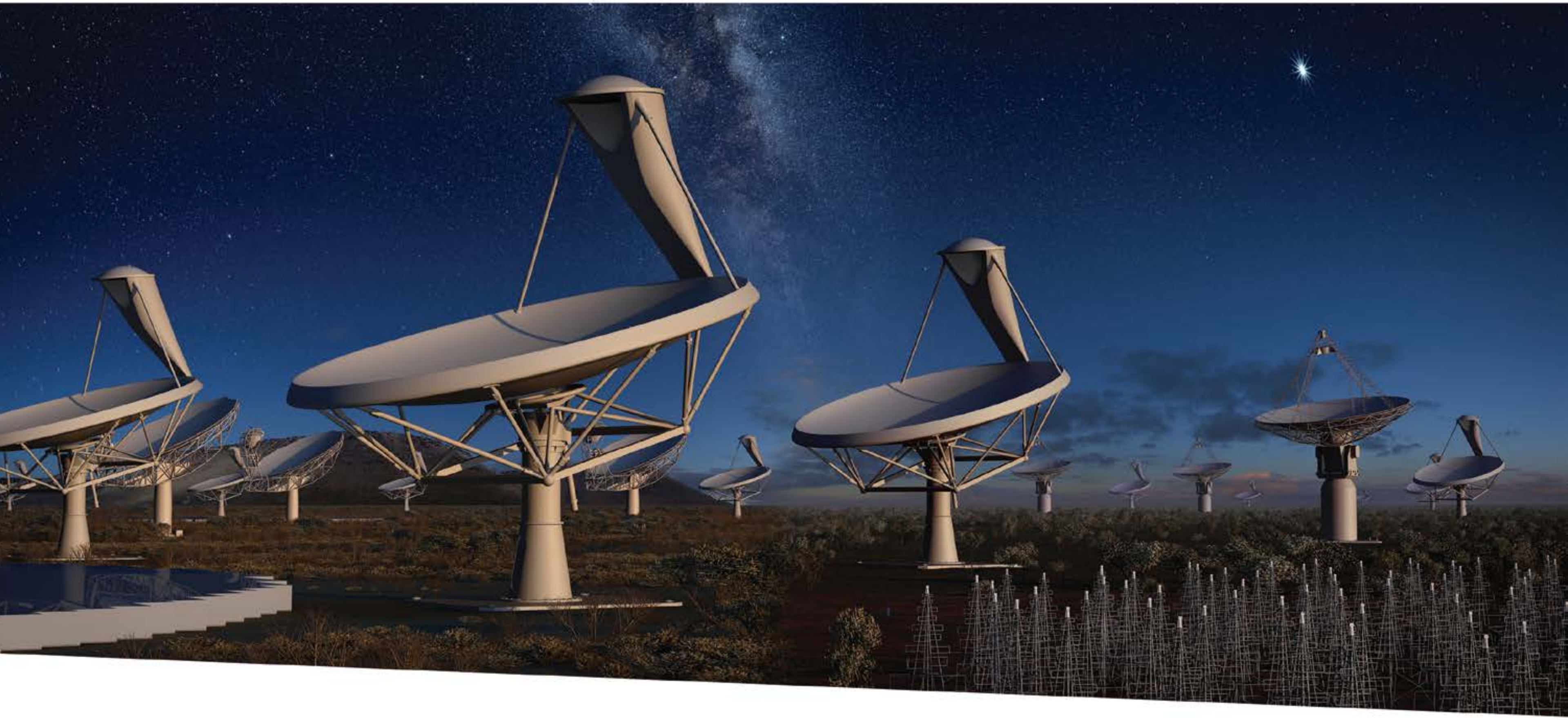
Road towards SKA2 and Mid Frequency Science



SQUARE KILOMETRE ARRAY

Exploring the Universe with the world's largest radio telescope

André van Es/Jeff Wagg SKAO

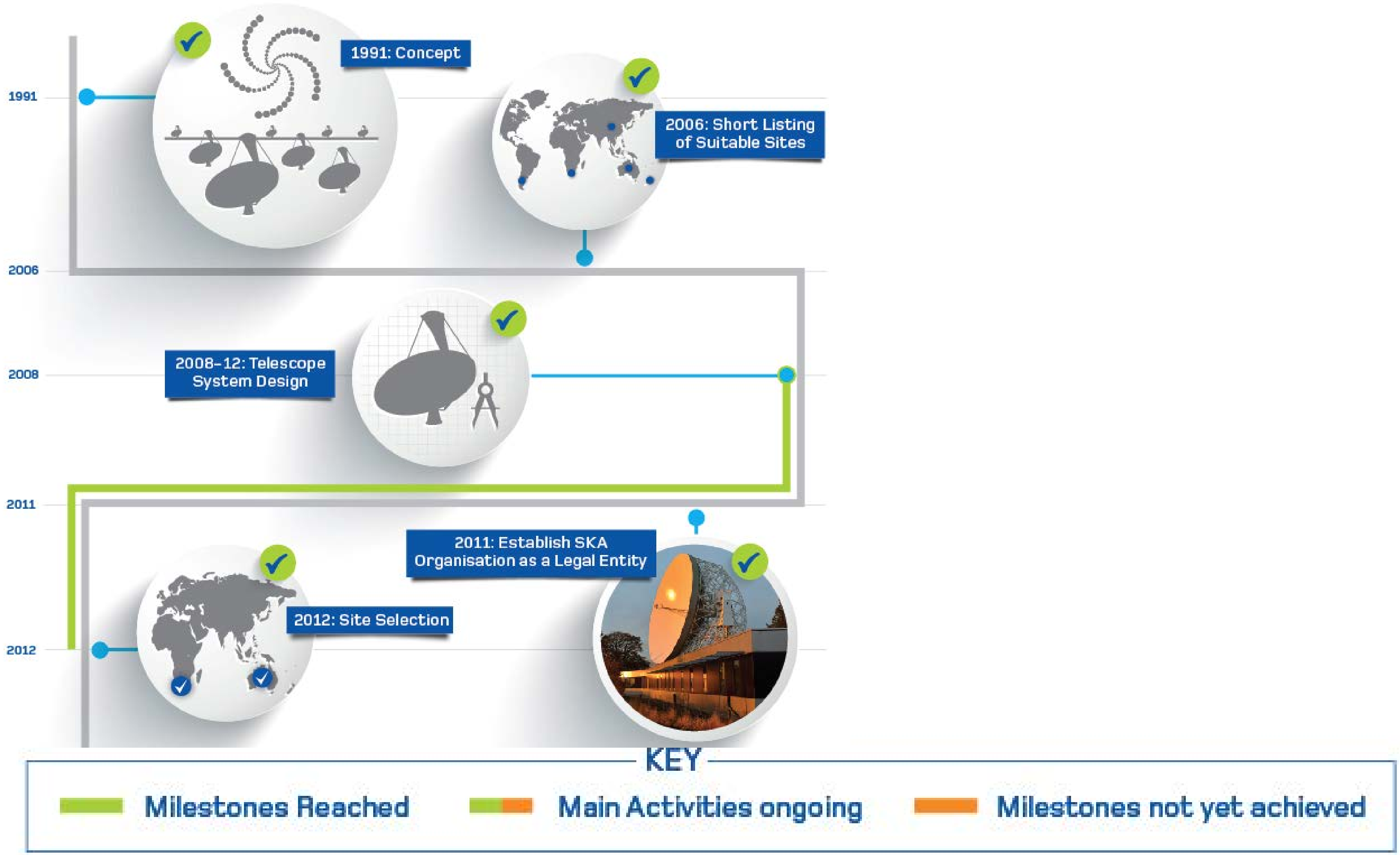
AAMID Workshop: March 7th 2016

Road towards SKA2

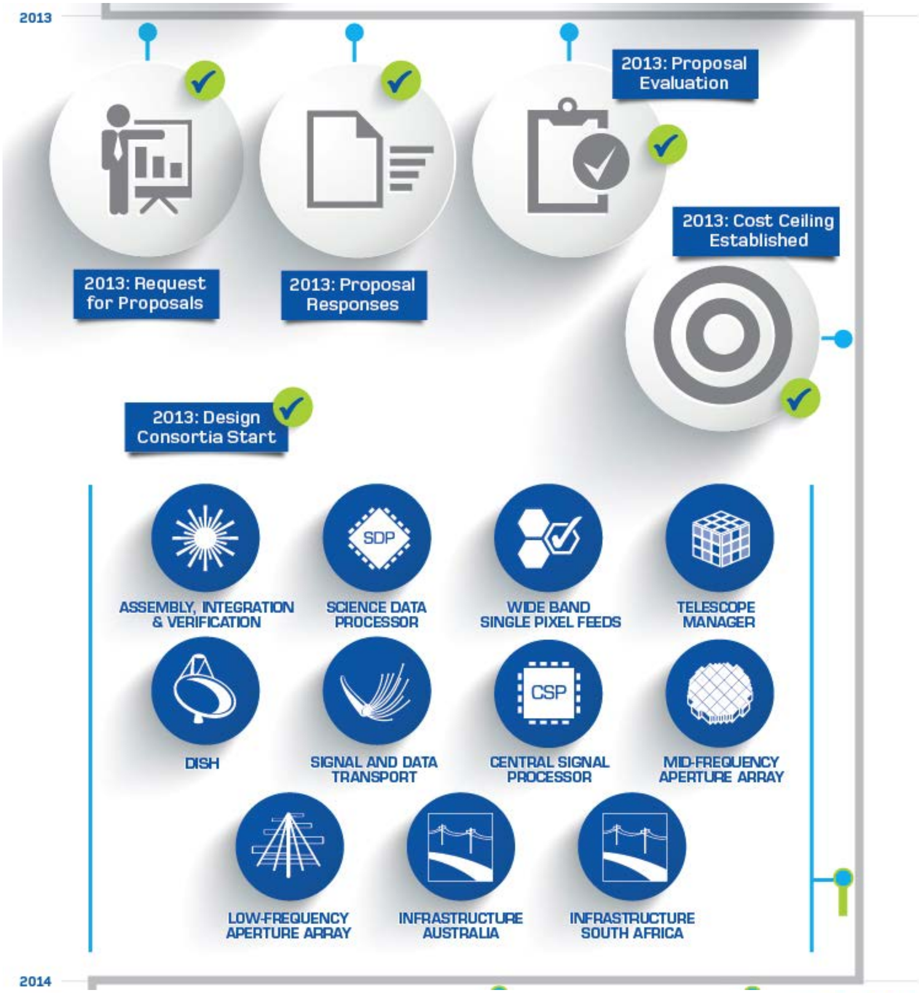
- Overview of SKA project timeline
  André van Es: SKAO EPM: MFAA/SADT

- Mid-frequency science with the SKA
  Jeff Wagg: SKAO Project Scientist

Past 1991– 2012 (Concept – SKAO)



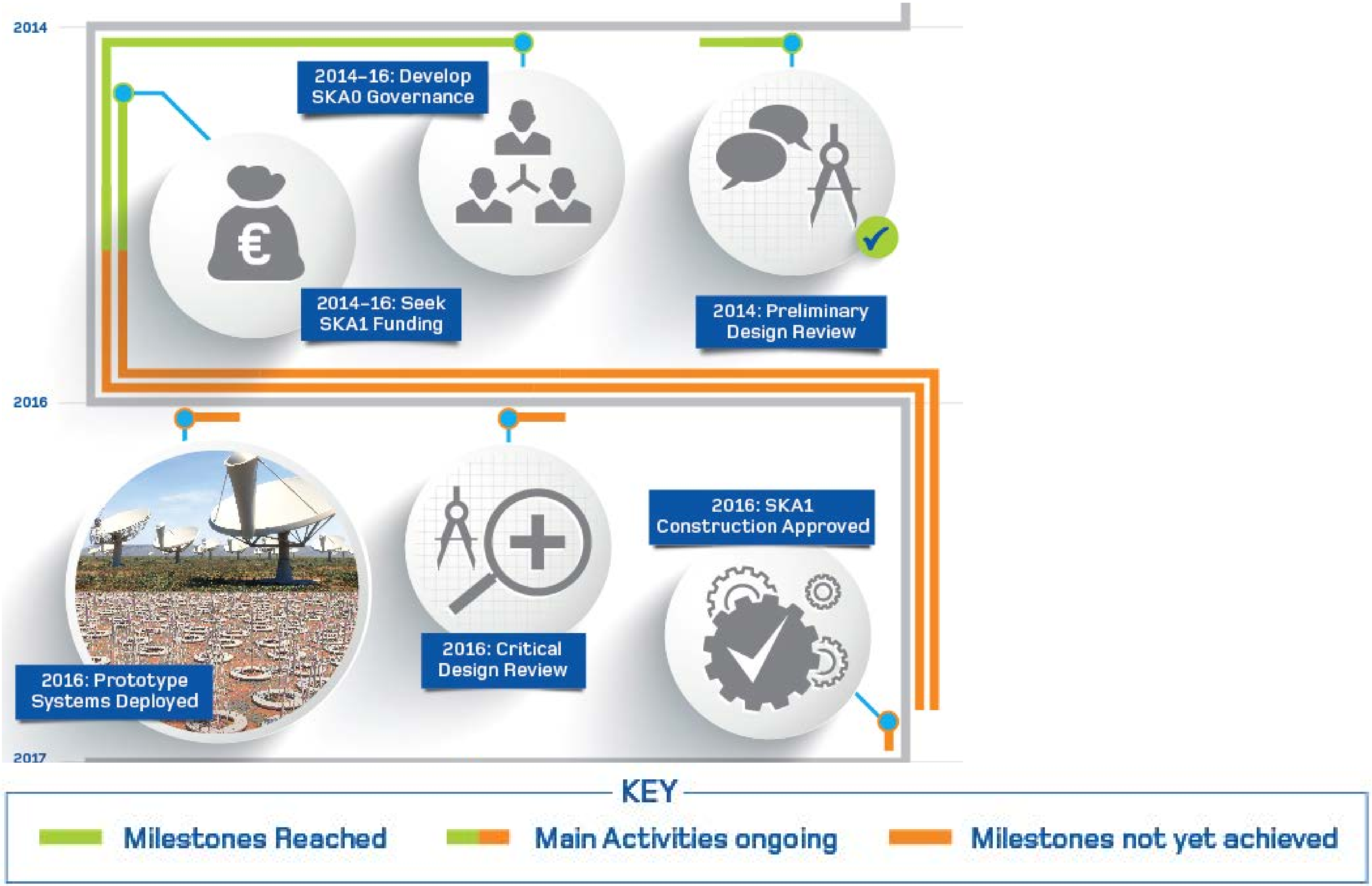
Past 2013 – 2014 RfP



KEY

Milestones Reached | Main Activities ongoing | Milestones not yet achieved

Present



2014
2014–16: Develop SKA0 Governance
2014–16: Seek SKA1 Funding
2014: Preliminary Design Review
2016
2016: Prototype Systems Deployed
2016: Critical Design Review
2016: SKA1 Construction Approved
2017
KEY
Milestones Reached
Main Activities ongoing
Milestones not yet achieved

Present Status of SKA

- PDR (including Delta-PDR) for all Elements in SKA1
- SRR for AIP program almost completed
- SKA System Review end of March
- Dish down-select completed
- Detailed Design work in all consortia is ongoing
- Negotiations for IGO are in process

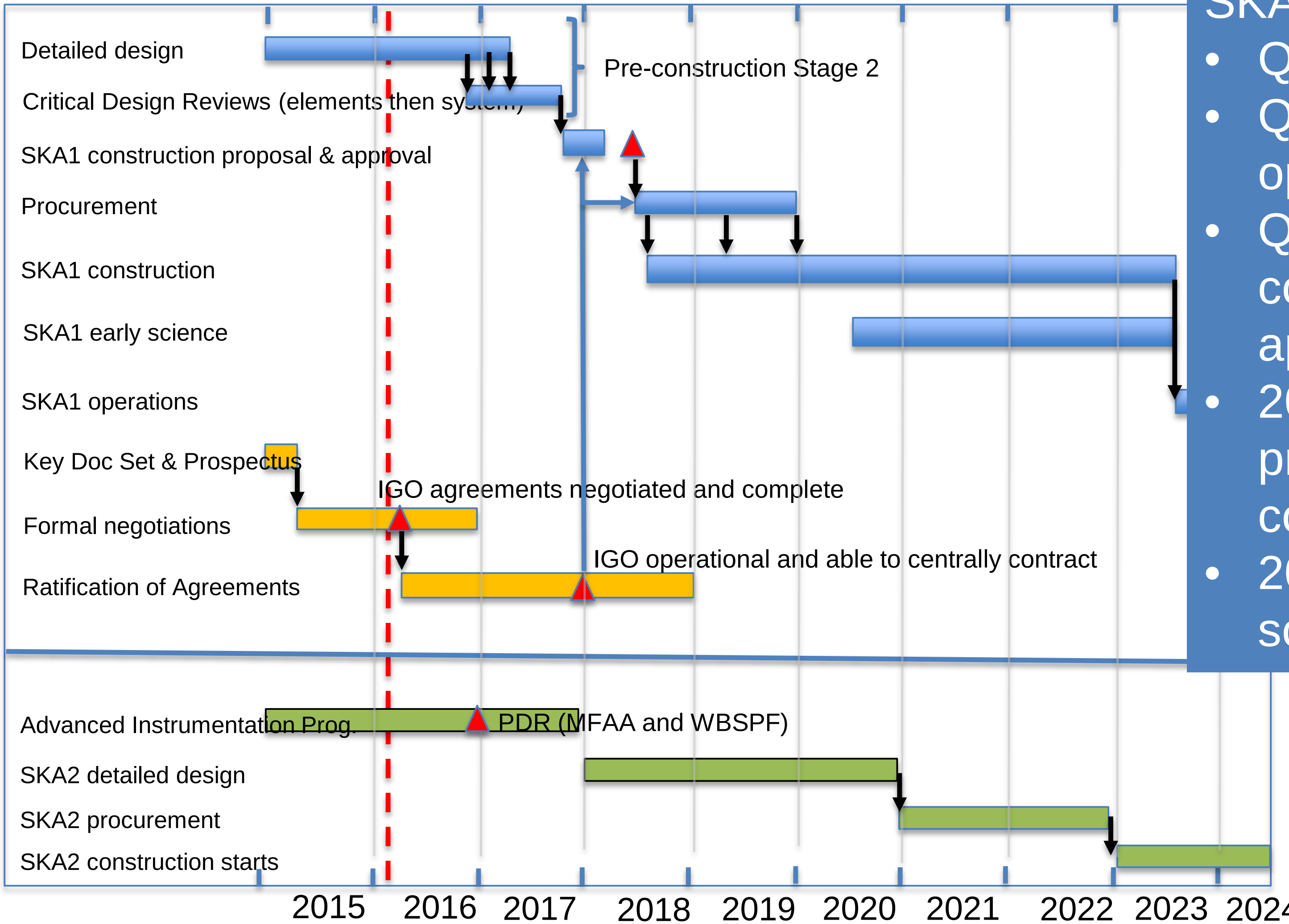
SKA1 + SKA 2 (2018 - 2030)

KEY

Milestones Reached | Main Activities ongoing | Milestones not yet achieved

High-level SKA Schedule

KEY: Blue = SKA1 science & engineering; orange = policy; green = SKA2



SKA1 Critical dates:

- Q3 2017: CDRs
- Q4 2017: IGO operational
- Q2 2018: construction approval
- 2018…. : procurement & construction
- 2020: early science

Important for SKA2

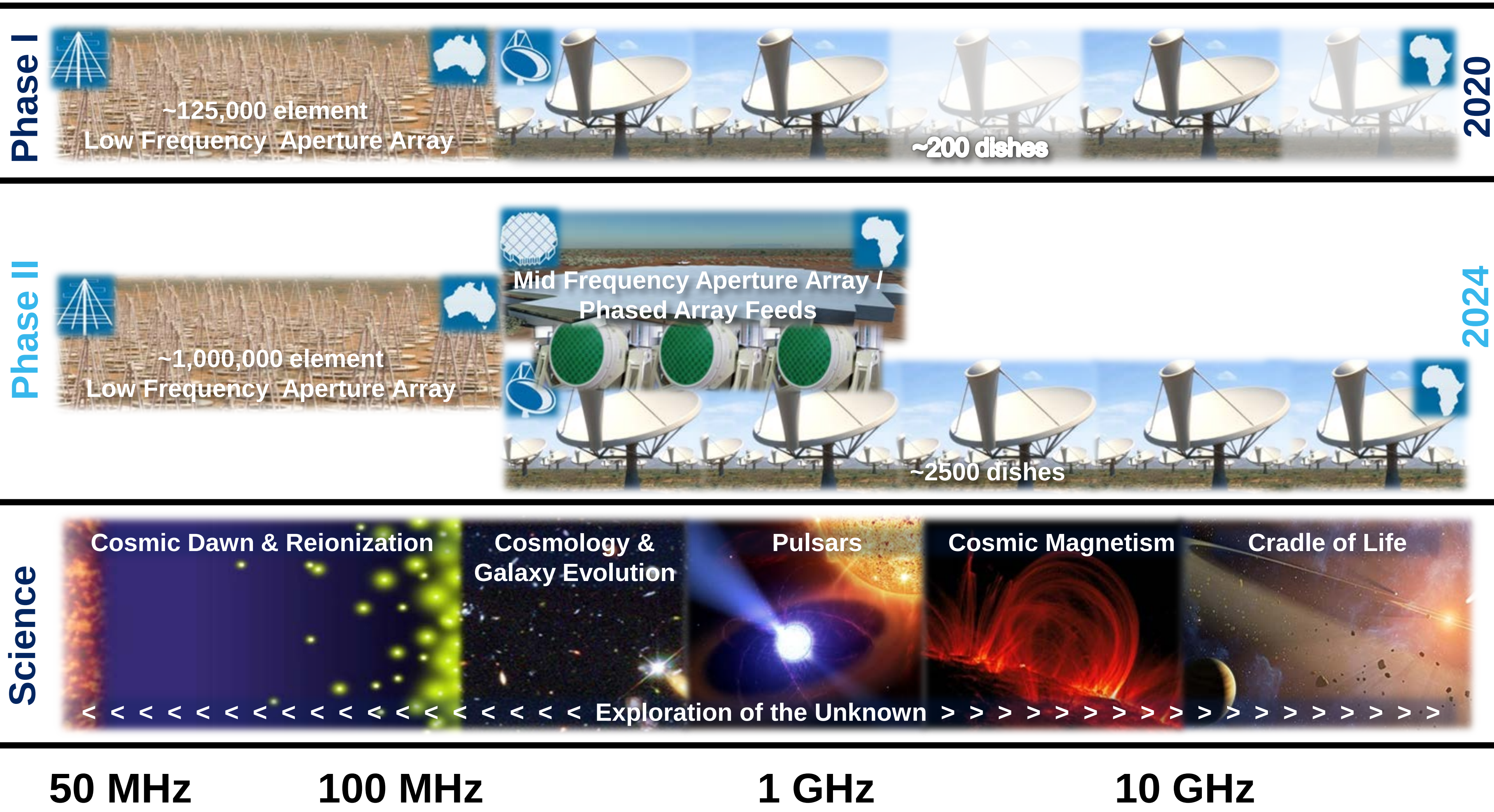
- Focus on SKA1, as successful operation of these two instruments will be important for SKA2
- Learn from SKA1, lessons from SKA1 will be essential for the success of SKA2:
  - Science Process
  - Project process
  - Element Model
  - Procurement
  - SKA Organisation
- SKA2 is planned to follow the full system engineering cycle

Mid-frequency science with the SKA

Jeff Wagg
SKAO
UK

Robert Braun, Tyler Bourke, Evan Keane
MFAA all-hands meeting, Cape Town
March 7, 2016

Overview of the SKA



Outline

- Update on recent SKAO science activities

- SKA1 high priority science goals

- mid-frequency science with the full SKA

Update on SKAO science activities

- August, 2015: “SKA Key Science Workshop”, Stockholm, Sweden
  - more than 130 participants
  - Begin collaborations that may evolve into future KSP teams
  - Generic surveys with SKA1?
- October, 2015: Level 0 requirements published
  - Scientific desires for the instrument
  - NOT requirements for consortia, design is based on the Level 1s
- October, 2015: Observing bands: scientific context document
  - Frequency ranges required for SKA1 science objectives

Update on SKAO science activities

- December, 2015: update to Level 1 requirements
  - post-rebaselining requirements
  - Implementation of accepted ECPs

- December, 2015: baselining of station positions for SKA1-LOW
  - Positions defined in ‘V4A’ calibration memo
  - Calibration risks deemed to be sufficiently low to proceed for environmental site surveys
  - Further work (ongoing) related to station definition

- Upcoming:
  - System review, end of March
  - New project scientist to replace Jimi Green -> Parkes
  - “SKA2016: Science for the SKA Generation”, Goa, India, November 7 – 11th
  - SKA workshop(s) to develop SKA2 science case in 2017 (TBC)

Overview of SKA headline science
(not in order of priority)

1) Pulsar surveys and timing
   – **Study of gravitational waves!**

SKA1 MID

2) The Cradle of Life & Astrobiology
   – **How do solar systems form and where could life emerge?**

3) Galaxy Evolution and Cosmology
   – **How do galaxies get their gas and form stars?**

SKA1 LOW

4) Cosmic magnetic fields
   – **When did ordered magnetic fields in galaxies form?**

5) Cosmic Dawn and the Epoch of Reionization
   – **When did the first galaxies form and begin to reionize the Universe?**

6) Radio transients and *Exploration of the Unknown*

Science Objectives

- Arranged by SWG
- Arbitrary order of SWG groups
- SWG priority order within each group

Science Goal	SWG	Objective	SWG Rank
1	CD/EoR	Physics of the early universe IGM - I. Imaging	1/3
2	CD/EoR	Physics of the early universe IGM - II. Power spectrum	2/3
3	CD/EoR	Physics of the early universe IGM - III. HI absorption line spectra (21cm forest)	3/3
4	Pulsars	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	Pulsars	High precision timing for testing gravity and GW detection	1/3
6	Pulsars	Characterising the pulsar population	2/3
7	Pulsars	Finding and using (Millisecond) Pulsars in Globular Clusters and External Galaxies	2/3
8	Pulsars	Finding pulsars in the Galactic Centre	2/3
9	Pulsars	Astrometric measurements of pulsars to enable improved tests of GR	2/3
10	Pulsars	Mapping the pulsar beam	3/3
11	Pulsars	Understanding pulsars and their environments through their interactions	3/3
12	Pulsars	Mapping the Galactic Structure	3/3
13	HI	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	HI	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	HI	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
16	HI	HI absorption studies out to the highest redshifts.	4/5
17	HI	The gaseous interface and accretion physics between galaxies and the IGM	5/5
18	Transients	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
19	Transients	Accessing New Physics using Ultra-Luminous Cosmic Explosions	=1/4
20	Transients	Galaxy growth through measurements of Black Hole accretion, growth and feedback	3/4
21	Transients	Detect the Electromagnetic Counterparts to Gravitational Wave Events	4/4
22	Cradle of Life	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
23	Cradle of Life	Characterise exo-planet magnetic fields and rotational periods	2/5
24	Cradle of Life	Survey all nearby (~100 pc) stars for radio emission from technological civilizations.	3/5
25	Cradle of Life	The detection of pre-biotic molecules in pre-stellar cores at distance of 100 pc.	4/5
26	Cradle of Life	Mapping of the sub-structure and dynamics of nearby clusters using maser emission.	5/5
27	Magnetism	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
28	Magnetism	Determine origin, maintenance and amplification of magnetic fields at high redshifts - I.	2/5
29	Magnetism	Detection of polarised emission in Cosmic Web filaments	3/5
30	Magnetism	Determine origin, maintenance and amplification of magnetic fields at high redshifts - II.	4/5
31	Magnetism	Intrinsic properties of polarised sources	5/5
32	Cosmology	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	Cosmology	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
34	Cosmology	Map the dark Universe with a completely new kind of weak lensing survey - in the radio.	3/5
35	Cosmology	Dark energy & GR via power spectrum, BAO, redshift-space distortions and topology.	4/5
36	Cosmology	Test dark energy & general relativity with fore-runner of the 'billion galaxy' survey.	5/5
37	Continuum	Measure the Star formation history of the Universe (SFHU) - I. Non-thermal processes	1/8
38	Continuum	Measure the Star formation history of the Universe (SFHU) - II. Thermal processes	2/8
39	Continuum	Probe the role of black holes in galaxy evolution - I.	3/8
40	Continuum	Probe the role of black holes in galaxy evolution - II.	4/8
41	Continuum	Probe cosmic rays and magnetic fields in ICM and cosmic filaments.	5/8
42	Continuum	Study the detailed astrophysics of star-formation and accretion processes - I.	6/8
43	Continuum	Probing dark matter and the high redshift Universe with strong gravitational lensing.	7/8
44	Continuum	Legacy/Serendipity/Rare.	8/8

Highest Priority SKA1 Science Objectives

- Arranged by SWG
- Arbitrary order of SWG groups
- Priority order within each group

Science Goal	SWG	Objective	SWG Rank
1	*CD/EoR*	Physics of the early universe IGM - I. Imaging	1/3
2	*CD/EoR*	Physics of the early universe IGM - II. Power spectrum	2/3
4	*Pulsars*	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection	1/3
5	*Pulsars*	High precision timing for testing gravity and GW detection	1/3
13	*HI*	Resolved HI kinematics and morphology of ~10^10 M_sol mass galaxies out to z~0.8	1/5
14	*HI*	High spatial resolution studies of the ISM in the nearby Universe.	2/5
15	*HI*	Multi-resolution mapping studies of the ISM in our Galaxy	3/5
18	*Transients*	Solve missing baryon problem at z~2 and determine the Dark Energy Equation of State	=1/4
22	*Cradle of Life*	Map dust grain growth in the terrestrial planet forming zones at a distance of 100 pc	1/5
27	*Magnetism*	The resolved all-Sky characterisation of the interstellar and intergalactic magnetic fields	1/5
32	*Cosmology*	Constraints on primordial non-Gaussianity and tests of gravity on super-horizon scales.	1/5
33	*Cosmology*	Angular correlation functions to probe non-Gaussianity and the matter dipole	2/5
37+38	*Continuum*	Star formation history of the Universe (SFHU) – I+II. Non-thermal + Thermal processes	1+2/8

Highest Priority SKA1 Science Objectives

- Arranged by SWG
- Arbitrary order of SWG groups
- Priority order within each group
- most science goals require frequencies below 1420 MHz

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Highest Priority Science Objectives

- Arranged by SWG
- Arbitrary order of SWG groups
- Priority order within each group
- most science goals require frequencies below 1420 MHz and survey speed

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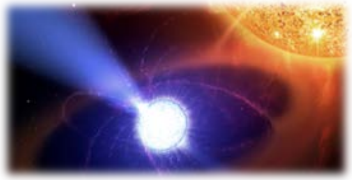
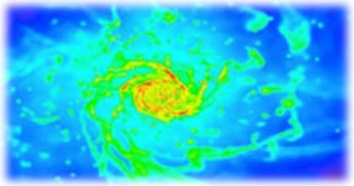
Headline Science with SKA1 and SKA2

	SKA1	SKA2
The Cradle of Life & Astrobiology	Proto-planetary disks; imaging inside the snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.
	Targeted SETI: airport radar 10^4 nearby stars.	Ultra-sensitive SETI: airport radar 10^5 nearby star, TV ~10 stars.
Strong-field Tests of Gravity with Pulsars and Black Holes	1st detection of nHz-stochastic gravitational wave background.	Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.
	Discover and use NS-NS and PSR-BH binaries to provide the best tests of gravity theories and General Relativity.	Find all ~40,000 visible pulsars in the Galaxy, use the most relativistic systems to test cosmic censorship and the no-hair theorem.
The Origin and Evolution of Cosmic Magnetism	The role of magnetism from sub-galactic to Cosmic Web scales, the RM-grid @ 300/deg2.	The origin and amplification of cosmic magnetic fields, the RM-grid @ 5000/deg2.
	Faraday tomography of extended sources, 100pc resolution at 14Mpc, 1 kpc @ $z \approx 0.04$.	Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ $z \approx 0.13$.
Galaxy Evolution probed by Neutral Hydrogen	Gas properties of 10^7 galaxies, $\langle z \rangle \approx 0.3$, evolution to $z \approx 1$, BAO complement to Euclid.	Gas properties of 10^9 galaxies, $\langle z \rangle \approx 1$, evolution to $z \approx 5$, world-class precision cosmology.
	Detailed interstellar medium of nearby galaxies (3 Mpc) at 50pc resolution, diffuse IGM down to $N_H < 10^{17}$ at 1 kpc.	Detailed interstellar medium of nearby galaxies (10 Mpc) at 50pc resolution, diffuse IGM down to $N_H < 10^{17}$ at 1 kpc.



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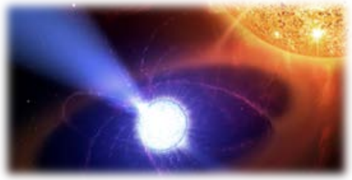

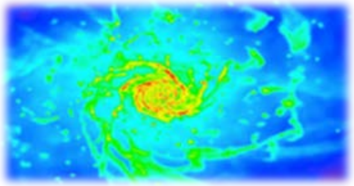

Requires mid-frequency survey speed

Headline Magnetism Science

Today

- 3D magnetic tomography of the Galaxy and distant universe; from current 1 RM deg^{-2}, SKA1: 300 deg^{-2} to SKA2: 5000 deg^{-2}

(Johnston-Hollitt et al. 2015)

Headline Science with SKA1 and SKA2

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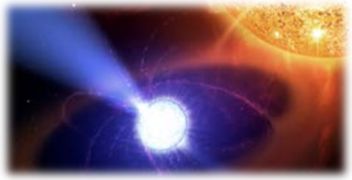
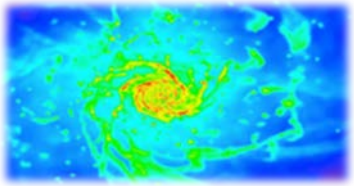


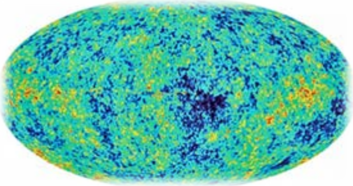
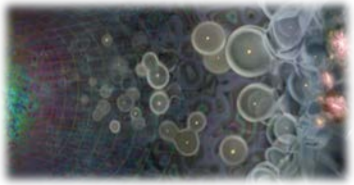


Requires mid-frequency survey speed

Headline Science with SKA1 and SKA2

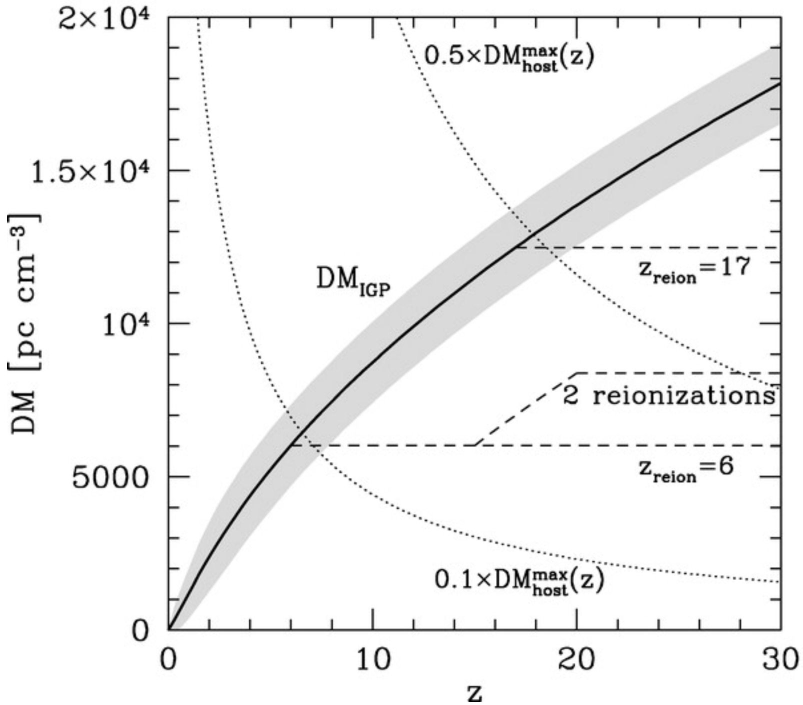
	SKA1	SKA2
The Transient Radio Sky	Use fast radio bursts to uncover the missing "normal" matter in the universe.	Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields.
	Study feedback from the most energetic cosmic explosions and the disruption of stars by super-massive black holes.	Exploring the unknown: new exotic astrophysical phenomena in discovery phase space.
Galaxy Evolution probed in the Radio Continuum	Star formation rates (10 M_Sun/yr to z ~ 4).	Star formation rates (10 M_Sun/yr to z ~ 10).
	Resolved star formation astrophysics (sub-kpc active regions at z ~ 1).	Resolved star formation astrophysics (sub-kpc active regions at z ~ 6).
Cosmology & Dark Energy	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: competitive to Euclid.	Constraints on DE, modified gravity, the distribution & evolution of matter on super-horizon scales: redefines state-of-art.
	Primordial non-Gaussianity and the matter dipole: 2x Euclid.	Primordial non-Gaussianity and the matter dipole: 10x Euclid.
Cosmic Dawn and the Epoch of Reionization	Direct imaging of EoR structures (z = 6 - 12).	Direct imaging of Cosmic Dawn structures (z = 12 - 30).
	Power spectra of Cosmic Dawn down to arcmin scales, possible imaging at 10 arcmin.	First glimpse of the Dark Ages (z > 30).



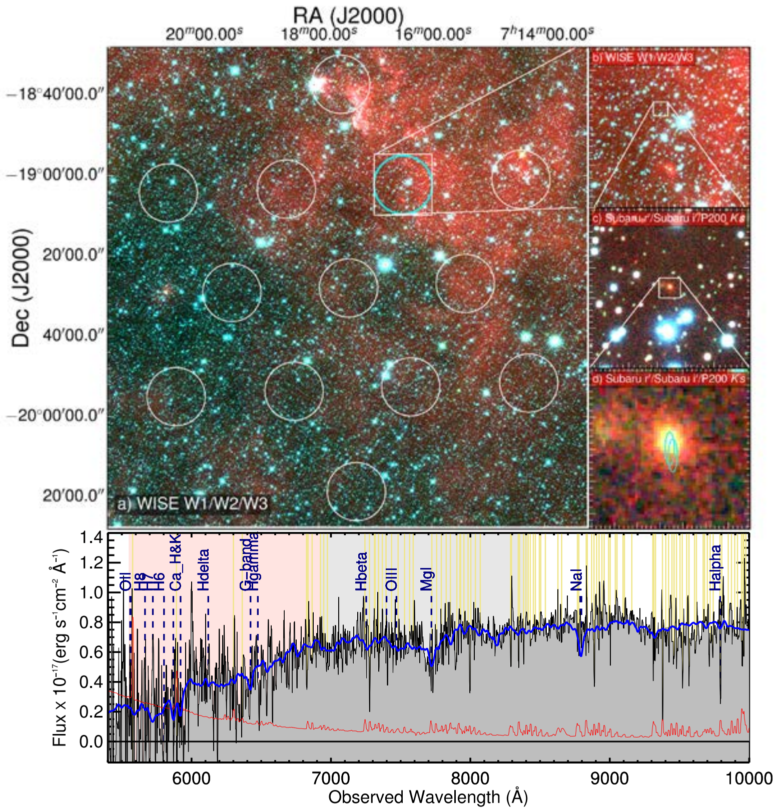



Requires mid-frequency survey speed

Fast Radio Bursts as a cosmological probe



(Ioka 2003)



(Keane et al. 2016)

- large samples (~1000) of spectroscopically identified FRBs may provide a means of probing the missing baryons

Headline Science with SKA1 and SKA2

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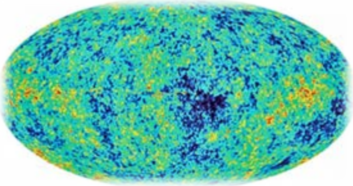
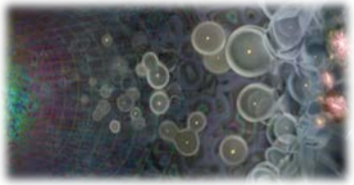




Requires mid-frequency survey speed

Some recommendations for MFAA

- Focus on strengths of the instrument (wide field of view and survey speed)

- Do not confuse the science cases for the (full) SKA with those of a demonstrator

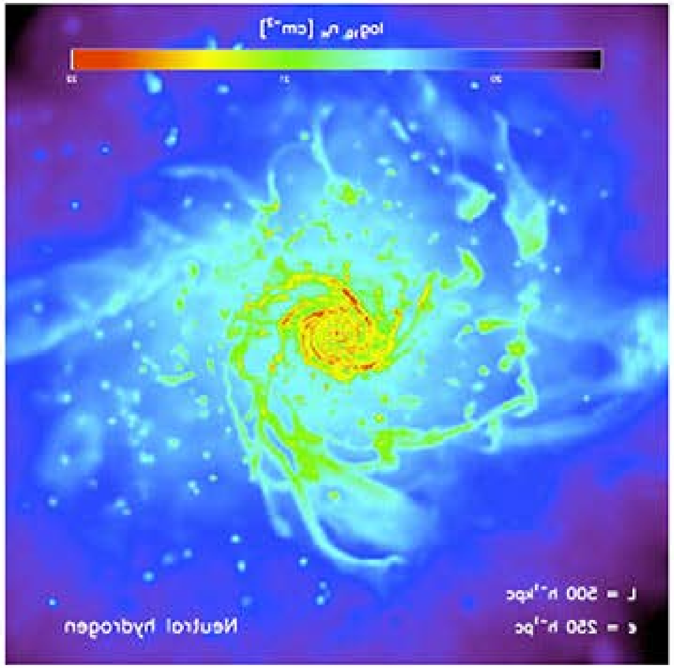
- Make your technology down selects early, otherwise you risk wasting time and resources

- Focus on getting a working prototype that is low cost, low power consumption and can be calibrated

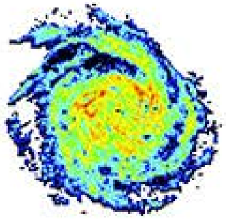
http://astronomers.skatelescope.org/

Atomic HI gas in galaxies

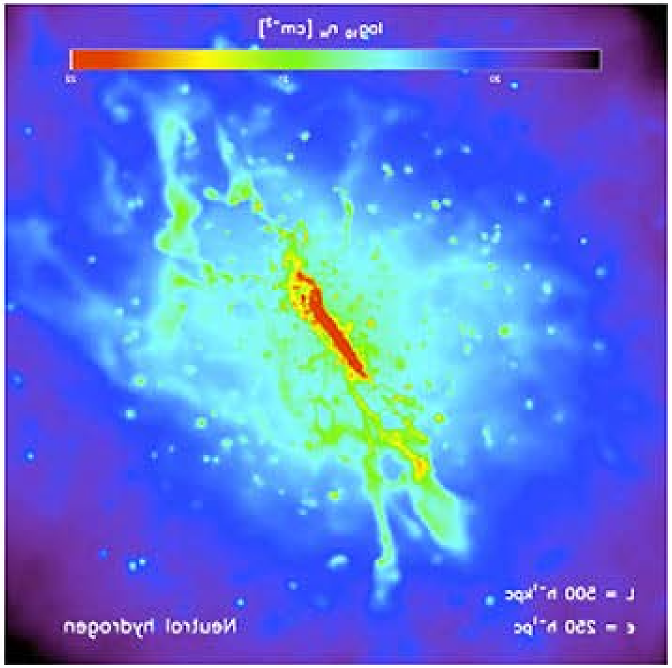
simulated HI



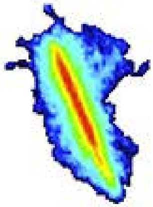
observed HI



simulated HI



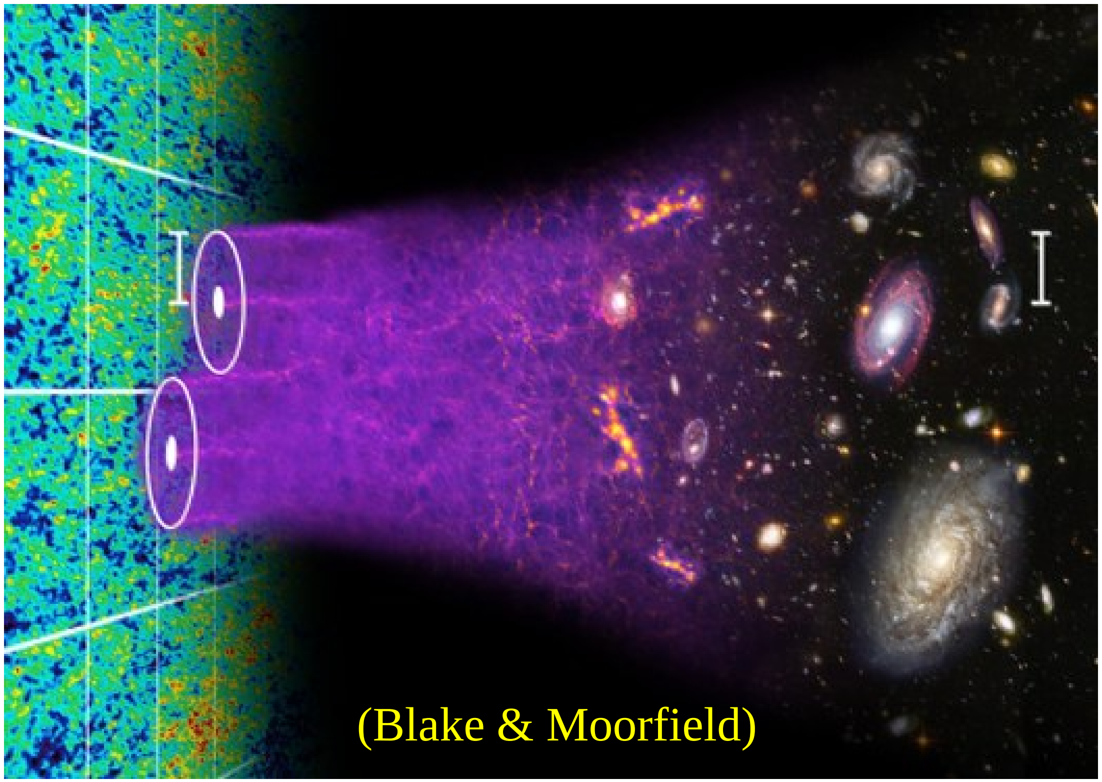
observed HI

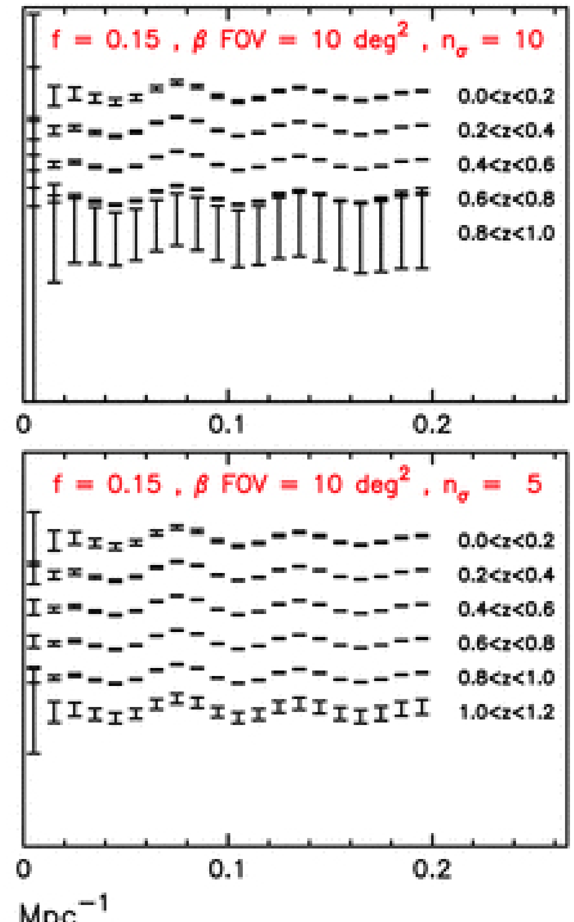


Images courtesy of Tom Oosterloo (HI science working group)
Simulations by Joop Schaye

- How do galaxies interact with the surrounding `Cosmic Web' (feeding and feedback)

HI Cosmology with SKA: Baryon Acoustic Oscillations

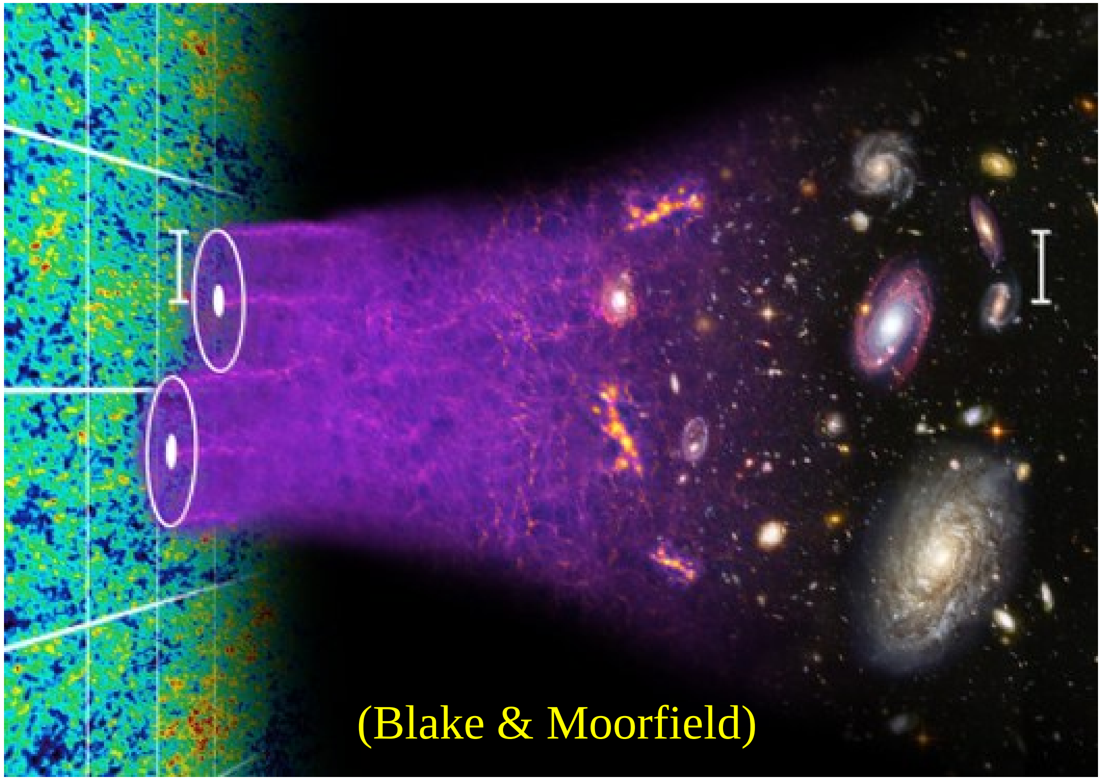


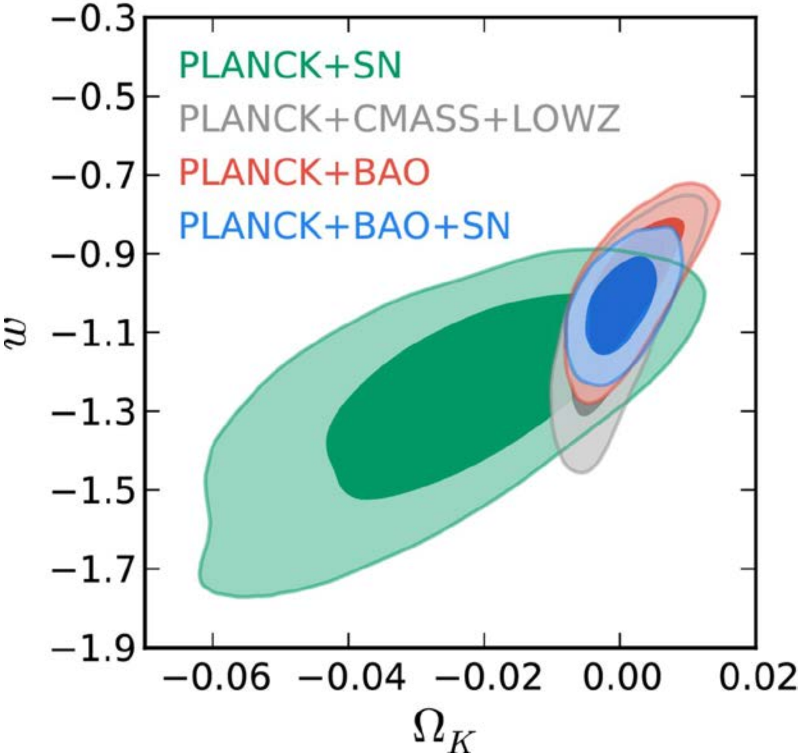


(Abdalla et al 2010; Bull et al. 2014)

- Constraining Dark Energy models with redshift-resolved BAO measurements as a "cosmic ruler"

HI Cosmology with SKA: Baryon Acoustic Oscillations

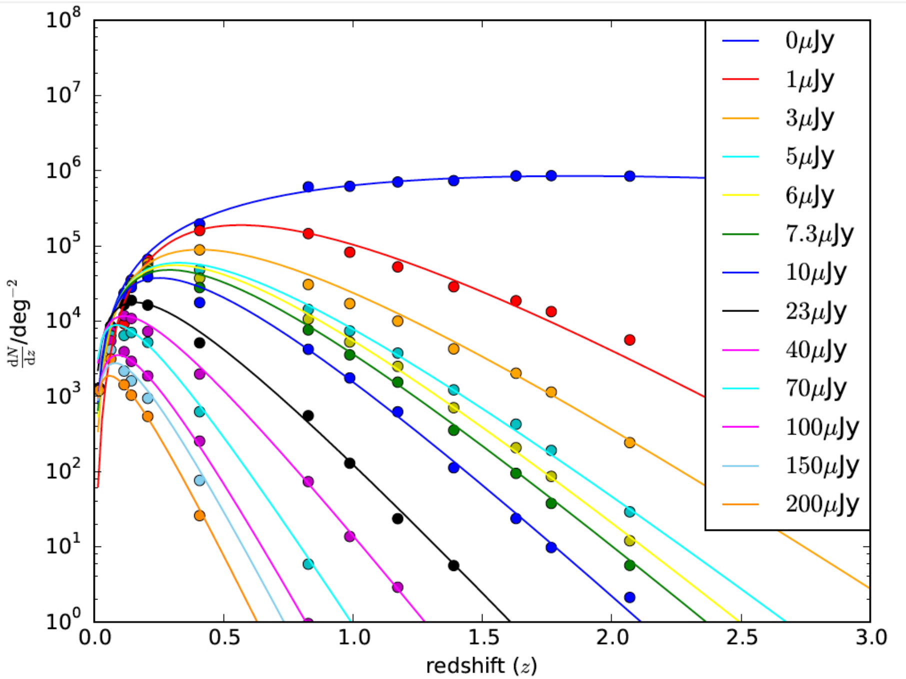




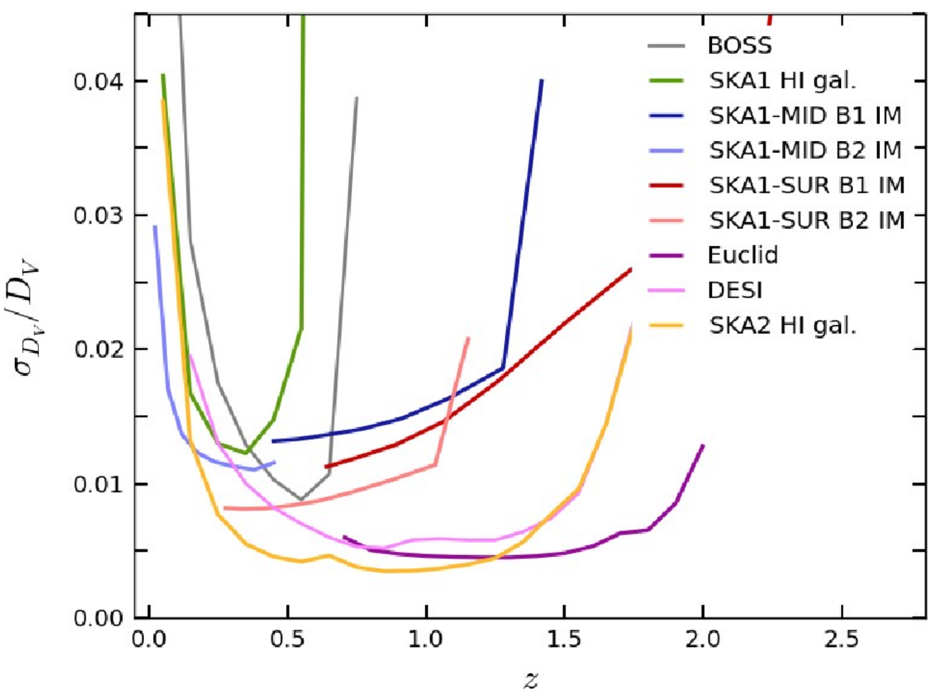
Anderson et al. 2012, 2014

- Constraining Dark Energy models with redshift-resolved BAO measurements as a "cosmic ruler"

HI Cosmology with SKA: Baryon Acoustic Oscillations



HI predictions using SKADS simulation (Santos et al 2015)

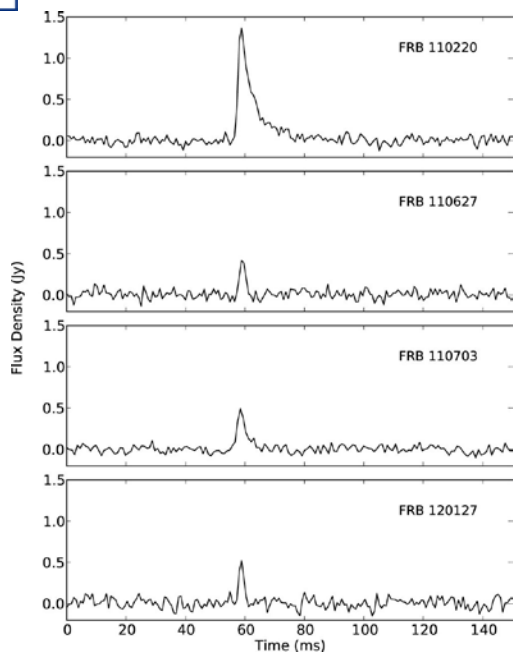


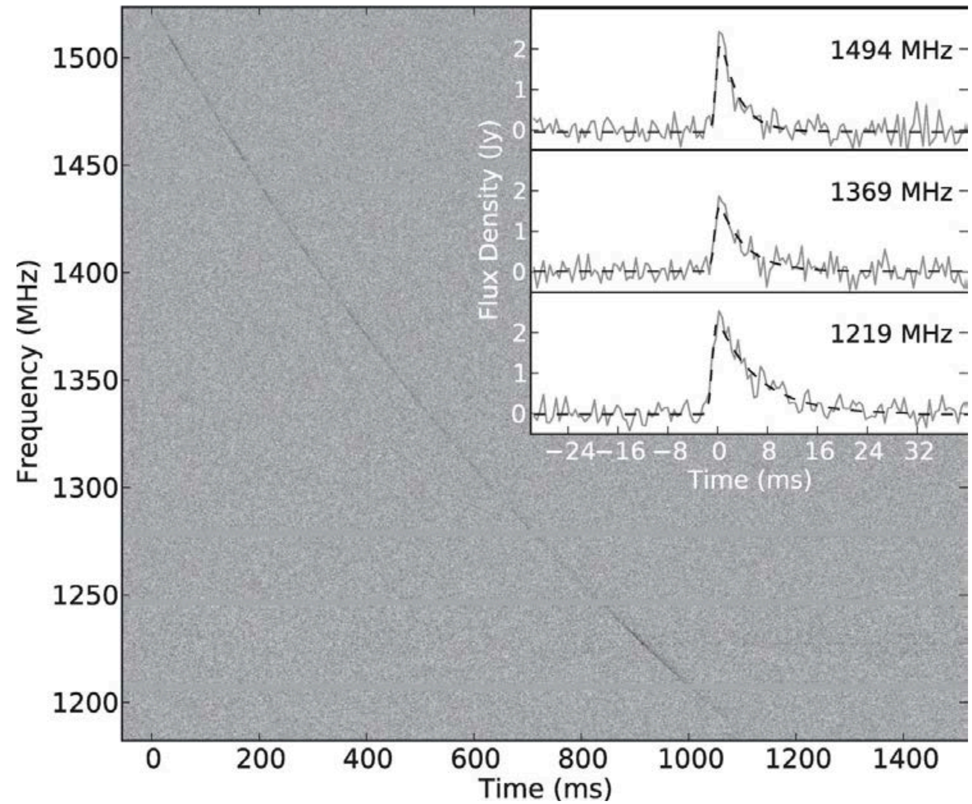
(Bull et al 2015)

- Reduced uncertainty on the *dilation factor* which depends on the evolution of dark energy

The transient radio sky: exploring the unknown

A Population of Fast Radio Bursts at Cosmological Distances
D. Thornton *et al.*
Science **341**, 53 (2013);
DOI: 10.1126/science.1236789

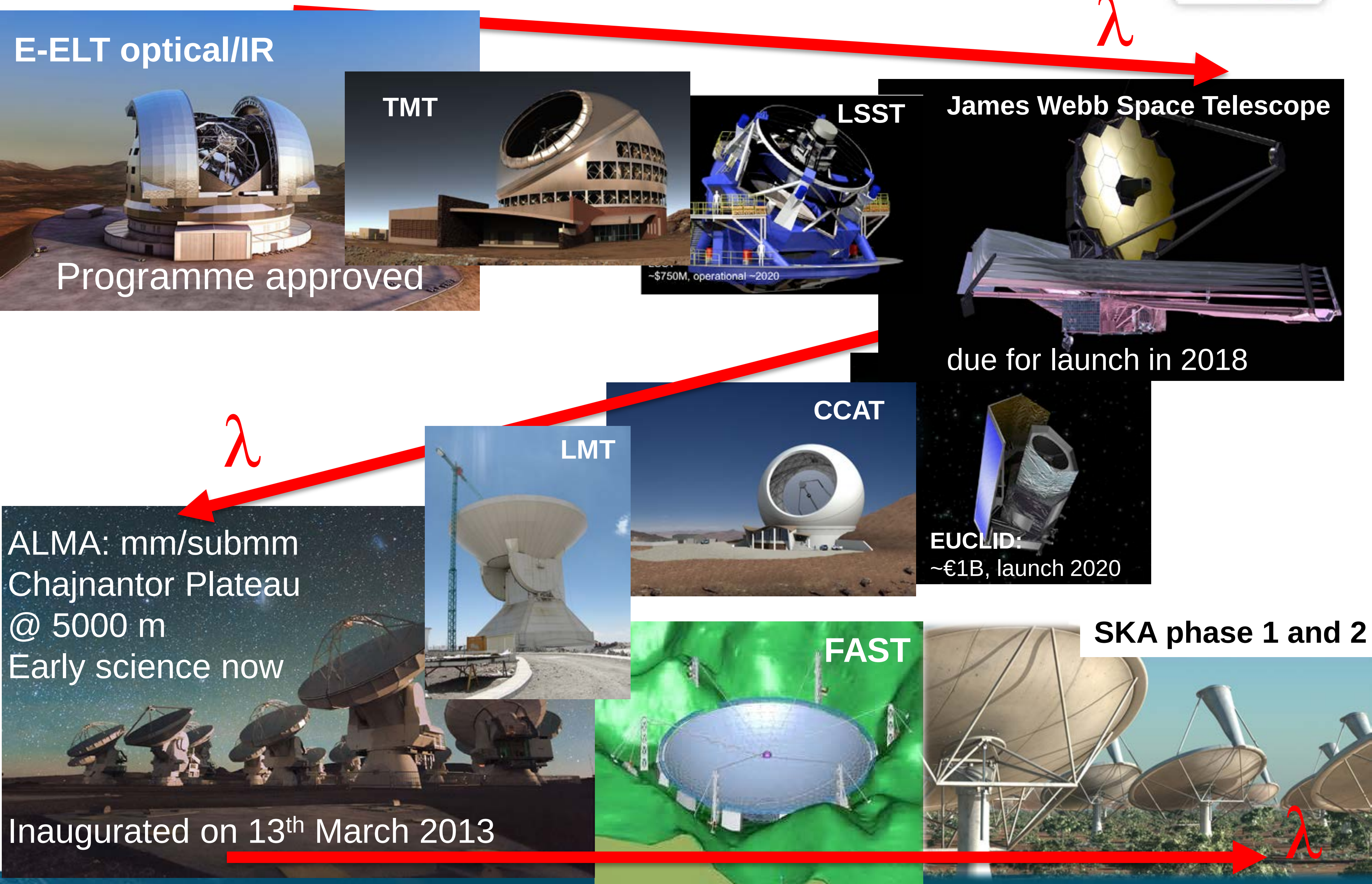




- More than 10 “FRB” events now detected (after first “Lorimer” burst):

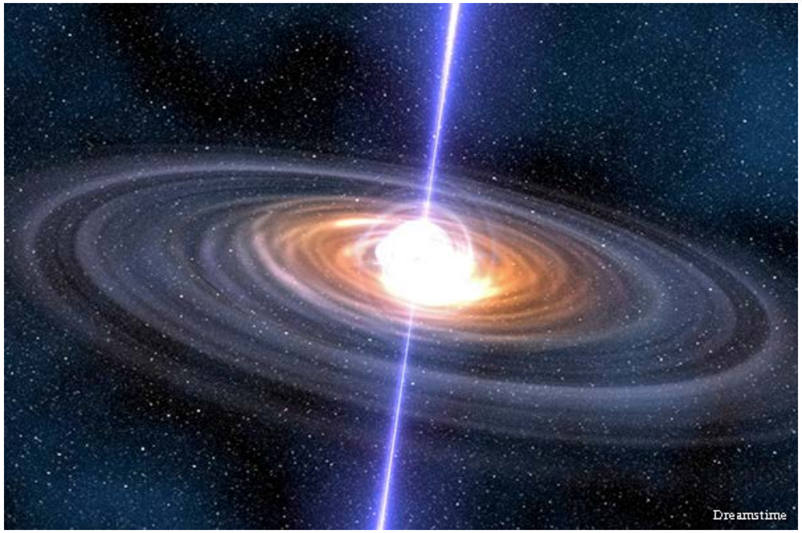
  $S = 0.5 – 1.3$ Jy, $\Delta t = 1 – 6$ msec, DM = $550 – 1100$ cm^{-3} pc
- Estimated event rate: 1×10^4 sky^{-1} day^{-1}
- Completely unknown origin, possibly at cosmological distances

2020 and beyond: A multi-wavelength view of the Universe



Pulsar surveys and timing

- cosmic lighthouses
- masses: ~1.4 $M_{\odot}$ within 20km
- B ~ 4.4×10^{13} Gauss
- periods: 1.4ms to 8.5s



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

<u>SKA1 MID: >350 MHz</u>

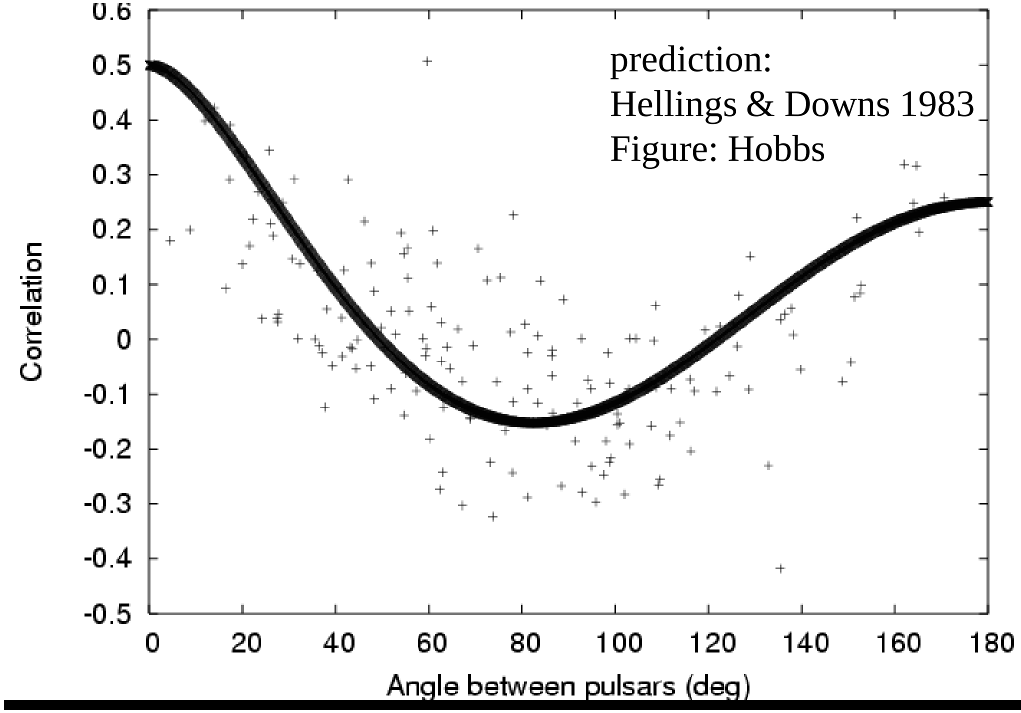
- timing precision increase by ~100x
- discovery of exotic pulsars and binaries: PSR-BH

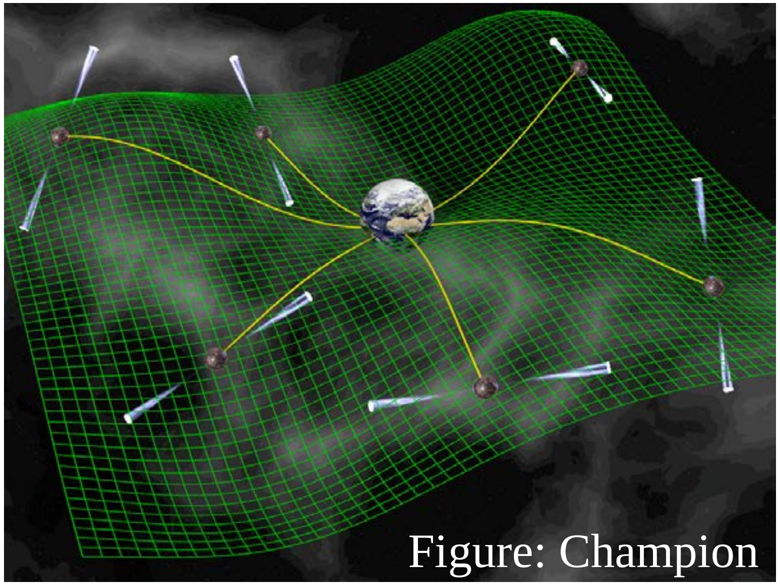
Current estimates are that 100% of the Galactic population will accessible with SKA2

(Cordes et al. 2004; Kramer et al. 2004; Smits et al. 2009; Pulsar SWG)

Pulsar surveys and timing: testing general relativity

correlation between msp timing residuals





- millisecond pulsars are very precise astrophysical clocks, eg:

PSR B1937+21, period = 1.5578064688197945 +/- 0.0000000000000004

- Timing residuals between ms pulsars can be used to directly detect the gravitational wave background (SMBH mergers)