Black Holes, Exploding Stars, and Clusters of Galaxies: 20 Years with NASA's Chandra X-ray Observatory

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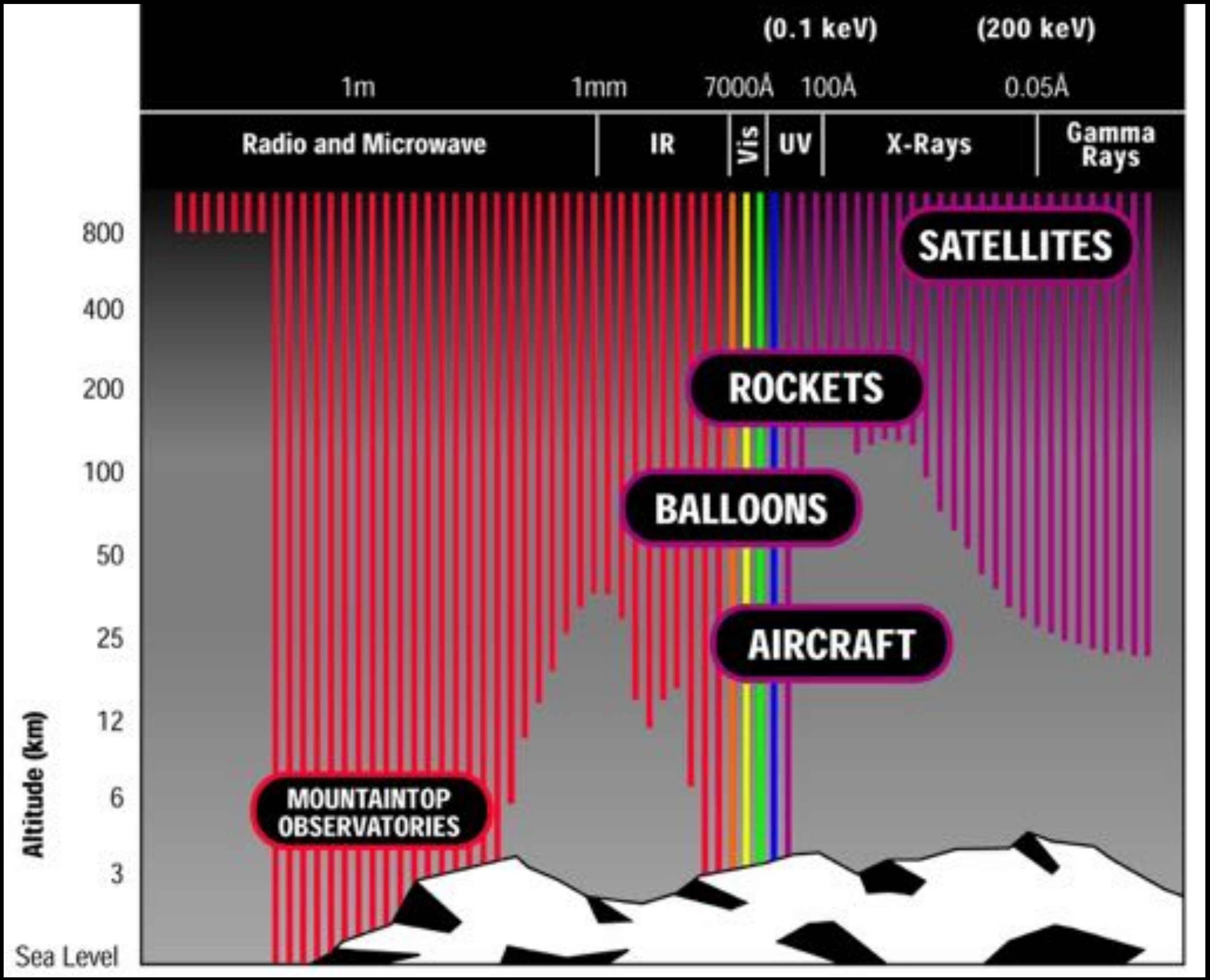
X-ray Astronomy and the Space Age

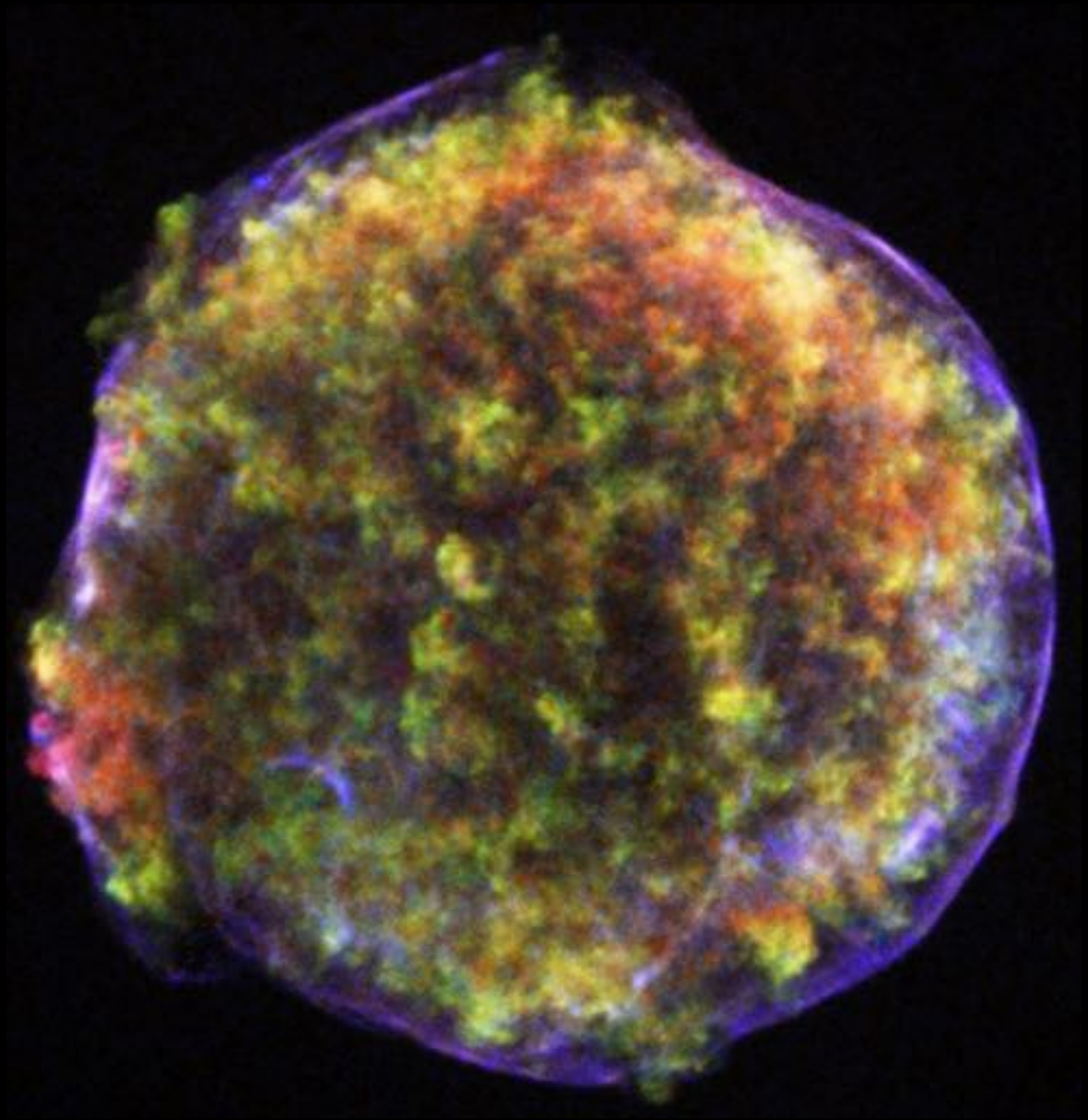


- 1942: Rocket detection of X-rays from the Sun
- 1962: First extrasolar X-ray source detected, Sco X-1
- 1970: Uhuru launches.
- 1978: Einstein launches.

Why X-rays?

X-rays come from the hottest, most "extreme" places in the Universe

- Black holes, neutron stars
- Stars being born, dying
- Massive clusters of galaxies



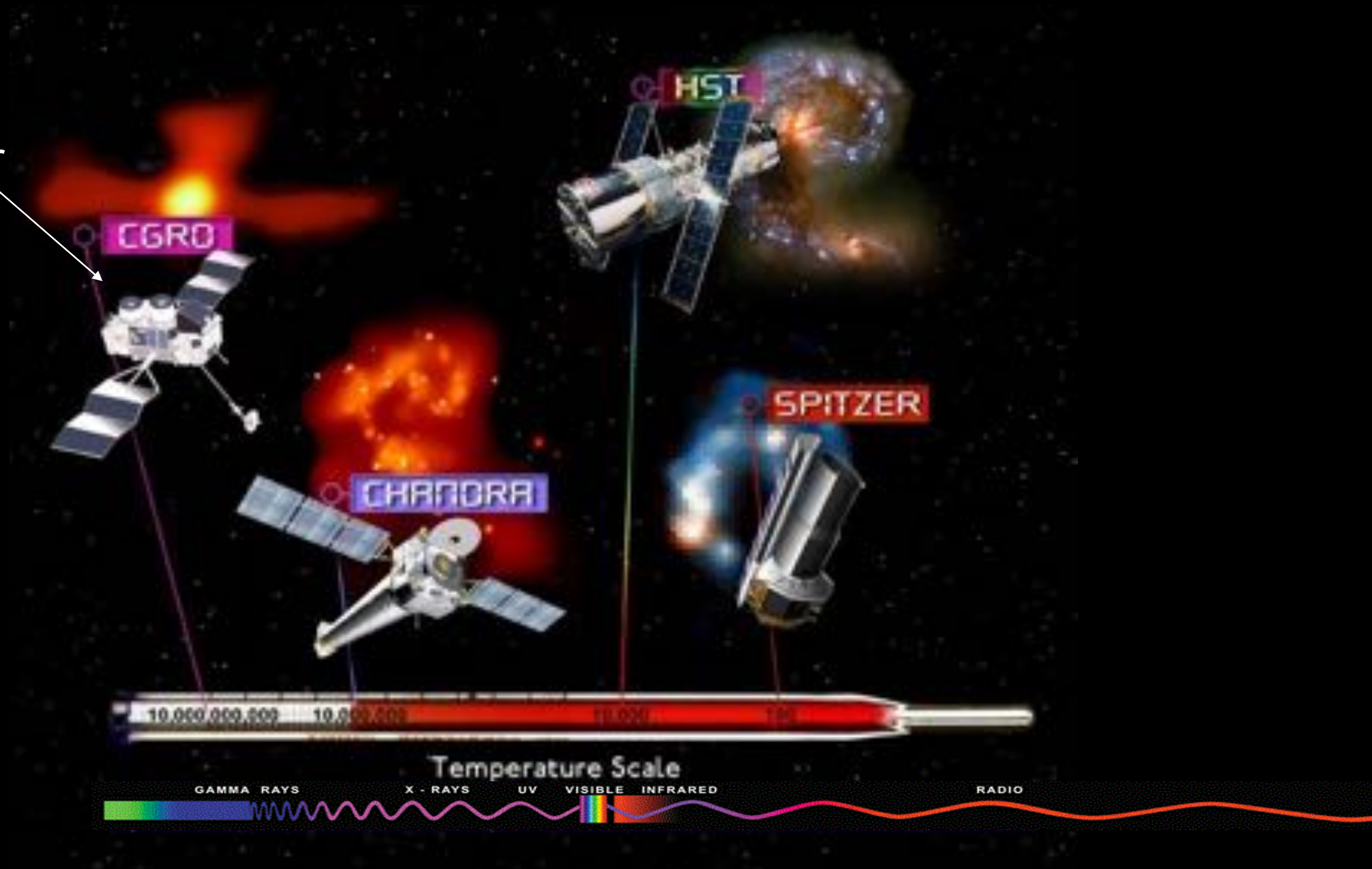
Tycho Supernova Remnant

NASA's Great Observatories

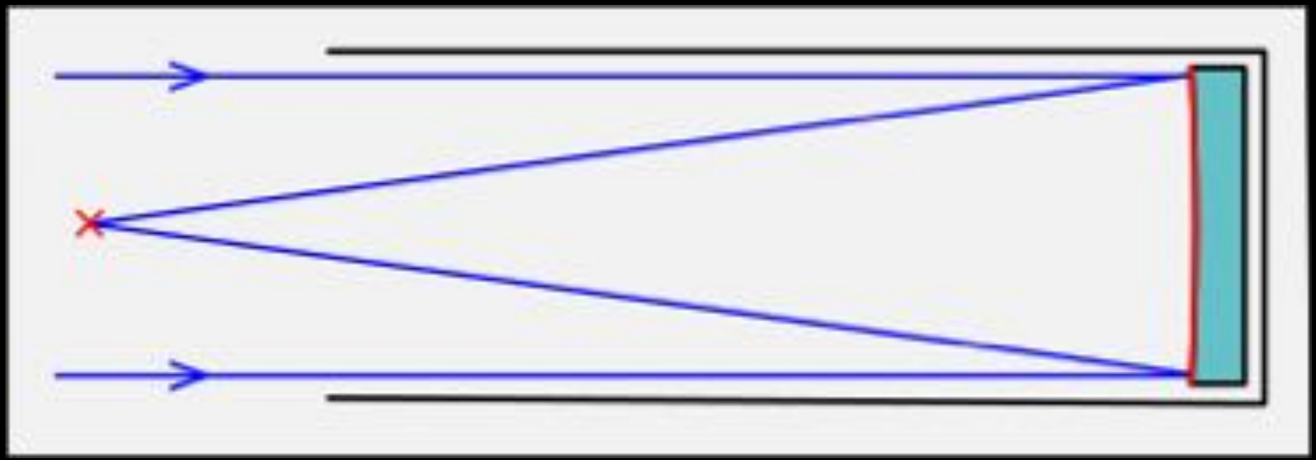
across the Electromagnetic Spectrum

No longer operating

2008: Fermi Gamma Ray Telescope

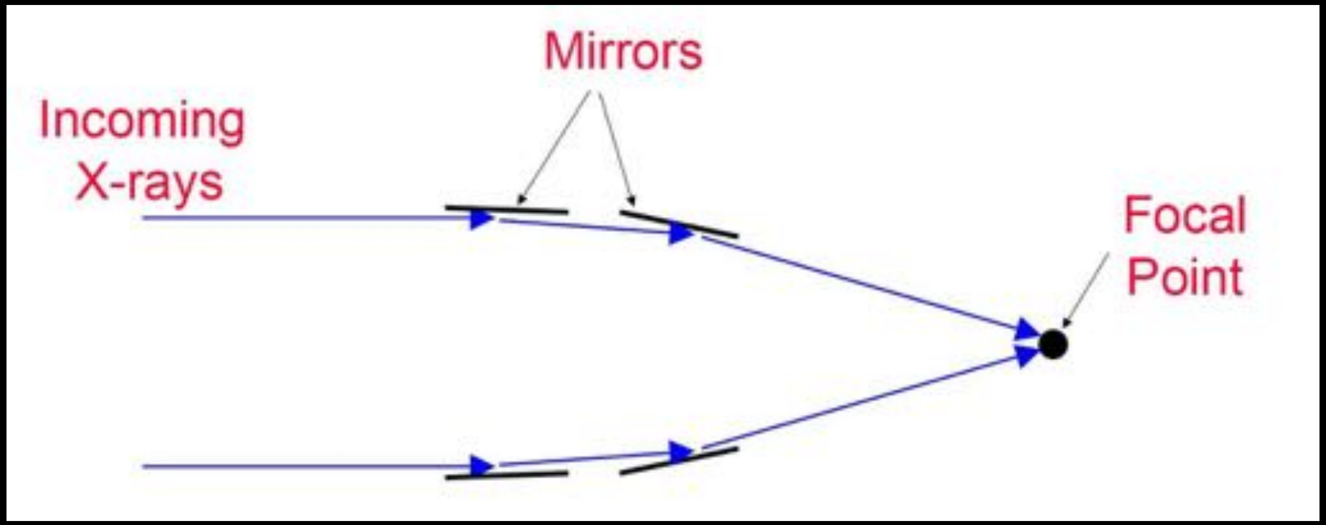


How does it work?



Visible light mirror

Normal Reflection

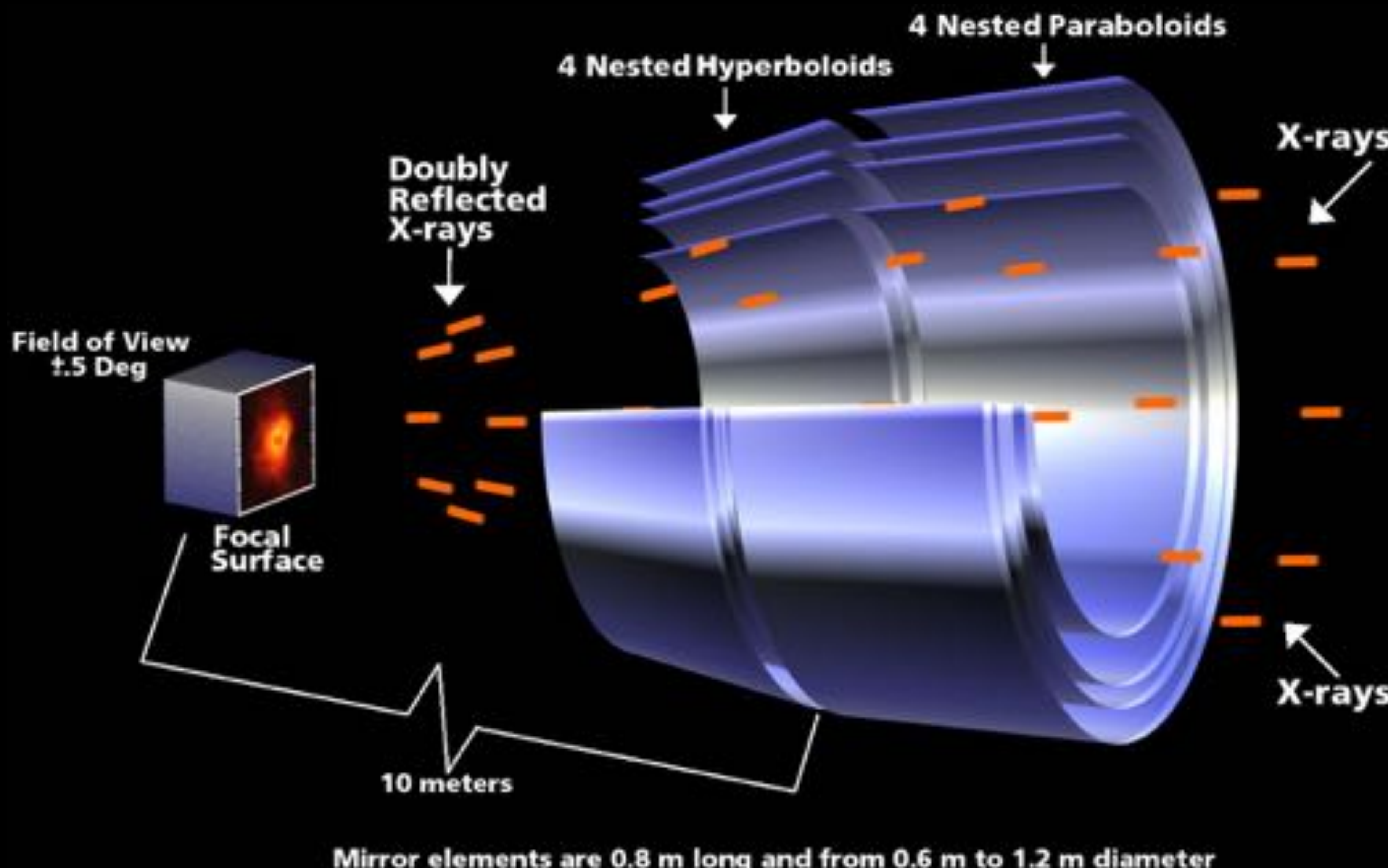


X-ray light mirrors

Grazing Incidence Reflection

Detects X-rays, does not transmit X-rays!

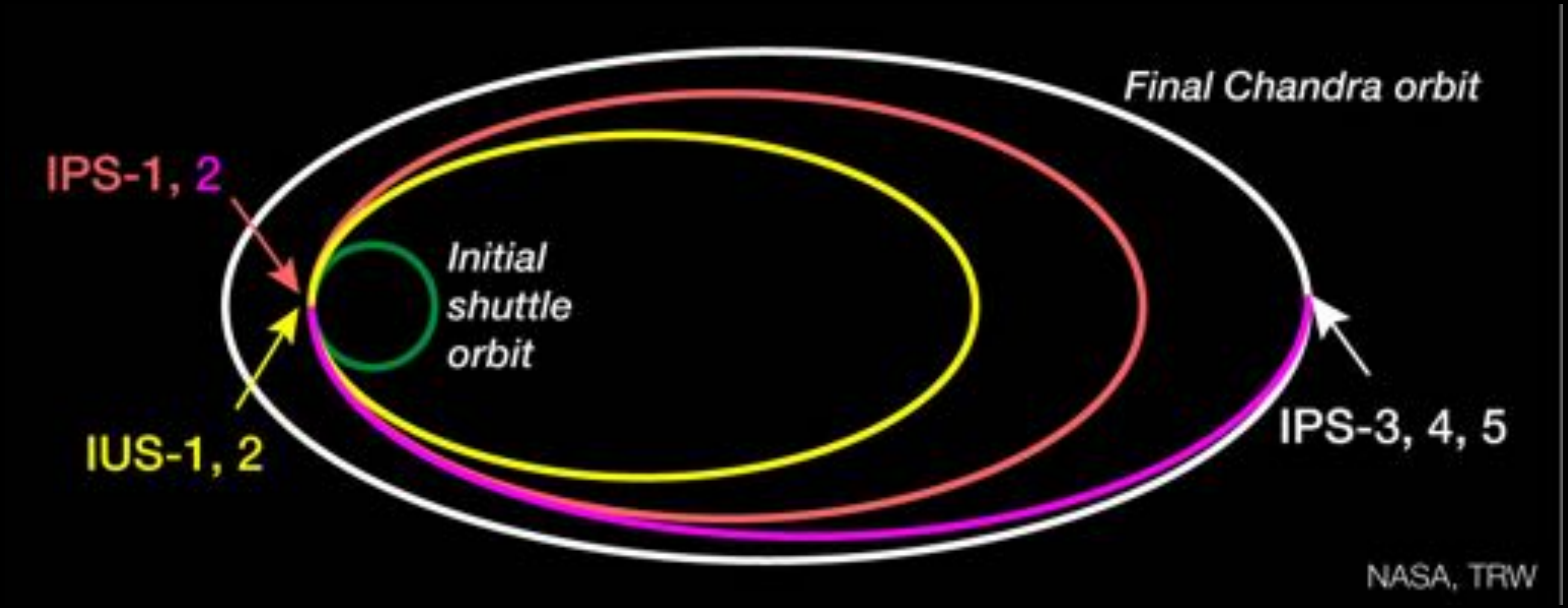
How does it work?



- Mirrors must be smooth down to the thickness of a few atoms, like smoothing the Earth so the tallest mountain is 78 inches tall!
- Chandra has the smoothest and cleanest mirrors ever made.

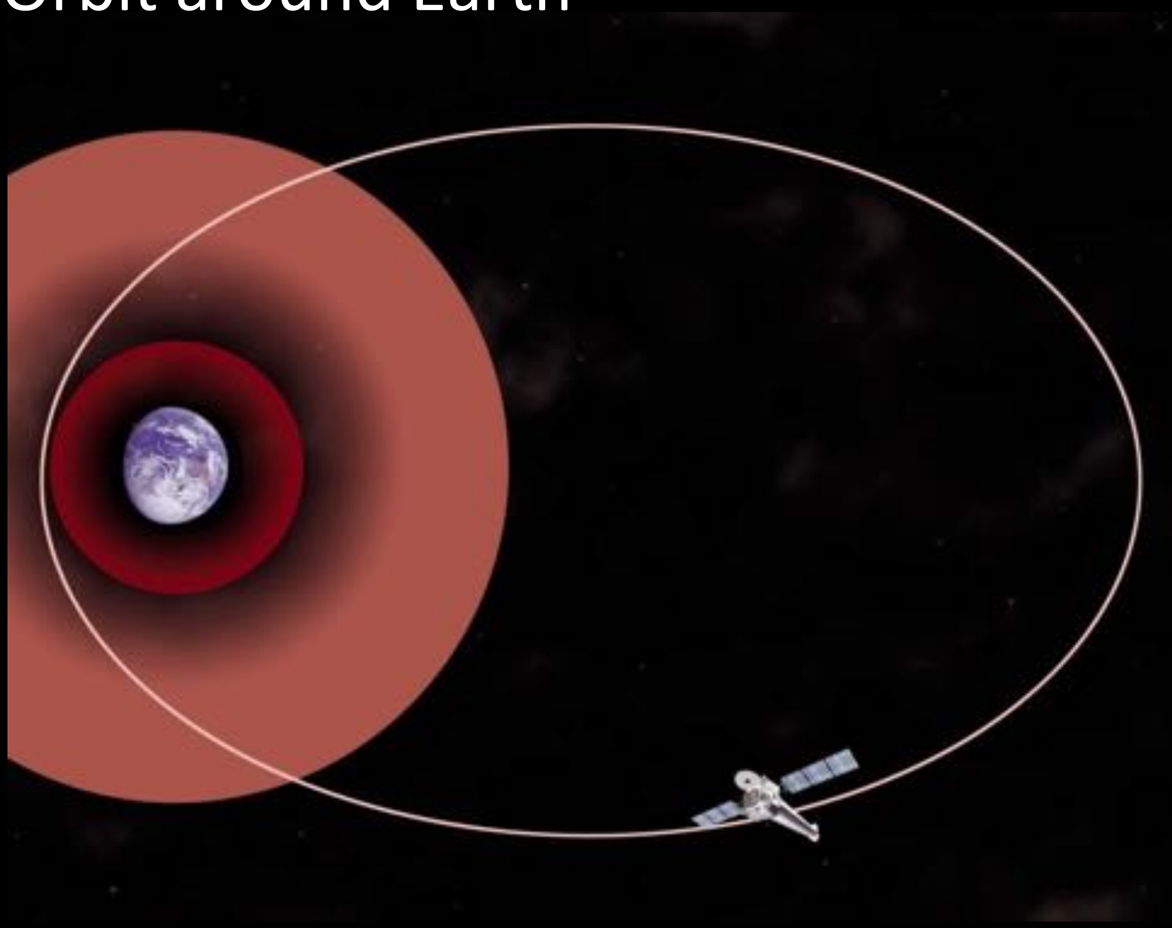
Deploying Chandra

Chandra's Orbit: 63.5 hours



Chandra’s Orbit in Space

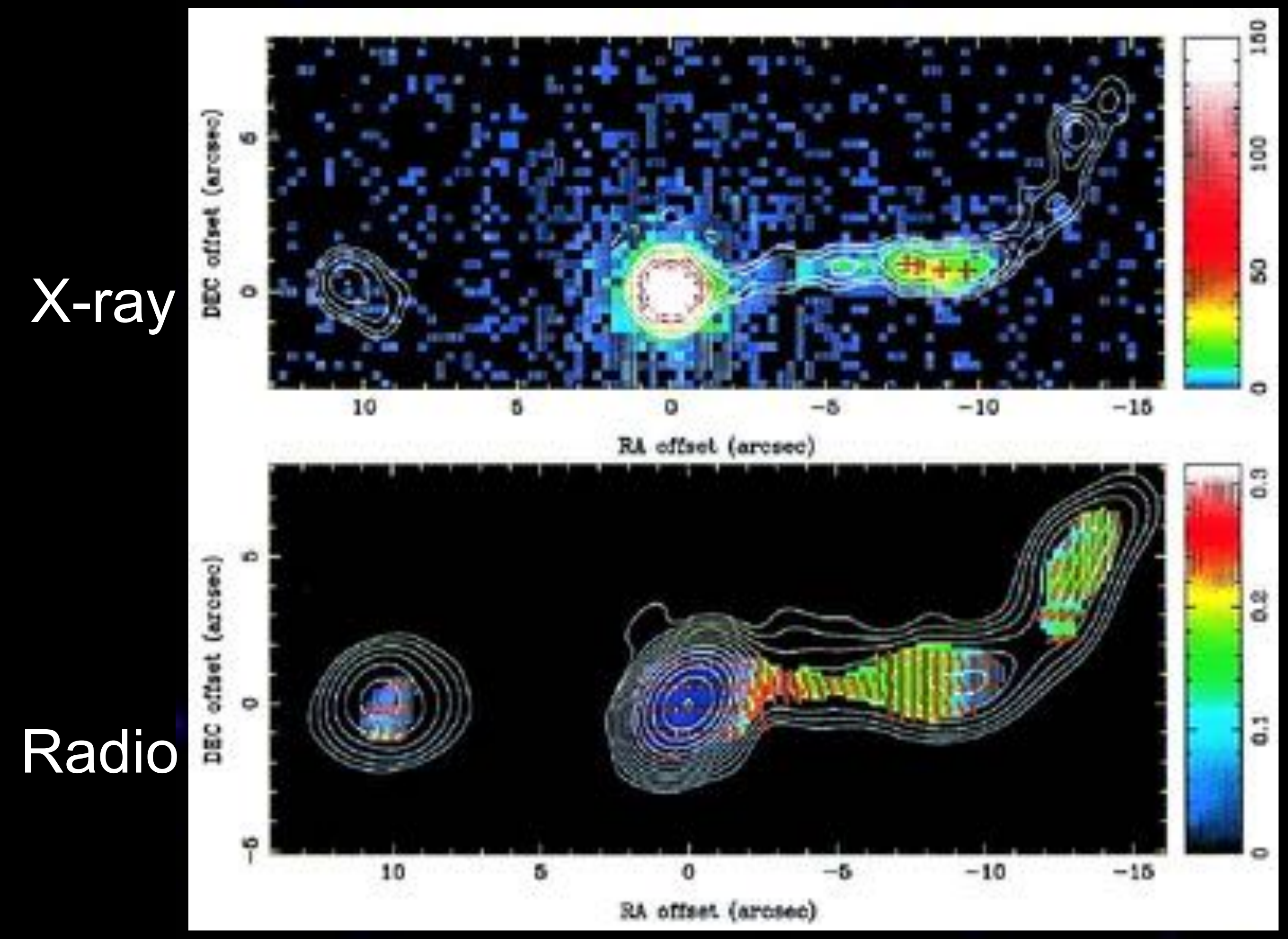
Orbit around Earth



Earth/Moon/Chand
ra

First Targeted Source: Quasar: PKS 0637-752

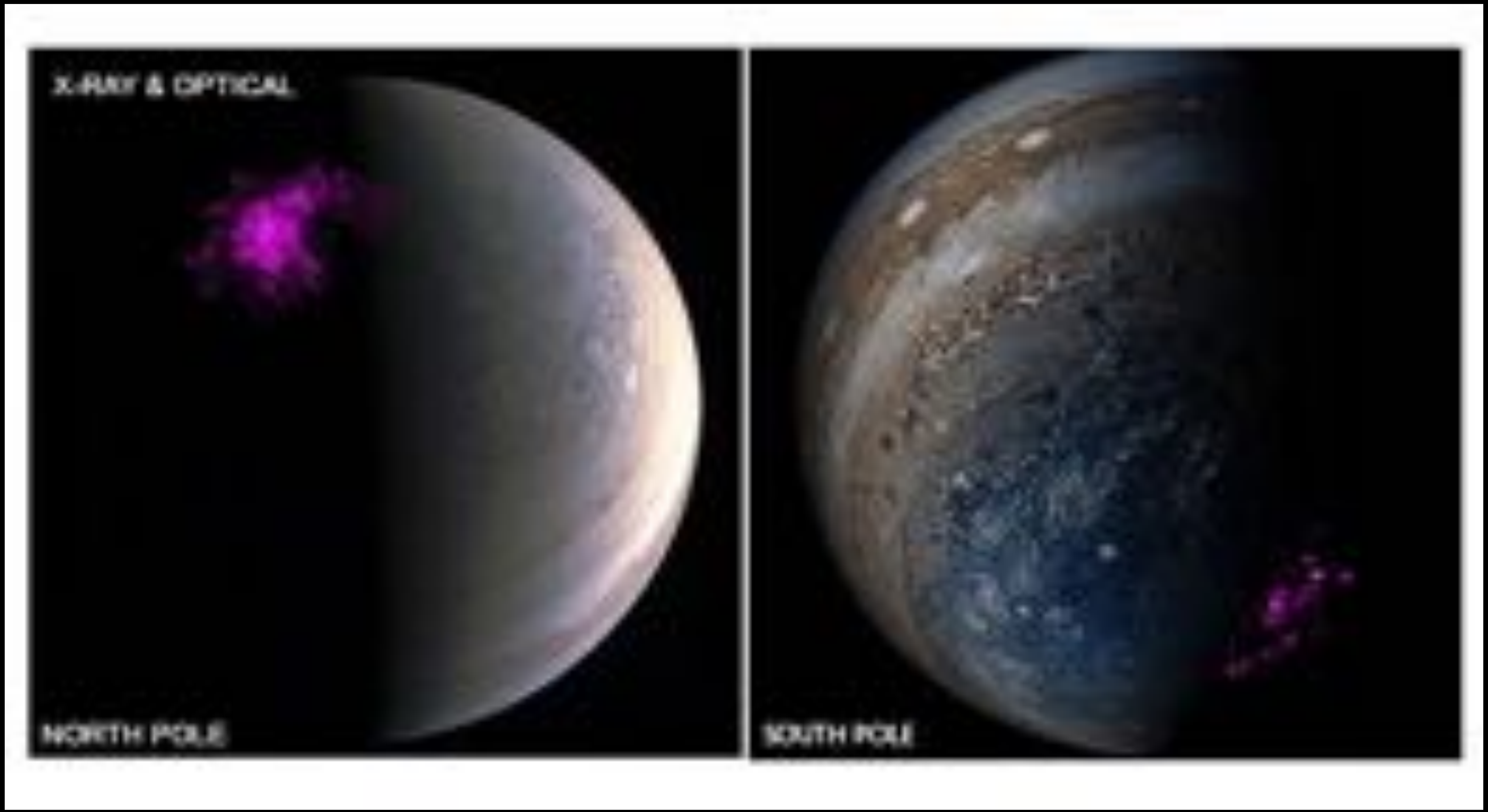
- Point Source to focus: Quasar z=0.659 (13 Gly)
- X-ray Jet visible: 300,000 ly long
- The birth of X-ray studies of jets



Neighborhood Watch

Chandra observations in our solar system

Solar System Objects



- X-ray emission
  - mostly due to charge-exchange of neutrals with solar wind ions
  - seen from comets, Venus, Mars, and Pluto (during New Horizon's Flyby)

- Jupiter
  - Aurorae at north and south poles
  - Observations during Juno mission, timed to investigate this interaction

A Star is Born

Chandra and stellar nurseries

Hubble Space Telescope


Hubble Space Telescope

Orion Nebula: star forming region

Exquisite Spatial Resolution

ROSAT:
~100 sources

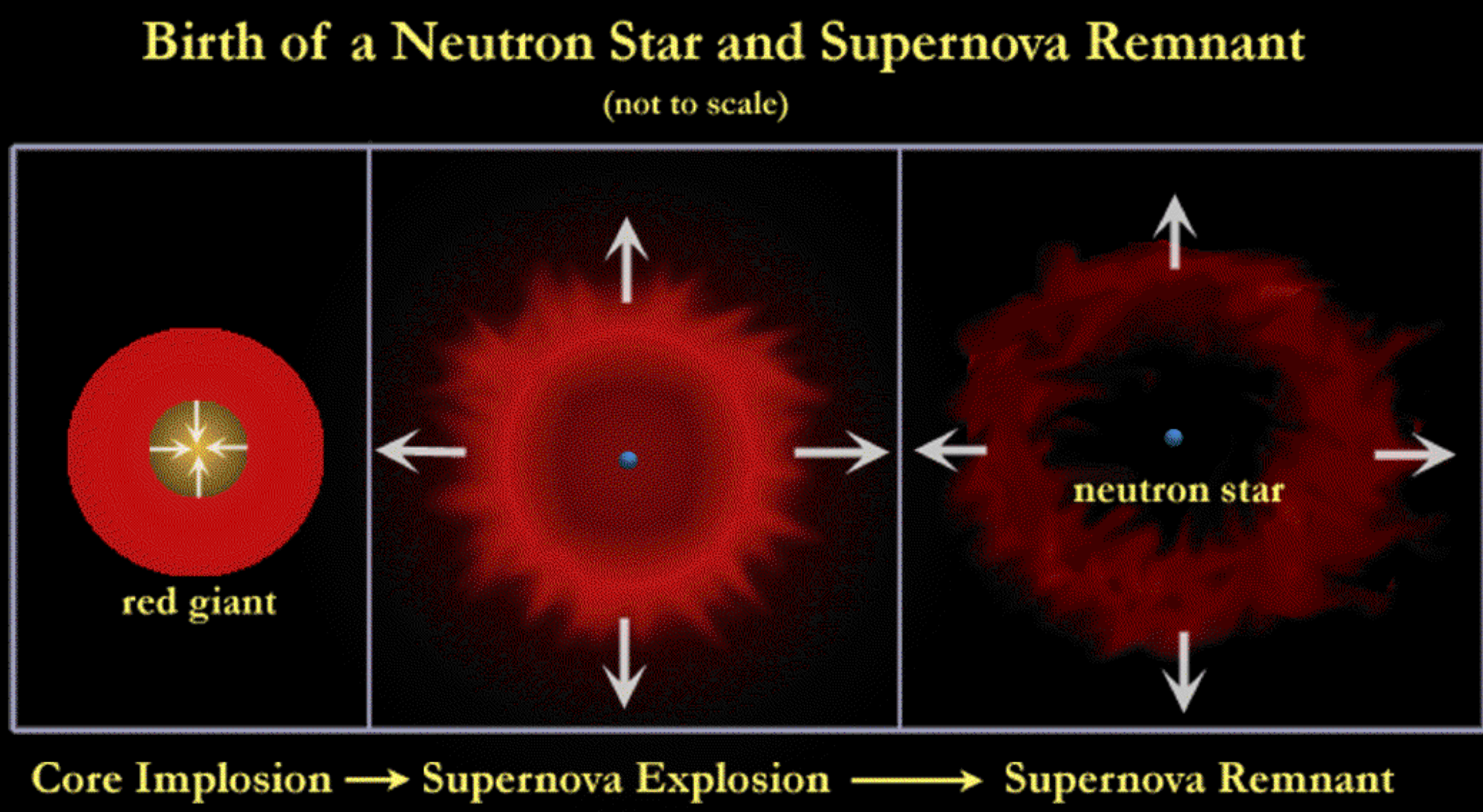
Chandra, deep:
~1400 source

Young stars are unstable and violent places

Chandra is an excellent "Young star finder"

Death of a Star

- When all fuel runs out, the core collapses → Neutron Star
- Outer regions of star explode outwards → Supernova (SN)
- SN shine more brightly than a galaxy for a few hours/days
- SN are the primary way heavy elements are distributed:
- We are made of Star Dust!

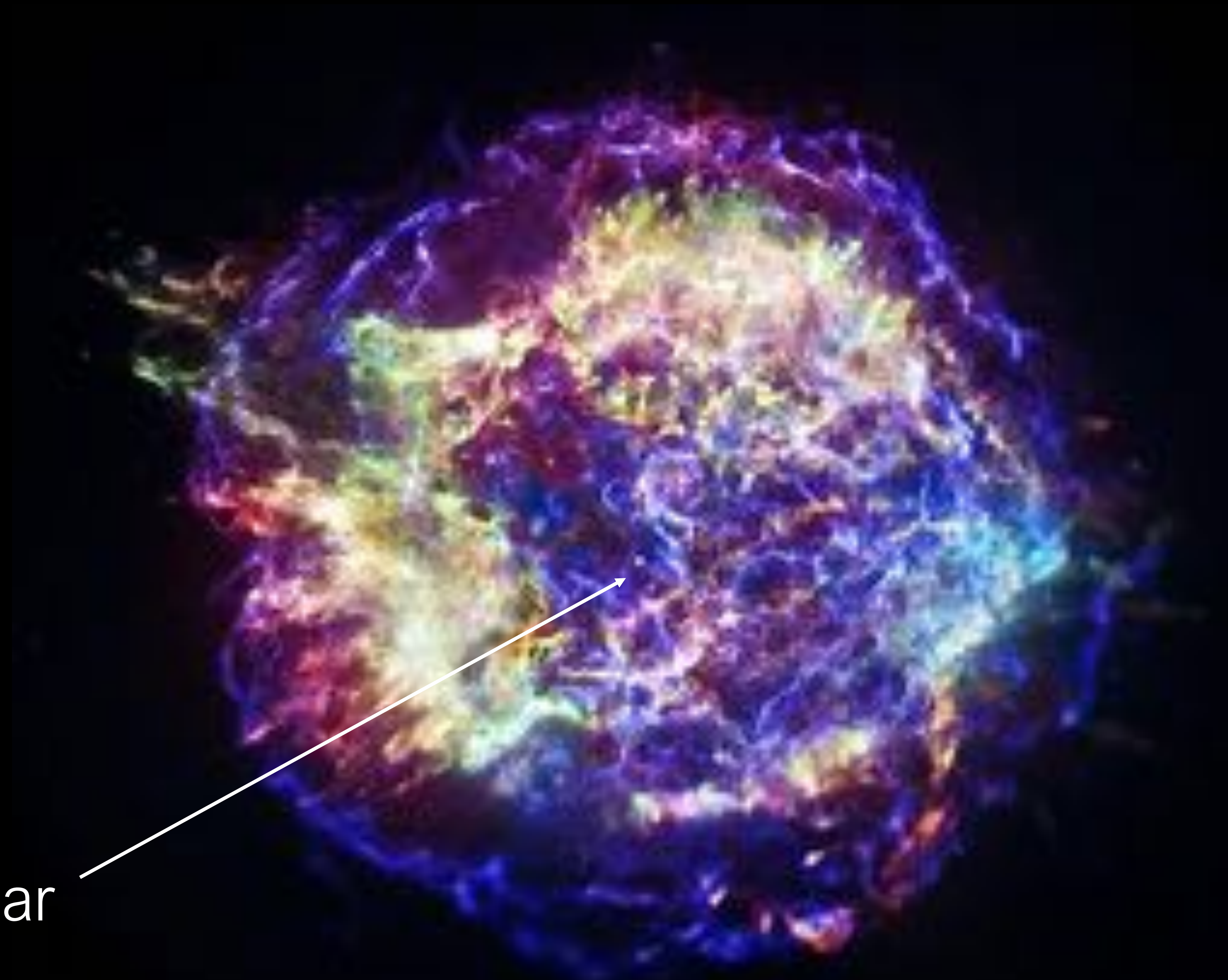


Cassiopeia A Supernova Remnant

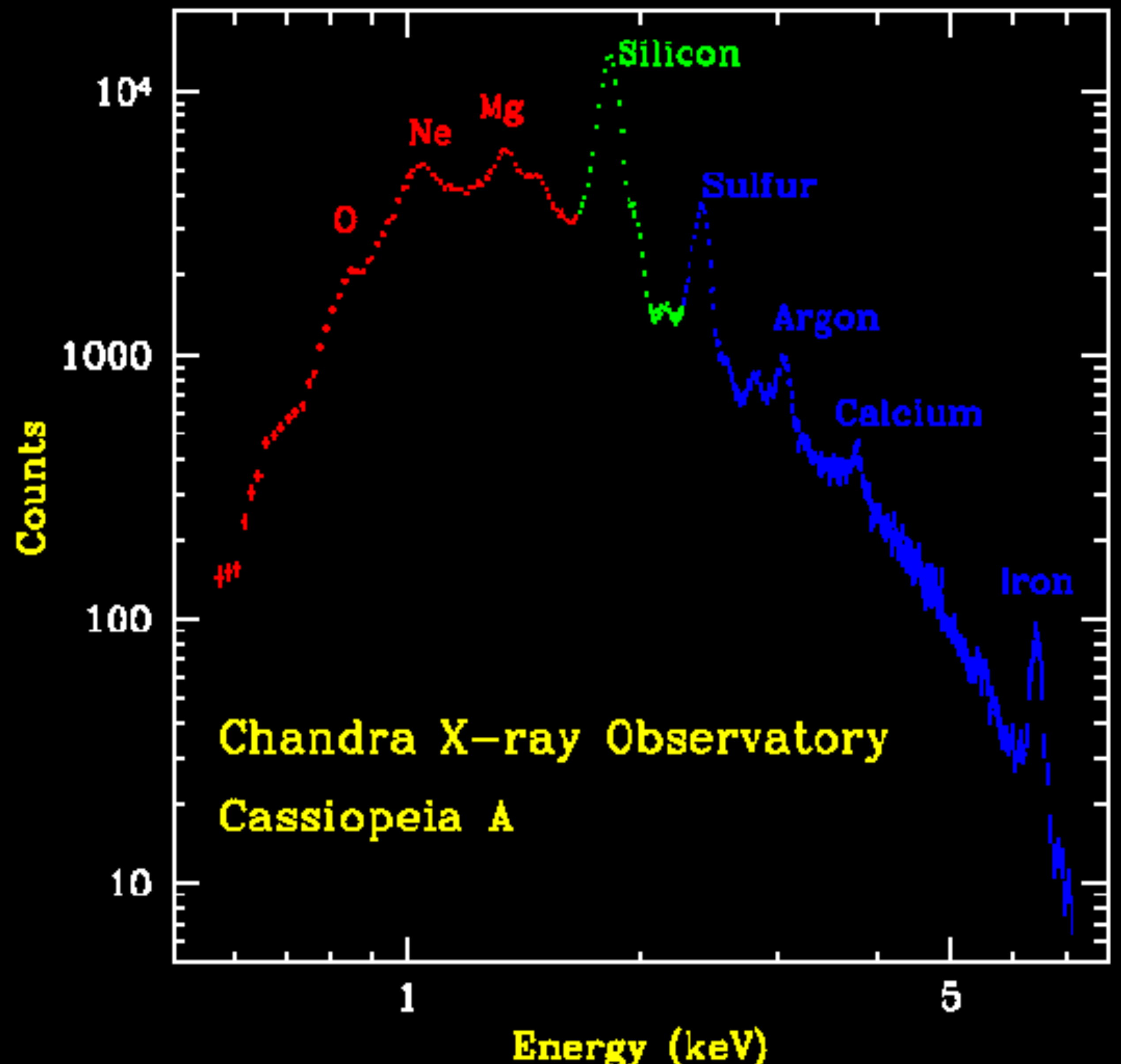
Age: 320 years

Size: 29 lyrs

1 Msec observation (12 days)



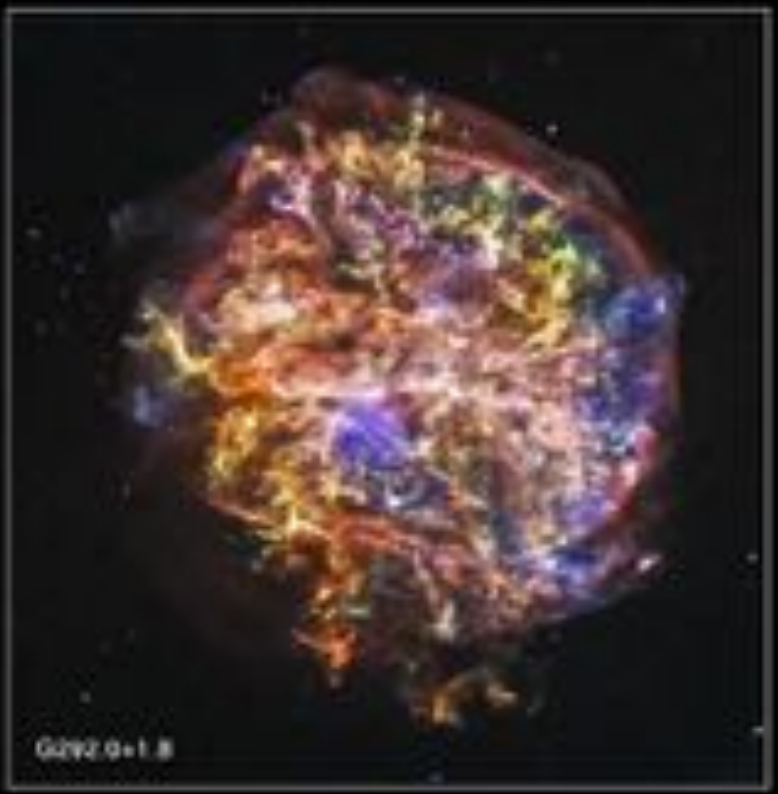
Cassiopeia A Supernova Remnant

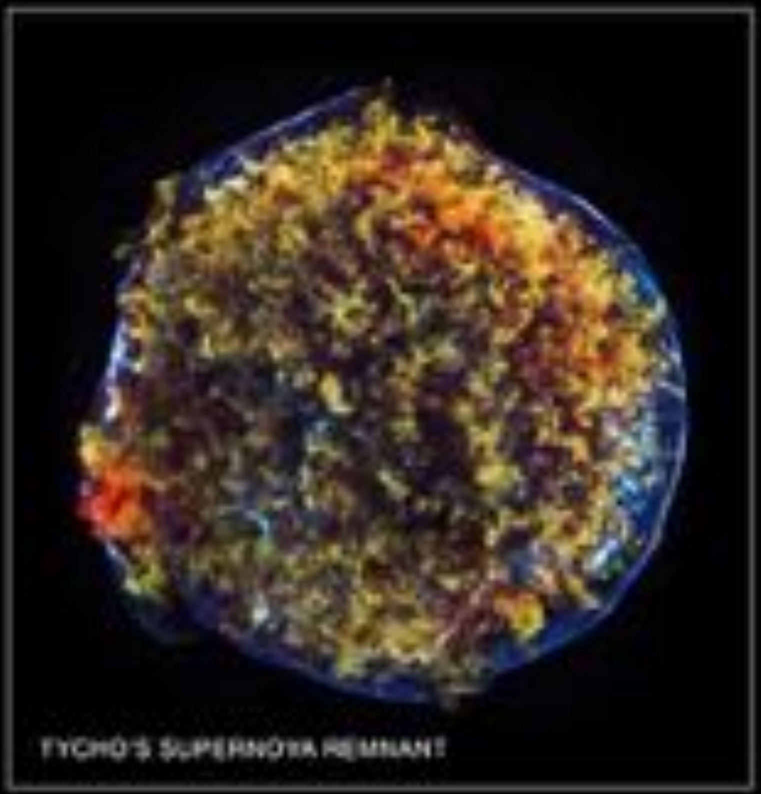


- Neutron Star: find and study
- SNR expansion
- Explosion – inside out

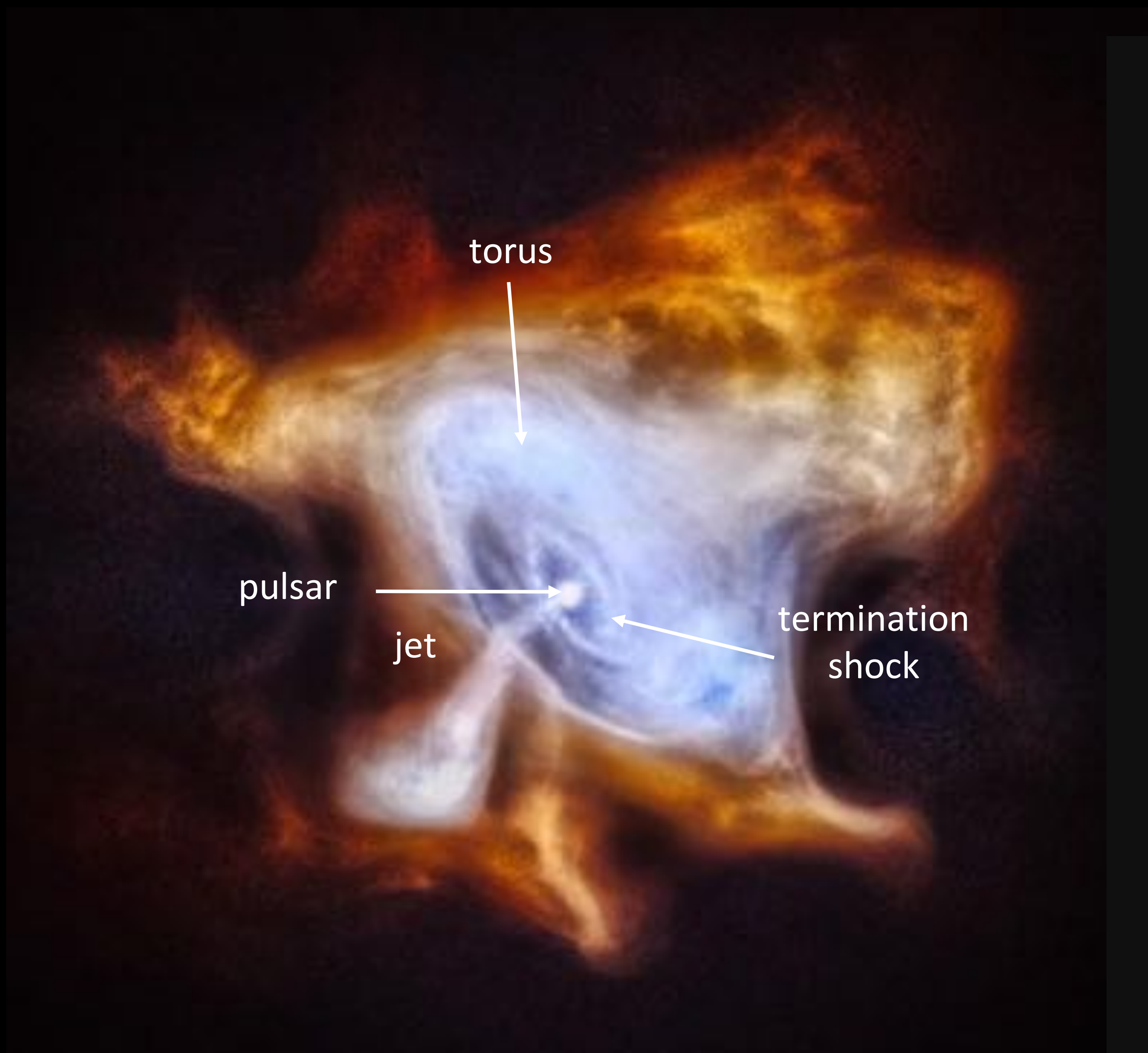
Cassiopeia A Supernova Remnant

SNR: Many shapes + sizes





Crab Pulsar Wind Nebula

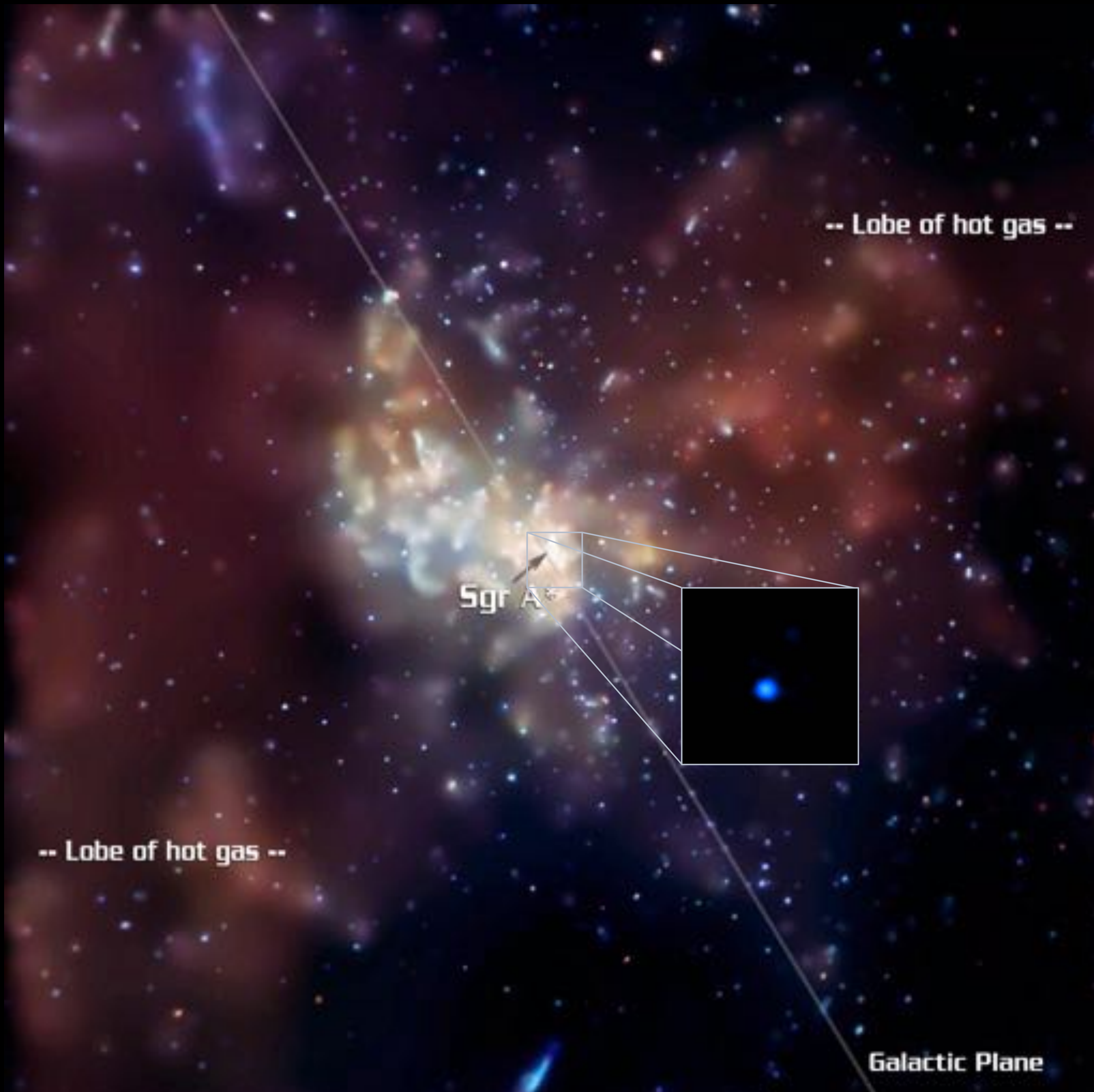


Supermassive Black Holes

A monster lives at the center of most (all?) galaxies…


Milky Way
Photograph by ESO/S. Guisard

Milky Way SMBH



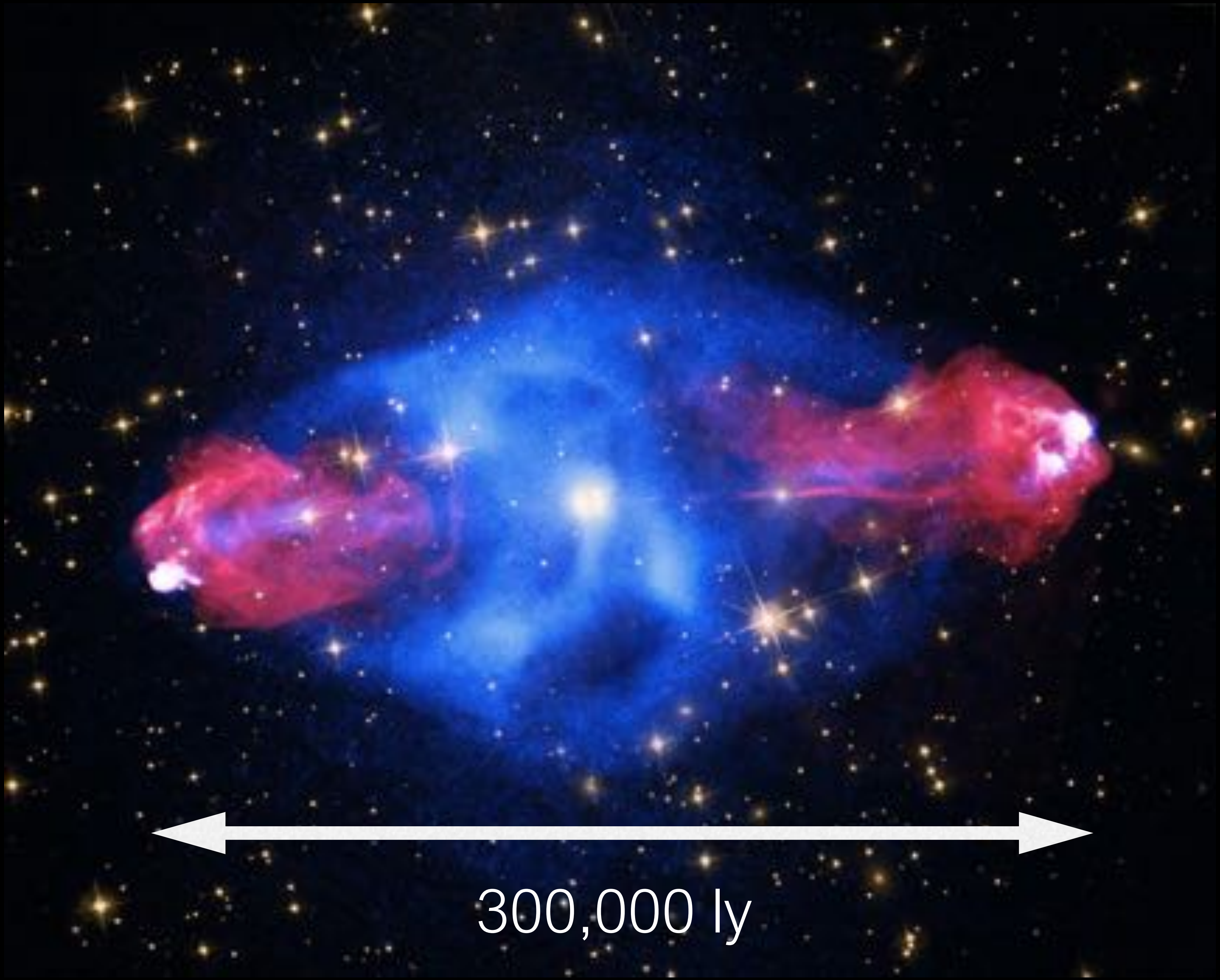
$4.6 \times 10^6 M_\odot$ BH in Milky Way center, but little activity. (Not much falling in…)

Occasional flaring may produce most of the observed emission.

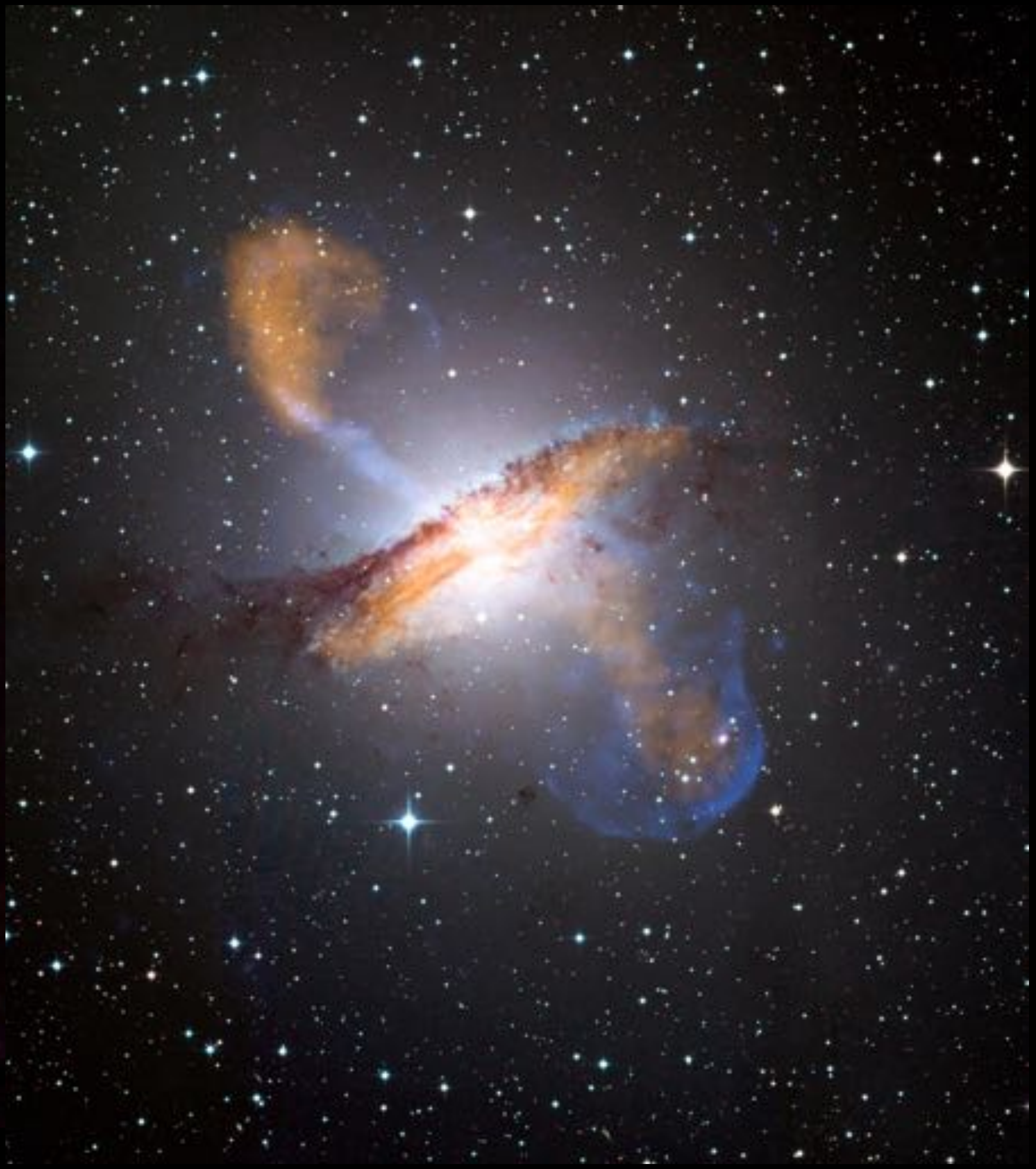
X-rays show evidence for past outbursts in form of lobes of hot gas.

Active Galactic Nuclei: Cygnus A

X-ray
Radio
Optical



Active Galactic Nuclei: Centaurus A



Galaxy clusters

The largest gravitationally bound structures in the Universe

Abell 1689

10^{14} - 10^{15} $M_{\odot}$

Around 10 million ly across

Contain over 100 - 1000 galaxies

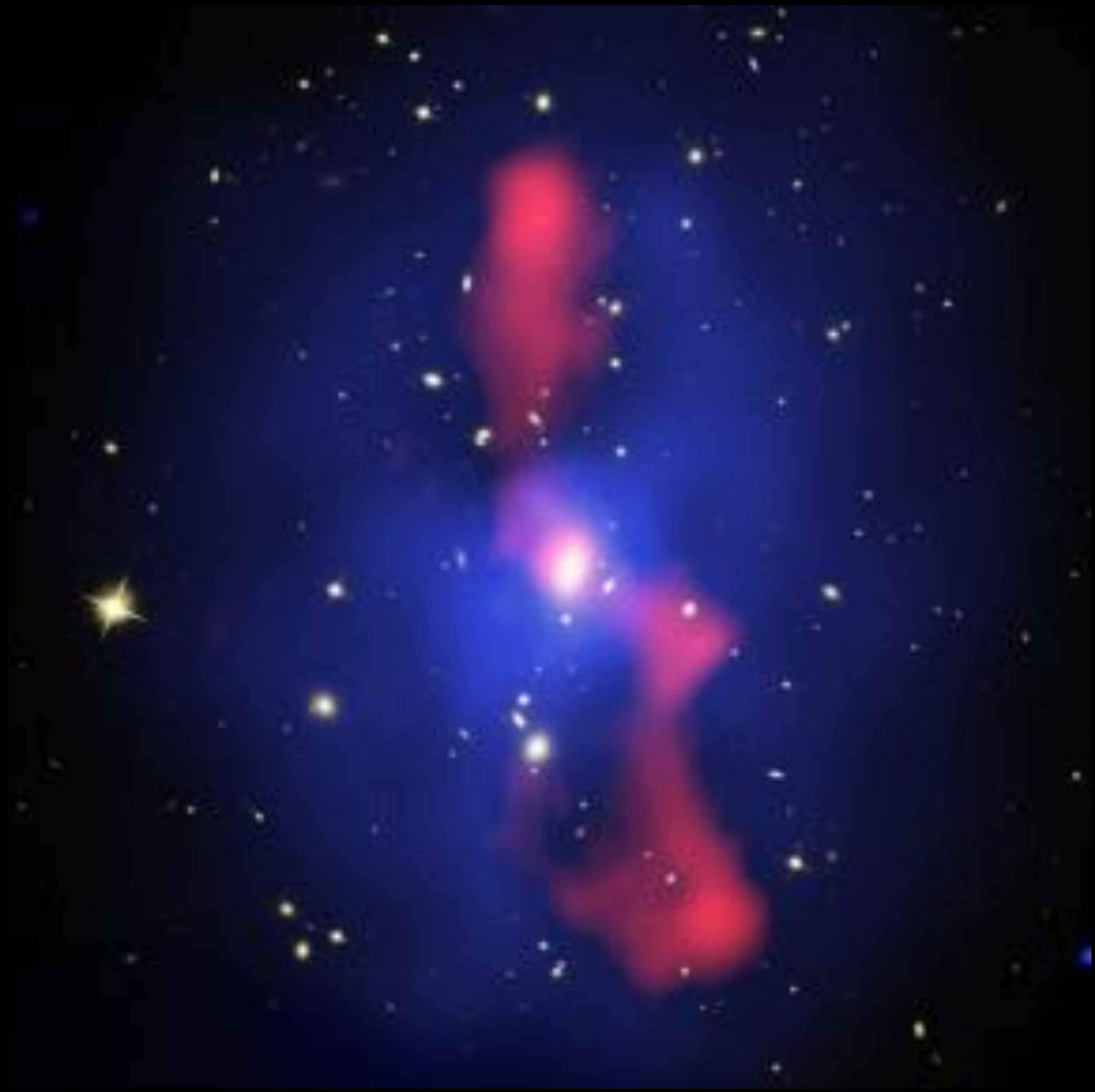
Gas heated to 1 -10 million degrees

~1% optical galaxies
~10% hot gas
~90% dark matter

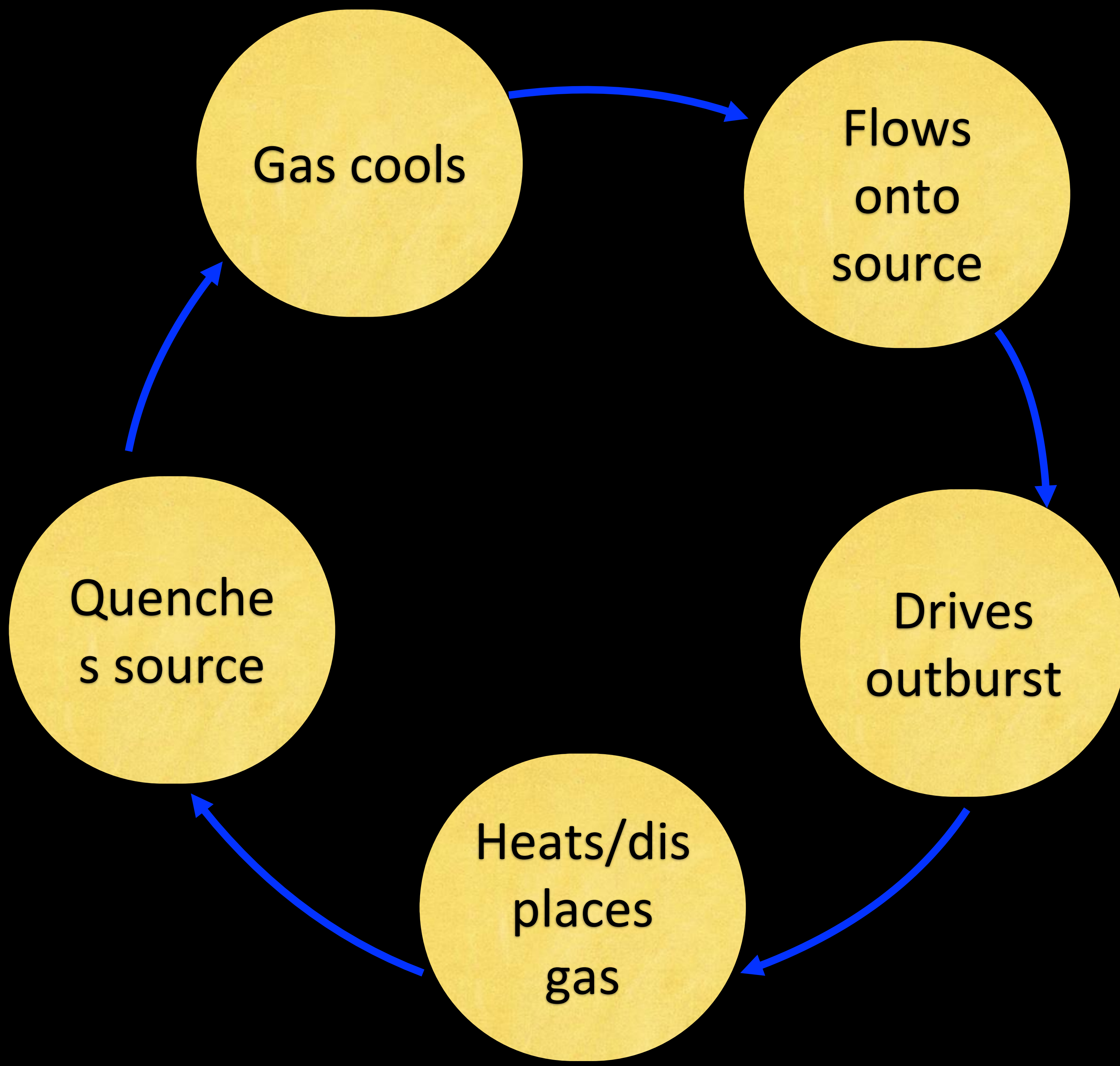
Perseus Cluster

Cluster: MS 0735.6+7421

- Galaxies and stars (white)
- Hot X-ray-emitting gas dominates normal matter
  - Cools and accretes onto central active nucleus
- Radio jets push hot gas aside, creating X-ray cavities
- Radio jets deposit energy in intercluster medium over ~10^8 yrs
- "Feedback" loop moderating star formation and SMBH growth



The AGN Feedback Cycle



Galaxy Group NGC 5813

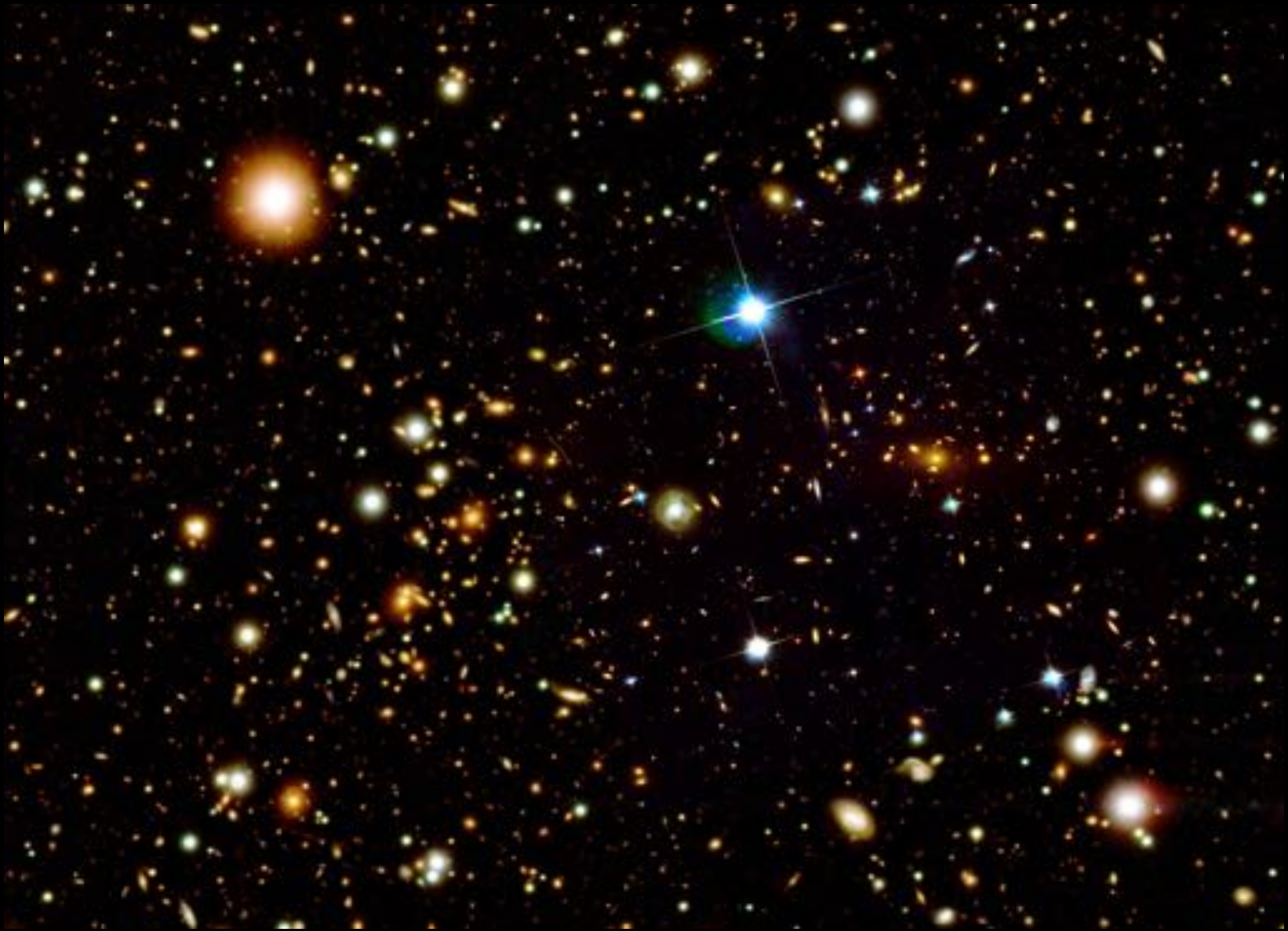
Jets from the SMBH blow giant bubbles in the gas.

The bubbles expand rapidly, driving shocks into the gas.

In NGC 5813, heating by the shocks from repeated outbursts can balance cooling

Shedding light on dark matter

Tracking the Dark Matter with The Bullet Cluster



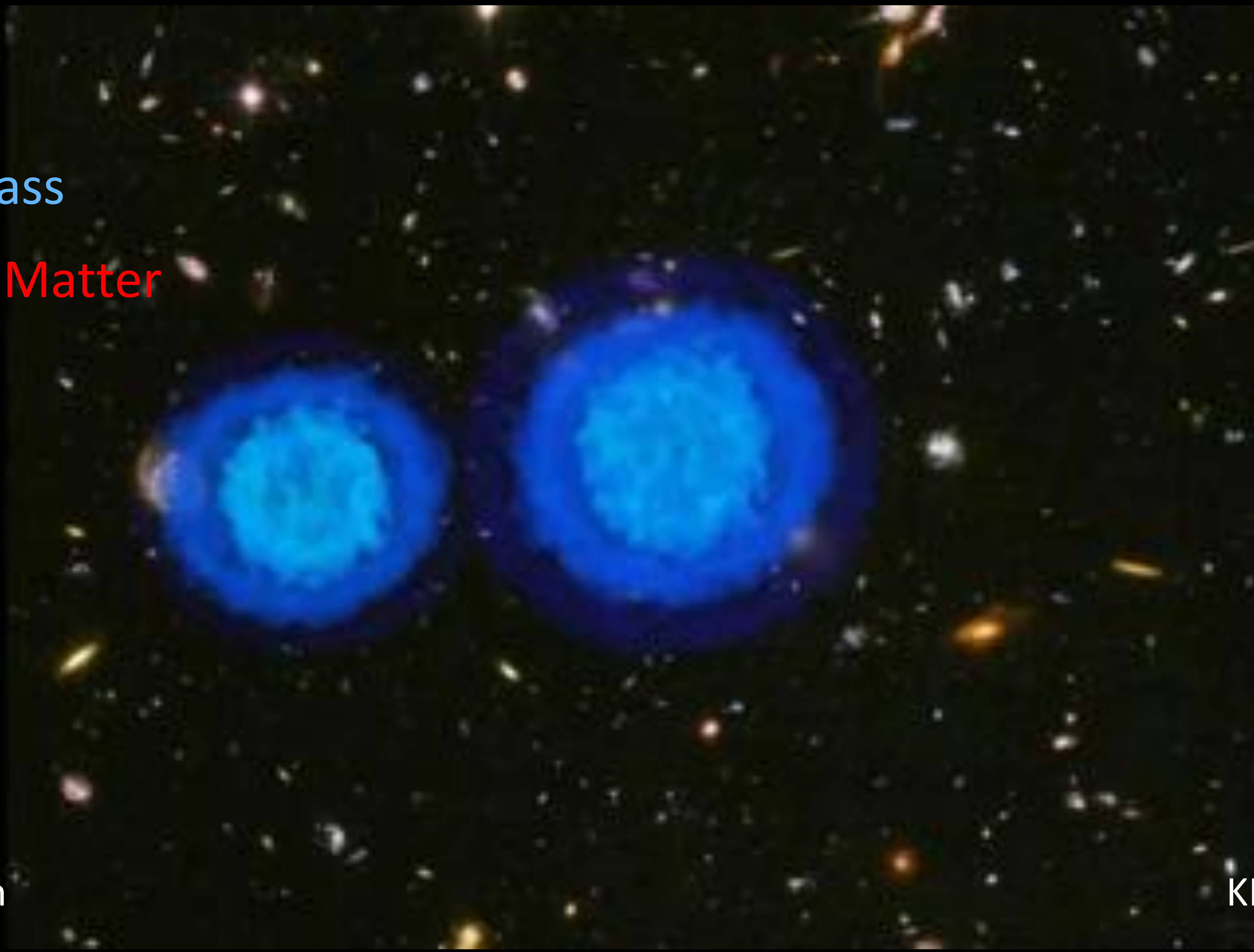
Tracking the Dark Matter with The Bullet Cluster

Tracking the Dark Matter with The Bullet Cluster

Tracking the Dark Matter with The Bullet Cluster

Total Mass

Normal Matter



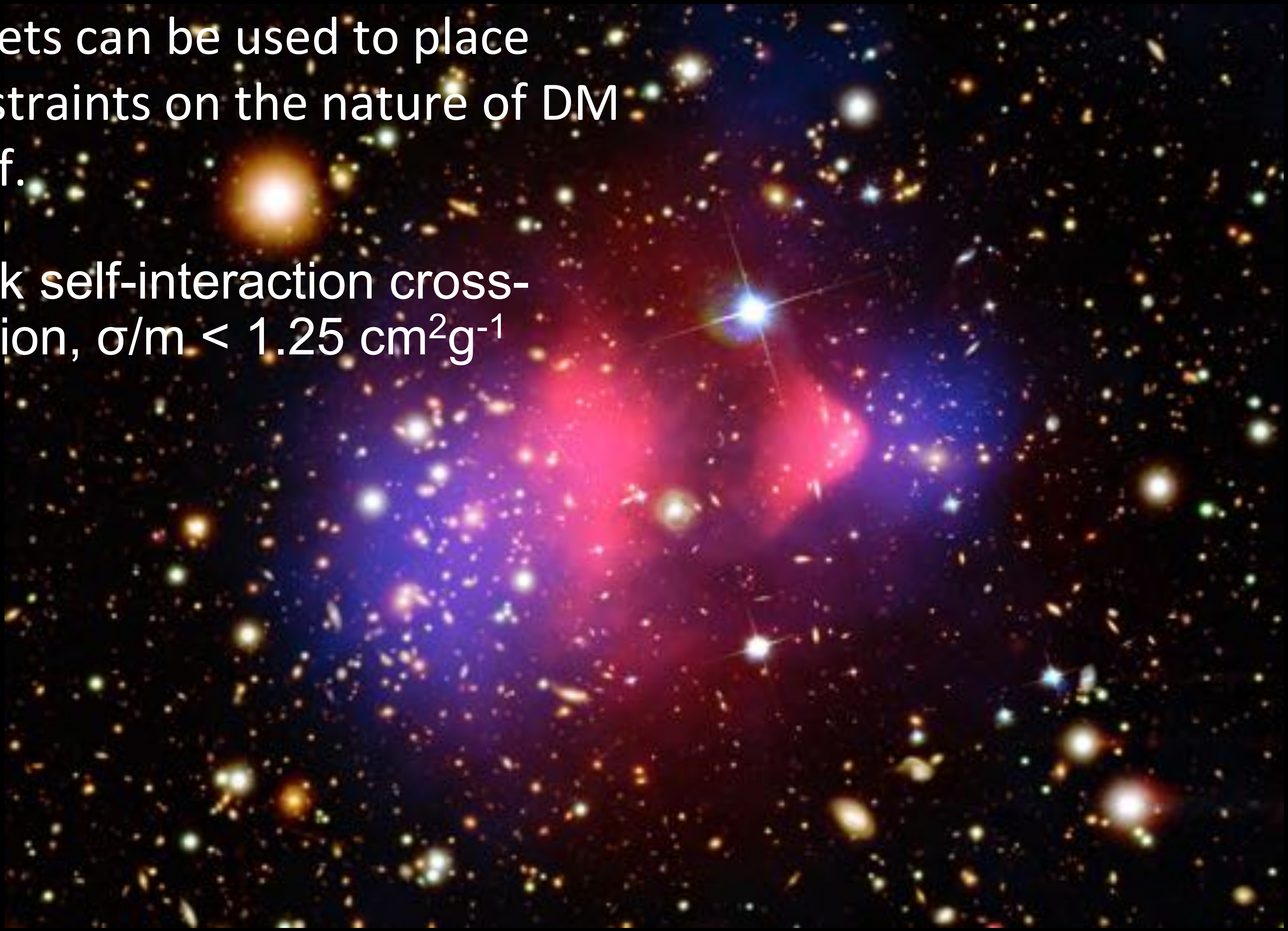
Simulation

KIPAC/John Wi

Tracking the Dark Matter with The Bullet Cluster

Offsets can be used to place constraints on the nature of DM itself.

weak self-interaction cross-section, $\sigma/m < 1.25\ cm^2g^{-1}$



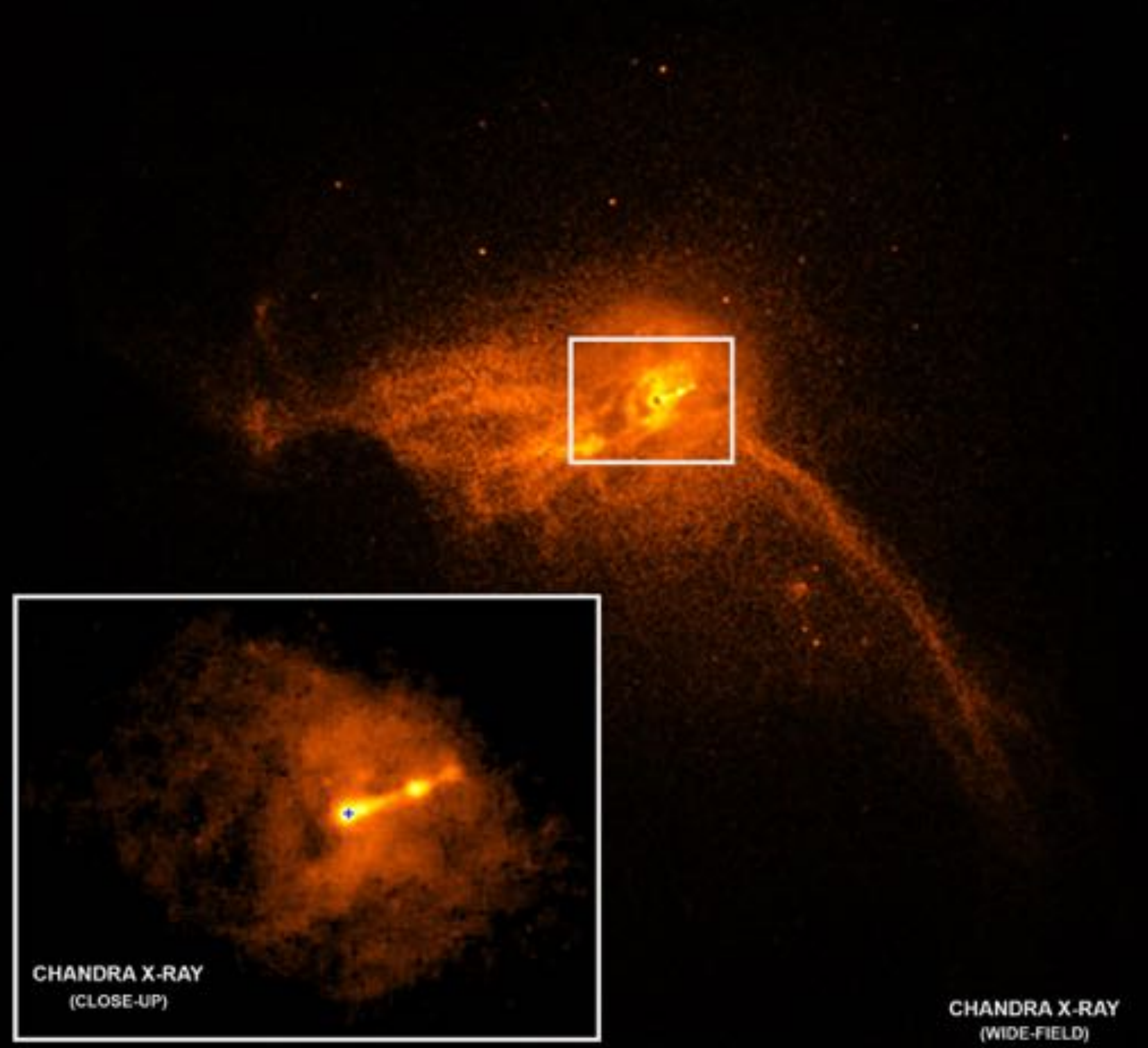
New Science and Chandra

EHT Images Black Hole Event Horizon!

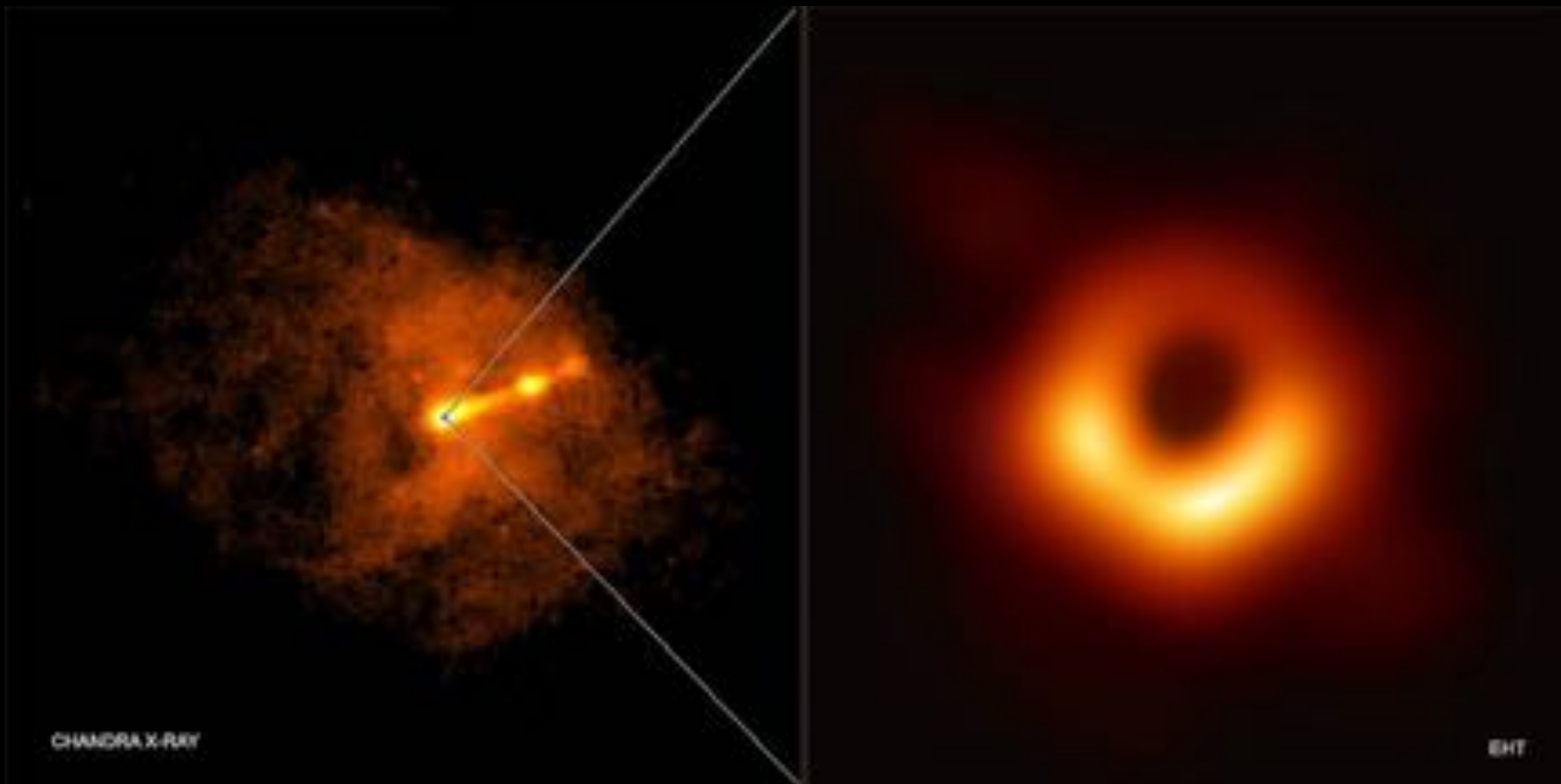
Image is warped by the intense gravity of the SMBH in M87

M_BH ~ $3.5 \times 10^9 M_\odot$

M87 with Chandra



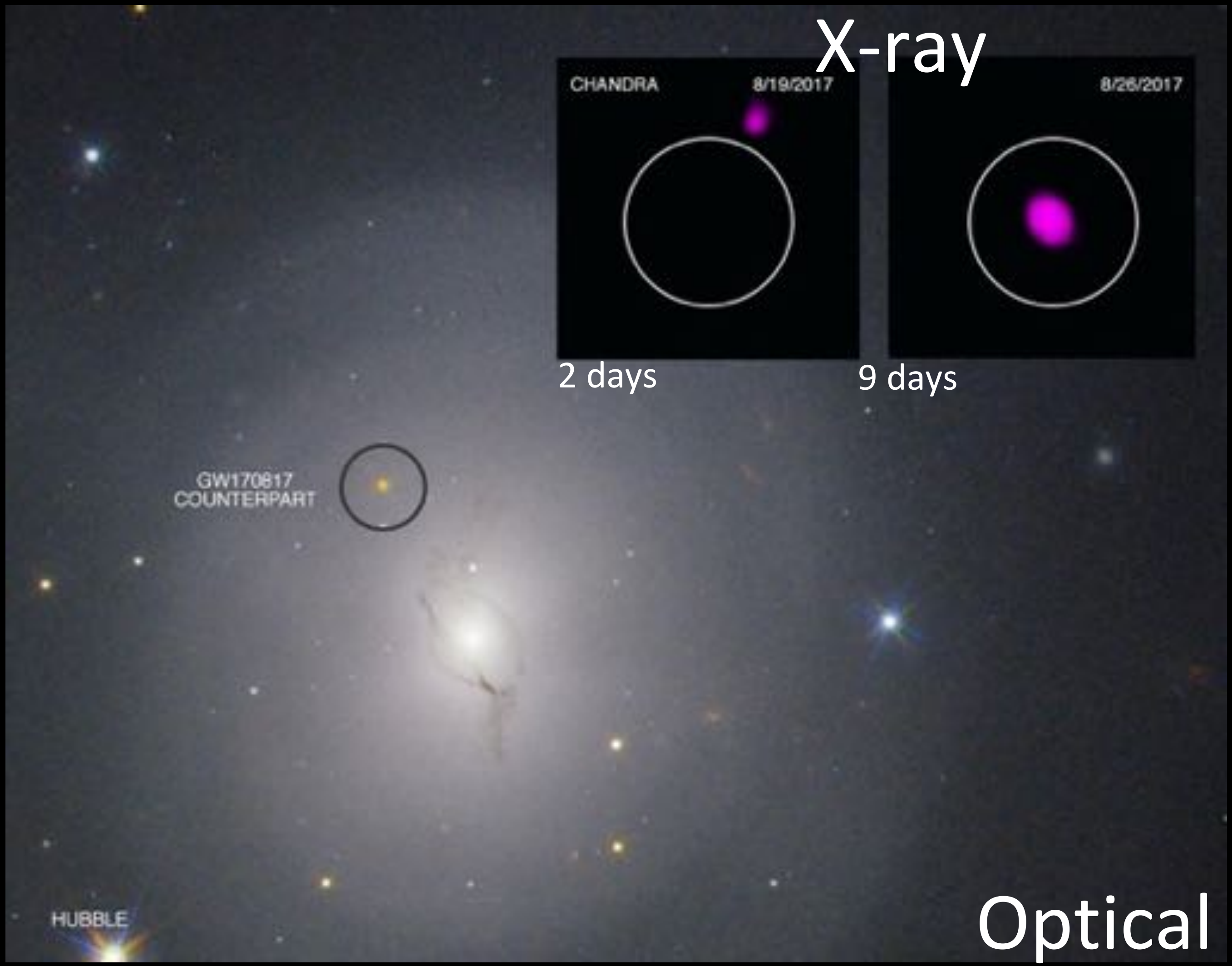
M87 with Chandra



Merging Neutron Stars, LIGO/Virgo: GW170817

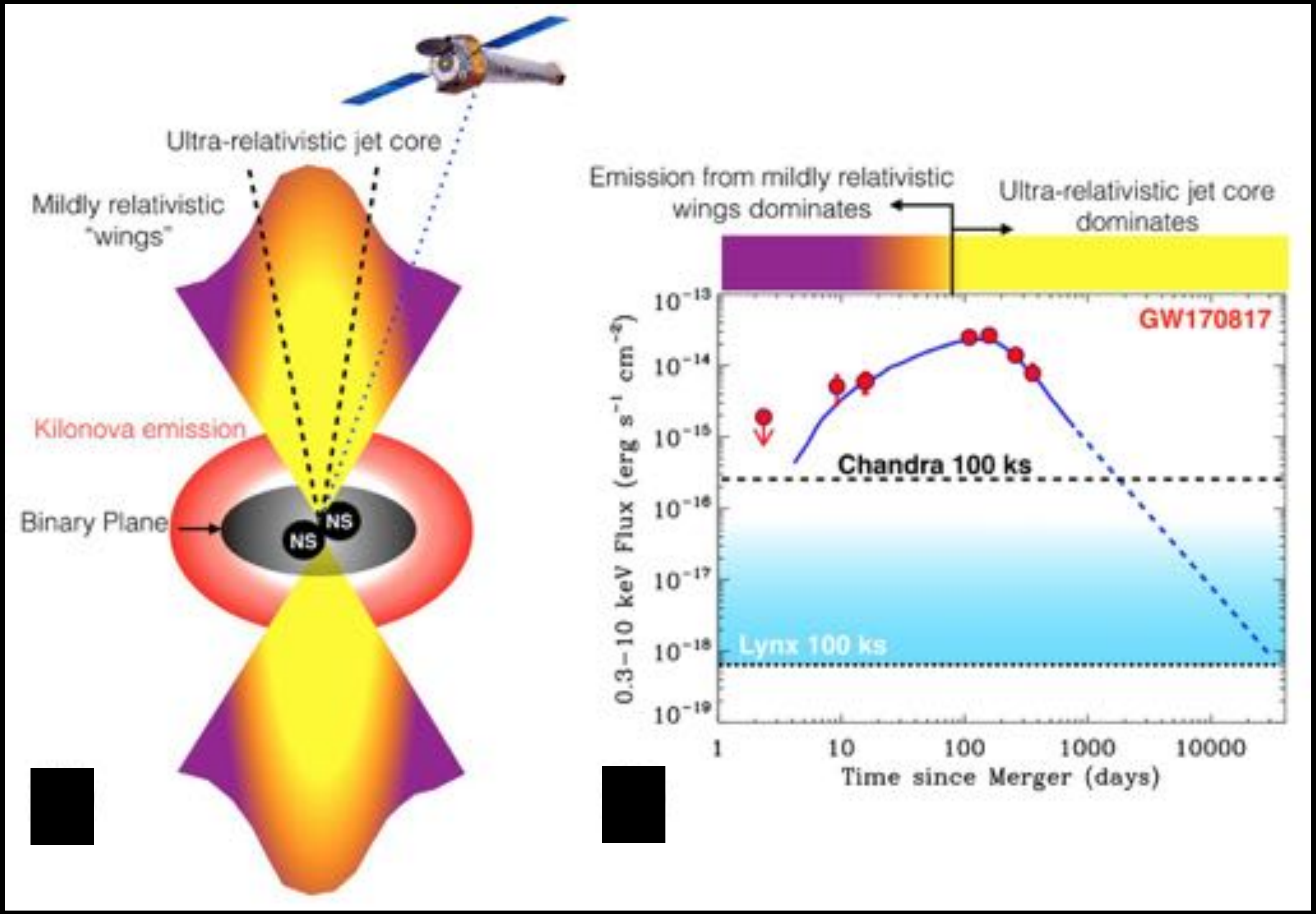
First EM detection of GW source!!

- Detected via gravitational waves
- Fermi & Integral: Faint, short gamma-ray burst ~2s later
- Optical counterpart found, tracked, faded and reddened over ~2 weeks (kilonova, r-process elements formed)
- → X-ray & γ-ray jet viewed off-axis
- Source went behind the sun – no X-ray observations until December
- X-ray & Radio emission continued to brighten, and is now fading



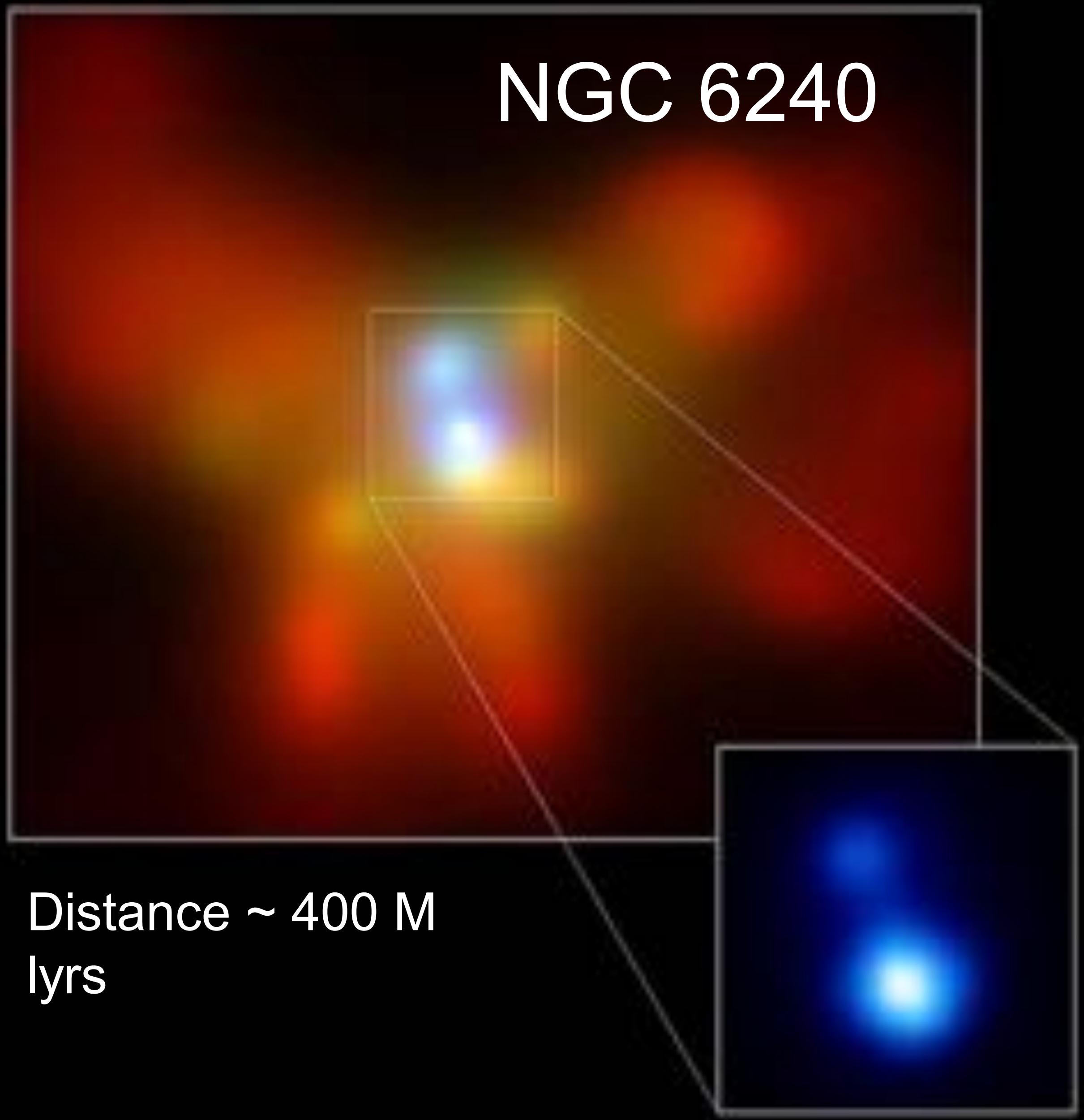
GW170817 (cont)

- *Chandra* X-rays key to constraining models
- Rise as jet expands
- Peak corresponds to view down jet core
- *Chandra* monitoring continues
- Awaiting next NS-NS or NS-BH GW trigger



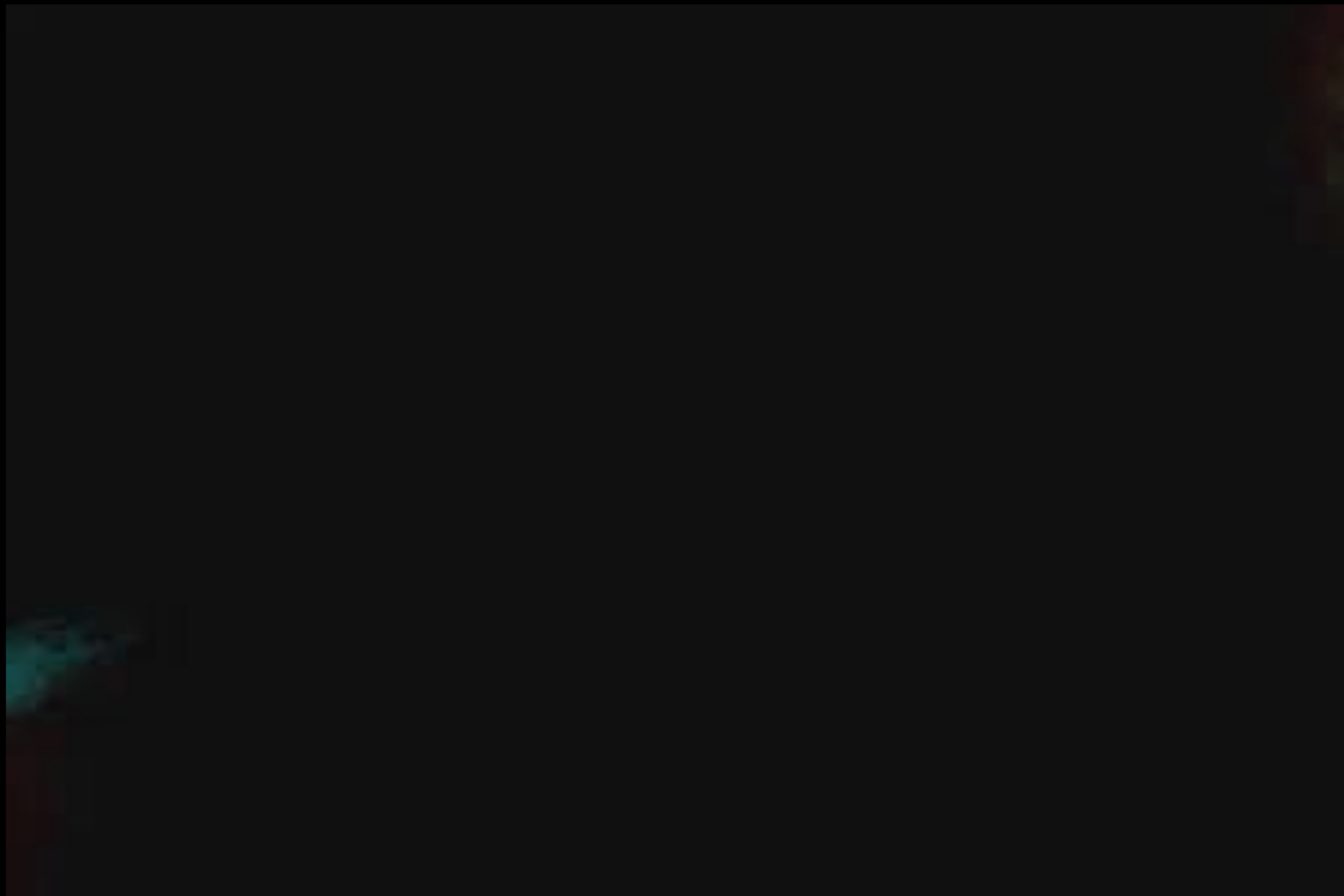
Credit: Margutti, Fong, Haggard, (Chandra Newsletter #26)

First Binary SMBH seen by *Chandra*



Distance ~ 400 M lyrs

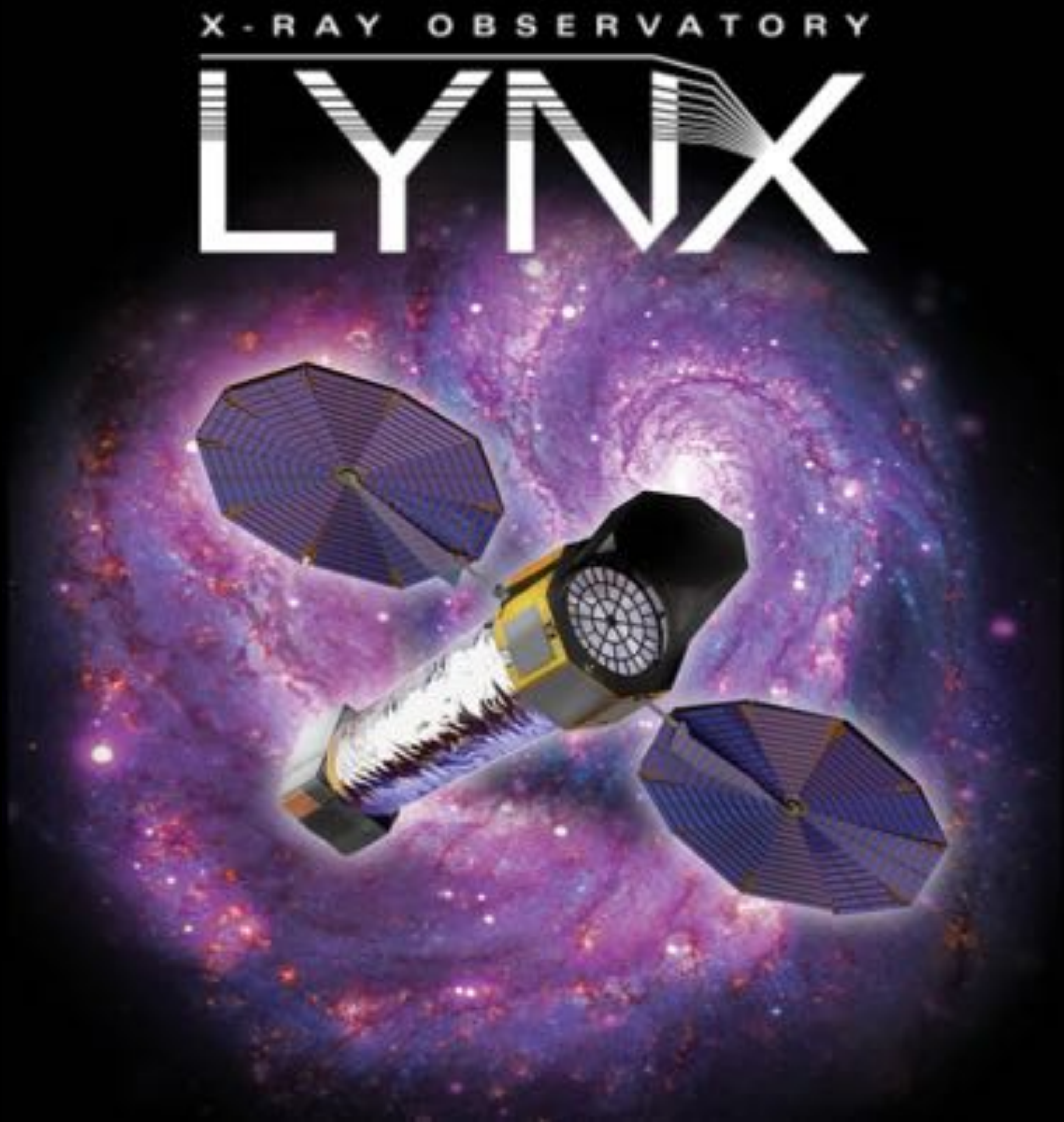
- Two galaxies merging
- Binary BHs will eventually merge
- → Hot topic since LIGO detections of merging stellar mass BHs
- Merging SMBHs are not detectable by LIGO
- ESA's LISA, launching ~2030s, will place detectors in space with larger separations



Chandra is good to go.

No showstoppers for 10 more years of operations.

What comes next?

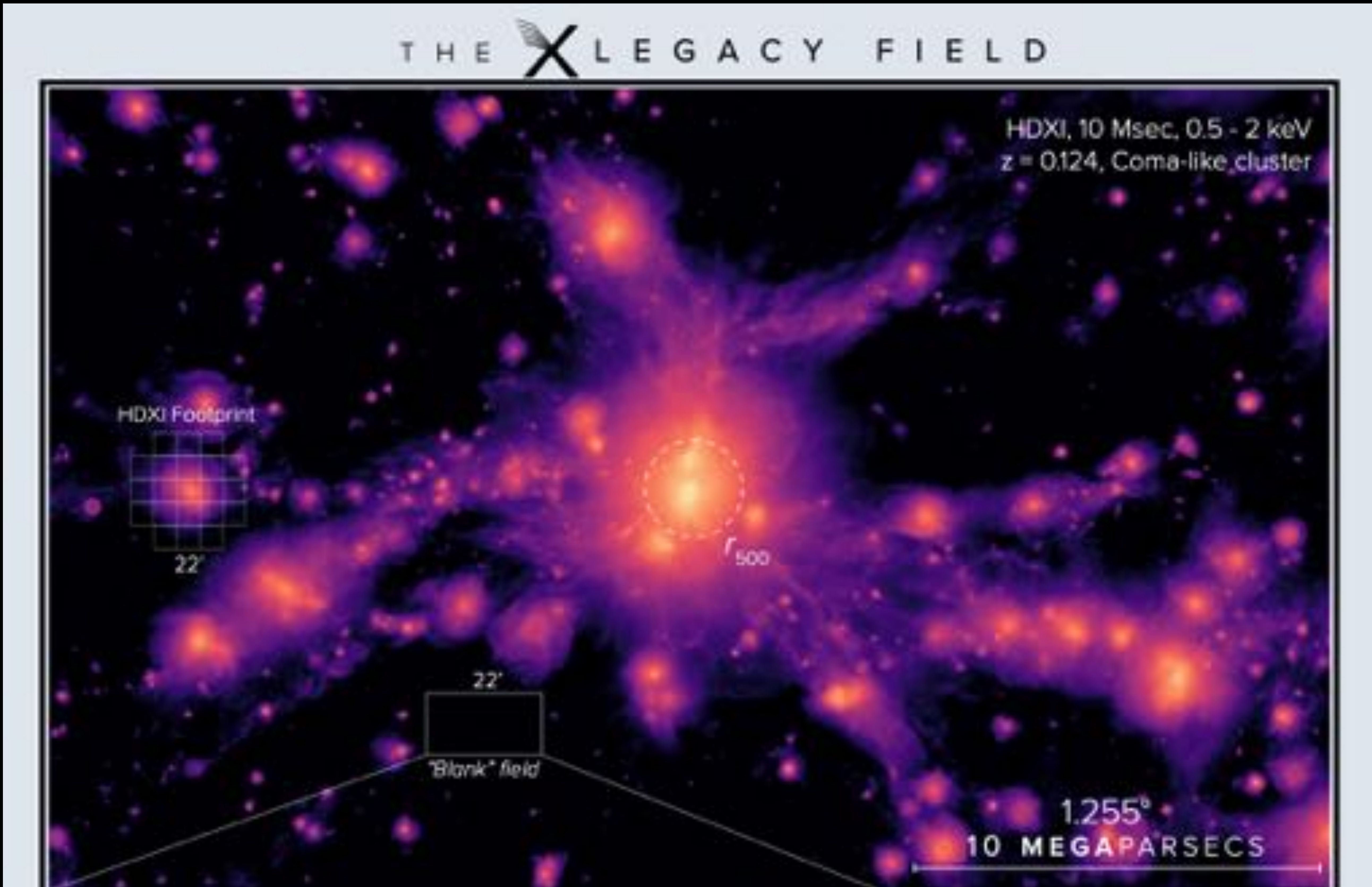


NASA mission concept for 2020 Decadal Survey

Every 10 years there is a decadal review to recommend the next major NASA mission(s)

Concept design for Lynx led by Harvard-Smithsonian Center for Astrophysics

50 times more sensitive than Chandra, even better vision, with better instruments


THE LEGACY FIELD
HDXI, 10 Msec, 0.5 - 2 keV
z = 0.124, Coma-like cluster
HDXI Footprint
22'
r_{500}
22'
"Blank" field
1.255°
10 MEGAPARSECS