Fundamental Physics enabled by Astrophysics

John Mather
NASA’s Goddard Space Flight Center

Sept. 30, 2009

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, Astronomy and Astrophysics 2000, http://www.nap.edu/openbook.php?isbn=0309070317; next one in 2010
- European Science Vision, 2007, http://www.astronet-eu.org/-Science-Vision

Conferences too...

- 2008 in Portugal: http://www.astro.up.pt/investigacao/conferencias/esf2008/files/C.J.A.P.Martins.pdf
- Quantum to Cosmos series:
  - 2006: http://funphysics.jpl.nasa.gov/quantum-to-cosmos/
  - 2008: http://physics.jpl.nasa.gov/Q2C3/
  - 2009: Bremen last week: http://www.zarm.uni-bremen.de/Q2C4/
- ESA 2010: http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=45427

Somewhere, a committee is deciding our future ...

- Decadal Survey on Biological and Physical Sciences in Space: http://sites.nationalacademies.org/SSB/CurrentProjects/ssb_050845#statementoftask
  - Fundamental Physical Sciences Panel, November 9-10, 2009, Irvine, CA
  - White papers due Oct. 17
- Decadal Survey on Astronomy and Astrophysics: 117 cosmology & fundamental physics white papers at http://sites.nationalacademies.org/BPA/BPA_050603

Particles, Fields, & Forces

- Quantum mechanics in the Big Bang
  - CMB: anisotropy, polarization, spectrum ➔ inflation fields & potentials, gravitational waves…
- Dark Energy (120 orders of magnitude off)
- Dark Matter (~ 6 x baryonic matter)
- Particle properties: neutrinos, antimatter (baryon asymmetry), proton lifetime, WIMP/dark matter reactions
- GR tests – Nature's experiments, & ours

Historical examples…

- Speed of light (1%, Ole Rømer, 1676)
- $1/r^2$ gravitation (Newton, 1686)
- Aberration of starlight (James Bradley, 1725)
- No ether (Michelson-Morley, tested Earth's spin & orbit modulation of c, 1887)
- Nuclear fusion in stars (Eddington 1920, Bethe 1939, Hoyle 1946, BBFH 1957…)
- Big Bang, Edwin Hubble, 1929
- Antimatter produced (in lab) by cosmic rays (Positron, Carl Anderson, 1932)
- Limits on variation of fine structure constant, hyperfine structure
- CMB temperature scales as (1+z)
- Proton, axion, etc. lifetime (would produce a cosmic background photon field, but none found yet)

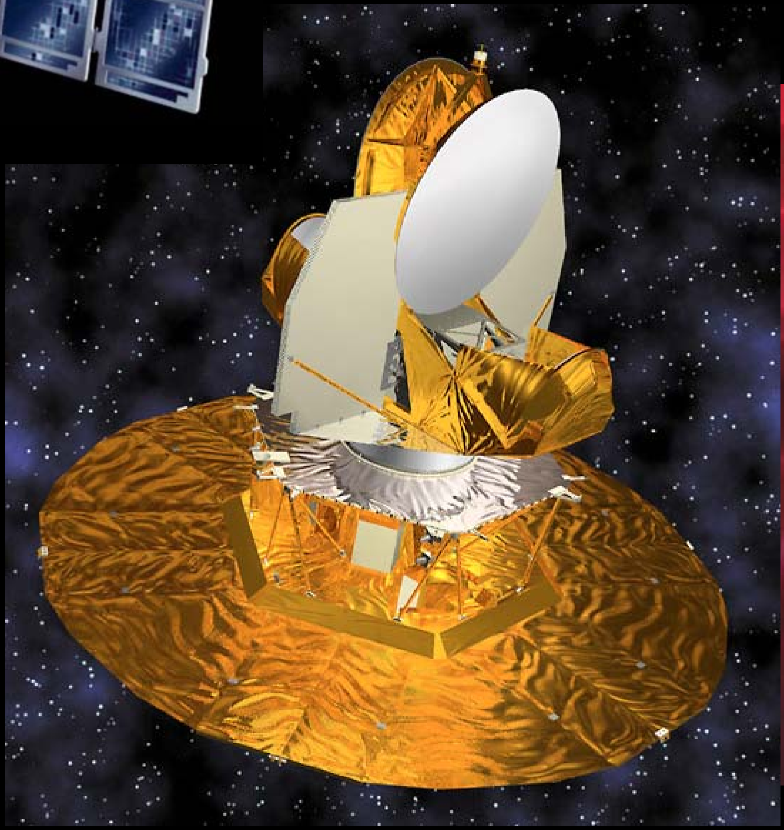
Neutrinos

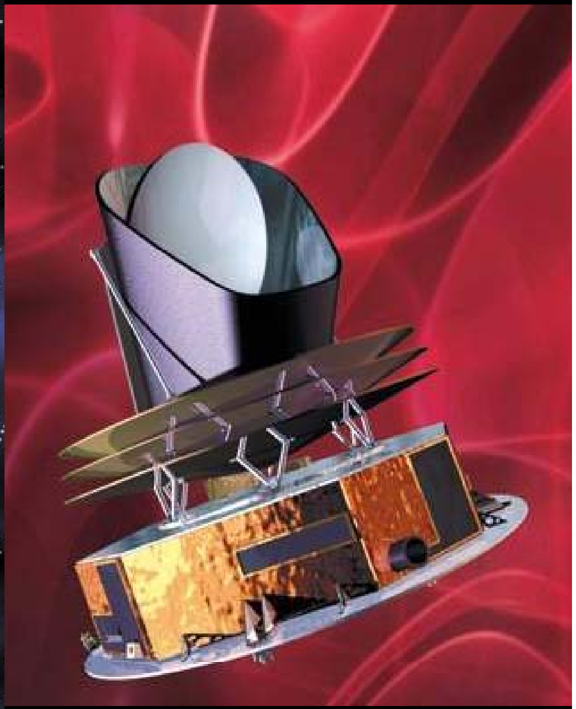
- Solar neutrino anomaly ➔ oscillations, neutrino mass differences
- SN 1987a neutrinos and antineutrinos arrive at same time (within 12 sec)
- Big Bang nucleosynthesis needs ~ 3 families to match element abundances
- CMBR fluctuations need ~ 3 families (WMAP team, 5 year data, 2008), and limit masses
- Dark matter studies – many limits on neutrino mass

Historical General Relativity Tests…

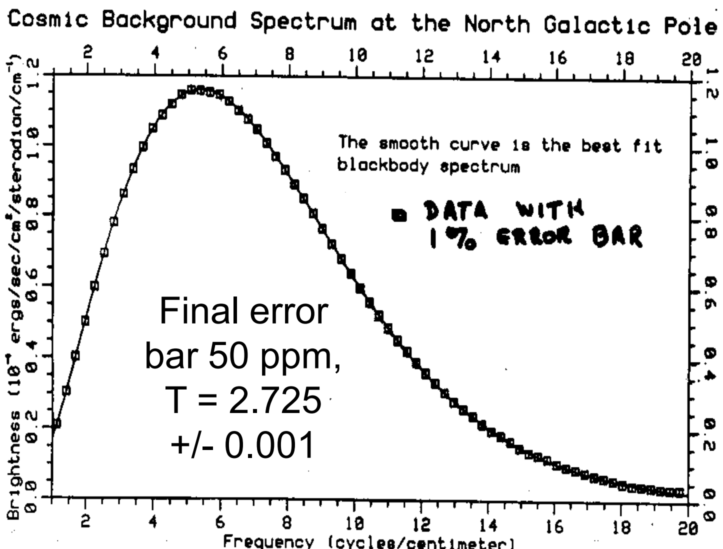
- Mercury orbit precession (already known), Einstein 1916
- Gravitational deflection of light (2x Newtonian), Eddington 1919
- Gravitational redshift on white dwarf (Sirius B, Walter Adams, 1925, arguable)
- Black hole observed: Cyg X-1
  - Discovered by Bowyer, Byram, Chubb, & Friedman1964
  - Webster, Murdin, & Bolton got binary orbit 1971
- Gravitational waves (binary pulsar, Hulse & Taylor, 1974)
- Gravitational Lens (Zwicky prediction, 1937; Twin QSO, Walsh, Carswell, & Weyman, 1979)
- Cosmology (many and continuing)
- Orbital dynamics, timing, & light deflection in solar system (many and continuing, including Pioneer, etc.)

COBE (1989), WMAP (2001), & Planck (2009)

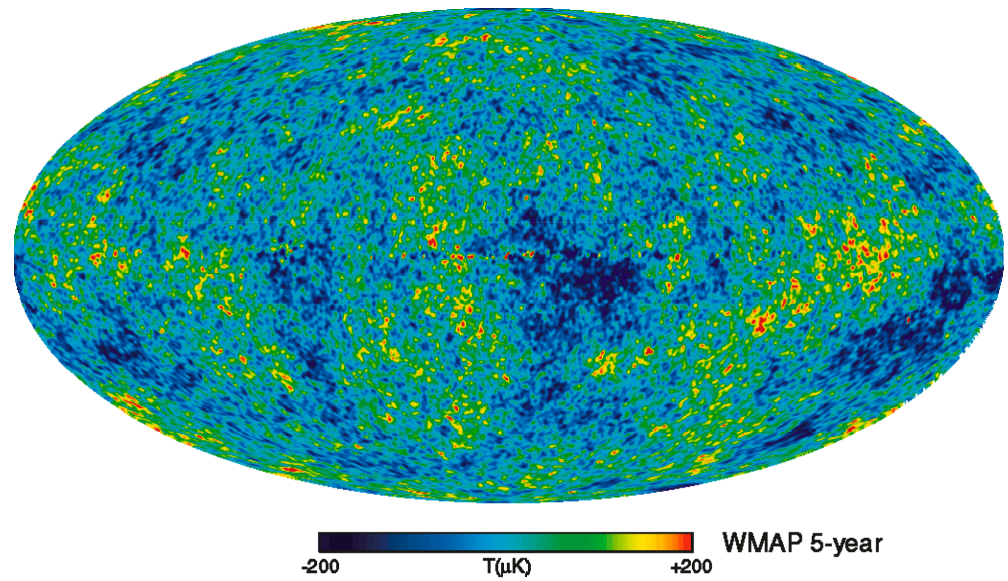




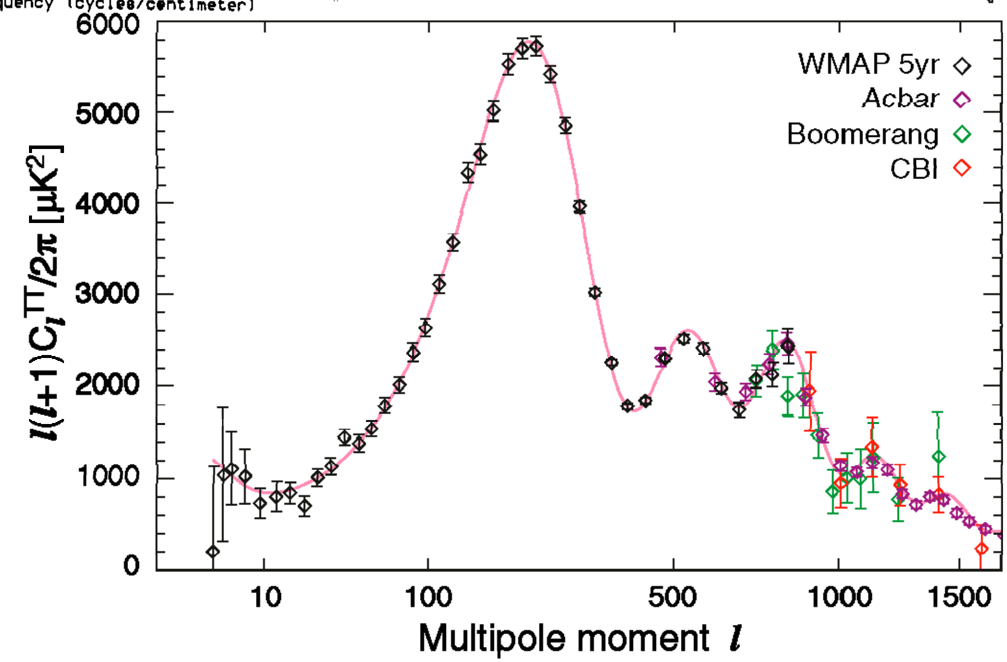
Key CMB results



COBE Science Team



WMAP Science Team



Big Bang & Quantum Gravity

- Nature’s experiment – but the only one (that we can see)
- Inflation theory: some scalar or other field or particle (the “inflaton”) has a potential energy, leading to a “false vacuum” that makes space expand exponentially (assuming General Relativity applies)
- At end of exponential expansion, potential energy converts to particles & fields of known physics
- General features don’t depend on quantum gravity (Steinhardt; good, but not much test!) or on details of the inflaton and its potential function
  – No center, no edge, no slope
  – ~ perfect isotropy – parts not now causally connected are equal
  – ~ scale-invariant initial fluctuations (from exponential expansion)
- Preposterous – but fits the data. Got a better idea?
- Where’s the quantum gravity part?

Testing Inflation and Quantum Gravity

- What were those fields and potential functions?
  - Influence slope of fluctuation spectrum (observable)
- Super-horizon effects (maybe observable – mystery of low multipole pattern)
- What governs the fluctuation amplitude? (theory question)
- Are they Gaussian? (very, but maybe not exactly)
- Any symmetries or conservation laws that prevent some fluctuation modes?
  - Isocurvature modes (don't fit data by themselves)
  - Tensor modes (gravitational waves, observable; WMAP5 says tensor/scalar = $r < 0.22$ (95% CL), Komatsu et al. 2009)
- Explain dark matter & dark energy (observable), smart person!

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
- BEPAC report
- White papers for 2010 A&A Decadal Survey

CMB Polarization – Dodelson et al. white paper

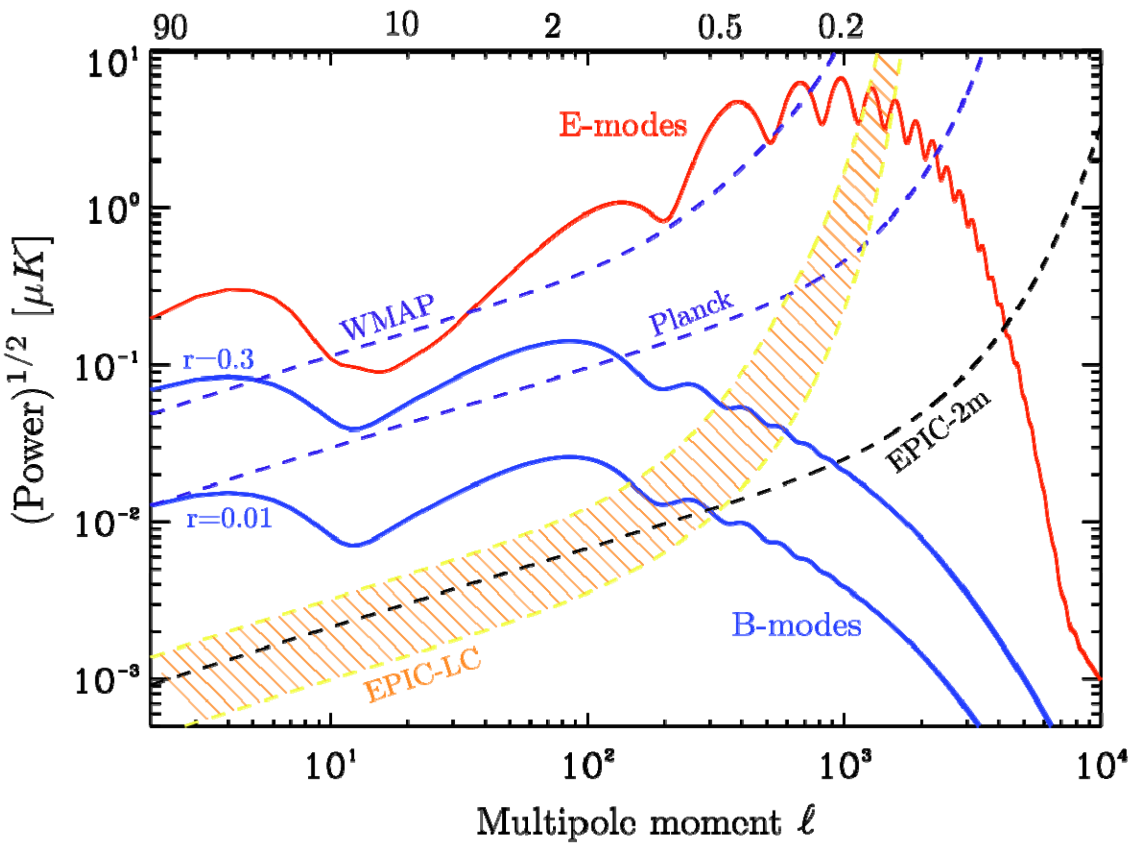
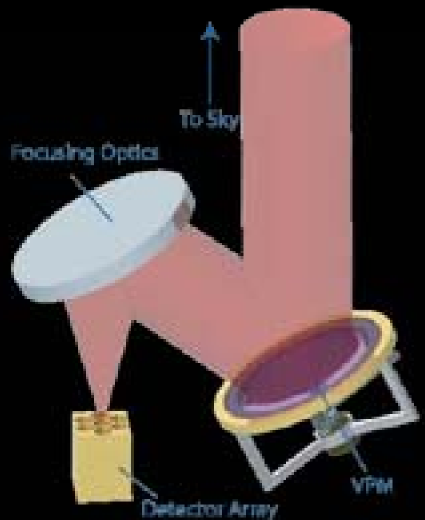
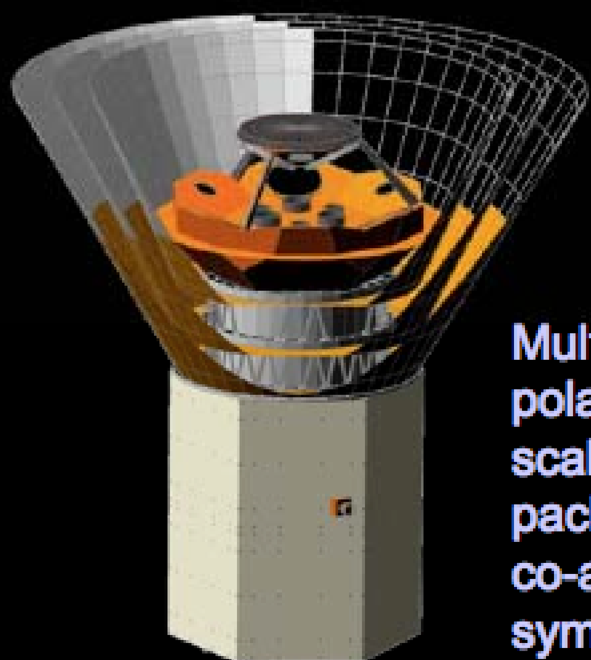


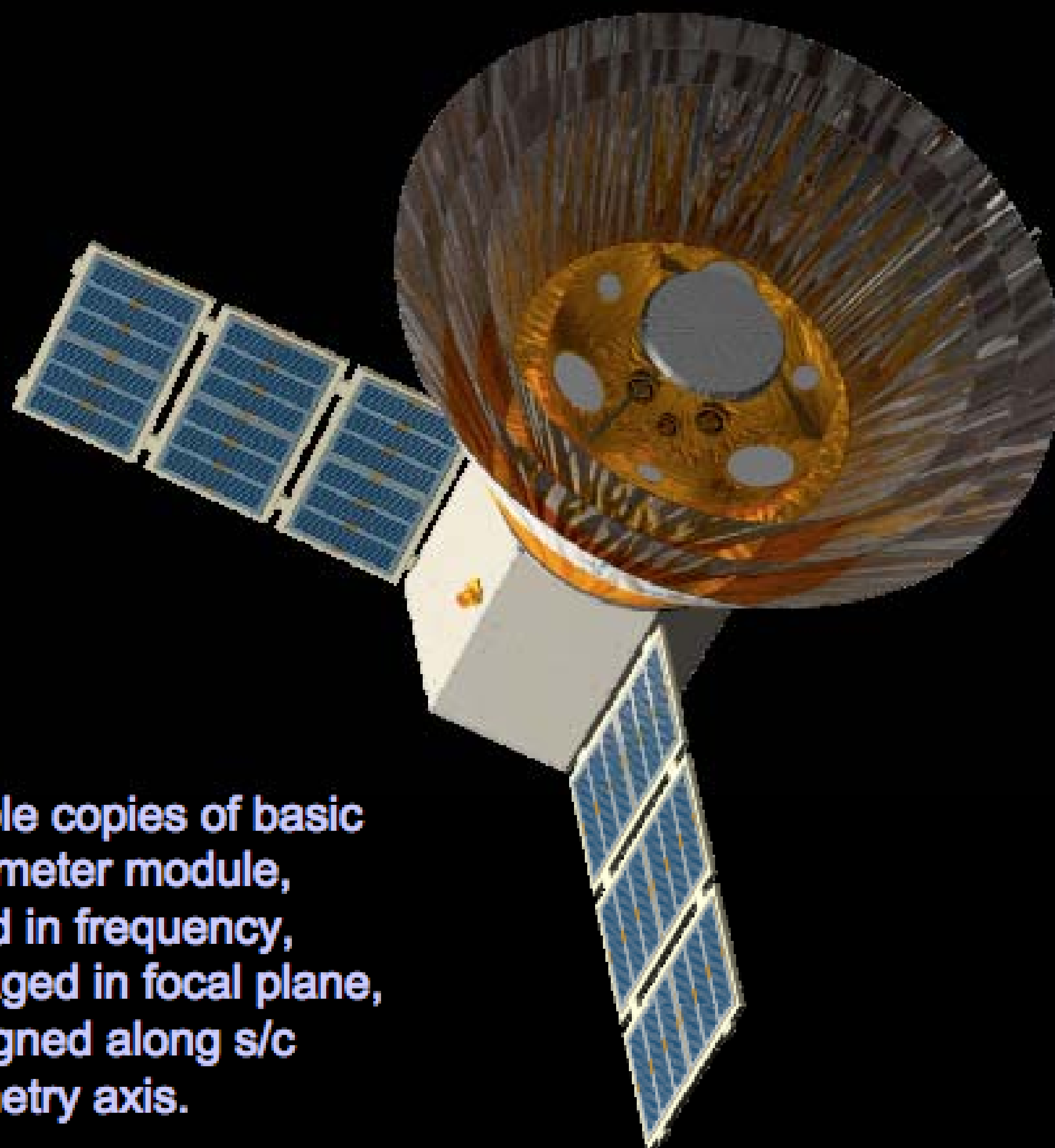
FIG. 2: Predicted spectra of E- and B-modes. The blue solid curves representing B-modes labeled r=0.3 and r=0.01 correspond to amplitudes just below current limits and within reach of a satellite mission dedicated to polarization, respectively. The hatched region and the dashed curve labeled "EPIC" show the noise levels projected for two possible implementations of this mission [4]. The dashed curves labeled "WMAP" and "Planck" correspond to the statistical noise limits for these satellites after 9 years and 1 year, respectively. All noise curves are averaged over bins of width $\Delta l = 0.3l$.

Candidate Observatory Concept





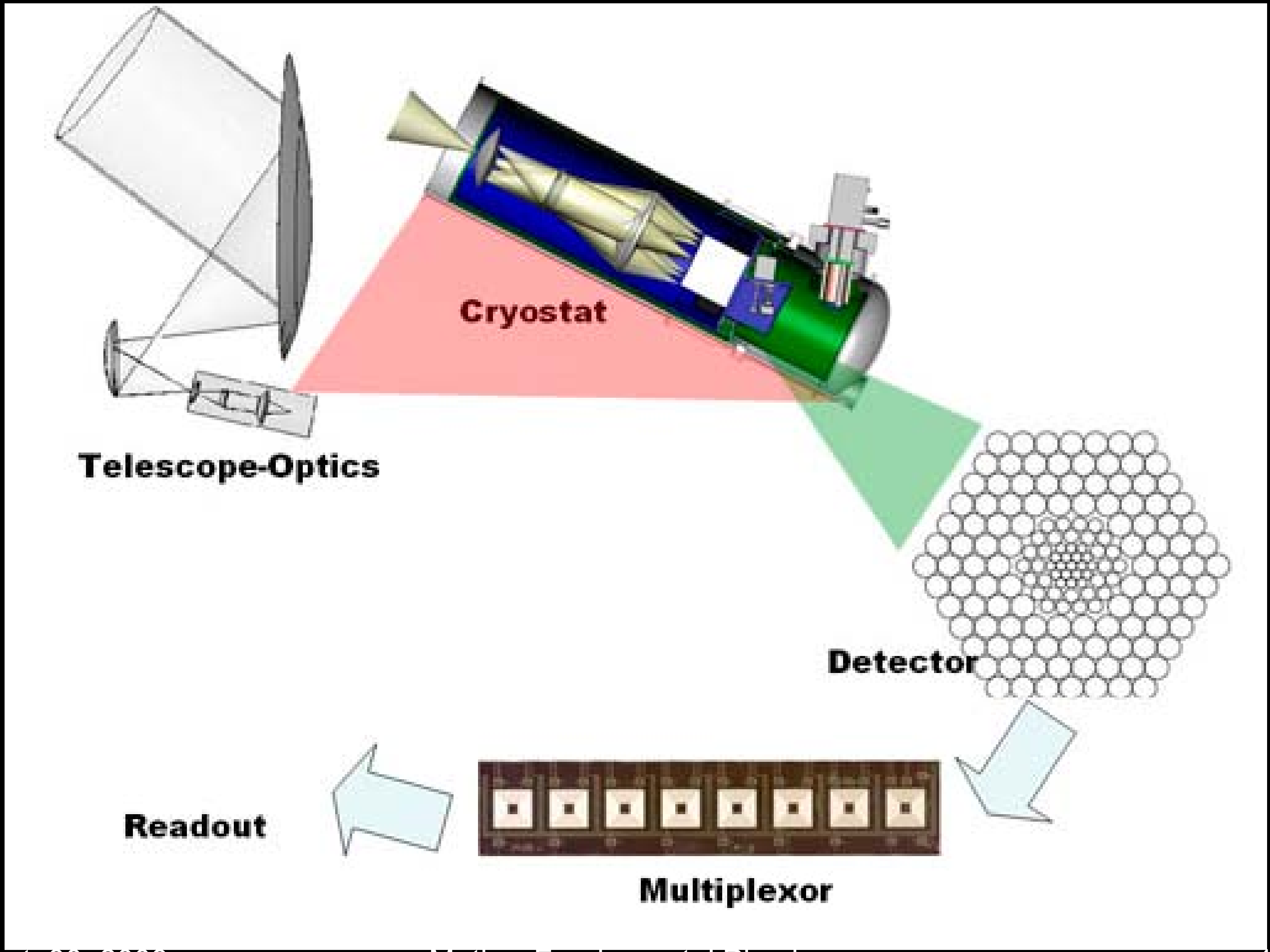
Multiple copies of basic polarimeter module, scaled in frequency, packaged in focal plane, co-aligned along s/c symmetry axis.



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



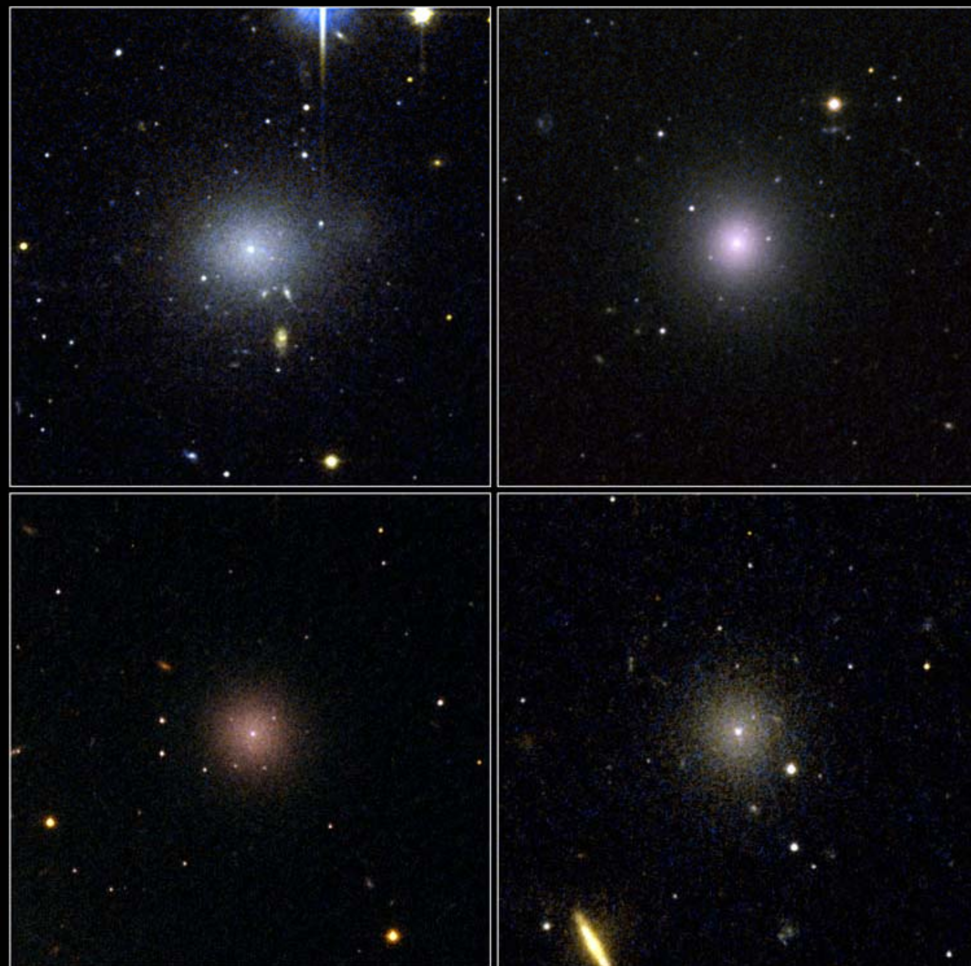
Dark Matter talks

- 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

Dwarf Galaxies rich in Dark Matter



Perseus Cluster Dwarf Galaxies
Hubble Space Telescope ▪ ACS/WFC

NASA, ESA, and C. Conselice (University of Nottingham) STScI-PRC09-11

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

Ongoing

Within a year

Not yet guaranteed

Survey	Telescope	Sky coverage	Filters	depth
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
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
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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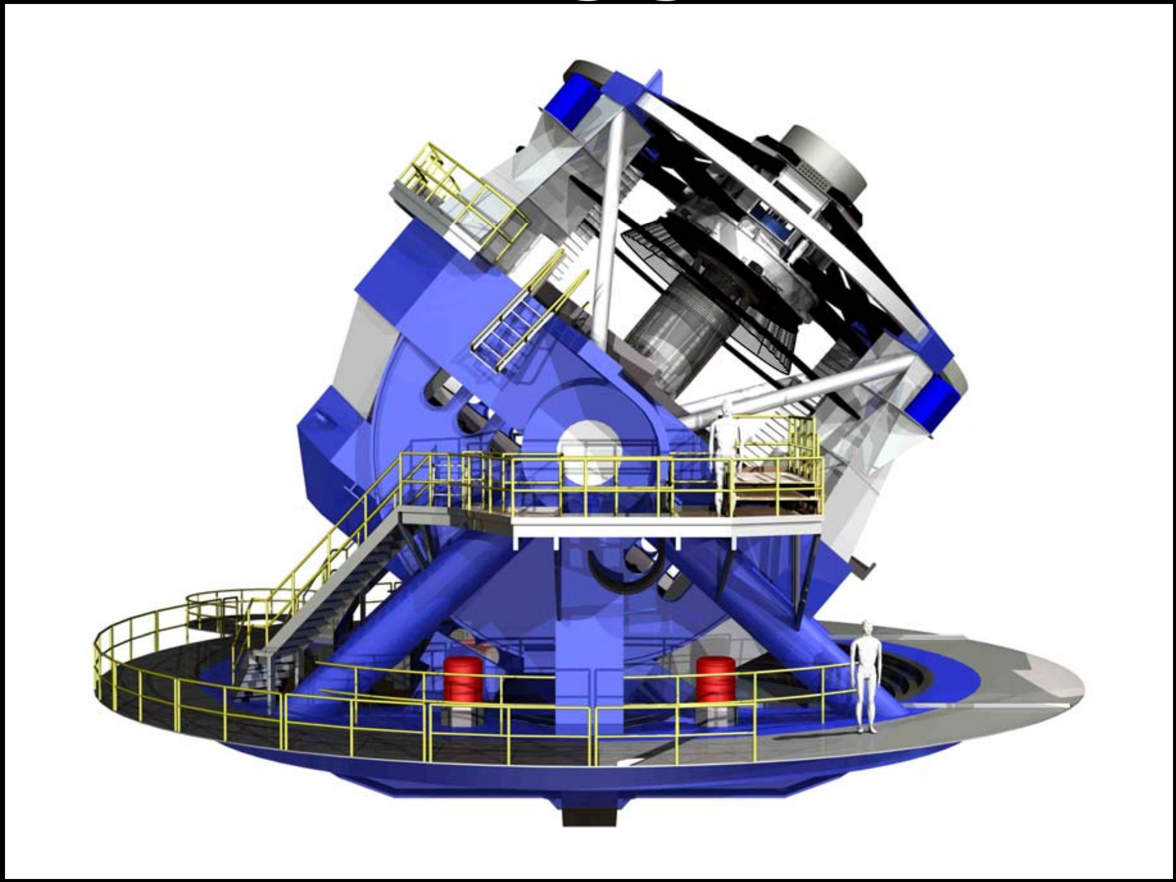
LSST



- 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 gravitational 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

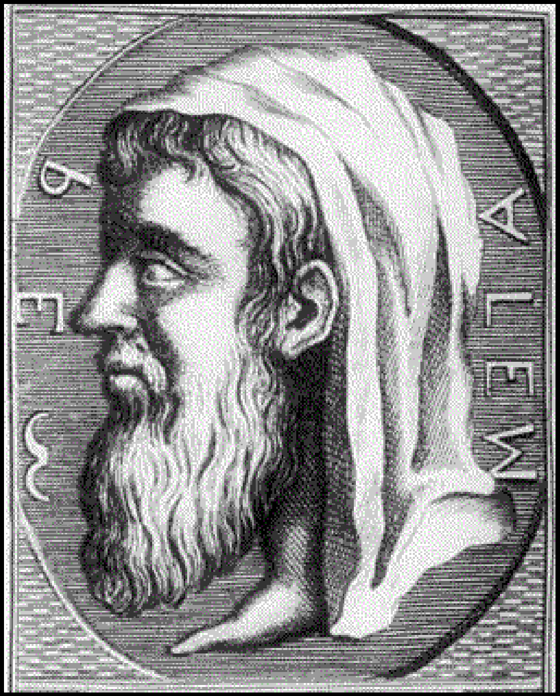
4. Four techniques at different levels of maturity:
   a. **BAO** only recently established. Less affected by astrophysical uncertainties than other techniques.
   b. **CL** least developed. Eventual accuracy very difficult to predict. Application to the study of dark energy would have to be built upon 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
- Collaboration of NASA, DoE, and (?) ESA
- http://jdem.gsfc.nasa.gov/ for defining documents
- All concepts include wide field of view, 2 m class visible &/or near IR telescope in space
- Need multiple techniques: potential for systematic errors
- Mission concept and teams not defined, pending Decadal Survey opinion and major negotiations

Euclid

ESA's mission to map the Dark Universe



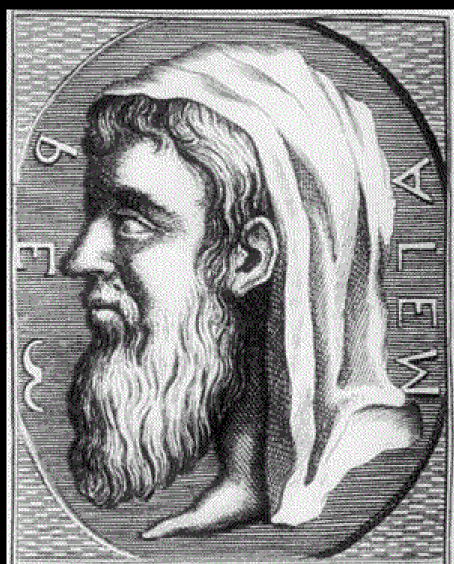
A Decade of Dark Energy

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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All-sky optical imaging for gravitational lensing

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

Selection of ESA's Dark Energy Mission

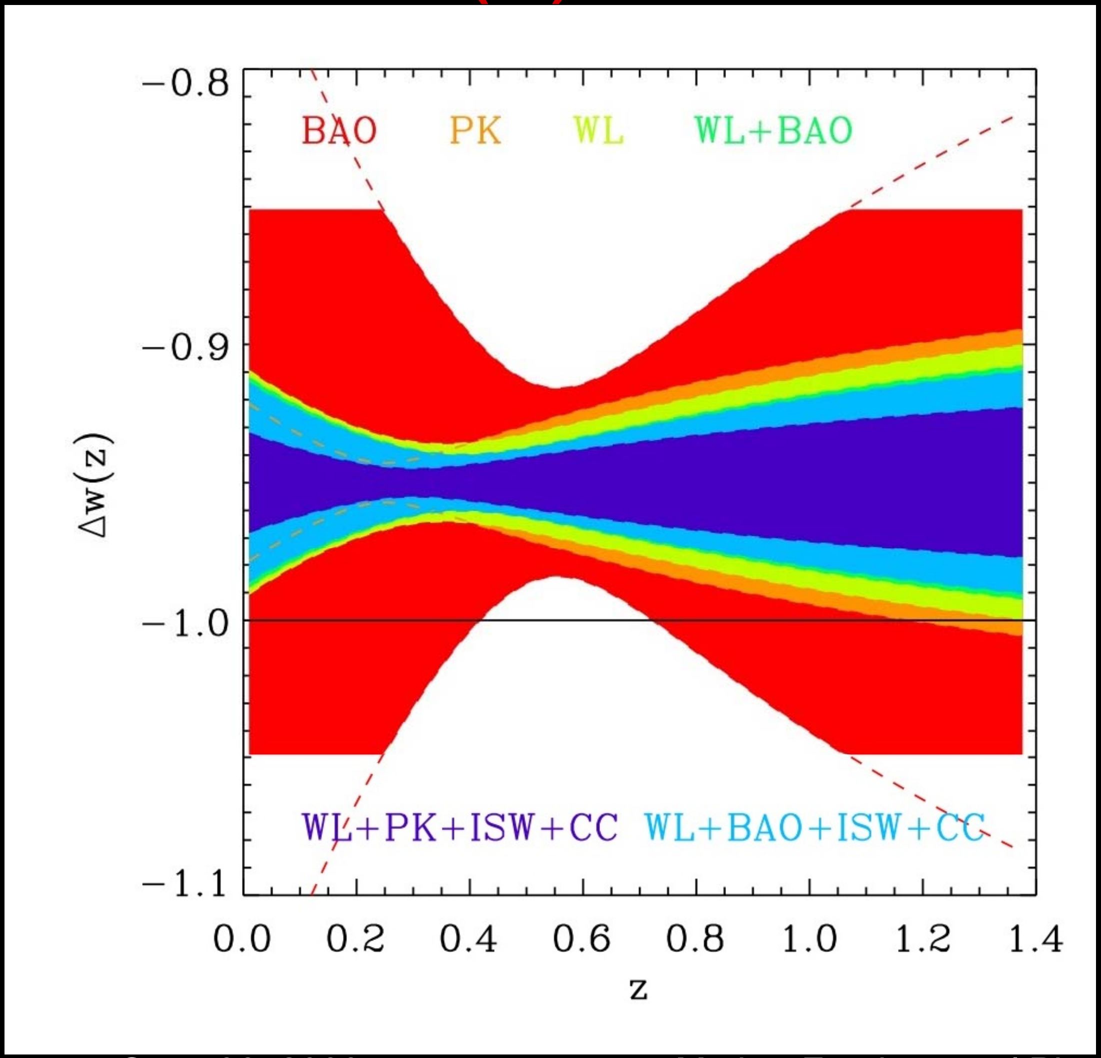
- ***Dark energy*** is recognized by the ESA Advisory Structure as the most timely and important science topic among the M mission proposals and is therefore recommended as the top priority.
- ***Dark energy*** has been addressed by two Cosmic Visions M proposals:
  - ***DUNE (PI: A. Refregier-CEA Saclay)*** – 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.

Euclid 8 May 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, σ_z<0.006
- With constraints:
  - Aperture: max 1.2 m diameter
  - Mission duration: max ~5 years

Predicted redshift dependence of w(z) errors from Euclid



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).

Everything about Luminous Matter – New Tools…

- HST – new & improved!
- JWST: 0.6 – 29 μm, 2014
- LSST: 8.4 m, 3.2 Gpix, 2014
- VLT, Keck, Gemini, …
- EELT, GSMT, TMT, etc.
- SKA: 2017
- FFTT: concept
- ATLAST: 3x HST diameter, in space
- Constellation - X

Probing Dark Energy with the SKA

- Standard ruler based on baryonic oscillations (wriggles)
- Need to reach z ~ 1
  - Current limit z = 0.2 so > x25 in sensitivity ✓
- Optimum strategy is the survey the largest area
  - Minimise cosmic variance
- Large FoV makes this practical ✓
- HI selection ⇒ strong bias to late type galaxies
- SKA FoV=1sq deg in 1 year
  - 10^9 galaxies, $0 < z < 1.5$ $\Delta\omega$ =0.01
- Or 1/10 area SKA phase I with FoV=100sq deg

Ron Ekers presentation in Munich, Aug 2005

$1B and 2020

$0.2B and 2012

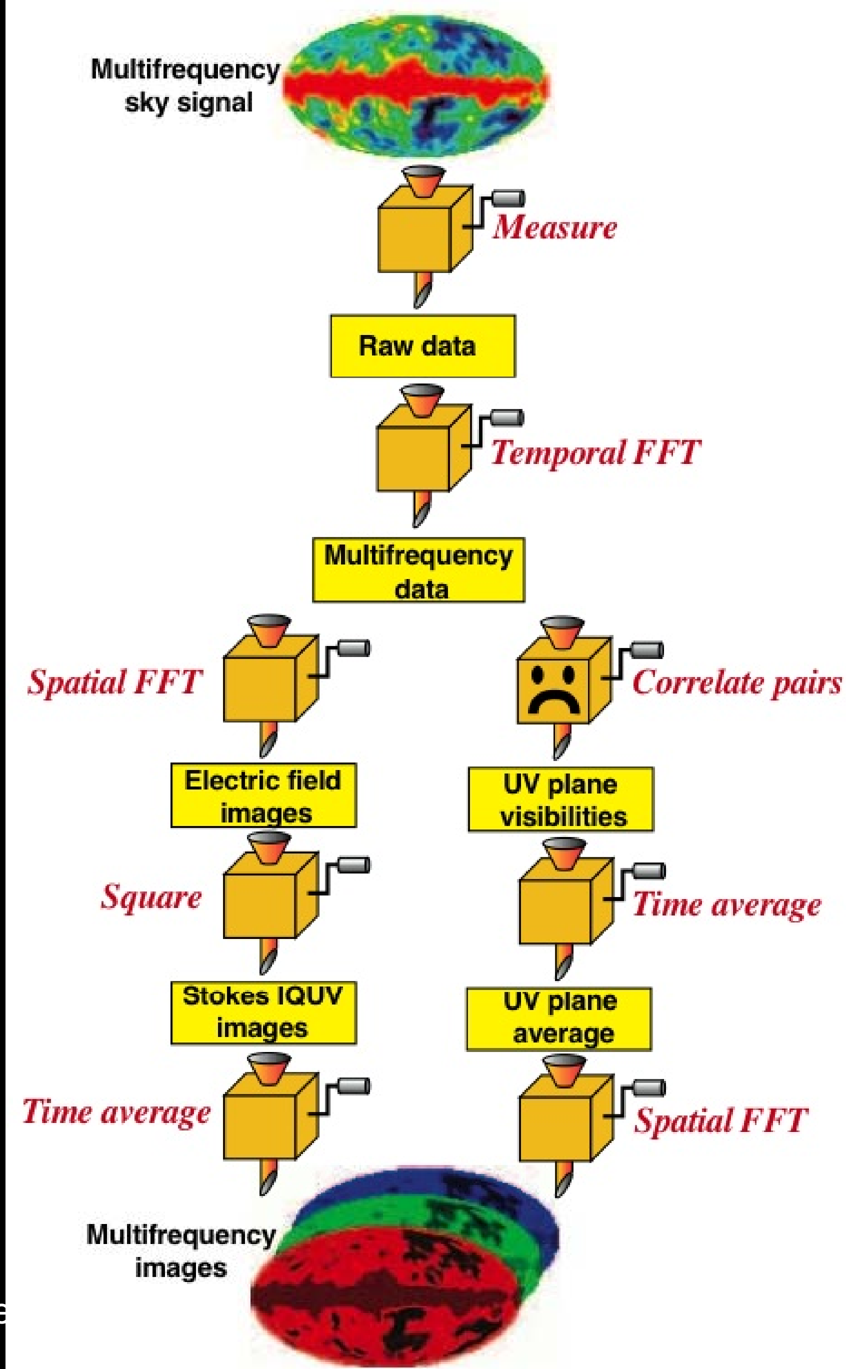
The Fast Fourier Transform Telescope

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.

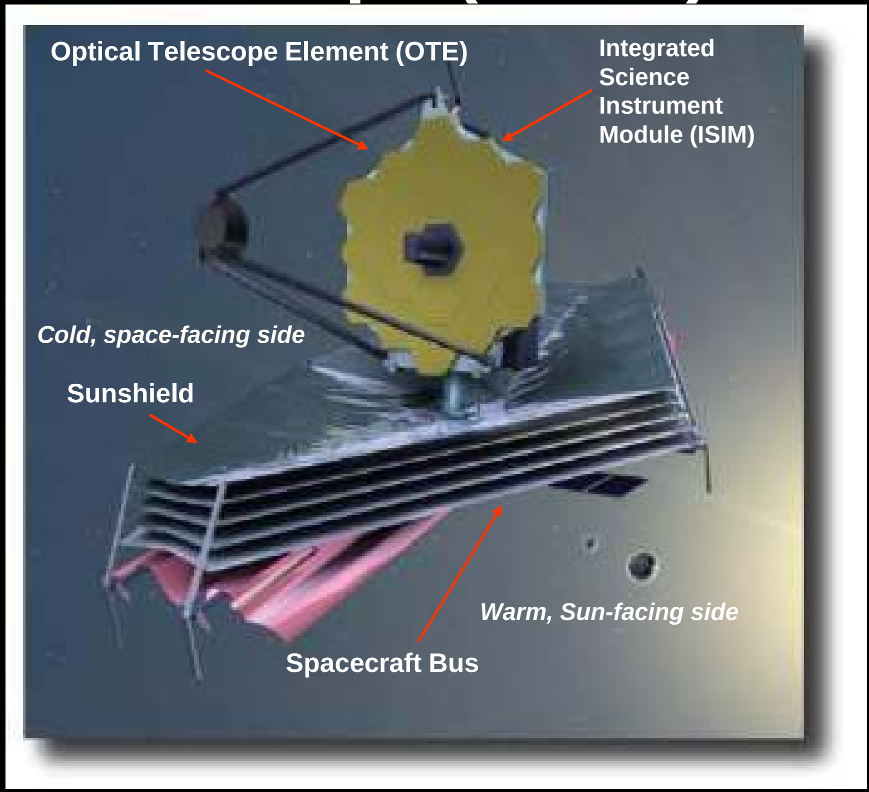
- FFTT concept of Tegmark & Zaldarriaga



James Webb Space Telescope (JWST)

<u>Organization</u>

- 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

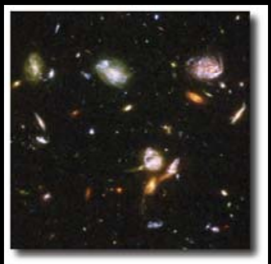


<u>Description</u>

- Deployable infrared telescope with 6.5 meter diameter segmented adjustable primary mirror
- Cryogenic temperature telescope and instruments for infrared performance
- Launch June 2014 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

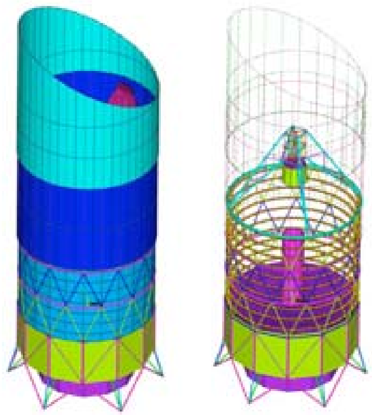
Cosmology with JWST

- 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

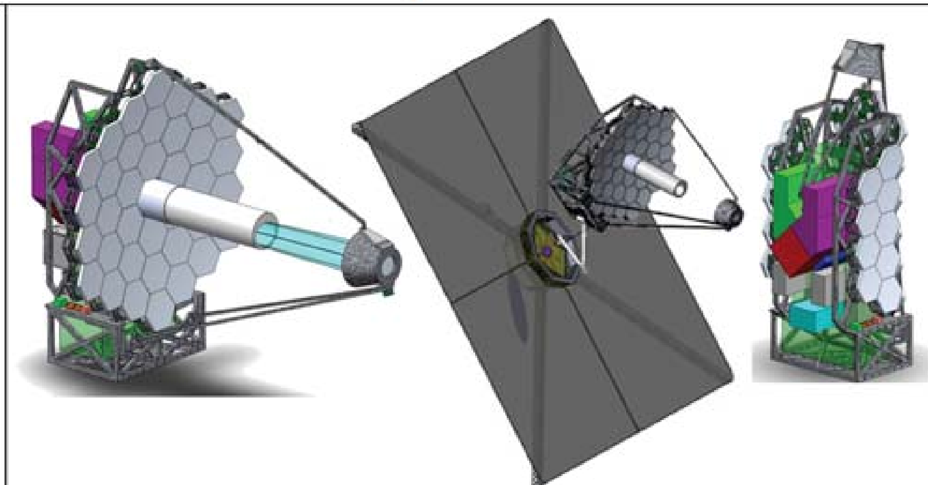
ATLAST = Advanced Technology Large Space Telescope

- Study started at STScI/JHU for Decadal Survey: http://www.stsci.edu/institute/atlast
- UV/optical successor for HST
  - Supernovae
  - Lensing
  - Clustering
- Reveal cosmic web: intergalactic medium
  - Lyman α absorption against distant objects
  - Hope: direct imaging of IGM

ATLAST Concepts

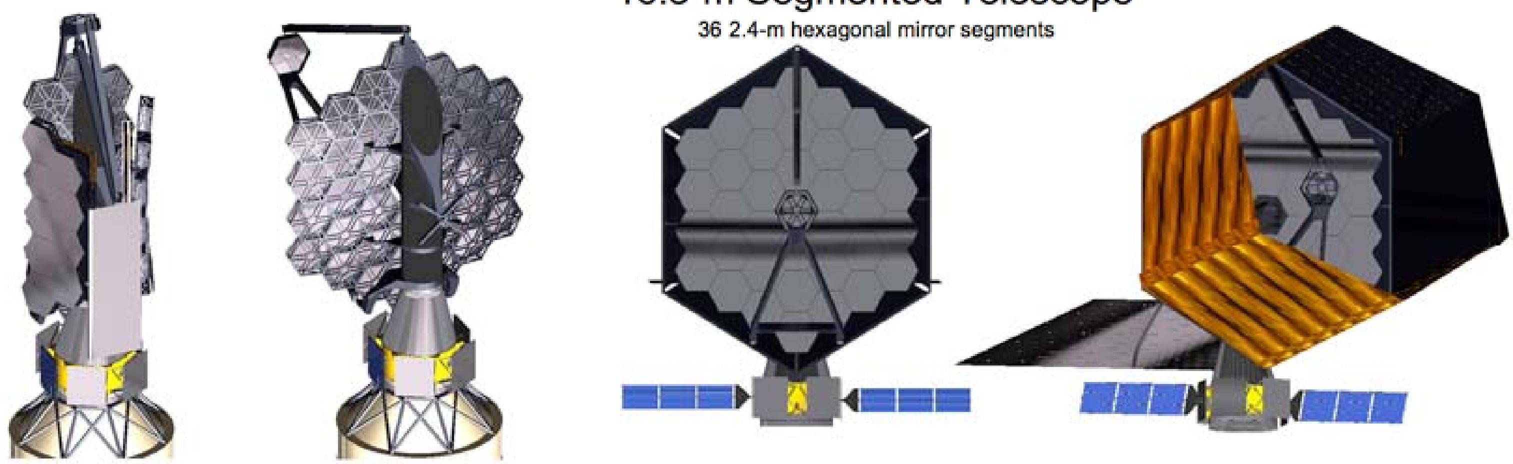


8-m Monolithic Primary
(shown with on-axis SM configuration)

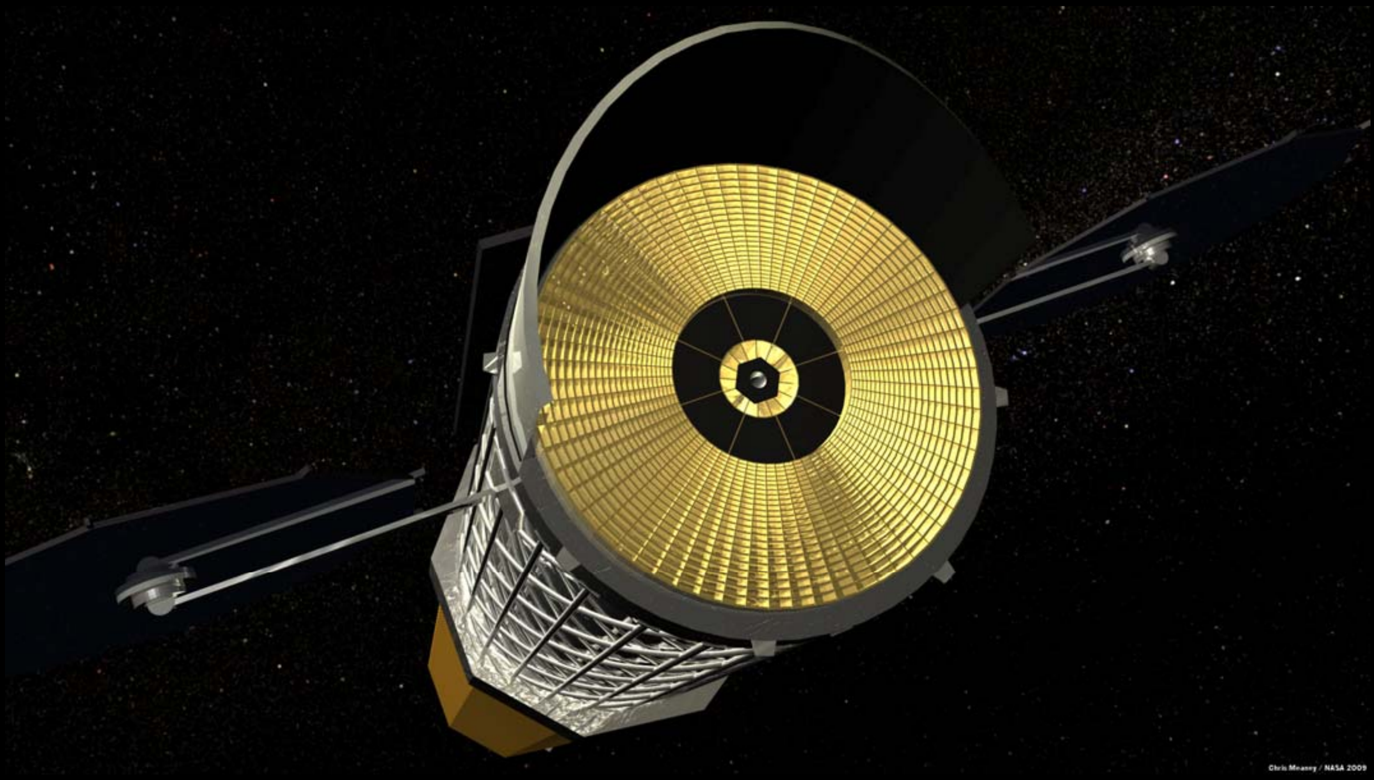


9.2-m Segmented Telescope
36 1.3-m hexagonal mirror segments

16.8-m Segmented Telescope
36 2.4-m hexagonal mirror segments



IXO = Constellation-X + XEUS



Imagers, grating and microcalorimeter spectrometers, polarimeters, high speed timing

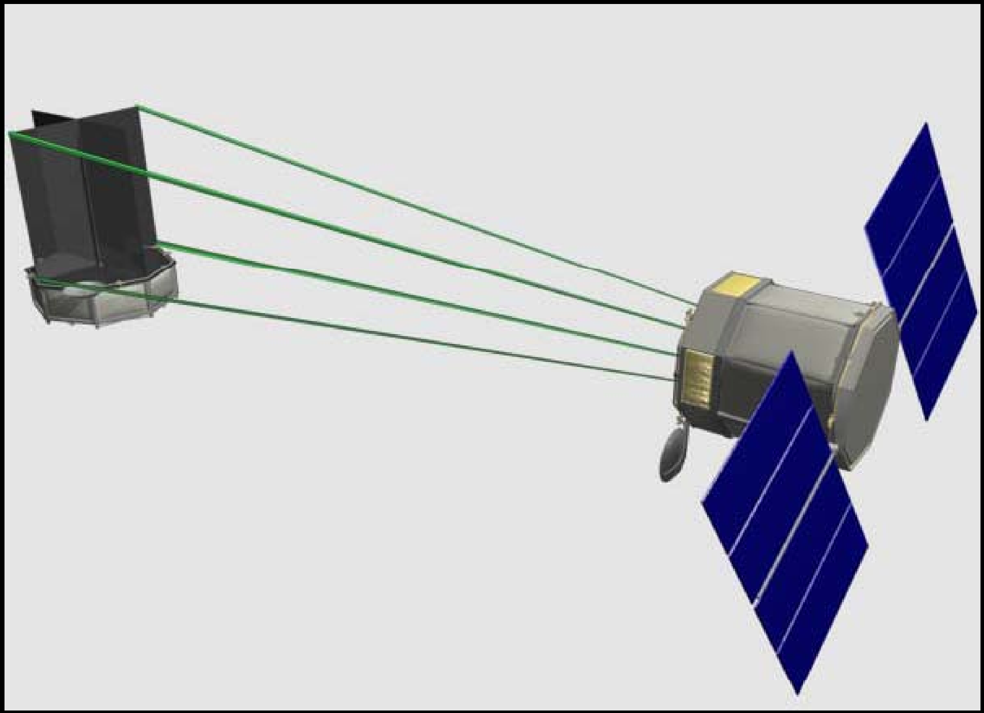
Formation Flying Fresnel Telescope

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:

$$\theta_d = 1.22\ \lambda/d$$

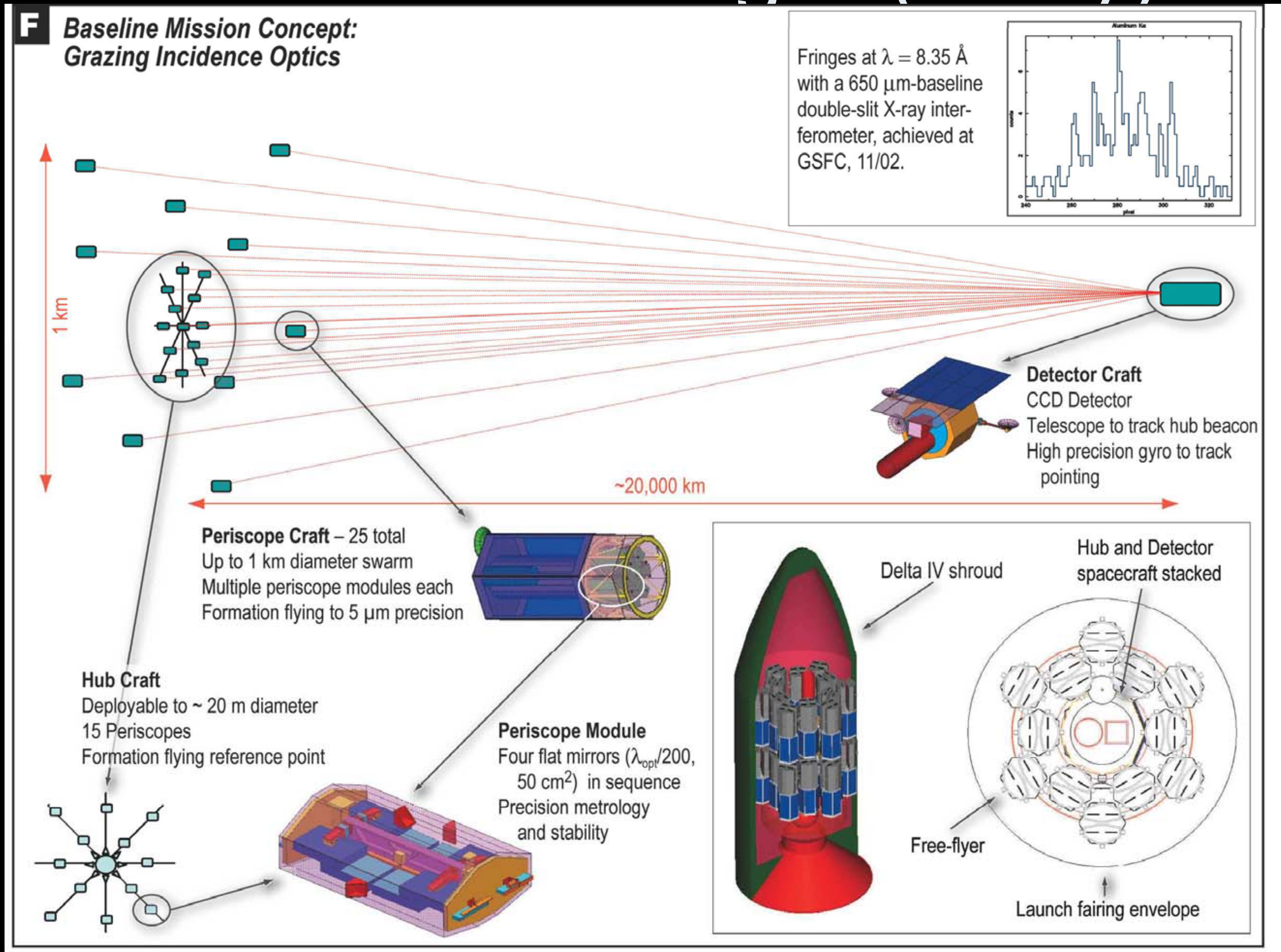
- Entire lens area effective → improvement in source sensitivity
- Long focal lengths require formation flying of lens-craft and detector-craft:



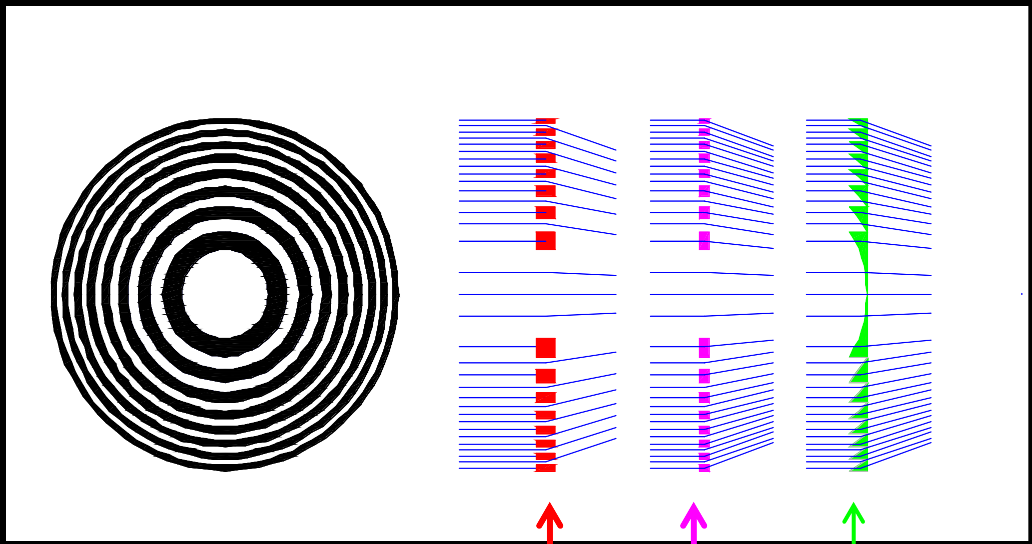
⇒ **milli-arcsecond mission → 1 - 100 km spacecraft separation**

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

Black Hole Imager (X-ray)



Overview: Phase Fresnel Lenses (PFLs)



(a) Fresnel Zone Plate (FZP) **$1/\pi^2 \approx 10\%$**

(b) Phase-reversal Zone Plate (PZP) **$4/\pi^2 \approx 41\%$**

(c) Phase Fresnel Lens (PFL) **$\approx 100\%$**

Maximum Efficiency

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

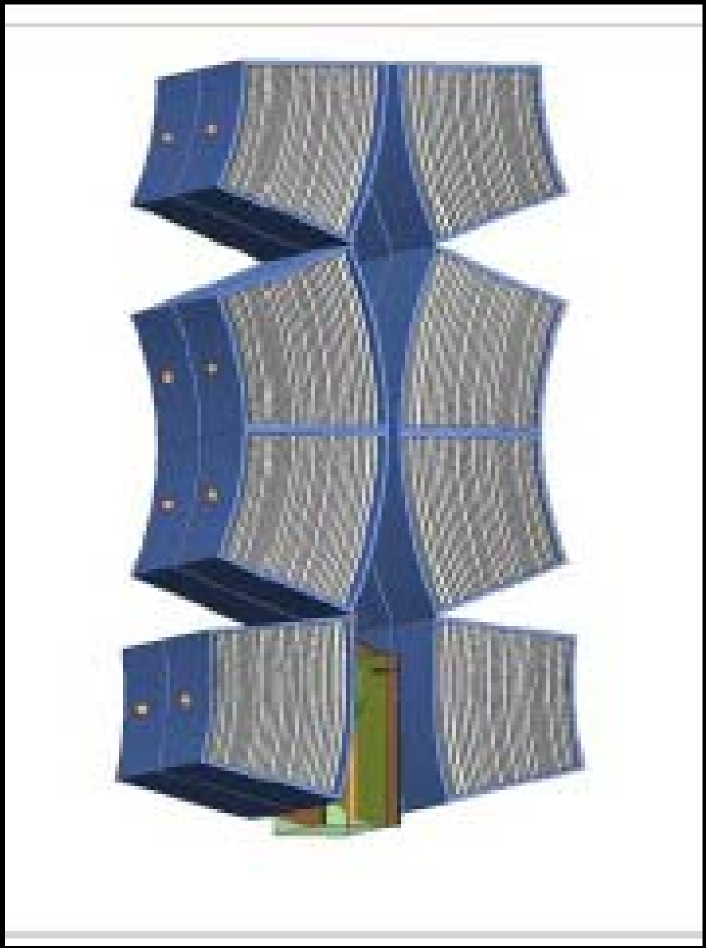
PFL - Potential

- 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

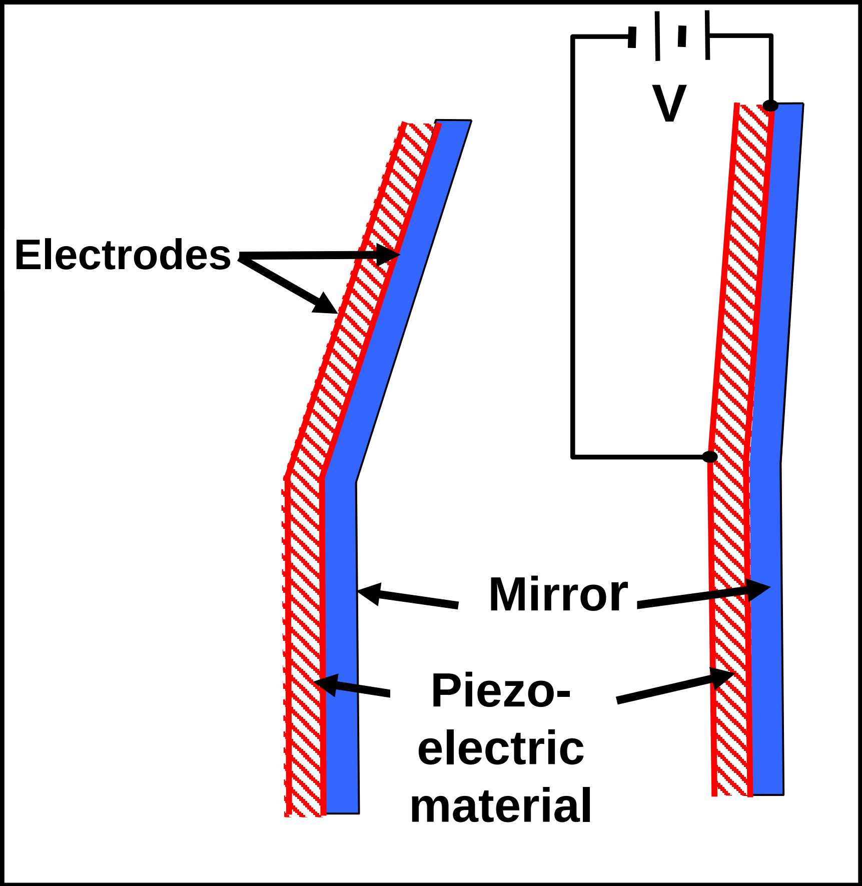
- Limited energy bandwidth
- Long focal lengths
  - 150 m for test PFL in x-ray band
  - ==> Formation flying for practical instrument

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 and EP tests

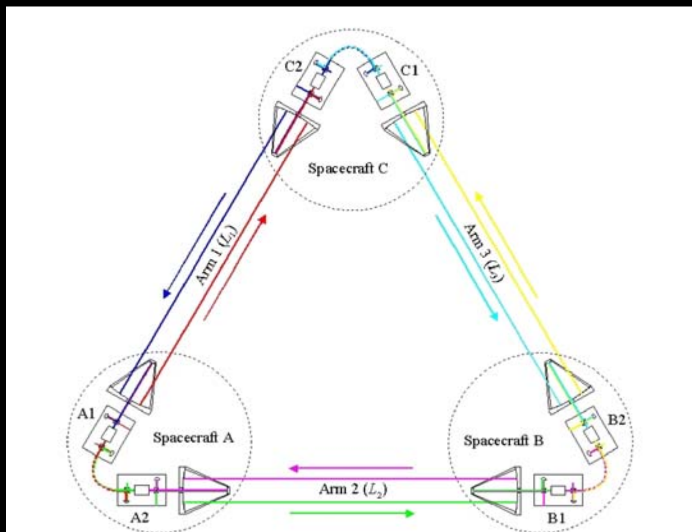
- Lunar laser ranging: more reflectors, active reflectors, mm precision
- Lab tests at even higher precision: short range forces
- Astrophysical tests of MOND and other modified gravity
- Binary pulsars – find more!
- GP-B analysis (imminent results)
- X-ray observations of line profiles in accretion disks – checks particle & photon orbits near rotating black holes
- Advanced LIGO: first direct gravitational wave detection?
- LISA, including gravitational wave distance measures, checks black hole merger theory
- Solar system tests: orbiting everything with space missions! Superclocks! PPN parameters to parts per billion!

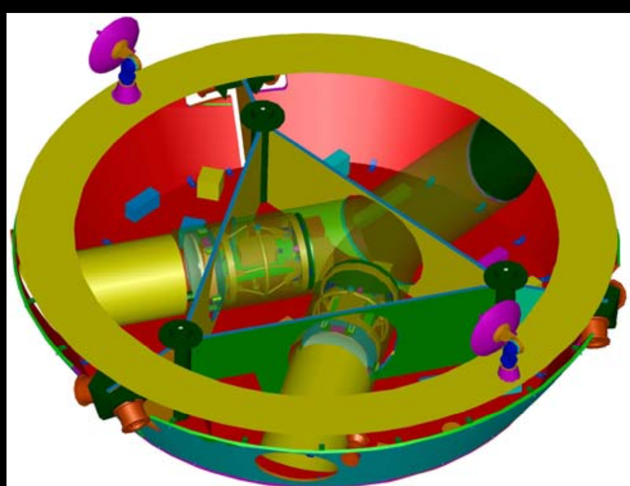
Galaxy Cluster Abell 370
Hubble Space Telescope ▪ ACS/WFC

NASA, ESA, the Hubble SM4 ERO Team, and ST-ECF

STScI-PRC09-25h

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)

Satellite Test of the Equivalence Principle (STEP)

- 1 part in 10^{18}
- Compare accelerations of four pairs of test masses in Earth orbit
- Superconducting shields and sensors (SQUIDs)
- Drag-free satellites (compensating for drag with thrusters)
- http://einstein.stanford.edu/STEP/index.html

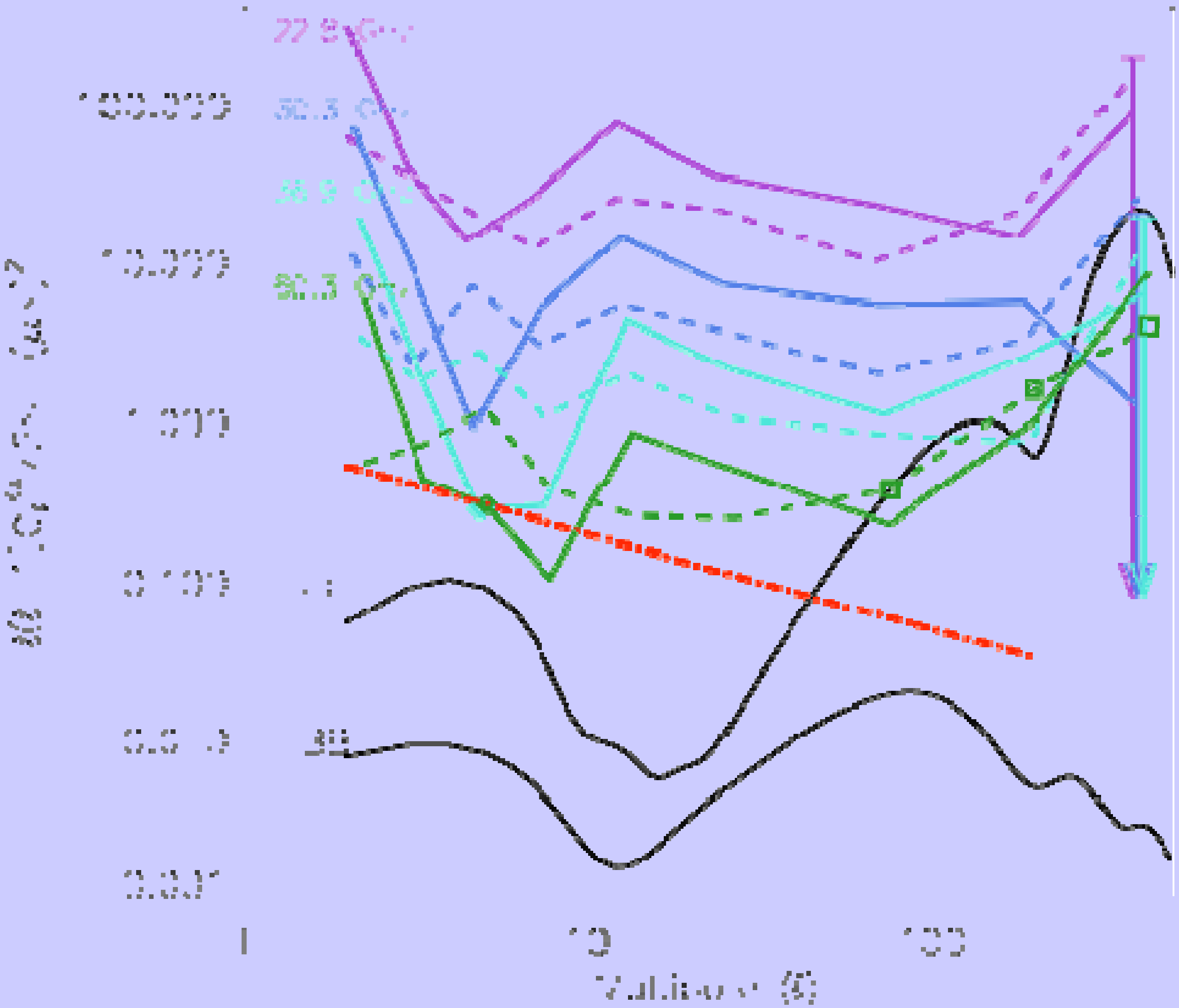
Particle Properties

- LHC results, Higgs boson? Supersymmetry? (big effect on dark matter astrophysics if found)
- Bigger colliders, future unknown
- Subtle deviations, special experiments based on predictions of theories
- Proton decay? Look for cosmic background radiation field, redshifted Υ (nothing yet…)
- Neutrino masses? Solar neutrino oscillations ➔ mass differences

The End and The Beginning

WMAP Foreground Spectra

Page et al., 2006



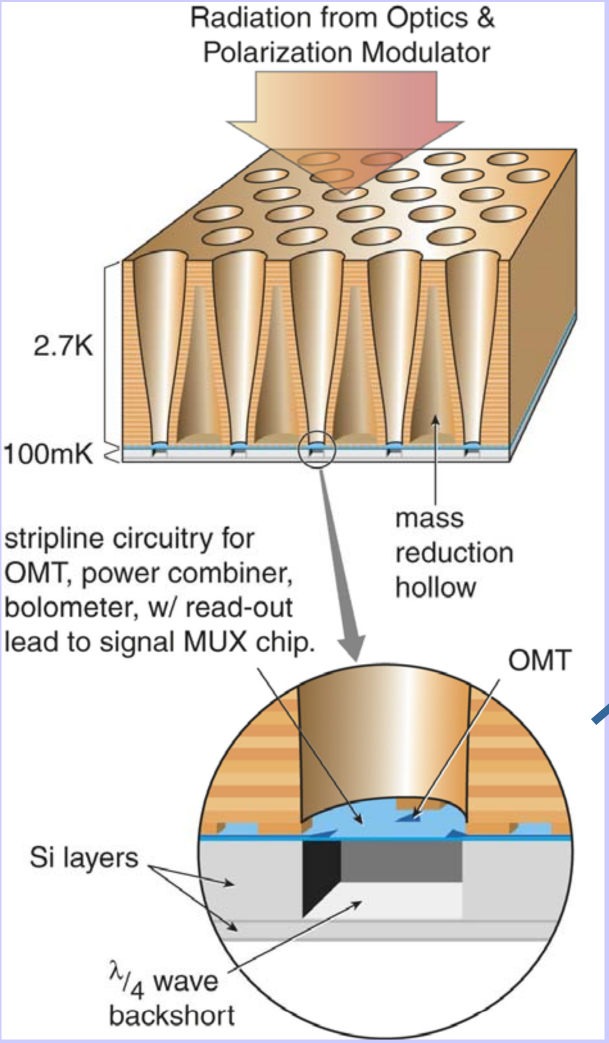
Solid colors - EE foreground

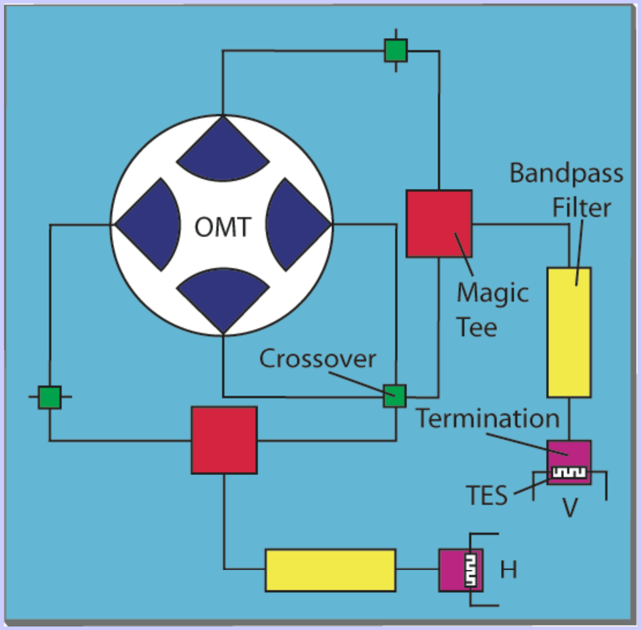
Dashed colors - BB foreground

Dot-dashed red - foreground estimate @ 60 GHz

Solid black - model CMB

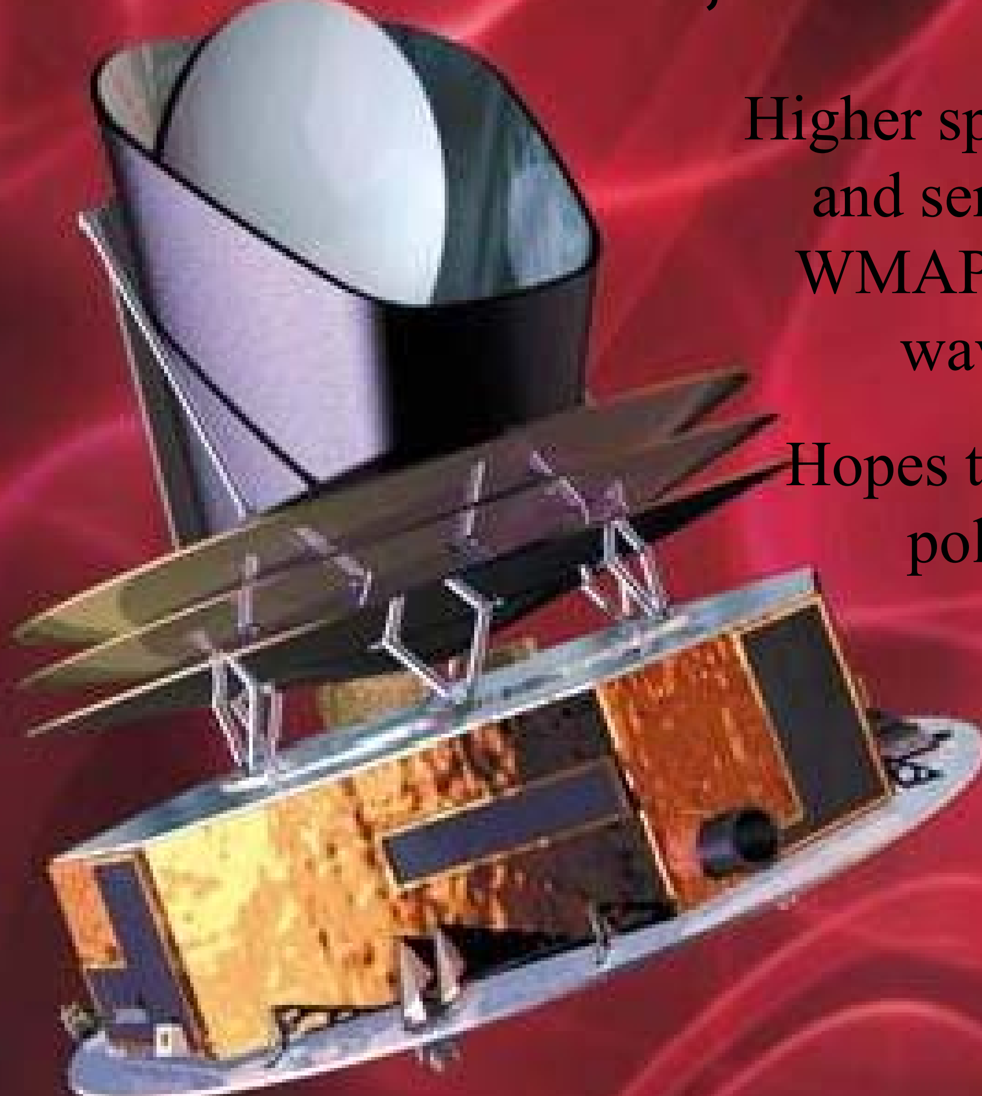
Candidate Instrument Concept - Detection





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

Planck Mission - ESA-led with NASA contributions, 2009 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	

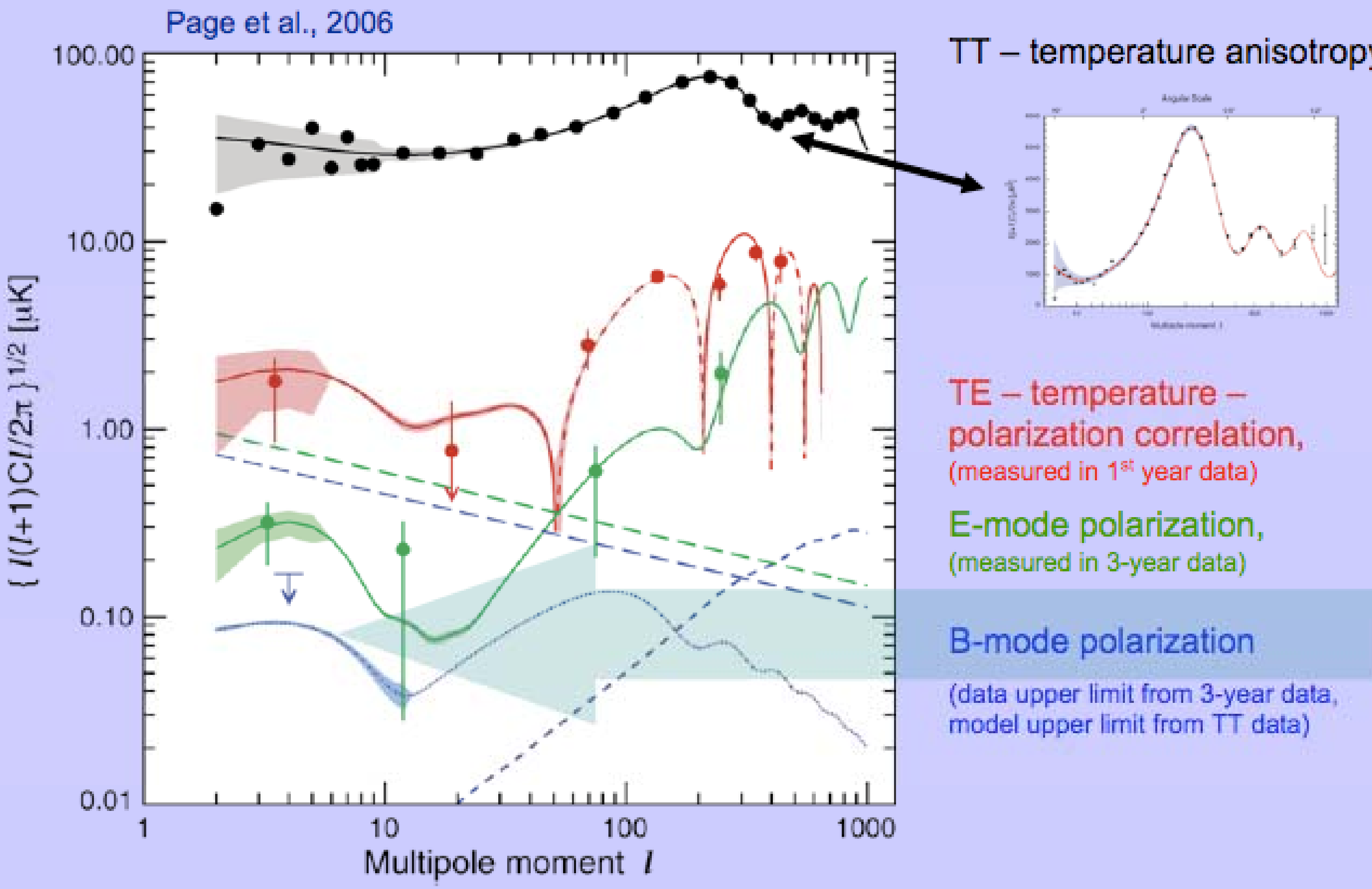
TABLE 2.D.2 Inflation Probe: Mission Instrument Properties

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

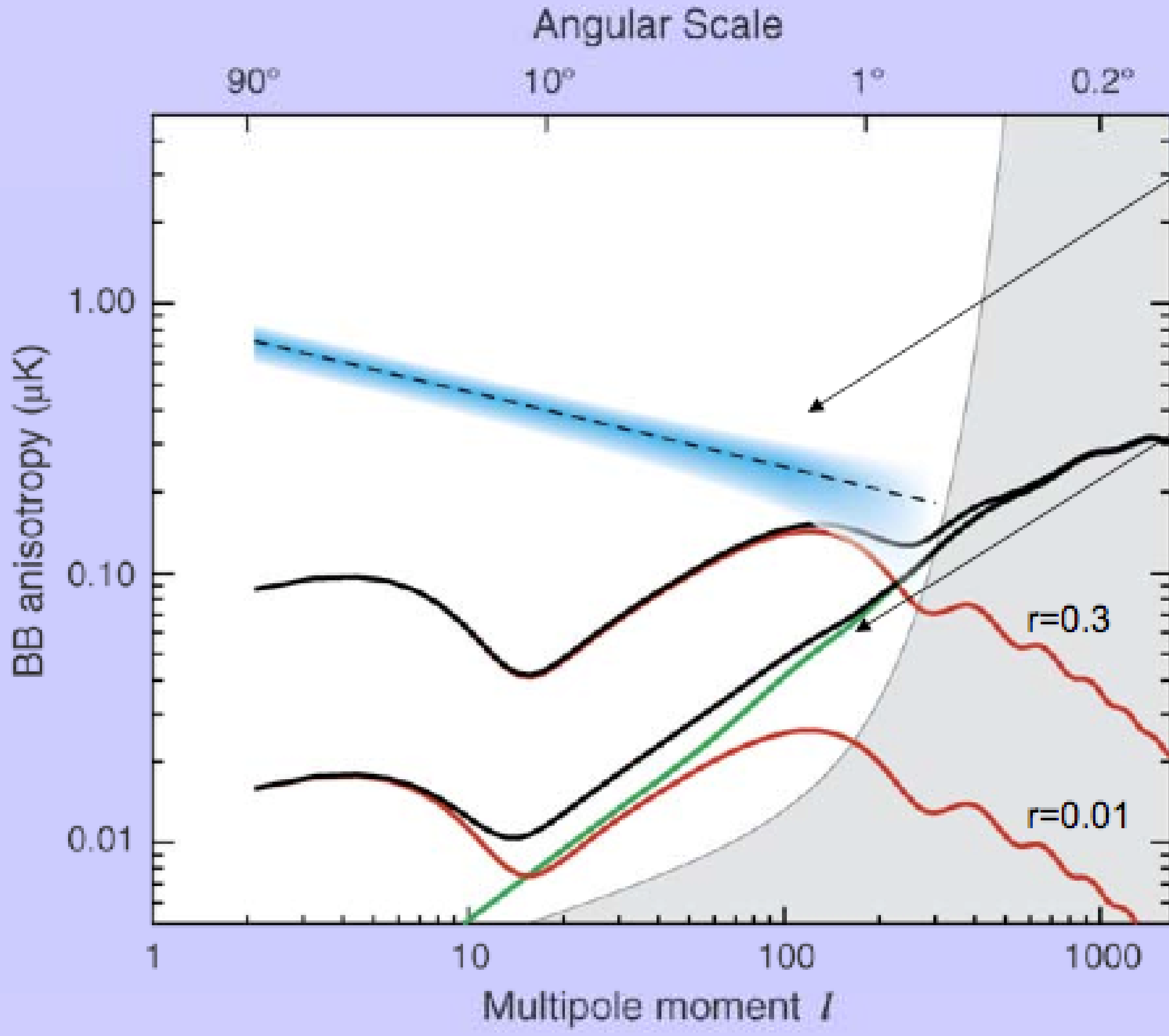
Charts from Gary Hinshaw for BEPAC

Current Polarization Data – WMAP3



Gary Hinshaw, NRC-BEPAC, 11/7/06

Sensitivity & Foreground Estimates



Blue band - Galactic foreground estimate from WMAP3, frequency dependent

Green line - Lensing (EE→BB), frequency independent

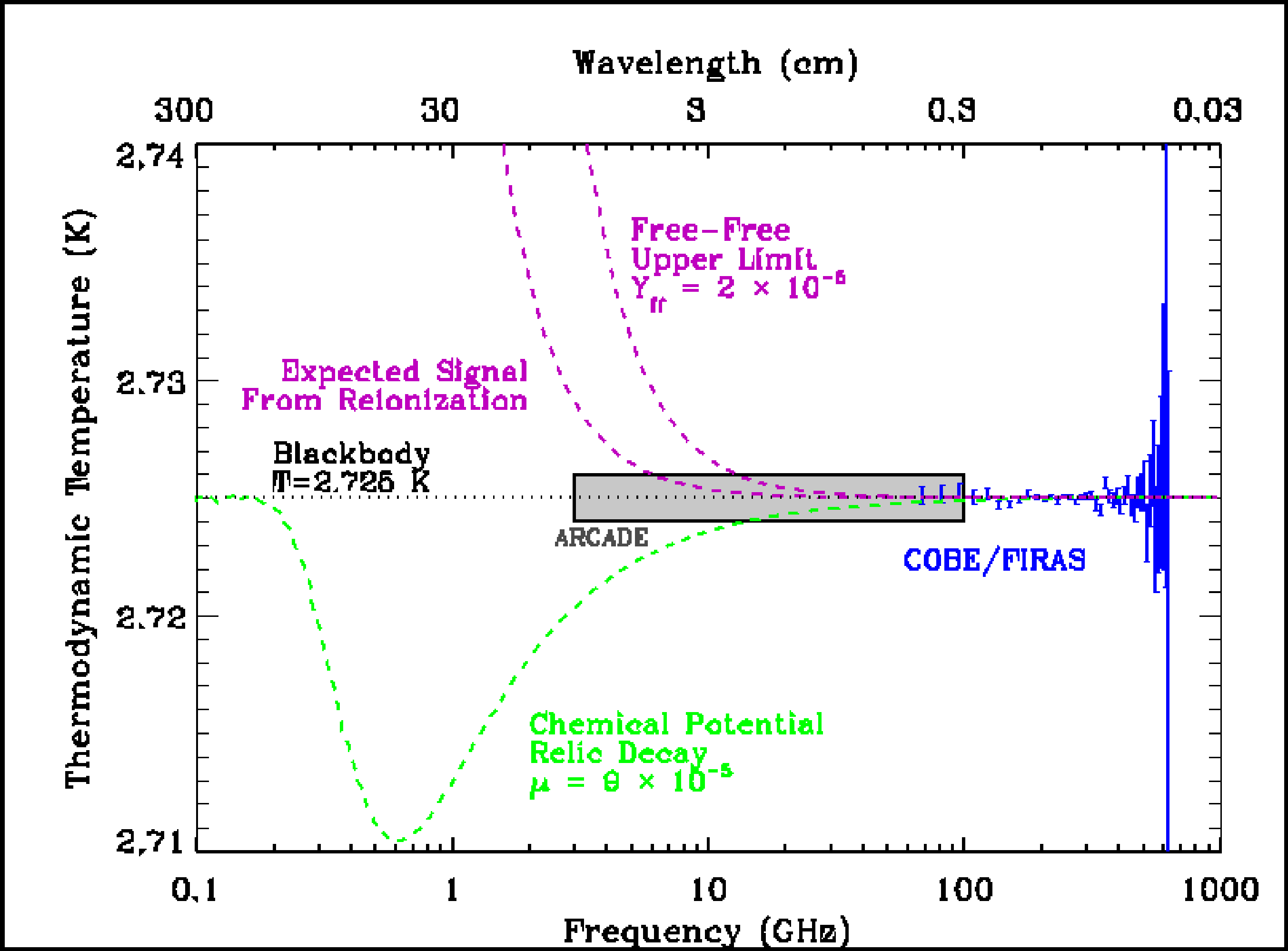
Red lines - Gravity wave signal(s)

Grey shaded band - 1-sigma sensitivity for 1000-channel system with 1-yr integration, 1°FWHM resolution

CMB Spectrum

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

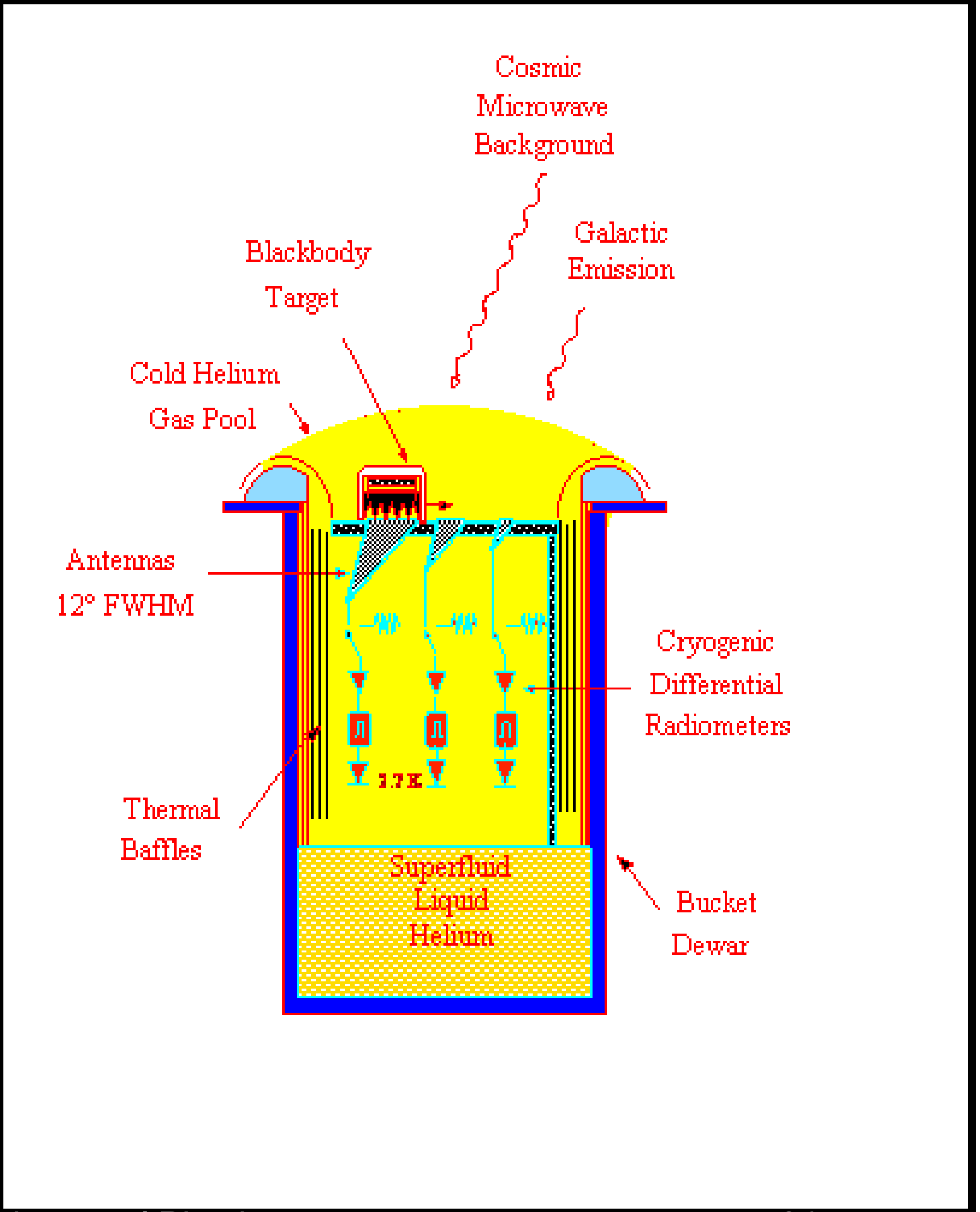
Longer Wavelength CMB Spectrum



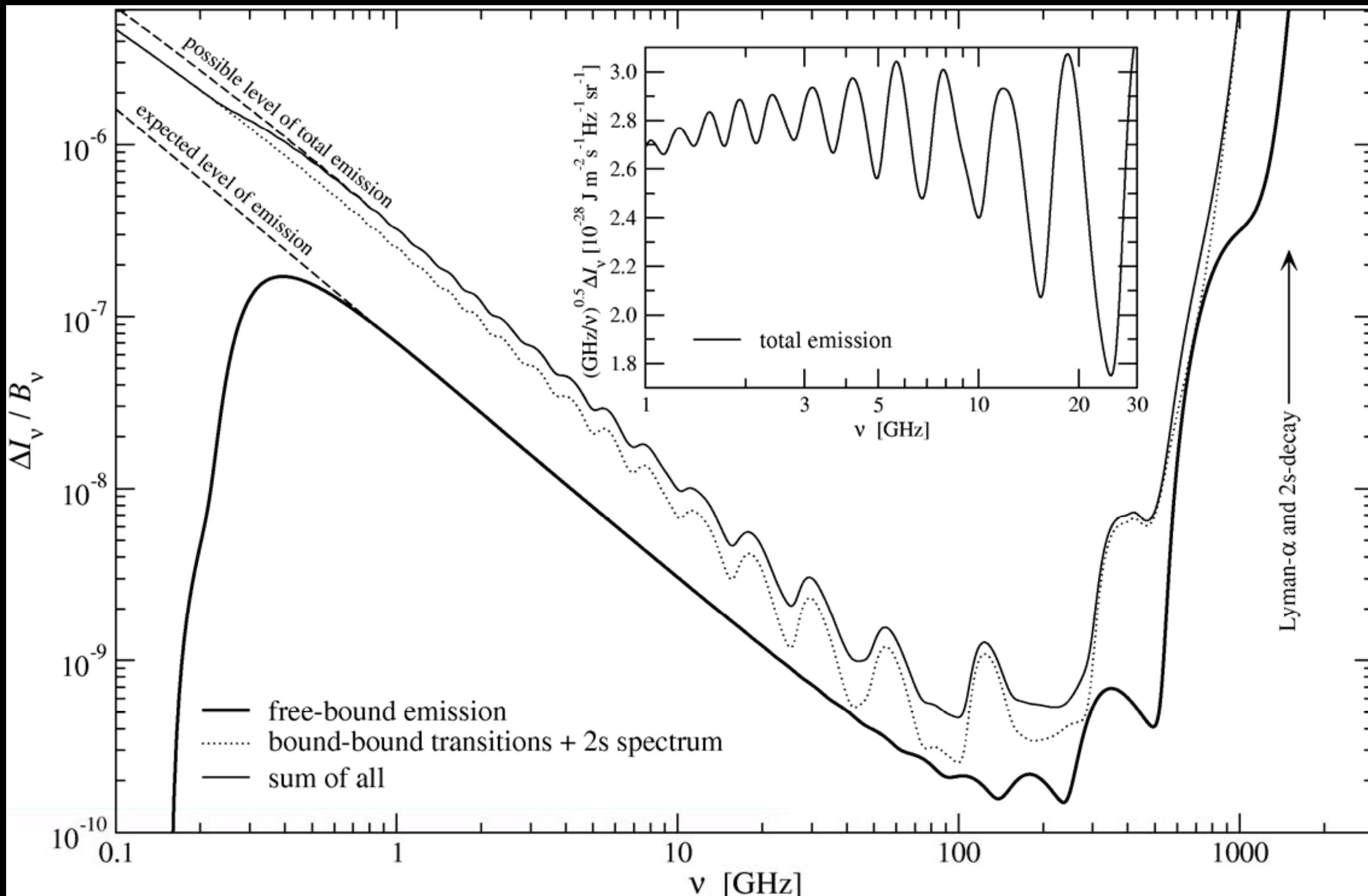
Predicted free-free signal from ionized gas to z ~ 6 must be > 0.3 mK at 3 GHz. Halo formation near reionization implies 2 mK < dT < 5 mK at 3 GHz. Predicted signal from reionization and structure formation (purple curve). (Arcade.gsfc.nasa.gov)

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 $< 10^{-6}$, $\mu < 2\times10^{-5}$
- http://arcade.gsfc.nasa.gov



FIRAS 2: Was recombination era out of equilibrium?



Sunyaev et al. predictions

Or, LiH lines, …

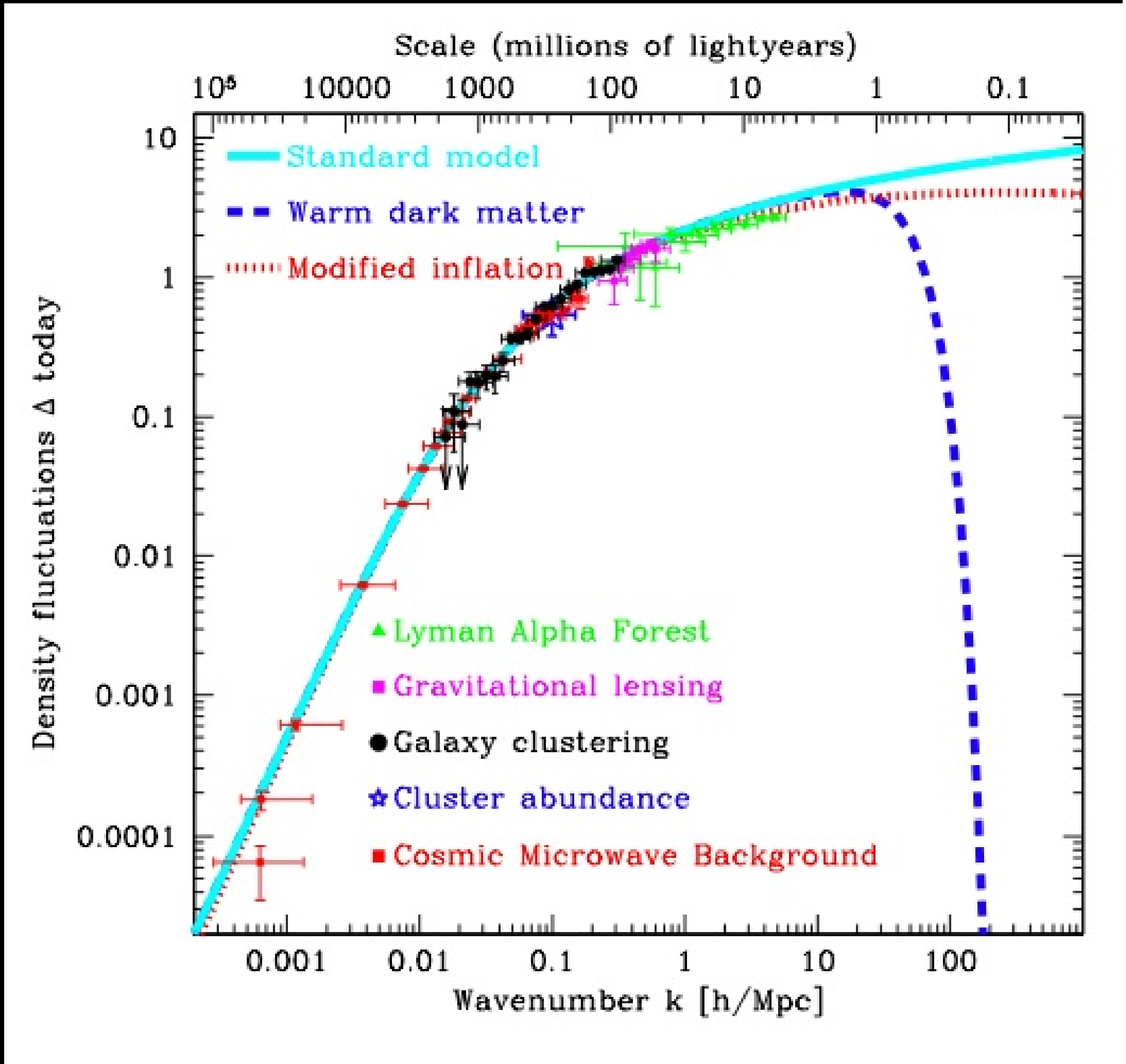
Improvements over FIRAS

- 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

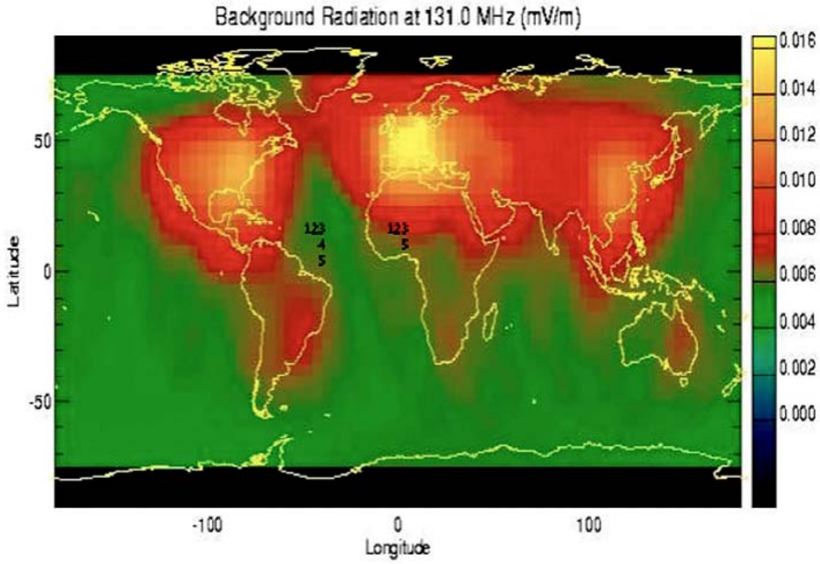
21 cm cosmology

- 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.



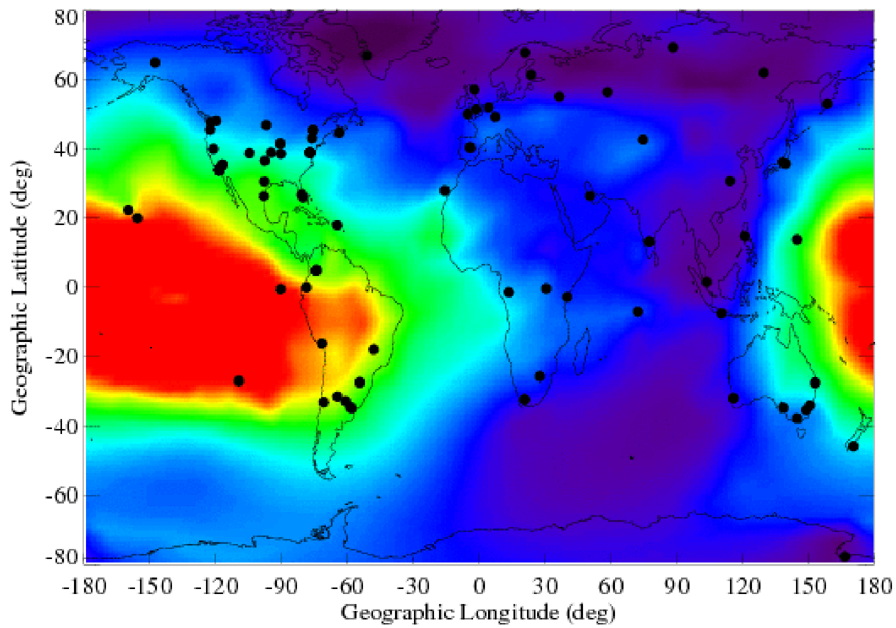
Radio Frequency Interference



FORTES satellite

01/02/07
22:10 UT

Ionospheric TEC Map



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)

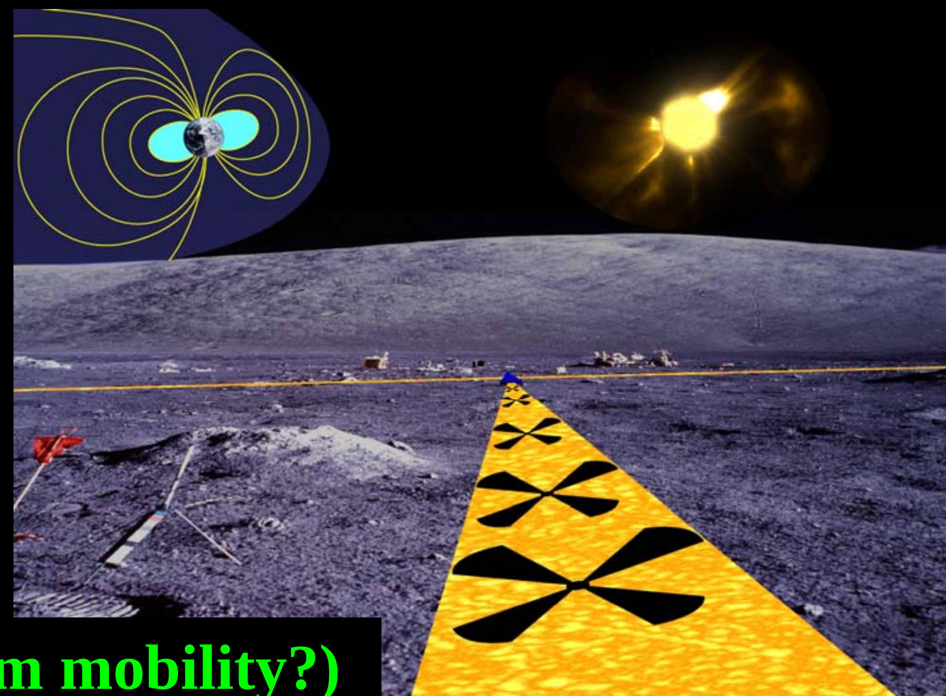
R. MacDowall (NASA/GSFC), J. Burns (CU), L. Demaio (NASA/GSFC), D. Jones (JPL), K. Weiler (NRL)

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

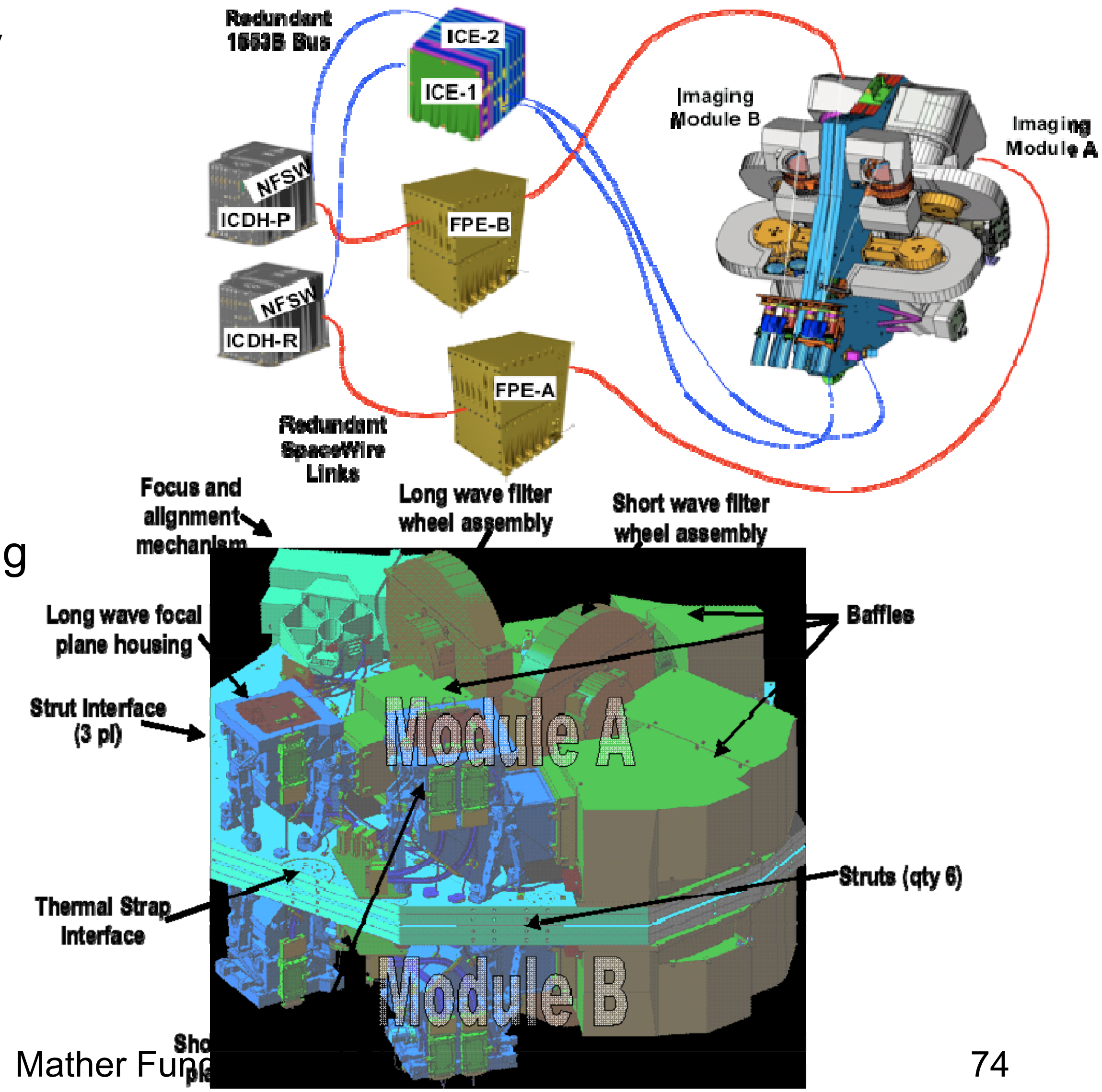
  First imaging instrument at these wavelengths
- 500-m length arms
  - 2º resolution (@ 30 m) **(but 20 km mobility?)**
  - Order of magnitude improvement in resolution at these wavelengths



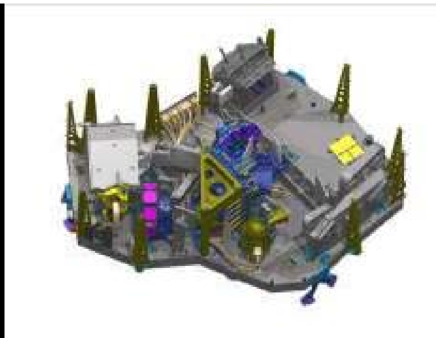
New Tools…

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

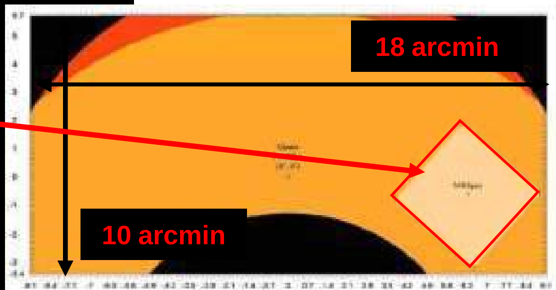


Near Infrared Spectrograph (NIRSpec) Overview



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

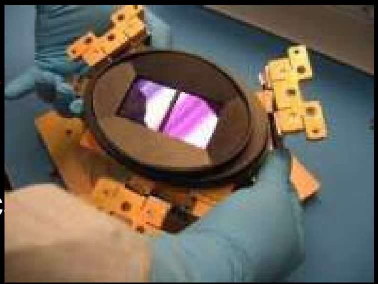


- 3 Spectral Resolutions:
  - R=100 (0.6 μm and 5.0 μm) → Redshift & Exploratory Spectra
  - R=1000 (1.0 μm and 5.0 μm) → Emission Line Diagnostic
  - R=2700 (1.0 μm and 5.0 μm) → Kinematics and Masses

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

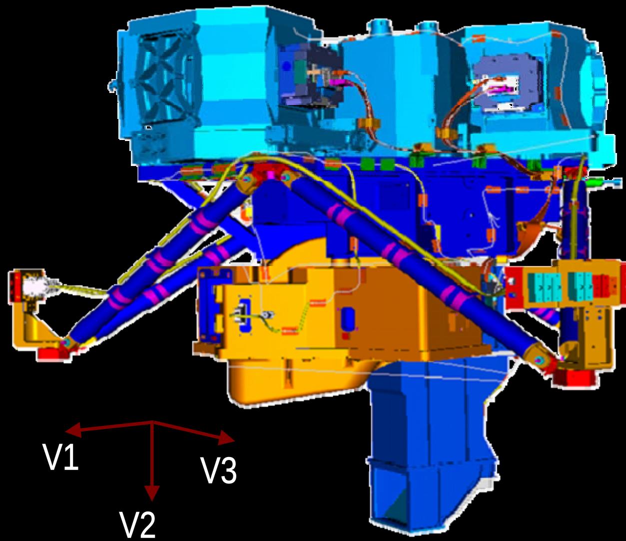
- First time in space more than 100 simultaneous spectra with a slits-based Micro-Shutter Assembly:
  - Mosaic of 4 arrays, each made up by 365 x 171 slits → ~ 250000 slits in total
  - Each 80 μm x 180 μm slit (200 x 460 mas) independently programmable
  - JWST "New Technology" – Passed TRL6 Review

- 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

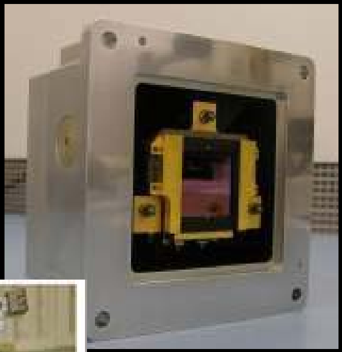


Mid-Infrared Instrument (MIRI) Overview

- 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



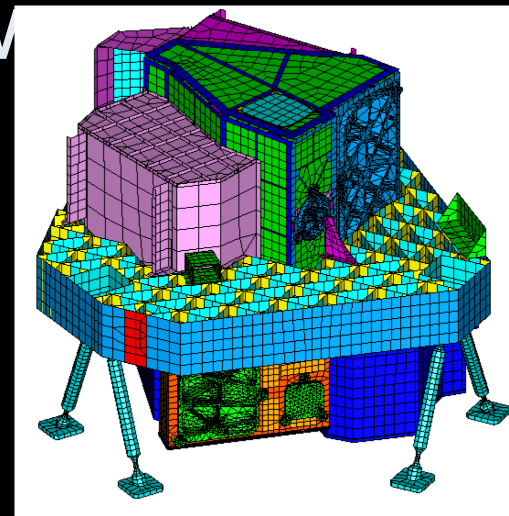

Contamination Control Cover


Engineering Model FPM


Filter Wheel Assembly

Fine Guidance Sensor (FGS) Overview

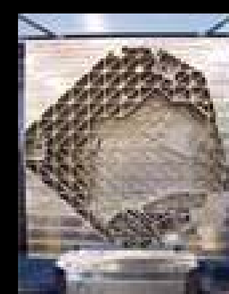
- FGS Provides:
  - Fine guidance to the overall JWST Observatory (Guider)
  - Science imagery between 1.6 and 4.9 microns (Tunable Filter Imager)
- FGS Team:
  - Canadian Space Agency
  - COM DEV Canada
  - Herzberg Institute of Astrophysics
  - Université de Montreal
  - FGS Science Team
- Critical 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

JDEM (Joint Dark Energy Mission) per BEPAC

TABLE 2.E.1 JDEM: Mission Description

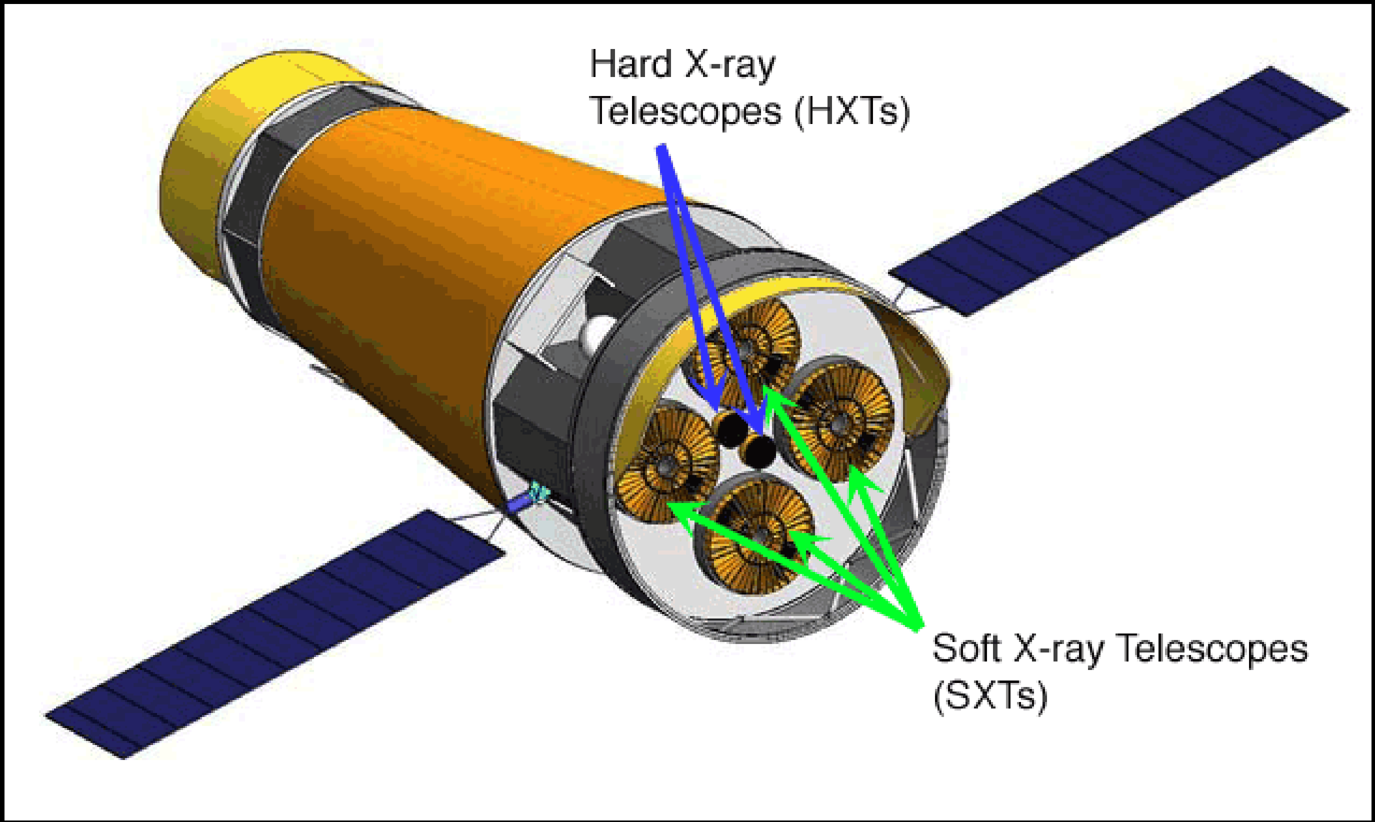
Primary Measurement	Optical/Near IR imaging and spectroscopy
Observatory Type	Optical/Near IR Wide Field Survey Telescope
Projected Years in Orbit	3 year primary, 5 year goal
Type of Orbit	LEO (ADEPT); L2 (DESTINY/SNAP)
Mission phases	ADEPT: full-sky survey DESTINY: 24 months SN survey, 12 months weak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

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