Future Radio Observatories for Pulsar Studies

Michael Kramer

University of Manchester – Jodrell Bank Observatory

17th August 2006

Many new facilities…

EMBRACE

LOFAR

LWA

LFD

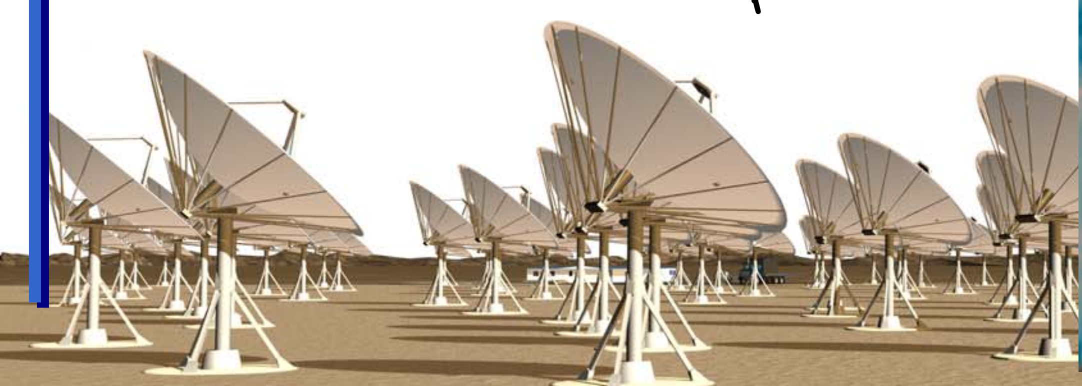
KAT

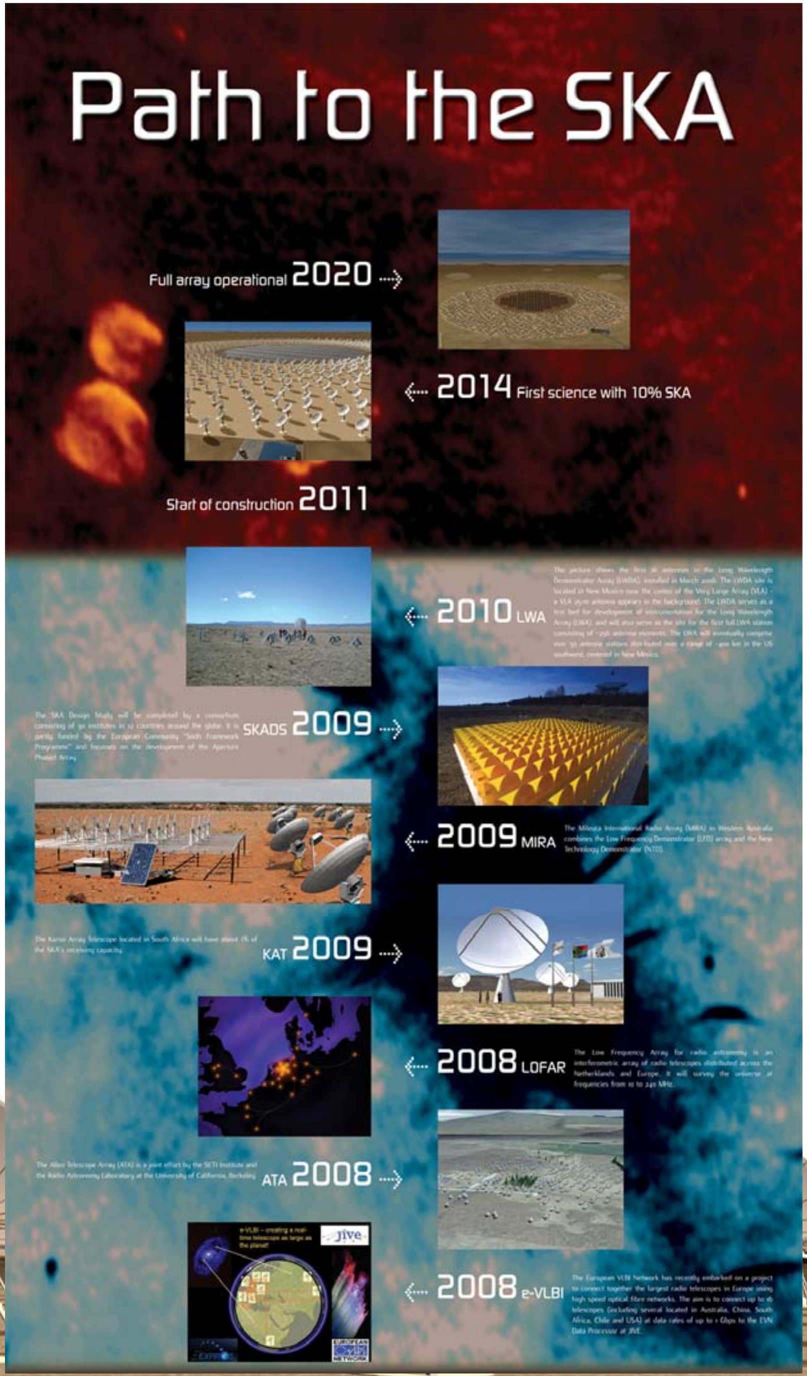
XNTD

SKA

MIRA

ATA





Outline

- Where are we…?
- SKA Pathfinders: ATA, KAT, MIRA
- LOFAR
- Square-Kilometre-Array

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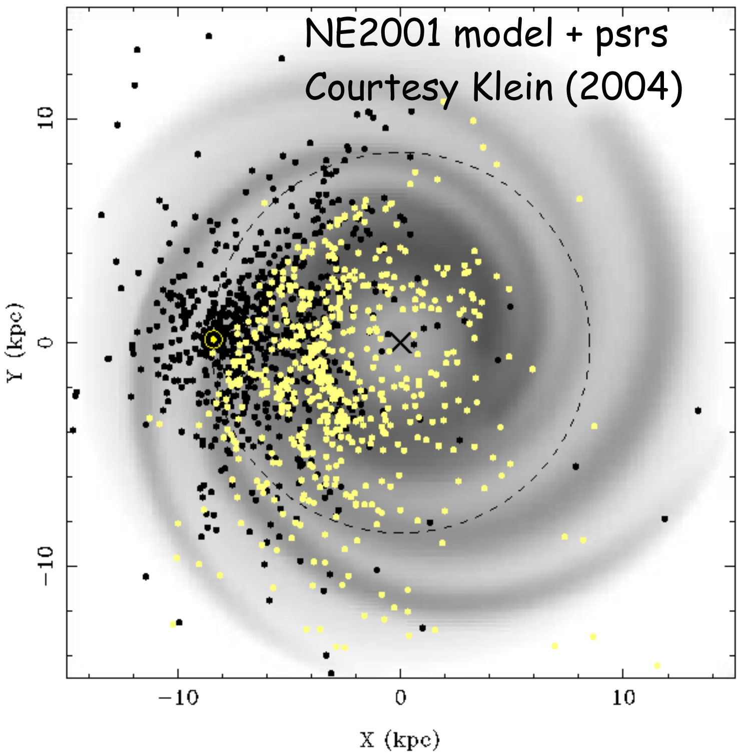
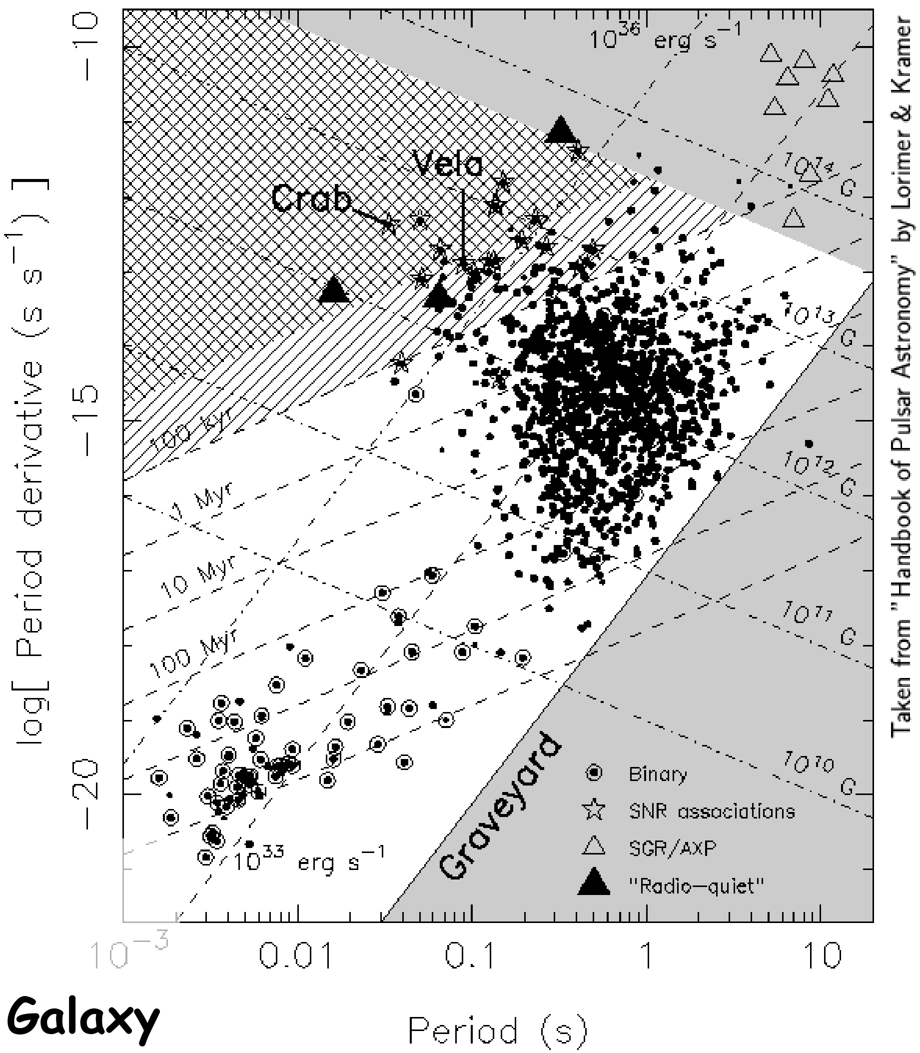
The current situation...

Radio emitting NS = ~1770 rotation-powered (radio) pulsars...



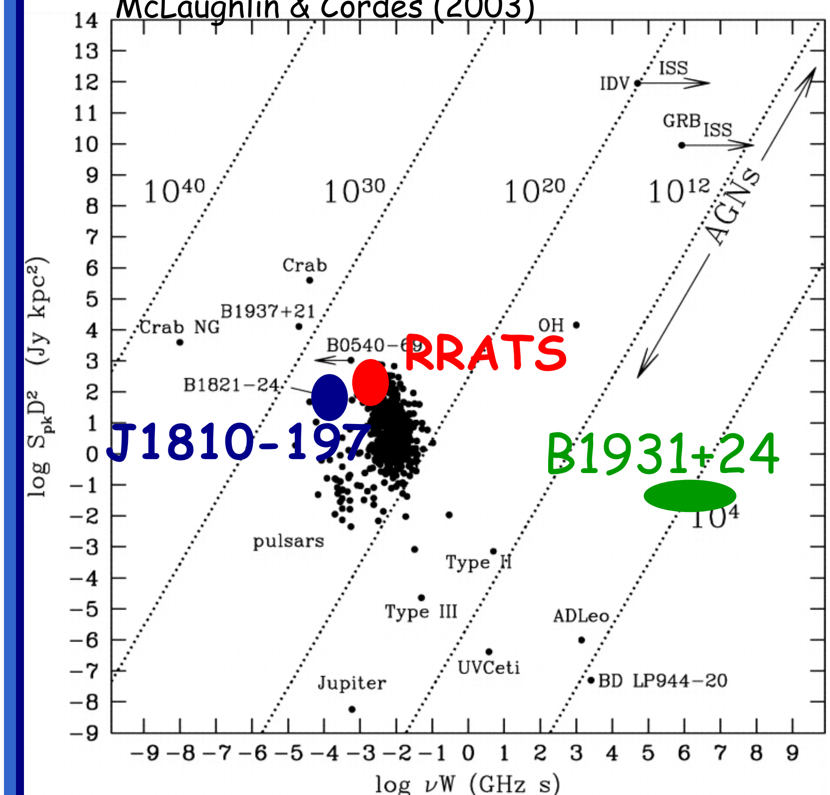


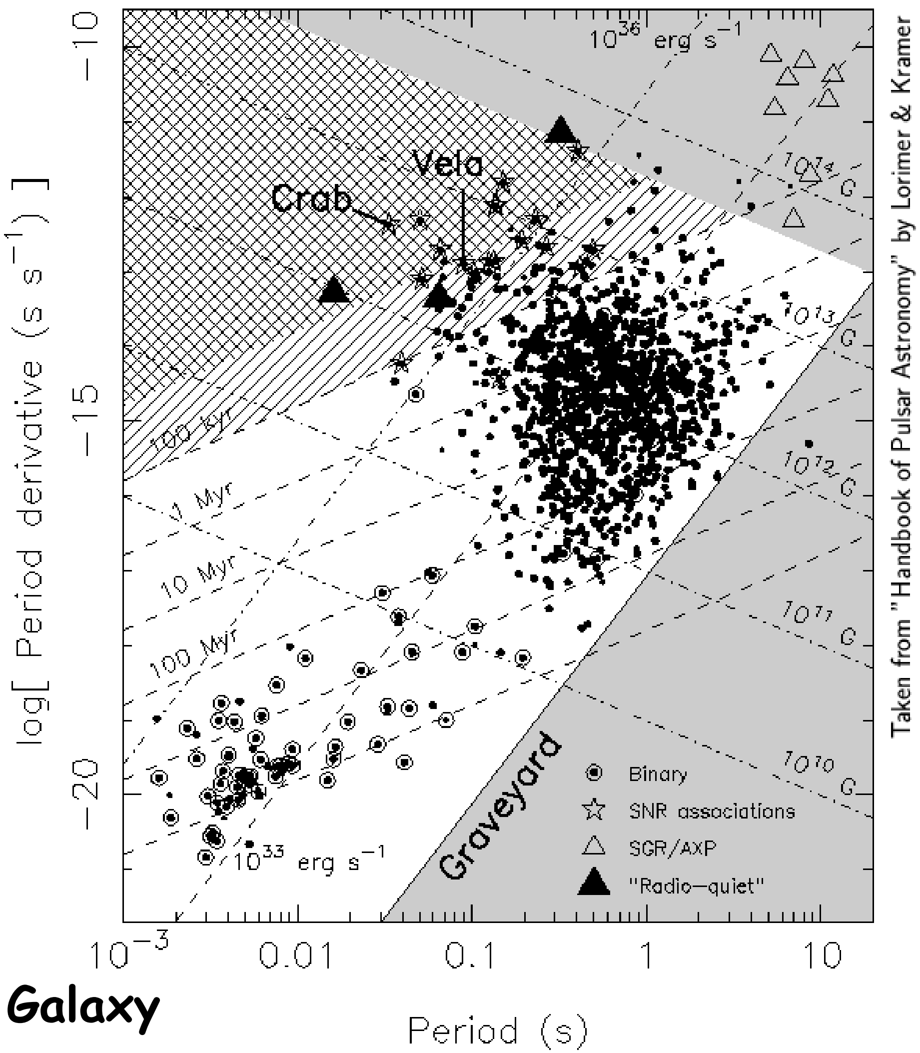
- **steady pulsed emission**
- **links to AXP/SGRs unclear**
- **about 100,000 active pulsars in Galaxy**

The current situation…

Radio emitting NS = ~1700 rotation-powered (radio) pulsars…

McLaughlin & Cordes (2003)





- **steady pulsed emission**
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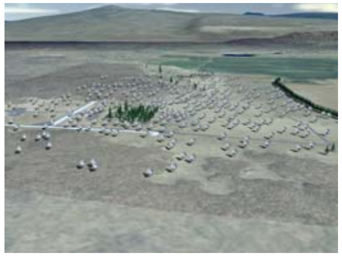
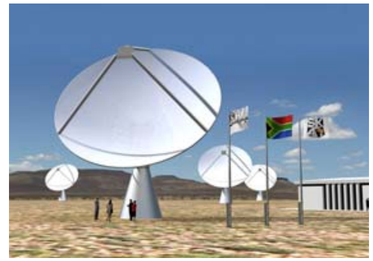
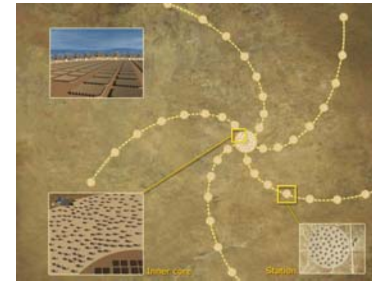
Timeline

ATA





KAT



10% SKA
Phase I

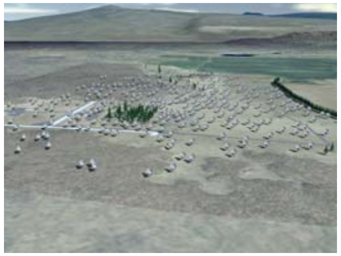
Full SKA

LOFAR

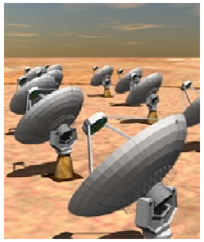
MIRA

Now 2008 2009 2014 2020

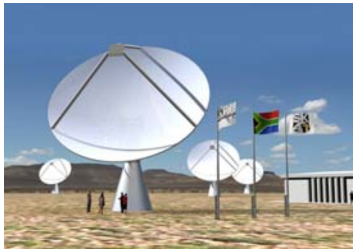
Size



ATA

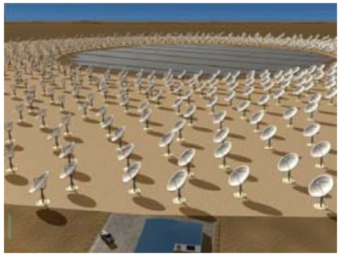


MIRA

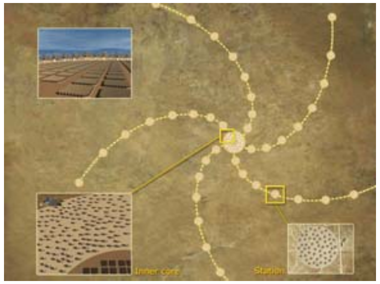


KAT

LOFAR



SKA Phase I



Full SKA

100-m class

Arecibo class

SKA

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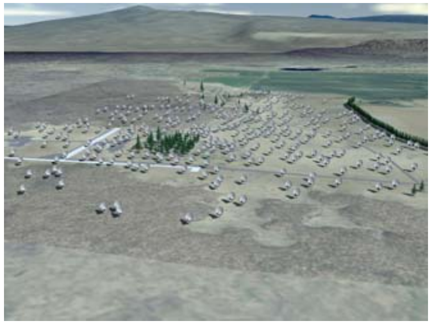
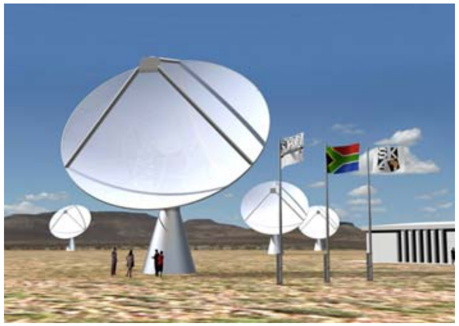
Allen Telescope Array (ATA)

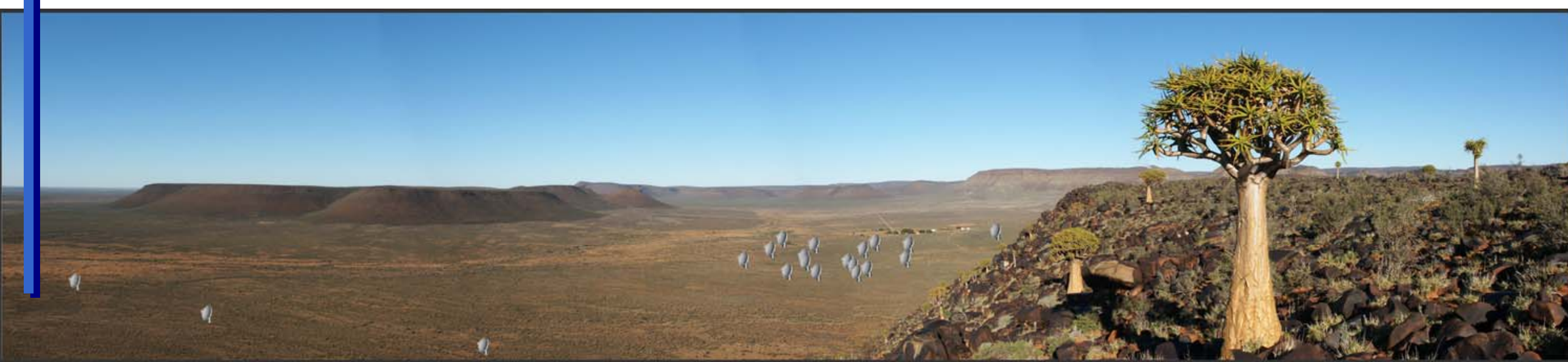


- Elements: 6.1-m hydroformed dishes
- Ultimate goal: 350 dishes (= 114-m dish)
  Off-set gregorian for unblocked aperture
- Frequency coverage: 0.5 – 11.5 GHz (simultaneously!)
- System temperature about 40 K
- FOV: 5 sq-deg at 1400 MHz
- Various phases: - ATA-42 (soon!, ~27 are up)
  - ATA-98
  - ATA-206
  - ATA-350 (in 2008)
- Science: with >ATA-206: pulsar timing (PTA)
  transient sky survey

Karoo Array Telescope (KAT)

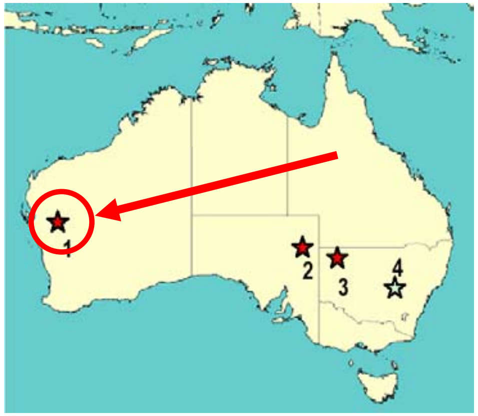


- Located at proposed South African SKA core
- Elements: ~20 15-m dishes (= Parkes)
- Frequency coverage ~600 – 1450 MHz
- Independent FoVs of ~1 sq-deg/1400 MHz
- Two stages: 1) multi-feed receivers
  2) focal plane arrays
- Science: - pulsar surveys
  - pulsar monitoring
  (glitches, timing noise, precession)



Mileura International Radio Array (MIRA)

(formerly known as xNTD)

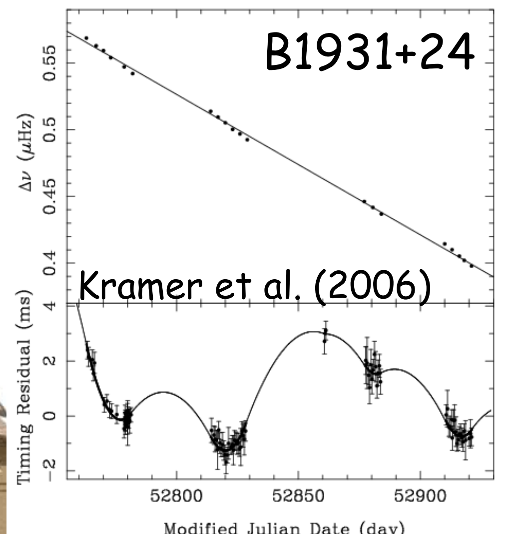


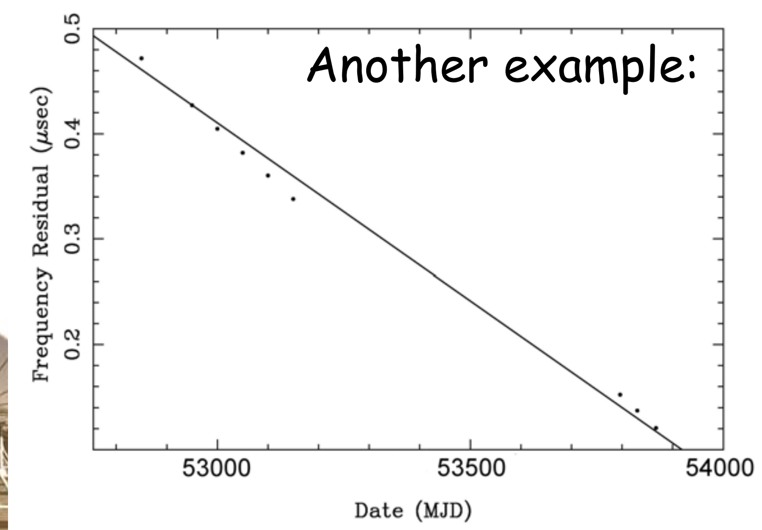
- Joint operation between xNTD and LFD
- Low-Frequency Demonstrator (LFD):
  - 8000 dual-pol dipoles in 500 tiles
  - frequency coverage: 80-300 MHz
  - collecting area: about 8000 sqm (=100-m dish)
  - Science: Transient survey & monitoring
- Extended New Technology Demonstrator (xNTD)
  - ~20 15-m dishes (= Parkes)
  - frequency coverage ~800 – 1800 MHz
  - 40 independent FoVs of ~1 sq-deg/1400 MHz
  - system temperature about 40 K
  - max baseline ~ 1km
- Science: pulsar surveys

Small-D, large-N telescopes

Generic science case:

- Large FoV (in particular after adding feed-arrays or FPA)
- Good for detecting transients, searching for RRATs
- Fast survey speed! We can do survey several times…!
- Good for monitoring pulsars: glitches, timing noise, precession…
- Find B1931-like pulsars – some of them are very bright but it is difficult to measure the changing spin-down – poor sampling!





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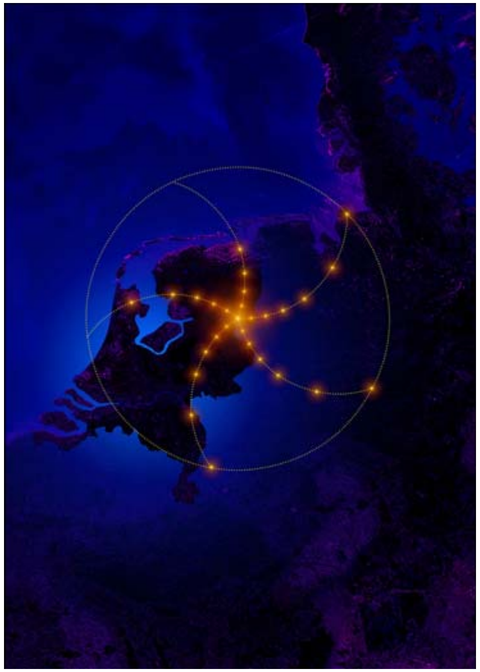
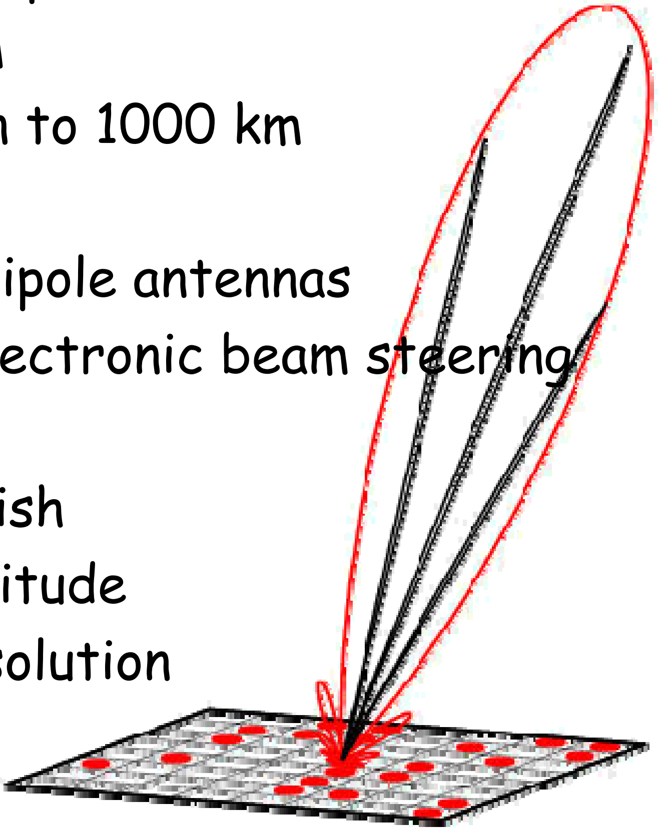
Using slides or material from B.Stappers produced with assistance from Jason Hessels, Joeri van Leeuwen, Dan Stinebring and MK

See also Posters JD02-51 and JD02-64!

Low Frequency Array (LOFAR)



- Telescope the size of the Netherlands plus parts of Germany
- Frequency coverage: 30 - 240 MHz
- 10% SKA at low-frequencies
- Baselines: ~100 km
- European Expansion to 1000 km
- Aperture array
- 77 stations of 96 dipole antennas
- No moving parts: electronic beam steering
- Supercomputer synthesizes giant dish
- Two orders of magnitude improvement in resolution and sensitivity



LOFAR stations

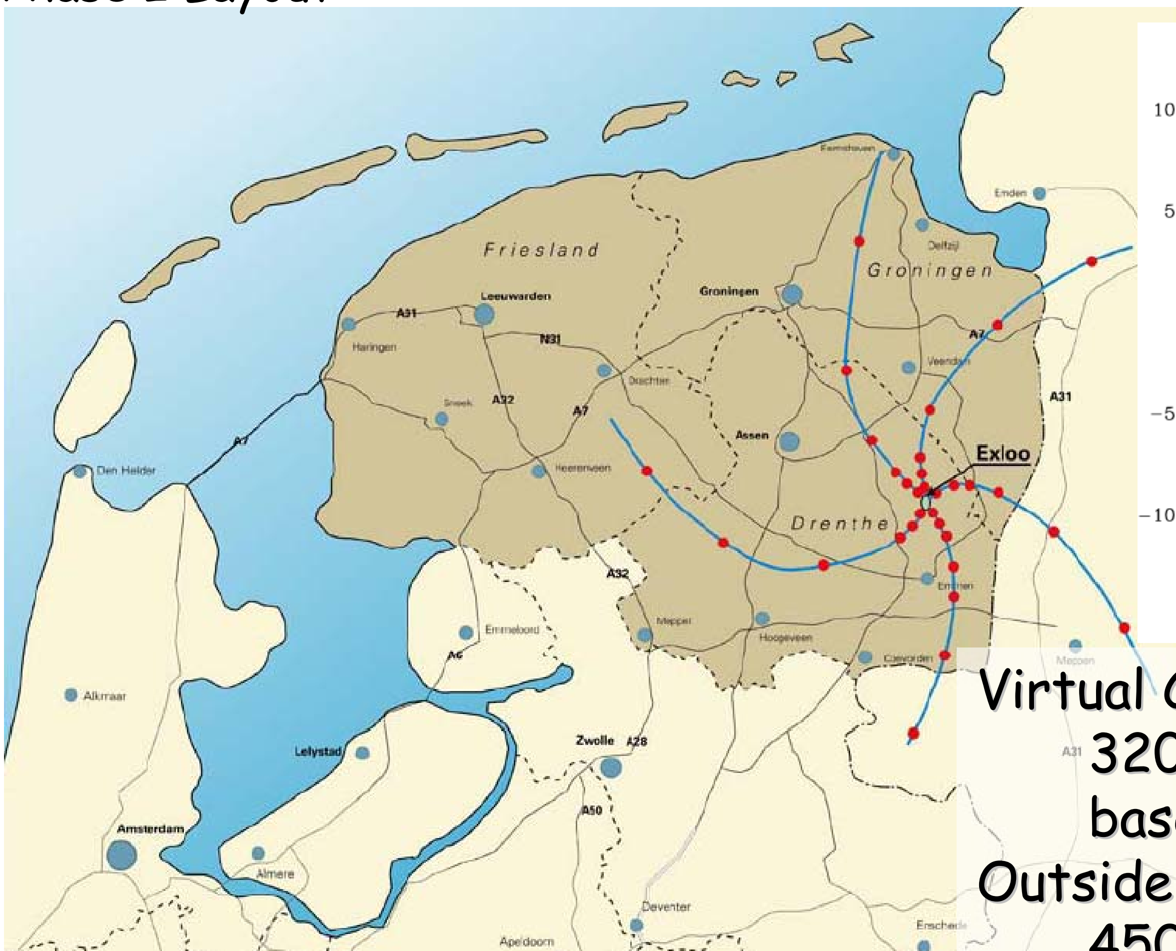
Two types of antenna:

- 96 Low Band Antenna's
- Distributed over ~60 m
- Optimized for 30-80 MHz

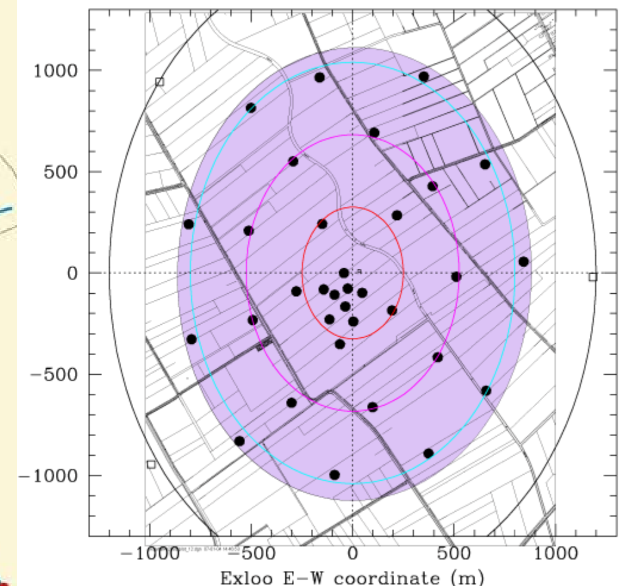
- 96 High Band Tiles
- 4x4 antenna's
- Distributed over ~50m
- Optimized ~115-240 MHz

LOFAR Configuration

Phase I Layout



Virtual Core



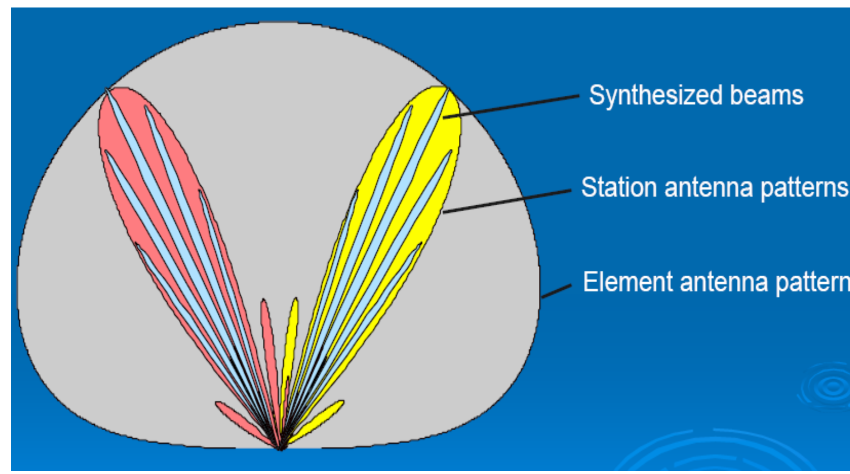
Virtual Core:
- 3200 antennas, 32 stations
- baselines 100 m - 2 km

Outside Core:
- 4500 antennas, 45 stations
- baselines up to 100 km


European Expansion ...
Current discussions:
Germany ~12 stations
UK ~3 stations
Italy ~2 stations
France ~1 station?
Poland ~1 station?

LOFAR Processing

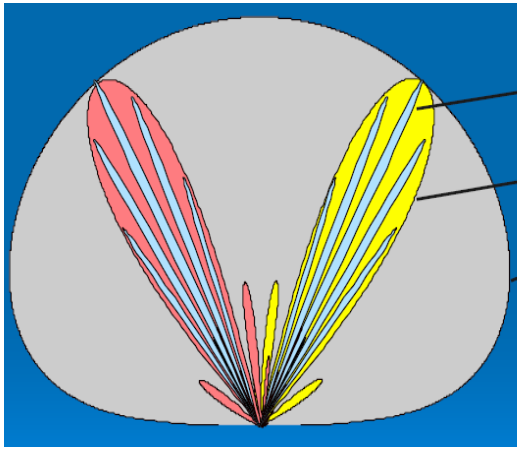
- IBM Blue Gene/L "Stella" operational
- 27,4 Tflop (= ~ 12000 PCs)
- 150 KW power consumption
- 0,5 Tbit/s input
- Large (100's processors) auxiliary clusters



- Full Array Imaging: 32 MHz - 12 bit
- Core Station Beams: up to 32 MHz, 20 beams, 4-bit
- Can trade bandwidth for station beams
- Possible to almost fully sample antenna beam with 4 MHz beams

LOFAR: Surveys

Two survey modes:



Wide-field Surveys:
- Sparse array
- Virtual core incoherent station beam
- 35 tied-array beams & pulsar backends
- ~20 VC station beams in 2008
- 32 MHz BW possible

Narrow-field Surveys & known sources:
- Use tied-array mode
- As many stations as possible
- Multiple tied-array beams possible
- 32 MHz BW anywhere in ~100 MHz range

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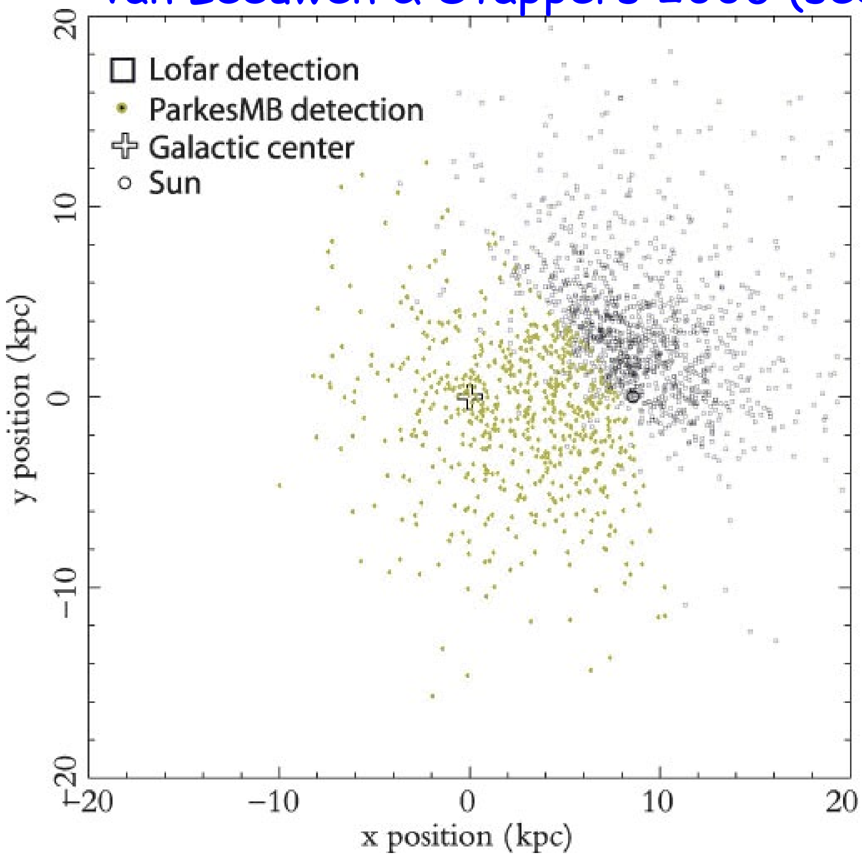
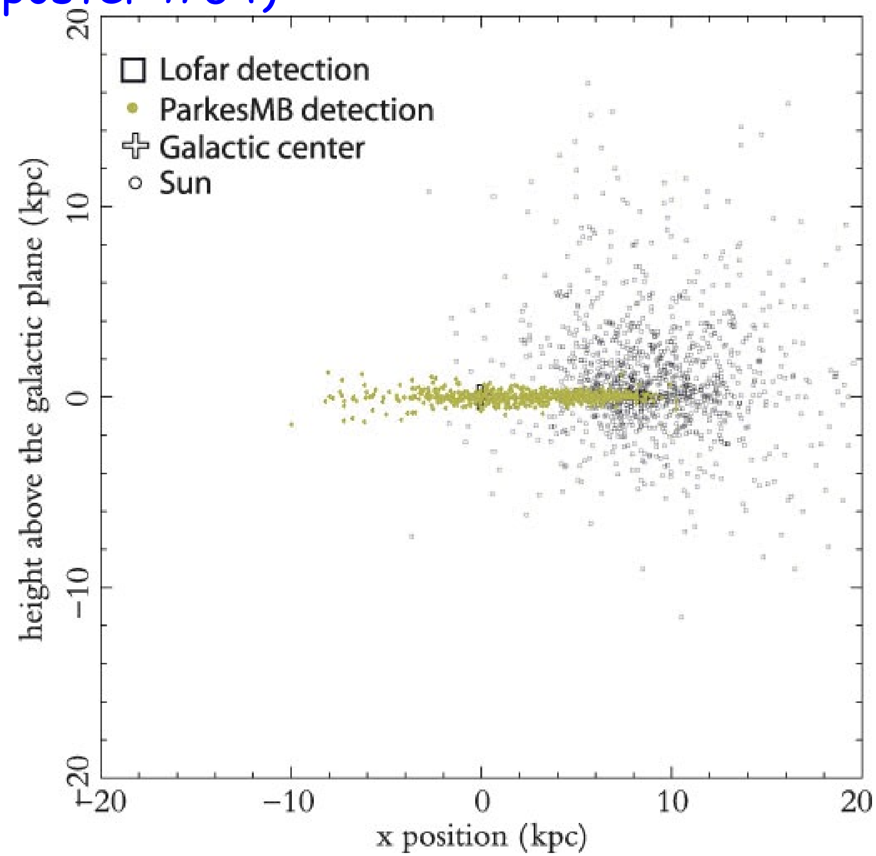
LOFAR: All-sky surveys

van Leeuwen & Stappers 2006 (see poster #64)





1500 new pulsars: A full *local* census of radio emitting NSs

- One hour pointings
- 150 MHz optimum frequency
- 20 beams simultaneously
- limited in gl. plane by scattering
- weak nearby MSPs
- Possibly exotic systems

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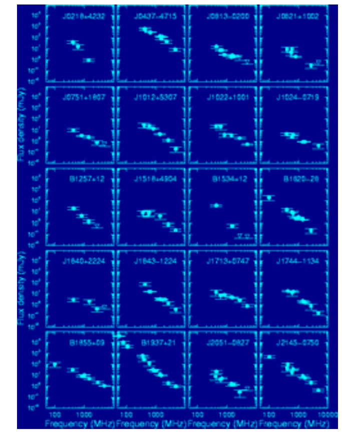
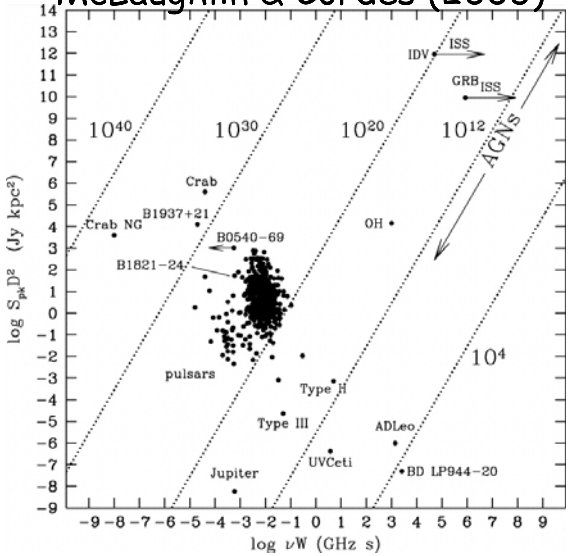
LOFAR: Full census of radio-emitting neutron stars

LOFAR will detect all kinds radio-loud neutron stars:

(Kramer et al. 1999)



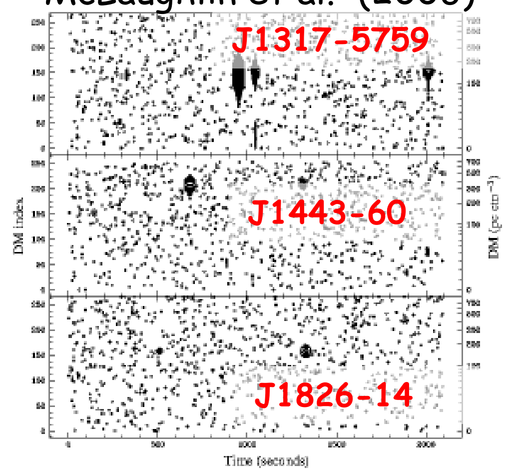
McLaughlin & Cordes (2003)



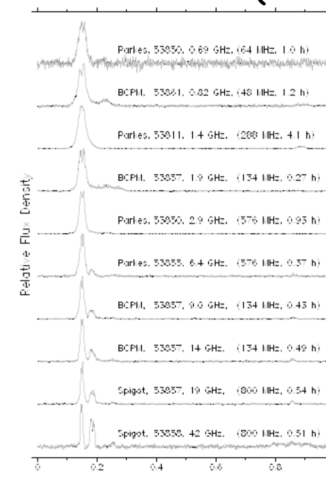
- Geminga-like
- Magnetars
- Steep spectrum (>-3,B0943)
- MSPs (unbroken spectra)
- RRATs
- B1931+24-like sources

Kramer et al. (2006)

McLaughlin et al. (2006)

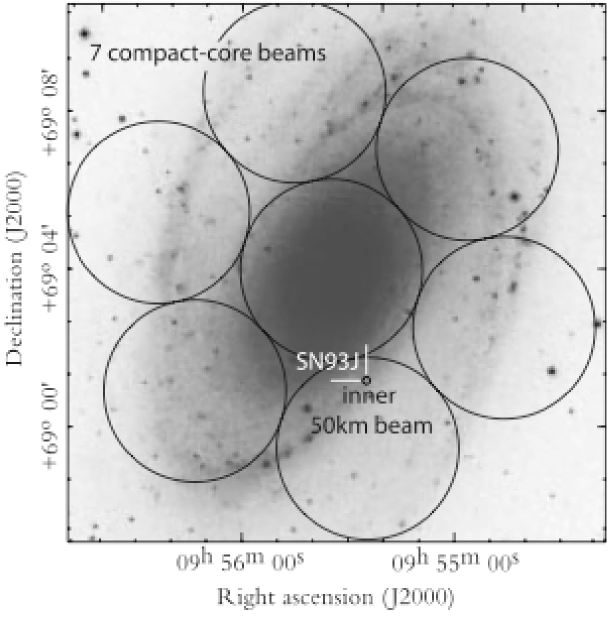


Camilo et al. (2006)



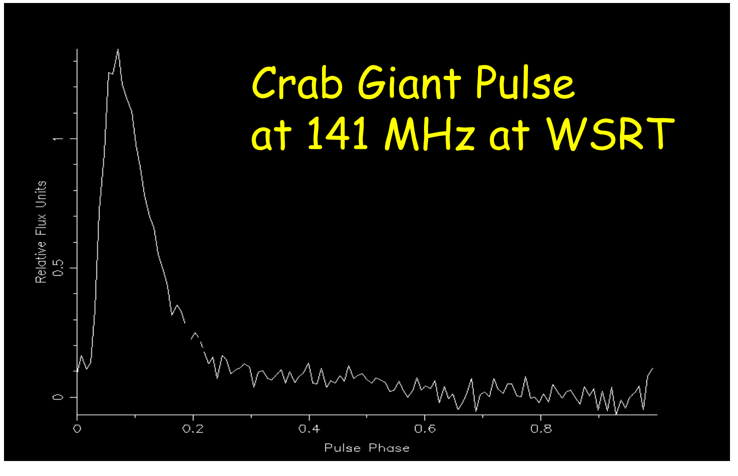
LOFAR: Extragalactic pulsars

van Leeuwen & Stappers (2006)



LOFAR will be sensitive to normal and giant pulse emission from nearby galaxies:

- In M33, 10 hour obsn can detect pulsars with L> 57 Jy kpc^2 , 10 pulsars known
- Brightest could be obs'd out to 1.2 Mpc
- Depending on SI can detect GPs out to 2- 4.5 Mpc



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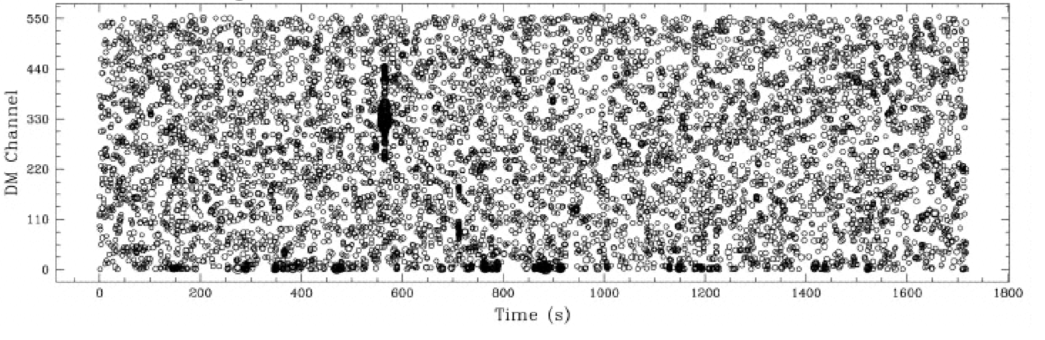
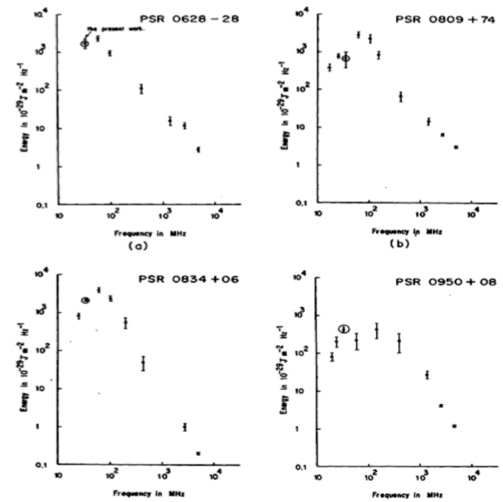
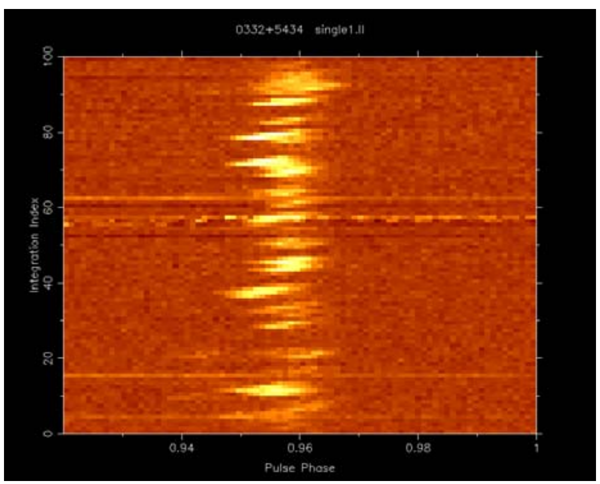


LOFAR: Emission physics

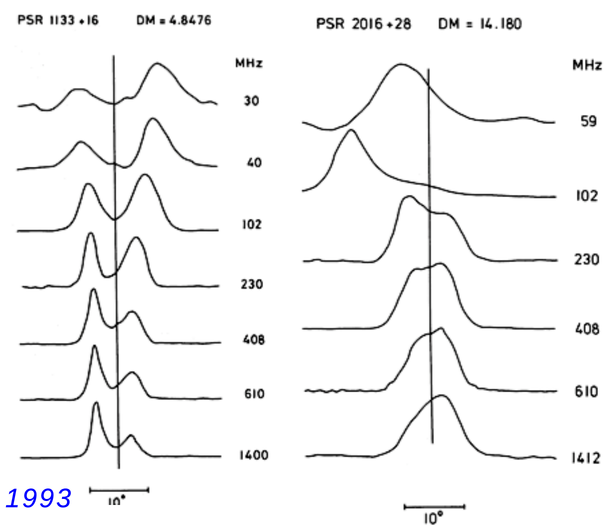
- Average profile evolution (radius-to-frequency mapping, aberration?)
- Pulse spectra (average and single pulses over all LOFAR bands, turn-overs?)
- Low-frequency polarization
- Single-pulse studies from both normal pulsars and millisecond pulsars(!)
- Drifting, nulling, moding etc.



Pulsar Spectra from Deshpande & Radhakrishnan 1992 (34.5 MHz data)



PSR B0329+54 observed with the WSRT at 141 MHz.



PSRs B1133+16 and 2016+28 showing Std. RFM and non-std RFM. Izvekova etal 1993

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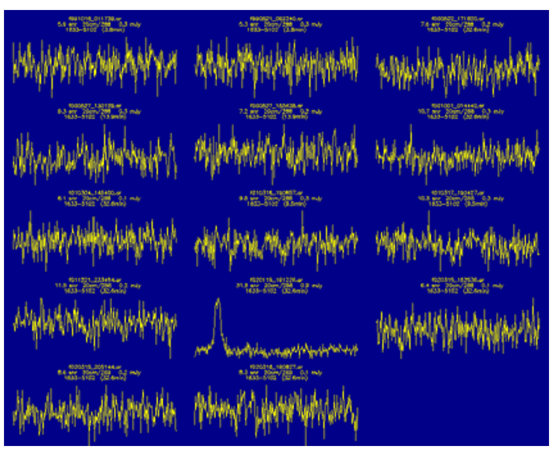
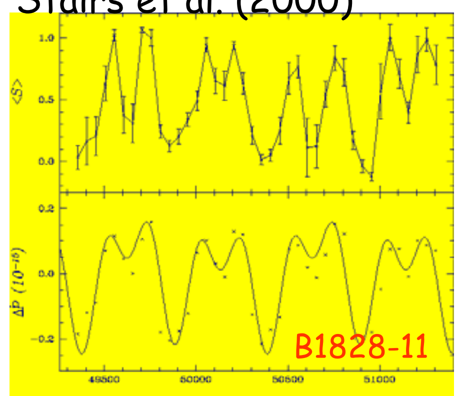
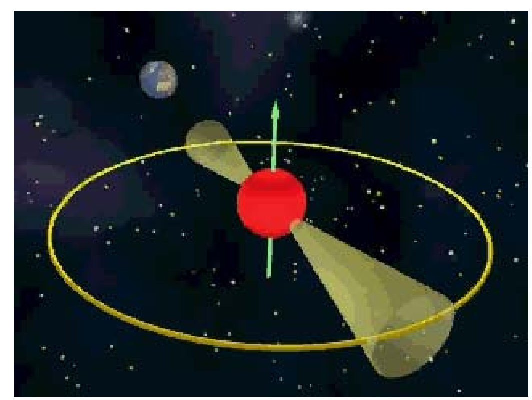
LOFAR: Pulsar monitoring –
ISM, IGM, neutron stars and all that

- Aperture arrays allow to monitoring of many sources
- Measuring and monitoring of DMs, SMs, and RMs
- Large sample to probe local interstellar medium and magnetic field
- Use extragalactic pulsars to study intergalactic medium
- Detect glitches as they happen
- Follow timing-noise of young pulsars, detect free precession
- Sample timescales yet largely unexplored in pulsar astronomy



Stairs et al. (2000)





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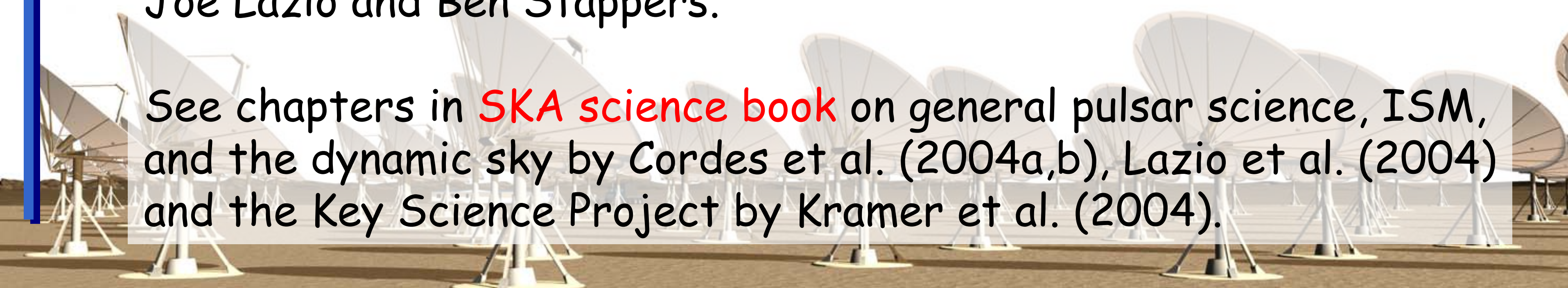
With assistance of Don Backer, Jim Cordes, Simon Johnston, Joe Lazio and Ben Stappers.

See chapters in SKA science book on general pulsar science, ISM, and the dynamic sky by Cordes et al. (2004a,b), Lazio et al. (2004) and the Key Science Project by Kramer et al. (2004).



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The Square-Kilometre-Array

- The biggest telescope ever built: global endevaour (18 countries, so far)
- Tackling Noble-prize science
- Construction 2011-2020, first science by 2014 (10% = Phase I)
- The science case requires:

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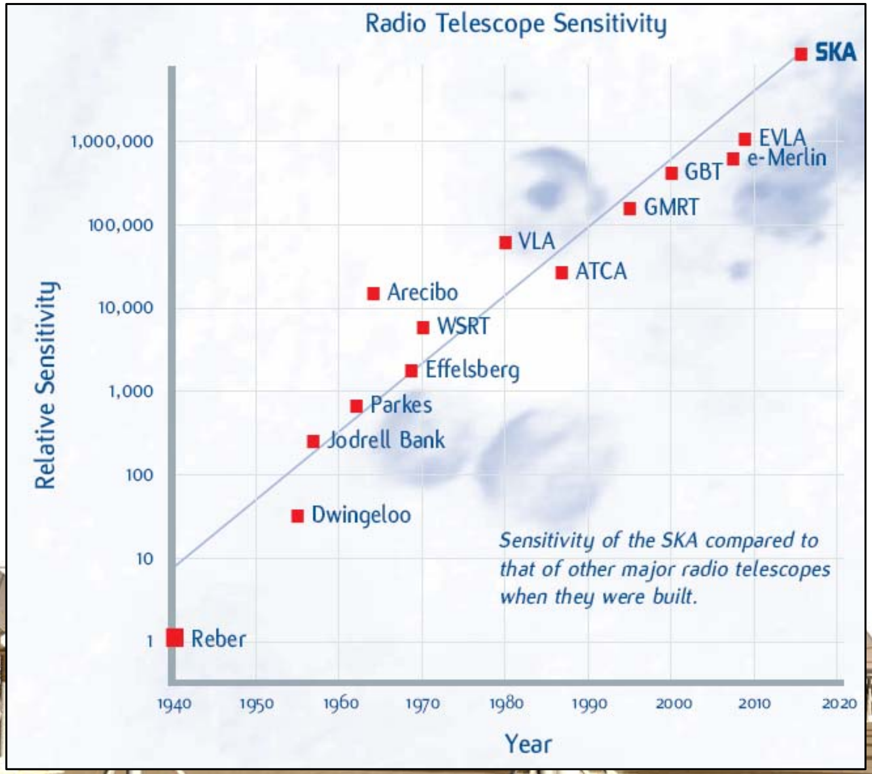

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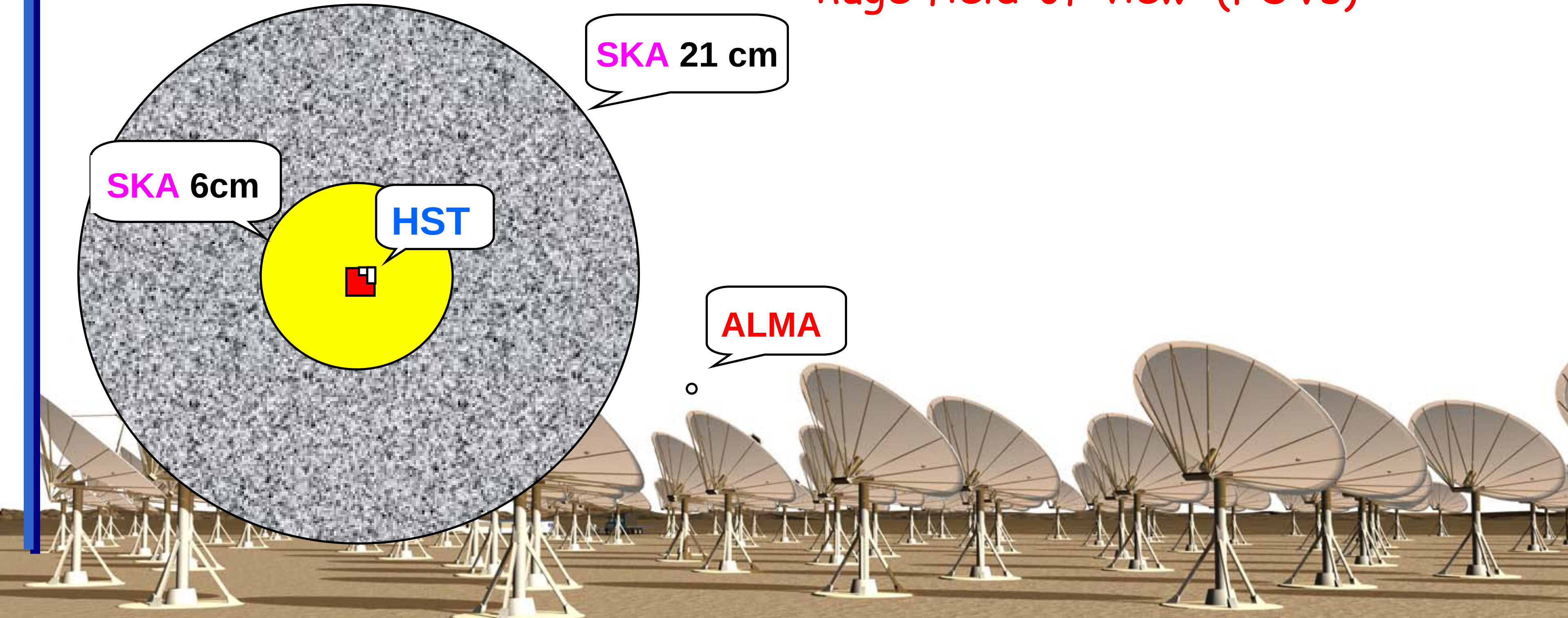

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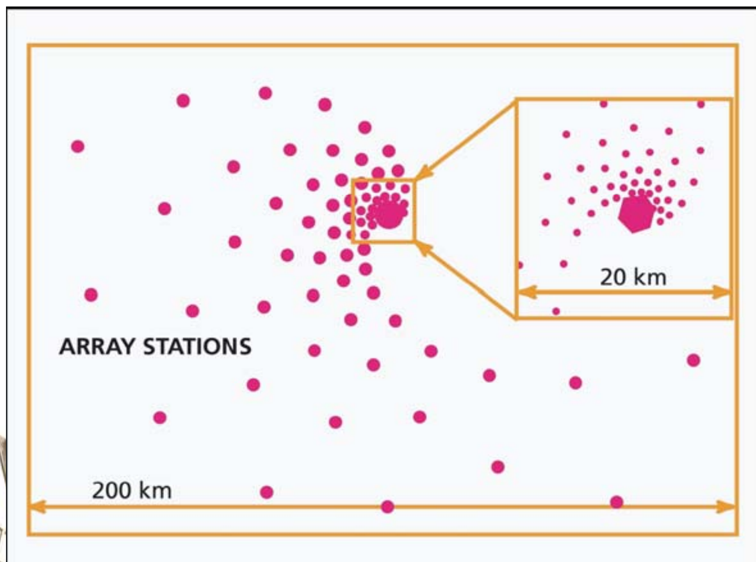
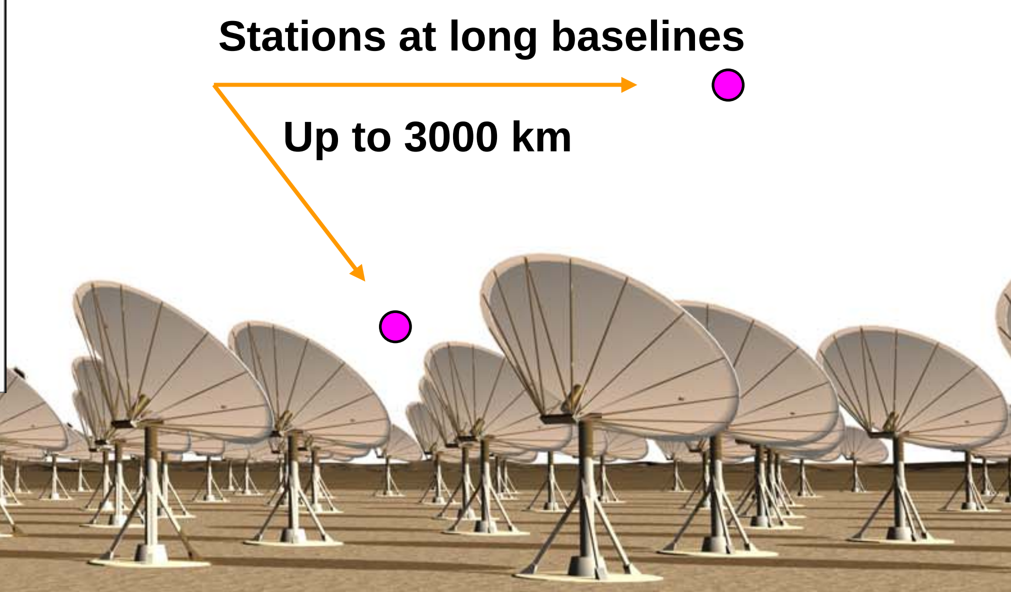
  large spatial resolution





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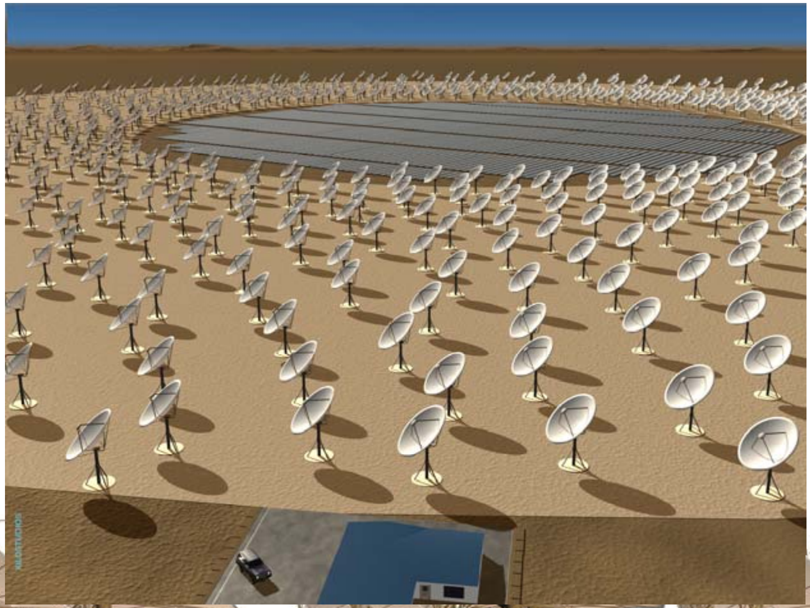
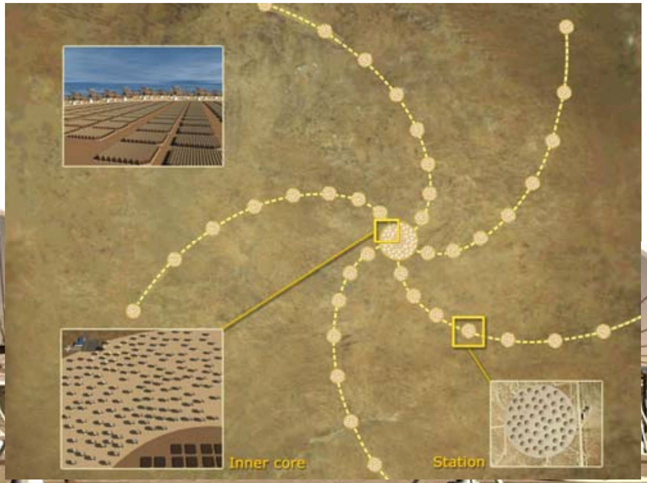
  - gigantic collecting area
  - huge field-of-view (FOVs)
  - large spatial resolution
  - core region and outer stations





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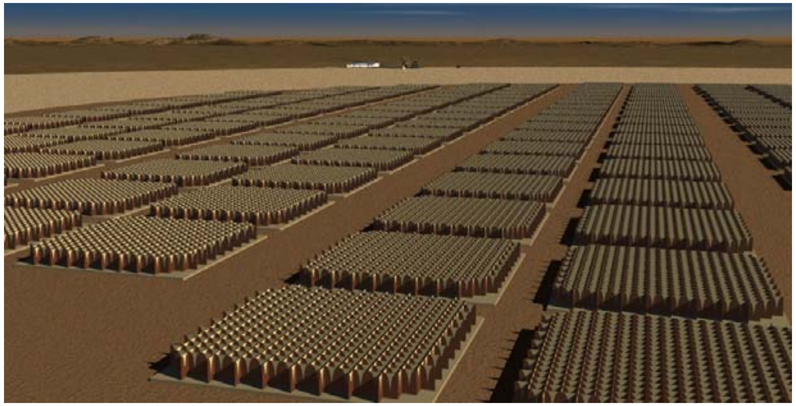
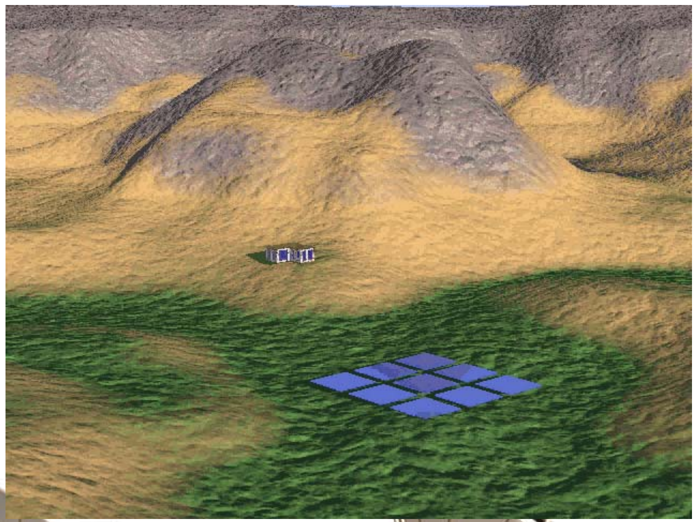


gigantic collecting area
huge field-of-view (FOVs)
large spatial resolution
core region and outer stations
hybrid telescope

The Square-Kilometre-Array

- The biggest telescope ever built
- Tackling Noble-prize science
- Construction 2011-2020, first science by 2014 (10% = Phase I)
- The science case requires:



gigantic collecting area
huge field-of-view (FOVs)
large spatial resolution
core region and outer stations
hybrid telescope
multiple independent FoVs

The SKA: Fundamental questions in physics and astronomy

"What are the basic properties of the fundamental particles and forces?"

Neutrinos, Magnetic Fields, Gravity, Gravitational Waves, Dark Energy

"What constitutes the missing mass of the Universe?"

Cold Dark Matter (e.g. via lensing), Dark Energy, Hot Dark Matter (neutrinos)

"What is the origin of the Universe and the observed structure and how did it evolve?"

Atomic hydrogen, epoch of reionization, magnetic fields, star-formation history……

"How do planetary systems form and evolve?"

Movies of Planet Formation, Astrobiology, Radio flares from exo-planets……

"Has life existed elsewhere in the Universe, does it exist elsewhere now?"

SETI

The SKA: Key Science Projects

Key science selected by international community:

- Strong-field tests of gravity using pulsars & black holes
- Galaxy evolution, cosmology and dark energy
- Probing the dark energy
- The origin and evolution of cosmic magnetism
- The cradle of life
- Exploration of the unknown

Detailed science case published in New Astronomy Reviews, 2004
eds Carilli & Rawlings, Vol 48, 11-12

The SKA: Key Science Project

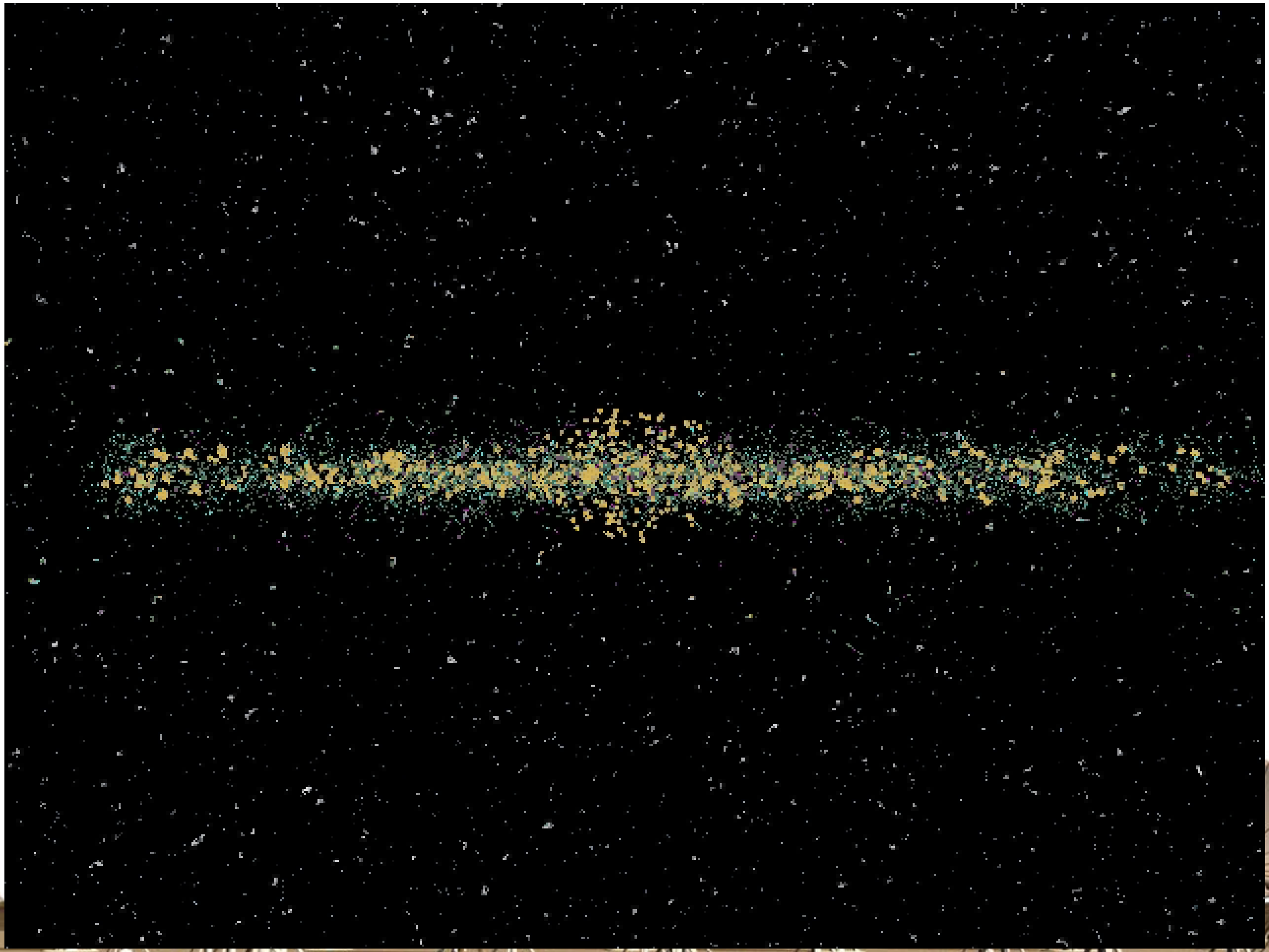
- Strong-field tests of gravity using pulsars & black holes

Find and time pulsars to test description of gravity in the strong field case (pulsar-Black Hole binaries), and to detect gravitational waves

Was Einstein right or
will general relativity eventually fail?
What are the properties of black holes?
Are there still ripples in space-time
from the early Universe?

Galactic Census with the SKA

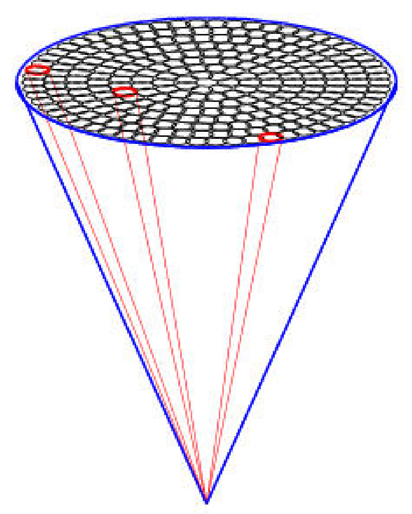
- Find the PSR-BH systems!
- Blind survey for pulsars with the SKA



The Galactic Census

Technical considerations:

- Blind surveys over the entire nominal FoV specification
- Requires ≥ 10^4 individual beams (per FoV)
- Implications of correlator and antenna connects



- **Number of pixels needed to cover FOV:**

  $N_{pix} \sim (b_{max}/D)^2 \sim 10^4 - 10^9$

- **Number of operations:**

  $N_{ops} \sim$ petaops/s

- **Post processing per beam: e.g. standard pulsar periodicity analysis**

Resulting in about: 20,000-30,000 pulsars incl. ~1,000 MSPs!

Birth Rates and Population Numbers

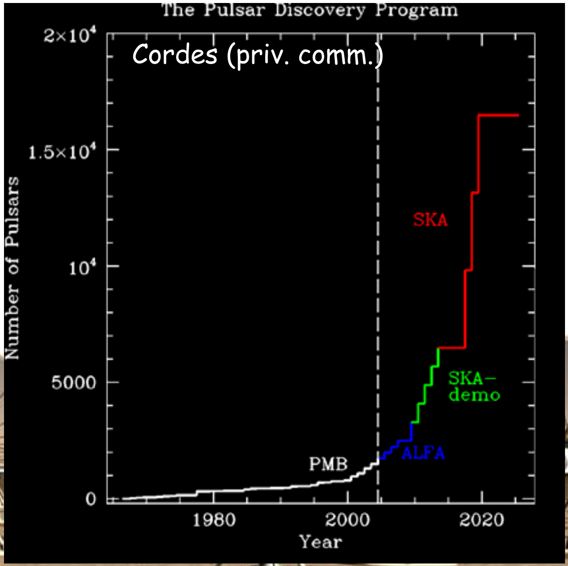
$$N_{\text{detectable}} = f_b \times R \times T_{\text{radio}}$$

f_b = beaming fraction
R = birth rate
T_{radio} = radio emitting lifetime

$\sim 0.2 \times 10^{-2}\,\text{yr}^{-1} \times 10^{7}\,\text{yr}$	$= 2 \times 10^{4}$	canonical pulsars
$\sim 0.2 \times 10^{-4}\,\text{yr}^{-1} \times 10^{9}\,\text{yr}$	$= 2 \times 10^{4}$	MSPs
$\sim 0.2 \times 10^{-4.5\pm0.5}\,\text{yr}^{-1} \times 10^{8}\,\text{yr}$	$= 200 - 2000$	NS – NS binaries
$> 10\% \times$ NS – NS binaries		NS – BH binaries

The SKA has high detection probabilities for most of these objects

$\Rightarrow$ "full Galactic census" of these NS sub- populations



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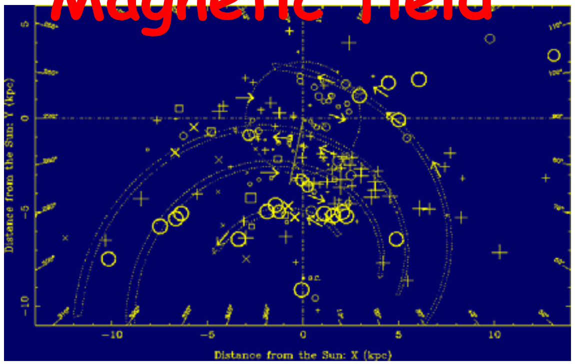
Pulsar Science with the SKA

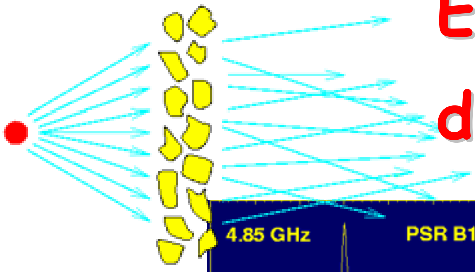
Very wide range of applications:

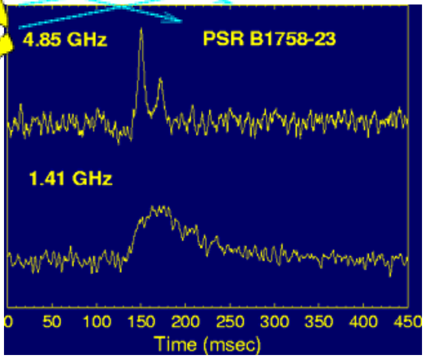
- Galactic probes

Magnetic field

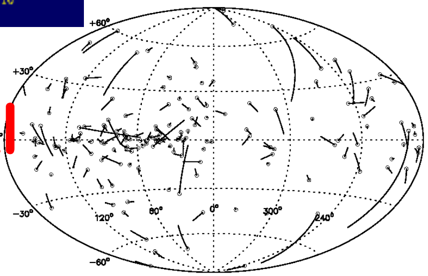


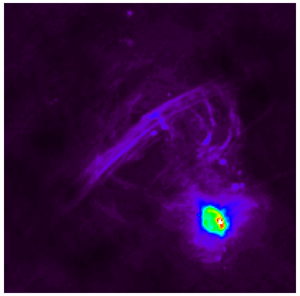
Electron distribution





Galactic potential





Galactic Centre

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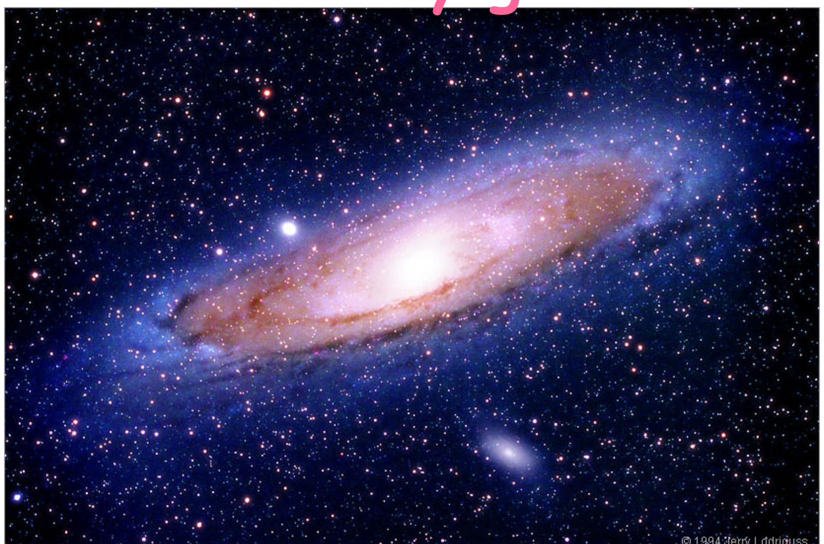
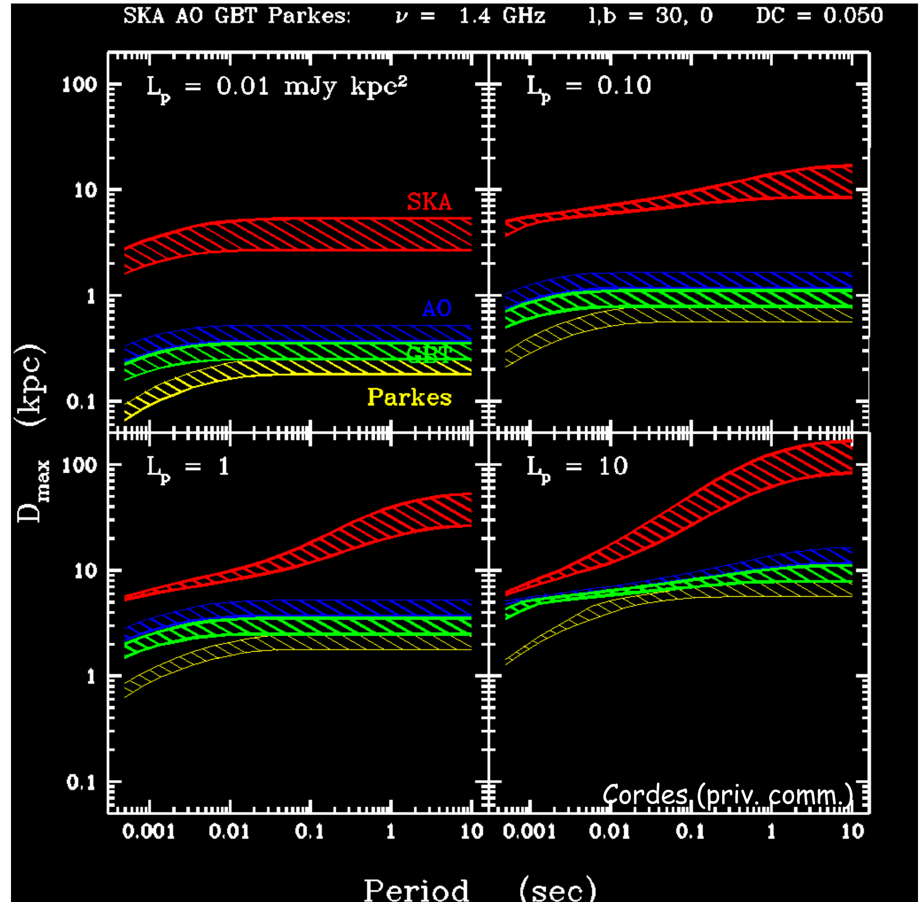
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars

Search nearby galaxies!



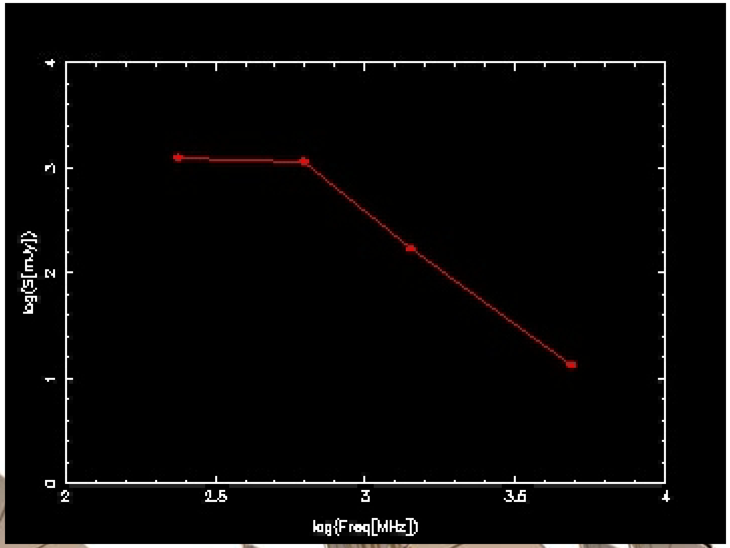


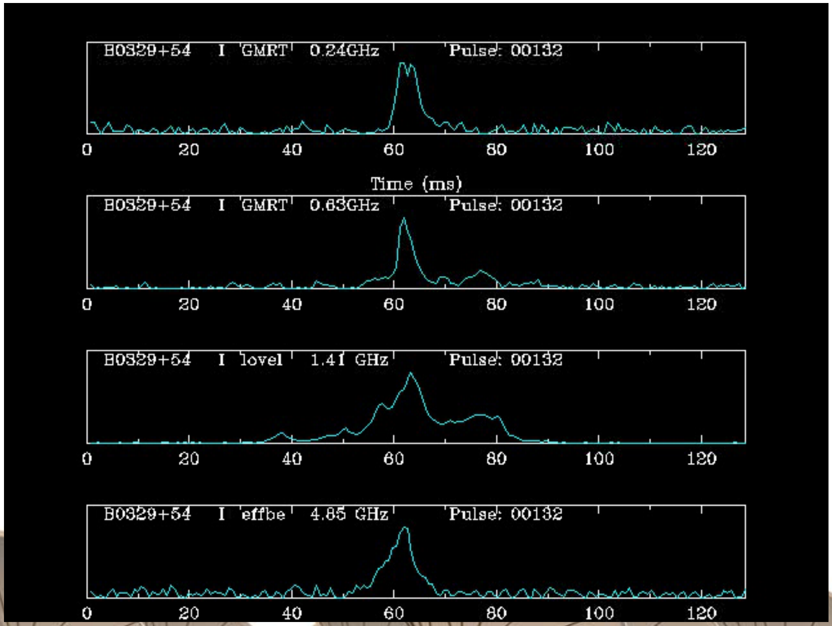
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics

Kramer et al. (2004)

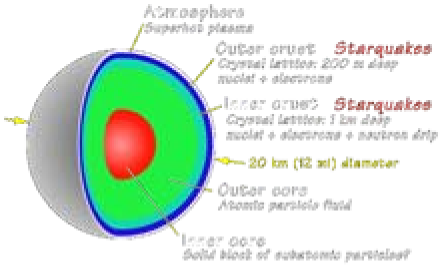


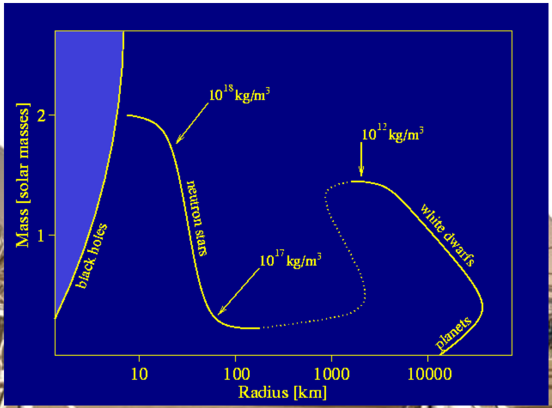


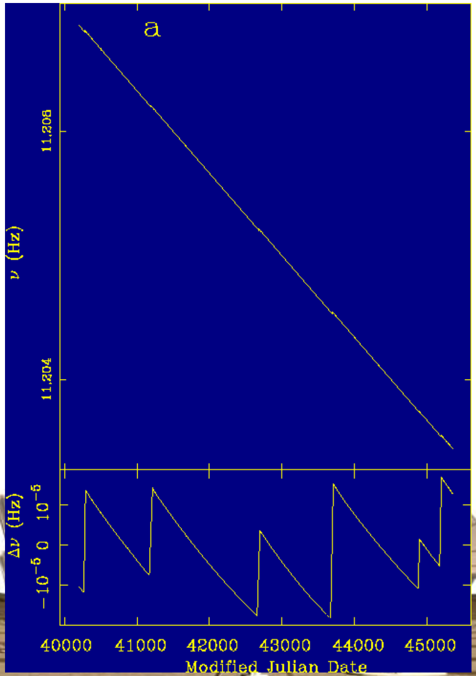
Pulsar Science with the SKA

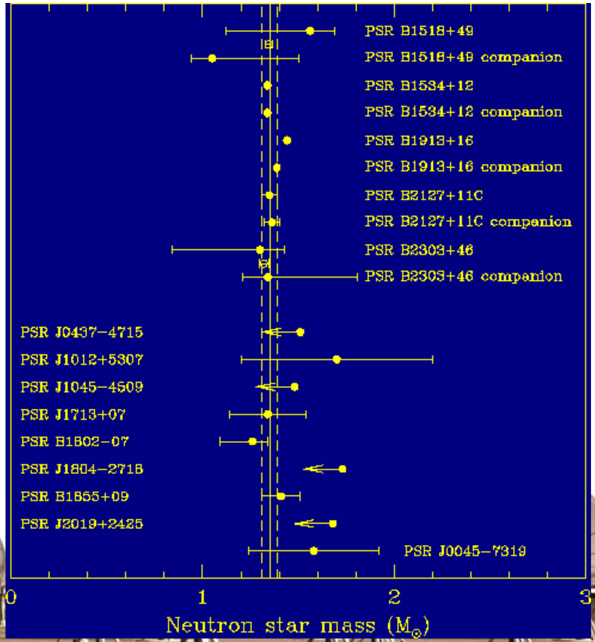
Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics





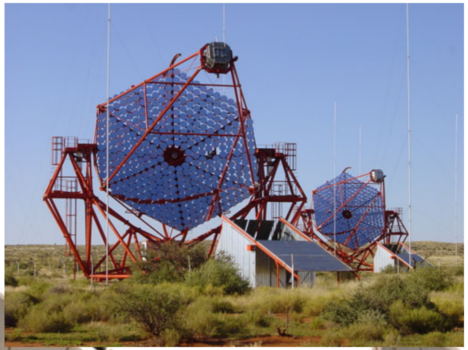




Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics
- Multi-wavelength studies



Pulsar Science with the SKA

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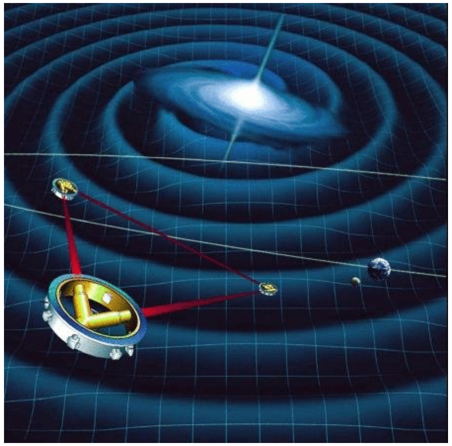
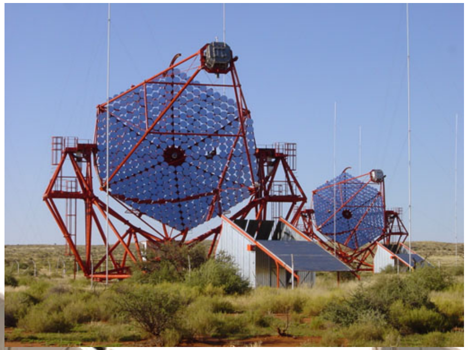


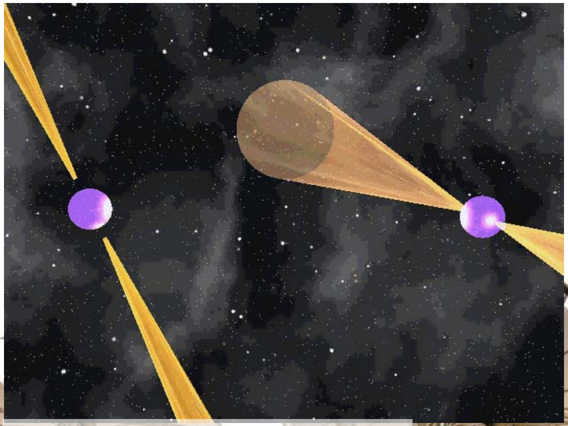


Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics
- Multi-wavelength studies
- Exotic systems: planets
  millisecond pulsars
  relativistic binaries
  double pulsars
  PSR-BH systems

3.Holy Grail: PSR-BH



Double Pulsars

Planets

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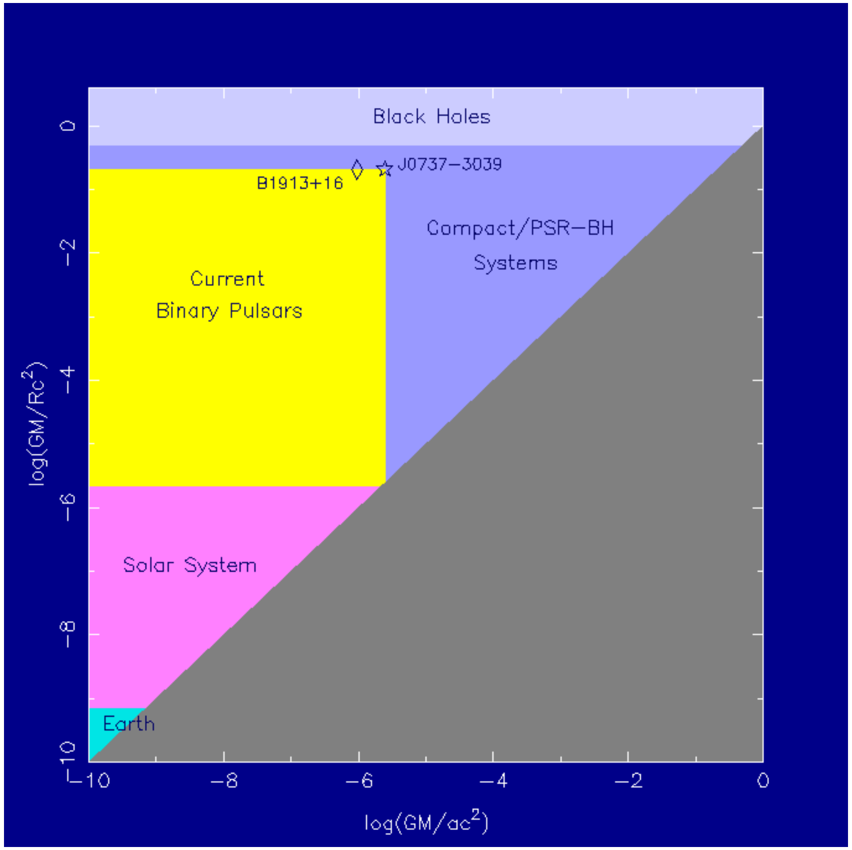
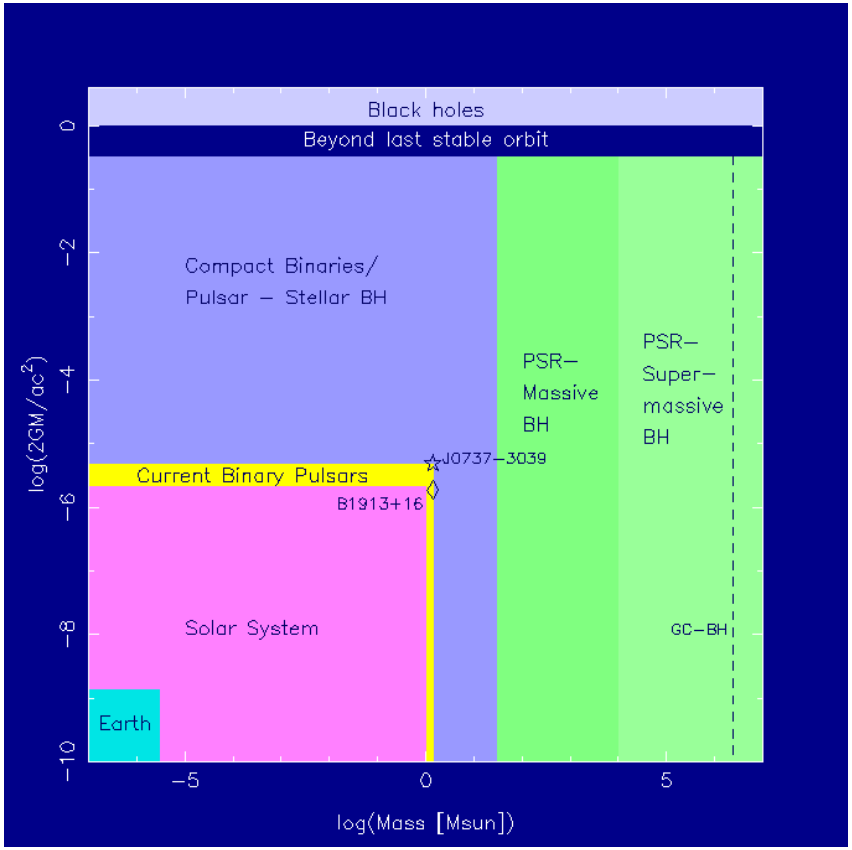
Pulsar Science with the SKA

Very wide range of applications:

- Galactic probes
- Extragalactic pulsars
- Relativistic plasma physics
- Extreme Dense Matter Physics
- Multi-wavelength studies
- Exotic systems
- Gravitational physics:
  - Ultra-strong gravity
  - BH properties
  - Cosmological Gravitational Wave Background

SKA Key Science: Was Einstein right?





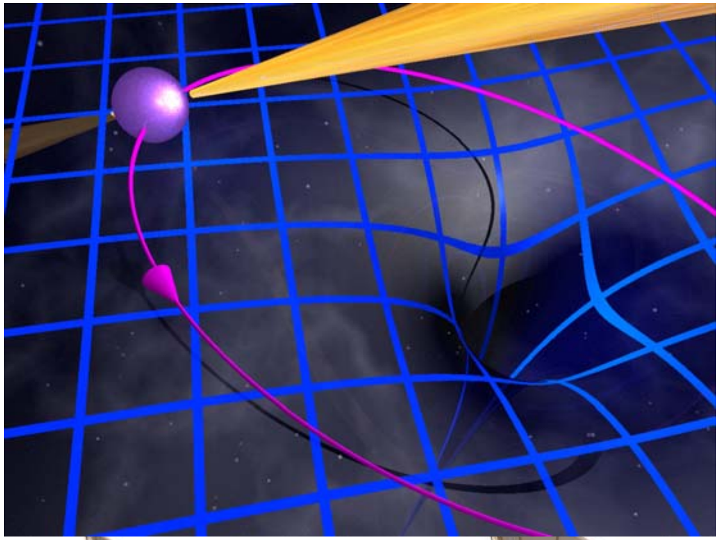
We fill space by probing BH properties with pulsars:

- precise measurements
- no assumptions about EoS or accretion physics
- test masses still well separated and not deformed as close to merger

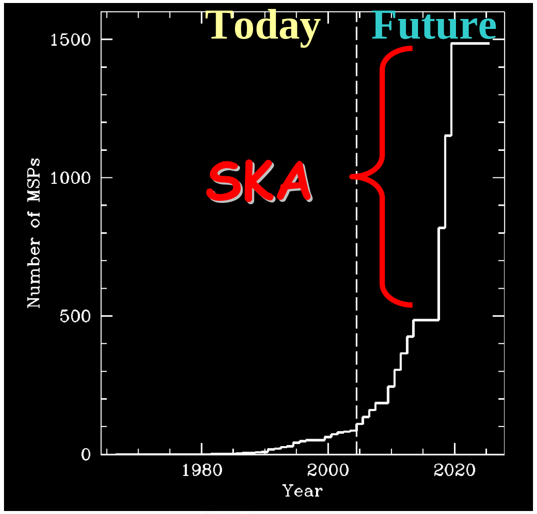
The SKA: Key Science Project

• Strong-field tests of gravity using pulsars & black holes

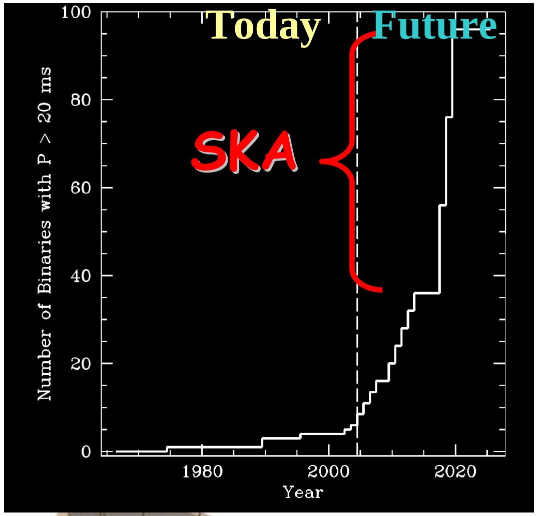
Find and time pulsars to test description of gravity in the strong field case (pulsar-Black Hole binaries), and to detect gravitational waves



Millisecond Pulsars



Relativistic Binaries



• Find pulsars around stellar BH and in Galactic Centre
• Measure BH properties: masses, spin & quadrupole moment
• Testing GR description of BHs, such as
  Cosmic Censorship Conjecture & No-hair theorem

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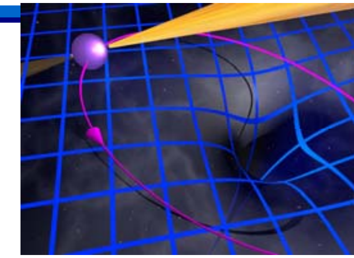
Cosmic Censorship Conjecture



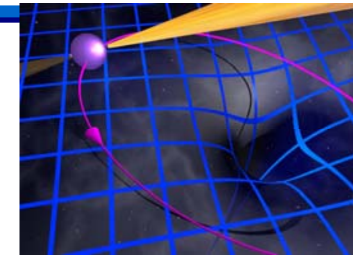
- For all compact massive, BH-like objects, we'll be able to measure spin χ very precisely
- In GR, for Kerr-BH we expect: $\chi \leq 1$
- But if we measure

$\chi > 1 \Leftrightarrow$ Event Horizon vanishes
$\Leftrightarrow$ Naked singularity!

Test of "Cosmic Censorship Conjecture" (Penrose 1969)

All singularities are
hidden within Event Horizon of BH!
They cannot seen by outside world, i.e.
No "Naked Singularities" allowed!

Black Hole properties



Black Hole spin:

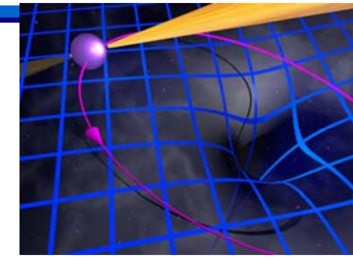
- Astrophysical black holes are expected to rotate

$$\chi \equiv \frac{c}{G}\frac{S}{M^2}$$

S = angular momentum

- Result is relativistic spin-orbit coupling
- Visible as a precession of the orbit:
  Measure higher order derivatives of secular changes in semi-major axis and longitude of periastron See Wex & Kopeikin (1999)
- Not easy! It is not possible today!
- Requires SKA sensitivity!

Black Hole properties



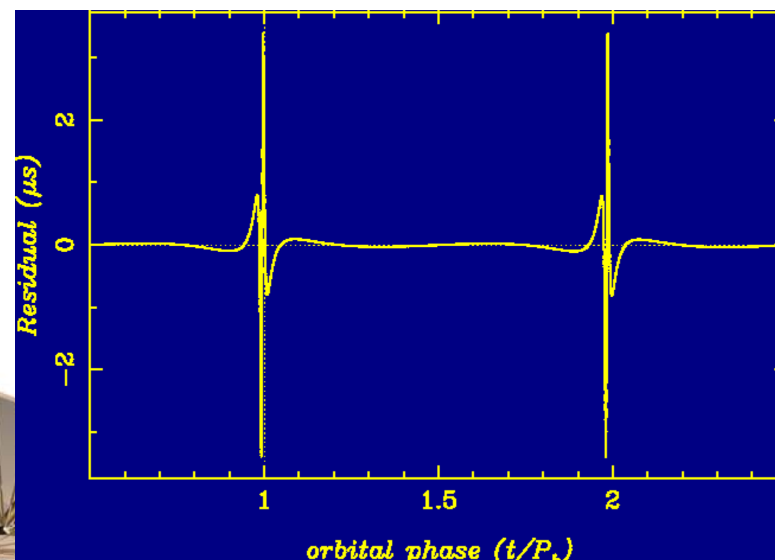
Black Hole spin:

- Spinning black holes are oblate

$$q \equiv \frac{c^4}{G^2}\frac{Q}{M^3}$$

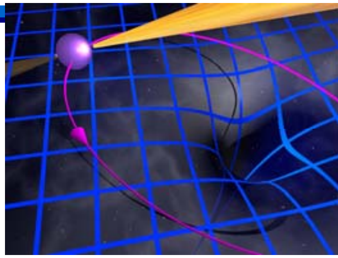
Q = quadrupole moment

- Result is classical spin-orbit coupling
- Visible as **transient signals in timing residuals**
- Even more difficult!
- Requires SKA!



Wex & Kopeikin (1999).

No-hair theorem



- We will try to measure Black Hole quadrupole moment q
- Like in Newtonian physics, one expects relationship between χ and q
- In GR, this relationship is very simple
- For Kerr-BH we expect:

$$q = -\chi^2$$

It reflects "no-hair" theorem:

The BH has lost all information about Collapsed progenitor star, but an astrophysical (uncharged) BH is fully described by its mass and spin!

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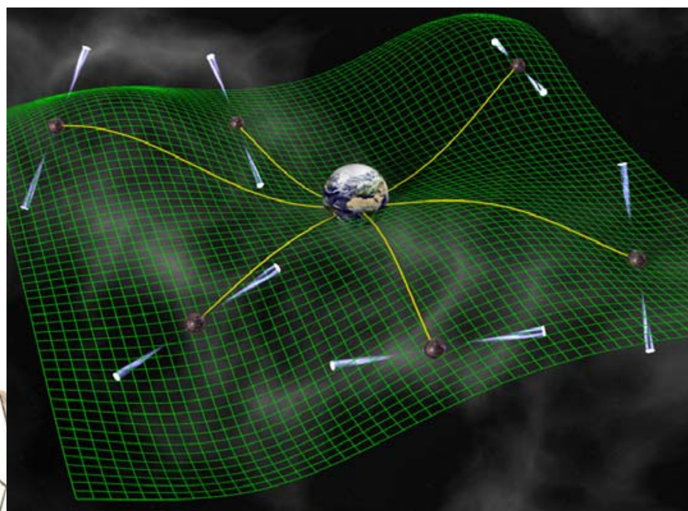
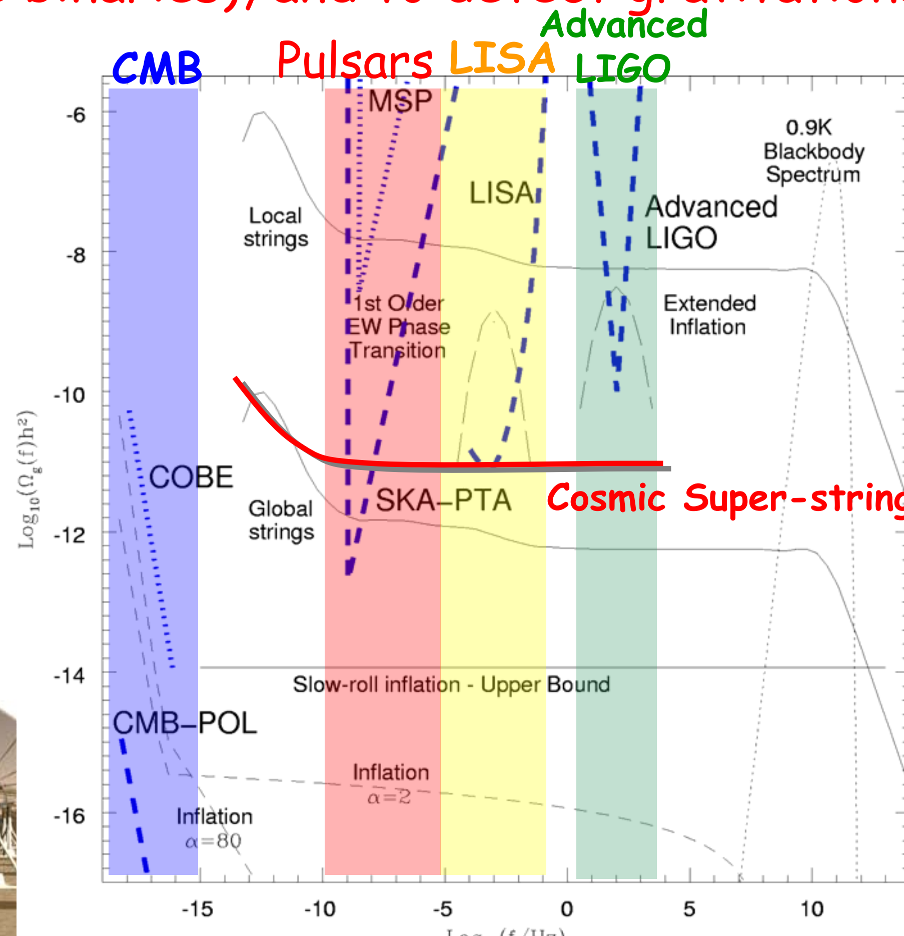
The SKA: Key Science Project

- Strong-field tests of gravity using pulsars & black holes

Find and time pulsars to test description of gravity in the strong field case (pulsar-Black Hole binaries), and to detect gravitational waves

Pulsar Timing Array:





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Precision Pulsar Timing

- **Fast(!) sampling:** 1 μs (or faster)
- **High sensitivity:** Wide bandwidth (20-50%), polarization
- **Repetition:** One observation per source every 2 weeks
- **Polarisation purity:** Pulse changes if not very well calibrated
- **Interstellar weather:** Multiple-frequencies, ideally 2-3 GHz
- **Pulse jitter:** Stabilization time scale vs. S/N ratio

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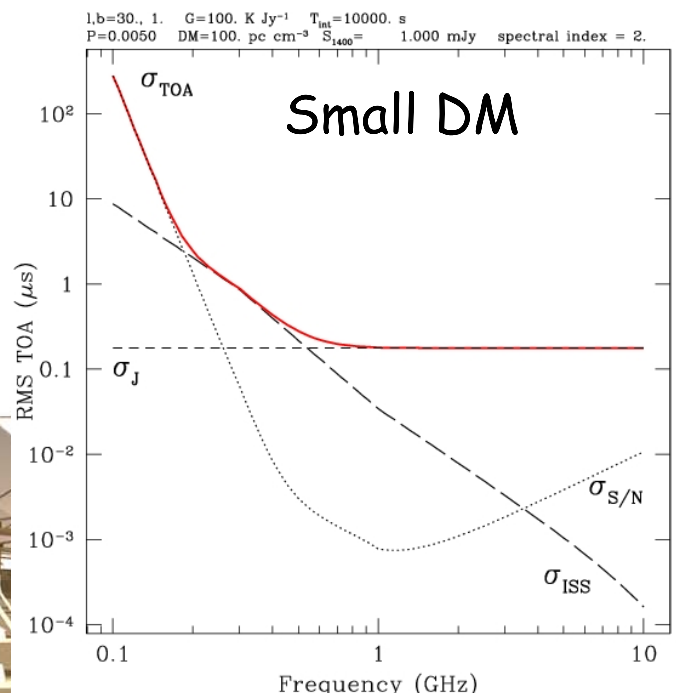

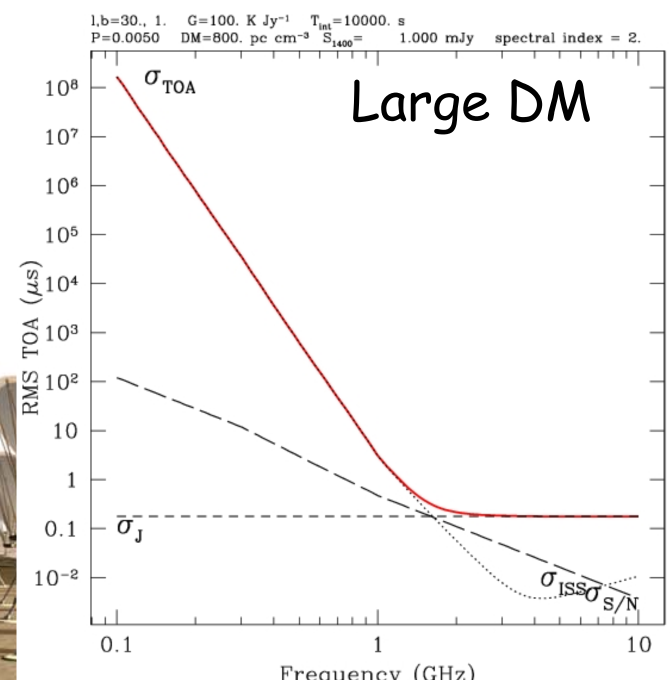

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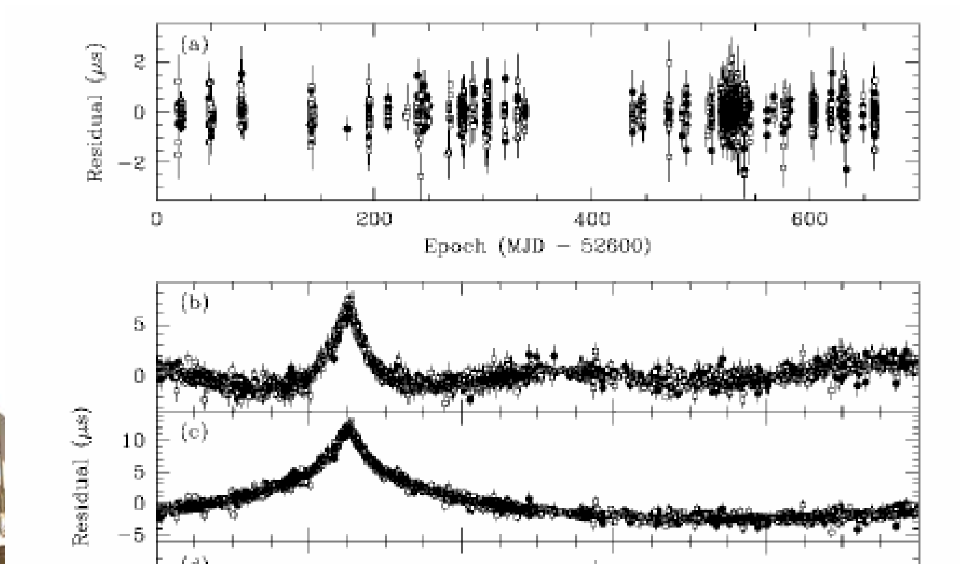


MSP J1909-3744 P=3 ms + WD

Jacoby et al. (2005)

Weighted σ_{TOA} = 74 ns

Precision Pulsar Timing

- Fast(!) sampling: 1 μs (or faster)
- High sensitivity: Wide bandwidth (20-50%), polarization
- Repetition: One observation per source every 2 weeks
- Polarisation purity: Pulse changes if not very well calibrated
- Interstellar weather: Multiple-frequencies, ideally 2-3 GHz
- Pulse jitter: Stabilization time scale vs. S/N ratio

The problem: How to time 20,000-30,000 pulsars?

Integration time = max(radiometer eqn, stabilization timescale)
> 5min, typically

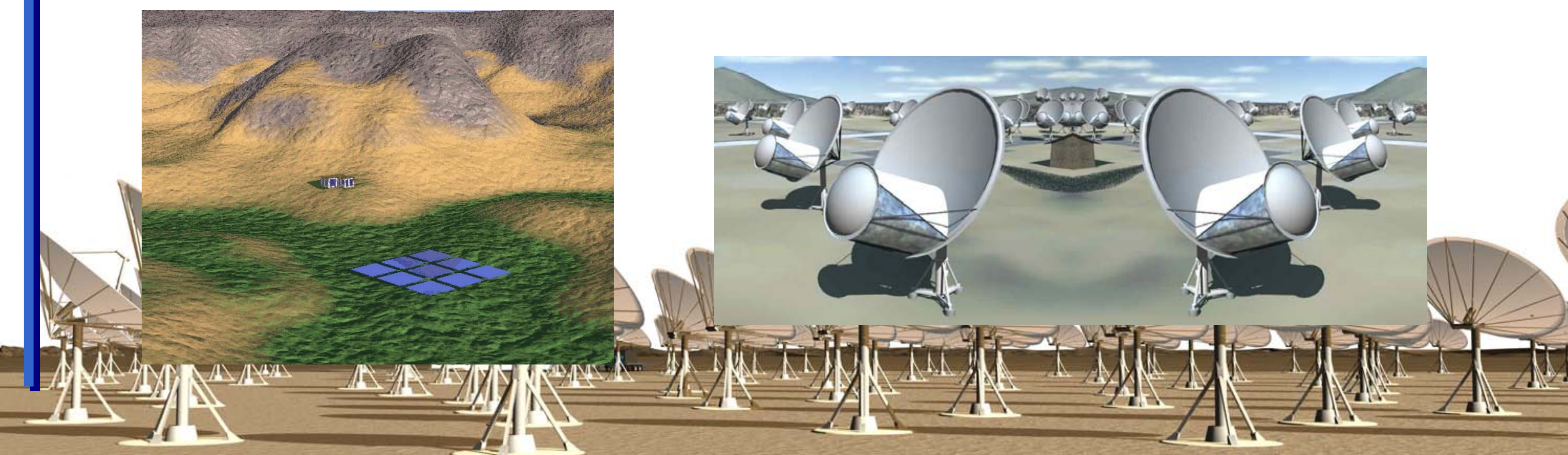
Hence, 20,000 psrs x 5 min = 70 days!

But required every 2 weeks or less!

How to time 20,000-30,000 pulsars?

Possible solutions:

- Efficient “weeding out” process (e.g. using VLBI)
- Multiple FoVs with many independent pencil beams
- Huge FoV with many independent pencil beams
- Sub-arraying (trading sensitivity for beams)
- Combination of the above?



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- Efficient "weeding out" process (e.g. using VLBI)
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- Combination of the above?

Will any of these methods work?

Also:

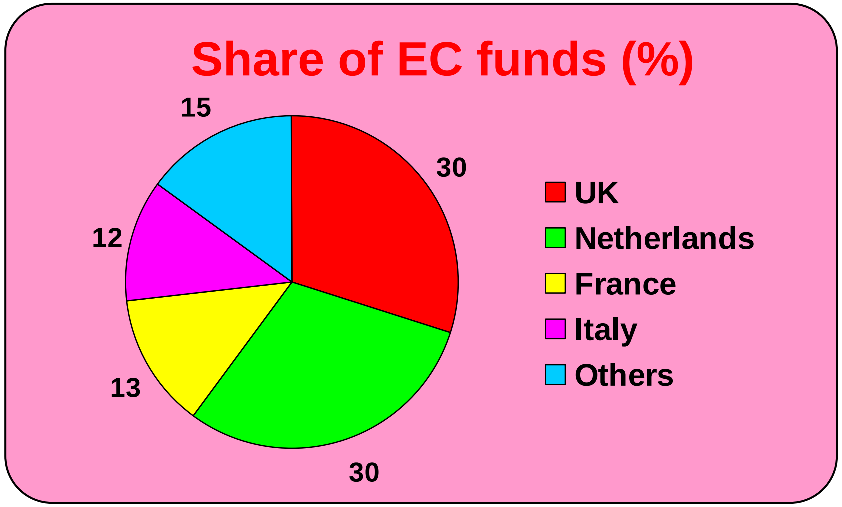
verify expectation that timing precision scales as expected
If necessary develop new techniques…

Simulations required!! Done as part of SKADS!

SKADS & UK-SKADS

A 38M€ FP6 program
(incl. 10.44M€ EC) to:

- Demonstrate Technological Readiness
- Demonstrate Scientific Readiness
- Target costing issues



EU SKADS

- FP6 initiative
- Consortium of 29 institutions
- Total funding is €38m
- EC funding of €10.44m
- Commence October 2005
- Results by 2009!

UK SKADS

- 6 institutions
- Total project £7.6m
- EC contribution £2m (€3m)
- Key science and tech. projects
- Strong 'technical triangle'

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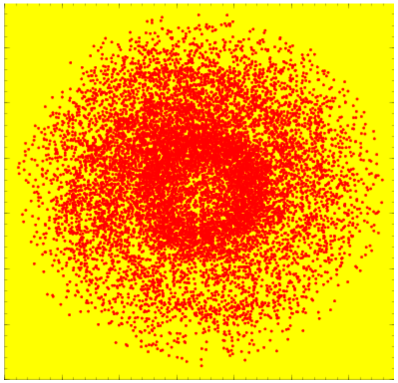
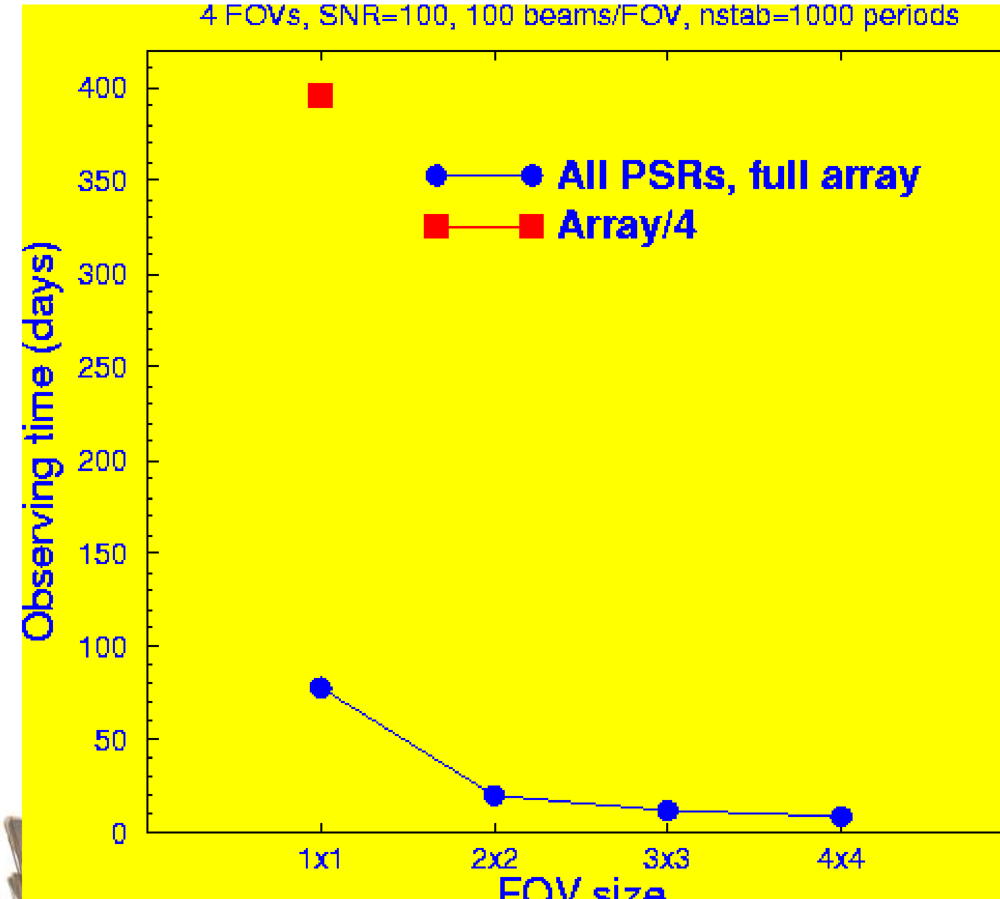
Initial Simulation Results

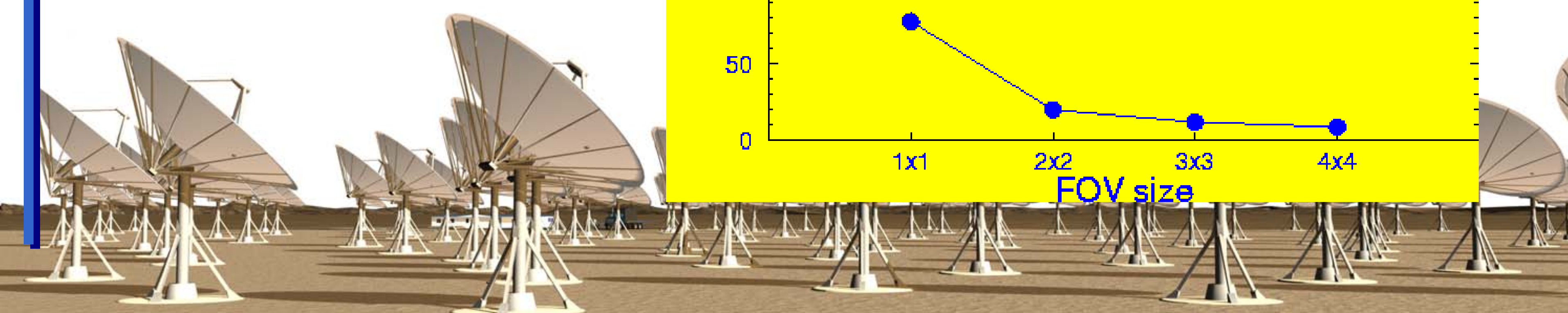
Simulated Population: ➡ **About 12,000 pulsars, ~1300 MSPs**



Needs improvement...



Required time for one(!) timing point:



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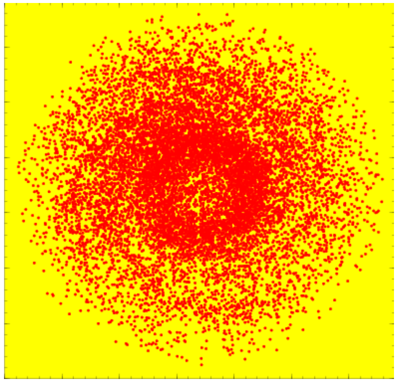

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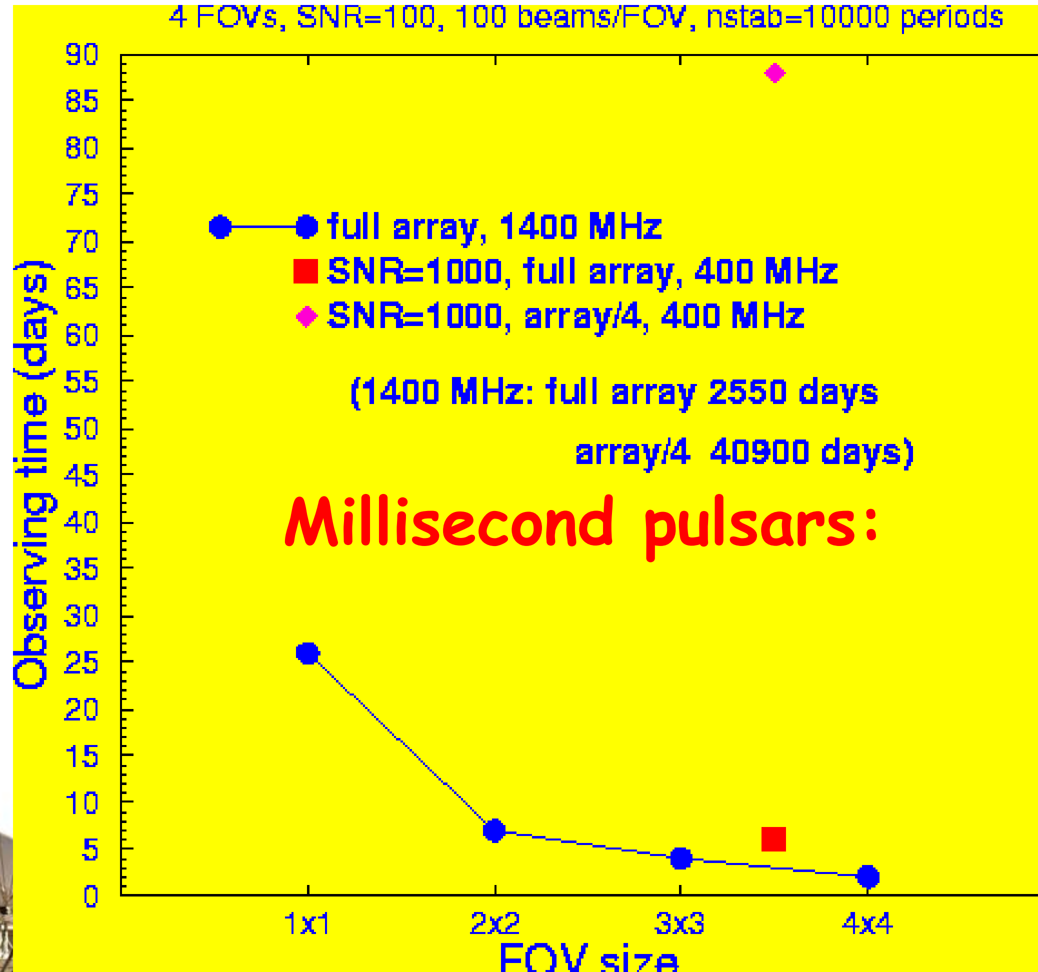
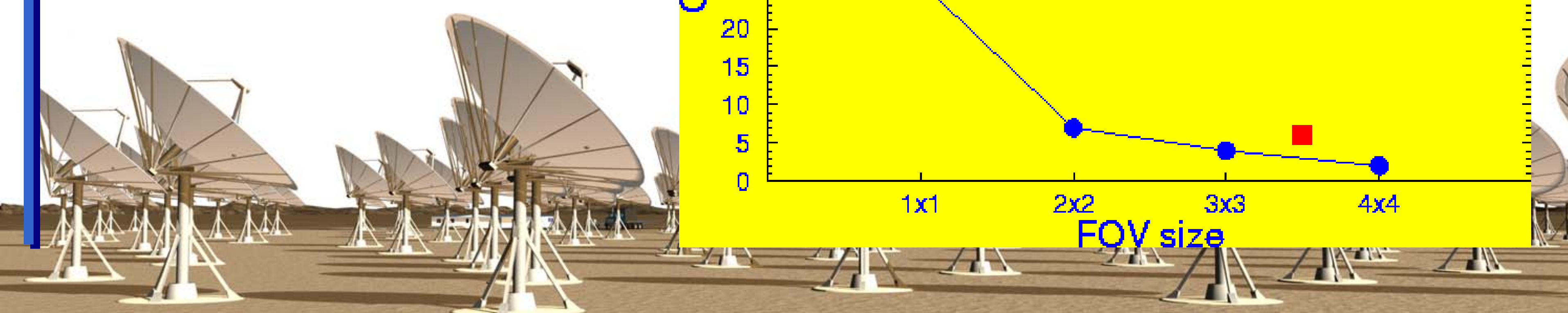
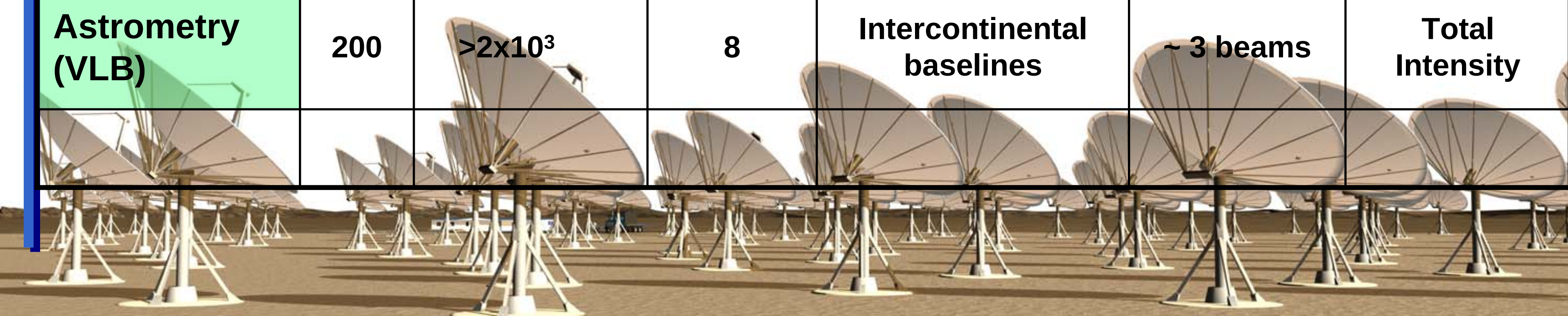




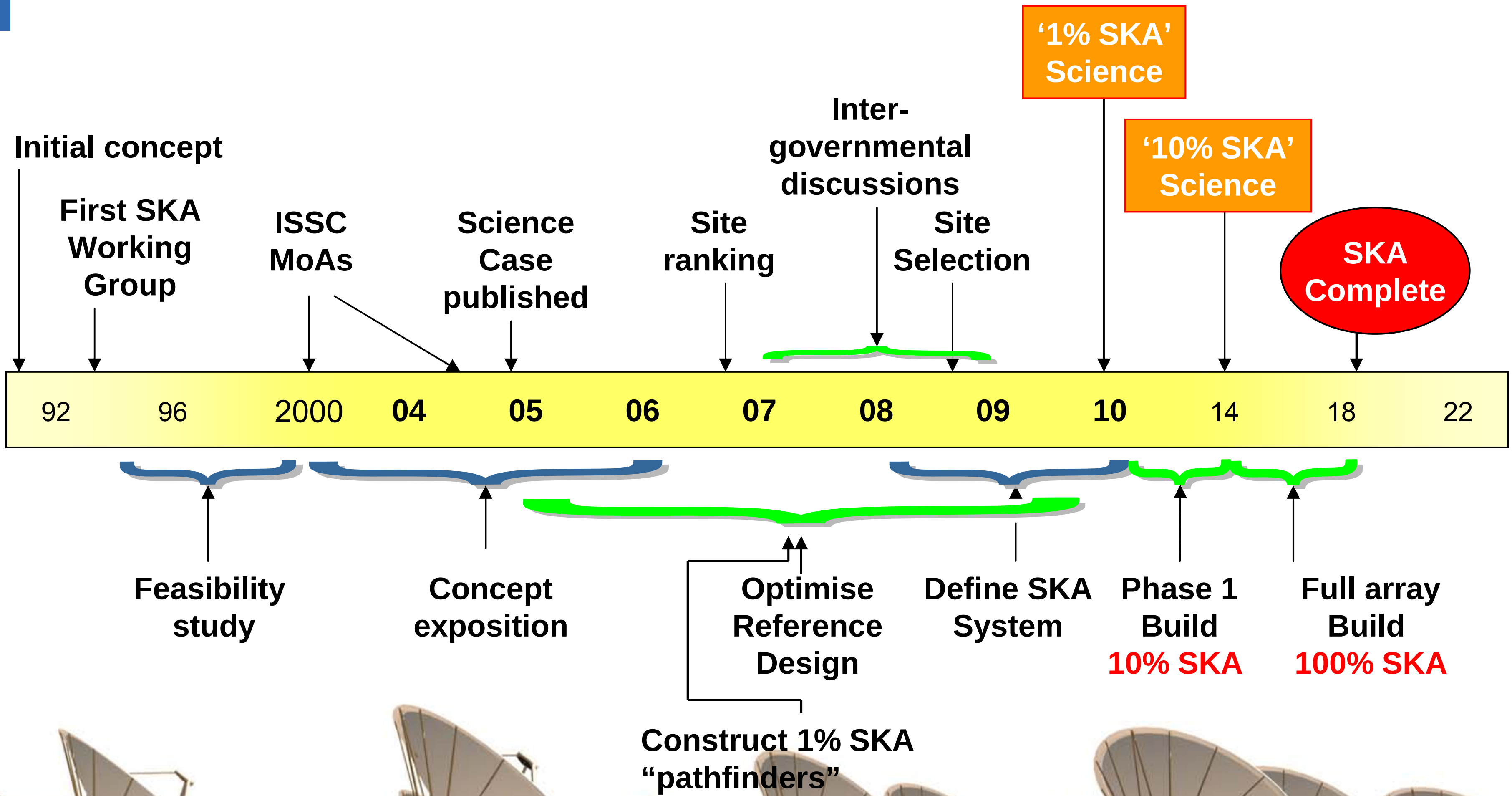
SKA Specifications Summary for Fundamental Physics from Pulsars

	Required Specification					
Topic	Δt (μs)	A/T (m^2/K)	ν_{max} (GHz)	Configuration	FOV Sampling	Polarization
Searching	**50**	**2×10^4 f_c**	**2.5 15 (GC)**	**Core with large f_c**	**full**	**Total Intensity**
Timing	**1**	**2×10^4**	**15**	**Non-critical if phasable**	**100 beams/deg^2**	**Full Stokes; -40 dB isolation**
Astrometry (VLB)	**200**	**$>2\times10^3$**	**8**	**Intercontinental baselines**	**~ 3 beams**	**Total Intensity**



The University of Manchester
Jodrell Bank Observatory

SKA Timeline



"Pathfinders" are world-class facilities in their own right!

It will be a lot of fun!!