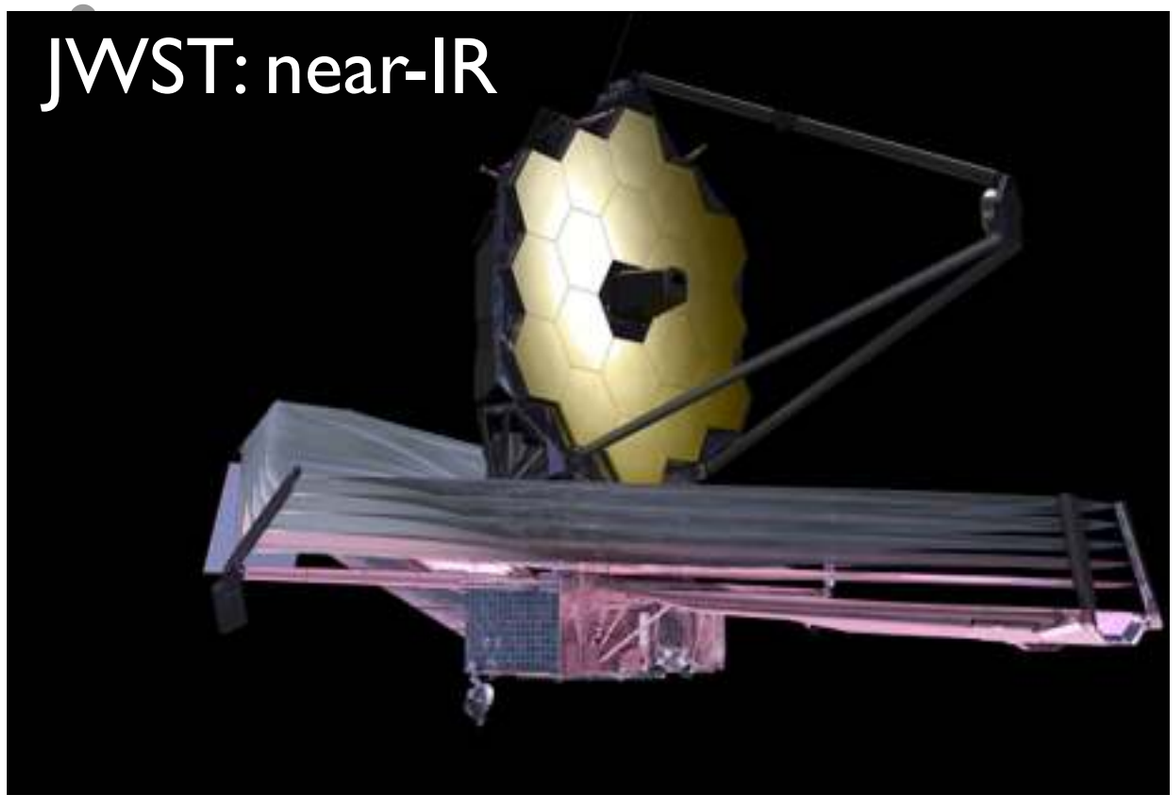
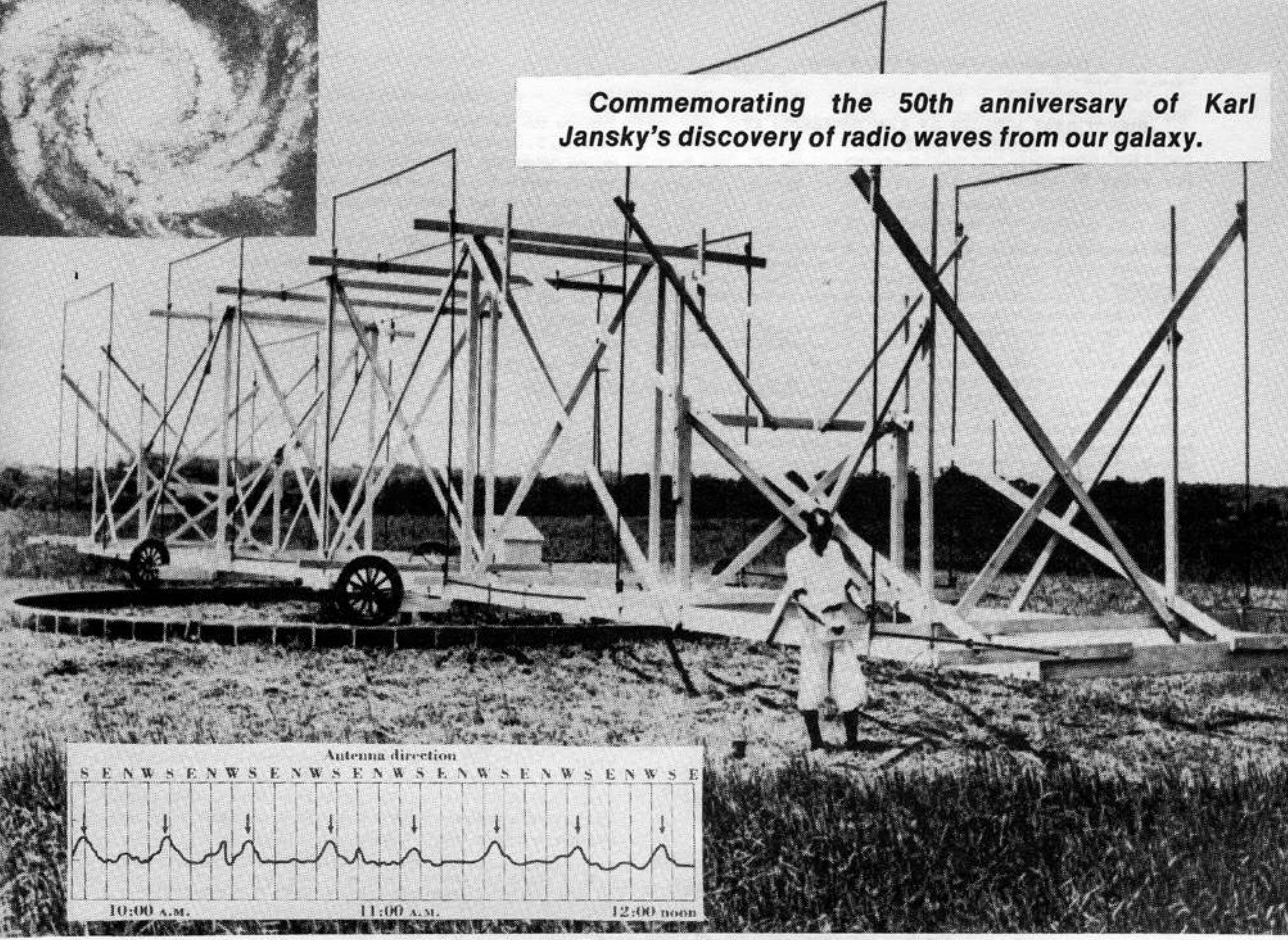
The Square Kilometre Array

Miguel Pérez-Torres (torres@iaa.es)
(IAA-CSIC)

Great Observatories for the coming decade

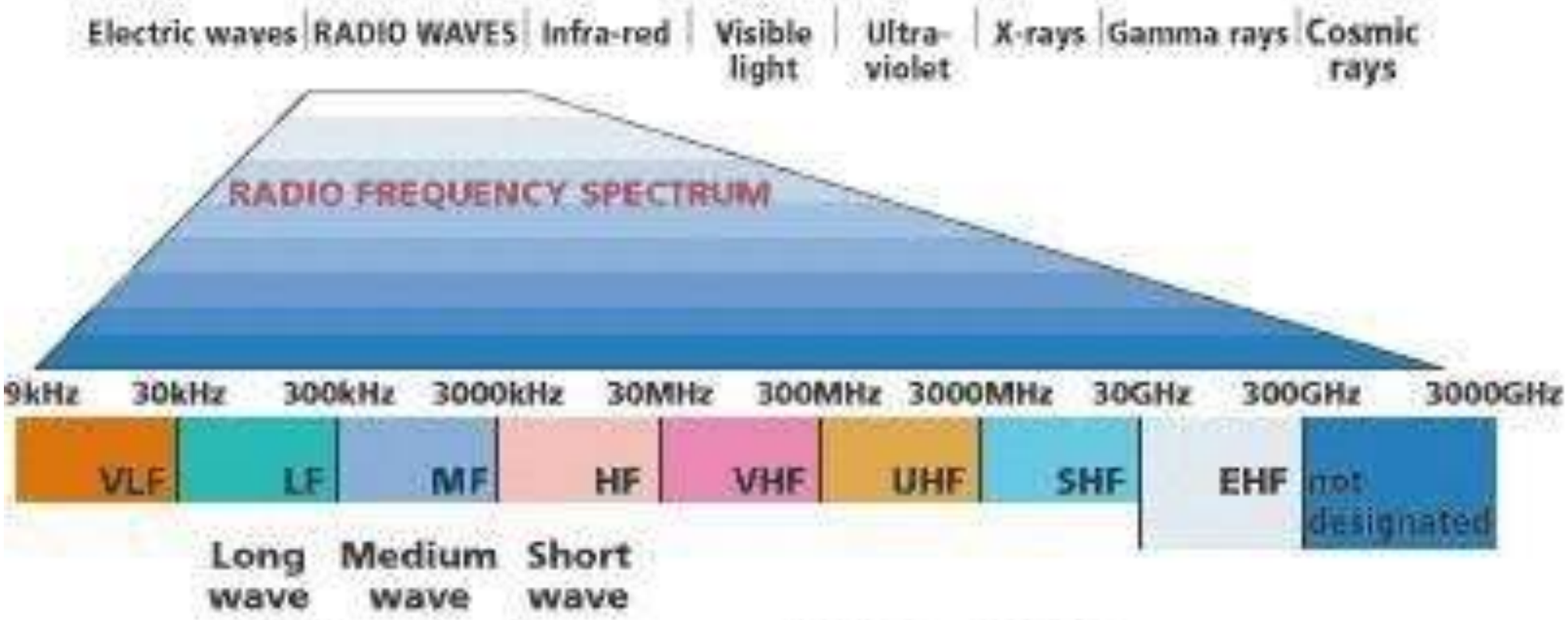


…and the SKA



Karl Jansky and his "merry-go-round" antenna — the first radio telescope with record of

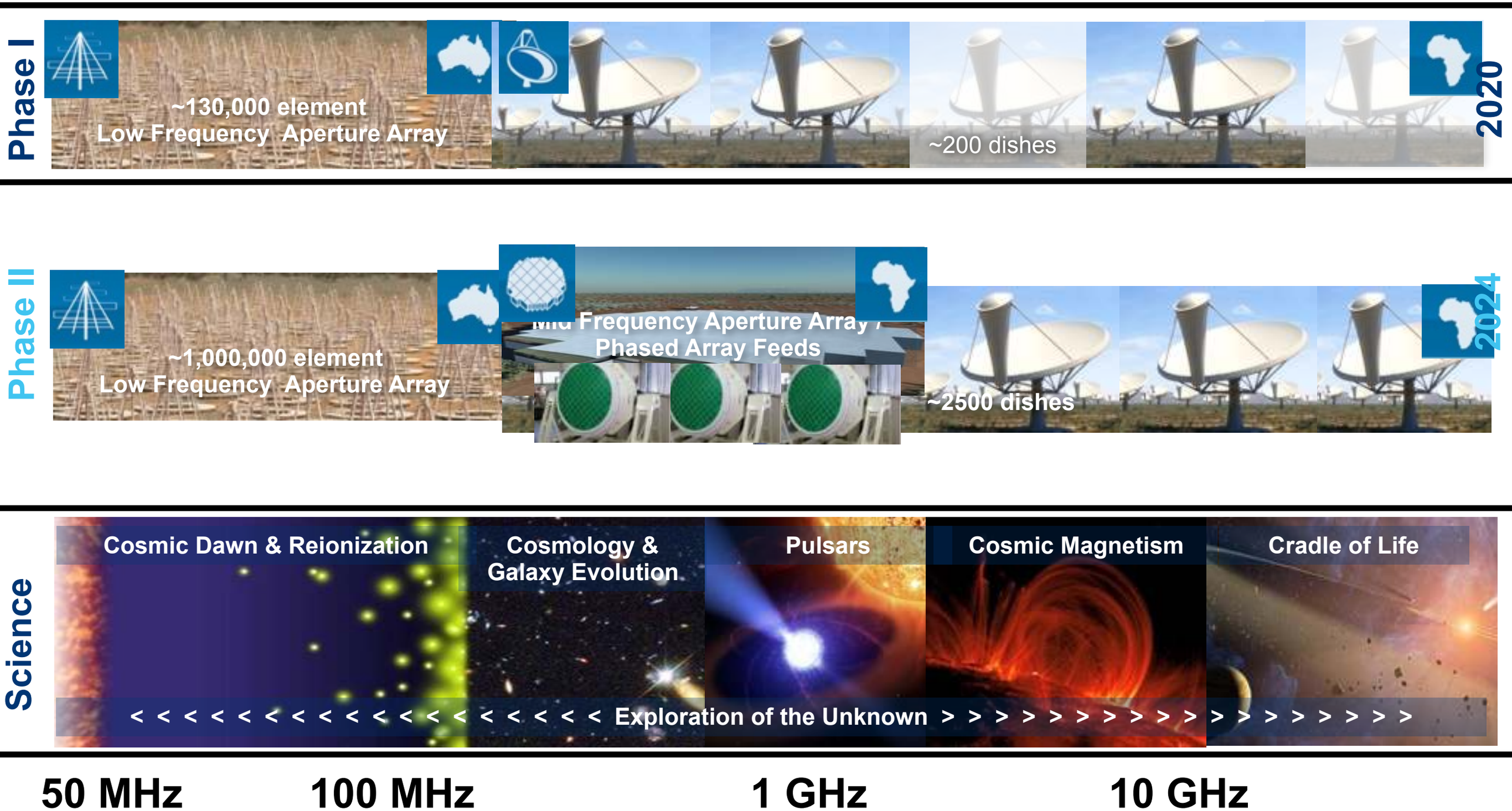
ELECTROMAGNETIC SPECTRUM
SHOWING THE RADIO FREQUENCY SPECTRUM



VLF Very Low Frequency
LF Low Frequency
MF Medium Frequency
HF High Frequency

VHF Very High Frequency
UHF Ultra High Frequency
SHF Super High Frequency
EHF Extremely High Frequency

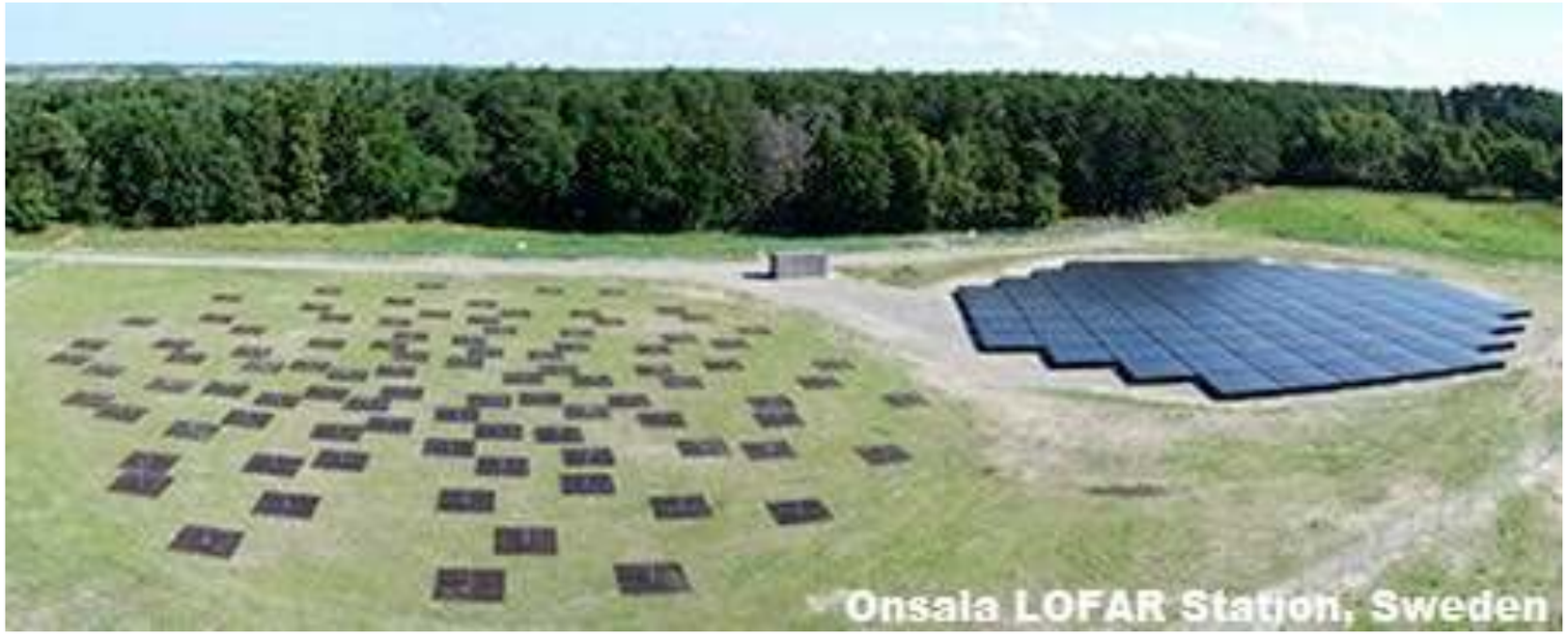
What is the SKA?




SMA
VLBA
JVLA
eMERLIN
EVN / eEVN
WSRT/Apertif
LOFAR
IRAM
KVN
GMRT
MeerKat
SKA1-MID
ALMA
ASKAP, MWA
SKA1-LOW

SKA Pathfinders - Northern hemisphere

Jansky Very Large Array
(JVLA, USA)



Low Frequency Array (LOFAR, Europe)

SKA Pathfinders - Southern hemisphere

MeerKAT (South Africa)

GMRT (India)

ASKAP (Australia)

MWA (Australia)

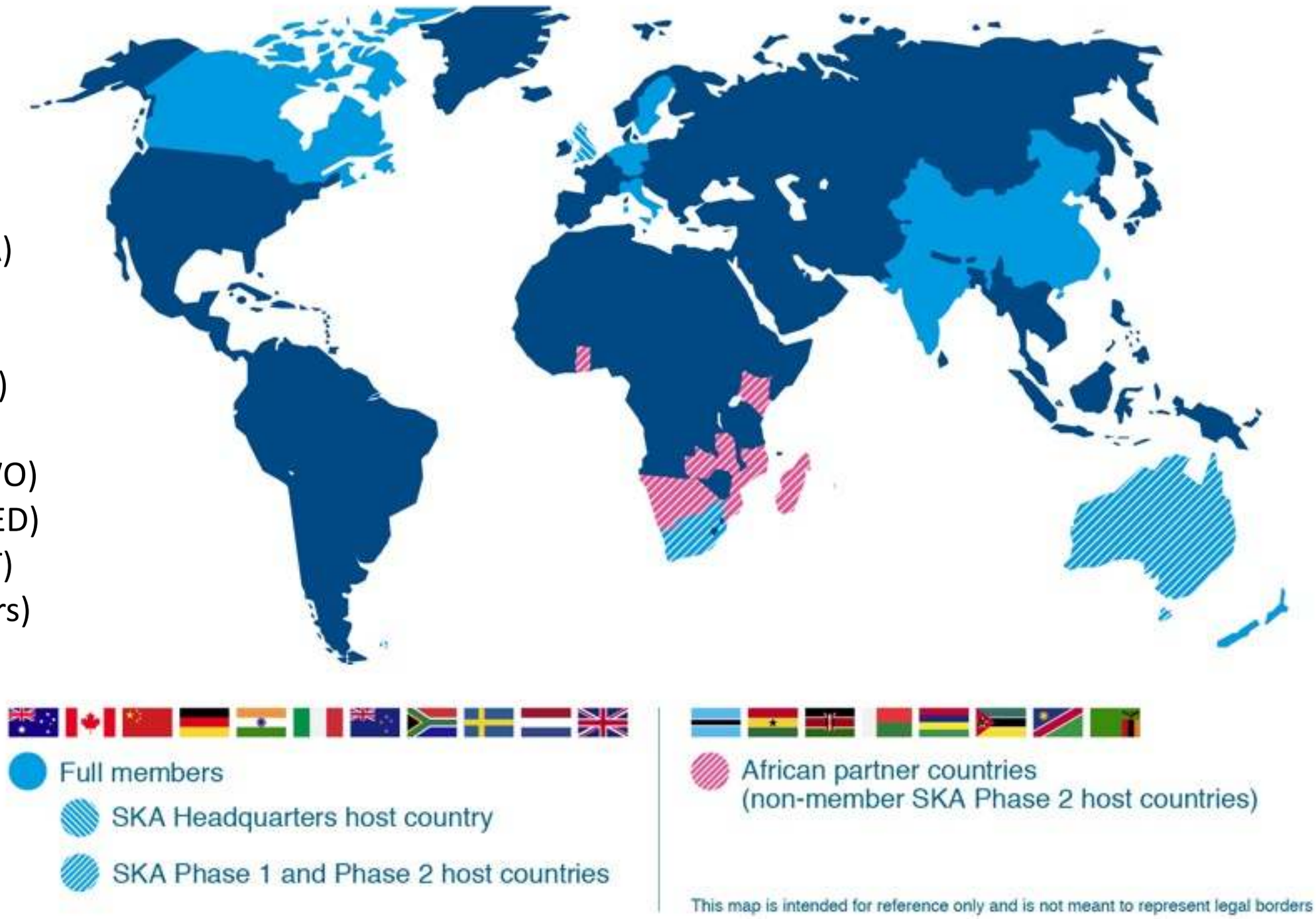
The SKA challenge

- Revolutionise our understanding of the universe
- >4x angular resolution (JVLA)
- >10x sensitive
- > 100x survey speed
- Lifespan >= 50 yr; upgradable
- Use new receiver technology, signal transport and processing techniques, and computer power on unprecedented scales.

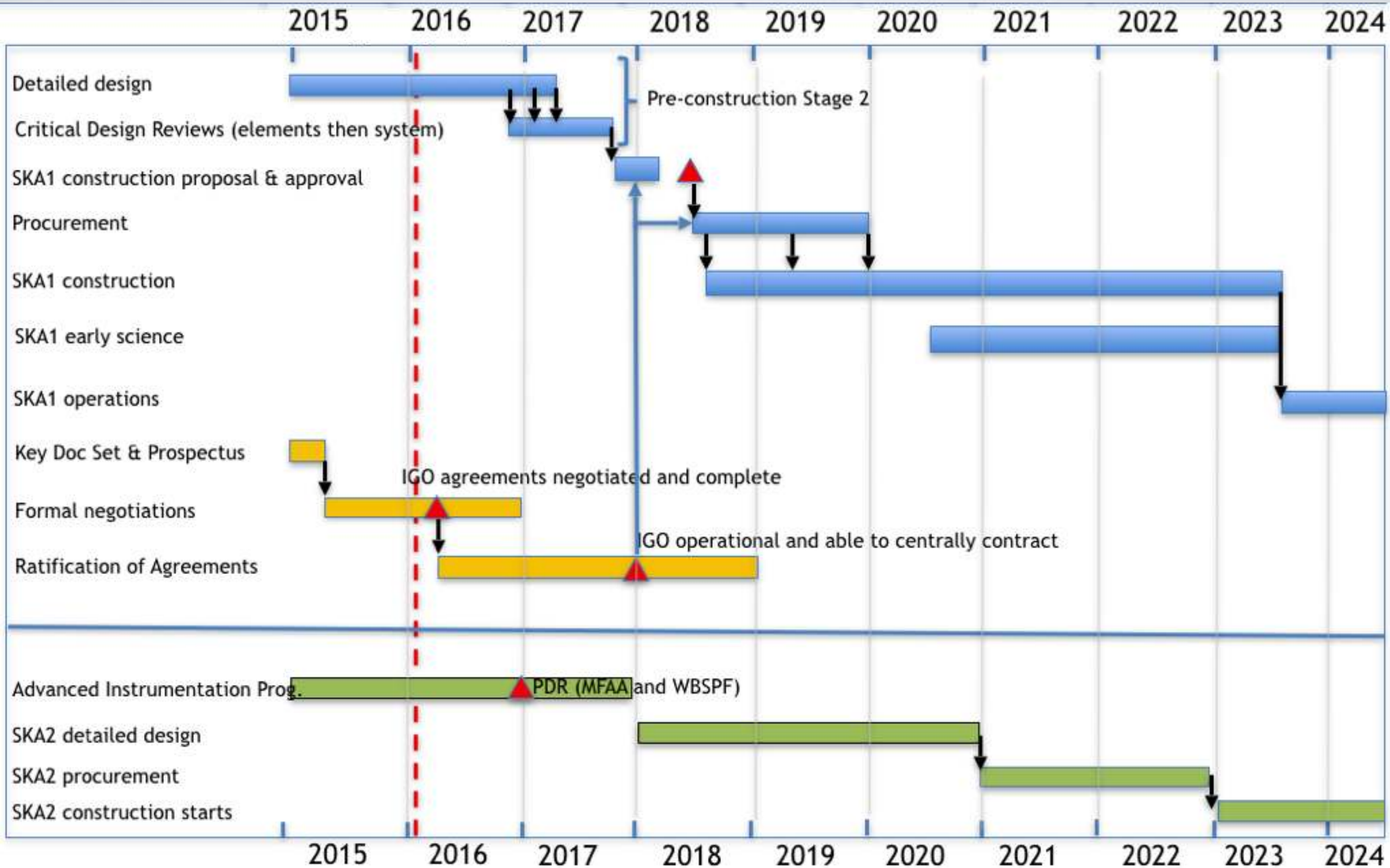
SKA Organisation

Australia (DoI&S)
Canada (NRC-HIA)
China (MOST)

India (NCRA/DAE)
Italy (INAF)
Netherlands (NWO)
New Zealand (MED)
South Africa (DST)
Sweden (Chalmers)
UK (STFC)



SKA SCHEDULE



SKA Science

- SKA: one of the great physics machine of the 21st century
- Science goals:
  - Fundamental Physics: Gravity, DE, Magnetism
  - Astrophysics: Cosmic Dawn, First galaxies, galaxy assembly and evolution; protoplanetary disks, biomolecules, SETI+...
  - The unknown: transients; +...???

SKA1 Scope (March 2015)

- SKA1-MID
  - 70% of planned SKA1 dishes (133x15 m)
  - Integration of MeerKAT (64x13.5 m)
  - Deployment of Freq. bands 2, 5 and 1.
  - B_max ~ 150 km
- SKA1-LOW
  - 131000 antennas (50% of total planned)
  - Freqs: 50-350 MHz; B_max ~ 65 km
  - Pulsar search
- Negotiate ASKAP integration into SKAO

SKA1-MID, Karoo, South Africa:

133 SKA1+64 MeerKAT dishes. B_max ~150 km

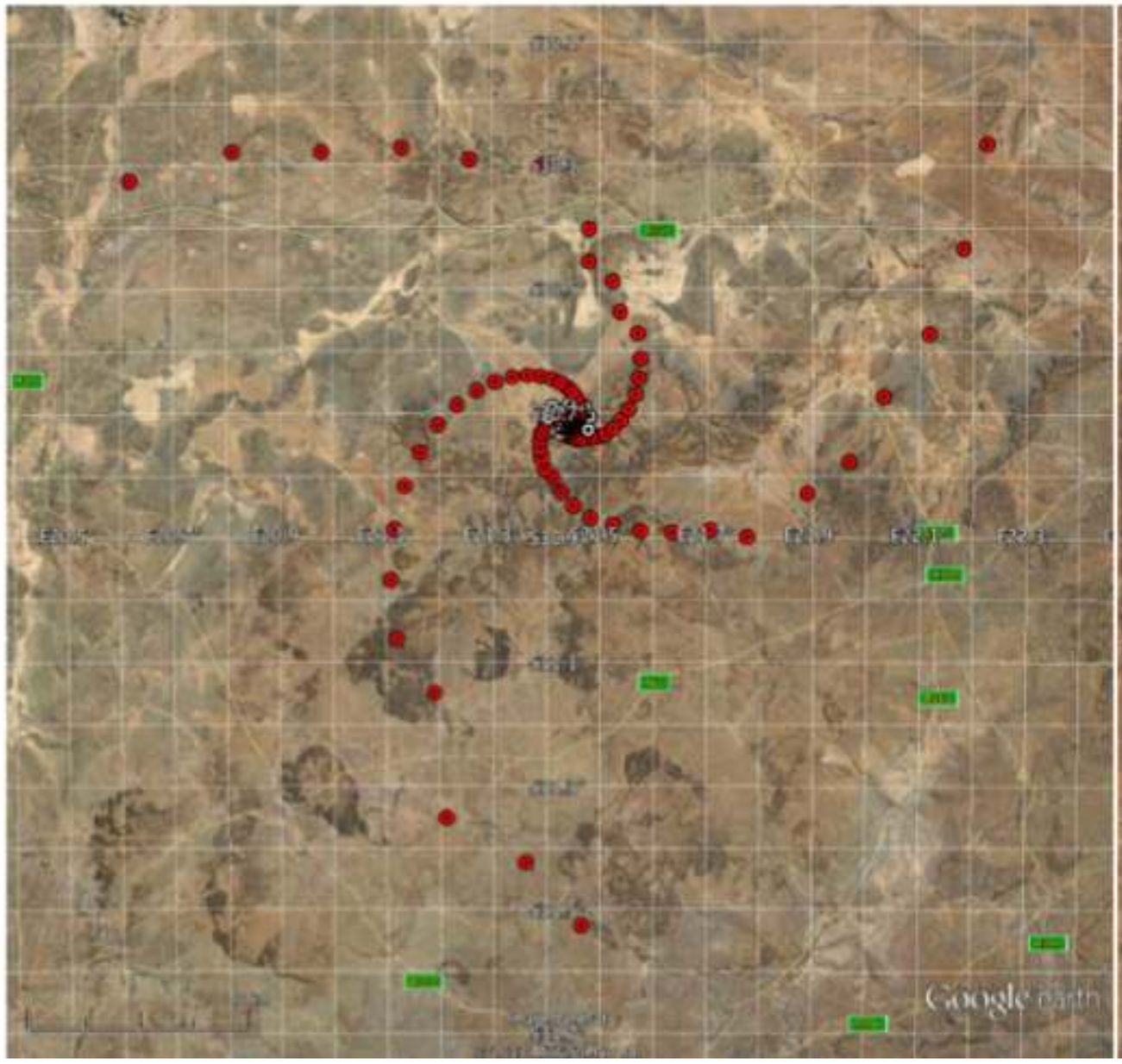
Bands: 1(0.35 - 1.05 GHz), 2(0.95 - 1.76 GHz), 5(4.6 - 13.8 GHz)

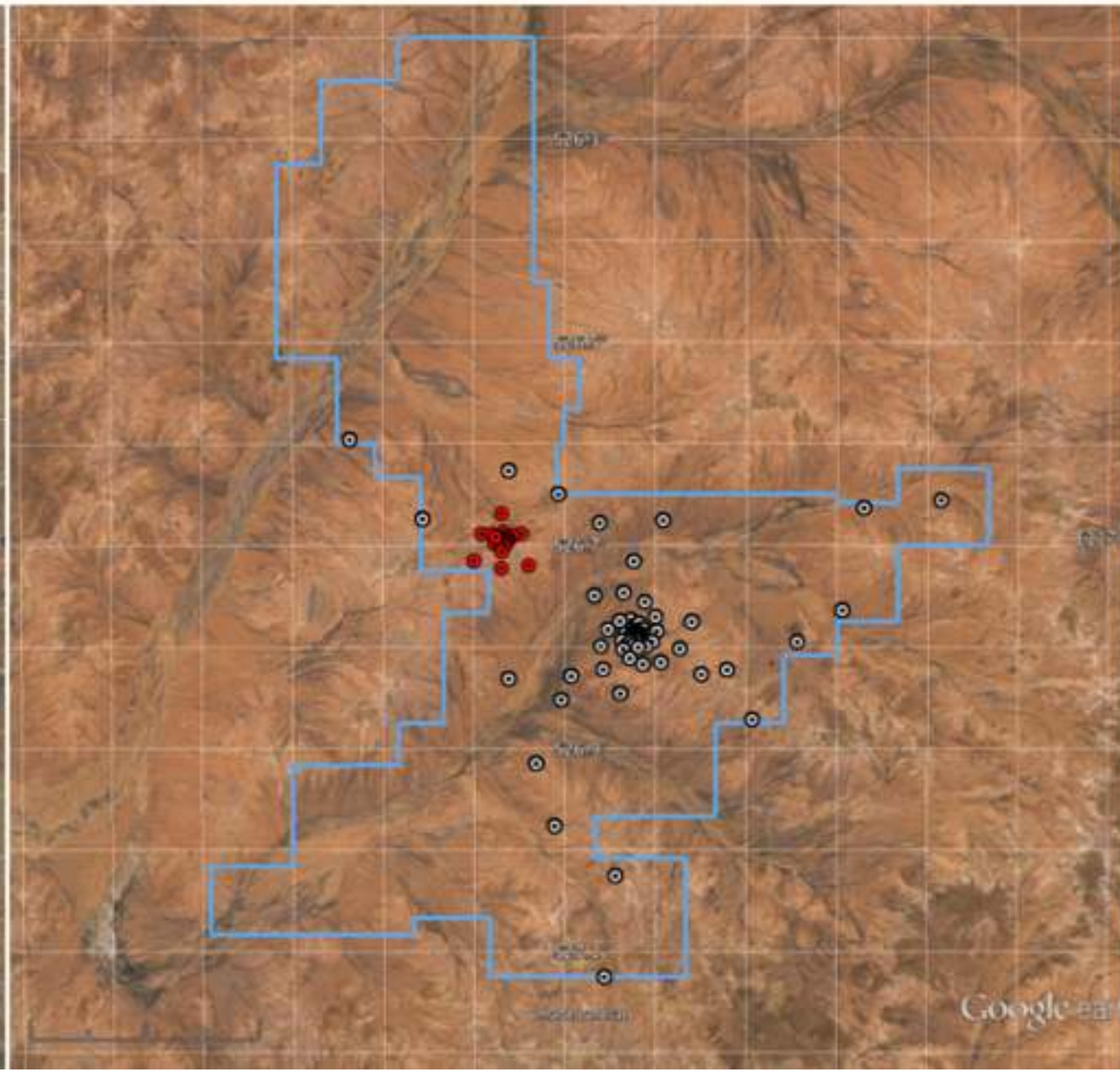
SKA1-LOW, Murchison, Australia:

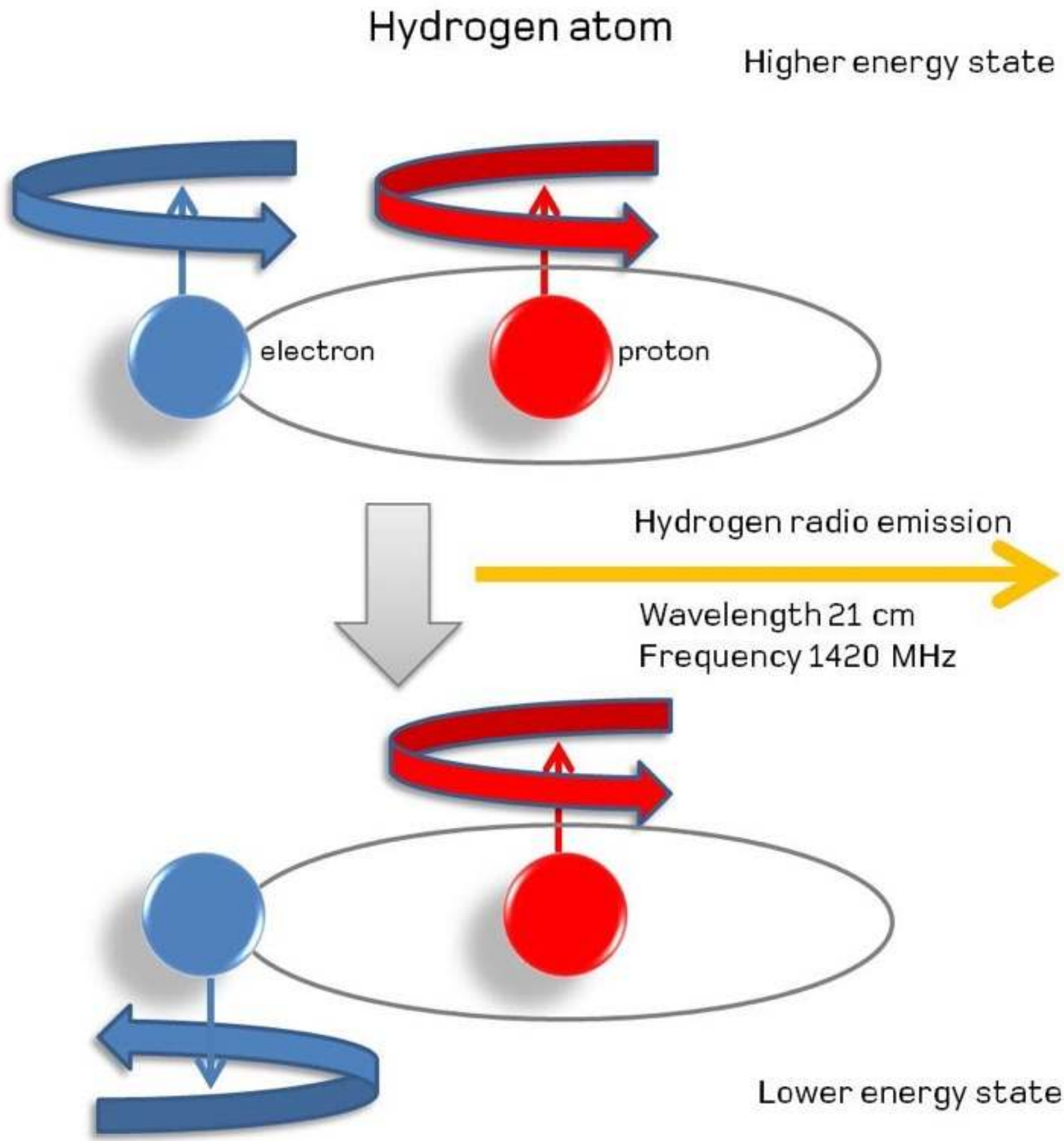
130000 dipoles (512 stations x 256 antennas/st), 50-350 MHz

B_max ~ 65 km; large concentration in the core

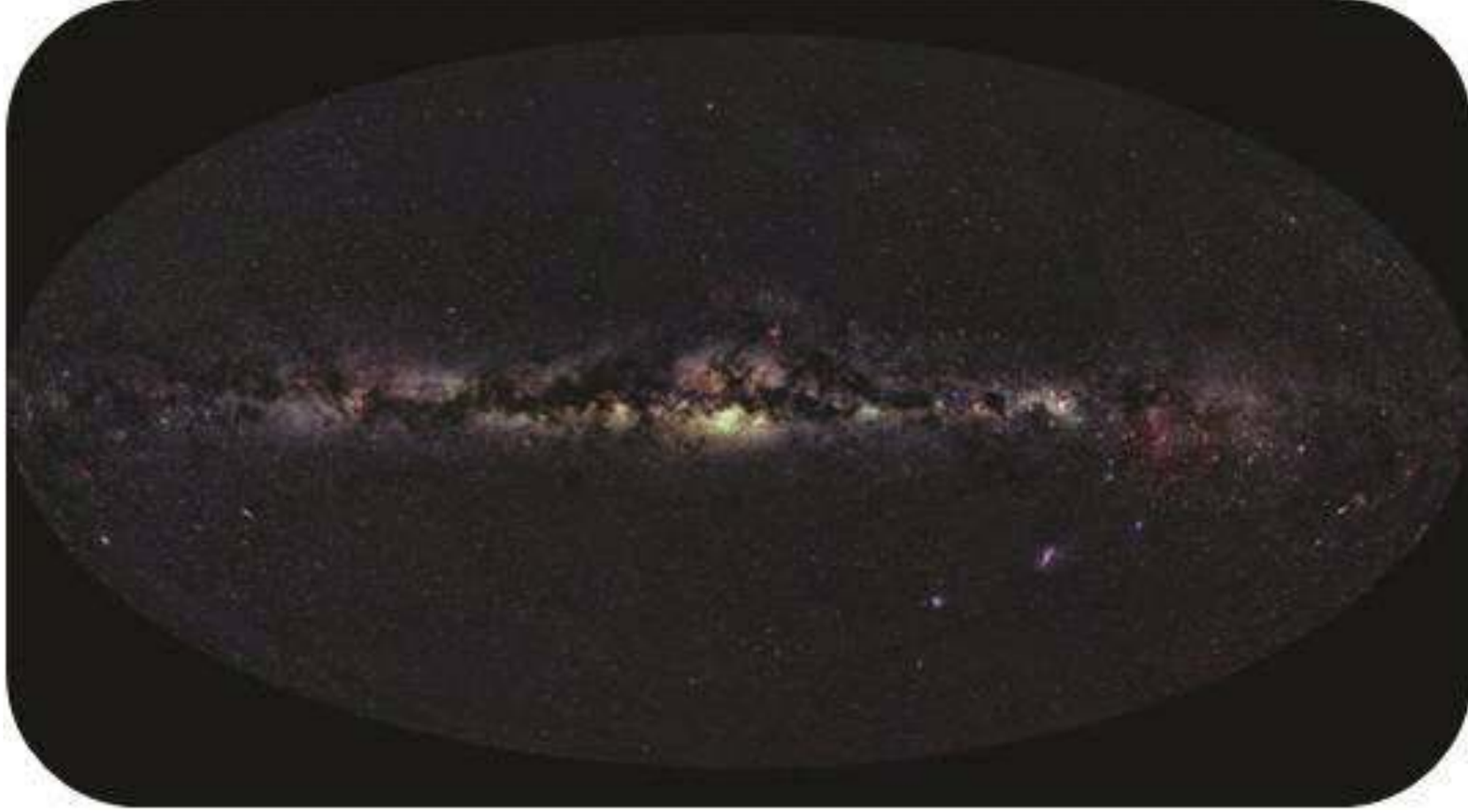
SKA1 Configurations



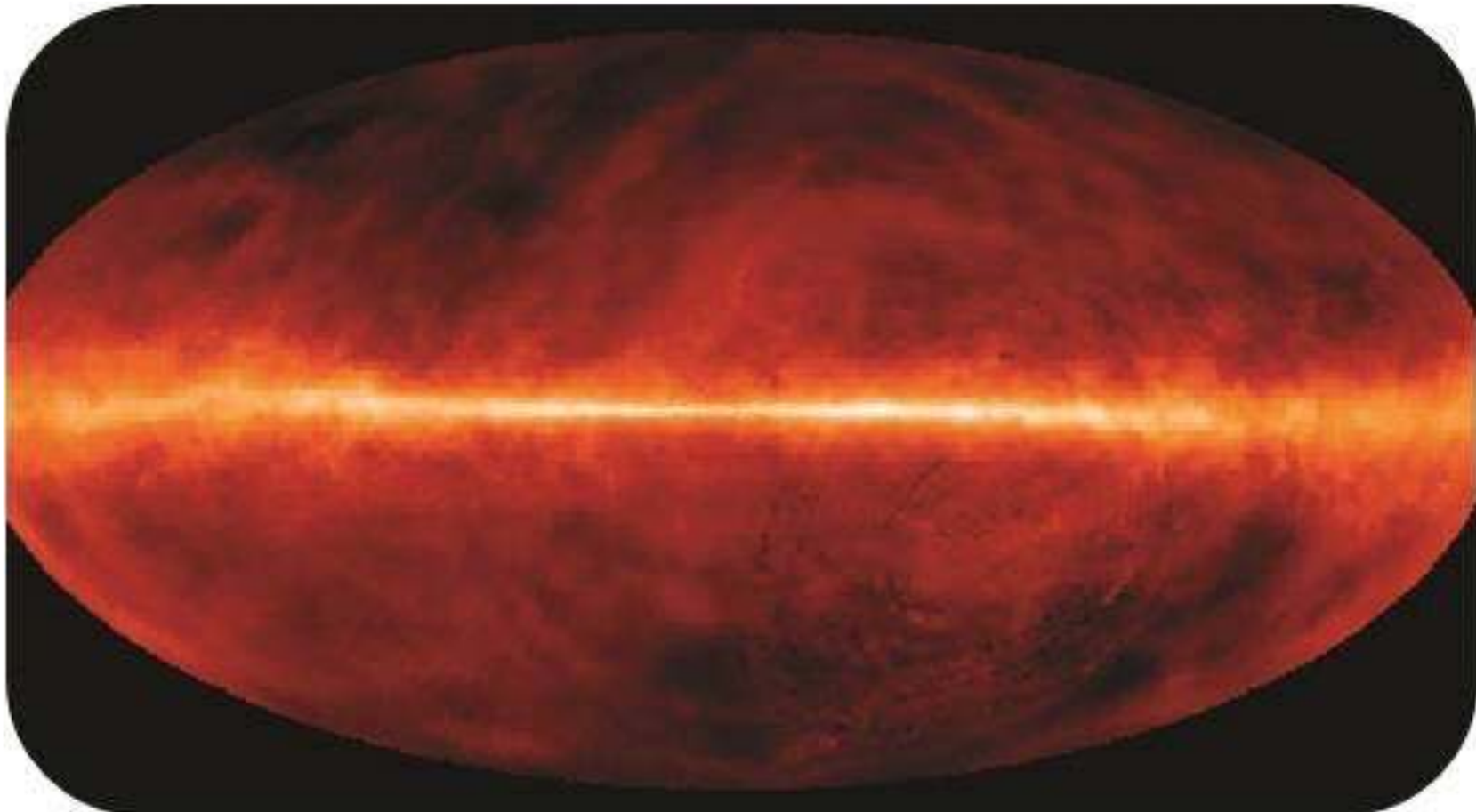



Hydrogen atom
Higher energy state
electron
proton
Hydrogen radio emission
Wavelength 21 cm
Frequency 1420 MHz
Lower energy state

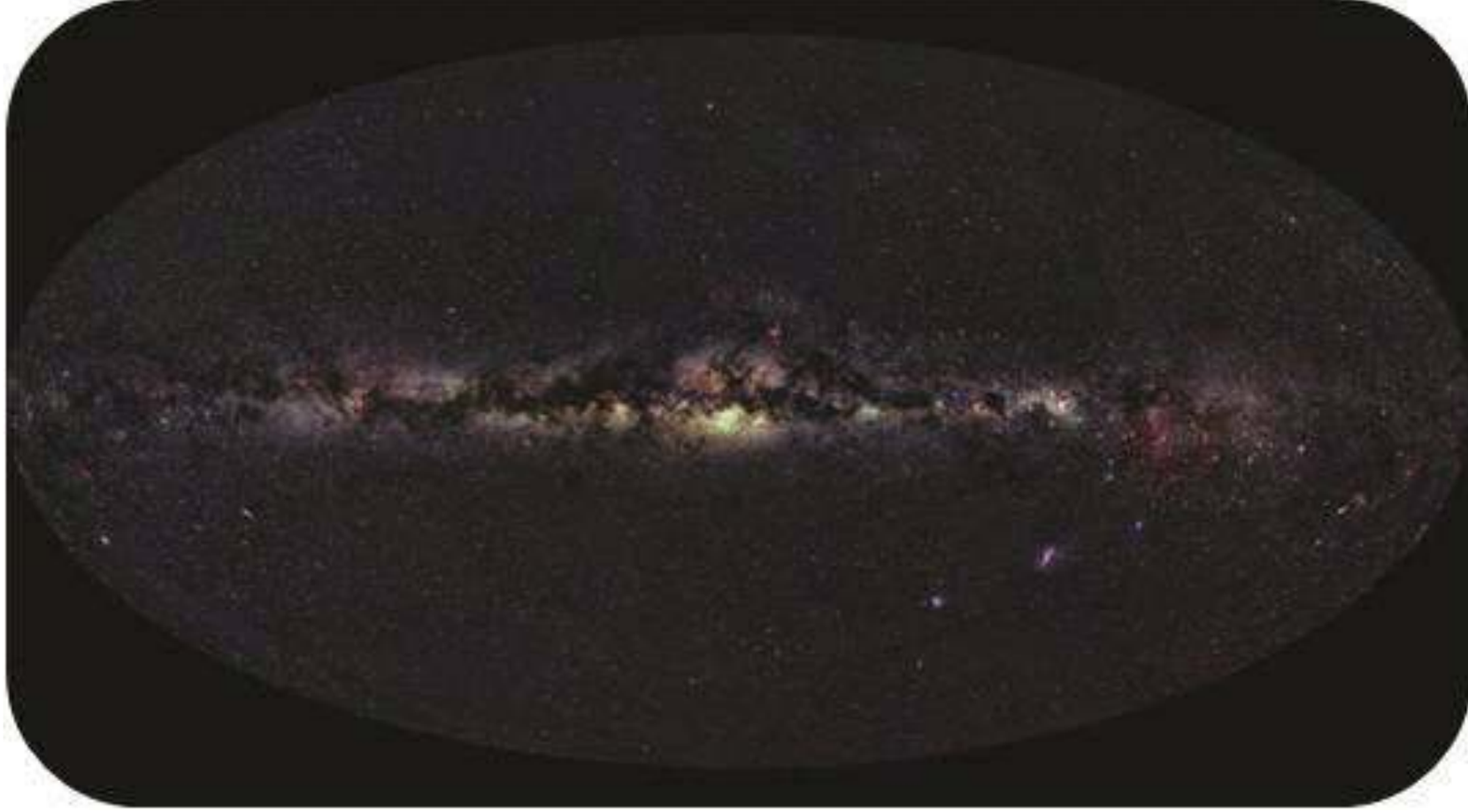
Sky in the optical



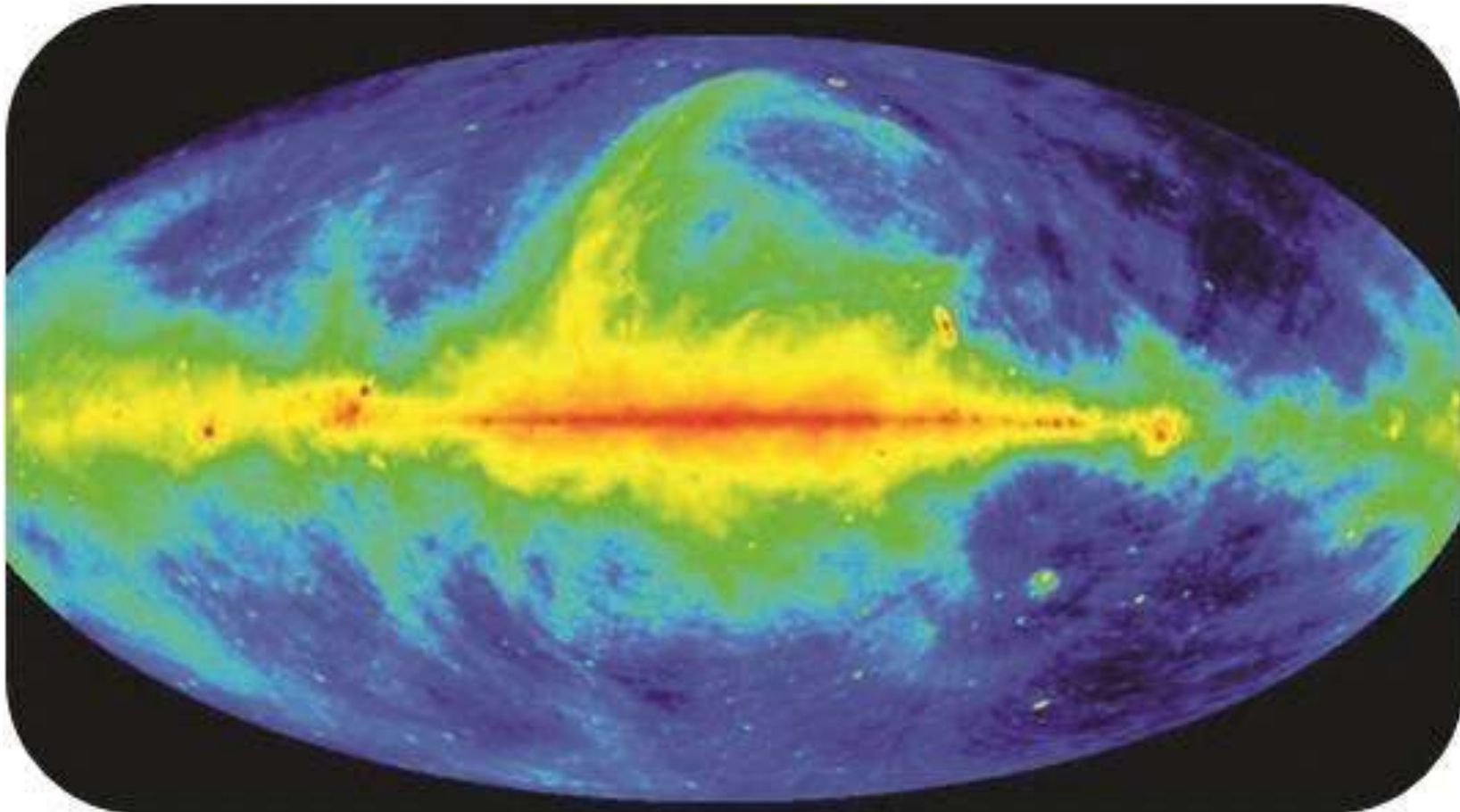
Sky in H I



Sky in the optical



Sky at 408 MHz
(~70 cm)



Does size matter?
Angular resolution

Human eye
1 arcmin

2 m optical
telescope (ground)
0.5 arcsec

HST
0.05 arcsec


1 arcmin

Angular resolution
(Human eye vs. telescope)

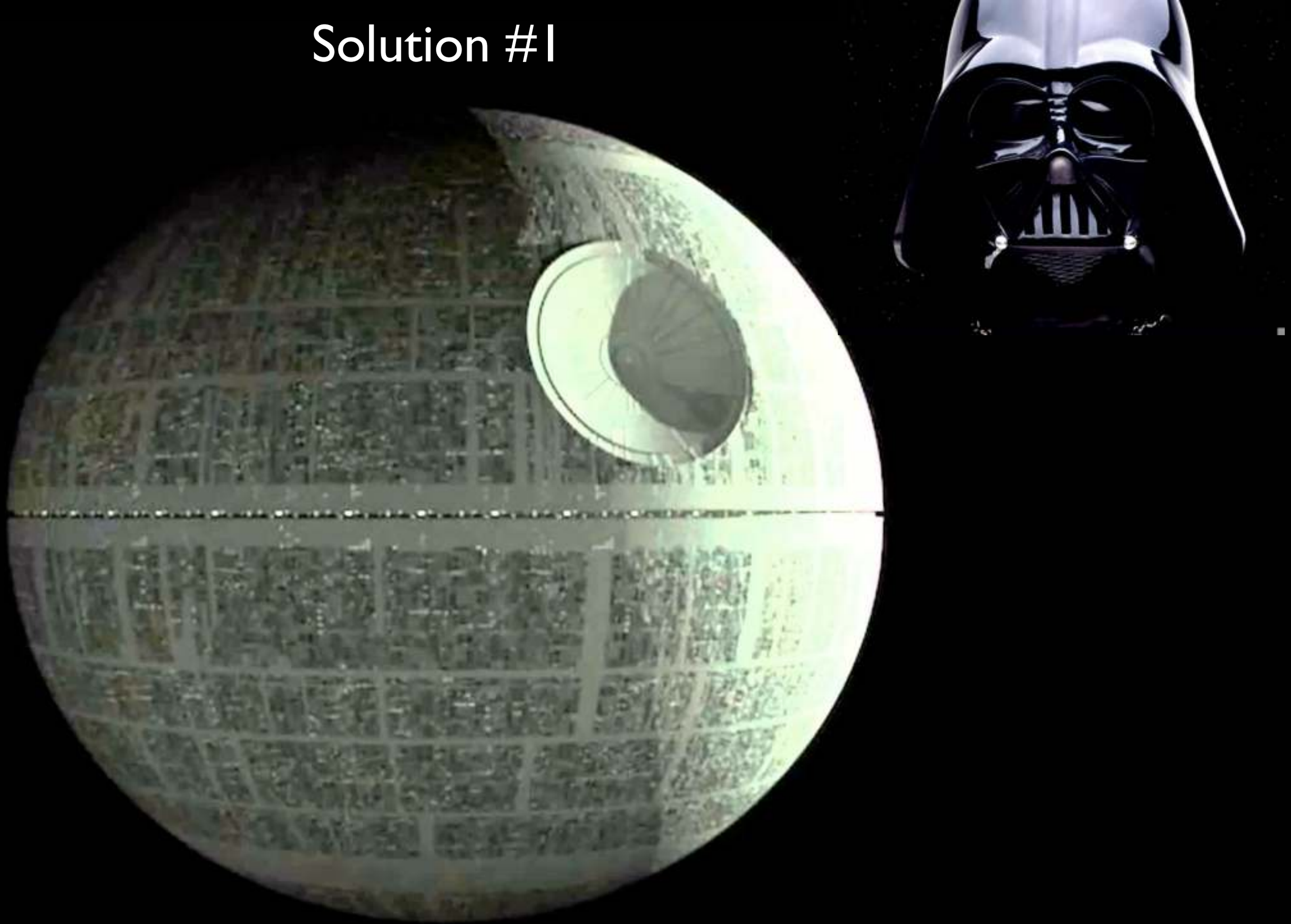
versus

Eye: 2mm
Wavelength = 580 nm
Angular resolution = 1 arcmin

Yebes radio telescope: 40 m
Wavelength = 1 cm
Angular resolution = 1 arcmin

So what do we do?

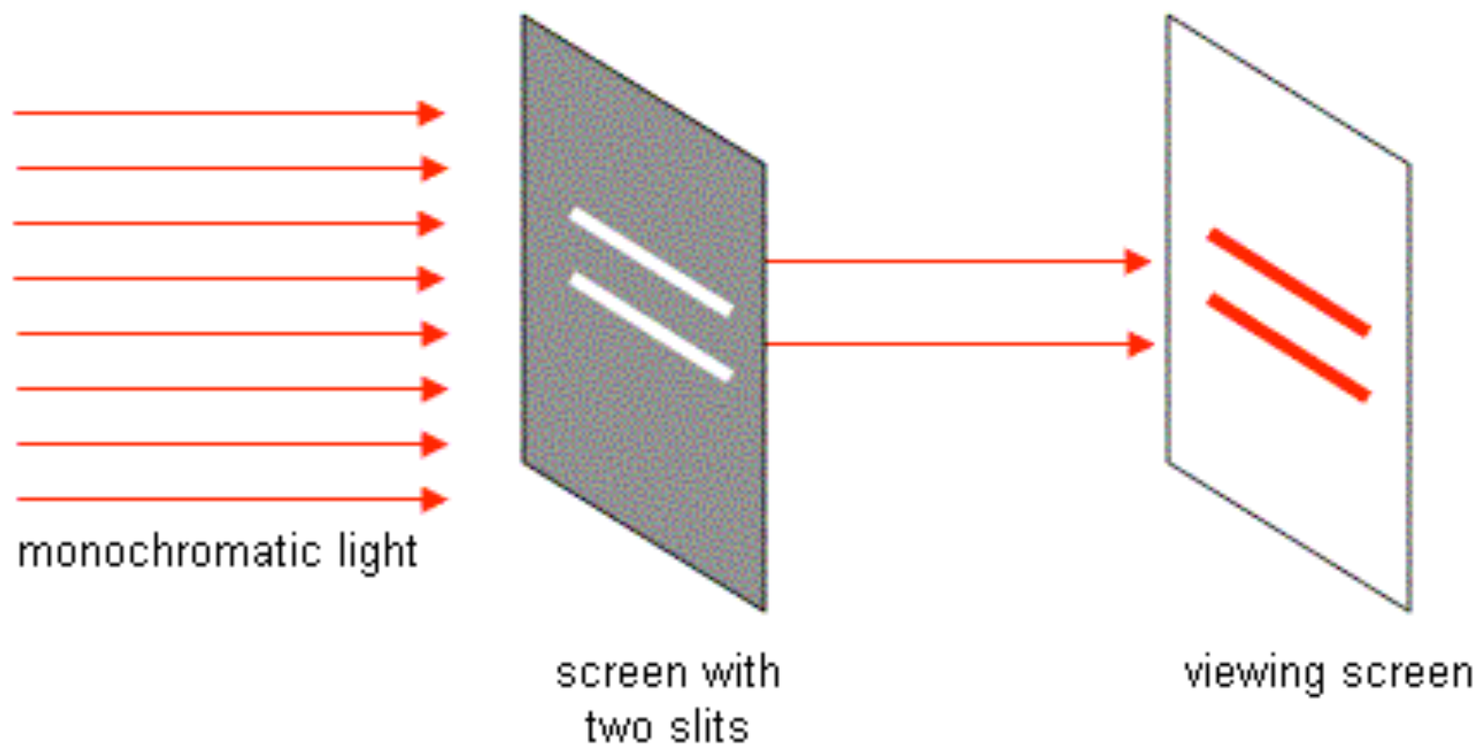
Solution #1

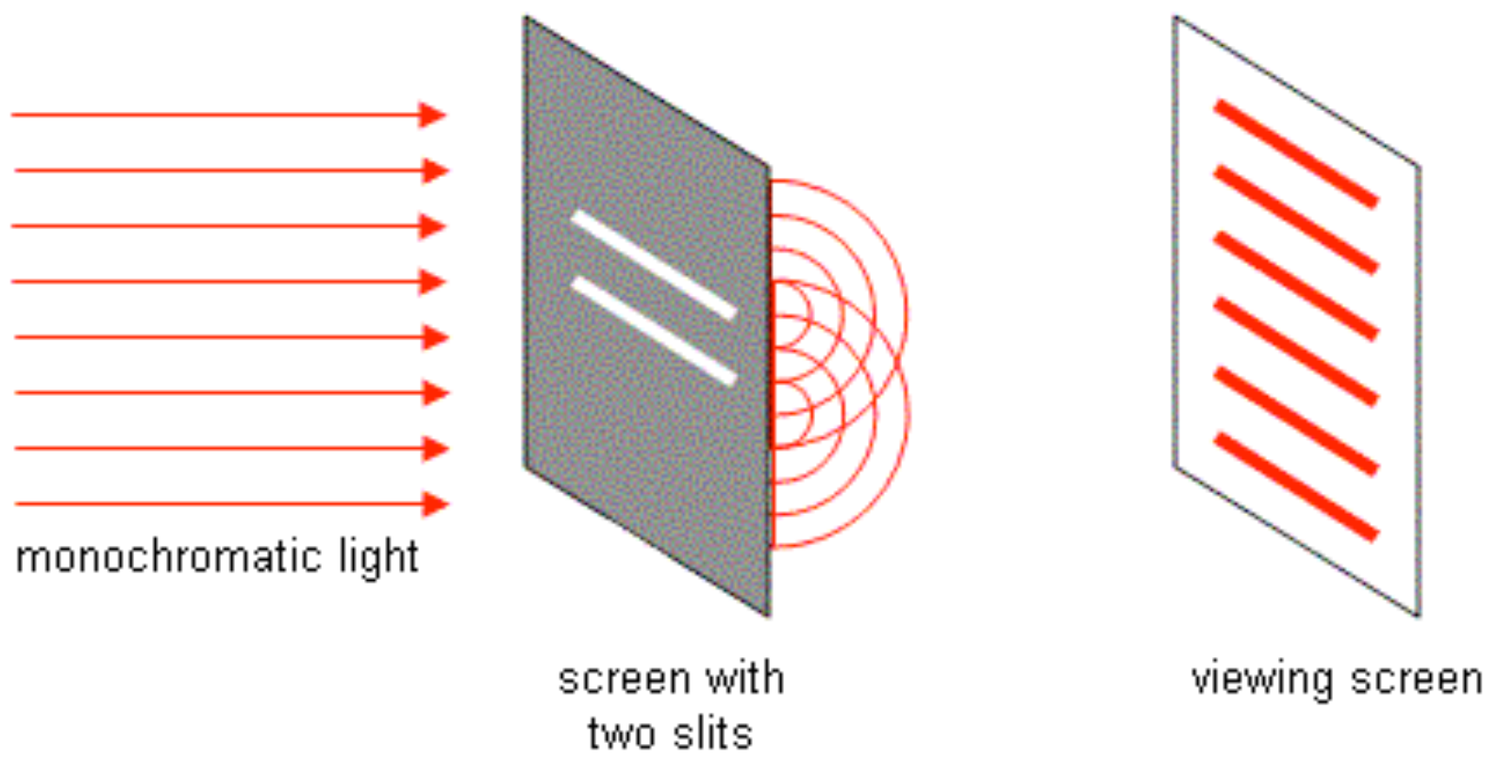


Solution #2

Radio interferometry

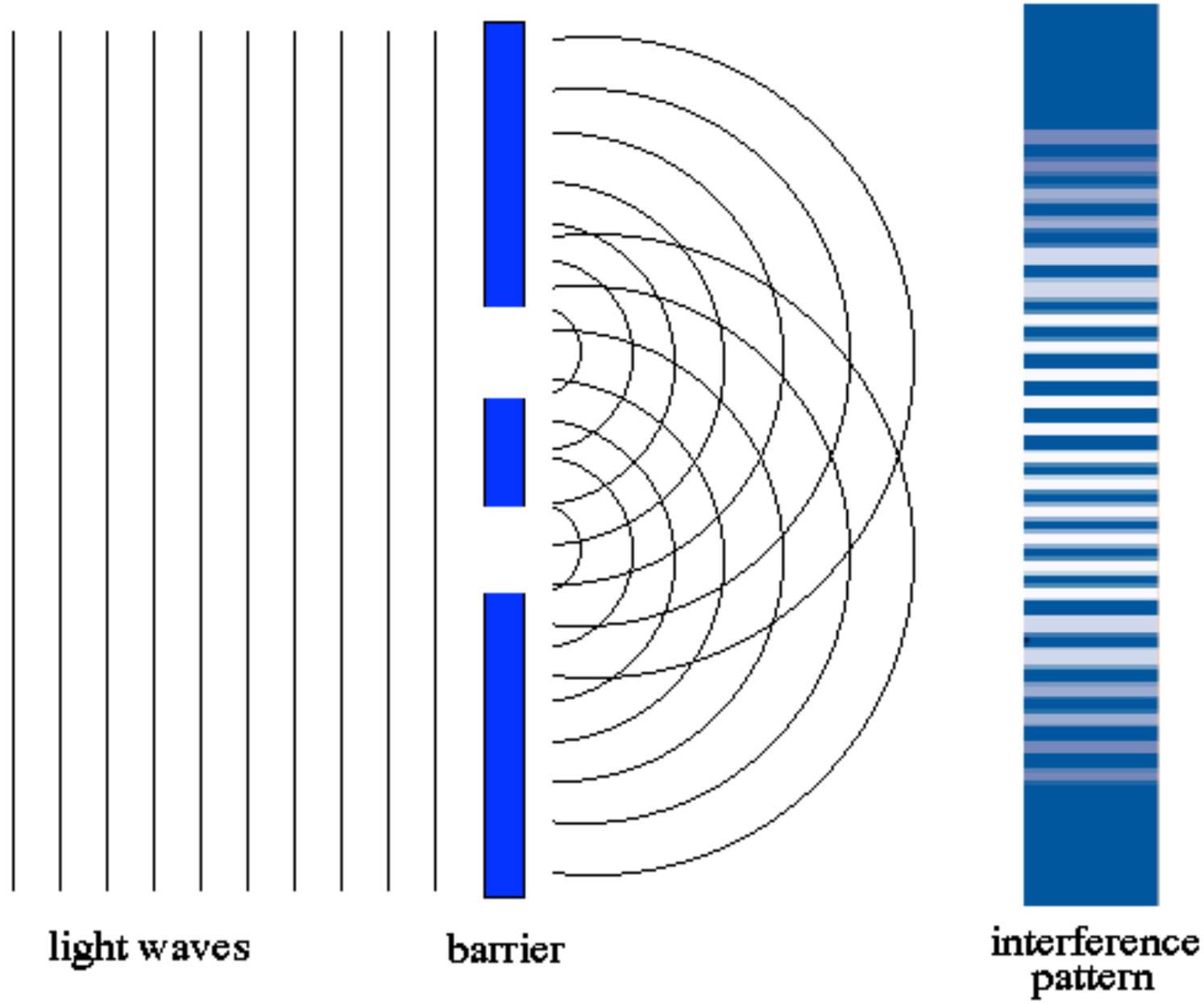
Double slit experiment



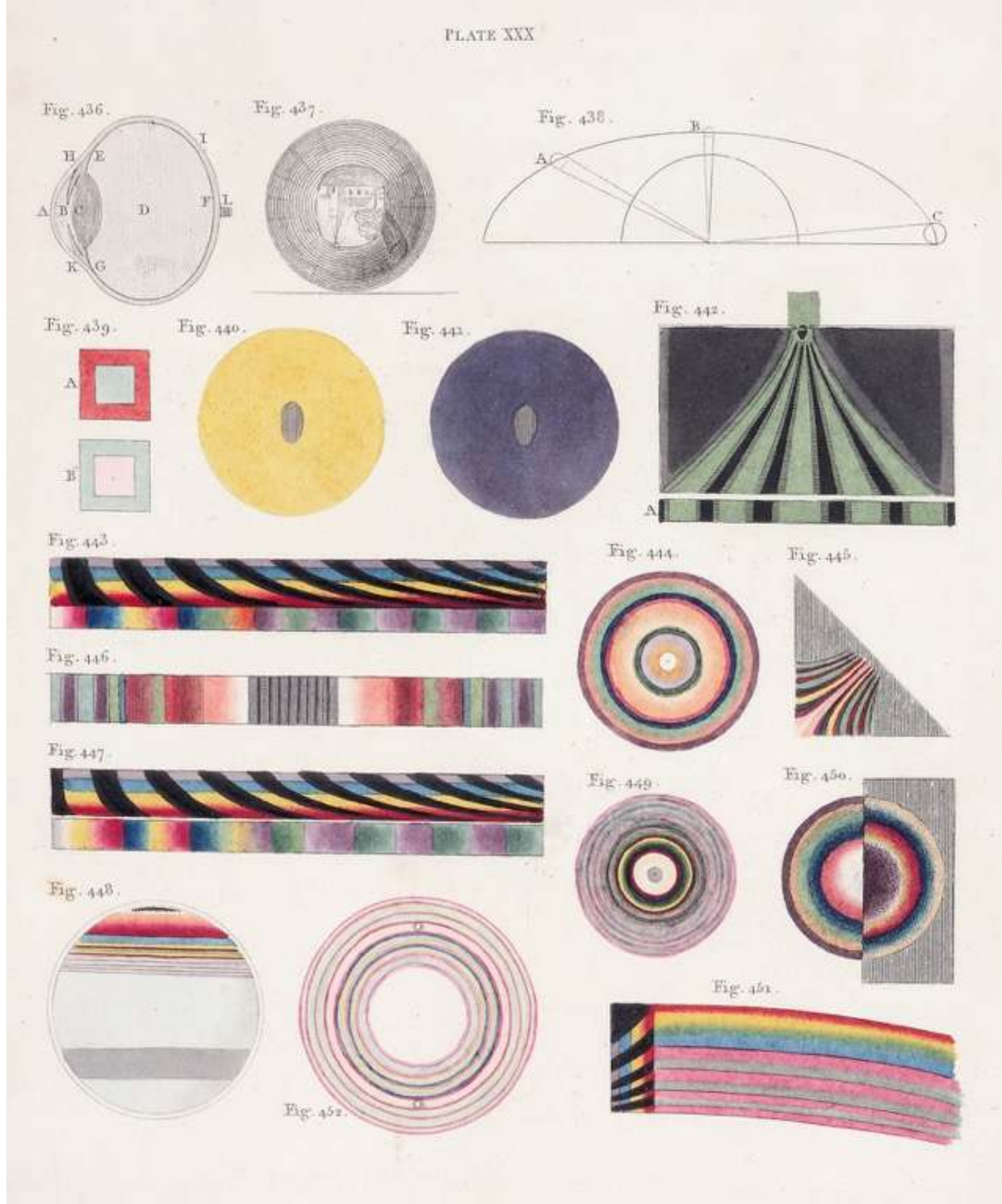


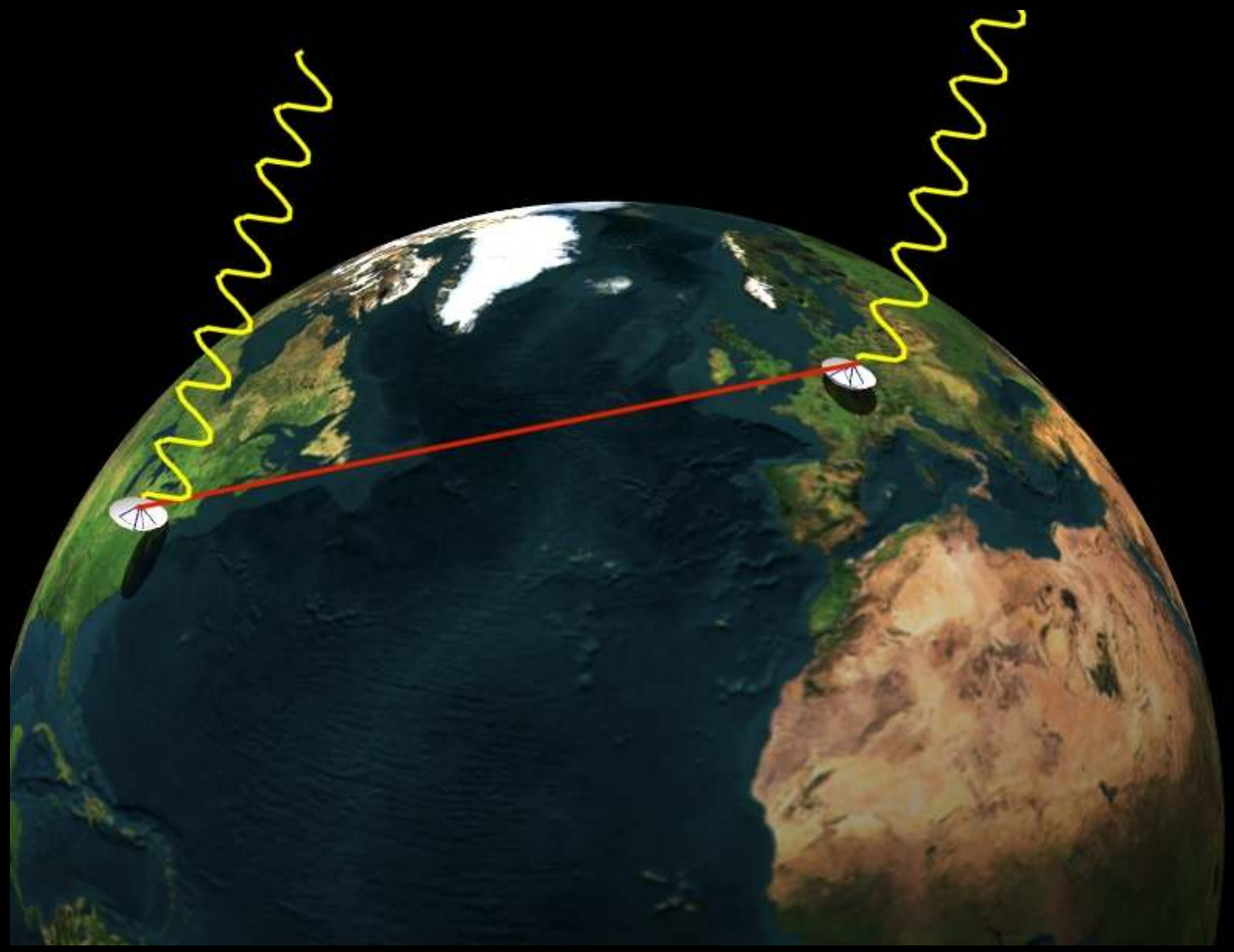
Interference

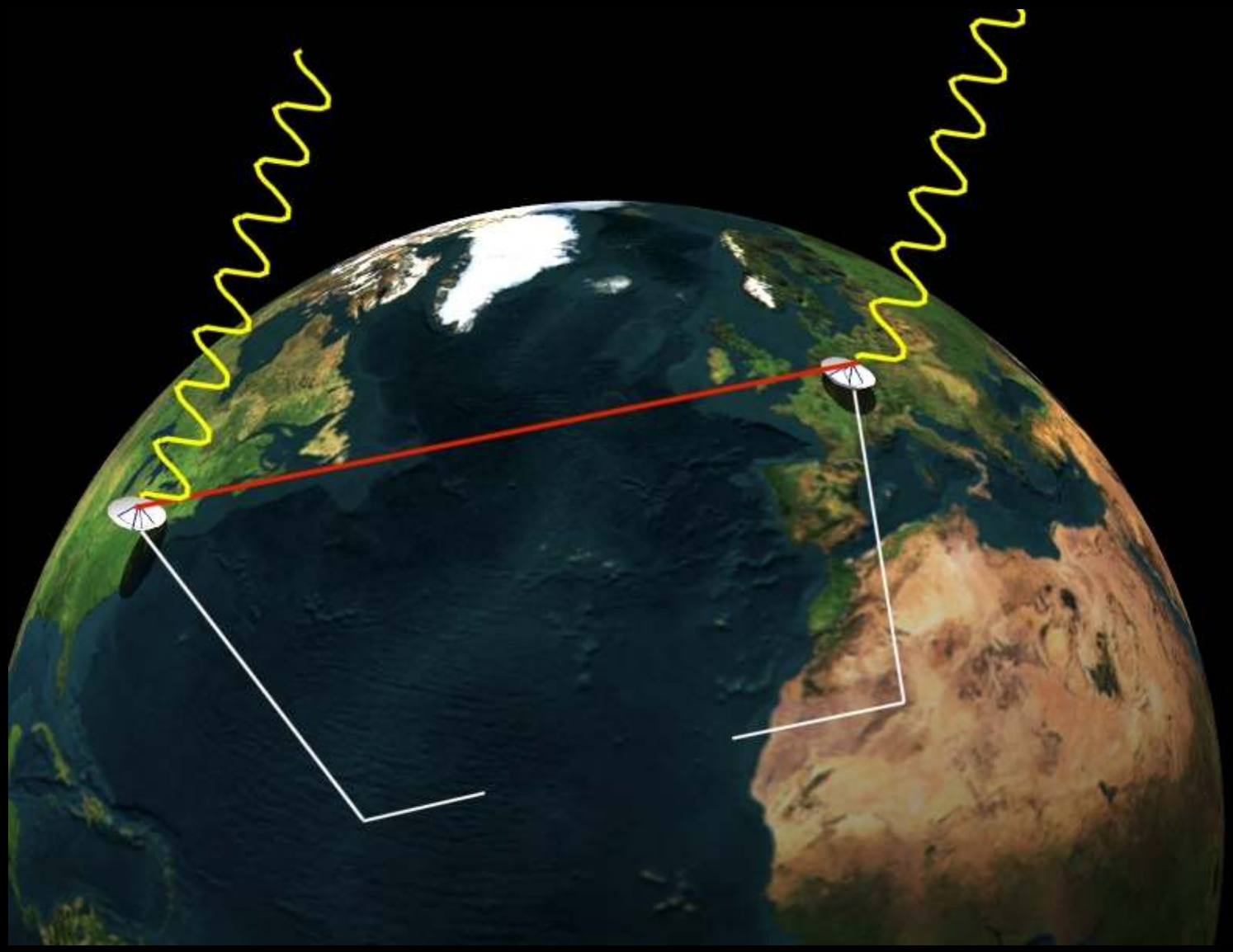
Thomas Young

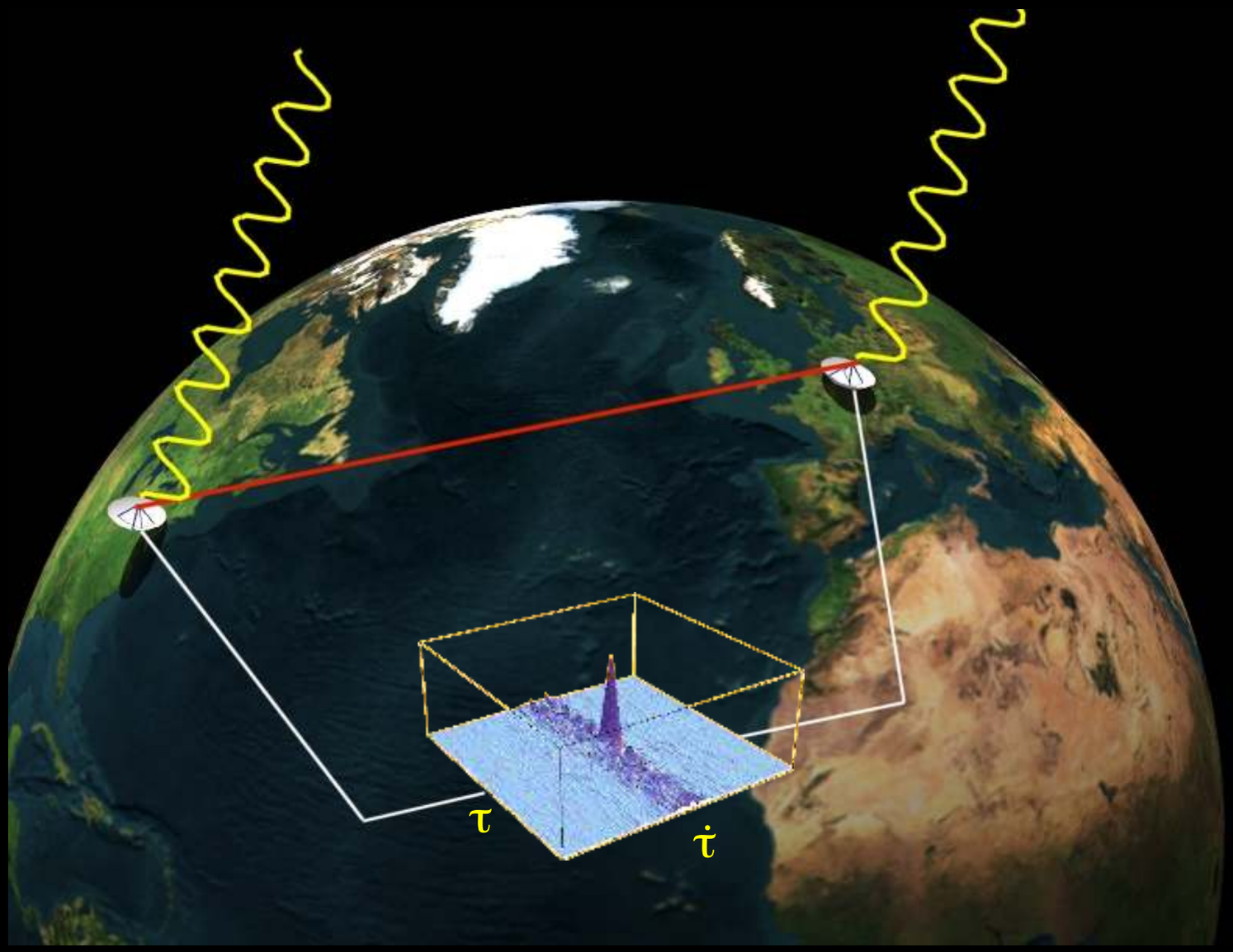


A Course of Lectures on Natural Philosophy and the Mechanical Arts.

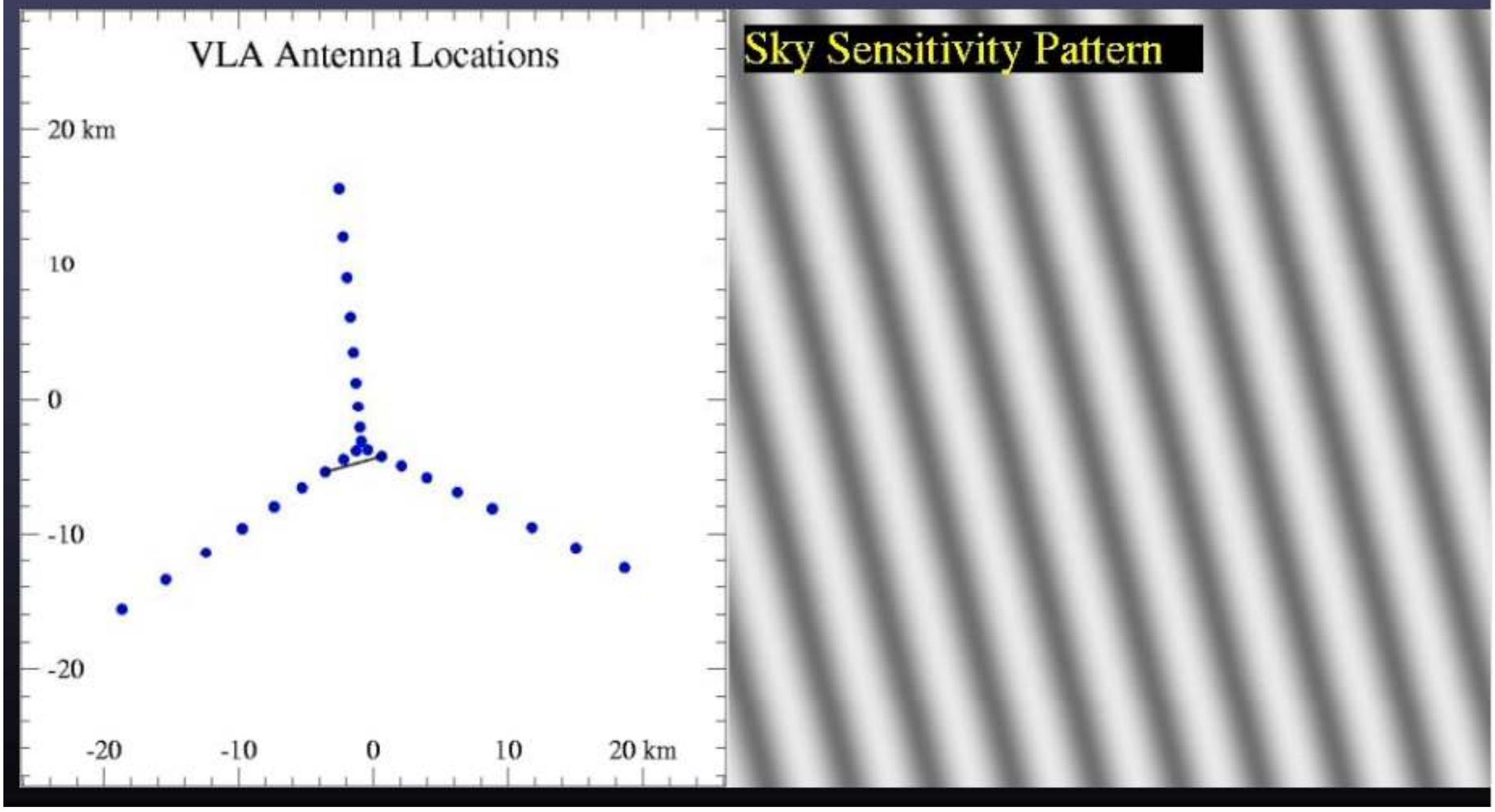




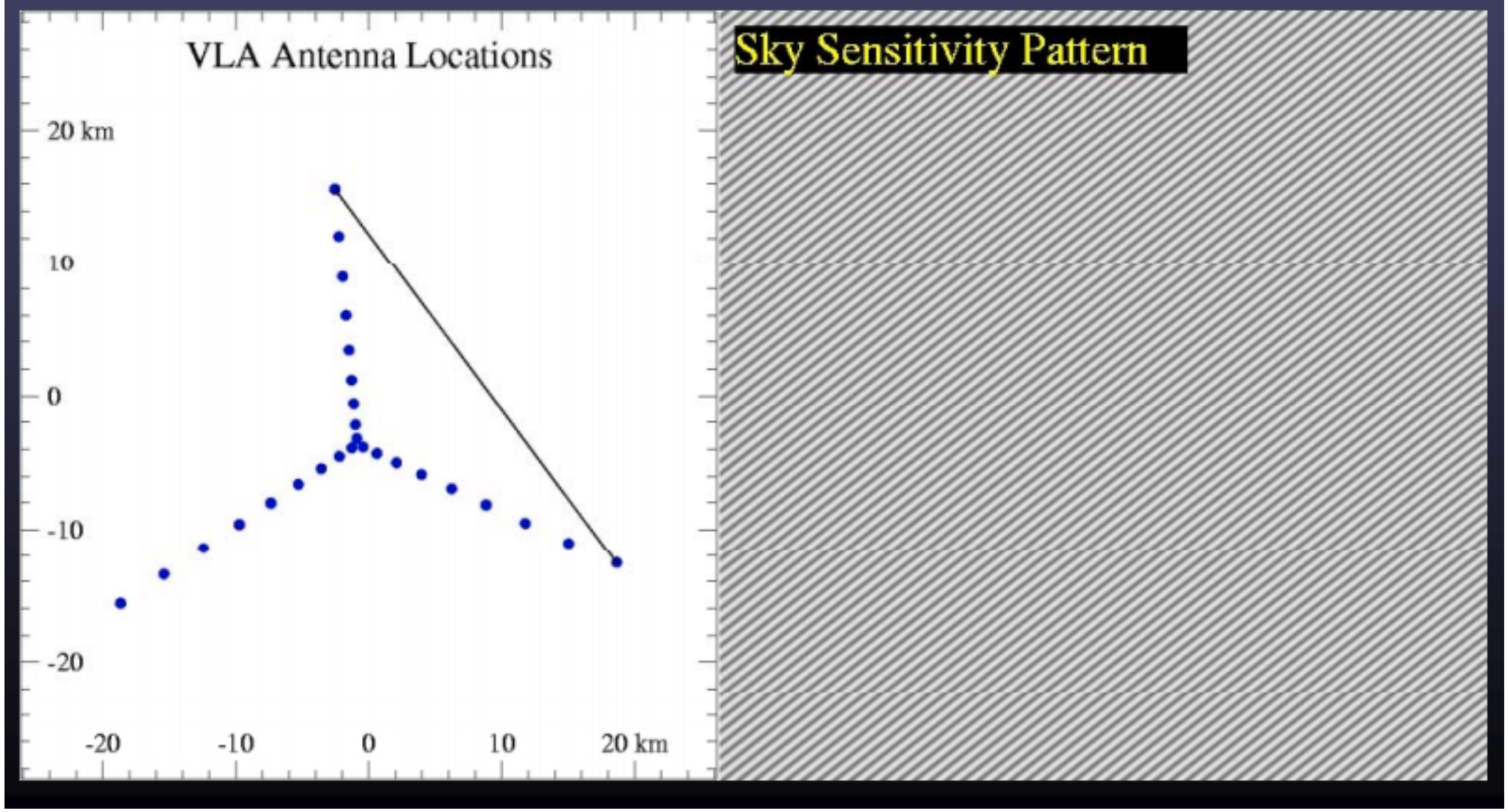


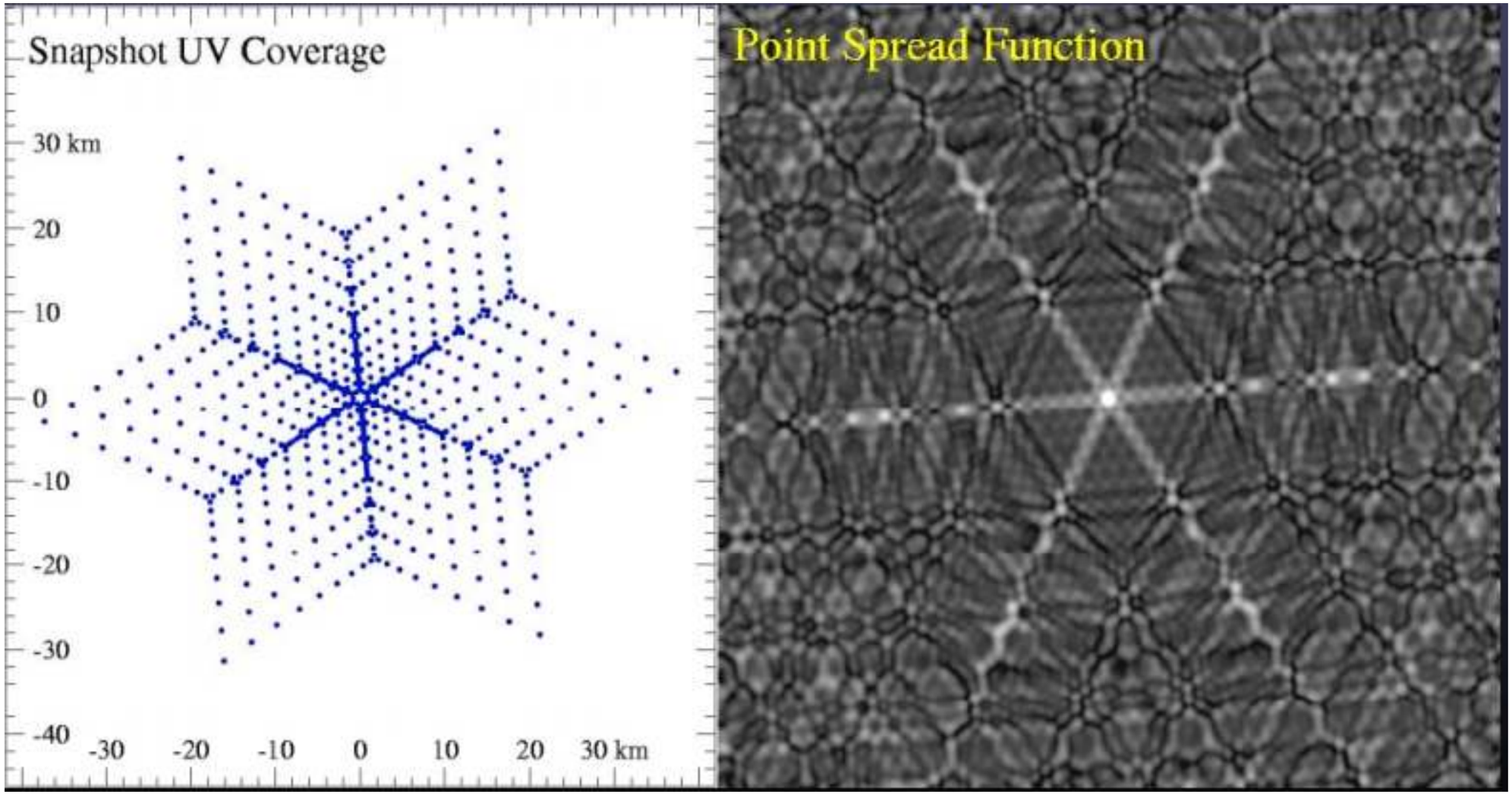

τ
τ̇

A single baseline has a sinusoidal sensitivity pattern across the sky, oscillating between constructive and destructive interference.

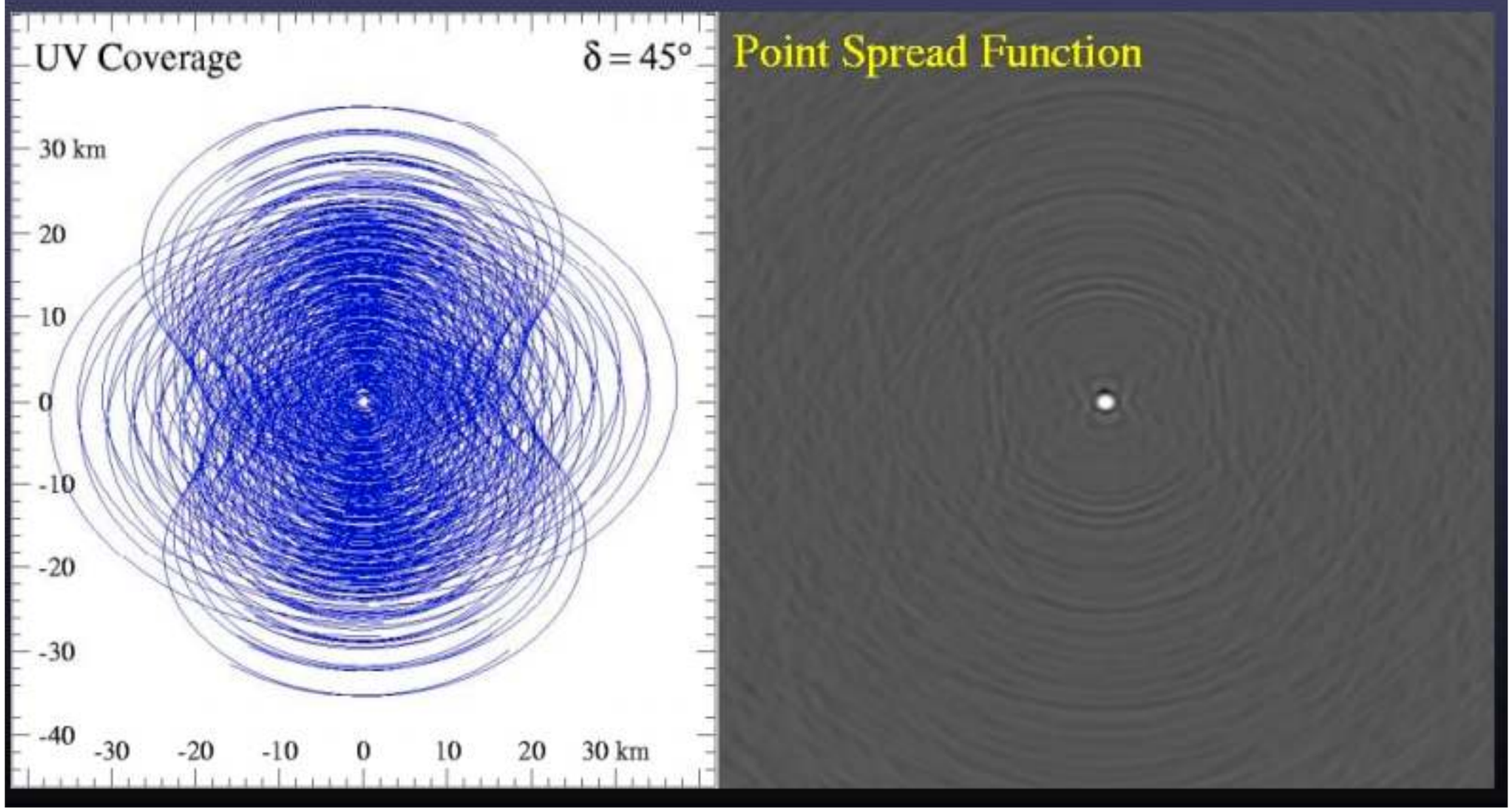


The oscillations in the sensitivity pattern have the same direction as the baseline, with a period determined by the baseline length in wavelengths

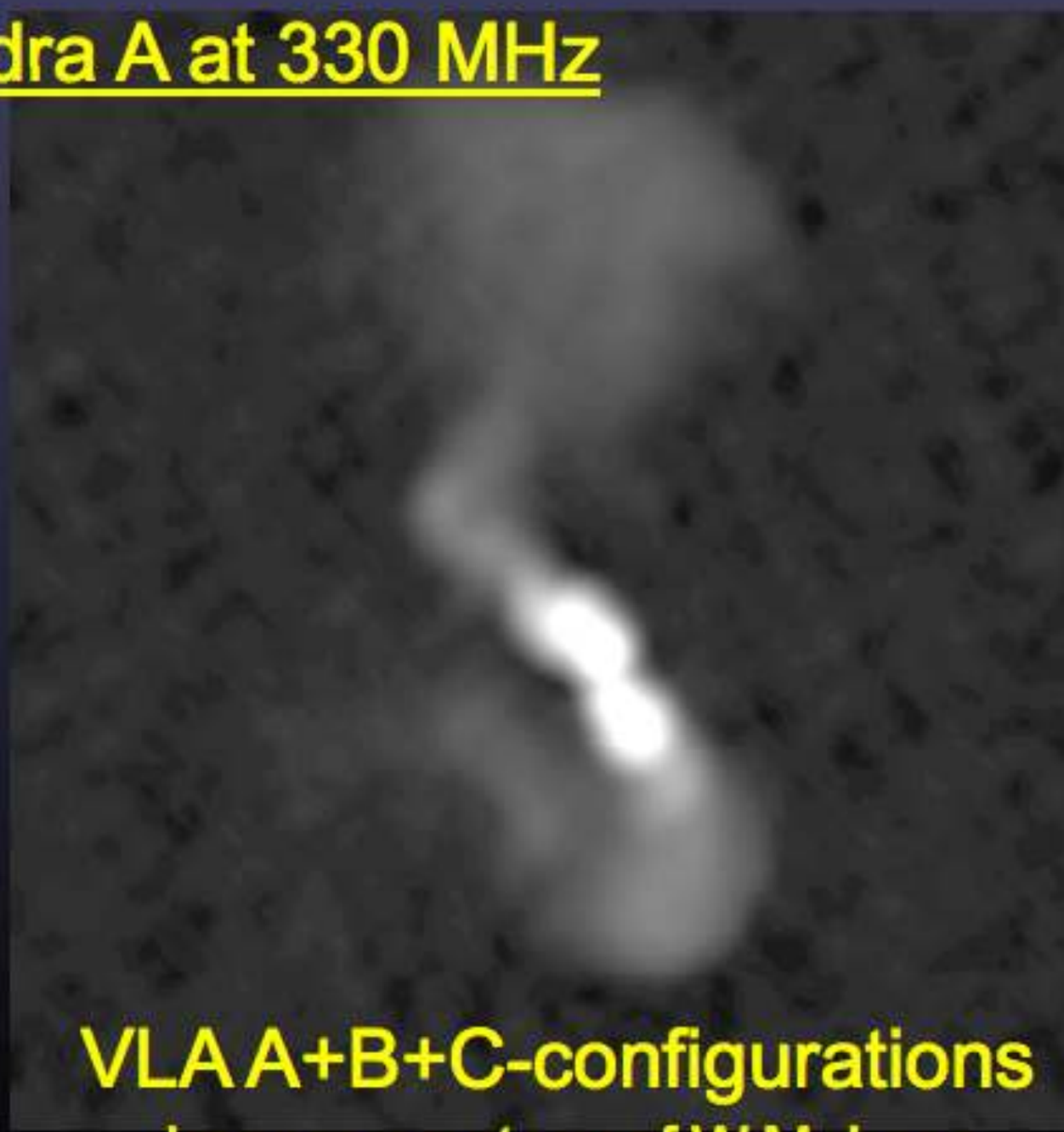



Snapshot UV Coverage
30 km
20
10
0
-10
-20
-30
-40
-30
-20
-10
0
10
20
30 km
Point Spread Function

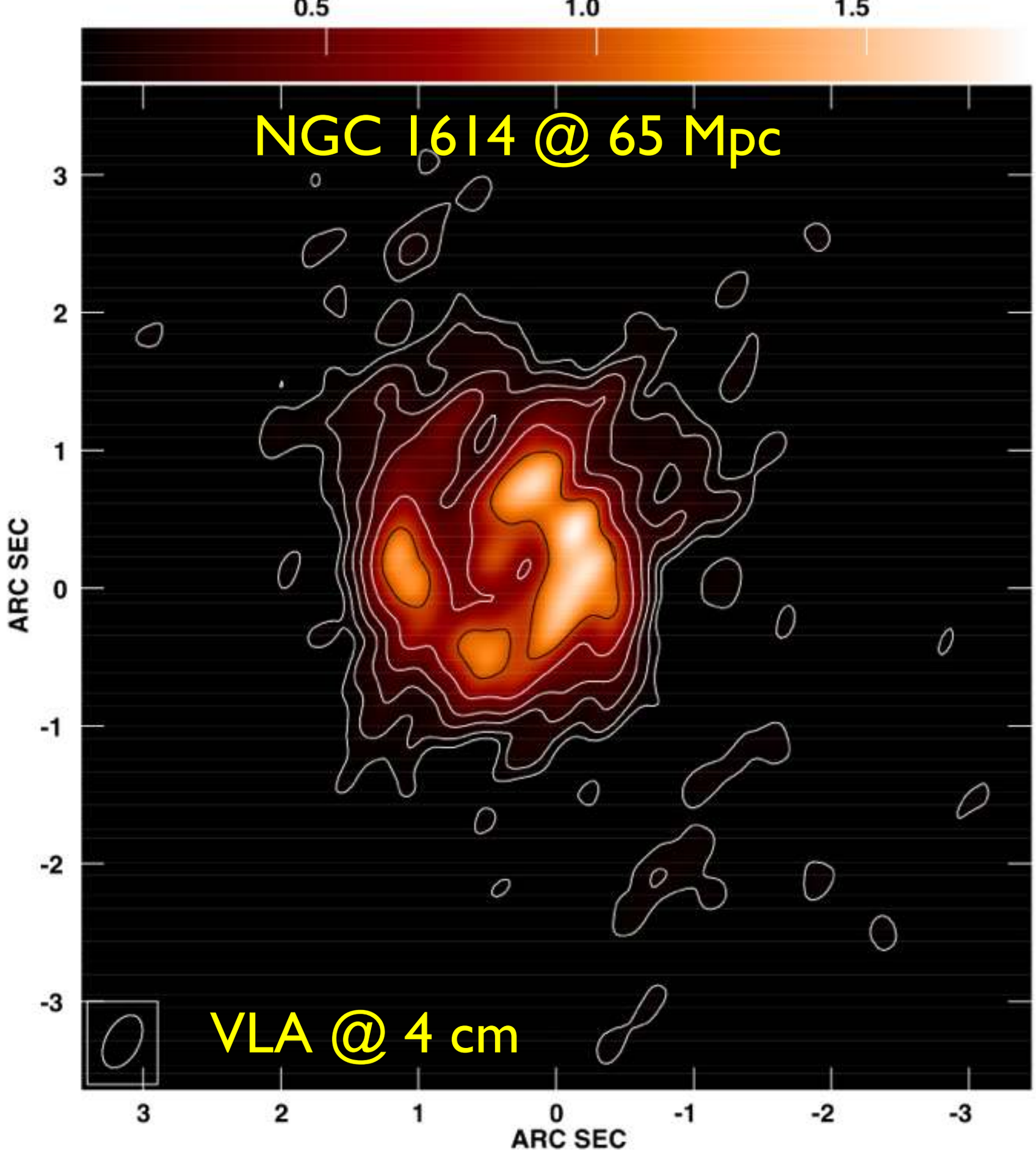
12 Hour Synthesis Observation

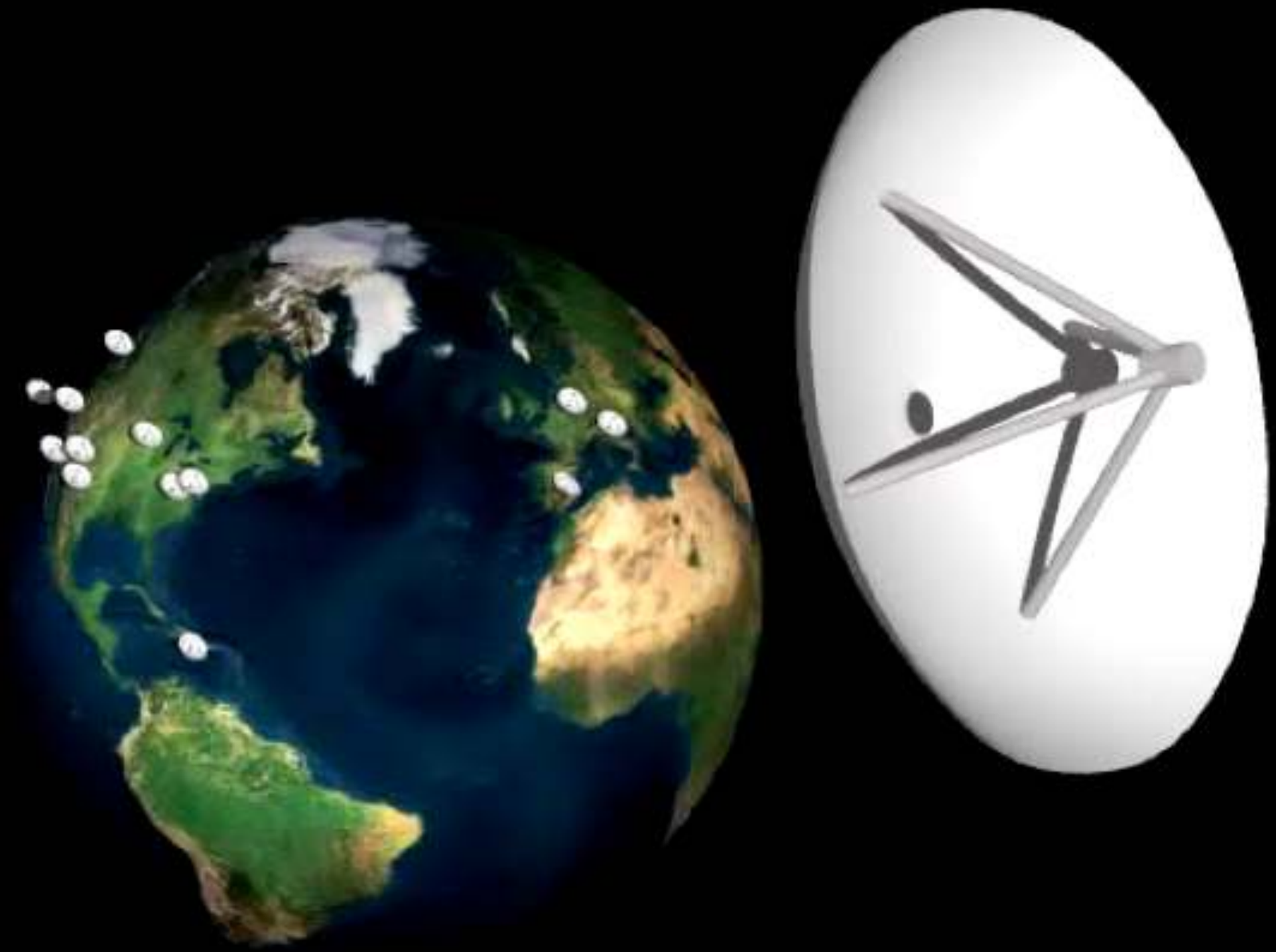


Radio Galaxy Hydra A at 330 MHz



Images courtesy of W.M. Lane


NGC 1614 @ 65 Mpc
VLA @ 4 cm
0.5
1.0
1.5
3
2
1
0
-1
-2
-3
ARC SEC
3
2
1
0
-1
-2
-3
ARC SEC



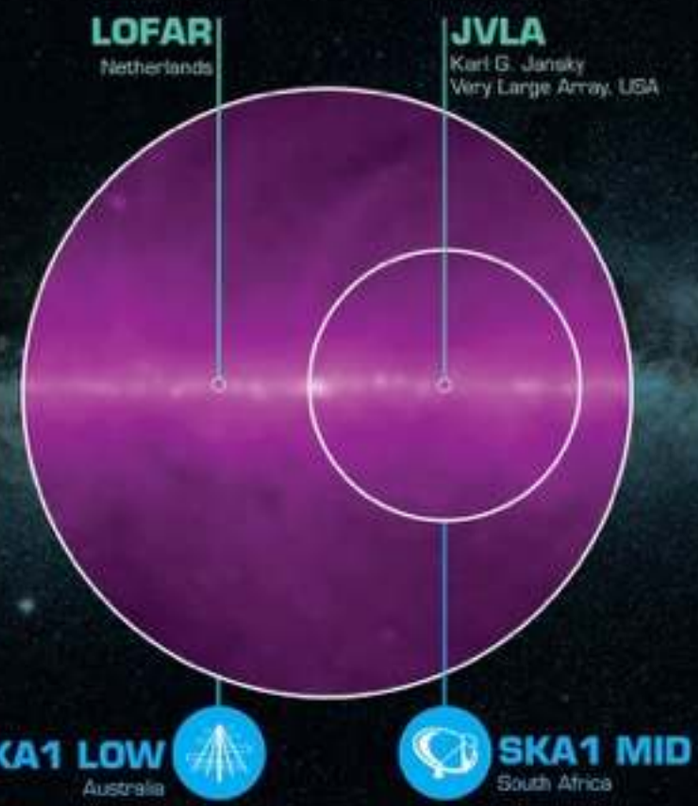
The European VLBI Network

…and the SKA

How will SKA1 be better than today's best radio telescopes?

Astronomers assess a telescope's performance by looking at three factors - **resolution**, **sensitivity**, and **survey speed**. With its sheer size and large number of antennas, the SKA will provide a giant leap in all three compared to existing radio telescopes, enabling it to revolutionise our understanding of the Universe.

The **Square Kilometre Array** (SKA) will be the world's largest radio telescope. It will be built in two phases - SKA1 and SKA2 - starting in 2018, with SKA1 representing a fraction of the full SKA. SKA1 will include two instruments - **SKA1 MID** and **SKA1 LOW** - observing the Universe at different frequencies.



SKA1 LOW x1.2 LOFAR NL

SKA1 MID x4 JVLA

RESOLUTION

Thanks to its size, the SKA will see smaller details, making radio images less blurry, like reading glasses help distinguish smaller letters.

SKA1 LOW x135 LOFAR NL

SKA1 MID x60 JVLA

SURVEY SPEED

Thanks to its sensitivity and ability to see a larger area of the sky at once, the SKA will be able to observe more of the sky in a given time and so map the sky faster.

SKA1 LOW x8 LOFAR NL

SKA1 MID x5 JVLA

SENSITIVITY

Thanks to its many antennas, the SKA will see fainter details, like a long-exposure photograph at night reveals details the eye can't see.

www.skatelescope.org Square Kilometre Array @SKA_telescope The Square Kilometre Array

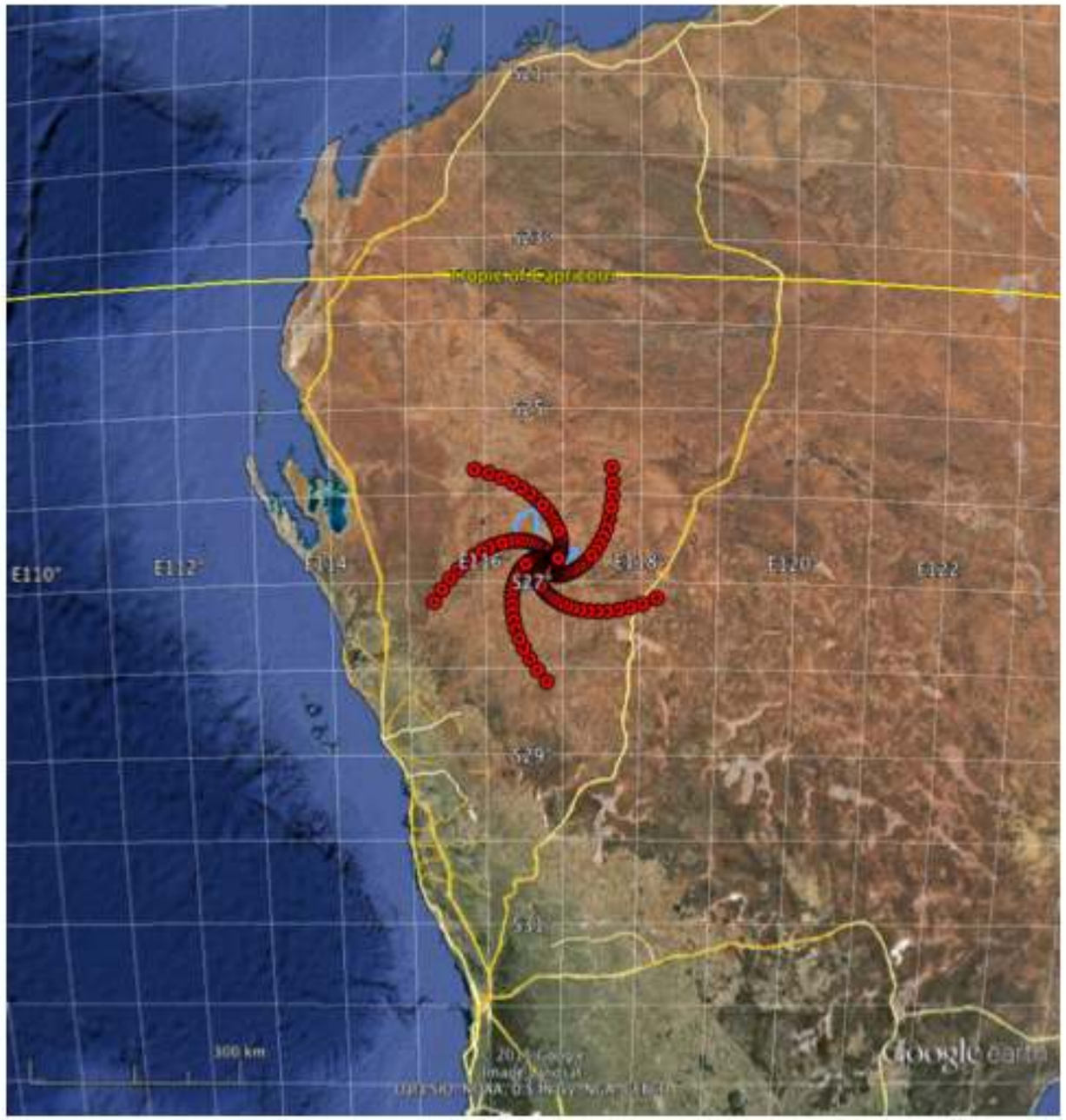
As the SKA isn't operational yet, we use an optical image of the Milky Way to illustrate the concepts of increased sensitivity and resolution.

Notional SKA1 KSPs

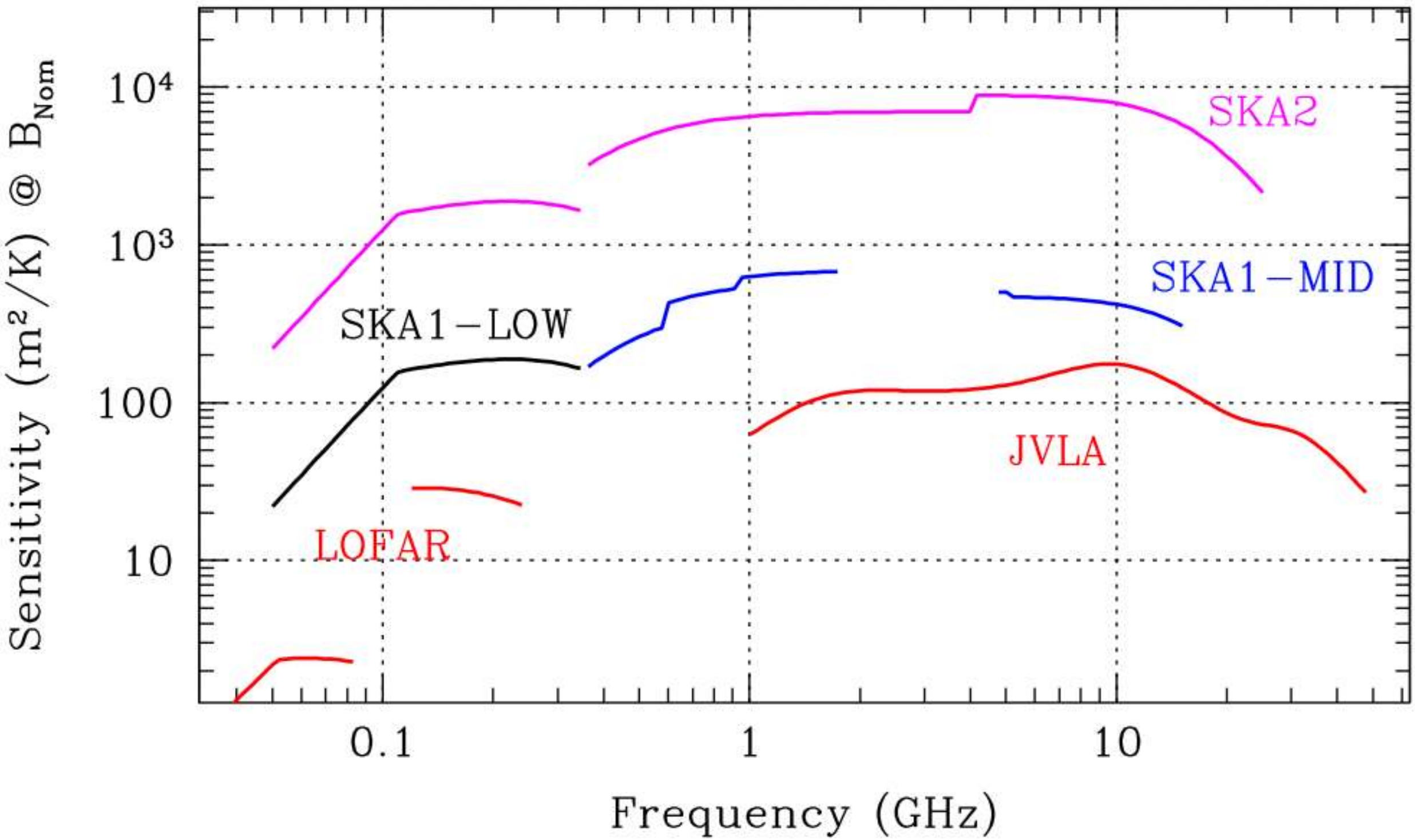
SWG	Objective
CD/EoR	Physics of the early universe IGM - I. Imaging
CD/EoR	Physics of the early universe IGM - II. Power spectrum
Pulsars	Reveal pulsar population and MSPs for gravity tests and Gravitational Wave detection
Pulsars	High precision timing for testing gravity and GW detection
HI	Resolved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

- All objectives originate with the science community
- Representative package of high-impact science deliverables for the first 5 yeas of science operations
- Maximize Commensality

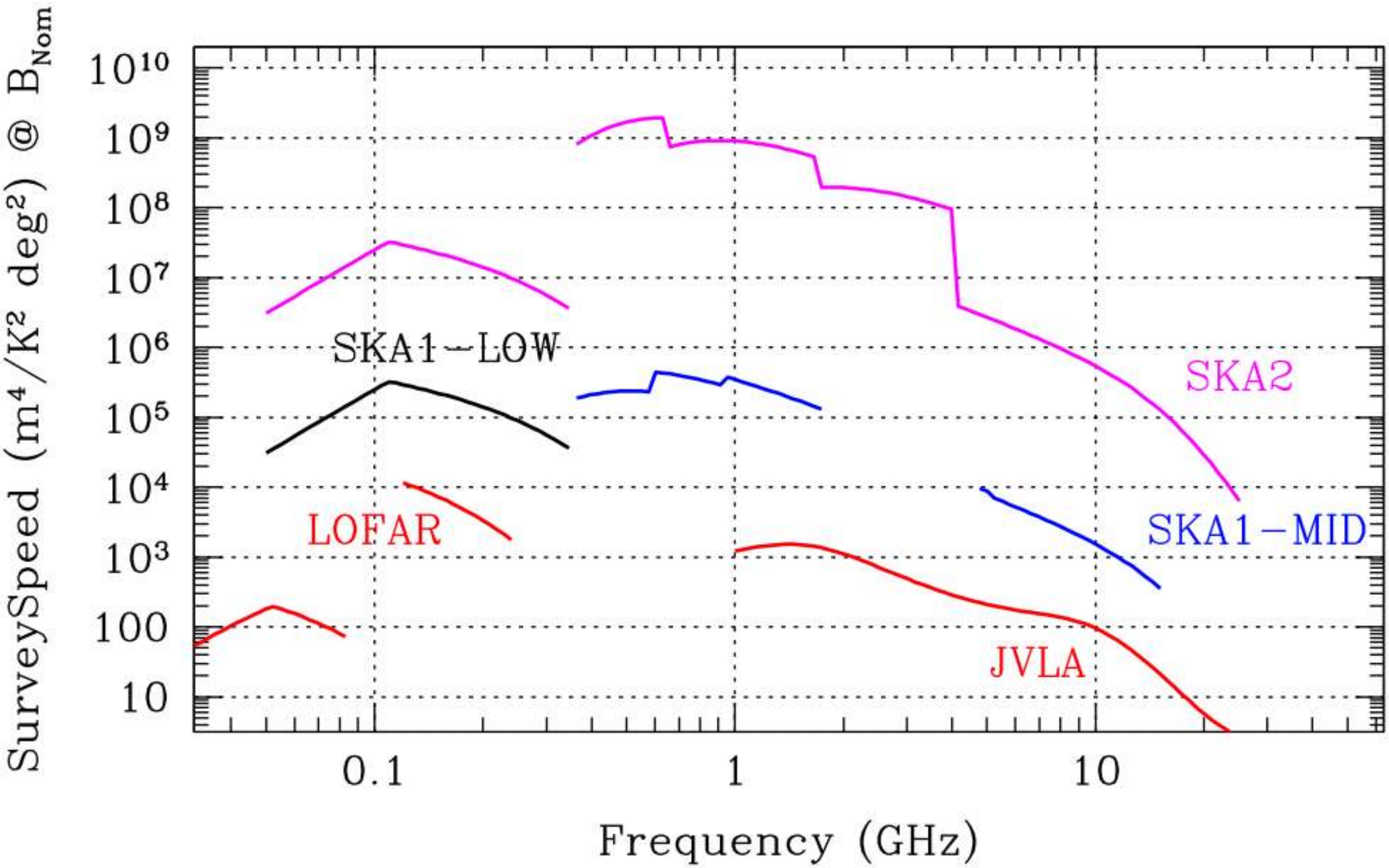
SKA2 Configurations



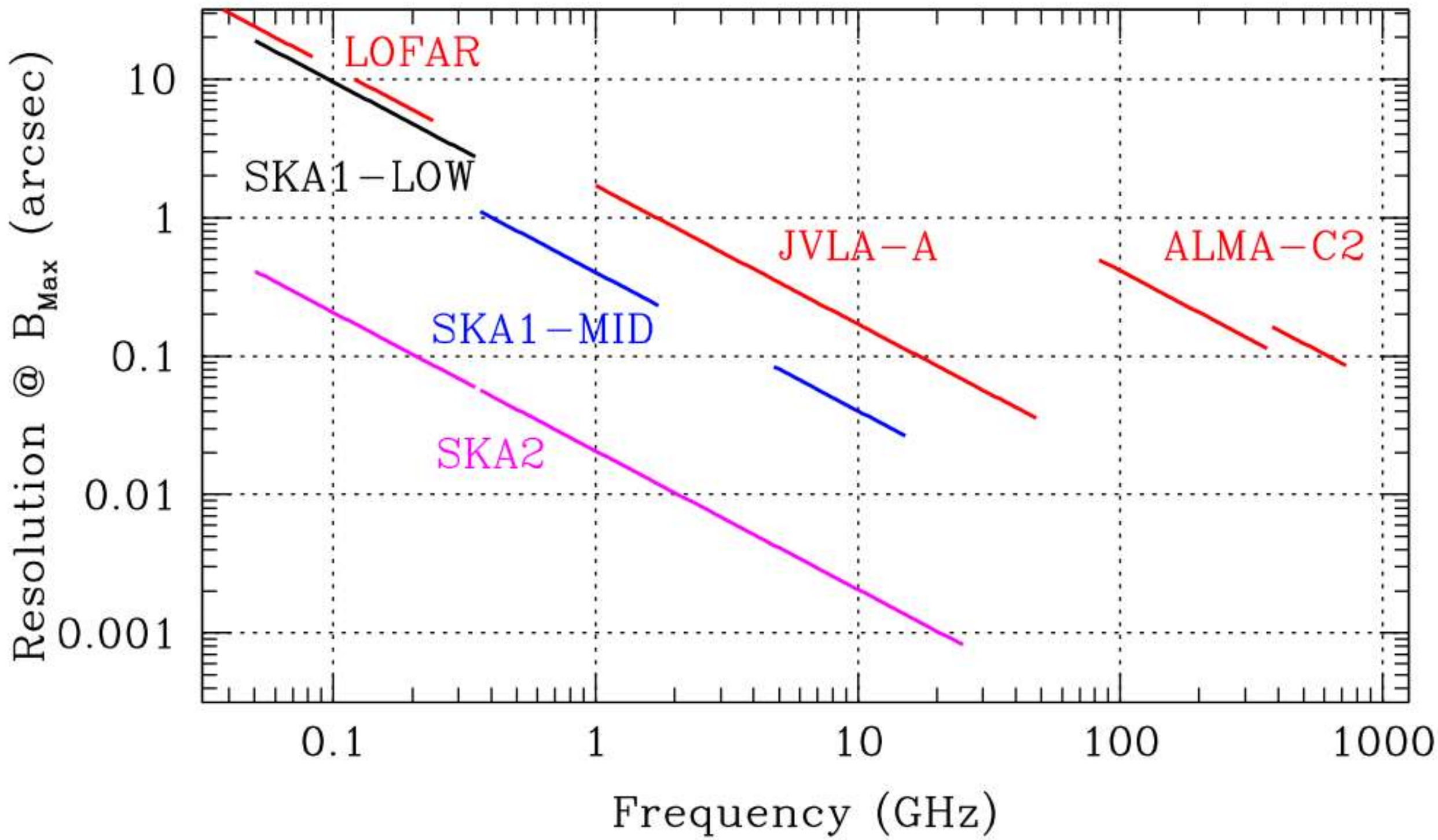
Sensitivity comparison



Survey speed comparison



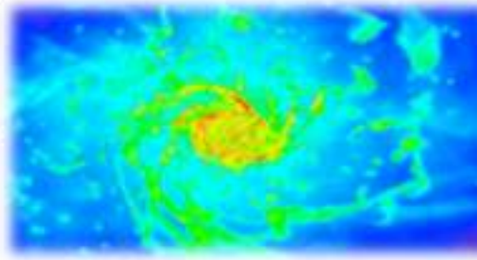
Angular resolution comparison



Headline Science with SKA

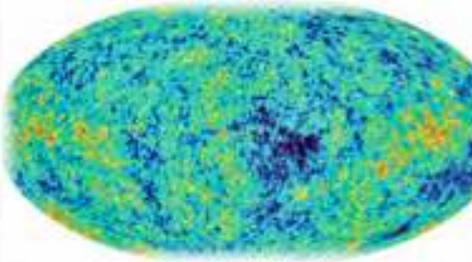
	SKA1	SKA2
The Cradle of Life & Astrobiology	Proto-planetary disks; imaging inside the snow/ice line (@ < 100pc), Searches for amino acids.	Proto-planetary disks; sub-AU imaging (@ < 150 pc), Studies of amino acids.
	Targeted SETI: airport radar 10^4 nearby stars.	Ultra-sensitive SETI: airport radar 10^5 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.

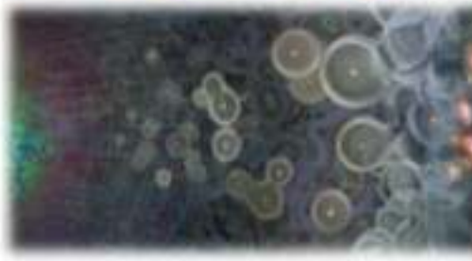


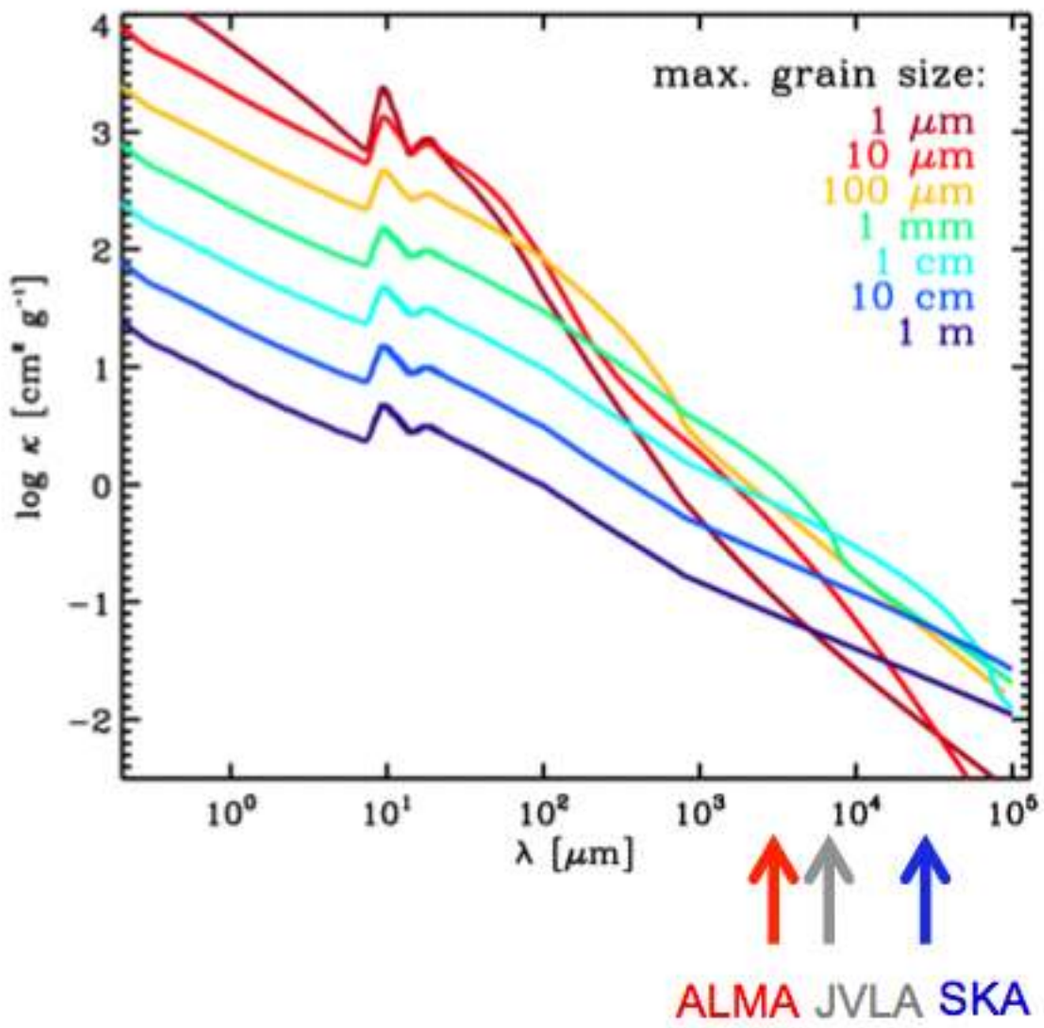
Headline Science with SKA

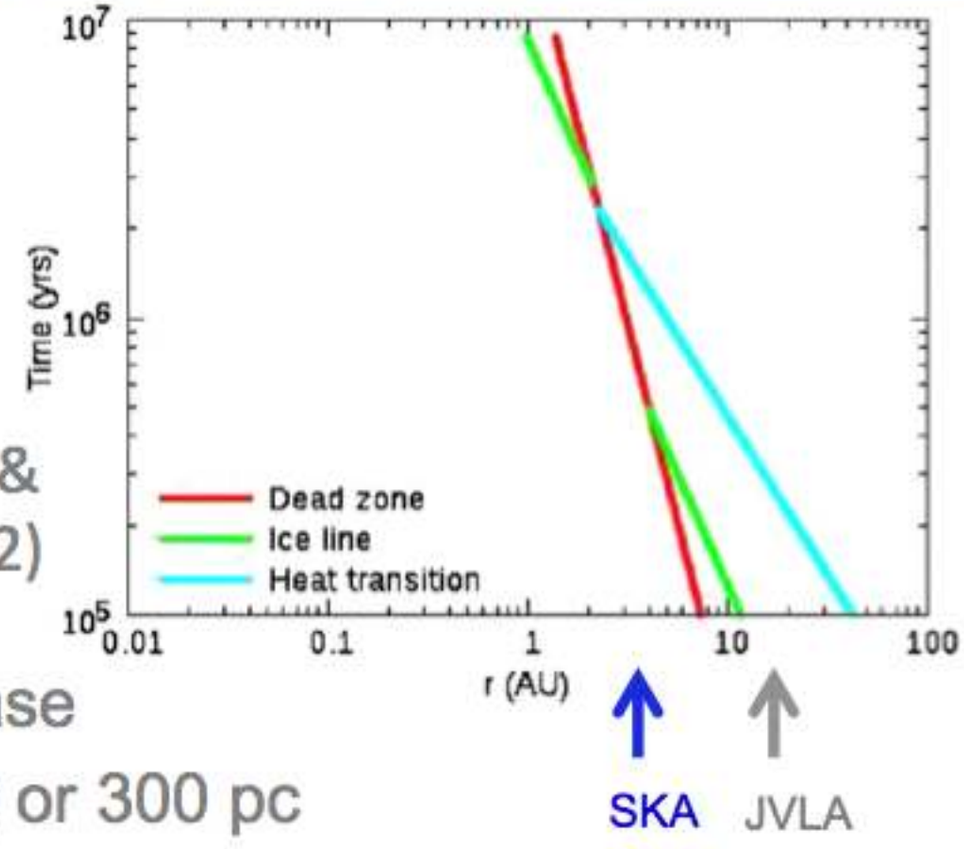
	SKA1	SKA2
The Transient Radio Sky	Use fast radio bursts to uncover the missing "normal" matter in the universe.	Fast radio bursts as unique probes of fundamental cosmological parameters and intergalactic magnetic fields.
	Study feedback from the most energetic cosmic explosions and the disruption of 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).





The Cradle of Life: Understanding planet formation

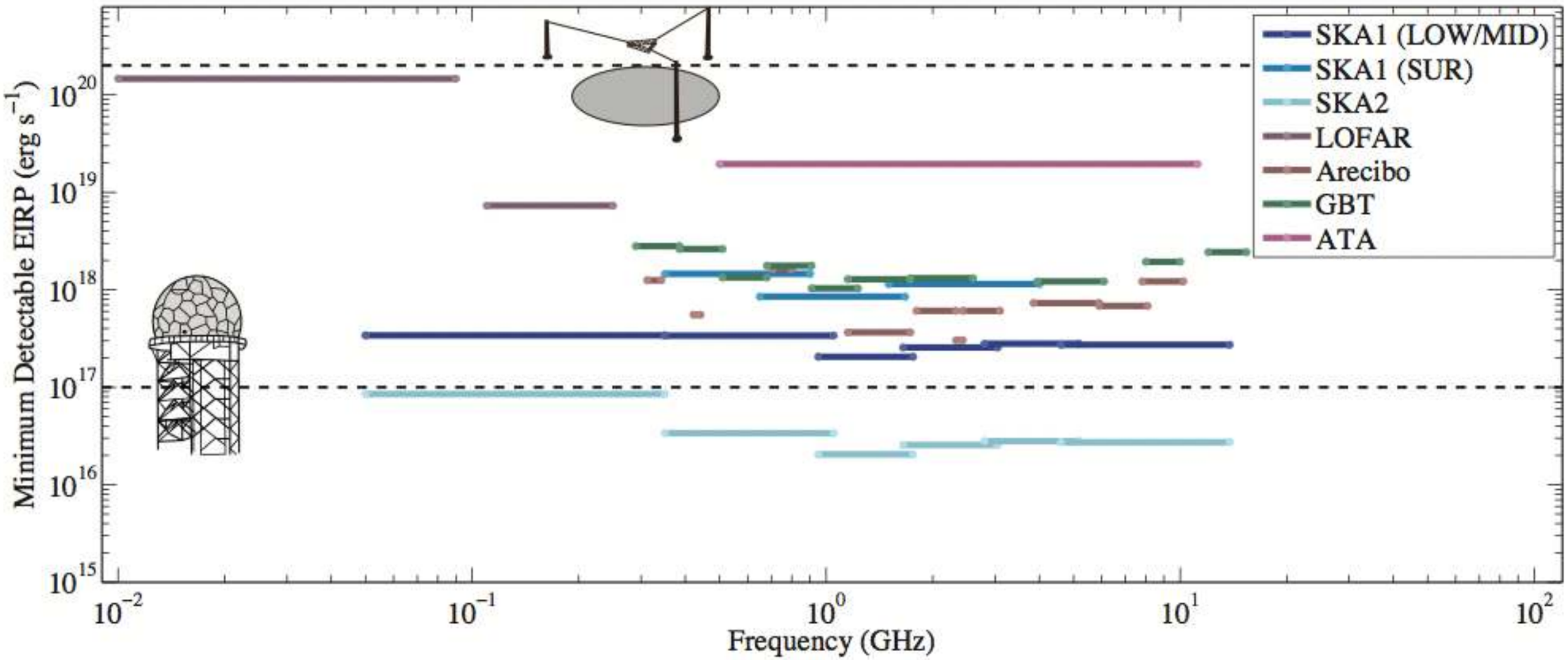




(Hasegawa & Pudritz 2012)

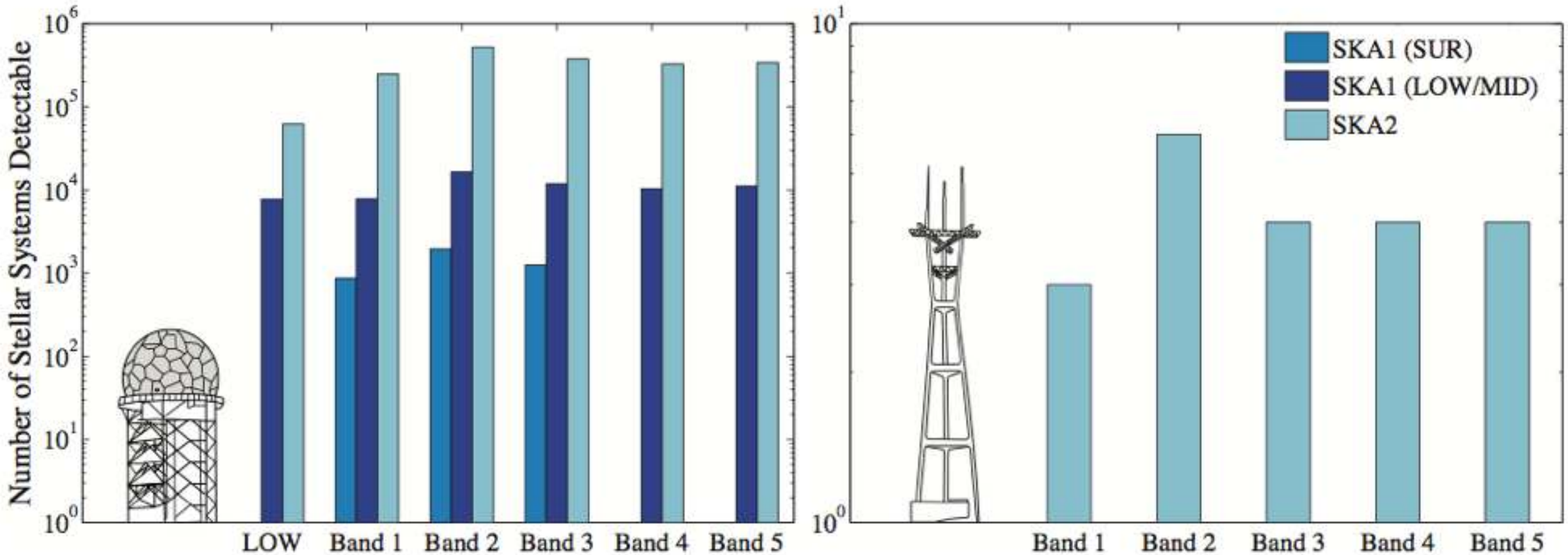
- Measuring grain growth through planetesimal phase
- Resolving proto-planetary disks at 100 pc (SKA1) or 300 pc (SKA2) inside the snow/ice line, sub-AU scales with SKA2

Headline SETI Science



- Detection thresholds for planetary and airport radars at 15 pc

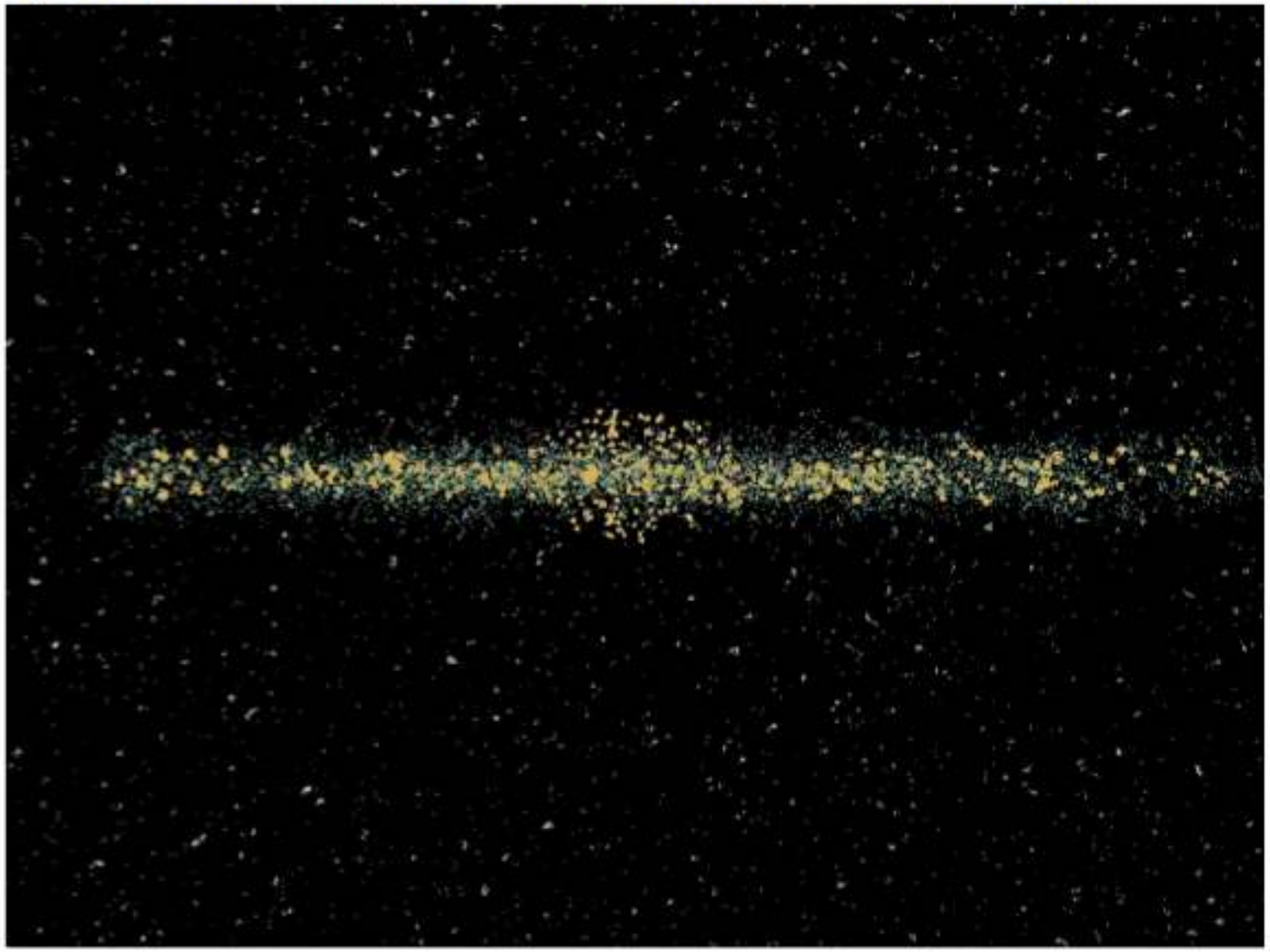
Headline SETI Science

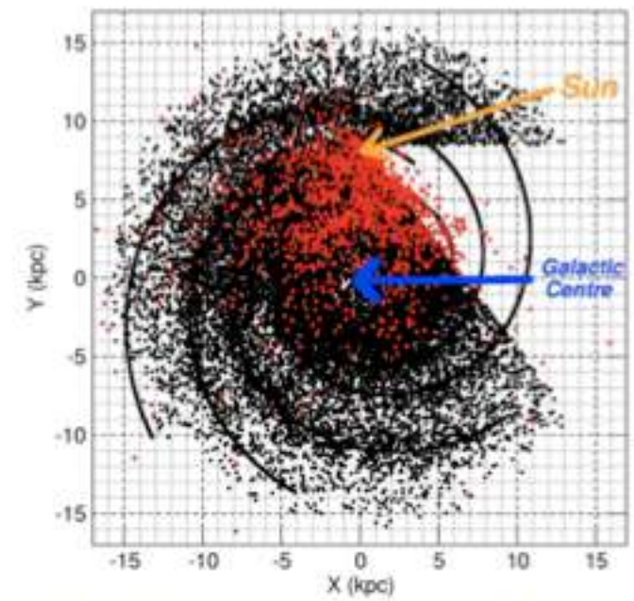


- Detectable stars with airport radar power ~ 10^4 with SKA1
- Detectable stars with TV transmitter power ~10 with SKA2

Finding all the pulsars in the Milky Way…

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

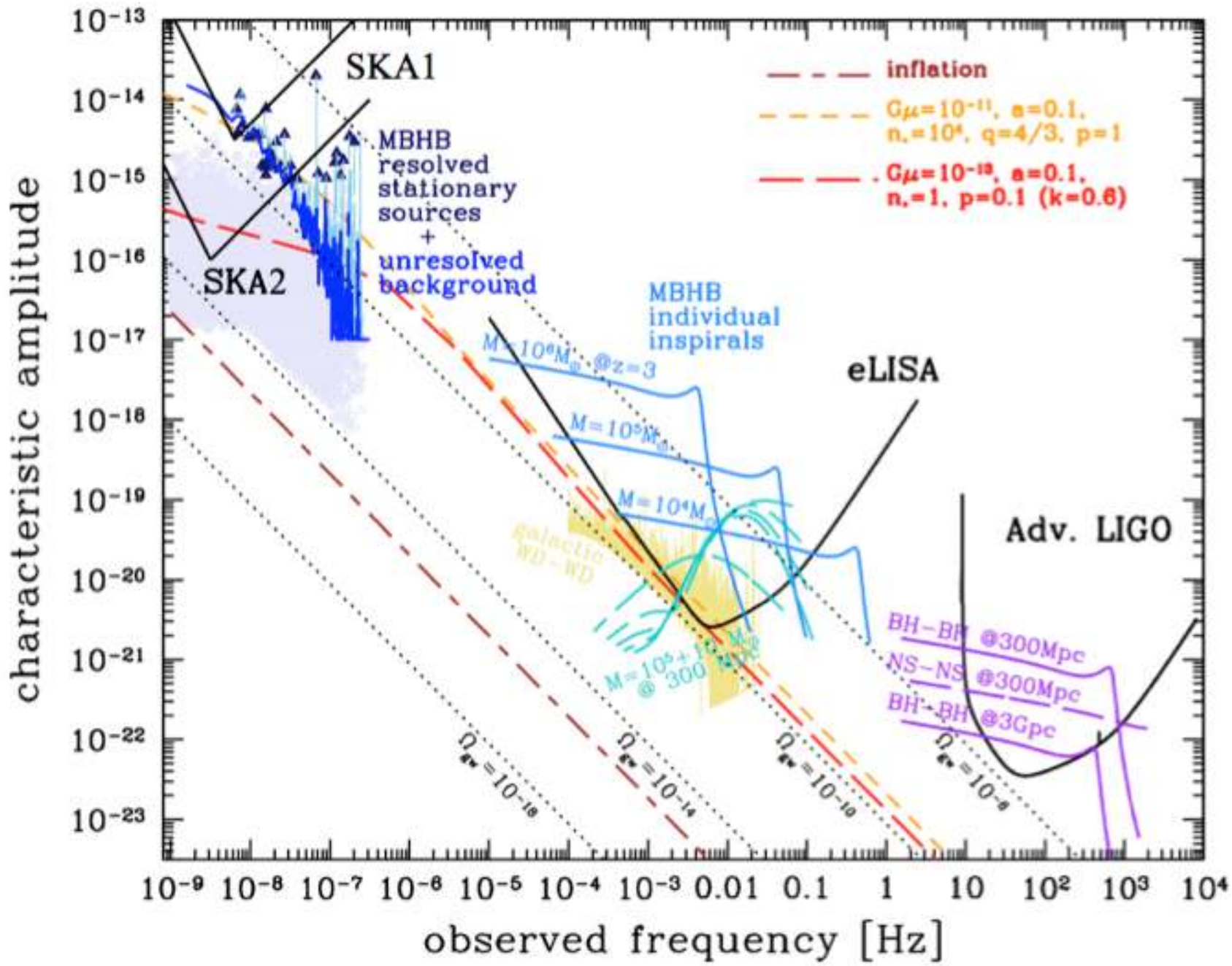




- ~40,000 normal pulsars
- ~2,000 millisecond psrs
- ~100 relativistic binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

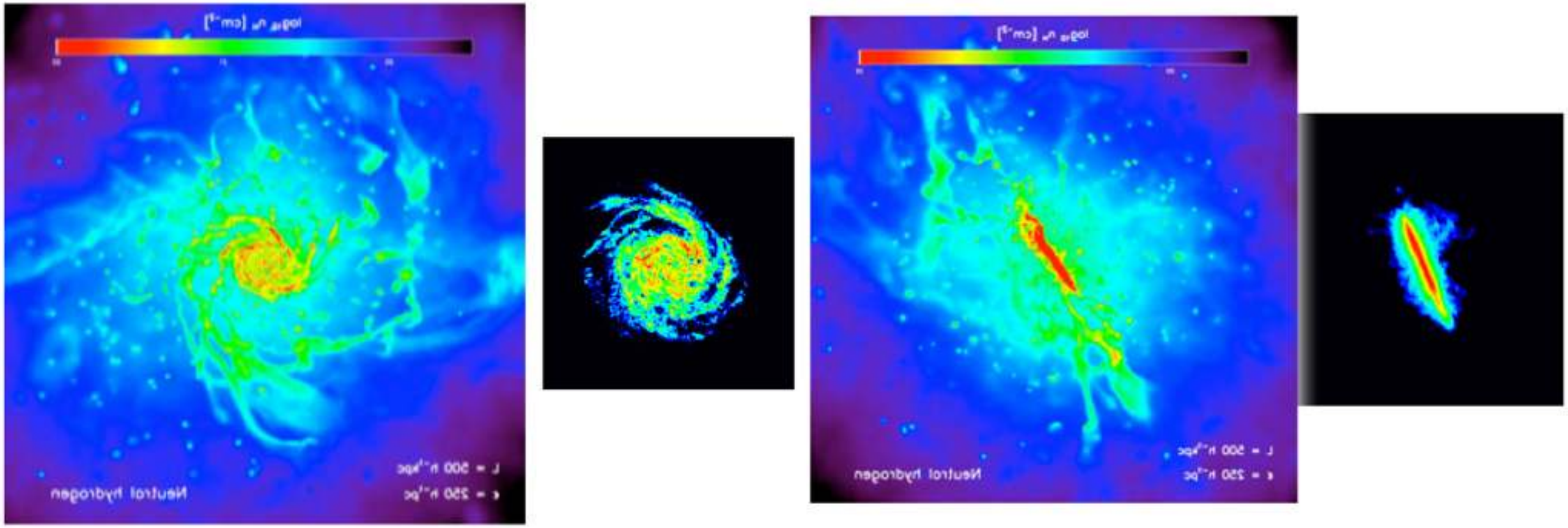
- Timing precision is expected to increase by factor ~100
- Rare and exotic pulsars and binary systems: including PSR-BH systems!
- Testing cosmic censorship and no-hair theorem
- **Current estimates are ~50% of population with SKA1, 100% with SKA2**

Headline Pulsar Science



- Detection thresholds for discrete GW source detection; the first discoveries with SKA1, “GW astronomy” with SKA2

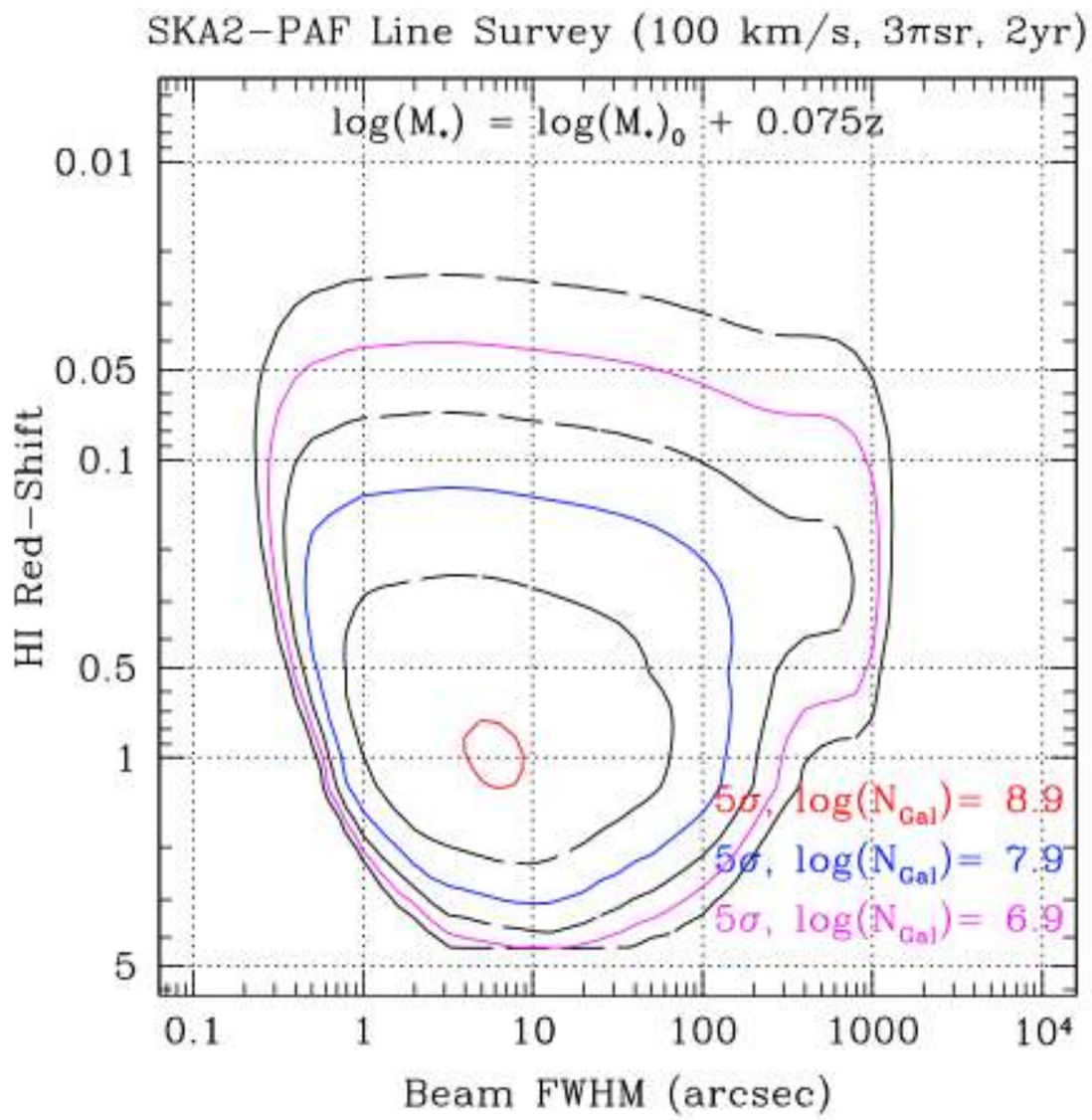
Galaxy HI Evolution: out to z ~ 1 with SKA1 and z ~ 5 with SKA2



(Simulations: Schaye et al. 2010, Images: Oosterloo 2014)

- Understanding galaxy assembly and the baryon cycle
  - Determine the impact of galaxy environments
  - Probe gas inflow and removal, diffuse gas $N_{HI} < 10^{17}$ cm^{-2}
  - Measure angular momentum build-up

Precision Cosmology with SKA2 HI

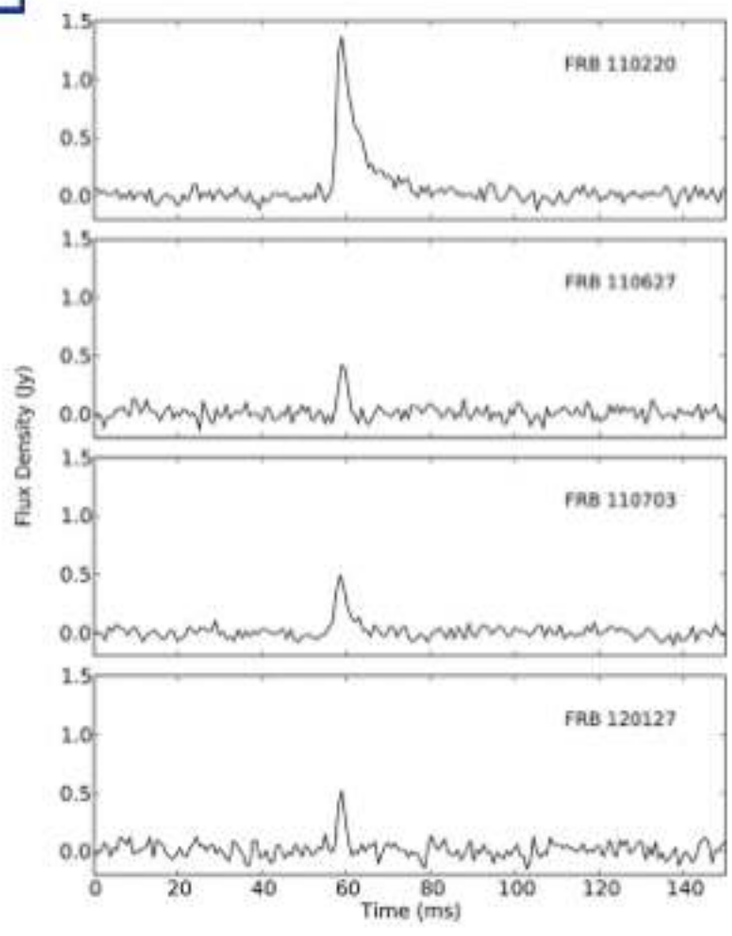


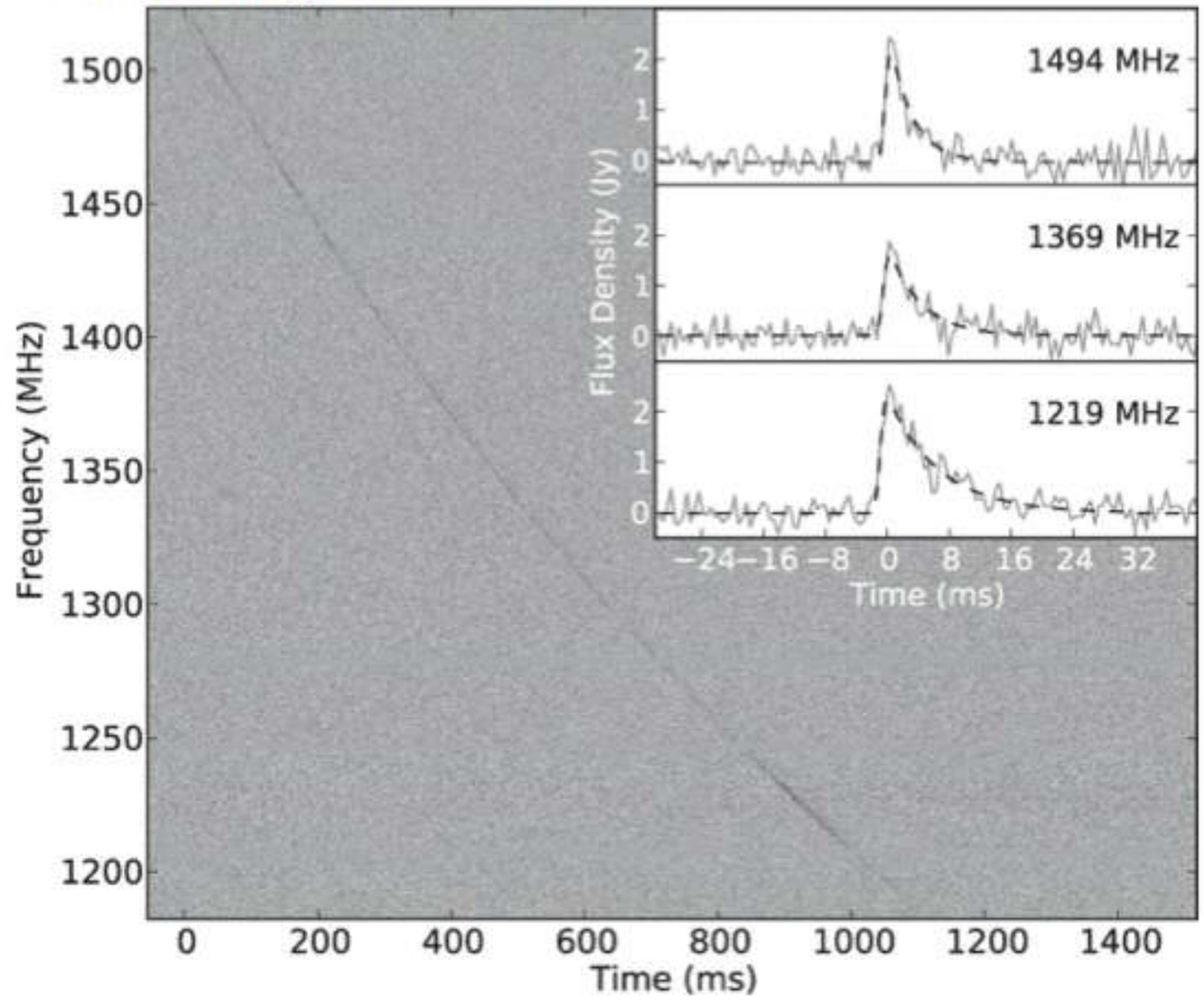
- Detect $10^{8.9}$ galaxies with <z> ≈ 1, $10^{7.9}$ with <z> ≈ 2
- Compare Euclid (2020+5?) target of 10^{8} spectra with <z> ≈ 1
- **SKA2 will provide an unrivaled capability for precision cosmology!**

The Transient radio sky

Science AAAS

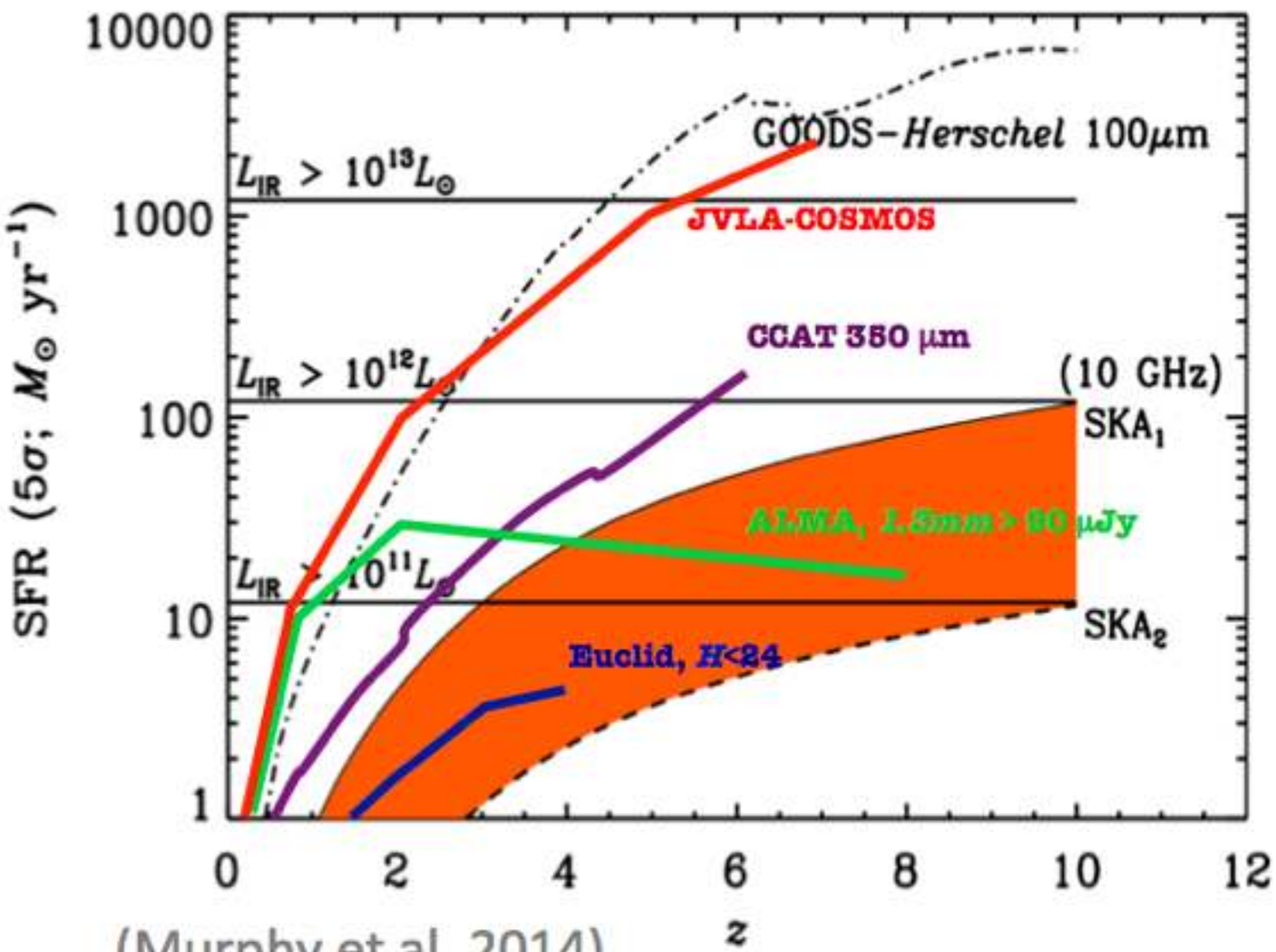
A Population of Fast Radio Bursts at Cosmological Distances
D. Thornton *et al.*
Science **341**, 53 (2013);
DOI: 10.1126/science.1236789



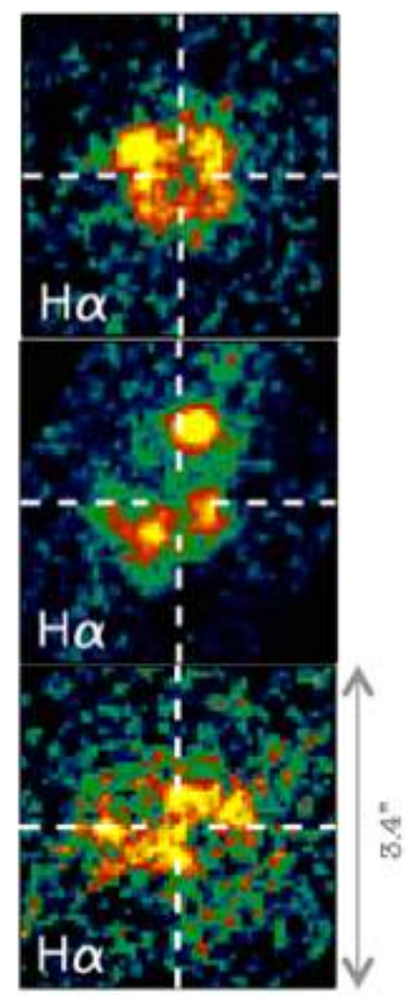


- Four celestial "FRB" events now detected (after first "Lorimer" burst):
  $S = 0.5 – 1.3$ Jy, $\Delta t = 1 – 6$ msec, DM = 550 – 1100 cm^{-3} pc
- Estimated event rate: 1×10^4 sky^{-1} day^{-1}
- Completely unknown origin, possibly at cosmological distances

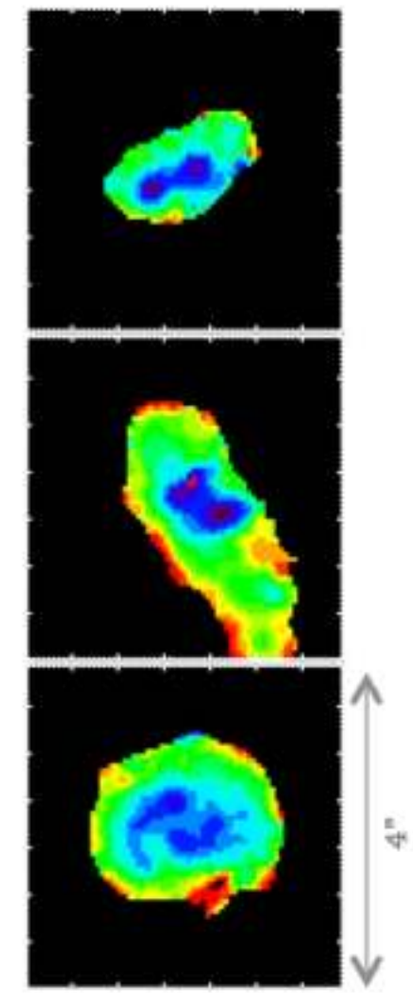
Galaxy Evolution Studies in the Radio Continuum: Understanding the Star Formation History of the Universe



(Murphy et al. 2014)

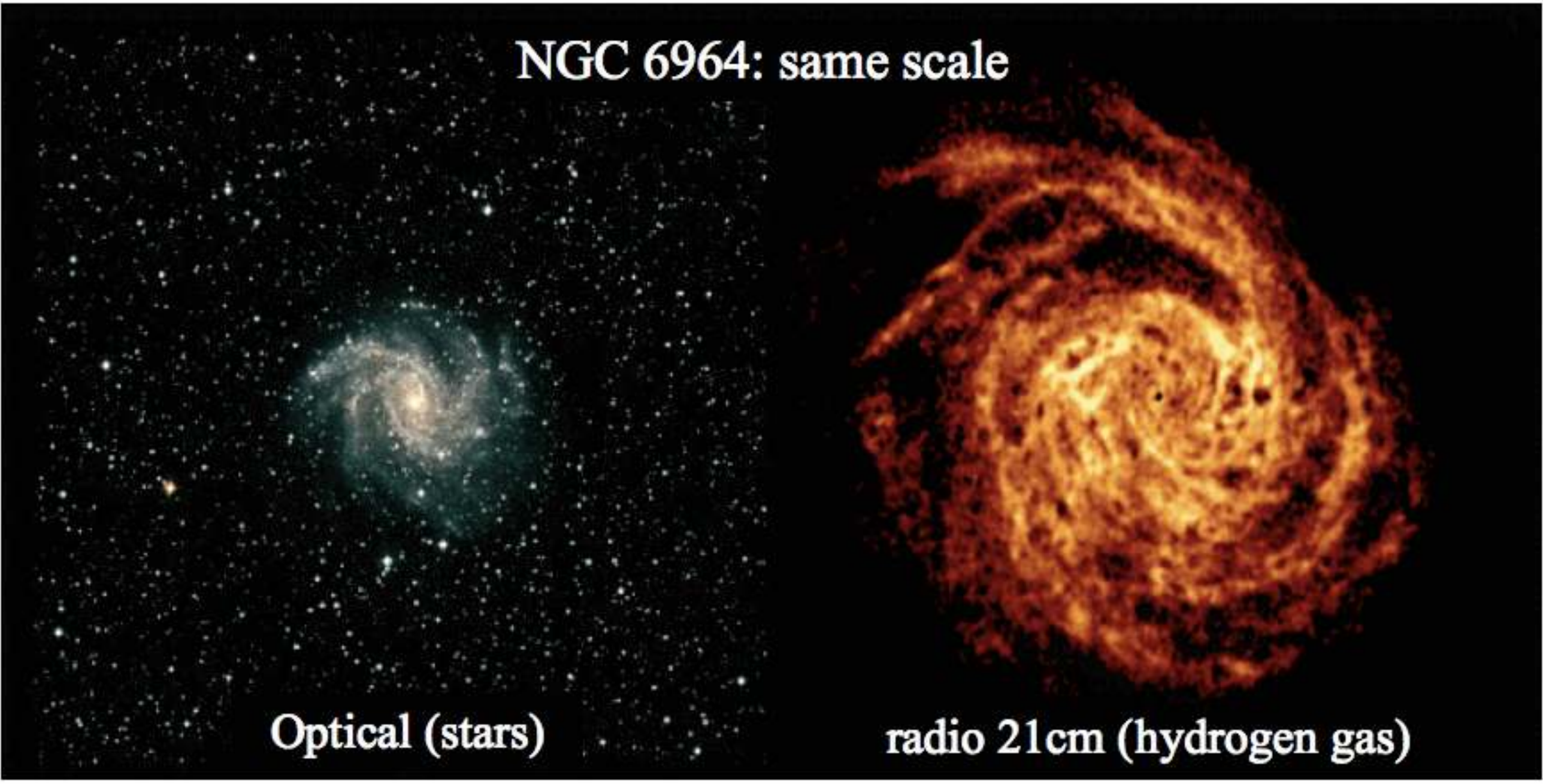


Wuyts et al 2013, z~1
Hα–based SFR-maps

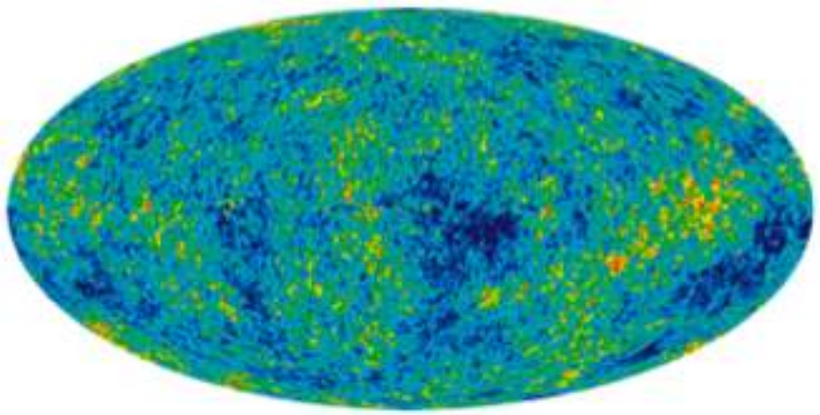


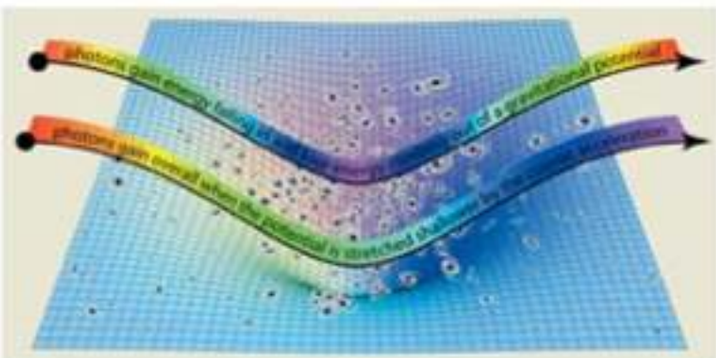
Cibinel et al 2014, z~2
UV-based SFR-maps

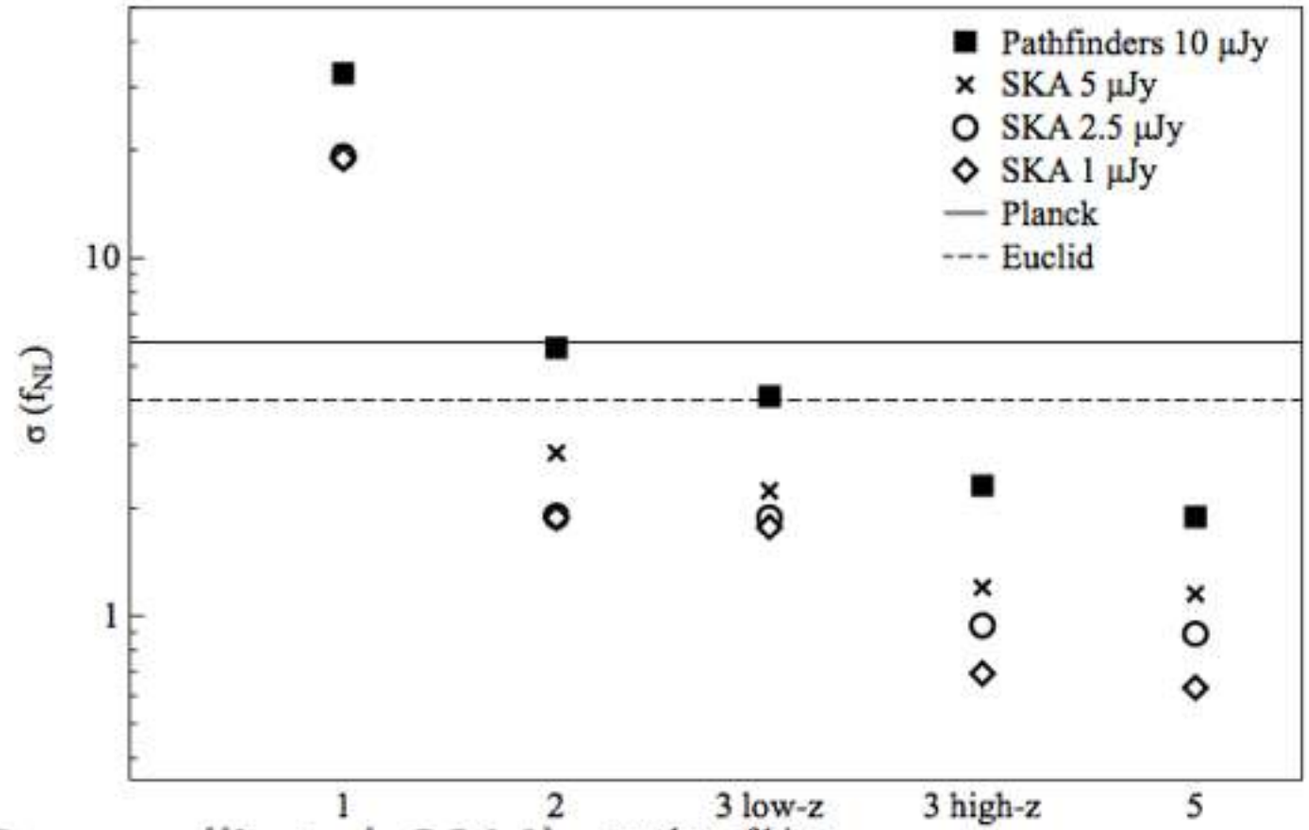
- Unmatched sensitivity to star formation rates (10 $M_\odot$/yr) out to z ~ 4 with SKA1 and z ~ 10 with SKA2
- Resolved (sub-kpc) imaging of star forming disks out to z ~ 1 with SKA1 and z ~ 6 with SKA2


NGC 6964: same scale
Optical (stars)
radio 21cm (hydrogen gas)

Cosmology with SKA: Integrated Sachs-Wolfe effect



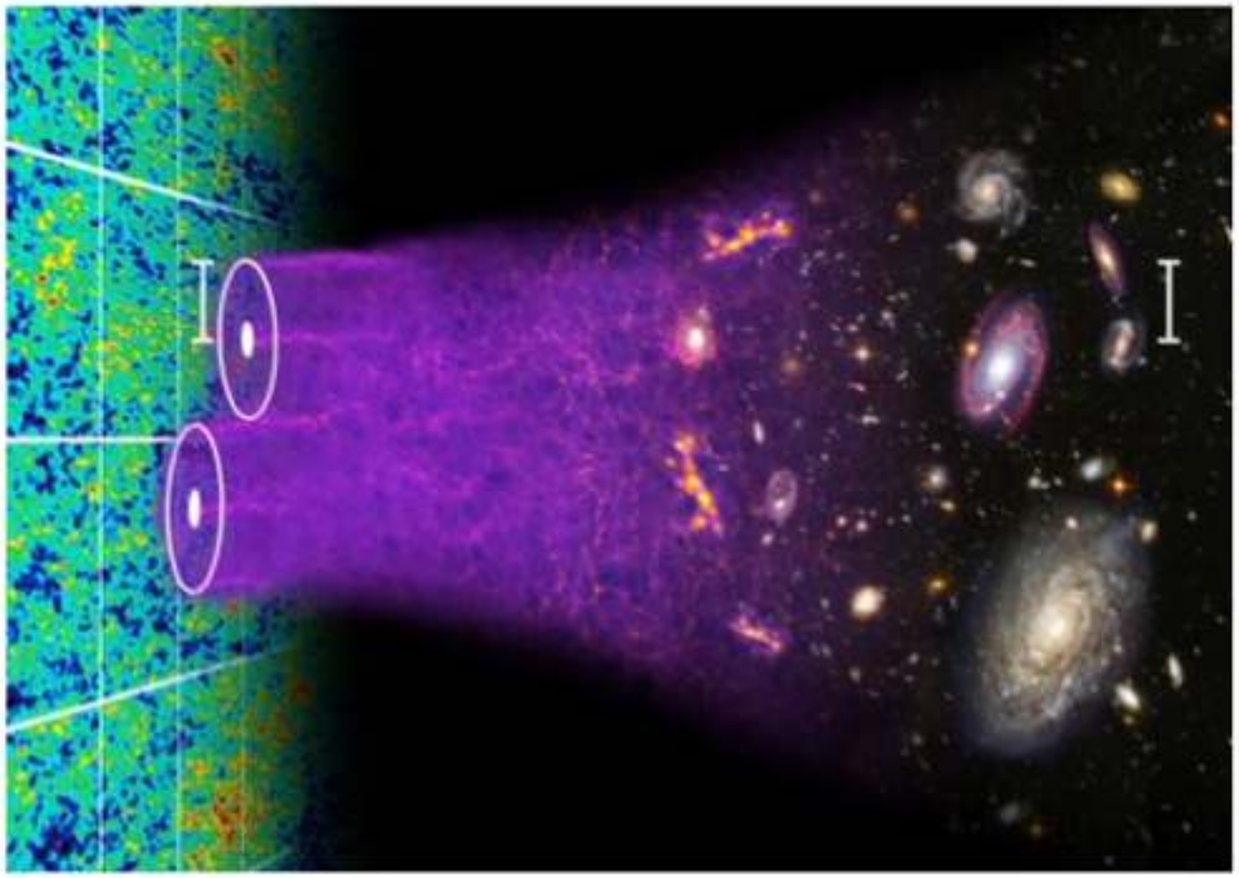




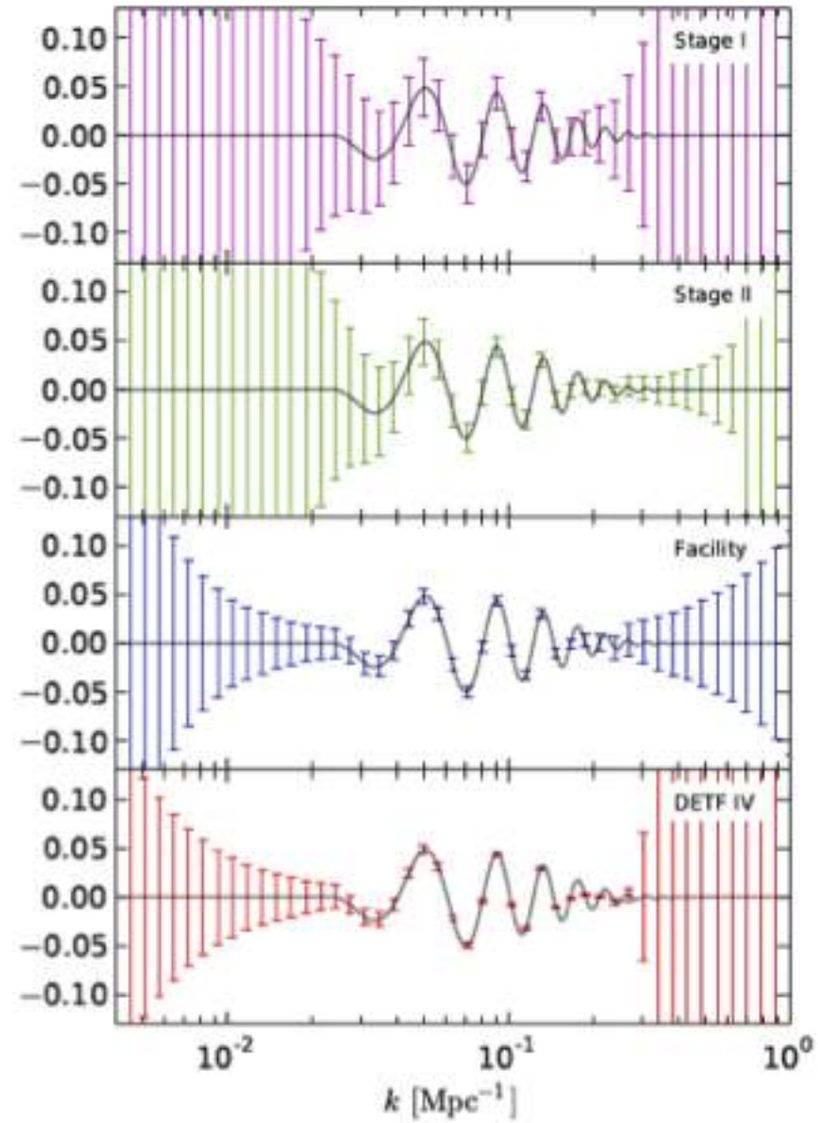
(Raccanelli et al. 2014)

- Constraining non-Gaussianity of primordial fluctuations with the Integrated Sachs-Wolfe effect: correlation of foreground source populations with CMB structures
  - Uniquely probing the largest scales

Cosmology with SKA: Baryon Acoustic Oscillations

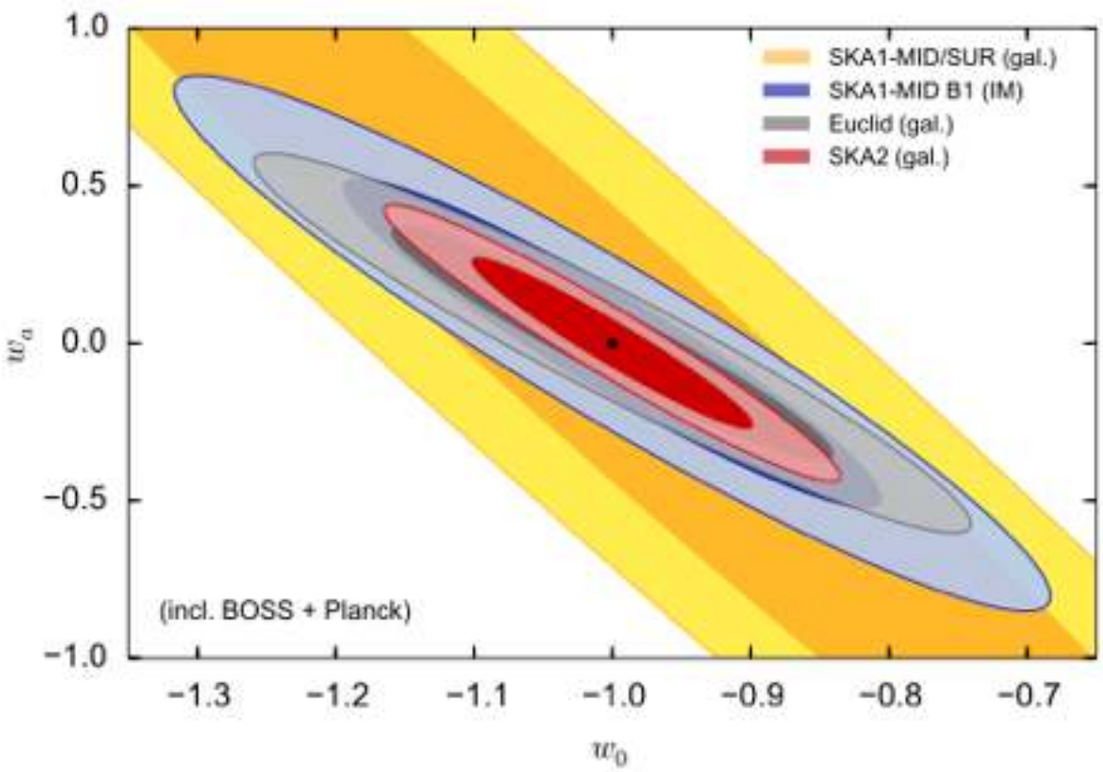


(Blake & Moorfield)

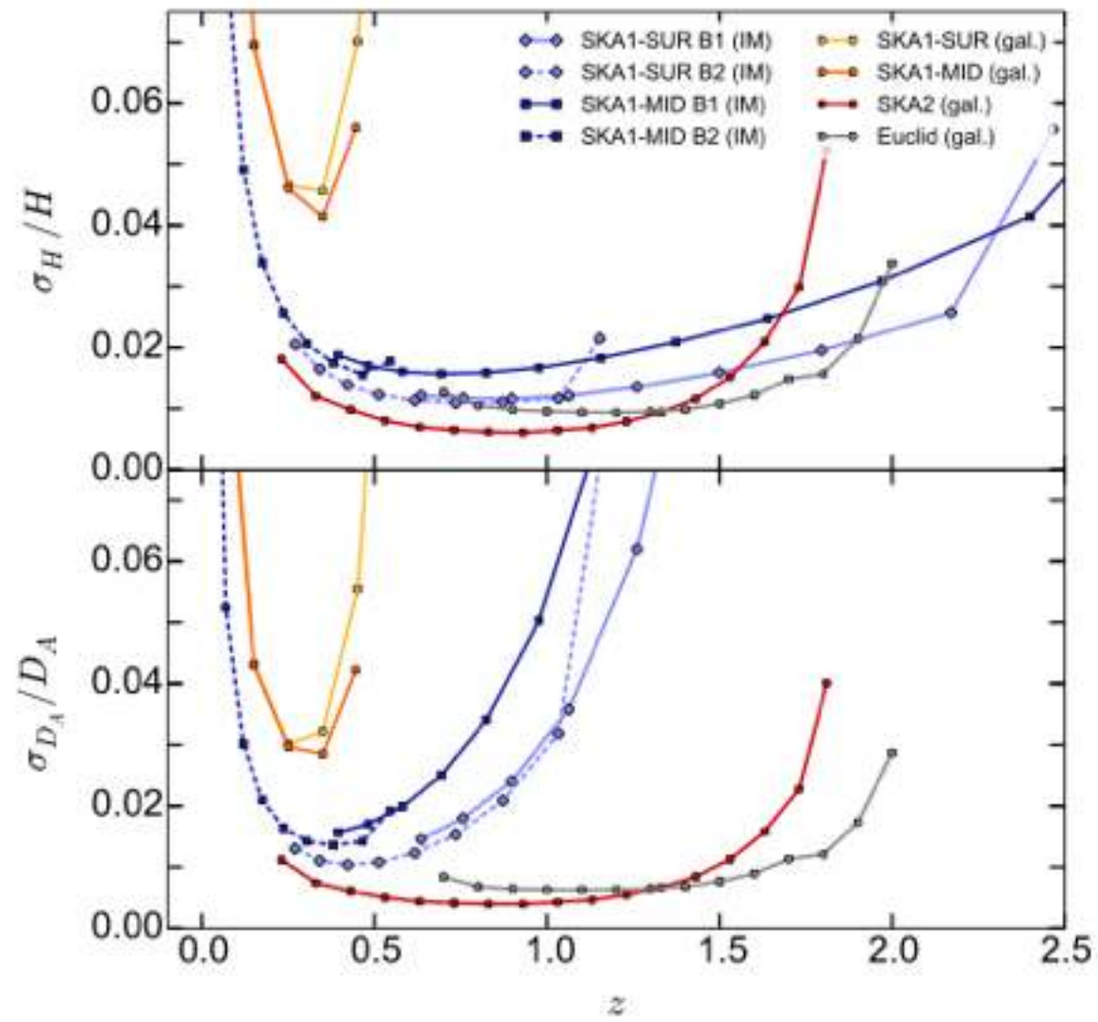


- Constraining Dark Energy models with redshift-resolved BAO measurements
  - Discrete detection is complementary with SKA1, cutting edge in SKA2
  - Intensity mapping is higher risk but world-class, even with SKA1

Cosmology with SKA: Baryon Acoustic Oscillations

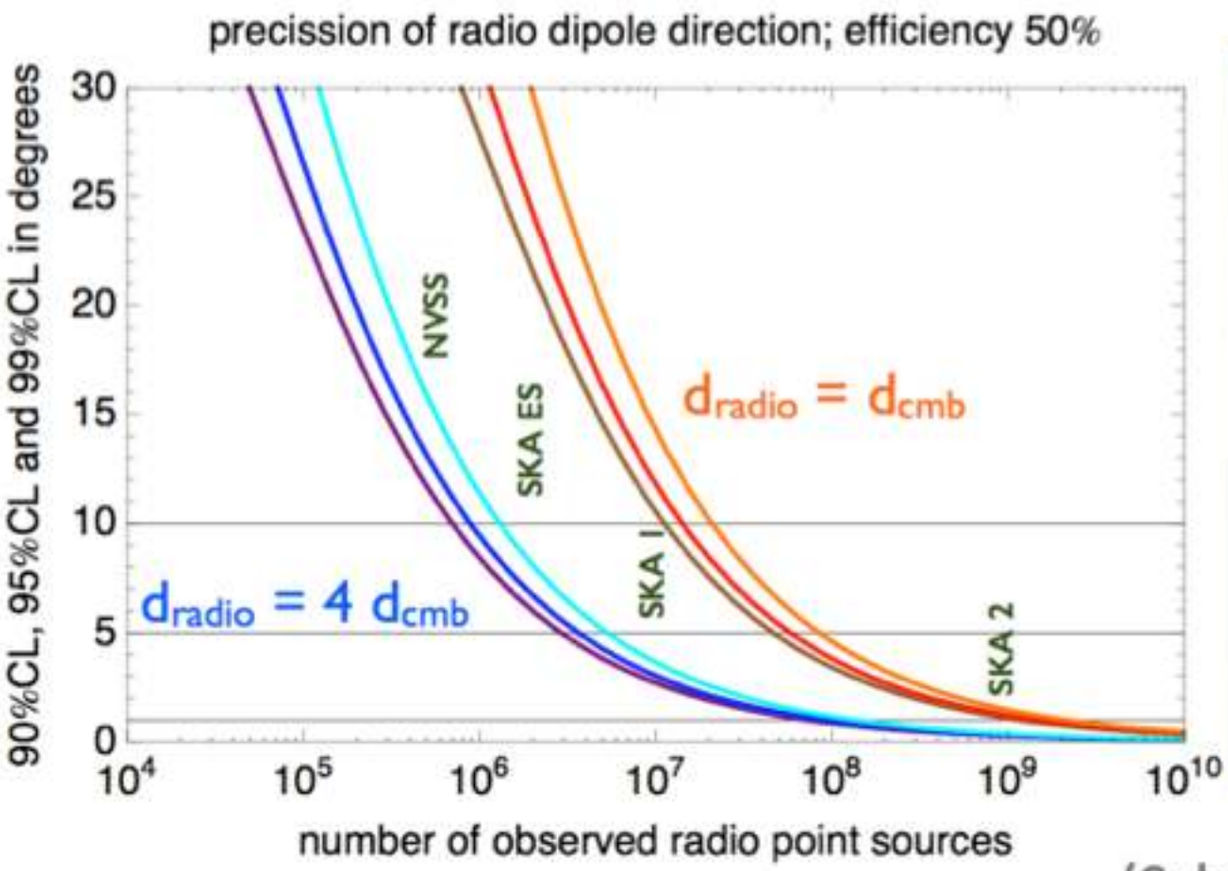


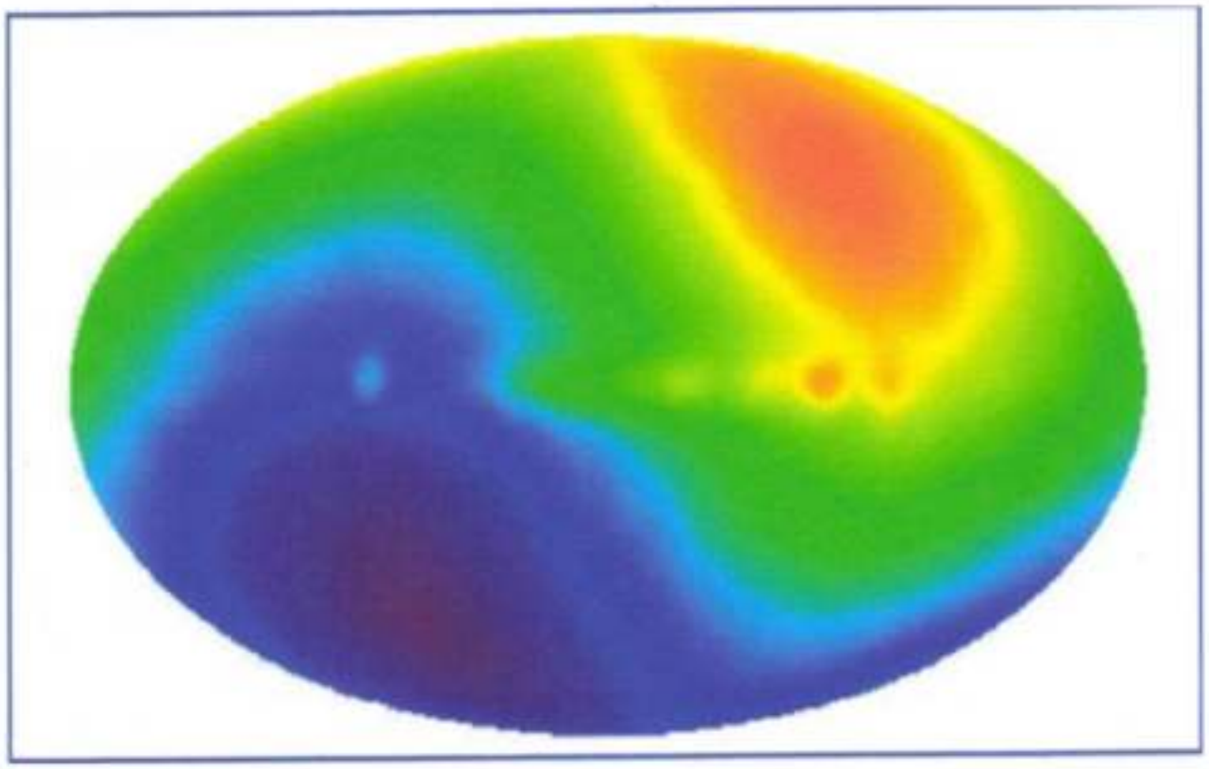
(Bull et al 2014)



- Constraining Dark Energy models with redshift-resolved BAO measurements
  - Discrete detection is complementary with SKA1, cutting edge with SKA2
  - Intensity mapping is higher risk but world-class, even with SKA1

Cosmology with SKA: Matter Dipole versus CMB Dipole

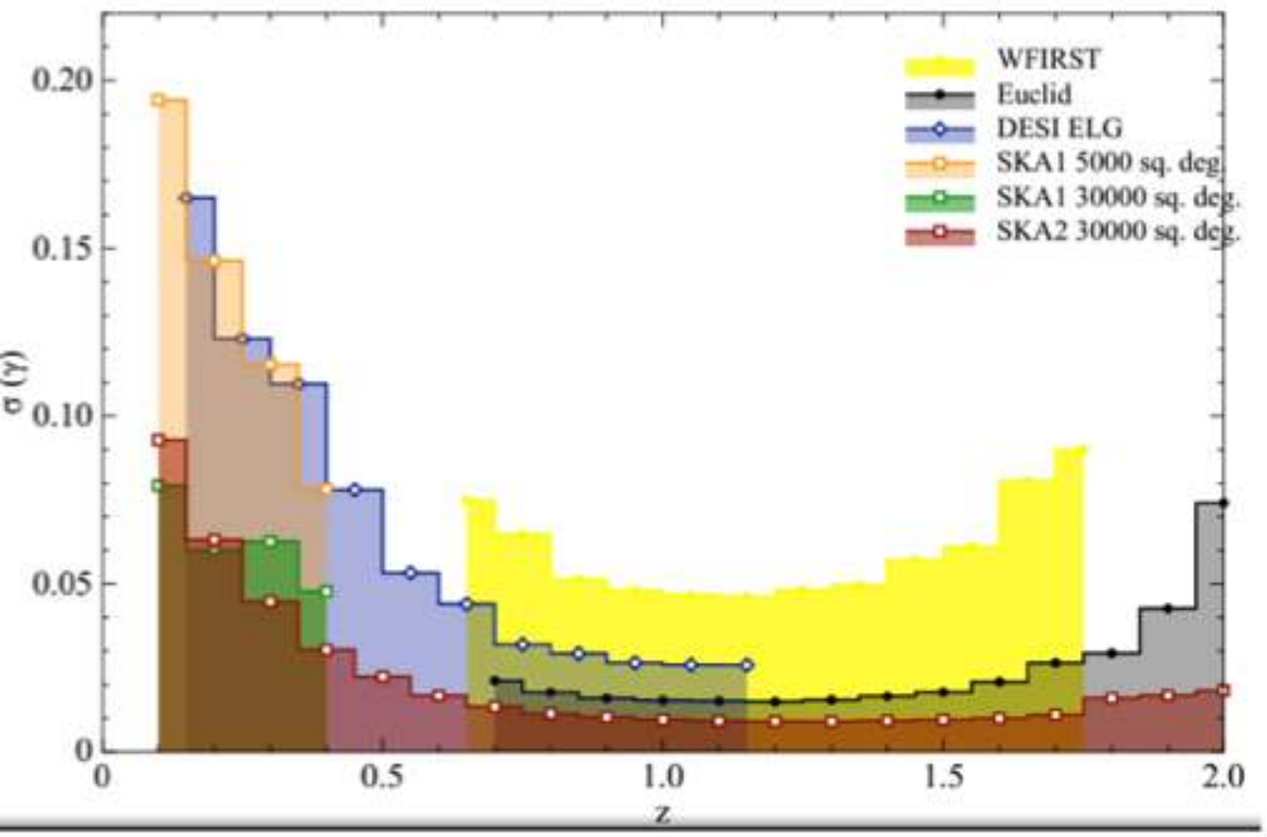




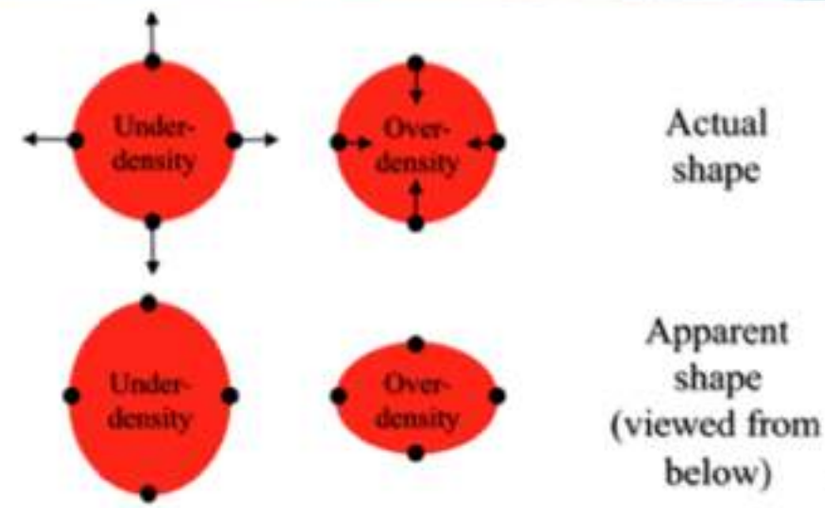
(Schwarz et al. 2014)

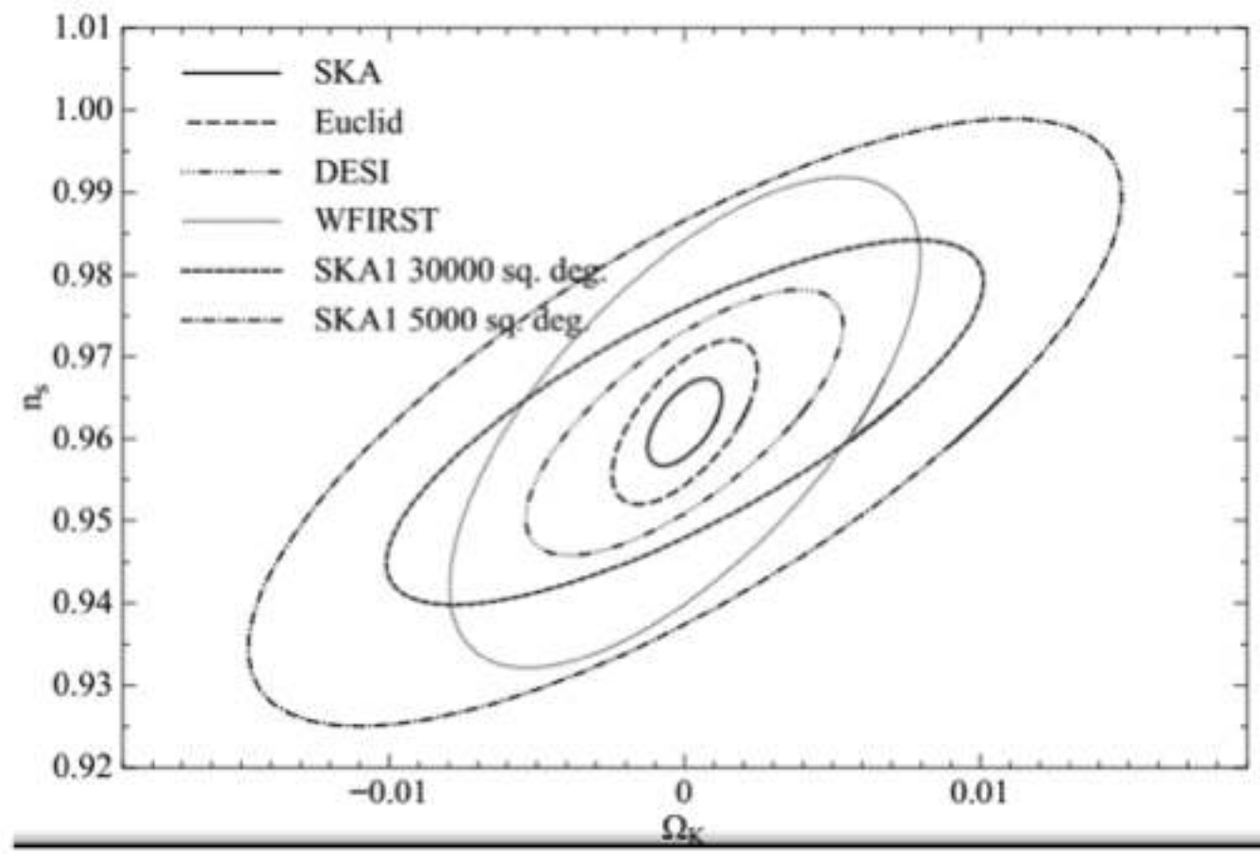
- Sensitive constraints on isotropy and homogeneity
  - Unique tests of isotropy at z ~ 1
  - Measure cosmic matter dipole with high precision

Cosmology with SKA: Redshift space distortions



Modified Gravity





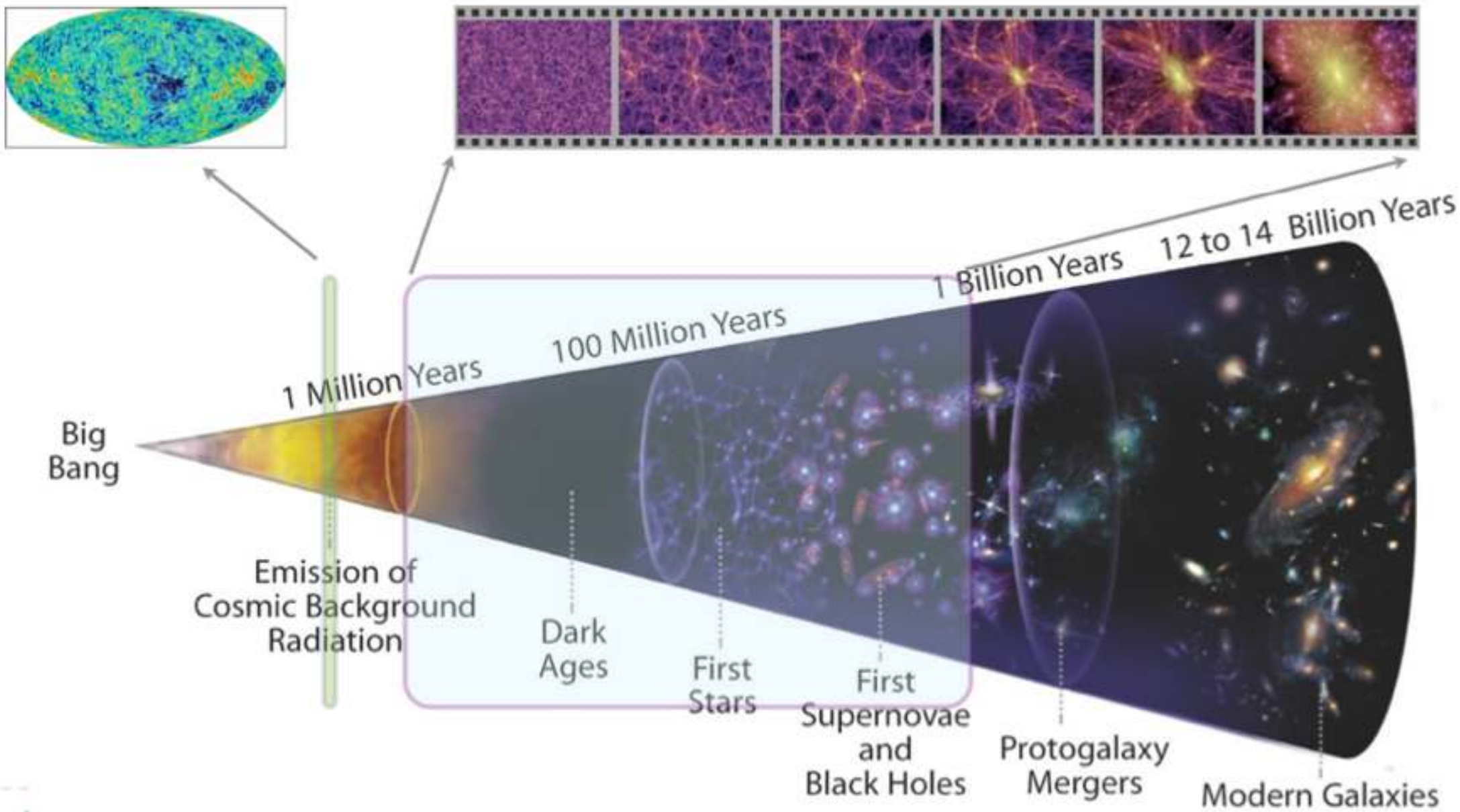
Curvature

- Constraining modified gravity and curvature with discrete HI galaxy surveys
  - Discrete detection is complementary with SKA1, cutting edge with SKA2

HI surveys of the EoR, Cosmic-Dawn & Dark Ages

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

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



SKA

SQUARE KILOMETRE ARRAY

Spain

- http://spain.skatelescope.org/
- Gathers Spanish efforts aimed at making Spain part of SKA
- Contact person: Lourdes Verdes-Montenegro (IAA-CSIC)

Spanish participation in SKA Science groups

Epoch of Re-ionization

- Diego Herranz (IFCA), A. Rubiño (IAC), J. M. Rodriquez (IAC)

Extragalactic Continuum (galaxies/AGN, galaxy clusters)

- Antxón Alberdi (IAA)
- Miguel Pérez-Torres (IAA)
- Iván Agudo (IAA)
- Fatemeh Tabatabaei (IAC)

Cosmology

- Enrique Martínez-González (IFCA)
- Diego Herranz (IFCA), Olga Mena (UV-CSIC)
- Jose A. Rubiño (IAC), Ricardo Génova (IAC)

HI Galaxy Science

- Lourdes Verdes-Montenegro (IAA)
- Bjorn Emonts (CAB)
- J. Sánchez-Almeida (IAC), J. Beckman (IAC)

Cosmic Magnetism

- Iván Agudo (IAA)
- Eduardo Battaner (UGR)
- Josep Miguel Girart (IEEC)
- F. Poidevin (IAC)

Our Galaxy

- Antxón Alberdi (IAA)
- Rainer Schöedel (IAA)

Transients

- Miguel Pérez-Torres (IAA)
- Iván Agudo (IAA)
- Eric Kuulkers (ESA)
- Simone Migliari (ESA)

Extragalactic spectral line
Craddle of life
Pulsars
Solar, heliospheric and ionospheric physics

SPANISH CONTRIBUTION TO SKA PRE-CONSTRUCTION

- **11 Spanish research centres and 12 companies participate in 7 SKA Pre-construction Consortia (~2 M€ Feb 2014):**

- Instituto de Física de Cantabria (CSIC) **Dish**
- Dpto. de Ingeniería de Comunicaciones (Universidad de Cantabria) **Dish**
- Universidad Pública de Navarra (UPN) **Dish**
- Instituto de Astrofísica de Andalucía (IAA-CSIC) **Science Data Processor; Infra-SA&AUS**
- Fundación Centro de Supercomputación Castilla-León (FCSCL) **Science Data Processor**
- Barcelona Supercomputing Center **Science Data Processor**
- Observatorio Astronómico Nacional (Instituto Geográfico Nacional) **Dish**
- Plataforma Solar de Almería (CIEMAT) **Infra-SA, Infra-AUS**
- Universidad Politécnica de Madrid **Central Signal Processor**
- Universidad de Granada **Synchronization and Data Transport**
- Universidad Politécnica de Valencia **Synchronization and Data Transport**

Under discussions:

- Institut de Ciències de l'Espai (CSIC) **Telescope Manager**

SPANISH CONTRIBUTION TO SKA PRE-CONSTRUCTION

- **11 Spanish research centres and 12companies participate in 7 SKA Pre-construction Consortia (~2 M€ Feb 2014):**

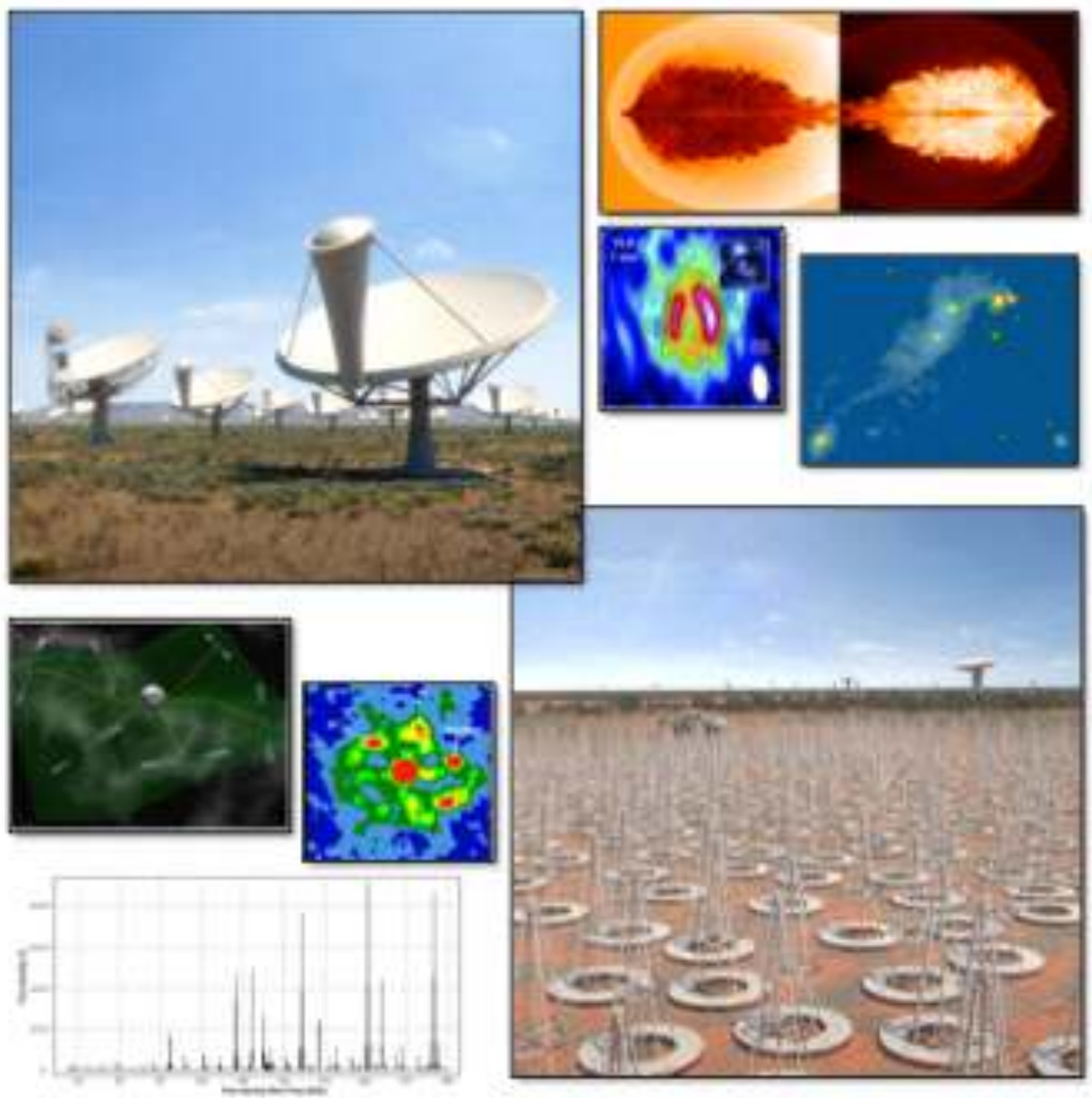
- TTI Norte
- Anteral
- 7 Solutions
- Das Photonics
- ISDEFE
- GTD
- iGrid-TD
- Arraela
- Aora Solar Spain
- CSP Sunless
- Torresol Energy
- GMV

- Dish
- Signal & Data Transport
- Central Signal Processor
- Science Data Processor
- Telescope Manager
- Infraestructure - Australia
- Infrastructure - South Africa

The Spanish Square Kilometre Array White Book

Editors
Miguel Pérez-Torres
Lourdes Verdes-Montenegro
José Carlos Guirado
Antonio Alberdi
Jesús Martín-Pintado
Rafael Bachiller
Diego Herranz
Josep Miquel Girart
Simone Migliari
José Miguel Rodríguez-Espinosa

SKA
SQUARE KILOMETRE ARRAY
Spain



- Make aware the whole Spanish astronomical community
- Show the interests of our community and our ability to successfully exploit the SKA capabilities
- 120 researchers involved
- 29 chapters
- SKA Science Headlines well represented

The SKA in one slide