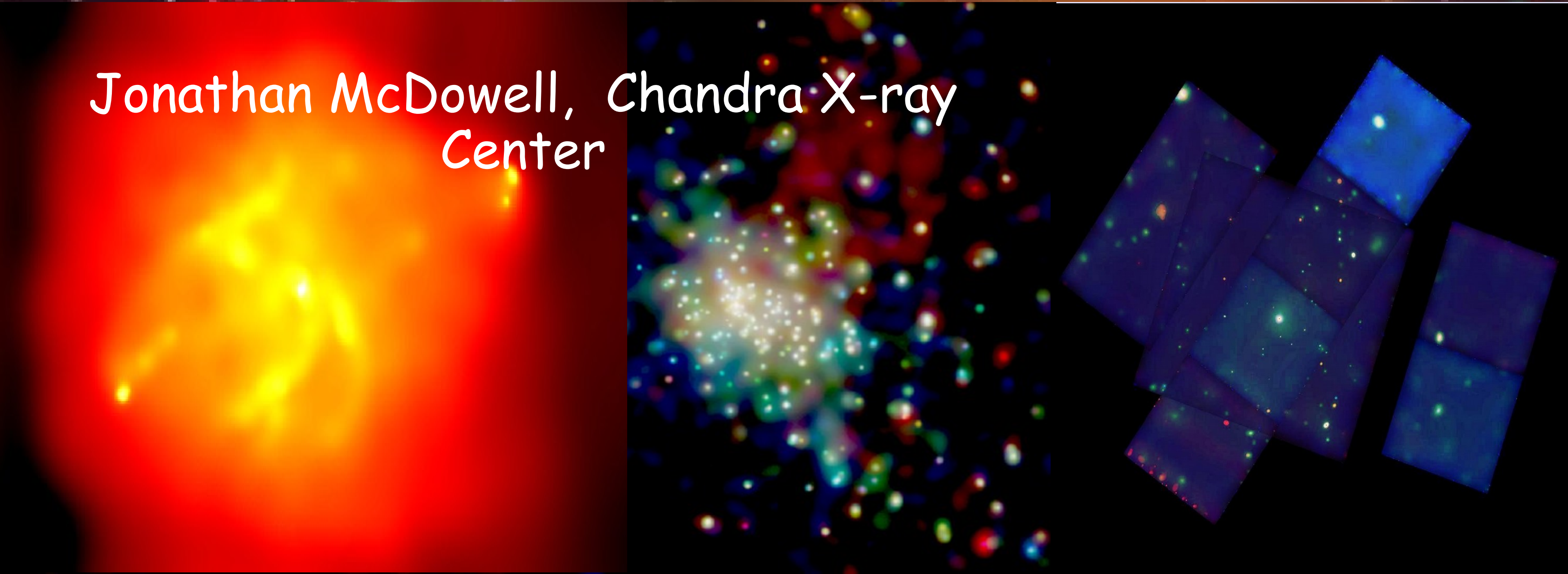
The Chandra X-ray Observatory



Jonathan McDowell, Chandra X-ray Center

The Chandra X-ray Observatory

Launched 5 years ago 23 July 1999

A revolution in X-ray astronomy

and astronomy in general

What can Chandra do?

Some science examples

Some comments on X-ray data

X-rays: A fundamental difference

When we look up at the night sky
we see it filled with stars

But,

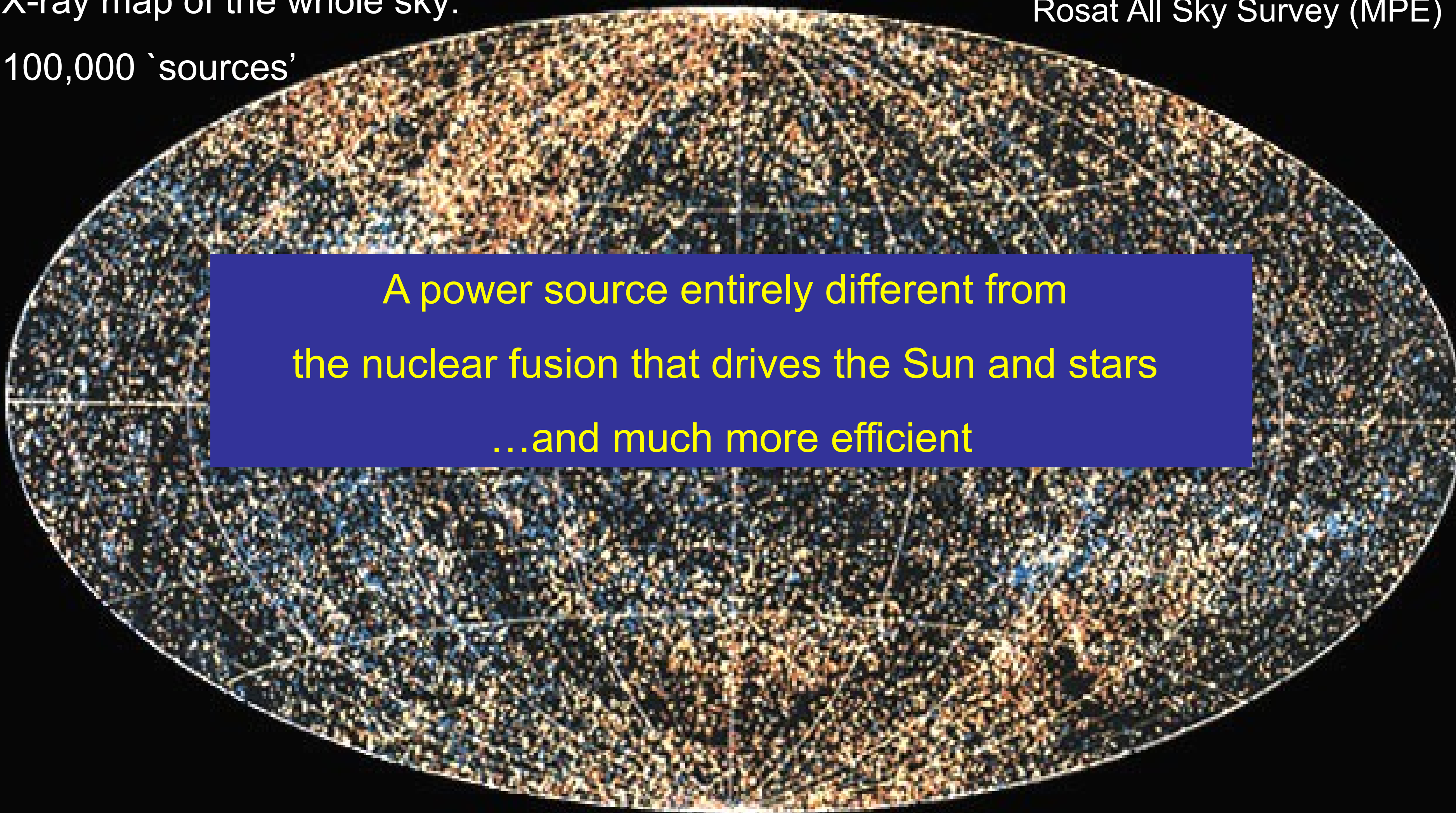
Outside the narrow range of colors
our eyes are sensitive to,
something quite different dominates
the night sky…

Powerful sources of X-rays

X-ray map of the whole sky:

Rosat All Sky Survey (MPE)

100,000 `sources’

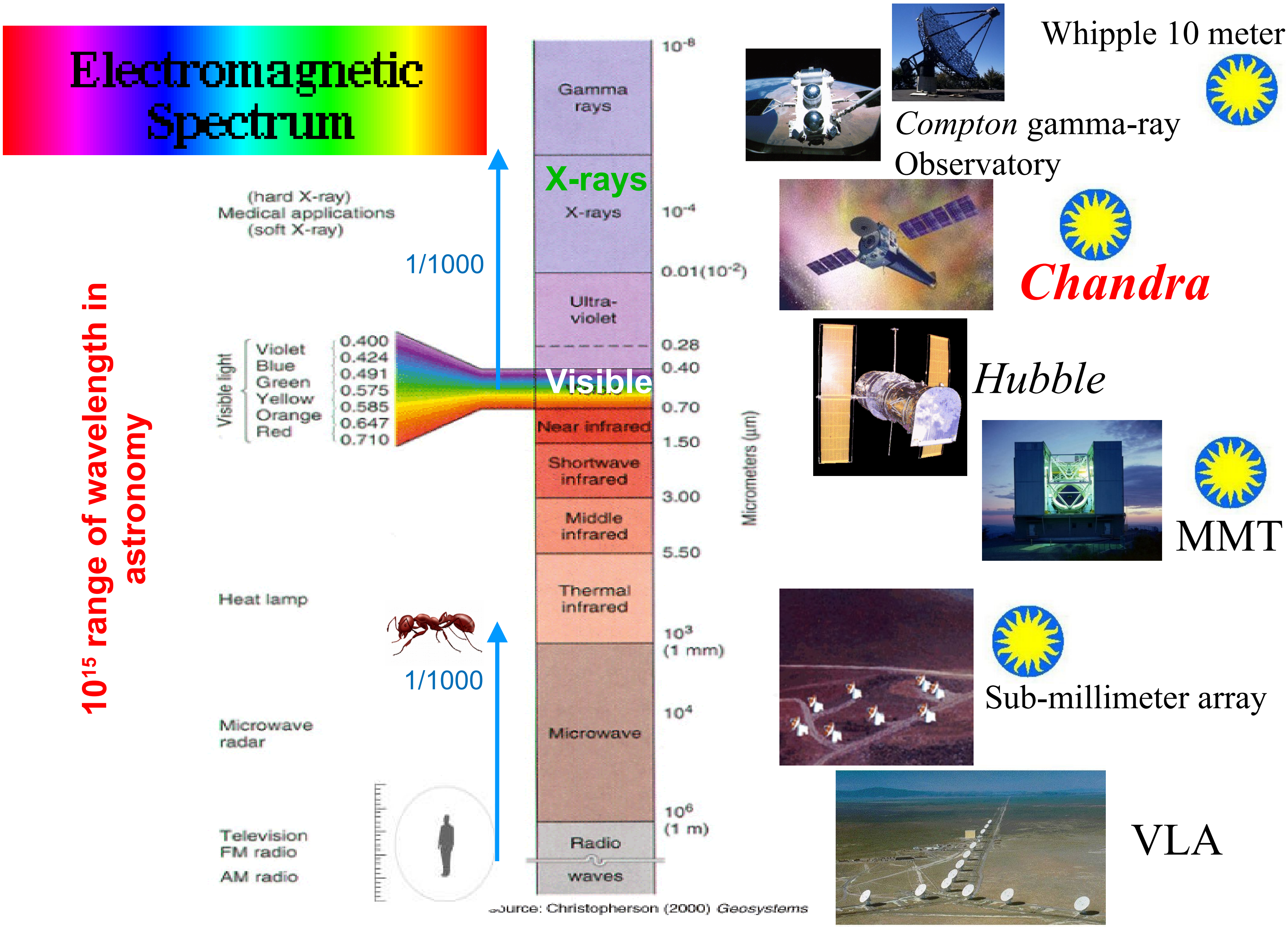


A power source entirely different from

the nuclear fusion that drives the Sun and stars

…and much more efficient

We are now in the era of multiwaveband astronomy



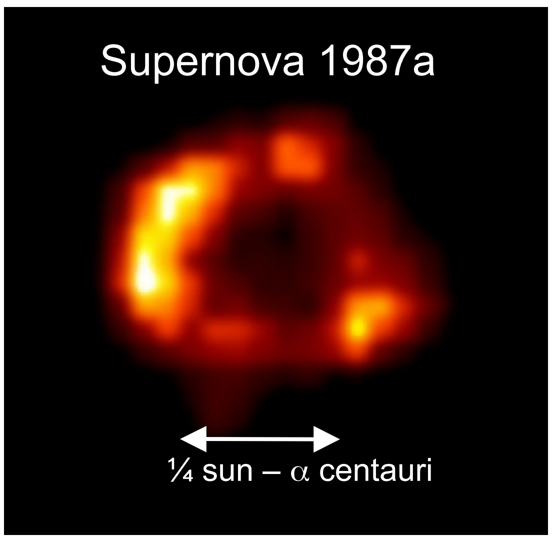
Sources of X-rays

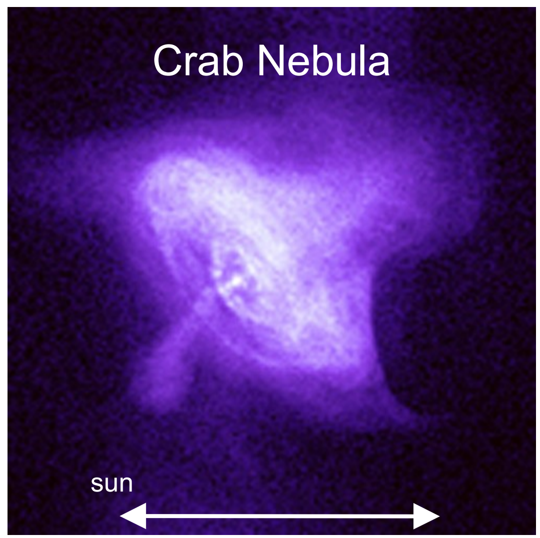
- Shocked plasma
- Relativistic synchrotron plasma (ang. mom. + B field)
- Energy release from gravity (accretion power)

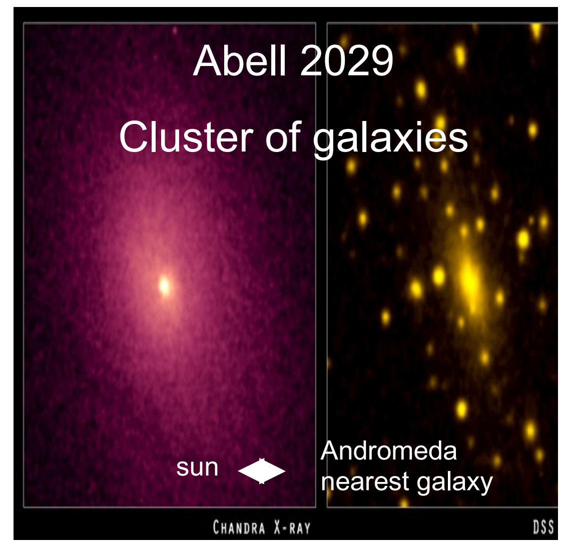
Explosions: Supernovae and their remnants

Particles moving near the **speed of light in magnetic fields**

Matter falling into **deep gravitational wells**





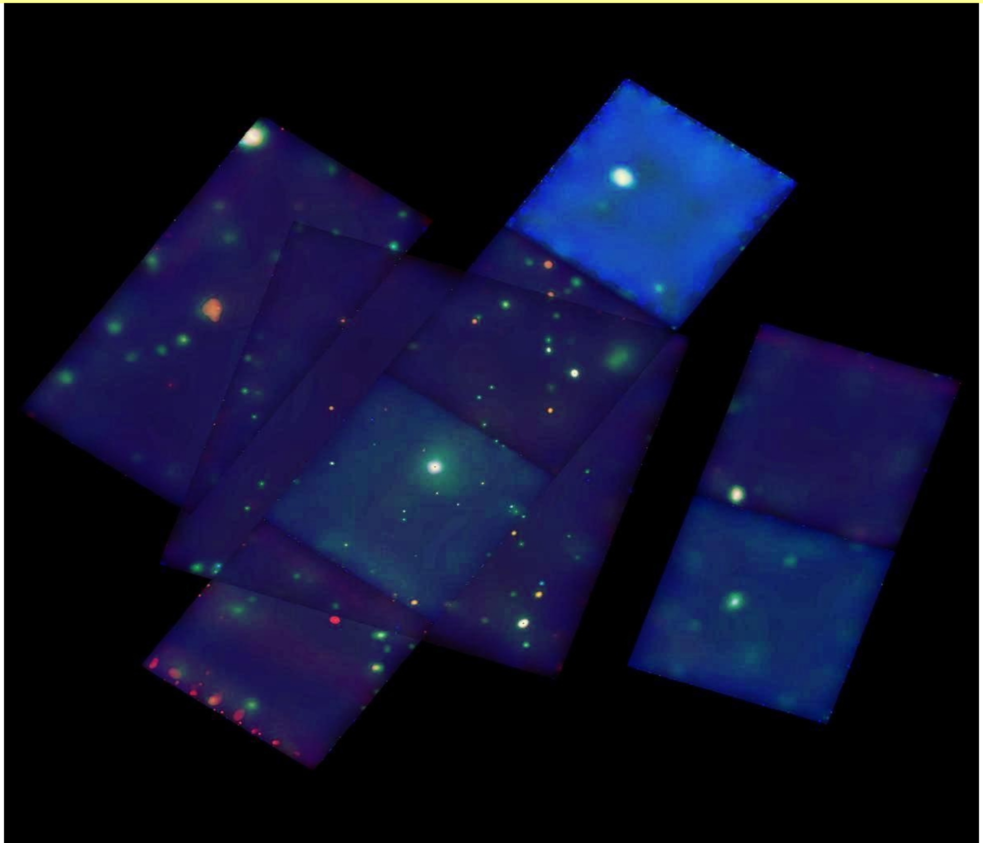


In the optical, we see mostly reprocessed fusion energy

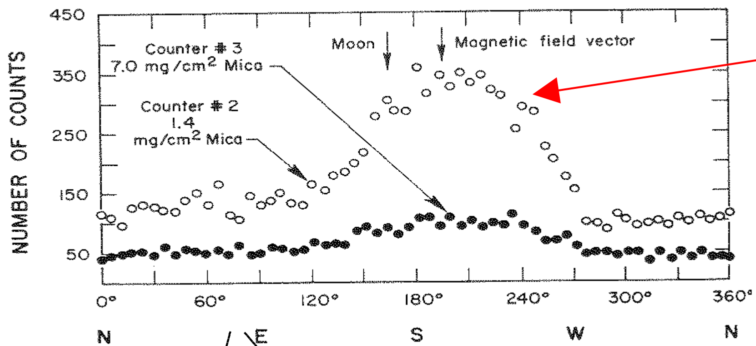
In X-rays, we see mostly accreting sources: energy from gravity!

X-rays in a galaxy

- X-ray binary systems (accretion onto compact objects)
- Nuclear X-ray source (accretion onto massive BH)
- Supernova remnants
- Gas heated by stellar processes and galaxy interactions



40 Years of X-ray Astronomy:
1 billion times more sensitive



Azimuthal distributions of recorded counts from Geiger counters flown during June, 1962. (R. Giacconi et al., *Physical Review Letters* 9 (1962),

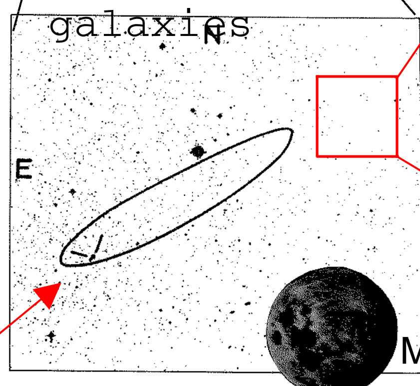
Sco X-1: the brightest source of X-rays in the sky

1962

Good for 1 (one) Nobel Prize

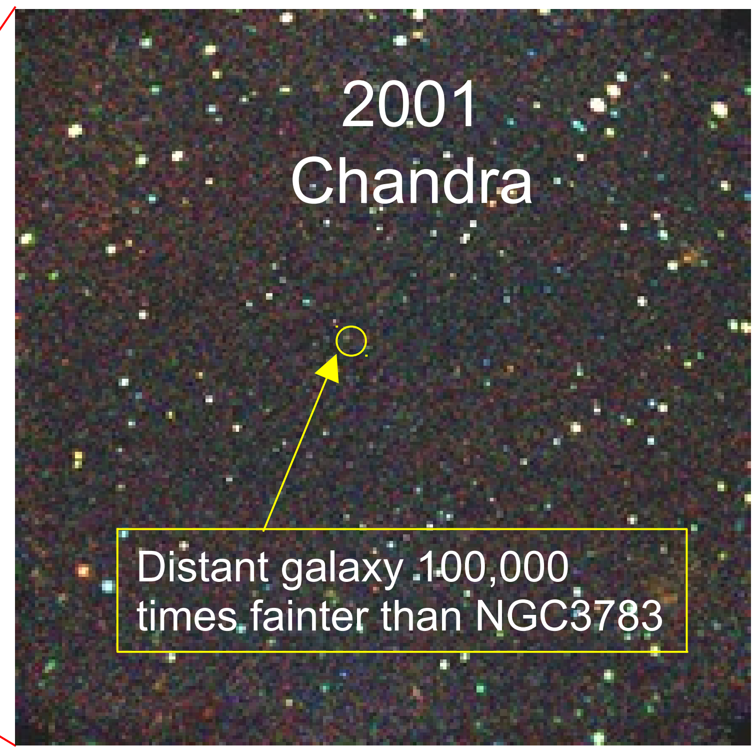
1978

good enough to ID bright galaxies



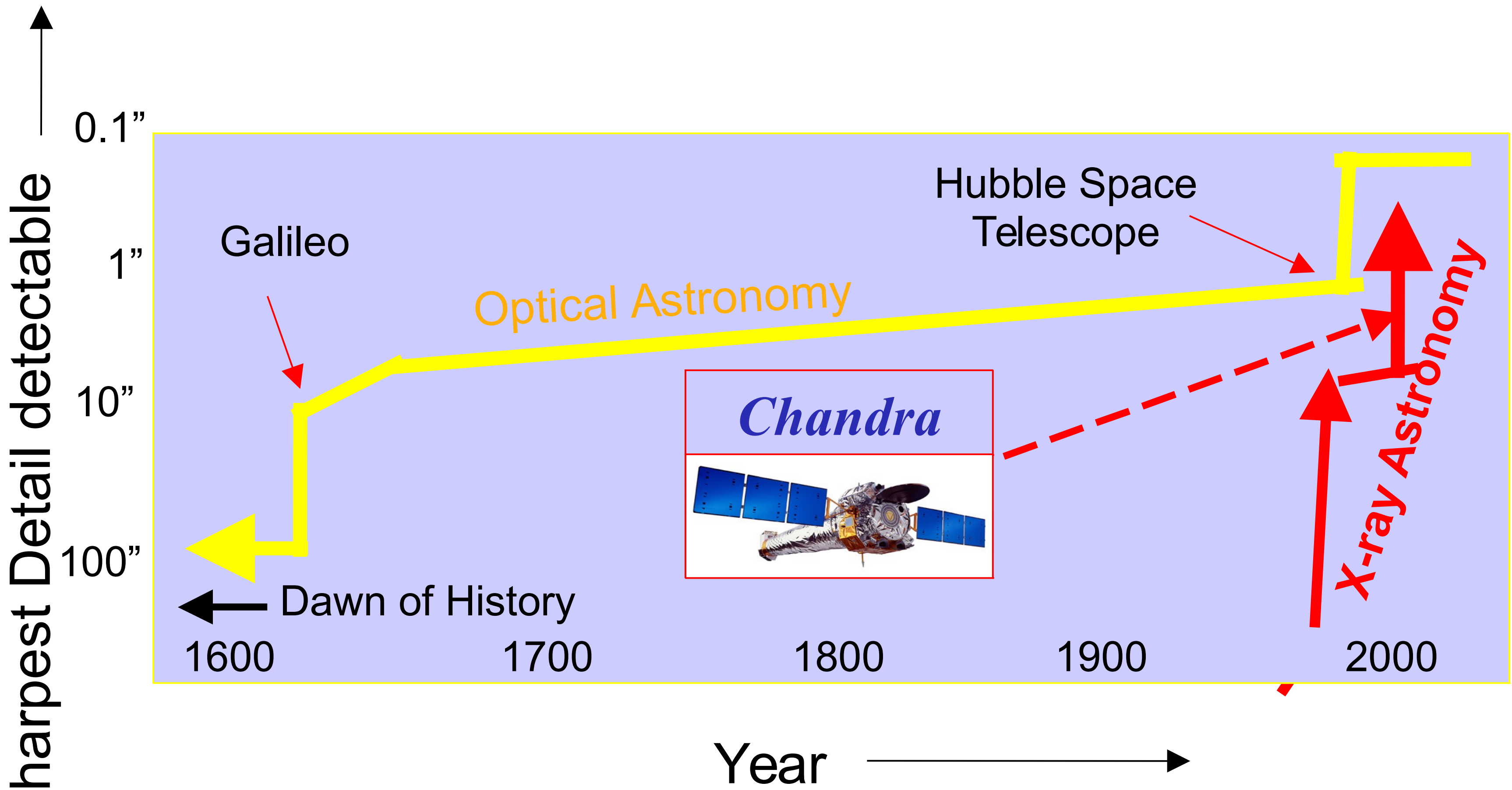
Moon to scale

NGC3783: a quasar appearing 10,000 times fainter than Sco X-1



Resolution is the key

Chandra takes X-ray Astronomy from its 'Galileo' era to its 'Hubble' era in a single leap



X-ray astronomy took just 40 years to match 400 years of optical astronomy

What is Chandra?

Chandra is the greatest X-ray Observatory ever built

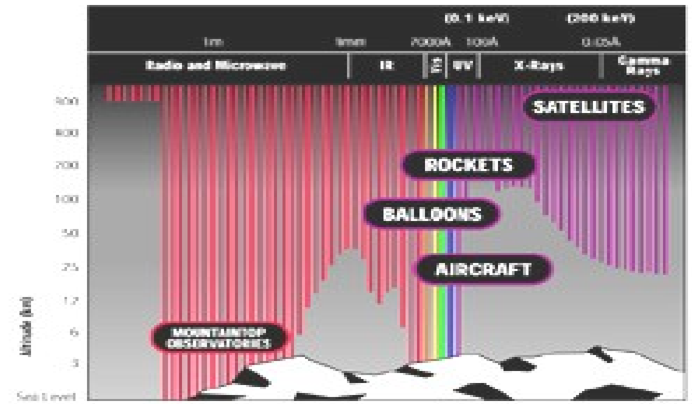
Orbits the Earth to be above the atmosphere (which absorbs X-rays, *luckily!)*

Goes 1/3 of the way to the Moon

every 64 hours (2 ½ days)

Chandra takes superbly sharp images:

with good spectral resolution too!



X-ray Telescopes are different

Chandra’s mirrors are almost cylinders

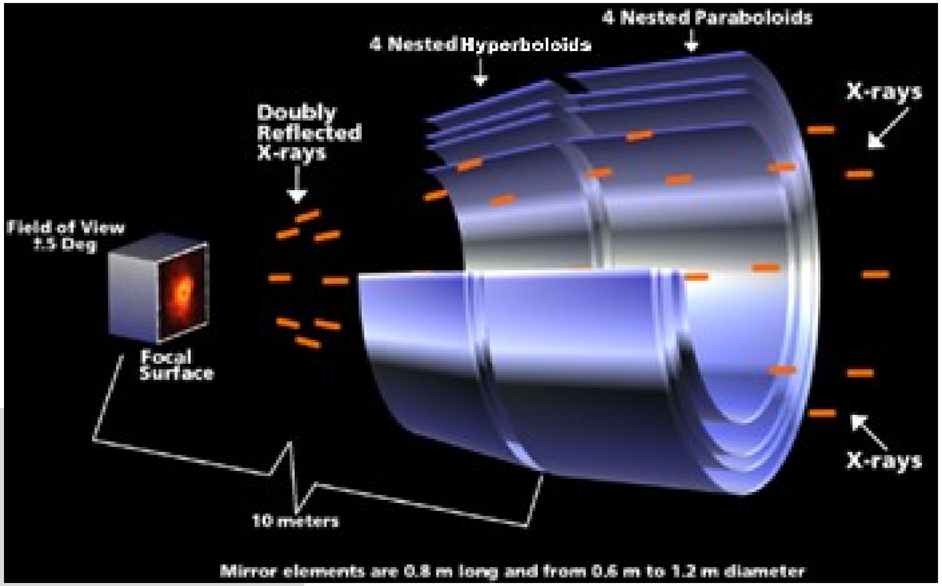
X-rays don’t reflect off a normal mirror – they get absorbed.

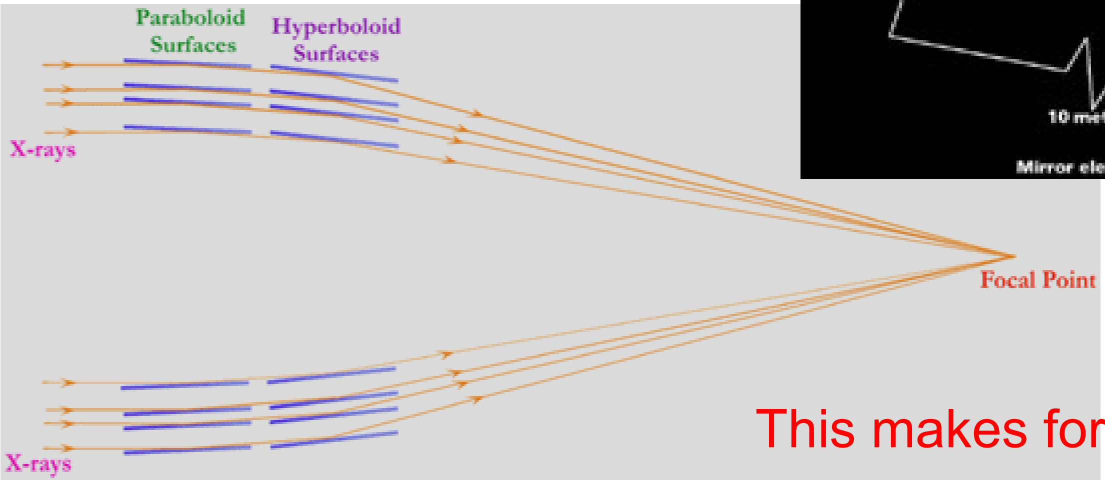
Only by striking a mirror at a glancing angle, about 1°,

do X-rays reflect.

Then they act like visible light

and can be focused

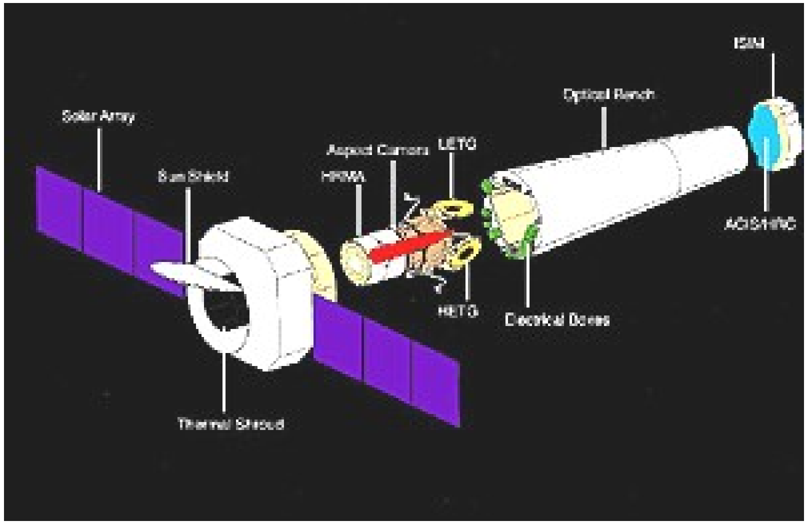




This makes for looooooooong telescopes

The Chandra spacecraft

10 meters (32 ½ ft) from mirror to detector, 1.2 meters (4ft) across mirror

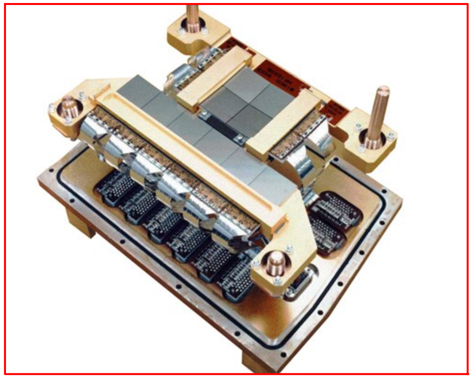


…but focuses X-rays onto a spot only 25 microns across

Chandra detects individual photons

10 meters (32 ½ ft) from mirror to detector, 1.2 meters (4ft) across mirror

CCD detectors count each X-ray individually

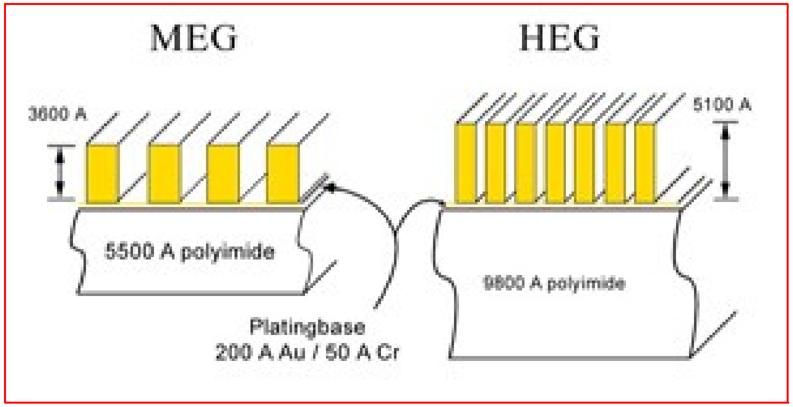


each X-ray knocks free enough electrons to detect as a pulse of electricity

→ **Light as particles**

…but can disperse the incoming X-ray light: **Light as Waves**

Delicate gold gratings diffract the light



Chandra provides a great example of how

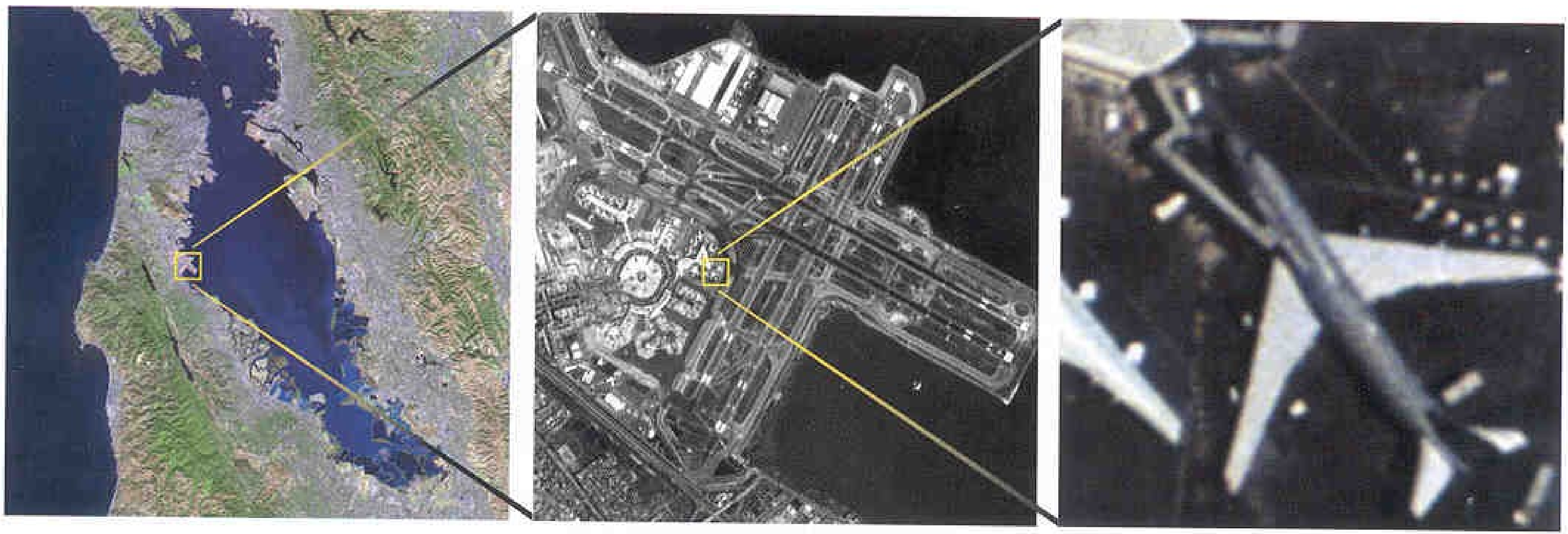
Quantum wave/particle duality

works in a real machine

Chandra's sharp focus revolutionizes our understanding

Earth observing satellite equivalents of …

SPACE IMAGING



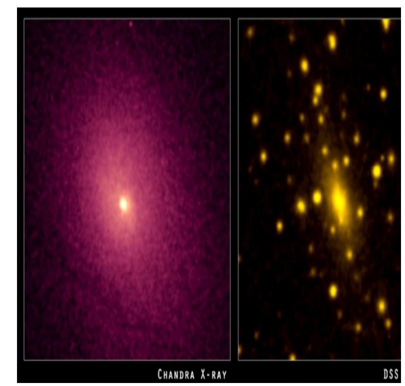
Best X-ray image of whole sky (ROSAT)	Best X-ray images before Chandra (ROSAT)	Chandra images
Any sign of life?	*What's this odd thing?*	*I get it!*

Like looking up the answers at the back of the book

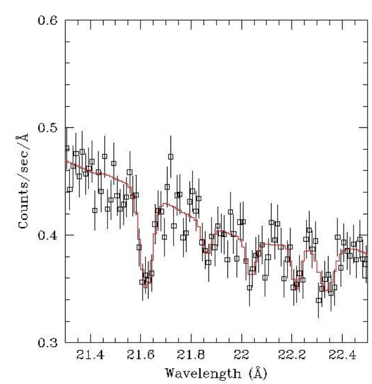
Chandra has solved 20 year old mysteries:

Yes – *the background X-ray light is made up of contributions from millions of quasars*

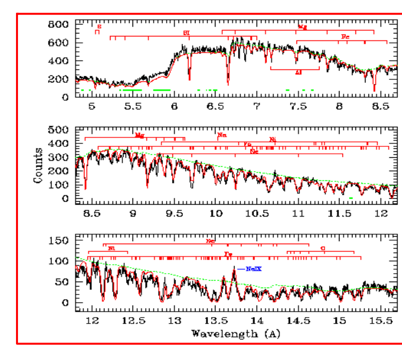
No – gas is not pouring down onto the galaxy at the center of a cluster of galaxies. Something stops it, but what?



Yes -- *Our Milky Way sits in a halo of hot gas stretching to the Andromeda galaxy and beyond*

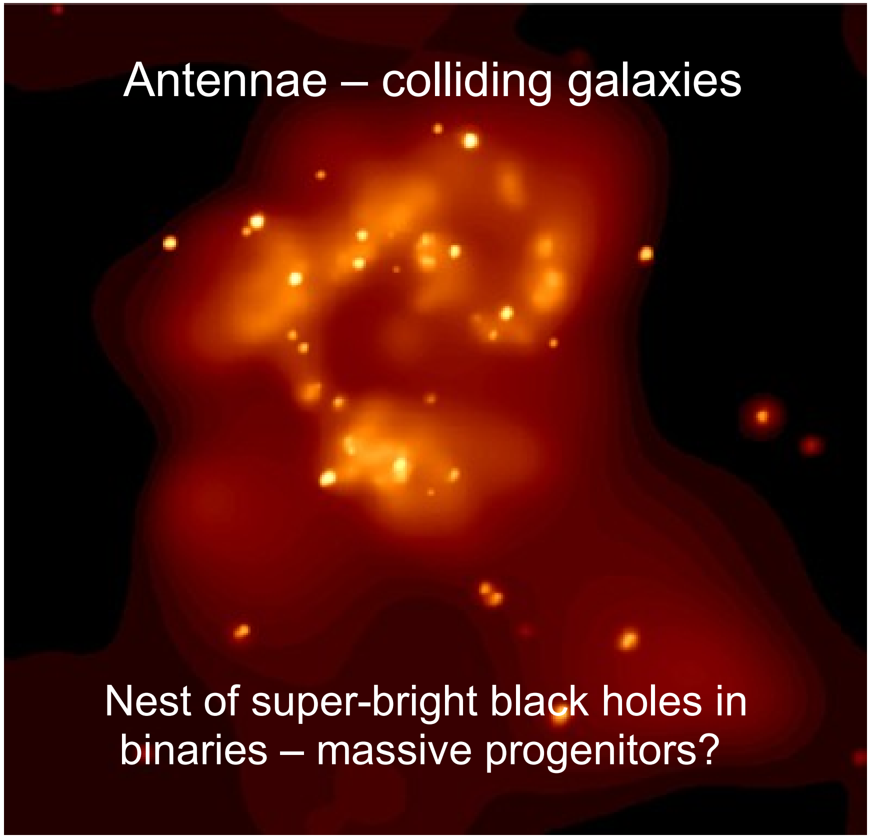


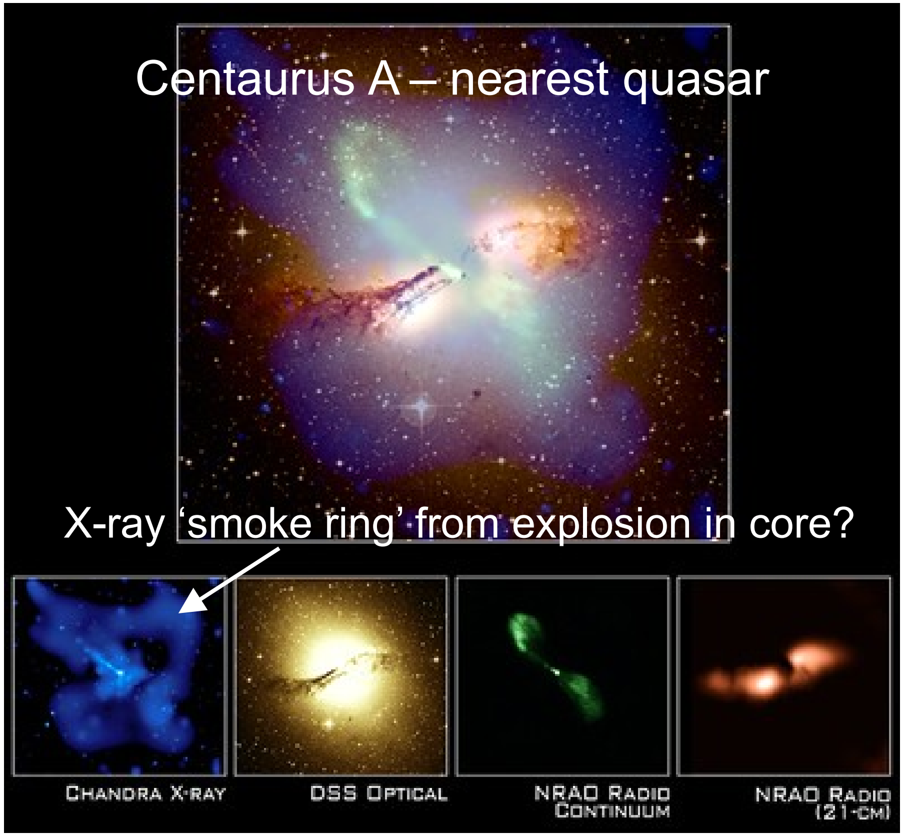
Yes – quasars have hot winds blowing from their cores at 1000 km/s



…and many new questions!

2 examples: What *are* we looking at?





Chandra's Revolution through Resolution continues…

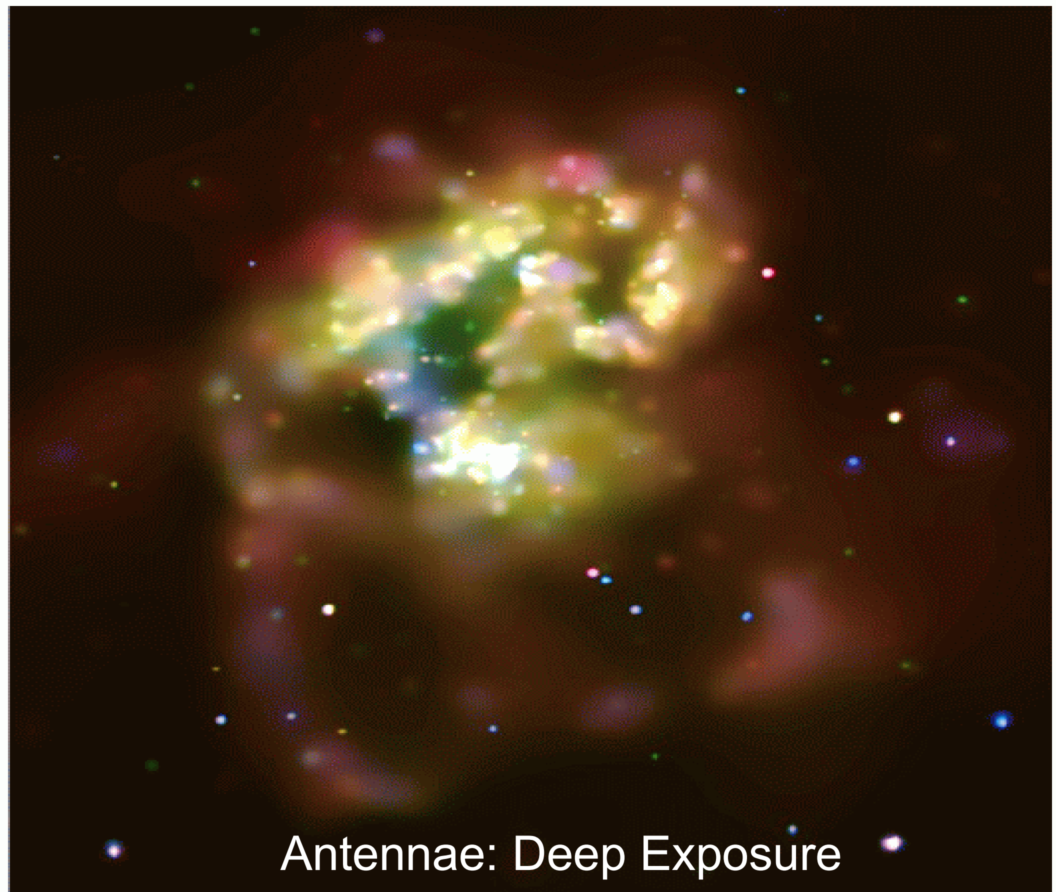
Chandra set to run for 5 more years

& may last much longer

All X-ray images are underexposed (limited by photon noise, not systematics)

Deeper looks show

- more morphological detail in diffuse emission,
- more spectral signal-to-noise in each pixel

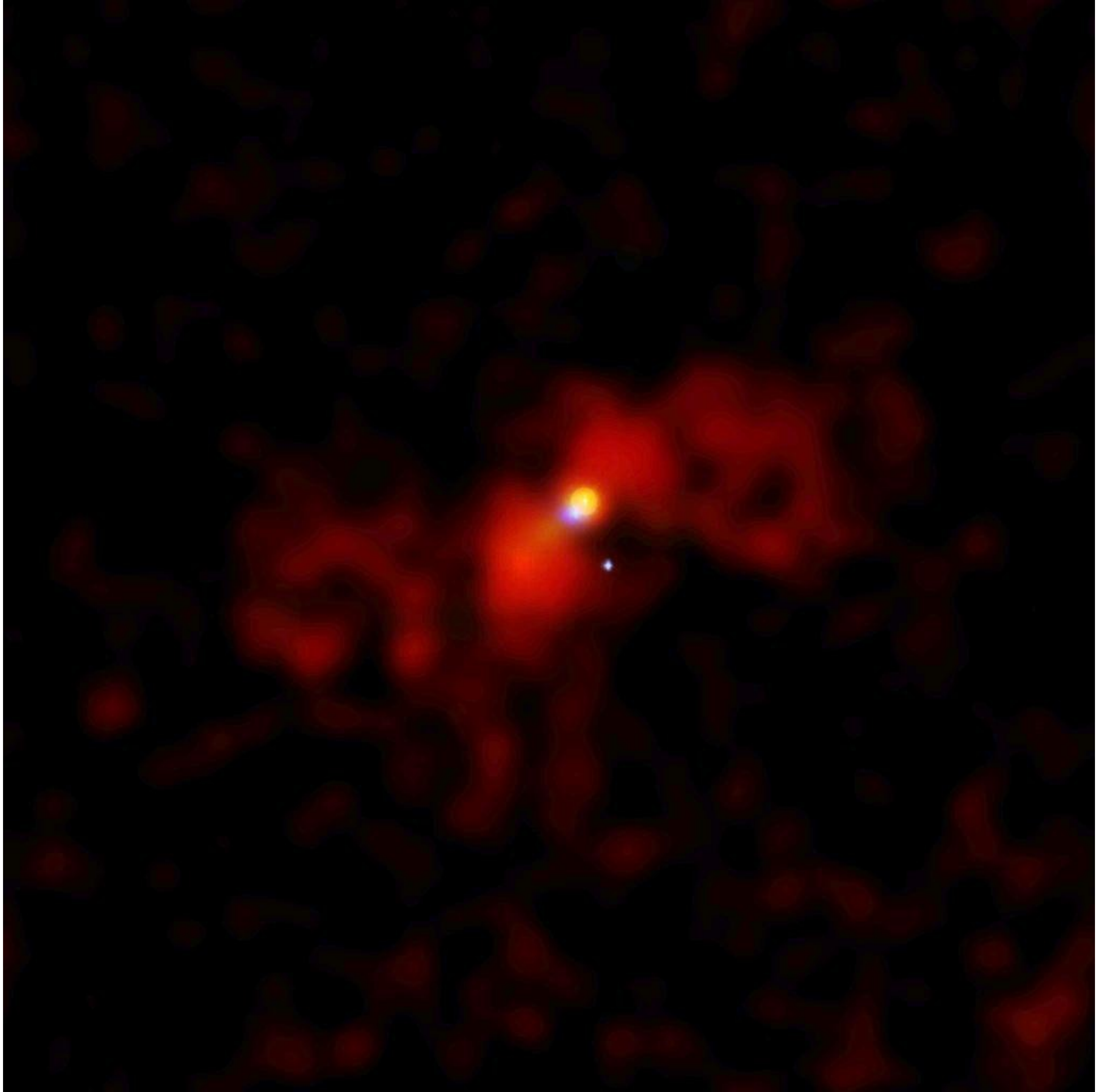


Antennae: Deep Exposure

Galaxy Arp 220

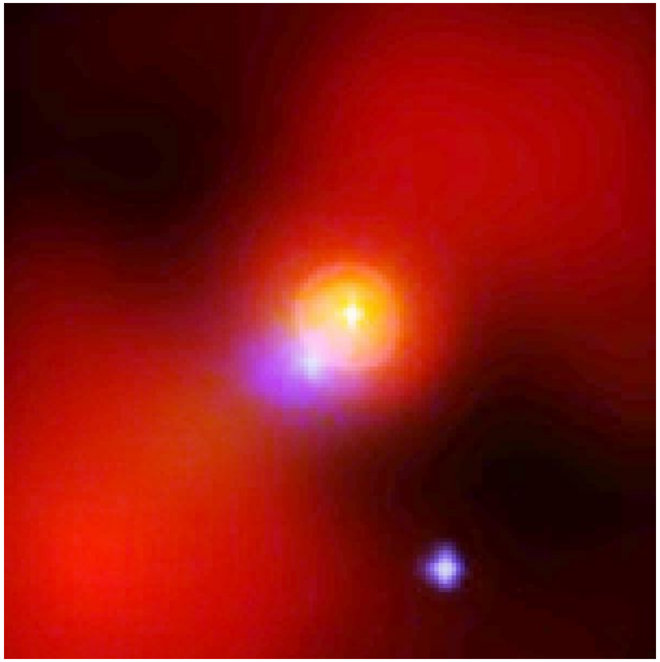
Merging galaxy Arp 220

- z=0.018 (250 million light years)
- Bolometric luminosity of 10**12 Lsun
- Most energy output in the infrared
- 20-year controversy: star formation or quasar?
- Answer: both, but mostly star formation
- Work with Dave Clements (Clements et al 2002, ApJ 581,974; McDowell et al 2003, ApJ 591,154)



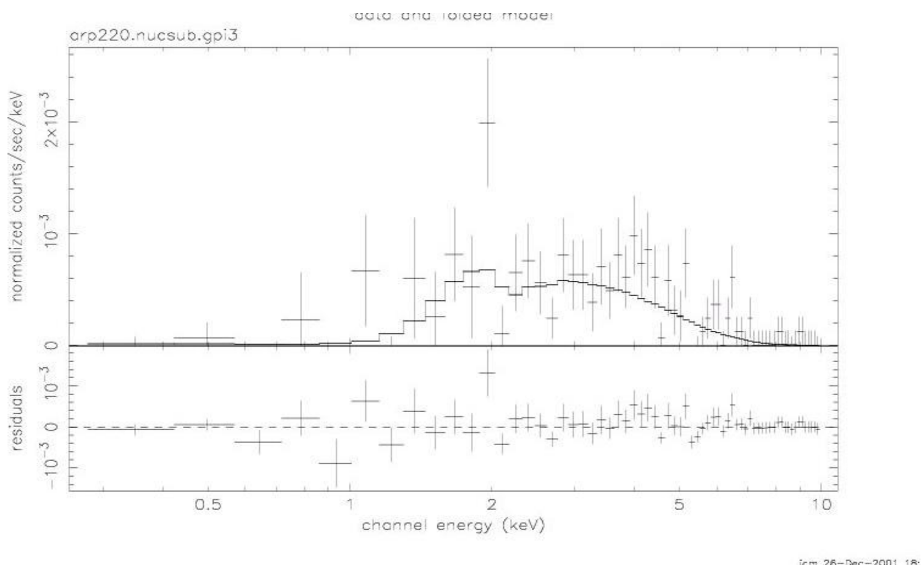
Arp 220 nucleus

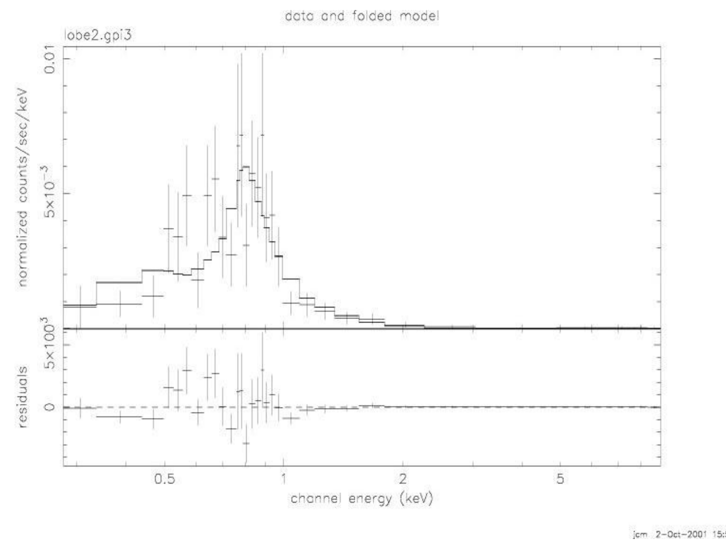
- Soft extended region of star formation
- Obscured hard point source coincides with radio nuclei
- Off-nuclear point source (ULX binary) 1E39 erg/s



Spectra in different regions

- Nuclear spectrum extends to > 7 keV





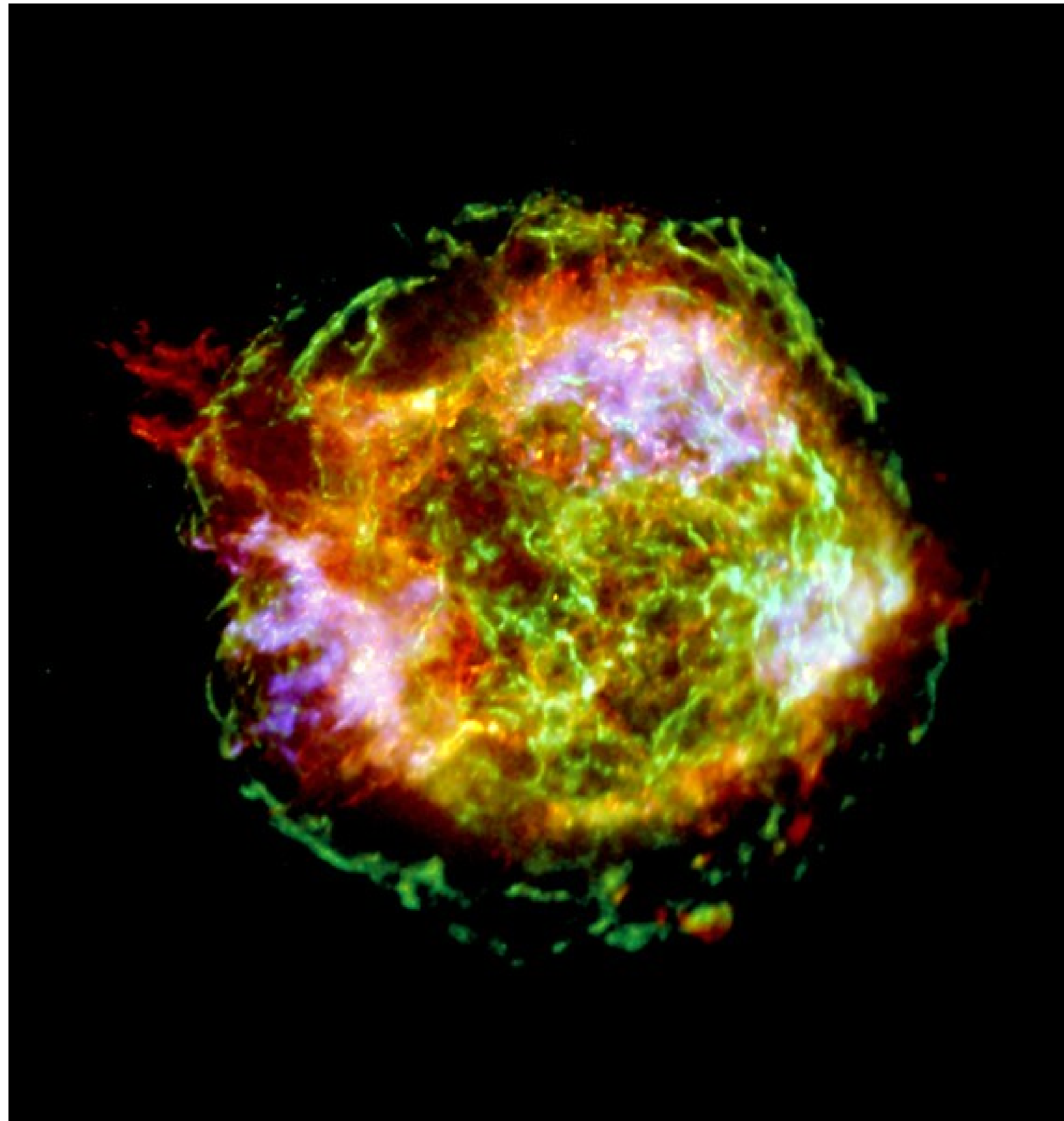
- Lobe spectrum much softer, < 1 keV

Arp 220: summary

- The AGN in Arp 220 is there!
- but it's only 4E40 erg/s...
- Even correcting for absorption, it can't be the source of most of Arp 220's luminosity
- ULX of 6E39 erg/s at 2.5 kpc from nucleus
- X-ray lobes to 15 kpc each side, correlates with H-alpha, 1E41 erg/s total
- Superwind plus merger remnants?

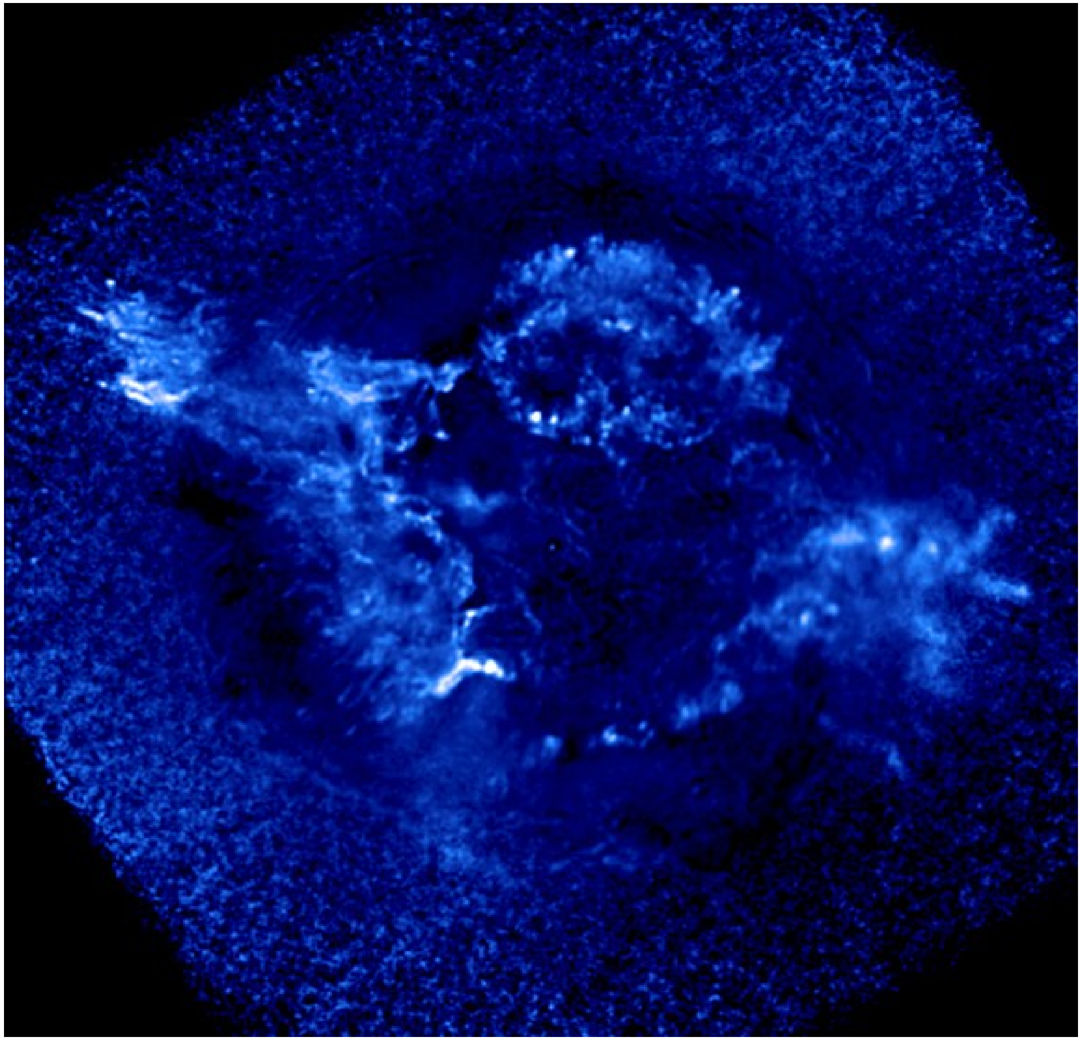
Cas A (Una Hwang)

- 1 megasecond (11 days)
- Blue: Fe
- Red: Si
- Green: outer shock wave



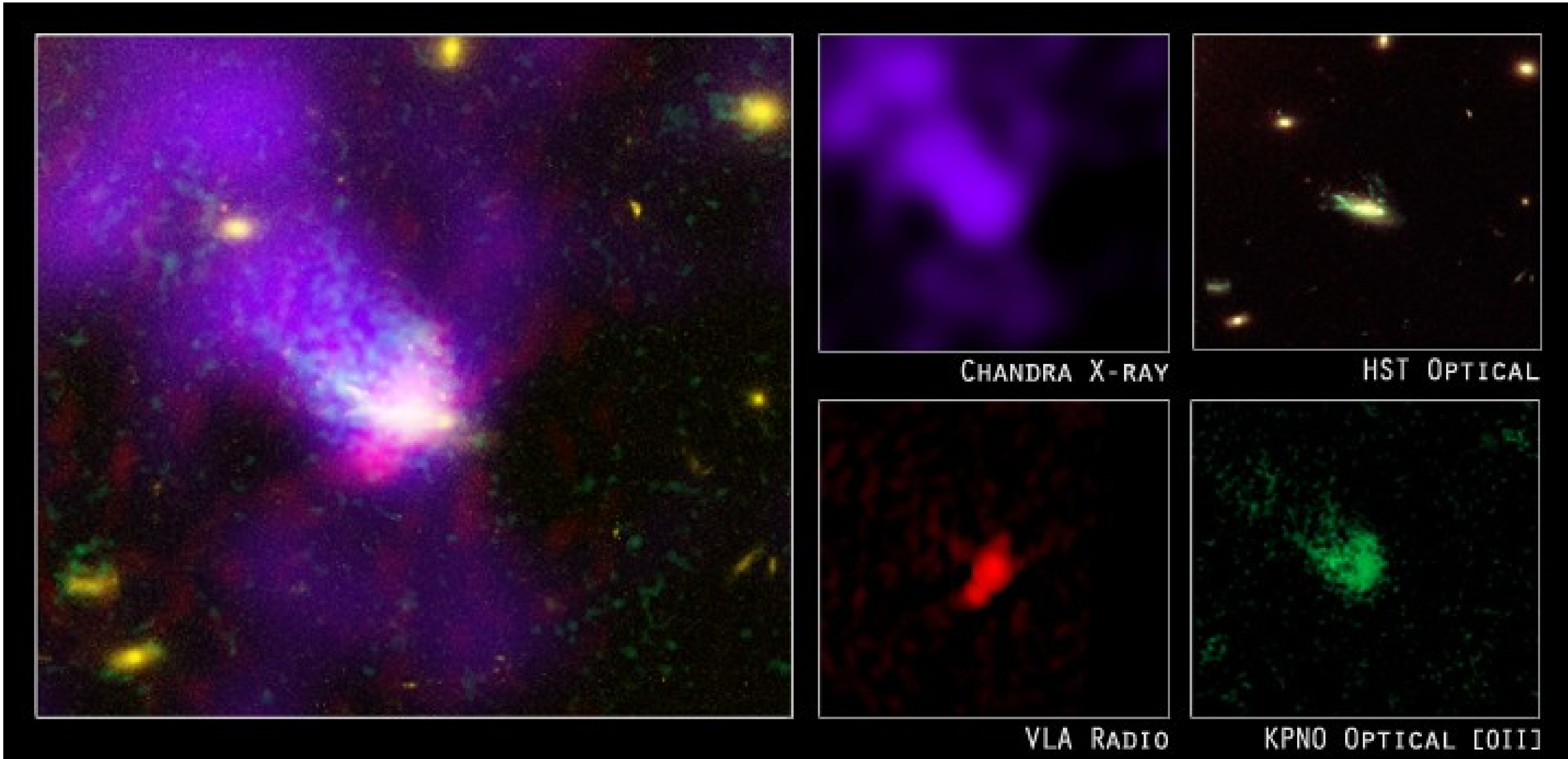
Cas A

- Si image shows "jets" from asymmetric explosion



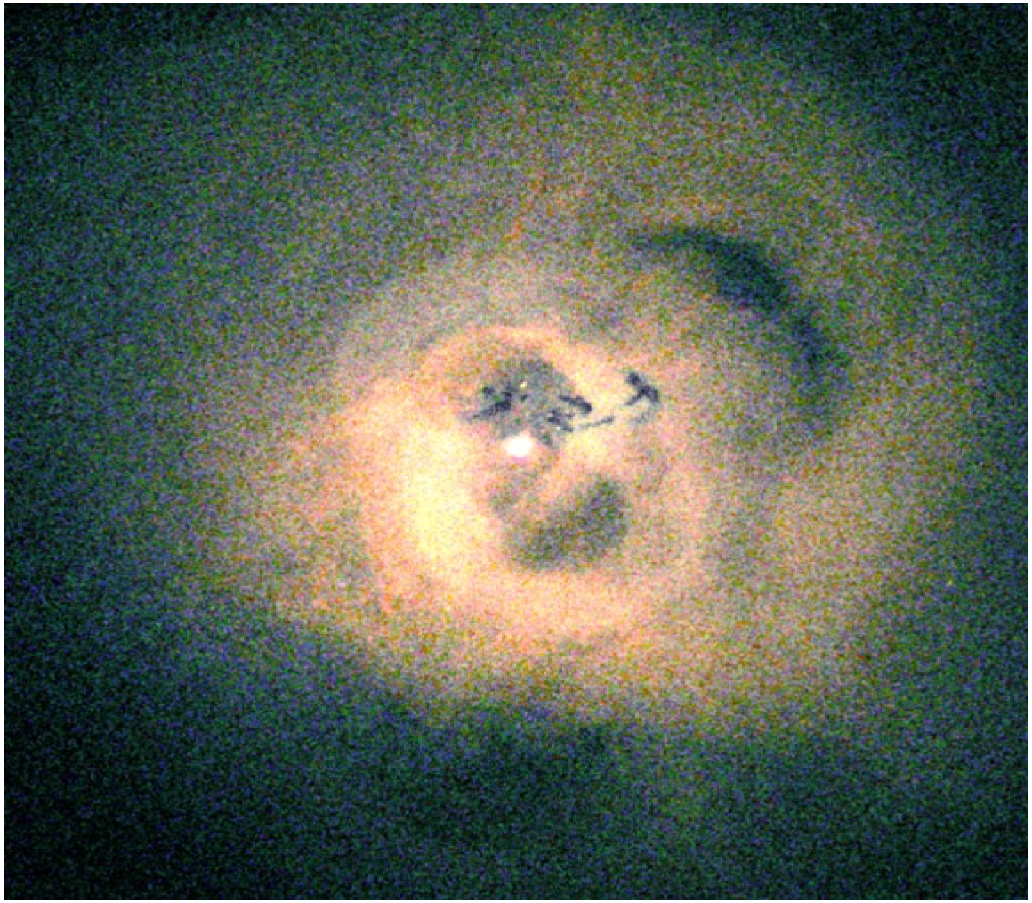
C153 (Dan Wang)

- Chandra data shows hot gas stripped from galaxy in cluster



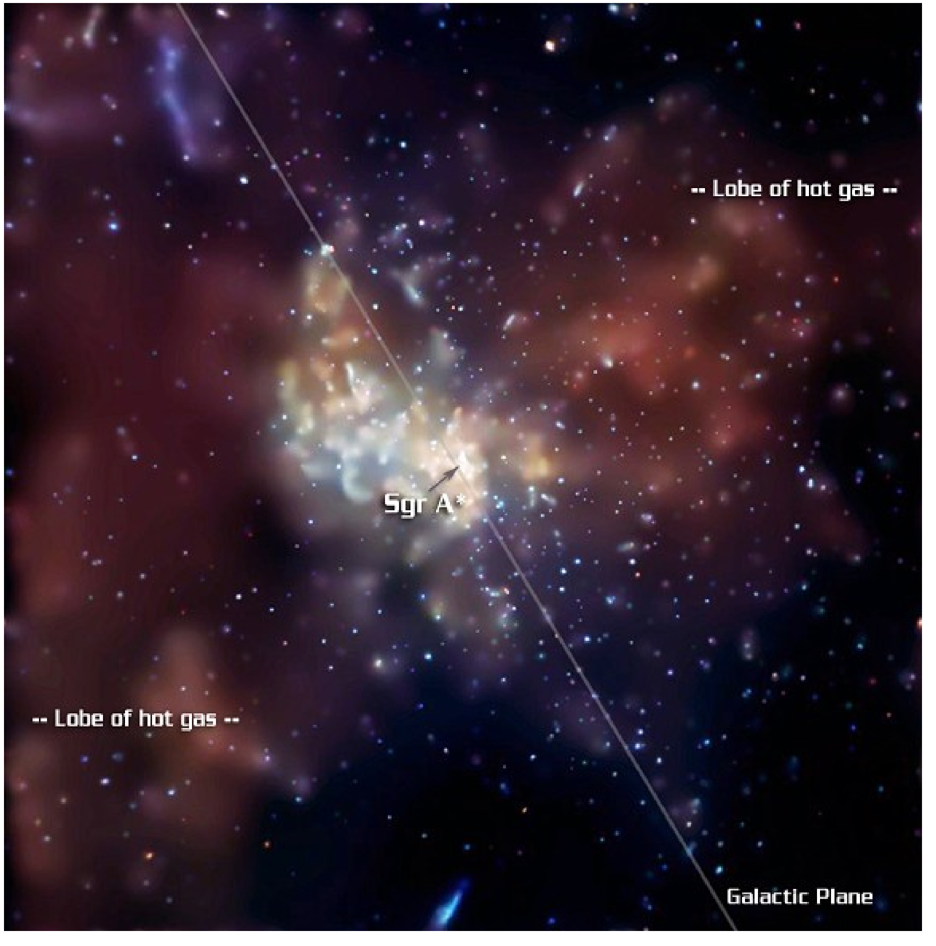
Perseus (Andy Fabian)

- Radio jets make cavities in X-ray cluster gas
- Shocks through cluster due to AGN?



Sgr A* (Fred Baganoff)

- Flaring from central source: smoking gun for the Galactic supermassive black hole?



Chandra data

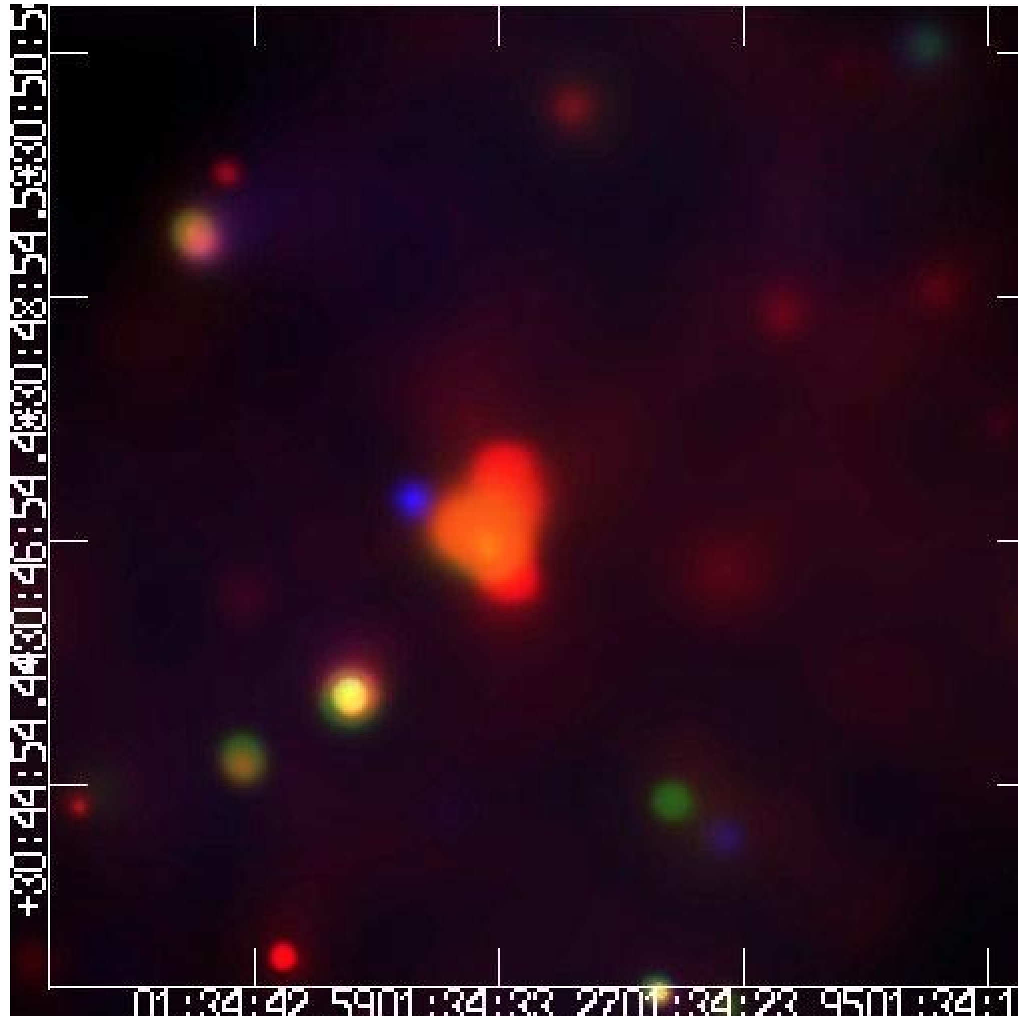
- Open competition for Chandra time
- SAO+MIT Chandra X-ray Center (CXC) in Cambridge, MA operates the satellite and supports observers
- CIAO data analysis system (Sun/Linux/OS10)
- chandra.harvard.edu (pretty pictures)
- cxc.harvard.edu (science, calibration, software, proposal submission)
- Our mission: make it possible for non-X-ray specialists to do X-ray astronomy
- All X-ray missions use (pretty much) common data format, good start for Virtual Observatory era

Chandra analysis issues

- Poisson noise - always too few photons
- Position: Astrometry is pretty reliable (1”); PSF degrades when far off-axis
- Time: ACIS has 3s exposure time, HRC can do 16 microsec. Calibration is good.
- Energy: Complicated energy response, varies with detector position and time, and has 'sidelobes'.
- Instrument problems: “CTI” energy resolution variation, “contamination” causing secular sensitivity loss at low energies, bad pixels and columns, background flares
- Universe problems: Cosmic X-ray background, solar X-rays, extinction by interstellar medium, etc.

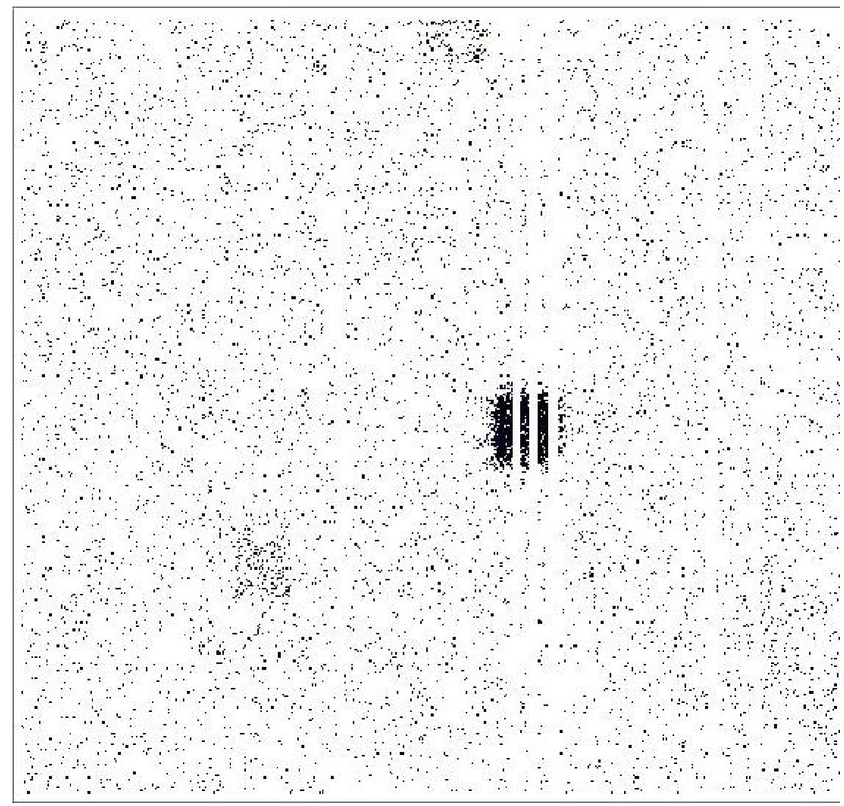
ACIS analysis

- Multicolor imaging helps in source identification
- Then define source regions and extract instrumental spectra
- Still can't deconvolve instrumental spectral response - forward model fitting required



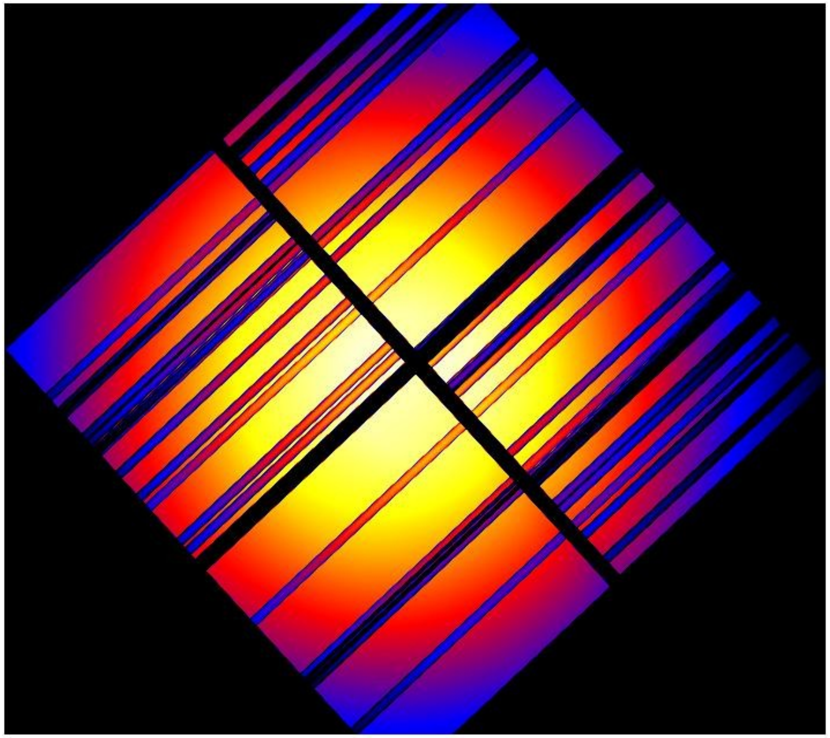
ACIS analysis

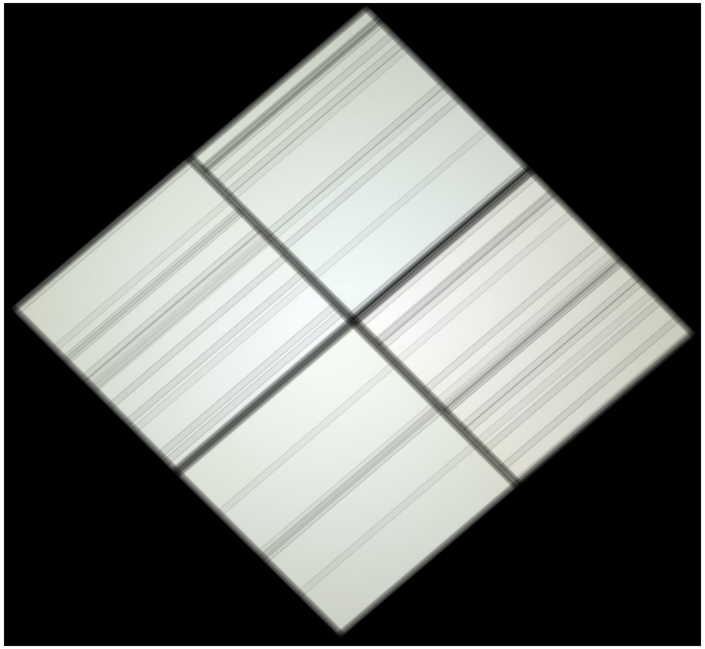
- In detector plane, sources are dithered
- Bad columns can affect effective exposure and introduce spurious time variability



ACIS analysis

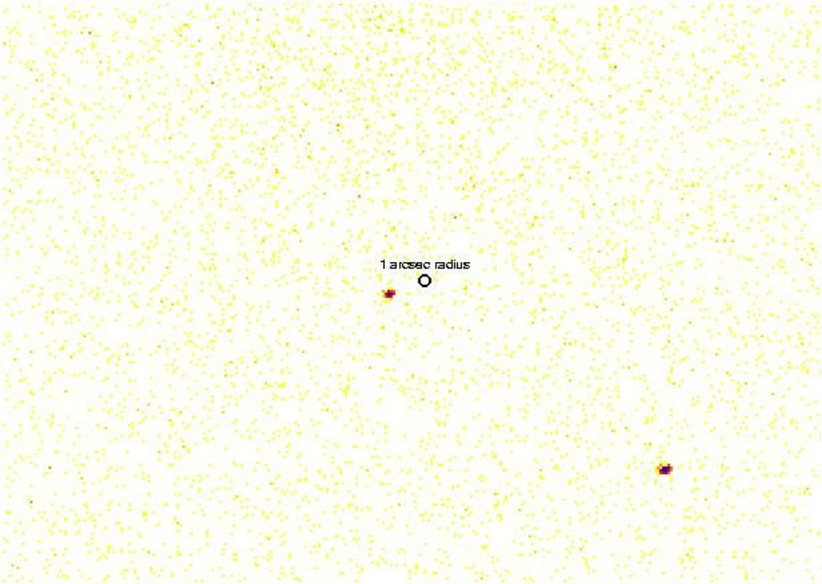
- Sensitivity varies by factor 2 across image
- Fairly insensitive to energy

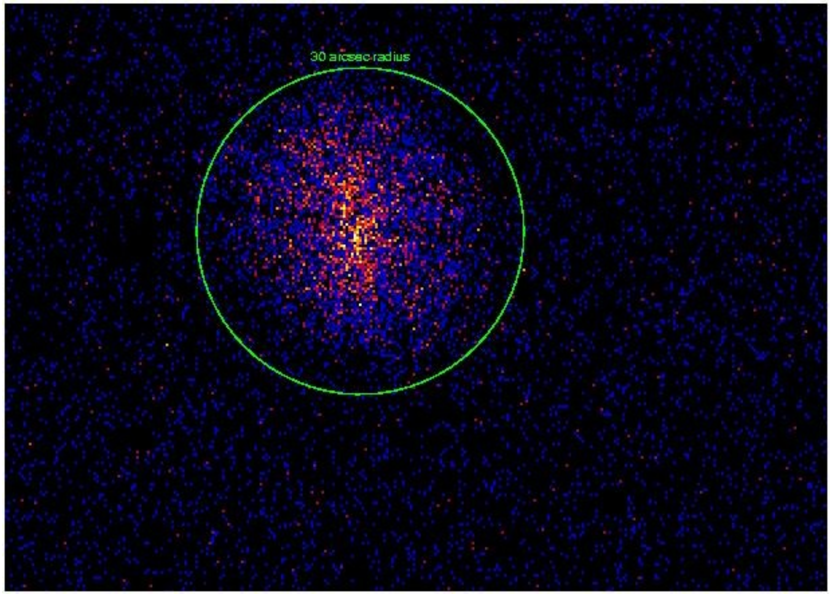


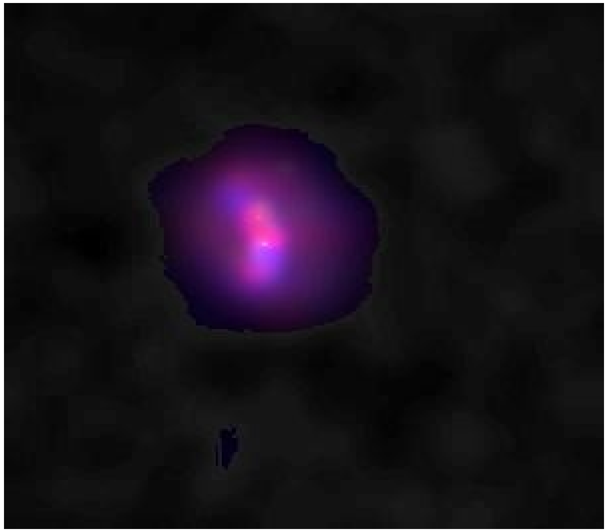


ACIS analysis

- PSF is awesomely good on axis, but (relatively) lousy at the edge of the field (cf 1' vs 16' offaxis)
- PSF is energy dependent

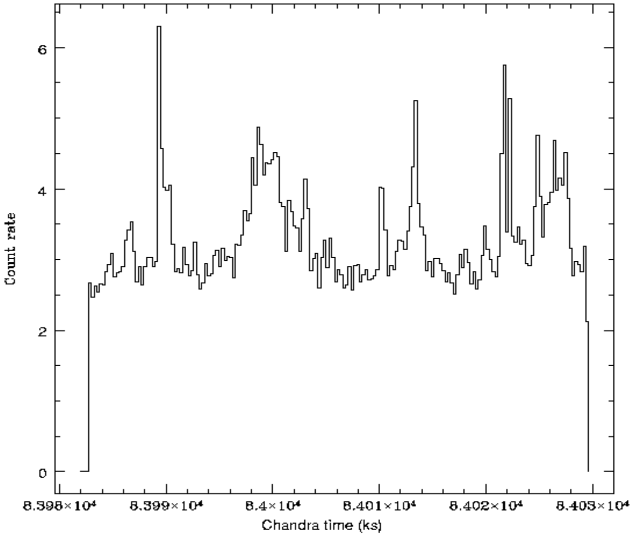


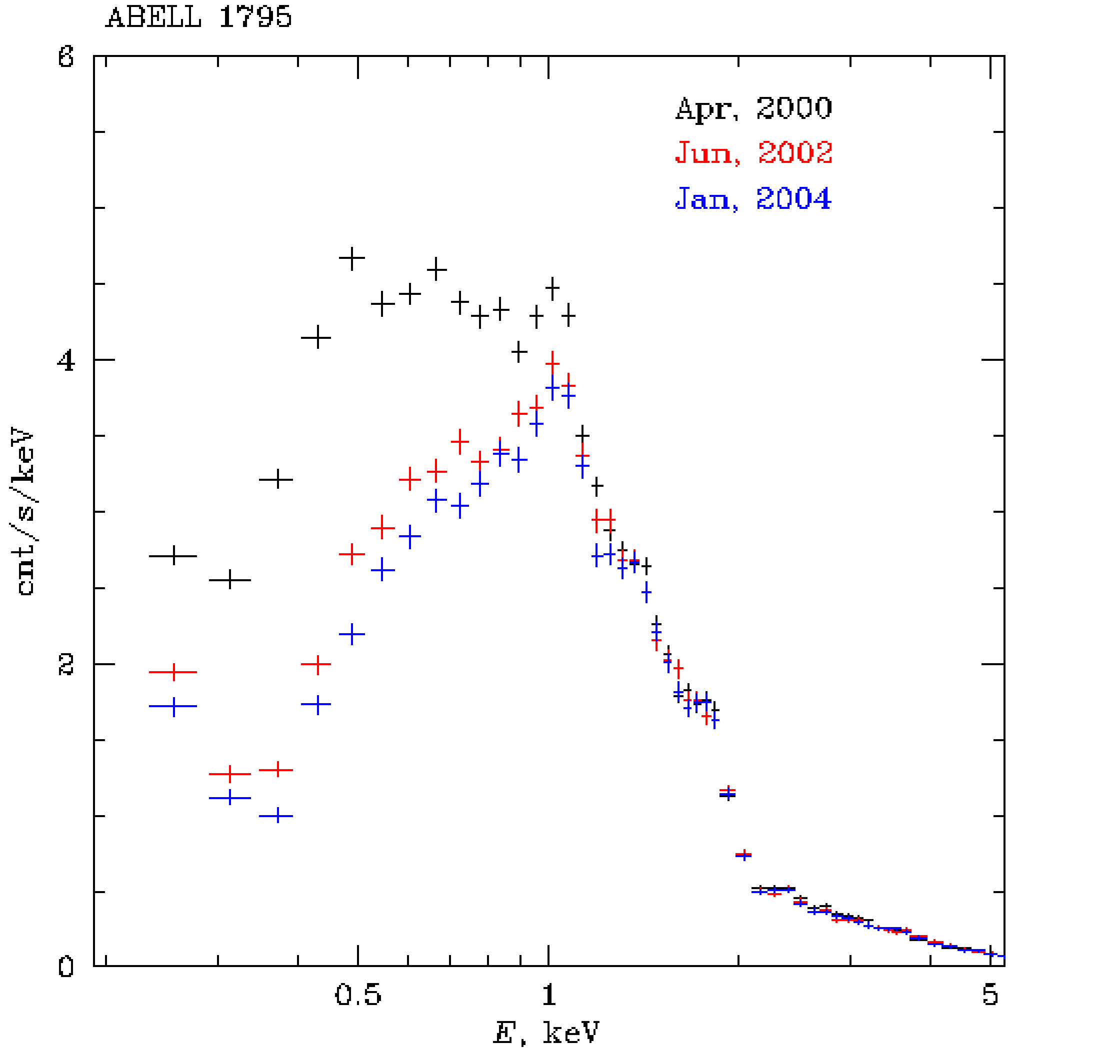




ACIS analysis

- Background flares
- CTI
- Contamination





Chandra

- 5 years of great science: spacecraft operating well
- Combining X-ray and optical (IR, radio) needed to untangle the physics
- High resolution imaging with spectra crucial to separate physical components of sources
- Next call for proposals early 2005