

# Oxford Physics: Part C Major Option Astrophysics



## **High-Energy Astrophysics**

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## **Synopsis**

- (i) Introduction; astrophysical objects observed at various energies; brightness temperature.
- (ii) Supernova blast waves; shocks.
- (iii) Acceleration of particles to ultra-relativistic energies.
- (iv-v) Synchrotron emission; total power; spectrum; self-absorption; spectral ageing.
- (vi) Accretion; properties of accretion discs; Eddington luminosity; evidence for black holes.
- (vii) Relativistic jets; models of jet production; relativistic projection effects; Doppler boosting.
- (viii) Cosmic evolution of AGN; high-energy background radiation and cosmic accretion history of black holes.
- (ix) Bremsstrahlung; inverse-Compton scattering; clusters of galaxies; Sunyaev-Zel'dovich effect.
- (x-xi) Cosmic rays and very high energy gamma rays; Cherenkov telescopes; example finals questions.

## Books

The single book which covers most material is *High Energy Astrophysics* by Malcolm Longair. The new one-volume edition is up-to-date with recent observations.

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

- Philosophy
- 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.

## **Philosophy**

Many of the physical processes we will study in this course have exact mathematical descriptions which are either very lengthy, or can only be solved by numerical methods. My aim is to focus on showing you as many interesting advanced physics topics in the time available, and we will often make approximations—justifiable approximations—to get to a shorter mathematical description of the situation.

You will learn a lot about how physics is actually done as a part of this process! But I will provide you with links to the relevant fully detailed research papers where possible.

## Observing the whole EM spectrum

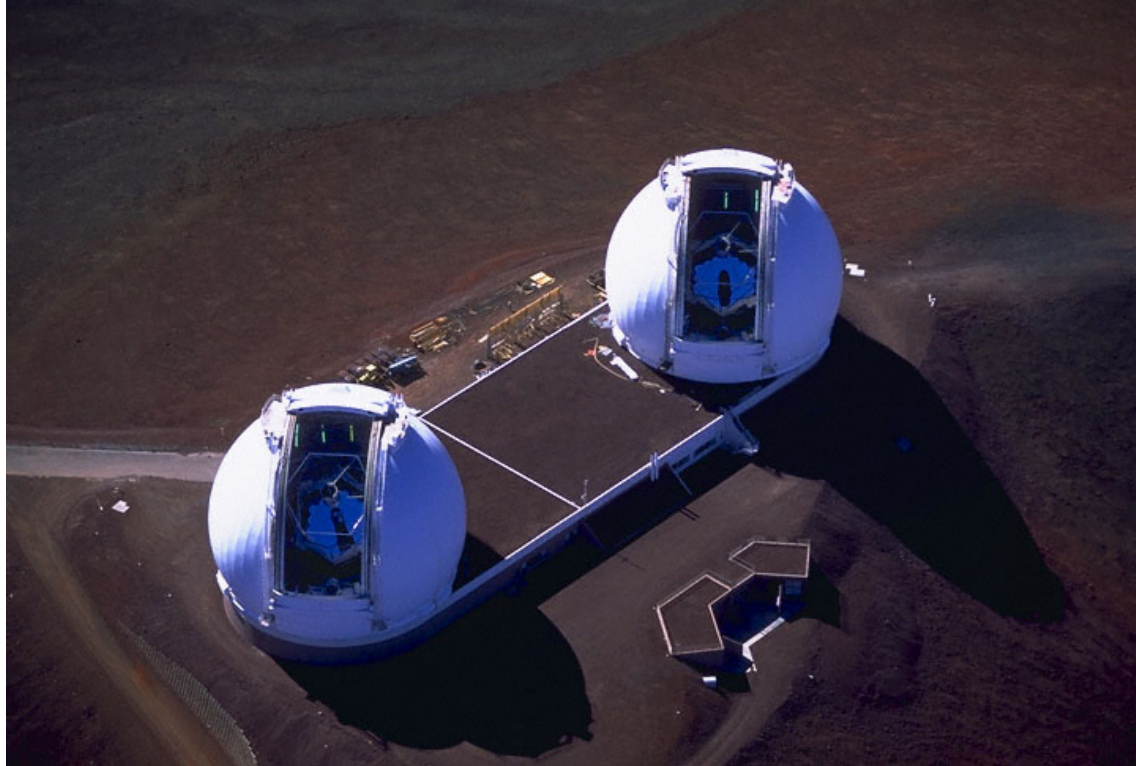
Modern astronomical telescopes and detectors span the observational range from tens of metres in the radio to hundreds of TeV for the highest energy gamma rays. The classification of different astronomical wavebands is generally driven by the technology used in the detectors.

- 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 ( $\sim 0.3$  mm to  $\sim 10$   $\mu\text{m}$ ). Bolometers onboard satellites and high-altitude terrestrial sites.

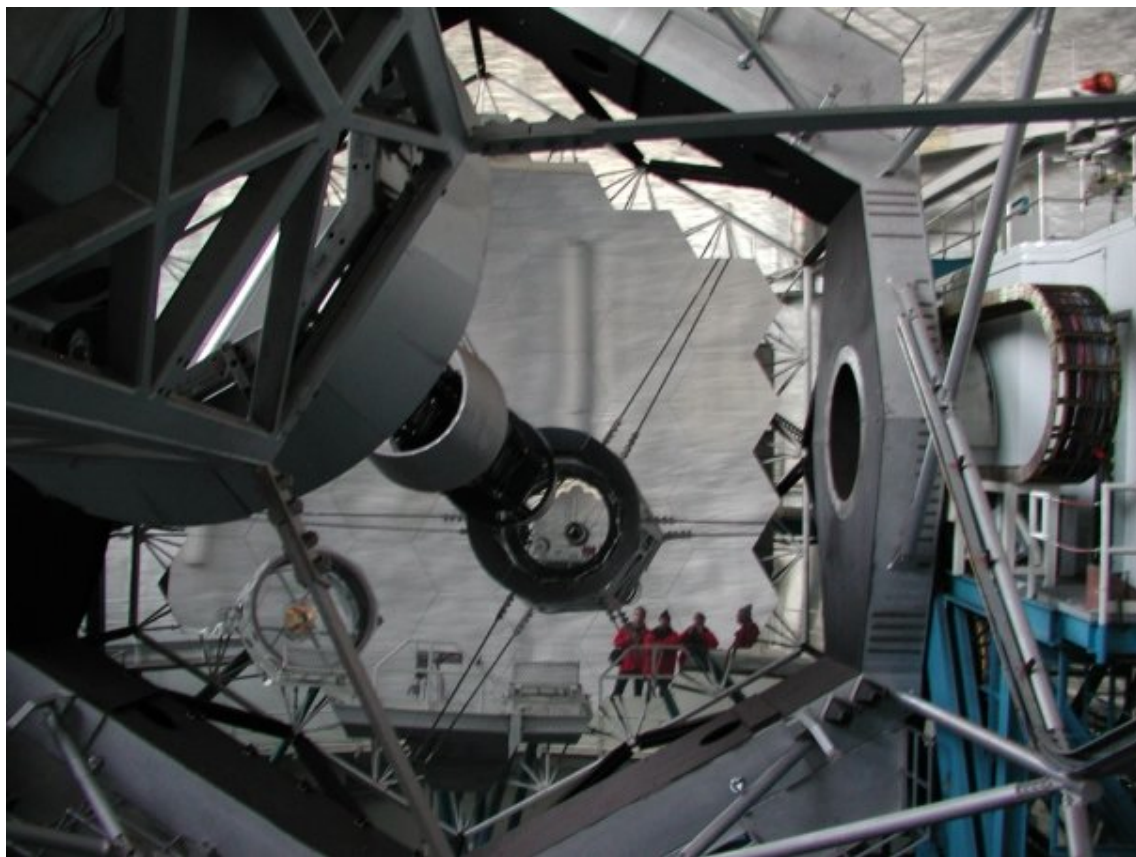
- Infrared ( $10\ \mu\text{m}$  to  $1\ \mu\text{m}$ ) and optical ( $1\ \mu\text{m}$  to  $0.3\ \mu\text{m}$ ). Almost all of “traditional” astronomy. Most stars put out most of their energy in this range. Unsurprisingly the human eye is adapted to use these wavelengths!
- Ultraviolet ( $0.3\ \mu\text{m}$  to  $\sim 3\ \text{nm}$ ). Satellite-borne instruments are needed because the atmosphere is opaque now; but we can still use essentially “ordinary” telescopes.
- X-rays ( $3\ \text{nm}$  to  $\sim 3 \times 10^{-12}\ \text{m}$ ;  $0.4\ \text{keV}$  to  $\sim 100\ \text{keV}$ ). Satellite- and rocket-borne instruments are needed. Special grating-incidence mirrors are used to focus X-rays.

- Gamma-rays ( $\sim 100 \text{ keV}$  up to hundreds of  $\text{GeV}$  ). Again telescopes are satellite-borne. Use similar detectors to particle physics experiments.
- Very high-energy photons and particles entering the Earth's atmosphere produce *Cherenkov 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.



European Southern Observatory, Cerro La Silla, Atacama Desert, Chile

August 2011

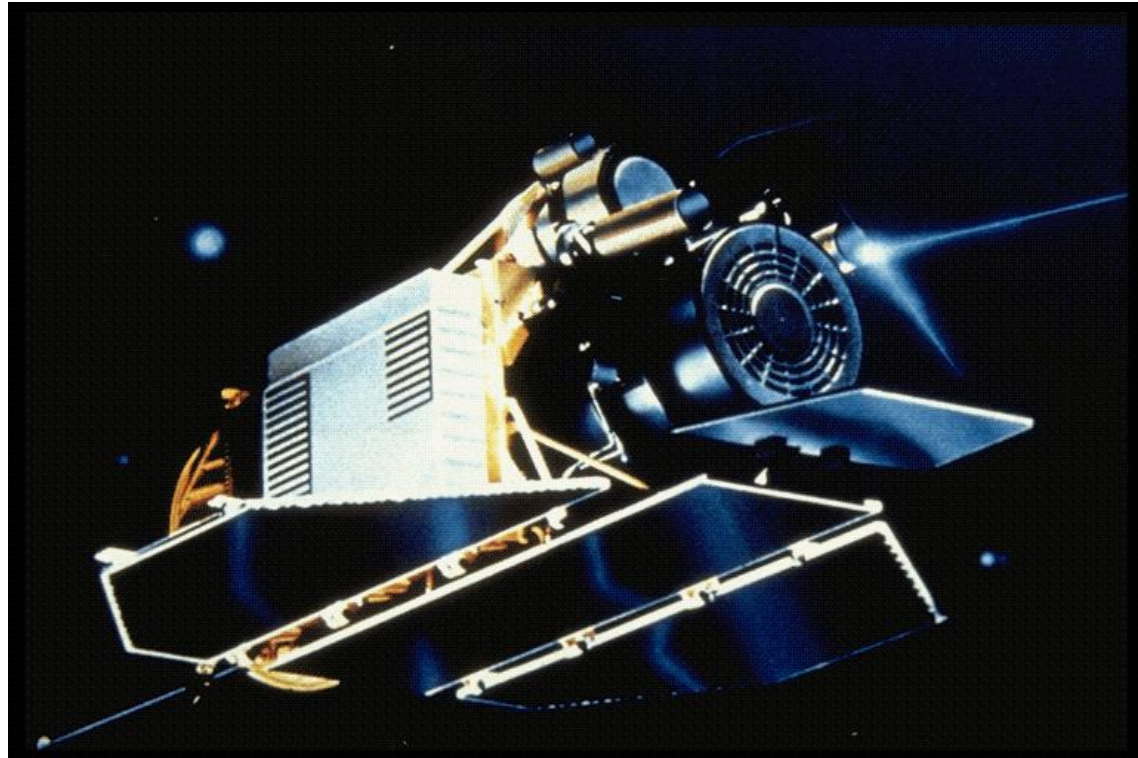




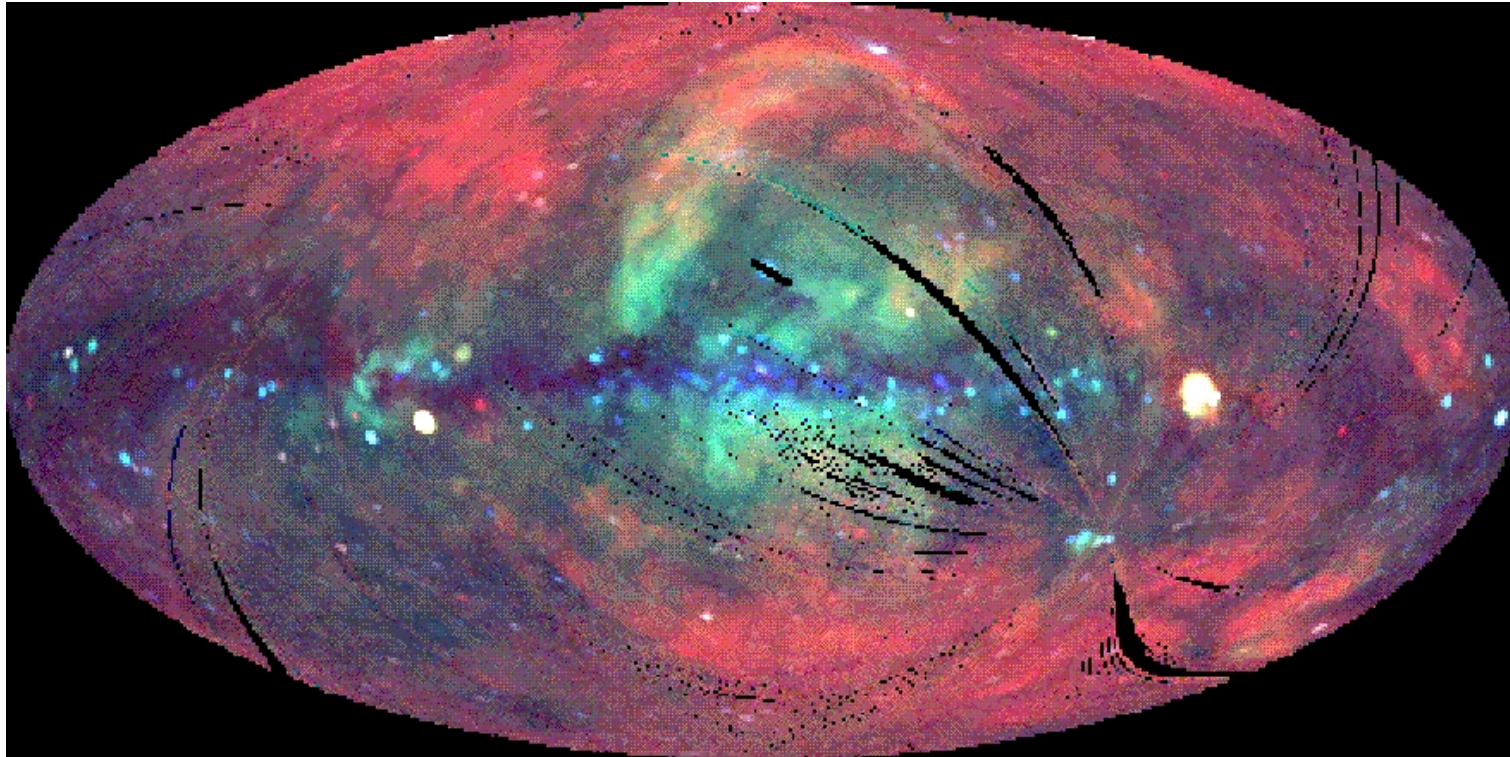
Very Large Array in New Mexico. Radio interferometer, 73 MHz—43 GHz. 27 antennae, baselines up to 36 km.



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)

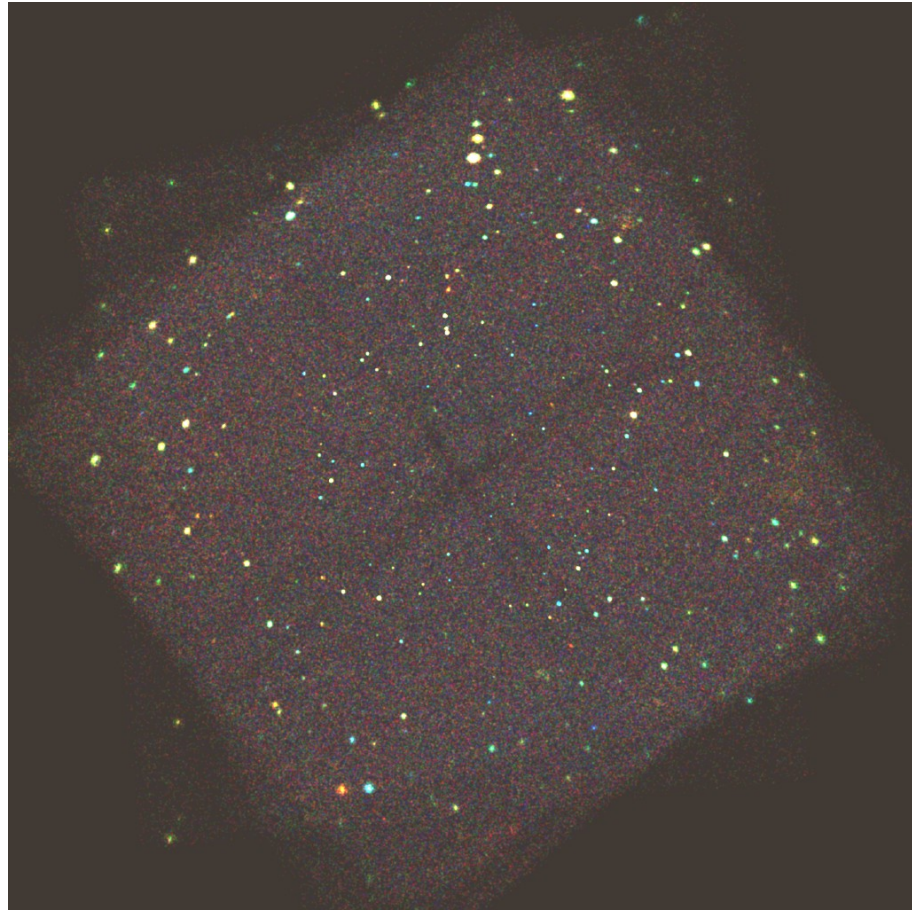


ROSAT (Röntgensatellit) X-ray observatory 1990—2011



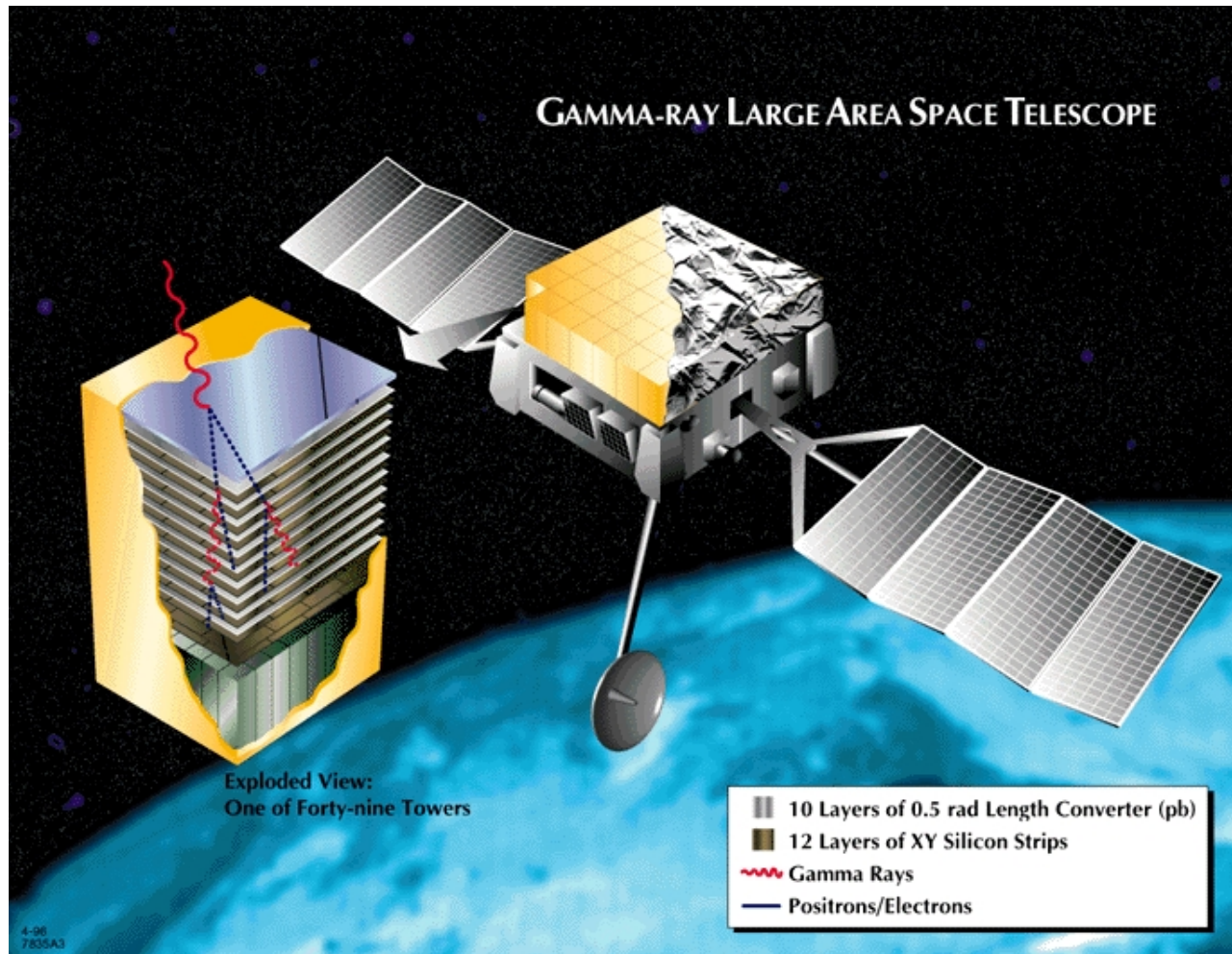
ROSAT all-sky survey. Note the fairly uniform background which is caused by unresolved extragalactic point sources





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

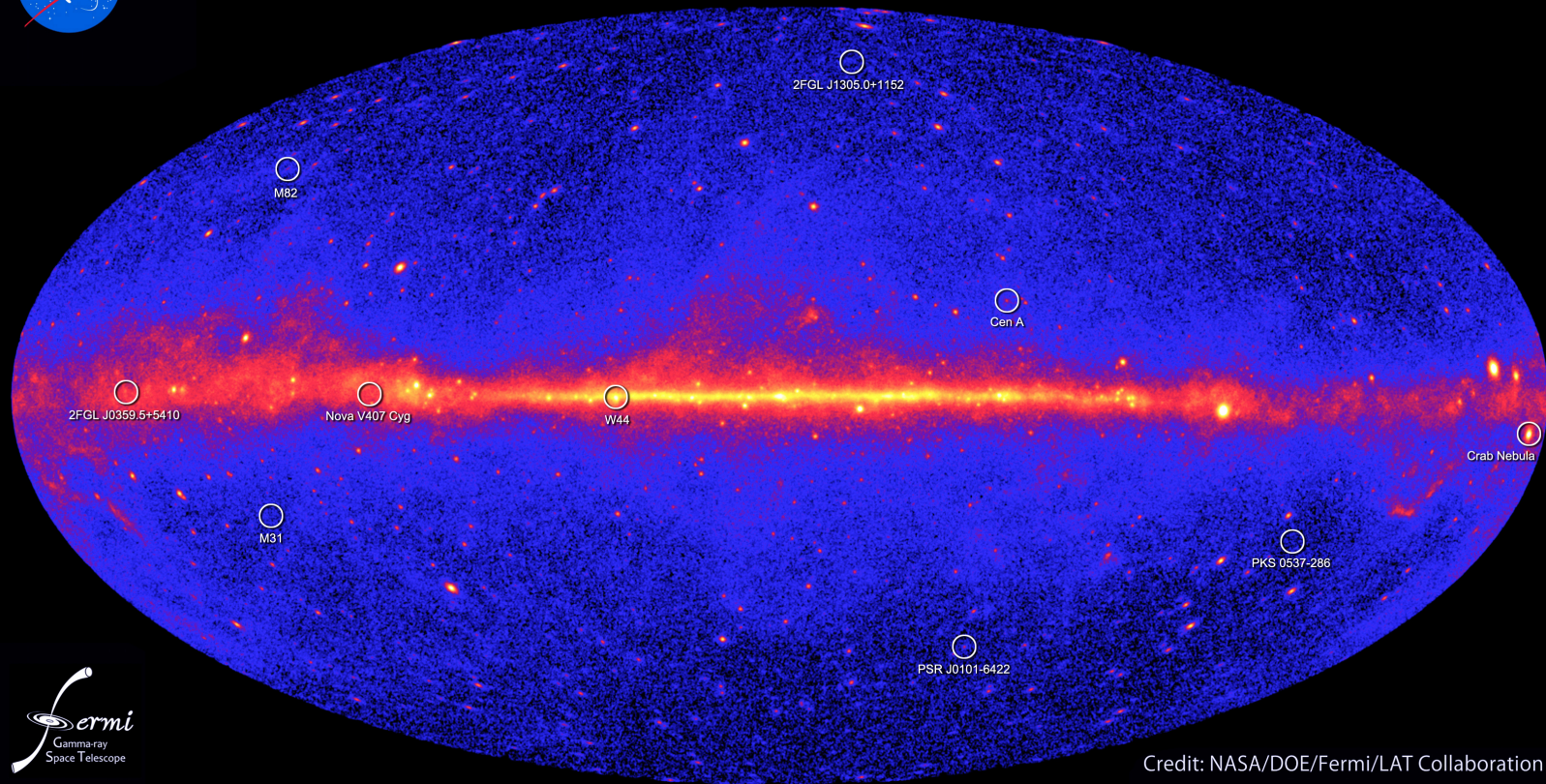
We can now see the individual X-ray sources.



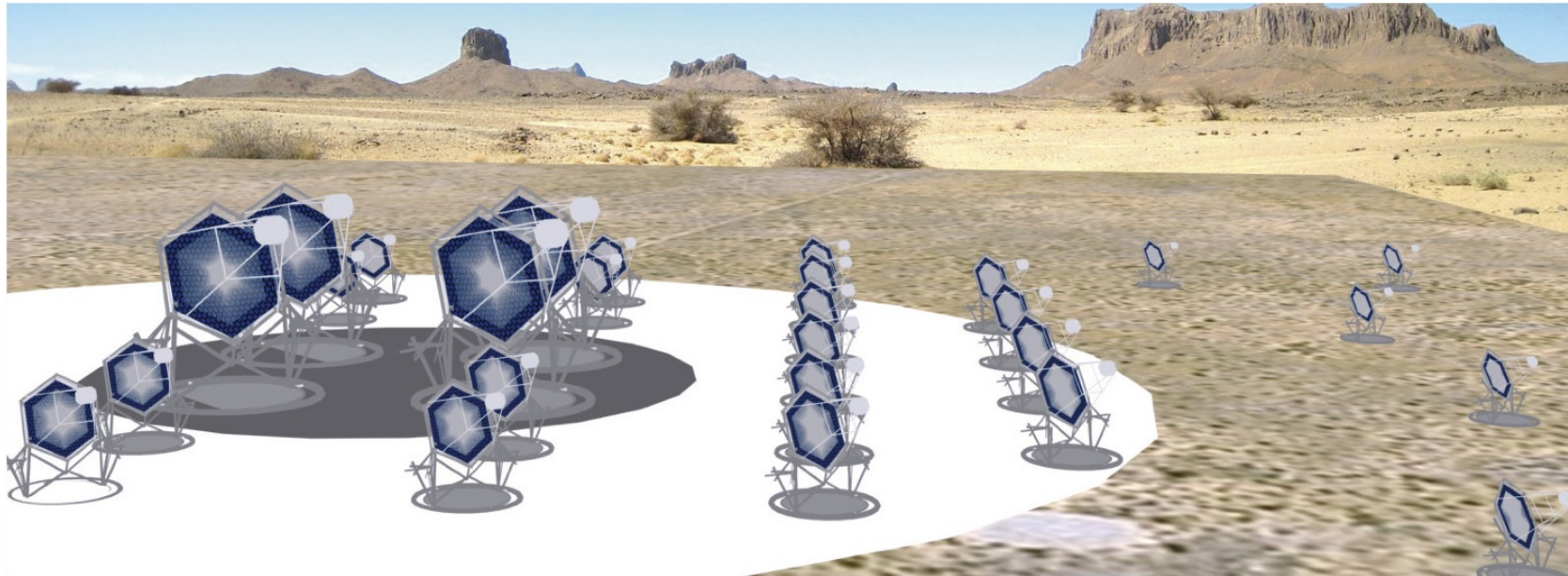
*Fermi* Gamma-Ray Space Telescope, launched June 11 2008.



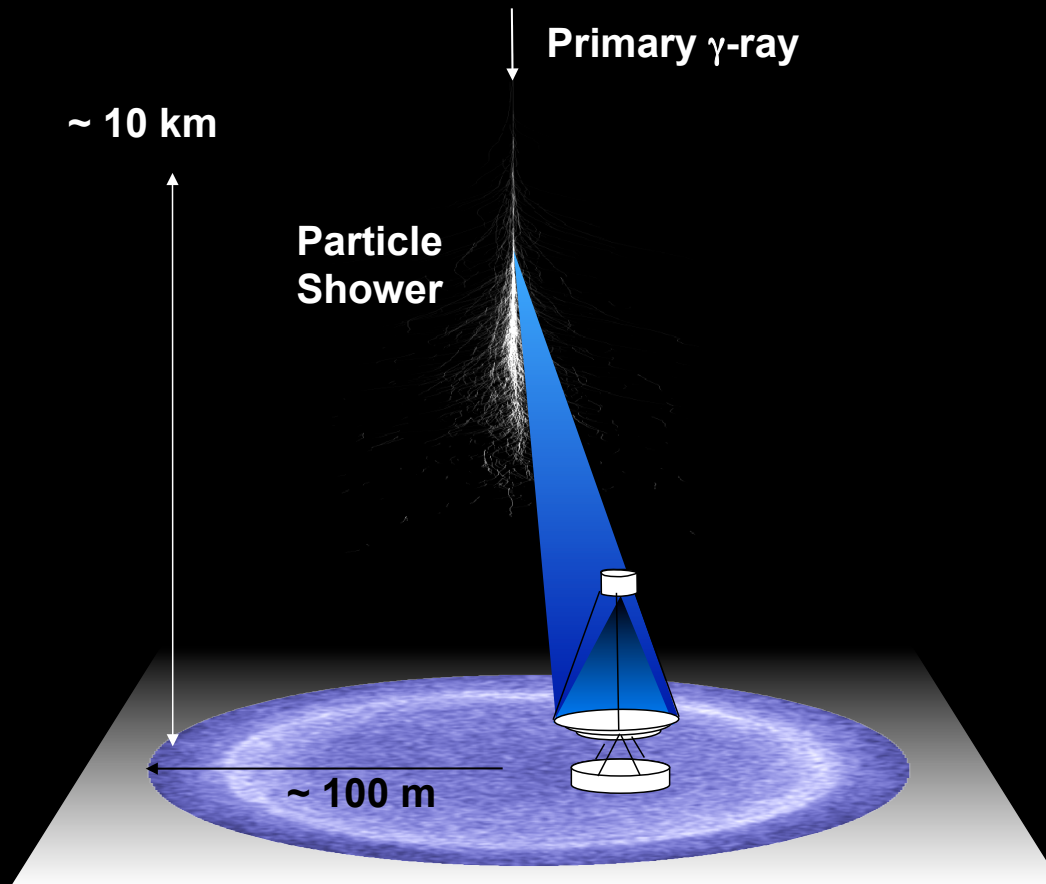
# Fermi two-year all-sky map



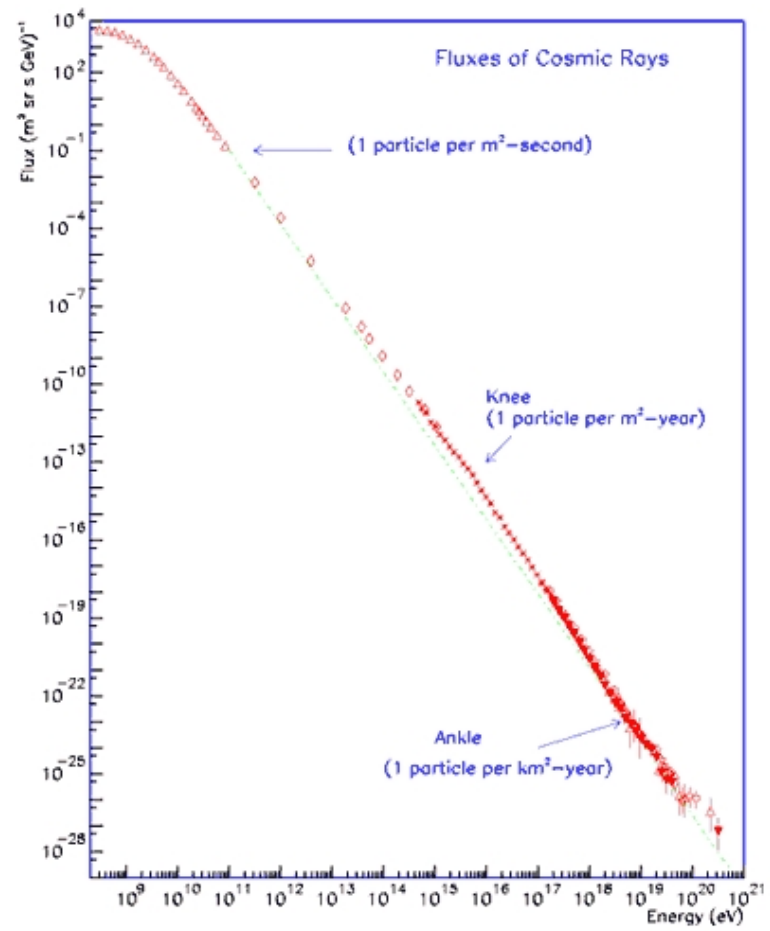
Credit: NASA/DOE/Fermi/LAT Collaboration



CTA - proposed array telescope for observing high-energy Cherenkov showers.



Cherenkov technique (figure from Prof J. Hinton, CTA collaboration).



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):

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

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  $\sim 1$  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

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

- 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  $I_\nu$ . You will often also see it in units such as Jansky per square arcsec, or Jansky per square arcminute.

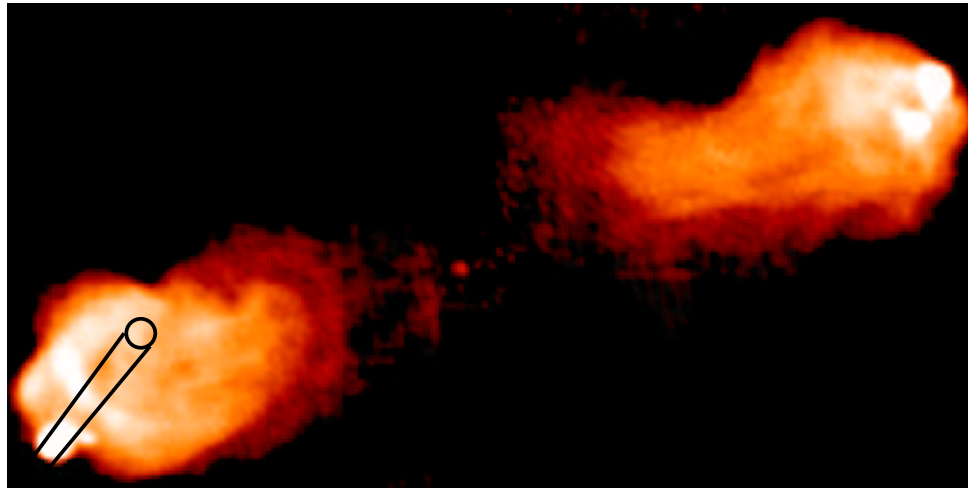




**IRT-3000**

Hand-held infrared thermometer measures temperature via  $\sigma T^4$ .

“Thermocouples were the traditional devices used for this purpose, but they are unsuitable for continuous measurement because they rapidly dissolve.”



Beam solid angle  $\Omega$

Receiver bandwidth  $\Delta \nu$

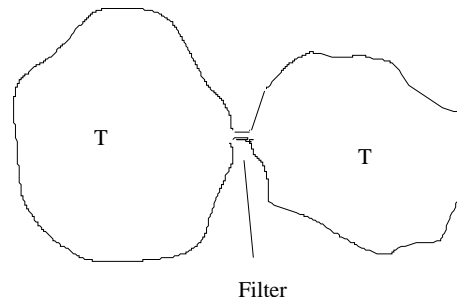


Antenna area  $A$

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  $I_{\nu}$  can only be a function of  $T$  and  $\nu$ .

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

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

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  $I_\nu$  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  $B_\nu$  when referring to the brightness of a black-body and  $I_\nu$  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*

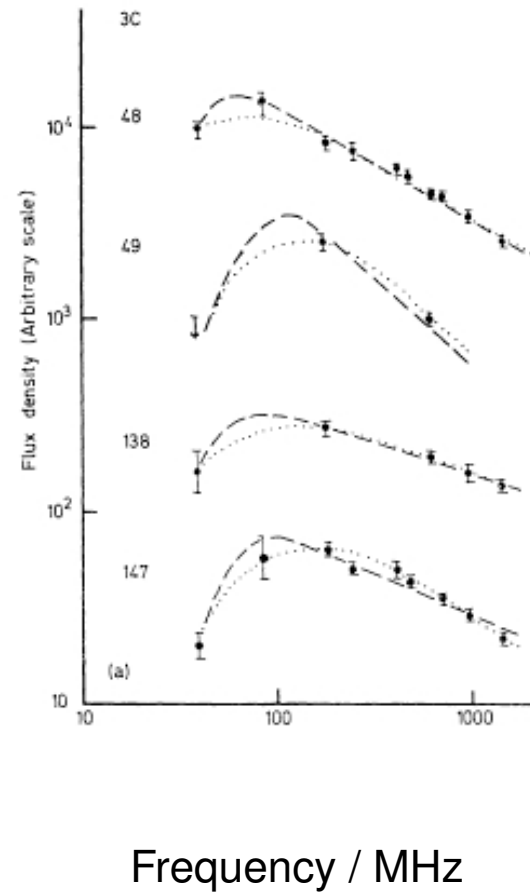
## Extremes of brightness and non-thermal spectra

Most stars radiate approximately as black-bodies, ranging from  $\approx 3000$  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.

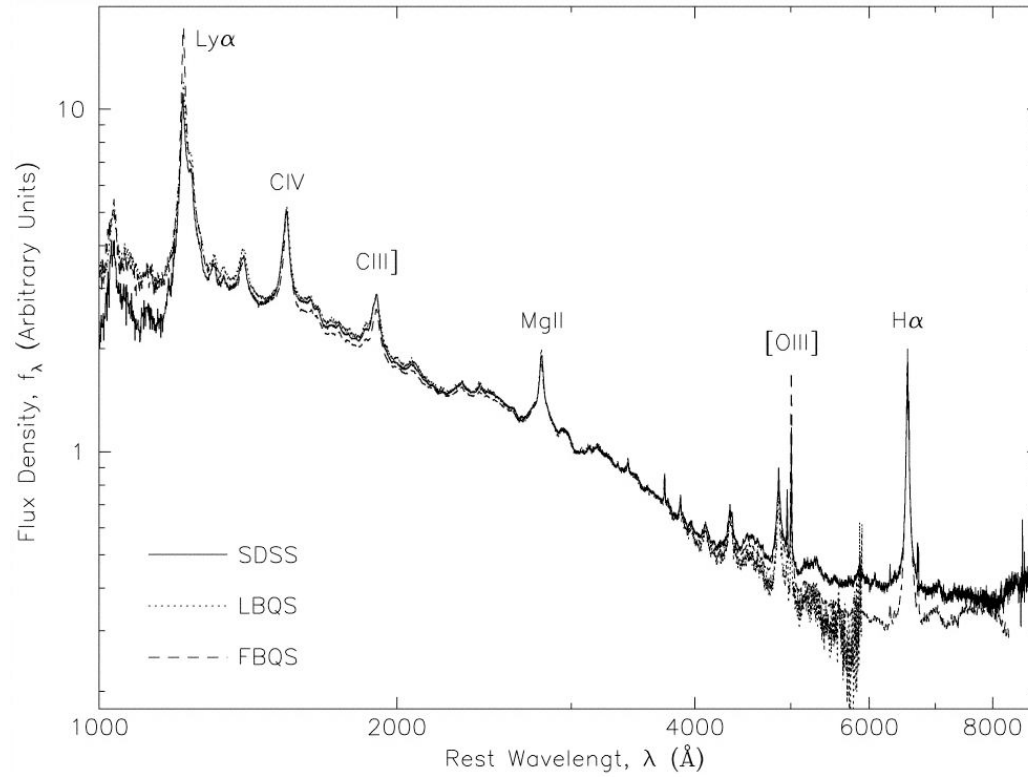
- Particles in the intracluster plasma of massive clusters of galaxies can have temperatures up to  $10^8$  K
- Radio emission from quasars can be sufficiently bright that a black-body would have to be at  $10^{12}$  K to produce the same emission at those wavelengths.

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

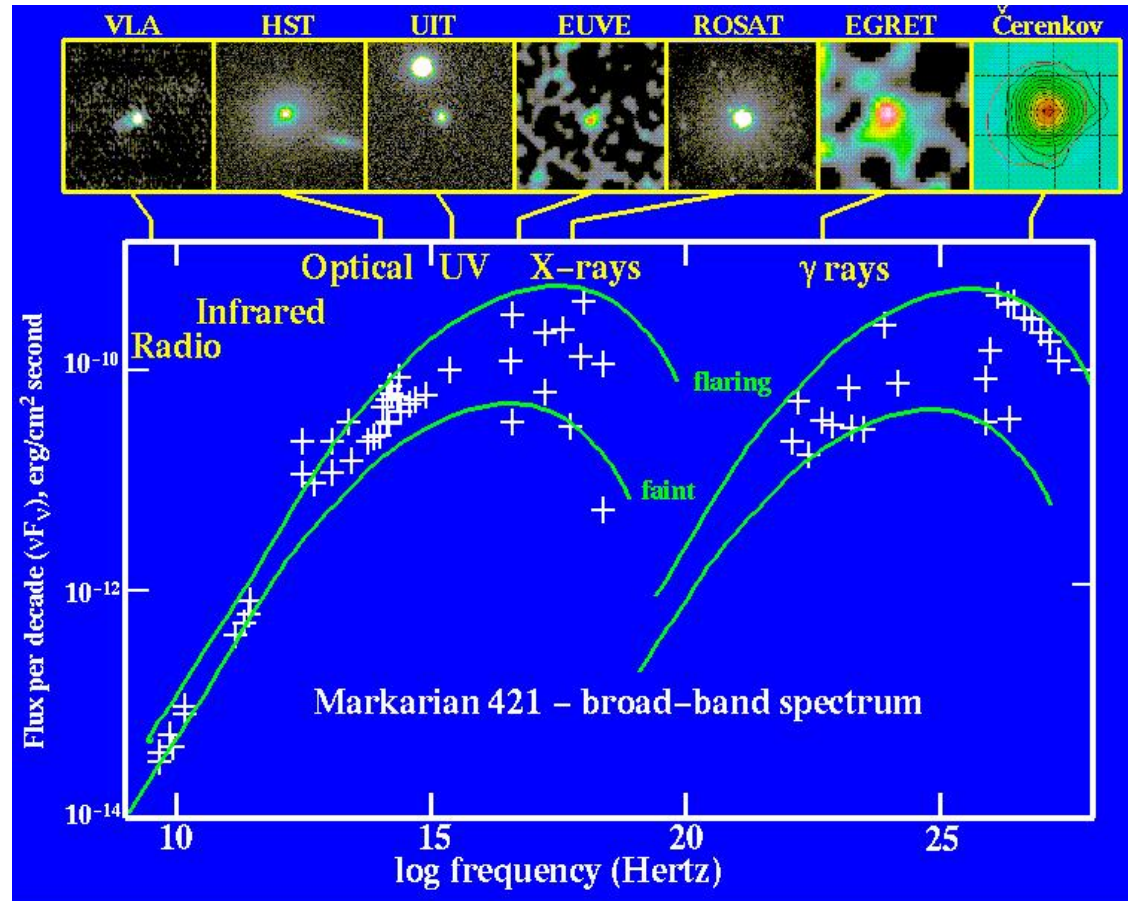


## Average optical/UV spectra of quasars



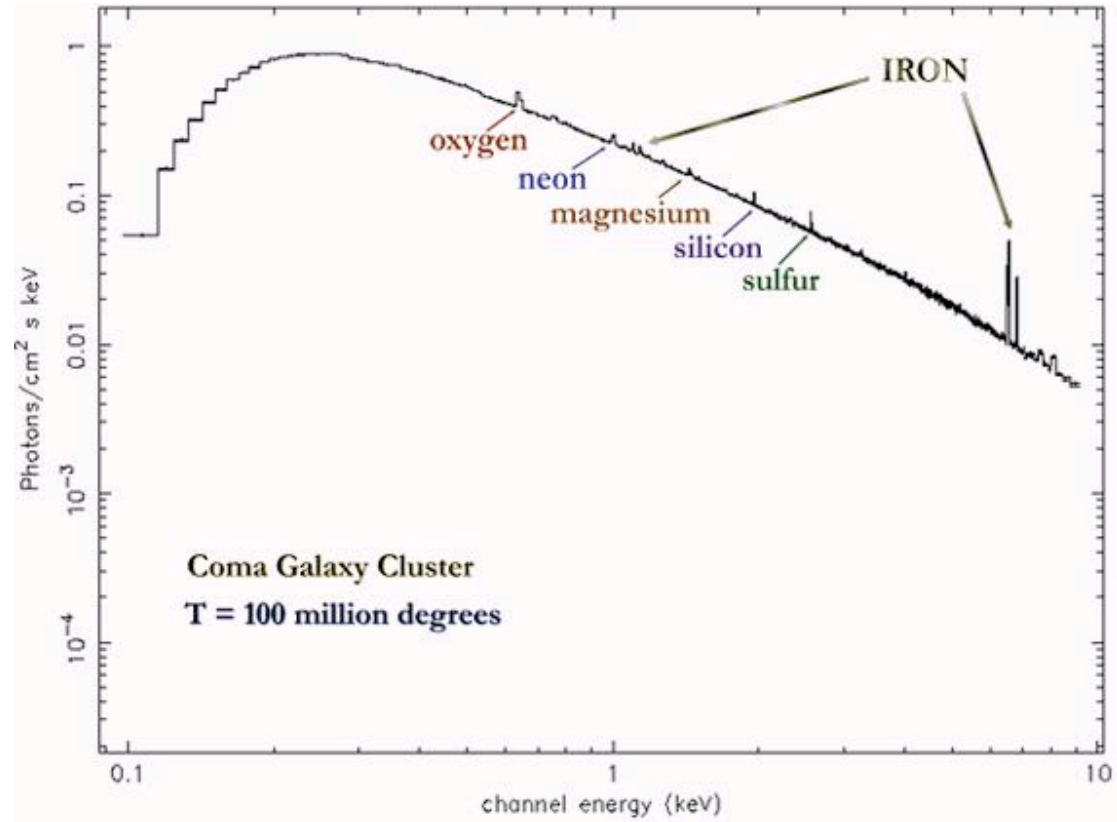
Note non-blackbody spectrum with prominent emission lines.

# Active galaxies: broad-band spectra



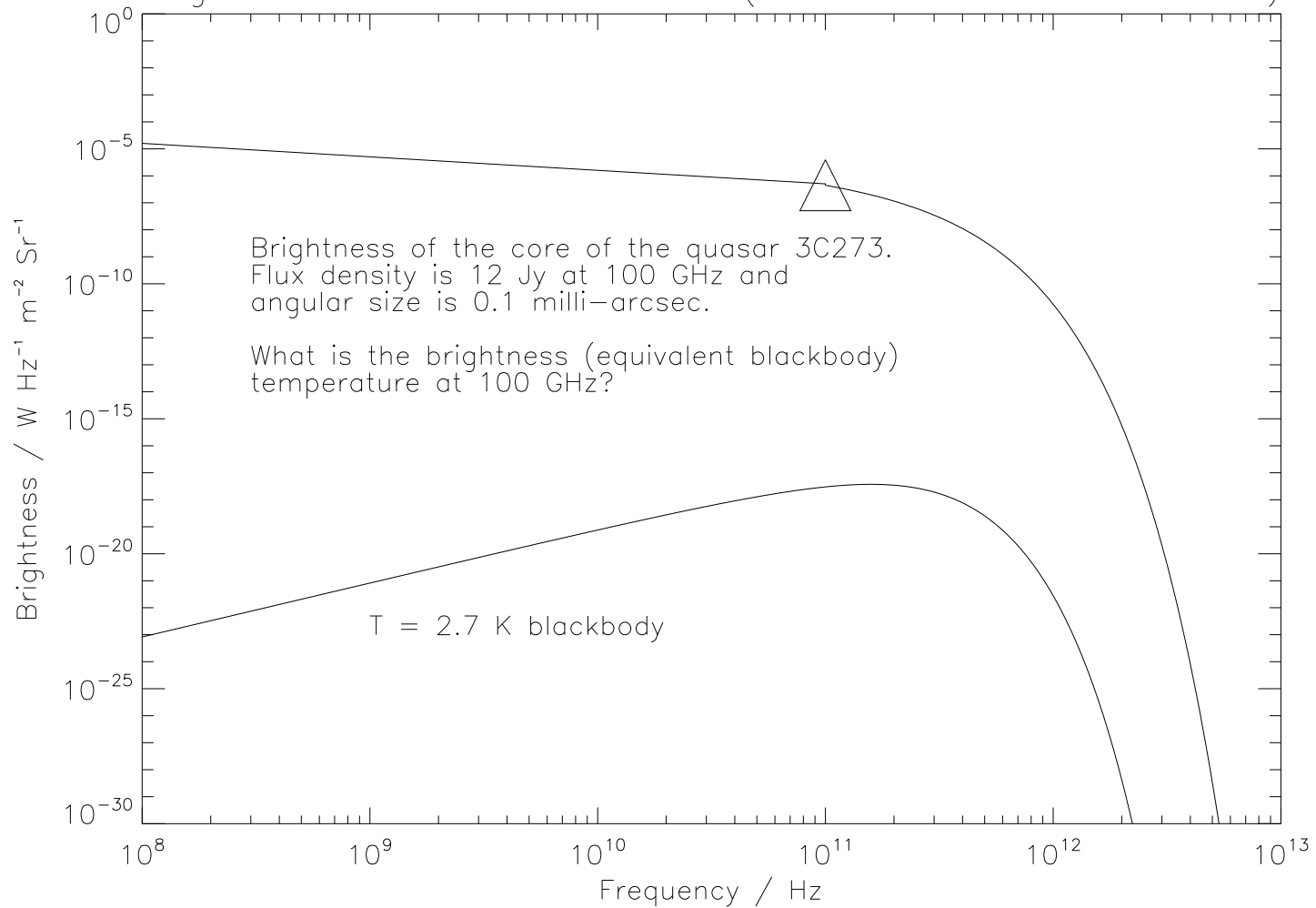


X-ray spectrum of intracluster plasma in the Coma cluster of galaxies

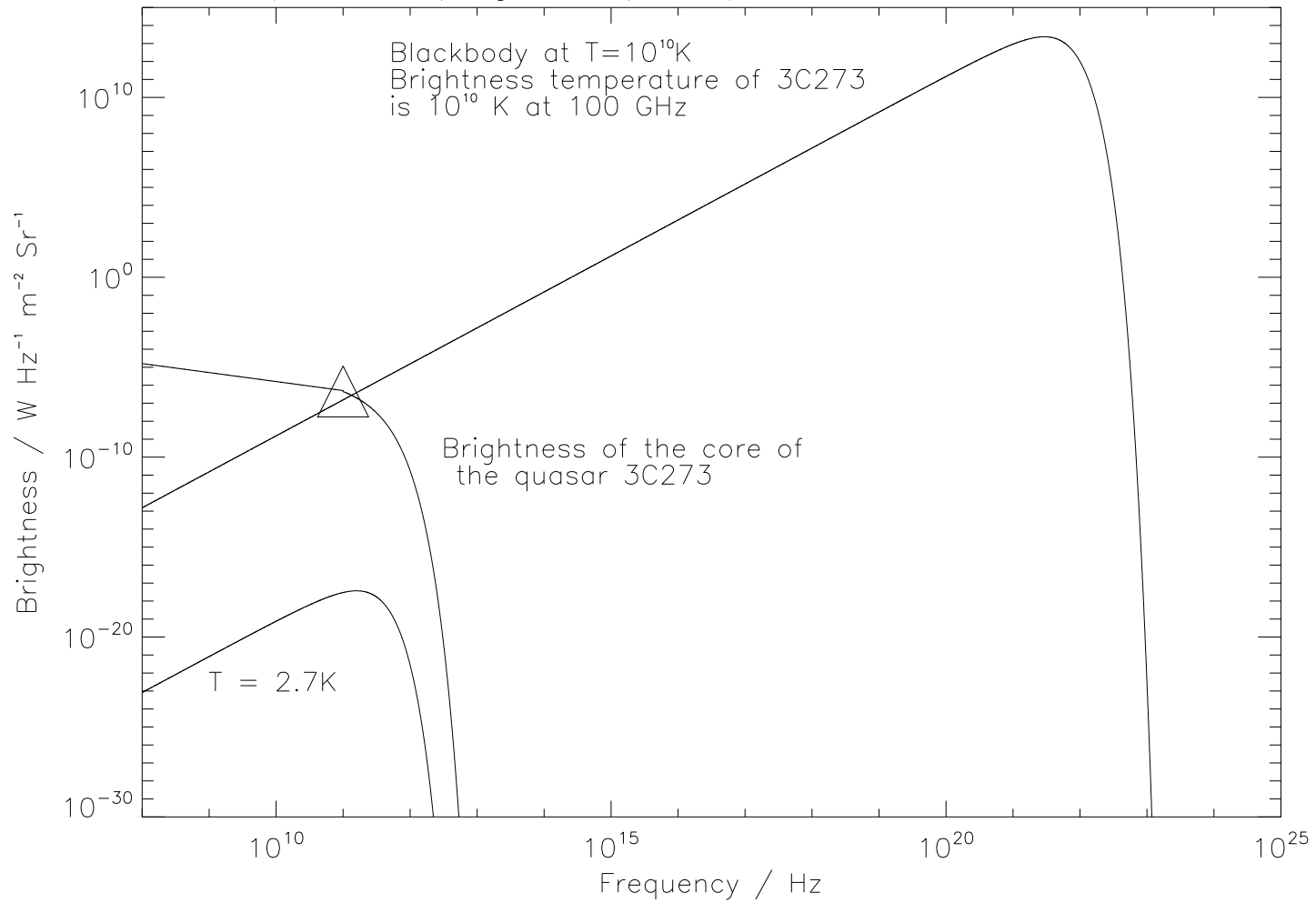


Again note non-blackbody and emission lines.

Brightness of the core of 3C273 (data from Greve et al. 2002)



# Equivalent (brightness) temperature of a radiosource



## **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

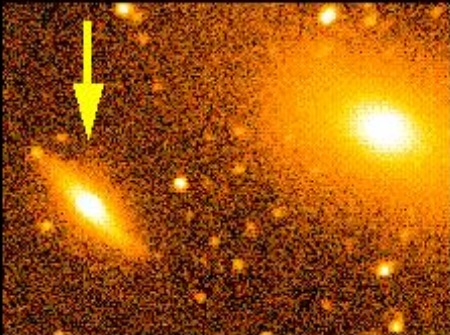
- Galaxies whose nuclei contain supermassive black holes.
- Accretion is the fundamental power source.
- Extremely high-energy particles and X-ray photons are produced near the black hole. The central region often outshines the starlight of the whole galaxy.
- Relativistic jets are sometimes produced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

## **Active galaxies: Seyferts**

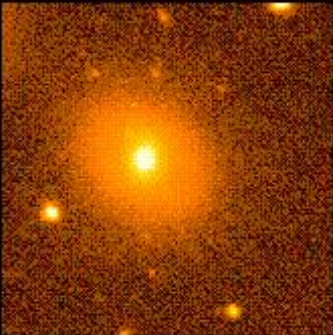
Optical (HST) images of some nearby, *relatively* low-luminosity active galaxies. These objects were first investigated by optical astronomers in the early- to mid-1900's. There is a very bright compact nucleus in normal optical images.

# Seyfert Galaxies

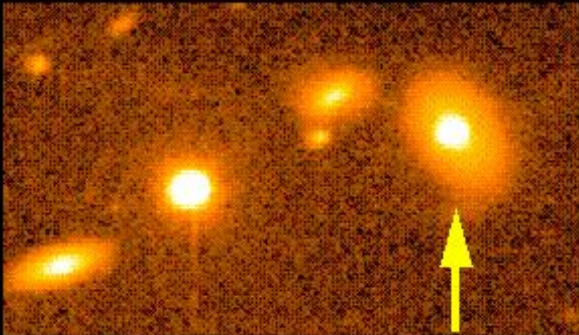
IC 4329A



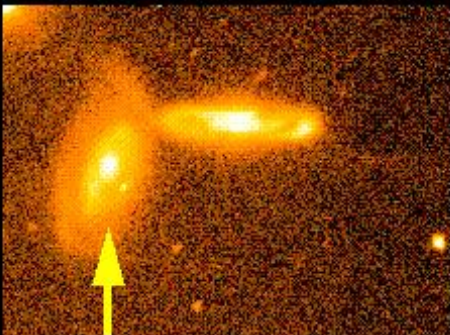
NGC 3516



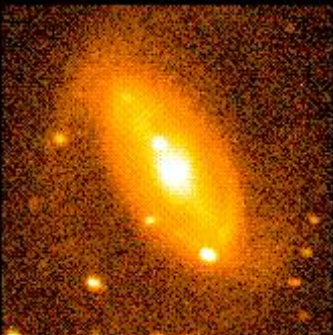
Markarian 279



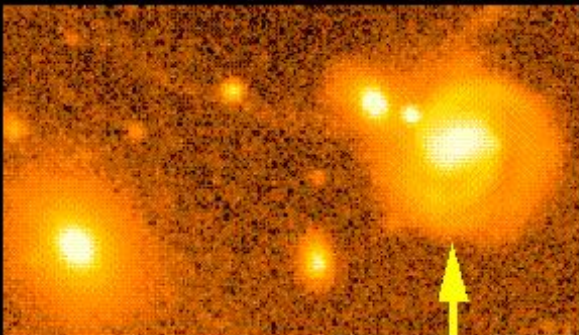
NGC 3786



NGC 5728



NGC 7674

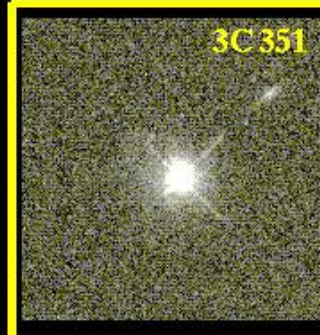


## **Active galaxies: quasars**

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.



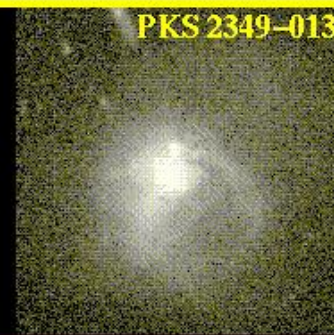
Radio-loud



3C 351



PKS 1302-102

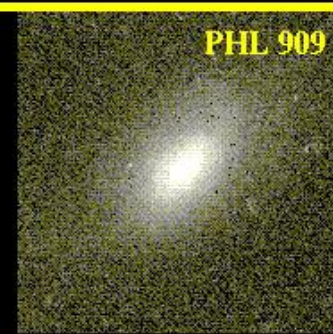


PKS 2349-013

Radio-quiet



PG 1116+215



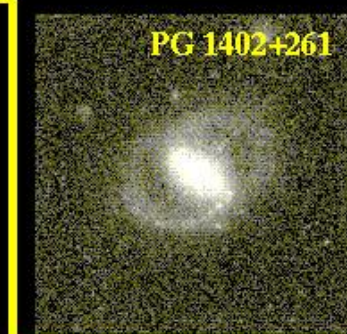
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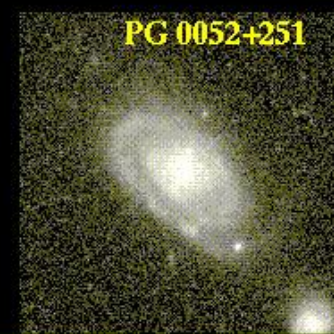
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## QSO Host Galaxies

*HST images*



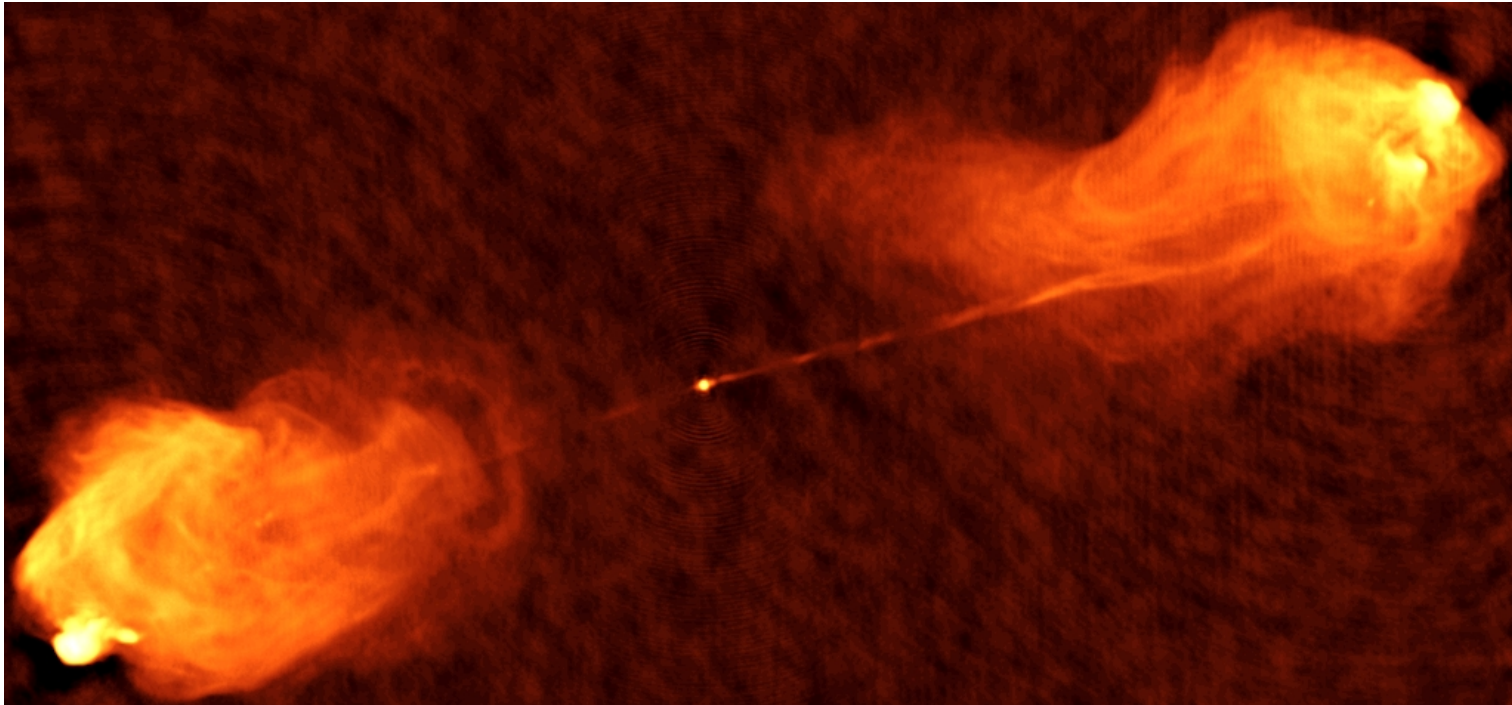
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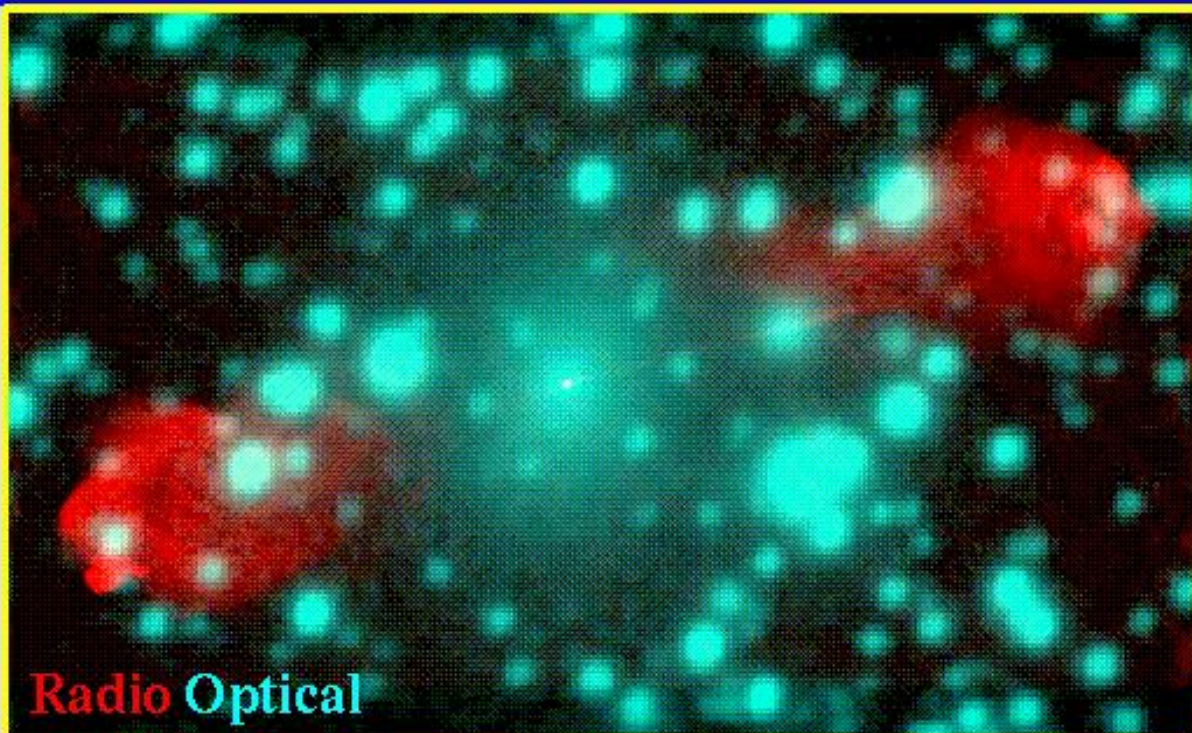
10"

## Active galaxies: jets



Cygnus A (3C405) imaged at 5GHz

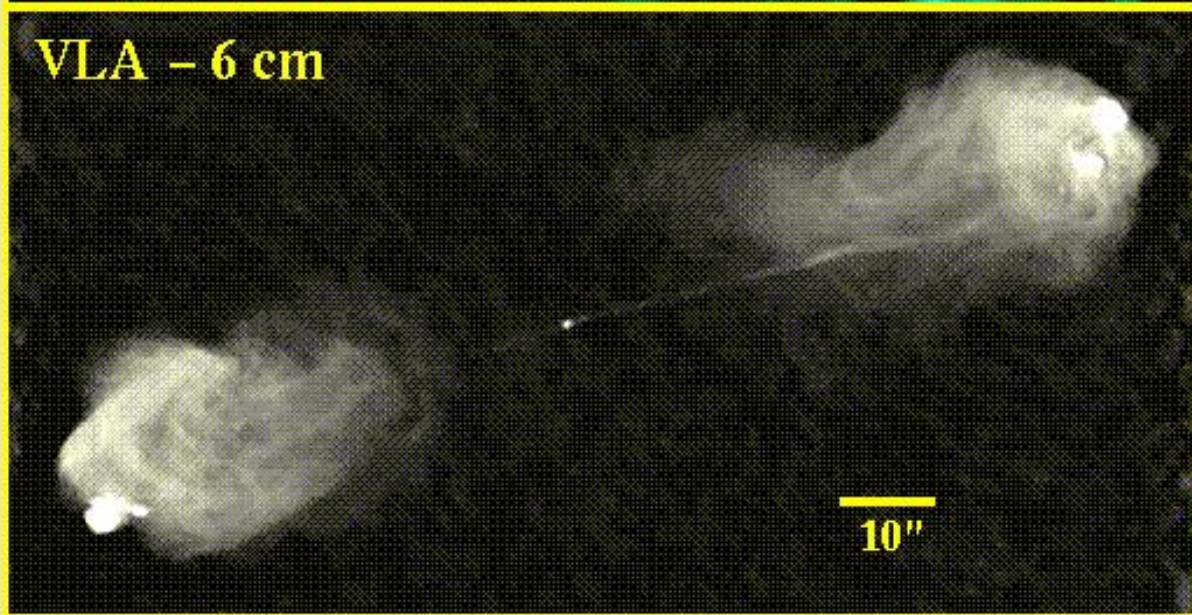
# Cygnus A (3C 405)



Radio Optical

HST closeup

VLA - 6 cm



10"



5"

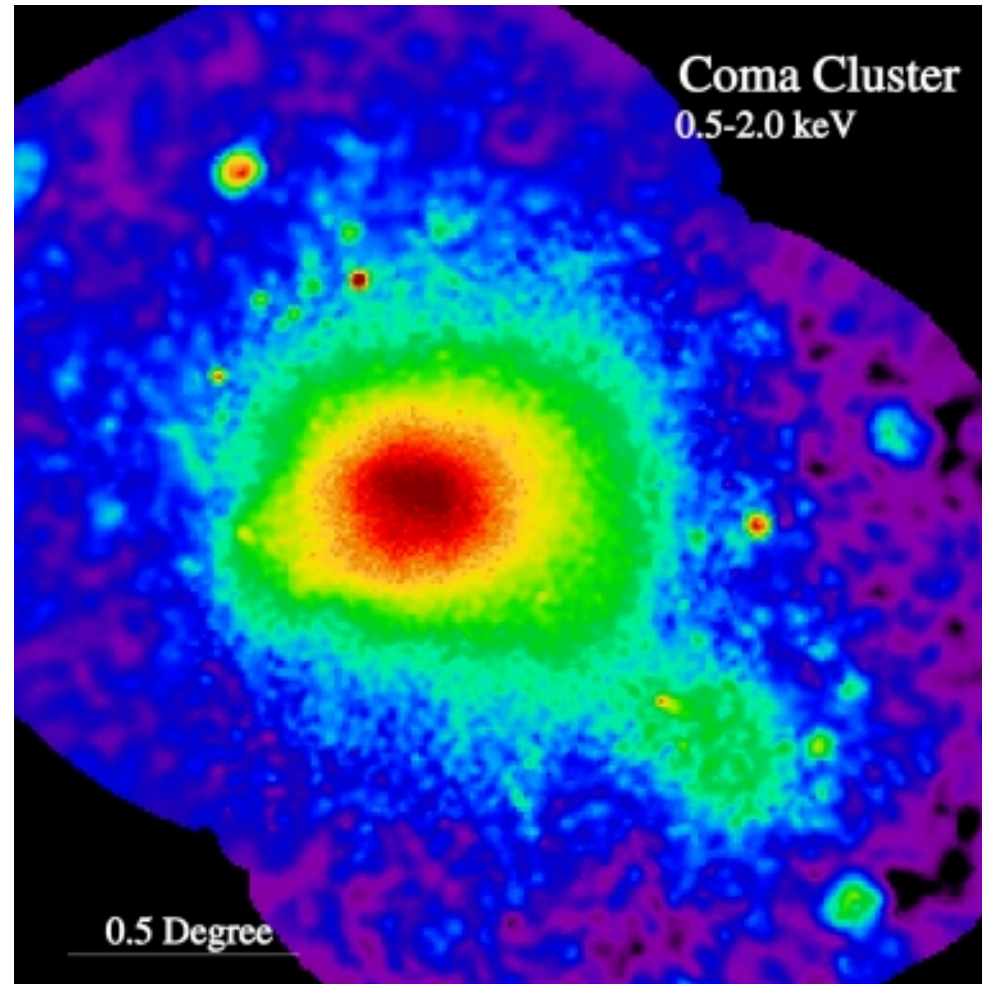
## Clusters of galaxies

- 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 hundreds 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. Podsiadlowski's course.

Cas A supernova remnant, 6cm radio image

