The Square Kilometre Array

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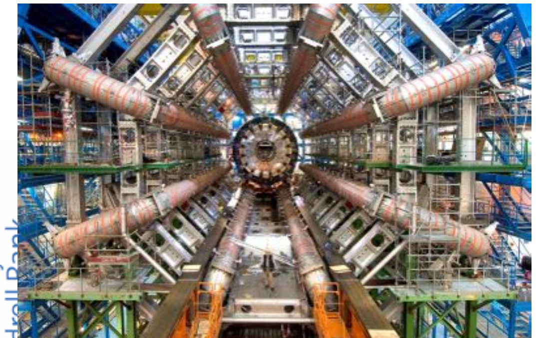
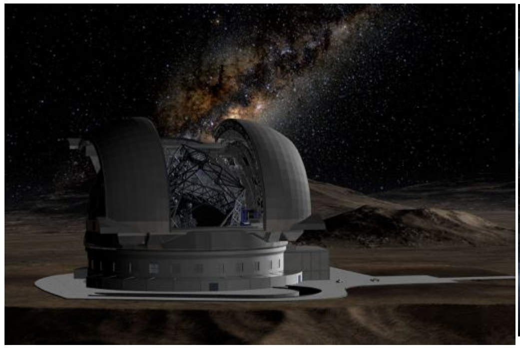
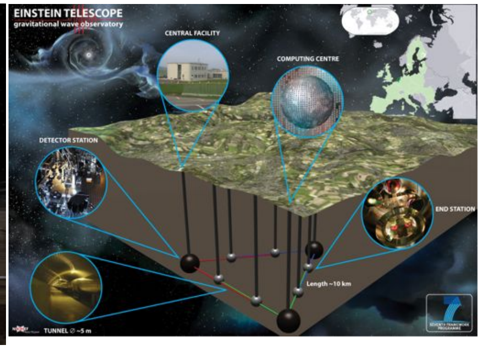
Time for Big Machines

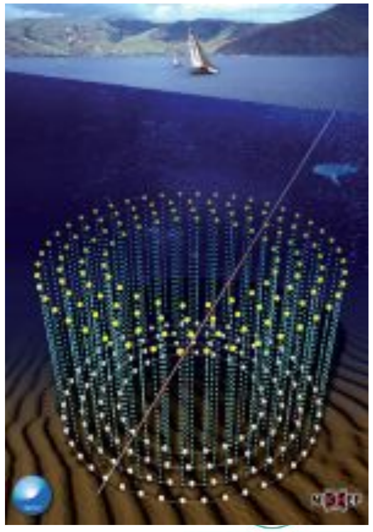
We live in exciting times:

- we are on the verge of confirming/disproving some of the most revolutionary theories of the last century
- we find clues as to whether these theories are complete or not
- we may find a way to describe large and small scales with one theory
- we are about to trace the complete history of the universe
- we are about to study extra-solar worlds and Earth-like planets
- we are about to open a truly new window to the Universe and its wonderful constituents









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But.... It takes increasing efforts to make such fundamental and important discoveries – it needs (typically) BIG machines in particular if we aim for versatile observatories not just experiments

➔ To make them happen requires multi-national/global collaborations

A prime example…

- Introduction
- The Square Kilometre Array
- Project details
- Technical Challenges
- Progress, status & timeline
- Science revisited

Introduction

The birth of a new idea…

It all started in 1990 with an IAU Colloquium and a simple question:

What telescope is needed to answer:

- How did the Universe achieve its present form?
- What and where is dark matter ?
- How did galaxies form ?
- What happened at the era that separated ionized from neutral hydrogen ?

One answer to the question:

"The Hydrogen Array" by Peter Wilkinson (1991)

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The Hydrogen 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

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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.

Swarup and colleagues have been stressing the advantages of large collecting areas at low frequencies for over twenty years. They are now constructing the Giant Metrewave Radio Telescope (GMRT – Swarup, this volume) which is essentially a 'pointable Arecibo' working up to L–band. Pariskii (this volume) discusses the trend of collecting area with time and points out that an instrument with an area of 10^6 m^2 is now required if we are to keep up with the progress made by the pioneers. I arrived at a similar conclusion in 1985 from the following argument: the VLA and the WSRT can only image in HI with a resolution of ~ 10 arcsec; to allow imaging at the much more useful resolution of 1 arcsec requires a telescope with ~ 100 times the collecting area. The reaction of colleagues at this conference to this idea convinced me that we should begin to think in earnest about a telescope with a collecting area of 1 km^2.

The first task is to establish a clear set of scientific goals. To my mind one goal stands out – a volume of the 'Encyclopaedia of the Universe' is written in 21cm typescript. Unfortunately the printing is rather faint and we need a large 'lens' to read the text! Hence the reason for dubbing the proposed instrument, 'The Hydrogen Array' or HIA for short.

SCIENTIFIC GOALS

Neutral Hydrogen Observations at z=0 to z=10: With a collecting area of 1km^2 the HIA could image nearby galaxies with a resolution of 1 arcsec. The detailed measurements of the HI distribution at this resolution would provide exciting new information on star formation, density waves and the amount and location of dark matter in individual galaxies. Some rotation curves are still flat where the surface brightness limit of current telescopes is reached. The HIA could detect galaxies > 4 times further away than Arecibo i.e. out to z=0.1–0.2 (500–1000 Mpc). Integrated HI observations of these galaxies will better constrain the value of H_o via the Fisher–Tully technique. Deep HI redshift surveys would then measure the departures from the local Hubble flow and hence constrain the matter distribution on large scales (the 'Great Attractor' debate). Studying the kinematics of many more clusters and groups of galaxies will also constrain the total (visible+dark) matter content of the Universe. HI can be studied in absorption against background quasars out to z>4 with the HIA. Several quasars show Lyα spectra which indicate column densities $\geq 10^{20}$ cm^{-2} which should readily be detectable. Observations in the redshifted HI line will provide information on the structure and kinematics of the absorber which cannot be obtained in any other way. Finally a search for redshifted HI in emission at z=3–10 will confront theories of galaxy formation following the era when the ionised gas combined to form HI. Observations with the HIA will be able to detect HI masses in the range 10^{12} $M_\odot$ to 10^{13} $M_\odot$.

Pulsar searches and timing: The HIA would be an exciting instrument for finding and studying pulsars, particularly millisecond ones, many of which have been found in globular clusters. The current searches with 70m class telescopes have found up to 7 pulsars in a cluster, a telescope > 100 times more sensitive would likely find an enormously larger number. Such a survey would place useful limits on the number of neutron stars in a cluster – a valuable constraint on the end–point of stellar evolution. The HIA will not only be able to find more pulsars it will also enable them to be studied in much greater detail. The accuracy of pulse timing on millisecond pulsars is limited by the achievable signal–to–noise ratio, even with Arecibo. Nevertheless timing of a few rapid pulsars in binary systems has yielded evidence for gravitational radiation and measured the absolute masses of the binary components. The periods of some isolated millisecond pulsars are extraordinarily stable. As well as producing a flood of new pulsars to study individually, an ensemble of millisecond pulsars could provide the most stable clock known to mankind. And a comparison of their periods could reveal the passage of long-wavelength gravitational radiation. Finally pulsars have already been detected in the Magellanic Clouds; with the > 100 times greater sensitivity of the HIA it will be possible to detect pulsars in Local Group galaxies.

More collecting area…and more…

Radio Astronomy Sensitivity

Sensitivity:

$$S_{\min} = \frac{2kT_{sys}}{A_{eff}\sqrt{\tau.\Delta\nu}} = \frac{T_{sys}}{G}\frac{1}{\sqrt{\tau.\Delta\nu}}$$

Gain:

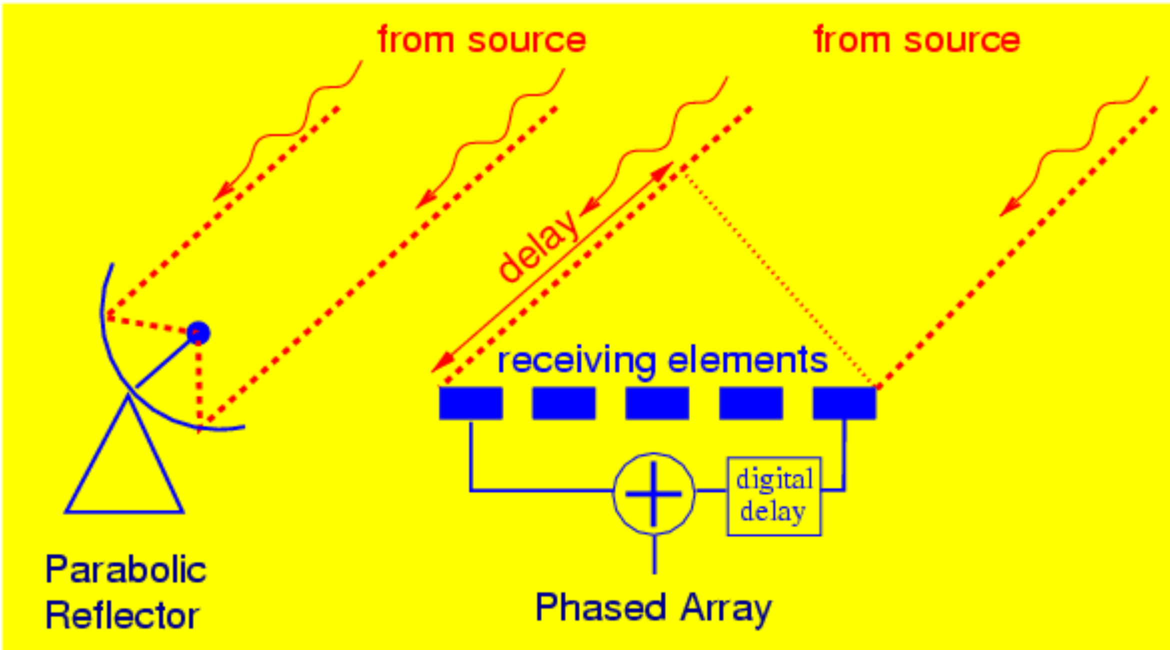
$$G = \frac{A_{eff}}{2k}$$

Most Receivers are already at the quantum limit = T_{sys} already minimal
Need to find other ways to improve sensitivity:

- Increase gain = collecting area = bigger telescopes!
- Increase bandwidth (despite increasing man-made RFI!)
- Enable longer integration time = cover more sky per minute!

A Revolution in Radio Astronomy

- Go digital! Ability to sample, digitze & process wide bandwidths
- Use of commodity computing power (incl. GPUs) and FPGAs
- Ways of obtaining "cheap" collecting area
- Replacing hardware (i.e. metal) with electronic and software
- Build "radio cameras" to increase "field-of-view" on sky and even allow to look in (sometimes) vastly different directions:



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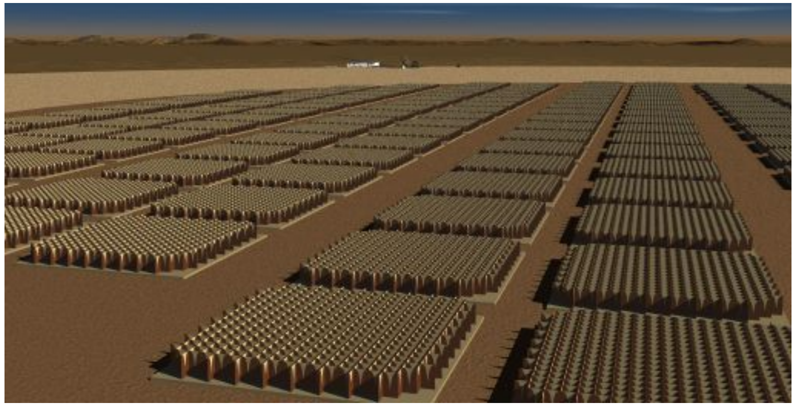
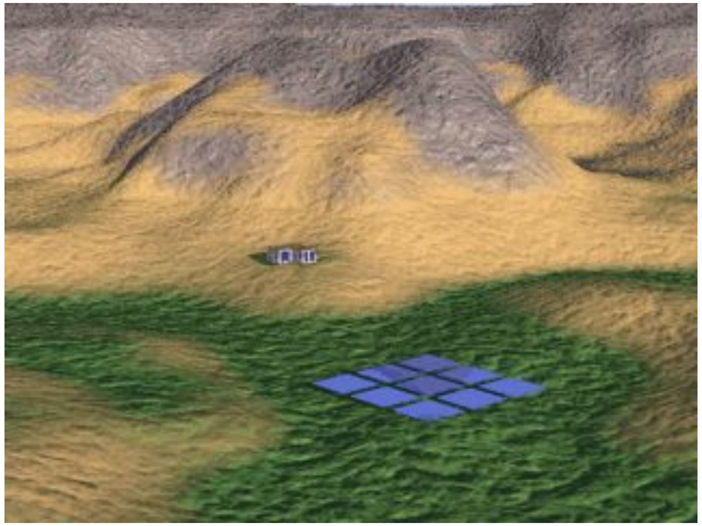
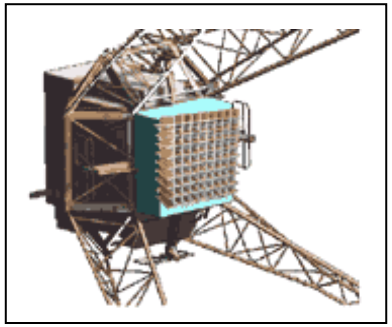
Aperture Arrays & Focal Plane Arrays

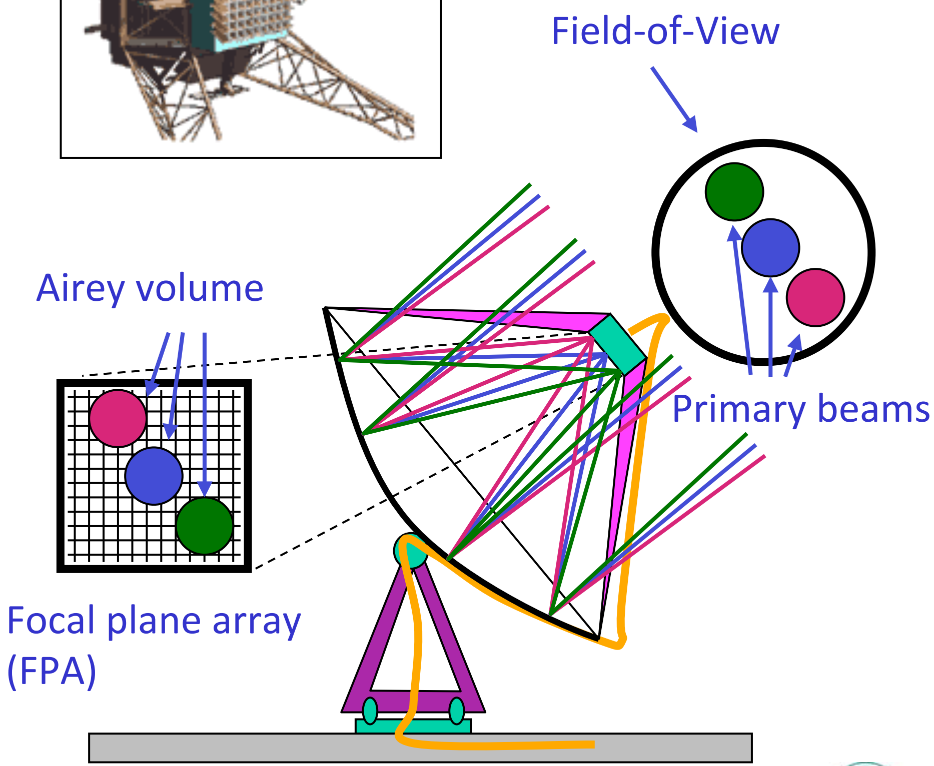
= phased array on ground





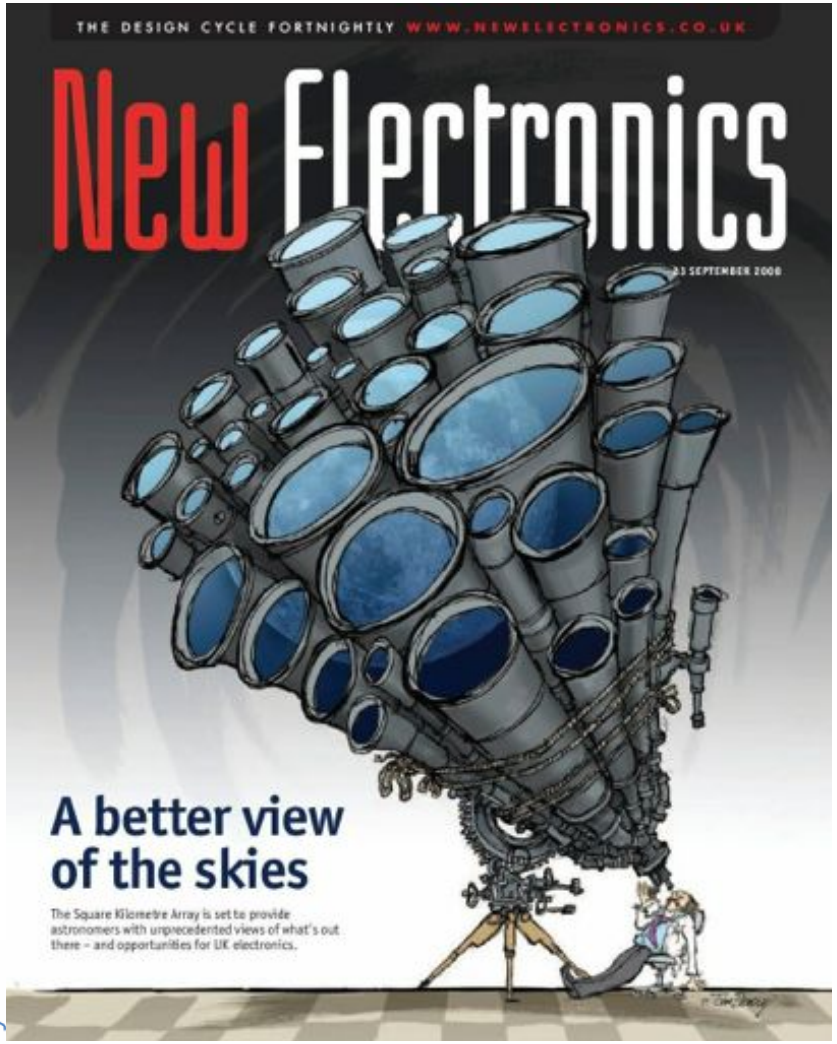
= phased array in focus of dish





NEW: HUGE Field-of-View and multiple beams within FoV!

Aperture Arrays & Focal Plane Arrays



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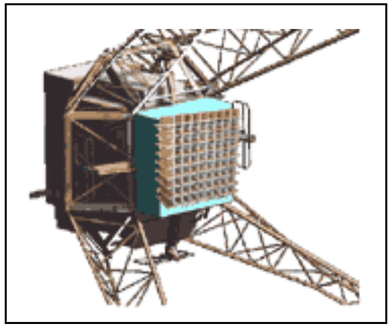

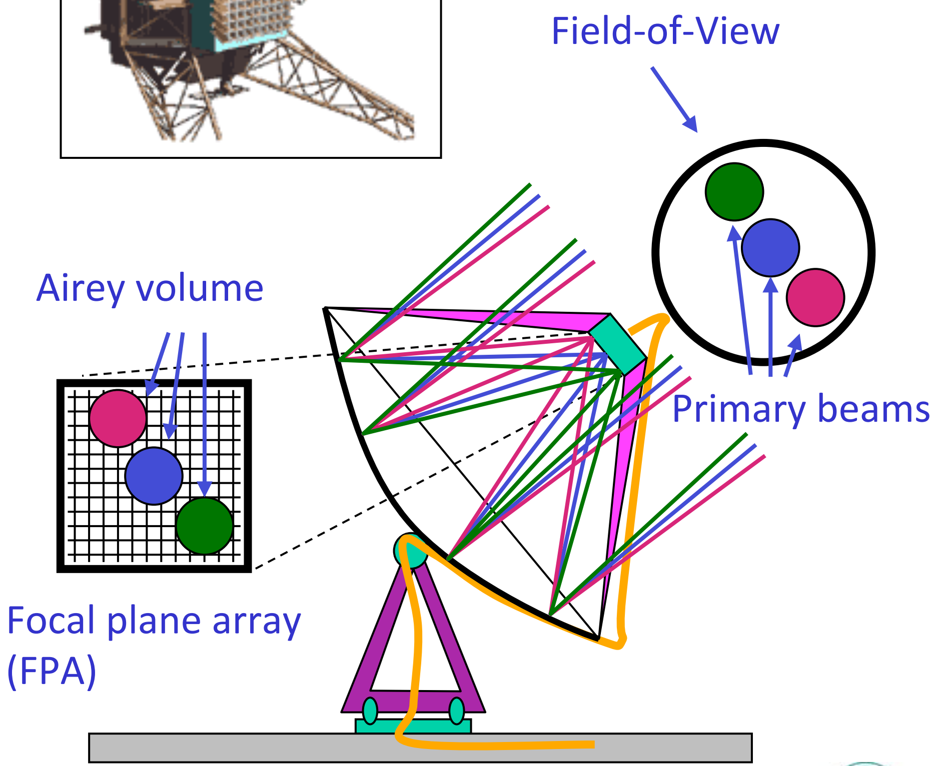

Like many different telescopes at the same time!

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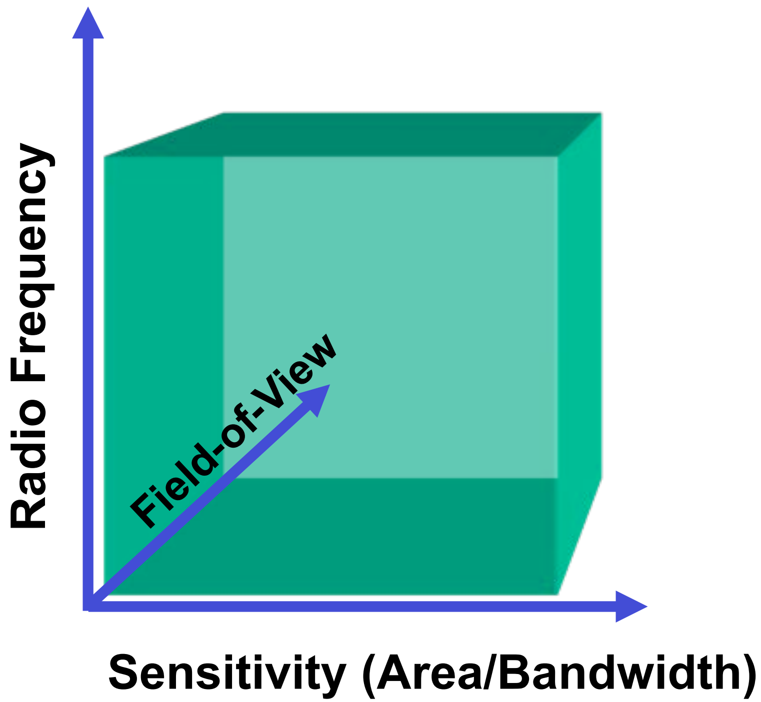
New technology: Huge increase in phase space



- Sampling large bandwidths (20-50%)
- Providing huge FoVs (>30 sq-deg) hence huge survey speed
- Large frequency range, e.g. opening low-frequency sky (LOFAR etc.)
- Brute-force increases in collecting area
- Digital signal processing
- Huge computing power…

The SKA pushes in all these areas

➔ New science and new discoveries!

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In a nutshell

The Square Kilometre Array

= The Global Radio Wavelength Observatory

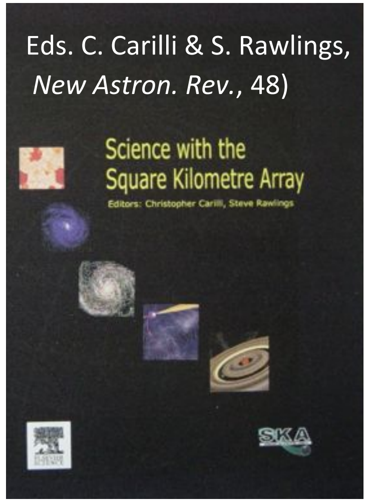
= Mega-Science research infrastructure
with very broad science case
(incl. multi-wavelength, multi-messenger)

= challenging technology project
with cyber-infrastructure and "big data"

SKA Key Science

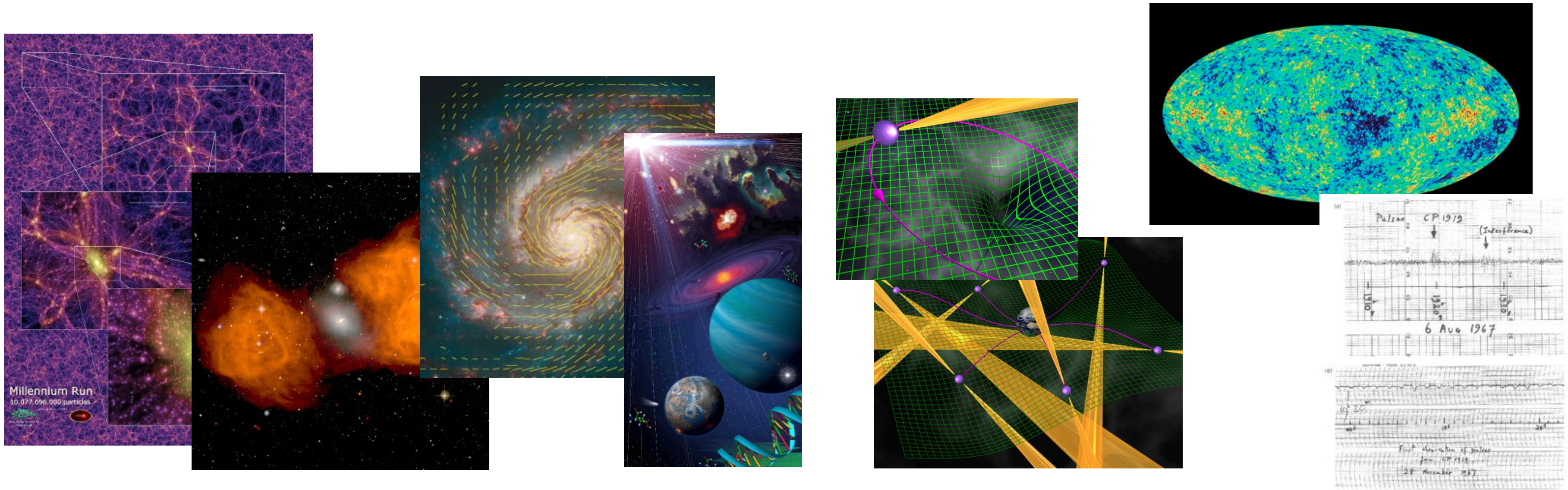
Five Key Science Projects:

- Dark matter, cosmology and Dark energy
- Dark ages: First stars and black holes
- Cosmic magnetism
- Cradle of life
- Strong-field tests of gravity using pulsars & black holes



Eds. C. Carilli & S. Rawlings, *New Astron. Rev.*, 48)

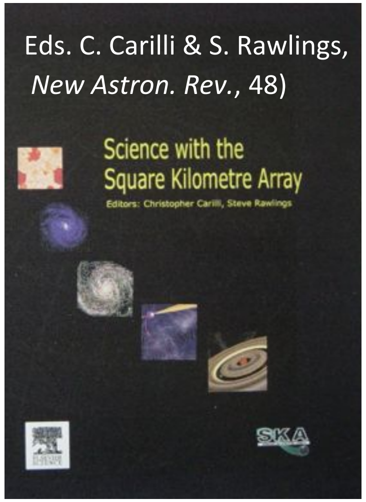
+ Exploration of Unknown



SKA Key Science in context

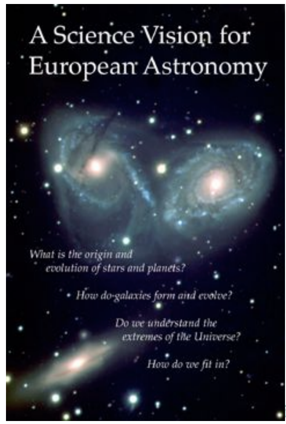
The laws of nature: *Fundamental Physics & Cosmology*

- Gravity:
  Is general relativity our last word in understanding gravity?
  What happens in strong gravitational fields?
  What are the properties of gravitational waves?
  What is Dark Matter?
  What is Dark Energy?



- Magnetism:
  What is the origin of cosmic magnetism?
  How did it evolve?
  What is its role in the formation and evolution of stars and galaxies?

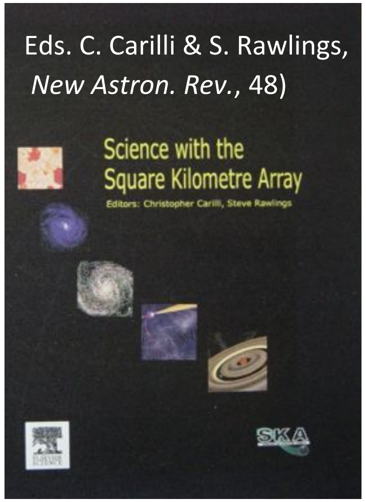
- Strong & weak forces:
  What are the properties of matter?
  What is the nuclear equation of state?



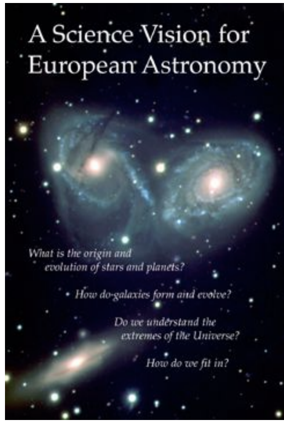
SKA Key Science in context

Origins: *Galaxies across cosmic time, Galactic neighbourhood, stellar & planetary formation*

- Galaxies and the Universe
  - How did the Universe emerge from its Dark Ages?
  - How did the structure of the cosmic web evolve?
  - Where are most of the metals throughout cosmic time?
  - How were galaxies assembled?



- Stars, Planets, and Life
  - How do planetary systems form and evolve?
  - What is the life-cycle of the interstellar medium and stars? (biomolecules)?
  - Is there evidence for life on exoplanets (SETI)?



New phenomena: *Exploration of the unknown*

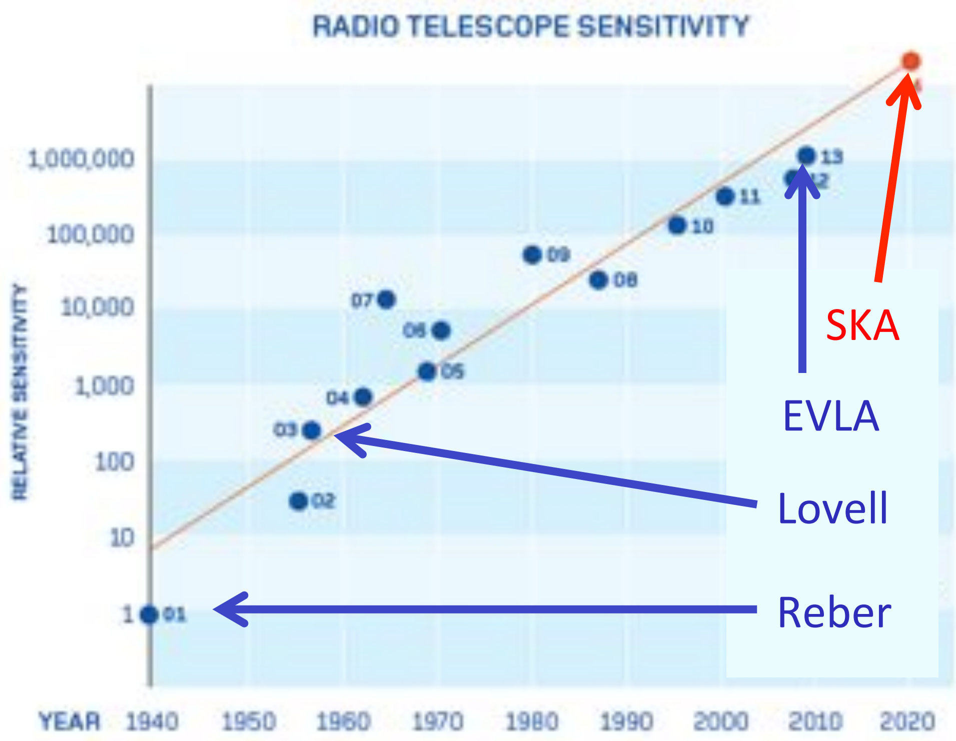
- Transients
- Multi-messenger science
- ????

The Telescope

The SKA is…

…a large radio telescope for transformational science

- up to 1 million m^2 collecting area distributed over a distance of 3000+ km
- operating as an interferometer at frequencies from 70 MHz to >10 GHz (4m-3cm) with two or more detector technologies
- connected to a signal processor and high performance computing system by an optical fibre network



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The Telescope

The SKA is…

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…a survey (=discovery) machine

- 100 x Effelsberg, and 10 x Arecibo, and
- at least 10,000 x survey speed of current telescopes

HST

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…a legal organisation preparing construction

- on ESFRI List as only global project (selected for construction)
- with E-ELT selected for highest priority on ASTRONET roadmap
- ASTRO2010: "long-term future of radio astronomy"
- Canadian Long-Range Plan: SKA next priority behind TMT (10%!)
- African Union Heads of State acknowledge importance
- Australia and South Africa already invest about €200M each

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The Telescope

The Telescope

Construction will proceed in two (three) phases: SKA_1 ➔ SKA_2 (➔ SKA_3)

- SKA_1 will be a subset (~10%) of SKA_2

- Major science observations already possible with SKA_1 in 2020:

"Headline science":

- Neutral hydrogen in the universe from Epoch of Re-ionisation to now
- Fundamental forces: pulsars, gravity and gravitational waves

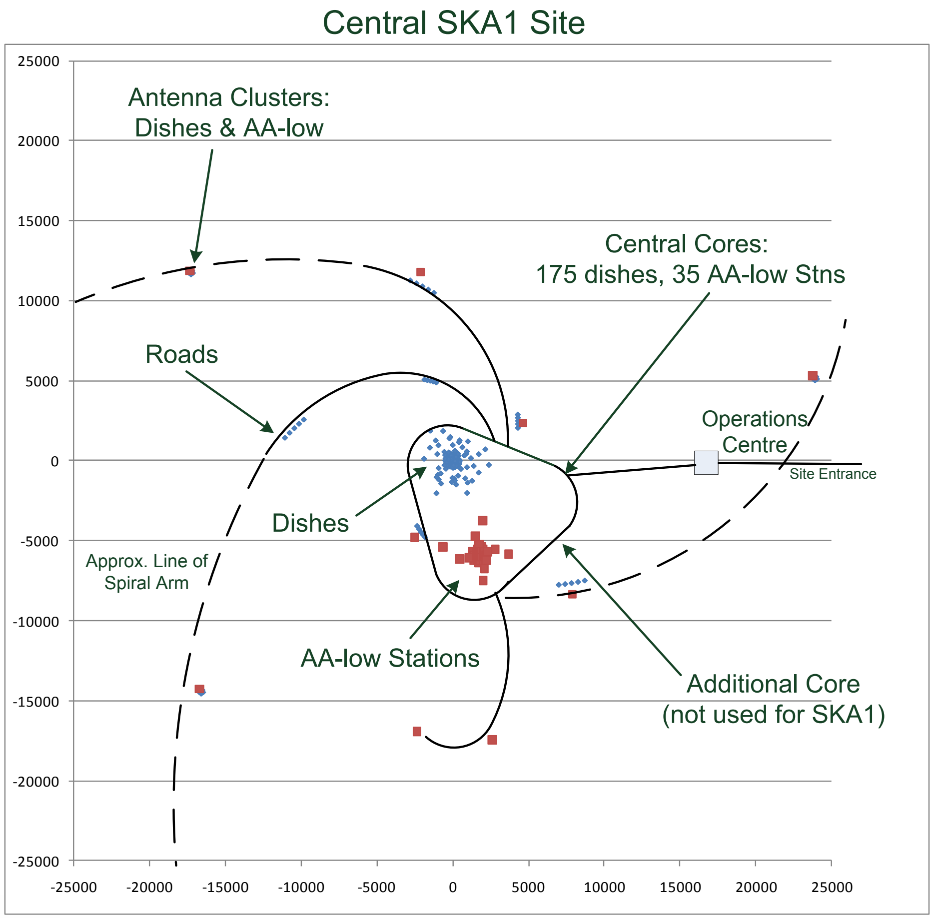
See later

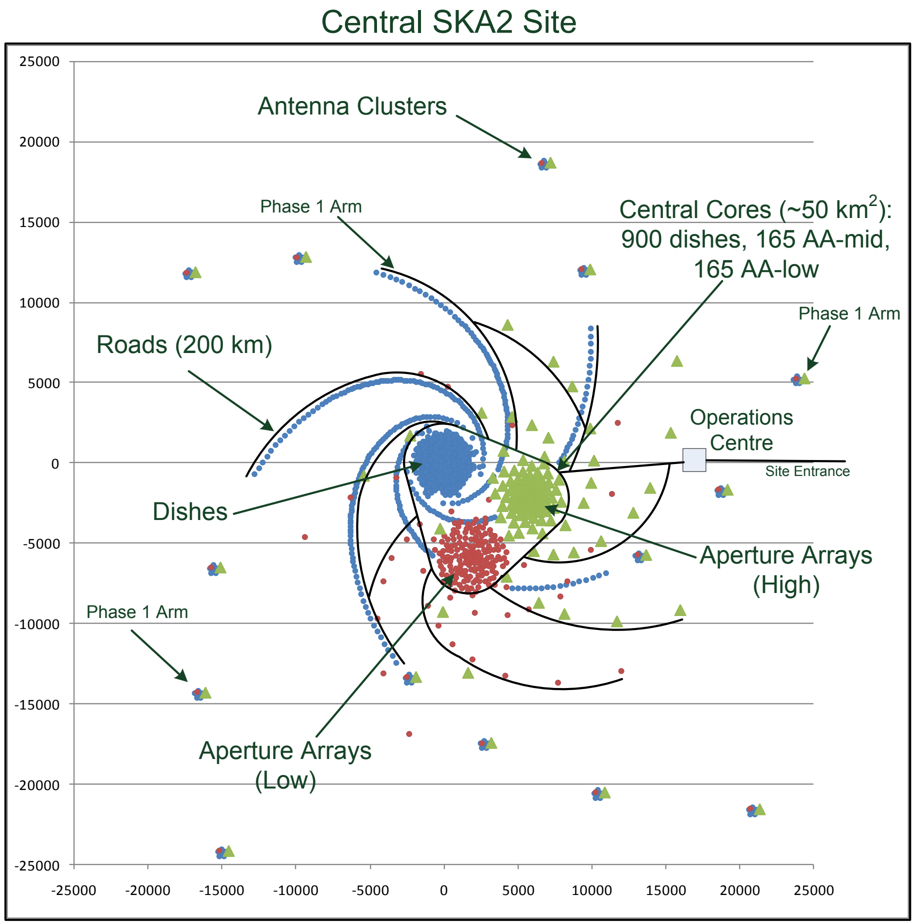
- Phased construction allows maximum use of advances in technology:

Phase I: SKA_1 can be built now with proven and secure technology (baseline)

Phase II: SKA_2 can make use of new, future matured technology (AIP)

From Phase I to Phase II





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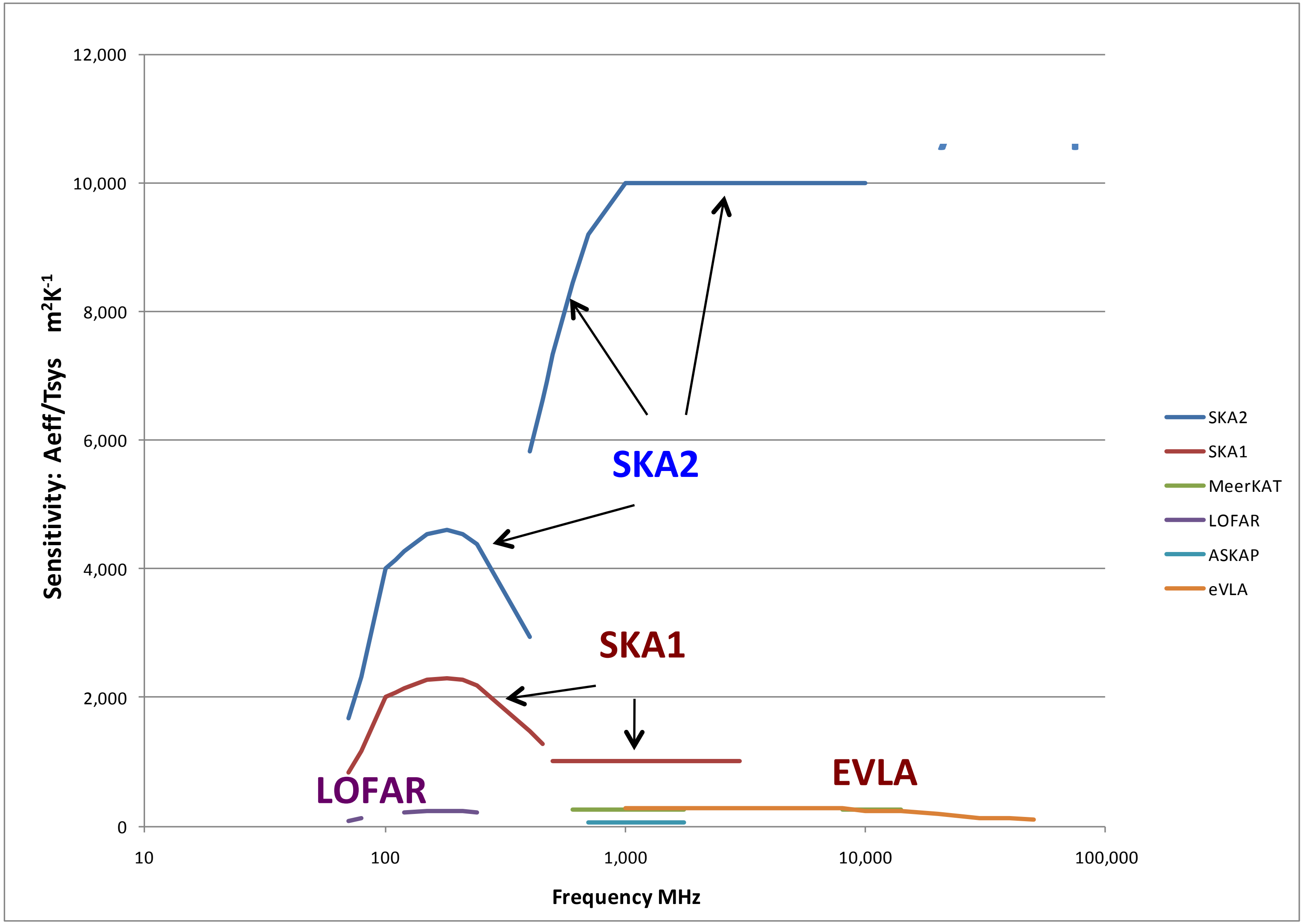
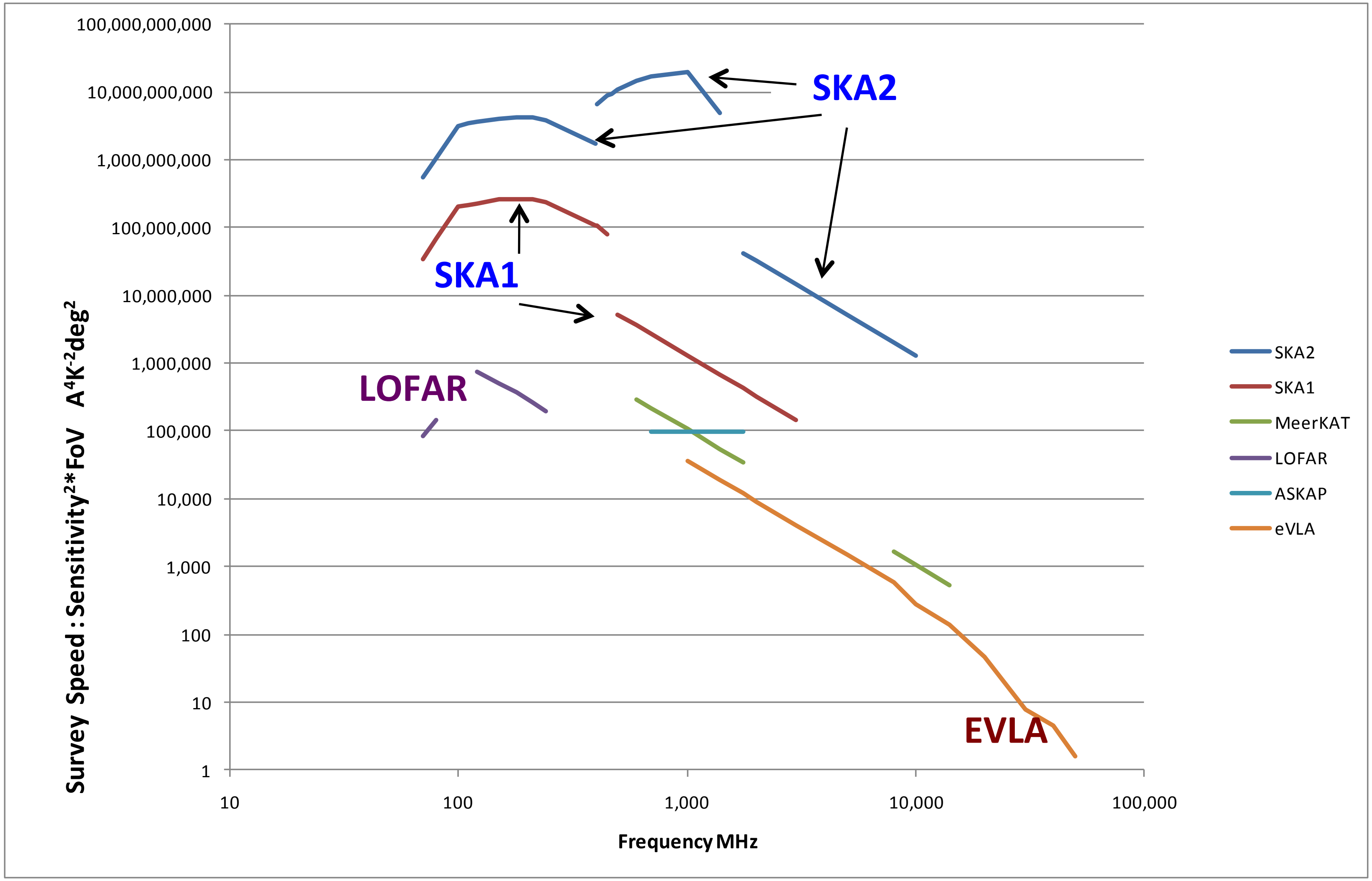
Sensitivity comparison

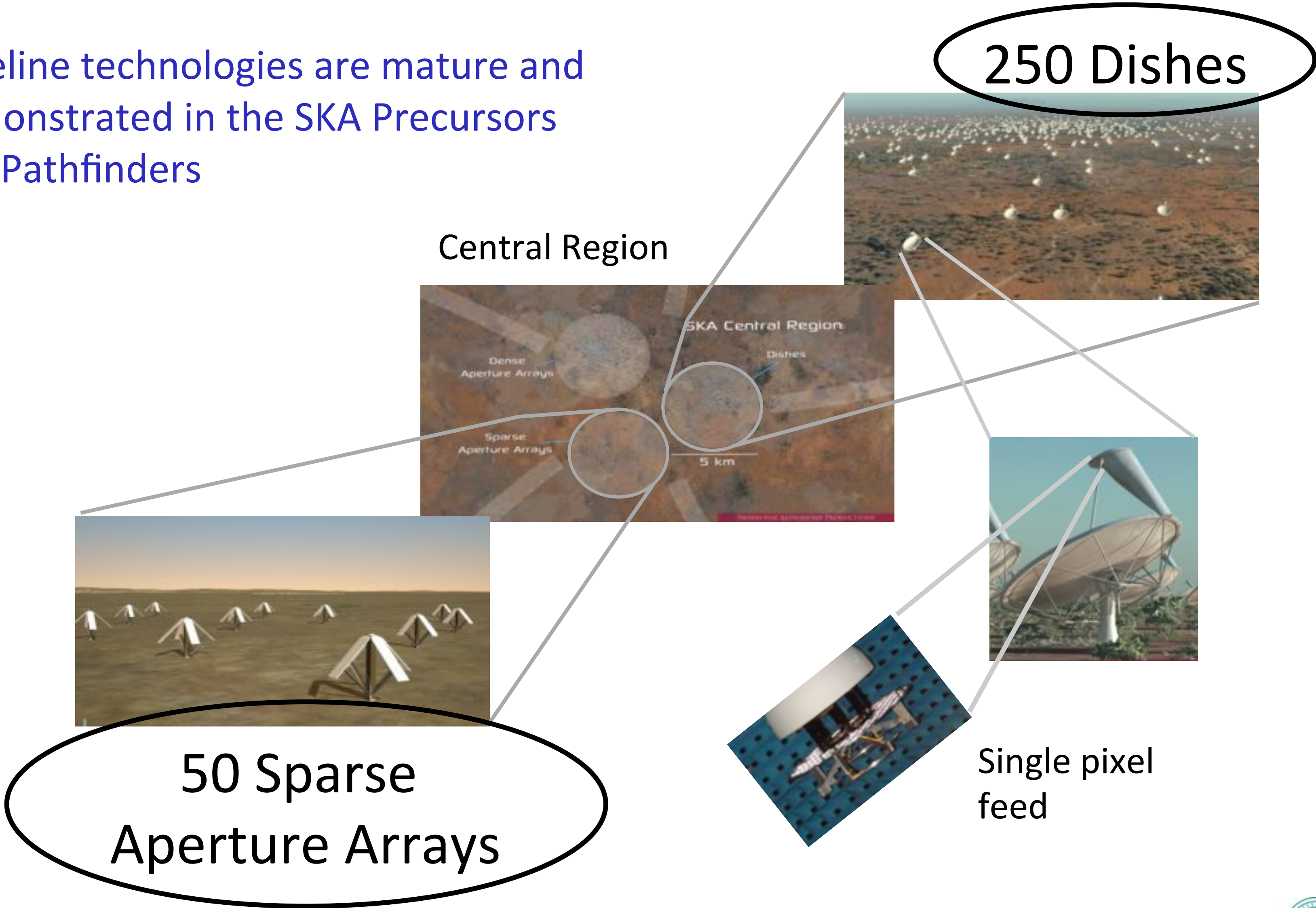


Survey speed comparison



SKA_1 baseline design

Baseline technologies are mature and demonstrated in the SKA Precursors and Pathfinders

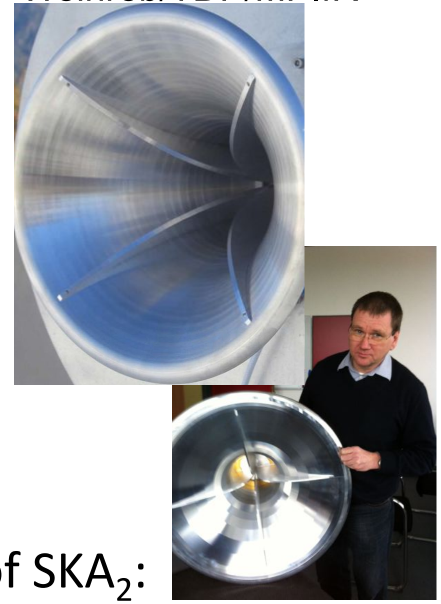


Advanced Instrumentation Program (AIP)

Development of innovative wide-field “radio camera” technologies at mid-frequencies:

- phased array feeds (PAFs) on the dishes (FoV ~ 30 deg^2)
- mid-frequency aperture array (FoV ~ 200 deg^2)

Weinreb/TDP/MPIfR



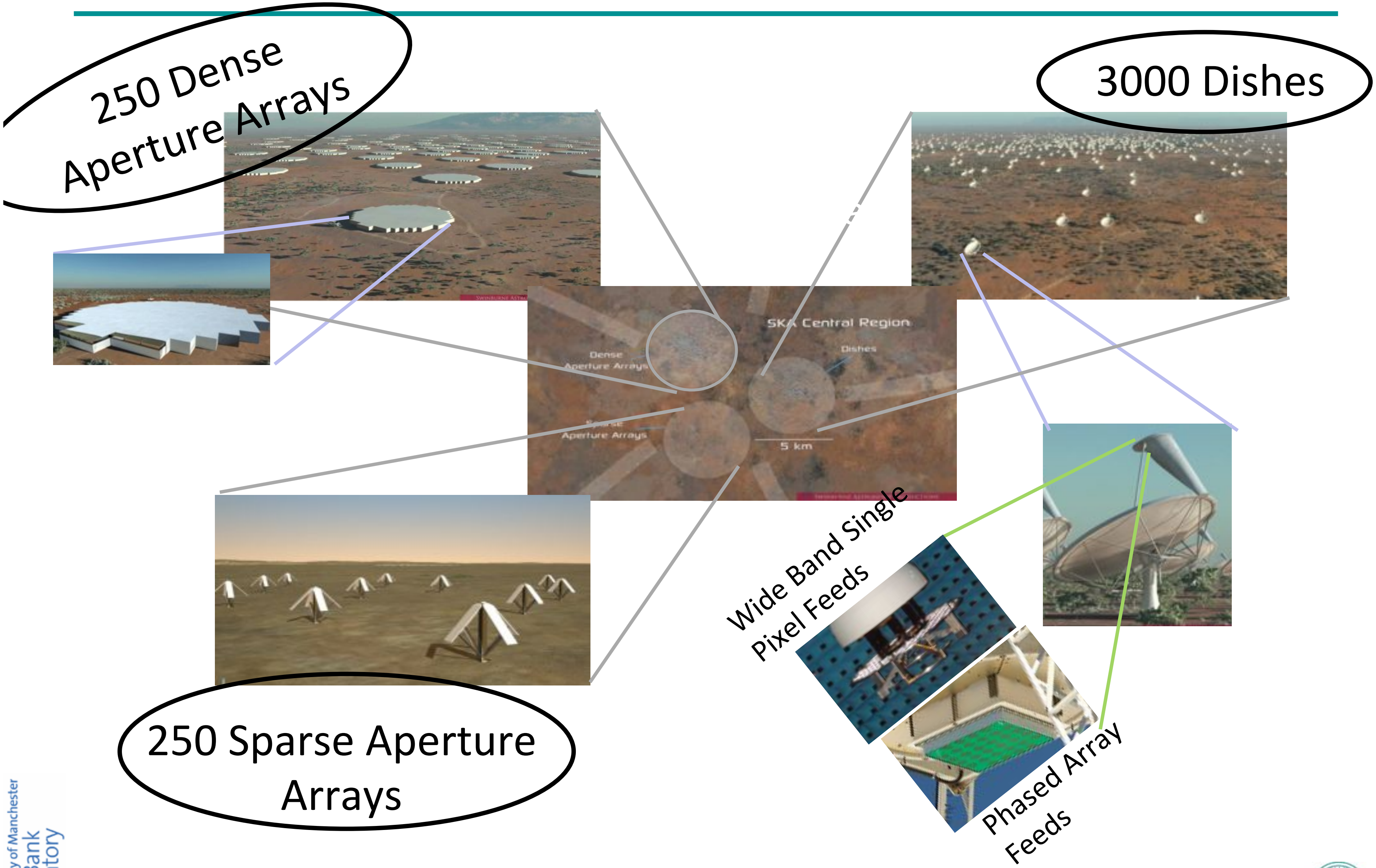
Ultra-wideband single pixel feeds

The AIP is designed to build maturity and retire risk

Has the potential for enhancing SKA_1 and being a major part of SKA_2:

- Evaluation point in 2014
- Final decision in 2016

SKA$_2$ including AIP technologies



Project Status

Project timeline

2008-12	telescope system design and cost
2012	site selection
2013-15	detailed design in the pre-construction phase
2014	approve construction funding for Phase 1 (350 M€, 2007)
2016-19	Phase 1 construction
2016	Advanced Instrumentation Program decision
2018	approve construction funding for Phase 2 (1.2 B€, 2007)
2018-23	Phase 2 construction
2020→	full science operations with Phase 1
2024→	full science operations with Phase 2

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Currently: Pre-construction phase

Goals:

1. Progress the SKA design and prototyping to production readiness
2. Establish industry participation strategies, procurement processes, and protocols governing the selection of work package consortia
3. Identify funding commitments for SKA Phase 1 (SKA_1) construction and operations
4. Prepare long-term SKA organisational structure and arrangements for the construction, verification and operation of the SKA
5. Build relationships with relevant national and international astronomy organisations

Convert the following SKA-relevant design and development into production-ready SKA-specific designs and costs!

Baseline design component

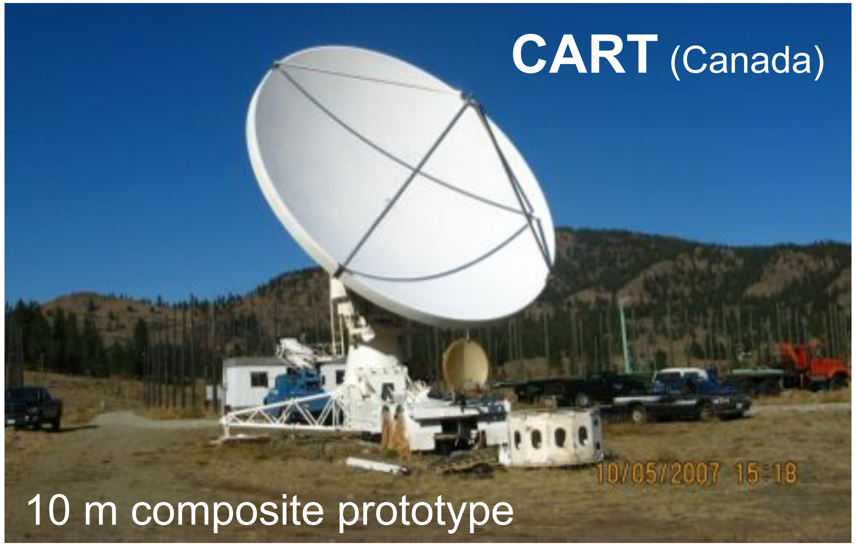
Low frequency aperture arrays

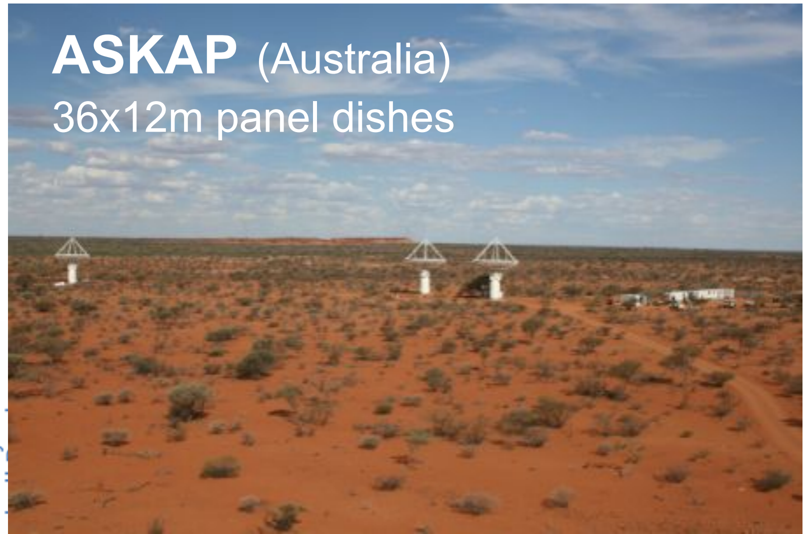
LOFAR (Netherlands et al)

MWA (Australia, India, USA)

Baseline design component

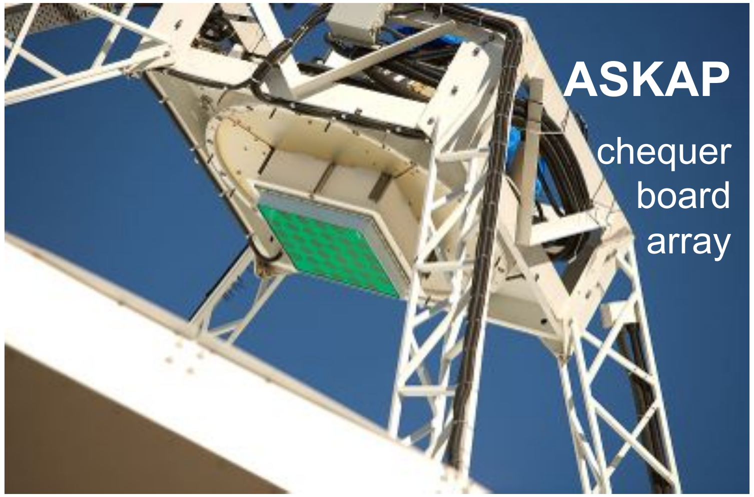
Dishes + single pixel feeds



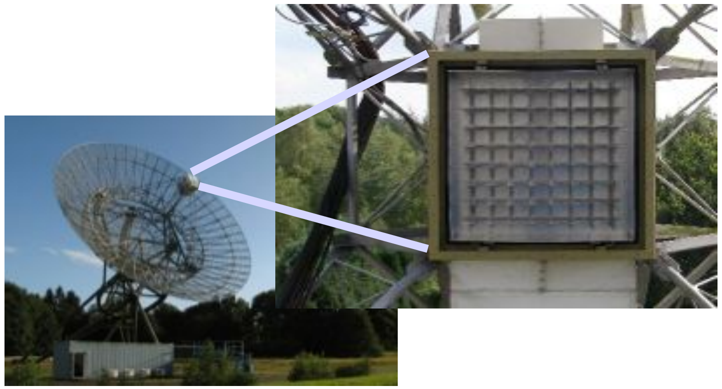


Advanced Instrumentation Program

Dishes + multi-pixel feeds



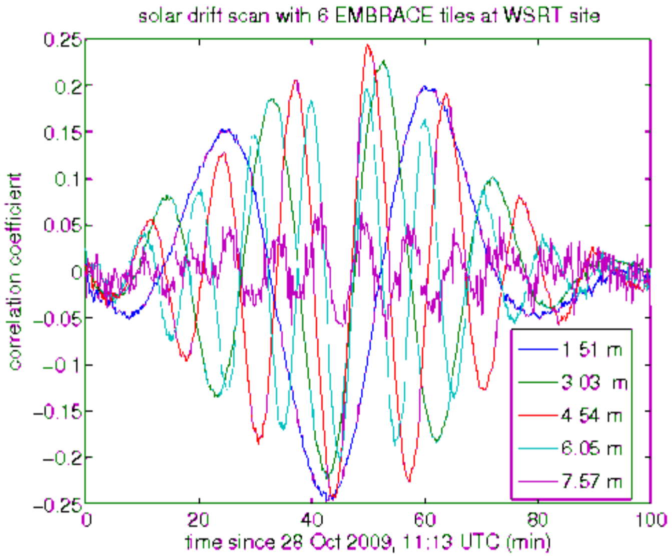
DRAO
Canada



APERTIF
(Astron, NL)

Advanced Instrumentation Program

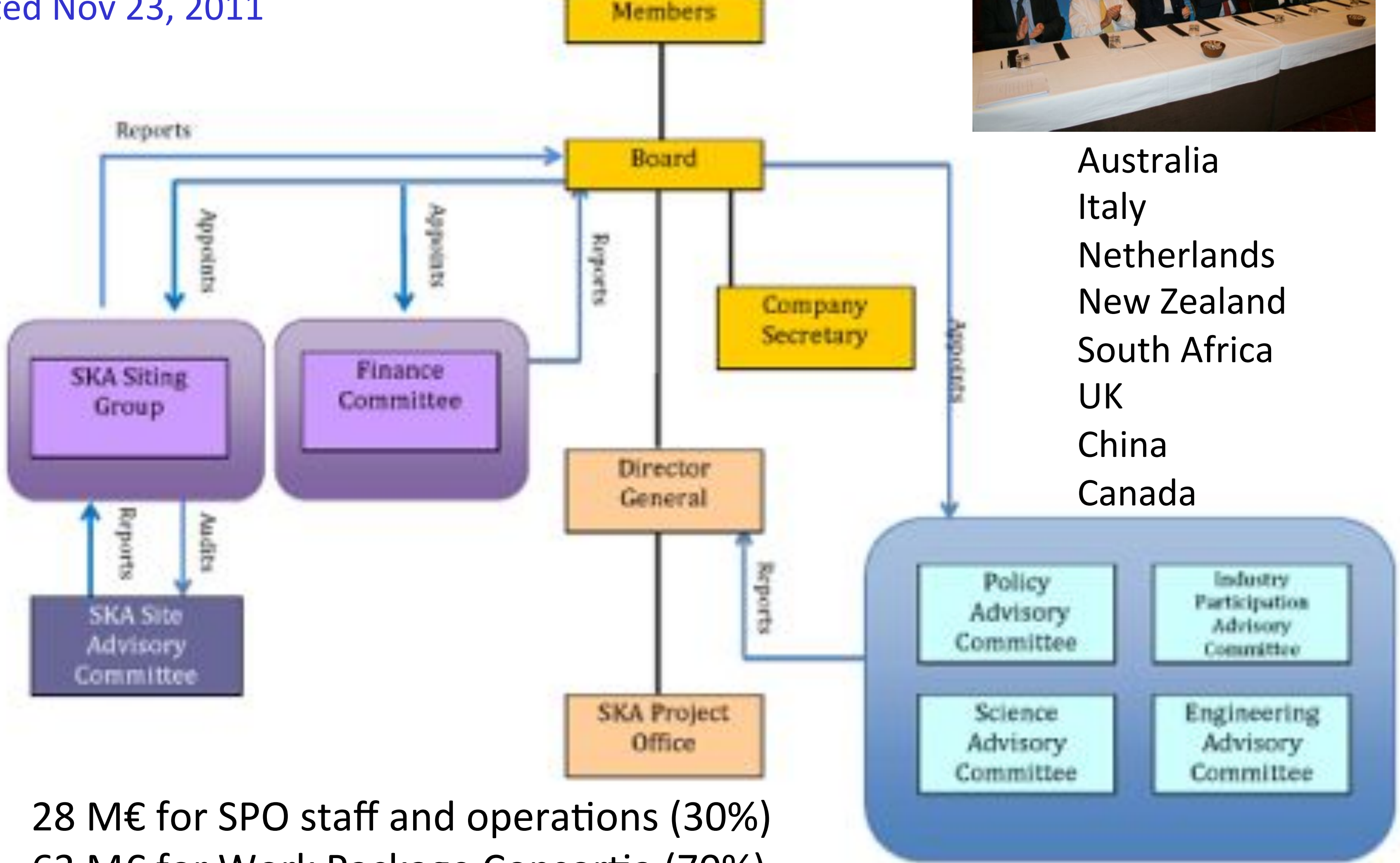
Mid-frequency aperture array



First Fringes

SKA Legal Organisation

- Company Limited by Guarantee in the UK
- Headquarter in the UK, Jodrell Bank
- Created Nov 23, 2011



Australia
Italy
Netherlands
New Zealand
South Africa
UK
China
Canada

28 M€ for SPO staff and operations (30%)
63 M€ for Work Package Consortia (70%)

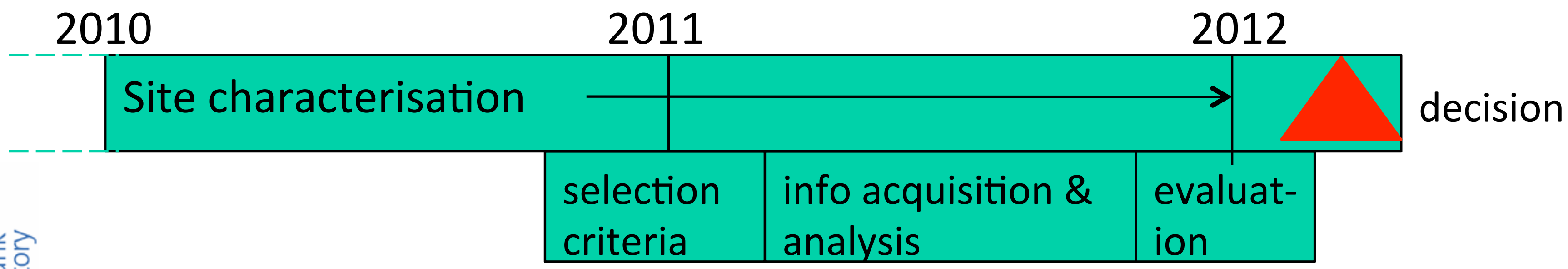
Site selection

Physical requirements

- Extremely radio quiet environment
- At least 3000 km in extent
- Low ionospheric turbulence
- Low tropospheric turbulence

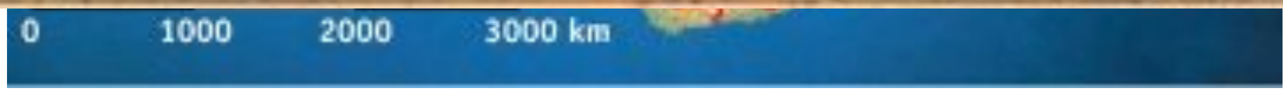
Two candidates short-listed in 2006: Western Australia and Southern Africa

Site selection process



Western Australia & New Zealand

South Africa + 7 countries



The Challenges

SKA: driving development of new science & technology

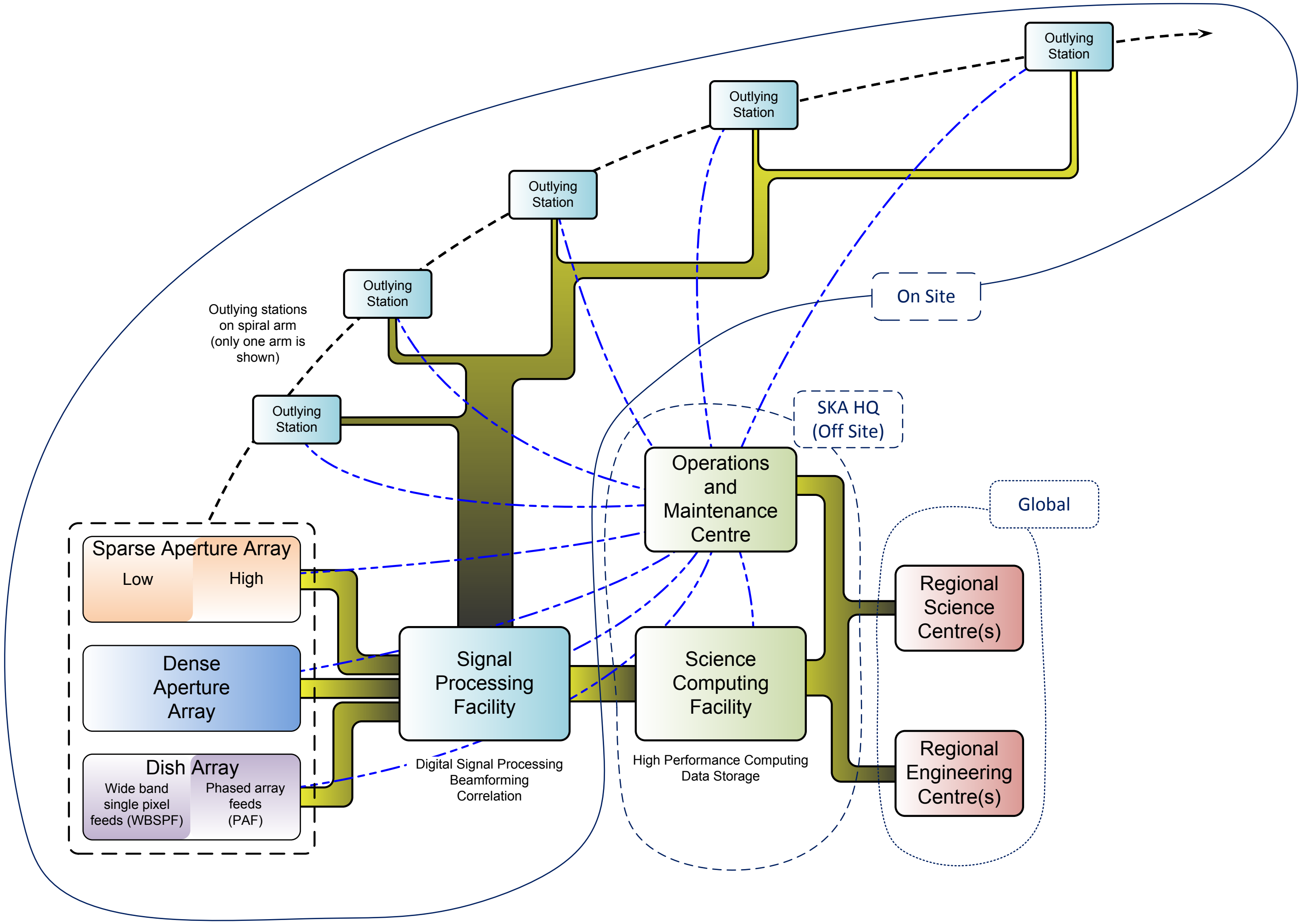
- Dishes, feeds, receivers (N=3000)
- Low and mid aperture arrays (N=250)

} ongoing verification programs

- Signal transport (10 Pbit/s)
- Signal processing (exa-MACs)
- Software engineering and algorithm development
- High performance computing (exa-flop capability)
- Data storage (exa-byte capacity)
- (Distributed) power requirements (50 -100 MW)

Industry engagement central to the SKA.

System Block Diagram



Signal transport networks

European Very Long Baseline Interferometry Network (1 Gbit/s)

EC-FP6 EXPReS

More than all information collected by humankind so far

SKA data rates

80 Gbit/s/beam/dish (<200km)

40 Gbit/s/station (20 dishes) (>200km)

~100 Tbits/sec!

About 1 Exabyte per day!!!!

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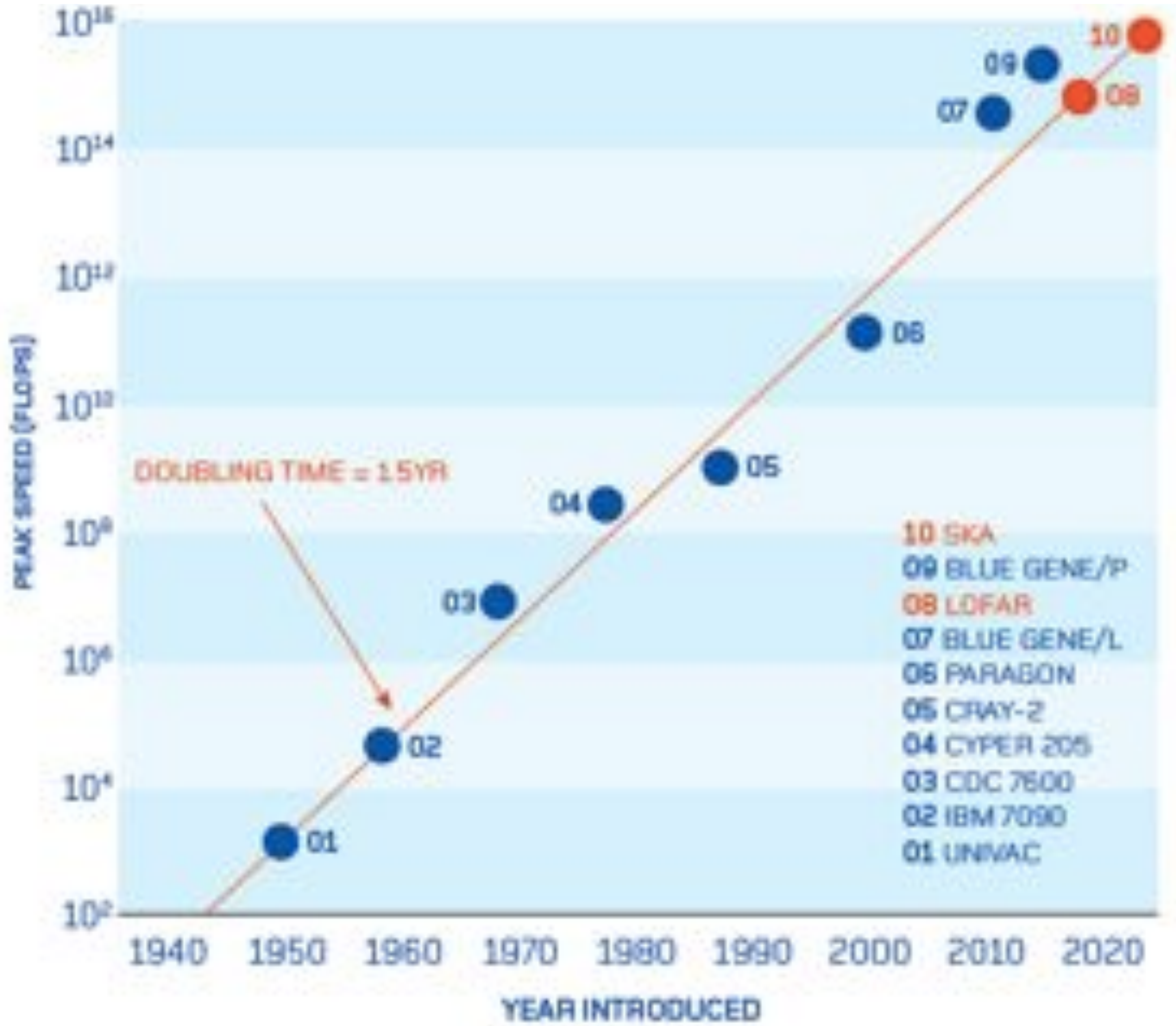
Need on-line HPC on Exaflop scale!



- In line with ESFRI PRACE initiative
- Still, challenges in data archiving and mining
- Also, need to reduce power requirements for computing!

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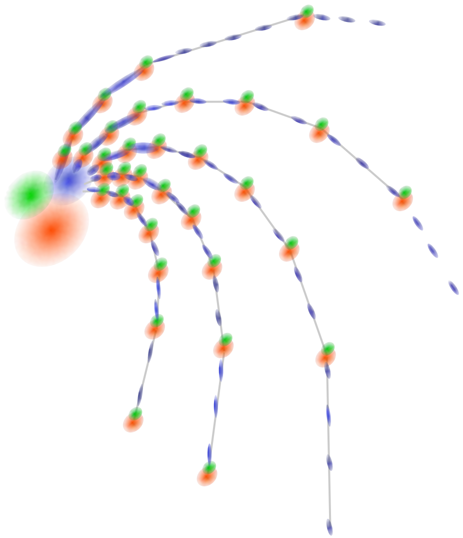
Energy supply

- Digital electronic needs power and needs cooling
- Running costs probably dominated by energy costs
- Site is far away from civilisation centres and power grid



- Different power requirements – energy mix!
  - Core(s): ~30 to 50 MW
  - HPC centre near core: ca. 50 MW
  - Distant stations: each ~100 kW for ca. 80 stations
  - Differences in peak and average demand (Electronic, cooling, telescope movements)
- Continuous operation 24/7: Storage required?!
- Avoid variations in power supply: power stability
- Environment: Temperature changes, wind, rain

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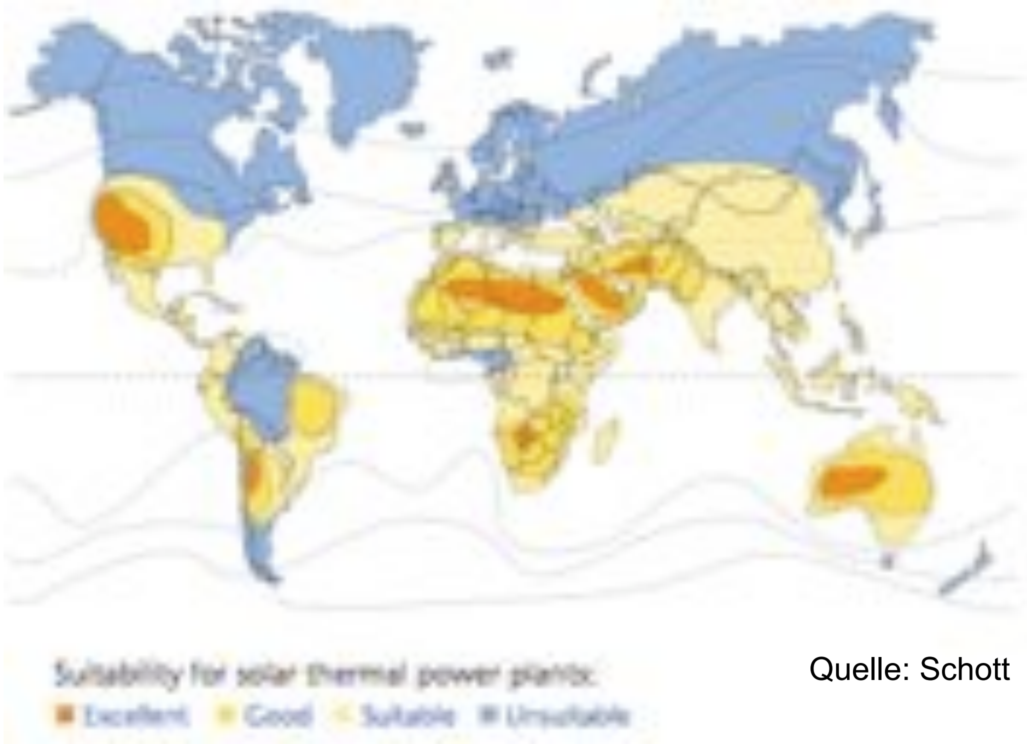
Power supply: My personal preference...

- Supply with solar energy obvious and but not cheapest solution – long-term?



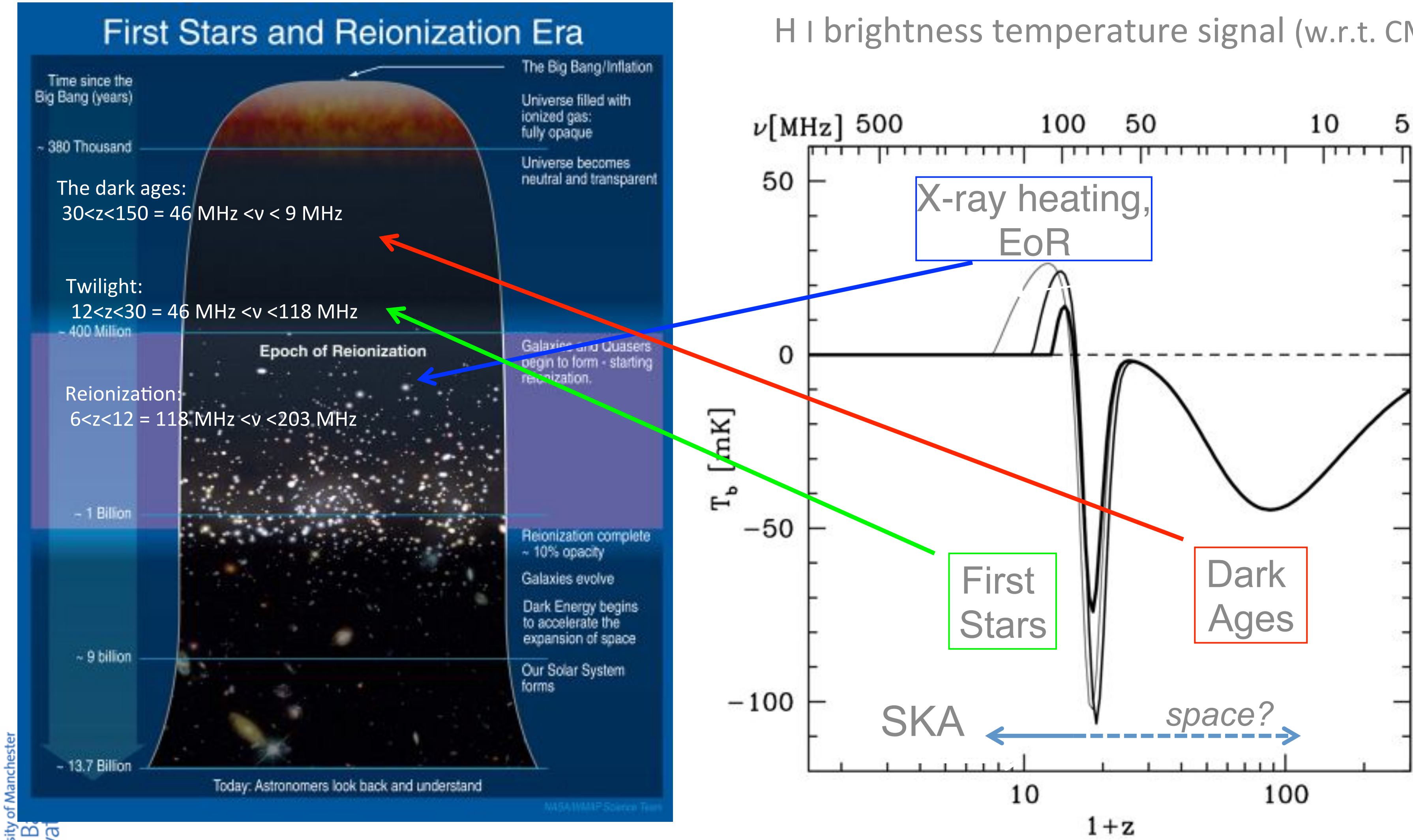
Quelle: Schott

- Excellent light house project for renewable energies
- Sustainable energy solution for the whole life time (~50 year)
- Opportunities to open new markets: 1.6 Billion people without grid access...
- Challenge would not be energy generation but night storage!

The Science

Evolution of the Universe

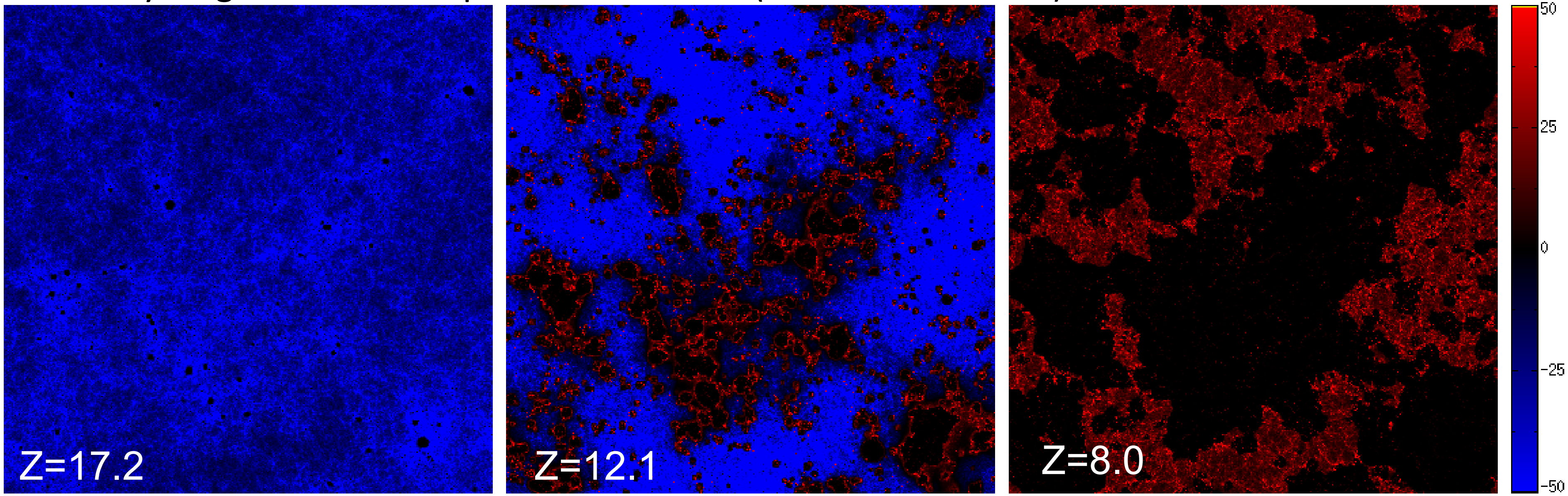
H I brightness temperature signal (w.r.t. CMB)



(Pritchard & Loeb 2008)

Epoch of Reionization

Trace hydrogen from absorption to emission (Santos et al. 2008)



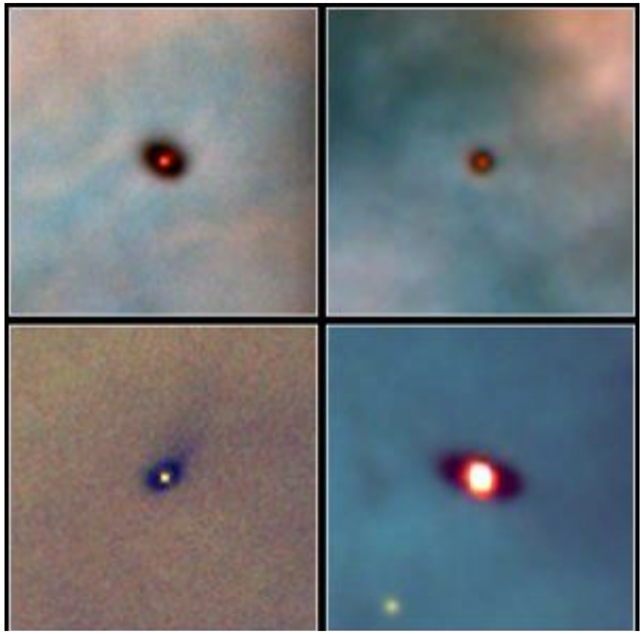
Alvarez et al.

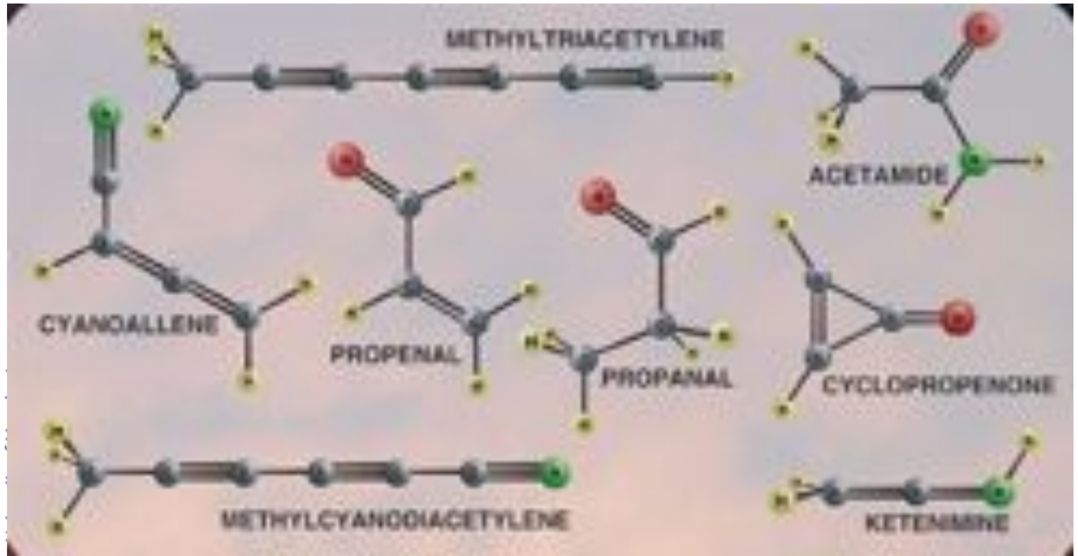
- 21cm-signal provides unique tomographic view
- High-redshift measurements provide important info on first luminous sources and thermal evolution of IGM
- Foreground and gas astrophysics to be under-understood
- Needs SKA sensitivity to study signal

Astrobiology at Long Wavelengths

Light at λ > 1 cm:

- Not affected by dust
- Complex molecules have transitions at longer wavelengths
- "Waterhole" (1.4–1.7 GHz)
- Magnetically-generated emissions from extrasolar planets

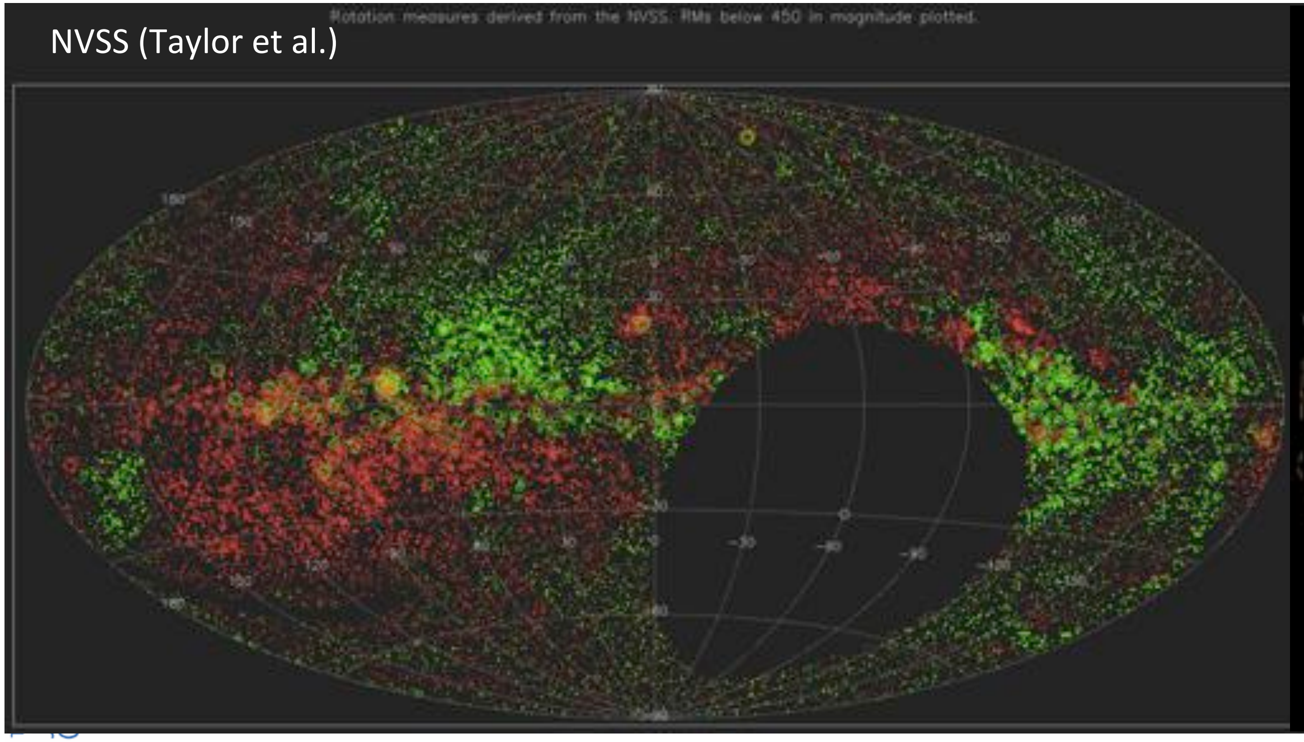


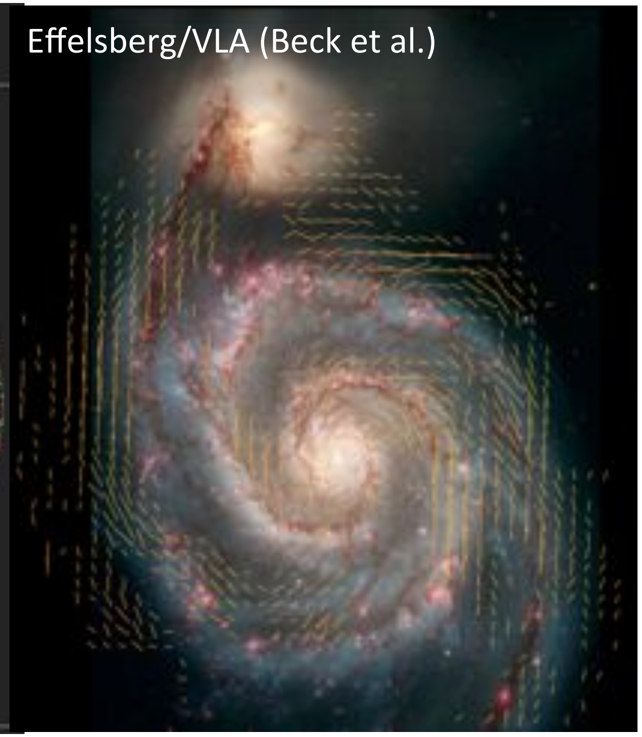


- Nearly 150 molecules detected in interstellar space.
- Many of these are "organic."
  - Illustrates importance of carbon in chemistry of life.
  - Are there biological molecules not yet detected? (amino acids?)
- Connection to proto-planetary disk chemistry?

Origin & Evolution of Cosmic Magnetism

- Magnetic fields are fundamental, but poorly constrained and their origin little understood. For instance,
  - Do they affect galaxy and cluster evolution?
  - How do they affect the propagation of cosmic rays in ISM and IGM?
- All-sky rotation measure surveys provide **B** fields along lines of sight
- Continuum in I, Q, and U!



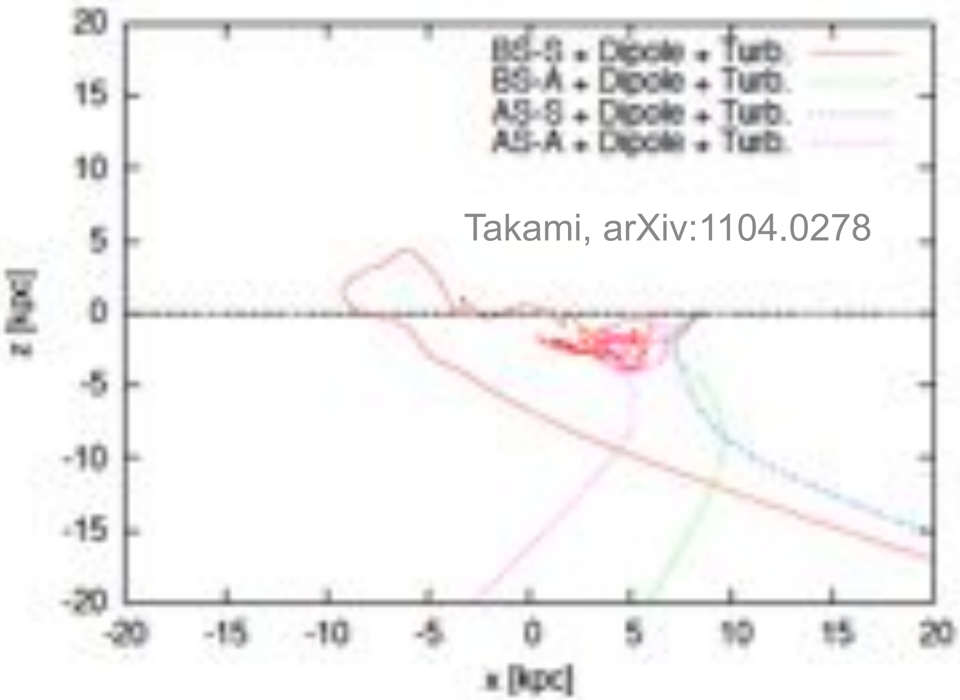


Magnetic Fields: Cosmic Rays, the Galaxy and the IGM

Q: Are ultra-high energy cosmic rays (UHECRs) produced in nearby AGN?

- Galactic magnetic field influences cosmic ray propagation
- Different models of Galactic field imply different arrival directions

    Axis-symmetric vs. bi-symmetric field directions above and below the Galactic plane? Effect of turbulence? …?

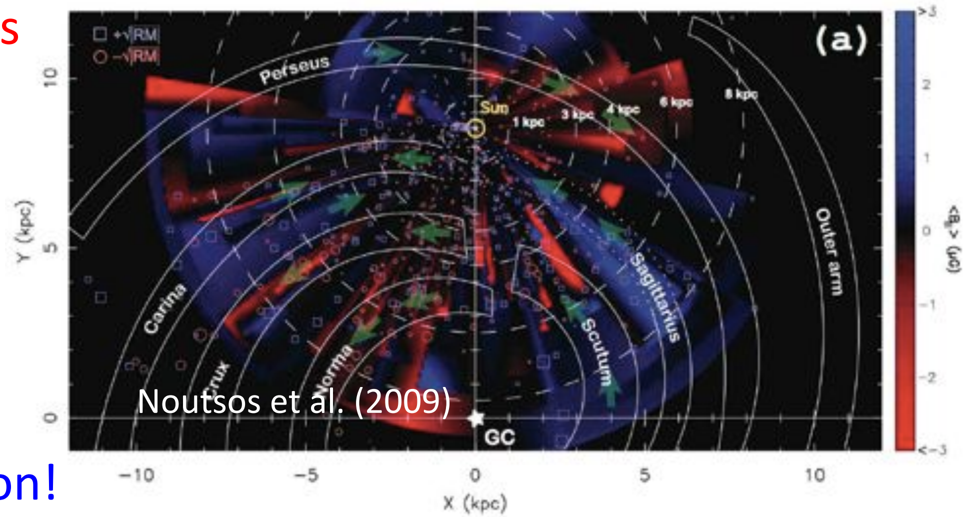


A: Rotation Measure (RM) measurements of millions of sources:

~500 RMs per sq. deg (one every 2'-3')

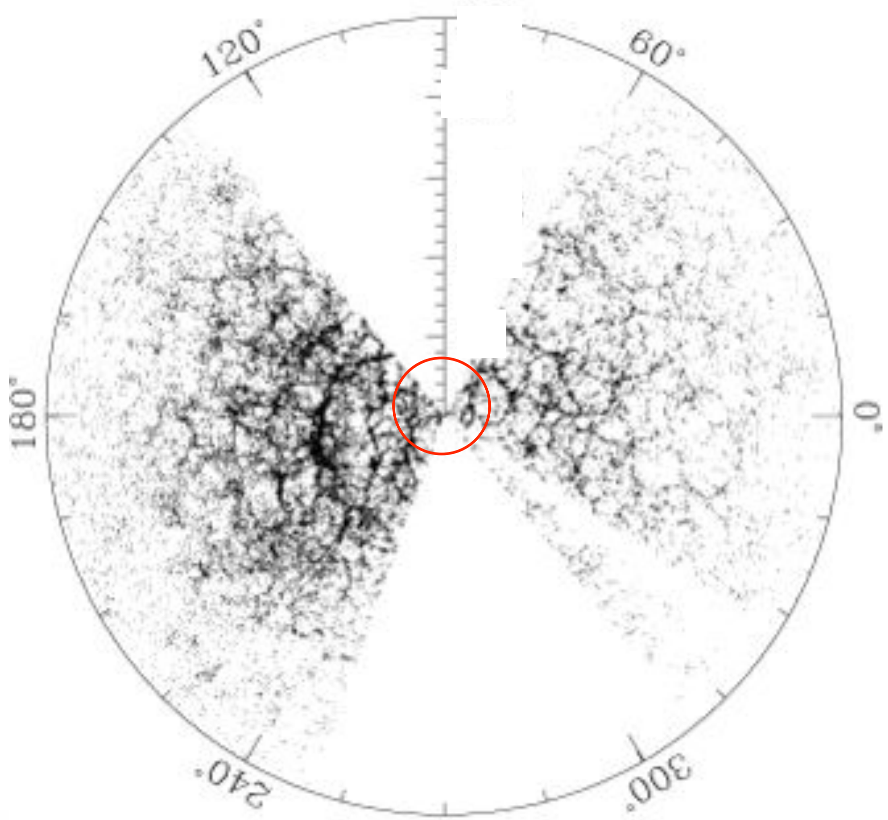
Study B in IGM with 3D information (z from HI)

Also essential if we are REALLY to understand physics of galaxy formation!



SKA = Stage IV BAOs Experiment

The nature of dark energy?



SDSS

- Next-generation goal (DETF):
  - Survey large volume
  - Slice into redshift bins
  - Detect BAOs in each *z* bin
- SDSS surveyed ~ 1 Gpc^3
- SKA goal ~ 100 Gpc^3 ($z > 1$)

  1,000,000,000 HI galaxies!
  - Intrinsically spectroscopic survey
  - Measure their distribution in time as standard ruler for expansion
  - Different biases than LSST, WFIRST/Euclid

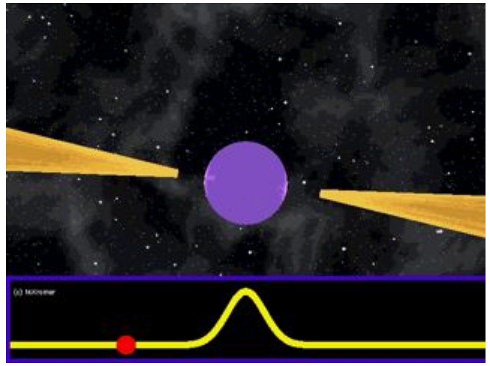
  ➔ EoS of dark matter, w=w(t)

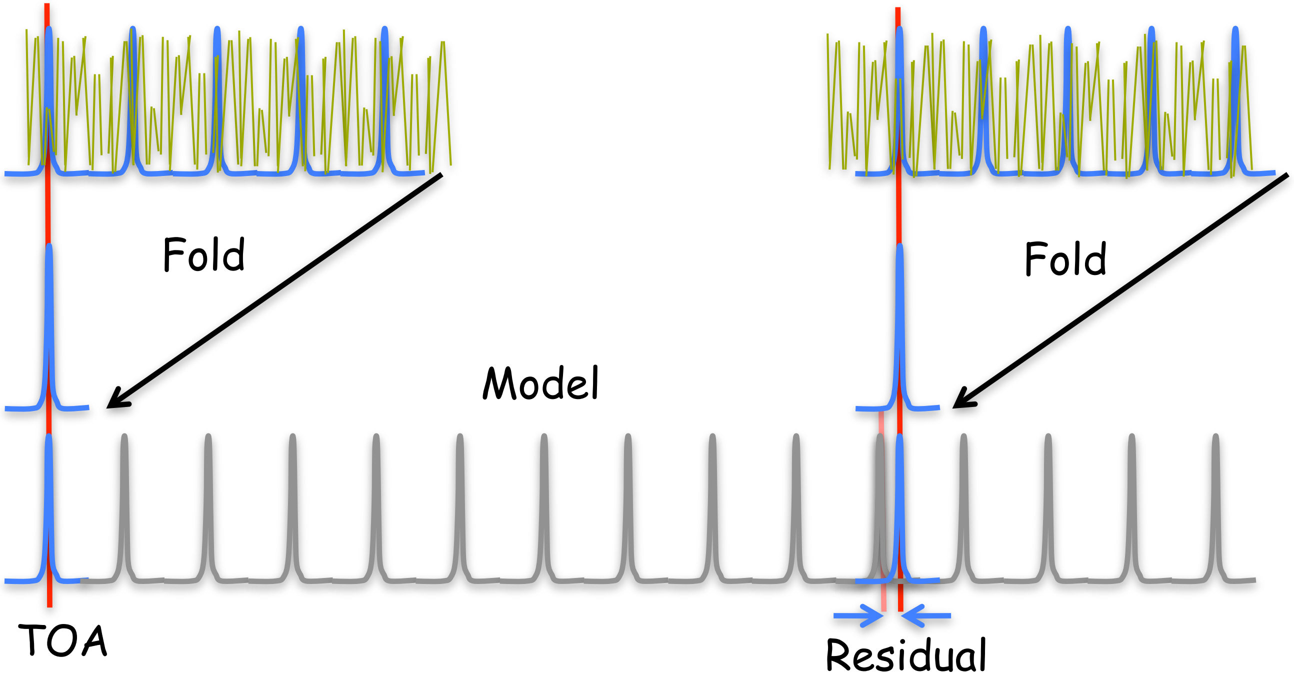
SKA and Pulsars

A simple and clean experiment: Pulsar Timing

Pulsars are…

- …cosmic lighthouses
- …almost Black Holes: ~1.4 $M_\odot$ within 20km
- …objects of extreme matter : 10x nuclear
- …massive flywheels, hence very stable clocks
- …pulsar timing measures arrival time (TOA):





Coherent timing solution about 1,000,000 more precise than Doppler method!

Already today, we can do amazing measurements…

Masses:

- Masses of neutron stars: m1 = 1.4398(2) $M_\odot$ and m2 = 1.3886(2) $M_\odot$ (Weisberg et al. 2010)
- Mass of WD companions:
  - Shapiro: 0.204(2) $M_\odot$ (Jacoby et al. 2005)
  - Optical: 0.181(7) $M_\odot$ (Antoniadis et al. subm.)
- Mass of millisecond pulsar: 1.67(2) $M_\odot$ (Freire et al. 2010)
- Main sequence star companion: 1.029(8) $M_\odot$ (Freire et al. 2010)

Spin parameters:

- Period: 5.757451924362137(2) ms (Verbiest et al. 2008) = 2 atto seconds uncertainty!

Orbital parameters:

- Period: 0.102251562479(8) day (Kramer et al. in prep.)
- Eccentricity: 3.5 (1.1) × 10^{-7} (Freire et al. subm.)

Astrometry:

- Distance: 157(1) pc (Verbiest et al. 2008)
- Proper motion: 140.915(1) mas/yr (Verbiest e t al. 2008)

GR tests:

- Periastron advance: 4.226598(5) deg/yr (Weisberg et al. 2010)
- Shrinkage due to GW emission: 7.152±0.008 mm/day (Kramer et al. in prep)
- GR validity (obs/exp): 1.0000(5) (Kramer et al. in prep.)

But with the SKA…we can do so much more, for instance:

- Measure mass of SGR A* to 10^{-6}!
- Measure spin of SGR A* to precision of 10^{-4} to 10^{-3}: Cosmic Censorship!
- Measure quadrupole moment to 10^{-3} to 10^{-2}: No hair! (Liu et al. 2012)

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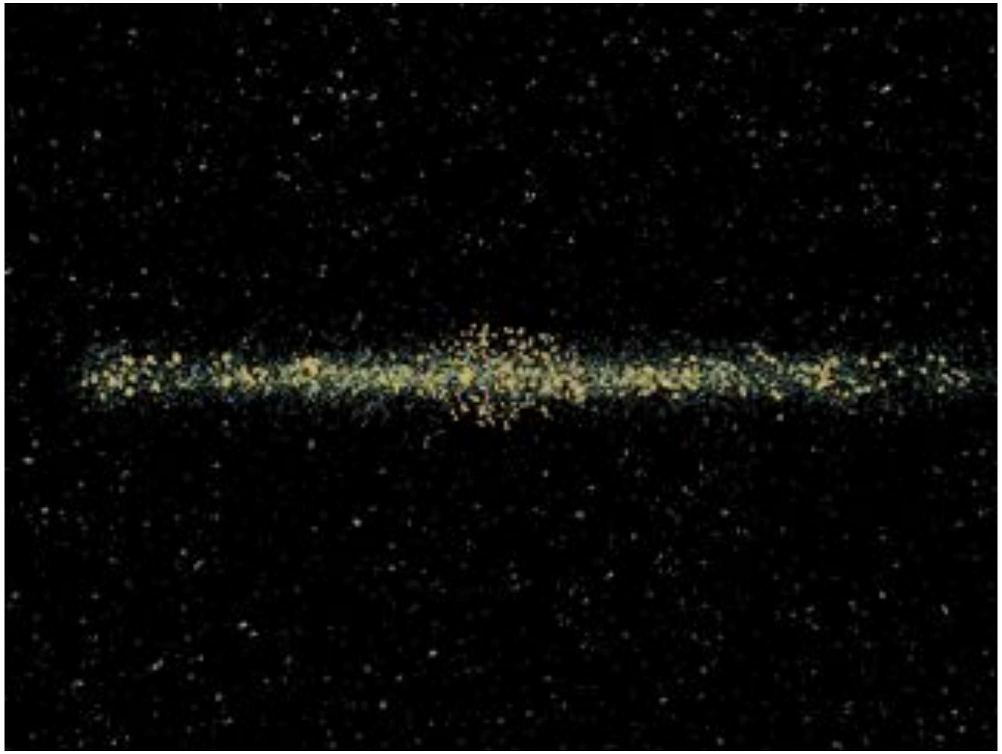
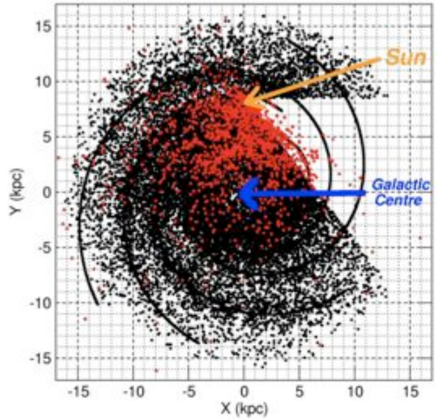
Galactic census with the SKA

With the SKA'S collecting area and increase in survey speed:

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





- ~30,000 normal pulsars
- ~2,000 millisecond psrs
- ~100 rel binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

➔ with sensitivity also timing precision is expected to increase by factor ~100

➔ rare and exotic pulsars and binary systems: including PSR-BH systems!

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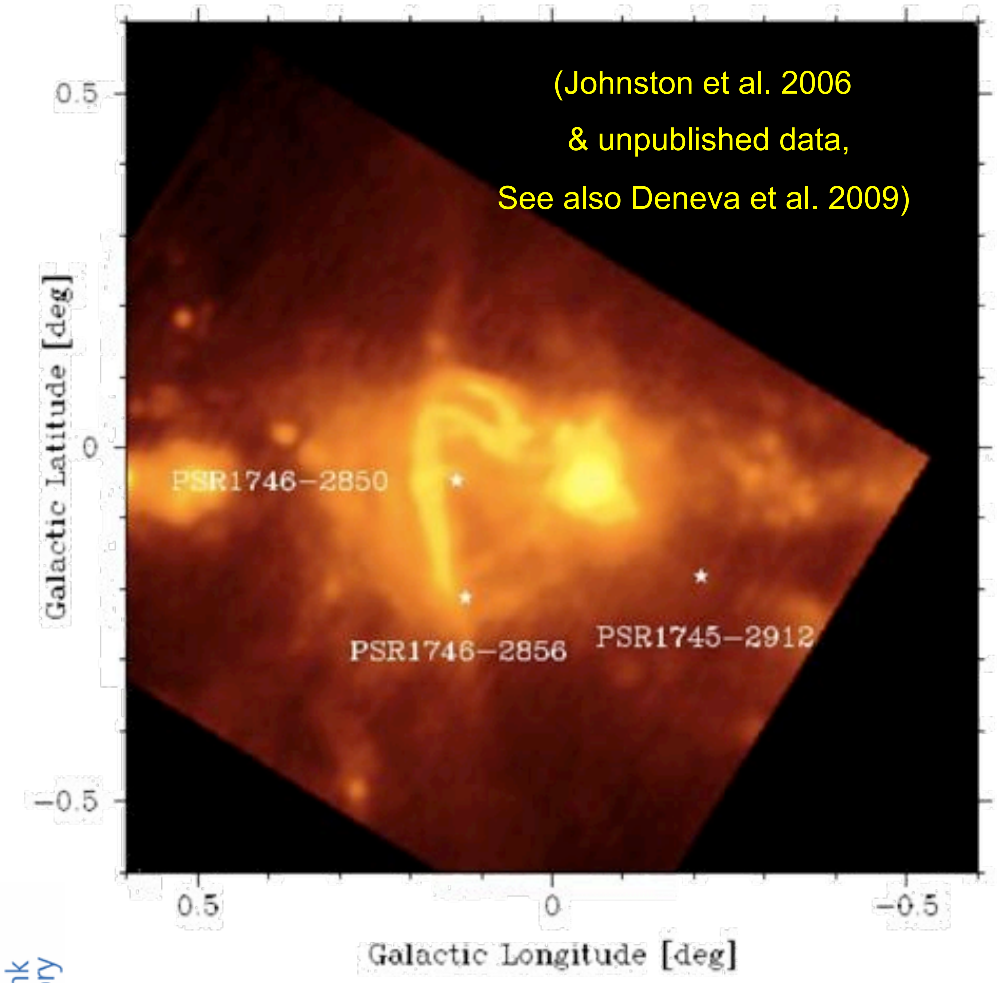
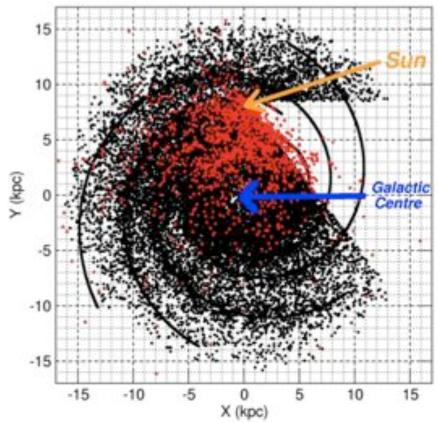
Galactic census with the SKA

With the SKA'S collecting area and increase in survey speed:





- ~30,000 normal pulsars
- ~2,000 millisecond psrs
- ~100 rel binaries
- first pulsars in Galactic Centre
- first extragalactic pulsars

Once pulsar in GC found, the experiment will be simple…

A pulsar around SGR A*

Extensive new study (Liu et al. 2012)

Sgr A*: $M = 4\,000\,000\ M_{\odot}$

$M_p << M \Rightarrow$ one post-Keplerian parameter gives the mass of Sgr A*

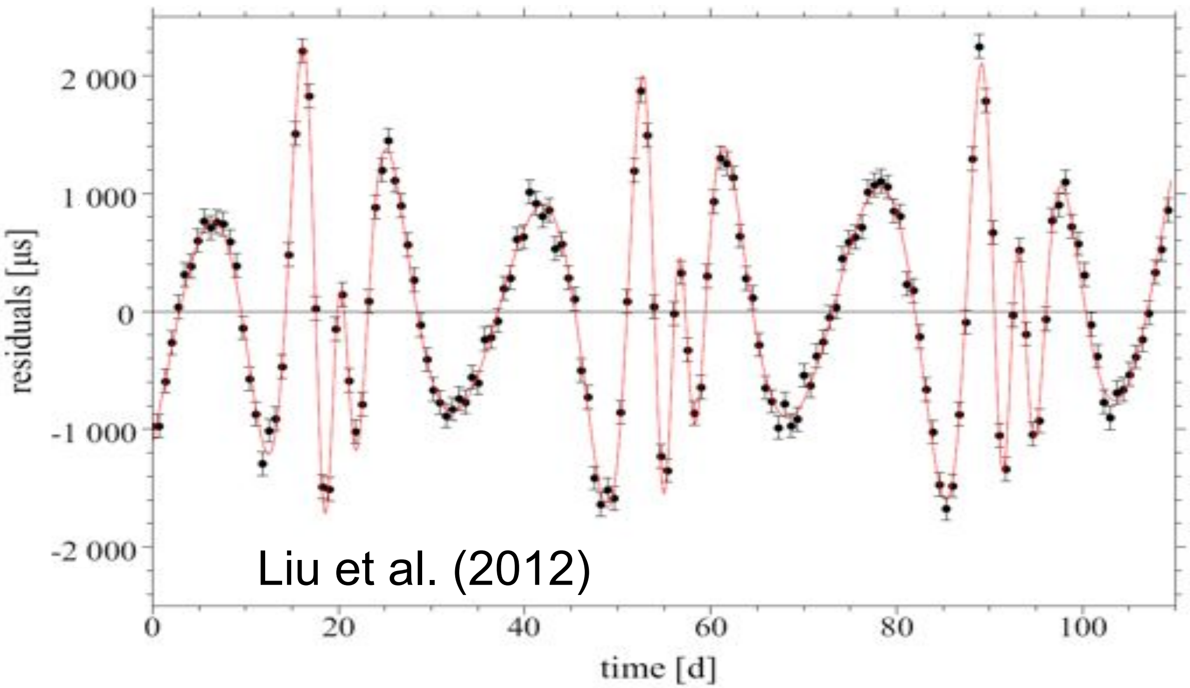
For a pulsar in a 0.1 yr orbit with an eccentricity of 0.4

- Precession of periastron: 14.8 deg/yr (1.5 deg / orbit)
- Einstein delay: 7.7 min
- Shapiro delay: > 33 s (depends on the inclination)

Testing the BH properties: Hairs, anyone?

A single pulsar in a few 0.1 yr orbit around Sgr A* would, within a few years,

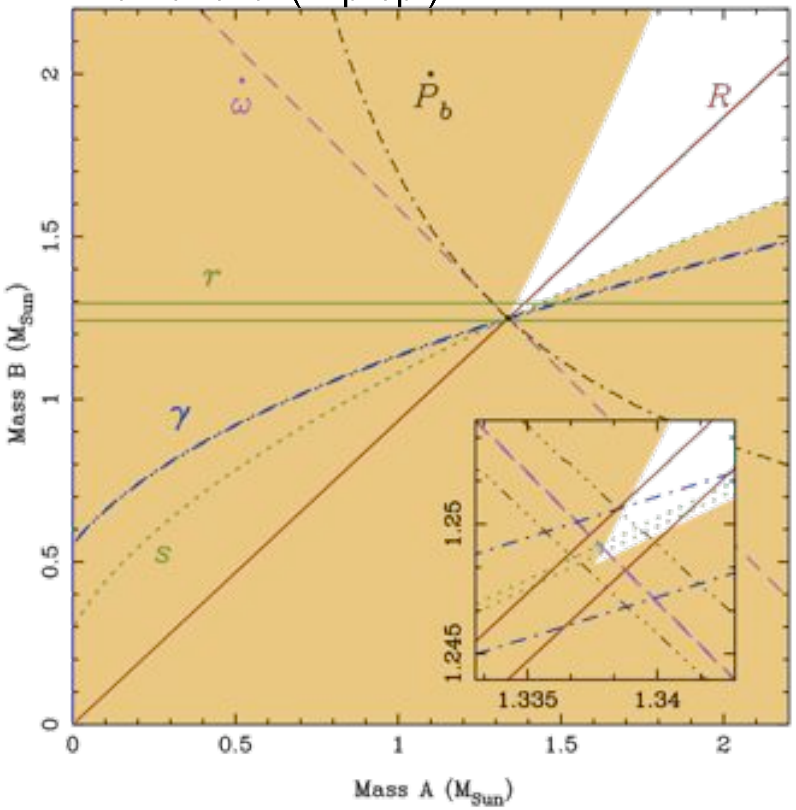
- …provide a mass measurment with a 10^{-6} precision
- …provide a spin measurment with a 10^{-3} -10^{-4} precision,
  a test for the Lense-Thirring effect, and the cosmic censorship conjecture
- …provide a quadrupole measurment with a ~1% precision,
  and test the no-hair theorem of GR
- …provide a test for spin precession in a black hole spacetime



➔ $\delta Q/Q = 0.008$

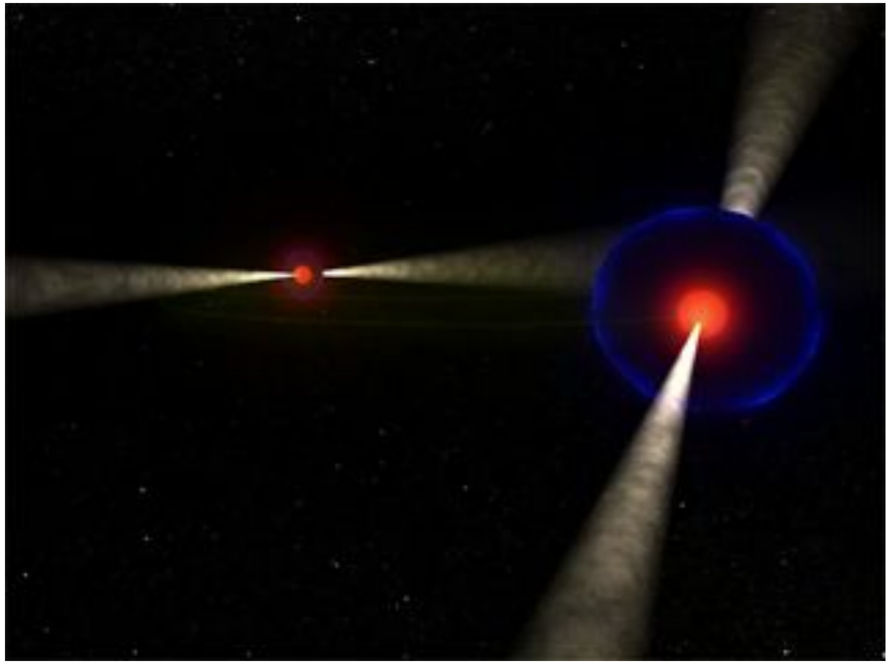
Best evidence to date – the Double Pulsar:

Kramer et al (in prep.)



Orbit shrinks every day by

7.152±0.008 mm/day



Precision measurements, e.g.

P (ms) = 22.6993785996213 ± 0.0000000000002 (measured to 0.2 picoseconds!)

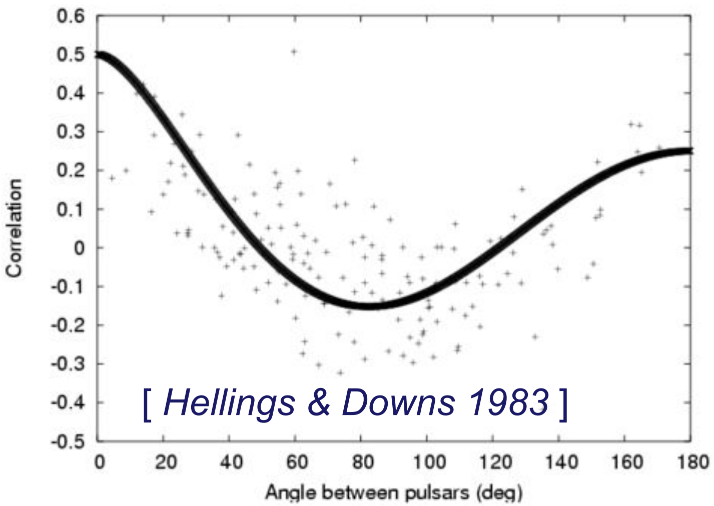
P_b (d) = 0.102251562452 ± 0.000000000008 (i.e. 2.45h measured to 691 ns!)

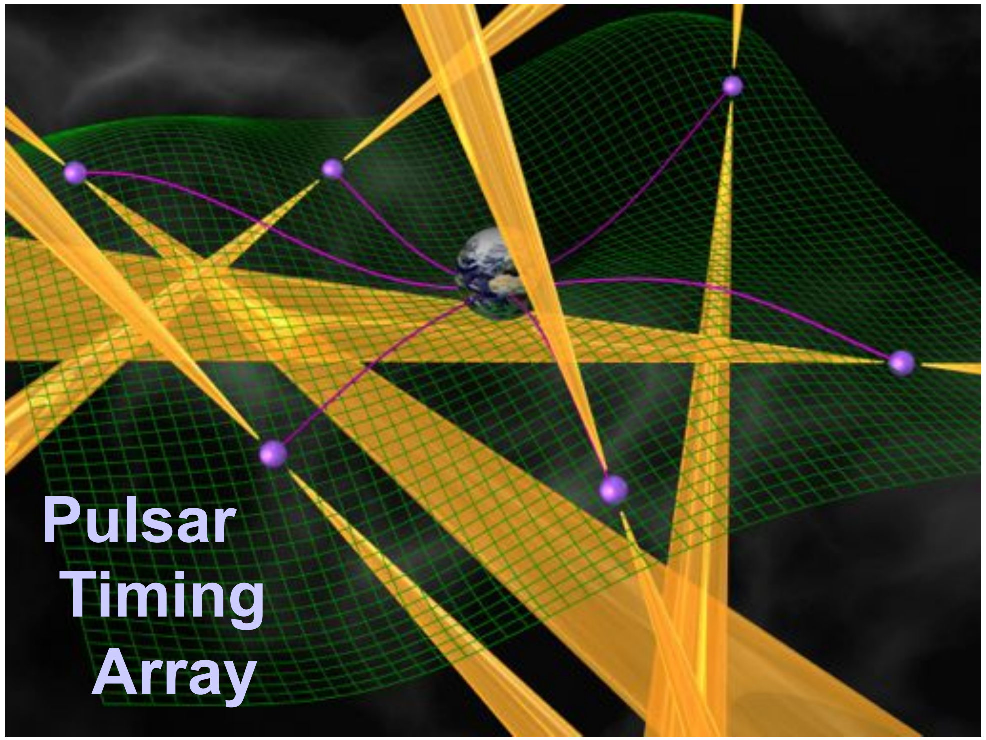
dP_b/dt = (-1.248±0.001) x 10^{-12} - agreement with GR at 0.1% - best radiation test!

Pulsars as gravitational wave detectors

Pulse arrival times will be affected by low-frequency gravitational waves – correlated across sky!

In a “Pulsar Timing Array” (PTA) pulsars act as the arms of a cosmic gravitational wave detector:

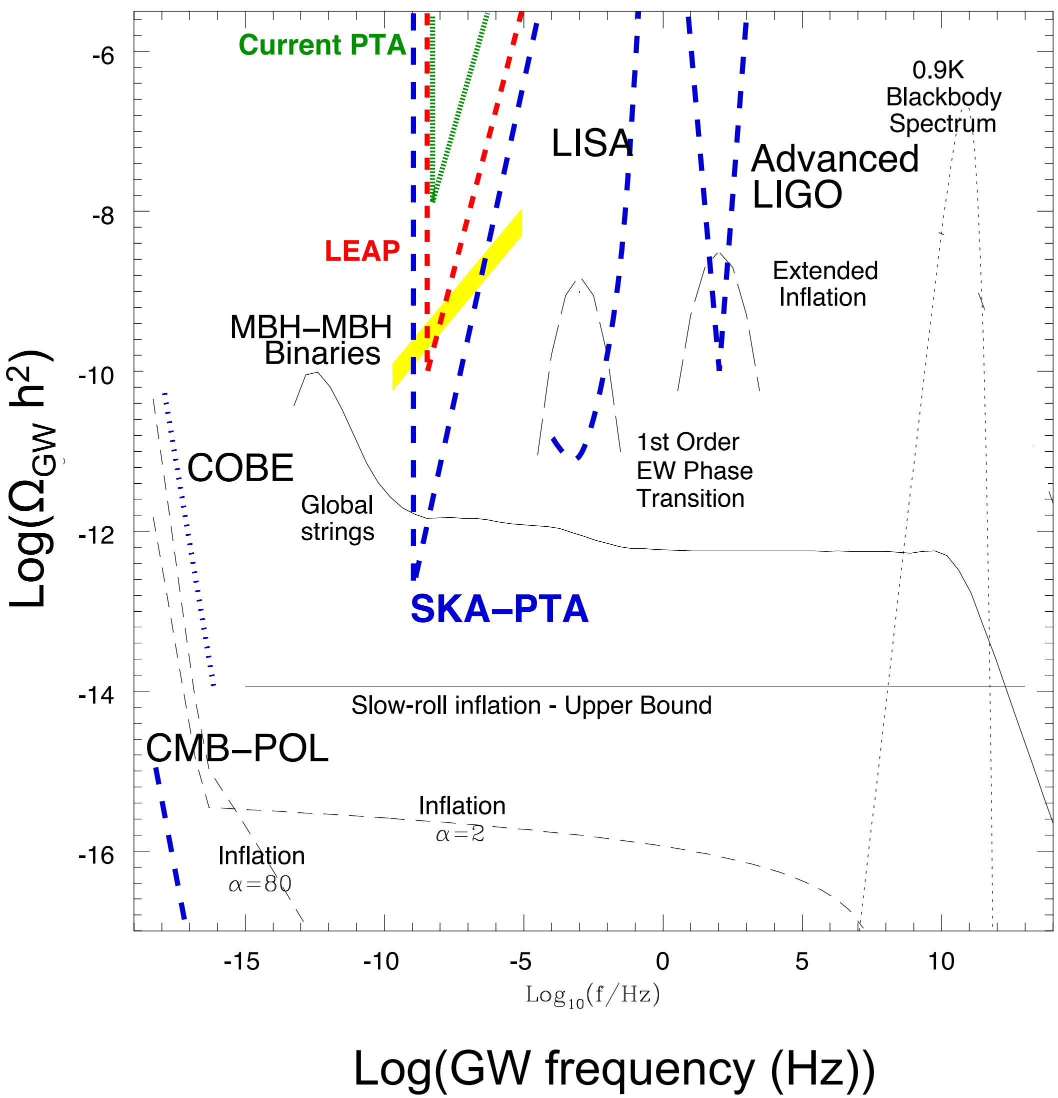




The SKA as a Gravitational Wave Detector

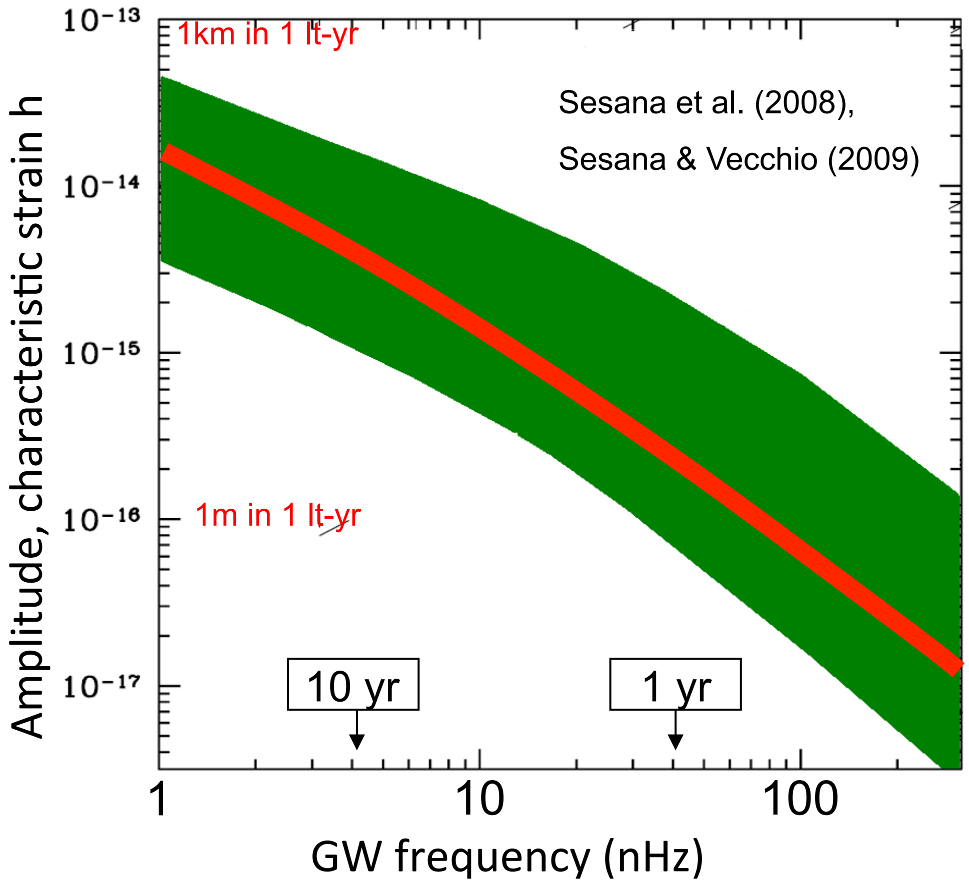
- SKA-PTA is sensitive to nHz gravitational waves
- Complementary to LISA, LIGO and CMB-pol band
- Expected sources:
  - binary super-massive black holes in early Galaxy evolution
  - Cosmic strings
  - Cosmological sources
- Types of signals:
  - stochastic (multiple)
  - periodic (single)
  - burst (single)

(Kramer et al. 2004)



Stochastic background

- Earliest signal expected from binary super-massive black holes in early galaxy evolution (PTA only way to detect $M>10^7 M_\odot$ P_{orb}~10-20yr)
- Amplitude depends on merger rate, galaxy evolution and cosmology but could be "soon" detectable (e.g. Sesana et al. 2008)



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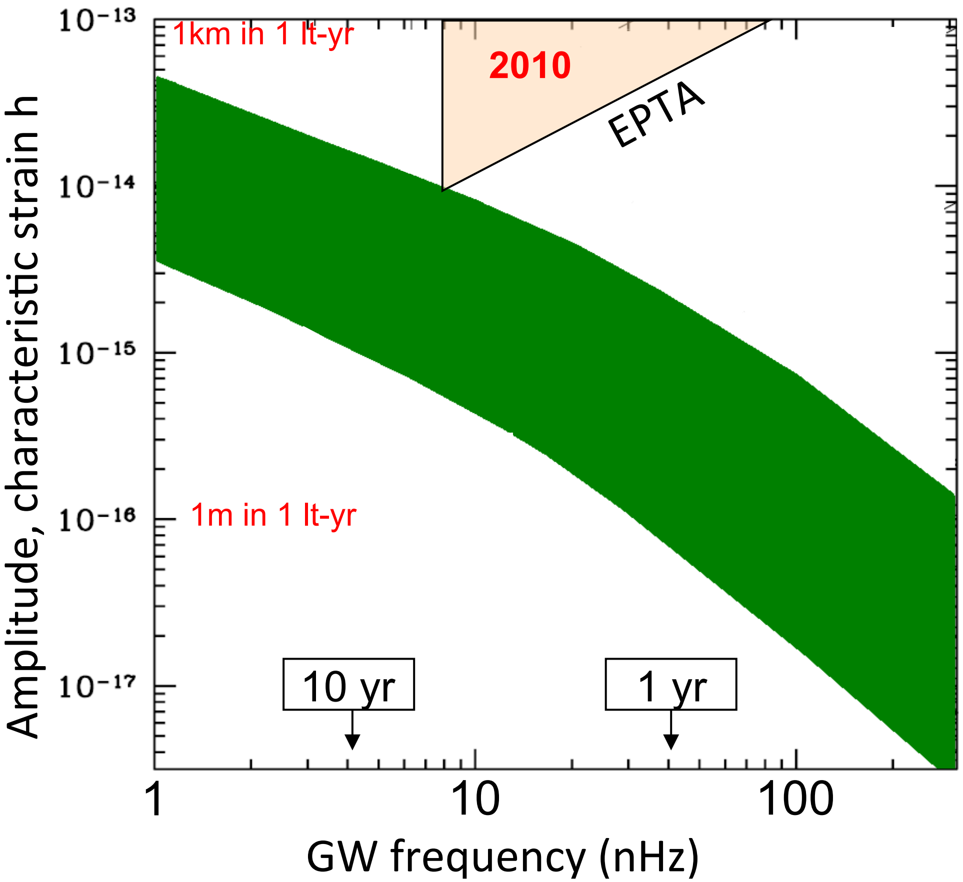

Note:

Current best limit from European Pulsar Timing Array by van Haasteren et al (2011) is tantalizingly close to expected detection limit!

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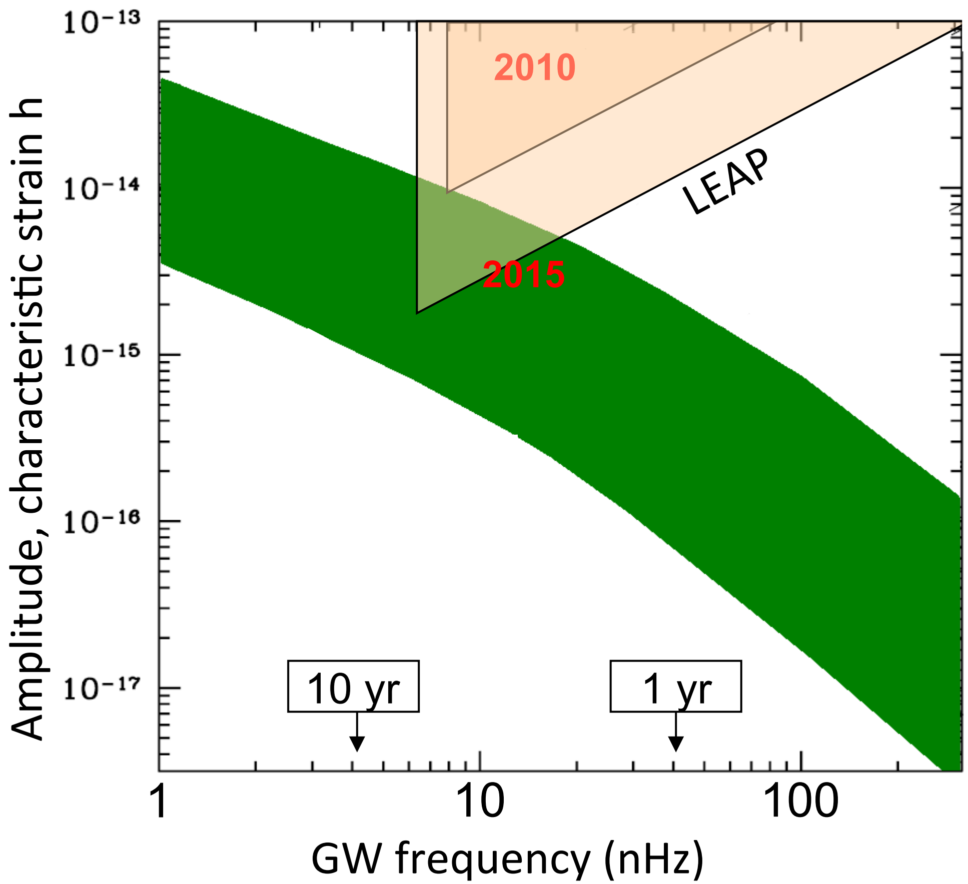

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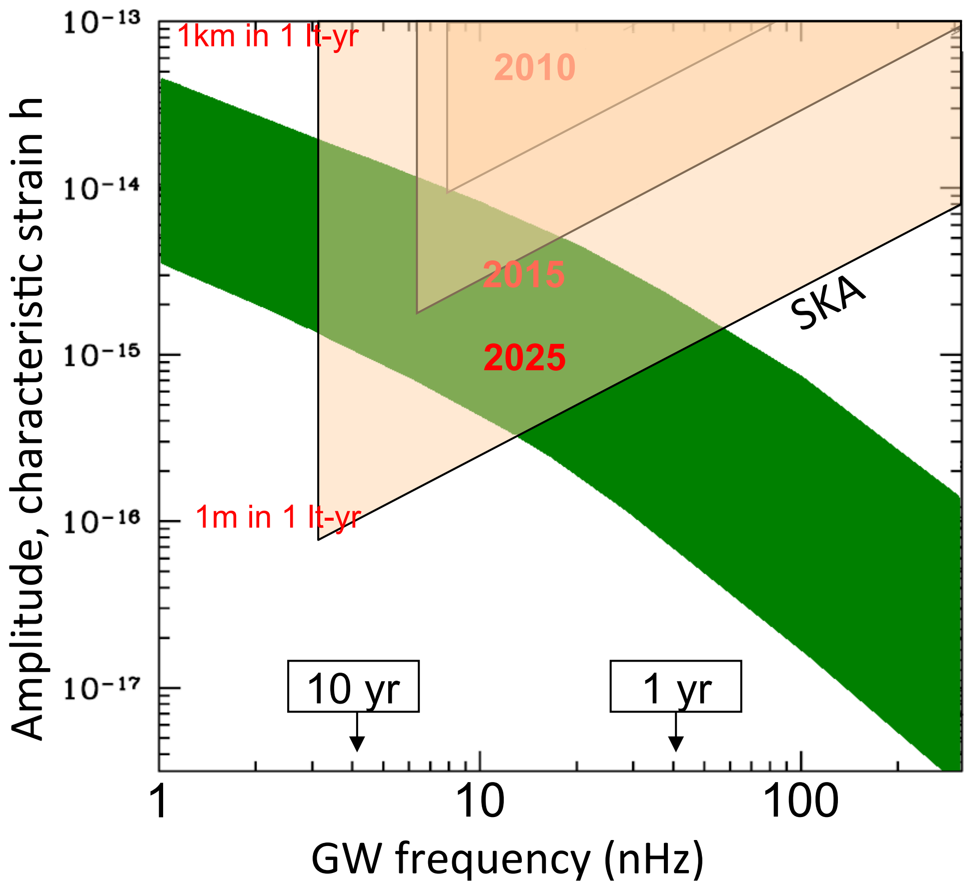

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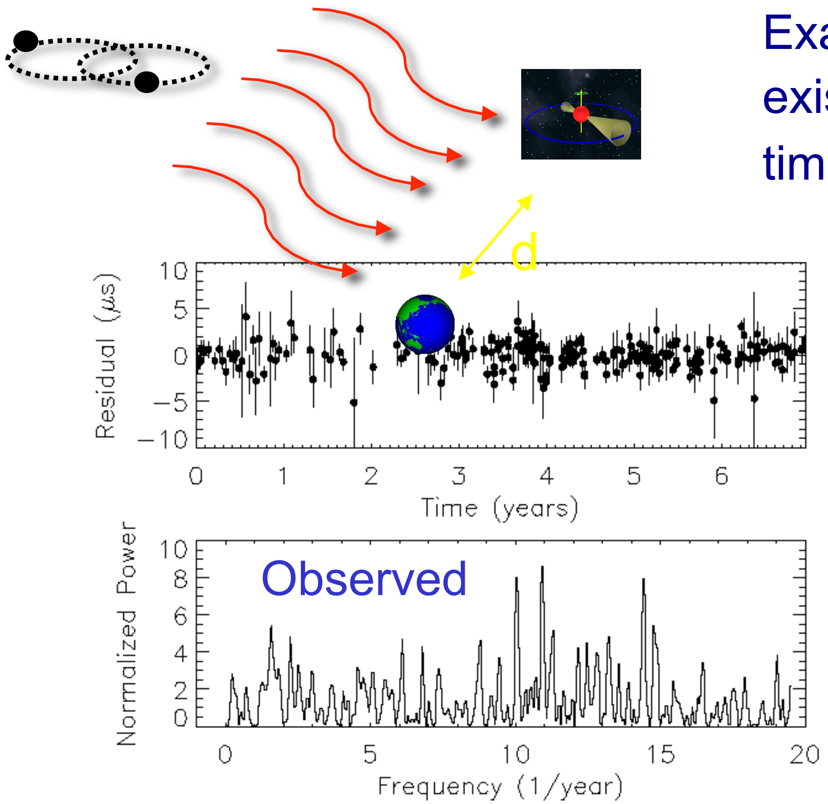
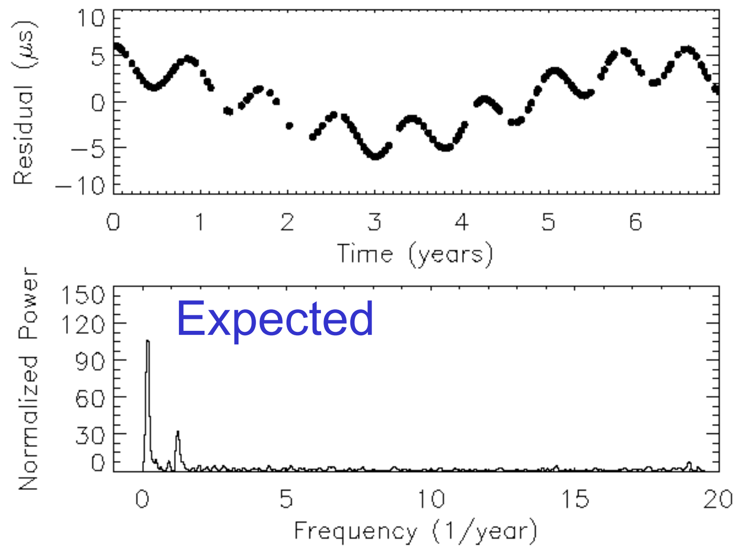
Single source detection

- Single binary super-massive black hole produces periodic signal
- Perhaps rare but complementary in mass range to LISA (Sesana et al. 2009, Sesana & Vecchio 2010)
- If SNR is high (or source and orbital period known!) we can search for signature
- Expect periodic signal but also dc-term due to memory effect (van Haasteren & Levin 2010)
- Signal contains information from two distinct epochs: t and t-d/c

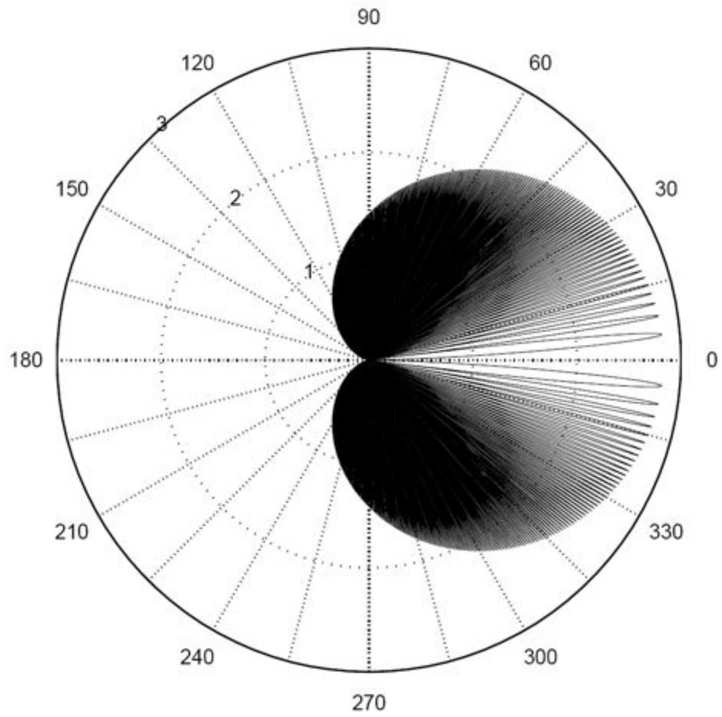


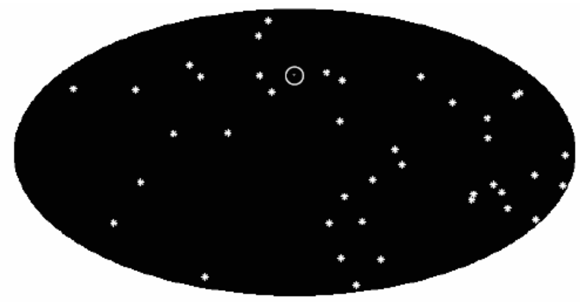
Example: if binary super-massive BH exists in 3C66B, we expected signature in timing data of PSR B1855+09 (Jenet et al 2003):

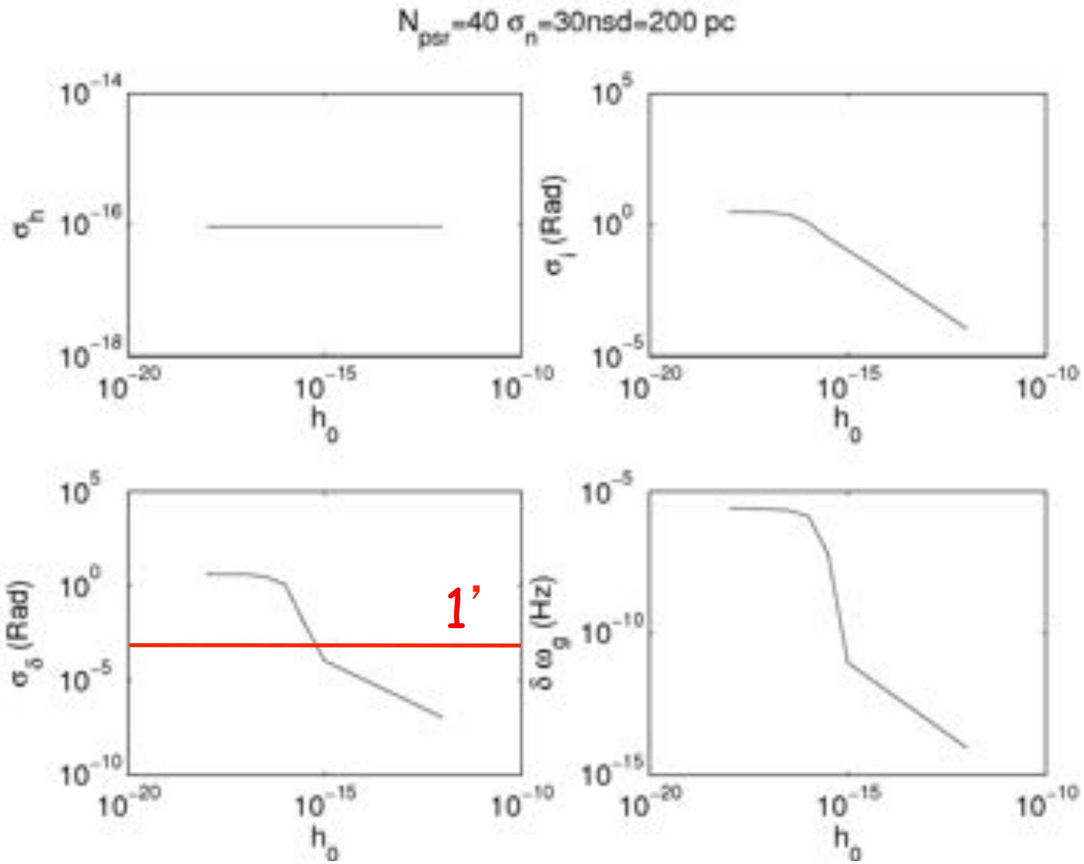


Gravitational Wave Astronomy

- We can pinpoint a single GW source (Lee et al. 2011):







Possible by amazing astrometry of SKA!
(e.g. parallax up to 100kpc!)

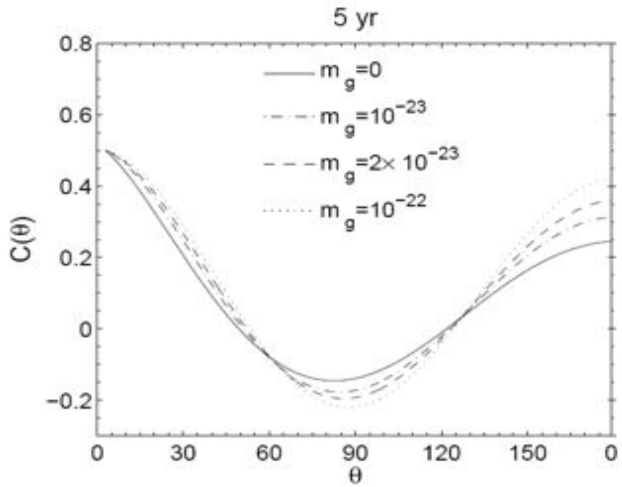
Properties of the graviton

- We can do more than "only" detect gravitational waves
- With SKA we can study GW properties: polarisation & graviton mass

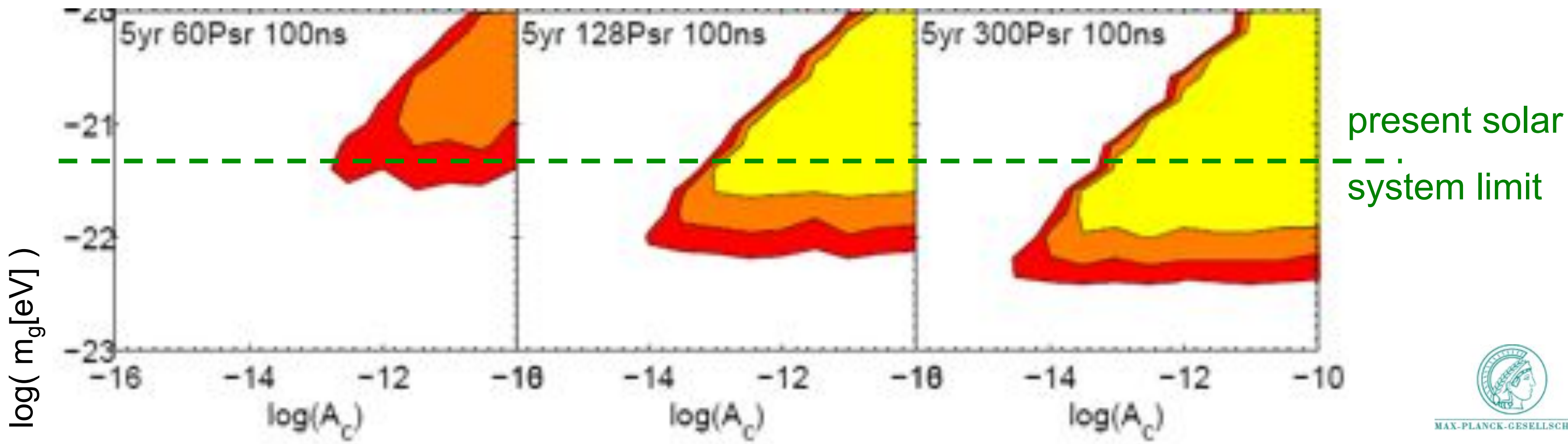
Lee et al. (2010)

$$\mathbf{k}_\mathrm{g}(\omega_\mathrm{g}) = \frac{\left(\omega_\mathrm{g}{}^2 - \omega_\mathrm{cut}{}^2\right)^{\frac{1}{2}}}{c}\,\hat{\mathbf{e}}$$

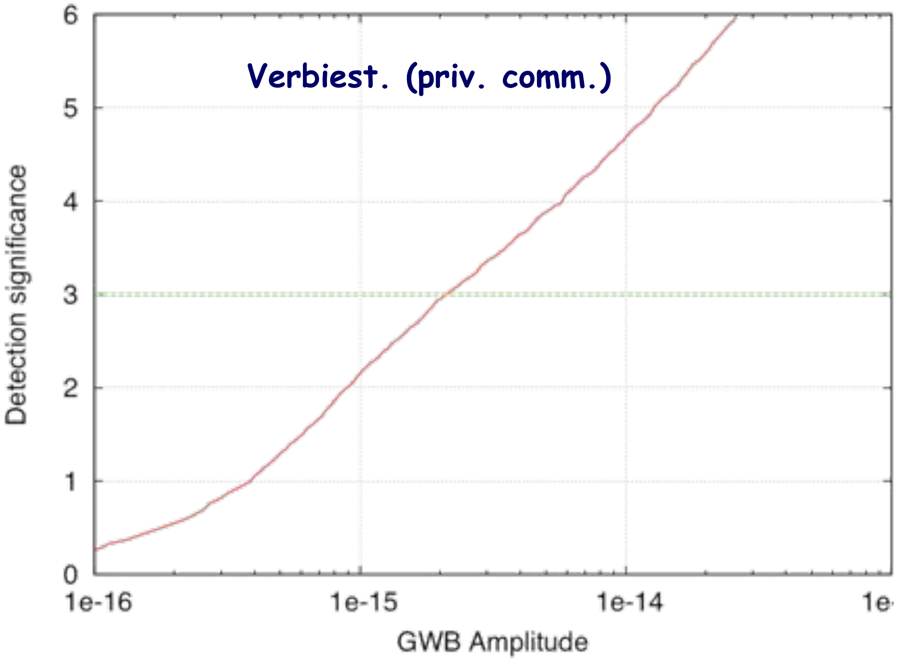
$$\omega_\mathrm{cut} = m_\mathrm{g} c^2/\hbar$$

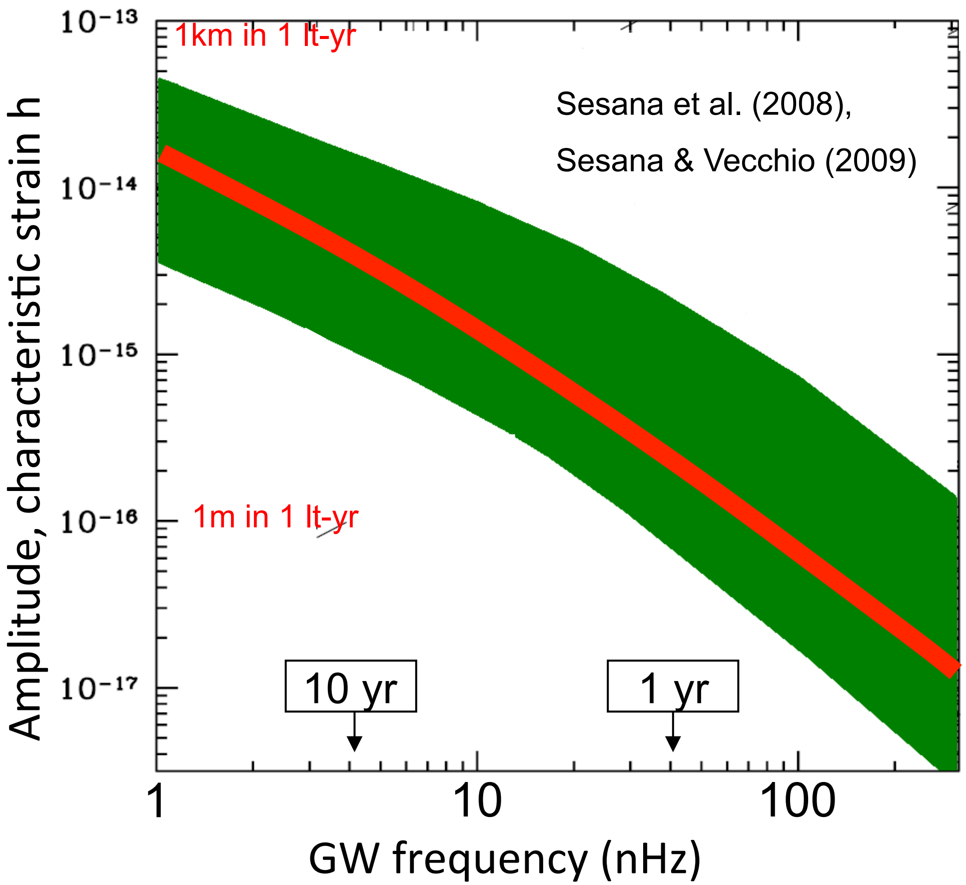


Graviton mass:



Gravitational wave detection with SKA_1





Phase 1 should make a detection – can also make use of IPTA data.

With the full SKA we can study GW properties and sources!

Already exciting science on the road to the full SKA: SKA$_1$

Phase 1 will be also an exciting search machine:

- Low-frequency array (AA, 400 MHz): 7800/950 PSRs/MSPs (Galactic)

  1-month only! 2200/750 (rest of sky)

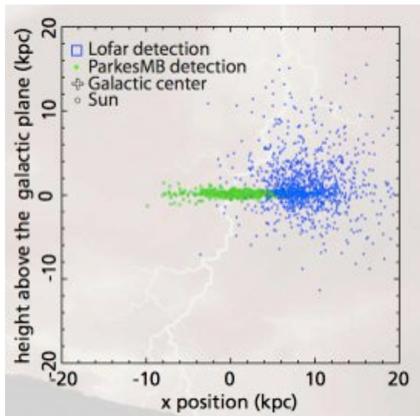
- Dishes allow to probe further into Galaxy

- Note that full SKA cannot use full area for searching (initially) due to processing requirements – will already discover interesting sources

- Complementing the on-going pre-SKA activities:

  e.g. HTRU (Parkes/Effelsberg) all-sky high survey

  and the exciting LOFAR activities:



Van Leeuwen & Stappers (2006)

Conclusions

- Note: There wasn't time to talk about ASKAP, MeerKAT, LOFAR etc.
- Lots of things are happening in all areas of SKA technology and science
- Politically, things are moving equally fast and decisions are made now
- We are trying to get a glimpse into the exciting science by testing SKA technology on existing telescopes (e.g. wide-bandwidth feed on Effelsberg, APERTIF on Westerbork) or new telescopes like LOFAR.
- SKA_1 will be a superb telescope for pulsars and EOR already!
- We are privileged to live in a time with exciting new facilities coming up, in particular NGO, E-ELT and SKA.

The scientific arguments for the facilities alone may be overwhelming

but it is the combination what matters – that makes it even bigger!

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