X-ray Astronomy
and the
Multicolored Universe

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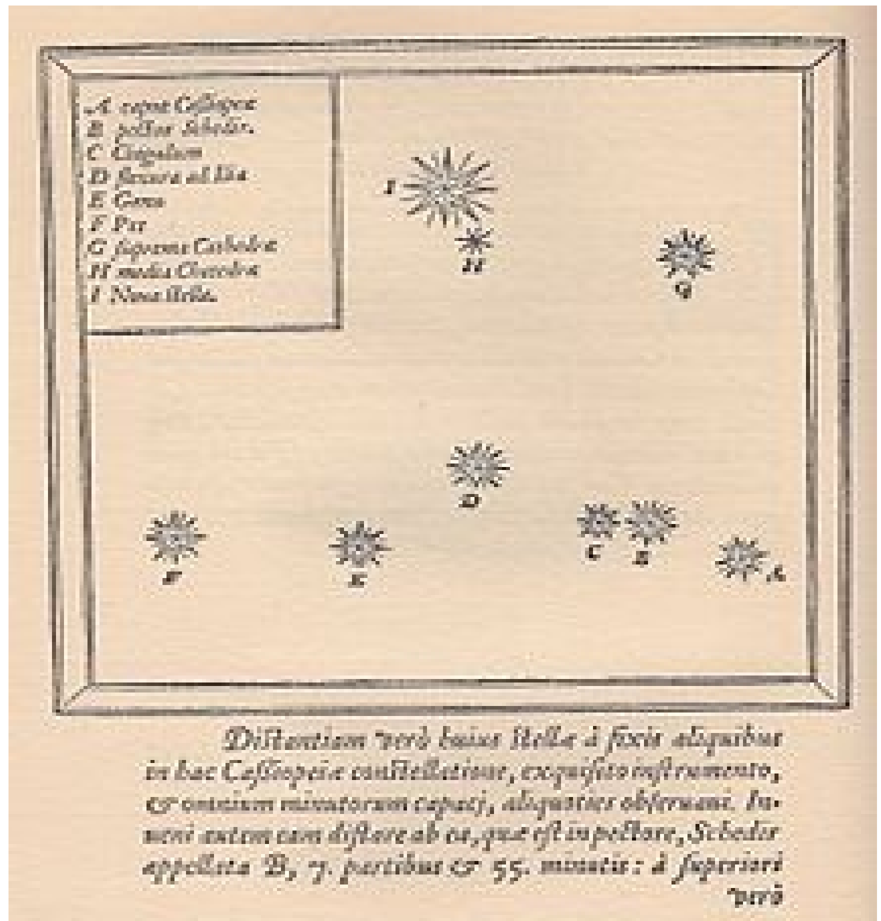
In 1572, Danish astronomer Tycho Brahe recorded a 'new star' in the constellation Cassiopeia

It was visible to the naked eye until 1574, slowly fading from view..



Part 1: A quick orientation tour of the Universe

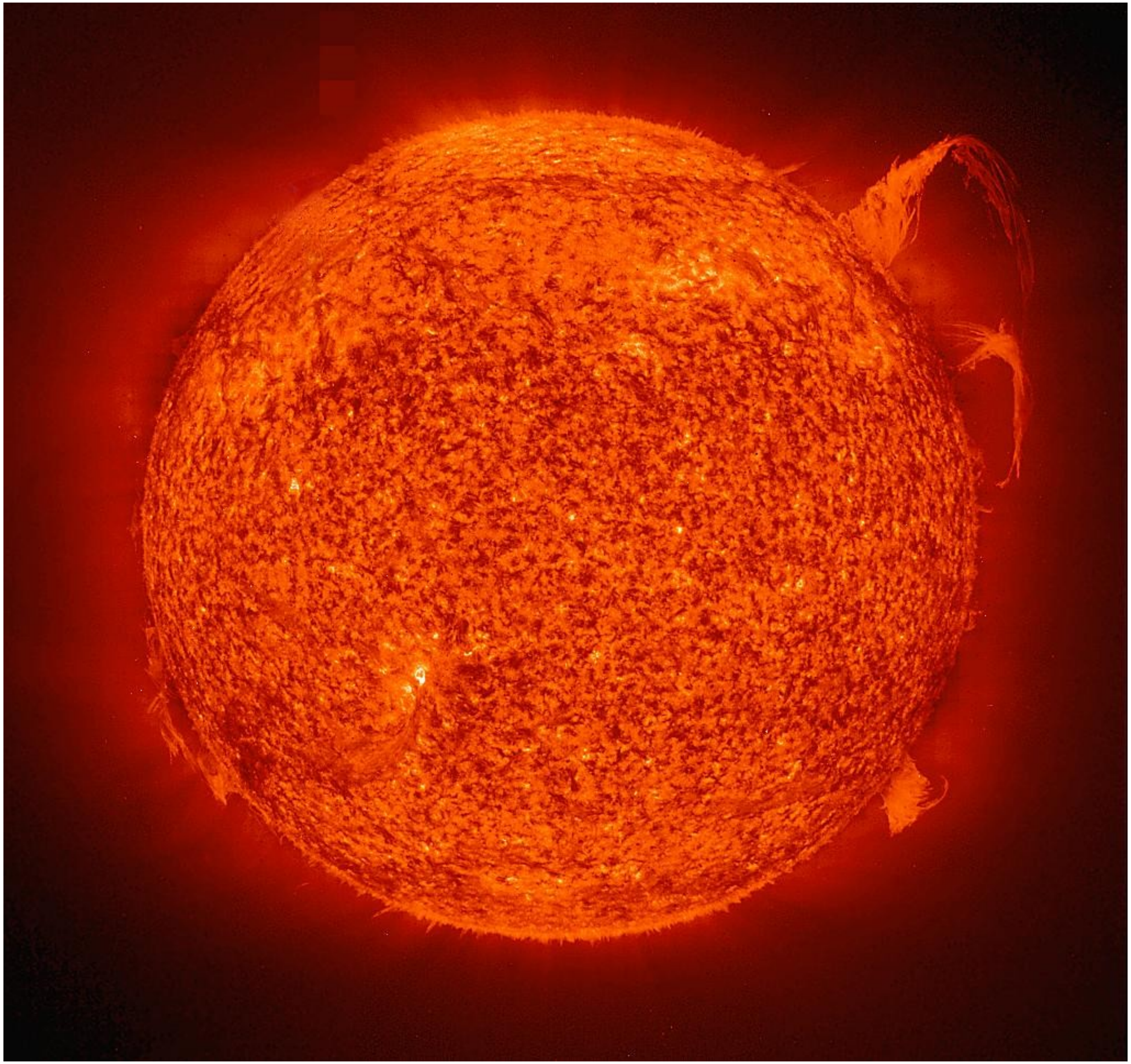
From the Earth to distant galaxies

Our Solar System: The Earth-Moon system

Earthrise over the Moon: 1969

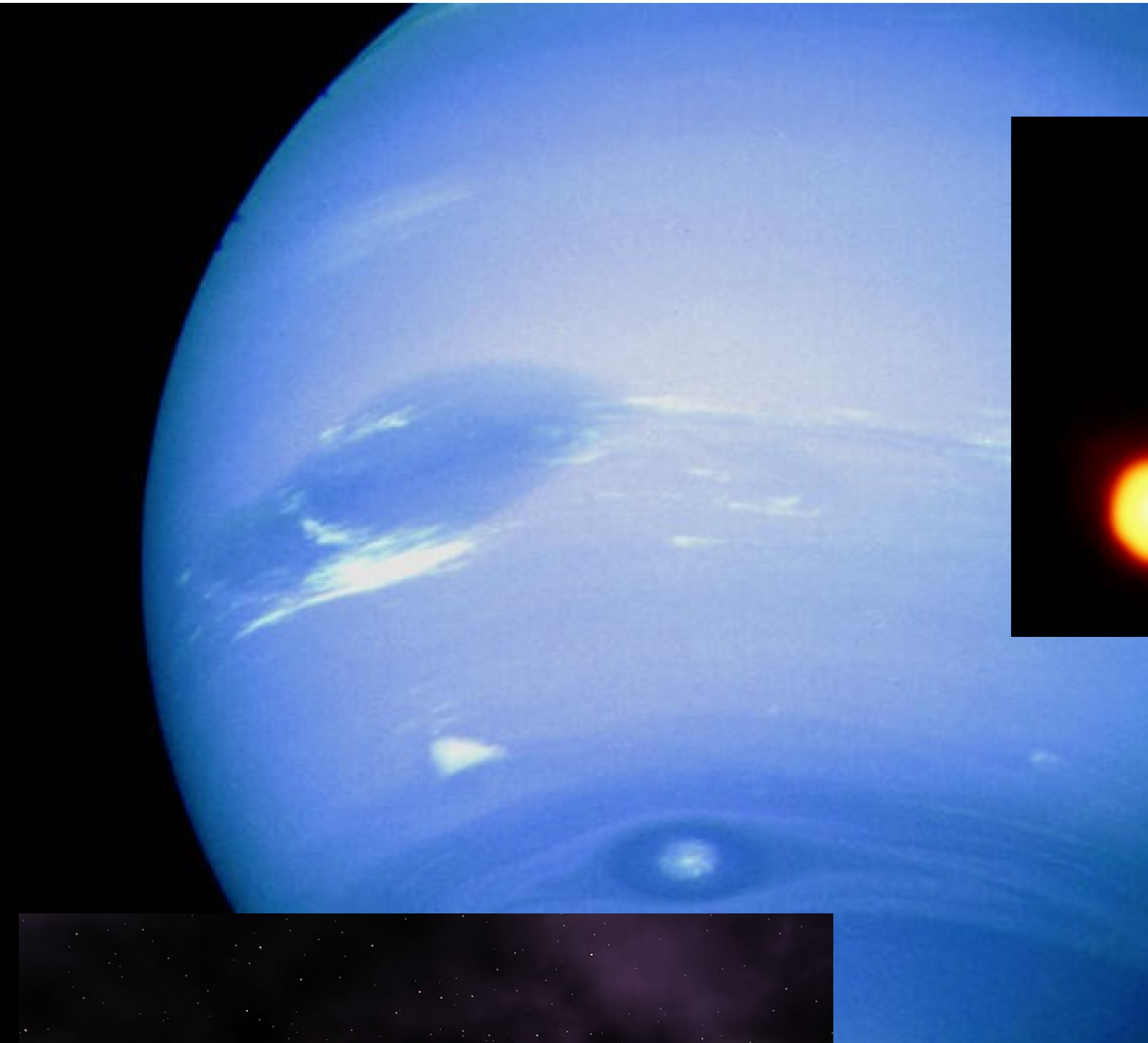
1.3 seconds away at the speed of light

Our Solar System: The Sun

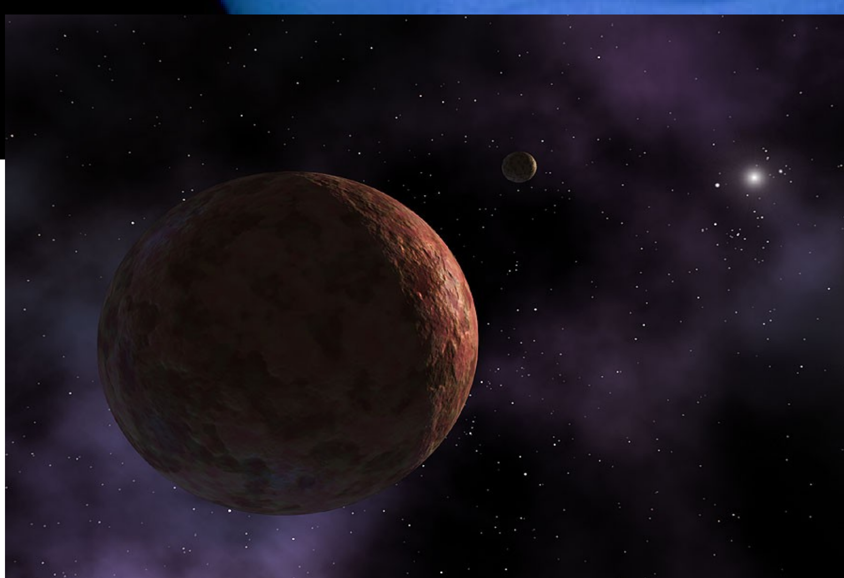


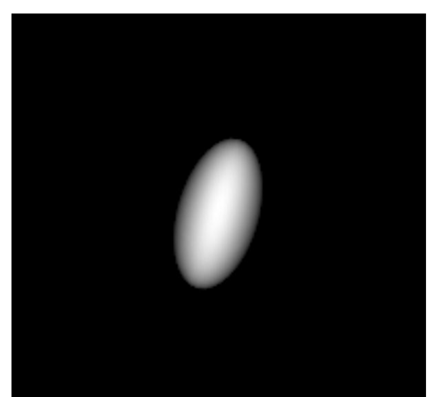
The Sun: 8 minutes away

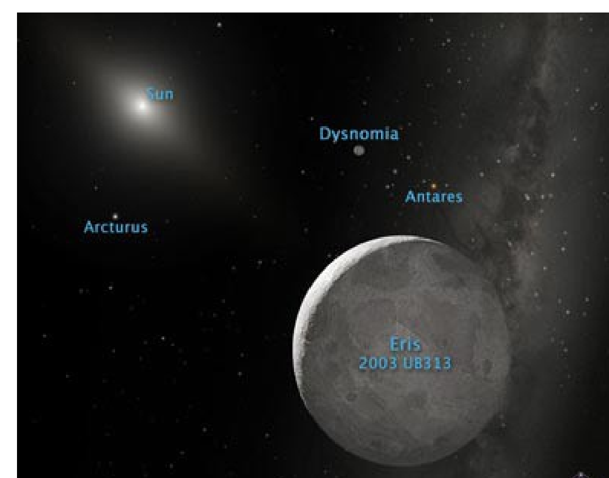
Our Solar System:
Neptune and Beyond



VIII Neptune:	4 hours	50000 km
134340 Pluto:	4h 24min	2300 km
136108 Haumea:	7h 4 min	1960 x 1000
136472 Makemake:	7h 13 min	1500 km?
136199 Eris:	13h 23 min	2600 km





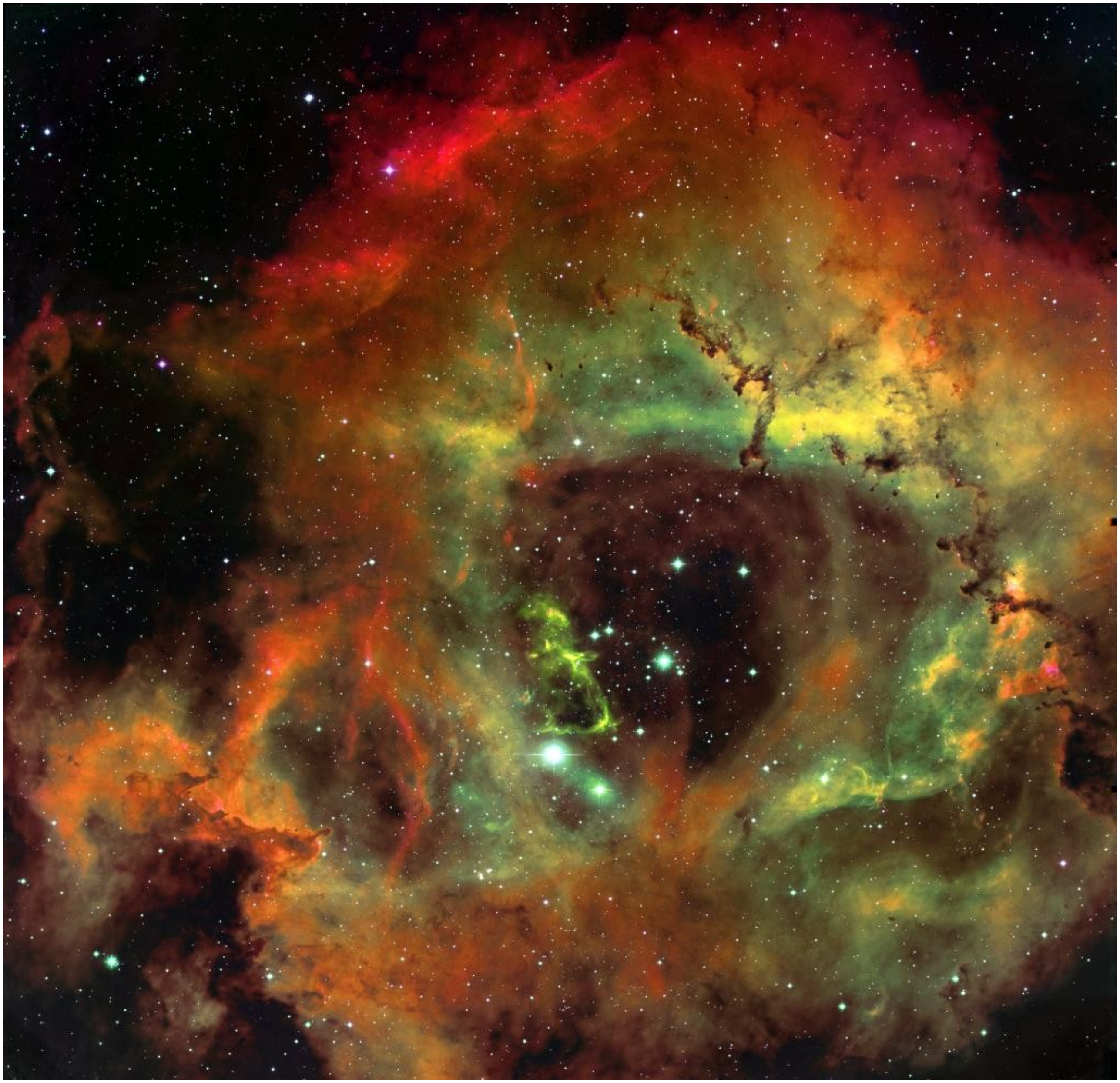


The Milky Way Galaxy: star clusters

Pleiades Star Cluster in Taurus: 440 years away

Seen as it was when Shakespeare was a child

The Milky Way Galaxy: Nebula



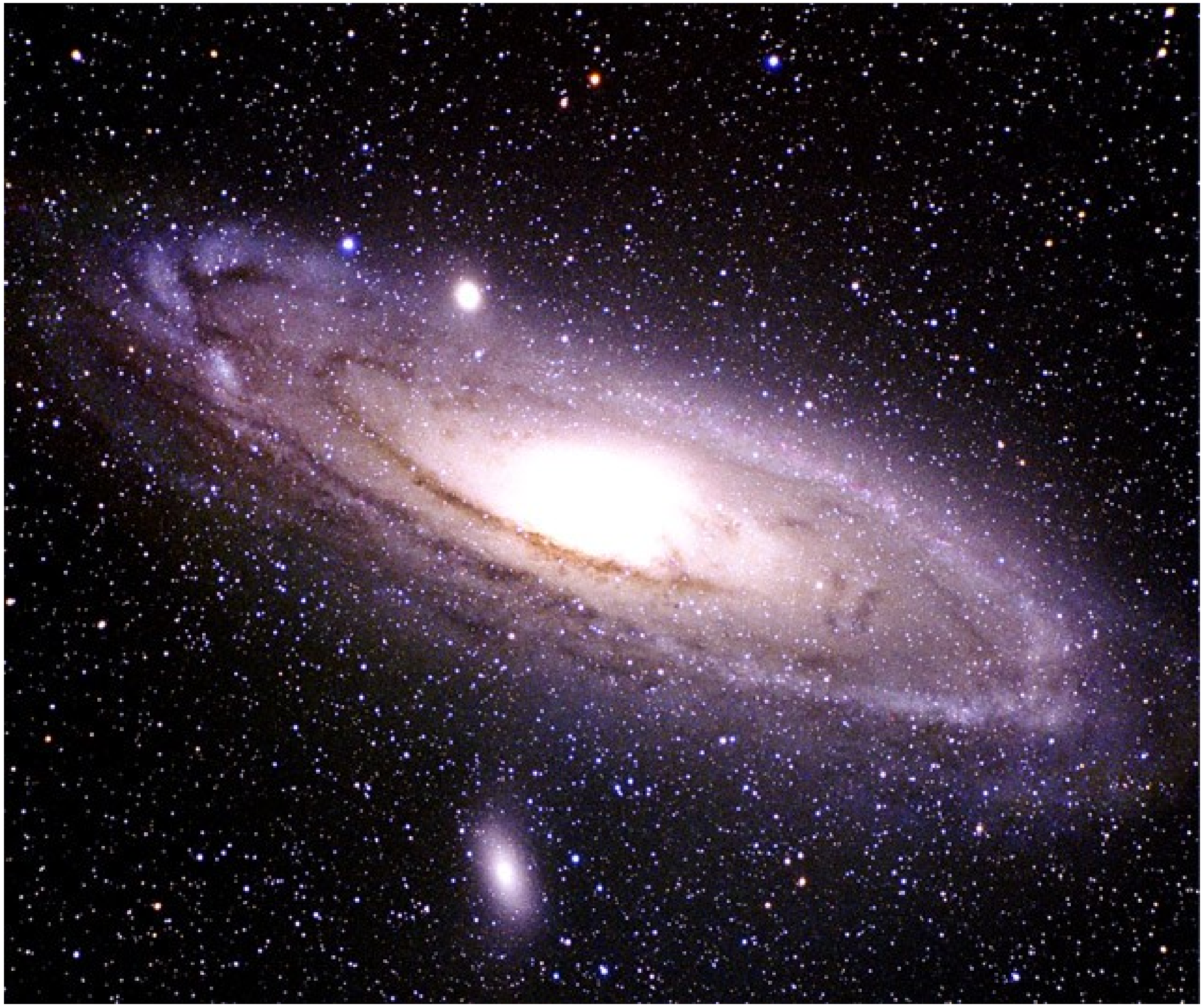
Rosette Nebula in Monoceros
4900 years away

Seen as it was when the first pyramids were built in Egypt

The Milky Way Galaxy: Galactic Center

Milky Way in Sagittarius: 30000 Years Away
Seen as it was when modern humans had just evolved

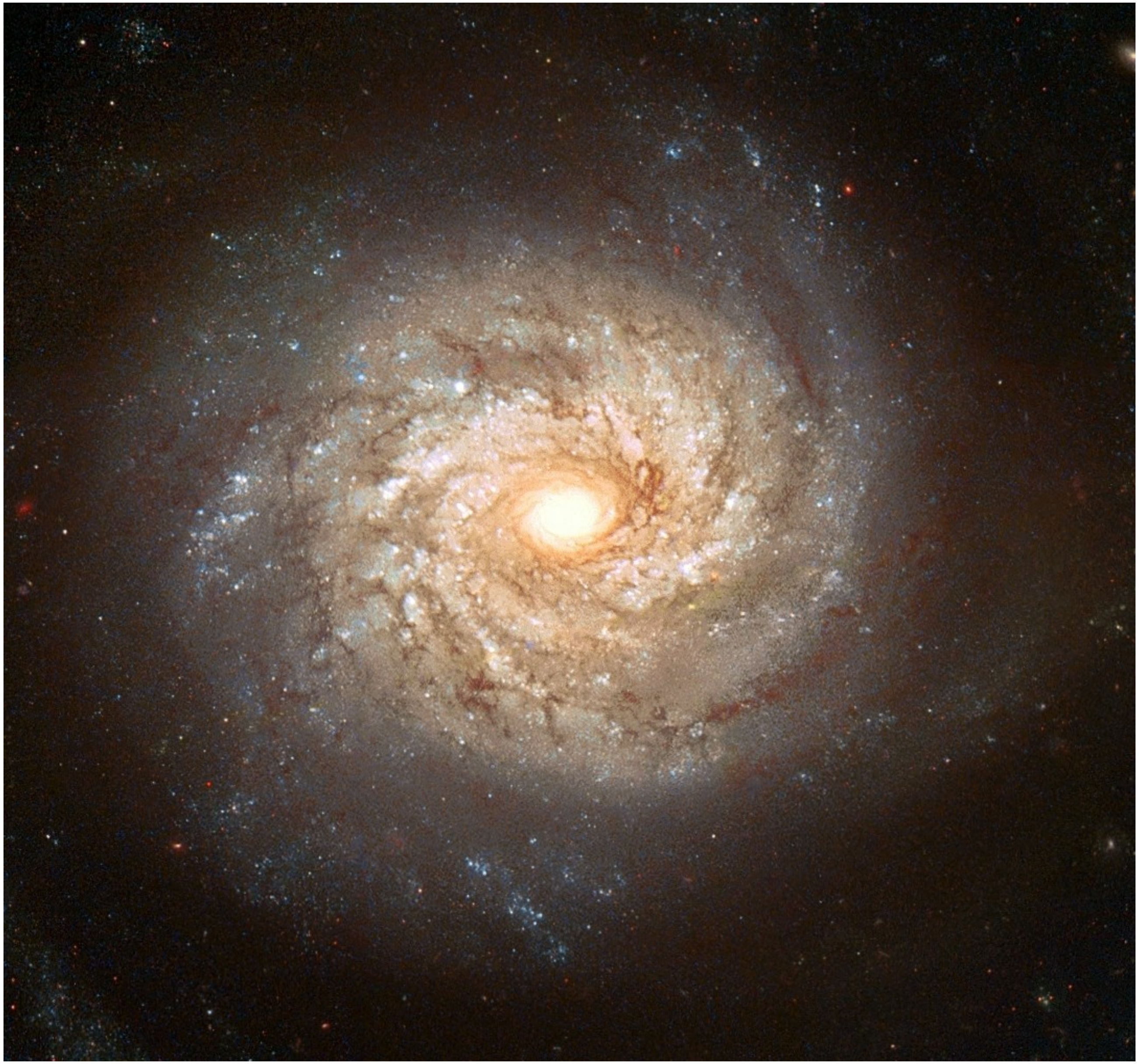
The Extragalactic Universe: Spiral Galaxy



Great Galaxy in Andromeda (M31): Our Next Door Neighbour - 2 Million Years Away

Seen as it was in the Pleistocene

Extragalactic Universe: Spiral Galaxy

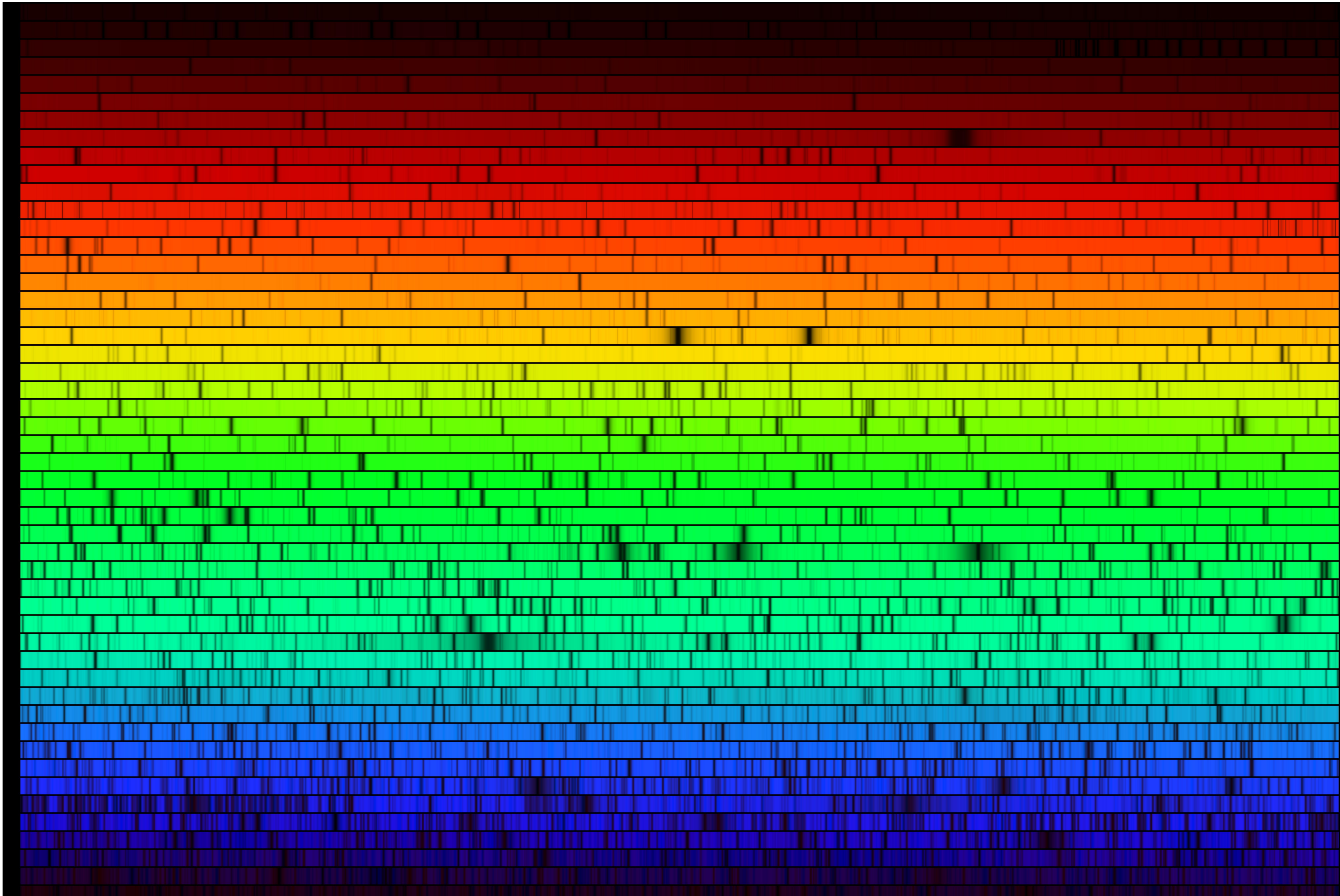


Galaxy NGC 3982 in Ursa Major – 60 Million Years Away

Tertiary (K-T boundary)

The Extragalactic Universe: Cluster of Galaxies

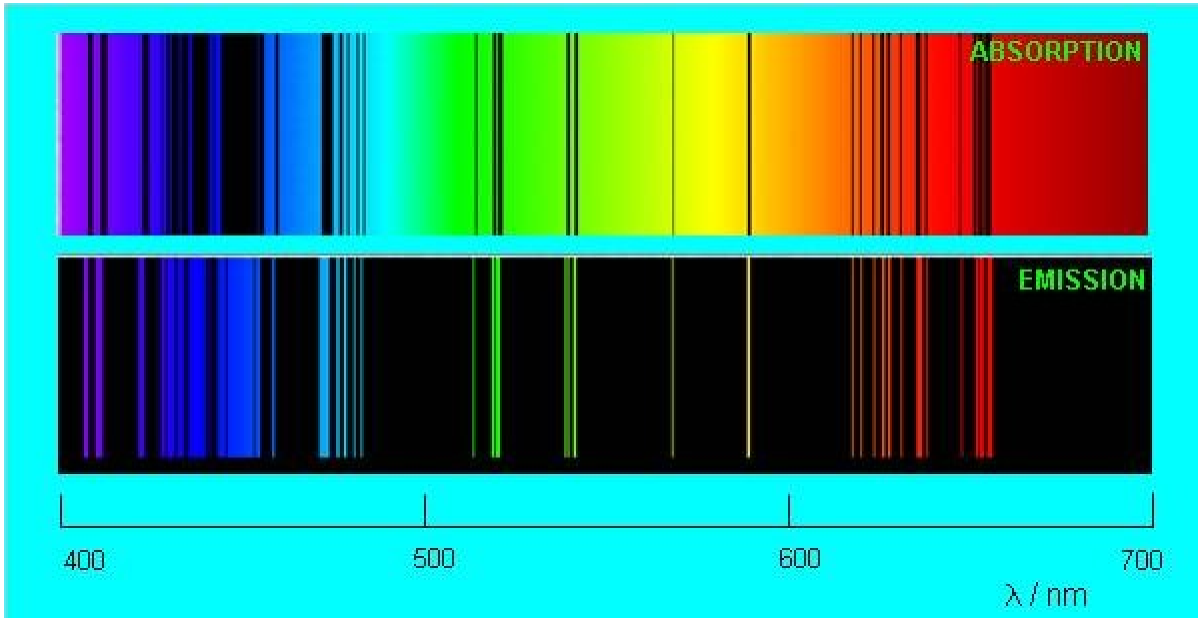
Abell 2744 - 3.5 billion light years away



Data: Bob Kurucz et al (SAO); Image: Nigel Sharp. NOAO; Telescope: KPNO-McMath

Solar spectrum, 2960-13000 Angstroms

What we can learn from a spectrum:



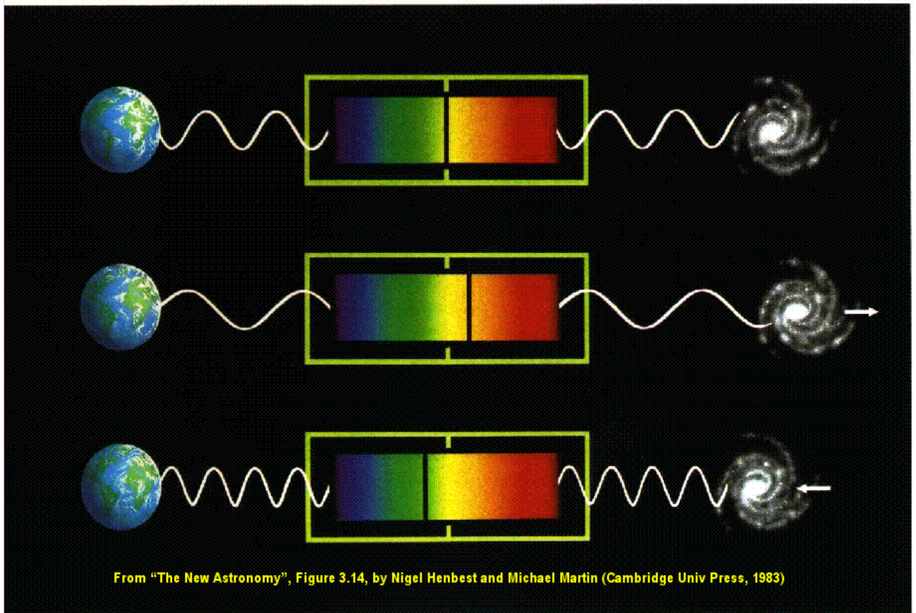
What is the light source made of?

- this is the “fingerprint' of sodium

What are the physical conditions like?

- relative brightness and thickness of different lines indicates temperature and density

How fast is it moving?
“Doppler Shift” stretches or squeezes the spectrum: read off the speed


From “The New Astronomy”, Figure 3.14, by Nigel Henbest and Michael Martin (Cambridge Univ Press, 1983)

Part 2:

The Electromagnetic Spectrum: from Radio Astronomy to to Gamma Ray Astronomy

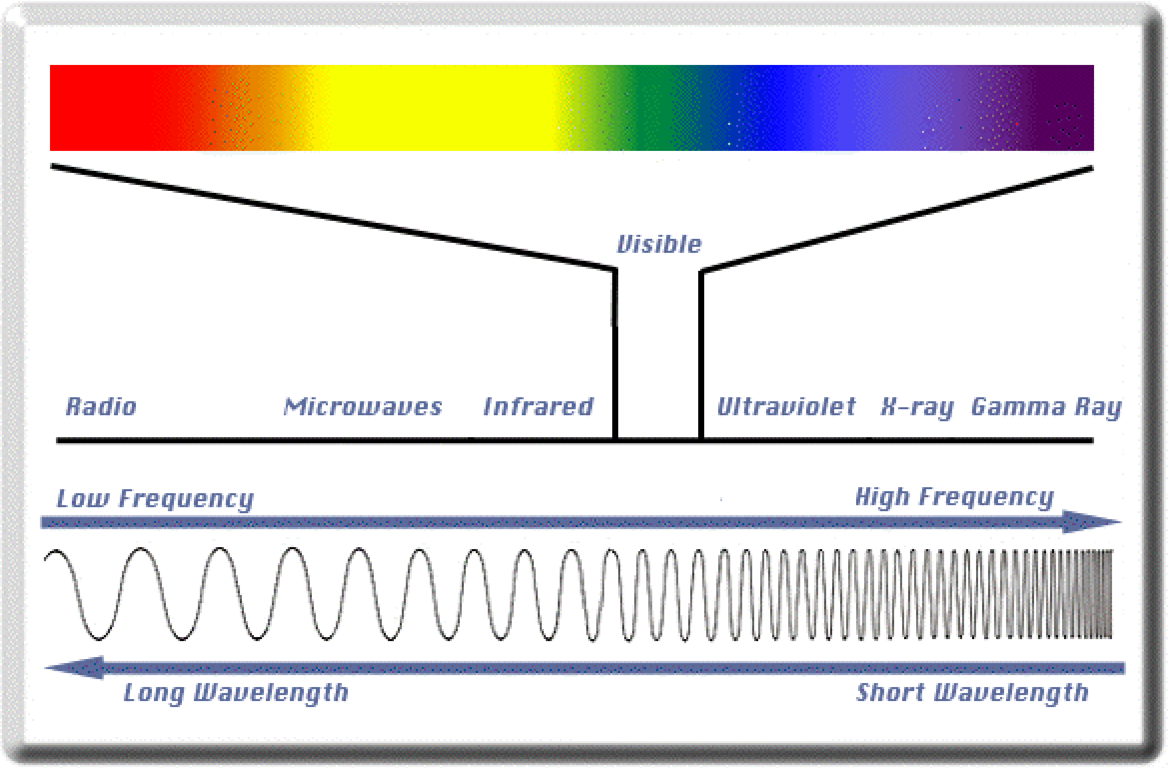
S125E011835

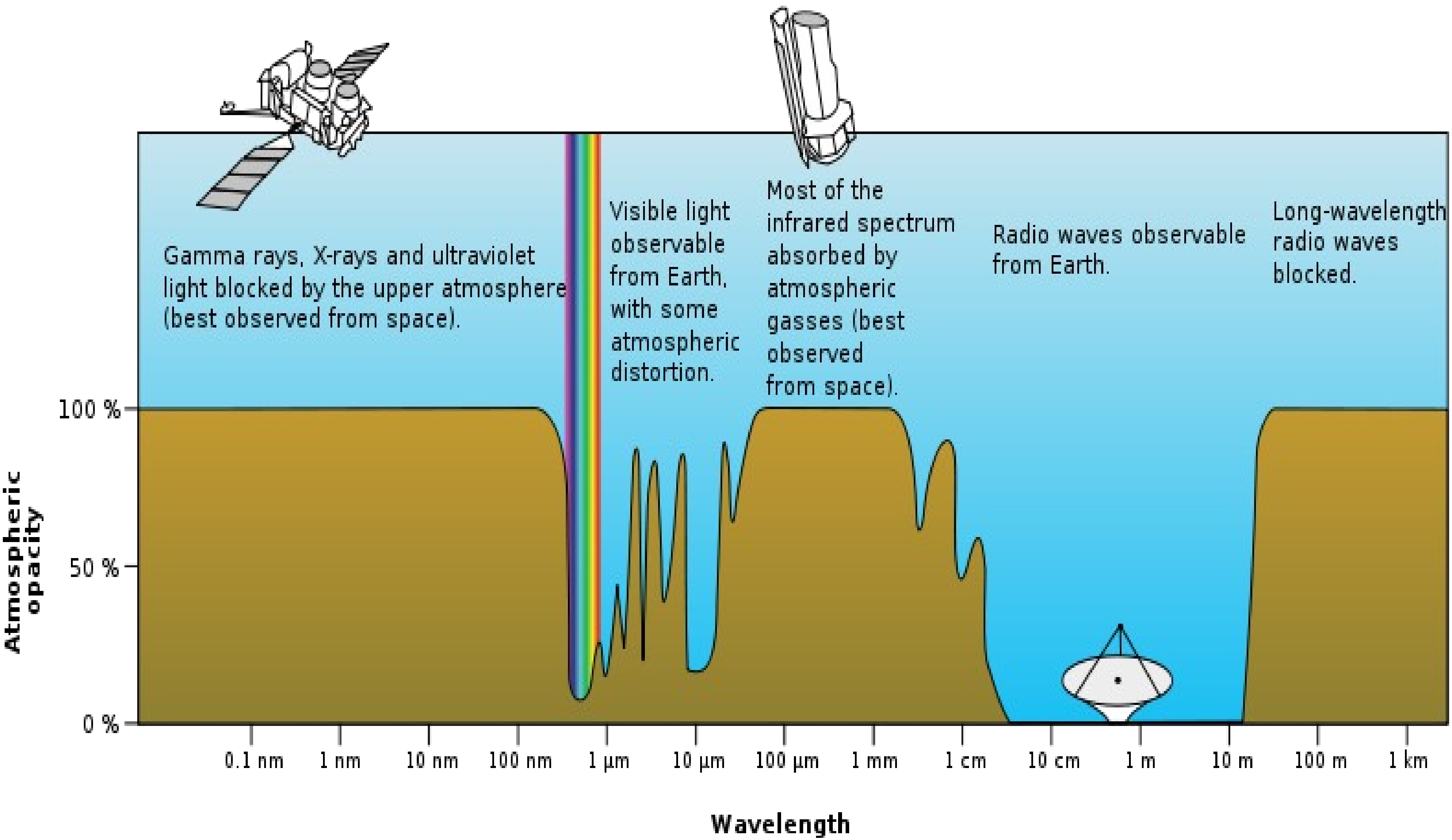
Astronauts' last view of Hubble in May 2009 after the final refurbishment mission

What's happing in the Universe these days?

We often divide up astronomy by the different WAYS WE LOOK AT THE SKY...

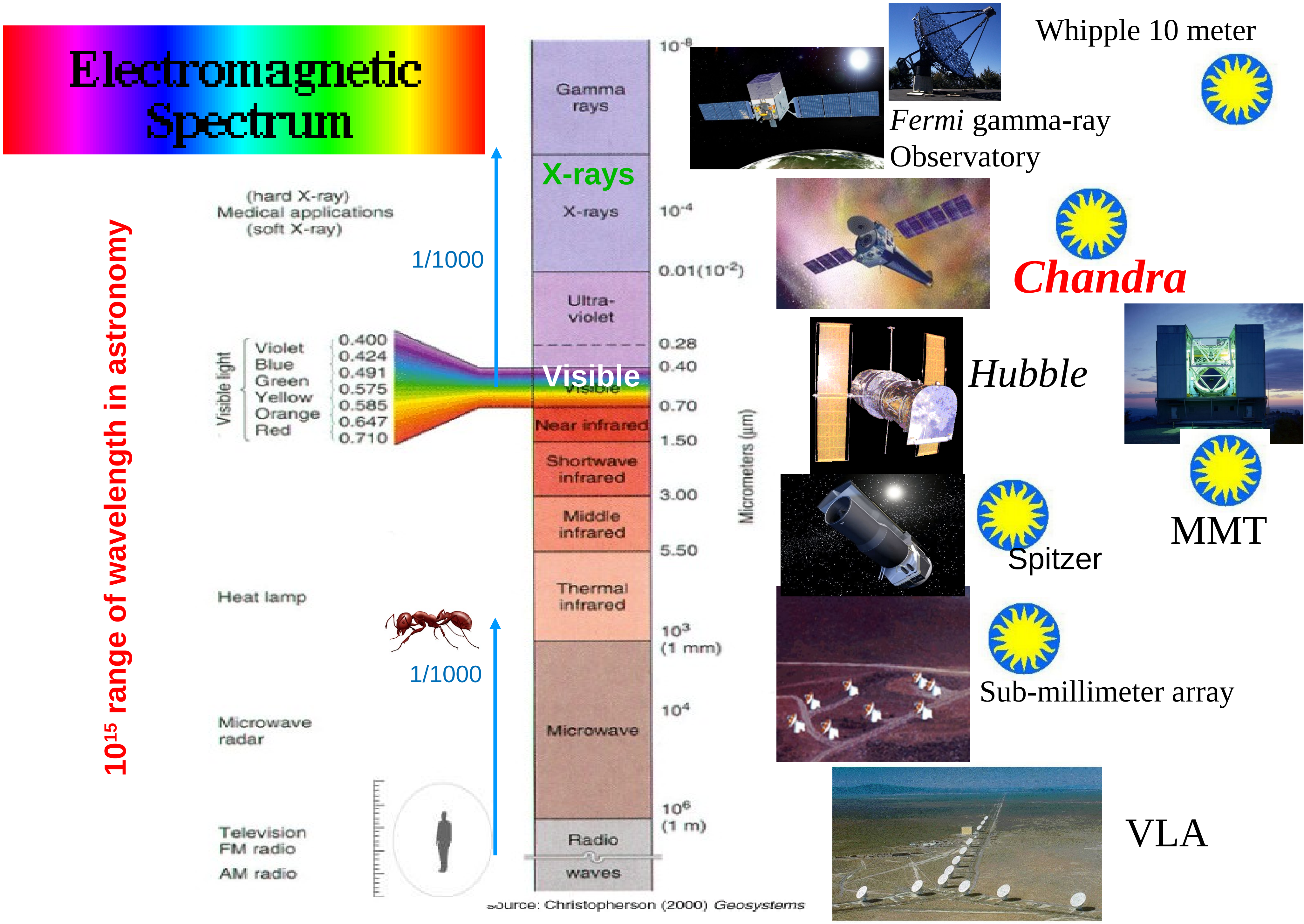
- RADIO telescopes which mostly see 'nonthermal' radiation
- INFRARED telescopes see cold (10-1000K) matter – star formation
- OPTICAL telescopes see warm (1000-100000K) matter – ordinary stars and gas
- X-RAY telescopes see hot (1 to 10 million K) matter – black hole accretion, supernovae and other drastic events





Gamma rays, X-rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
100 %
50 %
0 %
Atmospheric opacity
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

We are now in the era of multiwaveband astronomy



Part 3: X-ray Astronomy with Chandra

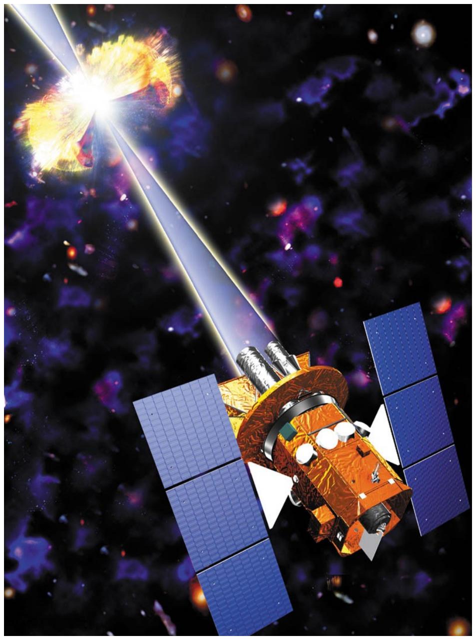
The Chandra X-ray Observatory

Launched 13 years ago 23 July 1999

A revolution in X-ray astronomy

and astronomy in general

X-ray satellites



SWIFT – Low Earth Orbit

Suzaku – Low Earth Orbit

Chandra

XMM – High Earth Orbit

What is Chandra?

The greatest X-ray telescope ever built!

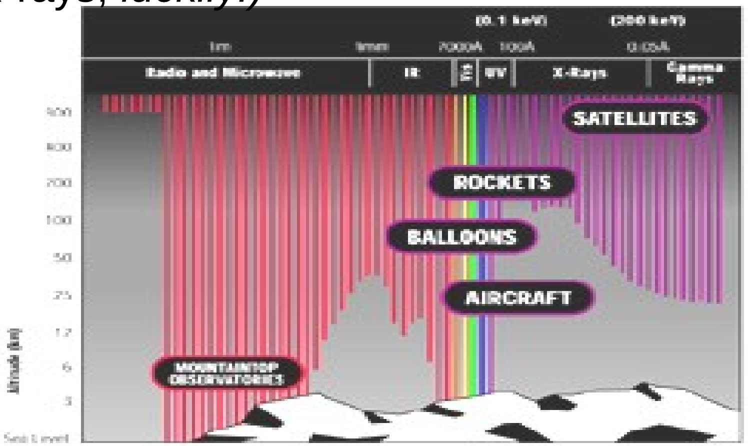
Orbits the Earth to be above the atmosphere (which absorbs X-rays, *luckily!)*

Goes 1/3 of the way to the Moon

every 64 hours (2 ½ days)

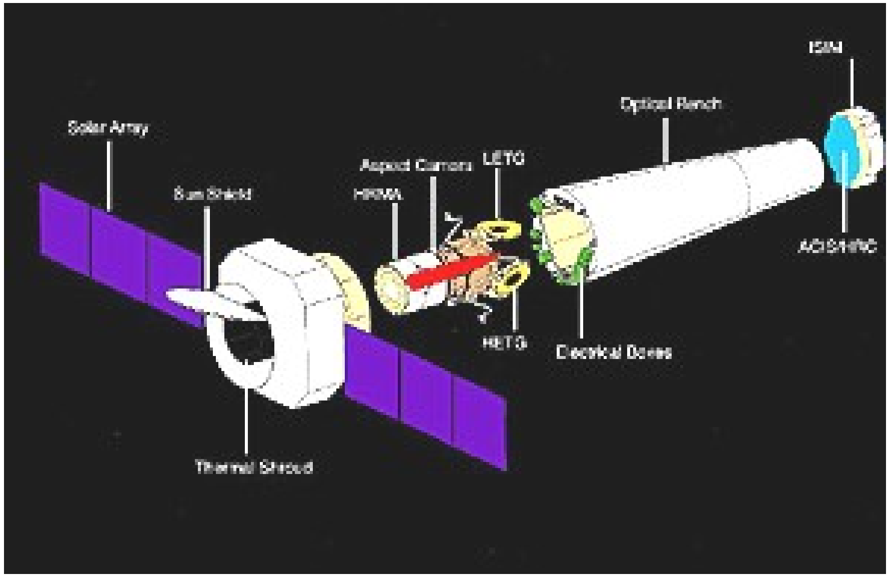
Chandra takes superbly sharp images:

with good spectral resolution (colors) too!

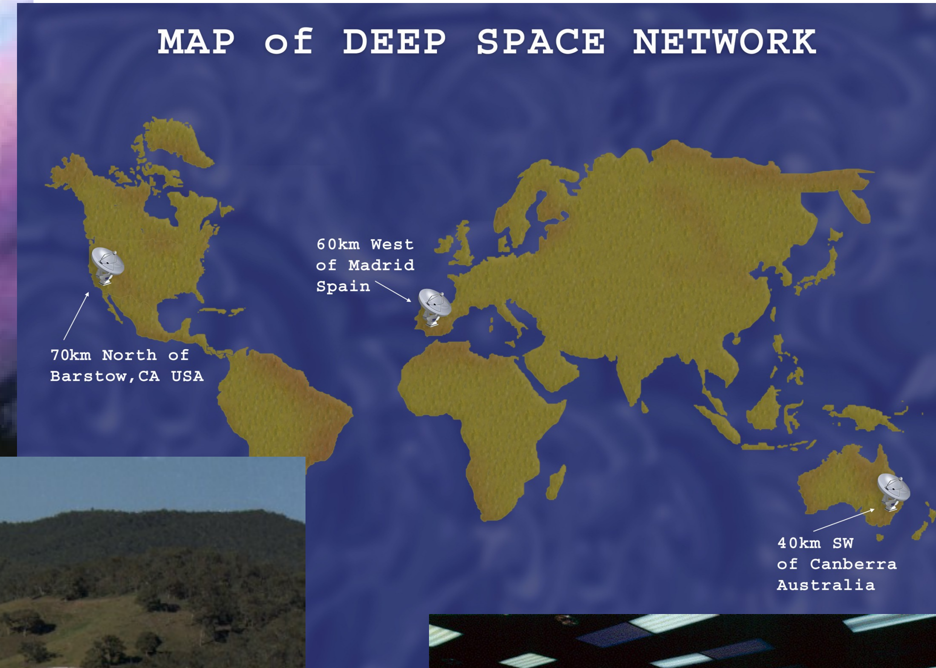


The Chandra spacecraft

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

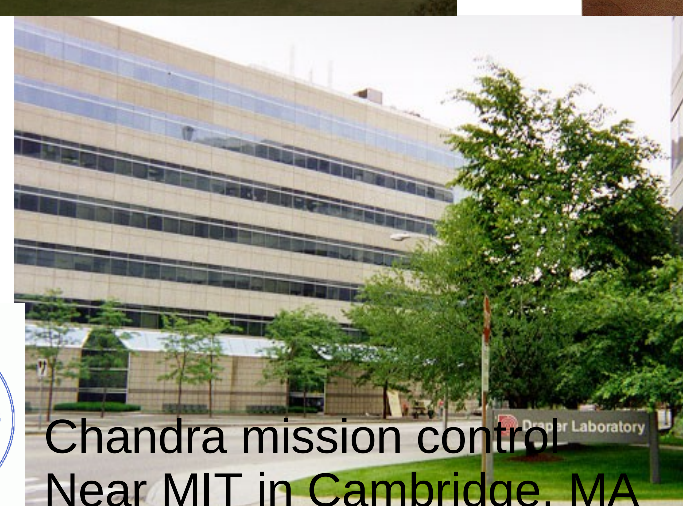


…but focuses X-rays onto a spot only 25 microns across



DSN control
at Jet Propulsion Lab
Pasadena, CA

Chandra science center
Smithsonian Observatory, at
Harvard (Cambridge, MA)



Chandra mission control
Near MIT in Cambridge, MA

Digression: What's an X-ray?

A lot of people are familiar with, but confused by, medical X-rays

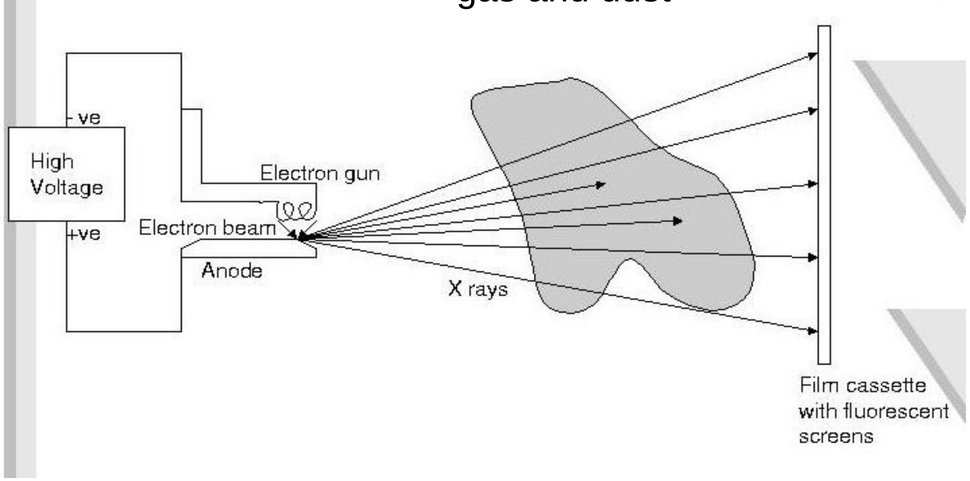
The photo at left is a picture of an X-ray light bulb, photobombed by someone's hand

The X-rays are the light bit. The dark areas are where there aren't any X-rays because the hand has blocked them.

X-ray bulb
= star,galaxy

Hand
= interstellar
gas and dust

X-ray
camera



In X-ray astronomy we are usually taking a picture of the “light bulb” (the star making the X-rays) and not interested in the “hand” (stuff blocking the X-rays between the star and us)

Visible-light photons are like raindrops
- each one is 'small' (has a small amount of energy)
- there are lots of them, but don't do any damage

X-ray photons are like hailstones
- each one is 'big' – lots of energy
- there are many fewer of them
- but each one packs a wallop

If you up the INTENSITY (number of photons) in a beam of light you increase the total energy you get but not the energy per 'packet'
If you want to get a tan (or worse) you have to increase the energy per photon, not just the number of photons.
We have a word for the energy of a photon: “COLOR”
(well, “COLOUR” but I'll defer to the local sensibility)

X-ray Telescopes are different

Chandra’s mirrors are almost cylinders

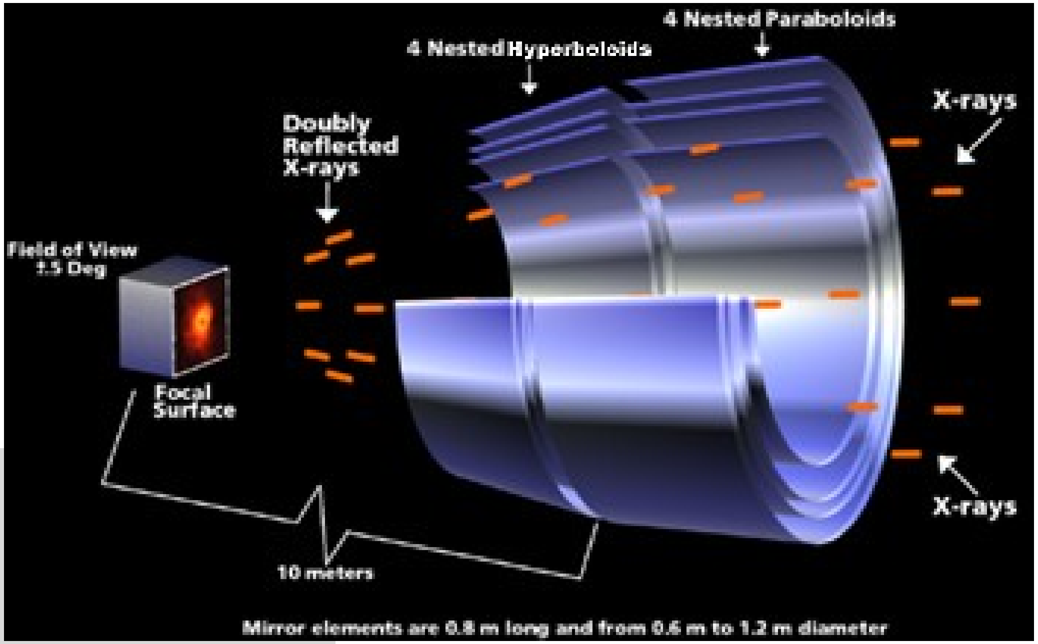
X-rays don’t reflect off a normal mirror – they get absorbed.

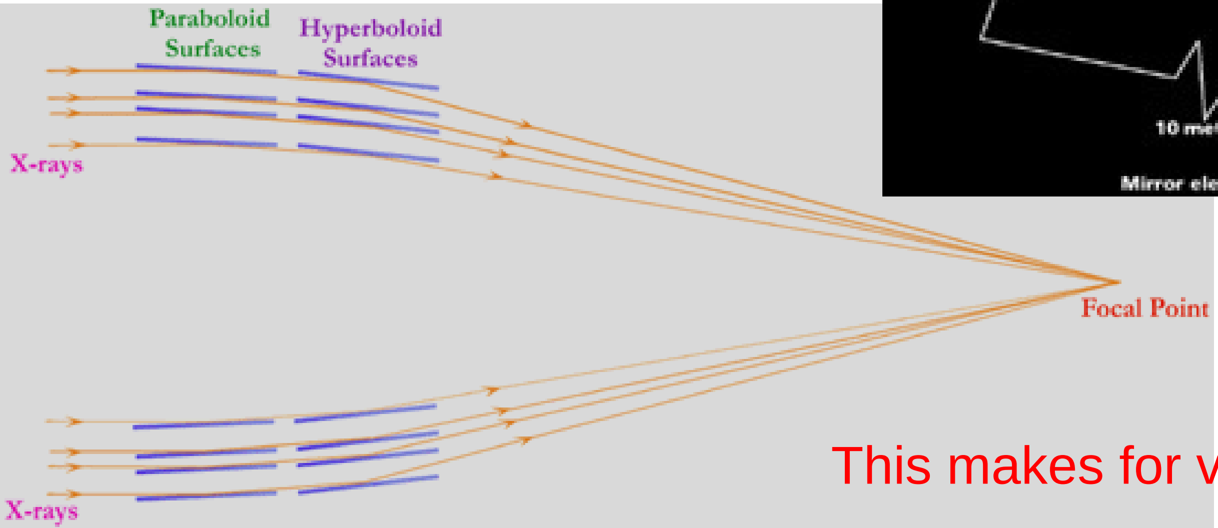
Only by striking a mirror at a glancing angle, about 1^{o},

do X-rays reflect.

Then they act like visible light

and can be focused





This makes for very long telescopes

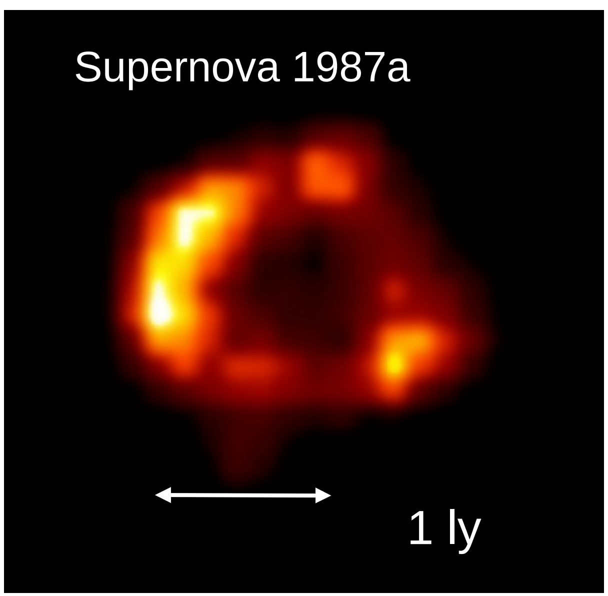
Sources of X-rays

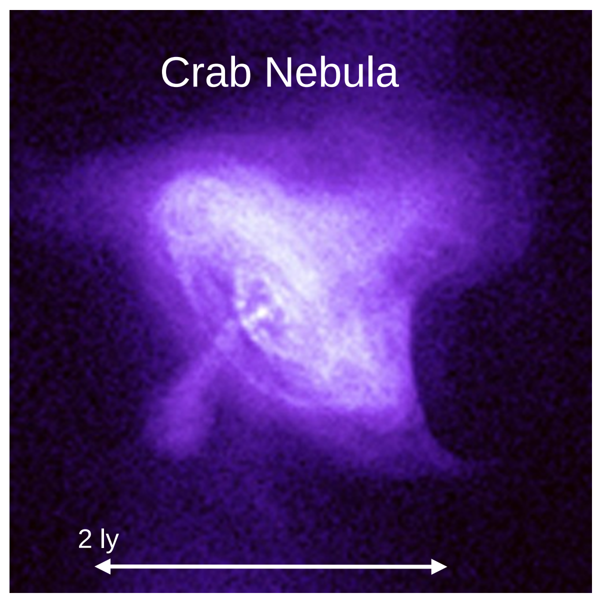
- Shock waves in plasma (ionized gas)
- "Synchrotron" caused by energetic particles in magnetic fields (like a natural particle accelerator)
- Energy release from gravity ("accretion" power)

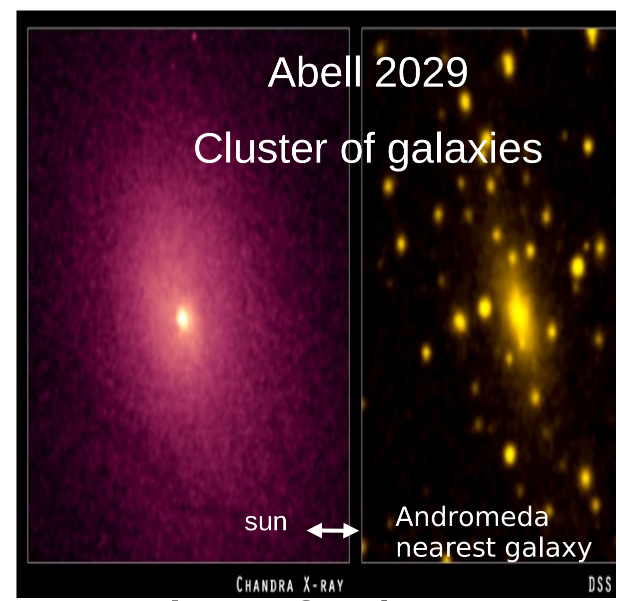
Explosions: Supernovae and their remnants

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

Matter falling into **deep gravitational wells**







In the optical, we see mostly energy from nuclear fusion

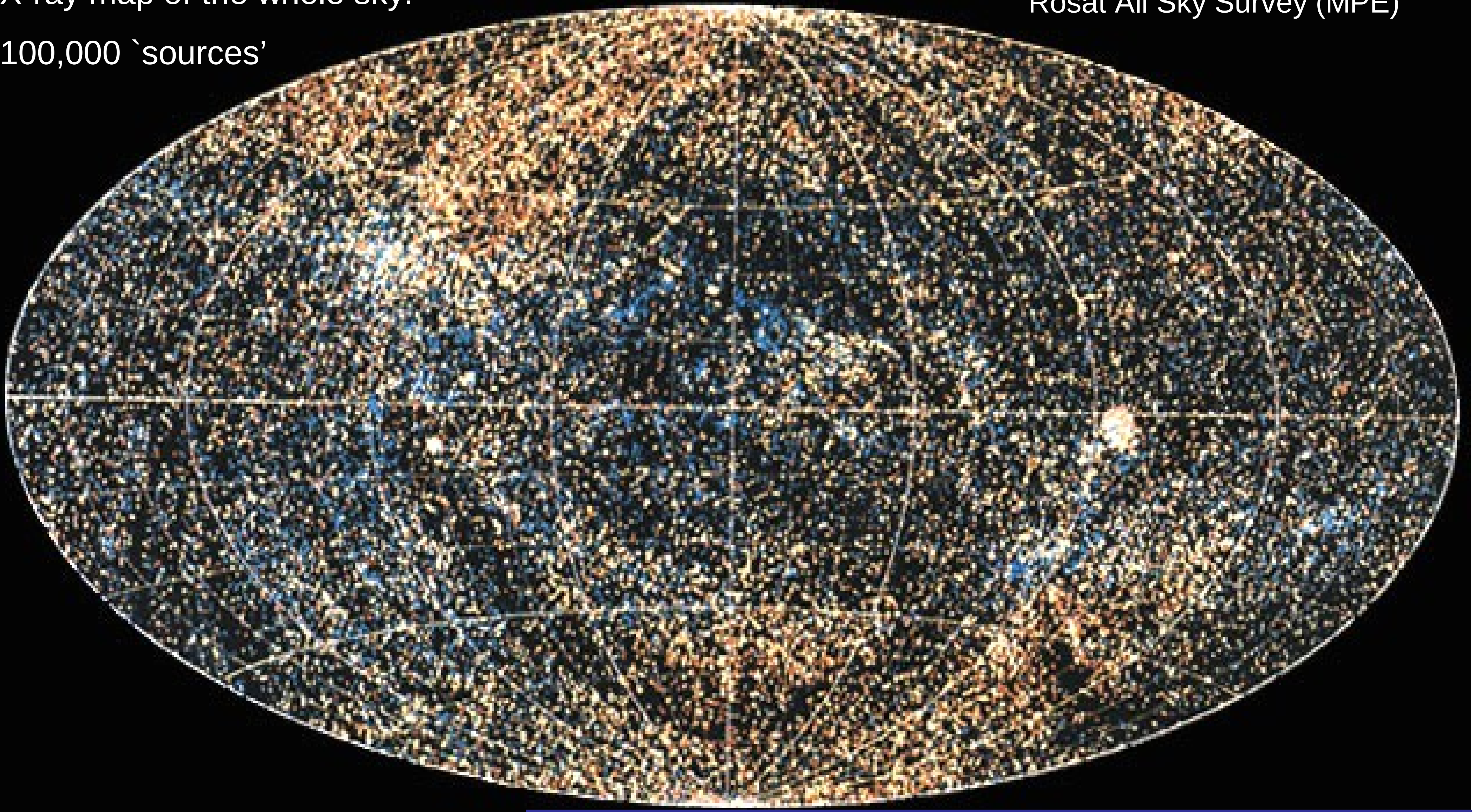
In X-rays, we see mostly accreting sources: energy from gravity!

Powerful sources of X-rays

X-ray map of the whole sky:

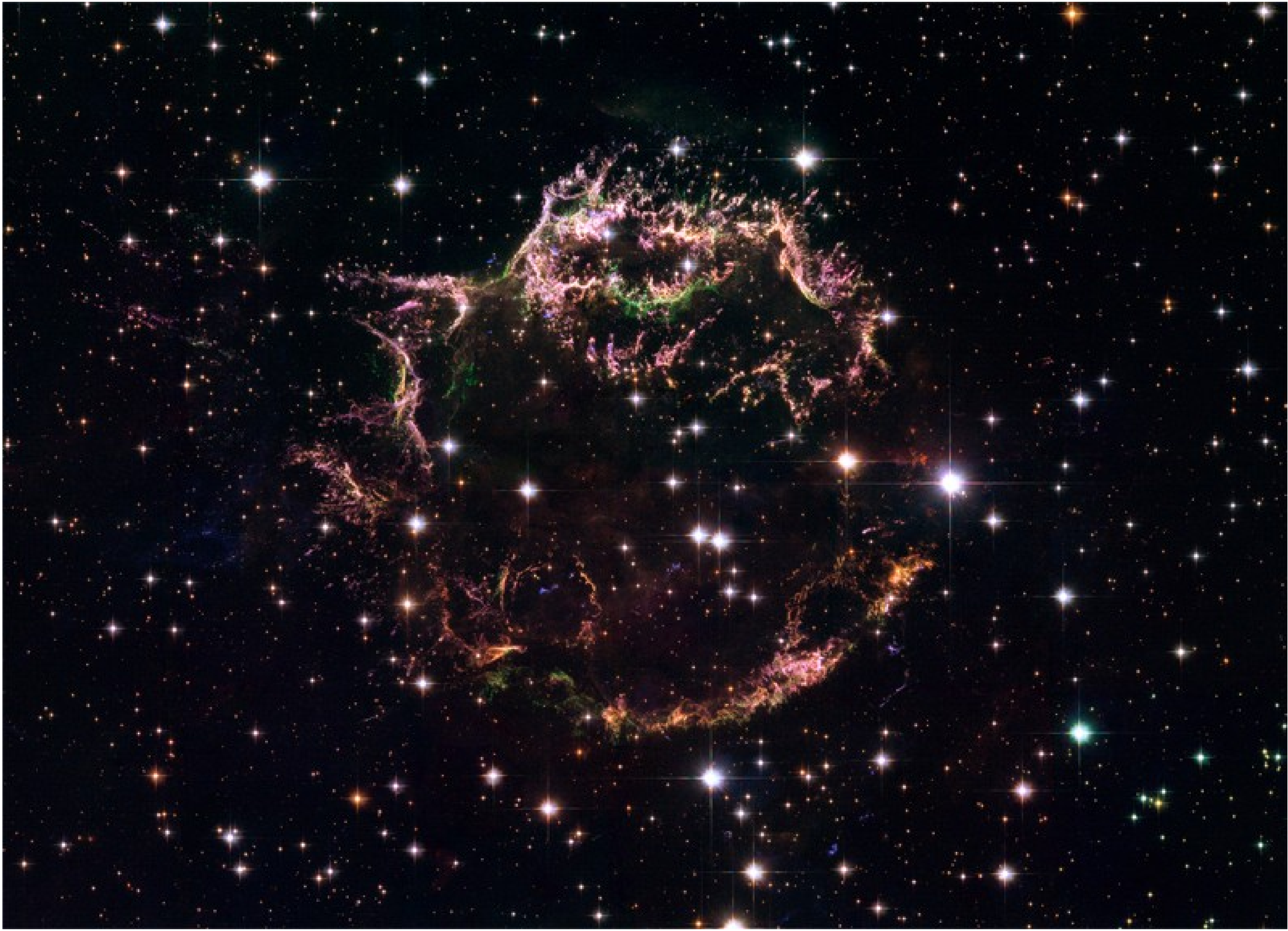
100,000 `sources'

Rosat All Sky Survey (MPE)

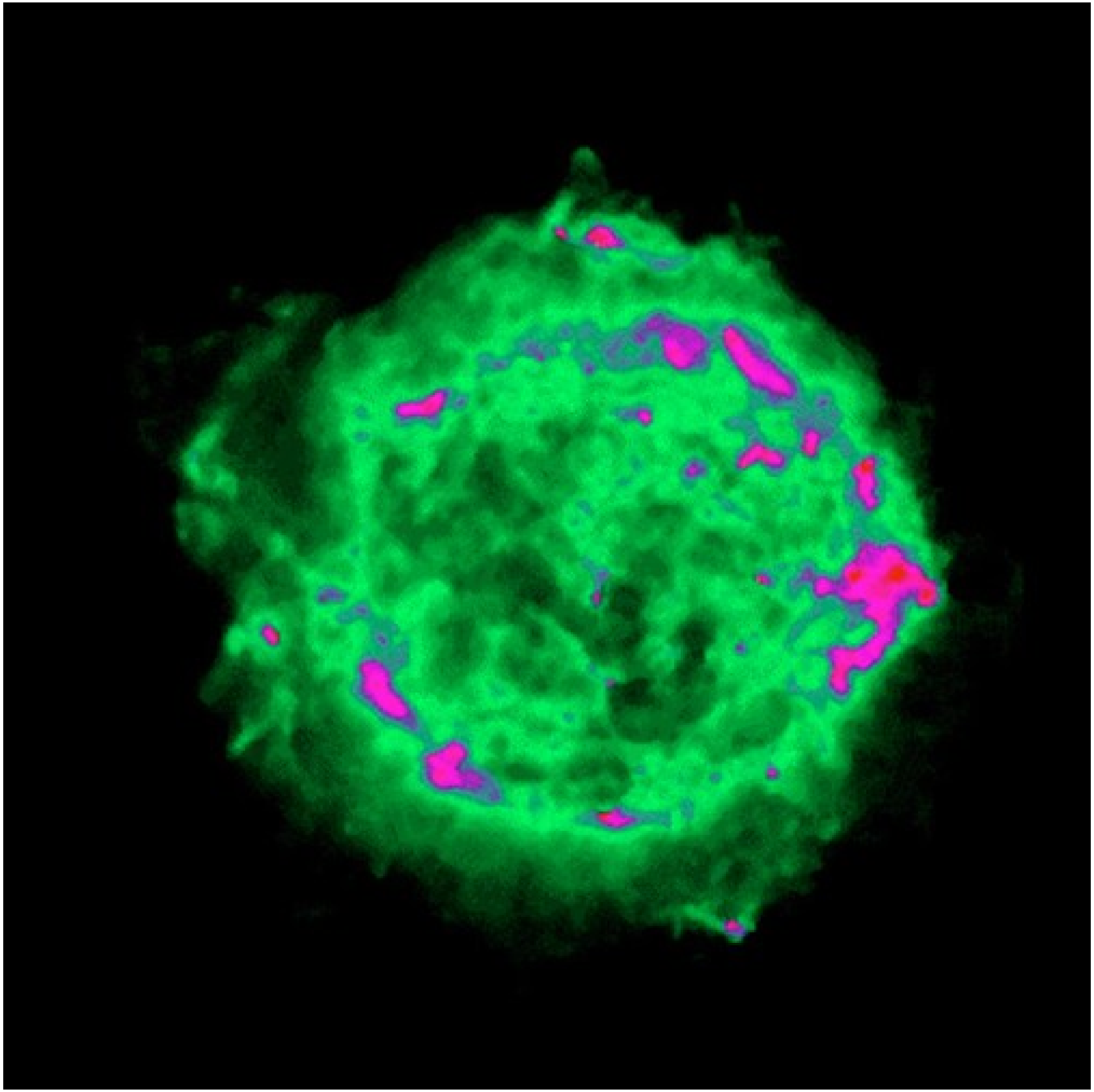


A power source entirely different from the nuclear fusion that drives the Sun and stars

…and much more efficient

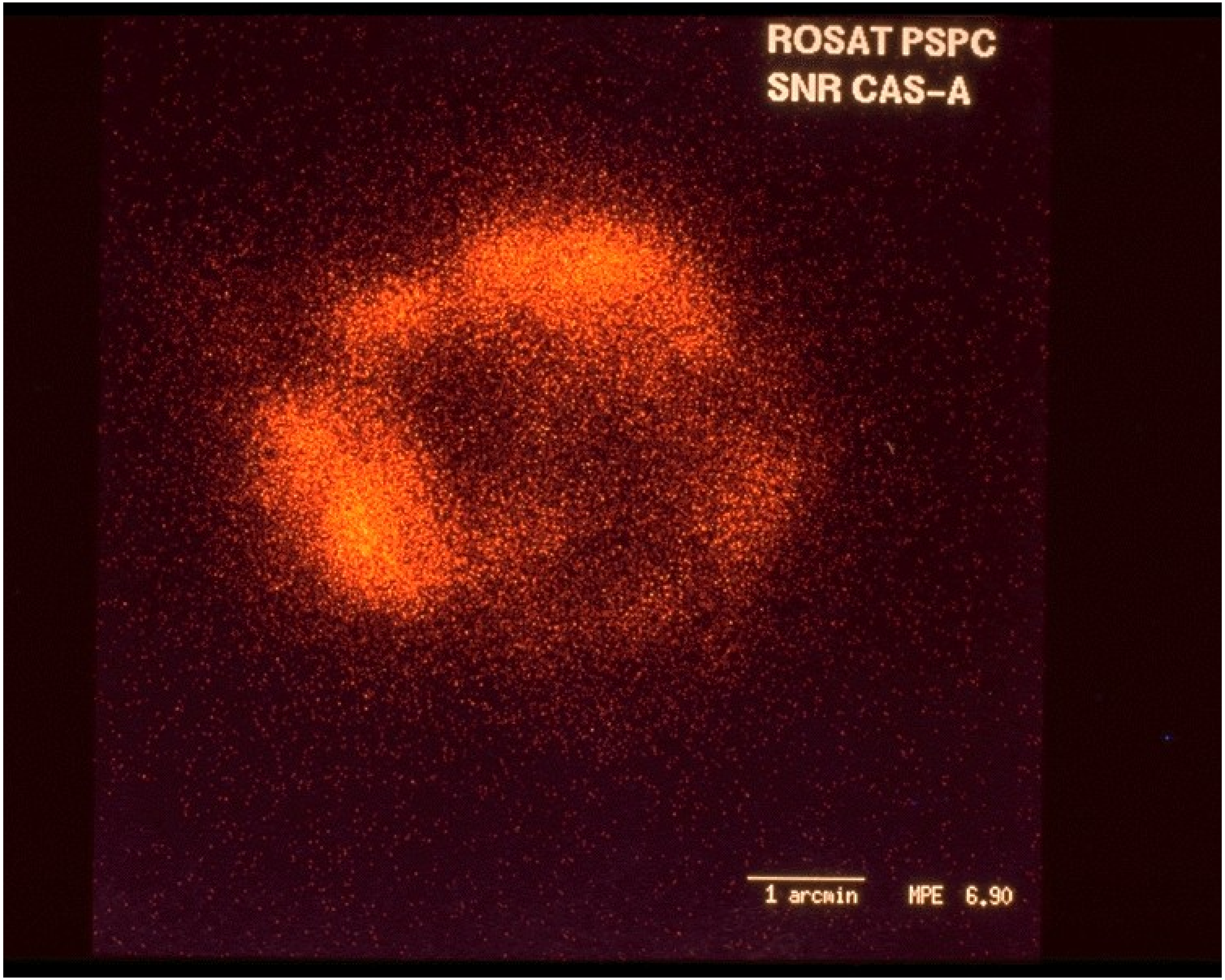


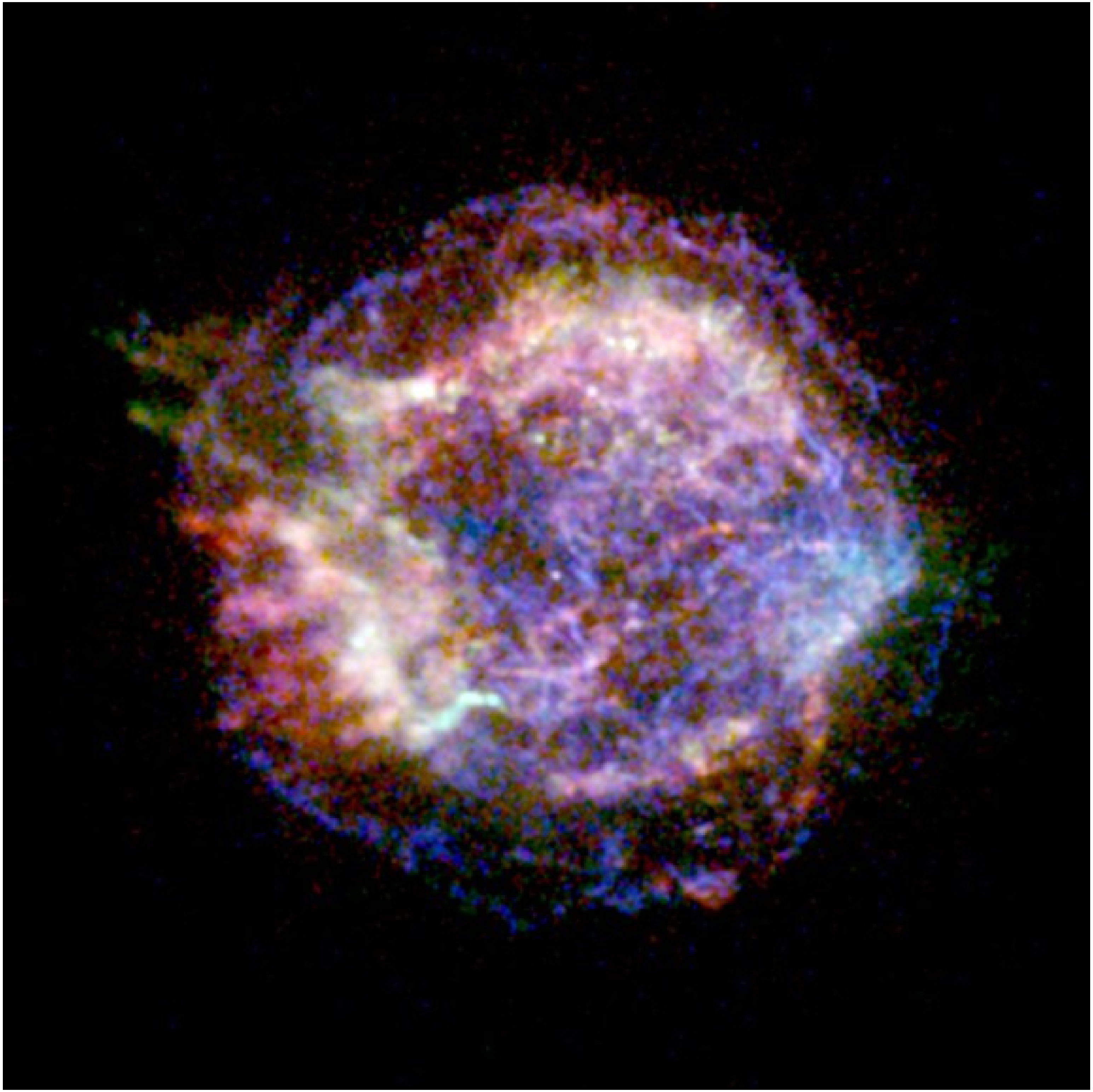
Milky Way galaxy: Supernova remmant (radio)



Cas A as seen by a radio telescope

Milky Way galaxy: Supernova remmant (X-ray)



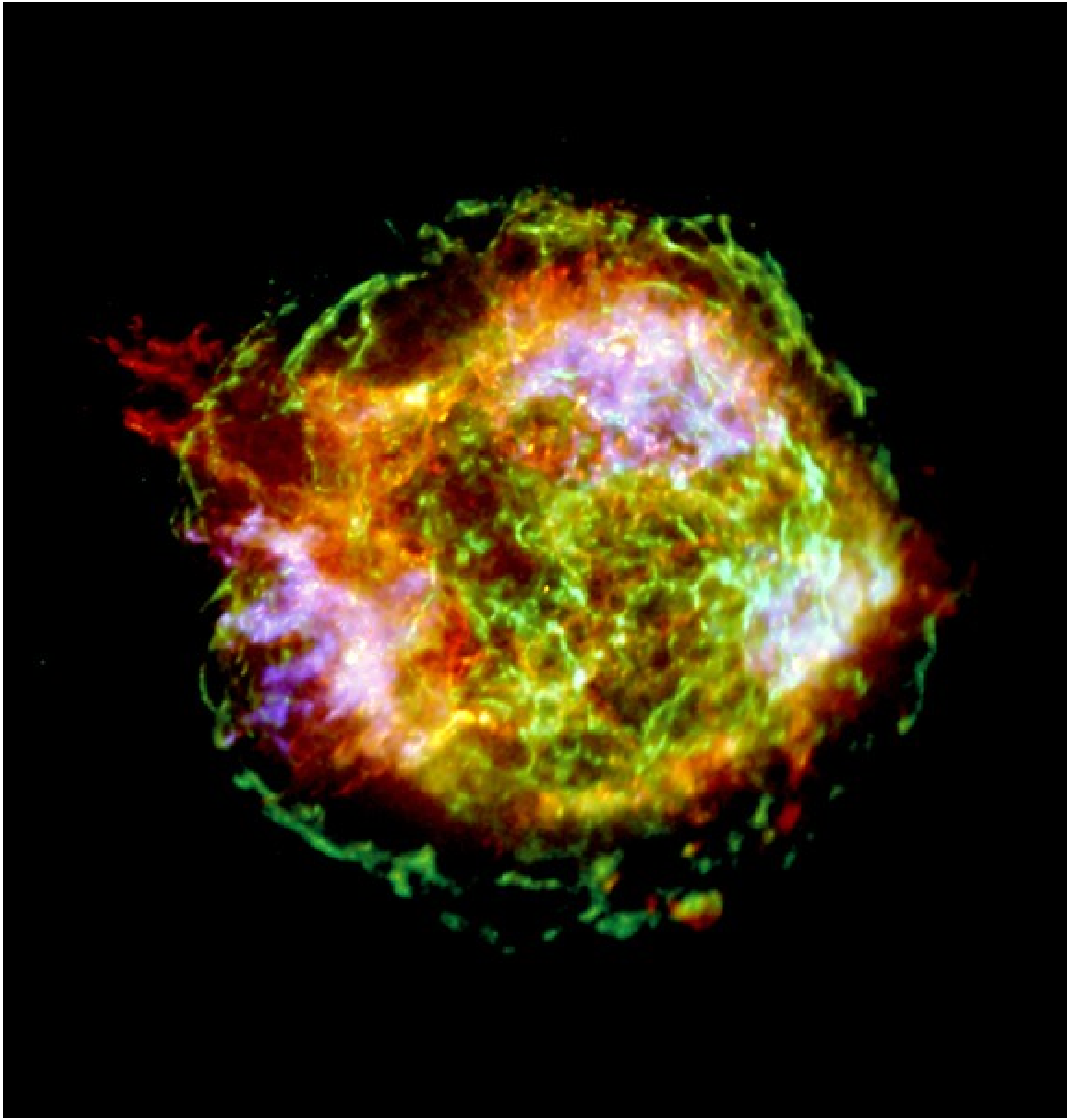


1 hour
with
Chandra

Milky Way galaxy: Supernova remmant (X-ray)

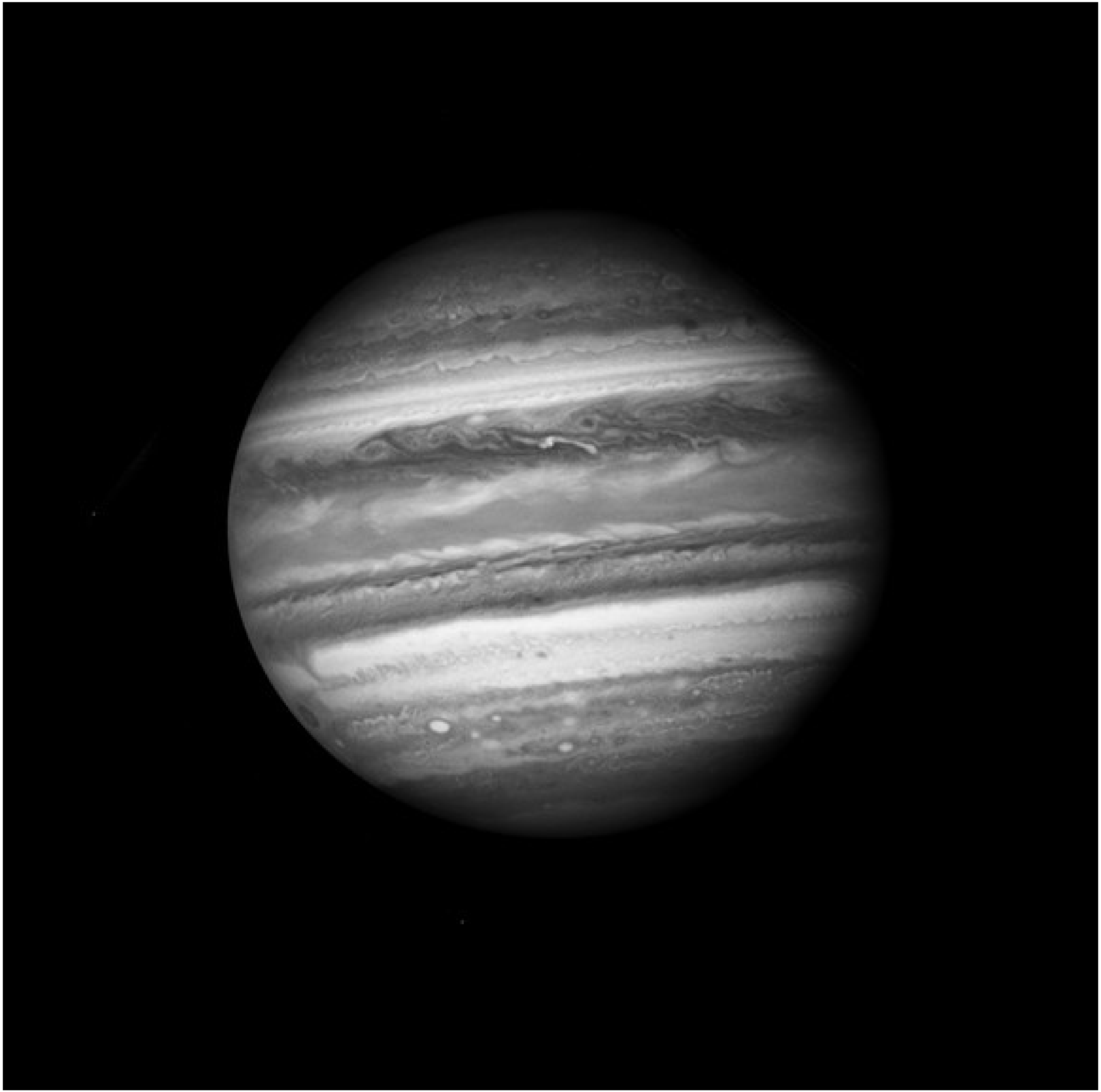
- 1 megasecond (11 days)
- Blue: Iron
- Red: Silicon
- Green: outer shock wave

Cas A with Chandra (Una Hwang)

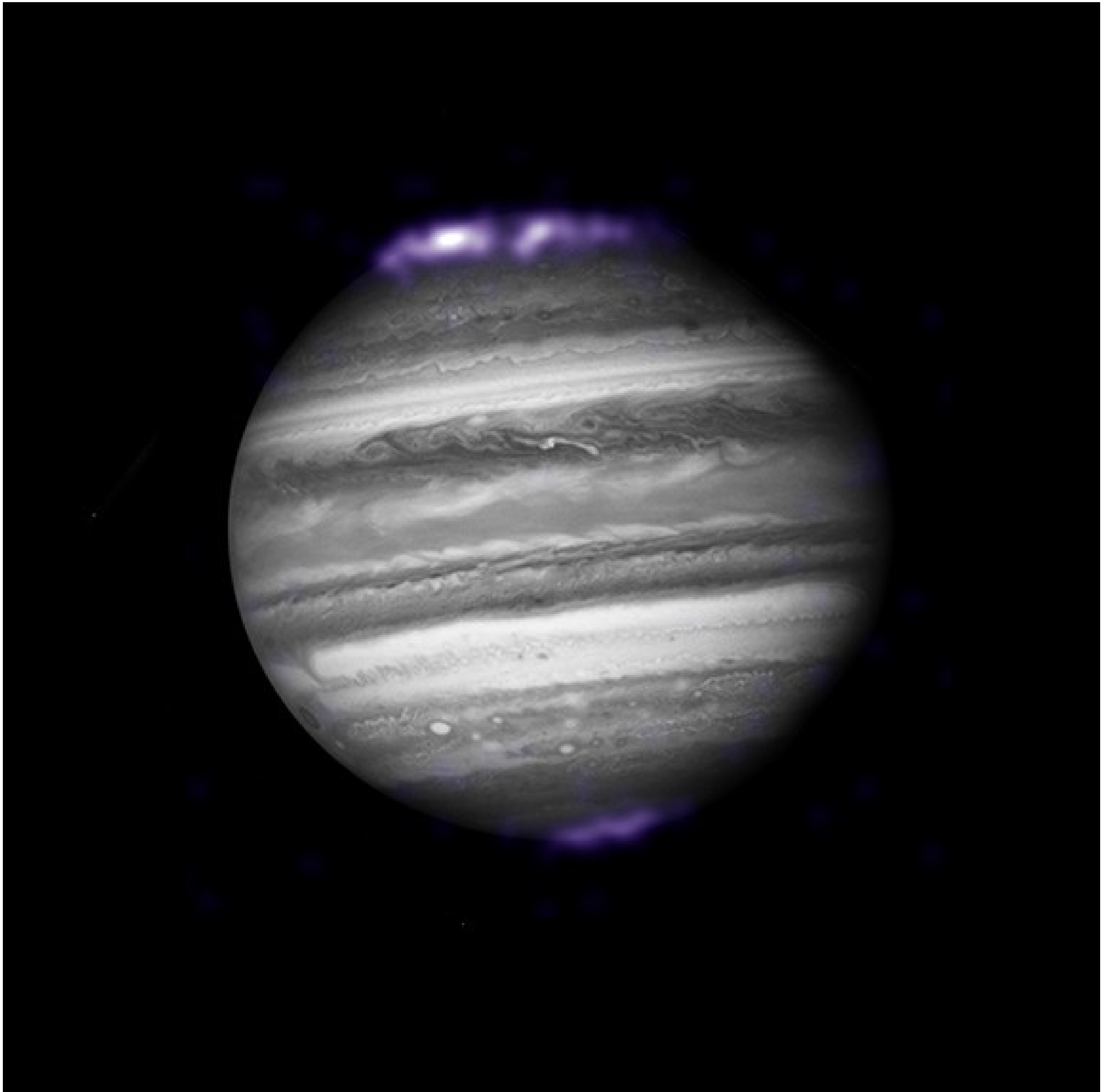


11000 light years away

16 light years across



Our solar system:
Jupiter
(visible light,
Hubble)

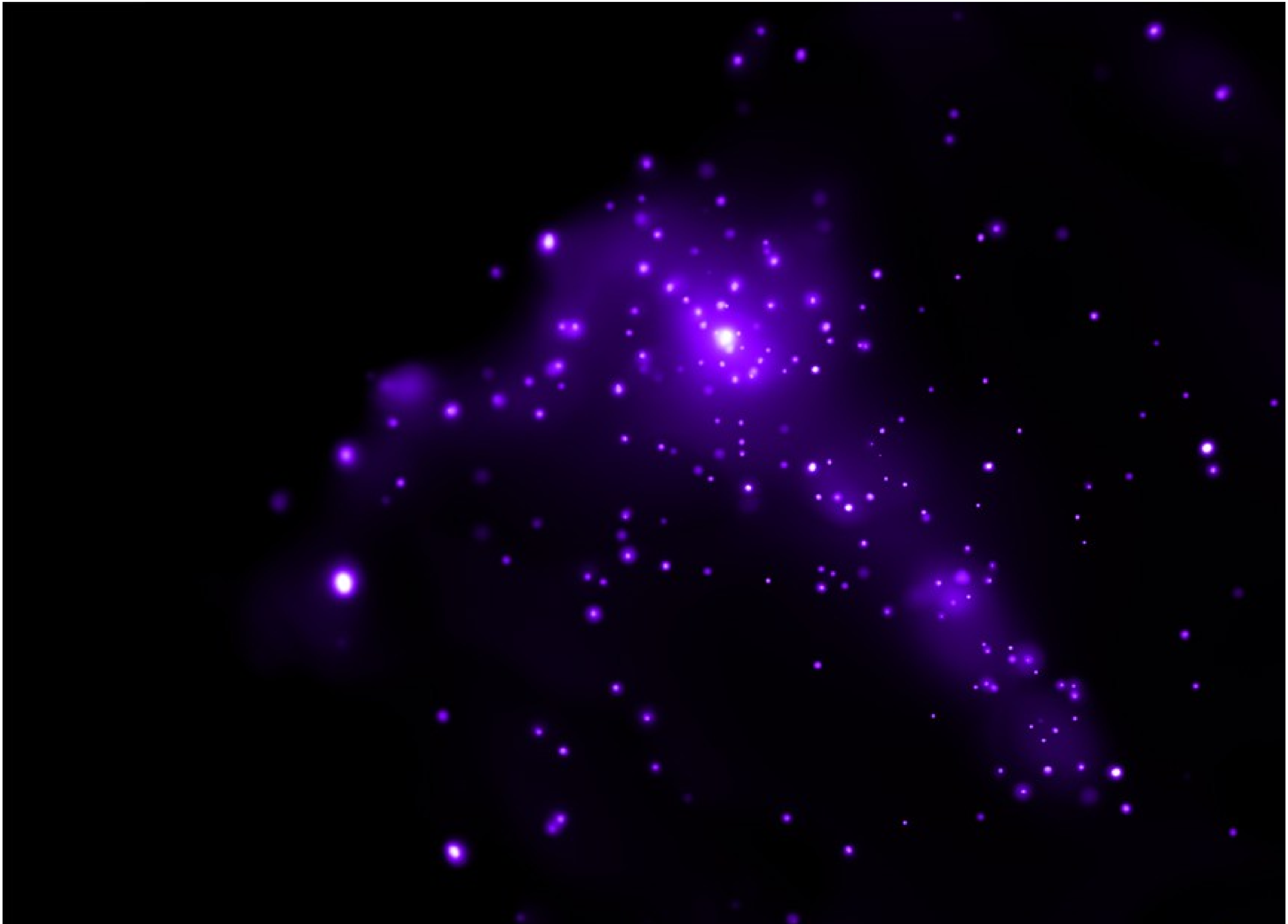


Milky Way galaxy: Star cluster NGC 281

Milky Way galaxy: star cluster (infrared)

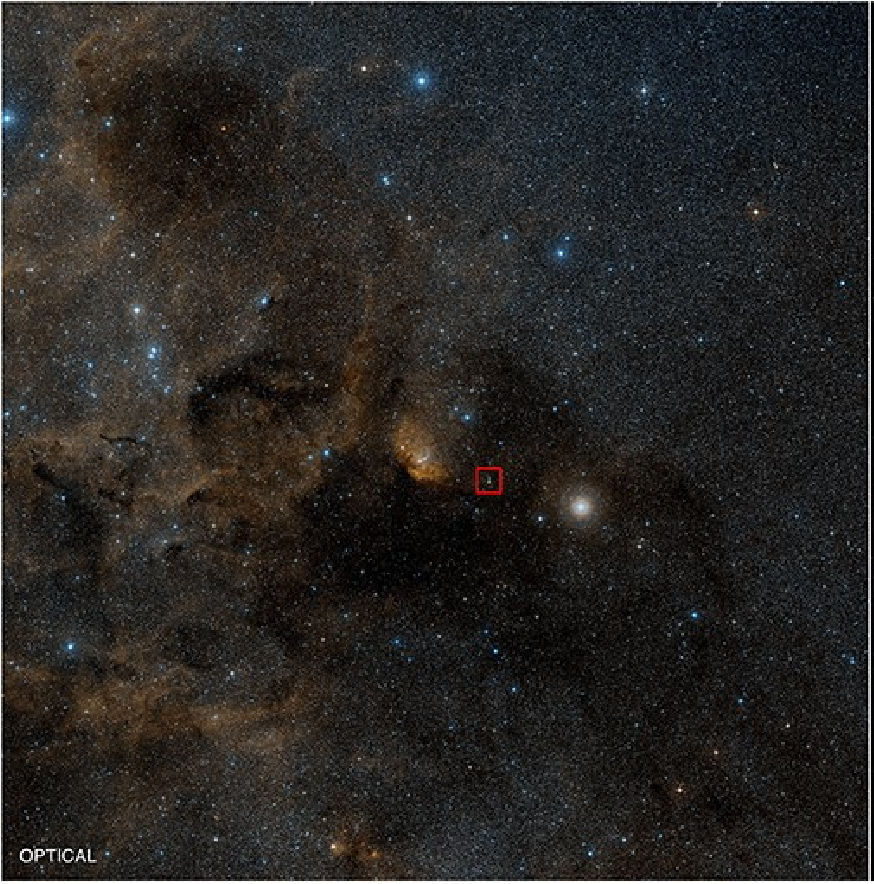
NGC 281 star cluster – infrared
10000 light years away

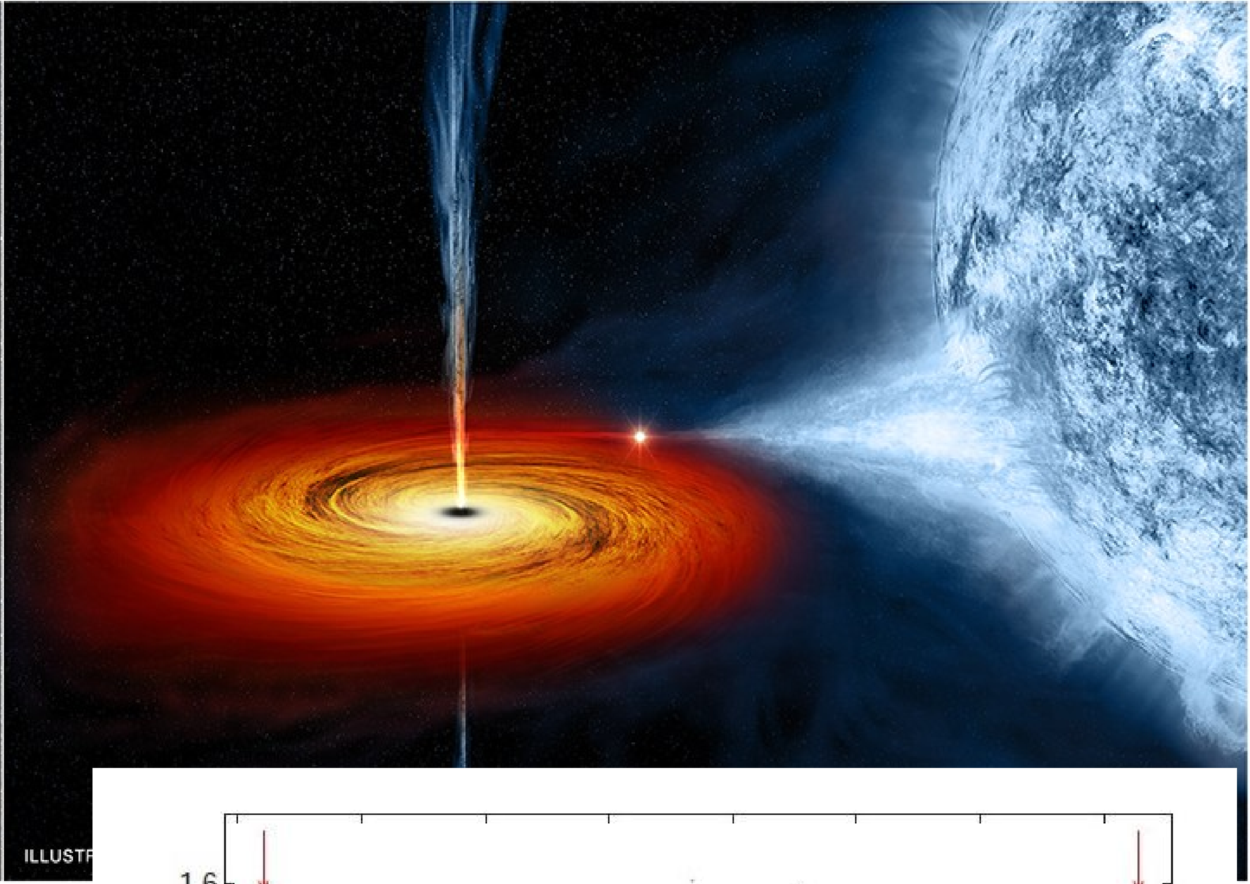
Milky Way galaxy: star cluster (X-ray)

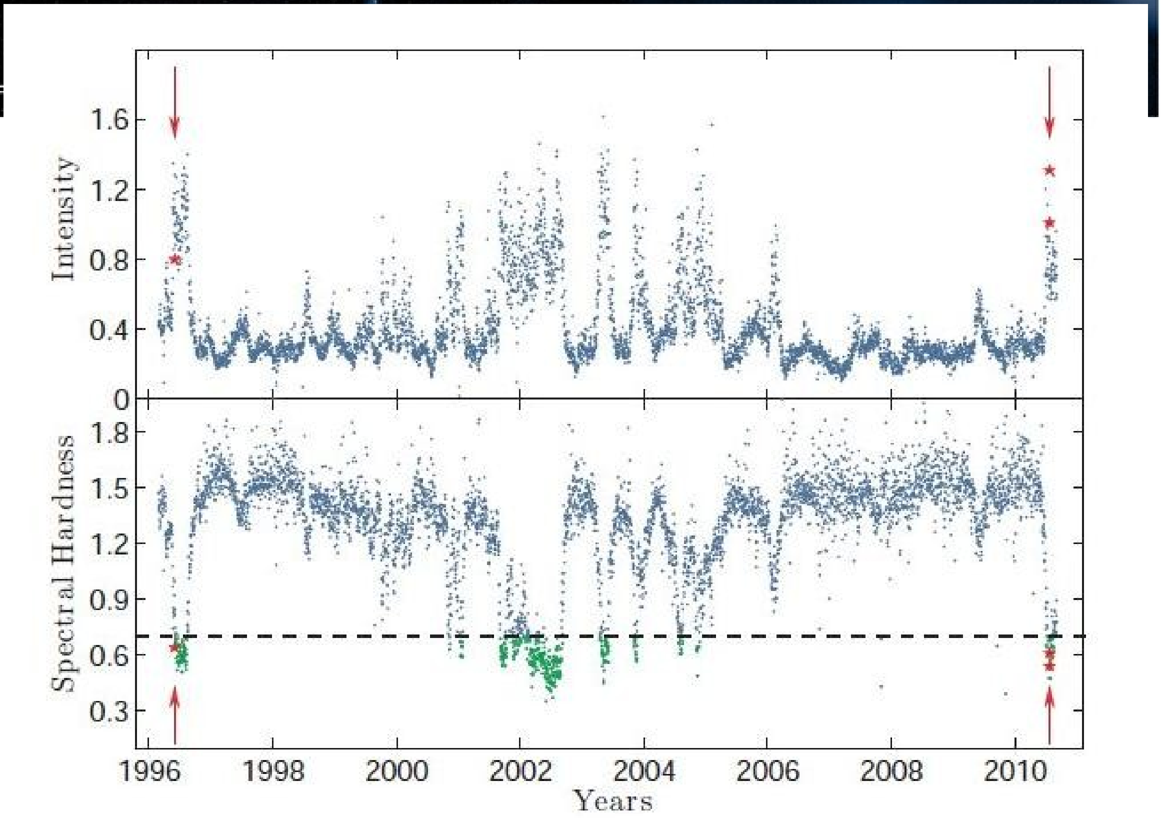


Milky Way galaxy: star cluster (infrared +X-ray)

NGC 281 (Scott Wolk, SAO)

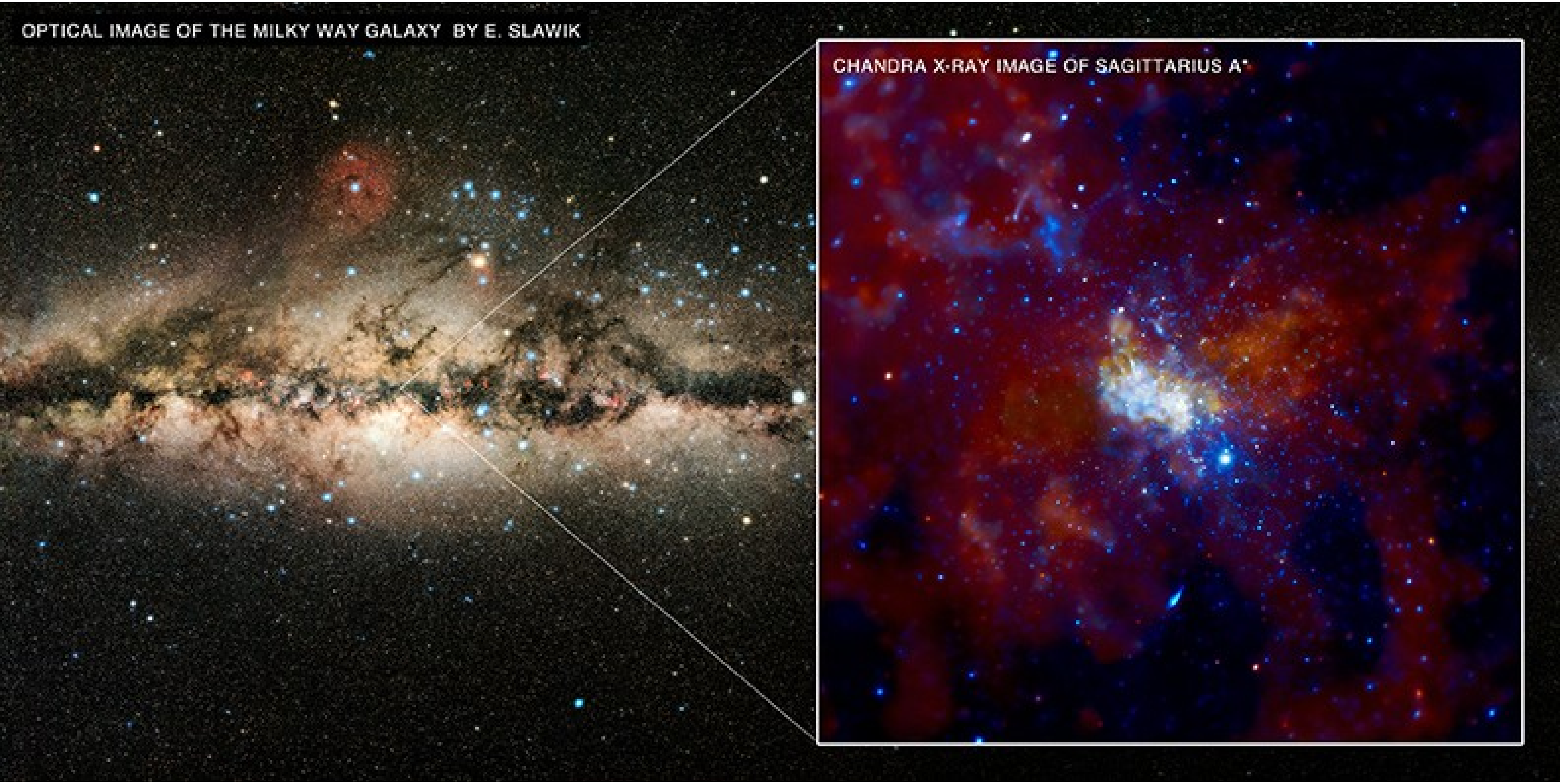




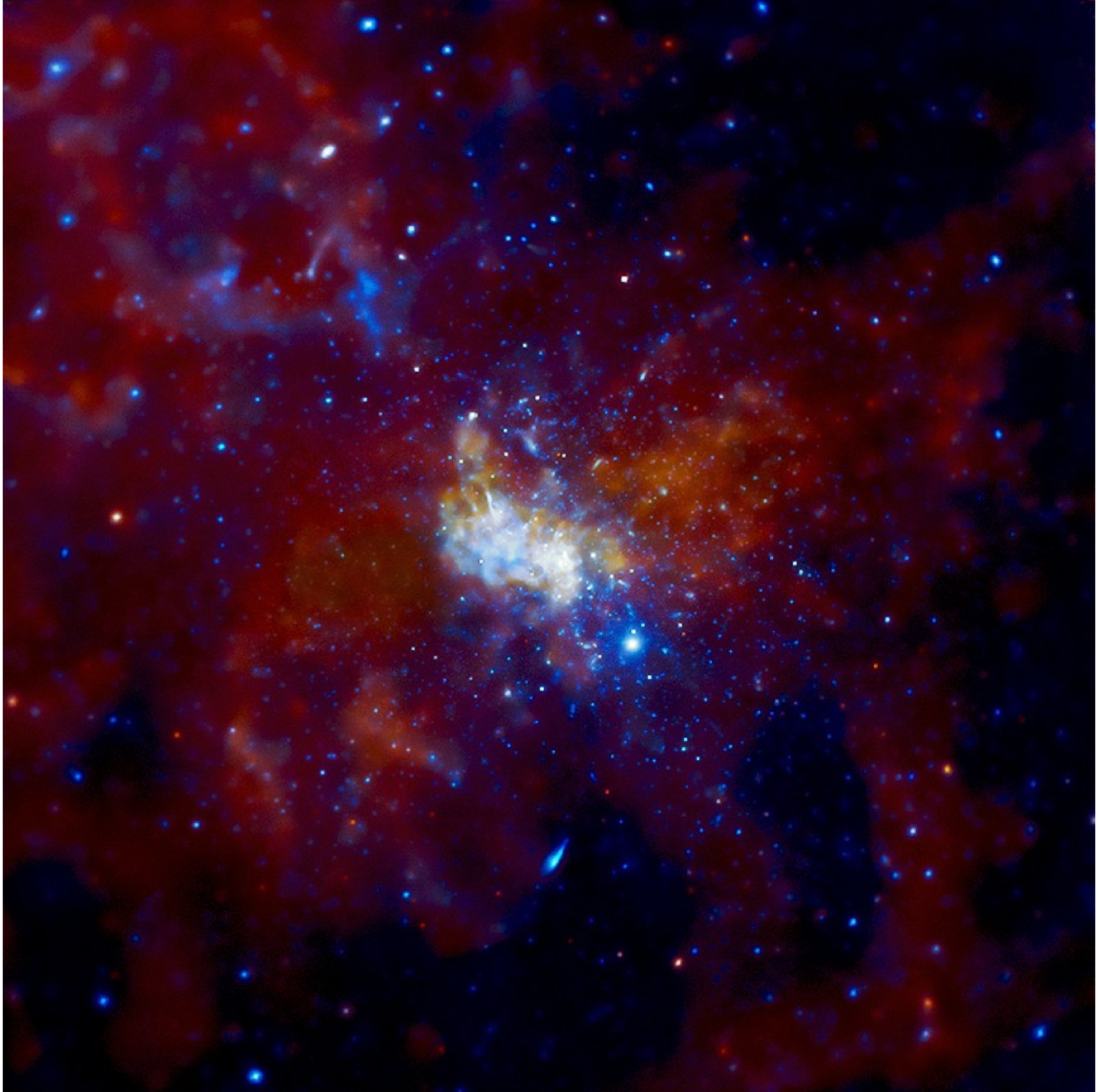


Cygnus X-1
A massive blue star slowly being eaten by its companion black hole
When the stream from the blue star hits the material swirling around the hole X-rays are produced

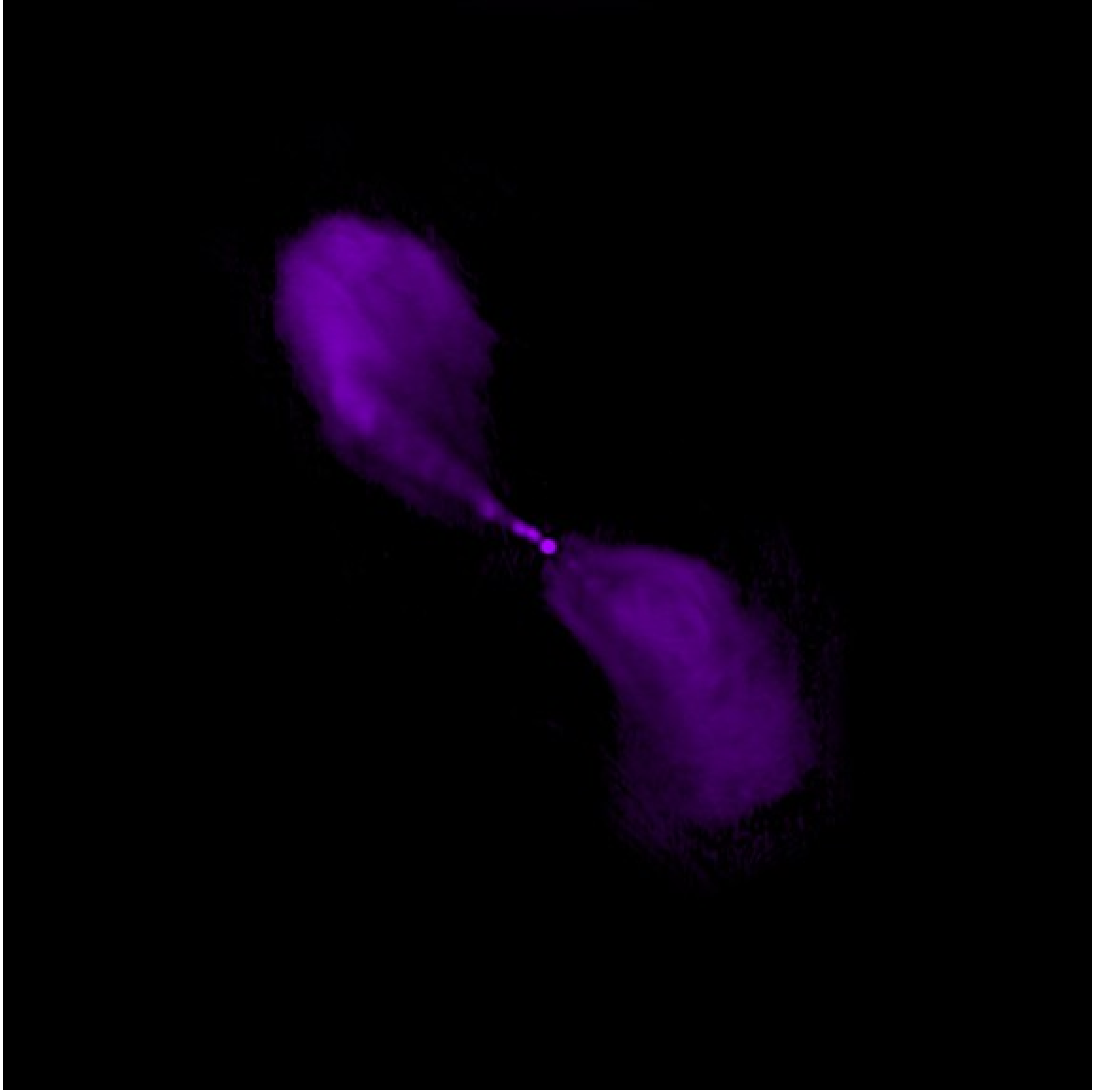
The Rossi XTE satellite monitored the brightness of Cyg X-1 over 14 years



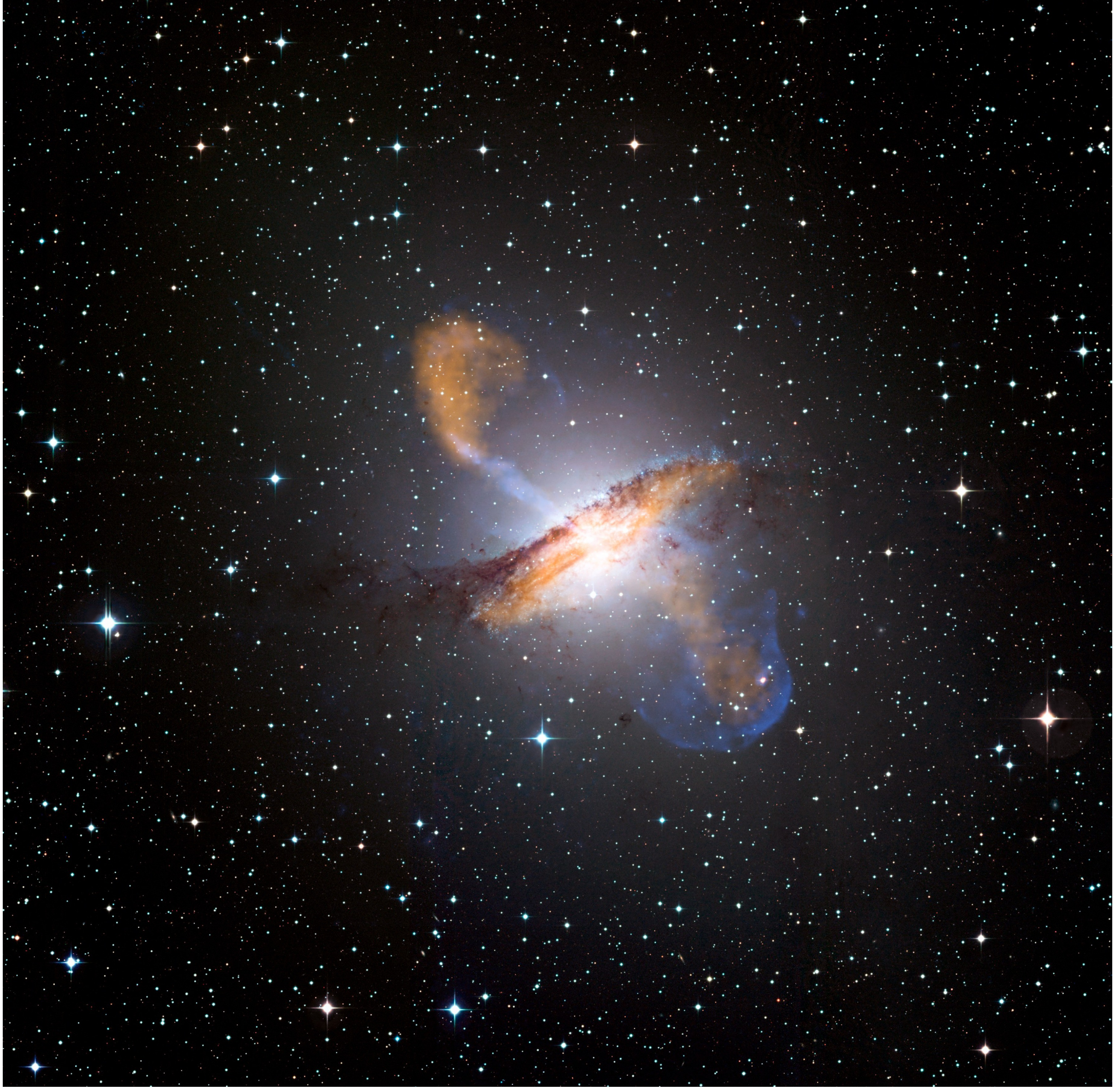
Milky Way Galaxy: Galactic Center

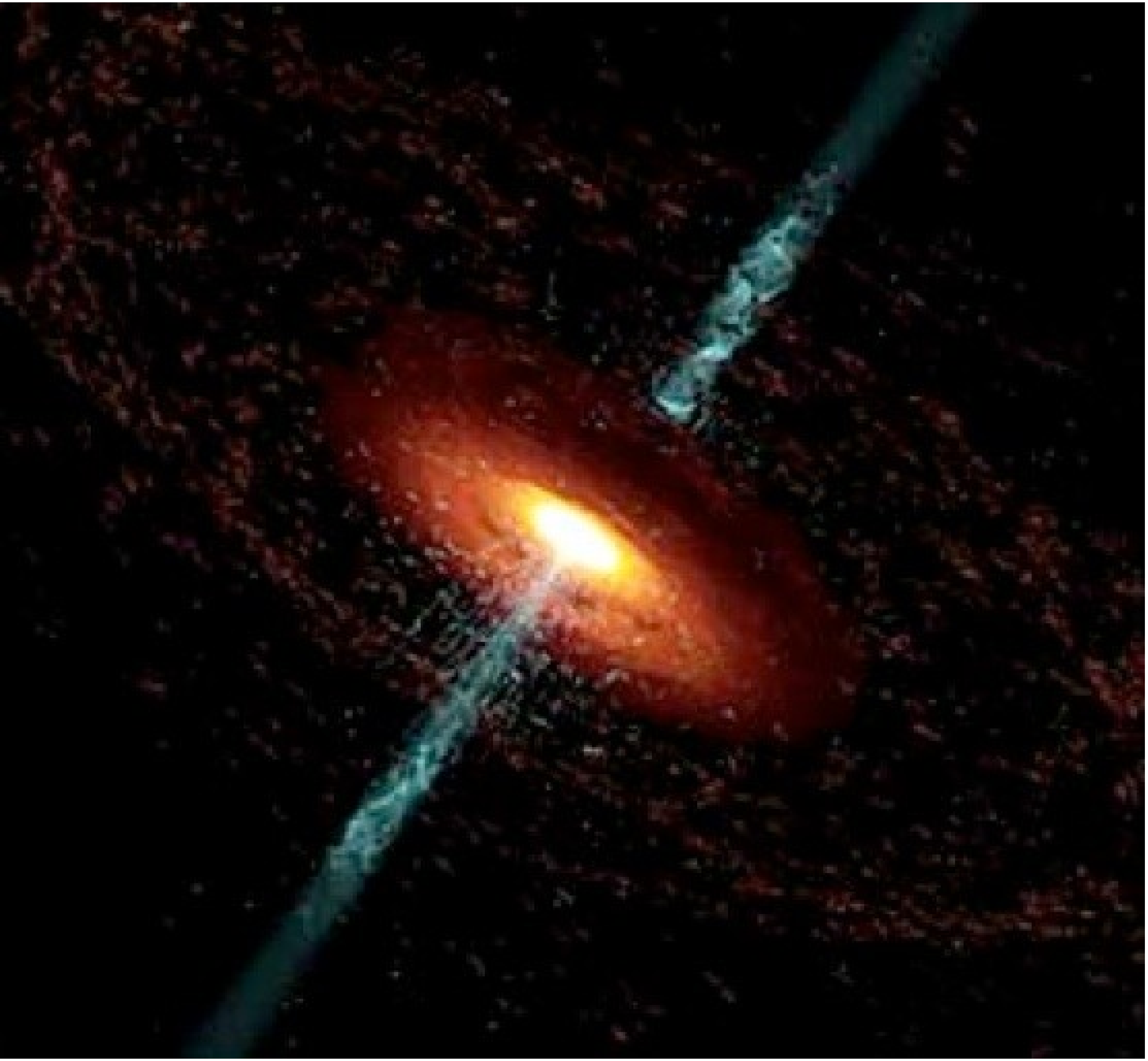


Galaxy Centaurus A (NGC 5128) - 12 million light years away



Extragalactic Universe: Active Galaxy (X-ray)





Artist's impression of a quasar

In the middle is a spinning supermassive black hole (SMBH)

Matter orbiting the hole slowly spirals down into it

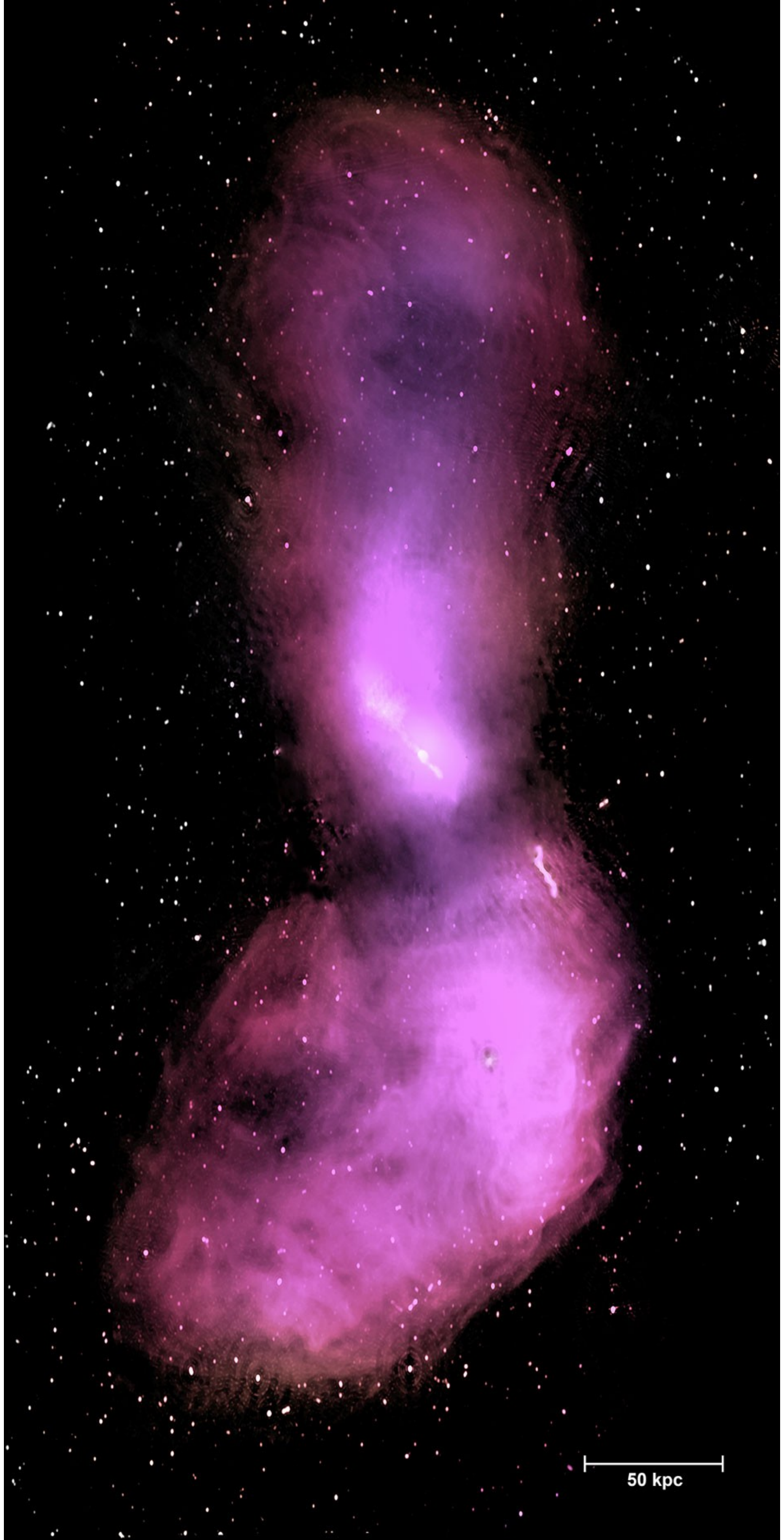
As the matter trickles downhill it gains energy from the black hole's gravity – the matter is squeezed and gets hot, and releases energy

LOTS of energy – more efficient than nuclear fusion

Some of the matter misses the hole and gets shot out the north and south poles at almost lightspeed - “jets”

We also see a big cloud of gamma rays

(Fermi data, Teddy Cheung)



Radio data
on an even
bigger scale

Feain et al
Australia Tel.

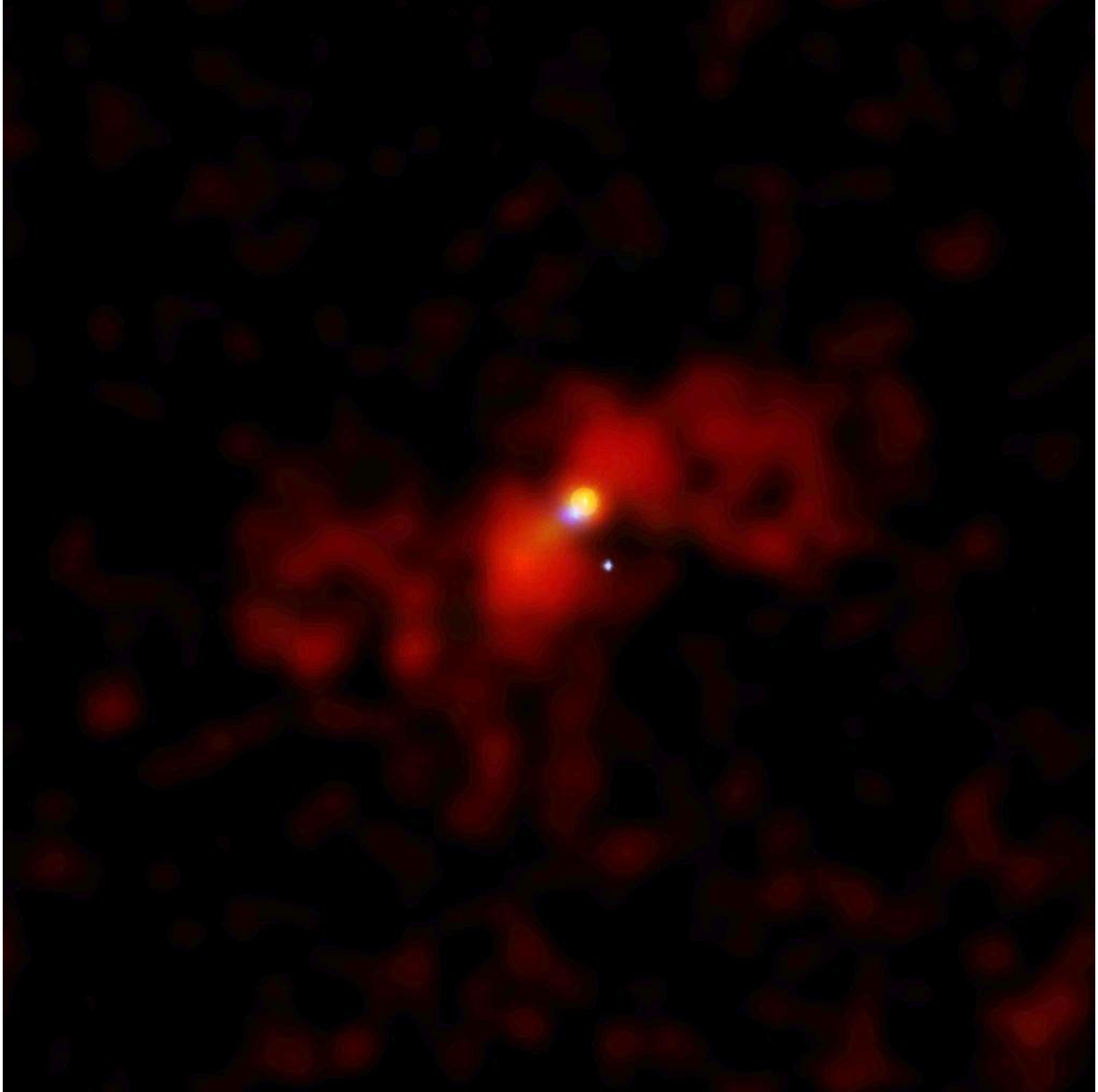
1.5 million light years
end to end

If you had radio eyes, Cen A would be the biggest thing in the sky, much bigger than the Moon

Extragalactic universe:
Merging galaxy (visible light)

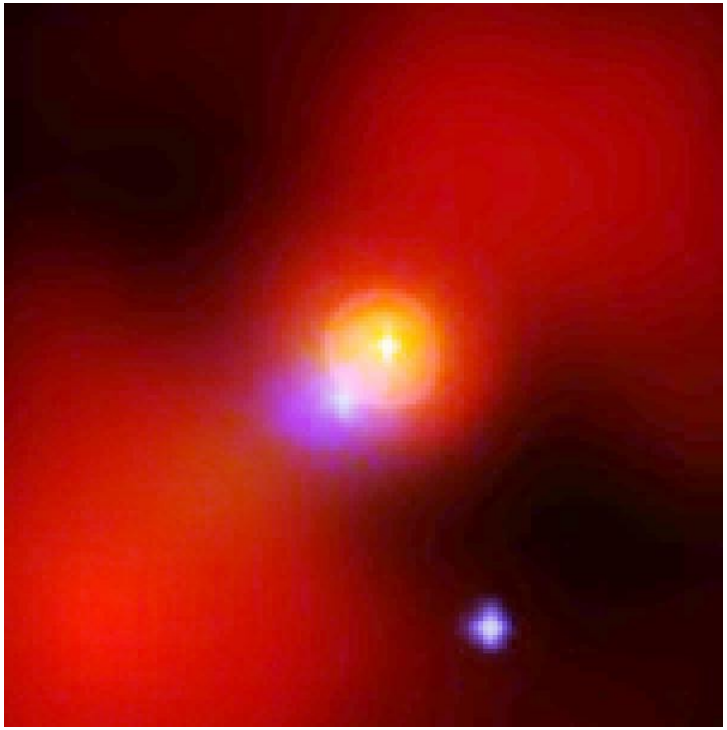
Merging galaxy Arp 220

- z=0.018 (250 million light years)
- Energy output: 1 trillion suns
- 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)



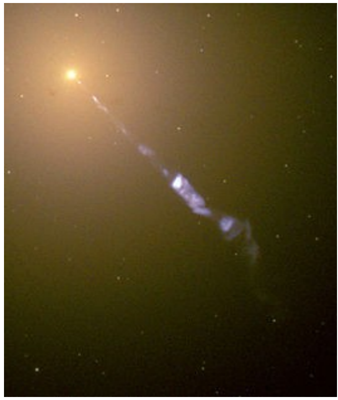
Arp 220 nucleus

- Deep in the galaxy, Chandra reveals:
-   - a large region of newly forming stars (yellow)
-   - a source of 'hard' X-ray radiation partly obscured by dust and gas, and coinciding with a pair of bright points seen with radio telescopes – at least one (and maybe 2) supermassive black holes at the very center of the galaxy
- Firther from the middle, a bright X-ray binary star, probably with a black hole – brighter than any x-ray star in our galaxy

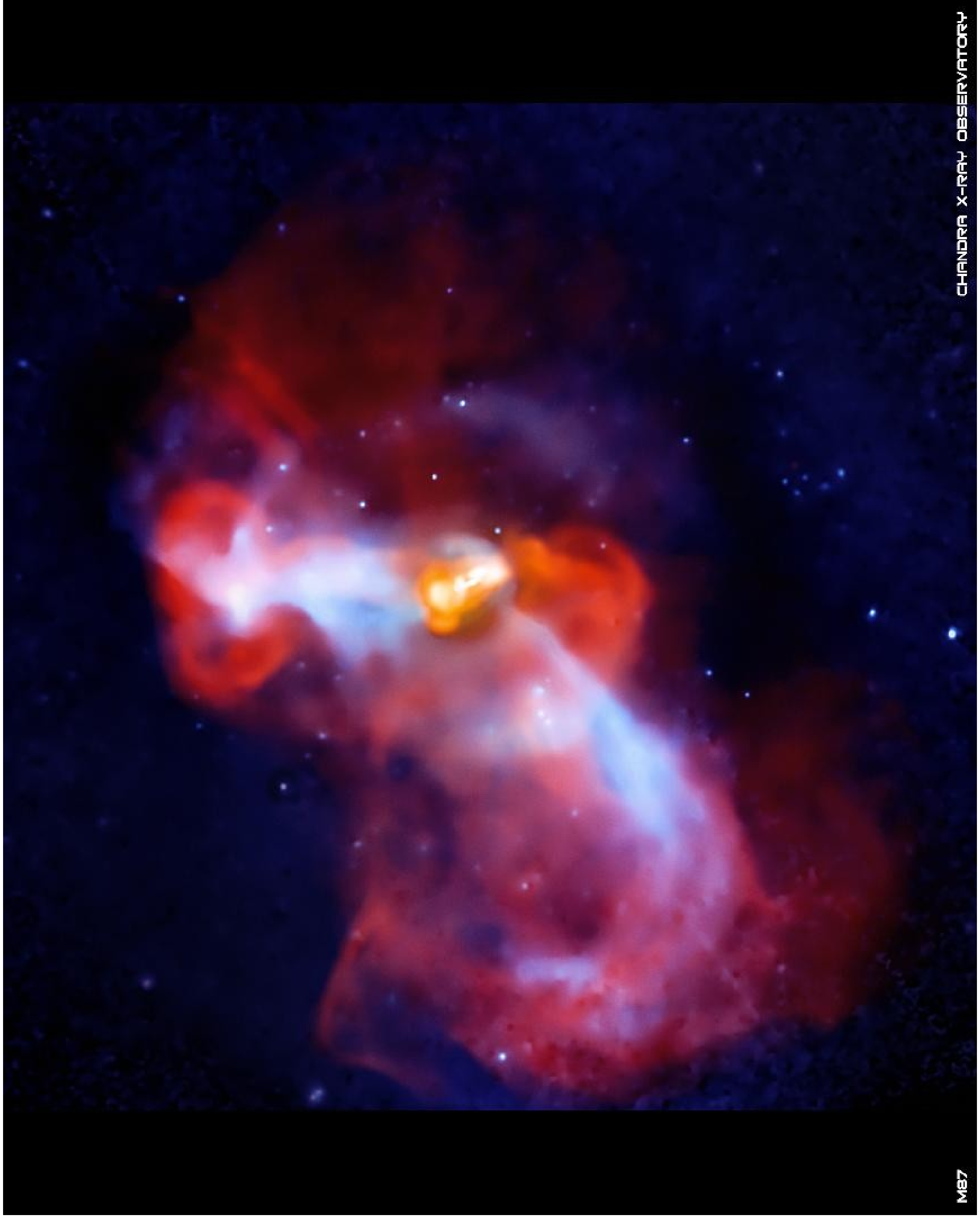


Virgo cluster
55 million
light years away

Extragalactic
universe:
Active galaxy
in cluster of
galaxies
(visible light)



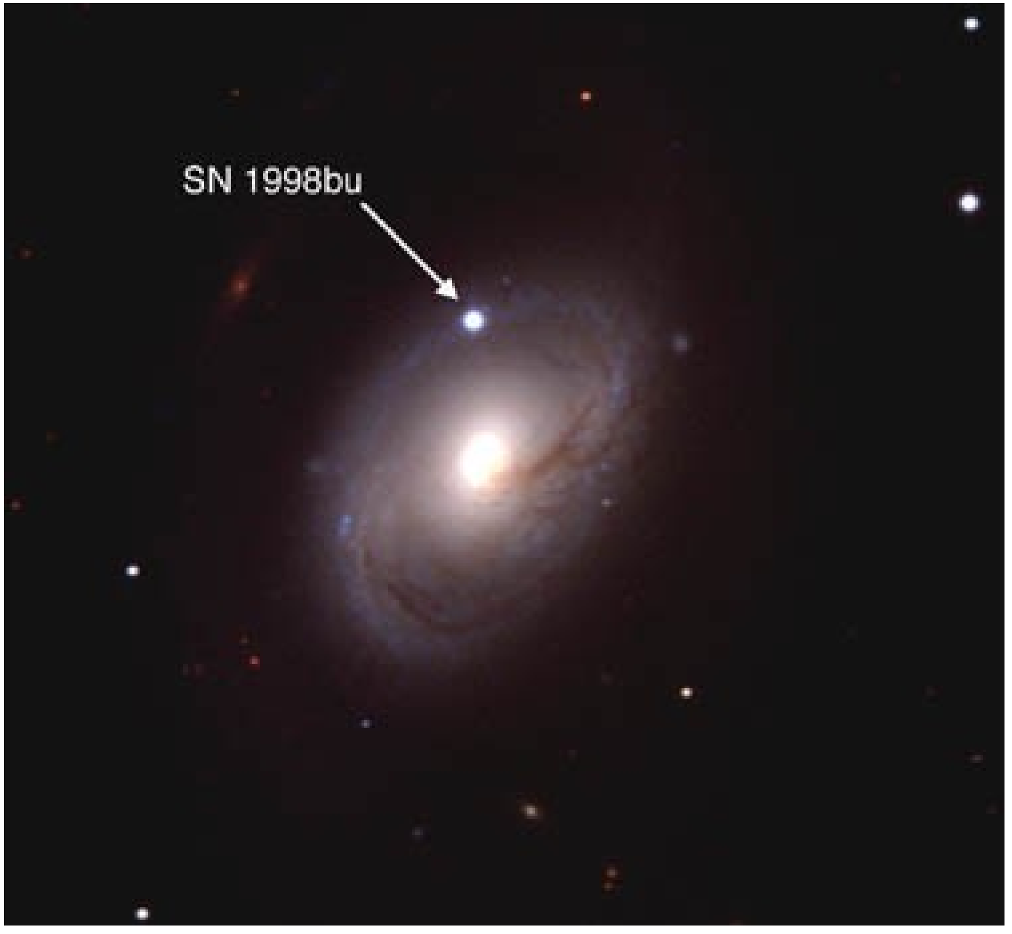
Extragalactic universe: Active galaxy in cluster of galaxies (X-ray)



M87

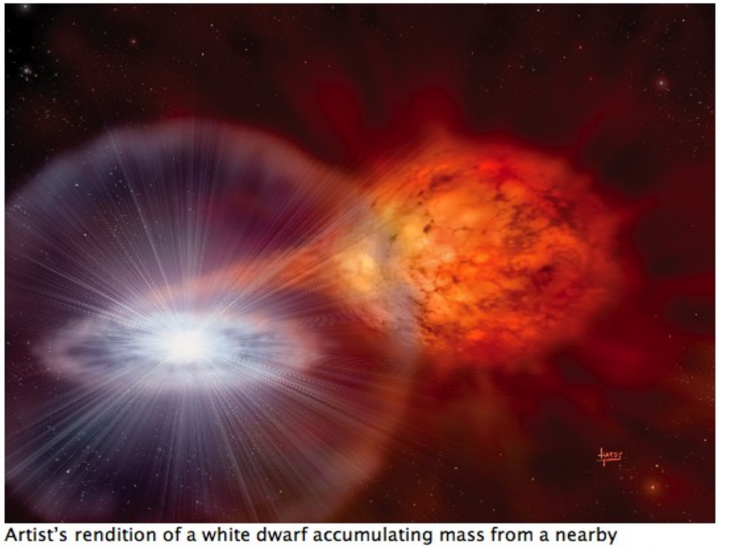
200000 l.y. across

SUPERNOVAE



Type 1a SN:

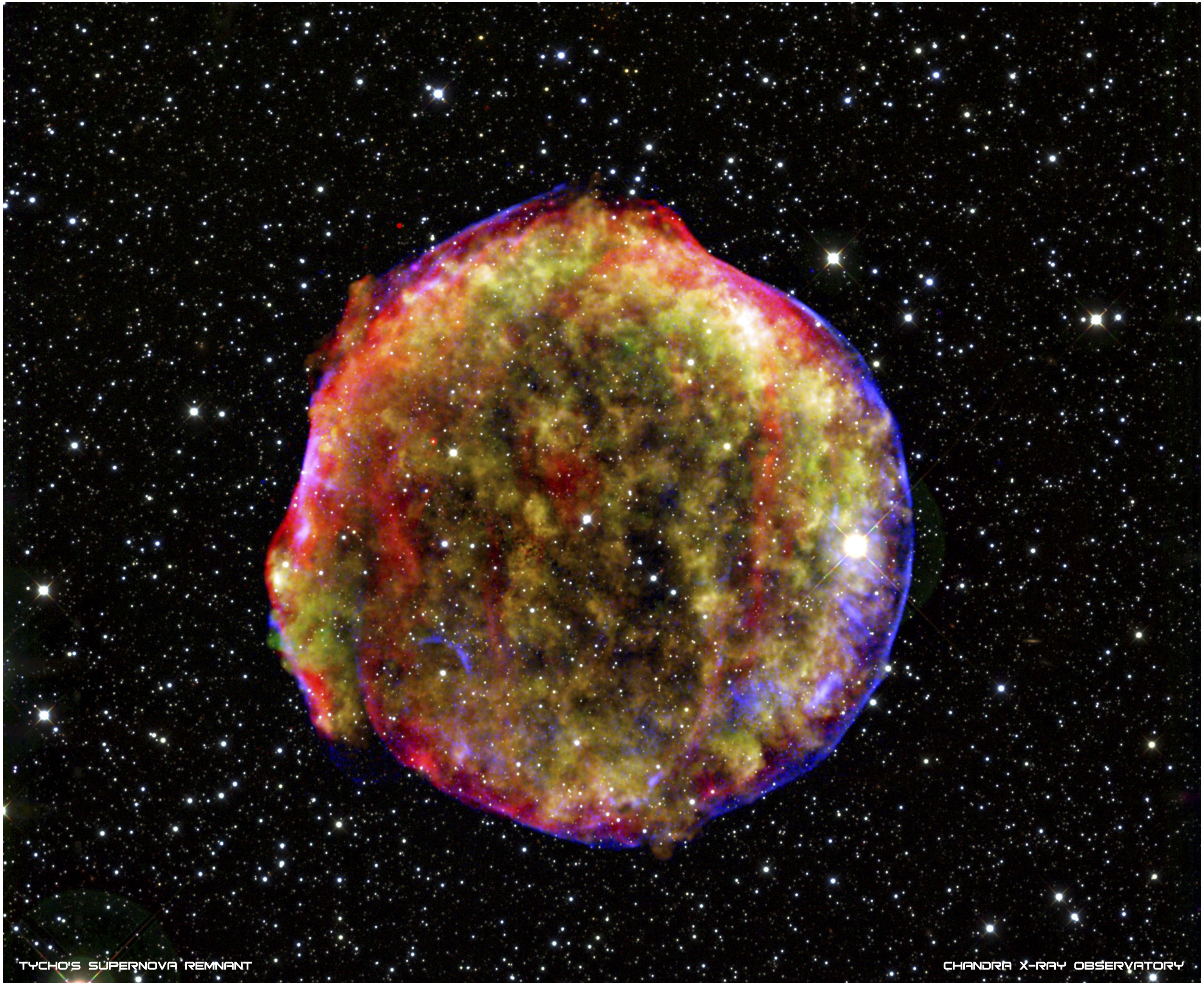
- White dwarf star in binary system
- Steals extra mass from companion
- Reaches critical mass
- Runaway fusion converts part of the star to energy within a few seconds
- Star flies apart
- Radioactive decay of newly made elements releases energy over months
- Can tell how much energy it's putting out from how long it takes to fade, so can tell how far away it is!
- Use them to map out the scale of the universe



Artist's rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered singly–degenerate.

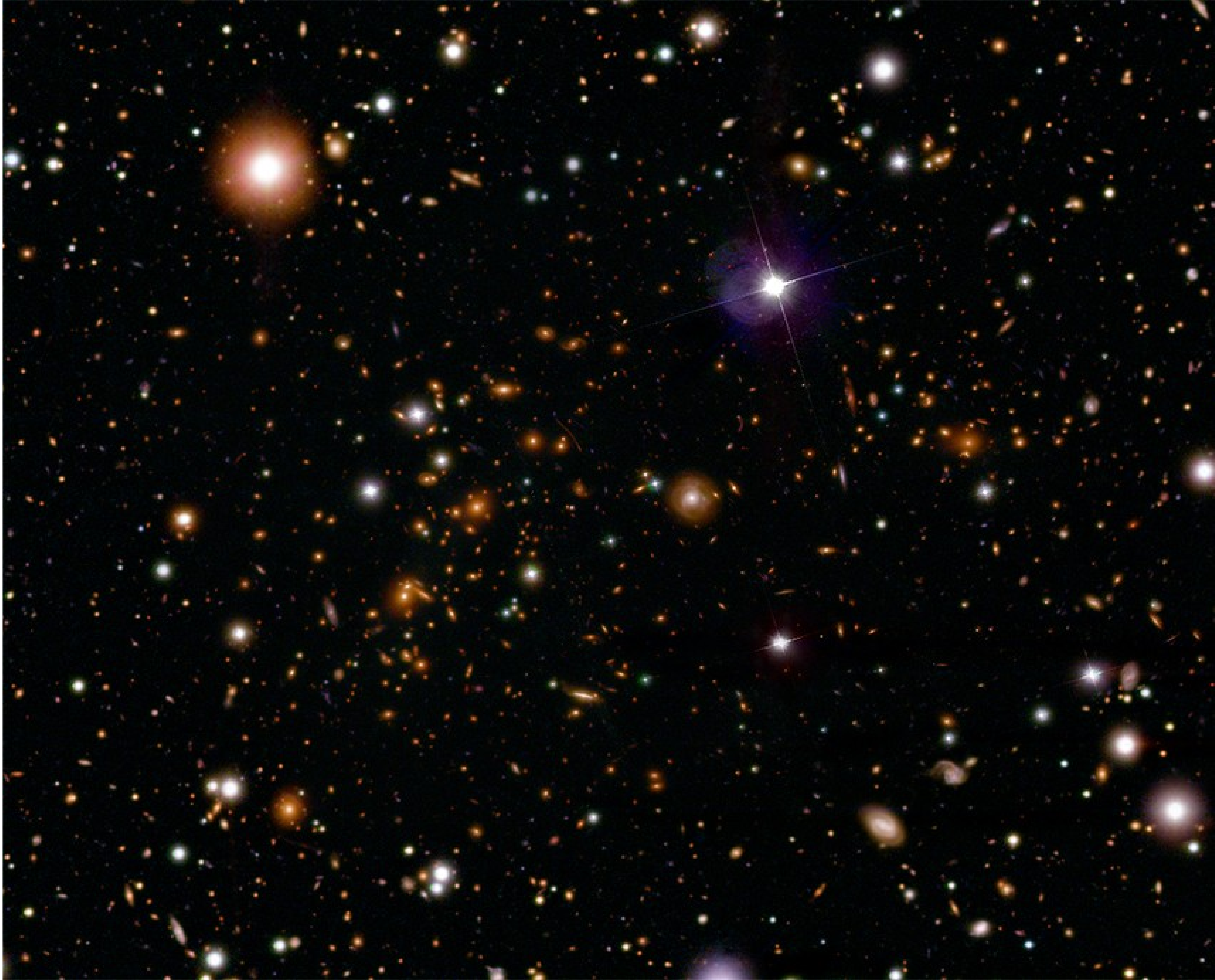
Image courtesy of David A. Hardy, © David A. Hardy/www.astroart.org.

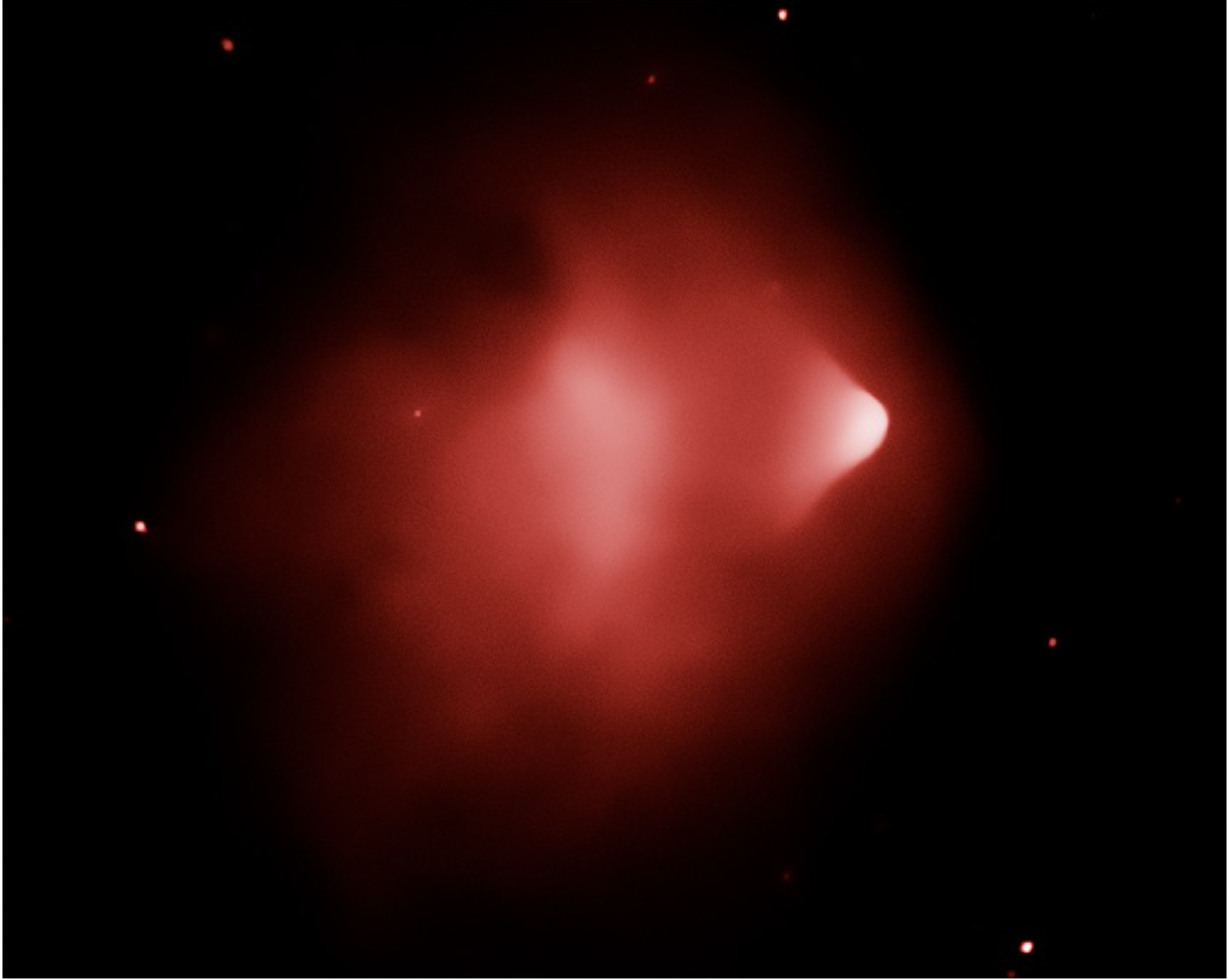
Milky Way Galaxy: Supernova remnant (X-ray)

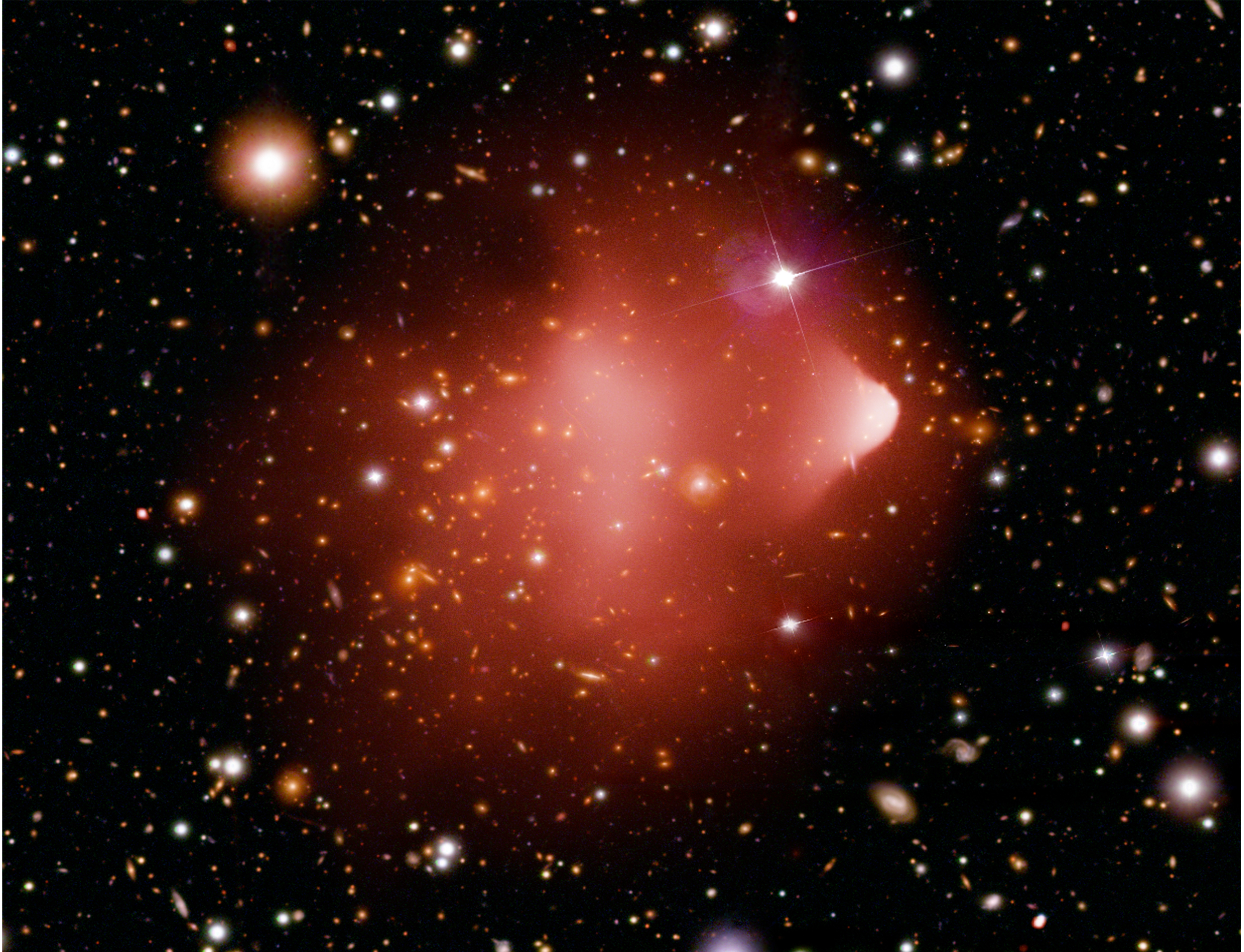


10000? light years away
15-30 light years across

Chandra obsns by Jack Hughes and Kris Eriksen (Rutgers)







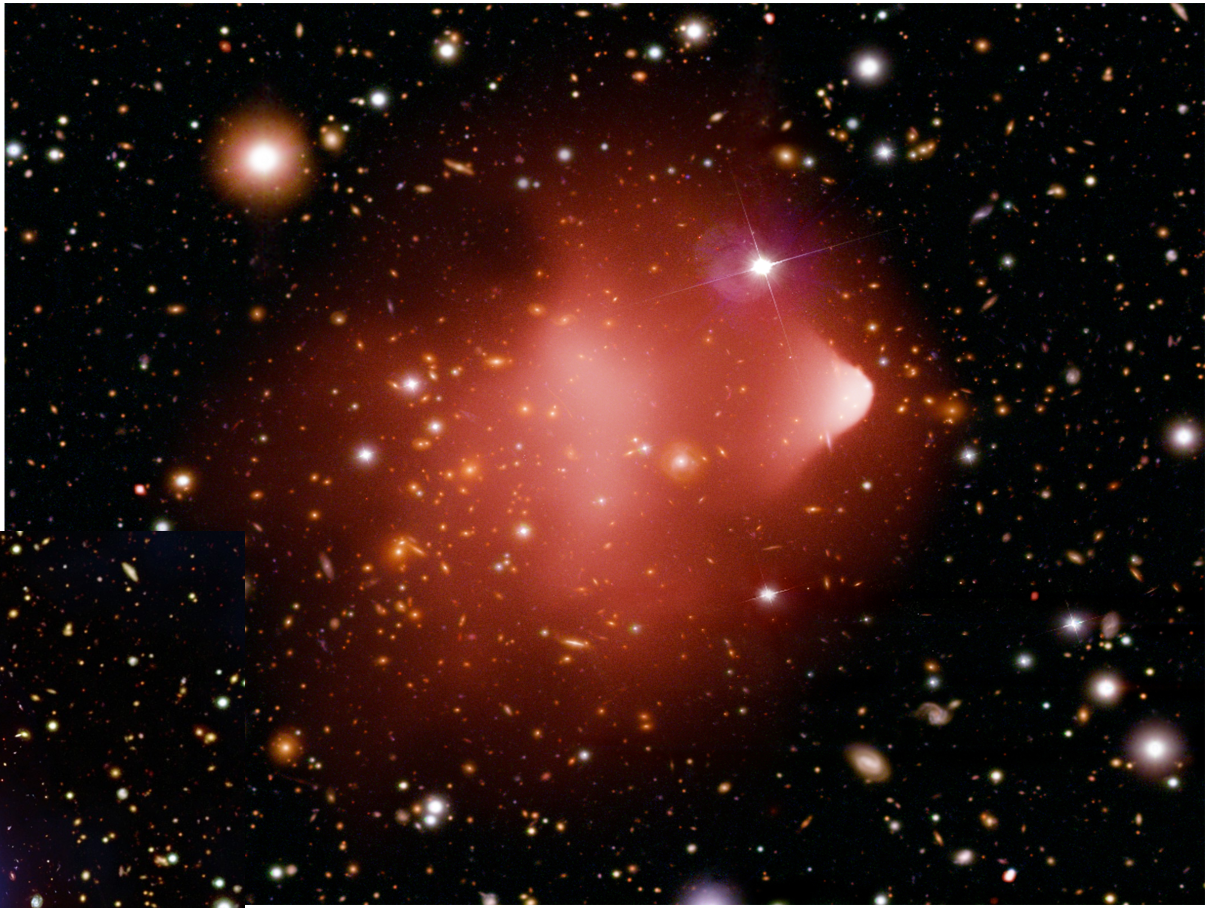
Extragalactic universe:
Cluster of galaxies (X-ray, visible and dark-matter model)

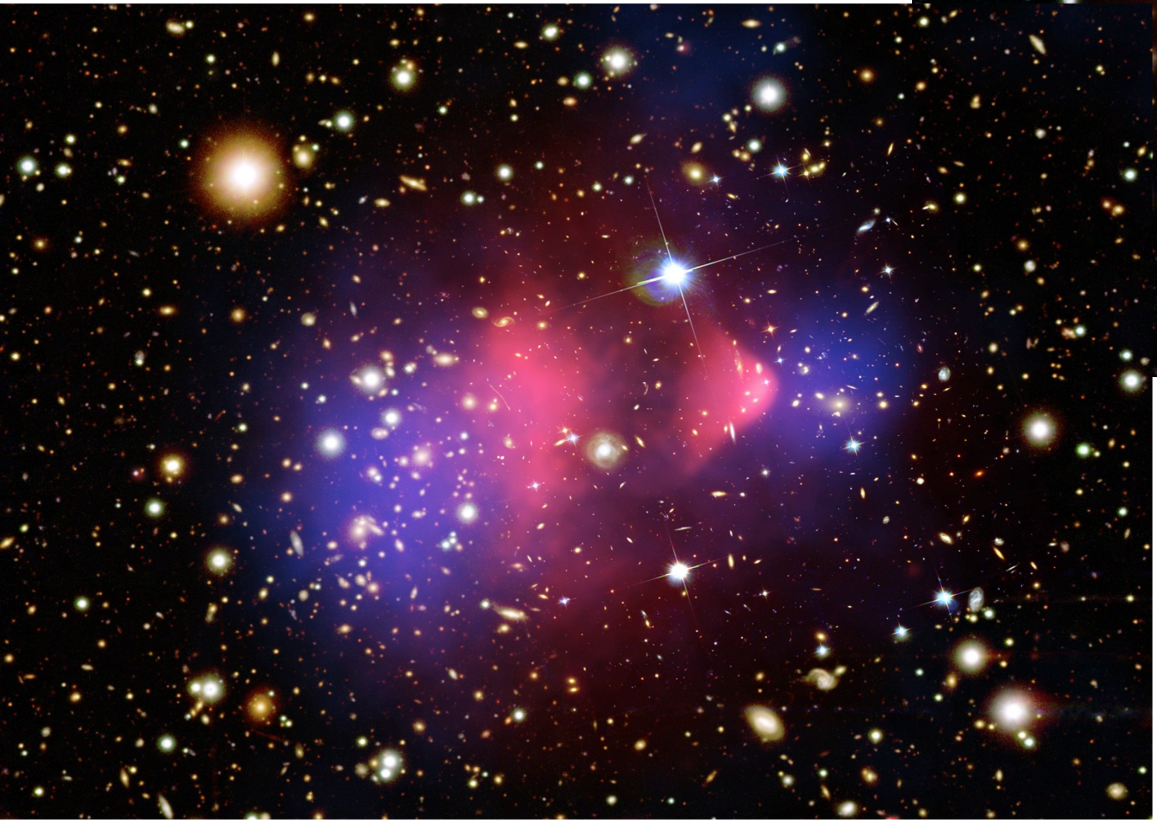
The Bullet Cluster, 1E0657-56

Two clusters in collision: studying this object let us measure the dark matter

Right: what we see directly in X-rays (red) and optical

Below: blue shows the matter distribution we infer



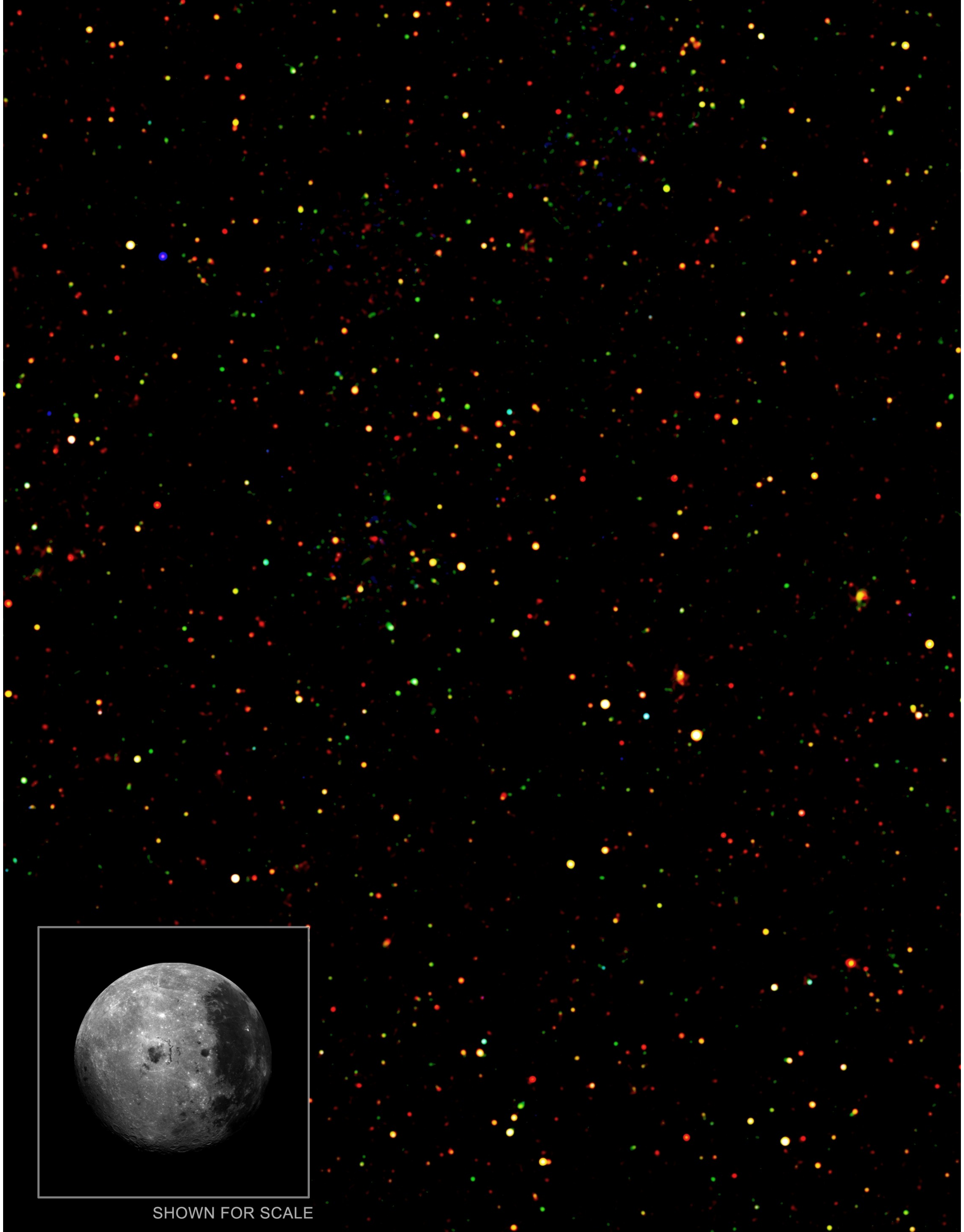


Distance: 3.3 billion light years

Size: 3 million l.y.

Data: Maxim Markevitch et al.

Extragalactic universe:
Quasars (X-ray)



The Bootes survey

1000 supermassive black holes

Hubble is not the only space telescope working at optical wavelengths – Here Jaymie Matthews shows off his tiny MOST satellite (which he calls the "Humble Space Telescope"). MOST studies bright stars to probe the seismology of their interiors.

COROT, searching for exoplanets

Kepler, exoplanet factory

Part 4: Earth's Fleet of Space Telescopes

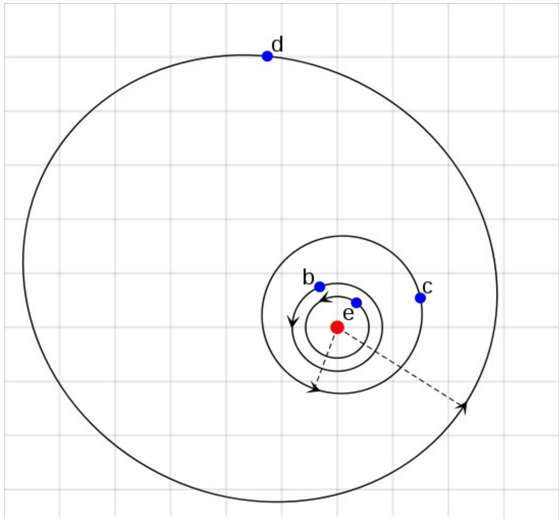
EXOPLANETS

1989: Dave Latham finds object around HD114762 – planet or brown dwarf?

1995: Discovery of 51 Pegasi b (Mayor and Queloz, Geneva)
a "Hot Jupiter", only 5 million mi (8 million km) from its parent star

2007-2009: Gliese 581 system
Gliese 581d, mass of 6-10 Earths
A "super-Earth" in the habitable zone

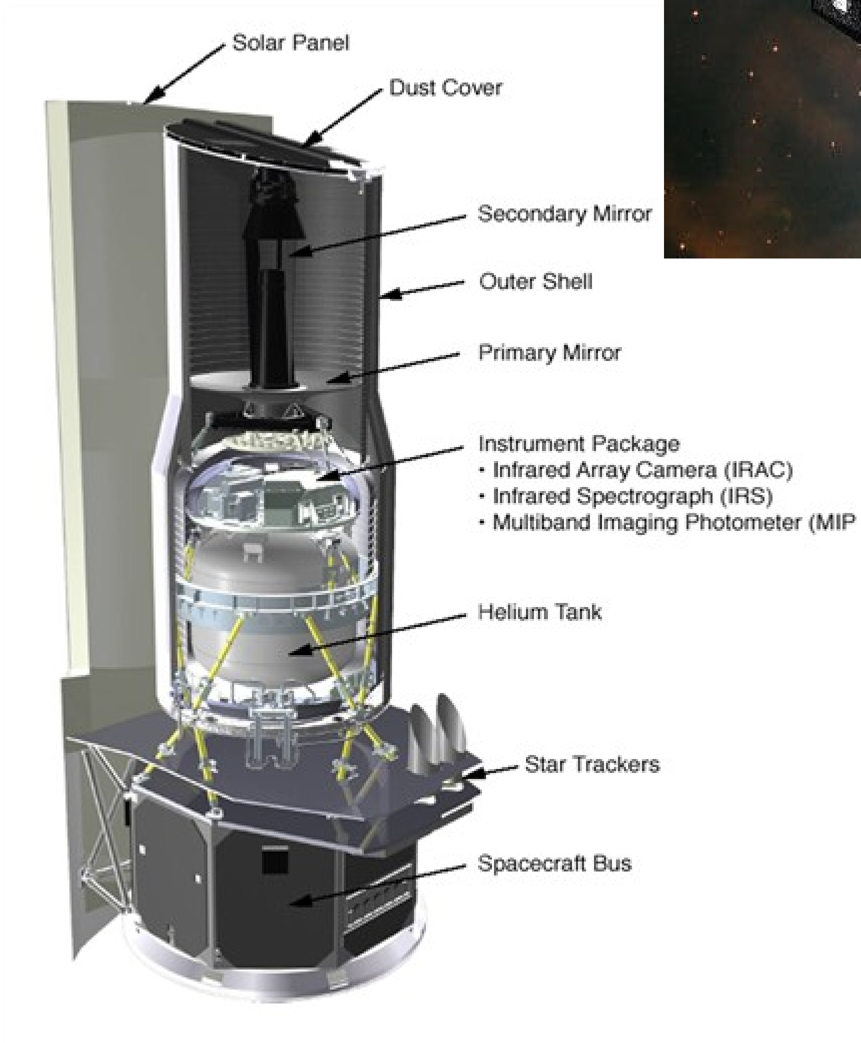
2012: 760 exoplanets now known
Kepler mission finding many new ones, including multiple-planet solar systems and **Earth-sized planets**



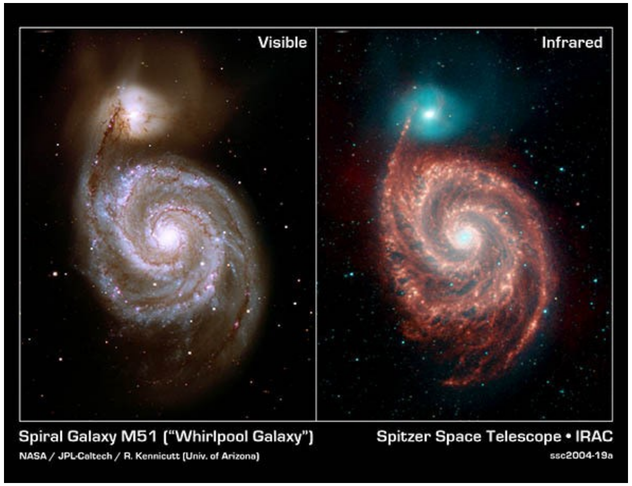
Blue: our solar system. Red: Pre-2012 Kepler planets, Green: new Kepler planets

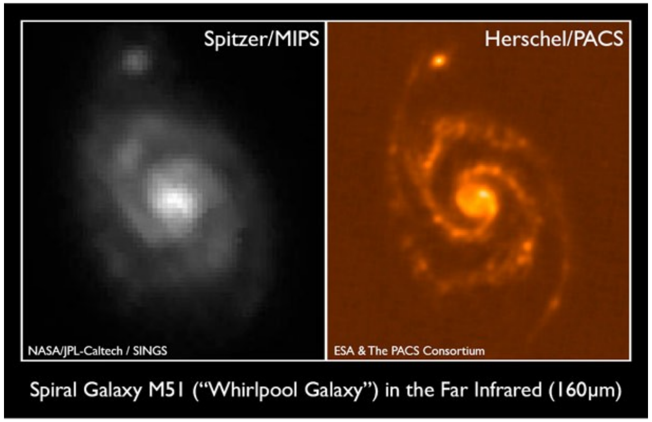
Infrared space telescopes

Herschel



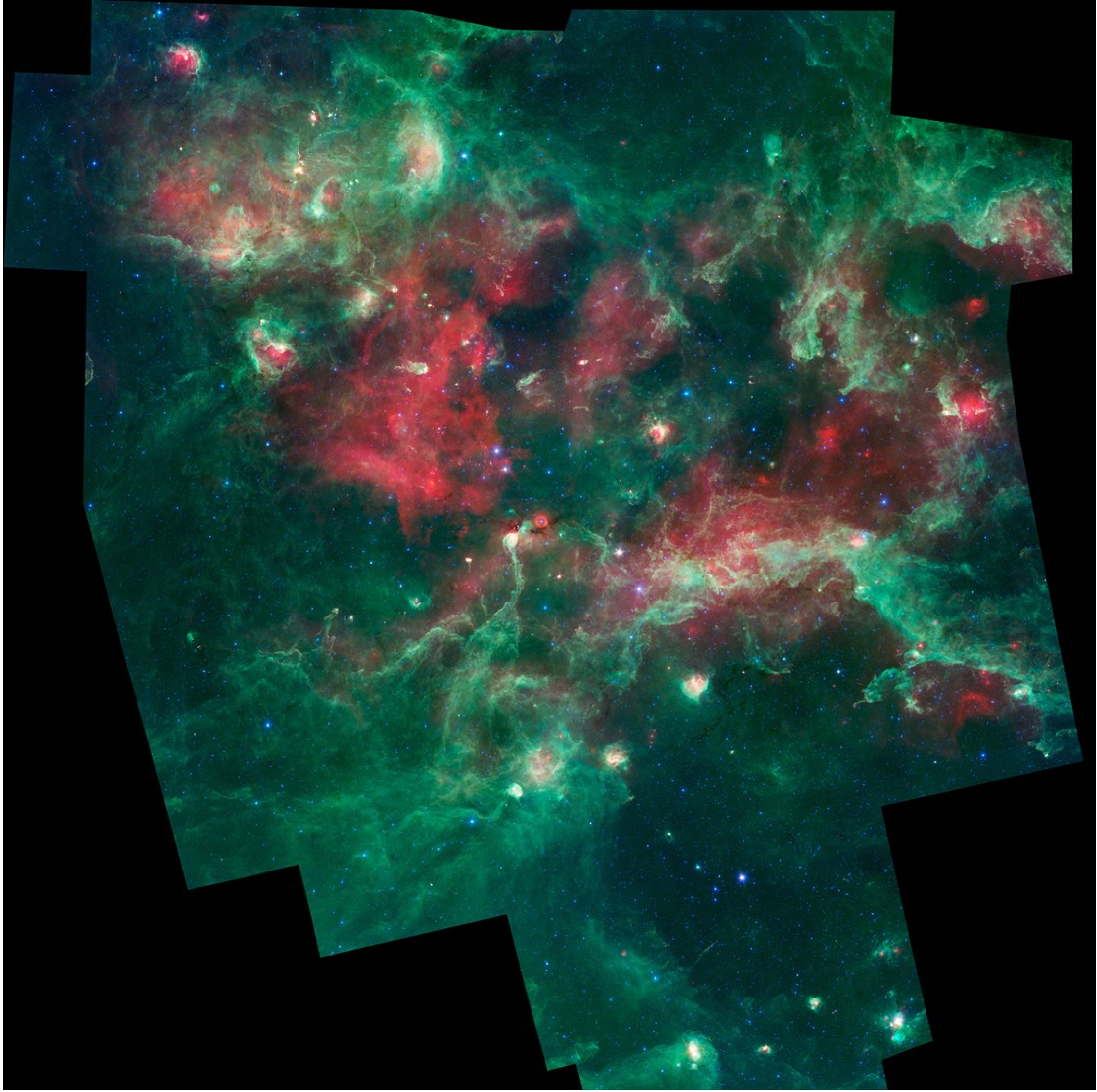
Spitzer





M51 in visible, near IR and far IR

Milky Way Galaxy:
Cygnus X region [Infrared]

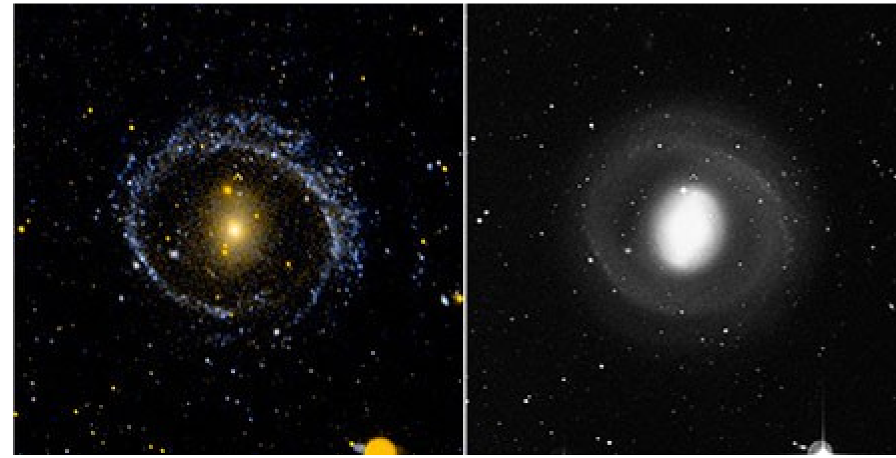


Infrared image of Cygnus X star forming region

The Spitzer telescope lets us peer through regions otherwise opaque and see the young stars shaping the environment around them

Ultraviolet satellites

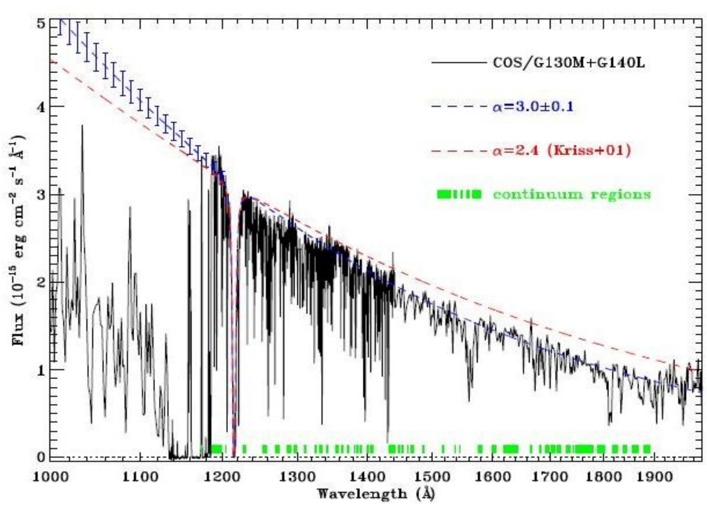
GALEX – an ultraviolet sky survey



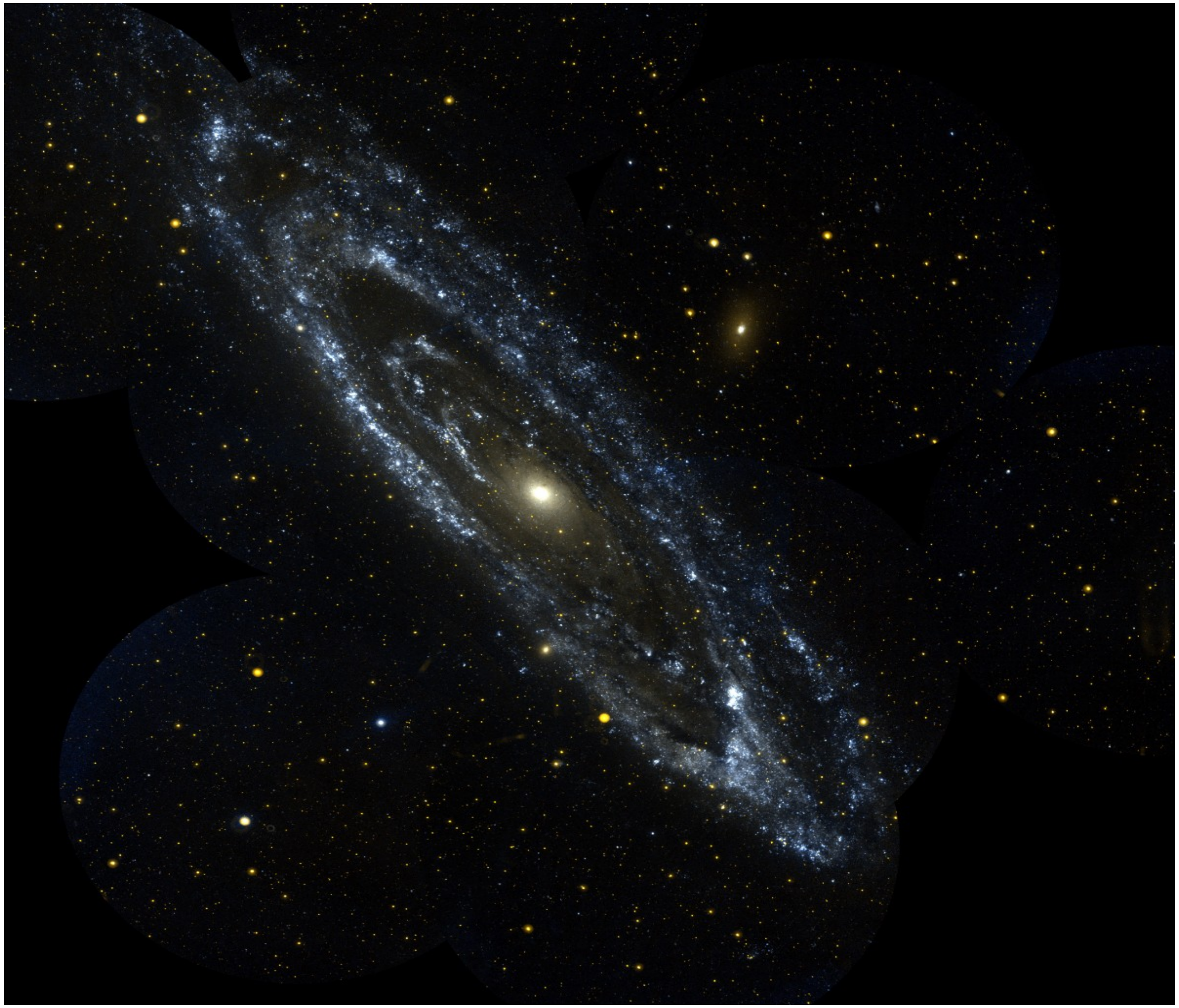
Spiral arms show up better in the UV image (left) - hot young stars

COS spectrograph on Hubble

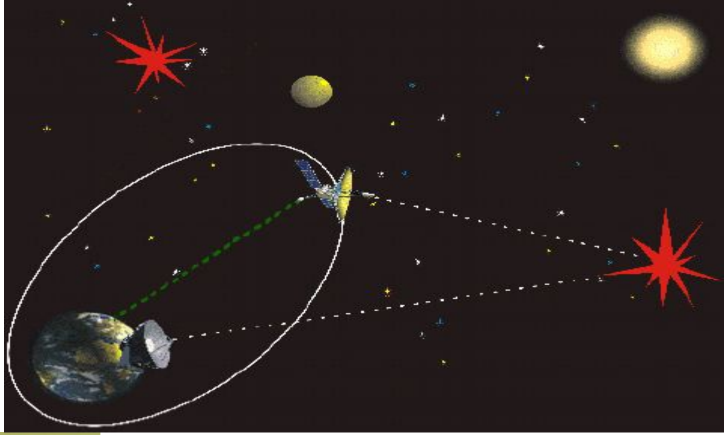
COS spectra map out
the intergalactic medium (Shull et al 2010)



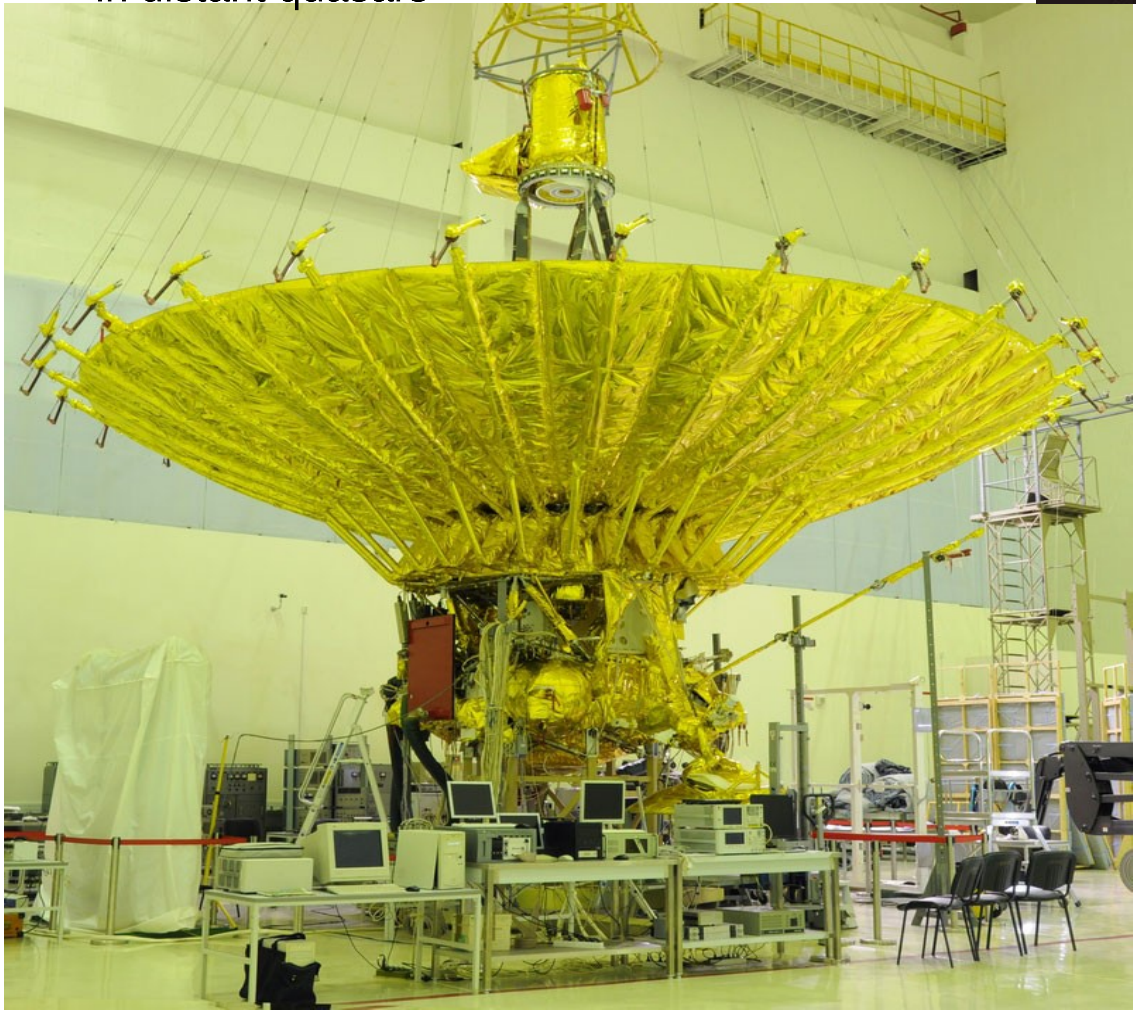
Extragalactic universe: Andromeda Galaxy
[Ultraviolet, GALEX satellite]



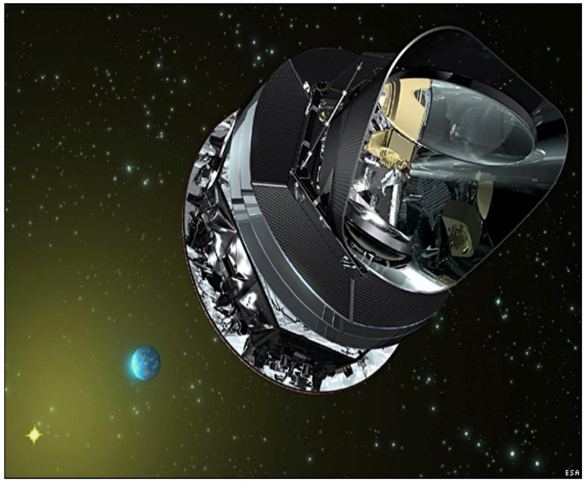
Radio Telescopes in Space



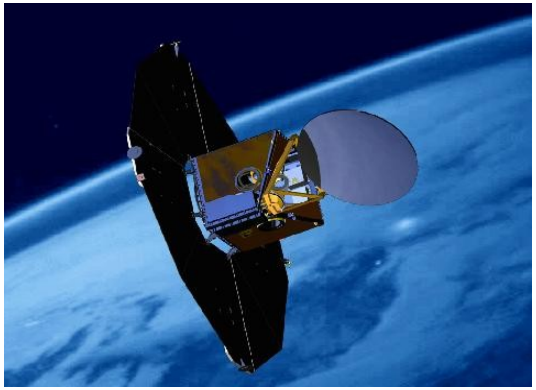
Spektr-R launched in 2011, its dish is combined with dishes on the Earth to make a psuedo-telescope 200000 miles in diameter to study structures only a few light years across in distant quasars



Planck – imaging the cosmic microwave background

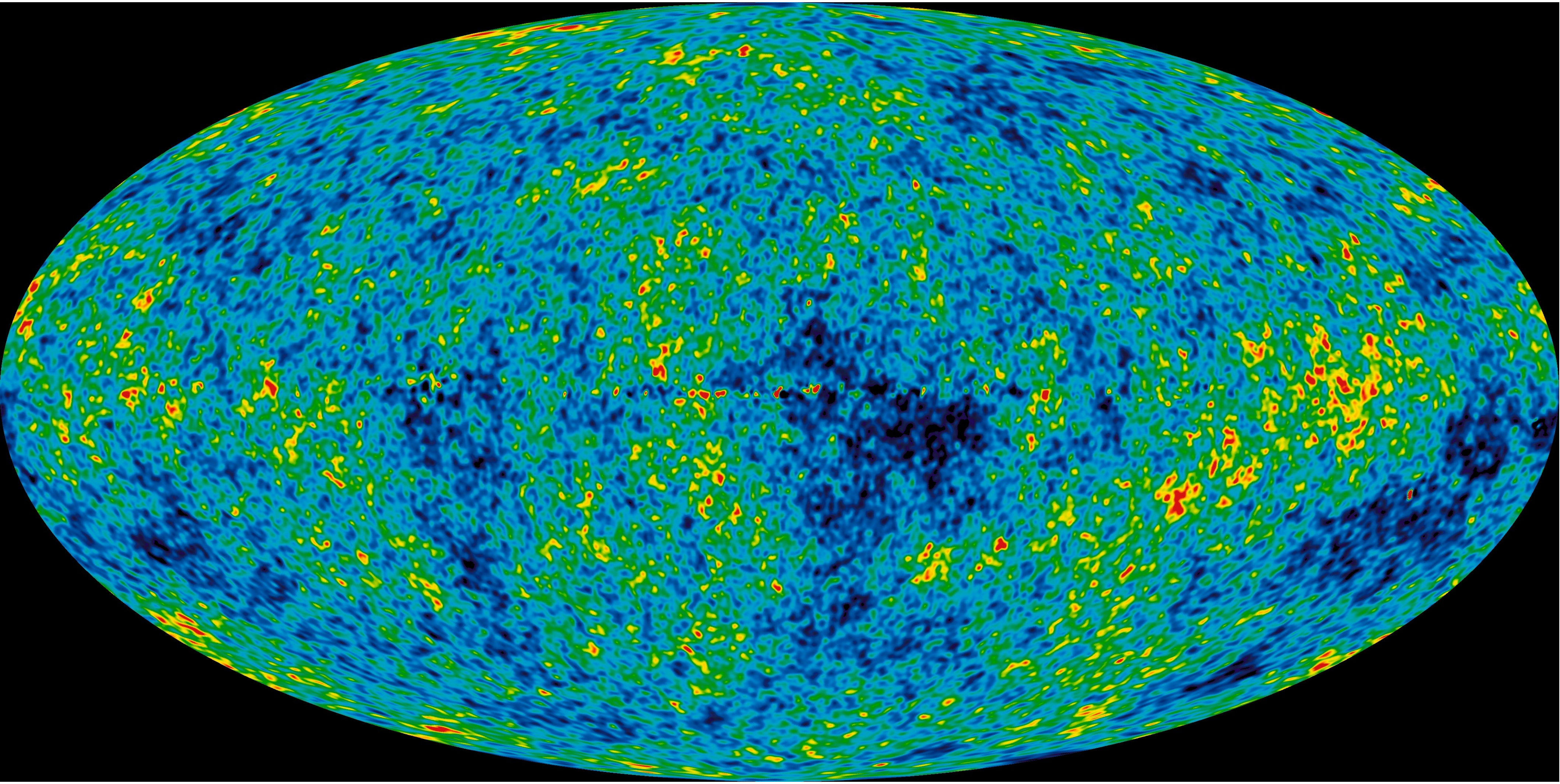


Swedish Odin satellite measures interstellar molecules



Whole sky view (Milky Way subtracted out) [Microwave, WMAP]

WMAP: Imaging the universe as it was 13.7 billion years ago
The specks are the seeds from which galaxy clusters will form
From their size we can work out the age of the universe



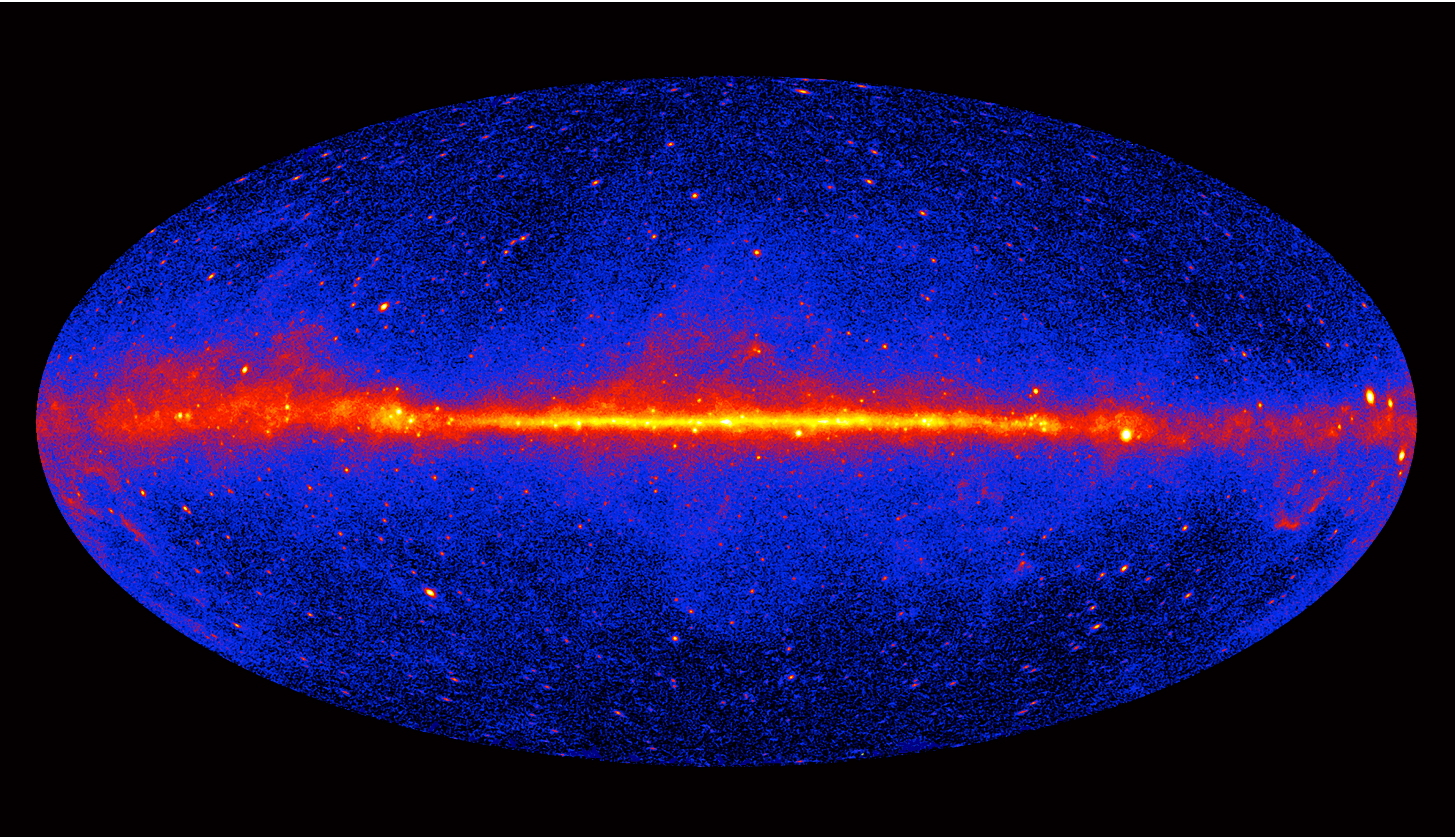
Gamma ray satellites

AGILE – low orbit

Integral – gamma ray satellite, High Earth Orbit

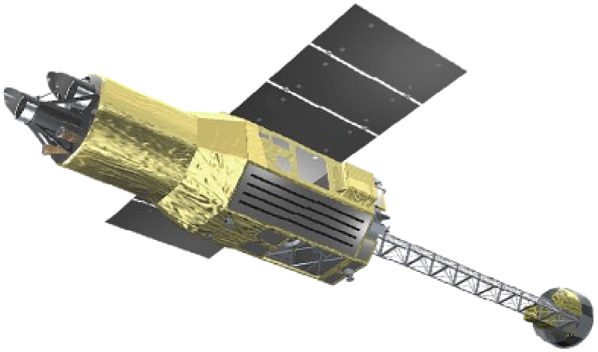
Fermi – gamma rays, low orbit

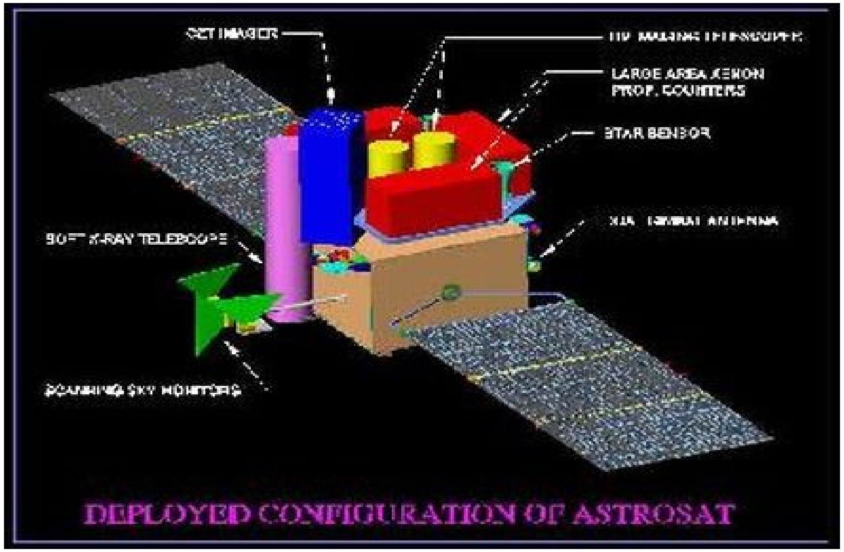
Whole sky view (Milky Way and extragalactic) [Gamma ray, Fermi satellite]



Gamma ray sky seen by Fermi
Gas in the Milky Way and a sprinkling of distant black holes

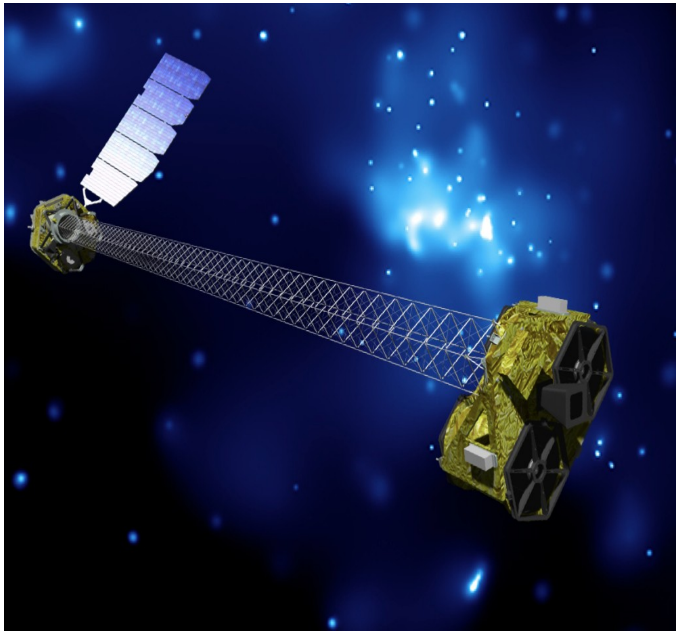
Postscript: The Future

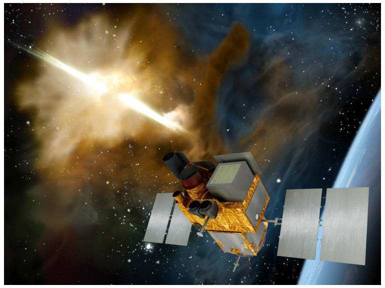


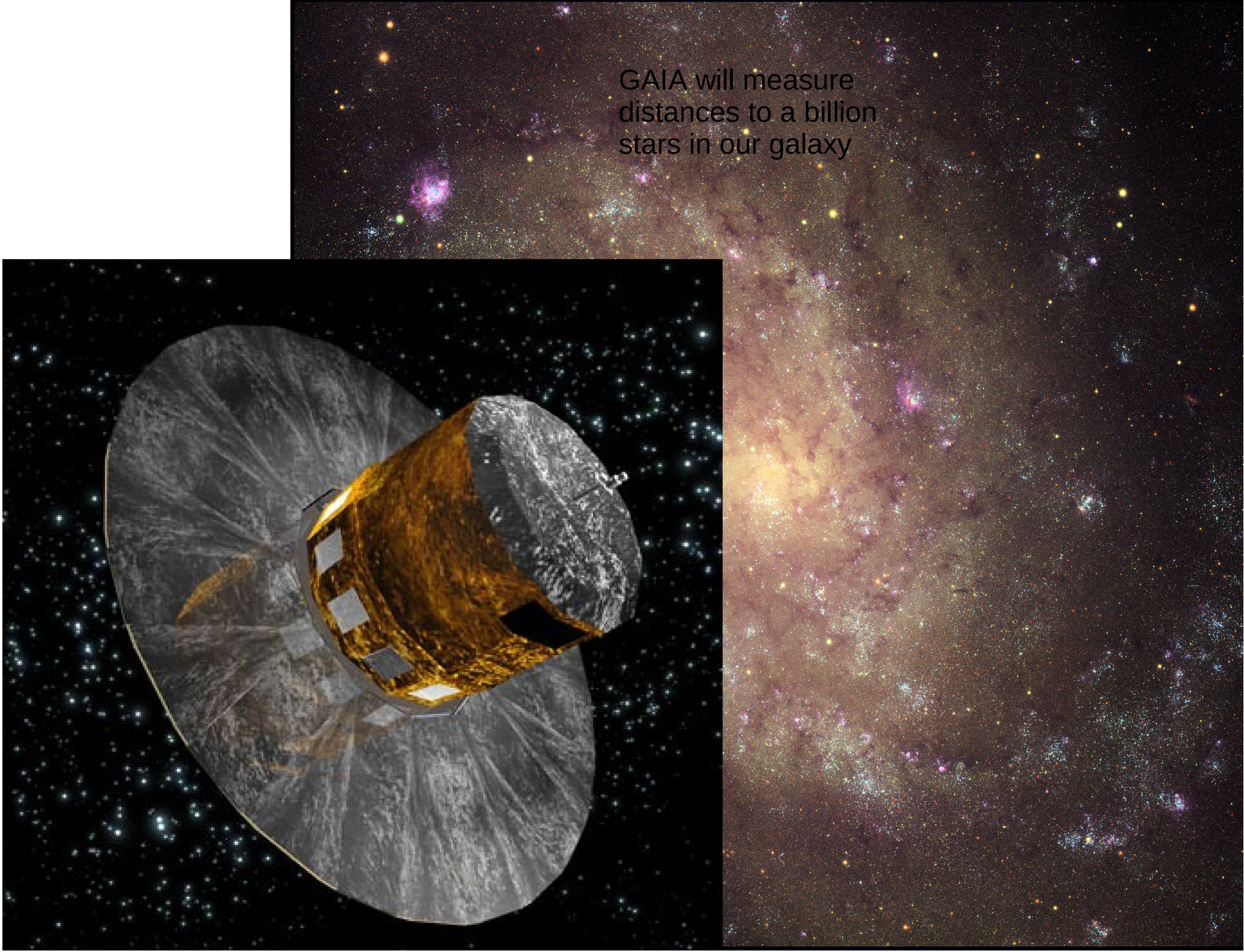


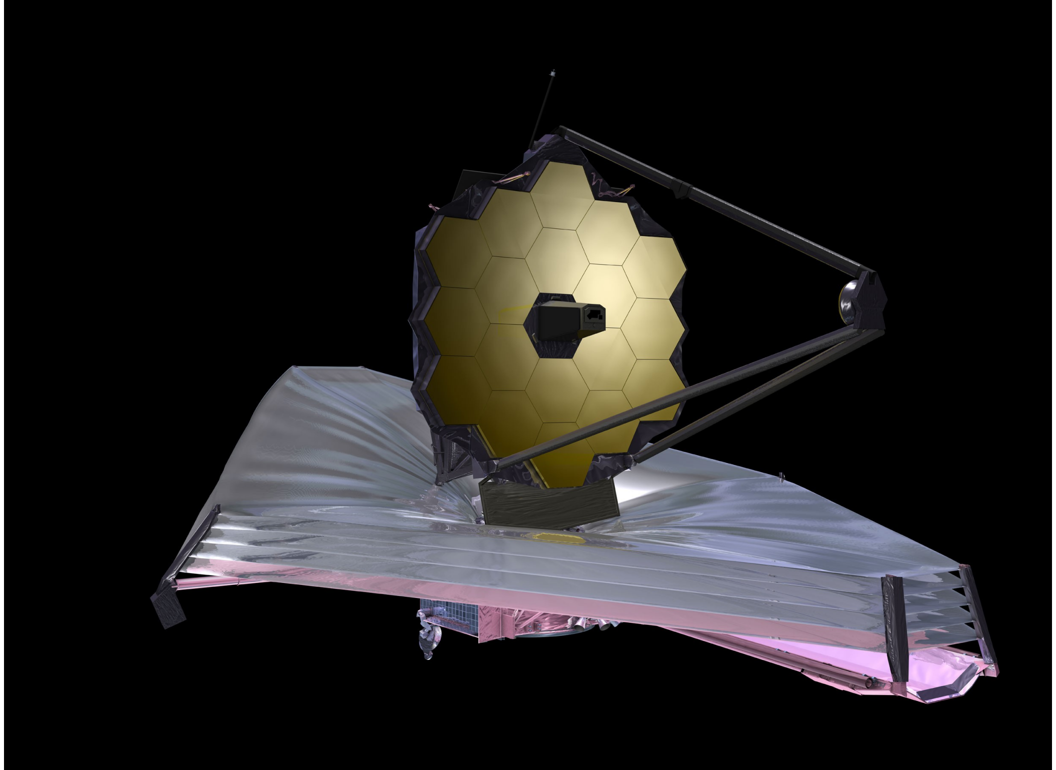
Future X-ray missions will probe the “harder” (bluer) X-ray colors that Chandra can't see well

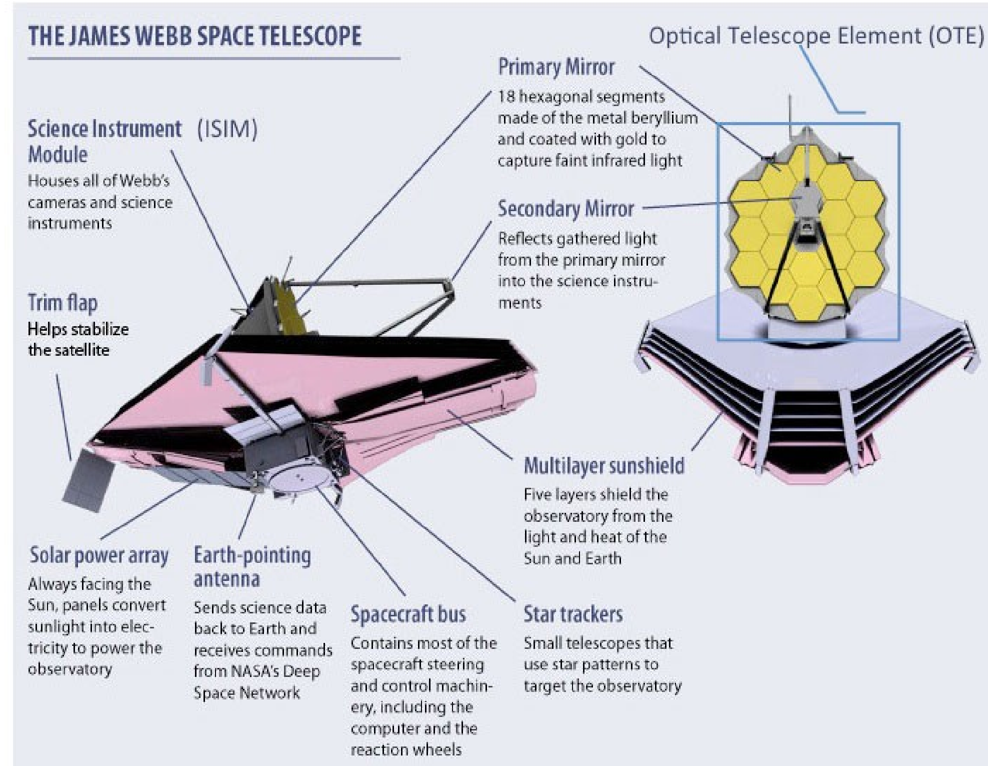
NuStar (USA) - Hard X survey
ASTRO-H (Japan)
GEMS (USA) - polarimetry
AstroSat (India) – wide band
SVOM (France/China) - bursts






GAIA will measure
distances to a billion
stars in our galaxy

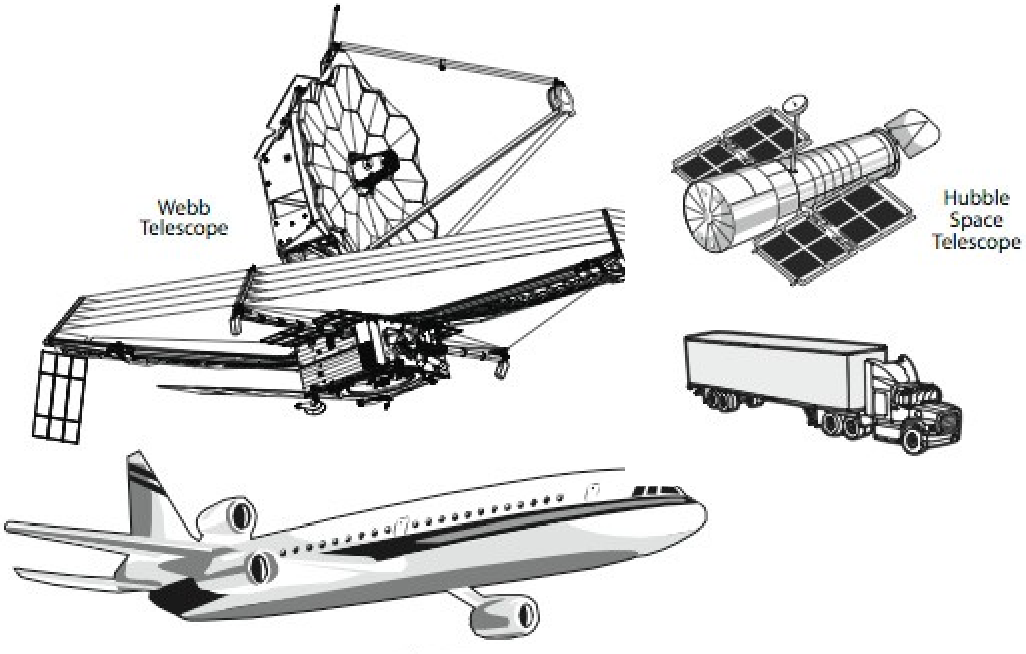




JWST – the James Webb Space Telescope
Launch 2018? by Ariane 5
NASA + European Space Agency+ CSA
6.6m dia. mirror
18 hex segments
Infrared telescope

NIRCam Near IR imager
MIRI Mir IR images/spectra
NIRISS Near IR images/spectra
NIRSpec Near IR spectra

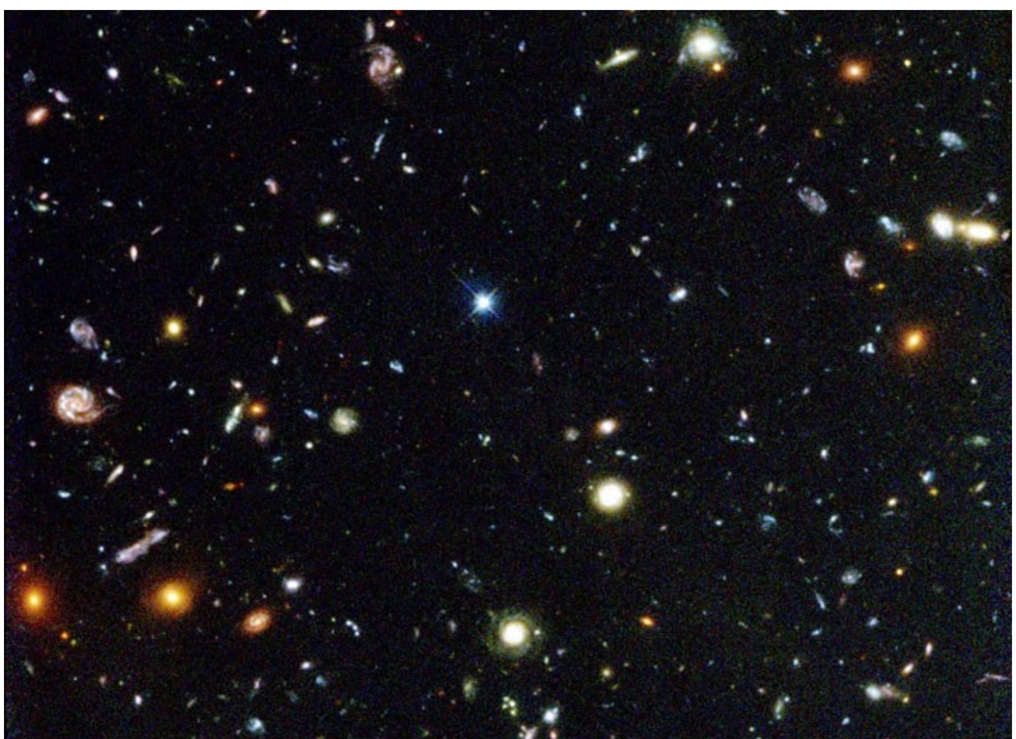
James Webb, 1906-1992, boss of NASA 1961-68



Ground based telescopes showed us what nearby galaxies are like

Hubble showed us what galaxies were like 10 billion yr ago (z=2)

JWST will do the same job for galaxies 12 to 13 billion years ago (z=5-6) when the first galaxies were forming



How did galaxies form?
How did the universe change between then and now?

JWST will also study protostars in our own galaxy, probing inside their dust cocoons and imaging the dusty disks from which planetary systems form

And JWST will have a limited ability to study the atmospheres of some exoplanets and extend the search for life – but most of that will have to wait for yet another generation of telescopes

The Lagrange Points: Gravity hills and valleys in the Sun-Earth system

Newton's gravity law with two point masses orbiting each other
and a third low-mass test particle - work in rotating frame, 5 solutions of the Lagrange Quintic
L1 is a stable point 1.5 million km from Earth towards midday
L2 is an unstable point 1.5 million km towards midnight
L4 and L5 are the stable equilateral-triangle 'Trojan' points; L3 is unstable (and counterintuitive!)