bad news
  - Radio waves are big
  - Need large aperture or an interferometer
- Good news
  - Radio frequencies are low
  - Interferometers are easy to build

Greenbank 300' Radio Telescope

Greenbank 300’ Radio Telescope

Remarks on Units

- I_ν = monochromatic intensity [W m^{-2} sr^{-1} Hz^{-1}]

  intensity (or brightness)

  independent of source distance

- $T_b = I_\nu (c^2 / 2k\nu^2)$ = Rayleigh-Jeans Brightness Temperature [K]

  for thermal emission T_b is the temperature of the emitting body,

  for other cases, radio astronomers still talk about T_b, the equivalent temperature that a blackbody would have to be as bright

- S_ν = flux density = integral of I_ν over solid angle [W m^{-2} Hz^{-1}]

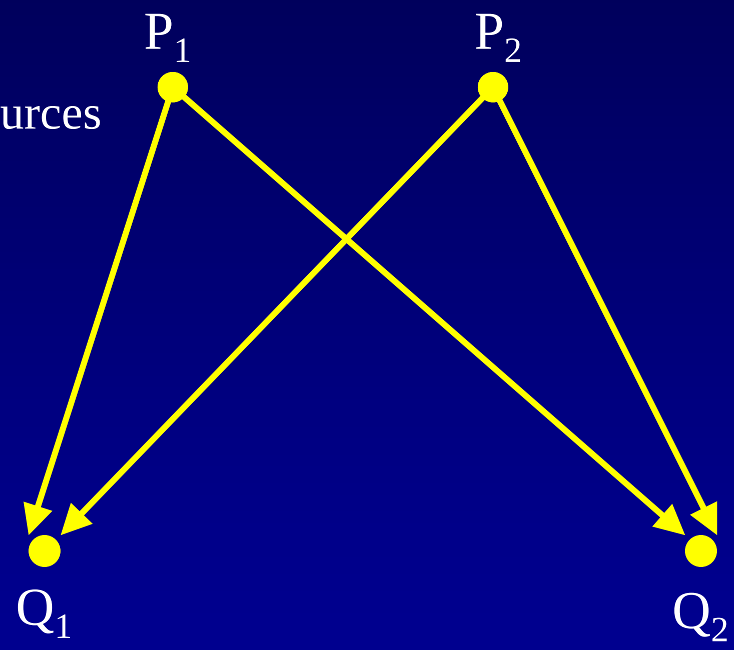
  flux density decreases with source distance squared

NRAO

- David Wilner, ANITA lectures, Swinburne, 2015

Spatial Coherence

P_1 & P_2
spatially incoherent sources



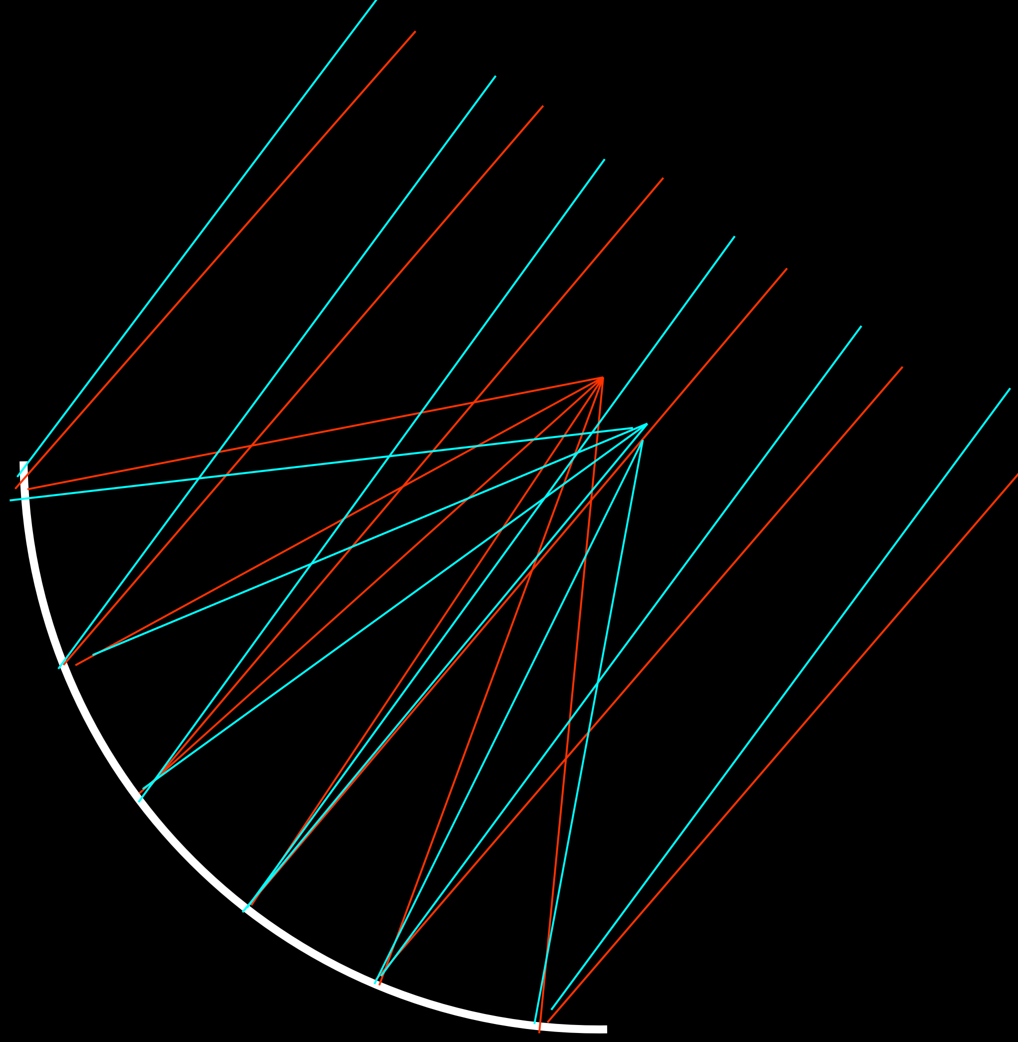
At distant points Q_1 & Q_2
The field is partially coherent

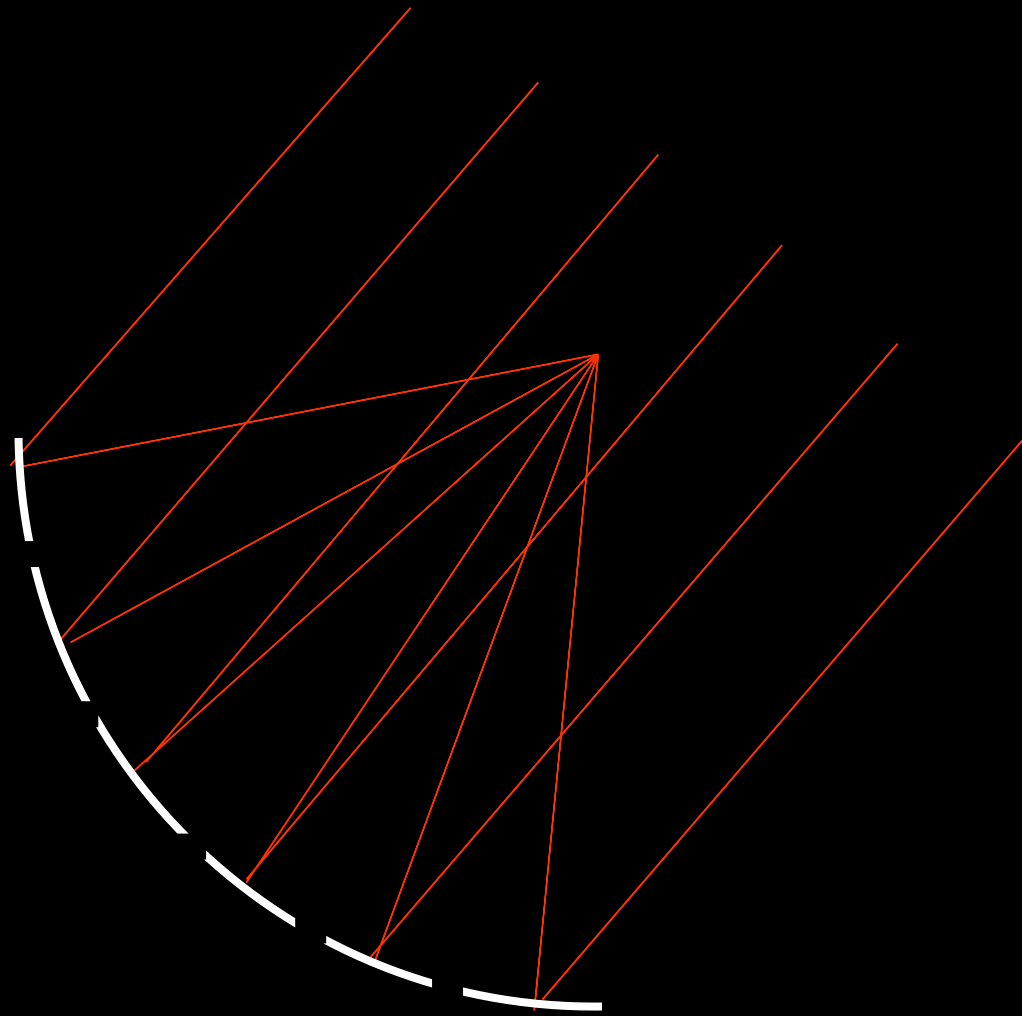
van Cittert-Zernike theorem

The spatial coherence function is the Fourier Transform of the brightness distribution

Analogy with single dish

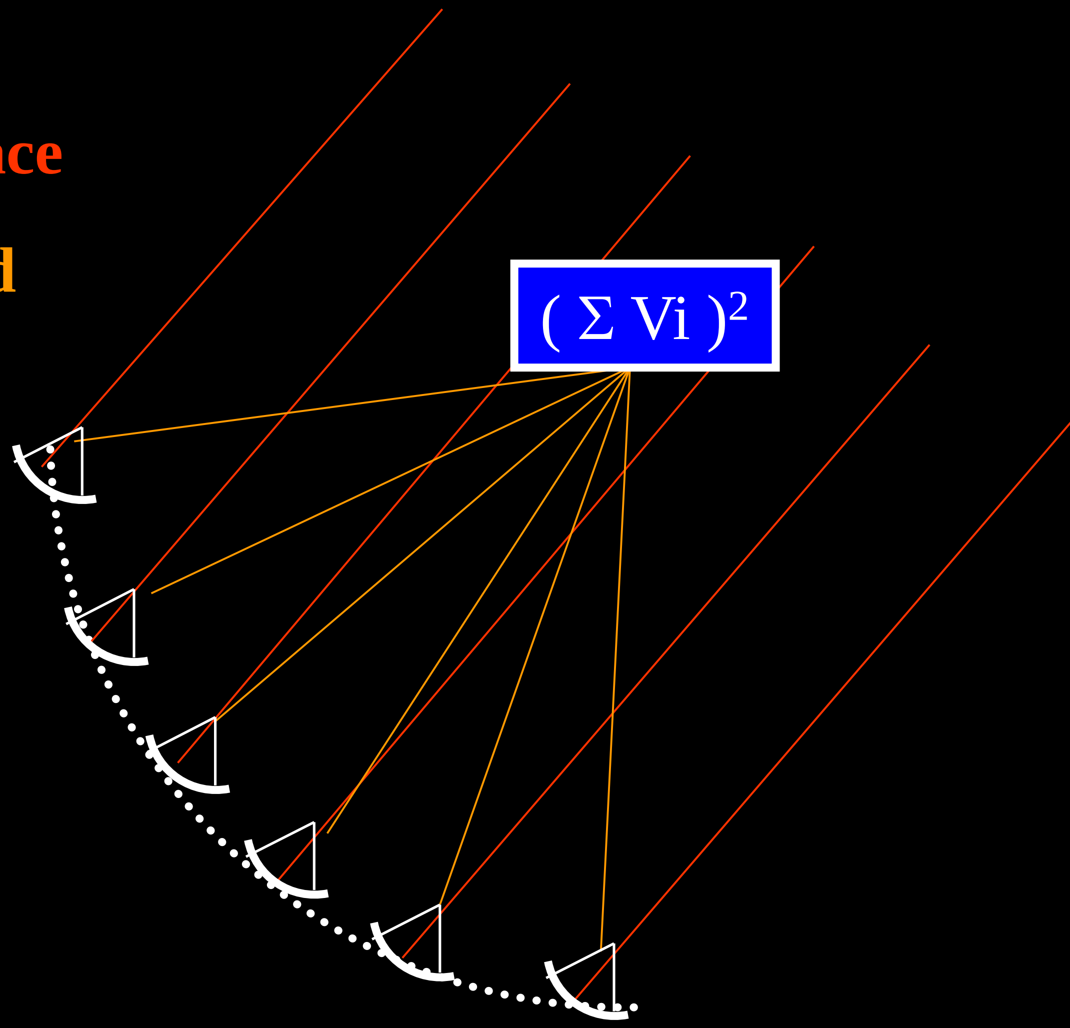
- Big mirror decomposition

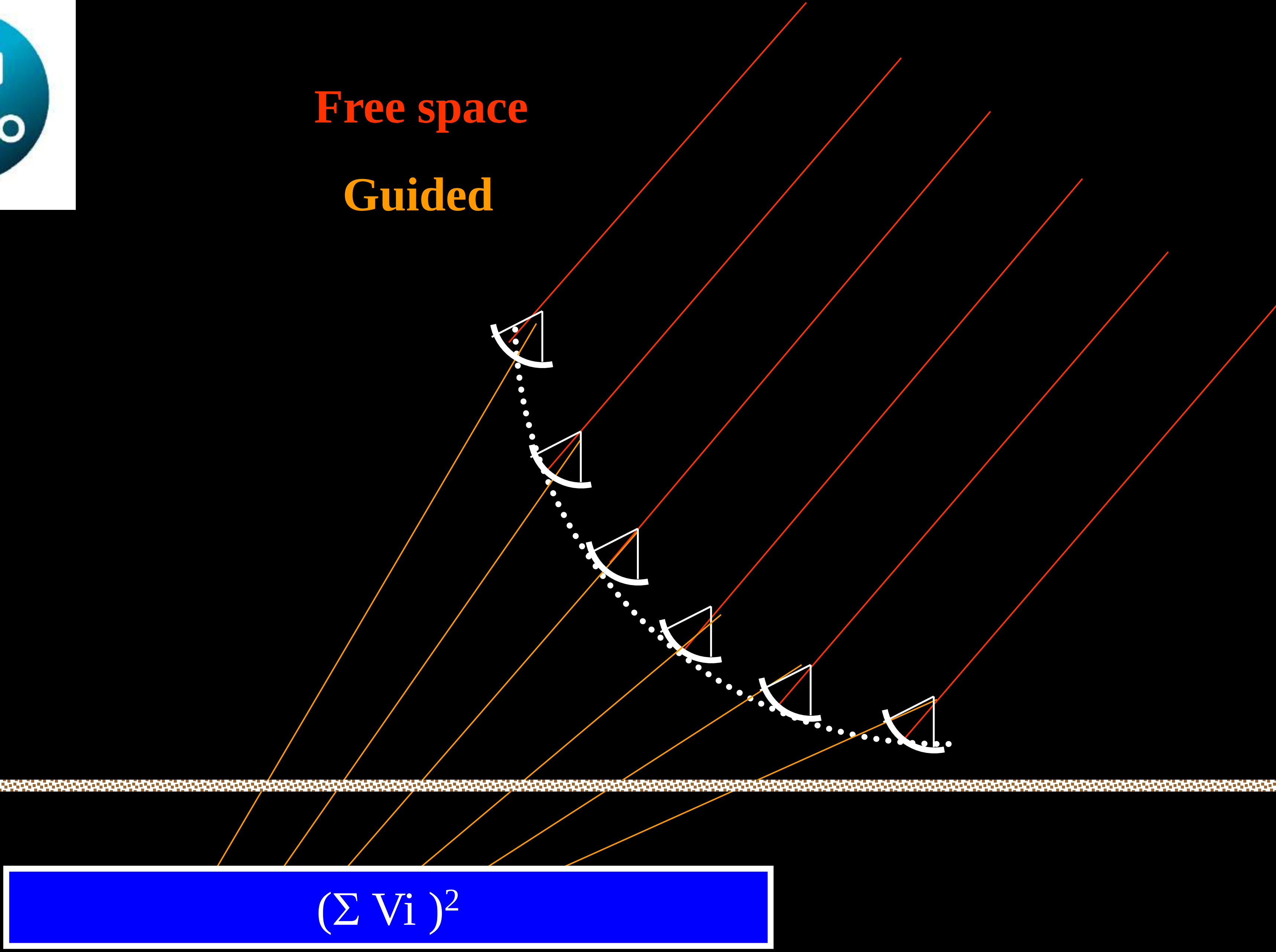


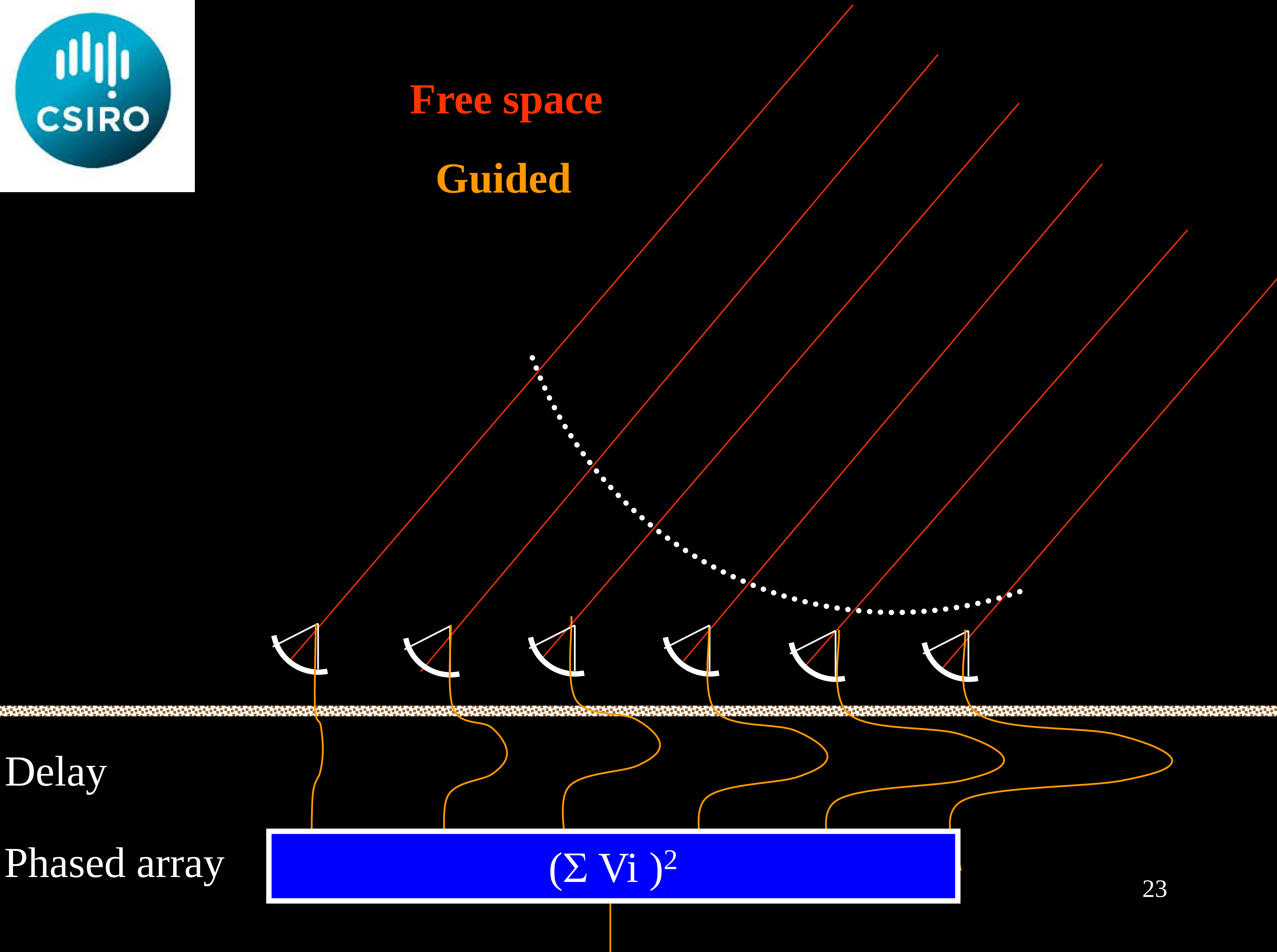


Free space

Guided



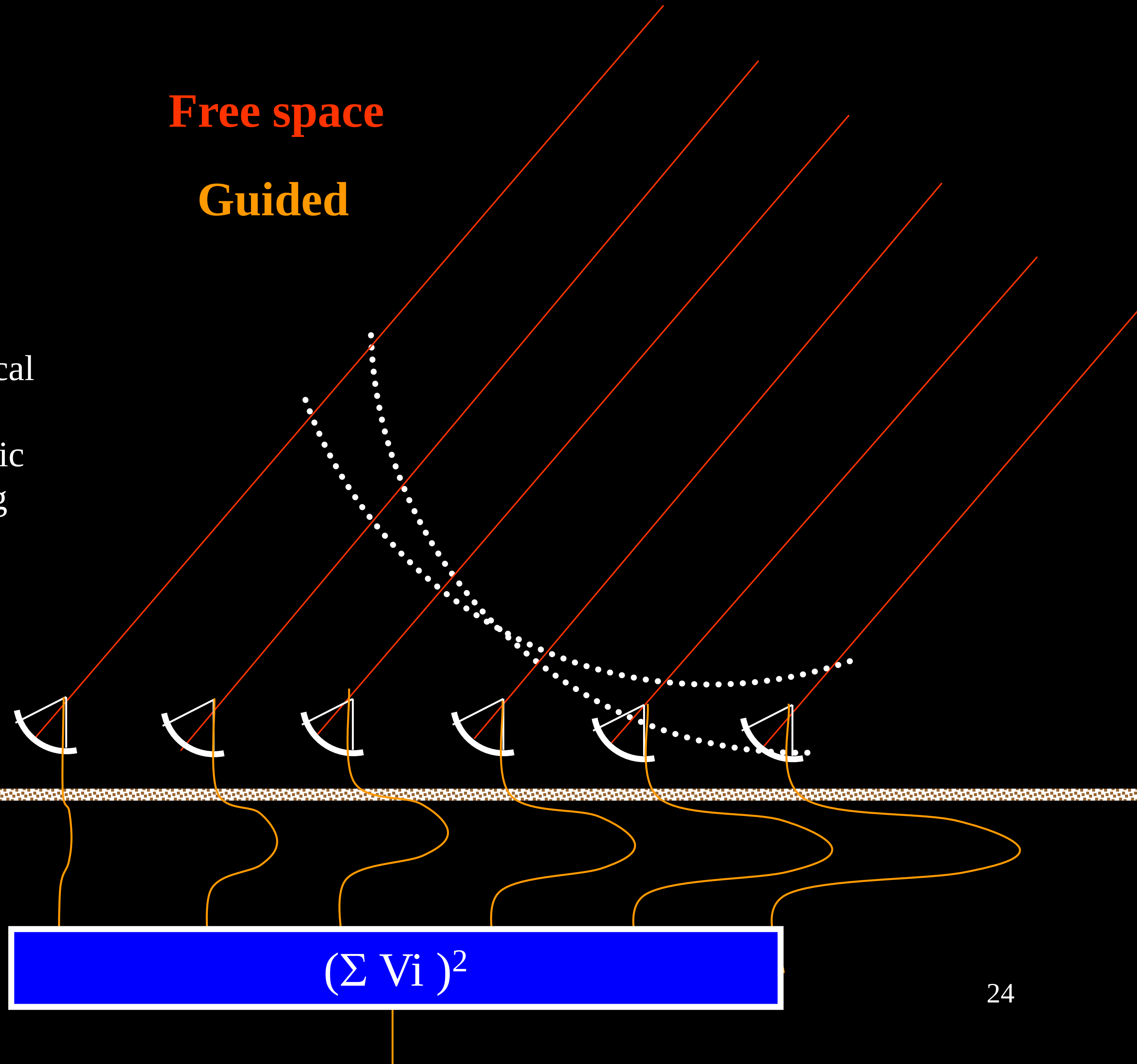

Free space
Guided
$(\Sigma\ Vi\ )^2$


Free space
Guided
Delay
Phased array
$(\Sigma \, Vi)^2$

Free space

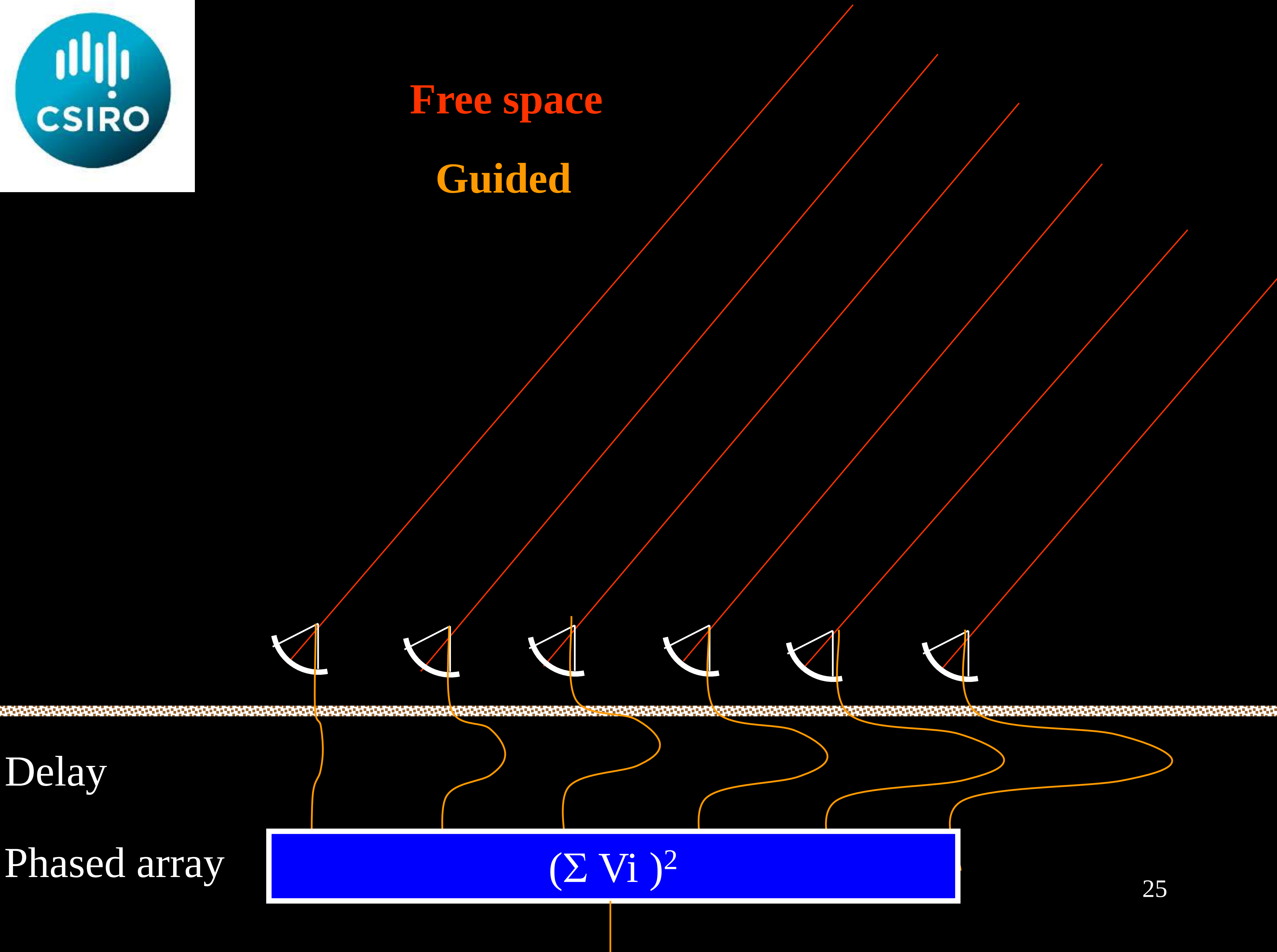
Guided

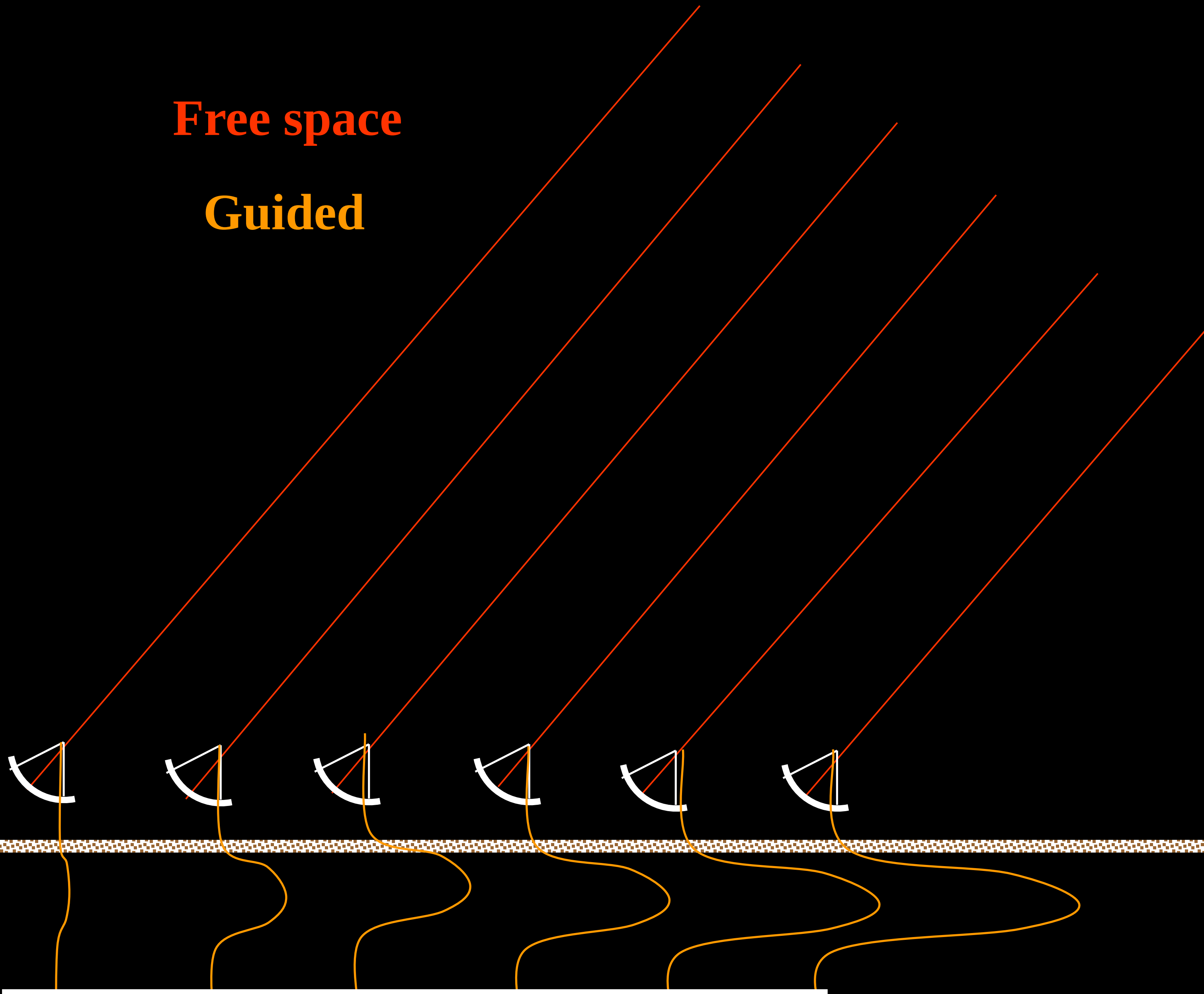
Mechanical
v
Electronic
steering



Delay

Phased array


Free space
Guided
Delay
Phased array
$(\Sigma\ V_i)^2$



Delay

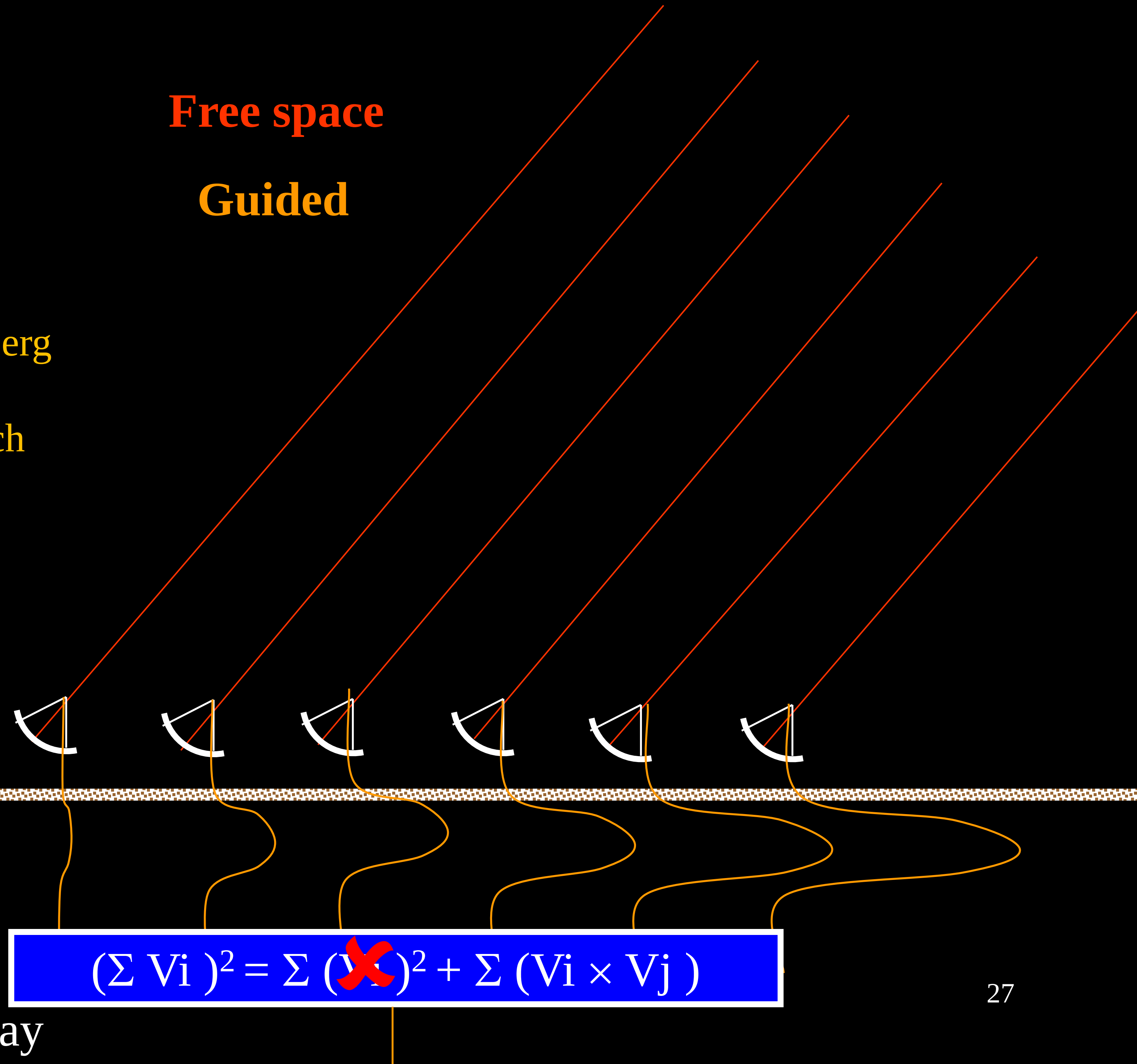
Phased array

$$(\Sigma\ V_i)^2 = \Sigma\ (V_i)^2 + \Sigma\ (V_i \times V_j)$$

Free space

Guided

Ryle & Vonberg
(1946)
phase switch

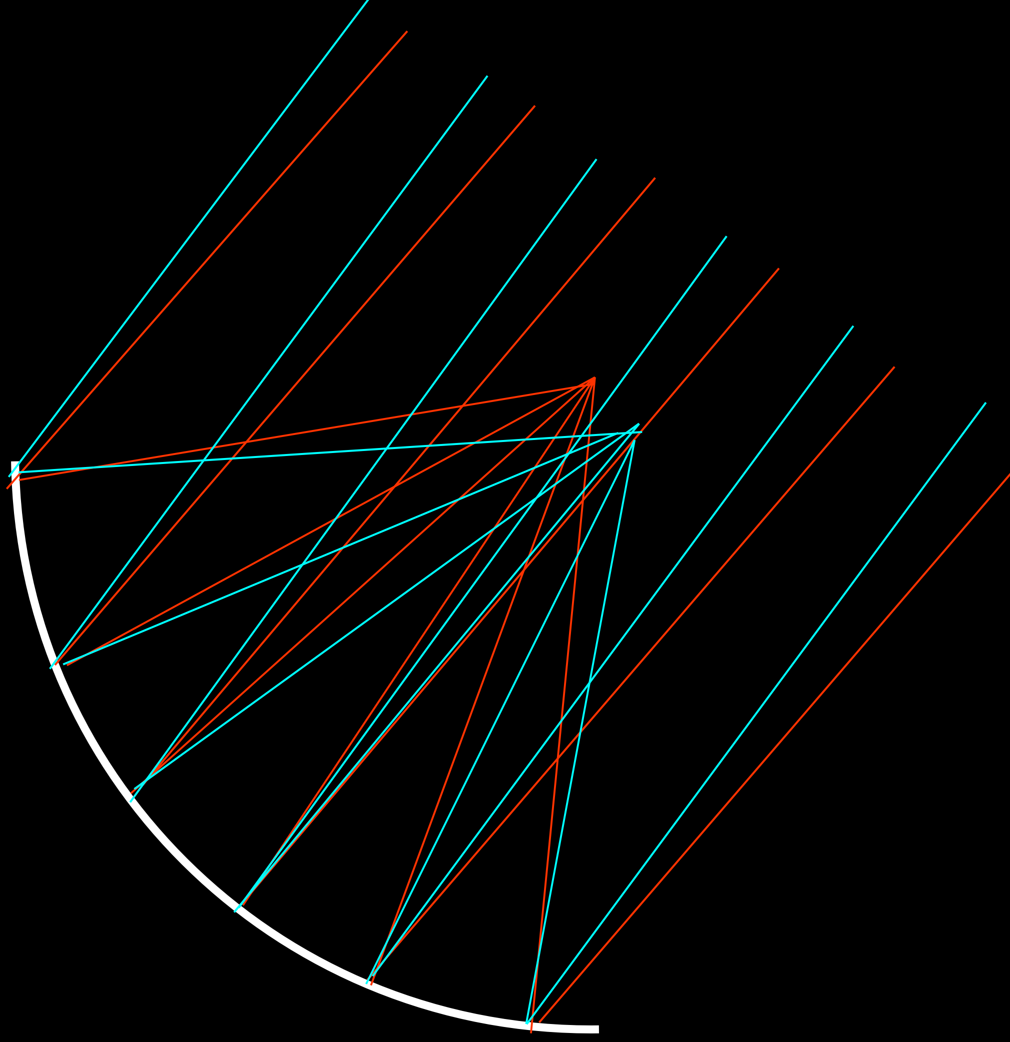


Delay

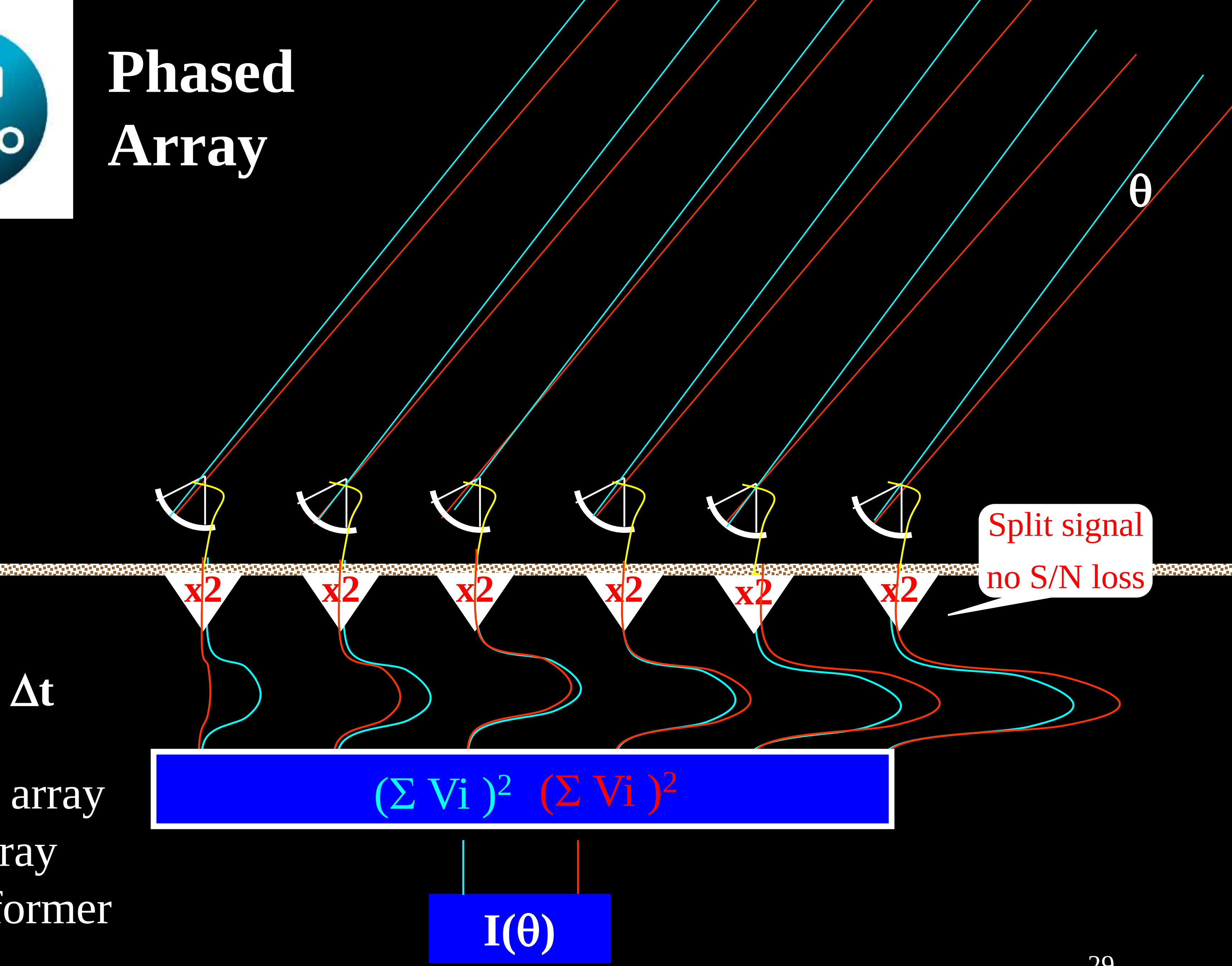
~~Phased array~~

Correlation array

$$(\Sigma\, Vi\,)^2 = \Sigma\,(\cancel{Vi})^2 + \Sigma\,(Vi \times Vj\,)$$

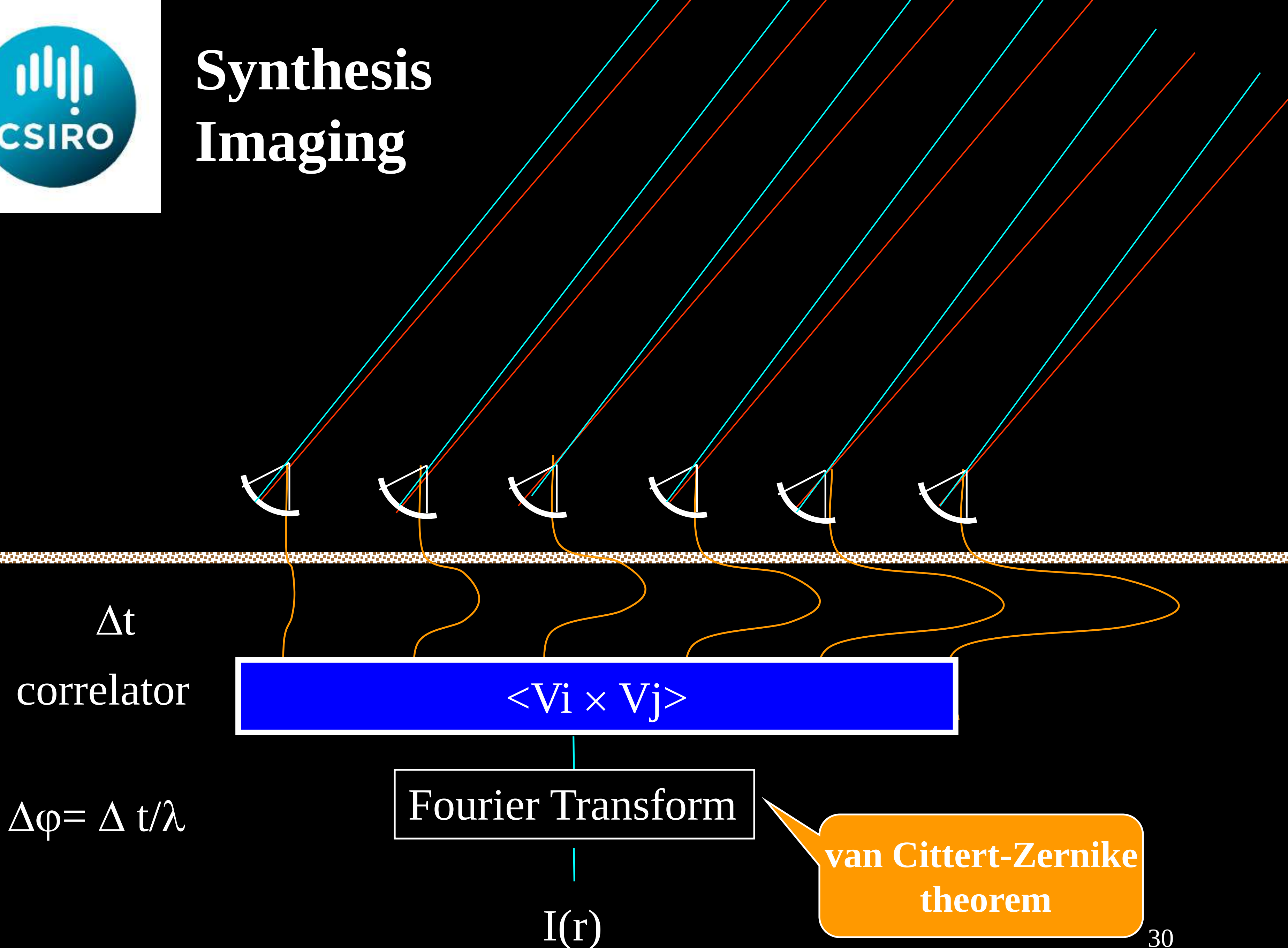


Phased Array



Phased array
Tied array
Beam former

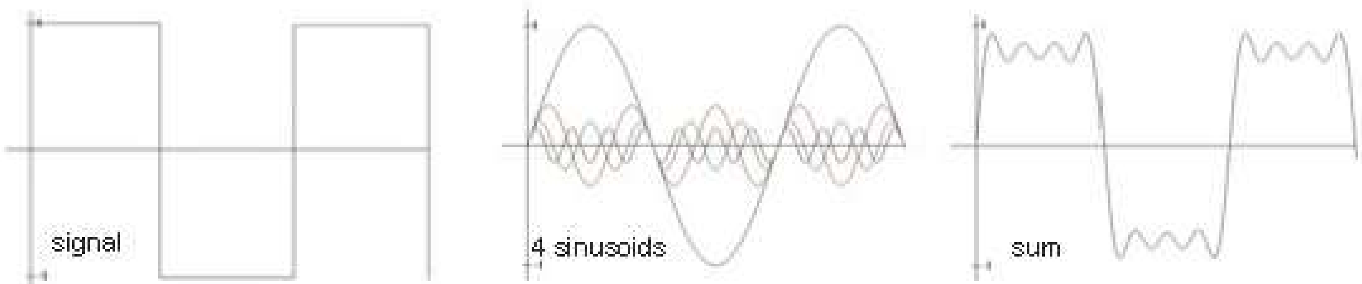
Synthesis Imaging



The Fourier Transform

- Fourier theory states and any well behaved signal (including images) can be expressed as the sum of sinusoids

Jean Baptiste
Joseph Fourier
1768-1830



$$x(t) = \frac{4}{\pi}\left(\sin(2\pi f t) + \frac{1}{3}\sin(6\pi f t) + \frac{1}{5}\sin(10\pi f t) + \cdots\right)$$

- the Fourier transform is the mathematical tool that decomposes a signal into its sinusoidal components
- the Fourier transform contains *all* of the information of the original signal

Analogy with single dish

- Big mirror decomposition
- Reverse the process to understand imaging with a mirror
  - Eg understanding non-redundant masks
  - Adaptive optics
- Single dishes and correlation interferometers
  - Darrel Emerson, NRAO
  - http://www.gb.nrao.edu/sd03/talks/whysd_r1.pdf

Filling the aperture

- Aperture synthesis
  - measure correlations with multiple dishes
  - moving dishes sequentially
  - earth rotation synthesis
  - store all correlations for later use
- Partially unfilled aperture
  - some spacings missing
- Redundant spacings
  - some interferometer spacings occur twice
- Non-redundant aperture

Redundancy

1unit 5x (source same atmosphere different)

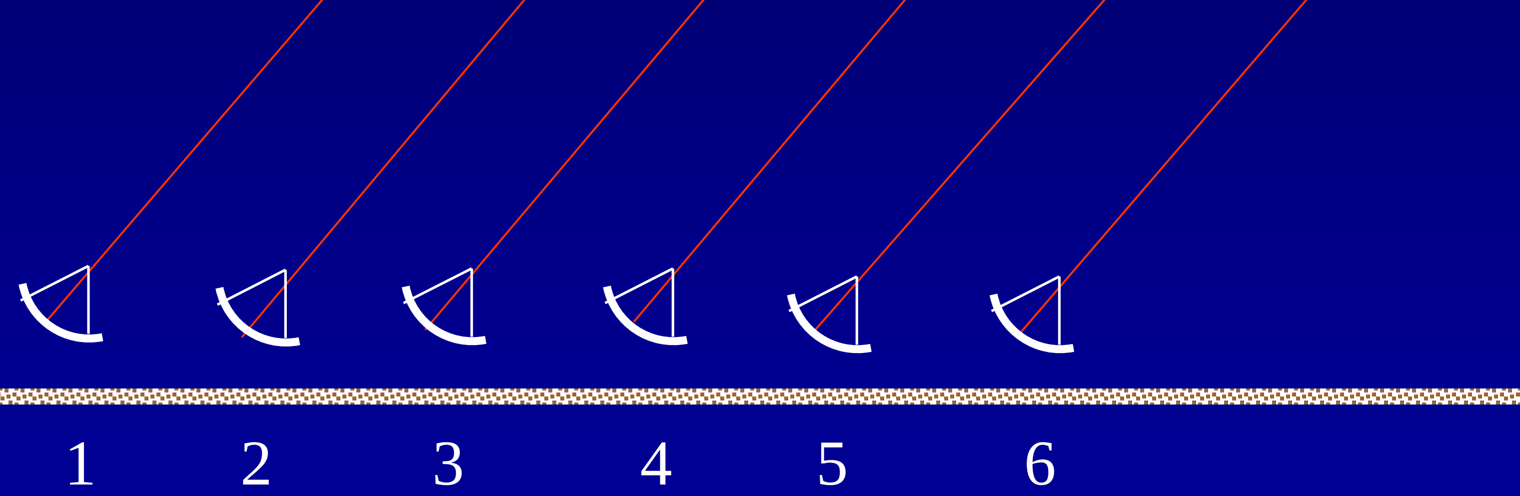
2units 4x

3units 3x

4units 2x

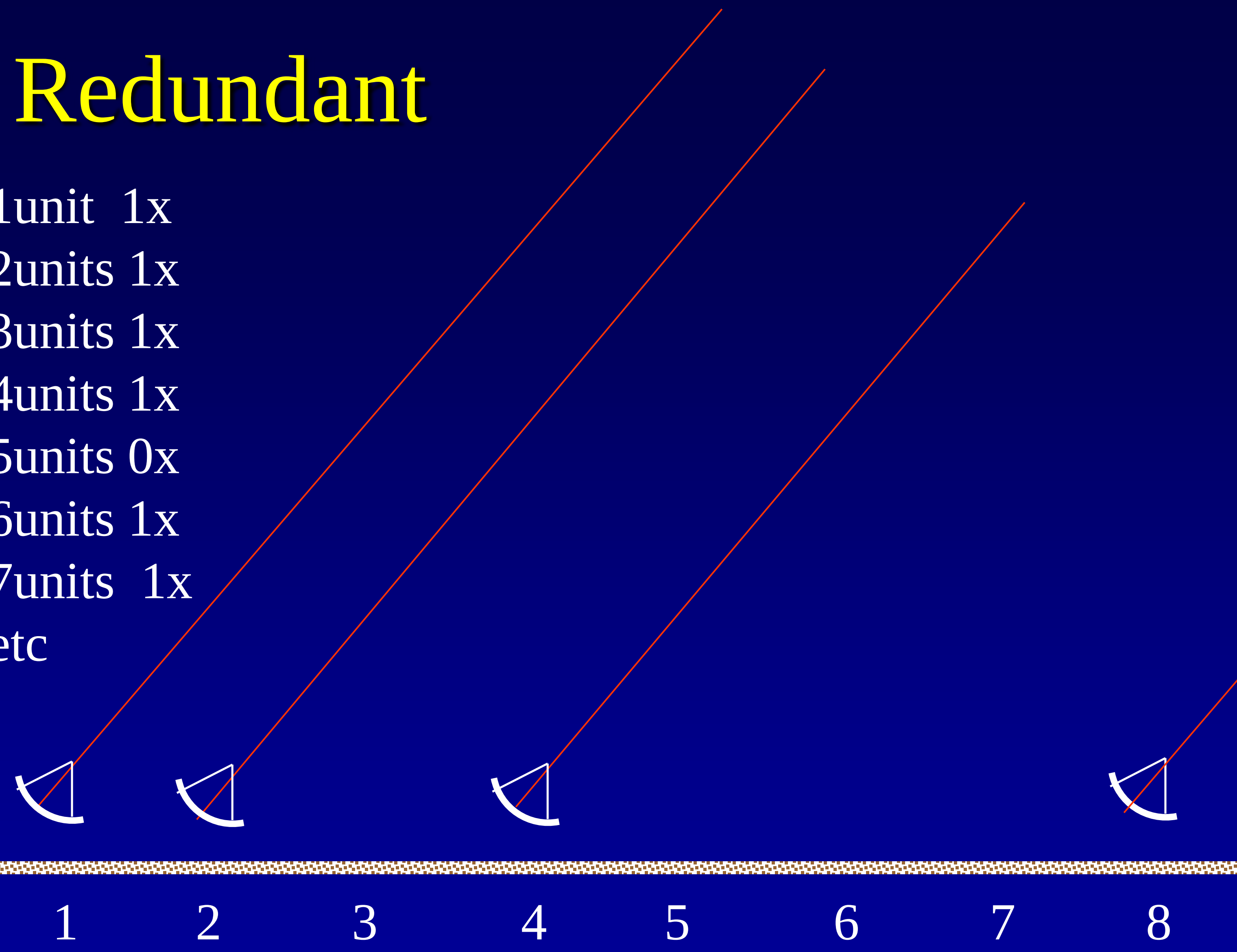
5units <u>1x</u>

n(n-1)/2 = 15



Non Redundant

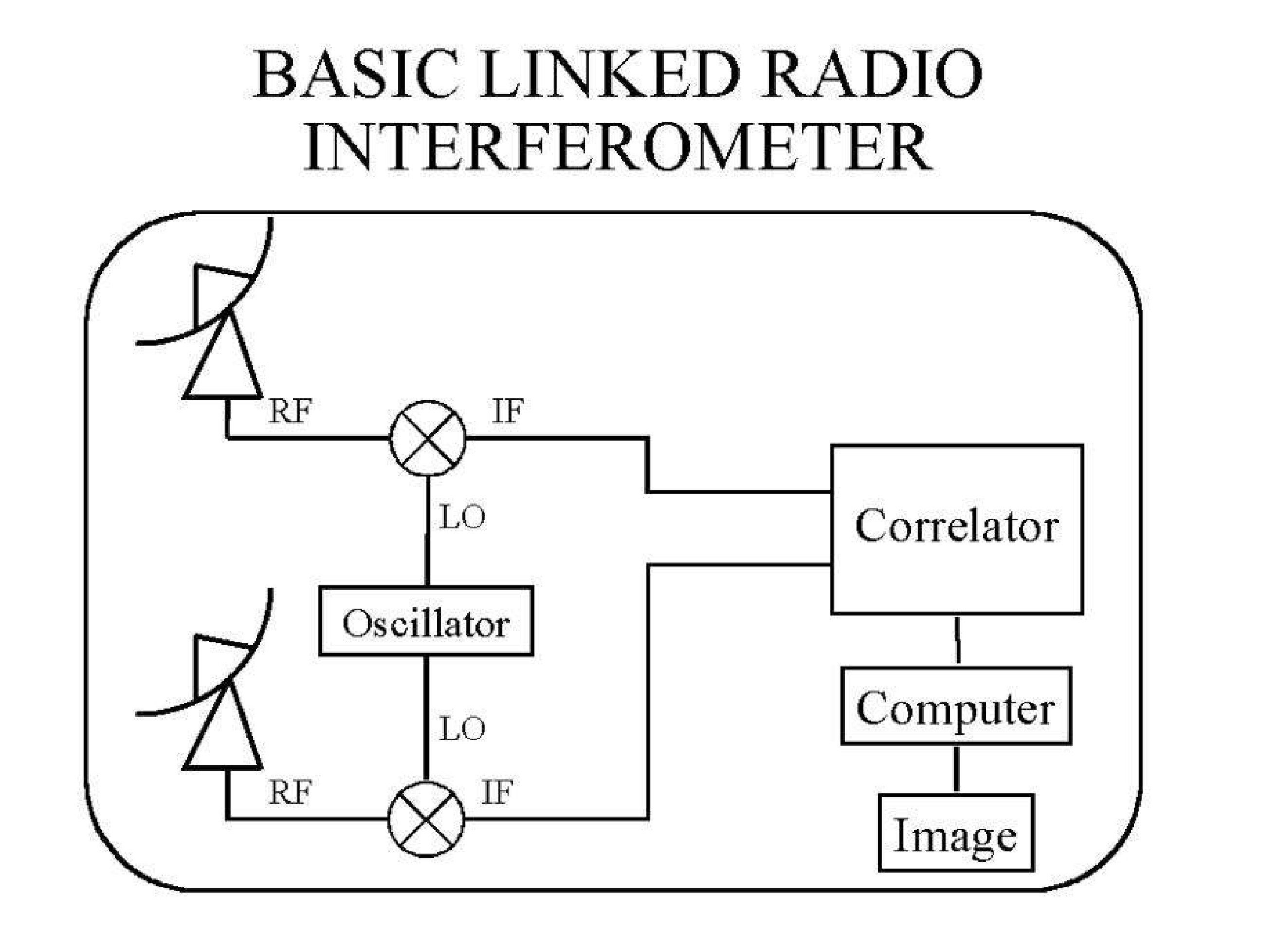
1unit 1x
2units 1x
3units 1x
4units 1x
5units 0x
6units 1x
7units 1x
etc



HERA
Epoch of Reinization Array

- Maximally redundant array to decouple the sky from the instrumental errors

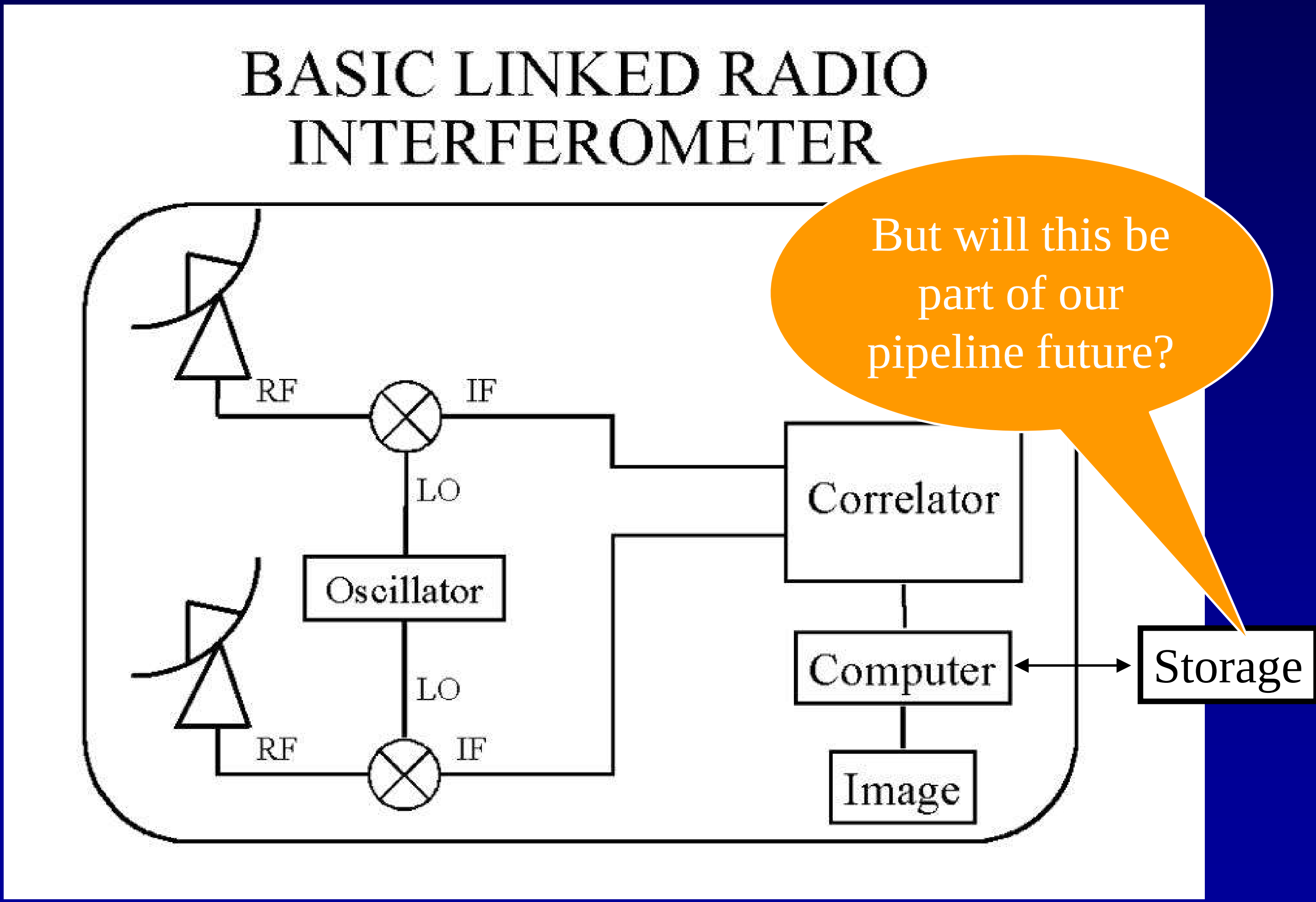
Basic Interferometer



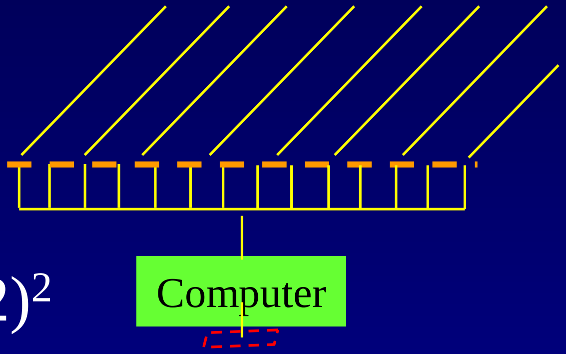
Storing visibilities

A powerful tool to manipulate the coherence function and re-image.

Not possible in most other domains

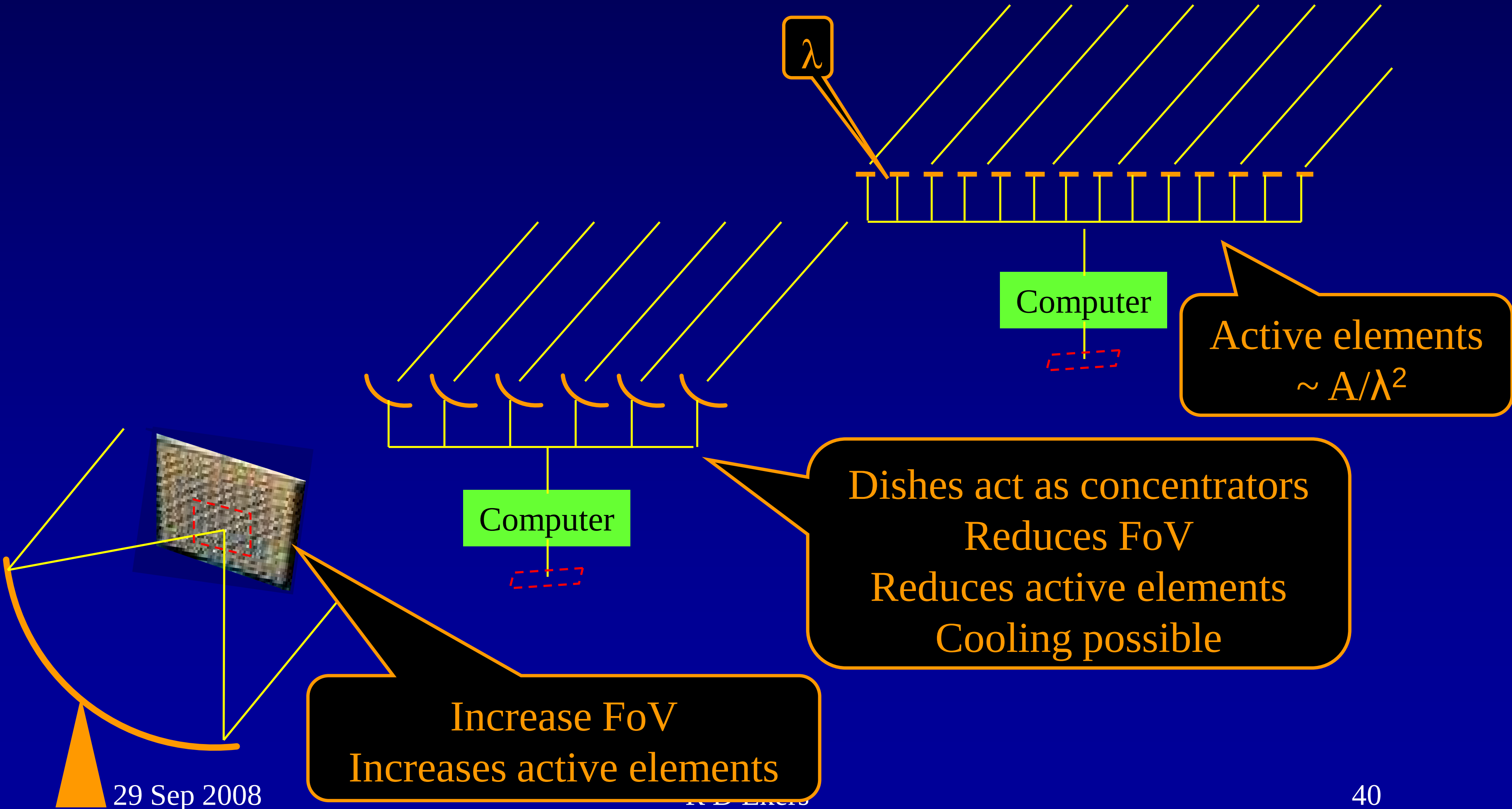


Aperture Array or Focal Plane Array?



- Why have a dish at all?
  - Sample the whole wavefront
  - n elements needed: $n \propto \text{Area}/(\lambda/2)^2$
  - For 100m aperture and λ = 20cm, $n=10^4$
    - » Electronics costs too high!

Radio Telescope Imaging image v aperture plane

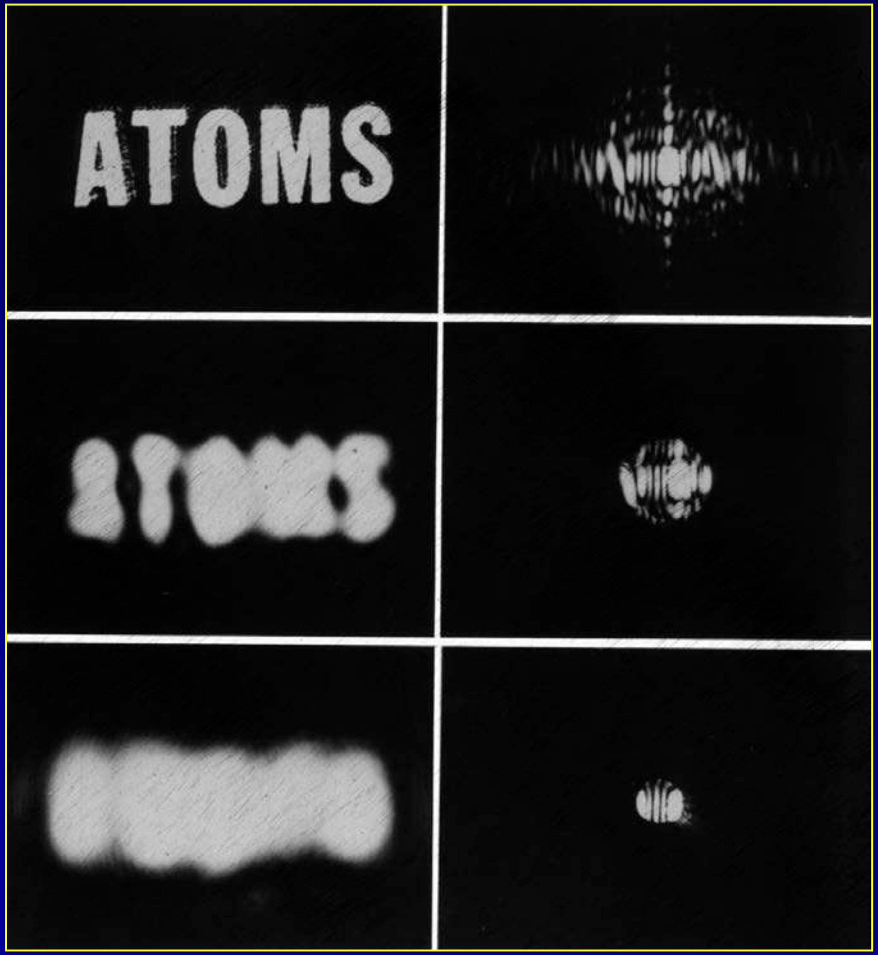


Radio Telescopes

aperture
plane

image
plane

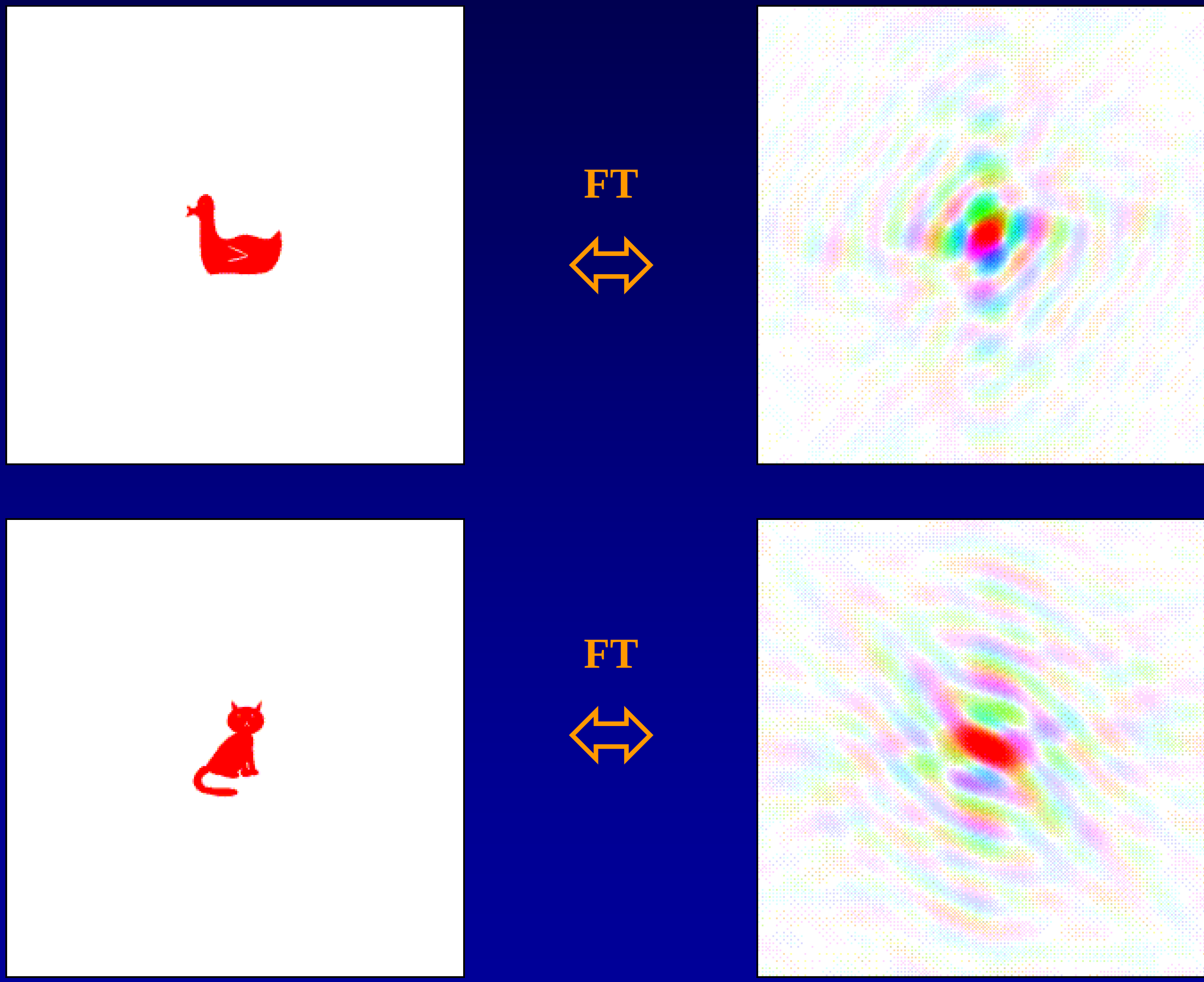
Fourier Transform and Resolution



- Large spacings
  - high resolution
- Small spacings
  - low resolution

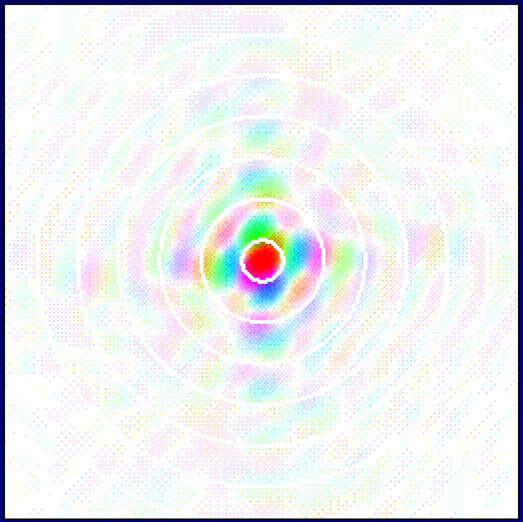
Fourier Transform Properties

from Kevin Cowtan's Book of Fourier



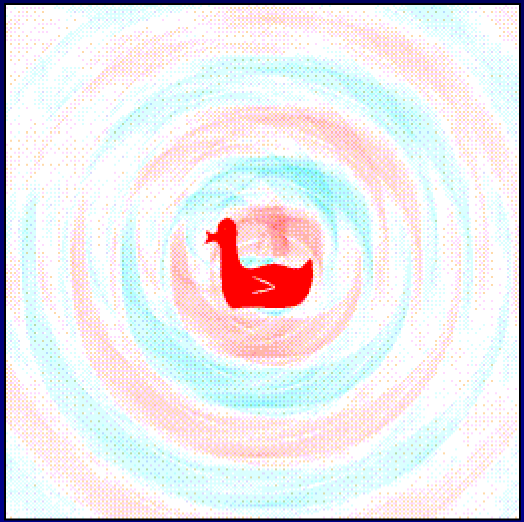
http://www.ysbl.york.ac.uk/~cowtan/fourier/fourier.html

Fourier Transform Properties



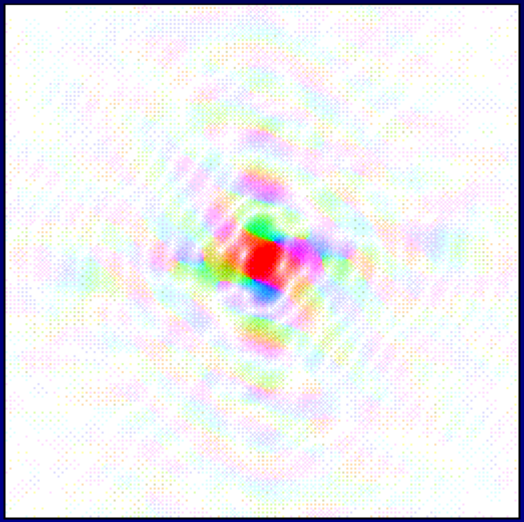
FT

⇔



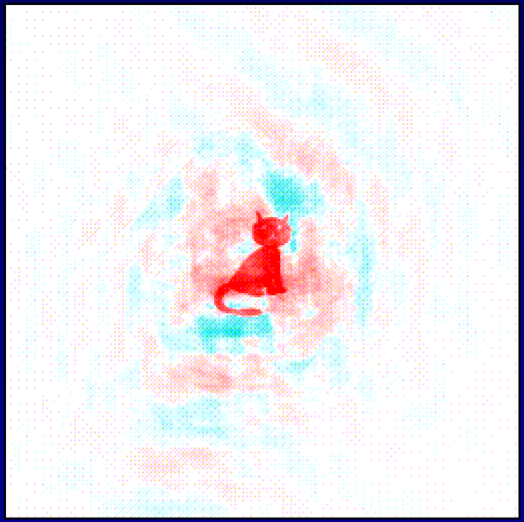
10% data omitted in rings

Fourier Transform Properties



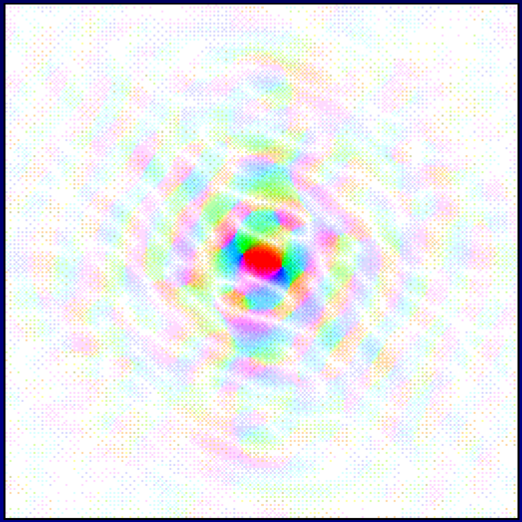
FT

⇔



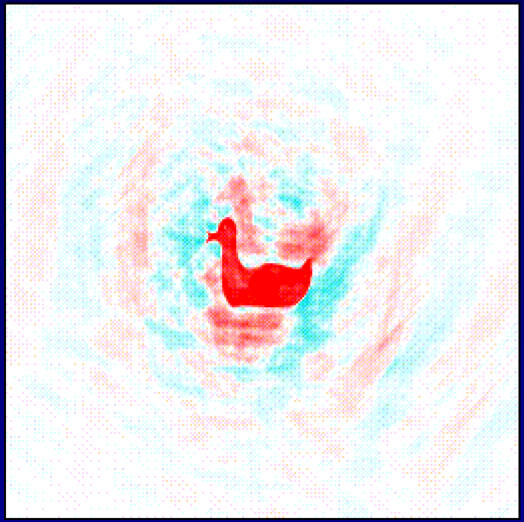
Amplitude of duck
Phase of cat

Fourier Transform Properties



FT

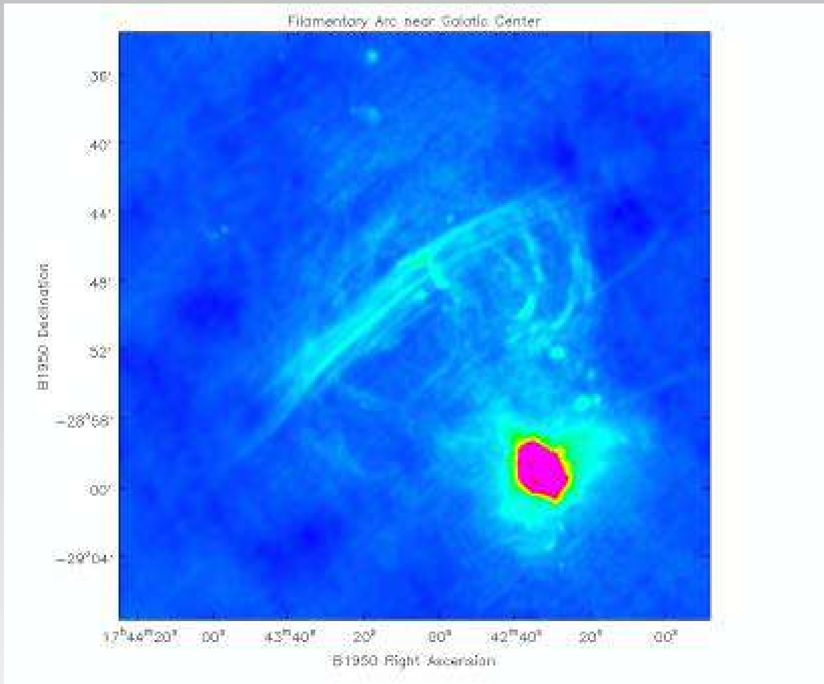
⇔



Amplitude of cat
Phase of duck

In practice...

1. Use many antennas (VLA has 27)
2. Amplify signals
3. Sample and digitize
4. Send to central location
5. Perform cross-correlation
6. Earth rotation fills the “aperture”
7. Inverse Fourier Transform gets image
8. Correct for limited number of antennas
9. Correct for imperfections in the “telescope” e.g. calibration errors
10. Make a beautiful image...



Terminology

RADIO		OPTICAL
Antenna, dish	⇔	Telescope, element
Sidelobes	⇔	Diffraction pattern
Near sidelobes	⇔	Airy rings
Feed legs	⇔	Spider
Aperture blockage	⇔	Vignetting
Dirty beam	⇔	Point Spread Function (PSF)
Primary beam (single pixel receivers)	⇔	Field of View

Terminology

RADIO		OPTICAL
Map	⇔	Image
Source	⇔	Object
Image plane	⇔	Image plane
Aperture plane	⇔	Pupil plane
UV plane	⇔	Fourier plan
Aperture	⇔	Entrance pupil
UV coverage	⇔	Modulation transfer function

Terminology

RADIO		OPTICAL
Dynamic range	⇔	Contrast
Phased array	⇔	Beam combiner
Correlator	⇔	*no analog*
no analog	⇔	Correlator
Receiver	⇔	Detector
Taper	⇔	Apodise
Self calibration	⇔	Wavefront sensing (Adaptive optics)