NASA's Beyond Einstein Program: An Architecture for Implementation

Committee Charge

1. Assess the five proposed Beyond Einstein missions (Constellation-X, Laser Interferometer Space Antenna, Joint Dark Energy Mission, Inflation Probe, and Black Hole Finder probe) and **recommend which of these five should be developed and launched first**, using a funding wedge that is expected to begin in FY 2009. The criteria for these assessments include:
   - Potential scientific impact within the context of other existing and planned space-based and ground-based missions; and
   - Realism of preliminary technology and management plans, and cost estimates.
2. Assess the Beyond Einstein missions sufficiently so that they can act as input for any future decisions by NASA or the next Astronomy and Astrophysics Decadal Survey on the ordering of the remaining missions. This second task element will assist NASA in its investment strategy for future technology development within the Beyond Einstein Program prior to the results of the Decadal Survey.

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Beyond Einstein Science

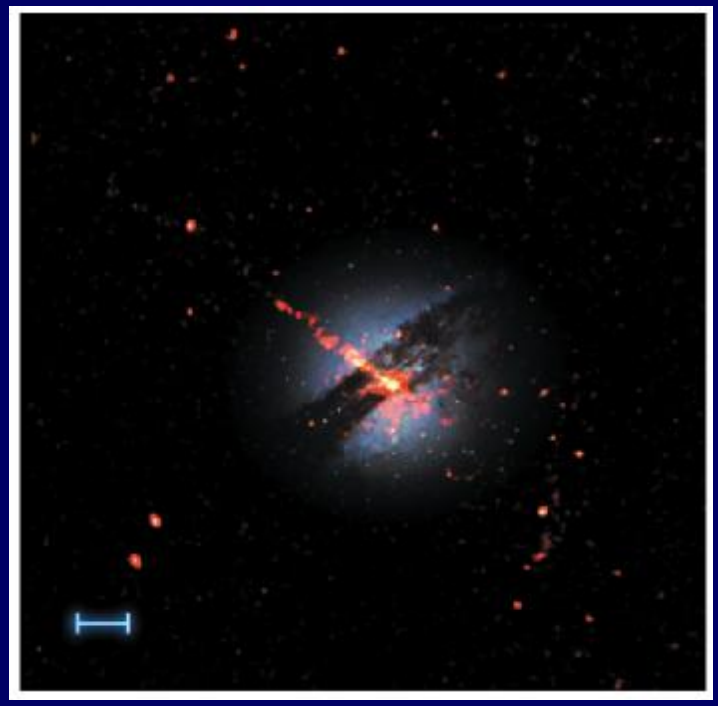
- Scientific challenges at the intersection of physics and astrophysics.
- Potential to extend our basic physical laws beyond where 20th century research left them.
  - Stringent new tests of Einstein's general theory of relativity
  - Indicate how to extend the standard model of elementary particle physics
  - Give astrophysics an entirely new way of observing the universe, through gravity waves
- New physical understanding may be required to explain cosmological observations
  - The challenge of investigating the laws of physics using astronomical techniques promises to bring higher precision, clarity, and completeness to many astrophysical investigations relating to galaxies, black holes, and the large-scale structure of the universe, among other areas.

Beyond Einstein Missions

- Five Mission Areas
  - Einstein Great Observatories:
    - Constellation-X (Con-X)
    - Laser Interferometer Space Antenna (LISA)
  - Einstein Probes:
    - Black Hole Finder Probe (BHFP)
    - Inflation Probe (IP)
    - Joint Dark Energy Probe (JDEM)
- Eleven Individual Mission Candidates
  - BHFP: Coded Aperture Survey Telescope for Energetic Radiation (CASTER), Energetic X-ray Imaging Telescope (EXIST)
  - Con-X
  - IP: CMB Polarization Mission (CMBPol), Cosmic Inflation Probe (CIP), Experimental Probe of Inflationary Cosmology (EPIC-F), Einstein Polarization Interferometer for Cosmology (EPIC-I)
  - JDEM: Advanced Dark Energy Physics Telescope (ADEPT), Dark Energy Space Telescope (DESTINY), Supernova/Acceleration Probe (SNAP)
  - LISA

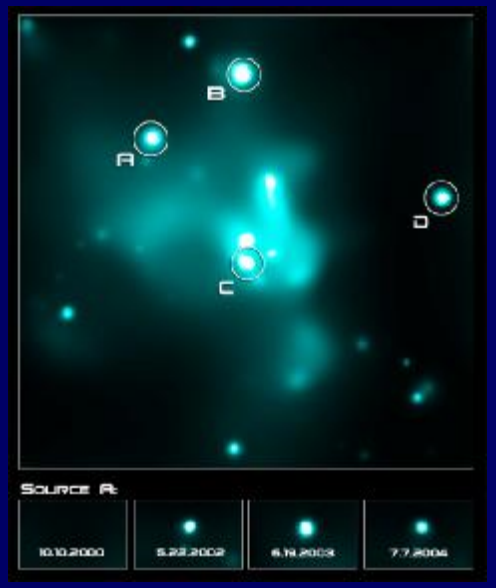
Black Hole Finder Probe: Science Goals

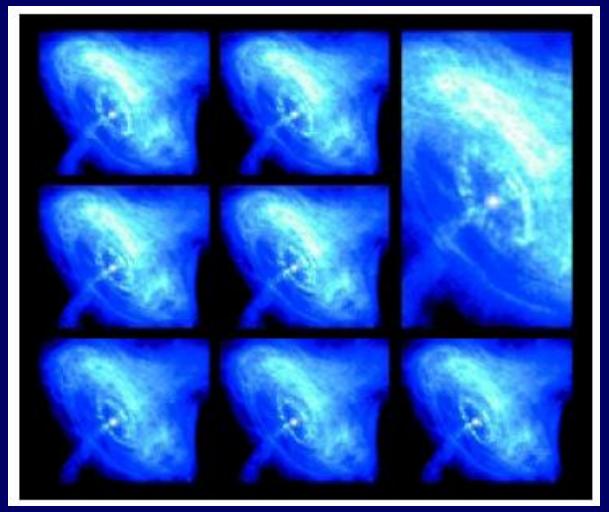
- Beyond Einstein science
  - perform a census of black holes throughout the Universe
  - determine how black holes evolve
  - observe stars and gas plunging into black holes
  - determine how black holes are formed
- Broader science
  - discover the origin of the 511 keV electron-positron annihilation line toward the center of the Milky Way
  - determine the rate of supernova explosions in the Milky Way
  - discover new types of hard x-ray sources revealed by a high-sensitivity survey



Constellation-X: Science Goals

- Beyond Einstein science
  - investigate motion near black holes
  - measure the evolution of dark energy using clusters of galaxies
  - determine where most of the atoms are located in the Warm Hot Intergalactic Medium (WHIM) and detect baryons
  - determine the relationship of supermassive black hole (SMBH) growth to formation of galactic spheroids
  - determine whether dark matter emits energy via decay or annihilation
- Broader Science
  - determine the equation of state of neutron stars
  - determine the size of the magnetic fields in young neutron stars
  - examine how supermassive black holes affect galaxies
  - discover where heavy elements originate
  - investigate the activity of Sun-like stars and how they affect their environments
  - investigate how comets and planets interact with the Solar wind

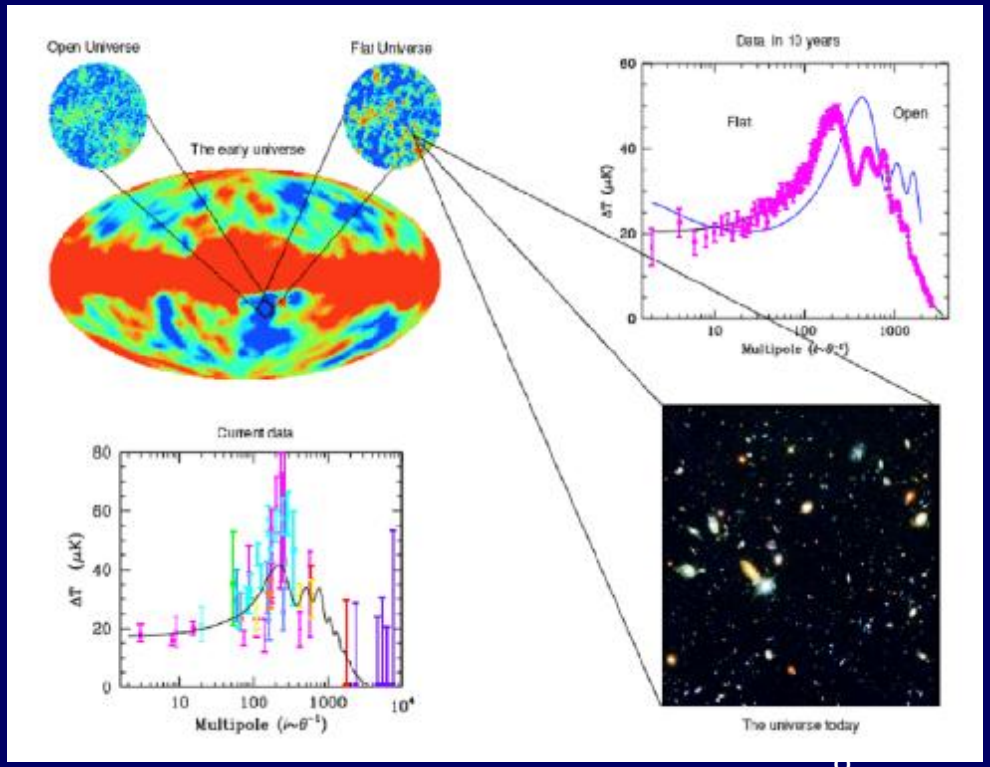




Inflation Probe: Science Goals

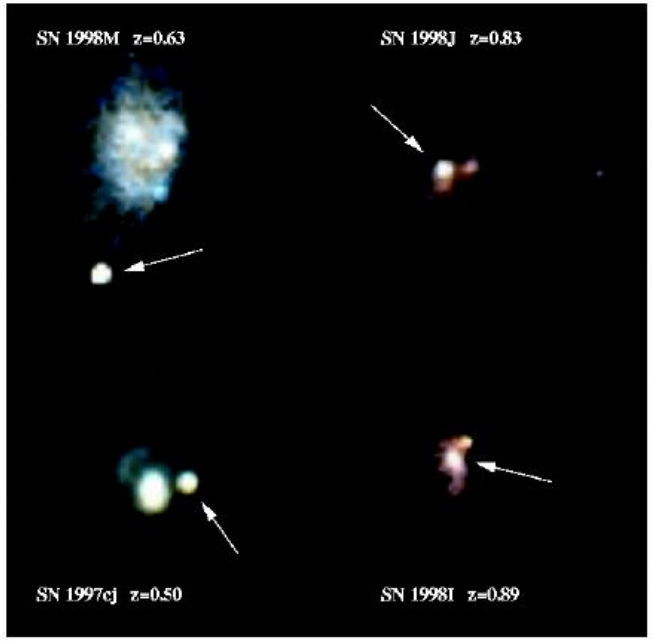
- Beyond Einstein science
  - detect gravitational waves sourced by inflation
  - constrain the physics of inflation
  - detect baryonic oscillations in the matter power spectrum

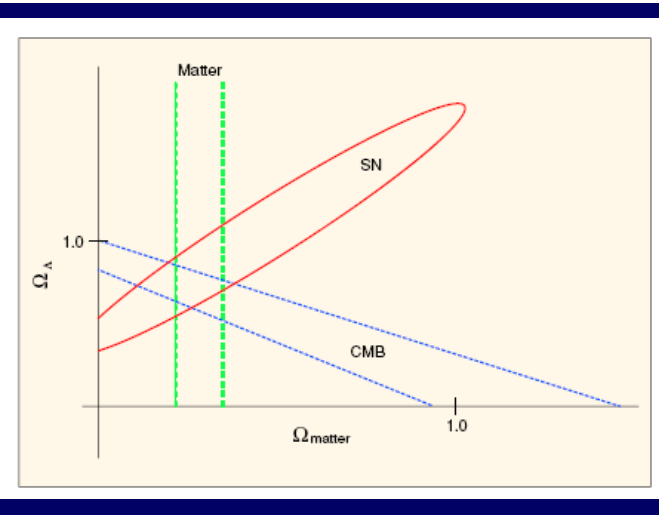
- Broader science
  - –determine the nature of galactic dust, galactic magnetic fields, and electron spectrum
  - –determine when the universe was reionized
  - –investigate the history of star formation for 3<z<6
  - –determine the masses of the three kinds of neutrinos



Joint Dark Energy Mission : Science Goals

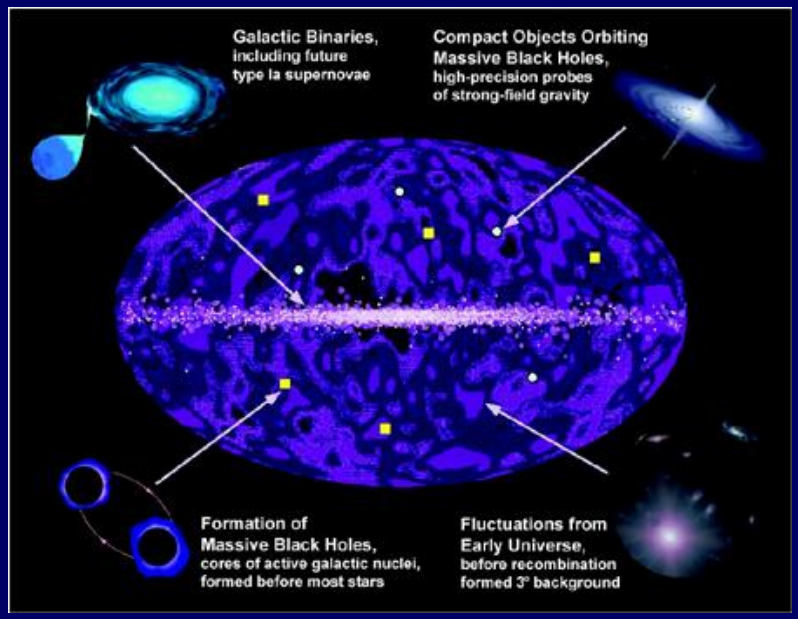
- Beyond Einstein science
  - precisely measure the expansion history of the universe to determine whether the contribution of dark energy to the expansion rate varies with time
- Broader science
  - investigate the formation and evolution of galaxies
  - determine the rate of star formation and how that rate depends on environment

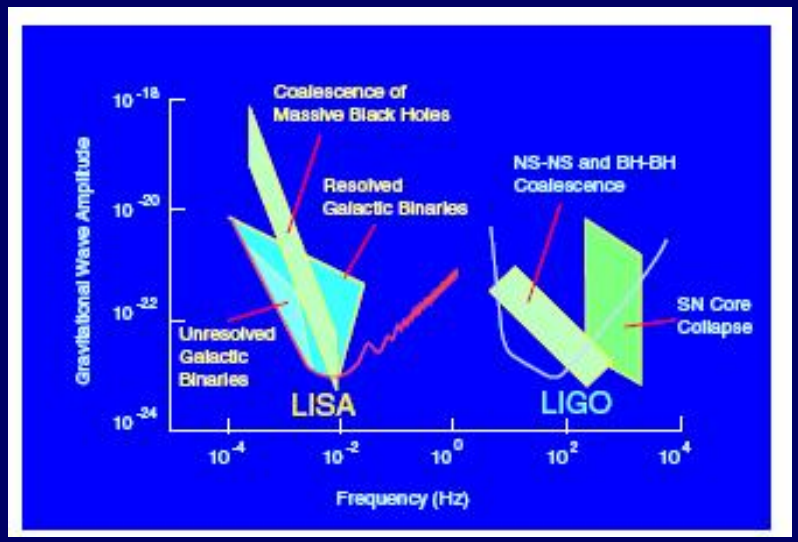




LISA: Science Goals

- Beyond Einstein science
  - determine how and when massive black holes form
  - investigate whether general relativity correctly describes gravity under extreme conditions
  - determine how black hole growth is related to galaxy evolution
  - determine if black holes are correctly described by general relativity
  - investigate whether there are gravitational waves from the early universe
  - determine the distance scale of the universe
- Broader science
  - determine the distribution of binary systems of white dwarfs and neutron stars in our Galaxy





Data Gathering Process

- First Committee Meeting (Nov 6-8, 2006)
  - Science presentations on selected questions from "Connecting Quarks With the Cosmos."
  - Initial presentations from the 11 Mission Candidates
  - Formulation of the committee's Request for Information
- RFI Sent to Teams (Dec 19, 2006)
- Second Committee Meeting (Jan 30-Feb 1, 2007)
  - Science presentations on areas of BE science not covered at the first meeting
  - Detailed presentations from the mission candidates, based on their responses to the committee's RFI
- Town Hall Meetings for Community Input (Feb-Apr, 2007)
  - Newport Beach, CA
  - Cambridge, MA
  - Baltimore, MD
  - Chicago, IL
  - NRC also established BeyondEinstein@nas.edu e-mail box for community input, and posted the input received on the committee's website.
- Third Committee Meeting (Apr 5-7, 2007)
  - Presentation on ESA plans for BE Science
  - Presentation on the ability of ground-based telescopes to investigate dark energy
- Fourth Committee Meeting (Jun 6-8, 2007)
  - Writing meeting for the committee

Report Table of Contents

1. Introduction
2. Science Impact
3. Technical Risk and Cost Assessment
4. Policy and Other Programmatic Issues
5. Recommendations and Conclusions

Evaluation of Science Impact

Five criteria for evaluation:

- Advancement of Beyond Einstein research goals.
- Broader science contributions.
- Potential for revolutionary discovery.
- Science risk and readiness.
- Uniqueness of the mission candidate for addressing its scientific questions.

Beyond Einstein Objectives*

- Find out what powered the Big Bang
- Observe how black holes manipulate space, time and matter
- Identify the mysterious dark energy pulling the Universe apart

**Objectives drawn from NASA's 2003 SEU Roadmap: "Beyond Einstein: From the Big Bang to Black Holes"*

Evaluation of Technical Readiness

- Technical Evaluation consisted of two parts
  - Technical readiness, including the following elements: the instrument, spacecraft, operations, and technical margins.
  - Management readiness, including: team organization, schedule and other special challenges.
- The committee, supported by SAIC, evaluated the technical readiness levels of the relevant scientific and engineering components for the 11 mission concepts.
- The mission candidates provided information on their missions in response to the committee's Request For Information (RFI) and to further questions from the committee.
- *The mission teams worked to meet difficult deadlines imposed by the committee's tight schedule, and the committee appreciates their efforts.*

Cost Estimates and Analysis

- The committee, supported by SAIC, developed independent cost estimates for each mission candidate, using three different models derived from historical databases.
- Models used:
  - QuickCost
  - NAFCOM
  - CoBRA

Policy Issues

- As directed in the statement of task, the committee made its recommendations based on assessments of scientific impact and technical and management realism of proposed missions.
- Policy issues are additional considerations, or external factors that provide underlying context and possibly influence future implementation of committee recommendations. These issues include:
  - Implications for U.S. science and technology leadership
  - Program funding constraints
  - Role of inter-agency and international partnerships
  - Investments in underlying research and technology and supporting infrastructure
  - Impact of International Traffic in Arms Regulations (ITAR)

Finding 1

- The Beyond Einstein scientific issues are so compelling that research in this area will be pursued for many years to come. All five mission areas in NASA's Beyond Einstein plan address key questions that take physics and astronomy beyond where the century of Einstein left them.

Findings 2 and 3

- The Constellation-X mission will make the broadest and most diverse contributions to astronomy of any of the candidate Beyond Einstein missions. While it can make strong contributions to Beyond Einstein science, other BE missions address the measurement of dark energy parameters and tests of strong-field General Relativity in a more focused and definitive manner.
- Two mission areas stand out for the directness with which they address Beyond Einstein goals and their potential for broader scientific impact: LISA and JDEM.

Finding 4

- LISA is an extraordinarily original and technically bold mission concept. LISA will open up an entirely new way of observing the universe, with immense potential to enlarge our understanding of physics and astronomy in unforeseen ways. LISA, in the committee's view, should be the flagship mission of a long-term program addressing Beyond Einstein goals.

Finding 5

- The ESA-NASA LISA Pathfinder mission that is scheduled for launch in late 2009 will assess the operation of several critical LISA technologies in space. The committee believes it is more responsible technically and financially to propose a LISA new start after the Pathfinder results are taken into account. In addition, Pathfinder will not test all technologies critical to LISA. Thus, it would be prudent for NASA to invest further in LISA technology development and risk reduction, to help ensure that NASA is in a position to proceed with ESA to a formal new start as soon as possible after the LISA Pathfinder results are understood.

Finding 6

- A JDEM mission will set the standard in the precision of its determination of the distribution of dark energy in the distant universe. By clarifying the properties of 70 percent of the mass-energy in the universe, JDEM's potential for fundamental advancement of both astronomy and physics is substantial. A JDEM mission will also bring important benefits to general astronomy. In particular, JDEM will provide highly detailed information for understanding how galaxies form and acquire their mass.

Finding 7

- The JDEM mission candidates identified thus far are based on instrument and spacecraft technologies that have either been flown in space or have been extensively developed in other programs. A JDEM mission selected in 2009 could proceed smoothly to a timely and successful launch.

Recommendation 1

- NASA and DOE should proceed immediately with a competition to select a Joint Dark Energy Mission for a 2009 new start. The broad mission goals in the Request for Proposal should be (1) to determine the properties of dark energy with high precision and (2) to enable a broad range of astronomical investigations. The committee encourages the Agencies to seek as wide a variety of mission concepts and partnerships as possible.

Recommendation 2

- NASA should invest additional Beyond Einstein funds in LISA technology development and risk reduction, to help ensure that the Agency is in a position to proceed in partnership with ESA to a new start after the LISA Pathfinder results are understood.

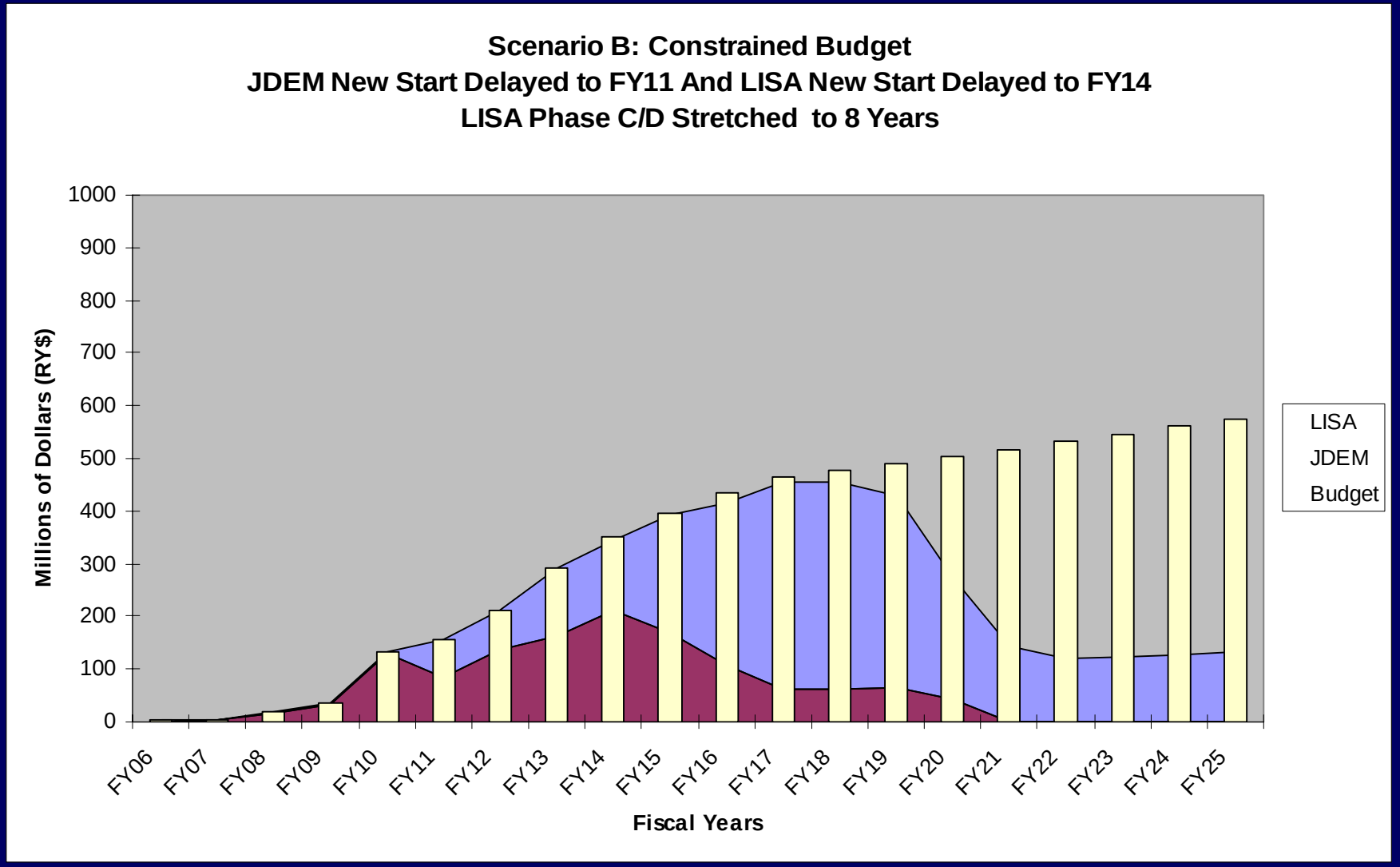
Recommendation 3

- NASA should move forward with appropriate measures to increase the readiness of the three remaining mission areas—*Black Hole Finder Probe, Constellation-X, and Inflation Probe*—for consideration by NASA and the NRC Decadal Survey of Astronomy and Astrophysics.

Finding 8

- The present NASA Beyond Einstein funding wedge alone is inadequate to develop any candidate Beyond Einstein mission on its nominal schedule.
- However, both JDEM and LISA could be carried out with the currently forecasted NASA contribution if DOE's contribution that benefits JDEM is taken into account and if LISA's development schedule is extended and funding from ESA is assumed.

BEPAC Recommended Program Phased to fit within the Projected NASA Beyond Einstein Budget Wedge



Selection Summary

- JDEM is the mission providing the measurements most likely to determine the nature of dark energy, and LISA provides the most direct and cleanest probe of spacetime near a black hole.
- Constellation-X, in contrast, provides measurements promising progress on at least two of the three questions, but does not provide the most direct, cleanest measurement on any of them. It was the committee's judgment that for a focused program like Beyond Einstein, it is most important to provide the definitive measurement against at least one of the questions.
- The committee concludes that JDEM is technologically mature enough to succeed on the timescale specified in the charge. LISA requires additional technology development and a successful pathfinder mission before it is ready for development.
- The committee recommends JDEM for a 2009 start.