Exploring the Physics of Galaxy Cluster Mergers and AGN Feedback:

Prospects with Emerging Centimeter to Meter Wavelength Instruments

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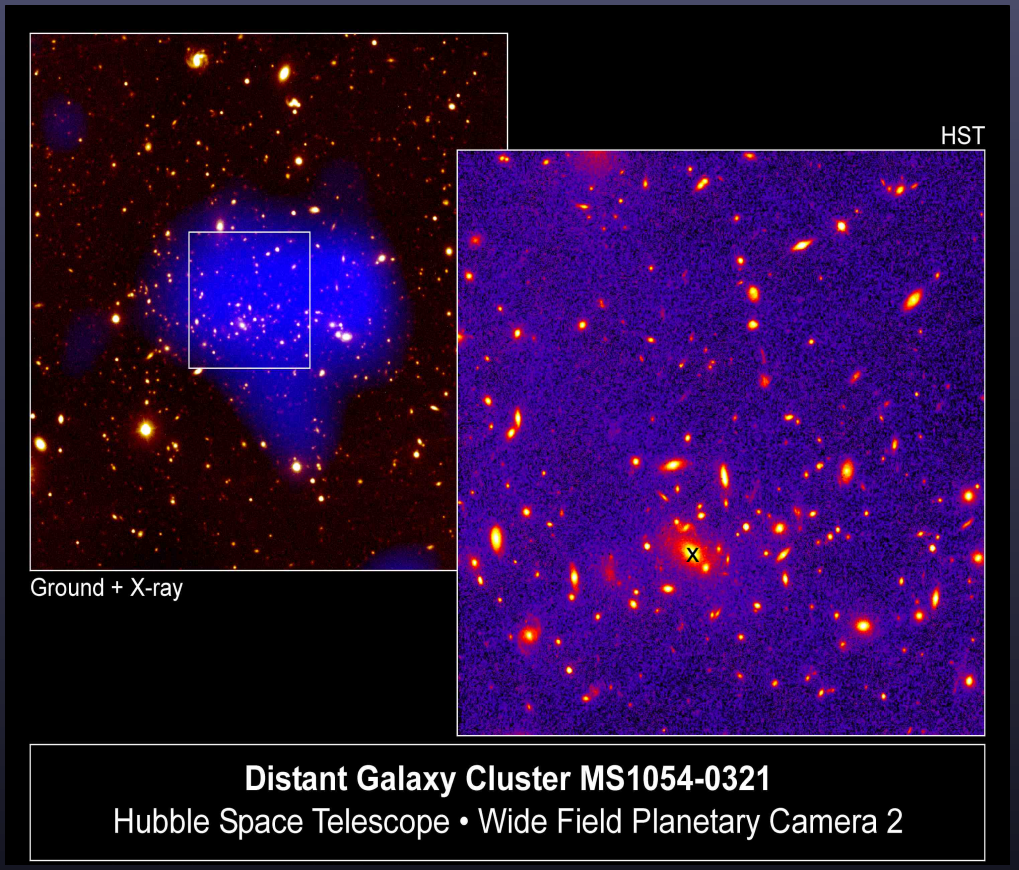
Galaxy Clusters

- Largest gravitationally bound objects in the Universe
- Few Mpc across
- Contain 100 – 1000 bound member galaxies
- Hot (10^7 K) X-ray emitting gas
- Dark matter (~75% mass)
- Central supermassive black hole powers active galactic nucleus (AGN) driven radio jets
- ICM is a reservoir of relativistic electrons embedded in magnetic fields ➔ synchrotron emission



Decadal Survey Astrophysical Challenges

The Origin of Galaxies & Large Scale Structure

- *"How do cosmic structures form and evolve?"*
  - ICM shocks and turbulence

Understanding the Cosmic Order

- *"How do black holes work and influence their surroundings?"*
  - *AGN feedback in ICM*

Frontiers of Knowledge

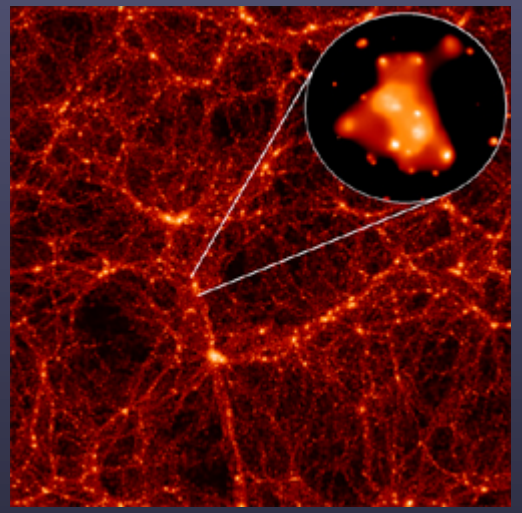
- *"Why is the Universe Accelerating?"*
  - *Non-thermal impact on mass proxies*

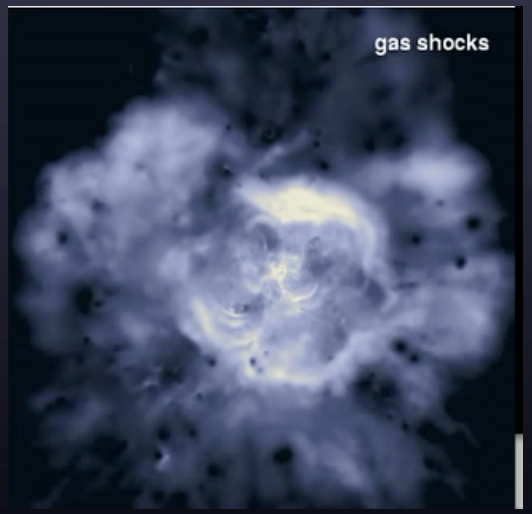
Connection: Low frequency radio interferometry combined with X-ray imaging/spectroscopy provides unique insight.

How Do Cosmic Structures Form and Evolve?

- Clusters form at the intersection of LSS filaments
- ICM is a relativistic electron reservoir ($\tau_{loss} \sim \tau_{Universe}$)
- Shocks and turbulence from mergers accelerate particles and compress magnetic fields
  - Acceleration models include turbulent plasma, shocks, and proton-proton collisions
- Current merger state is traced by peripheral radio relics
  - Fermi-I DSA *or* adiabatic compression
- Past merger state is traced by central radio halo
  - Proton-proton collisions *or* turbulence

✧ Synchrotron Key – faint, steep spectrum diffuse radio emission is (so far) only seen in merging clusters

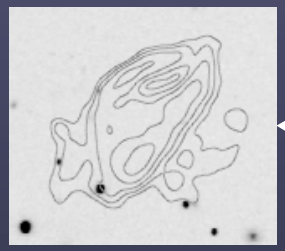




Steep Spectrum Tracers of Mergers

Abell 2256, z=0.058

α=-1.8



Miller et al. (2003)

α<-1.95

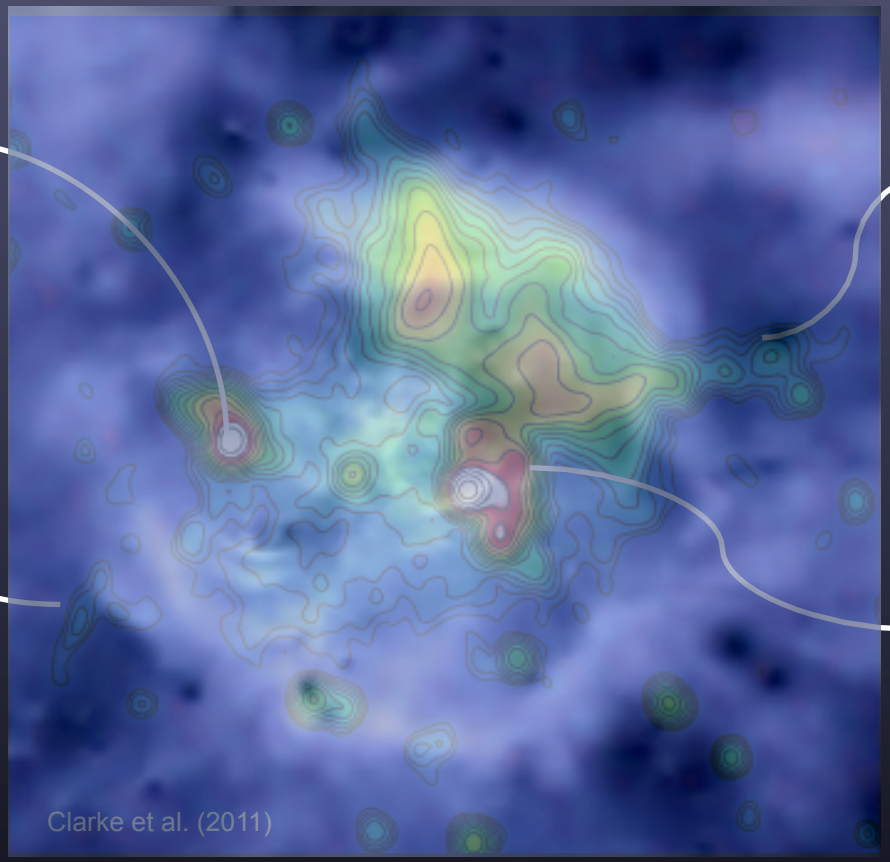
van Weeren et al. (2009)

α< -1.45

van Weeren et al. (2009)

α~-2.1

Intema et al., submitted

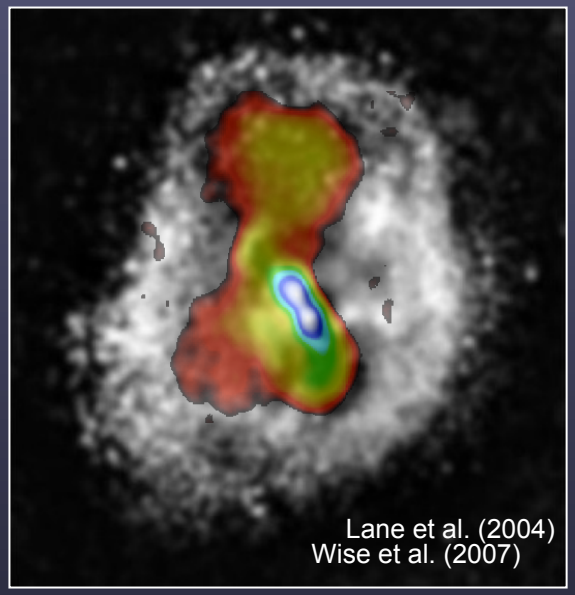


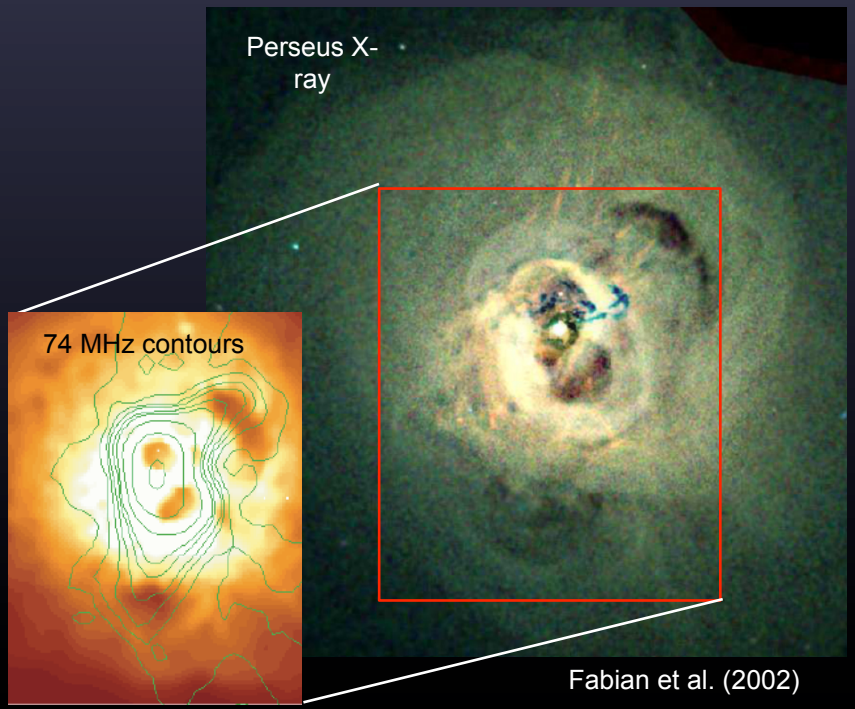
- Well known merger system:
  - 1.4 GHz VLA mapped halo (σ=0.02 μJy/□", Clarke & Ensslin 2006)
  - USS relics discovered at 325 MHz with GMRT (σ=0.2 μJy/□", van Weeren et al. 2009) and GMRT 153 MHz (σ=5.0 μJy/□", Intema et al. submitted)
- USS sources may dominate planned LF surveys allowing us to trace the merger shock locations and map large scale structure formation and evolution

How do BHs Work and Influence their Surroundings?

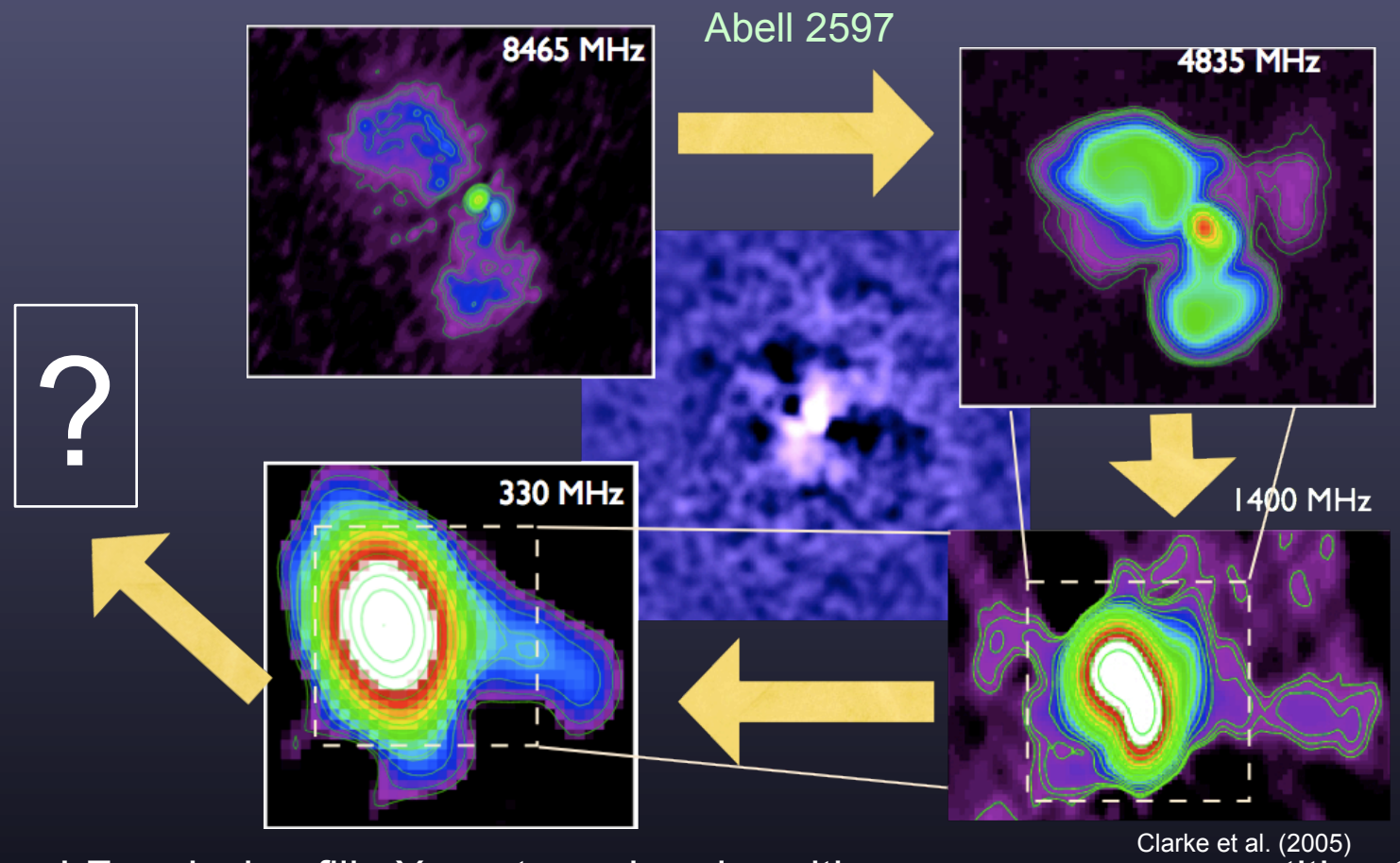
- ICM cooling via thermal Bremsstrahlung
- Predict massive amounts of gas cool, condense and forms stars (> 100 $M_{\odot}$/yr)
  - SF rates are 1-10% expected
  - X-ray spectroscopy does not detect gas below ½ - ⅓ <kT>
- AGN feedback is best candidate to solve the 'Cooling Flow Problem'
  - Suppress of star formation and the growth of luminous galaxies

✧ Synchrotron Key – low frequency observations can trace steep spectrum emission from past AGN outbursts





Radio History of AGN Feedback



Clarke et al. (2005)

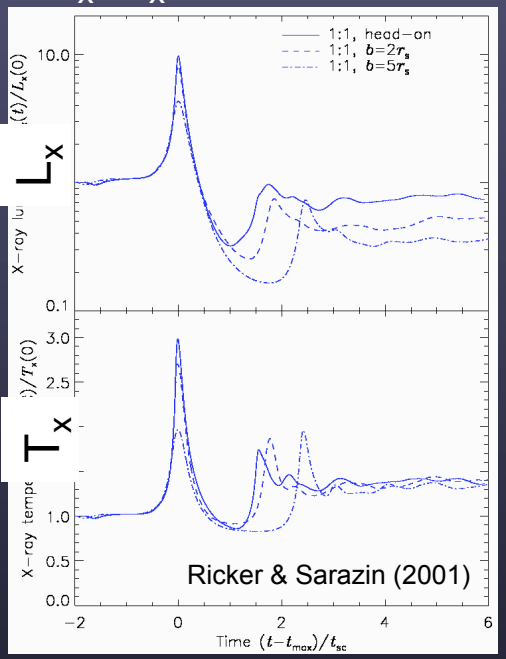
- LF emission fills X-ray tunnel and cavities, e.g. measure repetition timescale of outbursts (~30 Myr), total energy in multiple outbursts (~10x current outburst)
- Need high spatial resolution at low frequencies
- Deep cm and m observations of cool cores will trace the history of AGN energy injection into the ICM to measure AGN physics as well as impact on surroundings

Why is the Universe Accelerating?

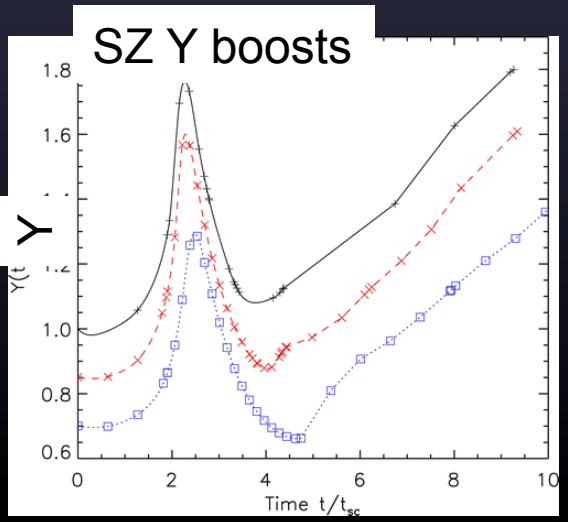
- Galaxy cluster mass function and its evolution both depend strongly on cosmology
- Clusters play a key role in precision cosmology studies of the dark energy equation of state
- Assumption of hydrostatic equilibrium to convert observables to mass estimates
- Deviations from equilibrium and non-thermal pressure support increase scatter in proxy relations

✧ Synchrotron Key – diffuse synchrotron connection to mergers ➔ 'Merge-o-Meter' to identify systems which are not in hydrostatic equilibrium

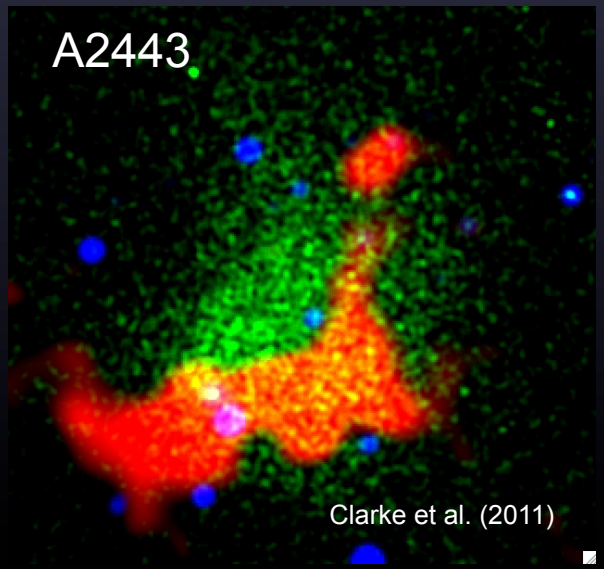
L_x, T_x boosts



SZ Y boosts

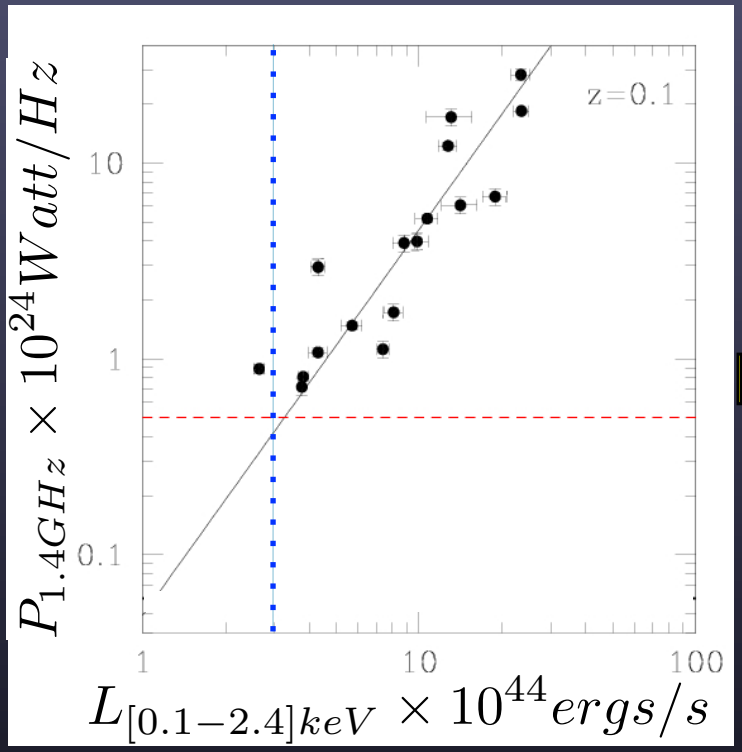


Wil et al. (2008)

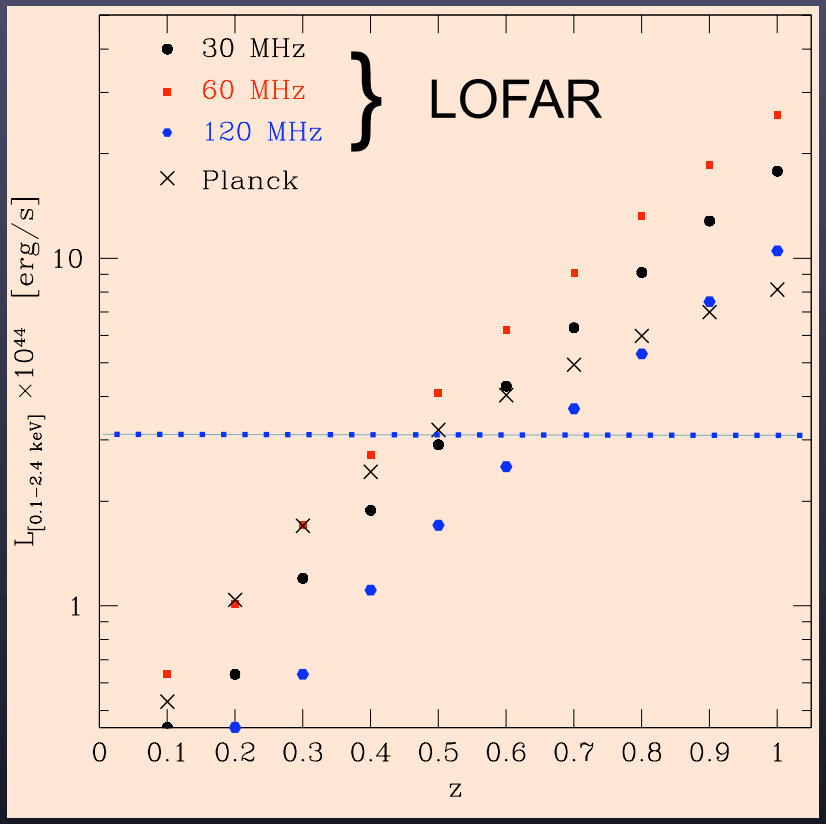


Tracing Merging Clusters

Observed correlation



Predicted redshift distribution



Ferrari et al. (2010)

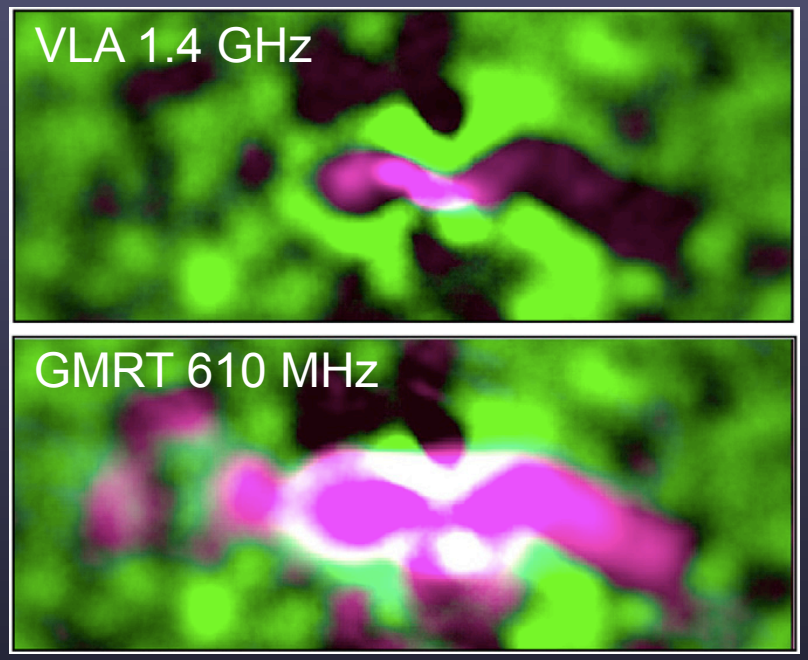
- Radio halo power appears correlates with host cluster X-ray luminosity
- Current studies probe halos in nearby clusters to L_x~3x10^{44} ergs/s
- Other tracers of the non-thermal cluster component will come from *Fermi*, *NuStar* and *IXO*
- Deep surveys at low frequencies will detect hundreds of halos at z<0.6

GMRT

	151	235	325	610	1420
Primary Beam (arc min)	186±6	114±5	81 ± 4	43 ± 3	$(24 \pm 2) * (1400/f$
Receiver Temperature (T_R)	295†	106†	53	60	45
Typical T_{sky} (off galactic plane)	308	99	40	10	4
Typical T_{ground}	12	32	13	32	24
Total System Temperature (K) ($T_R + T_{sky} + T_{ground}$)	615	237	106	102	73
Antenna Gain (K/Jy/Antenna)	0.33	0.33	0.32	0.32	0.22
Synthesised Beam (arcsec)					
Whole Array	20	13	9	5	2
Central Square	420	270	200	100	40
Largest Detectable Source(arcmin)	68	44	32	17	7
Usable Frequency Range (MHz)					
Observatory default	150 to 156	236 to 244	305 to 345	580 to 640	1000 to 1450
Range allowed by electronics	130 to 190	230 to 250	305 to 360	570 to 650	1000 to 1450
Fudge Factor(actual to estimated time)					
For Short Observations	10	5	2	2	2
For Long Observations#	5	2	2	1	1
Best rms sensitivies achieved so far as known to us (mJy)	0.7	0.25	0.04	0.02	0.03
Typical Dynamic Ranges	> 1500	> 1500	>1500	>2000	>2000

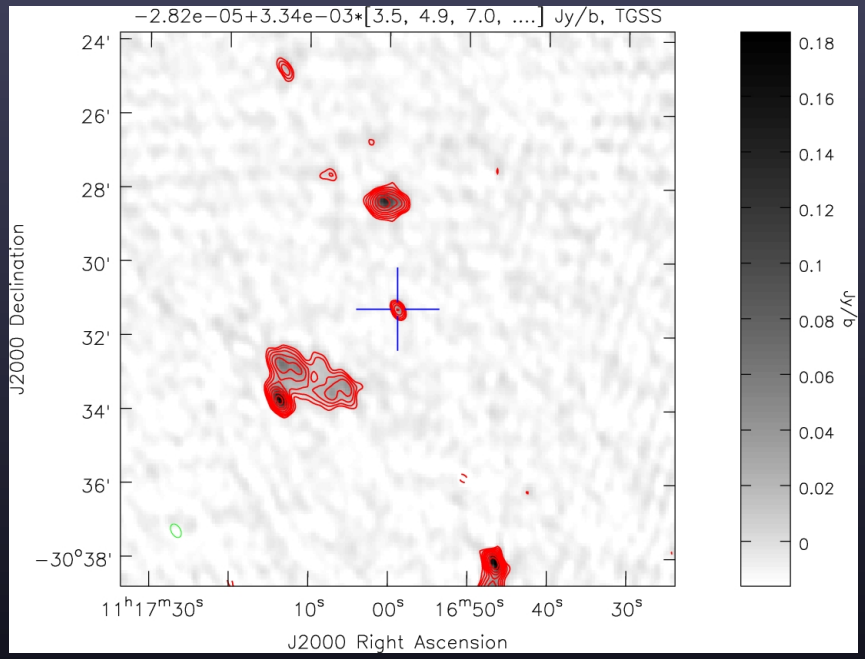
TIFR GMRT Sky Survey

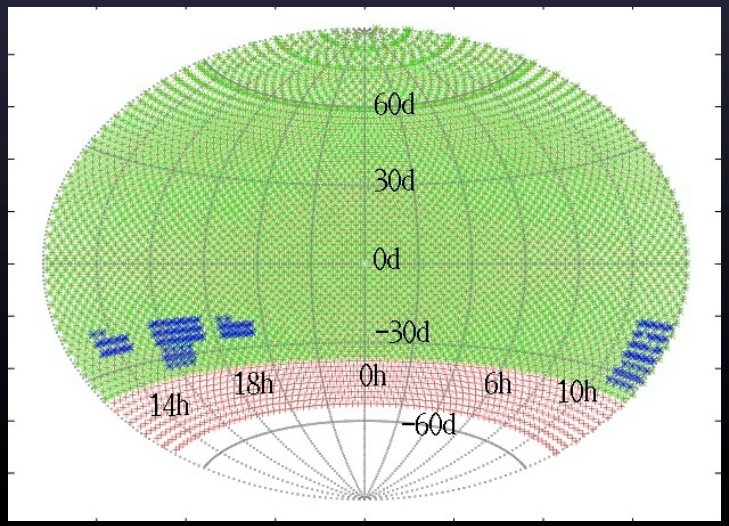
Abell 262



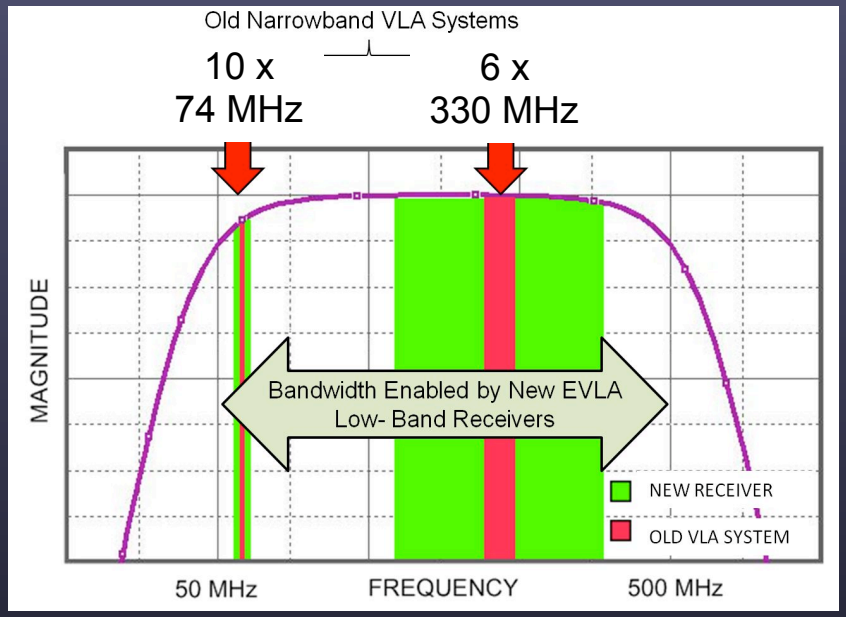
Clarke et al. (2009)

- TGSS at 150 MHz
  - δ > -30
  - σ~9 mJy/bm
  - θ~20”





EVLA Low Band Upgrade



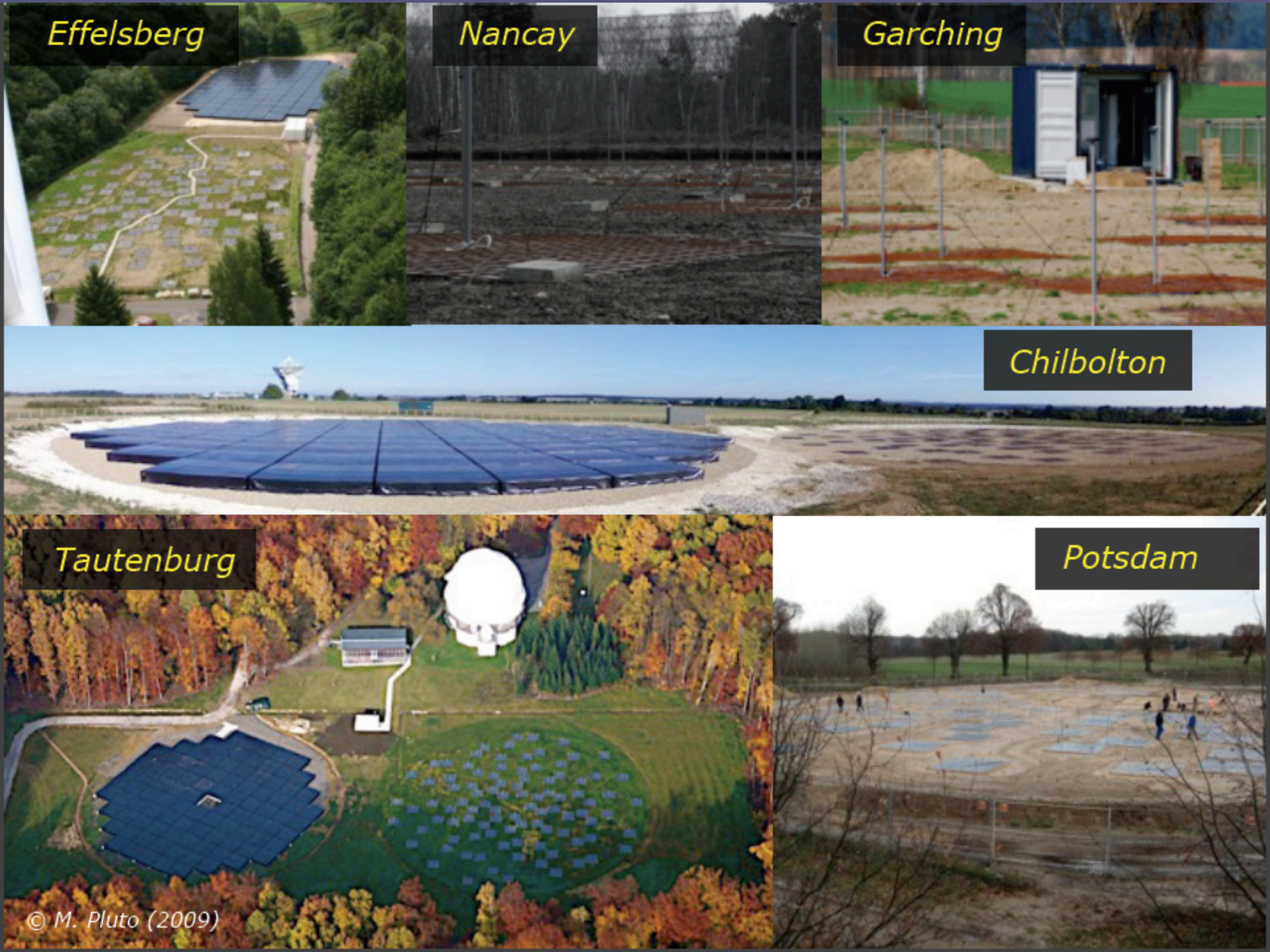
Abell 521 with EVLA LB

Additional sensitivity and resolution possible with LWA tied into EVLA WIDAR or as stand alone 53 station array

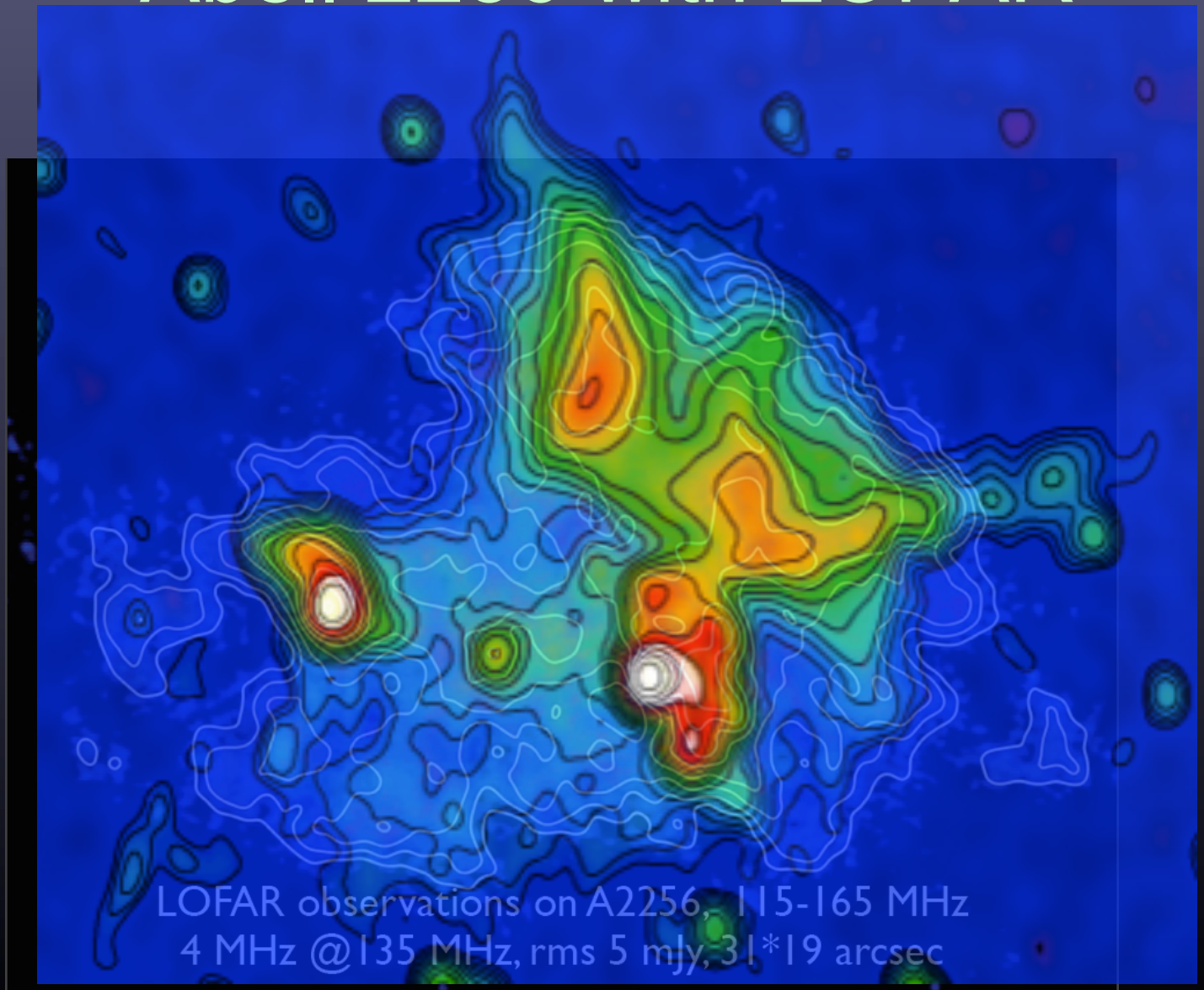
LOFAR

Superterp

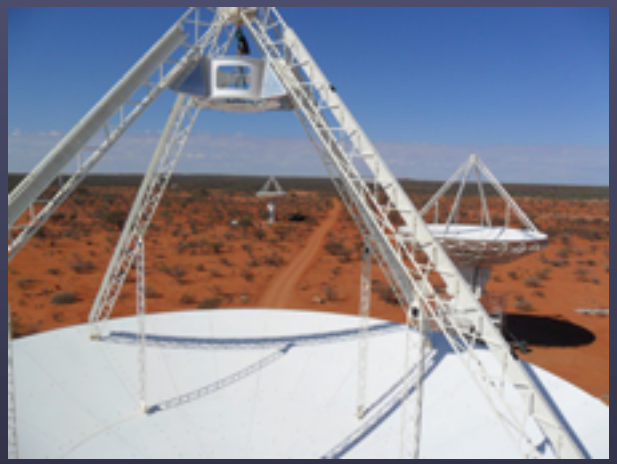
- LOFAR Low
  - 10 – 90 MHz
  - 96/station
- LOFAR High
  - 110 – 250 MHz
  - 48/station


Effelsberg
Nancay
Garching
Chilbolton
Tautenburg
Potsdam
© M. Pluto (2009)

Abell 2256 with LOFAR



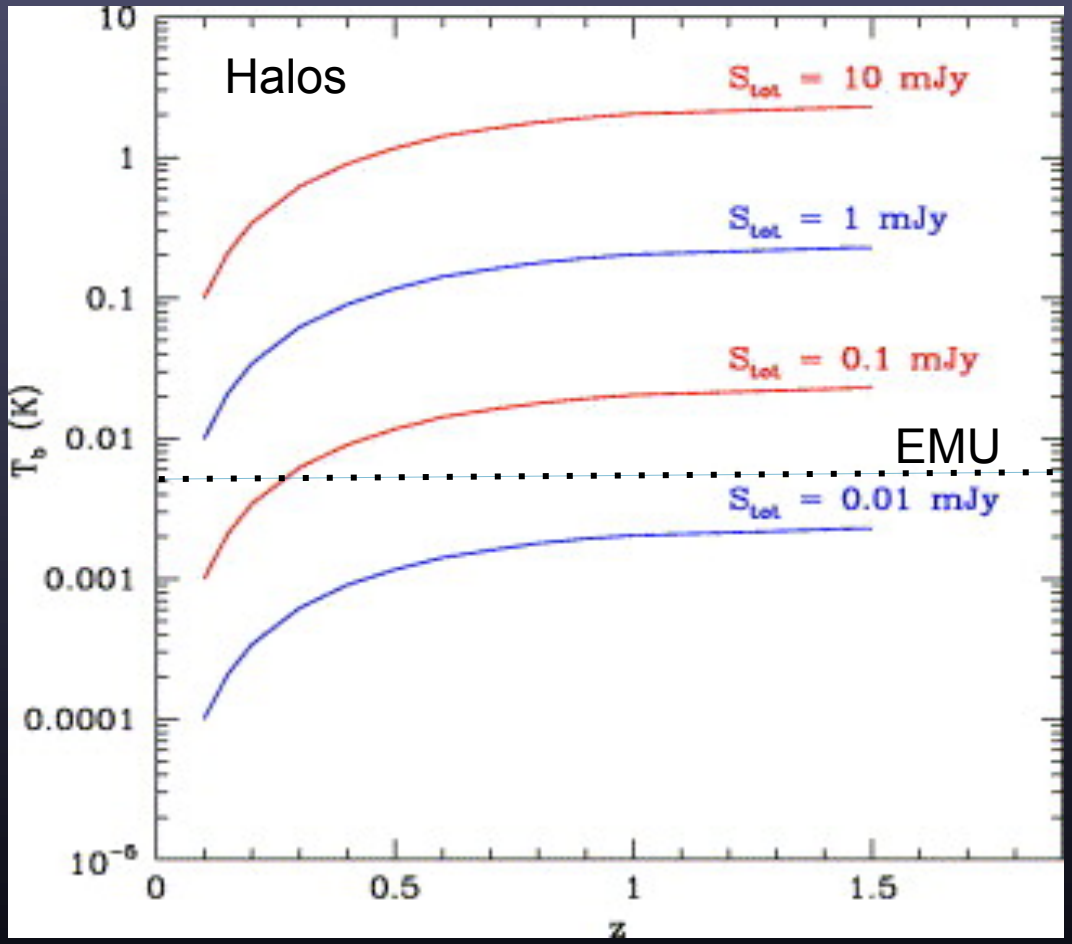
Australian SKA Pathfinder



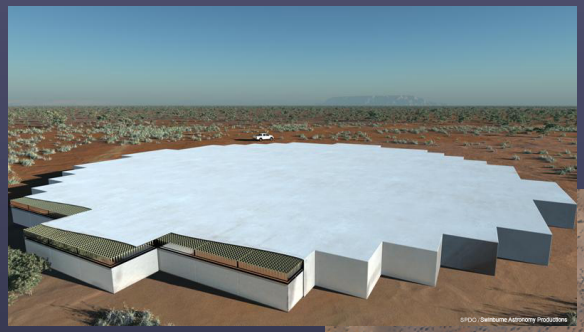
- 36 x 12 m antennas
- 6 in 2011, complete 2013
- 700 MHz -> 1800 MHz
  - 300 MHz instantaneous
- 30 independent beams

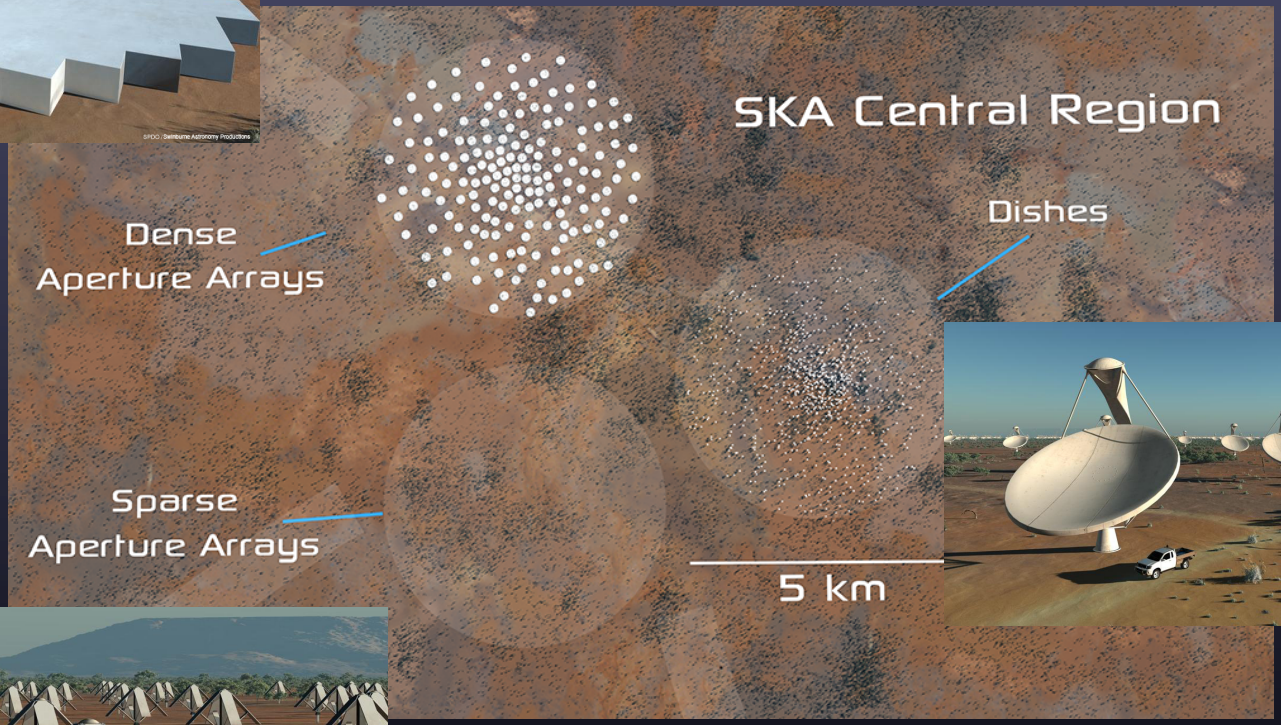
Evolutionary Map of the Universe

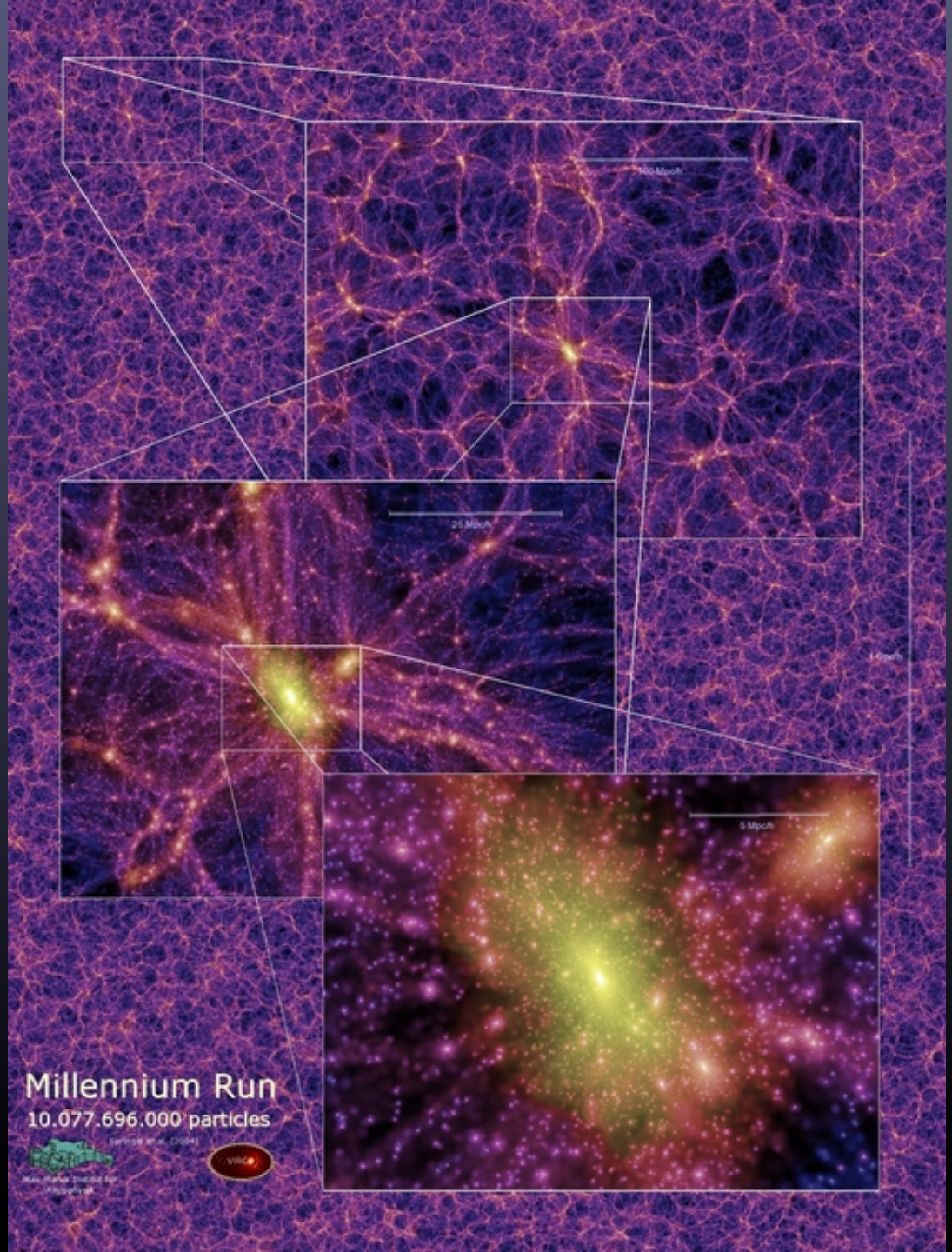
- Australian SKA Prototype (ASKAP) survey EMU:
  - 1130-1430 MHz
  - ~10 μJy rms
  - δ < 30°
- Expect more than 300 halos and a similar number of relics
- Trace evolution of AGN across the Universe



Square Kilometer Array






Millennium Run
10.077.696.000 particles