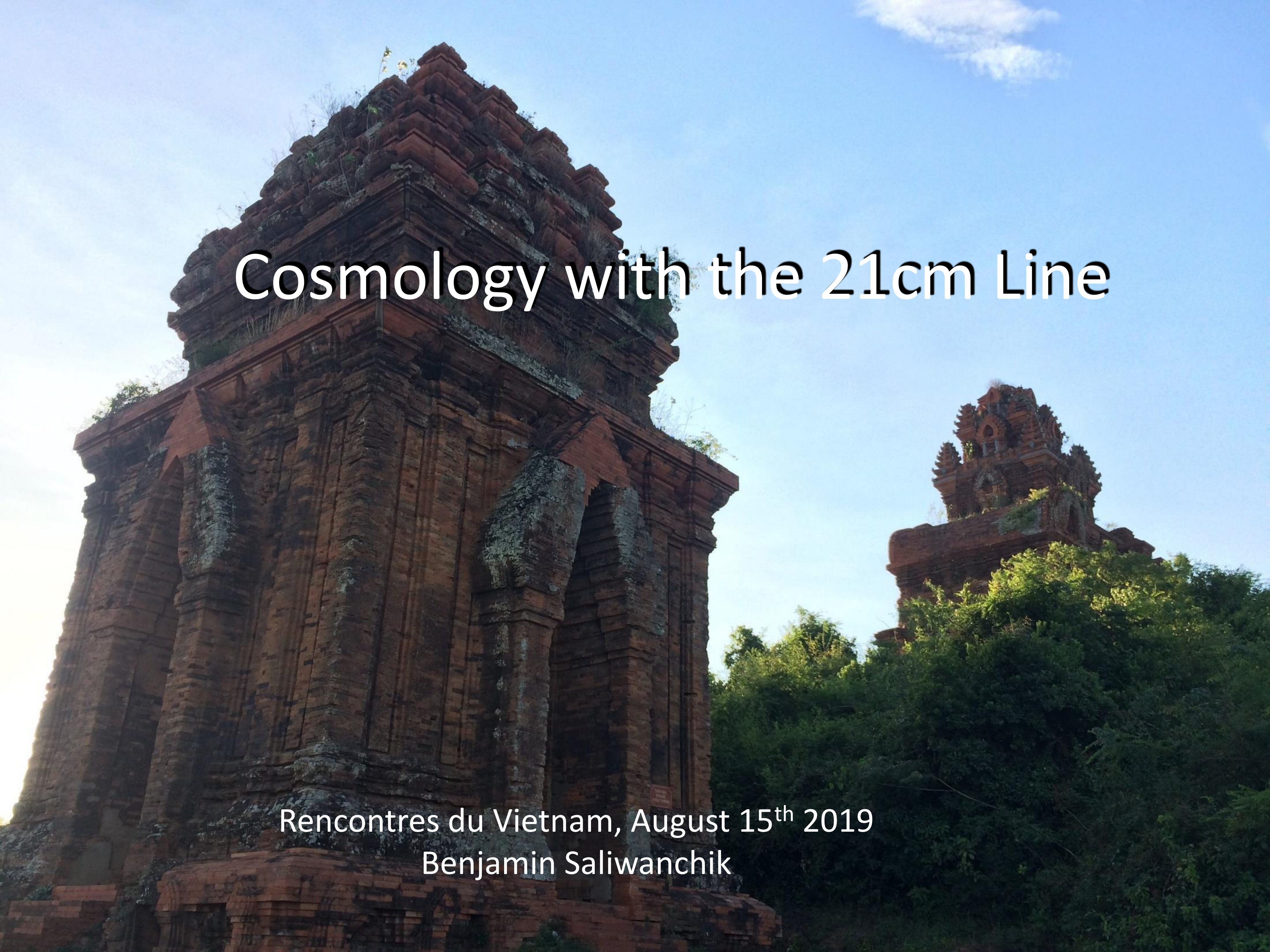
Cosmology with the 21cm Line



Rencontres du Vietnam, August 15th 2019

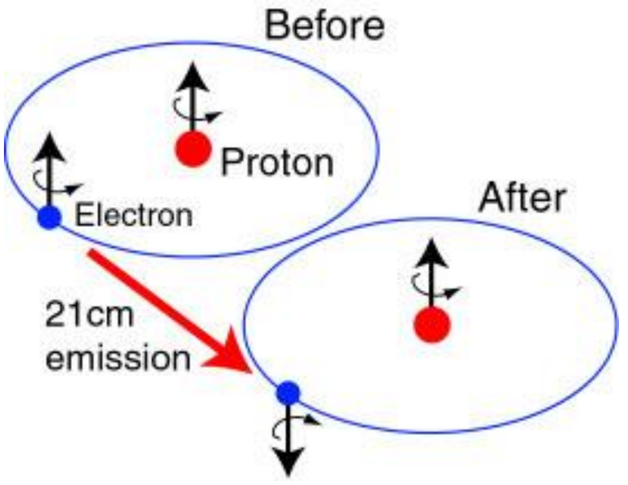
Benjamin Saliwanchik

Outline

- The 21cm: What is it, and why is it interesting for cosmology?
- Survey of current experiments: EDGES, PRIZM, HERA, HIRAX, CHIME
- Future work: development requirements

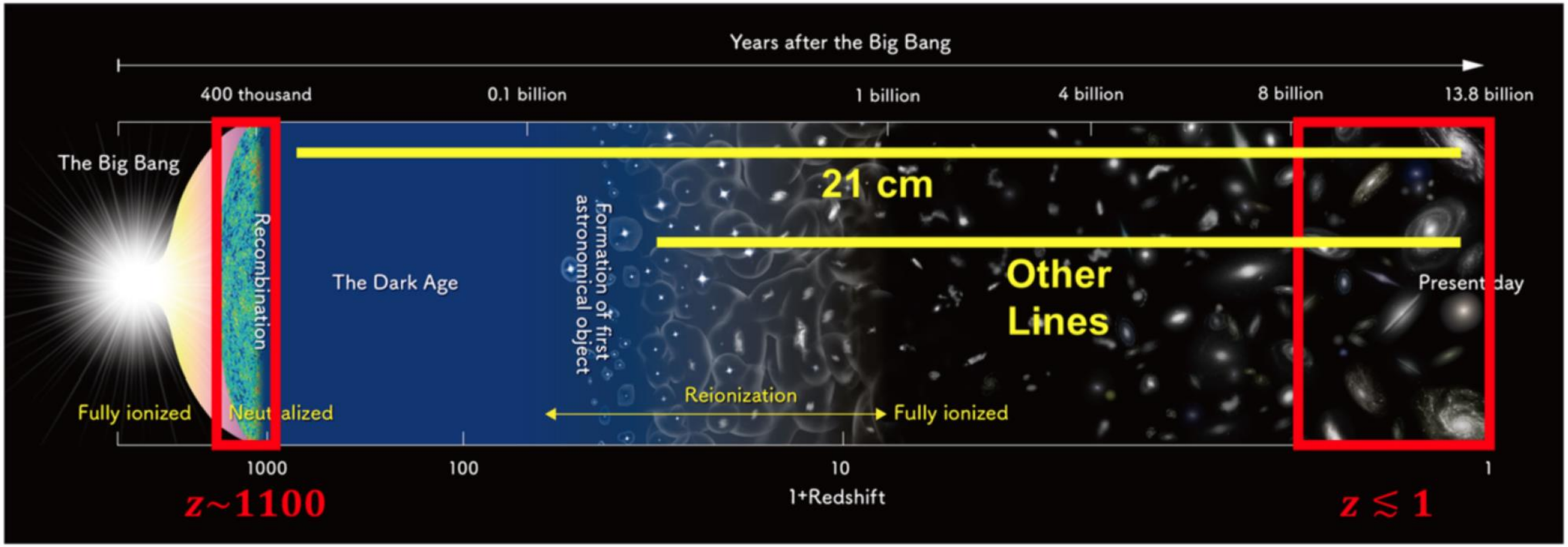
21 cm Line as Cosmological Probe

- Hydrogen atom has slightly higher energy when electron and proton spins are aligned, this produces the hyperfine splitting of energy levels
- Transition in 1s orbital corresponds to emission of a photon with wavelength 21.1cm (1.42GHz)
- This is a "forbidden" transition, ~10Myr lifetime of excited state => observed frequency gives good measurement of redshift of emission.
- Long lifetime means kinetic temperature T_k (atomic motions) can decouple from spin temperature T_s, set by fraction of HI.



21 cm Line as Cosmological Probe

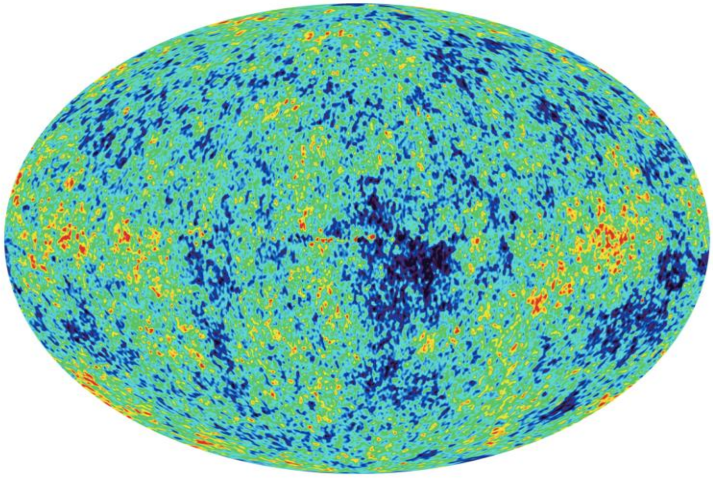
- 21 cm line is a promising cosmological probe, Hydrogen abundant, not much confusion from other lines
- Can use 21 cm line to study history of matter and growth of structure in universe over bulk of cosmological time
- Dark energy drives expansion of universe in late times: 21cm measurements of BAO provide standard ruler for measuring expansion



Line Intensity Mapping: 2017 Status Report (arxiv 1709.09066)

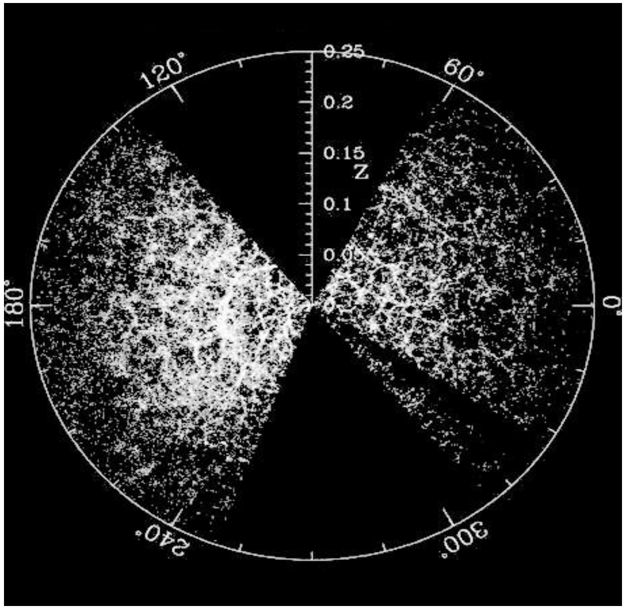
Origin of Baryon Acoustic Oscillations

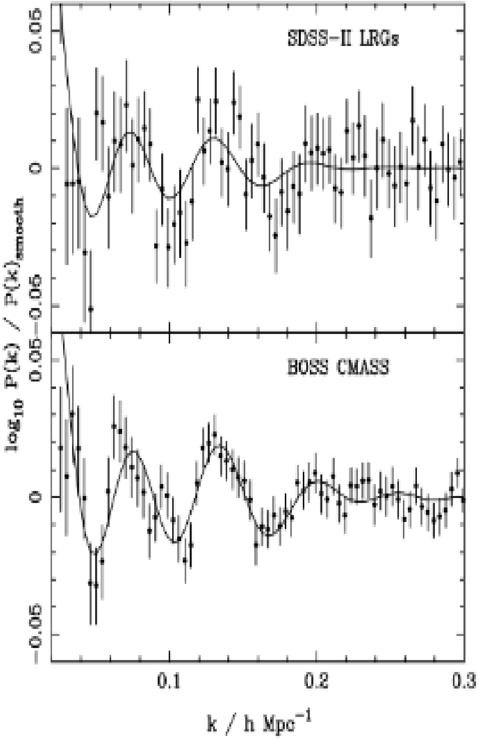
- Before CMB, sound waves in primordial plasma produce density variations. Gravity drives collapse, photon pressure provides restoring force.
- Photons coupled to matter by free electrons, density field produced by sound waves gets locked in when electrons recombine into neutral hydrogen.
- Sound horizon at recombination produces characteristic length scale in density perturbations (~150 Mpc).



Baryon Acoustic Oscillations

- Structures preferentially form in peaks of BAO density field.
- Should see rings of correlation in galaxy positions.

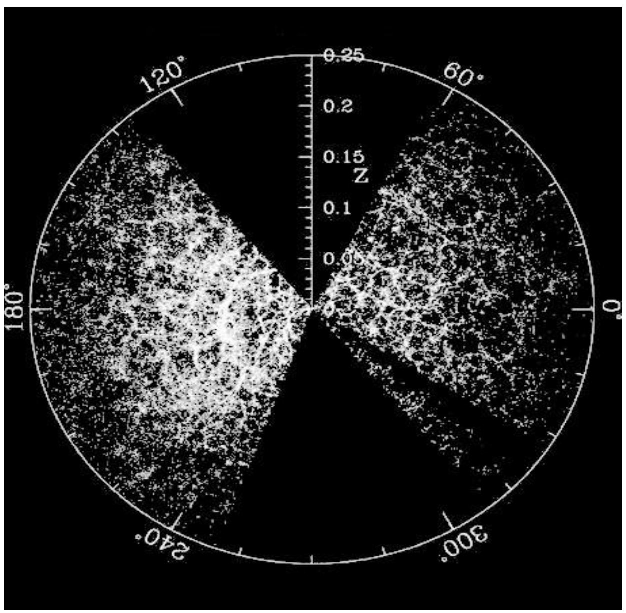


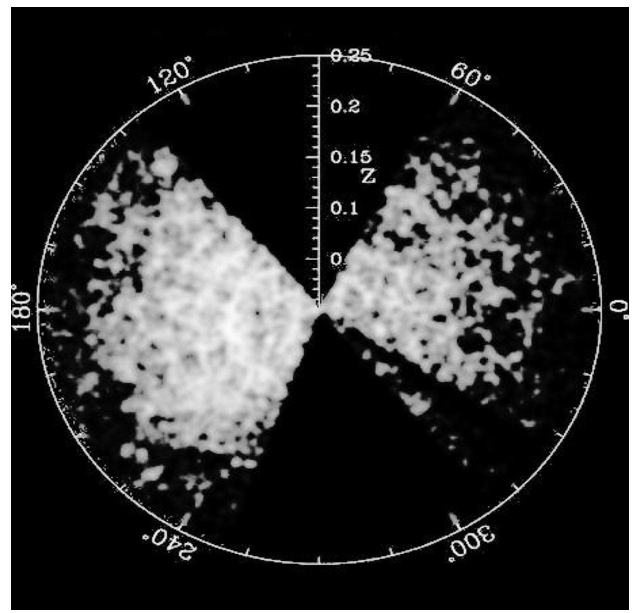


SDSS galaxy power spectrum (Image from SDSS).

Baryon Acoustic Oscillations

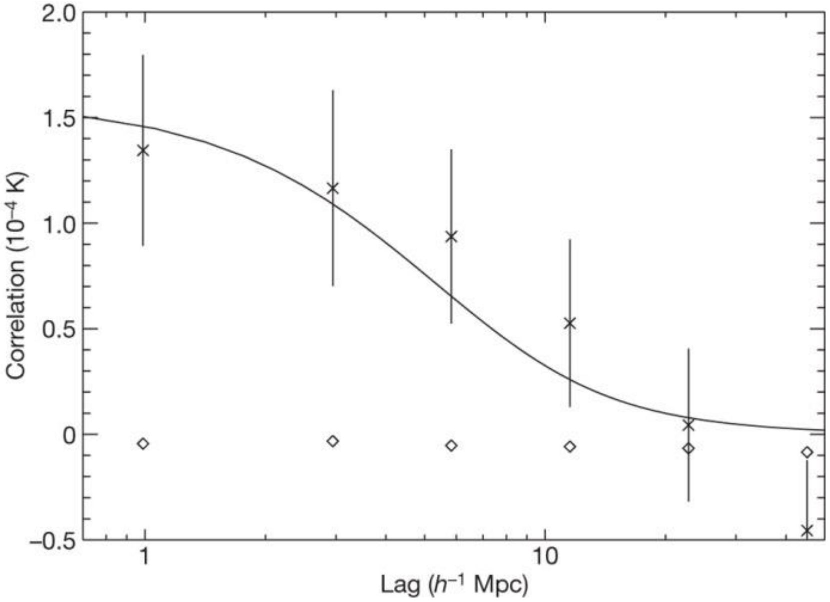
- BAO scale large, to do precision cosmology need lots of volume => large sky area, redshift range.
- Since characteristic scale is large, fine resolution is not necessary.
- Large beams beneficial for increased mapping speed.





Intensity Mapping

- Have ~10^5 L_* galaxies/BAO volume - individual galaxies not that important. Use aggregate signal from many galaxies with low resolution survey.
- Signal is O(0.1 mK), while galactic foreground is O(10^5 K)
- Sample variance limits => map sensitivity of 1-2μJy necessary



- First HI intensity mapping detection, DEEP2 density field x GBT HI brightness temperature cross correlation at z=0.8

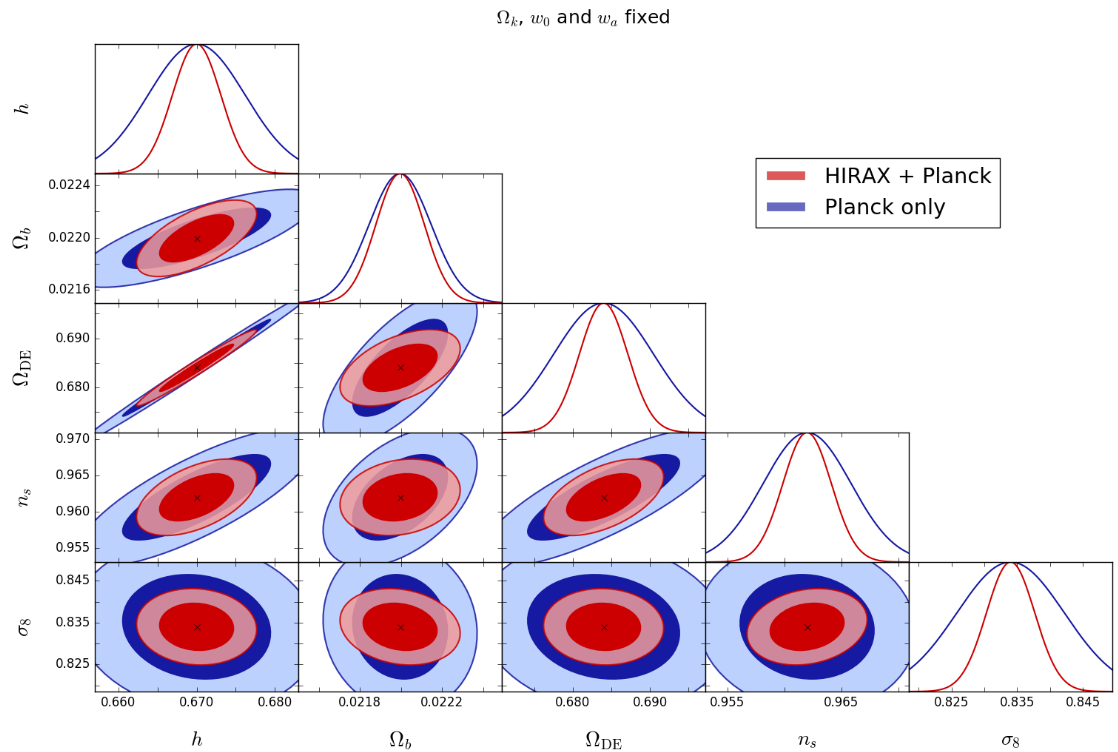
T-C Chang *et al. Nature* **466**, 463-465 (2010) doi:10.1038/nature09187

Why is 21cm Interesting?

- Orders of magnitude increase in number of measurable cosmological modes over CMB and galaxy surveys
- Large period of cosmological time accessible, including only probe of epoch before formation of luminous objects “dark ages”
- Ability to probe very small (down to Jeans) and very large (large FOV) scales
- Breaking degeneracies in cosmological parameters (notably τ)
- Potential for cross-correlation with other observations (optical LSS, CMB lensing)
- “Secondary science” including EoR, FRBs, GR constraints from pulsar timing, neutral hydrogen absorbers, detailed studies of polarized radio emissions of Milky Way and IGM (i.e. “foregrounds”).

Cosmological Parameter Forecasts

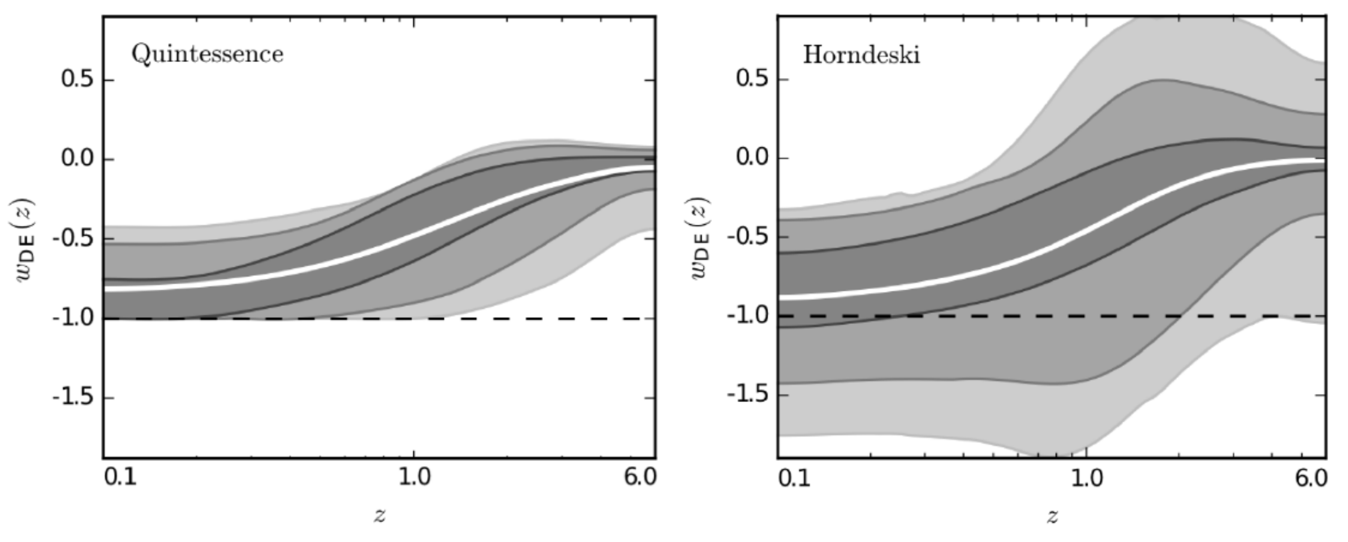
- Example forecast of "current gen" constraints, for HIRAX based on 2000 sq deg survey with 1024 element array, 50K noise temperature, and 10,000 hours observing, with Planck priors
- Expect to improve constraints on late-time cosmological parameters (σ_8, Ω_b, Ω_{DE}, n_s) to <1%



Newburgh et al. 2016 Plots by Amadeus Witzemann

Time Variations in Dark Energy

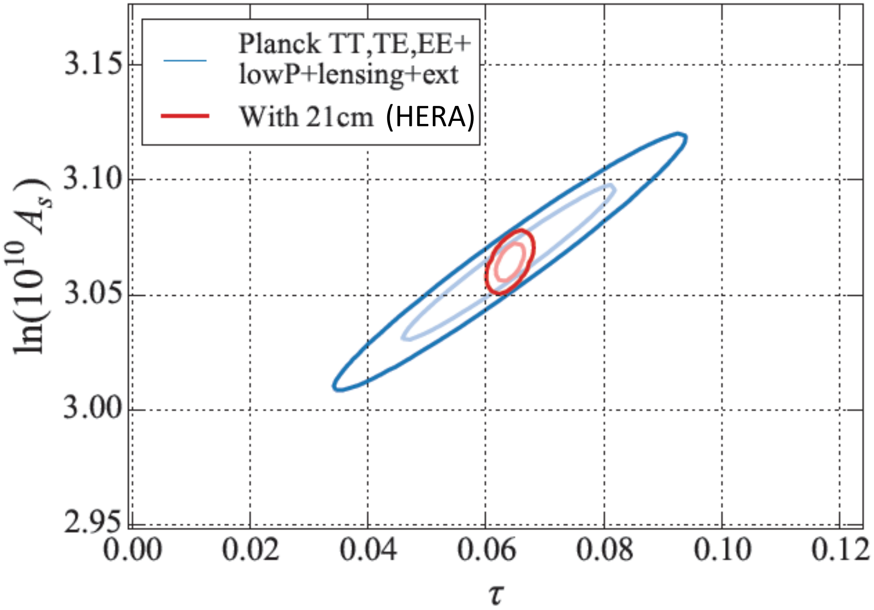
- Moving beyond standard ΛCDM model, dynamics of dark energy are easiest to distinguish from cosmological constant at early times (z > 1) when dark energy is first turning on.
- 21cm observations have potential to give powerful statistical measurements at appropriate redshifts.



Line Intensity Mapping: 2017 Status Report (arxiv 1709.09066)

Breaking degeneracies

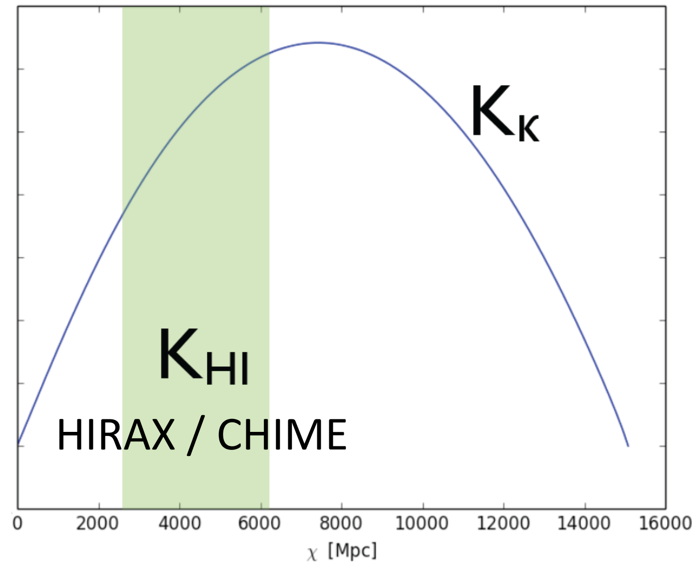
- 21cm observations provide a measurement of the optical depth to Recombination, τ, which is independent of CMB derived τ.
- This allows 21cm to break degeneracies in existing CMB measurements, and significantly improve cosmological parameter constraints.

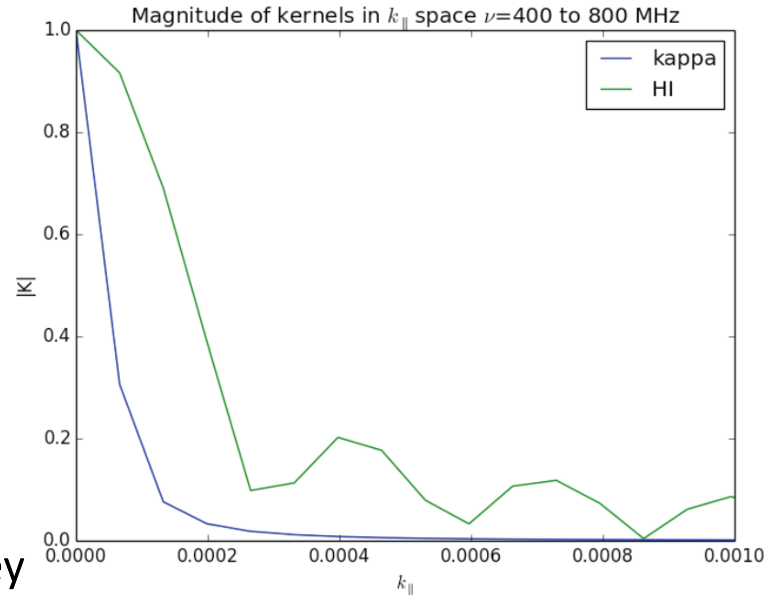


Cosmology with the Highly Redshifted 21cm Line (arxiv 1903.06240)

Cross-correlations

- Cross correlation with optical galaxy surveys or cosmic shear surveys can measure redshift dependent hydrogen ionization fraction Ω_{HI} and bias b_{HI}.
- Good redshift overlap between κ and 21cm, similar physical scales
- κ-δT_{21} power spectrum vanishes because large 21cm modes are lost in foreground removal ($k_{||}$ modes below ~0.01Mpc^{-1}), but can use bispectrum to recover large modes
- Decent S/N (~18) expected with current generation 21cm and CMB experiments (HIRAX/CHIME x ACTpol/SPT-3G). CMB-S4 or SO significantly better.

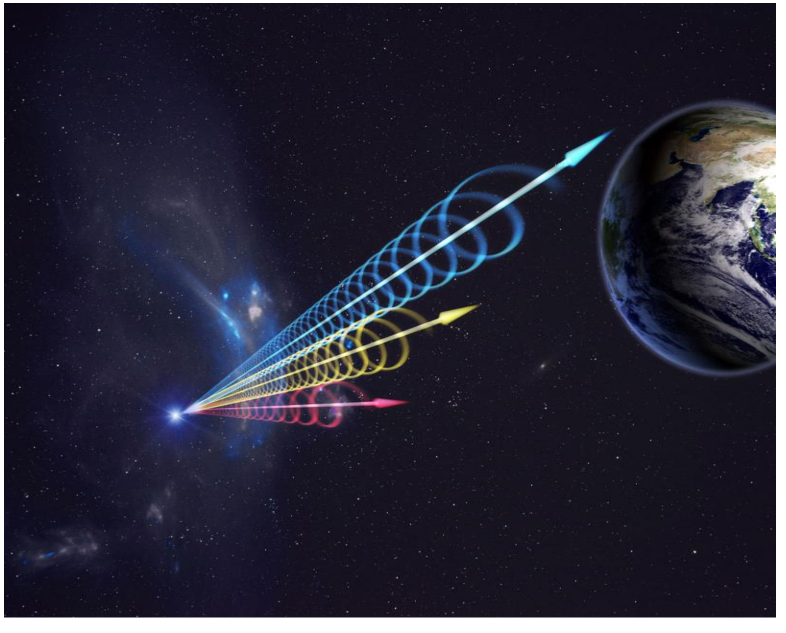


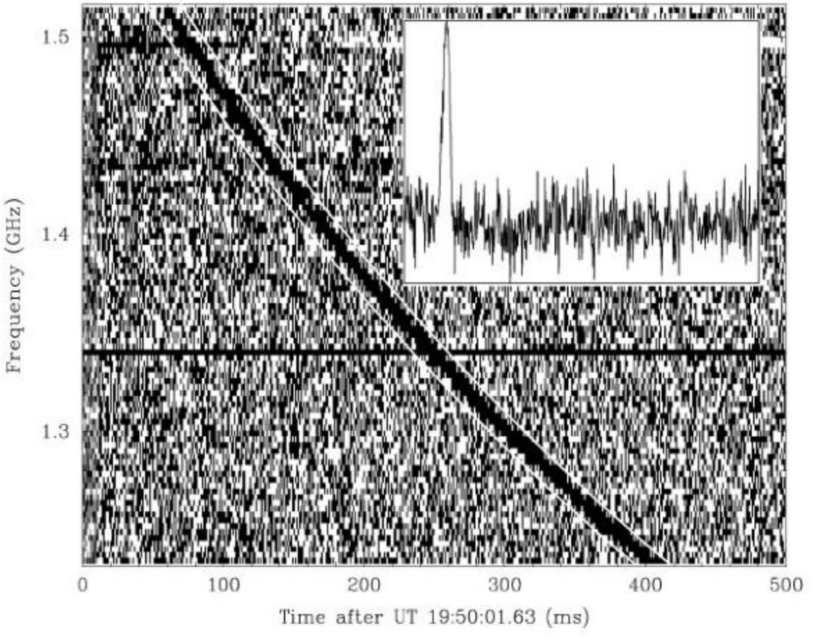


Plots from Kavi Moodley

Fast Radio Bursts

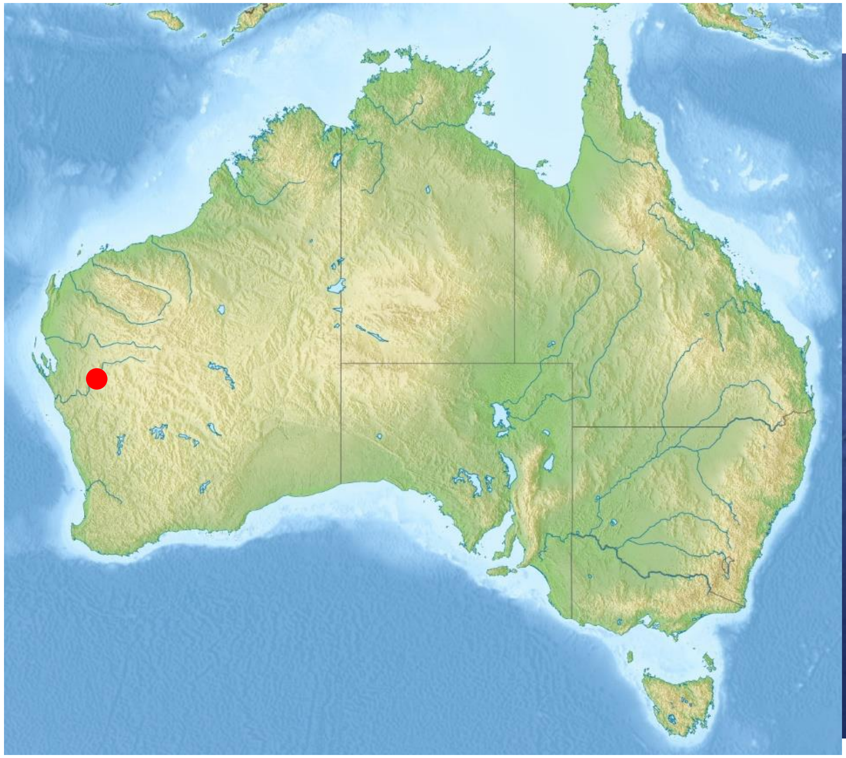
- Fast radio bursts: short (~ms), bright (~Jy) radio transients
- Distances are likely cosmological because of observed dispersion measure (integrated column density of free electrons between observer and source)
- Only ~40 detected, but total event rate ~10^4 per day over full sky
- Event rate prop. to D_dish*N_beams, so full CHIME/HIRAX arrays should detect dozens per day
- Potentially new method to independently constrain τ





Current Experiments: Experimental Sites

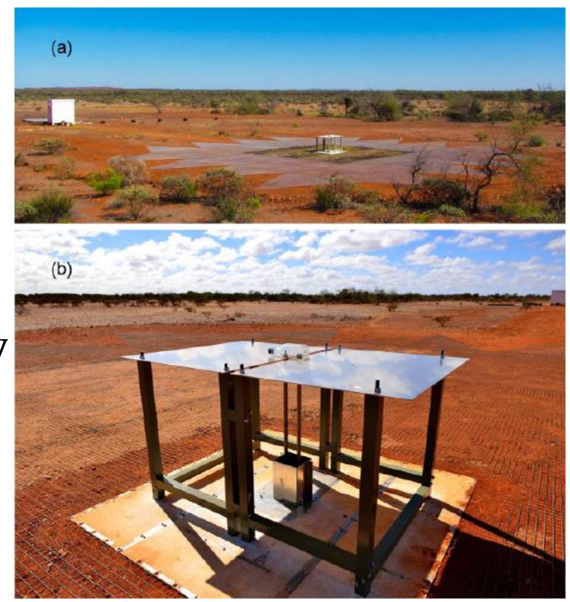
Australian Radio Quiet Zone – Western Australia (ARQZWA)
"Murchison Site"

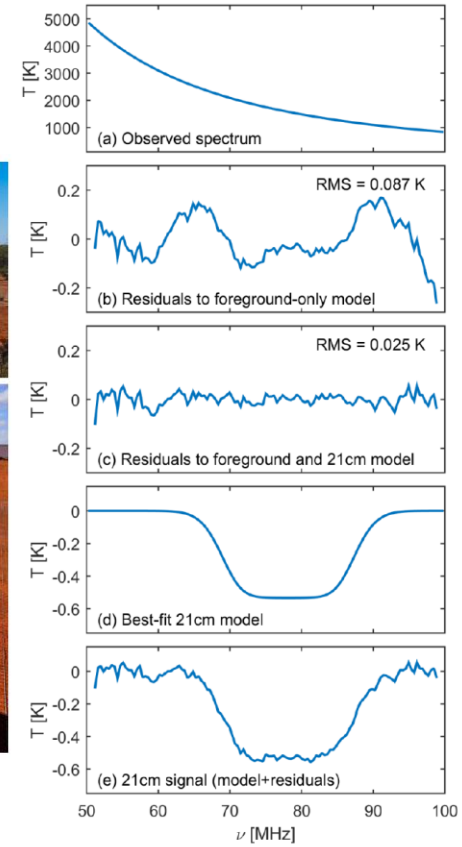


South African Karoo Radio Quiet Zone (SAKRQZ)
"The Karoo" or "SKA-SA Site"

Current Experiments: EDGES

- At Murchison Site, measures "global" or "monopole" 21cm signal at high redshift
- Low band: 50-100 MHz, $27 < z < 13$
- High band: 90-190 MHZ, $15 < z < 6.5$
- Measure absorption profile indicating first stars at z~180 My after Big Bang
- Cosmological implications of depth of absorption disputed
- PRIZM and LEDA will make measurements in similar redshift range.

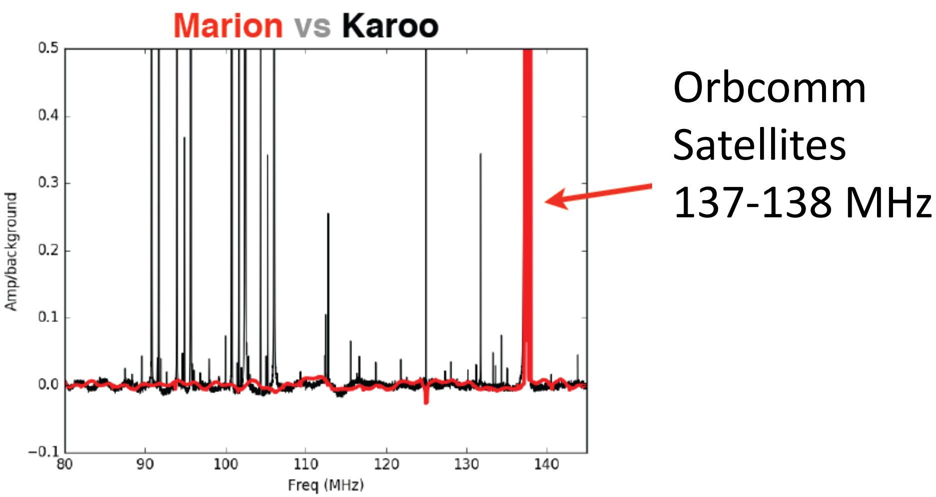


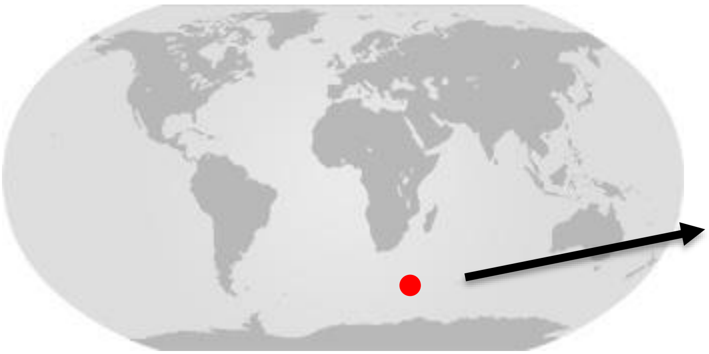


EDGES collaboration (arxiv 1810.05912)

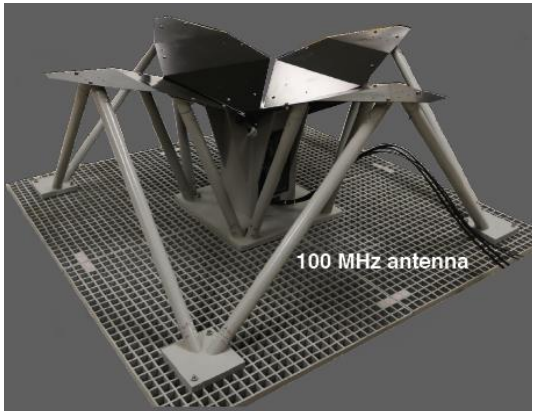
Current Experiments: PRI^{Z}M

- Located at Marion Island, 2000 km south of South Africa
- 70 MHz and 100 MHz antennas, $9 < z < 25$
- Pristine RF environment for low frequency instruments
- First science observing season in progress, will observe for three more years



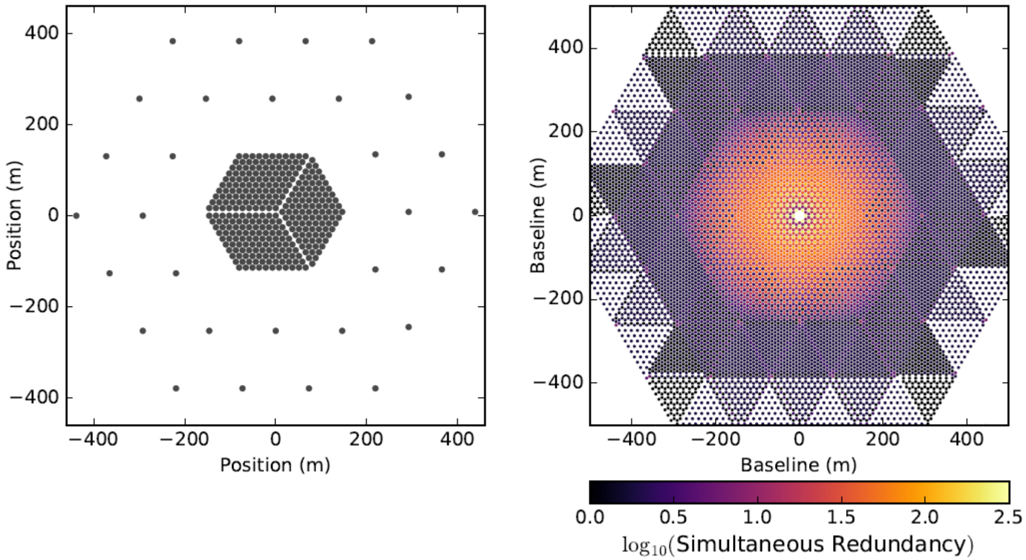


20 km x 12 km



Current Experiments: HERA

- 350 14m diameter dishes, located at the SKA-SA site
- 100-200 MHz ($6 < z < 30$), designed to probe reionization history
- Highly redundant array layout for ease of calibration
- Intentionally broken symmetry (offset diamond sections) plus outriggers improves *uv* coverage and suppresses grating lobes in synthesized beam



Current Experiments: HIRAX and CHIME

	CHIME	**HIRAX**
Site	DRAO, Canada	SKA site, South Africa (lower RFI, no snow)
Telescope	Cylinder array	Dish array (easier to baffle)
Field of view	100° NS, 1°– 2° EW	5° – 10° deg
Beam size	0.23° – 0.53°	0.1° – 0.2°
Collecting area	8000 m^2	28,000 m^2
Sky coverage	North	South
Frequency	400-800 MHz	
Redshift	0.8-2.5	
δz/z	0.003 (min)	
Goals	BAO cosmology, radio transient searches, pulsar searches/timing, neutral hydrogen absorbers, diffuse polarization of Milky Way	

System Requirements/Challenges

- Significant science payoff expected from first generation 21cm experiments, but will need second generation (at least) to fully realize much of the potential from 21cm observations (extend to higher redshift, improve sensitivity)
- Plans for second generation experiments already underway (CHORD, PUMA, HIRAX++), and some 1st gen experiments are consciously tech demonstrators for SKA (HERA, HIRAX).
- What challenges do we need to overcome with current generation experiments to demonstrate capability to build 2nd gen?

System Requirements/Challenges

- Wide band ant. for survey volume, narrow frequency bins for redshift resolution
- Low system temperature
- Low/controlled electronic systematics
- Repeatability and stability of hardware
- Efficient correlation
- Precision calibration
- Demonstrate effective foreground removal

System Requirements/Challenges

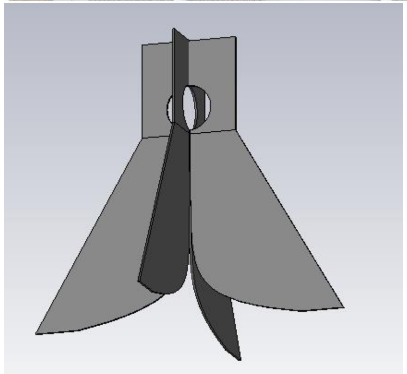
• Wide band ant. for survey volume, narrow frequency bins for redshift resolution	✓
• Low system temperature	✓
• Low/controlled electronic systematics	?/✓
• Repeatability and stability of hardware	?/✓
• Efficient correlation	✓
• Precision calibration	?
• Demonstrate effective foreground removal	?

Feed and Signal Chain

- CHIME/HIRAX antennas are dual polarization "cloverleaf" antennas based on four square antenna
- Low loss (< 0.15dB) and small reflectivity (< -0.15dB) across wide band (400-800 MHz)
- Cheap, easy to assemble, FR-4 dialectric (PCB) with metalized layer
- "Can" ring choke circularizes beam, decreases crosstalk and ground spillover
- HERA antenna is crossed dipole with similar metal mesh "can"
- Comparable low loss across 100-200 MHz band
- HERA and HIRAX investigating upgrading to Vivaldi quad-ridge feedhorns to extend bandwidth further (disadvantage is size and weight)

HIRAX

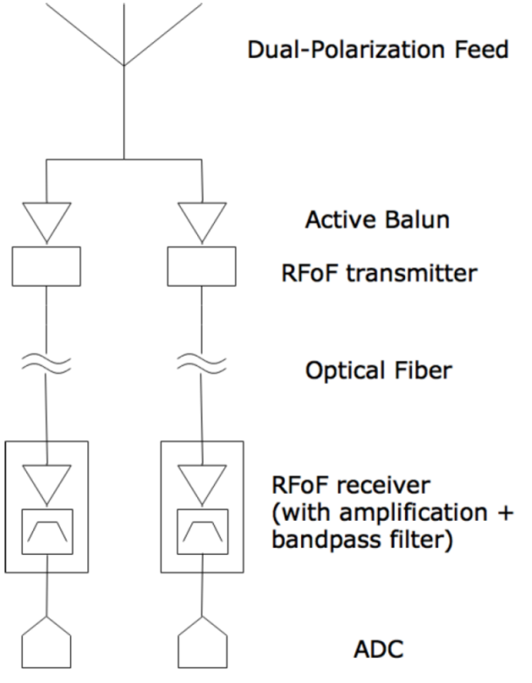
HERA



Early HERA
Vivaldi prototype

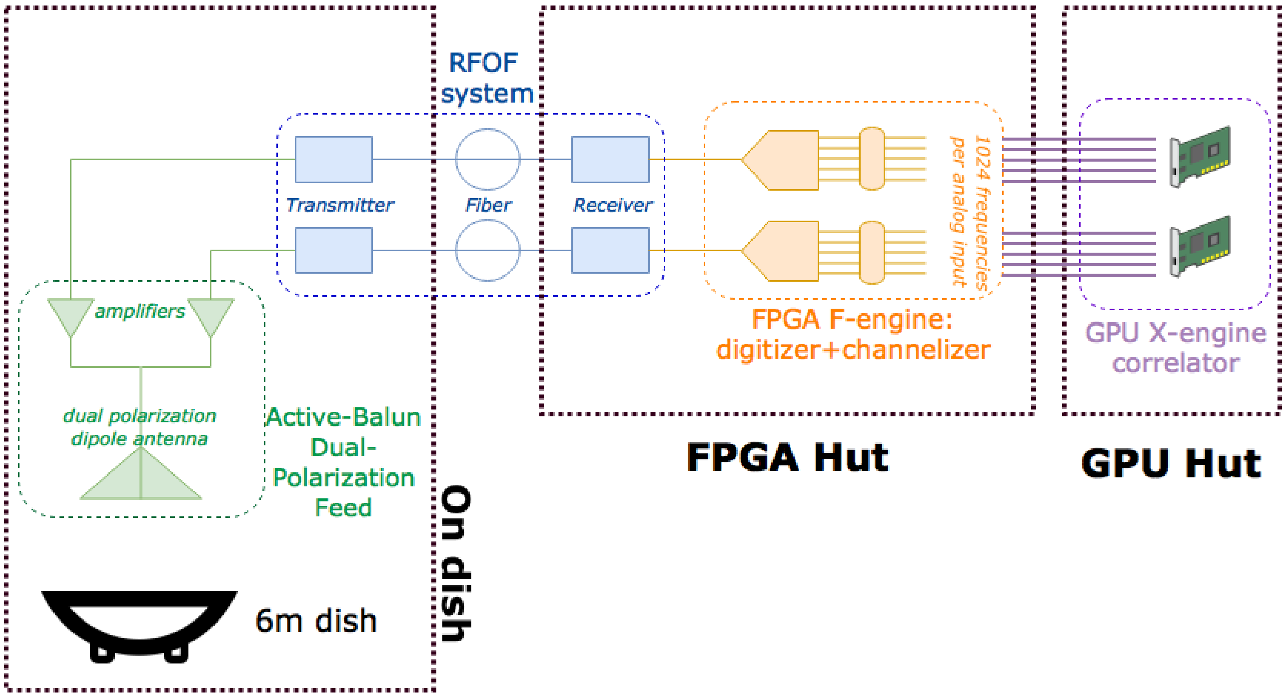
Feed and Signal Chain

- Room temp LNAs with effectively “cryogenic” noise temps enable cheap low T_{sys} instruments.
- Controlling systematics in backend electronics is challenging but feasible. Need uniformity across array, and stability across time.
- Reflections in coax cabling, loss, and thermal variation in loss and reflections motivate move to RFoF. New technology, still being optimized.
- Optical laser modulated at radio frequency on dish, signal transmitted over fiber with essentially zero loss, demodulated at central backend processing location.



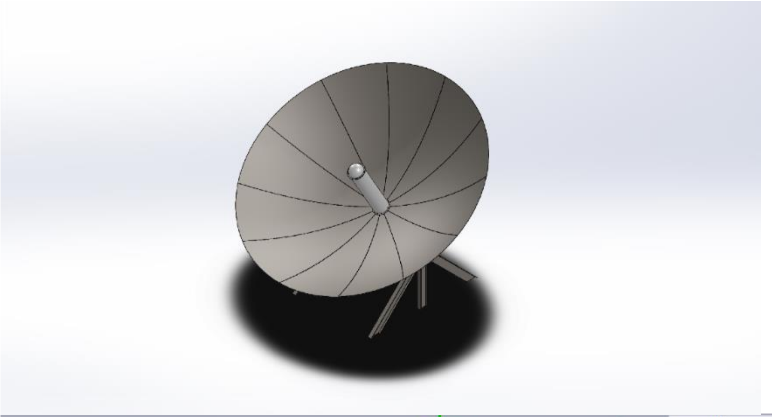
Backend Electronics

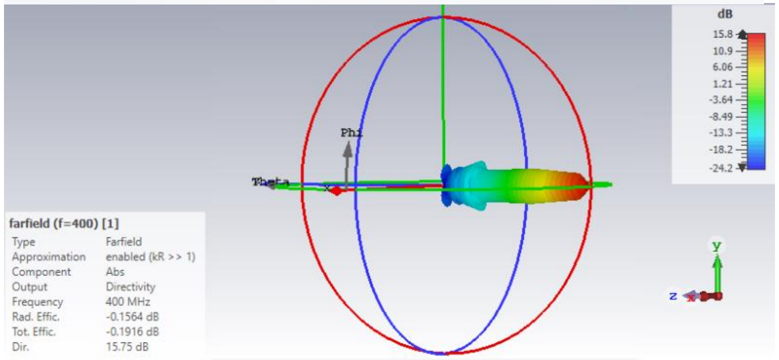
- Interferometric arrays typically use “FX engine” for correlations
- F-engine digitizes and channelizes signal from each element, performs “corner-turn” operation (transform from input of all freq. channels on single element to bundles of single freq. from all elements)
- X-engine correlates all sky inputs at each frequency channel
- Correlation typically scales as N^2, redundancy in array can be exploited to reduce to N log N. Methods still being developed.

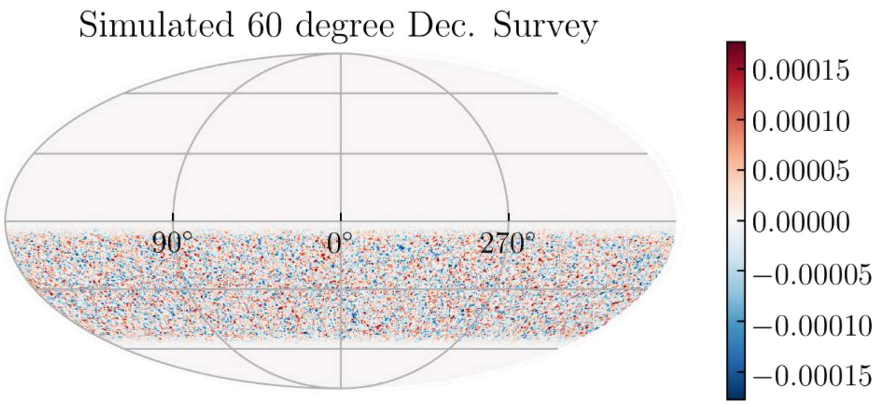


Beam Stability/Uniformity/Crosstalk

- Want beams with very low coupling to neighboring dishes. => low sidelobes, deep dishes
- Want uniform beams across array (determined by uniformity of fab, environmental conditions)
- Want beam that is stable over time (environmental and mechanical)
- HIRAX working on “end-to-end” mechanical to cosmology pipeline: simulate effects of dish fab, mech support, wind, gravity on beams, propagate to cosmology, feed back to instrument design

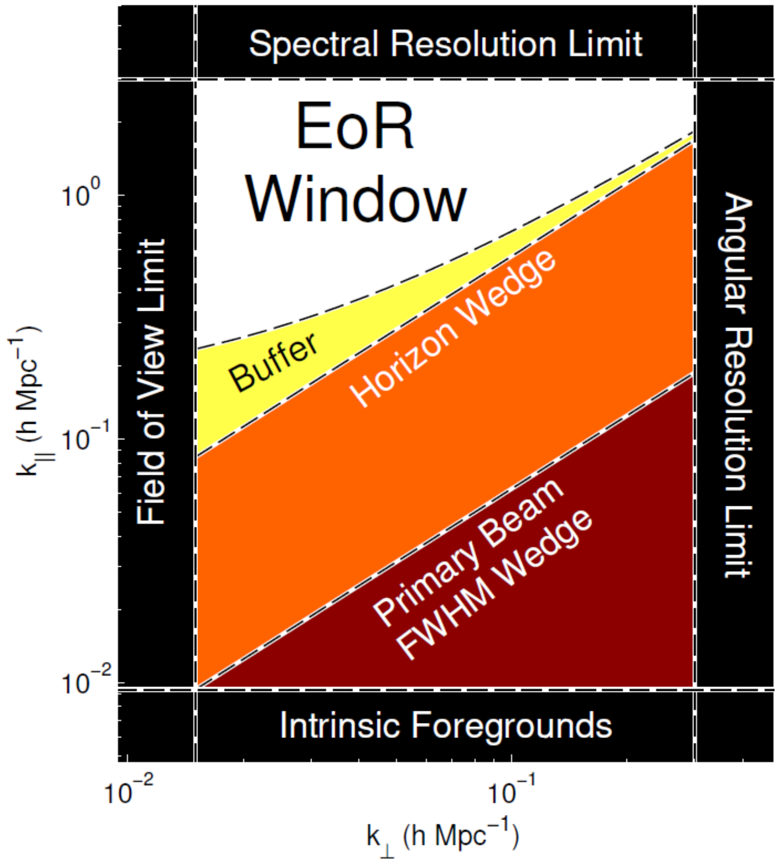






Foreground Removal

- "0^{th} order" foreground removal method relies on fact that smooth spectrum foregrounds are limited to region below k-space "wedge", while line emissions have power that extends beyond wedge.
- Wedge determined by maximum delay possible for a smooth spectrum source as a function of baseline.
- People investigating improved removal methods: polynomial foreground subtraction, principle component analysis.
- Removal is still open problem, and likely one of the hardest parts of extracting LSS information from 21cm observations

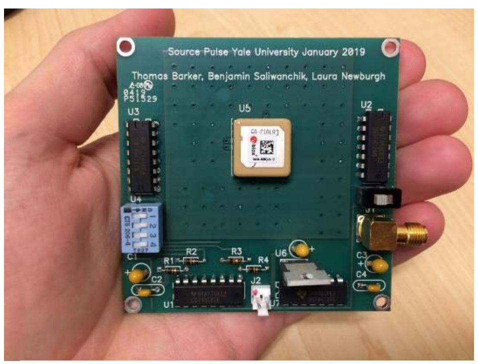


Mapmaking for Precision 21cm Cosmology (arxiv 1410.0963)

Difficulty of Calibration

- For foreground removal, estimate we need 1% calibration in gain, polarization, 0.1% in beam shape.
- Most arrays are drift scan => Can’t steer telescope, look through array at source on ground
- Astrophysical sources, and artificial satellites have limited declinations
- Calibration with incomplete sky data difficult
- Solution: Drones! Fly a calibrated source, with a known beam, in a custom pattern over your telescope. So simple!
- Challenges are calibration and stability of source and antenna, flight time, and accuracy of position recovery. Esp. position.
- Believe challenges are surmountable, several experiments developing drone calibration systems. (HERA, LOFAR, HIRAX/CHIME/BMX)

Yale Drone System for HIRAX/CHIME



- Yale currently using DJI Matrice drone. Can easily reach HIRAX far field. (For 6m dish, 2*D^2/λ is 200m at 800 MHz)
- Custom designed noise source, 400-800 MHz, broad band switchable from GPS PPS.
- BicoLog 30100 broadband antenna. Frequency range of 30 MHz to 1 GHz
- RTK GPS for ~1cm positional accuracy

Measurement	Accuracy requirement
Position	16 mm
Tilt	0.57 degrees
Polarization angle	0.8 degrees

Table 1: Requirements for drone location, tilt, and polarization angle. This assumes a biconical antenna pattern from the drone.

Conclusions

- There is a vast amount of cosmological information that has not been probed that is accessible through 21cm observations, including some epochs that may only be accessible by 21cm.
- There are significant technical and technological challenges to making such measurements, but good progress is being made by a cohort of current experiments.
- The future is (radio) bright!