DUNLAP INSTITUTE
for ASTRONOMY & ASTROPHYSICS

Design Considerations for Radio Telescopes

CSIRO / Swinburne ;
Hindson et al. &
Johnston-Hollitt et al.

Bryan Gaensler (he/him)
Director, Dunlap Institute
University of Toronto

@SciBry

#DSS2019

New Technologies for Canadian Observatories (NTCO)

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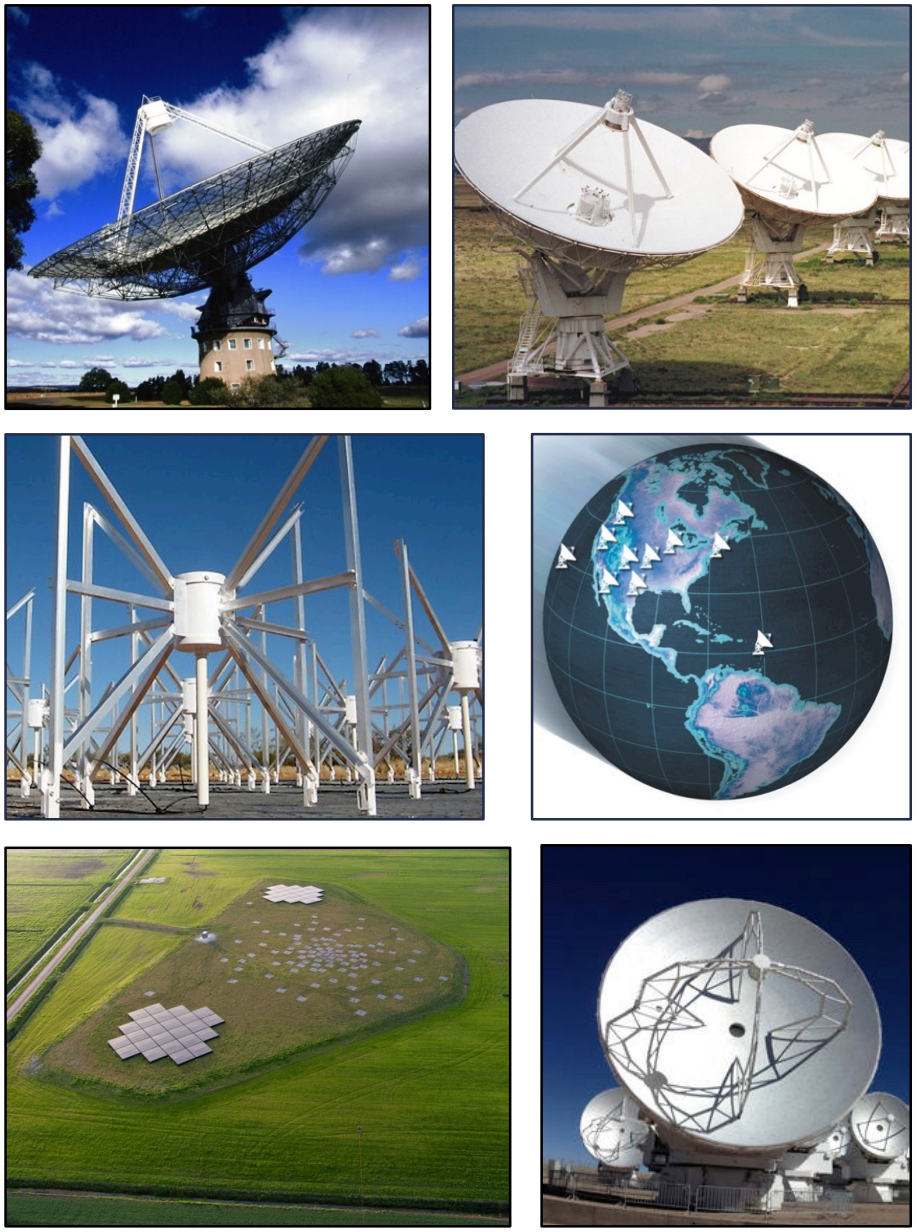
- Six year program funded by NSERC CREATE
- Goal: address the need for technological innovation in the next generation of astronomical instrumentation
- Members: U. Victoria, U. Toronto, McMaster, Laval, NRC
- Student stipends and funding!
- Courses and training in professional skills and development
- 20% of academic time conducting research in Canadian industry
- More information: ntco@uvic.ca or http://bit.ly/NTCO_CREATE

Radio Telescopes

- Sky coverage
- Point-source sensitivity vs surface brightness sensitivity
- Angular resolution and confusion
- Snapshot coverage vs full-synthesis coverage
- Frequency and bandwidth
- Largest angular scale, field of view and survey speed
- Spectral resolution, time resolution & data rate
- Polarimetry



CSIRO; NRAO/AUI, Natasha Hurley-Walker;
© Top Foto, Assen; NRAO/NAOJ/ESO

Supernova Remnants

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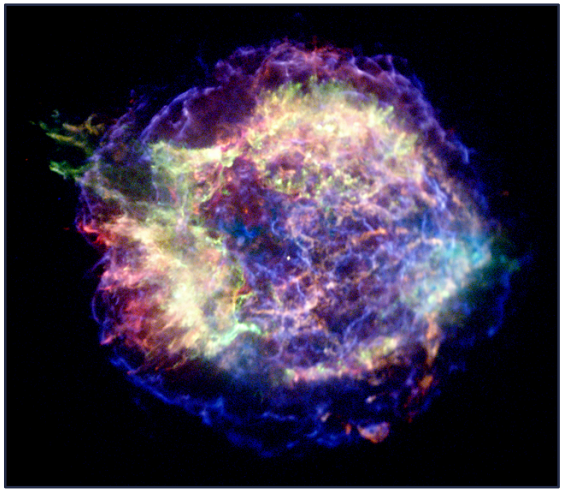
- Fossil record of explosion and progenitor star
- Illumination of the invisible interstellar medium
- Shock physics and acceleration of cosmic rays

- Faint, non-thermal (S ~ $\nu^{-0.5}$), continuum emission
  - low frequencies ($\lesssim$ 5 GHz)
  - broad bandwidth (~ 1 GHz)
  - coarse spectral resolution (~10 MHz)



Cassiopeia A
(Stage et al. 2006)

SNR 1006
(Cassam-Chenaï et al. 2008)

Supernova Remnants II

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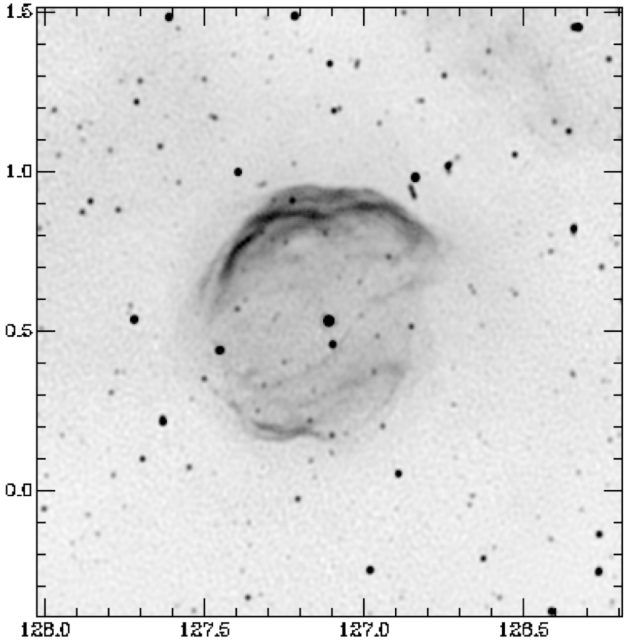
- Generally small angular diameter, (e.g. ~3 – 60 arcmin across)
  - λ = 0.2 m, D = 50 m: θ ≈ 1.2 λ / D = 17’
  - array, not single dish
- Complex structure on many angular scales
  - good u-v coverage needed
  - many baselines (many antennas, long tracks, multiple arrays)
  - integration time probably not set by sensitivity!
- Suitable telescopes: VLA (compact configuration), DRAO Synthesis Telescope



MPIfR, NRAO/AUI. CGPS

VLA in D configuration (Ceravolo Images)

Single Dish / Array Combination

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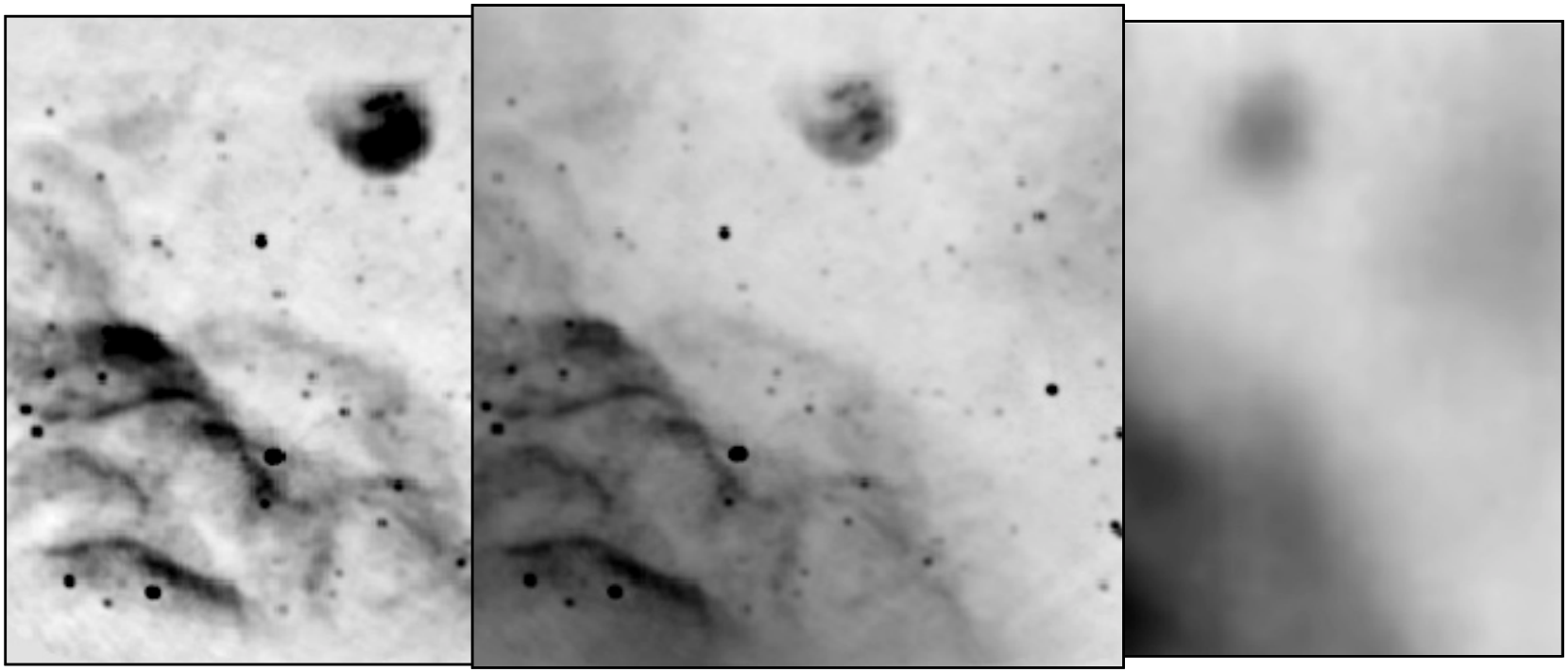
- Longest baseline sets smallest scale of image
  … but shortest baseline gives largest scale of image!
  → interferometer misses large-scales; fluxes and spectra wrong
  → need to combine with single-dish data to see full picture



Vela SNR & RCW 32 (ATCA only) (SGPS; McClure-Griffiths 2001)

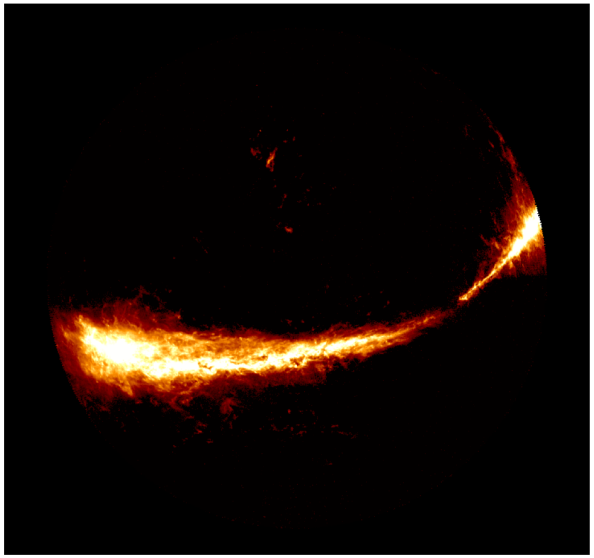
Vela SNR & RCW 32 (Parkes + ATCA combined)

Vela SNR & RCW 32 (Parkes only) (SGPS; McClure-Griffiths et al 2001)

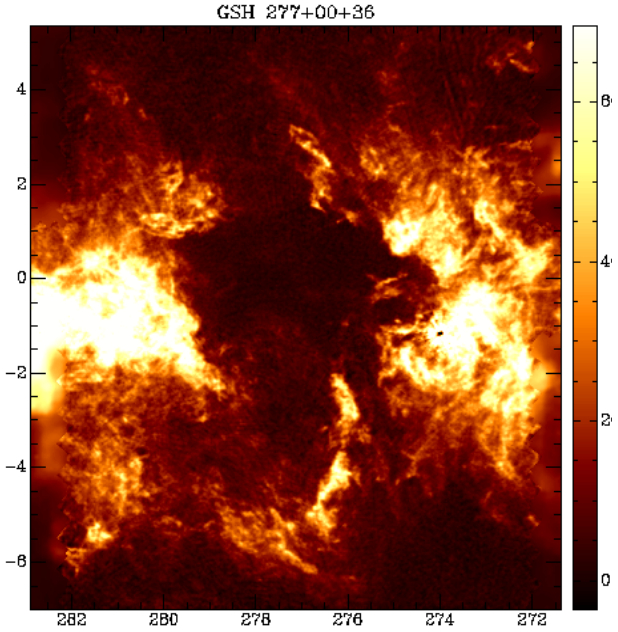
Galactic Hydrogen

- "HI" is an emission line of neutral hydrogen at 1420.406 MHz (21 cm)
- Traces distribution, temperature, density of cold and warm atomic gas
- Doppler shift gives Galactic rotation and Galactic structure
- Narrow bandwidth (~10 MHz = 2000 km/s), high spectral resolution (4 kHz = 0.8 km/s)
- Large-scale emission: single dish (e.g. Parkes)
- Small-scale emission: dish + array (Parkes+ATCA)

CSIRO



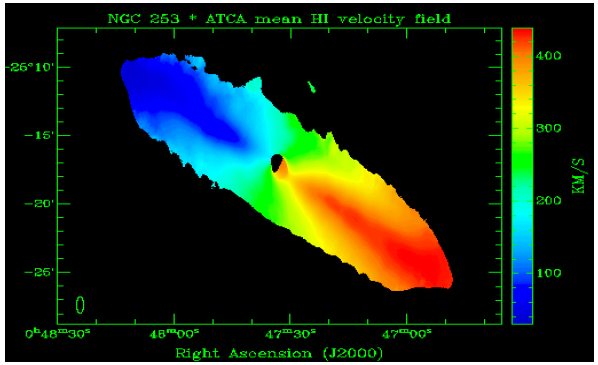
GASS (McClure-Griffiths et al. 2009)



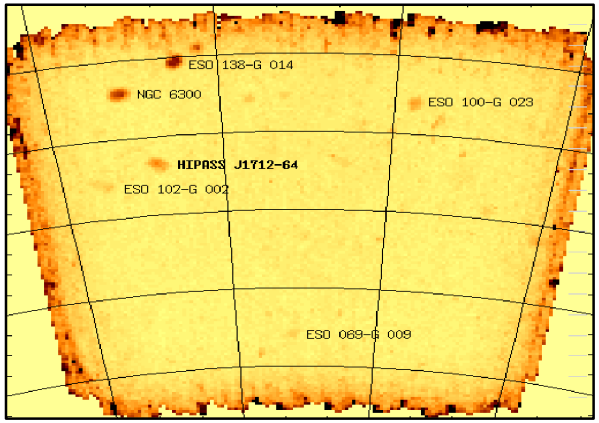
SGPS (McClure-Griffiths et al. 2003)

Extragalactic Hydrogen I

- Structure, rotation, dynamics, turbulence of other galaxies
- Trace assembly of galaxies over cosmic time
- Individual galaxies: array, single pointing
  - high angular resolution (arrays)
  - narrow bandwidth (~10 MHz)
  - intermediate spectral res (~20 kHz)
- Large volumes: single dish, survey
  - low angular resolution
  - broad bandwidth
    ($\Delta\nu$ = 100 MHz $\rightarrow$ Δz = 0.08)
  - intermediate spectral res (~20 kHz)



Koribalski et al.



HIPASS

CSIRO

Array Configuration

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- Some arrays are re-configurable (e.g. VLA, ATCA, WSRT, DRAO)
- Extended arrays:
  - high resolution, slow survey speed, poor surface brightness sensitivity
  - e.g., observations of individual distant radio galaxies
- Compact arrays
  - coarse resolution, rapid survey speed, high surface brightness sensitivity
  - e.g., survey of large nearby galaxy
- East-west arrays
  - need coverage over 12 hours
- Two-dimensional arrays
  - single “snapshot” *may* be sufficient
- Independent of config: field of view, theoretical point-source sensitivity

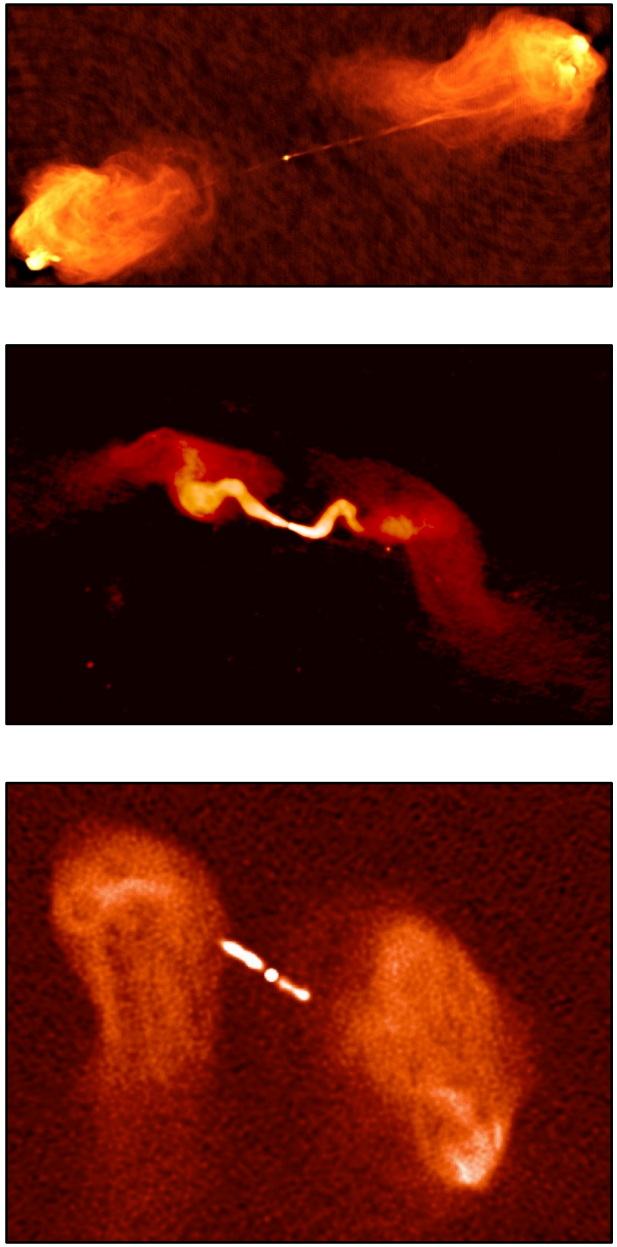
VLA in A configuration (Ceravolo Images)

VLA in D configuration (Ceravolo Images)

Radio Galaxies

- Large-scale interaction of supermassive black holes with their environments
- Conversion of gravitational energy into relativistic particles, electrical currents, kinetic energy
- Feedback: regulates star formation in host galaxy

- Bright, non-thermal (S ~ $\nu^{-0.7}$) continuum
  - range of frequencies (~0.1 – 10 GHz)
  - broad bandwidth
  - coarse spectral resolution (~10 MHz)
  - usually small in scale: need long baselines, ~arcsec resolution
  - considerations: u-v coverage, dynamic range



NRAO / AUI

Radio Galaxies

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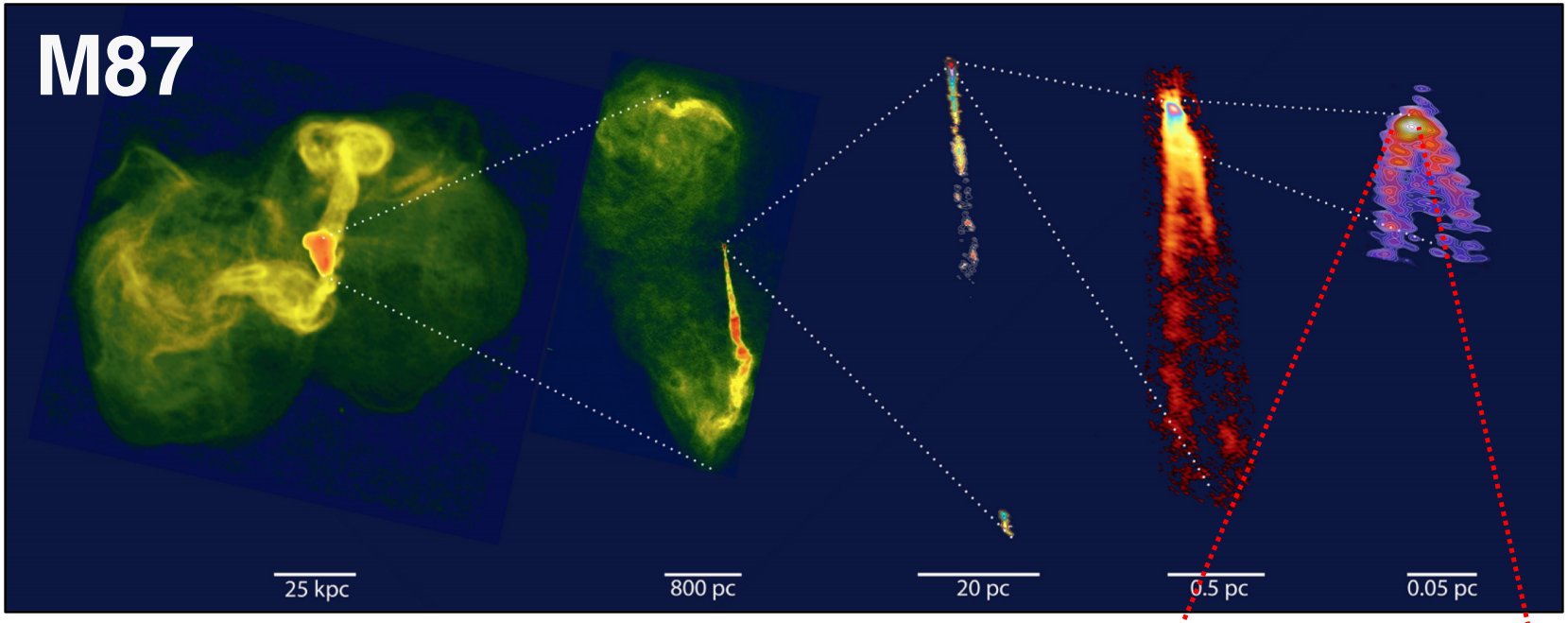
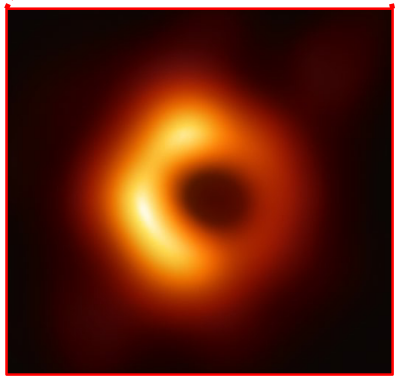
Blandford, Meier & Readhead (2019)



0.003 parsecs!



EHT Collaboration

Confusion & Sensitivity

- Ideally, sensitivity set by the radiometer equation

$$N = \frac{T_{sys}}{\sqrt{\Delta\nu_{RF}\tau}}$$

  - bandwidth, integration time, system temperature

- But beware confusion!

- Classical confusion ("forest for the trees")
  - at low angular resolution, sensitivity is **not** set by radiometer equation, but by "confusing" sources!
  - confusion level is function of frequency, resolution

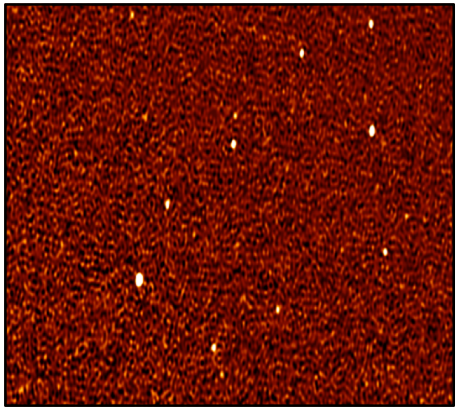
  → know your faint foregrounds/backgrounds

  → set resolution so that confusion < sensitivity

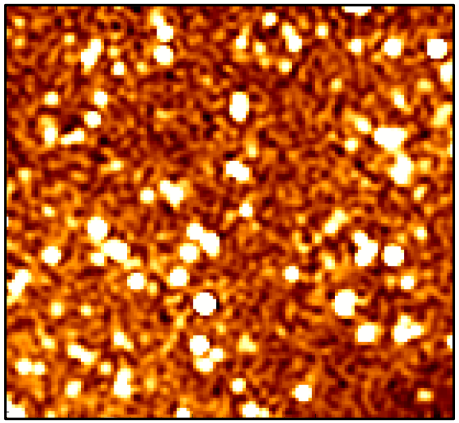
- Sidelobe confusion (dynamic range limitations)
  - if some sources are bright, bad calibration will mess up the rest of the image

  → know your faint foregrounds/backgrounds

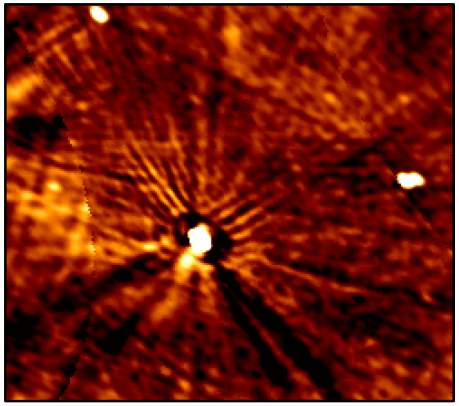
  → u-v coverage and calibration strategy affect sensitivity



ATLAS (Norris et al. 2006)



André Offringa



MGPS (Green et al. 1998)

Quasar Variability & Scintillation

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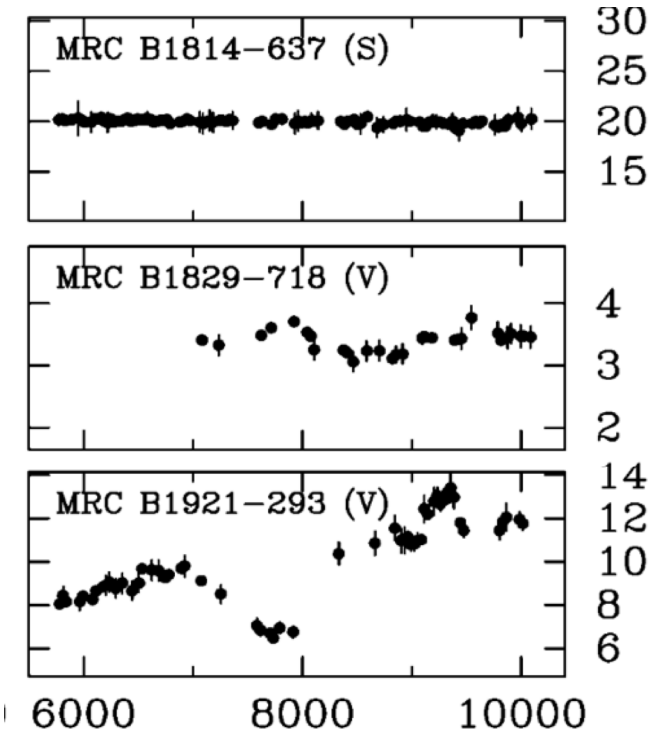
- Intrinsic variability: small-scale structure in jet and accretion disk around black hole
- Scintillation: refraction effects probe turbulence in invisible foreground gas in the Milky Way
- Intrinsic effects: high freq ($\gtrsim$ 5 GHz)
- Propagation effects: low freq ($\lesssim$ 5 GHz)
  - frequency dependent
  - coarse resolution (~10 MHz)
- Sources unresolved, just want fluxes
  - bright: single dish OK
  - faint: array needed to overcome confusion; sub-arrays may be efficient

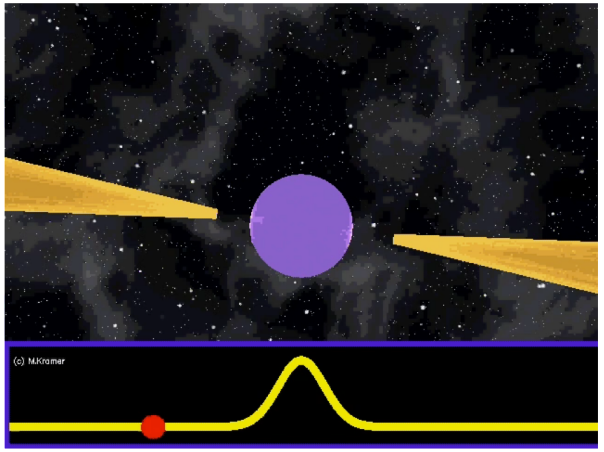


Gaensler & Hunstead (2000)

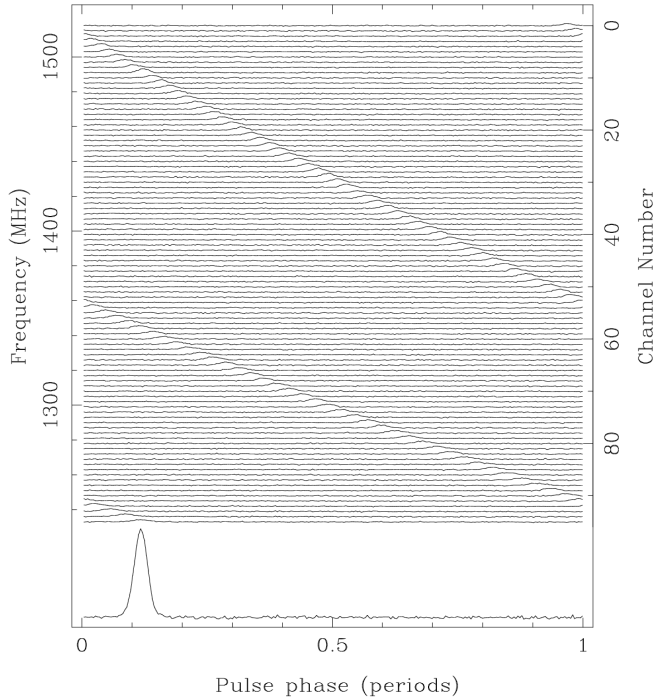
Hayley Bignall

Pulsars

- Tests of General Relativity, binary evolution and high-energy astrophysics
- Precision probe of interstellar medium
- Extremely non-thermal ($S \sim \nu^{-2}$) continuum
  - low frequencies ($\lesssim$ 2 GHz)
- Brief point-like signal, dispersed by interstellar medium
  - high time resolution (<1 ms)
  - broad bandwidth, high spectral resolution



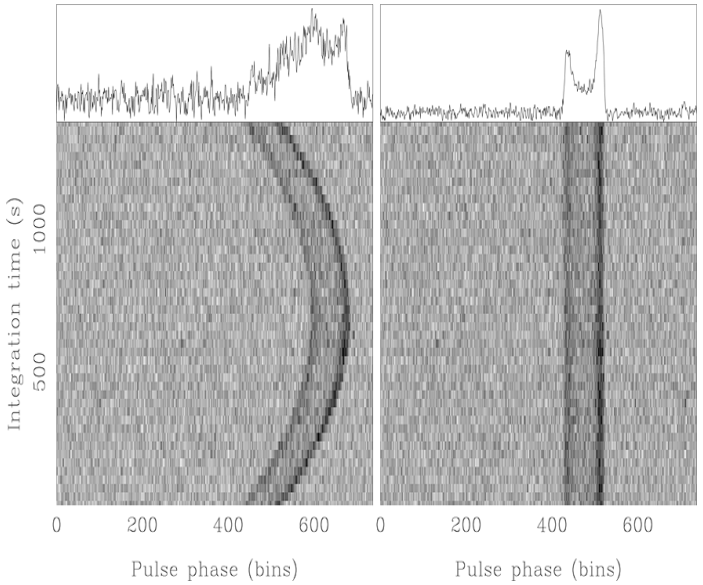
Michael Kramer



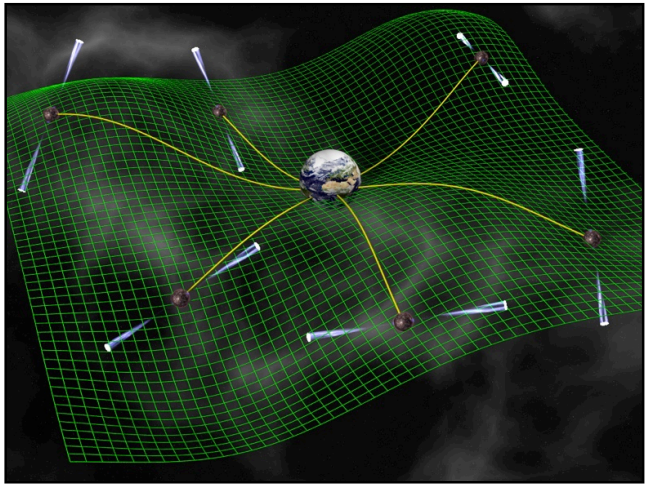
Lorimer & Kramer

Pulsars II

- Imaging & resolution unimportant, driven only by sensitivity
  - biggest possible collecting area (single dish → array)
  - integration time set by signal-to-noise, binary motion
  - field of view hugely important for searches
  - field of view less important for timing
- Pulsar timing arrays
  - good sky coverage needed



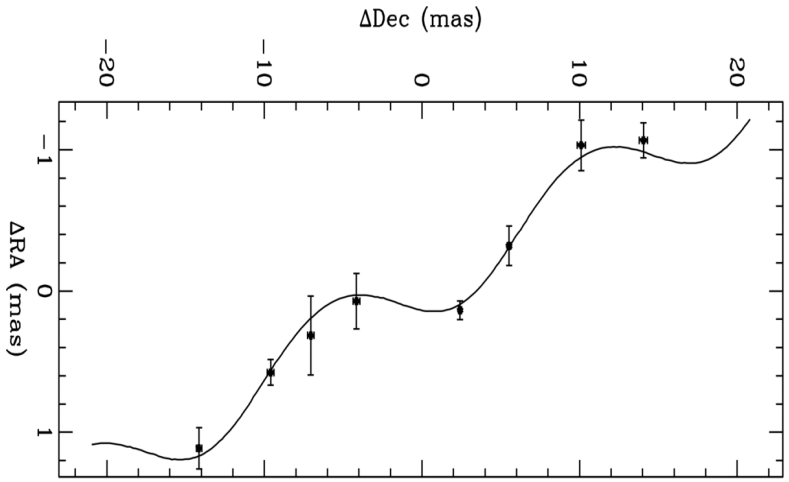
Lorimer (2008)



Michael Kramer

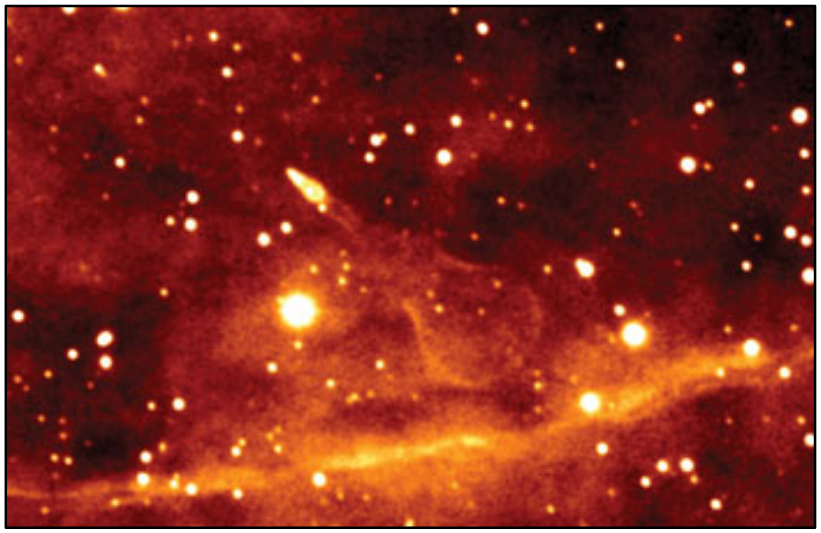
Pulsar Astrometry

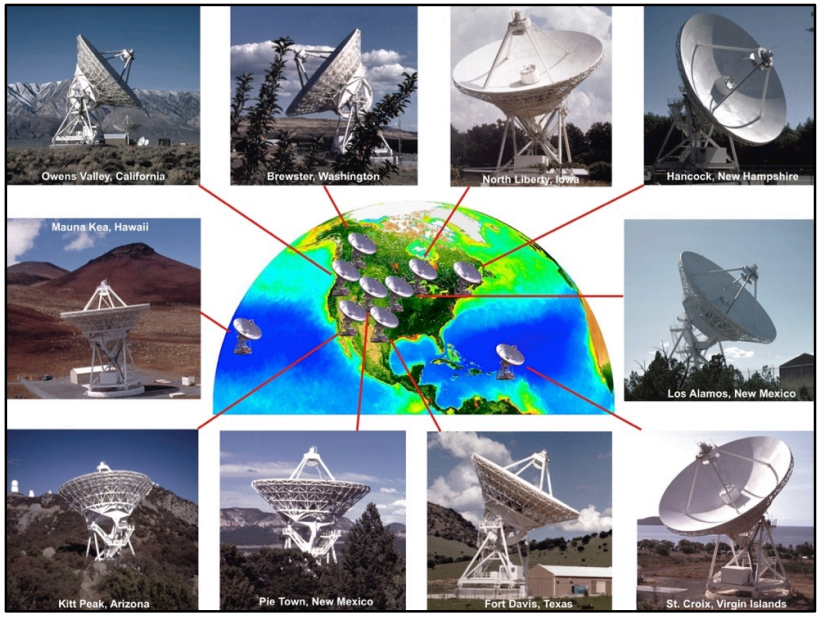
- Distances: Galactic structure
- Velocities: supernova physics
- Parallax: d = 1 kpc
  → π = 1/d = 0.001 arcsec
- Proper motion: V = 100 km/s
  → μ = V/d = 0.02 arcsec/year
- At 5 GHz, λ = 0.06 m and need θ = 0.001 arcsec
  → D ≈ 1.2 λ / θ = 15000 km !



Chatterjee et al. (2004)

"Guitar Nebula" (Palomar Observatory)





NRAO/AUI ; SeaWiFS / NASA / GSFC / ORBIMAGE

Star Formation & Proto-stars

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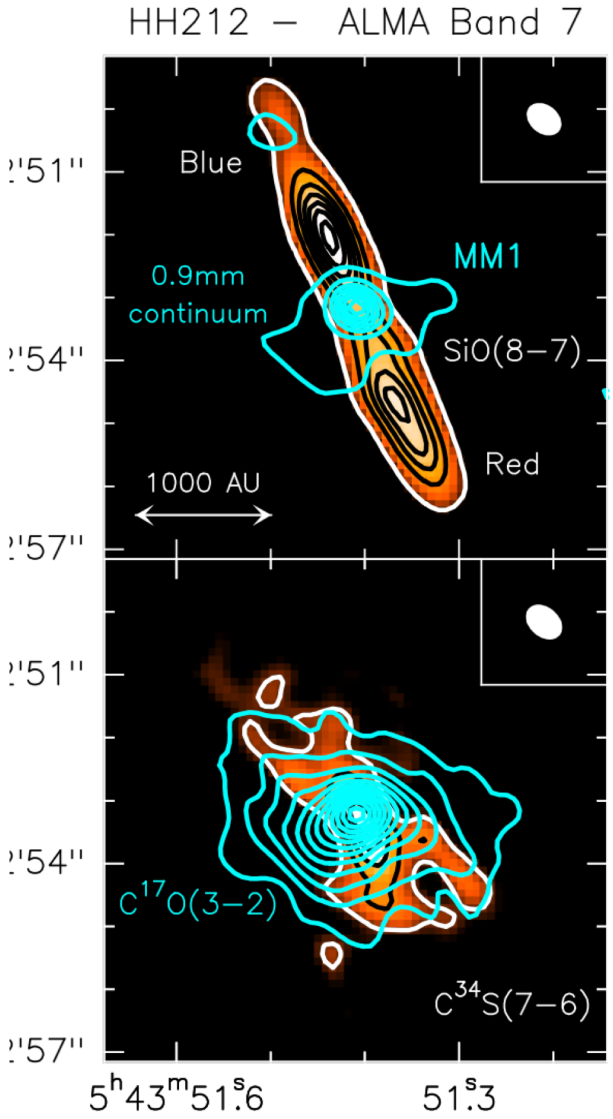
- Morphology, time scales, dynamics uncertain
- Process of planet formation

- Thermal emission from cold dust
- Molecular lines
- Compact structures (≪ 10 arcsec)
  - → high frequencies (e.g., 350 GHz)
  - → array with baselines ≥ 500 metres

- High-altitude site, dishes with very high surface accuracy and pointing stability

ALMA (ESO/ NAOJ/NRAO)



Codella et al. (2014)

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ASKAP and the Square Kilometre Array

Bryan Gaensler (he/him)
Director, Dunlap Institute
University of Toronto

@SciBry

#DSS2019

The Wajarri Yamatji people are the traditional owners of the observatory site

Yamatji Marlpa
ABORIGINAL CORPORATION

CSIRO / Swinburne ;
Mihos / Huey / Science

Australian Square Kilometre Array Pathfinder (ASKAP)

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- Array of 36 antennas, 12-m diameter
- Baseline lengths: 23 m – 6 km
- Angular resolution 10” – 30” at 1.4 GHz
- 304 MHz instantaneous bandwidth
- Frequency range: 700 – 1800 MHz
- Spectral resolution: 1 MHz or 18.5 kHz

CSIRO

Where Is ASKAP?

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Steven Tingay

A Unique Radio-Quiet Environment

Dunlap Institute for Astronomy & Astrophysics
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Sydney

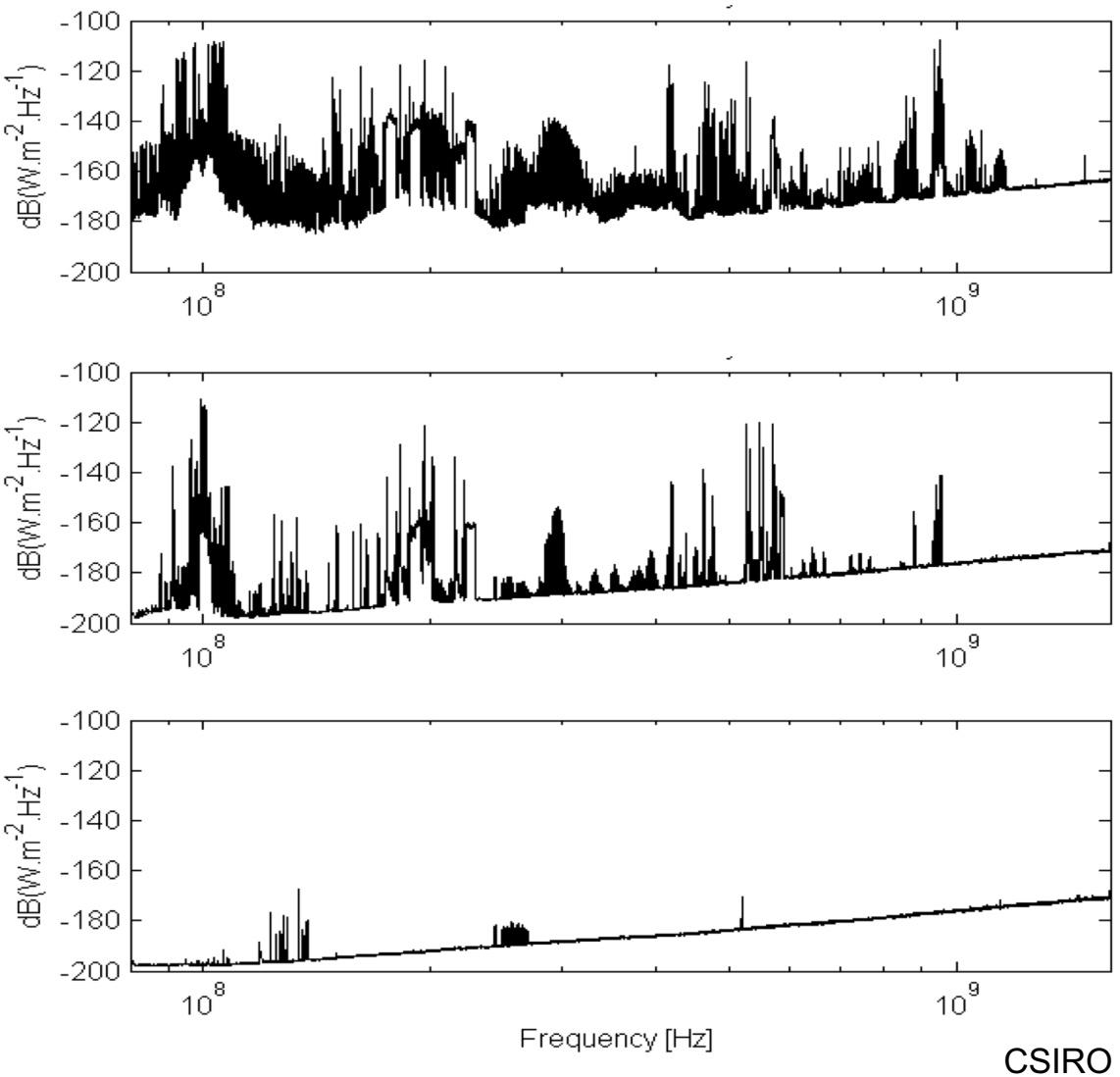
Pop. 4.8 million

Narrabri

Pop. 5,900

Murchison Shire

Pop. 114



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Phased Array Feeds

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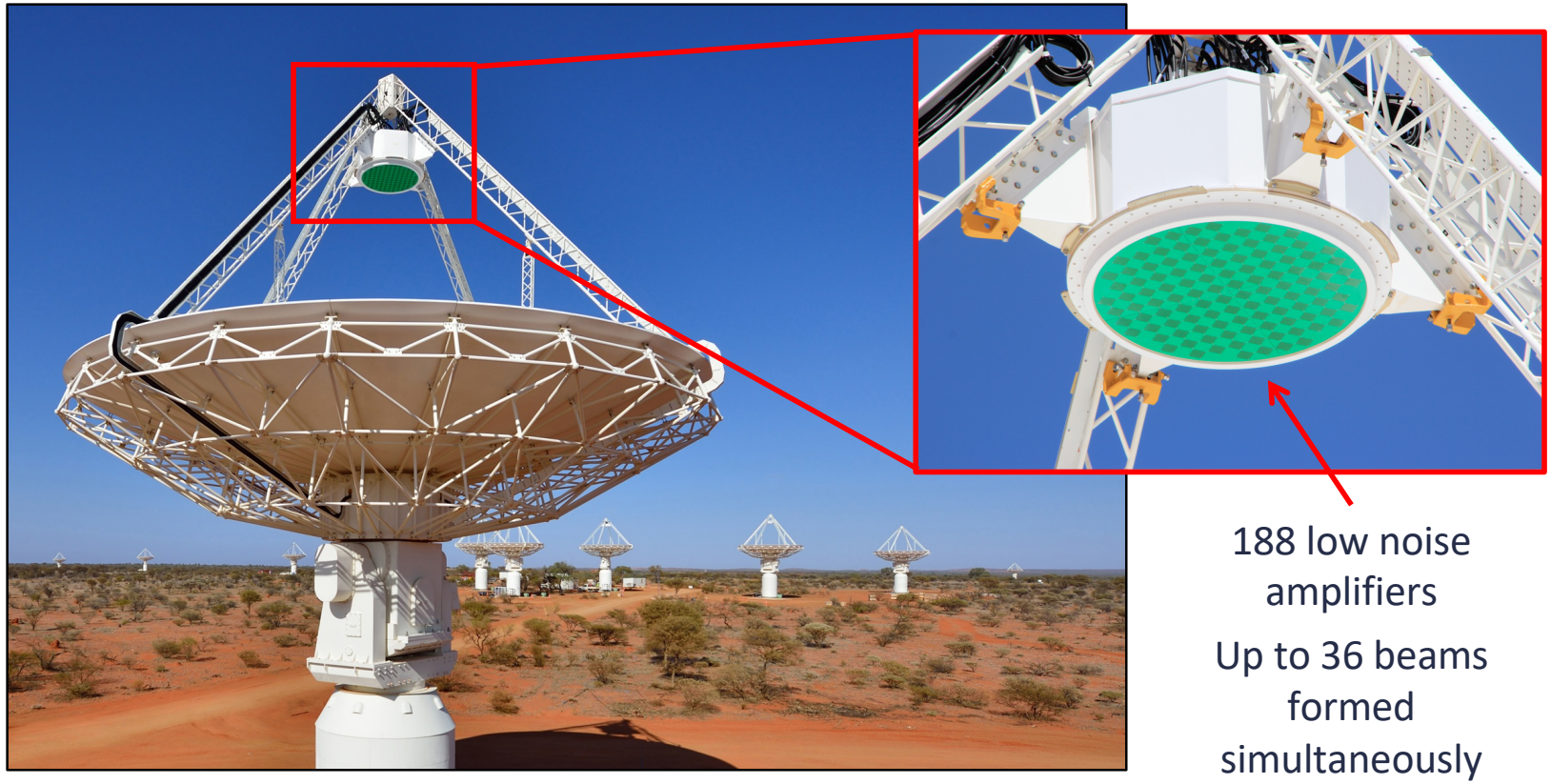
› 30 deg^2 field of view !



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188 low noise amplifiers

Up to 36 beams formed simultaneously

How Big Is 30 Square Degrees?

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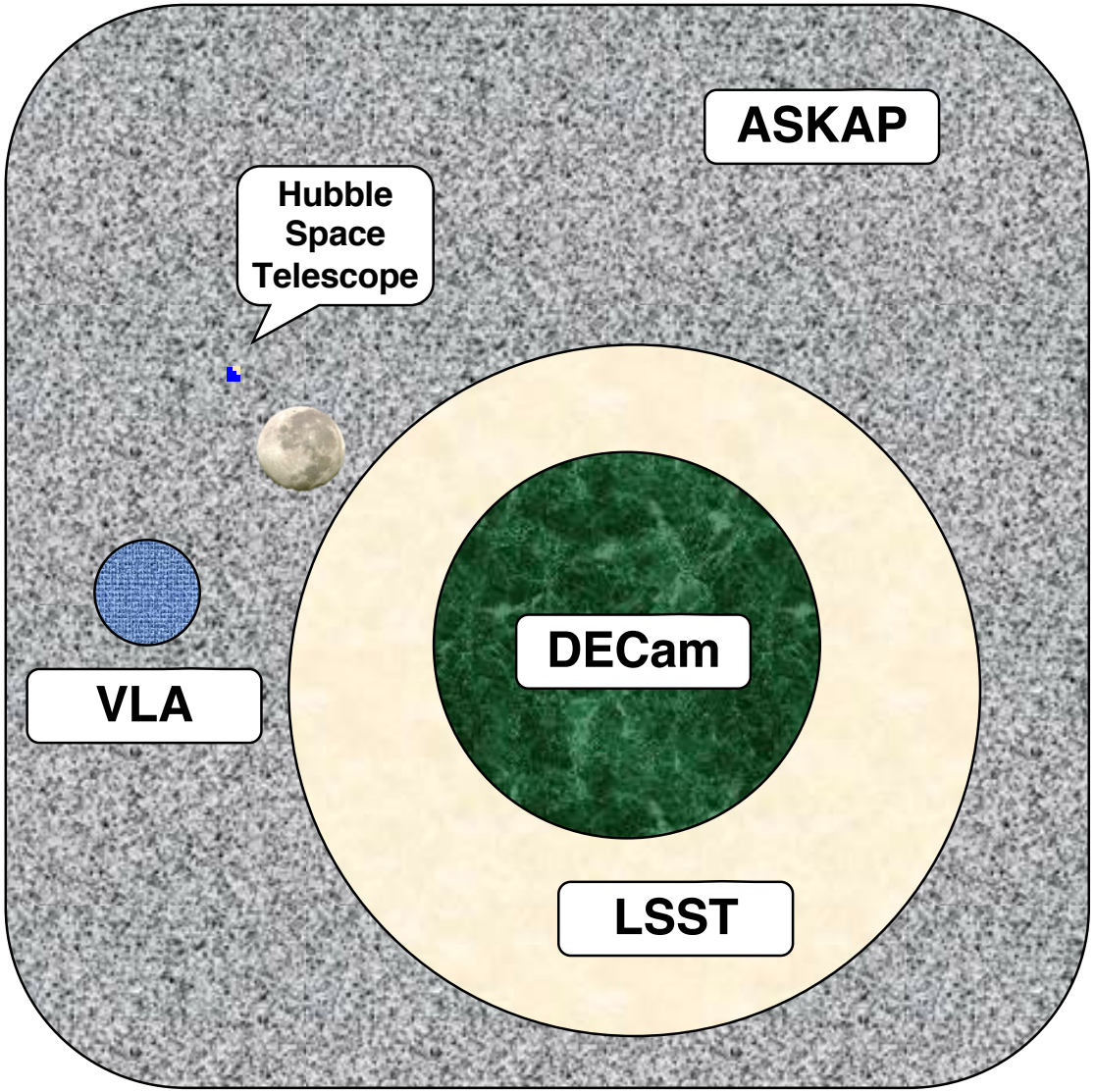

Mapping The Entire Southern Sky

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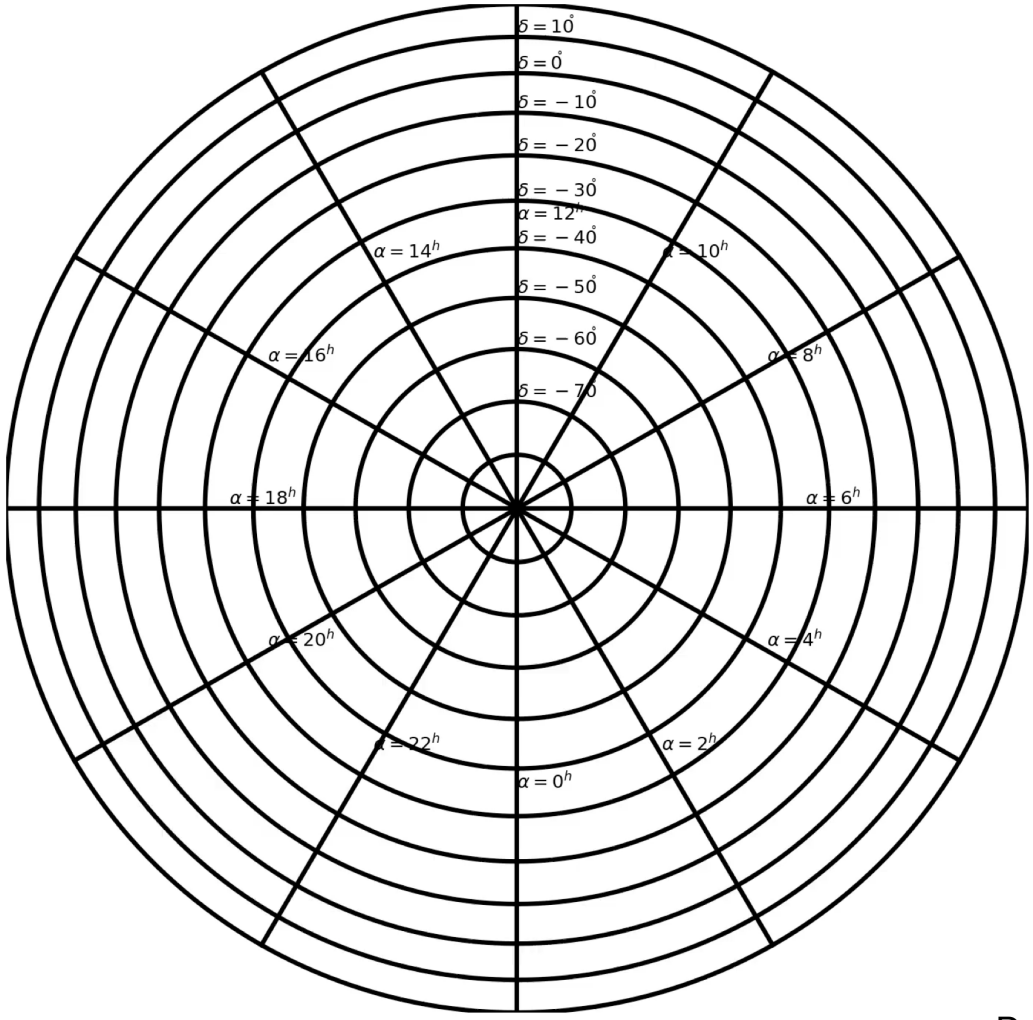

David Kaplan

Extragalactic Hydrogen II

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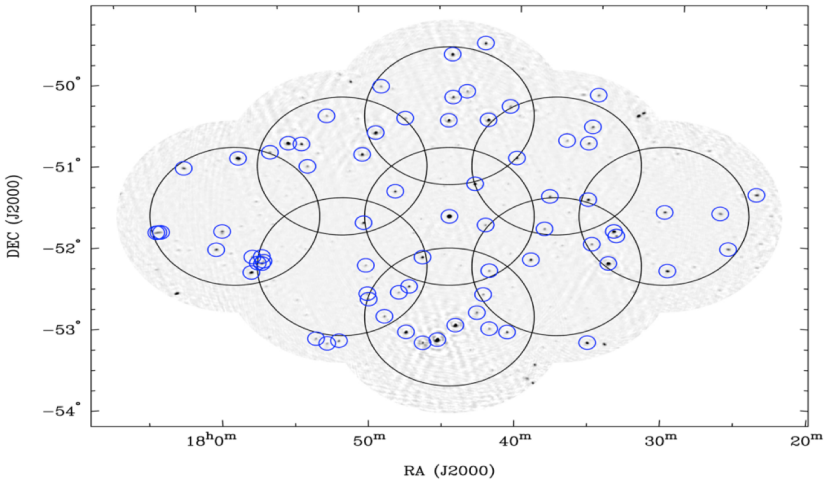
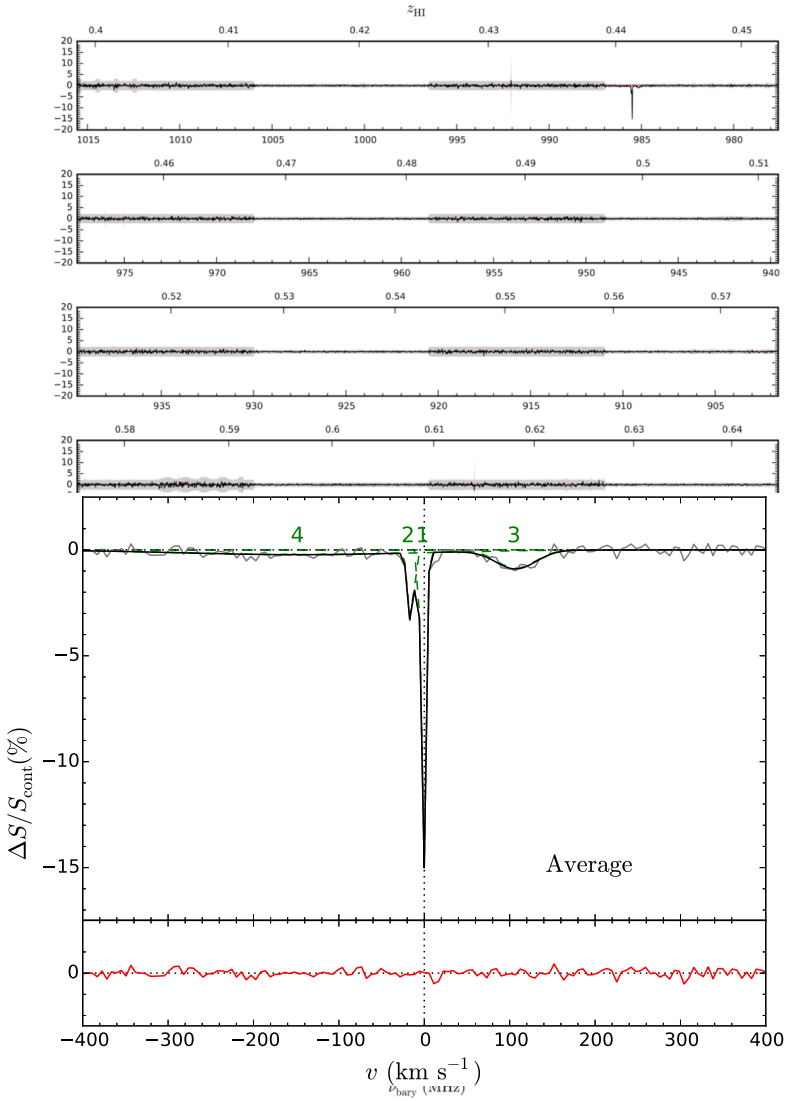
- Hydrogen in *absorption*
  - produced by galaxy along line of sight to bright background continuum source
  - signal-to-noise independent of distance
  - can trace galaxies to high redshift
  - “needle in a haystack” problem in x, y, ν
- New frontier: focal plane arrays with ultra-wide fields of view and broad bandwidths
  - ASKAP: 700–1000 MHz over 30 deg^2



Allison et al. (2015)



Allison et al. (2015)

Mapping Magnetic Fields I

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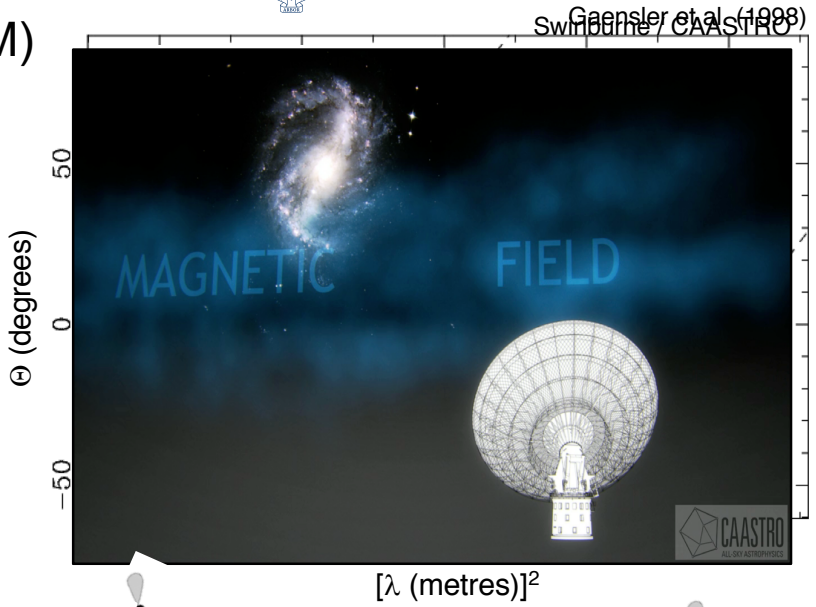
› ***Faraday rotation*** & ***rotation measure*** (RM) are powerful probes of $B_{\parallel}$

$$\Theta = \Theta_0 + \mathrm{RM}\,\lambda^2 \qquad \mathrm{RM} = K\int_L^0 n_e \vec{B}\cdot d\vec{l}$$

$$\mathrm{RM} \approx 4000\ \mathrm{rad\ m^{-2}} \left(\frac{n_e}{0.1\ \mathrm{cm^{-3}}}\right)\left(\frac{B_{\parallel}}{5\ \mu\mathrm{G}}\right)\left(\frac{L}{10\ \mathrm{kpc}}\right)$$

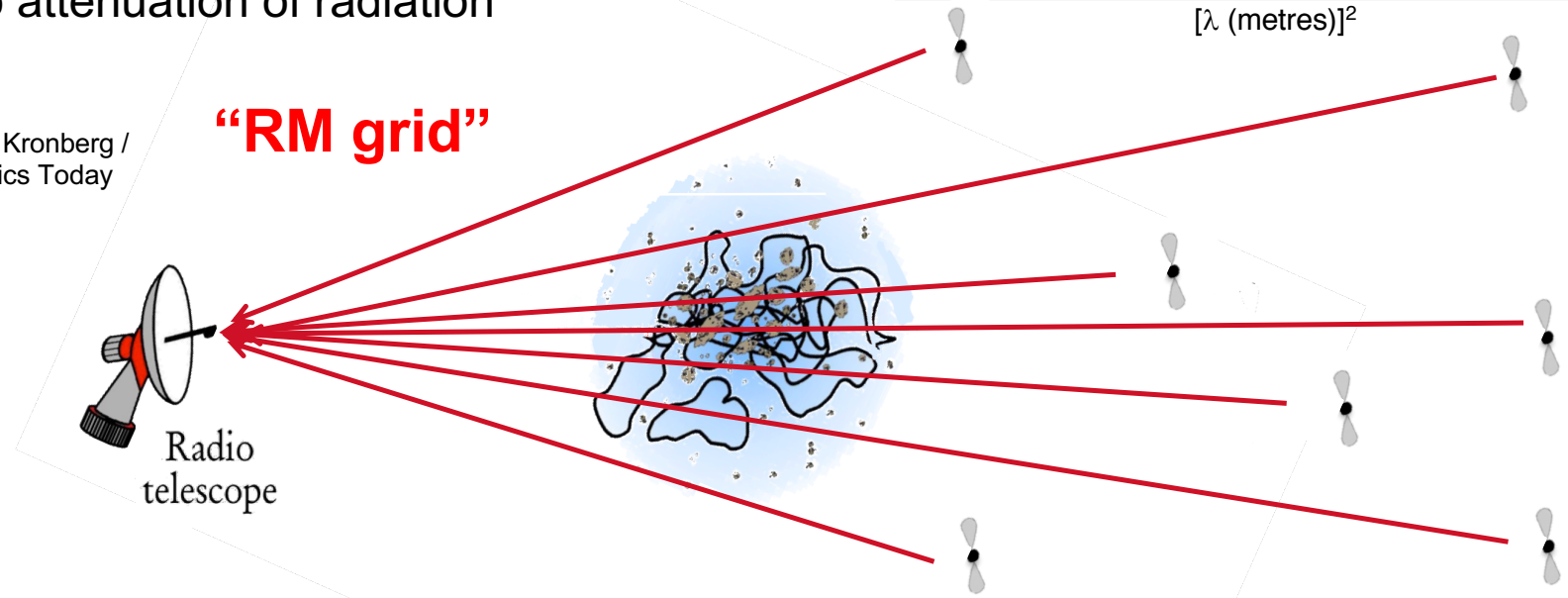
– provides *direction* of *B*

– radio wavelengths: no attenuation of radiation



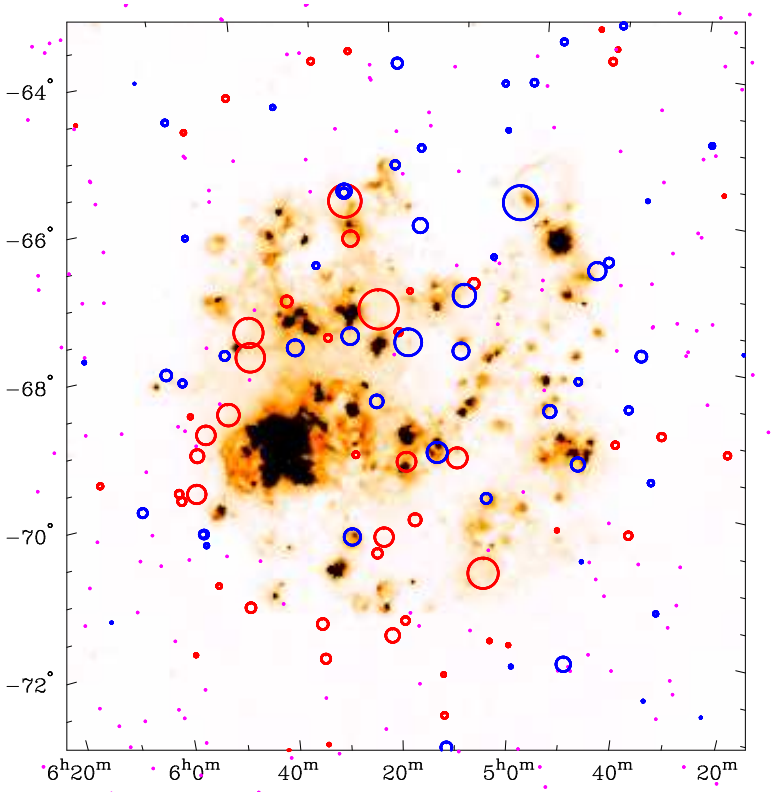
Philipp Kronberg / Physics Today

"RM grid"

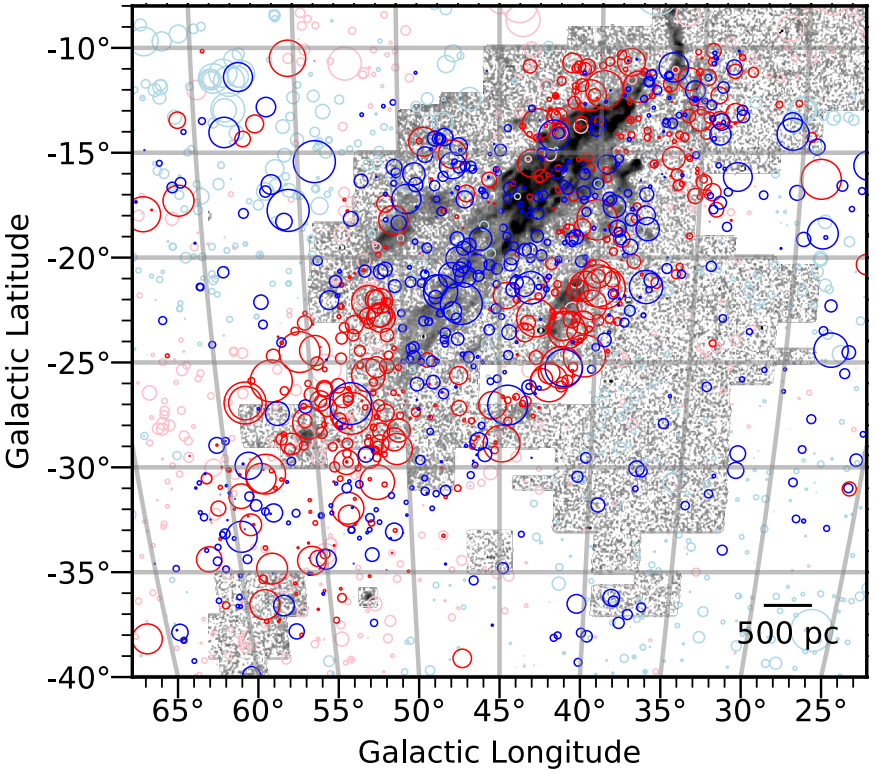


Mapping Magnetic Fields II

› State of the art:
1-3 RMs per square degree



Large Magellanic Cloud (Gaensler et al. 2005)



The Smith Cloud (Betti et al. 2019)

POSSUM on ASKAP

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› POlarisation Sky Survey of the Universe's Magnetism (PIs: Gaensler, Heald, McClure-Griffiths; askap.org/possum)
  - ASKAP: 36 12-m dishes, *30-deg^2 field of view*
  - 30,000 deg^2 to ~20 μJy, 15" resolution, 0.8-1.1 GHz
  - RM grid at density of ~40 RMs/deg^2

› Main science goals
  - magneto-ionic properties of interstellar gas
  - structure & geometry of large-scale field of Milky Way
  - magnetic properties of galaxies & clusters
  - evolution of magnetic fields with cosmic time?

› Extended data products via Canadian Initiative for Radio Astronomy Data Analysis (CIRADA)

› Time line
  - Q2 2019: Rapid ASKAP Continuum Survey (RACS)
  - Q3-Q4 2019: Pilot survey (200 hours, 0.8-1.4 GHz)
  - 2020- : Full POSSUM survey

CSIRO / Swinburne

CSIRO

POSSUM: Early Results (I)

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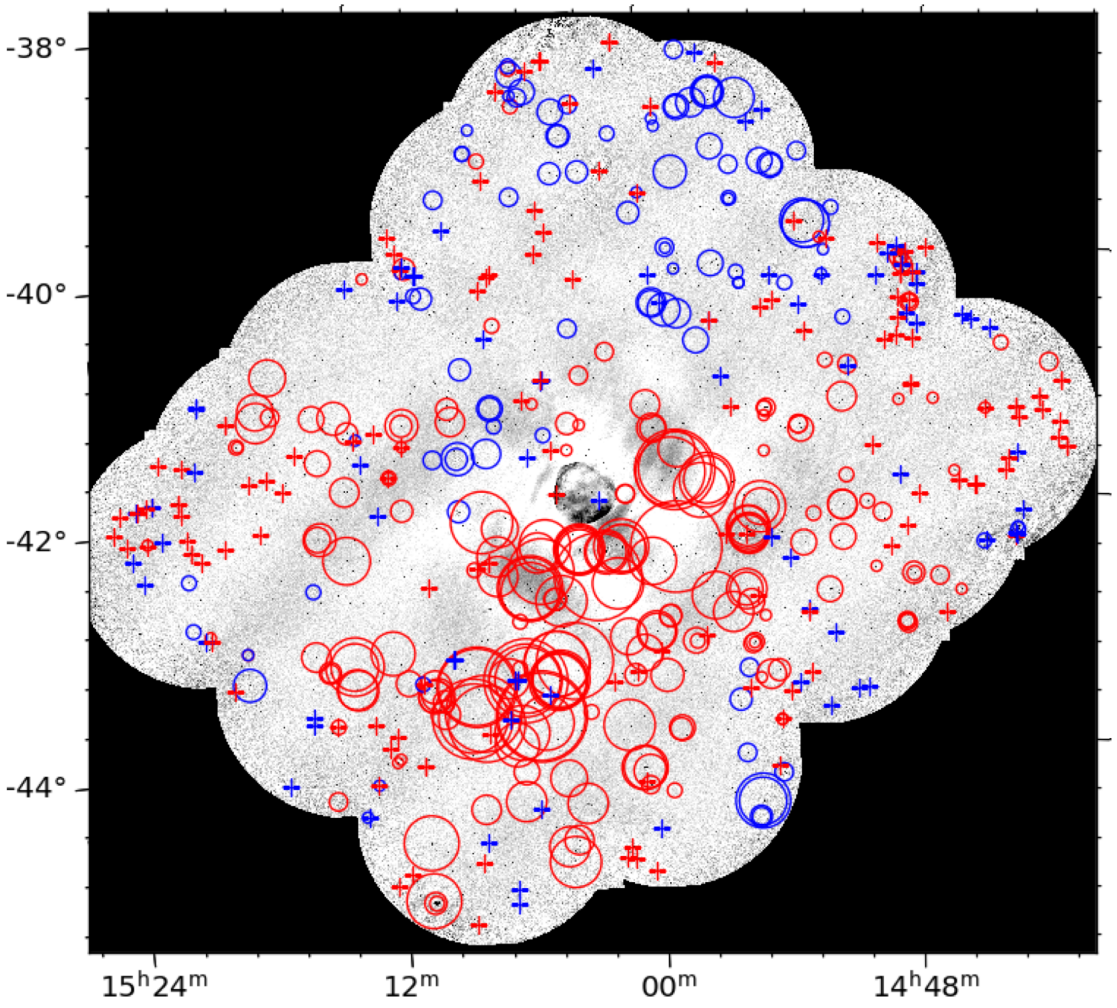
- A prototype RM grid (Vanderwoude, West, Gaensler et al. 2019)
  - 28 antennas, 4 hours, 745-1033 MHz
  - centred on supernova remnant SN 1006
- 516 RMs
  - 17 RMs per deg^2 !

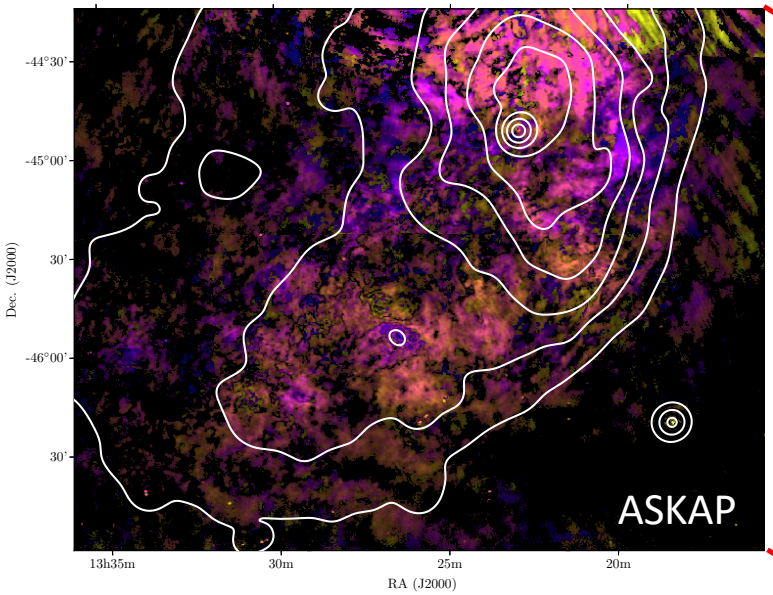


Positive RM
Negative RM

Vanderwoude et al. (2019)

POSSUM: Early Results (II)

Anderson, Gaensler et al. (2018)



Great Observatories for the Coming Decades

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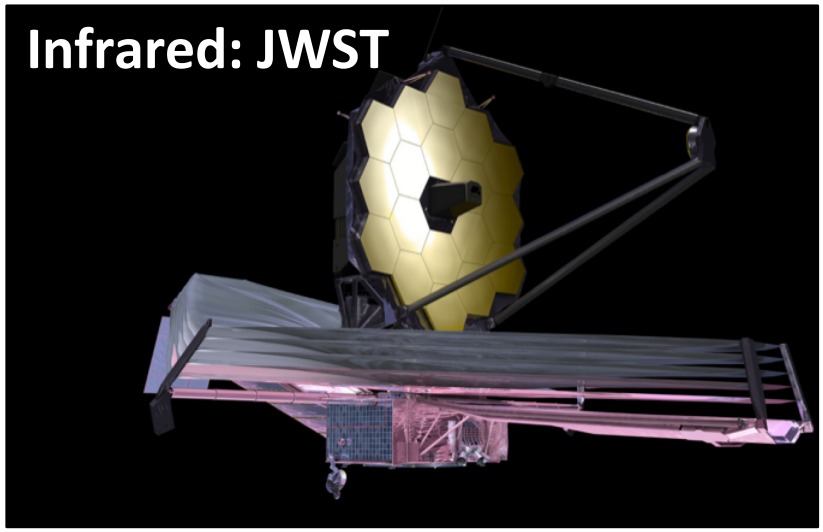

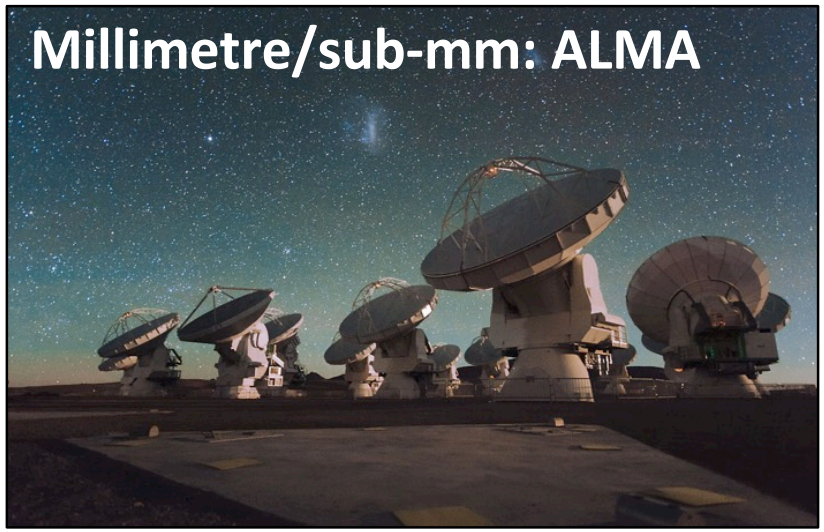

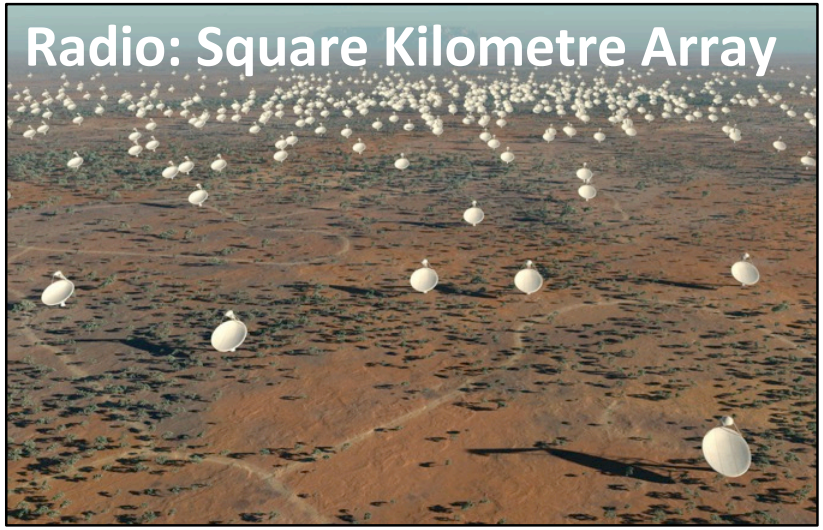

Square Kilometre Array

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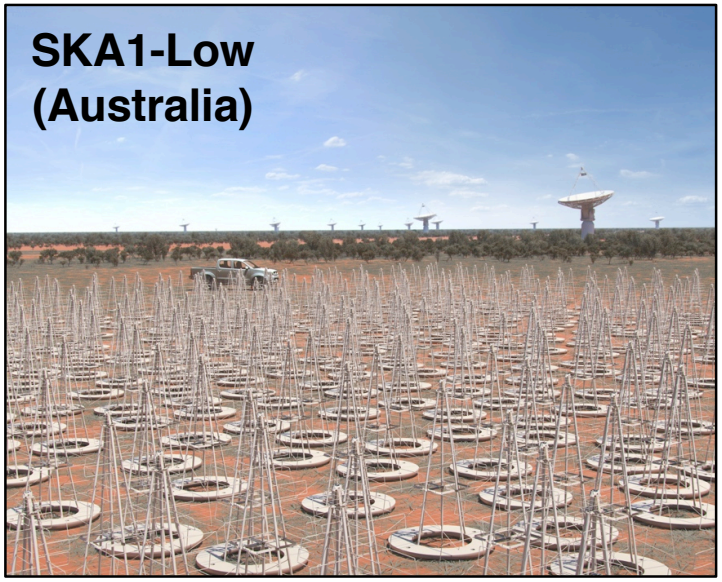
- SKA1: two sites, South Africa and Australia
  - SKA1-Mid (South Africa): 197 dishes, 0.3” res, 0.35-15+ GHz,
  - SKA1-Low (Australia): 130,000 dipoles, 4” res, 50-350 MHz
- Construction starts Q2 2021 ;
  key science programs commence 2029



SKA Organisation

SKA Sites

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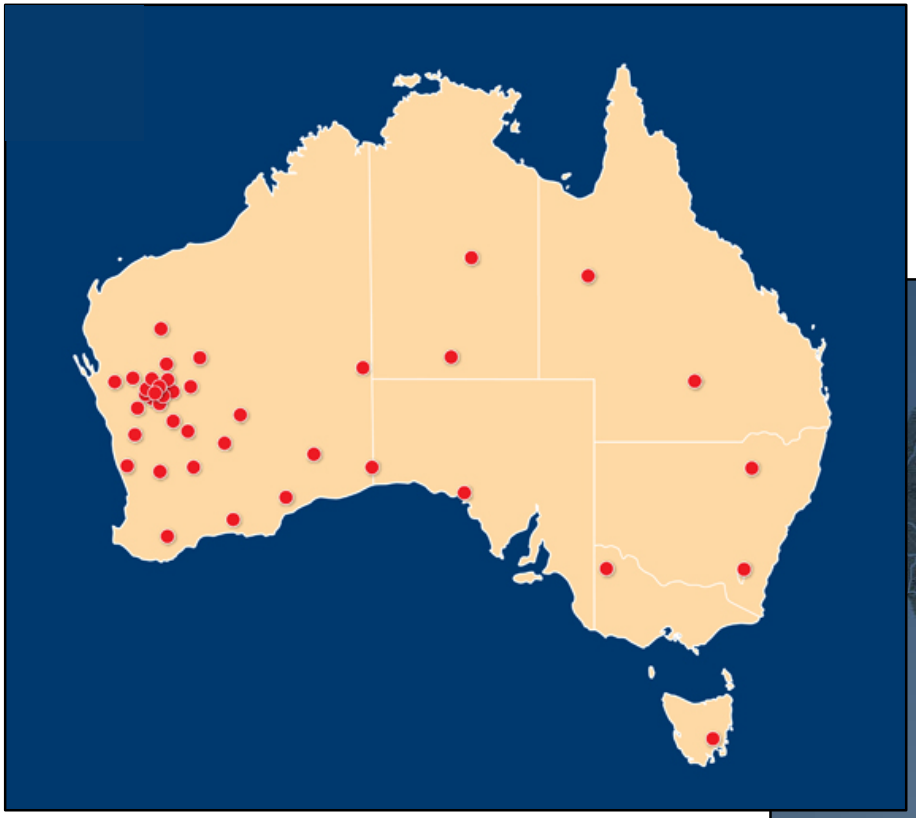
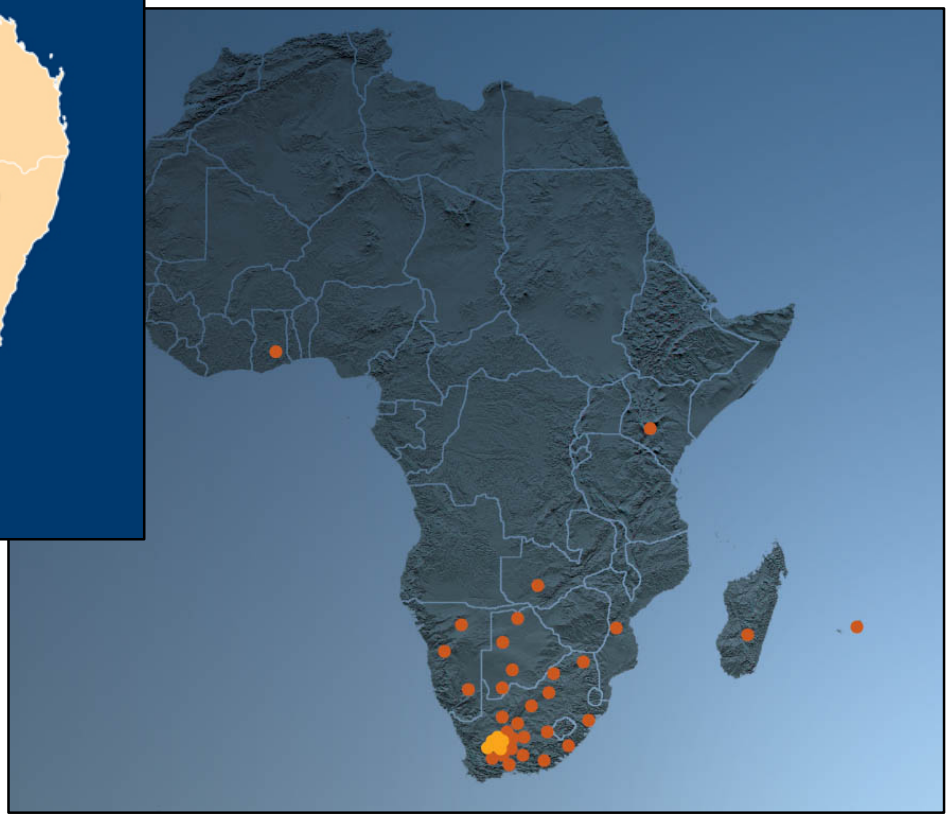


SKA Australia / New Zealand

SKA South Africa



SKA Science

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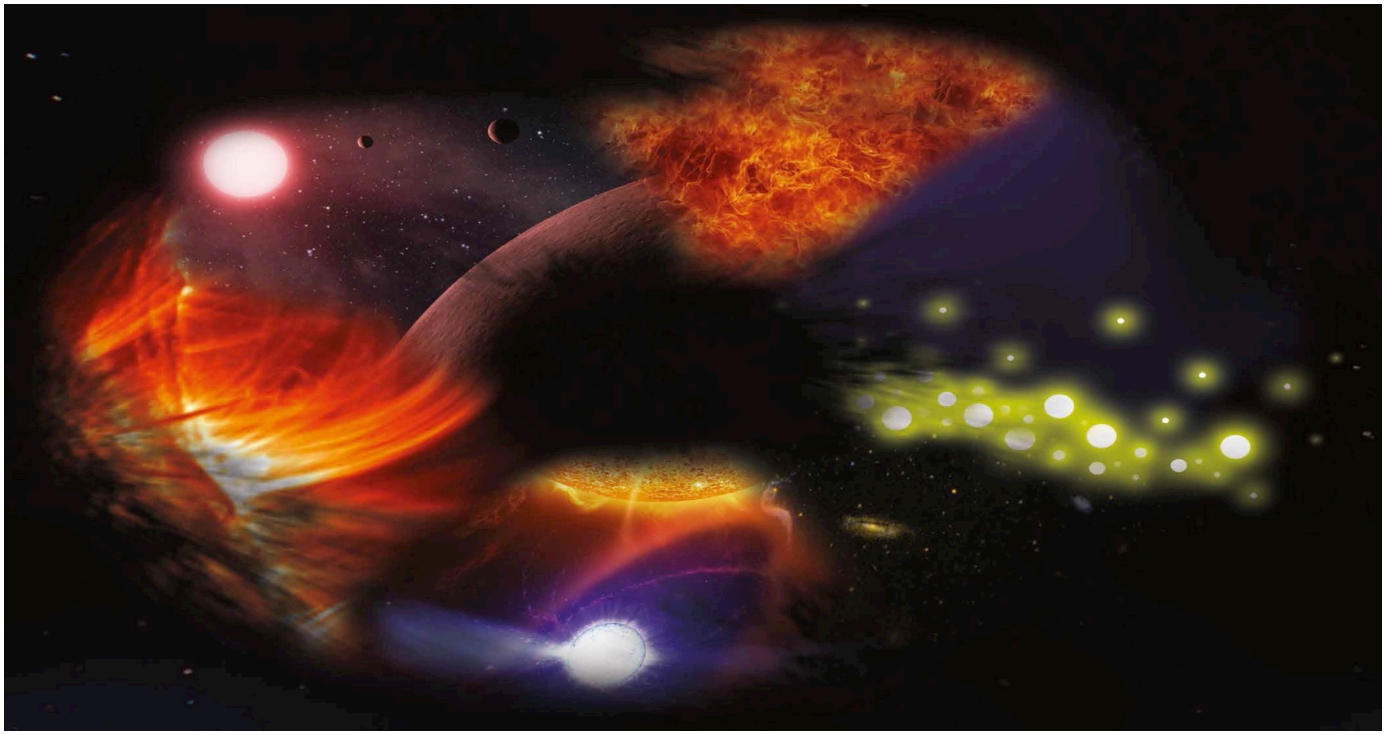
- Fundamental Physics with Pulsars
- Cosmology
- Cosmic Magnetism
- Epoch of Reionisation
- The Transient Universe
- The Continuum Universe
- The Hydrogen Universe
- The Cradle of Life & Astrobiology



SKA Organisation, Djorgovski et al., C. Reed NASA / JPL-Caltech / SSC, NASA / Stanford Lockheed-Martin Institute for Space Research's TRACE team

Magnetism with SKA

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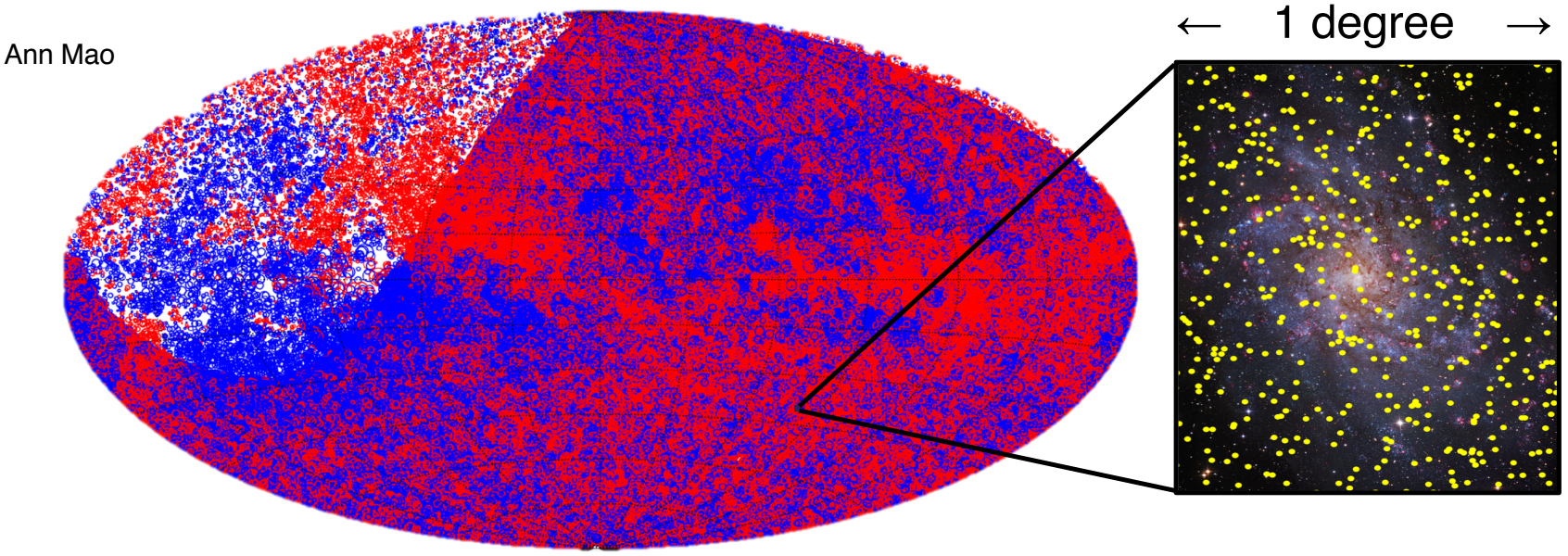
- Baseline survey: 7-14 million RMs all-sky (up to 450 RMs per deg^2)



- Strength + structure of magnetism in galaxies, galaxy clusters & IGM
- Evolution of magnetic fields in galaxies and clusters over cosmic time
- When and how was the Universe magnetised?

Summary

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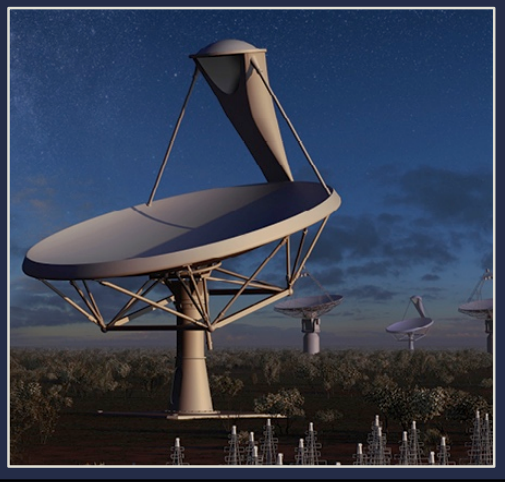
- Single dish
  - total fluxes, pulsars, hydrogen surveys
- Compact arrays
  - extended/diffuse objects, wide area maps
- Extended arrays
  - detailed studies of individual small objects
- Phased array feeds
  - all-sky surveys, cosmic magnetism
- The future: the Square Kilometre Array
  - we have spent 30 years designing this next-generation radio telescope!

CSIRO

NRAO/AUI



SKA

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