Connecting Quarks with the Cosmos:
Eleven Science Questions for the New Century

What is the nature of the Dark Energy? ✓
How did the Universe begin? ✓
Did Einstein have the last word on gravity? ✓
What are the masses of the neutrinos and how have they shaped the evolution of the Universe? ✓
What is Dark Matter? ✓
How do cosmic accelerators work and what are they accelerating? ✓
Are protons unstable?
What are the new states of matter at exceedingly high density and temperature?
Are there additional space-time dimensions?
How were the elements from iron to uranium made?
Is a new theory of matter and light needed at the highest energies?
21st century astronomy will be global astronomy

- Globally funded
- Globally R&D and science teams
- Globally distributed data and computing resources
Radio Telescopes

H (1.4GHz) + optical

optical
Magnetism and Extreme Energies

Solar prominence

Radio Jets 1 million ly long
Gravity Waves and Galactic GPS

Pulse arrival accuracy \( \sim 10^{-19} \)

Pulsar (GPS) network of Clocks used to detect GW
Are we alone?

Proto-planetary disk

<table>
<thead>
<tr>
<th>Survey</th>
<th>Freq.</th>
<th>Range</th>
<th># of stars</th>
<th>Detect</th>
<th>EIRP at 4 ly</th>
<th>EIRP at 1000 ly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>span</td>
<td>or</td>
<td>Thresh.</td>
<td>(W m⁻²)</td>
<td>(W)</td>
</tr>
<tr>
<td></td>
<td>(MHz)</td>
<td>(MHz)</td>
<td>% of sky</td>
<td>(W)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phoenix (SETI Inst.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arecibo</td>
<td>2100</td>
<td>1800</td>
<td>280</td>
<td>8E-27</td>
<td>1E+08</td>
<td>9E+12</td>
</tr>
<tr>
<td>Parkes</td>
<td>2100</td>
<td>1800</td>
<td>156</td>
<td>2E-25</td>
<td>4E+09</td>
<td>2E+14</td>
</tr>
<tr>
<td>NRAO</td>
<td>2100</td>
<td>1800</td>
<td>600</td>
<td>3E-25</td>
<td>5E+09</td>
<td>3E+14</td>
</tr>
<tr>
<td>Serendip III (Berkeley)</td>
<td>29</td>
<td>12</td>
<td>28%</td>
<td>3E-25</td>
<td>5E+09</td>
<td>3E+14</td>
</tr>
<tr>
<td>Serendip IV (Berkeley)</td>
<td>1520</td>
<td>200</td>
<td>28%</td>
<td>1E-24</td>
<td>2E+10</td>
<td>1E+15</td>
</tr>
<tr>
<td>META (Harvard)</td>
<td>1420</td>
<td>3</td>
<td>68%</td>
<td>2E-23</td>
<td>3E+11</td>
<td>2E+16</td>
</tr>
<tr>
<td>BETA (Harvard)</td>
<td>1580</td>
<td>320</td>
<td>68%</td>
<td>1E-22</td>
<td>2E+12</td>
<td>1E+17</td>
</tr>
<tr>
<td>SKA</td>
<td>5500</td>
<td>9000</td>
<td>1E+05</td>
<td>8E-29</td>
<td>1E+06</td>
<td>9E+10</td>
</tr>
</tbody>
</table>

TV station

~1 MW

Interplanetary Radar

Arecibo ~10¹³ W
The Expansion of Astronomy Capabilities

"Eye Balls" doubling ~20 years
Data Capture

ESO VLT
10 MB/s

Murchison Wide-field Array 16,000 MB/s

High resolution numerical cosmology
100 MB/s
Data Explosions

ESO Science Archive Facility

T$_2$ < 6 months

T$_2$ < 12 months

ALMA at Chajnantor

100

1

TB

1998

2000

2001

2002

2003

2004

2005

2006

2007

2008

2009

2010

2011

2012

Year

ESO Science Archive Facility

VISTA

VST
Challenges: interoperability

- Joining Data from different experiments
  - To form a complete physical picture of an object it has to been seen in different wavelengths and over a period of time.
Digital Archives

Kohenon Self-organizing Map – Visir catalogue Archive

HST data reuse

“access to data is as valuable as the resource that generates the data”
OECD GSF ‘04
• International Virtual Observatory Alliance (IVOA)

• Europe (ESA, ESO), China, India, Canada, Italy, France, Germany, Hungary, Japan, Korea, USA, Russia, UK, Australia, Spain

http://www.ivoa.net
Cosmic History

Hydrogen @100 MHz
1,000,000 sq m

Limit largest current
Radio telescopes
~10,000 sq m

Hydrogen @1.4 GHz
1000 sq m
The International SKA

An International mega-science project
- $2.5 billion AUD total cost, with an operating budget ~$200m AUD p.a.
- Full operations by 2025 – lifetime of 50+ years

International consortium carrying SKA project
- 19 countries participating via international working groups - $450m AUD current investment
- www.skatelescope.org
Possible SKA Sites

- Away from radio interference (cities, towns and people!)
- Flat open spaces for 10s - 1000s km
- Dry and geological stable
- Good global location for astronomy
- Access to high technology industry and infrastructure
- Access to a technical and scientific community
- Stable economy and government

- Argentina
- Southern Africa
- Western Australia
Australia and Southern Africa chosen

Final international decision on site in 2012
Prime Minister Kevin Rudd:
“I regard this project [SKA] of sufficient significance to Australia to have raised it yesterday with the Vice President and with the Secretary of State. This is a big project for Australia. And I am dead serious about long term investment in science in Australia. This is a big part of it”. Washington 30 March 2008

Federal Science Minister Kim Carr:
“To begin with, the SKA will generate huge spin-offs in supercomputing, fibre-optics, non-grid and renewable energy, construction and manufacturing over its fifty-year life” Canberra 19 March 2008
WA Premier and Science Minister Alan Carpenter:

"This [the SKA] is an exciting, once in a century project, that would place WA at the world forefront of radio astronomy,"

Murchison Radio-astronomy Observatory

15,400 sq KM

Geraldton

300 km
Population density (people/sq km)

- NL
- World
- Aus
- Alaska
- Midwest WA
- Greenland
- Murchison
International site testing
Australia/US MWA: MIT, Harvard, Australian universities
UC Berkeley: PAPER project

Parkes 12m Phased Array prototype
A new radio telescope for Australia
1% of the SKA in size
Data collected in first 6 hours = all data collected, ever!
Built on the new Murchison Radio-astronomy Observatory
A demonstration of quality of the Australian site
A showcase for Australian technology and science
Fully funded with $106m in Federal funding
ASKAP technologies

- Phased Arrays
- Digital beam forming
- Low noise receivers (on a chip)
- FPGA, GPU correlation
- 12m dish design and construction
- HPC
ASKAP phased-array technology

Phased Array Feed prototype #1
June 2008
ASKAP Data Flow

Forty five antennas
One beamformer per antenna

1Tb/s
10Tc/s
0.2Tb/s

20Tcmac/s

Correlator

Central processor

2GB/s
15 - 150 Tflop/s
4GB/s

Central archive

ASKAP control facility

Astronomers

Boolardy

Geraldton or Perth

Anywhere
ASKAP Data and Processing

In 12 hours

• 270 TB of raw data averaged to 4.5 TB
• Data Products:
  • Continuum images: 4GB
  • 7D Spectral cubes: 16 TB
  • Time series (5 sec): 10 TB

System requirements

• 20,000 core
• 600 x 1 TB drives
• 60 TB memory
• $5m-$10m in 2011 + $250k/yr in power
Explosion continues

$T_2 = 18 \text{ mth}$

$T_2 = 6 \text{ mth}$

Graph showing data for the years 2008, 2015, and 2022, with labels for VLT, LSST, and SKA.
### Processing speed ASKAP and SKA

- Costs go as number of channels, second power of antennas, second power of baseline length

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Channels</th>
<th>Antennas</th>
<th>Baseline</th>
<th>Field of view</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASKAP</td>
<td>1x</td>
<td>1x</td>
<td>1x</td>
<td>1x</td>
<td>15-150 Tflops</td>
</tr>
<tr>
<td>- 45 antennas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 2.5km baselines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 16384 channels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKA Phase 1</td>
<td>1x</td>
<td>120x</td>
<td>4x</td>
<td>0.6x</td>
<td>3-30 Pflops</td>
</tr>
<tr>
<td>- 490 antennas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- 5km baselines</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- 16384 channels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SKA Phase 2</td>
<td>2x</td>
<td>2000x</td>
<td>16x</td>
<td>0.6x</td>
<td>0.6-6 Eflops</td>
</tr>
<tr>
<td>- 2000 antennas</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- 10km baselines</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>- 32768 channels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adapted from Cornwell
Progress....

- In September 2007, following agreement from Premier Carpenter and Minister Julie Bishop, a new State-Federal committee has been created to coordinate and promote Australia’s SKA bid.
- Australian SKA Coordination Committee (ASCC “Team Australia” DII SR, DOIR, WA DPC, UWA and CSIRO)
- Mission:
  - ★ “win the bid”
  - ★ RQZ legislation and MRO protection
  - ★ Communications and strategic planning
- www.ska.gov.au
New International Centre in Perth

- February 29 2008, Premier Carpenter announced $20m to establish a new international research centre for radio astronomy in Perth
- Joint venture partnership of UWA, Curtin University, CSIRO, other Australian and international organizations and industry – projected $60m in resources over 5 years
- Launch April 2009
The Square Kilometre Array (SKA) will be the largest international astronomical facility of the 21\textsuperscript{st} century. If built in Australia, it will be the largest single endeavour in Australia’s scientific history.

Every year the world currently produces 1,000,000,000,000,000,000 bytes of information. The SKA will produce this data volume in one day.