Radio interferometry in astronomy: a view into the XXI century

Lecture 3

SKA: the road to high sensitivity

Leonid Gurvits

with contributions by K. Kellermann, J. Lazio, R. Schilizzi

JIVE JOINT INSTITUTE FOR VLBI IN EUROPE

Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands

TU Delft

Delft University of Technology, Faculty of Aerospace Engineering, The Netherlands

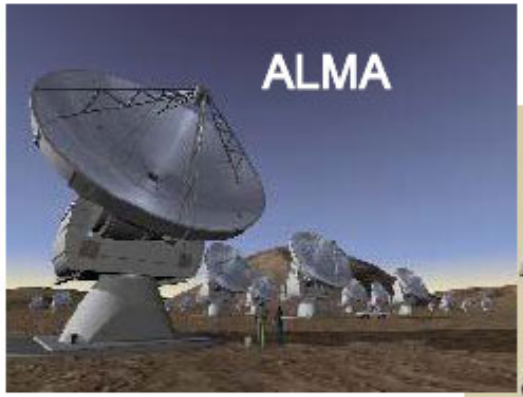
SKA science

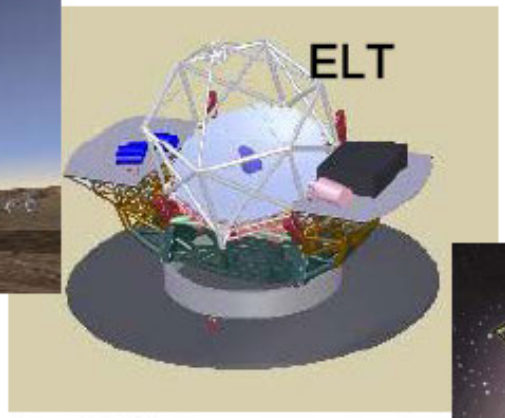
It' s all about sensitivity – in all senses!

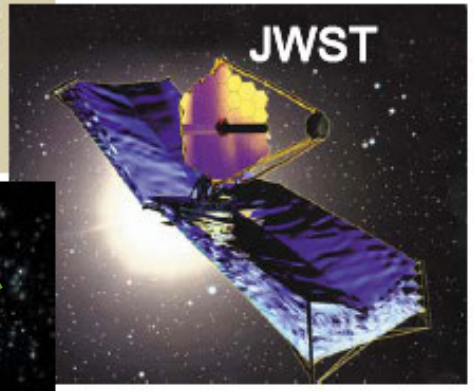
Big questions in astrophysics and cosmology

- How and when did the first stars and galaxies form in the Universe?
- What are the mysterious dark energy and dark matter that fill the universe?
- How did the Universe, and the galaxies in it, evolve?
- Was Einstein always right about gravity?
- Where did the magnetic fields in the Universe come from?
- Is there life of any sort anywhere else in the Universe, and is it intelligent (like us?)

Tools to answer these questions







2012

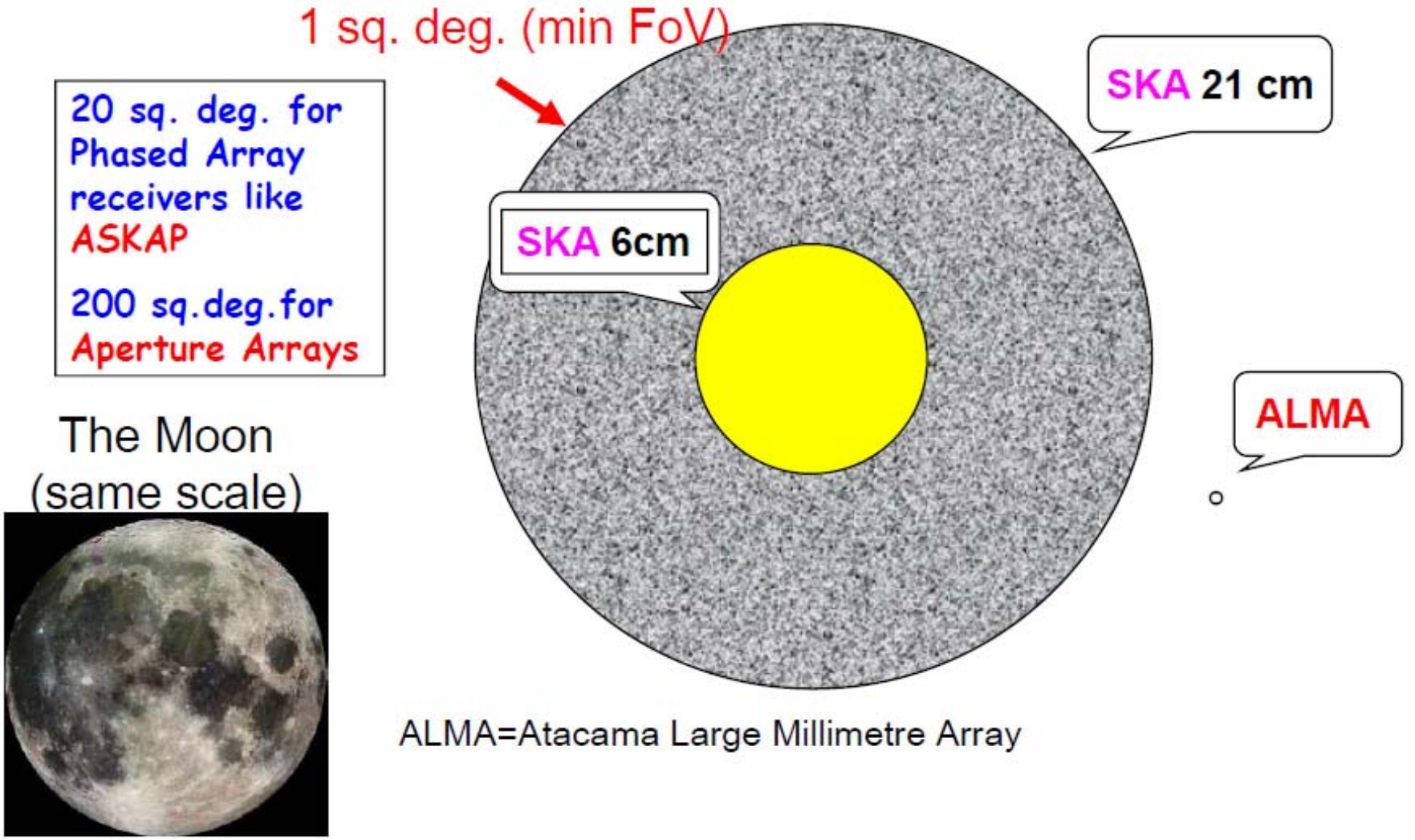
SKA: the Square Kilometre Array

4 prime characteristics

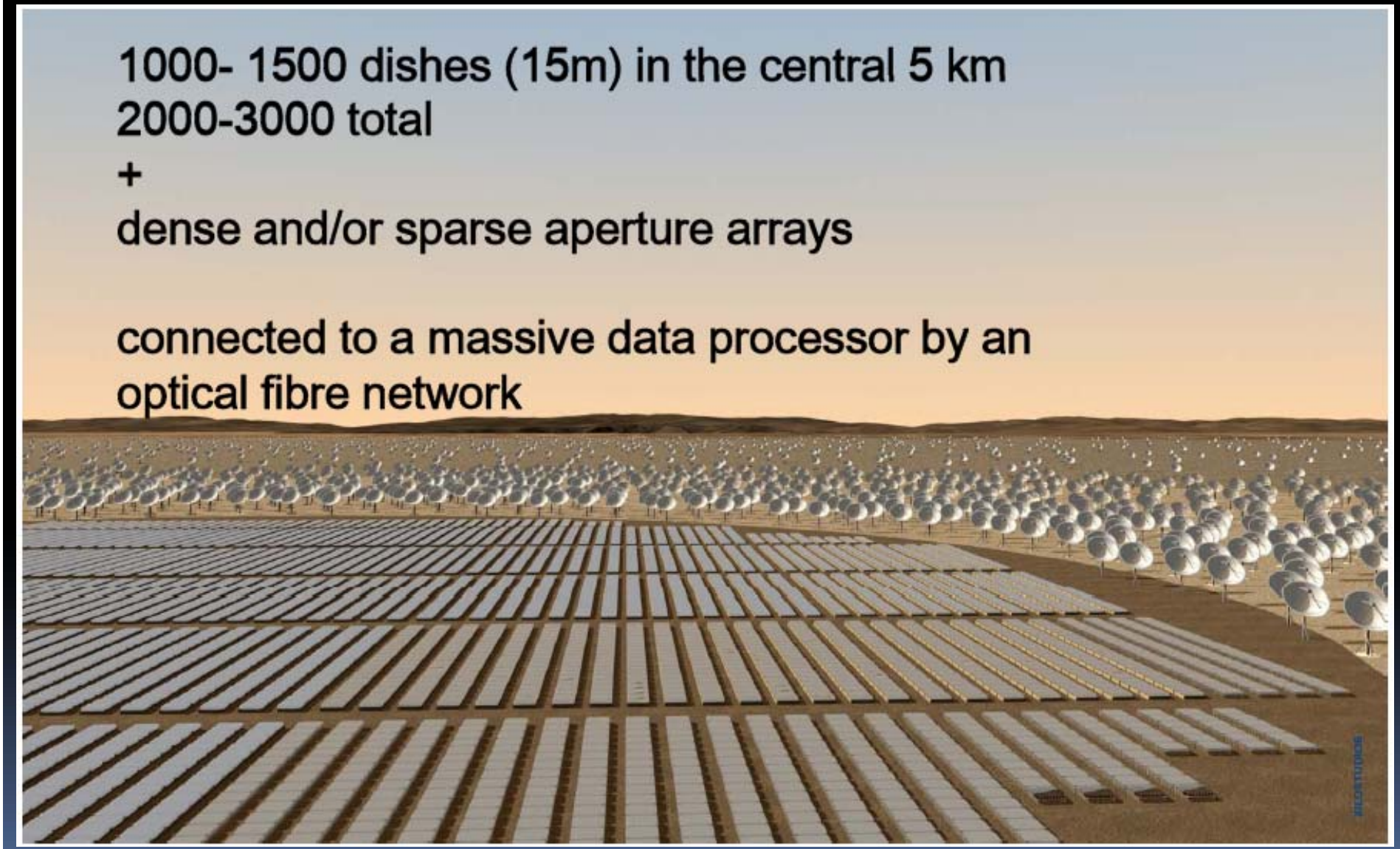
- *very large collecting area (km^2)* → sensitivity to detect and image hydrogen in the early universe
  - *sensitivity ~ 50 x most powerful current telescopes (EVLA, LOFAR)*

- *Very large field of view* → fast surveying capability over the whole sky
  - *survey speed ~10^4– 2 x10^6 x EVLA*
- *wide frequency range required for the Reference Science Mission*
  - *low : 70-300 MHz*
  - *mid: 300 MHz-10 GHz*
  - *high: 10-25+ GHz*
- *large physical extent (3000+ km)* → capability for detailed imaging of compact objects and astrometry with milli-arcsec angular resolution

Wide field of view



Artist's impression on SKA



SKA Key Science Drivers

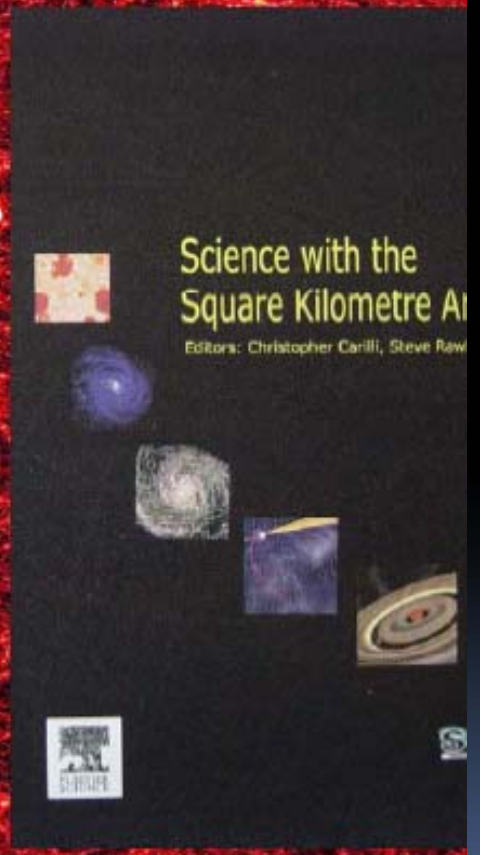
ORIGINS

- **Cosmology and Galaxy Evolution**
  Galaxies, Dark Energy and Dark Matter
- **Probing the Dark Ages**
  When & how were the first stars formed?
- **Cradle of Life**
  What are the conditions for life and where can it be found?

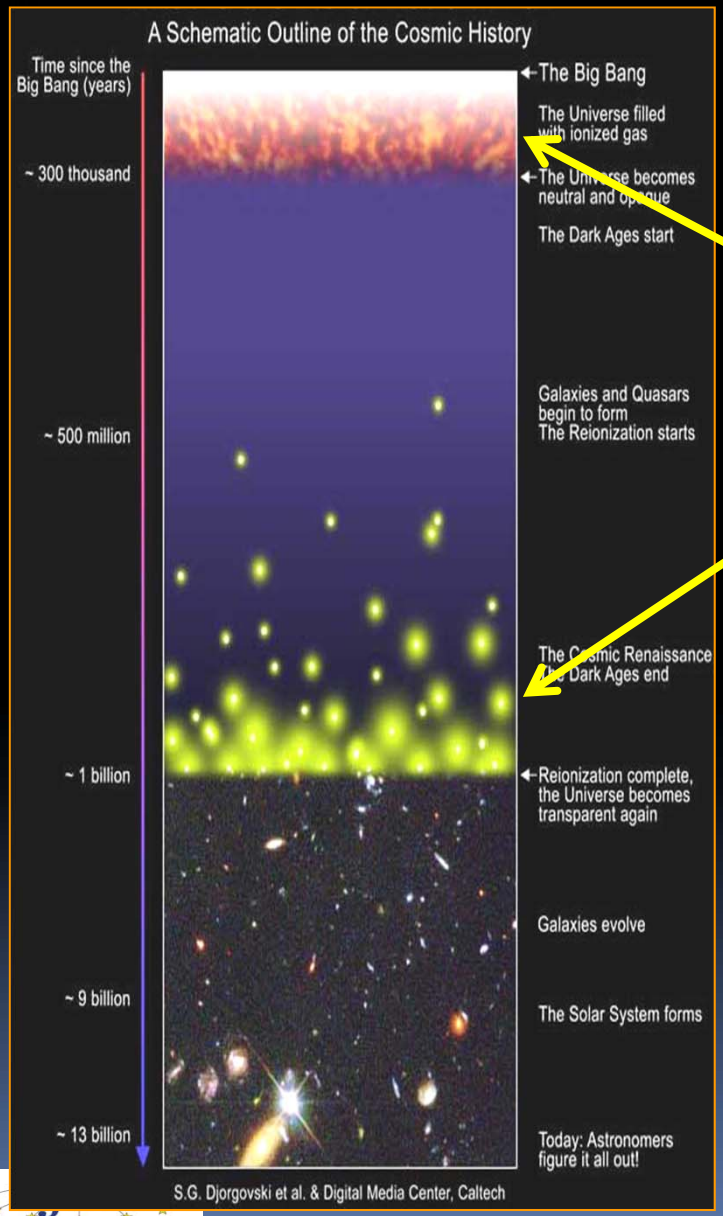
FUNDAMENTAL FORCES

- **Strong-field tests of General Relativity**
  Was Einstein correct?
- **Origin & Evolution of Cosmic Magnetism**
  Where does magnetism come from?

plus **The Exploration of the Unknown** as an underlying philosophy for design & costing



Evolution of the Universe



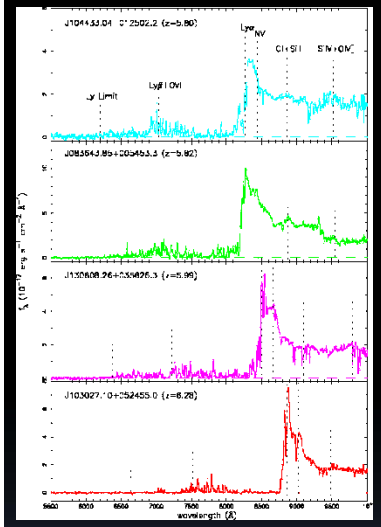
Between recombination and the appearance of first luminous objects

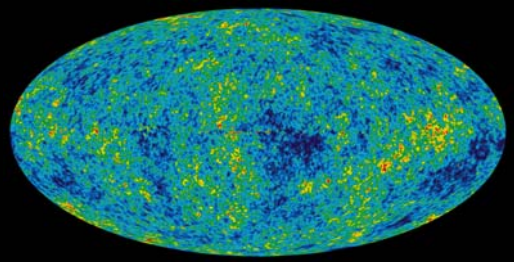
- Recombination: z = 1089 (370,000 yr); CMB forms
- Epoch of Reionization: z ~ 6 (~ 1 Gyr)

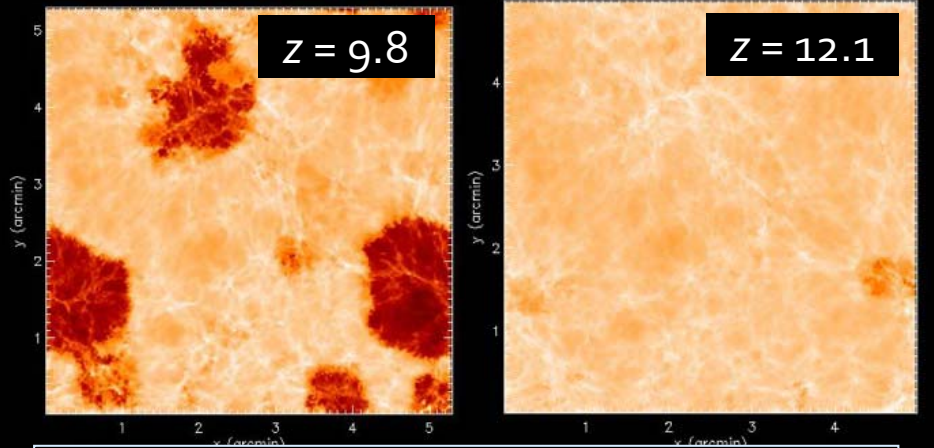
- Most baryons in form of H I (neutral hydrogen)
- H I begins collapsing into dark matter-dominated, overdense regions (dark matter halos).
- These halos are the sites of first star formation and large-scale structure formation.

Epoch of Reionization

Universe made rapid transition from largely neutral to largely ionized (z_{ion} ~ 6–11)







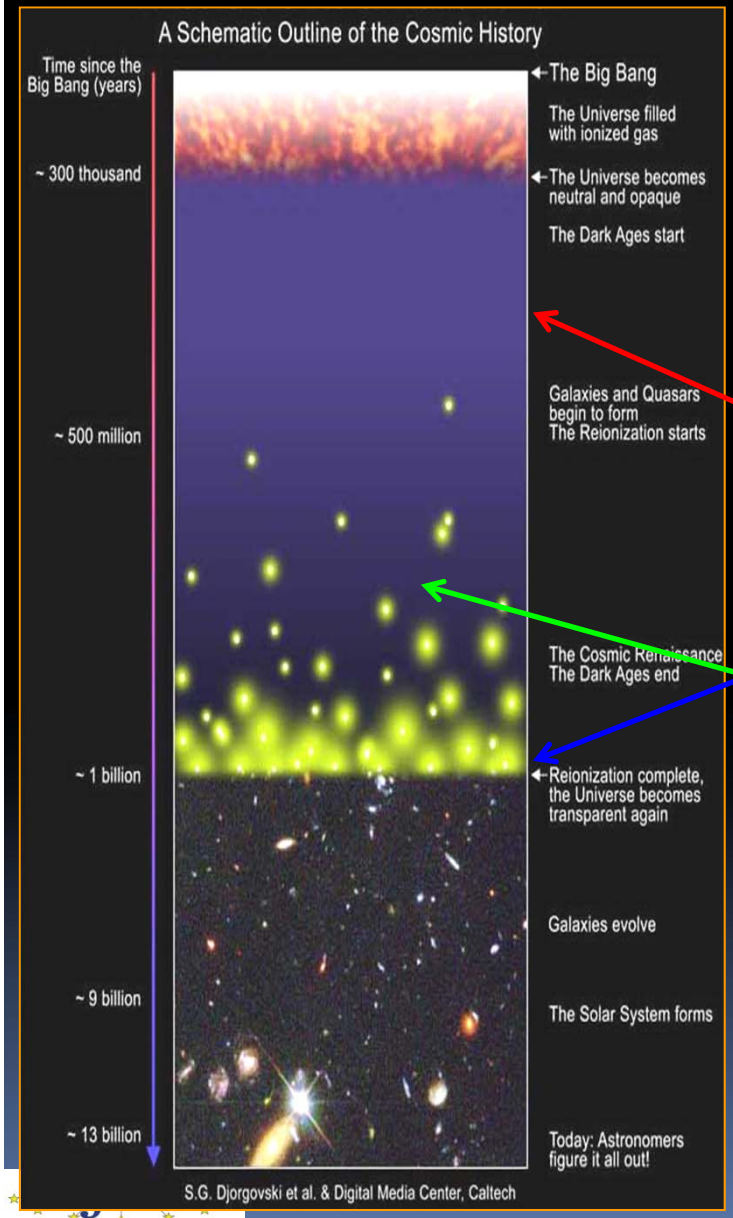
SKA objective: Image the IGM transition in the H I (21-cm) line

QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

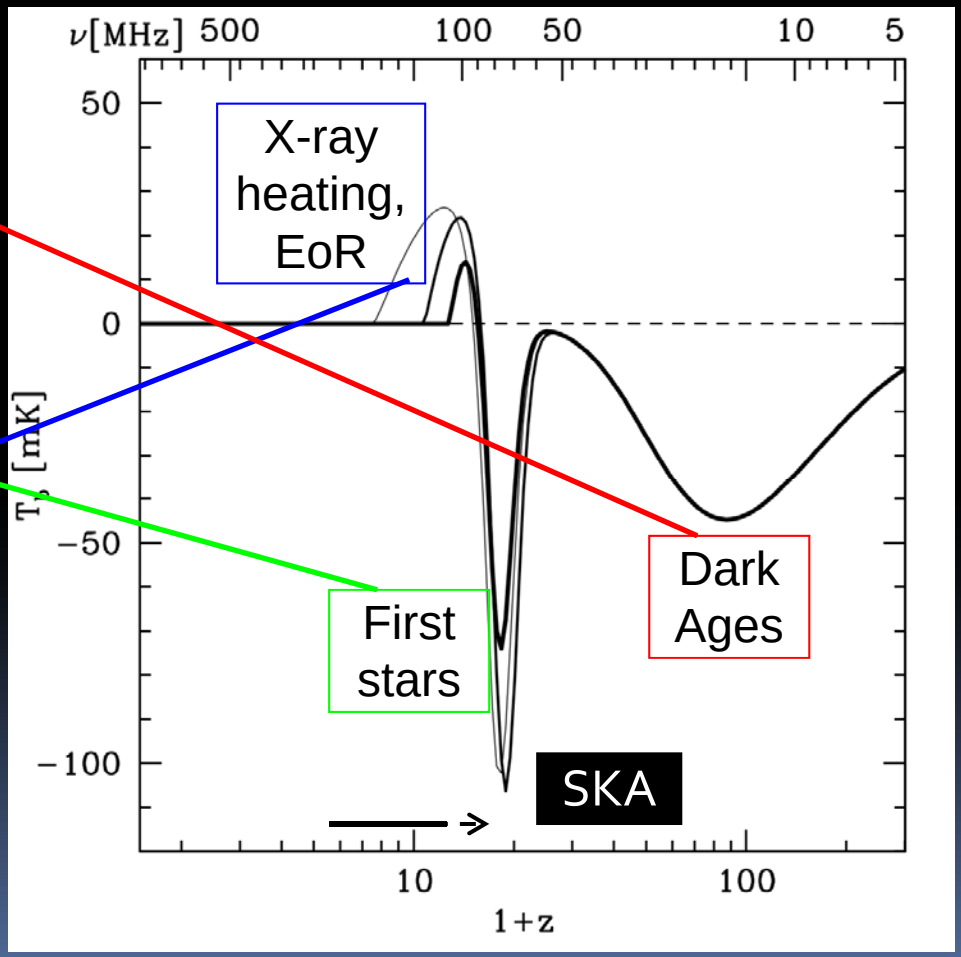
- Gunn-Peterson trough in high-z quasars
- Electron scattering opacity in CMB analysis

Furlanetto et al.; Gnedin

Evolution of the Universe

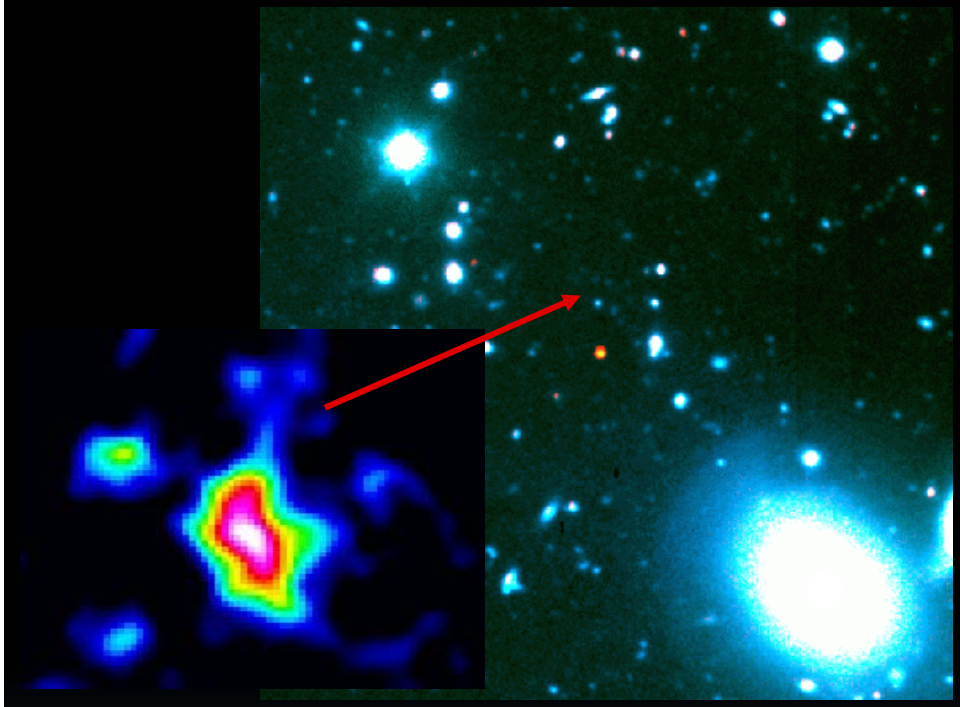


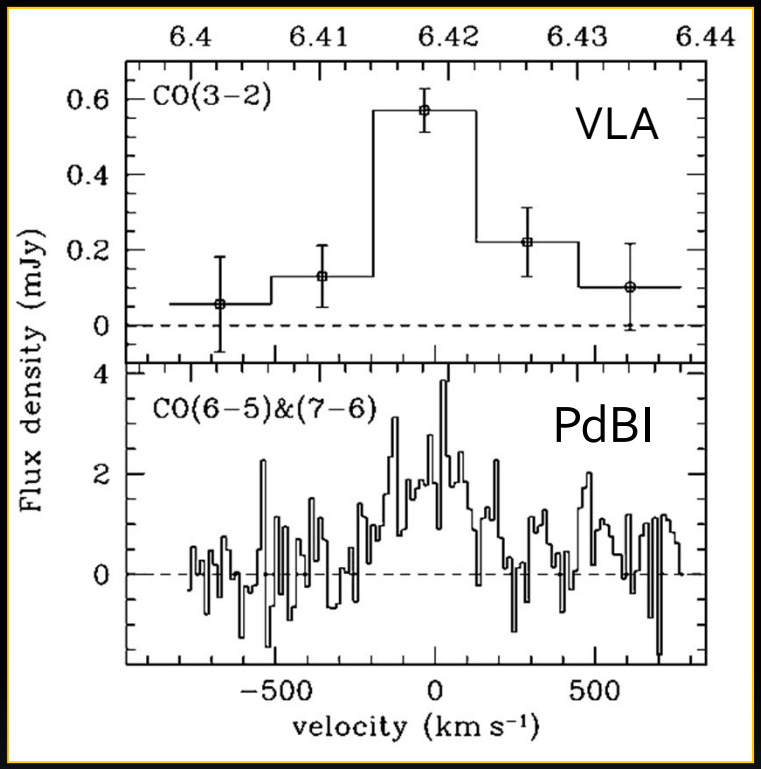
H I brightness temperature signal (w.r.t. CMB)



(Pritchard & Loeb 2008)

First Galaxies





SDSS J1148+52: Gas detection

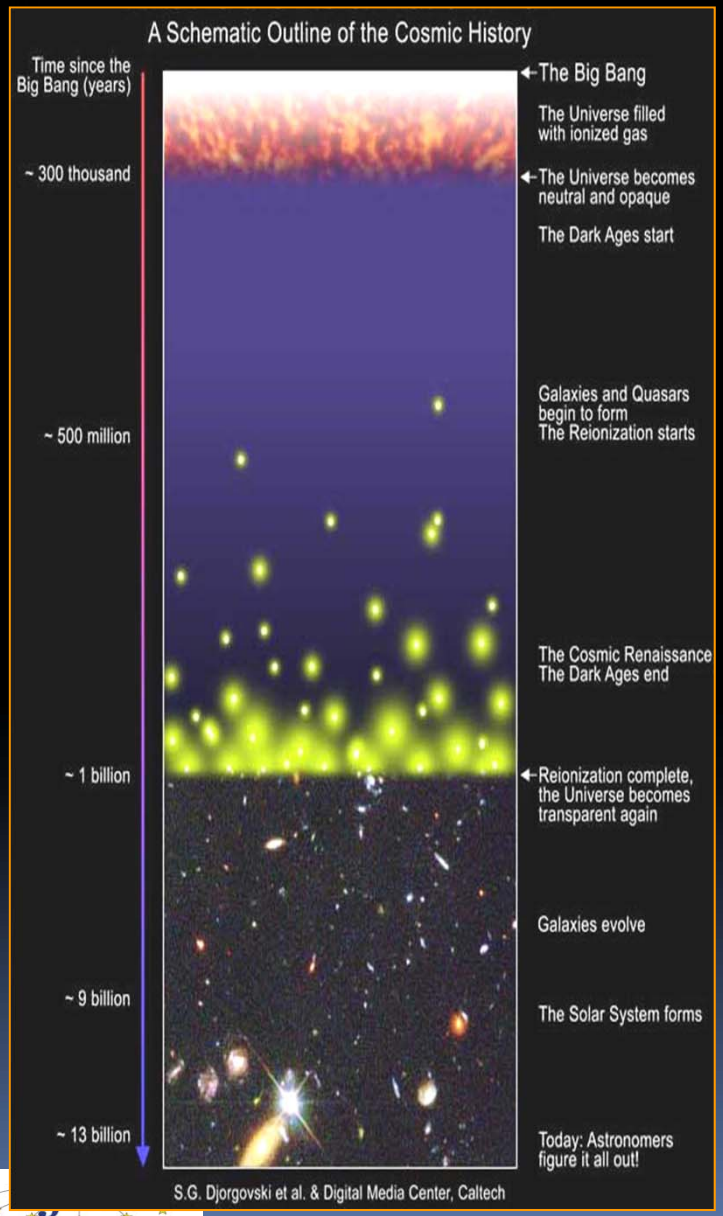
- $z = 6.42$ ($t = 0.87$ Gyr)
- $L_{bol} = 10^{14}\ L_{\odot}$
- SMBH ~ $3 \times 10^{9}\ M_{\odot}$ (Willot et al.)
- $M(H_2) \sim 2 \times 10^{10}\ M_{\odot}$

Fuel for Galaxy Formation

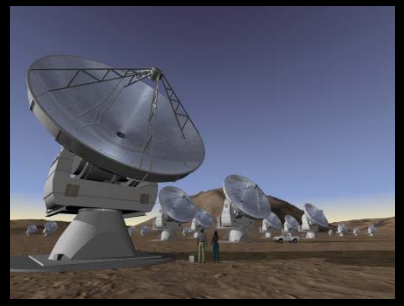
- Size ~ 5.5 kpc
- Radio-FIR SED follows star forming galaxy
- SFR ~ 3000 $M_{\odot}$/yr

Carilli et al.

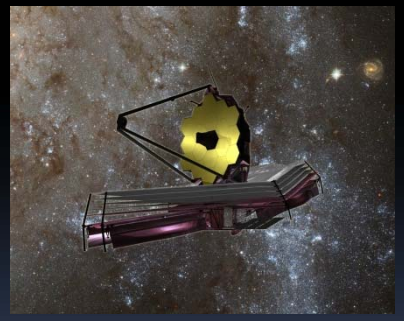
Epoch of Reionization



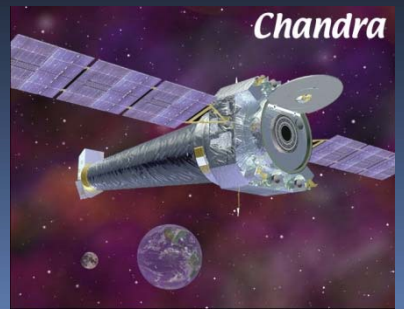
SKA: IGM and First Galaxies



ALMA: First Galaxies



JWST: First Stars and Galaxies

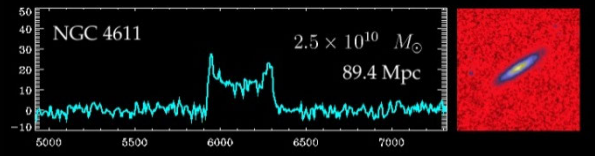


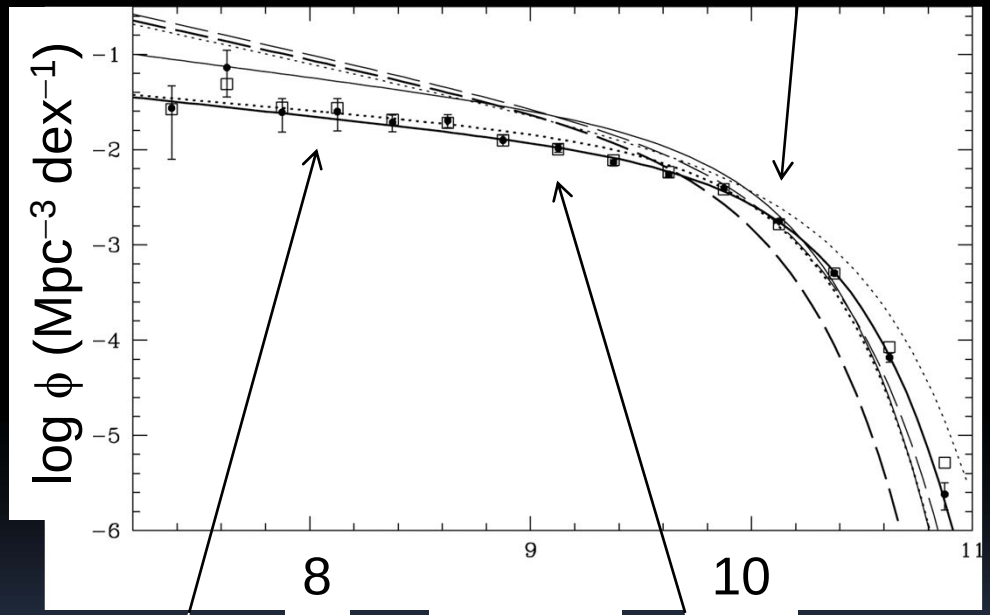
X-rays: First Black Holes

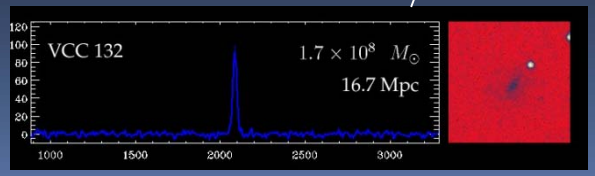
Galaxy Assembly & Evolution

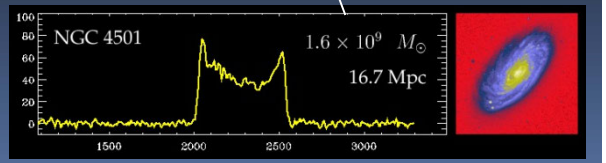
H I is the raw material for galaxies and star formation.

- How do galaxies turn gas into stars?
- How does gas content vary with
  - Morphology;
  - Redshift;
  - Environment;
  - Mergers;
  - Feedback;
  - …









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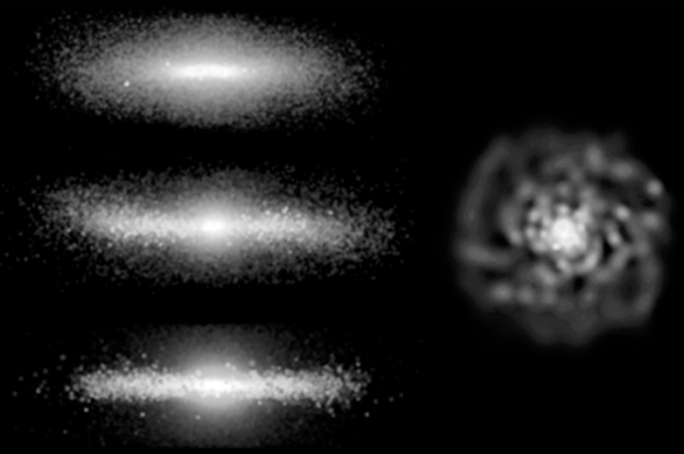
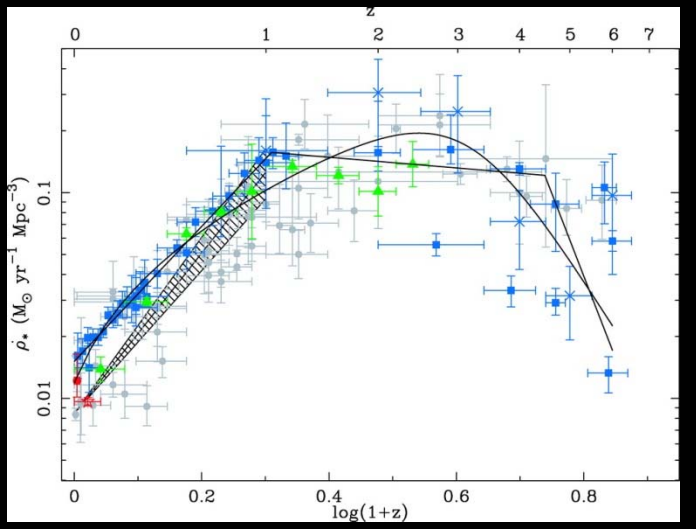
Galaxy Assembly Stars *and* Gas

- Stellar
- … but
- Gas co
  critical

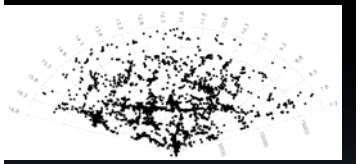


star → s

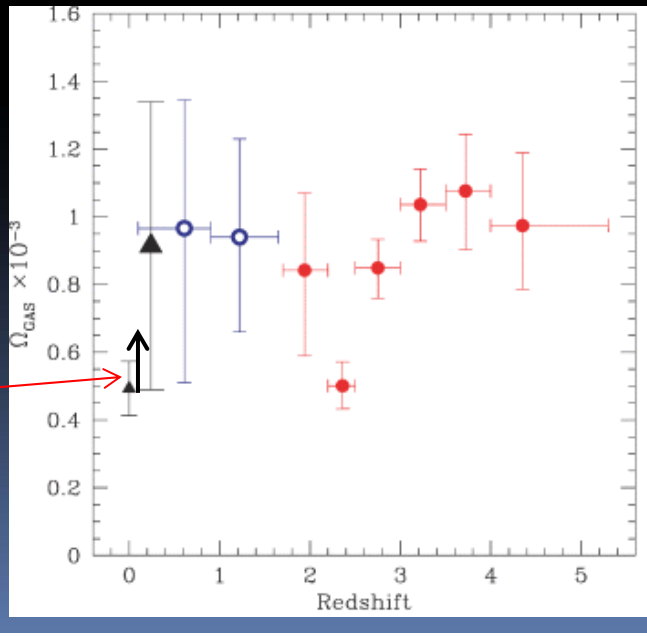
gas ↓

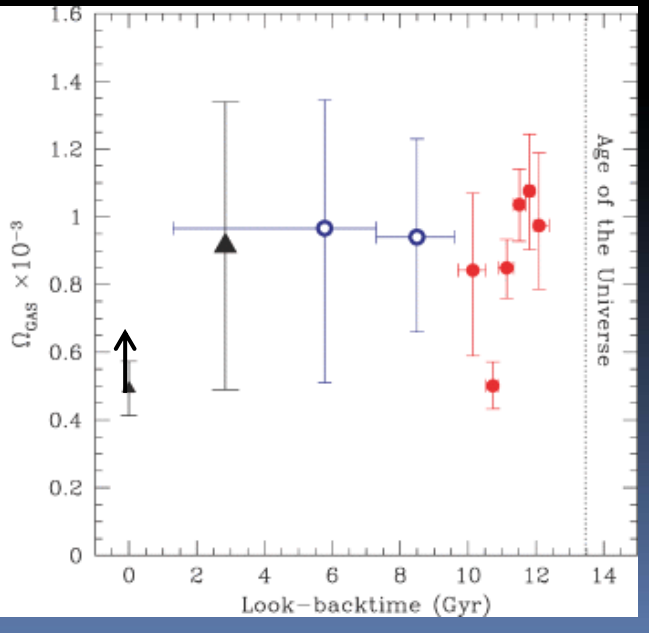


Hopkins & Beacom



HIPASS (Parkes), ALFALFA (Arecibo)





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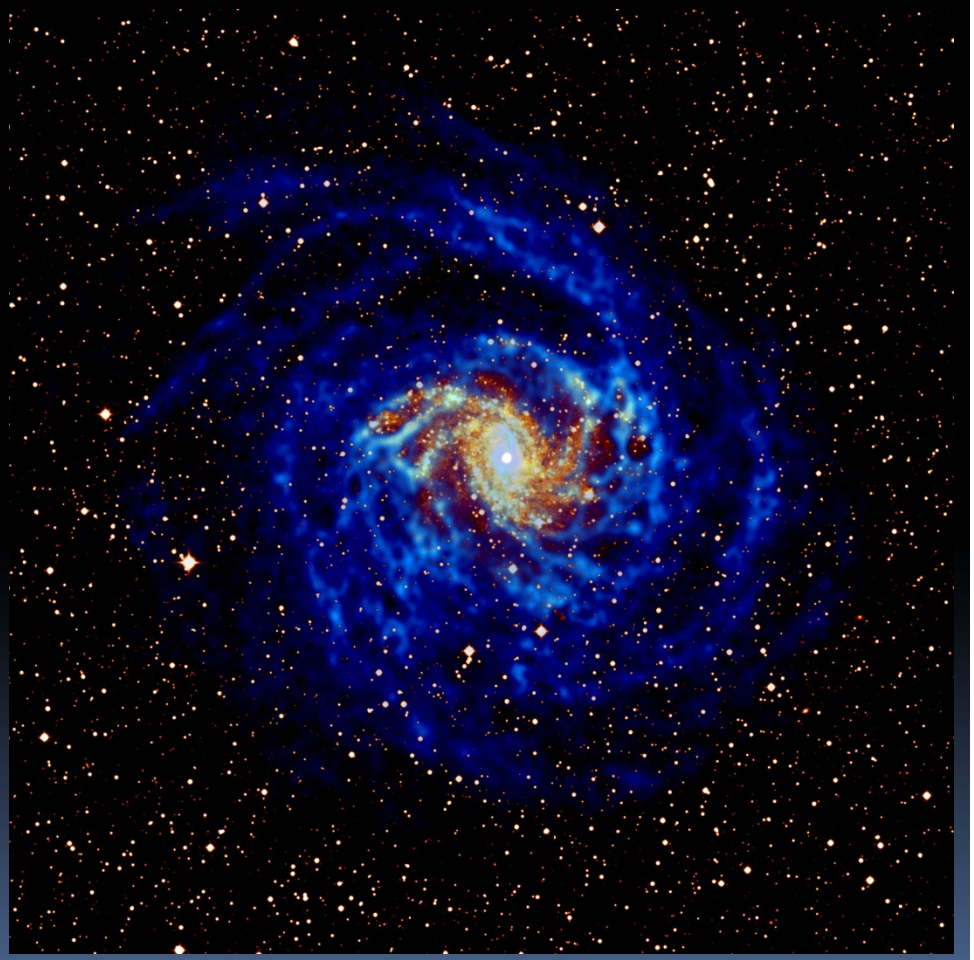
Galaxy Assembly

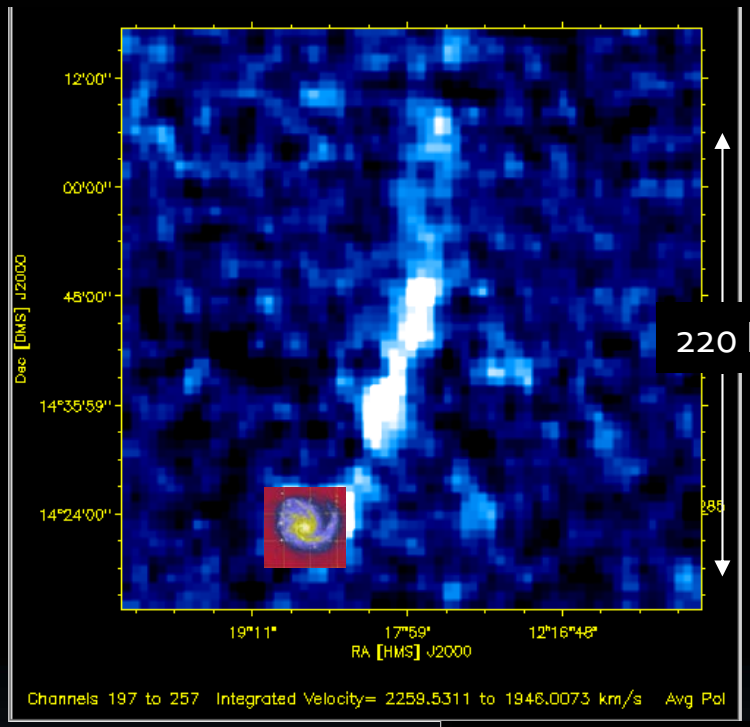
Multi-wavelength view of galaxies

- H I and optical
- Part of a study on gas (H I) flows from the disk into the halo
- Involves radio (H I and continuum), Hα, X-ray

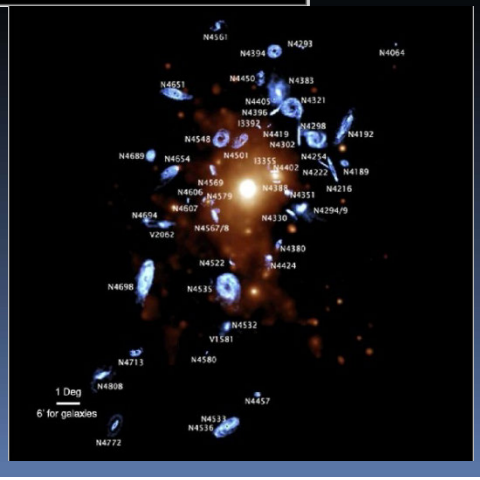


NGC 6946 (T. Oosterloo)

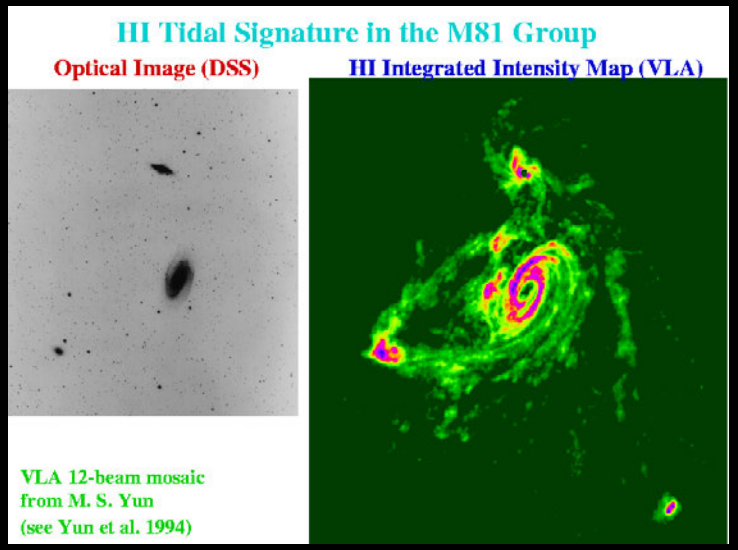
Evolution and Environment



NGC 4254 in Virgo (ALFALFA)



VIVA



- How do galaxies gain and lose gas?
- Infall vs. removal processes
- Gas serves as a tracer of interactions.

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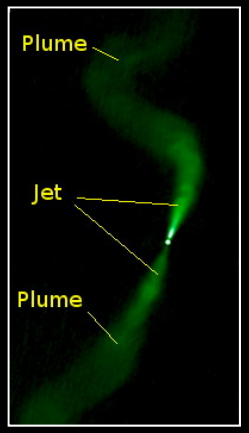
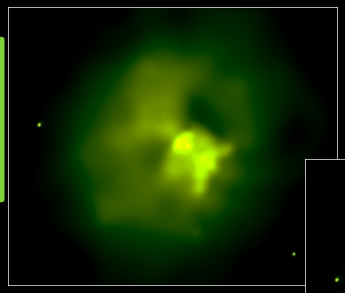
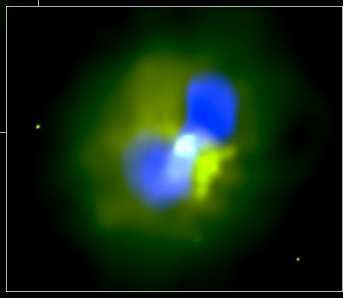
… and Feedback



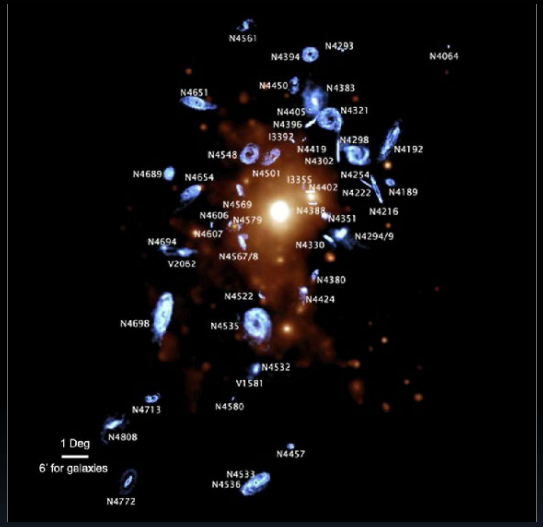
Radio Jet activates

Heats X-ray gas





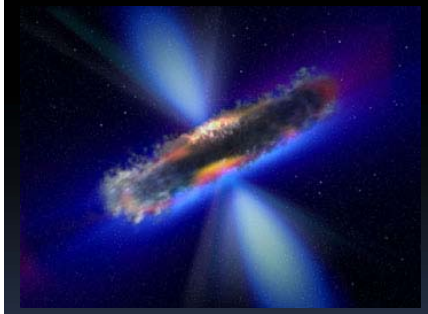
Offset X-ray cooling



BH stops accreting

RG is quiescent

X-ray cooling



BH accretion

Clarke, Feretti

Astrobiology at Long Wavelengths

Long Wavelengths ($\lambda > 1$ cm)

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

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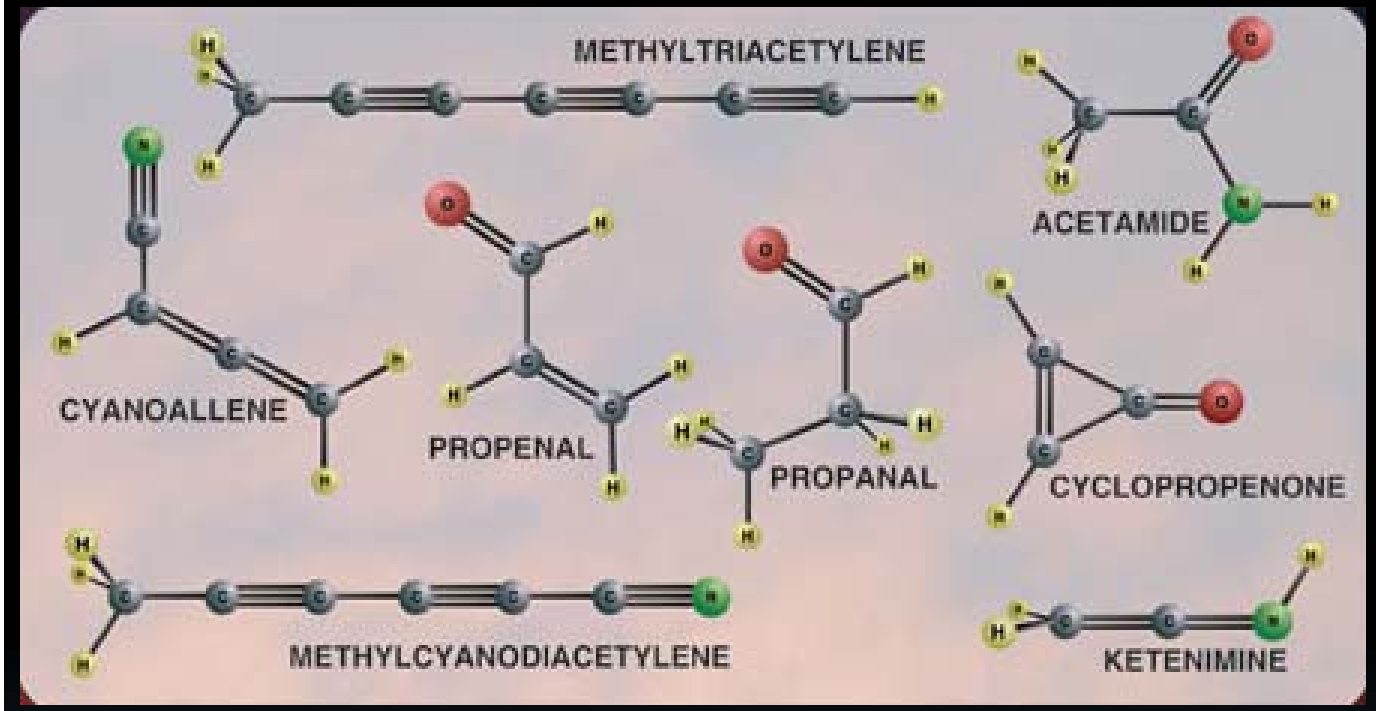
Interstellar Molecules

Nearly 150 molecules detected in interstellar space



Recently detected interstellar molecules from the GBT (Hollis and collaborators)

- Many of these are "organic."
  - Illustrates importance of carbon in chemistry of life.
  - Are there biological molecules not yet detected? (Amino acids?)
- Connection to protoplanetary disk chemistry?

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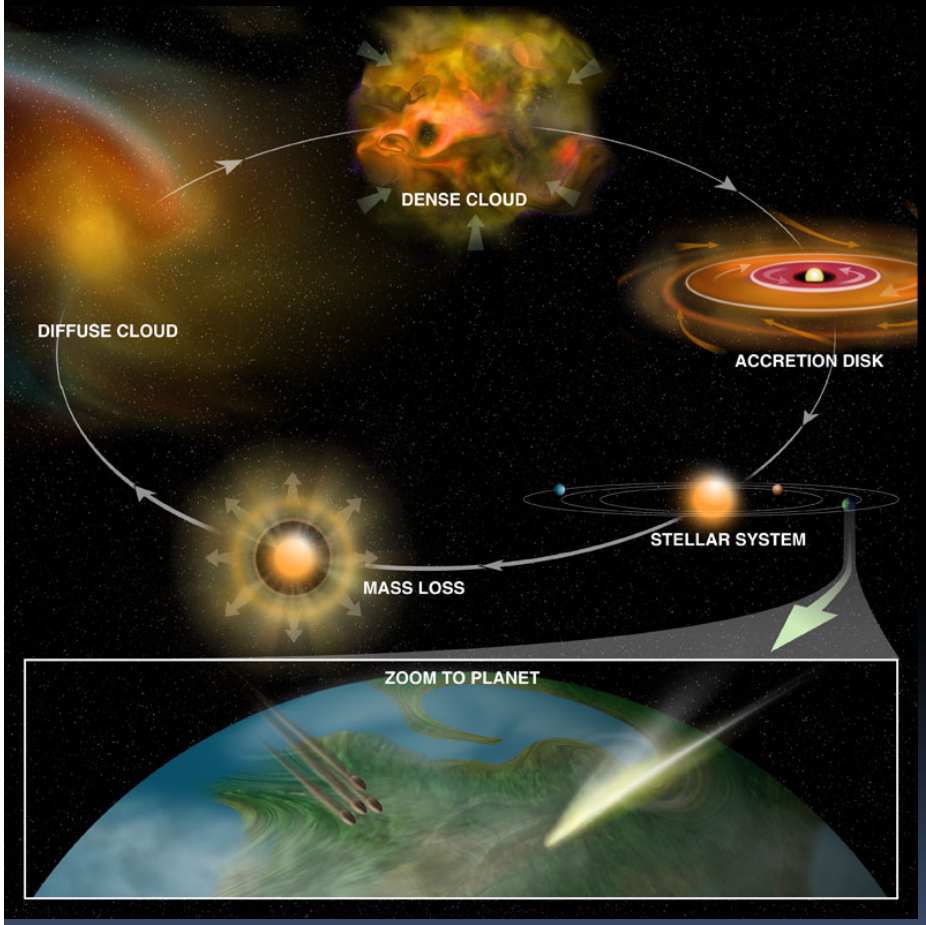
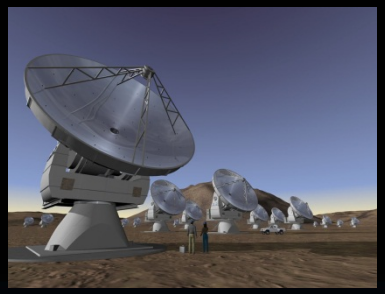
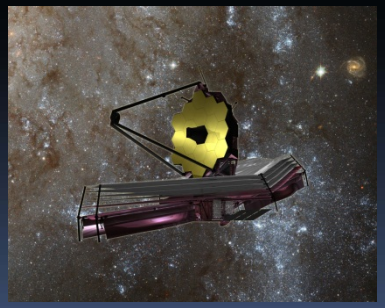
Astrobiology



SKA: protoplanetary disks, molecules, planets, SETI



ALMA: protoplanetary disks, molecules



JWST: protoplanetary disks

Optical: protoplanetary disks, planets

Emerging Themes for 21st Century Astrophysics

20th Century: We discovered our place in the Universe

21st Century: We understand the Universe we inhabit

Fundamental Forces and Particles

- Gravity
  - Radio pulsar tests of GR
  - Dark Energy and BAOs with H I galaxies
- Magnetism
- Strong force

  Nuclear equation of state

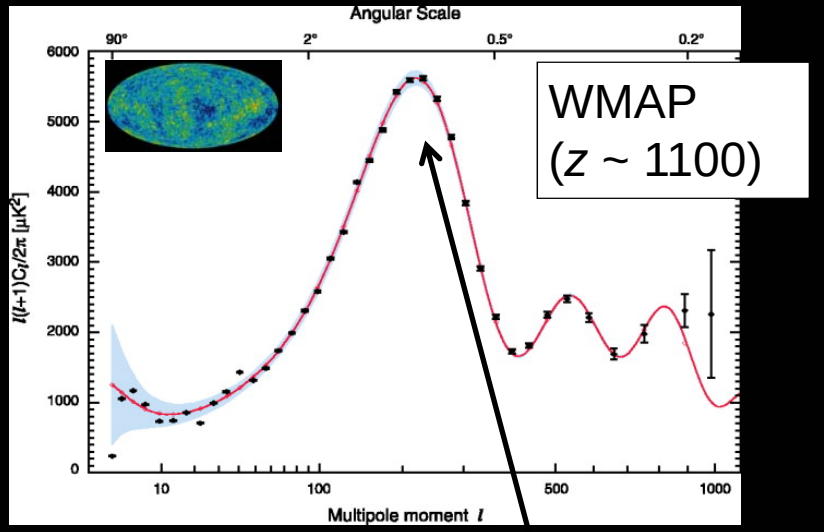
Origins

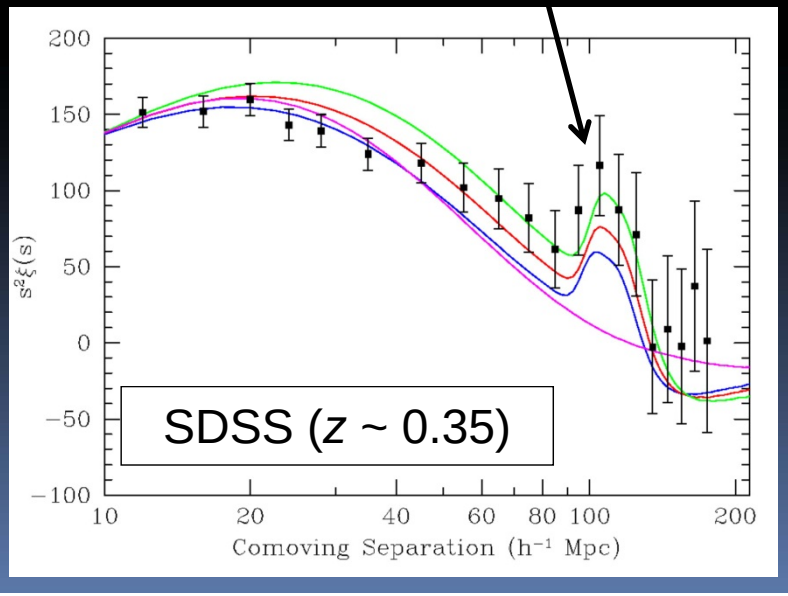
- Galaxies and the Universe
  - IGM and First Galaxies @ Epoch of Reionization
  - Galaxy Assembly and Evolution (a.k.a. "Billion Galaxy Survey")
- Stars, Planets, and Life
  - Protoplanetary disks
  - Biomolecules
  - SETI

Baryon Acoustic Oscillations

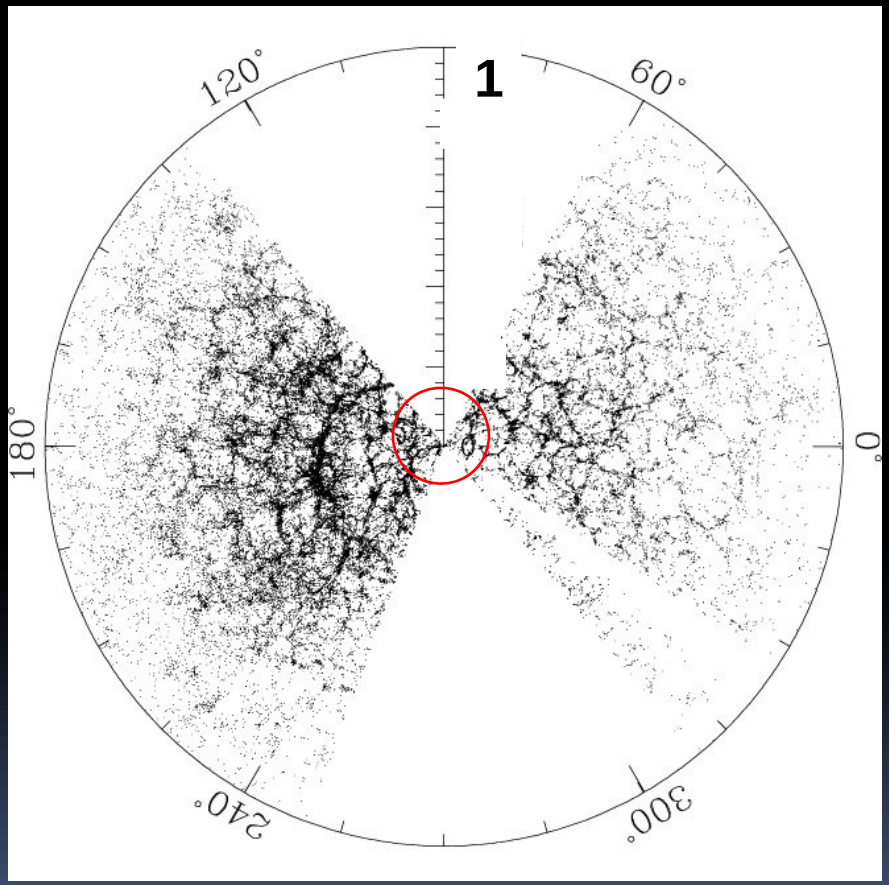
Remnant of plasma acoustic oscillations in early Universe

- $D_A(z)$ = angular size distance as a function of redshift
- ~ 100 h^{-1} Mpc "standard ruler"
- Measures expansion rate of Universe





SKA: Stage IV BAOs



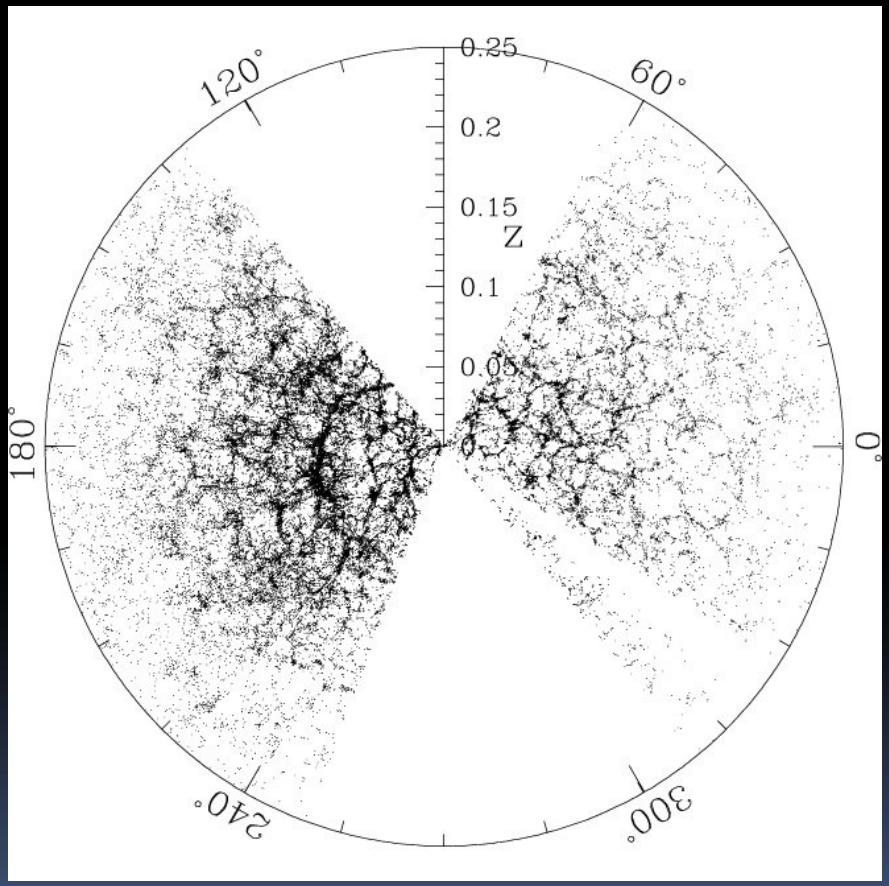
SDSS

SKA

- Next-generation goal:
  - Survey large volume
  - Slice into redshift bins
  - Detect BAOs in each *z* bin
- SDSS surveyed ~ 1 Gpc^3

  One redshift bin ~ 0.35
- SKA targeting 100 Gpc^3 ($z > 1$)
- H I galaxies
  - Intrinsically spectroscopic survey
  - Different biases than LST, JDEM

SKA: Stage IV BAOs



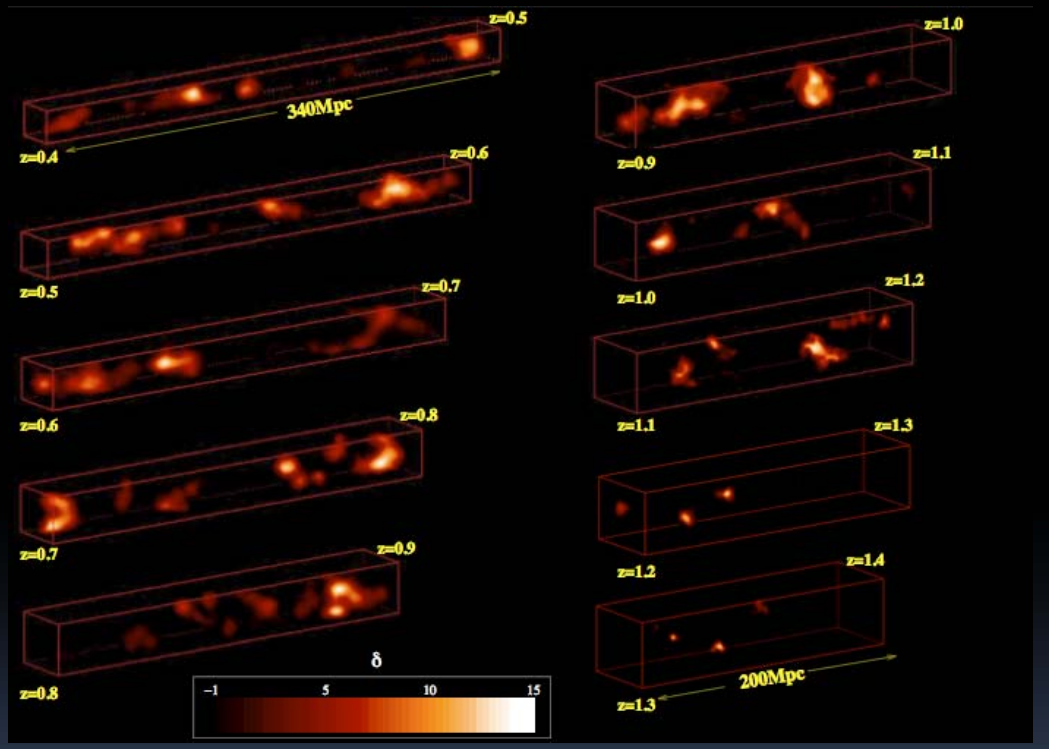
SKA: H I BAOs ("Billion-Galaxy Survey")

LST: BAOs, supernovae, weak lensing, …

JDEM: supernovae, …

Galaxy Biasing and Large-Scale Structure Growth

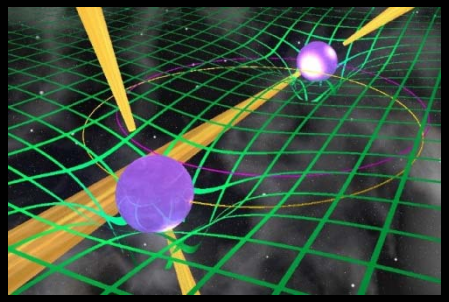
- VVDS finds complex structure to $z \sim 1$
- Statistics of galaxy distribution consistent with growth of instabilities in the framework of general relativity over $0 < z < 1.5$ …
- *Only with* biasing
- Pencil-beam survey, to $2L_*$
- ➢ H I galaxies present the same biasing?

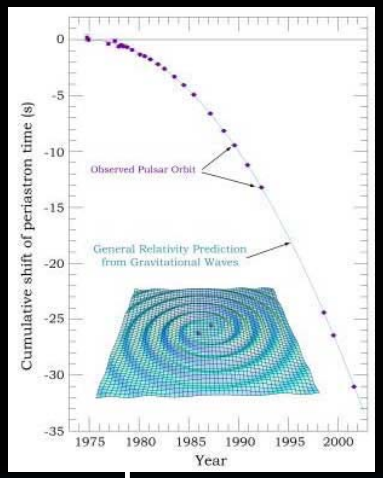


galaxy overdensities in VVDS (Marinoni, VVDS Team)

Did Einstein Have the Last Word on Gravity?

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

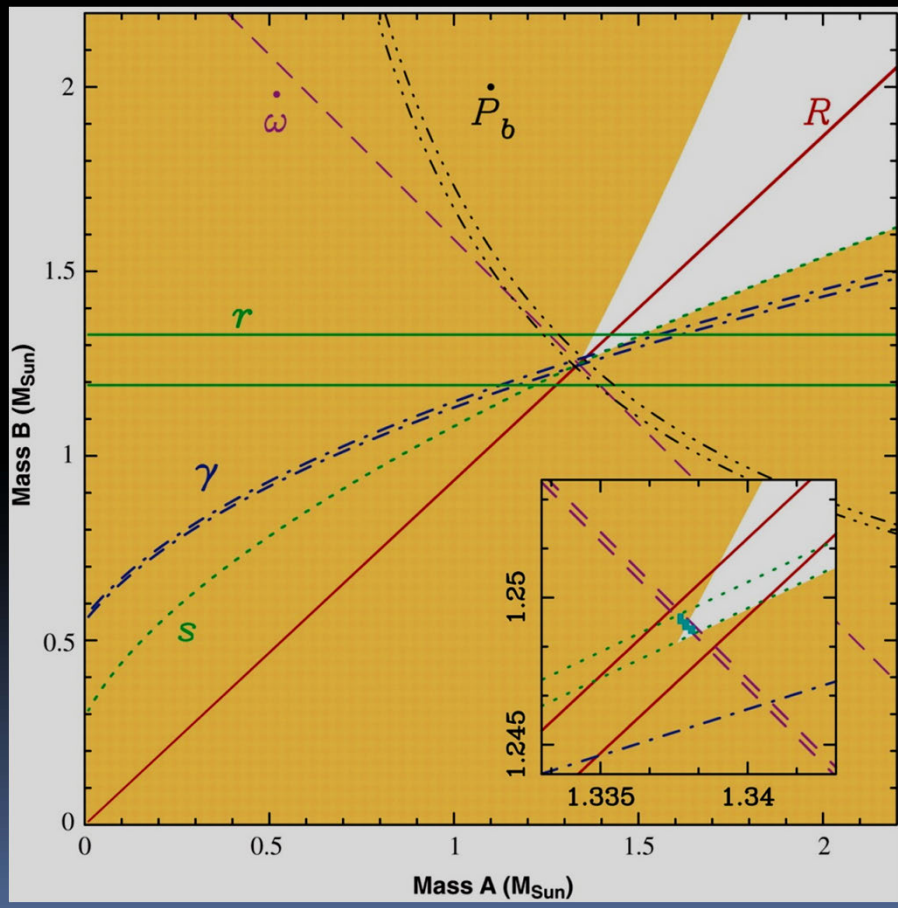




- Relativistic binaries probe
  1. Equivalence principle
  2. Strong-field tests of gravity
- Only neutron star-neutron star binaries known

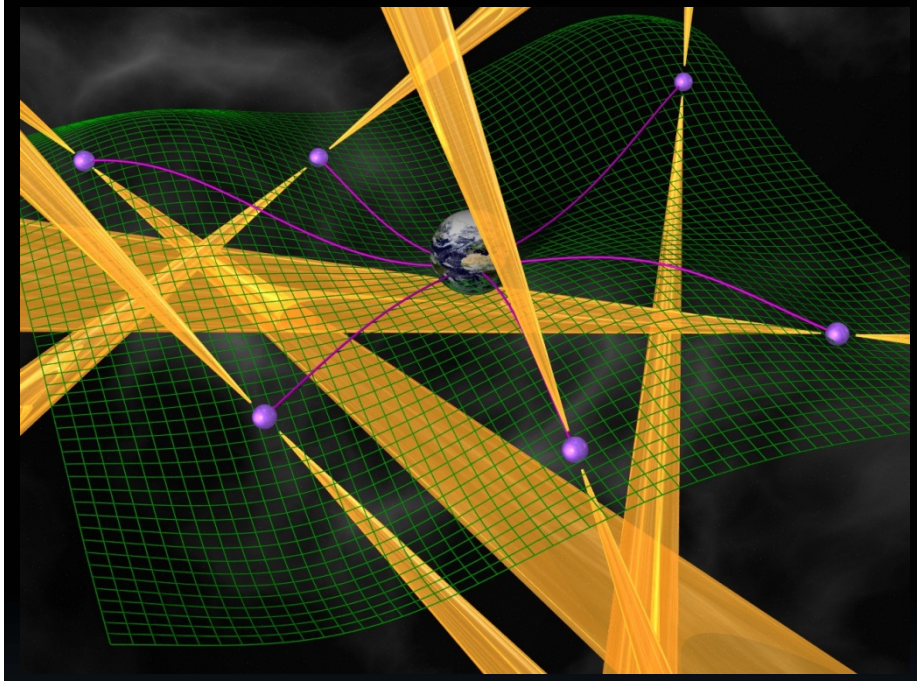
? Black hole-neutron star binaries?

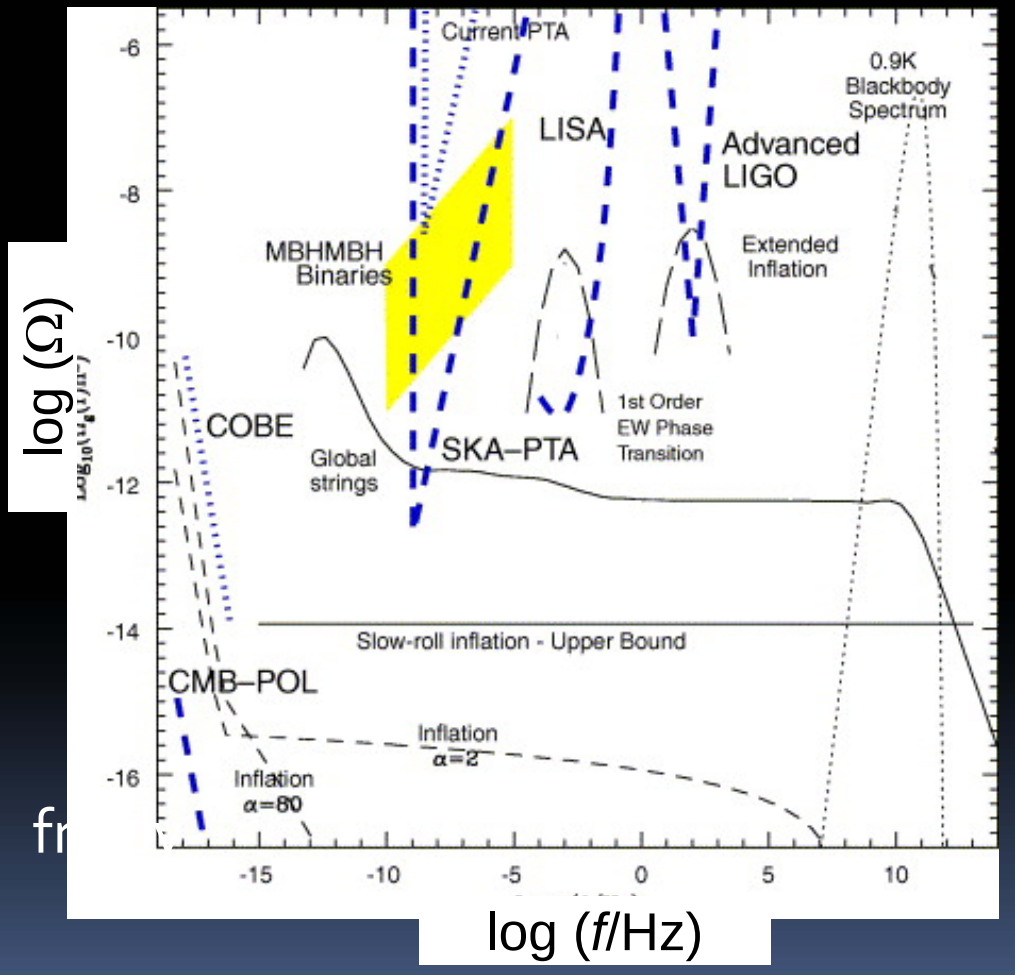
PSR J0737–3039



Kramer et al.

SKA: Gravitational Wave Detector





Test masses on lever arm

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

JOINT INSTITUTE FOR VLBI IN EUROPE

EoS of Nuclear Matter

"New States of Matter at High Density and Temperature?"

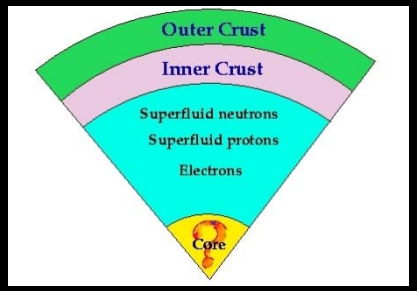
Connecting Quarks to the Cosmos

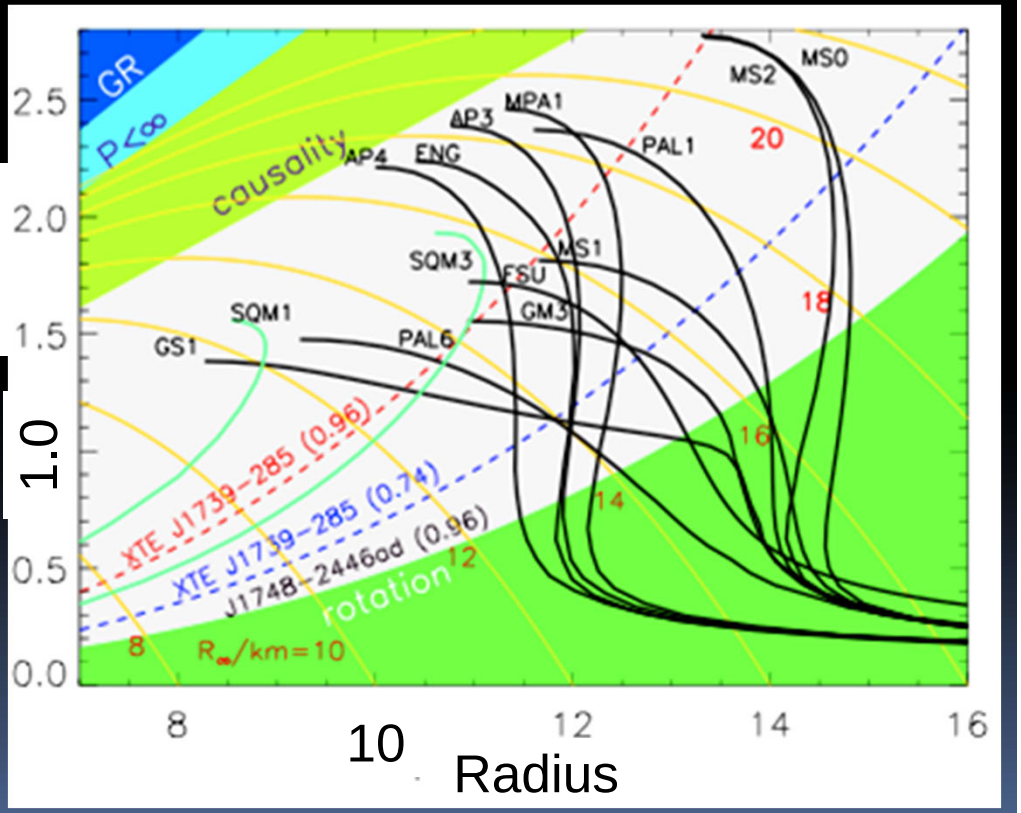
- Central density > 10^{14} g cm^{-3}

  Existence of stable states beyond "normal" nuclear matter? (Quark stars, …)

- Mass and radius
  - Same object?
  - M > 2 $M_\odot$ (Freire et al.)
- Rotation rates
  - 30 pulsars with P < 3 ms
  - 7 pulsars with P < 2 ms
  - 1 pulsar with P < 1.5 ms

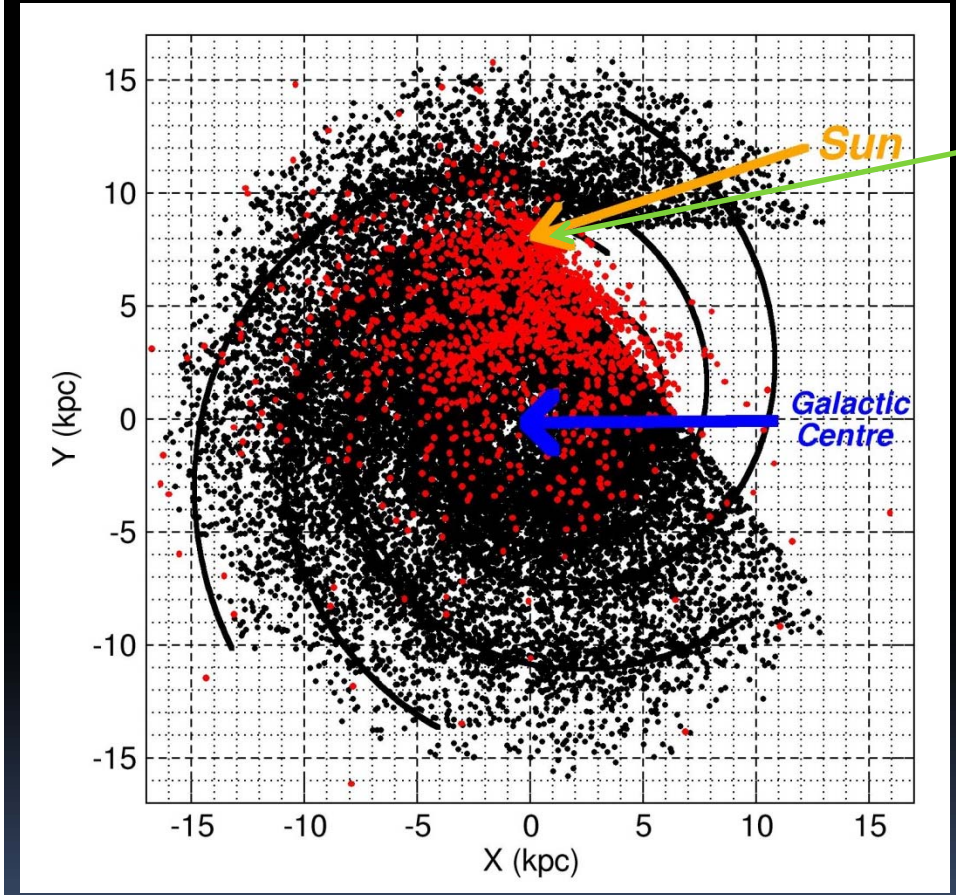
    J1744−2446ad





Lattimer & Prakash

Galactic Pulsar Census



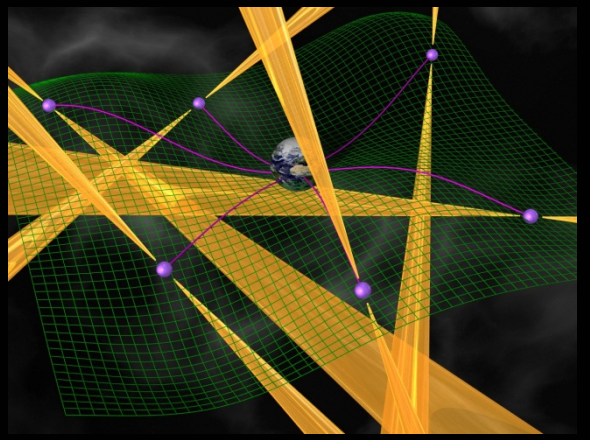
- "Interesting" pulsars < 1% of population
  - Rapidly spinning millisecond pulsars
  - Ultra-relativistic binaries
  - Ultra-stable millisecond pulsars
- Find only the most interesting by finding all!

- Understand the interstellar medium
- Galaxy as a prototypical $z = 0$ galaxy

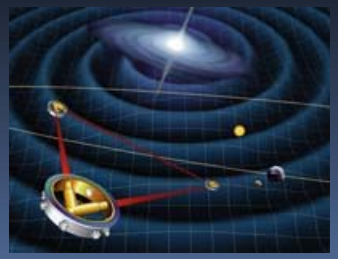
Fundamental Forces

SKA: gravity, strong force, magnetism

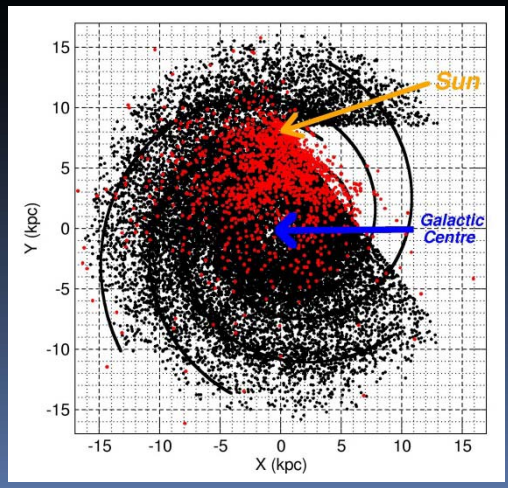
$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}/c^4$$



X- and γ-rays: gravity, strong force



LIGO, LISA: gravity



21st Century Astrophysics

Fundamental Forces and Particles

- Gravity
- Magnetism
- Strong force

Origins

- Galaxies and the Universe
- Stars, Planets, and Life

"The Universe is patiently waiting for our wits to grow sharper."

Photon frequency/wavelength/energy

Time

Polarization

Sensitivity

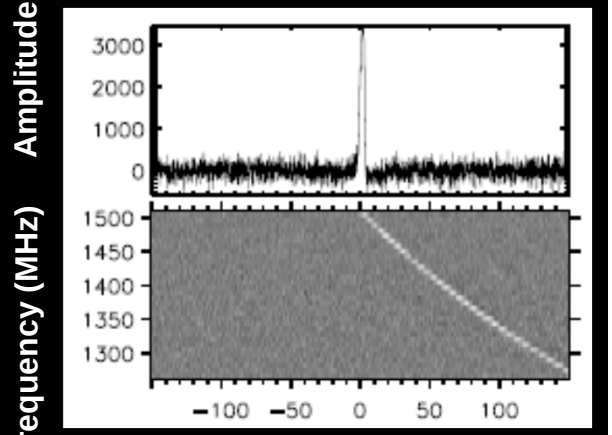
Field of View

Angular Resolution

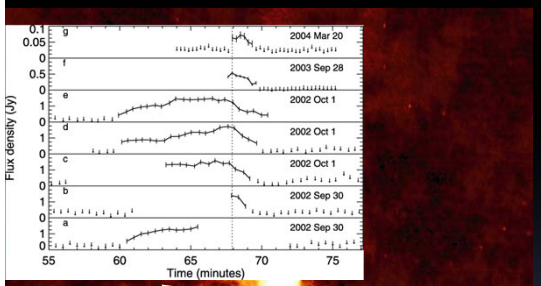
The Dynamic Radio Sky

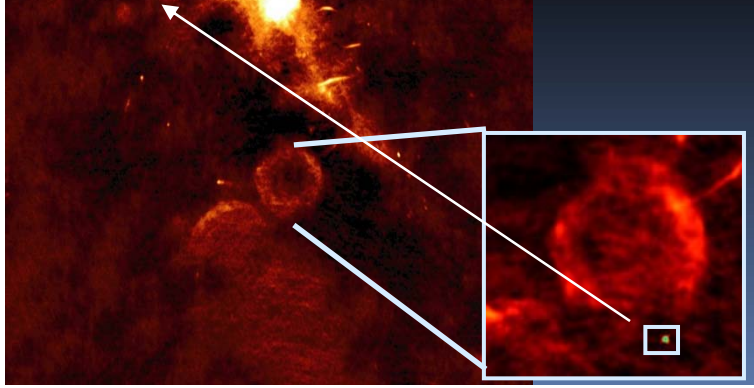
- Neutron stars
  - Magnetars
  - Giant pulses
  - Short GRBs?

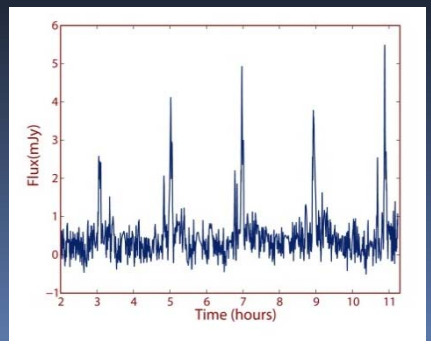
- GRBs (γ-ray loud; γ-ray quiet?)
  - Afterglows
  - Prompt emission?
- Sub-stellar objects
  - Brown dwarfs
  - Extrasolar planets?
- Microquasars
- Scintillation
- UHECRs
- ETI
- Exploding black holes
- ???

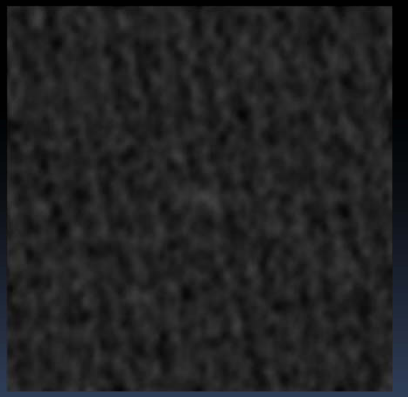


Rotating Radio Transients (RRATS)









Pulsating Brown Dwarfs

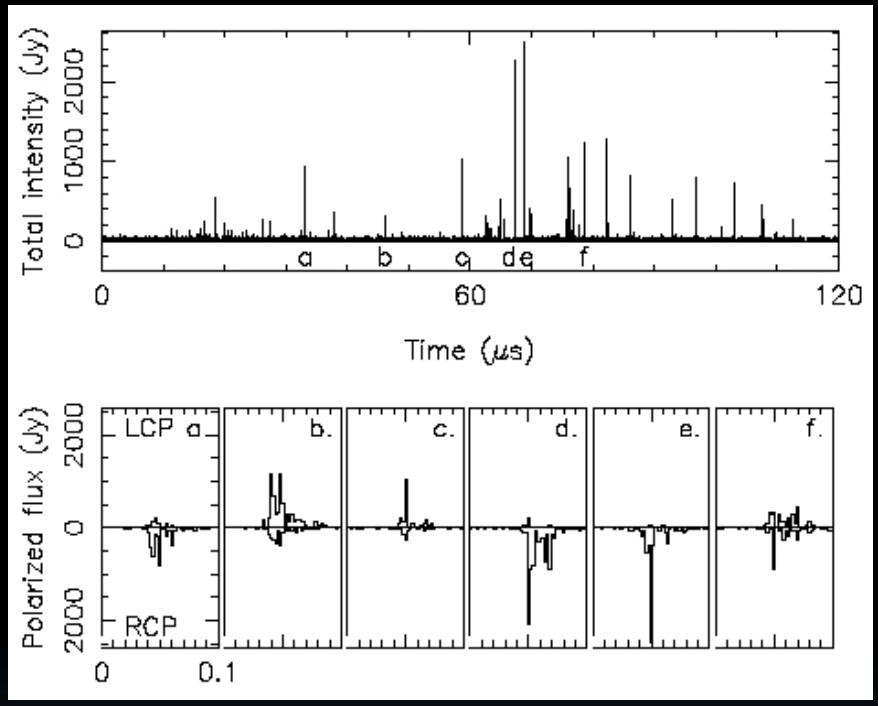
Dynamic Radio Sky

All-sky surveys

(3C, NVSS, …)

+

(?)



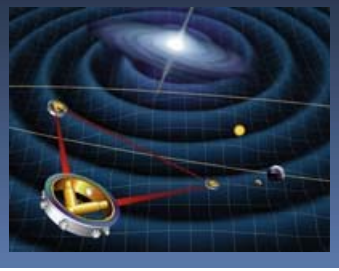
Nano-second pulses from the Crab pulsar, from Arecibo

Dynamic Radio Sky and 21st Century Astrophysics

SKA

Optical survey telescopes

X- and γ-rays



LIGO, LISA

Transient sources are necessarily compact

- Locations of explosive or dynamic events
- Probe fundamental physics and astrophysics
- Radio signals modified by, and are powerful probes of, intervening media
  - Dispersion
  - Scattering
  - Faraday rotation
- Media include
  - Interplanetary medium (IPM)
  - Interstellar medium (ISM)
  - Intergalactic medium (IGM)

21st Century Astrophysics

Fundamental Forces and Particles

- Gravity
- Magnetism
- Strong force

Origins

- Galaxies and the Universe
- Stars, Planets, and Life

"The Universe is patiently waiting for our wits to grow sharper."

Photon frequency/wavelength/energy

Time

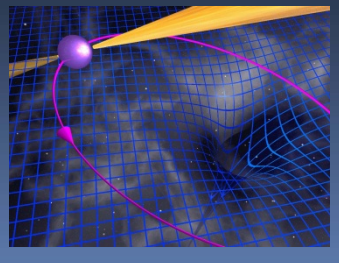
Polarization

Sensitivity

Field of View

Angular Resolution

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.



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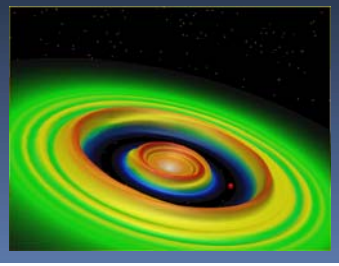
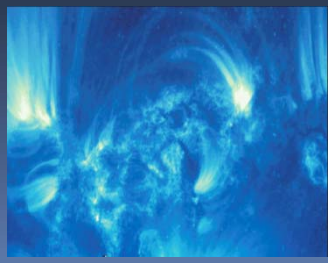
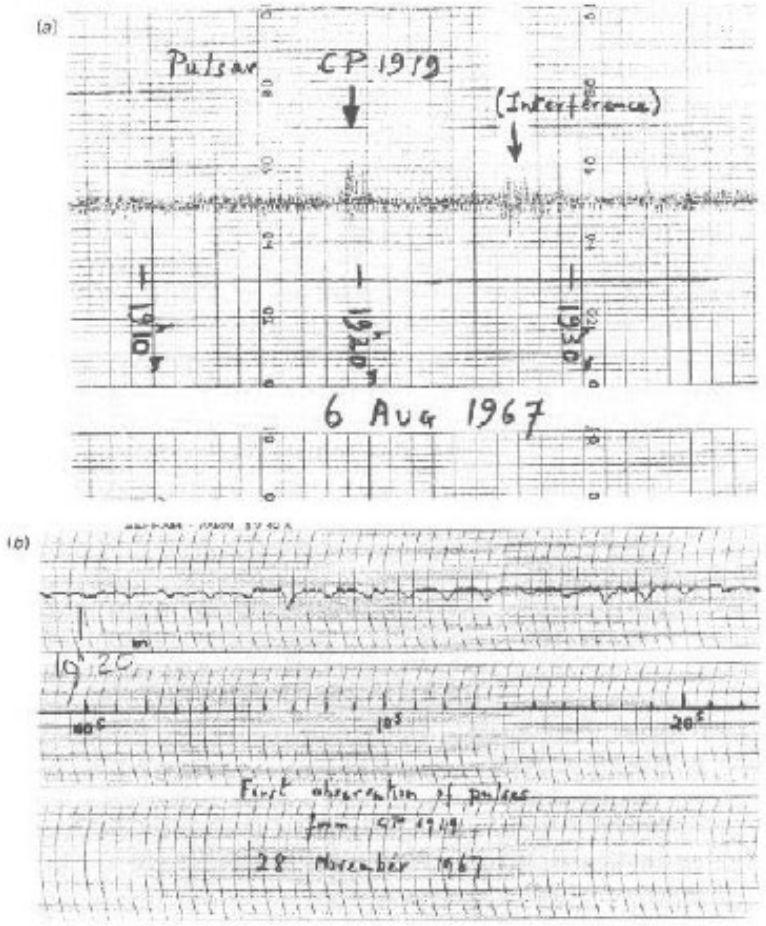




Exploration of the unknown

- **Unplanned discoveries**
  - Pulsars
  - Microwave Background
  - Cosmic Evolution
  - Dark Matter in galaxies
  - Quasars
  - Jets + Superluminal motion
- **Transients**



Radio Astronomy
The first of the new astronomies

- Cosmic radio emission
- Non-thermal radiation
- Solar radio bursts
- Radio galaxies
- Mercury/Venus rotation
- Interstellar molecules
- CMB
- Jupiter bursts
- Gravitational waves
- Gravitational lensing
- Cosmic masers
- Quasars
- Pulsars

SKA specifications

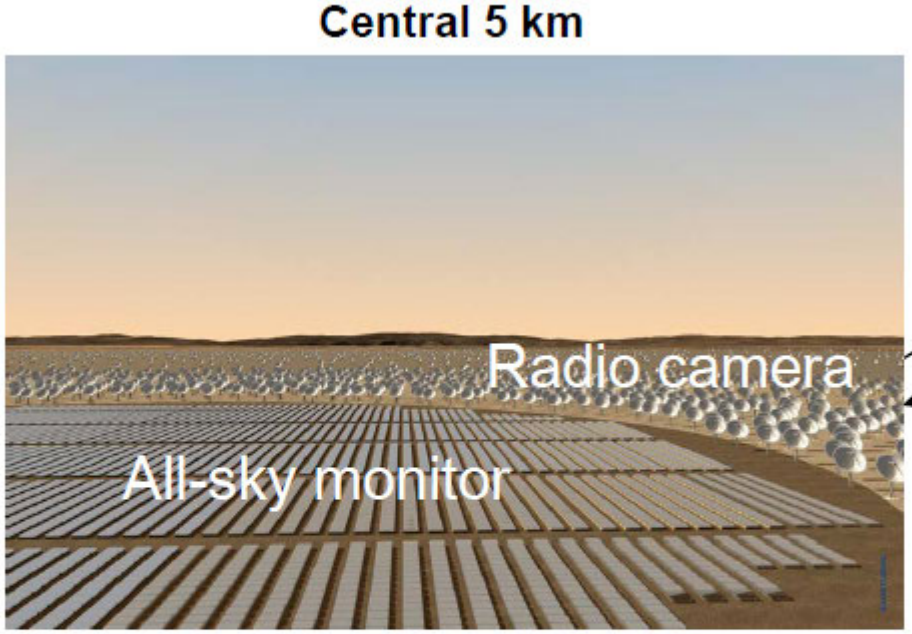
SKA reference design

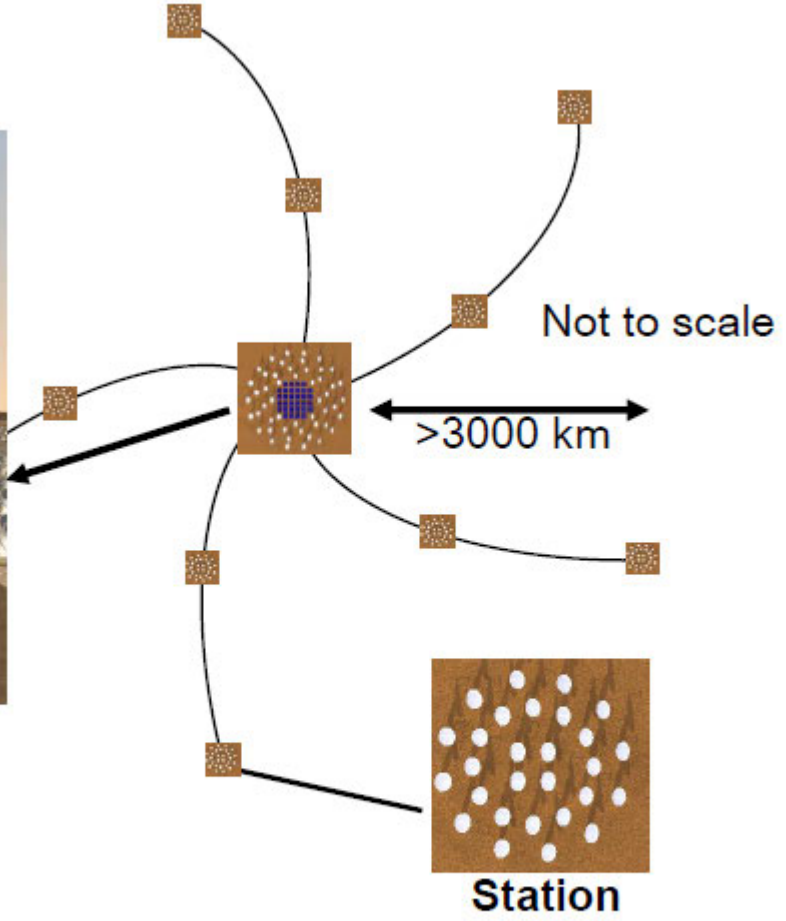
(SKA R&D has been going on since ~1995)

- Interferometer array of sensors centred on a massive data processor

- Sensor types
  - Dishes + wide band single pixel feeds *(baseline)*
    (mid-band + high-band)
  - Dishes + multi-pixel phased array feeds
    (mid-band)
  - Aperture arrays
    (low-band, mid-band)

Reference design





SKA will be built out from the centre

First 15% (phase 1) will have max baselines ~50 km

SKA: preparatory work packages

WP1 PrepSKA management

WP2 Costed telescope design

WP3 Further site characterization in Australia and Southern Africa

WP4 Governance

WP5 Procurement and involvement of industry

WP6 Options for funding

WP7 Impact on broad government priorities

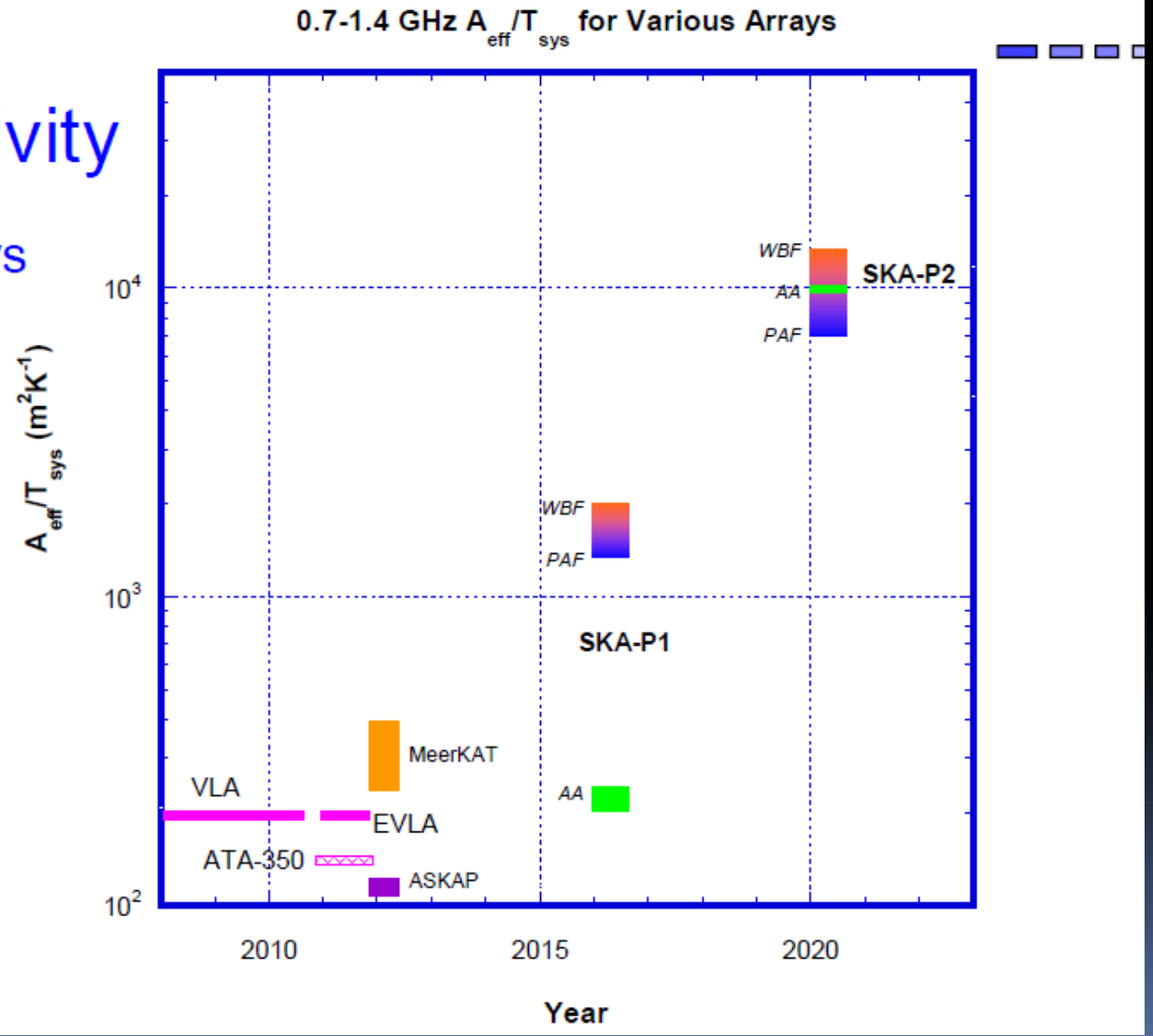
SKA WP2: telescope design and cost

Coordinated by the SKA Program Development Office in Manchester

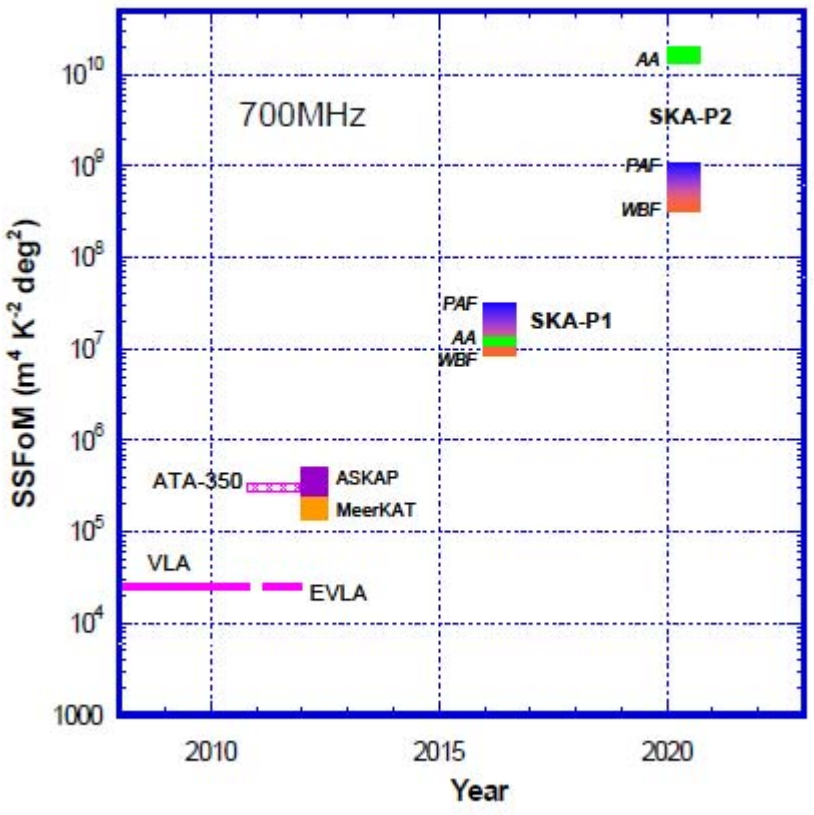
- Dishes, feeds, receivers
- Aperture arrays
- Signal transport
- Signal processing
- Software
- High performance computers
- Data storage
- Power requirements

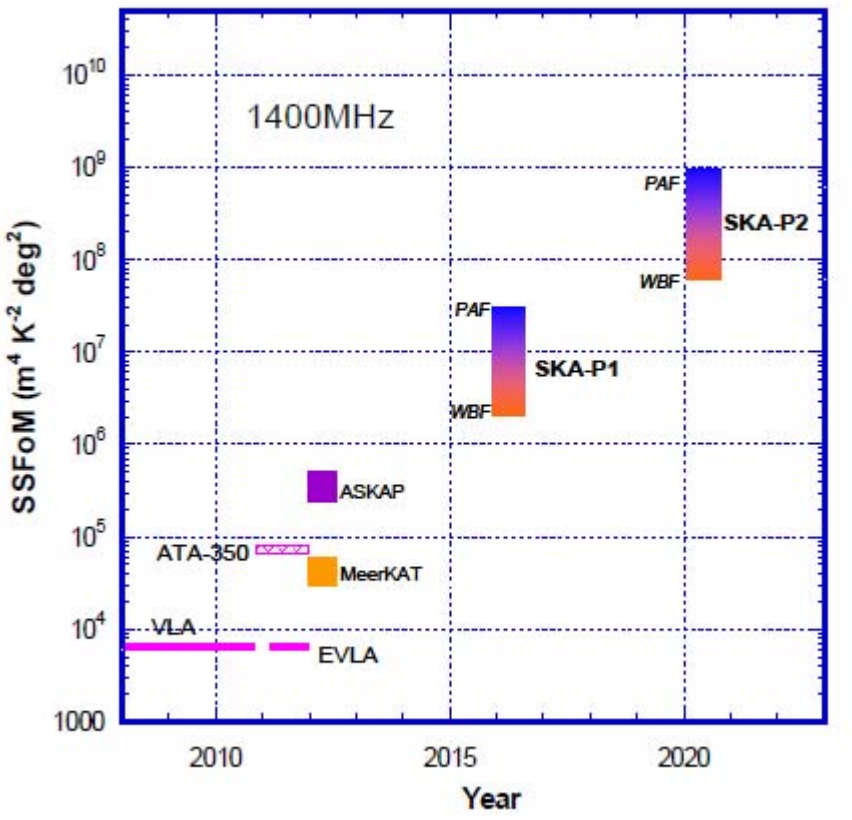
Sensitivity!!!

Sensitivity
A_{eff}/T_{sys}

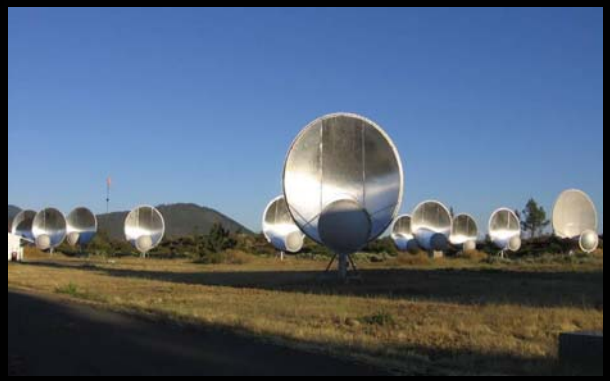


Survey speed





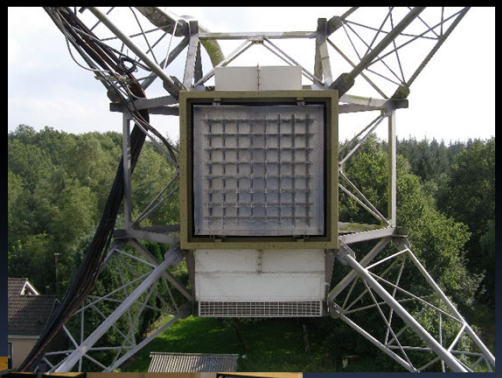
SKA Technologies



Novel antenna construction

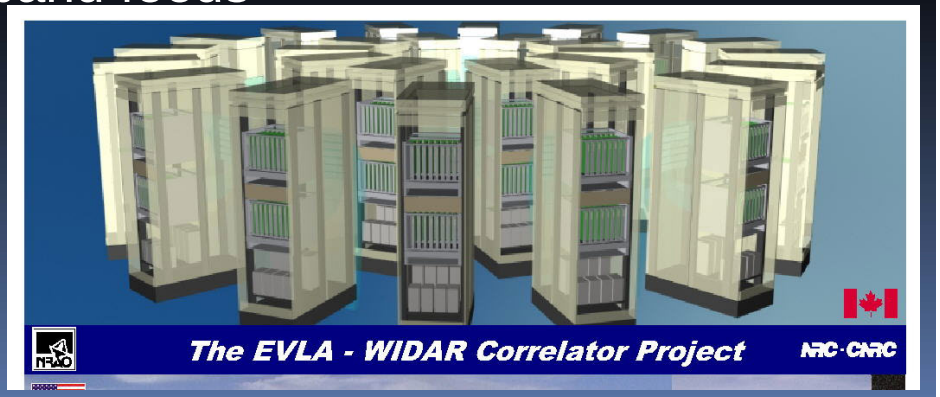
Fiber optic transmission

Ultra wide-band feeds



Phased arrays

(FoV expansion)



Dishes+single-pixel feeds

USA

ATA 6m
hydroformed dish

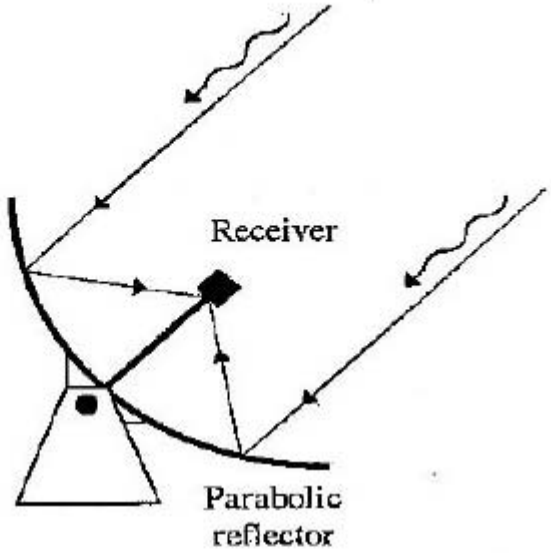
Canada

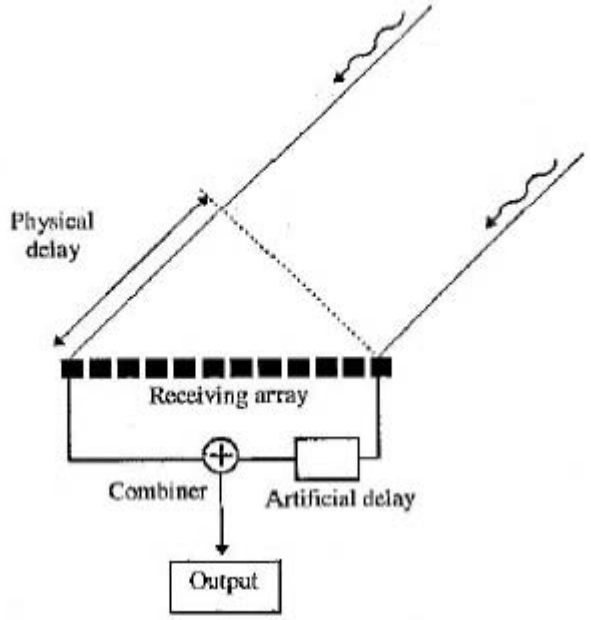
10 m composite dish

South Africa

15 m composite dish

Electronic beam-forming





Processing of wavefront by "optical" beam-former

Processing of wavefront by electronics and software

- cost decreases with time – Moore's law
- aperture re-use – many telescopes at once!
- individual apertures can be part of much bigger "aperture synthesis" correlation array

e-EVN: an SKA pathfinder

Fibre connections

High speed data processing and storage

Cost

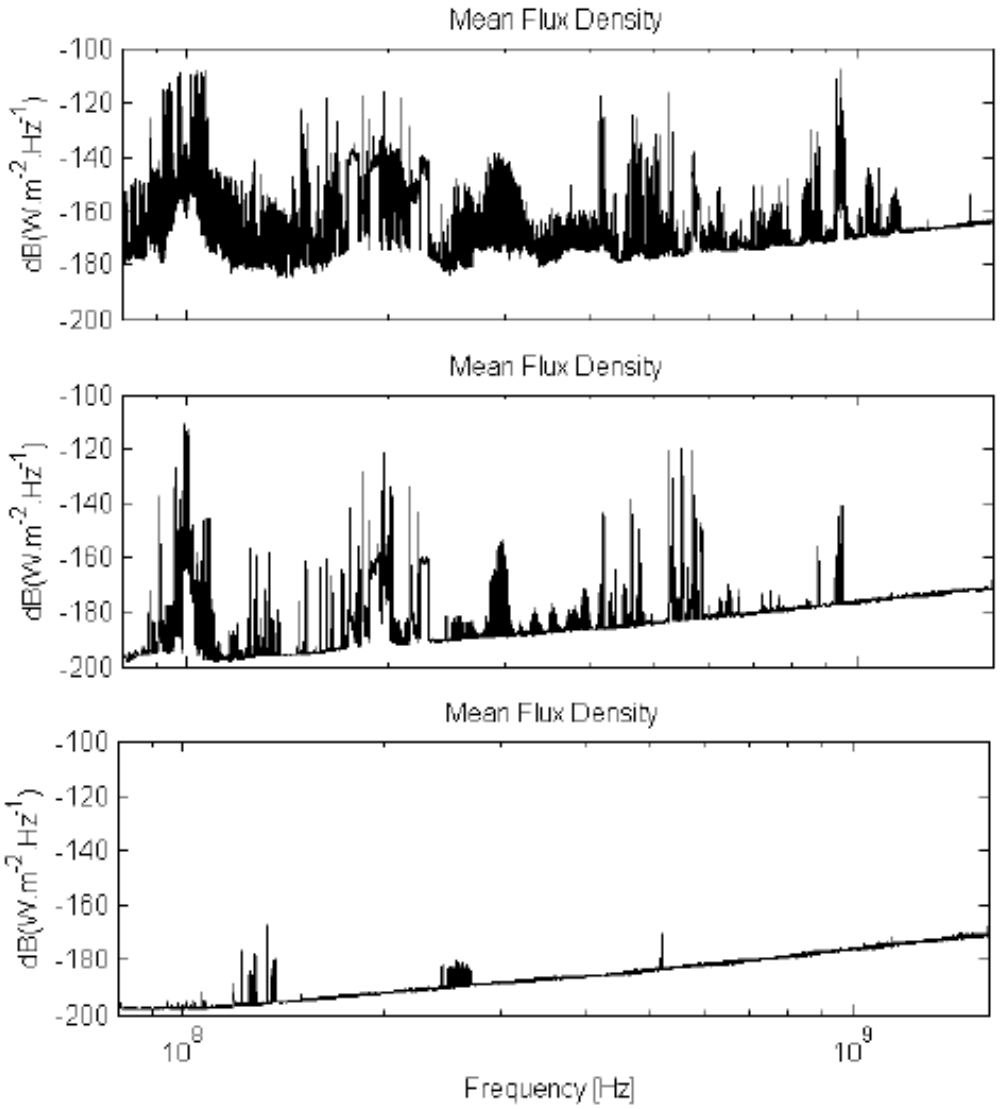
- Target construction cost: 1.5 billion € for Phases 1+2
- Expected operating costs: 100+ million €/year
  - Energy costs a big contributing factor
- Currently funded SKA R&D (2007-2012) via national and regional projects: 140 M€
  - PrepSKA (FP7) funds the SPDO engineering team
  - Design Studies (FP6 SKA Design Study, US Tech Dev Program)
  - Pathfinders (ASKAP, MeerKAT, LOFAR, Apertif, ATA, MWA, LWA, EVLA, eMERLIN, eEVN)

SKA site selection

- Physical characteristics required
  - Very quiet radio frequency environment, particularly for the core region
  - Large physical extent (>3000 km)
  - Low ionospheric turbulence
  - Low troposphere turbulence

- Favourable socio-political environment
  - Stability
  - Predictability

Radio-frequency interference (RFI)



Large city
population: several million

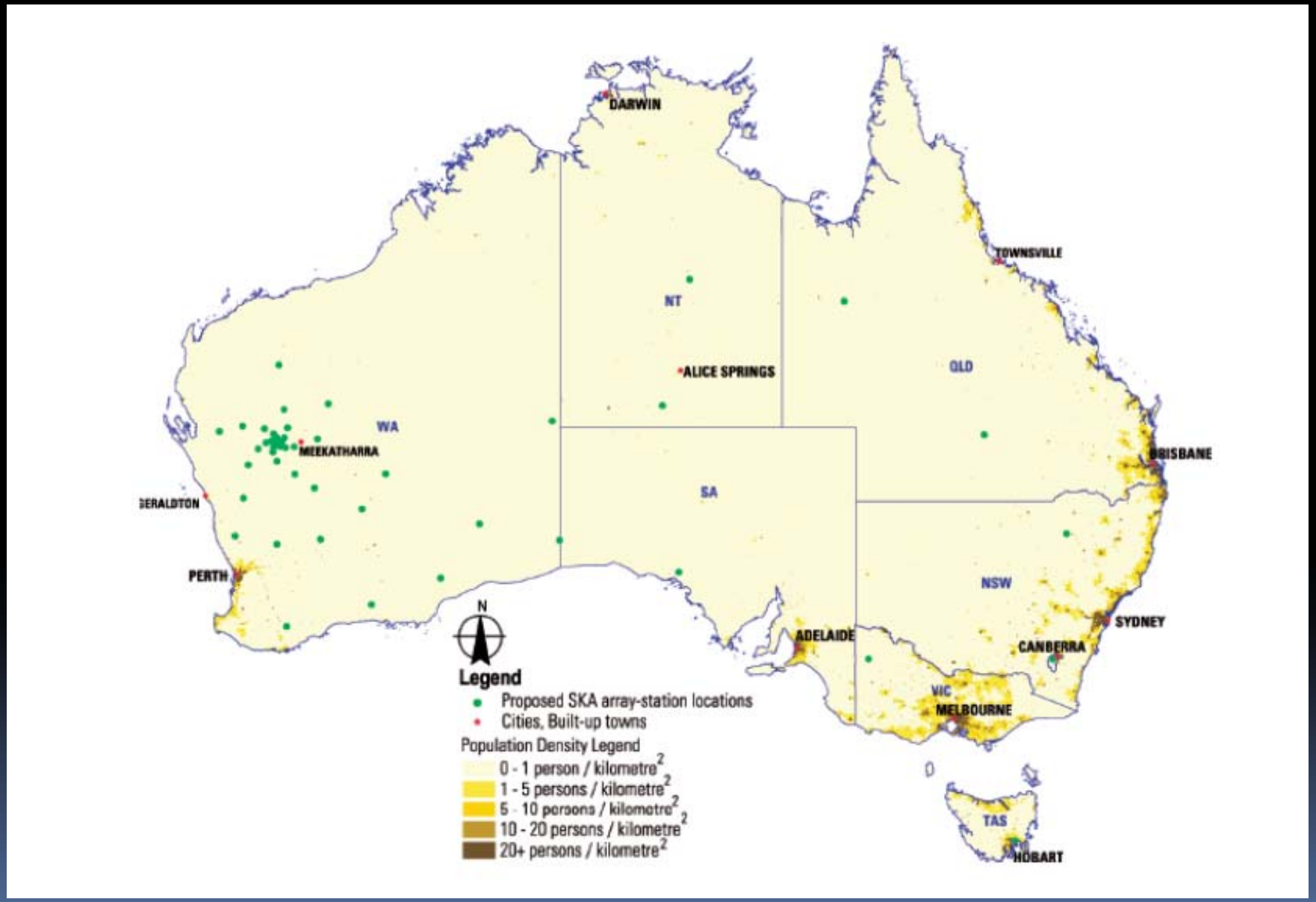
Town
population: several thousand

Candidate SKA core site
population: a few

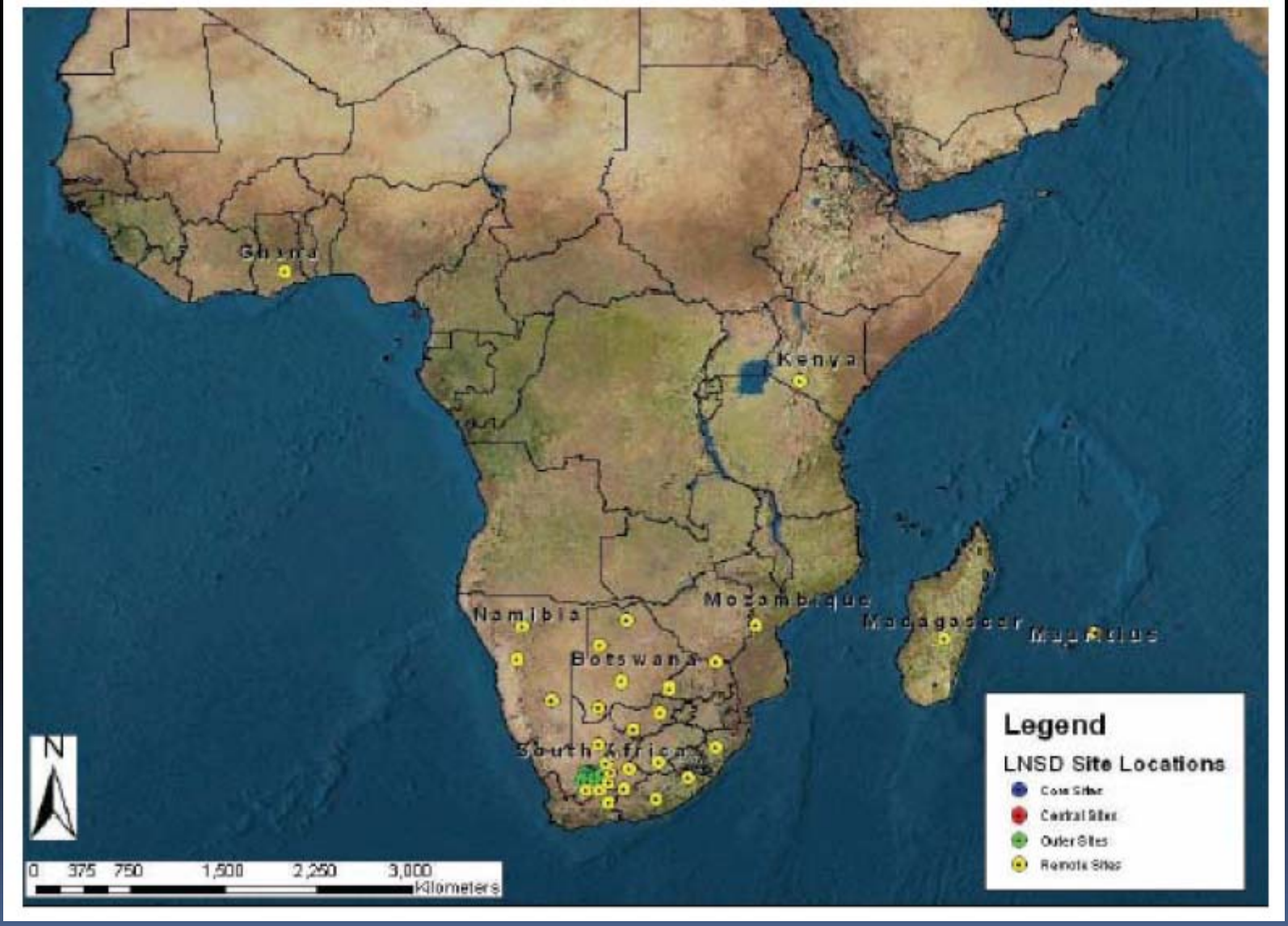
Site selection process

- Physical characteristics required
  - Very quiet radio frequency environment, particularly for the core region
  - Large physical extent (>3000 km)
  - Low ionospheric turbulence
  - Low troposphere turbulence
- Not many suitable sites in the world
- Site selection process started in 2003
  - Request for full proposals issued 1 September 2004
  - Four proposals received on 31 December 2005
  - Short-list of acceptable sites 30 August 2006
    - » Southern Africa, Australia
- Site selection 2012

Australia + New Zealand



South Africa + 7 African countries



…and the winner is…

Radio astronomy

Further information: