The Square Kilometre Array
Cosmic Origins, Gravitational Waves, and Astrobiology

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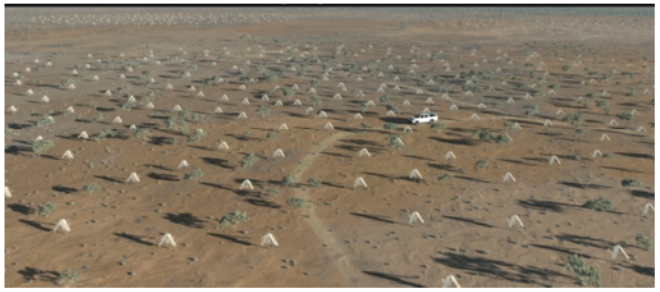
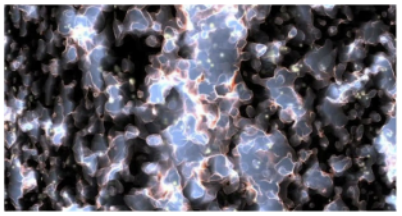
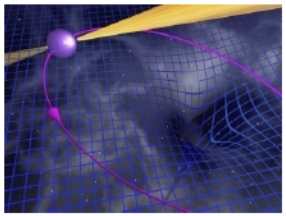
Square Kilometre Array

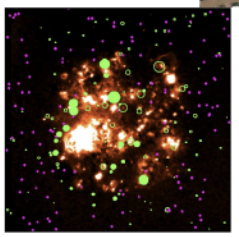
Global Radio Wavelength Observatory

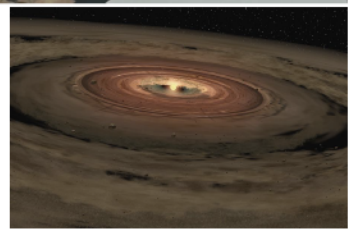


- Originally: “Hydrogen telescope”
  - Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$
- SKA science much broader
  - ⇒ Multi-wavelength, multi-messenger
- On-going technical development
- International involvement









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

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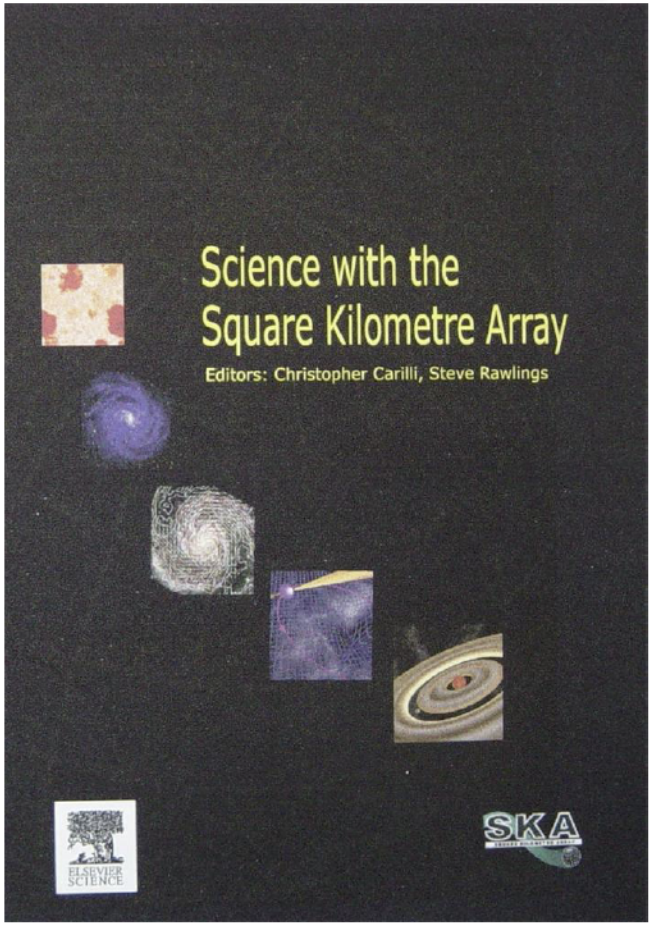
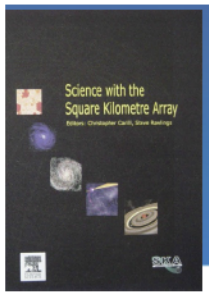
- The Cradle of Life & Astrobiology
- The Origin and Evolution of Cosmic Magnetism

With design philosophy of *Exploration of the Unknown*



Science with the Square Kilometre Array
(Carilli & Rawlings)



21st Century Astrophysics

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

21st Century: We understand the Universe we inhabit.

Cosmology & Fundamental Physics

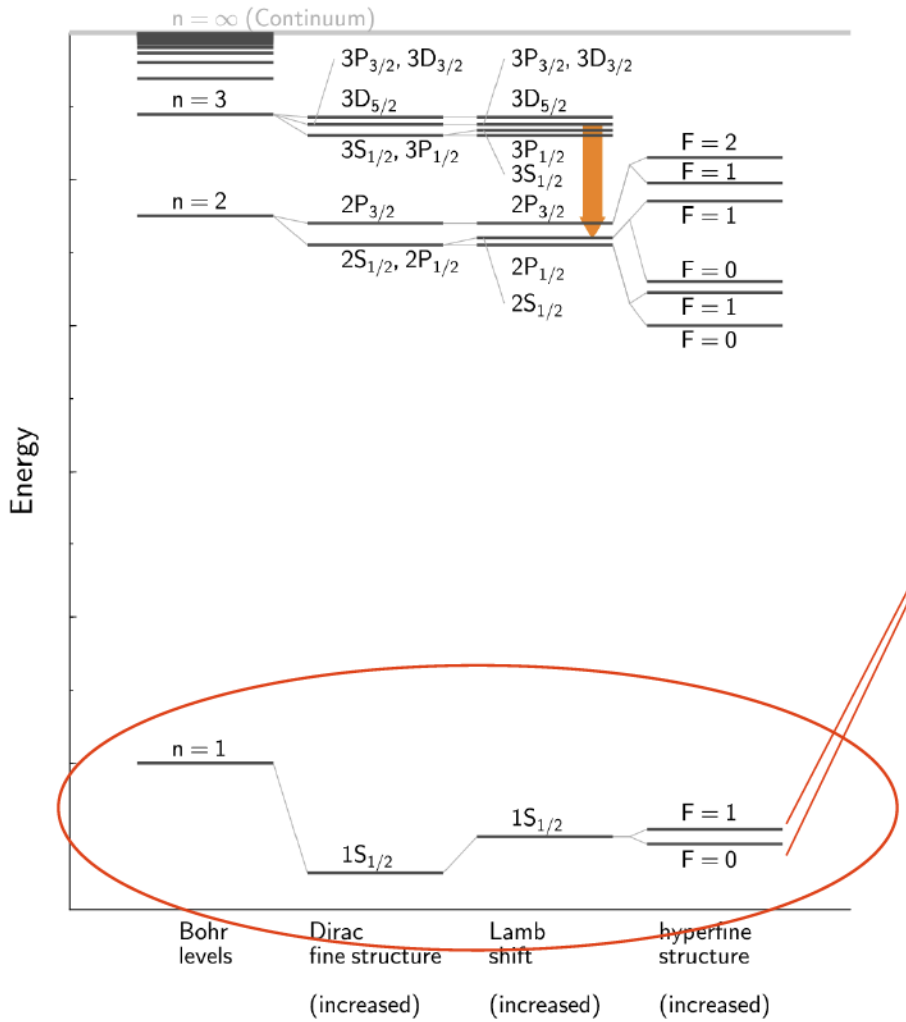
- Gravity
  - Can we observe strong gravity in action?
  - What is dark matter and dark energy? (dark energy and BAOs with H I galaxies)
- Magnetism
- Strong force

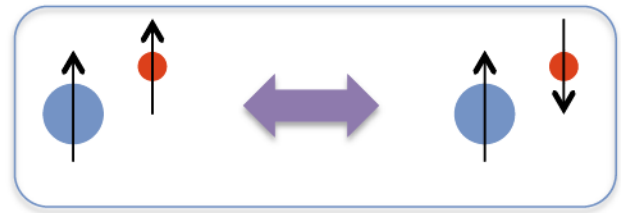
  Nuclear equation of state

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

- Galaxies and the Universe
  - How did the Universe emerge from its Dark Ages?
  - How did the structure of the cosmic web evolve?
  - Where are most of the metals throughout cosmic time?
  - How were galaxies assembled?
- Stars, Planets, and Life
  - How do planetary systems form and evolve?
  - What is the life-cycle of the interstellar medium and stars? (biomolecules)
  - Is there evidence for life on exoplanets? (SETI)

Hydrogen Atom





$n = 1, F = 1 \rightarrow 0$

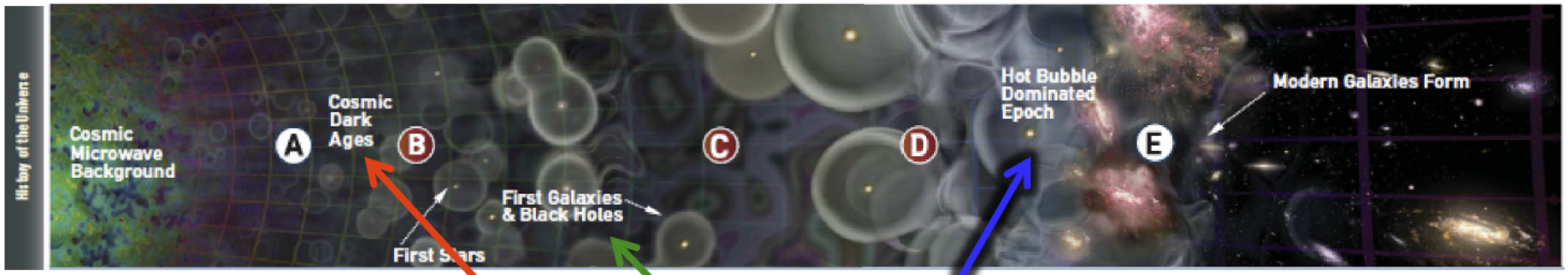
$E_{10} = h\nu = 5.8743253\ \mu eV$

$T_* = E_{10}/k = 0.068\ K$

$\nu = 1420.405752\ MHz$

$\lambda = 21\ cm$

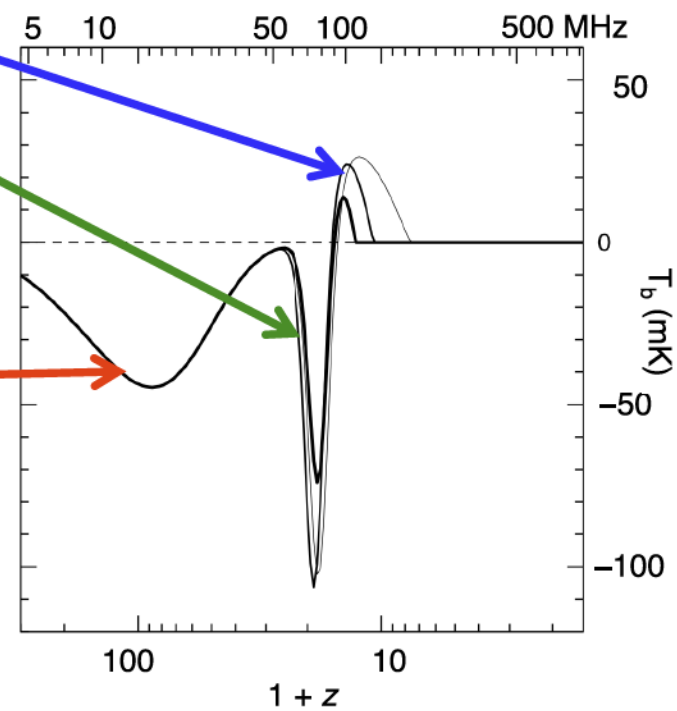
Cosmic Origins
Hydrogen Signal



EoR

Cosmic Dawn

Dark Ages

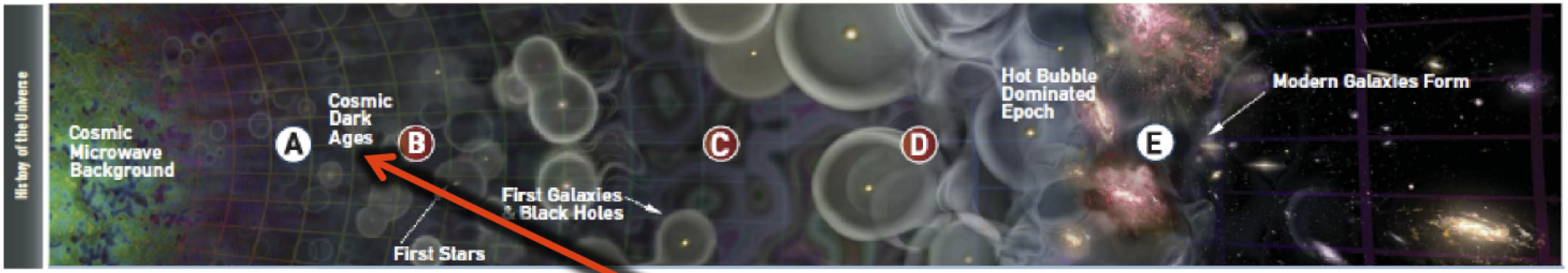


Neutral Hydrogen 21 cm spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

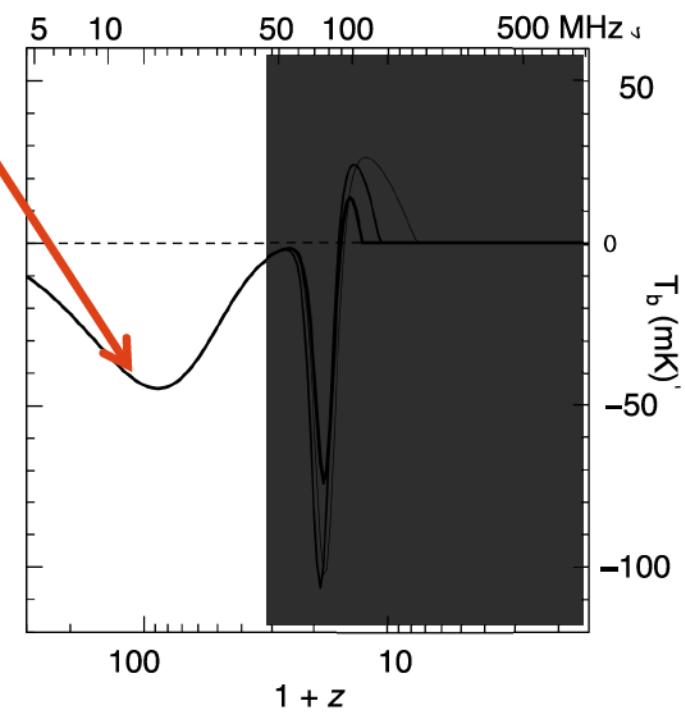
$\nu = 1420\ \text{MHz}/(1 + z)$

$\lambda = 21\ \text{cm}\ (1 + z)$

Dark Ages
Hydrogen Signal



Dark Ages



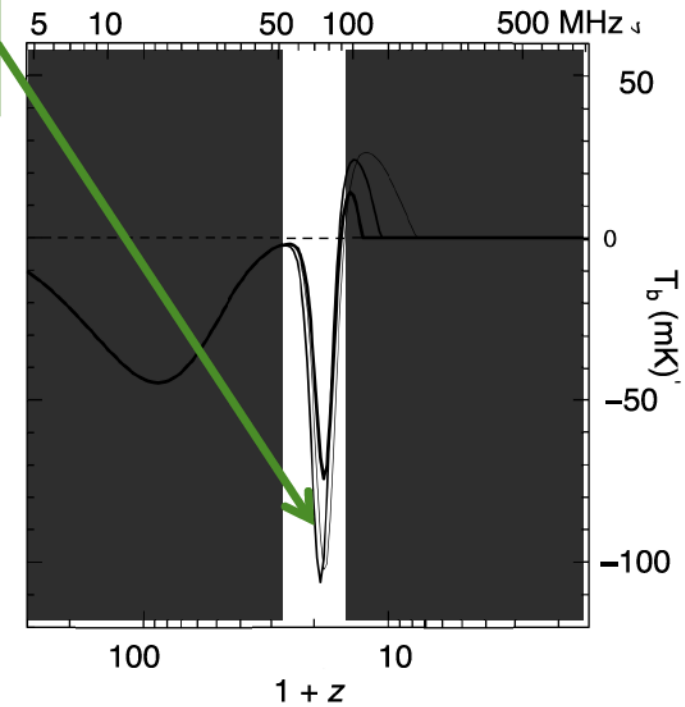
Dark Ages

- Hydrogen gas cools more rapidly than photon gas
- 21 cm signal in *absorption*
- T_s relaxes to T_{CMB} as expansion continues and collisions decrease

$$\nu = 1420 \text{ MHz}/(1 + z)$$
$$\lambda = 21 \text{ cm } (1 + z)$$

Cosmic Dawn
Hydrogen Signal

Cosmic Dawn

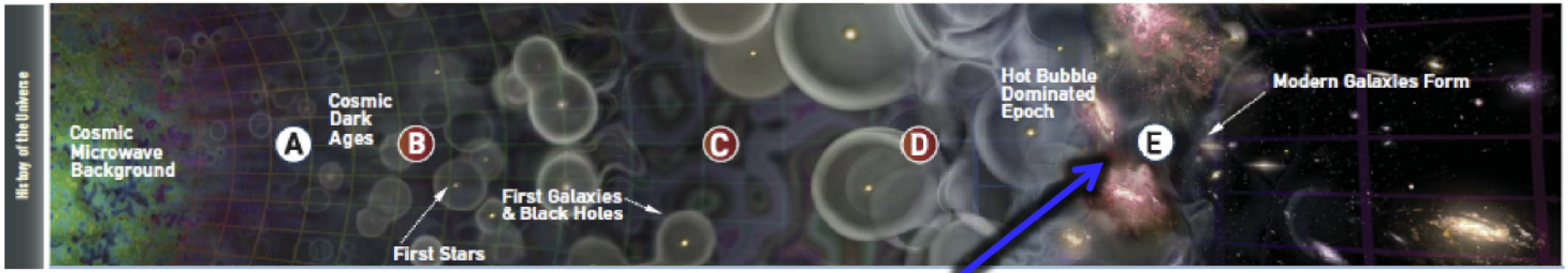


Cosmic Dawn

- Wouthuysen-Field effect couples UV radiation from first stars and 21 cm transition
- Gas *much* cooler than CMB, 21 cm line in absorption until …
- First heating (first accreting black holes?) from X-rays
  - X-rays penetrate much further into gas

$$\nu = 1420 \text{ MHz}/(1 + z)$$
$$\lambda = 21 \text{ cm } (1 + z)$$

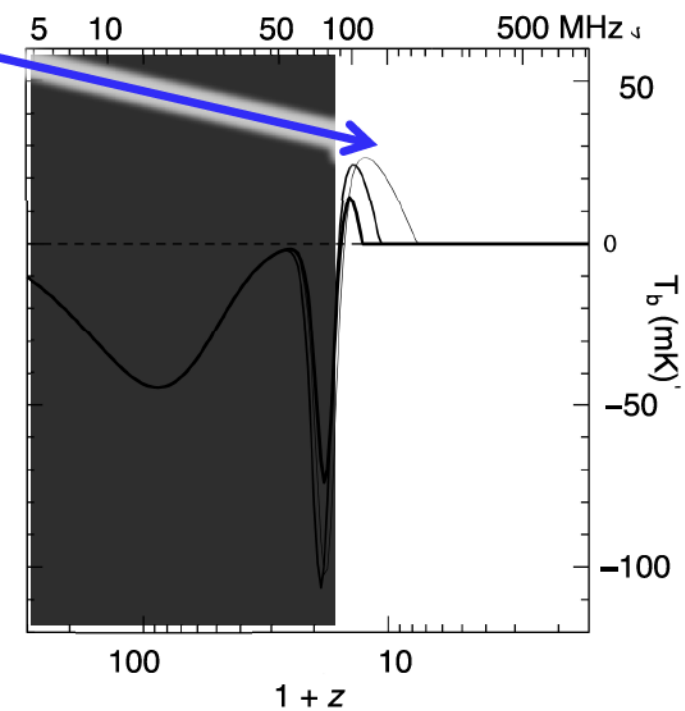
Epoch of Reionization
Hydrogen Signal



EoR

Epoch of Reionization

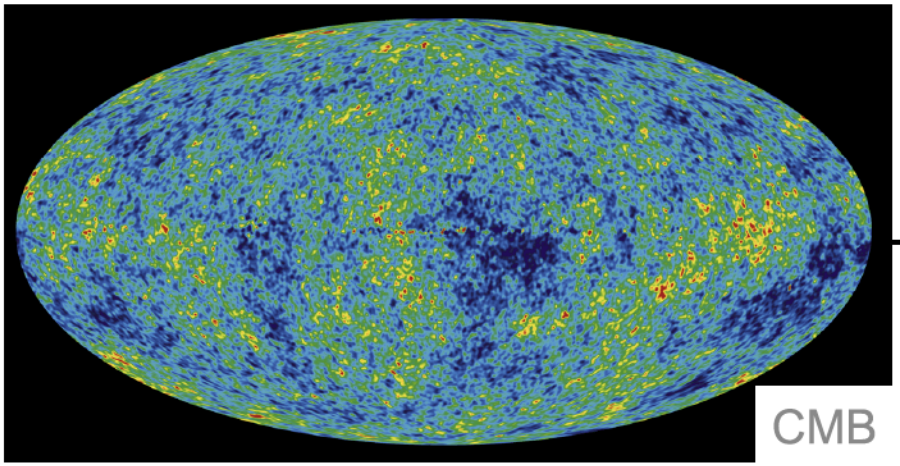
- Gas being heated rapidly
- T_s exceeds T_{CMB}, 21 cm line in emission
- Signal persists until neutral gas destroyed by increasing temperature of IGM
  - Focus of many emerging and proposed arrays



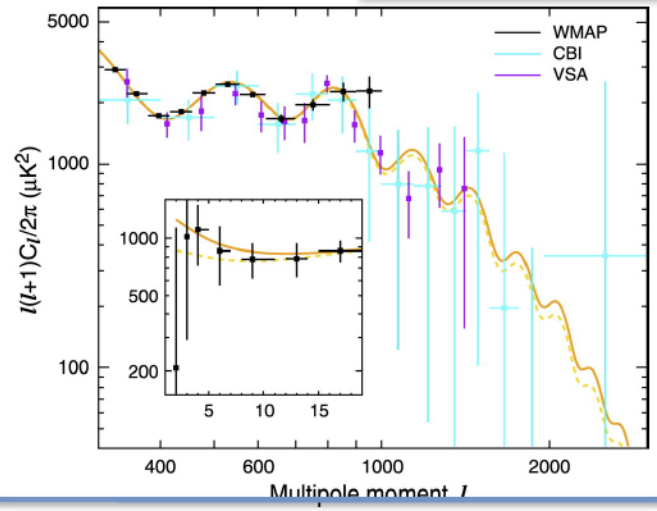
$\nu = 1420\ \text{MHz}/(1 + z)$

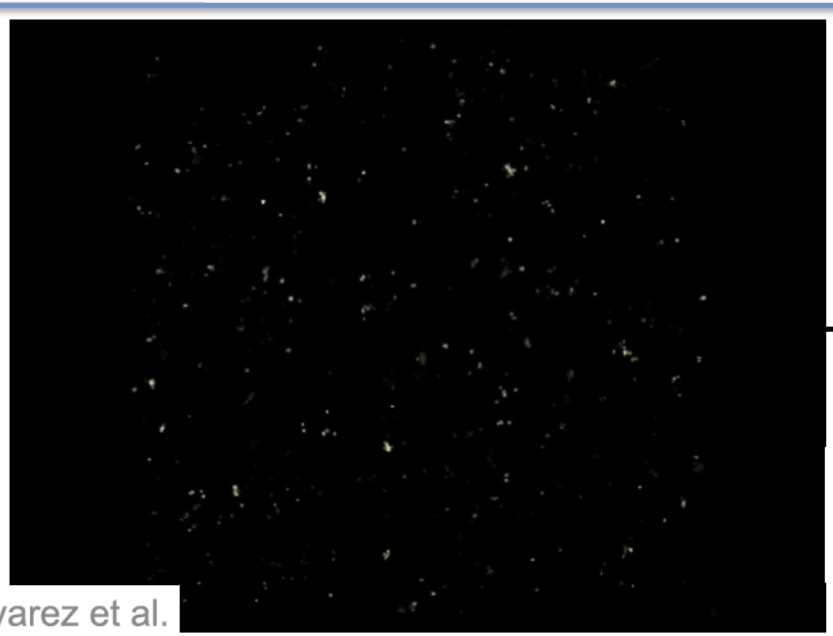
$\lambda = 21\ \text{cm}\ (1 + z)$

Cosmic Origins
H I Imaging and Power Spectra



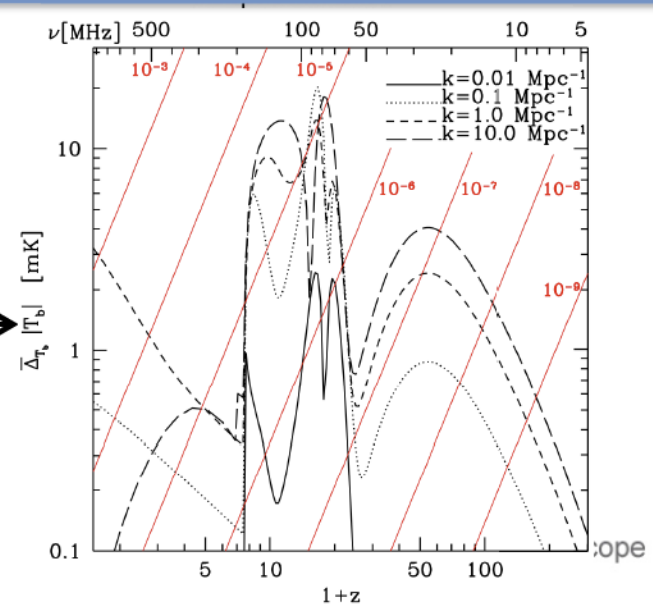
CMB





Alvarez et al.

H I power spectrum

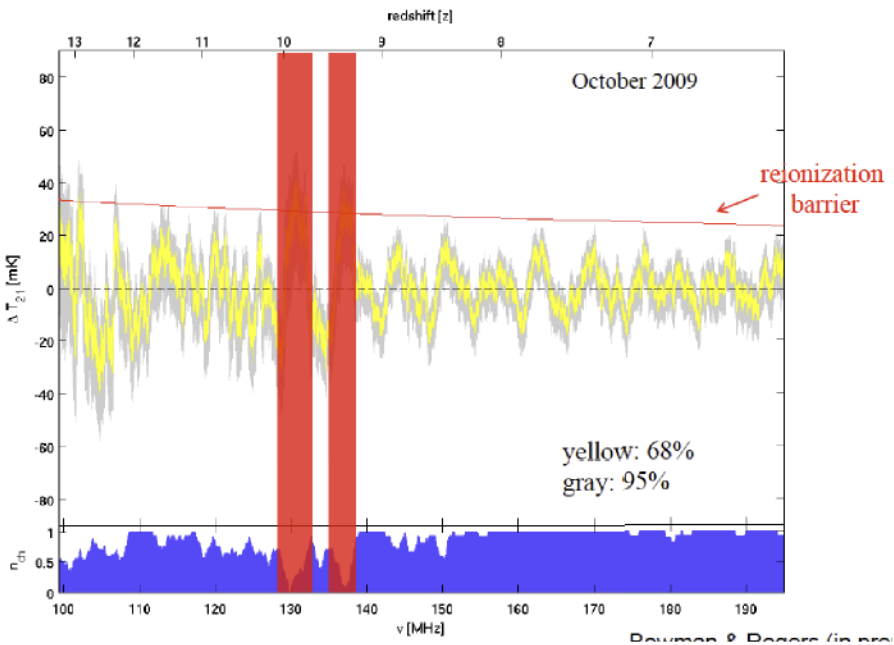


Cosmic Origins
Epoch of Reionization

SKA science starting now …!

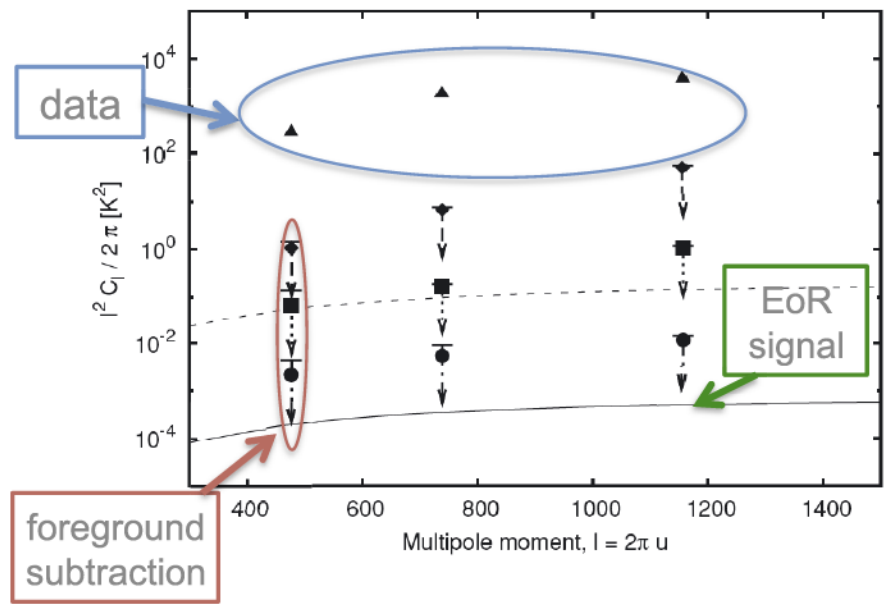
Global signature

Confidence intervals on ΔT_{21} with fixed $\alpha=\infty$



EDGES (Bowman et al. 2008)

Power Spectrum



GMRT (Paciga et al. 2011)

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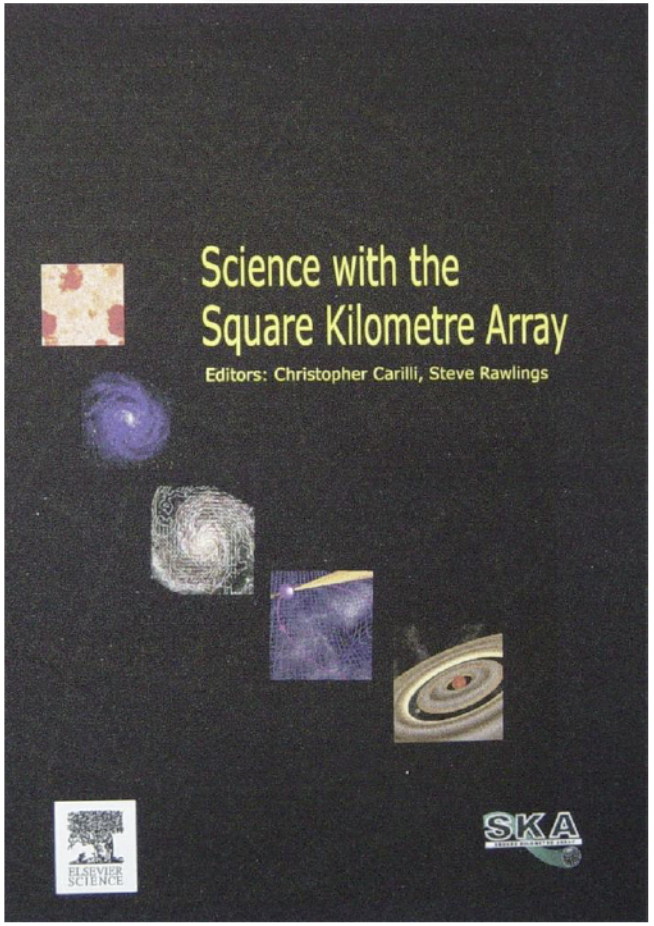
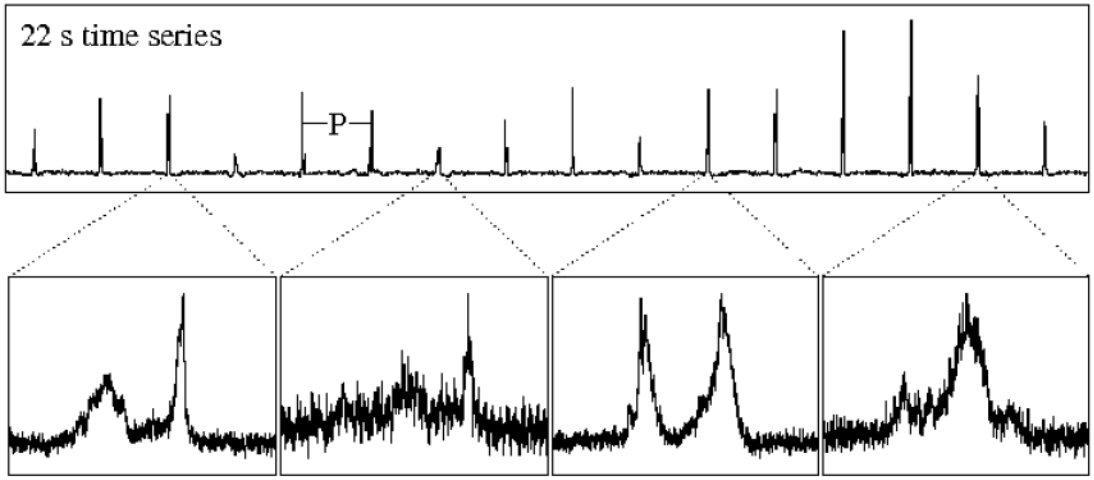


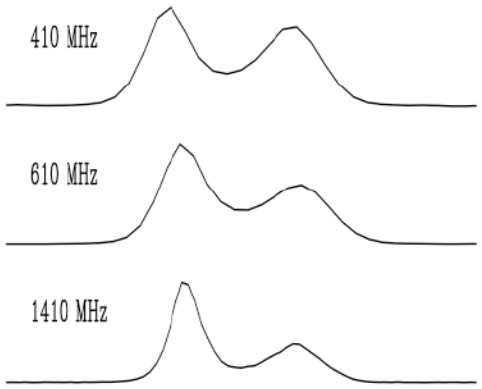
Science with the Square Kilometre Array
(Carilli & Rawlings)

Pulse Time-of-Arrival (TOA)

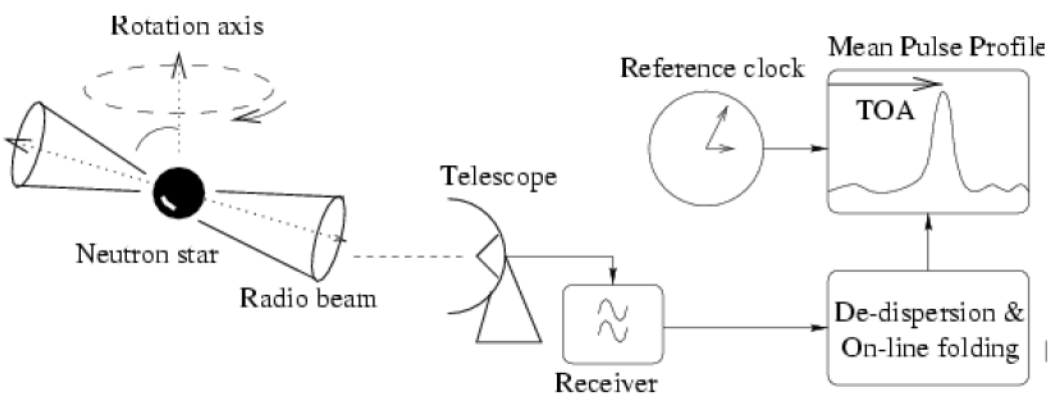


individual pulses

> 1000s of pulses ➔



mean profile



From Lorimer & Kramer, *Handbook of Pulsar Astronomy*

Measuring a Pulse Time-of-Arrival (TOA)

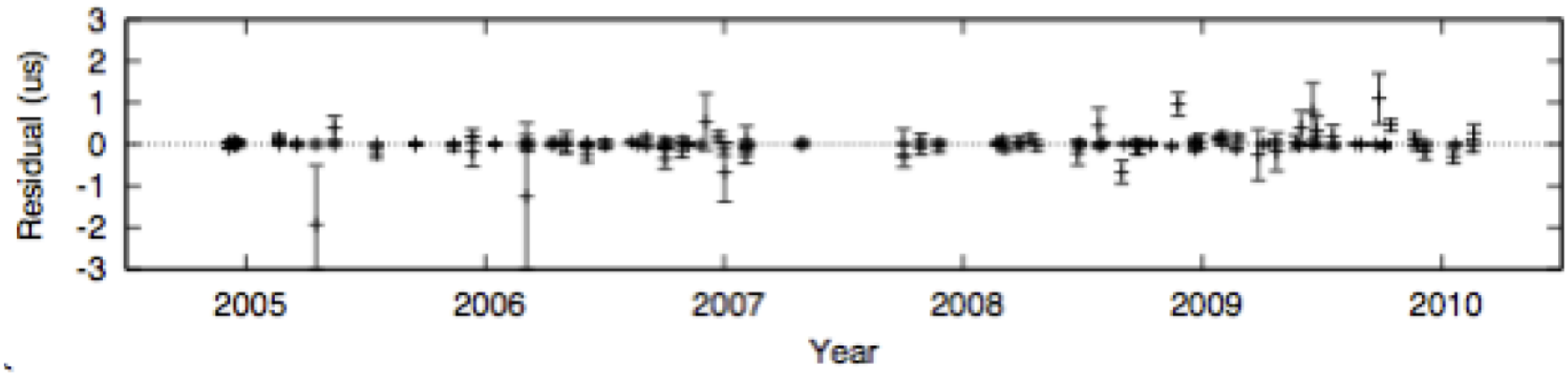
Observed TOA = Time of pulse emission
+ Orbital effects of pulsar
+ Light travel time
+ Plasma delays from intervening media
+ Gravitational wave delays
+ Solar system travel time

Residuals = Observed TOA − Model TOA

Residuals for a Millisecond Pulsar

J1713+0747

P = 4.57 ms

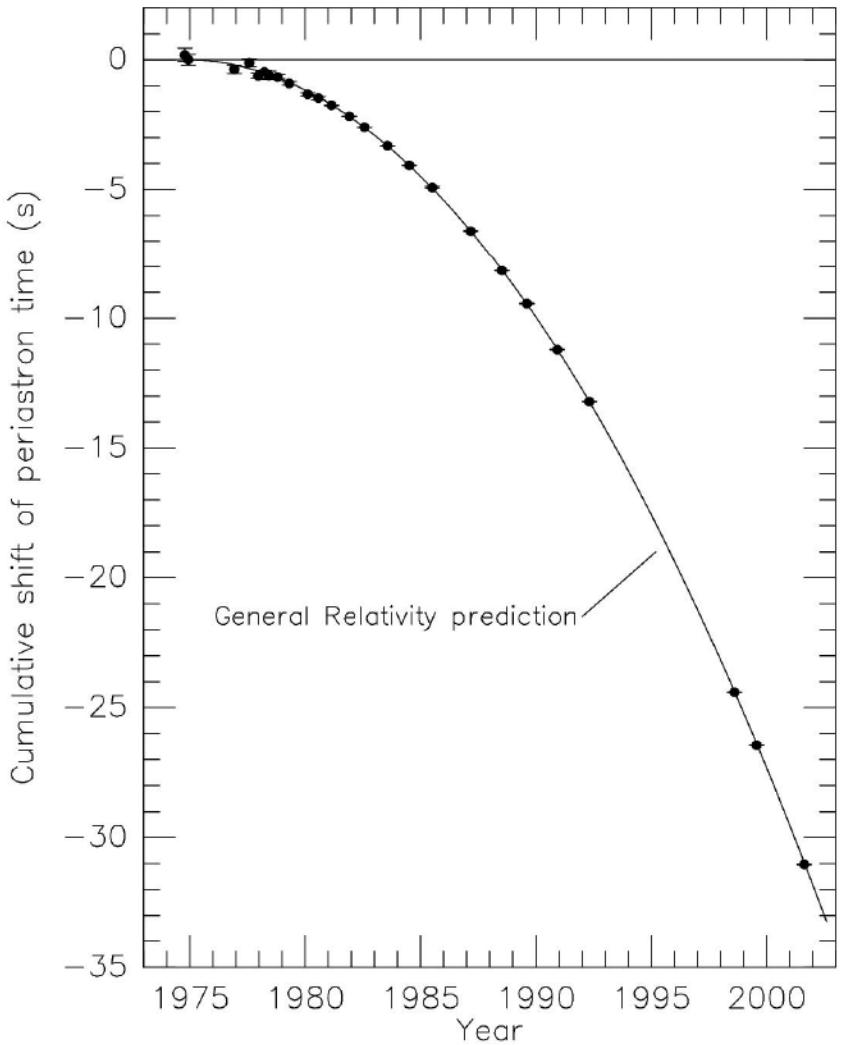


σ_{RMS} = root-mean-square residual = 30 ns (6×10^{-6} P)

… after fitting for spin, astrometric, Keplerian, and post-Keplerian parameters and time-variable dispersion measure changes.

(Demorest et al. 2012)

Gravitational Wave (Indirect) Detection



Hulse & Taylor, 1975, ApJ, 195, L51
Weisberg & Taylor, 1984, PRD, 52, 1348

Nobel Prize in Physics 1993

"… for the discovery of a new type of pulsar, a discovery that has opened up new possibilities for the study of gravitation."

Awarded jointly to Russell A. Hulse & Joseph H. Taylor Jr.

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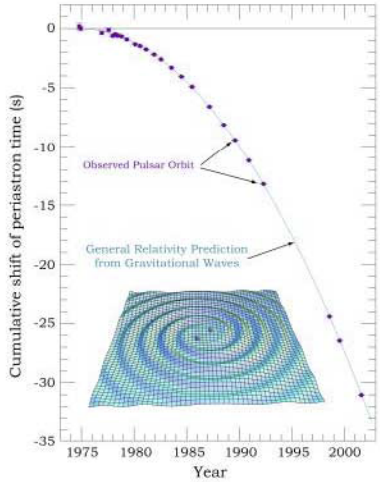
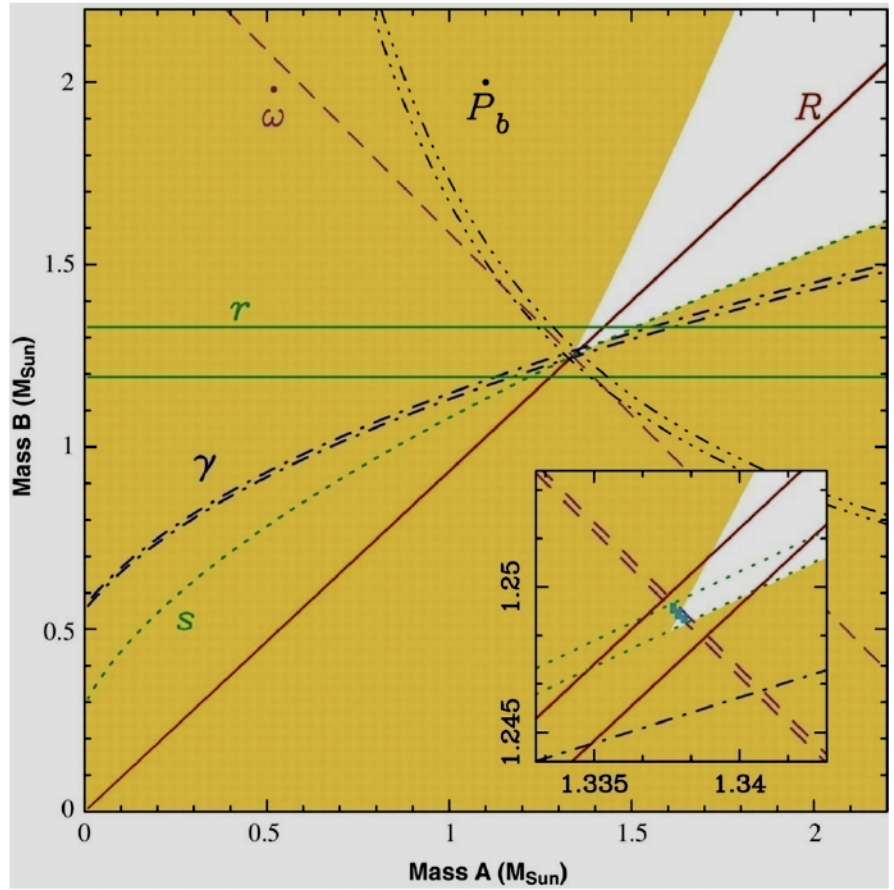
Did Einstein Have the Last Word on Gravity?

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



PSR J0737-3039



Relativistic binaries probe

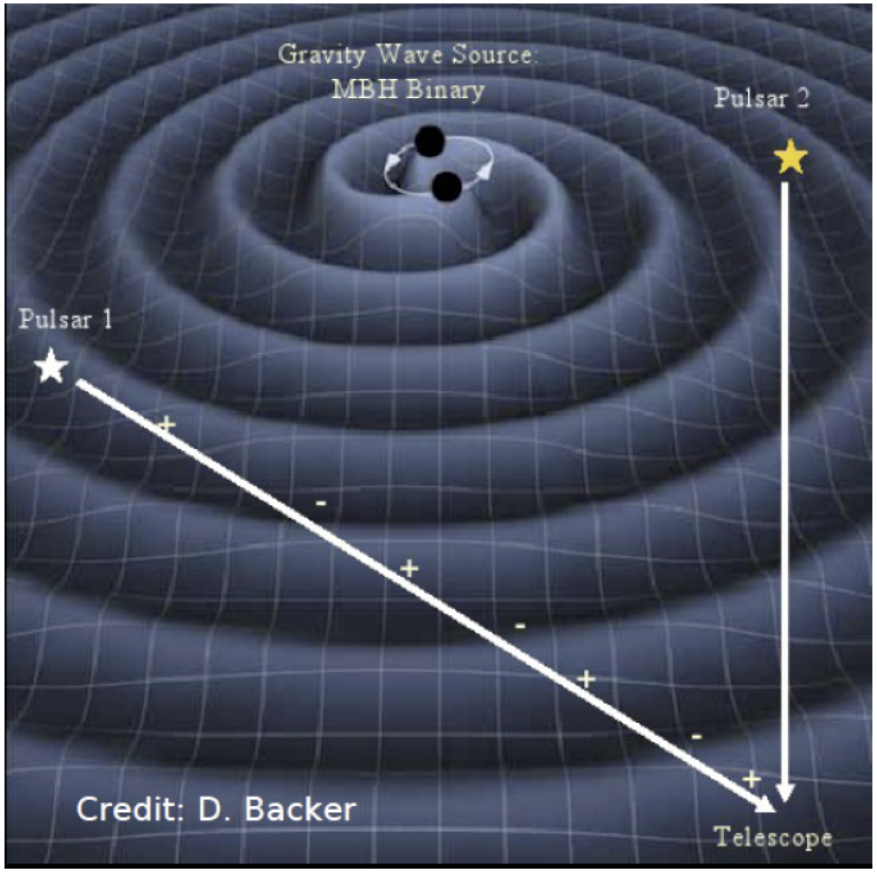
1. Equivalence principle
2. Strong-field tests of gravity

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

? Black hole-neutron star binaries?

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

Pulsars for *Direct* GW Detection



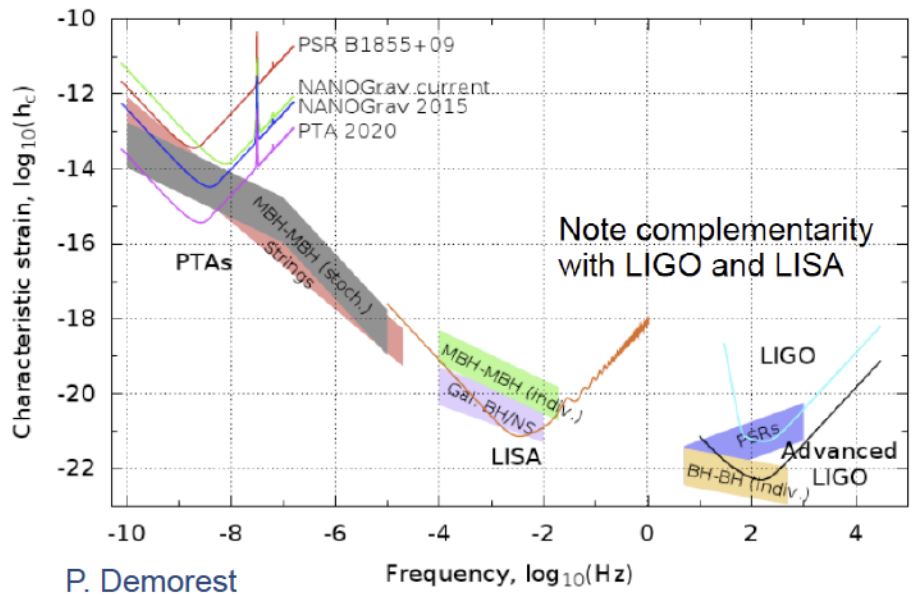
$\Delta t \sim h/f$

both pulsar and Earth terms

$f \sim 1/\text{weeks to } 1/\text{years } (10^{-6} - 10^{-9}\ \text{Hz})$

$h \sim \sigma_{rms}/T \sim 100\ \text{ns}/5\ \text{years} \sim 10^{-15}$

$\lambda_{gw} \sim 1\text{-}10\ \text{lyr};\ D_{psr} \sim 1000\ \text{lyr}$



P. Demorest

First discussed by Sazhin (1978, Sov. Astron., 22, 36), Detweiler (1979, ApJ, 234, 1100)

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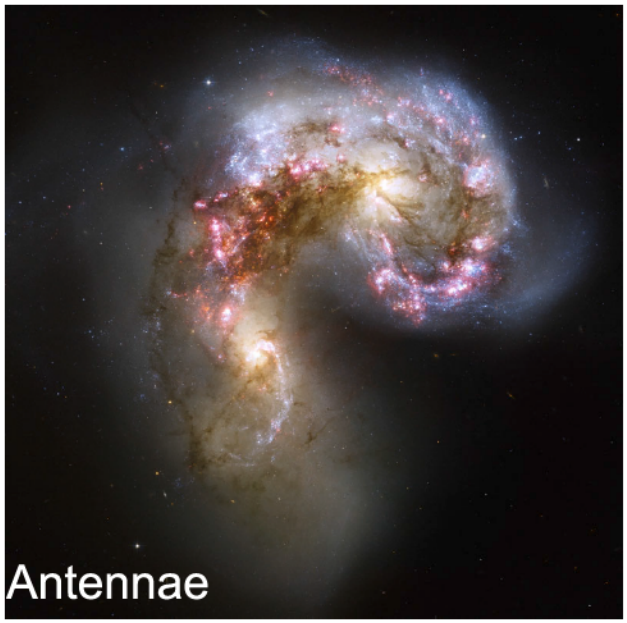
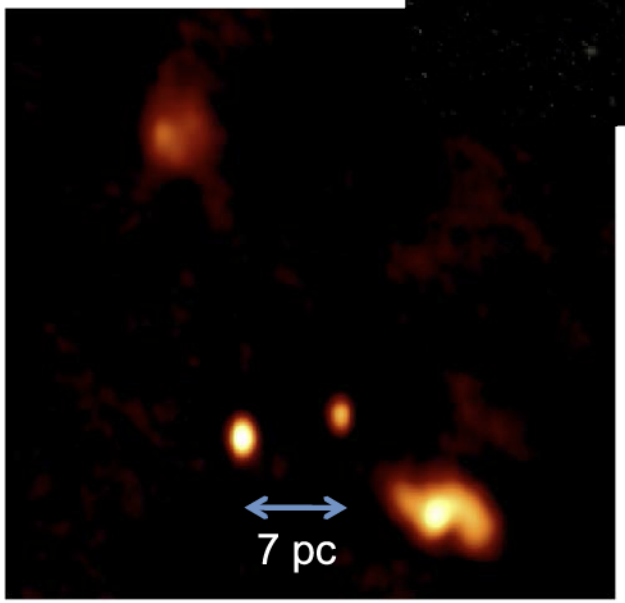
Super-Massive Black Hole Binaries

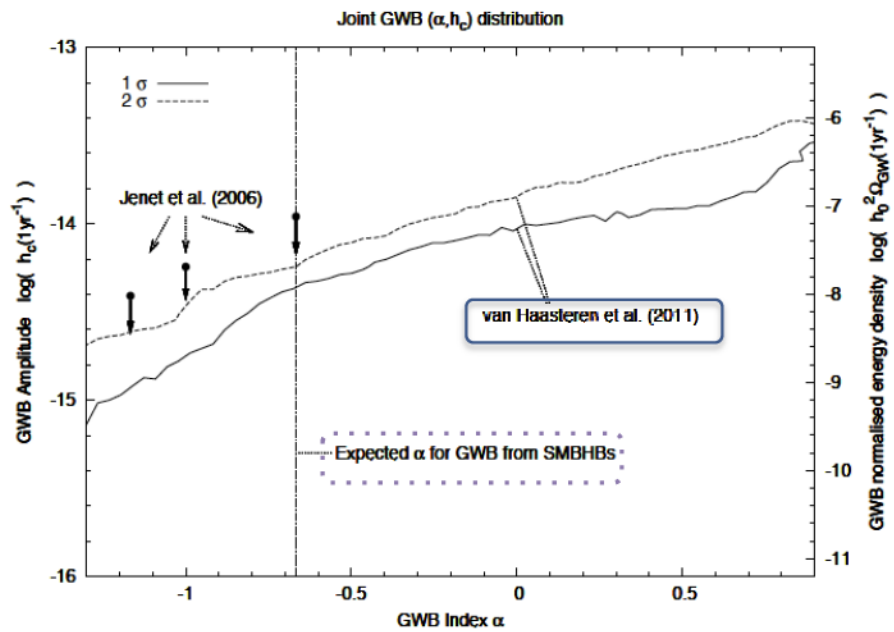
- Galaxy mergers appear to be frequent event, necessary part of galaxy evolution and formation
- Expect large number of super-massive black hole binaries ($M \sim 10^{7\text{-}8}\ M_{\odot}$, $N \sim 10^{-3}\ \mathrm{Mpc}^{-3}$) in the Universe
  (Jaffe & Backer, 2003, ApJ, 583, 616; Sesana et al., 2008, MNRAS, 290,192)





Radio (VLBA) image of B0402+379 (Rodriguez et al. 2006)

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.)*

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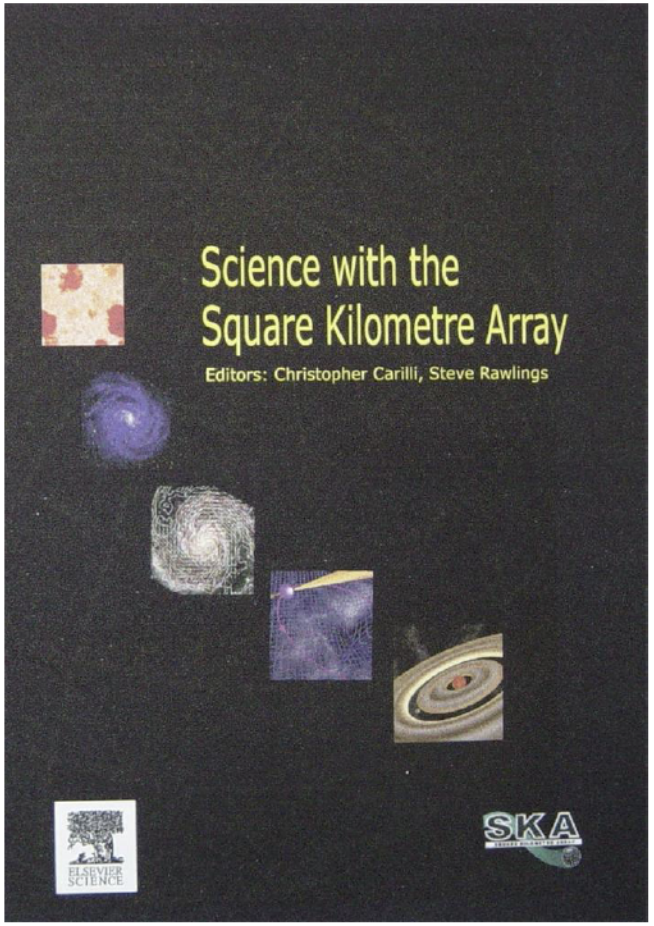


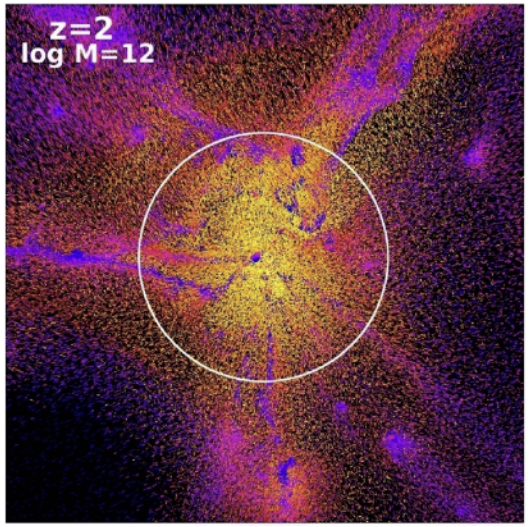
Science with the Square Kilometre Array
(Carilli & Rawlings)

Galaxy Assembly
Stars *and* Gas

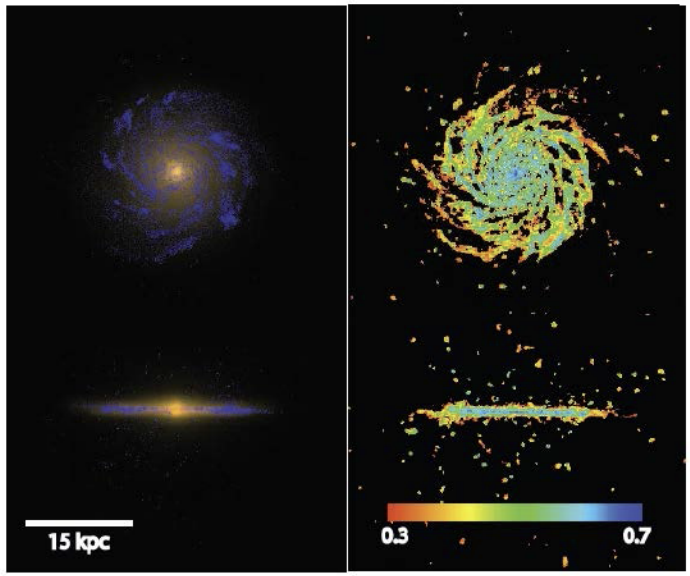
- Gas content and dynamics becoming critical part of simulations.
- Astronomy is an *observational* science.

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

observation vs. simulation



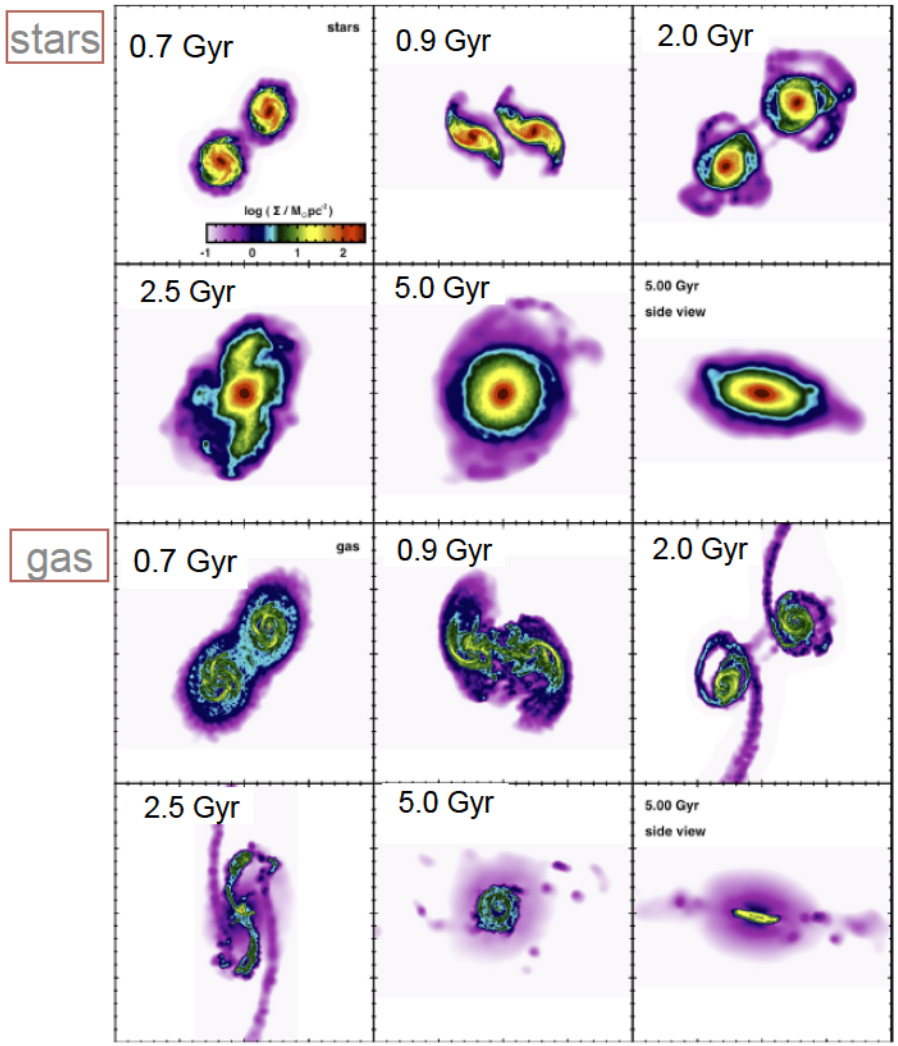
Keres et al.



Eris simulation (Guedes et al.)

NGC 6946 (T. Oosterloo)

Galaxy Assembly
The Role of Mergers



(Moster et al. arXiv:1104.0246)

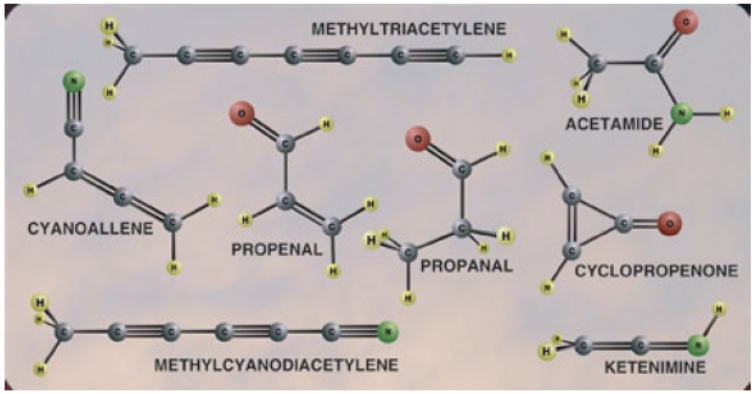
- Mergers are recognized as important aspect of galaxy evolution and formation
- Gas can be sensitive tracer of interactions, long after original event took place

  E.g., Holwerda et al. with THINGS

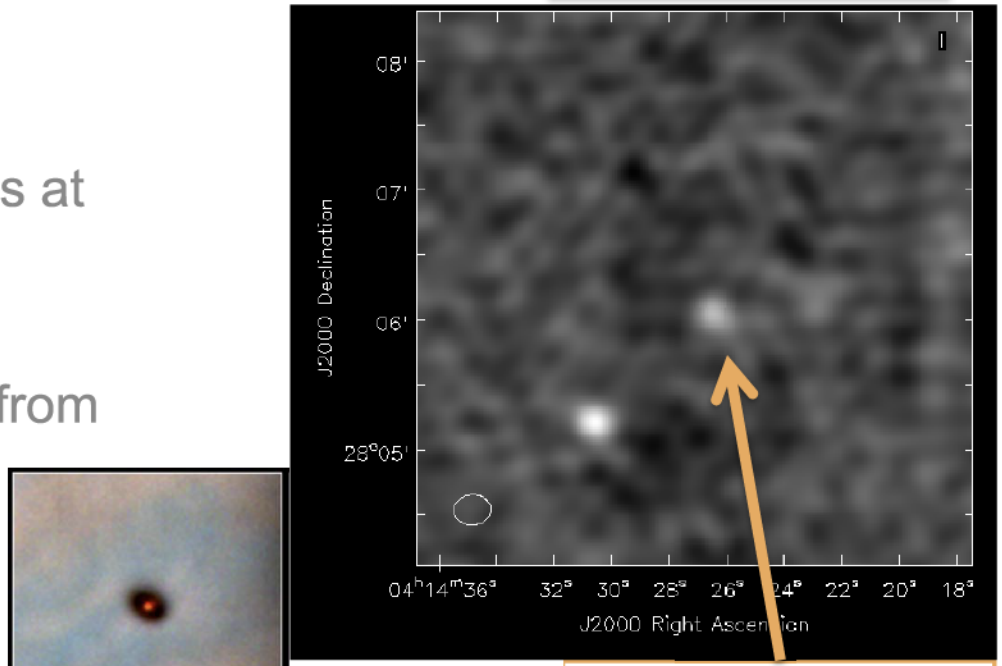
Astrobiology at Long Wavelengths

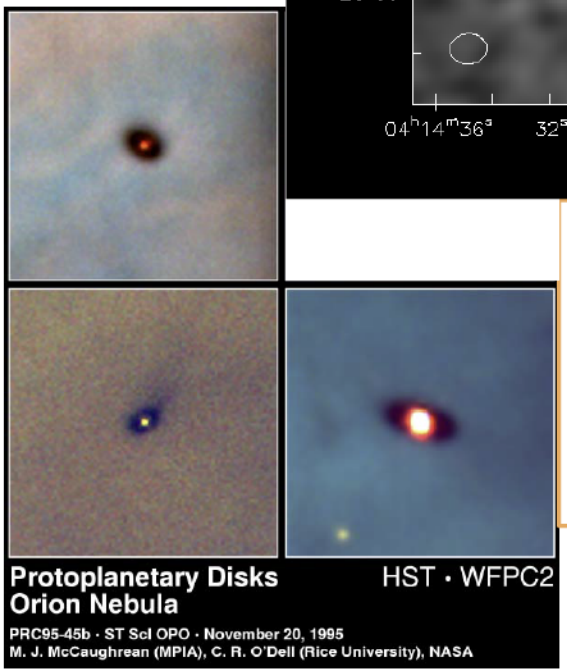
$\lambda > 1$ cm

- 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

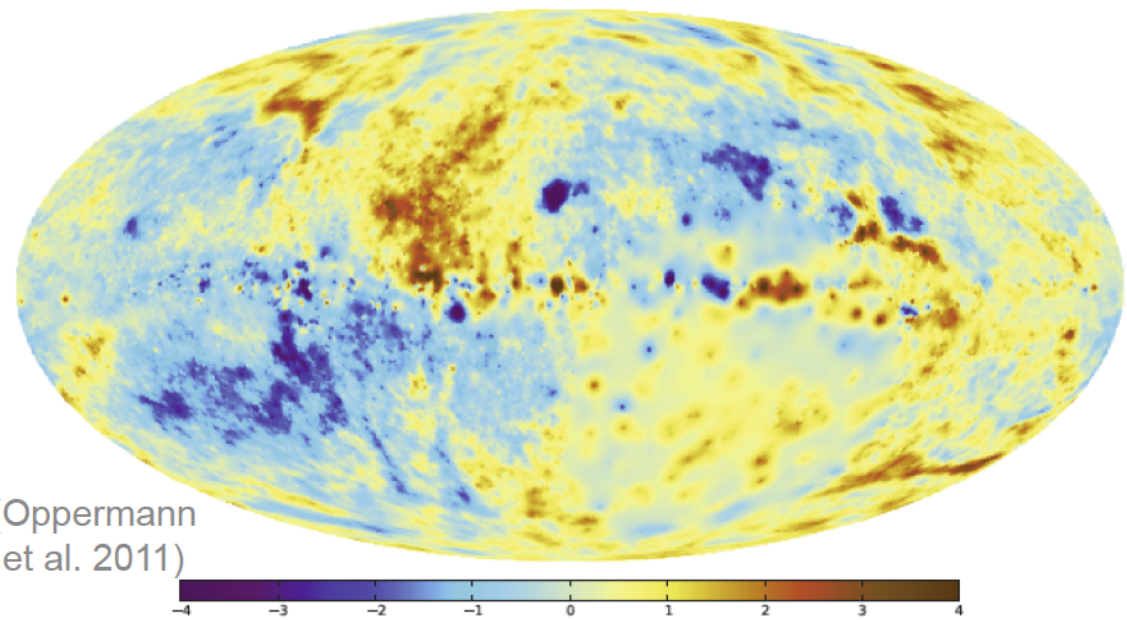




EVLA 6 cm observations of protoplanetary disks; PEBBLES on e-MERLIN coming soon

Origin & Evolution of Cosmic Magnetic

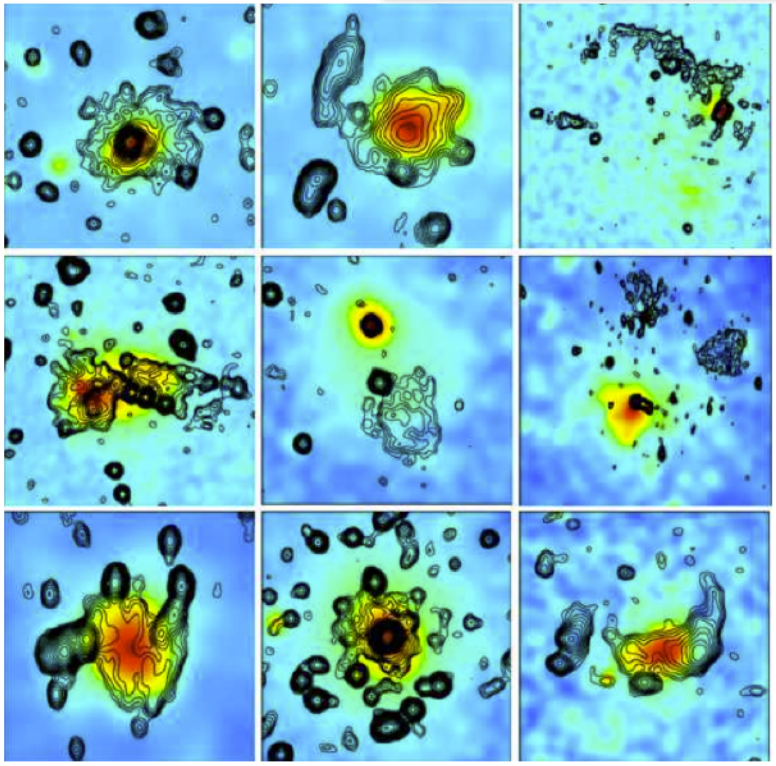
- Magnetic fields are fundamental, but poorly constrained
  - Affects galaxy, cluster evolution?
  - Affects propagation of cosmic rays in ISM and IGM
- All-sky rotation measure surveys provide **B** fields along lines of sight



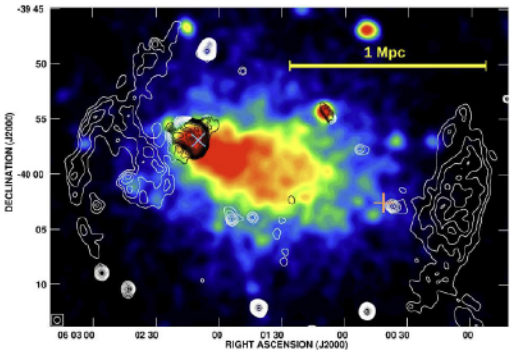
(Oppermann et al. 2011)

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
  - …



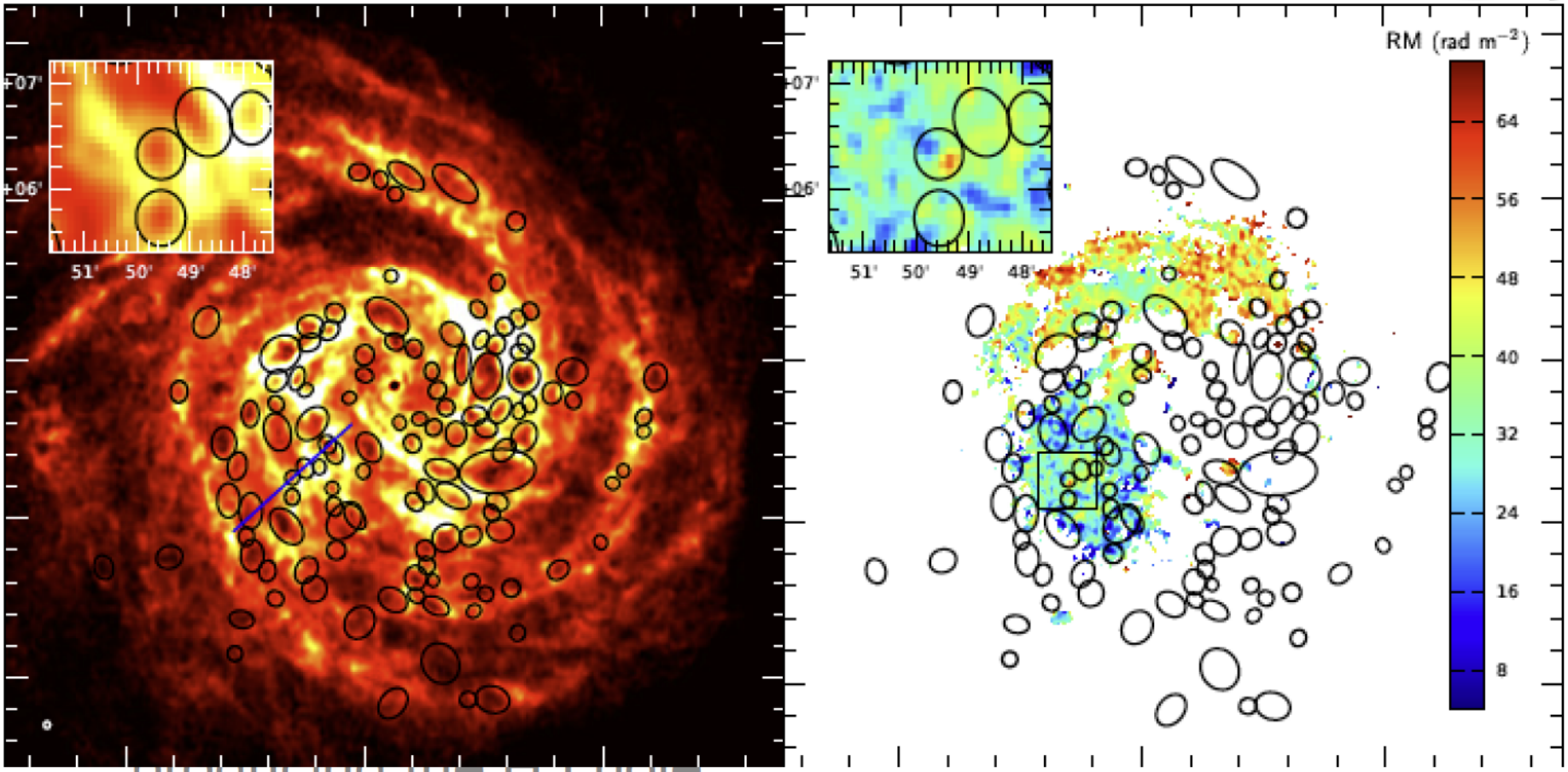
Feretti et al.



Kale et al.

ld's largest radio telescope

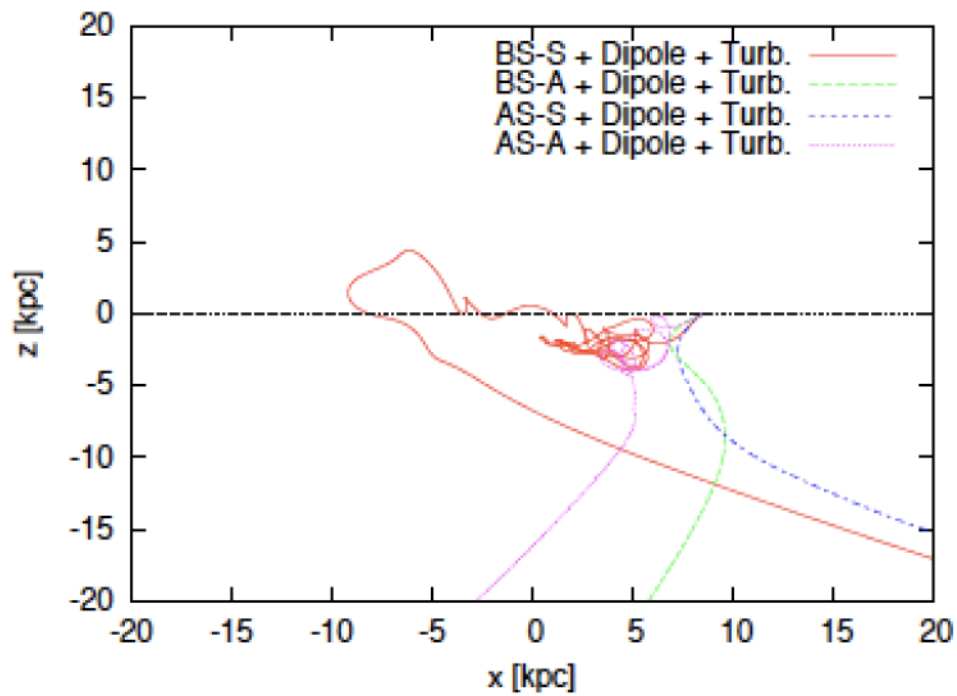
New Slide



producing the HI hole

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?
  - …?



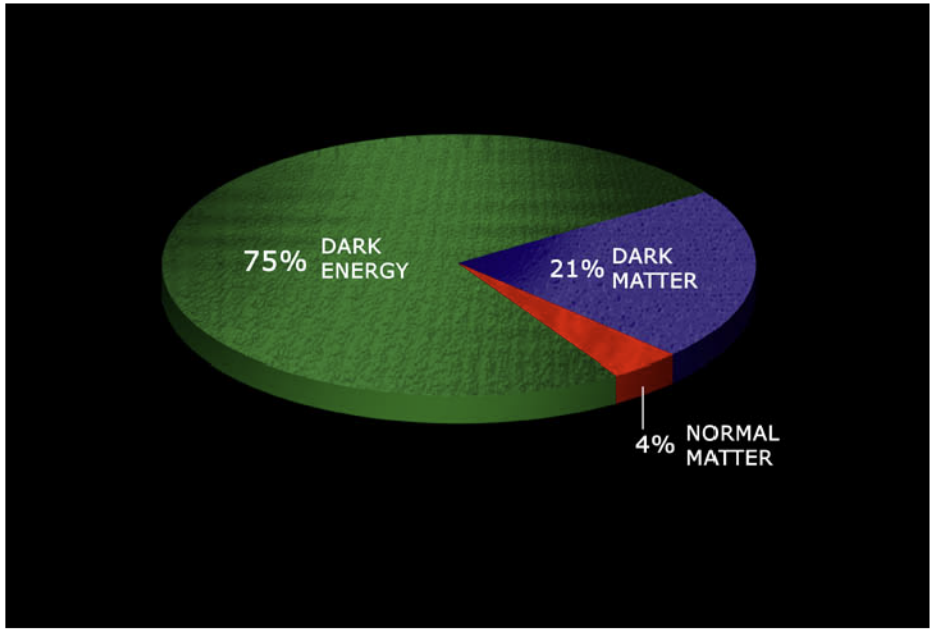
Takami, arXiv:1104.0278

Cosmology and Gravity

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

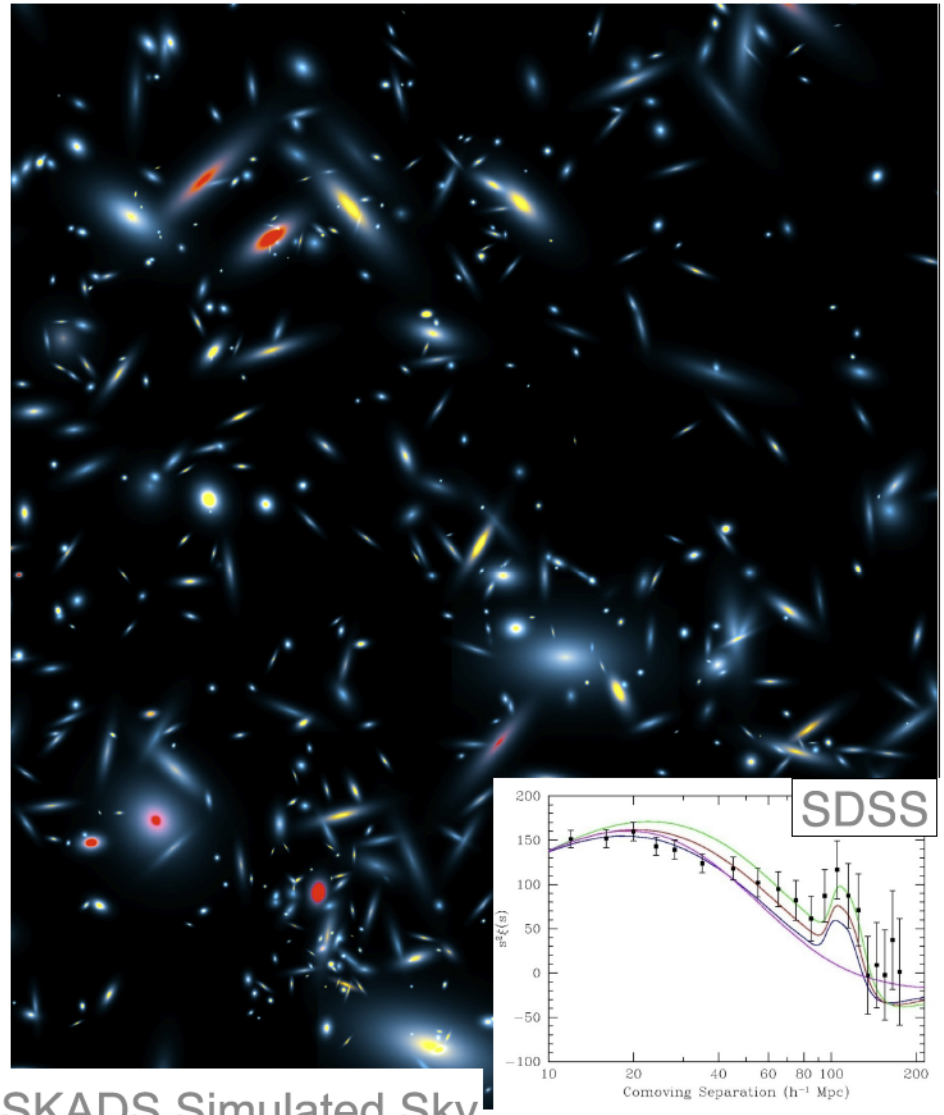
Origin and Fate of the Universe

- 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

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

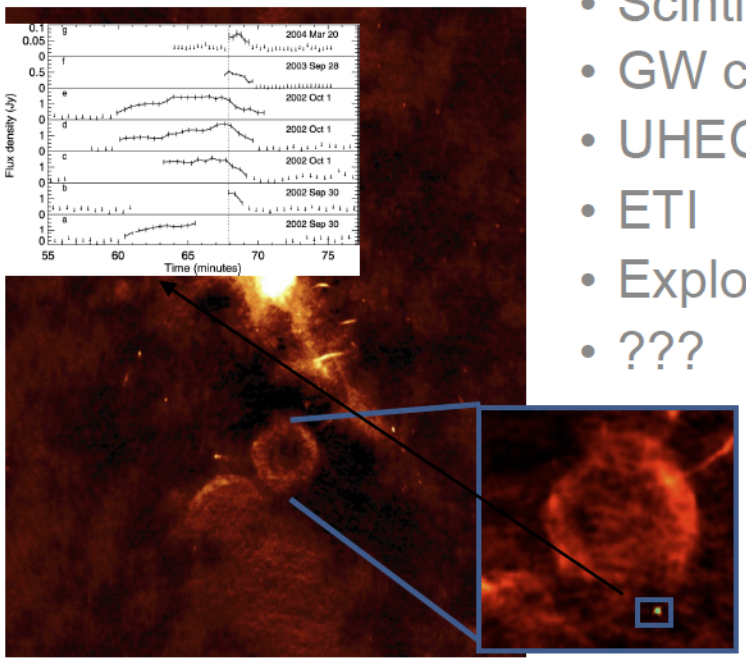
Sensitivity

Field of View

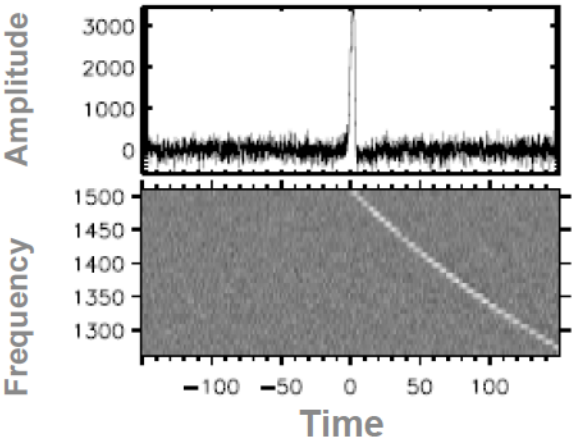
Angular Resolution

The Dynamic Radio Sky

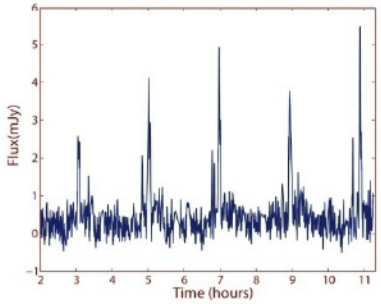
- Neutron stars
  - Magnetars
  - Giant pulses
  - Short GRBs?
- Microquasars
- Tidal Disruption Events

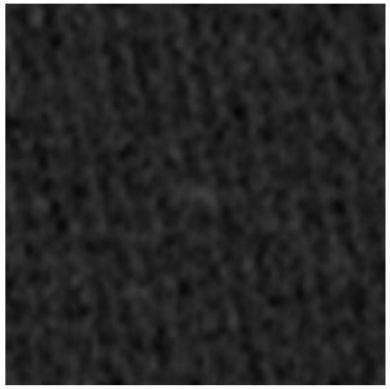


- GRBs (γ-ray loud; γ-ray quiet?)
  - Afterglows
  - Prompt emission?
- Sub-stellar objects
  - Brown dwarfs
  - Extrasolar planets?
- Scintillation
- GW counterparts
- UHECRs
- ETI
- Exploding black holes
- ???



Rotating Radio Transients (RRATS)



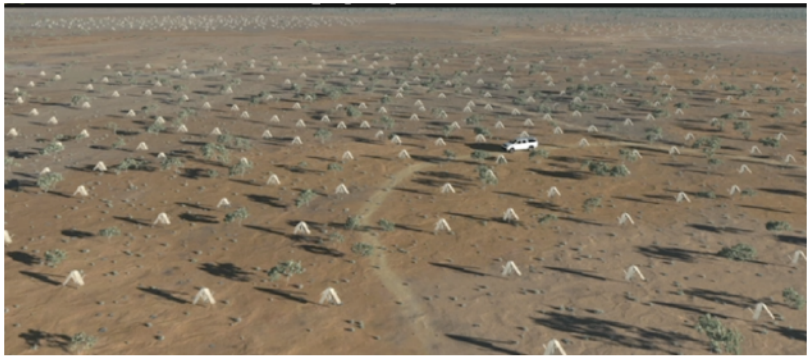


Pulsating Brown Dwarfs

The SKA
A Radio Telescope

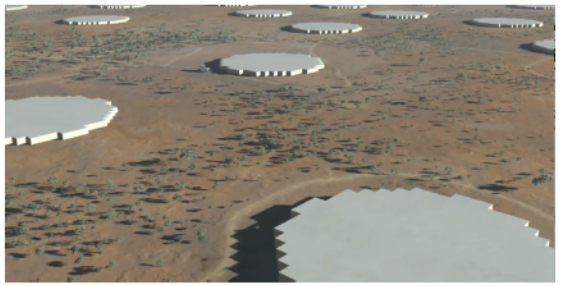
SKA-Low

Low frequency aperture arrays



SKA-Mid

dishes

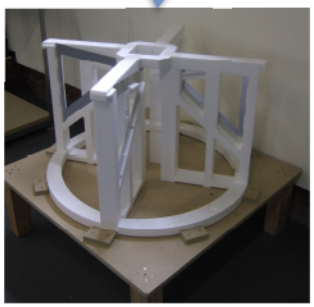


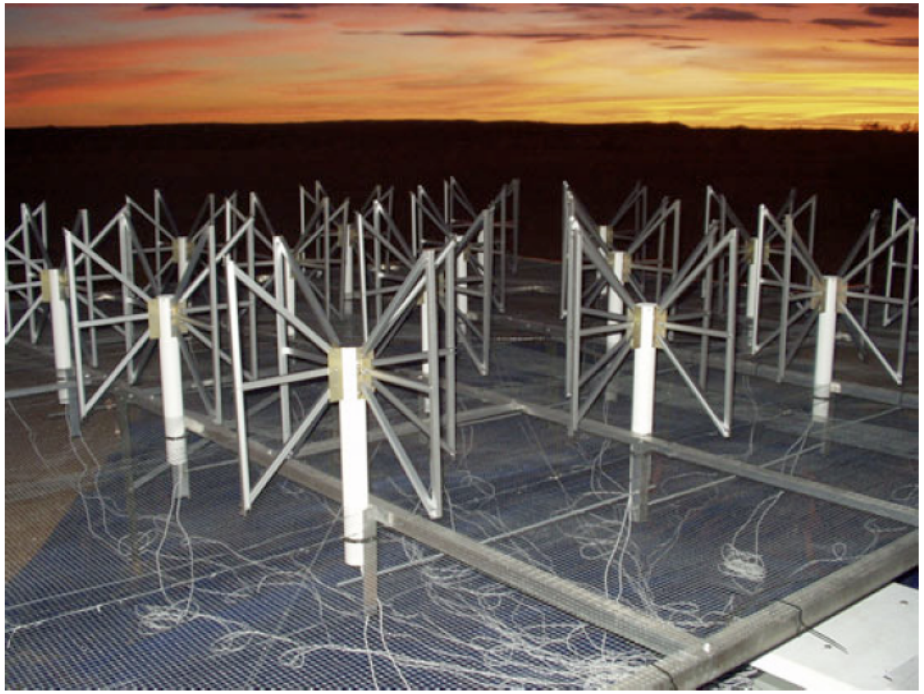
SKA-Mid (AA)

Dense aperture arrays

SKA-Low
Low-Frequency Component

LOFAR (Netherlands et al.)

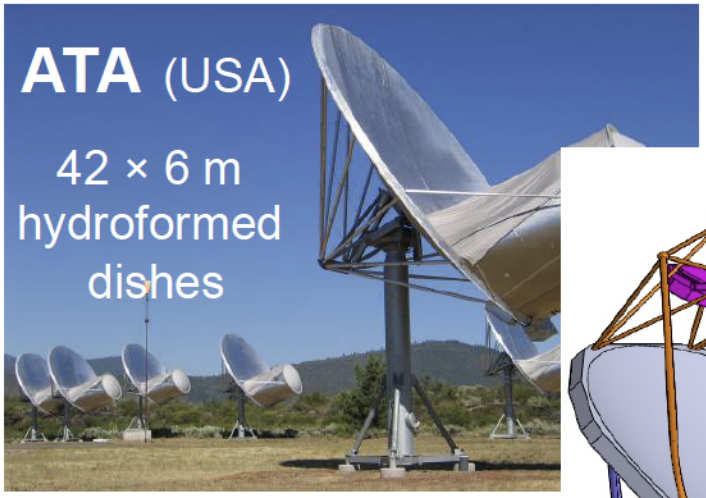


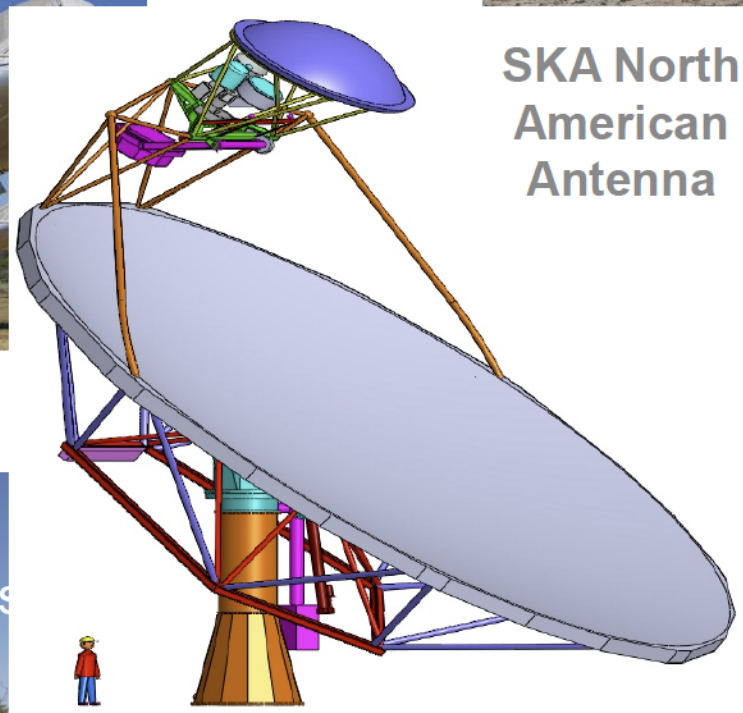


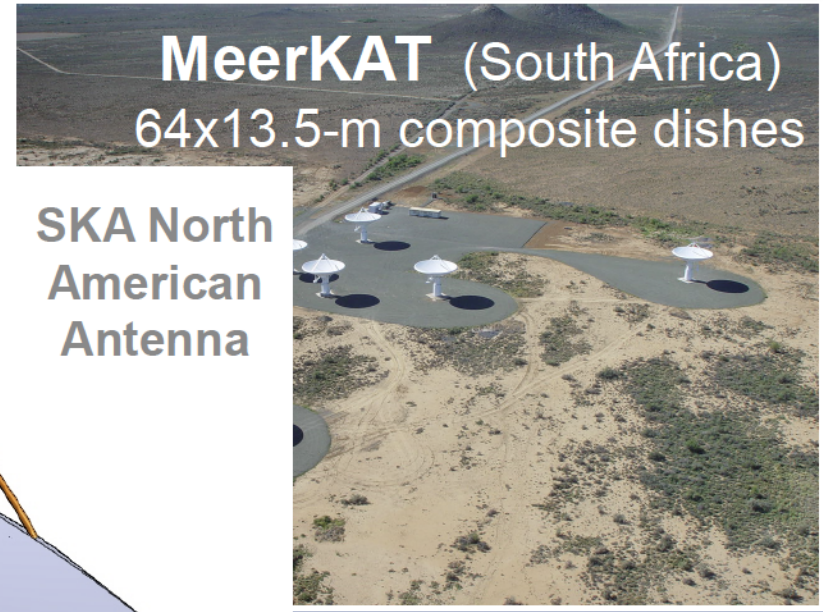
MWA (Australia, India [USA])

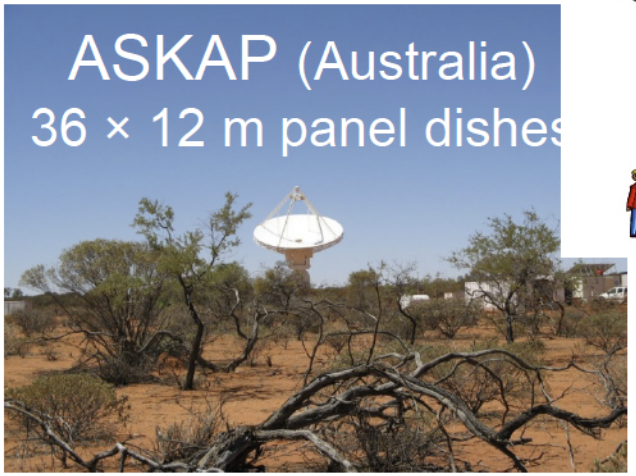
Exploring the Universe with the world's largest radio telescope

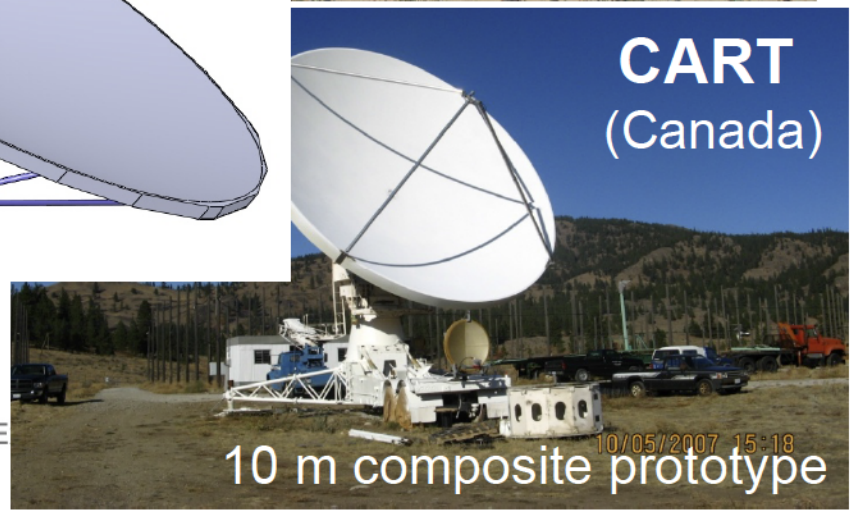
SKA
Middle-Frequency Component



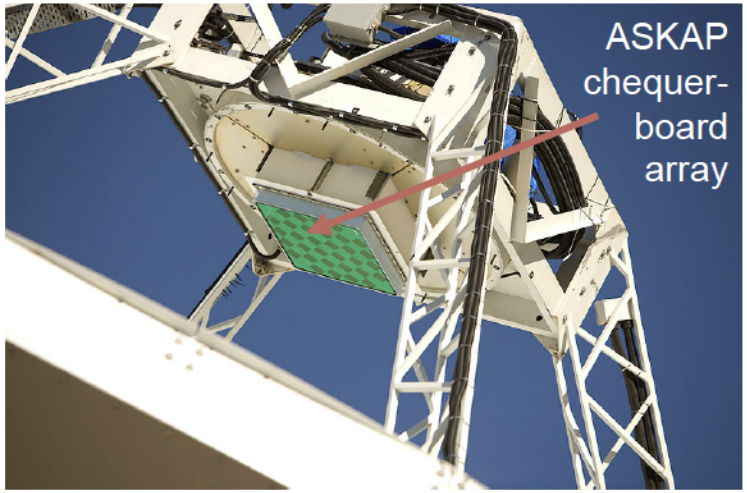




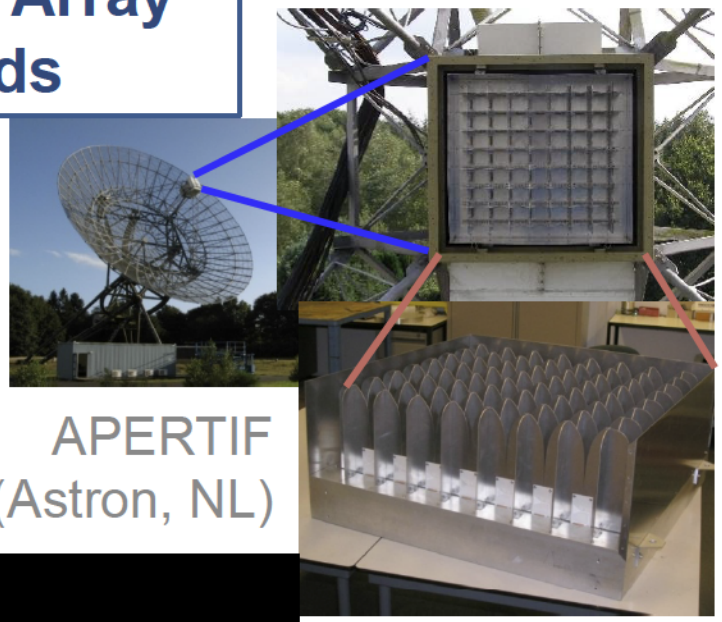




Phase 1 → Phase 2 SKA Field of View Expansion

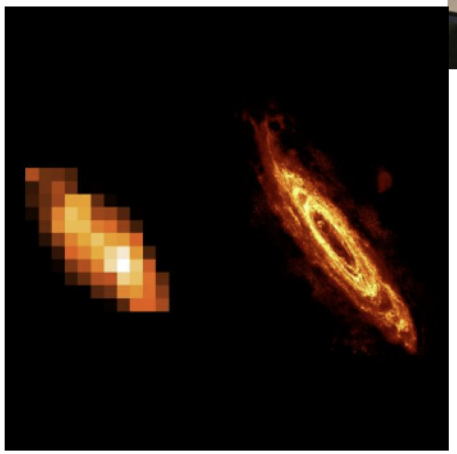


Phased Array Feeds

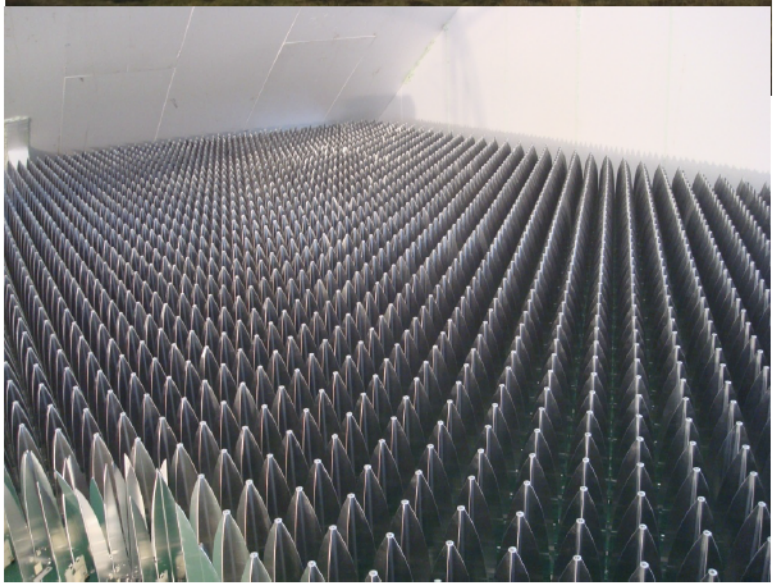


APERTIF
(Astron, NL)

DRAO
Canada



Phase 1 → Phase 2 SKA Field of View Expansion



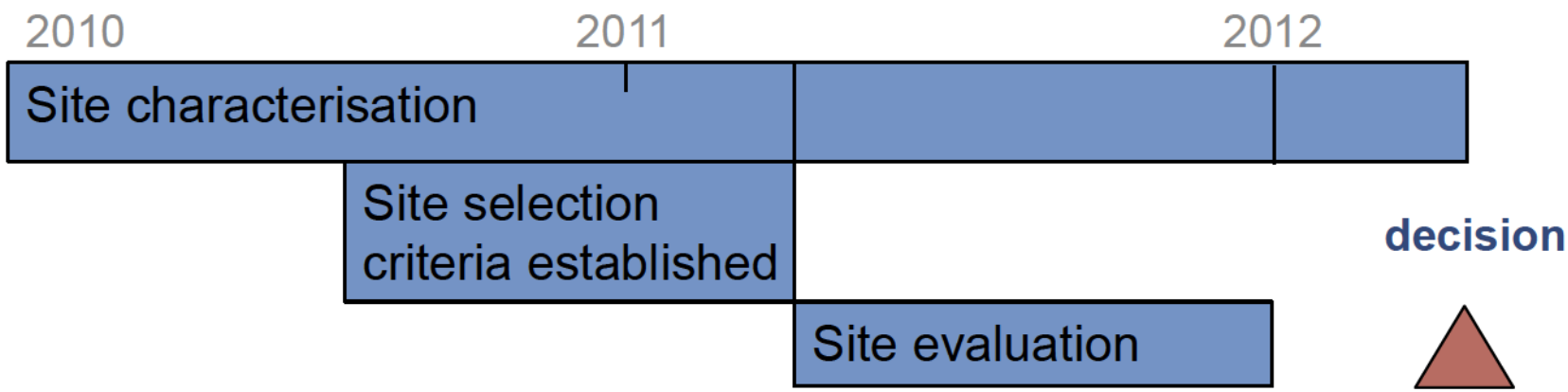
Dense Aperture Arrays

FP6-SKADS

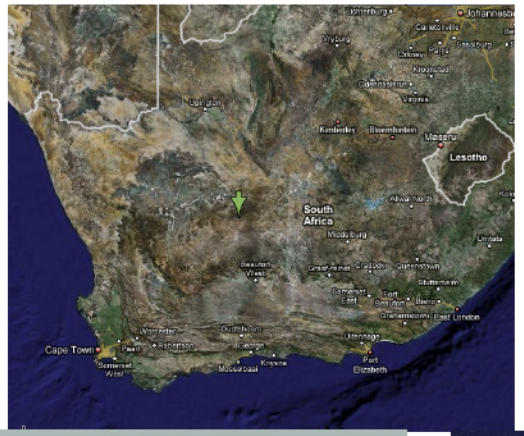
Where in the World is the SKA?

- Physical requirements
  - Extremely radio quiet environment
  - At least 3000 km in extent
  - Low ionospheric turbulence
  - Low tropospheric turbulence
- Two candidates short-listed in 2006

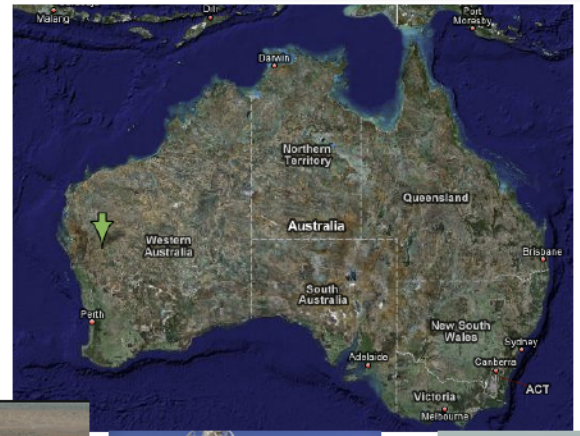
  Australia (Australia-New Zealand) and South Africa (& surrounding countries)
- Site selection process

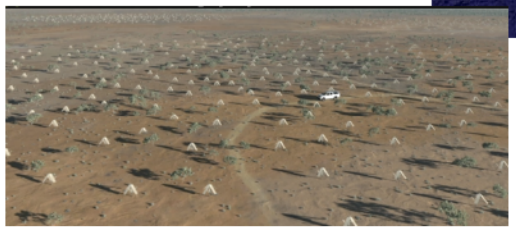


SKA1 Dual Site Implementation

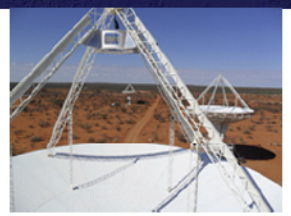


SKA1_Mid





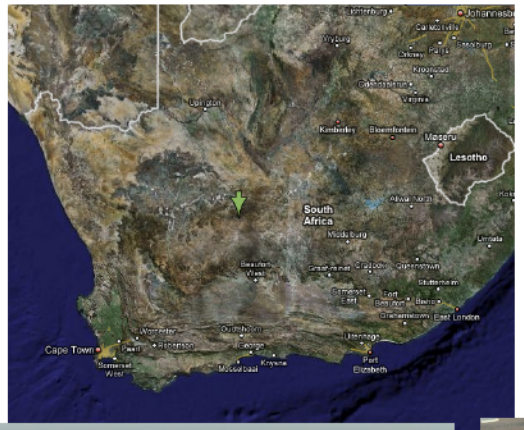
SKA1_Low



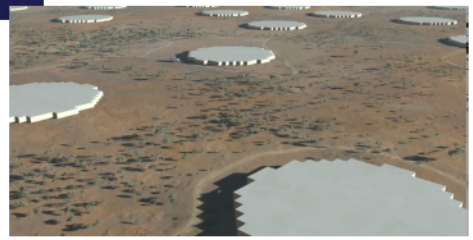
SKA1_AIP_Survey

	SKA Element	Location	Comment
Dish Array	SKA1_Mid	RSA	190 SKA + 64 MeerKAT
Low Frequency Aperture Array	SKA1_Low	ANZ	50 stations
Survey Instrument	SKA1_AIP_Survey	ANZ	60 SKA + 36 ASKAP

SKA2 Dual Site Implementation



SKA2_Mid_Dish



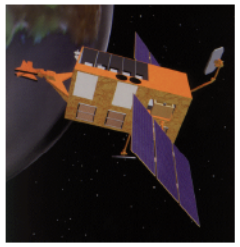
SKA2_AIP_AA

SKA2_Low

	SKA Element	Location	Comment
Low Frequency Aperture Array	SKA2_Low	ANZ	250 stations
Mid Frequency Dish Array	SKA2_Mid_Dish	RSA+	3000 dishes
Mid Frequency Aperture Array	SKA2_Mid_AA	RSA	250 stations

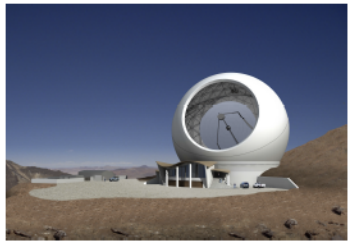
Multi-wavelength Astronomy

Surveys



- RXTE

- Pan-STARRS, SkyMapper, LSST, …

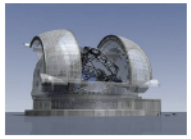
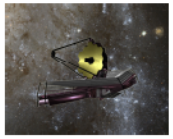


- CCAT

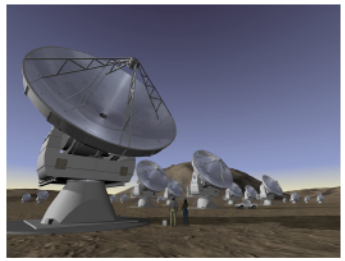
Targeted

- Chandra, XMM-Newton

- E-ELT, TMT, GMT, JWST

- ALMA



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, …

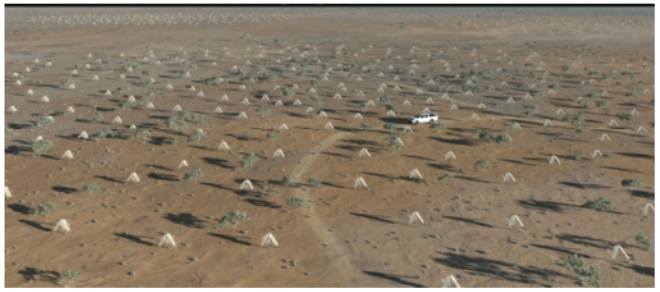
Targeted Observations

- 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
- …

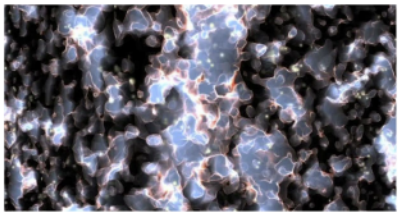
E.g., PTAs, THINGS, JVLA Deep H I field, JVLA Deep Polarization field, ATCA observations, VLBI observations, …

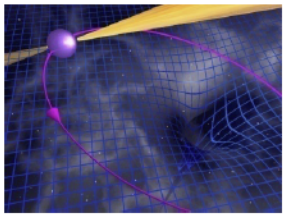
Square Kilometre Array

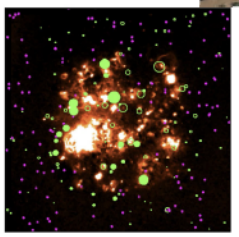
Global Radio Wavelength Observatory

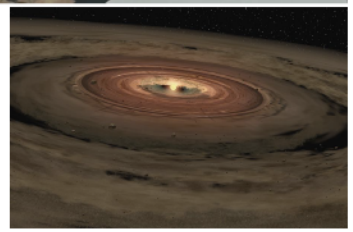


- Originally: “Hydrogen telescope”
  - Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$
- SKA science much broader
  - ⇒ Multi-wavelength, multi-messenger
- On-going technical development
- International involvement









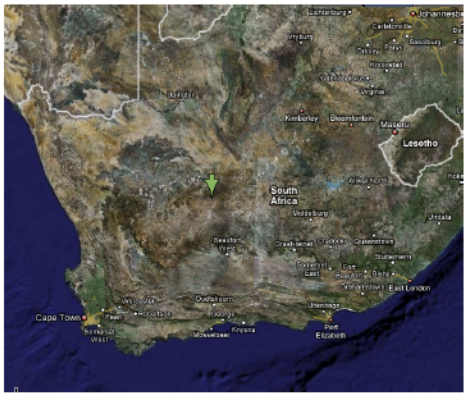
backup

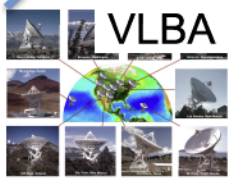
SKA1_Mid

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

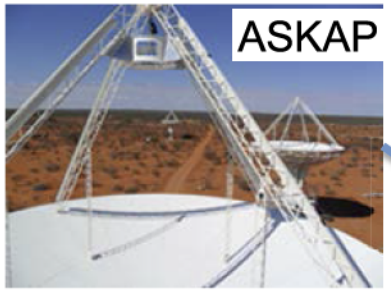
eMERLIN

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

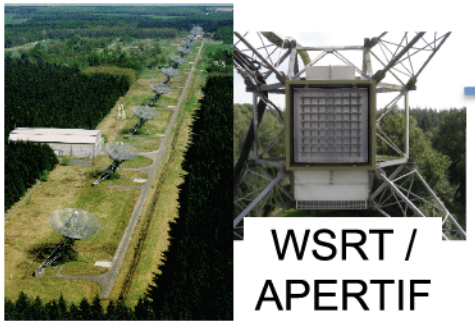


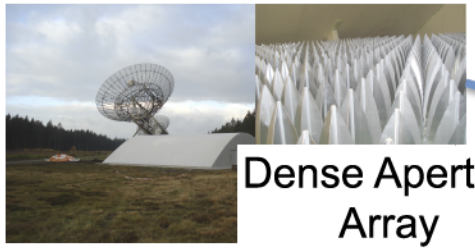


SKA1_Survey



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

Exploring the Universe with the world's largest radio telescope

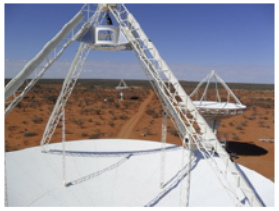
SKA Pathfinding

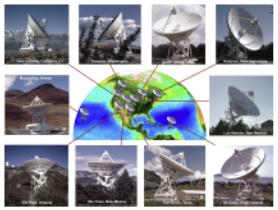
SKA is ultimate goal, though long-term program

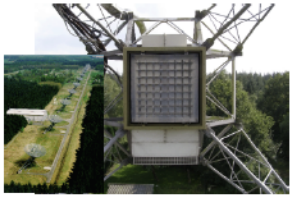
- Precursors and many pathfinders in existence or under construction

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

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

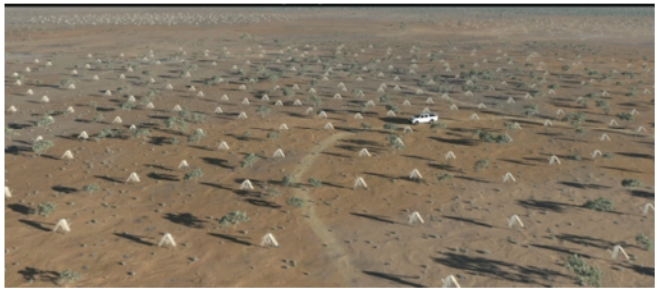




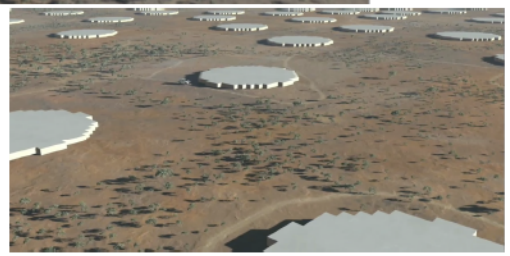


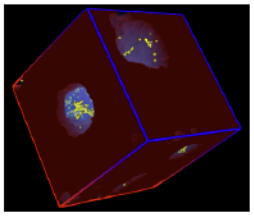
Square Kilometre Array

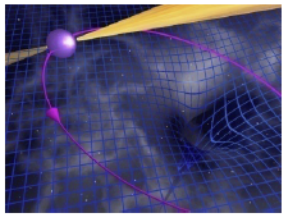
Global Radio Wavelength Observatory

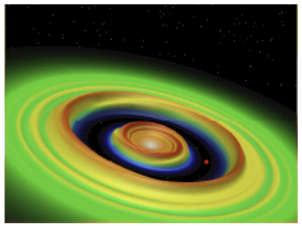


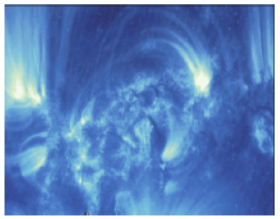
- Originally: “Hydrogen telescope”
  - Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$
- SKA science much broader
  - ⇒ Multi-wavelength, multi-messenger
- On-going technical development
- International involvement





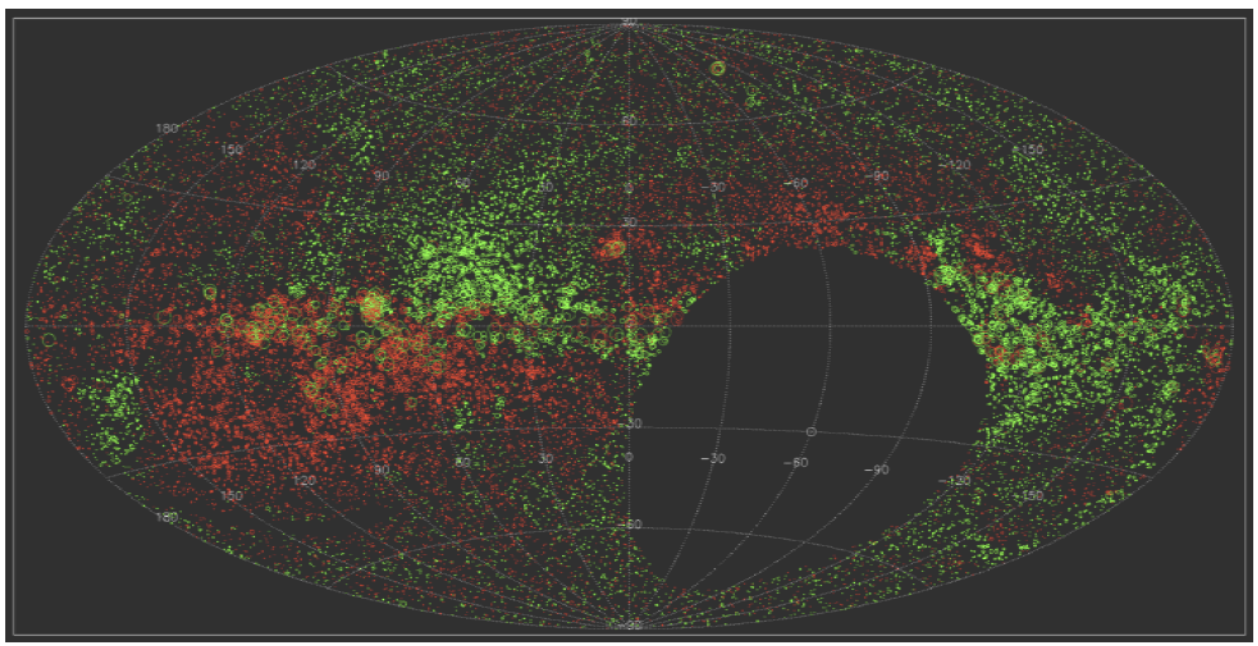


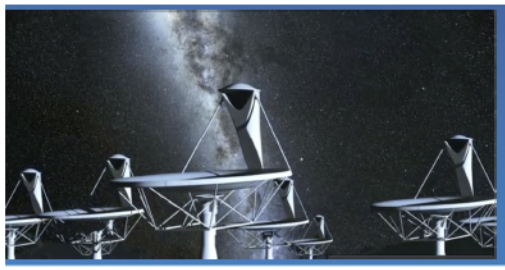




Origin & Evolution of Cosmic Magnetic

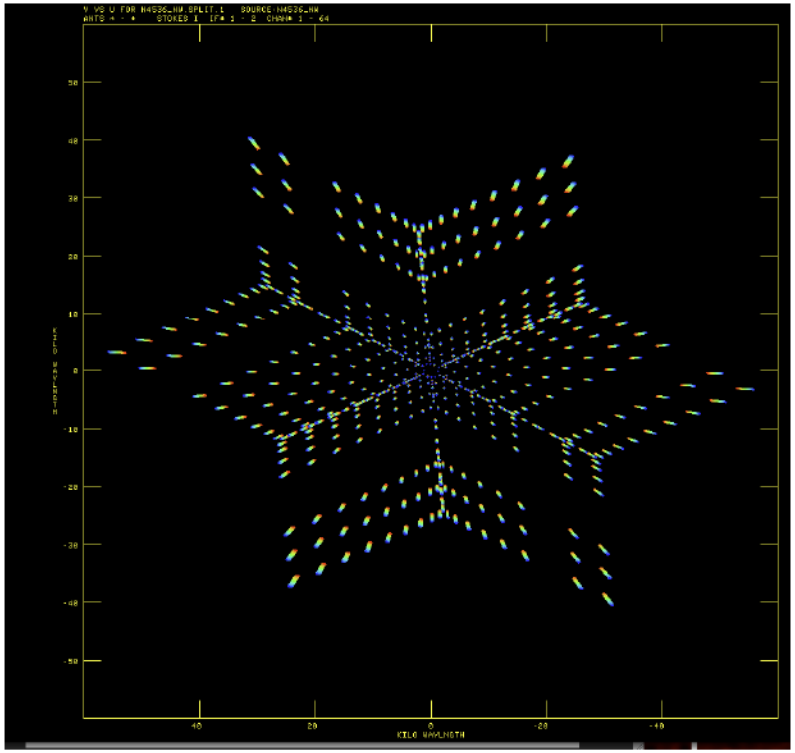
- Magnetic fields are fundamental, but poorly constrained
  - Affects galaxy, cluster evolution?
  - Affects propagation of cosmic rays in ISM and IGM
- All-sky rotation measure surveys provide **B** fields along lines of sight
- Continuum in I, Q, and U!





Imaging with Arrays

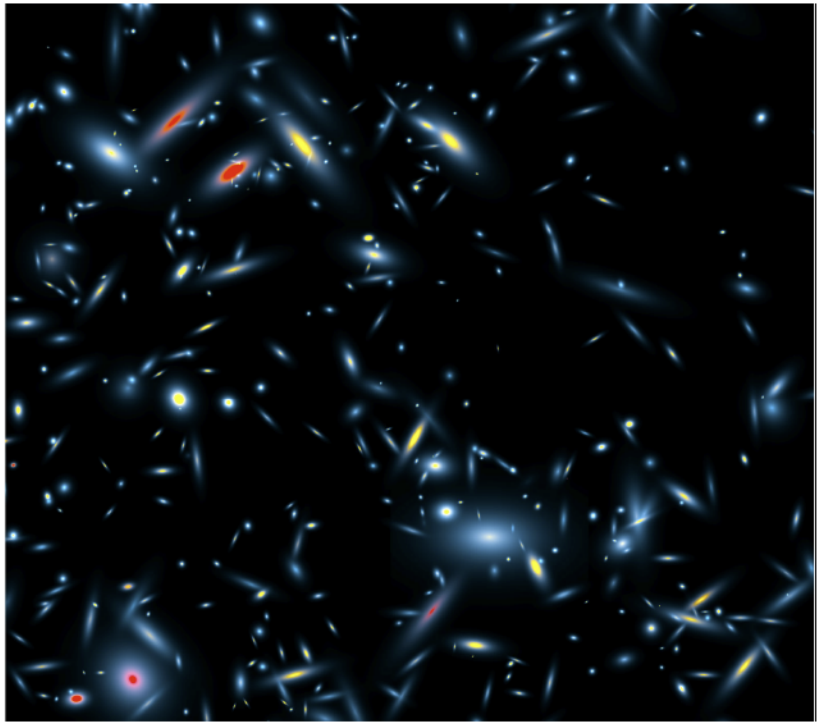
Fourier transform (*u*-*v*) plane



$$N_{data} \sim N_{antenna}^{2}\, N_{frequency} N_{time}$$

Fourier Transform ↔

Image plane



Exploring the Universe with the world's largest radio telescope

Imaging Surveys

Requirements

- Many antennas in order to provide sensitivity and image quality
  - large $N_{antenna}$
- Spectral resolution because of wide-field effects, line emission from galaxies, or both
  - large $N_{frequency}$
- Long integrations in order to obtain adequate signal-to-noise ratio
  - large N_{time}, e.g., 1 hr at 1 s sampling?

$$N_{data} \sim N_{antenna}^2 N_{frequency} N_{beams} N_{time}$$

ASKAP	SKA Phase 1	SKA Phase 2
$N_{antenna} = 30$	$N_{anntena} \sim 250$	$N_{antenna} \sim 1000$
$N_{beams} = 30$	$N_{beams} = 1$	$N_{beams} = 1?$
$N_{frequency} \sim 16k$	$N_{frequency} \sim 16k?$	$N_{frequency} \sim 16k?$

Imaging Surveys II

ASKAP	SKA Phase 1	SKA Phase 2
$N_{antenna} = 30$	$N_{anntena} \sim 250$	$N_{antenna} \sim 1000$
$N_{beams} = 30$	$N_{beams} = 1$	$N_{beams} = 1?$
$N_{frequency} \sim 16k$	$N_{frequency} \sim 16k?$	$N_{frequency} \sim 16k?$
$N_{time} \sim 4k$		
$N_{data} \sim 1.8 \times 10^{12}$	$N_{data} \sim 4 \times 10^{12}$	$N_{data} \sim 65 \times 10^{12}$
$N_{OPS} \sim 18 \times 10^{15}$	**$N_{OPS} \sim 40 \times 10^{15}$**	**$N_{OPS} \sim 650 \times 10^{15}$**

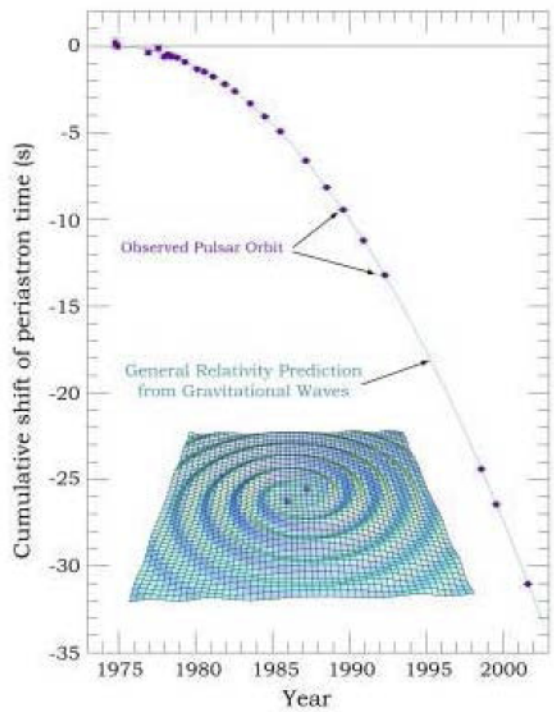
- Imaging is more than "just" an FFT.
  Gridding, deconvolution, wide-field corrections, self-calibration, …
- Community estimates are 10^4 to 10^5 ops per visibility datum(!).
- Leads to significant power challenges
  - Related to moving data on/off chips
  - Careful design can yield significant savings, e.g., D'Addario (SKA Memo 130)

Fundamental Physics with Radio Pulsars

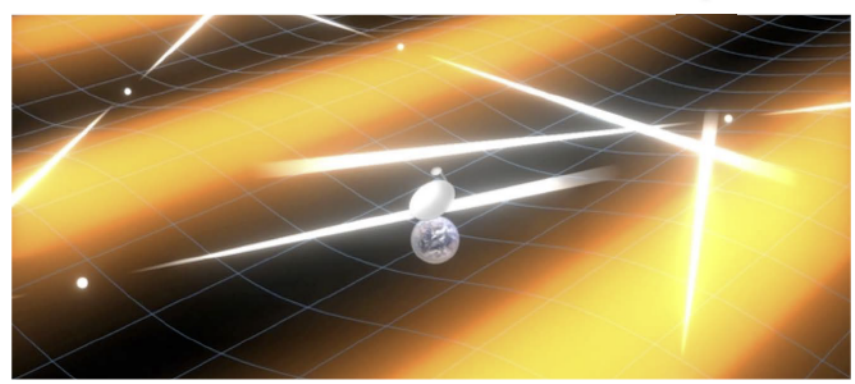
Arrival times of pulses from radio pulsars can be measured with phenomenal accuracy

- Better than 100 ns precision in best cases
- Enables high precision tests of fundamental physics
  - Theories of gravity, gravitational waves, nuclear equation of state
  - 1993 Nobel Prize in Physics
- Problem: Not all pulsars are equal!
- Good "timers" < 10% of total population
- Need to find many more!

➢ All-sky survey



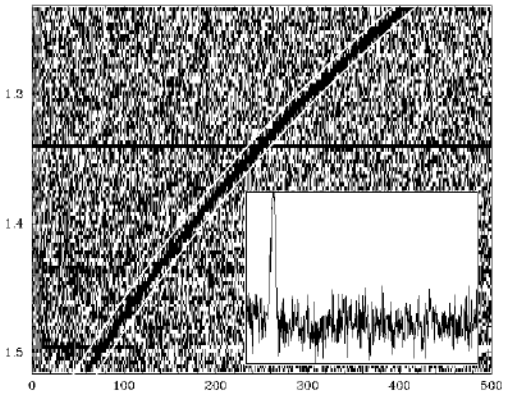
← Ultra-relativistic binaries & gravitational wave studies



Pulsar Surveys I

Requirements

- Large bandwidths because pulsars are faint
- Long integration times because pulsars are faint
- Rapid time sampling in order to resolve pulse profile
- Narrow frequency channelization in order to mitigate interstellar scattering



- For a "pixel" on the sky, accumulate data for a time Δt over a bandwidth $\Delta\nu$

  Suppose Δt = 20 min., $\Delta\nu$ = 800 MHz

- Time sampling δt with frequency channelization $\delta\nu$

  For GBT GUPPI, δt = 81.92 μs, $\delta\nu$ = 24 kHz

➢ 60 GB data sets per pixel …

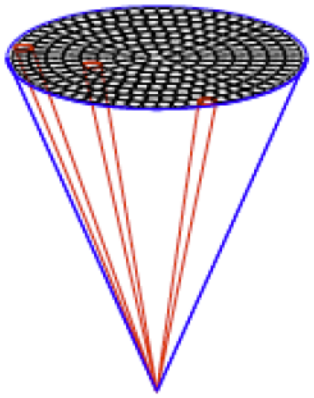
Pulsar Surveys II

For GBT

- At 800 MHz, “pixel” ~ 16' = 0.3°
- About 350 kpixels in the sky
- 20 PB data set

For SKA

- At 800 MHz, “pixel” = 1.2'
- About 76 Mpixels in the sky
- 4.6 EB data set



Data Intensive Astronomy
("There is nothing new under the Sun.")

Data Volumes

Ιππαρχος (Hipparcus)
- ca. 135 BCE
- Stellar catalog with 850 entries
- ➢ **SKA pulsar survey**

Computational Limitations

Harvard computers
- Production of stellar plates and spectra ("data rate") was increasing enormously
- Examined and classified telescope output
- ➢ **SKA all-sky survey**

SKA Science and Design

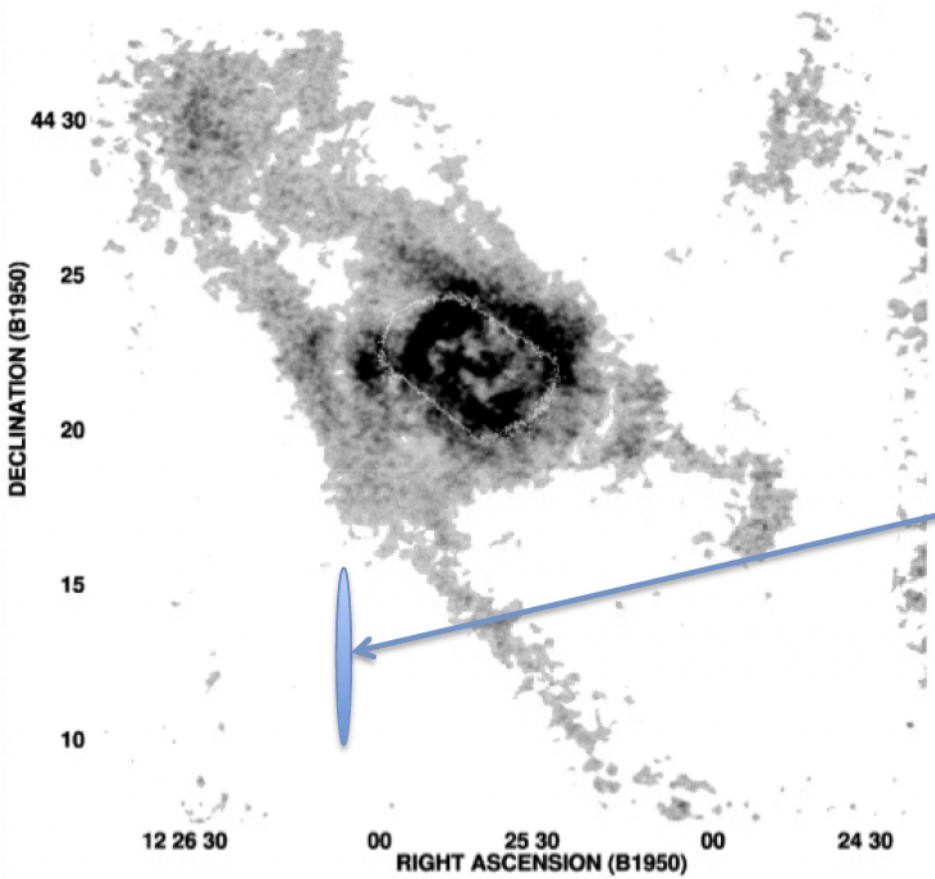
SKA Survey

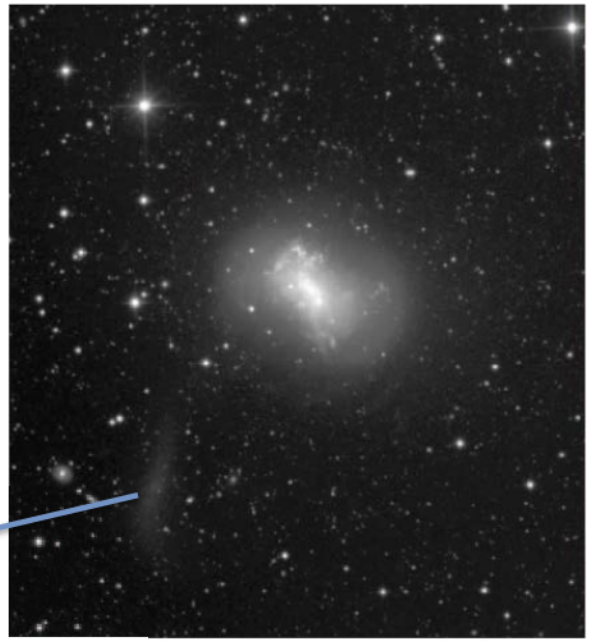
- Only about 50% of the telescope is useful for most surveys (

SKA Deep (or SKA Targeted)

- Only some fraction useful?
- Phase 1

Galaxy Assembly
The Role of Mergers





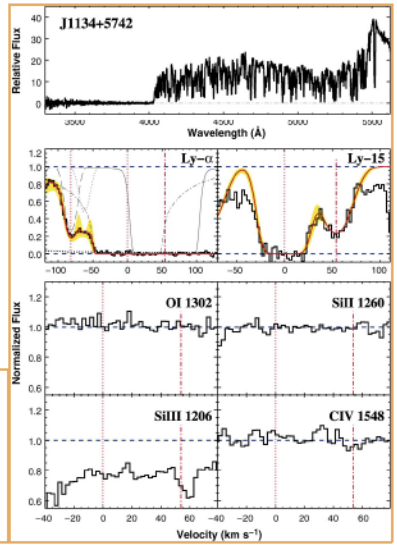
"A Tidally Distorted Dwarf Galaxy near NGC 4449"

NGC 4449 (Hunter et al. 1999; Rich et al. 2012)

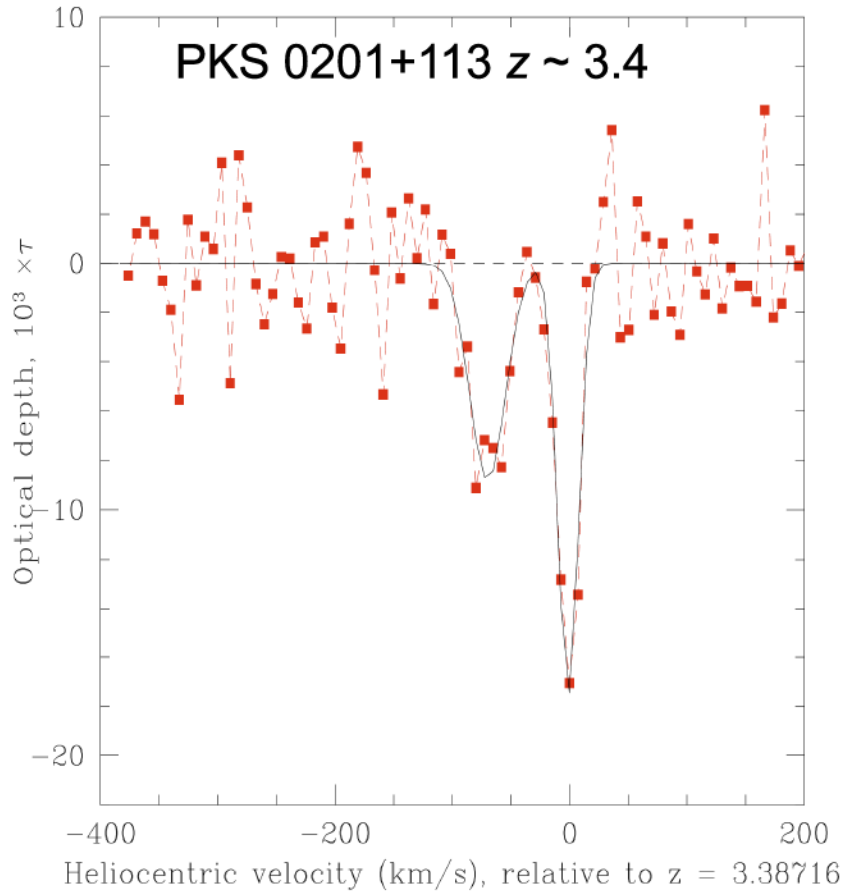
Galaxy Assembly
H I Absorption

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)

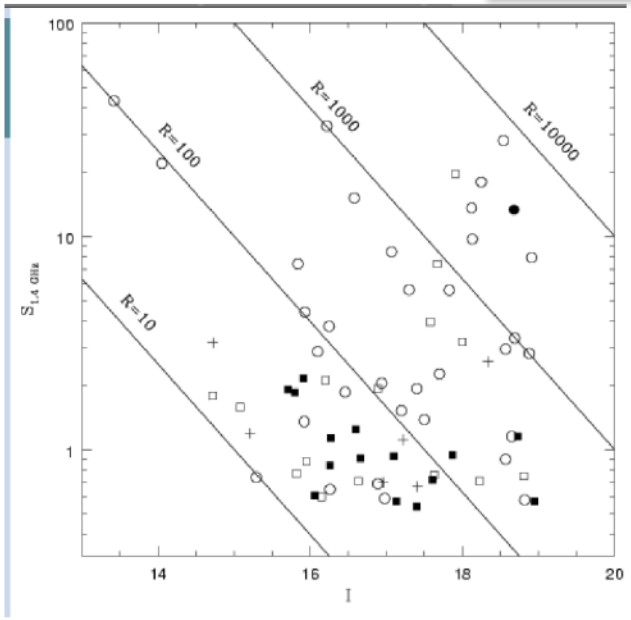


(Kanekar et al. 2007)

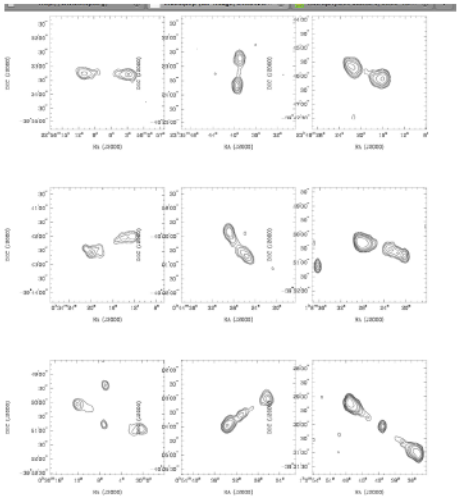
Galaxy Evolution
Accretion vs. Fusion

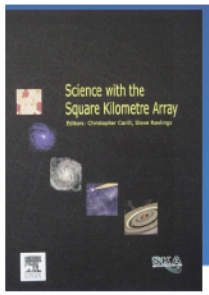
Radio wavelengths important to understand balance between AGN and star formation (SF) for galaxy luminosity

- 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)





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?
  - Where are most of the metals throughout cosmic time?
  - How were galaxies assembled?
- Stars, Planets, and Life
  - How do planetary systems form and evolve?
  - What is the life-cycle of the interstellar medium and stars? (biomolecules)
  - Is there evidence for life on exoplanets? (SETI)