Surveying the Cosmic Web with the Radio Synoptic SKA (RSSKA)

Steven T. Myers

National Radio Astronomy Observatory

Socorro, NM

The Radio Synoptic SKA

- SKA as Radio Synoptic Survey Telescope (RSST)
  - say “risque”
  - there may be other RSST concepts out there (ATA?)
- The RSSKA is a “SKA-mid” facility
  - the “SKA-mid” from a US science perspective (for the Decadal Review)
  - this IS the International SKA! not a new project
- Built for the Primary Science Goals
  - HI for Cosmology and Galaxy Evolution
  - Deep continuum imaging
  - Transient detection and monitoring

The RSSKA is part of the SKA Program

- The SKA is an international program to build the next generation of large radio arrays
  - SKA-low : 10-300 MHz
    - Epoch of Reionization (EoR) and Dark Ages Telescope (DAT)
    - Pathfinders/Precursors: MWA, PAPER, LWA, GMRT, LOFAR
  - SKA-mid : 0.3-10 GHz
    - the RSSKA!
    - Pathfinders/Precursors: ALFALFA, EVLA, ATA, ASKAP, MeerKAT
  - SKA-high: 1-25 GHz
    - Cosmic Star Formation and the "Cradle of Life"
    - Pathfinders/Precursors: EVLA, ATA
    - Plan for 2025+?

The RSSKA is …

- Radio?
  - core frequency range 0.4-1.4 GHz (z<2.5) "HSST"
    - some science cases may want 0.3-10 GHz (must justify $$)
- A Square Kilometer Array
  - square kilometer of something (not white papers)
  - high gain/low noise $A/T_{sys} \approx 2\times10^4\ m^2\ K^{-1}$
    - don't throw away all that collecting area!
  - wide field-of-view, target 1 square degree
    - $A\Omega/T \approx 2\times10^4\ m^2\ K^{-1}\ deg^2 \sim n_a n_b/T$ "uv megapixels"
- A Survey Telescope
  - cover large areas of sky $10^4\ deg^2$ = ¼ sky
    - survey speed $(A\Omega/T)(A/T)\Delta\nu = n_a n_b\ A/T^2\ \Delta\nu$

The Synoptic Part

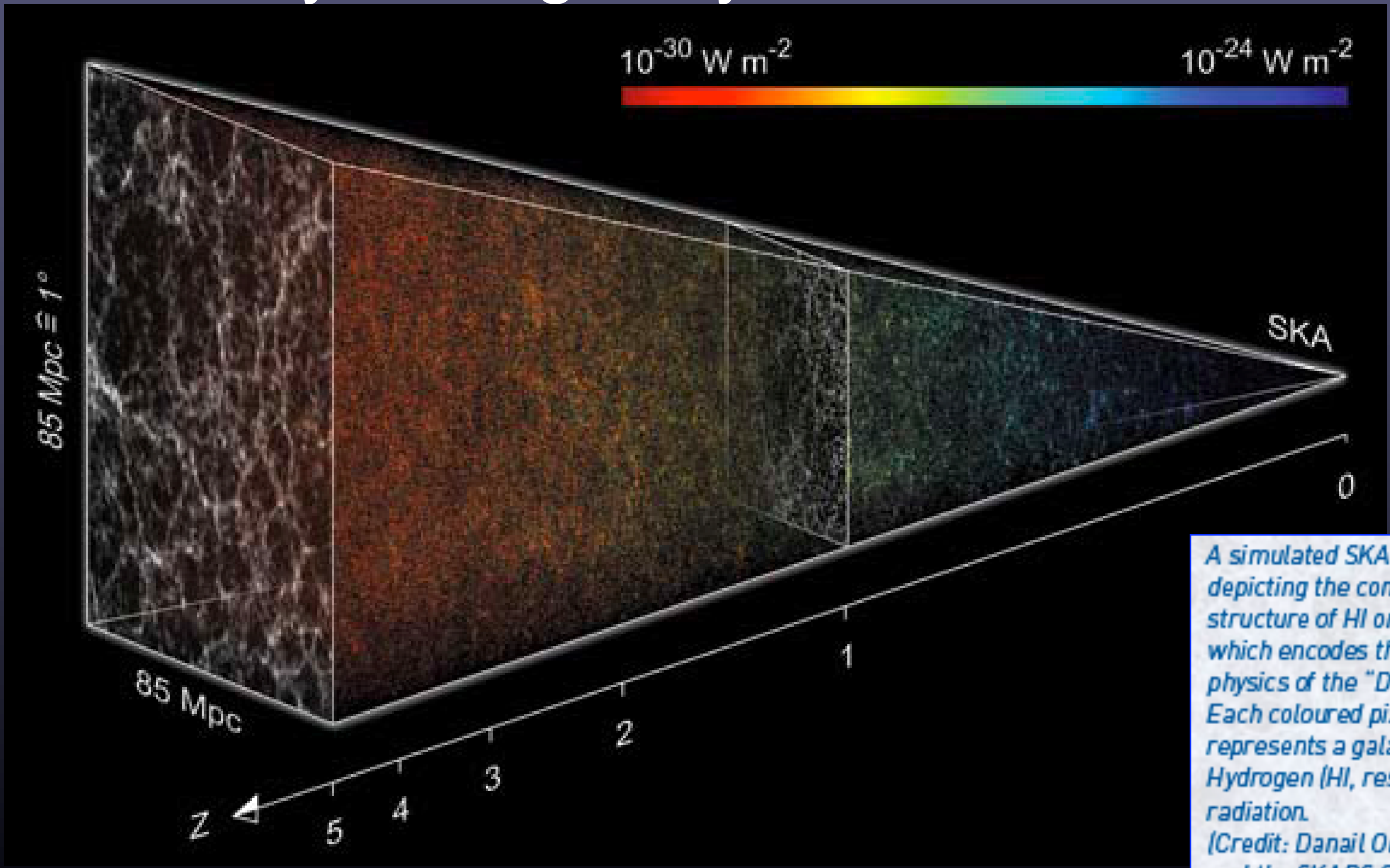
- Revisit the sky regularly
  - if you want to cover 10^4 deg^2 with $1deg^2$ FOV
  - can do so in 1 day with 8^s per deg^2
  - different parts of survey can have different depths (and thus cadences)
- What cadence? Depends on the science
  - many short visits or fewer longer ones?
  - looking for individual “bursts” or “pulses”?
  - looking for groups or trains of pulses?
  - classical variability curves (e.g. microlensing)?
  - also remember, many compact radio sources are variable (both intrinsic and scintillation)

RSSKA Science

Key science drivers

The Cosmic Web with the RSSKA

- Survey of HI galaxy emission to z > 1



A simulated SKA observing cone depicting the complex filamentary structure of HI on cosmic scales, which encodes the mysterious physics of the "Dark Universe". Each coloured pixel in the cone represents a galaxy emitting neutral Hydrogen (HI, rest-frame 21-cm) radiation. (Credit: Danail Obreschkow (Oxford) and the SKADS Sky Simulation team.)

RSSKA Science: HI Cosmology

- "billion galaxy" HI survey
  - redshifts for gas-rich galaxies out to z=1.5 (and beyond)
  - Baryon Acoustic Oscillations (BAO)
  - cosmography of Universe d(z) , V(z) ⇔ H(z)
  - growth of structure and Cosmic Web
  - HI is critical window on galaxy formation and evolution
- complementarity with "Dark Energy" surveys
  - e.g. JDEM, LSST,DES, SDSS, DES, LSST, PanSTARRS
    - RSSKA is in the DETF as a "Stage IV" project
  - mutual interest with the DOE community (JDEM)
  - engage O/IR extragalactic and cosmology communities
  - NASA missions (JDEM, Planck, JWST, GLAST, etc.)

RSSKA for Cosmology

- RSST can see HI galaxies out to redshift z > 2
  - > 10^9 galaxies for 10^4 deg2
  - counts are HIMF dependent
  - needs sensitivity of SK area
- Survey Strategy
  - tradeoff between wide and deep
  - 1 Gpc^3 comov = 250 deg^2 z=1.5
- Cosmology
  - HI galaxies will have different bias to O/IR galaxies
  - we are working on simulations to see results of BAO and correlation function studies
  - target precision requires survey speed of 4-6 x 10^9 $m^4K^{-2}deg^2$

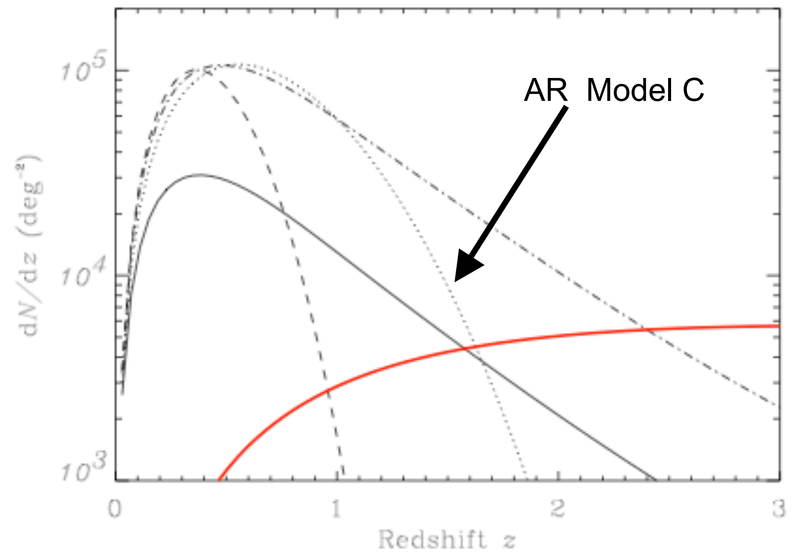


Figure 3. Predictions of dN/dz per deg^2 for an SKA survey with an exposure time of 4 hours, a signal-to-noise detection limit of 10 and assumptions about the properties of the HI-emitting galaxies and the SKA detailed in Sec. 2. The same linestyles are used as in Fig. 1 to discriminate between the different AR2004 models; the prediction of a 'no-evolution' model is shown by the solid (black) line. Also shown (thicker red line) is the surface density of galaxies needed for a survey to be limited by cosmic variance rather than shot noise (AR2004).

Rawlings et al. SKA Science Book

O/IR Spectroscopic BAO Surveys

Survey[a]	Redshift Range	Sky Area (deg^2)	Millions of Galaxies	Effective Volume[b] (Gpc^3)[c]
ADEPT	$1 < z < 2$	28,600	~100	180
SDSS DR4 Main+2dF	$z < 0.3$	7,000	0.7	0.50
SDSS LRG	$0.16 < z < 0.47$	3,800	0.047	0.52
SDSS-II 8-yr LRG	$0.16 < z < 0.47$	7,600	0.094	1.0
WiggleZ/AAT (220 nights)	$0.5 < z < 1.0$	1,000	0.4	0.64
APO-LSS	$0.2 < z < 0.8$	10,000	1.5	10
FMOS/Subaru (200 nights)	$1.4 < z < 1.7$	300	0.6	0.7
HETDEX	$1.8 < z < 3.8$	250	1.0	2.0
WFMOS/Subaru (150 nights)	$0.5 < z < 1.3$	2,000	2.	3.8
WFMOS/Subaru (150 nights)	$2.3 < z < 3.3$	300	0.6	1.2

Notes to the Table: a. The SDSS surveys in the 2nd and 3rd rows are the only ones completed; the rest are planned or proposed. They are all spectral line surveys. LSST plans a large (~10,000 deg^2) photometric redshift survey, perhaps observing >10^9 galaxies at $0.5 < z < 3.5$. The photometric redshift errors would degrade the equivalent effective volume of the LSST survey to < 25 Gpc^3. **b.** Effective volume accounts for the limited sampling of the survey volume due to the discrete number of galaxies as a function of redshift. It is evaluated at the scale of the BAO, $k = 0.15h$ Mpc^{-1}. **c.** Assumes $h = 0.7$.

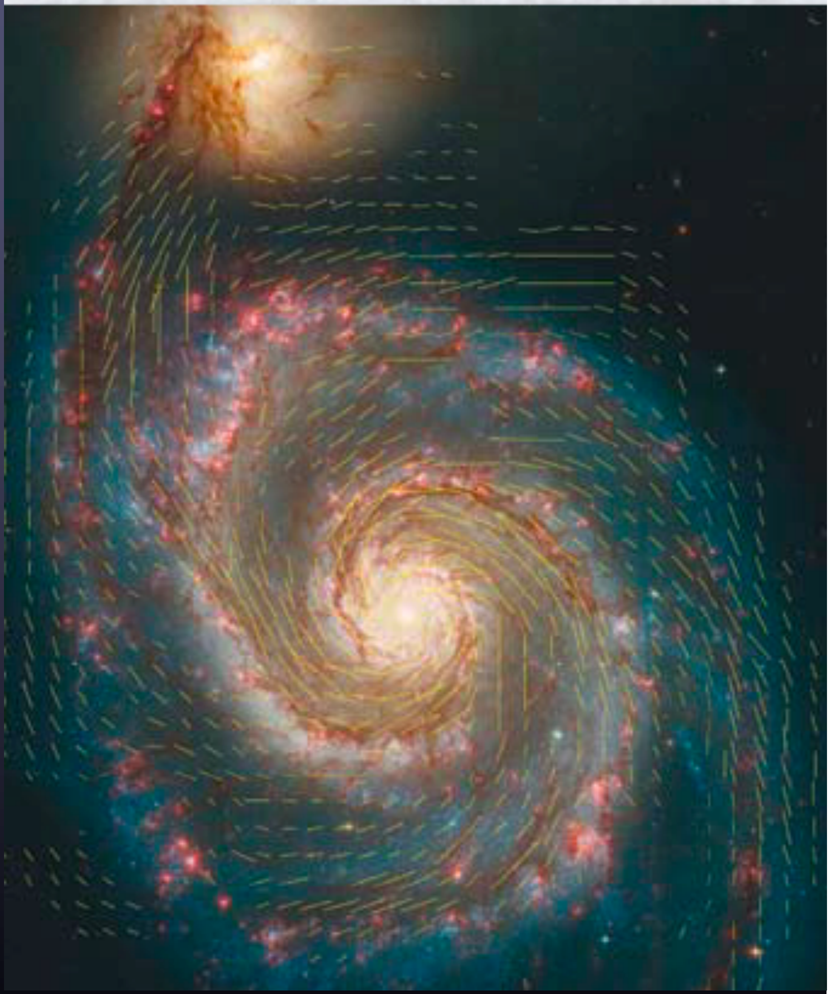
Warren Moos: presentation to BEPAC

- RSSKA in context: ~1000 million galaxies z<2.5 in 8-60 Gpc^3 comoving!

RSSKA Science Example: Continuum

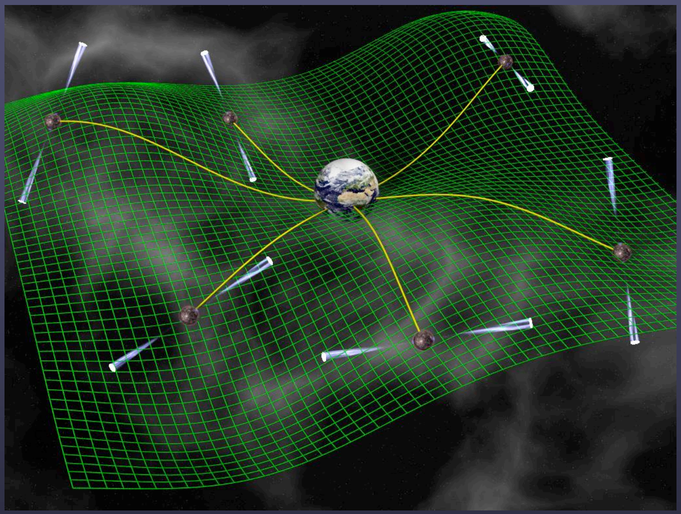
- Extremely deep (10 nJy) continuum survey
  - "billion" extragalactic radio sources
  - AGN
  - star-forming galaxies
  - SNR and HII regions in galaxies
- Census of rare phenomena
  - Gravitational Lenses (e.g. CLASS)
- Polarimetry
  - Rotation Measure (RM) survey
  - galactic and extragalactic magnetic fields

Optical image of the spiral galaxy M51 with the magnetic field determined from radio observations superimposed (Credit: Hubble Heritage/NASA/STScI, R.BECK/MPIfR)

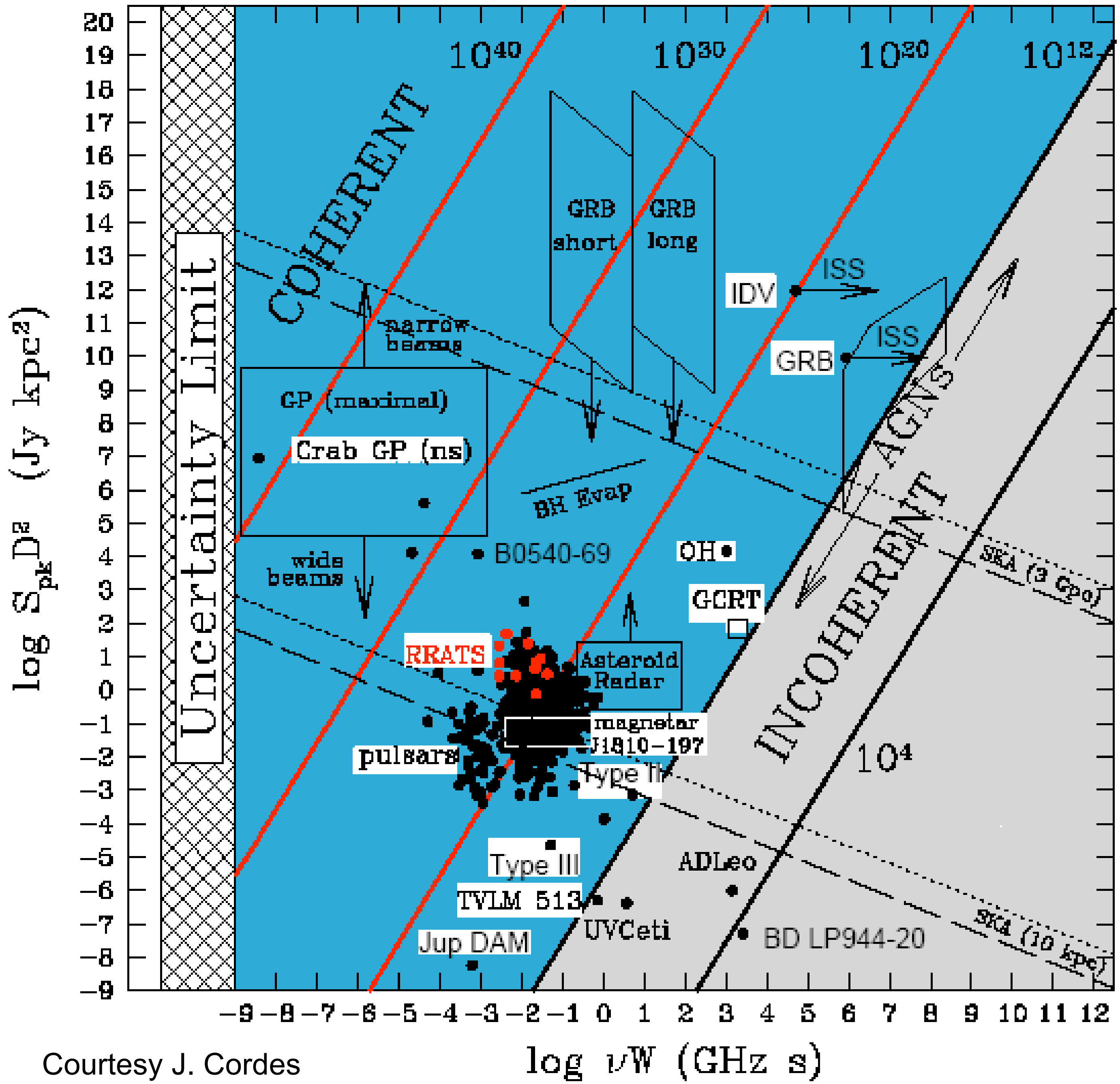


RSSKA Science Example: Transients

- Bursty phenomena - a new frontier
  - giant pulsar pulses out to Virgo
  - brown dwarf flares
- Variability
  - compact radio sources
    - intrinsic, IDV, scintillation, etc.
  - flares
  - GRB afterglows
- Exotica
  - UHE particles in lunar regolith
  - SETI
- Pulsars
  - provide spigot Pulsar Machine attachment



Pulsars discovered and monitored with the SKA will act like a cosmic gravitational wave detector, allowing the study of ripples in the fabric of space-time that propagate at ultra-low frequencies. (Credit: D.Champion, M.Kramer/JBO)



Courtesy J. Cordes

Phase Space for Transients:

Detection limit for SKA:

$S_{pk}D^2$ >threshold

⇐ Prompt GRBs and GRB afterglows easily seen to cosmological distances

Giant pulses detectable to Virgo cluster

Radio magnetars detectable to Virgo

ET radar across Galaxy

$$kT_b = \frac{2S_{pk}D^2}{(\nu W)^2}$$

W = pulse width or characteristic time scale

RSSKA Key Science Surveys

- Key Projects (example)
  - Cosmological HI Large Deep Survey (CHILDS)
    - billion galaxies to z~1.5 (and beyond)
    - HI redshift survey for cosmology
    - galaxy evolution
  - Deep Continuum Imaging Survey (DeCoIS)
    - radio photometric and polarimetric survey (static sky)
    - commensal with CHILDS, extracted from spectral data
  - Transient Monitoring Program (TraMP)
    - bursts, variability, pulsars, etc.
    - commensal with other RSSKA surveys – freeloading!
- These are part of one big survey (Big Sur)

Realizing the RSSKA

The RSSKA Roadmap

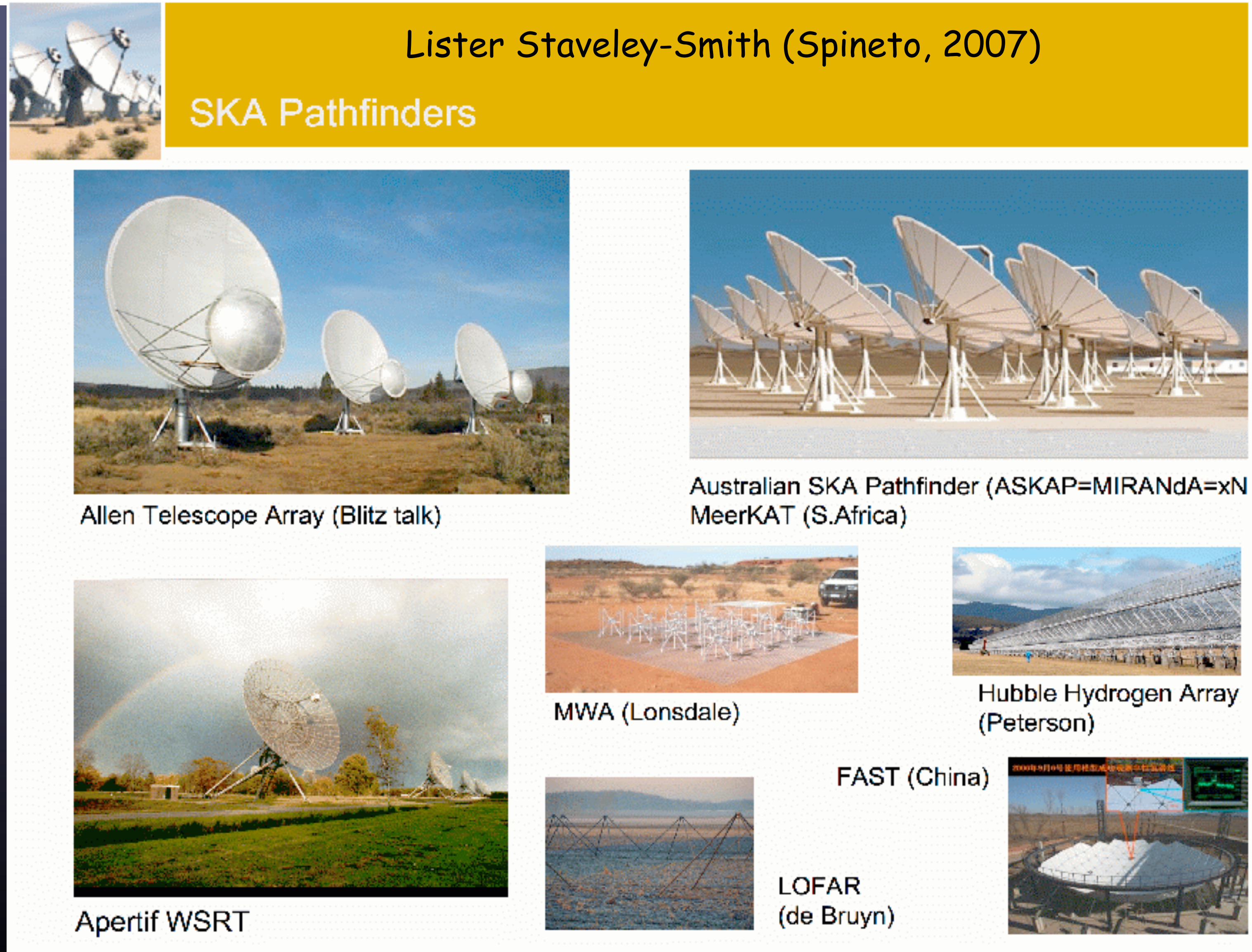
- RSSKA planning
  - US-SKA and International consortia drafting for Decadal Review
- Science Precursors
  - use EVLA, Arecibo, ATA, etc. to pioneer science areas
- Technology Demonstrators & Pathfinders
  - US-SKA TechDev program, ATA, EVLA, EOR projects, …
  - International: ASKAP, MeerKat (1% SKA pathfinders)
- Staged Construction
  - milestones for construction and limited operation
    - e.g. proposed “10% RSSKA”
- Operations
  - Science Operations (20+ years)
    - US RSSKA Science Center?
    - what is model for community involvement?
  - Upgrade Plan (10 years)
    - build into project (e.g. add multi-beam capabilities, computing upgrades)

Precursors: What we can do Now

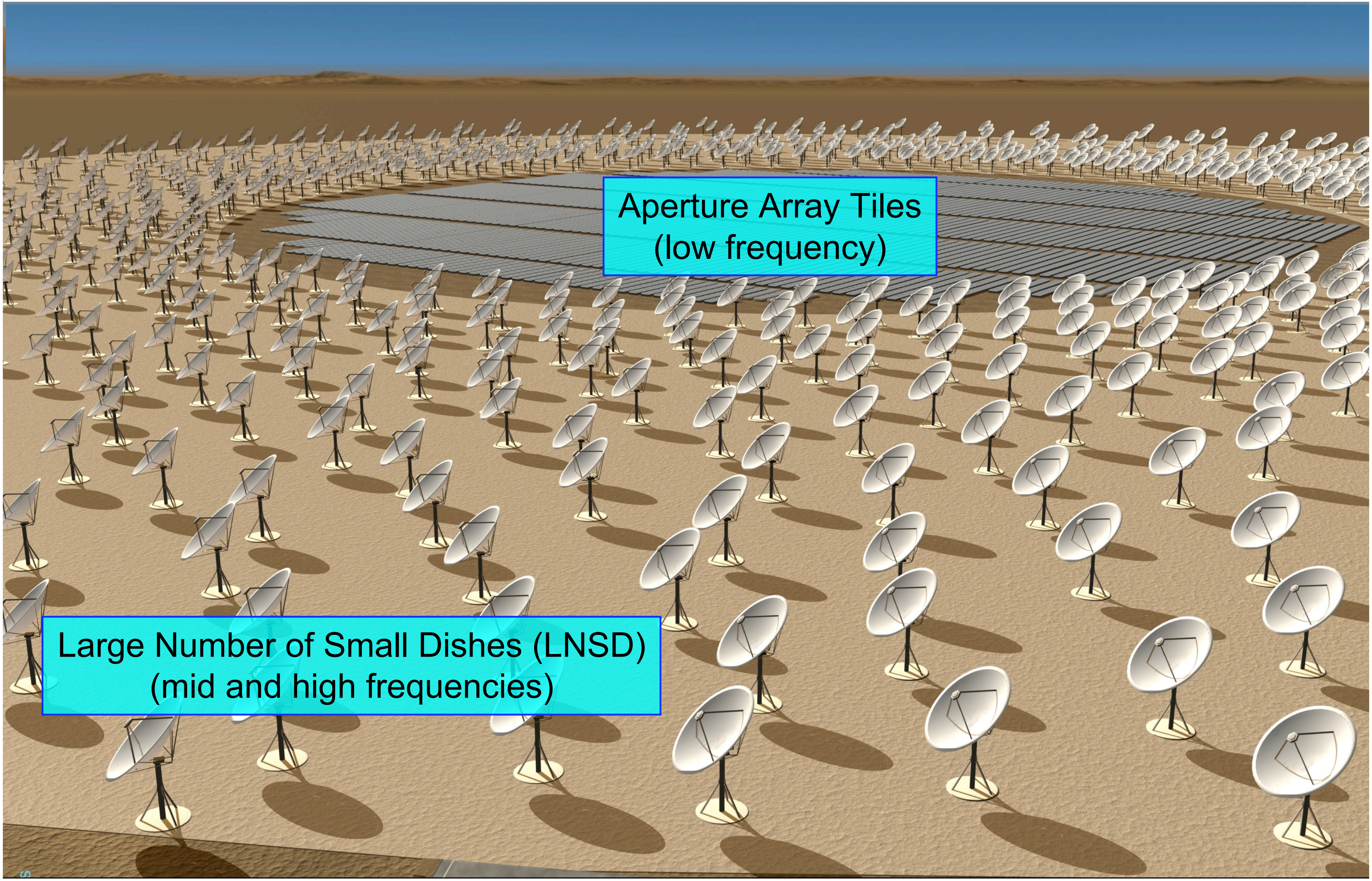
- HI Cosmology Simulations
  - need good enough models to make credible projections
  - where are we now and what do we need to get there?
  - $\phi(M,z)$ and $f(M_{HI}/M \mid M,z,\rho,\ldots)$ link to halos
  - semi-analytics vs. N-body/hydro
  - techniques: galaxy counts vs. emission power spectrum
    - as in CMB (Wyithe & Loeb 2008)
- Science Precursors
  - what can we do NOW to pave the way?
  - can we learn anything about HI in galaxies at z=0.5?
  - should we change the way we use existing facilities?
    - big EVLA surveys (commensal?)
    - beyond ALFA? ATA?
  - what about the pathfinders? NRAO involvement?
  - are there intermediate stages to full RSST?

SKA Pathfinders

- ATA
- WSRT
- MWA
- ASKAP
- MeerKAT
- LOFAR
- LWA
- PAPER
- HHA
- FAST



The SKA Artist's Concept



RSSKA HI: Descoping Issues

- Draft Preliminary Specs v2.7.1
  - 3000 x 15m single-pix survey speed
  - 40x slower than SKA of AR2005
  - could get back w/multi-feed upgrade
  - or implement as separate Aperture Array
    - e.g. 4x scaled-up EOR array
  - also configuration issues (core vs. res)
- HI mass function
  - z=2 HIMF steep above 10^{10} M_{sun}
  - if M_{lim} x2 then N x 10^{-3} to 10^{-4} or worse!
    - in danger of getting < 10 million galaxies at z>1
  - Dark Energy not do-able with PS
    - need SSFoM > 4-6 x 10^9 $m^4K^{-2}deg^2$
    - is this important enough?
  - this is a critical issue to deal with in RSSKA DR planning

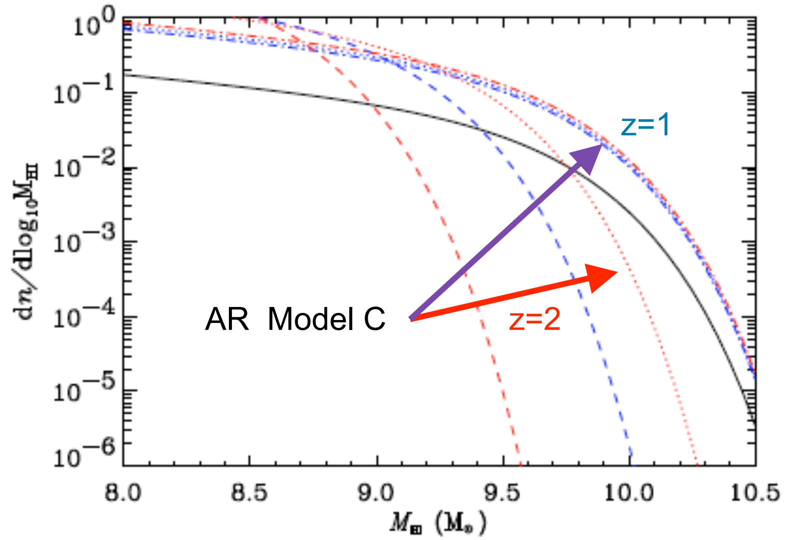


Figure 1. Predictions of the evolution in the HI mass function from AR2004. The dot-dashed lines show their 'Model A' at $z = 1$ (lower, blue) and $z = 2$ (upper, red) with the solid (black) line showing the measured local HI mass function (Zwaan et al. 2003). The dashed lines show their 'Model B' at $z = 1$ (right-most, blue) and $z = 2$ (leftmost, red), and the dotted lines their 'Model C' at $z = 1$ (upper, blue) and $z = 2$ (lower, red).

Rawlings et al. SKA Science Book

Do we accept the Preliminary Specs?
What up-scoping do we advocate?

Example: HI Survey Strategies

- Benchmark design (BD): 3000 15m antennas
  - only 0.36 of SKA (7500 m^2/K vs. 20000 m^2/K)
  - 40x slower than SKA for precision BAO (Abdalla & Rawlings 2005)
  - FOV = 0.73deg^2 at z=0 (1.4GHz) and 4.54deg^2 at z=1.5 (560MHz) "single pixel"
  - target: 10 deg^2 or more at z=0 (1.4GHz) - need upgrade!
- Duration of Survey: 20 year mission
  - 5 years Wide, 5 years Deep, 3 years med-deep Galactic plane
  - 2 x 1 year ultra-deep fields (Galactic Center, Virgo deep, other?)
  - 5 years GO or TOO and follow-up (25%)
- Wide "Quarter Sky" = 10000 deg^2
  - 8.64s per deg^2 per day = 4.38 hours per deg^2 in 5 years
  - BD: 19.9h per z=1.5 FOV per year
    - S_{lim}=1.75 μJy $\Rightarrow$ M_{lim}=4.1x10^9 M_{sun} at z=1.5 ($\Delta\nu$=0.38MHz)

Example: more HI Survey Strategies

- Deep region = 200 deg^2
  - 432s per deg^2 per day = 219 hours per deg^2 in 5 years
  - BD: 110h per z=1.5 FOV per year
    - S_{lim}=0.39 μJy ⇒ M_{lim}=8.8x10^8 M_{sun} at z=1.5 ($\Delta\nu$=0.38MHz)
- Medium-deep Gal Plane Survey = 750 deg^2
  - 115.2s per deg^2 per day = 35 hours per deg^2 in 3 years
  - BD: 25 hours per z=0 FOV
- Ultra-Deep field = 4.5 deg^2
  - 173s per deg^2 per day = 1931 hours per deg^2 per year
  - BD: 1931 hours per z=1.5 FOV per year
    - S_{lim}=0.13 μJy ⇒ M_{lim}=3x10^8 M_{sun} at z=1.5 ($\Delta\nu$=0.38MHz)

RSSKA in Perspective

- A square kilometer array is
  - 100 times the size of the EVLA (10x Arecibo)
  - would take 2700 VLA 25-m dishes
    - take ~10000 times the processing of the VLA
  - would take 12000 12-m dishes
    - take ~100000 times the processing of the VLA
- Equivalent EVLA data rates ~250 MB/s
  - RSSKA would be ~2.5TB/s to 25TB/s
  - data volumes ~200 to 2000 PB per day
  - there are higher rate modes (transients)
  - cannot store all raw data, only products (images)
    - it will come down to “real time” imaging & processing

Great Surveys
and the New Mexico Connection

Making a Map of the Universe

- The Whole Universe Telescope
  - must see all the universal constituents
    - luminous matter - stars, HII regions, thermal emissions
    - quiescent gas - HI, molecular clouds and cores
    - planetary objects - exo-planets, proto-planetary & debris disks
    - energetic particles - cosmic rays, “jets”, neutrinos
    - magnetic fields - galactic, intergalactic, cosmological
    - collapsed objects - black holes, AGN, pulsars, gravity waves
    - dark matter - galaxy/cluster cores, gravitational lensing, direct
    - dark energy - cosmological
    - gravity waves - gravitational collapse, GW background
- The RSSKA is part of this future

Great Surveys for a "2020 Vision"

- The SKA is part of a grand vision for the coming decades, including:
  - Large Synoptic Telescope (LSST, Pan-STARRS)
  - Giant Segmented Mirror Telescope (GSMT)
  - Square Kilometer Array (RSSKA, EoR/DAT)
  - Great Space Surveys (JDEM, LISA, ConX, CMBPol)
- These next-generation telescopes are not just great observatories, but are parts of a Great Survey of the Universe
  - These are the instruments that we want to have available to do our science in 2015+

Common Cause

- All these next-generation surveys and telescopes have challenges
  - in particular in the Data Management area!
- The Science is cross-cutting
  - multi-wavelength (or particle) and multi-instrument
  - interest is multi-agency (NSF, DOE, NASA, other)
  - realize the Whole Universe Telescope
- Proposal: “Great Surveys” Workshop
  - bring together workers from the next-gen projects
  - plannng to hold in Santa Fe in Fall 2008

RSSKA & Great Surveys in New Mexico

- Infrastructure
  - (E)VLA, VLBA, LWA, AP/SDSS, MRO
  - Universities, Observatories, and Labs
  - Supercomputing
  - Lambda Rail
- Expertise
  - observational and theoretical community
    - LANL, NMSU, NMT, NRAO, UNM
  - HPC and data mining (e.g. LANL, SDSS)
- Networking
  - use ACCent as vehicle for collaborations
  - connections to rest of community (UC, FNAL, …)
  - collaborations for RSSKA science (observing & theory) precursors

The RSSKA Data Challenge

- Large numbers of antennas
  - operations, maintainance and data networking issues
  - full capital costs need to be ~$1000 per square meter!
- Data management
  - this is a "software telescope", with ~1/3 of cost in DM
  - huge data rates and volumes possible
  - high dynamic range imaging
    - reach <100nJy in wide fields with 1-10Jy sources (>10^7:1)
    - will need new algorithms (and must be efficient to handle rates)
  - likely will require real-time imaging
    - how long can we afford to archive visibility data (200PB/day)?
    - can we make a robust interferometric imaging pipeline?
- Complications
- radio interference (RFI), ionosphere, antenna polarization, data transmission, survey scheduling, uniform calibration, data mining, prompt transient detection

For more information…

- RSST Proto-White Paper (draft)
  - on the Arecibo Frontiers conference website:
    http://www.naic.edu/~astro/frontiers/RSST-Whitepaper-20070910.txt
- my RSST/RSSKA page
  - http://www.aoc.nrao.edu/~smyers/rsst
- SKA Info
  - http://www.skatelescope.org
  - particularly see the "Science Book"
    - "The Dynamic Radio Sky" by Cordes, Lazio & McLaughlin
    - "Galaxy Evolution, Cosmology, and Dark Energy with the SKA" by Rawlings et al.
    - others…