Radio Astronomy Facilities

Exploring the Cosmic Frontier

Berlin May 18

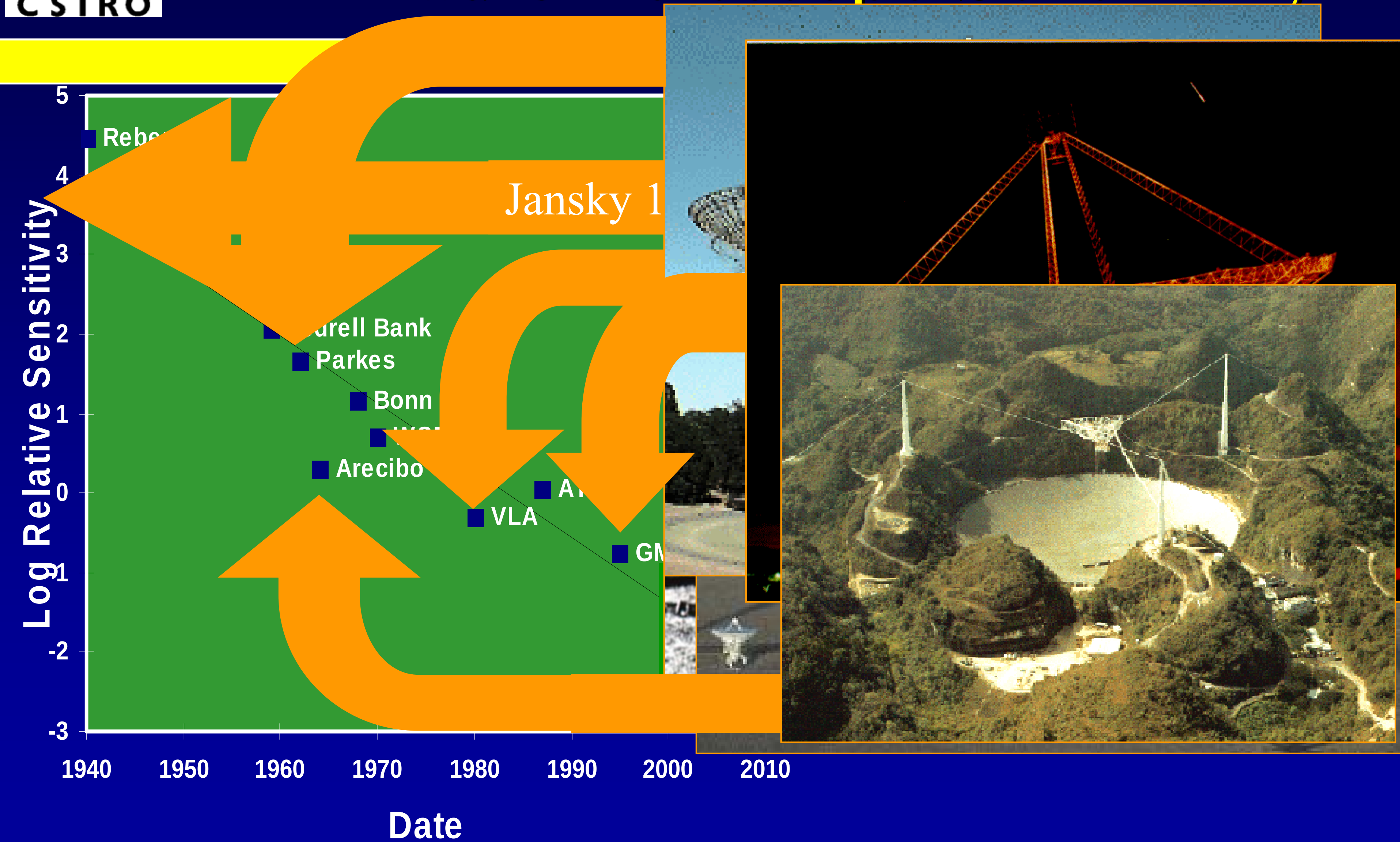
Ron Ekers

CSIRO, Australia

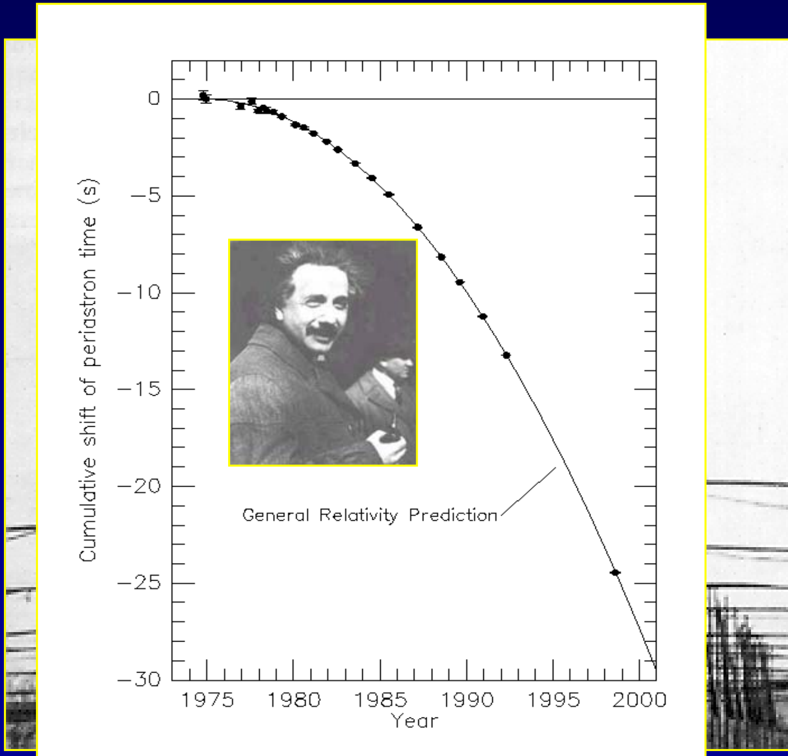
Outline

- A Brief History of Radio Astronomy
- Astronomy at radio wave lengths
- Impact of new technology
- Science Opportunities
  - Key experiments with some of the proposed facilities
- Future Facilities
  - e-MERLIN
  - EVLA I & II
  - ATA
  - GMRT, LOFAR
  - FPA’s (Parkes, Arecibo)
  - SKA, DSN array
  - ALMA

Radio Telescope Sensitivity



The 3 Nobel prizes in Radio Astronomy



- Cosmic Microwave Background
  - Nobel prize to Penzias and Wilson
    - » Bell Telephone Labs
  - Technology driven serendipity
- Discovery of neutron stars
  - radio pulsations (pulsars)
  - Jocelyn Bell & Tony Hewish
- Verification of Einstein's pred[illegible] of gravitational radiation
  - 1993 Noble prize to Taylor and Hulse

Provides unique information about the Universe

- Non-thermal processes: qu
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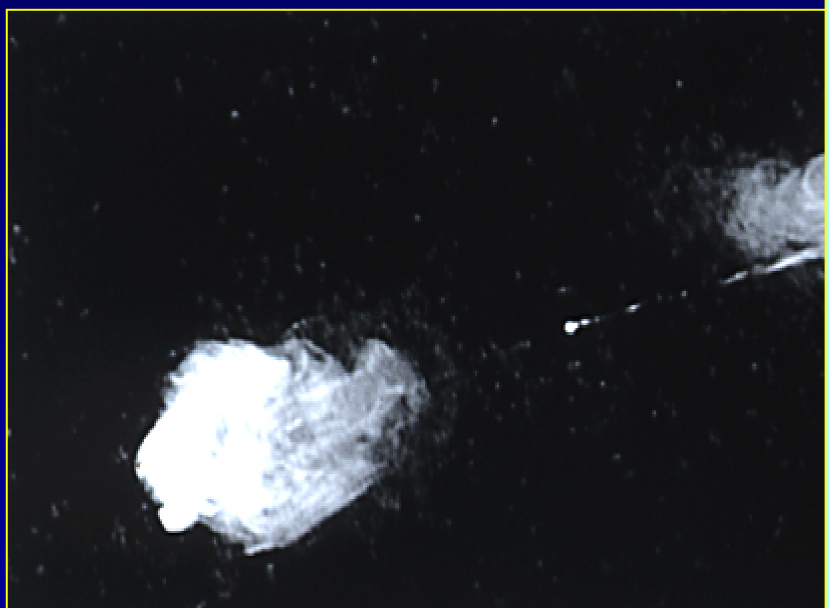
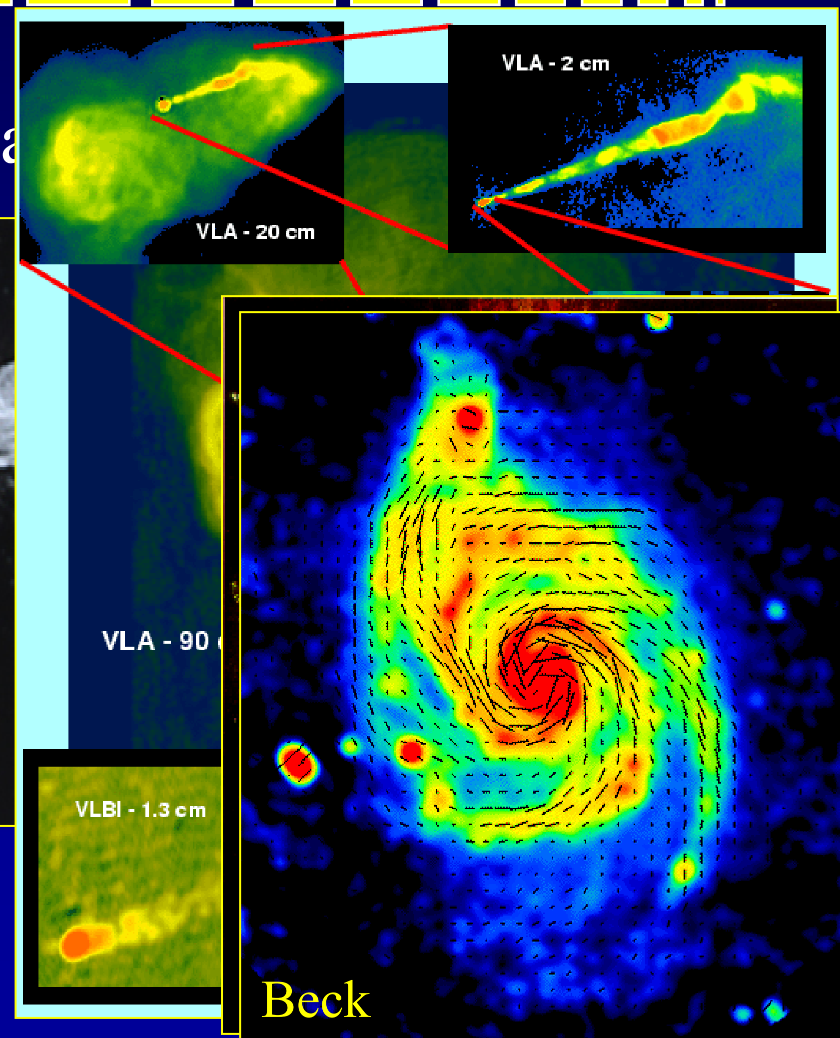
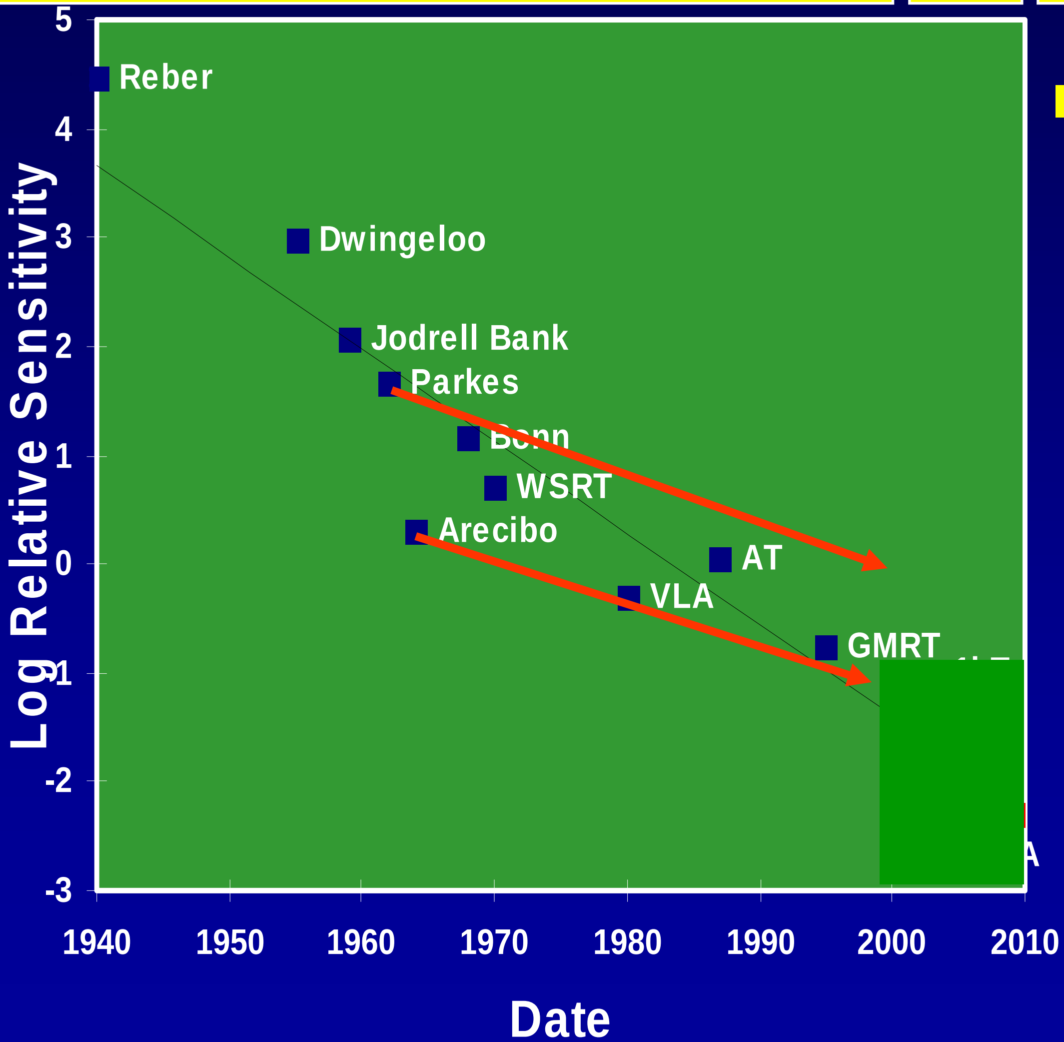


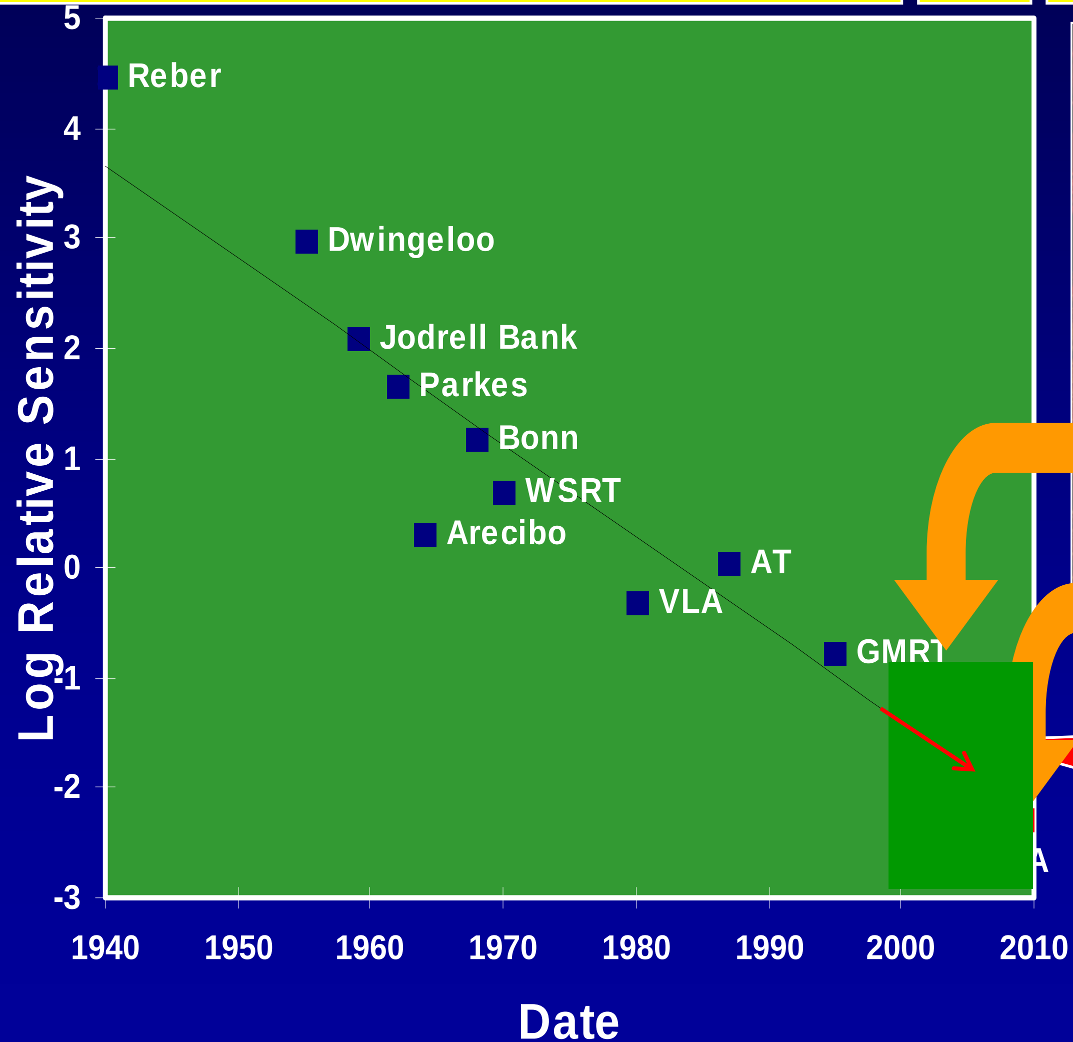


Radio Telescope Sensitivity



- Exponential increase in sensitivity x 10^5 since 1940 !
- Upgrades can't sustain an exponential increase
  - » Eg Arecibo upgrade
  - » Parkes upgrade
  - » Exponential growth needs new technology

Radio Telescope Sensitivity the Future



Large radio telescopes make discoveries!

✓Quasars and radio galaxies

- 21cm HI line

✓Cosmological evolution of radio sources

✓Cosmic Microwave Background

✓Jets and super-luminal motions

✓Dark matter in spiral galaxies

✓Masers and megamasers

- Mass of the blackhole in AGN NGC4258

✓Pulsars

- Gravitational radiation (pulsar timing)
- First extra-solar planetary system

✓Serendipity

Impact of new technology

Quantum v Classical

- At radio wavelengths the relevant technology applies to the classical not the quantum limit
- Number of photons per state is so high that quantum effects can be ignored and the signal streams behave classically
  - Ability to split signal streams with no loss in S/N leads to a big advantage in arraying technology
  - Wave-fronts can be recorded digitally and the whole imaging process (including detection) moved into software.
  - Eg self cal is the equivalent of adaptive optics but doesn't have to be done in real time.

Commercial Drivers for Technology

- The advances described by Moore's Law are directly applicable to radio telescope design
- MMIC (large scale integrated circuit) technology allows cheap duplication of complex circuits
  - Driven by eg mobile radio communications technology
- Optical fibre communications
- Cheap mass storage
- The R&D needed at radio wavelengths is directly relevant to the broader S&T research priorities in most countries

Conclusion

- The combination of the classical signal properties and the MMIC technology generates totally new opportunities in which large dishes can be replaced by arrays of smaller elements
  - This not only delivers imaging capability but dramatically reduces costs of the collecting area
  - This is the technology driver for the ATA and SKA
- A large FOV is physically easy at these long wavelength and is mainly dependent on the signal processing capability.
  - This lets us increase FOV at the Moore's law rate.

New Parameter Space

- Wide FOV
  - Feed arrays
- Sensitivity
  - Collecting area
- Wide bandwidth
  - Signal processing
- Very high angular resolution
  - Wide band communications links
- Interference mitigation

SKA Key Science Projects

Leiden Nov 2004

- The evolution of galaxies and large scale structure
- Probing the Dark Ages – the first black holes and stars
- Strong field tests of gravity using pulsars and black holes
- The origin and evolution of Cosmic Magnetism
- Cradle of Life

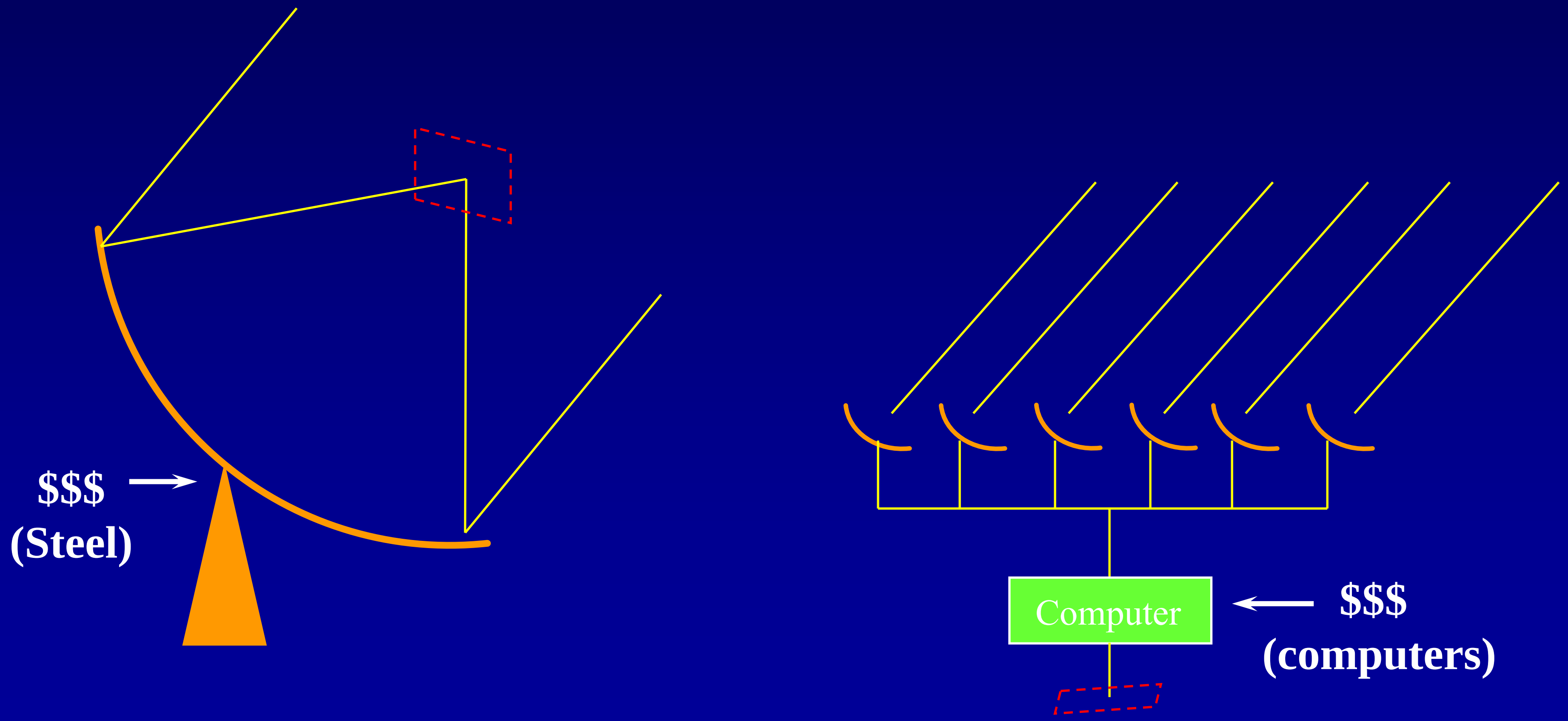
Science Opportunities

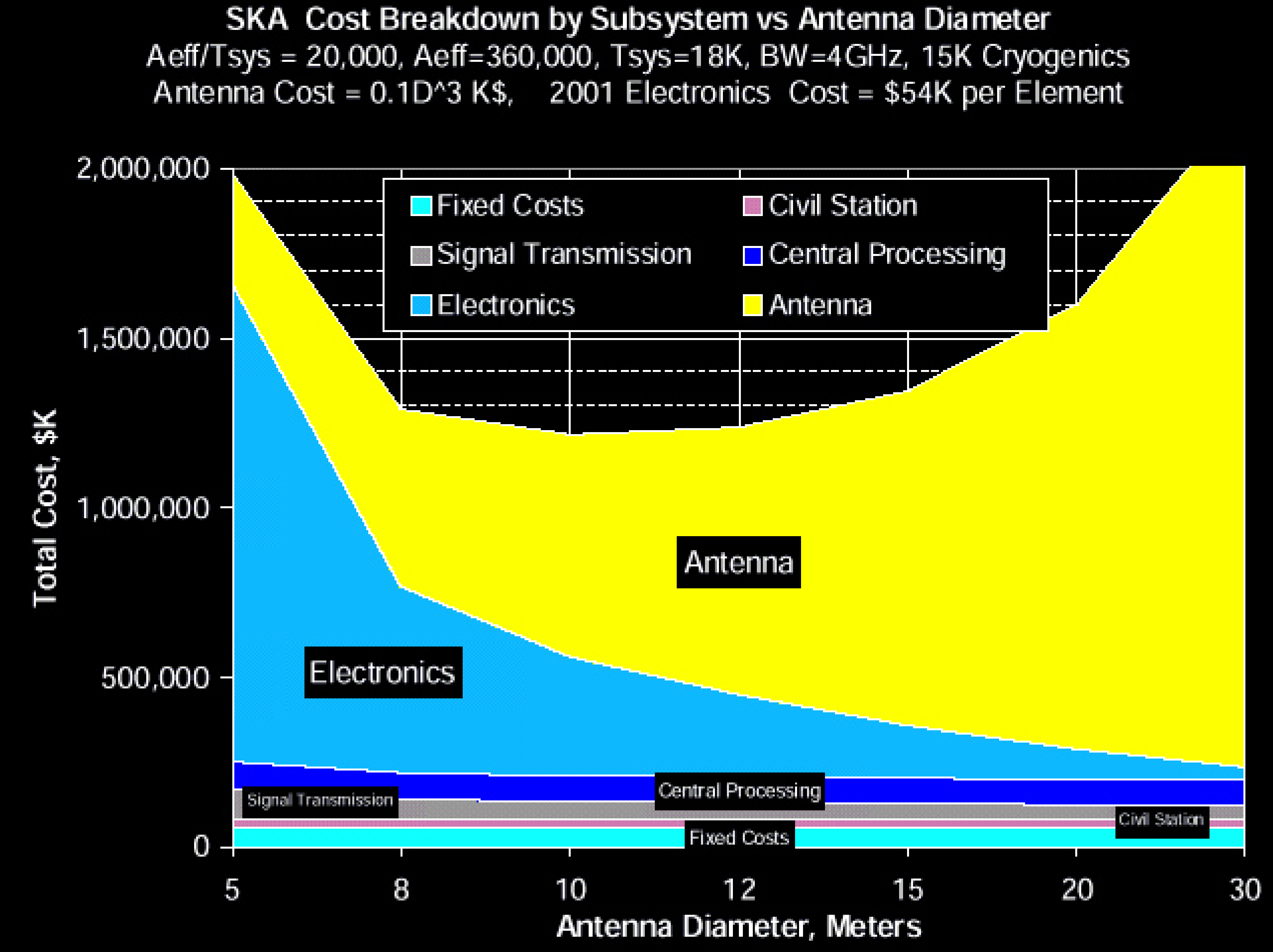
- The product of all astronomy touched by radio, and all the opportunities opened up by the new parameter space, is too large to cover
- A taste
  - try to touch all the ideas in the recent review of Key Science drivers
    - Leiden Nov 2003
  - A few key experiments with some of the proposed facilities

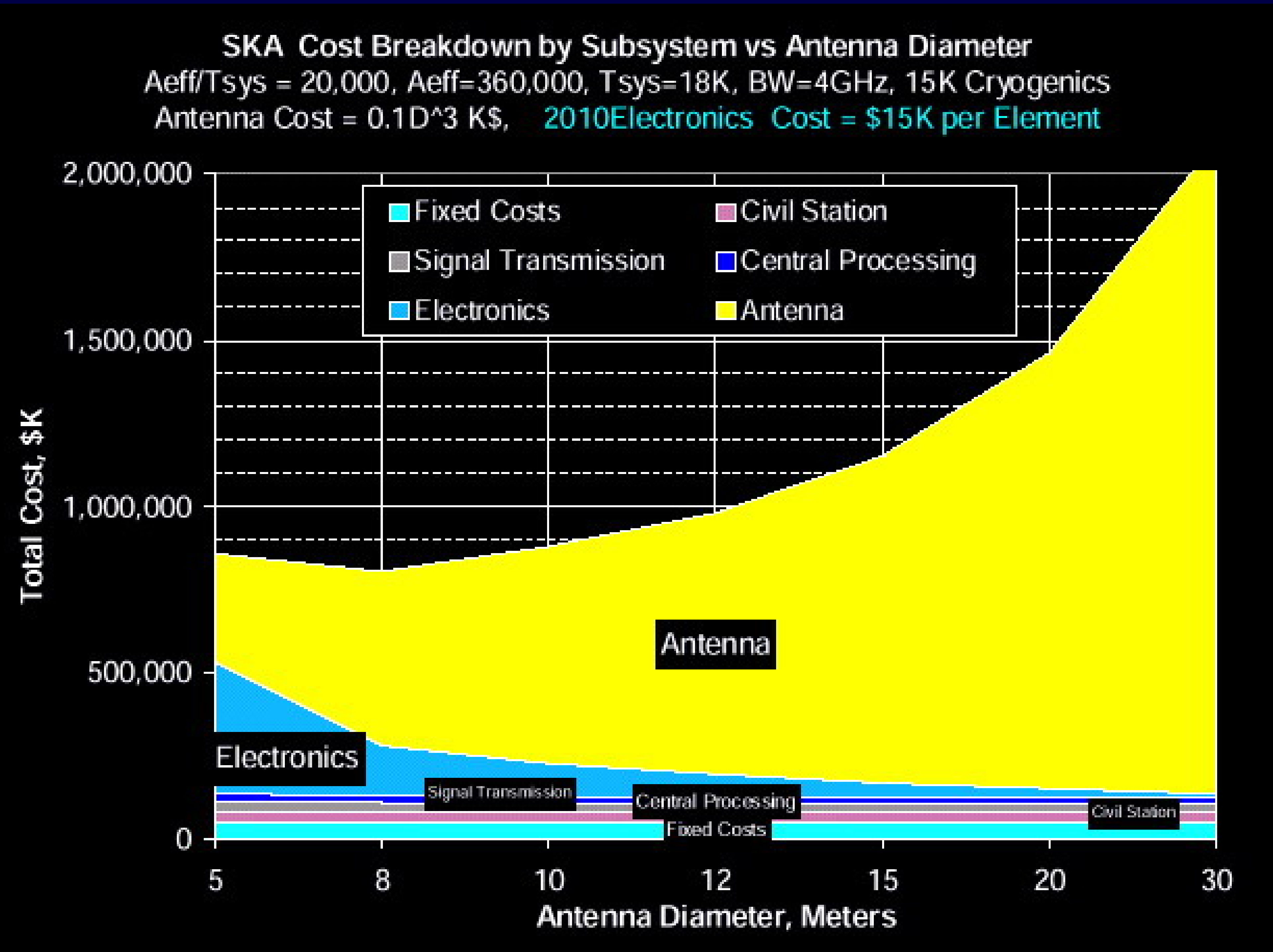
Rawlings 2003

Sensitivity

Big Dishes or Arrays




SKA Cost Breakdown by Subsystem vs Antenna Diameter
Aeff/Tsys = 20,000, Aeff=360,000, Tsys=18K, BW=4GHz, 15K Cryogenics
Antenna Cost = 0.1D^3 K$, 2001 Electronics Cost = $54K per Element
Fixed Costs
Civil Station
Signal Transmission
Central Processing
Electronics
Antenna
Total Cost, $K
2,000,000
1,500,000
1,000,000
500,000
0
Antenna
Electronics
Signal Transmission
Central Processing
Civil Station
Fixed Costs
5
8
10
12
15
20
30
Antenna Diameter, Meters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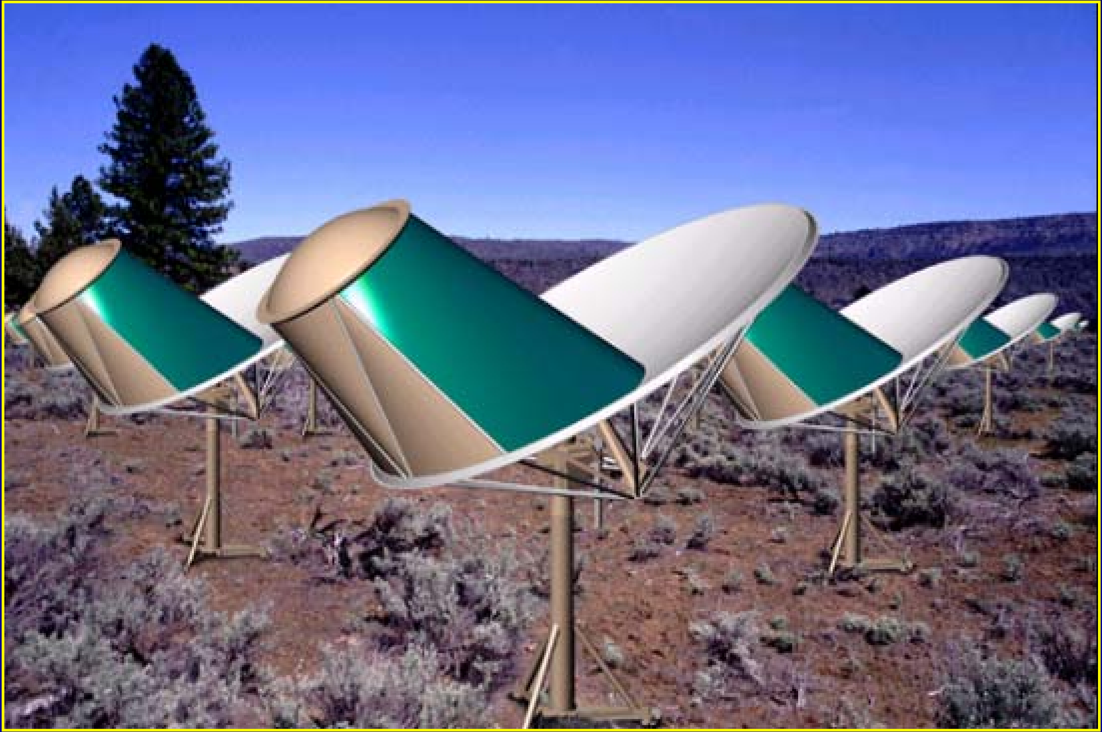
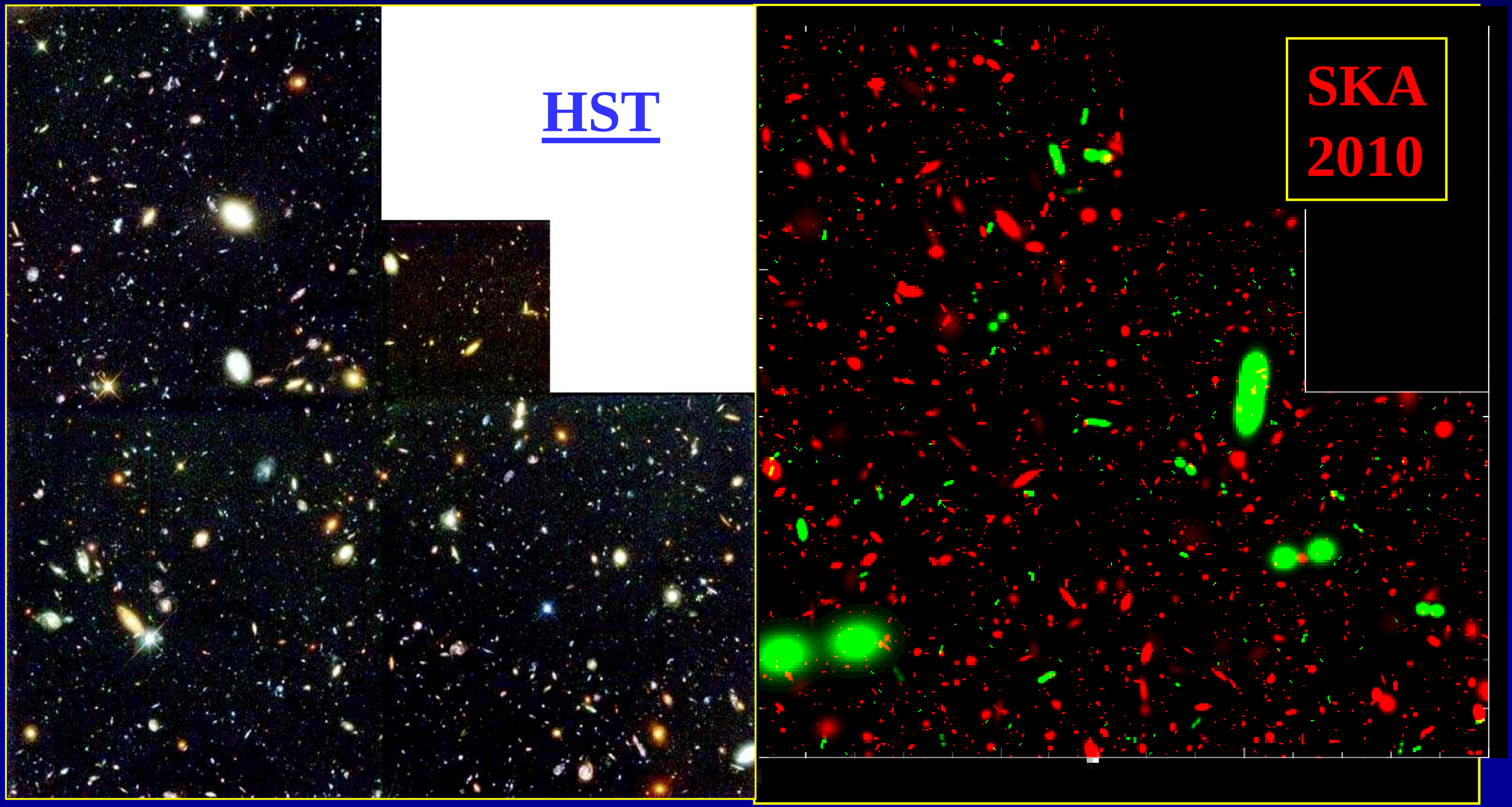
Fixed Costs
Civil Station
Signal Transmission
Central Processing
Electronics
Antenna
2,000,000
1,500,000
1,000,000
500,000
0
Total Cost, $K
Antenna
Electronics
Signal Transmission
Central Processing
Civil Station
Fixed Costs
5
8
10
12
15
20
30
Antenna Diameter, Meters

Mass-produced parabolas: The Allen Telescope Array

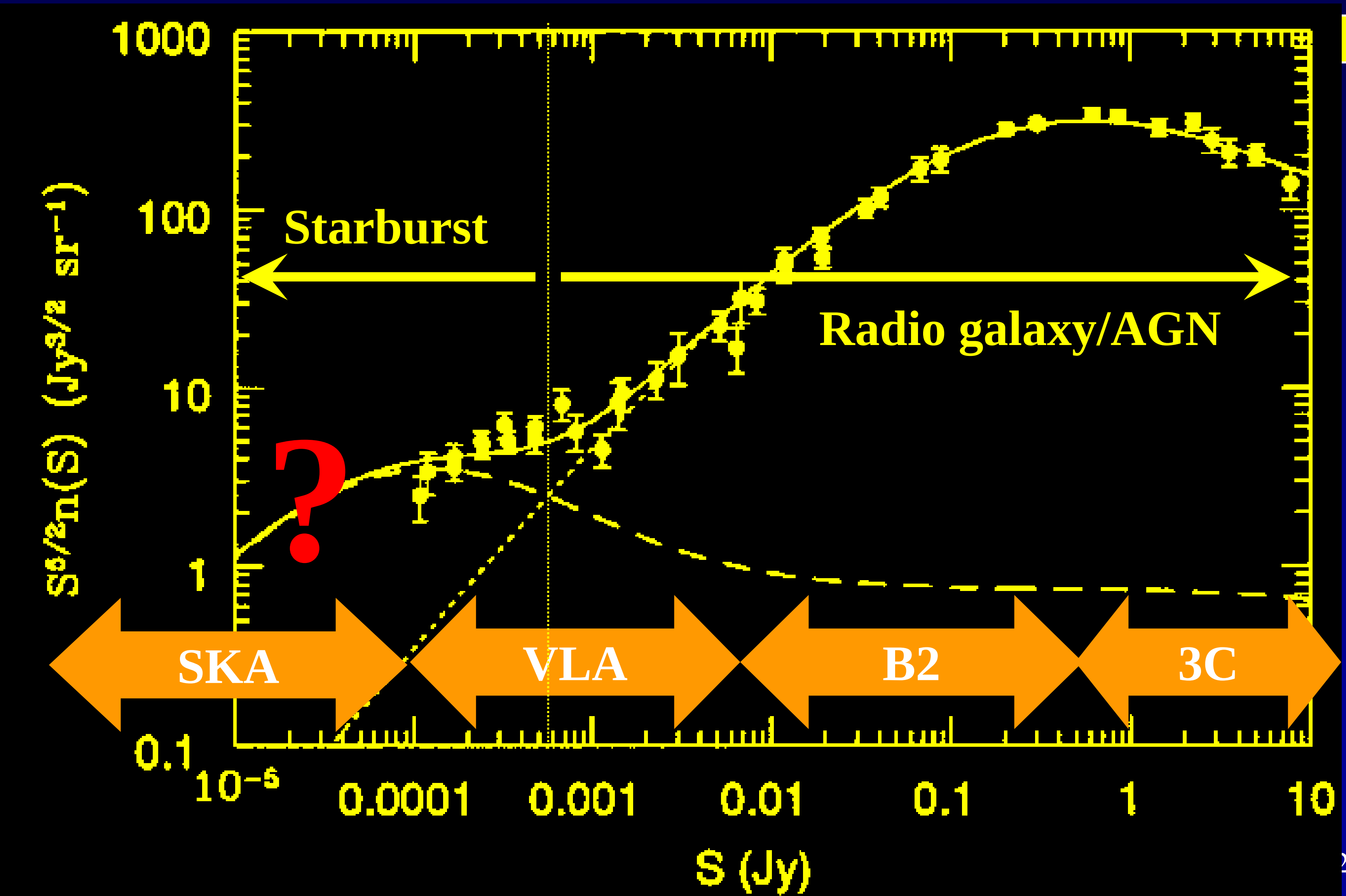


- SETI Institute
  UC Berkeley
  100m equivalent
  350 x 6.1 m parabolas
  0.5-11 GHz (simultaneously)
  2.5^{o} FOV at 1.4 GHz
  4 simultaneous beams
  Complete 2005

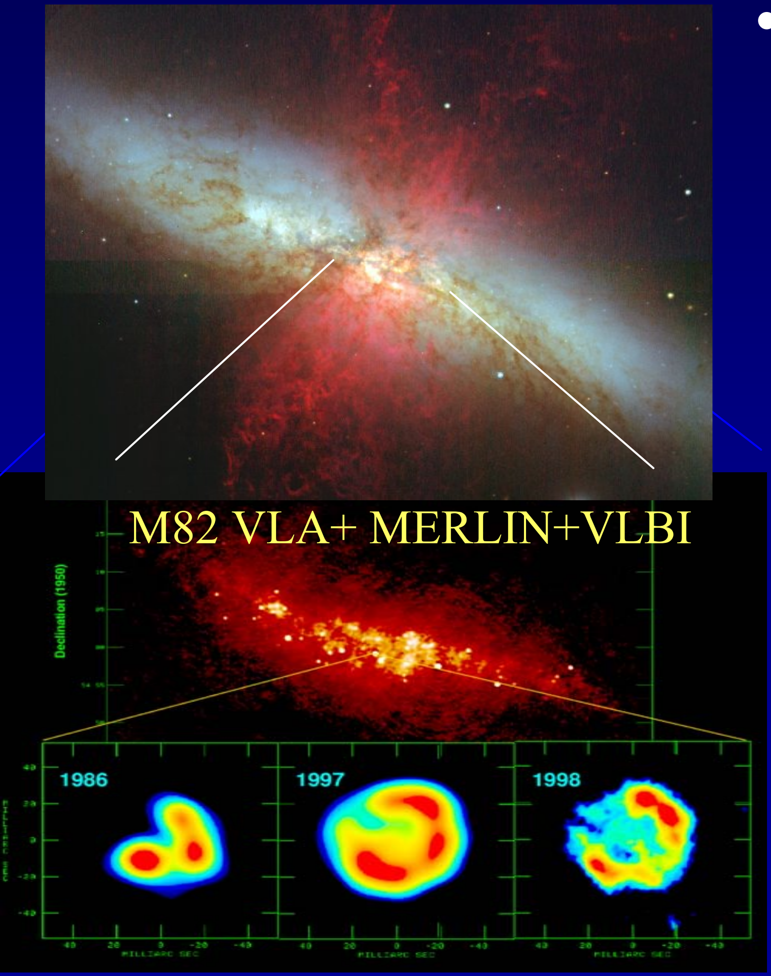
Future Sensitivity



Radio Source Counts



Evolution of star formation rates

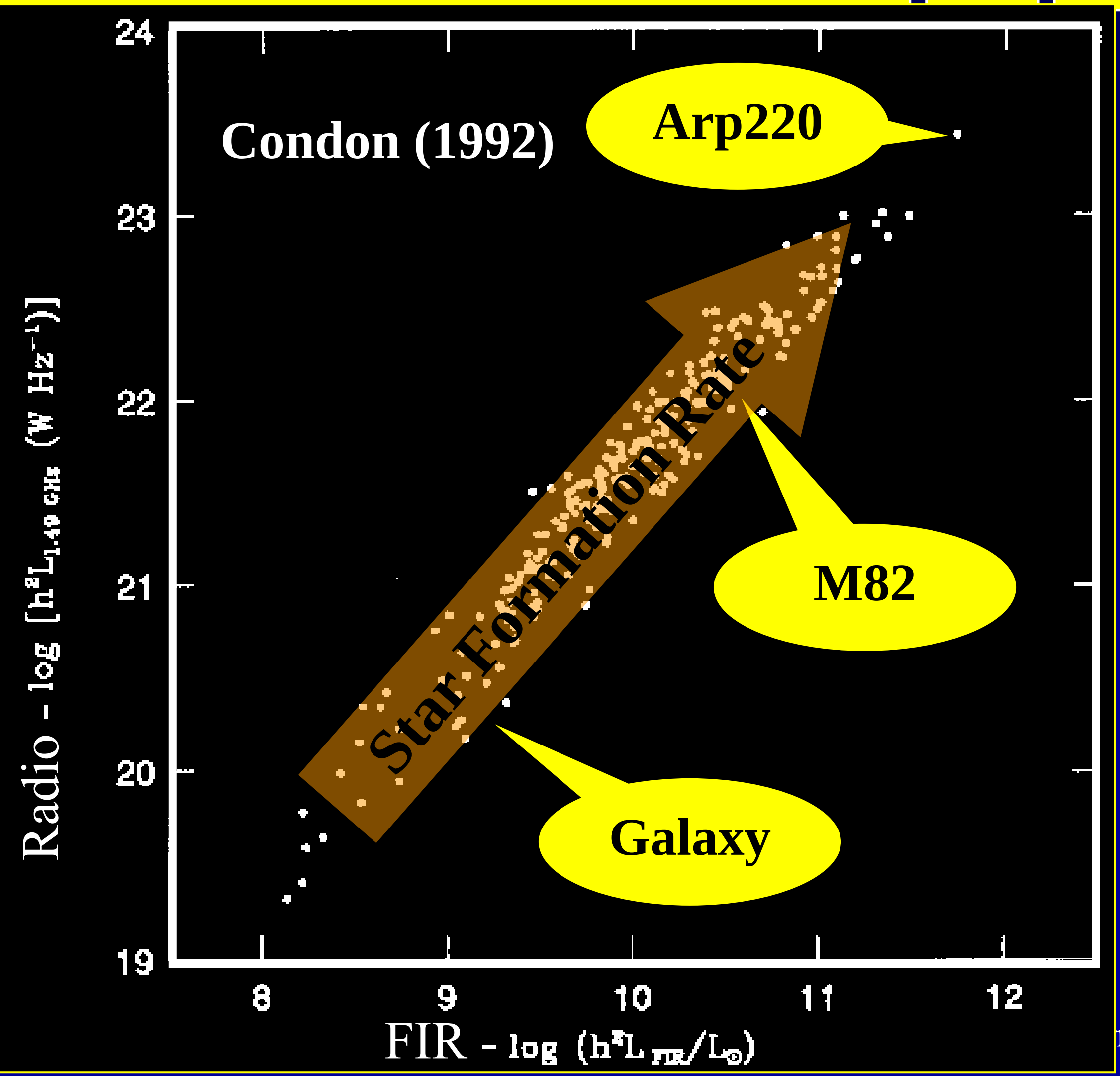


M82 VLA+ MERLIN+VLBI

- Starburst galaxies e.g. M82
  - Radio reveals starburst region <u>through dust</u>
  - VLBI resolves expanding supernovae
  - Infer star birth rate from death rate more directly than other means
  - Calibrate integrated radio continuum → SFR at high z

SKA can do this at any redshift → Cosmological history of star formation

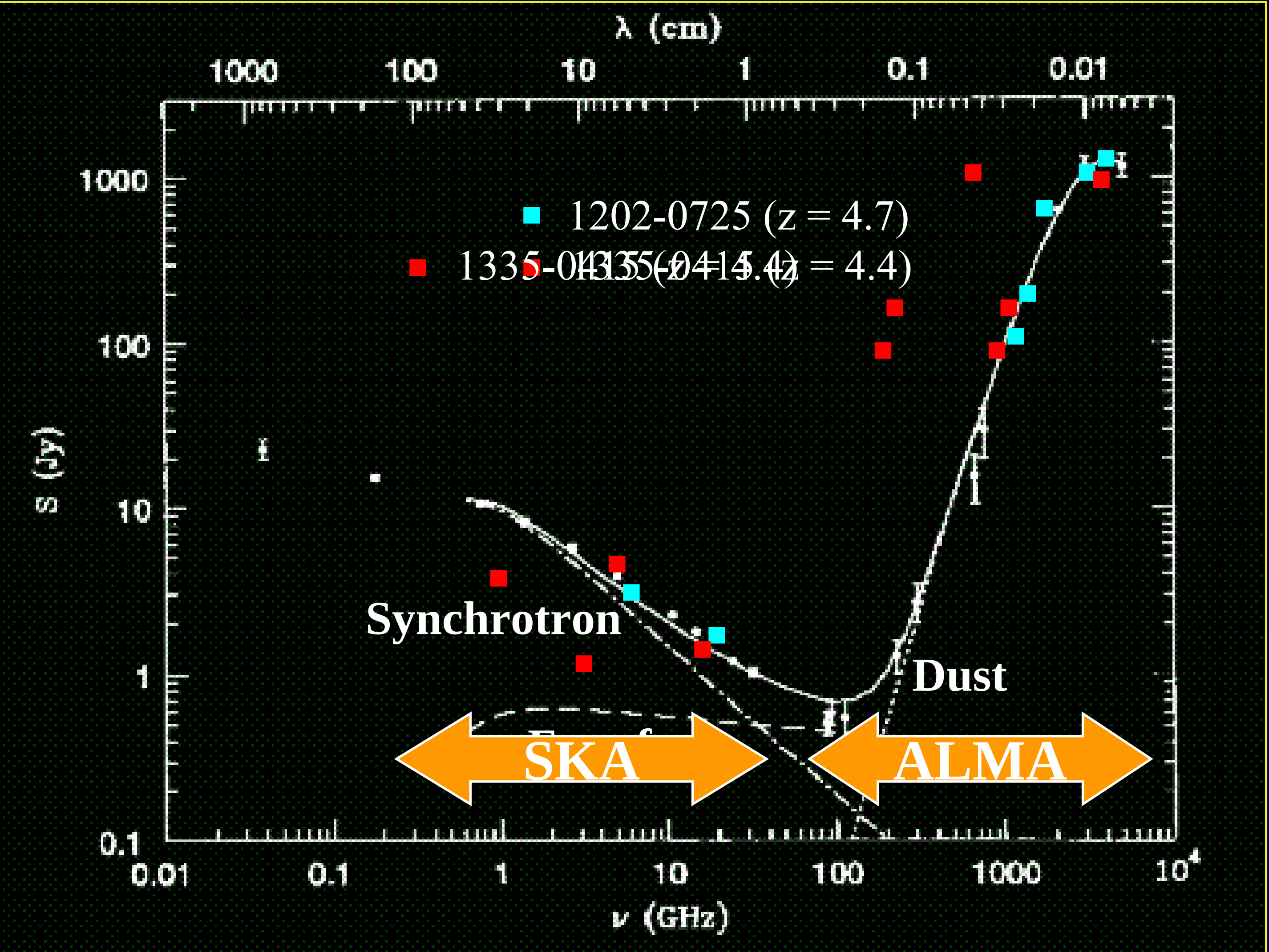
Far Infra-Red v Radio Continuum correlation



- Dickey & Salpeter (1984)
  - Discovered while searching for cluster HI
- Condon

  Ann Rev. 30: 576-611 (1992)
- Linear correlation over a luminosity range of 10^4
- Radio continuum is the best known measure of starformation rate
- SKA can reach z = 4

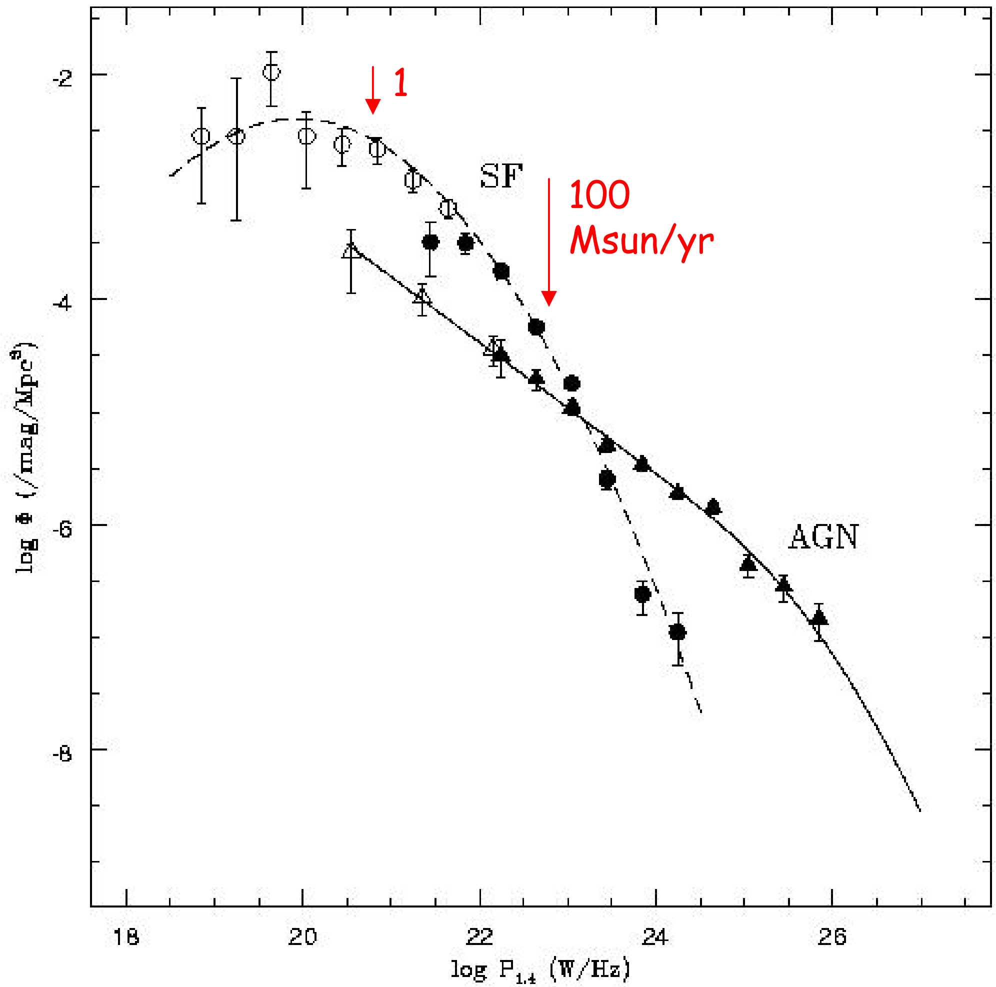
Radiometric Redshifts



M82 Spectrum
Condon *Ann Rev.* 30: 576-611 (1992)

Radiometric redshifts
Carilli
Ap J 513 (1999)

Local radio luminosity function of active and star-forming galaxies



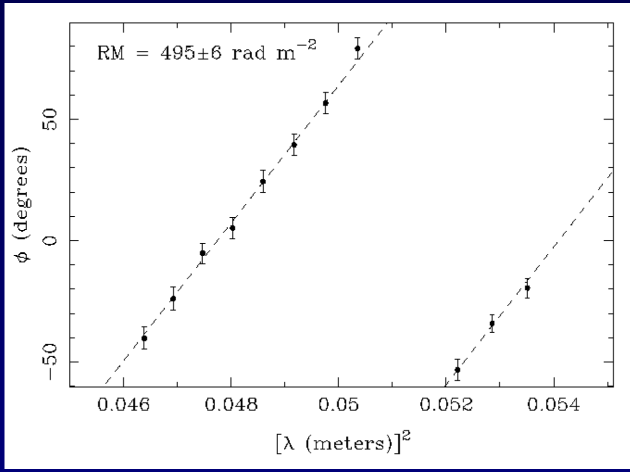
Below 10^{25} W/Hz, the local radio source population is **always** a mixture of AGN and star-forming galaxies.

i.e. There is probably **no** observational regime where radio surveys detect only star-forming galaxies.

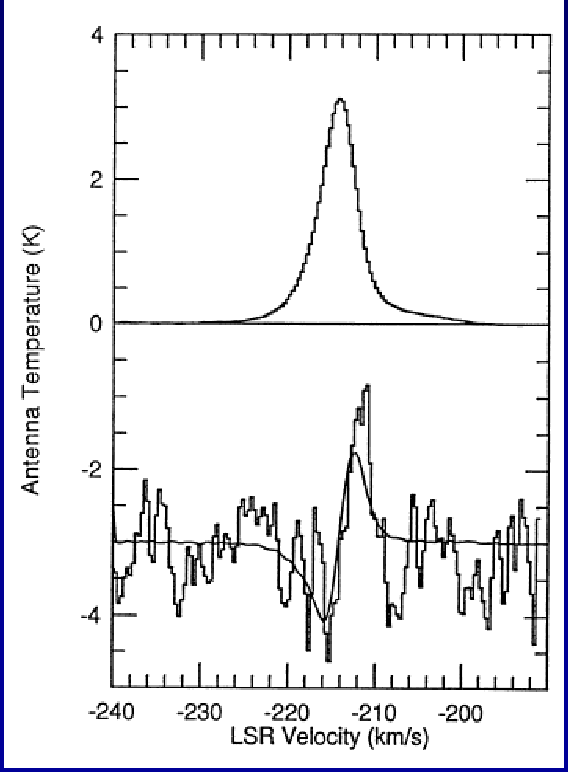
Magnetism and Radio Astronomy

Most of what we know about cosmic magnetism is from radio waves!

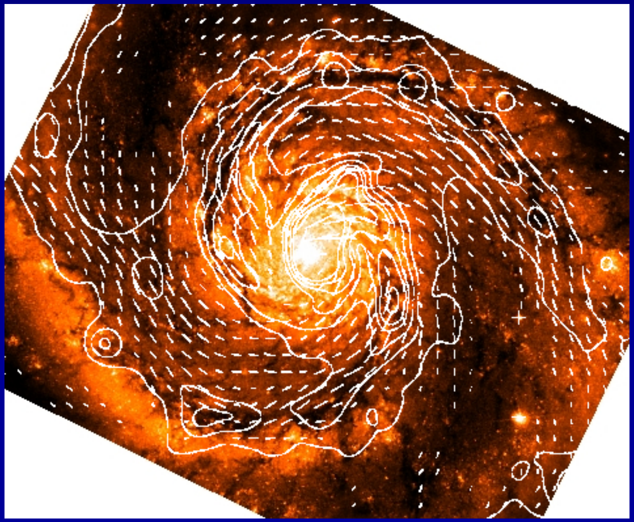
- Faraday rotation → $\langle B_{||} \rangle$
- Synchrotron emission → orientation, $|B_{\perp}|$
- Zeeman splitting → $B_{||}$



Gaensler et al (1998)



Kazès et al (1991)

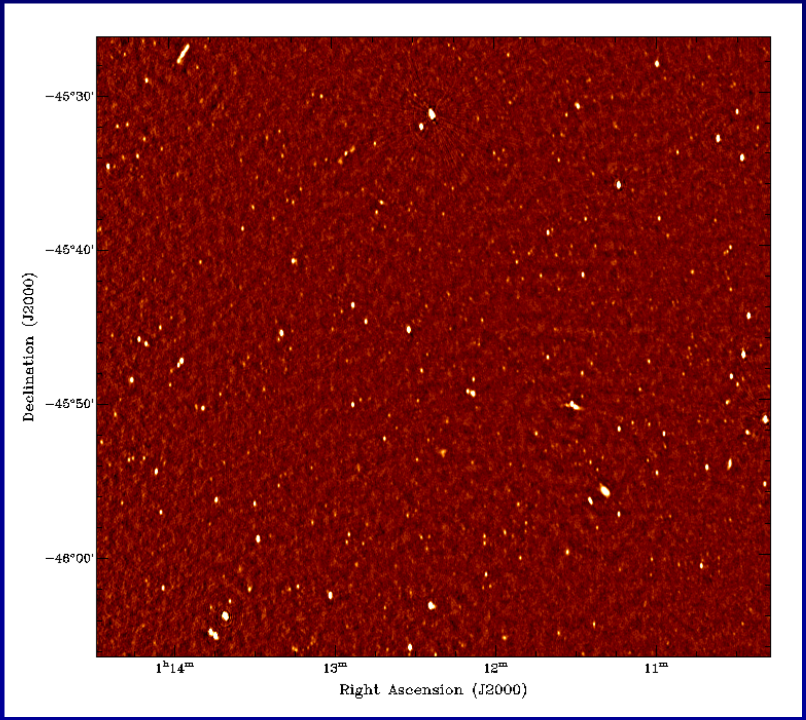


Fletcher & Beck (2004)

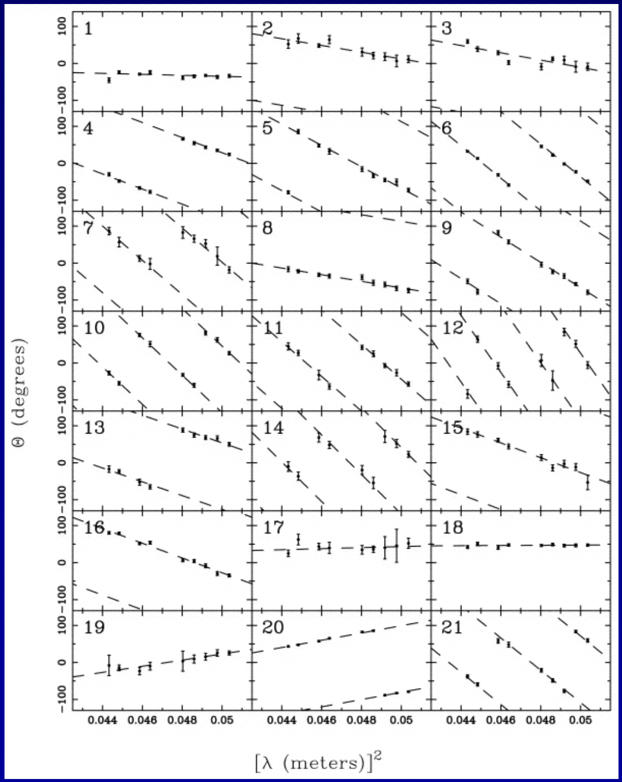
An All-Sky RM Survey with SKA

- Image the entire sky to $\sigma \approx 0.1$ μJy at 1.4 GHz ("SKA FIRST")
- One hour per pointing; for FOV = 1 deg^2, total time = 1 year
- If $\langle p \rangle = 5\%$, then 10σ detection of polarization for I = 20 μJy

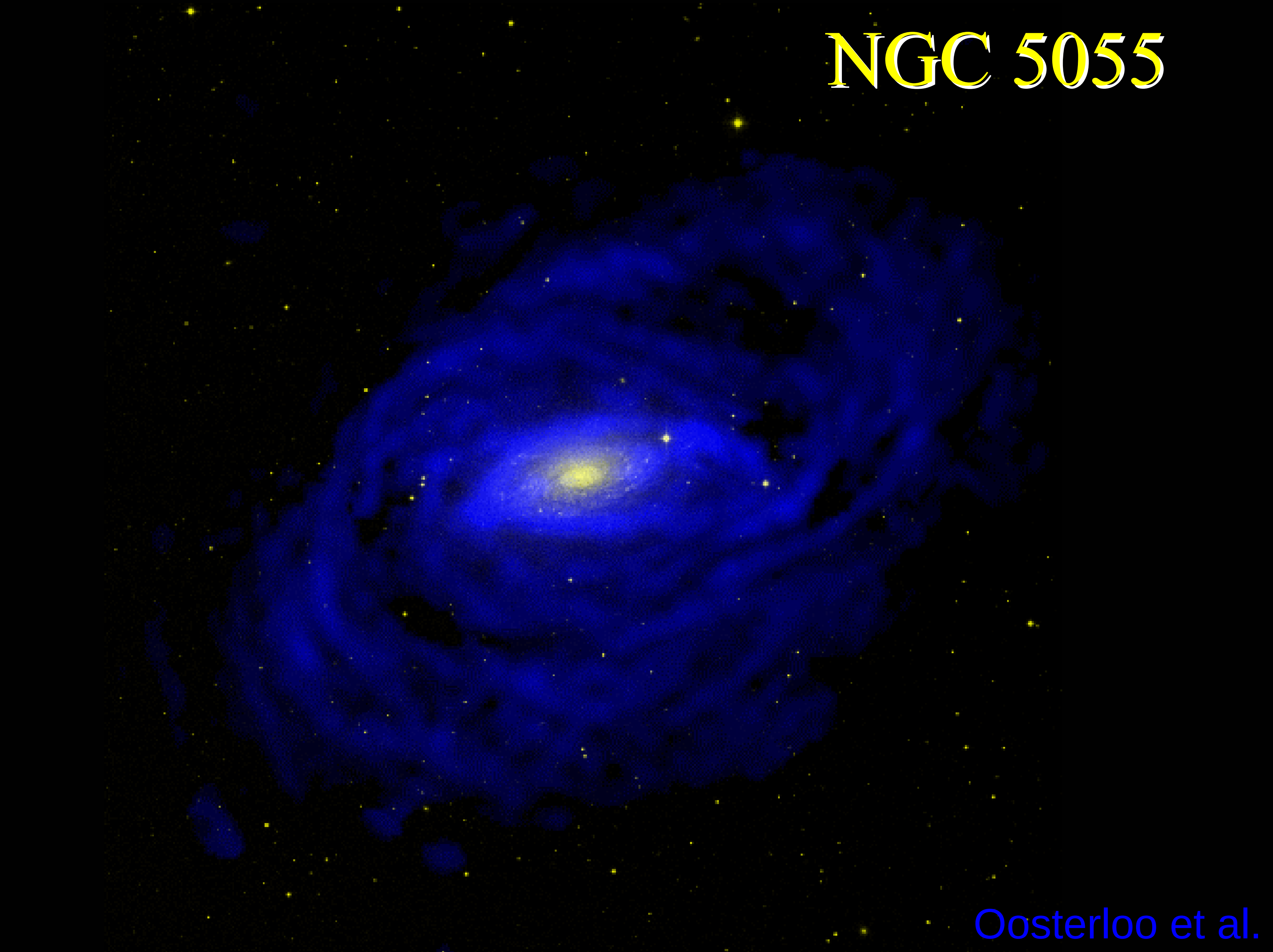
→ ~ (1–5) x 10^8 x-gal sources with RMs, spaced by ~ 30"–50" on the sky!
(plus thousands of pulsar RMs also)



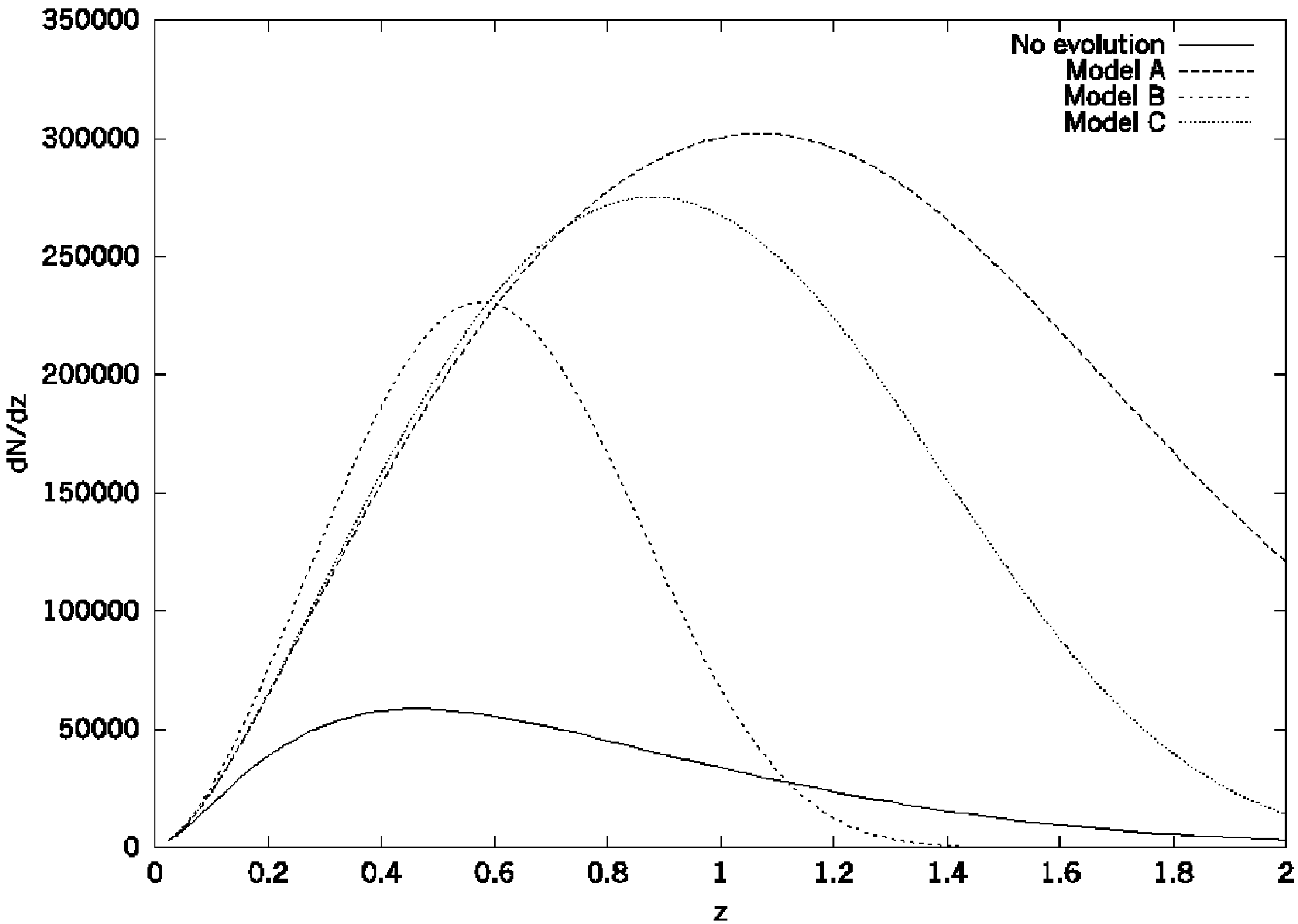
Phoenix Deep Field (Hopkins et al 2003)



SGPS RMs (Gaensler et al 2001)


NGC 5055
Oosterloo et al.

What will the SKA see? Part II

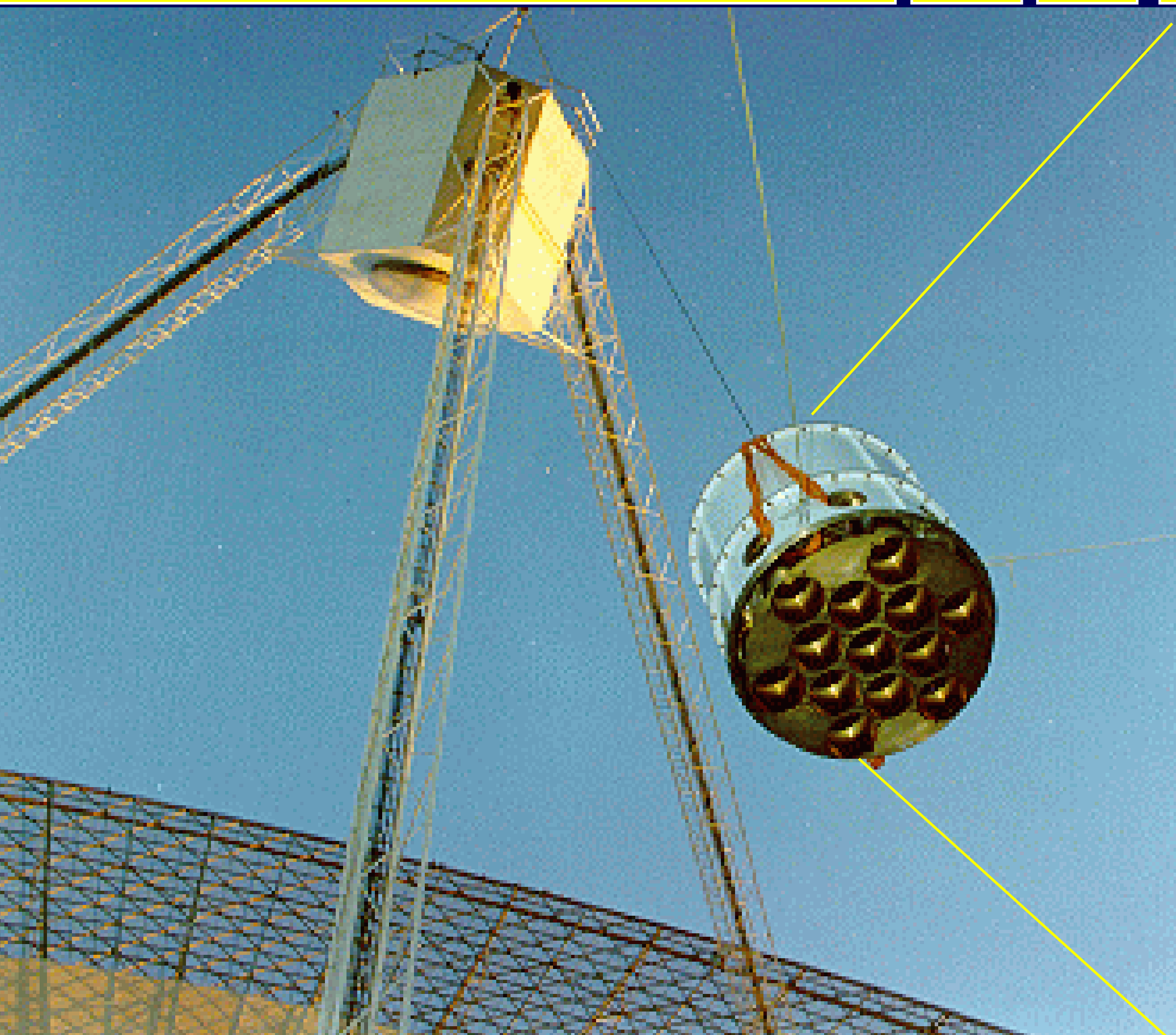


In 24 hours ~10^5 HI galaxies in a 1 deg FOV (@1.4 GHz) over several independent redshift bins.

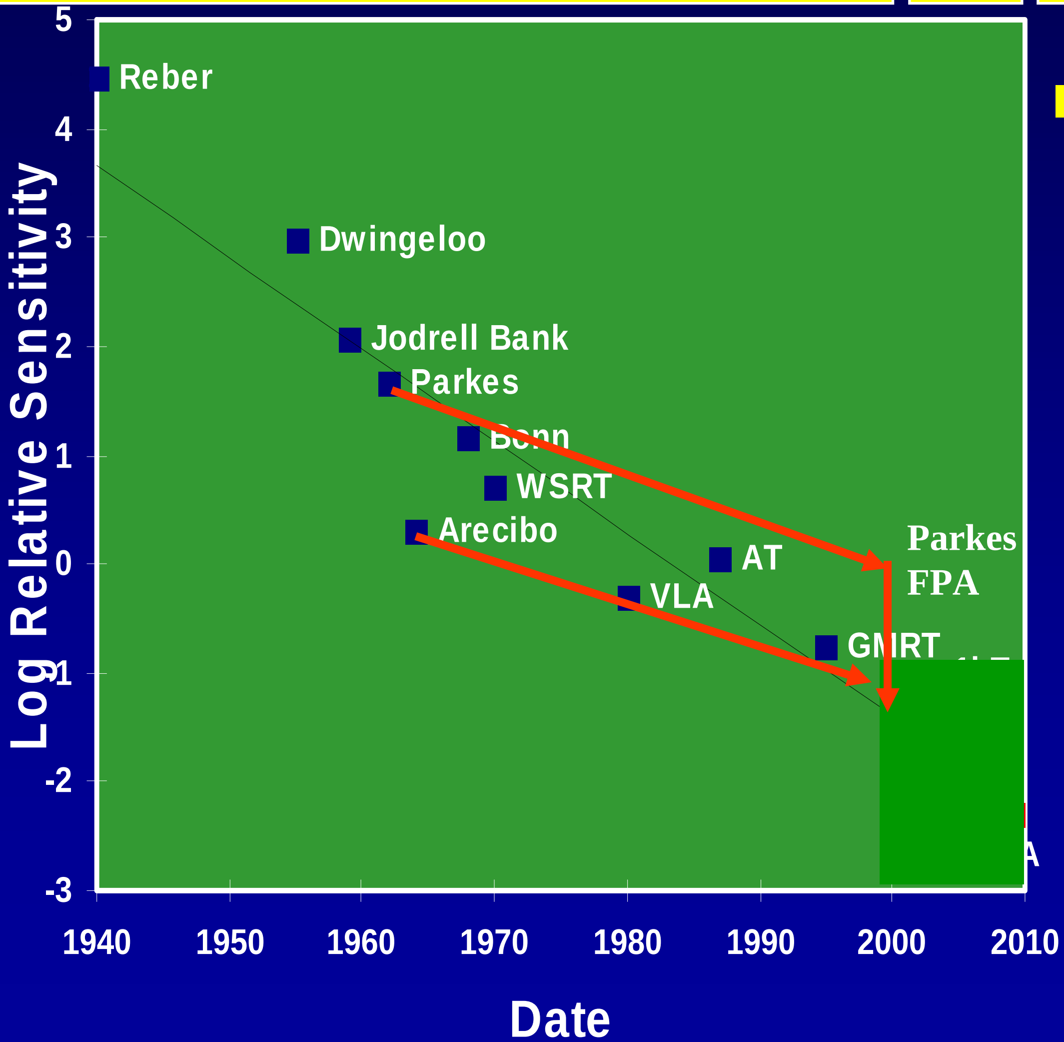
Abdalla & Rawlings 2003

Field of View

Installing the Parkes 21cm Multibeam Receiver



Radio Telescope Sensitivity



- Exponential increase in sensitivity x 10^5 since 1940 !
- Upgrades can't sustain an exponential increase
  - Eg Arecibo upgrade
  - Parkes upgrade
  - Exponential growth needs new technology
  - Eg effect of Parkes FPA

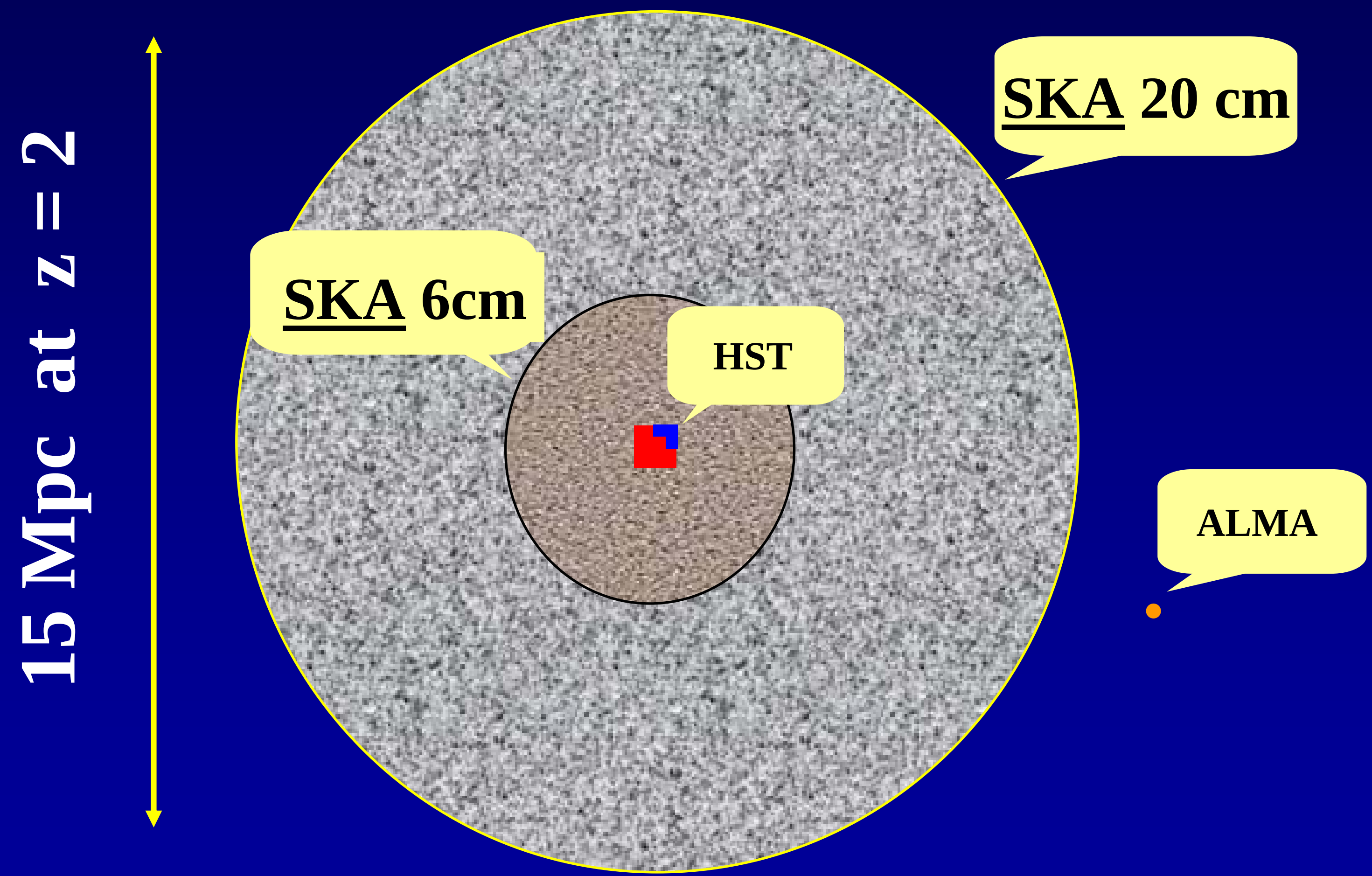
Arecibo upgraded

Arecibo Multibeam
ALFA

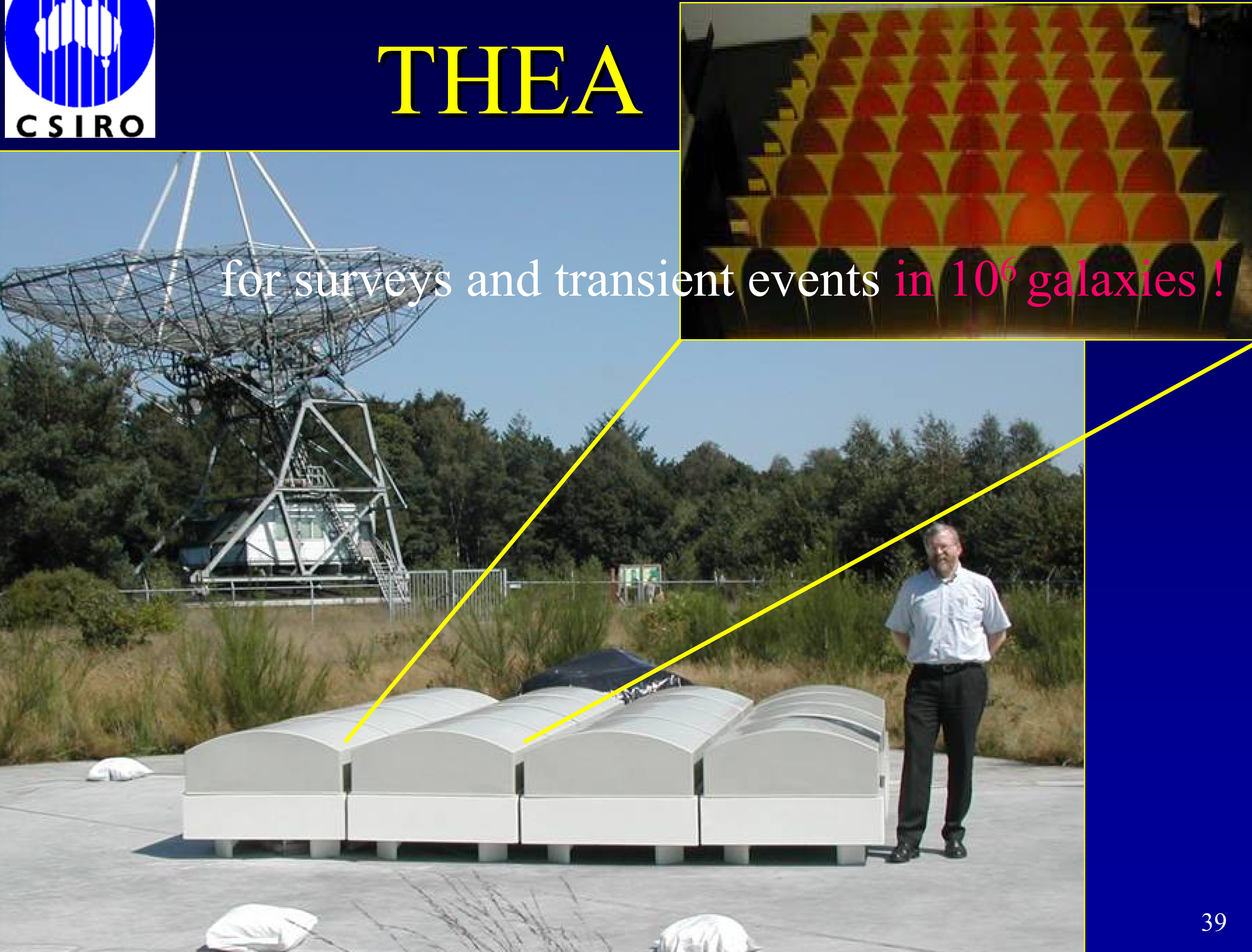
GBT

- Penn Bolometer Array
- 3mm
- 64 pixels

SKA's original 1° field-of-view



THEA



for surveys and transient events in 10^6 galaxies !

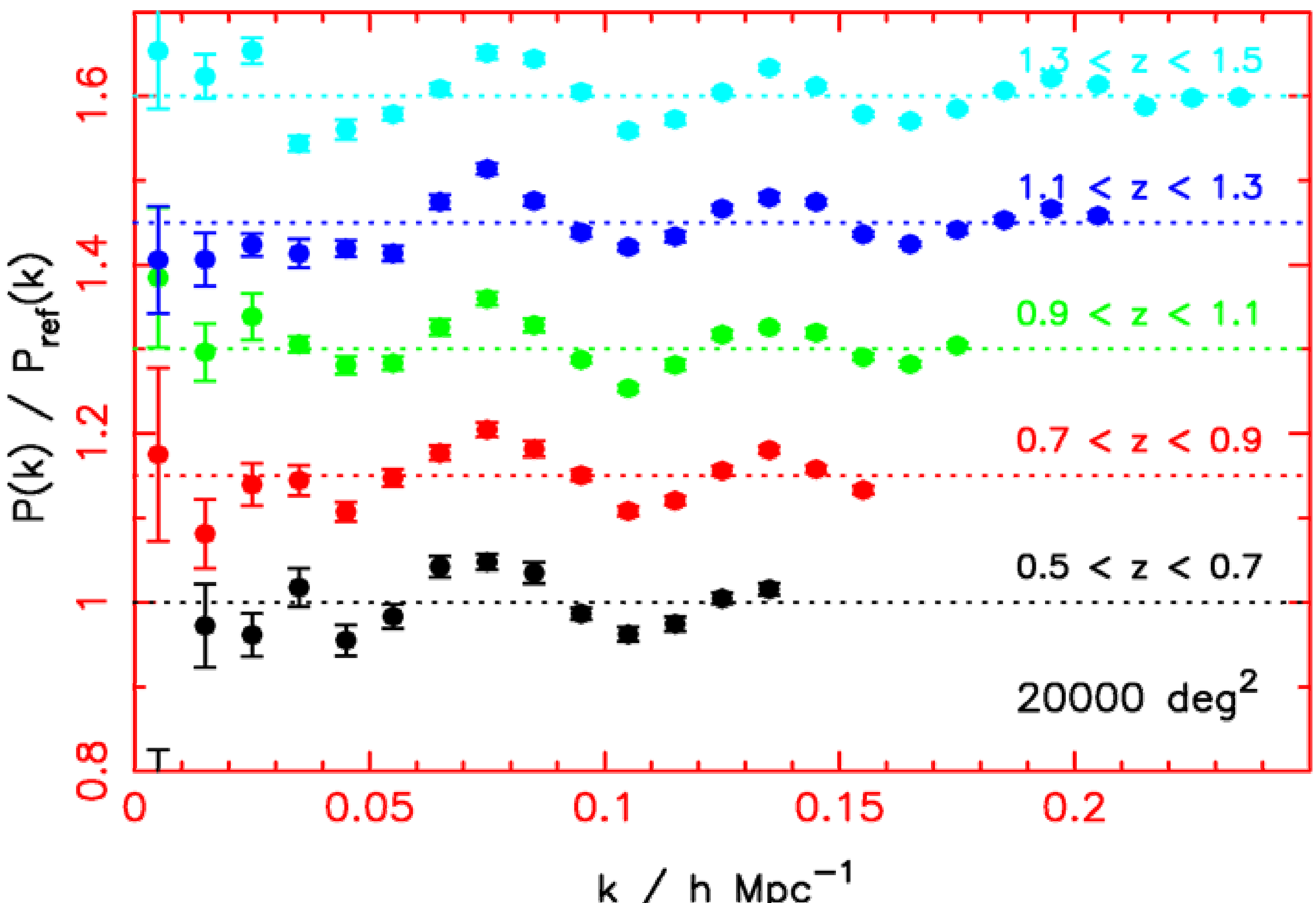
Even More FoV!

- Phased arrays make total FoV a signal processing rather than a physical limitation
- Hence FoV becomes limited only by the cost of the signal transport and processing
  - it can expand with Moore's Law!
  - And this time without software constraints
- Aperture phased arrays are still expensive at higher frequencies
- Phased arrays in the focal plane provide an intermediate solution with lower cost for collecting area
- 100 sq deg at 1GHz is possible now!

Probing Dark Energy

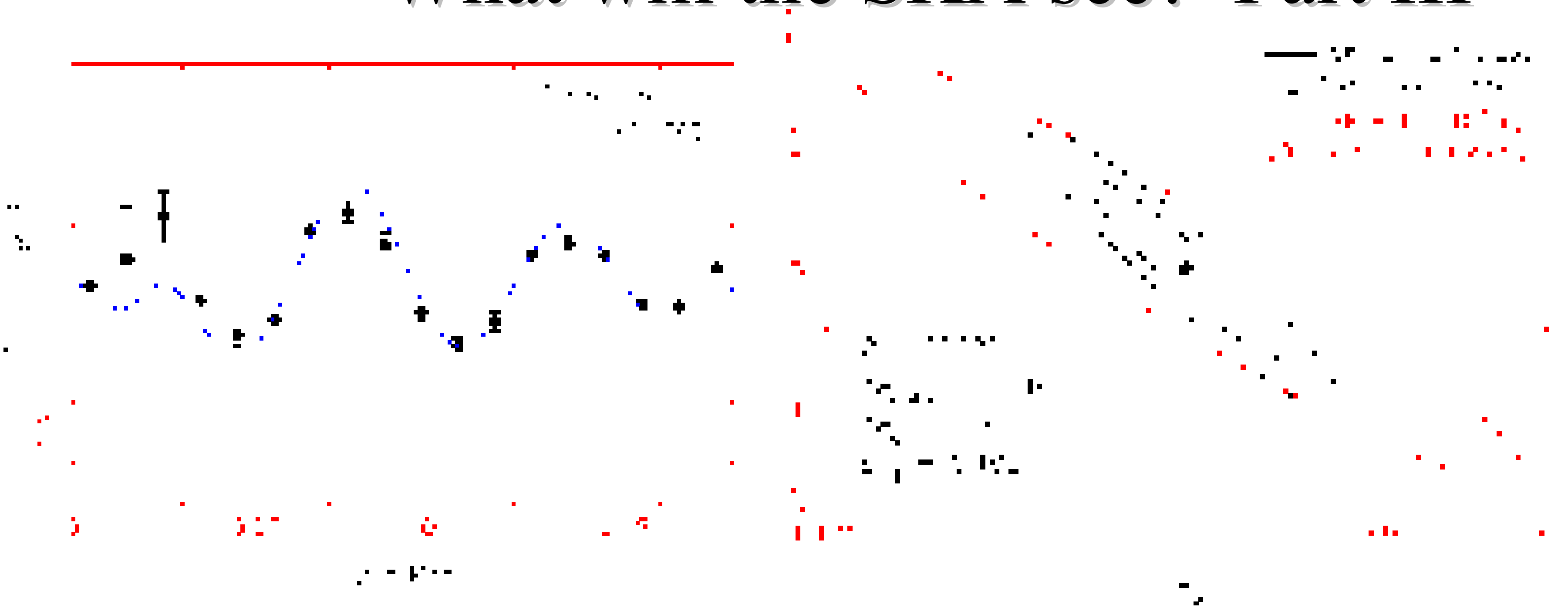
- Standard ruler based on baryonic oscillations (wriggles)
- Need to reach z ~ 1
  - Current limit z = 0.2 so > x25 in sensitivity
- Optimum strategy is the survey the largest area
- Large FoV makes this practical
- 1/10 SKA pathfinder with FoV=100sq deg is competitive
  - See HYFAR poster
- SKA FoV=10 in 1 year
  - 10^9 galaxies, $0 < z < 1.5$ $\Delta\omega = 0.01$
- Uncertainty because we don't know HI evolution

Dark energy wiggles



Abdalla, Blake, Glazebrook & Rawlings (2003)

What will the SKA see? Part III

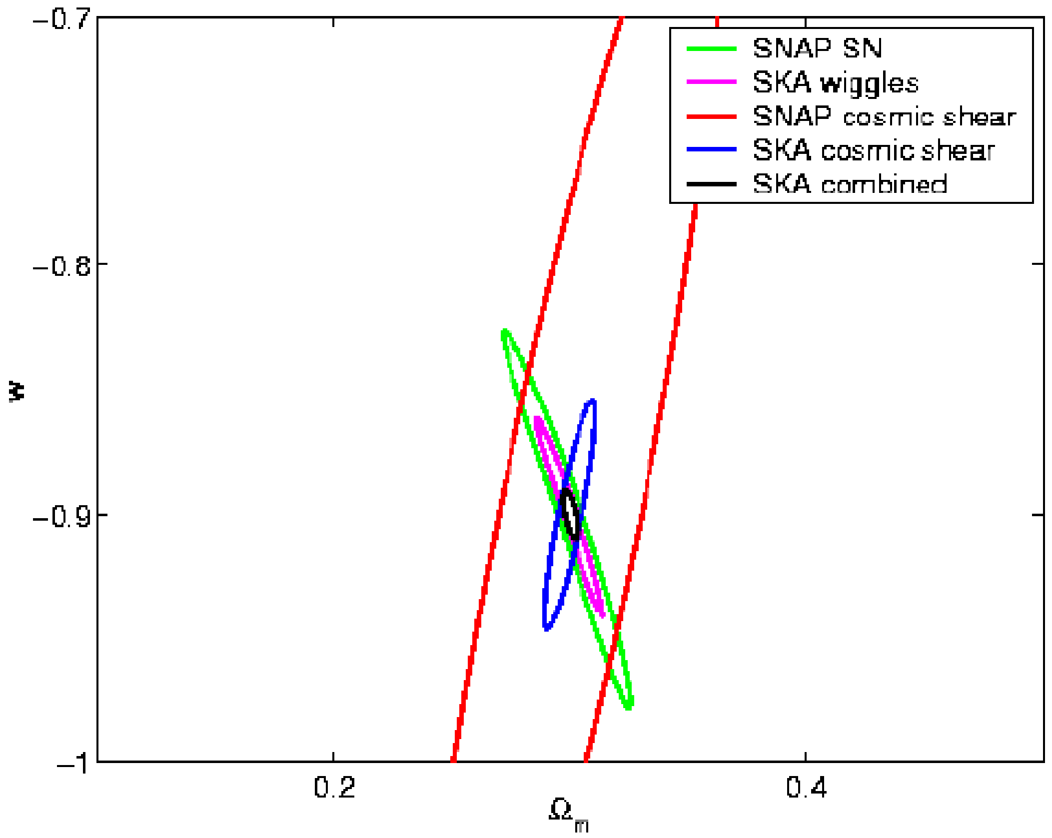


Assumes SKA with 10 deg^2 and shared beams

4000 deg^2 + $w(z) = w_0 + w_1 z$ with delta $w_1 = 0.3$ in ~2 months

`all sky' (right panel) ~1yrs

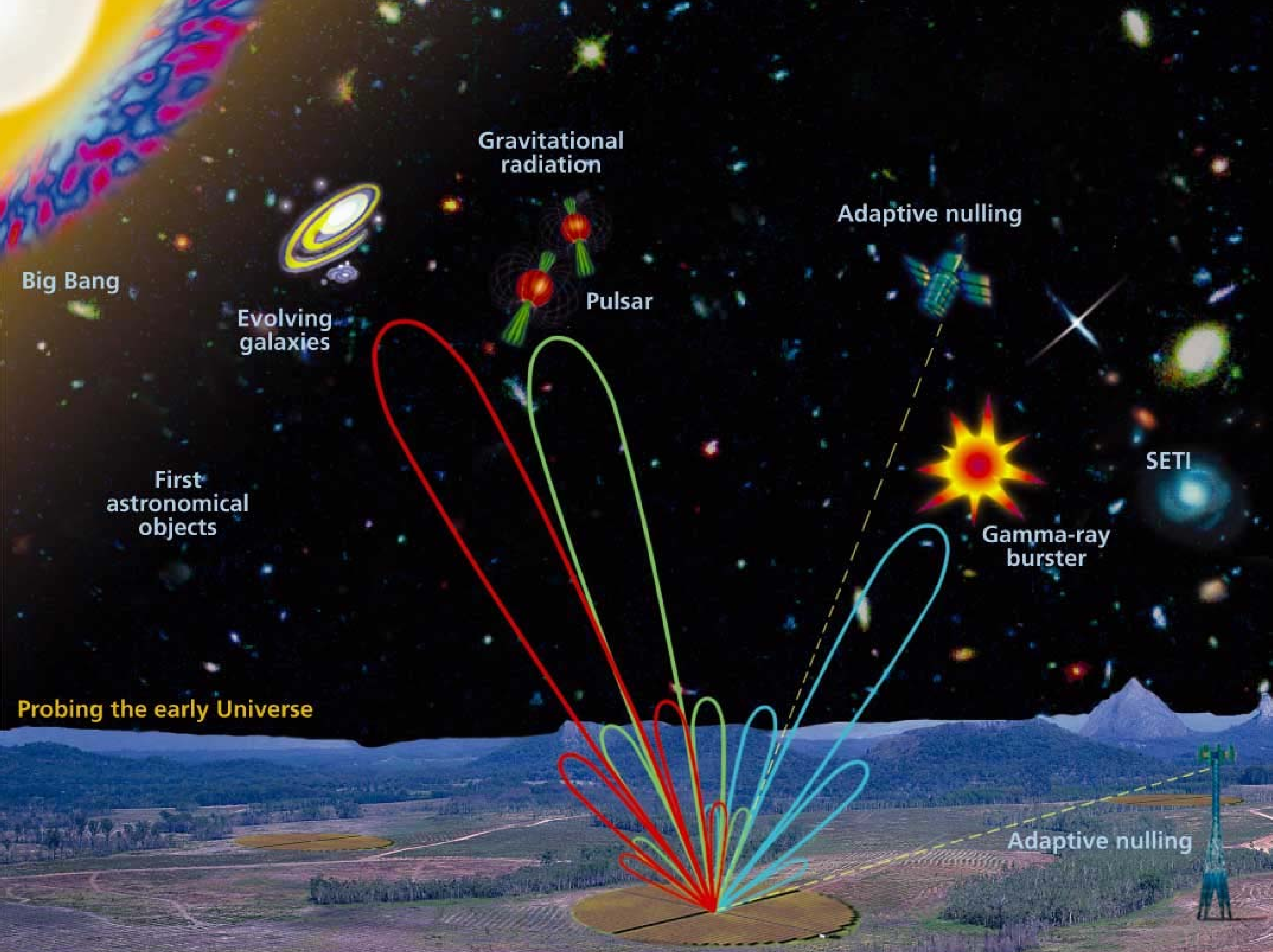
Omega – W plane



Conclusions

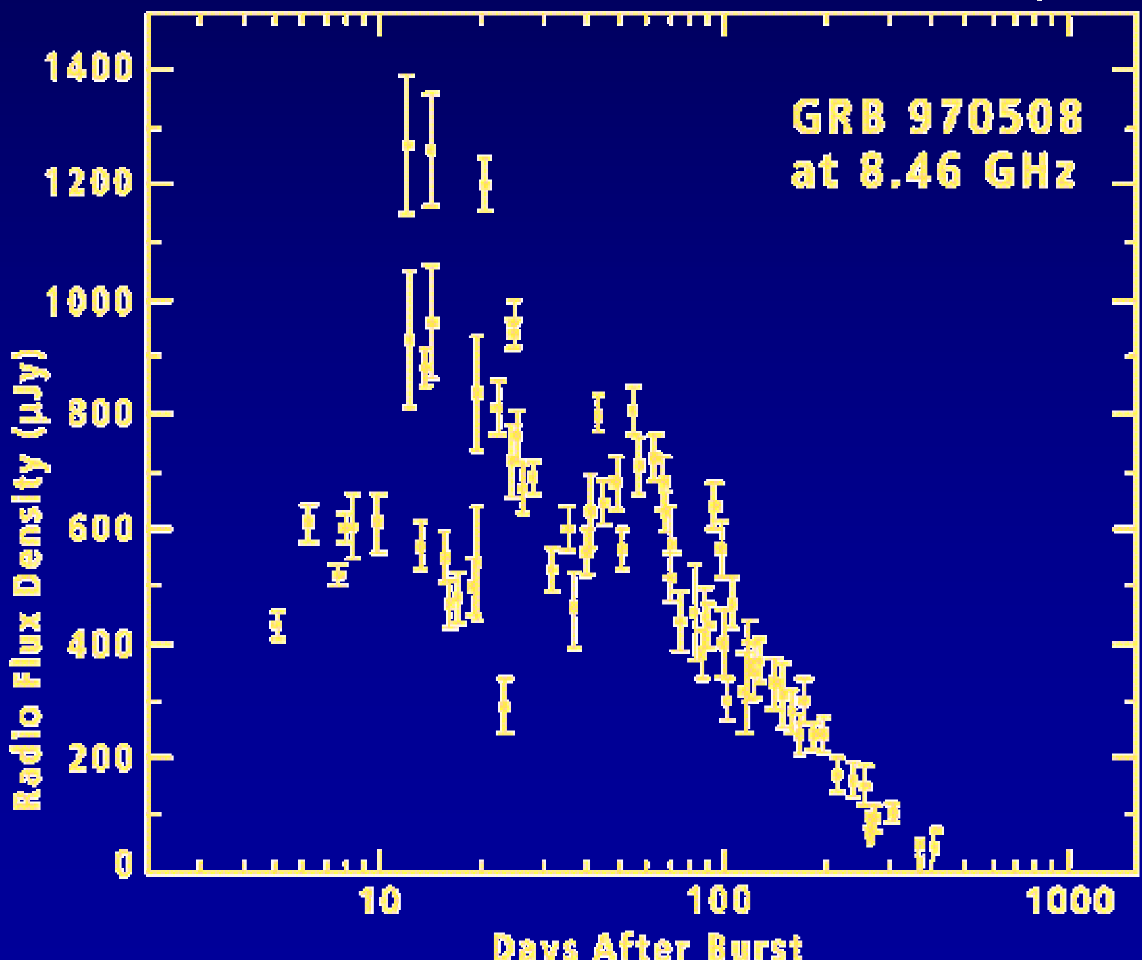
- By 2020, SKA could TOTALLY DOMINATE LSS measurements, locating in 3D `all' ~10^9 galaxies to redshifts ~2.
- This will be the only clean way of measuring LSS on Gpc scales.
- It should determine whether or not Einstein's cosmological constant IS THE DARK ENERGY. It allows unique probes of the INFLATION of the Universe.
- A wide field capability for the SKA is absolutely essential!

Multiple Beams

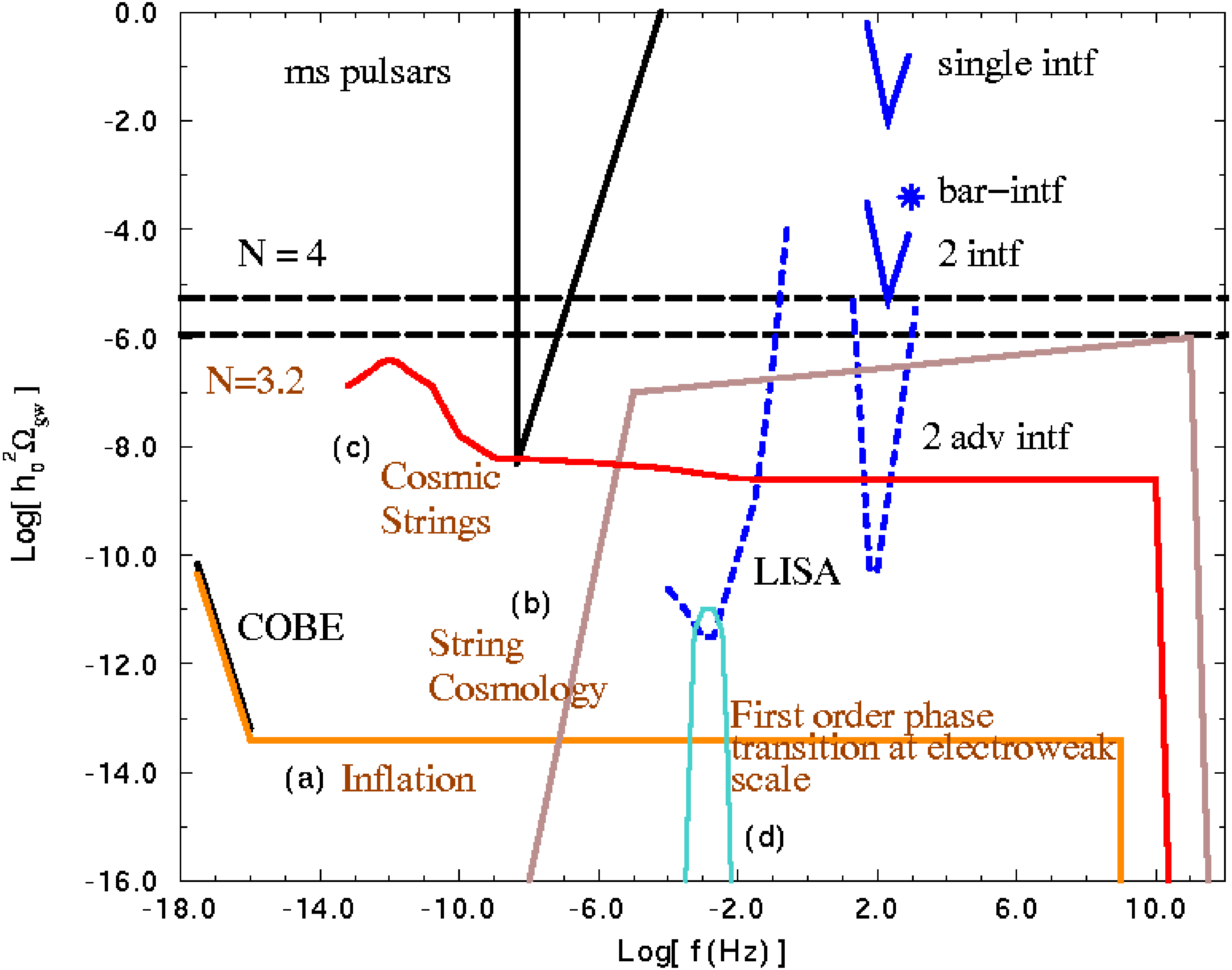


Gravitational radiation
Adaptive nulling
Big Bang
Pulsar
Evolving galaxies
SETI
First astronomical objects
Gamma-ray burster
Probing the early Universe
Adaptive nulling

Interstellar Scintillation



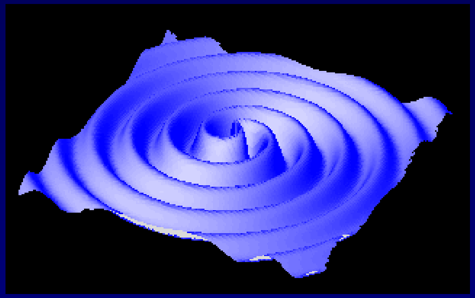
- Frail & Kulkarni
  - VLA 8GHz
  - Scintillates if $\theta < 10$ μas
  - Calibrate of field SNR's
- Only 1 GRB strong enough in 4 years
  - Many days integration

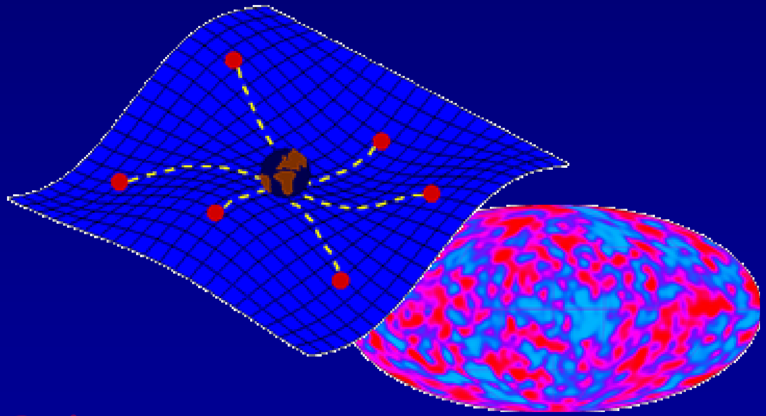


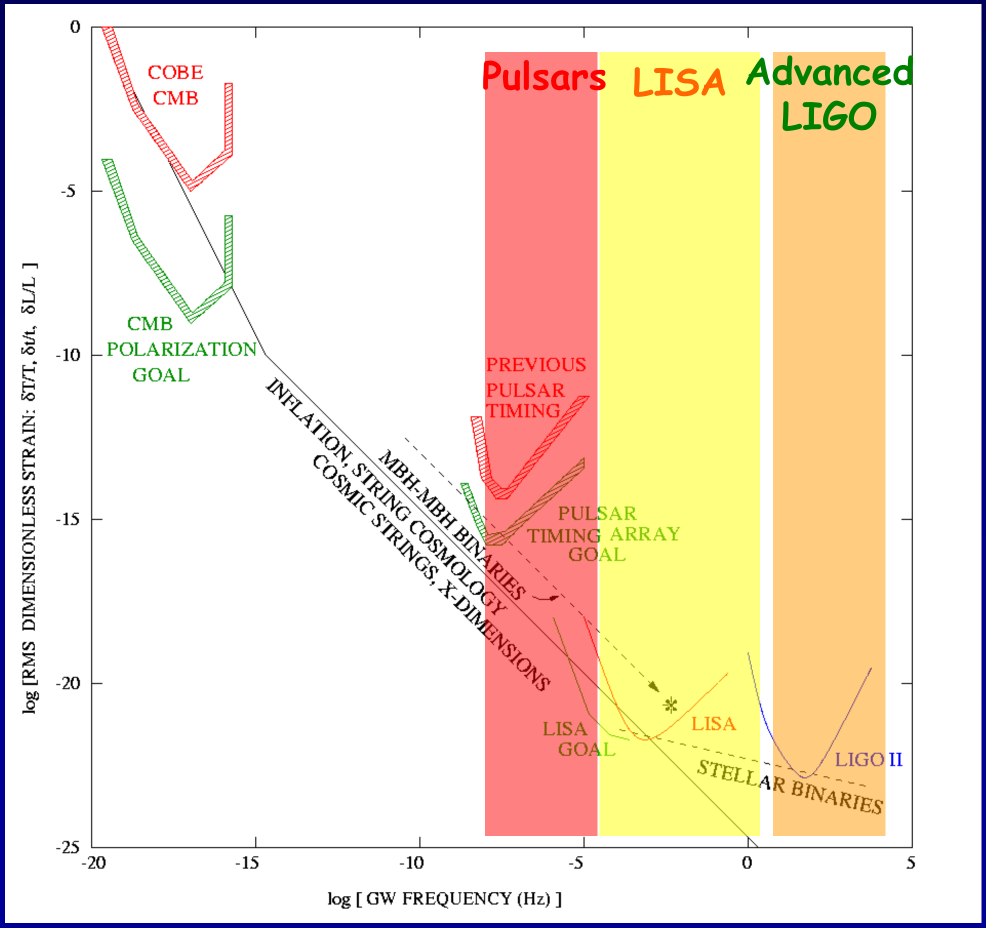
0.0
-2.0
-4.0
-6.0
-8.0
-10.0
-12.0
-14.0
-16.0
Log[$h_0^2 \Omega_{gw}$]
-18.0
-14.0
-10.0
-6.0
-2.0
2.0
6.0
10.0
Log[f (Hz)]
ms pulsars
single intf
bar−intf
2 intf
N = 4
N=3.2
2 adv intf
(c)
Cosmic
Strings
LISA
(b)
COBE
String
Cosmology
First order phase
transition at electroweak
scale
(a) Inflation
(d)

Cosmological Gravitational Wave Background

- Millisecond pulsars act as arms of huge detector:







Pulsar Timing Array:
Look for global spatial pattern in timing residuals!

- Complementary in Frequency!

Surprising Science

- Searching for redshifted CO
  - Session SM3 Friday July 5
- S-Z at cm wavelengths
  - Use longer spacings and spectrum to remove non-thermal foreground sources
- High Energy Neutrinos
  - Lunar Cherenkof at cm wavelengths
- Transients before they happen
  - Baseband buffer

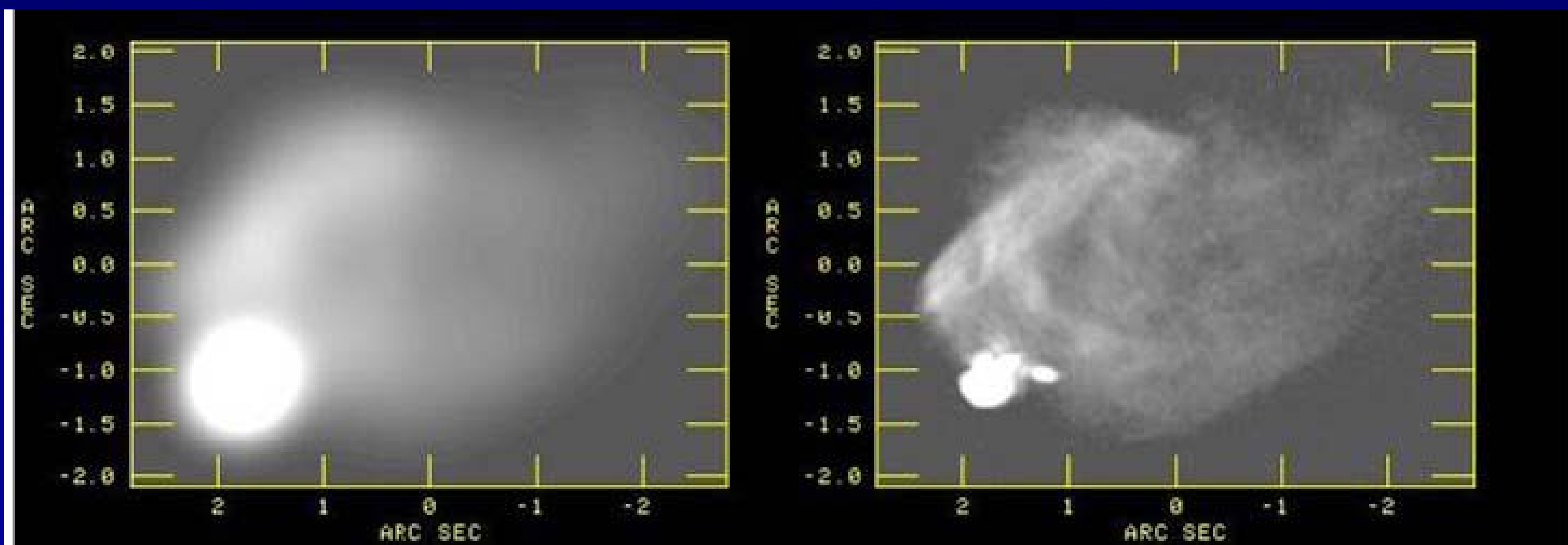
Signal processing

Very High Resolution

- Wide bandwidth communications
- Data storage
- Space VLBI

Cygnus A in the Early Universe: z = 2

The EVLA can resolve details in power radio galaxies at arbitrary redshift.   Shown is Cygnus A at z = 2, at 3 GHz.



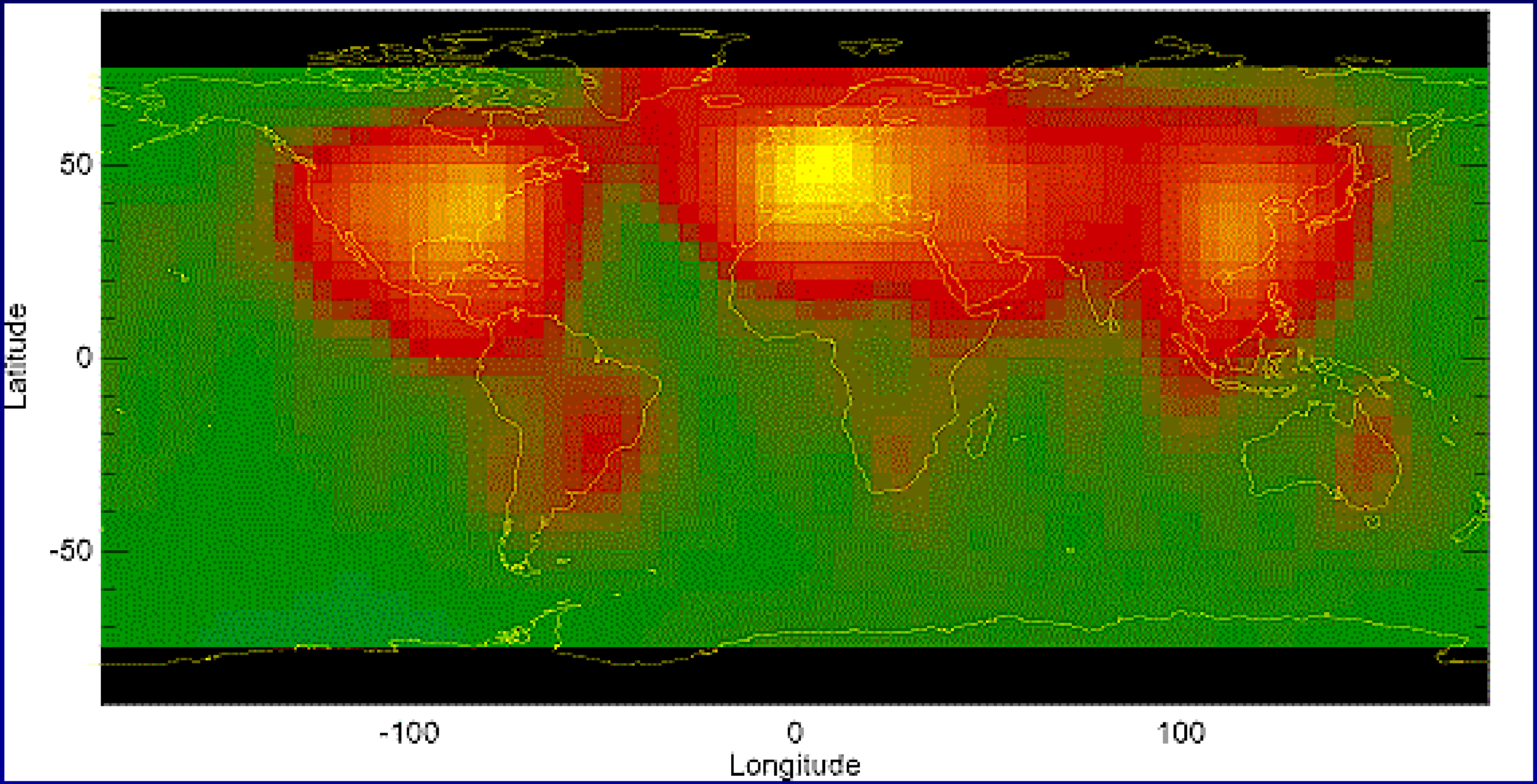
With the VLA only.

With the full EVLA

Interference mitigation

- The FM radio transmission band is at redshift = 10-11
- This is unusable from most places on Earth

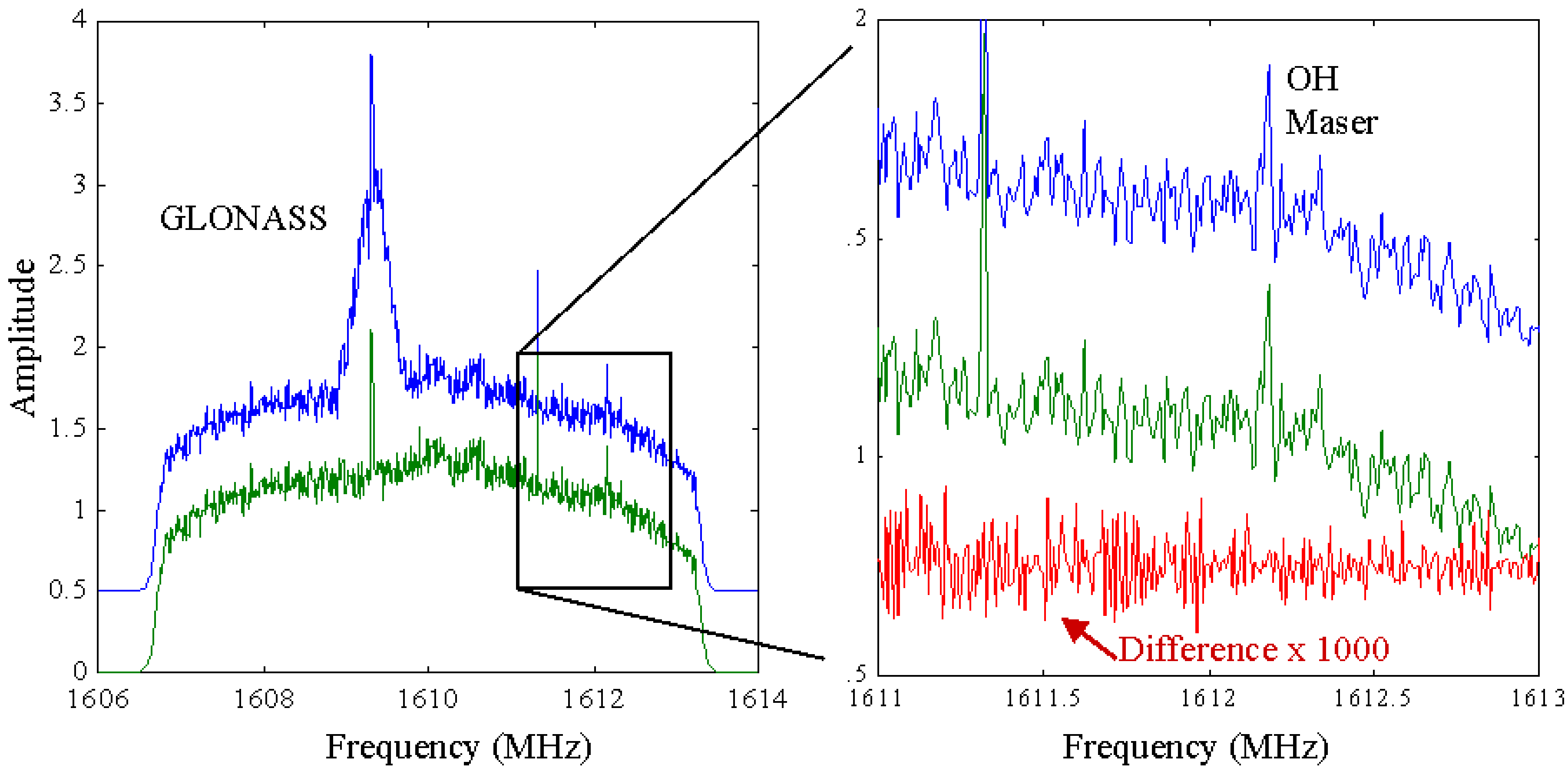
Terrestrial Interference
at z (HI) = 10



FORTÉ satellite: 131 MHz

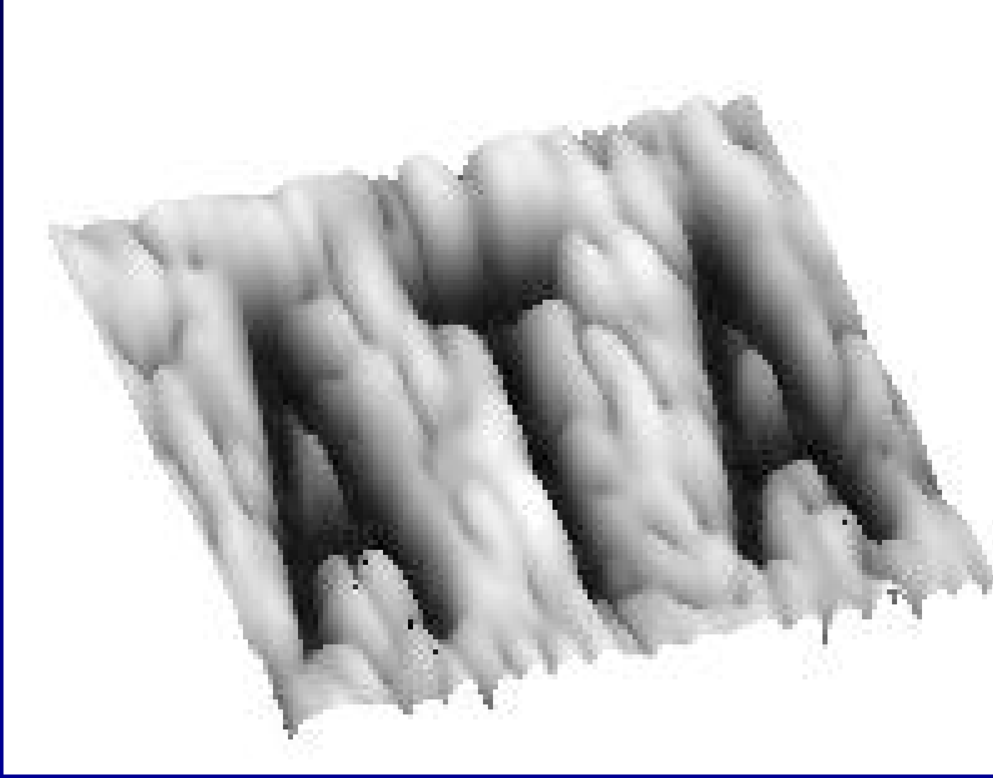
GLONASS signal removed from astronomy data

Data obtained at CSIRO ATCA. Adaptive cancelling algorithm by Steve Ellingson, Ohio. Left plot: top (blue) curve: raw data (raised for clarity), OH maser source @ 1612 MHz, test tones inserted (in software, prior to cancellation) at 1609.3 and 1611.3 MHz. Left plot: lower (green) curve: data with GLONASS removed. Right plot: blow up of region around OH source. The bottom (red) curve shows the difference of the pre and post cancellation spectra multiplied by 1000 (and raised for clarity), indicating that the rest of the spectrum is not changed by more than a few parts in 10000.



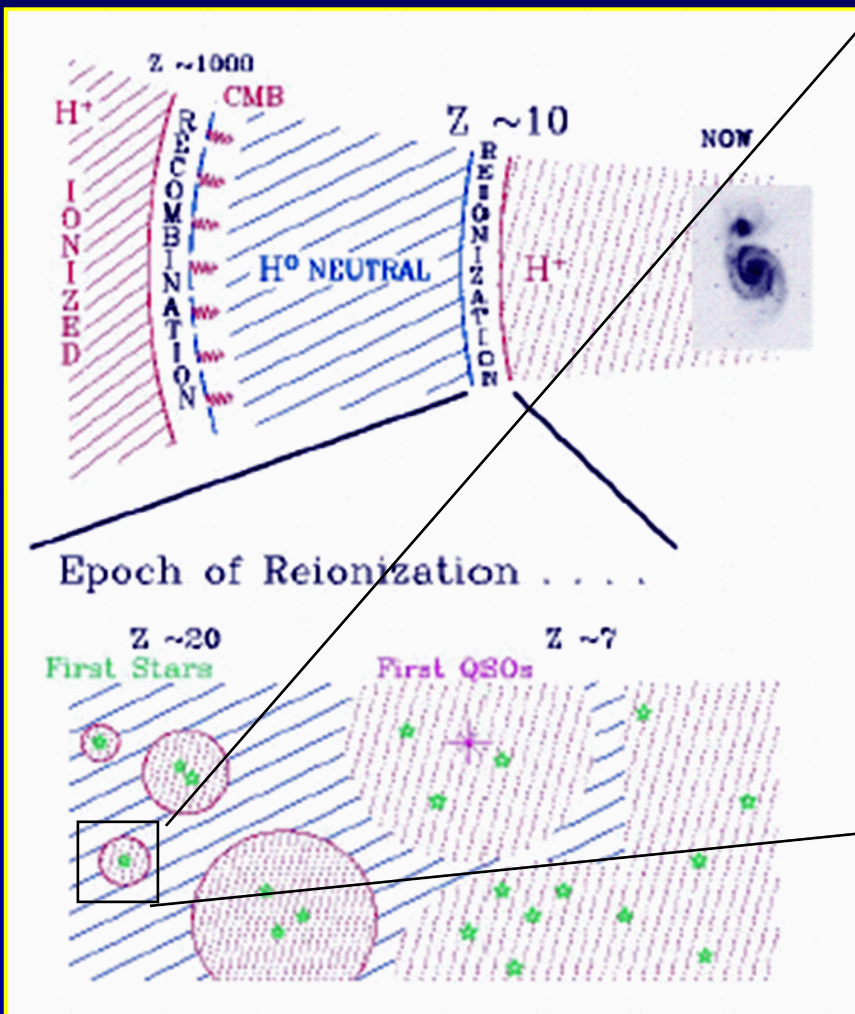
ATA Can Null Out Interfering Satellites

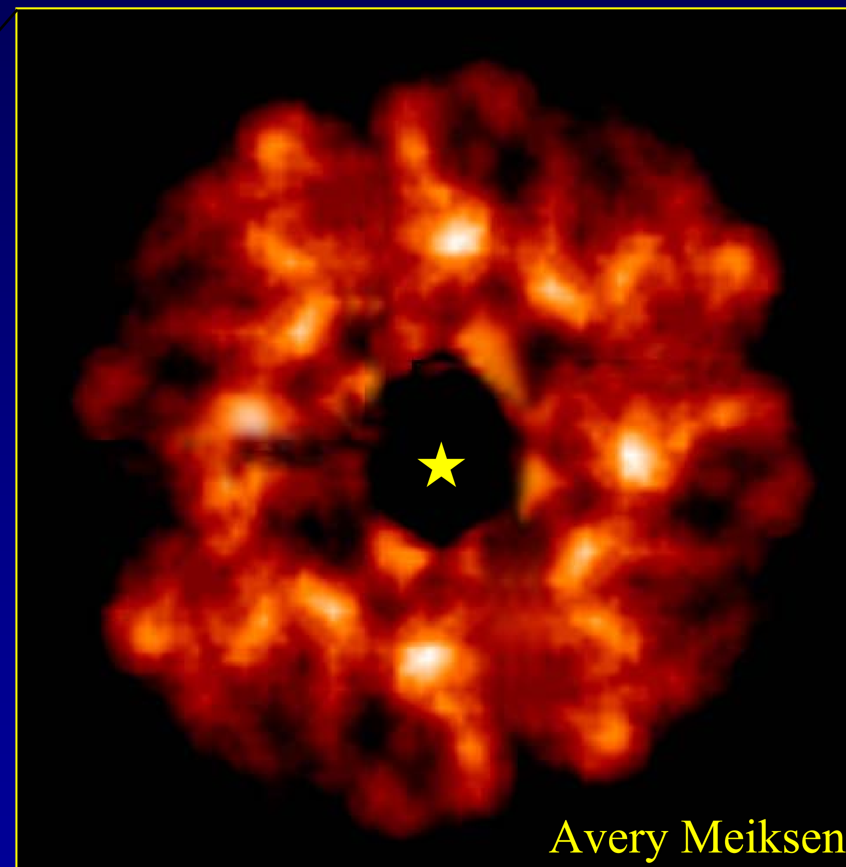
- 350 antennas imply 700 independent degrees of freedom
- Nulls can be created anywhere on the sky
- Nulls can be arbitrarily deep in intensity or broad in frequency
- Nulls can track satellite orbits in real-time



Our own brand of skywriting!

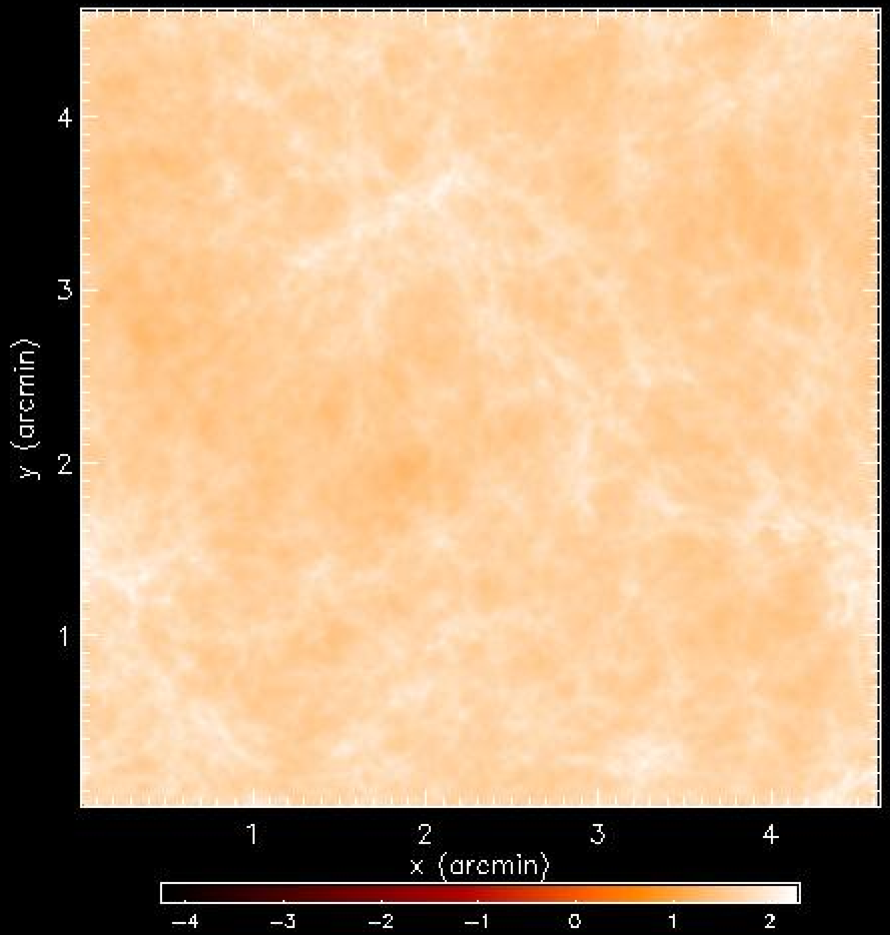
Epoch of reionization





Avery Meiksen

21 cm Observations: Emission



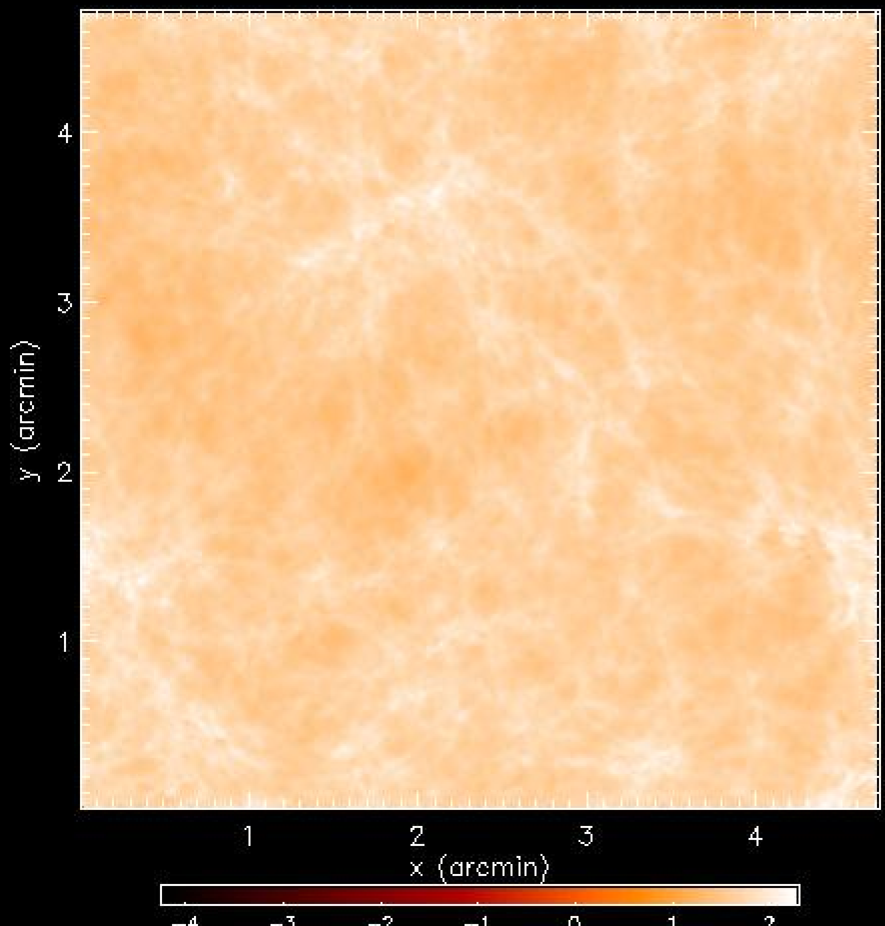
z=18.3

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



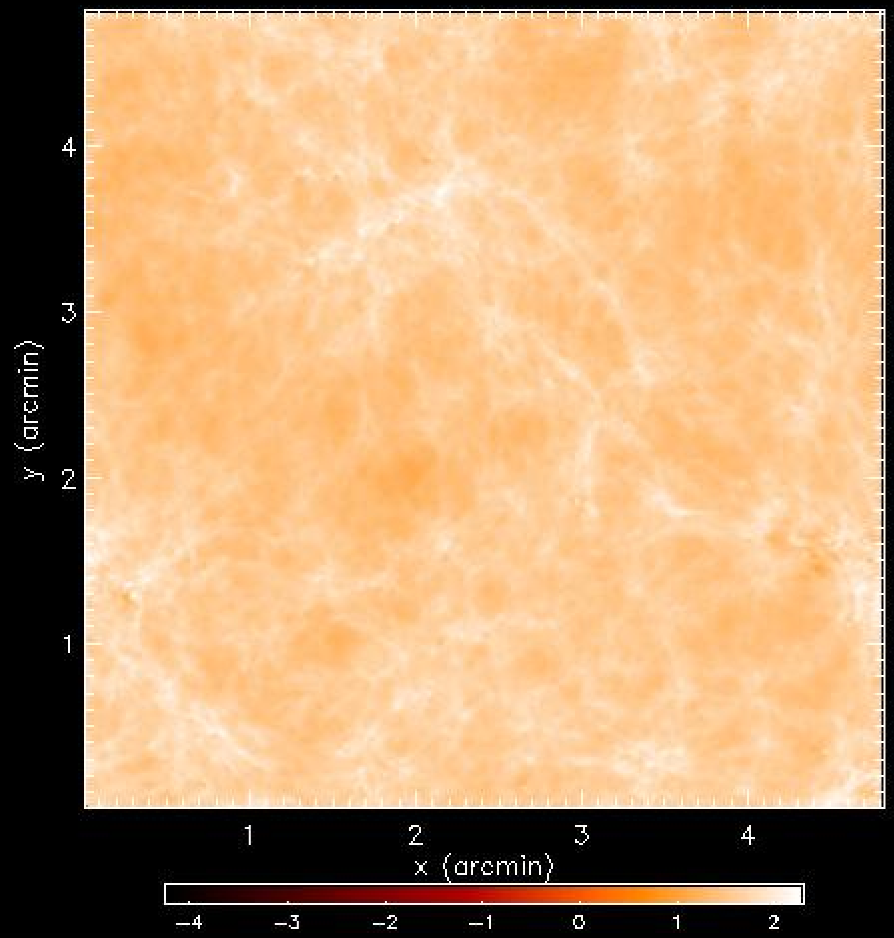
z=16.1

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



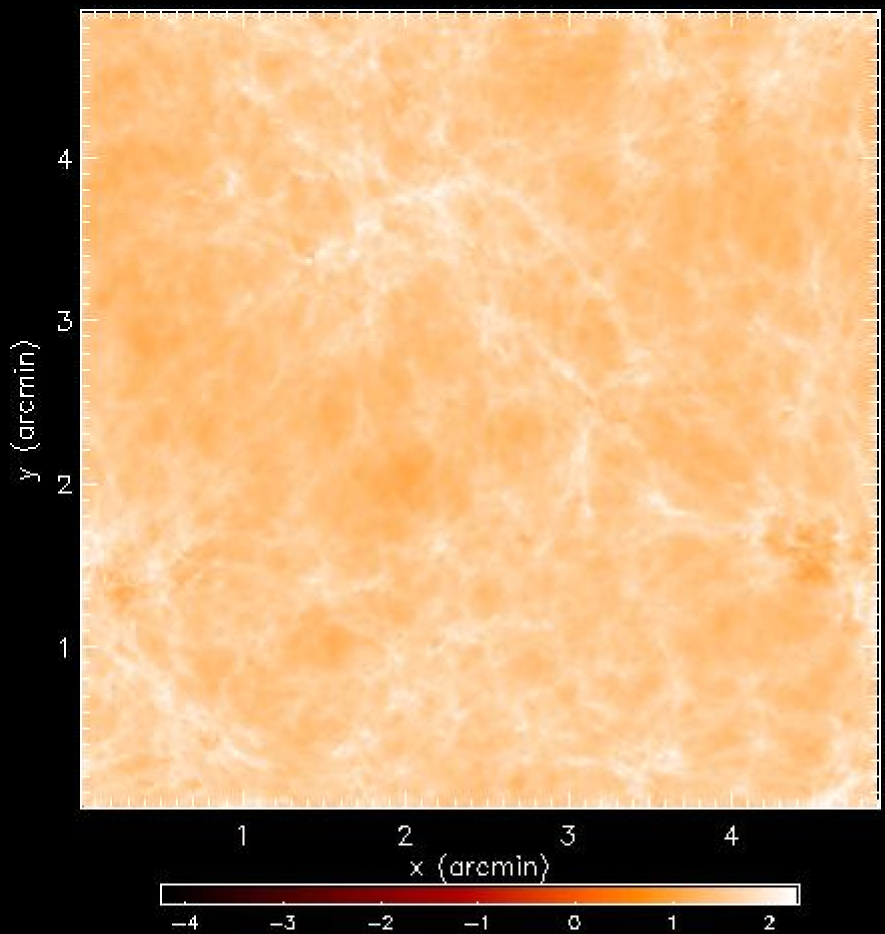
z=14.5

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



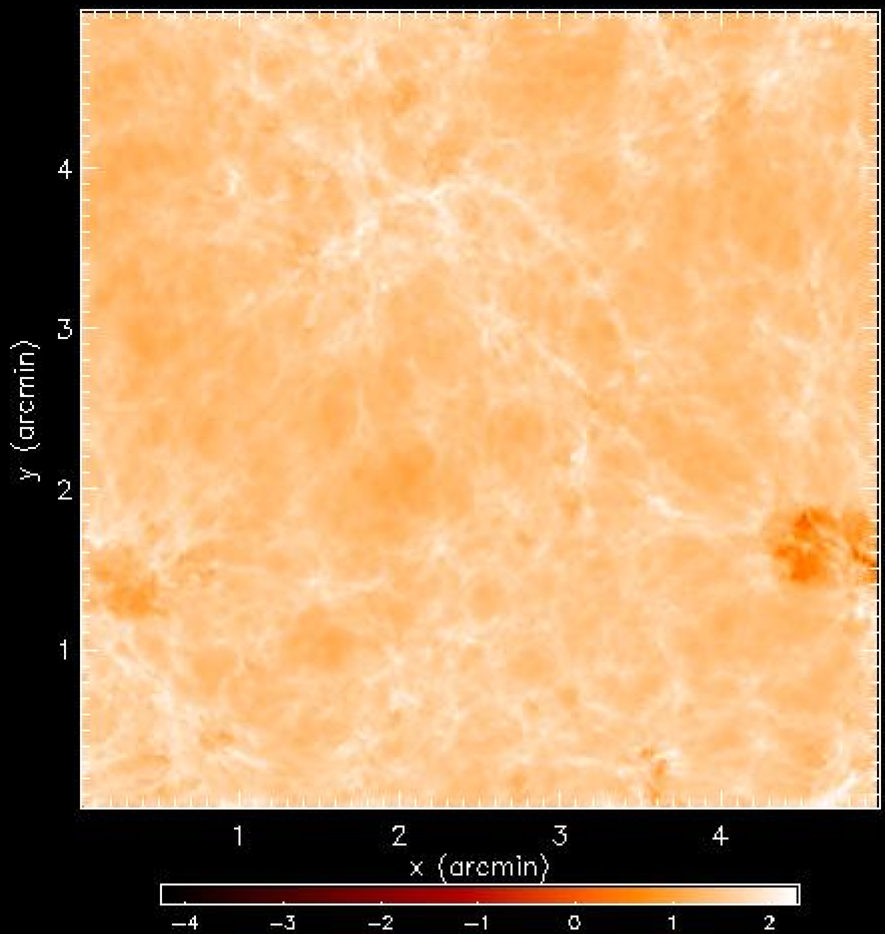
z=13.2

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



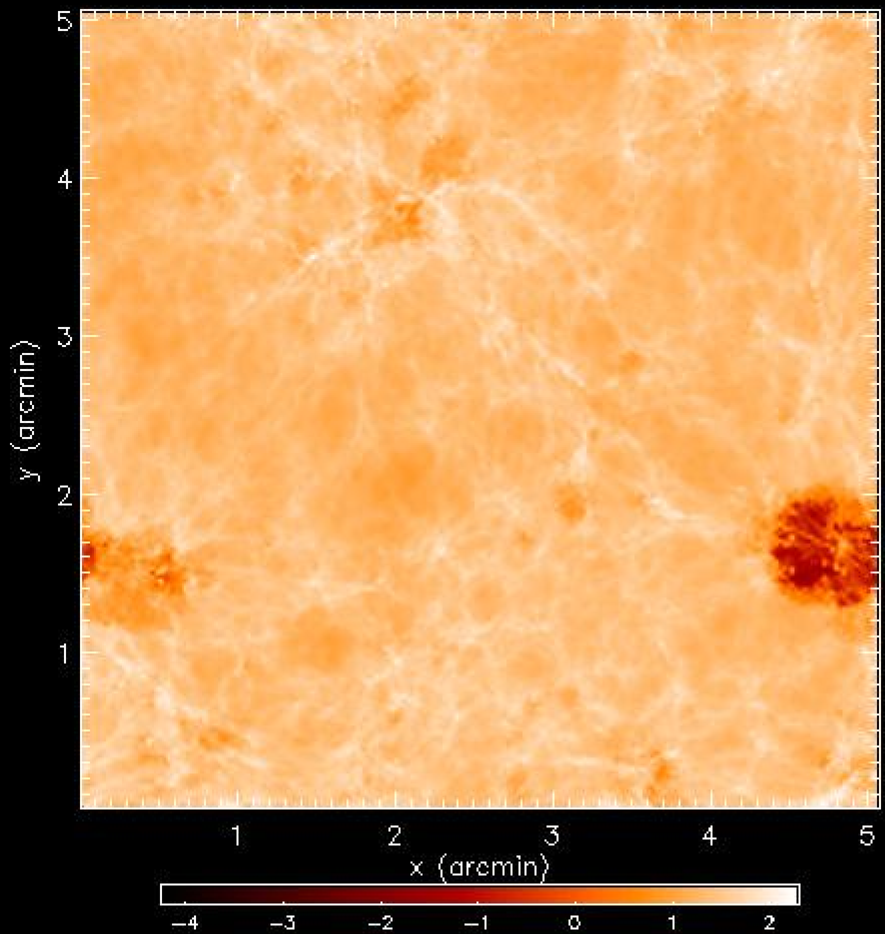
z=12.1

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



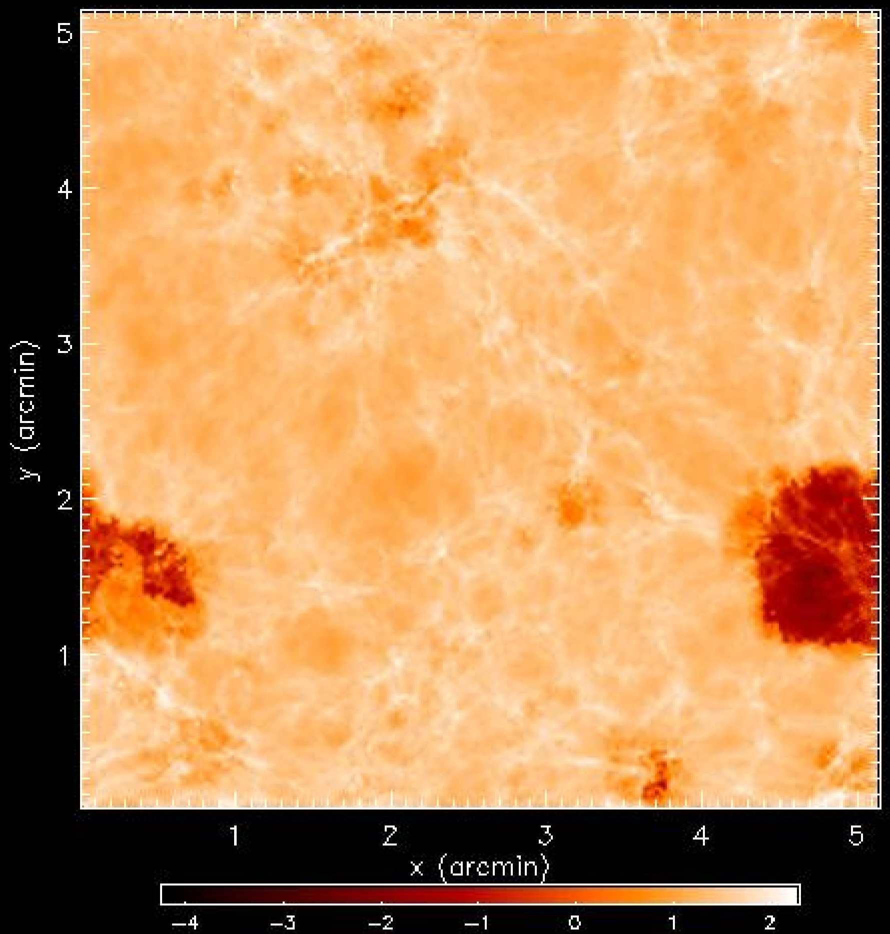
z=11.2

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



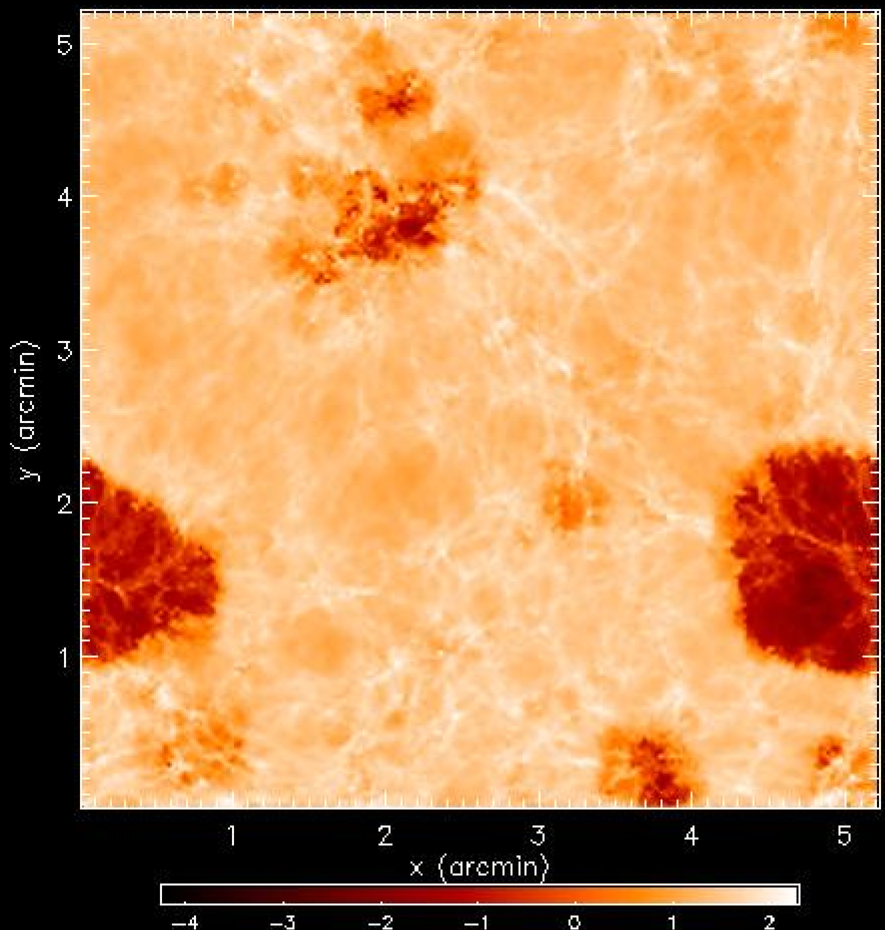
z=10.4

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



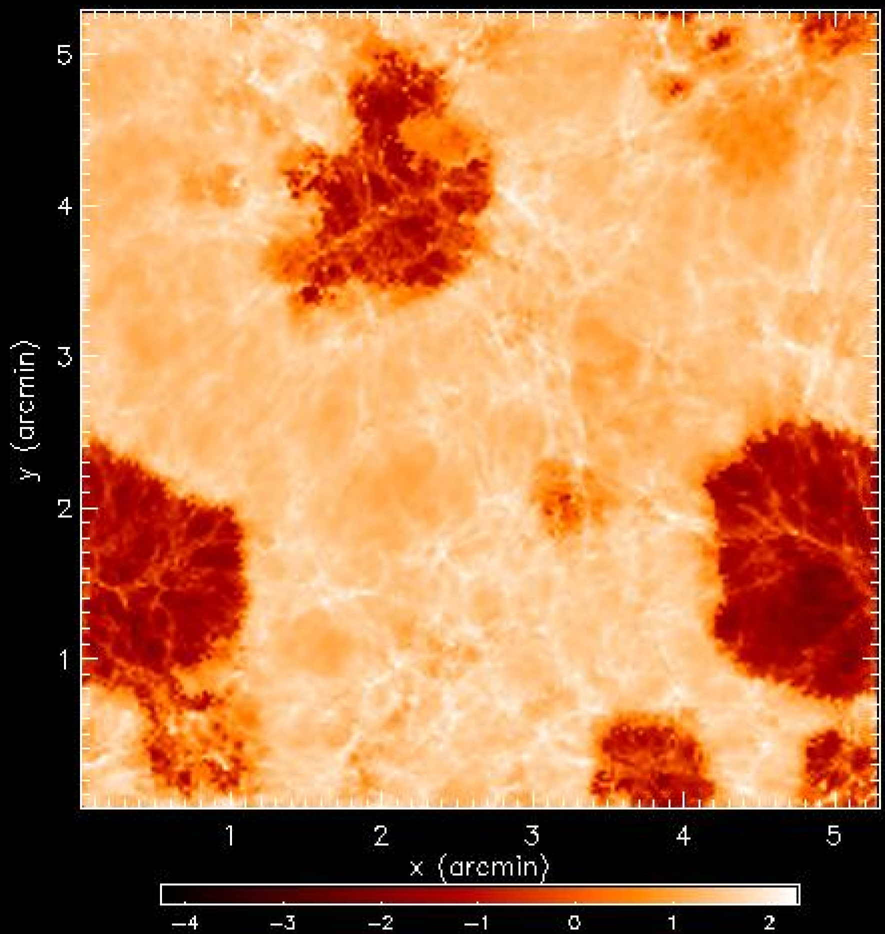
z=9.8

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



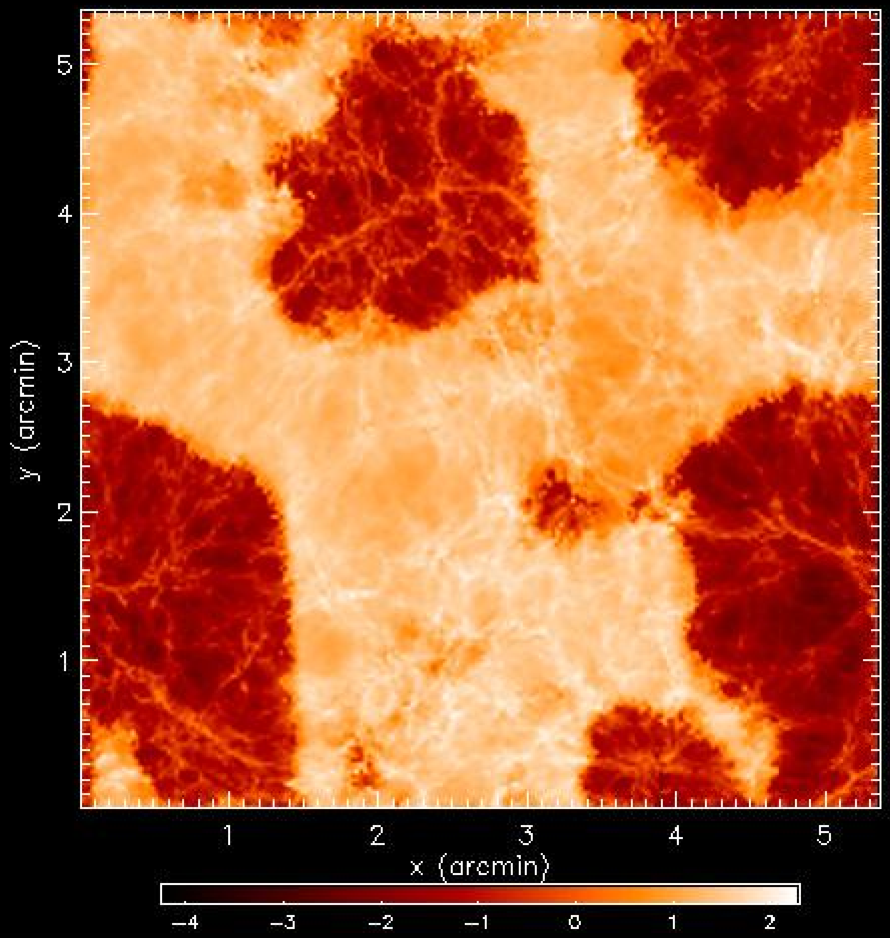
z=9.2

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



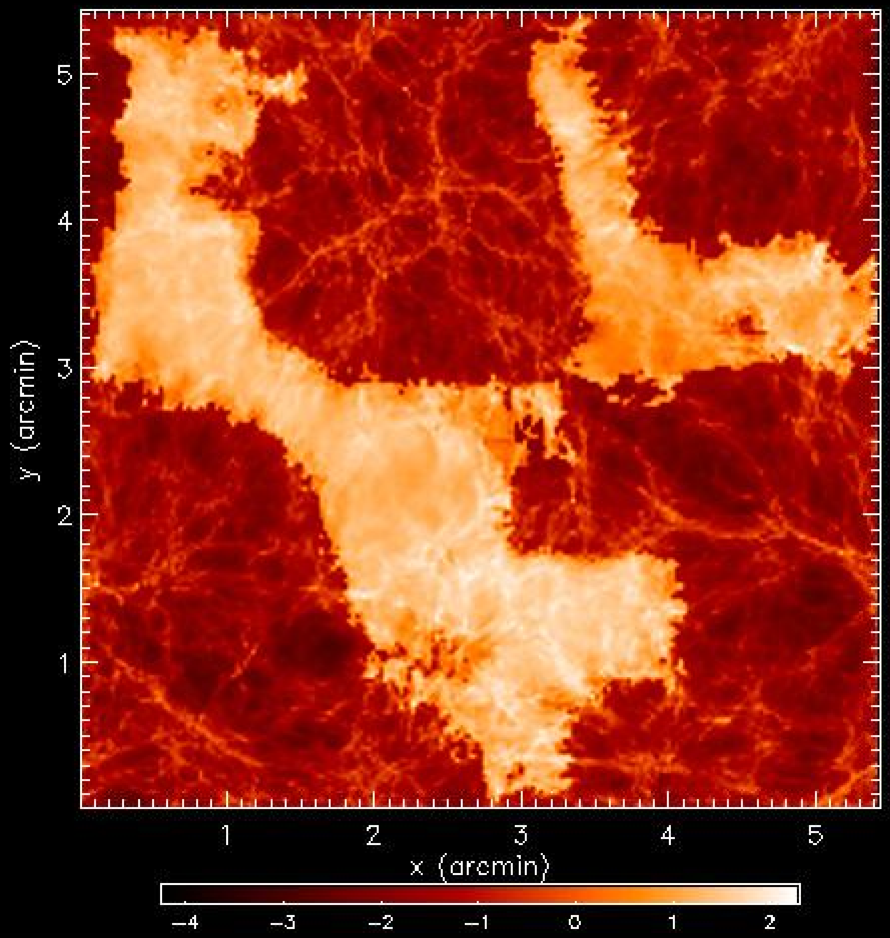
z=8.7

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



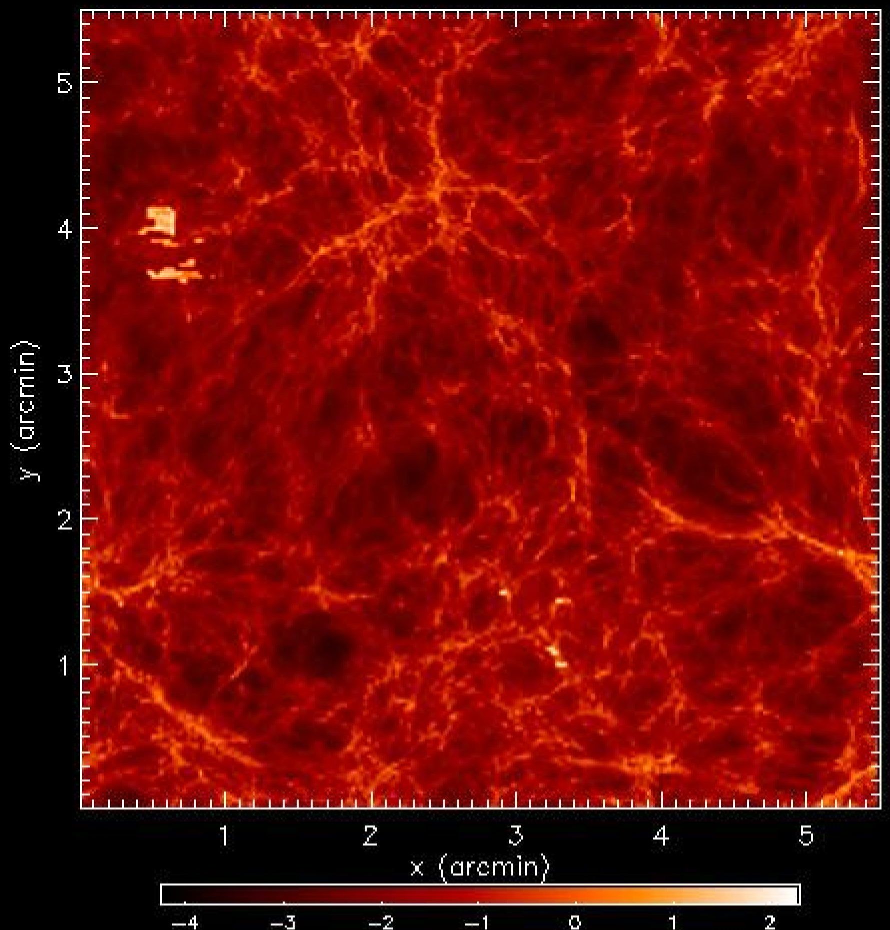
z=8.3

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



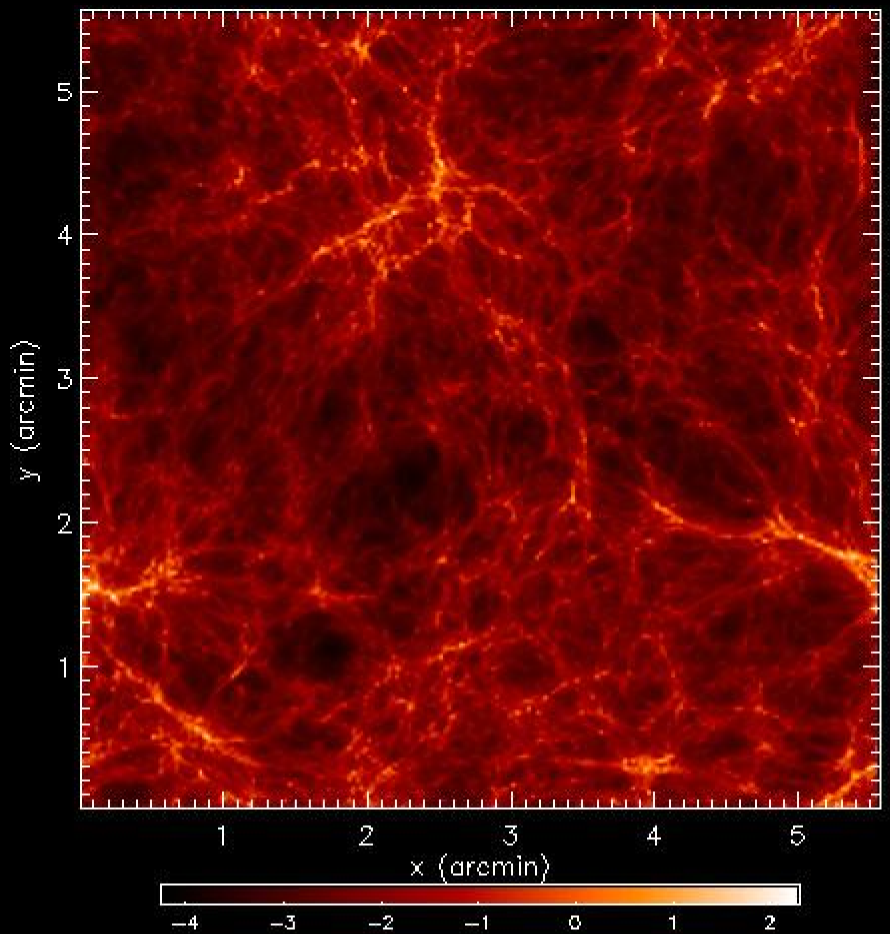
z=7.9

10 Mpc comoving

$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

21 cm Observations: Emission



z=7.5

10 Mpc comoving

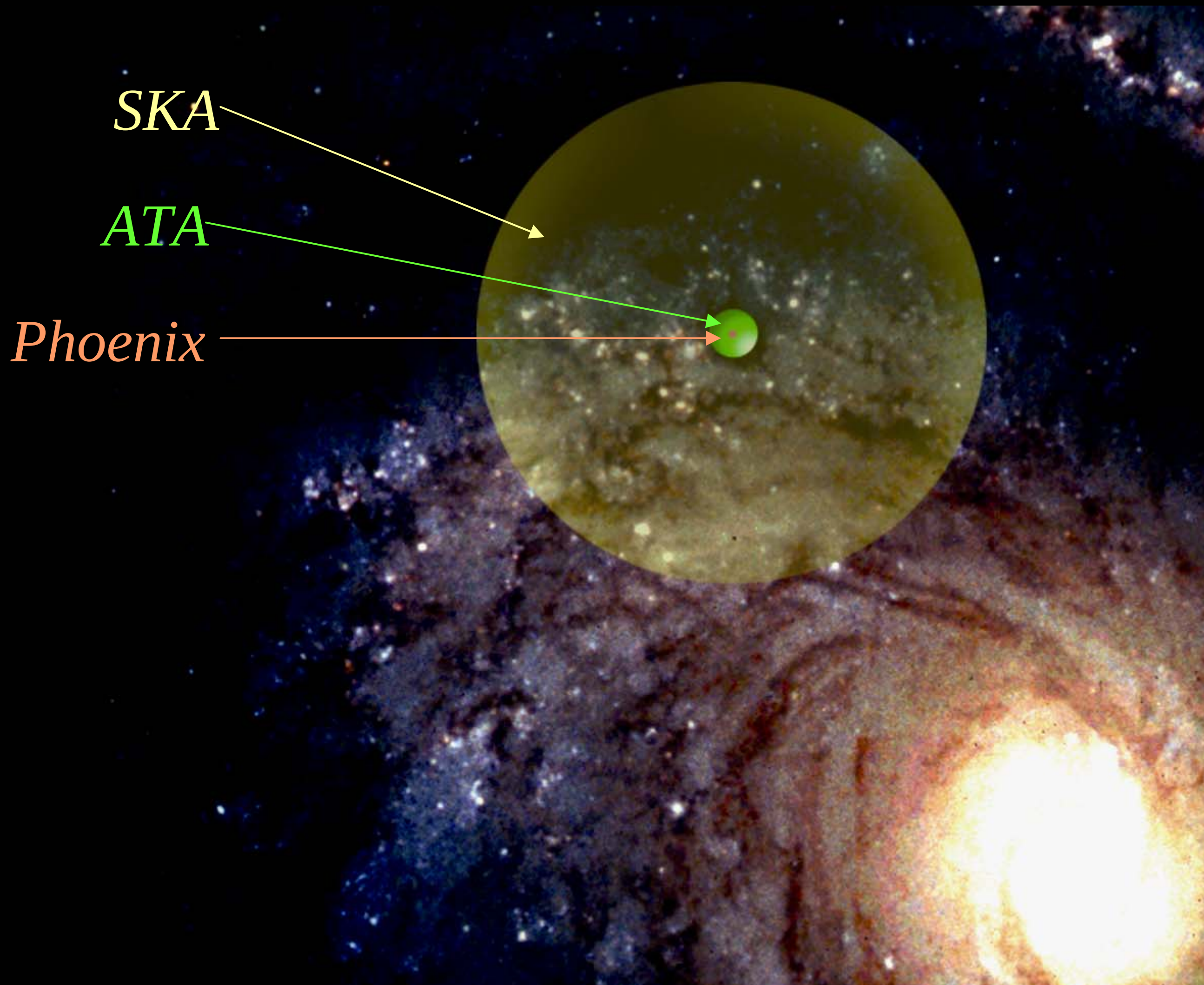
$\Delta\nu$=0.1 MHz

Furlanetto et al. (2003)

Conclusions

- Redshifted 21 cm observations are unique
  - Line --> redshift information
  - Probe middle phases of reionization
- We learn fundamental astrophysics
  - Matter power spectrum at high redshifts
  - Probes initial stages of structure formation
  - Tomography of reionization
  - Small-scale structure at high redshifts (“21 cm forest”)
- Excites broader community
  - Answers questions about the first sources of light in the universe
  - Close relation to CMB & radio/infrared detections of first sources

Enhanced SETI Searching



Future Facilities

- e-MERLIN
- EVLA I & II
- ATA
- GMRT, LOFAR
- FPA's (Parkes, Arecibo)
- SKA, DSN array
- ALMA

LOFAR

Time Magazine's Opinion

Square km telescope: the concept

- Frequency range 0.03 - 20GHz
- Sensitivity 100 x VLA
- Resolution 0.1" – 0.001"
- Multibeam (at lower frequencies)
- Need innovative design to reduce cost
- International funding unlikely to exceed $1000m
  - 10^6 sq metre => $1000 / sq metre
    - » cf VLA $10,000 / sq metre (50GHz)
    - » GMRT $1,000 / sq metre (1GHz)
    - » ATA $2,000/sq metre (11GHz)

EVLA II
Location of the NMA Antennas

- The new antennas are shown in white.
- Upgraded VLBA antennas are in yellow.
- Proposed new location of Los Alamos antenna is SE of Albuquerque.
- All sites are on public land, with road access, nearby power and fiber.
- Fiber rental costs very modest

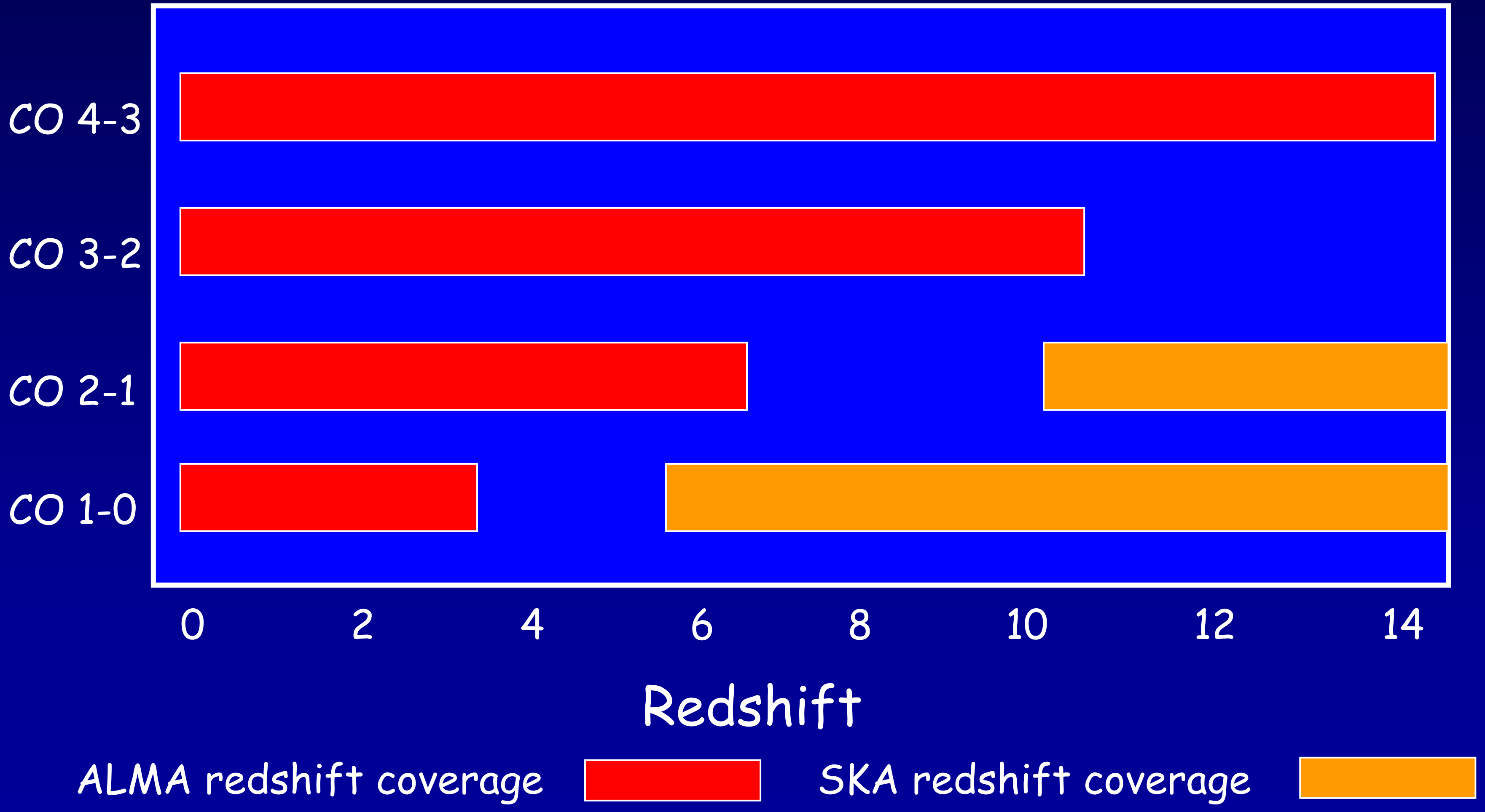
VLA upgrade options on the path to the One Square Km Array

- EVLA I
  - sensitivity, correlator, frequency coverage
- EVLA II
  - Resolution – high and low
- Real time links to VLBA antennas
- Correlator
- Wideband antenna feeds
- LO and IF distribution
- Array control and imaging software development
- cm wavelength technology development

SKA's basic specifications

- Sensitivity: 50--100x VLA at same wavelength
  - → Brightness sensitivity ~1K
- Frequency coverage: ~150 MHz to ~22 GHz
  - only ~2% reserved for astronomy → interference mitigation techniques required
- Max. Resolution: <0.1 arcsec to match/exceed HST, JWST, ALMA
- Field-of-view: > 1 square degree
- Ideally multiple beams

Redshift coverage (20 GHz highest SKA frequency)



High z CO Survey Speed

	ALMA	SKA
Line strength (ALMA >2:1)	x100	1
Redshift	any	>4.5
Collecting area	1	x200
Survey area	1	x25
Redshift search space	1	x5

ALMA and the SgrA* Black Hole

- VLBI at sub mm wavelengths to ALMA would have 10 μas resolution
- It could see the distortion of the SgrA* image by the black hole (Falke 2003)

Putting it all together: Radio Imaging Arrays