# Cosmology with the Radio Synoptic SKA (RSSKA)

Steven T. Myers

***National Radio Astronomy Observatory***

***Socorro, NM***

# 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: ALFA, EVLA, ATA, ASKAP, MeerKAT
  - SKA-high: 1-50 GHz
    - Cosmic Star Formation and the "Cradle of Life"
    - Pathfinders/Precursors: EVLA, ATA, ALMA
    - Plan for 2025+?

# The Radio Synoptic SKA (RSSKA)

- SKA as Radio Synoptic Survey Telescope (RSST)
  - say “risque”
- The RSSKA is …
  - radio: HI core 0.4-1.4 GHz (0.3-10 GHz goal)
  - square kilometer: large collecting area for sensitivity
    - high gain/low noise $A/T_{sys} > 10^4\ m^2\ K^{-1}$
  - survey telescope: wide-field for survey speed
    - survey speed FOM $\Omega(A/T_{sys})^2 > 4 \times 10^9\ deg^2\ m^4\ K^{-2}$
- Built for the Primary Science Goals
  - HI for Cosmology and Galaxy Evolution
  - Deep continuum imaging
  - Transient detection and monitoring

# The Synoptic Part

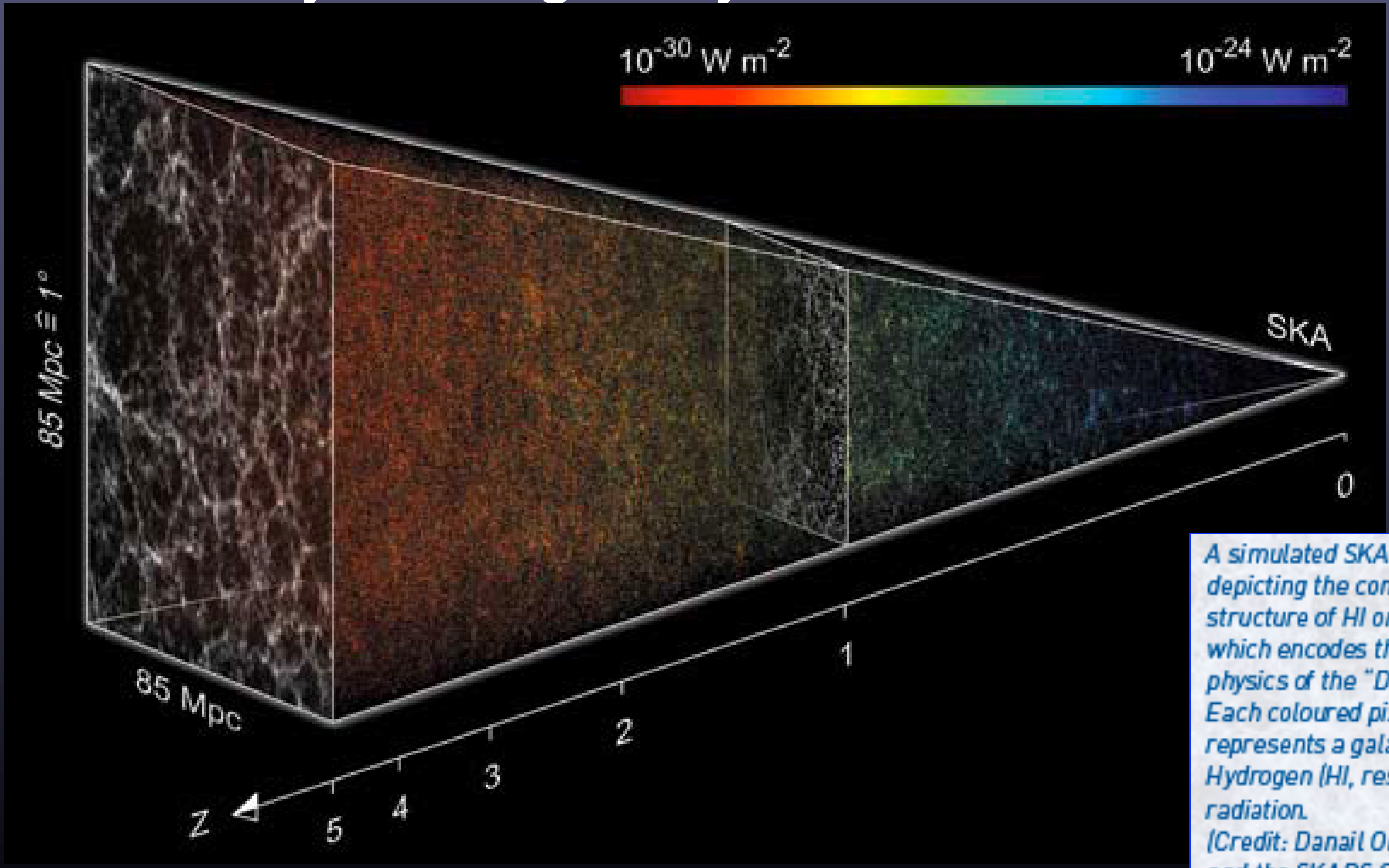
- Revisit the sky regularly
  - if you want to cover $10^4$ $deg^2$ with $1deg^2$ FOV
  - can do so in 1 day with $8^s$ per $deg^2$
  - different parts of survey can have different depths (and thus cadences)
- What cadence? Depends on the science
  - many short visits or fewer longer ones?
  - looking 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

# Cosmology 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) [$\sigma_w$ ~ 0.01]
  - 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 = SKA
  - mutual interest with the DOE community
  - engage O/IR extragalactic and cosmology communities
  - NASA missions (JDEM, Planck, JWST, GLAST, etc.)

# RSSKA for Cosmology

- RSSKA 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 $\mathrm{Gpc}^3$ comov = 250 $\mathrm{deg}^2$ 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 galaxy distribution function studies
  - redshifts are limited only by galaxy HI profile

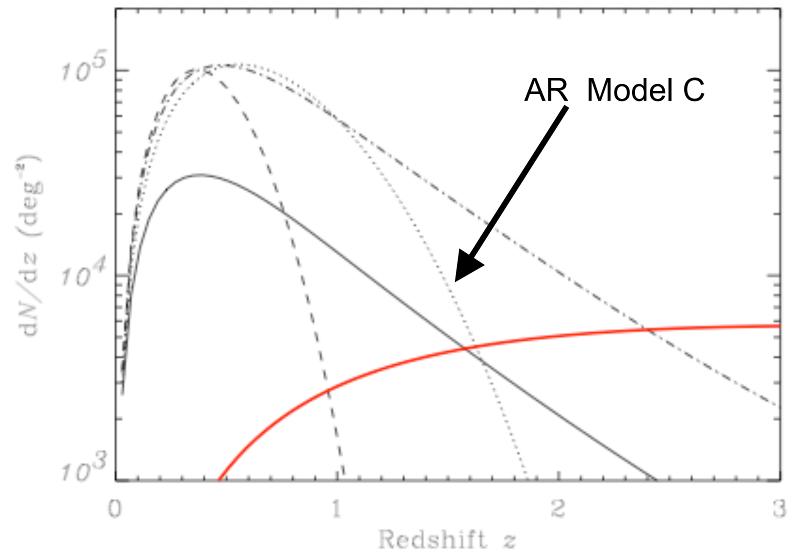
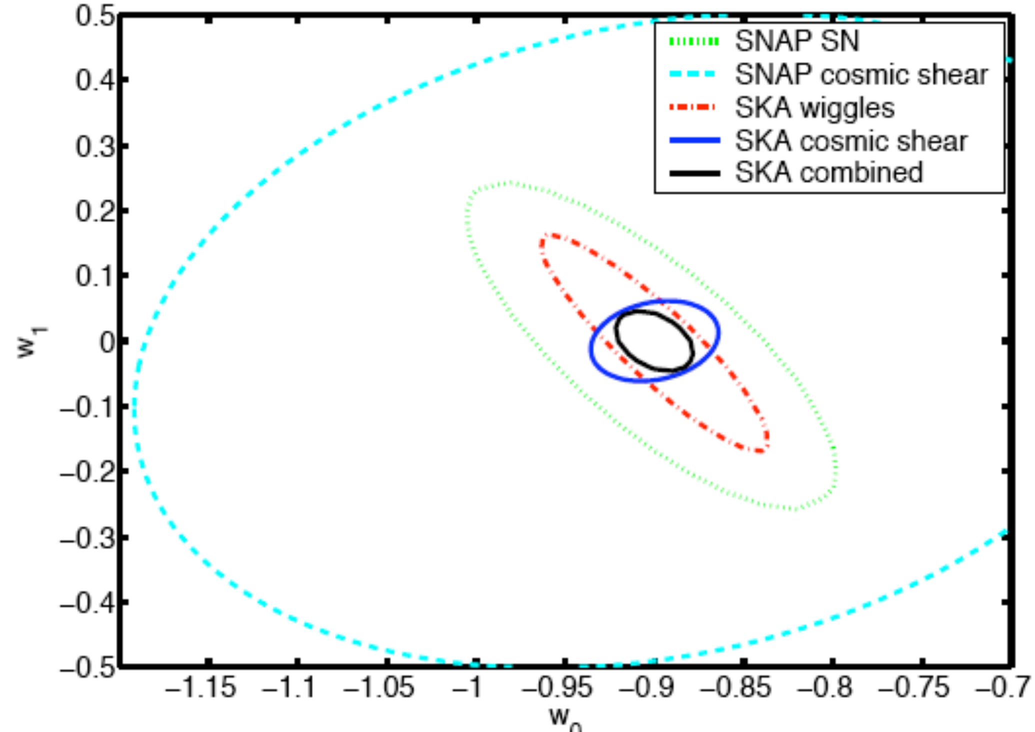



Figure 3. Predictions of d$N$/d$z$ per deg$^2$ for an SKA survey with an exposure time of 4 hours, a signal-to-noise detection limit of 10 and assumptions about the properties of the HI-emitting galaxies and the SKA detailed in Sec. 2. The same linestyles are used as in Fig. 1 to discriminate between 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

# RSSKA for Dark Energy

- RSSKA as w-machine
  - $10^9$ galaxy BAO survey
  - also weak lensing (continuum)
  - target 0.01 in *w*
- Design Driver
  - target precision requires survey speed of 4-6 x $10^9$ $m^4 K^{-2} deg^2$
  - this is a SK area with 10 $deg^2$ FOV
  - would also like to identify individual galaxies (need arcsecond resolution)
  - survey database for other science
- Options
  - might be able to do BAO power spectrum with ultra-compact Hydrogen array/telescope
  - but will not be of general use…



Rawlings et al. SKA Science Book

Rawlings et al. SKA Science Book

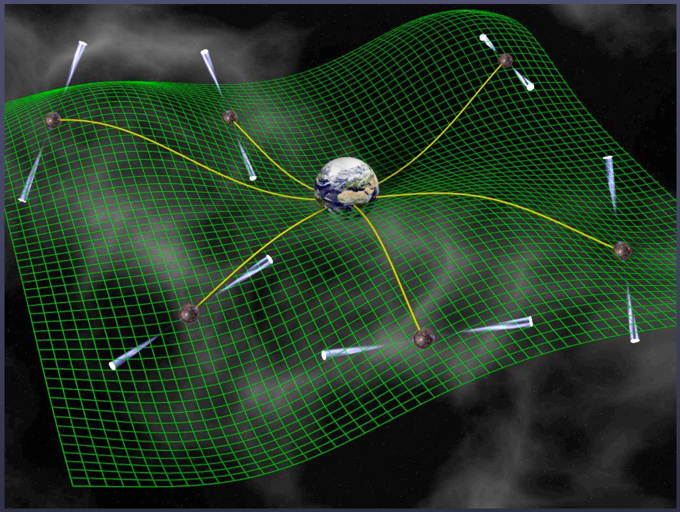
# RSSKA Science: Continuum

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

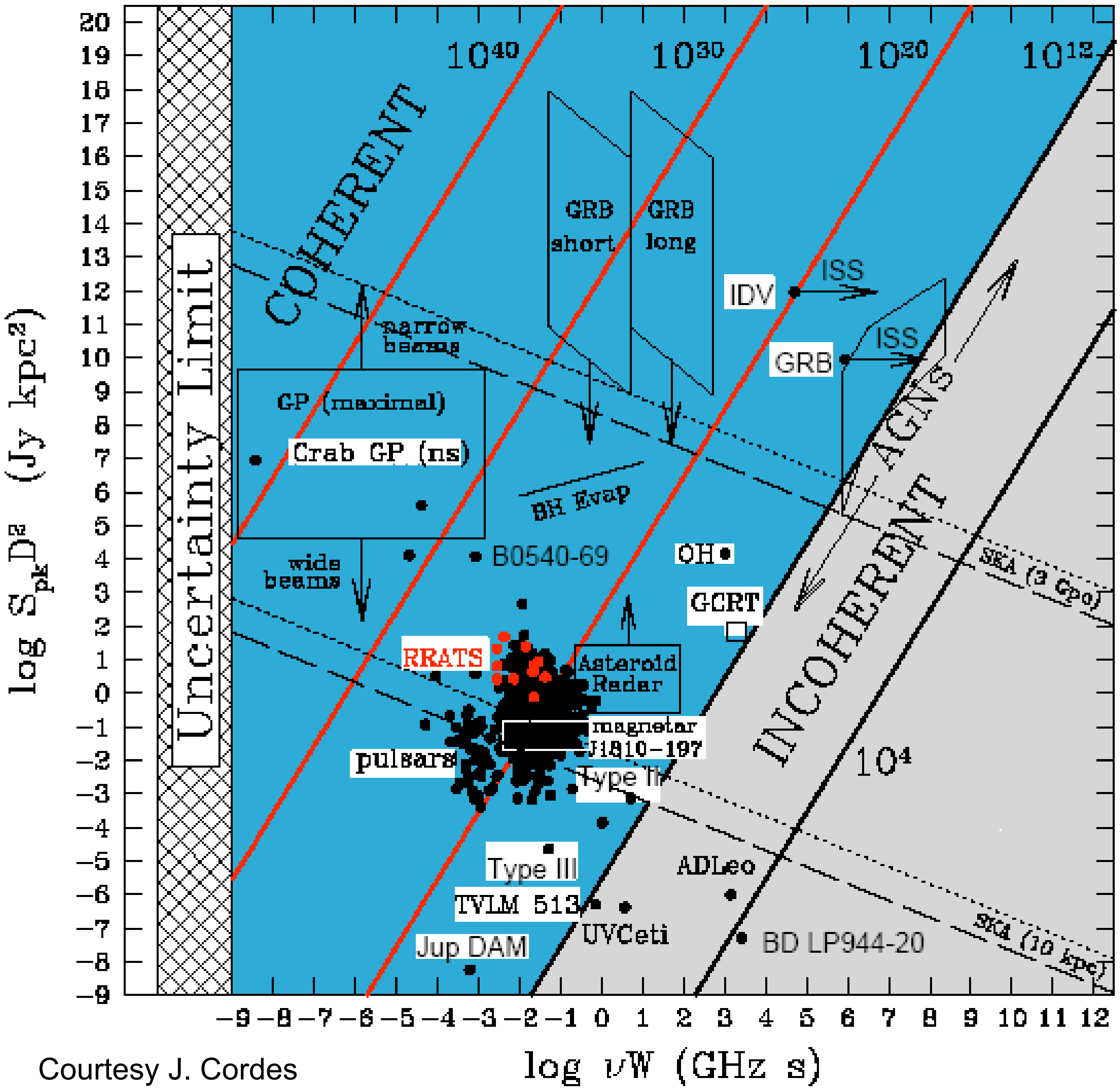
*Optical image of the spiral galaxy M51 with the magnetic field determined from radio observations superimposed (Credit: Hubble Heritage/NASA/STScI, R.BECK/MPIfR)*

# RSSKA Science: Pulsars & 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)

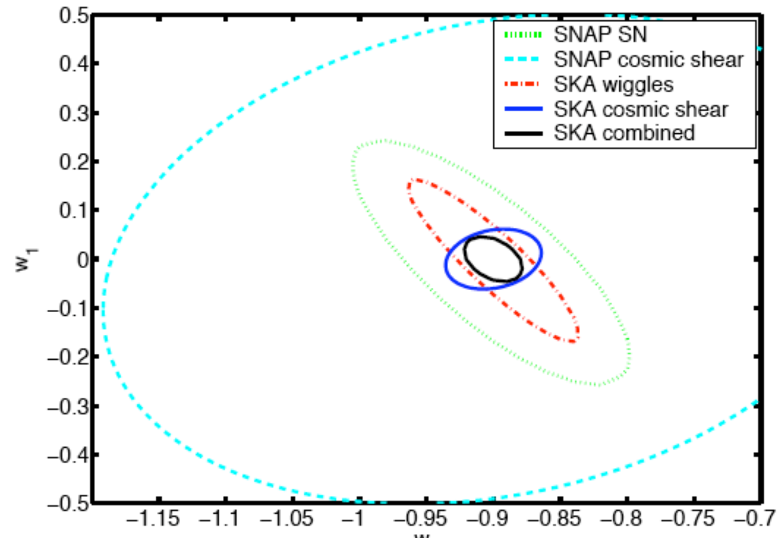
# Realizing the RSSKA

# 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 TDP, ATA, EVLA, EOR projects, 1% SKA pathfinders)
- Staged Construction
  - milestones for construction and limited operation
    - e.g. a “10% RSSKA” for HI power-spectra?
- Operations and Staged Upgrade
  - 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
  - models to make credible projections
    - $\phi(M,z)$ and $f(M_{HI}/M \mid M,z,\rho,\ldots)$
    - link to halos
  - semi-analytics vs. N-body/hydro
  - galaxy counts vs. emission power spectrum
    - as in CMB (Wyithe & Loeb 2008)
- Science Precursors
  - what can we do NOW to pave the way?
  - HI in galaxies at z=0.5?
  - how to best use existing facilities?
    - big EVLA surveys (commensal?)
    - beyond ALFA?
    - ATA?



Rawlings et al. SKA Science Book

# SKA Pathfinders

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

Lister Staveley-Smith (Spineto, 2007)

## SKA Pathfinders

Allen Telescope Array (Blitz talk)

Australian SKA Pathfinder (ASKAP=MIRANdA=xN
MeerKAT (S.Africa)

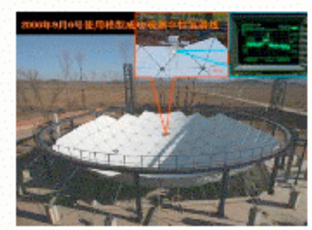
Apertif WSRT

MWA (Lonsdale)

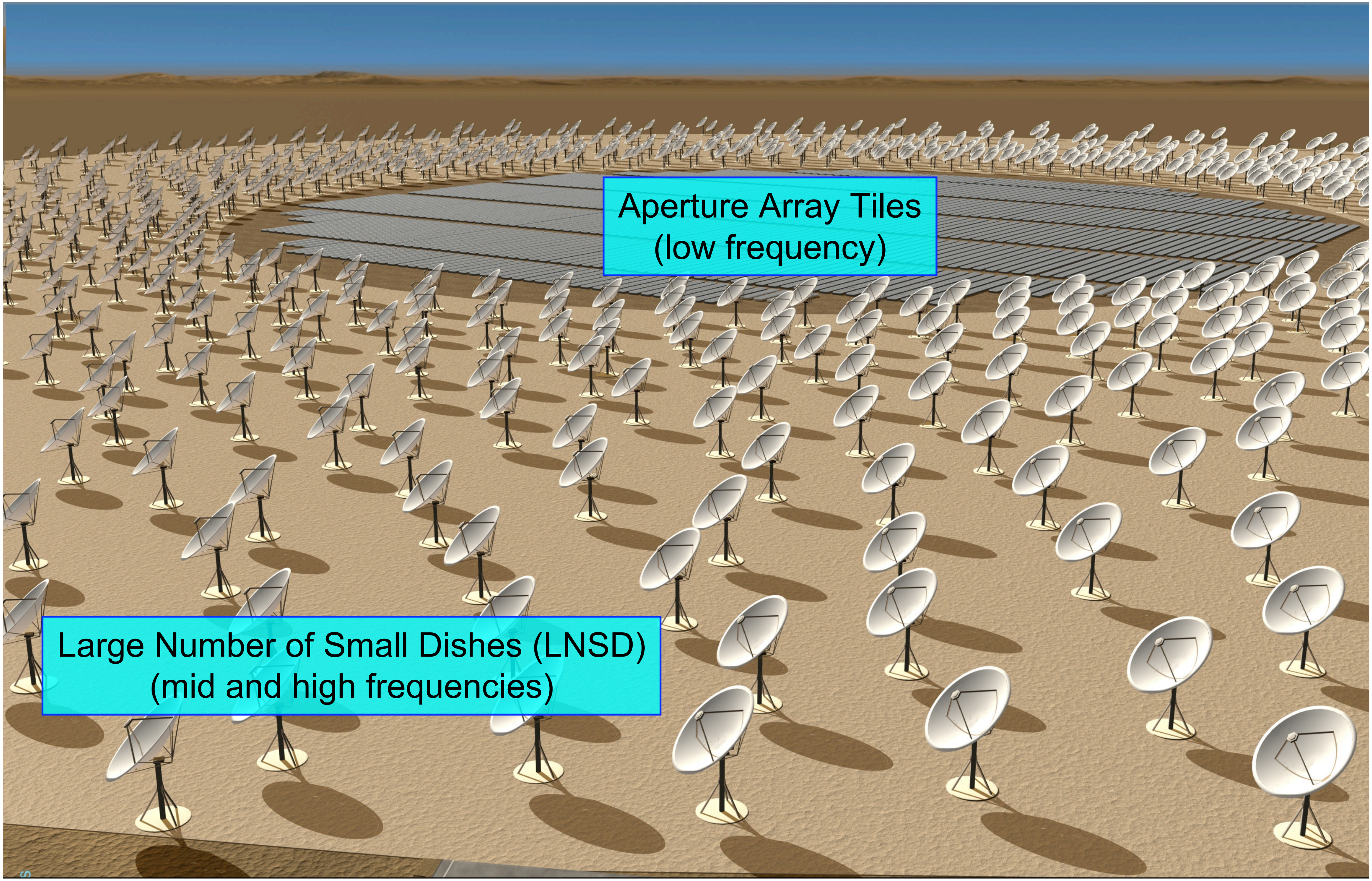
Hubble Hydrogen Array (Peterson)

LOFAR (de Bruyn)

FAST (China)



# 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 $10^9$ $m^4 K^{-2} deg^2$
    - is this important enough?
  - this is a critical issue to deal with in RSSKA DR planning

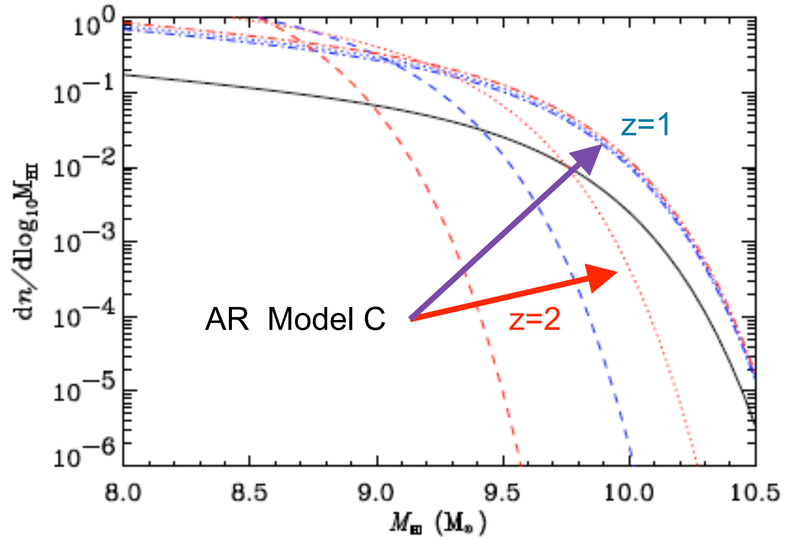



Figure 1. Predictions of the evolution in the HI mass function from AR2004. The dot-dashed lines show their 'Model A' at $z = 1$ (lower, blue) and $z = 2$ (upper, red) with the solid (black) line showing the measured local HI mass function (Zwaan et al. 2003). The dashed lines show their 'Model B' at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

How do we get to precision "DE" sensitivity?

# Example: HI Survey Strategies

- Reference design (RD): 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
  - RD: 19.9h per z=1.5 FOV per year
    - $S_{lim}$=1.75 μJy $\Rightarrow$ $M_{lim}$=4.1x$10^9$ $M_{sun}$ 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
  - RD: 110h per z=1.5 FOV per year
    - $S_{lim}$=0.39 μJy $\Rightarrow$ $M_{lim}=8.8\times10^8$ $M_{sun}$ 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
  - RD: 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
  - RD: 1931 hours per z=1.5 FOV per year
    - $S_{lim}$=0.13 μJy $\Rightarrow$ $M_{lim}=3\times10^8$ $M_{sun}$ 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 ~$10^4$ times the processing of the VLA
  - would take 12000 12-m dishes
    - take ~$10^5$ 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

# Challenges

- Scope of RSSKA
  - current design is as “general purpose” radio array
  - could cut costs by:
    - relaxing upper frequency (10GHz) to 3 GHz
    - possibly by focusing on low-resolution power spectra
    - aperture (dipole) arrays like EOR-SKA (but 1/4 wavelength)
- Costing of RSSKA
  - technology choices, wide-field upgrades, computing
- Data Management
  - is >1/3 the capital cost, and thus must be designed
  - how much processing is “real-time”?

# Great Surveys
## and the RSSKA

# 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
- "Great Surveys" Workshop
  - bring together workers from the next-gen projects
  - hold in Santa Fe in November 20-22 2008
  - organization underway

# 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…