Computing & data for the SKA

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Oct 2016

This talk

- What is the SKA telescope?
- Science cases for the SKA
- What is the Science Data Processor?
- Models of the computation
- Parallel software & system architecture

Acknowledgement:

A large group of people are working on this
Background can be found in the SDP Preliminary Design Review documentation
Many slides contain materials from other SKA presentations & documents

My role

- Computation project is led by Cambridge University
- I’ve been an advisor & consultant to SKA since 2013 &
- Visiting Academic

What is the SKA?

The Square Kilometre Array (SKA)

Next Generation radio telescope – compared to best current instruments it offers ...

- ~100 times more sensitivity
- ~ 10^6 times faster imaging the sky
- More than 5 square km of collecting area over distances of >100km

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

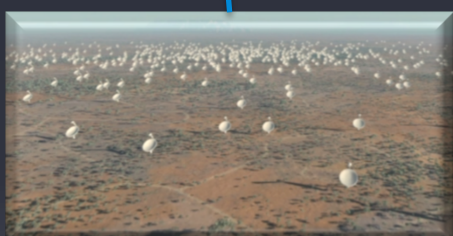
- Builds on techniques developed originally in Cambridge
- It is an Aperture Synthesis radio telescope (“interferometer”)

Uses innovative technologies...

- Major ICT project
- Need performance at low unit cost

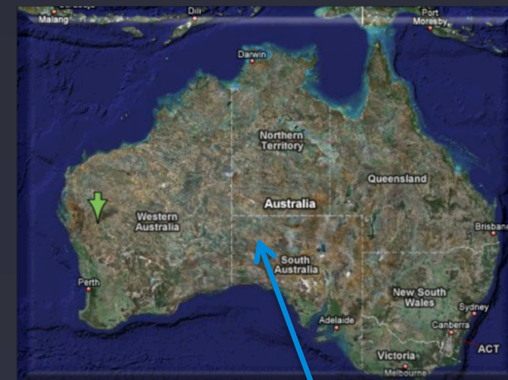
SPDO/Swinbur

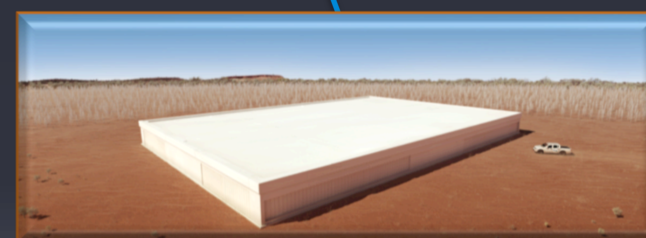
SKA1 Implementation



Mid Frequency Array

250 dishes with single receiver
Karoo, SA - 3 humans / sqkm
Compute in Cape Town (400m)

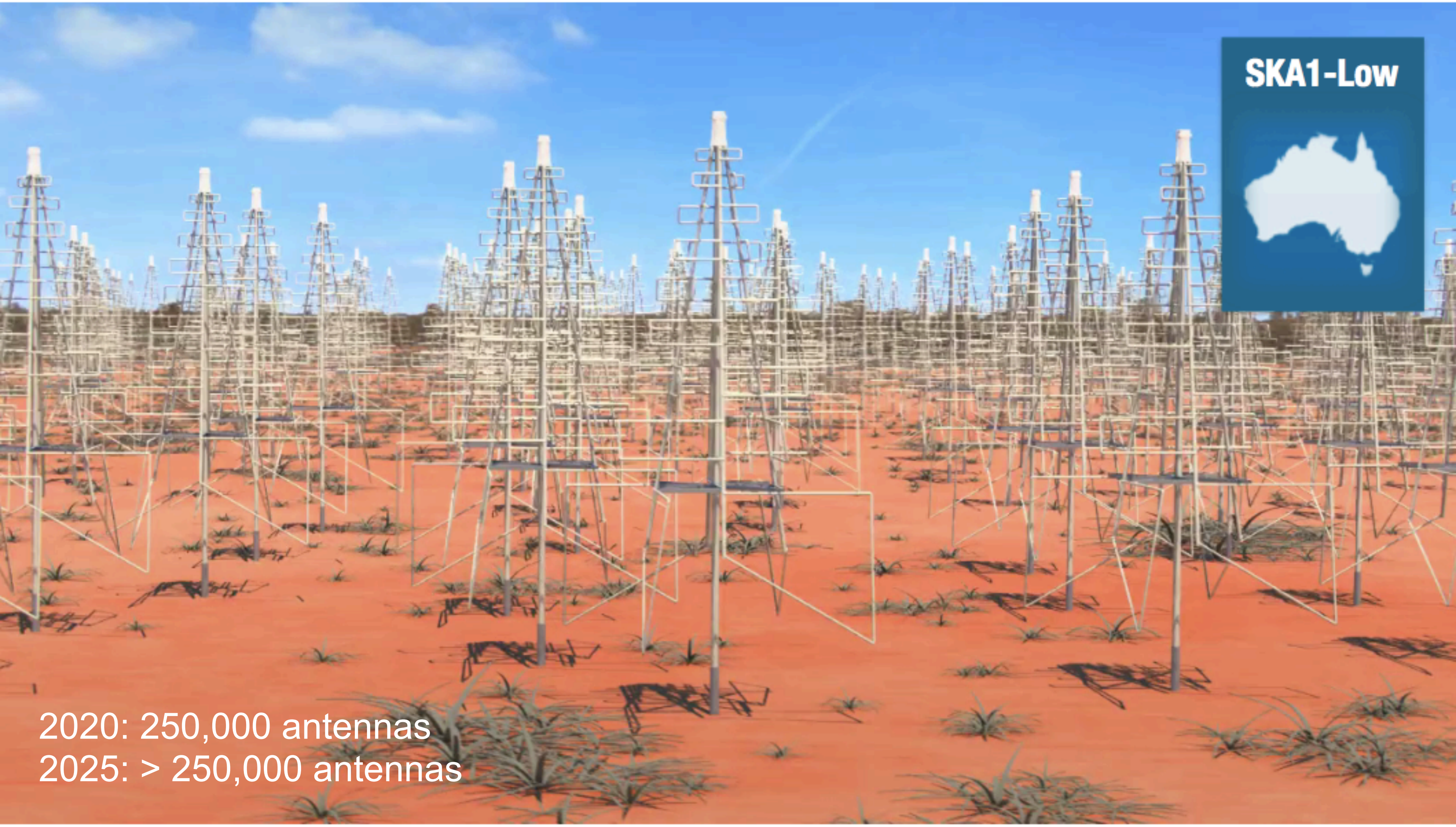




Low Frequency Aperture Array

1000 stations 256 antennas each
Murchison, AU - 0.05 humans / sqkm
Compute in Perth

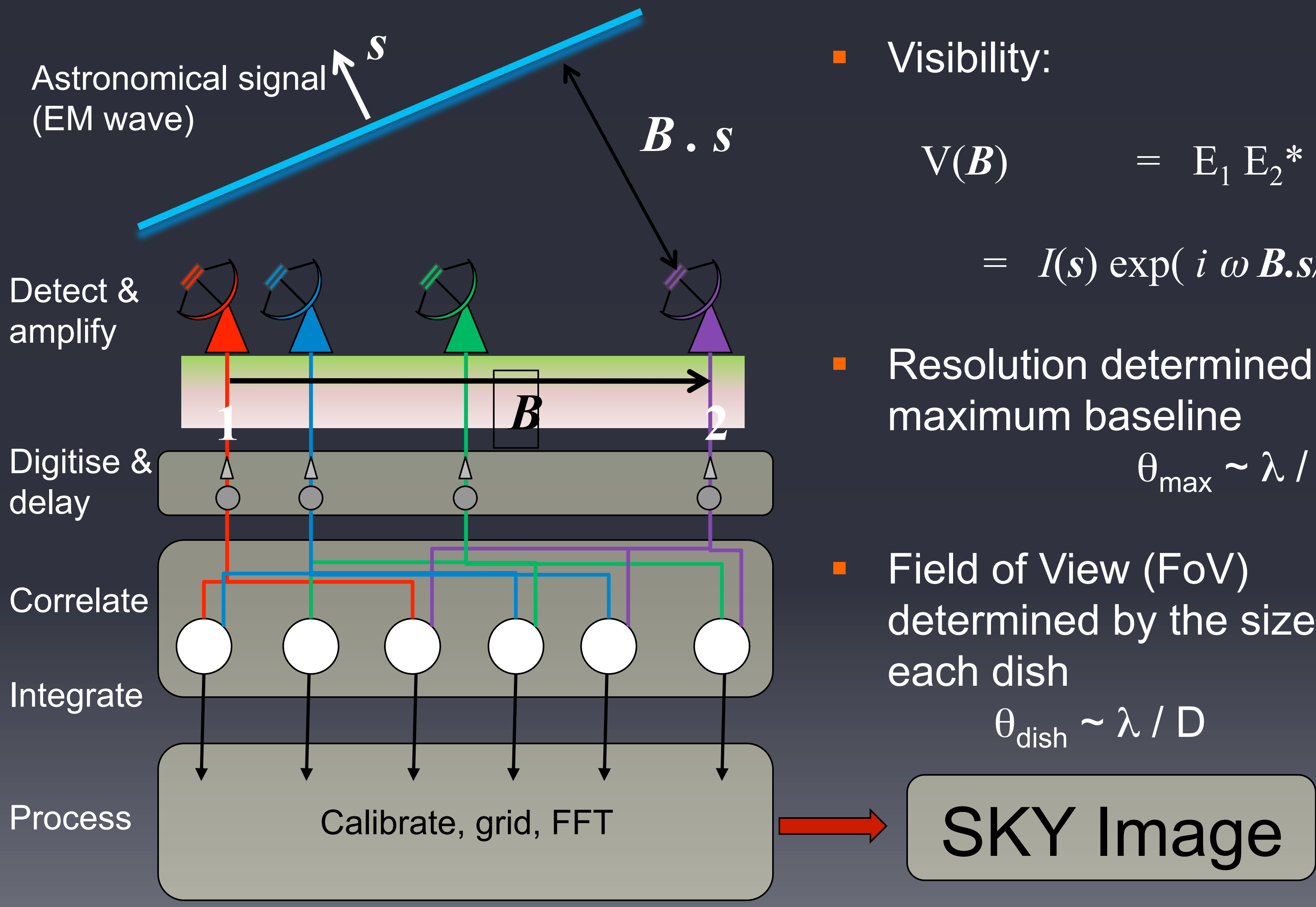
SKA Telescopes



SKA Telescopes

2020: 250 dishes
2025: 2500 dishes

Standard interferometer



- Visibility:

$$V(\boldsymbol{B}) = E_1 E_2^*$$

$$= I(\boldsymbol{s}) \exp(i\, \omega\, \boldsymbol{B.s}/c)$$

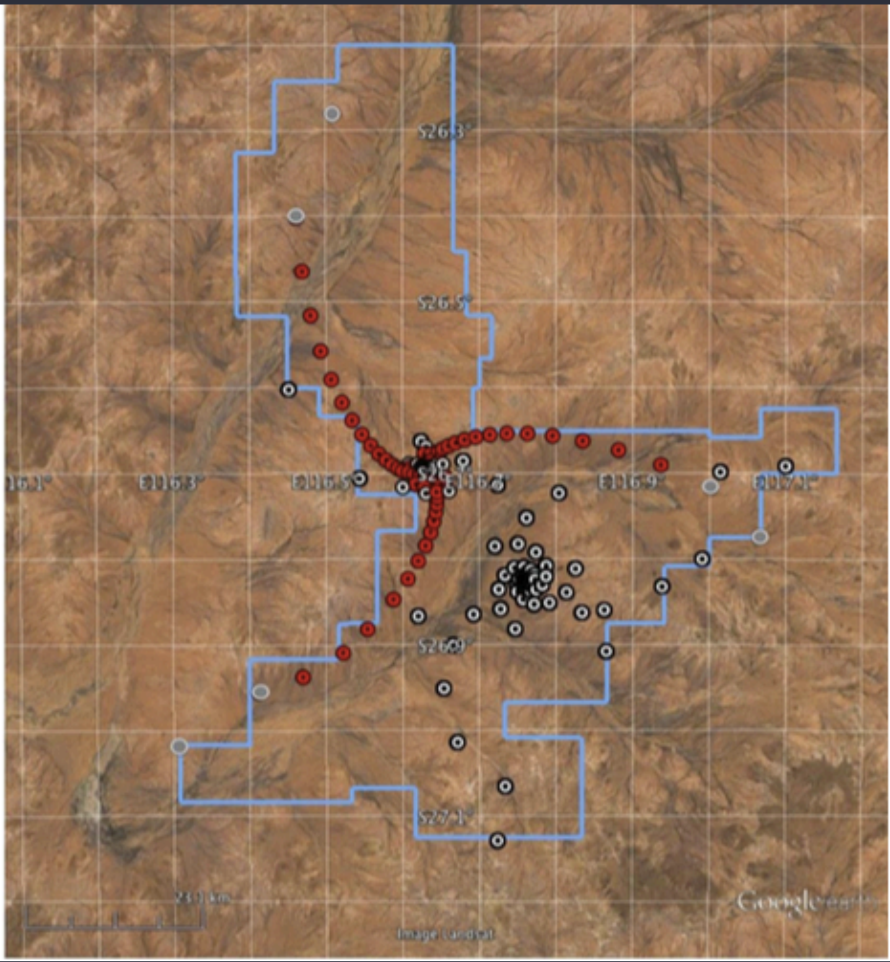
- Resolution determined by maximum baseline

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

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

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

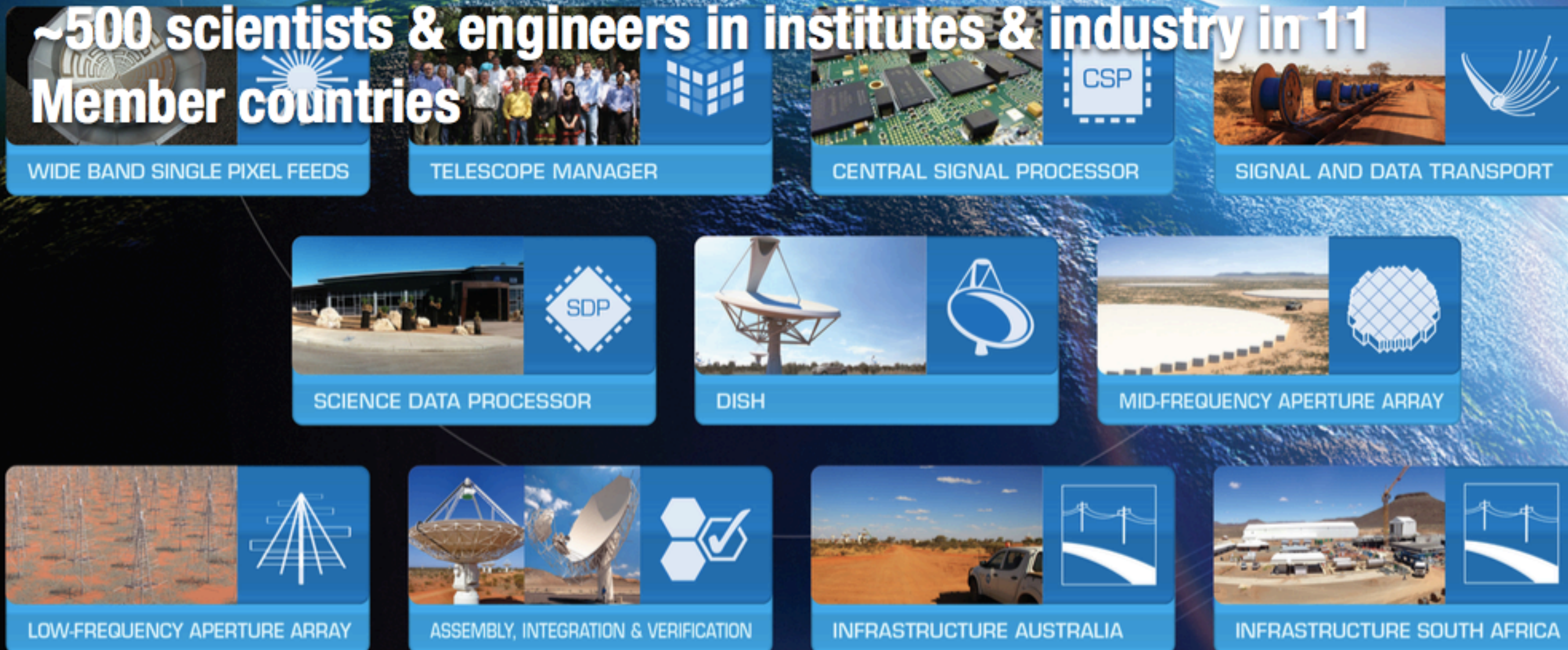
Antenna array layout



SKA1–MID, –SUR, –LOW: BMax = 156, 54, 65 km

SKA International Design Consortia

- Project Management and System Engineering Team based at JBO (UK)
- ~500 scientists & engineers in institutes & industry in 11 Member countries



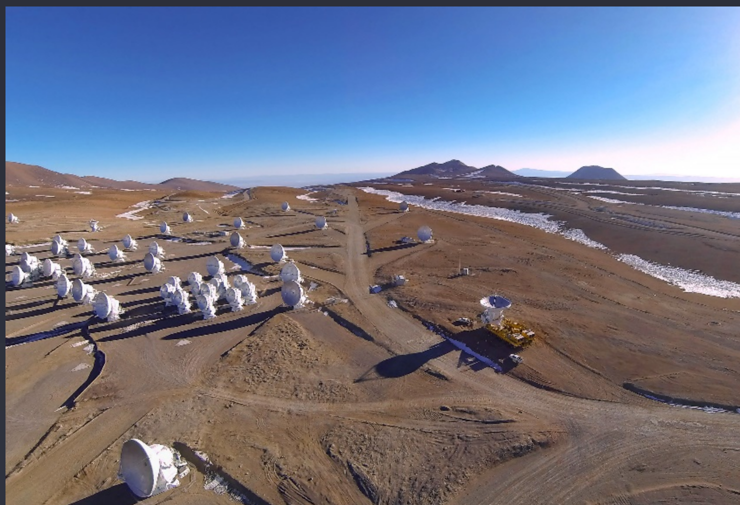
In summary …

- SKA aims to be an “instrument” like CERN
- This discussion focuses on SKA1 - 2023
  - Strong funding and support from participating countries (budget ~$1B)
- SKA2 should have 10x more antennas – 2028
  - not yet substantially funded
- Caveat
  - Ongoing changes – e.g. a third telescope was removed in 2015
  - Some inconsistencies in the numbers
    - Cf. NYT Oct 2016:

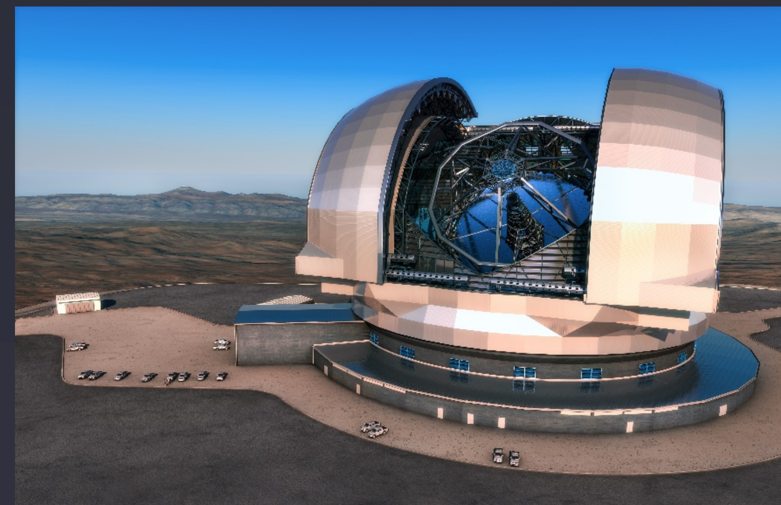
    “Maybe there are 100x more galaxies than we previously thought.”

Science cases

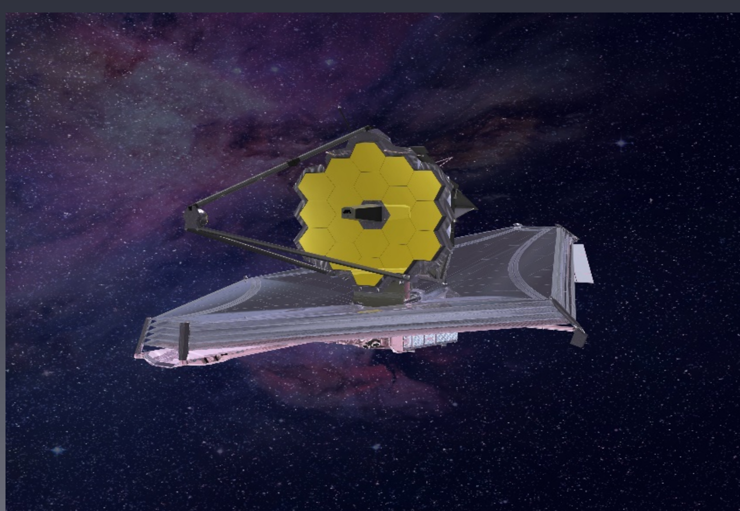
SKA – a partner to ALMA, EELT, JWST



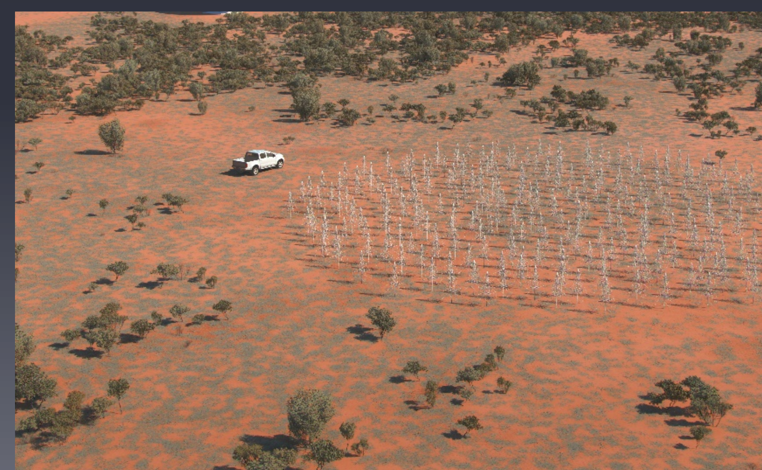
Credit:A. Marinkovic/XCam/ALMA(ESO/NAOJ/NRAO)



Credit:ESO/L. Calçada (**artists impression**)



Credit: Northrop Grumman (**artists impression**)



Credit: SKA Organisation (**artists impression**)

SKA – a partner to ALMA, EELT, JWST

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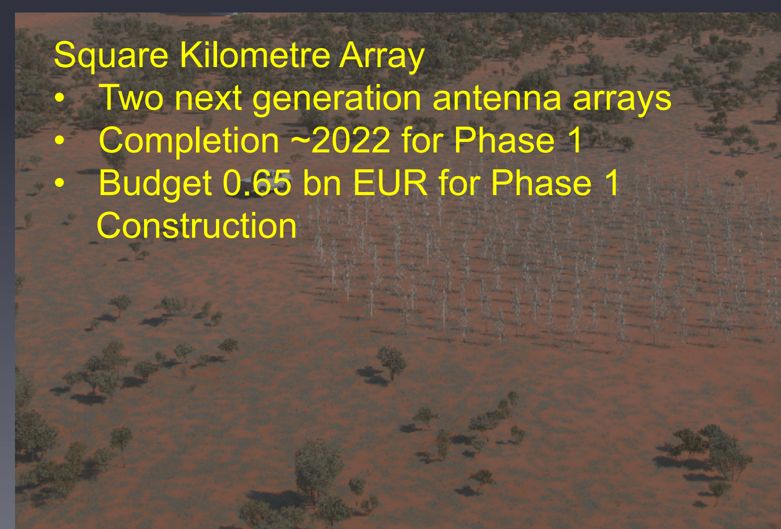


Credit: SKA Organisation (**artists impression**)

Science Headlines

Fundamental Forces & Particles

Gravity

- Radio Pulsar Tests of General Relativity
- Gravitational Waves
- Dark Energy

Magnetism

- Origin and Evolution of Cosmic Magnetism

Origins

Galaxy & Universe

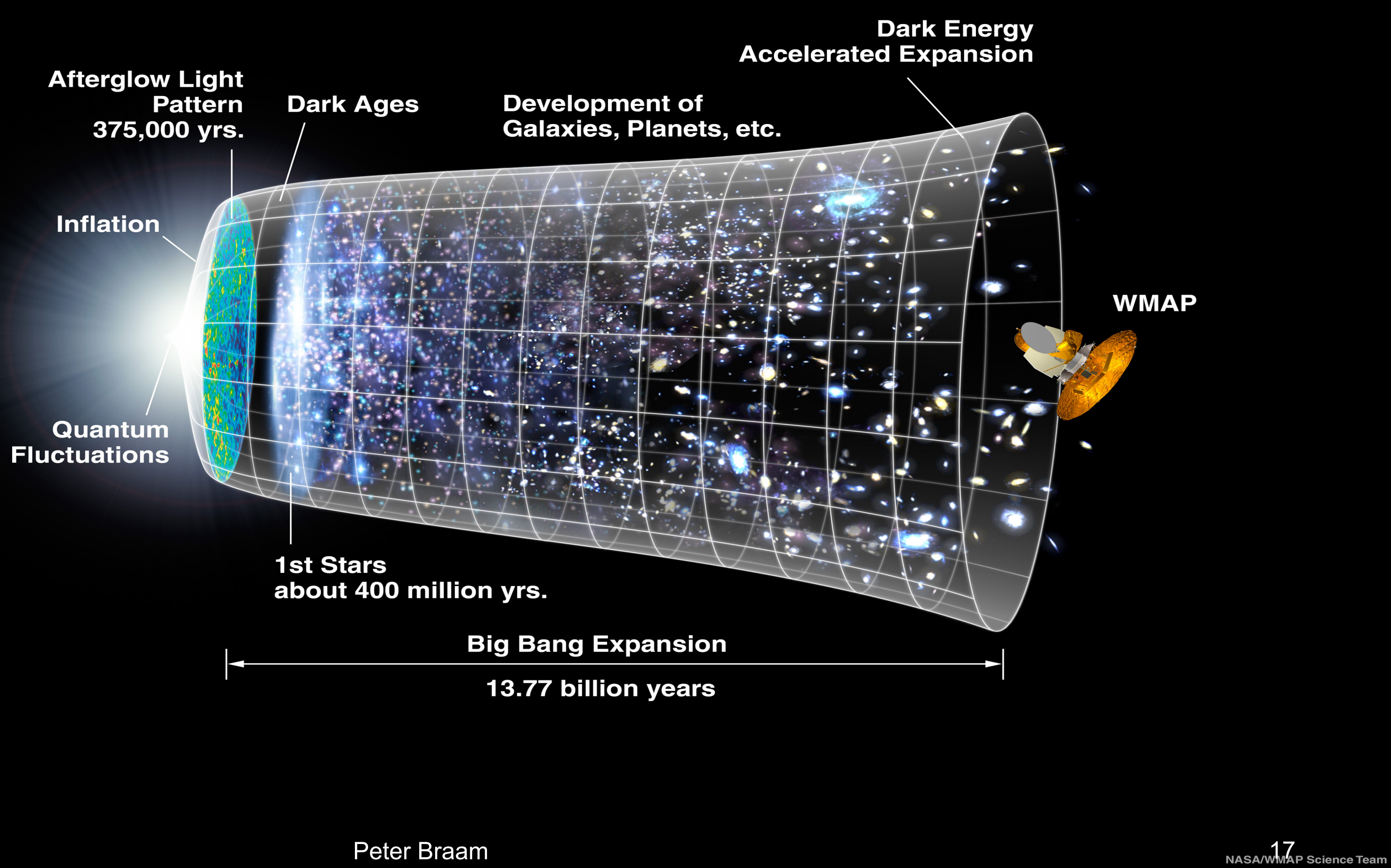
- Cosmic dawn
- First Galaxies
- Galaxy Assembly & Evolution

Stars Planets & Life

- Protoplanetary disks
- Biomolecules
- SETI

skatelescope.org –
two very large books (free!) with science research articles surrounding SKA

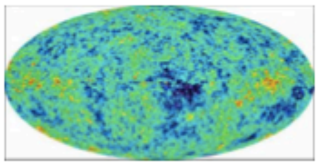
Epoch of Re-Ionisation

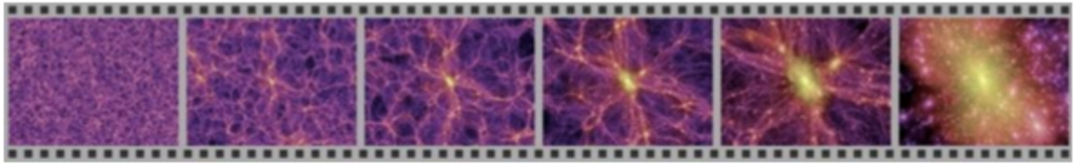


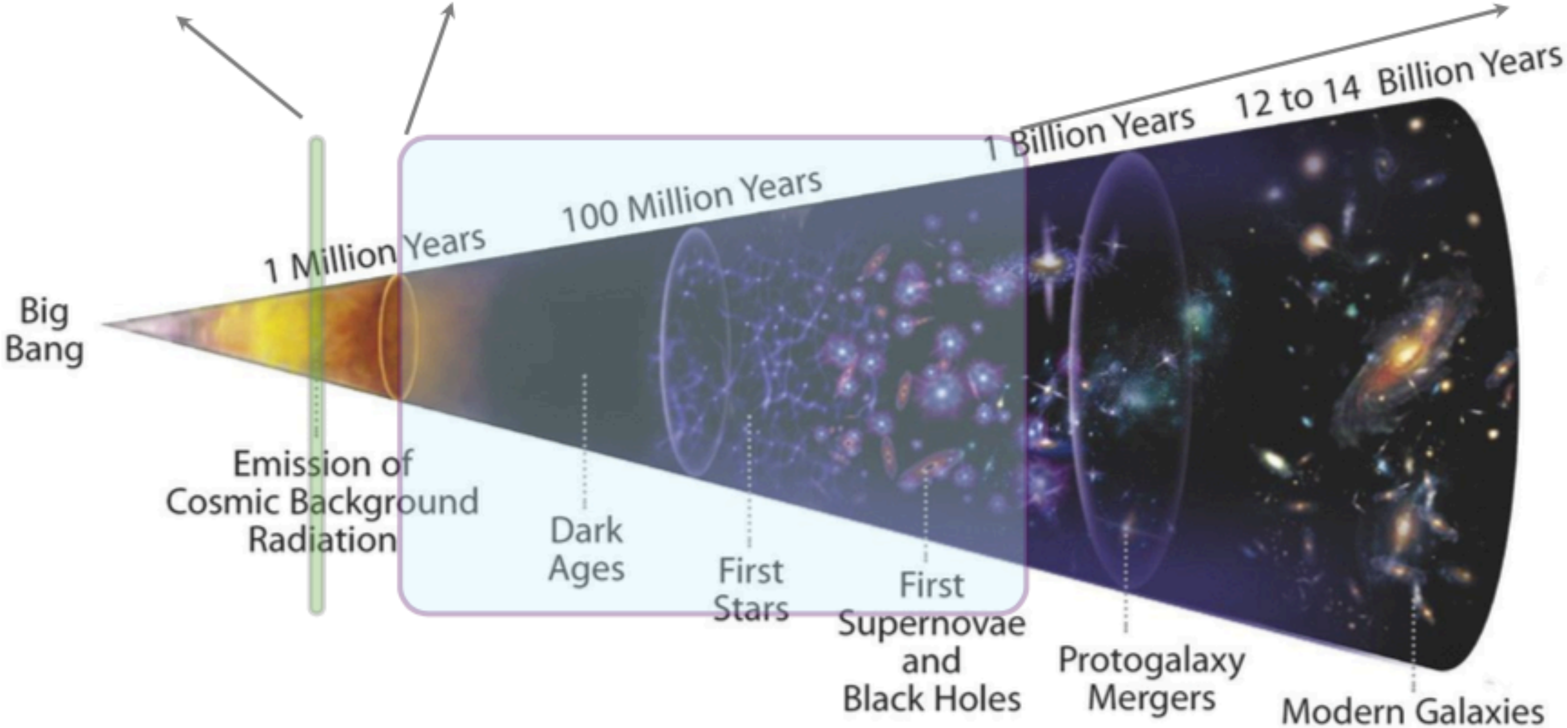
HI surveys of the EoR & Cosmic-Dawn

CMB displays a single moment of the Universe. Its initial conditions at ~400,000 yrs

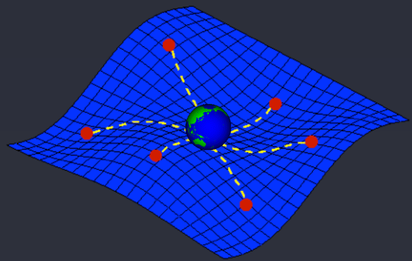
HI emission from the Dark Ages, Cosmic Dawn & EoR traces an evolving "movie" of baryonic and DM structure formation at $t_{univ}<10^9$ years.

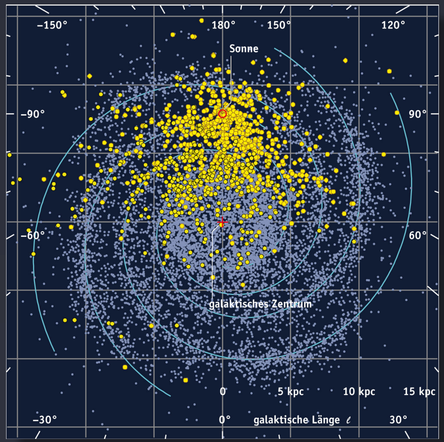


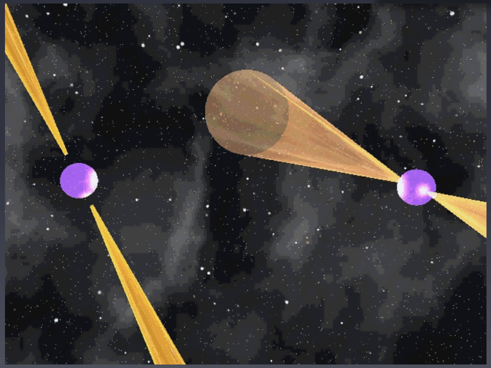




SKA & gravitational waves



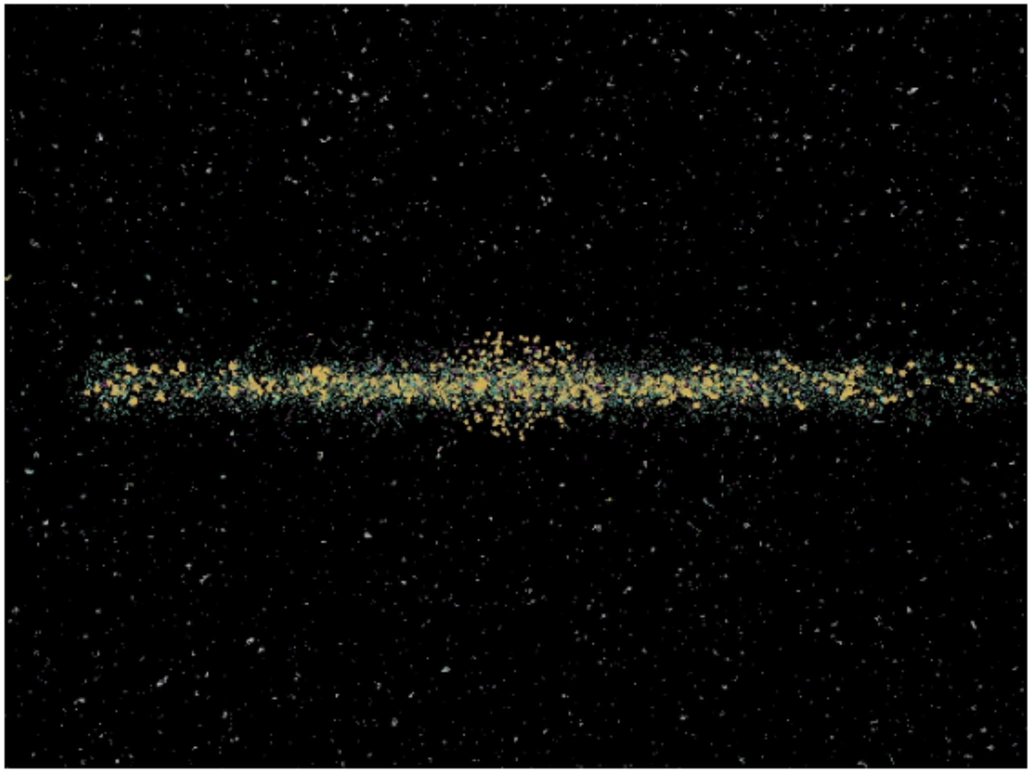


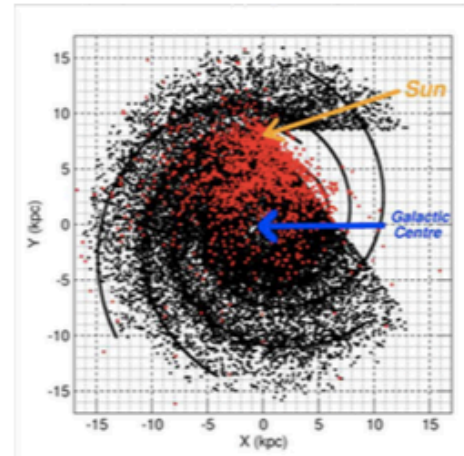


- The SKA will detect around 30,000 pulsars in our own galaxy, 2000 msec pulsars → accurate clocks
- Relativistic binaries give unprecedented strong-field test of gravity expect ~100
- Timing net of ms pulsars to detect gravitational waves via timing residuals
- Expect timing accuracy to improve by ~100

Finding all pulsars in the milky way

(Cordes et al. 2004, Kramer et al. 2004, Smits et al. 2008)

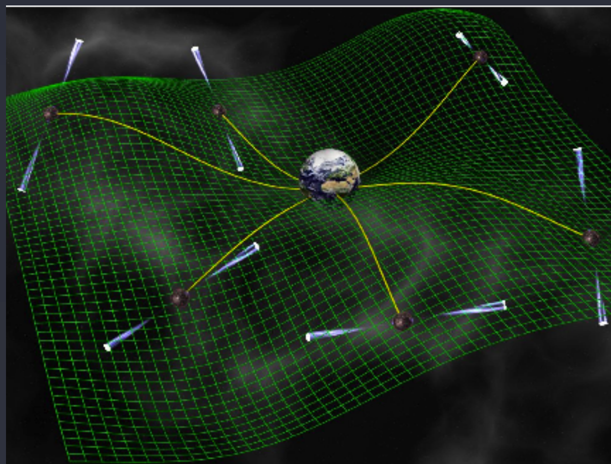


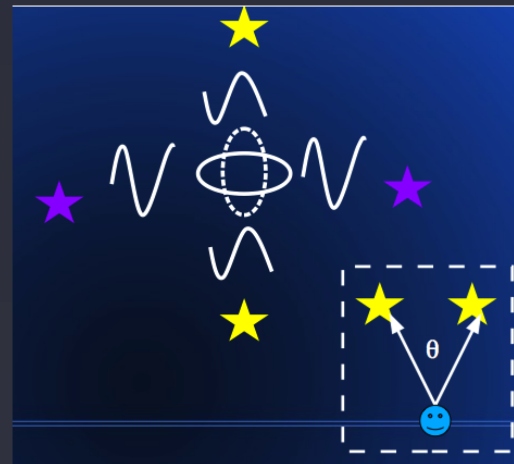


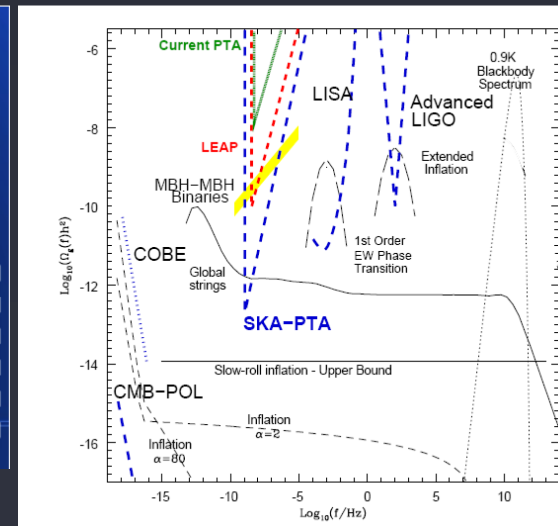
- ~30,000 normal pulsars
- ~2,000 millisecond psrs
- ~100 relativistic binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

- Timing precision is expected to increase by factor ~100
- Rare and exotic pulsars and binary systems: including PSR-BH systems!
- Testing cosmic censorship and no-hair theorem
- **Current estimates are that ~50% of entire Galactic population in reach of SKA1**

Pulsar Timing Array

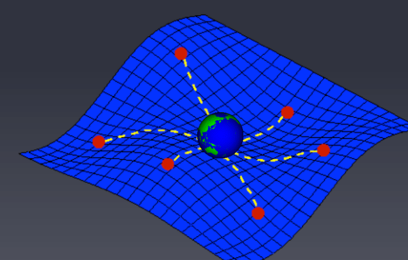




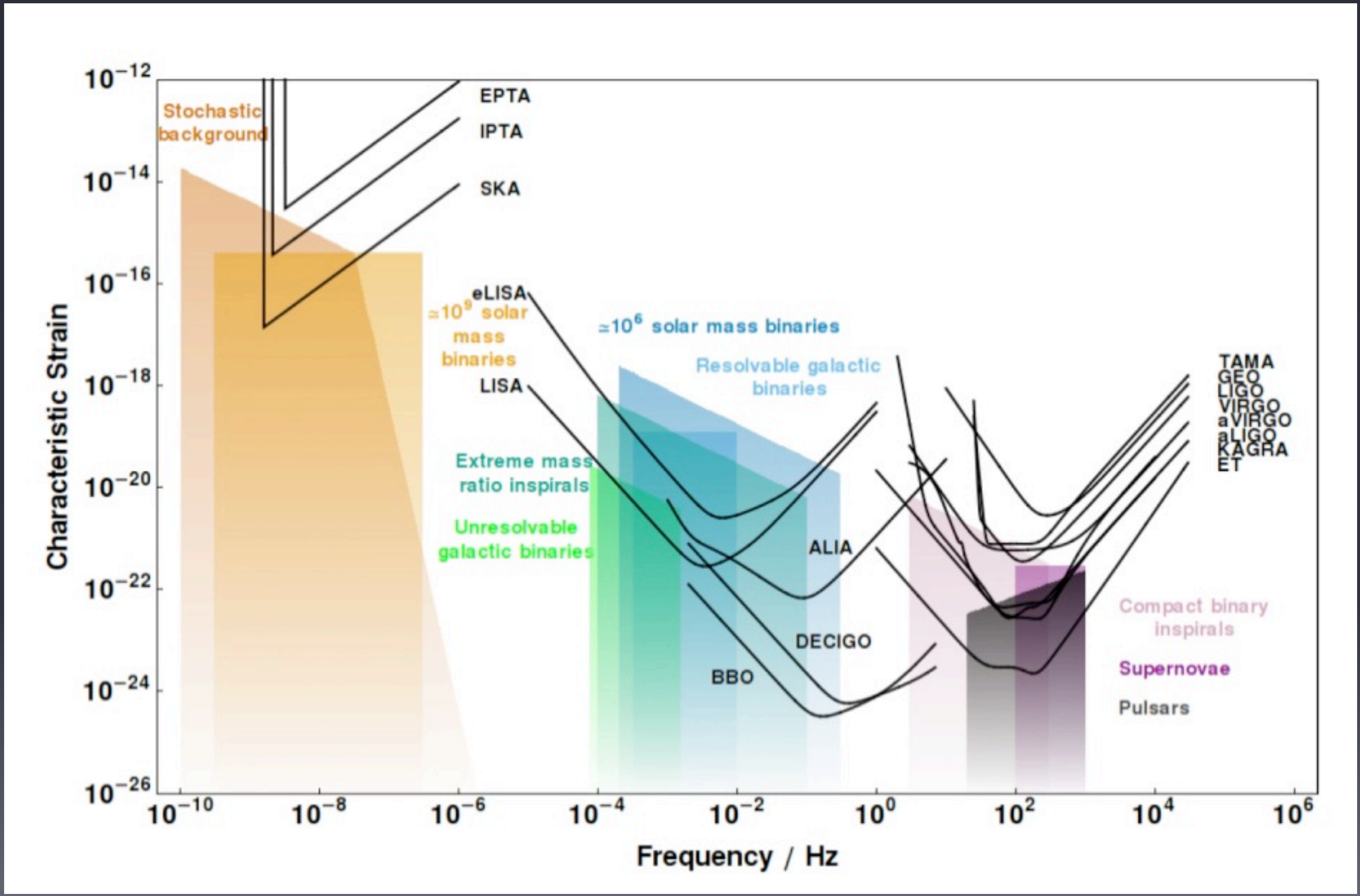


Nano-Hertz range of frequencies

- MBH-MBH binaries: resolved objects and stochastic background
- Cosmic strings and other exotic phenomenon
- Timing residual ~10s ns → need ms pulsars



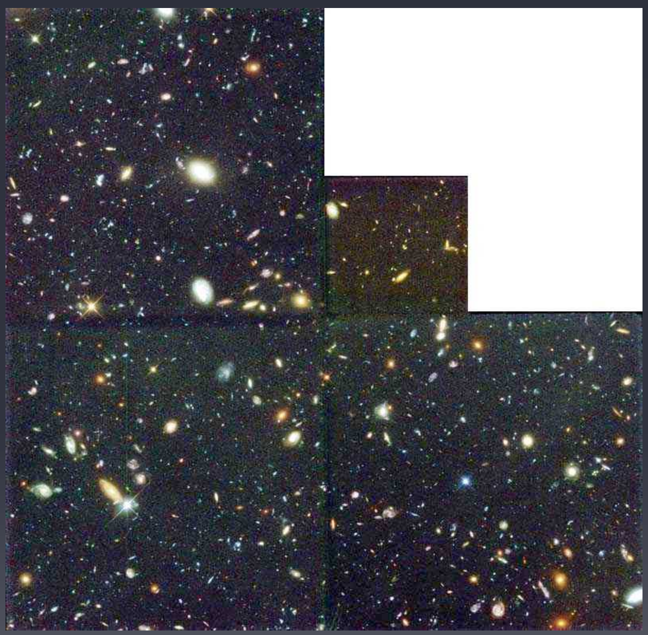
Gravitational Waves – Role of the SKA



From: C J Moore et al, LIGO-P1400129.

Finding the unexpected

Hubble Deep Field (HDF)



~ 3000 galaxies

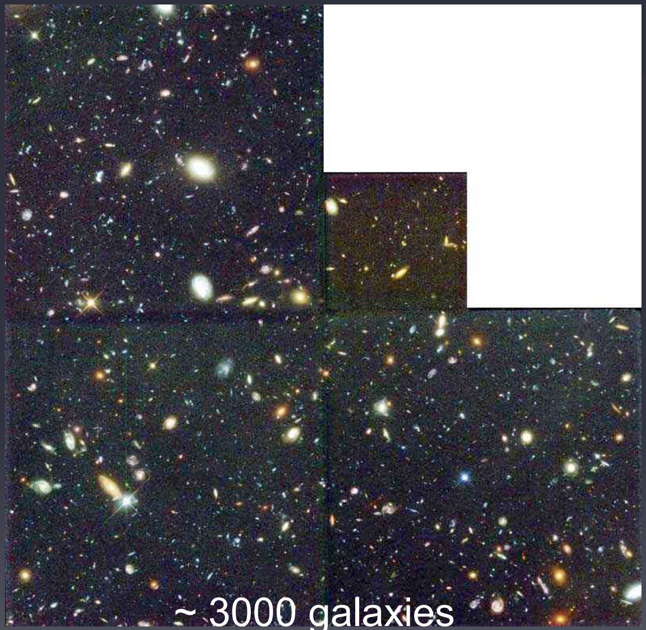
Very Large Array observation of HDF

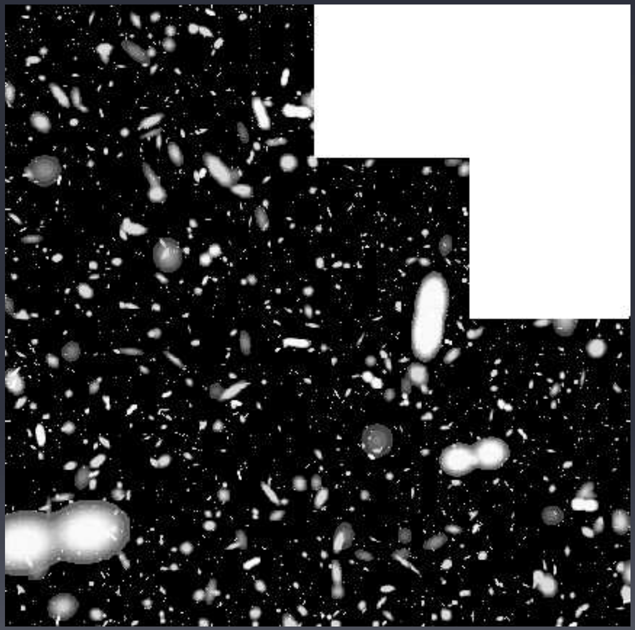
~15 radio sources

Finding the unexpected (2)

Hubble Deep Field (HDF)

Simulation of SKA Observation





Computing in the SKA?

Challenge

Turn telescope data into science products

Scientists will consume this worldwide

The SKA telescope will probably live ~50 years

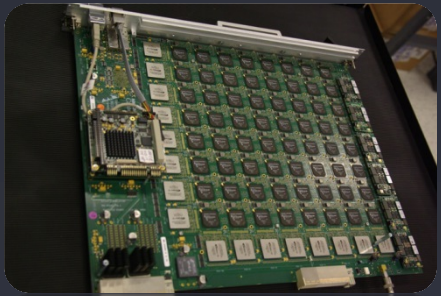
SDP computing hardware will refresh ~every 5 years

The initial 2023 computing system should exploit the SKA instrument sufficiently to deliver a competitive instrument

SKA – data schematic

Antennas

Central Signal Processing (CSP)



Transfer antennas to CSP
2020: 20,000 PBytes/day
2028: 200,000 PBytes/day

Over 10’s to 1000’s kms

Imaging (SDP) – HPC problem
2020: 100 PBytes/day
2028: 10,000 PBytes/day

Over 10’s to 1000’s kms

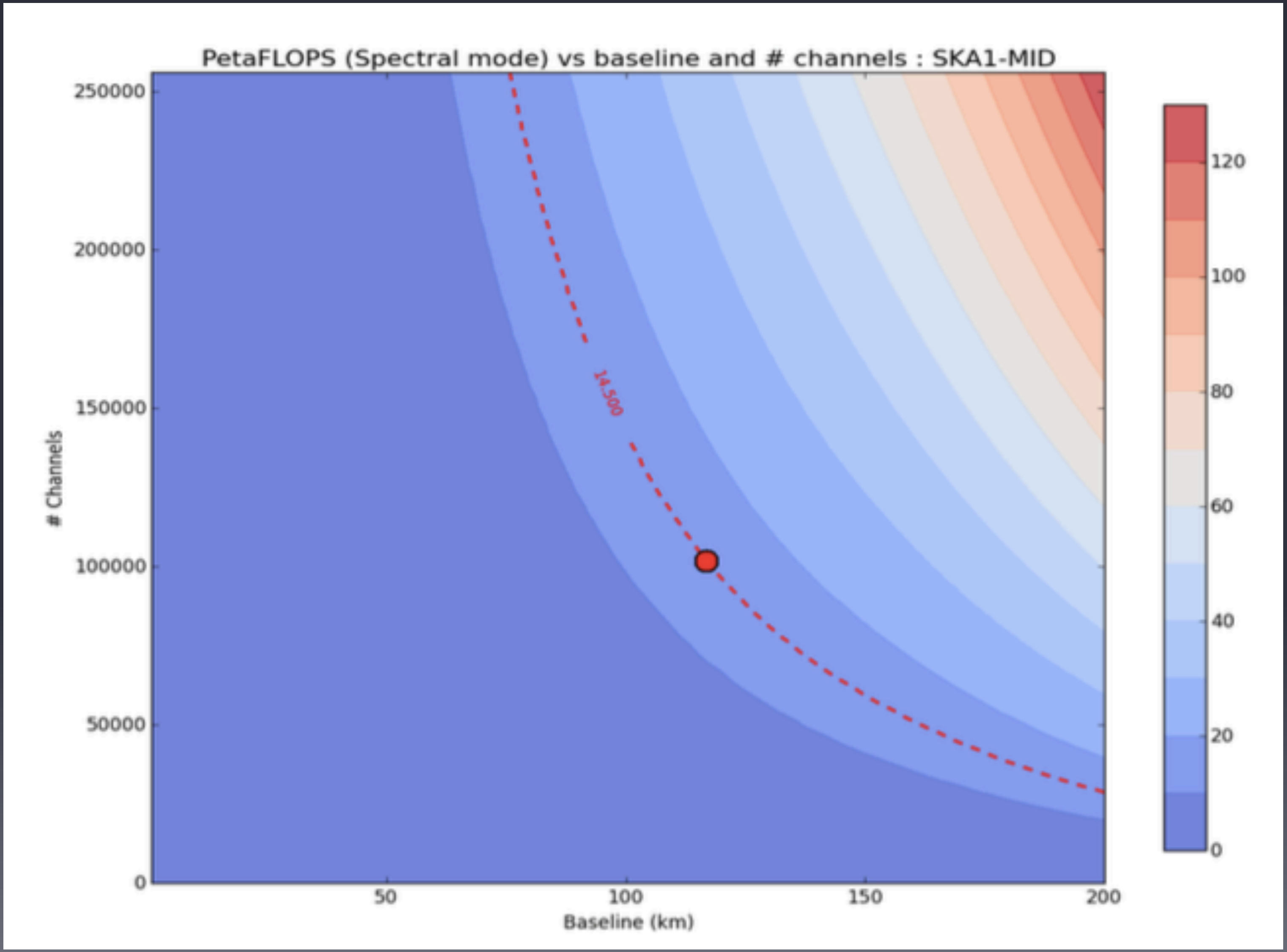
High Performance Computing Facility (HPC)

HPC Processing
2020: 300 PFlop
2028: 30 EFlop

Radio astronomy 0.101

- **@Antennas**: wave guides, clocks, beam-forming, digitizers
- **@Correlator (CSP):** DSP for antenna data
  - Delivers data ***for every pair of antenna's (a "baseline")***
  - Dramatically new scale for radio astronomy ~500K baselines
  - Correlator averages and reduces data, delivers sample every 0.3 sec
  - Data is delivered in frequency bands: ~100K bands
  - 3 complex numbers delivered / band / 0.3 sec / baseline
  - Do math: ~ 1 TB/sec of so called ***visibility data***
- **@Science Data Processor (SDP)** – process correlator data
  - Create images & find transients – these are "science products"
  - A total measurement lasts up to 6 hours, transients detected in ~10s

Flops vs. #channels & baseline



Baseline distribution

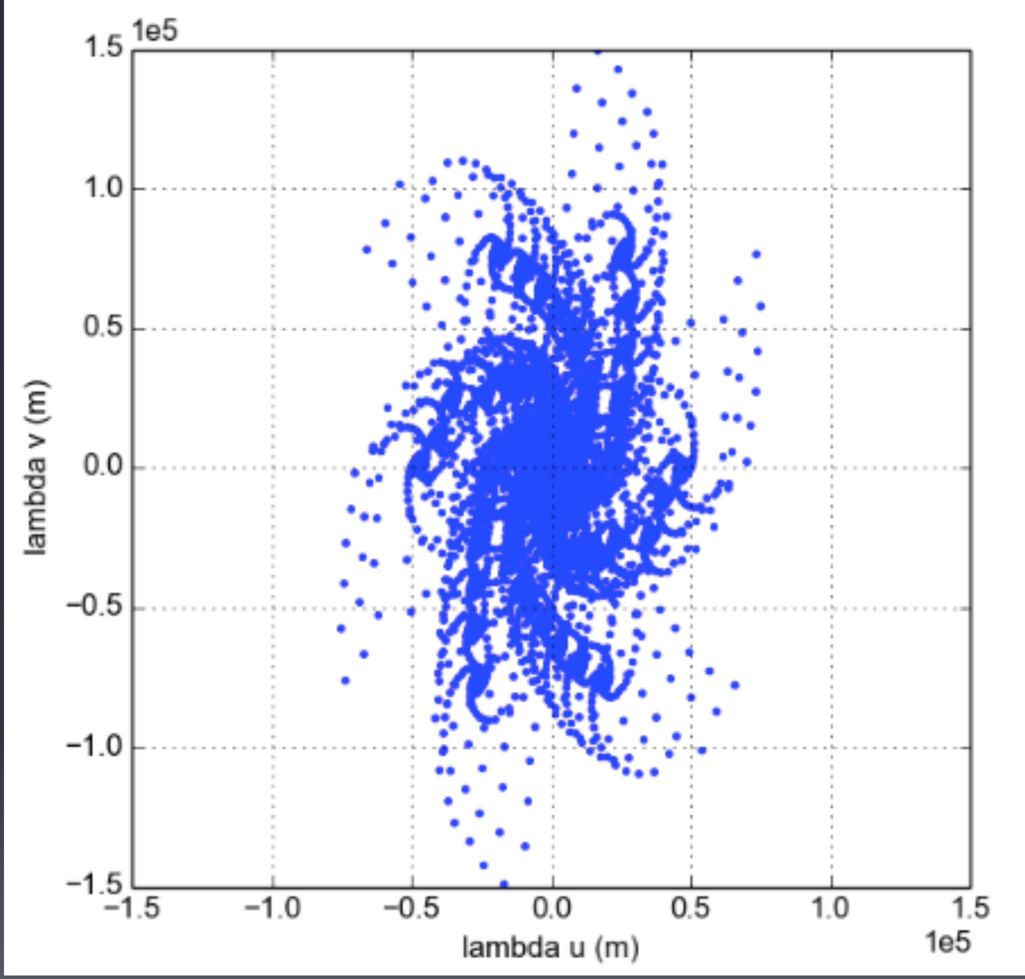
Each pair of telescopes has a baseline

Baselines rotate as time progresses

Each baseline has associated visibility data (“sample”)

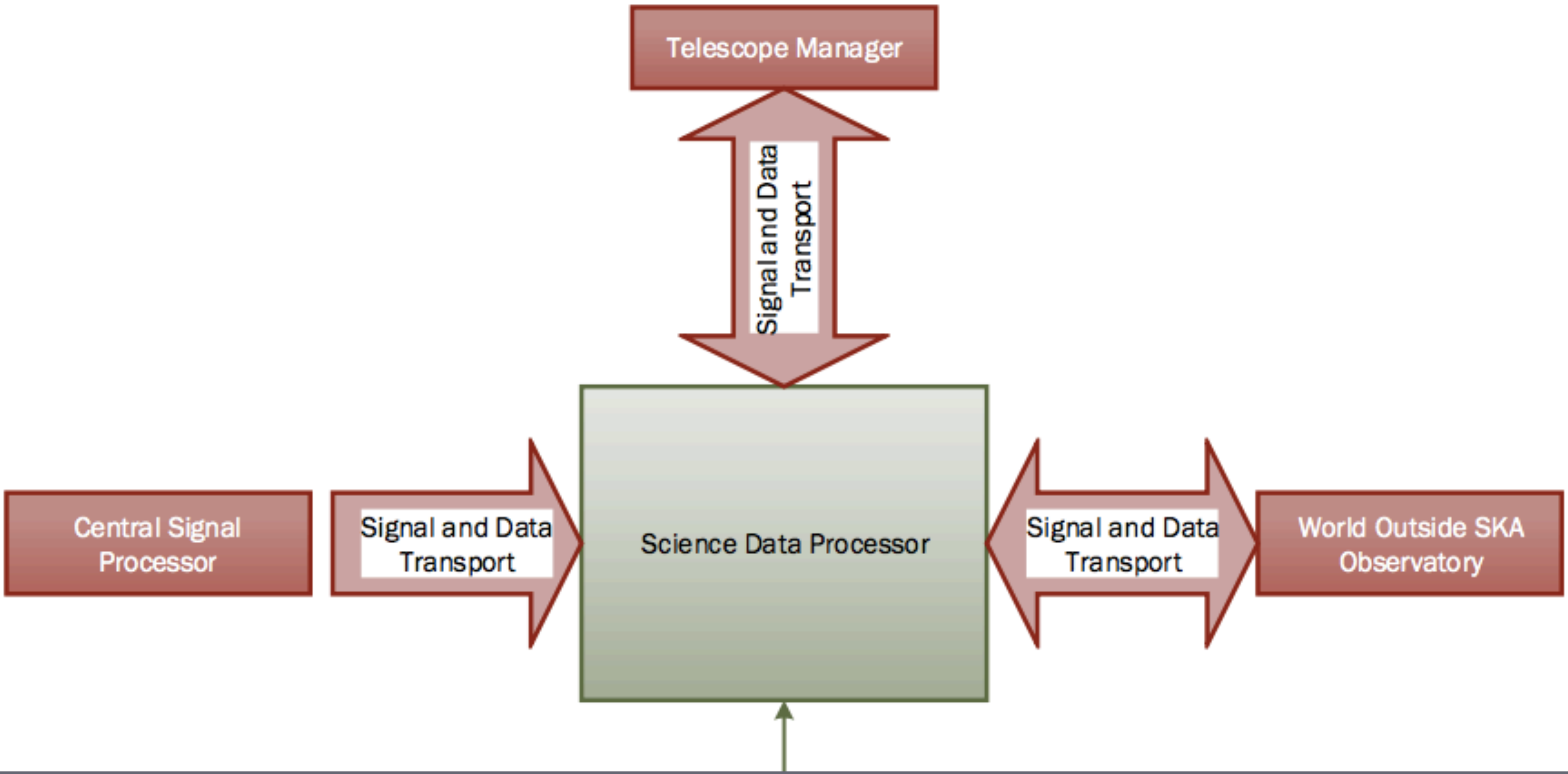
Baselines are sparse & not regular, but totally predictable

The physical data structure strongly enables and constrains concurrency & parallelism



Simulated data from 250 SKA1-MID dishes

Orchestration – interfaces



SDP top-level compute challenge

Telescope Manager

Science Data Processor

SDP Local Monitor & Control

C S P

Data Processor

High Performance
~100 PF/sec
Data Intensive
~100 PB/job
Partially real-time
~10s
Read-intensive
Constrained

Long Term Archive

EB volume

100PB annually

Infrequent access

Delivery System

Distribution
~100PB/y

From Cape Town & Perth to rest of World

Visualisation of 100k by 100k by 100k voxel cubes

Regional Centres & Astronomers

Understanding data & computation: Parametric model

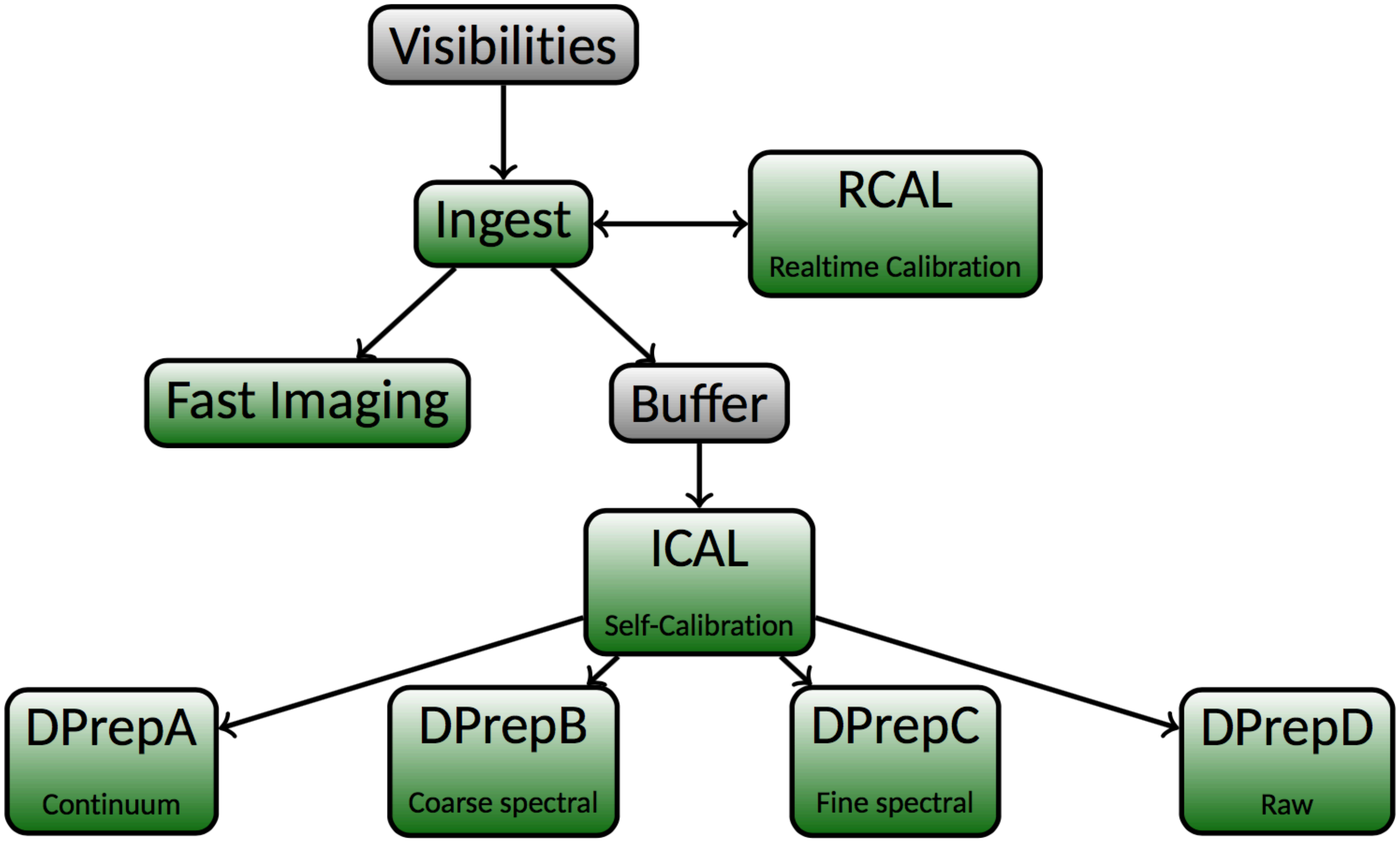
SDP pipelines computing

- **Solve for:**
  - Imaging of the sky – every ~6 hour period
  - Transients – to be found within ~5 sec
  - Effects of the atmosphere, imperfect sampling and imperfect telescope mechanics/electronics (“calibration”)

- **In soft-real time**

- **In order to:**
  - Find/measure very faint signals
  - Correct for some of the atmospheric/mechanical problems in real time
  - Produce “science-ready” data products

Pipelines Structure

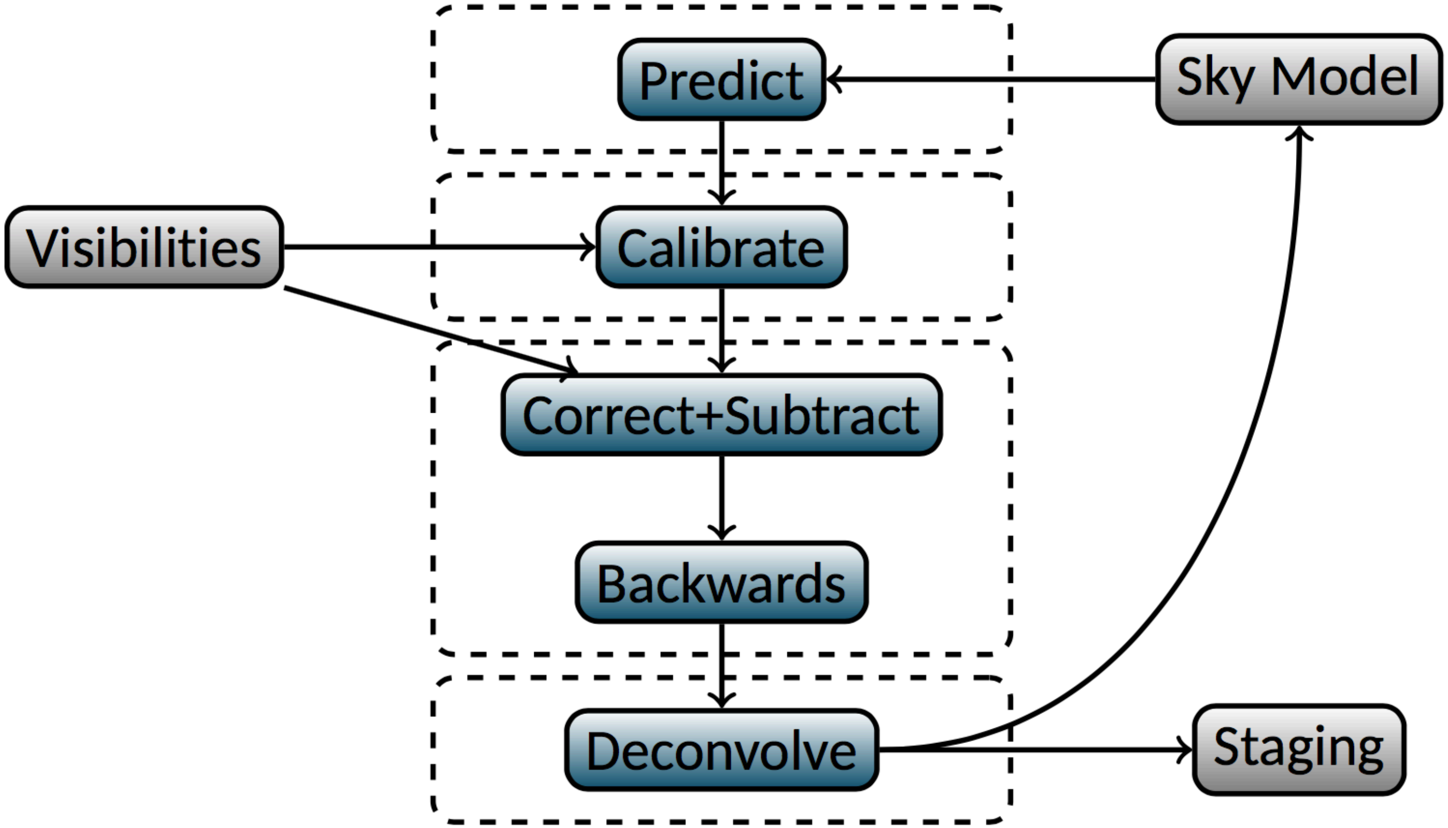


Follows architecture, allows running multiple data preparations.

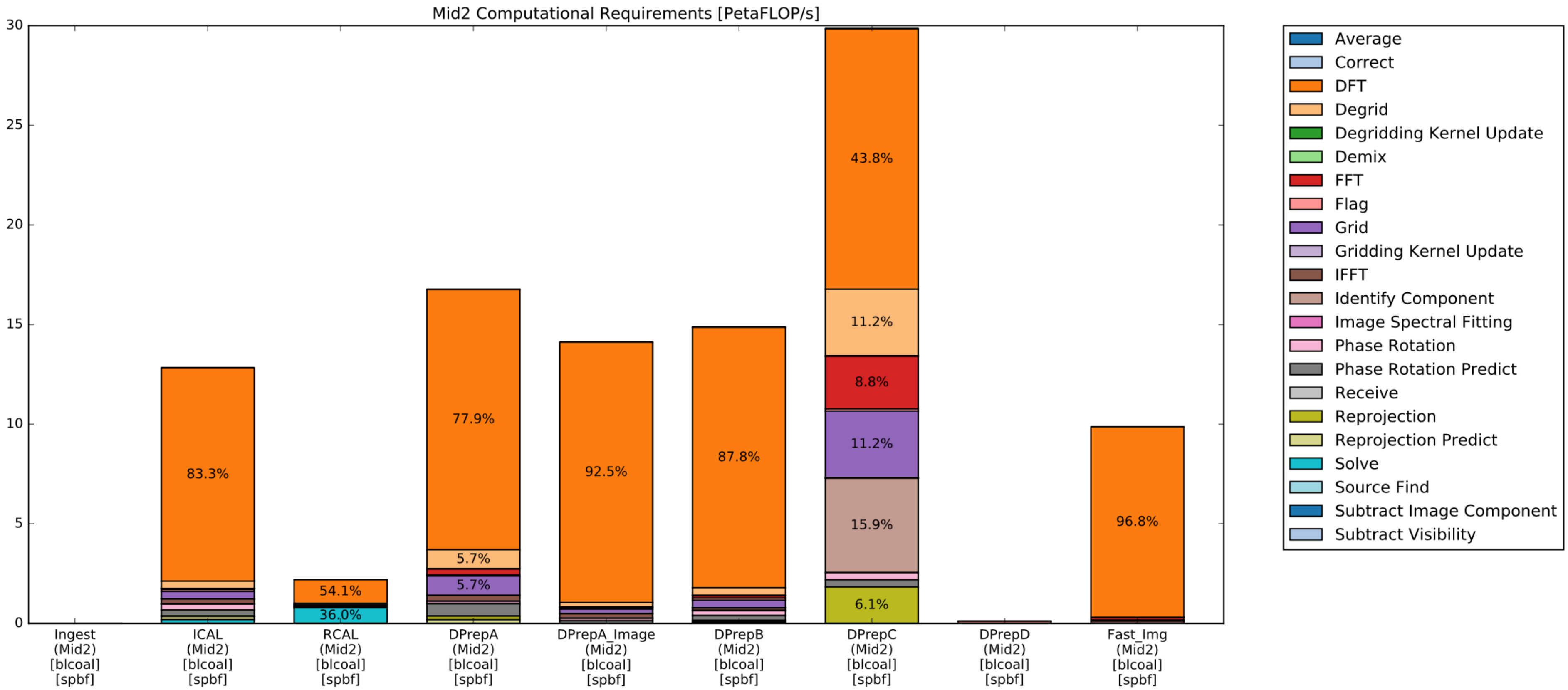
Pipelines

- Many similarities with other image processing
- Each step is
  - Convolution with some kind of a "filter"
  - Fourier transform
  - E.g. "gridding" – approximating irregularly sampled data with a regular sample
- Why new & different software?
  - The input data is sampled not on a grid, but on baselines
  - The scale of the problem is much larger than RAM

Rough structure and distribution pattern of most pipelines:



Relative kernel cost

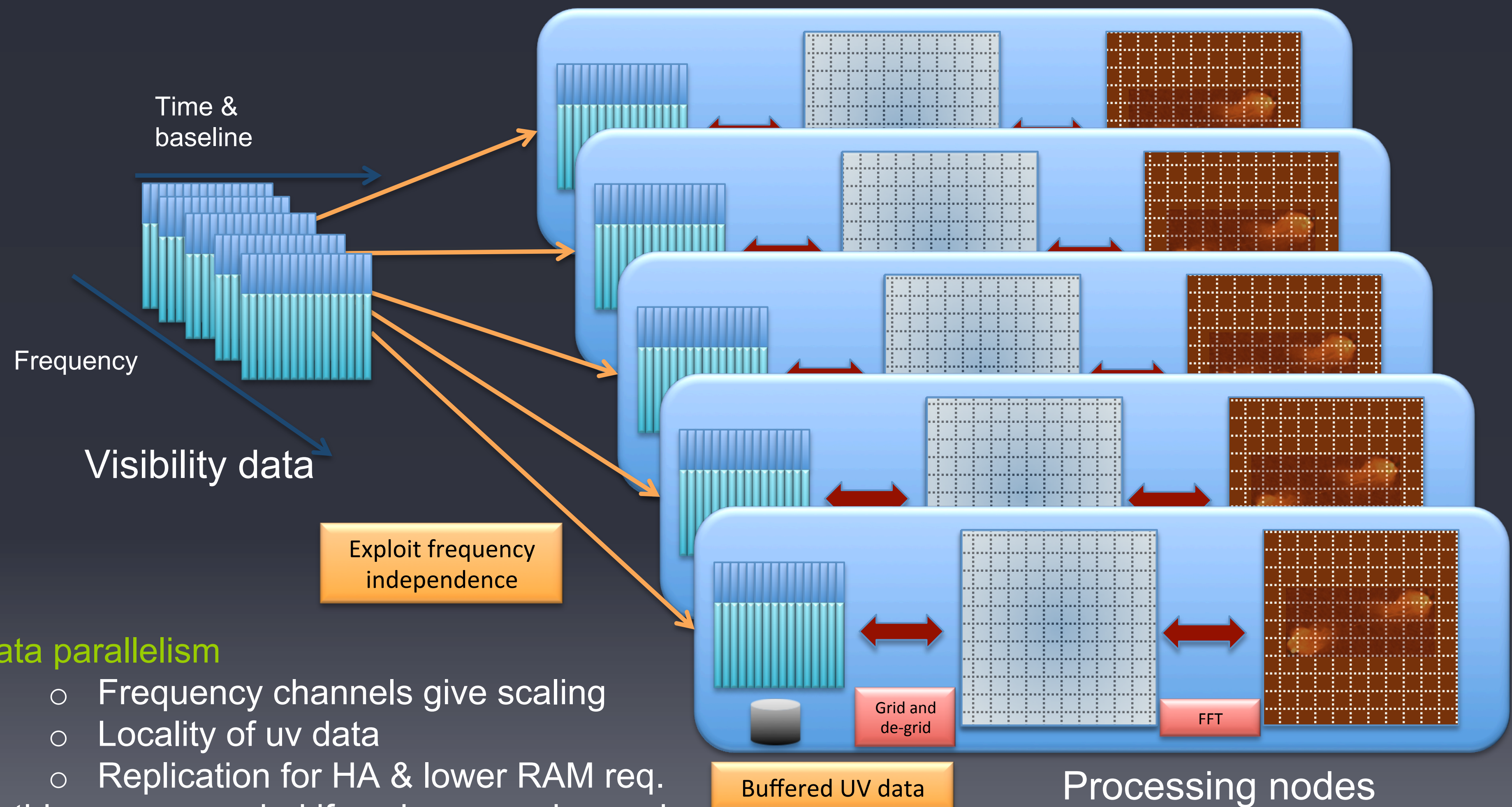


Imaging analysis summary

- About 10,000 operations per byte of I/O input
- Iterate through the dataset about 10 times
  - read = 10x write – need 10TB/sec read IO
- Need about 100 PetaFLOP/second
- 0.5 Flops / byte read from RAM
  - 200 PB/sec memory BW

Parallel implementation & system architecture

Data Flow on System Architecture



Data parallelism

- Frequency channels give scaling
- Locality of uv data
- Replication for HA & lower RAM req.

Nothing more needed if each processing node can process a frequency channel completely

Data in the computation

- Two principal data types
  - input is visibility – irregular, sparse uv grid of baselines
  - output regular grid is sky image
  - Messages can be “GB size”

- Different kinds of locality
  - Splitting the stream by frequency
  - Grouping visibilities by region
  - Duplicating input data for fail over
  - Duplicating input data for faceting – less memory use / more I/O

Supercomputer parameters

2023	LFAA (AU)	Mid (SA)
FLOPS	100 PF	360 PF
Buffer Ingest	7.3 TB/s	3.3 TB/s
Budget	45 M€	50 M€
Power	3.5 MW	2 MW
Buffer storage	240 PB	30 PB
Storage / node	85 TB	5 TB
Archive storage	0.5 EB	1.1 EB

Efficiency

Computation demands 89 PF/sec sustained

Efficiency is estimated at 9 – 30%. More validation needed!

Tied to **energy related hardware parameters** &

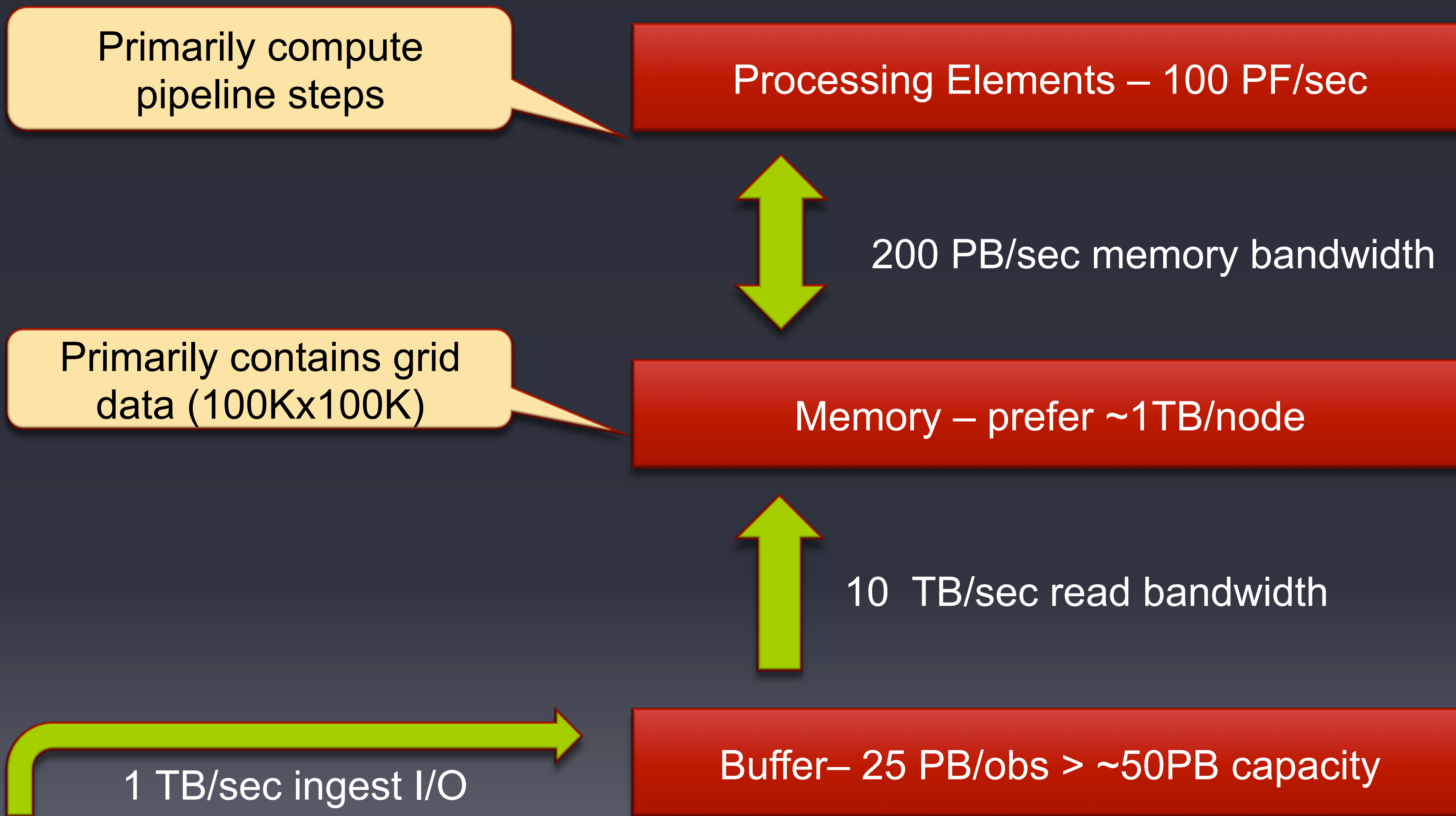
Physical data layout & cache re-use

Memory Technology

The memory bandwidth of 200PB/sec remains the most problematic.

- it probably requires on-package memory (HMC, HBM)
- High Bandwidth Memory / Hybrid Memory Cube
- this offers ~10x BW of RAM
- it consumes too much energy (~50 pJ/byte)
- today we would look at 200K modules
  - somewhat too many

Problem size – locality view

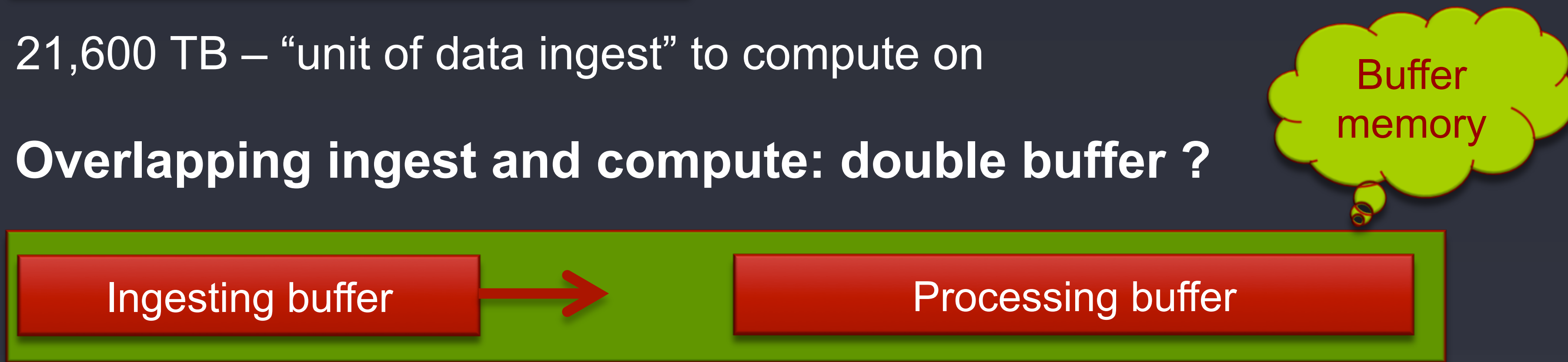


Long vs short buffer question

Processing requires up to 6 hours of ingest – buffer that.

21,600 TB – “unit of data ingest” to compute on

Overlapping ingest and compute: double buffer ?

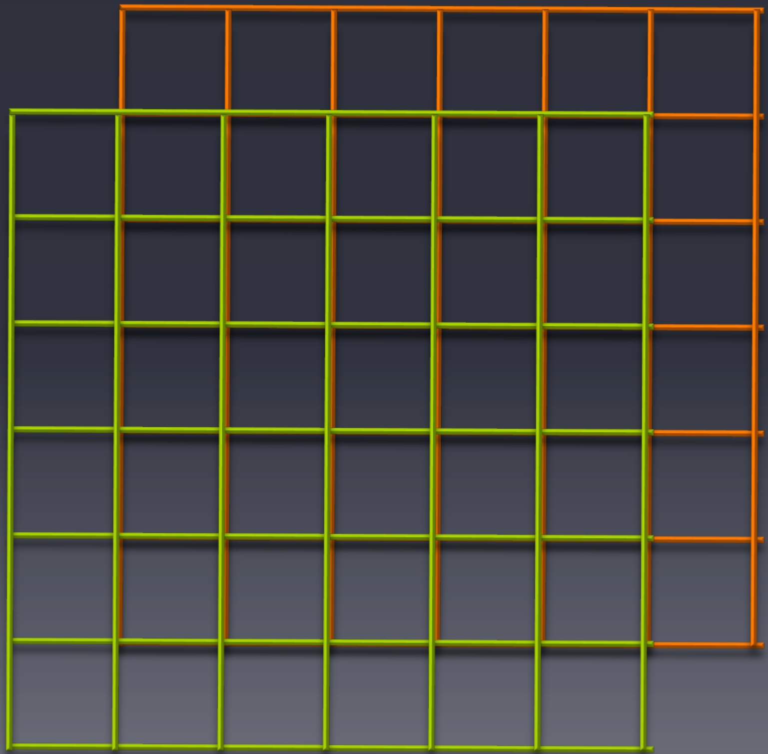


Double Buffer: ~100PB, write 1TB/sec, read 10TB/sec

But processing time is uneven – double buffer:

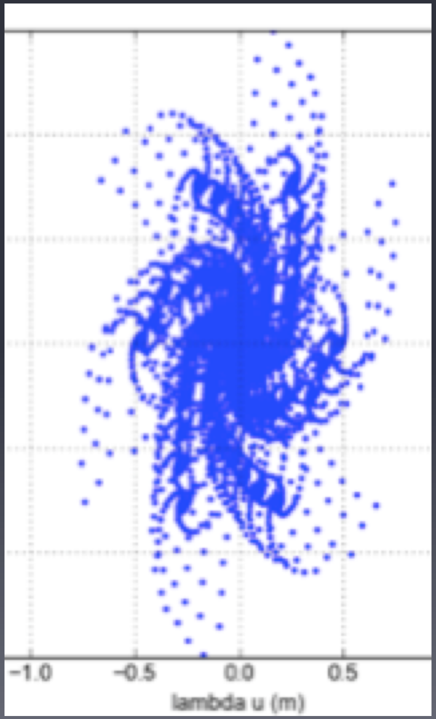
minimizes storage cost, increases compute cost

Visibility gridding & cache re-use



Time rotation of
UV grid.

Only fetch edges
Re-use core



Stream fusion

- Some kernels exchange too much data
- Solution: deviate from pipeline actors by doing more operations and less data movement.
- Few compilers / frameworks support this with automatic computation
- Doing it manually is awkward for portability

Software approaches

- Creating software is a very high risk part of the project
- Ideal perspective:
  - Execution framework from 3rd party
  - Domain specific application language for pipelines
  - Automatic optimization
- Many approaches:
  - Adapting existing packages – MPI C++ applications
  - Use a big-data framework like Spark
  - Use HPC frameworks like Swift/T, Legion
- Remains undecided.

Storage hardware

NVM solutions - xPoint and other

- Could deliver ~50 GB/sec / node
- 200 nodes could get 10TB/sec I/O BW
- But distributed storage remains hard

Summary

- SKA next generation telescope
  - Mass manufacturing of low cost receptors
  - Order of magnitude improvement
  - Key science drivers: gravitational waves, ionisation of primordial gas by first galaxies
- Timeline
  - Design finishes in 2017
  - Construction starts 2017/2018
  - Commissioning 2019
  - Full operations 2022
- Science Data Processor
  - Aligned with computational model & industry data

Thank you! Questions?

Sensor

HPC Data / Big Data

Sensor big data

- Radio astronomy
- Remote sensing
- Earth observation
- Geophysics
- Medical (imaging or other)
- Internet of Things?
  – 10 Hz sampling air temperature inside your fridge?

Tentative big data classification

Application	Input data volume	Input data density	Computational density	Message rate
HPC simulation	low	high	high	medium
Map reduce analytics	high	high	medium	low
Graph analytics	medium	high	low	high
Sensor data	high	low	medium	low

Characteristics of sensor big data

Noisy	• Information content << sampling rate • Combination/correlation of data necessary to find signals of interest -> volume!
Multiple Streams of Input Data	• Volume/shape/ characteristics of data known in advance • High degree of inherent parallelism at the front-end of processing
Calibration effects	• Large sensors networks can not be made perfect • Allow biases in measurement and find and correct for these in post-processing
Incomplete/ imperfect sampling	• Poor control over "experiment" • Expensive to precisely specify the sampling points • Non-parametric statistics from incomplete/imperfect data