

structure and evolution of the universe

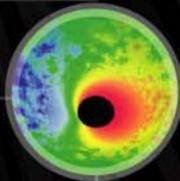
# BEYOND EINSTEIN:

from the big bang to black holes

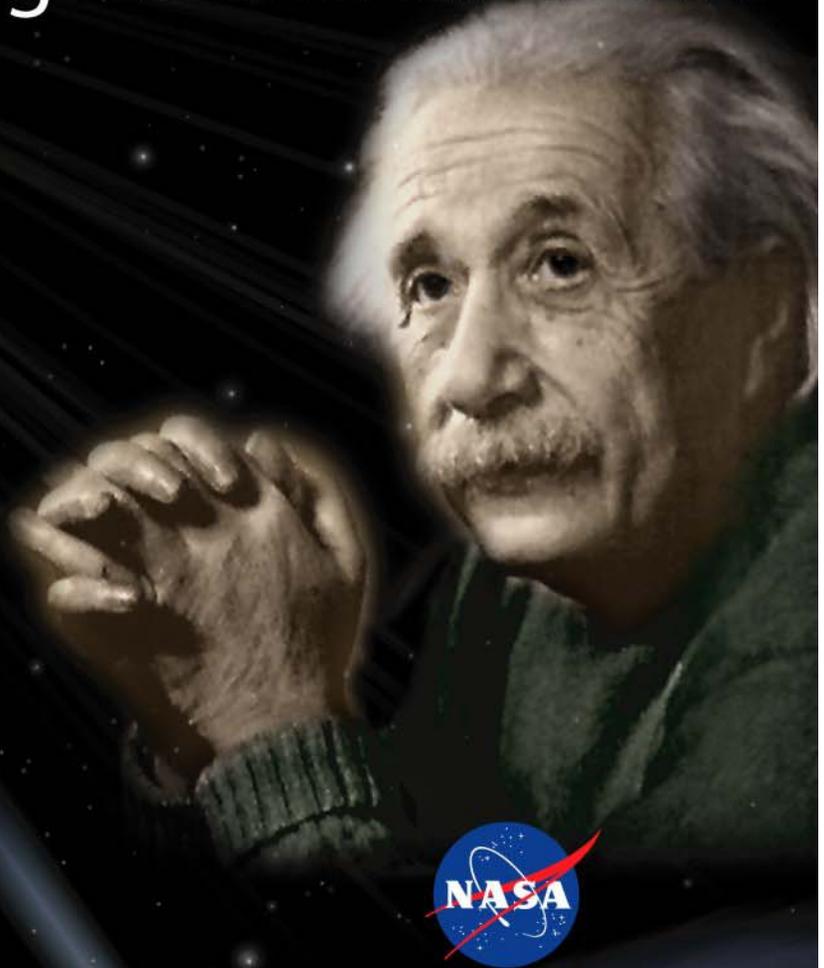
WHAT POWERED  
THE BIG BANG?



WHAT HAPPENS  
AT THE EDGE  
OF A BLACK HOLE?



WHAT IS  
DARK ENERGY?



National Aeronautics and  
Space Administration



# SEU 2003 Roadmap



## SEUS

- Rocky Kolb, Chair (Fermilab)
- Joel Bregman (Michigan)
- Lynn Cominsky (Sonoma State)
- Chuck Dermer (NRL)
- Kathy Flanagan (MIT)
- Tim Heckman (JHU)
- Jackie Hewitt (MIT)
- Dan Lester (Texas)
- Brad Peterson (Ohio State)
- Sterl Phinney (Caltech)
- Simon Swordy (Chicago)
- Nick White (GSFC)
- Ned Wright (UCLA)
- Hal Yorke (JPL)
- Paul Hertz, Exec Sec (NASA)

## Roadmap Team

- \*Sterl Phinney, Chair (Caltech)
- Sean Carroll (Chicago)
- Sarah Church (Stanford)
- \*Kathy Flanagan (MIT)
- Roy Gould (CfA)
- Craig Hogan (Washington)
- Steve Kahn (Columbia)
- \*Dan Lester (Texas)
- Bob March (Wisconsin)
- Mike Shull (Colorado)
- \*Simon Swordy (Chicago)
- \*Nick White (GSFC)
- \*Rocky Kolb, SEUS Chair (Fermilab)
- \*Paul Hertz, Exec Sec (NASA)



## SEU Science

. . . accretion disks, Big Bang, black holes,  
cosmic magnetic fields, cosmic rays, dark energy,  
dark matter, extreme environments, gamma-ray bursts,  
jets, large-scale structure, microwave background,  
neutron stars, nucleosynthesis, relativity,  
supernovae, . . .

$10^{-25}$  cm (UHE Cosmic Rays) to  $10^{15}$  cm (Gravitational waves)

### **Great Decade:**

CMB fluctuations (COBE, BOOMERanG, MAXIMA, MAP, . . .)

Gamma-Ray Bursts (CGRO, HETE-2, Swift, Glast, . . .)

Ubiquity of black holes (Chandra, ASCA, HST, . . .)

**Top priority: Answer the most profound questions  
raised, but not answered, by Einstein.**



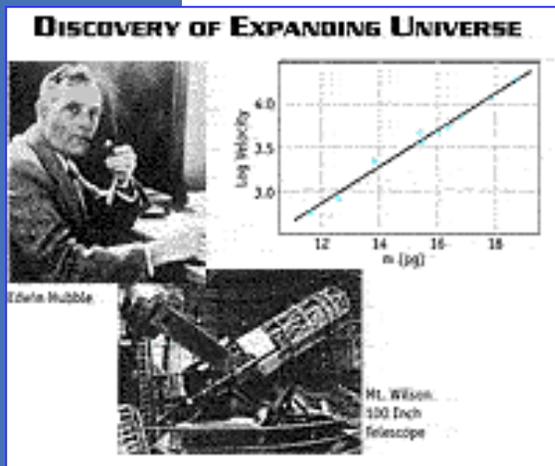
# Einstein's Predictions

Three startling predictions of Einstein's relativity:

- The expansion of the Universe (from a big bang)
- Black holes
- Dark energy acting against the pull of gravity

Observations confirm these predictions . . .

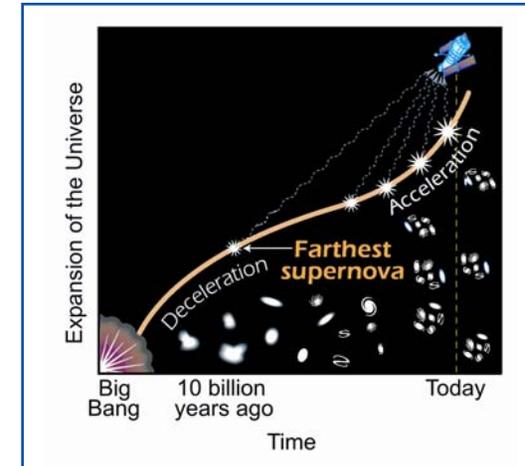
. . . the last only four years ago



Hubble discovered the expanding Universe in 1929



Black holes found in our Galaxy and at the center of quasars over the past three decades



Evidence for an accelerating Universe was observed in 1998



# Completing Einstein's Legacy

*Einstein's legacy is incomplete, his theory fails to explain the underlying physics of the very phenomena his work predicted*

## BIG BANG

**What powered the Big Bang?**

## BLACK HOLES

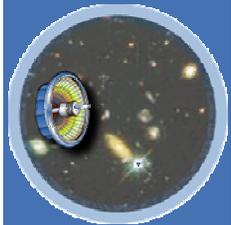
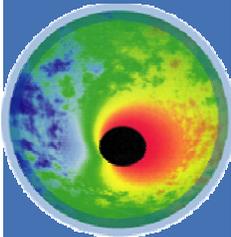
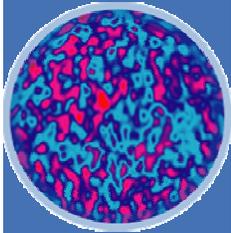
**What happens at the edge of a Black Hole?**

## DARK ENERGY

**What is the mysterious Dark Energy pulling the Universe apart?**

*Beyond Einstein will employ a series of missions linked by powerful new technologies and common science goals to answer these questions ...*

*... and launch the revolution of the 21<sup>st</sup> century!*





# Realizing Science Beyond Einstein

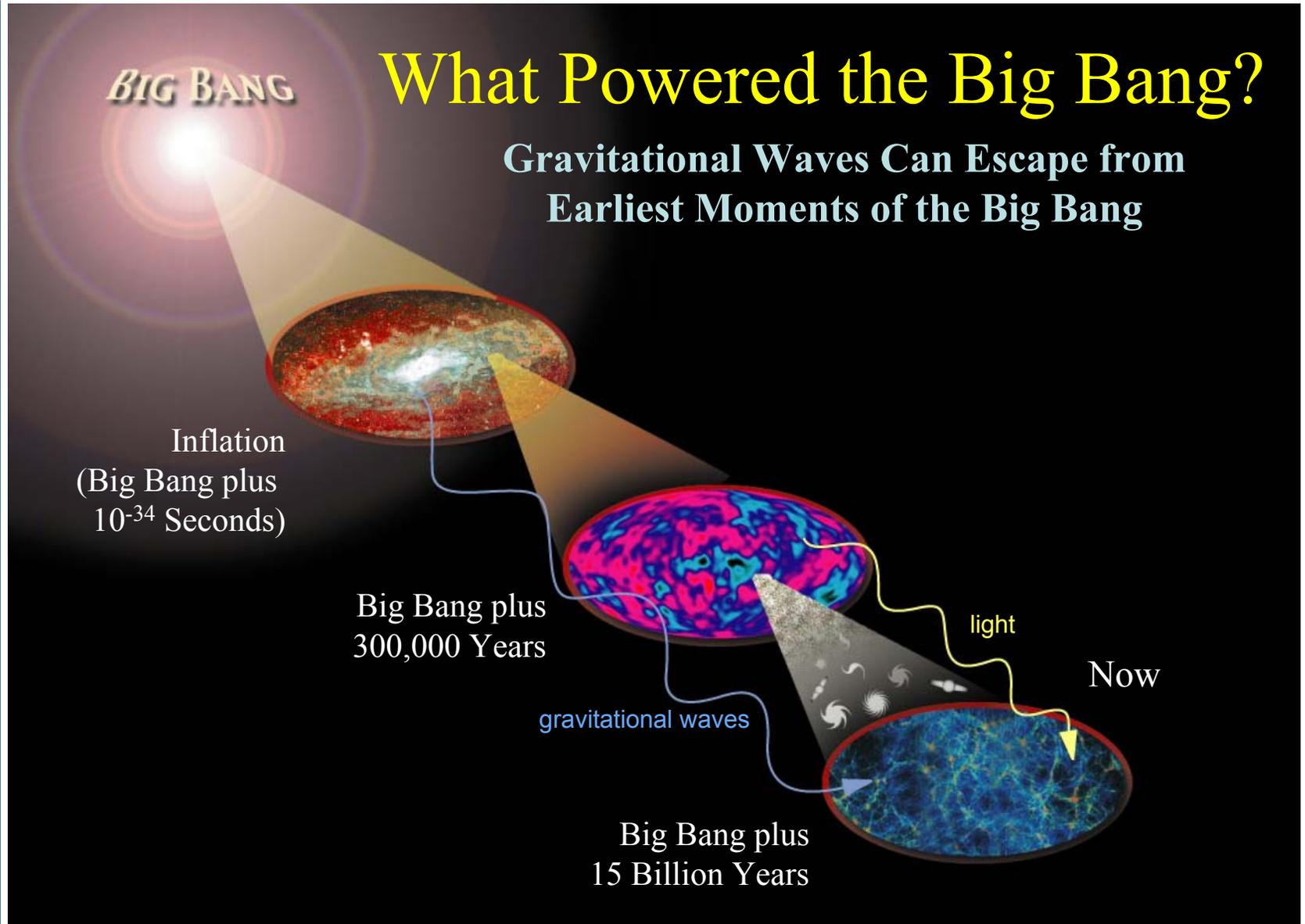
*Three inter-linked elements that work together:*



1. Einstein Great Observatories providing breakthrough increases in capabilities to address all Beyond Einstein science:
  - LISA: Gravitational waves from merging black holes and the early Universe
  - Constellation-X: Spectroscopy close to the event horizon of black holes and place constraints on dark side of the Universe
2. Einstein Probes to address focused science objectives:
  - Determine the nature of the Dark Energy
  - Search for the signature of inflation in the microwave background
  - Take a census of Black Holes of all sizes in the local Universe
3. A technology program, theoretical studies and an education program to inspire future generations of scientists and engineers towards the vision:
  - Directly detect the gravitational waves emitted during the Big Bang
  - Image and resolve the event horizon of a Black Hole



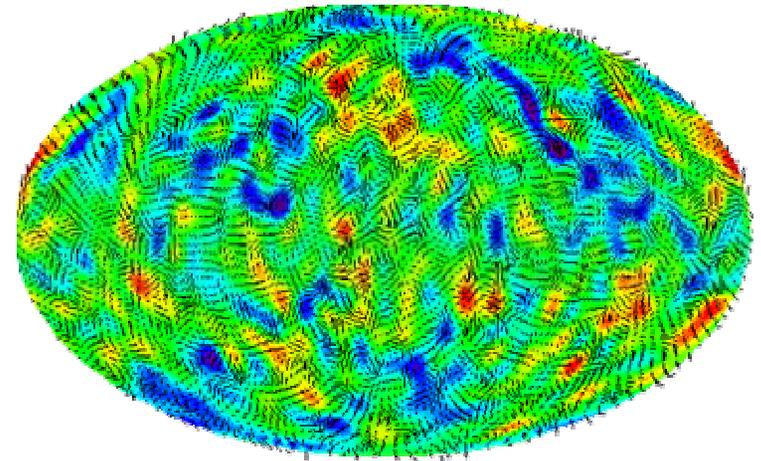
# What Powered the Big Bang?





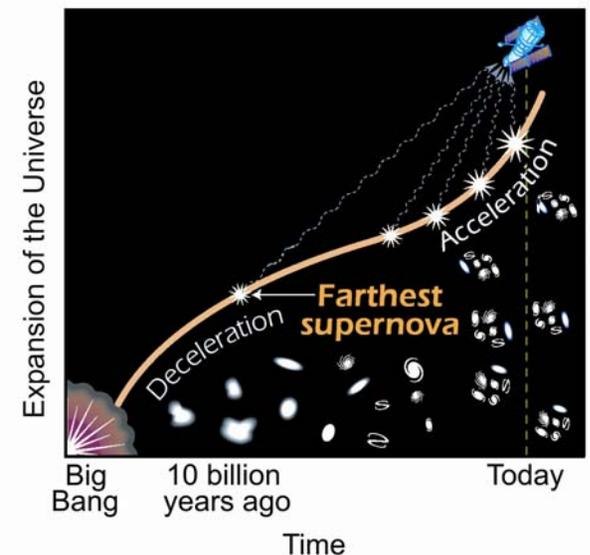
# What Powered the Big Bang?

Gravitational waves leave a distinctive imprint on polarization pattern of CMB



Gravitational waves from inflation and phase transitions may be detected directly

Vacuum energy powered inflation-some form of it may be the “dark energy”



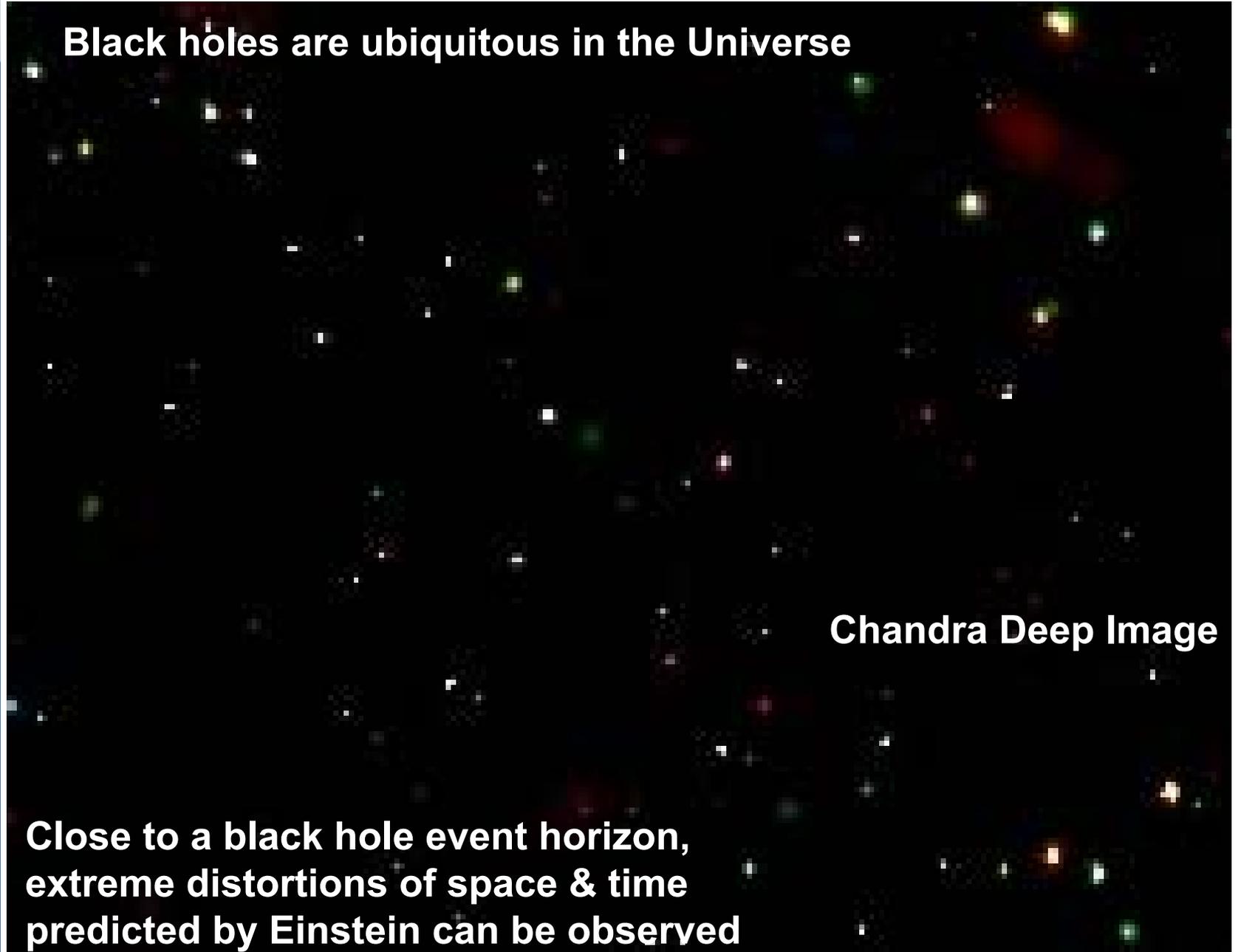


BEYOND EINSTEIN

# What Happens at the Edge of a Black Hole?



**Black holes are ubiquitous in the Universe**

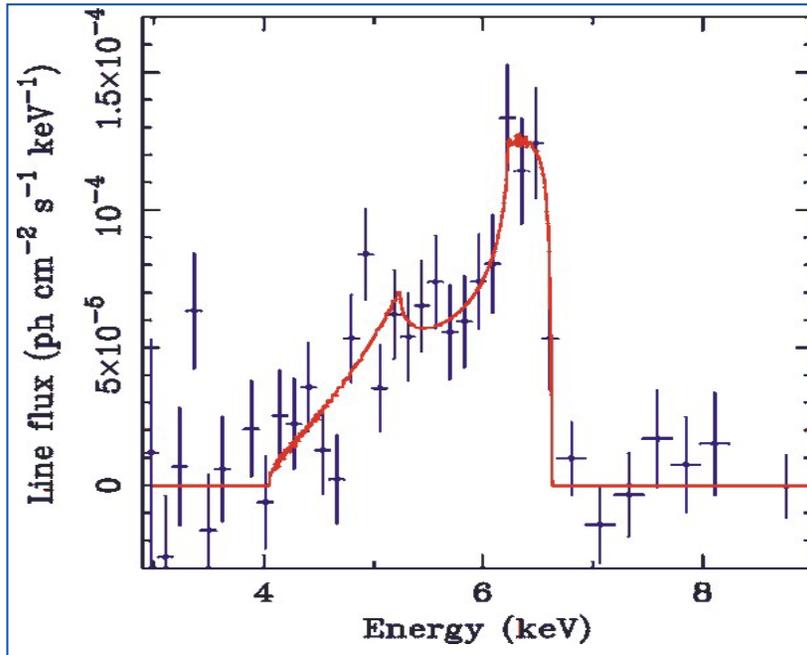


**Chandra Deep Image**

**Close to a black hole event horizon,  
extreme distortions of space & time  
predicted by Einstein can be observed**

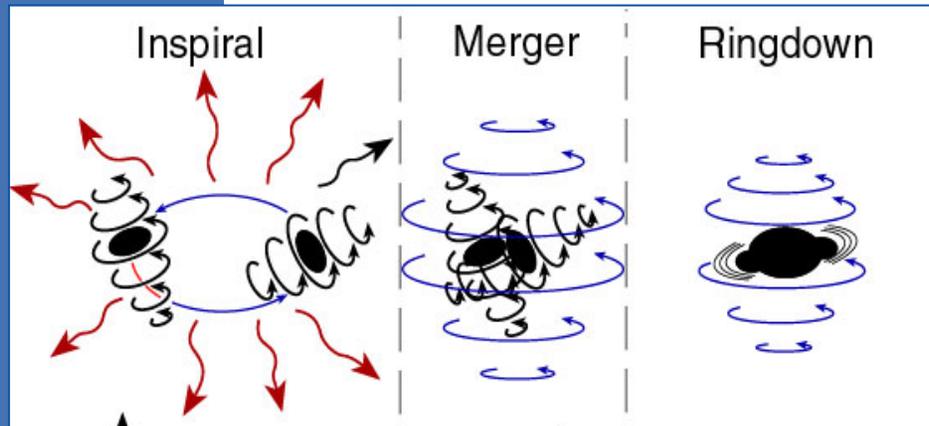


# What Happens at the Edge of a Black Hole?



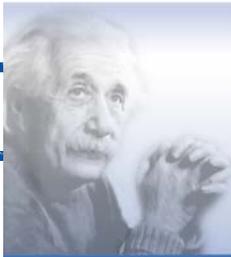
## X-Ray Spectroscopy

- Japan-US ASCA satellite discovered iron lines near the event horizon of a black hole
- Line exhibits a strong redshift and provides a unique probe of the inner regions of black holes



## Gravitational Radiation

- Black hole binaries produce gravitational waves in all phases of their evolution
- Test of GR in all three phases

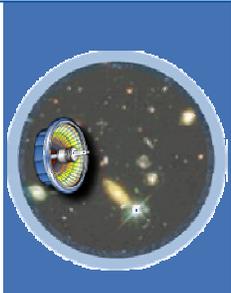
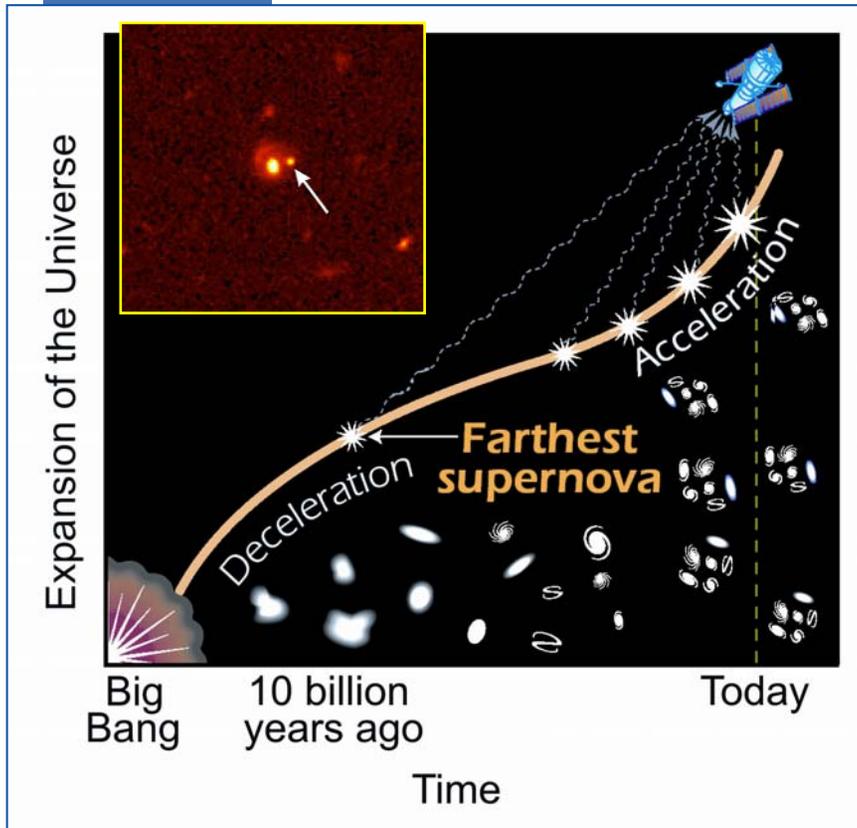


# What is the Dark Energy?

Einstein introduced the Cosmological Constant to explain what was then thought to be a static Universe, “*my biggest mistake . . .*”

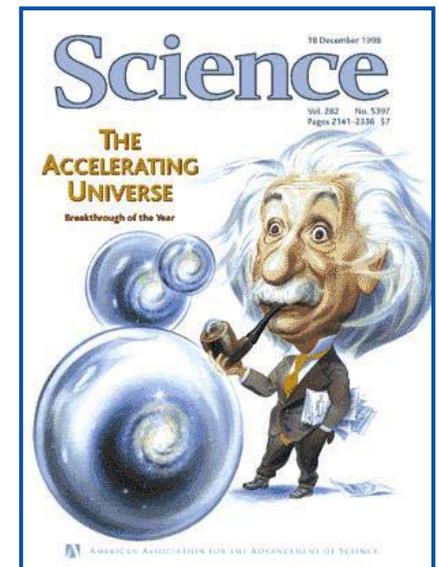
A surprising recent discovery has been the discovery that the expansion of the Universe is accelerating.

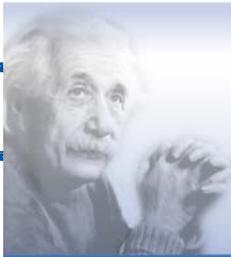
Implies the existence of *dark energy* that makes up 70% of the Universe



Dark Energy maybe related to Einstein’s Cosmological Constant; its nature is a mystery.

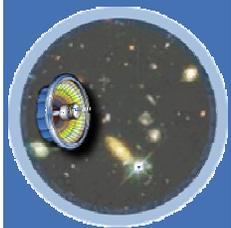
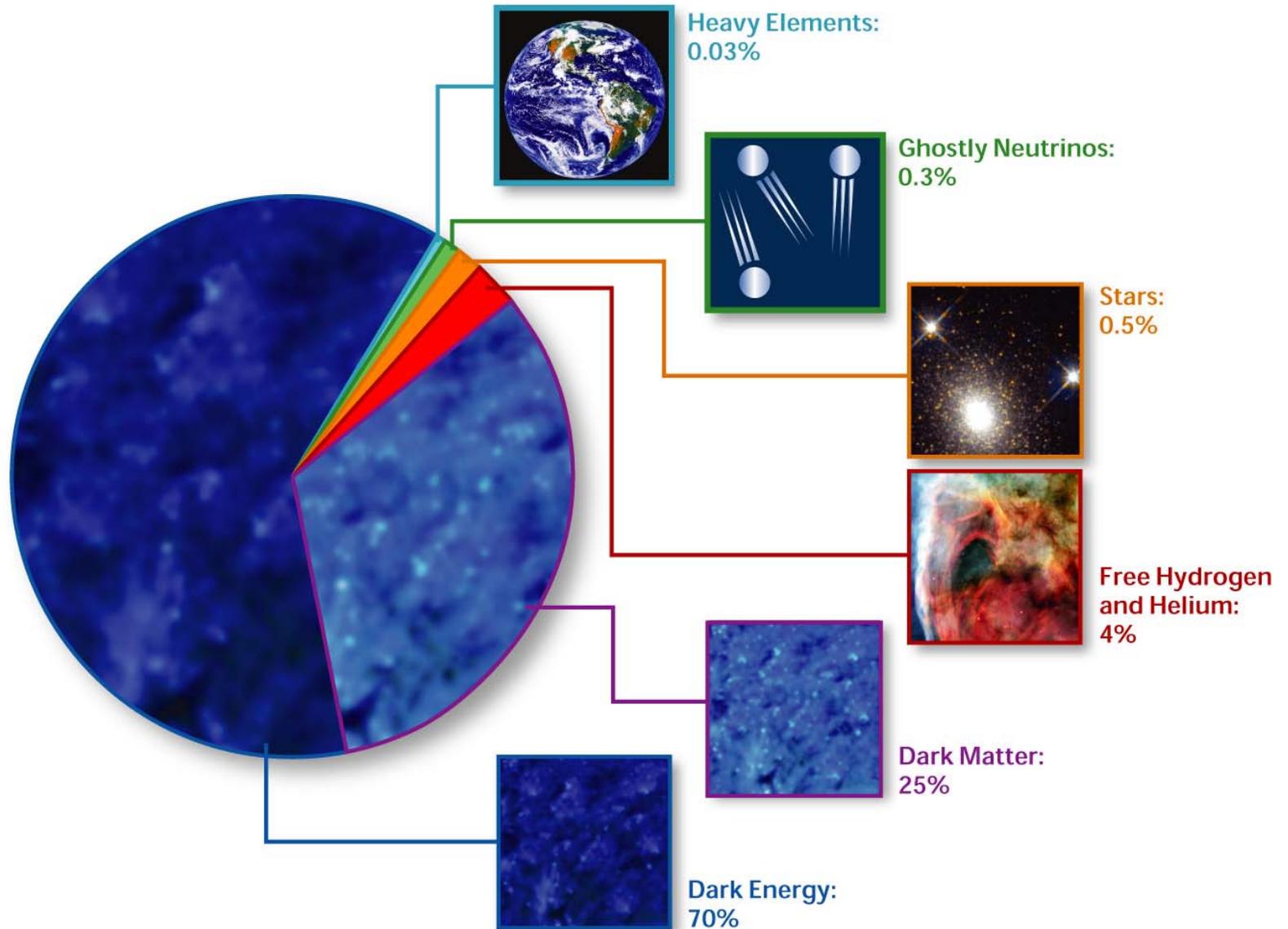
Solving this mystery may revolutionize physics . . .





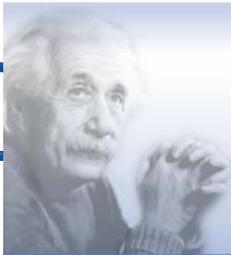
# What is the Dark Energy?

We do not know what 95% of the universe is made of!

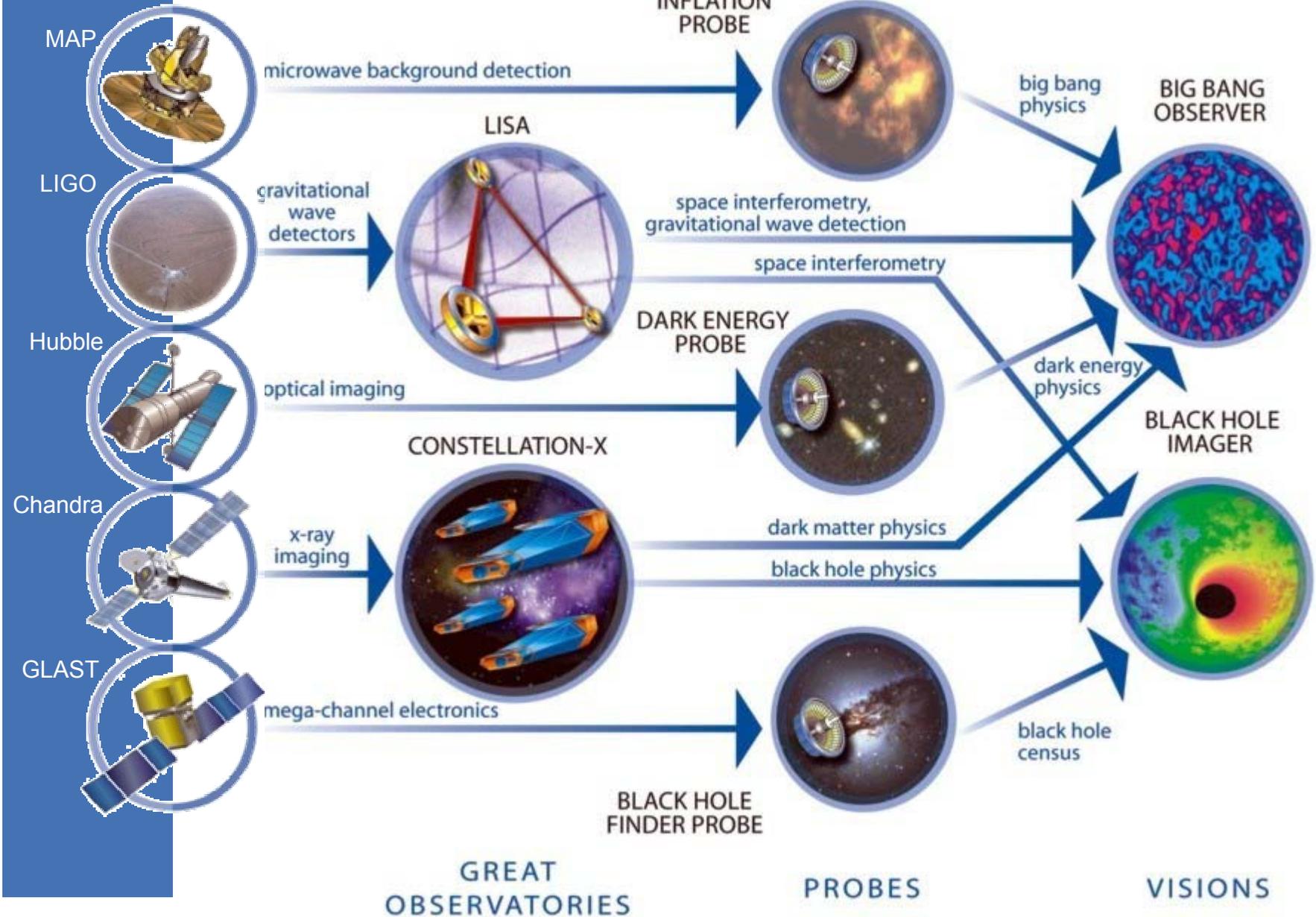


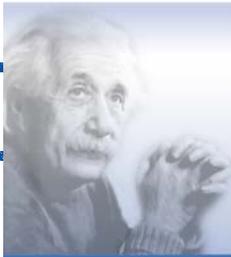


# Beyond Einstein Program



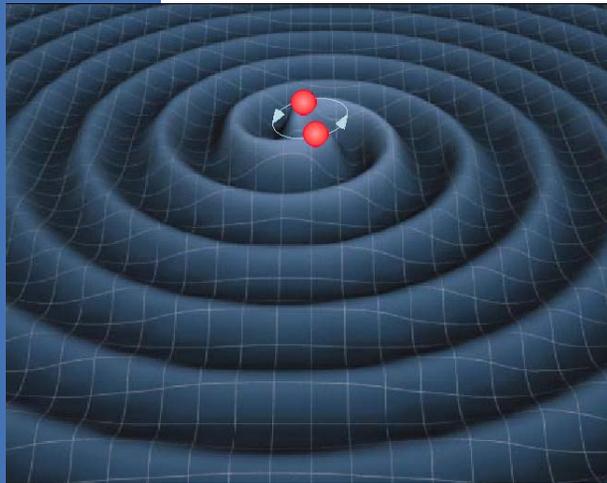
Science and Technology Precursors



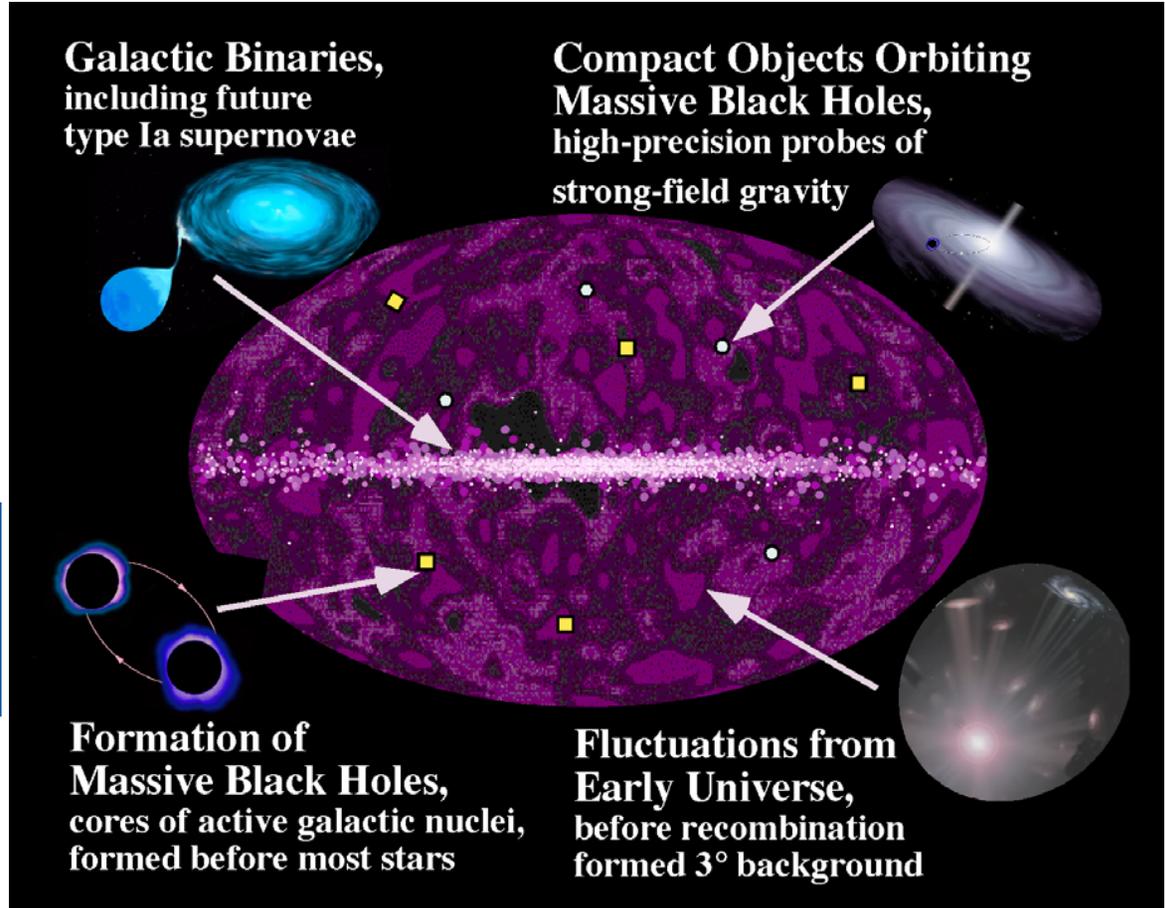
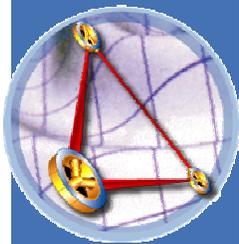


# Gravitational Wave Astronomy

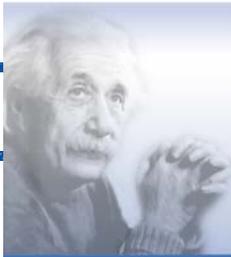
Black holes, neutron stars, and white dwarfs orbiting each other emit gravitational waves



Gravitational radiation from black hole mergers can be used to test General Relativity



The real voyage of discovery consists not in seeing new landscapes, but in having new eyes. - Marcel Proust



BEYOND EINSTEIN

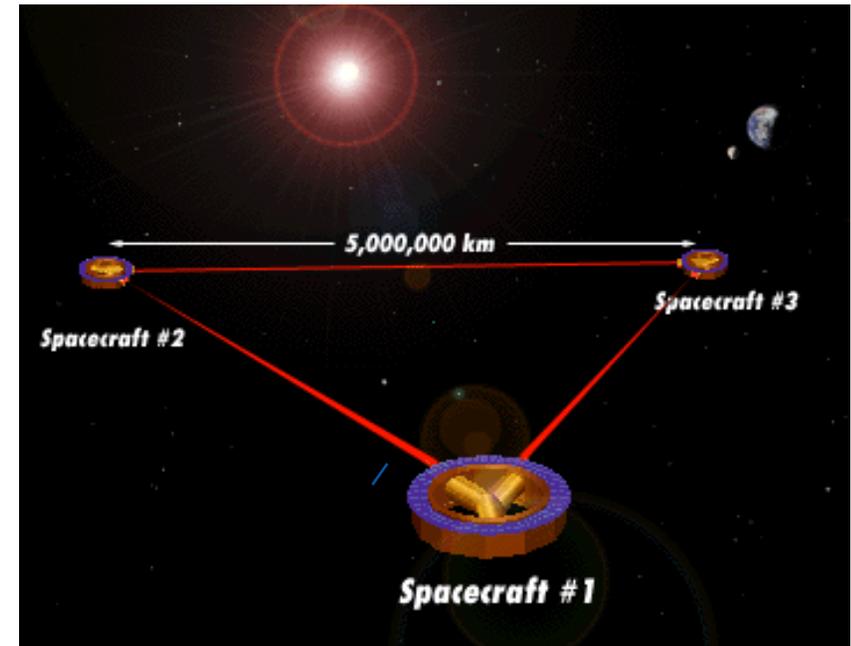
# Laser Interferometer Space Antenna (LISA)



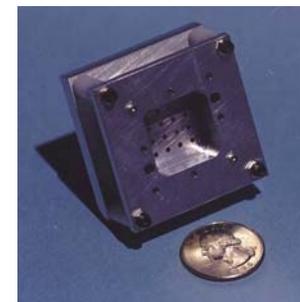
Joint ESA-NASA project

LISA uses a laser based Michelson interferometer to monitor the separation between proof masses in separate spacecraft

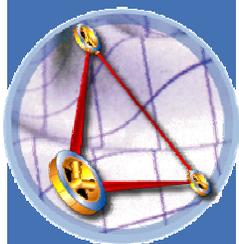
- Three spacecraft separated by 5 million km
- Each spacecraft includes two freely falling test masses with drag free operation
- Distance changes measured with precision of 4 ppm RMS over 100 seconds



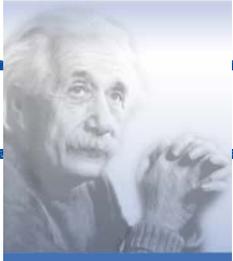
Flight demonstration of disturbance reduction system ST-7 on ESA SMART-2 mission in 2006



micro-newton thrusters



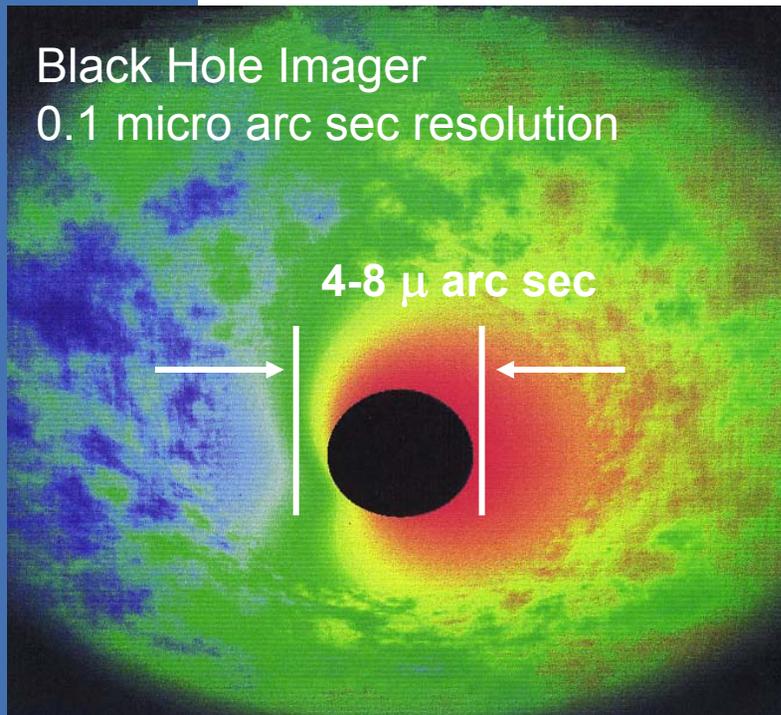
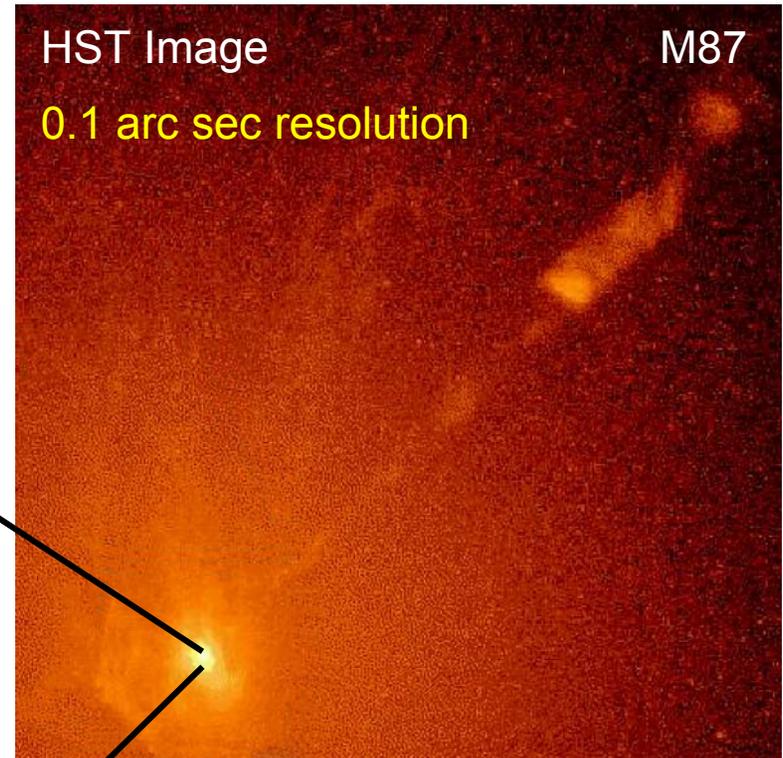
LISA, the first space-based gravitational wave antenna, was given strong endorsement by US National Academy of Sciences McKee-Taylor and Turner Committee Reports



# Image a Black Hole!

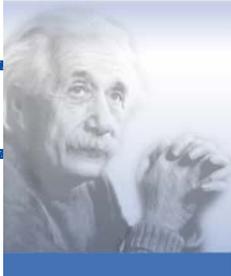
Hubble, Chandra, and other observatories are showing black holes are common place in the Universe

Black holes provide a unique laboratory to test Einstein's theory of gravity



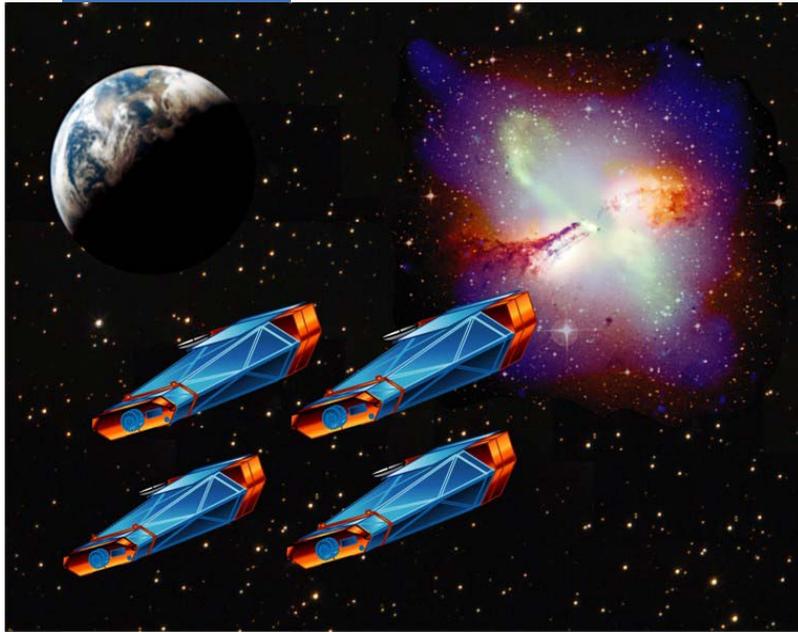
A future black hole imager with a resolution one million times Hubble will observe the effects Einstein predicted

X-ray emission from close to the event horizon provides a powerful probe



# Constellation-X

## Use X-ray spectroscopy to observe



- **Black holes:**
  - Probe close to the event horizon
  - Evolution with redshift
- **Dark side of the Universe:**
  - Clusters of galaxies and large-scale structure
- **Production and recycling of the elements:**
  - Supernovae and interstellar medium

- **25-100 times sensitivity gain for high resolution spectroscopy in the 0.25 to 10 keV band**
- **Four satellites at L2 operating as one with advanced X-ray spectrometers**

*Enable high resolution spectroscopy of faint X-ray sources*

**Constellation-X given strong endorsement by  
US National Academy of Sciences  
McKee-Taylor and Turner Committee Reports**

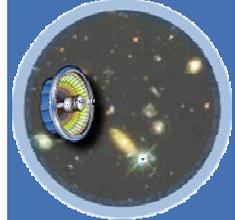
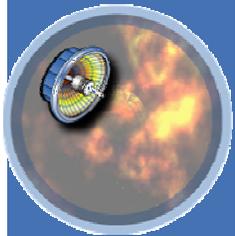




# Einstein Probes

**Three focused missions, each designed to address a single high priority science question**

- **Priority and science topic determined via NASA strategic planning process, using National Academy recommendations**
  - **Dark Energy Probe**
  - **Inflation Probe**
  - **Black Hole Finder Probe**
  
- **Competed Principal Investigator missions**
  - **Implementation approach determined by peer review**
  - **Launched every 3-4 years**
  - **\$350-500M class missions**





## National Research Council Endorsements

### Astronomy & Astrophysics in the New Millennium 2001 Decadal Survey (McKee-Taylor)

#### Major Initiatives:

1. NGST
2. Constellation-X Observatory
3. Terrestrial Planet Finder
4. Single Aperture Far Infrared Observatory

#### Moderate Initiatives

1. Gamma-ray Large Area Space Telescope
2. Laser Interferometer Space Antenna
3. Solar Dynamics Observatory
4. Energetic X-Ray Imaging Survey Telescope
5. Advanced Radio Interferometry Between Space & Earth



## National Research Council Endorsements



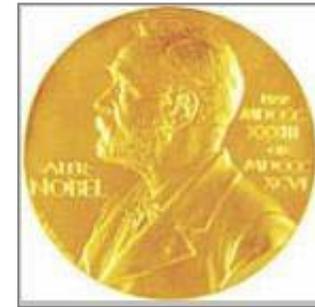
### Connecting Quarks with the Cosmos 2002 (Turner) Not a priority list.

- Measure the polarization of the CMB
- Determine the properties of dark energy
- Use space to probe basic laws of physics  
(Con-X, LISA)
- (Highest energy cosmic rays)
- (High-energy-density physics)
- (Interagency Initiative)
- (Neutrino masses)



## Other Endorsements

### Royal Swedish Academy of Sciences 2002 Nobel Prize in Physics



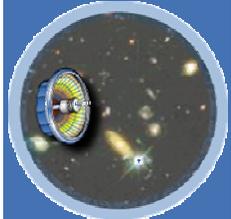
Riccardo Giacconi

*“for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources”*

Hulse & Taylor (1993); Fowler & Chandrasekhar (1983);  
Penzias & Wilson (1978); Hewish (1974); Hess (1936);  
Einstein (1921)



# Beyond Einstein Timeline



RESEARCH AND ANALYSIS

TECHNOLOGY DEVELOPMENT

EDUCATION AND PUBLIC OUTREACH

FIRST EINSTEIN GREAT OBSERVATORY

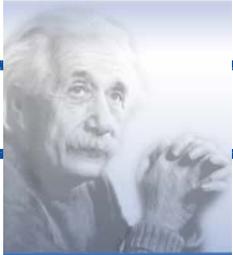
FIRST EINSTEIN PROBE

SECOND EINSTEIN GREAT OBSERVATORY

SECOND EINSTEIN PROBE

THIRD EINSTEIN PROBE





## Education and Public Outreach

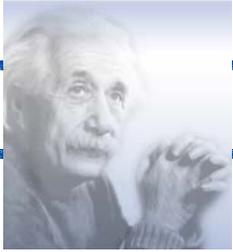


Big Bang and black holes capture the imagination and can be used to teach physical science at all levels

Beyond Einstein will address the national education priority by inspiring future generations of scientists and engineers, as only NASA can . . .



Children on the Einstein statue at the National Academy of Sciences in Washington, DC, remind us that there is no more important task before us than education and inspiration.



BEYOND EINSTEIN

# The 21<sup>st</sup> Century



How did the Universe begin? Does time have beginning & an end? Does space have edges? The questions are as old as human curiosity. But the answers have always seemed beyond the reach of science. . .

*until now!*