The Radio Synoptic Survey Telescope (RSST):
a SKA mid-frequency concept

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What is the RSST?

The Radio Synoptic Survey Telescope

- The RSST concept is for a “SKA-mid” facility
  - it is proposed here as the “SKA-mid” from a US science perspective
  - name tentative: possibly RSSKA (say “risque”) :)
- Primary Science Goals
  - Cosmological HI
  - Deep continuum imaging
  - Transient detection and monitoring
- Also
  - other redshifted lines (e.g. OH mega-masers)
  - exploring the unknown…

The International "SKA-mid"

- from the Preliminary Specifications document
  - see http://www.skatelescope.org
  - would be located in Southern radio-quiet site
    - Western Australia or South Africa
  - design not settled, still a number of options explored
  - large number of small dishes (LSND)
    - 3000 x 15m dishes, single-pixel feeds
    - or 2000 x 15m dishes, plus phased-array feeds (20deg^2)
    - possibly plus dense aperture tile array at 500-800 MHz
    - only 0.25-0.36 square kilometer of effective area
    - preliminary upper frequency limit 10 GHz
    - lower frequency limit in range 300-500 MHz
  - co$t: spec-ed 950M€ (ph1+2), ~ ALMA

The RSST is …

- NOT a new concept
  - pretty much what is proposed in SKA Science Book
  - is what appears in the DETF report as the “SKA”
- NOT a technology development project
  - pathfinders and technical demonstrators are underway
  - builds on the USSKA Technical Development Program
- NOT unconnected to the rest of Astrophysics
  - complementary to other big multi-wavelength surveys
  - e.g. LSST, PanSTARRS, JDEM, …
  - for the physics and astronomy of 2020

The RSST 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 ~ $n_a n_b/T$ “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 $2\text{-}8^s$ per point
  – 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)

Is the RSST a …

- National Facility?
  - well, its an international facility, but an National resource for US astronomers
- targeted experiment?
  - the primary science goals & key projects are big surveys
- general observer facility?
  - probably not primarily, but perhaps 10-25% of time could be made available for proposers (and for TOO)
- an exclusive club?
  - No! RSST must involve and support a large part of the US astronomy community

RSST 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 Survey (DeCoS)
    - 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 RSST surveys – freeloading!
- These are part of one big survey (Big Sur)

Example: HI Survey Strategies

- Benchmark design (BD): 12m antennas
  - FOV = 6.28deg^2 at z=1.5 (560MHz) "single pixel"
- Wide "Quarter Sky" = 10000 deg^2
  - 8.64s per deg^2 per day = 52.6m per deg^2 per year
  - BD: 5.5h per FOV per year
    - S_{lim}=1.12 μJy $\Rightarrow$ M_{lim}=2.6x10^9 M_{sun} at z=1.5 ($\Delta\nu$=0.38MHz)
- Deep region = 500 deg^2
  - 173s per deg^2 per day = 17.1h per deg^2 per year
  - BD: 110h per FOV per year
    - S_{lim}=0.25 μJy $\Rightarrow$ M_{lim}=5.7x10^8 M_{sun} at z=1.5 ($\Delta\nu$=0.38MHz)
- Duration of Survey: 10 year mission
  - 5 years Wide (0.5μJy) and 5 years Deep (0.1μJy)
  - room for other surveys (Galactic Plane/Center, Virgo deep, other?)

Example: Synoptic Cycle for SKA-RSST

- A 10-day total cycle: variable scanning rates
  - Fast scan for extragalactic sky (away from Galactic plane)
    - E.g.
      - 1 deg^2 single pixel FoV
      - Full sky survey (80% of 40,000 deg^2)
      - T_{scan} = 5 days
      - T ~ 10 sec = time per sky position
      - S_{min} ~ 15 μJy at 10σ with full sensitivity and on axis
      - Multiple pixel systems (PAFs) increase sensitivity (for fixed total time)
      - Subarrays reduce sensitivity but speed up the survey
  - Slow scan for deep extragalactic fields and Galactic plane
  - Galactic center: staring mode
  - Repeat scans many times
  - Break out of scanning mode for targeted observations (10%?)
  - Break out for targets of opportunity
- Issues for pulsars (~steady amplitudes):
  - Need minimum contiguous dwell time for Fourier transforms (e.g. 100 – 1000 s for large-area blind surveys)
  - Need frequent re-observation coverage for long-term timing followup

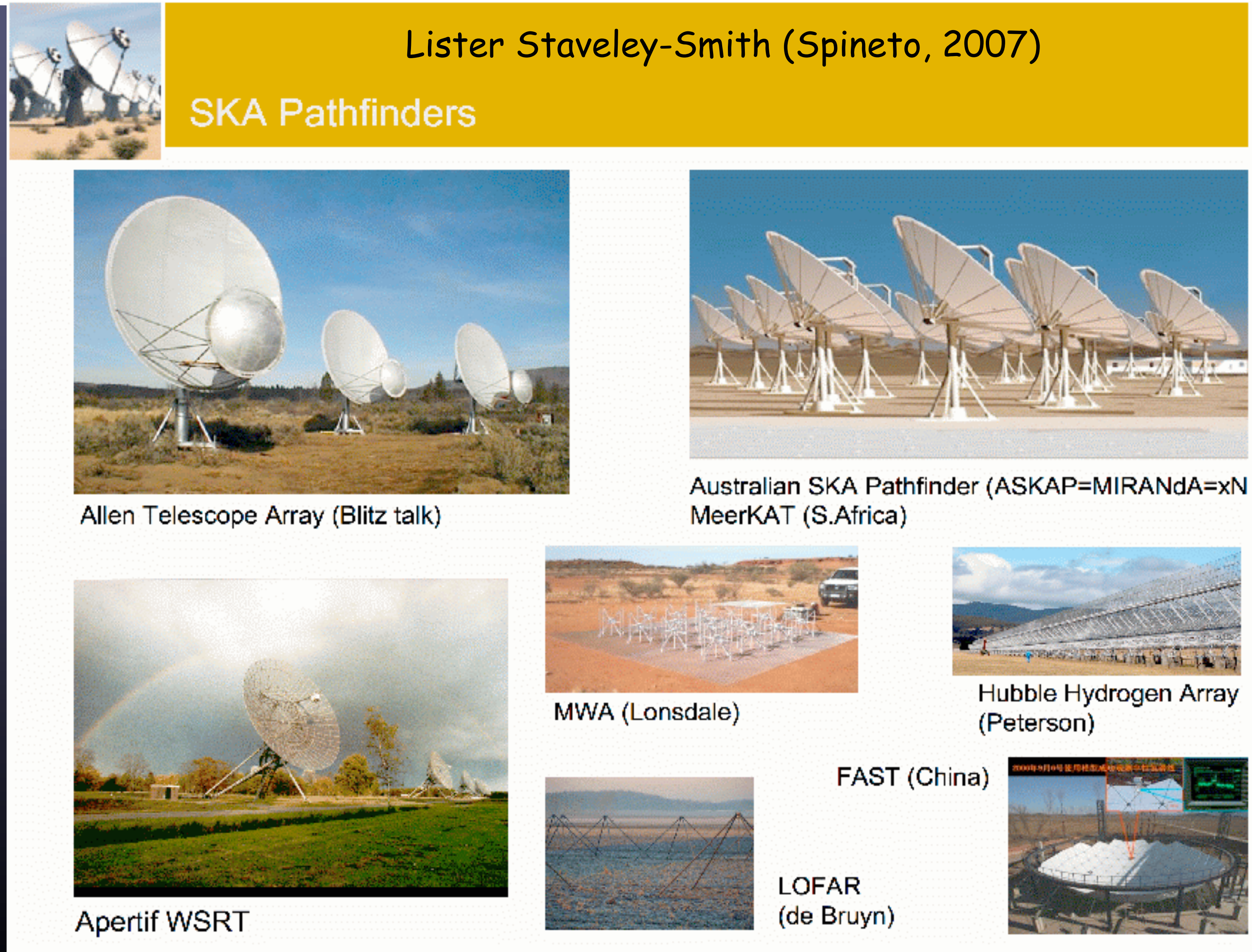
Realizing the RSST

Science Precursors

- The case for precursor science
  - do not just “stop everything” to build new stuff
  - need science output throughout decade
- Use “current” facilities
  - Arecibo, EVLA, GBT, VLBA, ATA
    - e.g. ALFA for HI surveys, large EVLA surveys
  - also mm/sub-mm : ALMA, CARMA, CSO, etc.
  - also other wavebands : O/IR, Xray, Gamma Ray, etc.
- Use in new (and complementary) ways
  - pilot surveys and special targets
  - also science with SKA demonstrators (ASKAP, meerKAT)

SKA Pathfinders

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



The RSST 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 RSST!
    - Pathfinders/Precursors: ALFA, EVLA, ATA, ASKAP, MeerKAT
  - SKA-high: 5-50 GHz
    - Cosmic Star Formation and the “Cradle of Life”
    - Pathfinders/Precursors: EVLA, ATA
  - eventually SKA-ultra-high: beyond ALMA?

SKA-RSST in Perspective

- A full 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
  - SKA-RSST 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)?

RSST Challenges

- Need lots of telescopes (most designs)
  - cost issues, e.g. want < $500 per square meter
  - maintainance issues
- Huge data volumes and rates
  - fairly aggressive for 2020 (but not forefront)
  - partner with other data-intensive projects
- Likely require real-time processing
  - must have fast and robust pipeline
- Need to estimate cost for Decadal Review
  - ~1/3 of project - this is what worries me most right now!

HI Evolution & Cosmology with the RSST

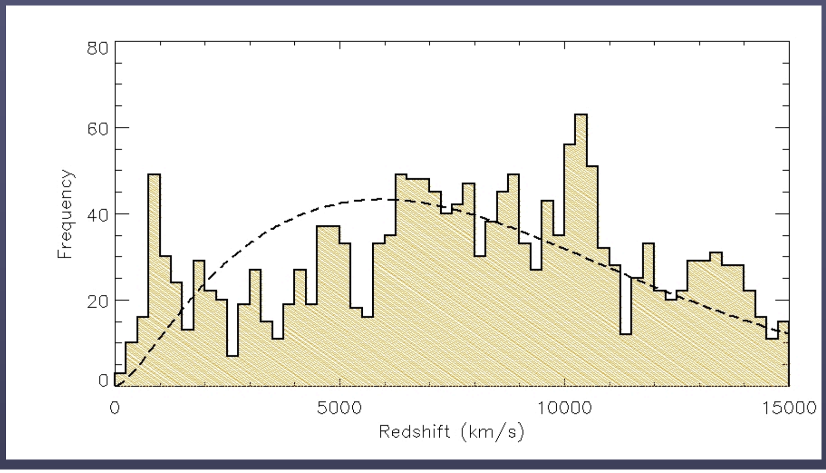
Making a Map of the Universe

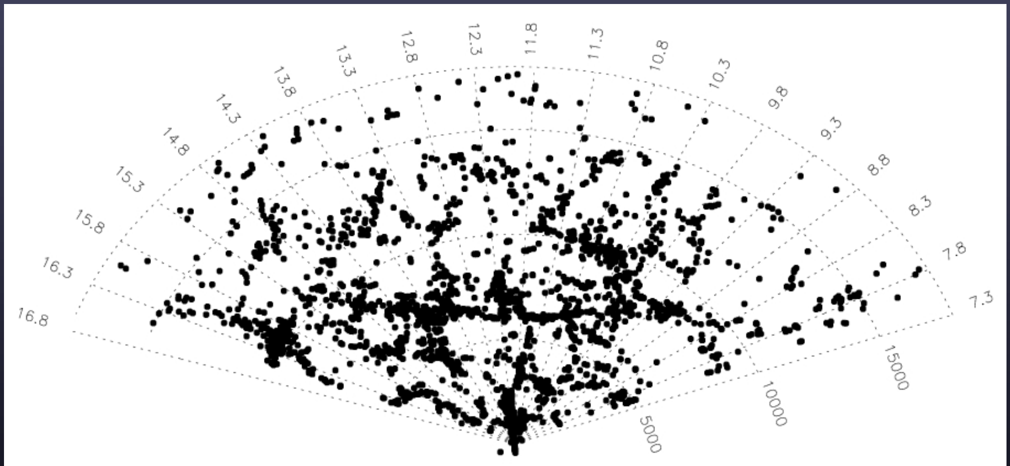
- The Whole Universe Telescope
  - must see all the universal constituents
    - luminous matter - stars, HII regions, thermal emissions
    - quiescent gas - HI, molecular clouds and cores
    - planetary objects - exo-planets, proto-planetary & debris disks
    - energetic particles - cosmic rays, “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 SKA-RSST is part of this future

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

RSST Science Example: HI Cosmology

- "billion galaxy" cosmological HI survey
  - redshifts for gas-rich galaxies out to z=1.5 (and beyond)
  - cosmography of Universe d(z) , V(z) ⇔ H(z)
  - Baryon Acoustic Oscillations (BAO) w/anti-biased tracers
  - 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
  - mutual interest with the DOE community (JDEM)
  - engage O/IR extragalactic and cosmology communities
  - NASA missions (JDEM, Planck, JWST, GLAST, etc.)

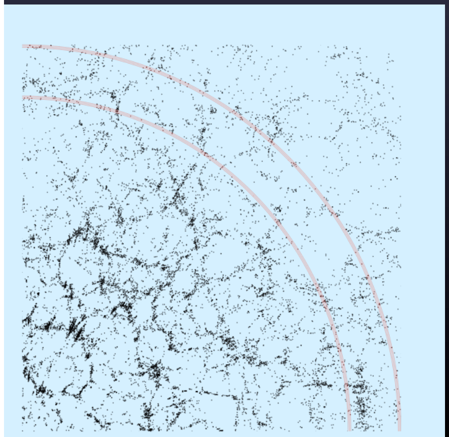
Current State of the Art in Surveys

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)
   221,000 galaxies in 0.2 $(h^{-1}Gpc)^3$ 5%
3. Padmanabhan et al 2007 (photo-z)
   Set of 2D maps from SDSS 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 woefully behind in numbers of detections

Thanks to Pat McDonald (CITA)

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

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

RSST 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 SKA
- 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

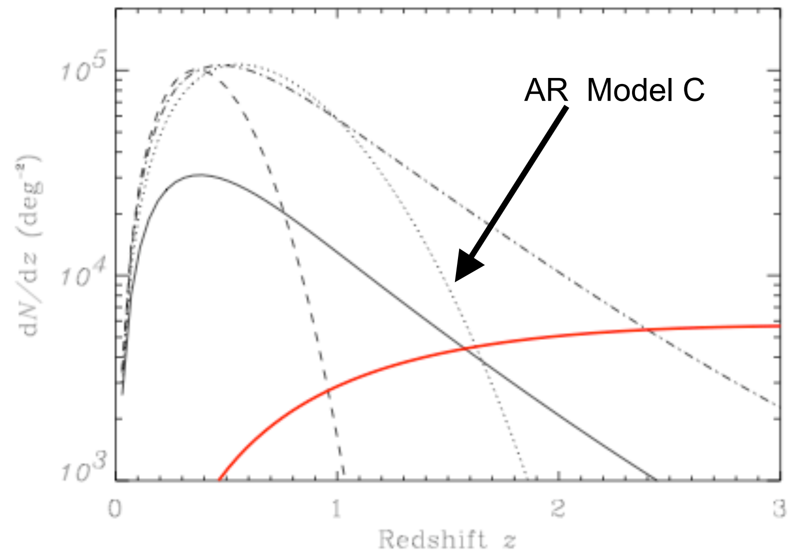


Figure 3. Predictions of dN/dz per deg^2 for an SKA survey with an exposure time of 4 hours, a signal-to-noise detection limit of 10 and assumptions about the properties of the HI-emitting galaxies and the SKA detailed in Sec. 2. The same linestyles are used as in Fig. 1 to discriminate between the different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

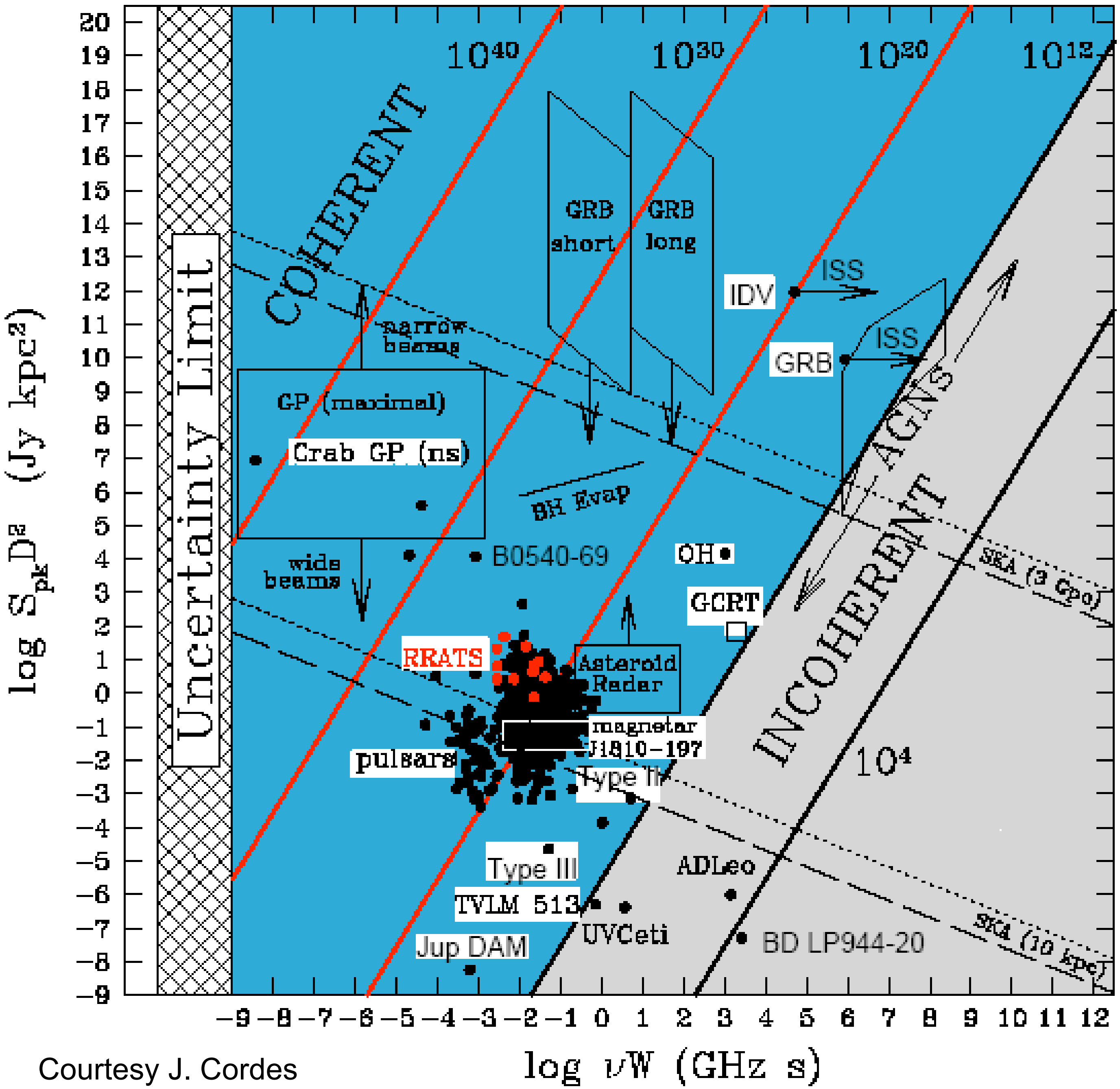
Rawlings et al. SKA Science Book

RSST Science Example: Continuum

- Extremely deep (10 nJy) continuum survey
  - "billion" extragalactic radio sources
  - locate counterparts to HI detections
  - 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

RSST Science Example: Transients

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



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

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

W = pulse width or characteristic time scale

Great Surveys

Great Surveys for a "2020 Vision"

- The SKA is part of a grand vision for the coming decades, including:
  - Large Synoptic Telescope (LST: LSST, Pan-STARRS)
  - Giant Segmented Mirror Telescope (GSMT: TMT, GMT)
  - Square Kilometer Array (RSST, 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 and Mining areas!
- A wide array of capabilities
  - large general purpose observatories
  - smaller more agile telescopes
  - targeted experiments
- 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

Astronomical Great Surveys

- 2015-2030 Era of “Great Surveys”?
  - all-sky and deep surveys in multiple wave-bands
  - billions of objects catalogued
  - extensive follow-up using big telescopes
  - data mining, virtual observatories, the wired world
- Astronomical “Great Surveys” Workshop
  - bring together workers from the next-gen projects and the current cutting-edge
  - science drivers and technical issues
  - hold in Santa Fe in July/Aug 2008
  - funded by LANL IAS & NRAO
  - scientific organization underway

Provocation: Discussion Topics

Open Questions for Discussion

- Key Science Drivers & Core Capability
  - what is it that forces you to build the RSST as a SKA?
  - HI Cosmology
    - must have SK area with high survey speed to see enough galaxies at z>1.5
    - must have good enough (1"?) resolution to identify with galaxies seen in O/IR surveys
  - Pulsar Gravity Probes
    - higher frequencies (5 GHz?) but low resolution
  - Deep Continuum Surveys
    - resolution to beat confusion limit and make IDs (see SF?)
    - high-quality polarimetry for RM "cosmic magnetism" surveys
  - co$ting: what do we keep and what do we drop?

Some tough questions

- Are there other (less expensive) ways?
  - targeted experiments (e.g. a HI Structure Experiment)?
  - is radio/HI the right waveband?
- How do you want to use the RSST?
  - focus on surveys? or more time for GO projects?
  - what sort of data products?
  - does the RSST need to be outfitted uniformly?
    - all frequency bands at start? or upgrade later?
    - all bands on all telescopes? core to higher frequency?
    - configurations: low-res core vs. high-res long baselines?
    - is the current "design" adequate?
  - what are the co$t impact of these issues?

More Questions

- 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
- 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 ALFALFA? ATA?
  - what about the pathfinders?
  - are there intermediate stages to full RSST?

… and finally

- Landscape 2012-2020+
  - radio is not all there is!
  - what other instruments will be there (first)?
    - LST = very large deep photometric surveys + transients
    - GSMT = deep spectroscopy
    - JWST = high-quality IR imaging
    - others (Planck &beyond, Herschel, GLAST, GAIA, Ligo2/LISA, ConX/Xray?, JDEM, other surveys)
  - what makes a RSST (or other SKA) compelling?
    - what things are unique?
    - what important things are complementary & supplementary?
  - does this have to be a competition (e.g. w/LST,GSMT)?
    - or part of a coherent vision for Astronomy in 2020?

For more information on RSST…

- RSST Proto-White Paper (draft)
  - on the Arecibo Frontiers conference website:
    http://www.naic.edu/~astro/frontiers/RSST-Whitepaper-20070910.txt
- RSST Web 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…
- stay tuned for Great Surveys workshop