Future Measurements in Cosmology - a small sampling

John Mather
NASA's Goddard Space Flight Center

July 4, 2008

The Crystal Ball

The Crystal Ball has been waiting for your visit! Do you have a question that you have been waiting to ask? Click on the Crystal Ball and your personal fortune-teller browser window will appear and ask for your question. Follow the instructions carefully and you will soon receive the answers to all your questions.

(http://predictions.astrology.com/cb/)

Major Reports

- Quarks to Cosmos report, http://books.nap.edu/openbook.php?isbn=0309074061
- BEPAC report, http://www.aura-astronomy.org/nv/bepac.pdf
- US Decadal Survey, 2000, http://www.nap.edu/openbook.php?isbn=0309070317; next one in 2010
- European Science Vision, 2007, http://www.astronet-eu.org/-Science-Vision-

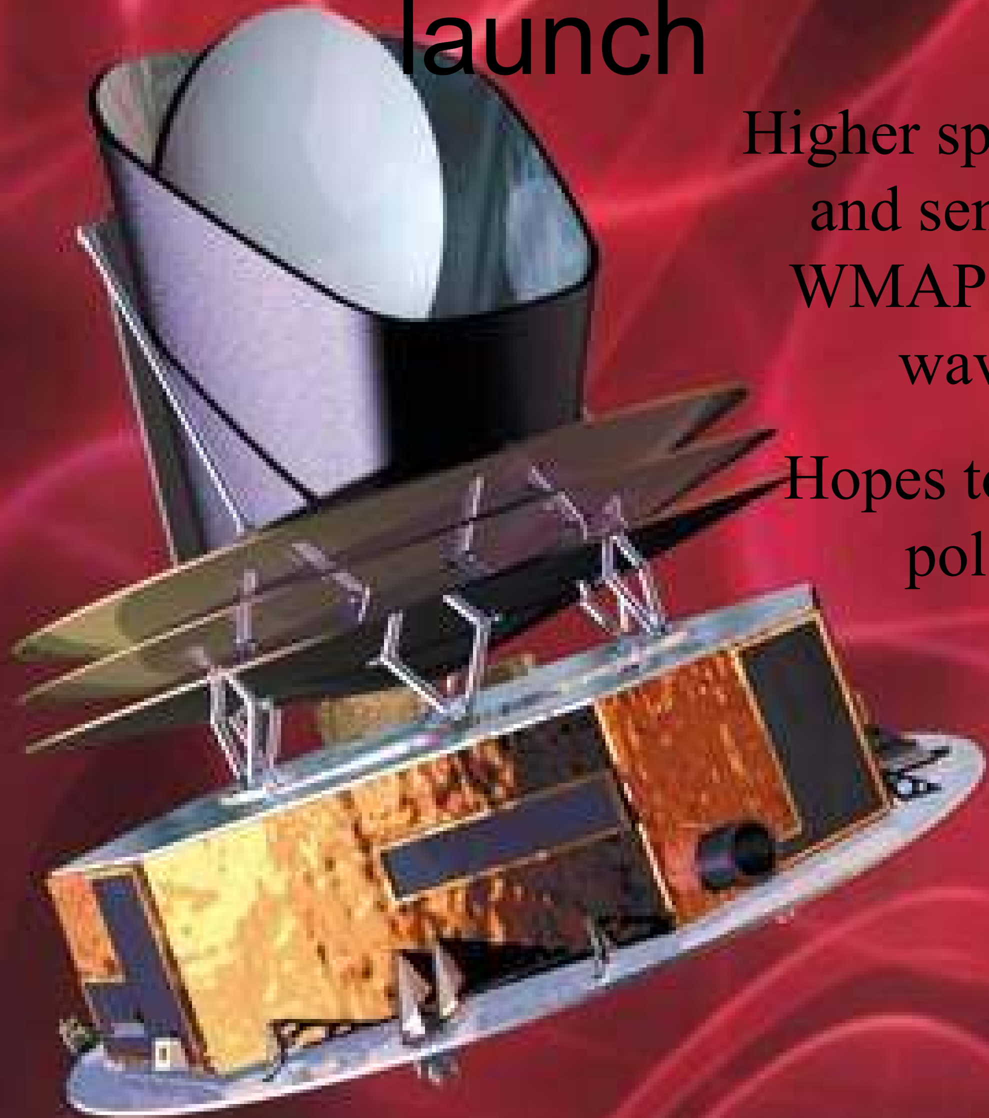
Major Topics

- CMB: anisotropy, polarization, spectrum
- Dark Energy
- Dark Matter
- 21 cm redshifted H surveys
- Everything about luminous matter
- GR tests
- Particle properties

CMB Polarization

- Reference: Weiss report, http://www.nsf.gov/mps/ast/tfcr_final_report.pdf
  - Definition of the challenge
  - Tutorial on all major effects
  - Comparison of ground and satellite requirements

Planck Mission - ESA-led with NASA contributions, for 2008 launch



Higher spatial resolution and sensitivity than WMAP, with shorter wavelengths

Hopes to see B-mode polarization

BEPAC summary of Inflation Probe

TABLE 2.D.1 Inflation Probe: Mission Description

	CMB polarization	CIP
Primary measurement	CMB B-mode Survey	H! galaxy survey
Observatory type	millimeter telescope	Passively cooled slitless grating spectrograph
Projected years in orbit	1	3
Type of orbit	L2 or IRAS/COBE	L2 or IRAS/COBE
Mission phases	One phase, full time scanning	One phase, full time scanning
Science operations	Full time scanning	Full time scanning
Other mission characteristics	Cryogenic	

TABLE 2.D.2 Inflation Probe: Mission Instrument Properties

Instrument	Spectral Range	Spatial Resolution	Spectral Resolution (" /#")	Collecting Area	Field of View
EPIC-F	30 – 300 GHz	0.25-2.5 degrees	3	0.4 m^2	5 degrees
CMBPol	30 – 300 GHz	1 degree	3	0.2 m^2	~15 degrees
EPIC-I	30 – 250 GHz	1 degree	3	0.002-0.1 m^2	7 degrees
CIP	2.5 – 5 μm	0.2 arcsec	600	2.54 m^2	20 arcmin

2.D.2 Mission Science Goals

Charts from Gary Hinshaw for BEPAC

QuickTime™ and a
decompressor
are needed to see this picture.

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decompressor
are needed to see this picture.

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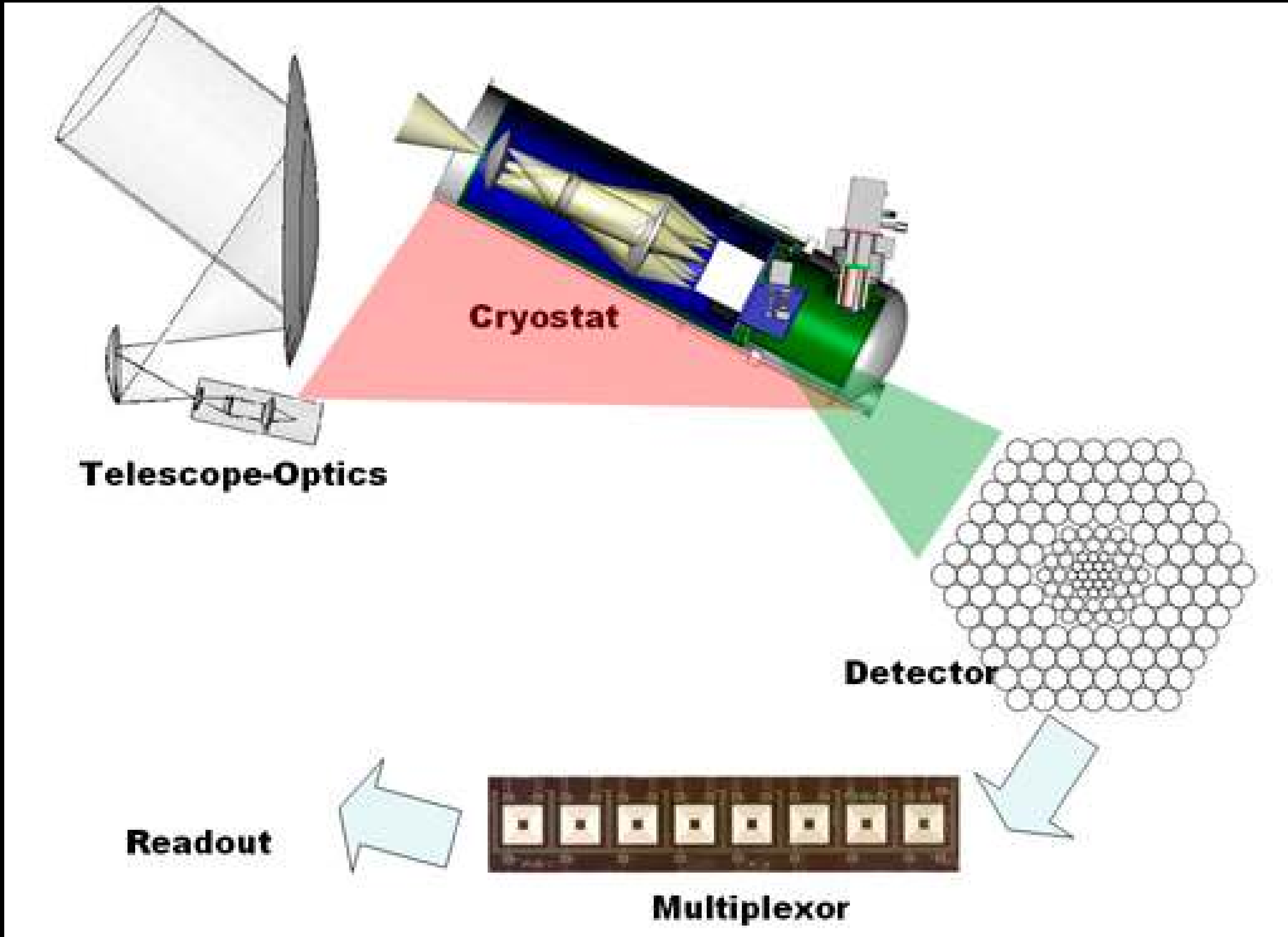
decompressor
are needed to see this picture.

Ground-based CMB polarization plans

- Balloons and low- to high-altitude sites
- Atmosphere not polarized (much) but limits sensitivity
- Need immense sensitivity, huge fields of view, large numbers of detectors, polarization modulation schemes, systematic error control, measurements of galactic foregrounds, ability to separate B and E modes, …
- Angular resolution not limited on ground, but balloons ~ space probes (diffraction limited)
- Atacama Cosmology Telescope ACT, CAPMAP, QuAD, Polar Bear, QUIET, …

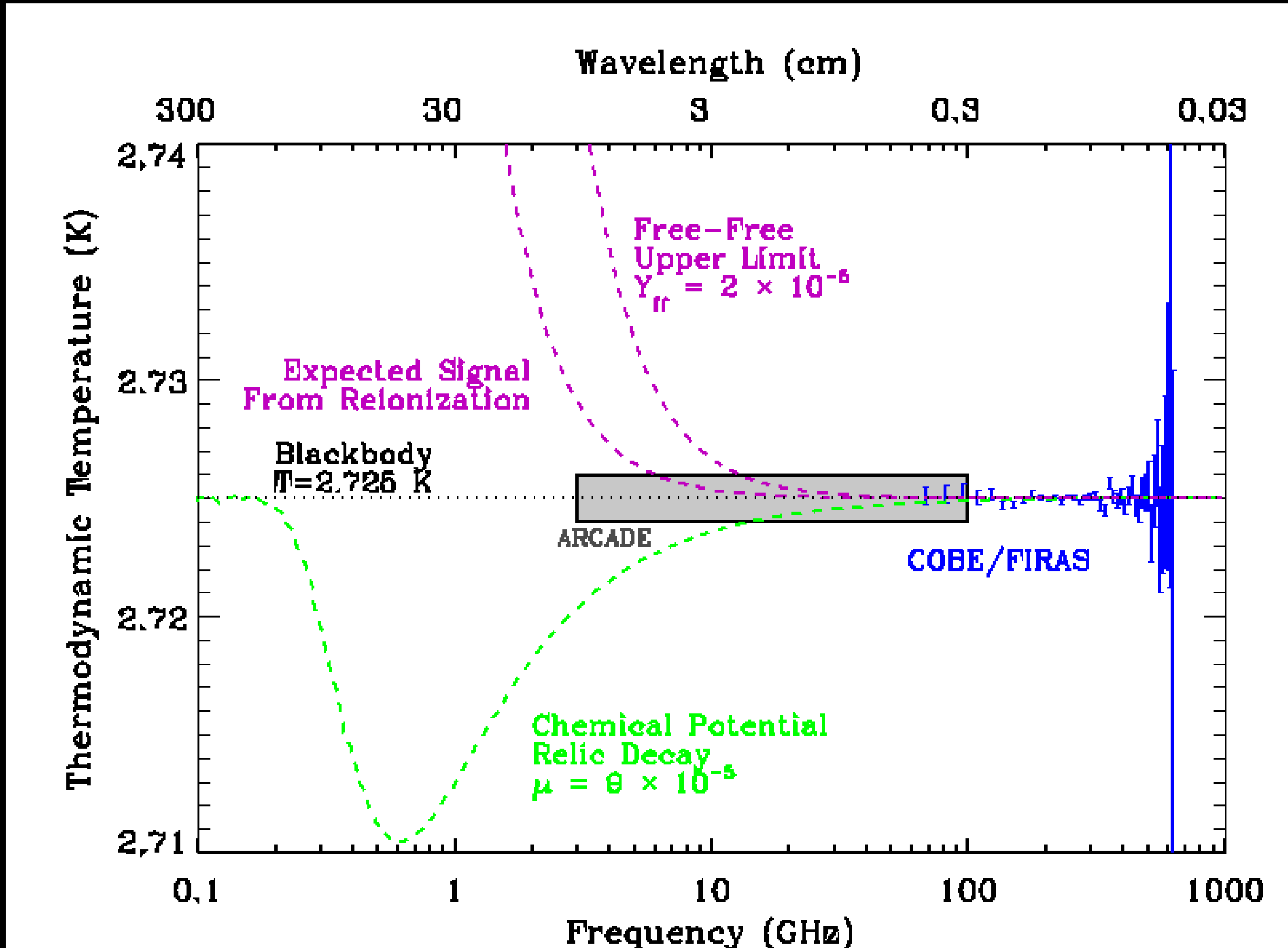
Polar Bear concept
http://bolo.berkeley.edu/polarbear/instrument/instrument.html



CMB Spectrum

- Kogut et al. ARCADE, possible future satellite missions, at long wavelength
- Sunyaev challenge: ppb at short wavelength

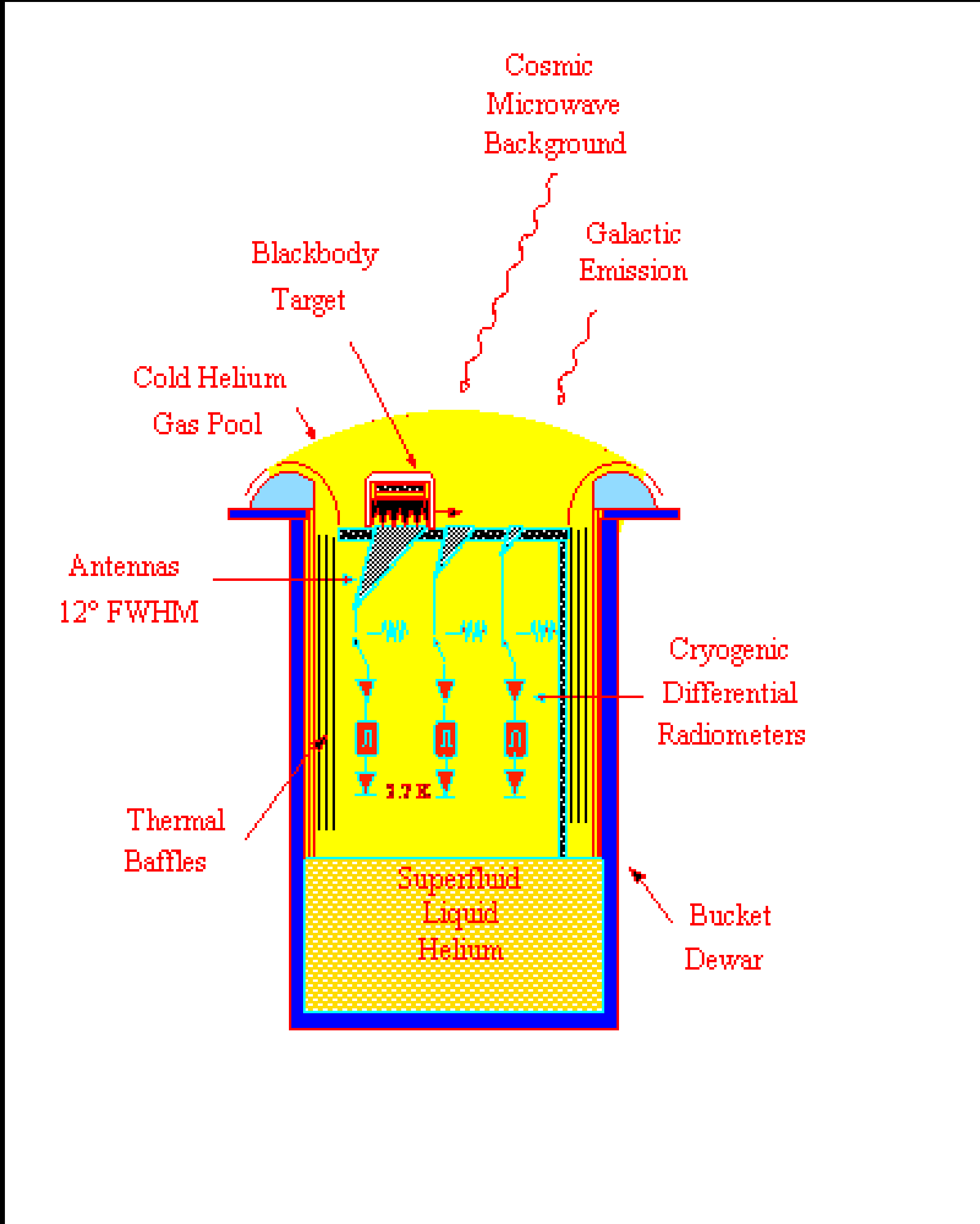
Longer Wavelength CMB Spectrum



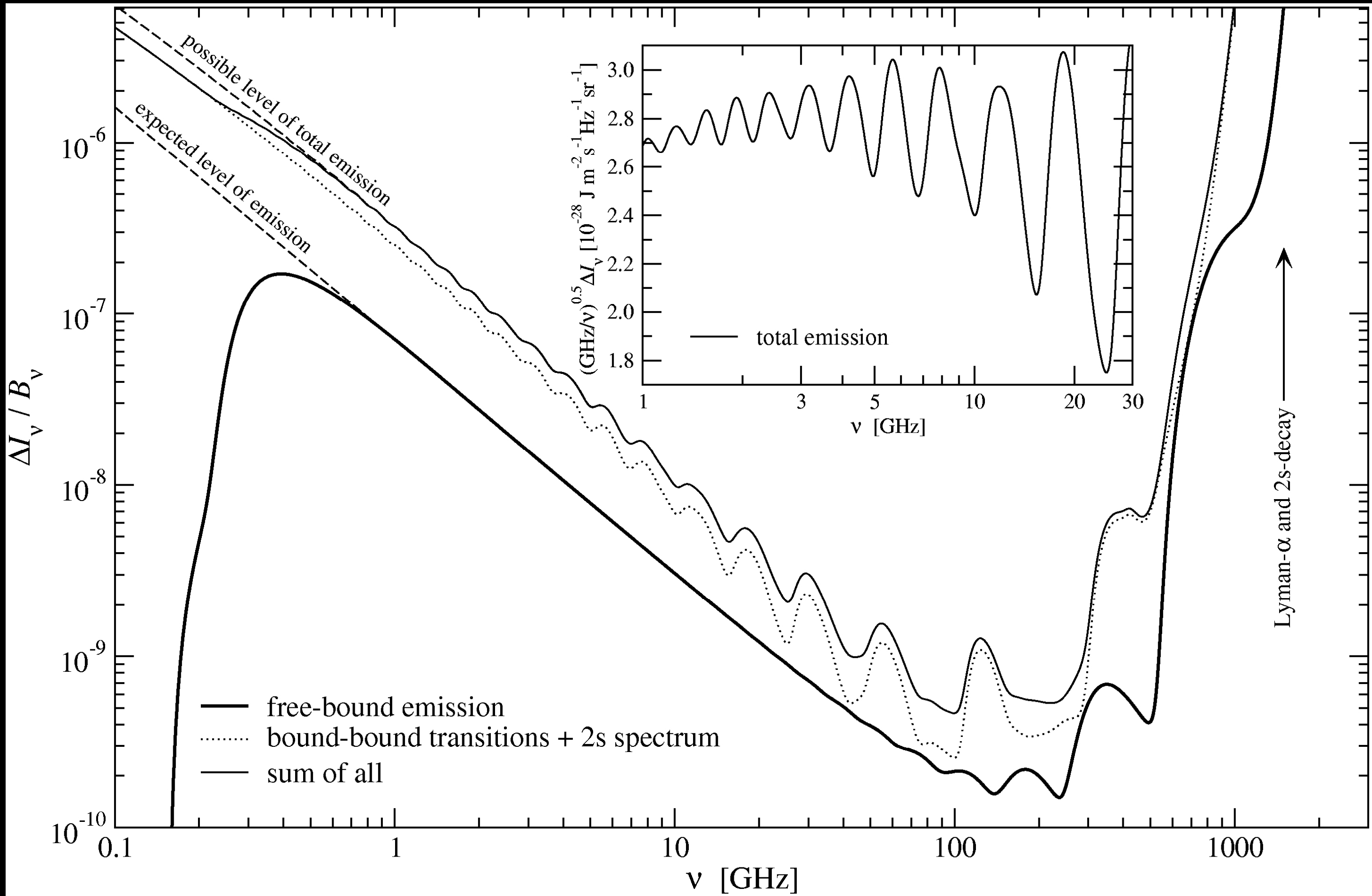
Predicted free-free signal from ionized gas to z ~ 6 must be > 0.3 mK at 3 GHz. Halo formation near reionization implies 2 mK < dT < 5 mK at 3 GHz. Predicted signal from reionization and structure formation (purple curve). (Arcade.gsfc.nasa.gov)

ARCADE

- Al Kogut, PI
- 3 to 90 GHz, with microwave technology
- Absolutely calibrated by full beam blackbody, mK accuracy
- Balloon payload, open helium bucket, helium outflow keeps equipment clean
- 4 flights completed
- Measurement sensitivity Y_ff < 10^{-6}, $\mu < 2 \times 10^{-5}$
- http://arcade.gsfc.nasa.gov



FIRAS 2: Was recombination era out of equilibrium?



Sunyaev et al. predictions

Or, LiH lines, …

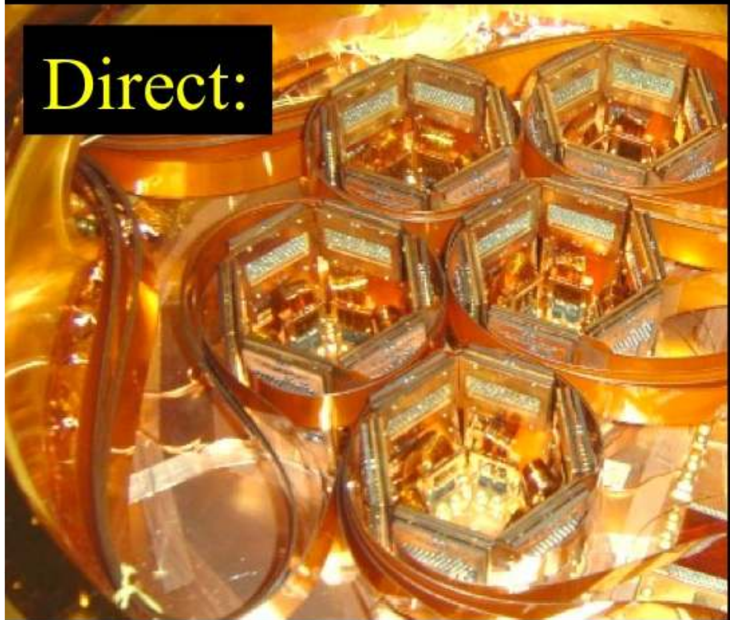
Improvements over FIRAS

- Totally symmetrical instrument
- Totally isothermal instrument, matching CMB temperature
- 1000x better detectors, possibly post-dispersed for better sensitivity: photon noise allows ppb (few nK)
- Isolators between (colder) detectors and instrument; alternatively, kinematic inductance thermometers for detectors without self-heating
- Possibly, use of paraboloid reflector for smaller beamwidth, to see through holes in local dust clouds
- Far from Earth, for better sidelobe control
- Better thermometers, for comparison with other instruments

Dark Matter talks

- http://www.physics.ucla.edu/hep/dm08/talks.html

Four roads to dark matter: *catch it, infer it, make it, weigh it*



Max Tegmark's Chart, UCLA Conf 2008

Indirect:

GLAST launch
scheduled for
May 16 2008

Weak lensing - measures distorted shapes of galaxies, to deduce intervening masses

- Wide field surveys with excellent image quality & control
- E.g., Large Synoptic Survey Telescope (LSST): 8.4 m telescope, huge detectors and computers, in progress http://www.lsst.org/lsst_home.shtml
- Aim to get 3 dimensional model of DM
- Many smaller competitors, ground & space

Upcoming lensing measurements:

More from Nick Scoville in next talk

	Survey	Telescope	Sky coverage	Filters	depth
Ongoing	Deep Lens Survey	CTIO	7x4 deg^2	BVRz'	R=25
	CFHTLS-Wide	CFHT	170 deg^2	ugriz	i_{AB}=24.5
	RCS2	CFHT	1000 deg^2	grz	i_{AB}=22.5
Within a year	KIDS	VST	1500 deg^2	ugriz	i_{AB}=22.9
	Pan-STARRS	PS1	30000 deg^2	grizy	i_{AB}=24
	VIKING	VISTA	1500 deg^2	zYJHK	i_{AB}=22.9
	Dark Energy Survey	CTIO	5000 deg^2	griz	i_{AB}=24.5
Not yet guaranteed	DarkCam	VISTA	10000 deg^2	ugriz	i_{AB}=24
	HyperCam	SUBARU	3500 deg^2	TBD	TBD
	SNAP	Space	300/2000 deg^2	Narrow band (0.35-1.6)	TBD
	LSST	6m ground	20000 deg^2	Narrow band (0.35-1.2)	i_{AB}=27
	DUNE	Space	20000 deg^2	TBD	i_{AB}=25.5

Compilation from Munshi, Valageas, van Waerbeke & Heavens 2007

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LSST

- 8.4-meter, 9.6-square-degree field telescope will provide digital imaging of faint astronomical objects across the entire sky, night after night. With 15-second exposures, LSST will cover the available sky every three nights.

Dark Energy Measurements

- Dark Energy Task Force (DETF): http://arxiv.org/abs/astro-ph/0609591
- BEPAC report: http://www.aura-astronomy.org/nv/bepac.pdf
- Curmudgeon viewpoint: Simon White, http://arxiv.org/abs/0704.2291
- John Peacock lecture at STScI: http://www.stsci.edu/institute/itsd/information/streaming/archive/SpringSymposium2008/JohnPeacock050808Hi_supporting/Peacock.ppt

Dark Energy Task Force

Report to the AAAC
13 February 2005

Rocky Kolb
Andy Albrecht

Fifteen Findings

1. Four observational techniques dominate White Papers:
   a. Baryon Acoustic Oscillations (**BAO**) large-scale surveys measure features in distribution of galaxies. BAO: $d_A(z)$ and $H(z)$.
   b. Cluster (**CL**) surveys measure spatial distribution of galaxy clusters. CL: $d_A(z)$, $H(z)$, growth of structure.
   c. Supernovae (**SN**) surveys measure flux and redshift of Type Ia SNe. SN: $d_L(z)$.
   d. Weak Lensing (**WL**) surveys measure distortion of background images due to garavitational lensing. WL: $d_A(z)$, growth of structure.
2. Different techniques have different strengths and weaknesses and sensitive in different ways to dark energy and other cosmo. parameters.
3. Each of the four techniques can be pursued by multiple observational approaches (radio, visible, NIR, x-ray observations), and a single experiment can study dark energy with multiple techniques. Not all missions necessarily cover all techniques; in principle different combinations of projects can accomplish the same overall goals.

Fifteen Findings

4. Four techniques at different levels of maturity:
   a. **BAO** only recently established. Less affected by astrophysical uncertainties than other techniques.
   b. **CL** least developed. Eventual accuracy very difficult to predict. Application to the study of dark energy would have to be built upon a strong case that systematics due to non-linear astrophysical processes are under control.
   c. **SN** presently most powerful and best proven technique. If photo-z’s are used, the power of the supernova technique depends critically on accuracy achieved for photo-z’s. If spectroscopically measured redshifts are used, the power as reflected in the figure-of-merit is much better known, with the outcome depending on the ultimate systematic uncertainties.
   d. **WL** also emerging technique. Eventual accuracy will be limited by systematic errors that are difficult to predict. *If* the systematic errors are at or below the level proposed by the proponents, it is likely to be the most powerful individual technique and also the most powerful component in a multi-technique program.

JDEM (Joint Dark Energy Mission) per BEPAC

TABLE 2.E.1 JDEM: Mission Description

Primary Measurement	Optical/Near IR imaging and spectroscopy
Observatory Type	Optical/Near IR Wide Field Survey Telescope
Projected Years in Orbit	3 year primary, 5 year goal
Type of Orbit	LEO (ADEPT); L2 (DESTINY/SNAP)
Mission phases	ADEPT: full-sky survey DESTINY: 24 months SN survey, 12 months weak lensing survey SNAP: 22 months SN survey, 12 months weak lensing survey
Science Operations	Continuous survey

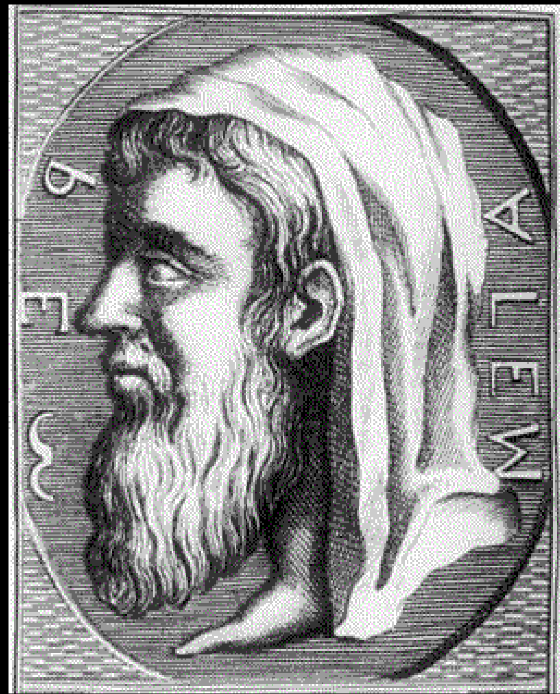
TABLE 2.E.2 JDEM: Mission Instrument Properties

Instrument	**Spectral Range (microns)**	**Spatial Resolution (arcsec)**	**Spectral Resolution ($\lambda/\Delta\lambda$)**	**Collecting Area (diameter in meters)**	**Field of View (sq.deg.)**
SNAP imager	0.35-1.7	0.14	5	1.8	0.7
SNAP Spectrometer	0.35-1.7	0.14	100 (visible) 70 (NIR)	1.8	Not applicable
DESTINY imager	0.85-1.7	0.15	5	1.65	0.12
DESTINY grism	0.85-1.7	0.15	75	1.65	0.12
ADEPT slitless spectrograph	1.3-2.0	Not available	Not available	1.3	Not available

2.E.2 Mission Science Goals

Euclid

ESA's mission to map the Dark Universe



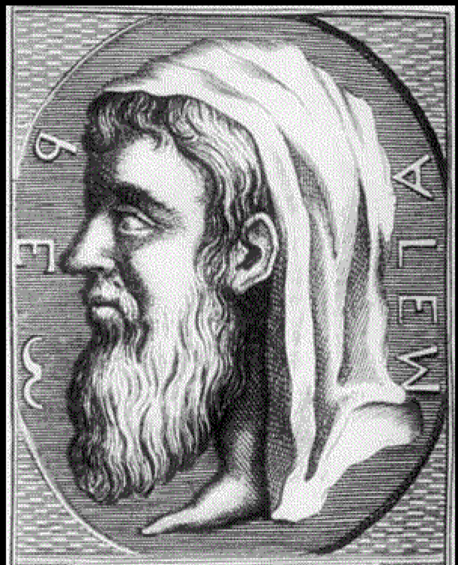
A Decade of Dark Energy

STScI 08 May 2008

John Peacock, on behalf of the Euclid Study Science Team

Euclid

A geometrical probe of the universe proposed for Cosmic Vision



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DUNE

All-sky optical imaging for gravitational lensing

+

SPACE

All-sky near-IR spectra to H=22 for BAO

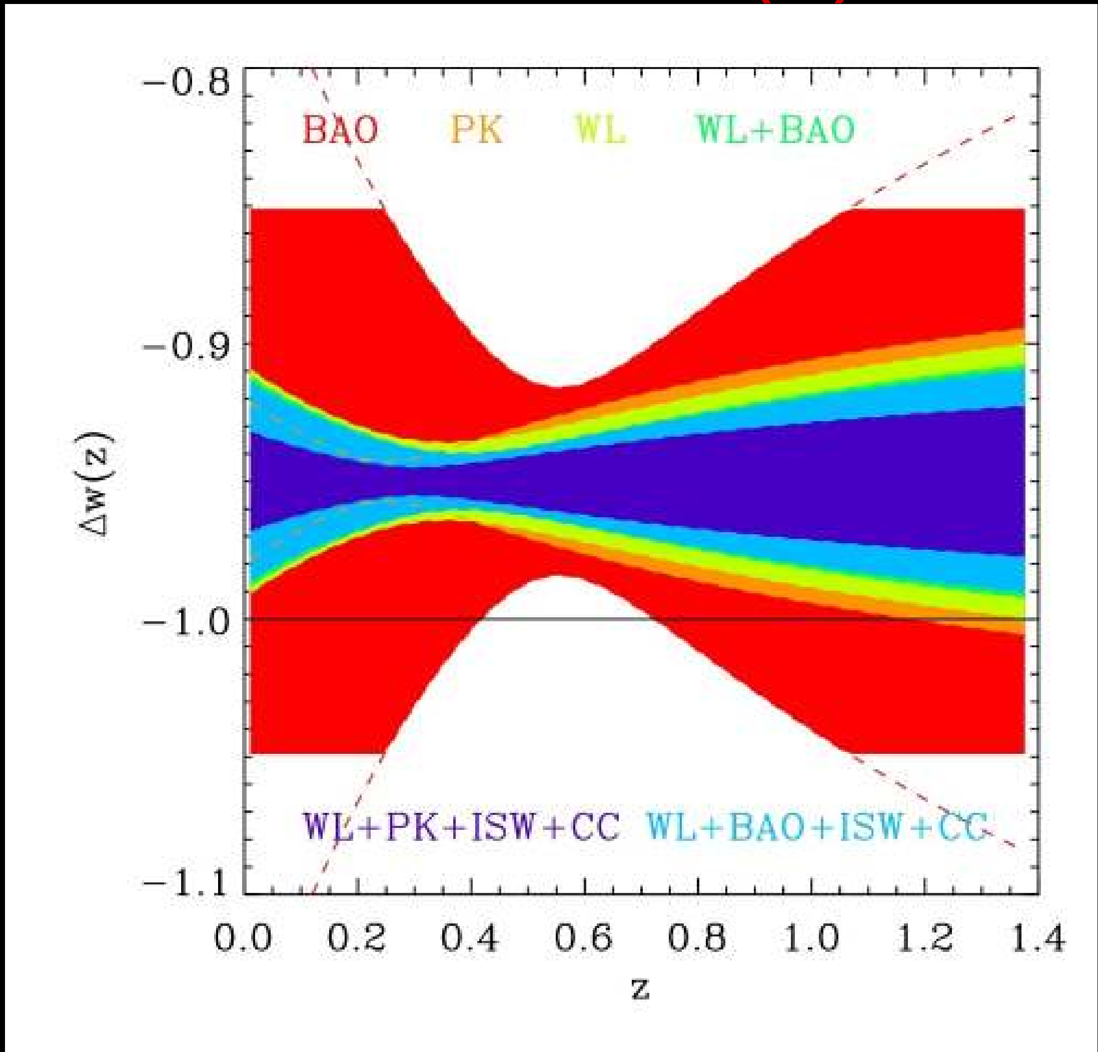
Selection of ESA's Dark Energy Mission

- ***Dark energy*** is recognized by the ESA Advisory Structure as the most timely and important science topic among the M mission proposals and is therefore recommended as the top priority.
- ***Dark energy*** has been addressed by two Cosmic Visions M proposals:
  - ***DUNE (PI: A. Refregier-CEA Saclay)*** – All sky visible and NIR imaging to observe weak gravitational lensing
  - ***SPACE (PI: A. Cimatti – Bologna Univ.)*** – All sky NIR imaging and spectroscopy to detect baryonic acoustic oscillations
- A Concept Advisory Team considered these and recommended a ***single*** M-Class Dark Energy Mission
  - The chair of the team – Malcolm Longair – will present the recommendation to the ESA Advisory Structure on May 13, 2008.

The Euclid Concept

- Named in honour of the pioneer of geometry
- Euclid will survey the entire extra-galactic sky (20 000 deg^2) to simultaneously measure its two principal dark energy probes:
  - **Weak lensing**:
    - Diffraction limited galaxy shape measurements in one broad visible R/I/Z band.
    - Redshift determination by Photo-z measurements in 3 YJH NIR bands to H(AB)=24 mag, 5σ point source
  - **Baryonic Acoustic Oscillations**:
    - Spectroscopic redshifts for 33% of all galaxies brighter than H(AB)=22 mag, $\sigma_z<0.006$
- With constraints:
  - Aperture: max 1.2 m diameter
  - Mission duration: max ~5 years

Predicted redshift dependence of w(z) errors

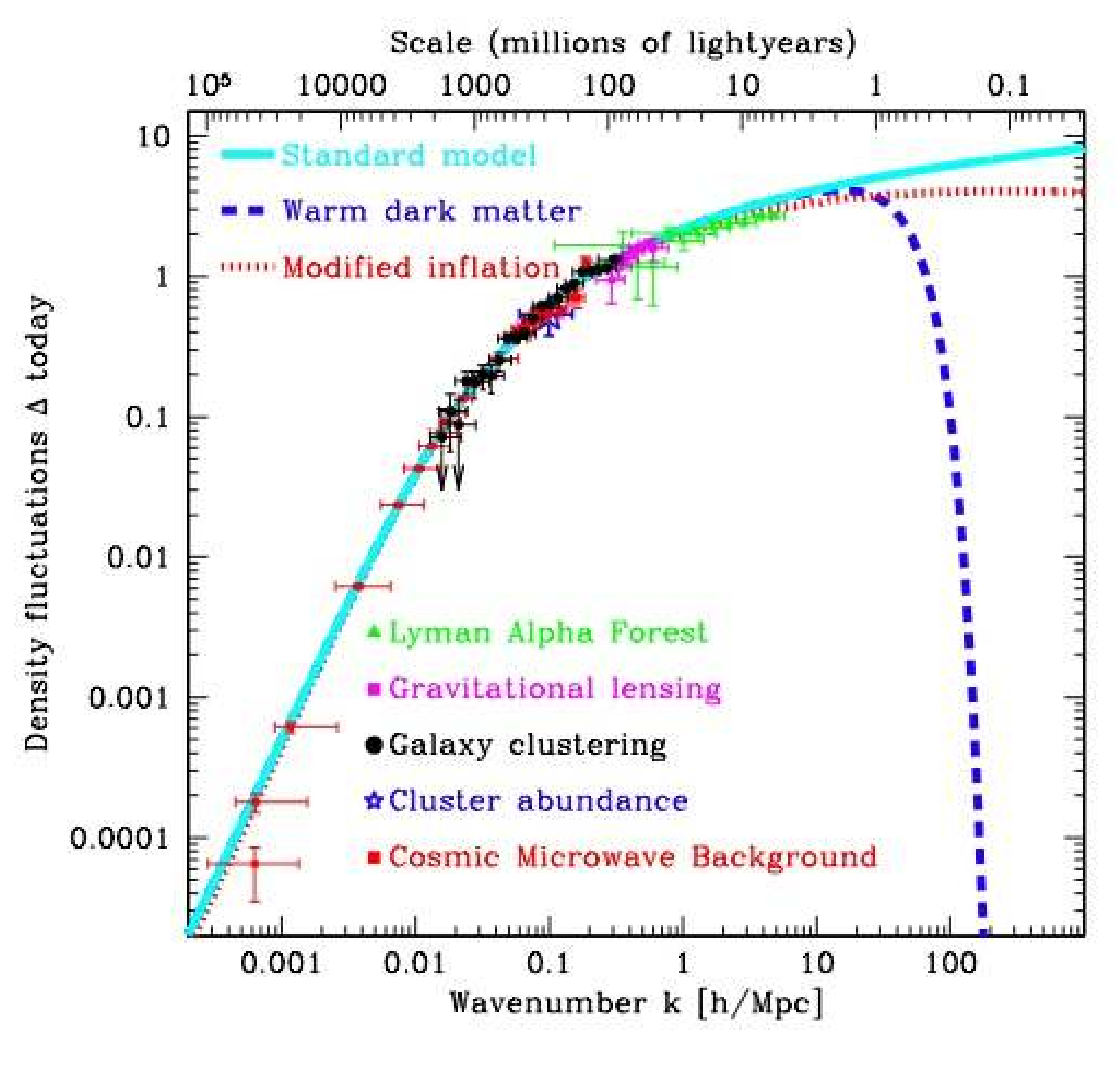


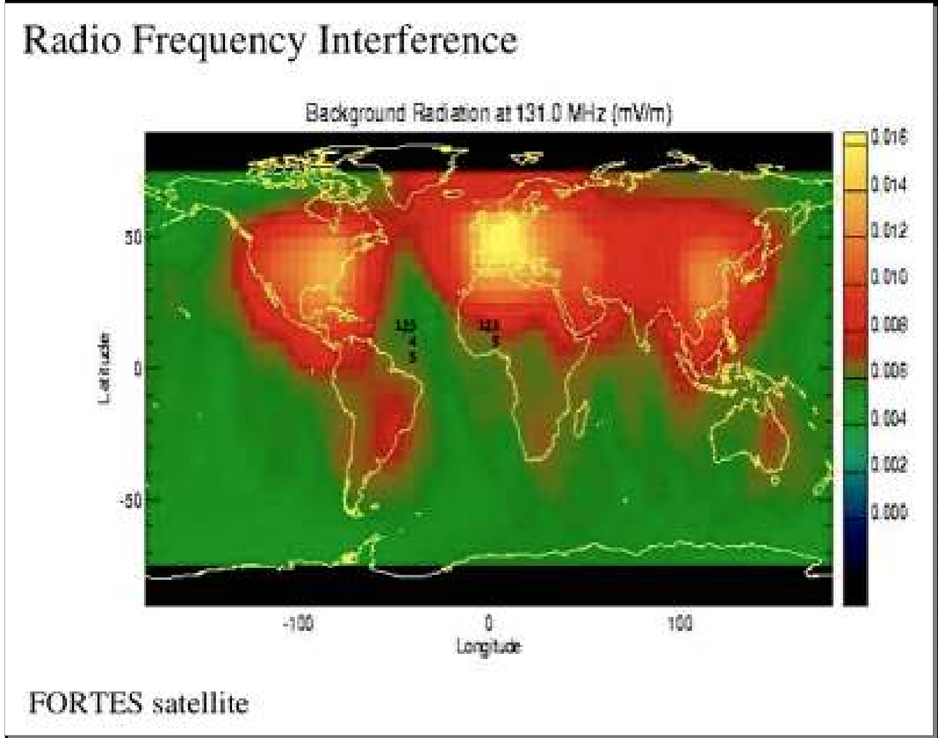
Planck prior is used. The errors are calculated using Fisher matrices using a $w(a)=w_0+(1-a)w_a$ model, hence the caveat that the errors shown here are correlated (from J. Weller).

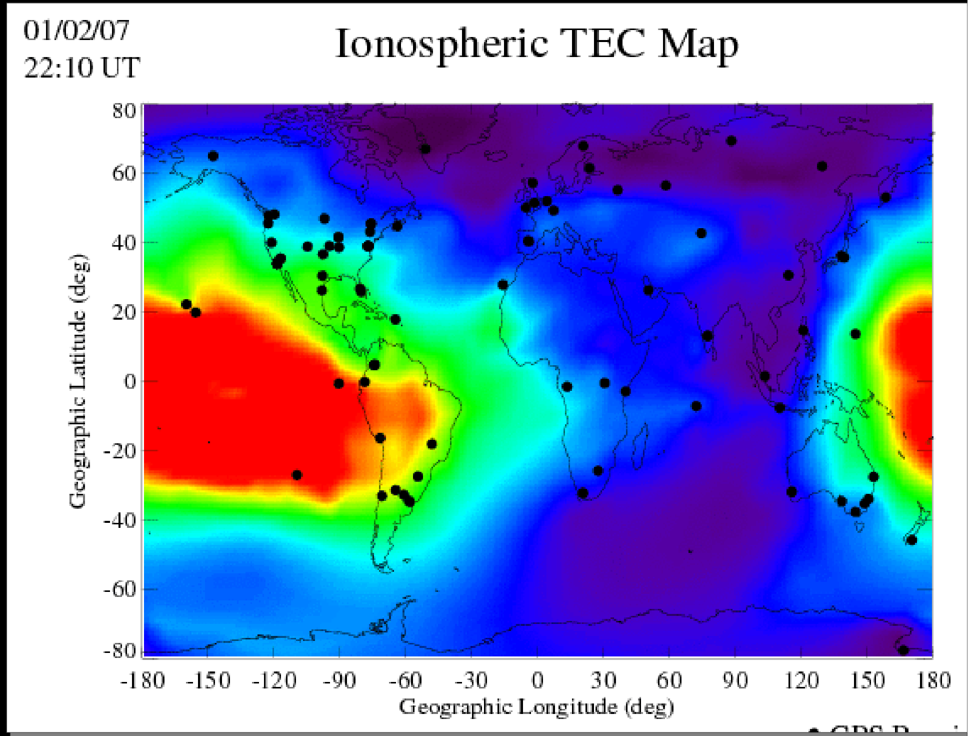
21 cm cosmology

- Reference: http://www.cfa.harvard.edu/events/2008/cos2008/
- MWA: Murchison Widefield Array, Australia, 8000 dipoles, 80-300 MHz, http://www.haystack.mit.edu/ast/arrays/mwa/index.html
- LOFAR: Low Frequency Array, http://www.lofar.org/, centered in Netherlands
- GMRT: Giant Metre-wave Radio Telescope, http://www.gmrt.ncra.tifr.res.in/, India
- SKA: Square Kilometer Array, www.skatelescope.org
- FFTT: Fast Fourier Transform Telescope, http://arxiv.org/abs/0805.4414
- Lunar Array for Radio Cosmology (LARC), NASA-funded study at MIT/Kavli, J. Hewitt
- Dark Ages Lunar Interferometer (DALI), NASA-funded study at NRL, J. Lazio

- Tegmark & Zaldarriaga Fig. 6. Push scale far down to Jeans scale at right edge of figure. Distinguish warm dark matter, inflation with more extreme index.




Radio Frequency Interference
Background Radiation at 131.0 MHz (mV/m)
Latitude
Longitude
FORTES satellite


01/02/07
22:10 UT
Ionospheric TEC Map
Geographic Latitude (deg)
Geographic Longitude (deg)

Murchison Array

- “The MWA will consist of 8000 dual-polarization dipole antennas optimized for the 80-300 MHz frequency range, arranged as 512 "tiles", each a 4x4 array of dipoles.”

Radio Wavelength Observatories in the Exploration Architecture

J. Lazio (NRL)

R. MacDowall (NASA/GSFC), J. Burns (CU), L. Demaio (NASA/GSFC), D. Jones (JPL), K. Weiler (NRL)

S. Bale (UC, Berkeley), N. Gopalswamy (NASA/GSFC), M. Kaiser (NASA/GSFC), J. Kasper (MIT)

ROLSS Technical Description

- 30–300 m wavelength (1–10 MHz frequency)
  - Relevant range for particle acceleration
  - Covers upper range for lunar ionosphere
  - Inaccessible from the ground
- 3-arm interferometer

  First imaging instrument at these wavelengths
- 500-m length arms
  - 2º resolution (@ 30 m) **(but 20 km mobility?)**
  - Order of magnitude improvement in resolution at these wavelengths

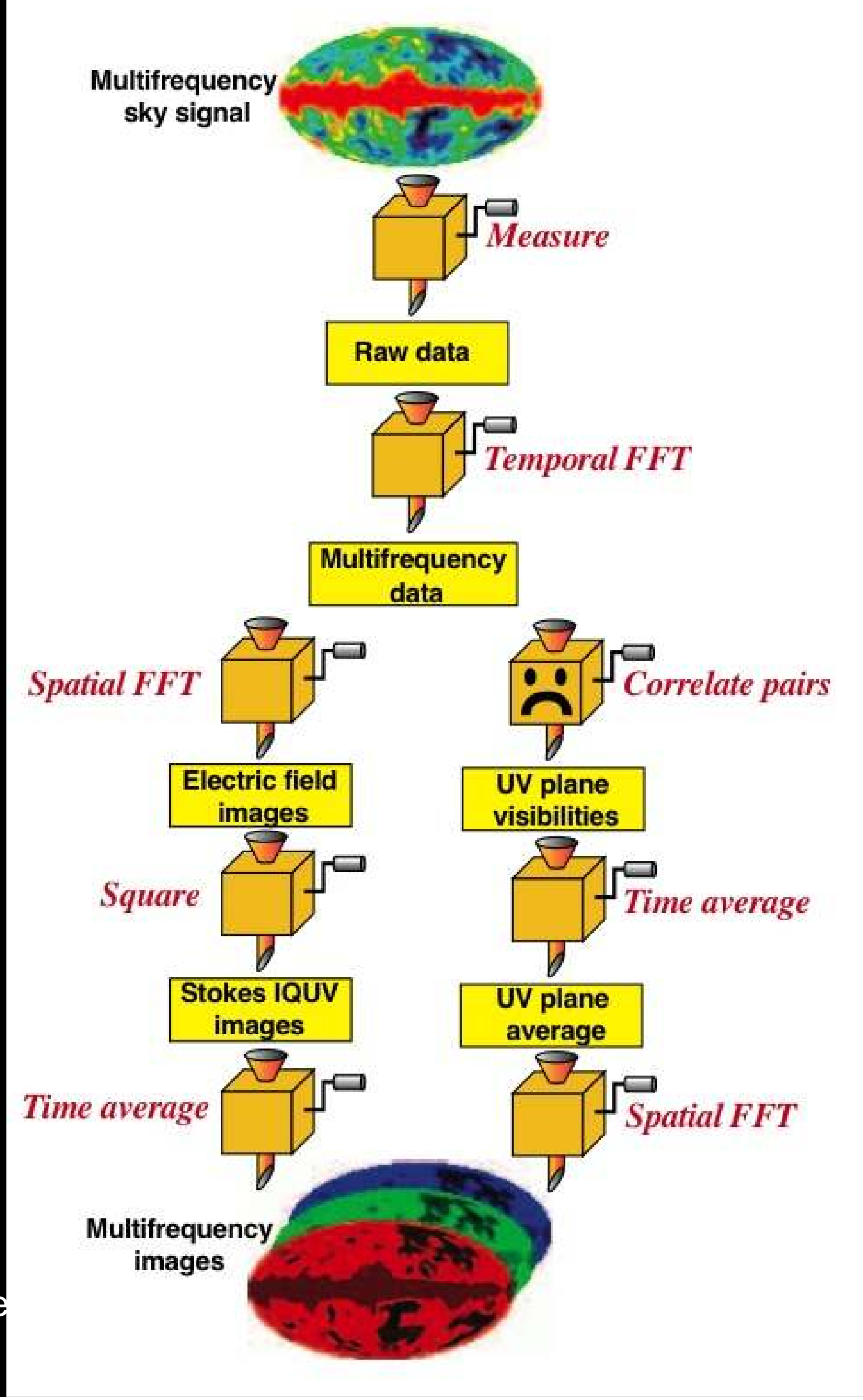
The Fast Fourier Transform Telescope

Max Tegmark
Dept. of Physics & MIT Kavli Institute, Massachusetts Institute of Technology, Cambridge, MA 02139

Matias Zaldarriaga
Center for Astrophysics, Harvard University, Cambridge, MA 02138, USA
(Dated: May 29, 2008. To be submitted to Phys. Rev. D)

We propose an all-digital telescope for 21 cm tomography, which combines key advantages of both single dishes and interferometers. The electric field is digitized by antennas on a rectangular grid, after which a series of Fast Fourier Transforms recovers simultaneous multifrequency images of up to half the sky. Thanks to Moore's law, the bandwidth up to which this is feasible has now reached about 1 GHz, and will likely continue doubling every couple of years. The main advantages over a single dish telescope are cost and orders of magnitude larger field-of-view, translating into dramatically better sensitivity for large-area surveys. The key advantages over traditional interferometers are cost (the correlator computational cost for an N-element array scales as $N \log_2 N$ rather than N^2) and a compact synthesized beam. We argue that 21 cm tomography could be an ideal first application of a very large Fast Fourier Transform Telescope, which would provide both massive sensitivity improvements per dollar and mitigate the off-beam point source foreground problem with its clean beam. Another potentially interesting application is cosmic microwave background polarization.

- FFTT concept of Tegmark & Zaldarriaga



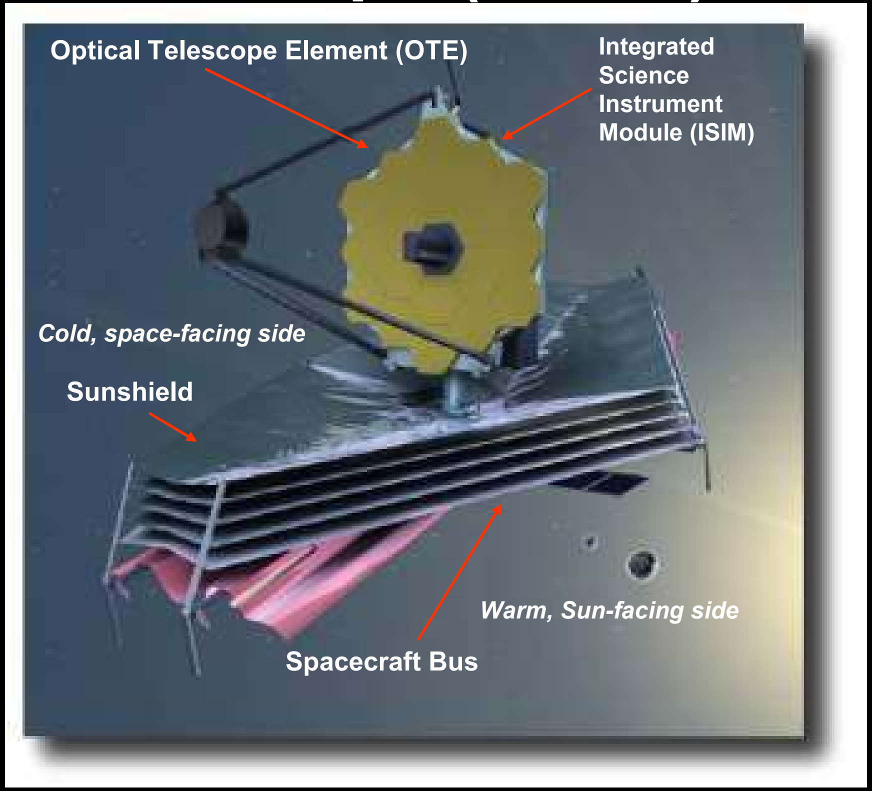
Everything about Luminous Matter

- HST
- JWST
- LSST
- VLT, Keck, …
- EELT, GSMT, TMT, etc.

James Webb Space Telescope (JWST)

Organization

- Mission Lead: Goddard Space Flight Center
- International collaboration with ESA & CSA
- Prime Contractor: Northrop Grumman Space Technology
- Instruments:
  - Near Infrared Camera (NIRCam) – Univ. of Arizona
  - Near Infrared Spectrograph (NIRSpec) – ESA
  - Mid-Infrared Instrument (MIRI) – JPL/ESA
  - Fine Guidance Sensor (FGS) – CSA
- Operations: Space Telescope Science Institute



Description

- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch June 2013 on an ESA-supplied Ariane 5 rocket to Sun-Earth L2
- 5-year science mission (10-year goal)

www.JWST.nasa.gov

JWST Science Themes


End of the dark ages: First light and reionization


The assembly of galaxies

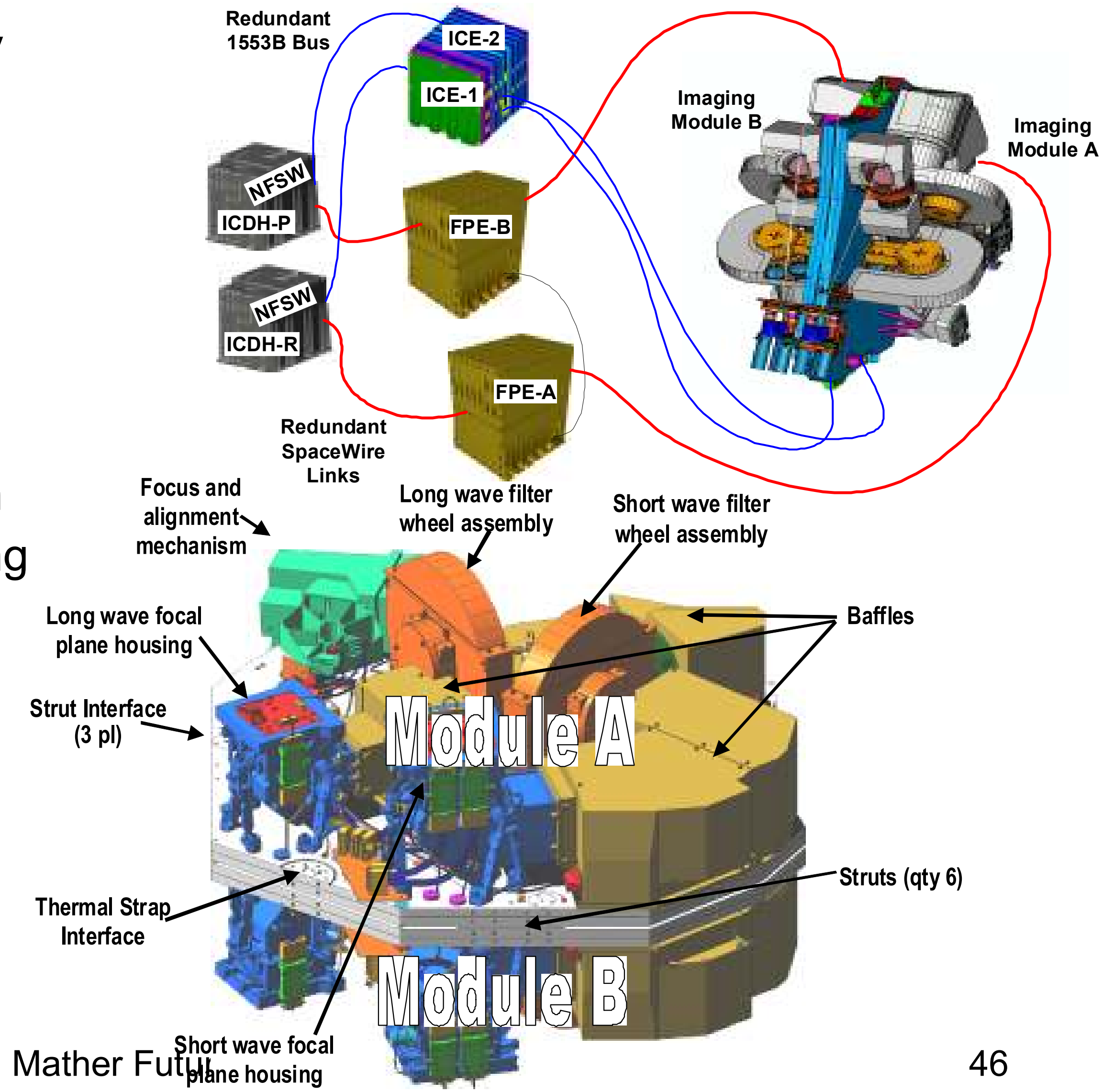

Birth of stars and proto-planetary systems


Planetary systems and the origin of life

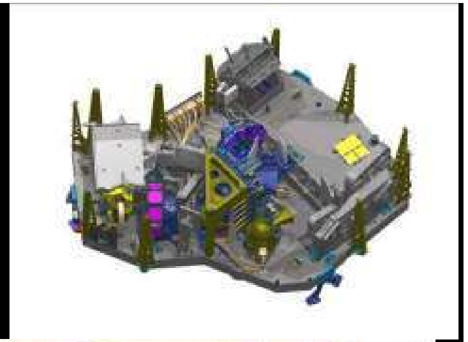
Full scale model at GSFC

Near Infrared Camera (NIRCam) Overview

- NIRCam Provides:
  - Science imagery between 0.6 and 5 microns
  - Wavefront Sensing
- NIRCam Team:
  - University of Arizona
  - Lockheed Martin
  - Teledyne Imaging Systems
- Passed CDR May 2006

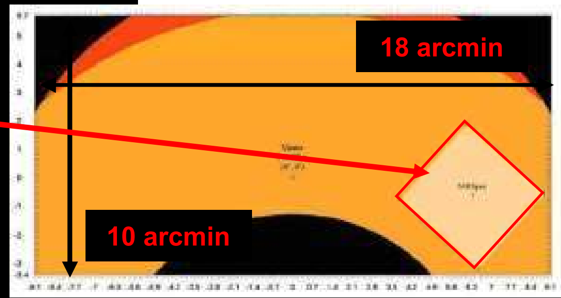


Near Infrared Spectrograph (NIRSpec) Overview

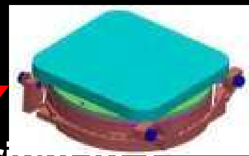


Near-Infrared, multi-object, dispersive spectrograph

- Wavelength Range**: 0.6 μm and 5.0 μm**
- Field of View
  - (with fixed slits): ~ 0.2 x 3.5 arcsec; 0.1 x 2.0 arcsec; 0.4 x 4.0 arcsec
  - (with Micro-Shutter Assembly): ~ 3 x 3 arcmin
  - (with Integral Field Unit): ~ 3 x 3 arcsec

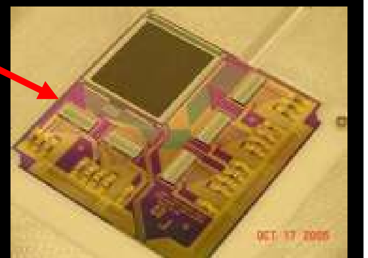


- 3 Spectral Resolutions:
  - R=100 (0.6 μm and 5.0 μm) → Redshift & Exploratory Spectra
  - R=1000 (1.0 μm and 5.0 μm) → Emission Line Diagnostic
  - R=2700 (1.0 μm and 5.0 μm) → Kinematics and Masses



- All reflective optics: **14 mirrors; 12 in SiC (9 aspherical in 3 TMA Assemblies)**

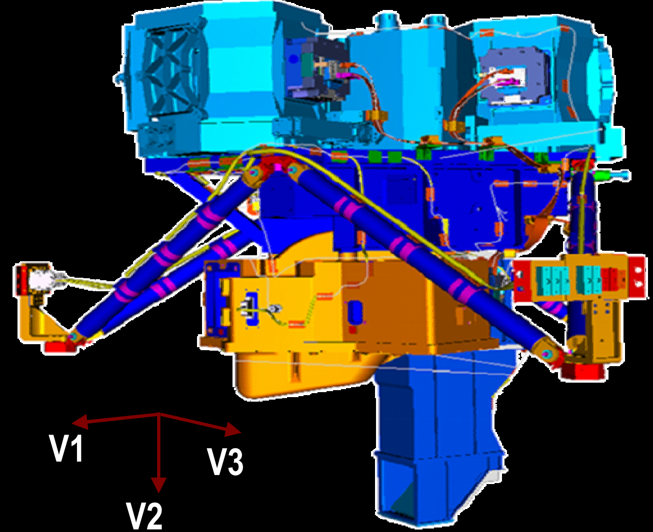
- First time in space more than 100 simultaneous spectra with a slits-based Micro-Shutter Assembly:
  - Mosaic of 4 arrays, each made up by 365 x 171 slits → ~ 250000 slits in total
  - Each 80 μm x 180 μm slit (200 x 460 mas) independently programmable
  - JWST "New Technology" – Passed TRL6 Review



- Detector:
  - 2 x [2048 x 2048 pixels]; HgCdTe; 18 μm size
  - JWST "New Technology" – Passed TRL6 Review
  - Detector Q.E. > 80 % , 1< λ < 5 micron
  - Total Detector Noise < 6 electrons

Mid-Infrared Instrument (MIRI) Overview

- MIRI capabilities:
  - Imaging from 5 – 28 microns
  - Low resolution slit Spectroscopy
  - Coronography
  - Medium resolution integral field unit spectroscopy from 5 – 28 microns
- MIRI Partnership:
  - European Consortium (EC) with 26 contributing Institutes in ten countries
  - Jet Propulsion Laboratory
  - European Space Agency
  - Goddard Space Flight Center
- Passed its Critical Design Review in Feb. 2007
- Development since MIRI Optical System CDR
  - Verification Model Cryo Testing –VM1 successfully completed



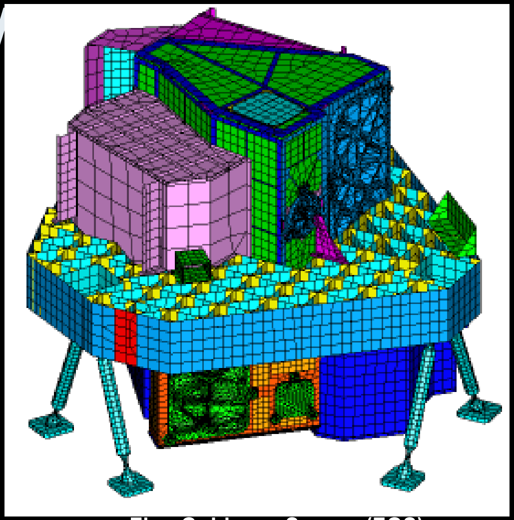

Contamination Control Cover


Engineering Model FPM


Filter Wheel Assembly

Fine Guidance Sensor (FGS) Overview

- FGS Provides:
  - Fine guidance to the overall JWST Observatory (Guider)
  - Science imagery between 1.6 and 4.9 microns (Tunable Filter Imager)
- FGS Team:
  - Canadian Space Agency
  - COM DEV Canada
  - Herzberg Institute of Astrophysics
  - Université de Montreal
  - FGS Science Team
- Critical Design Reviews:
  - Guider CDR Mar 07 (No outstanding RIDs)
  - System/TFI CDR Mar 08



Fine Guidance Sensor (FGS)

Focus Mechanism DM

Prototype Etalon

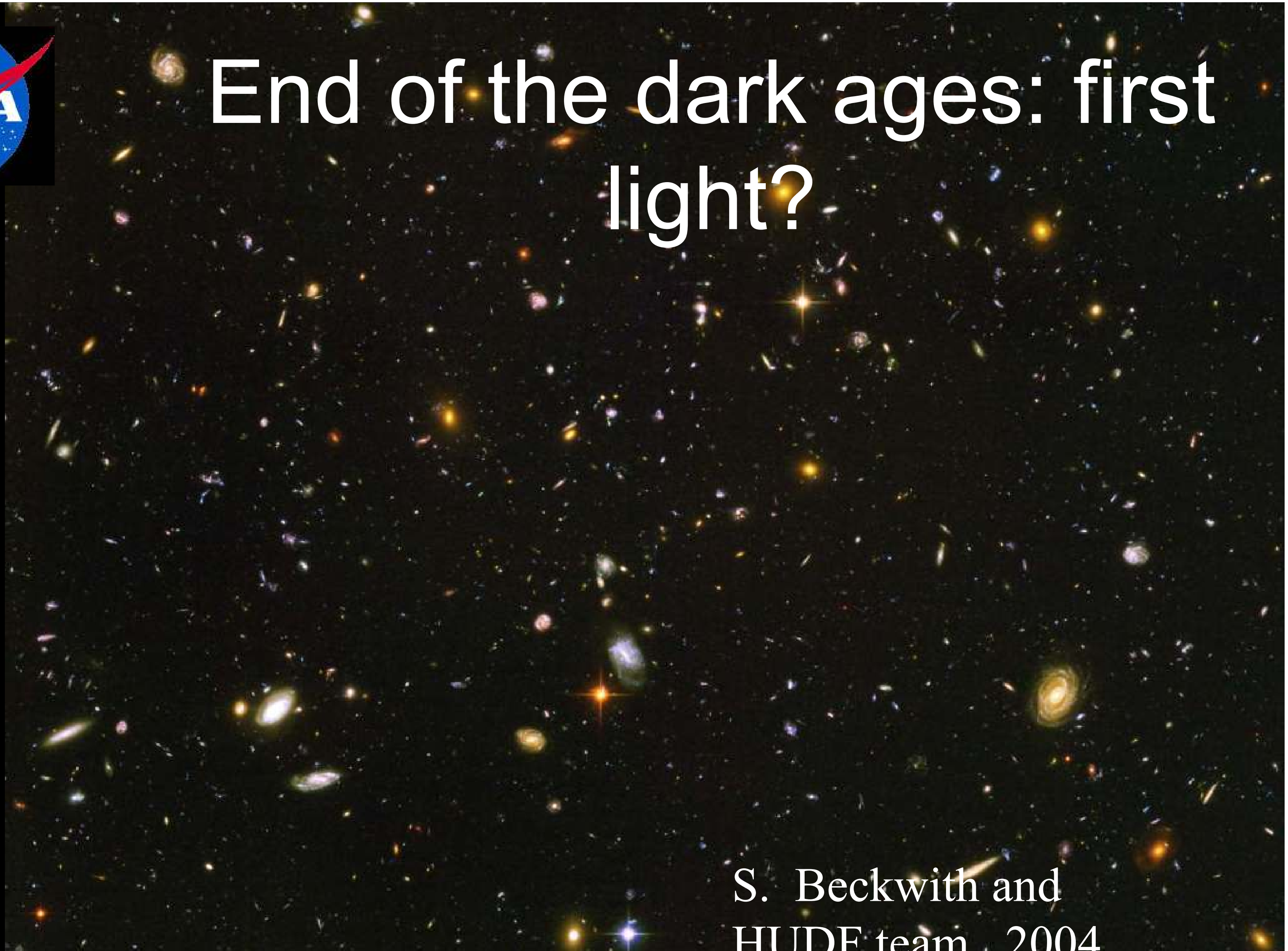
Guider TMA

ETU bench

Cosmology with JWST

- Everything about galaxies, first objects
- Supernovae to z = 10-20; are they like recent ones? IR photometry has less dispersion; could be tool of choice when fully calibrated.
- Black hole formation, migration, effects on galaxies
- Weak lensing to higher redshift (but not a wide field of view)
- Clustering growth at high redshift
- Using “nature’s telescope” of cluster lensing to see farther

End of the dark ages: first light?

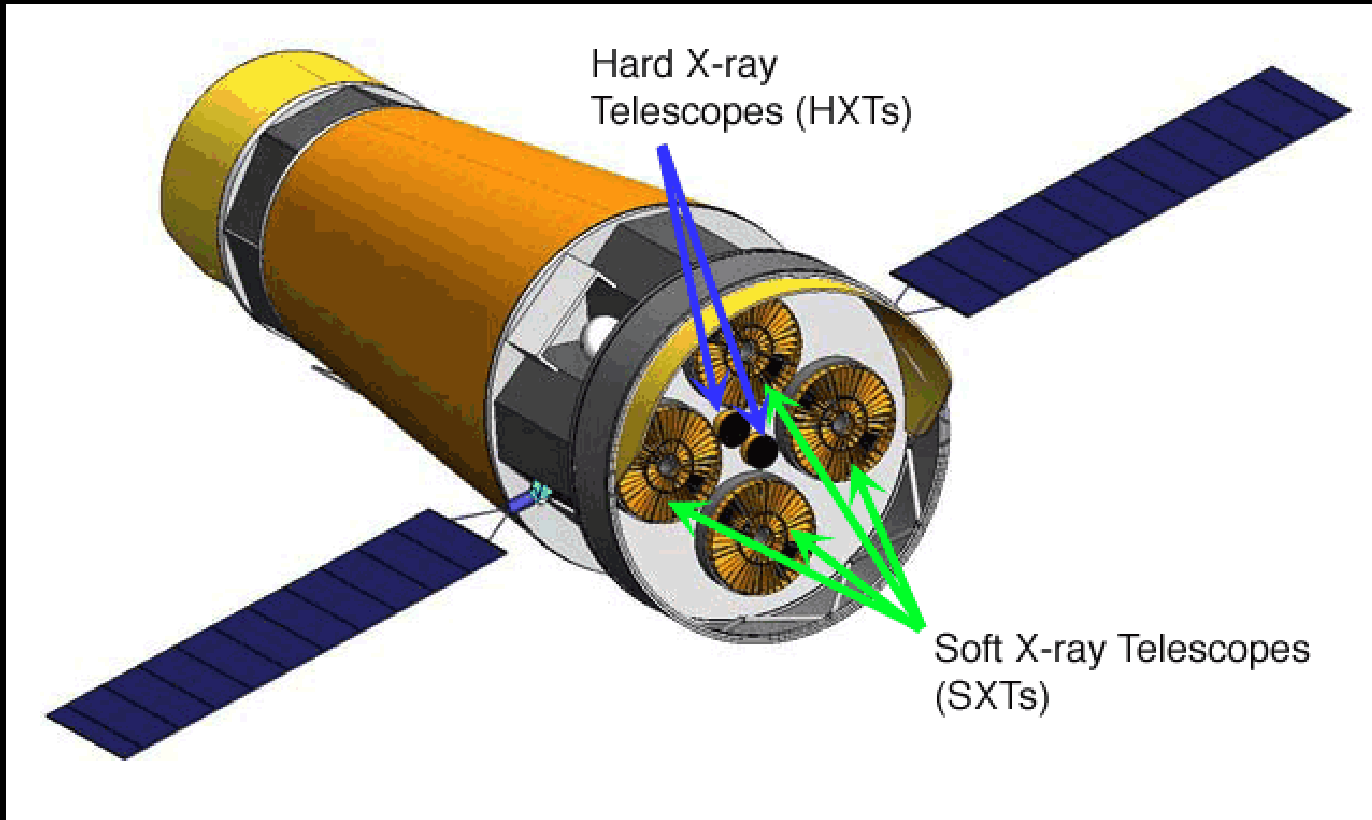


S. Beckwith and HUDF team , 2004

ATLAST = Advanced Technology Large Space Telescope

- Study started at STScI/JHU in preparation for Decadal Survey
- UV/optical successor for HST
  - Supernovae
  - Lensing
  - Clustering
- Reveal cosmic web: intergalactic medium
  - Lyman α absorption against distant objects
  - Hope: direct imaging of IGM

Constellation X (cf. XEUS)

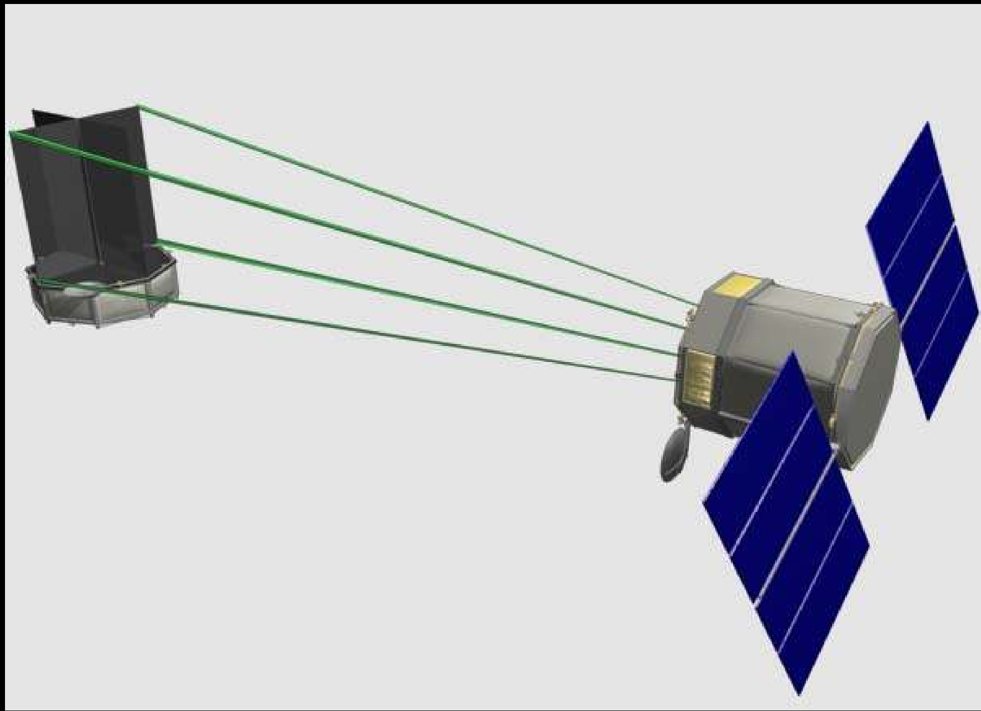


Spectroscopy X-ray Telescope (SXT)
Hard X-ray Telescope (HXT)
SXT consists of a single mirror assembly (SXT FMA) shared by two instruments
- Reflection Grating Spectrometer (RGS)
- X-ray Microcalorimeter Spectrometer (XMS)

HXT consists of 3 mirror assemblies, each with a detector at its focus

Formation Flying Fresnel Telescope

X-ray/Gamma-ray Imaging with milli-arcsecond to micro-arcsecond Angular Resolution



- Diffractive Fresnel optics can achieve milli-arcsecond → micro-arcsecond angular resolution in the x-ray/gamma-ray band (5 - 1000 keV)
- Diffraction limited performance:

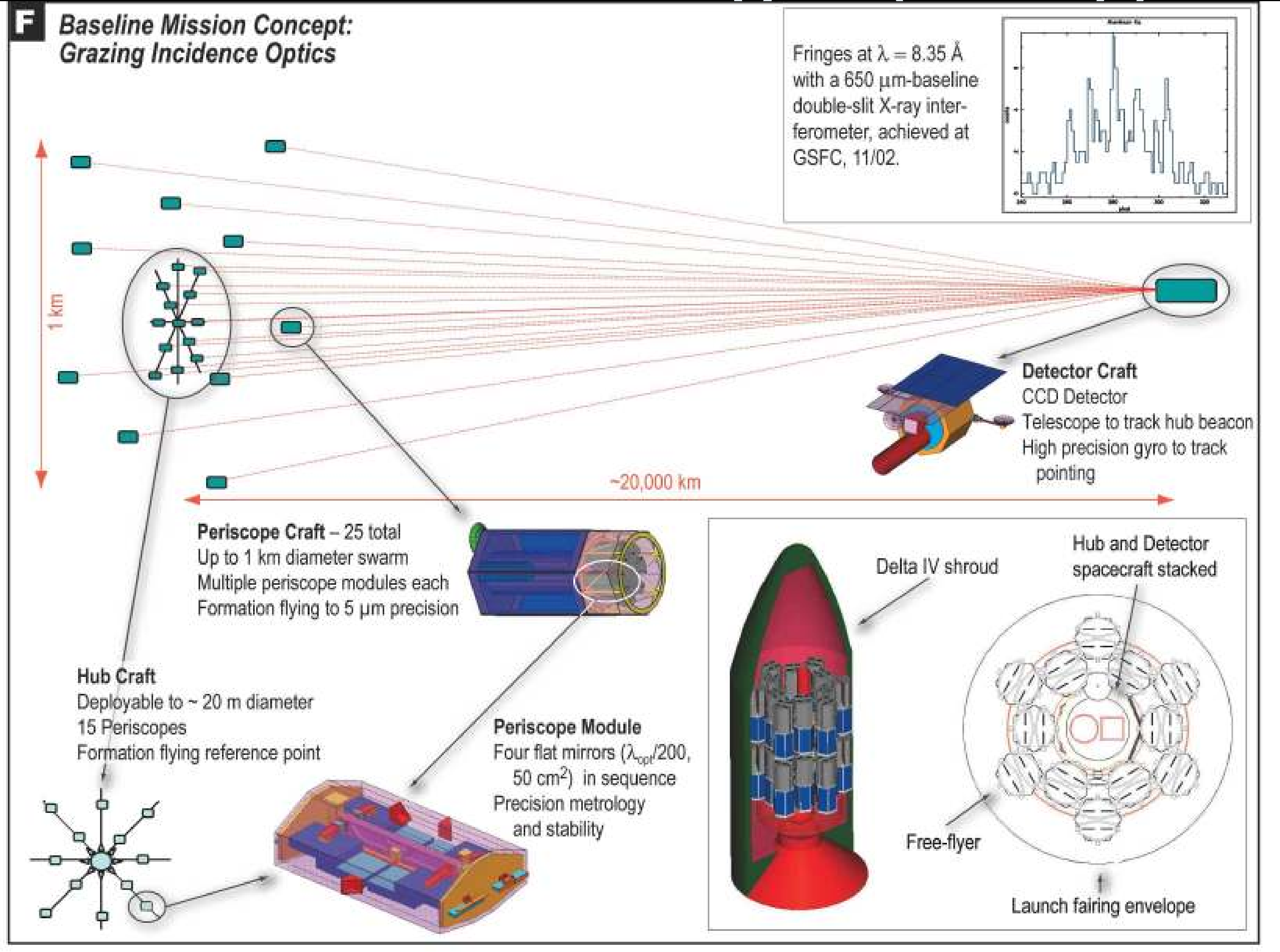
  $\theta_d = 1.22\ \lambda/d$

- Entire lens area effective → improvement in source sensitivity
- Long focal lengths require formation flying of lens-craft and detector-craft:

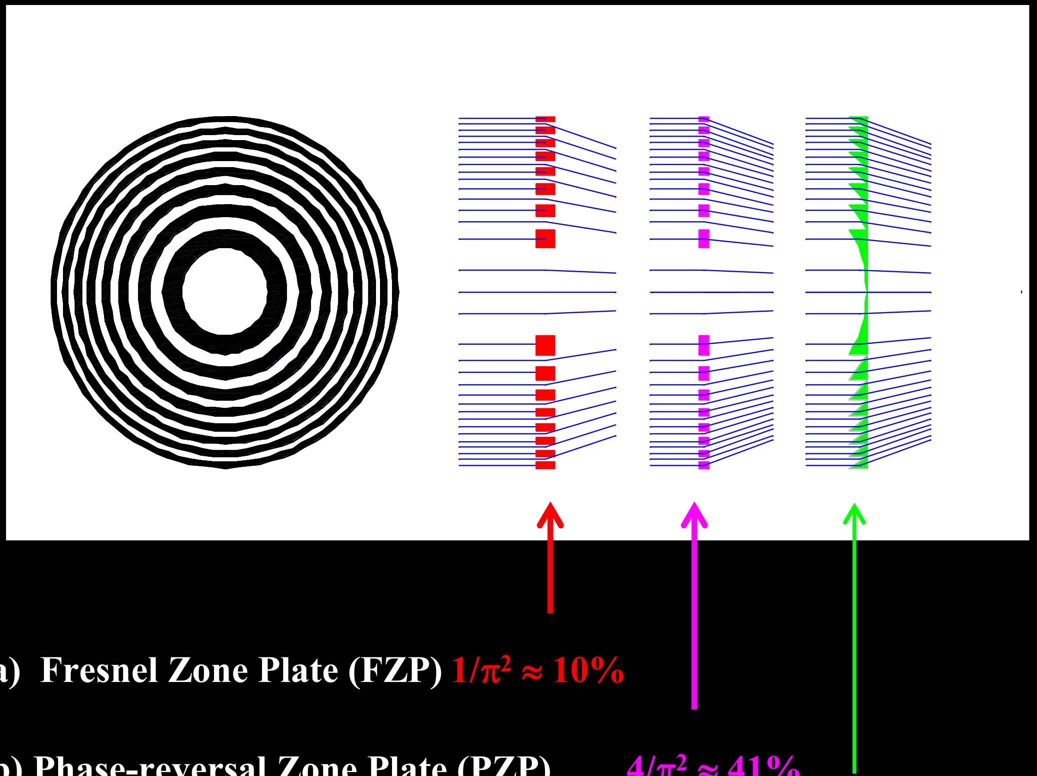
⇒ **milli-arcsecond mission → 1 - 100 km spacecraft separation**

⇒ micro-arcsecond mission → 10^4 - 10^6 km spacecraft separation

Black Hole Imager (X-ray)



Overview: Phase Fresnel Lenses (PFLs)



Skinner (2001) Astron. Astrophy. **375**, 691

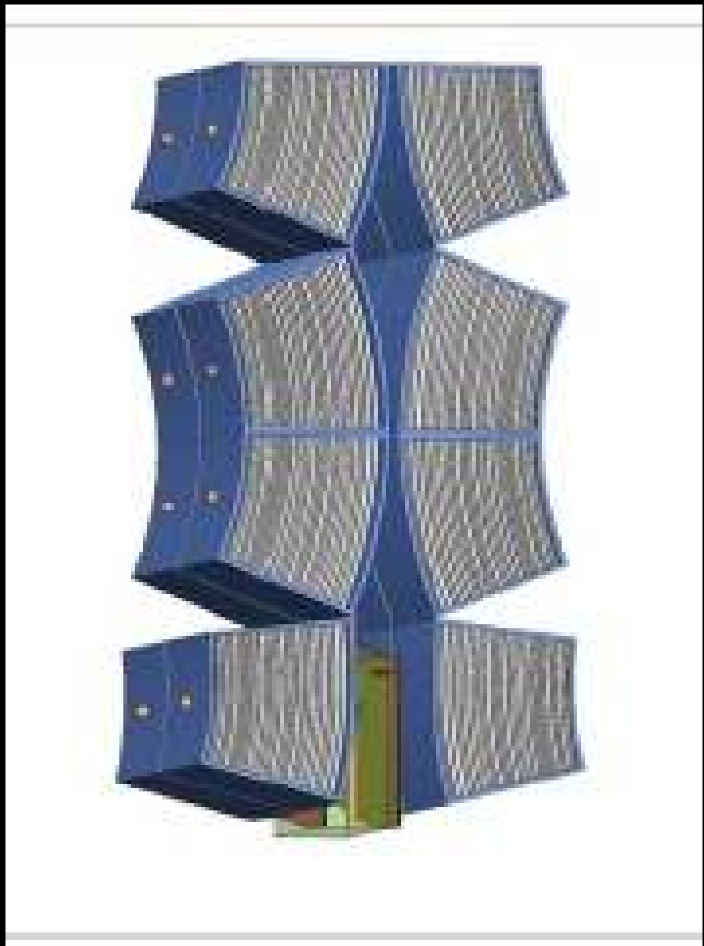
PFL - Potential

- Diffractive Optics
  - Diffraction-limited optics in hard x-ray, gamma-ray range
- Entire area of lens effective
- Maximum efficiency ≈100%
- May be scaled to large areas
  - Coded arrays or "tiling"
- Break into the resolution-desert below an arc-second (m″ → μ″)

PFL - However

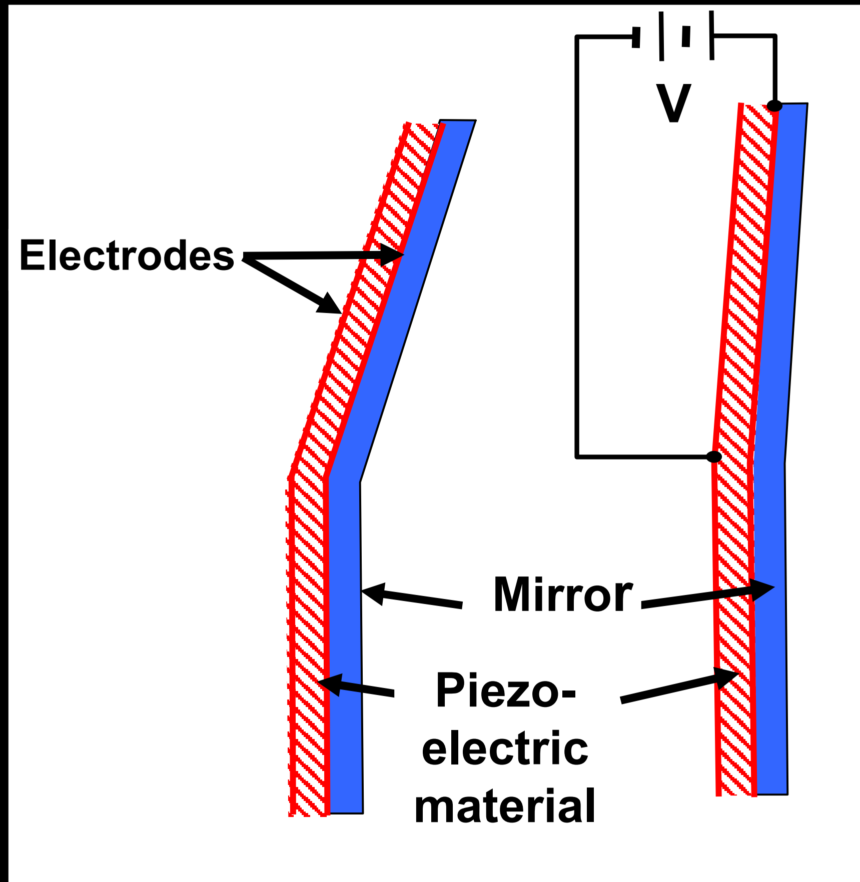
- Limited energy bandwidth
- Long focal lengths
  - 150 m for test PFL in x-ray band
  - ==> Formation flying for practical instrument

Technologies for X-ray mirrors



20 m Diameter, Folded Mirror

Innovative Technology:
Adjustable bi-morph mirror

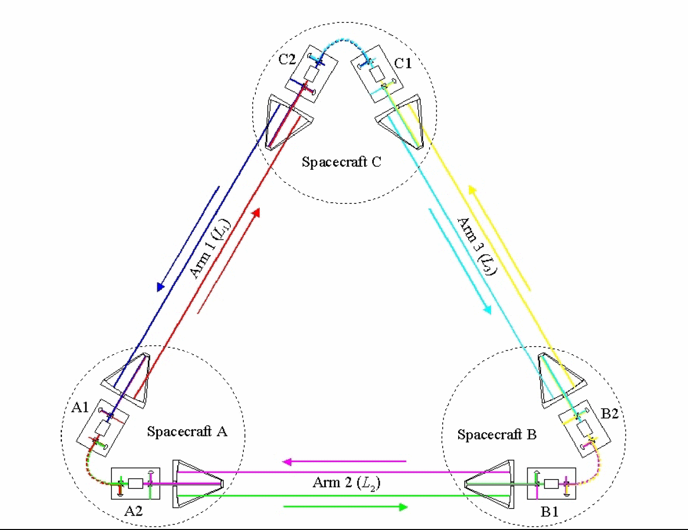


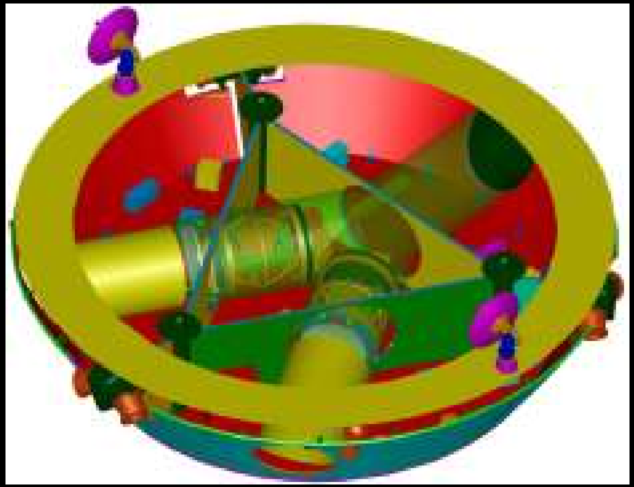
Under applied voltage V, the piezo materia
imparts a force to the mirror, bending it

GR tests

- Lunar laser ranging: more reflectors, active reflectors, mm precision
- Lab tests at even higher precision: short range forces
- Astrophysical tests of MOND
- Binary pulsars
- GP-B analysis (imminent)
- X-ray observations of line profiles in accretion disks
- Advanced LIGO: first direct gravitational wave detection?
- LISA, including gravitational wave distance measures
- Etc.

LISA Overview





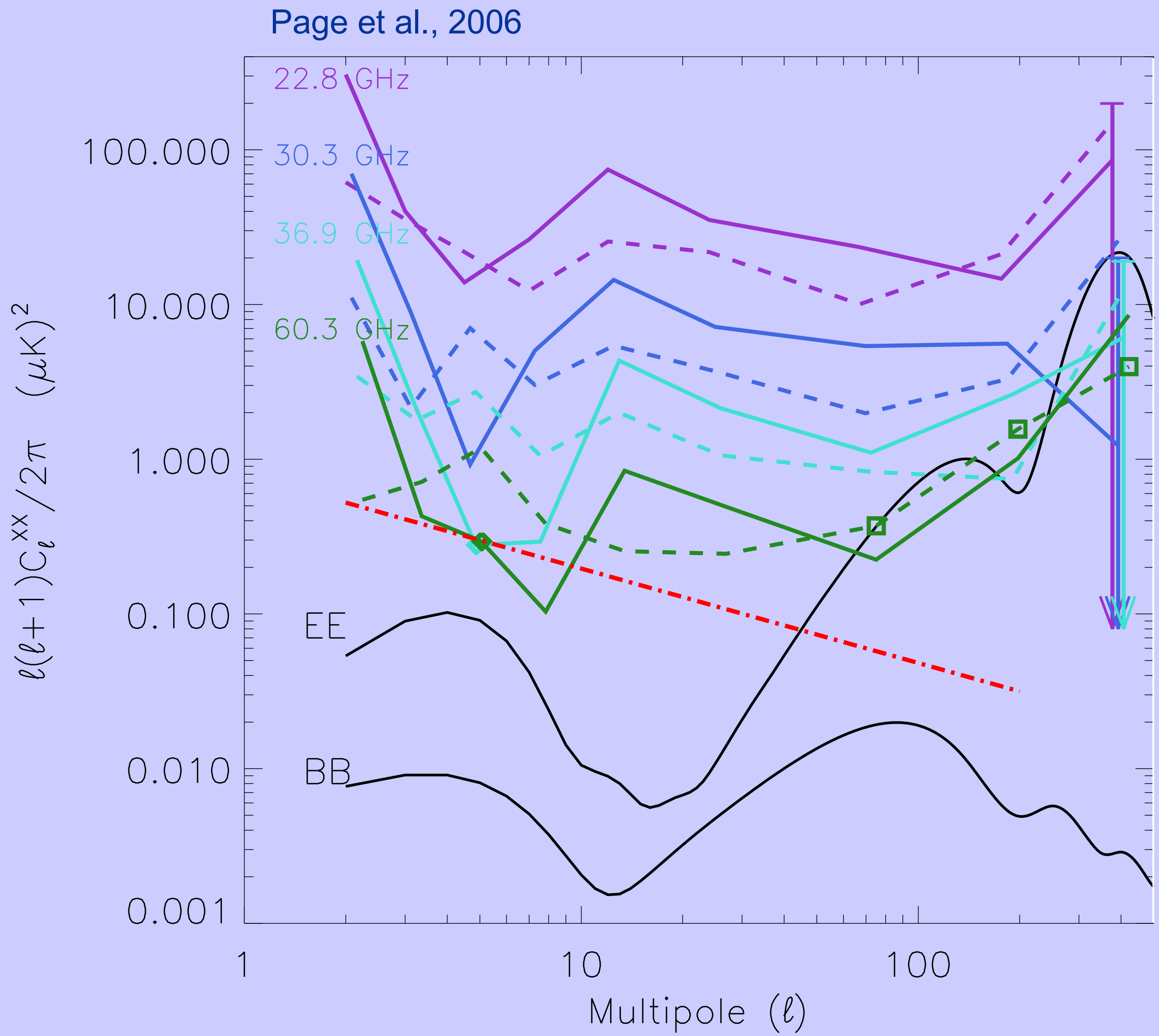
- The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA mission to design, build and operate the first space-based gravitational wave detector.
- The 5 million kilometer long detector will consist of three spacecraft orbiting the Sun in a triangular formation.
- Space-time fluctuations induced by gravitational waves are detected by using a laser-based Michelson interferometer to monitor the ***changes*** in separation between test masses in the separate spacecraft to very high accuracy (1/100th the size of an atom)

Particle Properties

- LHC results, imminent!
- Bigger colliders, future unknown
- Subtle deviations, special experiments based on predictions of theories
- Proton decay?
- Neutrino masses?
- Higgs boson?

The End and The Beginning

WMAP Foreground Spectra



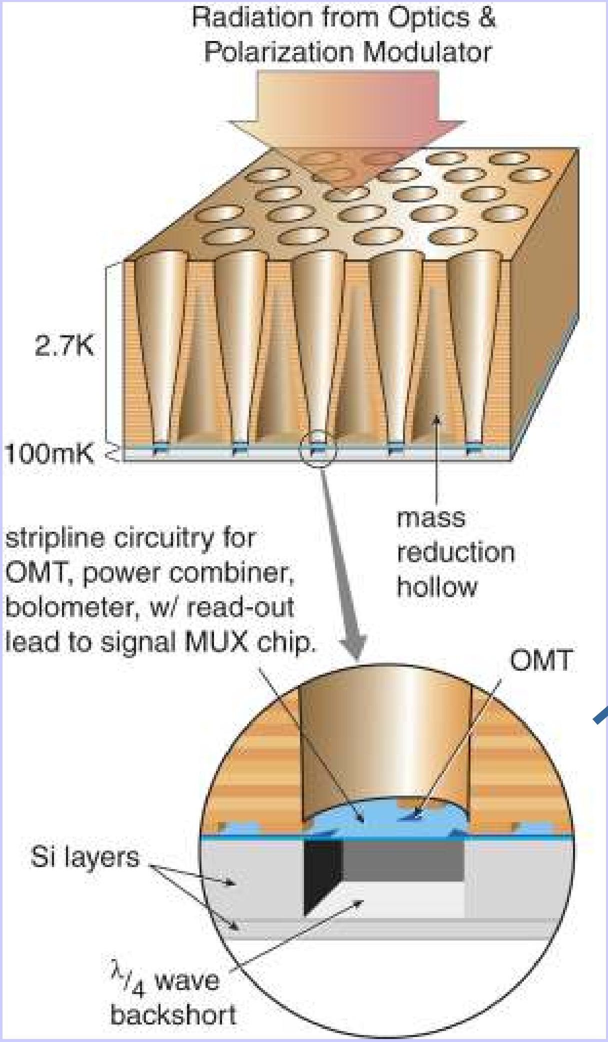
Solid colors - EE foreground

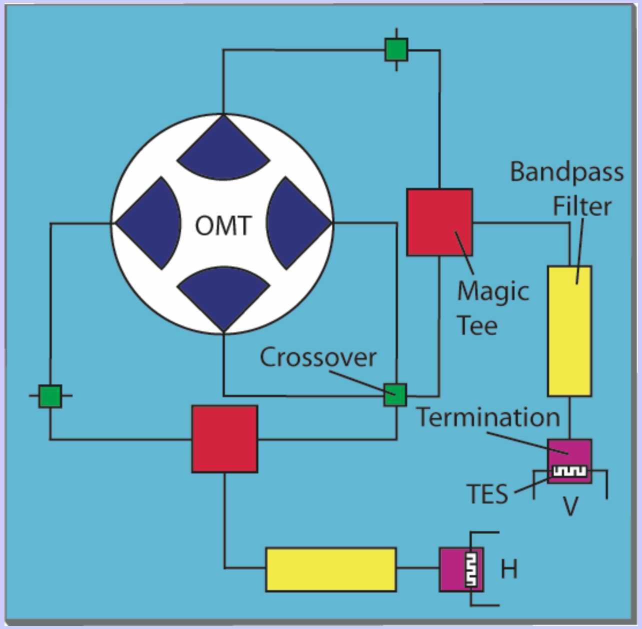
Dashed colors - BB foreground

Dot-dashed red - foreground estimate @ 60 GHz

Solid black - model CMB

Candidate Instrument Concept - Detection





A schematic diagram of the superconducting circuit for extracting the H and V polarizations from the beam.