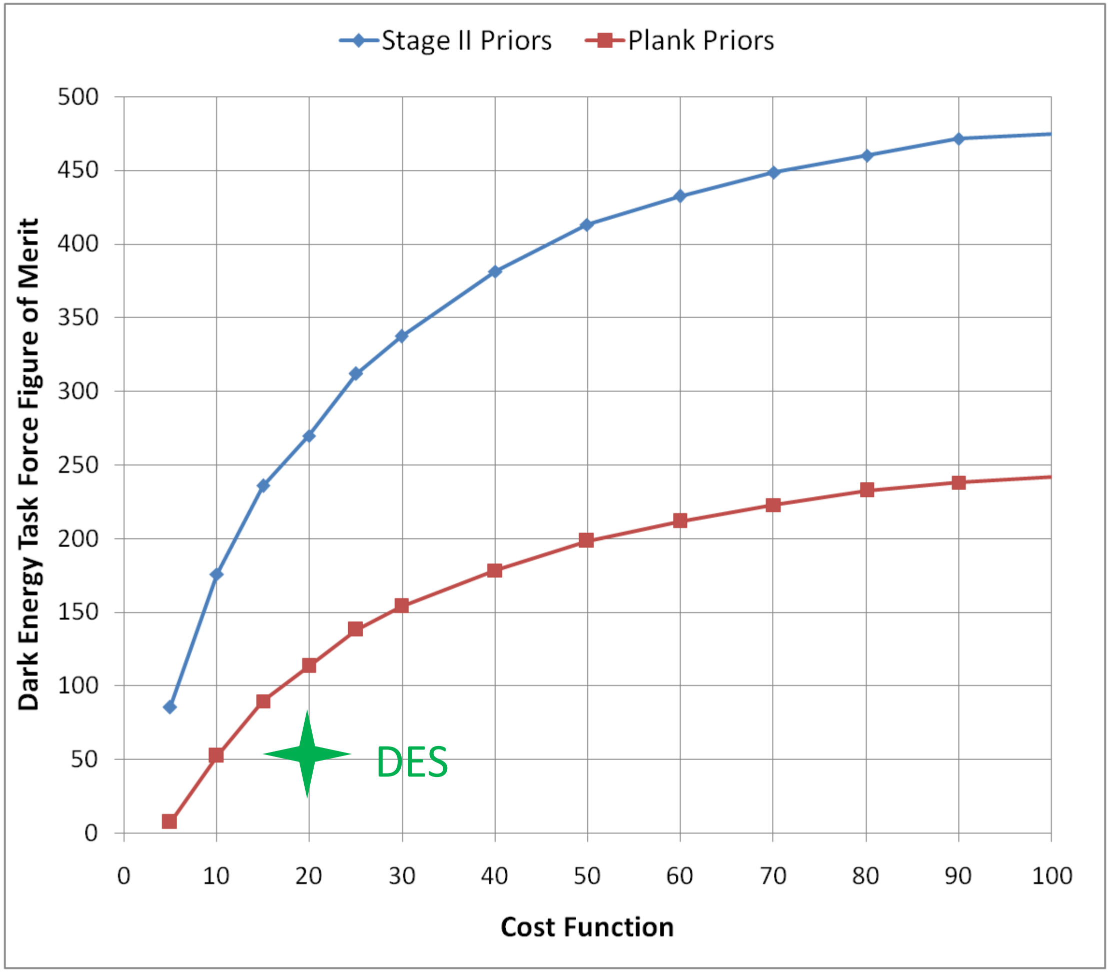
21cm Plan and Fermilab

Dave McGinnis

April 23, 2010

Science Reach

- The 21cm Cylindrical Radio Telescope (CRT)
  - is a single purpose project to parameterize dark energy expansion
  - by measuring baryon acoustic oscillations (BAO) at large red-shifts.
- The CRT can
  - reach a Dark Energy Task Force Figure of Merit (FoM) of 250 (> 4x DES BAO FoM)
  - for a cost below 30M$



21cm Intensity Mapping

- To peer deep into large red-shifts, we use a hydrogen hyperfine transition at 1.42 GHz to make a 3-D radio intensity map of the universe
- By intensity map, we mean that:
  - galaxies are not spatially resolved
  - the 21cm line is not resolved in frequency

3-D Radio Maps

- With the 3-D radio intensity map, we will pull the unique BAO signal out of a map that is dominated by foregrounds.
  - Foregrounds consist of galactic synchrotron emission, point radio sources, etc.
  - Foreground subtraction will be the most difficult part of the project
- 3-D sky surveys require
  - Large aperture
  - Good resolution
  - Large bandwidth
  - High speed

High Speed Radio Telescopes

- The CRT is inexpensive for the science it can reach because the CRT is a member of the new breed of radio telescopes called omni-scopes[1].
- Omni-scopes are:
  - arrays of low gain, wide beam width, antennae
  - connected to low-noise, high speed, electronics.
- Omni-scopes are just recently possible because of:
  - Advances in room temperature, wideband, low noise electronics developed for the cell phone industry
  - Availability of low cost, high-speed data processers
    - Field Gate Programmable Arrays (FGPA's)
    - Graphical Processing Units (GPU's)

[1]Omniscopes: Large Area Telescope Arrays with only N log N Computational Cost, M. Tegmark - http://arxiv.org/abs/0909.0001v1

The 21cm CRT

- The CRT takes the omni-scope concept one step further by arranging the CRT as an 2-D collection of 1-D arrays operating in drift-scan mode.[2]
  - The 1-D arrays sit at the focal point of cylindrical reflectors aligned to the meridian
  - The CRT consists of 4 cylinders
    - Each cylinder is 150m long by 20m wide
    - Each cylinder has 512 channels per polarization
    - Operating at a frequency range of 500-1000MHz
    - Each cylinder costs on the order of 5M$
- The CRT has:
  - Lower cost
  - Higher stability – Experience at other large radio telescopes show that drift scanning provides the superior stability that is required for large area surveys.

[2] The Hubble Sphere Hydrogen Survey, J Peterson , K. Bandura, U. Pen -arXiv:astro-ph/0606104

Match to Fermilab

- The science is very well aligned with Fermilab's interest in dark energy
- The 21cm CRT technology is very well aligned to Fermilab's expertise. Fermilab has
  - A long history in sky surveys (SDSS, DES)
  - The in-depth technical expertise in:
    - large data acquisition systems (collider detectors)
    - digital signal processing (collider detectors , accelerator control)
    - radio frequency technology (accelerators)
  - The management expertise in middle and large scale projects and collaborations
- Could be Fermilab's next dark energy experiment after DES.
- Ground-floor opportunity
  - Just like CMB, 21cm could be an enabling technology in cosmology – particularly for the study of early epochs

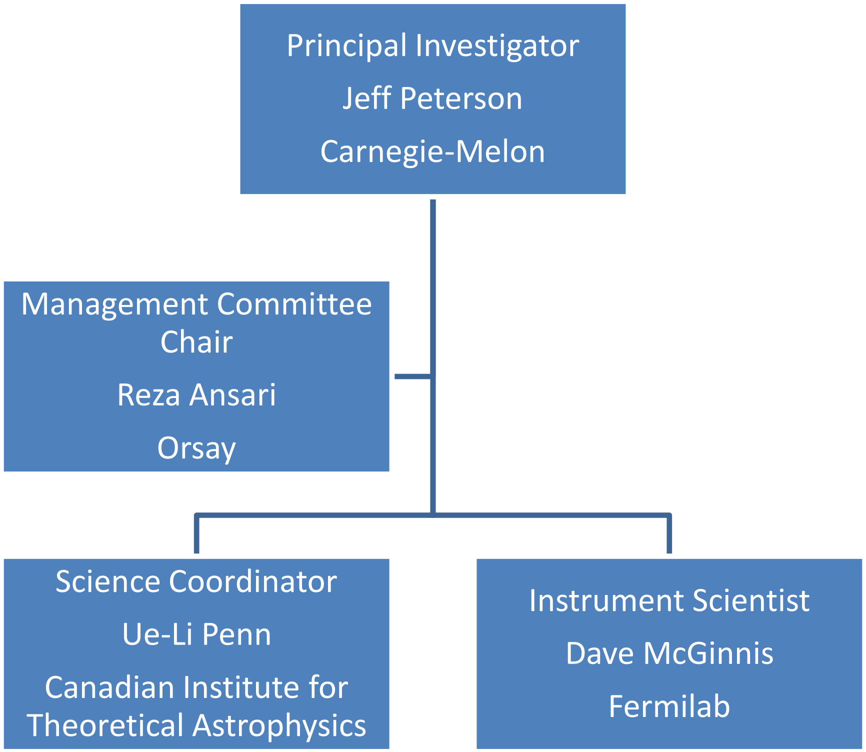
CURRENT STATUS

CRT Collaboration

- The CRT is a world-wide collaboration with participants from 8 institutions
  - Carnegie–Melon, AUI (Morocco), CEA (Saclay), CITA (Canada), CSRIO (Australia), Fermilab, LAL (Orsay), University of Wisconsin
- A significant amount of work has been done
  - A two cylinder prototype has been built (Carnegie–Melon)
  - Front end and beam-forming electronic prototypes have been built and tested at the two cylinder prototype (LAL (Orsay), CEA (Saclay))
  - Three site selection measurement trips have been made (AUI (Morocco), Carnegie–Melon, **Fermilab**, CEA (Saclay), LAL (Orsay))
  - In-depth requirement study has been completed (**Fermilab**)
  - Sky map simulation software completed (**Fermilab**)
  - Initial foreground removal algorithms have been designed and simulated (**Fermilab**)
  - An initial proposal has been written (Carnegie–Melon, **Fermilab**)
  - Two face-to-face collaboration meetings have occurred (**Fermilab**, AUI)
  - Science workshop was held (**Fermilab**)

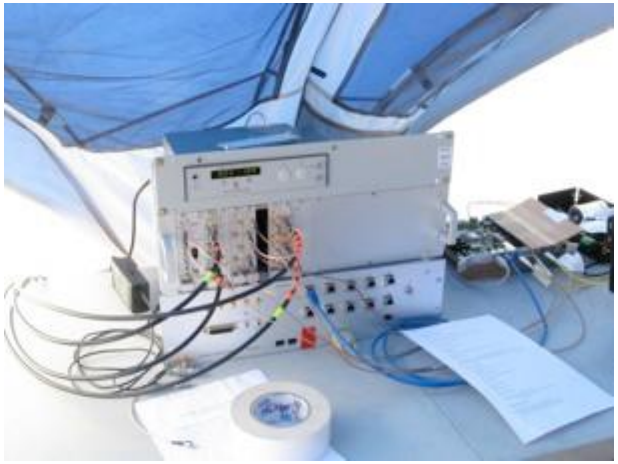
21cm CRT Project Management

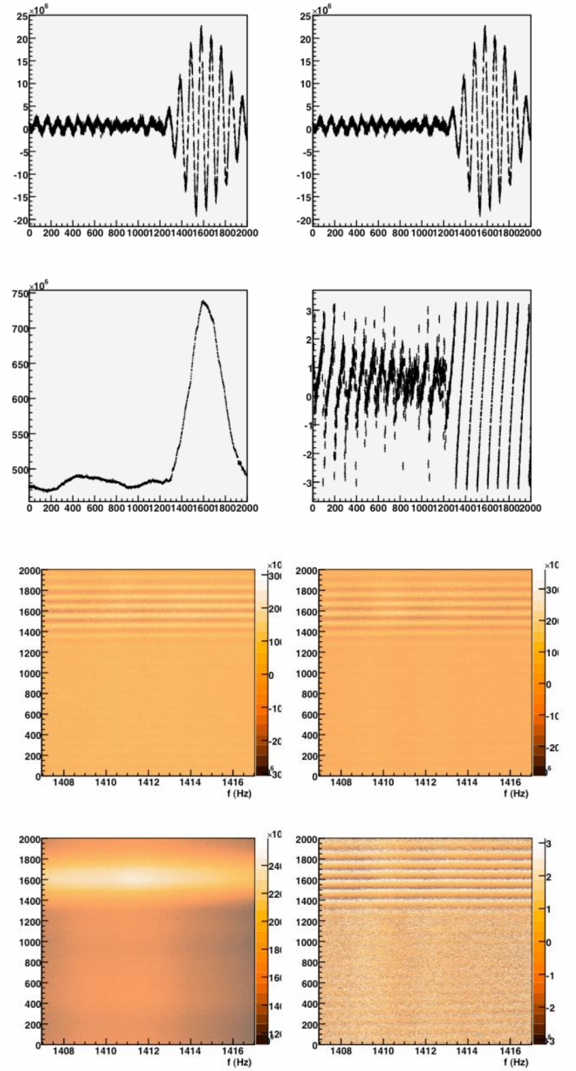
- The PI represents the collaboration in the scientific community and in front of different funding agencies.
- The management committee contains one member from each institution
- This management committee will decide on new appointees and may choose to appoint the same individual for more than one consecutive term.
- The Management committee chair and Science coordinator positions are one year terms.
- The PI and instrument scientist positions are for at least two years.



Pittsburgh Prototype

French Electronic Tests at Pittsburgh





Site Tests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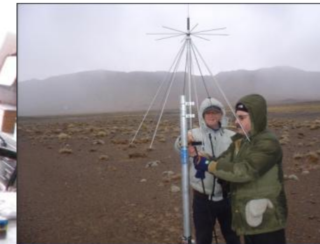


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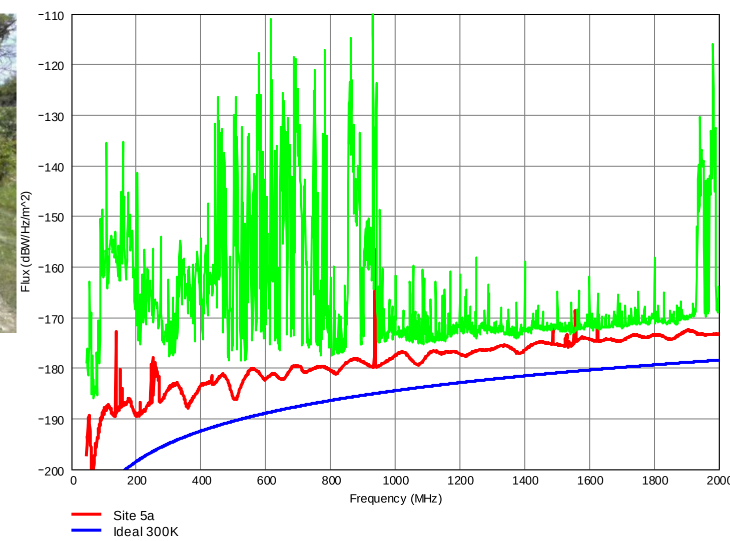
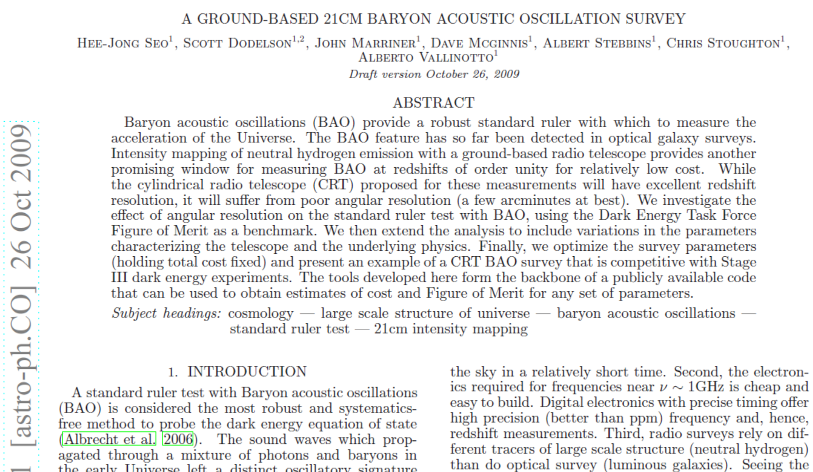

-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
Flux (dBW/Hz/m^2)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Frequency (MHz)
Site 5a
Ideal 300K
Fermilab

Fermilab 21cm Document Database

Projects-doc-#	Title	Author(s)	Topic(s)	Last Updated
784-v3	Initial Pittsburgh Cylinder Simulations results	David McGinnis	21CM	02 Dec 2009
778-v1	Formulation Cylinder Visibilities	David McGinnis	21CM	05 Nov 2009
473-v4	General Requirement Formulae for the 21cm Cylindrical Radio Telescope	David McGinnis	Technical Notes	20 Oct 2009
653-v2	Signal to Noise for an FFT Antenna array	David McGinnis	Technical Notes	12 Oct 2009
713-v1	Fermilab Presentations at the Spet 9, 2009 21cm collaboration meeting	John Marriner *et al.*	21CM	10 Sep 2009
670-v1	Pine Bluff Observatory RFI Measurements	David McGinnis	21CM	10 Aug 2009
656-v1	21cm Calibration by Ue-Li Pen	----- -----	21CM	23 Jul 2009
626-v1	Morocco Site Testing for the Cylinder Radio Telescope	----- -----	21CM	09 Jul 2009
566-v1	Positioning and orienting a static radio-reflector	----- -----	21CM	30 Jun 2009
562-v1	21cm Collaboration Meeting June 2009 in Ifrane Morocco	----- -----	21CM	26 Jun 2009
284-v1	Rates and Resolutions	Chris Stoughton	Technical Notes	22 Jun 2009
476-v3	Martin Leung Thesis: A Wideband Feed For a Cylindrical Radio Telescope	----- -----	Technical Notes	27 May 2009
543-v1	Dave's 21cm Five Magic Numbers	David McGinnis	21CM	08 May 2009
542-v1	Measuring BAO with the 21cm line of Hydrogen			
475-v1	April 9 2009 21cm CRT Collaboration Meeting			
474-v1	Comments on the Performance of a Adjacent Fee			
469-v2	Integration Time for 21cm Parabolic Cylinder Rad			
471-v1	Phased Array Antenna			
467-v1	Status of Aperture Feed Simulations for the 21cm			
444-v4	Putting Documents into the 21 cm DocDb			
450-v1	The Cylinder Radio Telescope			
449-v1	21 cm Telescope Simulation			
366-v2	Spherical Coordinates for a Parabolic Cylinder Ant			
432-v7	Fermilab Morocco Site Visit Summary			
435-v1	Antenna Factor for the 21 cm Simulation			
407-v1	Fermilab 21cm Morocco Site Evaluation Status			

467-v1	Status of Aperture Feed Simulations for the 21cm CRT	David McGinnis	Meeting Minutes	31 Mar 2009
444-v4	Putting Documents into the 21 cm DocDb	David McGinnis	Technical Notes	02 Mar 2009
450-v1	The Cylinder Radio Telescope	John Marriner	Technical Notes	24 Feb 2009
449-v1	21 cm Telescope Simulation	John Marriner *et al.*	Technical Notes	24 Feb 2009
366-v2	Spherical Coordinates for a Parabolic Cylinder Antenna	David McGinnis	Technical Notes	02 Feb 2009
432-v7	Fermilab Morocco Site Visit Summary	David McGinnis	Technical Notes	02 Feb 2009
435-v1	Antenna Factor for the 21 cm Simulation	David McGinnis	Technical Notes	26 Jan 2009
407-v1	Fermilab 21cm Morocco Site Evaluation Status	David McGinnis	Meeting Minutes Technical Notes	22 Dec 2008
373-v2	21cm Meeting at University of Chicago	John Marriner *et al.*	Meeting Minutes	22 Oct 2008
372-v1	21cm Cylinder Cartoon Pictures	David McGinnis	Technical Notes	01 Oct 2008
367-v1	Ray Tracing for an Offset Focus Parabolic Cylinder Antenna	David McGinnis	Technical Notes	22 Sep 2008
320-v1	HSHS Power Spectra	----- -----	Technical Notes	30 Jun 2008
311-v2	Initial Measurements of Radio Frequency Interference at 1 GHz at Fermilab	David McGinnis	Technical Notes	02 Jun 2008
310-v1	Average Noise Power for a Low Noise Amplifier	David McGinnis	Technical Notes	02 Jun 2008
282-v1	Directivity of a Parabolic Cylinder Antenna	David McGinnis	Technical Notes	05 May 2008
290-v5	Integration Length for 21cm	David McGinnis	Technical Notes	05 May 2008
303-v1	Integration Time for a Parabolic Dish Radio Telescope	David McGinnis	Technical Notes	05 May 2008
297-v1	Radiometer Equation	John Marriner	Technical Notes	01 Apr 2008
292-v1	3-D Intensity Mapper Project Description	----- -----	Technical Notes	11 Mar 2008
291-v1	NSF ATI Proposal (2007)	----- -----	Technical Notes	10 Mar 2008
286-v1	21 CENTIMETER FLUCTUATIONS FROM COSMIC GAS AT HIGH REDSHIFTS	----- -----	Publications	03 Mar 2008
285-v1	THE HUBBLE SPHERE HYDROGEN SURVEY	----- -----	Publications	03 Mar 2008
283-v1	Digitized response function of a phased array of Antennae	John Marriner	Technical Notes	03 Mar 2008
281-v1	21-cm Baryon Acoustic Oscillation Survey	Scott Dodelson	Technical Notes	03 Mar 2008
280-v1	3-D Intensity Mapper Project Description	----- -----	Technical Notes	03 Mar 2008

CRT Design Requirements



arXiv:0910.5007v1 [astro-ph.CO] 26 Oct 2009

A GROUND-BASED 21CM BARYON ACOUSTIC OSCILLATION SURVEY

HEE-JONG SEO[1], SCOTT DODELSON[1,2], JOHN MARRINER[1], DAVE MCGINNIS[1], ALBERT STEBBINS[1], CHRIS STOUGHTON[1], ALBERTO VALLINOTTO[1]

Draft version October 26, 2009

ABSTRACT

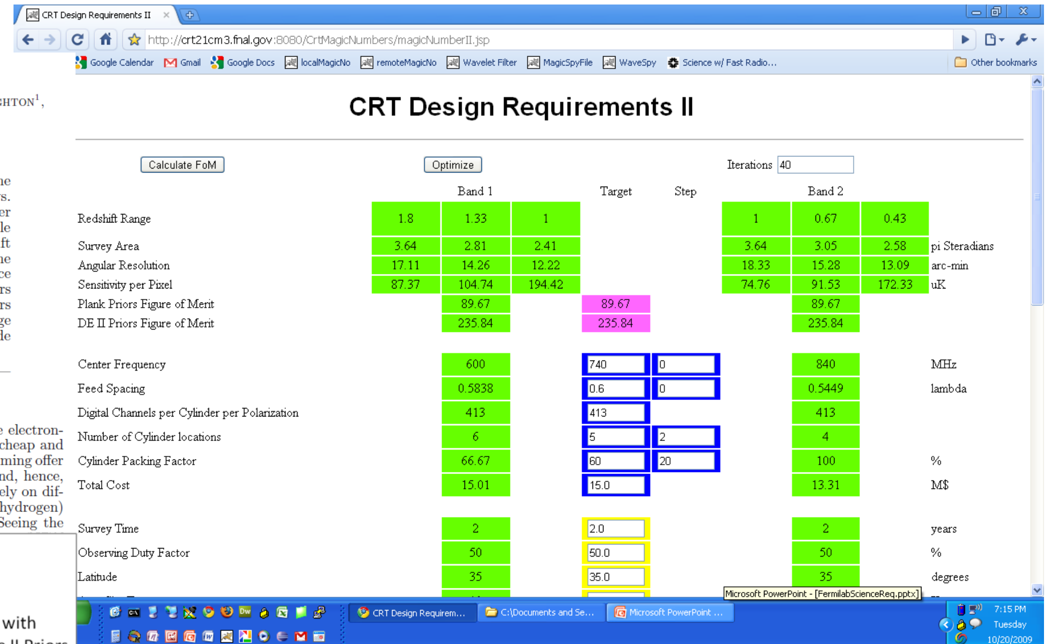
Baryon acoustic oscillations (BAO) provide a robust standard ruler with which to measure the acceleration of the Universe. The BAO feature has so far been detected in optical galaxy surveys. Intensity mapping of neutral hydrogen emission with a ground-based radio telescope provides another promising window for measuring BAO at redshifts of order unity for relatively low cost. While the cylindrical radio telescope (CRT) proposed for these measurements will have excellent redshift resolution, it will suffer from poor angular resolution (a few arcminutes at best). We investigate the effect of angular resolution on the standard ruler test with BAO, using the Dark Energy Task Force Figure of Merit as a benchmark. We then extend the analysis to include variations in the parameters characterizing the telescope and the underlying physics. Finally, we optimize the survey parameters (holding total cost fixed) and present an example of a CRT BAO survey that is competitive with Stage III dark energy experiments. The tools developed here form the backbone of a publicly available code that can be used to obtain estimates of cost and Figure of Merit for any set of parameters.

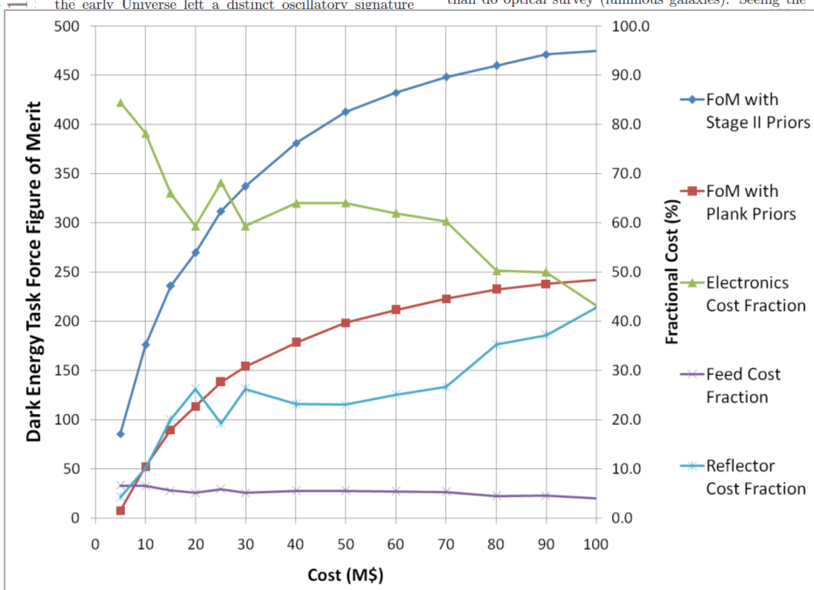
Subject headings: cosmology — large scale structure of universe — baryon acoustic oscillations — standard ruler test — 21cm intensity mapping

1. INTRODUCTION

A standard ruler test with Baryon acoustic oscillations (BAO) is considered the most robust and systematics-free method to probe the dark energy equation of state (Albrecht et al. 2006). The sound waves which propagated through a mixture of photons and baryons in the early Universe left a distinct oscillatory signature

the sky in a relatively short time. Second, the electronics required for frequencies near $\nu \sim$ 1GHz is cheap and easy to build. Digital electronics with precise timing offer high precision (better than ppm) frequency and, hence, redshift measurements. Third, radio surveys rely on different tracers of large scale structure (neutral hydrogen) than do optical survey (luminous galaxies). Seeing the



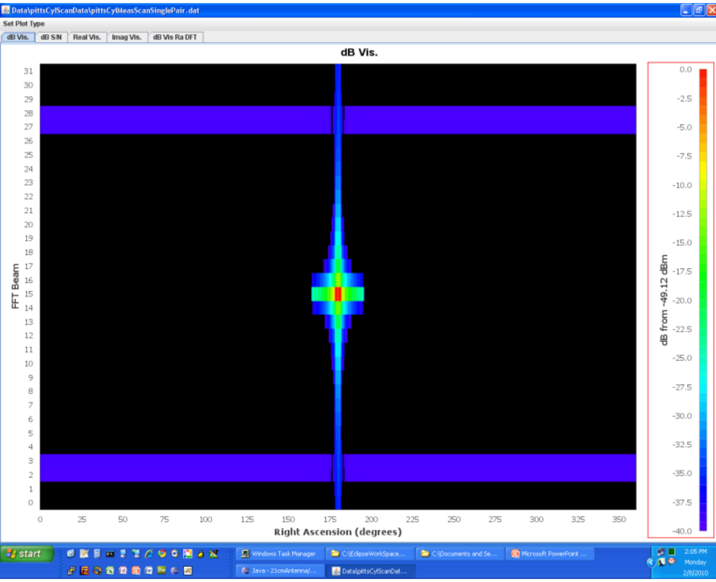


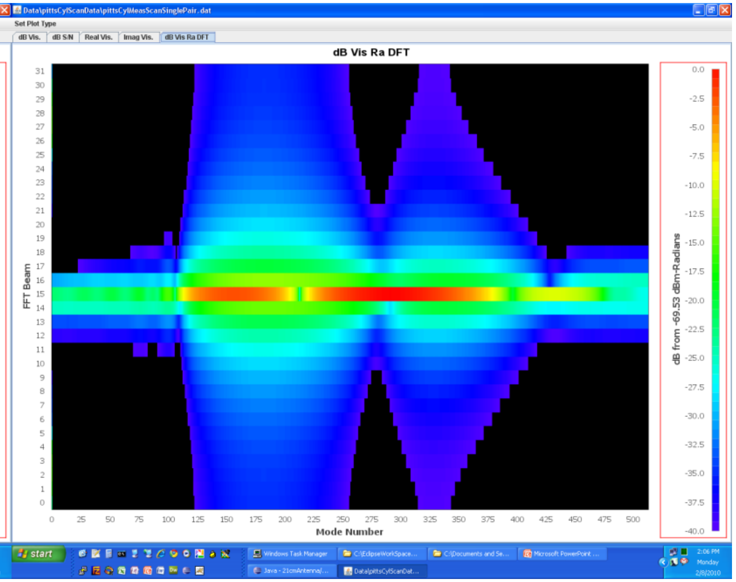
- Define the science
  - Dark energy
- Define parameter that measures success
  - Dark Energy Task force Figure of Merit
- Define science technique
  - Baryon Acoustic Oscillations with intensity mapping
- Pick an Instrument
  - Develop a rough engineering model
  - Estimate the cost versus science of the instrument
  - Pick a parameter set or “punt”

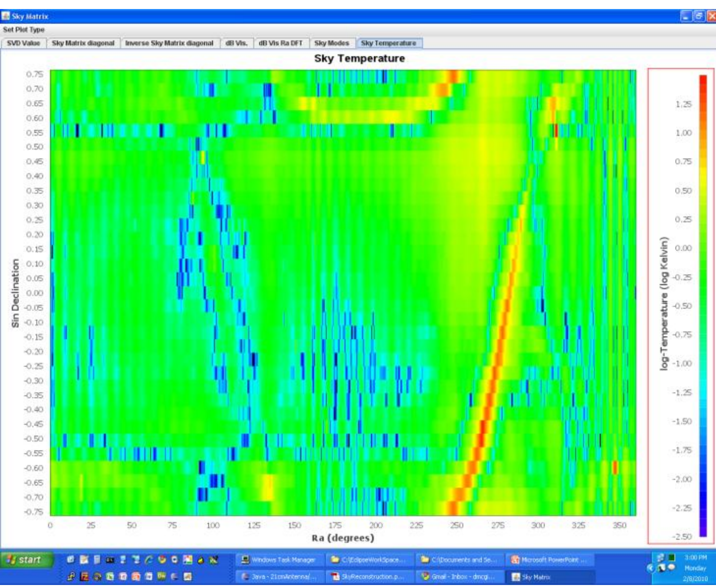
CRT Requirements Table (Fermilab)

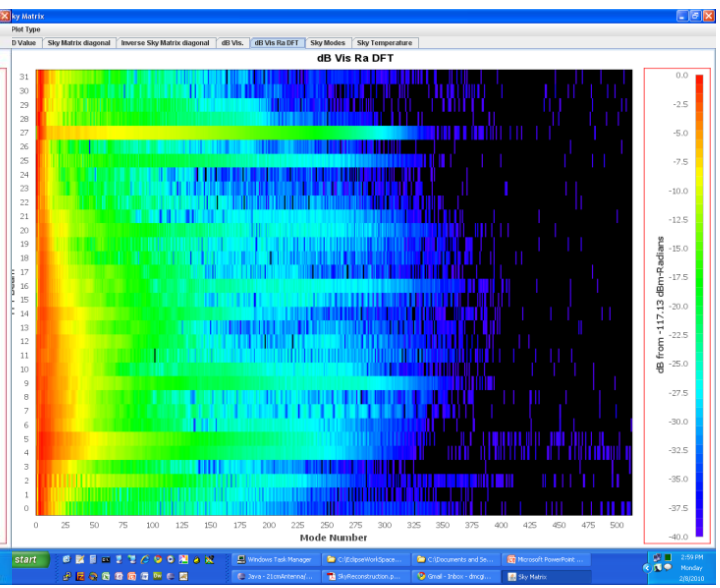
	Cost	5	10	15	20	25	30	40	50	60	70	80	90	100	M$
SCI.01 - SCI	Redshift Range	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	1.33	
SCI.03	Survey Area	2.81	2.9	2.81	2.81	2.9	2.81	2.9	2.9	2.9	2.9	2.81	2.9	2.81	pi Steradians
SCI.04	Angular Resolution	33.65	18.58	14.26	11.94	12.78	11.94	11.34	11.36	10.76	10.32	9.65	8.09	8.2	arc-min
SCI.05	Sensitivity per Pixel	47.92	88.24	104.74	123.8	82.28	82.14	70.01	57.26	55.52	53.53	58.33	78.33	73.4	uK
SCI.06	Plank Priors Figure of Merit	7.42	52.28	89.67	113.32	138.2	153.96	178.23	198.43	211.6	222.86	232.45	237.88	242.19	
SCI.07	DE II Priors Figure of Merit	85.58	175.9	235.84	269.75	311.76	337.08	381.2	412.95	432.37	448.41	460.06	471.24	474.71	
	Cost	5	10	15	20	25	30	40	50	60	70	80	90	100	M$
DYE.01	Center Frequency	600	600	600	600	600	600	600	600	600	600	600	600	600	MHz
DYE.02	Feed Spacing	0.5838	0.5676	0.5838	0.5838	0.5676	0.5838	0.5676	0.5676	0.5676	0.5676	0.5838	0.5676	0.5838	lambda
DYE.03	Digital Channels per Cylinder per Polarization	175	326	413	493	474	493	534	533	563	587	610	749	718	
DYE.04	Number of Cylinder locations	6	7	6	6	7	6	7	7	7	7	6	7	6	
DYE.05	Cylinder Packing Factor	66.67	57.14	66.67	66.67	85.71	100	114.29	142.86	157.14	171.43	183.33	142.86	166.67	%
DYE.06	Total Cost	4.97	10	15.01	19.94	25.02	29.91	40.06	49.92	59.95	70.05	80.09	89.97	100.27	M$
	Cost	5	10	15	20	25	30	40	50	60	70	80	90	100	M$
DRE.01	Number of Cylinders	4	4	4	4	6	6	8	10	11	12	11	10	10	
DRE.02	Cylinder Length	51.08	92.51	120.55	143.9	134.51	143.9	151.54	151.26	159.77	166.58	178.05	212.55	209.58	meters
DRE.03	Cylinder Width	6.81	10.57	16.07	19.19	15.37	19.19	17.32	17.29	18.26	19.04	23.74	24.29	27.94	meters
DRE.04	Cylinder Spacing	8.51	13.22	20.09	23.98	19.22	23.98	21.65	21.61	22.82	23.8	29.68	30.36	34.93	meters
DRE.05	Declination Span	117.85	123.51	117.85	117.85	123.51	117.85	123.51	123.51	123.51	123.51	117.85	123.51	117.85	degrees
DRE.06	Feed Length	29.19	28.38	29.19	29.19	28.38	29.19	28.38	28.38	28.38	28.38	29.19	28.38	29.19	cm
DRE.07	Feed Spacing	29.19	28.38	29.19	29.19	28.38	29.19	28.38	28.38	28.38	28.38	29.19	28.38	29.19	cm
DRE.08	Frequency	600	600	600	600	600	600	600	600	600	600	600	600	600	MHz
DRE.09	Wavelength	50	50	50	50	50	50	50	50	50	50	50	50	50	cm
DRE.10	Frequency Span	200	200	200	200	200	200	200	200	200	200	200	200	200	MHz
DRE.11	Res. Bandwidth	4.87	2.69	2.07	1.73	1.85	1.73	1.64	1.65	1.56	1.49	1.4	1.17	1.19	MHz
DRE.12	Minimum Digital Memory	104	188	245	293	274	293	309	308	325	339	363	433	427	
DRE.13	Integration Time per Pixel	14.53	10.29	7.16	6.12	7.48	6.12	6.75	6.76	6.45	6.26	5.1	5.08	4.44	days
DRE.14	Number of Channels per polarization	700	1304	1652	1972	2844	2958	4272	5330	6193	7044	6710	7490	7180	
DRE.15	Electronics Cost	4.2	7.82	9.91	11.83	17.06	17.75	25.63	31.98	37.16	42.26	40.26	44.94	43.08	M$
DRE.16	Feed Structure Cost	0.47	0.85	1.11	1.32	1.86	1.99	2.79	3.48	4.04	4.6	4.5	4.89	4.82	M$
DRE.17	Reflector Volume Cost	0.3	1.32	3.99	6.78	6.1	10.17	11.64	14.46	18.75	23.18	35.32	40.14	52.37	M$
	Cost	5	10	15	20	25	30	40	50	60	70	80	90	100	M$
STE.01	Survey Time	2	2	2	2	2	2	2	2	2	2	2	2	2	years
STE.02	Observing Duty Factor	50	50	50	50	50	50	50	50	50	50	50	50	50	%
STE.03	Latitude	35	35	35	35	35	35	35	35	35	35	35	35	35	degrees
STE.04	Avg. Sky Temperature	10	10	10	10	10	10	10	10	10	10	10	10	10	K
STE.05	Maximum Span	300	300	300	300	300	300	300	300	300	300	300	300	300	MHz
STE.06	Center Freq / Freq Span	3	3	3	3	3	3	3	3	3	3	3	3	3	
STE.07	Number of Polarizations	2	2	2	2	2	2	2	2	2	2	2	2	2	
STE.08	Antenna Efficiency	80	80	80	80	80	80	80	80	80	80	80	80	80	%
STE.09	Antenna Width Fill Factor	80	80	80	80	80	80	80	80	80	80	80	80	80	%
STE.10	Amplifier Temperature	50	50	50	50	50	50	50	50	50	50	50	50	50	K
STE.11	Electronics Cost per Channel	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	$
STE.12	Feed Structure Cost Rate	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	2300	$/meter
STE.13	Reflector Volume Cost Rate	32	32	32	32	32	32	32	32	32	32	32	32	32	$/meter^3

Instrument Simulation Software (Fermilab)



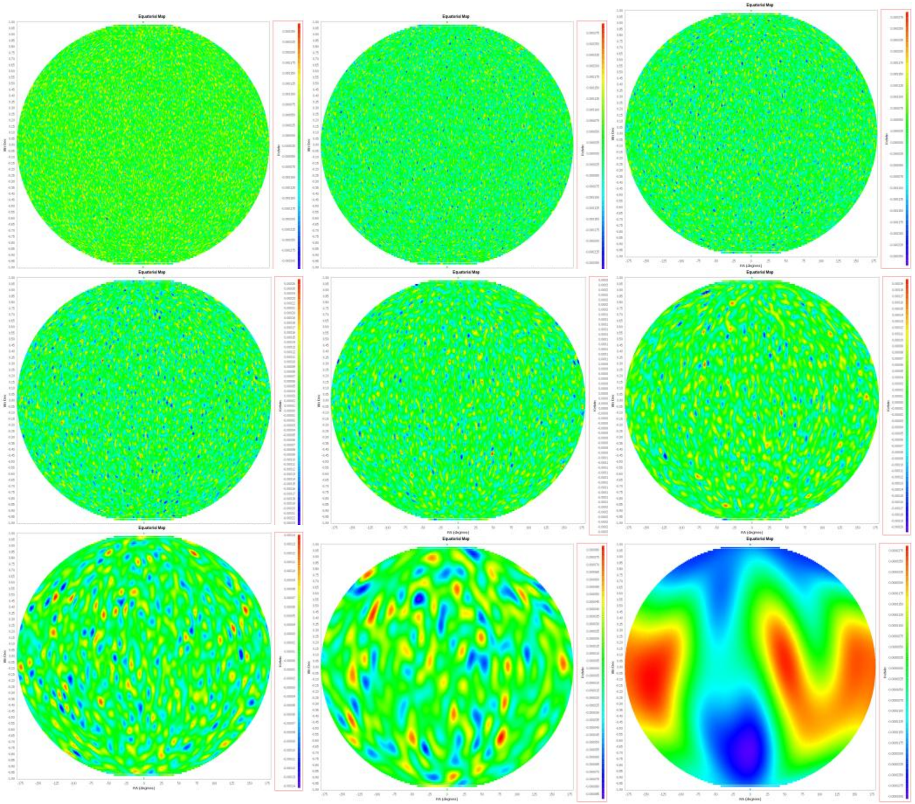




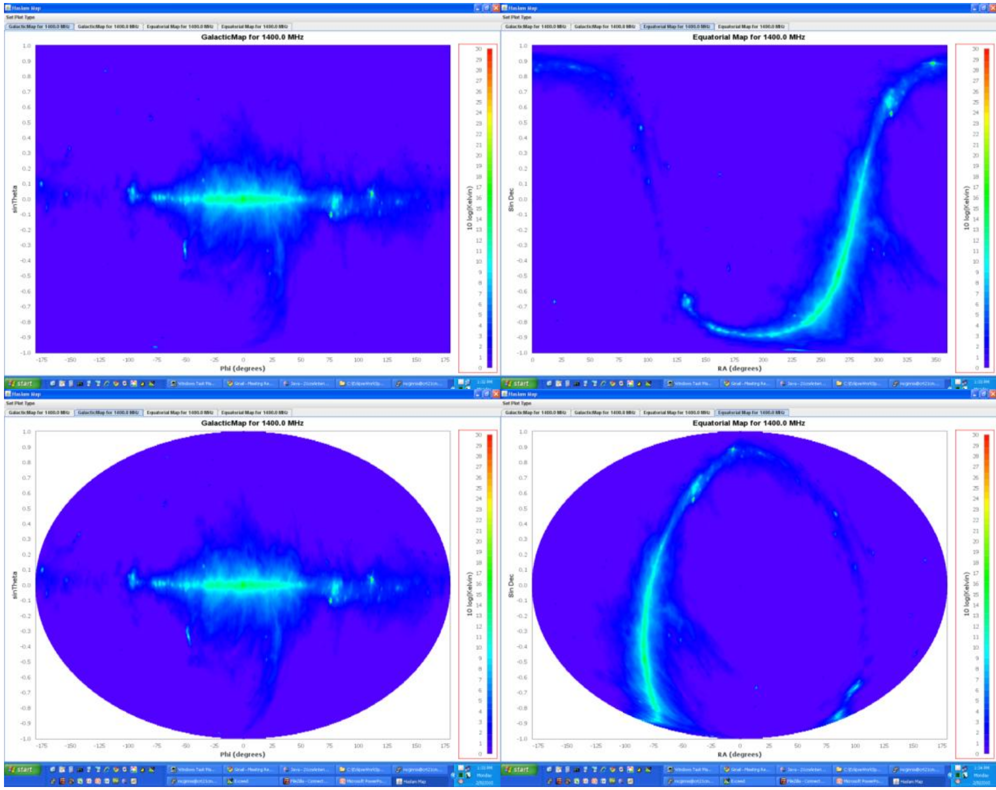


- 20 Java classes organized into 7 packages
- Major Packages
  - Sky Map Generator
  - Cylinder Visibility Simulator
  - Cylinder Visibility Modeler
  - Sky Reconstructor

Foreground Removal



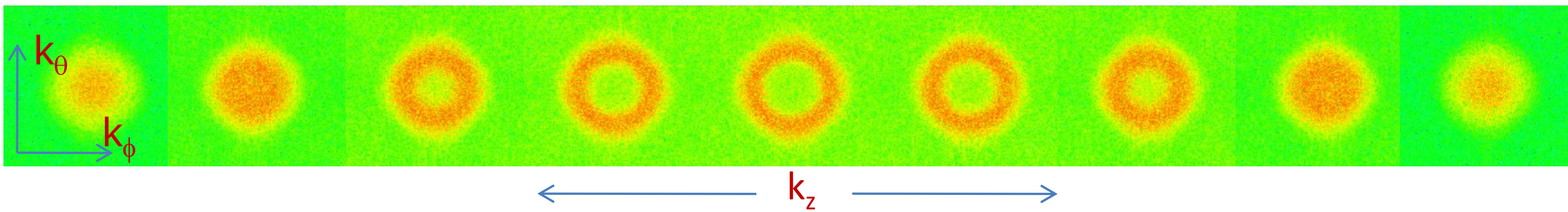
BAO first Peak from 500-1400MHz
(~200uK) (Gnedin)



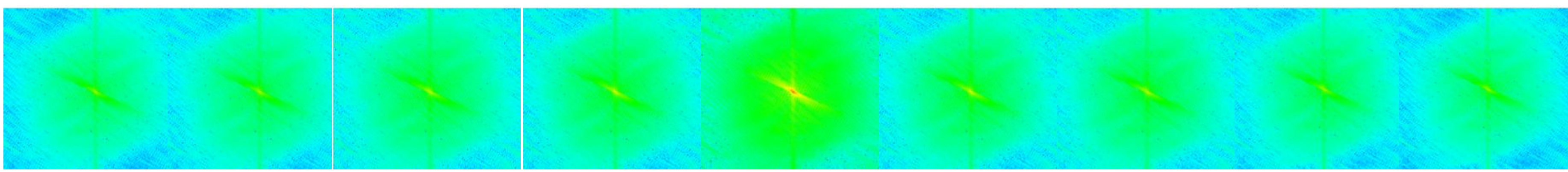
Foreground Sky
(Max > 1000K)

Foreground Removal (Fermilab)

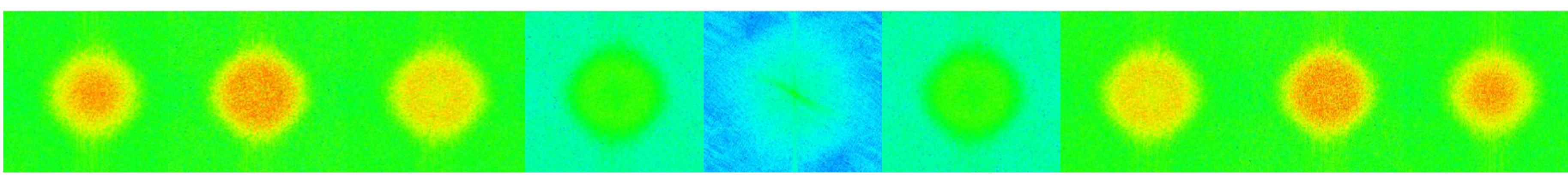
BAO First Peak in 3-D k-Space (Gnedin)



BAO First Peak and Foreground in 3-D k-Space



BAO First Peak and Foreground with Foreground Removal in 3-D k-Space



2010 Work Plan

- Organize project management structure
- Complete foreground simulations
- Finalize requirements
- Write conceptual design report (CDR)
- Define funding plan
- External review of the CDR and funding plan
- Pursue funding

Funding Sources

- While writing the CDR and searching for external collaborators, the collaboration will identify an number of possible funding plans
- For example, one scenario could be:
  - 25% DOE
  - 25% NSF
  - 25% in-kind contributions from foreign collaborators
  - 25% from the host country that would cover infrastructure costs.
  - Fermilab would likely be a major player in this scenario
- Another scenario could be
  - 25% from an outside contributor (i.e. The Dubai Institute)
  - 20% NSF
  - 25% in-kind contributions from foreign collaborators
  - 25% from the host country that would cover infrastructure costs.
  - 5% from DOE
  - Fermilab would be a minor player in this scenario
- The amount that DOE contributes would be proportional to how large a roll Fermilab plays in the overall project.

Review of the CDR and Funding Plan

- We would like to have a series of reviews.
- The first review is an internal collaboration review of the CDR
- The second review is a technical and cost review of the CDR by a panel of external reviewers. The purpose of the review is to
  - Receive an endorsement of the CDR from a panel of experts
  - And/or find weak points in the CDR that can be corrected before we pursue funding
- The third review is a presentation to the Fermilab PAC. The purpose of the review is to:
  - Inform the directorate and the Fermilab PAC of the results of the technical CDR review
  - Propose a funding plan
  - Receive permission to pursue funding

Summary

- The 21cm CRT is a Dark Energy Task Force Stage III-IV experiment that can be completed for under 30M$
  - The science is very well aligned with Fermilab's interest in dark energy
  - The 21cm CRT technology is very well aligned to Fermilab's expertise.
  - The project could be Fermilab's next dark energy experiment after DES.
  - The project is a ground-floor opportunity
- We have a new management structure for the project
- Fermilab is a major contributor to this project
  - Site selection
  - Management
  - Telescope simulations
  - Foreground removal
- We want to complete a CDR by the end of 2010 and have an external review.
- We would like the Fermilab Center for Particle Astrophysics to be an **advocate** for the 21cm project