Cosmological Galaxy Surveys:

Future Directions at cm/m Wavelengths

Steven T. Myers* (NRAO),

J. Lazio (NRL), P.A. Henning (UNM)

**National Radio Astronomy Observatory, Socorro, NM*

Science Goal: Cosmology

- Cosmological HI Galaxy Survey
  - HI spectra for > billion galaxies to z > 1.5
  - cosmological parameters (DE) through BAO
  - growth of structure (counts, galaxy evolution)
  - the focus of this talk
- Galaxy Continuum Photometry
  - cosmic ray continuum in Milky Way-like galaxies
  - weak lensing studies (DE)
  - AGN surveys
- Magnetic Field Mapping
  - Faraday rotation mapping
  - intergalactic/primordial fields

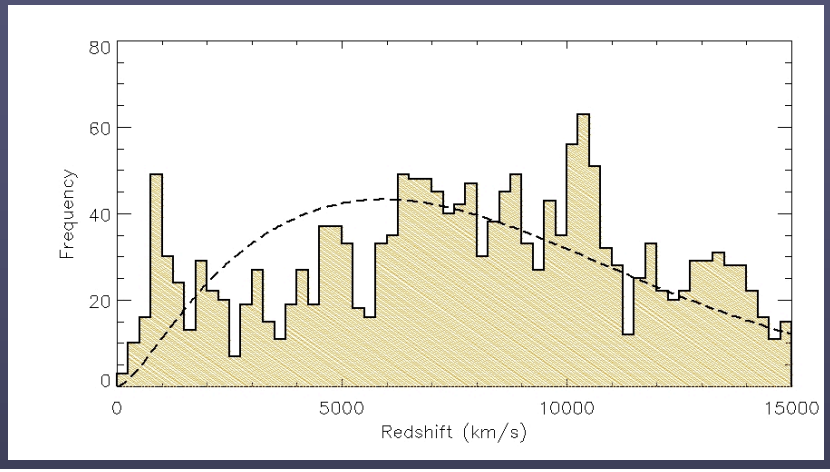
Instrumenting the Science

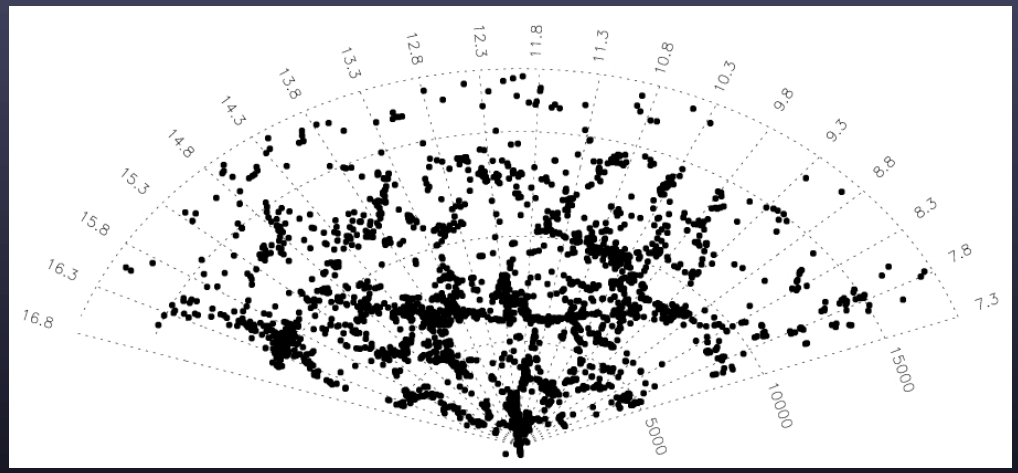
- Science Precursors (z < 0.5)
  - Expanded Very Large Array EVLA (NM)
  - Allen Telescope Array ATA (CA)
  - Arecibo Observatory AO (PR)
  - Green Bank Telescope GBT (WV)
- Pathfinders (z < 0.8)
  - ASKAP (Australia)
  - MeerKAT (S.Africa)
- Ultimate Science 2020
  - the Square Kilometer Array (SKA)

State of the Art: ALFALFA Local Cone

- The Arecibo ALFALFA survey will see 2000-3000 galaxies with HI mass to 10^7 M_{sun}
- The SKA pathfinders will improve mapping speeds by 10-25x
- The SKA-RSST will see around 1 billion galaxies to z=1.5

courtesy M. Haynes





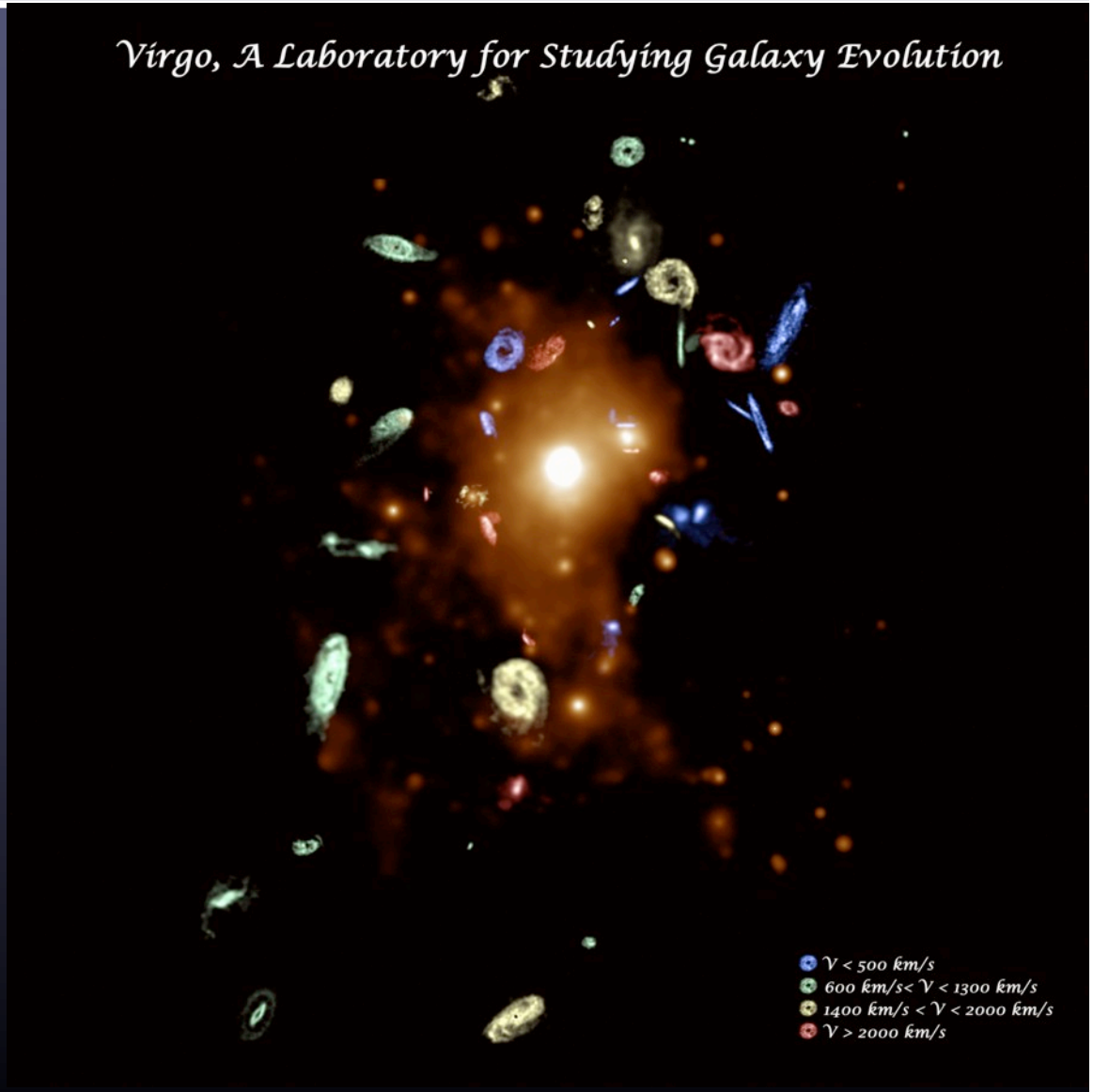
current science precursors can push us out to z~0.2

S. T. Myers-SKA

339.02 AAS Long Beach – 06 Jan 2009

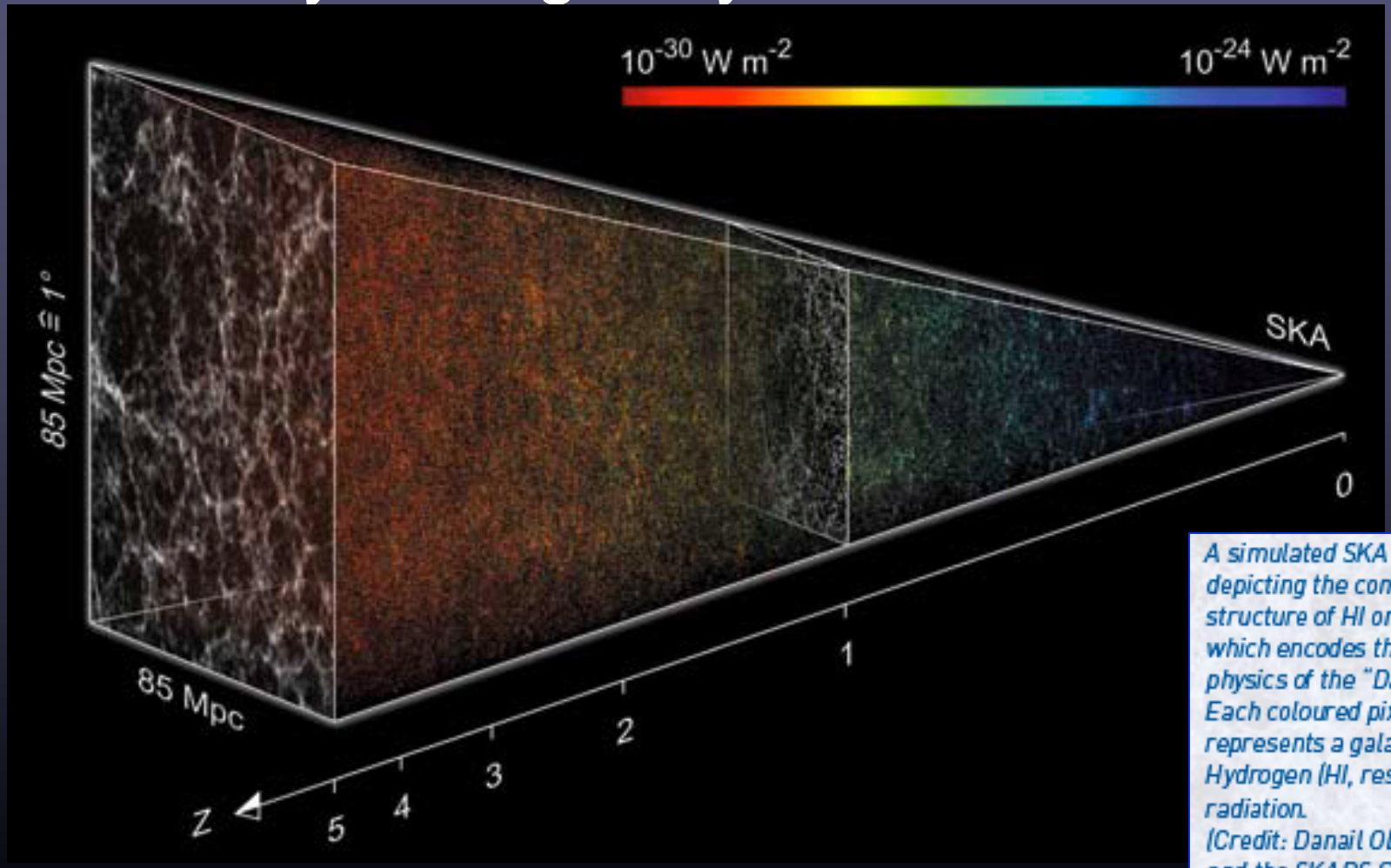
State of the Art: VLA VIVA survey

- Virgo cluster
  - 47 galaxies
  - HI size magnified x10
  - 20 x 20 deg field
  - A. Chung et al.
- High resolution
  - ID with O/IR
  - kinematics of gas
  - dynamics of mass



Ultimate Cosmology: Billion Galaxies

- 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.)

HI Cosmology

- "billion galaxy" HI survey
  - redshifts for gas-rich galaxies out to z=1.5 (and beyond)
  - Baryon Acoustic Oscillations (BAO) [$\sigma_w \sim 0.01$]
  - 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 & NASA communities
  - engage O/IR extragalactic and cosmology communities
  - NASA missions (JDEM, Planck, JWST, GLAST, etc.)

Outfitting a SKA for Cosmology

- SKA could 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 galaxy distribution function studies
  - redshifts are limited only by galaxy HI profile
- Ref: Abdalla & Rawlings 2004

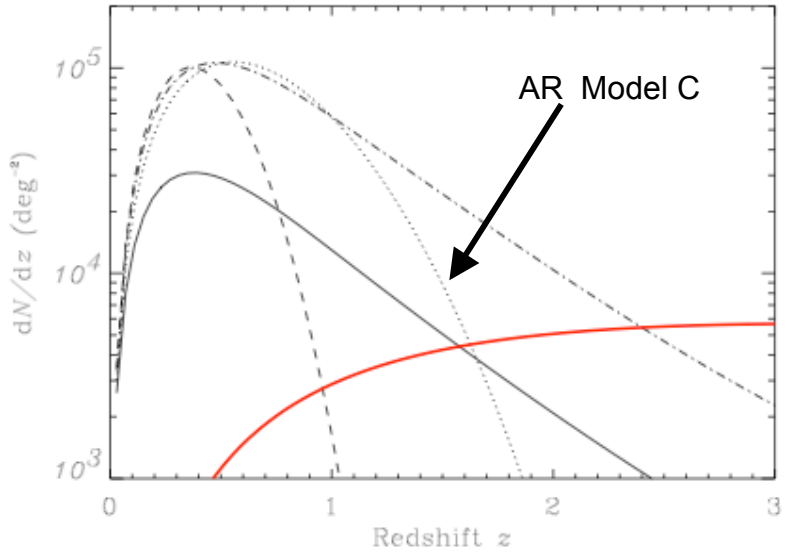
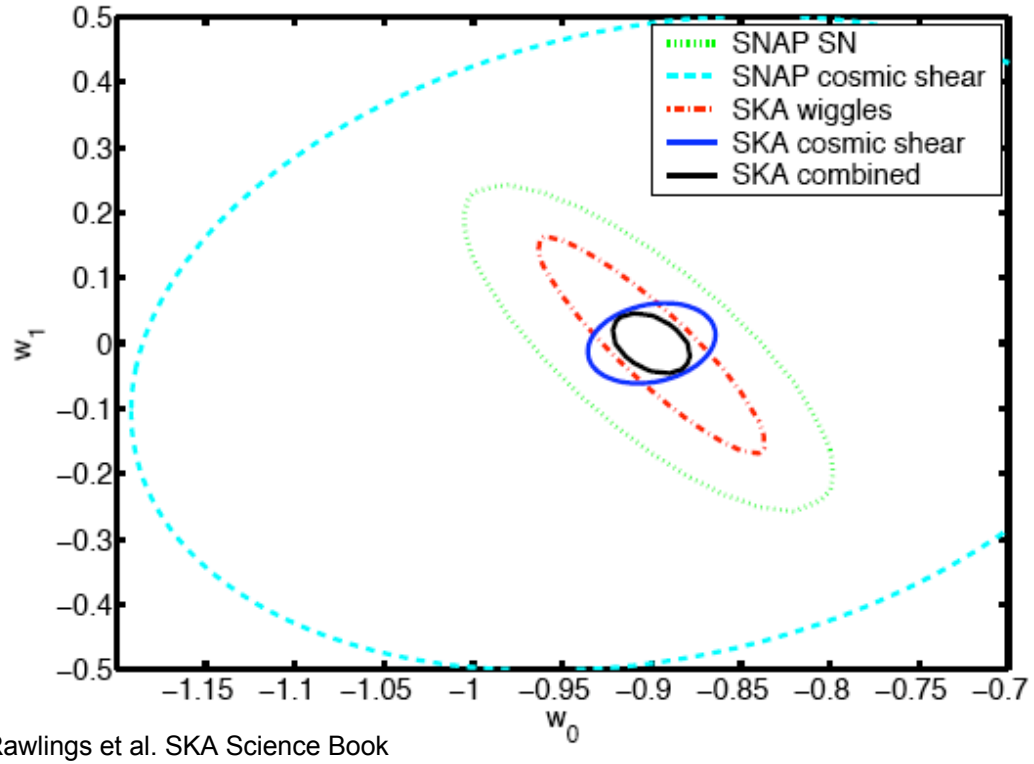


Figure 3. Predictions of dN/dz per deg^2 for an SKA survey with an exposure time of 4 hours, a signal-to-noise detection limit of 10 and assumptions about the properties of the HI-emitting galaxies and the SKA detailed in Sec. 2. The same linestyles are used as in Fig. 1 to discriminate between the different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

SKA for Dark Energy

- SKA 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 $m^4K^{-2}deg^2$
  - 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

SKA for Dark Energy

- SKA 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 $m^4K^{-2}deg^2$
  - 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…

Tang et al. arXiv:0807.3140 (astro-ph)

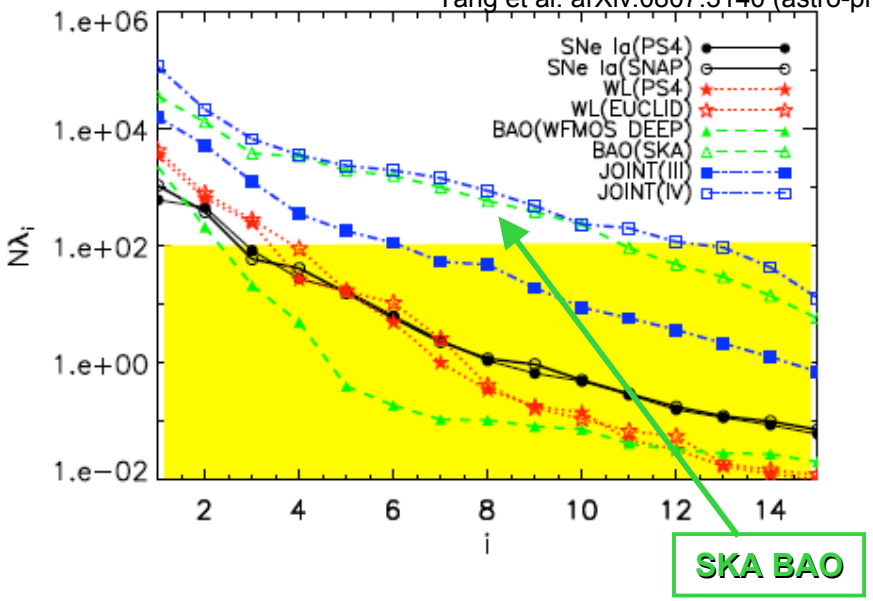


Figure 19. The weighted eigenvalues for the surveys that we used in the joint analysis. Every line represents a survey. All the surveys are marginalized over other parameters including Planck priors. The (black) solid line shows SNe Ia surveys with the filled and unfilled circles indicating PS4 and SNAP, respectively. The (red) dotted lines represents WL surveys with the filled and unfilled stars indicating PS4 and EUCLID, respectively. The (green) dash lines represents BAO surveys with the filled and unfilled triangles indicating WFMOS deep and SKA, respectively. We also show the joint analysis with the (blue) dotted-dash lines; the filled and unfilled squares indicating stage III and IV, respectively.

Rawlings et al. SKA Science Book

The z>1 HI Challenge!

- SKA Reference Design (v2.7.1)
  - RD: 3000 x 15m single-pixel feeds
  - 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
- HI mass function
  - z=2 HIMF steep above 10^{10} M_{sun}
    - HIMF target for science precursors
  - if M_{lim} x2 then N x 10^{-3} to 10^{-4} or worse!
    - in danger of getting < 10 million galaxies at z>1
  - precision Dark Energy not do-able with BD
    - need SSFoM > 4-6 x 10^9 $m^4K^{-2}deg^2$
    - is this important enough?
  - upgrade path and technology development key to ultimate HI cosmology goals

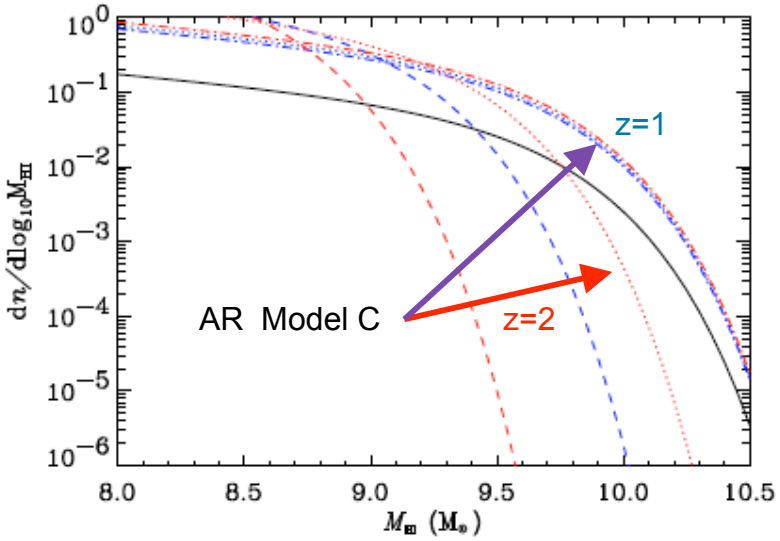


Figure 1. Predictions of the evolution in the HI mass function from AR2004. The dot-dashed lines show their 'Model A' at $z = 1$ (lower, blue) and $z = 2$ (upper, red) with the solid (black) line showing the measured local HI mass function (Zwaan et al. 2003). The dashed lines show their 'Model B' at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

The Road to the SKA

The Radio Synoptic SKA (RSSKA)

- SKA as Radio Synoptic Survey Telescope
  - 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
- Commensal Surveys
  - cadences of synoptic observation to accommodate transients

Example: HI Survey Strategies

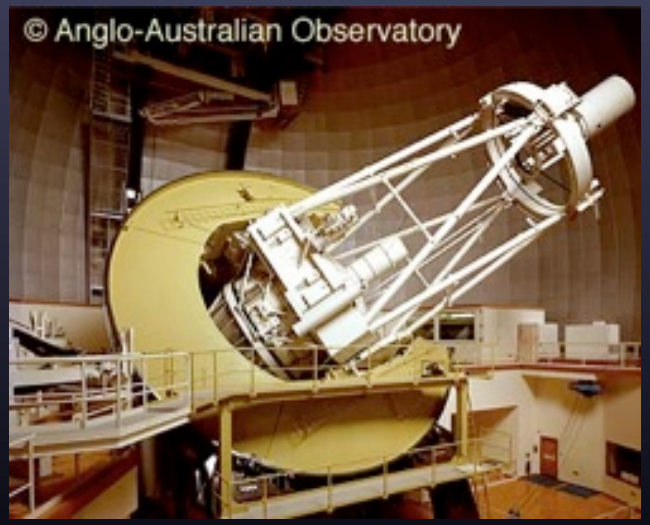
- Duration of Survey: 20 year mission
  - 5 years Wide, 5 years Deep, 3 years med-deep Galactic plane
  - 2 x 1 year ultra-deep fields (Galactic Center, Virgo deep, other?)
  - 5 years GO or TOO and follow-up (25%)
- Wide "Quarter Sky" = 10000 deg^2
  - 8.64s per deg^2 per day = 4.38 hours per deg^2 in 5 years
  - RD: 19.9h per z=1.5 FOV per year
    - S_{lim}=1.75 μJy $\Rightarrow$ M_{lim}=4.1x10^9 M_{sun} at z=1.5 ($\Delta\nu$=0.38MHz)
- 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}=8.8x10^8 M_{sun} at z=1.5 ($\Delta\nu$=0.38MHz)
- 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}=3x10^8 M_{sun} at z=1.5 ($\Delta\nu$=0.38MHz)

Current State of the Art in Surveys

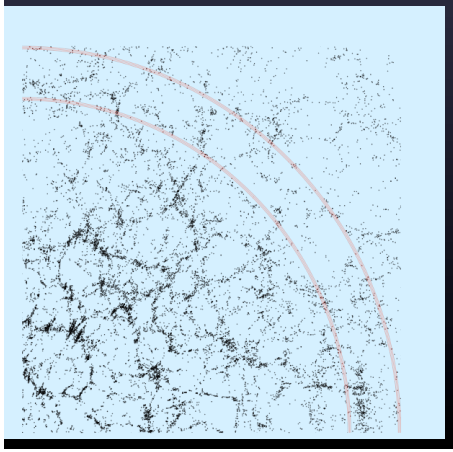
Four published results

1. Eisenstein et al 2005 (spectro-z)
   3D map from SDSS 3%
   46,000 galaxies in 0.72 $(h^{-1}Gpc)^3$
2. Cole et al 2005
   3D map from 2dFGRS at AAO (spectro-z) 5%
   221,000 galaxies in 0.2 $(h^{-1}Gpc)^3$
3. Padmanabhan et al 2007
   Set of 2D maps from SDSS (photo-z) 5%
   600,000 galaxies in 1.5 $(h^{-1}Gpc)^3$
4. Blake et al 2007
   (Same data as above)

SDSS 2.5-m telescope, Apache Point, NM



AAO 4-m telescope at Siding Spring, Australia



HI surveys are currently lagging in numbers of detections

Thanks to Pat McDonald (CITA)

Complementarity: O/IR Spectroscopic 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!

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)

For more information…

- AAS Town Halls / Community Meetings
  - ATA Surveys
    - Tuesday Jan 6 (6pm-10pm Hyatt Seaview Ballroom)
  - NRAO Town Hall
    - Wed Jan 7 (5:30pm-7pm Hyatt Seaview Ballroom)
- my RSST/RSSKA page
  - http://www.aoc.nrao.edu/~smyers/rsst
- Great Surveys Workshop Nov 2008
  - http://t8web.lanl.gov/people/salman/grsurveys/
- SKA Info
  - http://www.skatelescope.org
  - particularly see the “Science Book”
    - “Galaxy Evolution, Cosmology, and Dark Energy with the SKA” by Rawlings et al.