Science Requirements for the SKA Dish Sub-system

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Government sponsorship acknowledged.

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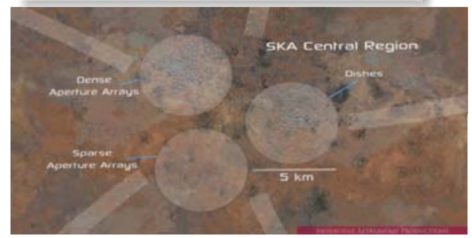
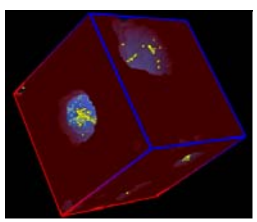
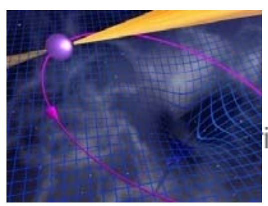
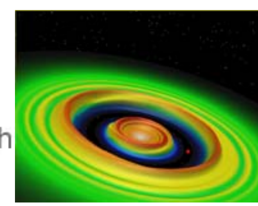
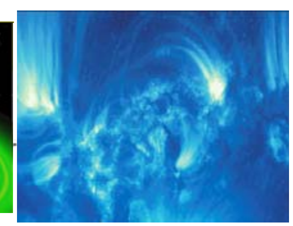
Square Kilometre Array

The Global Radio Wavelength Observatory



- Originally: “Hydrogen telescope”
  - Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$
- SKA science much broader
  - ⇒ Multi-wavelength, multi-messenger
- On-going technical development
  - ⇒Importantly in the Dish Sub-system
- International involvement

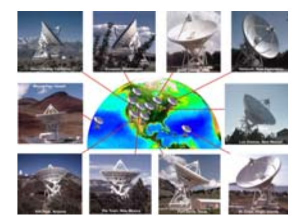



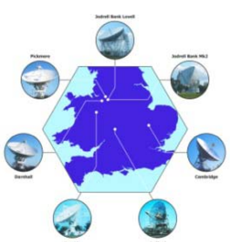
Dishes and SKA Pathfinding

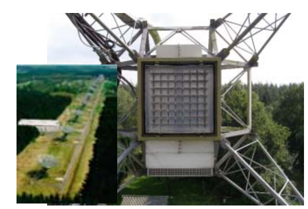
Radio astronomy has been making use of dishes for a **long** time

- Experience leads to high expectations
- Dish-based Precursors and many pathfinders in existence or under construction

  Provide valuable experience





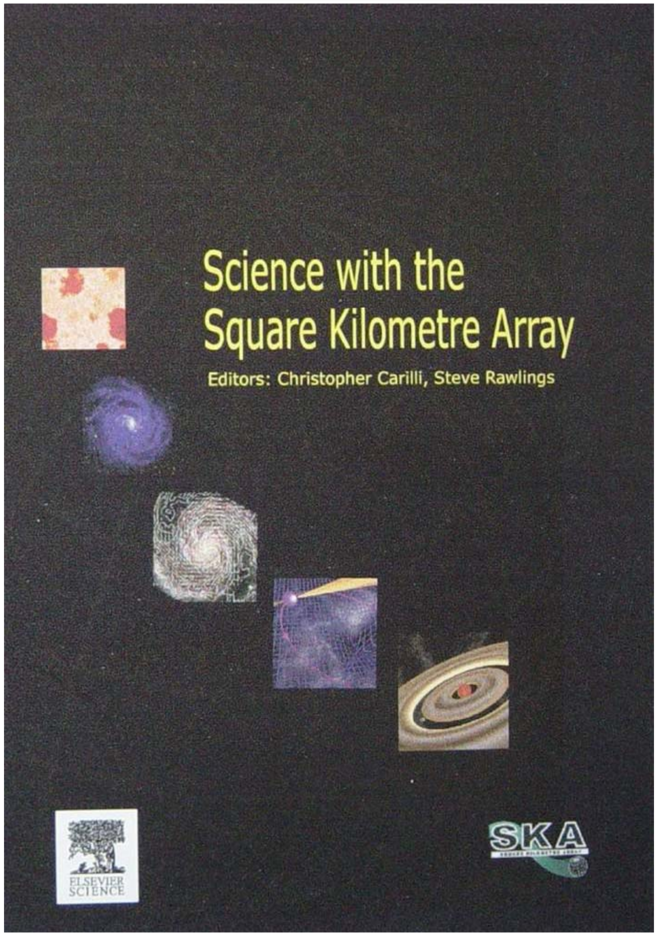


SKA Key Science

International working group

- Strong-field Tests of Gravity with Pulsars and Black Holes
- Galaxy Evolution, Cosmology, & Dark Energy
- Emerging from the Dark Ages
- The Cradle of Life & Astrobiology
- The Origin and Evolution of Cosmic Magnetism

With design philosophy of *Exploration of the Unknown*



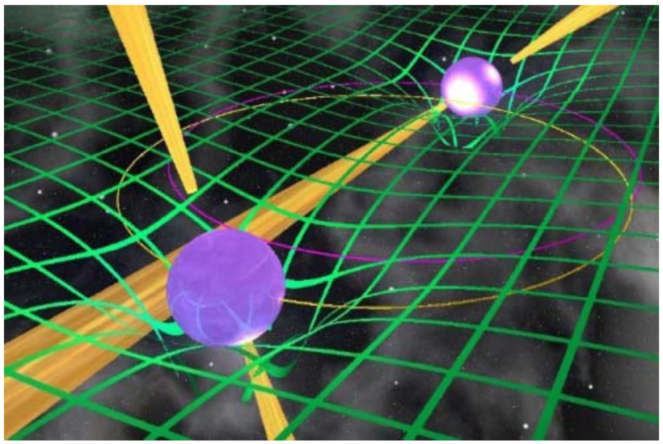
Science with the Square Kilometre Array (2004, eds. Carilli & Rawlings, *New Astron. Rev.*, **48**)

Key Science and Key Technology

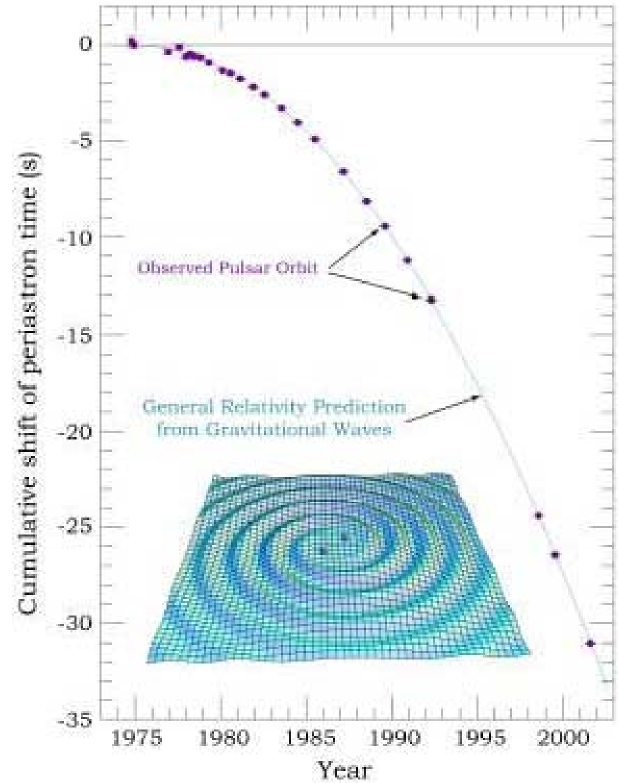
Key Science	Dishes in Phase 1	Dishes in Phase 2
Strong-field Tests of Gravity with Pulsars and Black Holes	✔	✔
Galaxy Evolution, Cosmology, & Dark Energy	✔	✔
Emerging from the Dark Ages	?	✔
The Cradle of Life & Astrobiology	?	✔
The Origin and Evolution of Cosmic Magnetism	✔	✔

Some aspect of all Key Science Programs will require a dish array sub-system to address.

Did Einstein Have the Last Word on Gravity?

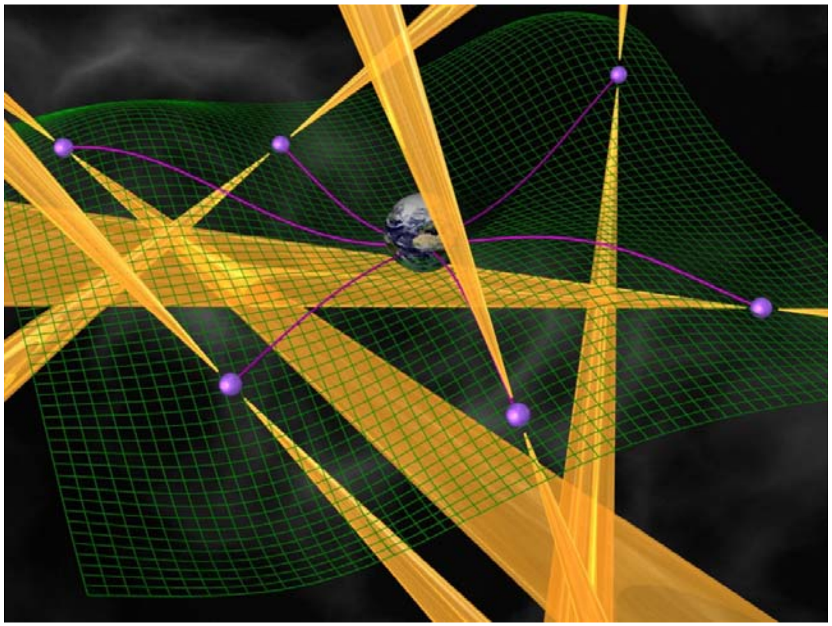


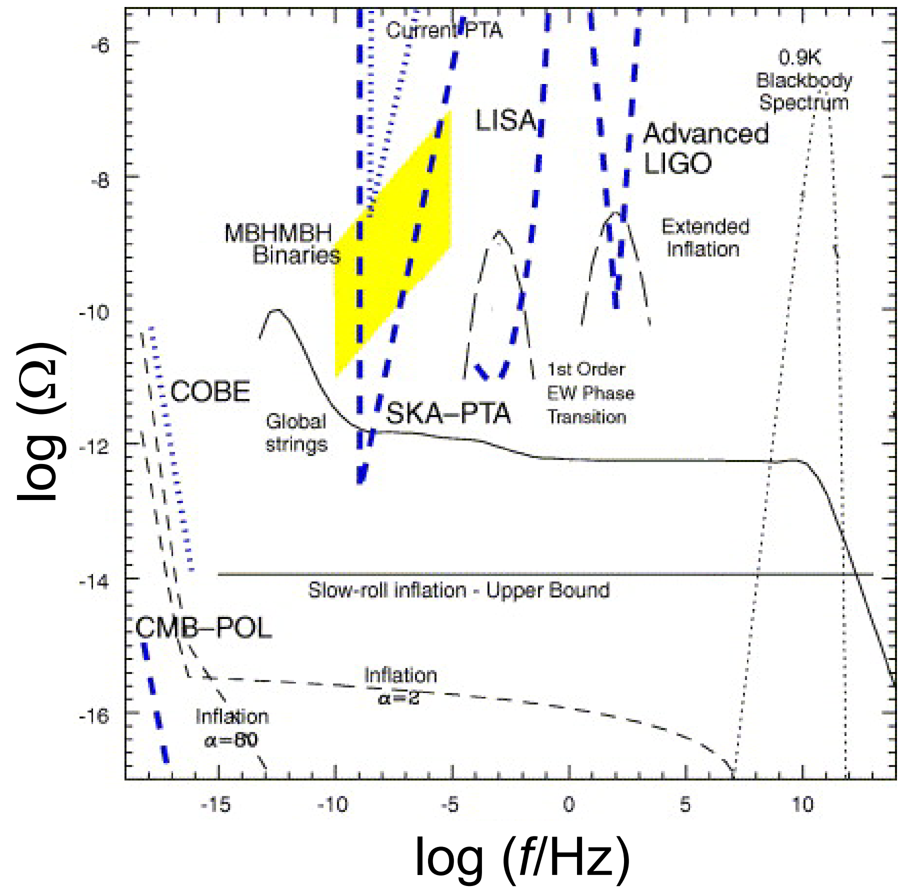
- Relativistic binaries probe
  - Equivalence principle
  - Strong-field tests of gravity
- Only neutron star-neutron star binaries known
  - Black hole-neutron star binaries?



Orbital decay of PSR B1913+16 (Weisberg and Taylor 2003)

SKA as a Gravitational Wave Detector





Test masses on lever arm

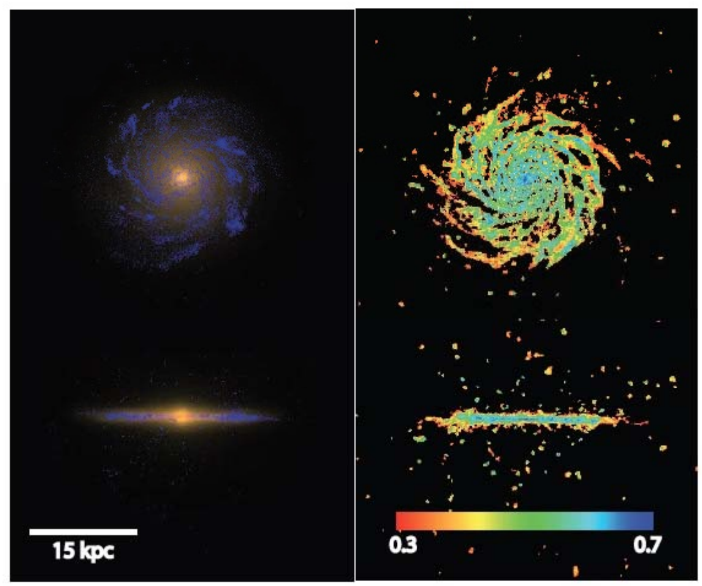
- Pulsar Timing Array = freely-falling **millisecond** pulsars
- LIGO = suspended mirrors
- LISA = freely-falling masses in space

Galaxy Assembly
Stars *and* Gas

- Neutral hydrogen (HI) is the raw material for galaxies and star formation
  - How do galaxies turn gas into stars?
  - How does gas content vary with
    - Morphology;
    - Redshift;
    - Environment/Mergers;
    - …

- Gas content and dynamics becoming critical part of simulations.
  - Astronomy is an *observational* science.

observation vs. simulation



Eris simulation (Guedes et al.)

NGC 6946 (T. Oosterloo)

Cosmology and Gravity

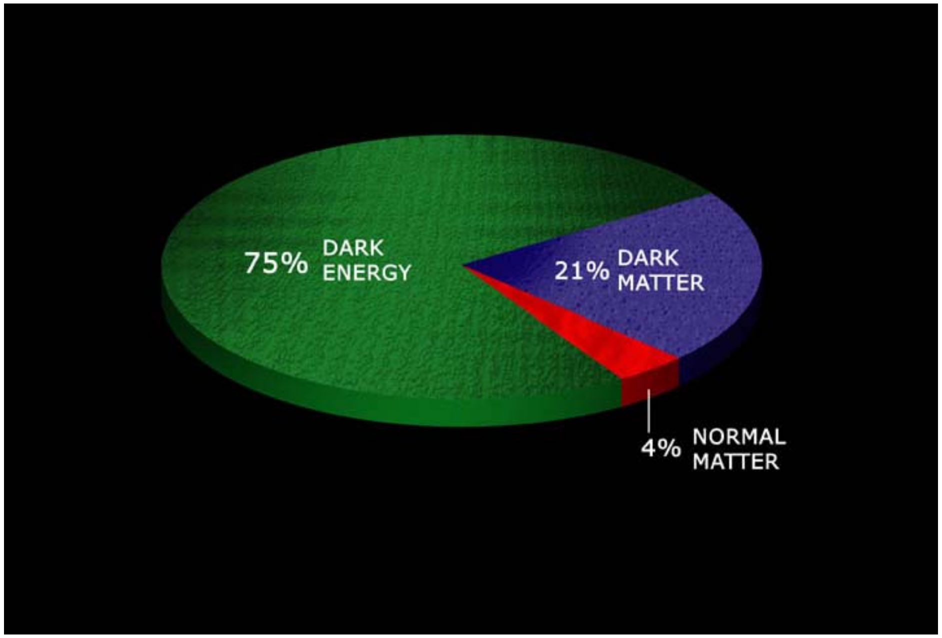
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}/c^4$$

Origin and Fate of the Universe

- Era of "precision cosmology"

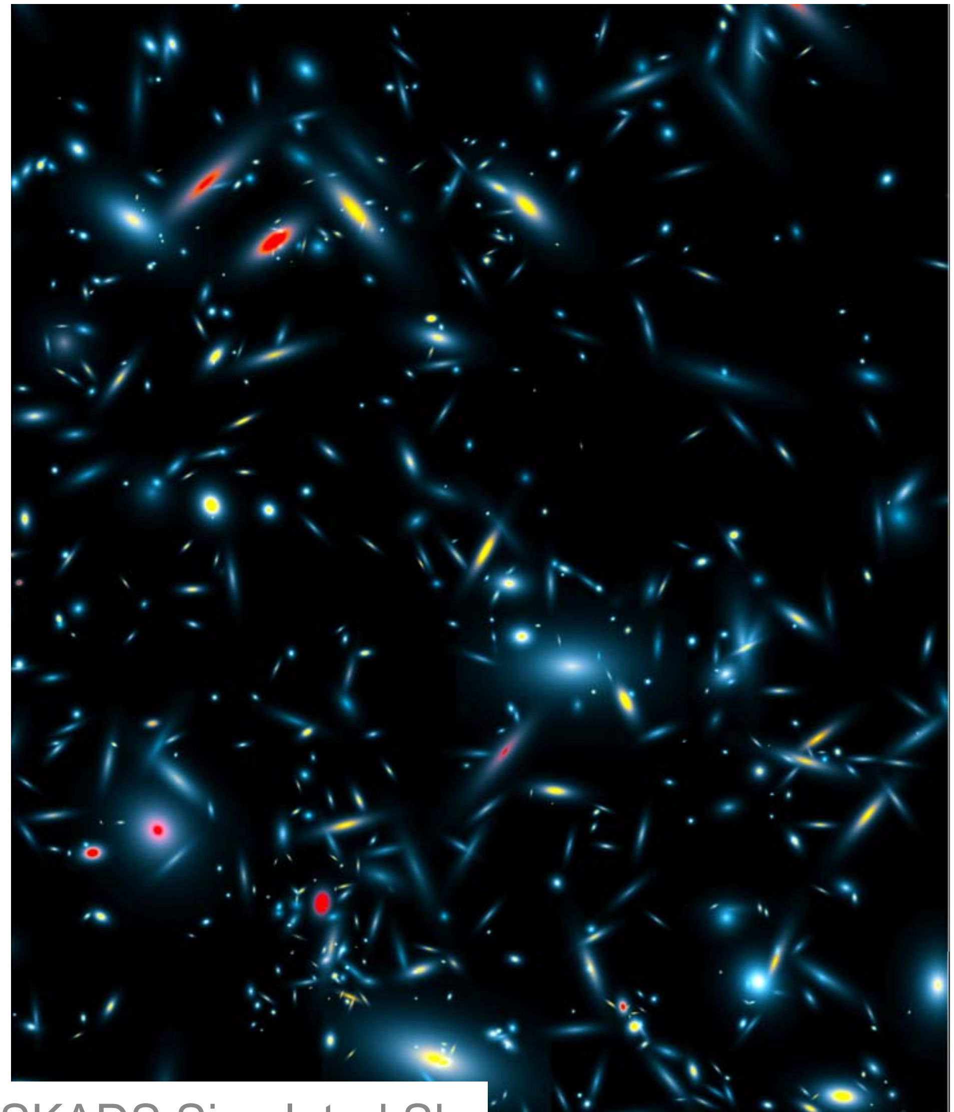
  … or precision ignorance

- Need to sample a substantial volume of the Universe



Composition of the Universe

Cosmology and Sky Surveys

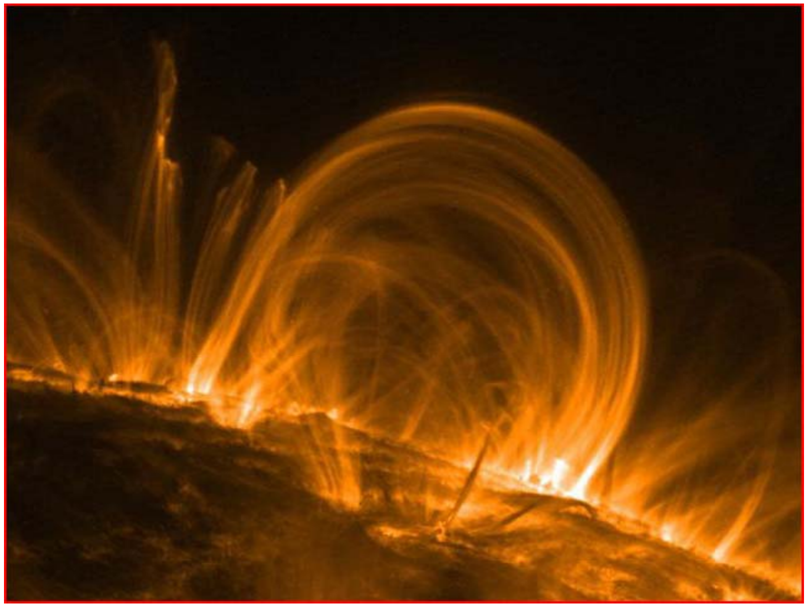


SKADS Simulated Sky

- Image the sky, locating galaxies
  - Analysis of locations compared with cosmological models to constrain parameters
- Two broad classes of surveys
  - Continuum: e.g., NVSS, FIRST, *ASKAP/EMU, WSRT/APERTIF/WODAN*
  - Spectroscopic: SDSS, Arecibo ALFALFA, *ASKAP/WALLABY, SKA H I survey*
    - Spectroscopic surveys locate in **3-D space!** very powerful
- Ultimate goal: spectroscopic survey of 1 billion galaxies

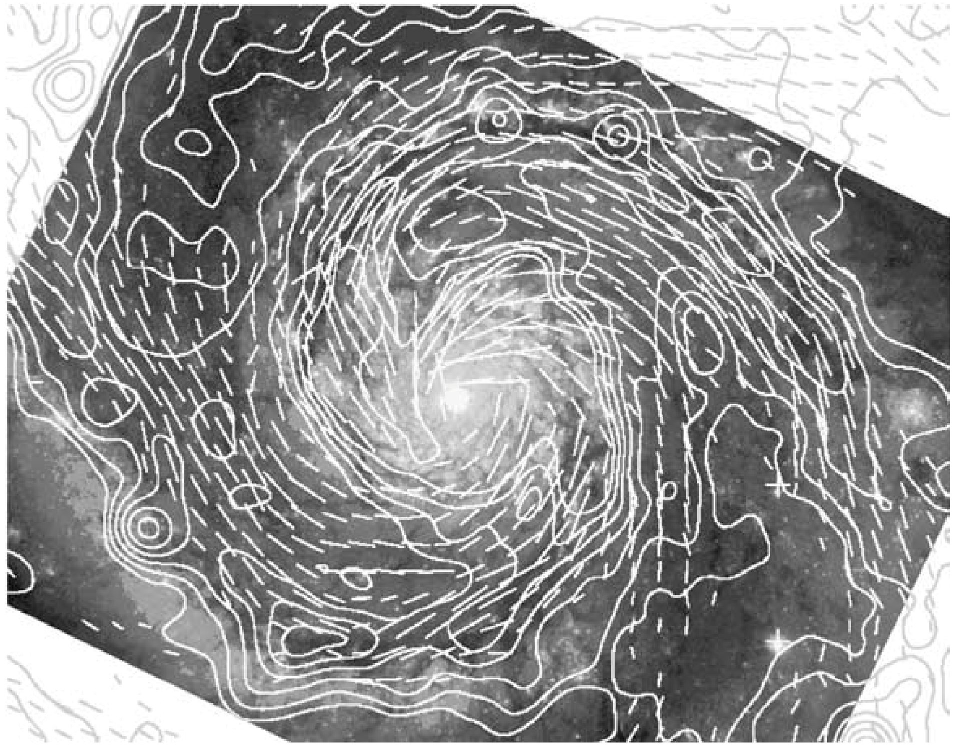
Cosmic Magnetism

- Fills intergalactic and interstellar space
- Essential for the onset of star formation
- Controls the density and distribution of cosmic rays in the interstellar medium (ISM)
- Affects the evolution of galaxies and galaxy clusters



Cosmic Magnetism

- How are magnetic fields generated and maintained?
- How do magnetic fields evolve as galaxies evolve?
- What is the strength and structure of the magnetic field of the intergalactic medium (IGM)
- Are magnetic fields in galaxies and clusters primordial or generated at later epochs?



Key Science and Key Technology

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Strong-field Tests of Gravity with Pulsars and Black Holes	✔	✔
Galaxy Evolution, Cosmology, & Dark Energy	✔	✔
Emerging from the Dark Ages	?	✔
The Cradle of Life & Astrobiology	?	✔
The Origin and Evolution of Cosmic Magnetism	✔	✔

Some aspect of all Key Science Programs will require a dish array sub-system to address.

BLUF
(Bottom Line, Up Front)

SKA has to beat current performance by a sufficient margin.

Pulsar Timing

Telescope	Sensitivity ($m^2 K^{-1}$)
Parkes	65
Arecibo	830
GBT / EVLA / GMRT	~ 250
MeerKAT	*155*
FAST	*1250*
Phase 1	**1000**

* Both metrics really should include the processed bandwidth

H I Surveys

Telescope	Survey Speed @ 1 GHz (10^4 m^4 K^{-2} deg^2)
AO/ALFA	4.7
WRST/APERTIF	*7.4*
ASKAP	*13*
FAST	*22*
AO40	*20*
GBT-PAF	*6.4*
Phase 1 (core)	**37**
Phase 1 (core+inner)	**52**

Scientific and Technical Requirements

- Sensitivity and survey speed
- Spectral characteristics
- Temporal characteristics
- Polarization characteristics
- Imaging characteristics
- Operational requirements

See Requirements Document for SKA Dish Array (WP2-020.030.020-RS-001)

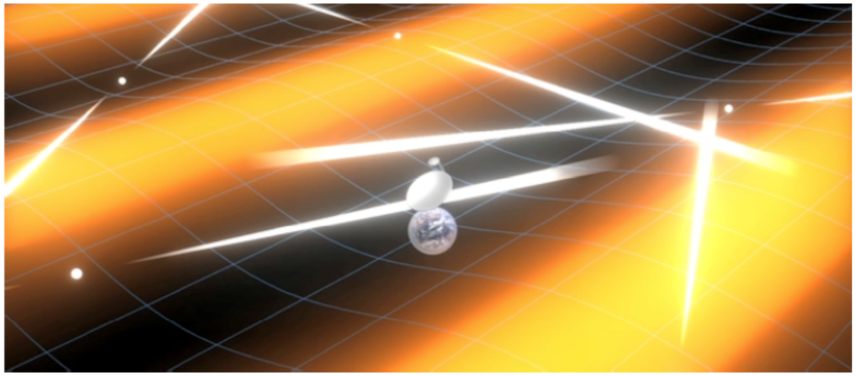
Technical Requirement
Sensitivity

Please, sir, I want some more.

Fundamental Physics via Pulsar Timing

Precise measurements of arrival times of pulsars can track changes in pulsar-Earth distance

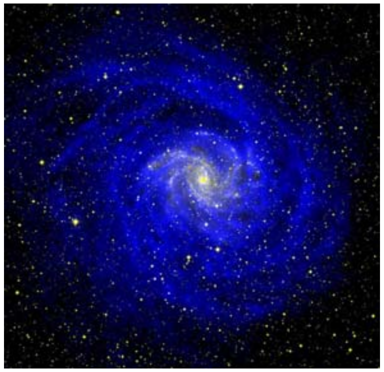
- Pulsars are faint, e.g., 0.1 mJy kpc^2



Galaxy Evolution

Track how gas flows into, out of, and within galaxies as a function of cosmic time

- Milky Way-like galaxy at $z \sim 2$ is 0.4 mJy in 200 km s^{-1} velocity channel



Technical Requirement
Survey Speed

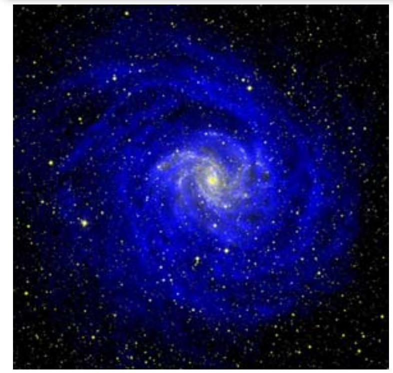
Please, sir, I want some more.

Survey speed figure of merit (SSFoM) =
$(A_{eff}/T_{sys})^2 \, \Delta\Omega \, \Delta\nu$

- Strictly, the “steady source” SSFoM
- Bandwidth not usually included, but important
  - Does one have to cover the sky twice for surveys of the H I line?
- Potentially more of a consideration for Phase 2 than Phase 1

Key Science and Key Technology

"Hydrogen telescope":
Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$



A_{eff}/T_{sys}	
20,000 m^2 K^{-1}	SKA Science Case (Carilli & Rawlings 2004)
7000 – 12,000 m^2 K^{-1}	Preliminary Specifications for the SKA, SKA Memo 100 (Schilizzi et al. 2007)
1000 m^2 K^{-1}	SKA Phase 1: Preliminary System Description, SKA Memo 130 (Dewdney et al. 2010)

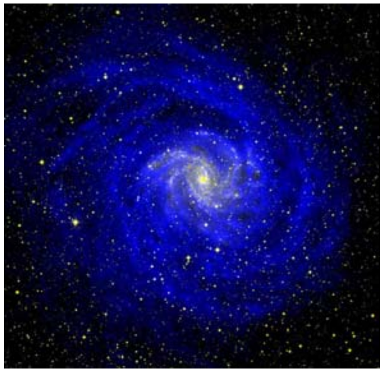
Technical Requirement
Spectral Characteristics

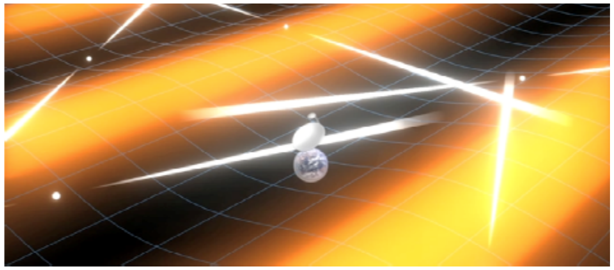
SKA
SQUARE KILOMETRE ARRAY

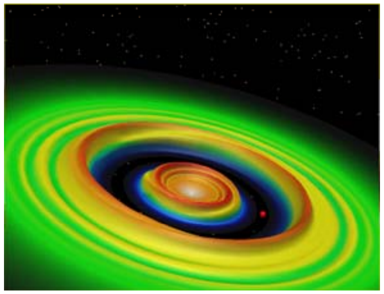
Frequency range

- H I line (1420 MHz) over redshift range $0 \le z \le 3$ (or 7)
  - At least 0.45 GHz–1.42 GHz
- Pulsar timing balances decreasing flux densities at higher frequencies and increasing propagation effects at lower frequencies.
  - Notionally 0.8–3 GHz
- Cradle of Life exploits ν^2 dependence of thermal emission
  - Above 5 GHz (to 25+ GHz)
    - Later stages of Phase 1 into Phase 2

Current radio astronomy dishes operate over at least 10:1, in some cases 100:1 frequency range



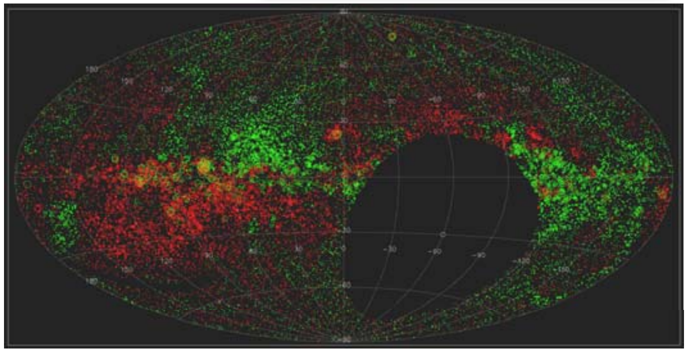




Technical Requirements
Temporal Characteristics

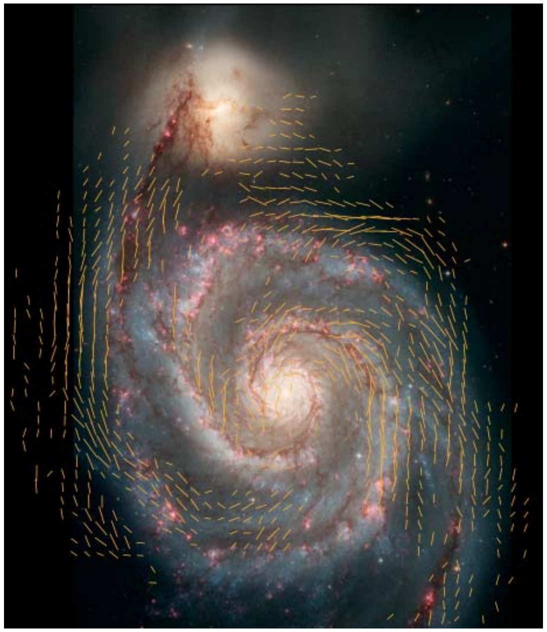
- Range of astronomical time scales is vast
  - Sub-millisecond pulse widths from millisecond pulsars
  - Hour-long variations in pulsar flux densities due to interstellar propagation effects
  - Month-long variations in extragalactic source flux densities due to interstellar propagation effects and in morphology of X-ray binaries due to jet formation and evolution
  - Decade-long changes in pulsar and black hole positions on the sky due to space motions
  - …
- Range of observationally-related time scale considerations is long
  - Minute (sub-minute?) time scales due to atmospheric changes (both neutral and ionized)
  - Daily variations due to thermal loading, elevation changes, …
  - Yearly variations due to seasonal effects
  - Monthly to multi-year observational campaigns for deep fields and surveys
    - 1000 hr (3 Ms) deep field
    - 2 year “on-sky” survey time, which does not include calibration or observational overheads

Technical Requirements
Polarization Characteristics



Track evolution of magnetic fields over cosmic time

- Wide range of angular scales required
  - ~ 10" for probing structures within the Galaxy (e.g., molecular clouds)
  - ~ 1' for probing galaxies, maybe clusters of galaxies
  - ~ 1° for clusters of galaxies
  - All-sky for Galaxy

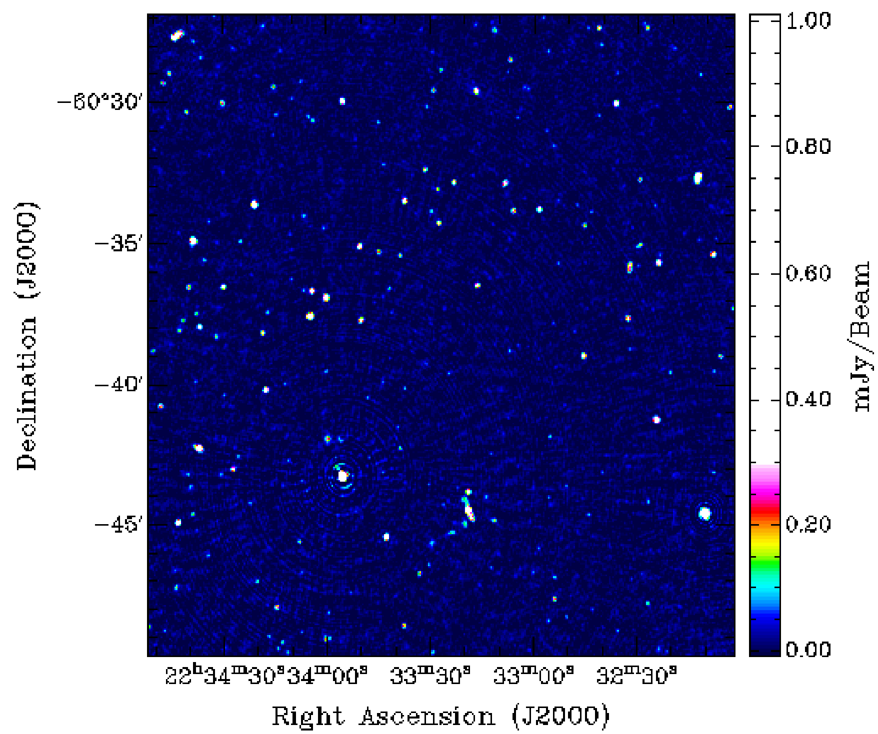


➢ Polarization characteristics should be *calibratible* over the field of view

Technical Requirements
Imaging Characteristics

Imaging performance is a *System* requirement, from which Dish requirements are derived.

- Science motivations
  - Star formation in high redshift galaxies
  - Dust enshrouded star forming galaxies at z ~ 3
  - Faint Galactic transients
  - Discovery
  - i.e., want to be able to use the telescope to the full range of implied capabilities
- Imaging Dynamic Range = 74 dB
  - Deep observations of selected fields, e.g., young galaxies at *z* ~ 7 (Phase 2 DRM)
  - All-sky imaging requirements *significantly* less severe



Australia Telescope Hubble Deep Field South field (~ 10 μJy/beam rms)

Technical Requirements
Operational Considerations

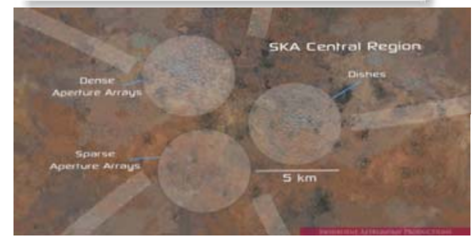
- Observational programs
  - 1000 hr deep fields
  - Multi-year surveys
- Large MTBF

  Of all components!
- Extensibility to Phase 2, notably future feed+Rx systems

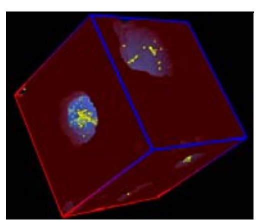
  Wider bandwidth systems, different center frequencies, PAFs, …
- Multi-decade operational lifetime (~ 50 yr)

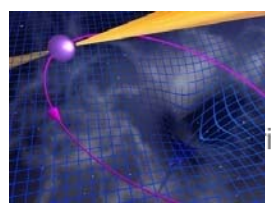
Square Kilometre Array

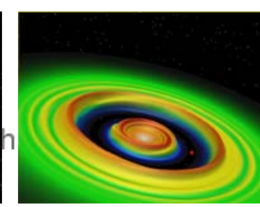
The Global Radio Wavelength Observatory

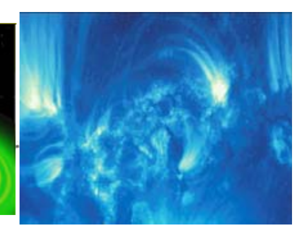


- Originally: “Hydrogen telescope”
  - Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$
- SKA science much broader
  - ⇒ Multi-wavelength, multi-messenger
- On-going technical development
  - ⇒Dish Sub-system incredibly important!









H I Surveys

- Science: Understand evolution of H I mass function, search for dark halos, …
- ALFALFA illustrating importance of “significant” volumes
- Technical parameter: Survey speed at 1 GHz

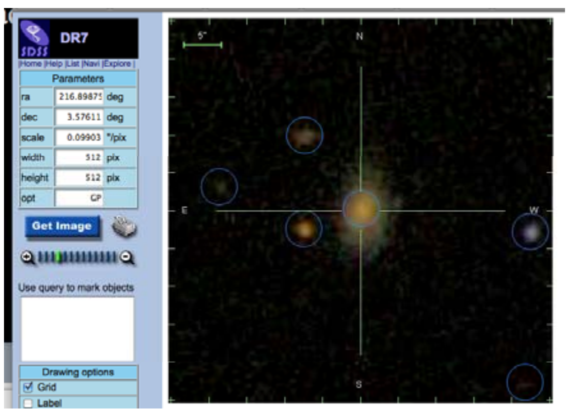
  Resolution not an important parameter, may be detrimental

Telescope	Survey Speed at 1 GHz (10^4 m^4 K^{-2} deg^2)
AO/ALFA	4.7
WRST/APERTIF	*7.4*
ASKAP	*13*
FAST	*22*
AO40	*20*
GBT-PAF	*6.4*
Phase 1 (core)	**37**
Phase 1 (core+inner)	**52**

H I Deep Field

- Science: Track gas inflow to galaxies, galaxy interactions
- Target *z* ~ 0.3
- Resolution ~ 5"
  - ~ 10 km baselines

Telescope	Sensitivity ($m^2\ K^{-1}$)
EVLA / GMRT	~ 250
MeerKAT (if spur exists)	*155*
Phase 1	**619**



SDSS J142735.69+033434.2

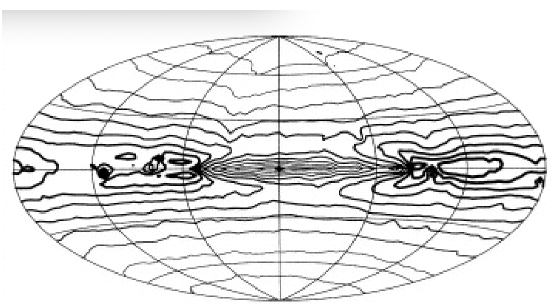
Pulsar Surveys I

- Science: Find additional millisecond pulsars, e.g., for gravitational wave studies
- Goal: wide distribution of MSPs across sky
- Frequency ~ 400 MHz
  - Target high Galactic latitudes, so propagation effects less important
  - Exploit steep spectra of MSPs

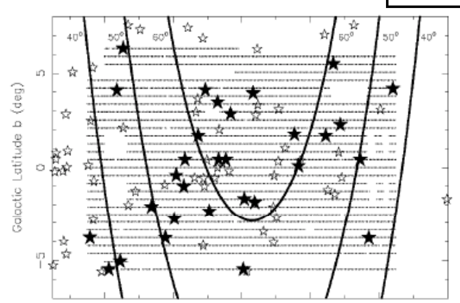
Telescope	**Survey Speed ~ 400 MHz (10^4 m^4 K^{-2} deg^2)**
AO	1.5
GBT	0.36
Parkes	0.04
LOFAR-HBA (core)	*(small)*
FAST	*2.5*
Phase 1 (core)	**160**

Notes!

- Sensitivity cannot be traded for FoV
- Resolution is bad -> higher signal processing costs



MSP detection volume @ 430 MHz (Cordes &



GBT 350 MHz drift scan survey (Hessels et al.)

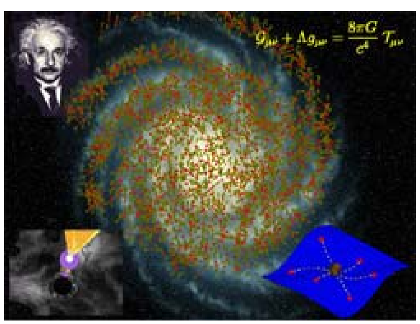
Pulsar Surveys II

- Science: Ultra-relativistic binaries
  - Likely requires surveys deep into Galactic plane
- Frequency ~ 1.4 GHz
  - Survey low Galactic latitudes
  - Balance typical pulsar spectrum with propagation effects

Telescope	Survey Speed ~ 1 GHz (10^4 m^4 K^{-2} deg^2)
AO/ALFA	4.7
GBT	0.01
Parkes MB	0.65
WRST/APERTIF	*7.4*
ASKAP	*13*
FAST	*22*
AO40	*20*
GBT-PAF	*6.4*
Phase 1 (core)	**37**

Notes!

- Sensitivity cannot be traded for FoV
- Resolution is bad -> higher signal processing costs
- Southern hemisphere location of SKA is unparalleled



Pulsar Timing

- Science: Testing fundamental physics
  - Gravitation
  - Strong force
- Frequency ~ 1.4 GHz (or higher!)

  Mitigate propagation effects
- Field of view unimportant

  Probably only 1 “interesting” PSR in FoV

Telescope	**Sensitivity ($m^2\ K^{-1}$)**
Parkes	65
Arecibo	830
GBT / EVLA / GMRT	~ 250
MeerKAT	*155*
FAST	*1250*
Phase 1	**1000**