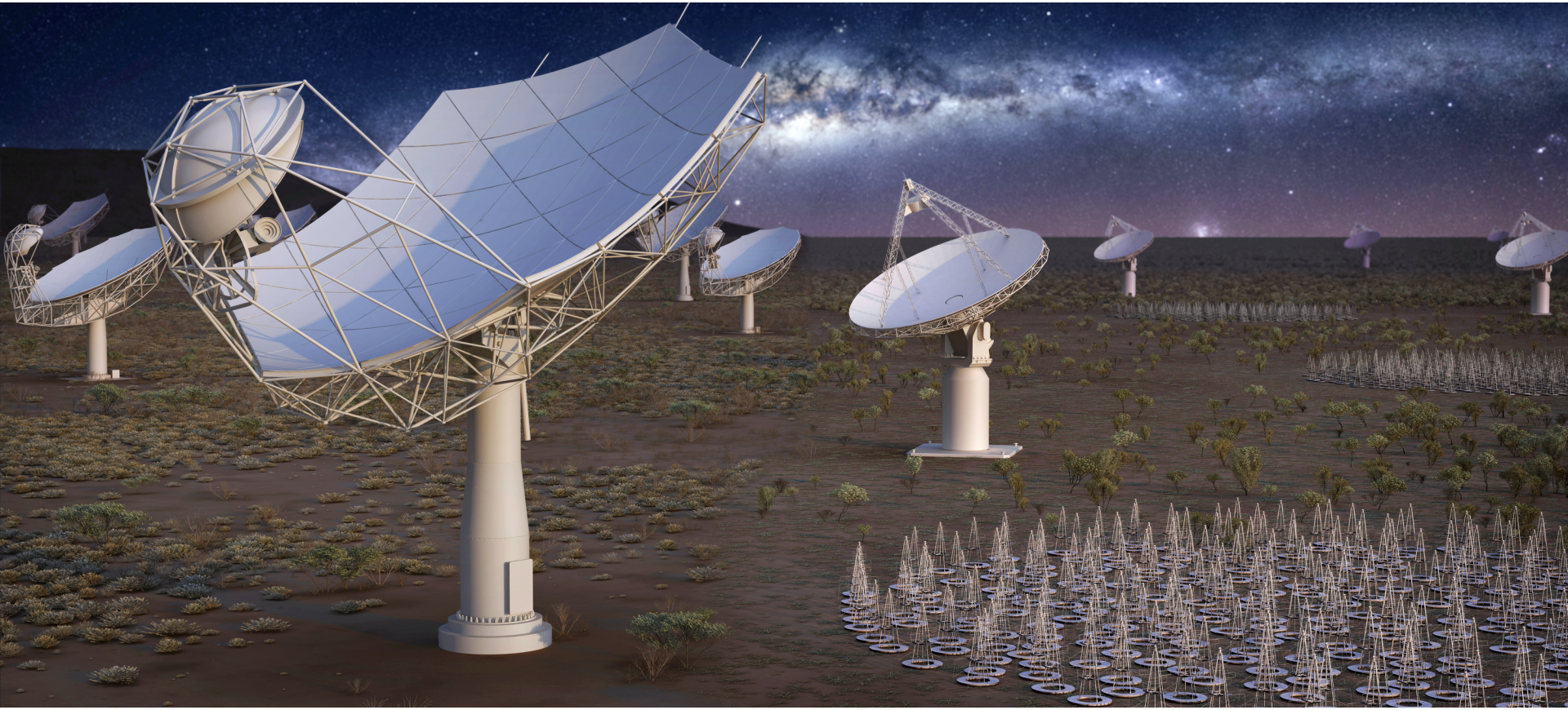
Square Kilometre Array : A New Observatory to Explore the Universe

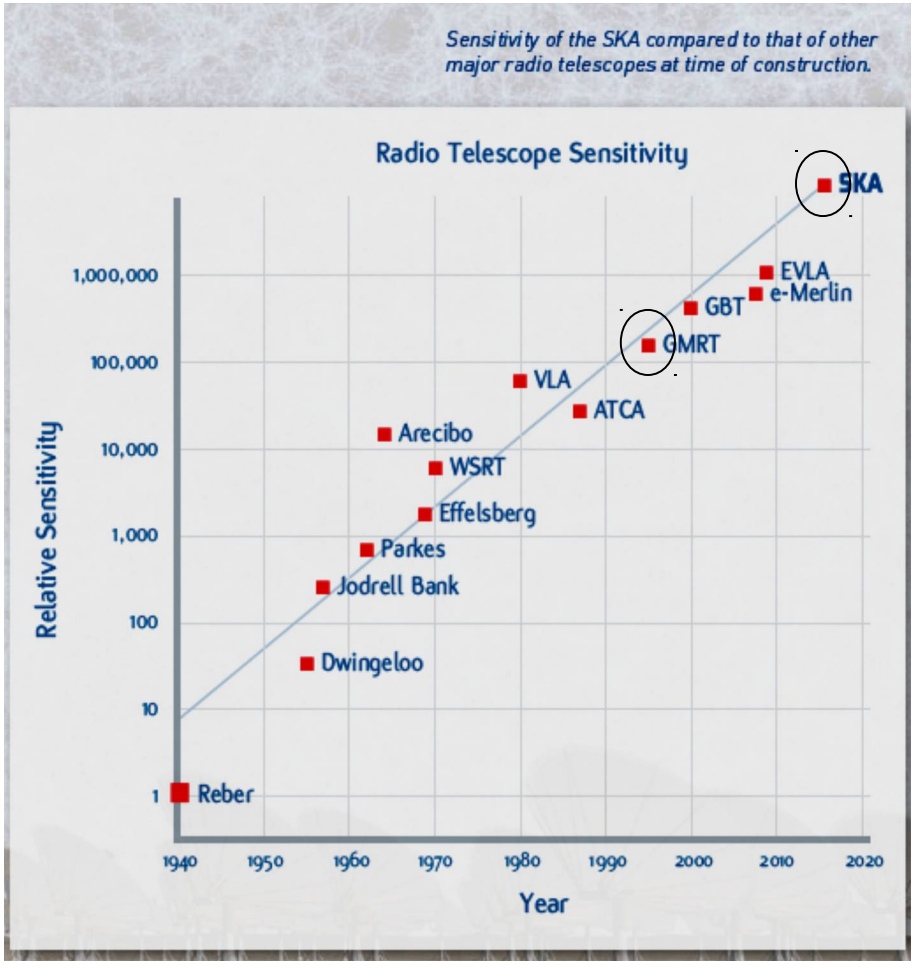


Debades Bandyopadhyay
Saha Institute of Nuclear Physics, Kolkata

Part I : About the SKA

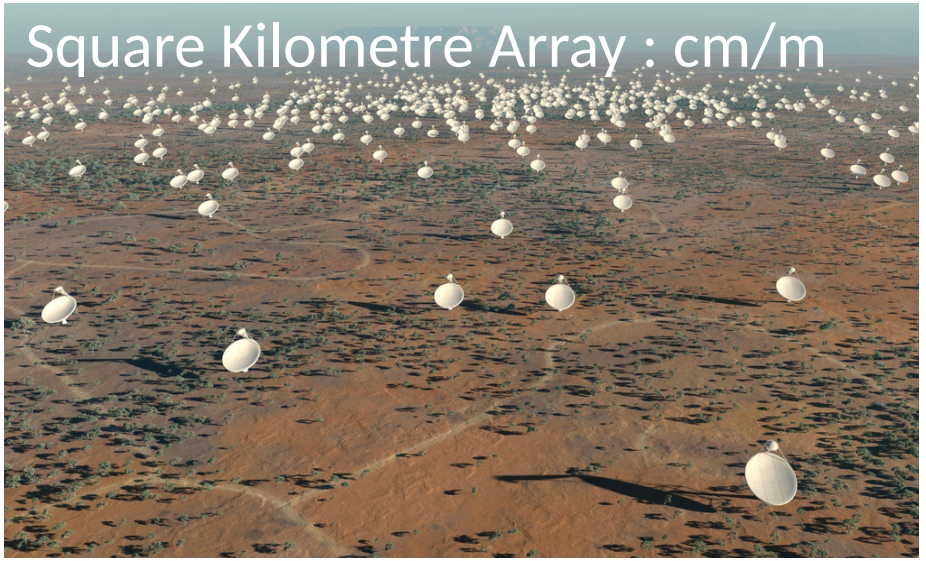
Background : what is the SKA ?

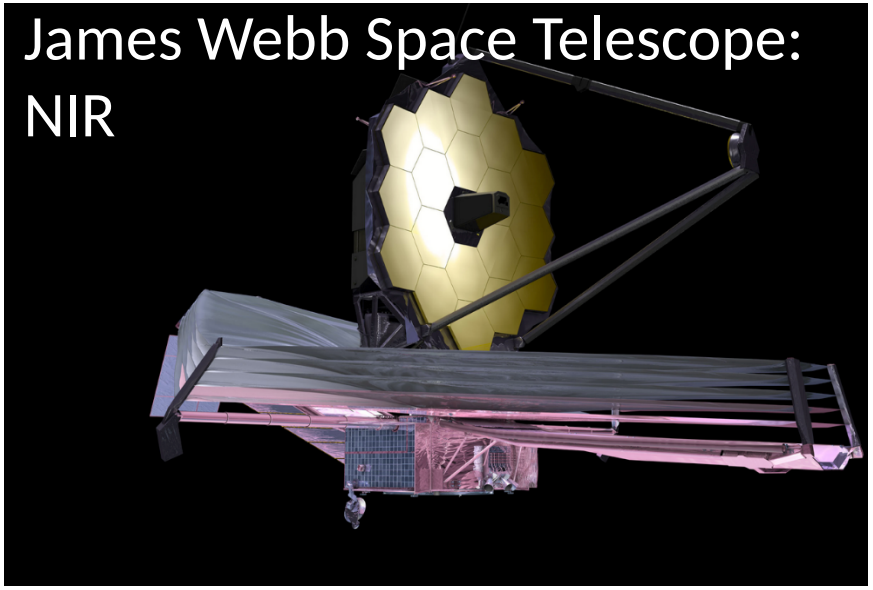
- The SKA is the most ambitious Radio Astronomy project ever attempted
- 1 square km (1,000,000 sq m) collecting area (~ 30 x GMRT !) ➔ ~ 3000 small sized antennas, with larger field of view
- High resolution ➔ antennas spread out over distances up to 3000 km, but connected in real-time (by optical fibre)
- Wide frequency range: 70 MHz - 10 GHz
- Location : Australia AND South Africa (radio quiet regions, far away from human habitat)
- Cutting edge science in all frontline areas
- Currently completing design phase; SKA Phase-1 completion expected by 2027.



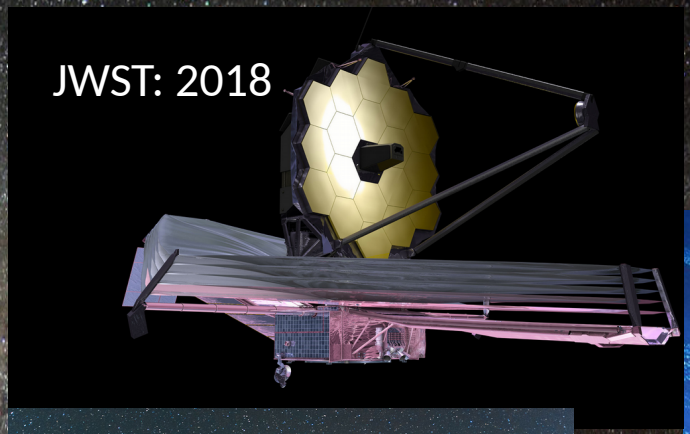
Radio telescope sensitivities over the years
SKA will be 50x better than today's best !

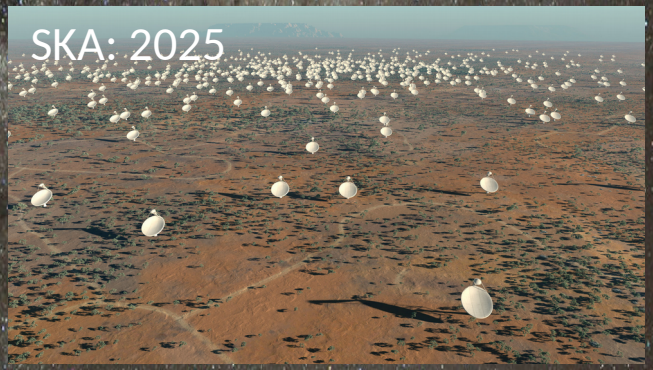
The SKA will be one of Great Multi-wavelength Observatories of the future decades

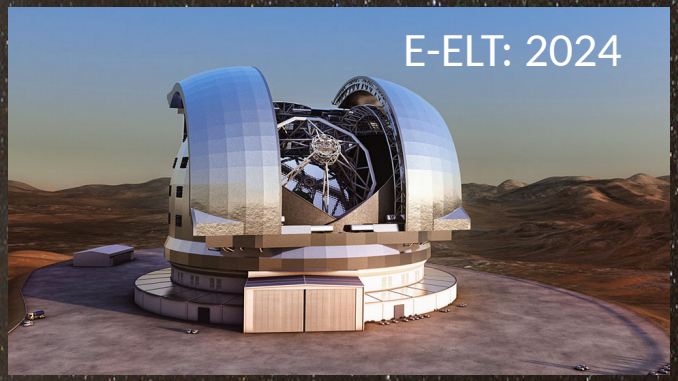


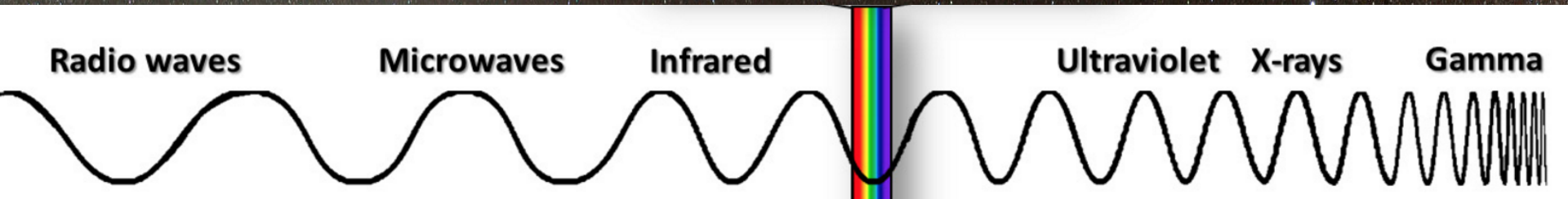


21st Century Observatories









SKA-MID : Karoo, South Africa

Phase 1 : 200 15m dishes spread over 150 km (2020 – 2025)

The Karoo

- 800 km north of Cape Town
- Radio quiet protected by Astronomy Advantage Act
- Building on MeerKAT

SKA-LOW : Murchison, Australia

Phase 1 : 130,000 dipole antennas over 80 km (2020 – 2025)

Murchison Desert

- 800 km north of Perth
- Very low popn density
- Radio quiet zone protected by ACMA
- ASKAP & MWA precursors

SKA HQ: ~150 staff; SKA Observatory: ~440 staff

€20M project.

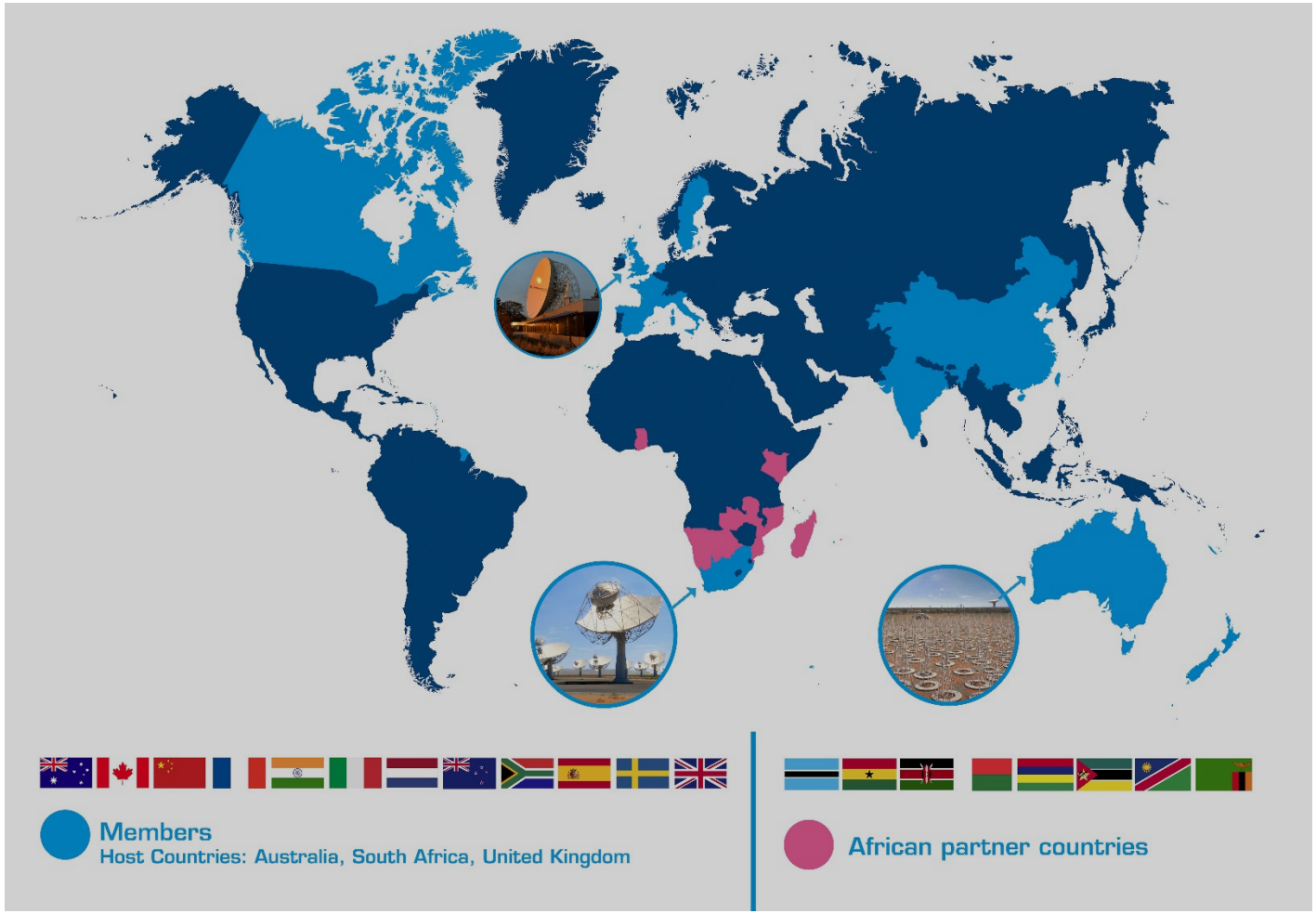
Complete June 2018

A ‘nexus for radio astronomy’

SKA-I : Members

Current Members :

- Australia
- Canada
- China
- France
- Germany
- India
- Italy
- Netherlands
- New Zealand
- South Africa
- Spain
- Sweden
- UK



Interested :

- Portugal
- Korea
- Japan
- Switzerland
- …

SKA-I : Timelines

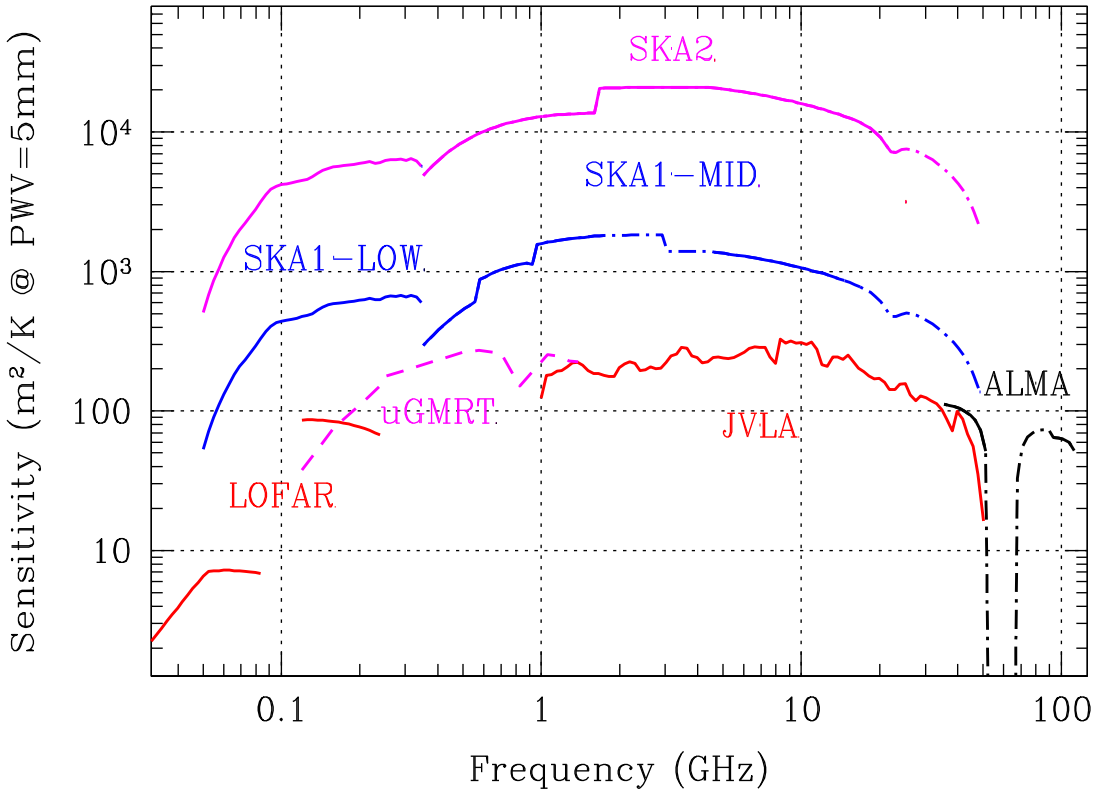
- Design work expected to conclude by end-2019, with the System CDR review; the CDR reviews for individual elements are ongoing (Telescope Manager was the first one – completed in June 2018).

- Construction of SKA Phase-1 expected to start sometime in 2021, and expected to continue till 2027.

- Commissioning and early science observations expected from 2024-25 – operations phase will start by then.

- SKA Inter-Governmental Organisation expected to form by mid-2020.

SKA1 Science Performance Update



- Improved performance predictions now available at all frequencies
- Opportunity for seamless interface of SKA to ALMA capabilities

Part II : Science with the SKA

SKA– Key Science Drivers: The history of the Universe

Cosmic Dawn
(First Stars and Galaxies)

Testing General Relativity
(Strong Regime, Gravitational Waves)

Galaxy Evolution
(Normal Galaxies z~2-3)

Cradle of Life
(Planets, Molecules, SETI)

Cosmology
(Dark Energy, Large Scale Structure)

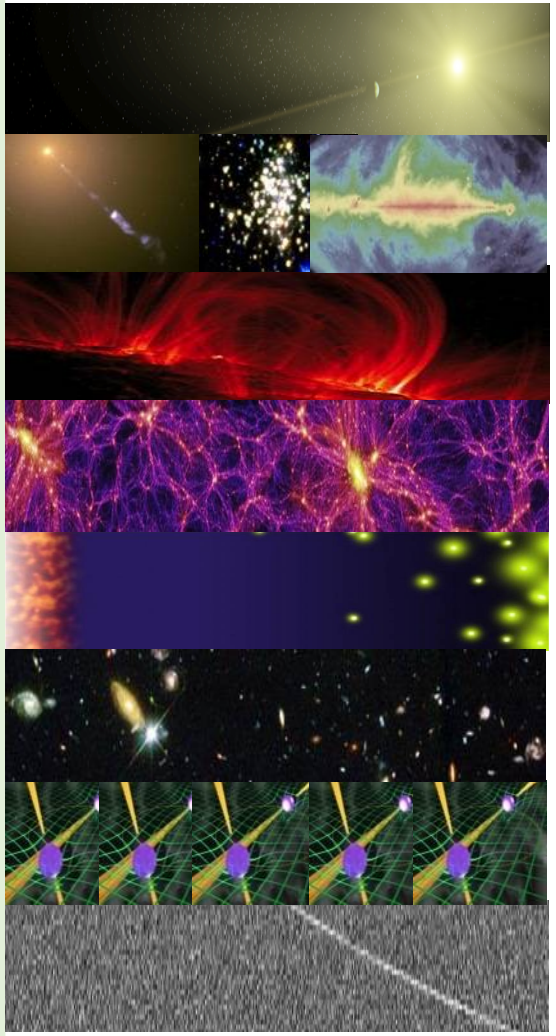
Cosmic Magnetism
(Origin, Evolution)

Exploration of the Unknown

Broadest range of science of any facility, worldwide

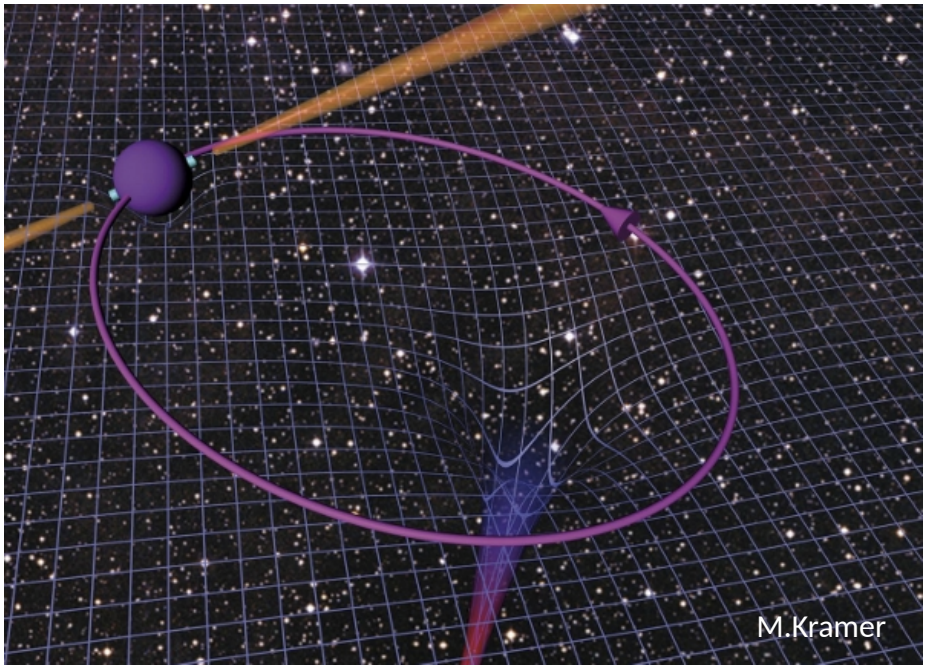
SKA Big Questions

- **The Cradle of Life & Astrobiology**
  - *How do planets form? Are we alone?*
- **Strong-field Tests of Gravity with Pulsars and Black Holes**
  - *Was Einstein right with General Relativity?*
- **The Origin and Evolution of Cosmic Magnetism**
  - *What is the role of magnetism in galaxy evolution and the structure of the cosmic web?*
- **Galaxy Evolution probed by Neutral Hydrogen**
  - *How do normal galaxies form and grow?*
- **The Transient Radio Sky**
  - *What are Fast Radio Bursts? What haven't we discovered?*
- **Galaxy Evolution probed in the Radio Continuum**
  - *What is the star-formation history of normal galaxies?*
- **Cosmology & Dark Energy**
  - *What is dark matter? What is the large-scale structure of the Universe?*
- **Cosmic Dawn and the Epoch of Reionization**
  - *How and when did the first stars and galaxies form?*



Test GR in strong field regime

Tests of GR in strong field regime via:
Neutron Star – White Dwarf binaries
Neutron Star – Neutron Star binaries
Pulsars around Galactic Centre
Neutron Star – Black Hole binaries



No Hair Theorem

Black Holes can be described by 3 classical parameters:

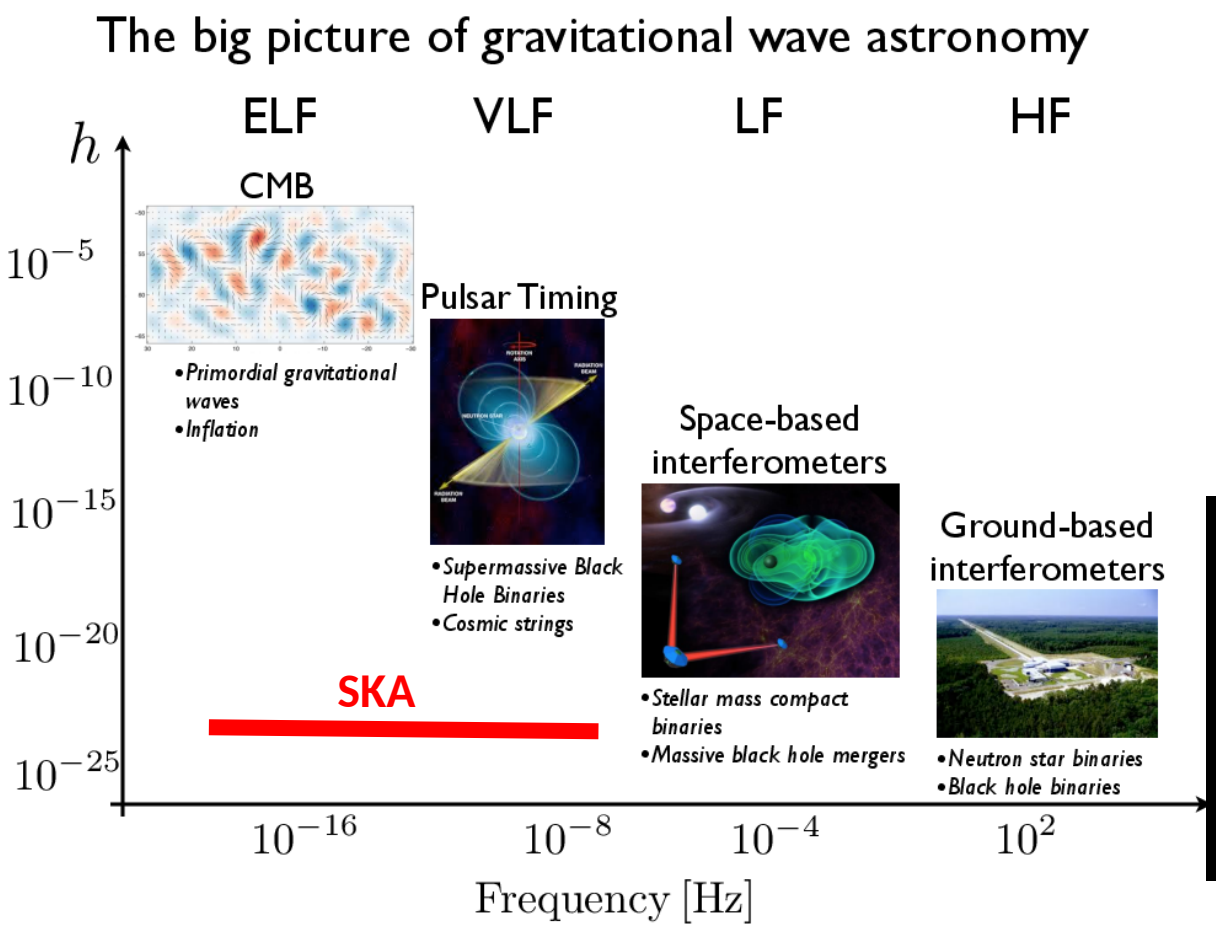
- Mass
- Electric Charge
- Angular Momentum (Spin)

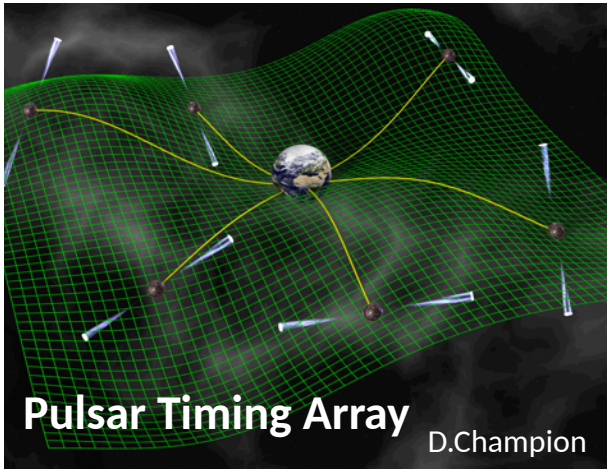
Cosmic Censorship

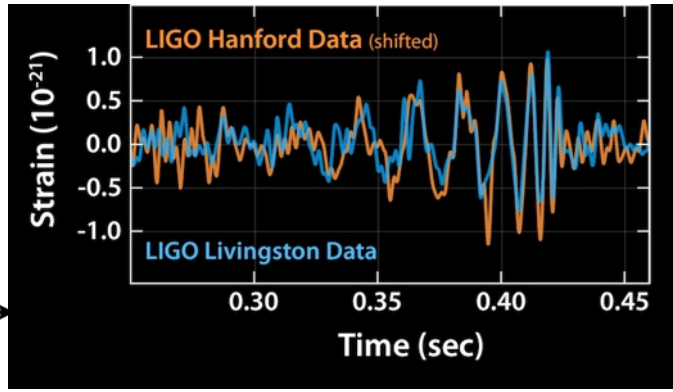
BHs have an event horizon which hides the singularity, i.e.., there are **no naked singularities**

Kramer & Stappers 2015

Gravitational Waves with Pulsars

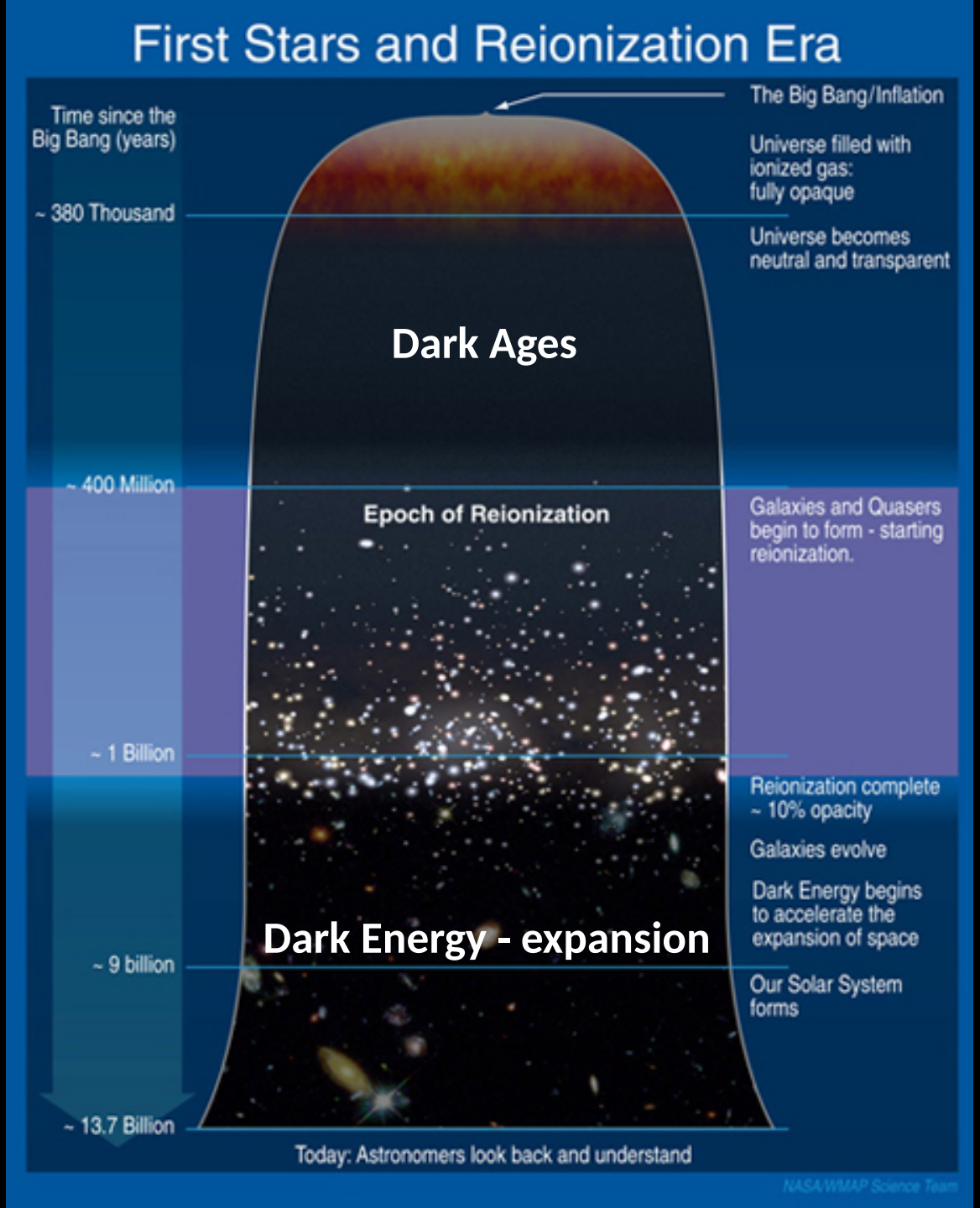






Discoveries with SKA1 (SMBH mergers, Primordial GWs)

"GW astronomy" with SKA2 (discrete sources)



380,000 yrs

CMB

400 million yrs

Stars form

1 Billion yrs

Galaxies evolve

9 Billion yrs

Solar System forms

13.7 Billion yrs

Humans

Part III : Indian participation in the SKA

Indian Strength in Radio Astronomy

- India has a strong tradition in Radio Astronomy, going back to 1960s.
- NCRA-TIFR & RRI are premier institutes in India for radio astronomy, with reputed global standing –both technology and science.
- NCRA has built and runs the world-class GMRT : attracts users from all over the world, for cutting edge experiments in radio astronomy; several new results since 2002; now nearing completion of a major upgrade.
- GMRT enjoys the status of a SKA Pathfinder facility : for both science and technology developments.
- RRI is actively involvement in the MWA, which is a SKA Precursor project, located at the SKA site in Western Australia.
- Strong and vibrant radio astronomy community in India, now covering many research organisations and universities, using both national and international facilities for cutting edge research.

Indian Participation in SKA : Overview

- India has been involved in the SKA Project since the early days of thinking & planning; and is a Full Member of the SKA Organisation.
- NCRA is the nodal organisation and DAE is the nodal ministry
- SKA India Consortium coordinates Indian activities -- has 20 member organisations : NCRA, RRI, SINP, IUCAA, IISc, IISERs, IITs, several universities and colleges…
- India hosted the SKA Board meeting in Pune in April 2016.
- India hosted the SKA Science Meeting in Goa in November 2016.
- India has participated actively in the negotiations for the SKA Treaty documents; keeping in mind the long-term interests of India in the project, including aspects such as IPR policy etc.
- Active participation in technical design of SKA-I (led the TM package)
- Preparation for science with SKA is ongoing; development of strong SKA India science case

India and the SKA : Science Activities

- After formation of the SKA India Consortium with 20 member organisations from India, there has been steady growth of science related activities.
- Indian Science Working Groups have been formed for almost all the main science goals or topics for which the SKA has international working groups.
- Indian Science Working Groups have produced a set of papers highlighting the SKA science areas of interest to Indian astronomers, giving the background of the ongoing activities in these areas and plans for the future. These have been published in a special issue of the Journal of Astronomy and Astrophysics in December 2016.
- Indian astronomers are improving their preparation towards SKA era science by carrying out next generation experiments using the current facilities.
- India hosted the 2016 Annual SKA Science meeting in Goa in November 2016, which was very well attended by a large population of researchers from India.
- A detailed science case and justification for Indian astronomers participating and benefiting from SKA is now ready.

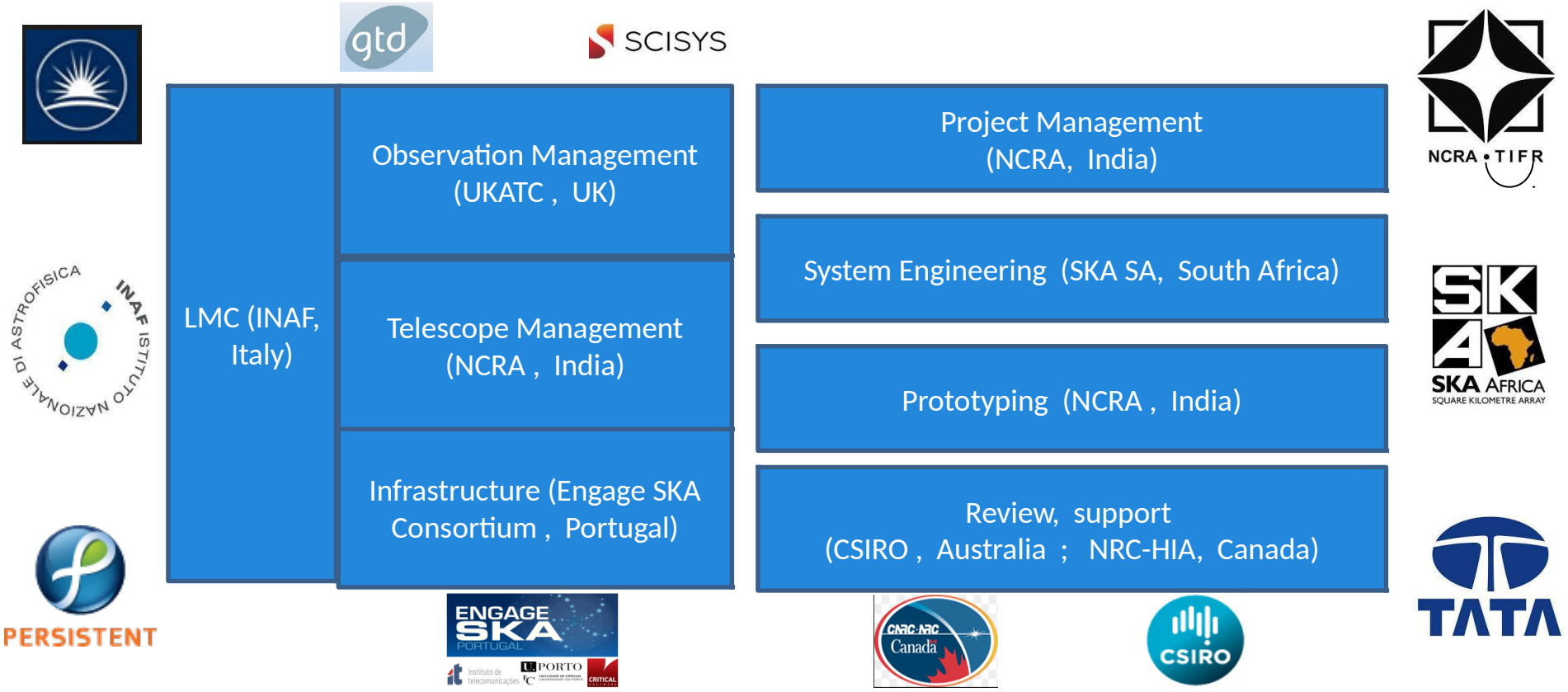
Indian Science Case for the SKA

- Dec 2016 : Special issue of Journal of Astrophysics & Astronomy carried papers by Indian astronomers on Indian perspective of science with SKA
- June 2018 : Detailed write-up on science case & benefits from participation in SKA finalised in last few months by Indian astronomers
- Indian science interests range from studies of the Sun to the early Universe
- More than 100 faculty, postdocs & students from ~ 20 different institutions involved in this exercise
- Number is expected to grow to more than 200 faculty, postdocs & students by the time SKA is ready for early science

Indian Participation : Technical Activities

- NCRA is involved in 3 of the design work packages : Telescope Manager (lead role), Central Signal Processing and Signal & Data Transport.
- RRI is actively involvement in the MWA, a SKA Pathfinder project
- NCRA, working with partners from software research groups & industry, has taken a lead role in the Telescope Manager (TM) work package
- TM is one of the critical systems of the SKA : it is the brain and nerve centre and provides end-to-end monitor & control for entire observatory; complex software needed for complete life-cycle management of SKA – from proposal submission by user to final data delivered to user.

TM Consortium : Partners & Roles



The Telescope Manager Consortium is led by the Indian team (NCRA + partners from research institutes & industry) and includes members from 7 other countries. Each member plays a specific role in the consortium, contributing to one or more of the major activities.

TM design completed by India led team

8/12/2018 Indian-led Telescope Manager consortium concludes design work on SKA - SKA Telescope

Home » Latest News » **Indian-led Telescope Manager consortium concludes design work on SKA**

Indian-Led Telescope Manager Consortium Concludes Design Work On SKA

Members of the Telescope Manager consortium gathered at SKA Global Headquarters in the UK for the Critical Design Review in April. Credit: SKAO

SKA Global Headquarters, 6 August 2018 – After four and a half years, the international Telesc (TM) consortium has formally concluded its work on the architectural design of a fundamental par for the Square Kilometre Array: the nervous system of the Observatory, which is called the Telesc

WWW.INDIANEXPRESS.COM
THE SUNDAY EXPRESS, AUGUST 5, 2018

Team led by Pune institute designs 'nervous system' of largest radio telescope

12 countries working together to build telescope that will provide closer look at 'one million square metres of sky'

ANJALI MARAR
PUNE, AUGUST 4

A TEAM of international scientists, led by Pune-based TIFR-National Centre for Radio Astrophysics (NCRA), has become the first among 12 other design teams to successfully develop a control system for the Square Kilometre Array (SKA), the world's largest radio telescope that is currently in the design and planning stage.

The NCRA team has developed, designed and received approval for the the Telescope Manager (TM), the key software and control system, or the 'nervous system', of the SKA. The TM

The international consortia has allocated a budget of 700 million euros for the first phase of the SKA. The Indian government has, so far, contributed Rs 30 crore for the first phase of the telescope's development.

To develop the TM's design, Indian scientists and their industry partners, TCS Research and Innovation, teamed up with experts from six countries - Commonwealth Scientific and Industrial Research Council (CSIRO), Australia, National Research Council of Canada (NRC), National Institute for Astrophysics (INAF), Italy, Instituto de Telecomunicacoes (IT) and School of Science of Porto University from

currently operational.

This highly complex engineering facility, with thousands of dish antennas, will offer researchers greater insight into one million square metres of the sky and faster surveying ability in a shorter span of time, to improve the overall understanding about the universe and to track some of the earliest star formations, among other functions.

The world's largest radio telescope is expected to generate astronomical data to the tune of 3 lakh terabytes annually. To draw a comparison, the NCRA-operated upgraded Giant Metrewave Radio Telescope (GMRT), located in Khodad near Pune, generates data ranging

Strong appreciation for Indian leadership and capability in TM design work !

Summary : How participation in SKA will benefit India

- Science objectives and benefits :
  - Priority access to best radio observatory in the future
  - 20 institutions, 100 scientists (faculty, postdocs, students) already engaged
  - Will grow to over 200 scientists by start of early science phase of SKA-1
  - Dedicated SKA Regional Data Centre in India will enhance science returns
  - Excellent synergy for data from large optical telescopes e.g. TMT
  - Growth of international collaborations and participation for Indian scientists
- Technology objectives and benefits :
  - New technology in many areas -- direct benefit to Indian industry as well as for in-house R&D programs : antennas, receiver electronics, optical fibre technology, signal processing, big data storage & analysis, algorithms and software for complex systems
  - Direct synergy and benefit for domestic programs : expanded GMRT, growth of radio astronomy in other institutions and universities
  - Leadership role for India in certain areas : Telescope Manager & associated software for management of complex systems – core area of research & interest for industry also.
  - Growth of big data science will drive technology benefits to industry partners
- Societal benefits :
  - Interest in science & technology in the general population : astronomy always attracts !
  - Development of large pool of trained manpower : technical & scientific
  - Spin-offs to industry from technical activities spurred by SKA participation
  - Enhance India’s standing in groups such as BRICS…

Indian Participation : Technical Activities

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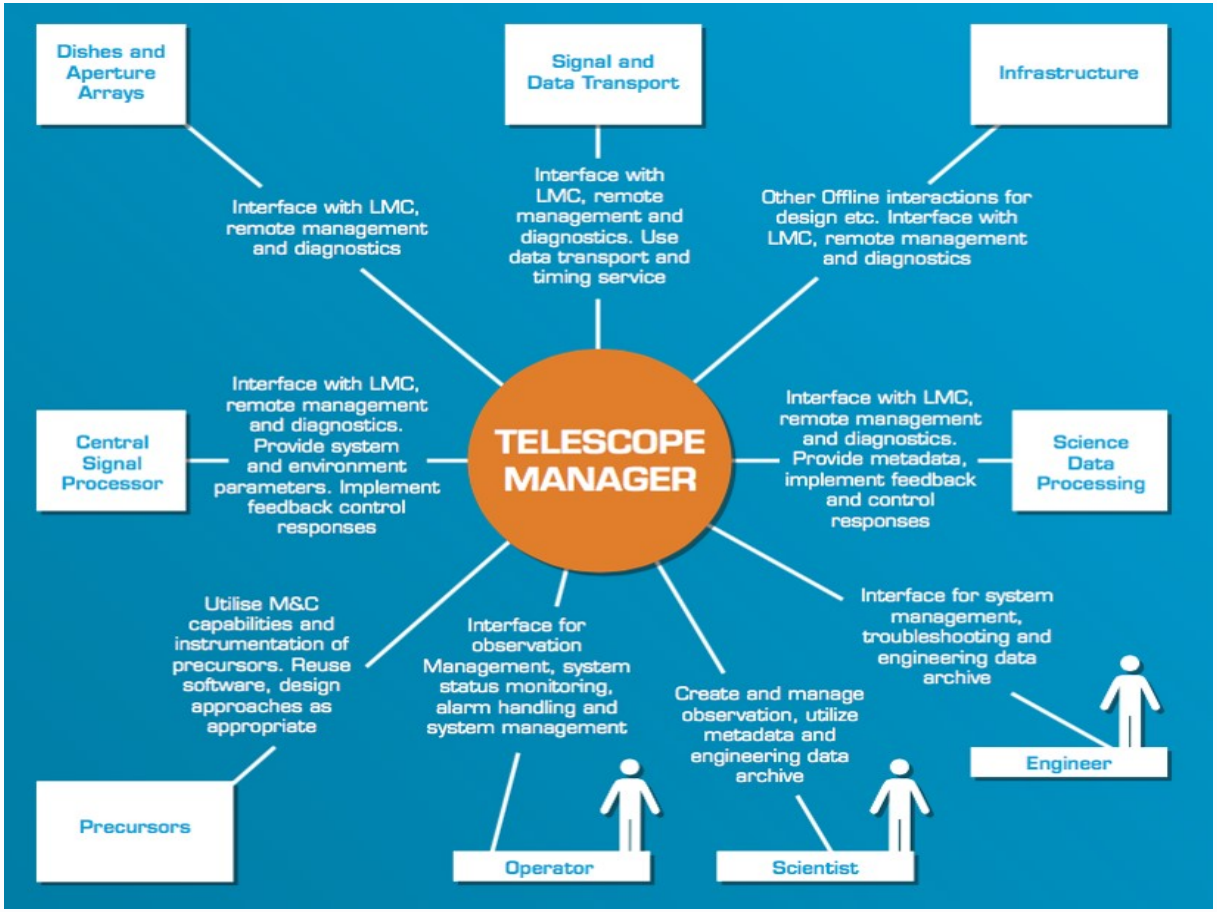
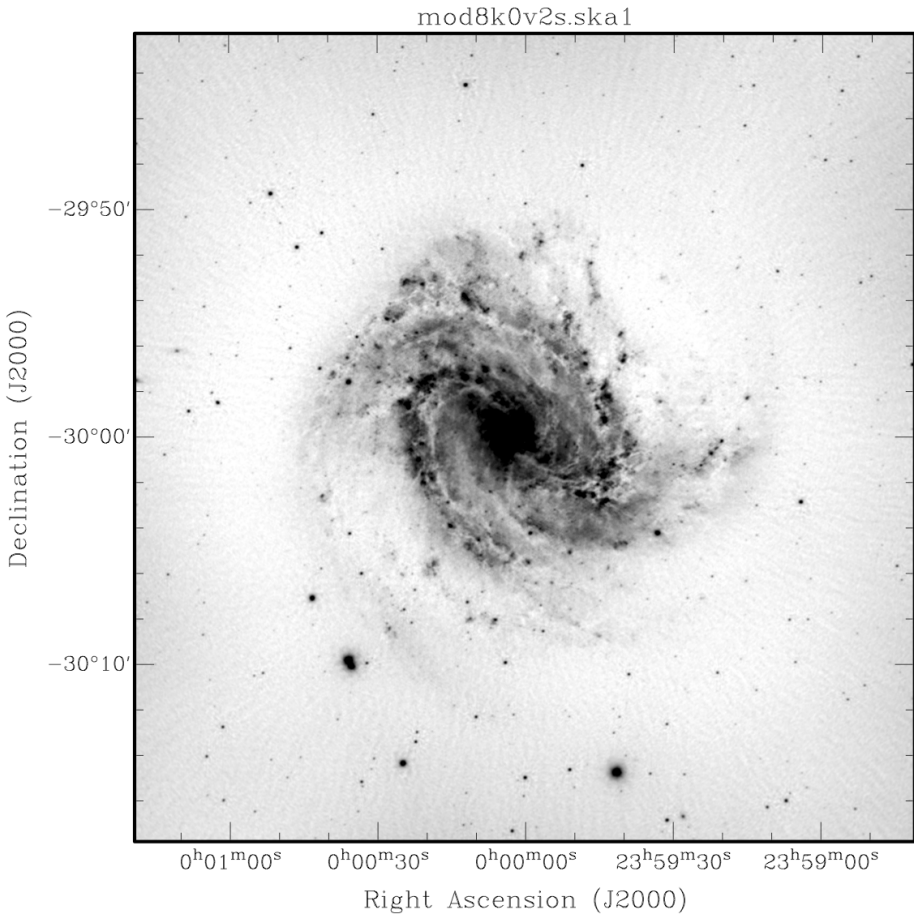
- NCRA, working with partners from software research groups & industry, has taken a lead role in the Telescope Manager (TM) work package
- TM is one of the critical systems of the SKA : it is the brain and nerve centre and provides end-to-end monitor & control for entire observatory; complex software needed for complete life-cycle management of SKA – from proposal submission by user to final data delivered to user.
- The TM team completed the design work with sucessfuldefensein the CDR in April 2018; final, updated design documents submitted to SKAO in July 2018.
- TM was the first design work package to complete CDR; work done by India in leading this effort has been highly appreciated by the SKAO.
- Strong industry participation and interaction has been built.

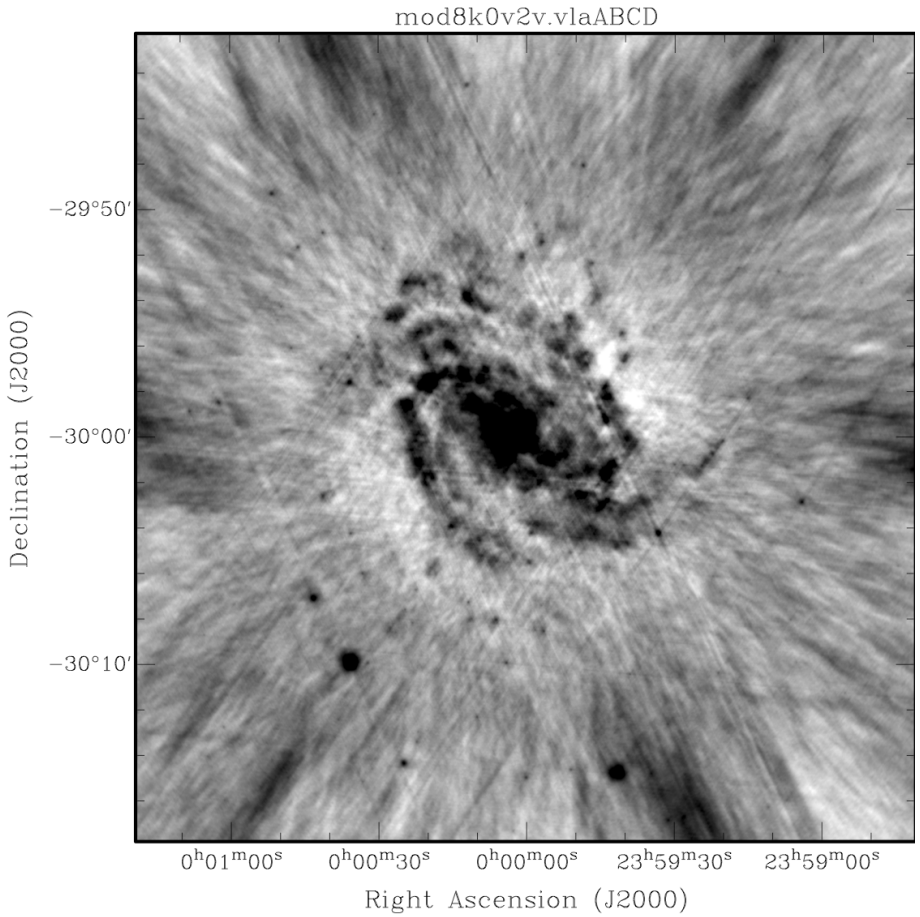
End-to-End management of the observatory

- SKA observatory will be a vast, distributed system requiring sophisticated end-to-end management system
- Telescope Manager : brain and nervous system of the observatory
- Design phase work (2014 – 2018) led by India (NCRA + industry partners)



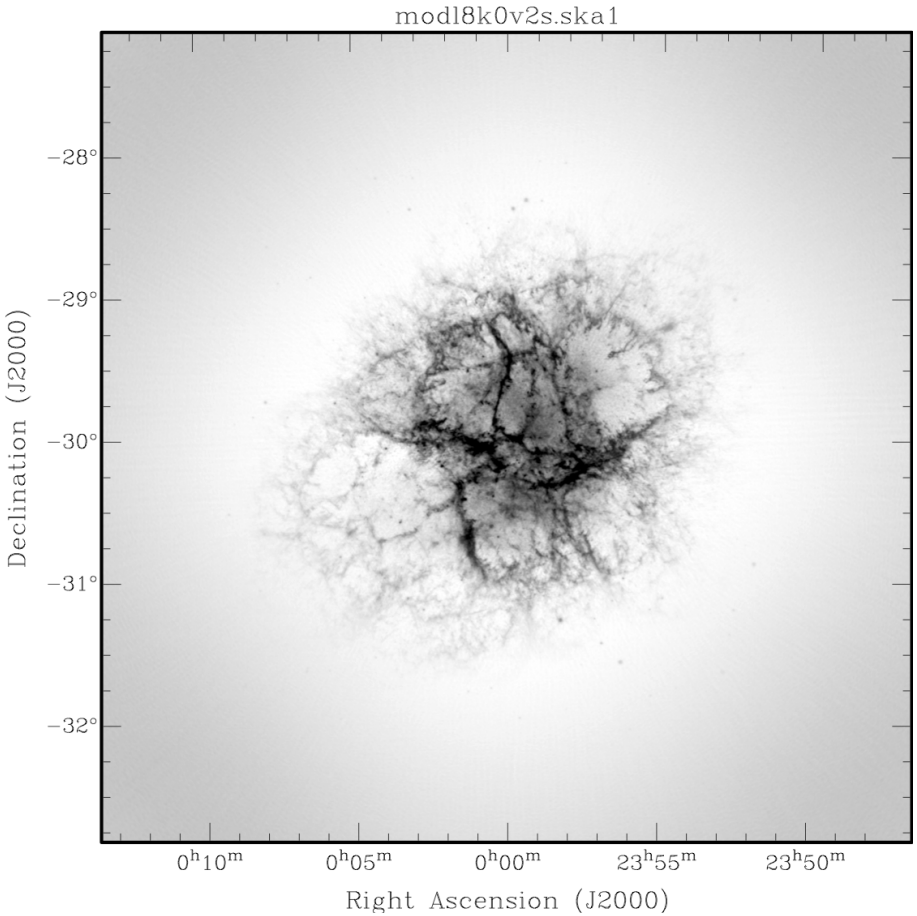
SKA1 Science Performance

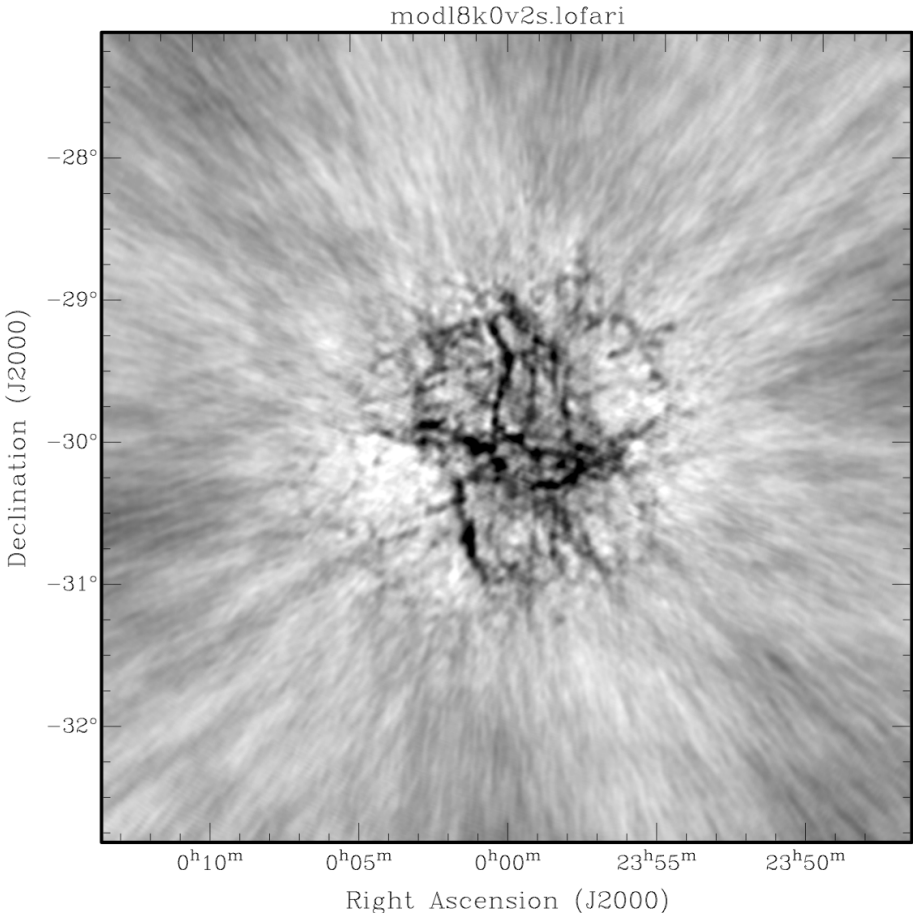




- Single SKA1-Mid dirty snap-shot compared to combination of snap-shots in each of VLA A+B+C+D (target PSF in both cases 1” FWHM Gaussian at 1.4

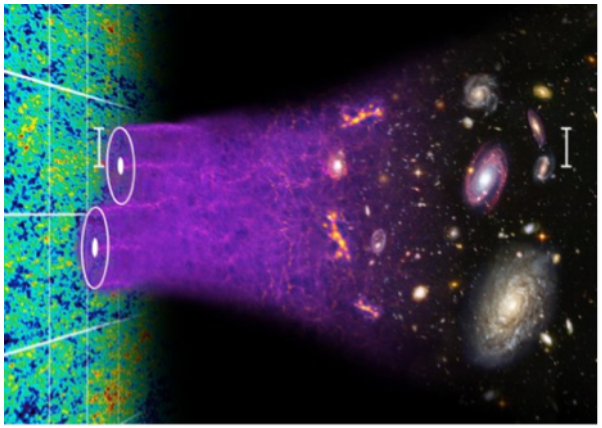
SKA1 Science Performance





- Single SKA1-Low snap-shot compared to LOFAR snap-shot (target PSF in both cases 10” FWHM Gaussian at 140 MHz)

What is Dark Energy?



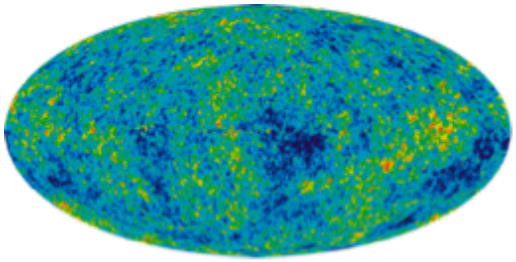
Baryon Acoustic Oscillations (BAO)

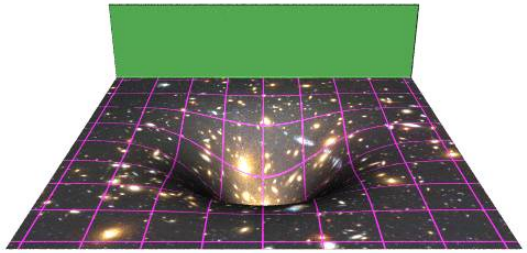
- Standard ruler to map expansion history of the Universe
- Test cosmological models incl. Dark Matter
- HI Intensity mapping with SKA

Does GR hold on large scales?

Constraining non-Gaussianity of primordial fluctuations

- Uniquely probes the largest scales
  - → tests of inflation models
- Cross-correlation of large-scale structure and CMB
  - Integrated Sachs-Wolf effect





What is the origin of B fields? How do they evolve?

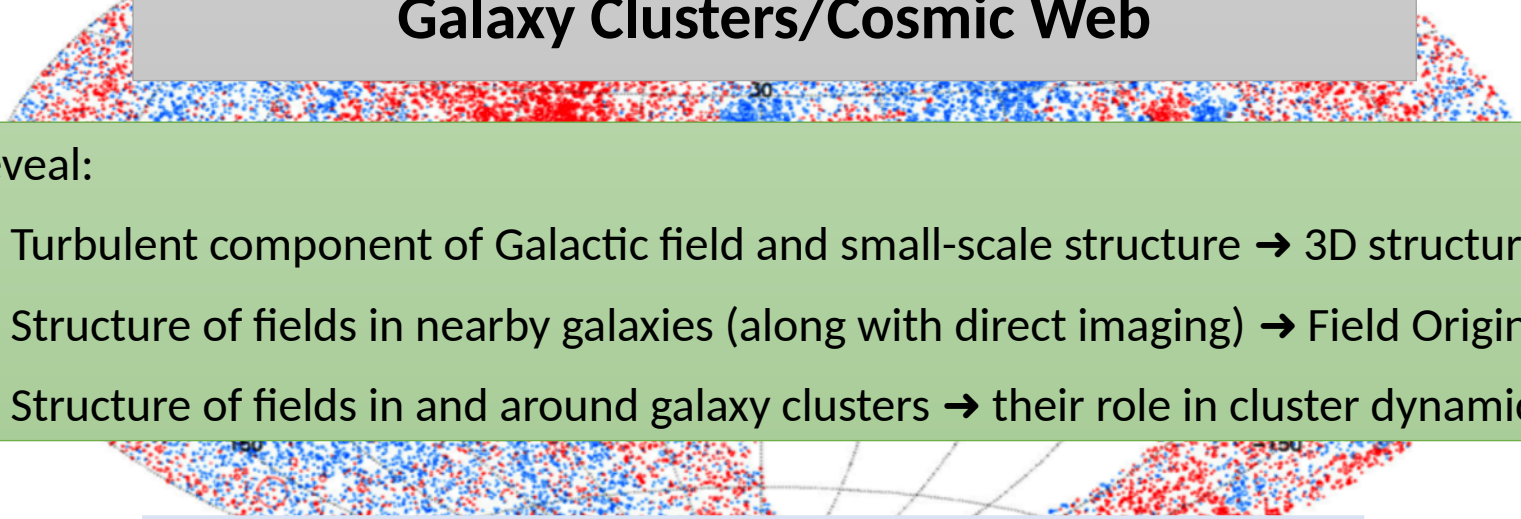
What is their role in galaxy and structure evolution?

Measure the magnetic field structure in:

Our Galaxy

Nearby Galaxies

Galaxy Clusters/Cosmic Web



Reveal:

- Turbulent component of Galactic field and small-scale structure ➜ 3D structure
- Structure of fields in nearby galaxies (along with direct imaging) ➜ Field Origin
- Structure of fields in and around galaxy clusters ➜ their role in cluster dynamics

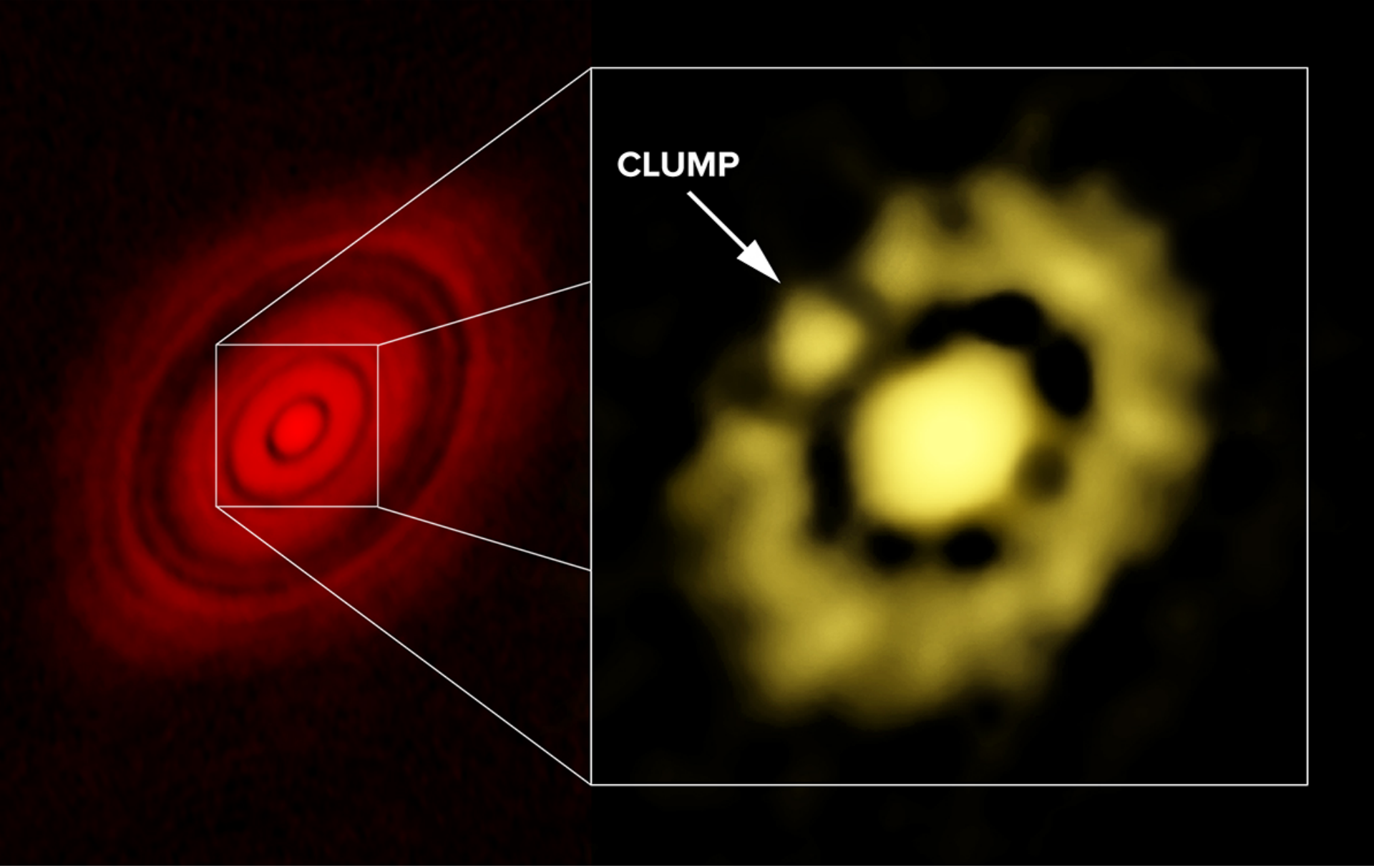
Rotation Measure Grid

NVSS 1 source/deg^2. SKA1 ~300x denser; SKA2 ~5000

Johnston-Hollitt+ 2015

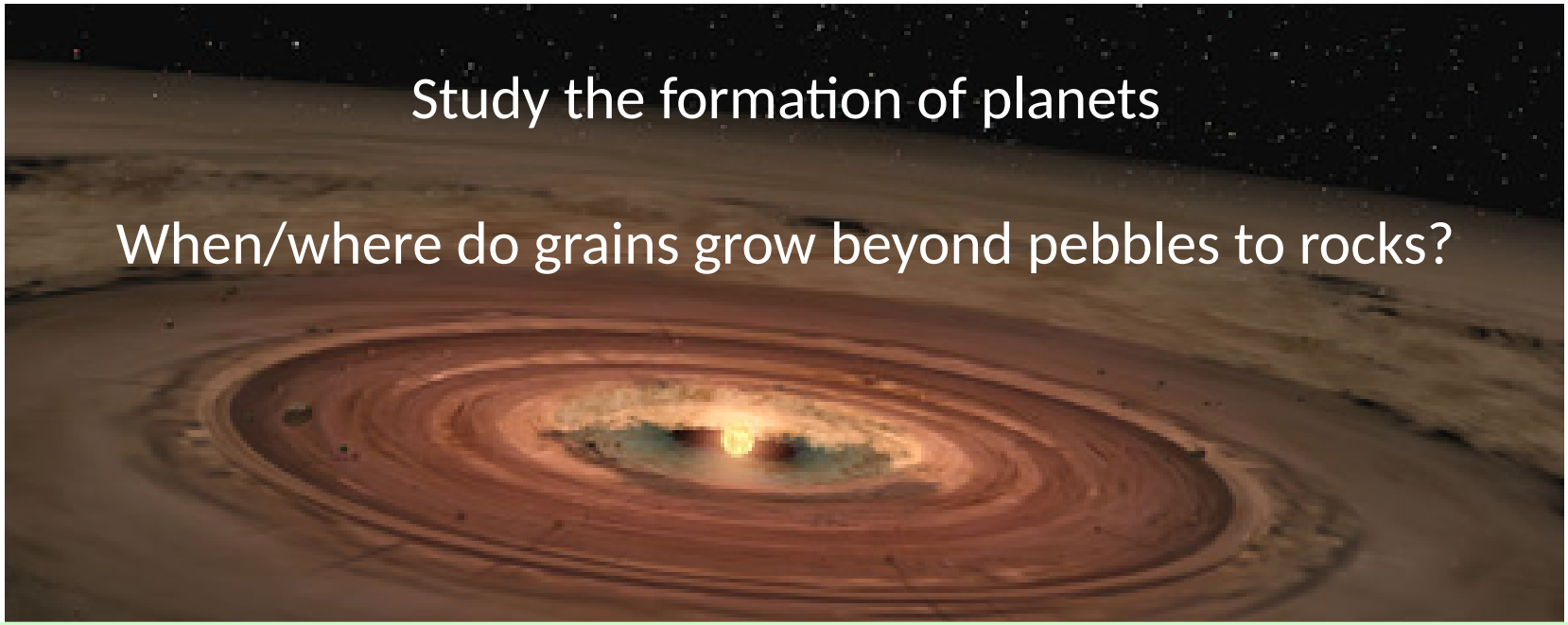
SKA will detect all pulsars in Milky Way

- ~30,000 normal pulsars
- ~2,000 millisecond pulsars
- ~100 relativistic binaries
- pulsar – Black Hole binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars



ALMA 1-mm image of HL Tau at left; VLA 7-mm image (70 mas), showing clump of dust, at right.
CREDIT: Carrasco-Gonzalez, et al.; Bill Saxton, NRAO/AUI/NSF.

Grain Growth in Protoplanetary Disks



Resolved disk observations allow for separation of free-free and thermal dust emission

SKA1 at 15 GHz will have 34 mas resolution, so 4-5 AU at 140 pc

Probing very large grains trapped in the terrestrial planet regime

→ SKA resolution and sensitivity at longer wavelengths sensitive to larger grain sizes

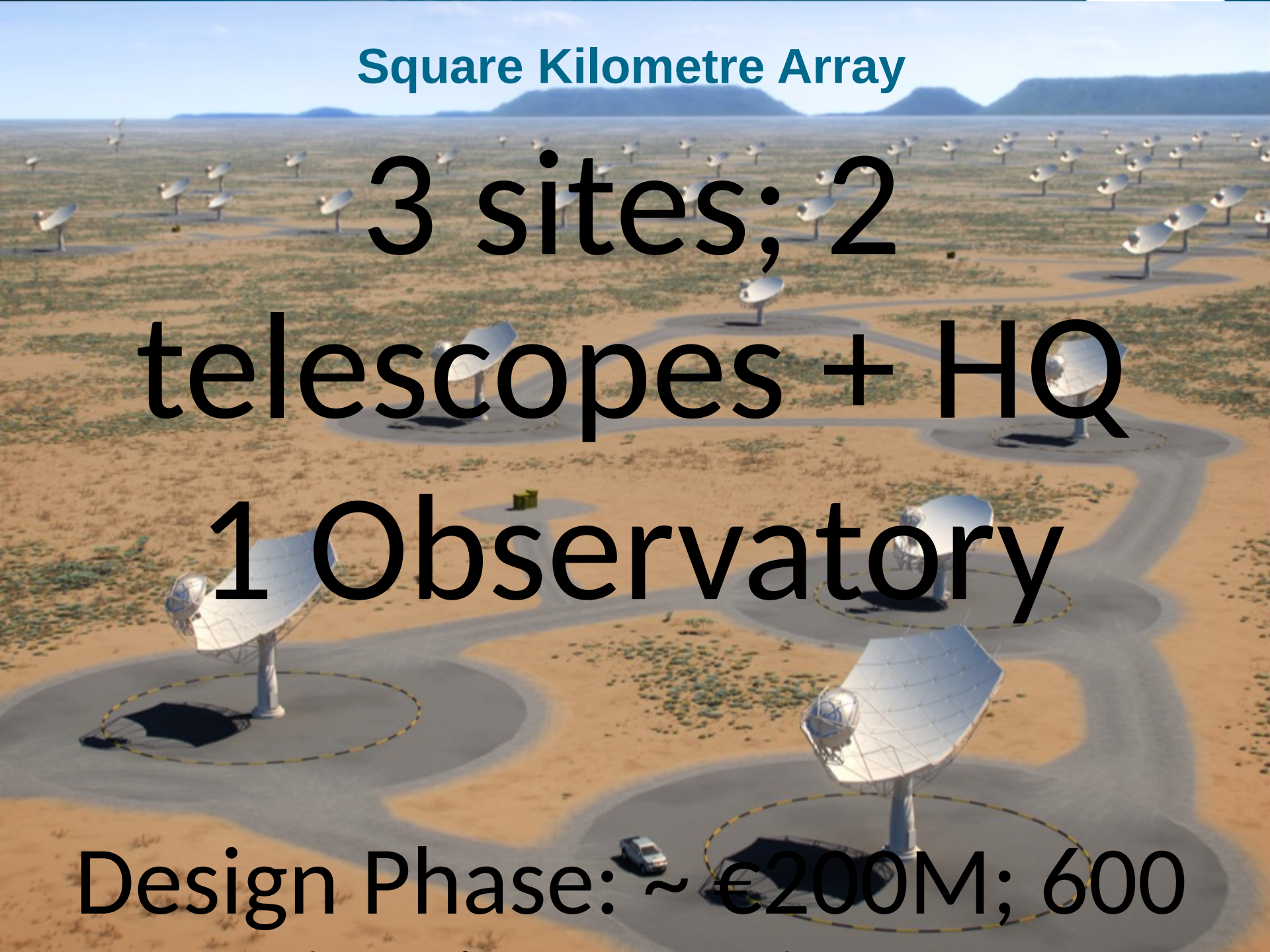
Hoare+ 2015, Testi+ 2015

Science with the SKA

- Evolution of galaxies and LSS:
  - large volume and upto high redshift HI survey
  - evolution of galaxy from z ~ 5 to present
  - matter power spectrum and dark energy
- Cosmic dawn: dark ages, Epoch of Reionization
  - redshifted HI to map the process of EoR
  - CO: star forming galaxies; continuum: AGN
  - tight constraints on first galaxies (and Bhs)
- Exploring unknown unknowns
  - unique capabilities of SKA: sensitivity, versatility ...

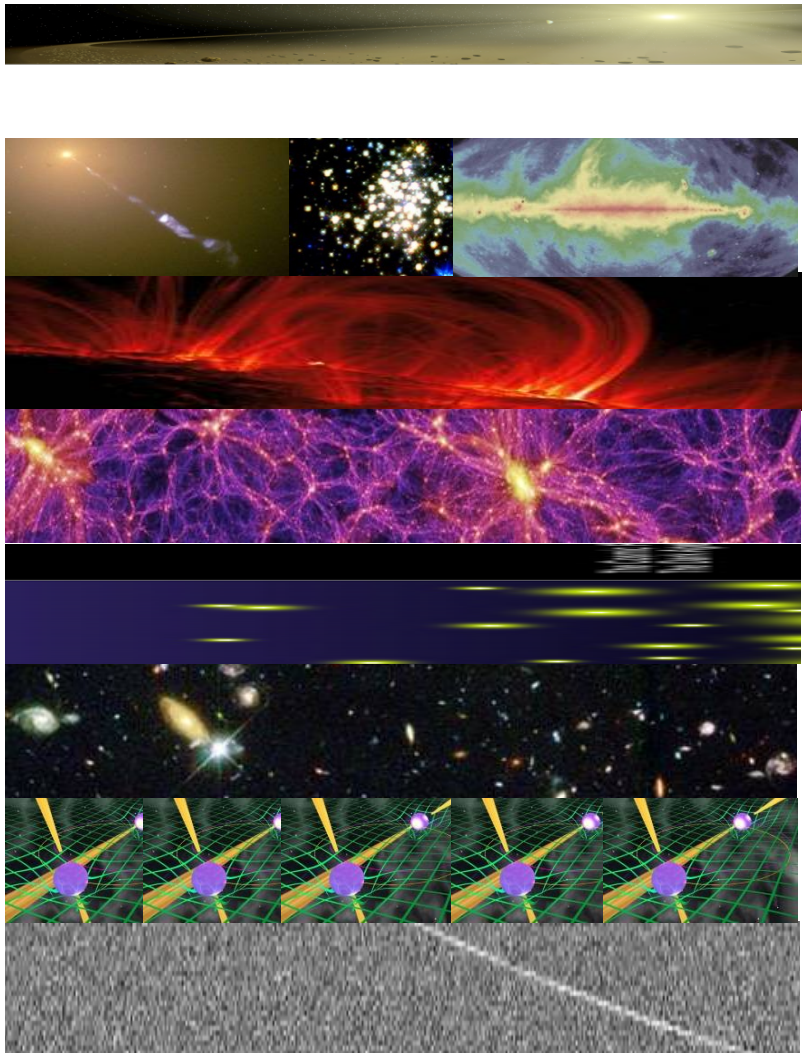
Science with the SKA

- Strong field test of gravity with pulsar survey:
  - thousands of ms pulsar for timing array
  - pulsars in close orbits around GC SMBH
  - pulsar in robit around stellar mass BH
- Cradle of Life: astrobiology/extra-solar planets/SETI
  - sub-AU resolution (at ~ 10 GHz), planet formation
  - spectral lines from complex (pre-)bio molecules
  - leakage radiation of ETI transmitters out to few 100 pc
- Origin & evolution of cosmic magnetism: z > 3 to present
  - Polarized synchrotron, Faraday rotation, Zeeman

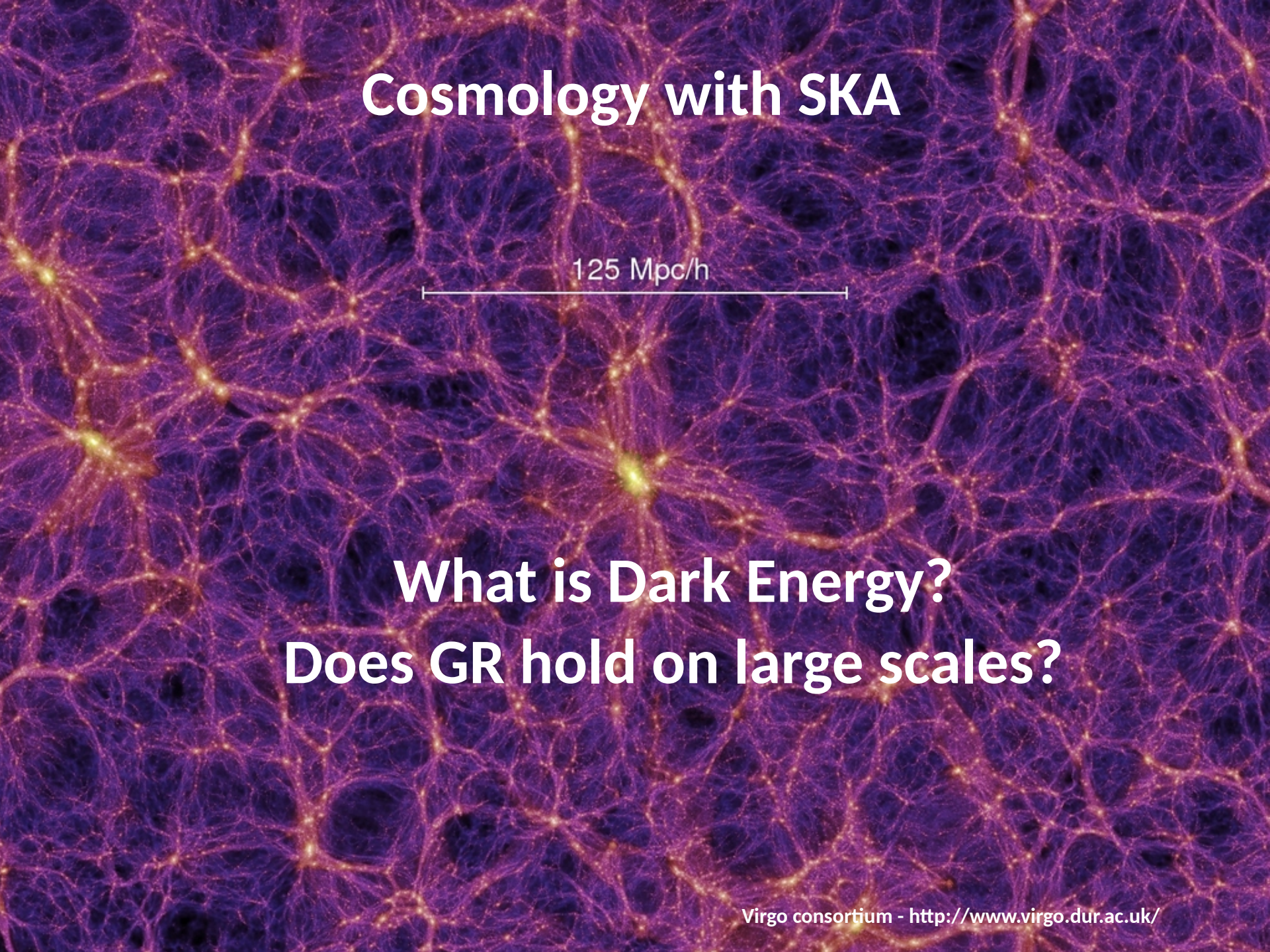

Square Kilometre Array
3 sites; 2 telescopes + HQ
1 Observatory
Design Phase: ~ €200M; 600

Science with the SKA

- Cosmic Dawn & EoR : direct imaging of the earliest structures
- Cosmology & Dark Energy : primordial non-Gaussianity, super-horizon scales and the matter dipole
- Galaxy Evolution (via Radio Continuum and Neutral Hydrogen) : star formation rates, resolved gaseous disks and angular momentum growth;
- The Origin and Evolution of Cosmic Magnetism : what generates the magnetic fields in space? ; the role of magnetism in galaxy evolution
- The Transient Radio Sky : Fast Radio Bursts as cosmological probes
- Strong-field Tests of Gravity with Pulsars & Black Holes : gravity waves & fundamental physics; was Einstein right ?
- The Cradle of Life & Astrobiology : detecting proto-planetary disks, search for complex molecules (building blocks of life), SETI
- Serendipitous science : the power & sophistication of the SKA will provide plenty of opportunities for new, unexpected discoveries !



Cosmology with SKA



What is Dark Energy?
Does GR hold on large scales?

Virgo consortium - http://www.virgo.dur.ac.uk/

The Unknowns (cf. HST)

Project	Key project	Planned?	Nat. Geo. top ten?	Highly cited?	Nobel prize?
Use Cepheids to improve value of H0	✔	✔	✔	✔	
Study intergalactic medium with uv spectroscopy	✔	✔			
Medium-deep survey	✔	✔			
Image quasar host galaxies		✔	✔		
Measure SMBH masses		✔	✔		
Exoplanet atmospheres		✔	✔		
Planetary Nebulae		✔	✔		

(Lallo: arXiv:1203.0002; Norris AASKA14)

SKA Phase I

- Frequency coverage : 70 MHz to 3 (10) GHz
- Max baseline : 150 km
- All infrastructure and designs to keep in mind the full SKA
- Two sites : Australia (SKA-low) and South Africa (SKA-mid)
- Global HQ : Jodrell Bank (UK)
- Detailed design & definition phase : 2012 - 2019 (~ 110 M Euros)
- Construction phase : 2021 - 2027 (~ 650 M Euros; Rs 4500 cr)

What is the origin of B fields? How do they evolve?

What is their role in galaxy and structure evolution?