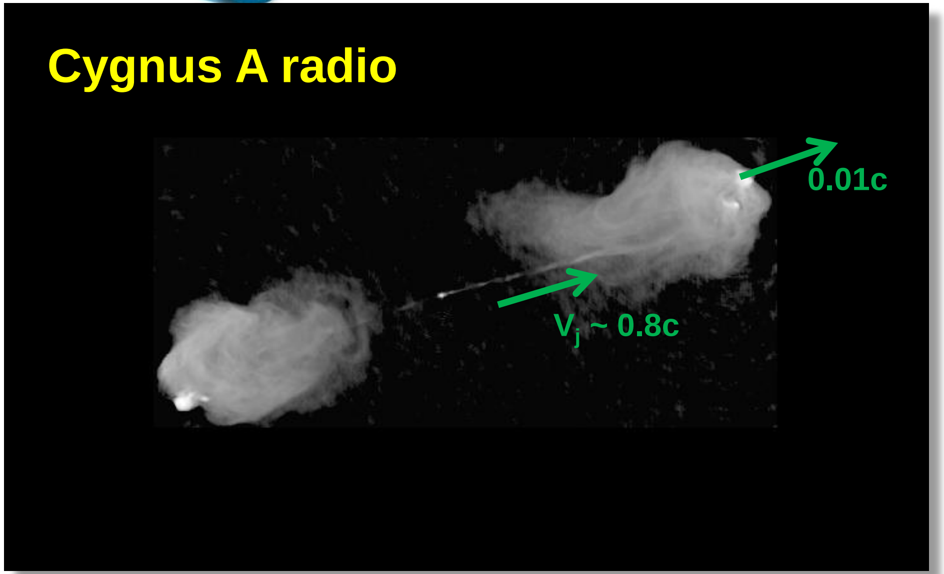
Delivering Transformational Science with the new generation of radio telescopes

Paul Alexander

Very Brief Introduction to Radio Astronomy Imaging

Radio Astronomy Imaging

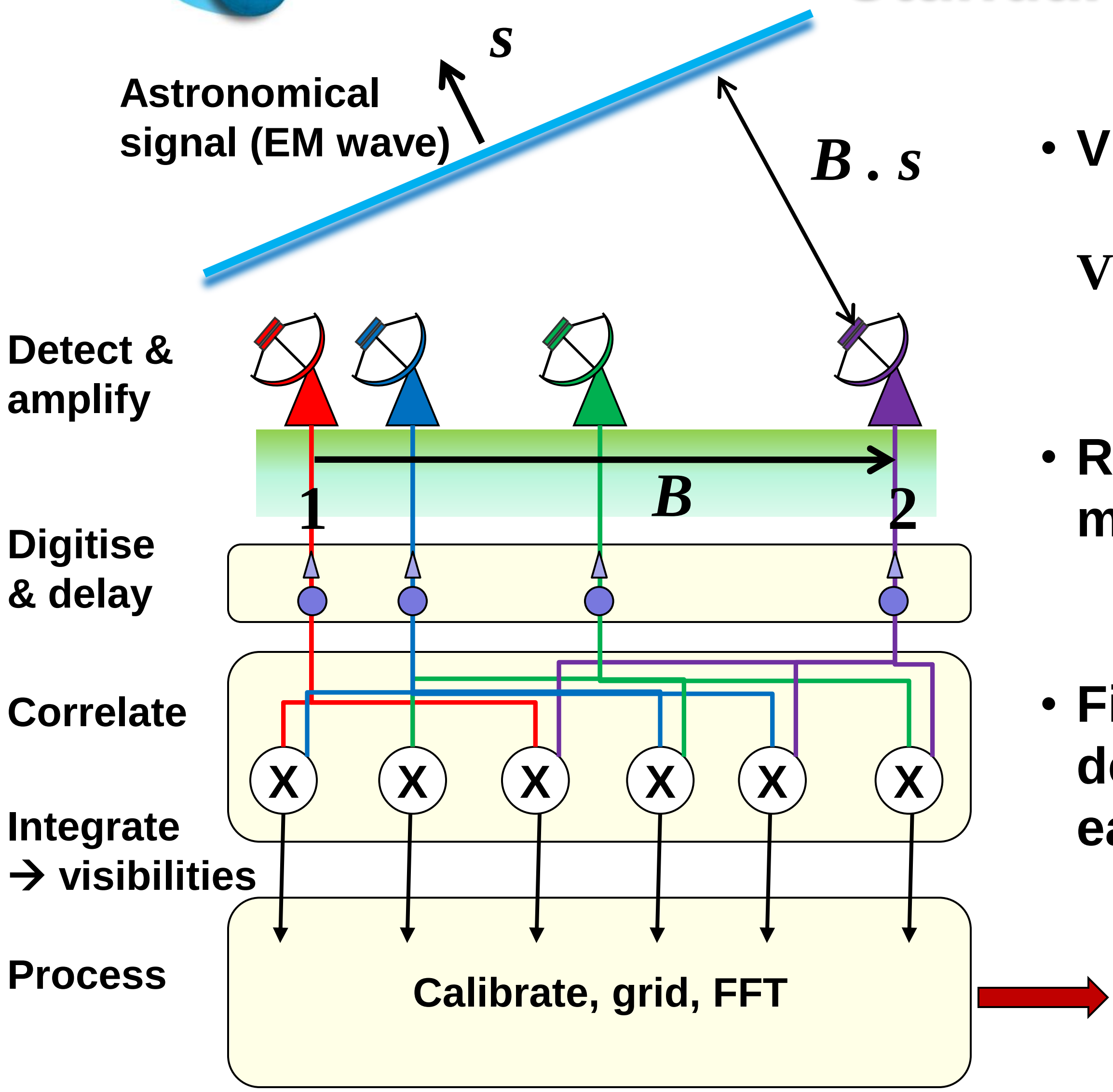

Cygnus A radio

- For imaging radio astronomy has for 5 decades made use of interferometers
- Provide a measurement of Fourier Components of the sky brightness distribution
- Approximate 2D Fourier relationship for small fields of view (FoV) relating sky and measurements

- Use rotation of the Earth relative to sky to measure different Fourier components
- Complications arise for large FoV due to spherical sky
- Complications arise due to telescopes moving in 3D as Earth rotates


eVLA 27 27m dishes
Longest baseline 30km

Standard interferometer



Astronomical signal (EM wave)

s

$B\,.\,s$

Detect & amplify

B

1

2

Digitise & delay

Correlate

X X X X X X

Integrate → visibilities

Process

Calibrate, grid, FFT

- **Visibility:**

$$V(B) = E_1 E_2^*$$
$$= I(s) \exp(\, i\, \omega\, B.s/c\,)$$

- **Resolution determined by maximum baseline**

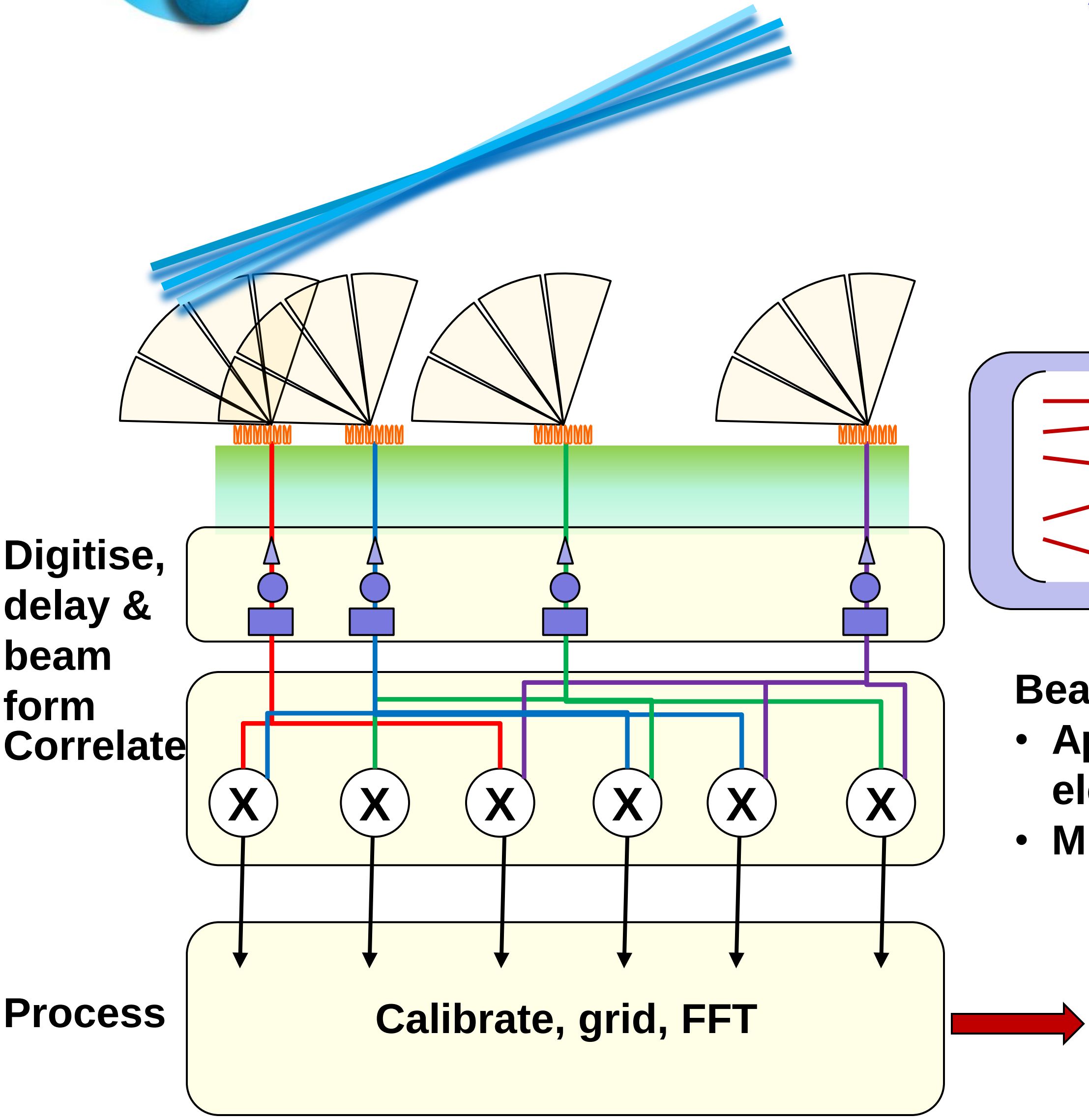
$$\theta_{max} \sim \lambda / B_{max}$$

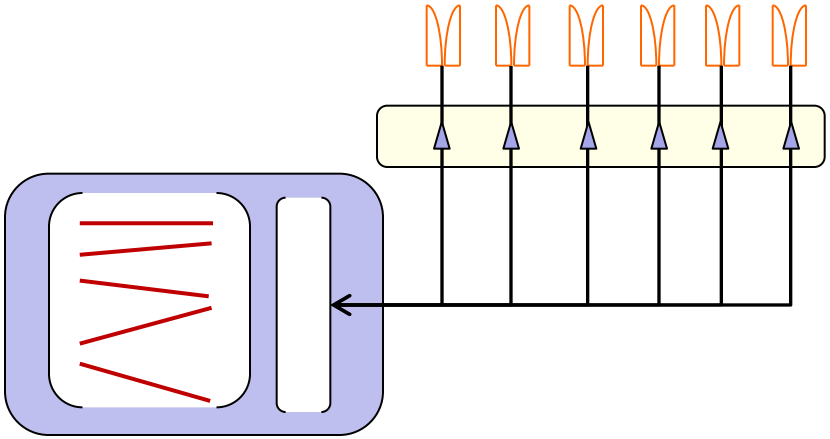
- **Field of View (FoV) determined by the size of each dish**

$$\theta_{dish} \sim \lambda / D$$

SKY Image

Aperture arrays





Beam form:

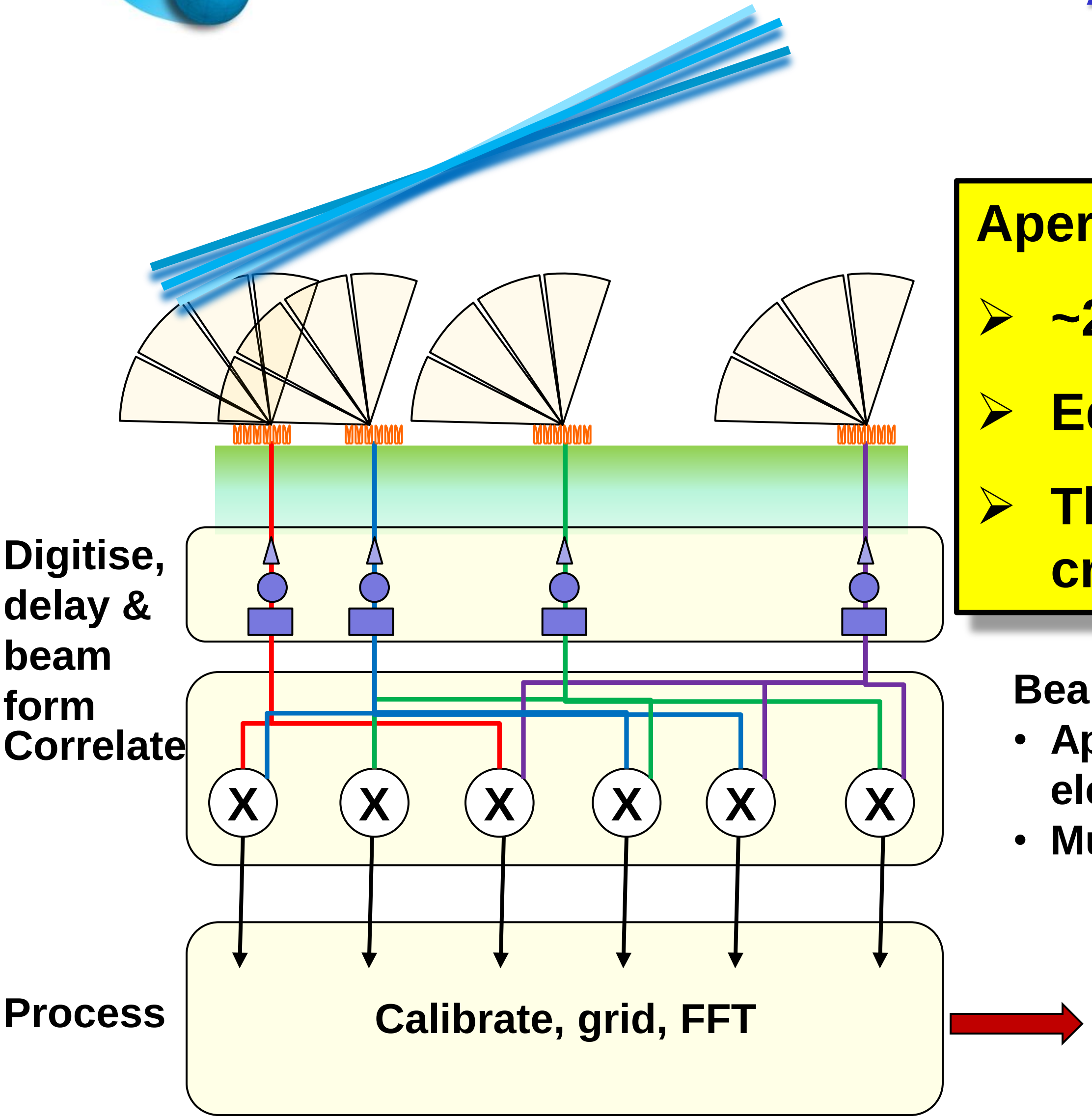
- **Apply delay gradients to point electrically**
- **Multiple delay gradients**
  - **➢ many beams and large FoV**

SKY Image

Aperture arrays

Aperture-Array station

- ~25000 phased elements
- Equivalent to one dish
- These are then cross-correlated



Digitise, delay & beam form

Correlate

Process

Calibrate, grid, FFT

SKY Image

Beam form:

- Apply delay gradients to point electrically
- Multiple delay gradients
  - many beams and large FoV

Formulation

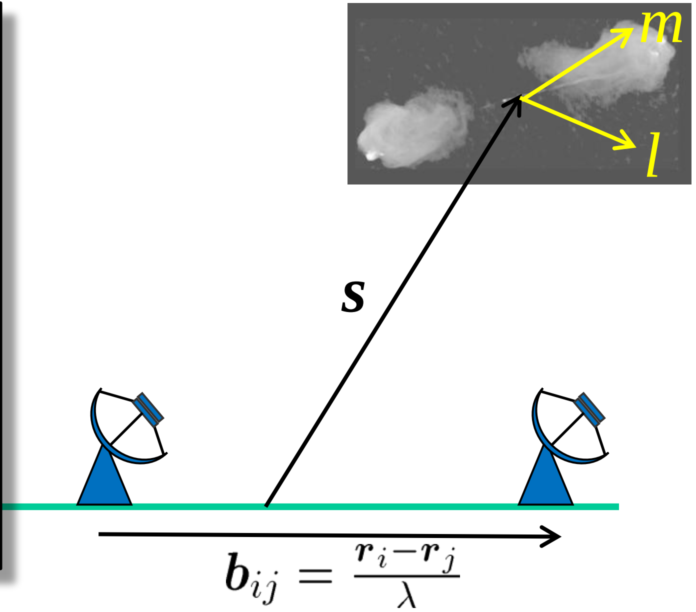
- What we measure from a pair of telescopes:

$$V_{ij} = \int \boldsymbol{J}_i \otimes \boldsymbol{J}_j^* < \boldsymbol{E}_0 \otimes \boldsymbol{E}_0 > \exp(i2\pi(\boldsymbol{s} \cdot \boldsymbol{b}_{ij} + f\tau_i - f\tau_j u))\mathrm{d}^2\boldsymbol{s}$$

- In practice we have to deal with this equation, but for simplicity consider a scalar model

$$V_{ij} = \int A_{ij} I \exp(i2\pi(\boldsymbol{s} \cdot \boldsymbol{b}_{ij} + f\tau_i - f\tau_j))\mathrm{d}^2\boldsymbol{s}$$

- The delays allow us to follow a point on the sky
- The ***J***$_i$ are direction dependent Jones matrices which include the effects of:
    - propagation from the sky through the atmosphere
    - scattering
    - coupling to the antenna/detector
    - gain



Formulation

- Where we include time delays to follow a central point. In terms of direction cosines relative to the point we follow and for a $\boldsymbol{b} = (u,v,w)$

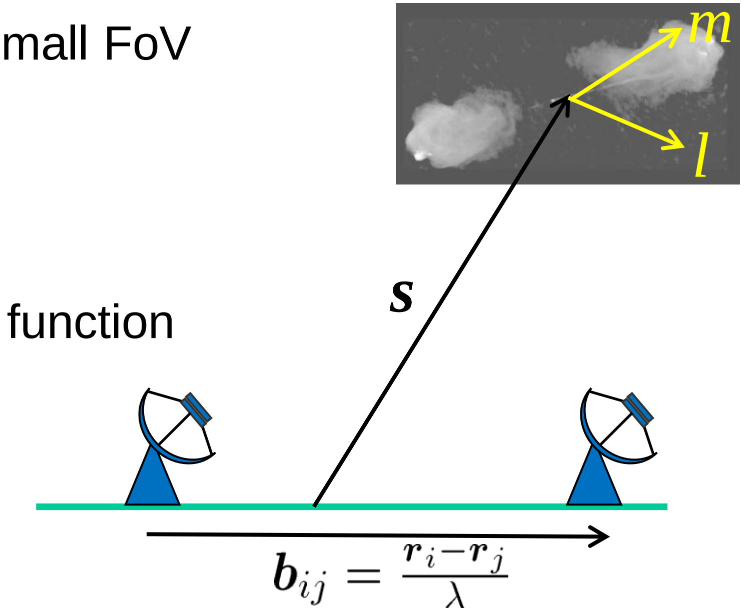
$$V_{ij} = \int A_{ij}(l,m) I(l,m) \exp(i2\pi(ul + vm + w(\sqrt{1-l^2-m^2} - 1))) \frac{\mathrm{d}l\mathrm{d}m}{\sqrt{1-l^2-m^2}}$$

- If we can calibrate our system we can apply our telescope-dependent calibrations and then for small FoV we can approximate

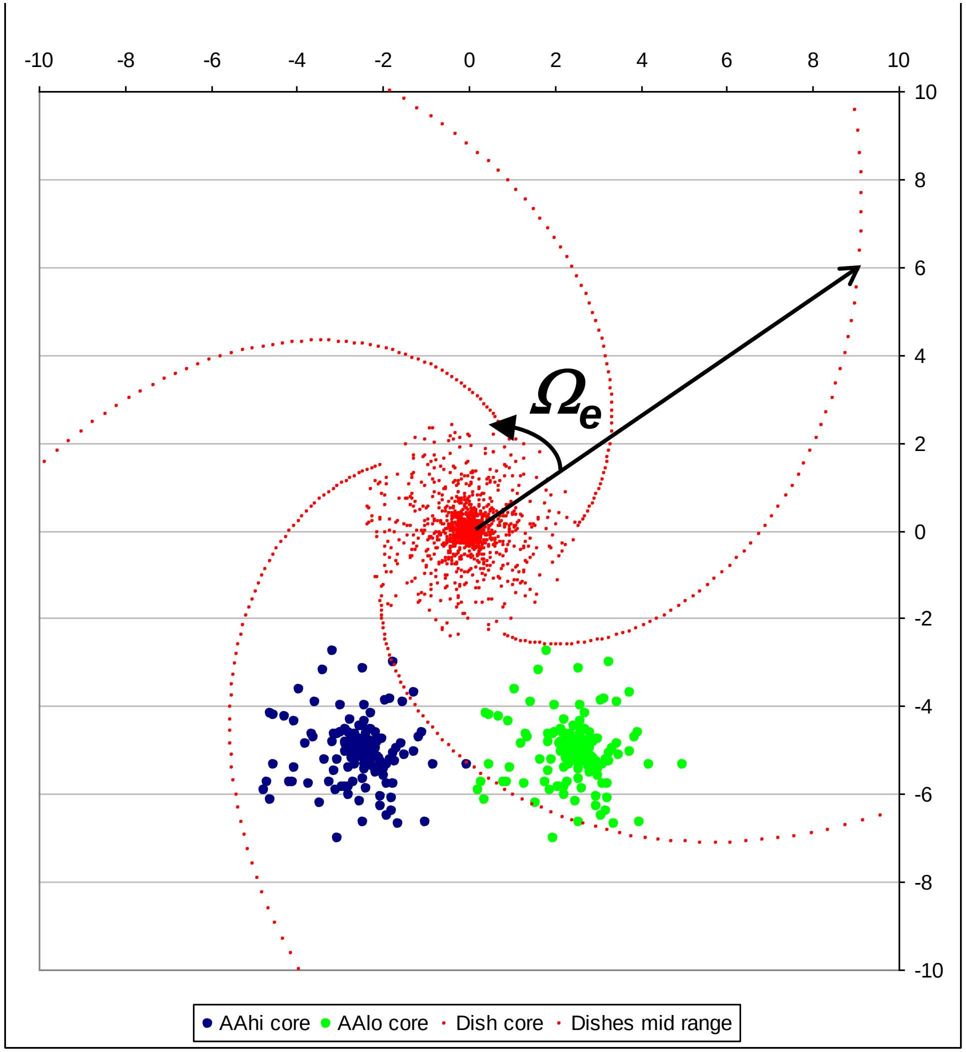
$$V(u,v) \approx \int A(l,m) I(l,m) \exp(i2\pi(ul + vm))$$

- And the measured data are just samples of this function

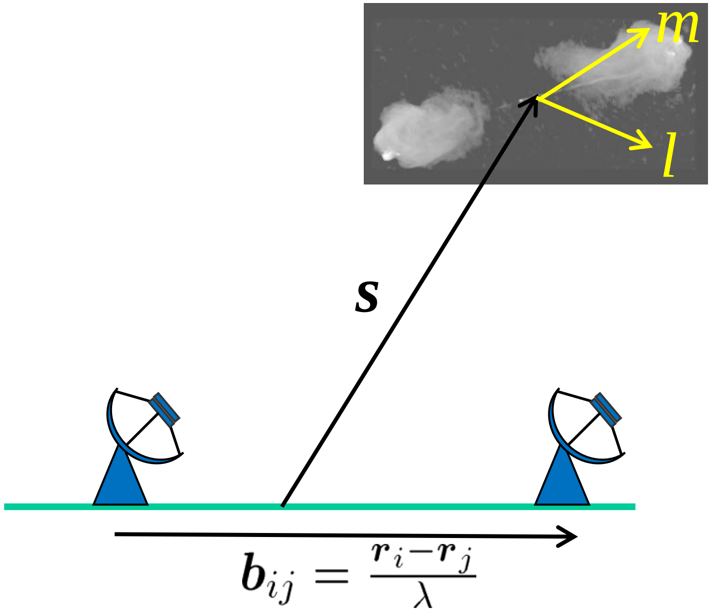
- In this case we can estimate the sky via Fourier inversion and deconvolution



Formulation



- Sampling of the Fourier plane is determined by the positioning of the antennas and improved by the rotation of the earth



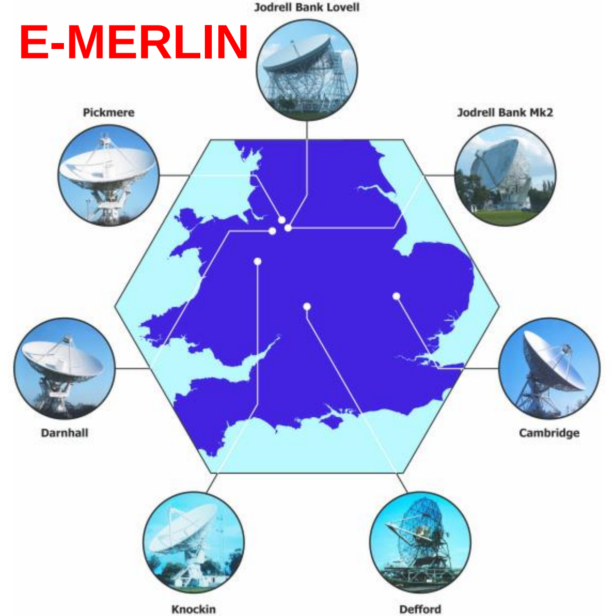
$$\mathbf{b}_{ij} = \frac{\mathbf{r}_i - \mathbf{r}_j}{\lambda}$$

The Square Kilometre Array

Precursors and Pathfinders

What is the Square Kilometre Array (SKA)

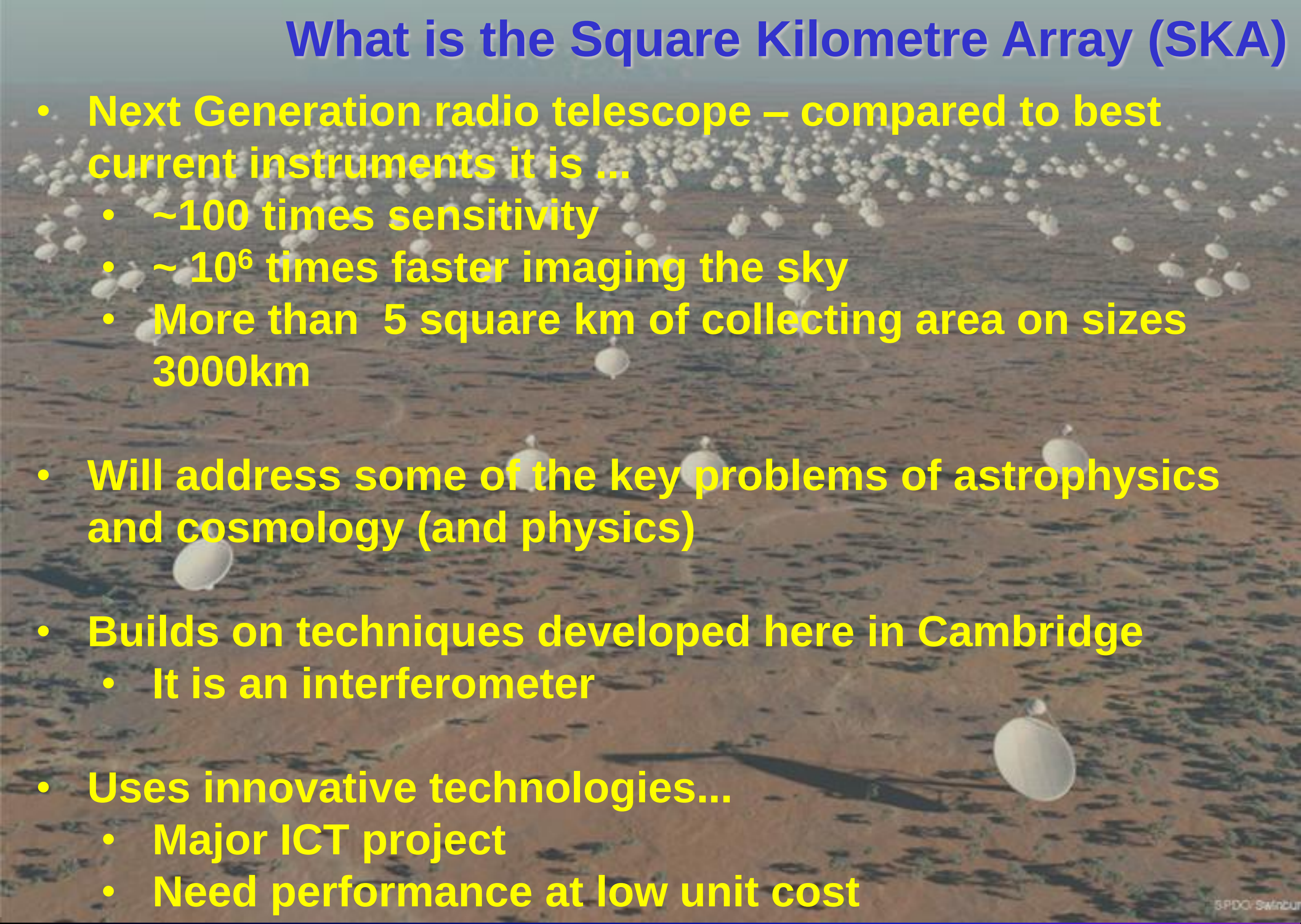
- Next Generation radio telescope – compared to best current instruments it is …
  - ~100 times sensitivity
  - ~ 10^6 times faster imaging the sky
  - More than 5 square km of collecting area on sizes 3000km


E-MERLIN


eVLA 27 27m dishes
Longest baseline 30km


GMRT 30 45m dishes
Longest baseline 35 km

What is the Square Kilometre Array (SKA)



- Next Generation radio telescope – compared to best current instruments it is ...
  - ~100 times sensitivity
  - ~ 10^6 times faster imaging the sky
  - More than 5 square km of collecting area on sizes 3000km

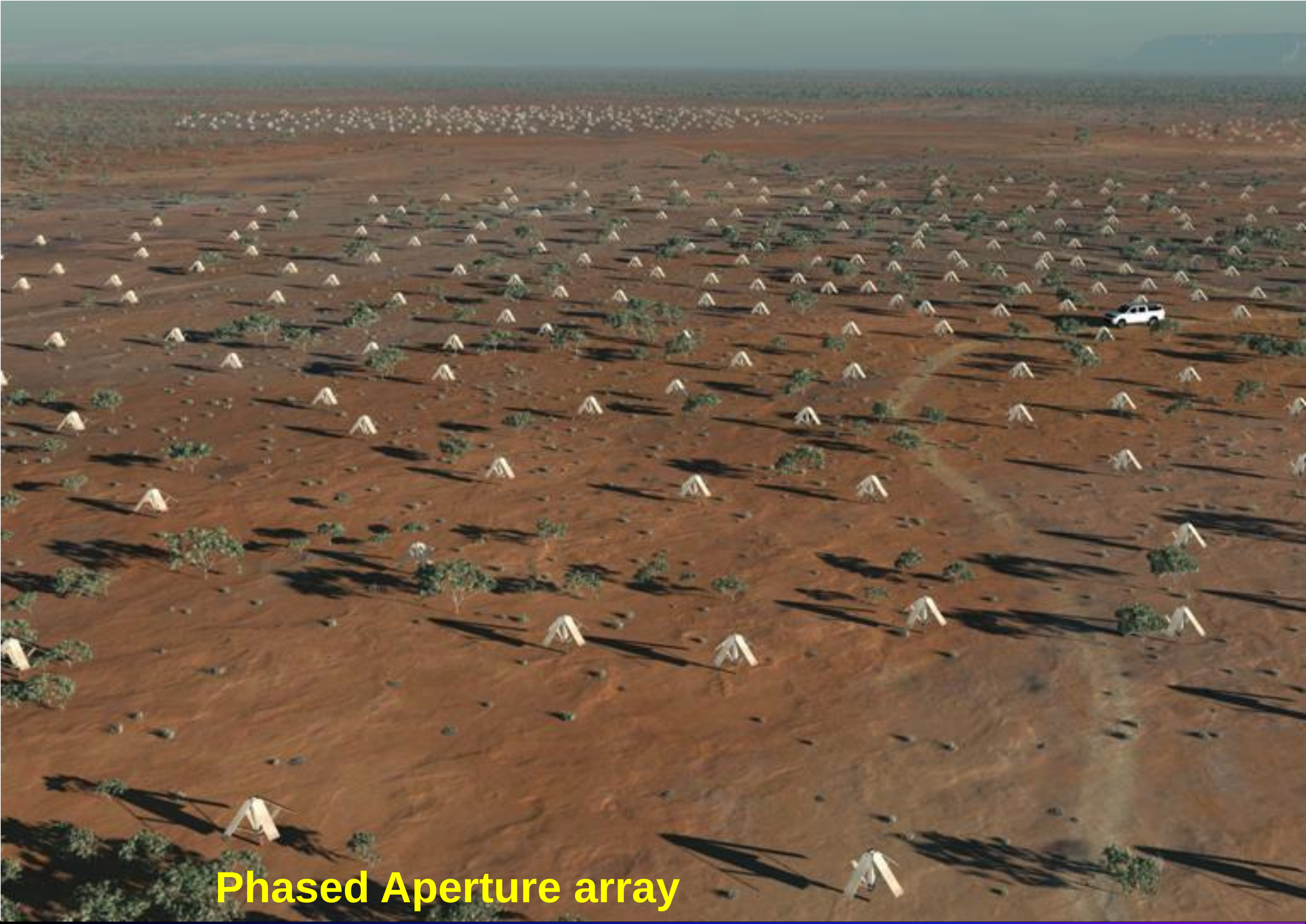
- Will address some of the key problems of astrophysics and cosmology (and physics)

- Builds on techniques developed here in Cambridge
  - It is an interferometer

- Uses innovative technologies...
  - Major ICT project
  - Need performance at low unit cost

Dishes

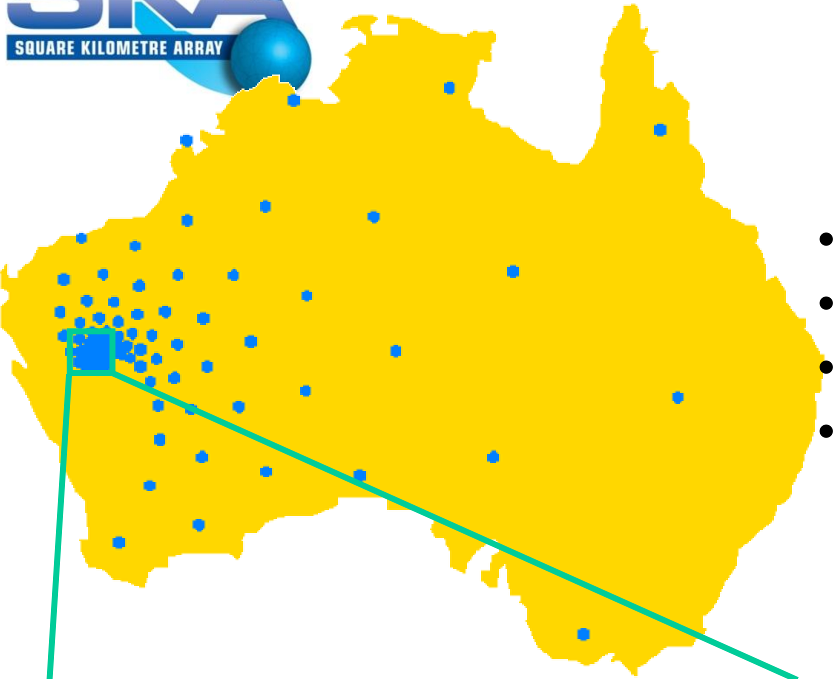
SPDO/Swinbur

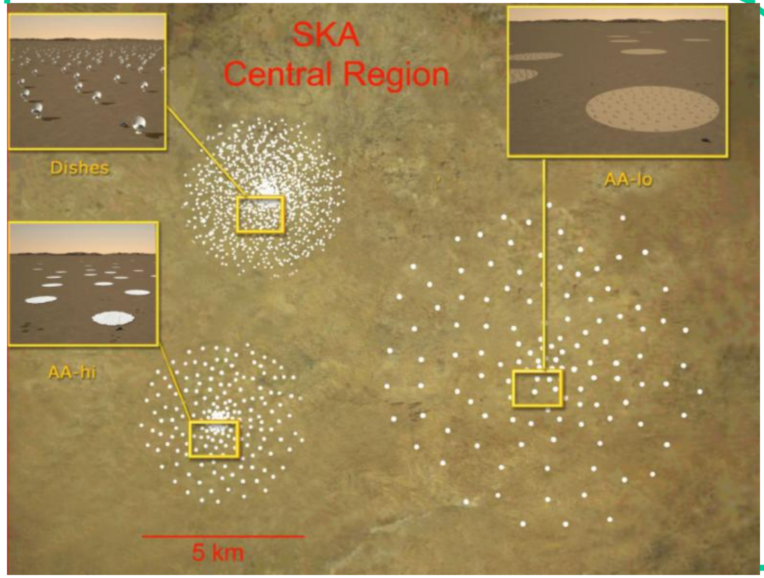


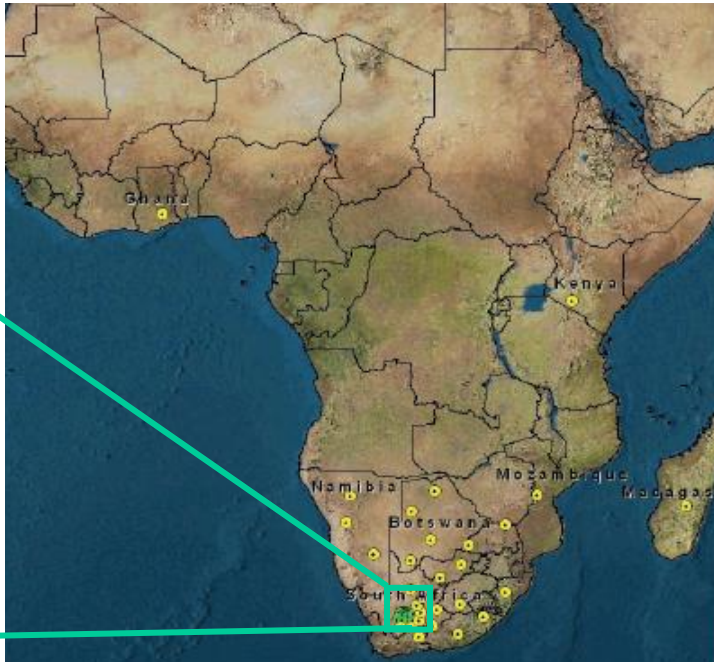
Phased Aperture array

also a Continental sized Radio Telescope

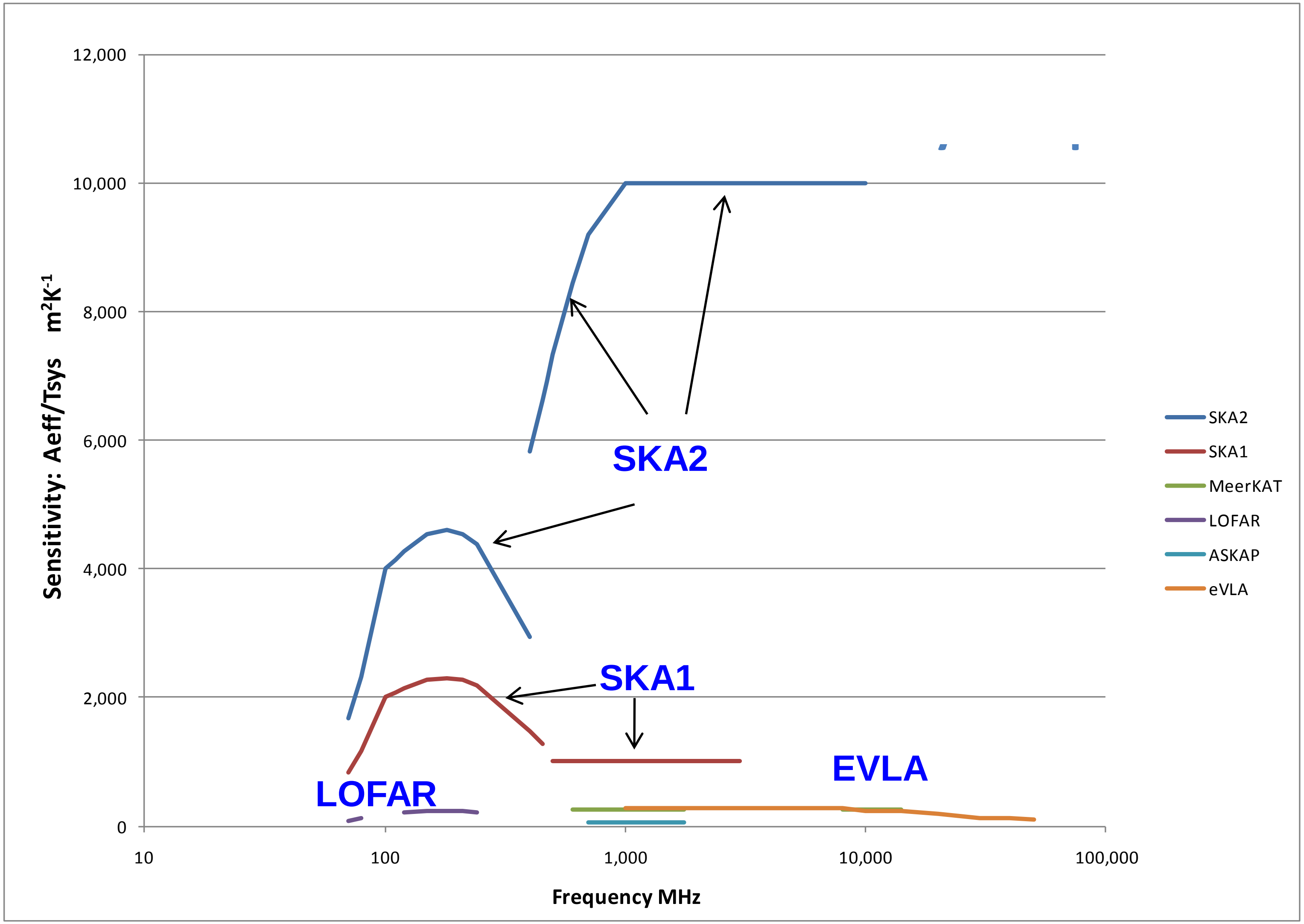
- Need a radio-quiet site
- Very low population density
- Large amount of space
- Possible sites (decision 2012)
  - Western Australia
  - Karoo Desert RSA



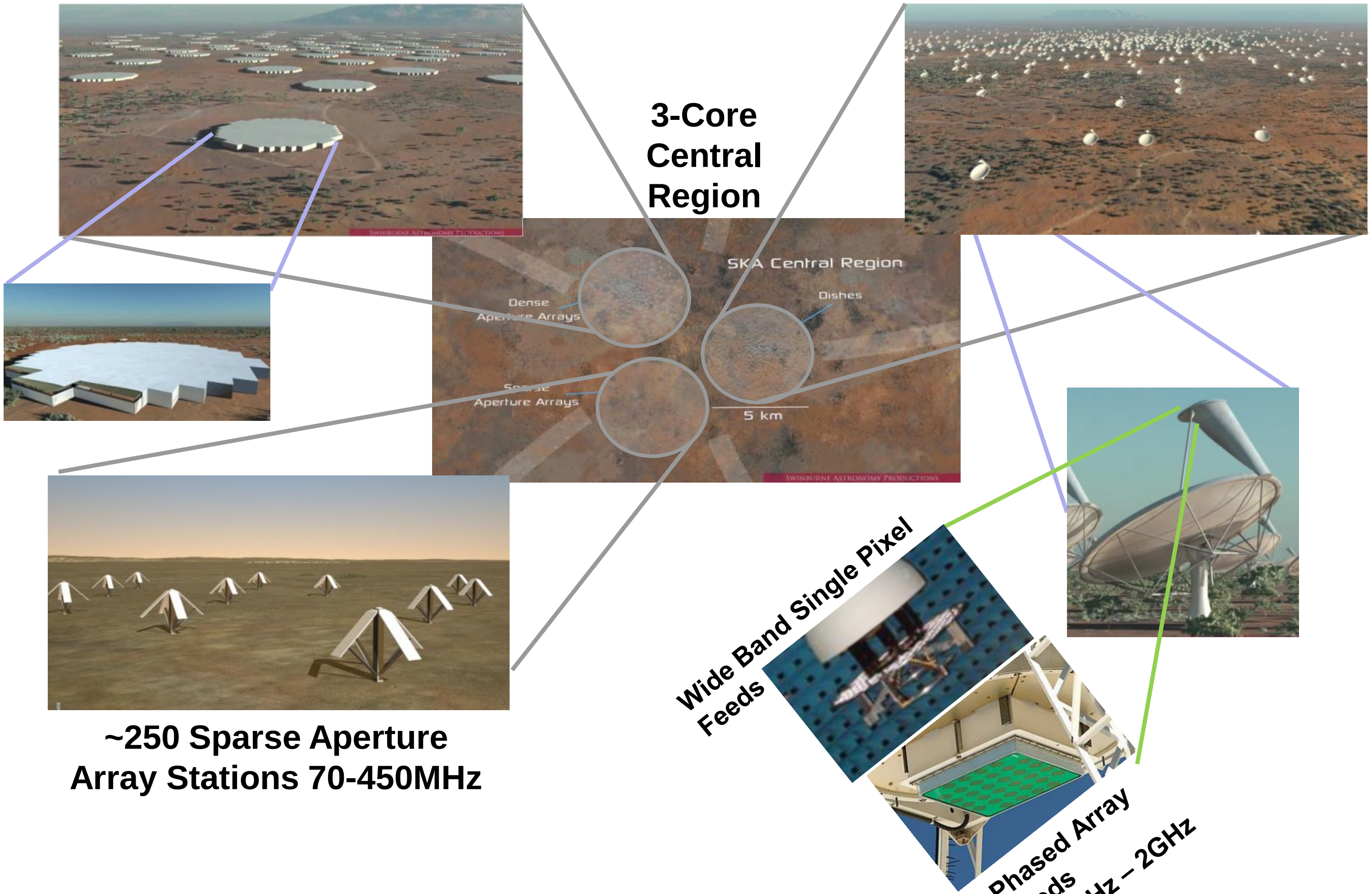




Sensitivity comparison



SKA2



~ 250 Dense Aperture Array Stations 300-1400MHz

3-Core Central Region

~ 2700 Dishes

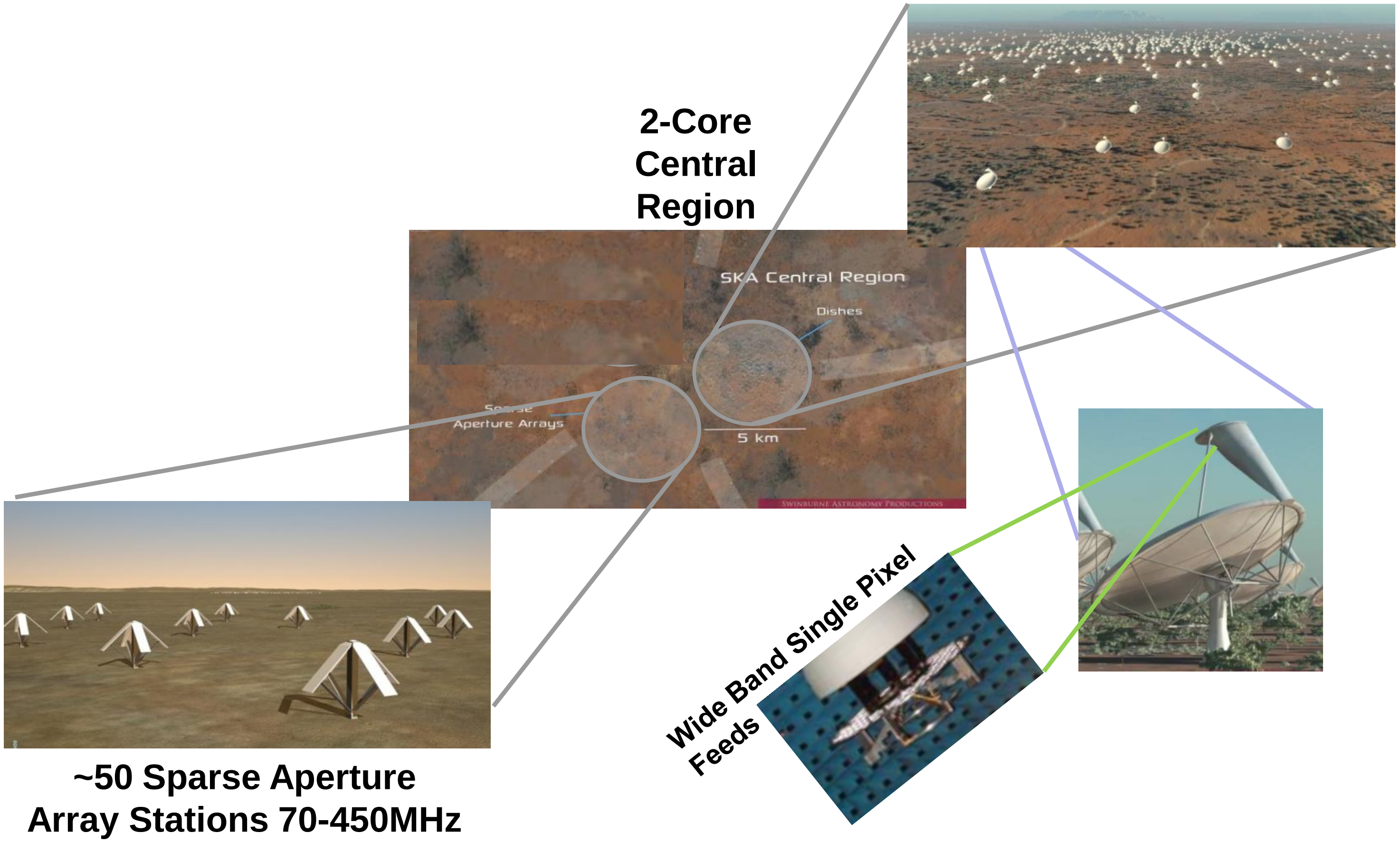
~250 Sparse Aperture Array Stations 70-450MHz

Wide Band Single Pixel Feeds

Phased Array Feeds 800 MHz – 2GHz

Artist renditions from Swinburne Astronomy Productions

SKA1



~ 300 Dishes

2-Core Central Region

Wide Band Single Pixel Feeds

~50 Sparse Aperture Array Stations 70-450MHz

Artist renditions from Swinburne Astronomy Productions

Programme leading to SKA

- **Science with pathfinders and precursors**
  - LOFAR – Now
    - 32 NL stations + >7 international
    - Aperture array 10-90MHz, 110-250MHz
    - Up to 32 fields of view
    - EoR, **cosmic magnetism**, **surveys for early AGN**
  - ASKAP – 2013 / 2014, AU
    - 30 12-m dishes equipped with PAFs
    - 20 sq-degrees FoV 800MHz - 2GHz
    - Local HI, **deep surveys**, pulsar search and timing, **cosmic magnetism**
  - MeerKAT – 2014, RSA
    - 70 13.5-m dishes SKA design
    - 1 sq-degree FoV 800MHz – 15GHz in 3 bands
    - Local HI, **deep surveys**, pulsar timing, **search for z~7-10 CO**

The Science Aims and the Imaging Challenges

SKA Key Science Drivers

ORIGINS

- Neutral hydrogen in the universe from the Epoch of Re-ionisation to now

  When did the first stars and galaxies form?
  How did galaxies evolve?
  Role of Active Galactic Nuclei
  Dark Energy, Dark Matter

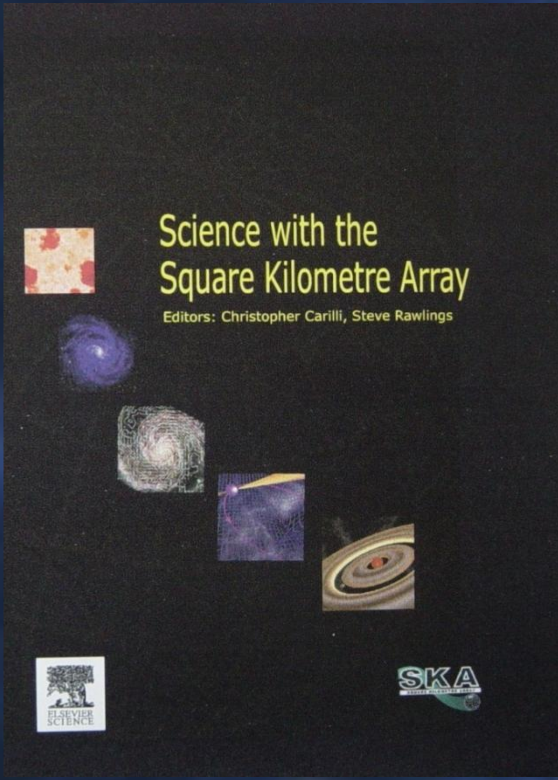
- Cradle of Life

FUNDAMENTAL FORCES

- Pulsars, General Relativity & gravitational waves

- Origin & evolution of cosmic magnetism

TRANSIENTS (NEW PHENOMENA)



Science with the
Square Kilometre Array

Editors: Christopher Carilli, Steve Rawlings

ELSEVIER
SCIENCE

SKA

Science with the Square Kilometre Array

(2004, eds. C. Carilli & S. Rawlings, *New Astron. Rev.*, 48)

Galaxy Evolution back to z~10?

HDF

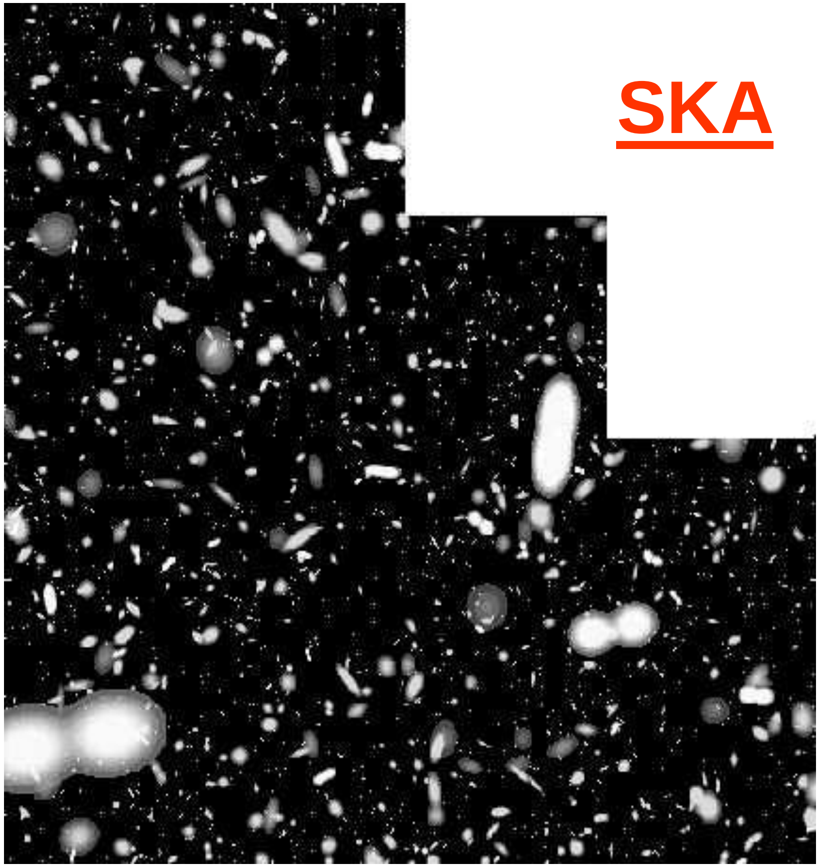
~ 3000 galaxies

VLA

~15 radio sources

Galaxy Evolution back to z~10?

HDF



SKA

The Imaging Challenge

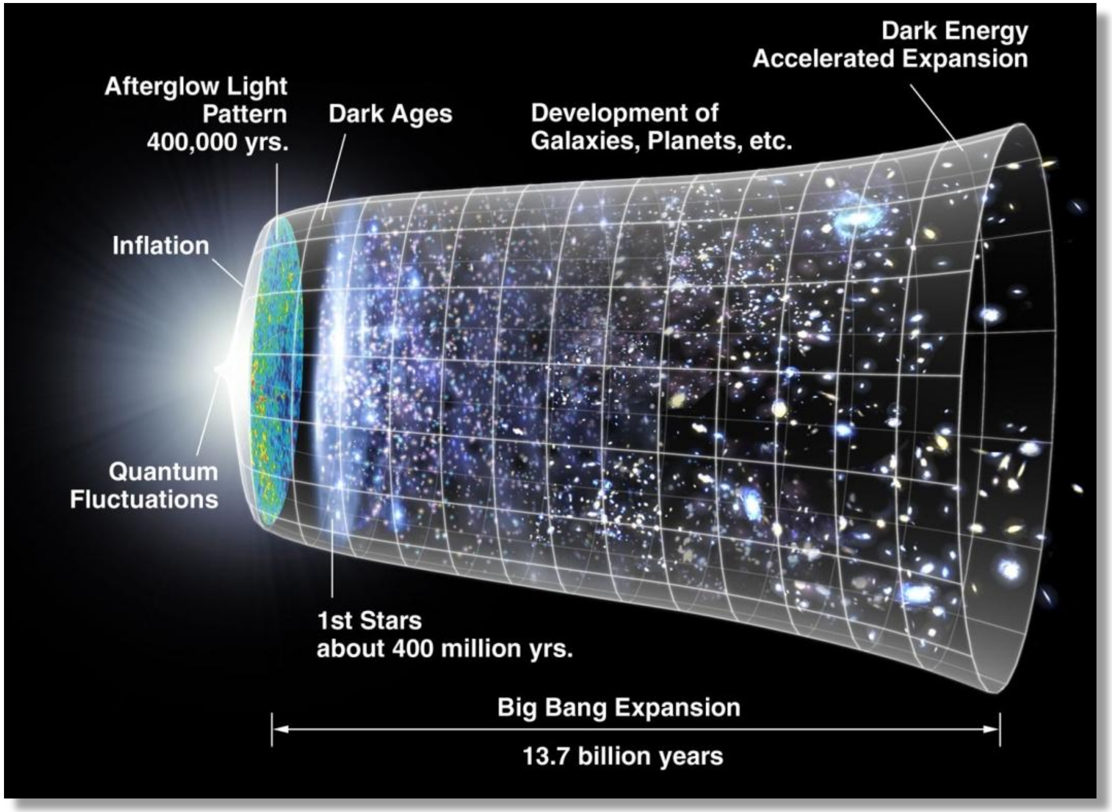
This illustrates one of our main challenges

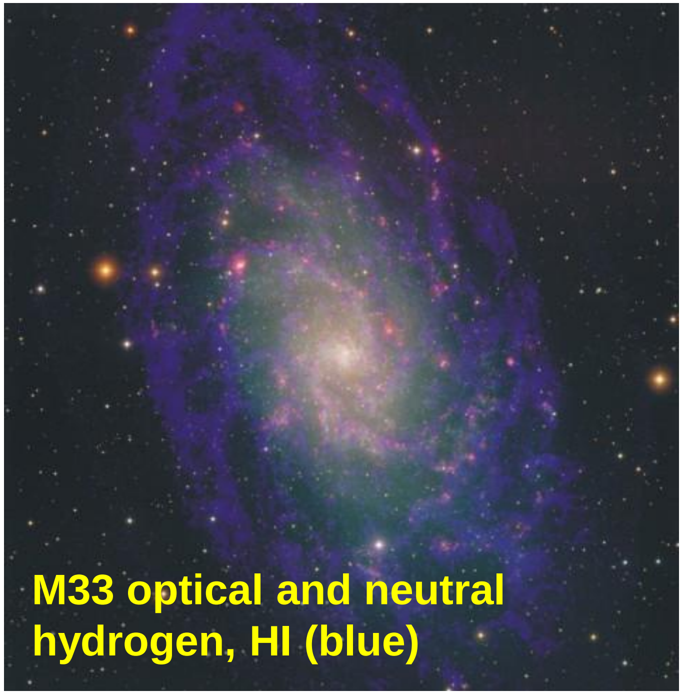
- To make effective use of the improved sensitivity we face an immediate problem
- Typically within the field of view of the telescope the noise level will be ~10^6 – 10^7 times less than the peak brightness
- We have to achieve sufficiently good calibration and image fidelity to routinely achieve a “***dyanamic range***” of > 10^7:1
- With very hard work now we can just get to 10^6:1 in some fields

The Imaging Challenge

- Telescope calibration now becomes critical
- We also want to survey the sky very quickly to achieve our science aims
  - ➢ We are designing our telescope to have a large FoV
  - ➢ **We can no longer make the approximation of we used above and must concern ourselves with (better approximations to) the full problem**

Cosmology & the History of Hydrogen



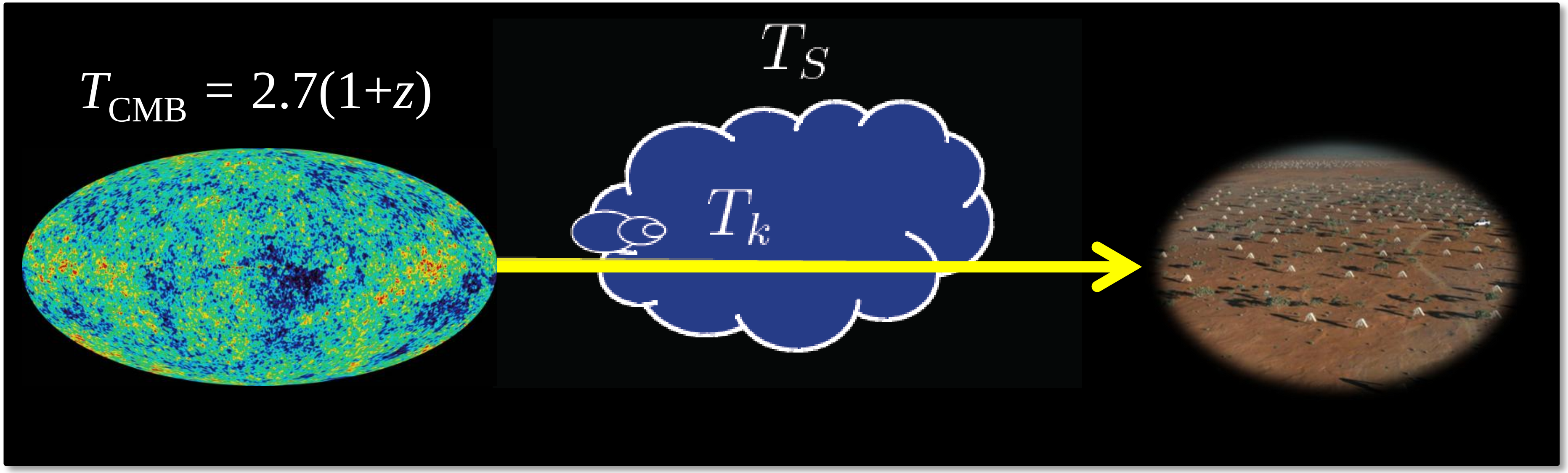

M33 optical and neutral hydrogen, HI (blue)

- After recombination (CMB) Universe if neutral, but we know that hydrogen (not in galaxies) is hot and ionised
- Re-ionization occurs when first objects (galaxies and AGN) form via UV- and X-ray emission
- Epoch of Reionisation – EoR next major challenge for Cosmology

- $^2S_{1/2}$ ground state of HI split by the effects of nuclear spin
- $\Delta E = 5.8 \times 10^{-6}$ eV

21-cm line at 1420 MHz.

Hydrogen Evolution



Spin temperature is defined via and radiation processes

$$\frac{n_2}{n_1} = \frac{g_2}{g_3} \exp\left(\frac{h\nu}{k_B T_S}\right)$$

and determined by collisional

The HI intensity in Rayleigh-Jeans limit is given by

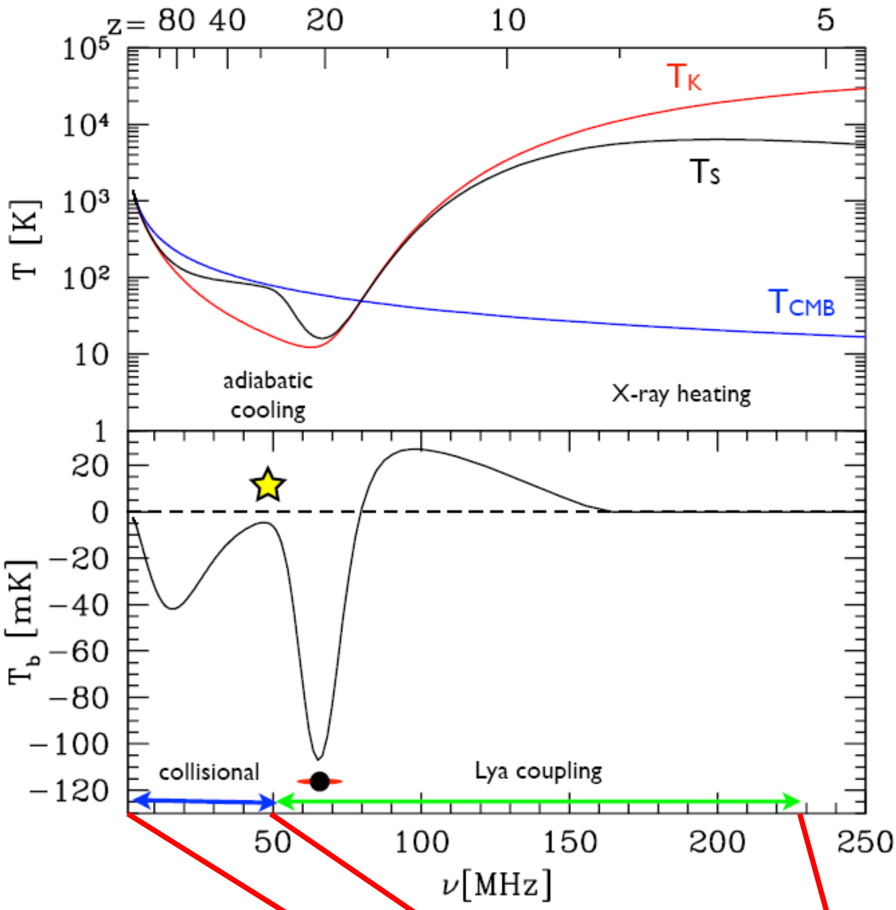
$$T_b = 27 x_{\rm HI}(1+\delta_B)\left(\frac{T_S - T_{\rm CMB}}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{\partial_r v_r}{(1+z)H(z)}\right)^{-1} \ \mathrm{mK}$$

Ionisation fraction

Baryon overdensity

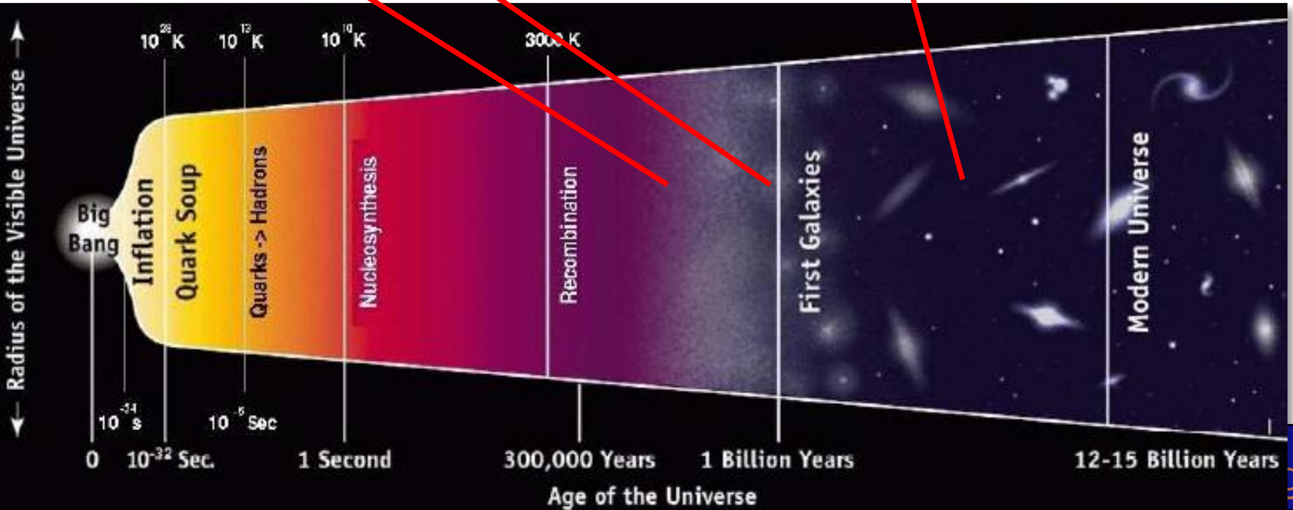
Peculiar velocity relative to Hubble flow

Hydrogen Evolution



Prichard and Loeb, 2010

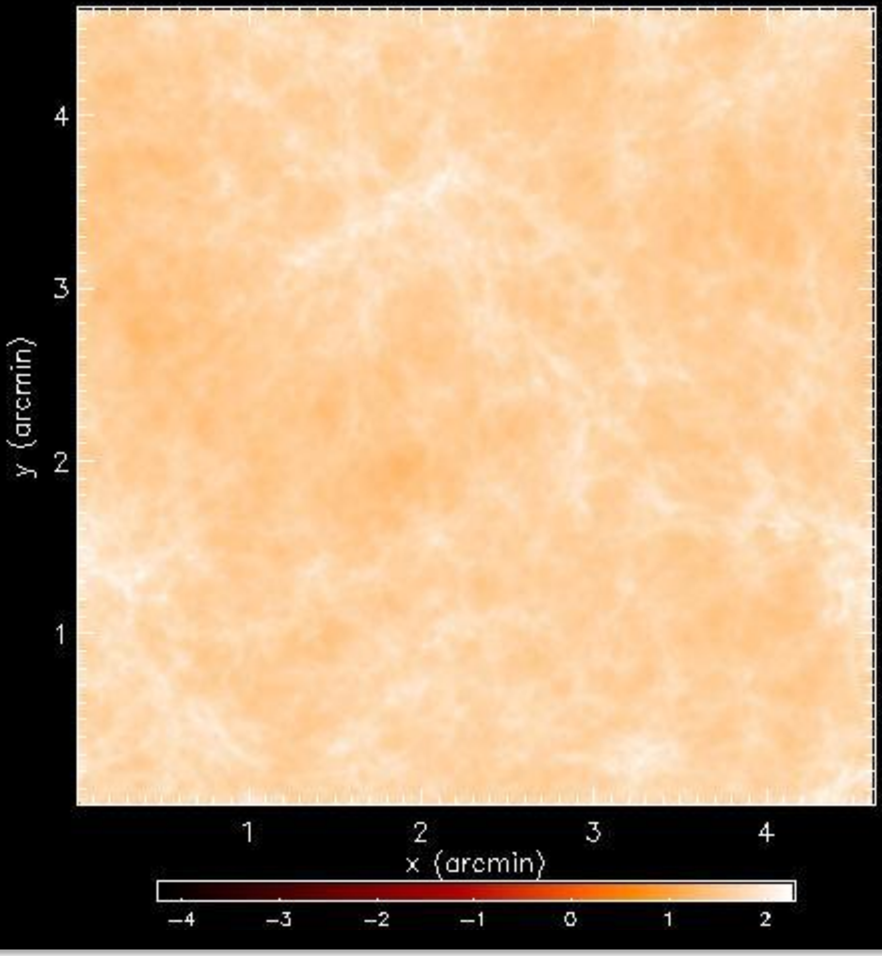
- After recombination gas and CMB cool adiabatically
  - Kinetic temperature: $T_K < T_{CMB}$
- Density is large enough that collisions give $T_S \sim T_K$
- As density falls CMB determines T_S and $T_S \rightarrow T_{CMB}$
- As first objects form UV resonant scattering couples T_S to T_K



- Overdensities in dark matter and baryonic gas collapse
- Gas temperature increases and so does T_S due to heating from first stars and AGN
- UV and X-ray flux also ionise the gas → $T_S \rightarrow 0$

Furlanetto et al. (2003)

Epoch of Re-ionization



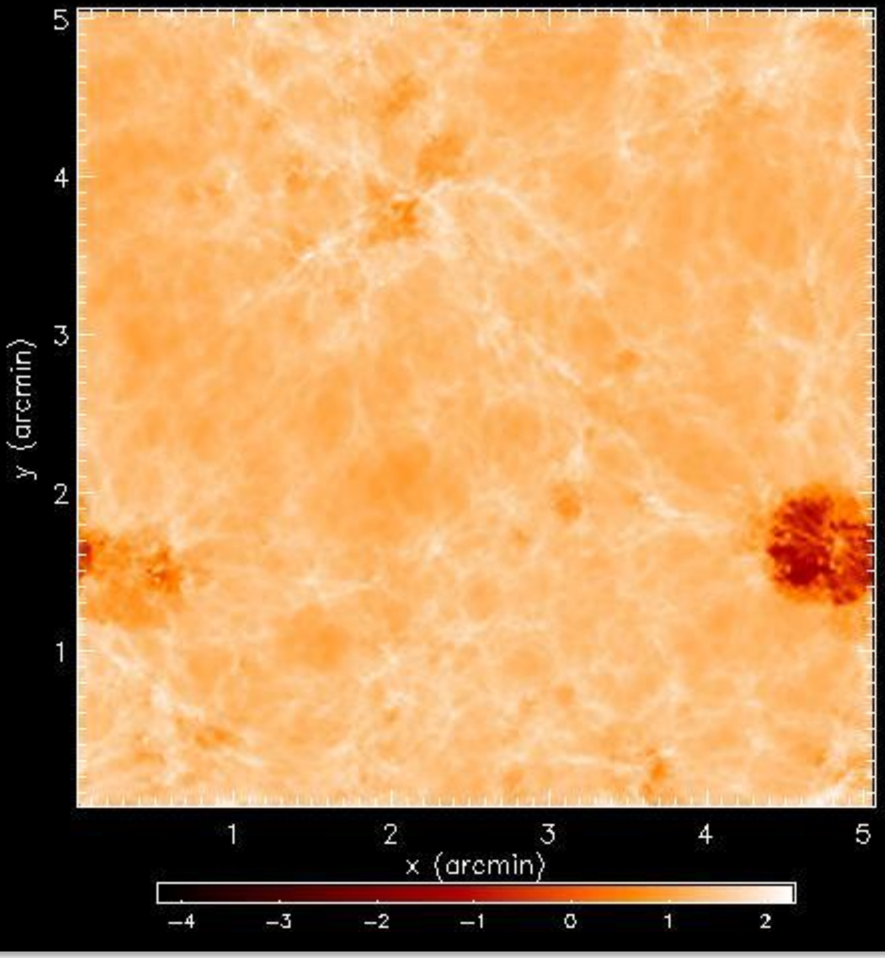
z=18.3

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

Epoch of Re-ionization



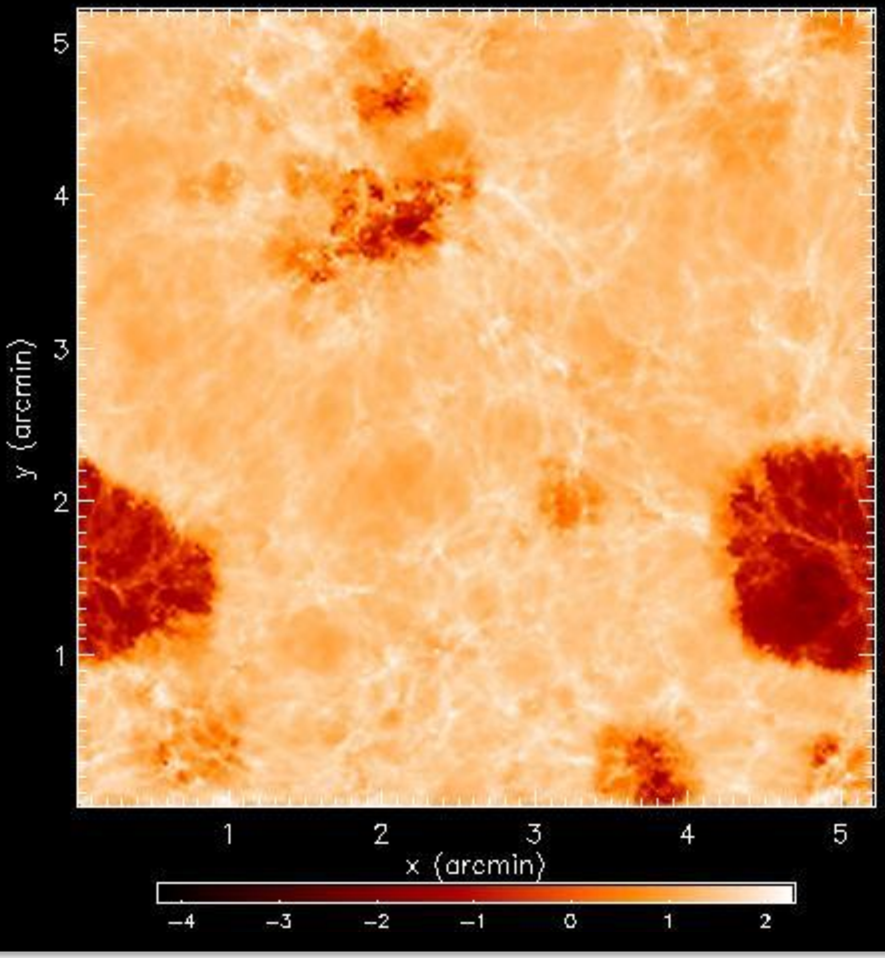
z=11.2

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

Epoch of Re-ionization



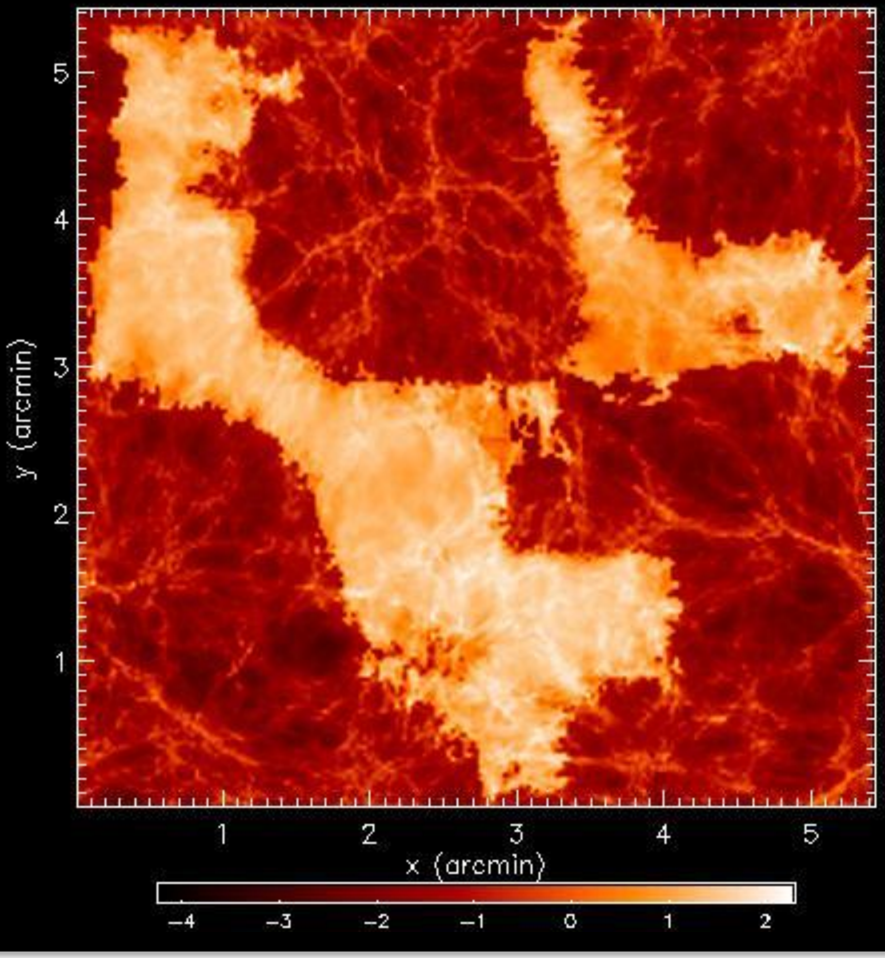
z=9.8

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

Epoch of Re-ionization



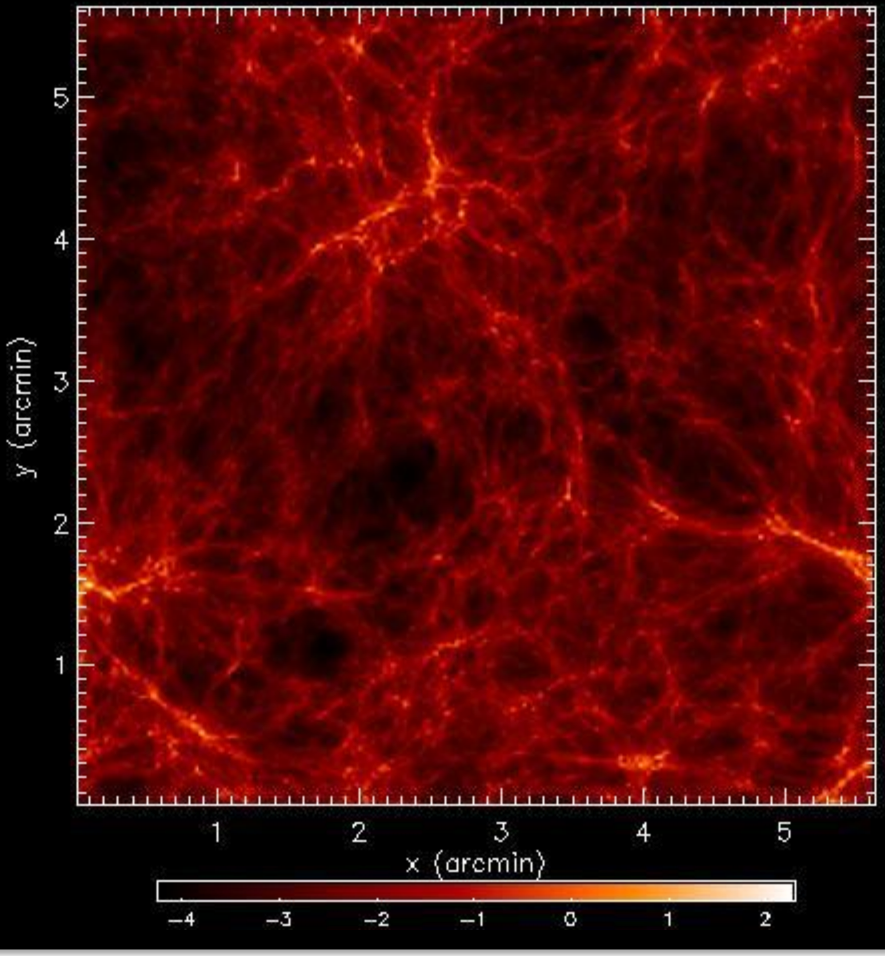
z=8.3

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Epoch of Re-ionization

Furlanetto et al. (2003)



z=7.2

10 Mpc comoving

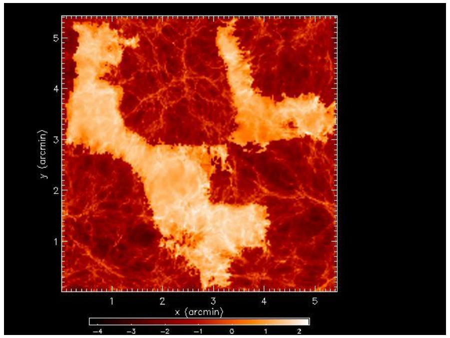
$\Delta\nu$=0.1 MHz

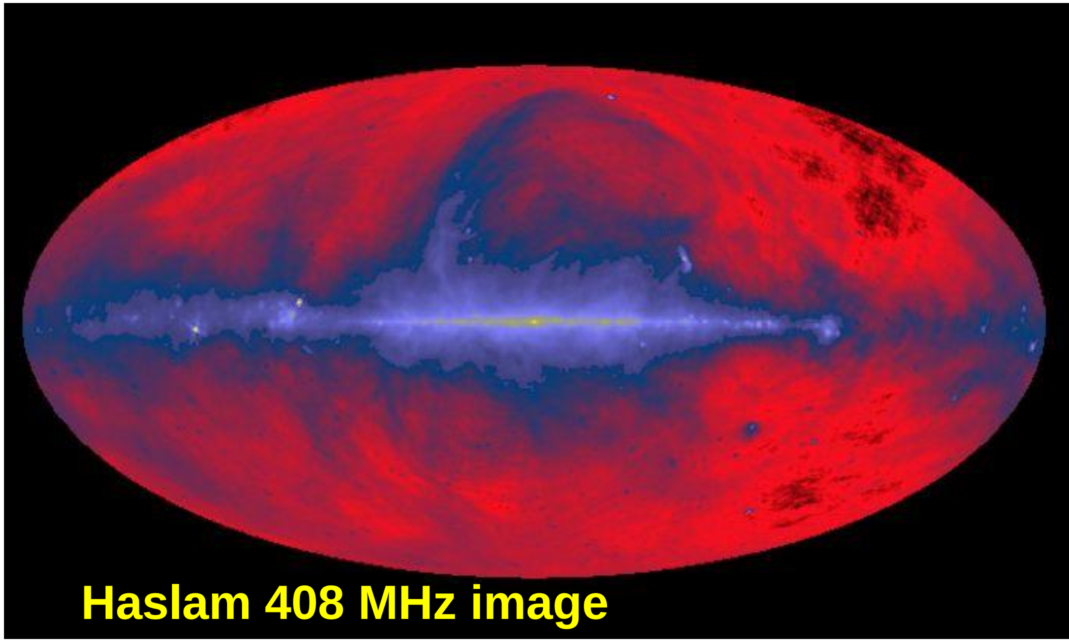
The Imaging and Data Processing Challenges of this Experiment

- The structures to be observed have a flux of
  0.3μJy/Beam (1 Jy = 10^{-26} Wm^{-2}Hz^{-1}sr-1)
- Need to observe a region of about 25 sq degrees
  - In this region expect to have at least one source **> 1 Jy**
  - "***dyanamic range***" of > 3 x 10^6:1
- In frequency range 50 – 250 MHz even in most remote areas must deal with man-made Radio Frequency Interference (RFI)
- We are attempting to measure a broad spectral signal is the presence of a very strong "foreground"

The Imaging and Data Processing Challenges of this Experiment

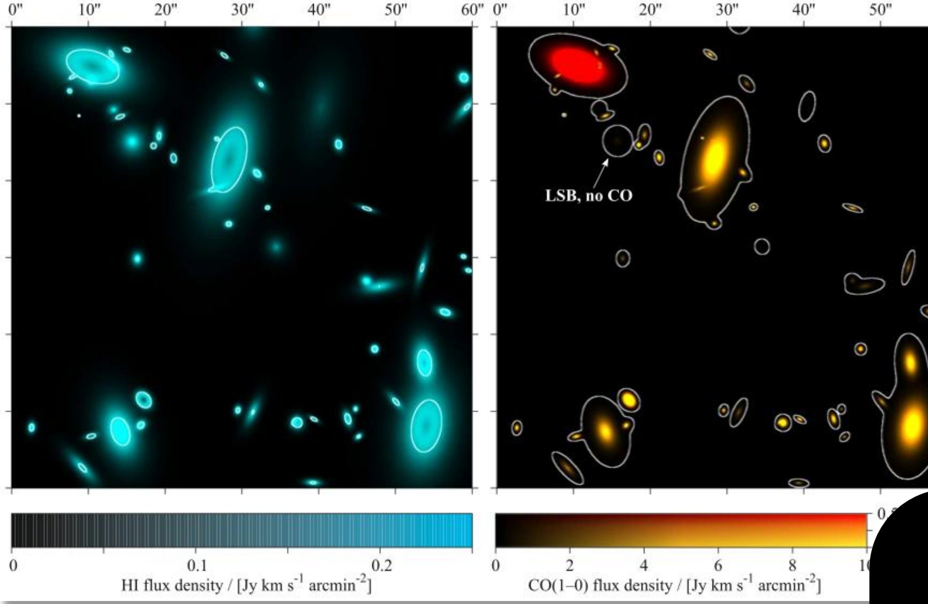
- Foreground is due to continuum emission from our own galaxy and discrete extragalactic sources
- Up to 10^5 times brighter than the signal we are measuring
- Need to filter or subtract this foreground
  - Frequency and spatial filtering
  - Challenge for calibration and imaging

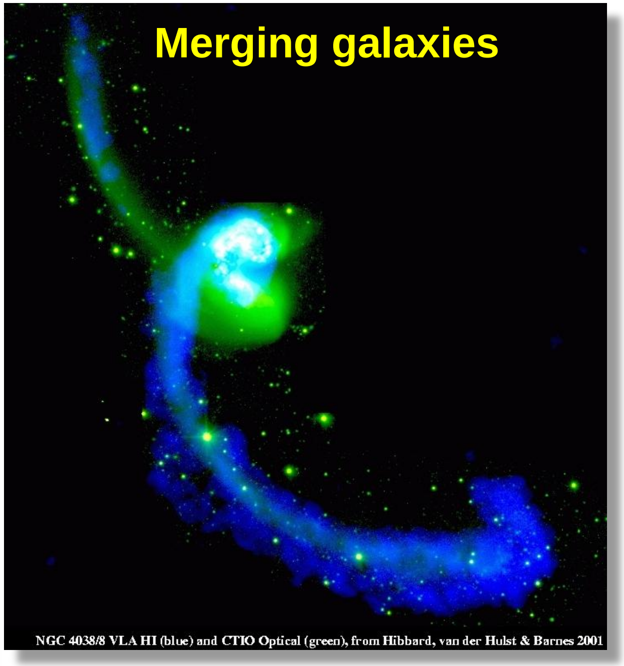



Haslam 408 MHz image

Galaxy Evolution

- **At the end of the EoR Neutral hydrogen is in galaxies – fuel for star formation**
- **SKA + ALMA will follow gas content**

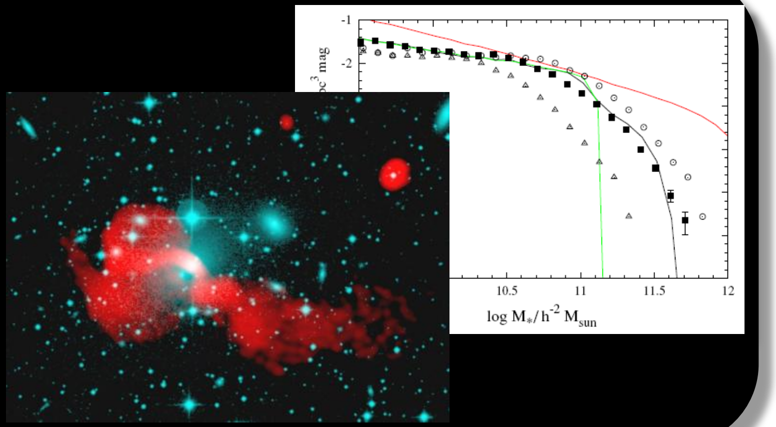



Merging galaxies

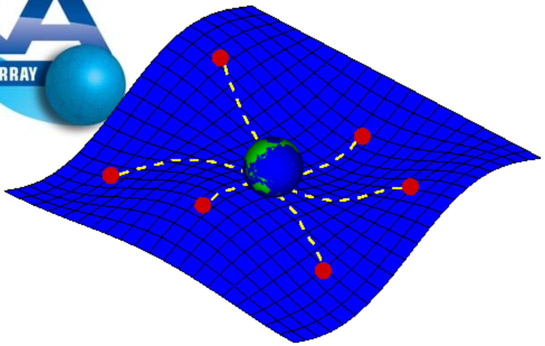
NGC 4038/8 VLA HI (blue) and CTIO Optical (green), from Hibbard, van der Hulst & Barnes 2001

Evolution of gas star formation and AGN in galaxies

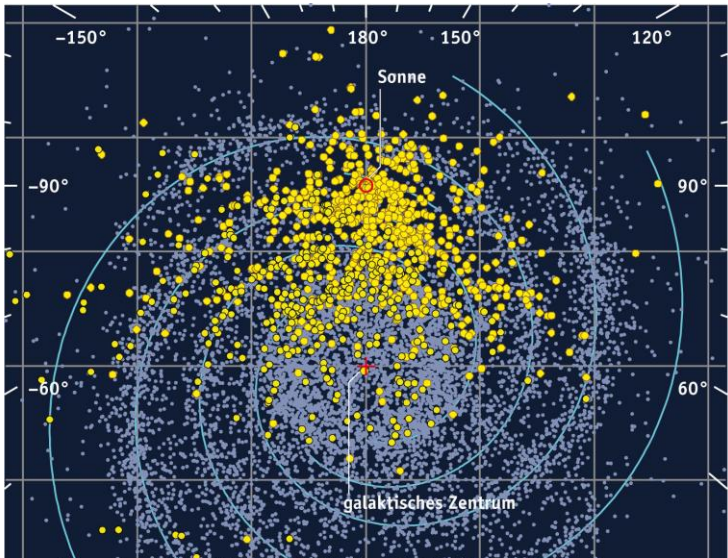
- **Detect SF galaxies to z = 7 (25 M/yr)**
- **Distinguish AGN in galaxies to z ~ 7**
- **HI in galaxies to z=2 in emission and higher in absorption → dynamical studies**

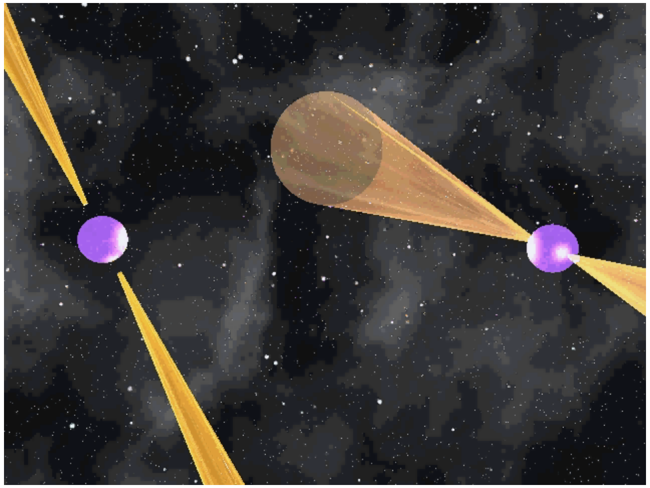


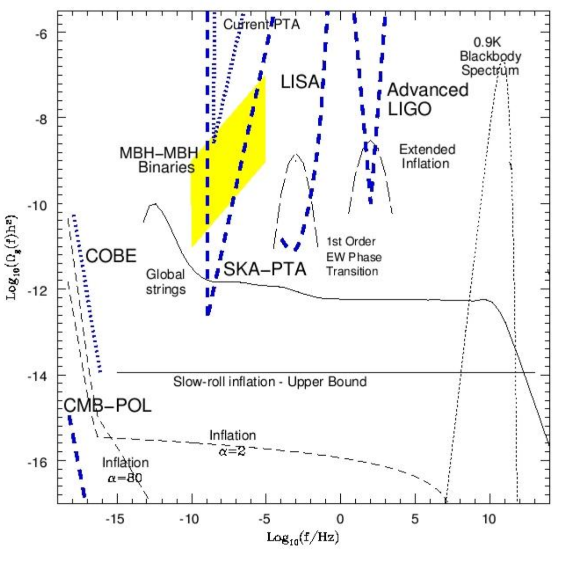
Pulsar Surveys: Testing gravity



- The SKA will detect around 20,000 pulsars in our own galaxy
- Timing net of ms pulsars to detect gravitational waves via timing residuals
- Relativistic binaries give unprecedented strong-field test of gravity







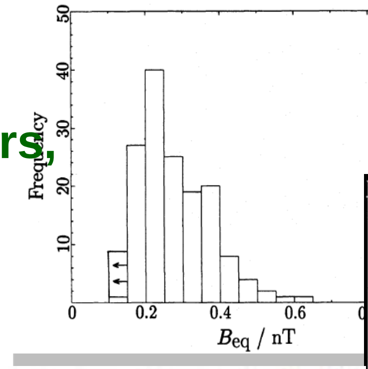
The Magnetic Universe

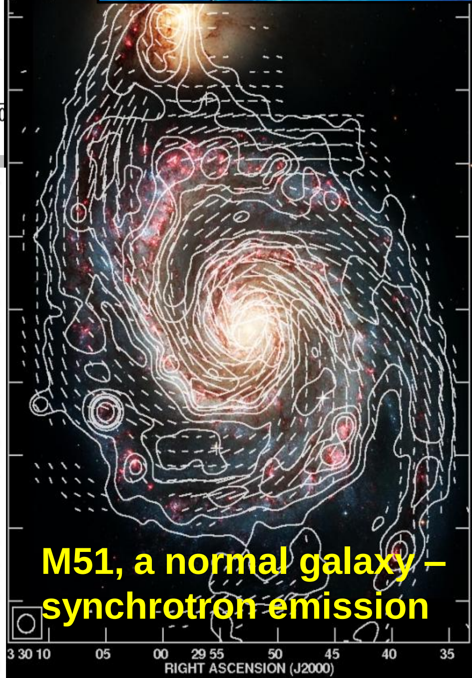
- Magnetic fields appear to be universal
  - Only large-scale manifestation of EM force
  - Highly ionised gas → flux conserved
- Magnetic fields can influence the dynamics of systems
  - Exert a magnetic pressure or tension
  - Known to be important in: AGN, star-forming regions, galaxy clusters, stars, large scales?

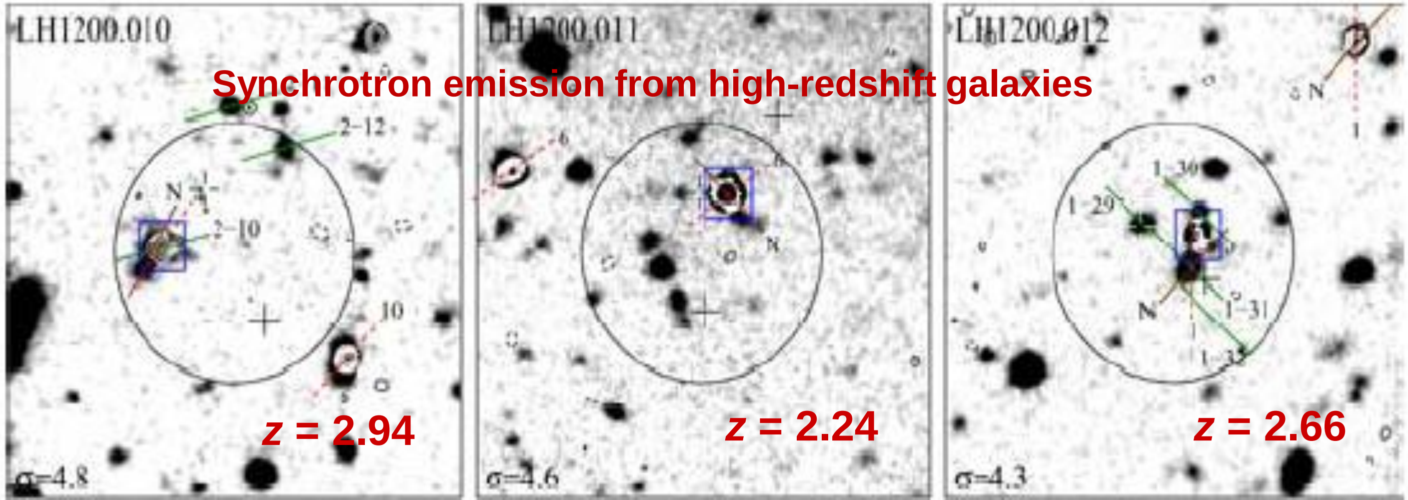
What is there cosmological origin & evolution?


AGN – synchrotron emission


Stars and solar system




M51, a normal galaxy – synchrotron emission

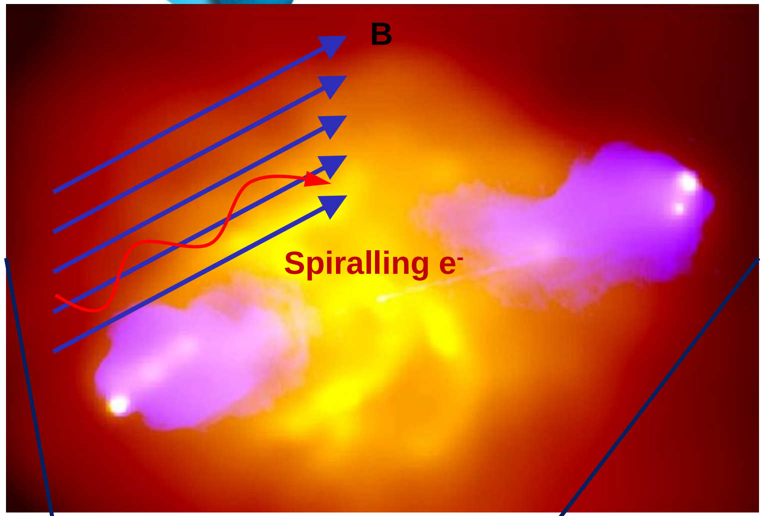

Synchrotron emission from high-redshift galaxies

z = 2.94

z = 2.24

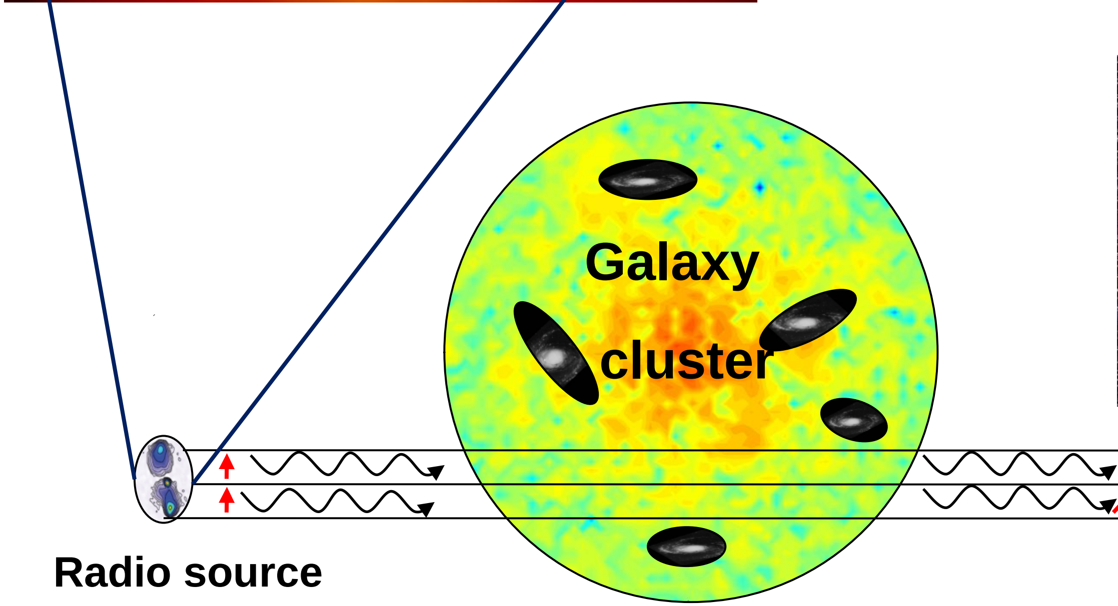
z = 2.66

Observing Magnetic Fields

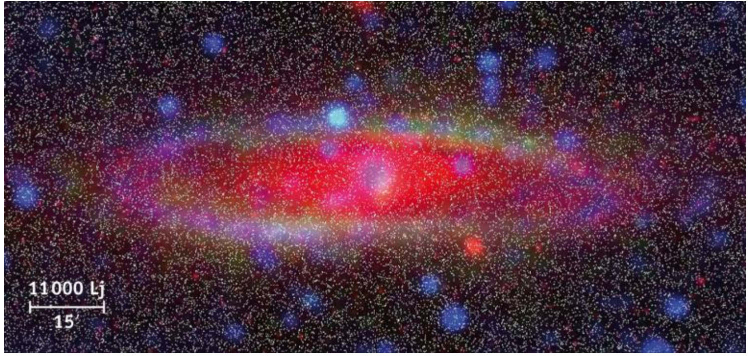


Observe Faraday Rotation against background polarized synchrotron source

$$\phi = 0.81 \int n_e B_{||} dl$$



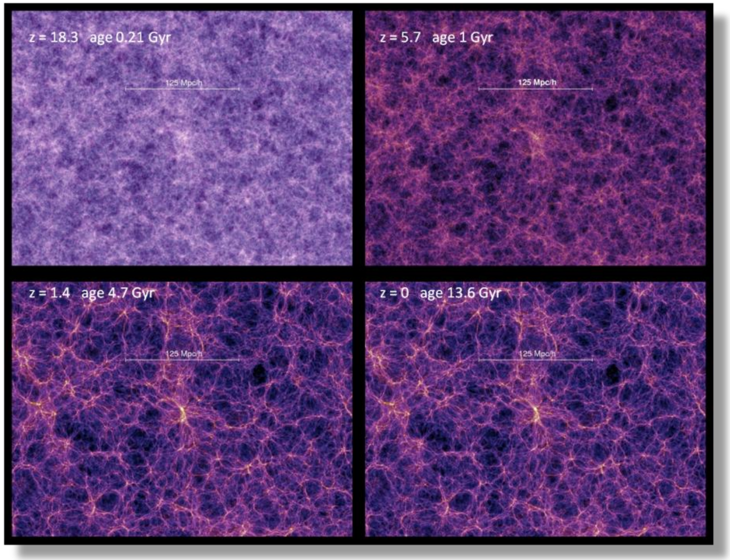
Simulation of background sources behind M31 expected with the SKA
Optical emission, radio emission, polarized radio emission

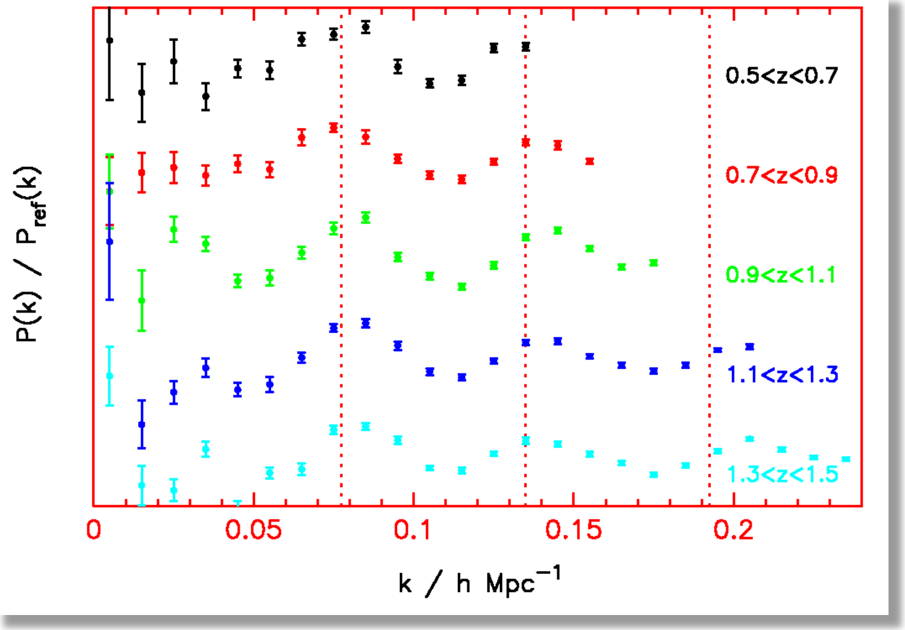


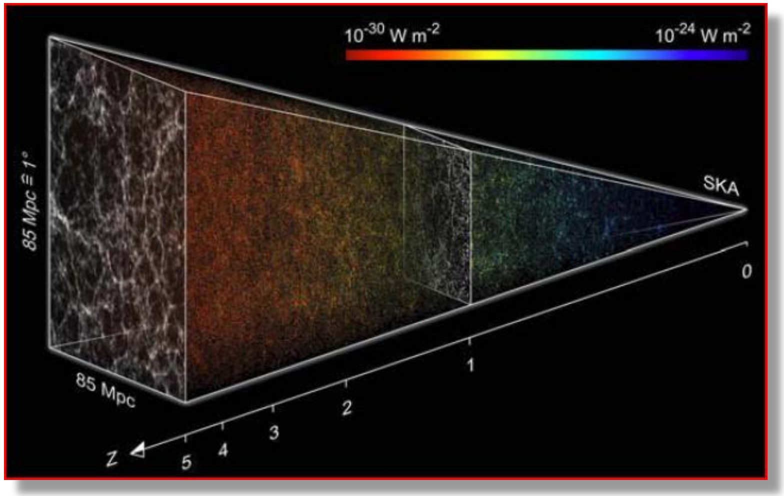
Beck and Gaensler

Large-Scale Structure

- Large-scale structure redshifts of 10^9 galaxies
  - Evolution of Baryonic Acoustic Oscillations with z – standard rod
  - Power-spectrum on largest angular scales as a function of z
  - Damping on large scales → constrains Neutrino mass







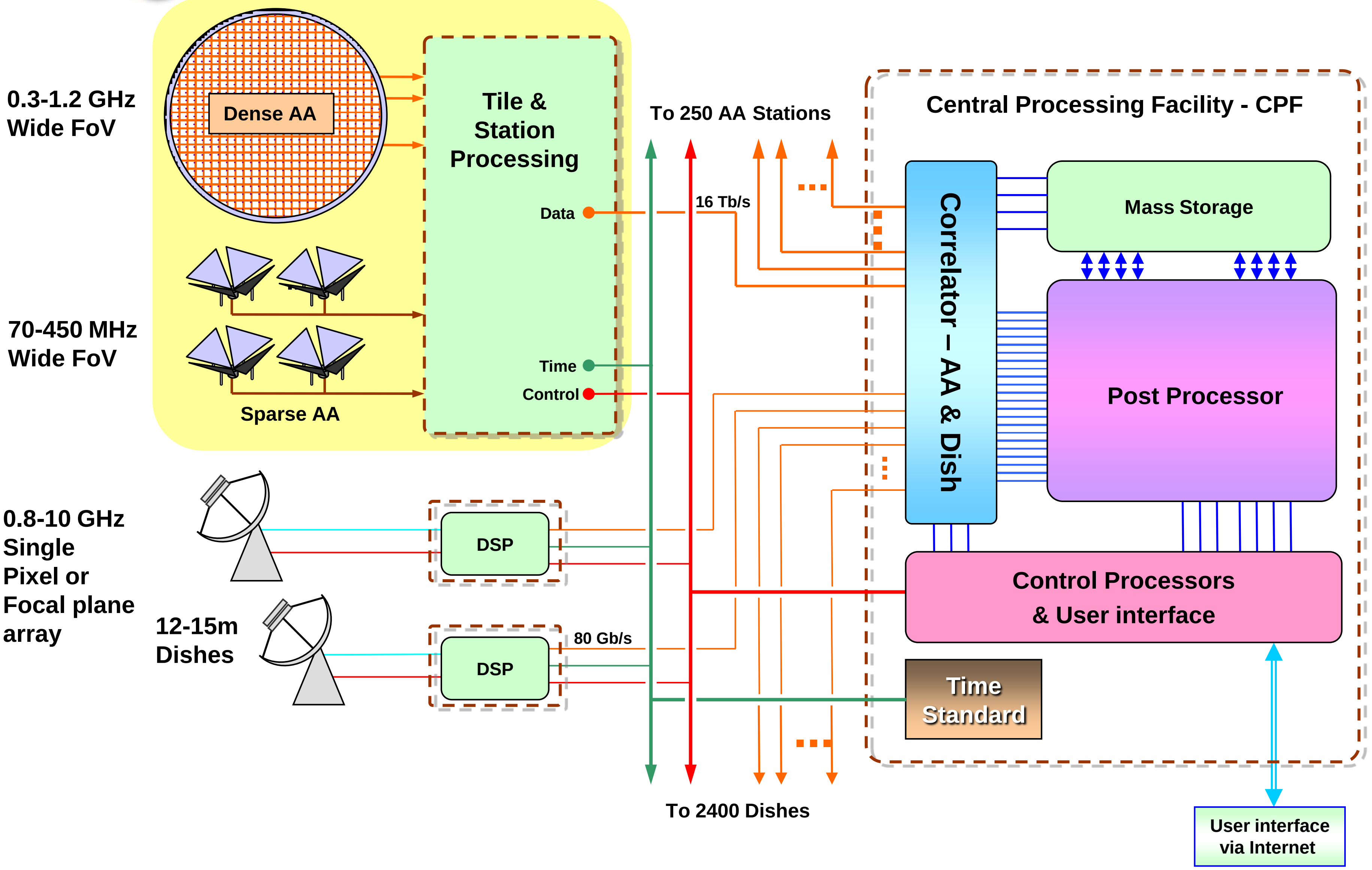
... and so much more

- Star formation history of the universe
- Physics of active galaxies, accretion discs, pulsars, jets, ...
- Radio emission from decaying dark matter
- The cosmic web and structure formation
- Measuring changes in the fine structure constant
- Interstellar medium of galaxies
- Astrobiology – direct detection of large molecules
    - ... and evidence for intelligent life?

Most importantly what we haven’t predicted

The Processing Challenge

SKA Overall System



Some numbers to remember

Fastest HPC today – 2 PFlop

Total internet data rate ~ 20 Tb/s

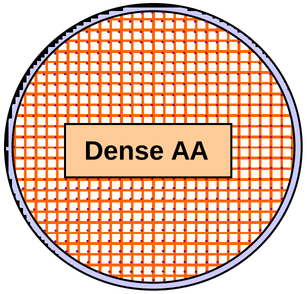
BUT on your desktop you can have ~1 TFlop

Data rates to the correlator

Data rate from each collector

$G_1 = 2\, N_p\, \Delta f\, N_{bit}\, N_b = 4\, \Delta f\, N_{bit}\, N_b$

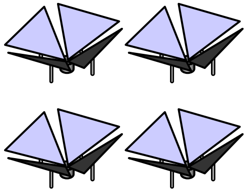
$$N_b = \frac{1}{\Delta f} \int_{f_{max}-\Delta f}^{f_{max}} n_b(f)\, df$$



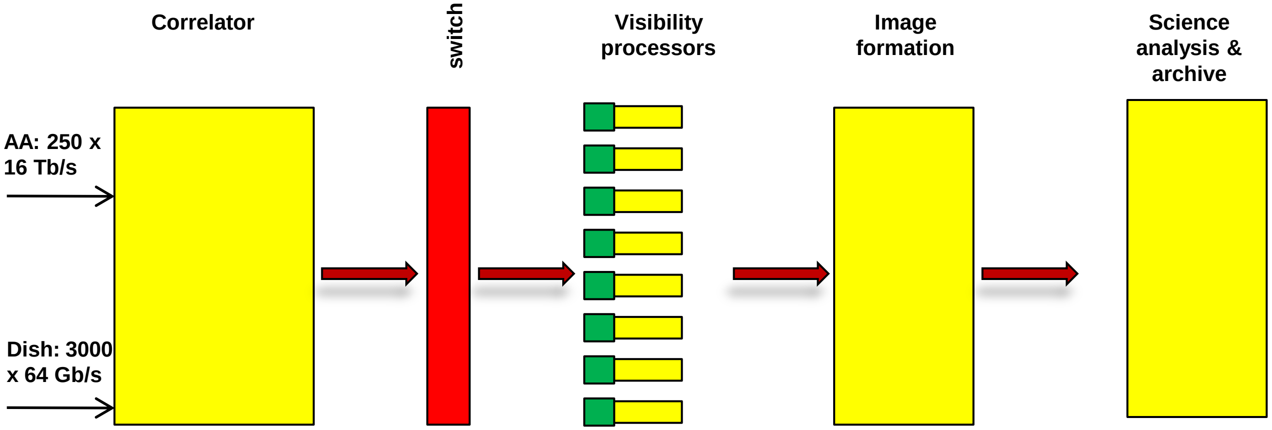
AA, Number of elements $N_e \sim 65000$; $N_b << N_e$ limited by data rate

250 sq-deg across band $N_b \sim 1200$ (Memo 100)

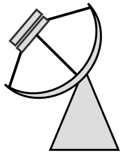
$G_1 \sim 16$ Tb/s



Sparse AA



12-15m Dishes



Dishes $G_1 \sim 64$ Gbs

PAFs FoV is constant across the band

$N_b \sim 7$ to give 20 sq-deg across the band $G_1 \sim 60$ Gb/s (Memo 100)

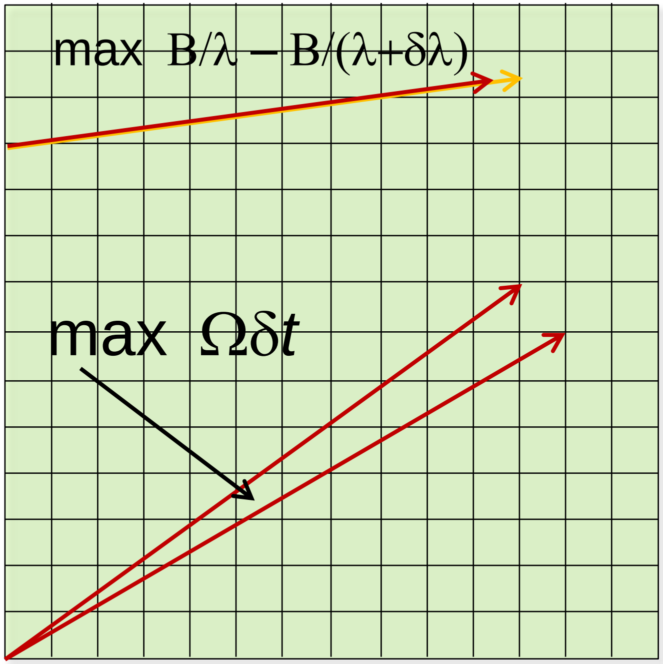
Data Rates

- After correlation the data rate is fixed by straightforward considerations
  - Must sample fast enough (limit on integration time) δt
  - Baseline $\propto$ B/λ
  - UV (Fourier) cell size $\propto$ D/λ

$$\Omega\delta t\frac{B}{\lambda} < \frac{1}{X}\frac{D}{\lambda}$$

  - Must have small-enough channel width to avoid chromatic aberration

$$\delta\left(\frac{B}{\lambda}\right) < \frac{1}{X}\frac{D}{\lambda}$$



Data rates from the correlator

- Standard results for integration/dump time and channel width

$$\frac{\delta t}{s} = a_t \frac{D}{B} \sim 1200 \frac{D}{B} \qquad \frac{\delta f}{f} = a_f \frac{D}{B} \sim \frac{1}{10} \frac{D}{B}$$

- Data rate then given by

$$G = g(B) \frac{1}{2} N^2 N_p^2 N_b \frac{1}{\delta t} \frac{\Delta f}{\delta f} 2N_w \qquad G = g\boxed{(B) N^2 N_w} N_p^2 N_b \frac{1}{a_t a_f} \boxed{\frac{\Delta f}{f} \left(\frac{B}{D}\right)^2}$$

\# antennas # polarizations # beams word-length

- Can reduce this using baseline-dependent integration times and channel widths

Example data rates SKA1

- Aperture Array Line experiment (e.g. EoR)
  - 100 sq degrees; 10000 channels over 250 MHz bandwidth
    - ➢ 5 GB/s sustained
- Pointed observations, for periods of up to an hour
  - Small FoV; 32000 channels over 1 GHz
    - ➢ 50 GB/s sustained
- Pointed observations, for periods of up to an hour
  - Data sets
    - ➢ Up to 50 TB UV (Fourier) data
    - ➢ Images ~ 4 TB; up to 250 TB/day to archive

Example Data rates SKA2

Experiment				**3000 Dishes + SPF**		**1630 Dishes + PAFS**		**250 AA stations**	
Description	B_{max} (km)	Δf (MHz)	f_{max} (MHz)	Achieved FoV[1]	Data rate (Tb/s)	Achieved FoV[1]	Data rate (Tb/s)	Achieved FoV[1]	Data rate (Tb/s)
Survey: High surface brightness continuum	5	700	1400	0.78	0.055	15	0.11	108	0.03
Survey: Nearby HI high res. 32000 channels	5	700	1400	0.78	1.0	15	2.0	108	2.6
Survey: Medium spectral resolution; resolved imaging (8000)	30	700	1400	0.78	1.2	15	2.4	108	5.4
Survey: Medium resolution continuum	180	700	1400	0.78	33.1	15	66	108	14.1
Pointed: Medium resolution continuum deep observation	180	700	1400	0.78	33.1			0.78	0.15
High resolution with station beam forming[2]	1000	2000	8000	0.0015	33.4				
High resolution with station beam forming[3]	1000	2000	8000	0.0015	429				
Highest resolution for deep imaging[2]	3000	4000	10000	0.001	391				

Notes

1. Achieved FoV is at f_{max} and has units of degrees squared. For the AA and PAFs we calculate the data rate assuming it is constant across the band.
2. Assuming that for the dynamic range the FoV of the station only has to be imaged

3. Assuming that for the dynamic range the FoV of the dish must be imaged

Data Products

Experiment	T_{obs}	B/km	D/m	N_b	N_{ch}	N_v	**Size / TB**
High resolution spectral line	3600	200	15	1	32000	$5\ 10^{13}$	200
Survey spectral line medium resolution	3600	30	56	1000	32000	$8\ 10^{13}$	330
Snapshot continuum – some spectral information	60	180	56	1200	32	$7\ 10^{12}$	30
High resolution long baseline	3600	3000	60	1	4	$7\ 10^{14}$	360

- **~0.5 – 10 PB/day of image data**
- **Source count ~10^6 sources per square degree**
- **~10^{10} sources in the accessible SKA sky, 10^4 numbers/record**
- **~1 PB for the catalogued data**

100 Pbytes – 3 EBytes / year of fully processed data

Where does the data rate drop?

For SKA$_2$

Data rate out of correlator exceeds input data rate for 15-m dishes for baselines exceeding ~ 130km (36km if single integration time)

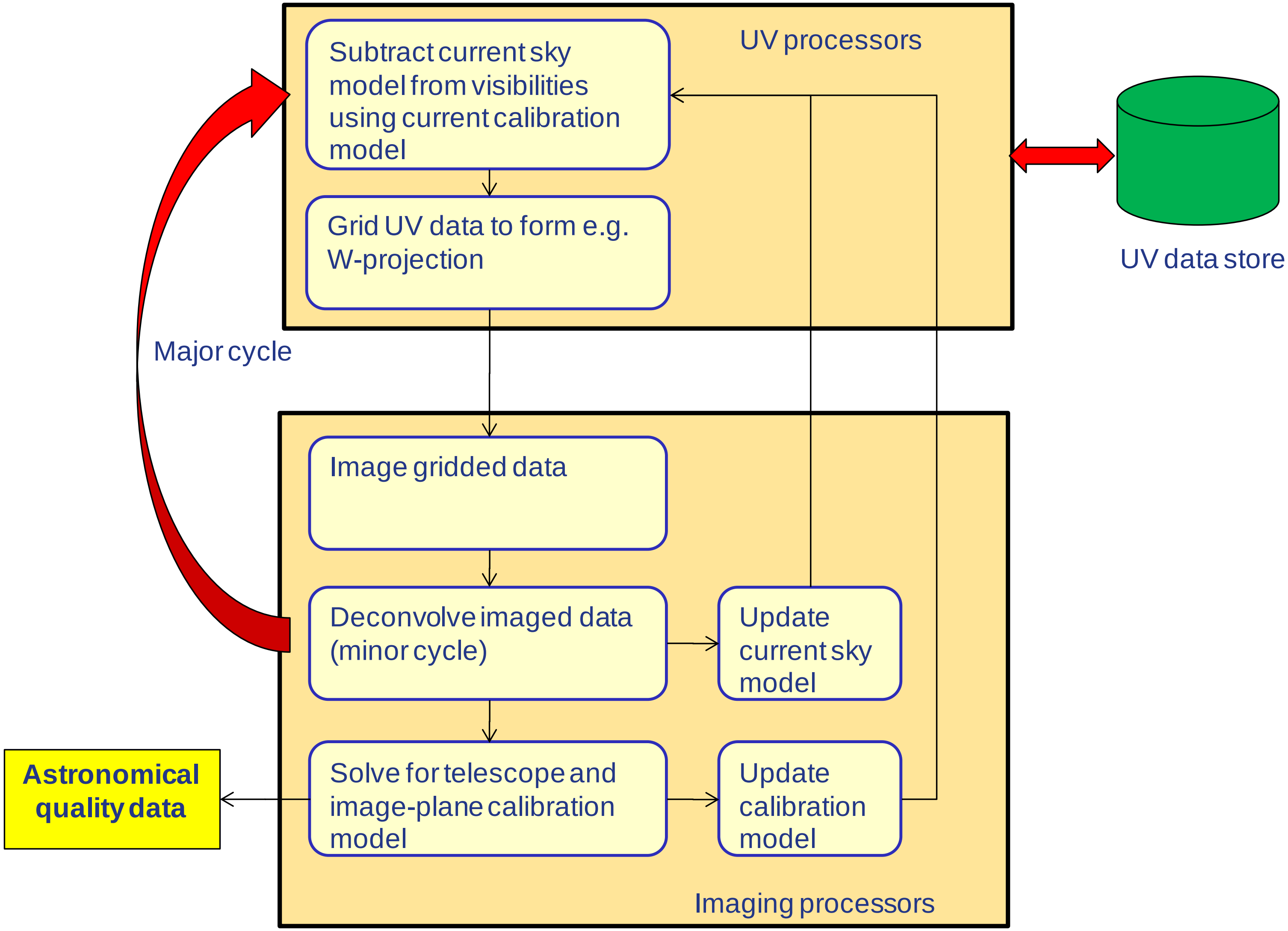
At best for dishes output data rate ~ input; AA's reduction by ~10^4

- Image size: $a^2 N_{ch} (B/D)^2 N_b$ Ratio UV to "image" data

$$\sim 0.06\, T_{obs}\, N^2 g(B) \frac{\Delta f}{f} \frac{1}{a_t a_f} \frac{1}{a^2} \frac{N_p^2}{N_{ch}} \quad \sim 210 \left(\frac{T_{obs}}{1\mathrm{min}}\right) \left(\frac{N}{1000}\right)^2 \left(\frac{N_{ch}}{32000}\right)^{-1}$$

Major reduction in data rate occurs between UV data and image data

Processing model



UV processors

Subtract current sky model from visibilities using current calibration model

Grid UV data to form e.g. W-projection

UV data store

Major cycle

Image gridded data

Deconvolve imaged data (minor cycle)

Update current sky model

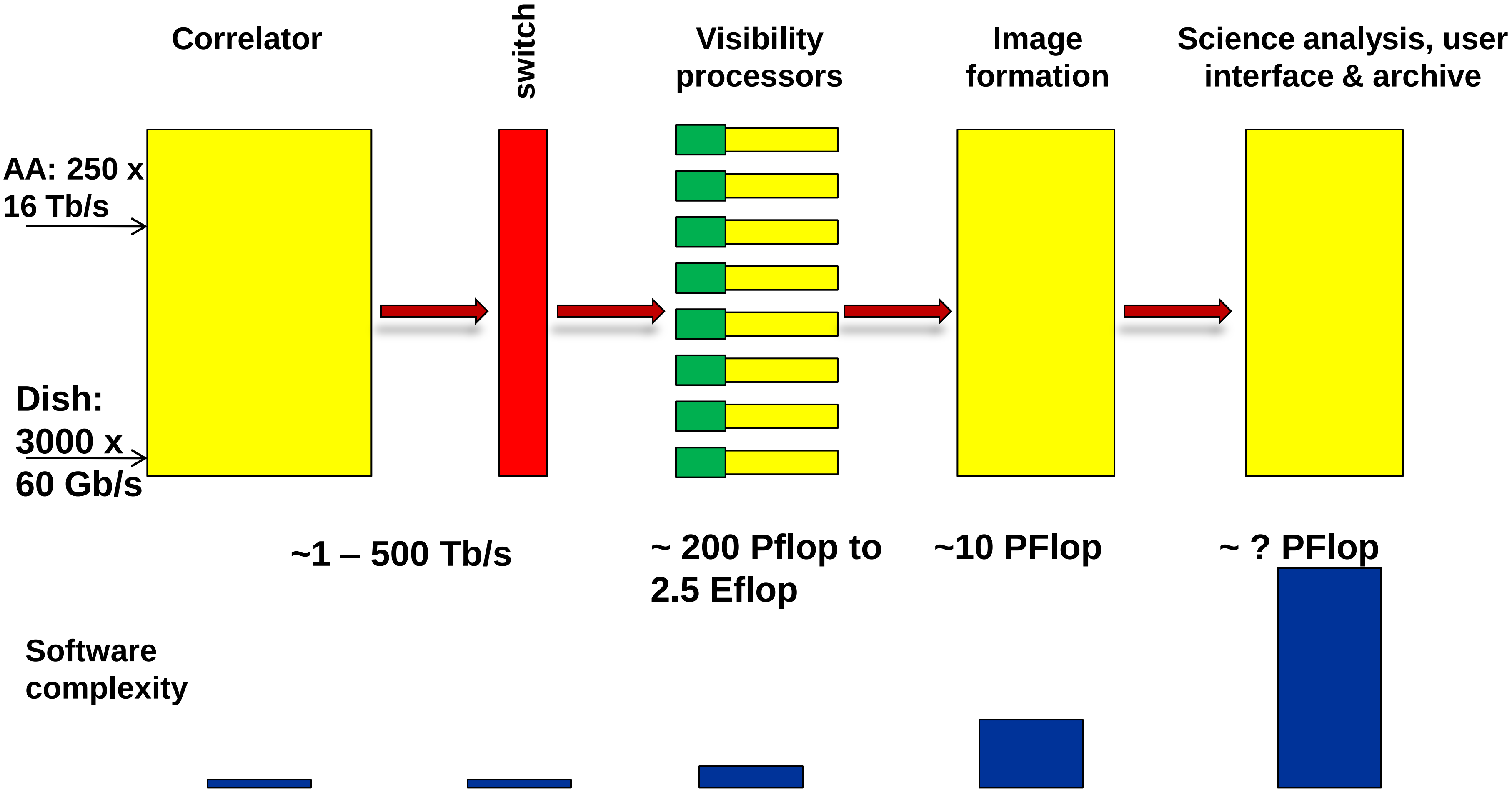
Solve for telescope and image-plane calibration model

Update calibration model

Astronomical quality data

Imaging processors

The SKA Processing Challenge



Correlator

switch

Visibility
processors

Image
formation

Science analysis, user
interface & archive

AA: 250 x
16 Tb/s

Dish:
3000 x
60 Gb/s

~1 – 500 Tb/s

~ 200 Pflop to
2.5 Eflop

~10 PFlop

~ ? PFlop

Software
complexity

Achieving high dynamic range now

What do we know we have to include in an analysis:

Include	Discussion	Maturity
Antenna-based complex gains	Standard calibration and self calibration – iterative	✓✓✓✓
Removing sources in global sky model	Removing bright sources from UV data even with local phase solution is relatively robust	✓✓✓
RFI and “bad data” excision	Can be critically important: • still largely done by hand for GMRT, eVLA and LOFAR • Expert algorithms not well developed	✓✓✓ ✓
Bandpass calibration	Well defined, but often more problematic than it should be – software limitation	✓✓✓?

Achieving high dynamic range now

Include	Discussion	Maturity
Debugging the system	We learn a great deal about our instruments over time and correct often 2nd order errors	✓✓✓✓
Position-dependent effects	Hugely Important relatively recent advance • Time dependent pointing errors – antenna models may be limit • Position-dependent phase screen – critically important for the ionosphere • Many algorithms (peeling. A-projection ...)	✓✓ ✓ ✓✓ ✓
Full stokes imaging	A position-dependent effect – polarization response changes across FoV	✓

Conclusions

The next generation radio telescopes offer the possibility of transformational science, but at a cost

A major processing challenge

- Need to analyse very large amounts of streaming data
    - Current algorithms iterative – need to buffer data
- Problem too large to, for example, use a direct Bayesian approach
- Are our (approximate) algorithms good enough to take into account all error effects that need to be modelled?
- Only recently have we had to consider most of the effects – what have we forgotten?
- Phased approach to SKA is very good for the processing – performance increasing and critically we can continually learn