# Mid-frequency science with the SKA

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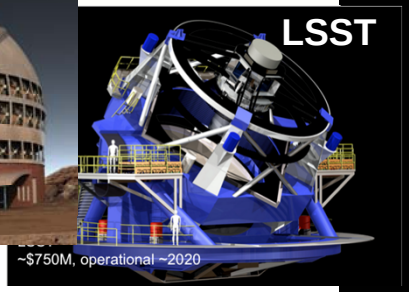
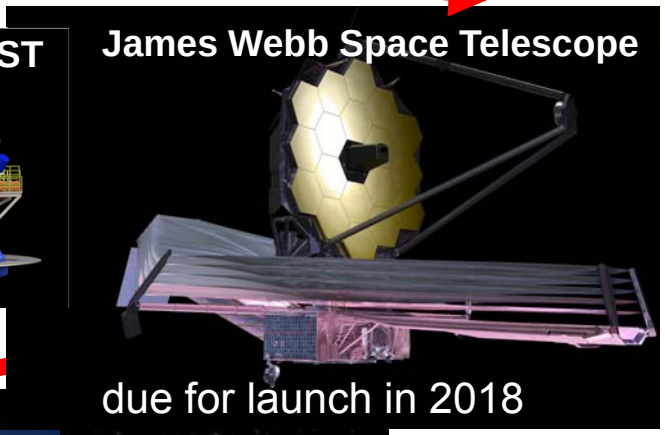
MFAA all-hands meeting, Aveiro, Portugal

April 20, 2015

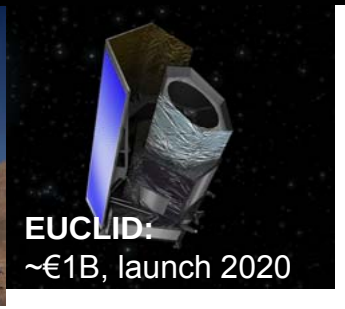
# 2020 and beyond: A multi-wavelength view of the Universe

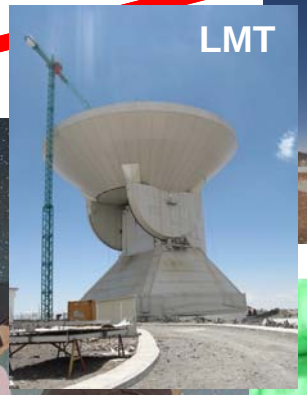




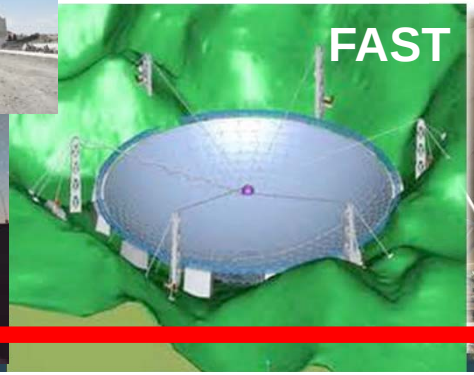


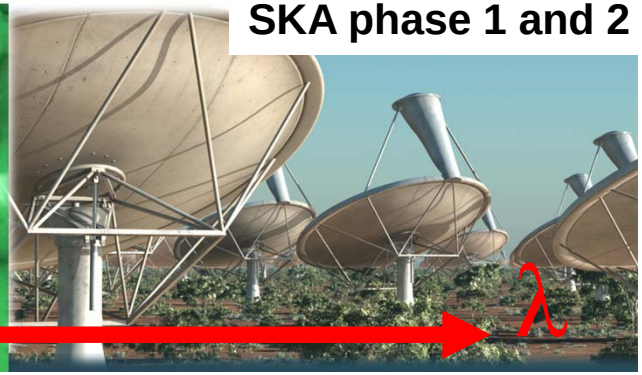


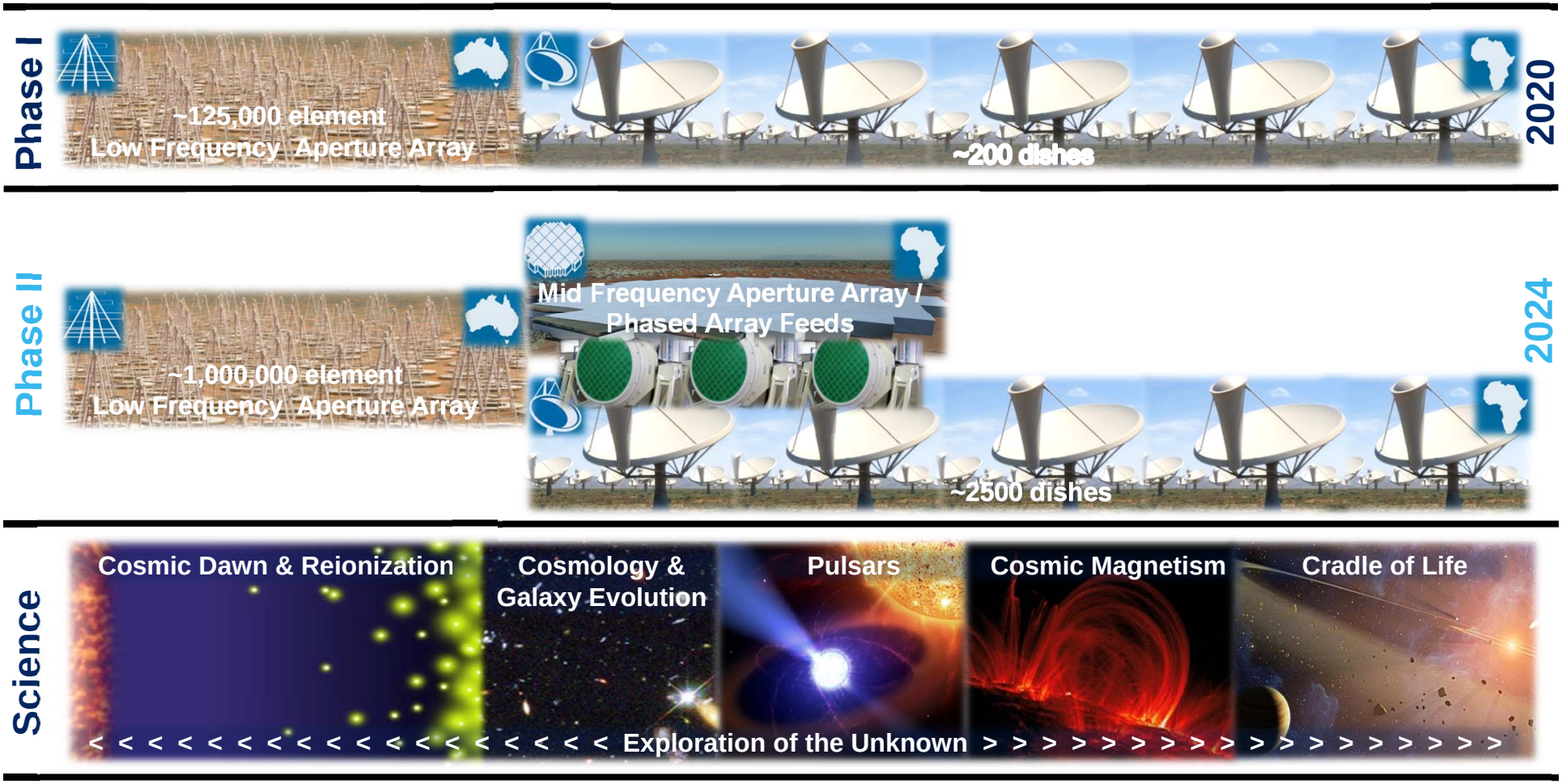






# Overview of the SKA



# Outline

- Update on recent SKAO science activities
- SKA1 high priority science goals
- mid-frequency MFAA SKA2 science

# Update on SKAO science activities

- June, 2014: “Advancing Astrophysics with the SKA”, Giardini Naxos, Italy
  - more than 250 participants
  - 130 chapter submissions for new SKA science book to be published middle of this year

- July to August: prioritization of SKA1 science goals
  - initial set of 44 science goals submitted by 8 science working groups
  - ranking undertaken by SKAO science team
  - following review by science review panel, list of top 13 high priority science goals was formulated and published

- December: “5 years in the life” (full) SKA1 model observing schedule published

# Update on SKAO science activities

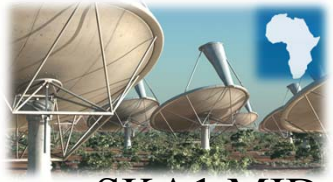
- Dec., 2014 to March, 2015: involvement in consortium PDRs

- Nov. to March, 2015: rebaselining

- Coming soon:
  - new release of Level 0s (May)
  - updated configurations for LOW and MID (July)
  - updated Level 1s (July)
  - SKA1 Key Science Project workshop in Stockholm (August)

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

1) Pulsar surveys and timing
   - **Does general relativity fail?**


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 Science Objectives

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| 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 Science Objectives

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- most science goals require frequencies below 1420 MHz

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# Highest Priority Science Objectives

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- 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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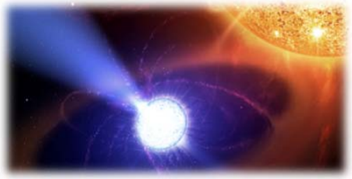
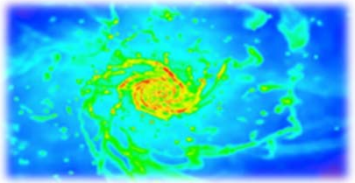
# Headline Science with SKA1 and SKA2

| | 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 ≈ 0.04. | Faraday tomography of extended sources, 100pc resolution at 50Mpc, 1 kpc @ z ≈ 0.13. |
| **Galaxy Evolution probed by Neutral Hydrogen** | Gas properties of 10^7 galaxies, <z> ≈ 0.3, evolution to z ≈ 1, BAO complement to Euclid. | Gas properties of 10^9 galaxies, <z> ≈ 1, evolution to z ≈ 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. |





# Headline Science with SKA1 and SKA2

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| **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. |
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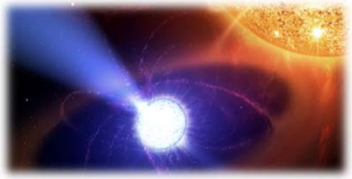
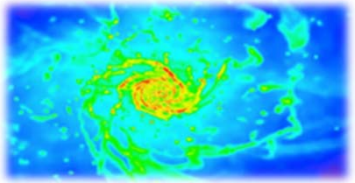
| **Galaxy Evolution probed by Neutral Hydrogen** | Gas properties of 10^7 galaxies, <z> ≈ 0.3, evolution to z ≈ 1, BAO complement to Euclid. | Gas properties of 10^9 galaxies, <z> ≈ 1, evolution to z ≈ 5, world-class precision cosmology. |
| | Detailed interstellar medium of nearby galaxies (3 Mpc) 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. |

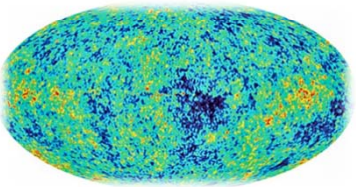


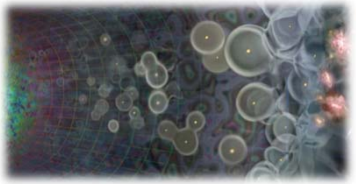


Requires mid-frequency survey speed

# 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). |

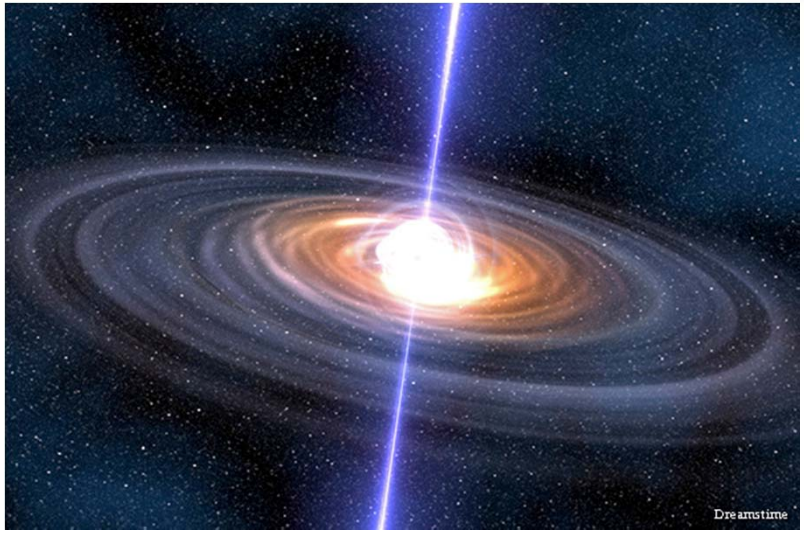




Requires mid-frequency survey speed

# Pulsar surveys and timing

- cosmic lighthouses
- masses: ~1.4 $M_\odot$ within 20km
- $B \sim 4.4 \times 10^{13}$ 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>

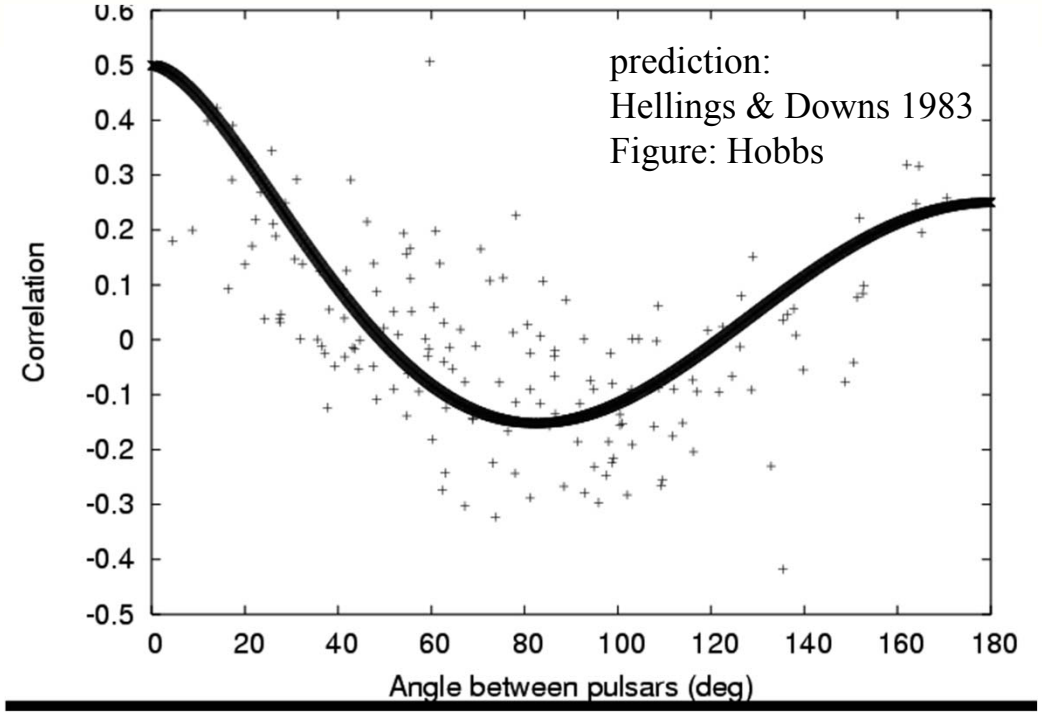
- timing precision increase by ~100x
- discovery of exotic pulsars and binaries: PSR-BH

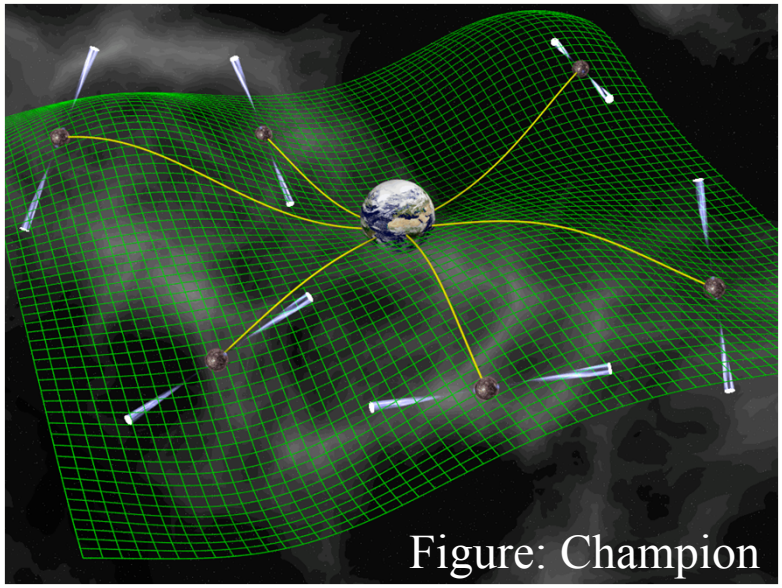
***Current estimates are that 100% of the Galactic population will accessible with SKA2***

(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



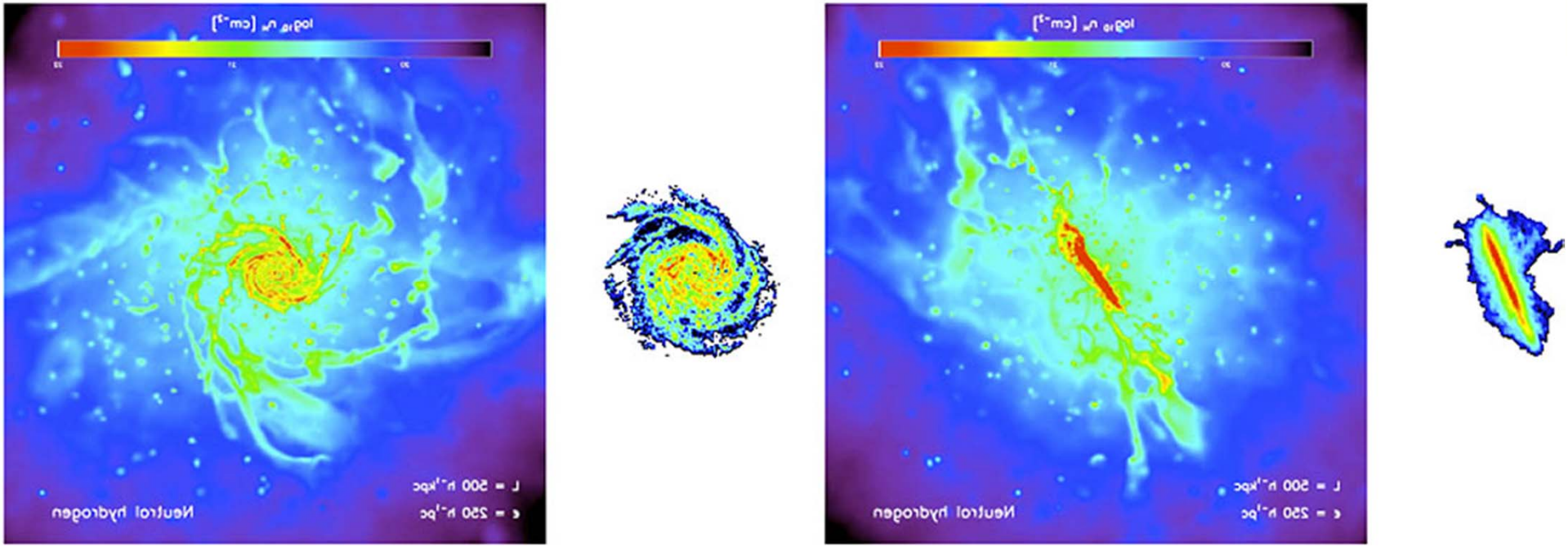

- millisecond pulsars are very precise astrophysical clocks, eg:

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)

# Atomic HI gas in nearby galaxies

simulated HI observed HI simulated HI observed HI

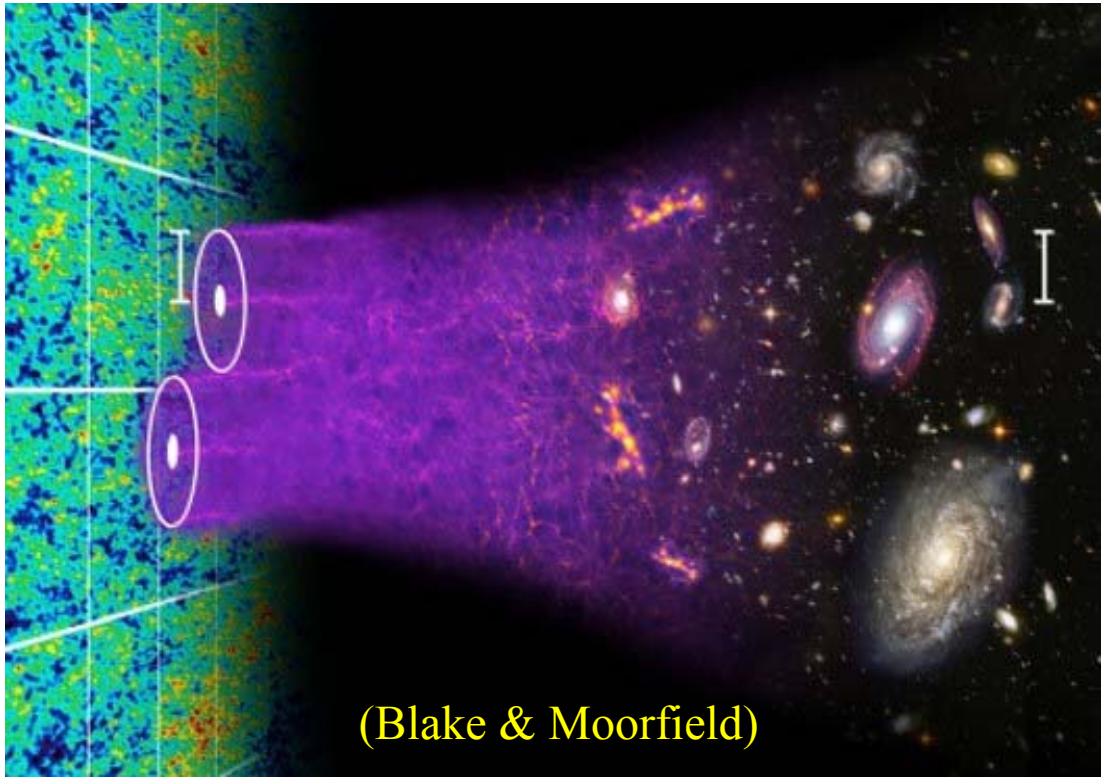


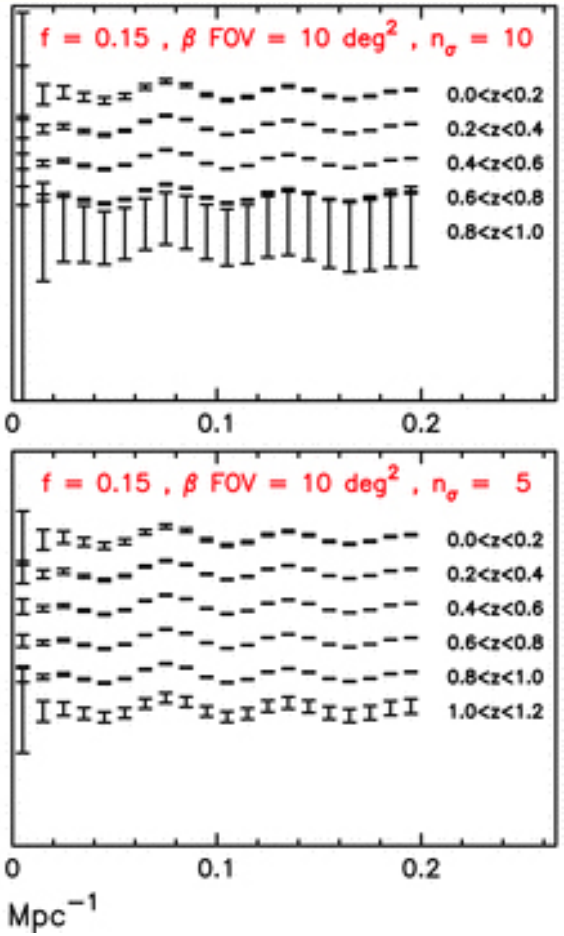
Images courtesy of Tom Oosterloo (HI science working group)

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

***SKA1 will probe low column density HI in nearby Universe ($n_{HI}$ ~ $10^{18}$ $cm^{-2}$)***

# 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”

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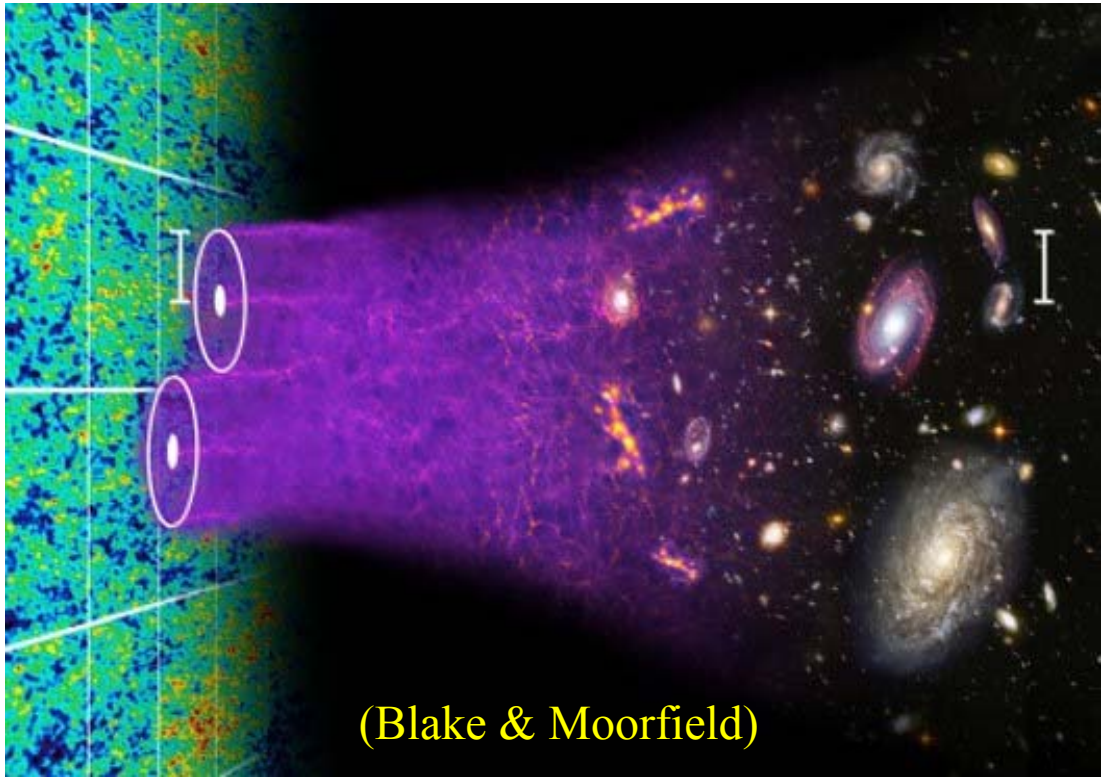
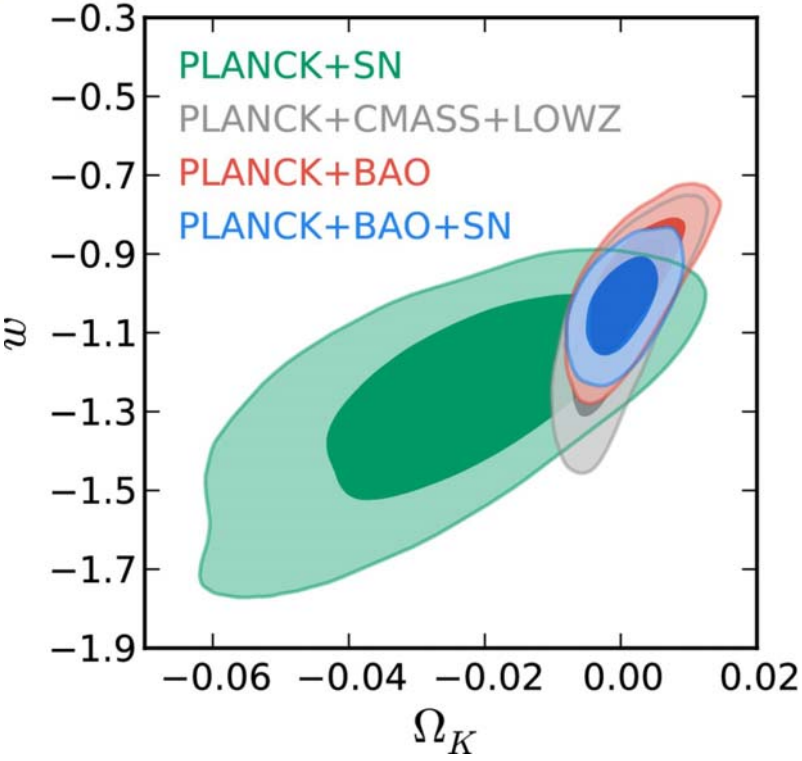
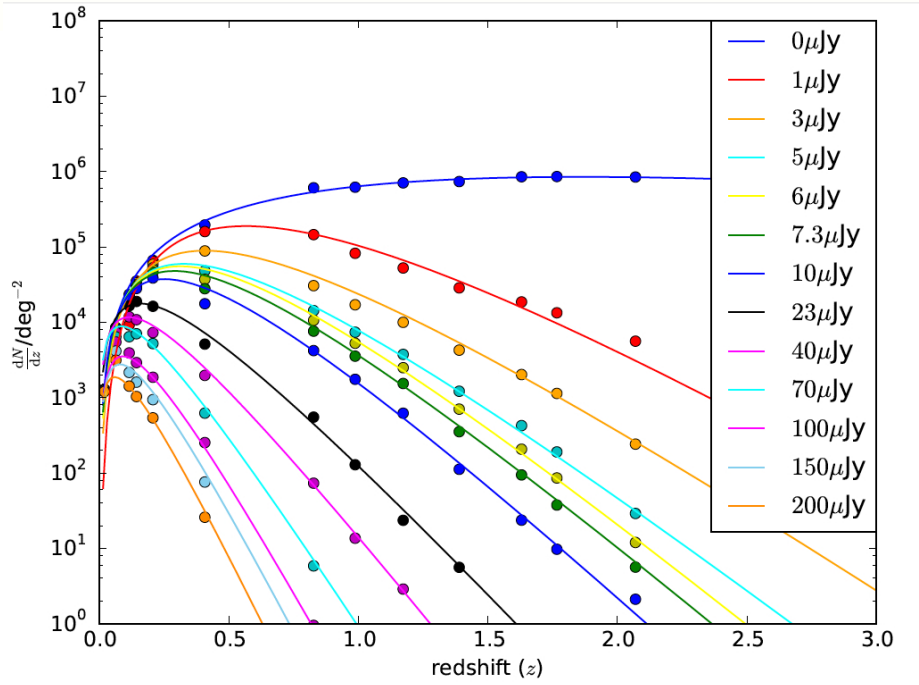


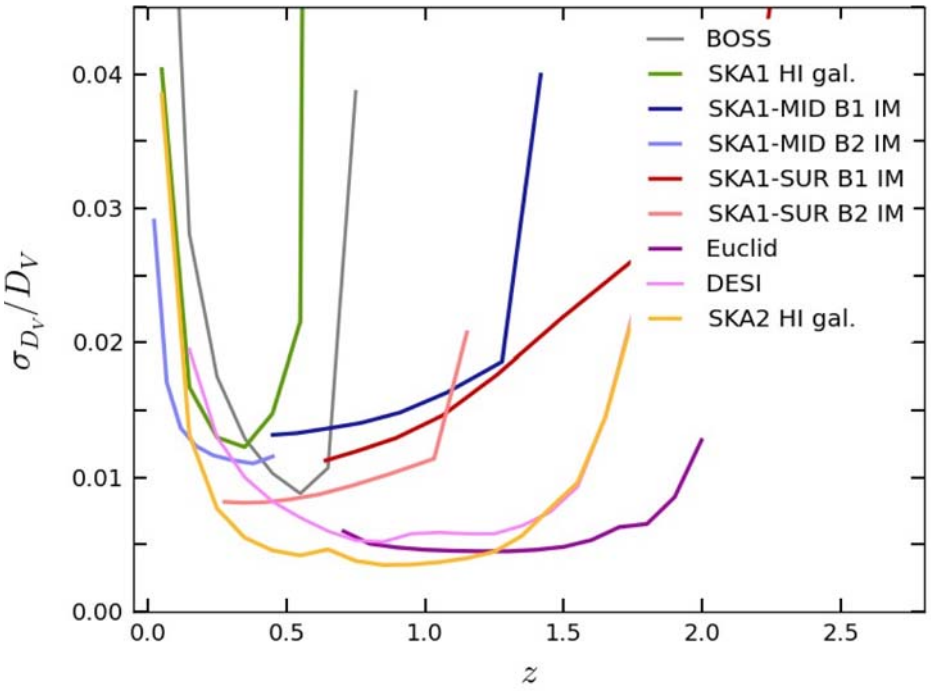

Anderson et al. 2012, 2014

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

# HI Cosmology with SKA: Baryon Acoustic Oscillations



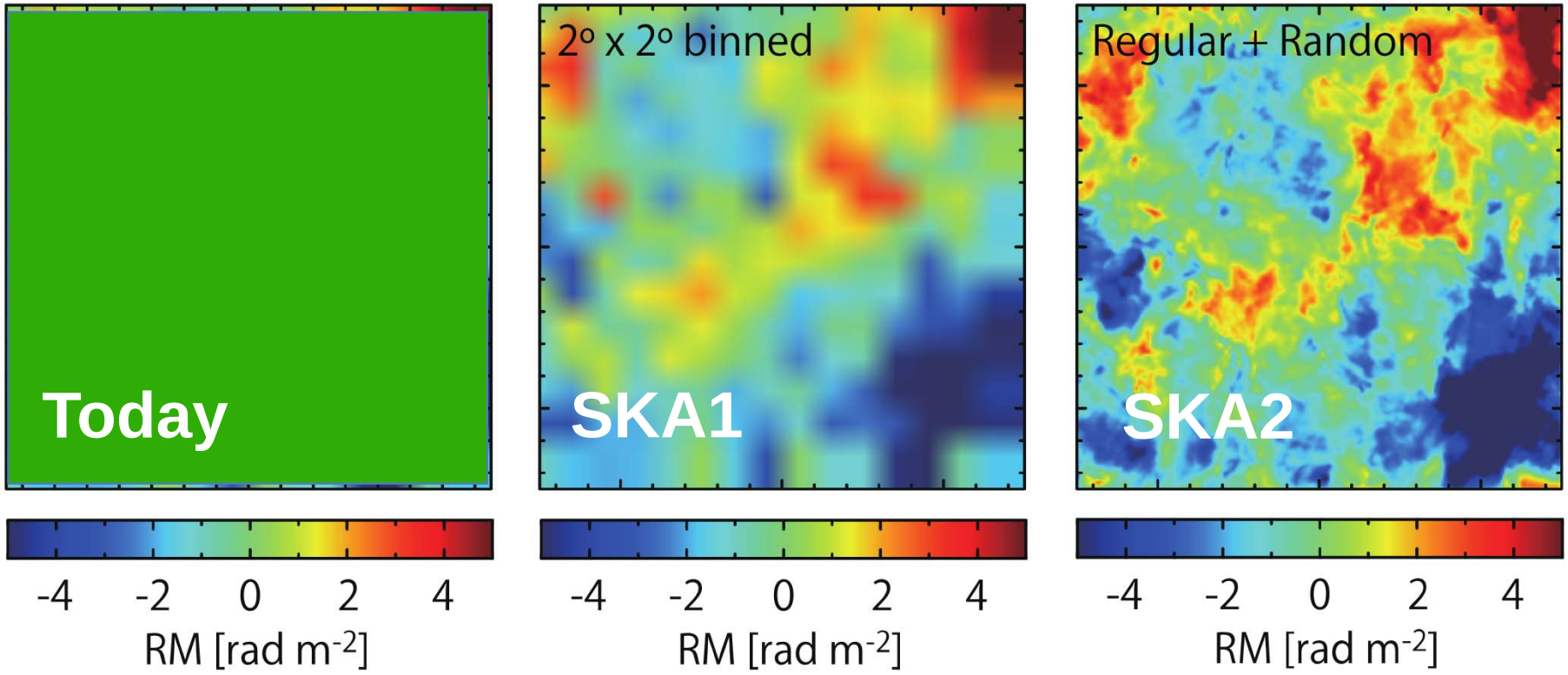

HI predictions using SKADS simulation (Santos et al 2015)




(Bull et al 2015)

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

# Headline Magnetism Science

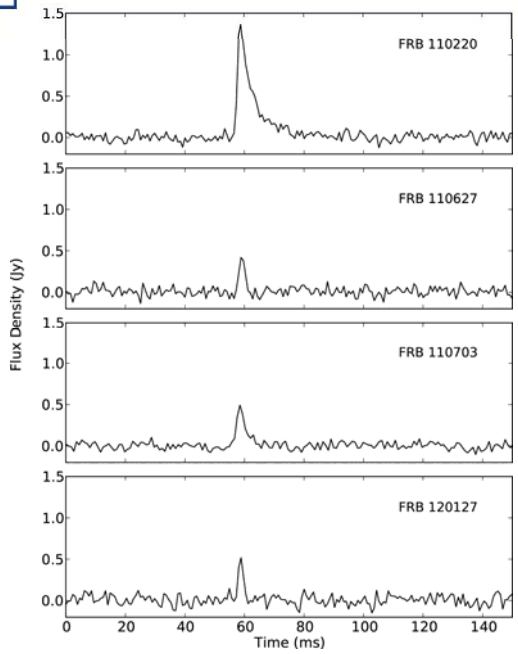


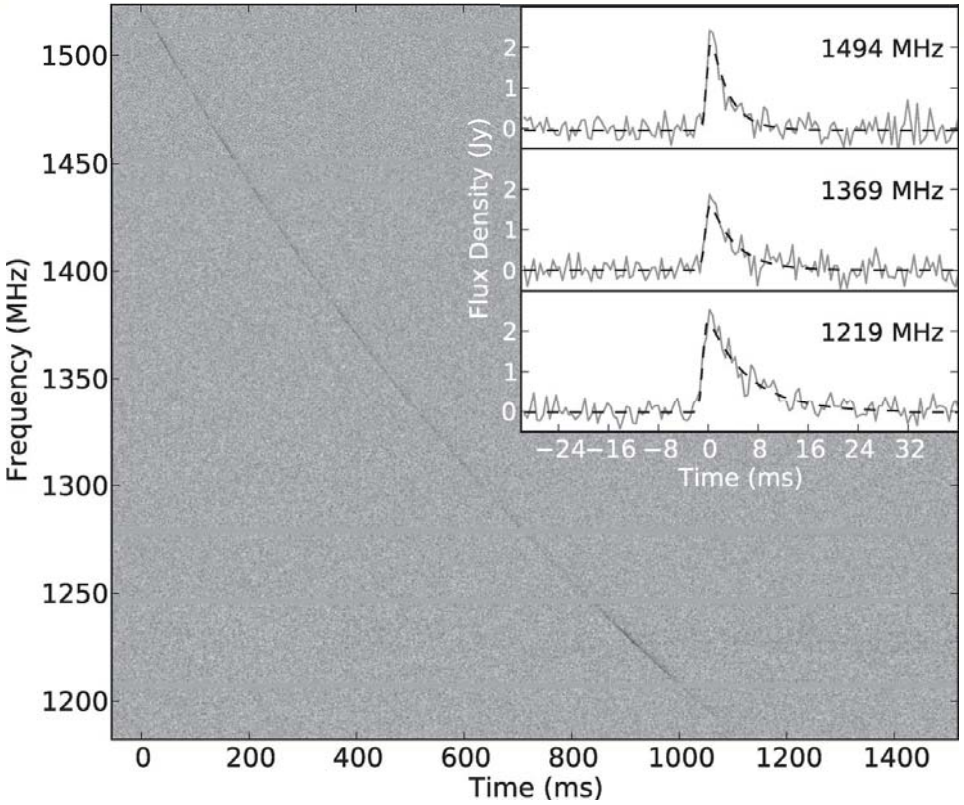

- 3D magnetic tomography of the Galaxy and distant universe; from current 1 RM deg$^{-2}$, SKA1: 300 deg$^{-2}$ to SKA2: 5000 deg$^{-2}$ (Johnston-Hollitt et al. 2015)

# The transient radio sky: exploring the unknown

Science
AAAS

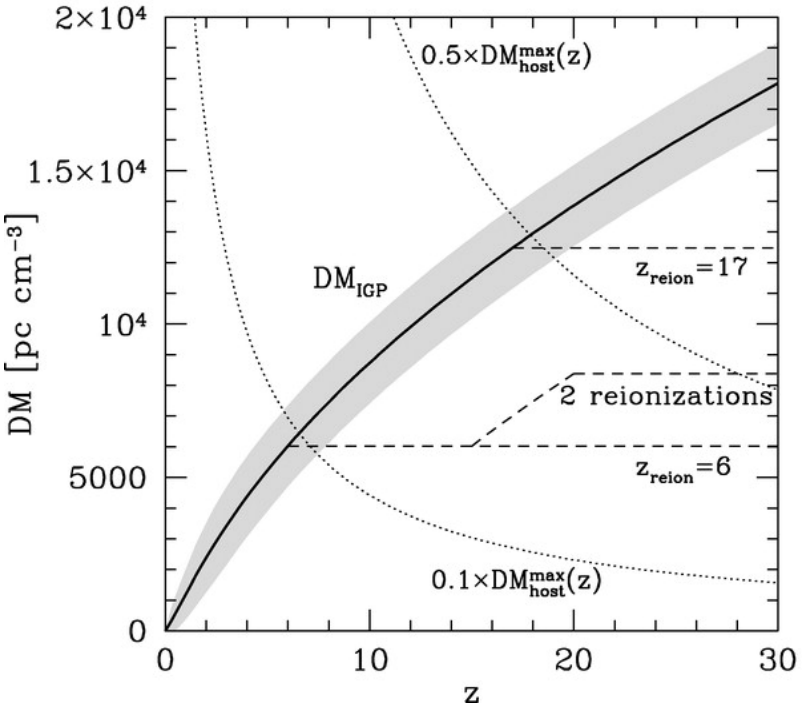
**A Population of Fast Radio Bursts at Cosmological Distances**
D. Thornton *et al.*
*Science* **341**, 53 (2013);
DOI: 10.1126/science.1236789



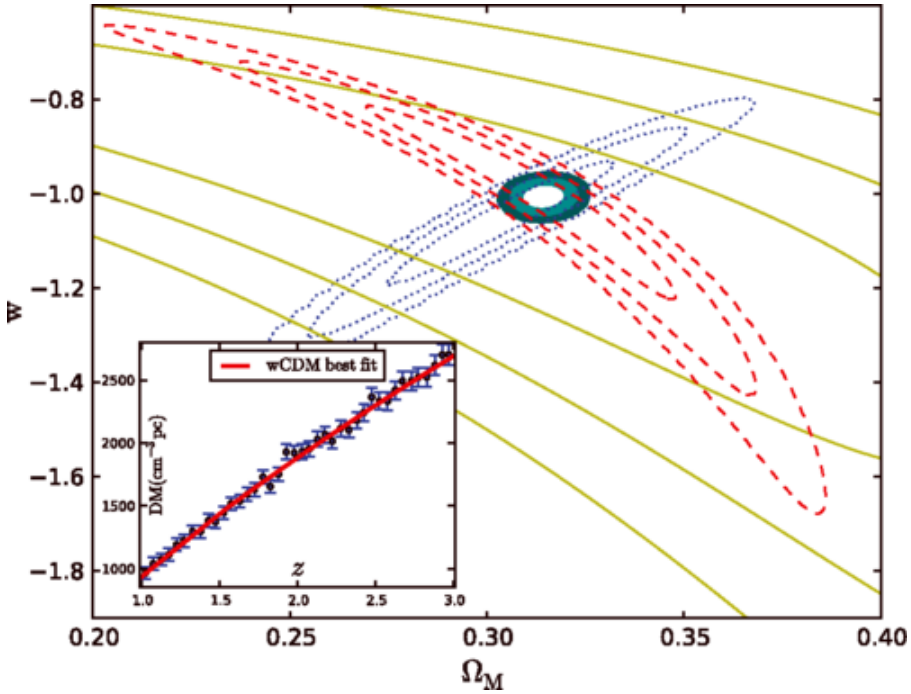




- More than 10 "FRB" events now detected (after first "Lorimer" burst):
  $S = 0.5 – 1.3$ Jy, $\Delta t = 1 – 6$ msec, DM = 550 – 1100 cm$^{-3}$ pc
- Estimated event rate: $1 \times 10^4$ sky$^{-1}$ day$^{-1}$
- Completely unknown origin, possibly at cosmological distances

# Fast Radio Bursts as a cosmological probe?




(Ioka 2003)



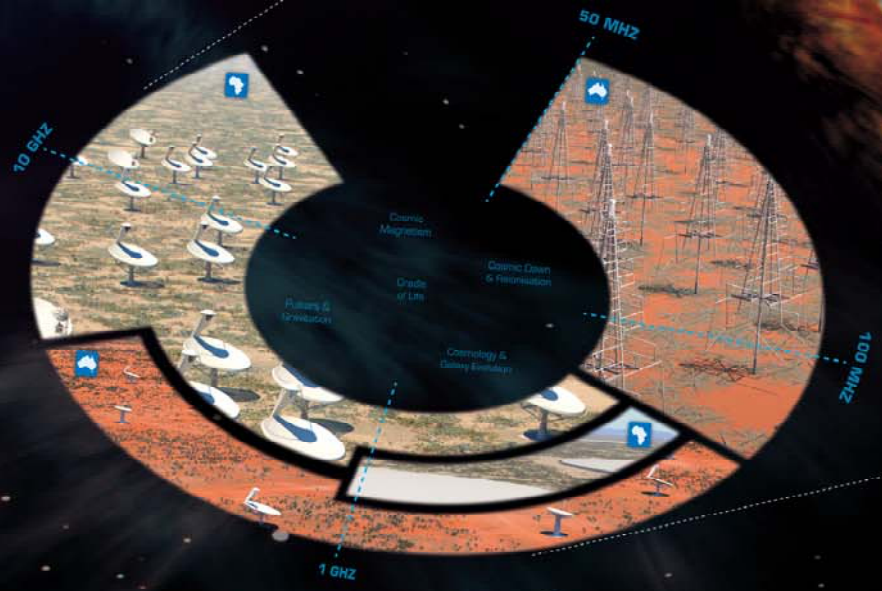

(Zhou et al. 2014)

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

# SKA Science

The SKA will revolutionise our
understanding of the Universe
and the laws of fundamental physics

http://astronomers.skatelescope.org/

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