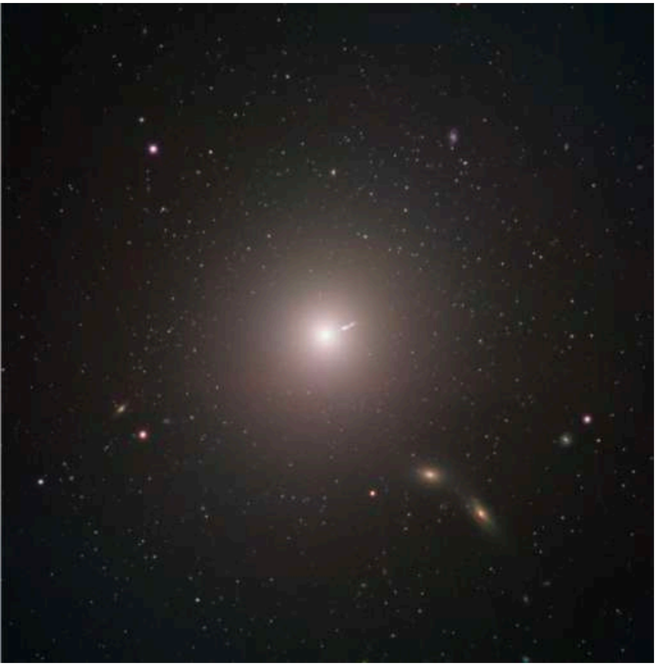
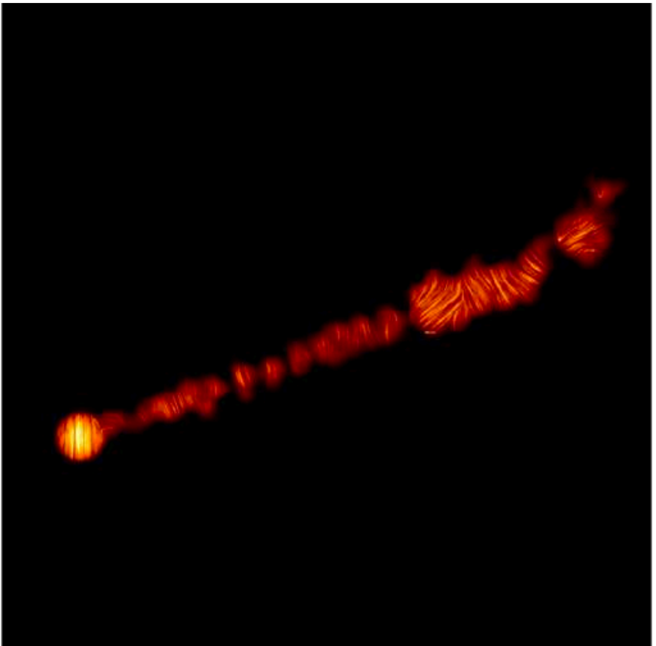
Lecture 10: Observational High-Energy Astronomy



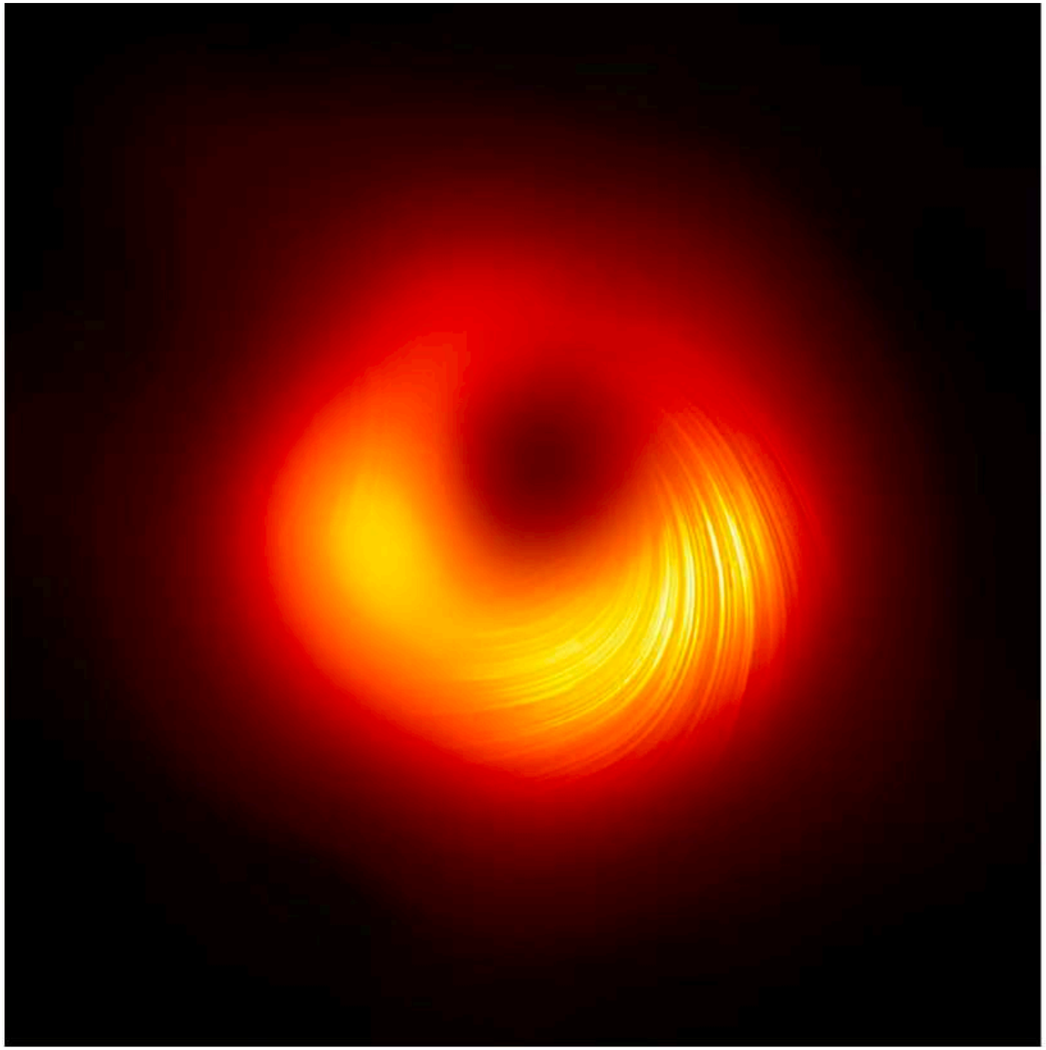


Left: optical image of M87

Right: EHT polarized image of supermassive black hole in M87

Left:
ALMA polarized image of 2kpc-long M87 jet

See NYT article



Rutgers Physics 346: Observational Astrophysics
March 30, 2021

Homework for Thursday, Mar. 32

Due: Quiz #9 will appear on Canvas Assignments at 4:20pm, due at noon tomorrow.

Due: Anonymous midcourse Evaluation will appear on Canvas tonight, due at 11:59pm tomorrow.

Do: Read the full instructions for your 2nd group project and be prepared to make progress during Thursday's Project Meeting.

Quiz #8: For a typical radio interferometer, explain (in words) why taking the two-dimensional Fourier transform of a set of visibilities isn't sufficient to produce a good representation of the true sky brightness distribution.

A: Measured visibilities only provide an incomplete sampling of the uv plane. Their two-dimensional Fourier transform is the true sky brightness distribution convolved with the dirty beam, and that convolution can differ significantly from the true sky brightness.

High-energy bands

At wavelengths shorter than the optical, light no longer reaches the Earth's surface, e.g., in the ultraviolet:

- **U-band: λ = 300–400 nm (some transmission)**
- **near-UV: λ = 200–300 nm**
- **far-UV: λ = 100–200 nm**

At still shorter wavelengths, bands are characterized in terms of energies in electron volts (eV):

- **extreme UV (EUV): E = 12–120 eV (λ = 10–100 nm)**
- **soft X-ray: E = 120–1200 eV**
- **hard X-ray: E = 1.2–120 keV**
- **soft gamma ray: E = 0.12–1.2 MeV**
- **hard gamma ray: E > 1.2 MeV**

...updating definitions of Kitchin, *Astrophysical Techniques*.

Detection: Geiger counters

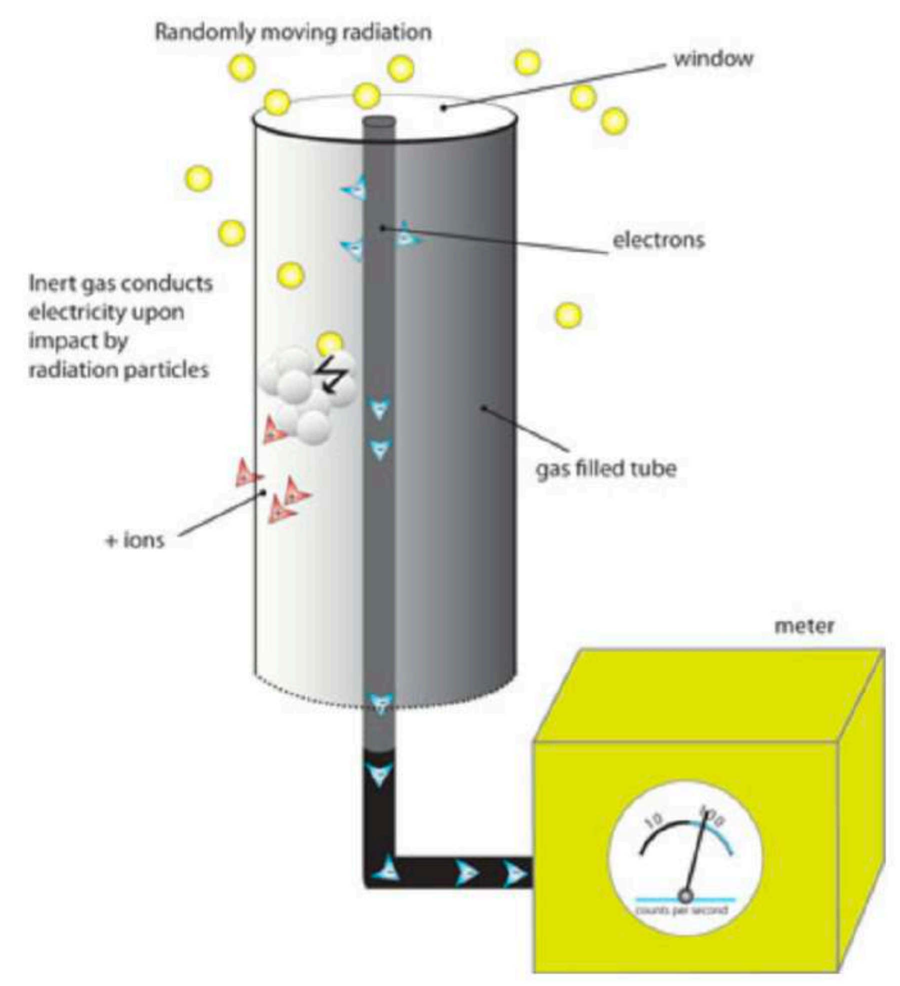
IT'S A QUESTION OF PHYSICS: WHAT IS A GEIGER COUNTER?

THE GEIGER COUNTER

Geiger counters are used to detect radioactive emissions, most commonly beta particles and gamma rays. The counter consists of a tube filled with an inert gas that becomes conductive of electricity when it is impacted by a high-energy particle. When a Geiger counter is exposed to ionizing radiation, the particles penetrate the tube and collide with the gas, releasing more electrons. Positive ions exit the tube and the negatively charged electrons become attracted to a high-voltage middle wire. When the number of electrons that build up around the wire reaches a threshold, it creates an electric current. This causes the temporary closing of a switch and generates an electric pulse that is registered on a meter, either acoustically as a click that increases in intensity as the ionizing radiation increases, or visually as the motion of a needle pointer.

Radioactivity can be measured in order to discover the amount of radiation a material emits or the amount of radiation absorbed by a human or mammal. The unit for measuring radioactive emissions is the becquerel (Bq). The Bq indicates the number of decays per second. The roentgen equivalent in man (rem) is an older standardized unit for measuring absorbed dose. The mrem, 1000th of that unit, is the unit used today in medicine.

Geiger Counter



(click for larger image)

From this website

Detection: Geiger counters

The earliest high-energy detectors were Geiger counters flown on sounding rockets:

– an enclosure is filled with gas (mainly an inert gas like argon, which can't lose energy to rotational or vibrational modes, at low pressure)

– a potential difference is applied between the walls of the enclosure and a central wire

– when a high-energy photon causes one or more initial ionizations, electrons trigger a cascade as they accelerate towards the central wire

Gain is very high (up to 10^8!)… good for detecting faint sources, but response is non-linear, and there is a detector dead time as potential difference is restored.

Detection: proportional counters

To obtain a linear response, apply a lower potential difference – lower gain (10^4–10^5), but reduced issues with saturation and dead time. Such an instrument is a proportional counter.

- at low energies, windows thin enough to let photons in are also thin enough to let gas leak out, so gas needs to be replenished
- at high energies, need to make enclosure big enough to capture all of the incident radiation (i.e., photons can't pass in and out without ionizing anything)

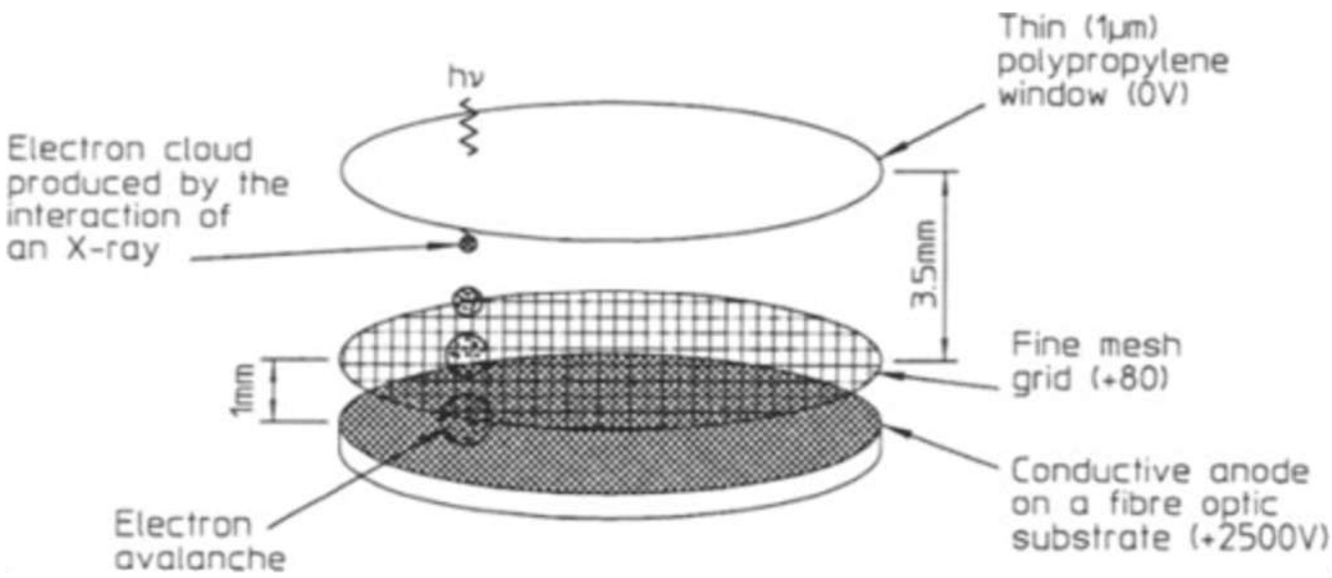
A proportional counter can tell us about photon energies… but can we get spatial information too?

Detection: proportional counters

A position-sensitive proportional counter (PSPC) uses a grid of resistive wires instead of a single wire at the center of the enclosure.

- by comparing arrival times of pulses at both ends of a wire, it is possible to where along the wire the ionizing event occurred
- grid of wires provides information on two spatial coordinates

image credit:
O. Siegmund



Early missions: *Einstein* & *ROSAT*

Einstein Observatory **was the first X-ray imaging mission (launched by NASA in 1978; led by Riccardo Giacconi, who later won the 2002 Nobel Prize), and had one PSPC detector.**

ROSAT **(*Röntgensatellit*) was launched in 1990 by a German, British, and American team; equipped with two PSPC detectors, and conducted the first X-ray all-sky survey in the 0.1–2.4 keV band.**

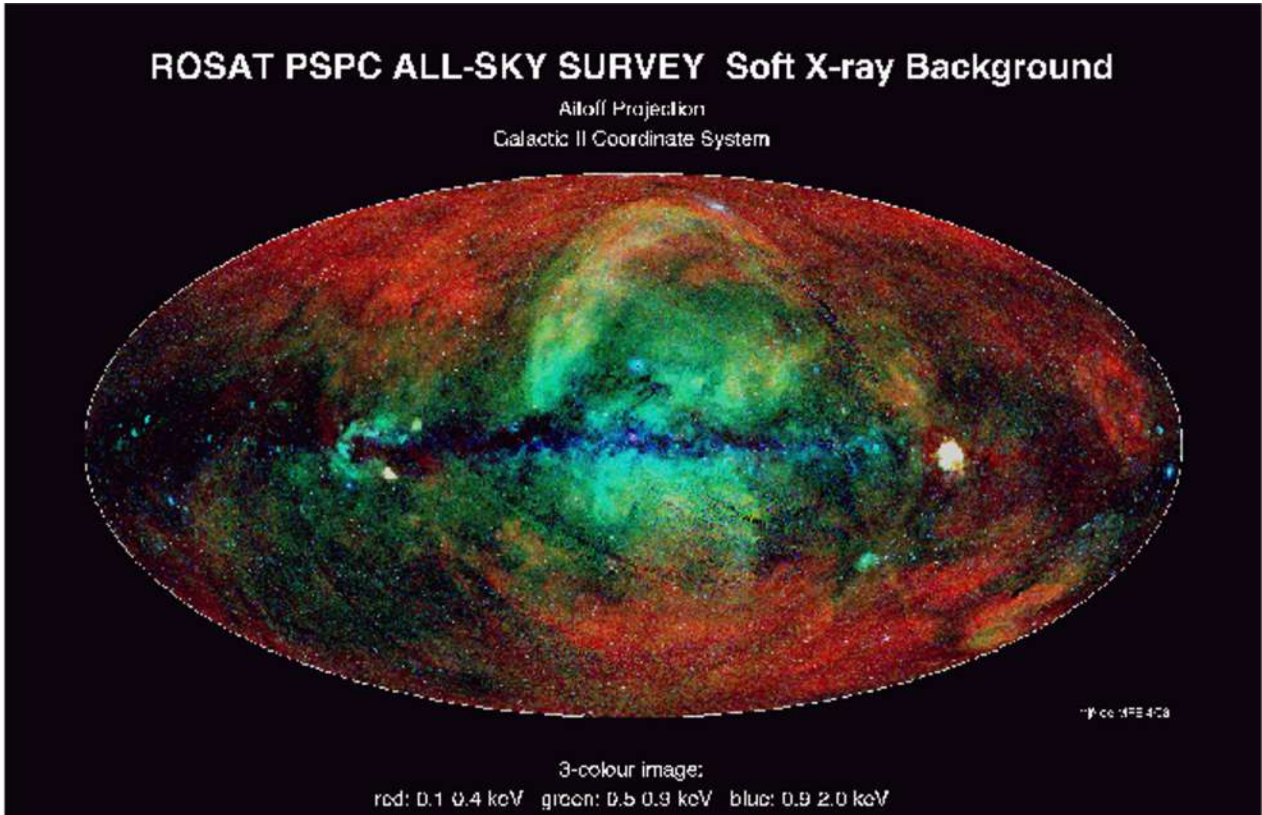


image credit: Freyberg & Egger (1999)

Detection: scintillation detectors

For the detection of even higher-energy (e.g., gamma ray) photons, we can use a scintillation detector:

- energetic incoming photon removes an inner electron from an atom in the detector
- an outer electron then drops down to replace the ejected electron, resulting in the emission of an lower-energy photon that is detected at optical wavelengths

- choice of material depends on desired energy range: sodium iodide (NaI) and cesium iodide (CsI) crystals are good for energies up to a few 100 keV; organic compounds and bismuth germanate ($Bi_4Ge_3O_{12}$) are good for energies above 100 keV

Early mission: *Compton GRO*

Scintillation detectors were used in several instruments on the *Compton Gamma-Ray Observatory* (1991–2000), which was NASA's gamma ray "great observatory" analog of the *Hubble Space Telescope*:

- Burst and Transient Source Experiment (BATSE) at 20 keV – 1 Mev, which confirmed that the distribution of gamma ray bursts is isotropic on the sky
- Energetic Gamma Ray Experiment Telescope (EGRET) at 20 MeV – 30 GeV, which conducted the first all-sky survey at > 100 MeV energies
- Oriented Scintillation Spectrometer Experiment (OSSE), which used four pointable detectors at 50 keV – 10 MeV
- Imaging Compton Telescope (COMPTEL), which used two detectors to confirm/localize 0.75–30 MeV photons

Gamma ray bursts = GRBs

GRBs are short, highly energetic events first detected in the 1960s (but not understood for decades)…

- mixture of short (< 2s) and long (> 2s) durations
- unknown sky distribution until *CGRO*/BATSE proved they are isotropic, thus not associated with disk of Milky Way (solar system? Galactic halo? extragalactic?)
- unknown distances until *BeppoSAX* localized the first X-ray afterglow in 1997 (as extragalactic)

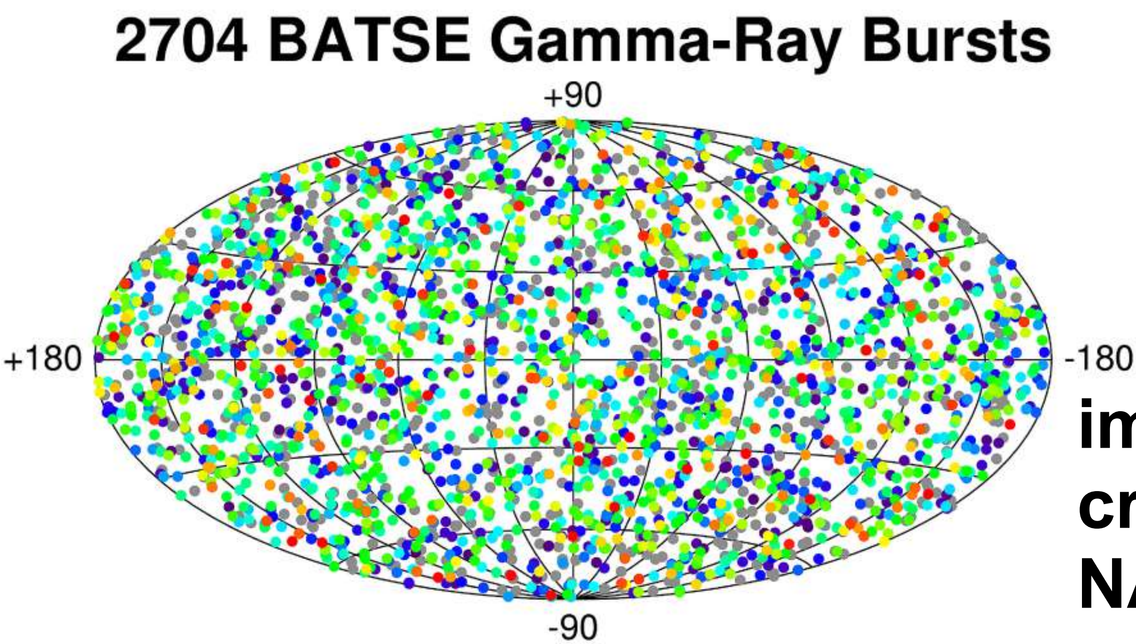
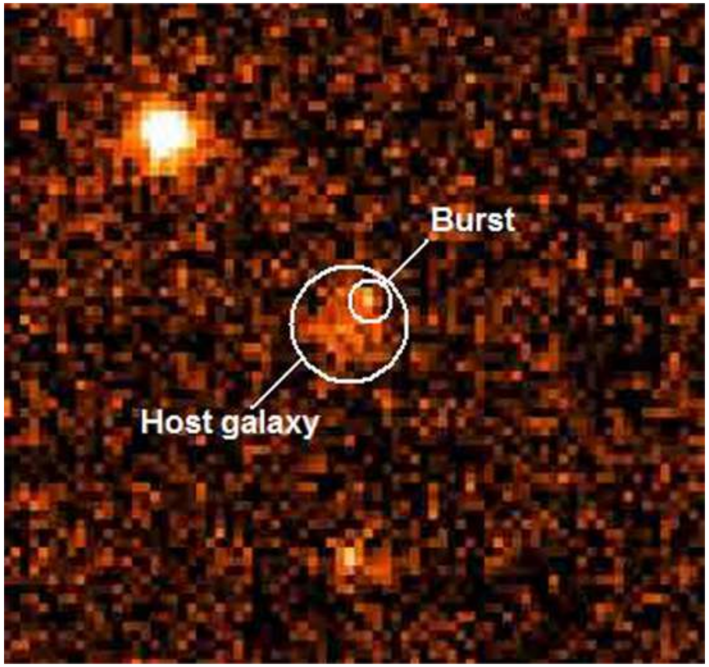


image credits: NASA



Gamma ray bursts = GRBs

GRBs are short, highly energetic events first detected in the 1960s (but not understood for decades)…

- mixture of short (< 2s) and long (> 2s) durations
- unknown sky distribution until *CGRO*/BATSE proved they are isotropic, thus not associated with disk of Milky Way (solar system? Galactic halo? extragalactic?)
- unknown distances until *BeppoSAX* localized the first X-ray afterglow in 1997 (as extragalactic)

Current understanding:

- short-duration GRBs are (mostly) associated with mergers of binary neutron stars – confirmed in 2017 by LIGO detection of GW 170817!
- long-duration GRBs are associated with core collapse supernovae
- GRBs are at cosmological distances; temporarily brighter than AGN as backlight for absorption systems; attempt to calibrate GRBs as standard candles failed

Detection: CCDs

Yes, digital cameras again!

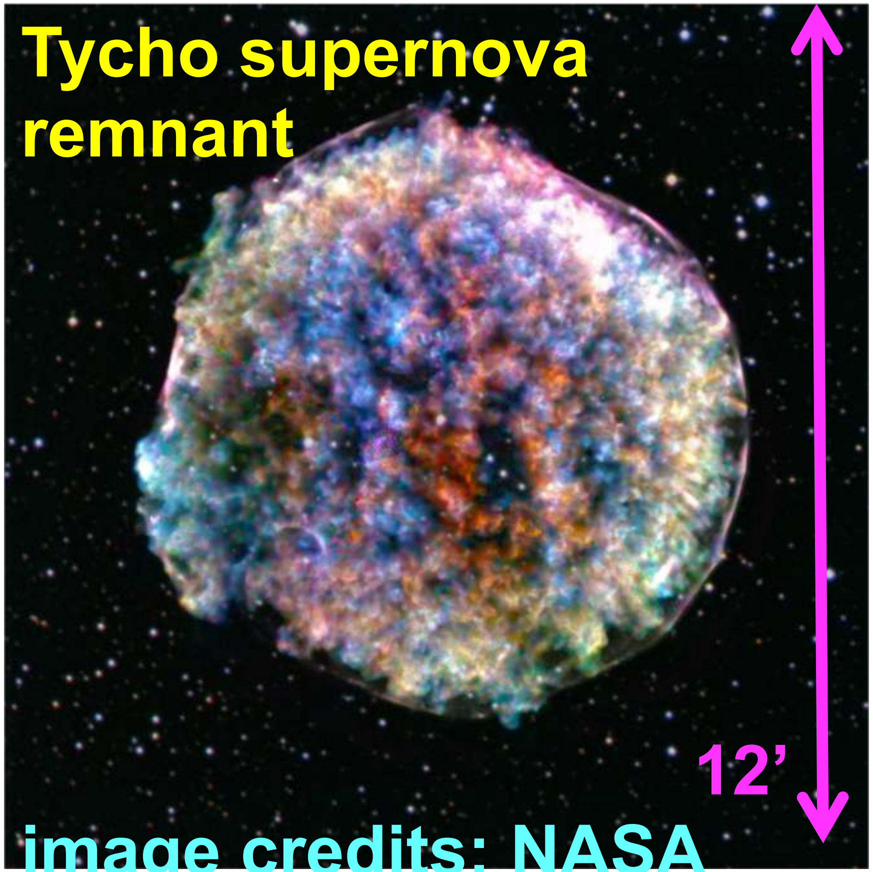
At short optical/UV wavelengths, electrode structure becomes opaque, so CCDs can no longer be used – but at X-ray energies, electrode structure becomes transparent (and CCDs become useable) again.

Unique aspect of X-ray work: if exposure times are short enough, we can detect individual photons and use the associated charge to measure their energies!

- **effectively, the CCD will do low-resolution spectroscopy for free**
- **only works as long as we avoid "pileup" (> 1 photon hitting a CCD pixel in the same time step)**

Chandra X-ray Observatory

The X-ray analog of the *Hubble Space Telescope* is the *Chandra X-ray Observatory* (named for Subrahmanyan Chandrasekhar, and used by Rutgers Prof. Jack Hughes).



Chandra instruments

Advanced CCD Imaging Spectrometer (ACIS) has ten CCDs (four for imaging, six for spectroscopy) – can be used with the high-energy transmission grating (HETG) for spectroscopy

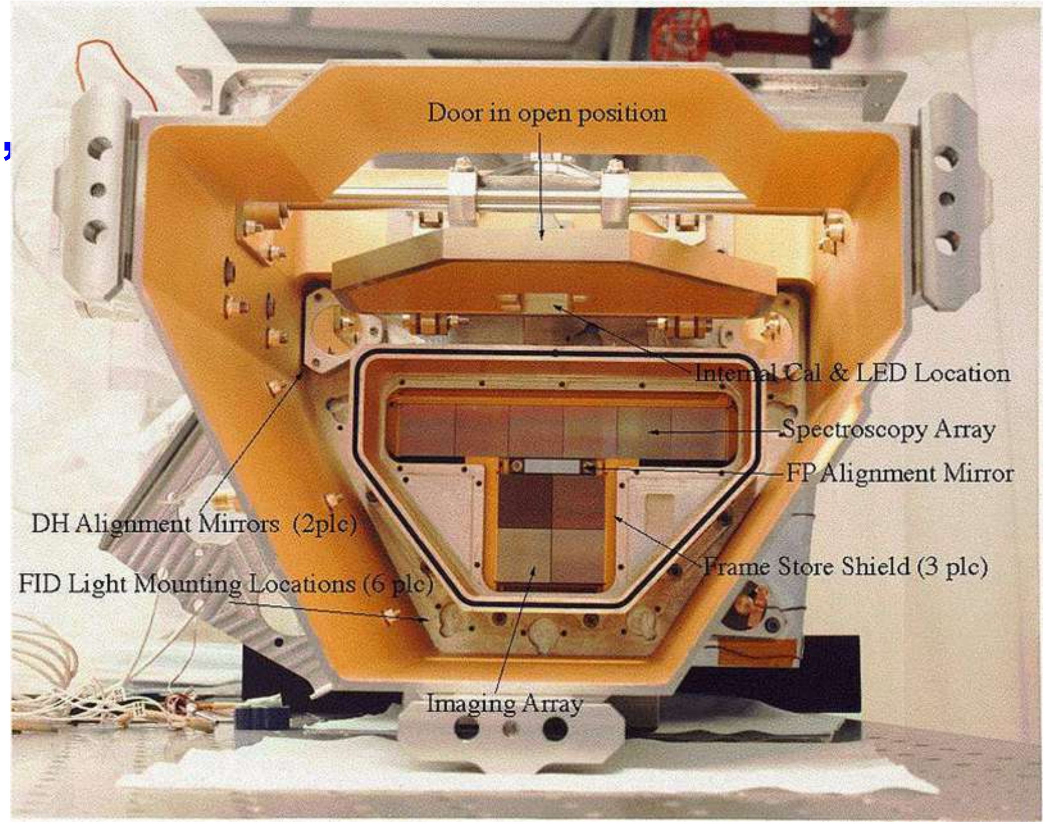


image credit: PSU

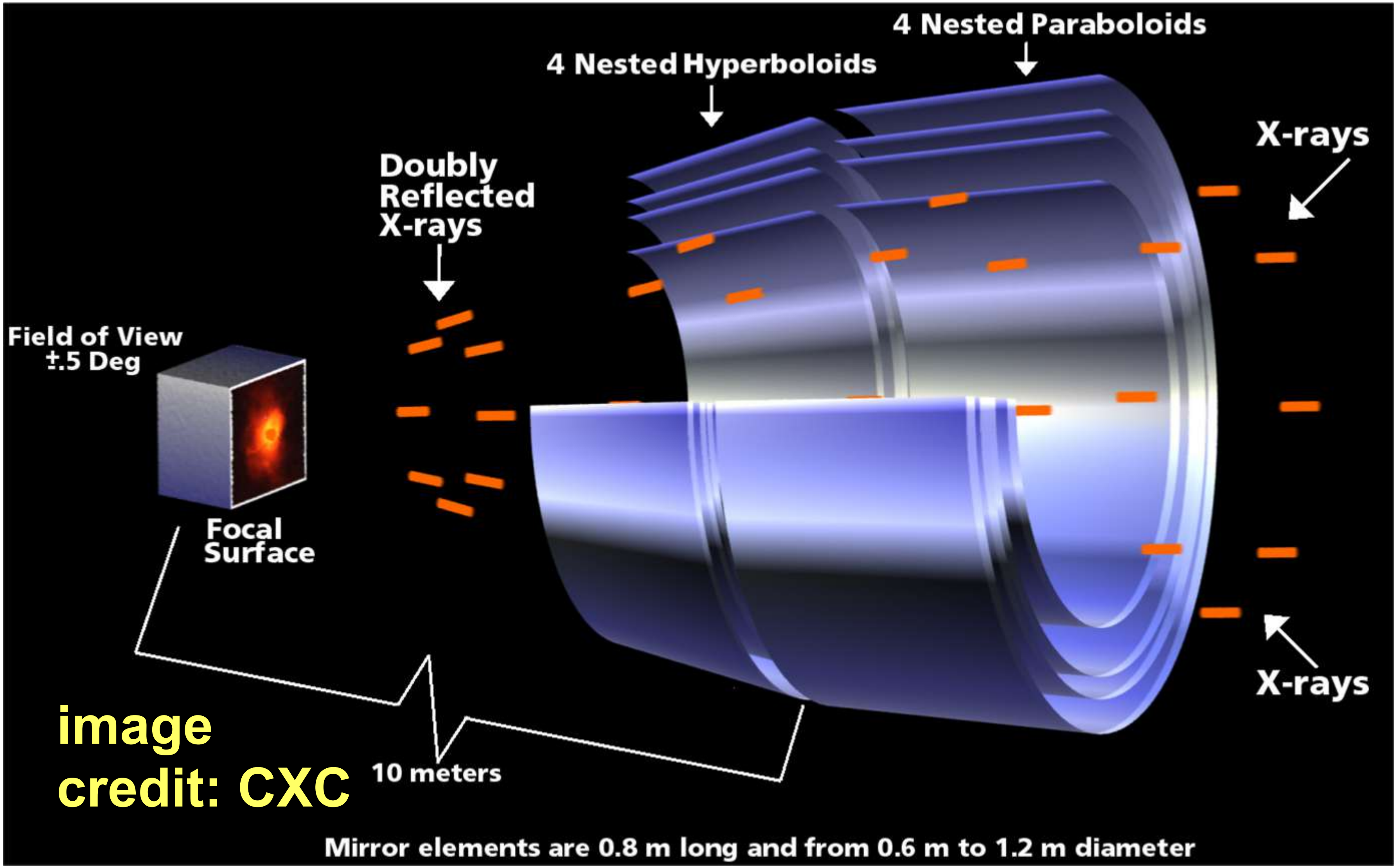
High resolution camera (HRC) has two microchannel plate detectors (one for imaging, one for spectroscopy).
– can be used with the low-energy transmission grating (LETG) for spectroscopy

***Chandra* mirrors**

Wait a minute – how do you focus X-rays?

Chandra mirrors

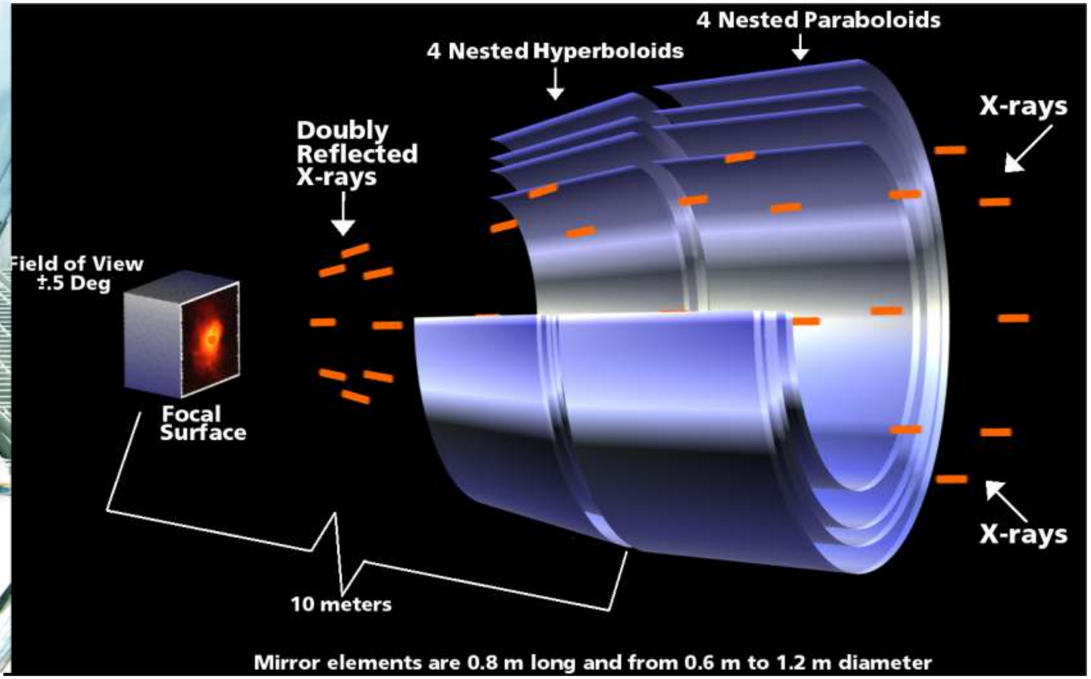
Chandra delivers images with fantastic (~1”) angular resolution… using two sets of grazing incidence mirrors.



Chandra mirrors

Chandra delivers images with fantastic (~1”) angular resolution… using two sets of grazing incidence mirrors.

X-rays would penetrate ordinary mirrors rather than reflect off them. Grazing incidence mirrors can deflect X-rays, analogous to ricocheting bullets.



Current missions: *Swift* and *Fermi*

NASA is currently flying two gamma-ray missions...

***Neil Gehrels Swift Observatory*:**
- **Burst Alert Telescope (BAT) at 15–150 keV**
- **X-ray Telescope (XRT) at 0.3–10 keV**
- **UV/Optical Telescope (UVOT) at 170–600 nm**
- **BAT detects ~ 100 GRBs per year; XRT and UVOT do afterglow localization and followup imaging and spectroscopy**

***Fermi Gamma-ray Space Telescope*:**
- **Gamma-ray Burst Monitor (GBM), which uses scintillation detectors to find and roughly localize GRBs**
- **Large Area Telescope (LAT), which uses electron/positron pair production in thin metal sheets + Si microstrip detectors (for directional information) + CsI scintillators (for energies)**

Fermi bubbles

Fermi unexpectedly detected two large bubbles above and below the plane of the Milky Way in high-energy gamma rays… perhaps related to a previous epoch of nuclear activity by the central supermassive black hole?