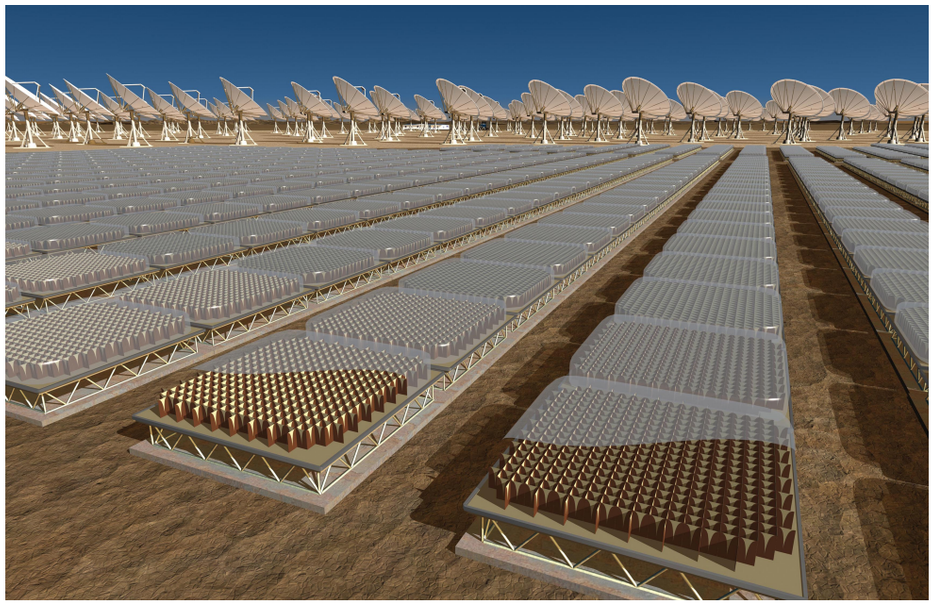
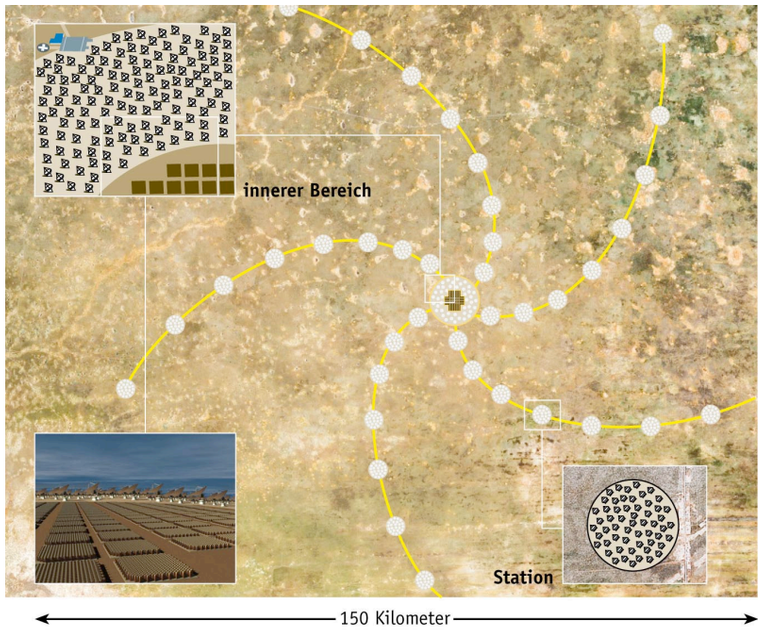
Square Kilometre Array & SKADS





Steve Torchinsky
SKADS Project Scientist
Observatoire de Paris

SKA & SKADS

- Some history
- Science goals
- SKA reference design and demonstrators
- SKADS
  - Science interactions
  - Benchmark
  - EMBRACE demonstrator

Radio Schmidt

- 1990-91: Dewdney et al
- Analogous to the optical Schmidt telescope
- Large collecting area
- Large field of view
- Aperture synthesis

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

THE PROPOSED RADIO SCHMIDT TELESCOPE: THE TECHNICAL CHALLENGES

P.E. DEWDNEY and T.L. LANDECKER
Dominion Radio Astrophysical Observatory, Penticton, B.C., V2A 6K3

ABSTRACT The concept of the Radio Schmidt Telescope is designed to fill a scientific requirement for a radio telescope which is very sensitive to diffuse, extended emission, but has much higher resolution than single-antenna telescopes. This telescope undertakes to utilize a new region of "parameter space" in the aperture synthesis technique. The emphasis of this article is on a process leading to the best implementation of the concept at reasonable cost while satisfying all the scientific objectives.

HIA: Square Kilometre Array

- Wilkinson coins the phrase 1km^2 Array

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.

Misconception of stunted development in Radio Astronomy

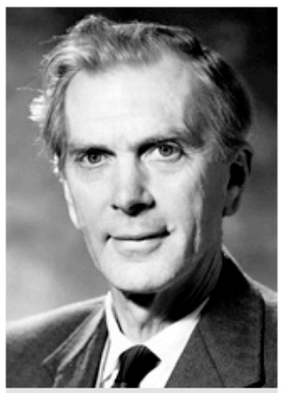
- Arecibo is the largest collecting area since 1963
- In the same time frame, ~3 “generations” of optical telescopes: 2m, 4m, 8-10m
- Radio astronomy concentrated on other areas of development

Radio Astronomy Developments since the 1960's

- Synthesis telescope
  - Ryle Nobel prize
- VLBI
- Extremely high spectral resolution
  - Heterodyne receivers, correlators
- Low noise systems
  - amplifiers, mixers, receivers
- Signal processing
- Observing strategies
  - Position switching
  - Frequency switching
  - Pulsar timing

The Nobel Prize in Physics 1974

"for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, and Hewish for his decisive role in the discovery of pulsars"



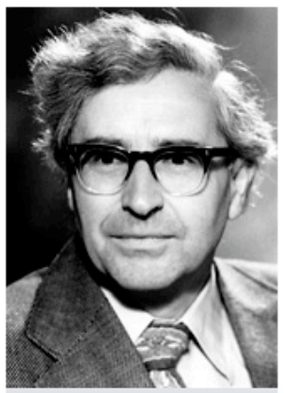
Sir Martin Ryle

1/2 of the prize

United Kingdom

University of Cambridge
Cambridge, United Kingdom

b. 1918
d. 1984



Antony Hewish

1/2 of the prize

United Kingdom

University of Cambridge
Cambridge, United Kingdom

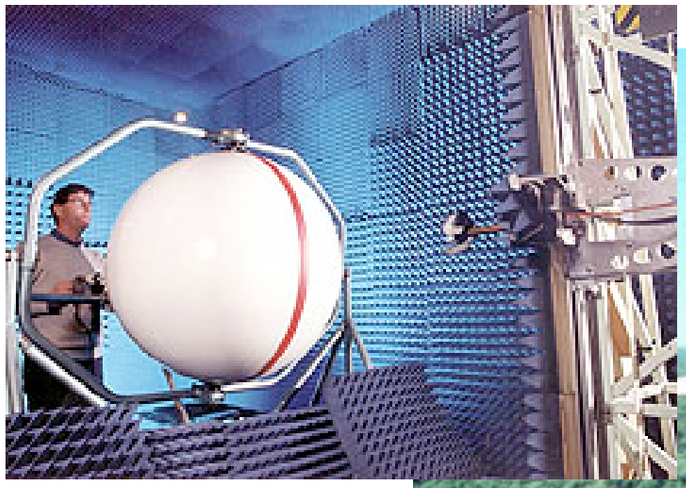
b. 1924

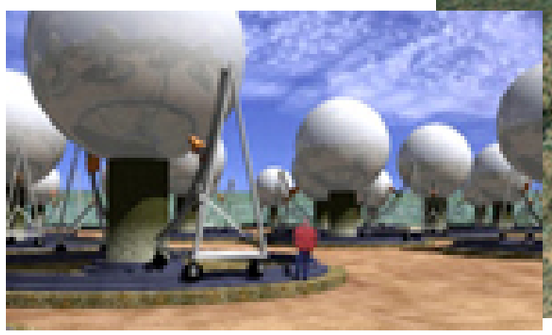
SKA gets started

- 1991 initial concept
- 1994 International Working Group
- 2000 MoU
- Survey instrument
  - Large field of view (at least 1sq deg)
  - O(10^2) more sensitive than current (1km^2)
- Main science motivation
  - HI survey of galaxies
    - HI mass function
    - (the idea of BAO was still to come)
    - Most distant galaxy in HI: z~0.18 (still true)
  - Pulsar searching and timing

SKA Proposals: Australia

- Luneburg lenses



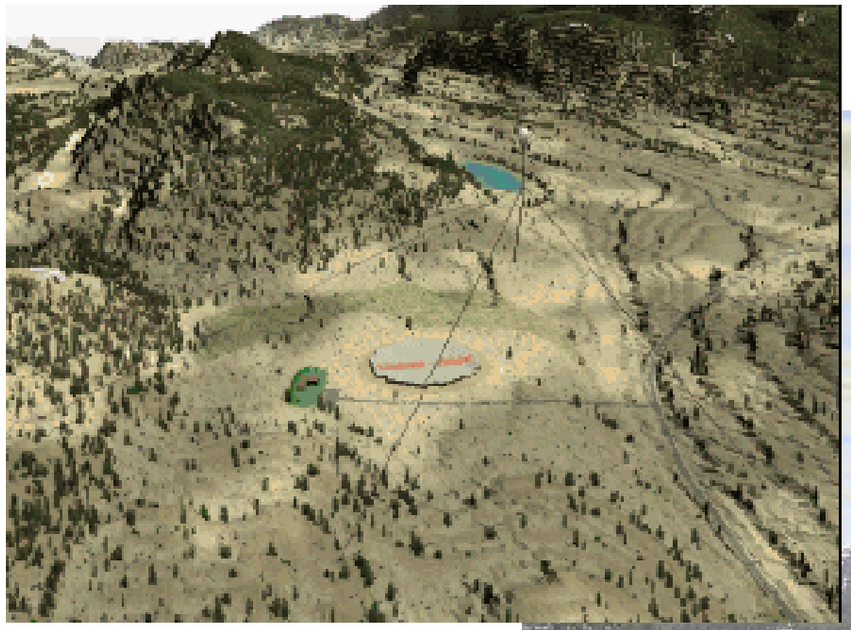


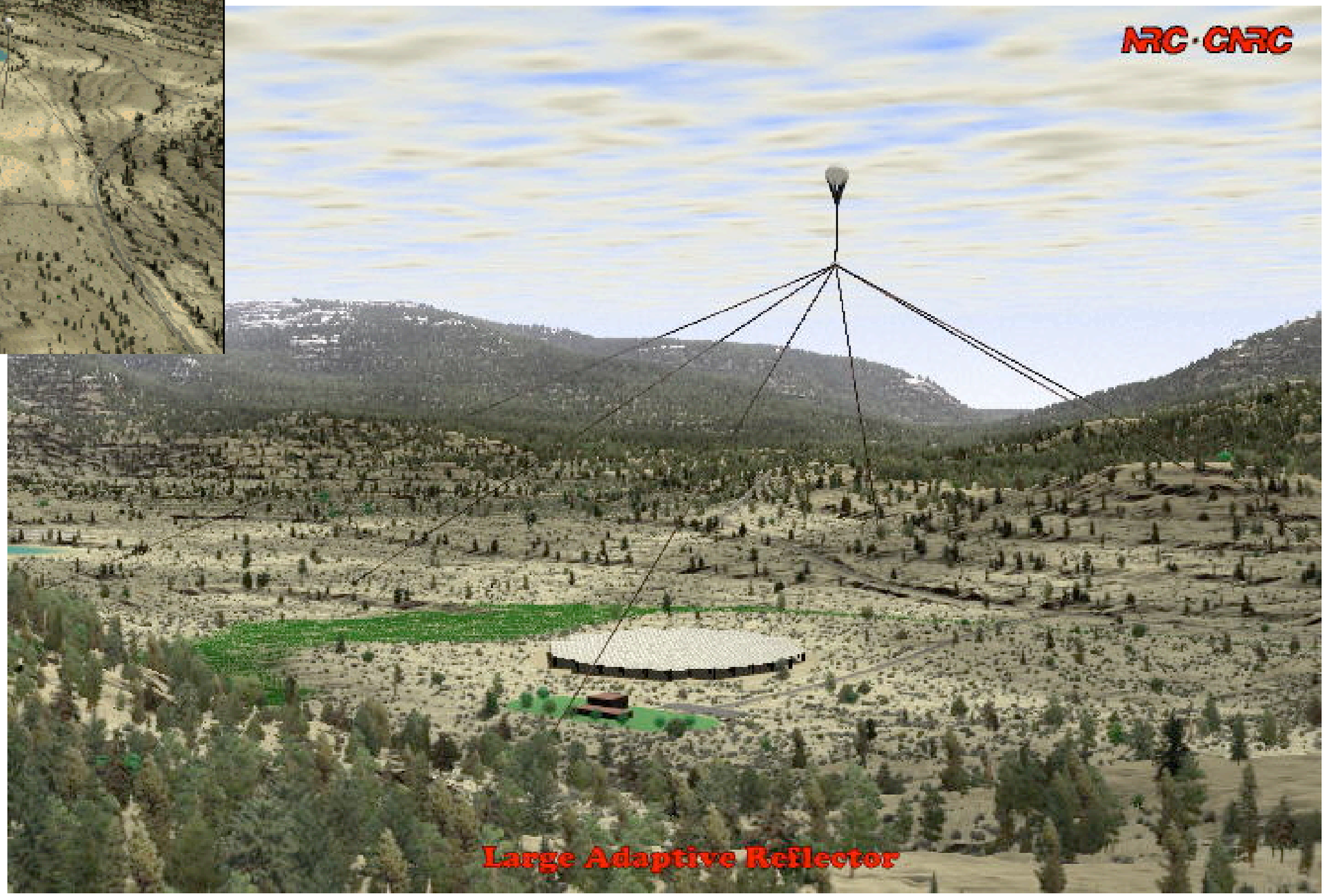
SKA Proposals: Australia (2)

- Cylinders
  - SKA Molongolo Prototype

SKA Proposals: Canada

- Large Adaptive Reflector



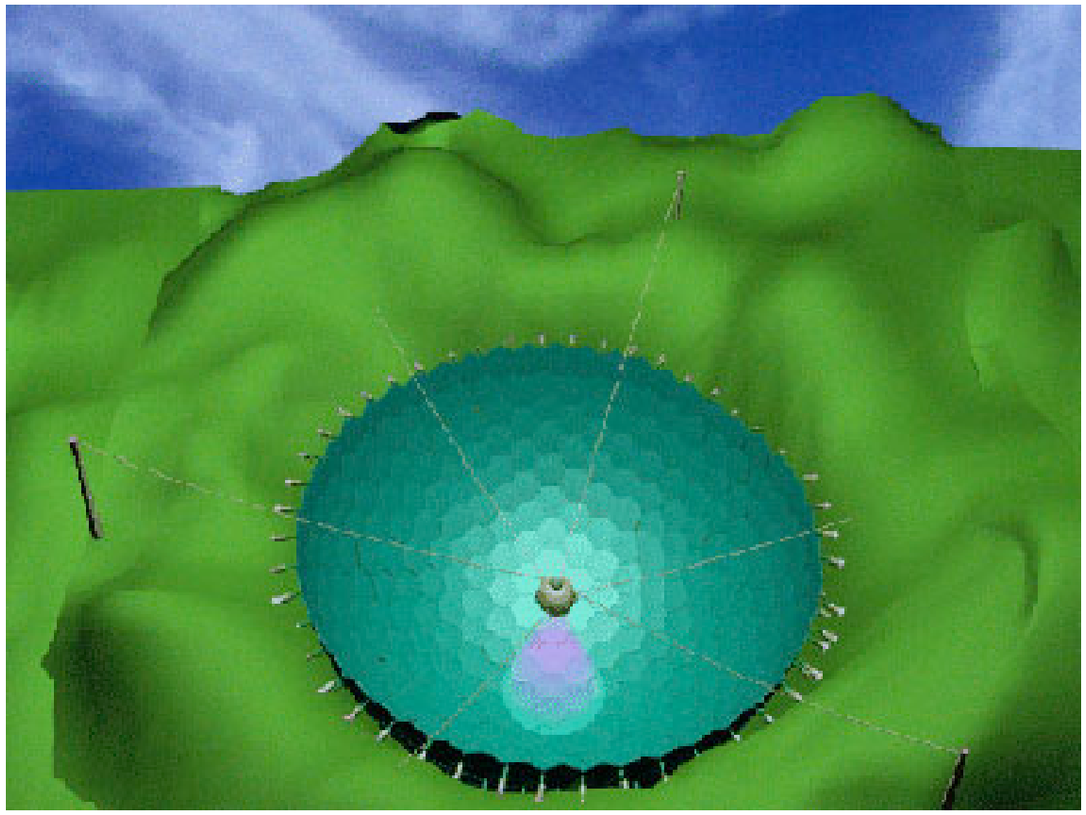


SKA Proposals: USA

- Large N small D
- Allen Telescope Array
- Single pixel
- Wideband feed

SKA Proposals: China

- FAST
- 500m Arecibo-like design with adaptive reflector



SKA Proposals: Europe (NL)

- Extremely large N, very small D
  - Dipoles for low frequency (LOFAR)
  - Densely packed aperture-plane phased-array (mid freq)
    - EMBRACE
  - Dishes (mid to high frequency)

2005: Key Science

- Pune meeting: Key Science agreed
  - Large Scale Structure (HI galaxy survey)
  - Epoch of Reionisation
  - Cosmic Magnetism
  - Tests of General Relativity in extreme fields (Pulsars)
  - Cradle of Life (protoplanetary disks, planets, organic molecules)

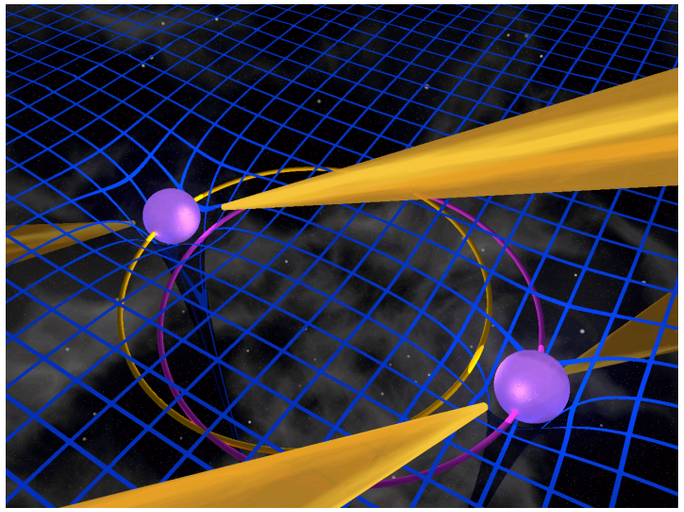
SKA Science Book

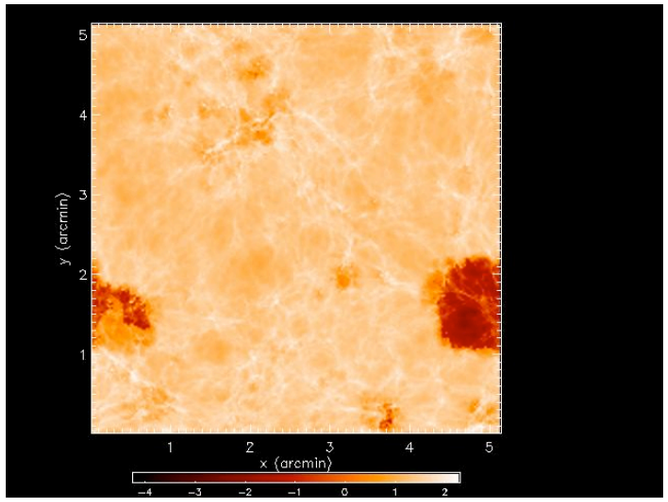
Chris Carilli & Steve Rawlings,

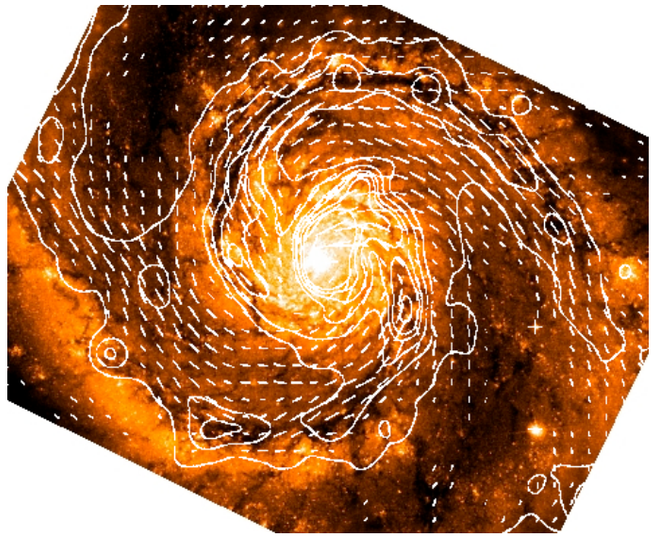
New Astronomy Reviews,
Vol.48, Elsevier, Dec. 2004

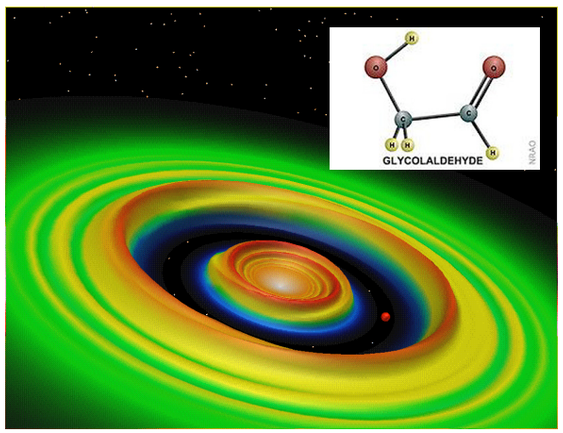
http://www.skads-eu.org/p/SKA_SciBook.php

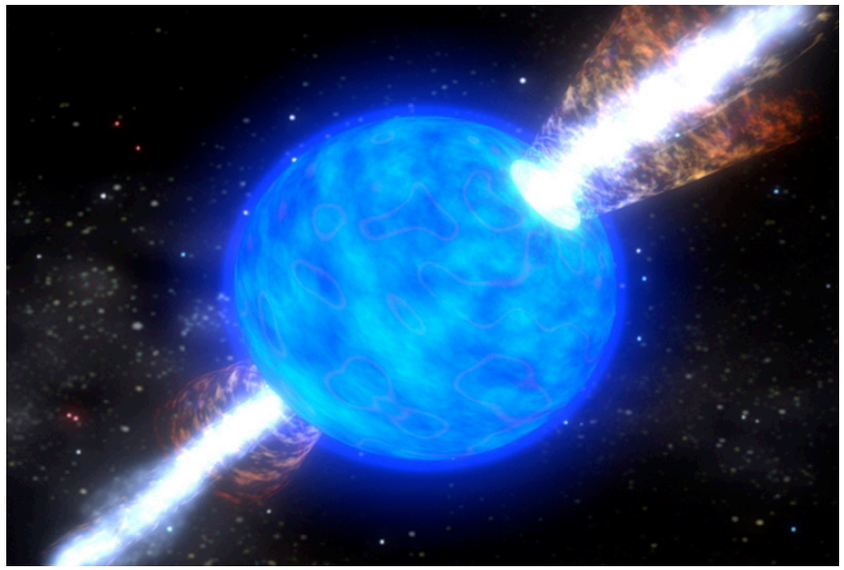
SKA Key Science

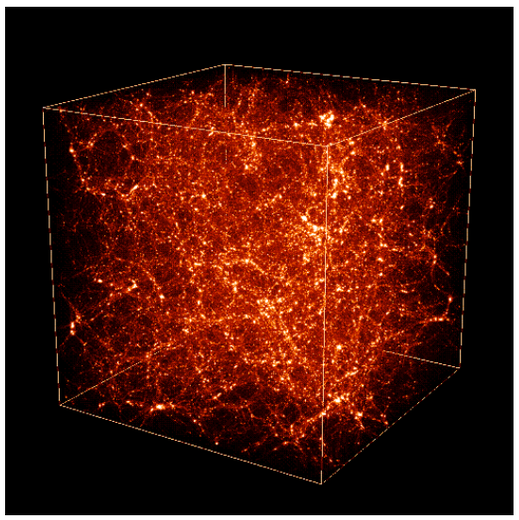




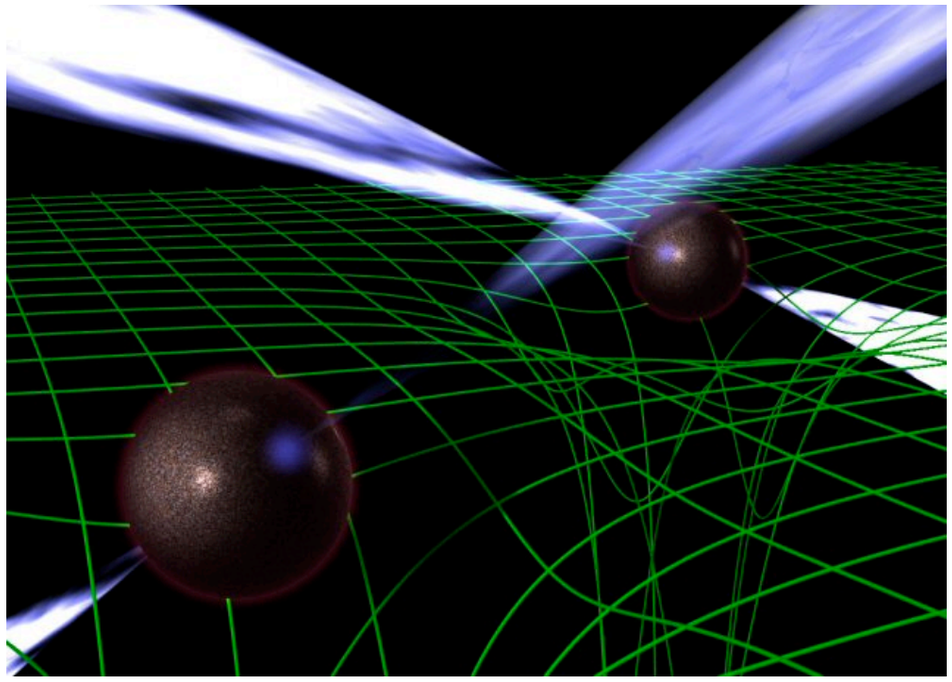






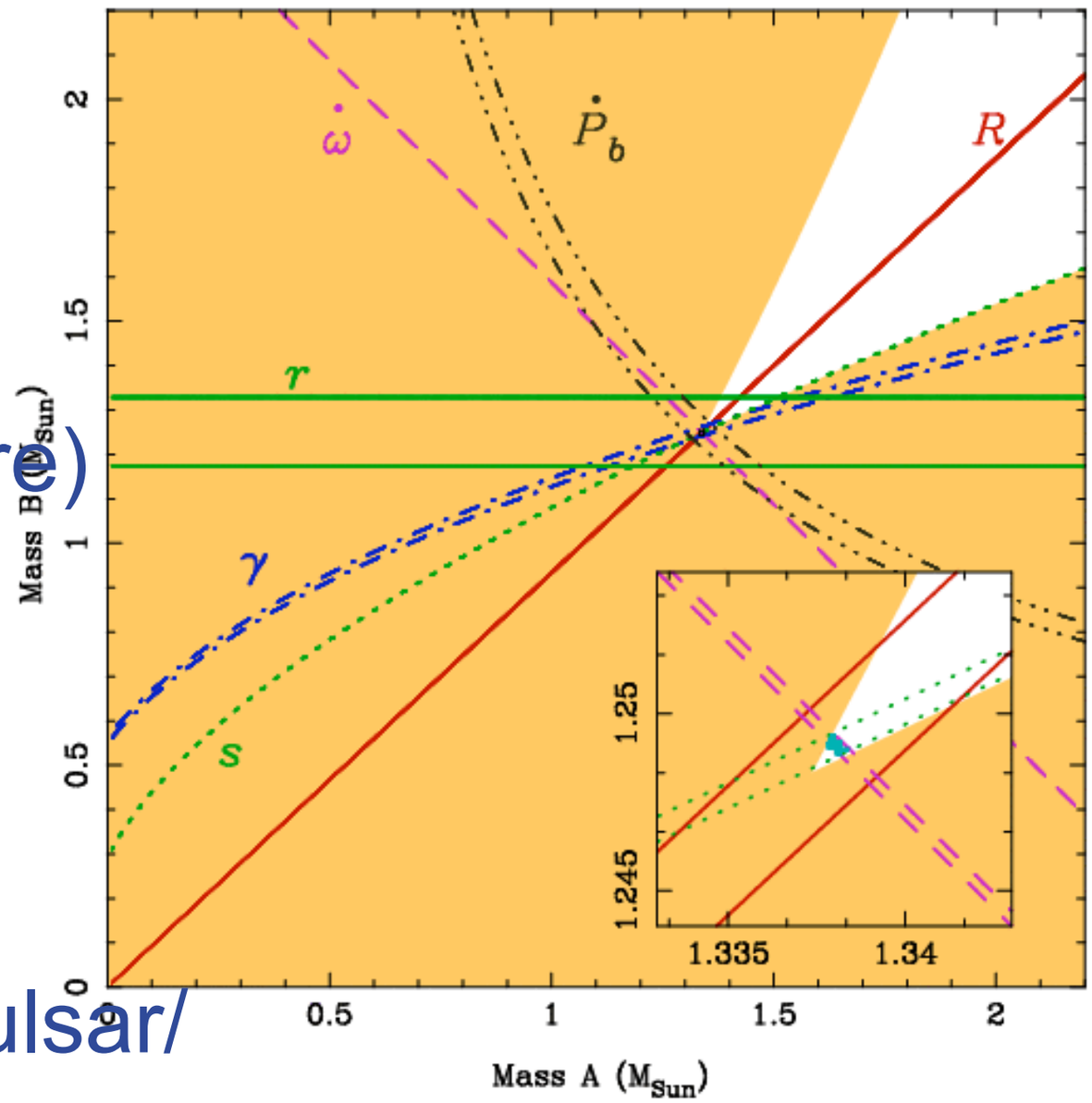


Strong Field Tests of Gravity



Relativistic effects permit (re) determination of masses.

Binary orbit permits determination of masses

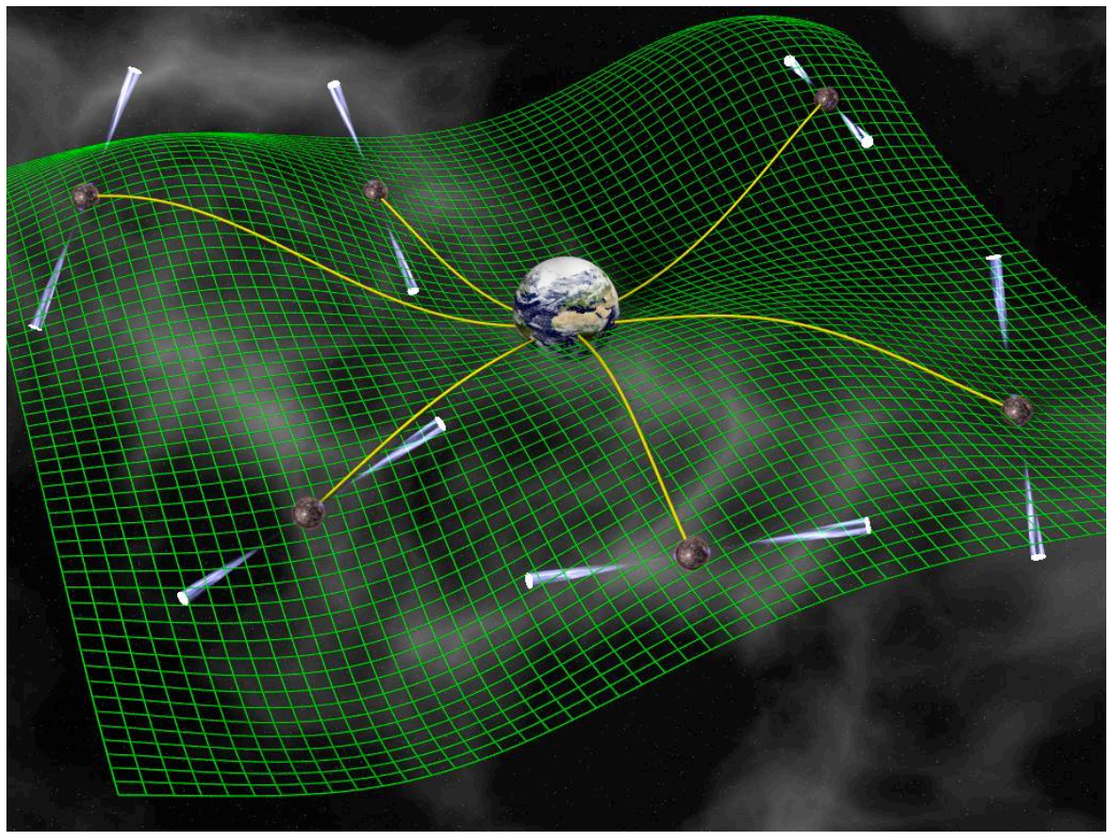


ALL MUST AGREE

http://www.jb.man.ac.uk/~pulsar/

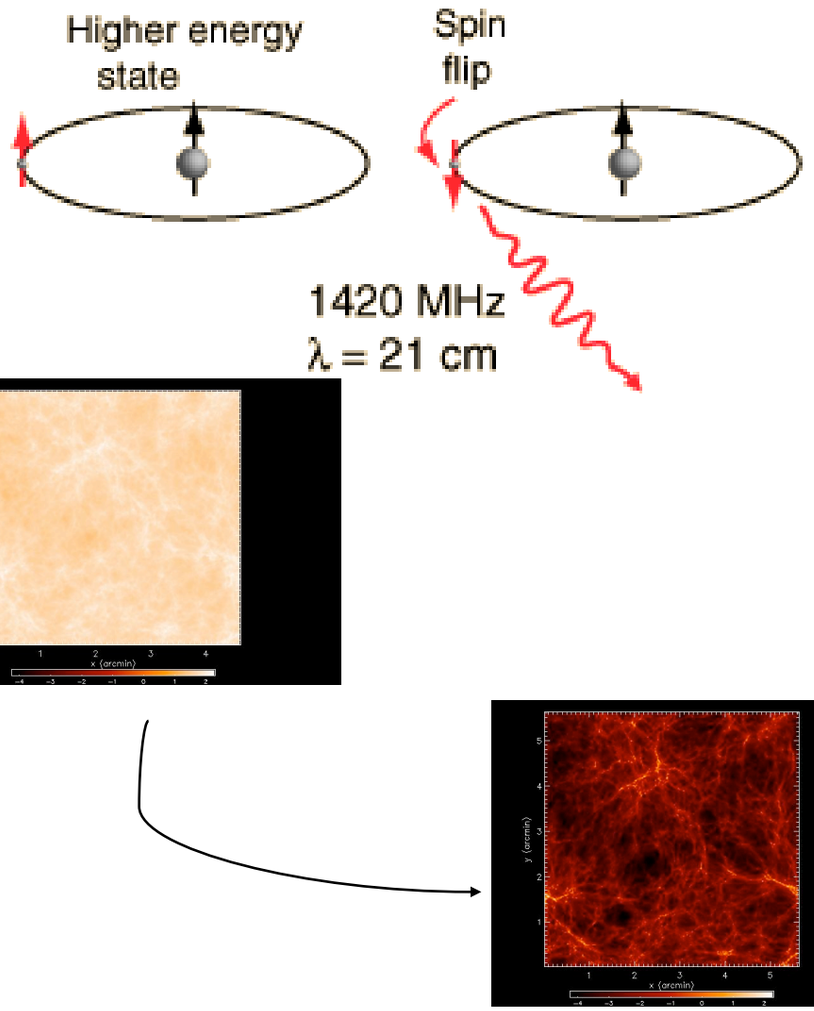
Strong Field Tests of Gravity

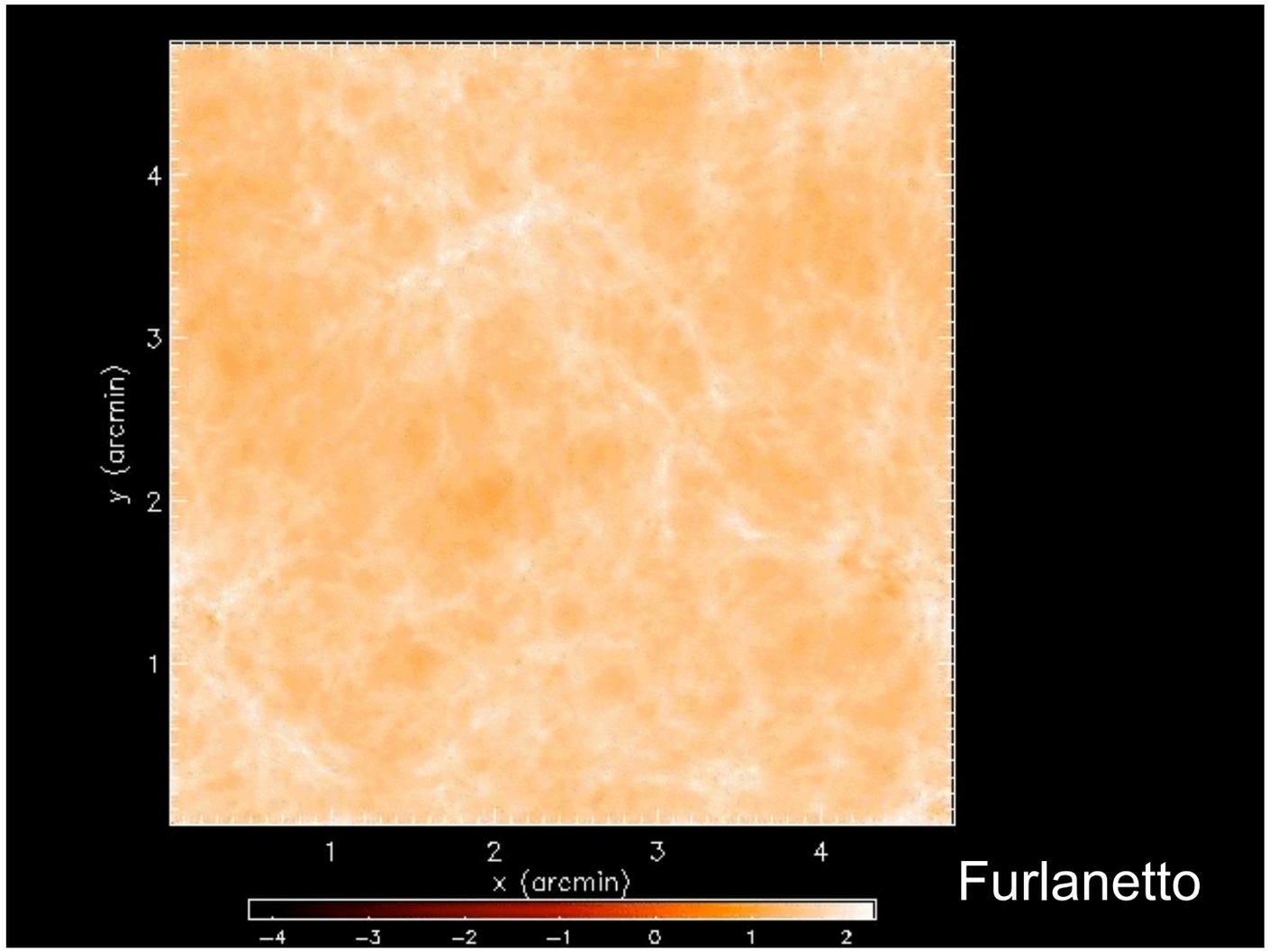
- Large surveys will find exotic binarys
  - ~20 000 pulsars in the galaxy
  - Edge-on Pulsar – Black-hole binary (at least one)
    - Probe eg. Frame dragging
- Pulsar timing array
  - Gravitational wave background



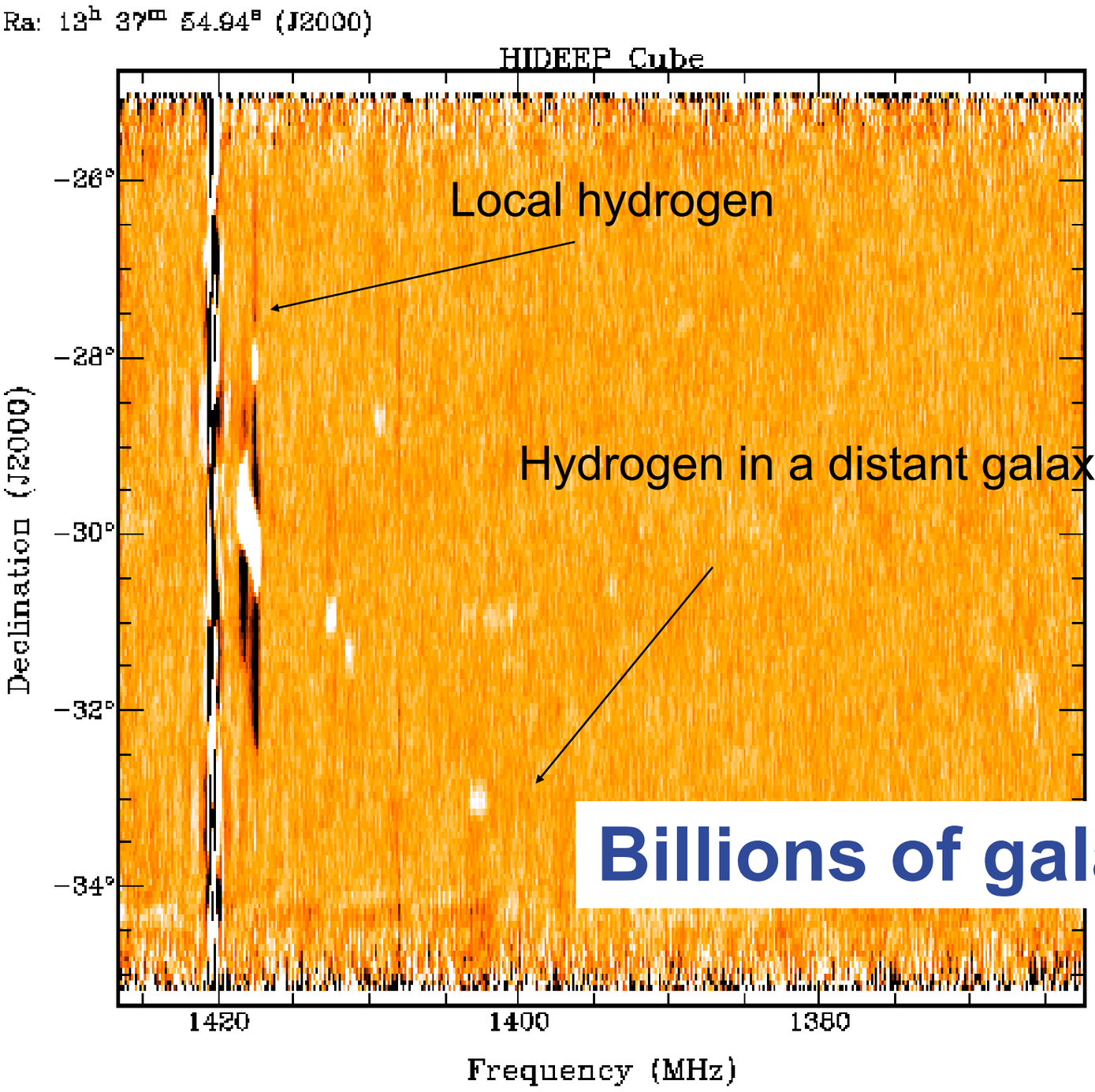
Probing the Dark Ages

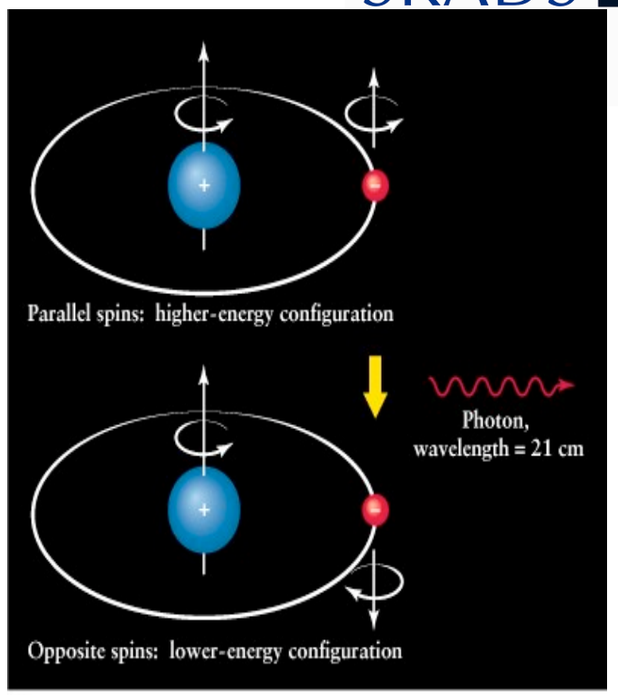
- When did the first luminous objects form?
- How did they form and over what period of time?
- SKA will detect the **Epoch of Reionisation** and map the evolution history of the first luminous objects

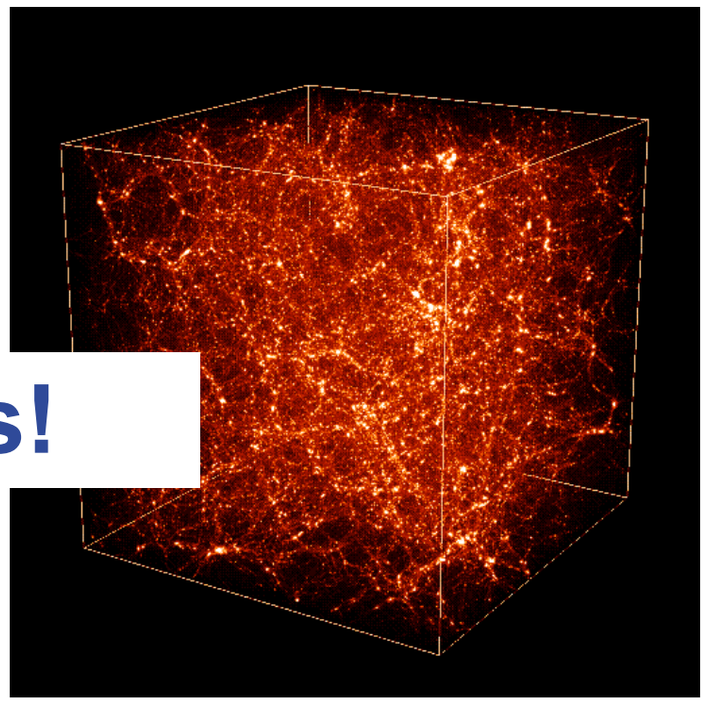




Large Scale Structure





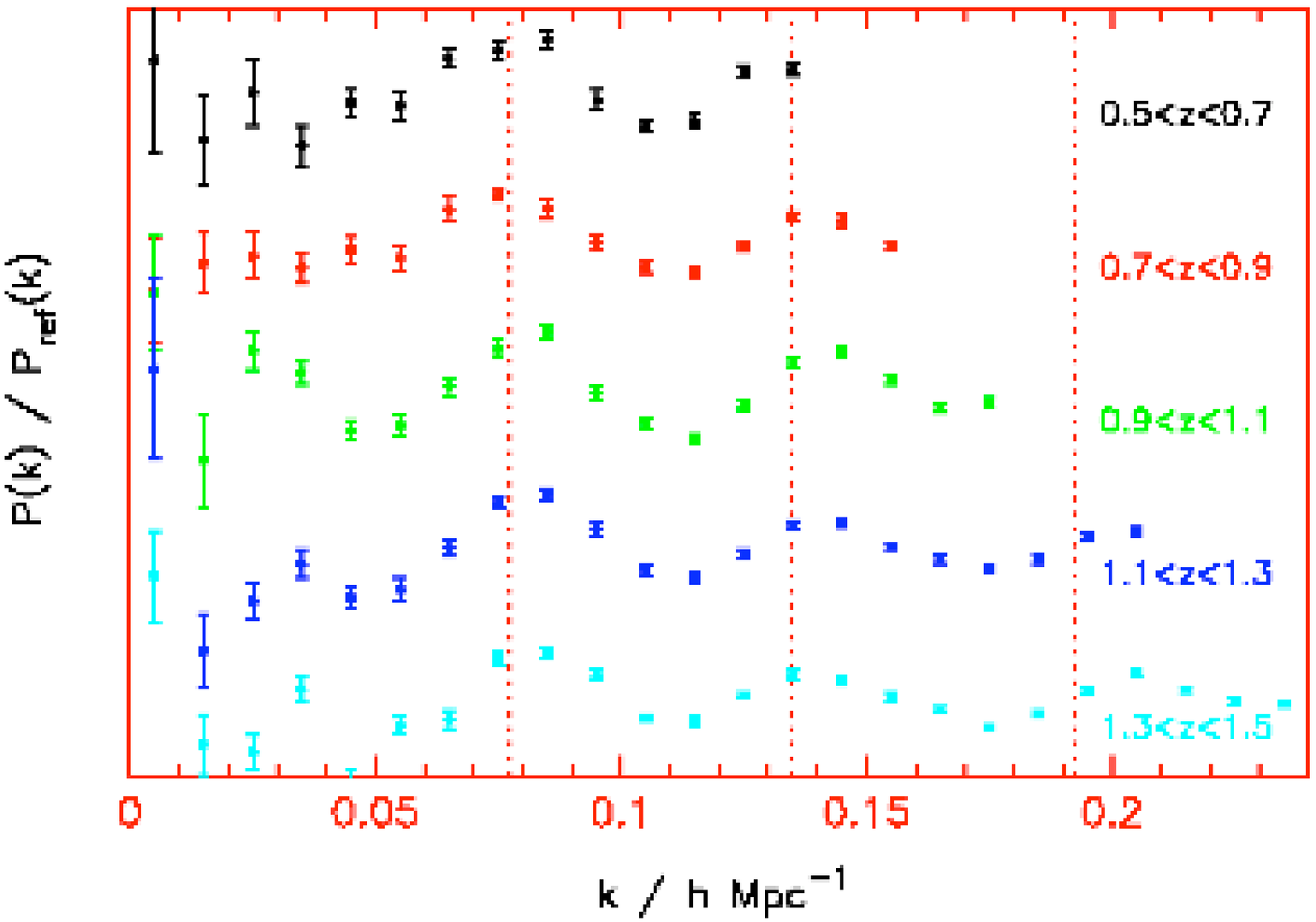


Dark Energy Experiments

- Baryonic Acoustic Oscillations
  - 10^9 galaxy redshift survey
- Cosmic Shear (weak lensing)
  - 10^{10} galaxy survey
- H_0 with water maser proper motions
- Dark Energy sound speed (CMB cross-correlation)

(venez ce soir !)

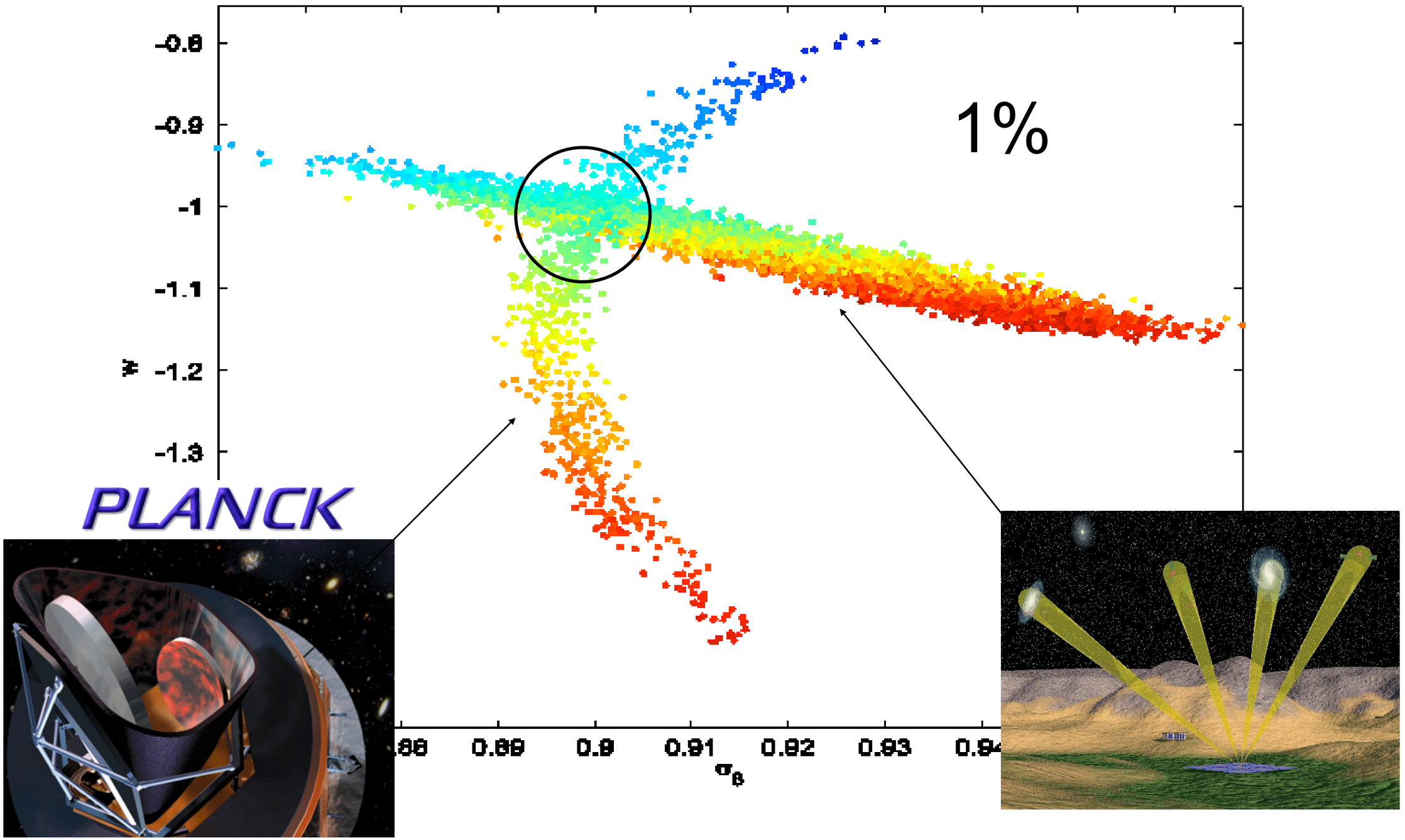
BAO in redshift bins



- Improve signal confidence by measuring wiggles in separate redshift bins

Blake et al 2004: example assuming w=-0.8, peaks don't line up with CMB peaks (vertical lines)

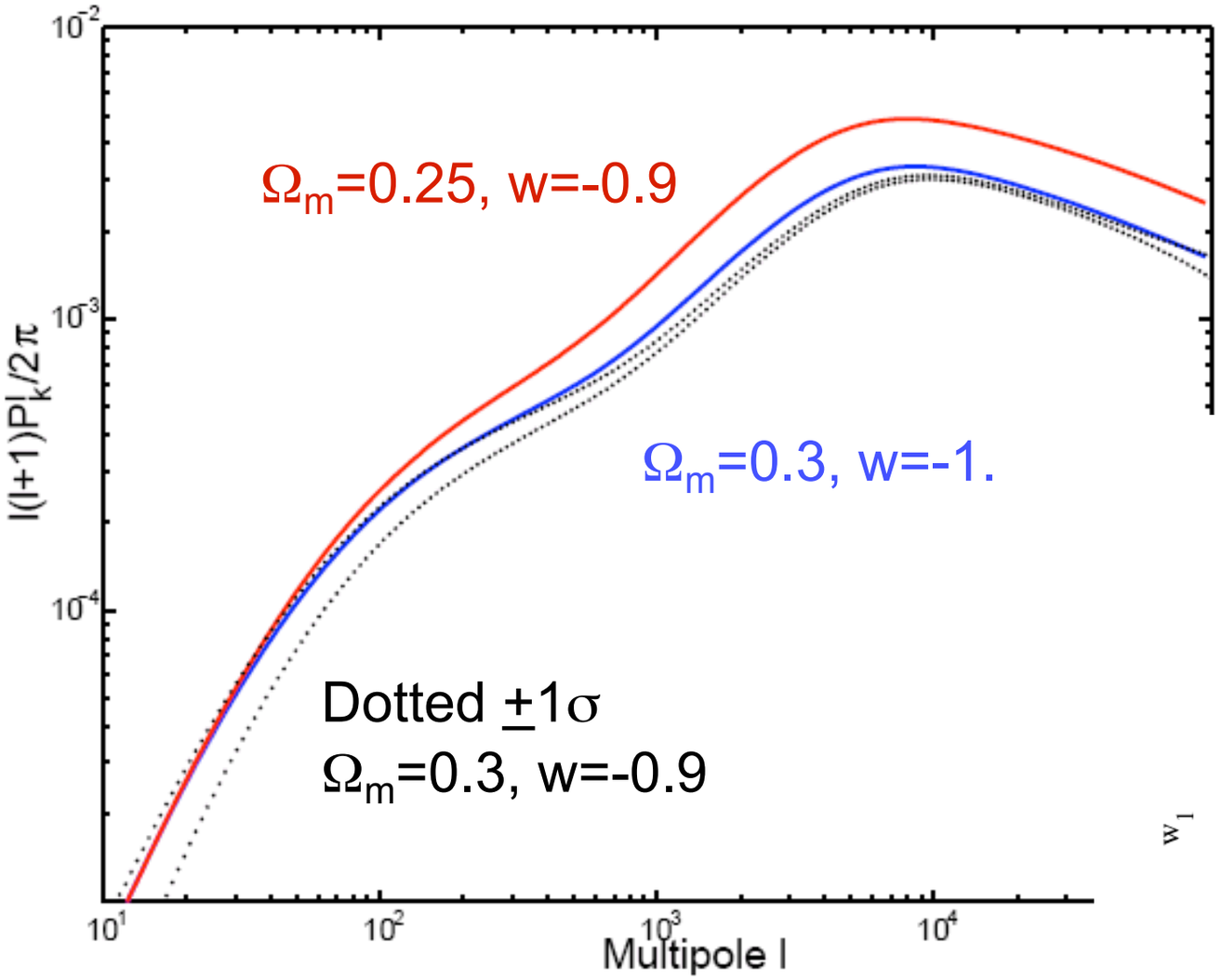
Complementarity with Planck



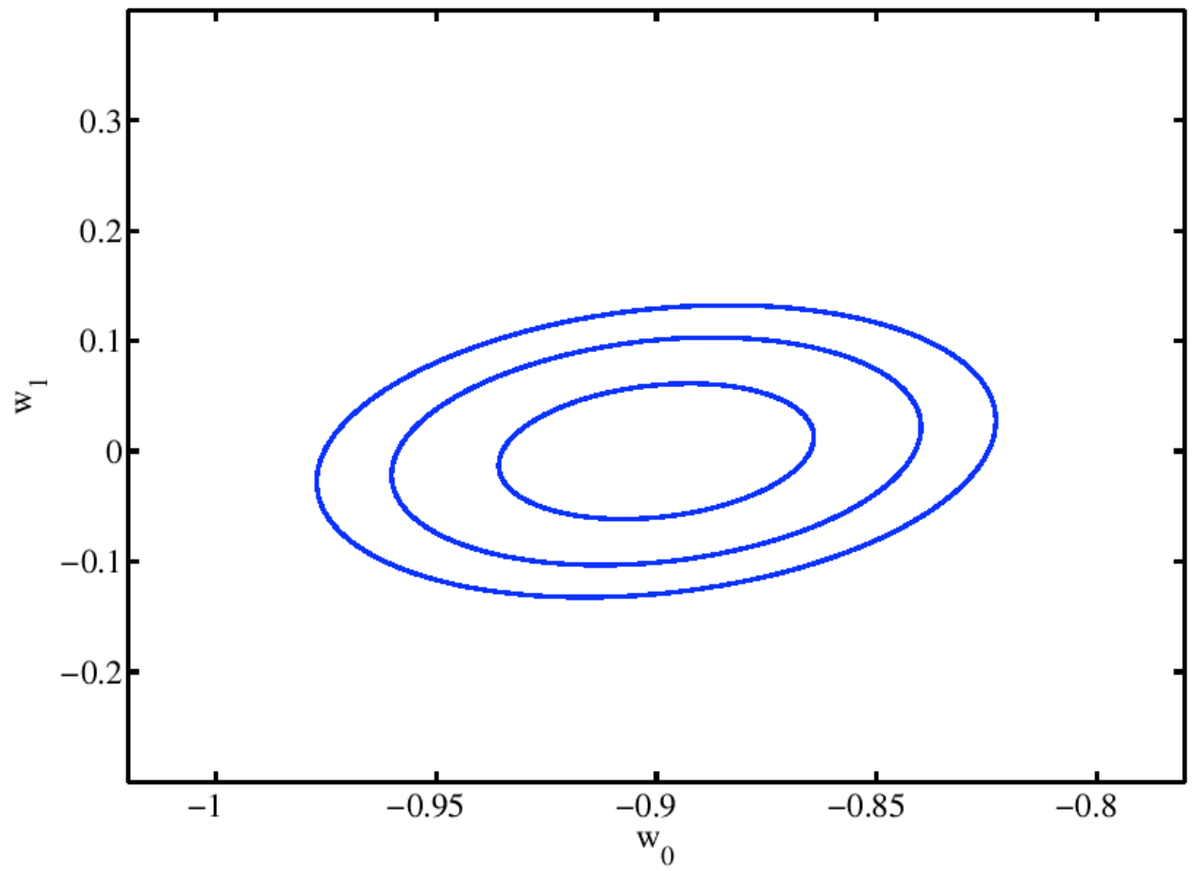
Cosmic Shear

- Integrated gravitational lensing along line-of-sight
  - "weak lensing"
- Requires large statistics
  - SKA continuum survey of 10 Billion galaxies
  - Clean sample
    - Reject star burst galaxies which may be the result of mergers (morphological alignment not the result of cosmic shear)
    - Still have a large sample with SKA
  - Improve result with analysis in redshift bins
    - Redshifts from SKA HI survey

SKA Weak Lensing



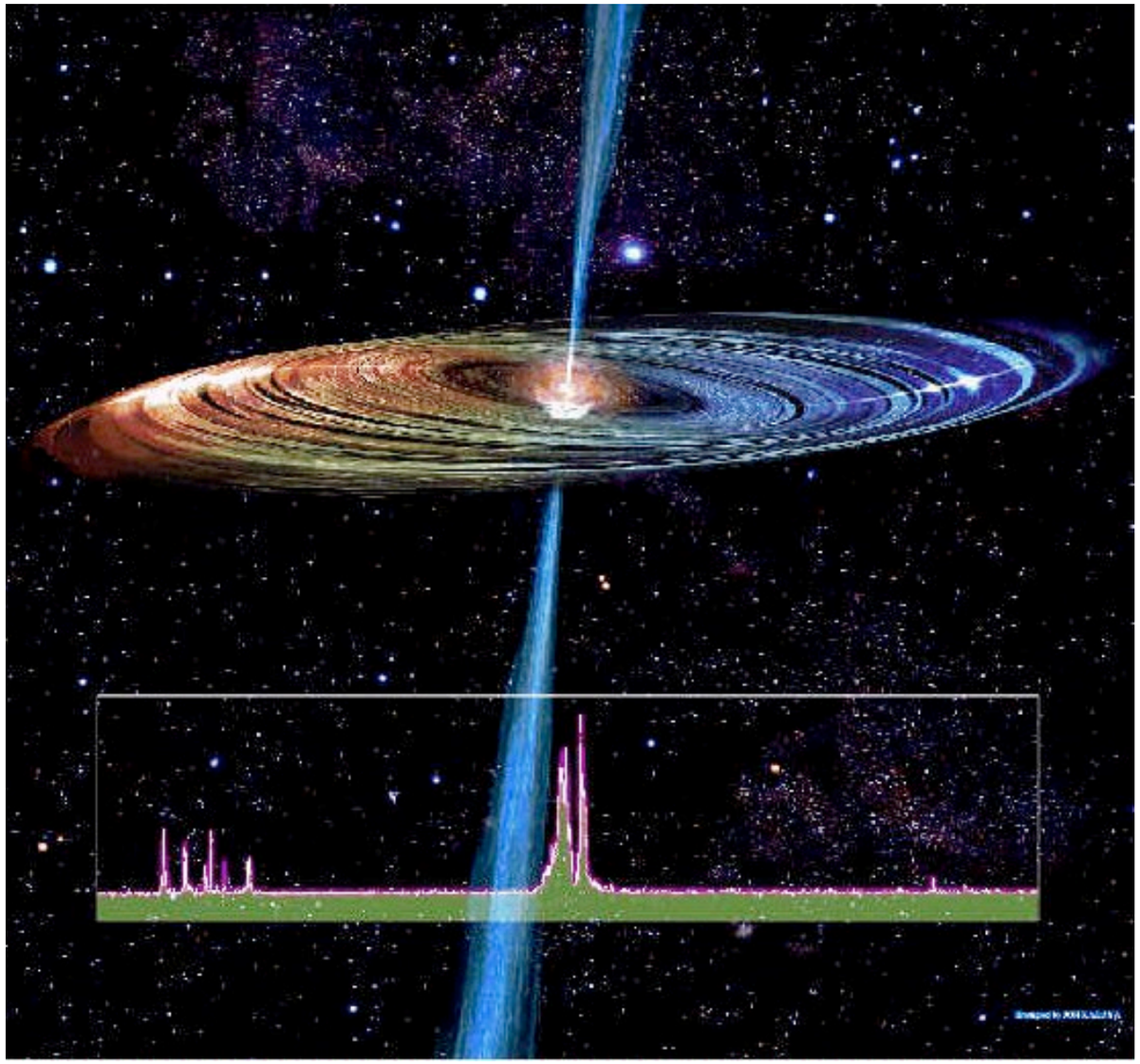
Could improve with redshift bins



68%, 95%, 99% likelihood contours

Blake et al 04

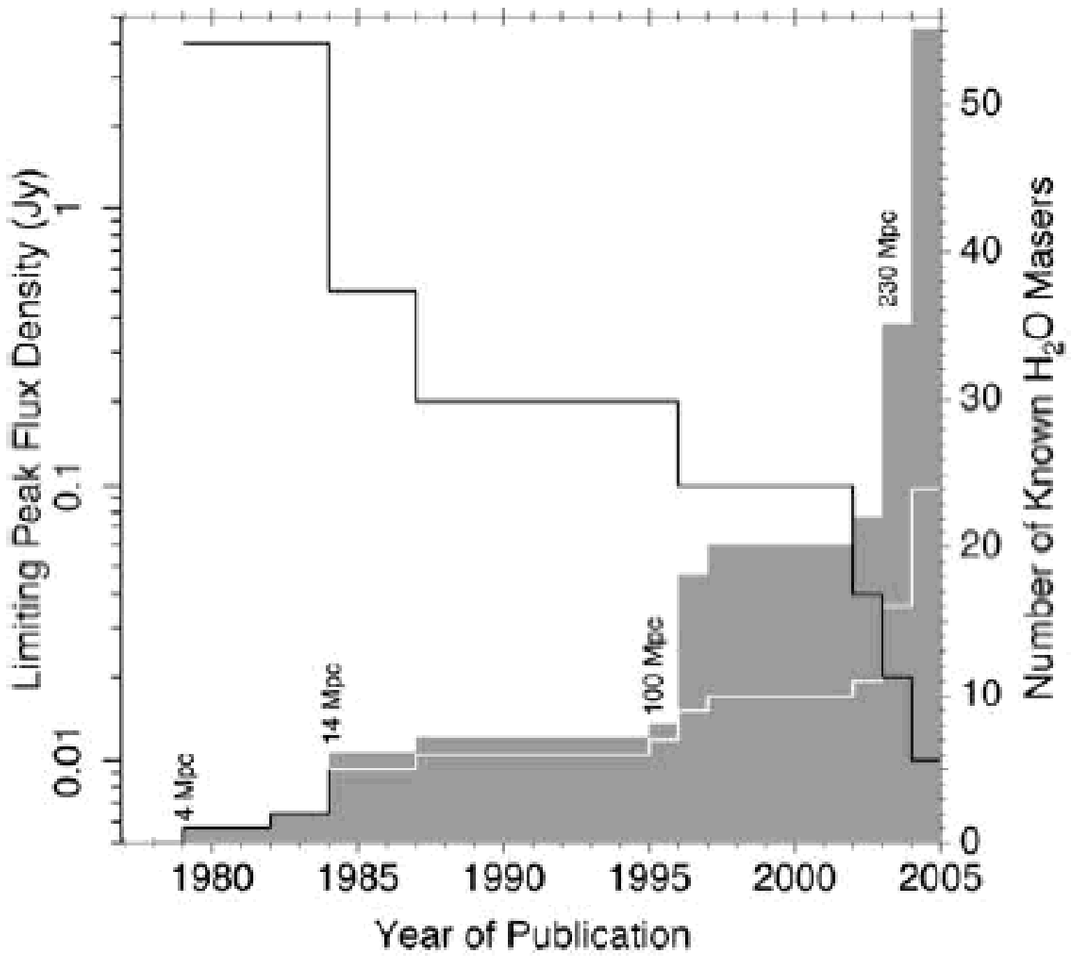
Measurement of H_0 with water masers



Case of NGC 4258:
(Greenhill et al, 1995,
Aragon et al 2007)

Water masers at various z
will provide H_0 with 1% precision

Proper motions of Water Masers



Greenhill 2004

50 masers known today (mainly GBT data)

For NGC 4258: 3% precision (proper motions over 6 yrs with VLBI)

SKA will find ~1000 masers

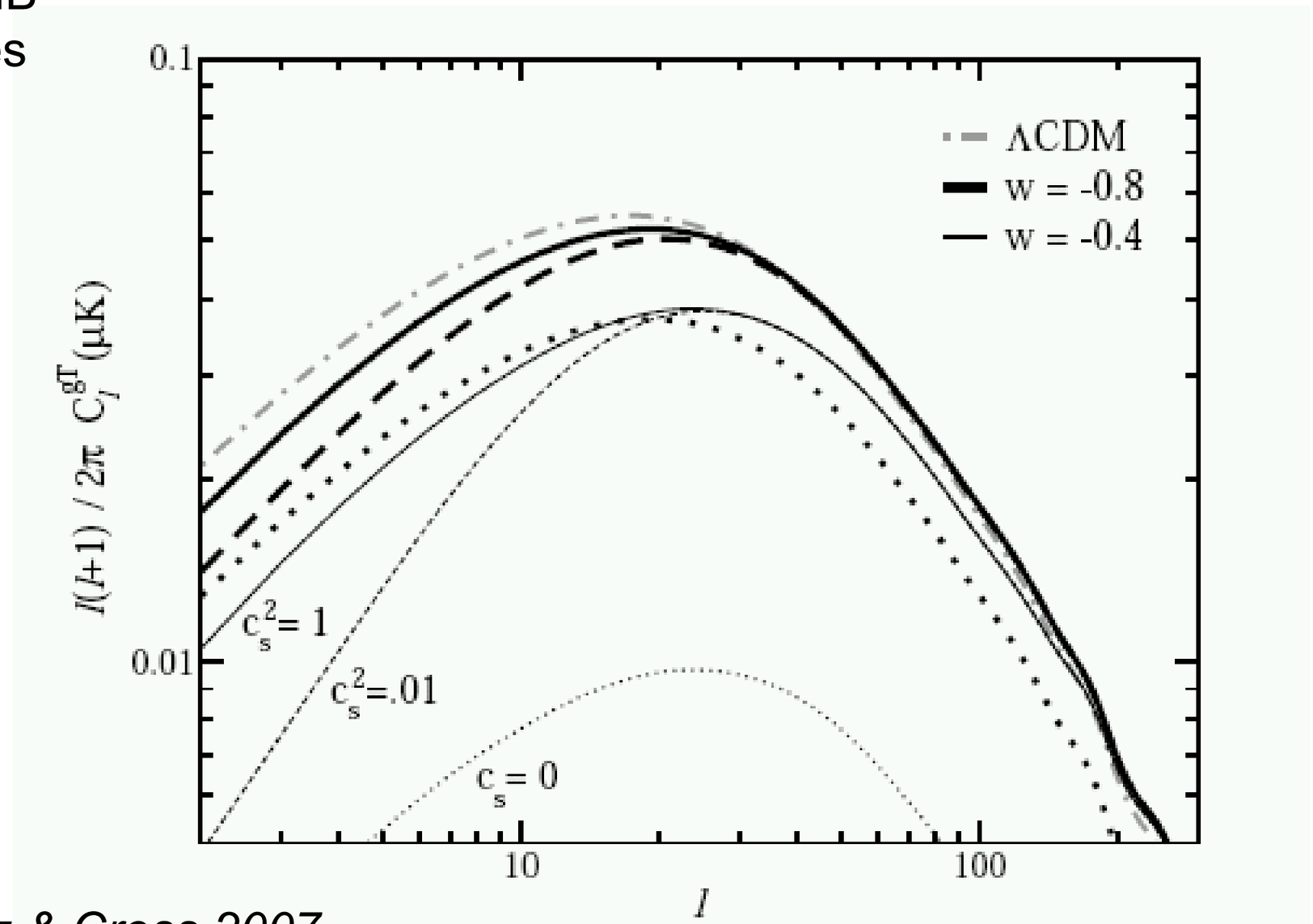
With ~10% useful for proper motion
100 masers
➔ 1% on H_0

DE sound speed c_s^2

Cross-correlation of CMB and galaxy overdensities

$0 < z < 2$

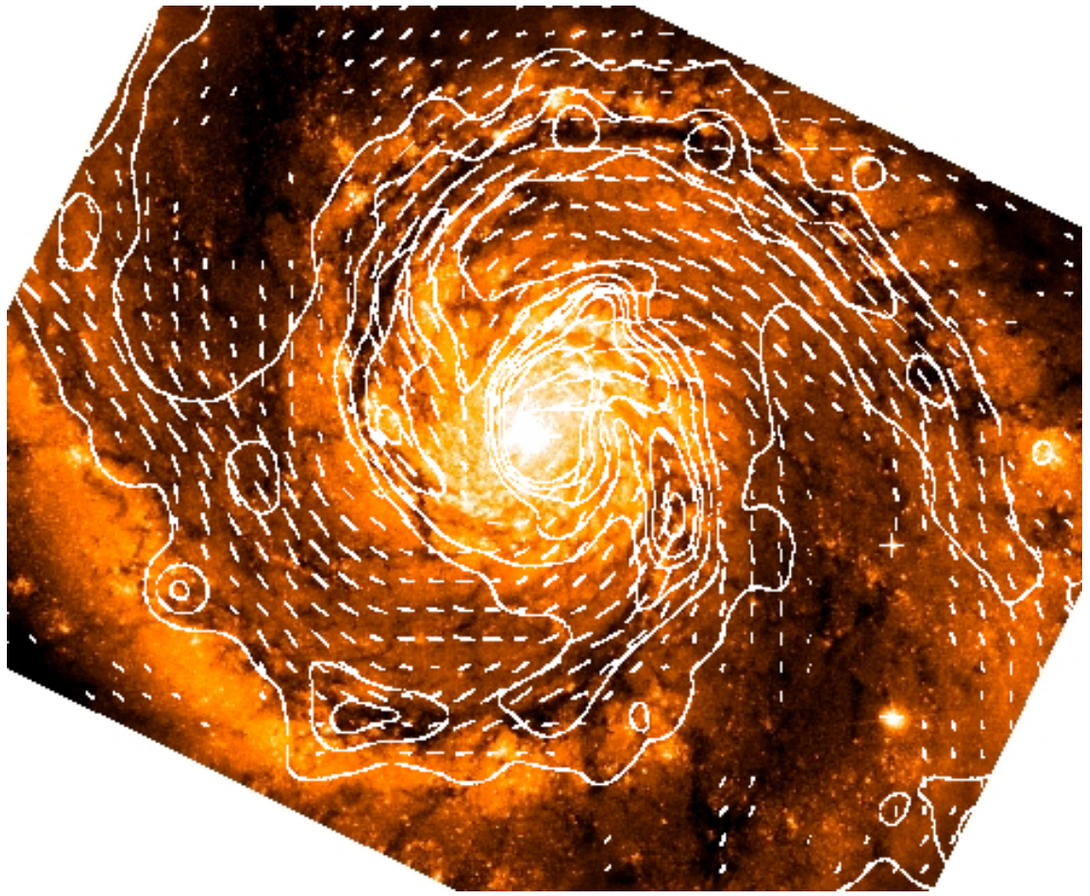
Only for $w \neq -1$



Torres-Rodriguez & Cress 2007

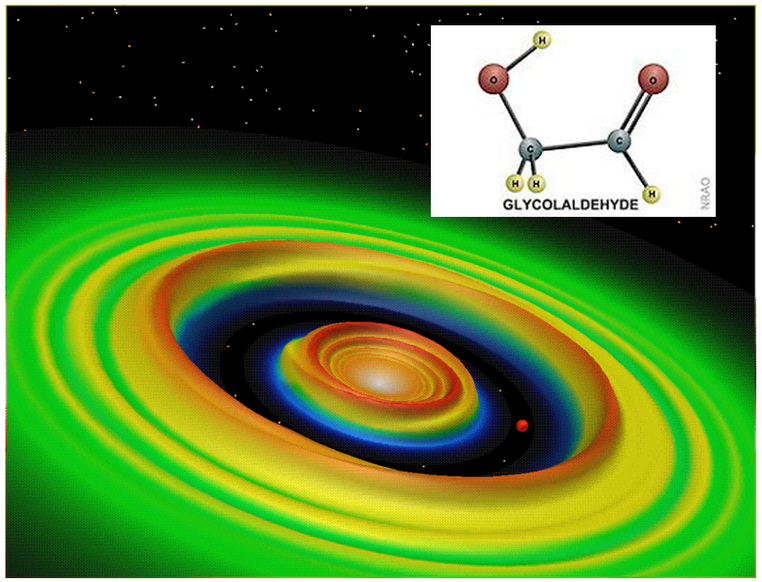
Cosmic Magnetism

- Origin of magnetic fields
  - Dynamo?
  - Primordial?



Cradle of Life

- Protoplanetary disks resolved to Earth-like orbits
- Organic molecules
- Extrasolar planets
- Extra terrestrial intelligence




M

Transients

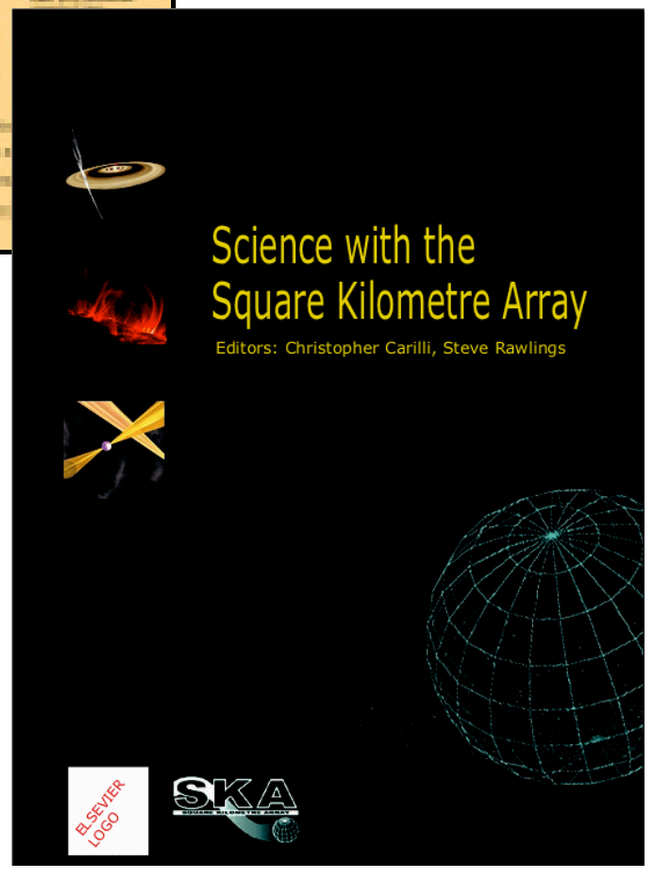
- Pulsar is a special case of transient phenomena (periodic)
- Giant pulses
- Supernova
- Bursters
- ETI

The Unknown

- New discoveries always result from observations in new parameter space
  - sensitivity
  - spatial resolution
  - spectral resolution
  - polarisation
  - time domain
  - observing speed (multibeaming)
- *eg*. CMB, pulsars, extra solar planets,…

SKA improves **all** of these

SKA Science Book



Chris Carilli & Steve Rawlings,

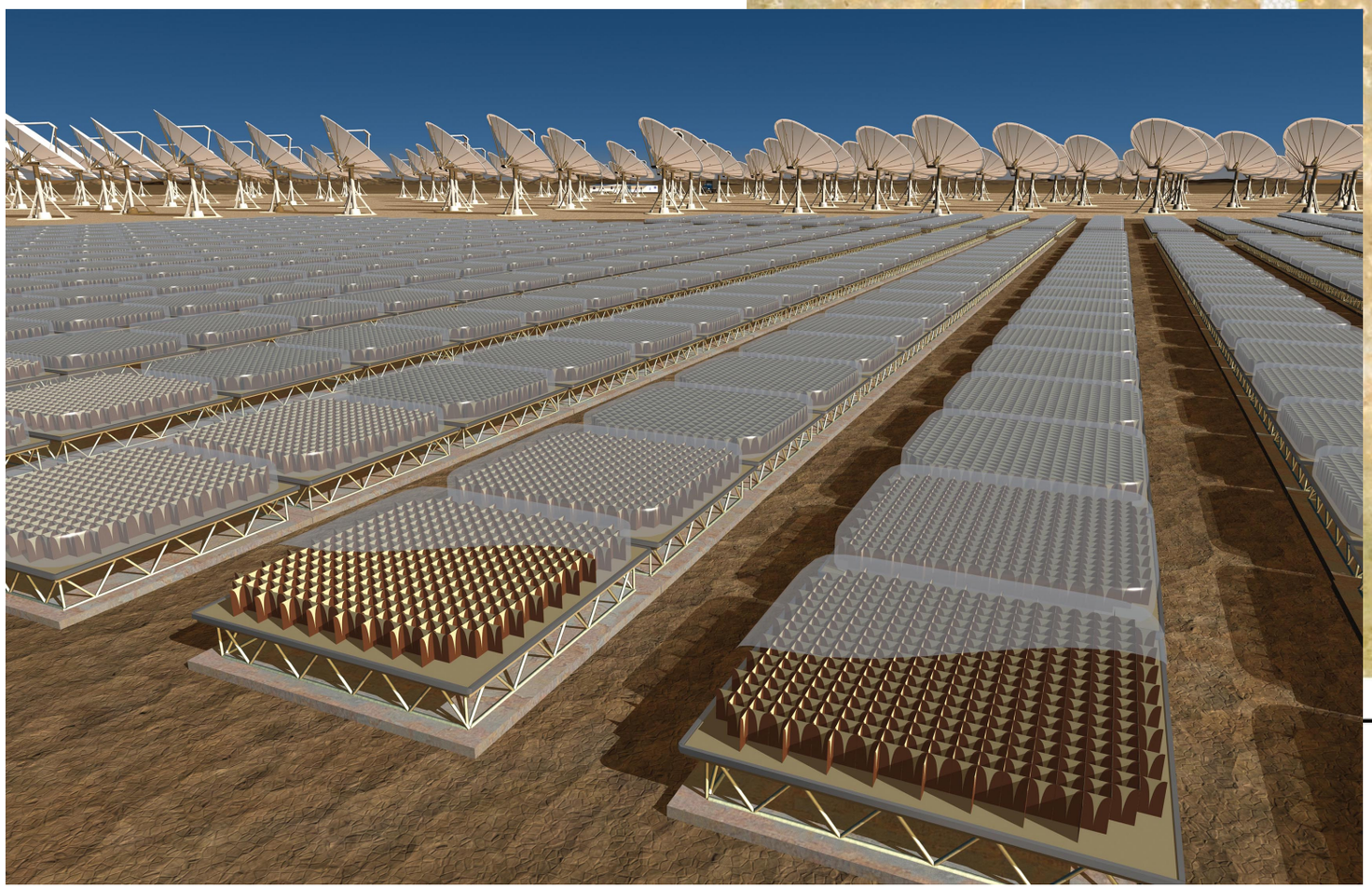
New Astronomy Reviews, Vol.48, Elsevier, Dec. 2004

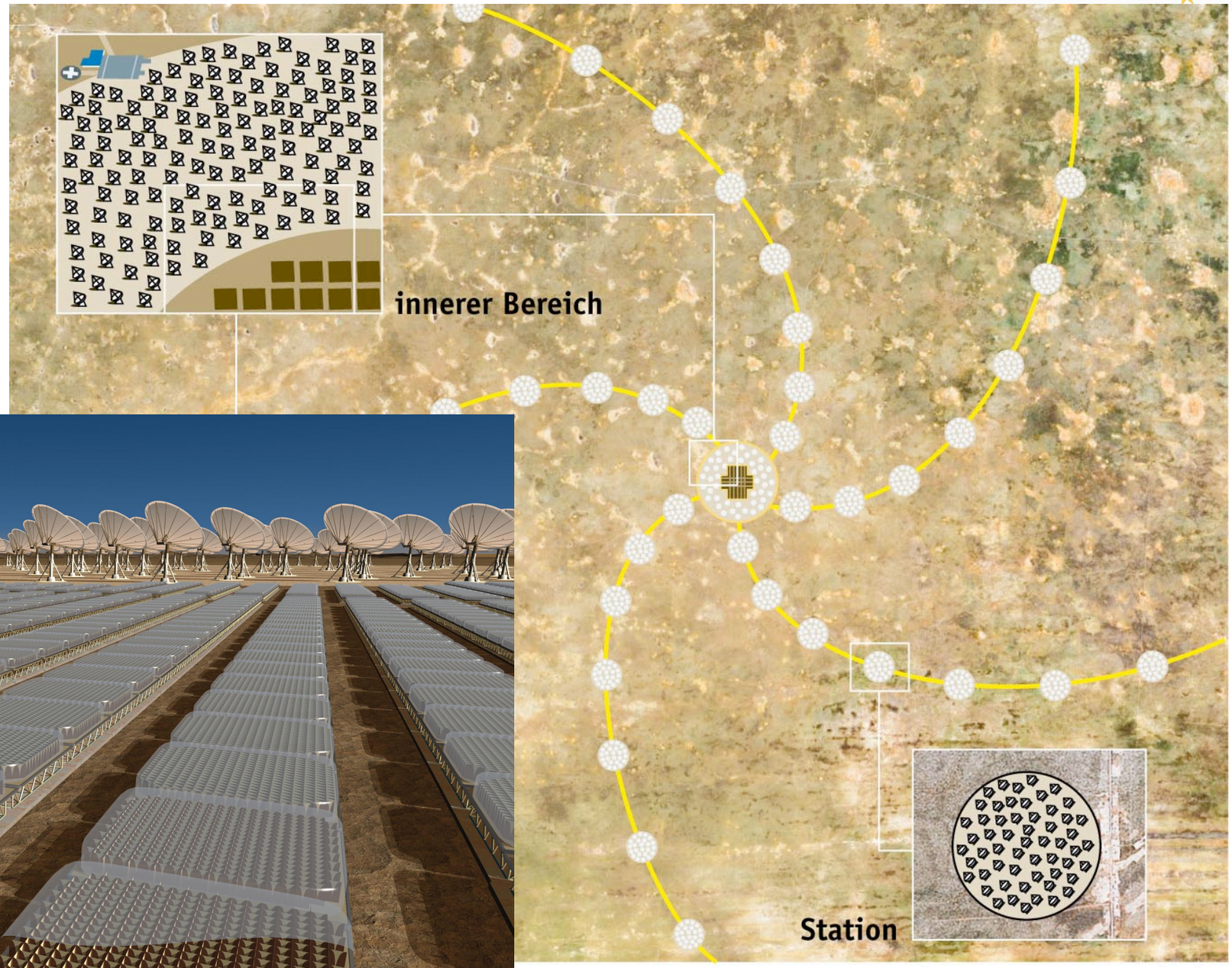
www.skatelescope.org/pages/science_genScBook.htm

2006: Reference Design

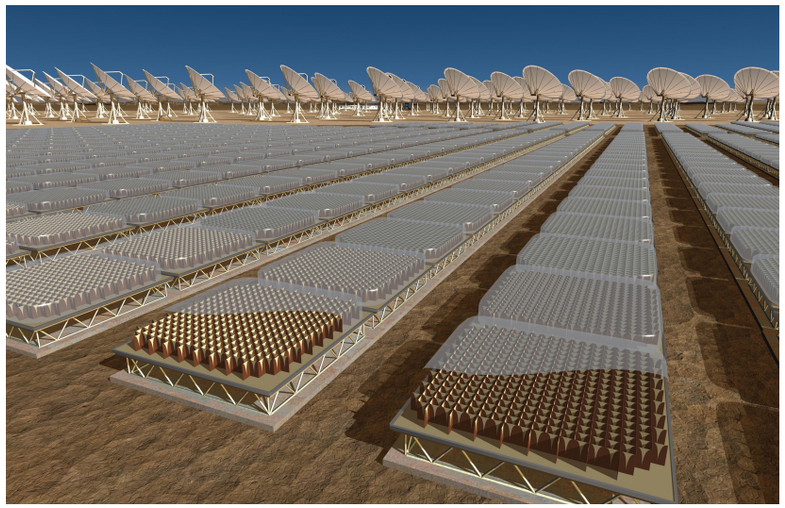
- Very large field of view (~10 sq deg)
- Large-D, small-N designs not competitive
  - Canadian LAR, Chinese FAST, Australian SKAMP
- SKA will be a phased array of
  - Dishes 6-15m diameter in ~100 stations
  - Dipoles for low frequency
  - Dense phased array for mid frequency
    - **IF SHOWN TO BE FEASIBLE/AFFORDABLE**

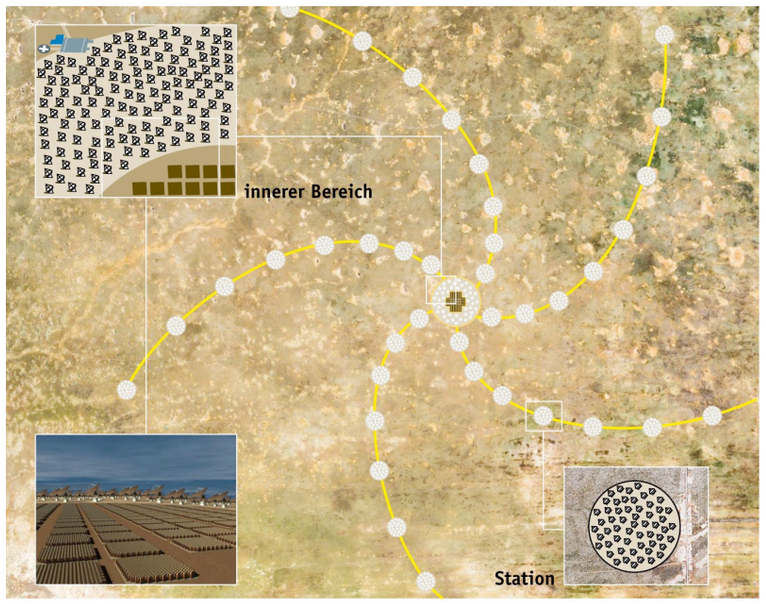
SKA Reference Design (2)





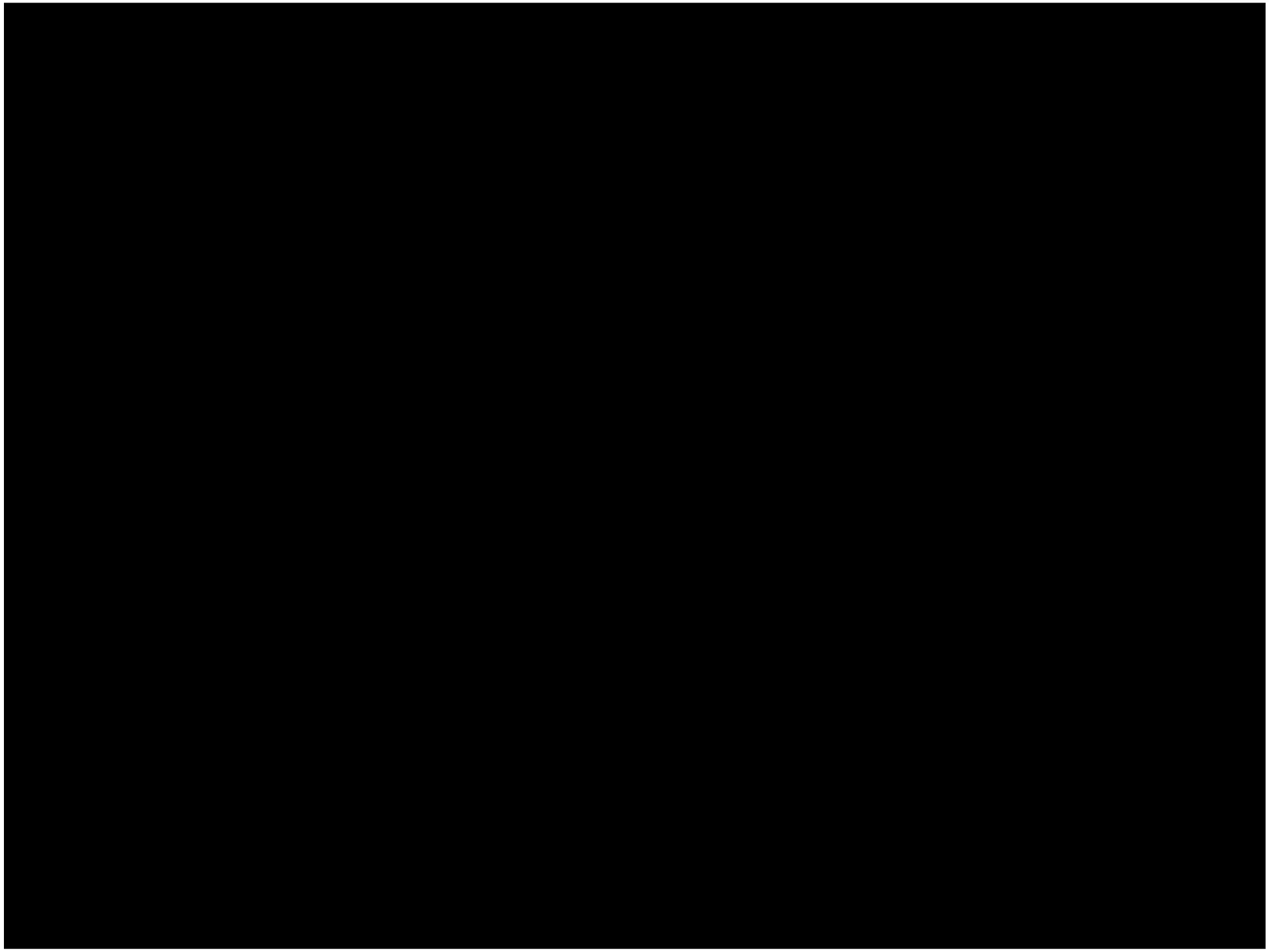
SKA Reference Design (3)





- Inner core (5km) of densely packed phased-array tiles
- Surrounded by paraboloid dishes (~10m diameter)
- Dishes may have multibeam feeds (phased arrays or horn clusters)
- ~200 stations of ~100 dishes each out to a baseline of 3000km

SKA Reference Design



Demonstrator: LOFAR

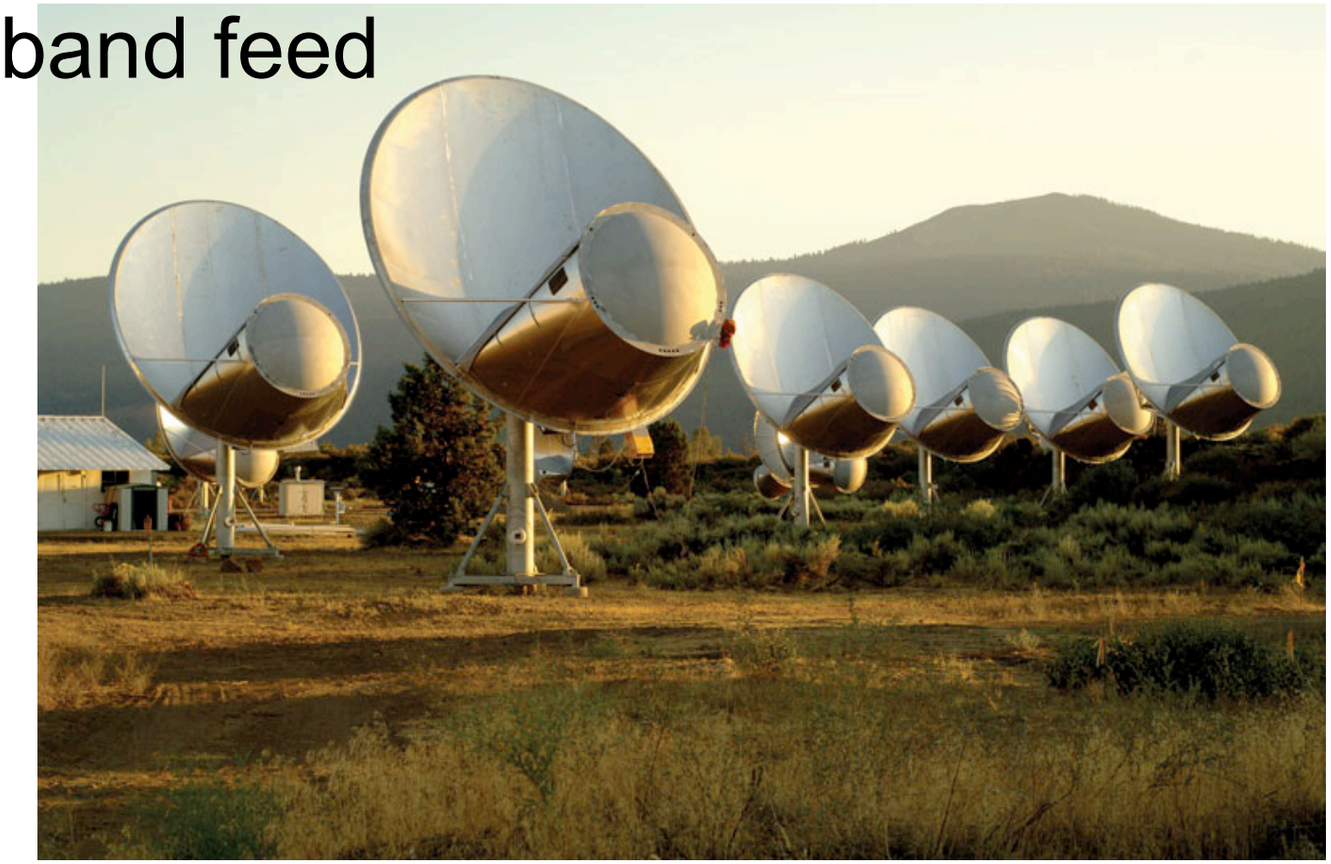
- Netherlands, with Germany, UK, France, …
- Low frequency: 80MHz – 225MHz

Demonstrator: Mileura Widefield Array

- Low frequency: (LOFAR competitor)
- USA: Massachusetts Institute of Technology
  - With Australia

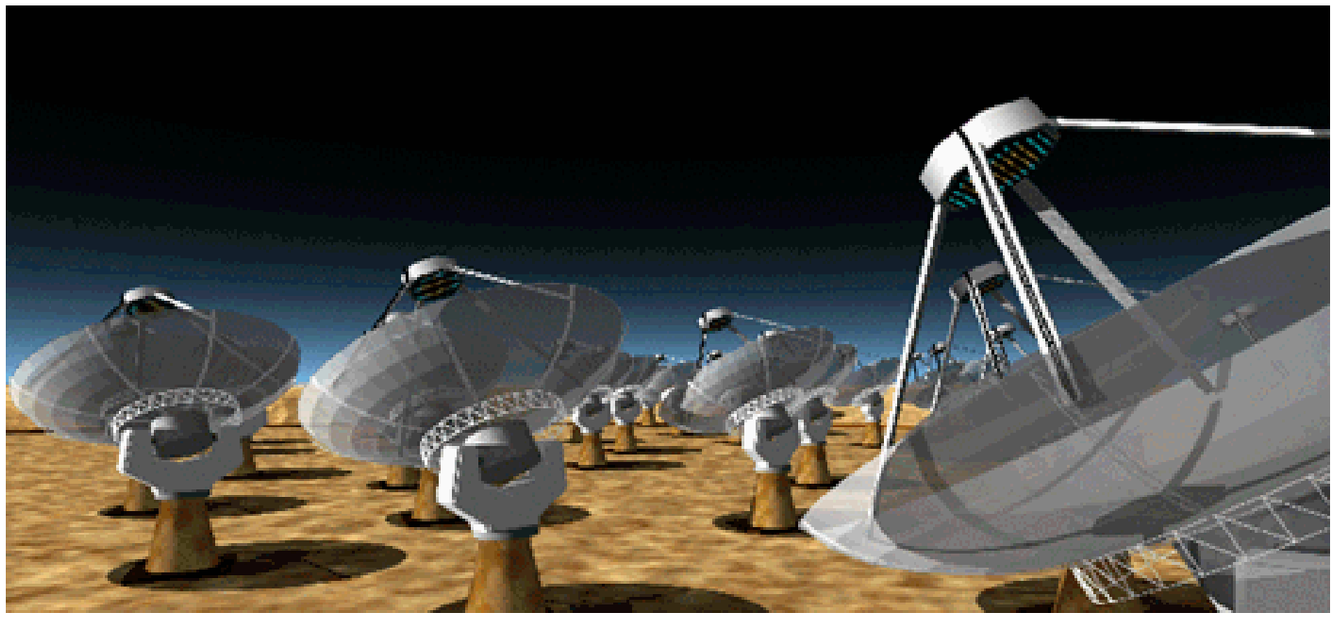
Demonstrator: Allen Telescope Array

- Full SKA frequency range (100MHz - ~20GHz)
- Large N, small D (6m)
- N=42 (currently: need ~30 000 for SKA)
- Planned for N=310 (ie. 1% SKA)
- Single pixel, ultra wide band feed



Demonstrator: MIRANdA

- Mileura International Radio Array large-N small-d Array
- ~15m dishes with phased-array feeds
- Partners: Australia and Canada



Demonstrator: KAT & MeerKAT

- South Africa: Karoo Array Telescope
  - 15m dishes with horn clusters
- MeerKAT
  - Possible SKADS Benchmark demonstrator
    - 6m dishes wide band feeds (ATA)
    - Central aperture-plane phased-array

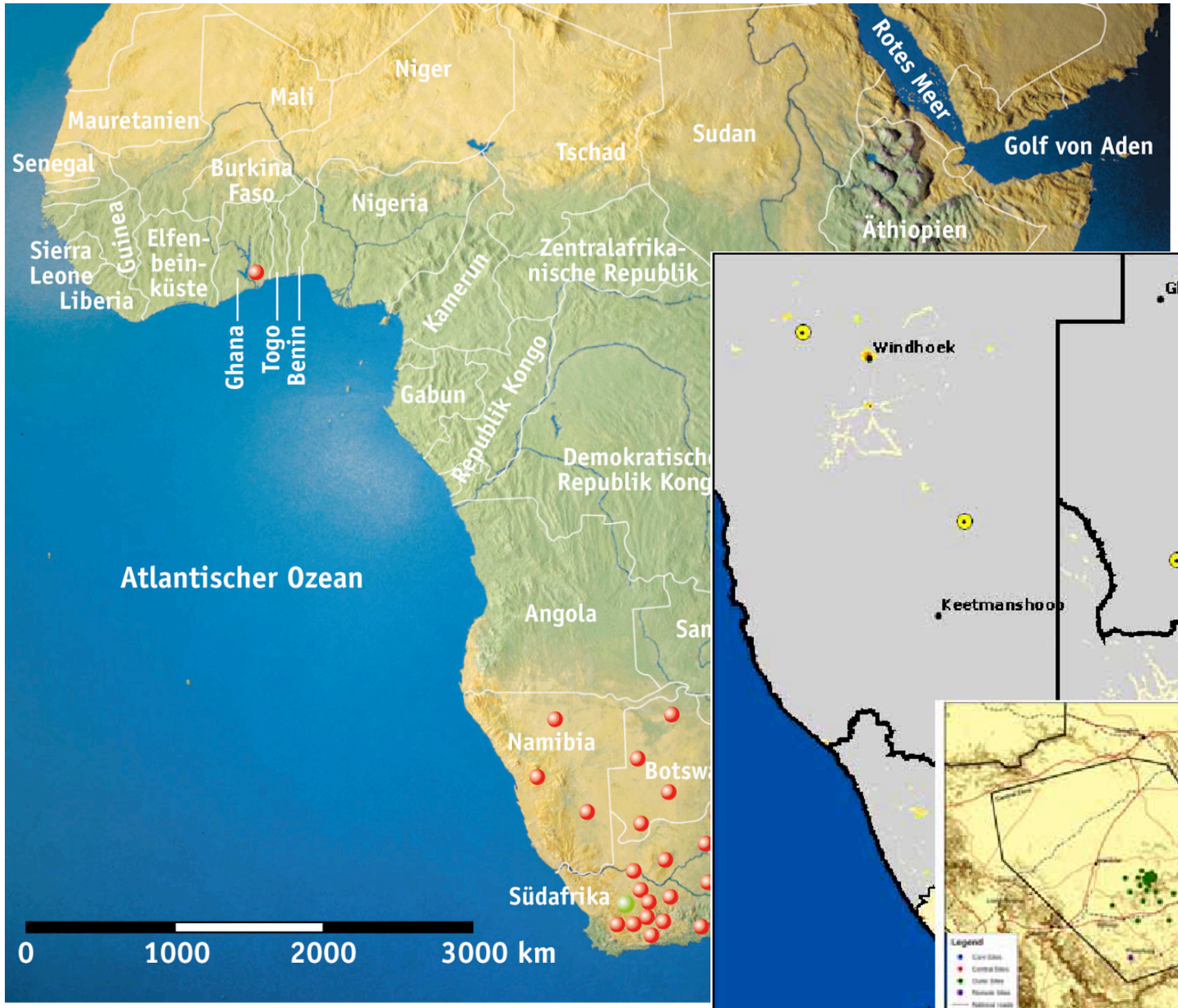
Worldwide SKA efforts

- Europe
  - LOFAR
  - Square Kilometre Array Design Studies
    - 4 year study, 38MEuro (10MEuro from EU Framework Programme 6)
    - EMBRACE demonstrator at Westerbork and Nançay

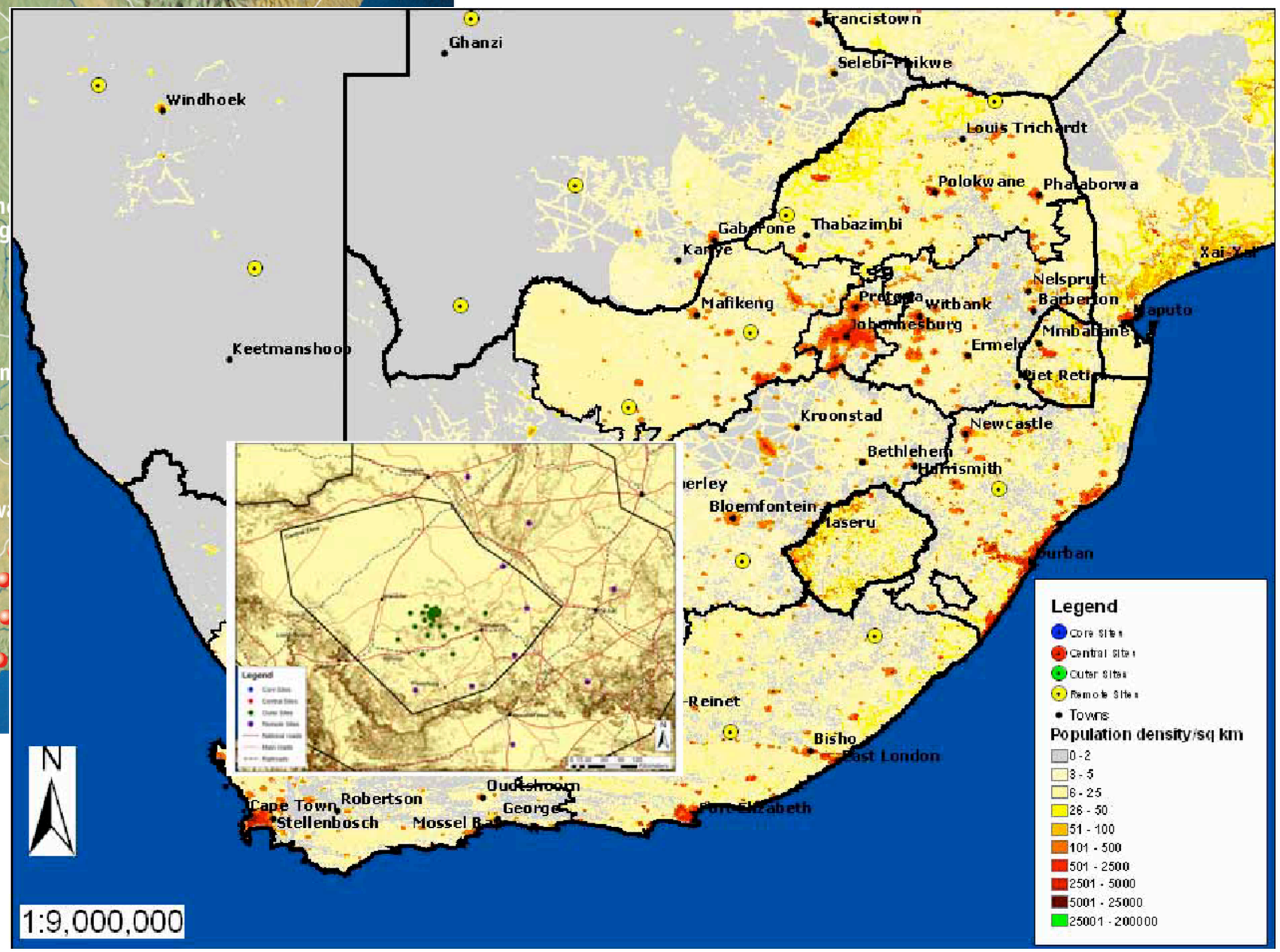
http://www.skads-eu.org

- Australia & Canada
  - AU$56M announced in 2007 Australian budget
  - MIRANdA demonstrator
- South Africa
  - Karoo Array Telescope and MeerKAT
  - Over US$200M confirmed by SA gov't for construction, infrastructure, including high capacity network to Karoo region.
- USA
  - Allen Telescope Array
  - Technology Demonstrator Programme (proposed)

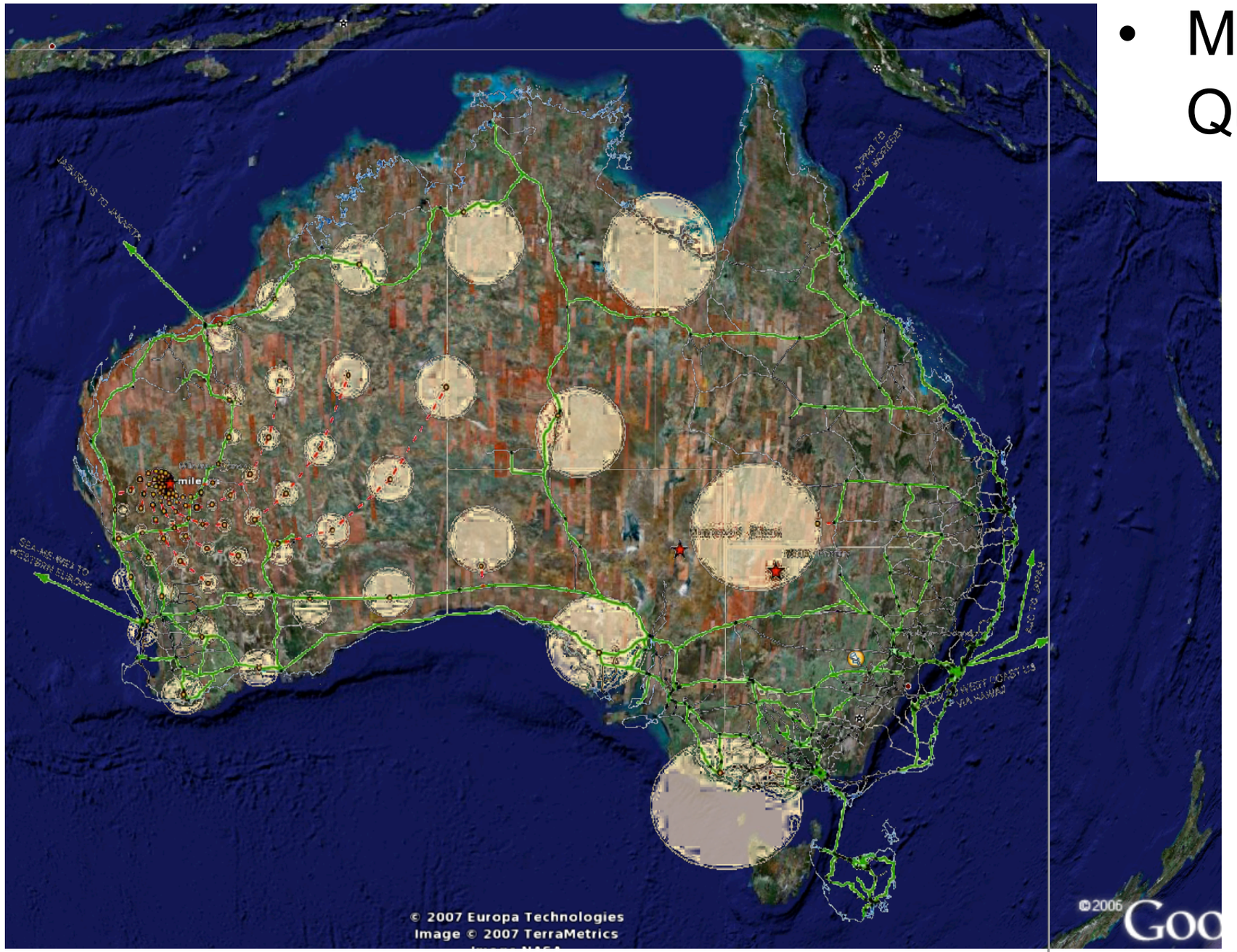
candidate site: South Africa



- Karoo radio quiet zone



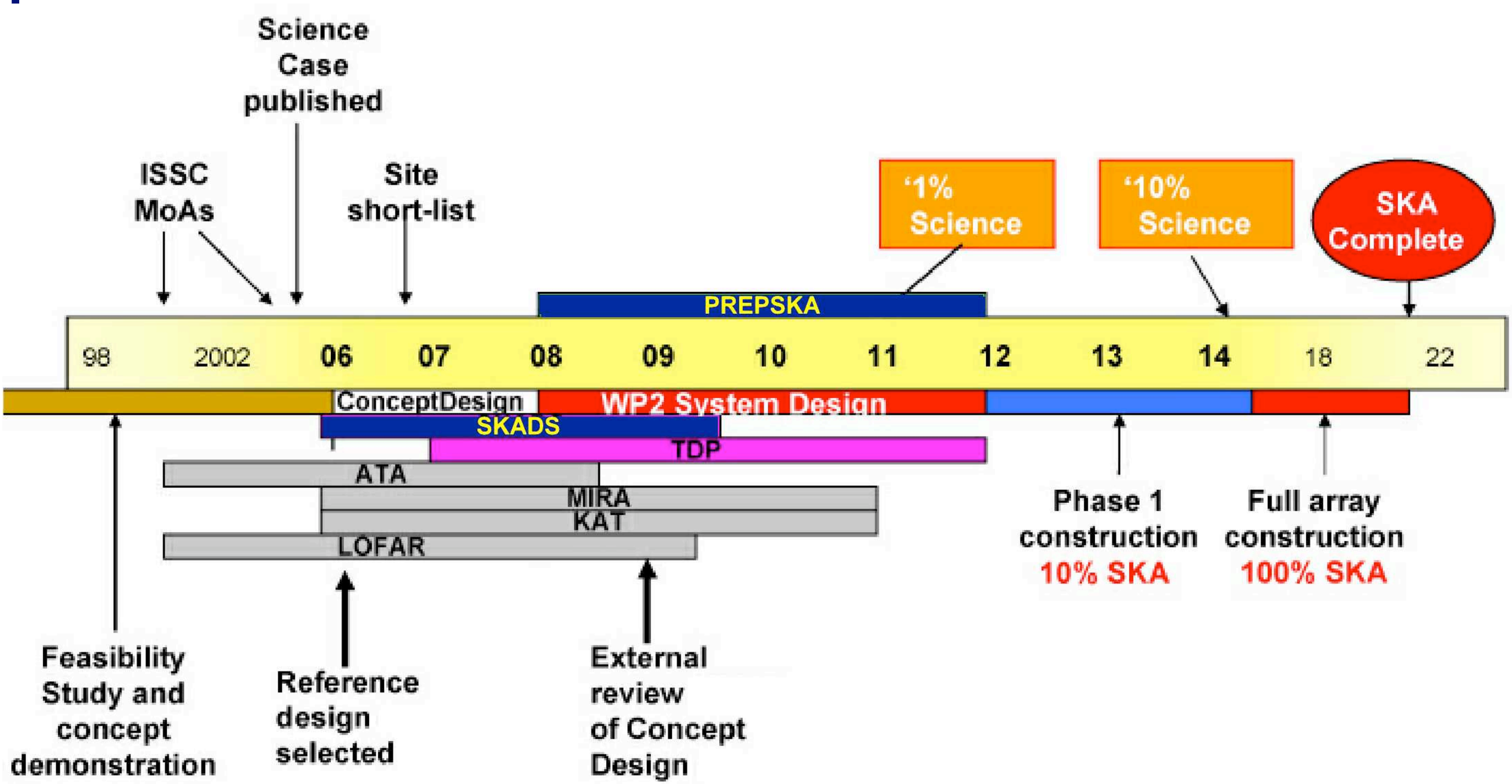
Candidate site: Australia



- Mileura Radio Quiet Zone

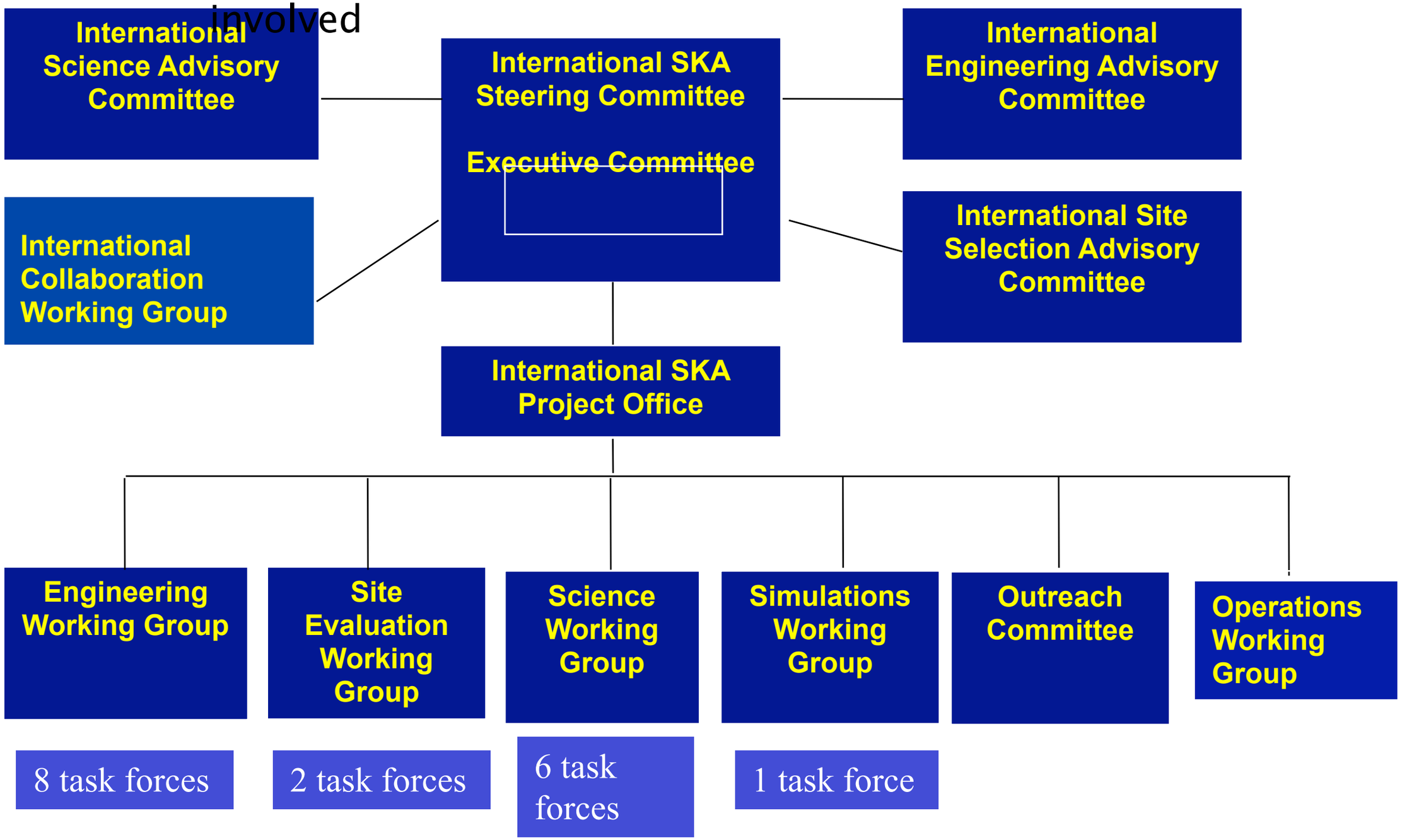
SKA Timeline

http://www.skatelescope.org



SKA Governance

SKA was "born global"; >50 institutes in 17 countries actively involved

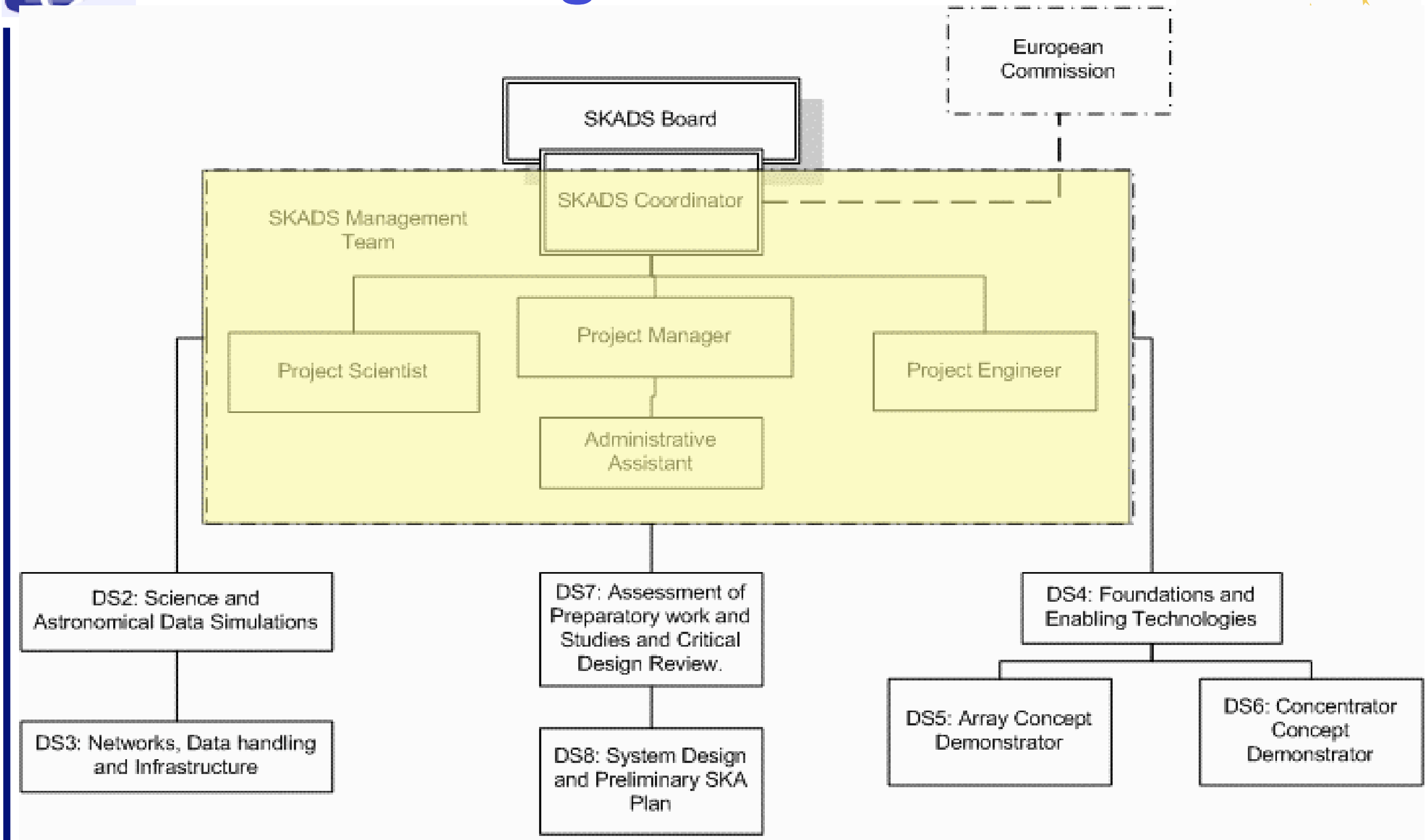


SKA Design Studies

- Square Kilometre Array Design Studies
  - 27 institutes in 13 countries
  - 38MEuro (including matching funds and EU funds)
  - Detailed design and costing, including signal transport, processing requirements, construction costs,…
  - www.skads.eu.org/p/memos.php

http://www.skads-eu.org

SKADS Organisation



SKADS Science Interactions

The Universe

observations

Our understanding of the Universe

brain power

Data analysis **(DS2)**

science goals achievable?

Request spec change **BENCHMARK**

Sky Simulation (DS2T1)

Catalogs, images, EM fields

Simulated telescope image

Technology development (DS4)

Technology demonstrators (DS5 & DS6)

measurements and simulated performance

Convolution with the telescope (DS2T2)

Data imaging (DS2T2)

voltages

Network simulator (DS3T3)

Backend data

SKADS Science Interactions

NO: not technologically feasible

NO: too expensive

Request spec change **BENCHMARK**

Data analysis **(DS2)**

science goals achievable?

Consider trade-offs

Sky Simulation (DS2T1)

Catalogs, images, EM fields

Simulated telescope image

Technology development (DS4)

Technology demonstrators (DS5 & DS6)

measurements and simulated performance

Convolution with the telescope (DS2T2)

Data imaging (DS2T2)

voltages

Network simulator (DS3T3)

Backend data

SKA Science Simulations

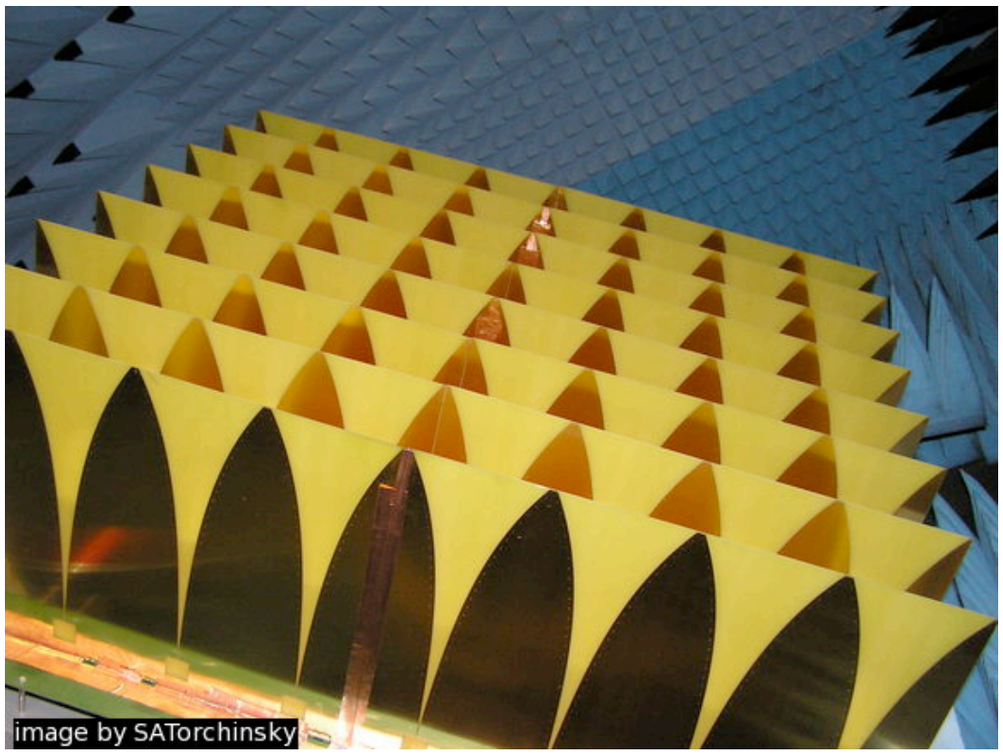
- Pushchino Radio Astronomy Observatory
- 31 july – 2 August 2007
- http://www.skads-eu.org/p/pushchino20070730.php

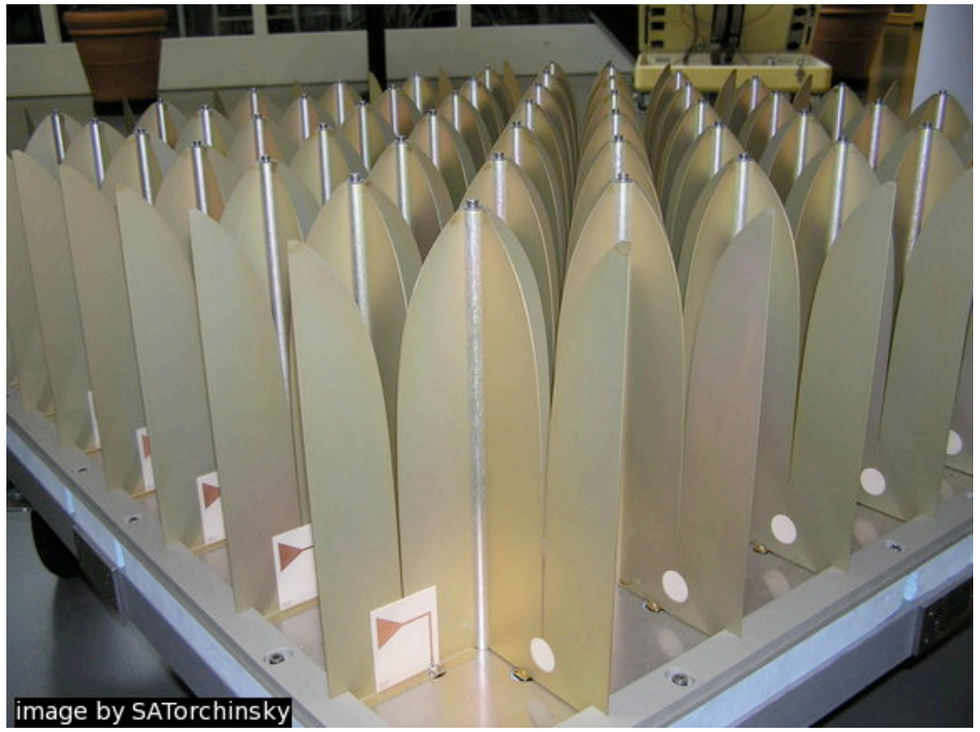
SKADS Benchmark

- Detailed implementation of the SKA reference design
- 100MHz – 300MHz sparse phased array (eg. LOFAR)
- 300MHz - ~2GHz dense phased array (eg. EMBRACE)
- >2GHz 6m dishes with FPA
- The benchmark is evolving…
  - http://www.skads-eu.org
    - Select “benchmark”
- First version of a costed design:
  - http://www.skads-eu.org
    - Select “documents”

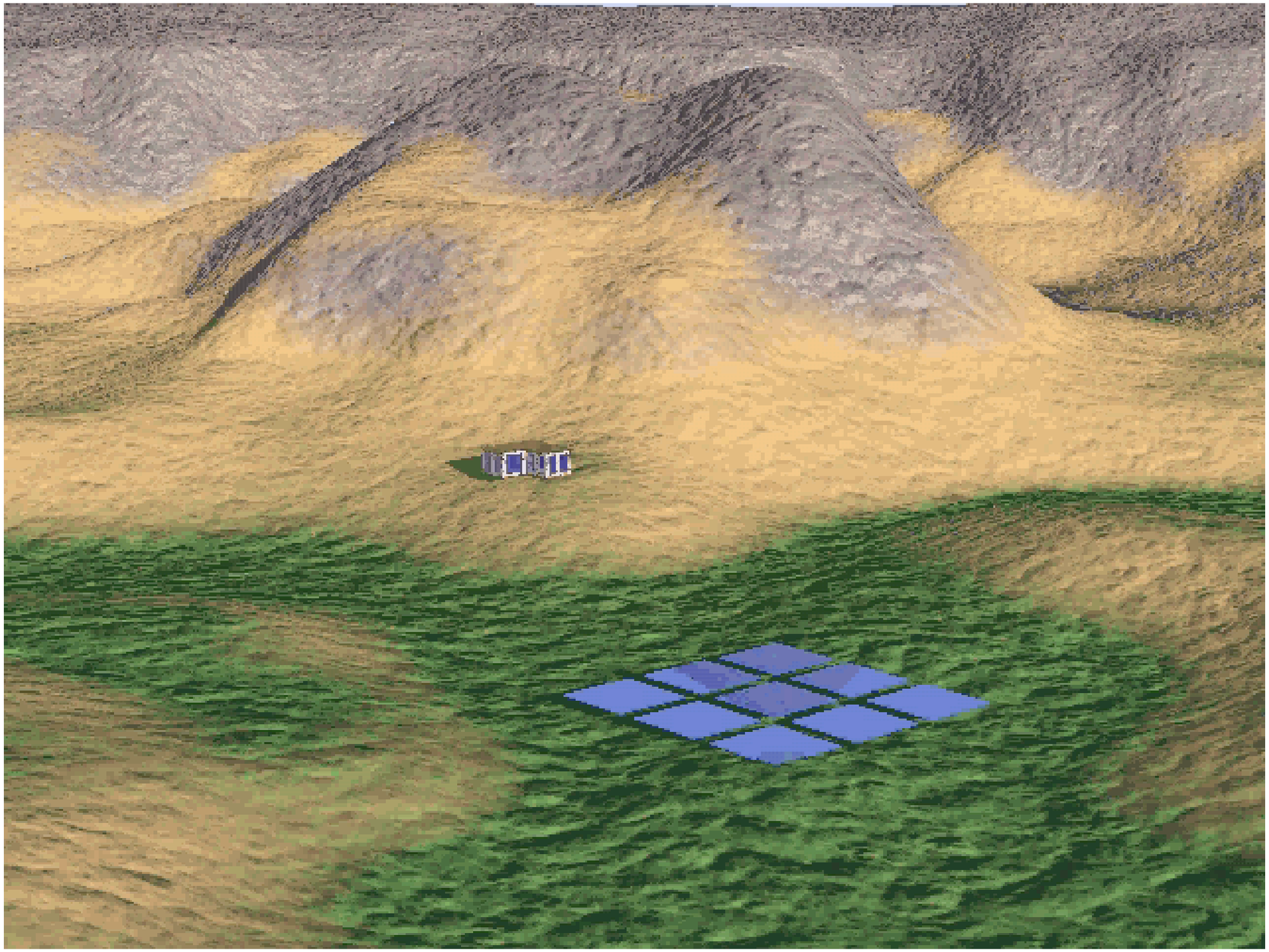
Densely packed Aperture-Plane Phased-Array

- Vivaldi planar feeds
- 300MHz – 1000MHz





Multibeaming with an Aperture Plane Phased Array



SKADS Benchmark

Parameter	Memos	Benchmark Spec.			Comments
	45/69	EOR AA	Mid-AA	Dishes	
Low Freq. *GHz*	≤ 0.1	0.1	**0.3**	1.0	*Probably should have some overlap*
High Freq *GHz*	≥ 25	0.3	**1.0**	25	*AA cost goes > square law with top frequency*
Bandwidth *GHz*	25%	0.2	**0.7**	5	*This may be unrealistic for the dishes*
Polarisations	2	2	**2**	2	*Default linear*
Pol error (after cal): FOV centre/edge *dB*	-40/-30	-40/-30	**-40 /-30**	-40/-30	*Important for dynamic range.*
FOV:					
0.1-0.3 GHz *deg²*	200	200			*This is really total beam size*
0.3-1.0 GHz *deg²*	50		**250**		*The FOV naturally scales as 250(1.0/f)²*
1.0-3.0 GHz *deg²*	1-10			$3(1.4/f)^2$	*Defined by a 6.1m dish natural beam size.*
3.0-25 GHz *deg²*	$0.33(3/f)^2$			$3(1.4/f)^2$	
FOV filling	100%	100%	**100%**	100%	*The full field of view should be filled with beams*
No. of steerable FOVs	1-4	4	**8**	1	*AA FOV count limited by comms.*
Survey @ 0.7GHz	1.5×10^{19}		**1.75×10^{19}**		*Assumes 10,000m²/K sensitivity*
Speed: @ 1.5GHz *deg² m⁴ K⁻² Hz⁻¹*	3×10^{17}			8.4×10^{17}	*Assumed 700MHz B/W at this freq, 3 deg² FOV (FoV x (A/T)² x BW)*
System temp Tsys *K*	50K	>100K	**50K**	≤30K	*Assumes dishes use at least 70K cooling*
Sensitivity @45° m^2K^{-1}					
>0.3 GHz	5,000	5,000			*The sky noise is v. high for low freq*
0.3 – 1.0 GHz	20,000		**5-10,000**		*Red. sensitivity by trading large FOV*
1-10 GHz	20,000			10,000	*Single pixel feed so can cool for low system temp*
>10 GHz	10,000			10,000	
Dynamic range	10^6	10^6	**10^6**	10^6	*Peak b'ness to rms noise level (not ADC range!)*

SKADS Benchmark (2)

Parameter	Memos	Benchmark spec		Comments	
	45/69	EOR AA	Mid-AA	Dishes	
Scan range *deg*	-	±45°	**±45°** ±60°	±75°	Dish limitation due to offset design Dish scan angle without shadowing
Max Baseline *km*	>3000	??	**3000**	3000	*Does the EOR array need long baselines?*
Min Baseline *m*	20	20	**20**	20	*Assumes AA can use sub arrays within a station.*
Concentration: *%* < 1km < 5km < 150 km	 20% 50% 75%	 ?50% ?100%	 **20%** **50%** **75%**	 20% 50% 75%	*Assumes mid-AA on the longest baselines.* *What distribution reqd. for EOR array?* *Pulsar search may require more concentration of the core.*
Max no. of image pixels	-	$10^5 \times 10^5$	**$10^5 \times 10^5$**	$10^5 \times 10^5$	*Should determine required station data rates*
Simultaneous ind. operating bands	2 pairs	ind	**ind**	ind	*All 3 collectors usable independently*
Beamformed data *Bits*	8	8	**8**	8	*May wish to modify this for different obs. Trading total comms capacity for B/W and resolution*
Antenna blind pointing *HPBW*	0.1	<0.05	**<0.05**	0.05	*Accuracy for obs.*
Antenna Slew rate *°/sec*	1.5	~0	**~0**	<1.5	*AA slew 'instantly'*
Slew 0.5 HPBW *sec*	3	~0	**~0**	<3	*Slew time between adjacent points*
Time of day effects	No comment	??	**??**	None	*Implies that the LNAs will need to be at least temp stabilised*

SKA & SKADS: summary (1)

- 60's – present: Radio astronomy improvements in receiver performance, spectral resolution, data processing
- Arecibo remains largest collecting area for ~50 years
- SKA: proposed as a survey instrument
  - Radio Schmidt proposal -> SKA
  - Finally improve collecting area
  - Global participation
- 2005/06: Key Science and Reference Design for SKA
- SKA demonstrators: LOFAR, MWA, ATA, KAT, MeerKAT, MIRANdA, (EMBRACE)

SKA & SKADS: summary (2)

- Key Science
  - Large Scale Structure
  - Epoch of Reionisation
  - Cosmic Magnetism
  - Tests of General Relativity in Extreme Fields
  - Cradle of Life
  - The Unknown
- SKA Reference Design
  - Central ~3km aperture-plane phased-array (EMBRACE)
  - Annulus of dishes out to 5km
  - ~200 stations of dishes (and dipoles for low frequency)

SKA & SKADS: summary (3)

- SKADS http://www.skads-eu.org
  - Mainly European
  - Concentrating on aperture-plane phased-array
  - EMBRACE demonstrator
  - Science simulations
  - SKADS Benchmark:
    - Detailed implementation of the SKA reference design
    - Costing analysis