Science with The Square Kilometre Array

Joseph Lazio
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&
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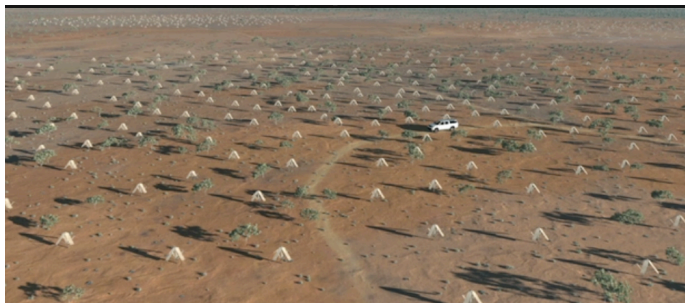
Euro 2012

- My father's family is from Italy.
- My mother's family is from Ireland.

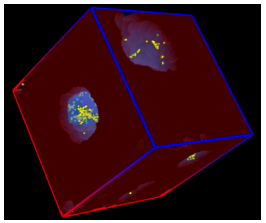
Which team should I support?

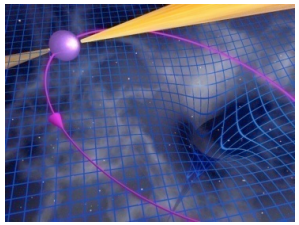
Square Kilometre Array

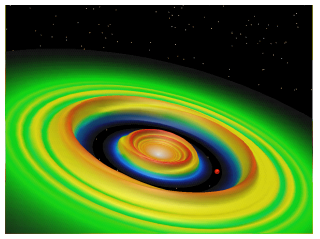
Global Radio Wavelength Observatory

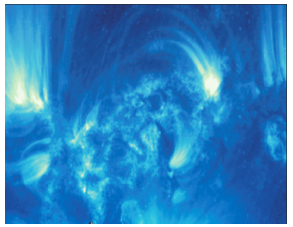


- Originally: “Hydrogen telescope”
  - Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$
- SKA science much broader
  - ⇒ Multi-wavelength, multi-messenger
- On-going technical development
- International involvement









SKA Key Science

International working group

- Strong-field Tests of Gravity with Pulsars and Black Holes

  Phase 1 headline science

- Galaxy Evolution, Cosmology, & Dark Energy

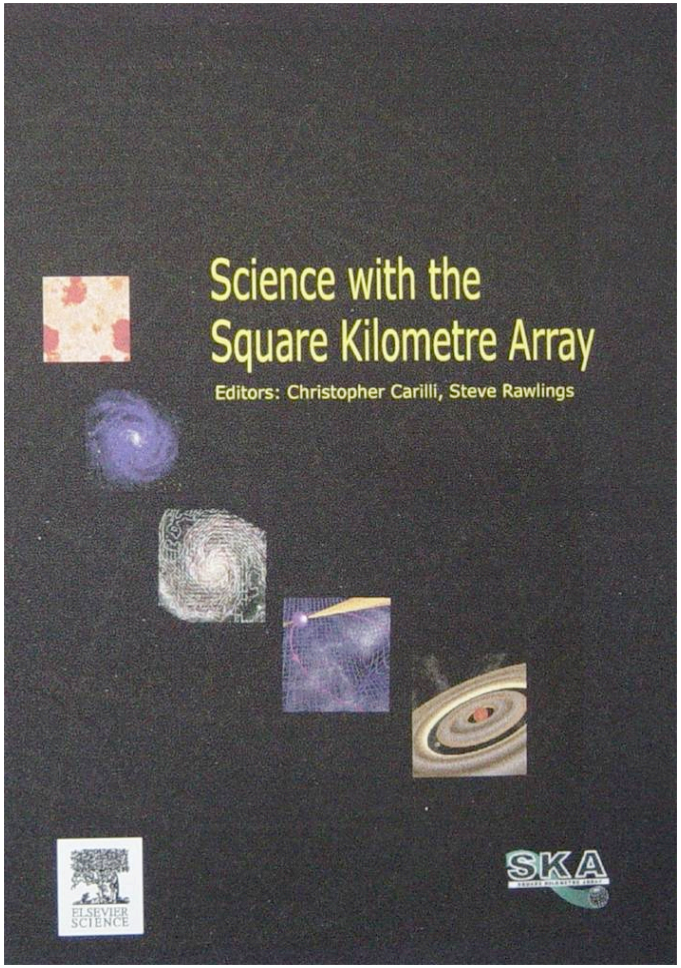
  Phase 1 "H I through cosmic time" headline science

- Emerging from the Dark Ages and the Epoch of Reionization

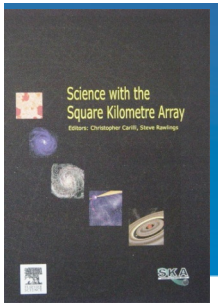
  Phase 1 "H I through cosmic time" headline science

- 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**)



21st Century Astrophysics

20th Century: We discovered our place in the Universe.

21st Century: We understand the Universe we inhabit.

Cosmology & Fundamental Physics

- Gravity
  - Can we observe strong gravity in action?
  - What is dark matter and dark energy? (dark energy and BAOs with H I galaxies)
- Magnetism
- Strong force

  Nuclear equation of state

Galaxies Across Cosmic Time, The Galactic Neighborhood, Stellar and Planetary Formation

- Galaxies and the Universe
  - How did the Universe emerge from its Dark Ages?
  - How did the structure of the cosmic web evolve?
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- Stars, Planets, and Life
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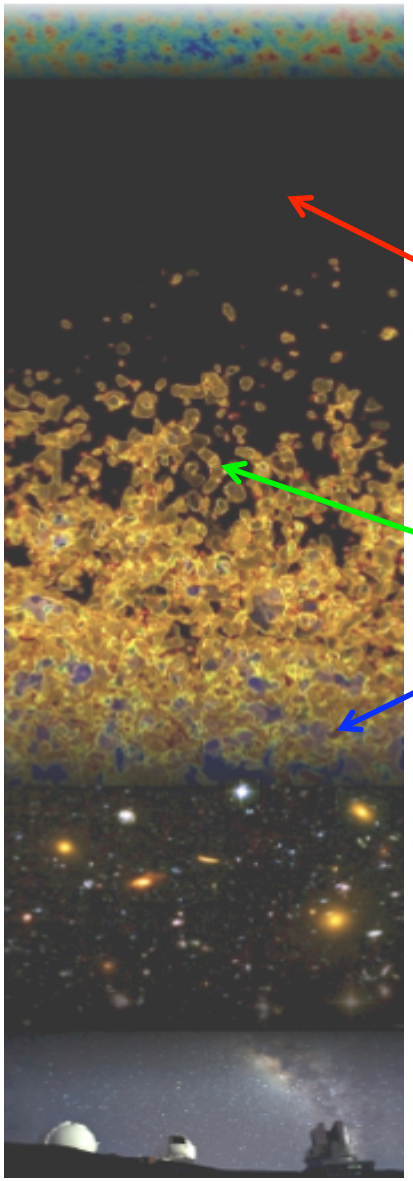
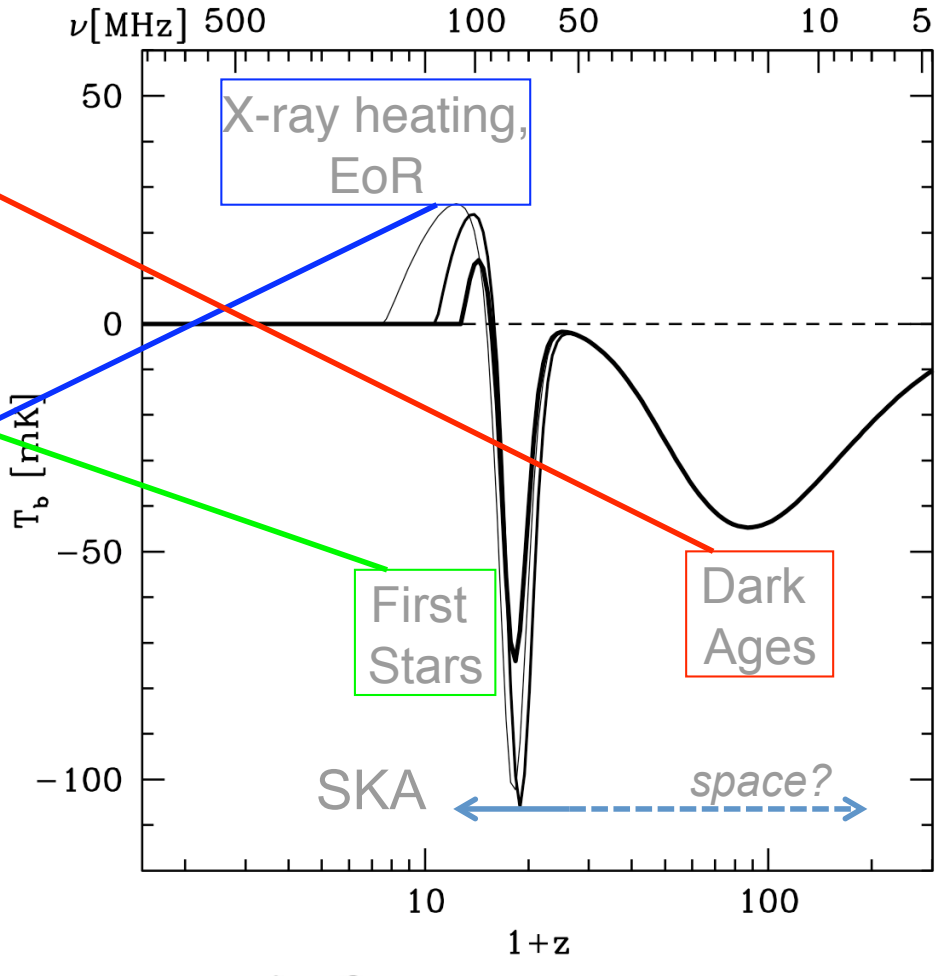
  - Is there evidence for life on exoplanets? (SETI)

Evolution of the Universe



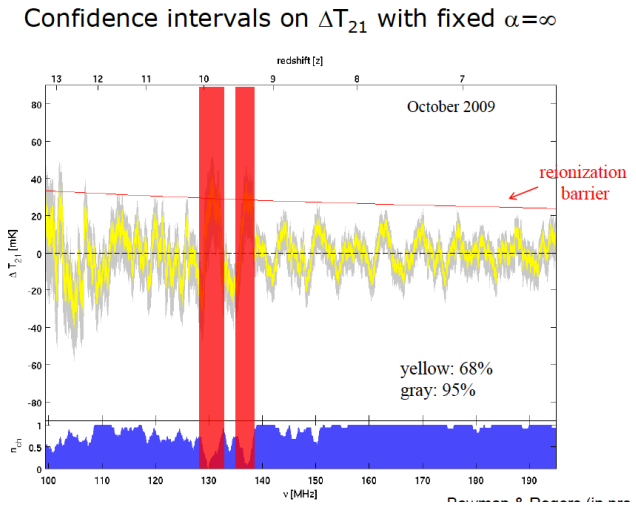
H I brightness temperature signal
(w.r.t. CMB)

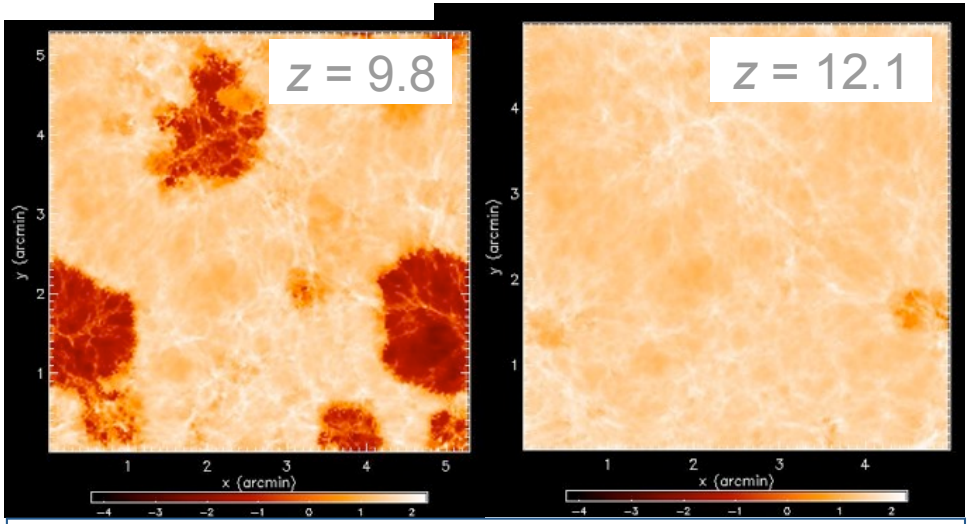


(Pritchard & Loeb 2008)

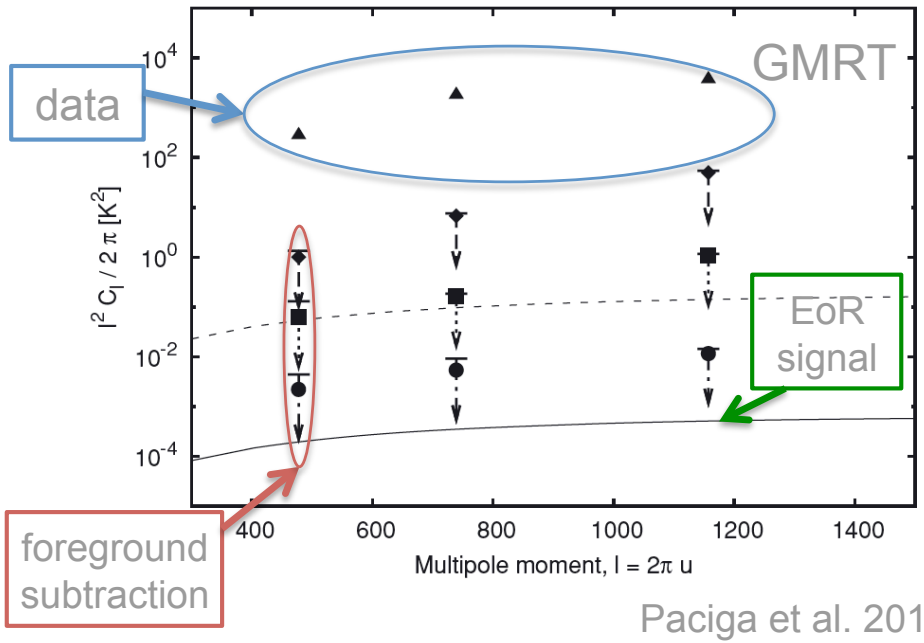
Evolution of the Universe
Epoch of Reionization

EDGES
(Bowman et al. 2008)

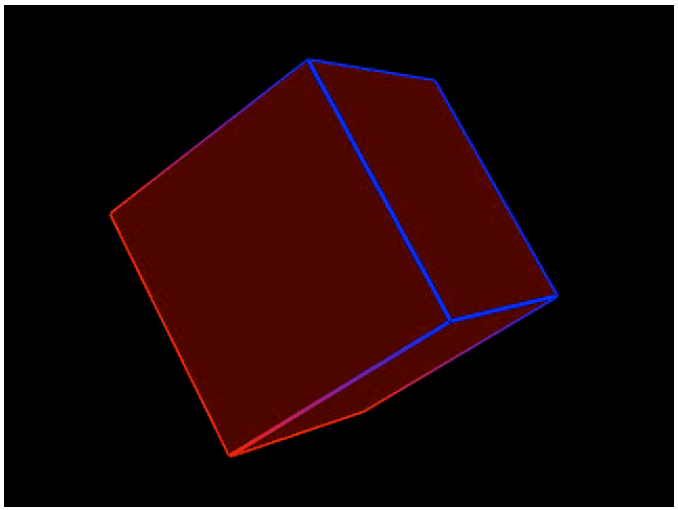




SKA objective: Image the IGM transition in the H I (21-cm) line



Paciga et al. 2011



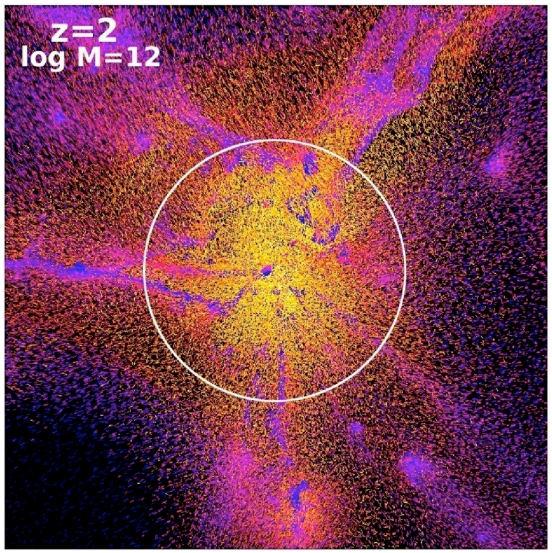
Furlanetto et al.; Gnedin

Galaxy Assembly
Stars *and* Gas

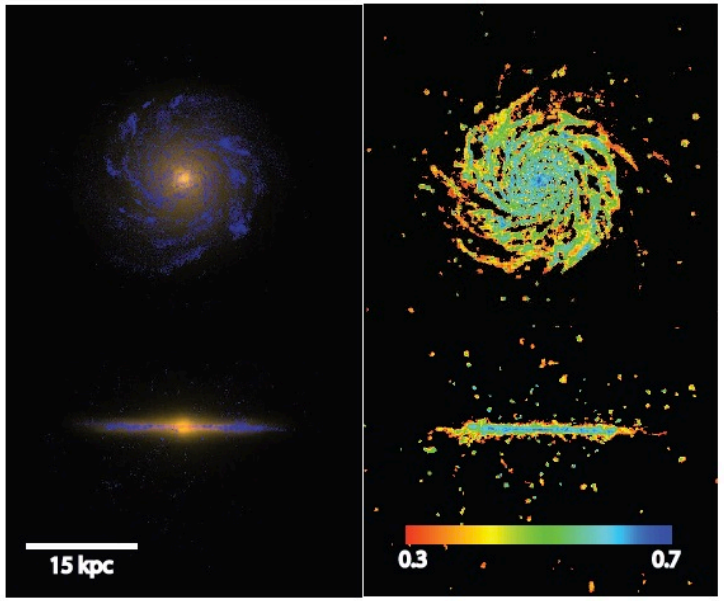
- Gas content and dynamics becoming critical part of simulations.
- Astronomy is an *observational* science.

➢ Need observations of gas content —over cosmic time—to understand galaxy formation!

observation vs. simulation



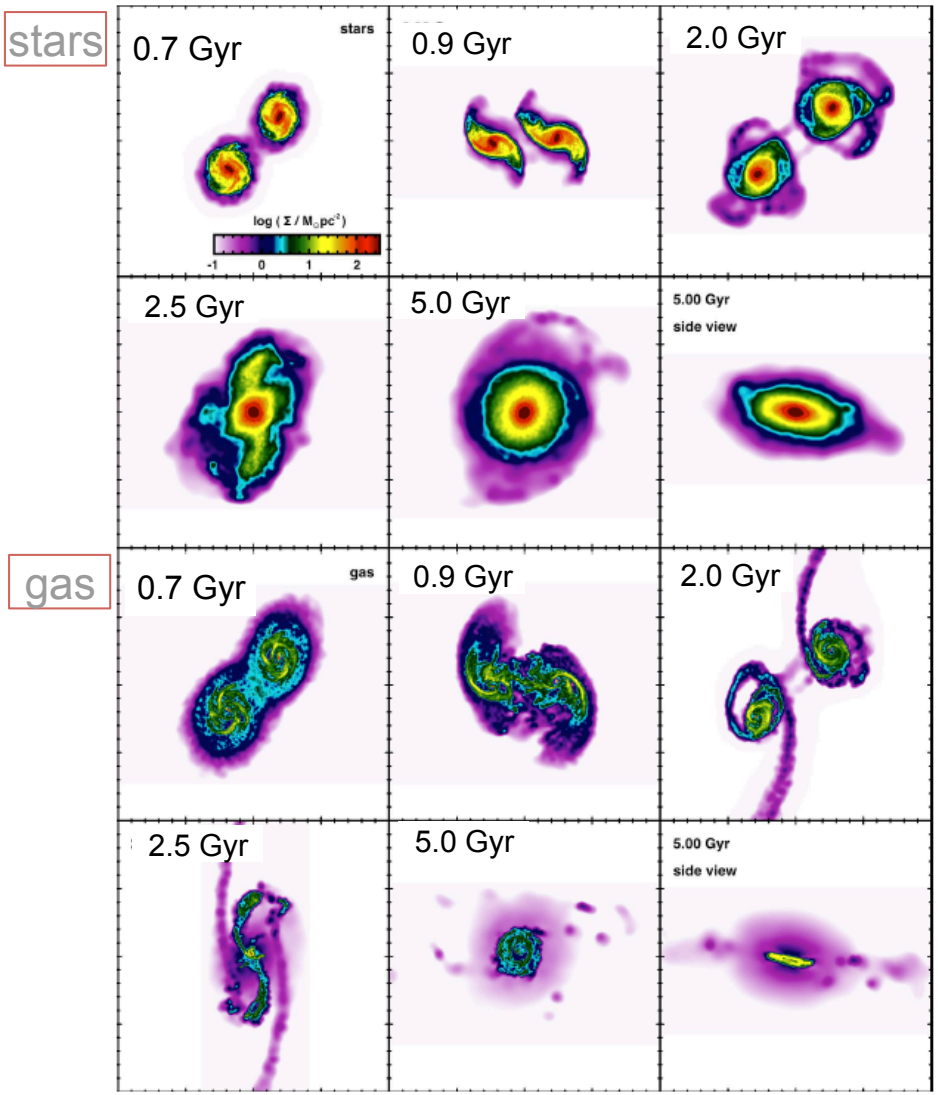
Keres et al.



Eris simulation (Guedes et al.)

NGC 6946 (T. Oosterloo)

Galaxy Assembly
The Role of Mergers



(Moster et al. arXiv:1104.0246)

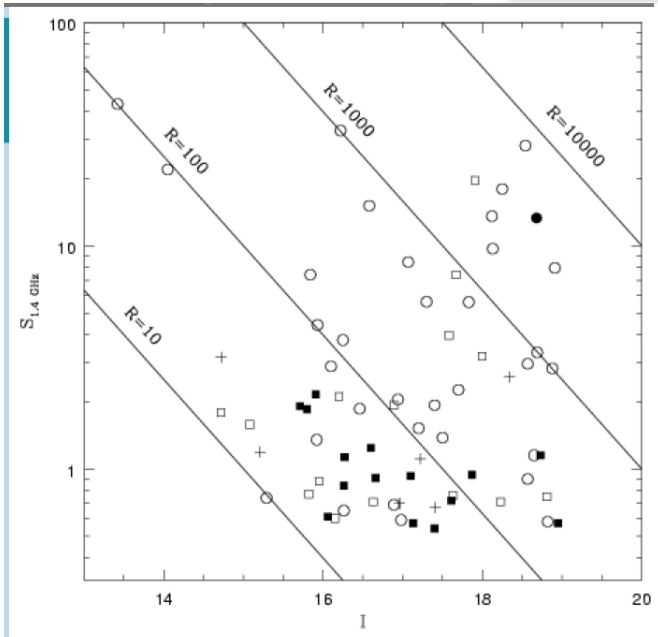
- Mergers are recognized as important aspect of galaxy evolution and formation
- Gas can be sensitive tracer of interactions, long after original event took place

  E.g., Holwerda et al. with THINGS

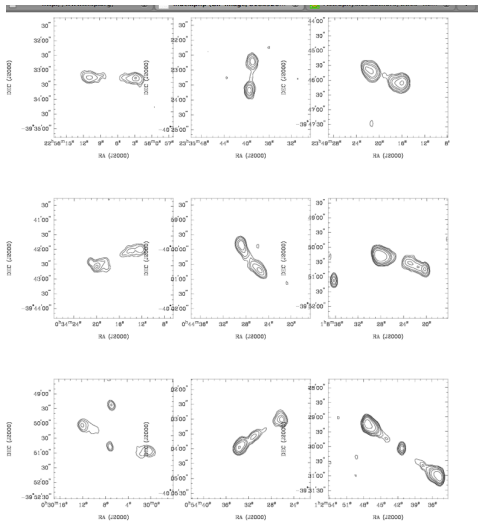
Galaxy Evolution
Accretion vs. Fusion

Radio wavelengths important to understand balance between AGN and star formation (SF) for galaxy luminosity

- Distinguish between AGN and SF
- Track over cosmic time
- Continuum observations useful
  - Requires telescope to be designed smartly



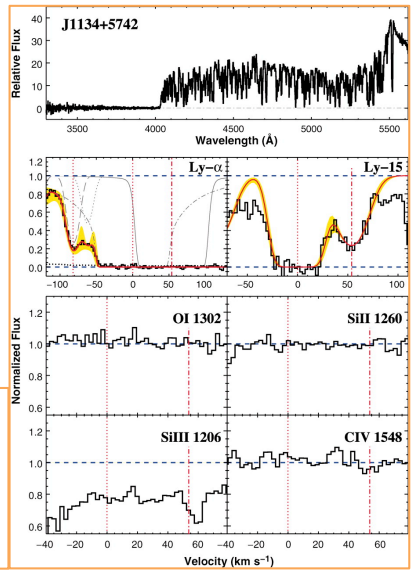
Well-known change in source population below 1 mJy (Prandoni et al. 2001)



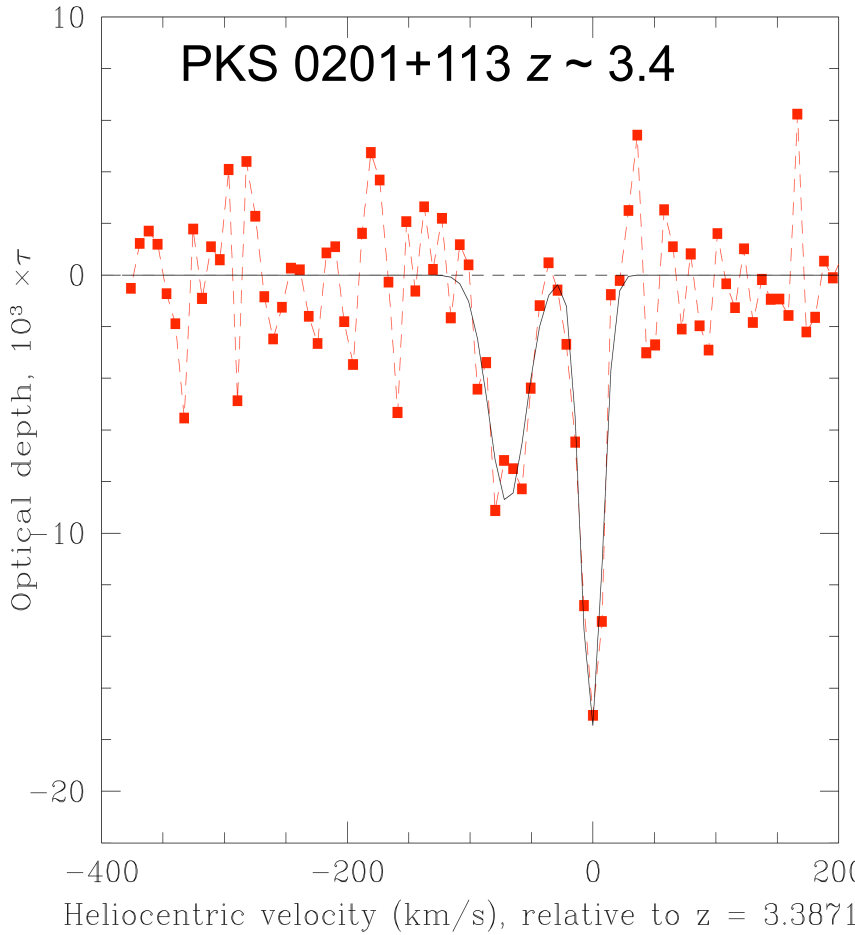
Galaxy Assembly
H I Absorption

Don't forget about H I absorption!

- Powerful tool
  - E.g., pristine gas
- Already detected to z ~ 3.4
  - Searched for z ~ 5
  - Well beyond what even Phase 2 will do in emission
- Only strong argument for continuous frequency coverage



Fumagalli et al., optical H I absorption, (2011, Science)

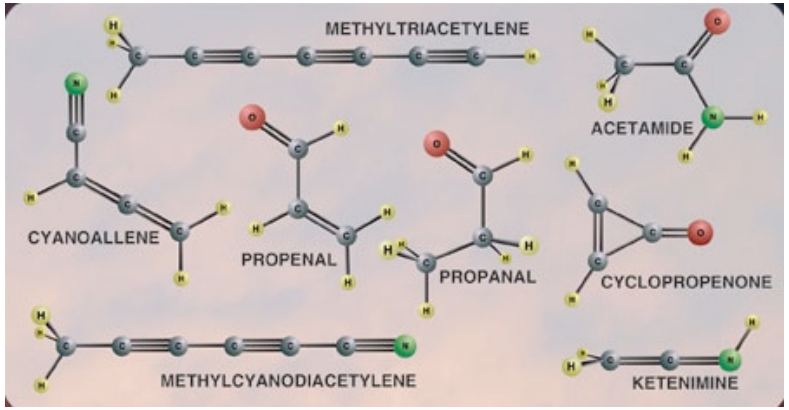


(Kanekar et al. 2007)

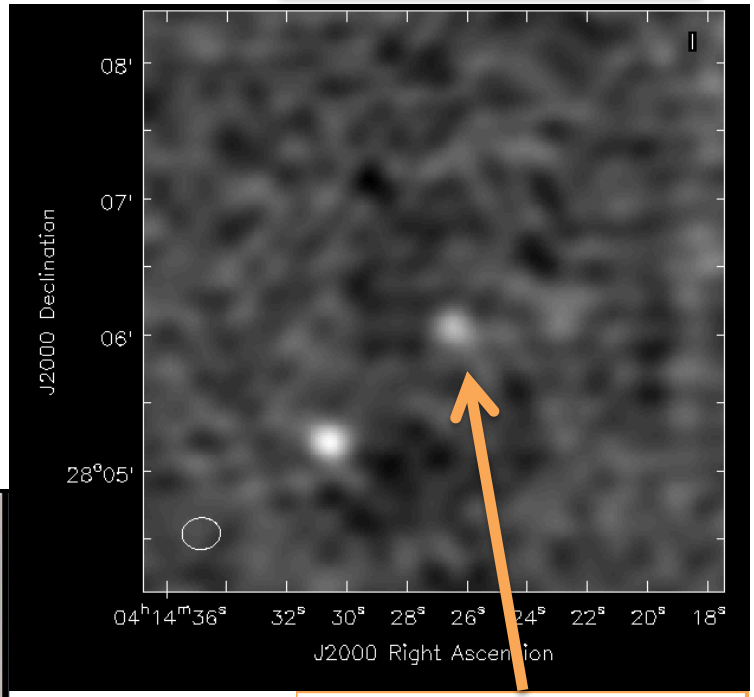
Astrobiology at Long Wavelengths

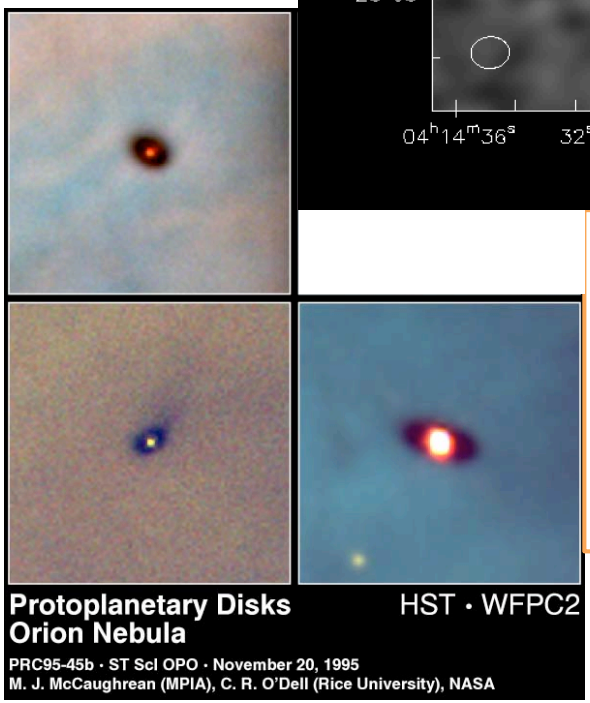
$\lambda > 1$ cm

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

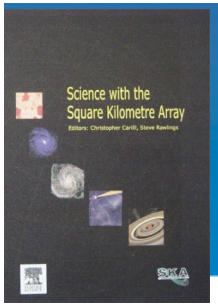


Complex organic molecules detected at radio wavelengths





EVLA 6 cm observations of protoplanetary disks; PEBBLES on e-MERLIN coming soon



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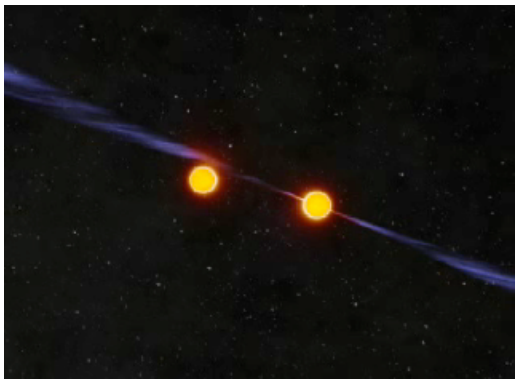
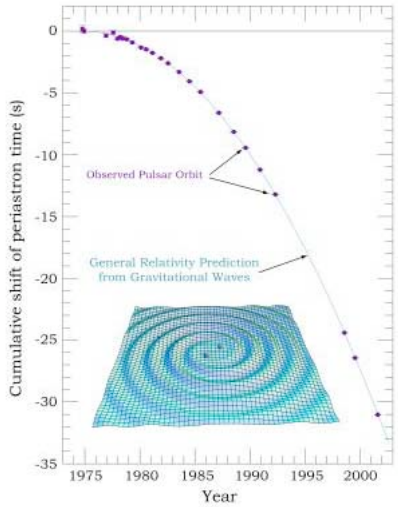
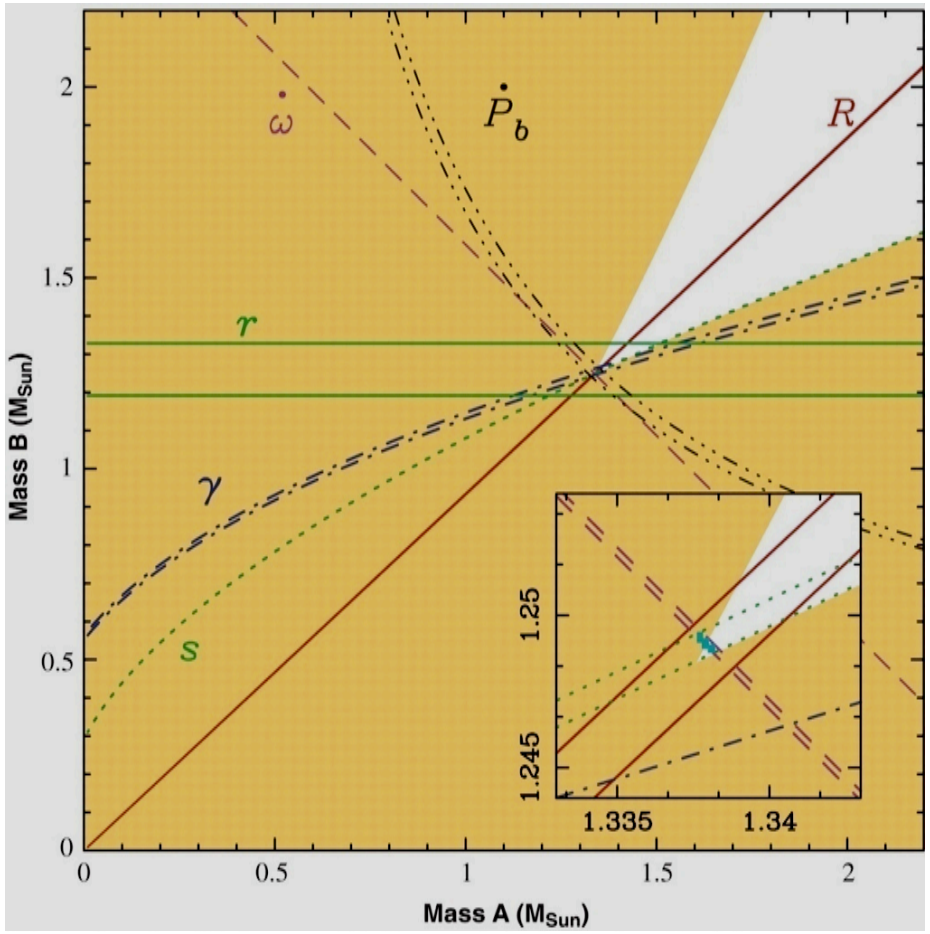
Did Einstein Have the Last Word on Gravity?

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





PSR J0737-3039



Burgay et al., Lyne et al., Kramer et al.

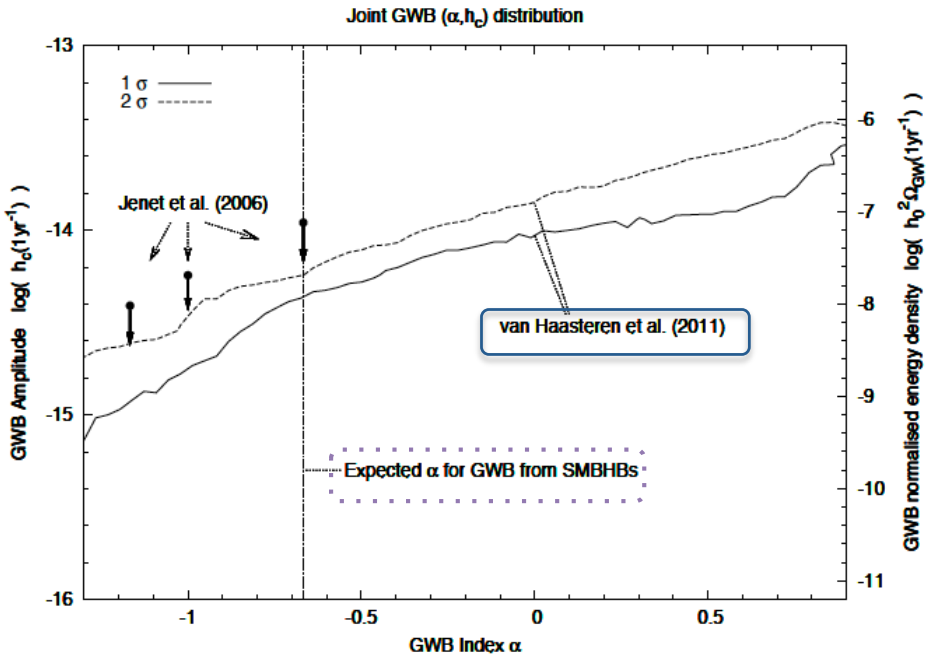
Relativistic binaries probe

1. Equivalence principle
2. Strong-field tests of gravity

- Neutron star-neutron star and neutron star-white dwarf binaries known

? Black hole-neutron star binaries?

SKA: Gravitational Wave Detector



Test masses on lever arm

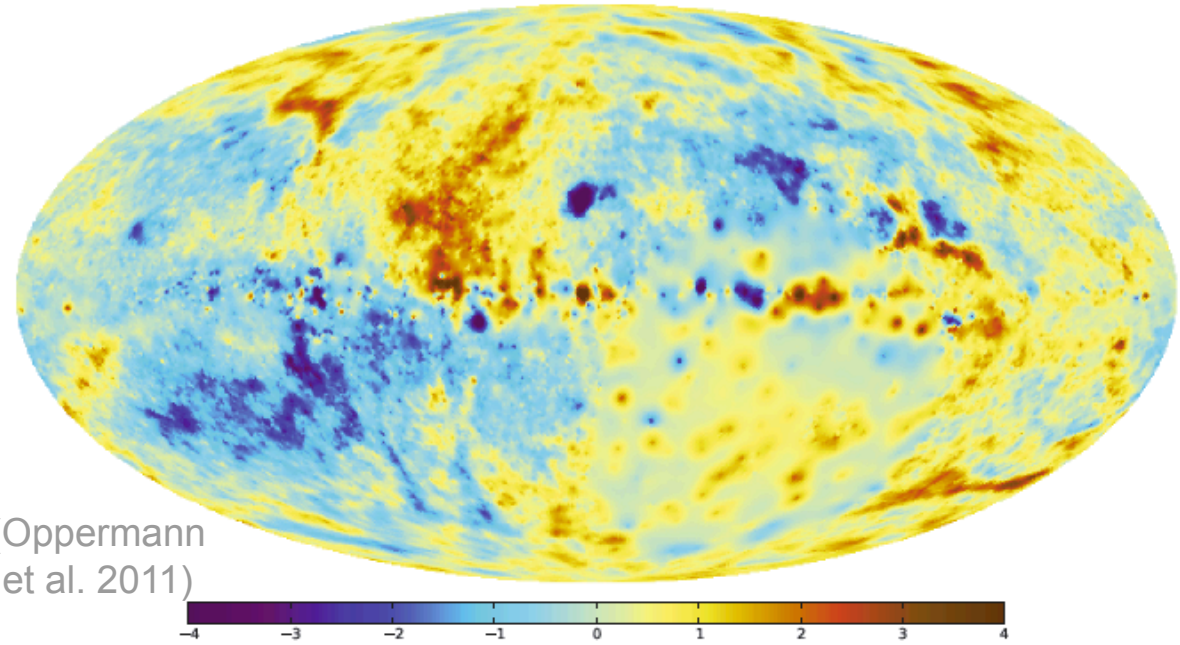
- ~ nHz ➔ Pulsar Timing Array = freely-falling **millisecond** pulsars
- ~ μHz ➔ freely-falling masses in spacecraft
- ~ Hz ➔ LIGO, VIRGO = suspended mirrors

Pulsar timing arrays starting to provide results from ensemble of pulsars

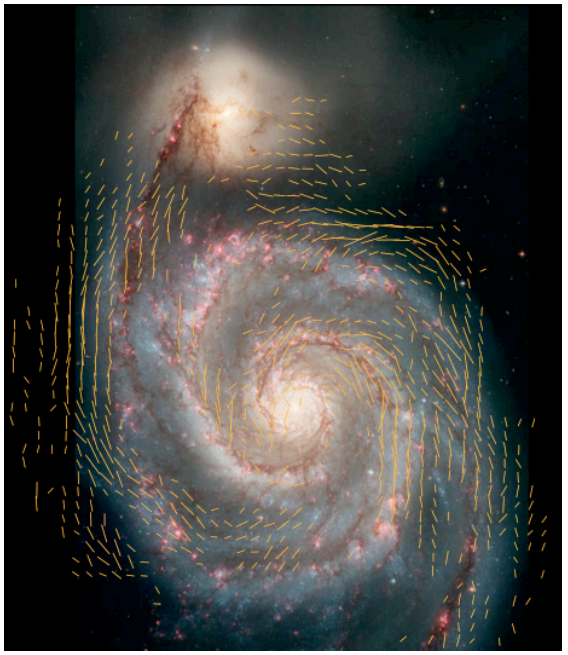
- EPTA (van Haastern et al., *above*)
- PPTA (Yardley et al.)
- *NANOGrav (Demorest et al.)*

Origin & Evolution of Cosmic Magnetic

- Magnetic fields are fundamental, but poorly constrained
  - Affects galaxy, cluster evolution?
  - Affects propagation of cosmic rays in ISM and IGM
- All-sky rotation measure surveys provide **B** fields along lines of sight

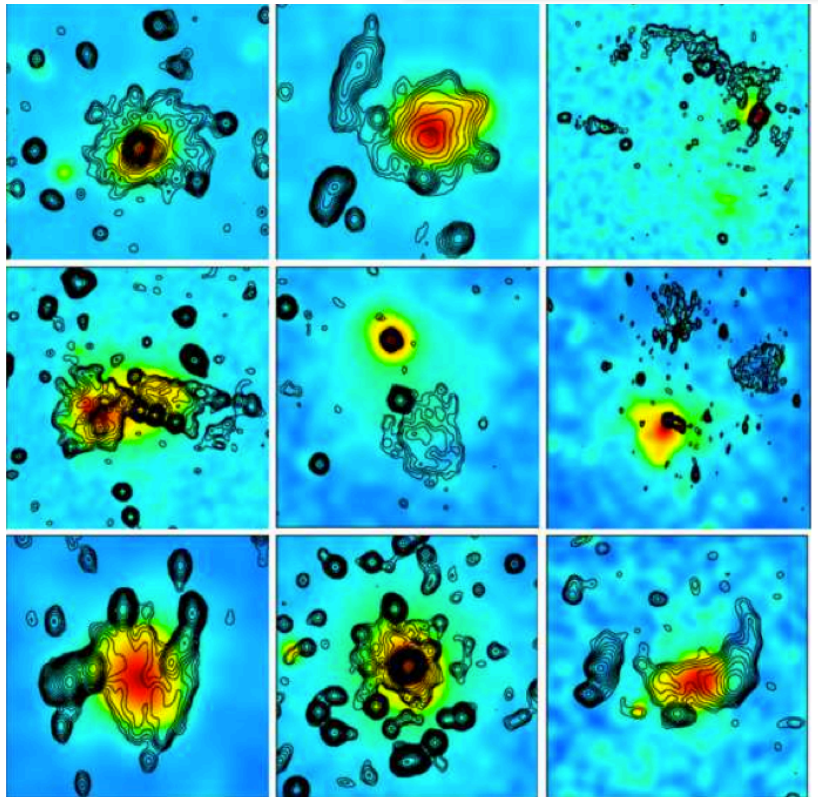


(Oppermann et al. 2011)

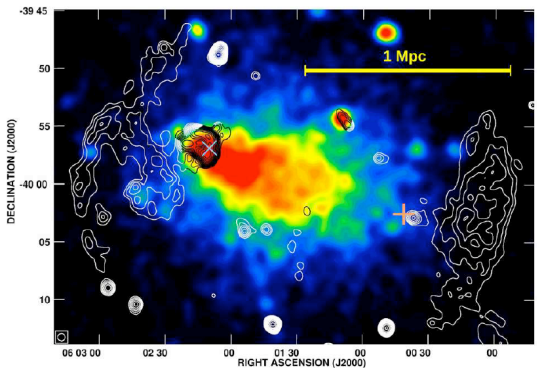


Magnetic Fields in Clusters of Galaxies

- Clusters can be used to track magnetic field growth over cosmic time
- Also …
  - Laboratory for understanding particle acceleration
  - Growth of large scale structure
  - …



Feretti et al.

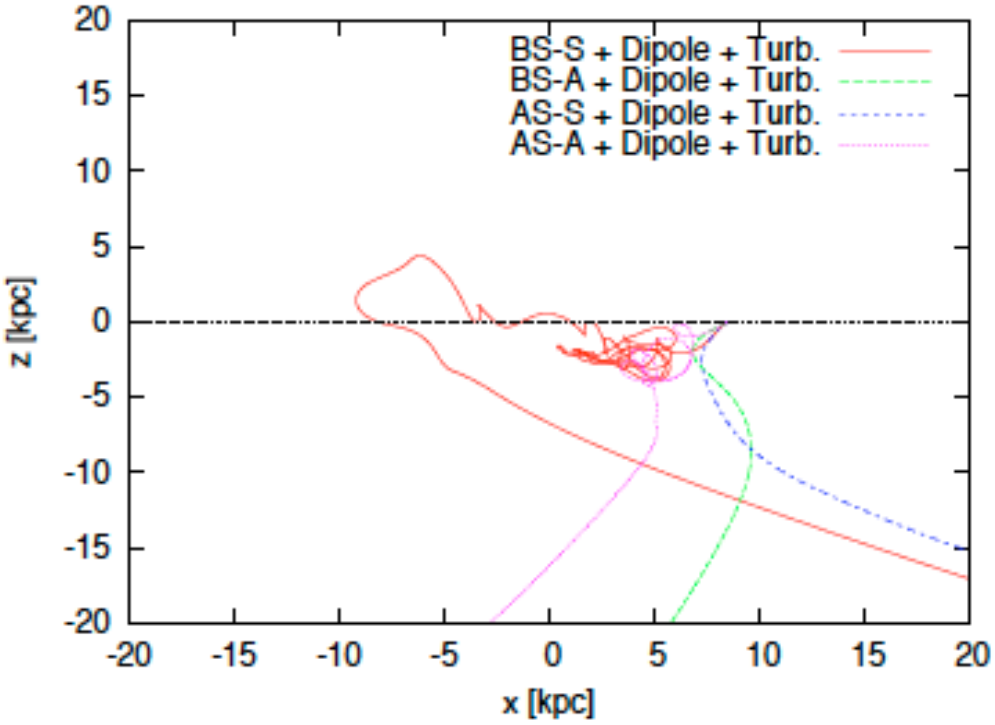


Kale et al.

ld's largest radio telescope

Magnetic Fields and Cosmic Rays

- Are ultra-high energy cosmic rays (UHECRs) produced in nearby AGN?
- Galactic magnetic field influences cosmic ray propagation
- ➢ Different models of Galactic field imply different arrival directions
  - – Axi-symmetric vs. bi-symmetric?
  - – Field directions above and below the Galactic plane
  - – Effect of turbulence?
  - – …?



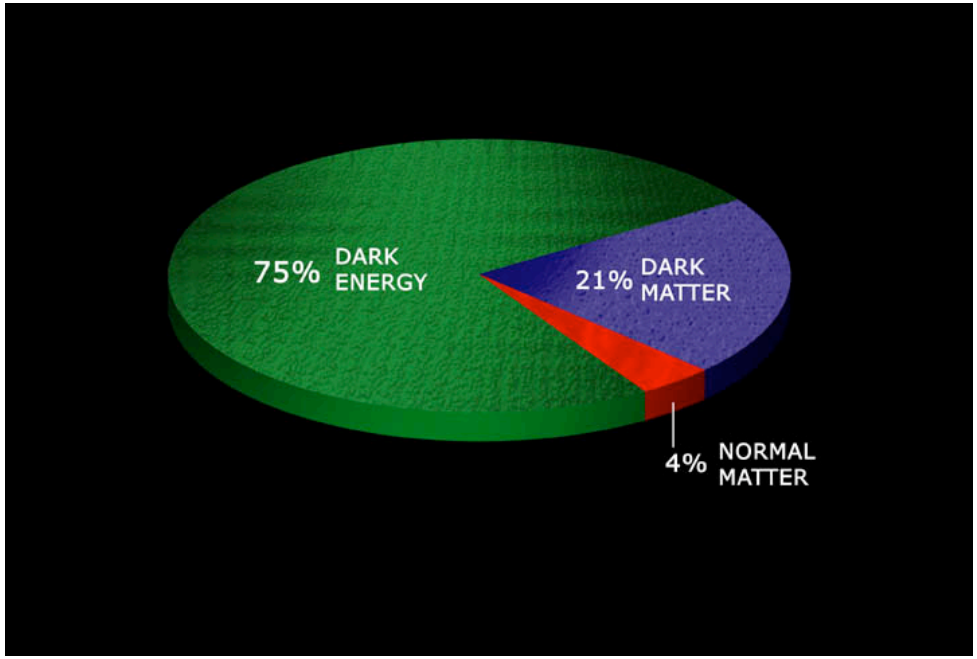
Takami, arXiv:1104.0278

Cosmology and Gravity

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

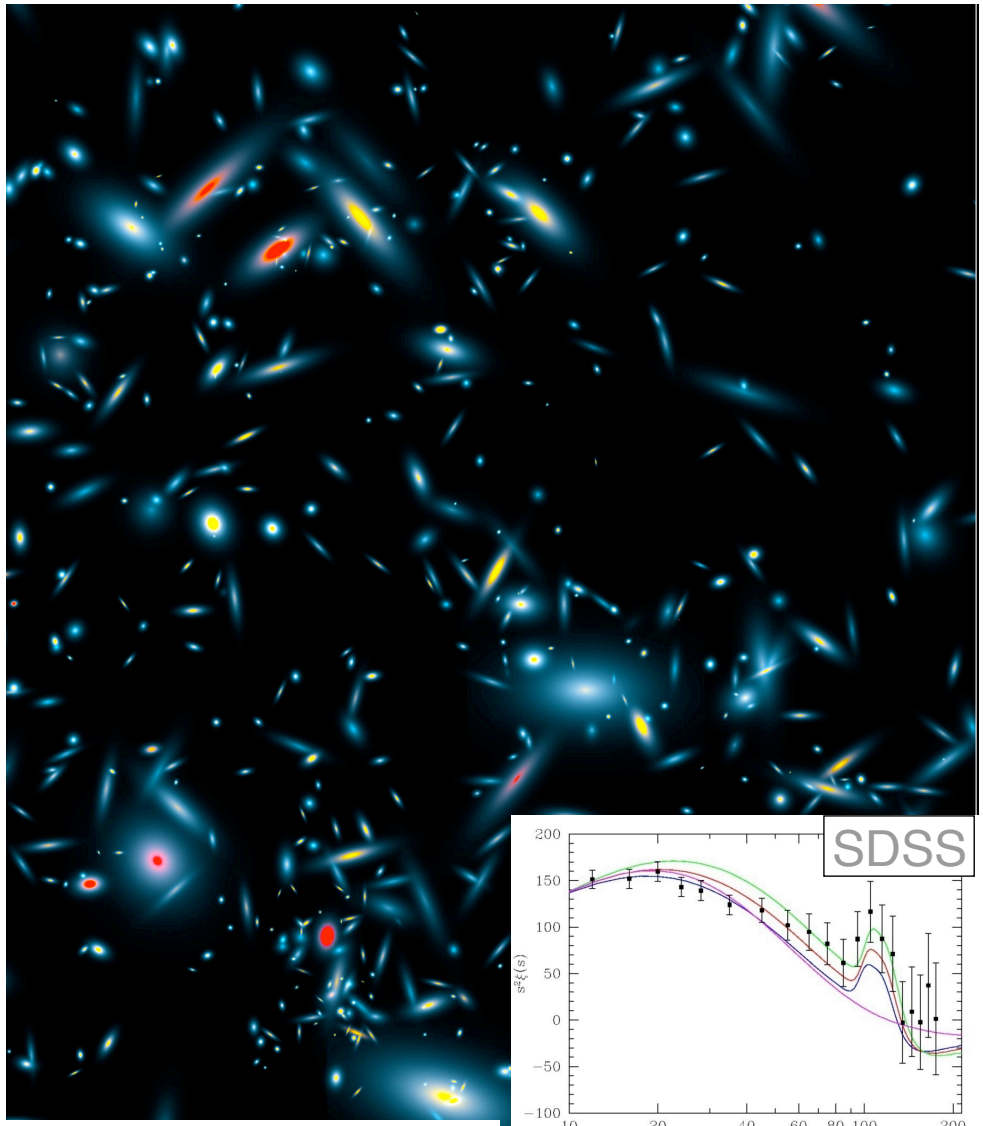
Origin and Fate of the Universe

- Era of "precision cosmology"
  … or precision ignorance
- Need to sample a substantial volume of the Universe
- Volume ~ $D^2\,\Delta D\,\Omega$
  - D – distance; Ω – solid angle
  - Surveying to larger D is difficult ➔ need larger telescopes
    "square kilometre" of SKA
  - Surveying larger sky areas Ω "just" requires more observing time



Composition of the Universe

Cosmology and Sky Surveys

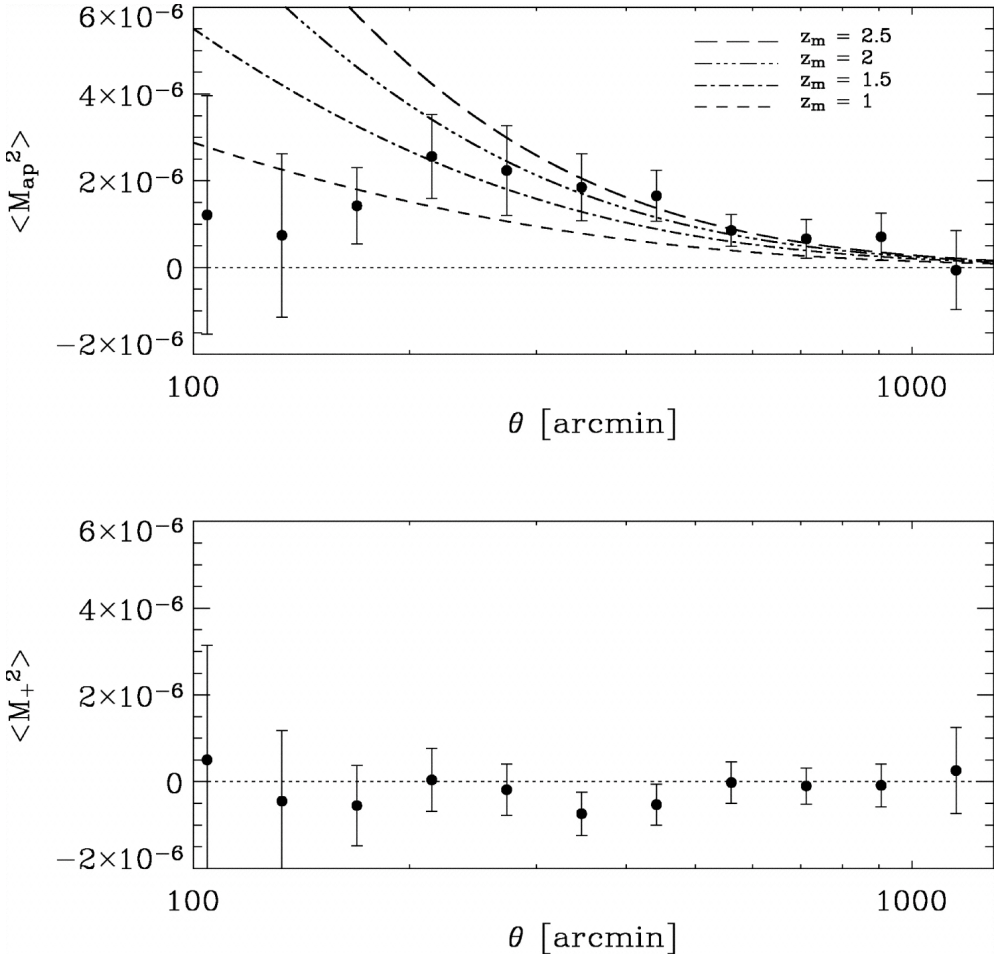


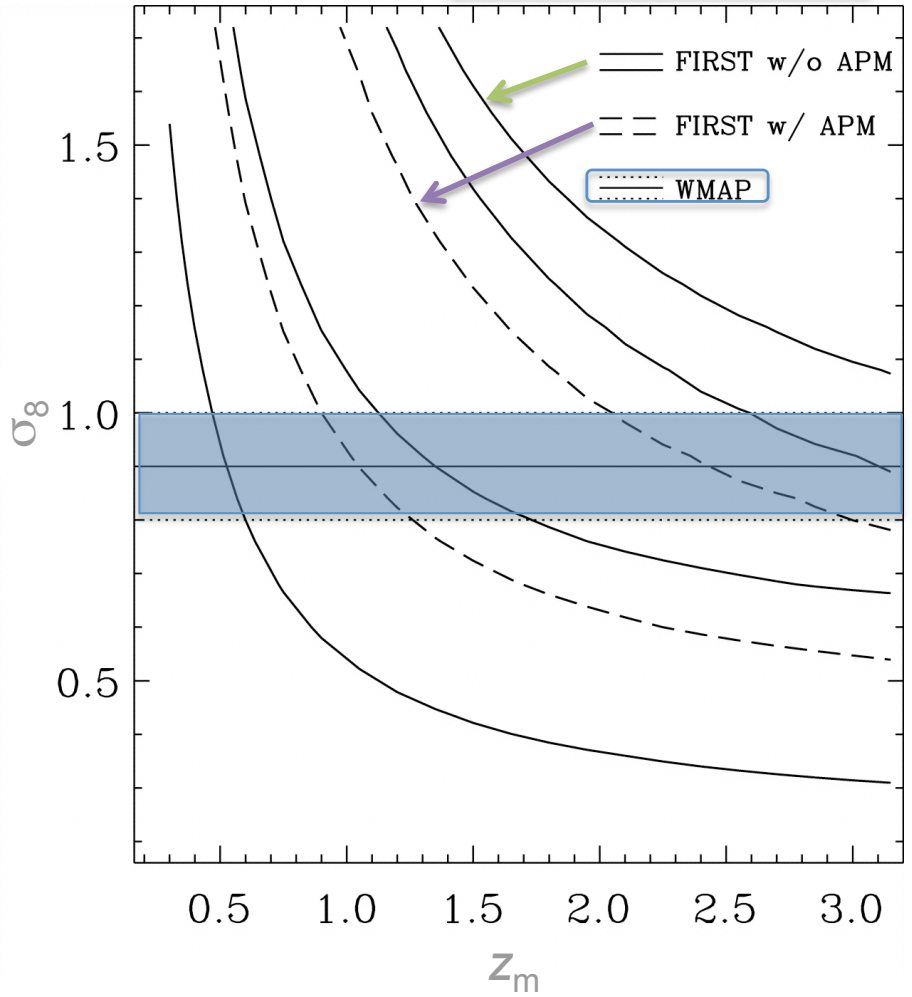
SKADS Simulated Sky

- 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

Cosmology and Gravity

Detection of weak lensing (E modes) from FIRST (Chang et al.)





Radio observations should have fewer (different) systematics

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

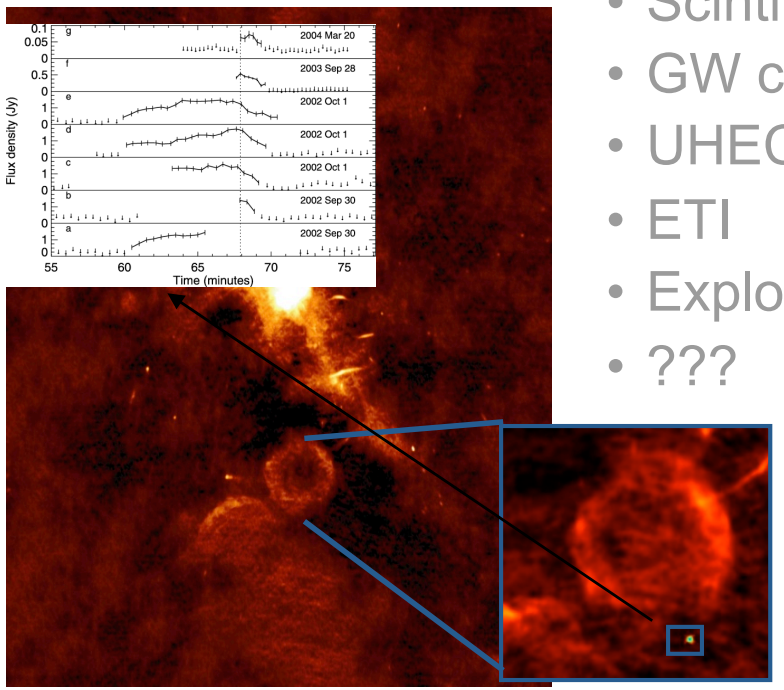
Sensitivity

Field of View

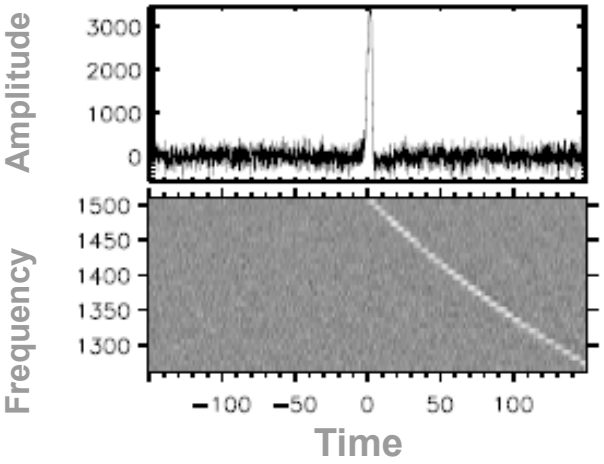
Angular Resolution

The Dynamic Radio Sky

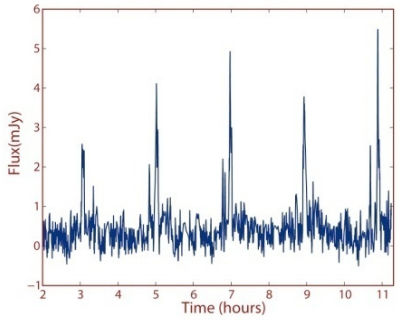
- Neutron stars
  - Magnetars
  - Giant pulses
  - Short GRBs?
- Microquasars
- Tidal Disruption Events

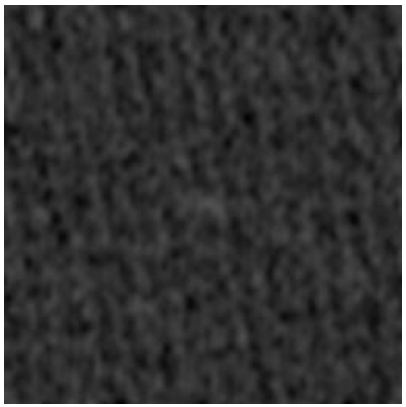


- GRBs (γ-ray loud; γ-ray quiet?)
  - Afterglows
  - Prompt emission?
- Sub-stellar objects
  - Brown dwarfs
  - Extrasolar planets?
- Scintillation
- GW counterparts
- UHECRs
- ETI
- Exploding black holes
- ???

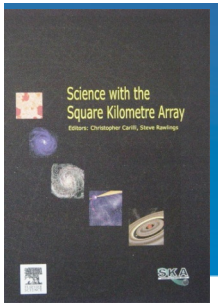


Rotating Radio Transients (RRATS)





Pulsating Brown Dwarfs



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SKA Science

Major Surveys

- Cosmological surveys, both continuum and H I
- Pulsar finding
- Polarization for RM grid
- SETI
- Time domain
- …

E.g., 3C, NVSS, FIRST, SUMSS, HIPASS, ALFALFA, HTRU, P-ALFA, GBNCC, …

Targeted Observations

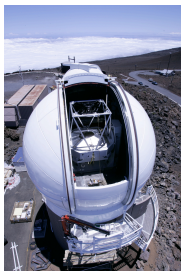
- Galaxy evolution, both deep H I field(s) and continuum field(s)
- Fundamental physics via high precision pulsar timing
- Proto-planetary disks
- Magnetic field evolution via deep polarization field(s)
- Triggered observations of transients
- …

E.g., PTAs, THINGS, JVLA Deep H I field, JVLA Deep Polarization field, ATCA observations, VLBI observations, …

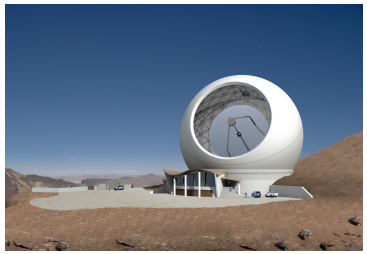
Multi-wavelength Astronomy

Surveys

- RXTE



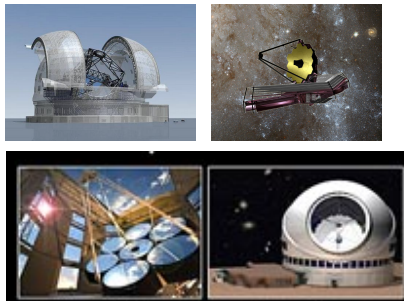
- Pan-STARRS, SkyMapper, LSST, …



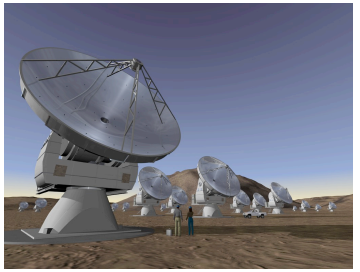
- CCAT

Targeted

- Chandra, XMM-Newton



- E-ELT, TMT, GMT, JWST



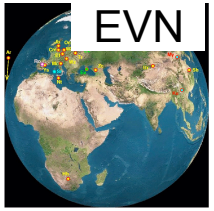
- ALMA

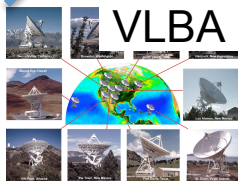
Exploring the Universe with the world's largest radio telescope

SKA1_Mid

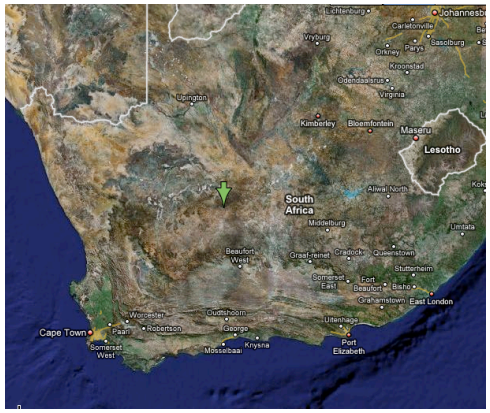
H I fields, pulsar timing, continuum fields, , …

eMERLIN



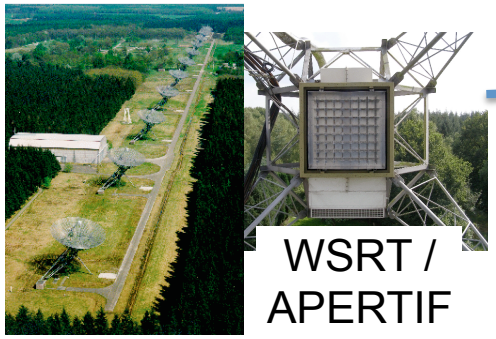


Science case, techniques, instrument parameters (e.g., baseline lengths) informed by other telescopes



SKA1_Survey

H I surveys, continuum surveys [w/ polarization], time domain



~ 2016--2018 Major surveys underway on PAF-enabled instruments (e.g., WALLABY, WODAN, …) --- Assessment of PAF capability

Aperture Array Verification Programme (AAVP) --- dAA assessment

SKA1_Survey
+
Enhanced survey capabilities for Phase 2

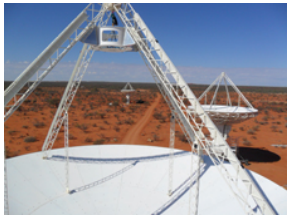
SKA Pathfinding

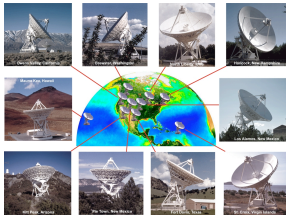
SKA is ultimate goal, though long-term program

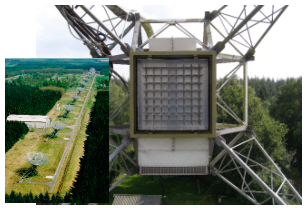
- Precursors and many pathfinders in existence or under construction

➢ Learn lessons from the Precursors and pathfinders across the full range of experience

Hardware, (firmware), software, data processing, operational modes, …

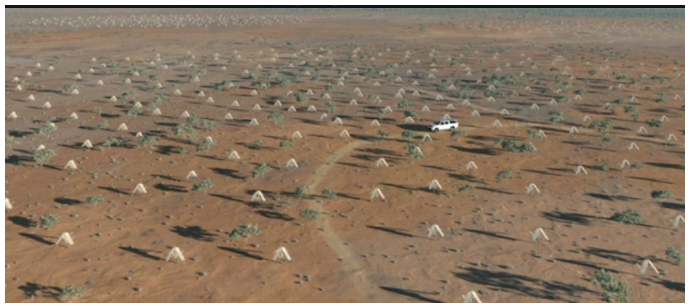






Square Kilometre Array

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
- International involvement