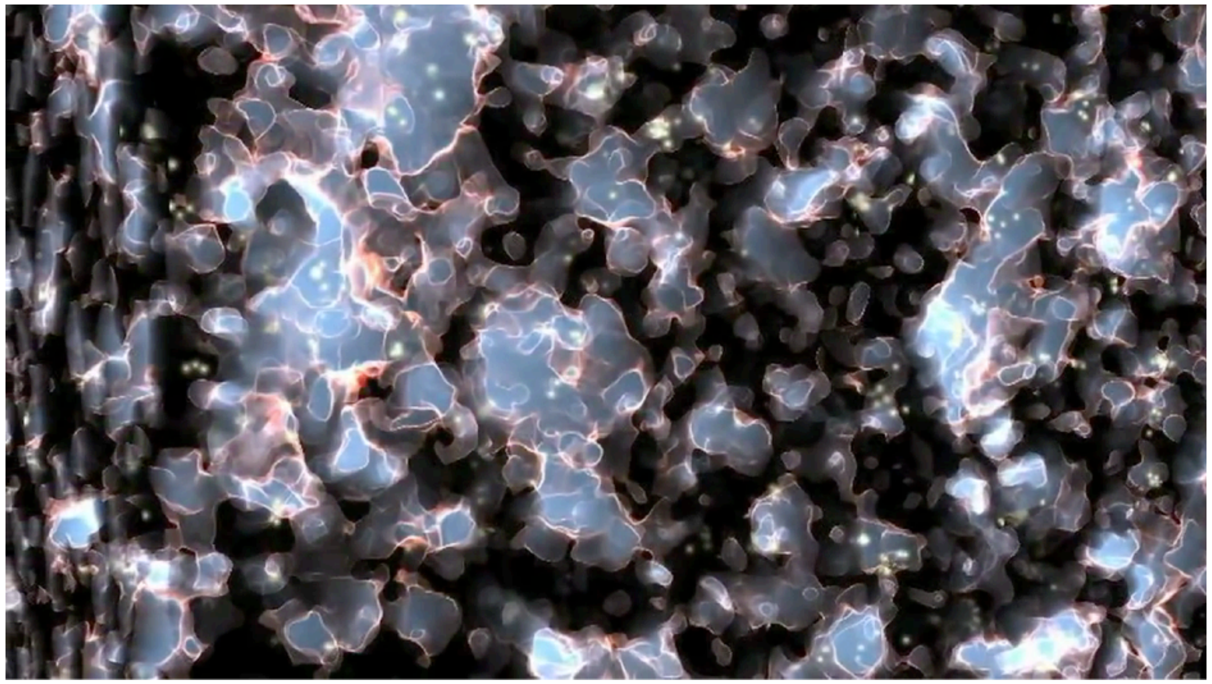
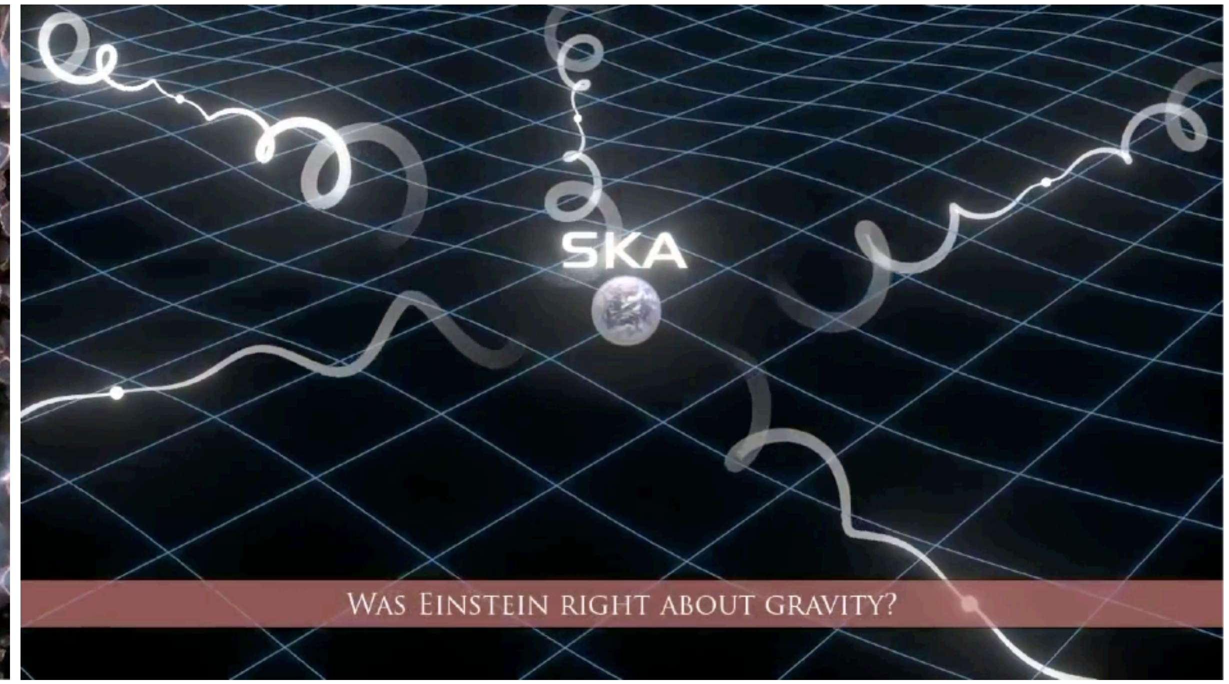
The University of Manchester
Jodrell Bank
Observatory

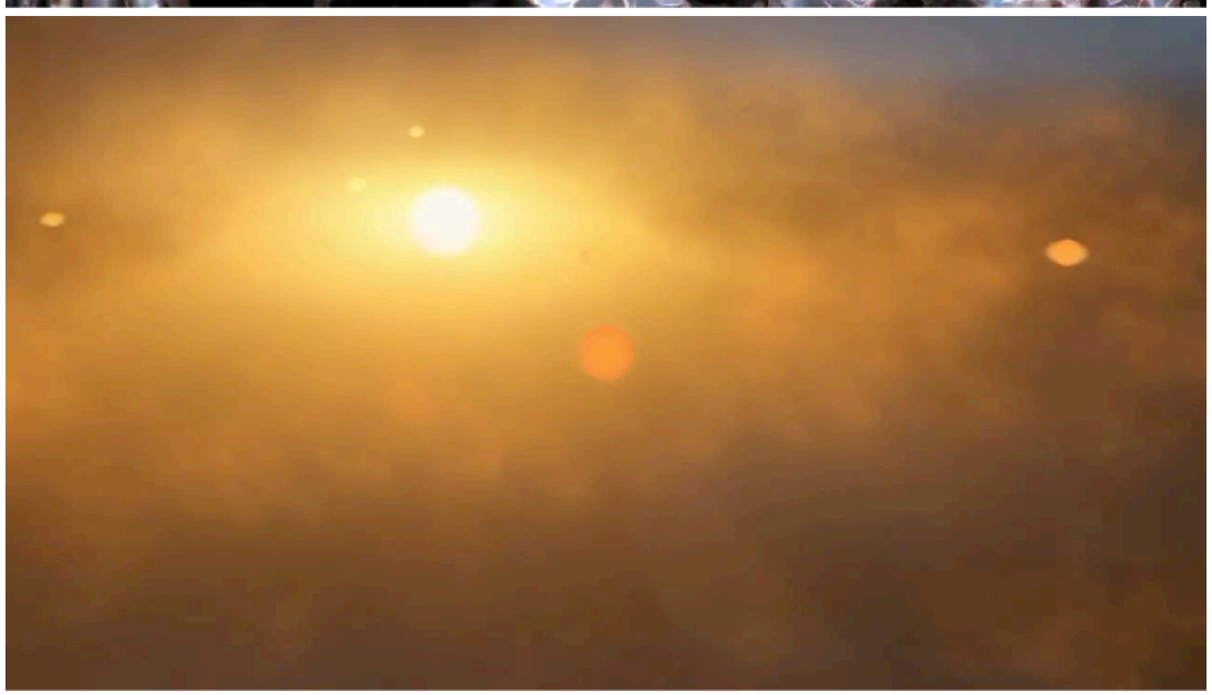
BIG TELESCOPE, BIG DATA: TOWARDS EXA-SCALE WITH THE SKA

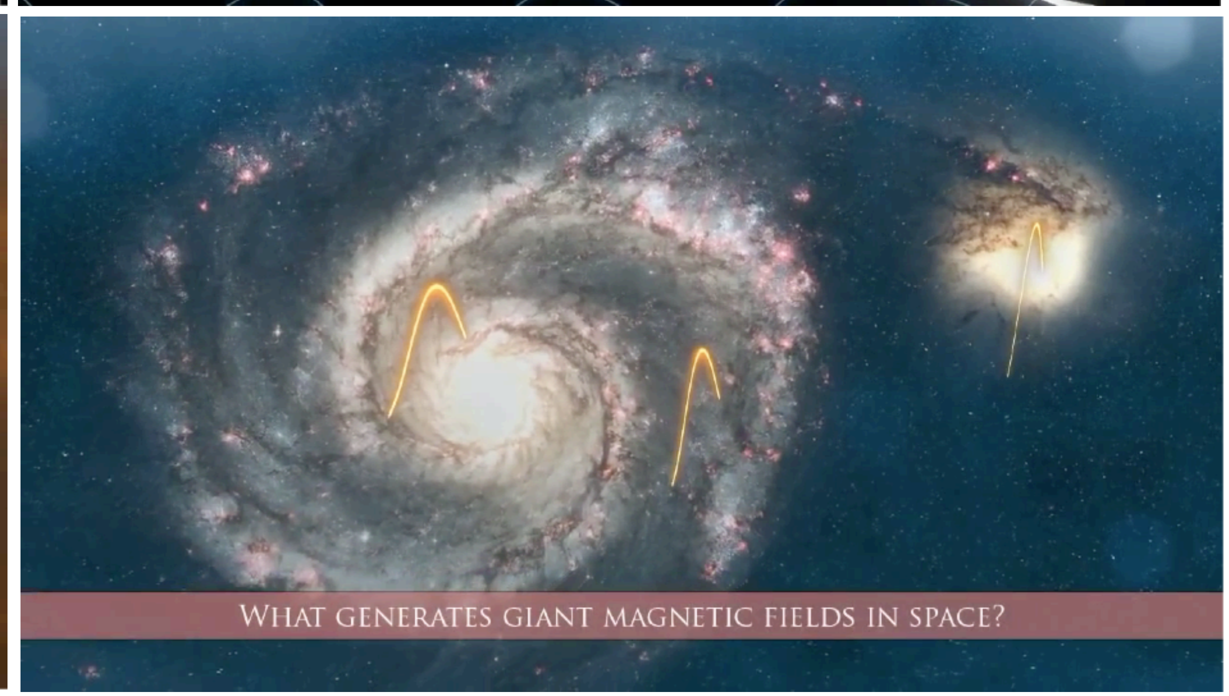
Anna Scaife
Jodrell Bank Centre for Astrophysics

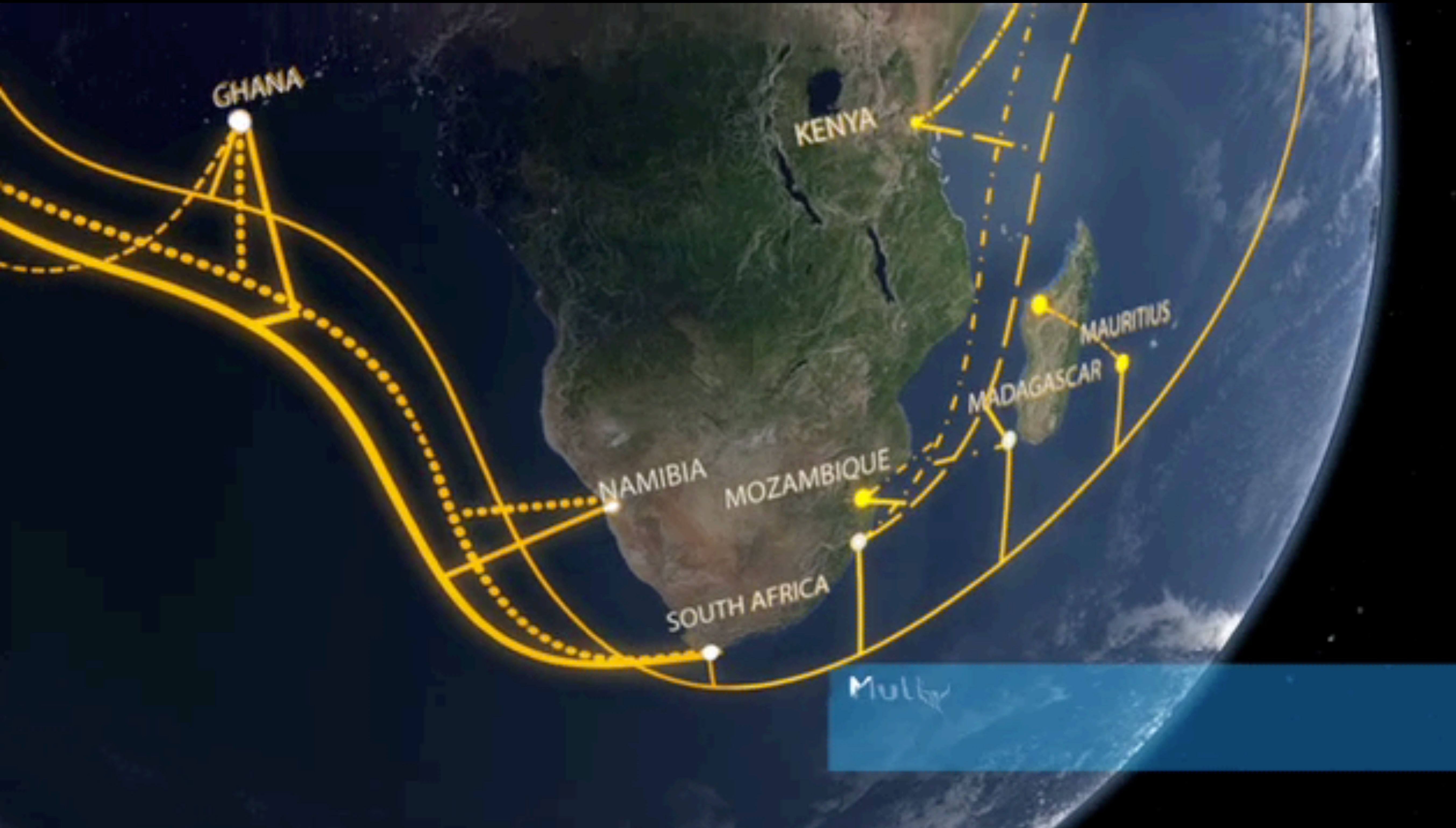
Royal Society ***8-9 April 2019*** *Numerical algorithms for high-performance computational science*

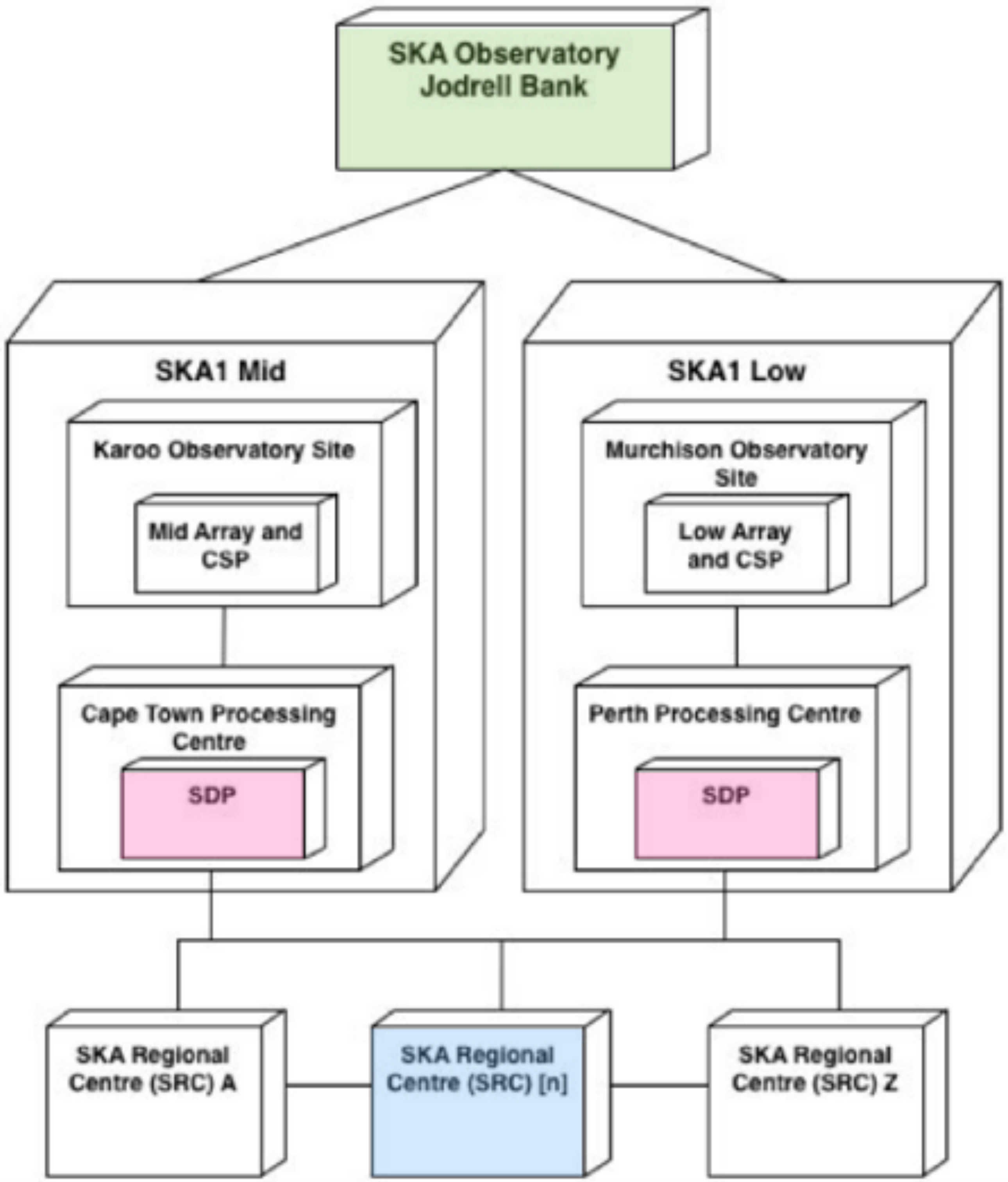



SKA
Was Einstein right about gravity?




What generates giant magnetic fields in space?

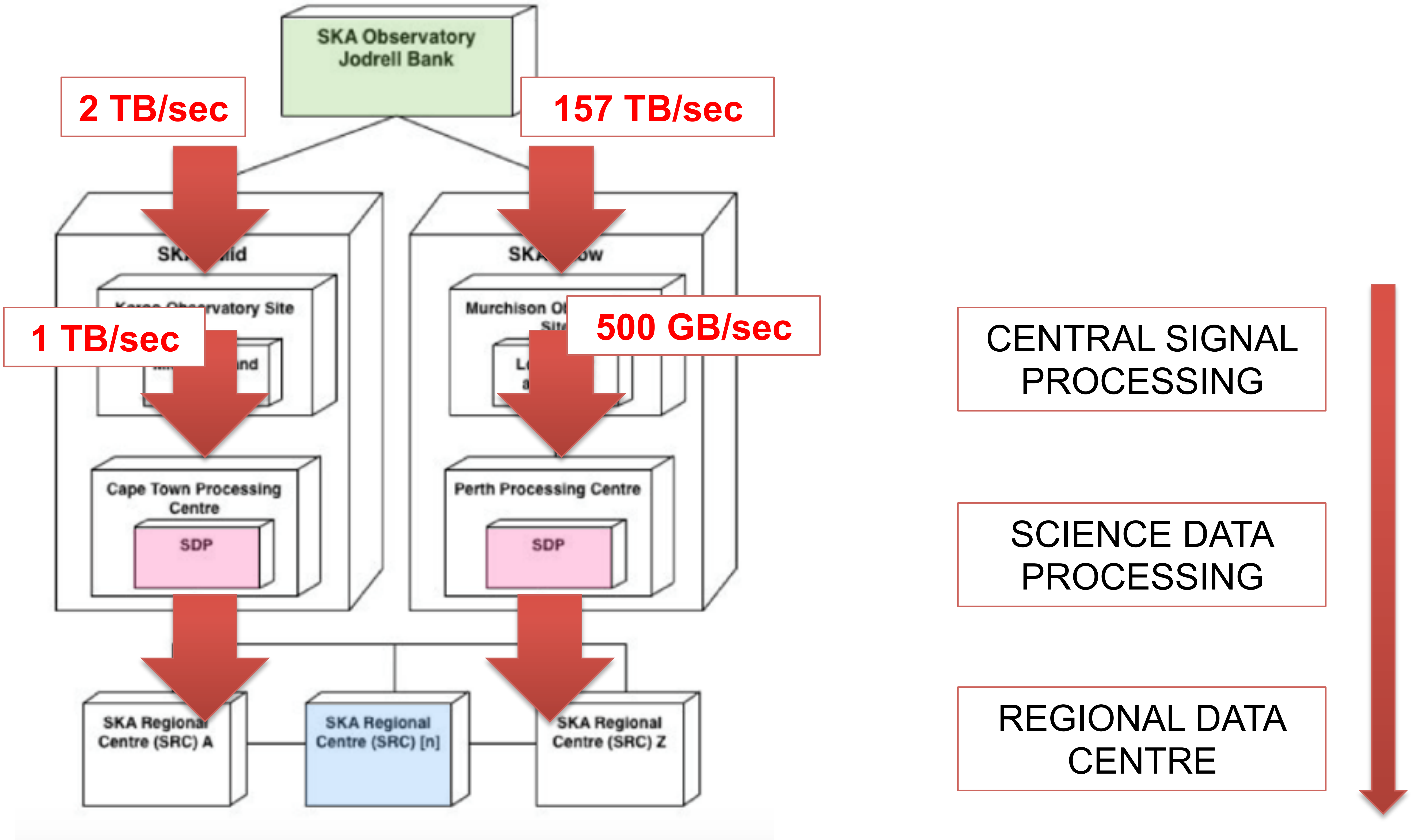

GHANA
KENYA
MAURITIUS
MADAGASCAR
NAMIBIA
MOZAMBIQUE
SOUTH AFRICA

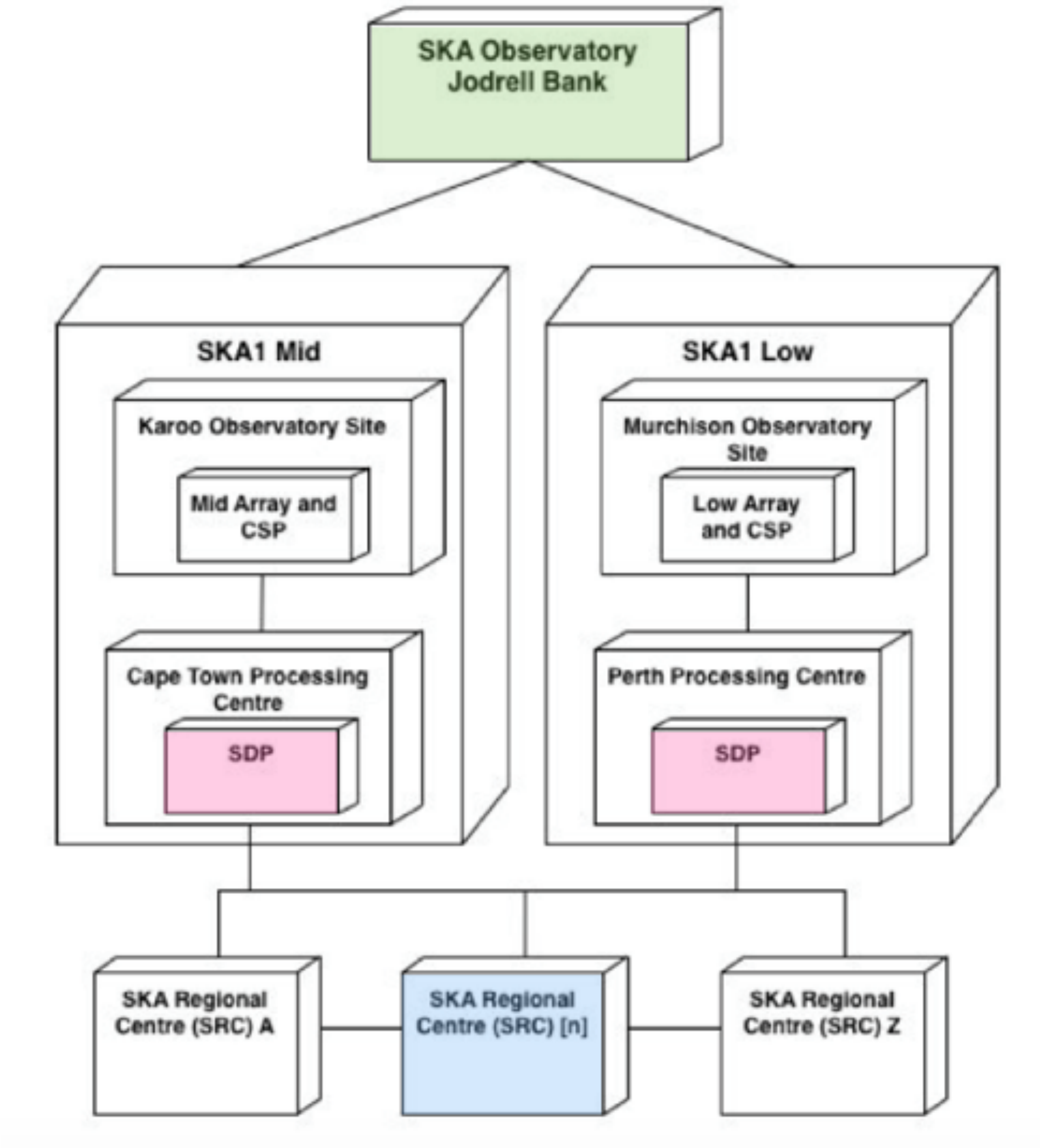


CENTRAL SIGNAL PROCESSING

SCIENCE DATA PROCESSING

REGIONAL DATA CENTRE


SKA Observatory
Jodrell Bank
2 TB/sec
157 TB/sec
1 TB/sec
500 GB/sec
Cape Town Processing
Centre
SDP
Perth Processing Centre
SDP
SKA Regional
Centre (SRC) A
SKA Regional
Centre (SRC) [n]
SKA Regional
Centre (SRC) Z
CENTRAL SIGNAL
PROCESSING
SCIENCE DATA
PROCESSING
REGIONAL DATA
CENTRE

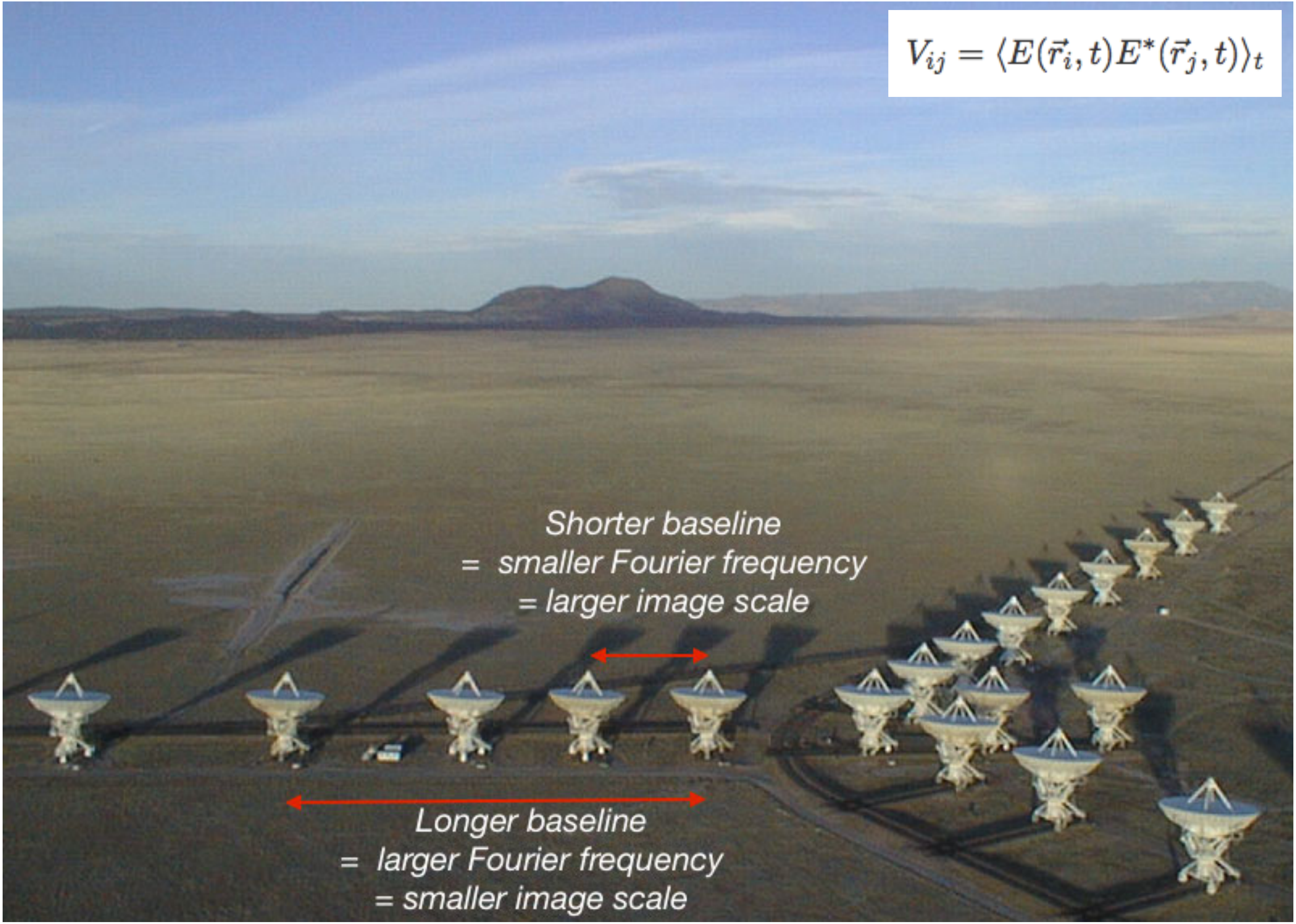


CENTRAL SIGNAL PROCESSING

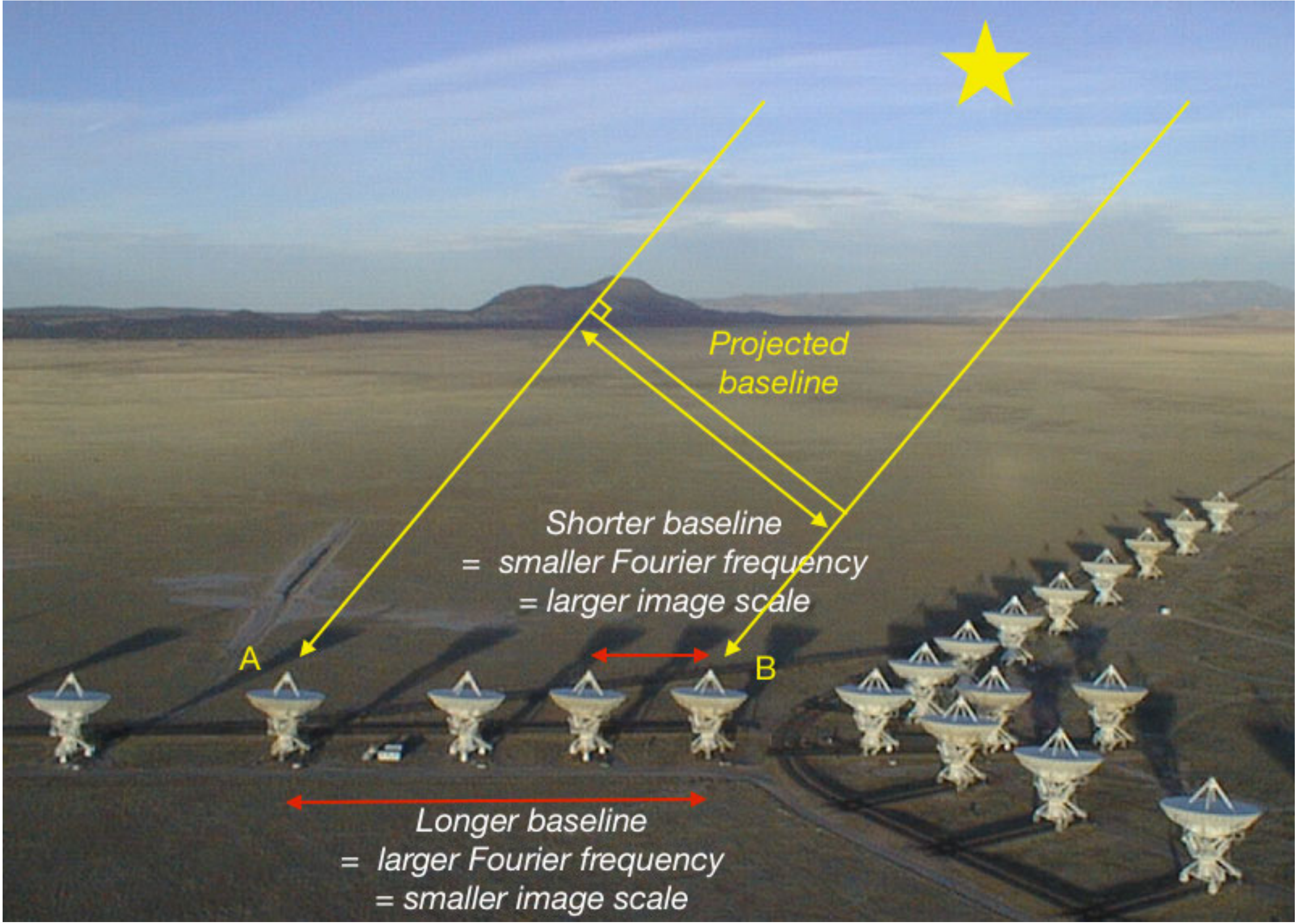
SCIENCE DATA PROCESSING

REGIONAL DATA CENTRE

Future SKA Science Archive



$$V_{ij} = \langle E(\vec{r}_i, t) E^*(\vec{r}_j, t) \rangle_t$$
Shorter baseline
= smaller Fourier frequency
= larger image scale
Longer baseline
= larger Fourier frequency
= smaller image scale


Projected
baseline
Shorter baseline
= smaller Fourier frequency
= larger image scale
A
B
Longer baseline
= larger Fourier frequency
= smaller image scale

$$V(u,v,w) = \int \frac{I(l,m)}{\sqrt{1-l^2-m^2}} \mathrm{e}^{-2\pi i(ul+vm+w(\sqrt{1-l^2-m^2}-1))}$$

$$I_{meas}(l,m) = \iint S(u,v)V(u,v)e^{2\pi i(ul+vm)}\,du\,dv$$

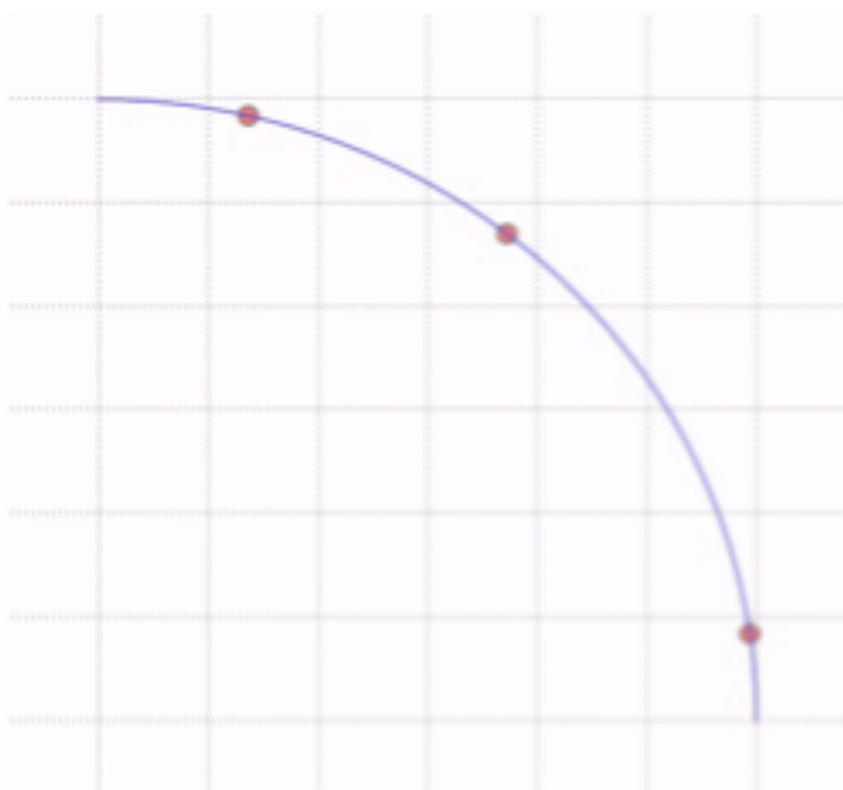
This sampling function identifies the values of (u,v) that we sample according to our baseline distribution.

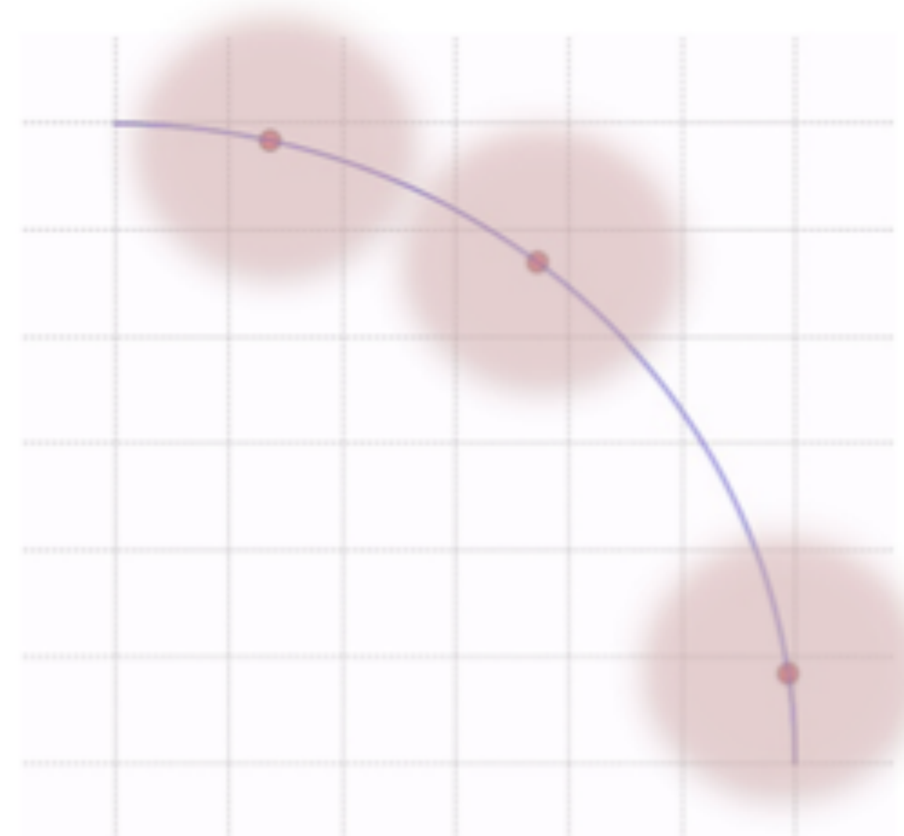
$$S(u,v) = \sum_{i=1}^{M} \delta(u-u_i, v-v_i)$$

Where M is the number of different visibilities that we have:

$$M = N_{\mathrm{ant}}(N_{\mathrm{ant}}-1)/2 \times N_{\tau} \times N_{\mathrm{f}}$$

$$V(u,v,w) = \int \frac{I(l,m)}{\sqrt{1-l^2-m^2}} \, \mathrm{e}^{-2\pi i(ul+vm+w(\sqrt{1-l^2-m^2}-1))}$$





$$V_{grid}(u_k, v_k) = \left[[V(u,v) \cdot S(u,v)] * C_{aa}(u,v) \right] \cdot III(u_k, v_k)$$

The gridded visibility data on a grid with $\sqrt{k}$ x $\sqrt{k}$ pixels

The input visibility data, sampled at a number of times and frequencies.

The convolution/ gridding kernel function.

Sample onto regularly spaced grid using the *Shah* function.

$$V_{grid}(u_k, v_k) = \Big[[V(u,v) \cdot S(u,v) \cdot W(u,v)] * C_{aa}(u,v)\Big] \cdot III(u_k, v_k)$$

To make an image we can now simply FFT our UV grid, but we must also correct for the gridding function that we have introduced and normalise the weights:

$$I_{\text{meas, dirty}}(l,m) = \frac{\text{FT}^{-1}[V_{\text{grid}}(u,v)]}{\left(\sum W_{\text{grid}}(u,v)\right)\text{FT}^{-1}[C_{\text{aa,grid}}(u,v)]}$$

The image that we have made is known as the DIRTY IMAGE, because we have not made any correction for the weighted sampling $S(u,v)W(u,v)$.

Because we are multiplying our continuous visibilities by $S(u,v)W(u,v)$ the DIRTY IMAGE shows us the convolution of their Fourier transforms.

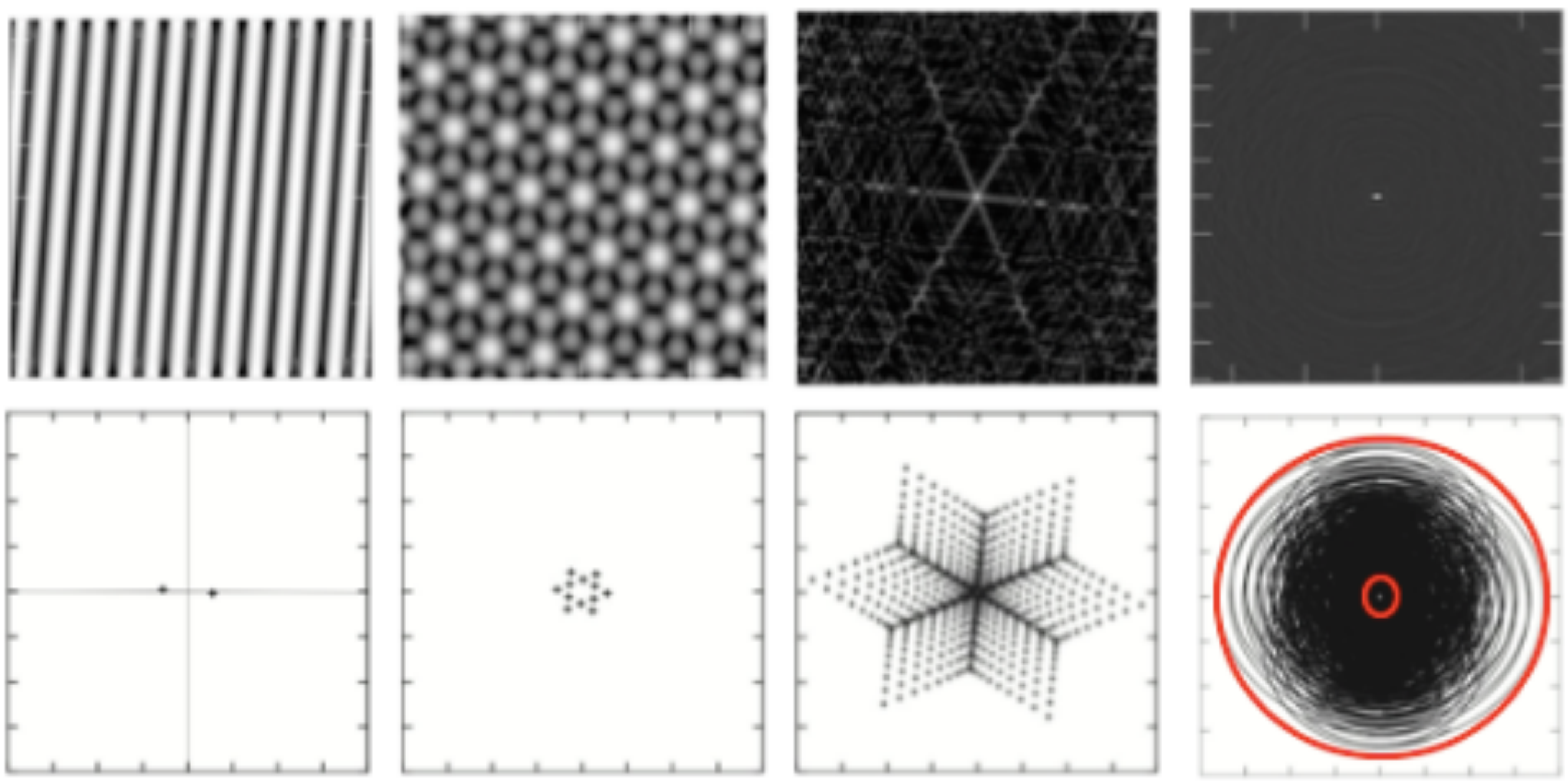
$$V(u,v)\cdot\left[S(u,v)\cdot W(u,v)\right] \Leftrightarrow I(l,m) * b_{\mathrm{PSF}}(l,m)$$

Where the point spread function, or synthesized beam, or dirty beam, is defined as

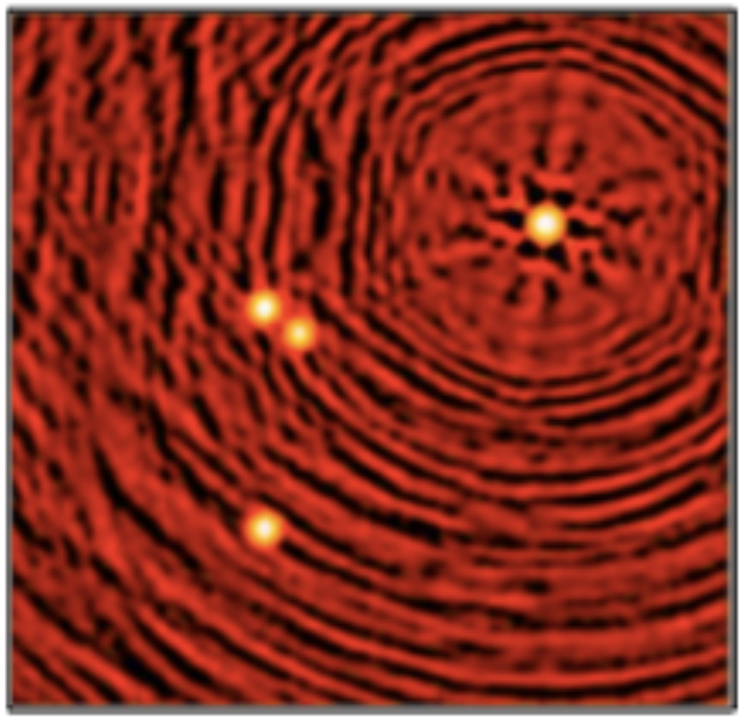
$$b_{\mathrm{PSF}}(l,m) = FT^{-1}\left[S(u,v)\cdot W(u,v)\right]$$

It would be nice if we could just divide out this multiplication directly in Fourier space, but we can't because it has zero-valued components.

Challenge 1: Undersampling

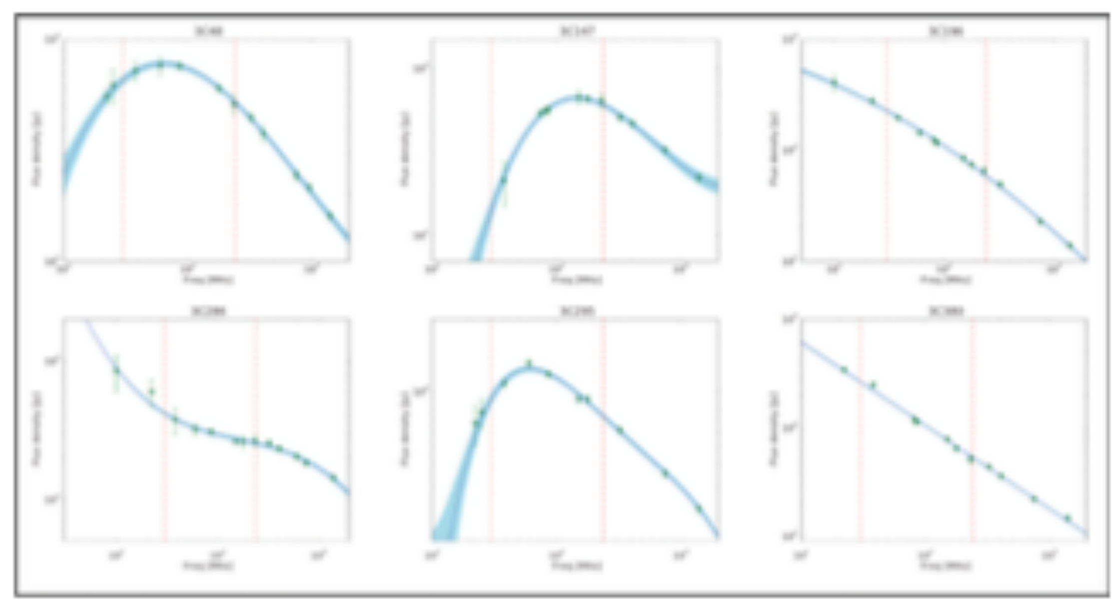


Challenge 2: Spectral behaviour



Gridding separate frequencies together results in image plane aberations.

This is because astrophysical radio sources have frequency dependent behaviour.
We can exploit this by taking a Taylor expansion of the frequency dependence.



Challenge 3: Non-coplanarity

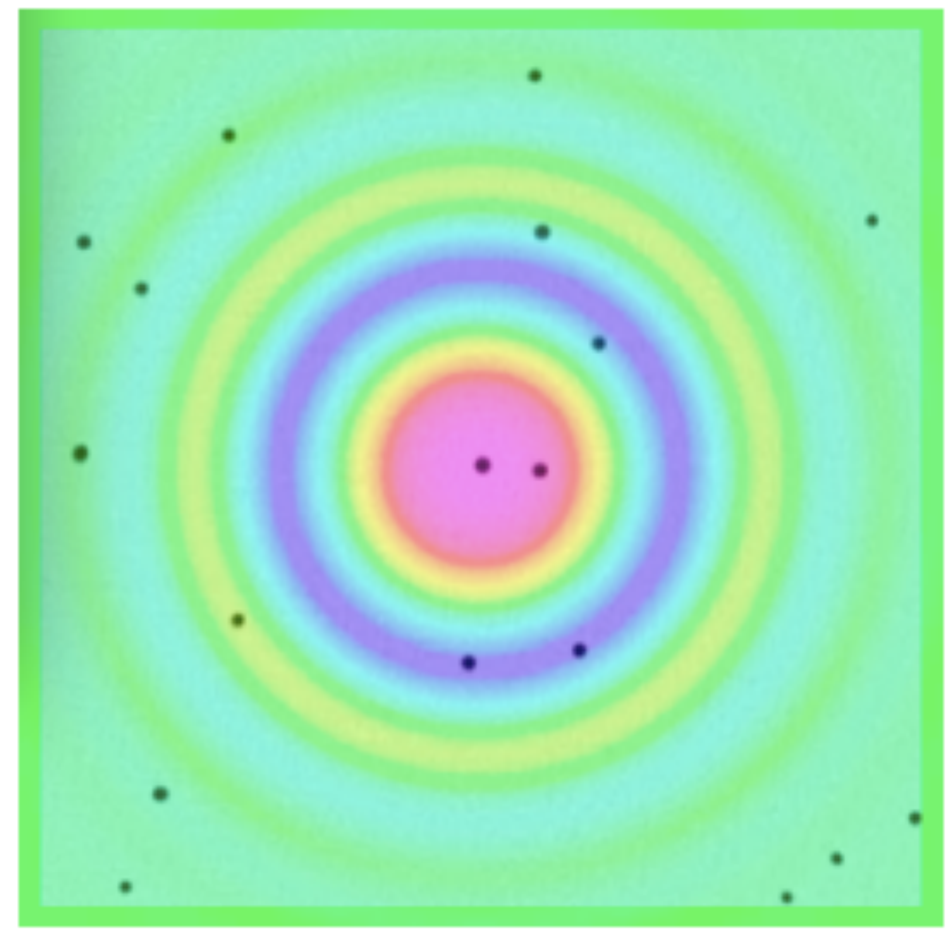
$$V(u,v,w) = \int \frac{I(l,m)}{\sqrt{1-l^2-m^2}} \mathrm{e}^{-2\pi i(ul+vm+w(\sqrt{1-l^2-m^2}-1))}$$

We think of images as being 2D, but in reality our **antennas are distributed in 3 dimensions** and **the sky is curved**.

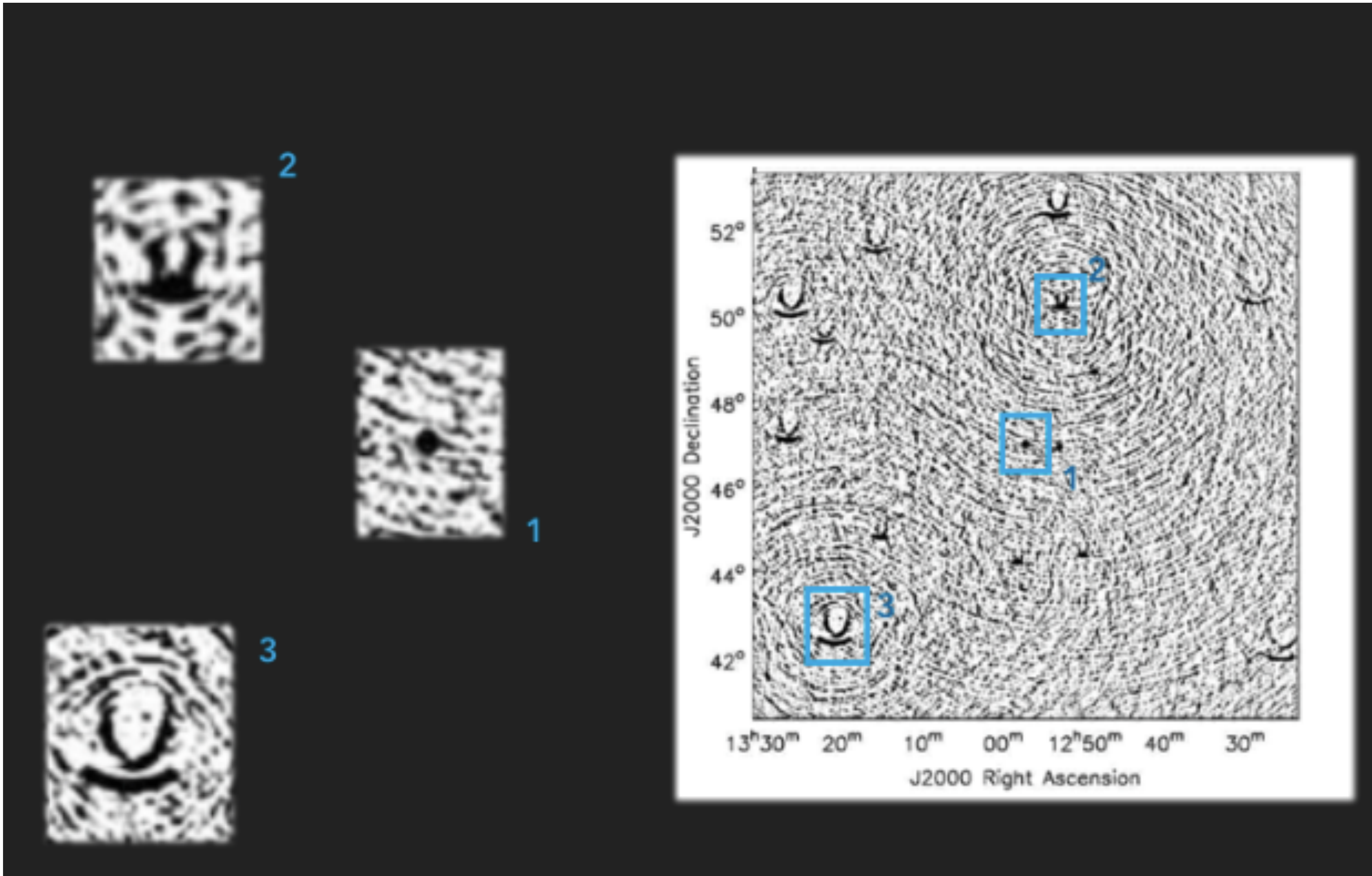
This is known as the **w-effect**.

It introduces a direction dependent **phase** that is different for each pair of antennas.

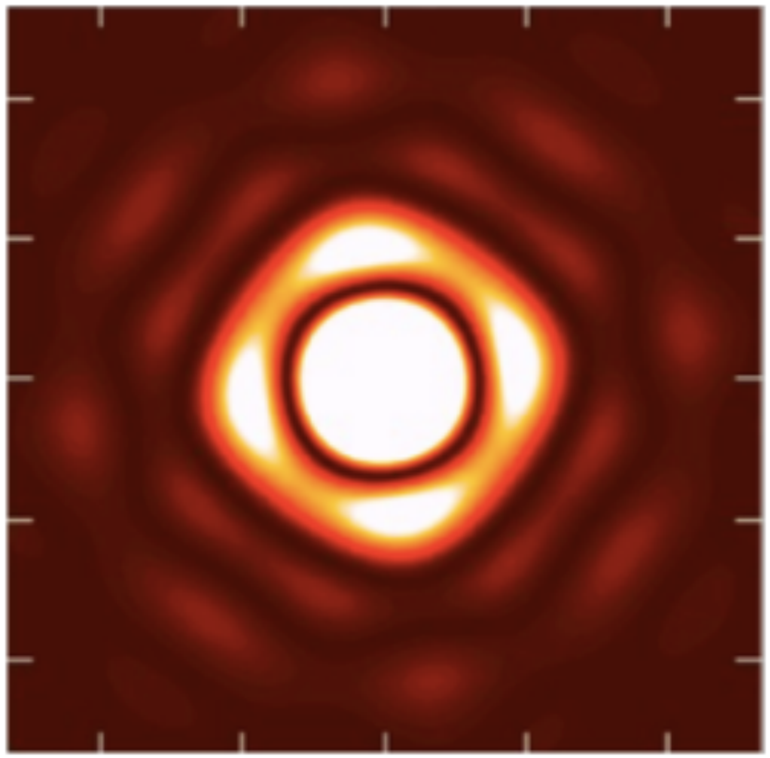
Effectively, each antenna pair sees a different sky.

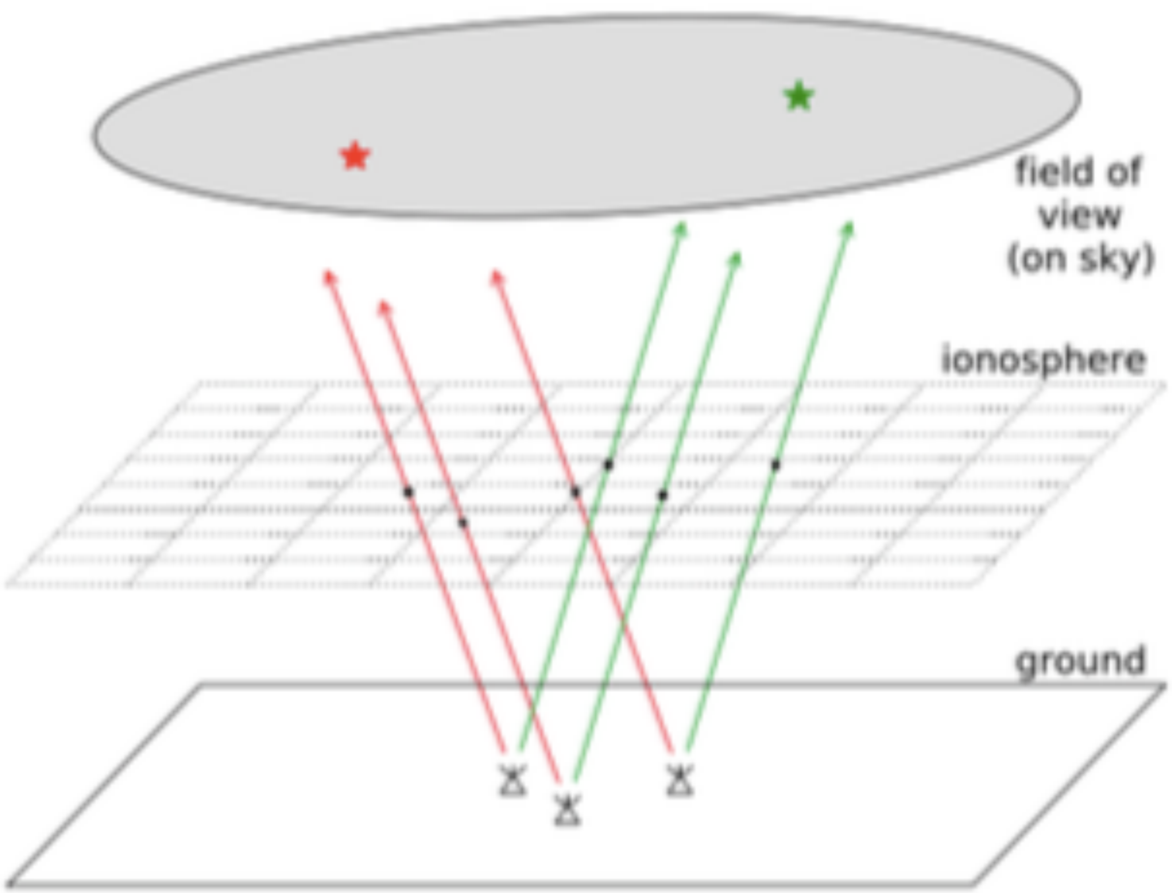


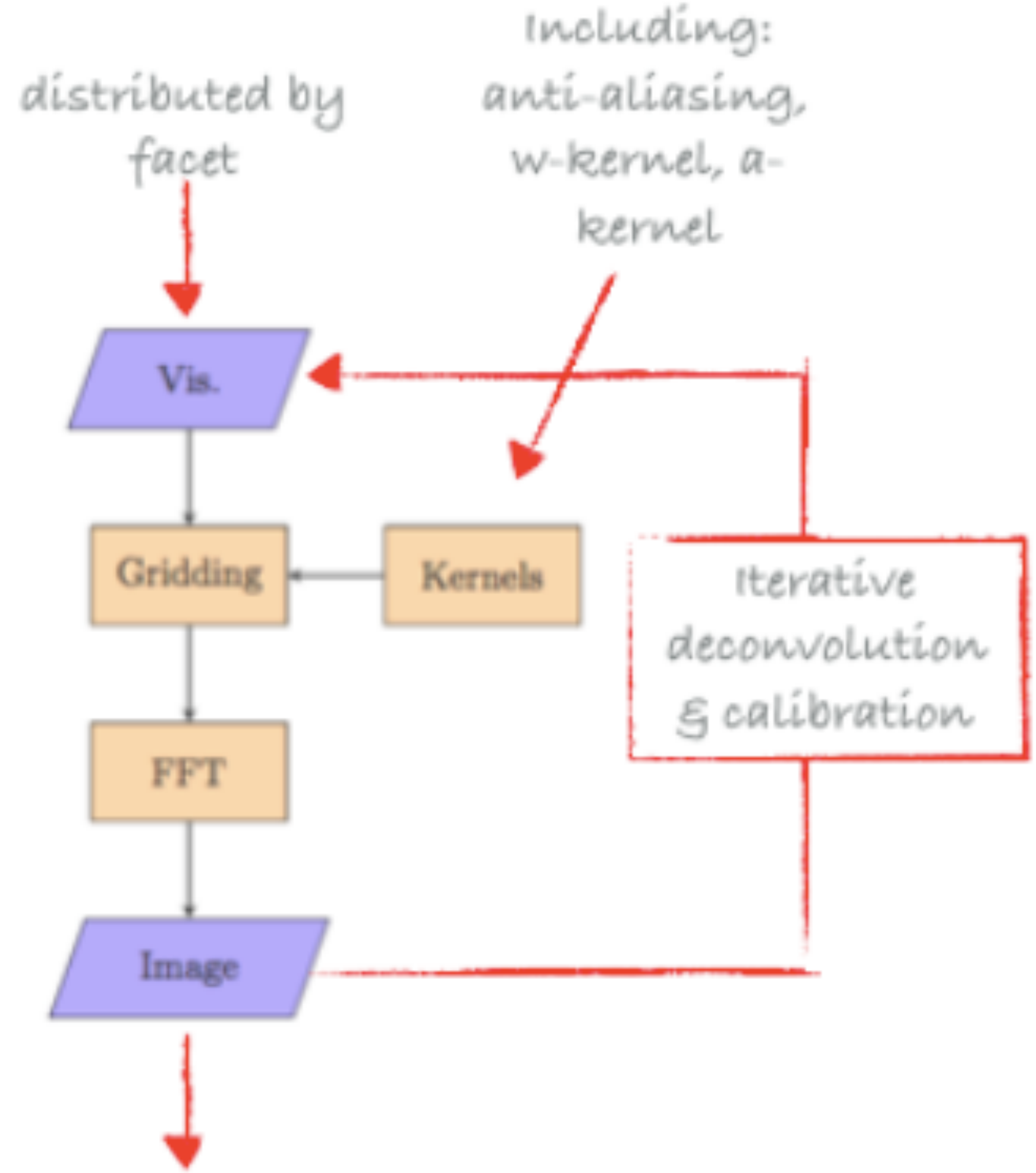
Challenge 3: Non-coplanarity

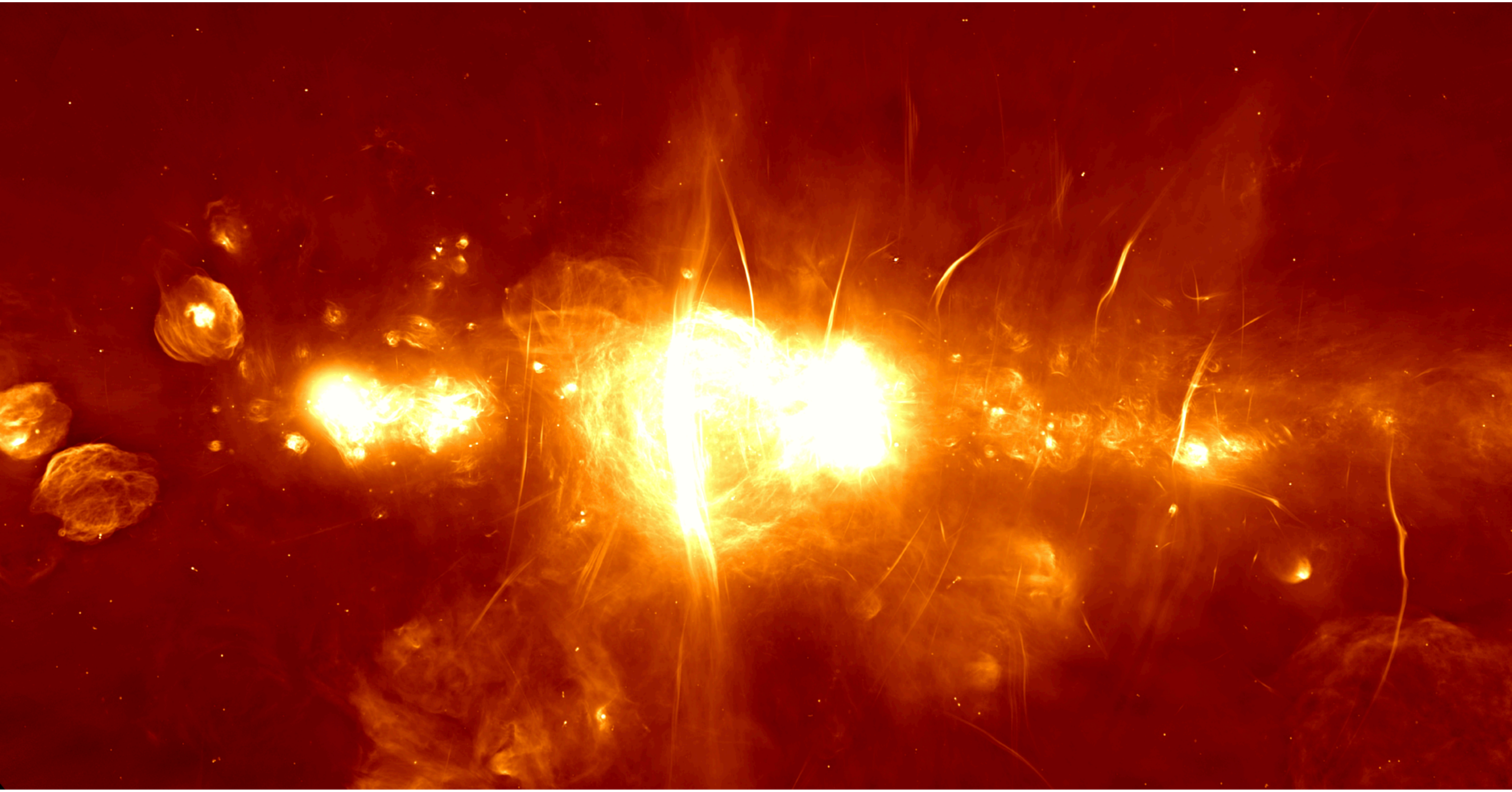


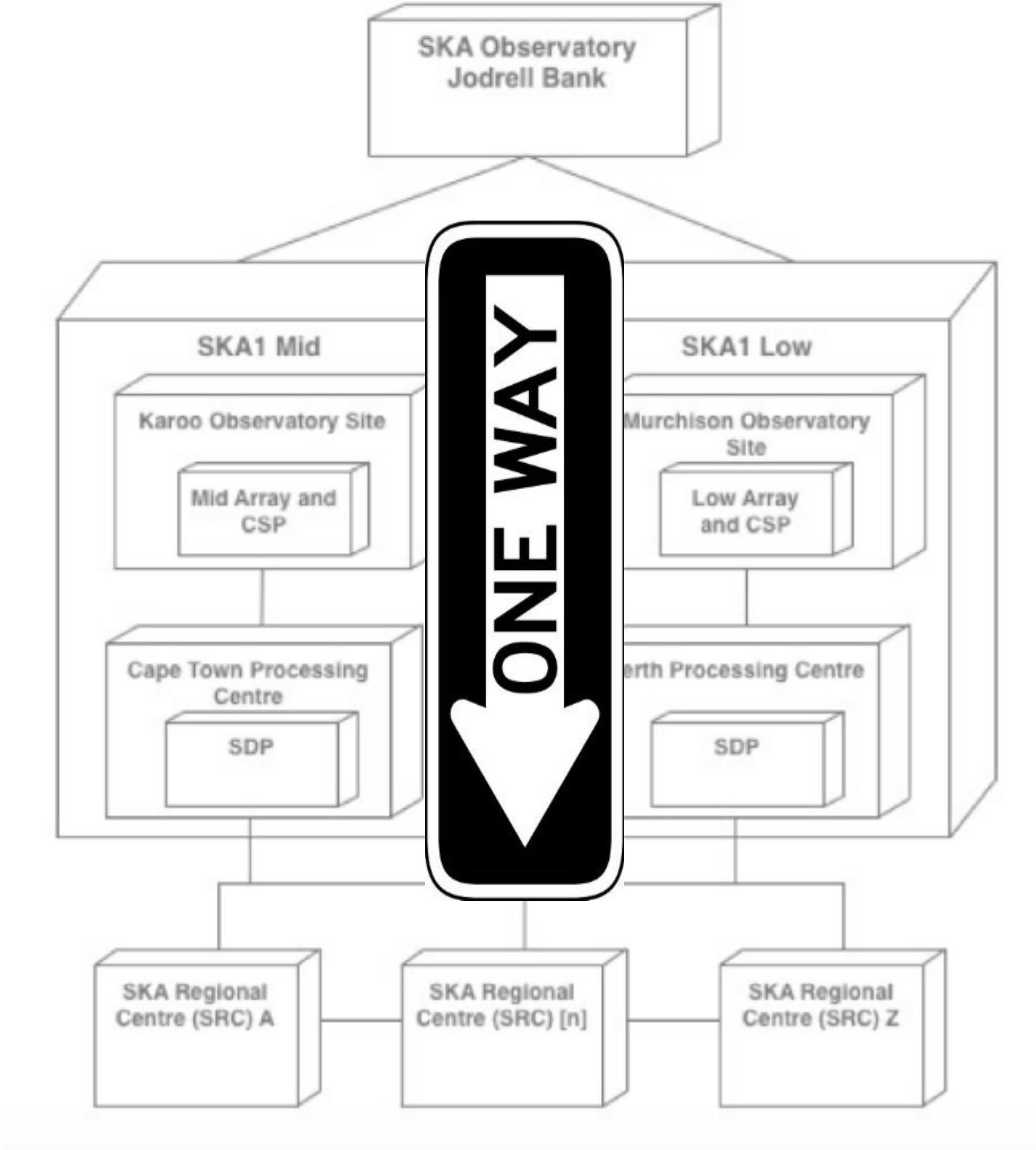
Challenge 4: Direction-dependent effects








MeerKAT Galactic Centre - SARAO



SDP will deliver **standard data products**

For imaging observations these are image data products

A standard SKA1-MID image data product has **30k x 30k pixels**

SKA1 will have up to **65k frequency channels** and **4 polarisations**

At 4 Bytes per voxel that equates to
30k x 30k x 65k x 4 x 4
= **936 TeraBytes**

- even for a snapshot image

The five stages of learning about SKA data products:

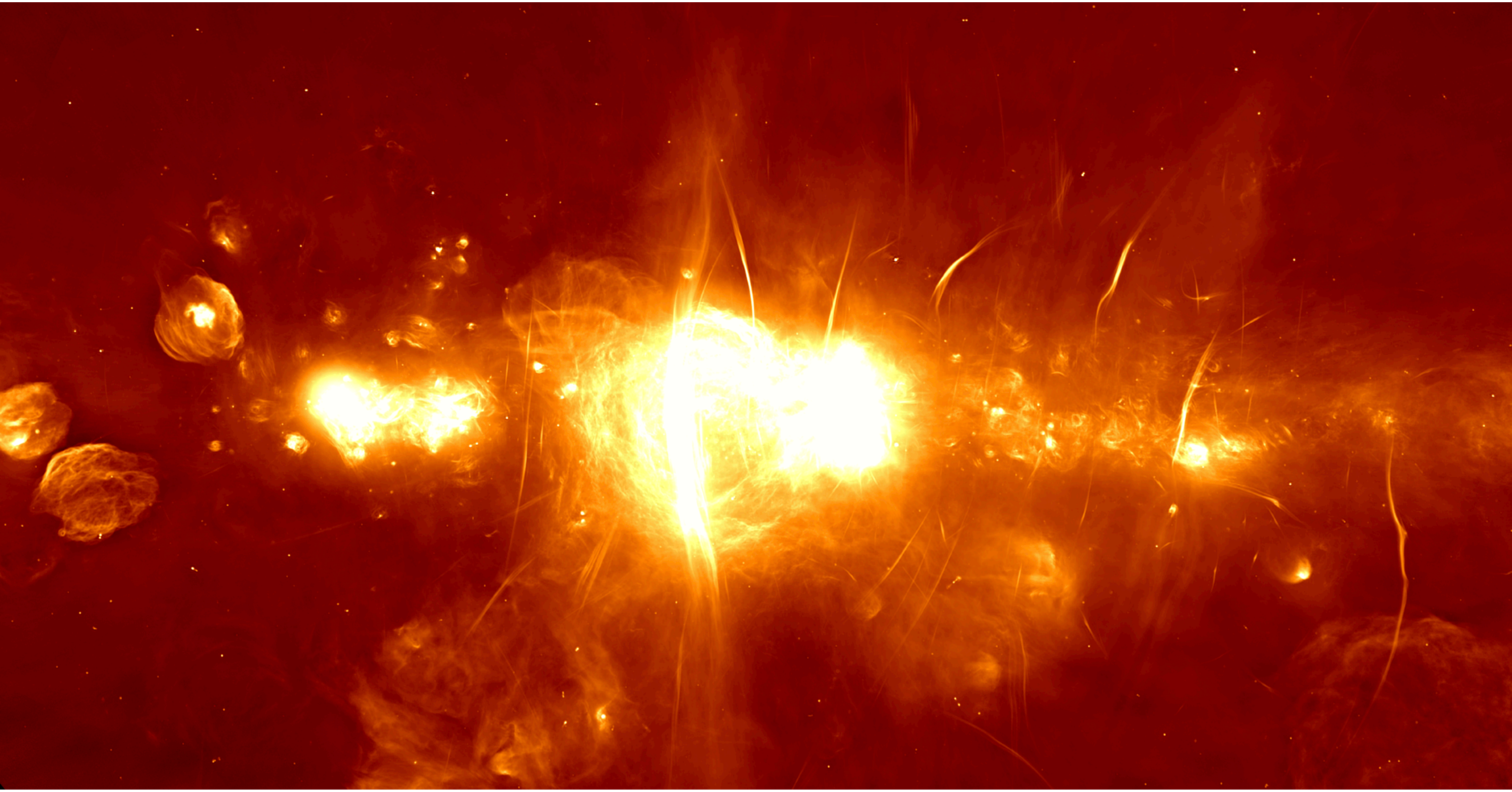
(1) **Denial**
"What do you mean I can't have the visibilities?"

(2) **Anger**
"That's crazy! I need the visibilities!"

(3) **Bargaining**
"What if I help with commissioning? Can I have the visibilities then?"

(4) **Depression**
"It's never going to work if I can't have the visibilities."

(5) **Acceptance**
" - "



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