Panel A / Chapter 2
Extremes of the Universe

23 January 2007

- Science Questions
  - Overview of observables & techniques for each
- Recommendations
- Community input and Iterating the draft SV

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Science Questions

- How did the Universe begin?
- What is dark matter and dark energy?
- Can we observe strong gravity in action?
- How do supernovae and gamma-ray bursts work?
- How do black hole accretion, jets and outflows operate?
- What do we learn about the Universe from energetic radiation and particles?

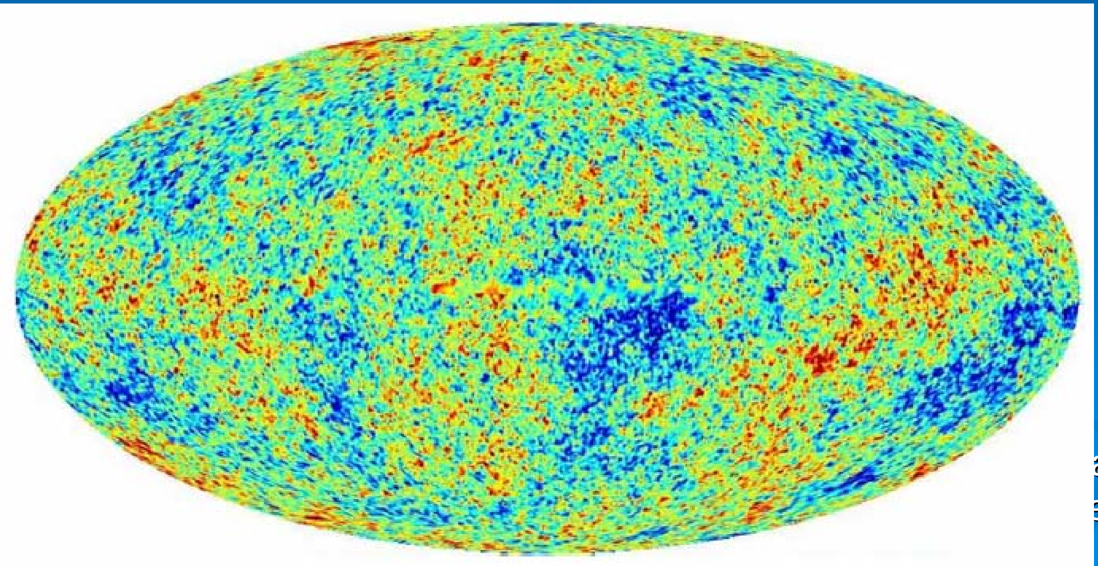
Broadest range of the panels:

Standard physics in exotic settings

But also the universe as a laboratory for new physics

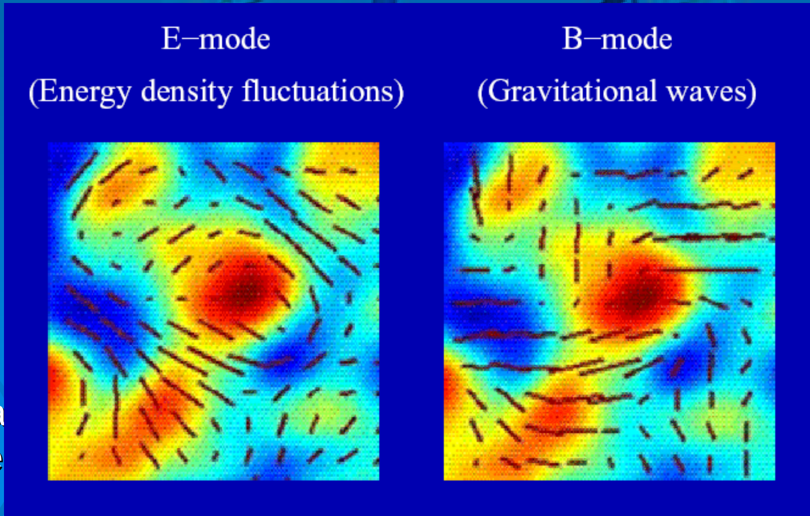
1: How did the Universe begin?

- Need a natural mechanism for a universe that
  - Expands and is nearly flat and homogeneous
  - Contains the seeds of future structures
- Inflation with scalar fields, M theory, or what?



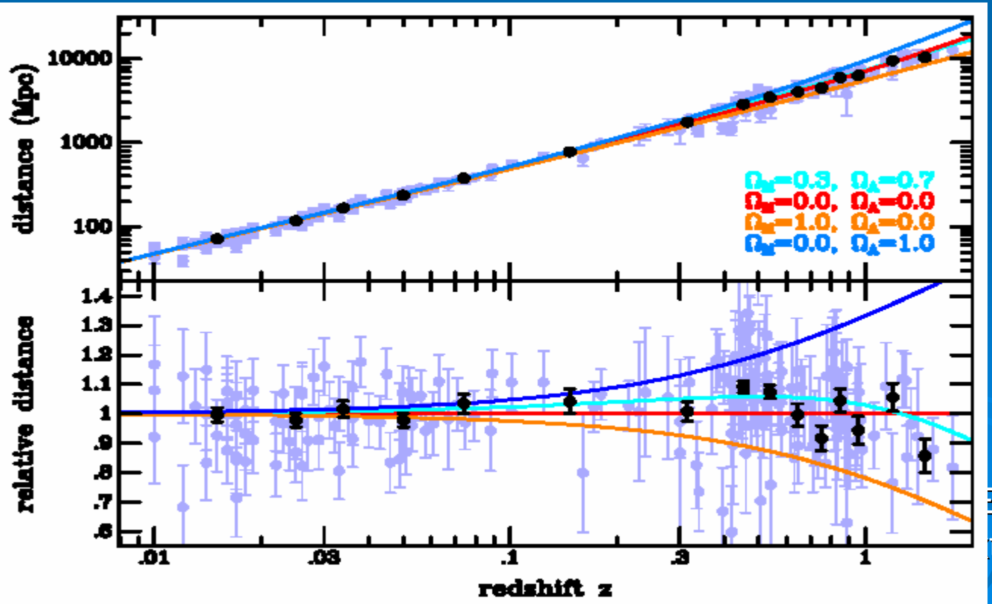
Observables and techniques

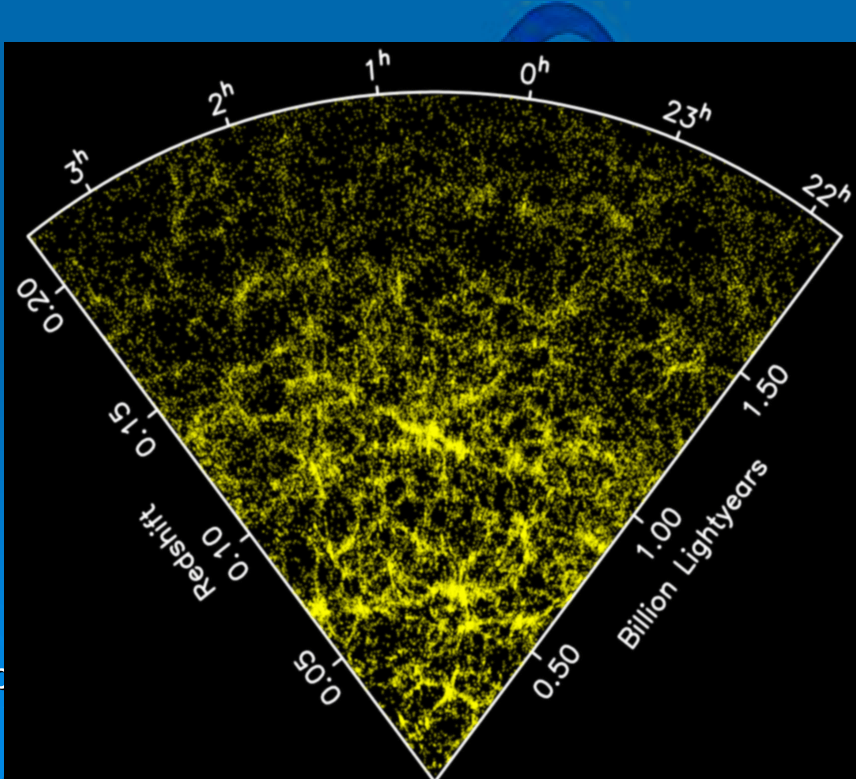
- Primordial signatures:
  - slope of P[k] (='tilt') + possible gravity waves
  - possible topological defects and other non-Gaussian signals (relic particles: next question)
- Experiments:
  - CMB polarization gives clean tensor detection / limit (needs to be all-sky). Aim to reduce curent tensor fraction limits of ~30% to 1%
  - Firm up current 2-3σ indications that n<1. Needs complementary data to CMB, as for Dark Energy



2: What is dark matter and dark energy?

- Multiple lines of evidence for DM & DE
  - DM: galaxy/cluster dynamics, lensing, LSS
  - DE: CMB/LSS, SNe, Clusters
- Assuming GR to be correct





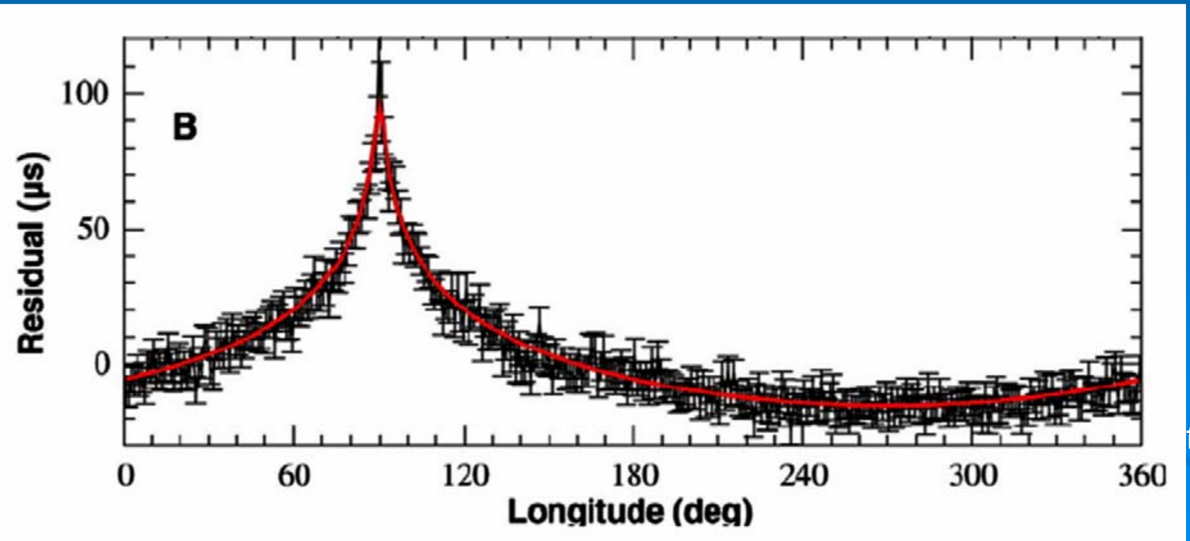
Observables and techniques

- DM: ideal is direct relic detection and LHC generation, if SUSY relic
  - Also γ-ray / ν / CR signatures of annihilation
- DE: cosmological constant, evolving, or failure of GR? Test by measuring evolution of density and LSS fluctuation amplitude. Large-scale surveys needed
  - Gravitational lensing
  - LSS as standard ruler (BAO)
  - Clusters (mass function; baryon fraction)
  - SNe as standard candles

  } Focus on independent measurements of $w(z) = P / \rho c^2$
- DE also connects to tests of non-standard physics: precision tests of GR, variability of fundamental constants

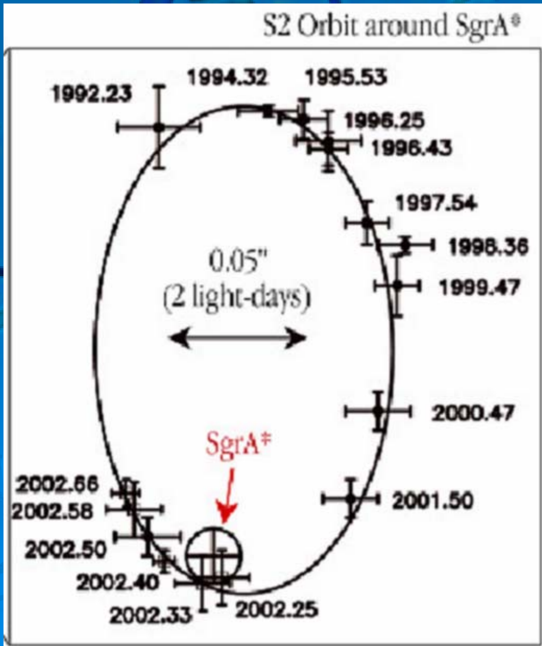
3: Can we observe strong gravity in action?

- Testing GR and limiting alternatives using post-Newtonian relativistic systems
- Probing strong-gravity effects
  - Horizon-scale objects (neutron stars; accretion disks)
  - Gravitational waves from BH mergers



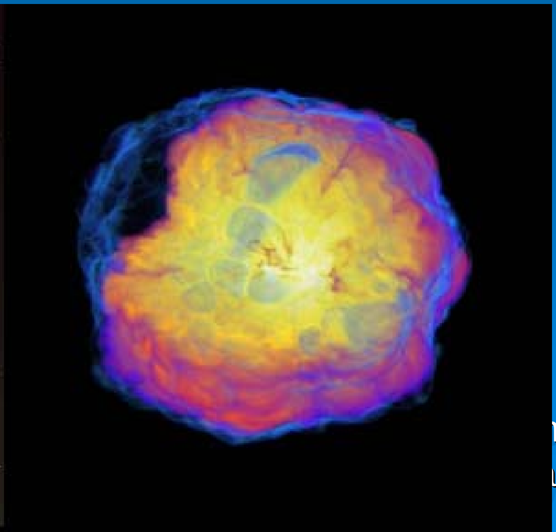
Observables and techniques

- Relativistic orbits
  - Galactic centre; new multiple pulsars
- Can we see near to event horizons?
  - Resolution feasible via VLBI or submm or near-IR interferometry
  - Fe 6.5-keV lines as diagnostic of gravitational redshift
- Gravitational waves
  - kHz from n-star mergers (ground-based)
  - milli-Hz from BH mergers (space)



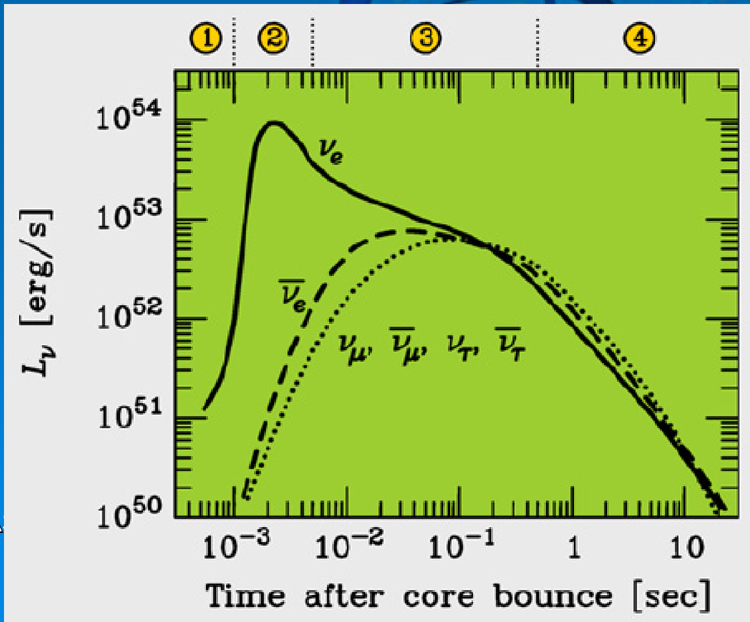
4: How do supernovae and gamma-ray bursts work?

- Need a better knowledge of progenitor stars
  - Relation of SNe & GRBs
- Need a full understanding of explosion physics
  - High-temperature nuclear equation of state
  - Neutrino radiative transfer
  - GR magnetohydrodynamics



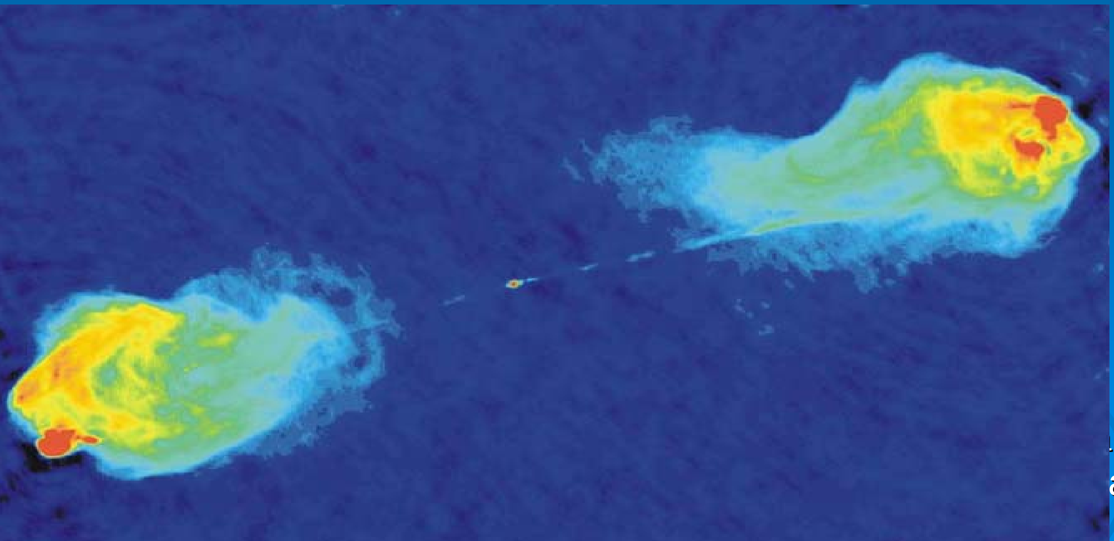
Observables and techniques

- Need high-resolution deep imaging to pick out progenitors of non-local SNe
- Need deep spectroscopy for faint high-z explosions
- Need deep continuum light curves in X-ray to radio to diagnose shock propagation
- Internal structure of explosions from neutrino observatories
- Confrontation with new supercomputer calculations



5: How do black hole accretion, jets and outflows operate?

- Ubiquity of directed outflows on all scales
- Need to understand coupling of jet and disk
  - Turbulence, magnetic field, radiative transfer
- Increasing appreciation of importance of environmental impact

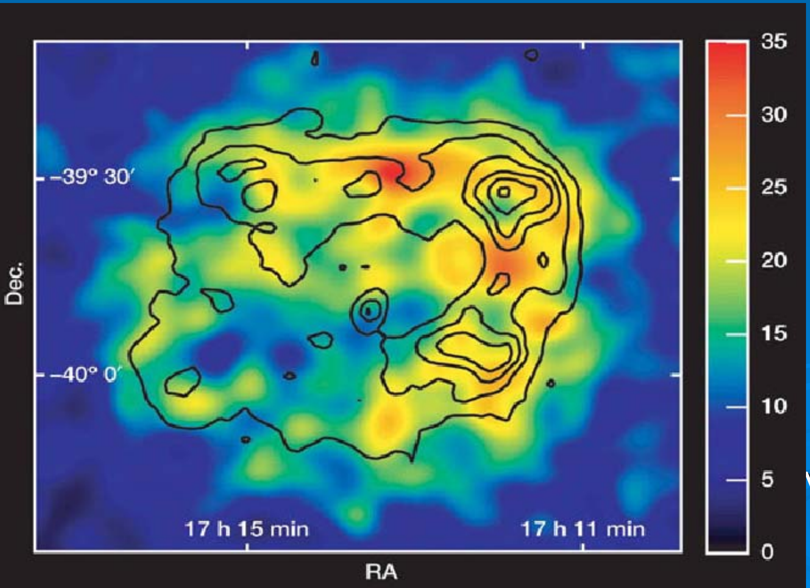


Observables and techniques

- High-resolution imaging and correlations with multifrequency data (and non-EM tracers)
- Time-domain studies important aspect
  - Studying outbursts
  - Monitoring large areas to find new outbursts
- Again, detailed simulations are essential for understanding jet origin (MHD turbulence and radiative transfer)

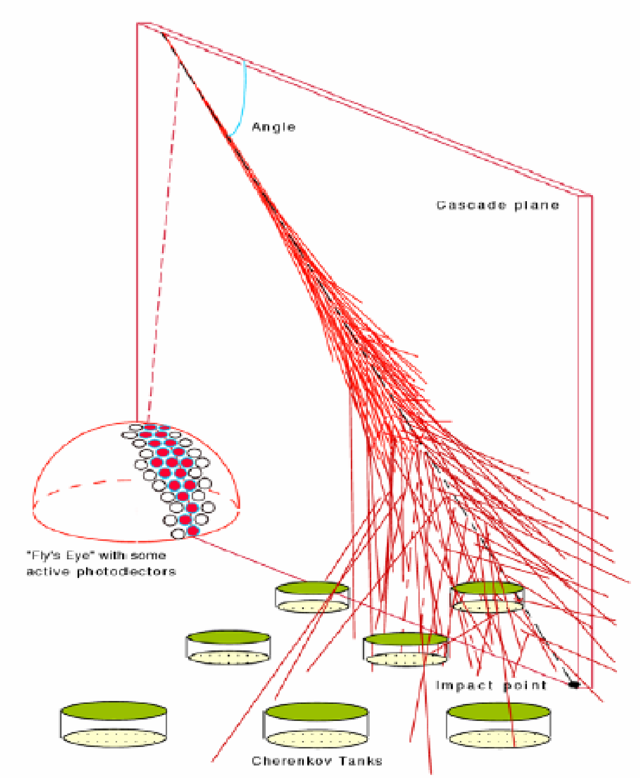
6: What do we learn about the Universe from energetic radiation and particles?

- New astronomy windows from CR (and soon from high-energy neutrino telescopes)
- Acceleration of highest-E CR still a challenge
  - Is synchrotron emission from pair plasma?
  - Are there super-GZK events at > 10^{20} eV?



Observables and techniques

- Large Cerenkov arrays can probe distribution and acceleration of most energetic particles in cosmic sources
- Large air-shower detectors will measure (or refute) GZK cutoff
- Under-sea (or –ice) neutrino telescopes of km^3 volume can begin source detections, and galactic centre DM annihilation



Recommendations: key science goals

- Measure the evolution of the dark-energy density with cosmological epoch, to search for deviations from a cosmological constant
- Using independent probes that are sensitive to dark energy in complementary ways, test for a consistent picture of dark energy – thus verifying general relativity or establishing the need for a replacement
- Measure the polarization of the microwave background at 10-degree scales, to search for the signature of relic gravitational waves
- Produce direct detections of astrophysically-generated gravitational waves, to measure strong-gravity effects – in particular black-hole coalescence
- Make direct images of the regions near the event horizon of supermassive black holes in galactic nuclei, to understand how large-scale relativistic jets are launched
- Understand the astrophysics of compact objects and their progenitors, particularly the functioning of the supernova explosion mechanisms
- Understand the origin and acceleration mechanism of cosmic rays and neutrinos, especially at the highest energies

Recommendations:
Requirements for principal facilities

- An optical / infrared multi-colour imaging survey across a major fraction of the sky for tests of dark energy: gravitational lensing, baryon oscillations in redshift shells, and new supernova samples. Near-infrared photometry is essential, and imaging in space offers huge advantages. Space-based optical imaging will also offer high image fidelity over an extremely wide field
- Beyond ESA's Planck, need to measure the polarization signal, sensitive to primordial gravitational waves from inflation. This effect is potentially detectable by Planck, according to simple inflation models combined with data from WMAP satellite. A next-generation polarization satellite would probe this signature in detail, providing a direct test of the physics of inflation and thus of the fundamental physical laws at energies ~ 10^{12} times higher than achievable in Earth-bound accelerators

Recommendations:
Requirements for principal facilities

- An additional method of probing the earliest phases of cosmology is to look for primordial gravitational waves at much shorter wavelengths. The space interferometer LISA has the potential to detect this signature by direct observation of the gravitational-wave background
- Studies of astrophysical gravitational waves are also of great importance, since they are expected to arise from some of the most extreme environments imaginable, such as the merging and coalescence of two black holes
- To determine the origin of high-energy cosmic rays will require huge air shower arrays and air fluorescence detectors, as well as Cerenkov and radio detectors for high-energy neutrinos employing very large volumes of water and ice. The next generation gamma-ray air Cerenkov telescopes will improve understanding of the acceleration of relativistic particles in supernova remnants and active galactic nuclei

Recommendations
Requirements for secondary facilities

- Emission processes close to the inner edge of black hole accretion flows can be probed by future X-ray and gamma-ray satellites, and also by large submillimetre interferometers. This will require missions with large collecting area, such as GLAST and XEUS / Constellation-X. Such experiments can also probe the nature of dark matter, by searching for the annihilation between dark particle-antiparticle pairs
- Some probes of cosmological geometry are also possible using an extremely large radio telescope at centimetre wavelengths. Improved tests of General Relativity can be expected from large samples of new pulsars from the proposed SKA, which will address many astrophysical problems: cosmic reionization to the formation of galaxies, stars, black holes, and magnetic fields

Recommendations

Requirements for secondary facilities

- Fundamental cosmology needs spectroscopic classification of high-z supernovae, and also hyper-accurate quasar spectroscopy, leading to limits on fundamental constants. Detailed quasar spectroscopy can also search for a coherence length in the dark matter distribution, and measure directly the acceleration of the Universe. The understanding of supernovae, as well as their connection to GRBs, needs detailed spectroscopic observations in the optical and near infrared of the debris. All the above require an optical / infrared telescope of significantly larger collecting area than is currently available
- Substantial high-performance computing facilities will be mandatory, both for the analysis of the extensive observational data, and for the careful comparison between these datasets and detailed predictions from theory and simulations (supply of postdocs is not to be neglected)

Iterating the science vision

- Known issues with web draft SVWG report:
  - Insufficient emphasis on power of X-ray telescopes
    - Strong-gravity tests should count as principal facility
    - X-ray surveys and clusters as geometrical probes
  - Insufficient emphasis on power of VLBI (esp. mm)
  - Need stronger cross-linkage with particle astrophysics studies (APEC)