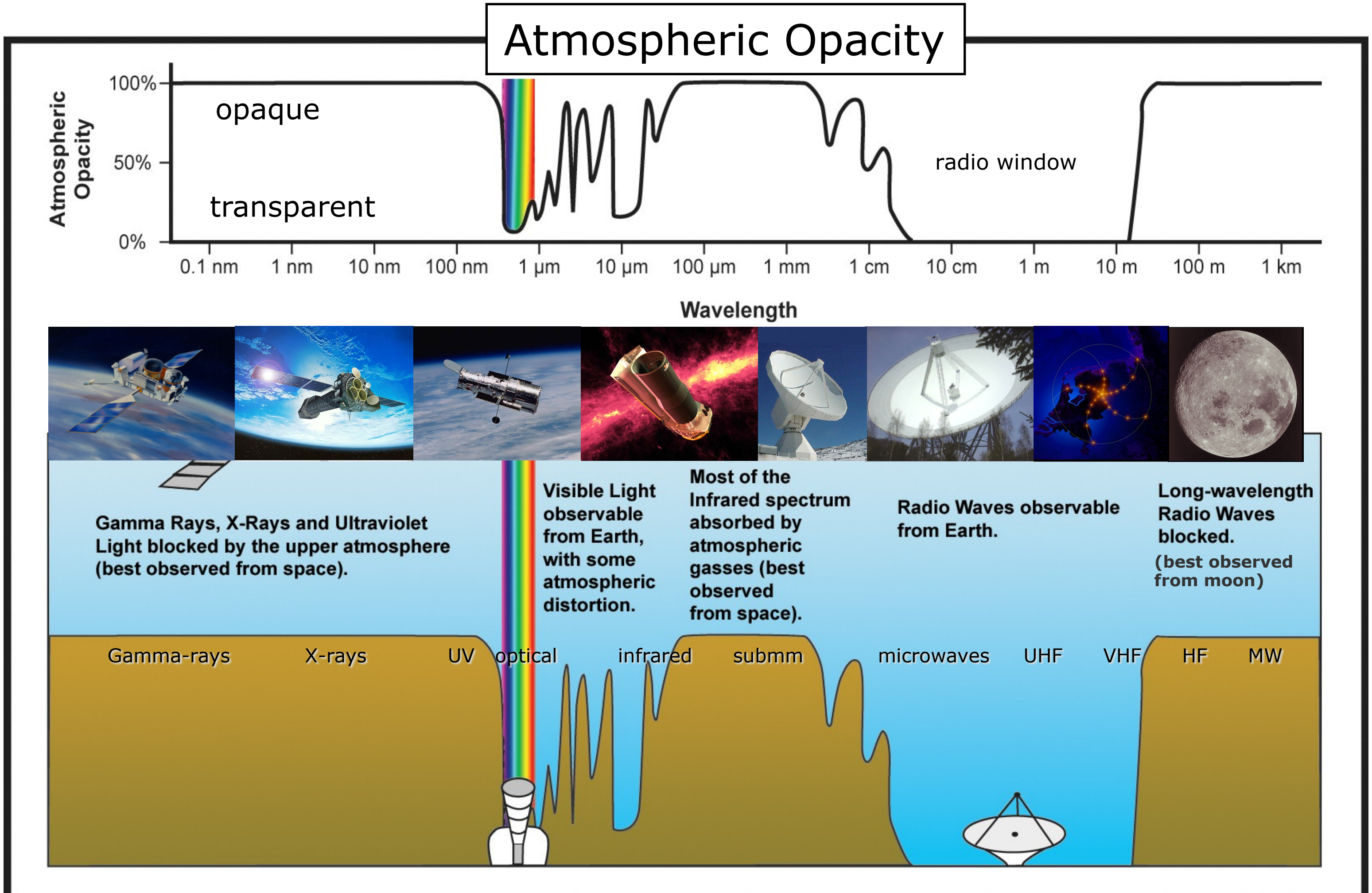
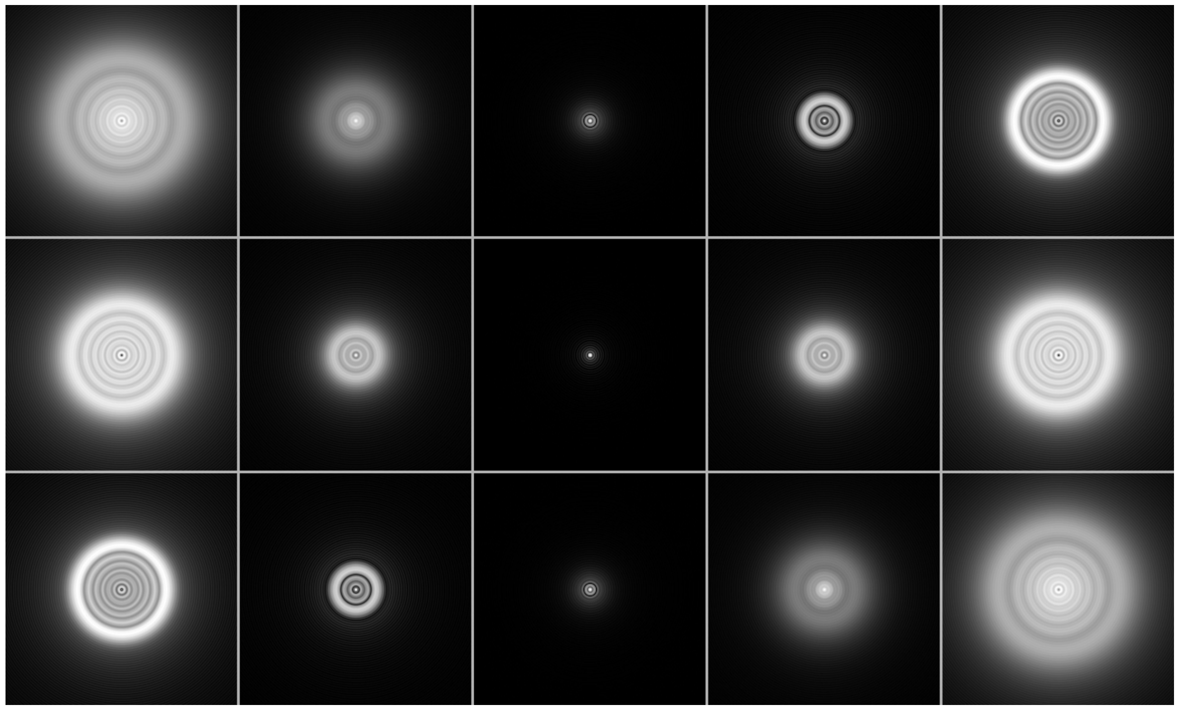
The radio Universe as seen through the Square Kilometre Array and its precursors

Marcus Brüggen
Universität Hamburg

Unser Fenster zum Universum



Light is a wave

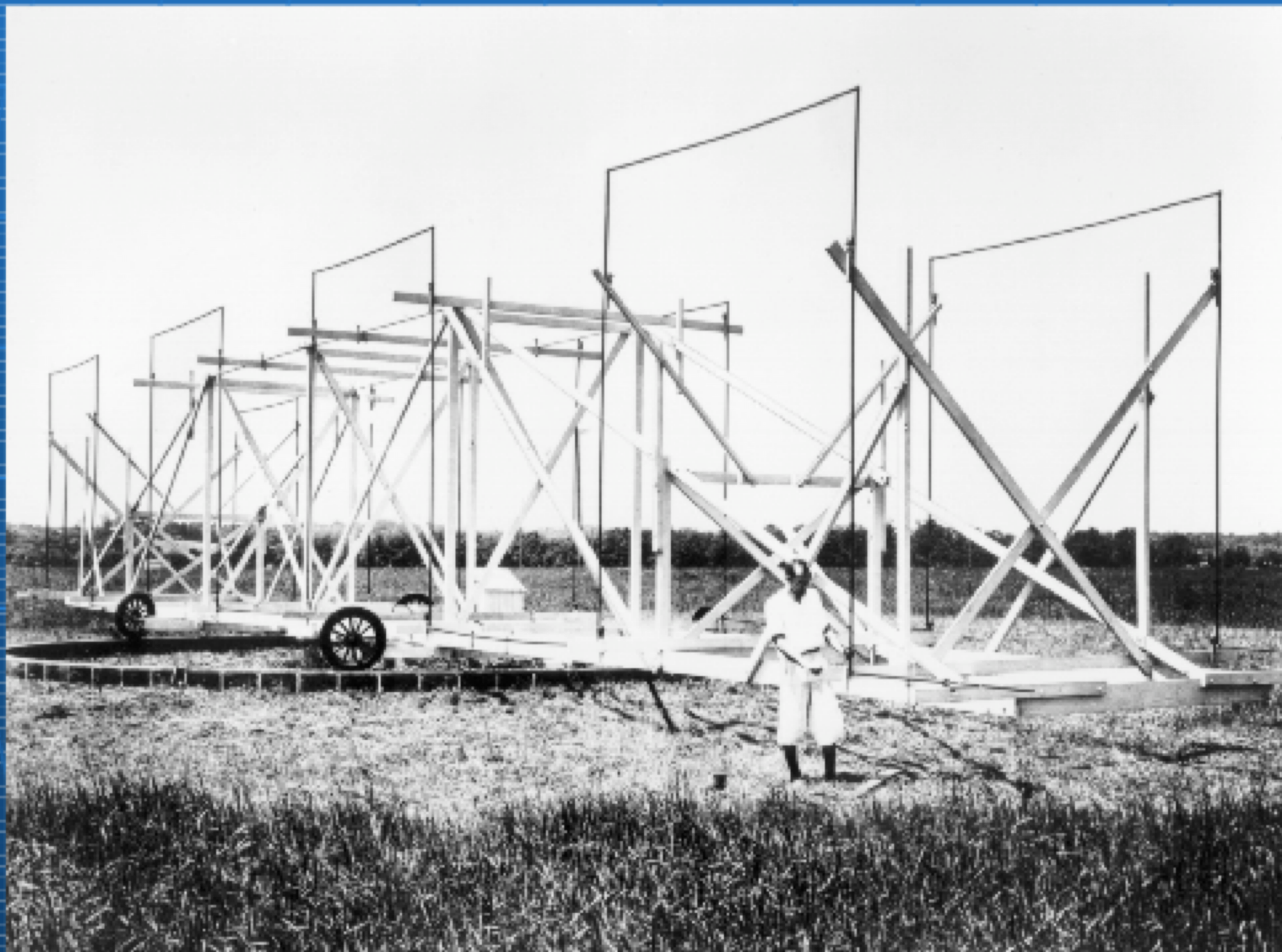


The resolution of a telescope $$\Delta\theta \sim \lambda/D$$

$$\lambda = 30\,\mathrm{m} \qquad D = 300\,\mathrm{m} \qquad \Delta\theta = 6^o$$

Das erste Radioteleskop

10 MHz (30 m)



Karl Jansky 1931 (USA)

NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY

Mysterious Static, Reported by K. G. Jansky, Held to Differ From Cosmic Ray.

DIRECTION IS UNCHANGING

Recorded and Tested for More Than Year to Identify It as From Earth's Galaxy.

ITS INTENSITY IS LOW

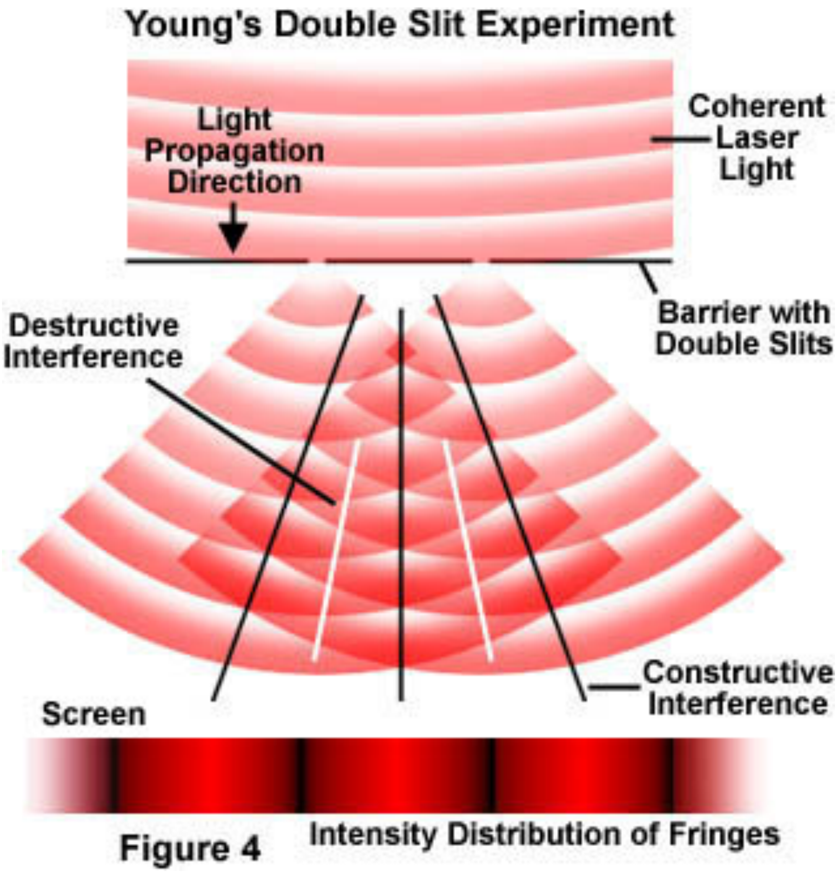
Only Delicate Receiver Is Able to Register—No Evidence of Interstellar Signaling.

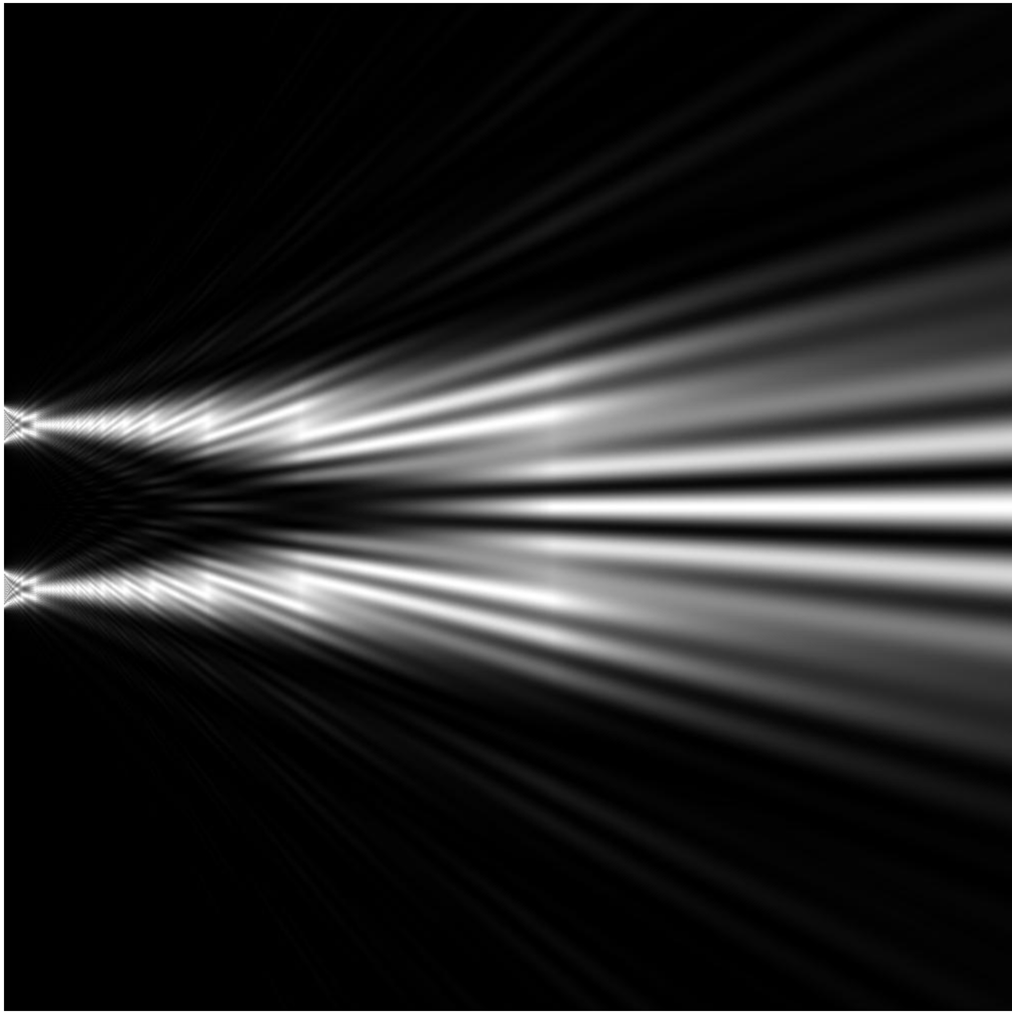
Discovery of mysterious radio waves which appear to come from the centre of the Milky Way galaxy was announced yesterday by the Bell Telephone Laboratories. The discovery was made during research studies on static by Karl G. Jansky of the radio research department at Holmdel, N. J., and was described by him in a paper delivered before the International Scientific Radio Union in Washington.

The galactic radio waves, Mr. Jansky said, differ from the cosmic rays and also from the phenomenon of cosmic radiation, described last week before the American Philosophical Society at Philadelphia by

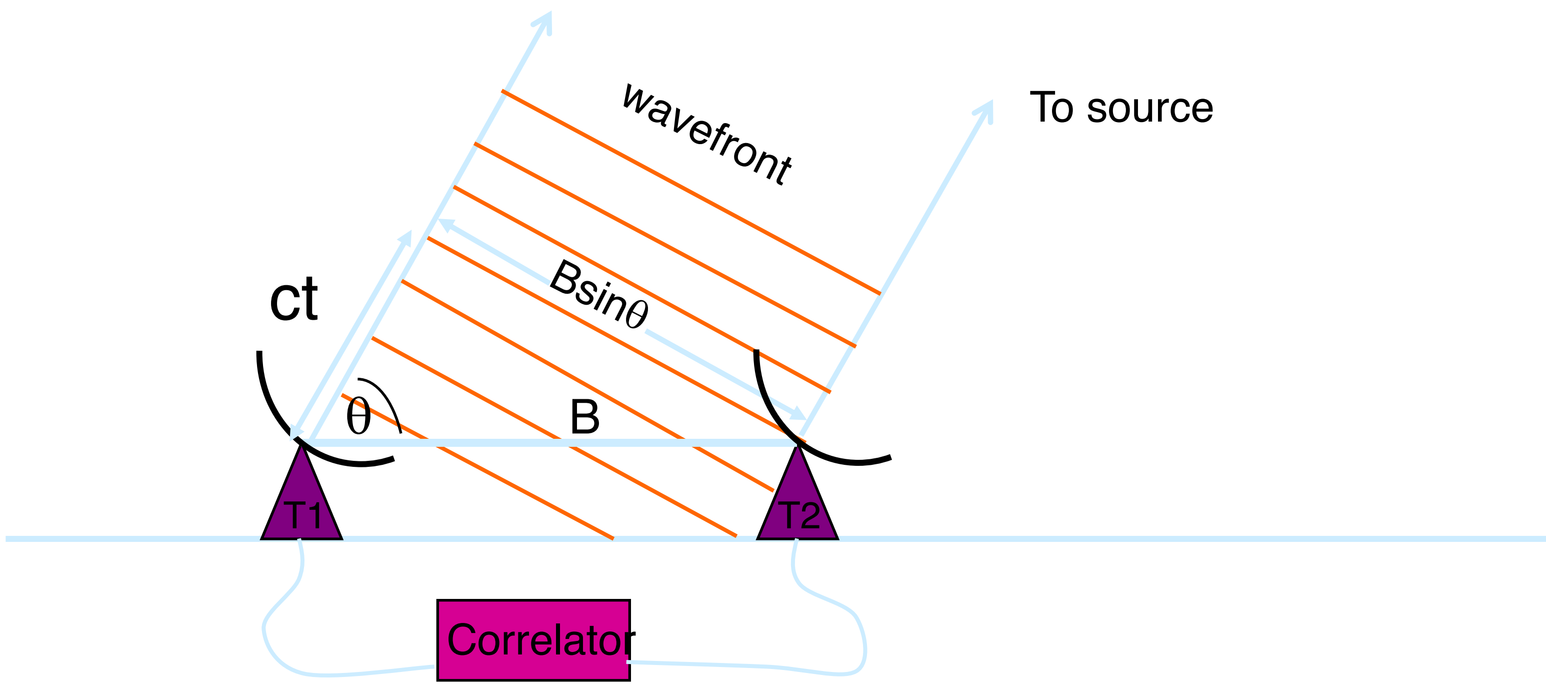
300 m dish in Arecibo: l / D ~ 48” at = 6 cm (5 GHz)

Double-slit Experiment



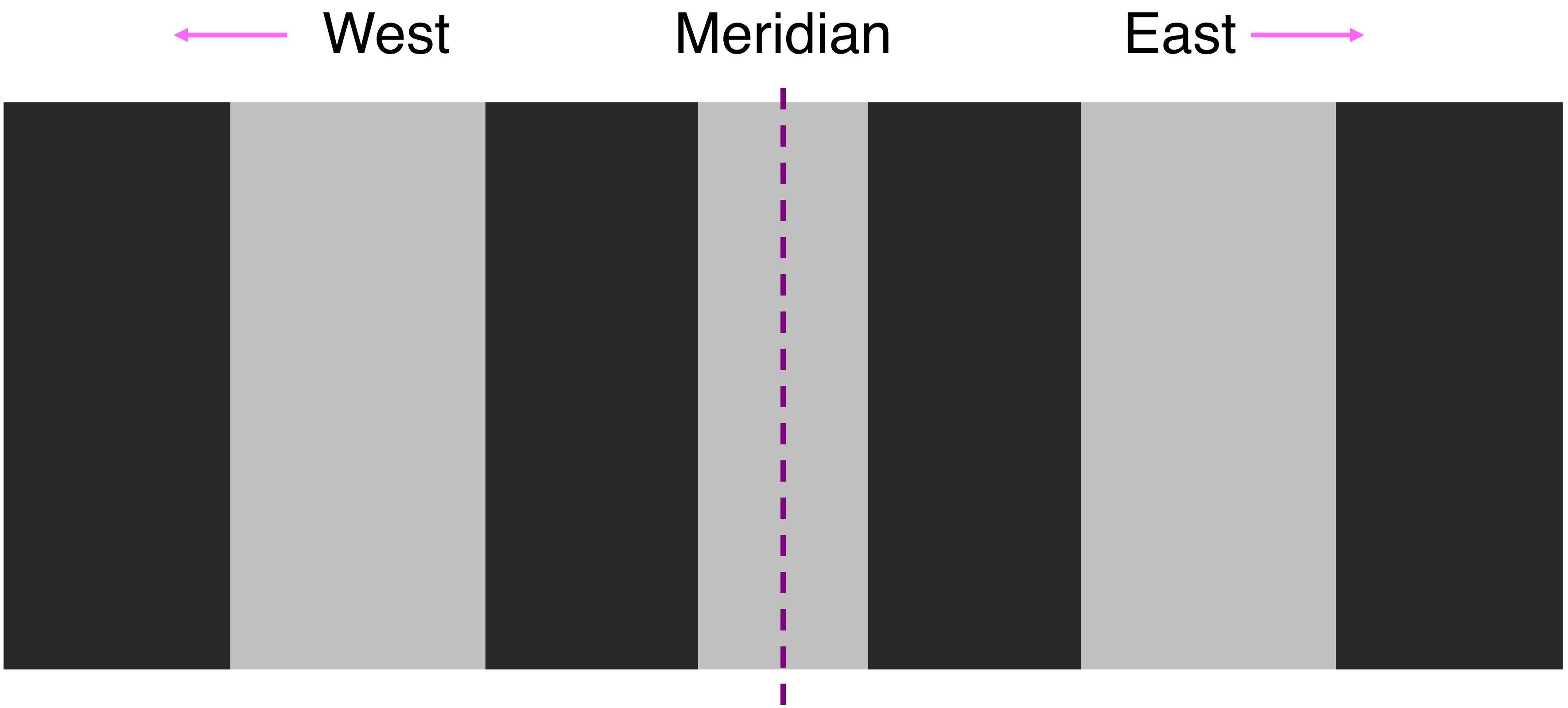


Interferometer

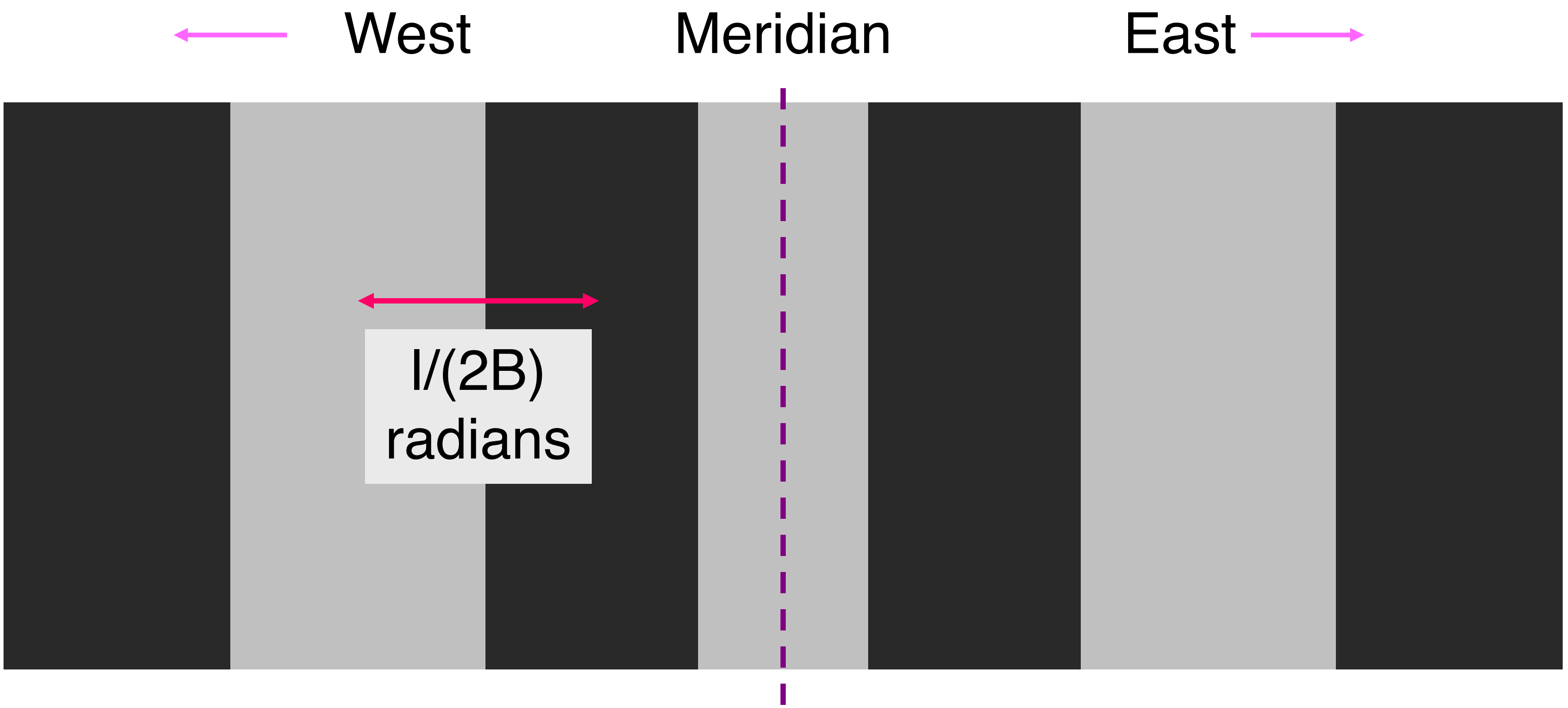


- Wegunterschied zu Teleskopen führt dazu, dass die Wellen mit verschiedenen Phasen ankommen

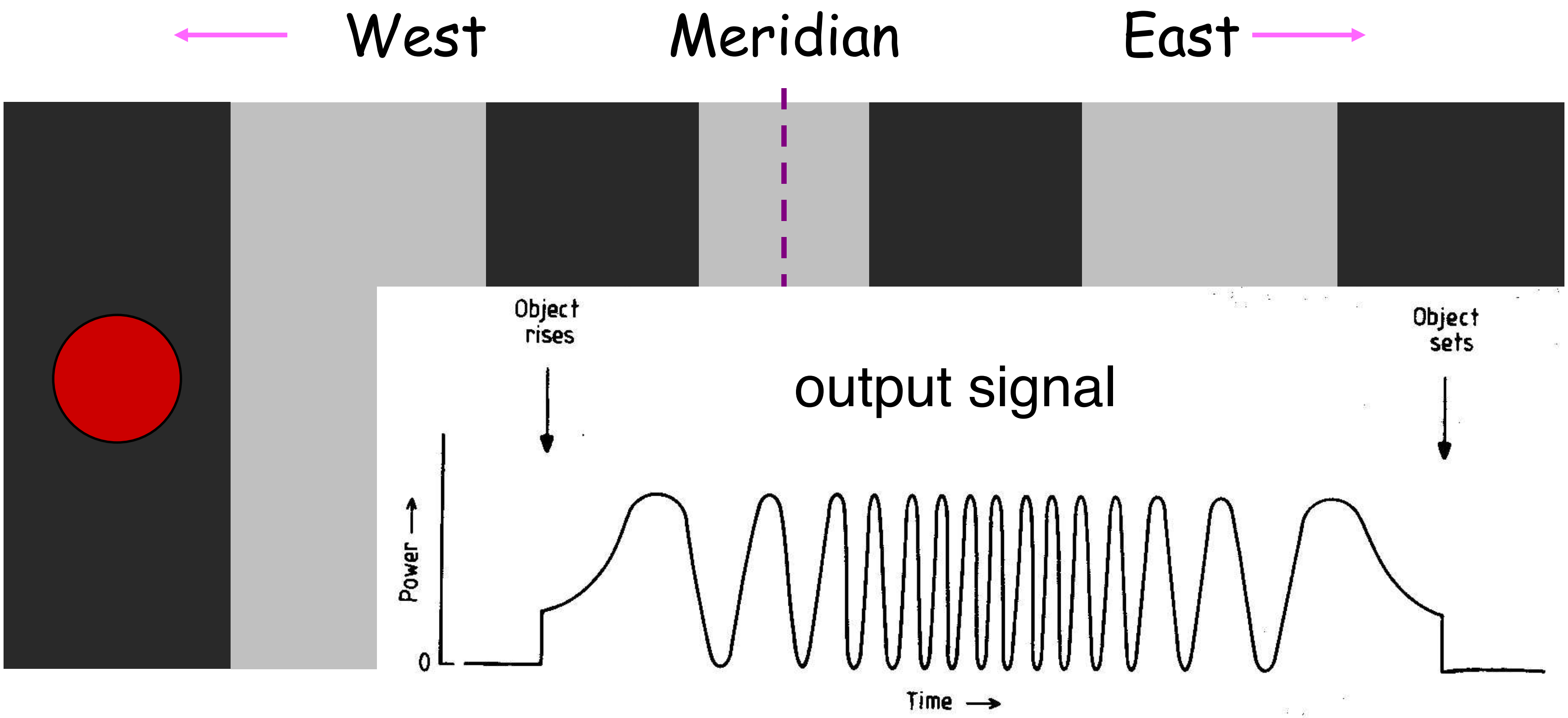
- Im Himmel gibt es Regionen die konstruktiv und destruktiv interferieren



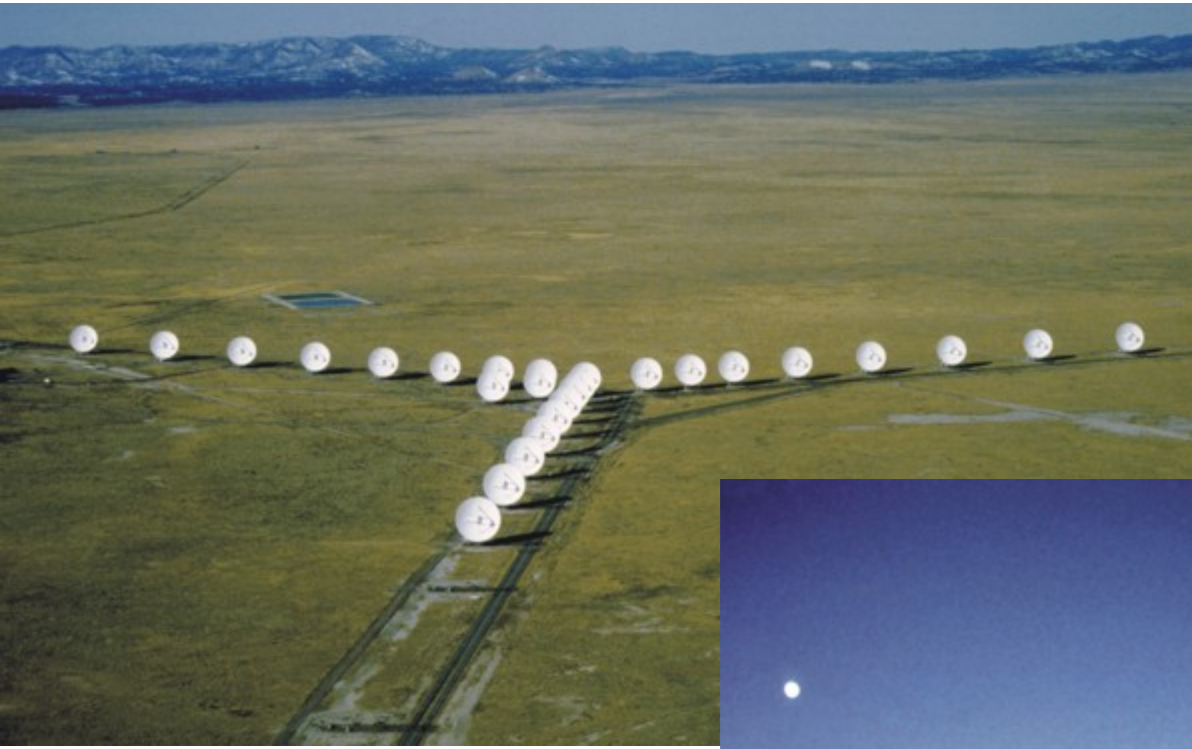
Breite der Streifen hängt von dem Abstand zwischen den Teleskopen und der Wellenlänge ab



- Da die Erde rotiert, bewegen sich Quellen über den Himmel und interferieren abwechselnd konstruktiv und destruktiv



Radiotelescope Arrays



VLA:

27 Antennas with 25 meters diameter

Maximal Baseline: 36 km

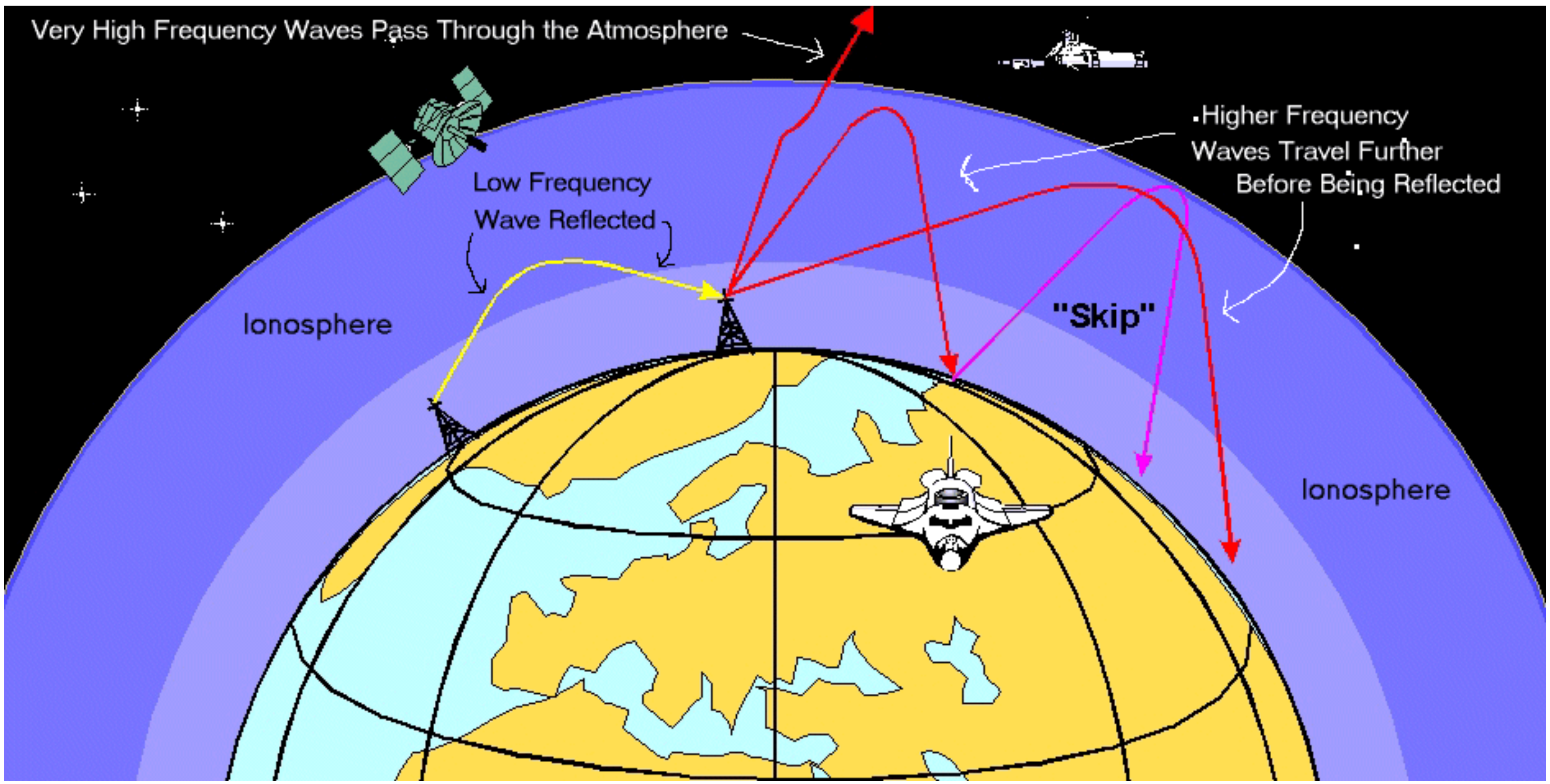
75 Mhz to 43 GHz

Very Long Baseline Array

- 10 × 25m Antennas
- Across continents: Durchmesser: 5400 Miles
  - 6 cm/5400 Miles
    = 0.001 arc-second
- Höchste Auflösung:

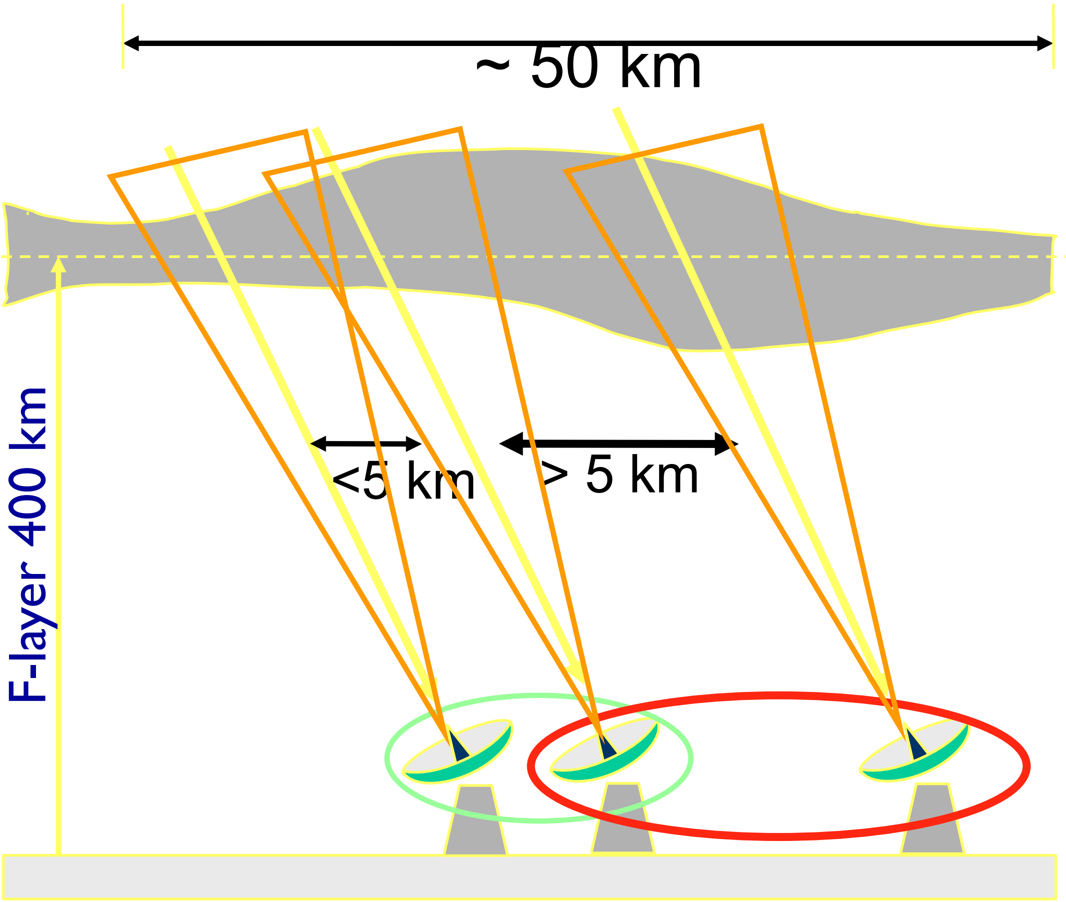
1 milli-arc-second = reading a newspaper from a distance of 2000 km

Lange Wellen werden von der Ionosphäre reflektiert



Ionosphere

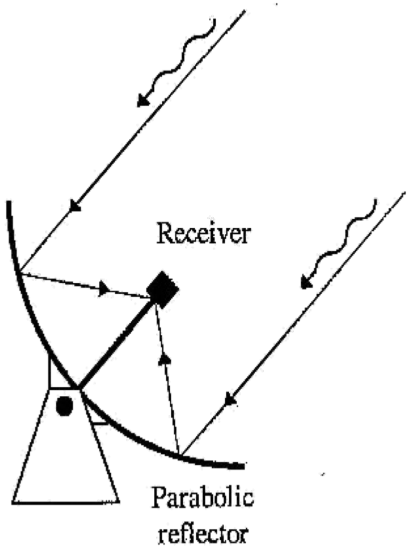
- Ionosphere introduces phase errors in radio signal

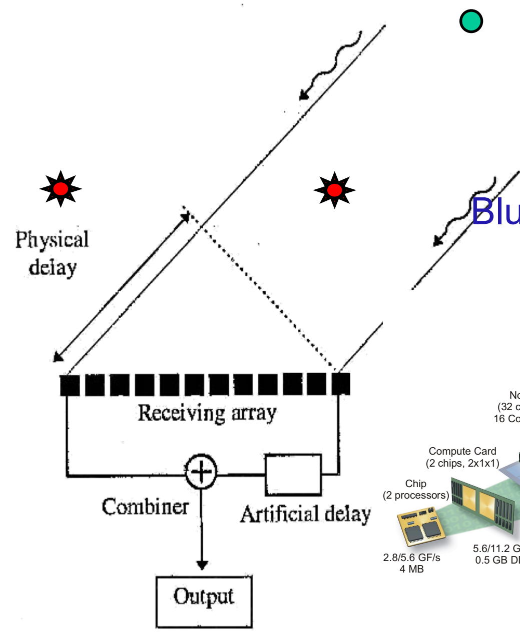


Correlation preserved Correlation destroyed

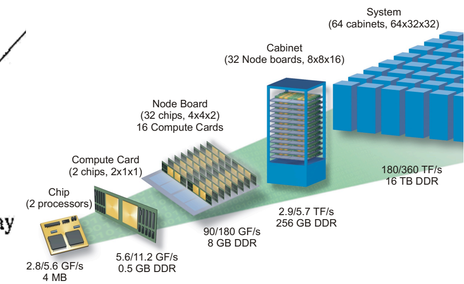
- Waves in the ionosphere introduce rapid phase variations (~1° /s on 35 km BL)
- Phase coherence is preserved on BL < 5km (gradient)
- BL > 5 km have limited coherence times
- Without proper algorithms this limits the capabilities of low frequency instruments

Electronic beamforming





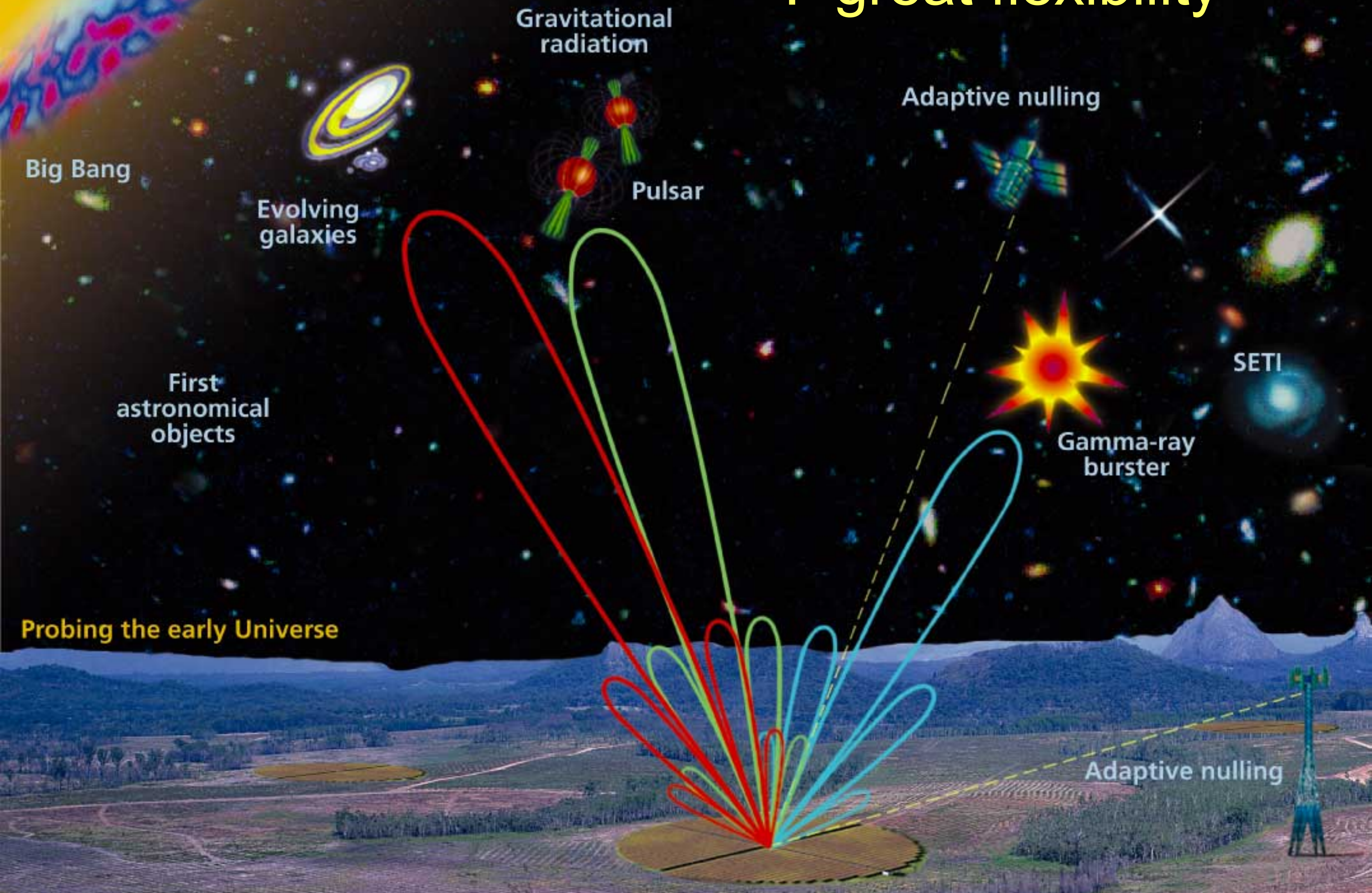
Blue Gene™ (IBM)

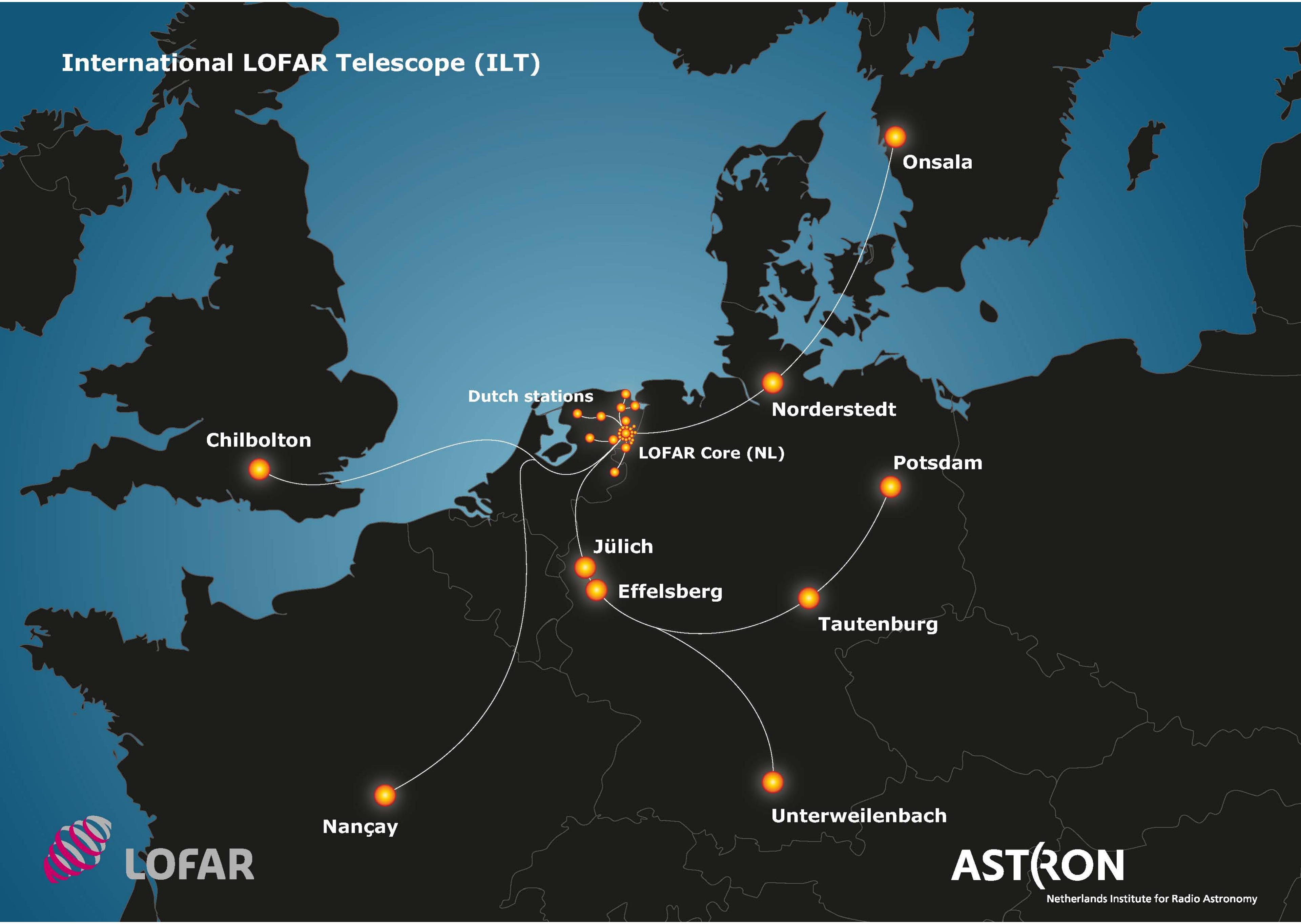


0.5 Tbit/s

25 Tflops

Phased arrays offer: many beams
: great flexibility




International LOFAR Telescope (ILT)
Onsala
Dutch stations
Norderstedt
Chilbolton
LOFAR Core (NL)
Potsdam
Jülich
Effelsberg
Tautenburg
Nançay
Unterweilenbach
LOFAR
ASTRON
Netherlands Institute for Radio Astronomy

UHH
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
Universität Bielefeld
Neubau einer Radioempfangsstation für astronomische Zwecke
(LOFAR)
Bauherrin und Bauplanung: Universität Hamburg
Bauleiter: Architekt M. Karzenburg, Universität Hamburg,
Mittelweg 177, 20148 Hamburg
Generalunternehmer: A. Hak Telecom B.V., Zwolle, NL

Why low frequencies?

Low Frequency Emission

Synchrotron Continuum:

- Best observed at $\nu < 1$ GHz
- Relativistic e^- in magnetic fields
- F(energy of the e^-, density, B)
- Emission is polarized
- Coherent or incoherent

Redshifted 21cm Line:

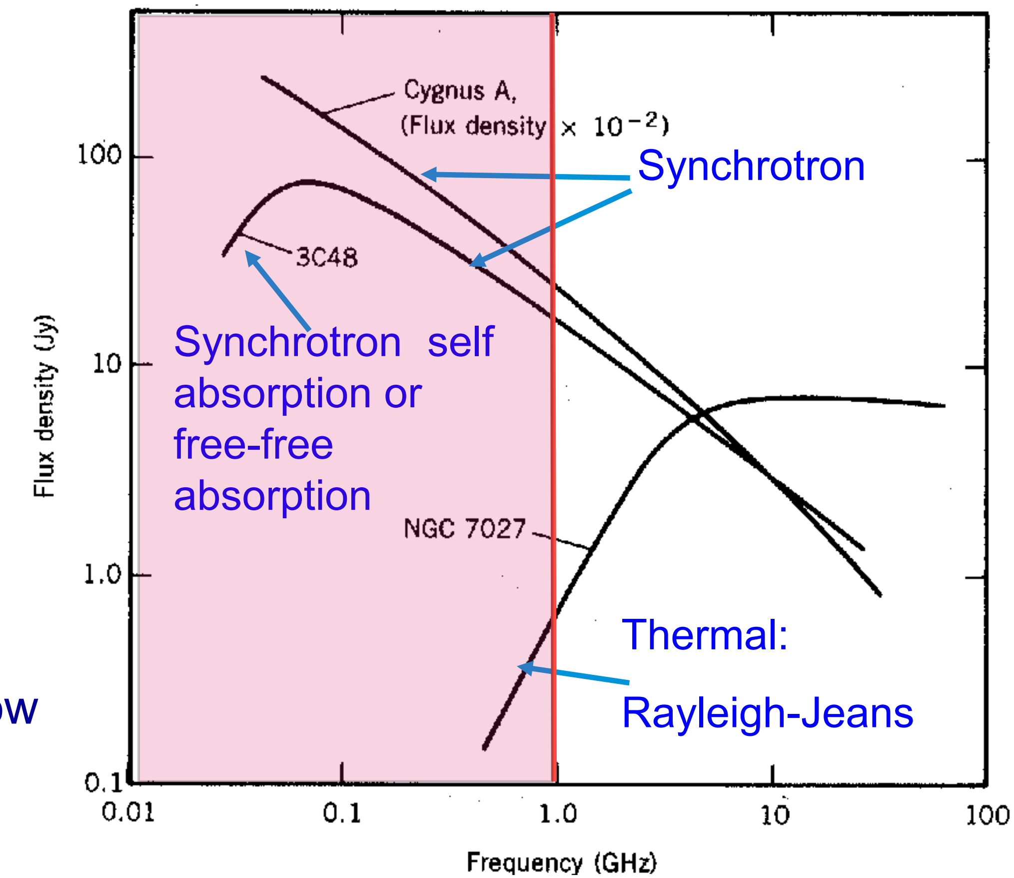
- ν = 1420/(1+z) MHz

Radio Recombination Lines:

- Probe of ISM conditions: low temp, low density

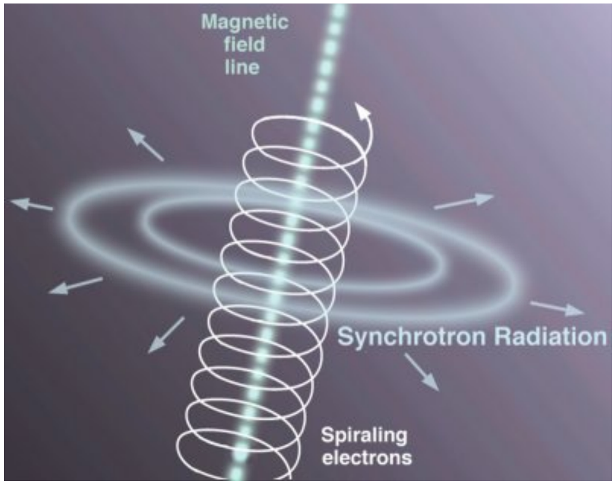
Bremsstrahlung: (thermal free-free):

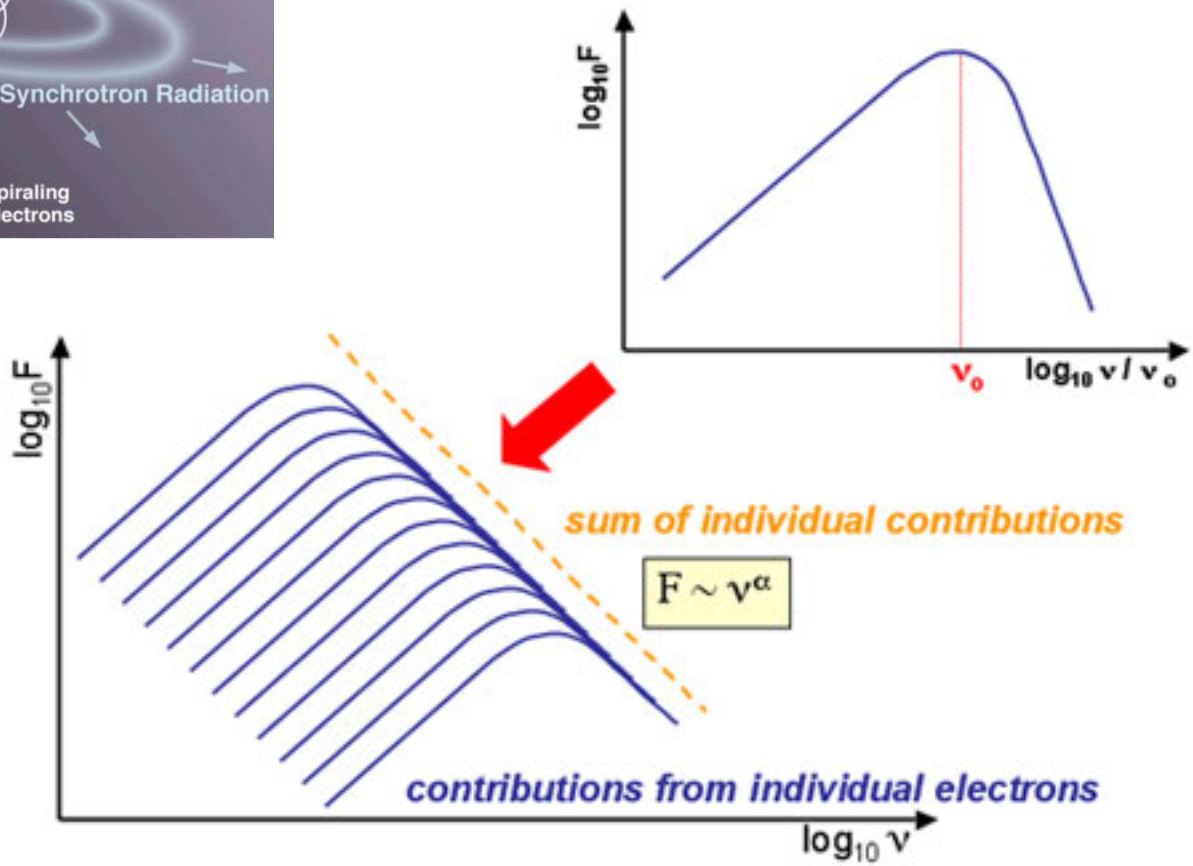
- Best observed at $\nu > 1$ GHz
- Acceleration of free electrons by ions



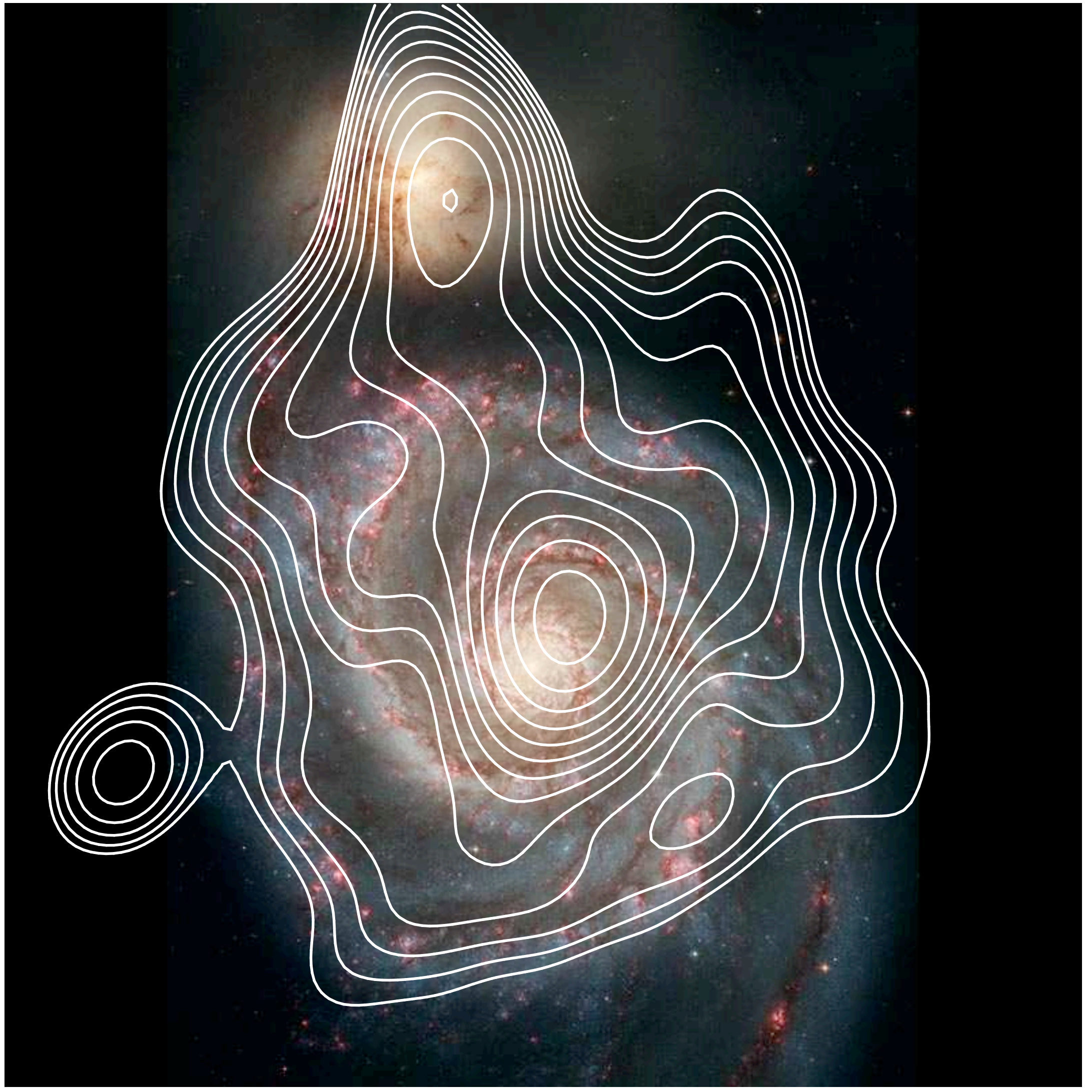
Thompson, Moran, & Swenson

Synchrotron Emission



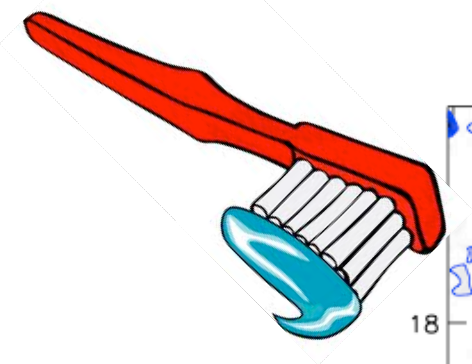


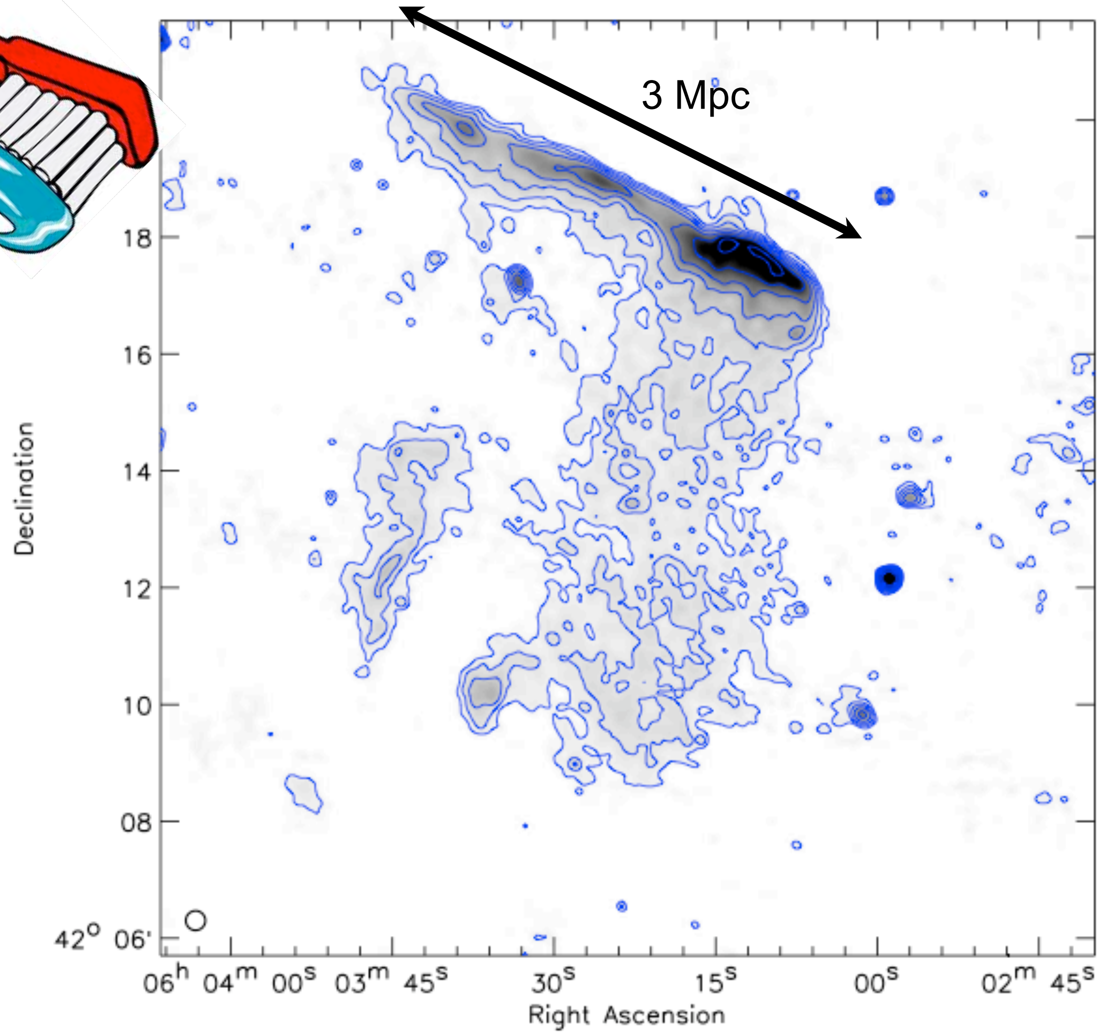
M51



Credit: G. Heald

1RXS J0603.3+4213



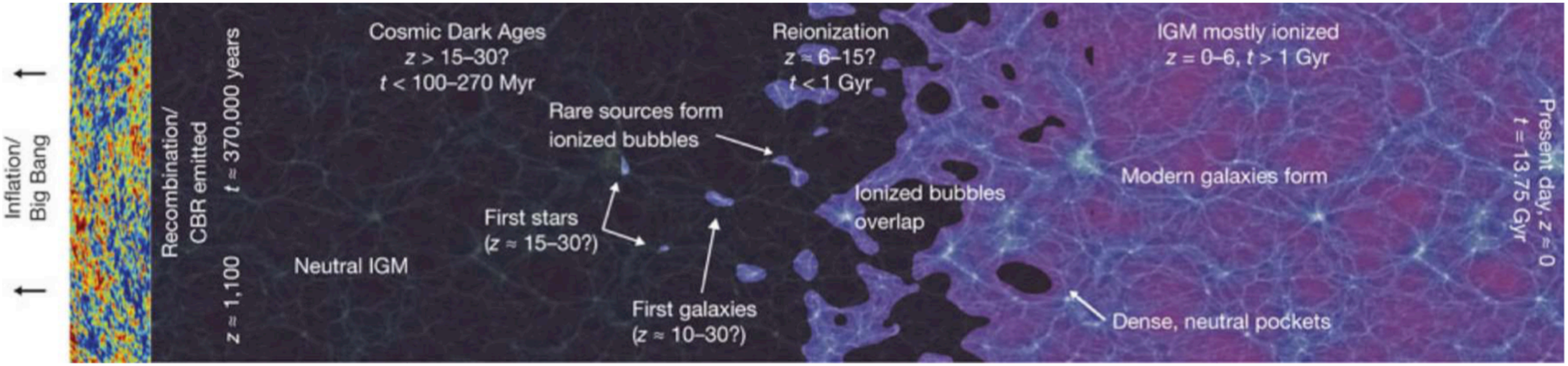


largest relic known to date

z=0.25

610 MHz GMRT map

Cosmic Dawn & EoR

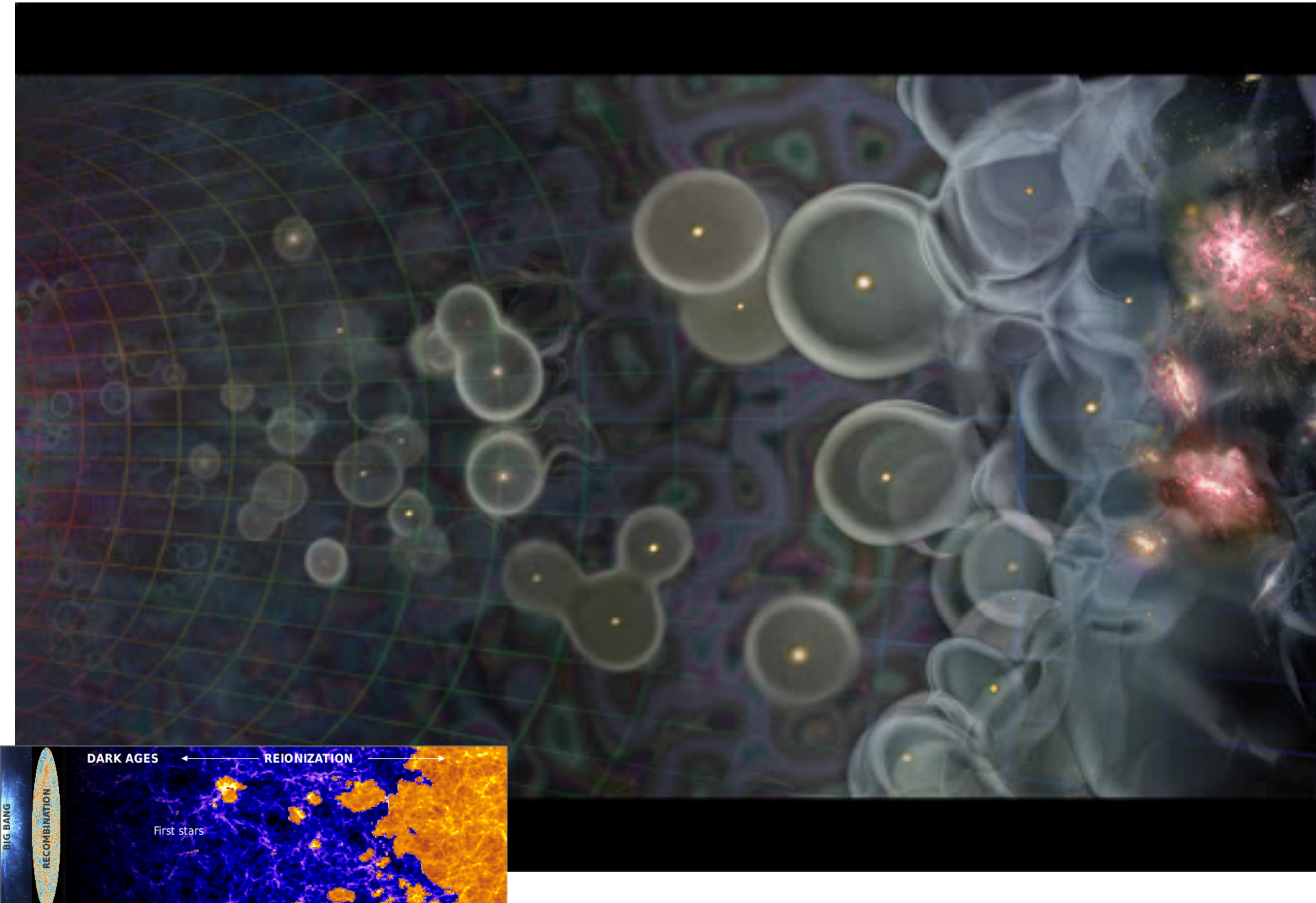


From Koopmans et al. *"The Cosmic Dawn and Epoch of Reionization with the Square Kilometre Array"* (2015)

"When was the last time your baryons did something interesting?"

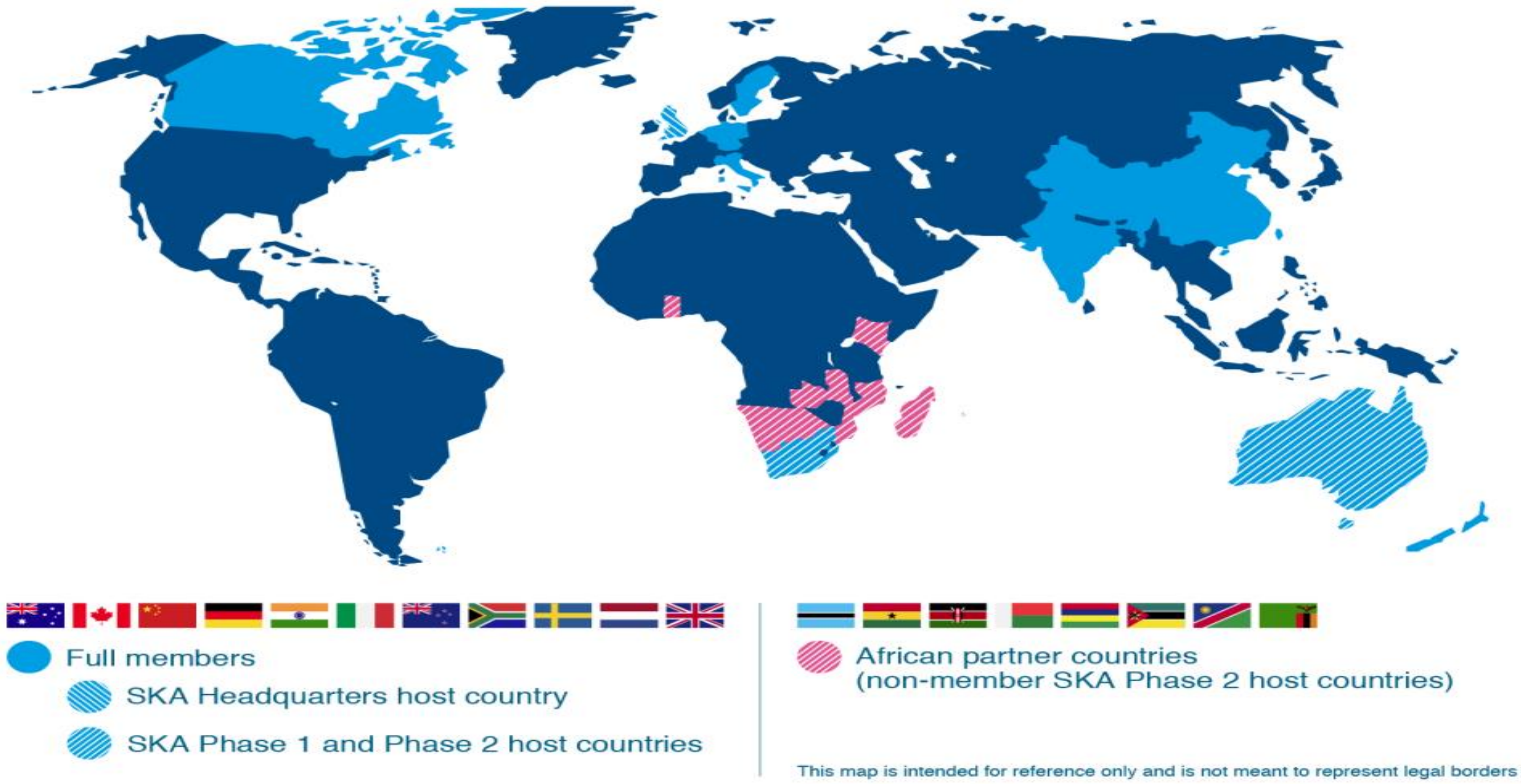
Sangeeta Malhotra

Epoch of Re-ionization



WHAT IS SKA?

- **Global non-profit Organisation**
- **Headquarters in Manchester, United Kingdom**
- **Ten member countries**



SKA: The Hydrogen Array

SQUARE KILOMETRE ARRAY

Early concept stated in in 1990

Core science already established:

- Neutral Hydrogen from z=1 to 10
- Continuum at 0.1 μJy 1σ noise level
- Pulsar searches and timing across the galaxy

1991ASPC...19..428W

Radio Interferometry: Theory, Techniques and Applications, IAU Coll. 131, ASP Conference Series, Vol. 19, 1991, T.J. Cornwell and R.A. Perley (eds.)

THE HYDROGEN ARRAY

P.N. WILKINSON
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield, Cheshire, SK11 9DL, United Kingdom

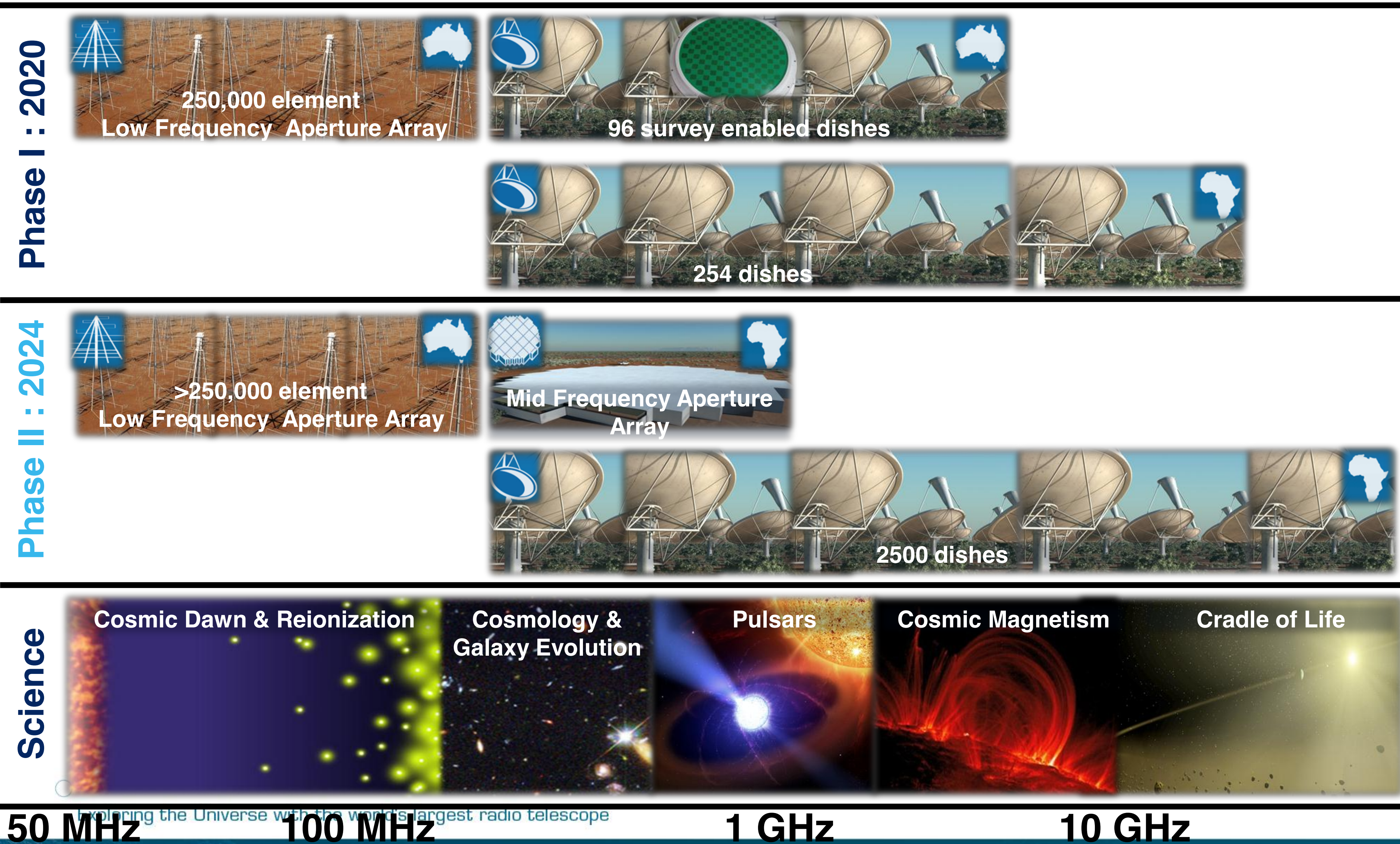
ABSTRACT The time is ripe for planning an array with a collecting area of 1 km^2 (14 times larger than Arecibo and 75 times larger than the VLA). In view of its major astronomical target I have dubbed this concept 'The Hydrogen Array', although 1μJy continuum sources will also be reliably detected. I present some initial thoughts about the issues involved.

INTRODUCTION

Since the late 1960s radioastronomers have increased the capability of their instruments many fold. The maximum resolution achieved with interferometry has increased from ~ 50 milliarcsec to ~ 50 microarcsec; the highest frequency in use has gone from ~ 10 GHz to > 350 GHz and the aperture plane coverage has improved from that of the One–Mile Telescope to that of the multi–configuration VLA. However, in terms of raw sensitivity the improvement has been less dramatic. The Arecibo telescope remains the world's largest and the improvements to system noise temperatures at decimetric and centimetric wavelengths have been relatively small ($\leq$ 5). Despite its limitations in sky and frequency coverage, the scientific output of the Arecibo telescope amply demonstrates the advantage of a collecting area 5–10 times larger than that of the largest steerable paraboloids.

https://ui.adsabs.harvard.edu/#abs/1991ASPC...19..428W/abstract

What is the SKA?



WHERE ARE THEY DOING IT?

South Africa

WHERE ARE THEY DOING IT?

South African Karoo Region

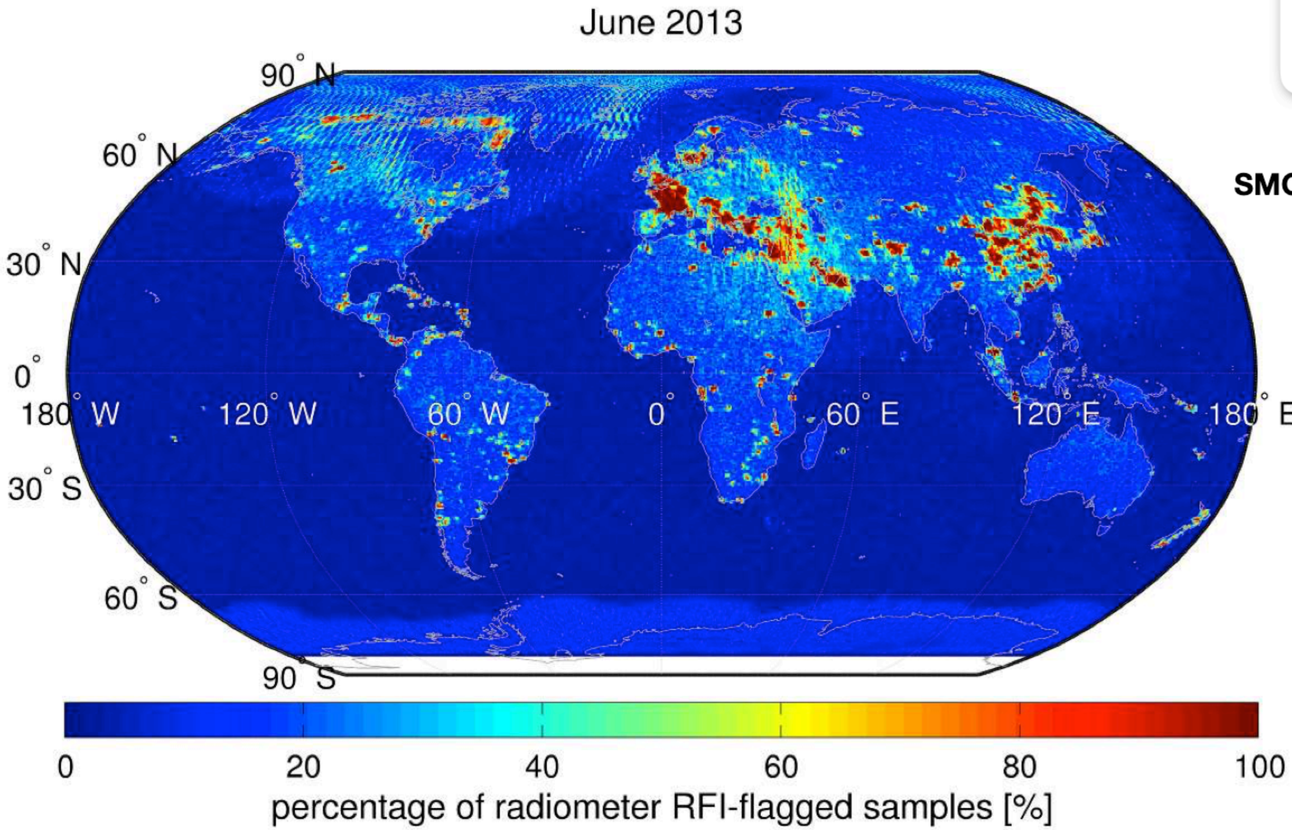
WHERE ARE THEY DOING IT?

Australia

WHERE ARE THEY DOING IT?

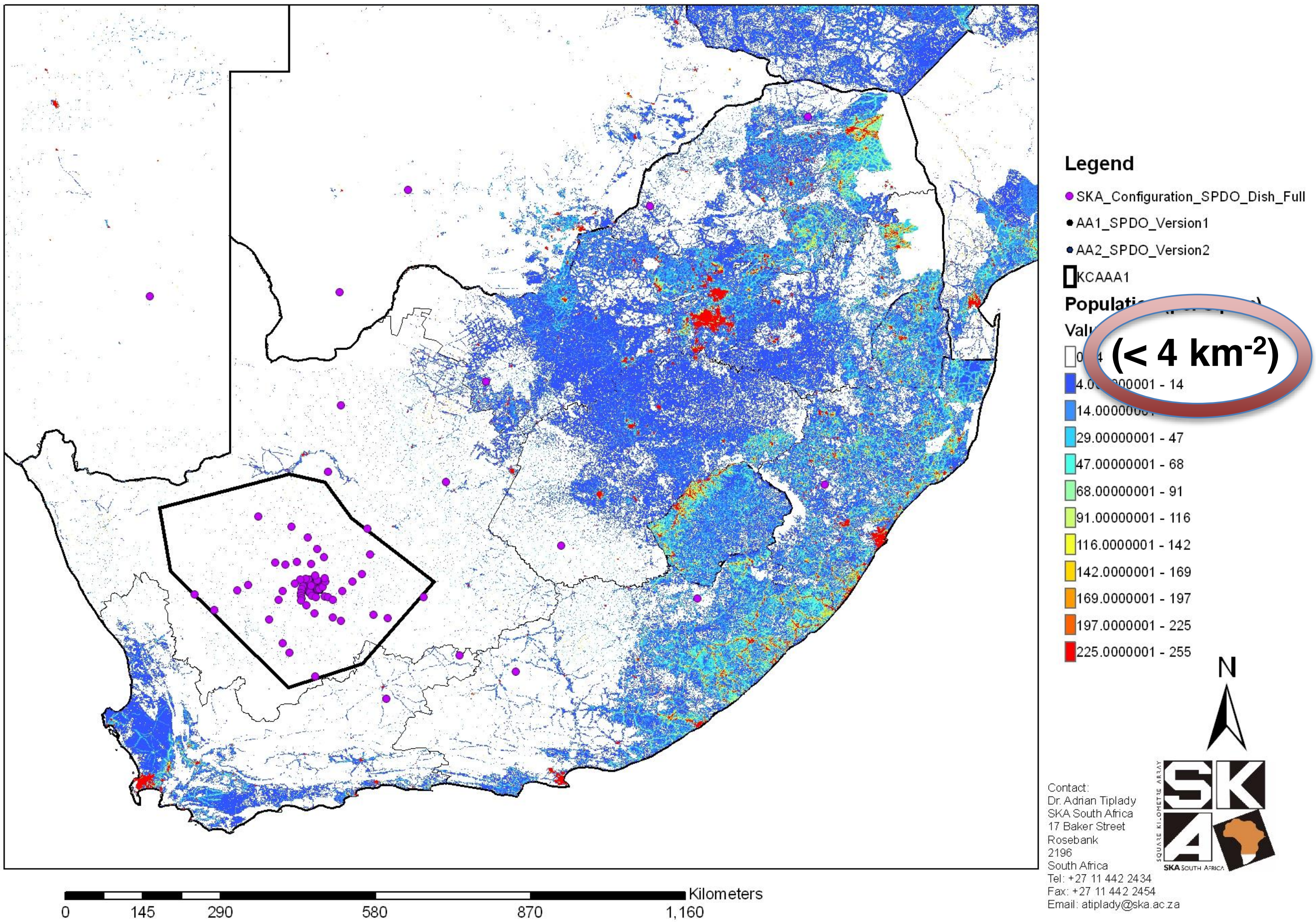
Western Australia’s Murchison Shire

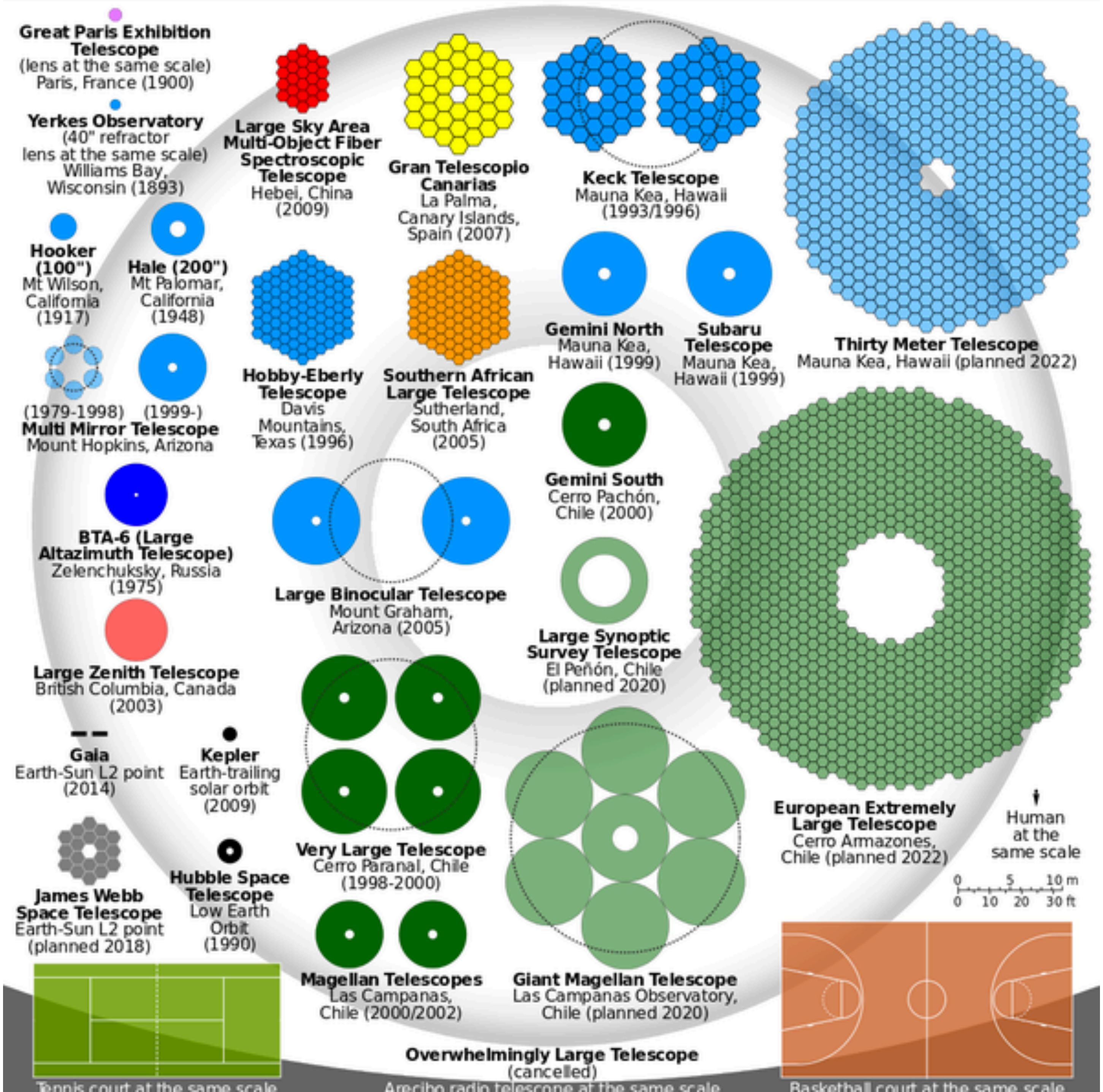
SKA Sites: RFI



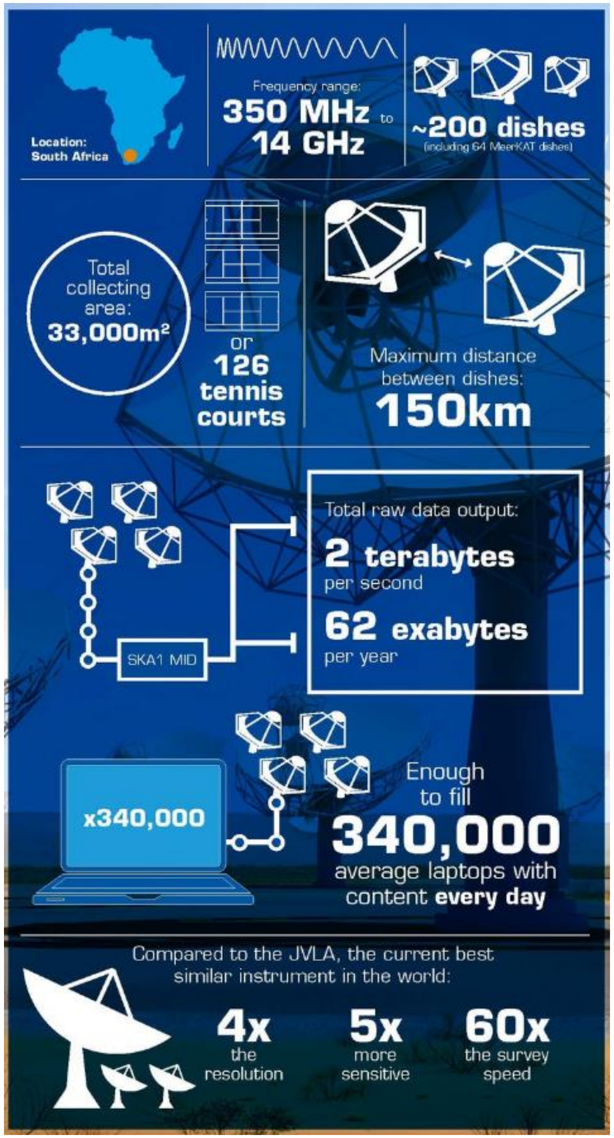
SMOS L-band (1-2 GHz)

How did we choose the sites?

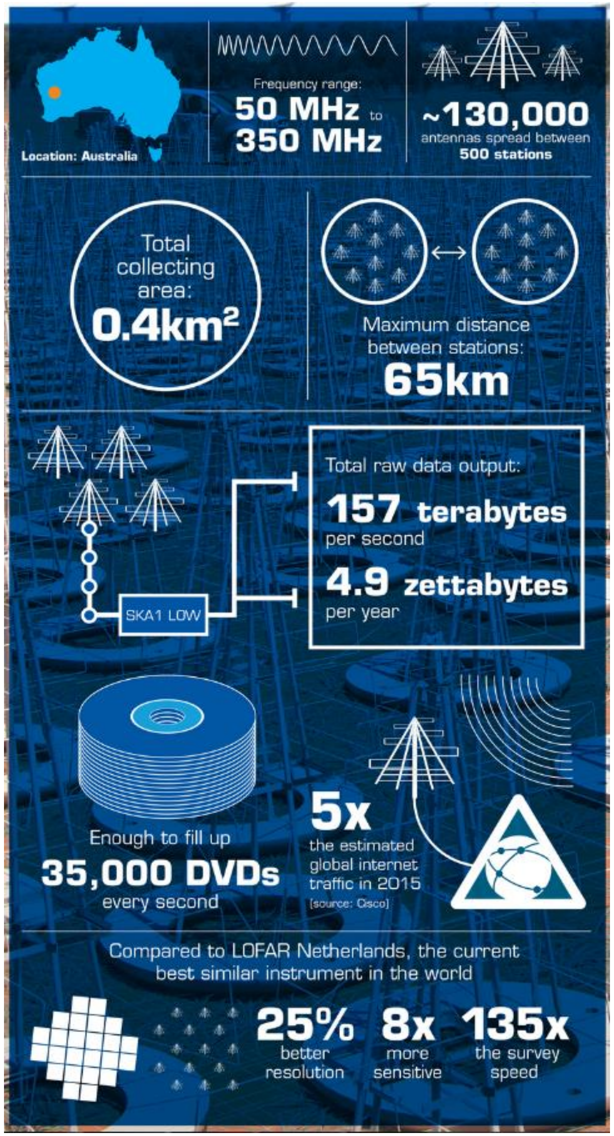



Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay,
Wisconsin (1893)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China
(2009)
Gran Telescopio Canarias
La Palma,
Canary Islands,
Spain (2007)
Keck Telescope
Mauna Kea, Hawaii
(1993/1996)
Hooker (100")
Mt Wilson,
California
(1917)
Hale (200")
Mt Palomar,
California
(1948)
Hobby-Eberly Telescope
Davis
Mountains,
Texas (1996)
Southern African Large Telescope
Sutherland,
South Africa
(2005)
Gemini North
Mauna Kea,
Hawaii (1999)
Subaru Telescope
Mauna Kea,
Hawaii (1999)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
(1979-1998) (1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
Gemini South
Cerro Pachón,
Chile (2000)
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia
(1975)
Large Binocular Telescope
Mount Graham,
Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile
(planned 2020)
Large Zenith Telescope
British Columbia, Canada
(2003)
Gaia
Earth-Sun L2 point
(2014)
Kepler
Earth-trailing
solar orbit
(2009)
Very Large Telescope
Cerro Paranal, Chile
(1998-2000)
European Extremely Large Telescope
Cerro Armazones,
Chile (planned 2022)
Human
at the
same scale
0 5 10 m
0 10 20 30 ft
James Webb Space Telescope
Earth-Sun L2 point
(planned 2018)
Hubble Space Telescope
Low Earth
Orbit
(1990)
Magellan Telescopes
Las Campanas,
Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory,
Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

SKA PHASE 1



Location: South Africa
Frequency range:
350 MHz to 14 GHz
~200 dishes
(including 64 MeerKAT dishes)
Total collecting area: 33,000m²
or 126 tennis courts
Maximum distance between dishes:
150km
SKA1 MID
Total raw data output:
2 terabytes per second
62 exabytes per year
x340,000
Enough to fill
340,000
average laptops with content every day
Compared to the JVLA, the current best similar instrument in the world:
4x the resolution
5x more sensitive
60x the survey speed



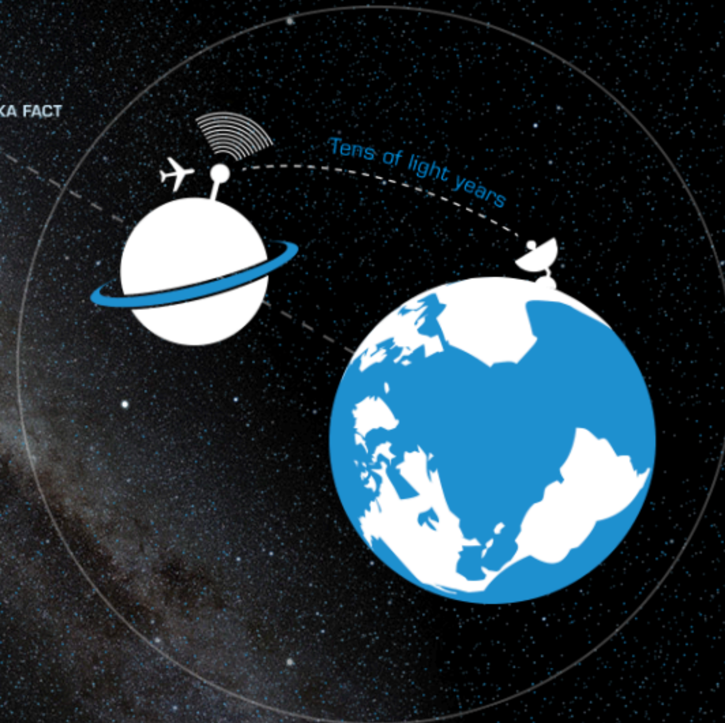
Location: Australia
Frequency range:
50 MHz to 350 MHz
~130,000
antennas spread between 500 stations
Total collecting area: 0.4km²
Maximum distance between stations:
65km
SKA1 LOW
Total raw data output:
157 terabytes per second
4.9 zettabytes per year
Enough to fill up
35,000 DVDs
every second
5x
the estimated global internet traffic in 2015
(source: Cisco)
Compared to LOFAR Netherlands, the current best similar instrument in the world
25% better resolution
8x more sensitive
135x the survey speed

SKA as the ultimate Big Data Challenge

- The SKA will generate 123 TB/s.
- Storage 1 Exabytes/yr
- The computer power needed for the SKA will be about 3 times more powerful than the most powerful supercomputer in 2013
- equivalent to the processing power of about one hundred million PCs of the same era. It is on the order of a trillion times more computing power than sent humankind to the Moon.

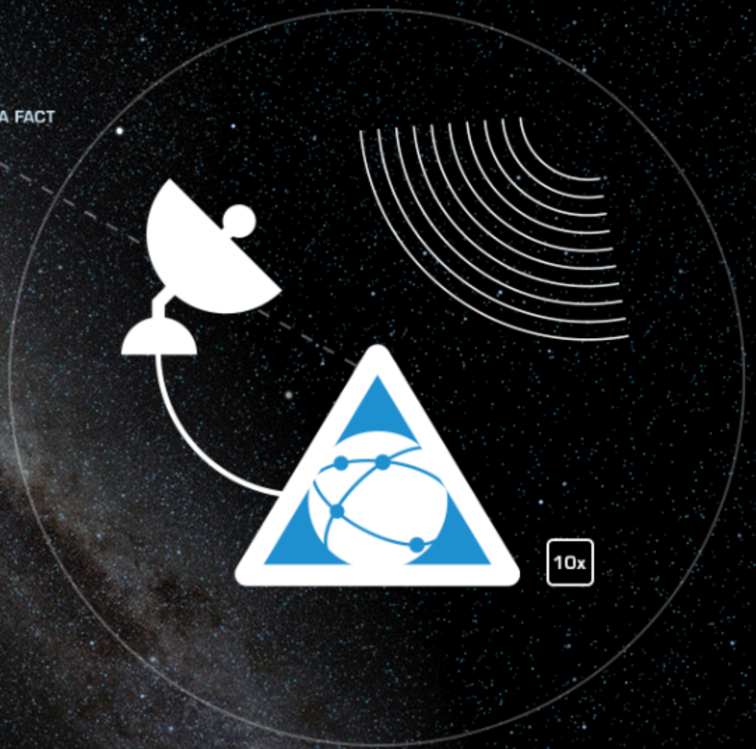
AMAZING 2 SKA FACT

The SKA will be so sensitive that it will be able to detect an airport radar on a planet *tens of light years away*.



AMAZING **4** SKA FACT

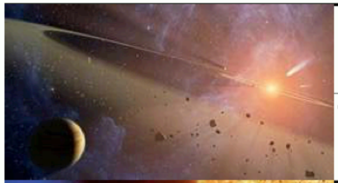
The dishes of the SKA will produce *10 times* the global internet traffic.



Headline SKA Science (1/2)

	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 SKA Science (1/2)

	SKA1	SKA2
	**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.
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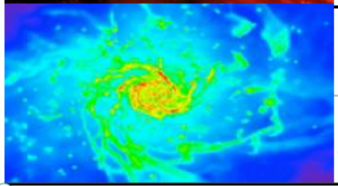
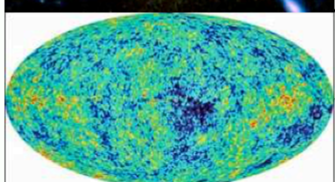
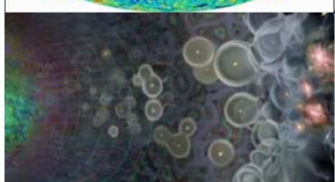
	1st detection of **nHz-stochastic gravitational wave background**.	Gravitational wave astronomy of discrete sources: constraining galaxy evolution, cosmological GWs and cosmic strings.
	Discover and use **NS-NS and PSR-BH binaries** to provide the best tests of **gravity theories and General Relativity**.	Find **all ~40,000 visible pulsars in the Galaxy**, use the most **relativistic systems to test cosmic censorship** and the **no-hair theorem**.
	The **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**.
	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.

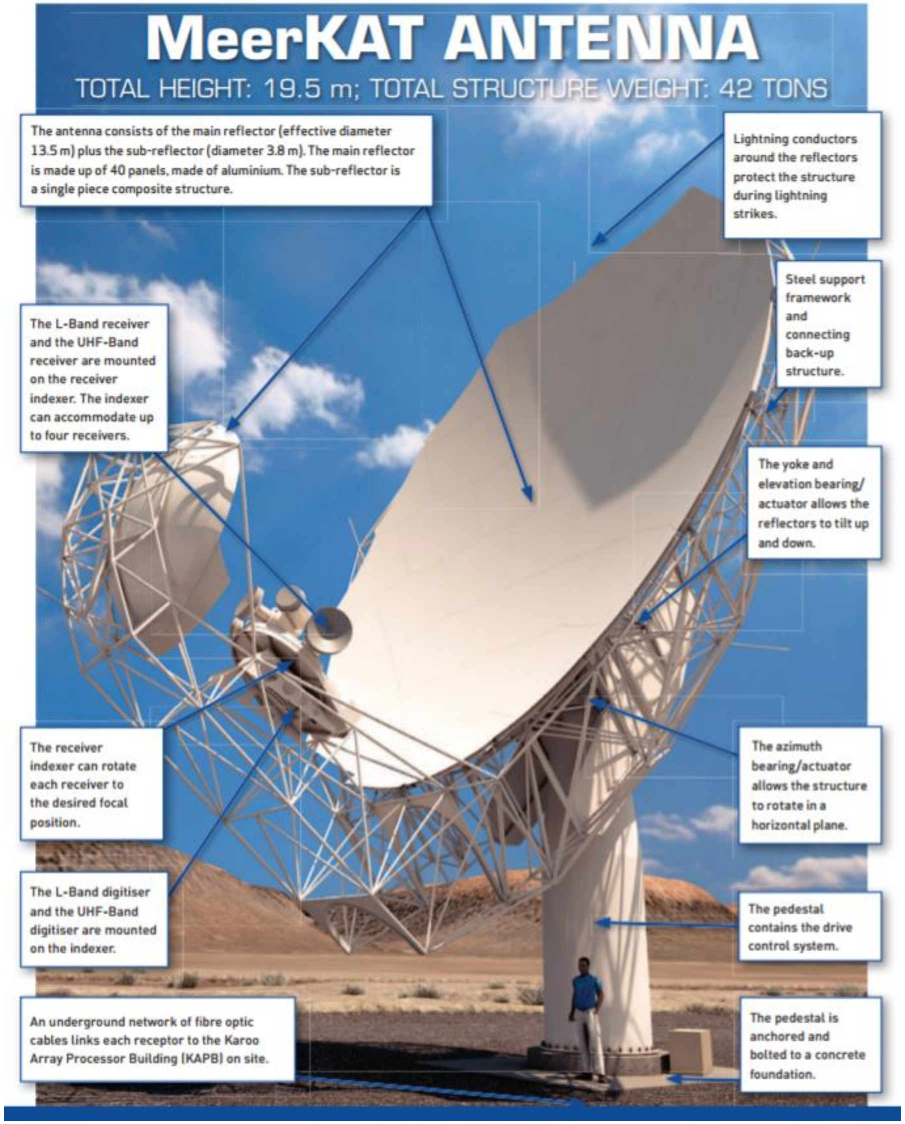
Headline SKA Science (2/2)

	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).

Headline SKA Science (2/2)

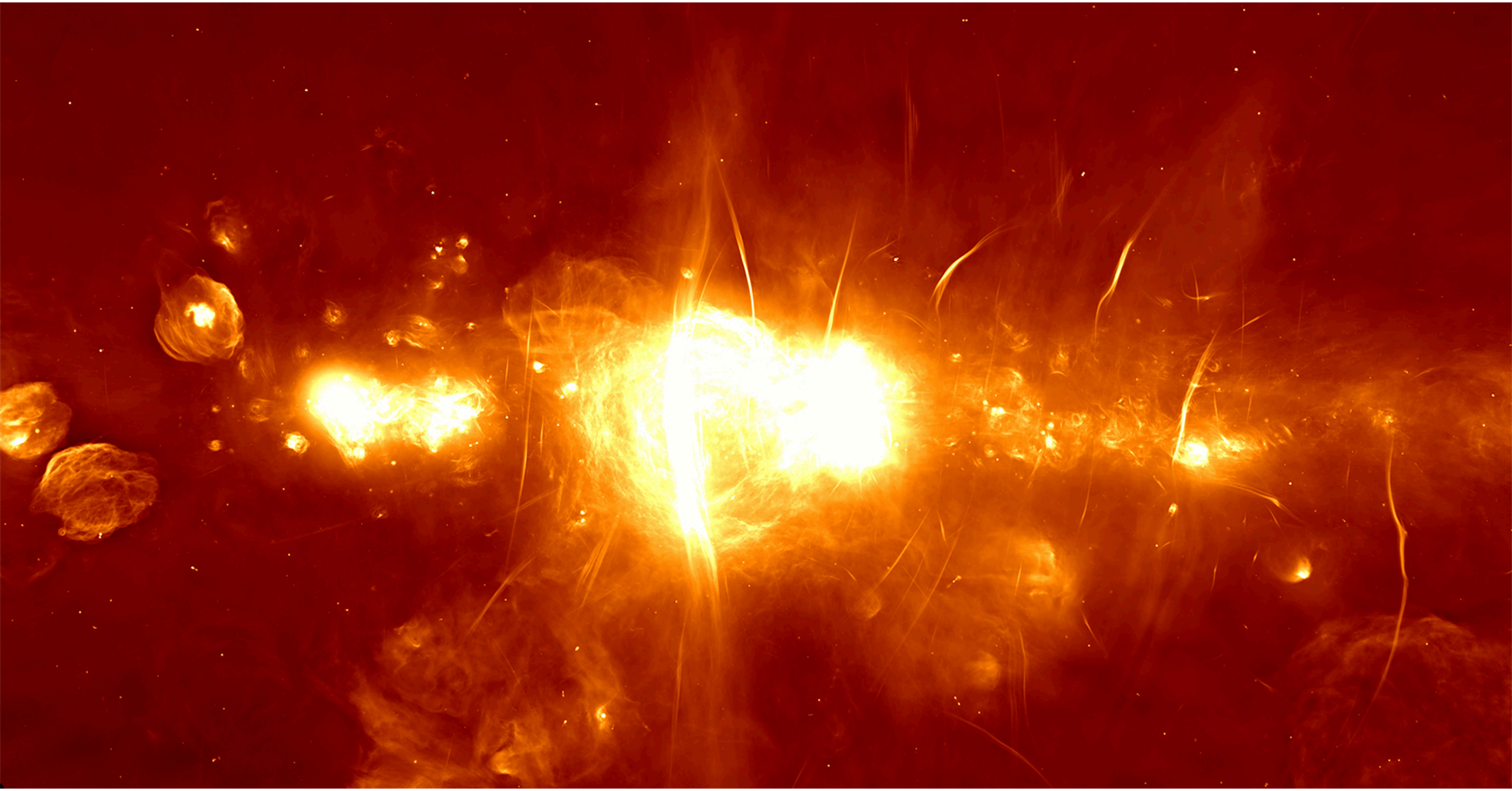
	SKA1	SKA2
	Use **fast radio bursts** to uncover the missing "normal" matter in the universe.	**Fast radio bursts as** unique **probes** of fundamental cosmological parameters and intergalactic magnetic fields.
	Study **feedback from the most energetic cosmic explosions** and the **disruption of stars by super-massive black holes**.	Exploring the unknown: new **exotic astrophysical phenomena in discovery phase space**.
	**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**).
	**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.**
	**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).

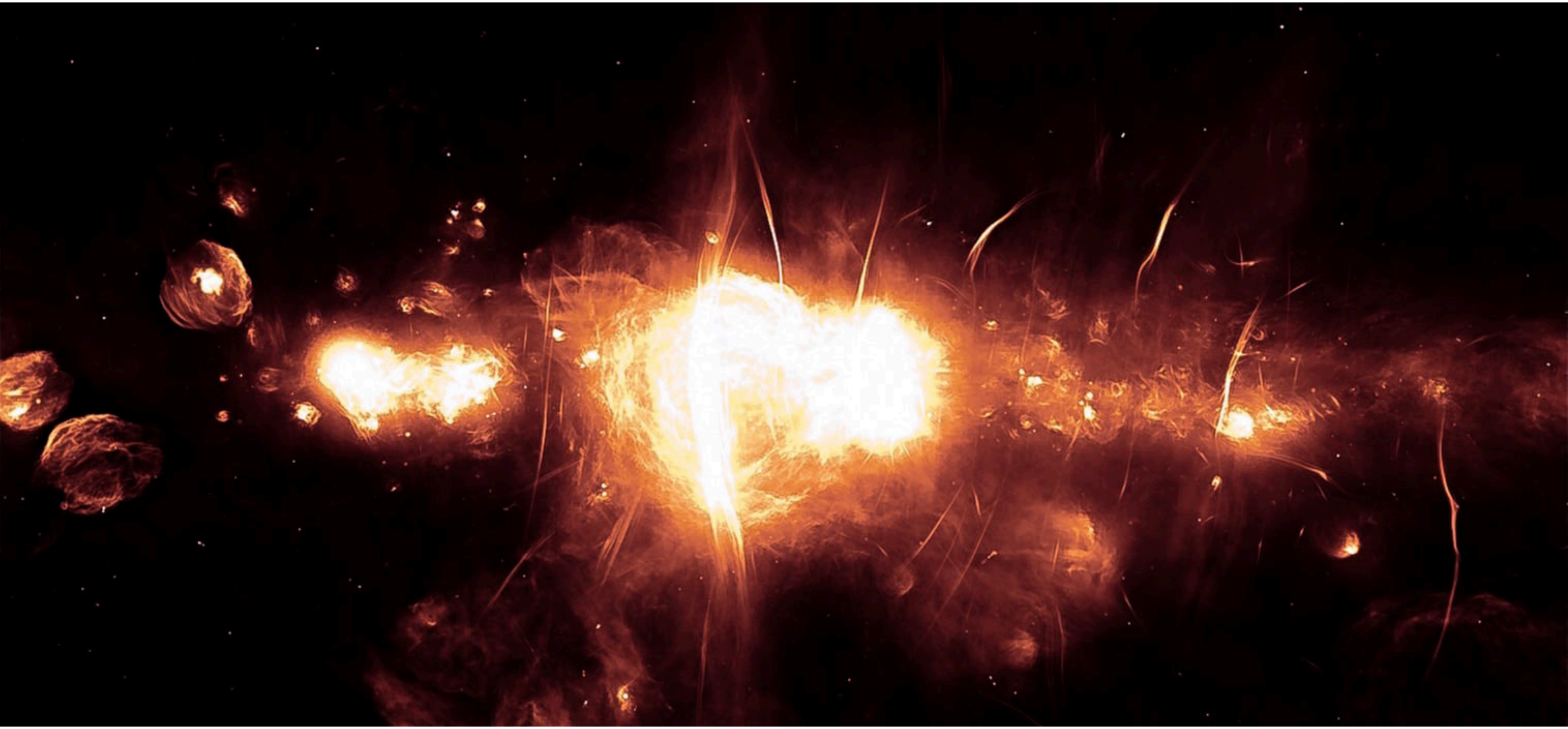
MEERKAT Antenna



MeerKAT

Dishes	64
Dish Diameter	13.5 m
Total collecting area	9161 m^2
Pairs of dishes	2016
Maximum baseline	8 km
Resolution	6" (robust = -0.5)
A_e / T_{sys} (per dish)	~6 m^2 K^{-1} (1.7 over spec!)
Observing frequency	580 – 3500 MHz
Bandwidth	~800 MHz
Spectral Channels	32,768





MeerKAT

s41586-019-1532-5.pdf (page 1 of 9)

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LETTER

https://doi.org/10.1038/s41586-019-1532-5

Inflation of 430-parsec bipolar radio bubbles in the Galactic Centre by an energetic event

I. Heywood[1,2,3]*, F. Camilo[3]*, W. D. Cotton[3,4], F. Yusef-Zadeh[5], T. D. Abbott[3], R. M. Adam[3], M. A. Aldera[6], E. F. Bauermeister[3], R. S. Booth[7], A. G. Botha[3], D. H. Botha[8], L. R. S. Brederode[3,17], Z. B. Brits[3], S. J. Buchner[3], J. P. Burger[3], J. M. Chalmers[3], T. Cheetham[3], D. de Villiers[9], M. A. Dikgale-Mahlakoana[3], L. J. du Toit[8], S. W. P. Esterhuyse[3], B. L. Fanaroff[3], A. R. Foley[3], D. J. Fourie[3], R. R. G. Gamatham[3], S. Goedhart[3], S. Gounden[3], M. J. Hlakola[3], C. J. Hoek[3], A. Hokwana[3], D. M. Horn[3], J. M. G. Horrell[10], B. Hugo[2,3], A. R. Isaacson[3], J. L. Jonas[2,3], J. D. B. L. Jordaan[3,8], A. F. Joubert[3], G. I. G. Józsa[2,3], R. P. M. Julie[3], F. B. Kapp[3], J. S. Kenyon[2], P. P. A. Kotzé[3], H. Kriel[3], T. W. Kusel[3], R. Lehmensiek[8,11], D. Liebenberg[3], A. Loots[12], R. T. Lord[3], B. M. Lunsky[3], P. S. Macfarlane[3], L. G. Magnus[3], C. M. Magozore[3], O. Mahgoub[3], J. P. L. Main[3], J. A. Malan[3], R. D. Malgas[3], J. R. Manley[3], M. D. J. Maree[3], B. Merry[3], R. Millenaar[3], N. Mnyandu[3], I. P. T. Moeng[3], T. E. Monama[3], M. C. Mphego[3], W. S. New[3], B. Ngcebetsha[2,3], N. Oozeer[3,13], A. J. Otto[3], S. S. Passmoor[3], A. A. Patel[3], A. Peens-Hough[3], S. J. Perkins[3], S. M. Ratcliffe[3], R. Renil[3], A. Rust[3], S. Salie[3], L. C. Schwardt[3], M. Serylak[3,14], R. Siebrits[3], S. K. Sirothia[2,3], O. M. Smirnov[2,3], L. Sofeya[3], P. S. Swart[3], C. Tasse[2,15], D. T. Taylor[3], I. P. Theron[2,8], K. Thorat[2,3], A. J. Tiplady[3], S. Tshongweni[3], T. J. van Balla[3], A. van der Byl[3], C. van der Merwe[3], C. L. van Dyk[16], R. Van Rooyen[3], V. Van Tonder[3], R. Van Wyk[3], B. H. Wallace[3], M. G. Welz[3] & L. P. Williams[3]

The Galactic Centre contains a supermassive black hole with a mass of four million Suns[1] within an environment that differs markedly from that of the Galactic disk. Although the black hole is essentially

progenitor event took place in the vicinity of the strong radio source Sgr A*, known to be coincident with the central black hole.

Coincident ionized gas near the base of the radio bubbles has a veloc-

Jordan Collier | 30 Oct 2019 | EMU Meeting

IDIA

University of Cape Town · iYunivesithi yaseKapa · Universiteit van Kaapstad

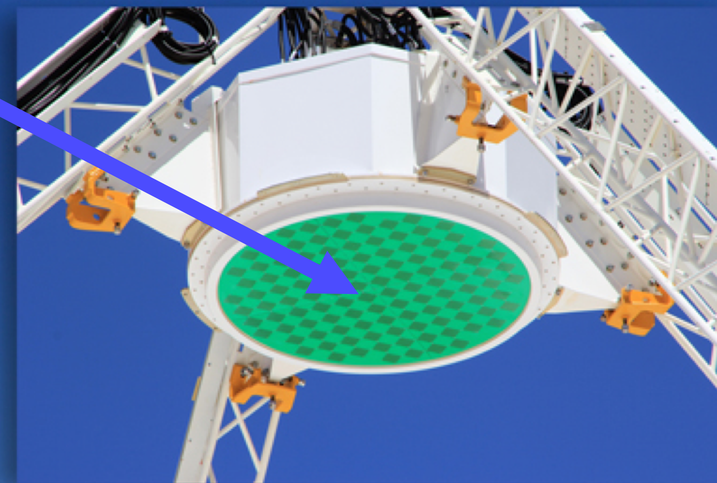
SPES BONA

ilifu

WESTERN SYDNEY UNIVERSITY

Key ASKAP innovation

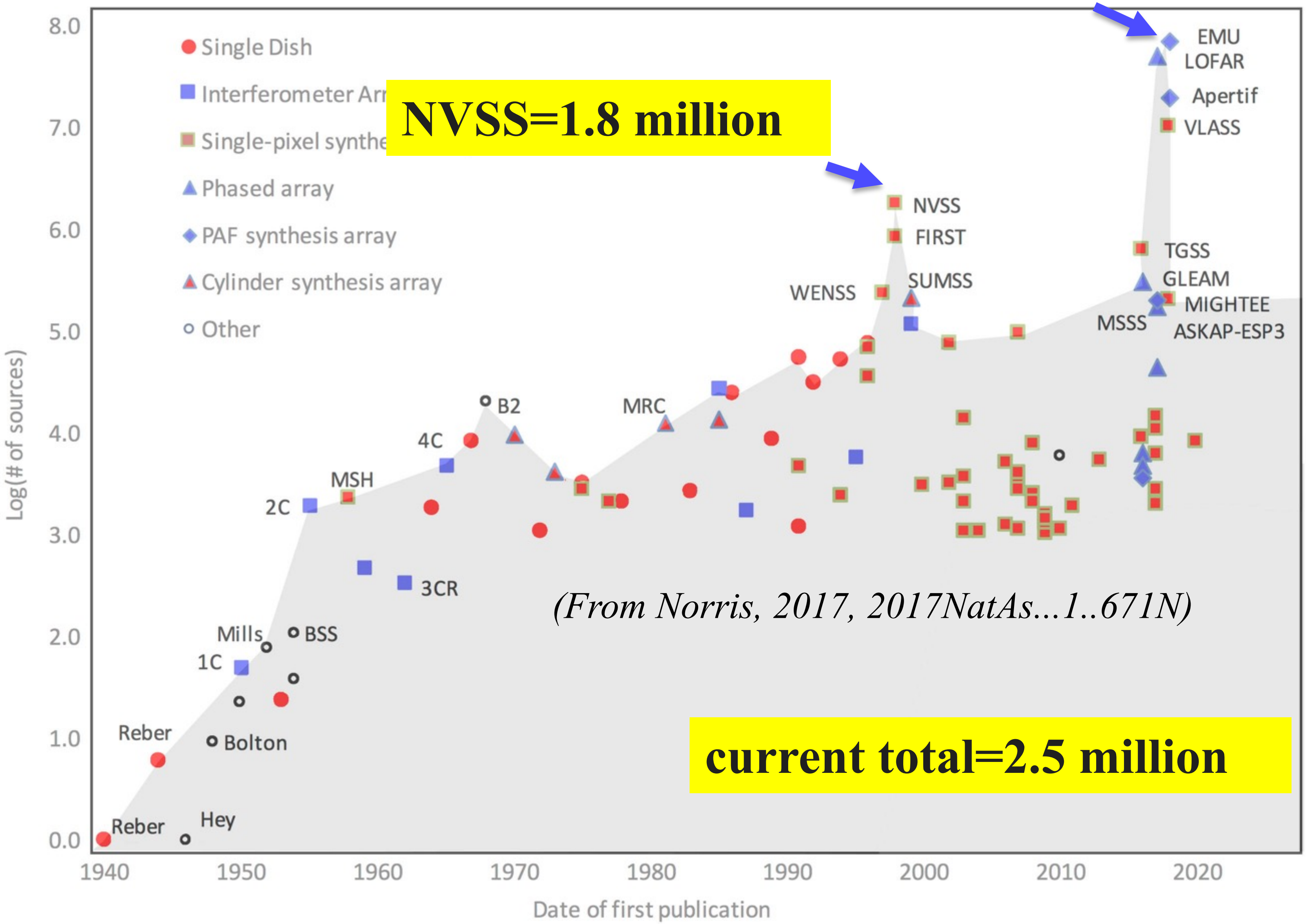
PAF = Phased Array Feed



- **Phased Array Feeds (PAF) give 30 sq deg FOV and an amazing survey speed**
- **Impact on radio-astronomy will be similar to the move in optical astronomy in the 1960’s from single-channel photometers to CCD’s**

Size of radio continuum surveys over time

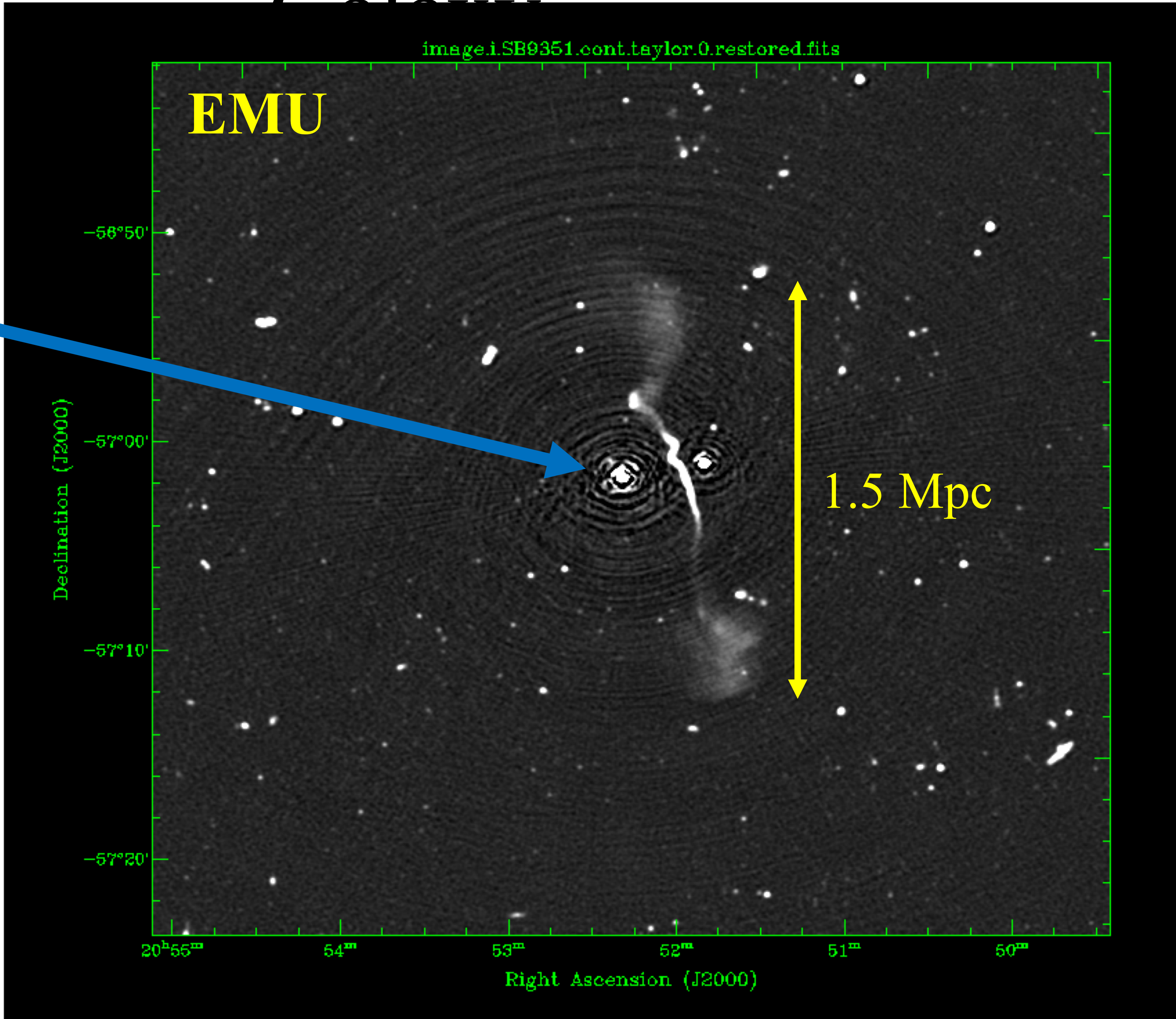
ASKAP Radio Continuum survey: EMU = 70 million

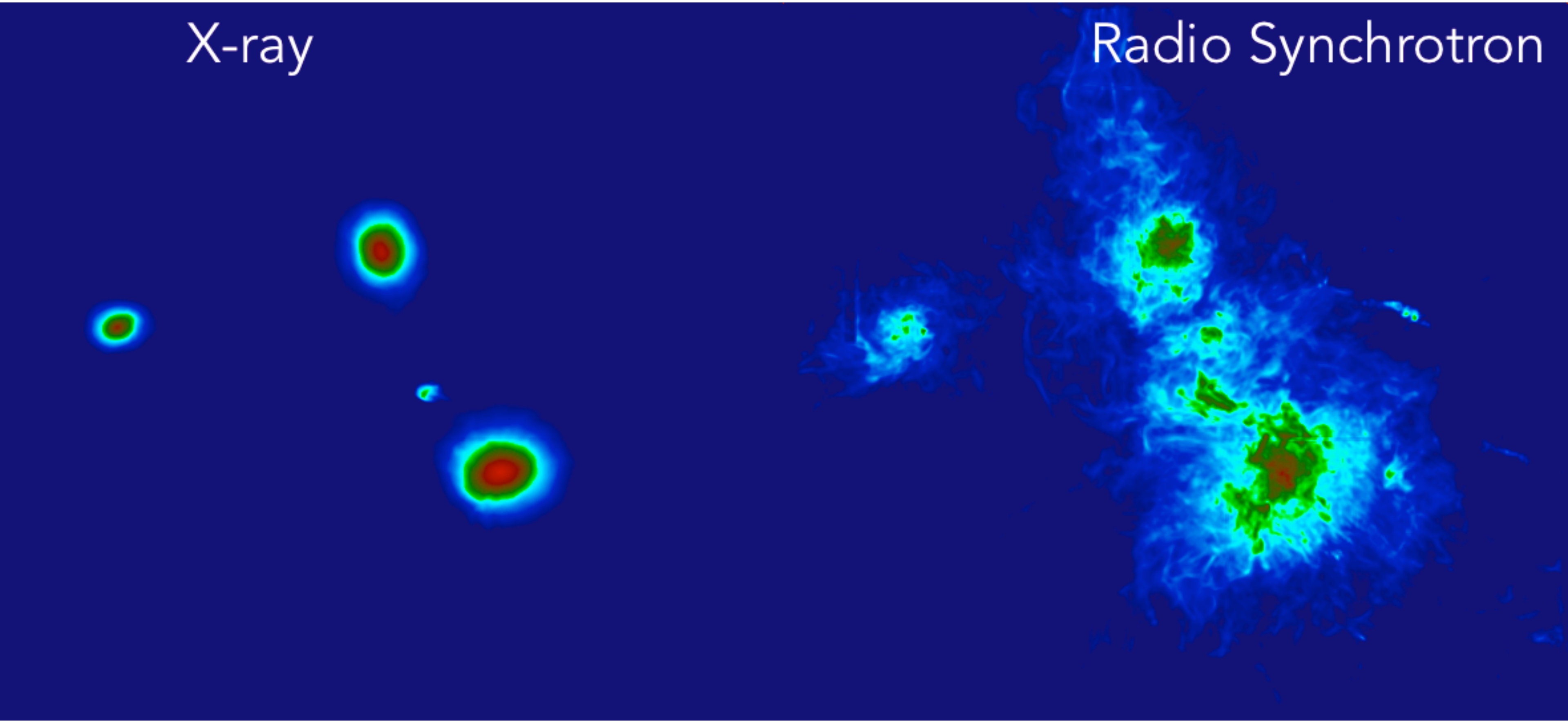


(From Norris, 2017, 2017NatAs...1..671N)

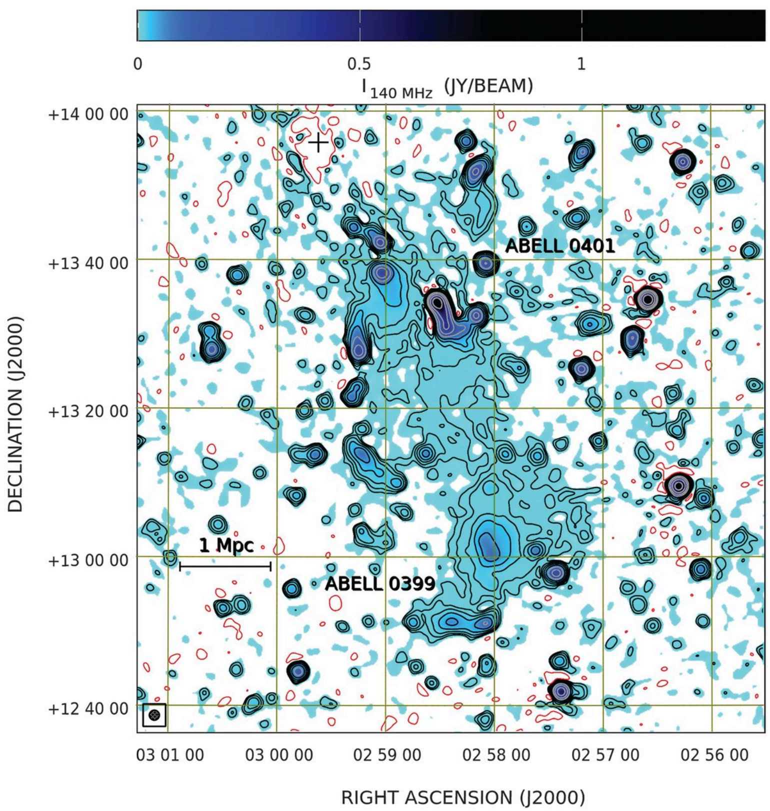
Wiggly jets and a Giant Radio Galaxy

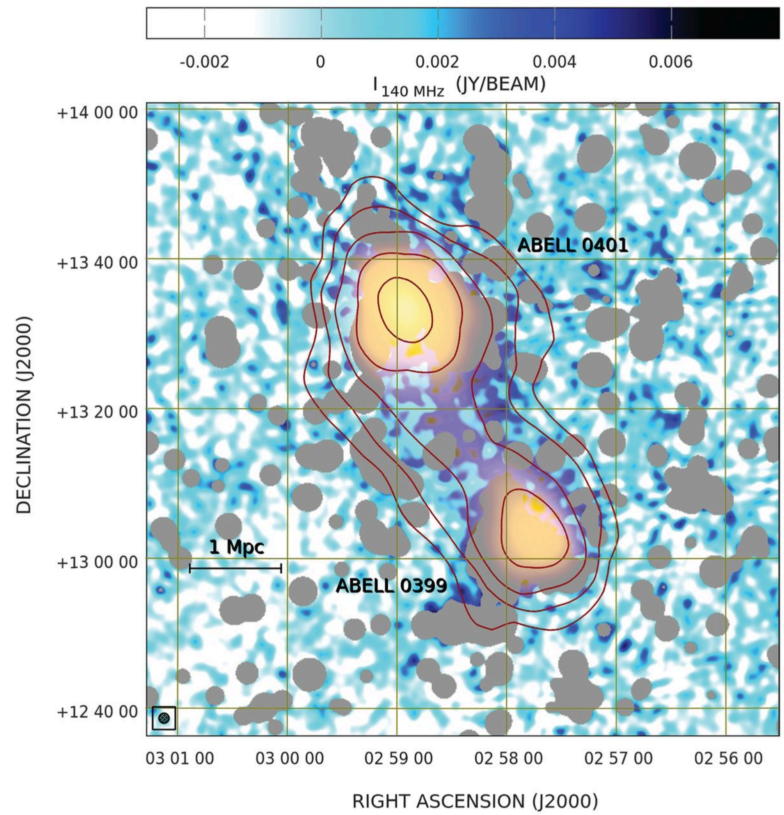
IC5063




X-ray
Radio Synchrotron

Continuum emission from bridges between clusters





LOFAR 140 MHz

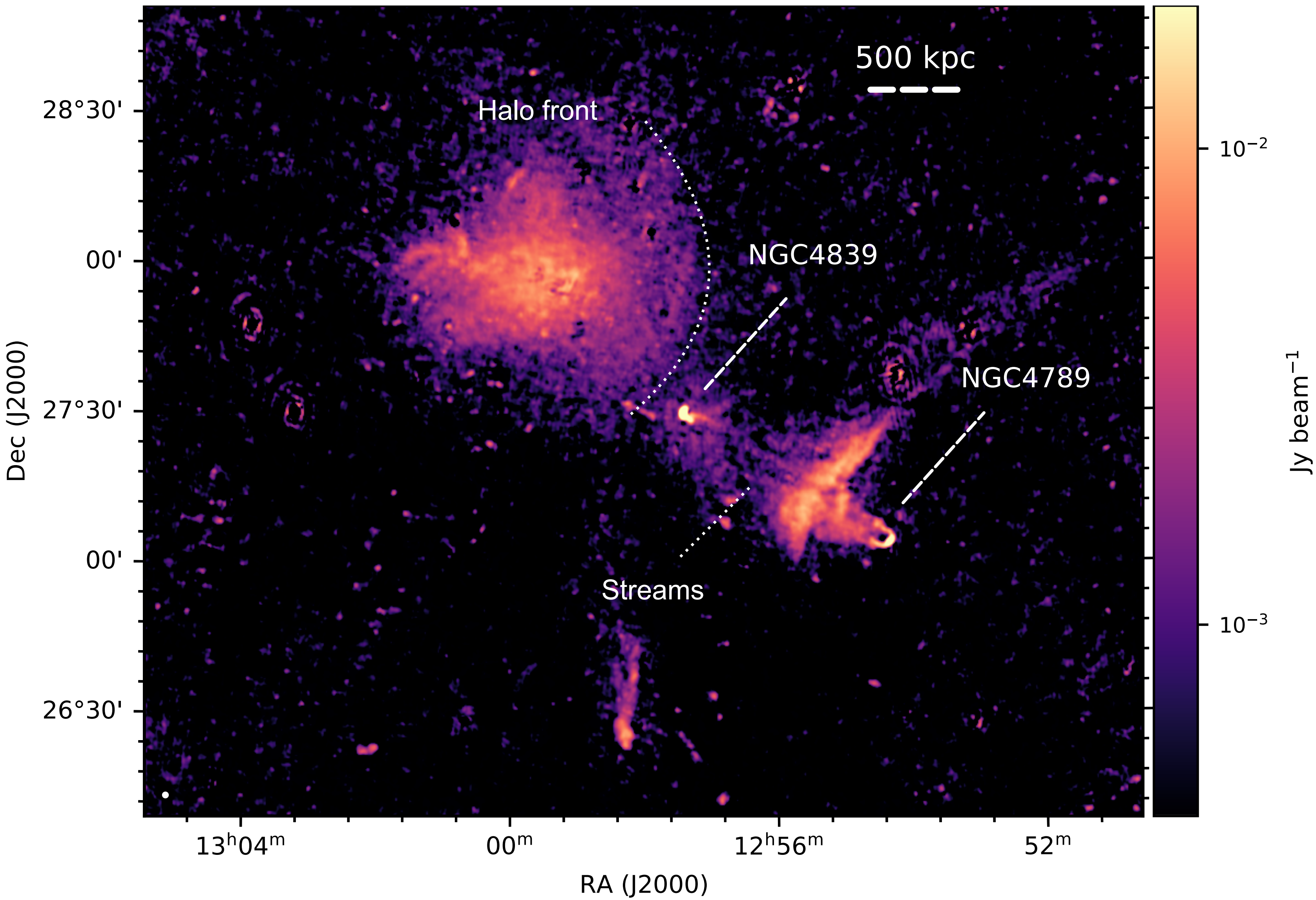
LOFAR + Plan

Weak shocks or volume-filling turbulence?

Only detected by LOFAR → no spectrum.

Govoni, MB, et al. (

The bridge in the Coma cluster seen with LOFAR



Bonafede, MB, et al. (

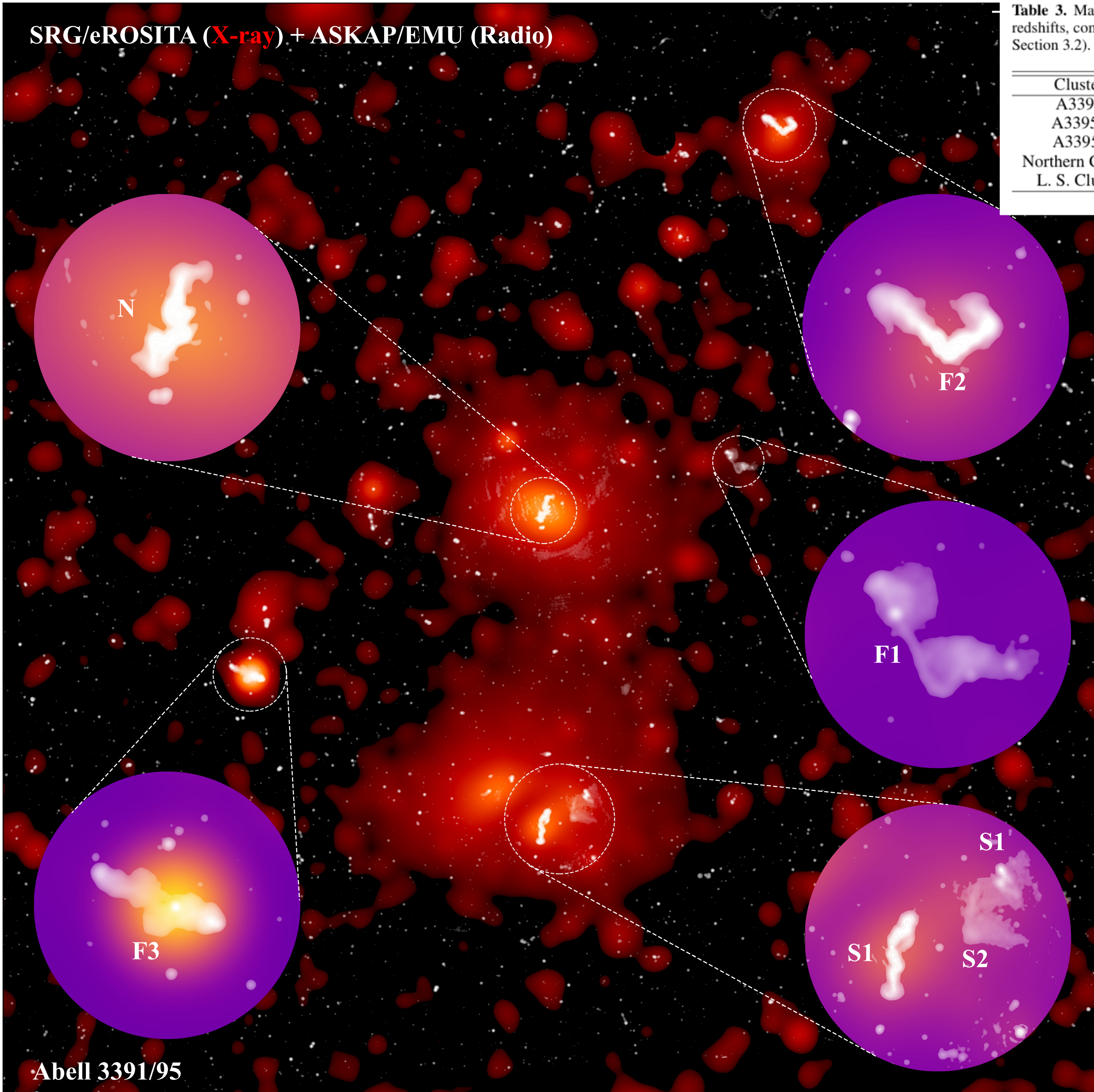


Table 3. Main cluster, Northern Clump, and Little Southern Clump redshifts, comoving distances, and approximate peculiar velocities (see Section 3.2).

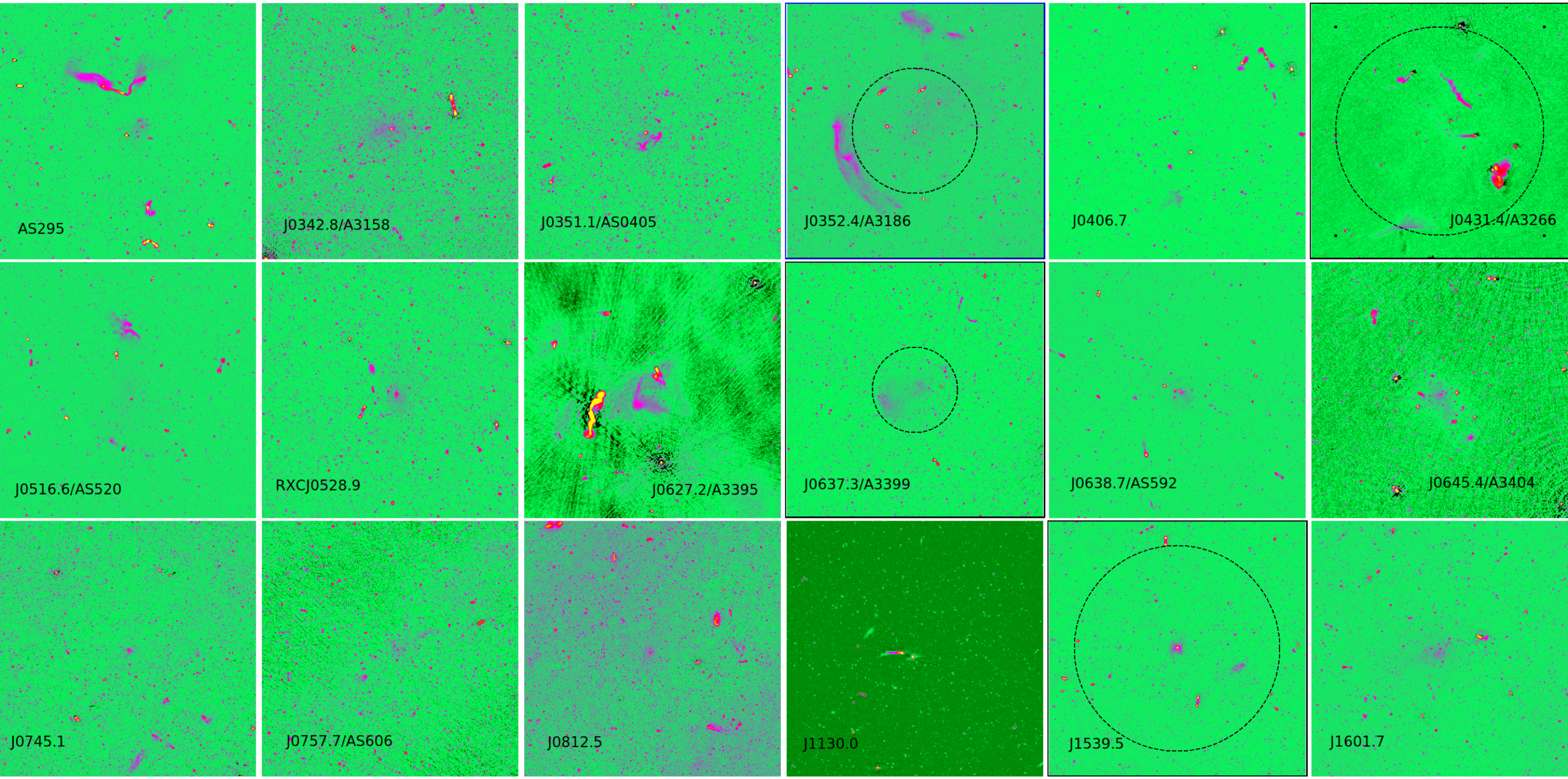
Cluster	N	z	D_c	v_{pec}
A3391	57	0.0555	234.7 Mpc	0 km/s
A3395n	133	0.0518	219.2 Mpc	1109 km/s
A3395s	64	0.0517	218.8 Mpc	1139 km/s
Northern Clump	3	0.0511	216.3 Mpc	1319 km/s
L. S. Clump	1	0.0562	237.6 Mpc	−209.9 km/s

Emissivity (1 GHz) < 1.2×10^{-44} W Hz^{-1} m^{-3}

Possible reason: Turbulent velocities small than in A399-401 because of smaller mass and earlier merger state.

Brüggen et al. (2020)

The future is bright...



Vielen Dank für Ihre Aufmerksamkeit!