Exploring the Invisible and Hot Universe:

A multi-wavelength view of galaxies and galaxy clusters

Spiral galaxy

Elliptical galaxy

Cluster of galaxies

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300 Million ly ($3x10^8$)

Galaxy Galaxy ClusterCluster

Galaxy cluster

3 Million ly (3x1

Galaxy

Galaxy

100 Thousand ly (

Molecul

Molecular Cloud

1 ly

Planetary Disk

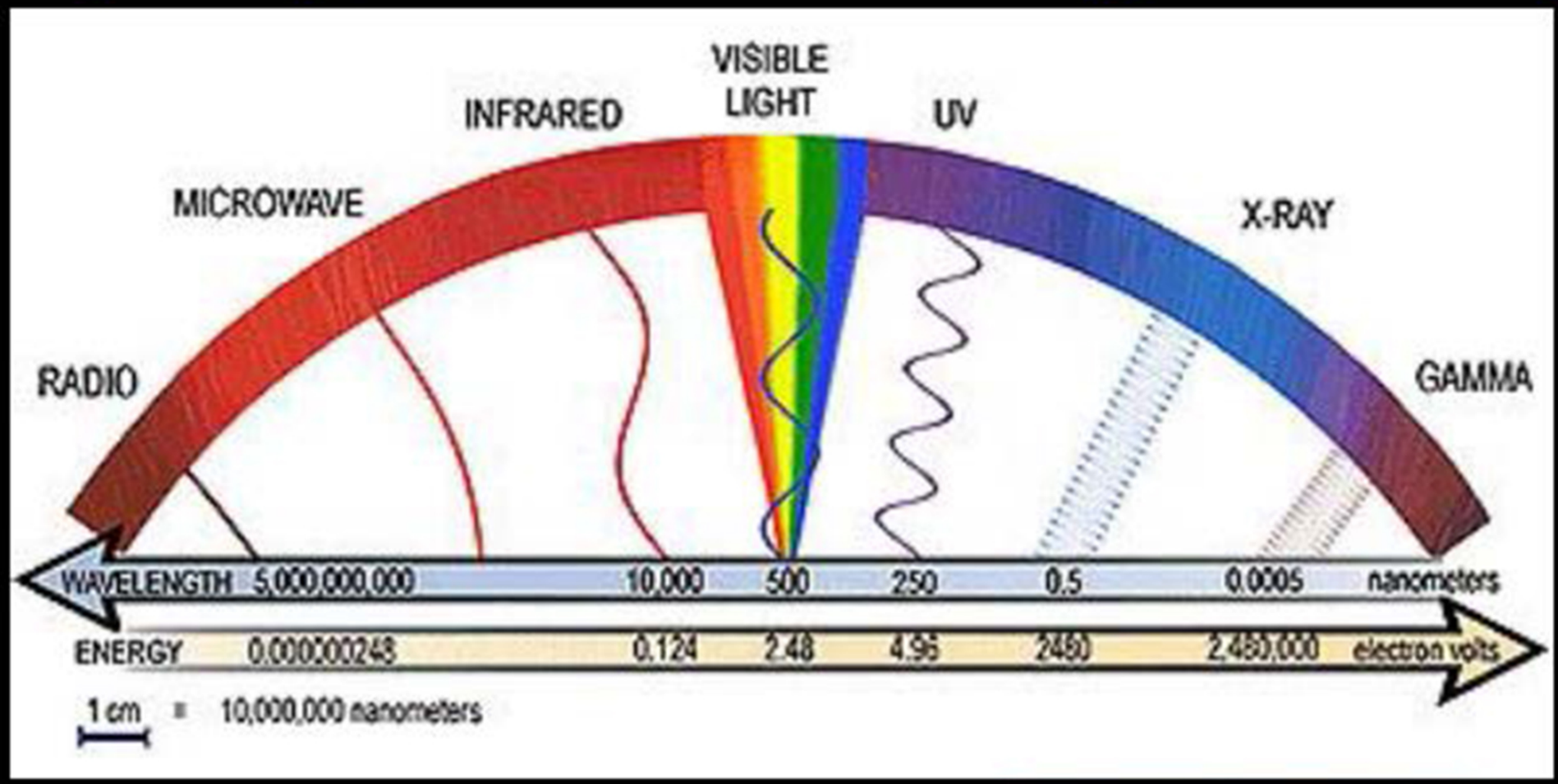
0.0001 ly (10^{-4})

100,000 km (10^{-8} ly)

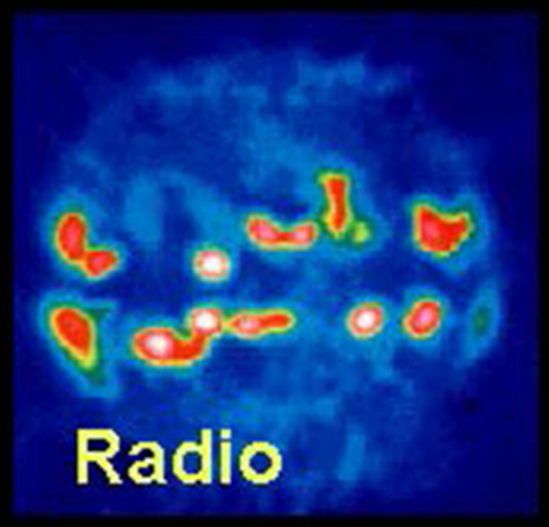
Light Year (ly): The distance light travels in one year (9,460,700,000,000 km)

Distance from Earth to Sun (AU) is about 8 light minutes

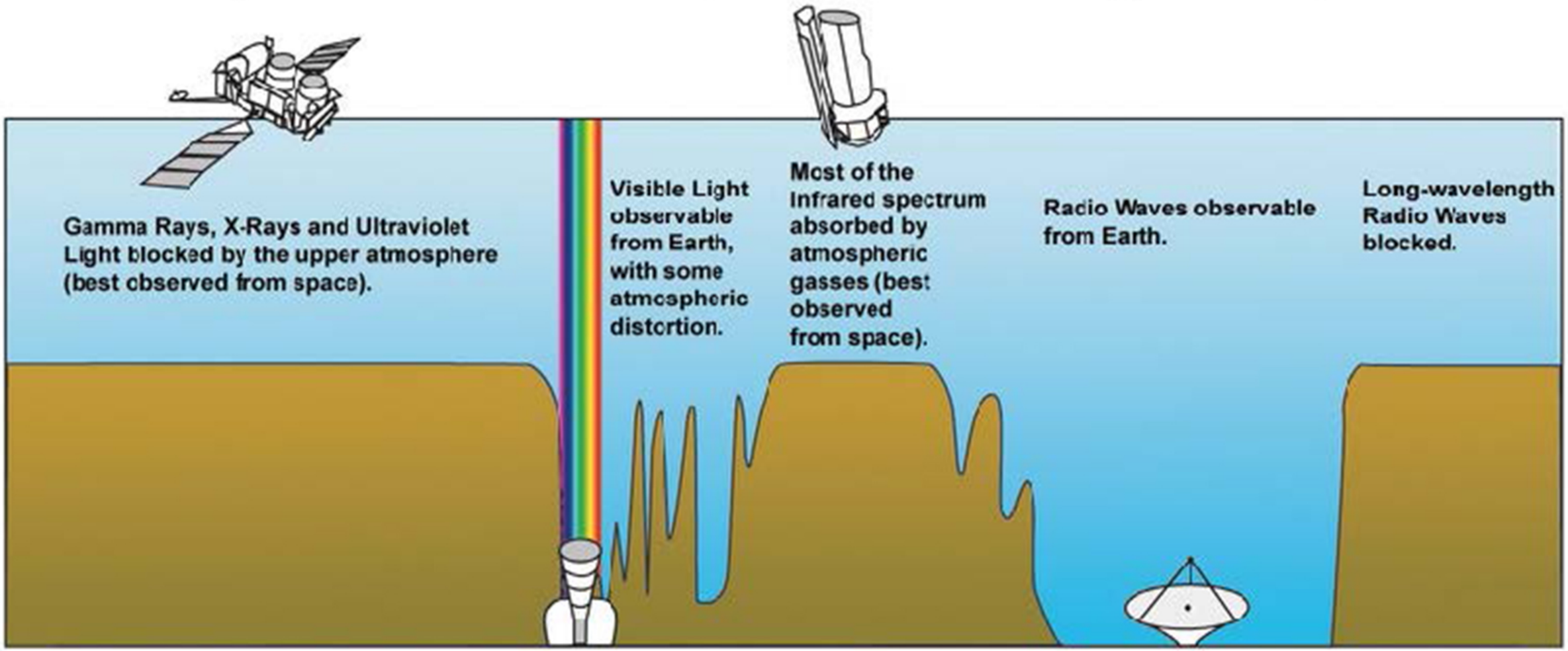
Spanning the Spectrum: Multiwavelength Astronomy



Our Sun



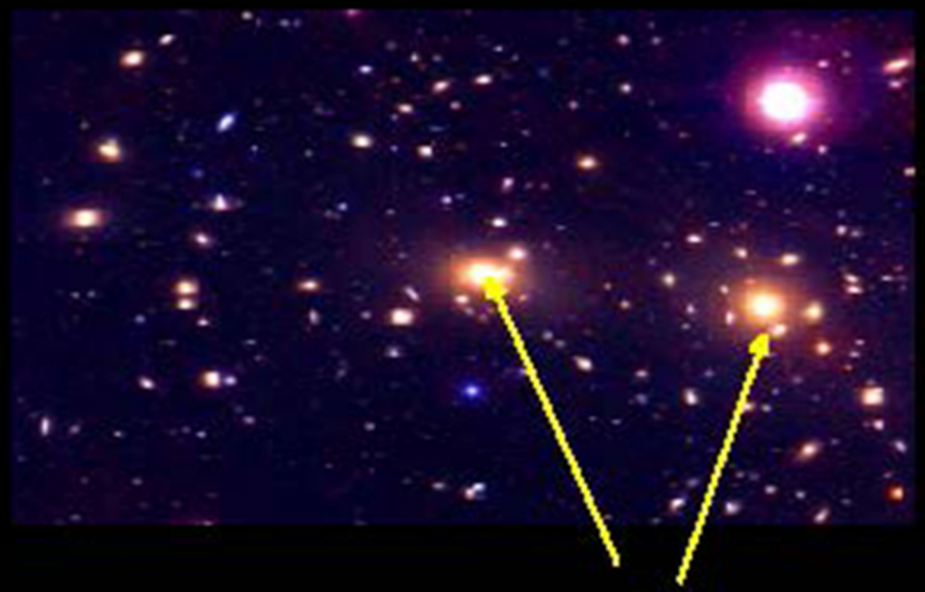
Although X-rays and Gamma rays are very energetic, they are absorbed by the Earth's atmosphere. Need to go into space.



primary gases that are responsible the atmospheric absorption of energy are water vapor, carbon dioxide, and ozone.

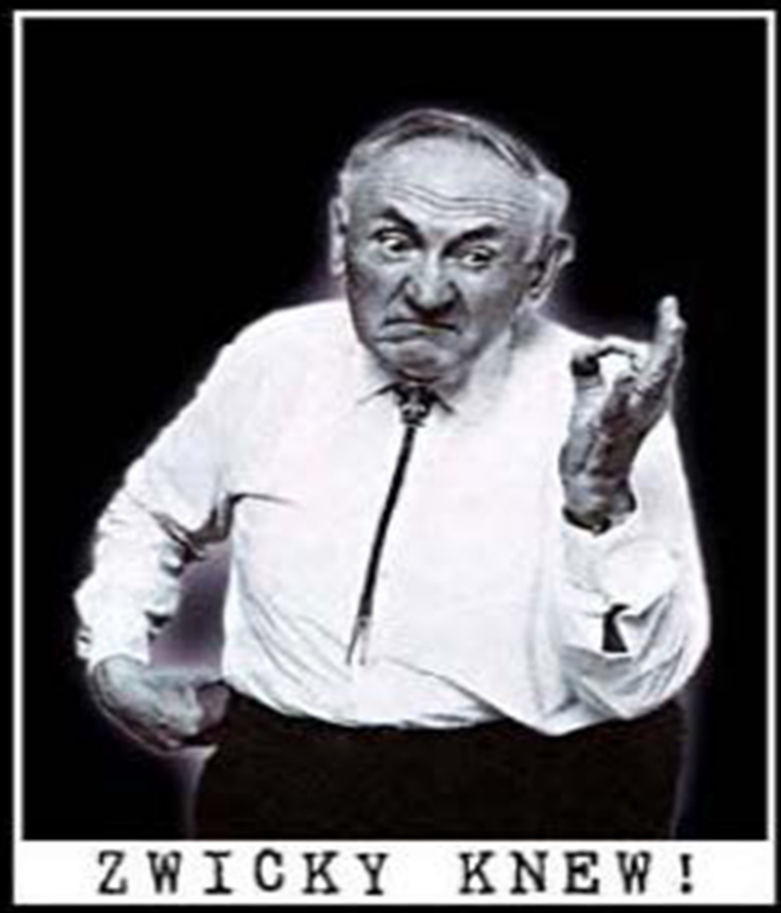
Early Evidence for Dark Matter

First suggested by Fritz Zwicky – 1933
Galaxies in the Coma cluster moving too FAST
Not enough **visible** matter to hold galaxies together
Cluster galaxies should just fly apart UNLESS the cluster is
filled with 10 times more matter than seen in visible light!



Coma Cluster - 1000 galaxies

Each galaxy has 100 billion stars



Dark Matter In Galaxies

Vera Rubin showed that in spiral galaxies there is not enough luminous matter to hold the stars together. Instead about 10 times more dark matter, than luminous matter is needed to hold the stars together.

M51

The Whirlpool
A typical spiral galaxy

Dark Matter in Clusters of Galaxies
Could the missing matter just be hard to see?

at least some matter is "hard" to detect

Zwicky's view of the Coma cluster

- Galaxies
- Stars
- Only about 2-5% of total mass

BUT THERE'S MORE THAN MEETS THE EYE

Clusters of galaxies

Chandra X-ray image on optical field

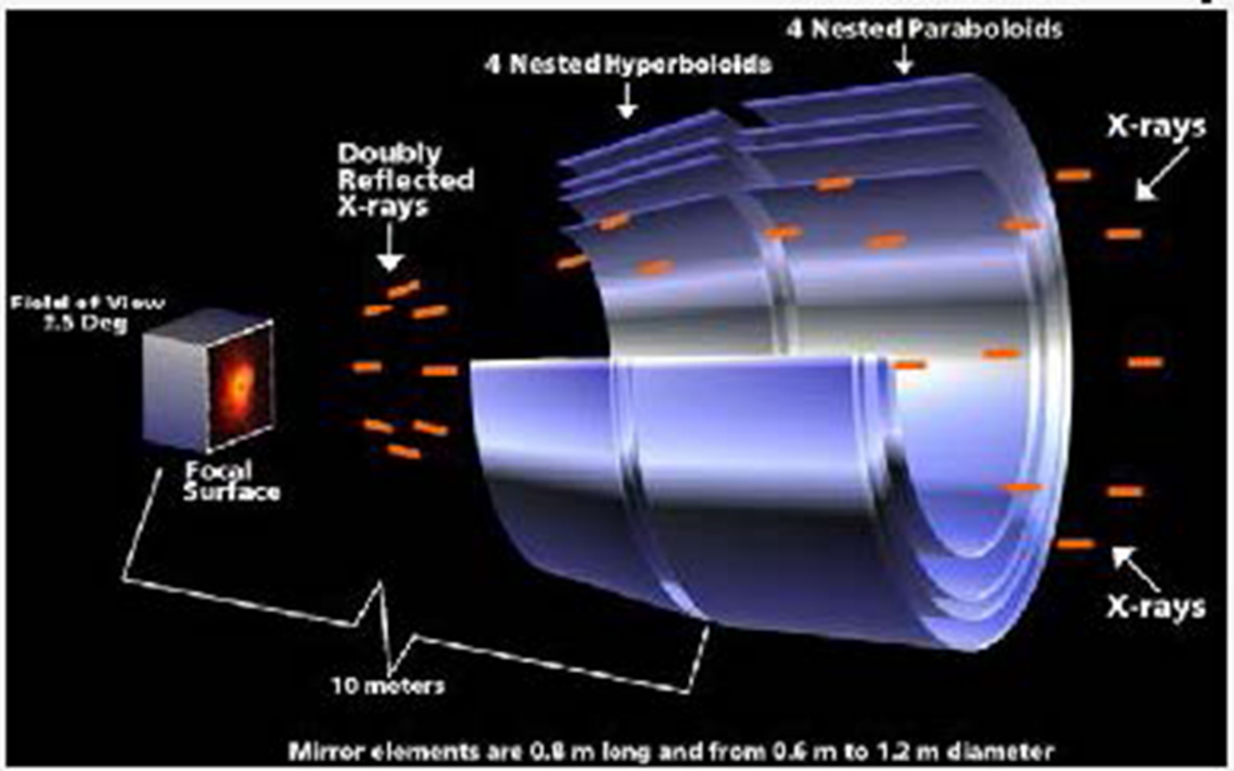
- Massive/gravitationally bound
- Galaxies - 2 - 5 % of total mass
- X-ray observations (first from Uhuru) found diffuse hot gas (10^8 K)
- Hot X-ray emitting gas ~15% of the total mass - **most "normal" matter is hot gas.**
- **Most of the mass in clusters of galaxies is dark matter**

X-ray Astronomy - from Sco X-1 to Chandra

3 inch diameter solar X-ray telescope mirrors

- 1962 - Detection of first non-solar X-ray source Sco X-1
- First imaging solar X-ray telescope (Giacconi 1963)
  - About the same diameter and length as Galileo's 1610 telescope
  - 380 years later, Hubble is 10^8 times more sensitive
- In 37 years X-ray astronomy achieved comparable increase in sensitivity with launch of Chandra (launched in 1999)
  - Largest/heaviest (22,000 kg) payload launched by shuttle (Chandra+IUS)
  - Orbit goes 1/3 of distance to the moon (64 hour orbit)
  - Power 2300 watts = 1 (good) hair dryer

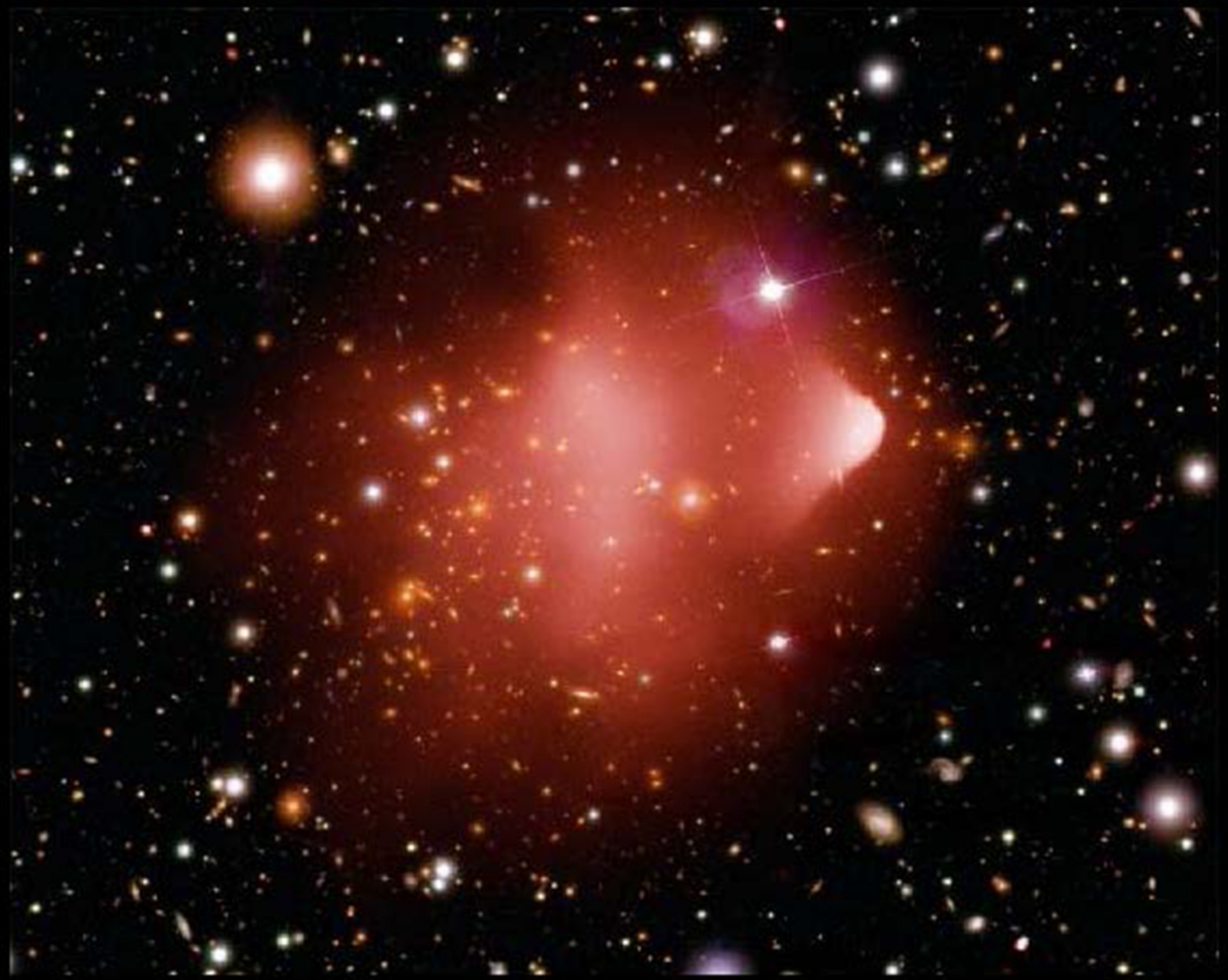
Chandra X-ray Telescope



- Focus with two grazing incidence reflections (paraboloid/hyperboloid)
- almost 20 sq m of area
- Mirrors are very smooth. If mirror were enlarged to size of Spain, largest "bump" would be <1 cm high

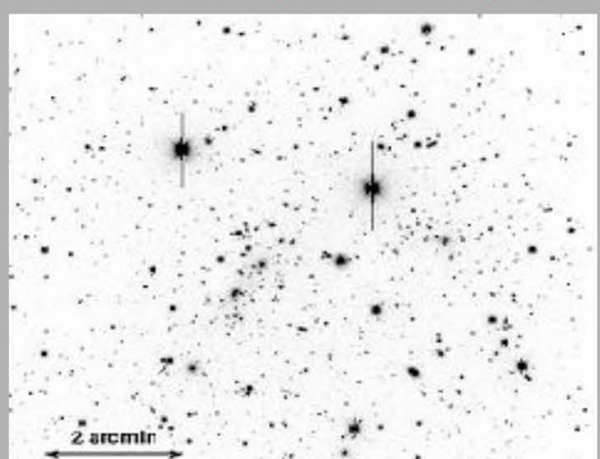
- **Detect individual photons (time, position, energy)**
- Chandra designed for 5 years - almost 20 years (July 23, 1999 launch)
- **planning for another 10 years is underway!!!**

The Bullet Cluster - X-ray and visible light

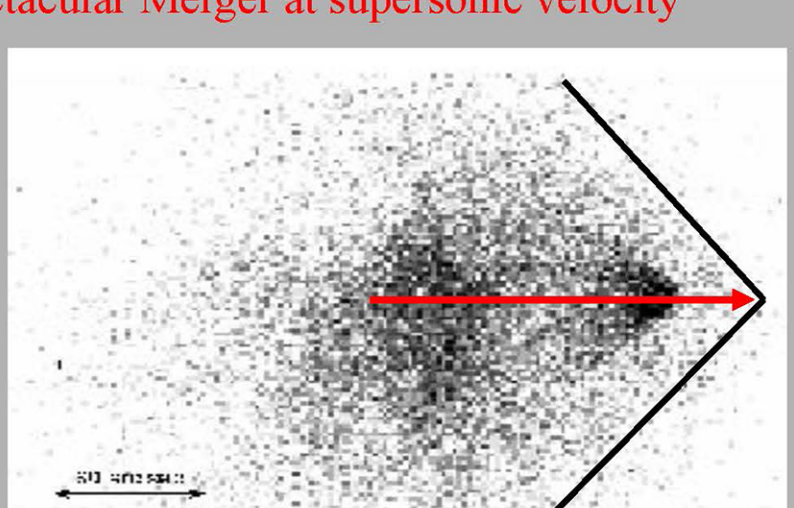


Dark Matter in Motion - The Bullet Cluster

- Visible image
- Galaxies, but nothing unusual

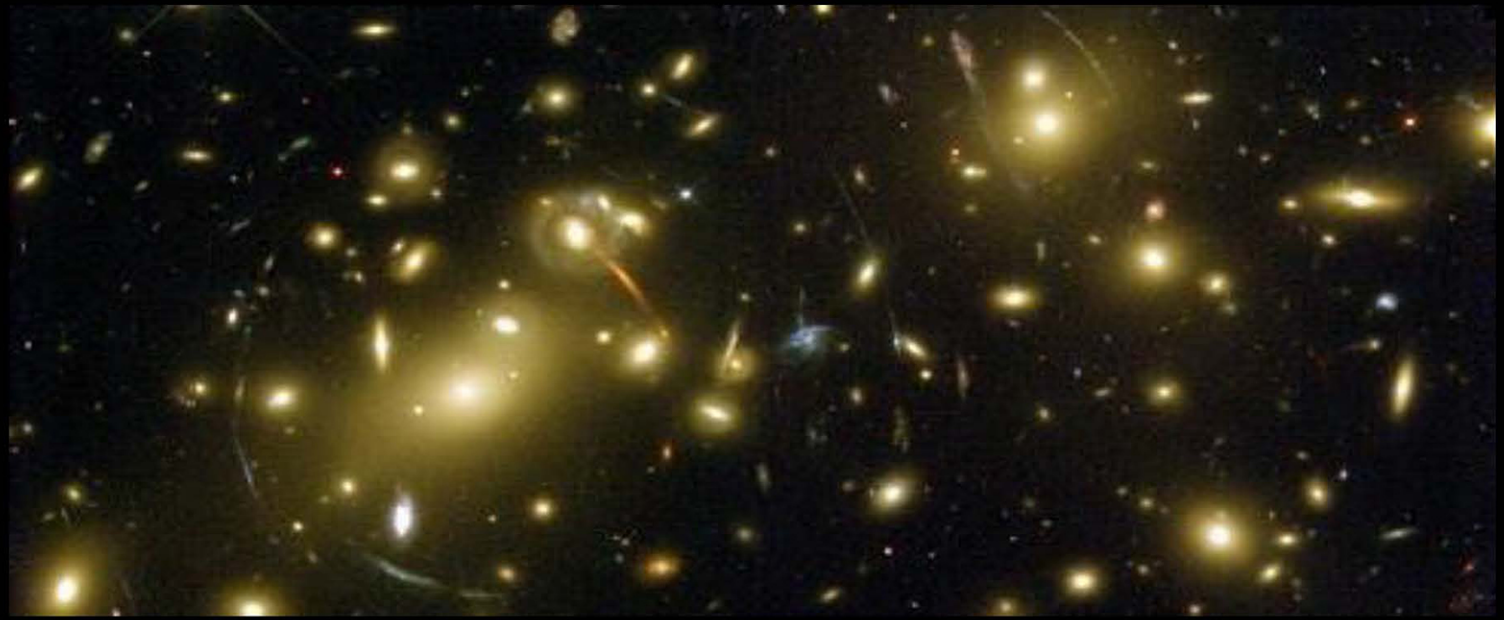


- Chandra X-ray image – shows the action
- Spectacular Merger at supersonic velocity



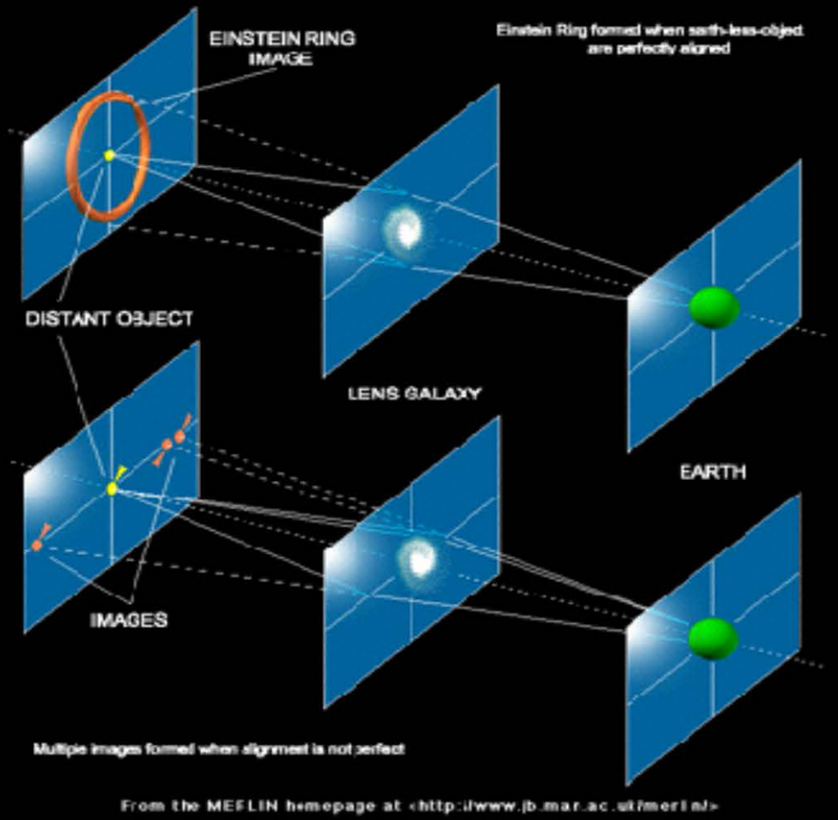
Hot gas moving through the dark matter at supersonic velocity of 3000 km/sec forms a Mach cone

Need to measure where the dark matter is



Background galaxies magnified and distorted by foreground cluster give direct measure of cluster mass

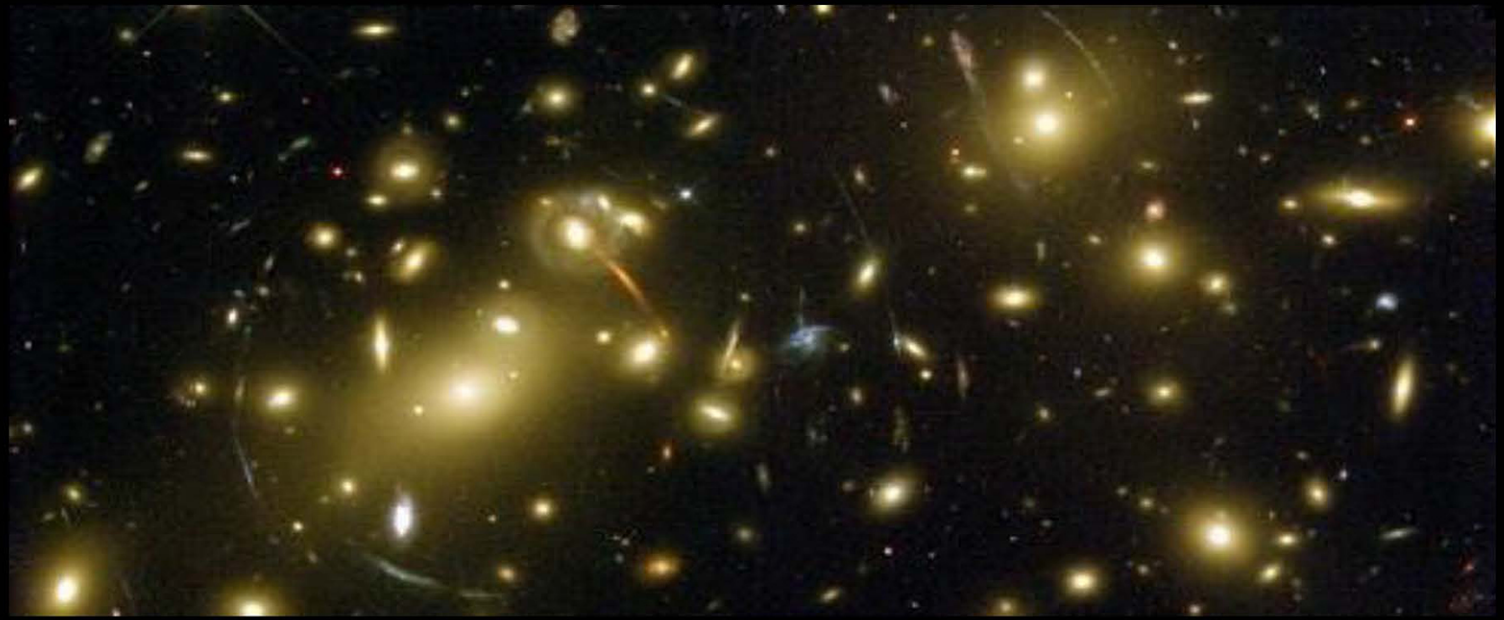
Gravitational Lensing



Add a black hole with the mass of Saturn over the middle of the Washington Mall, and view the Smithsonian Castle through the resulting gravitational lens.

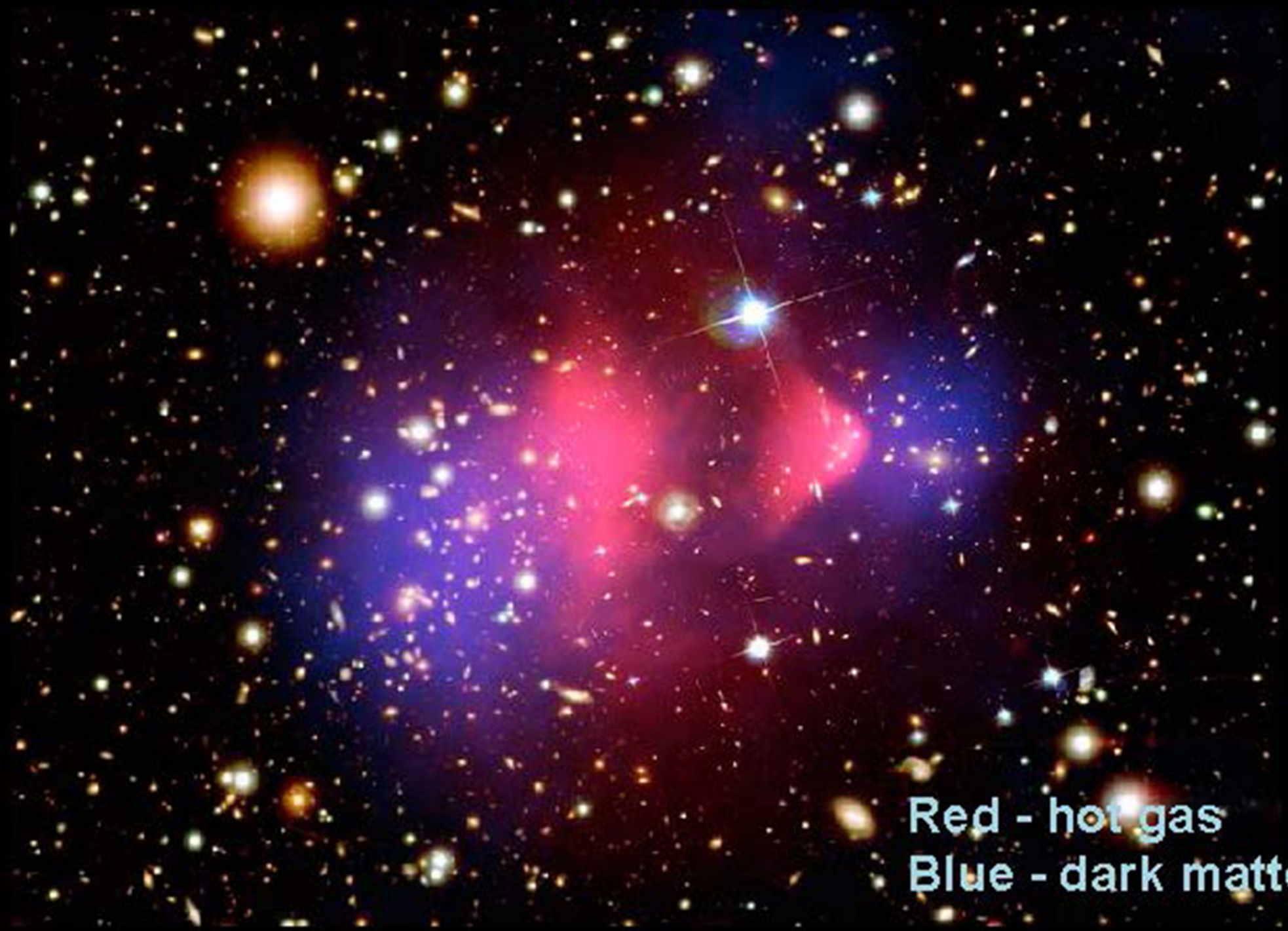
Through a gravitational lens

Need to measure where the dark matter is

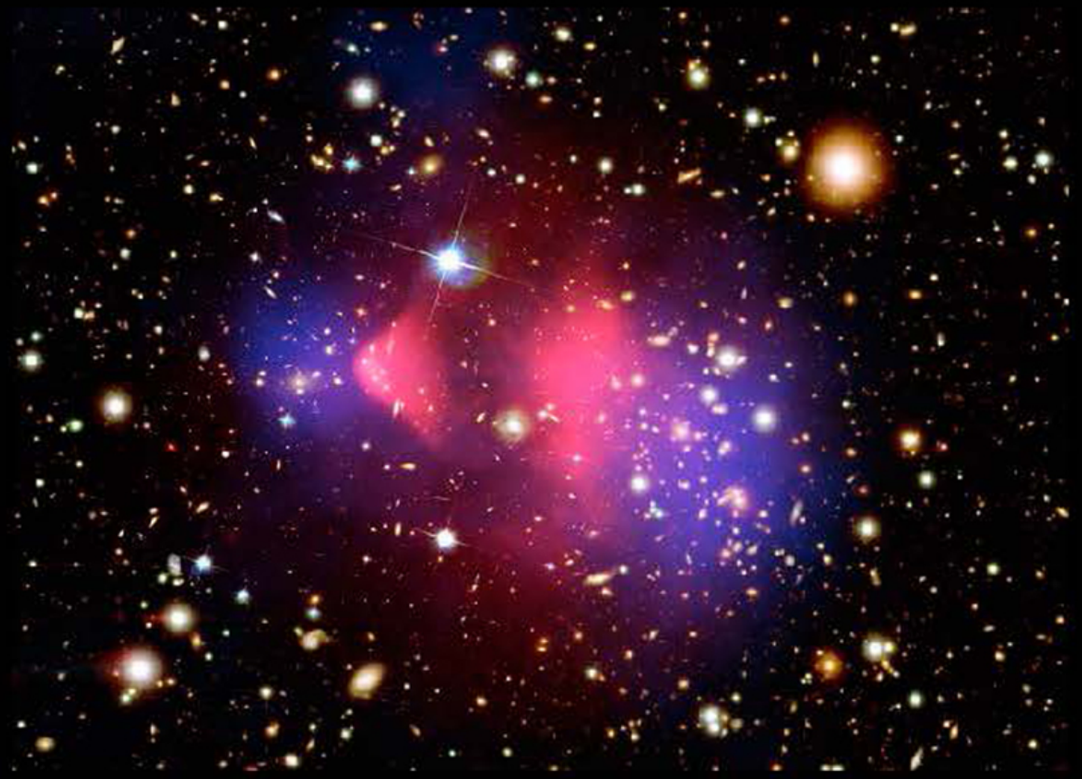


Background galaxies magnified and distorted by foreground cluster give direct measure of cluster mass

The Bullet Cluster



The Bullet Cluster

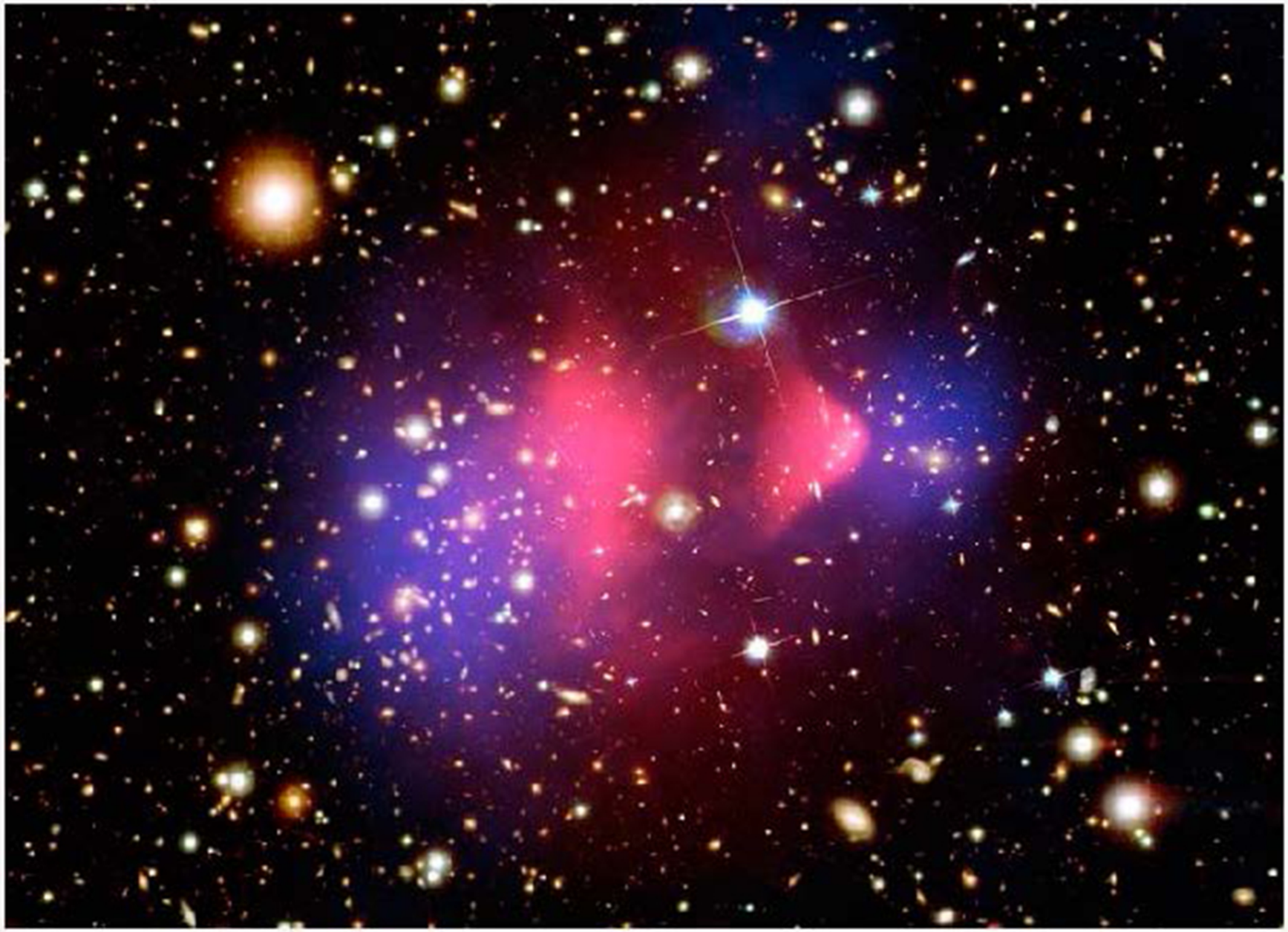


What are clusters of galaxies made of?

1) Galaxies

2) Hot gas 10^8 K

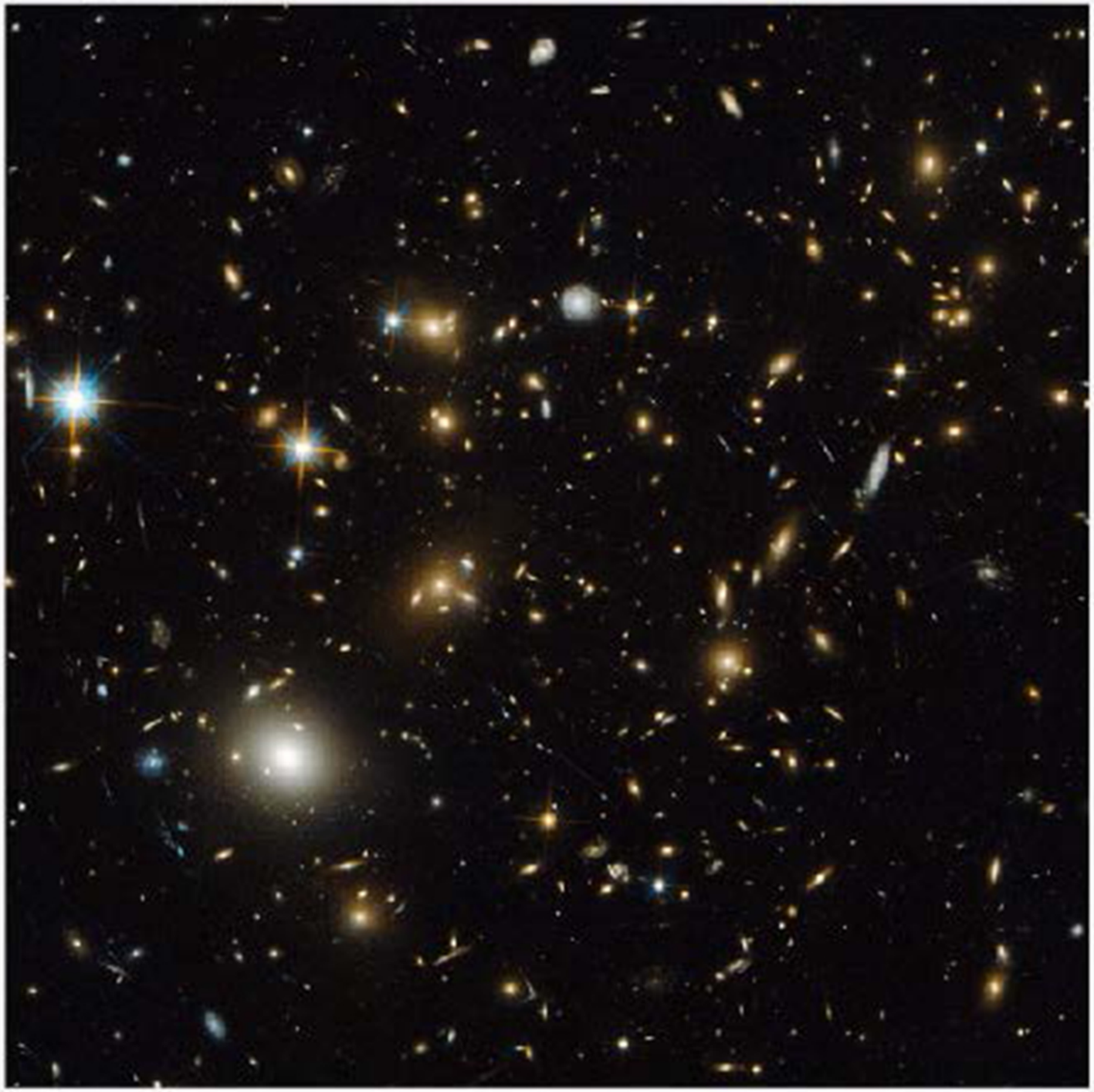
3) Dark Matter



MACS0717 - one of the richest, most massive clusters in the Universe.

Visible light image of HST frontier fields galaxy cluster *MACS0717*

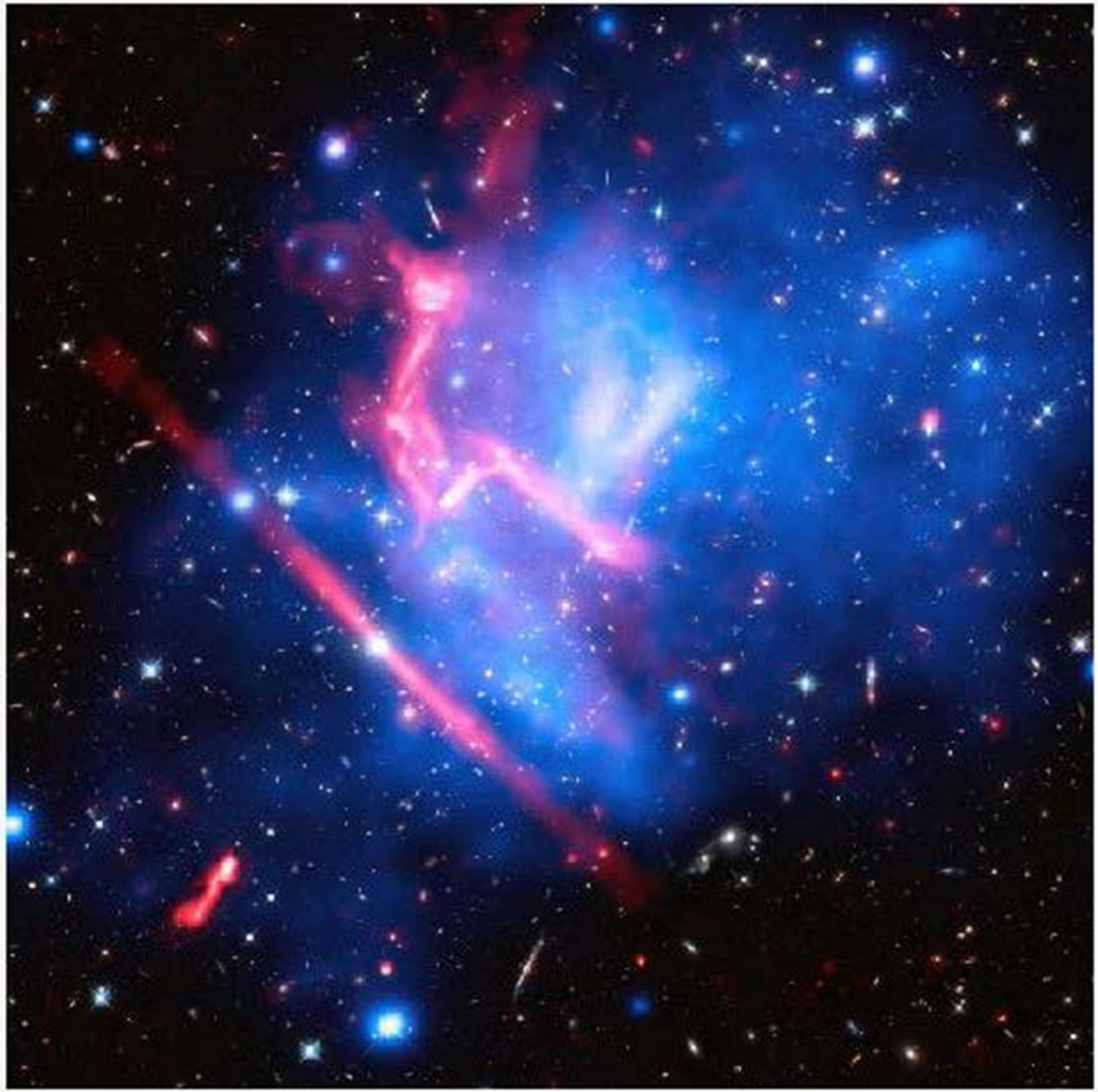
Multi-wavelength observations are critical to understand cluster merging



Multiwavelength view of MACS0717

X-ray (hot gas, blue), radio (red) and visible light of rich cluster of galaxies.

Major merger of smaller clusters of galaxies.



Nobody knows what Dark Matter is.

- "Cold" –it falls into galaxies and into clusters
- Best guess – exotic particles from the very early Universe
  - WIMPS – weakly interacting massive particles
  - Examples - Axions, neutralinos
- Active searches to find this missing component of the Universe

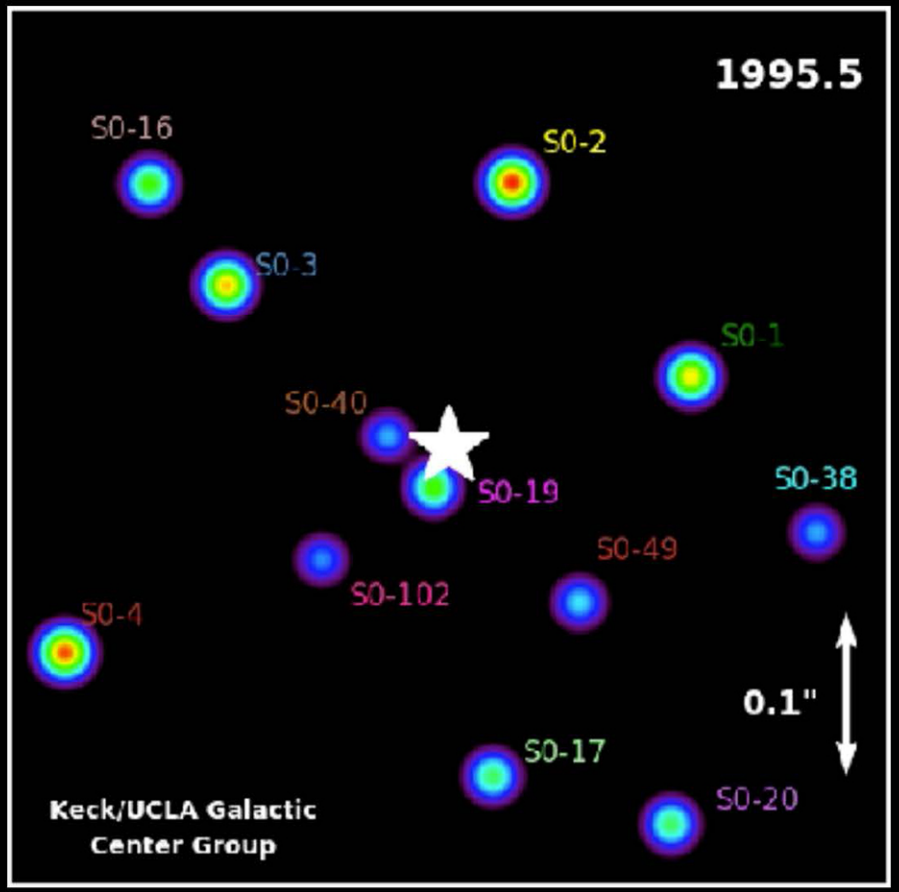
Supermassive black holes lie at the centers of galaxies

100 Thousand ly (10^5)

The more massive the dark matter halo, the more massive the black hole

Our Milky Way is a spiral galaxy with a relatively small central bulge, and a relatively small black hole ($4 \times 10^6 M_{sun}$)

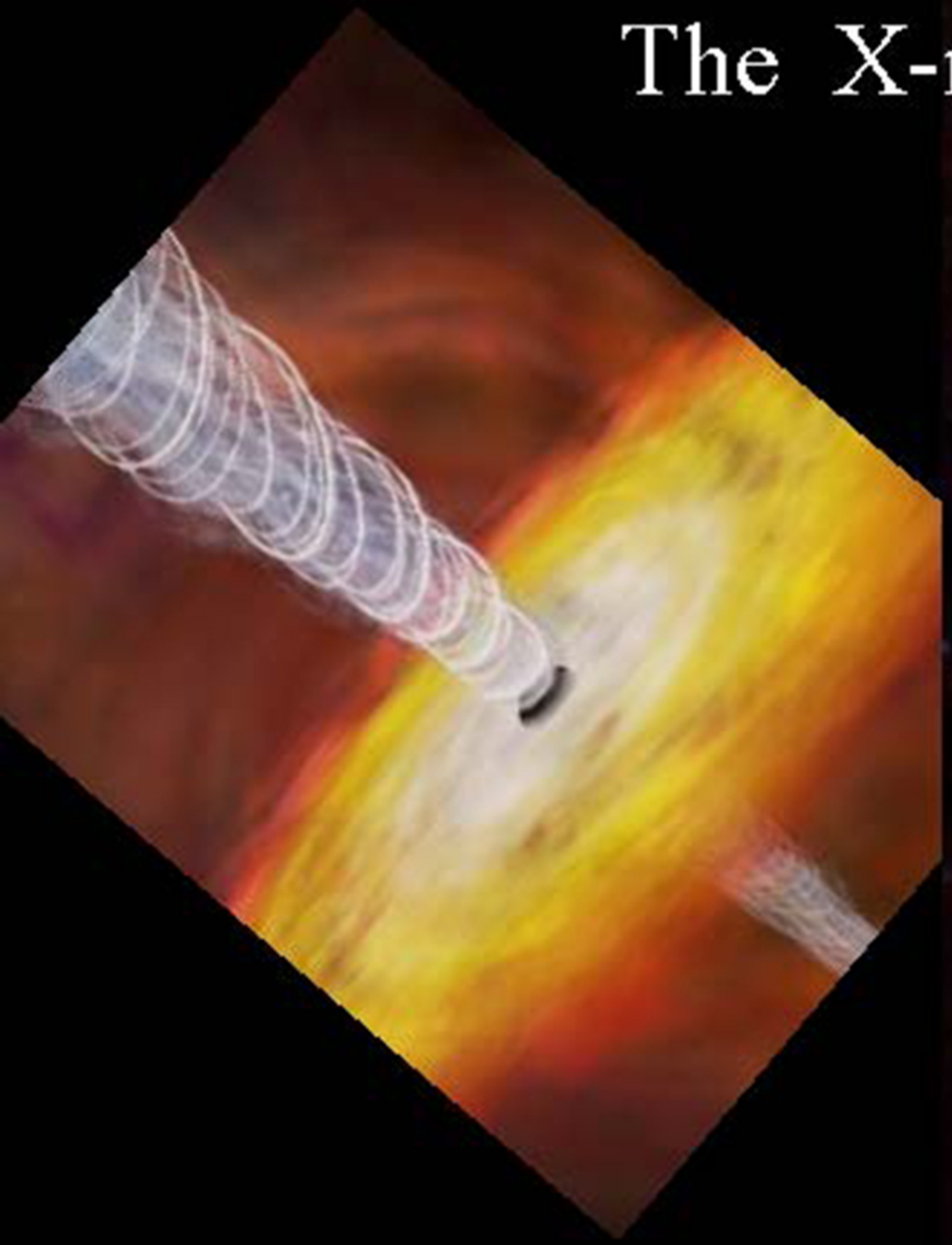
Motions of stars around the Black Hole in our Galactic Center (Ghez+ 2008)



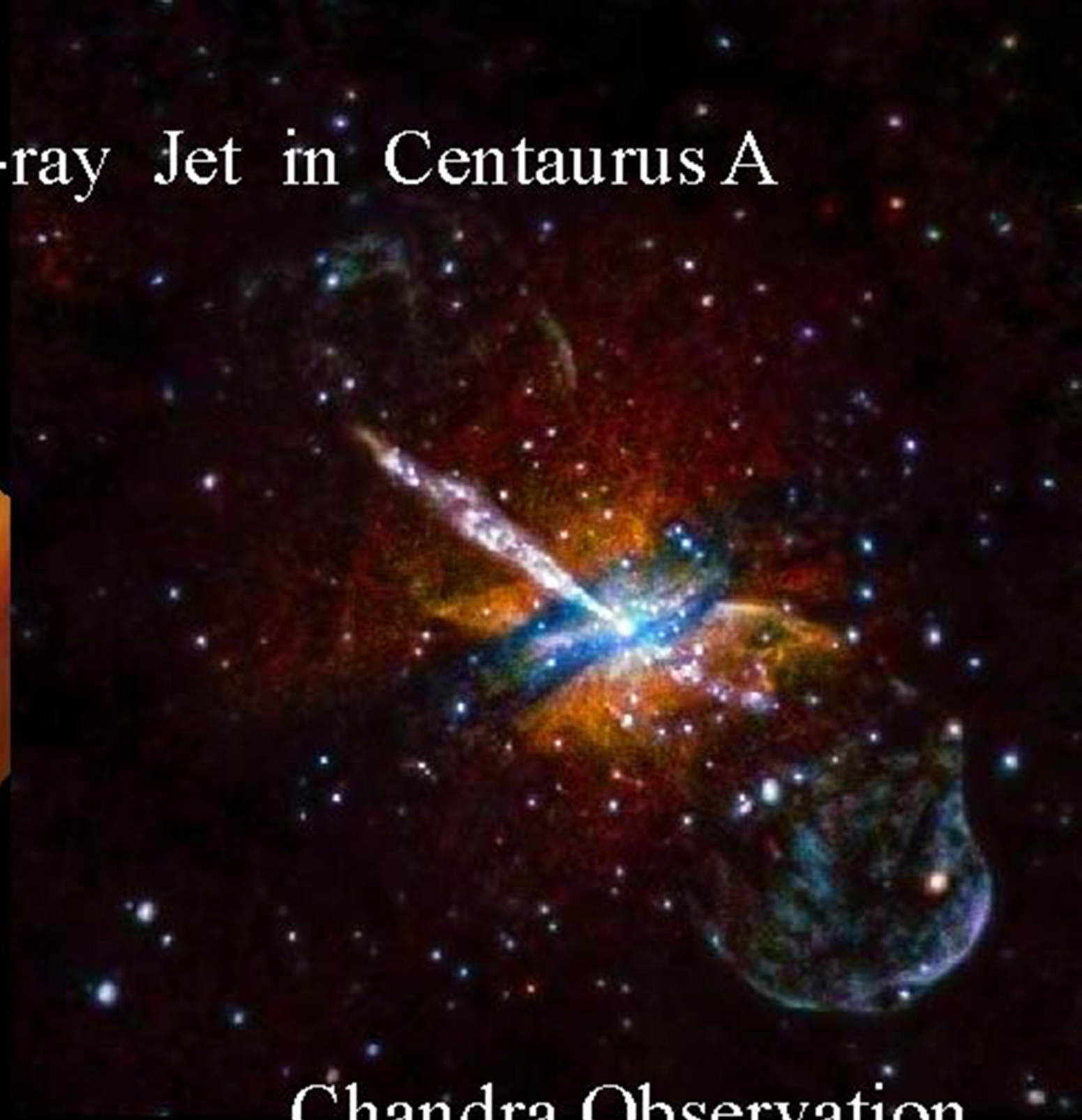
Centaurus A – the Nearest Radio Galaxy

Merger with gas rich galaxy

The X-ray Jet in Centaurus A

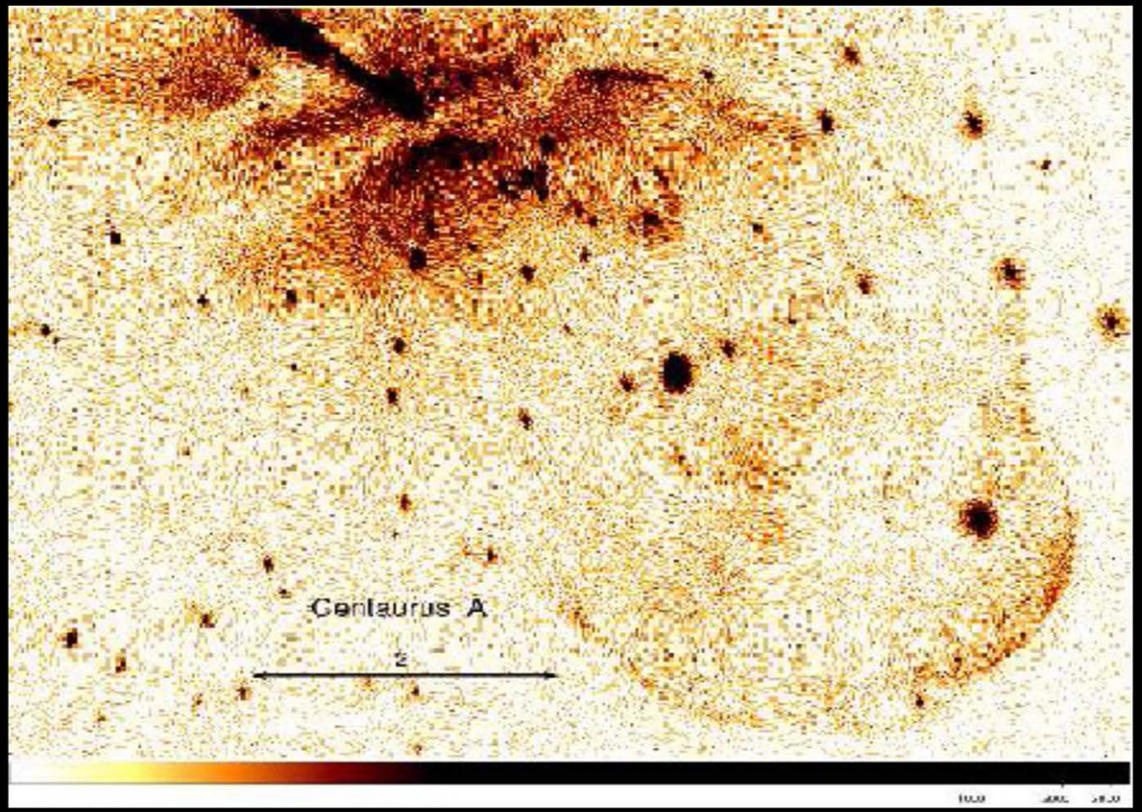


Simulation



Chandra Observation

Centaurus A in X-rays – Bubbles and Jets

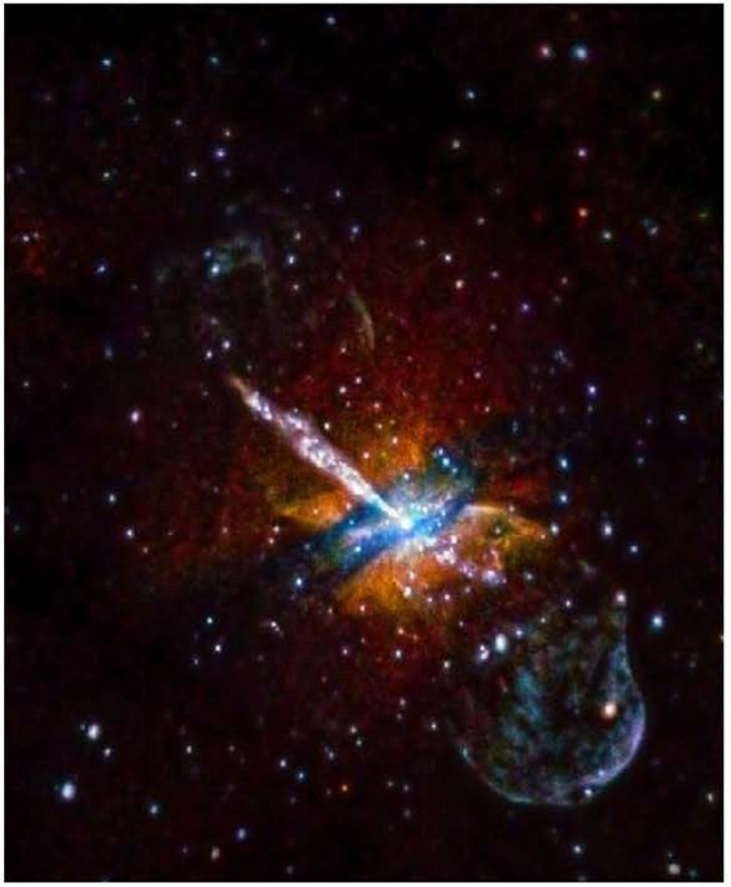


Bubble diameter 3 kpc

- Counter-jet
- Southern lobe - sharp, smooth

Centaurus A

Visible light



Chandra X-ray

Visible + VLA Radio

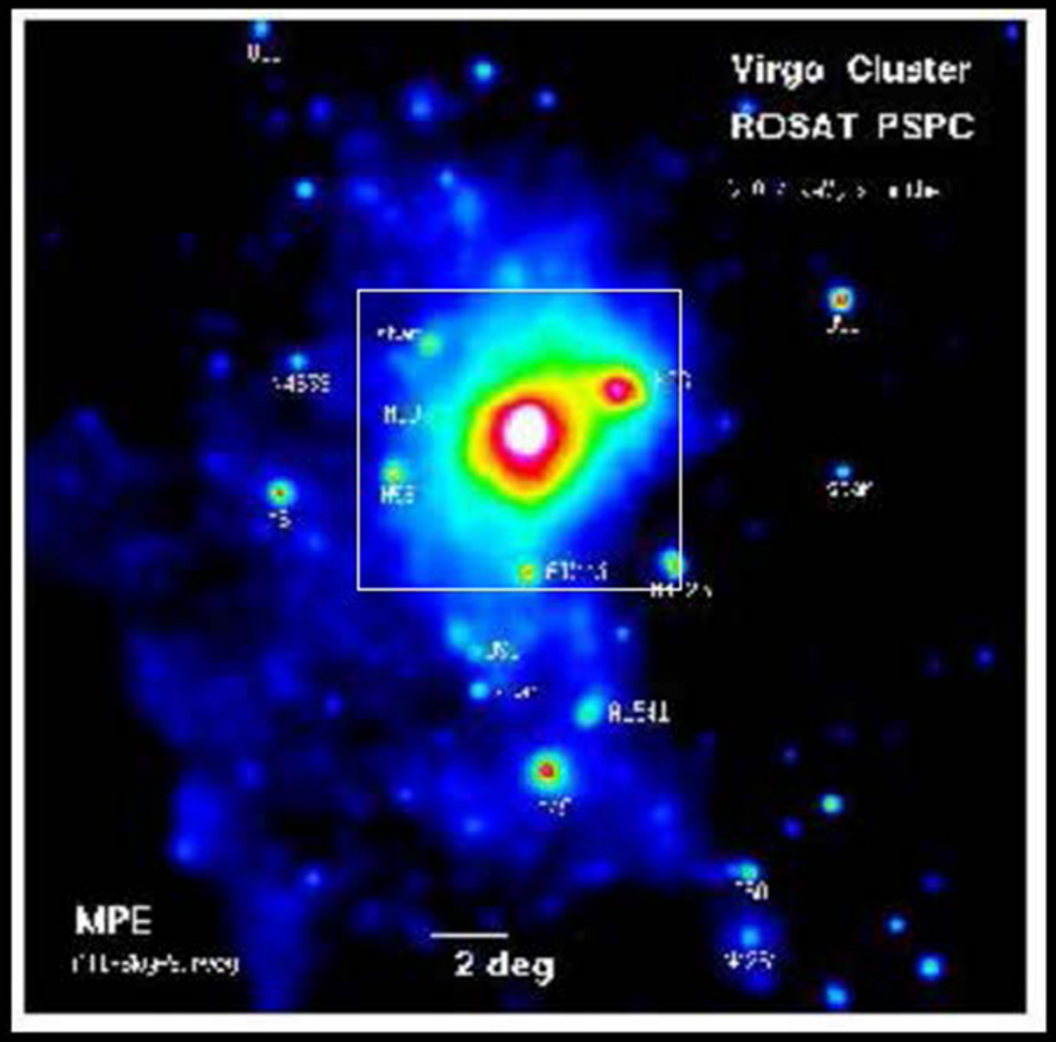
"Bubbles" are not empty,

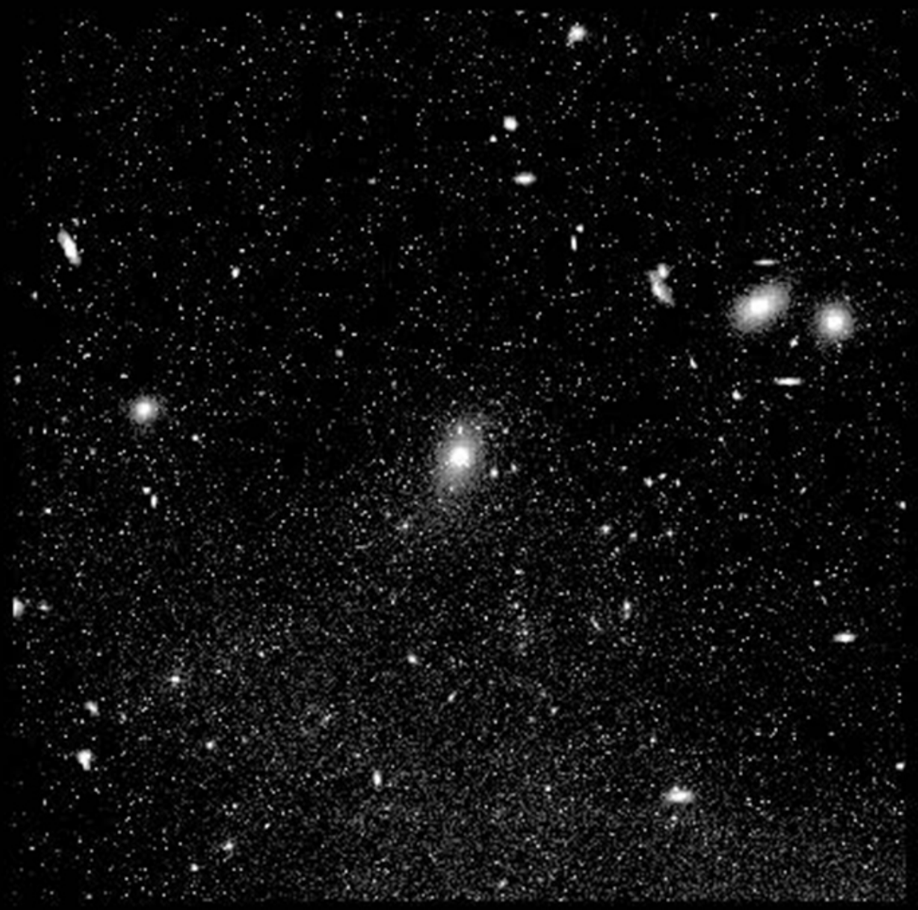
but are filled with energetic particles and magnetic fields

Clusters of Galaxies - Virgo Cluster - Optical

Central galaxy (M87) in Virgo cluster

Virgo Cluster - X-ray/Optical

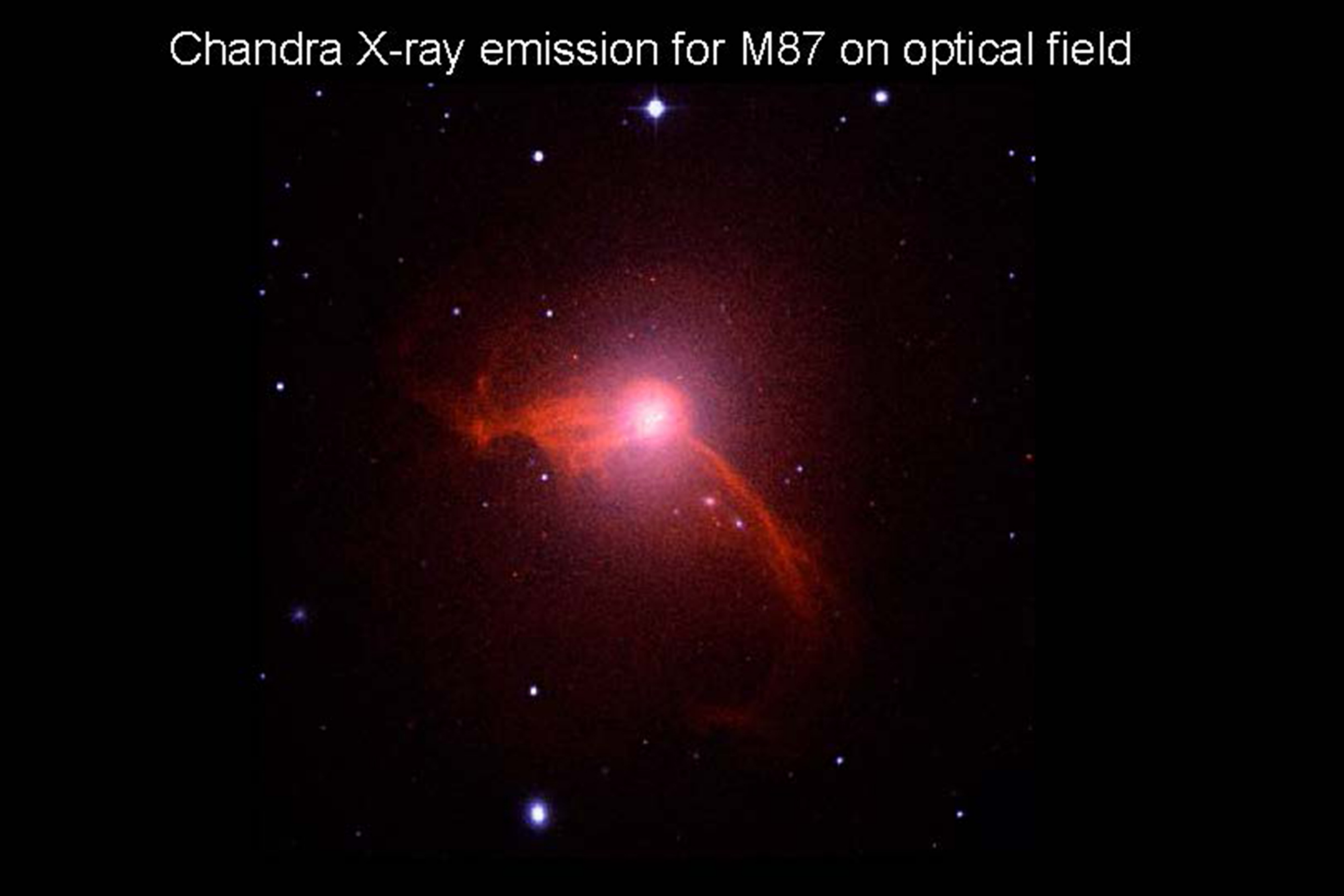




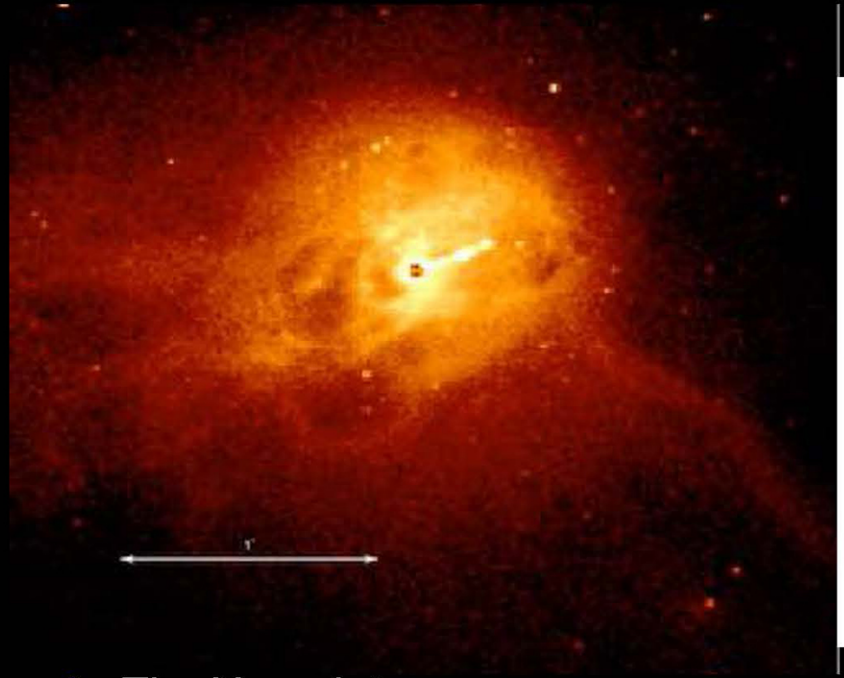
Central galaxy (M87) in Virgo cluster
Distance = 16 Mpc

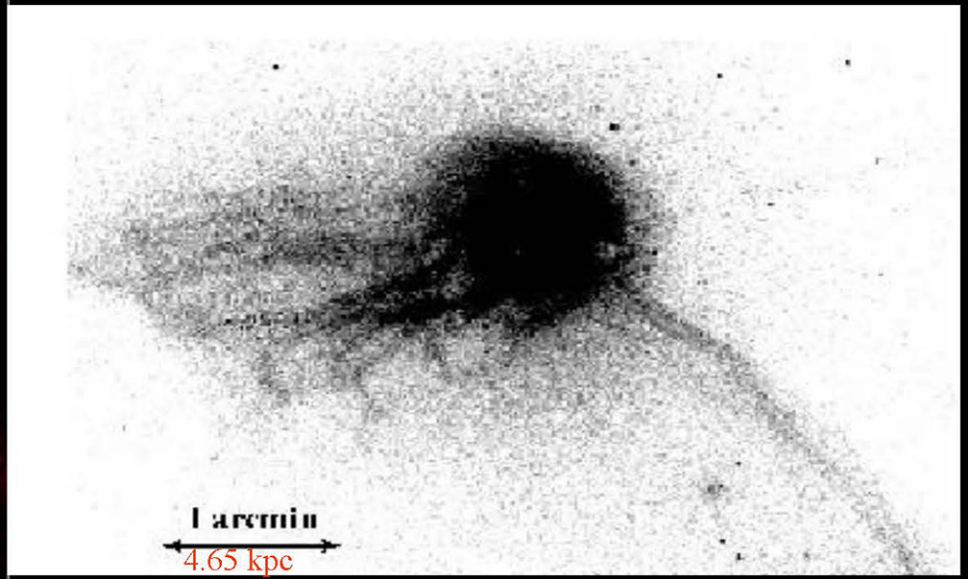
- Extensive gaseous atmosphere
- $6 \times 10^9 M_{sun}$ supermassive black hole in M87
- Ideal system to study SMBH/gas interaction

Chandra X-ray emission for M87 on optical field



X-ray Features in the Central Region of M87





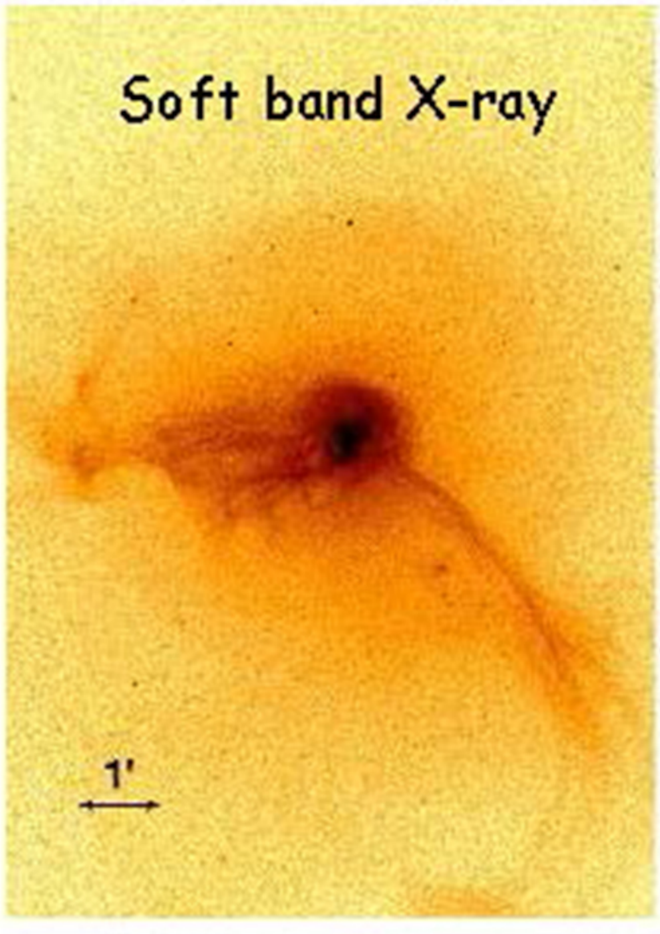
- The X-ray jet
- X-ray cavities surrounding the jet and the (unseen) counterjet
- X-ray cavity associated with the ‘budding’ bubble to the S/SW
- Cavities/bubbles in the eastern arm

Chandra view of M87

"Raw" images

Just select different energy bands

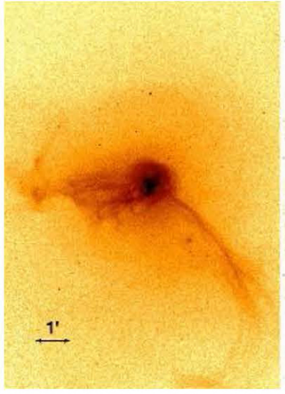
See the over-pressurized regions = shocks



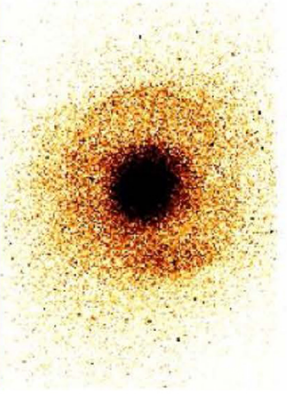
Matched scales

The M87 galaxy - Latest News!

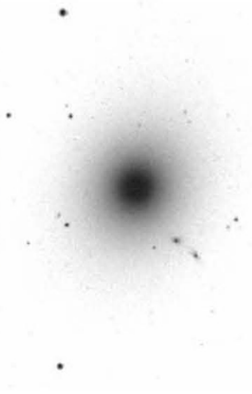
Only resolved black hole image by Event Horizon Telescope (asymmetry from rapidly rotating plasma and relativistic beaming.



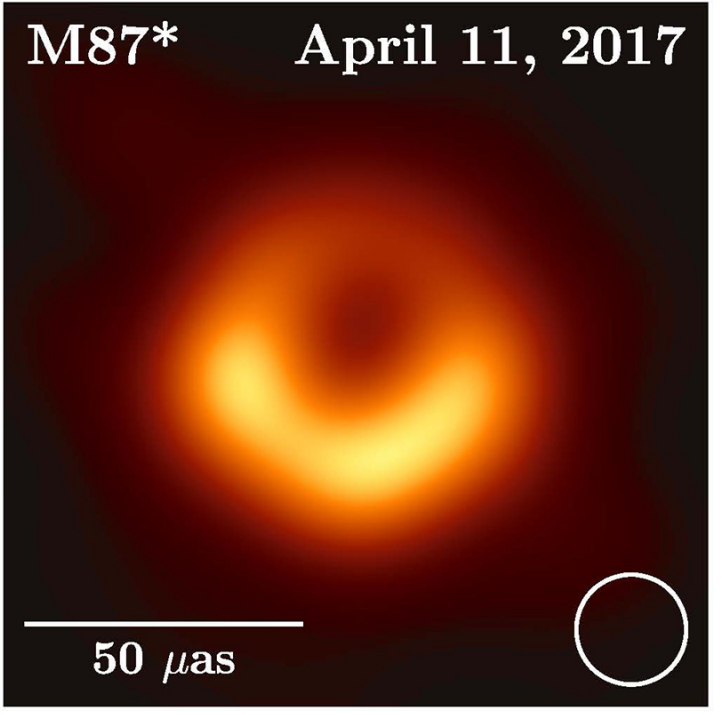
X-ray (soft)



Xray (hard)

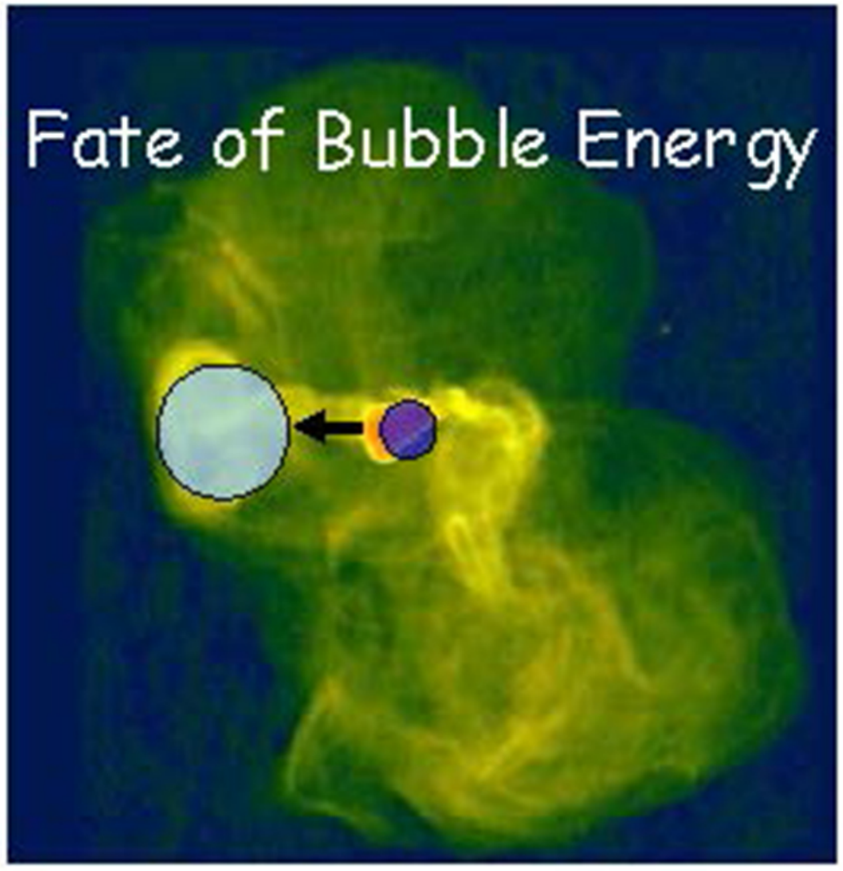


Optical



ISCO - innermost stable circular obit

EHT Paper 1; fig. 3. 2019 ApJ L 875, 1



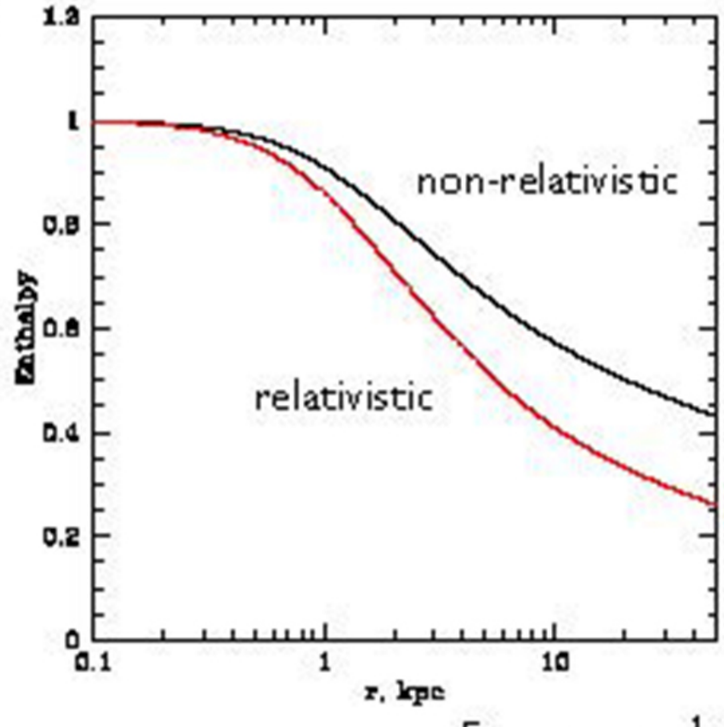
Rising bubble loses energy to surrounding gas

$$f = (p_1 / p_0)^{(\gamma-1)/\gamma}$$

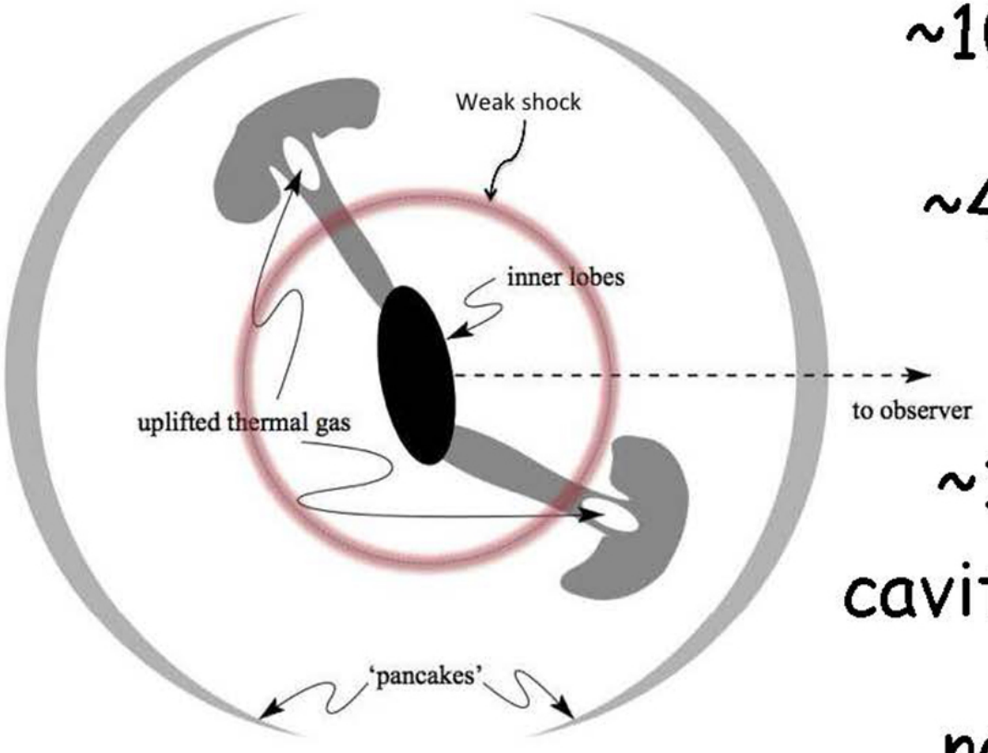
Generates gas motions in wake

Kinetic energy (eventually) converted to thermal energy (via turbulence)

Bubble energy remaining vs. radius



$$\Delta E_{gas} = -\Delta E_{Bubble} = -\Delta \frac{\gamma}{\gamma - 1} PV = E_0 \left[1 - \left(\frac{P}{P_0} \right)^{1-1/\gamma} \right]$$



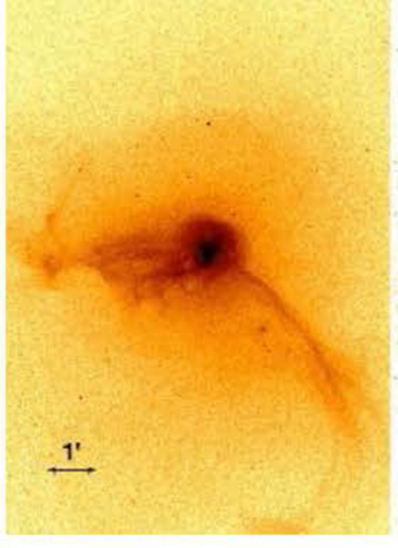
~100 Myr - old (radio) bubbles

~40 Myr - torus & uplifted arms

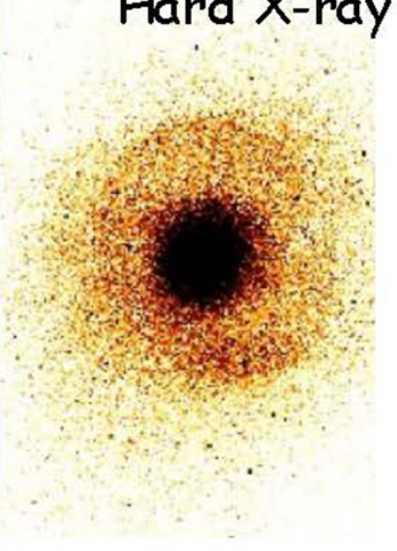
~12 Myr - shock & initial cavity (still surrounds SMBH)

now - re-inflating cavity

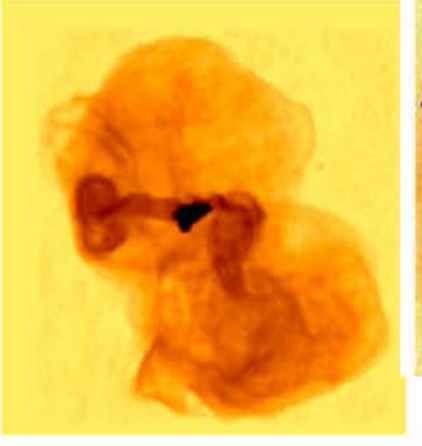
Soft band X-ray

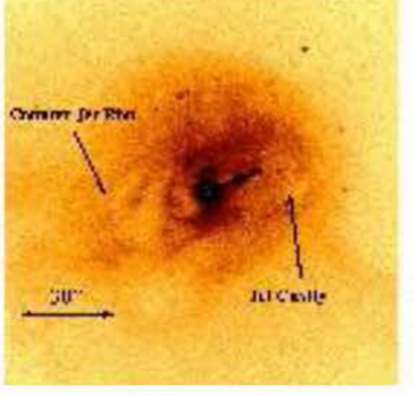


Hard X-ray

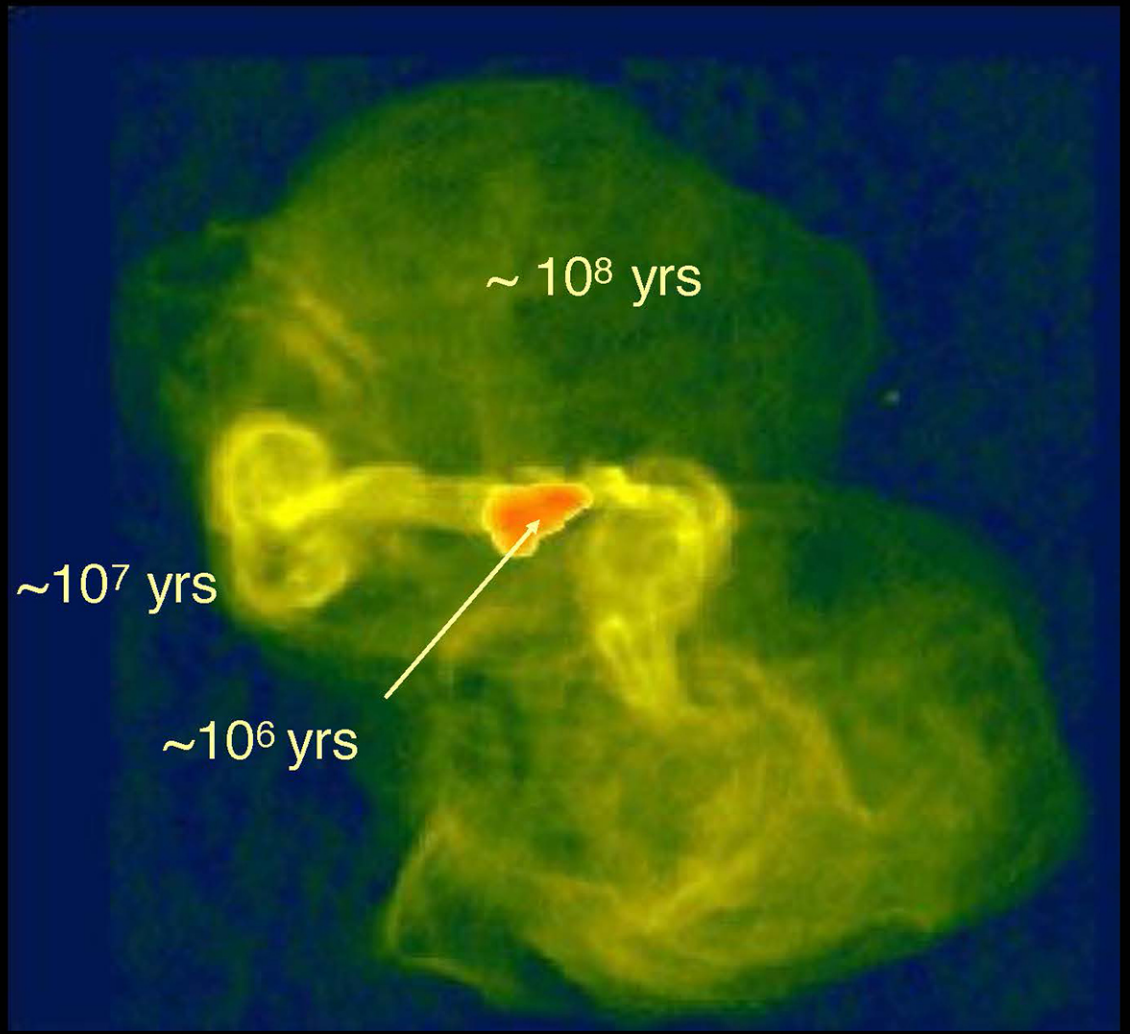


Radio





Repetitive Radio Outbursts in M87



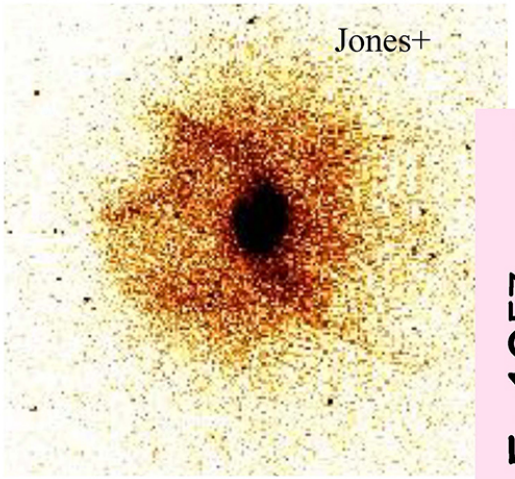
Energy input into the radio halo around M87 on three different time scales

within ~ 40 kpc

total energy ~ 3 10^{59} ergs

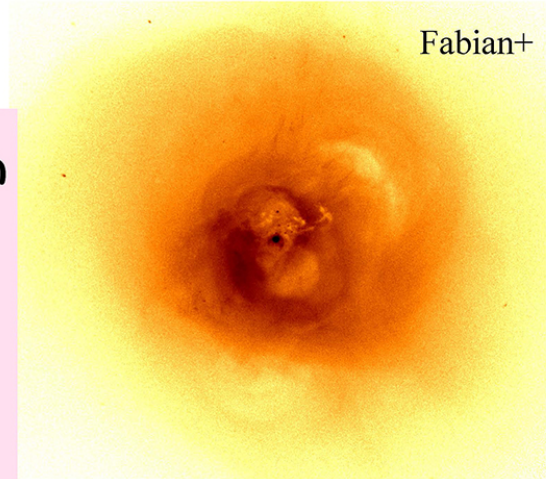
(= Sun's total energy over its lifetime)

Family of early type Galaxies with hot gas
Evidence of Supermassive Black Hole Outbursts in Atmospheres

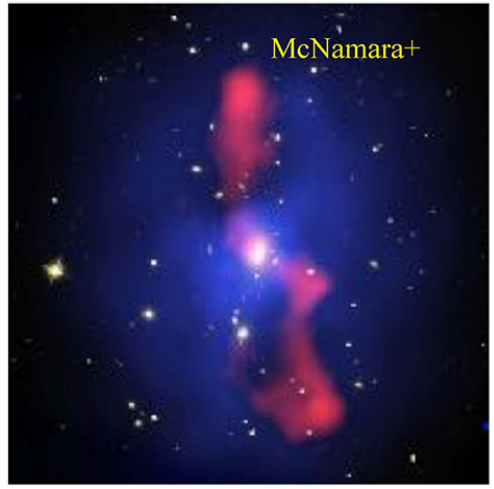


NGC4636 Galaxy
1 kpc
10^{56} ergs
10^{42} erg/s

M87 ~ 5×10^{57} ergs



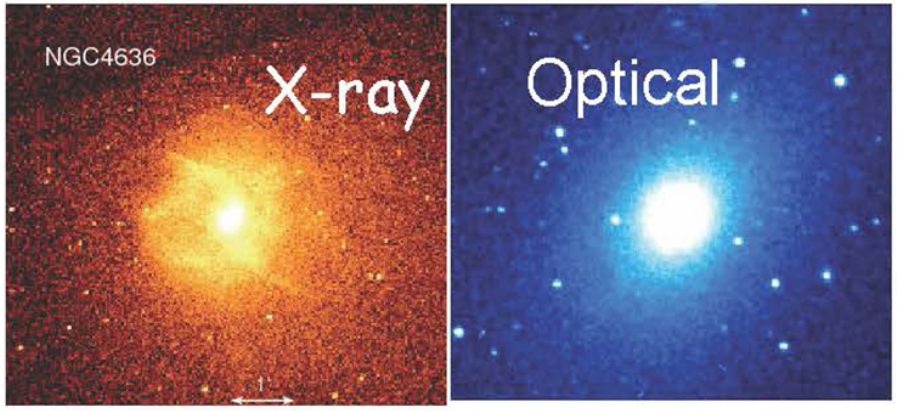
Perseus Cluster
10 kpc
10^{59} ergs
10^{45} erg/s

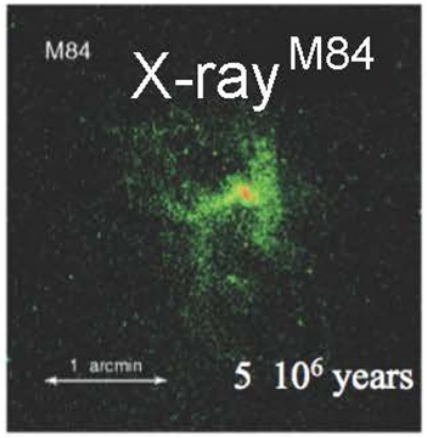


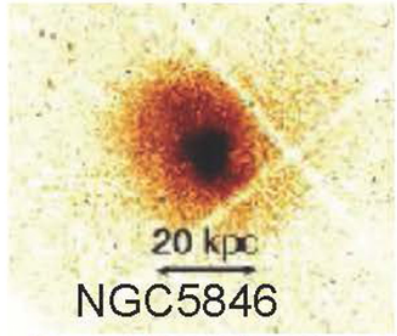
MS0735 Cluster
100 kpc
10^{62} ergs
10^{46} erg/s

Powerful outflows from the SMBH
Little radiation from black hole - not the familiar "AGN"
Span a wide range of dark matter halo mass
Bubbles are very common across the mass range

Gas Rich Early Type Galaxies

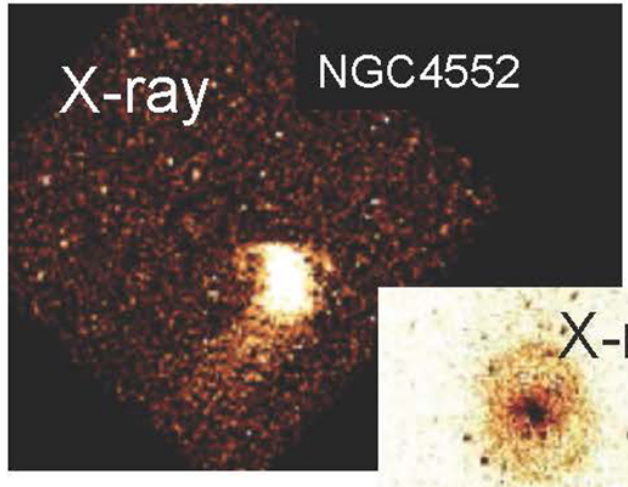


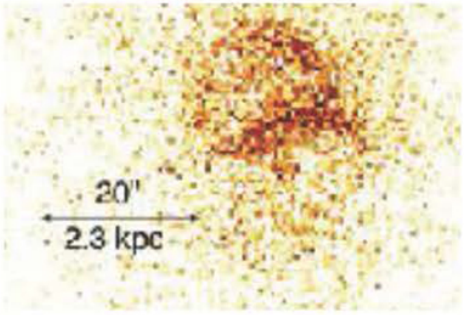


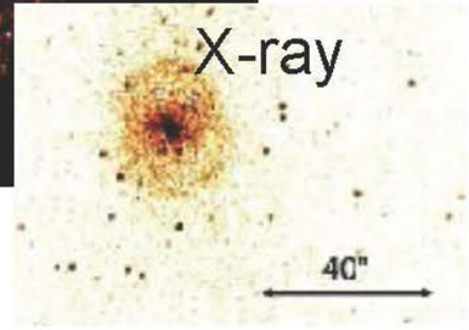


As a class, luminous early type galaxies ($L_K > 10^{11} L_{sun}$) have hot corona

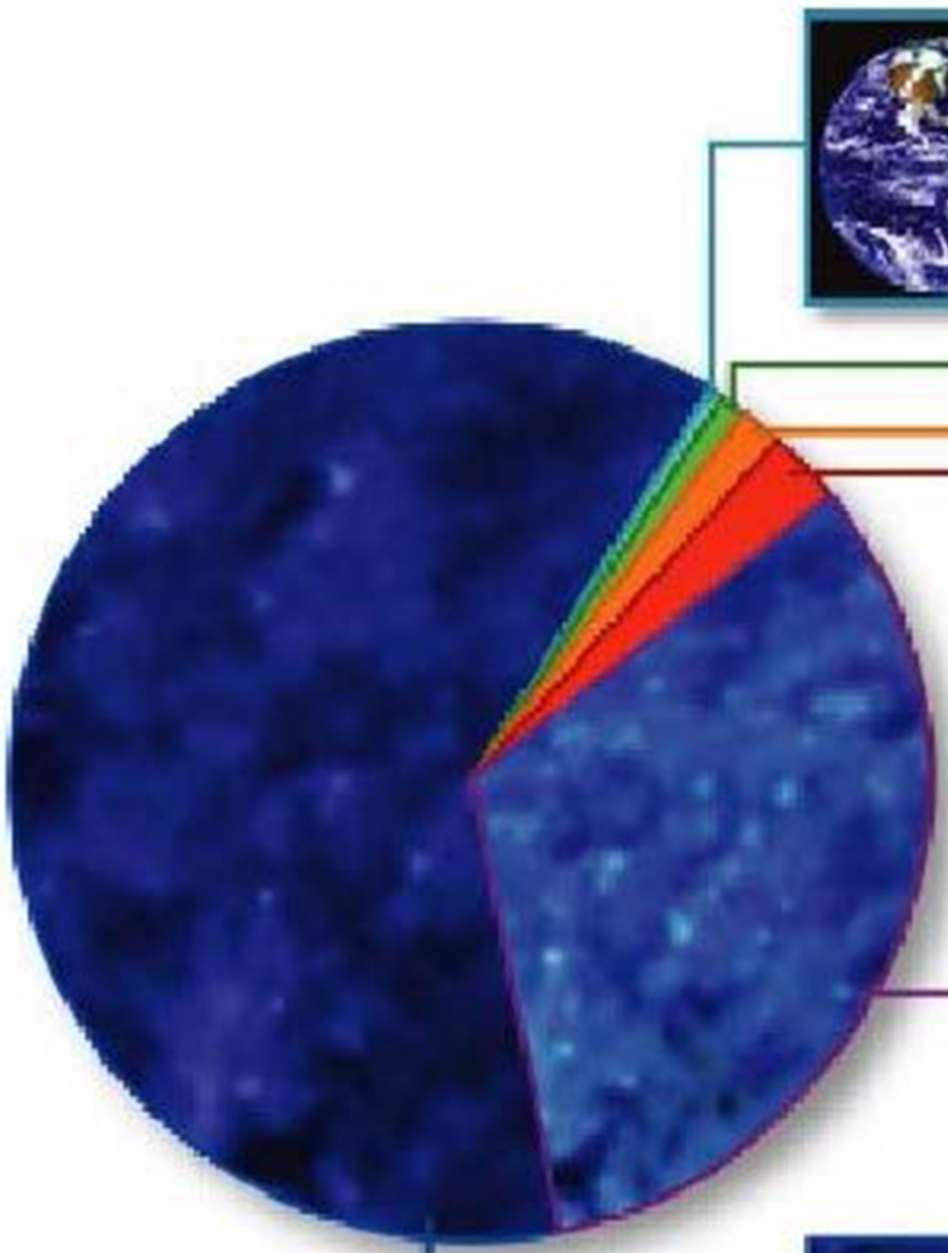
- AGN outbursts, typical
- Massive galaxies do NOT have "dry" mergers
- Complementary view from optical







Dark Energy – Most of the mass-energy in the Universe

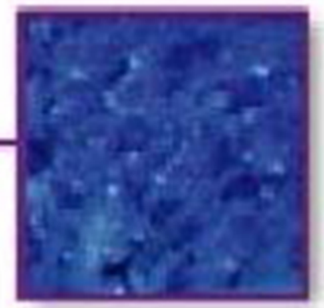


Heavy Elements:
0.03%

Ghostly Neutrinos:
0.3%

Stars:
0.5%

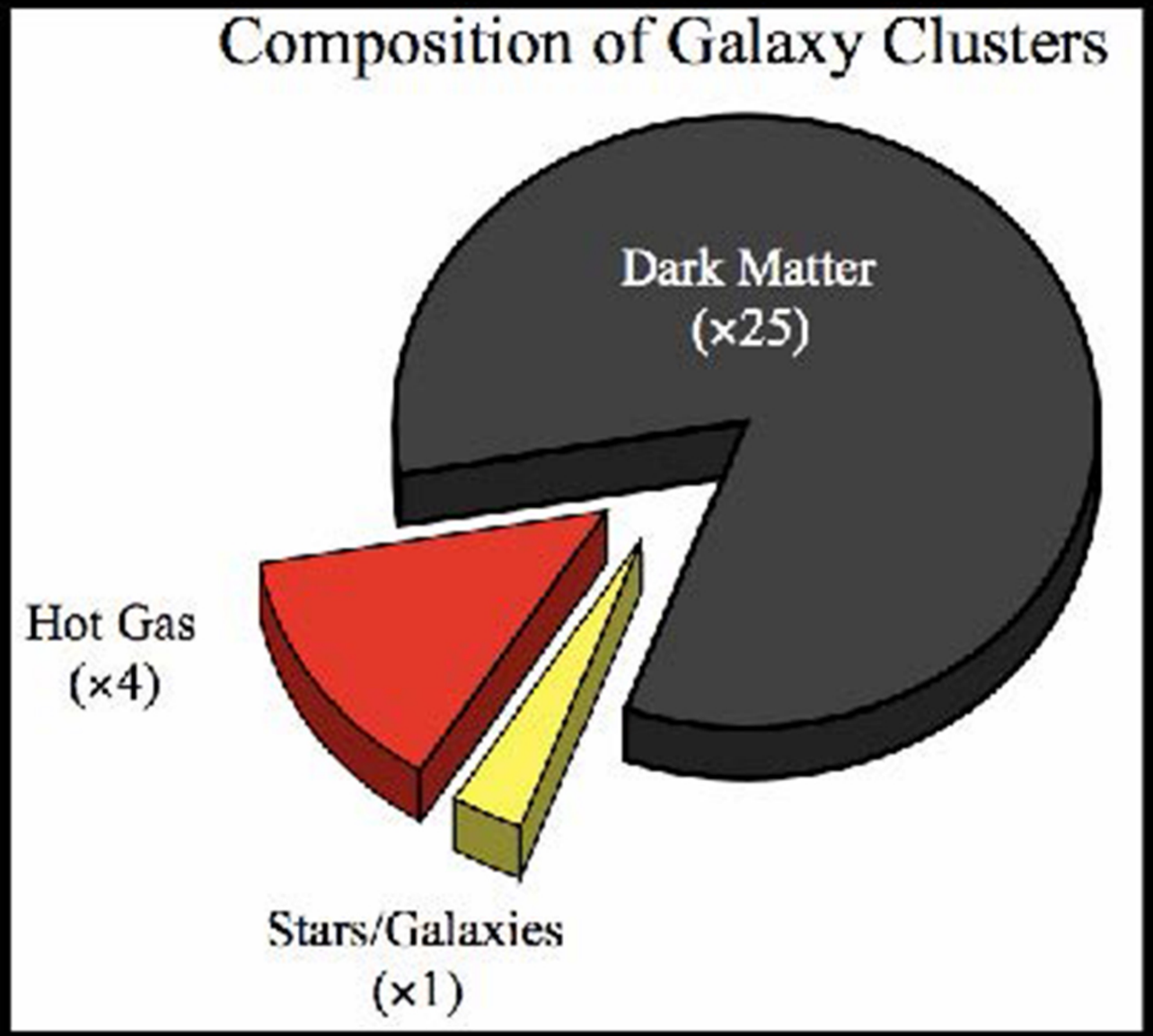
Free Hydrogen
and Helium:
4%

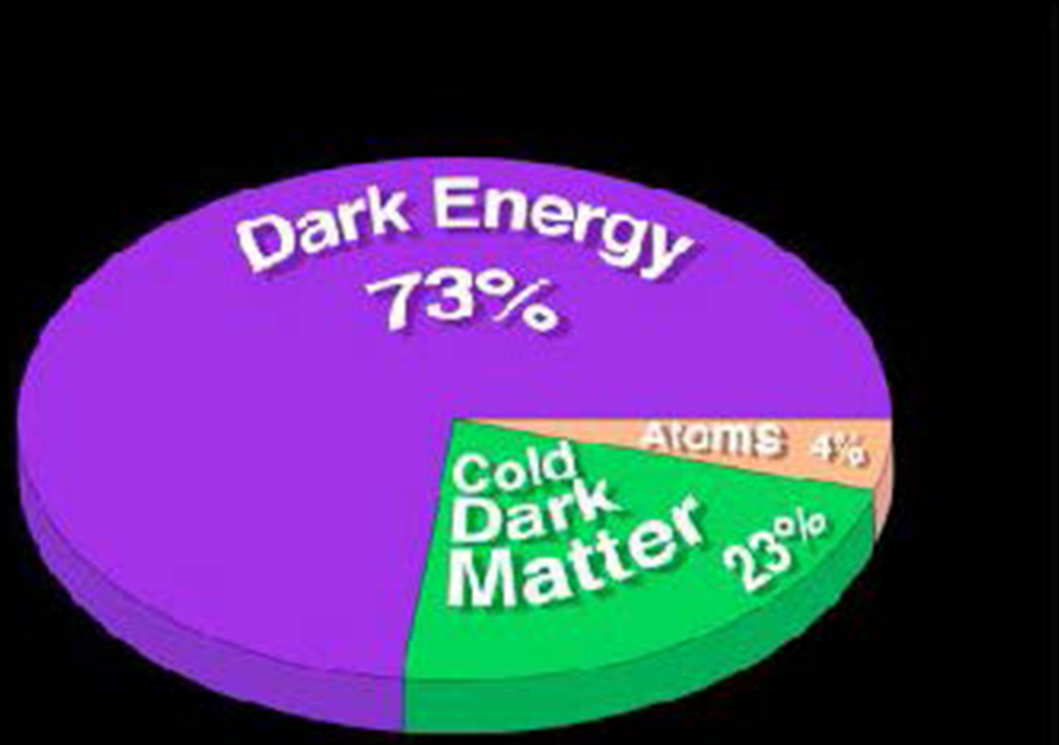


Dark Matter:
25%

Dark Energy:
70%

Dark Matter and Dark Energy

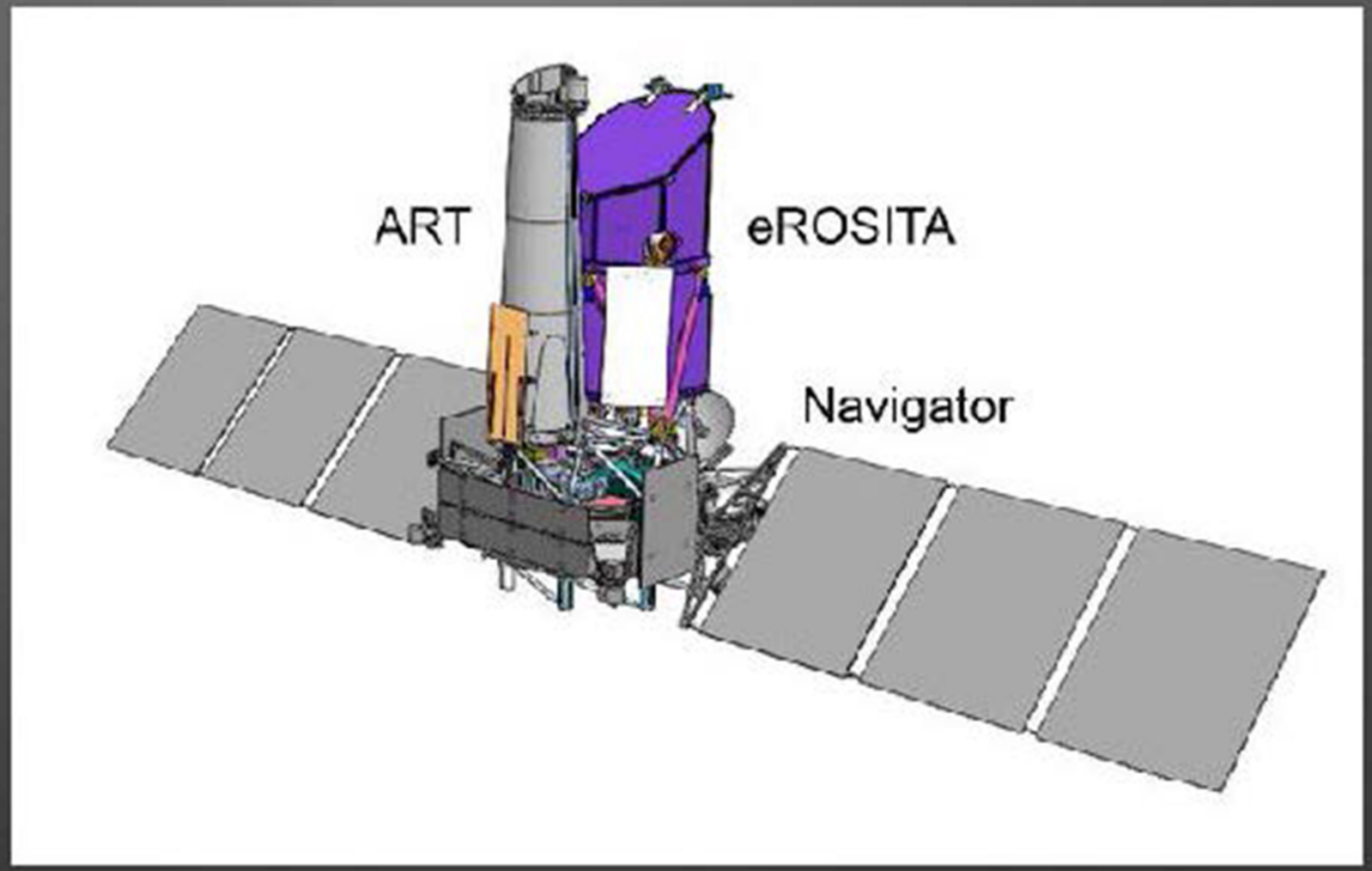




Spectrum-Roentgen-Gamma (eRosita)

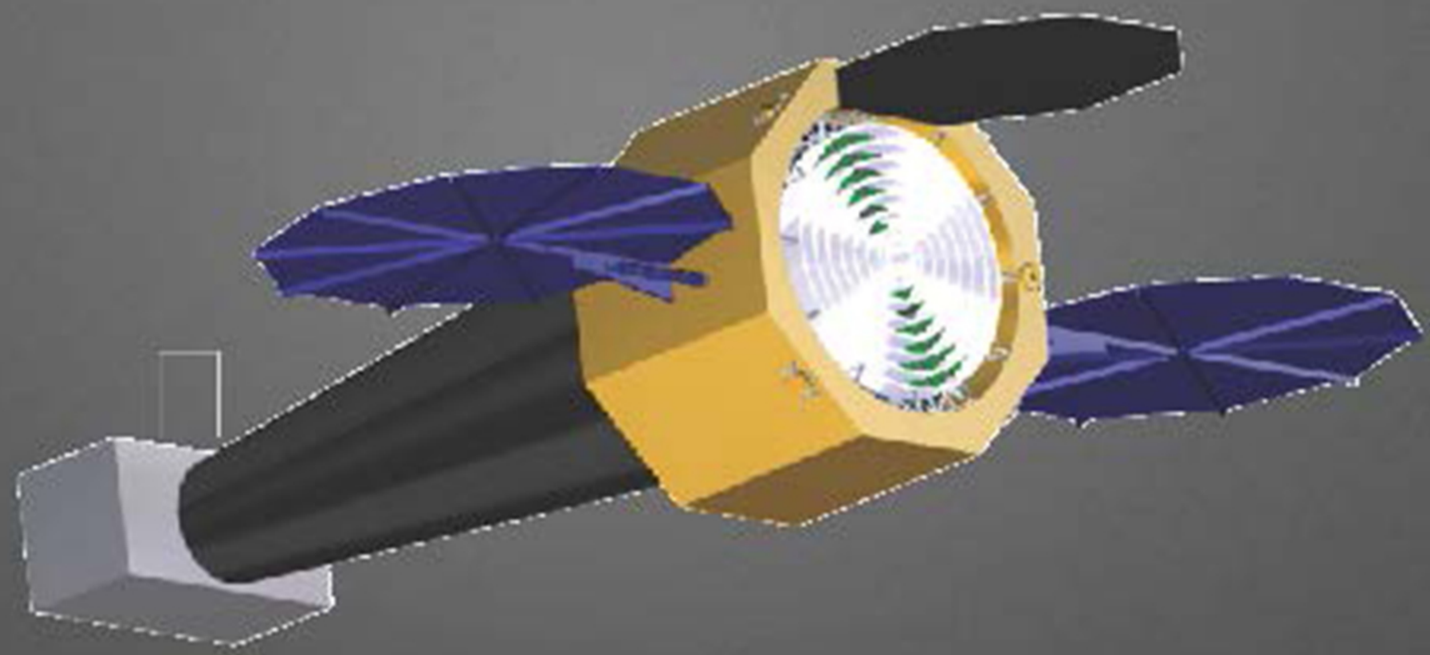
Launch 2019

All Sky Survey



Athena X-ray mission - launch 2028

Lynx mission concept in a nutshell



- Ambitious concept for X-ray optics. Mirrors work at grazing incidence, and are tightly packed into a **~3m diameter** envelope. New technologies are needed for manufacturing such a mirror.
- We currently aim at **~ 0.5″ angular resolution** (half-power diameter), detailed trades are pending
- **Focal length ~10m**, providing 0.2-10 keV energy band
- **A suite of 3 advanced science instruments, with requirements TBD. Instrument Working Group is in place**
  - X-ray microcalorimeter array with ~1″ pixels
  - High-definition X-ray images (Si-based active pixels array)
  - X-ray gratings with high efficiency and spectral resolving power >~ 5000

If I had been present at the creation, I would have given some hints for the better arrangement of the Universe.

Alfonso the Wise - king of Castile and León (1252-1284),

patron of the arts and learning

The most incomprehensible thing about the world is that it is comprehensible.

Albert Einstein

THANKS !