Part C Major Option Astrophysics

High-Energy Astrophysics

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Synopsis

- Introduction; astrophysical objects observed at various energies; brightness temperature.
- Supernova blast waves; shocks.
- Acceleration of particles to ultra-relativistic energies.
- Synchrotron emission; total power; spectrum; self-absorption; spectral ageing.
- Accretion; properties of accretion discs; Eddington luminosity; evidence for black holes.
- Relativistic jets; models of jet production; relativistic projection effects; Doppler boosting.
- Cosmic evolution of AGN; high-energy background radiation and cosmic accretion history of black holes.

- Bremsstrahlung; inverse-Compton scattering; clusters of galaxies; Sunyaev-Zel'dovich effect
- (Cosmic rays, example finals questions)

Books

The single book which covers most material is Volume 2 of *High Energy Astrophysics* by Malcolm Longair (CUP, ISBN 0521434394). This is very good on physical processes but some of the observational material is now a bit dated.

The chapters on active galaxies in the following two books are at about the same level as the course and provide complementary material to the lectures:

Galaxy Formation, Malcolm Longair, Springer, ISBN: 3540637850

Cosmological Physics, John Peacock, CUP, ISBN: 0521422701

The following books provide more detailed background reading, especially if you have chosen an M.Phys. project in this area or if you are considering going on to a research degree:

The Physics of Extragalactic Radio Sources, David de Young, Chicago, ISBN: 0226144151

Beams and Jets in Astrophysics, eds P.A. Hughes et al., CUP, ISBN: 0521335760

Accretion Power in Astrophysics, Frank, King & Raine, CUP, ISBN 0521629578

Today's lecture

- Observations across the electromagnetic spectrum: finding things that aren't stars!

- Brightness and temperature: just what do we mean by high-energy astrophysics?

- The processes we will study and examples of where they occur.

Observing the whole EM spectrum

Modern astronomical telescopes and detectors span the observational range from tens of metres in the radio to tens of TeV for the highest energy gamma rays. The classification of different astronomical wavebands is generally driven by the technology used in the detectors.

- Radio (from $\sim$ 10 MHz to $\sim$ 100 GHz) very highest spatial resolution because coherent detection of the EM field allows interferometry.

- Millimetre, sub-millimetre and far-infrared (~ 0.3 mm to $\sim$ 10 μm). Bolometers onboard satellites and high-altitude terrestrial sites.

- Infrared (10 μm to 1 μm) and optical (1 μm to 0.3 μm). Almost all of “traditional” astronomy. Most stars put out most of their energy in this range. Unsurprisingly the human eye is adapted to use these wavelengths!

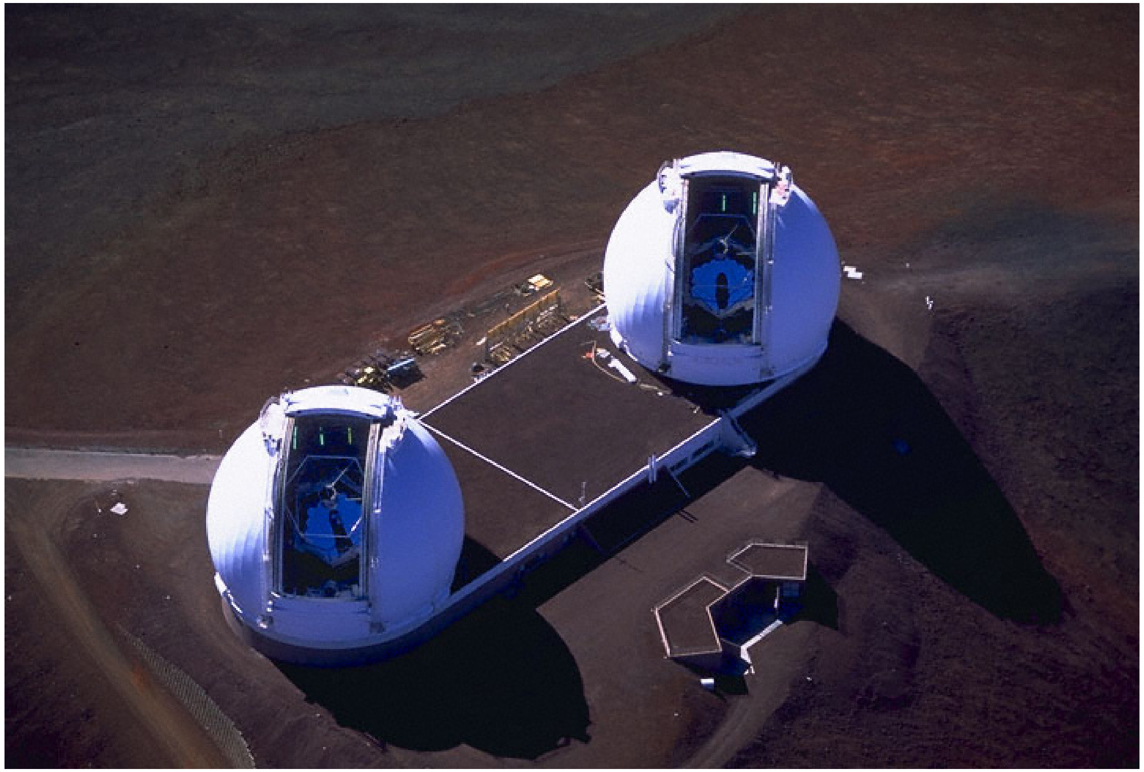
- Ultraviolet (0.3 μm to $\sim$ 3 nm). Satellite-borne instruments are needed because the atmosphere is opaque now; but we can still use essentially “ordinary” telescopes.

- X-rays (3 nm to $\sim 3 \times 10^{-12}$ m; 0.4 keV to $\sim$100 keV). Satellite- and rocket-borne instruments are needed. Special grating-incidence mirrors are used to focus X-rays.

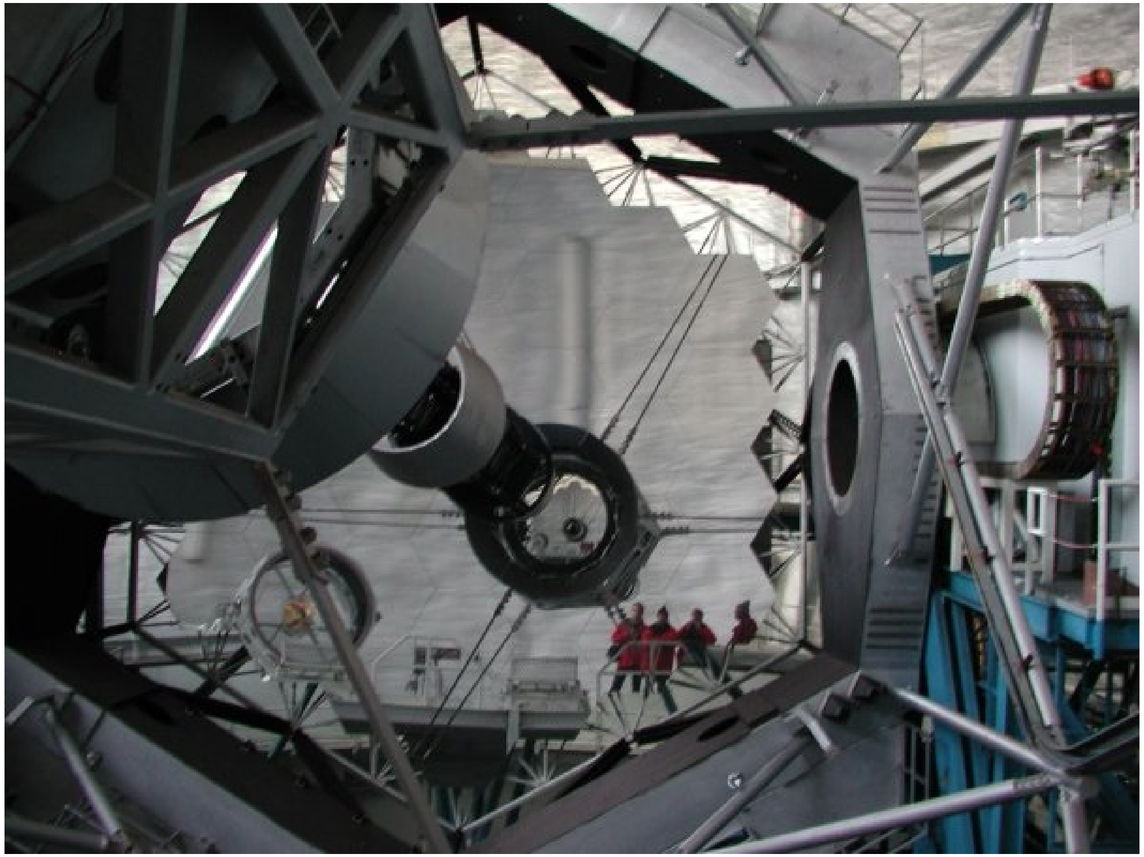
- Gamma-rays ($\sim$ 100 keV up to hundreds of GeV). Again telescopes are satellite-borne. Use similar detectors to particle physics experiments.

- Very high-energy photons and particles entering the Earth's atmosphere produce *Cerenkov radiation*. This is detected by very large "light bucket" telescopes which don't need finely-figured mirrors.

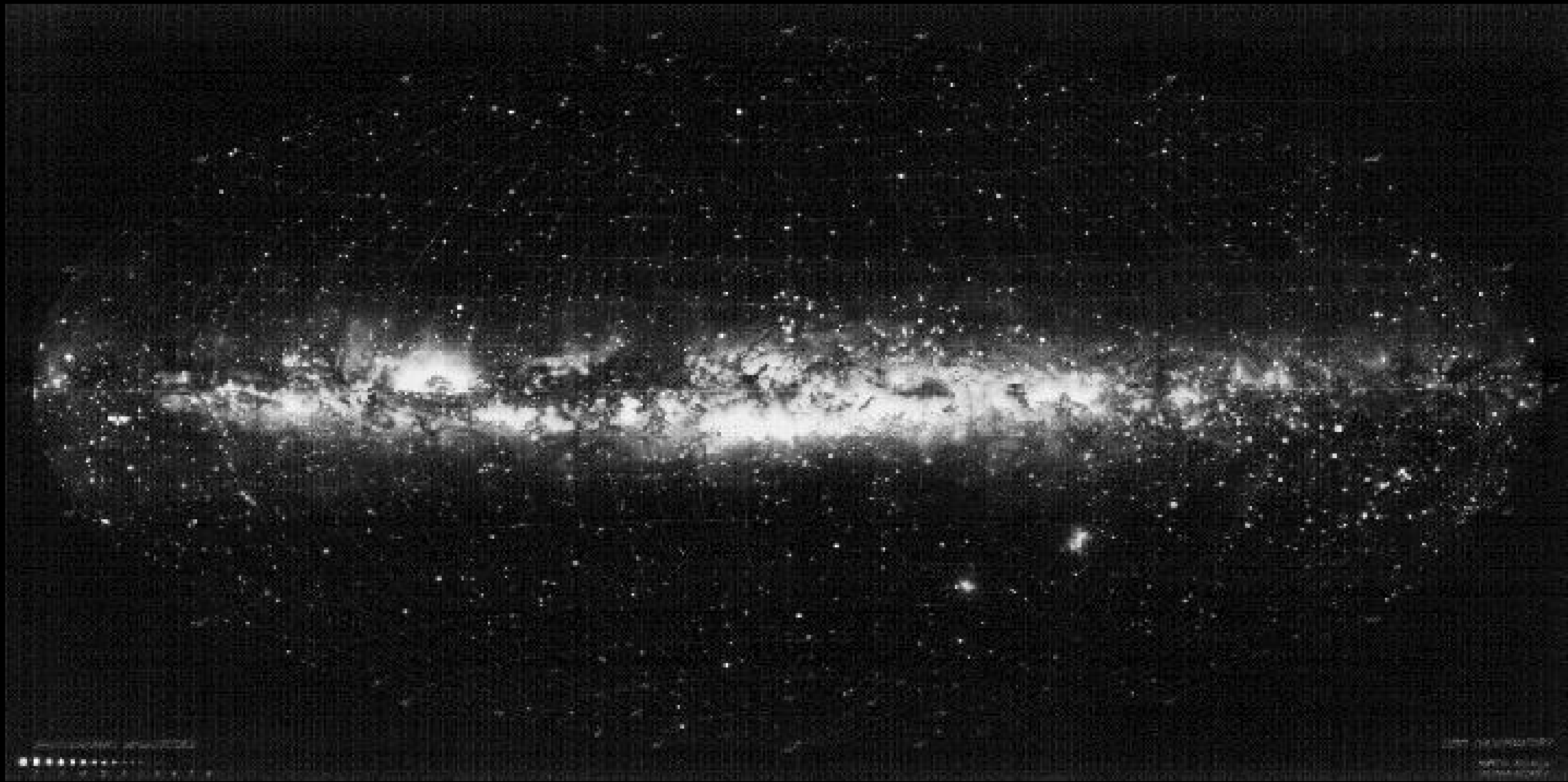
- Exotica: neutrinos, gravitational waves...



W.M. Keck observatory, Mauna Kea, Hawai'i.



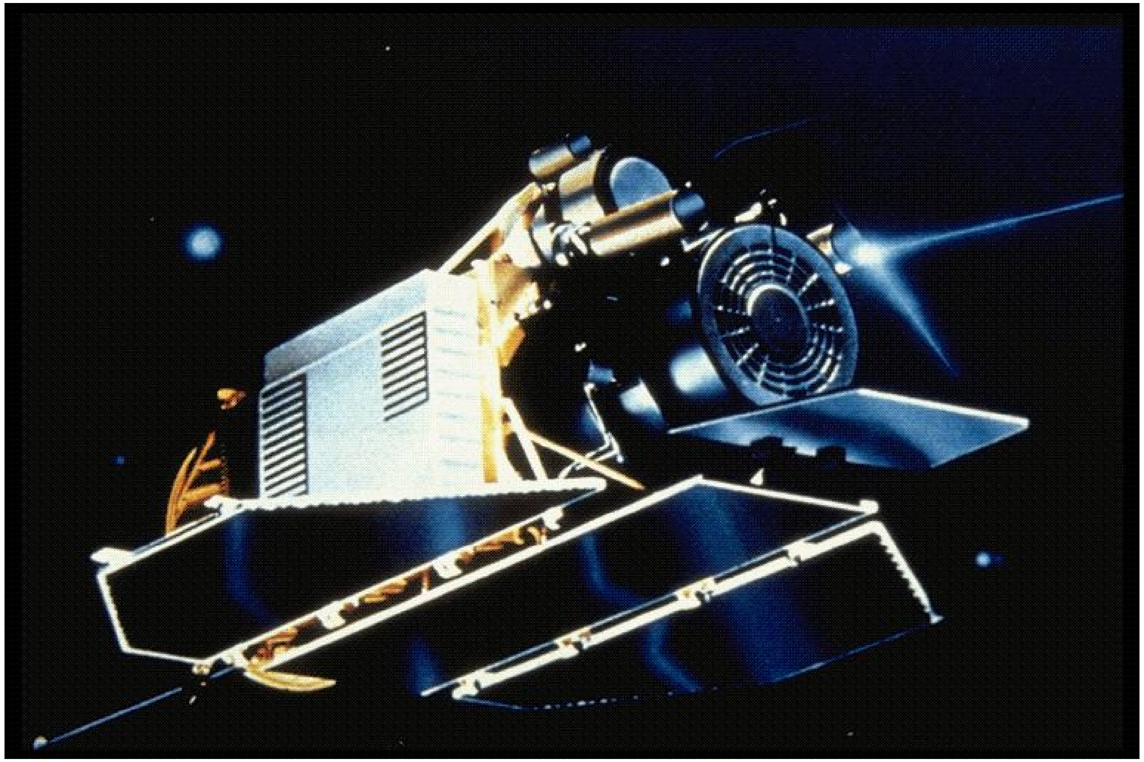
Keck telescope 10-m segmented mirror.



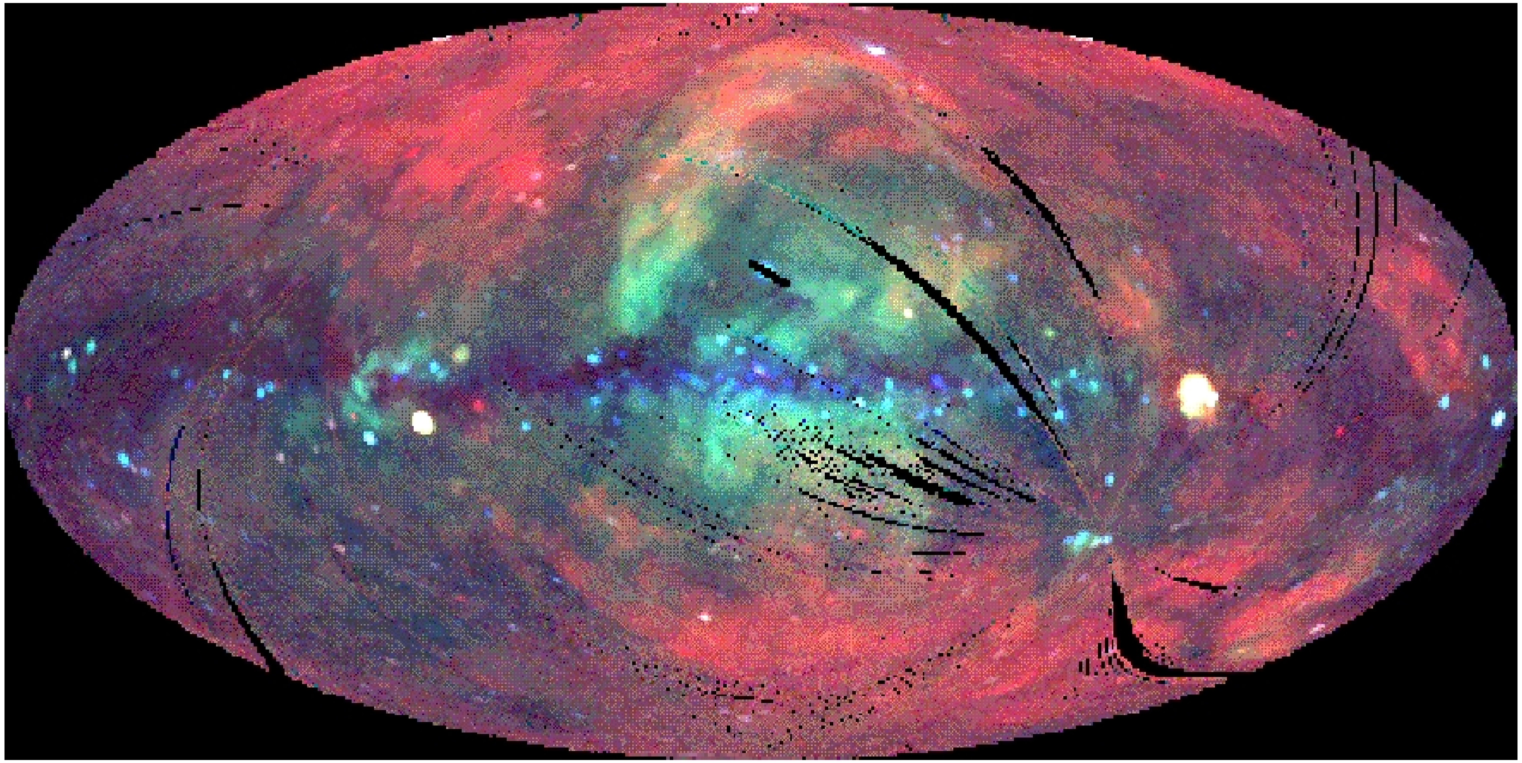
Optical view of the whole sky.

Very Large Array in New Mexico. Radio interferometer, 73 MHz—43 GHz. 27 antennae, baselines up to 36 km.

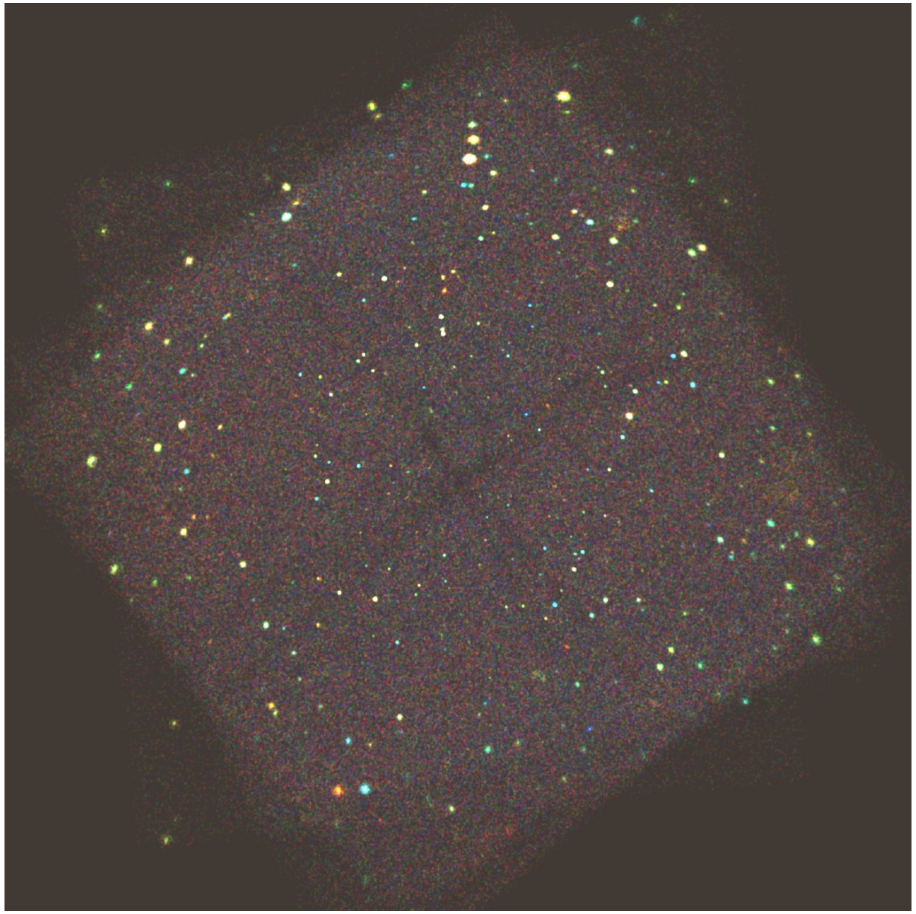
The sky as it would appear if we could see at 1.4 GHz. Almost all the sources lie far beyond the Milky Way. (Credit: NRAO / AUI / NSF)



ROSAT (Röntgensatellit) X-ray observatory

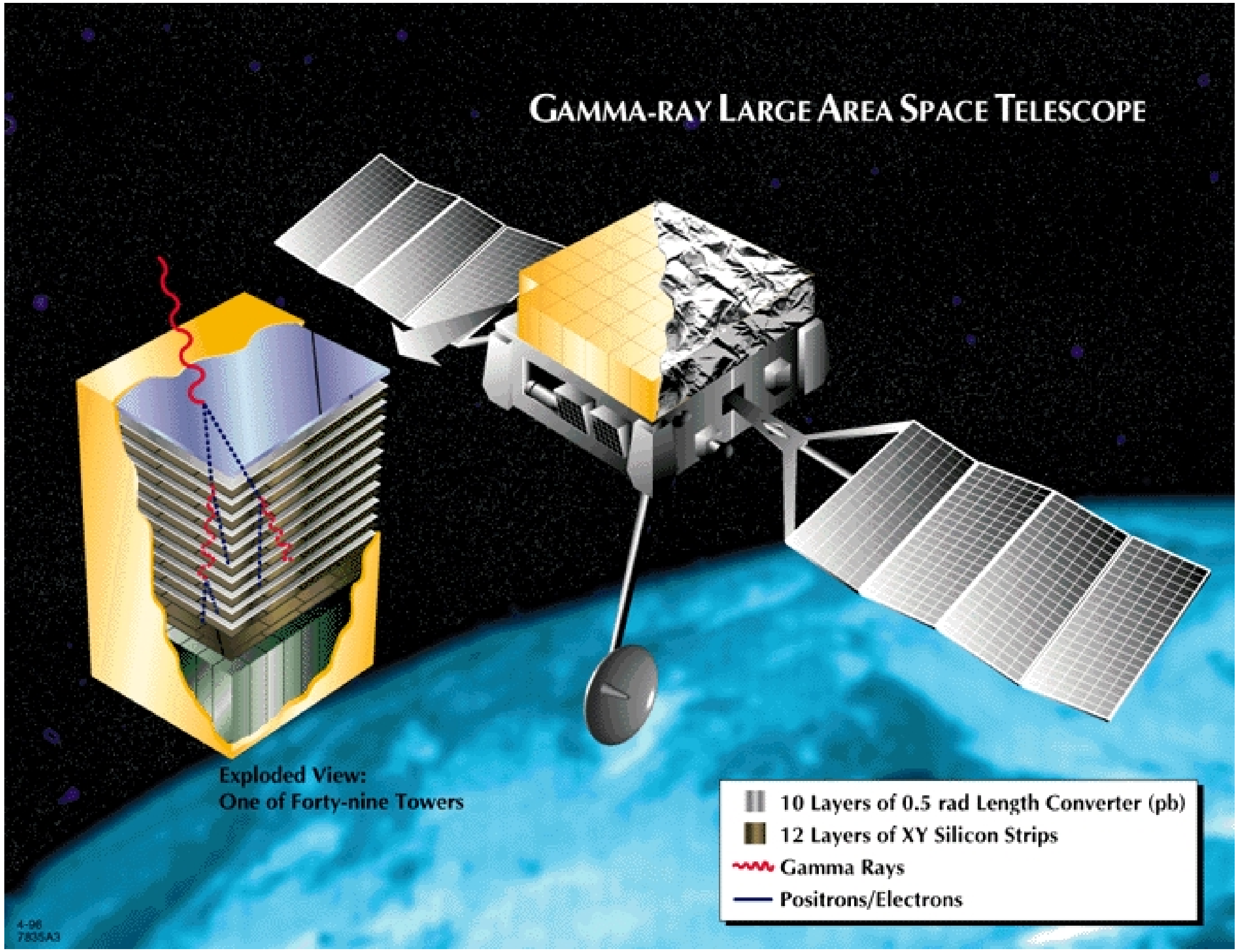


ROSAT all-sky survey. Note the fairly uniform background which is caused by unresolved extragalactic point sources

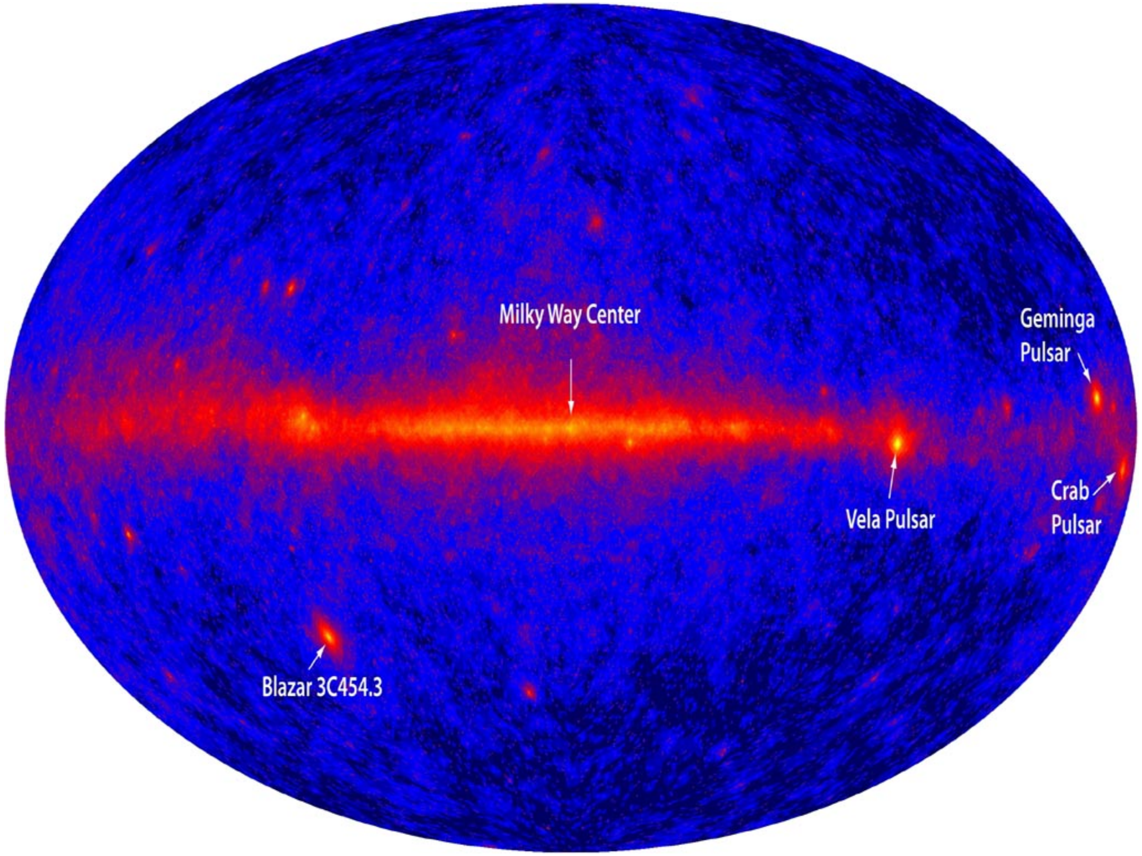


X-ray “zoom-in” from the high-resolution *Chandra* satellite.

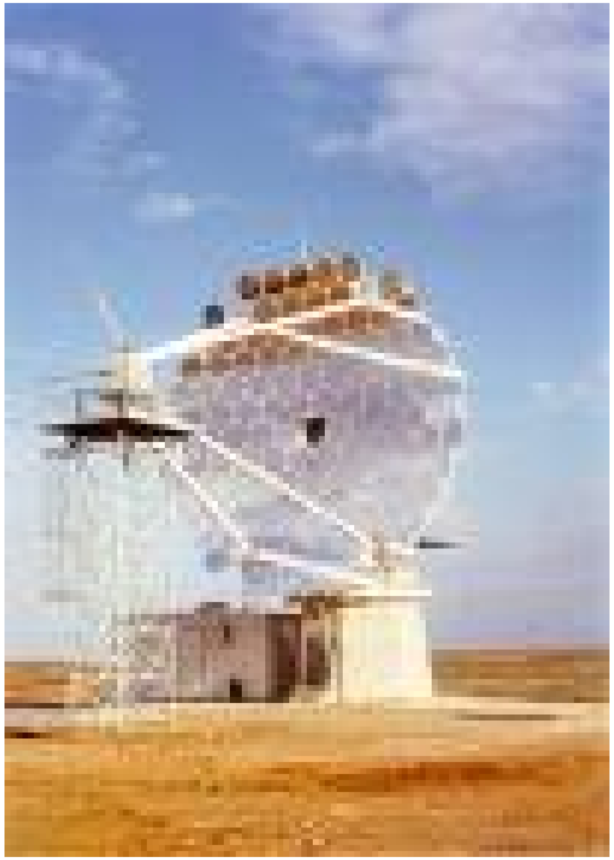
We can now see the individual X-ray sources.



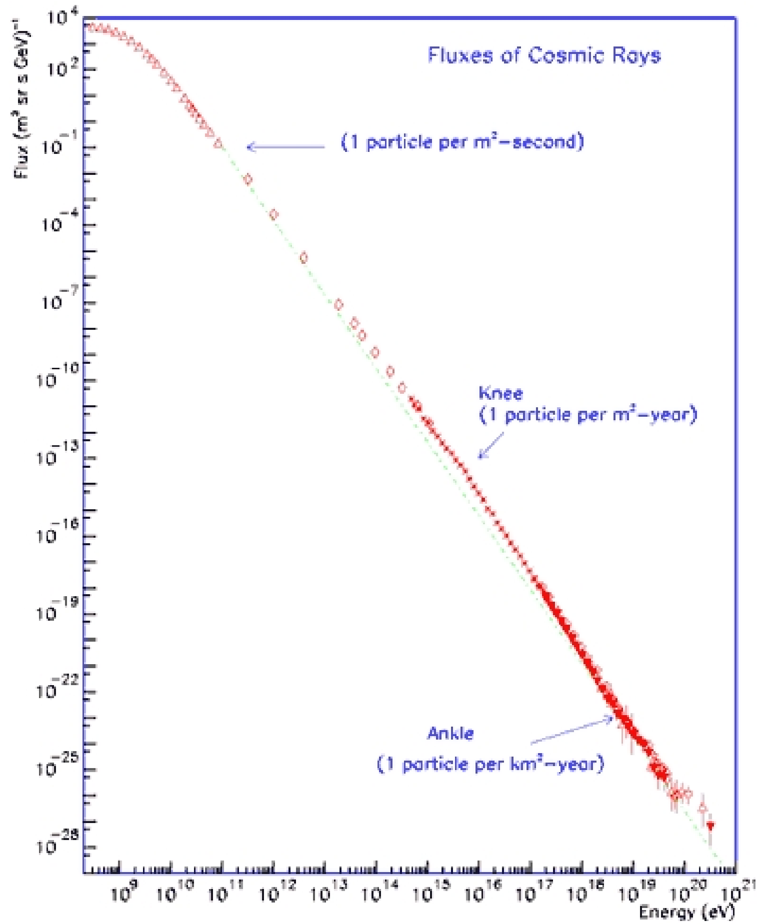
Fermi Gamma-Ray Space Telescope, launched June 11 2008.



Fermi “first-light” map: 4 days into 10-year mission. The bright object at lower left is 4 billion light-years away.



CANGAROO telescope for observing high-energy Čerenkov showers.



Observed spectrum of high-energy particles hitting the atmosphere.

Surface brightness

You will recall from last year (no doubt with frustration) that optical astronomers describe the observed flux of stars in magnitudes:

$$m_{\text{star}} = -2.5 \log_{10} \left(\frac{\text{flux}_{\text{Vega}}}{\text{flux}_{\text{star}}} \right)$$

so, e.g., a star 100 times fainter than Vega through a V-band filter has $V = 5$.

Astronomers at radio, far-infrared, X-ray etc. wavelengths are a more enlightened lot and use physical units. One of the most common is the unit of flux density, the Jansky (Jy, named after the discoverer of radio waves from the Milky Way):

$$1\,\text{Jy} = 10^{-26}\,\text{W}\,\text{Hz}^{-1}\,\text{m}^{-2}$$

i.e. the units are power collected per square metre of telescope collecting area per unit bandwidth of the receiving device. As a yardstick, Vega has a flux density of about 3600 Jy at 500 nm.

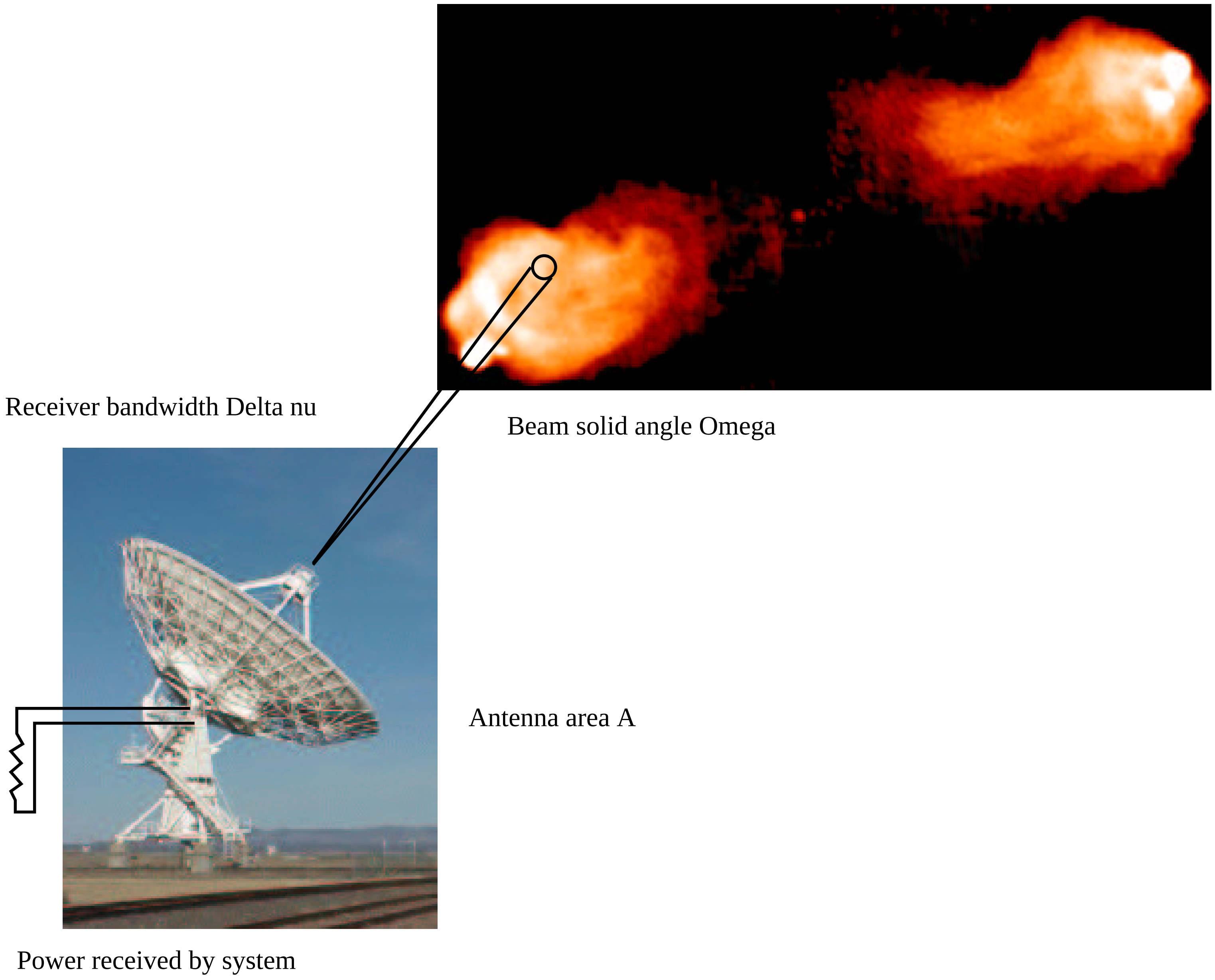
(For fun: The faintest stars the human eye can see at a dark site are about magnitude 6. How much power does the eye receive from them? How many photons does it take to trigger a light-sensitive cell in the eye? Take the integration time to be $\sim$ 20 ms and the starlight to be spread over $\sim$ 10 cells in the eye.)

In virtually all of optical astronomy stars are effectively point sources (their angular size is much smaller than the ~ 1 arcsec limit imposed by atmospheric turbulence). However in high-energy astrophysics we often deal with objects whose angular extent can be resolved, and this leads us to a perhaps more fundamental quantity, the *surface brightness*. This is the flux density per solid angle, and has SI units of

$$\mathrm{W\ Hz^{-1}\ m^{-2}\ Sr^{-1}}$$

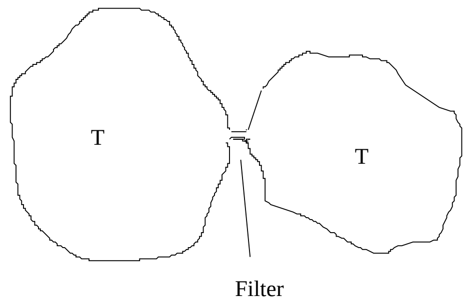
- Power developed in the detector,
- per unit bandwidth of the detector,
- per square metre of telescope collecting area,
- per unit solid angle of sky from which the telescope is collecting energy.

Surface brightness also called “specific intensity” or simply “brightness”. Notation is conventionally I_ν. You will often also see it in units such as Jansky per square arcsec, or Jansky per square arcminute.


Receiver bandwidth Delta nu
Beam solid angle Omega
Antenna area A
Power received by system

Brightness and temperature

Thought experiment: take two cavities of different size and shape, but both filled with black-body radiation at the same temperature T. Suppose there is an aperture between the cavities and that in this aperture there is a filter which transmits only through some narrow range of frequencies.



We know from the Zeroth Law that there is no heat transfer between box 1 and box 2 so $I_{\nu,1} = I_{\nu,2}$ i.e. for black-body radiation I_ν can only be a function of T and ν.

So brightness and temperature are intimately linked. The brightness of a black-body as a function of frequency is given by the Planck function:

$$B_\nu = \frac{2h\nu^3}{c^2}\left\{\exp\left(\frac{h\nu}{k_{\mathrm{B}}T}\right) - 1\right\}^{-1}$$

This is simply $c/4\pi$ times the $u(\nu)$ form. It gives the flux per unit frequency *through* an element of area *from* an element of solid angle. So if we know I_ν for an astronomical object from observation, we can calculate the temperature of a blackbody that would have the same brightness at that frequency: the "brightness temperature".

Jargon alert: Pedantically, one should use B_ν when referring to the brightness of a black-body and I_ν when referring to the brightness of an object with an arbitrary spectrum. But don't be surprised if you sometimes see them interchanged. That's astronomers for you.

"I learned very early the difference between knowing the name of something and knowing something." - Feynman

Extremes of brightness and non-thermal spectra

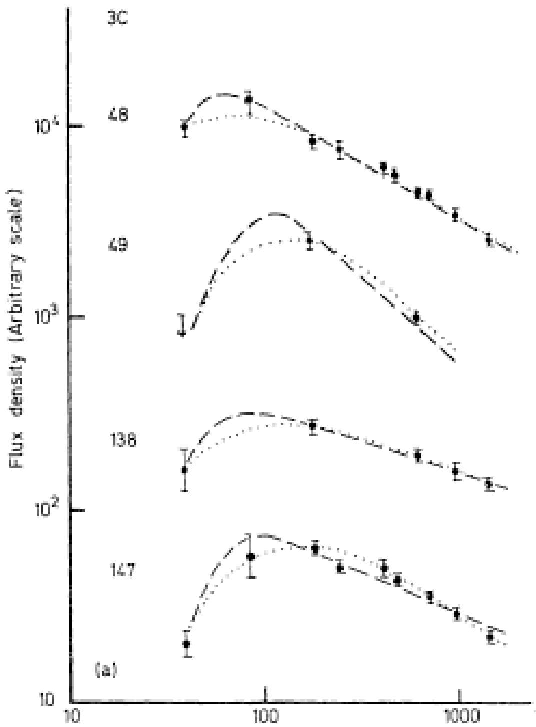
Most stars radiate approximately as black-bodies, ranging from ≈ 3000 K for M-type red dwarfs to $\approx 50\,000$ K for O-type supergiants. The spectra peak in the infra-red to ultraviolet regions of the EM spectrum and are the backbone of traditional observational astronomy. But when we go to *both* long (radio) and short (X-ray) wavelengths, we find objects which have brightnesses far in excess of those achieved by blackbody processes in stars.

- Particles in the intracluster plasma of massive clusters of galaxies can have temperatures up to 10^8 K

- Radio emission from quasars can be sufficiently bright that a black-body would have to be at 10^{12} K to produce the same emission at those wavelengths.

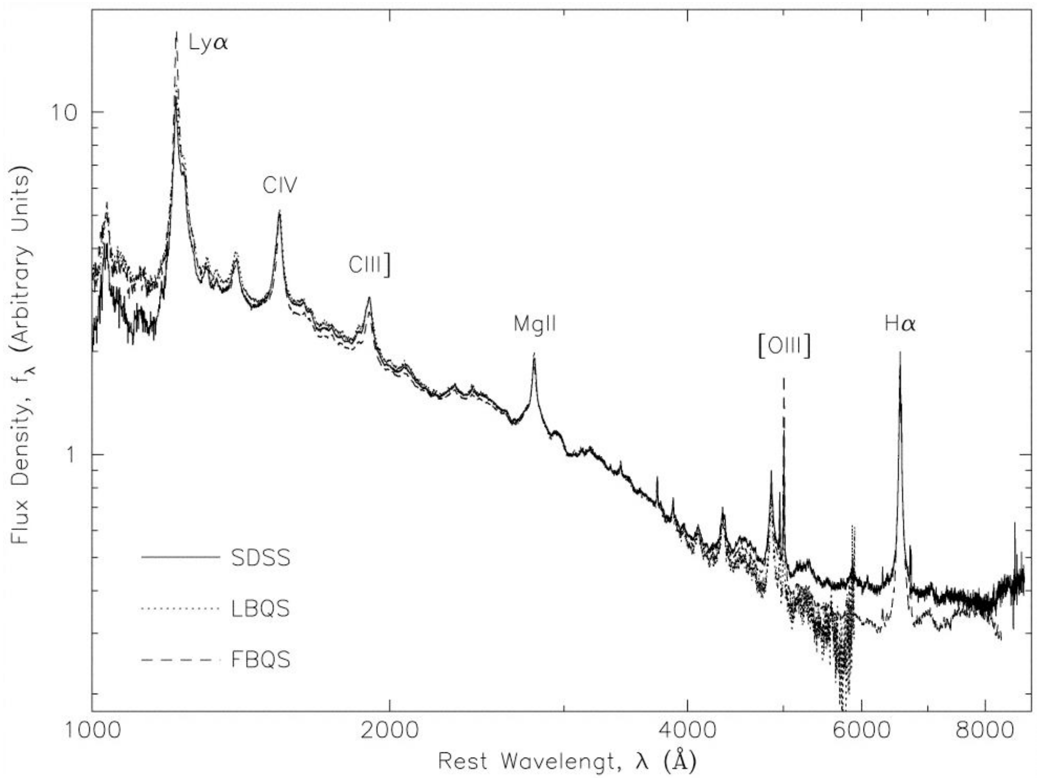
Broadly speaking, high-energy astrophysics encompasses physical process and objects where the energies and temperatures involved are far in excess of those observed in normal stellar systems (often implying that the energy source is not nuclear fusion). And we often find cases where the temperatures and densities of the material involved lend themselves to spectral energy distributions that are greatly different from a black-body.

Radio spectra of some sources from the 3C survey



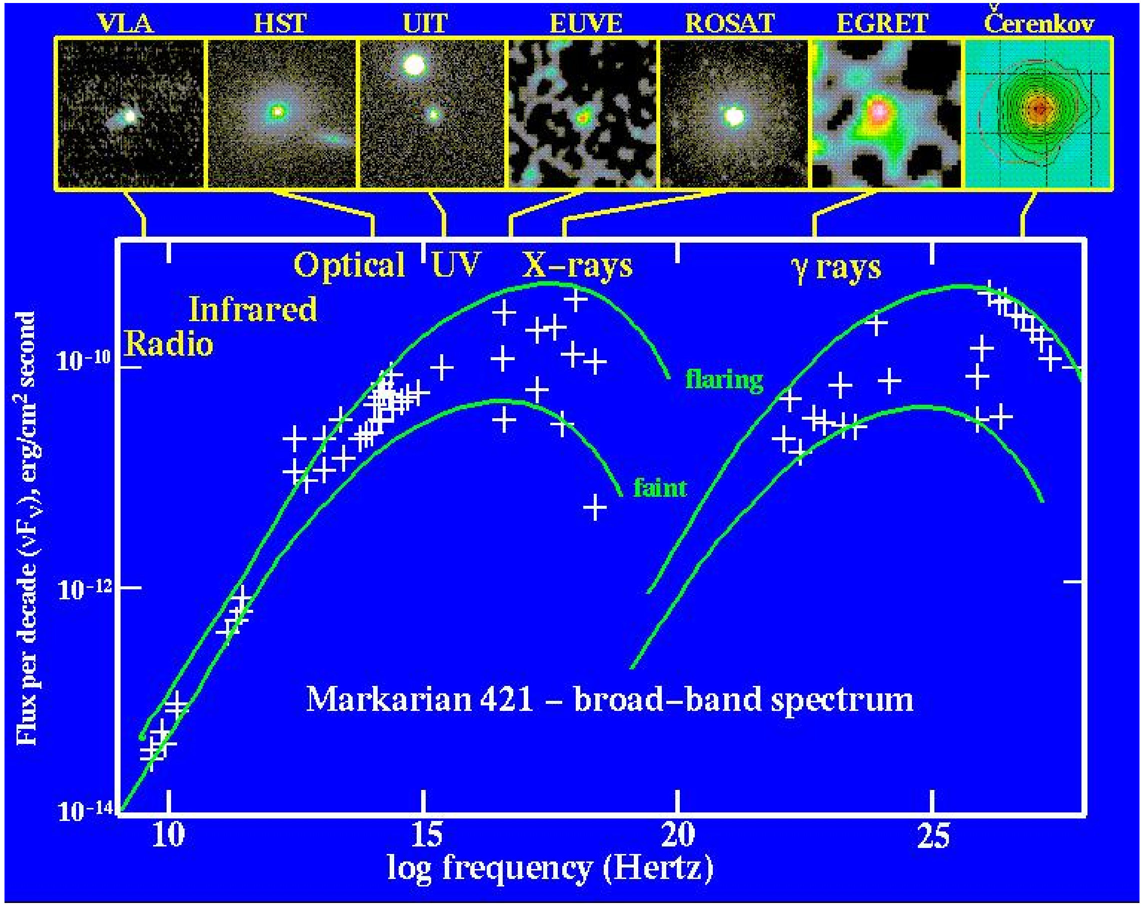
Frequency / MHz

Average optical/UV spectra of quasars

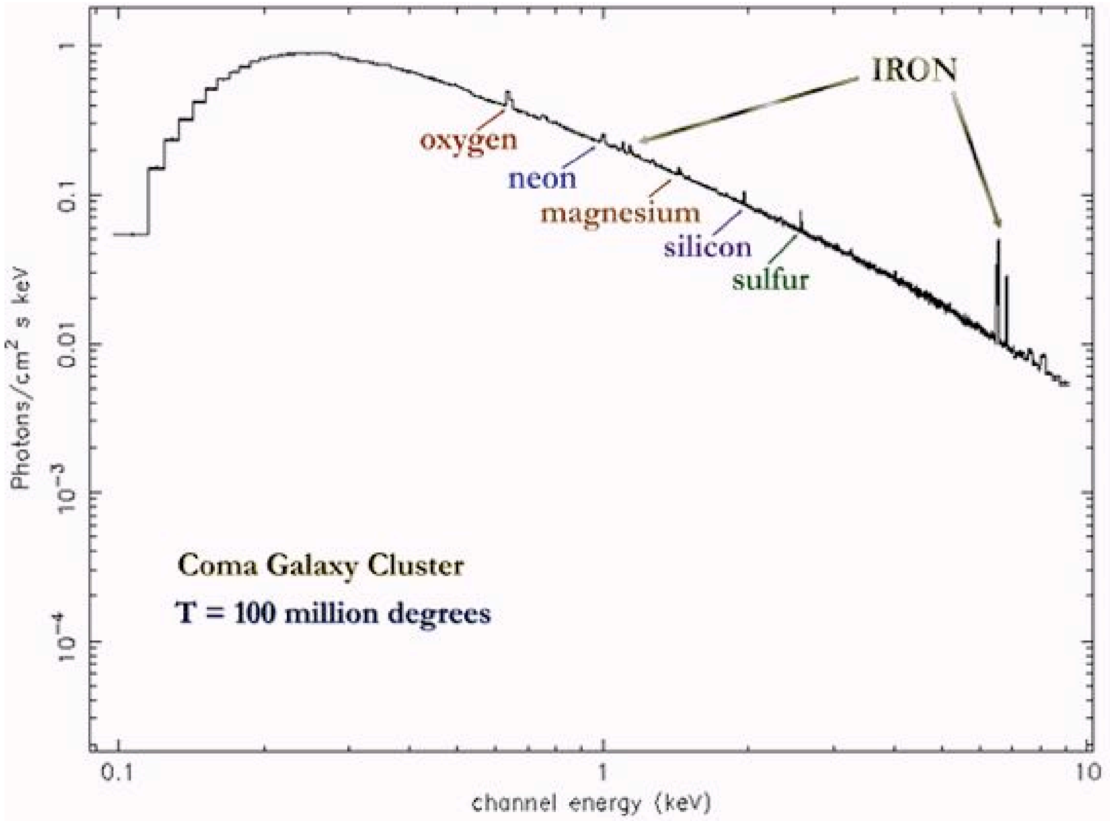


Note non-blackbody spectrum with prominent emission lines.

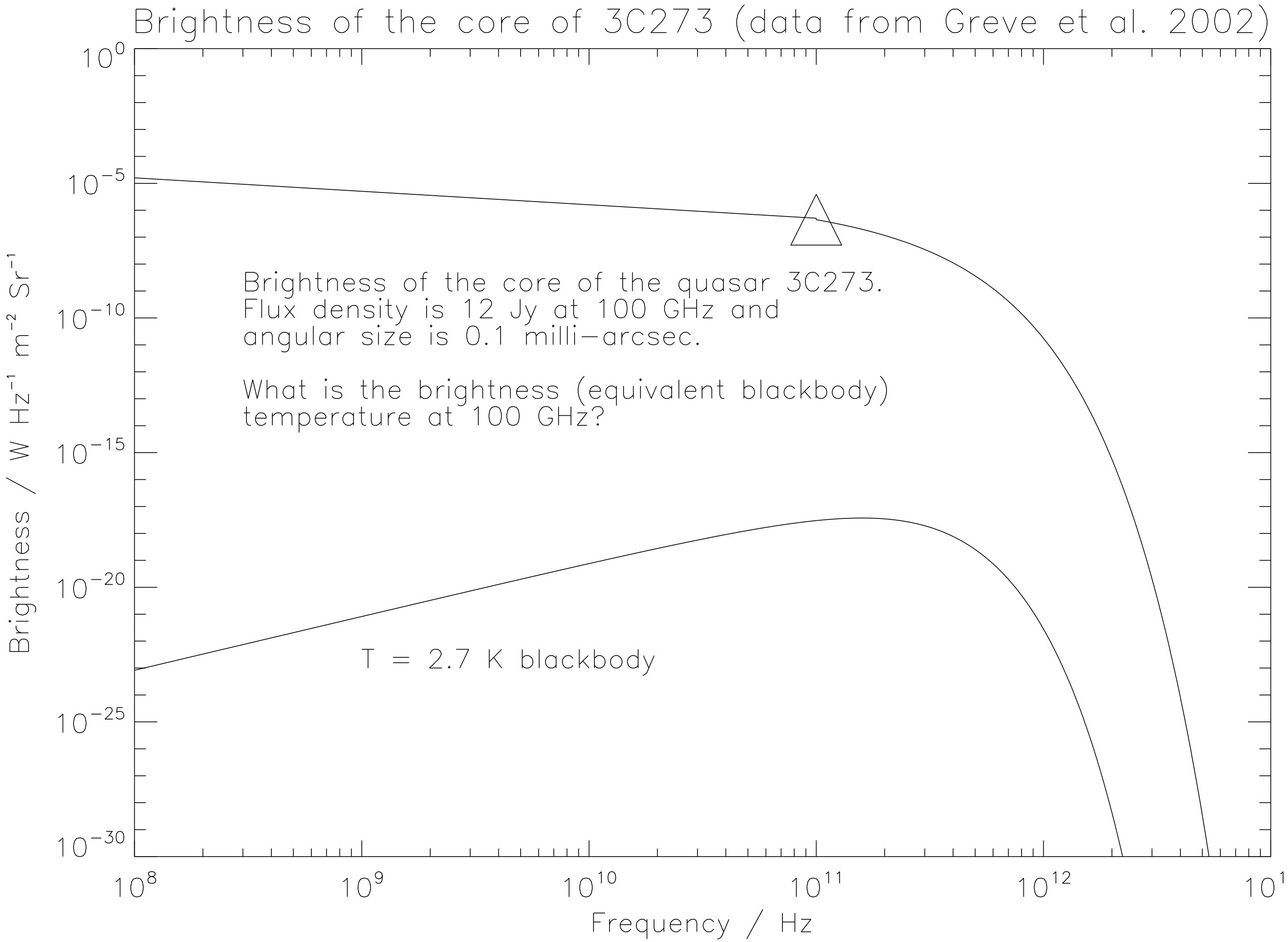
Active galaxies: broad-band spectra



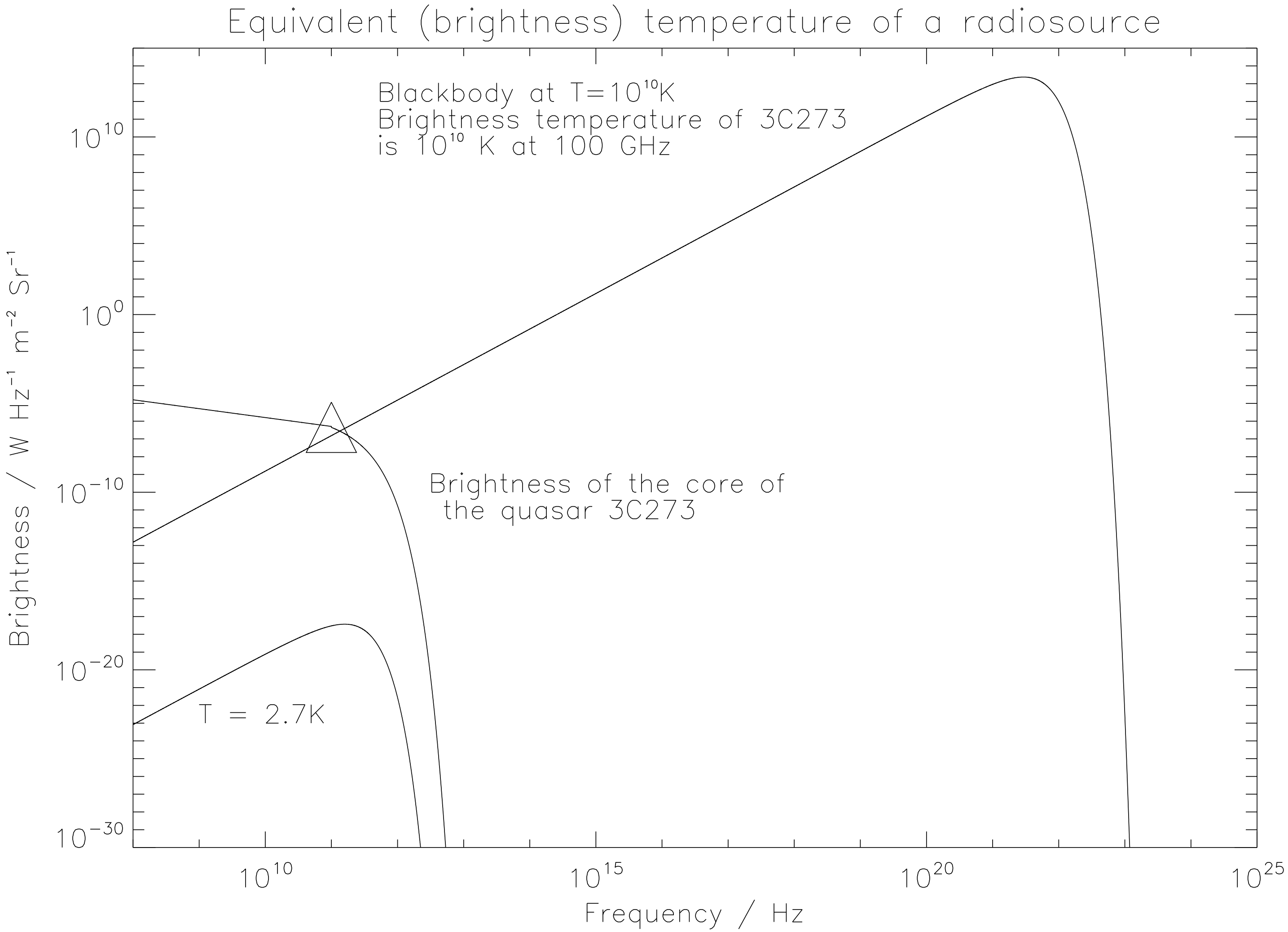
X-ray spectrum of intracluster plasma in the Coma cluster of galaxies



Again note non-blackbody and emission lines.



Brightness of the core of 3C273 (data from Greve et al. 2002)
10^0
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
Brightness / W Hz^{-1} m^{-2} Sr^{-1}
Brightness of the core of the quasar 3C273.
Flux density is 12 Jy at 100 GHz and
angular size is 0.1 milli-arcsec.
What is the brightness (equivalent blackbody)
temperature at 100 GHz?
T = 2.7 K blackbody
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
Frequency / Hz


Equivalent (brightness) temperature of a radiosource
Blackbody at T=10^10 K
Brightness temperature of 3C273
is 10^10 K at 100 GHz
Brightness of the core of
the quasar 3C273
T = 2.7K
Brightness / W Hz^-1 m^-2 Sr^-1
Frequency / Hz
10^10
10^0
10^-10
10^-20
10^-30
10^10
10^15
10^20
10^25

Classes of object and radiation processes

In this course our main example systems will be supernova blast waves, active galaxies, and clusters of galaxies. The physical processes we will study are:

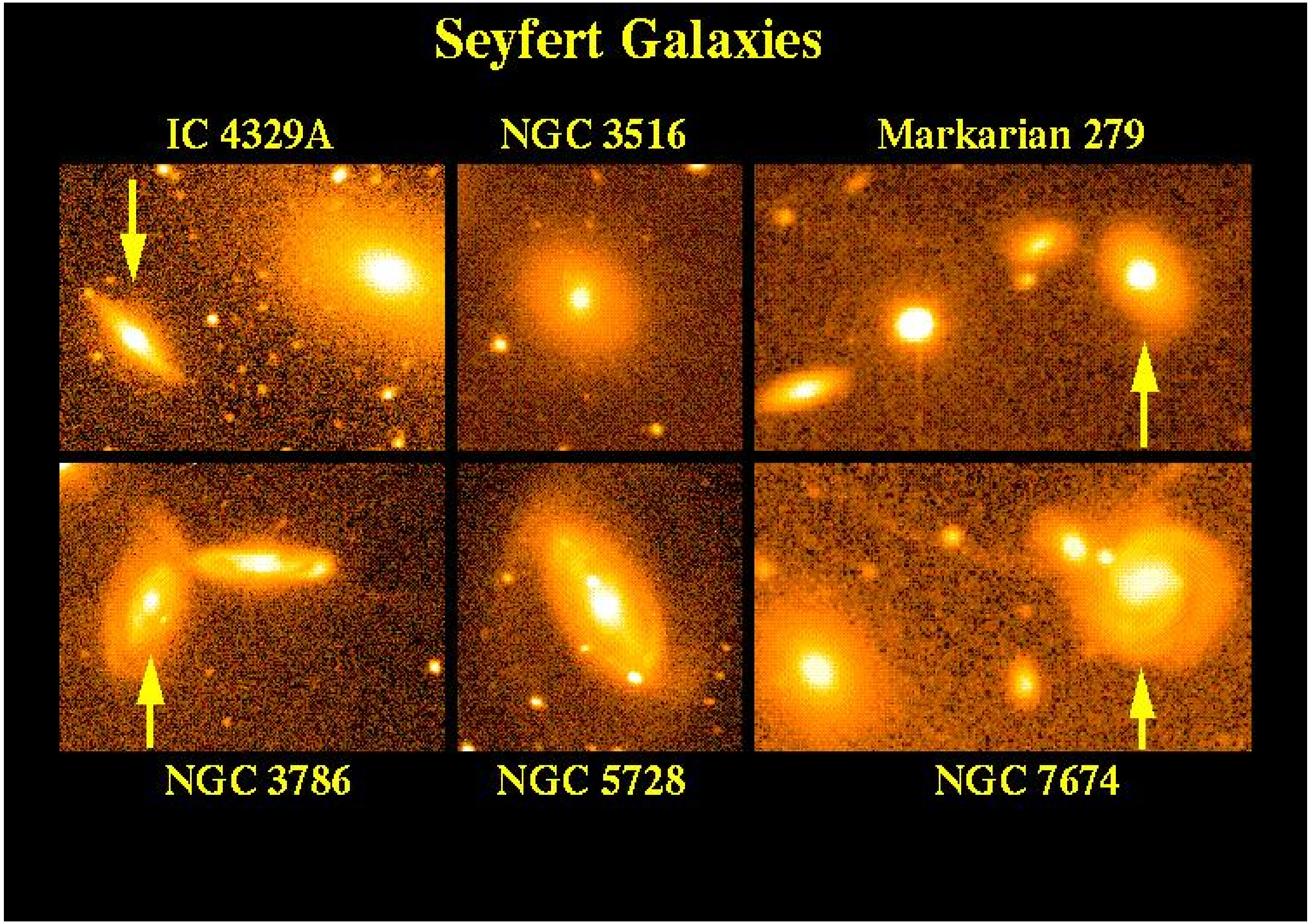
- Strongly supersonic shocks.
- Particle acceleration: how to create ultra-relativistic particles.
- Synchrotron and inverse-Compton radiation: produced by the interaction of charged particles with magnetic fields.
- Accretion discs around black holes: how to produce extreme-UV and Xray radiation, and how to tap the rotational energy of a black hole to produce a jet.
- Relativistic "optical illusions" in jets from active galaxies and what they tell us about the intrinsic properties of these objects
- The production of the high-energy background radiation by active galaxies at early cosmic times.
- Thermal bremsstrahlung: the spectrum of very hot low-density plasma.

Active galaxies

- Galaxies whose nuclei contain supermassive black holes.
- Accretion is the fundamental power source.
- Extremely high-energy particles and X-ray photons are produced near the black hole. The central region often outshines the starlight of the whole galaxy.
- Relativistic jets are sometimes produced which extend far beyond the host galaxy.

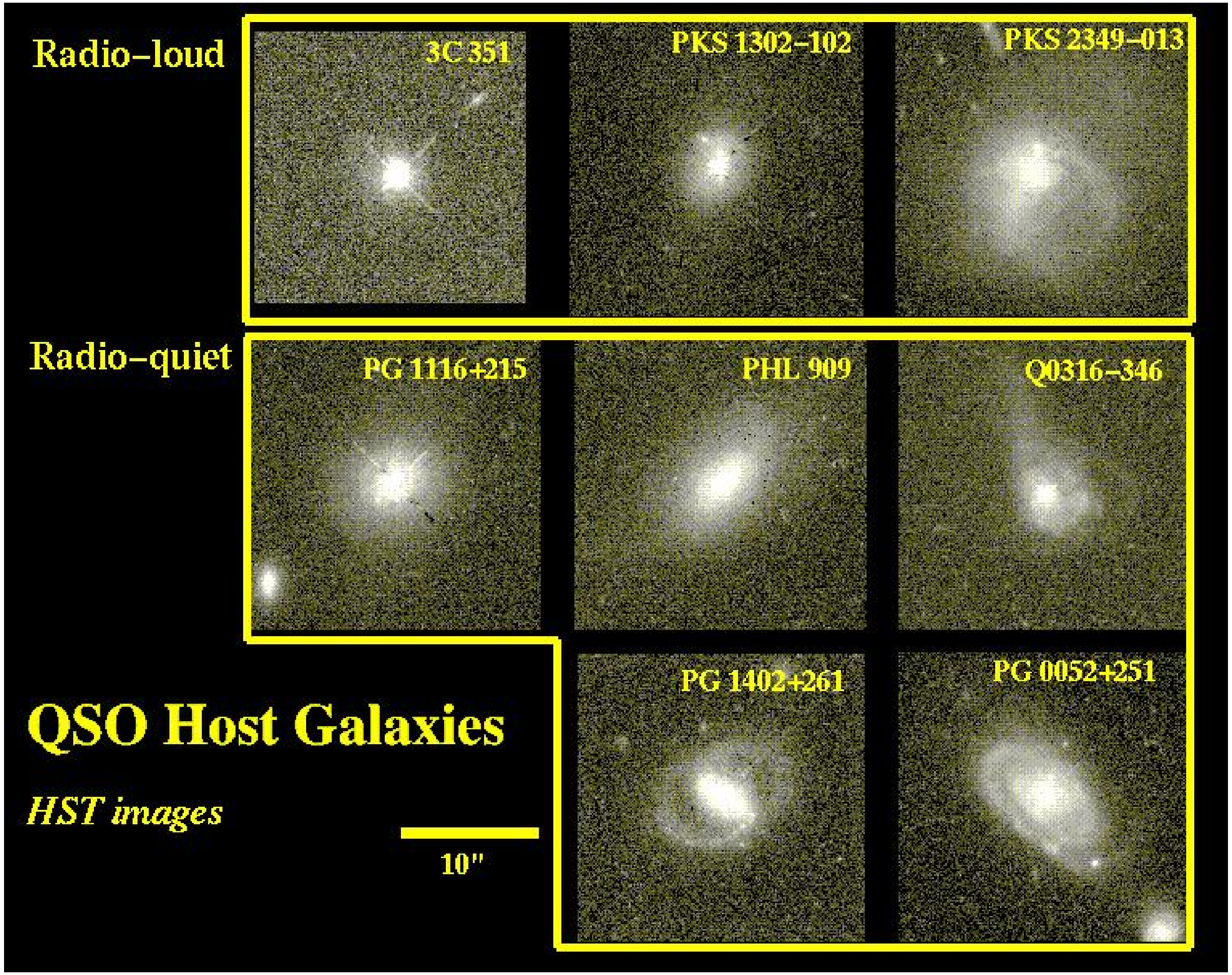
Active galaxies: Seyferts

Optical (HST) images of some nearby, *relatively* low-luminosity active galaxies. These objects were first investigated by optical astronomers in the early- to mid-1900's. There is a very bright compact nucleus in normal optical images.

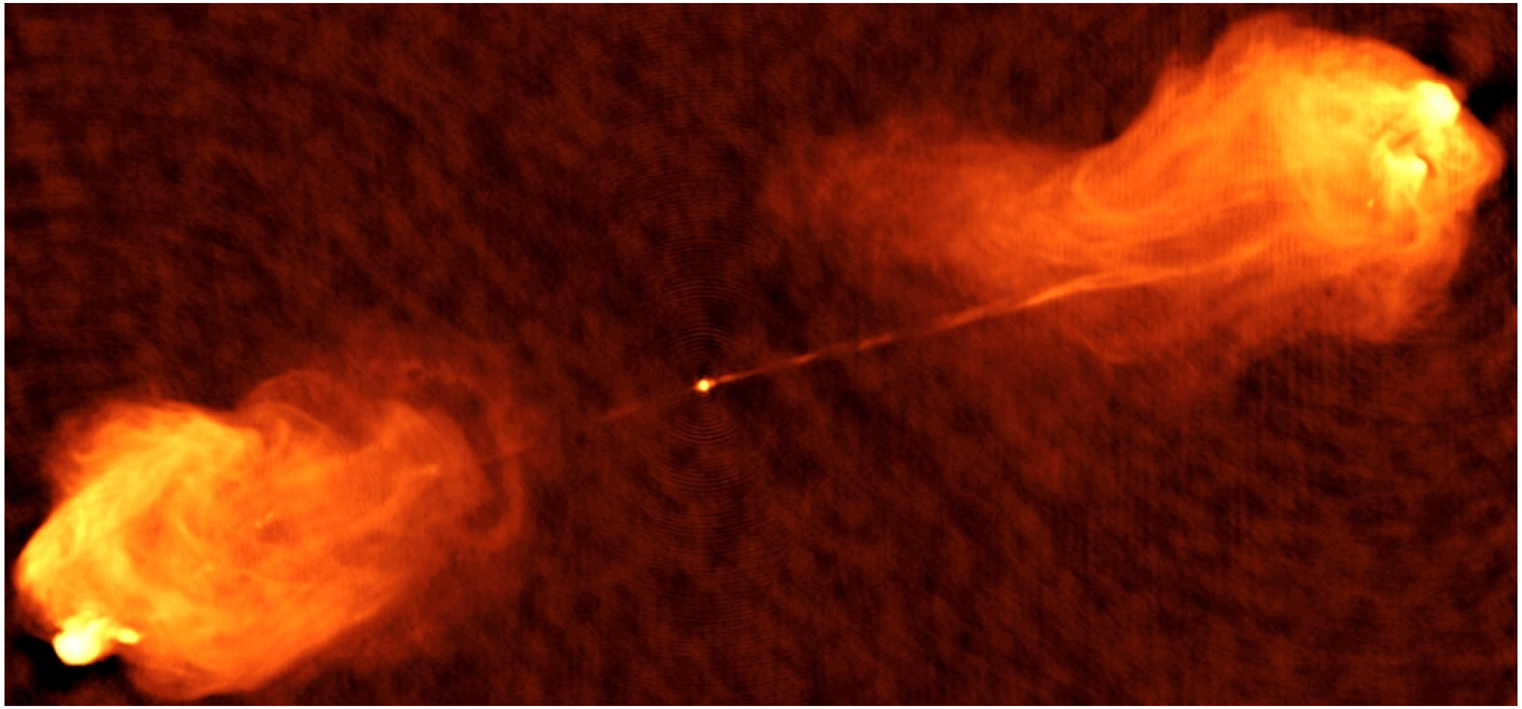

Seyfert Galaxies
IC 4329A
NGC 3516
Markarian 279
NGC 3786
NGC 5728
NGC 7674

Active galaxies: quasars

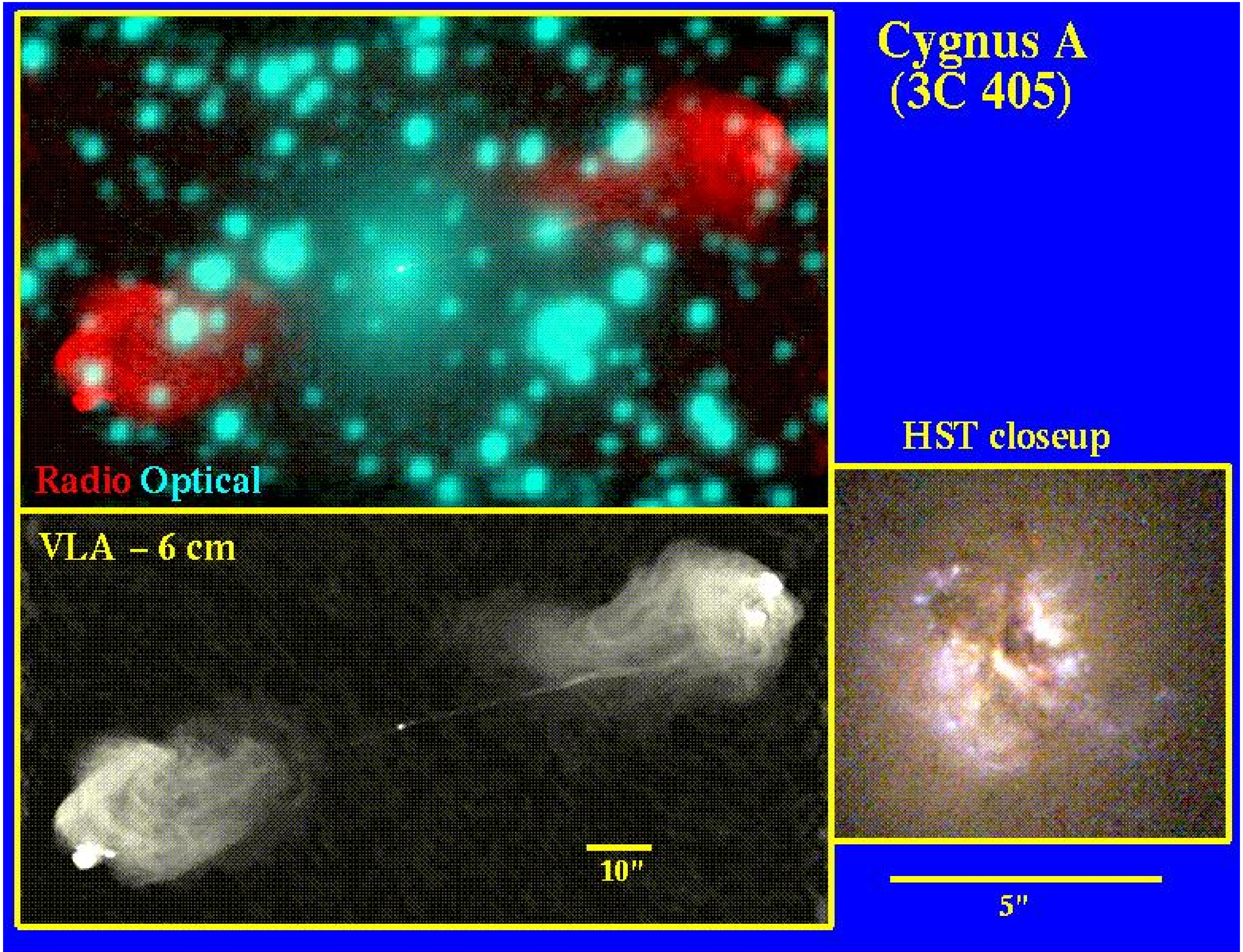
HST images of more luminous and more distant active galaxies. Here the compact nucleus easily outshines the host galaxy and it requires a very high-quality image to detect the galaxy at all. Hence the name quasar, or QSO: “quasi-stellar” object. In a short exposure optical image, we just see the compact nucleus, so it’s indistinguishable from a star.


Radio–loud
3C 351
PKS 1302–102
PKS 2349–013
Radio–quiet
PG 1116+215
PHL 909
Q0316–346
PG 1402+261
PG 0052+251
QSO Host Galaxies
HST images
10″

Active galaxies: jets



Cygnus A (3C405) imaged at 5GHz


Cygnus A
(3C 405)
Radio Optical
VLA – 6 cm
10″
HST closeup
5″

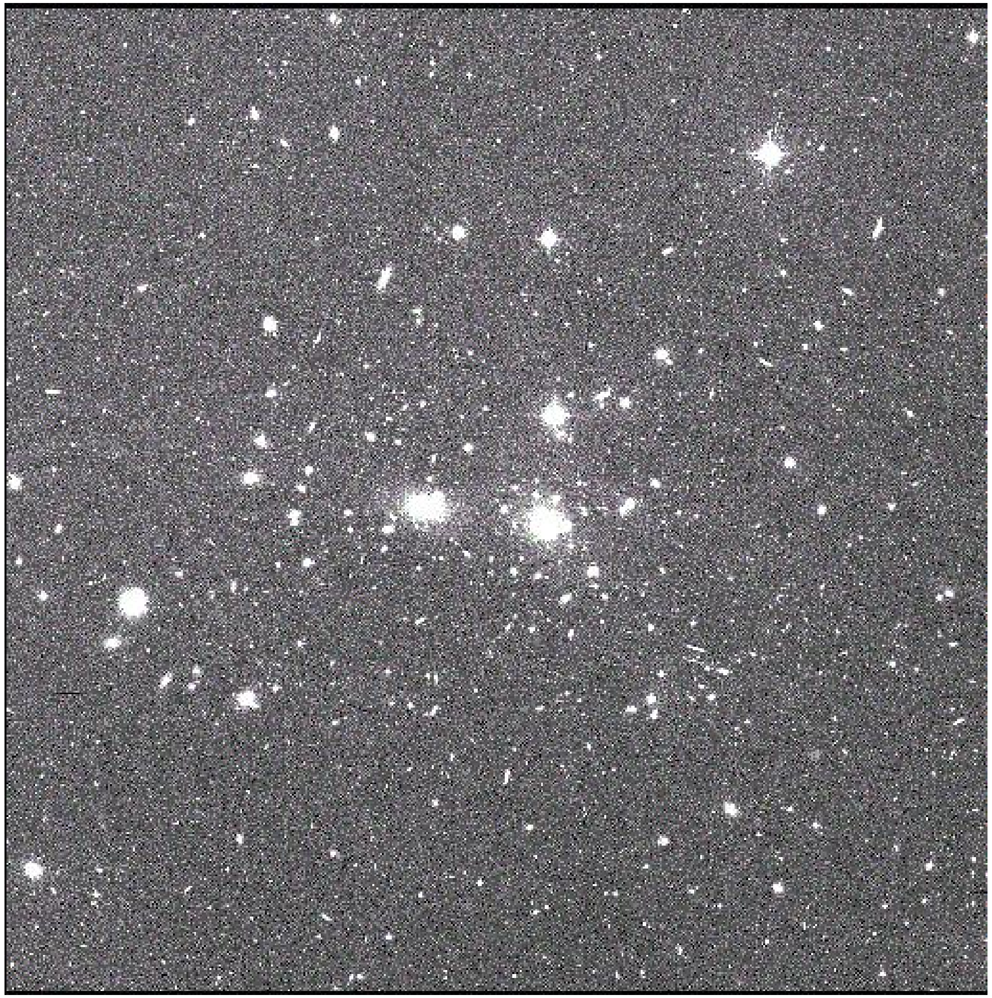
Clusters of galaxies

- The galaxies themselves comprise only a small fraction of the mass of a cluster.

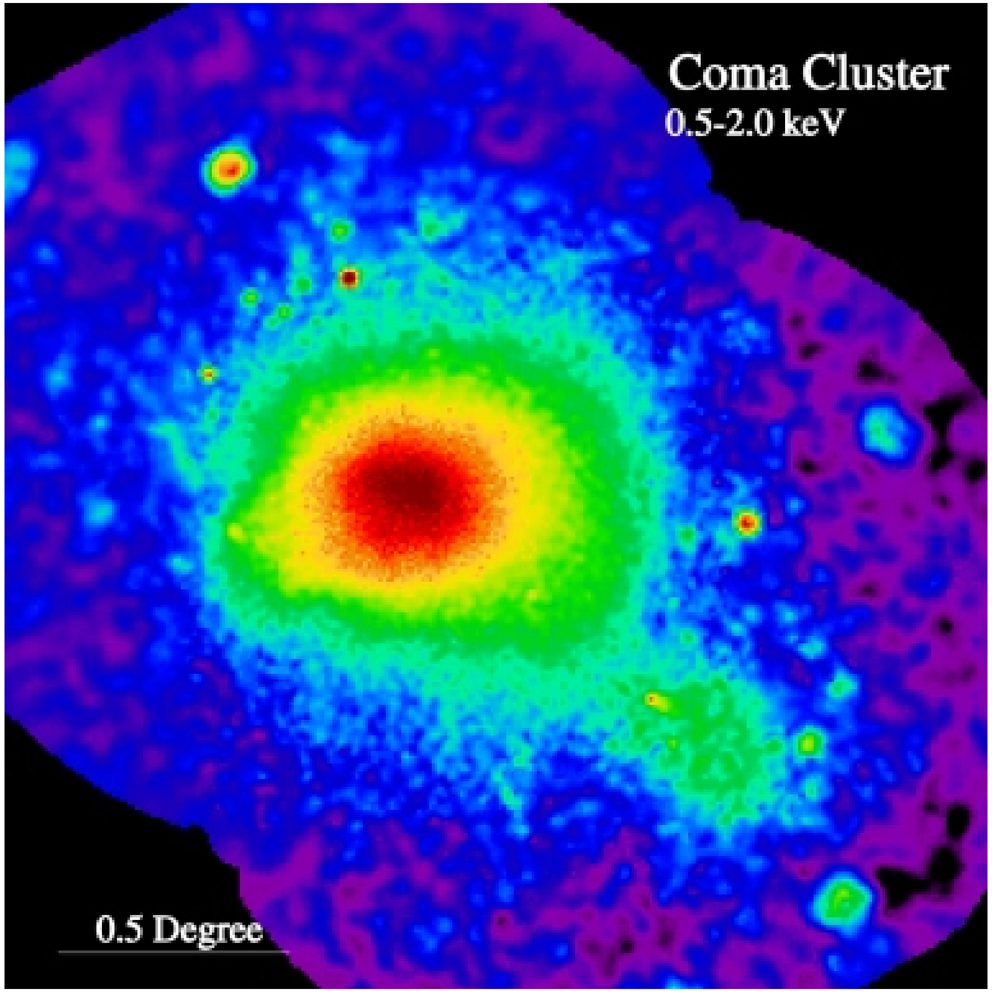
- About ten times as much mass is present in diffuse plasma lying between the galaxies, and about ten times as much again is in *dark matter* which gravitates but otherwise does not interact with the rest of the matter.

- Thus the gravitational potential well is about one hundred times as deep as would be expected from the mass of the galaxies alone. The most massive clusters have masses up to 10^{15} times that of the sun, and the intracluster gas can reach temperatures of hunderds of millions of kelvin.

Galaxy clusters: Coma cluster in optical



Galaxy clusters: Coma cluster in X-rays



Dead stars and their remnants

The most massive stars, and white dwarfs which accrete over the Chandrasekar limit, end their lives as supernovae or even hypernovae. The explosions can send out enormous quantities of energy in gamma-rays and neutrinos which can be seen at intergalactic distances. The blast waves of the explosion then create strong shocks in the interstellar medium, which in turn accelerate electrons and produce bright synchrotron emission. Details of the processes which create the supernovae in the first place will be dealt with in Prof. Podsiodlowski's course.

Cas A supernova remnant, 6cm radio image