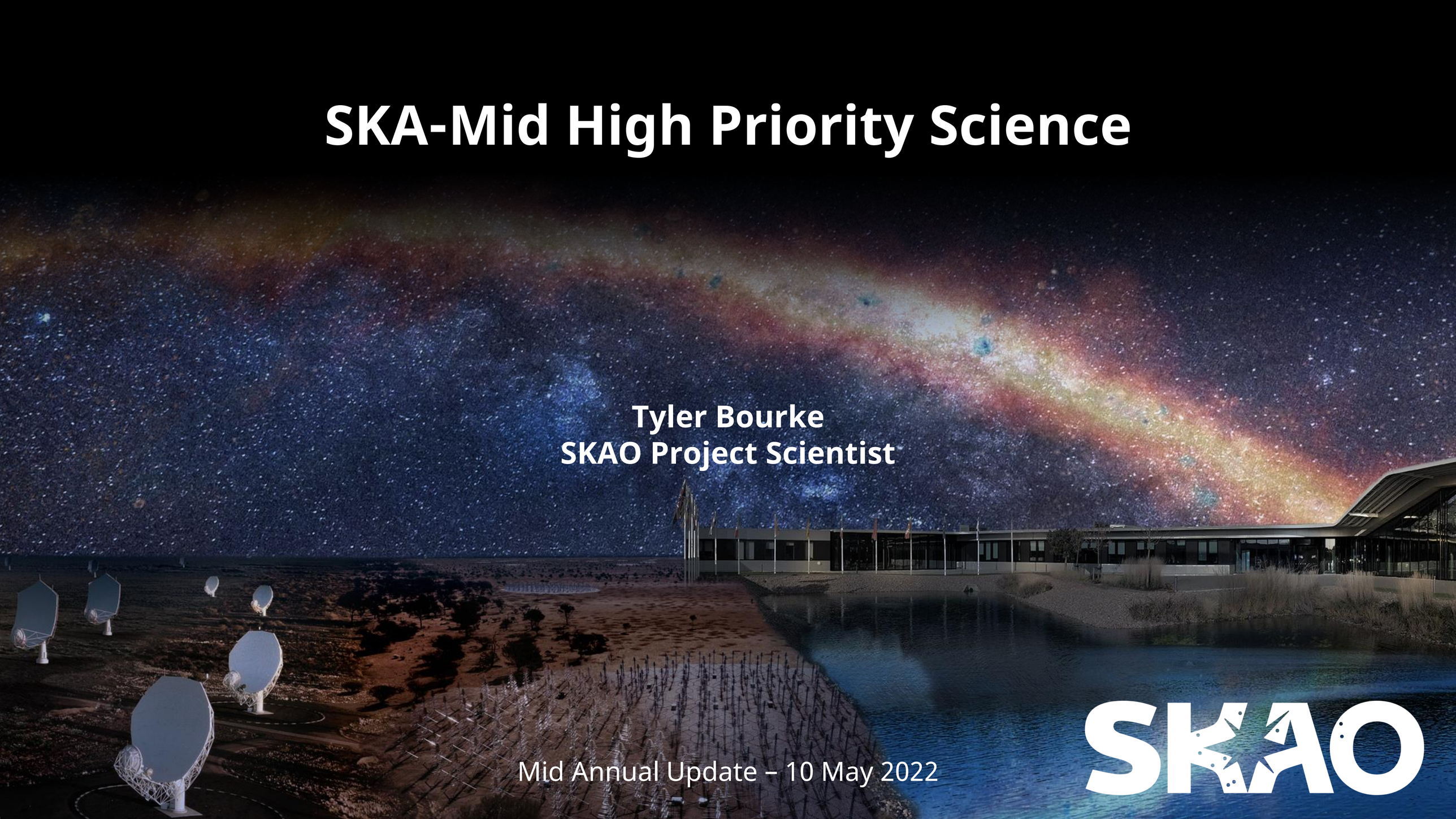
# SKA-Mid High Priority Science



**Tyler Bourke**
**SKAO Project Scientist**

Mid Annual Update – 10 May 2022

# SKA– Key Science Drivers
# The history of the Universe

Testing General Relativity
(Extreme Gravity, Gravitational Waves)

Cosmic Dawn & Reionisation
(First Stars and Galaxies)

Cradle of Life
(Planets, Molecules, SETI)

Galaxy Evolution
(Normal Galaxies z~2-3)

Cosmic Magnetism
(Origin, Evolution)

Cosmology
(Dark Matter, Large Scale Structure)

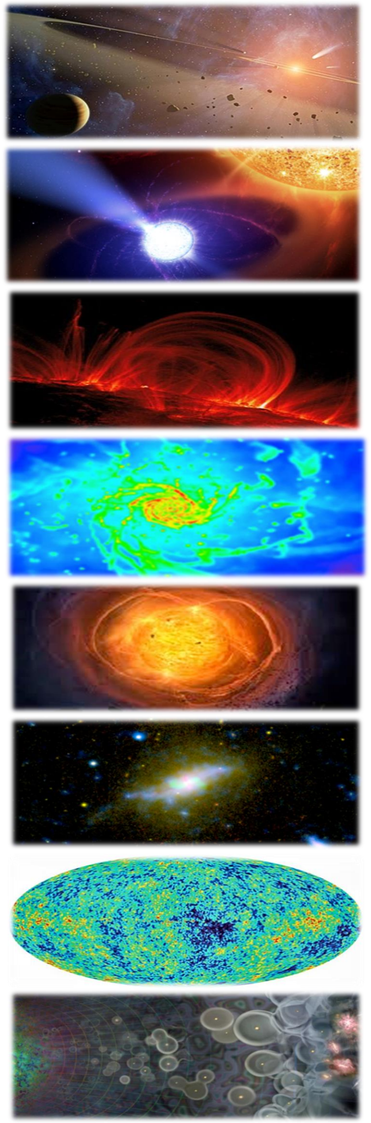
Our Galaxy
(Star Birth & Death, Matter Evolution, Structure)

Exploration of the Unknown

**Huge range of transformational science enabled by SKAO**

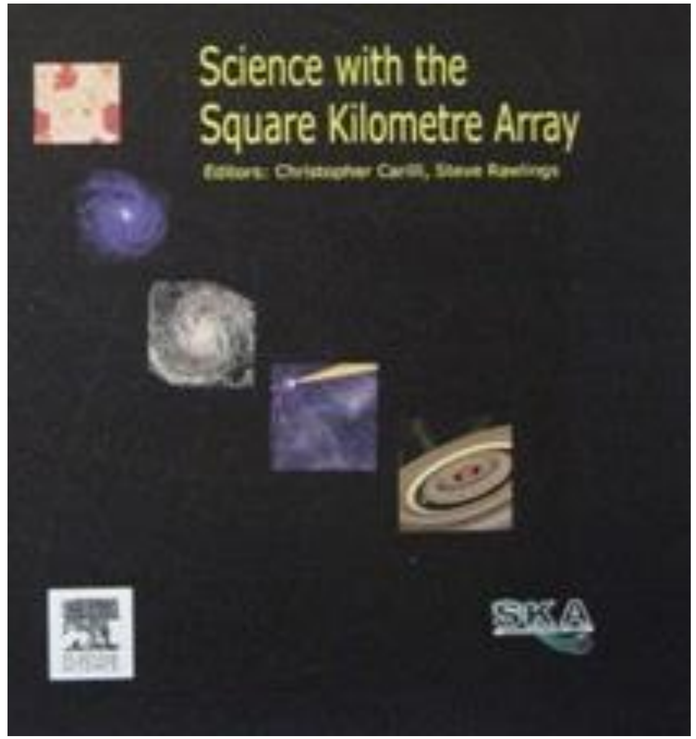
# SKA Big Questions

- **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?*
- **Our Galaxy, The Milky Way**
  *How does matter cycle between stars and the Interstellar Medium?*
- **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 and Radio Continuum**
  *How do normal galaxies form and grow? What is their star-formation history?*
- **The Transient Radio Sky**
  *What are Fast Radio Bursts and how can we utilise them? What haven't we discovered?*
- **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?*



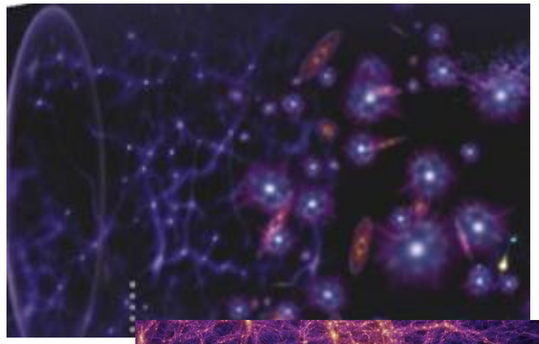
# High Priority Science – Pre SKAO

- Science case evolution
  - Workshops/Books (1999, **2004**)
  - Design Reference Mission (2011)

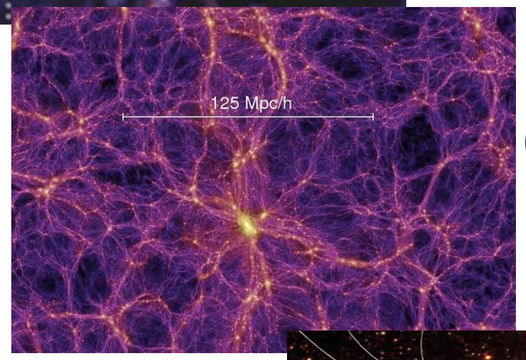



- Technical evolution
  - Memo 100 “Preliminary Specifications …” (Schilizzi et al. 2007)
  - Memo 125 “Concept Design …” (Garrett et al. 2010)
  - Memo 130 “SKA Phase 1 Preliminary Design … ” (Dewdney et al. 2010)

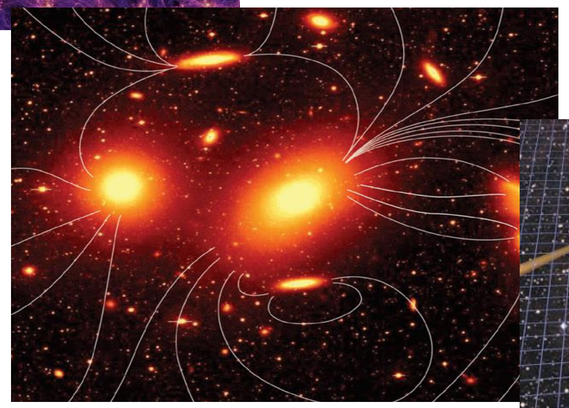
# The Broad SKA Science Case pre-SKAO



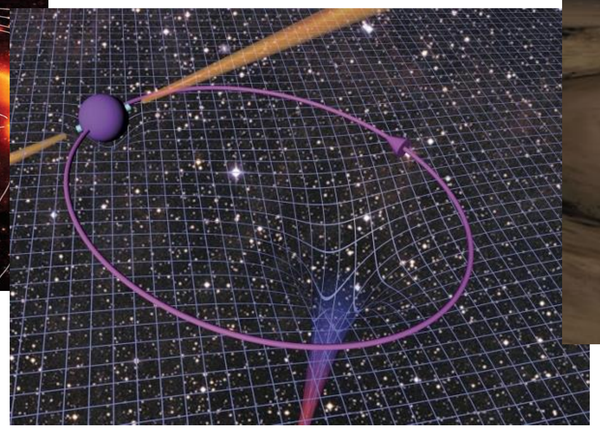
The First Stars



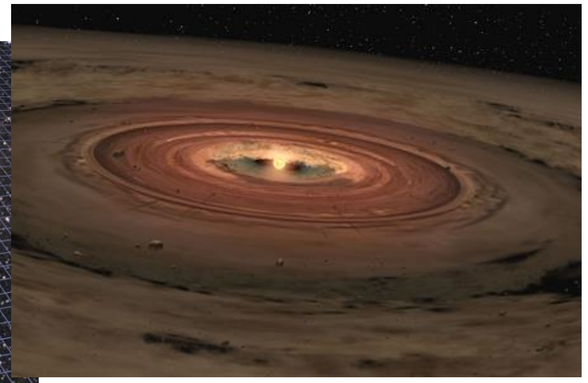

Cosmic Evolution



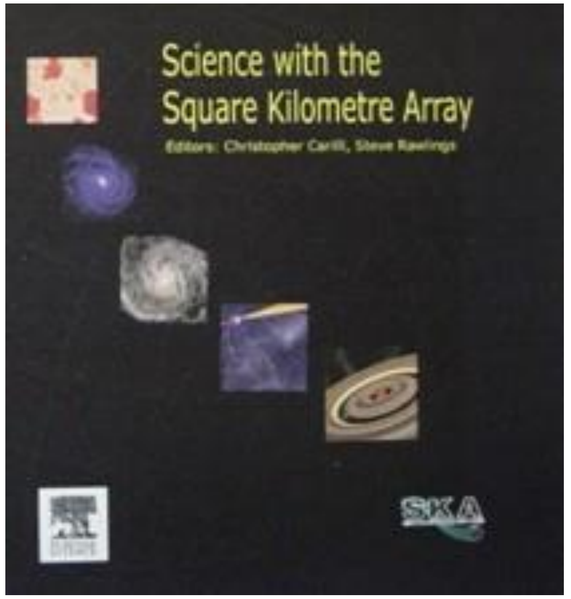
Cosmic Magnetism



Gravitational Physics



Origins of Life

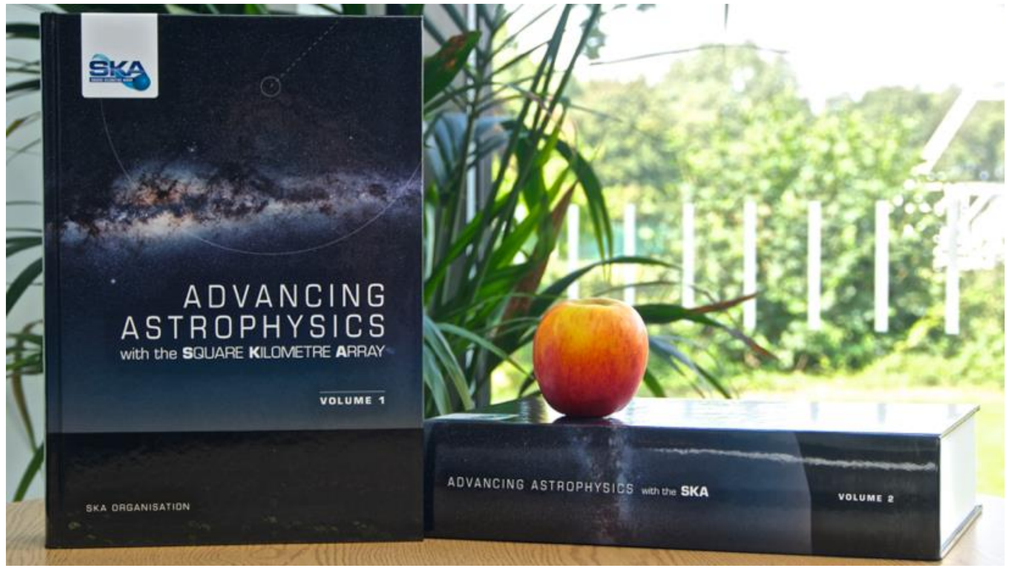


# High Priority Science – SKAO era

- Science case evolution
  - SWGs/Science Assessment Workshops

    (2013-14)
  - Level 0 requirements
  - Advancing Astrophysics with the SKA

    (2014 meeting, 2015 books; https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215)
  - Science Prioritisation … (next slides)
- Technical evolution
  - Baseline Design V1 …" (Dewdney+ 2013)
    - Evolution of Level 1 requirements
    - Rebaseling 2015




**SKA1 SYSTEM BASELINE DESIGN**

Document number ..... SKA-TEL-SKO-DD-001
Revision ..... 1
Author ..... P.E. Dewdney
Date ..... 2013-03-12
Status ..... Released

| Name | Designation | Affiliation | Date | Signature |
|---|---|---|---|---|
| Owned by: | | | | |
| P. E. Dewdney | SKA Architect | SKA Office | Peter E. Dewdney | Digitally signed by Peter E. Dewdney DN: cn=Peter E. Dewdney, o=SKA Organisation, ou, email=dewdney@skatelescope.org, c=GB Date: 2013.03.12 07:50:17 Z |
| Additional Authors | | | | |
| W. Turner, R. Millenaar, R. McCool, J. Lazio, T. J. Cornwell | | | | |
| Approved by: | | | | |

# SKA1 Science Prioritisation

Effort led by Science Team (SKA-ST) in 2014

Assisted by Science Working Groups (SWGs) – Science Cases

Supported by (through reviews)

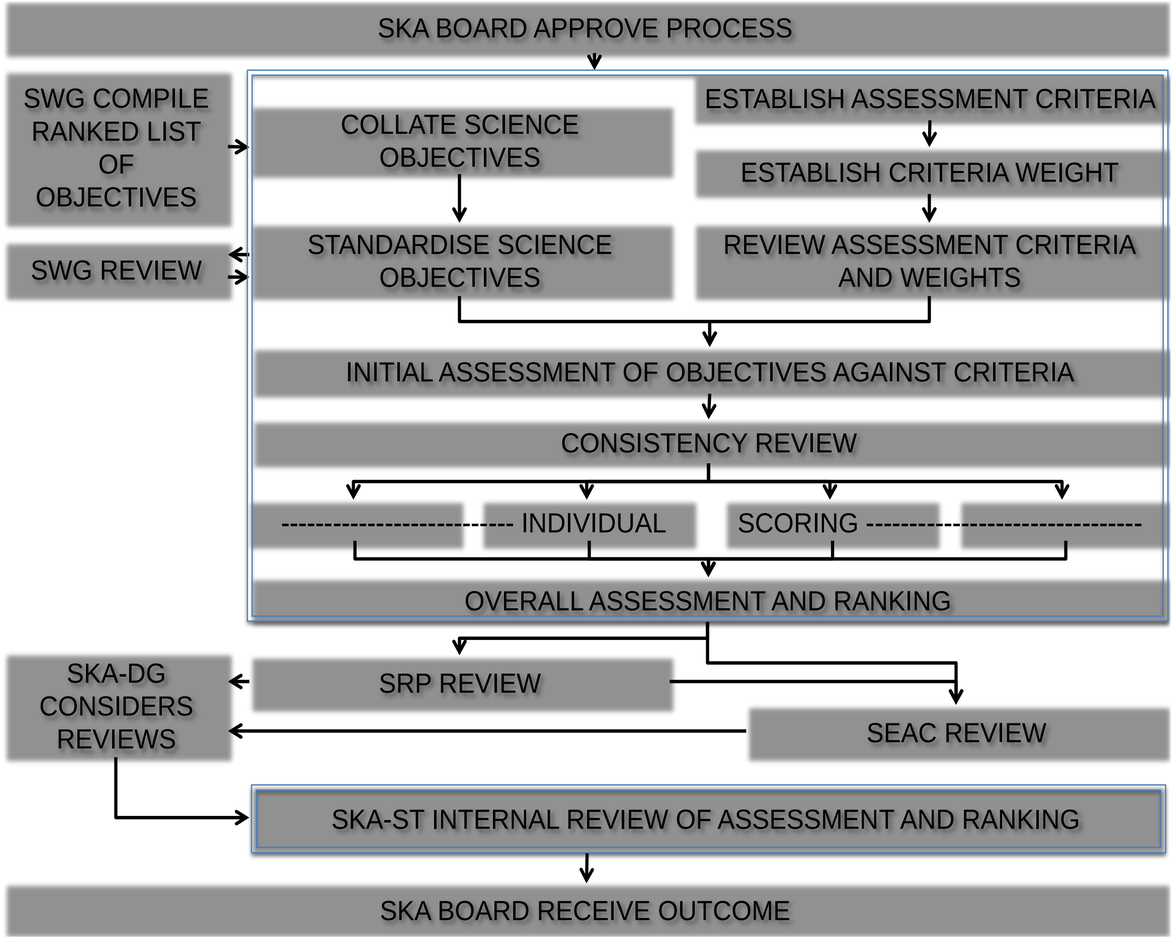
- ad-hoc Science Review Panel (SRP; External Experts + SWG Chairs)
- SEAC

Why?? Goals:

- **To guide re-baselining options (construction cost-cap)**
- To guide SKA1 Level 0 science requirements (Update), and L1s
- To guide the formation of a “notional” package of Key Science Projects (KSPs) for SKA1 (no guaranteed time, used for planning purposes)

# SKA1 Science Prioritisation

## The Process




## The Outcomes

SQUARE KILOMETRE ARRAY

### SKA1 SCIENCE PRIORITY OUTCOMES

| | |
|---|---|
| Document number | SKA-TEL-SKO-0000122 |
| Context | SCI-REQ-RE |
| Revision | 1 |
| Author | R. Braun, T. Bourke, J. Green, J. Wagg |
| Date | 2014-09-25 |
| Document Classification | FOR PROJECT USE ONLY |
| Status | Released |

# SKA1 Science Prioritisation

Science priorities submitted by SWGs (their rankings)

ST weighted scoring for, e.g.,

- science impact
- radio importance
- SKA1 uniqueness
- risk
- … (read the report)

| 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 |

# SKA1 Highest Priority Science Objectives (HPSOs)

| 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 |

Outcome of weighted scoring
Confirmed by SRP and SEAC reviews
(Listed by SWG, not by overall ranking)

# SKA1 Highest Priority Science Objectives (HPSOs)

| 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 |

Enabled by SKA1-Mid (partially or wholly)

Also led to Band prioritization – Deploy Band 2, 5, 1 in that order

# SKA1 Science

*Philosophy – Guiding Principles*

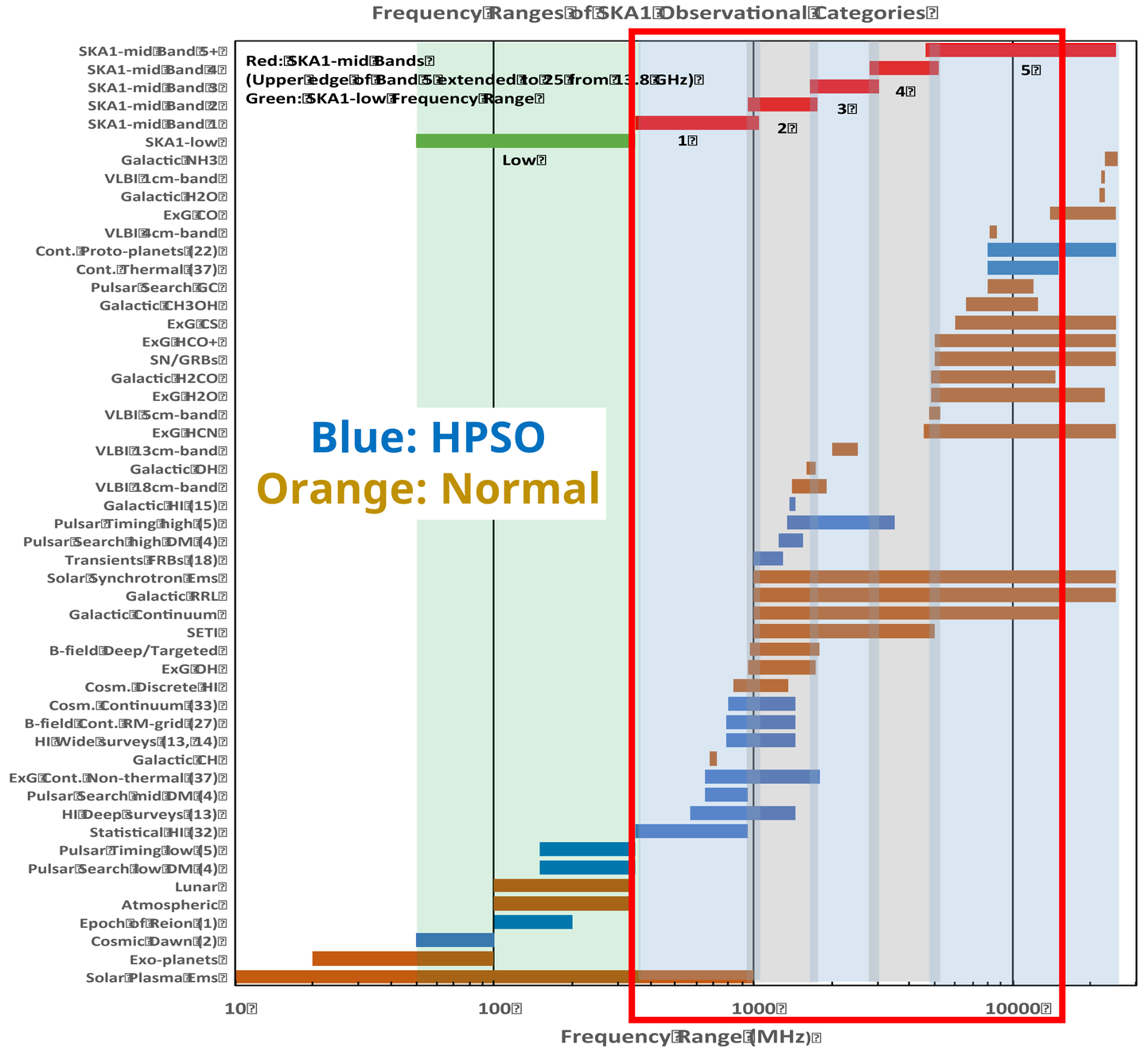
- ✓ the Telescopes should be able to deliver the HPSOs in a ~5 year window (proto-KSPs)
- ✓ by enabling the HPSOs, all 44 science objectives should be possible
- ✓ … and should have sufficient design flexibility to enable a broad range of science not covered in the objectives (missing SWGs, unanticipated discoveries)
  - ✓ Our Galaxy ⇒ high spectral resolution (masers, …) ⇒ **zoom modes**
  - ✓ Extragalatic Spectral Lines ⇒ masers ⇒ **zoom modes**
  - ✓ VLBI capabilities (many science cases)
  - ✓ Solar observing ⇒ signal attenuation
  - ✓ Wide area mapping ⇒ Transients, efficient large-area mapping

**All indicative – there is no guaranteed time, no time yet assigned**

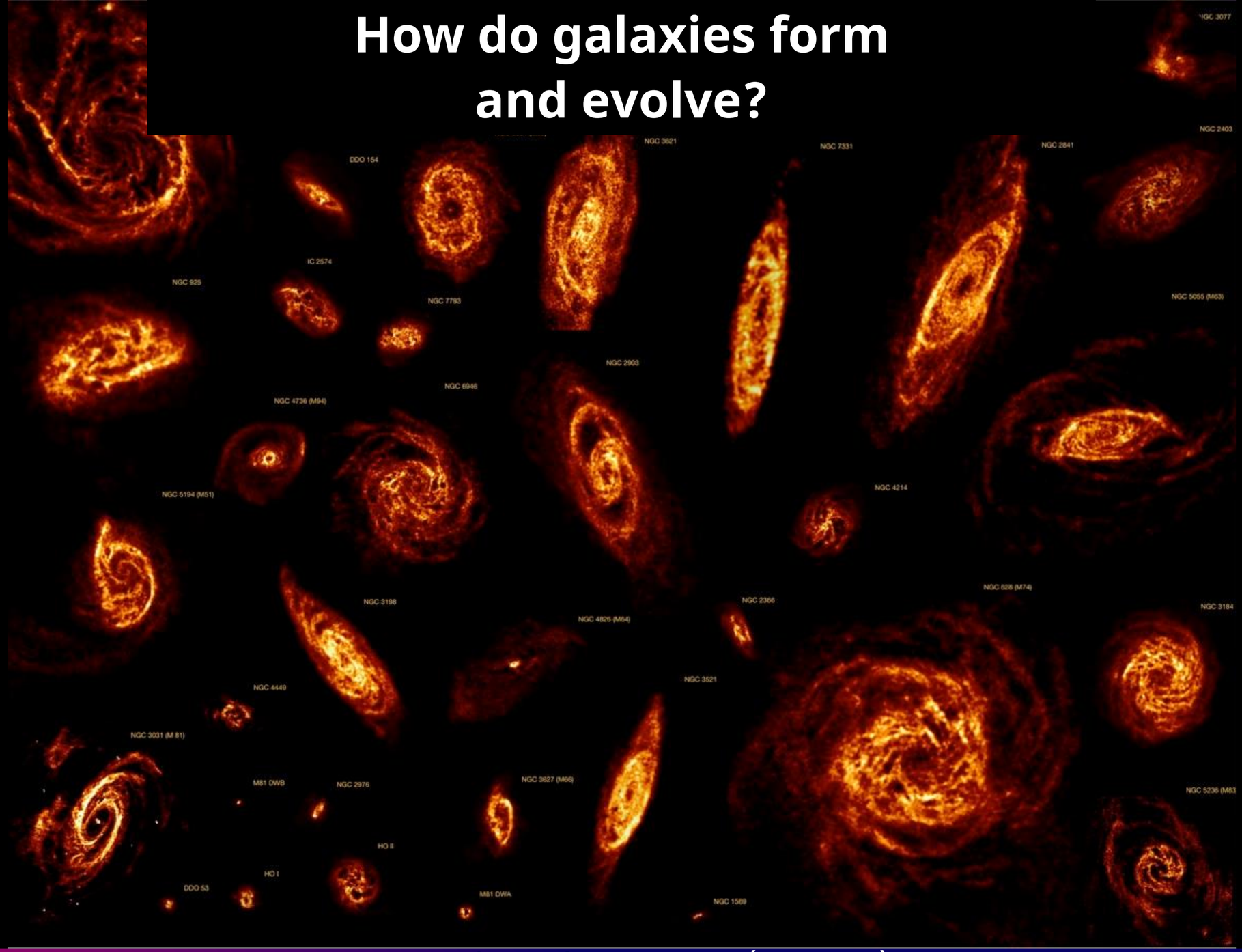
# Science Objective v Frequency

Science Prioritisation
+
AASKA “Science Book”

Source:
Baseline Design V2
(Dewdney 2016)

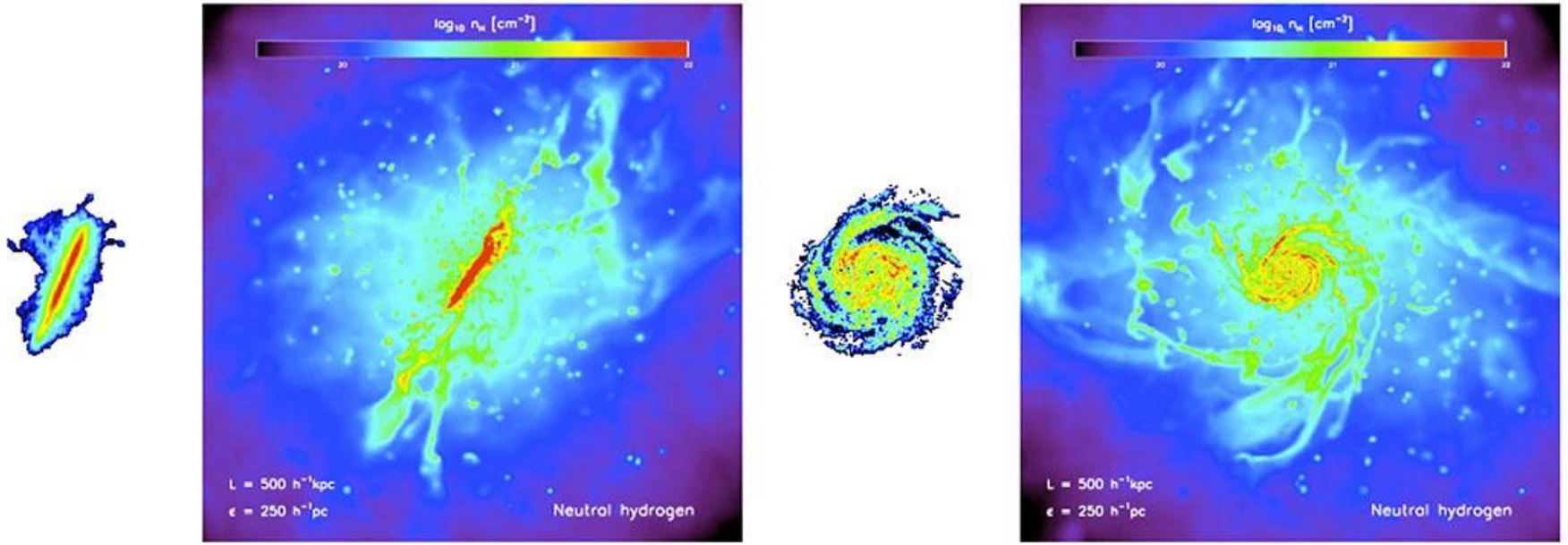


# How do galaxies form and evolve?



# How do Galaxies form and evolve?

observed HI simulated HI observed HI simulated HI




Images courtesy of Tom Oosterloo (SKA HI science working group)

How do galaxies accrete and grow from the `Cosmic Web' (feeding and feedback)?

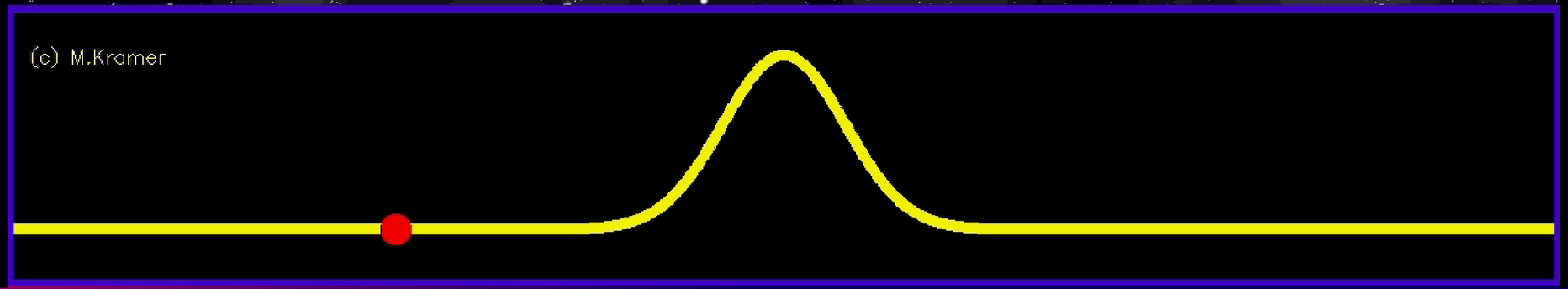
Observations miss the low-density IGM

**SKA1 will provide resolved HI observations out to z ~ 0.8 (6.8 Gyr; 0.78 GHz)**

Measure angular momentum build-up (rotation curves out to large radius)

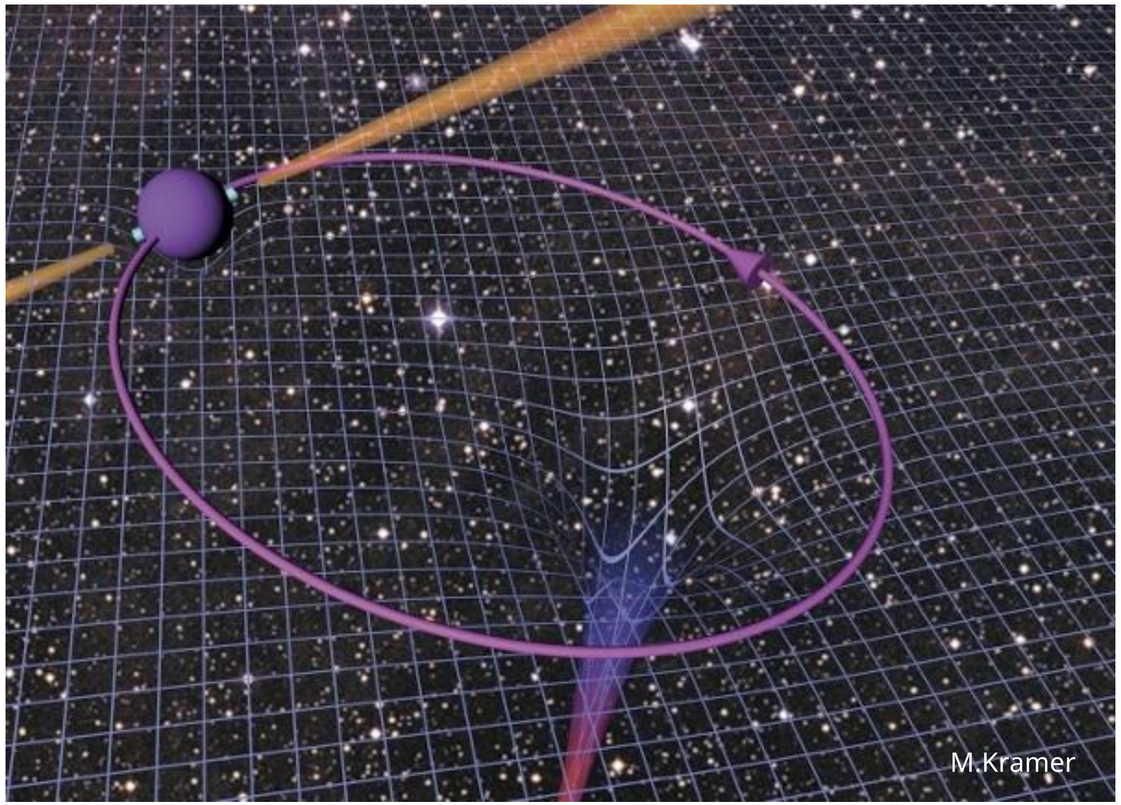
***SKA1 will probe low column density HI in nearby Universe ($N_{HI} < 10^{18}$ cm$^{-2}$)***

5.757451924362137(2) ms (Verbiest et al. 2008) = 2 atto ($10^{-18}$) seconds uncertainty!



# 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:

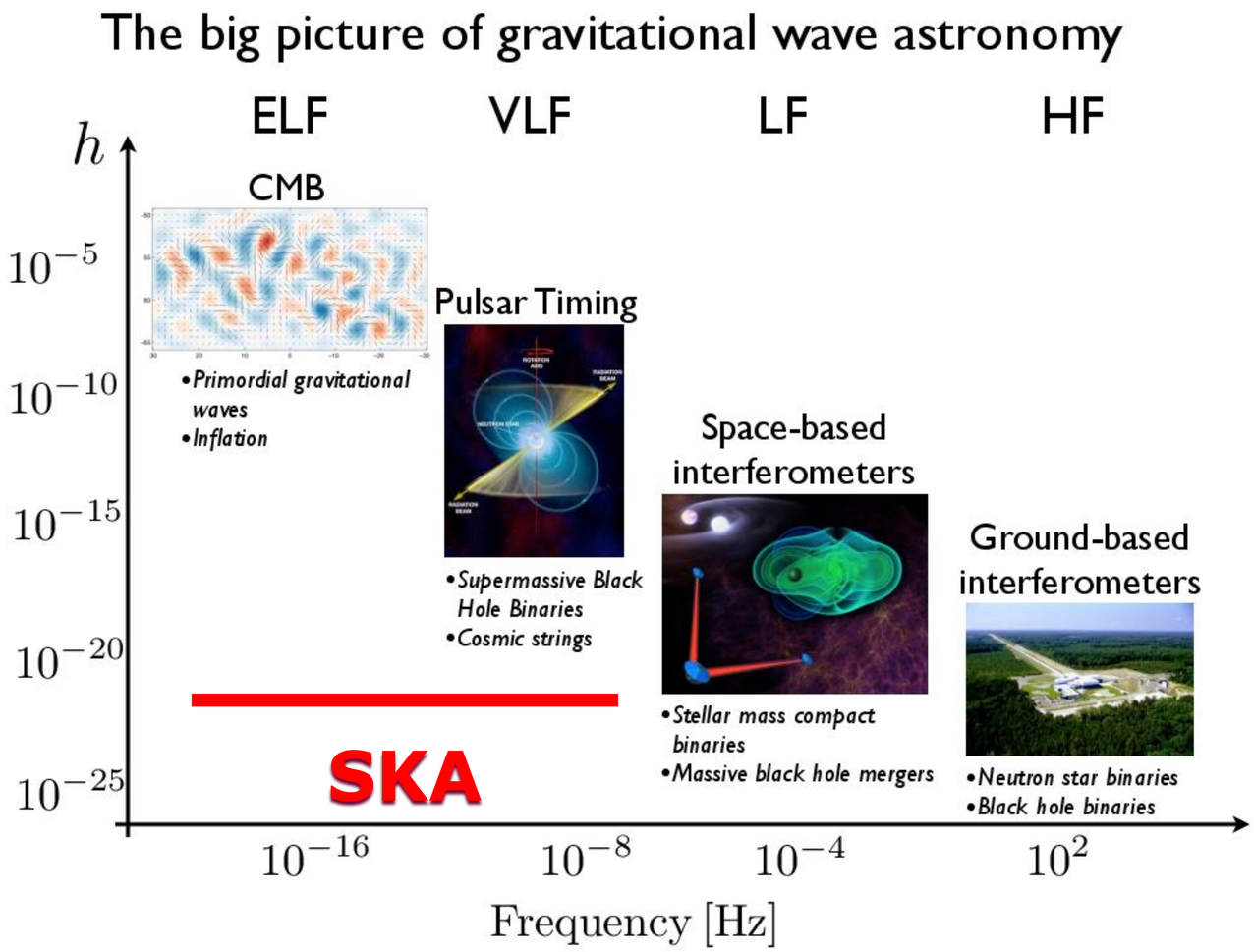
- Mass
- Electric Charge
- Angular Momentum (Spin)

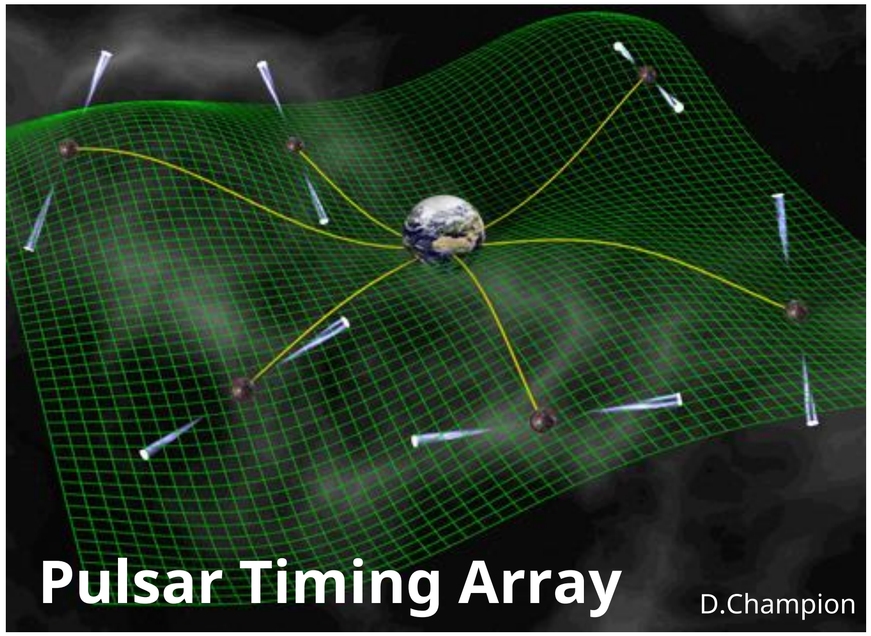
## Cosmic Censorship

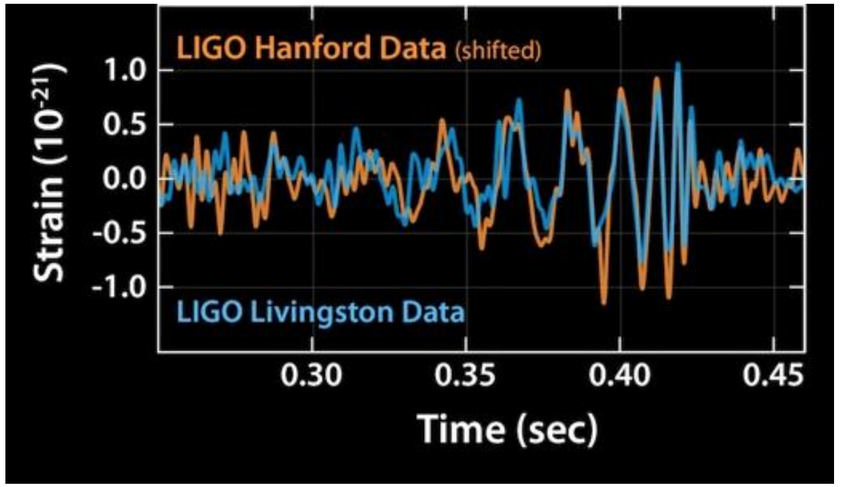
BHs have an event horizon which hides the singularity, i.e.., there are **no naked singularities**

Kramer & Stappers 2015, AASKA

# Gravitational Waves with Pulsars



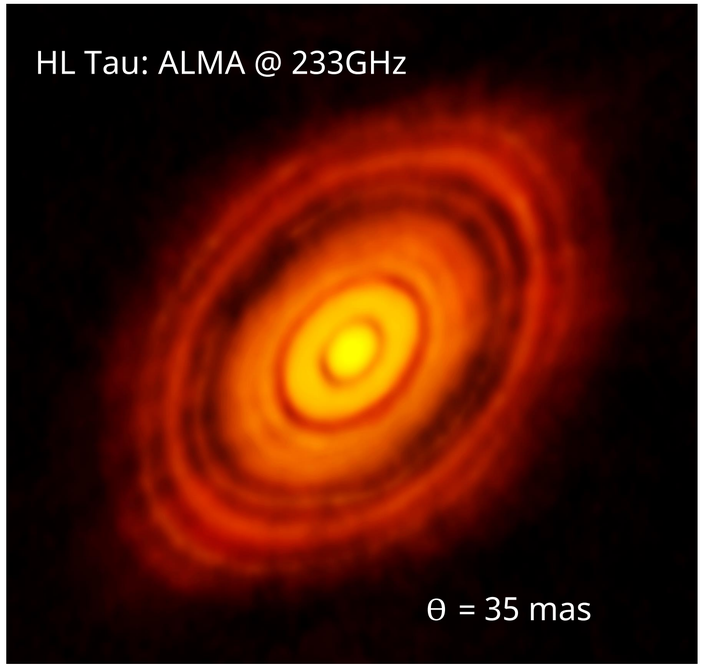



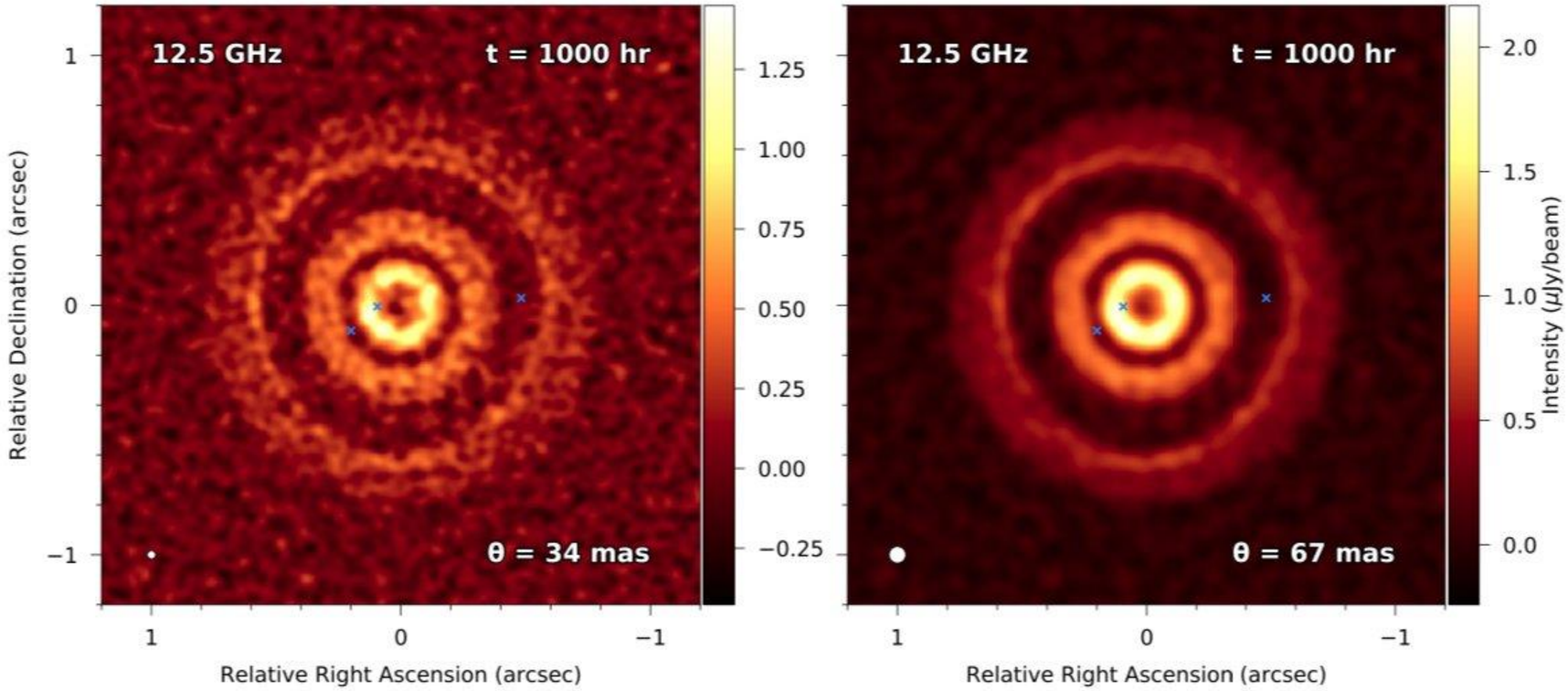

**Discoveries with SKA1 (SMBH mergers, Primordial GWs)**
**"GW astronomy" with SKA2 (discrete sources)**

# When/Where do Earth-like Planets form in Disks

Formation of cm+ sized grains is a crucial step on the road to terrestrial planet formation

Where and how does grain growth proceed?




SKA covers the right λ's to probe cm-size grains

Simulations clearly show deep SKA observations will be able to observe pebbles in disks, and gaps/ring structure due to forming planets

(Band 5 simulation – Ilee et al. 2020)

# The Unknowns (cf. HST)

| Project | Key project? | Planned? | Nat. Geo. top ten? | Highly cited? | Nobel prize? |
|---|---|---|---|---|---|
| Use Cepheids to improve value of H0 | Y | Y | Y | Y | |
| Study intergalactic medium with uv spectroscopy | Y | Y | | | |
| Medium-deep survey | Y | Y | | | |
| Image quasar host galaxies | Y | Y | Y | | |
| Measure SMBH masses | | Y | Y | | |
| Exoplanet atmospheres | | Y | Y | | |
| Planetary Nebulae | | Y | Y | | |
| Discover Dark Energy | | | Y | Y | Y |
| Comet Shoemaker-Levy impact on Jupiter | | | Y | | |
| Deep fields (HDF, HDFS, UDF, FF, etc) | | | Y | Y | |
| Protoplanetary disks (Proplyds )in Orion | | | Y | | |
| GRB Hosts | | | Y | | |

(Lallo: arXiv:1203.0002; Norris AASKA14)

# Over 1000 scientists in 14 Working Groups

## Extragalactic Continuum
Science Working

## Our Galaxy
Science Working

## Extragalactic Spectral Lines
Science Work

## High Energy Cosmic Particles
Focus Group

## Cosmology
Science Working

## VLBI with the SKA
Science Working Group

## HI Galaxy Science
Science Working Group

## Cosmic Magnetism
Science Working Group

## Transients
Science Working

## Cradle of Life
Science Working Group

## Solar and Heliospheric Physics
Science Working Gro

## Epoch of Reionization
Science Working

## Pulsars
Science Working Group

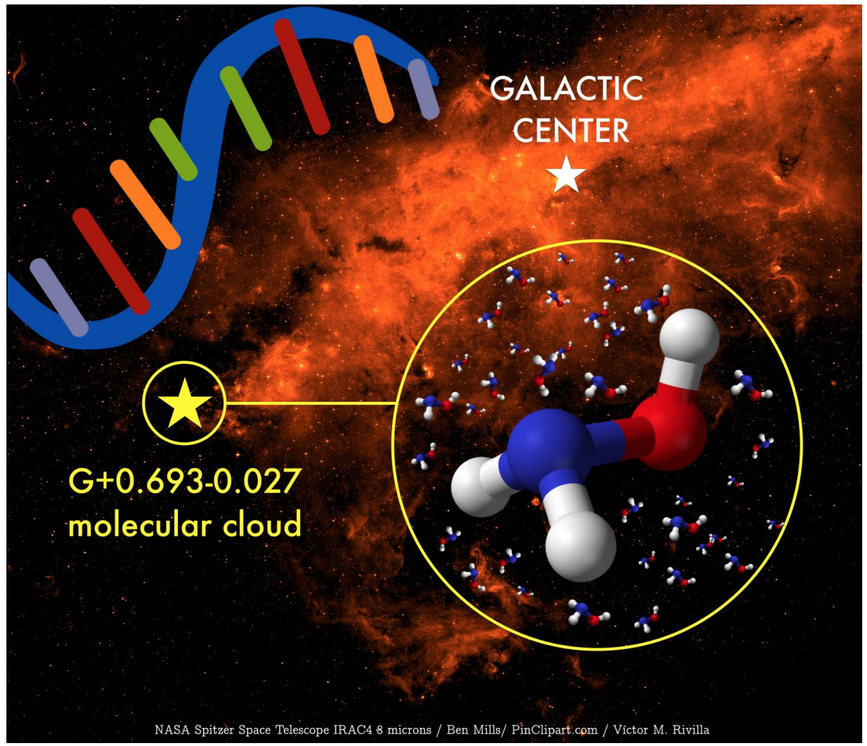
+Gravitational Waves
(in progress)

Breakthrough Listen / Danielle Futselaar

SKAO

# Pre-biotic molecules in star-forming regions

- Building blocks for life on Earth may have arrived from space (panspermia hypothesis)
- Detection of key pre-biotic molecules (e.g. amino acids, complex sugars) in interstellar space is a “holy grail” of Cradle of Life studies

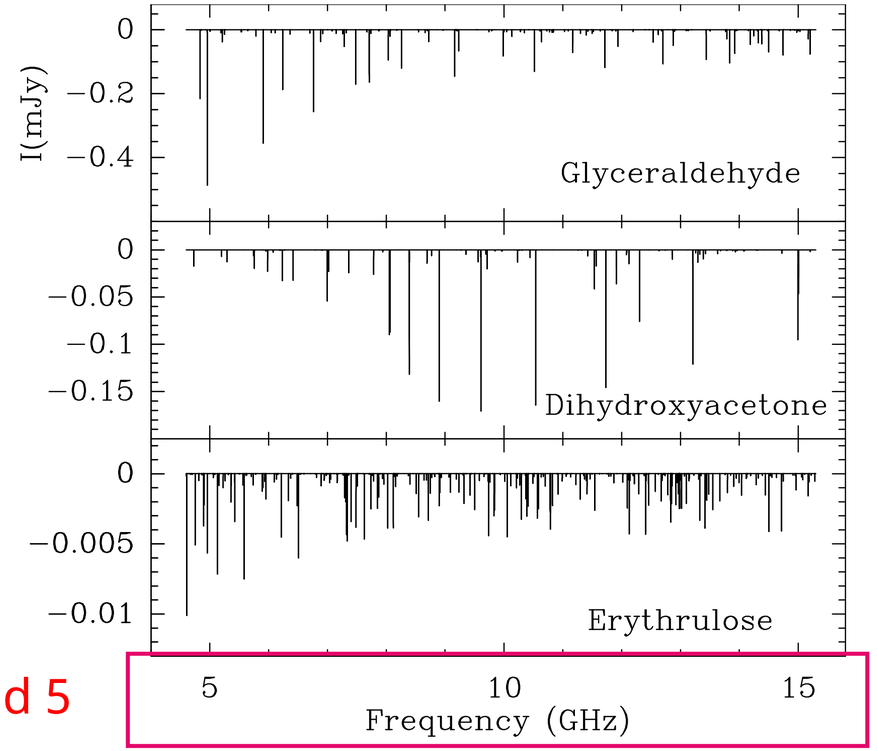



Detection of hydroxylamine ($NH_2OH$), key precursor to RNA
(IRAM 30-m; Rivilla et al. 2020)

$CHOCHOHCH_2OH$

$CH_2OHCOCH_2OH$

$C_4H_8O_4$




SKA Band 5

Predicted spectrum of key large sugars toward G+0693.
Detection of the brightest (ie. deepest) lines requires 10s of hours integration with SKA1 (Jimenez-Serra et al. 2022)