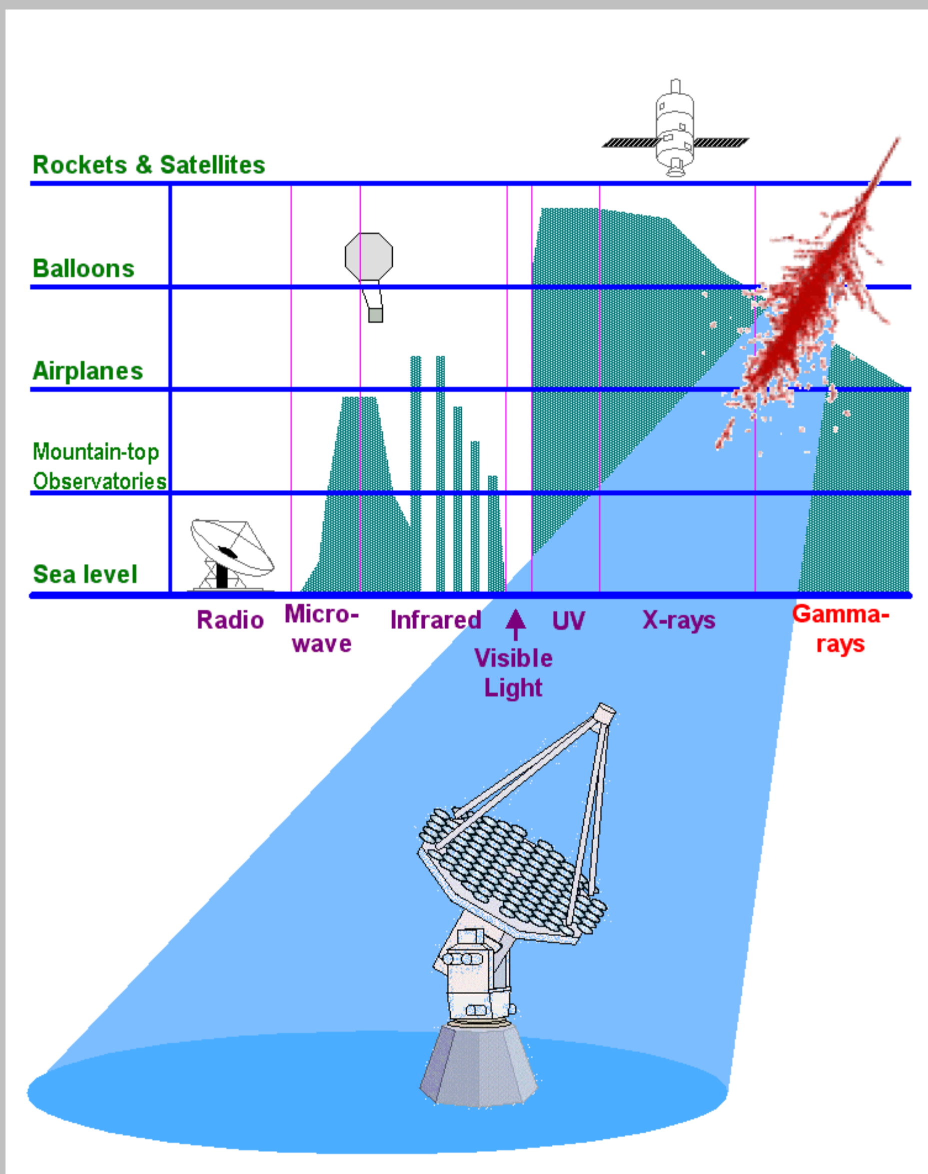
Study of Celestial Objects with Very High Energy Gamma Rays

CANGAROO III

Project Description

— Collaboration between Australia and Nippon for a GAmma Ray Observatory in the Outback —



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Observation site: International Astrophysical Observatory, University of Adelaide, Woomera, Australia

We Explore the Frontier of "High Energy Universe"

- Gamma (γ) rays are the highest energy band of electromagnetic radiation; located at the shortest wavelength and having a "particle (*i.e. photon*) nature" in its interaction with energetic particles, rather than behaving as "wave".
- The energy $\approx 10^{12}$ eV of gamma rays we observe corresponds to, if translated to temperature, more than 10^{15} degrees Kelvin, a number of orders magnitude exceeding the temperature of their environments.
- Gamma ray photons provide the means to study "High Energy Objects", most violent phenomena in the present Universe as examples shown in Figure 1, where protons and electrons are accelerated to energies much higher than available by man-made accelerators.
- The ground-based technique has opened a window of seeing very high energy gamma rays in the region by about two decades of energy exceeding that of satellite detection. Figure 3 demonstrates the recent rapid growth of gamma-ray astronomy.
- In this project we are constructing a system of four 10m telescopes in Woomera, South Australia to open a new era of exploring the "High Energy Universe".

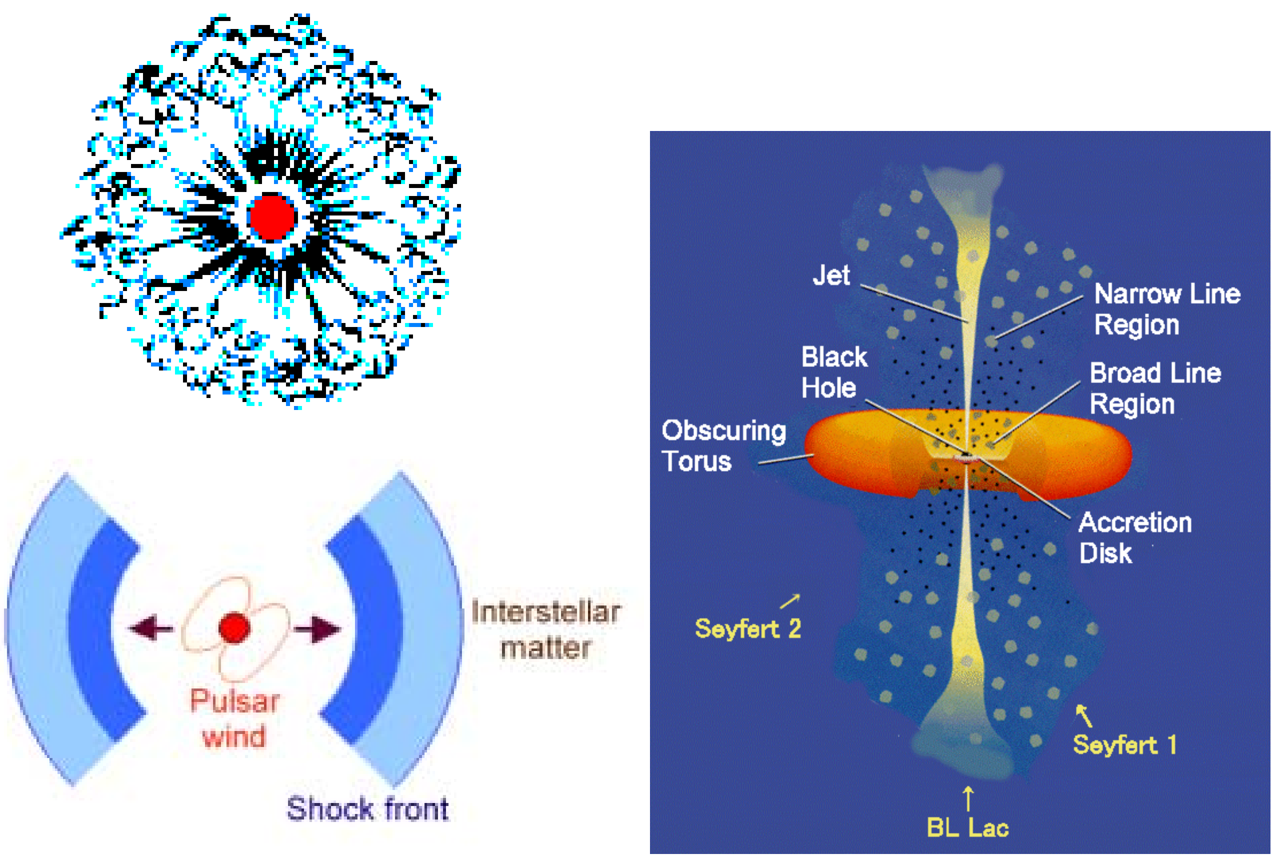


Figure 1. A schematic figure of a supernova (top left), a pulsar nebula (bottom left), and a unified model of AGN (right).

The Gamma-ray Window to the Universe has been opened !

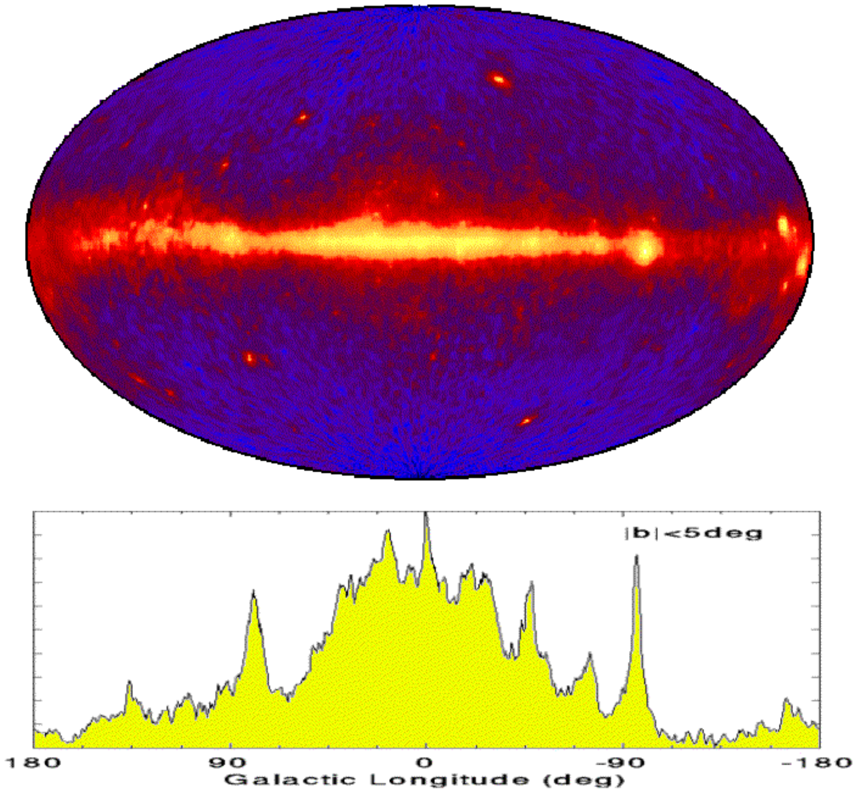


Figure 2. Gamma-ray sky observed by the EGRET detector on board the Compton gamma-ray satellite.

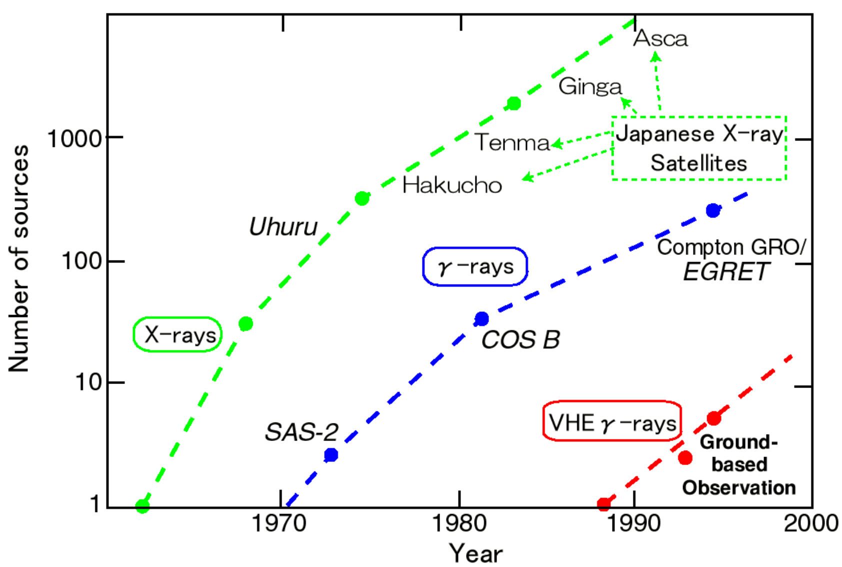


Figure 3. X-ray and gamma-ray source population with time. A number of X-ray and gamma-ray satellites are listed.

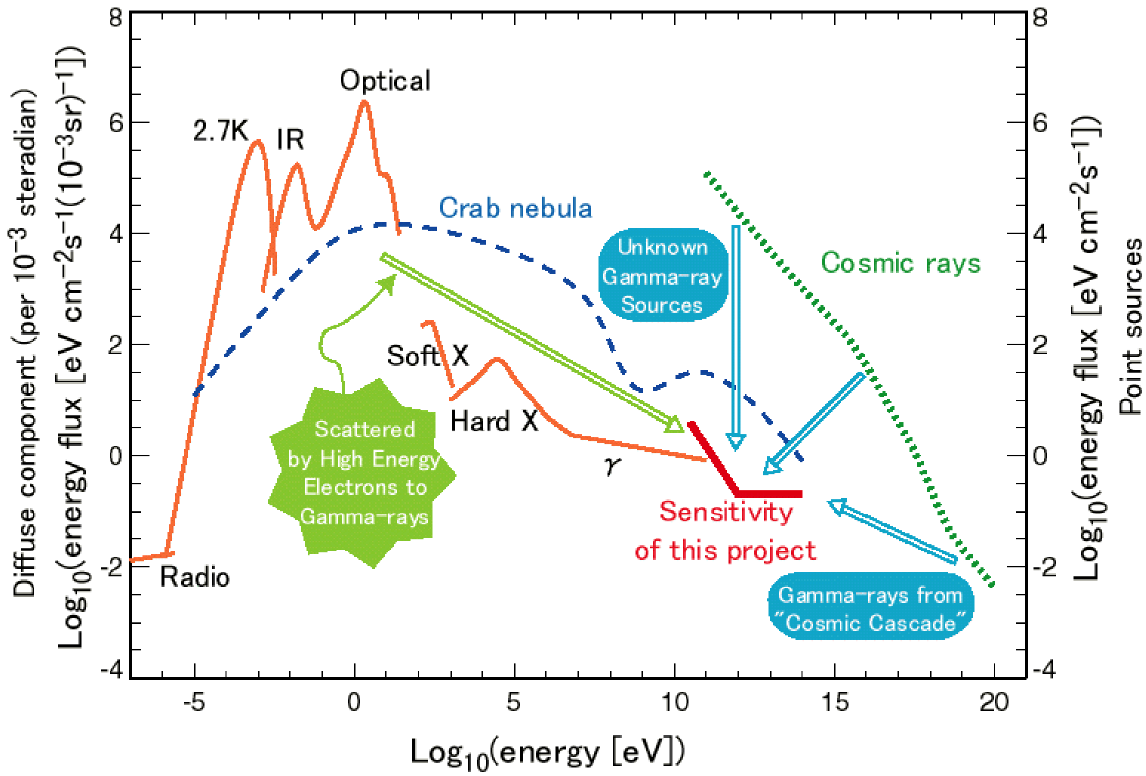


Figure 4. Electromagnetic radiation in the Universe and cosmic-ray spectrum. High energy gamma-rays are related to cosmic rays and other bands of electromagnetic radiation through the interaction of high-energy electrons and soft ambient photons, for example, inverse Compton scattering and pair creation of electron and positron.

High Energy Processes in the Universe

- The energy budget and expense of high energy processes in the Universe are uncovered by utilizing the very high energy gamma-ray window.
- **SNR**: Supernova explosions impart enormous energy into surrounding matter via shock fronts. As a result, matter are accelerated to TeV energies.
- **Pulsars**: Compact objects left over after supernova explosions have extremely high magnetic fields and rotation rate. In the case of young pulsars, we see in Figure 5 that a major part of the "spindown energy" available

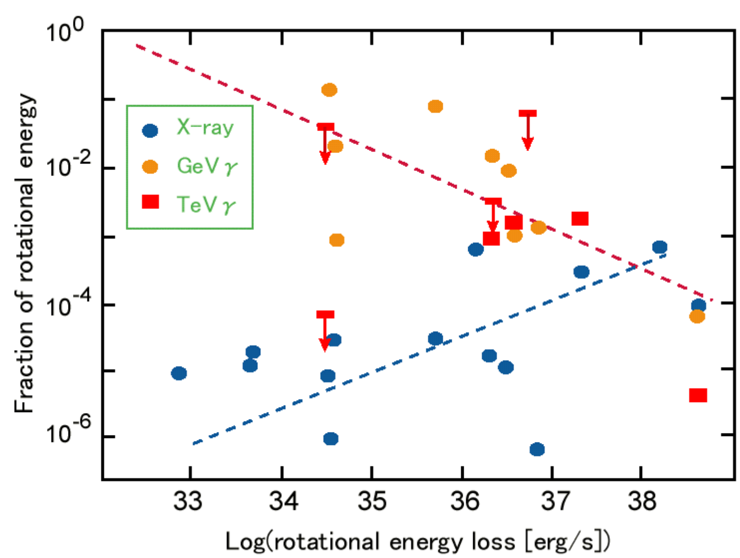


Figure 5. Relation between rotational energy loss and emission power of pulsars. Each point corresponds to data and dotted lines show their average tendency.

from pulsars is output in the form of gamma-rays.

- **AGN**: Active galaxies contain tightly beamed jets, along which matter becomes ultra relativistic. If the viewing angle is favorable (i.e. blazars), the doppler boosting of secondary gamma-rays is sufficient to produce TeV gamma-rays.
- **Gamma-ray bursts**: Fireballs expanding with relativistic speed explain gamma-ray bursts at cosmological distances, and are considered to provide the origin of ultra-high energy cosmic rays and gamma rays.

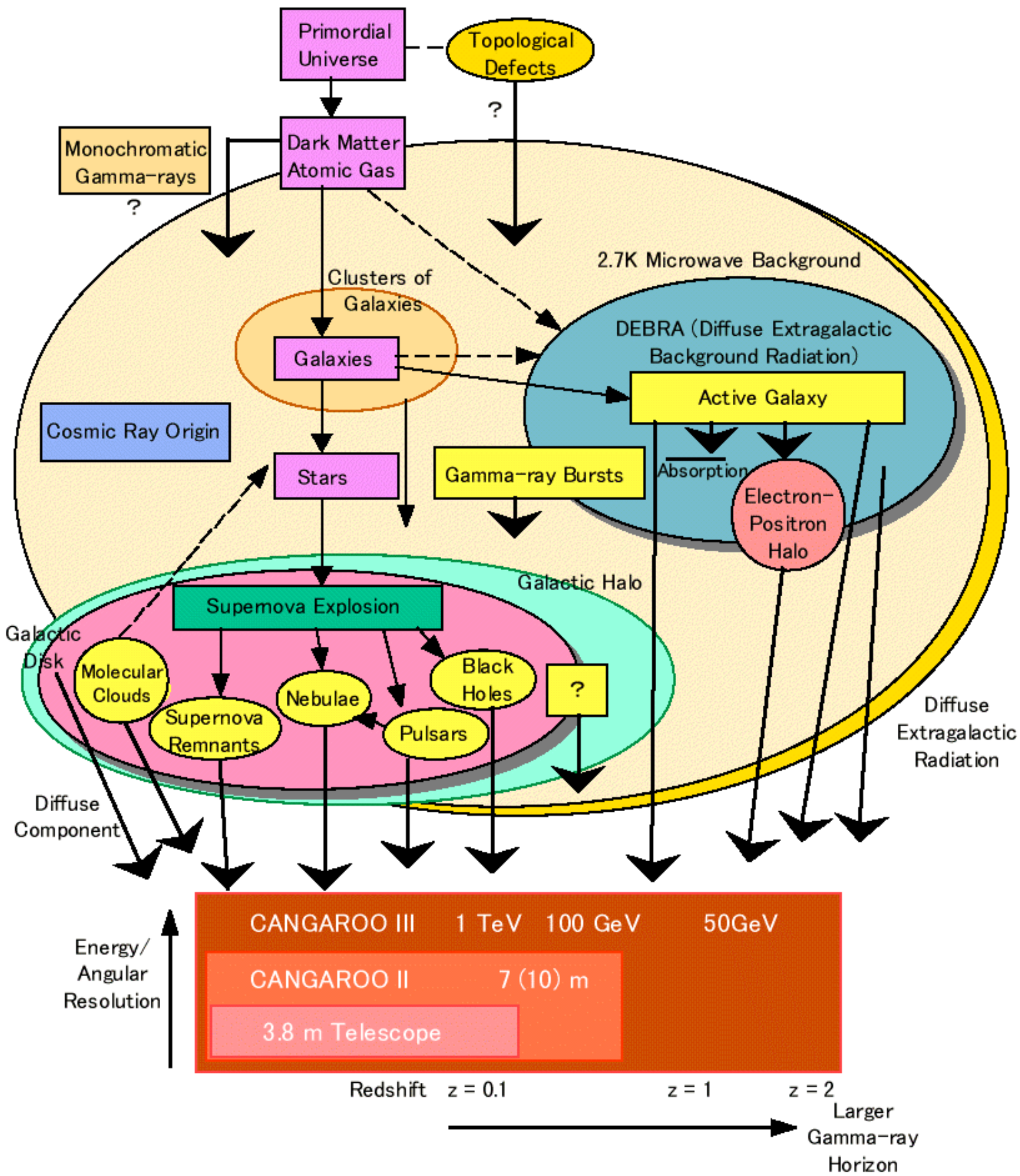


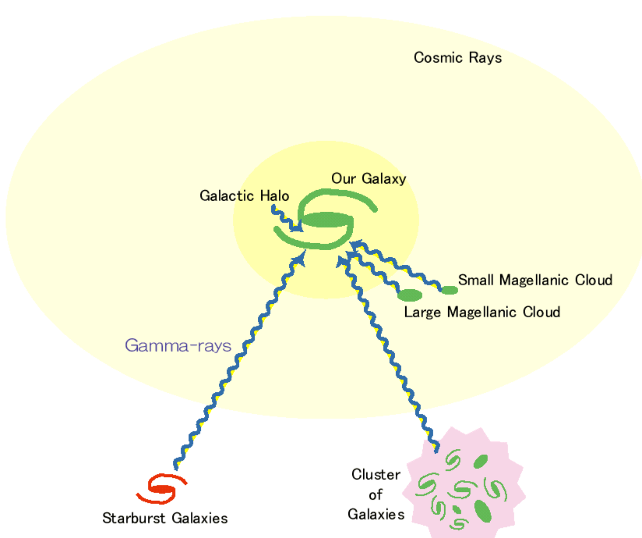
Figure 6. Gamma-ray production sites in the universe and their respective energies. Improved power of the CANGAROO projects will enable us to investigate these objects in greater detail.

Physics under Extreme Condition

- Observation of high energy gamma-rays has shown that electron-positron pairs are created abundantly in high-energy objects.
- Enormous spatial densities of energy are expected near compact objects like black holes and neutron stars.
- Electron-positron pairs are copiously produced in the magnetosphere of pulsars (B=10^{13} Gauss): this is a cosmic laboratory for material physics under extremely high magnetic and electric fields and also for the high matter density of neutron stars.
- AGN nuclei are associated with massive black holes such that gamma-rays collide with radiation field producing electron-positron pairs: this is also a cosmic laboratory for high-energy processes under the high-density radiation field.

Origin of Cosmic Rays

- Cosmic rays and gamma-rays are linked to the same source via particle interactions. Inverse Compton scattering of electrons and decay of neutral pions (resulting from hadronic interactions) are considered the prime mechanisms for TeV gamma-ray production. Since gamma-ray trajectories are not isotropized by magnetic fields, gamma-rays will preserve their origin location unlike cosmic-rays which are isotropic.
- Gamma-ray astronomy has provided us with the means of extending our cosmic-ray studies beyond our Galaxy. We aim to investigate cosmic rays in other galaxies as well as clusters of galaxies (Figure 7).
- Detailed studies will tie gamma-ray astronomy closely to many important topics of astrophysics such as: formation of galaxies and stars in the past through cosmic-ray activity; cosmic ray heating matter against the contraction process by gravitation; dark matter investigation through the structure of gamma-ray emission in galactic halos.



Cosmic rays are not universal in the Universe, but vary from galaxy to galaxy.

Figure 7. Extragalactic gamma-rays.

Very High Energy Gamma Ray Detection

- The ground-based method of very high energy gamma-ray astronomy utilizes the images of the Cherenkov emission from extensive air showers initiated by primary gamma-rays. Primary cosmic-rays also form EAS and make up the background against which gamma-ray EAS must be identified. TeV gamma-ray EAS are dominated by electromagnetic processes and consist of over 10^5 electron/ positron pairs, creating the bulk of Cherenkov light.

  Significant hadronic interactions present in cosmic-ray EAS render them statistically different from gamma-ray EAS. Moreover, the isotropic trajectories of cosmic rays impart a random orientation to their Cherenkov images in the focal plane. Gamma-ray images are aligned to their source. An effective area much greater than the telescope mirror area can be achieved by virtue of the extent of the Cherenkov light pool at ground level (Figure 8).

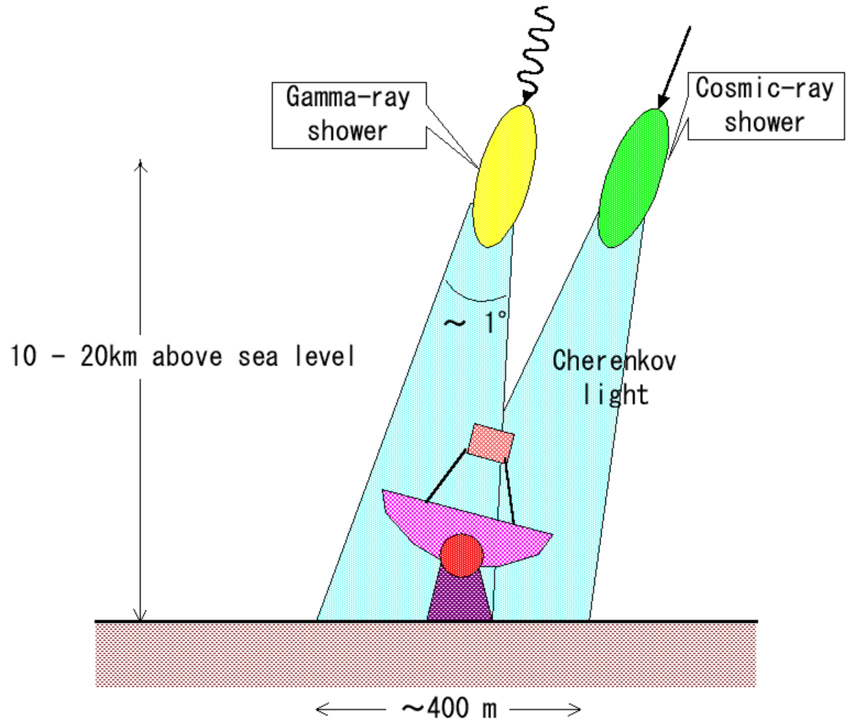


Figure 8. Principle of atmospheric Cherenkov telescope.

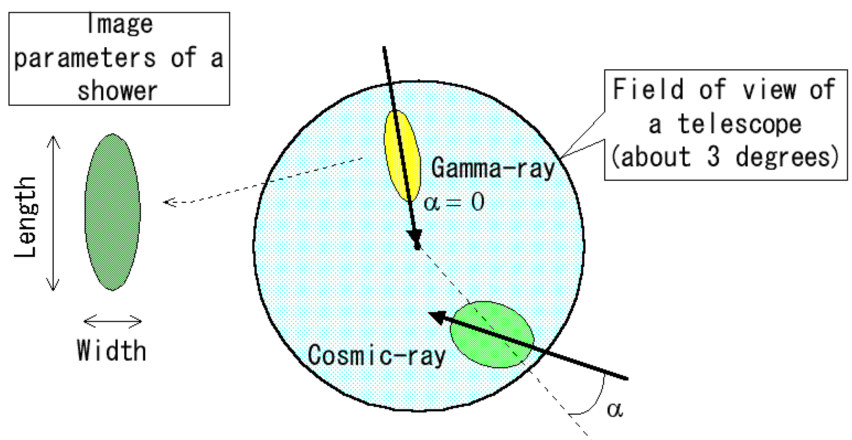


Figure 9. Discrimination of gamma-ray showers from proton showers.

- The Chereknov image is parametrized at the focal plane by a multi-pixel array of phototubes. The image size, shape and orientation forms the basis on which the gamma-ray image sample can be statistically enhanced at the expense of cosmic-ray images (Figure 9). Our current telescope rejects about 99% of cosmic-ray events while retaining about 50% of gamma-ray events above an energy threshold of 1-2 TeV.

Why to see the southern sky with mutliple telescopes

- Our telescope of 3.8m diameter, in operation since 1992, has discovered 4 sources of 10^{12} eV gamma rays in the southern sky, contributing to the opening of very high energy gamma-ray astronomy together with the Whipple group in USA seeing the northern sky.
- In the southern sky, we see the Galactic Center right at the zenith, and lots of interesting Galactic objects near the center.
- We enjoy the starry sky of Australia as well as the dry, fine climate, which are vitally important for the success of observation.
- The results so far obtained ensure us that a greater number of interesting objects remain to be disclosed with better sensitivity of detection technique.
- The large aperture of 10m diameter reduces the detectable energy of gamma rays down to 100 GeV, filling the unexploited region that exists between the ground-based and satellite measurement.
- We see the "stereoscopic" image of cascades of interactions that gamma ray causes in the upper atmosphere, by using 4 telescopes, just as we have two eyes to know the shape and distance of what are in front of us.

Table 1. Summary of CANGAROO observations

Object	Energy (TeV)	Flux ($10^{-12}cm^{-2}s^{-1}$)	Comment
Crab nebula	7	0.80	*d*=2 kpc
Vela pulsar	2.5	2.9	*d*=0.5 kpc
PSR 1706-44	2	3.5	*d*=1.8 kpc
PSR 1509-58	1.5	3.1	*d*=4.2 kpc
PSR 1055-52	2	< 0.95	*d*=1.5 kpc
SNR 1006	3	2.4	*d*=2 kpc
RXJ 1713.7-3946	1.8	5.3	*d*=6 kpc
W28	1.5	< 6.6	*d*=2-3 kpc
Cen A	2	< 1.5	*z*= 0.0018
EXO 0423-084	2	< 1.1	*z*=0.039
PKS 2005-489	2	< 1.1	*z*=0.071
PKS 2316-423	2	< 1.1	*z*=0.055

Figure 10. CANGAROO 3.8m telescope operating in Woomera since 1992.

CANGAROO-I (the 3.8m telescope) and CANGAROO-II (the 7m telescope) were constructed by the support of Grant-in-aid for scientific research of the Ministry of Education, Science and Culture of Japan. The CANGAROO-III (four 10m telescopes) is funded by the COE (Center of Excellence) program of the Ministry. These projects are also supported by the Australian Research Council.

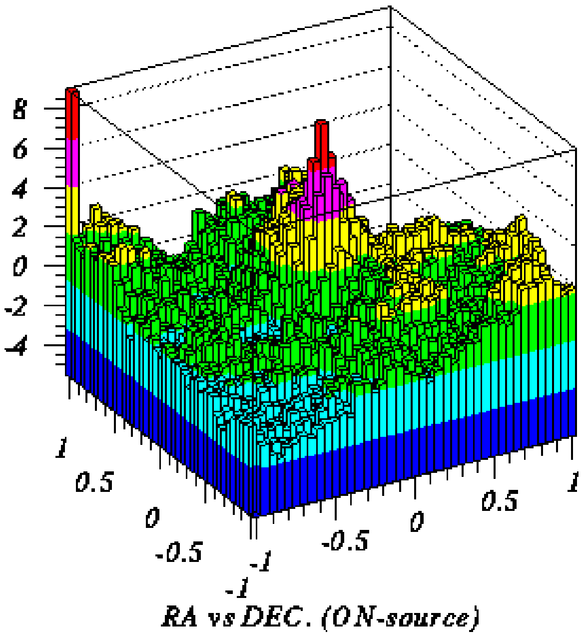


Figure 11. Map of statistical significance of the gamma-ray signal around PSR 1706-44.

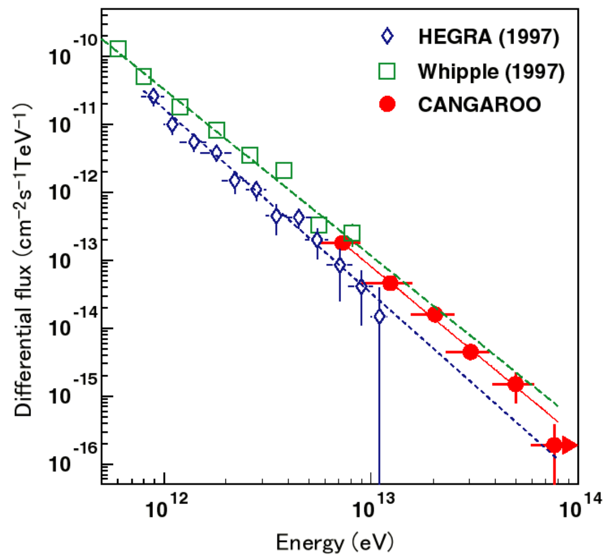


Figure 13. Energy spectrum of gamma rays from the Crab nebula

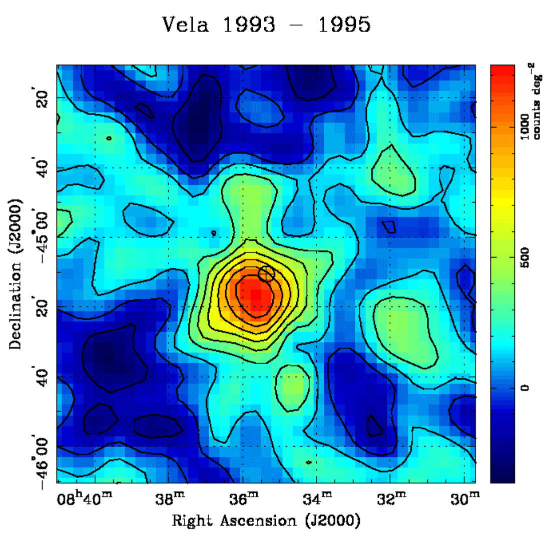


Figure 12. Map of excess events around the Vela pulsar showing the gamma-ray signal. The peak is separated from the pulsar position and is near the birth place of the pulsar.

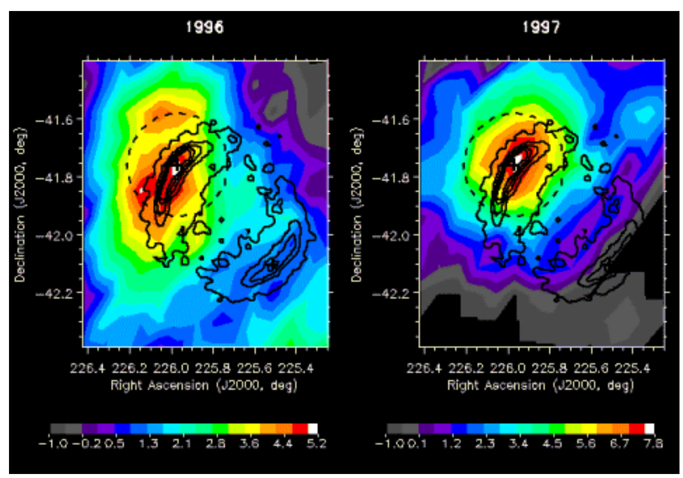


Figure 14. Map of statistical significance of the gamma-ray signal of SNR 1006. Contours are X-ray intensities observed by the ASCA satellite.

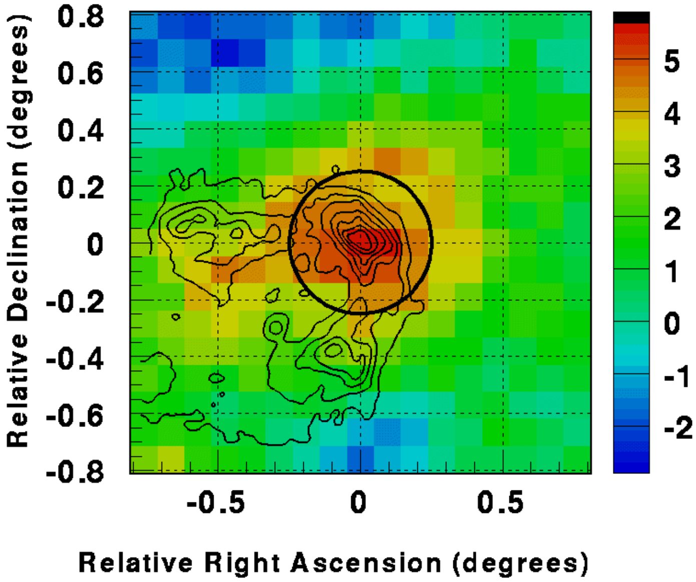


Figure 15. Map of statistical significance of the gamma-ray signal of the supernova remnant RXJ1713.7-3946. Contours are X-ray intensities observed by the ASCA satellite.

◆ Energy of a gamma-ray photon

Satellites :
1 MeV (= 10^6eV)
~10 GeV (= 10^{10}eV)

Ground-based :
>100 GeV (= 10^{11}eV)

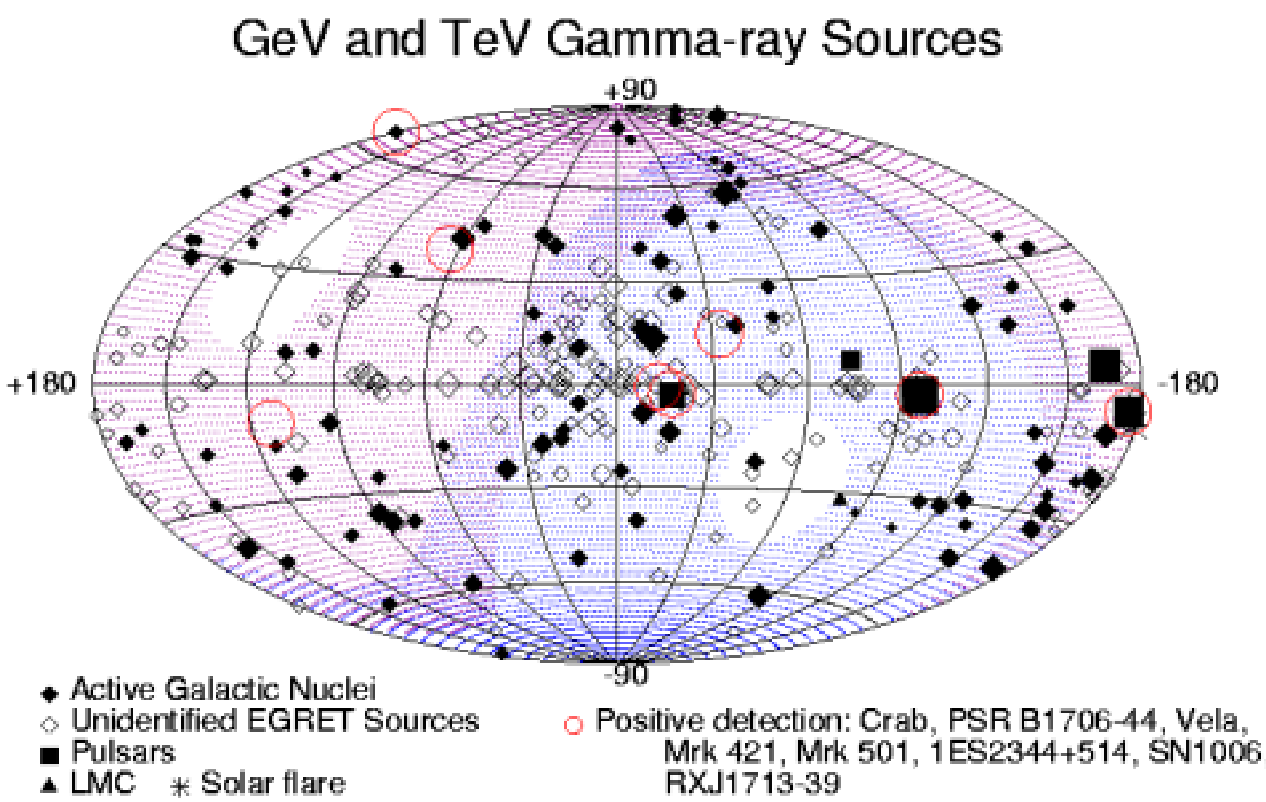


Figure 16. CANGAROO telescope will provide 100 GeV gamma ray data from objects in the southern sky, as shown by blue dots. Its coverage of the sky is compared with a telescope in the northern sky shown by purple dots (such as the Whipple 10 m telescope).

CANGAROO-I
(3.8m)

In operation since 1992

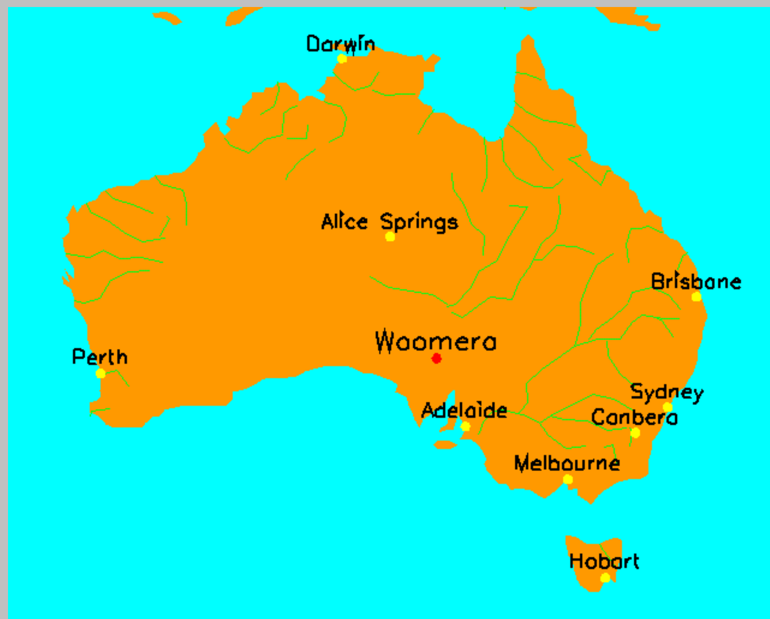
Step by step, but urgently!

CANGAROO-II
(7/10m)

Completed in March 1999 / March 2000

CANGAROO-III
(10m x 4)

This project



CANGAROO

(Collaboration of Australia and Nippon for a GAmma Ray Observatory in the Outback)

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- Ibaraki University
- Ibaraki Prefectural University of Health Science
- Institute of Space and Astronautical Science
- Institute of Physical and Chemical Research (RIKEN)
- Kanagawa University
- Konan University
- Kyoto University
- National Astronomical Observatory of Japan
- Osaka City University
- STE Laboratory, Nagoya University
- Tokai University
- Tokyo Institute of Technology
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