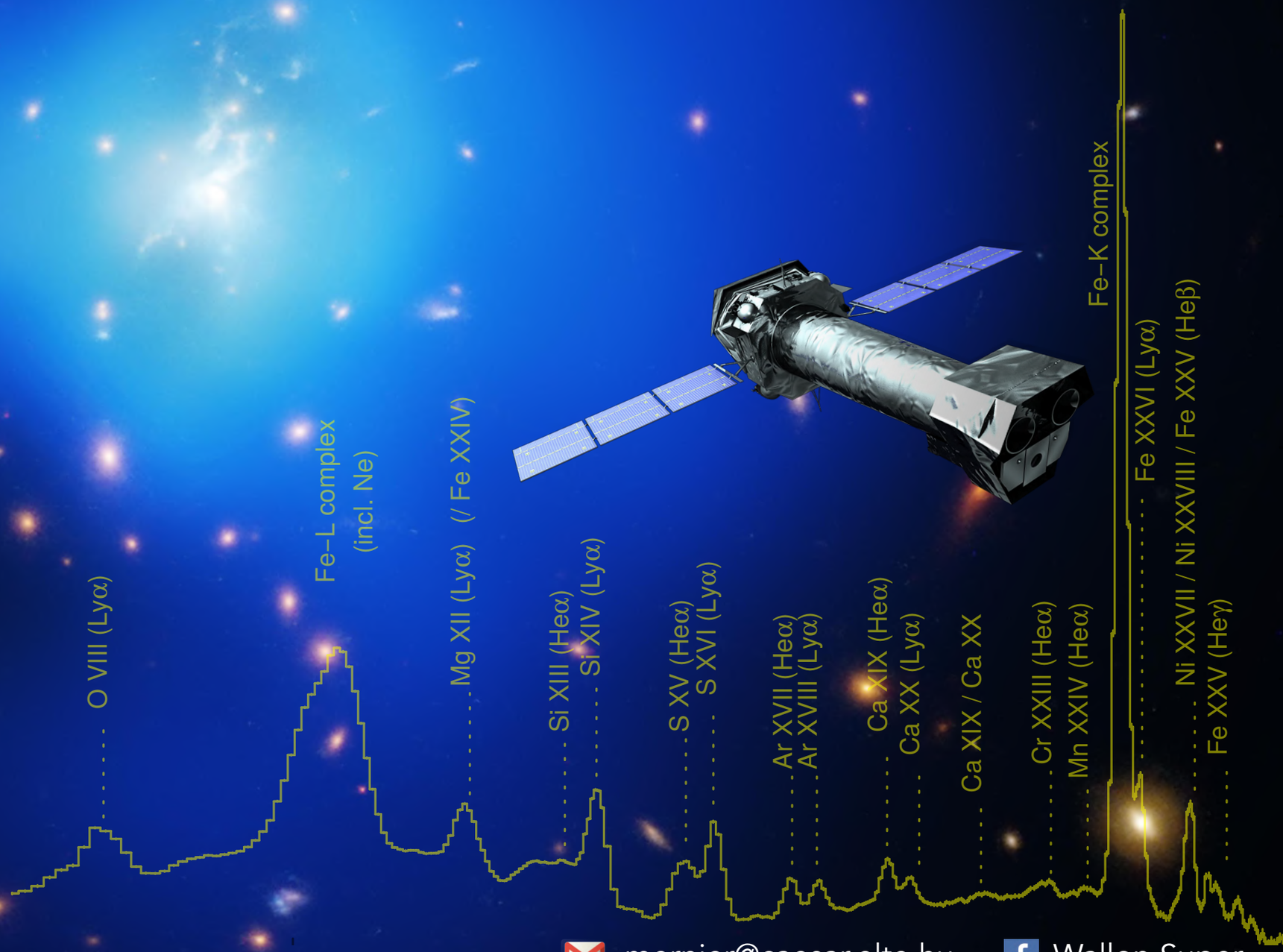
Clusters of galaxies...

...and the surprises of their spectacular hot atmospheres

François Mernier

MTA-Eötvös University, Budapest



mernier@caesar.elte.hu - Wallon Super


You are here!
Budapest
1 km = 10³ m
PASARÉT
RÓZSADOMB
ORSZÁGÚT
Országház
Terror Háza
Halászbástya
Szent István Bazilika
Dohány utcai Zsinagóga
Arena Mall
Városliget
Szechenyi Gyógyfürdő és Uszoda
MOM Park
Citadella
Nagy Vásárcsarnok
BELVÁROS
LÁGYMÁNYOS
KELENFÖLD
SASAD
GAZDAGRÉT
Barba Negra
Kopaszi gát
Le Danube
IX. ARRONDISSEMENT
Magyar Természettudományi...
Népliget
Gábor Áron u.
Bimbó út
Margit krt.
Istenhegyi út
Németvölgyi út.
Alkotás u.
Attila út
Jagelló út
Hegyalja út
Villányi út
Bartók Béla út
Budaörsi út
Sasadi út
Rétköz u.
Etele út
Podmaniczky u.
Andrássy út
Damjanich u.
Hermina út
Ajtósi Dürer sor
Thököly út
Hungária krt.
Róna u.
Rákóczi út
Fiumei út
Üllői út
Lónyay u.
Haller u.
Vágóhíd u.
Könyves Kálmán krt.
Ecseri út
Kerepesi út
Baross u.
Vajda Péter u.

You are here!
(somewhere
behind...)

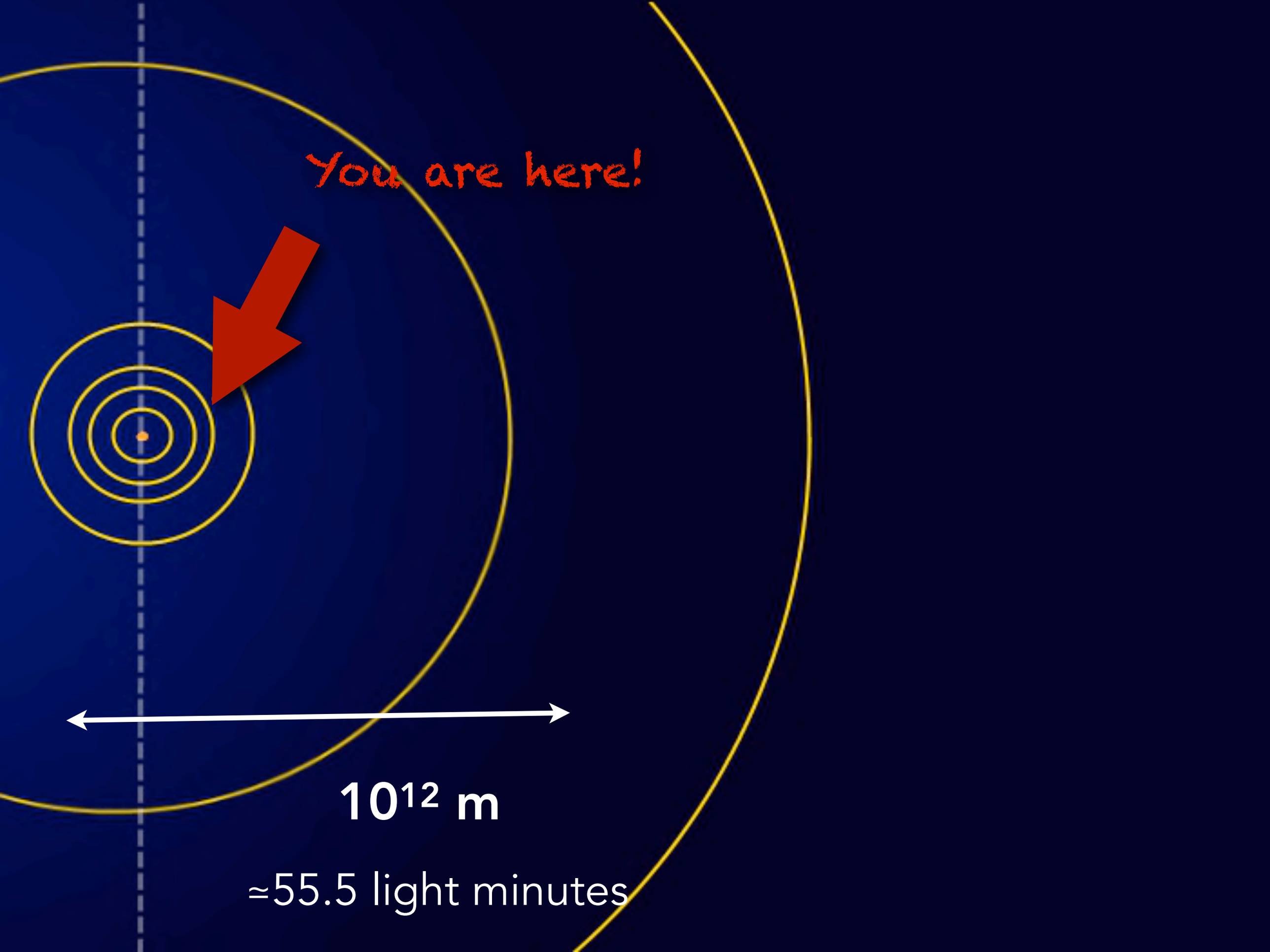
10^7 m

You are here!

(and this is the Moon)

10^9 m

≈3.3 light seconds


You are here!
10^{12} m
≃55.5 light minutes

10^{13} m

136199 Eris

90377 Sedna

10^{14} m

≃4 light days

You are here!

Cygni System

Andromedae System

ss 248

Barnard's Star

Ross 154

You are here!

Lalande 21185

EZ Aquarii System

Sun

Ross 128

10^{17} m

Proxima Centauri

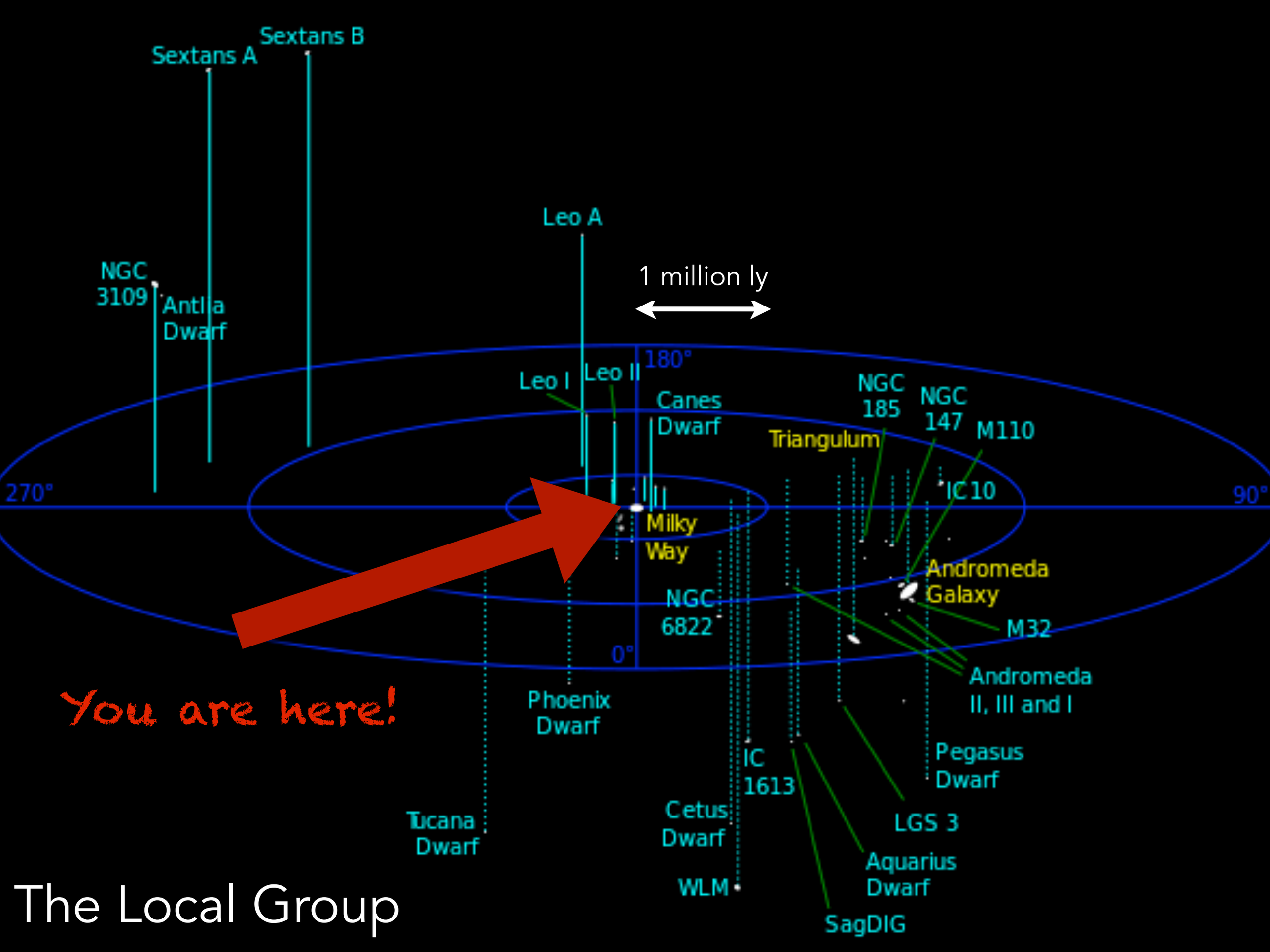
Wolf 359

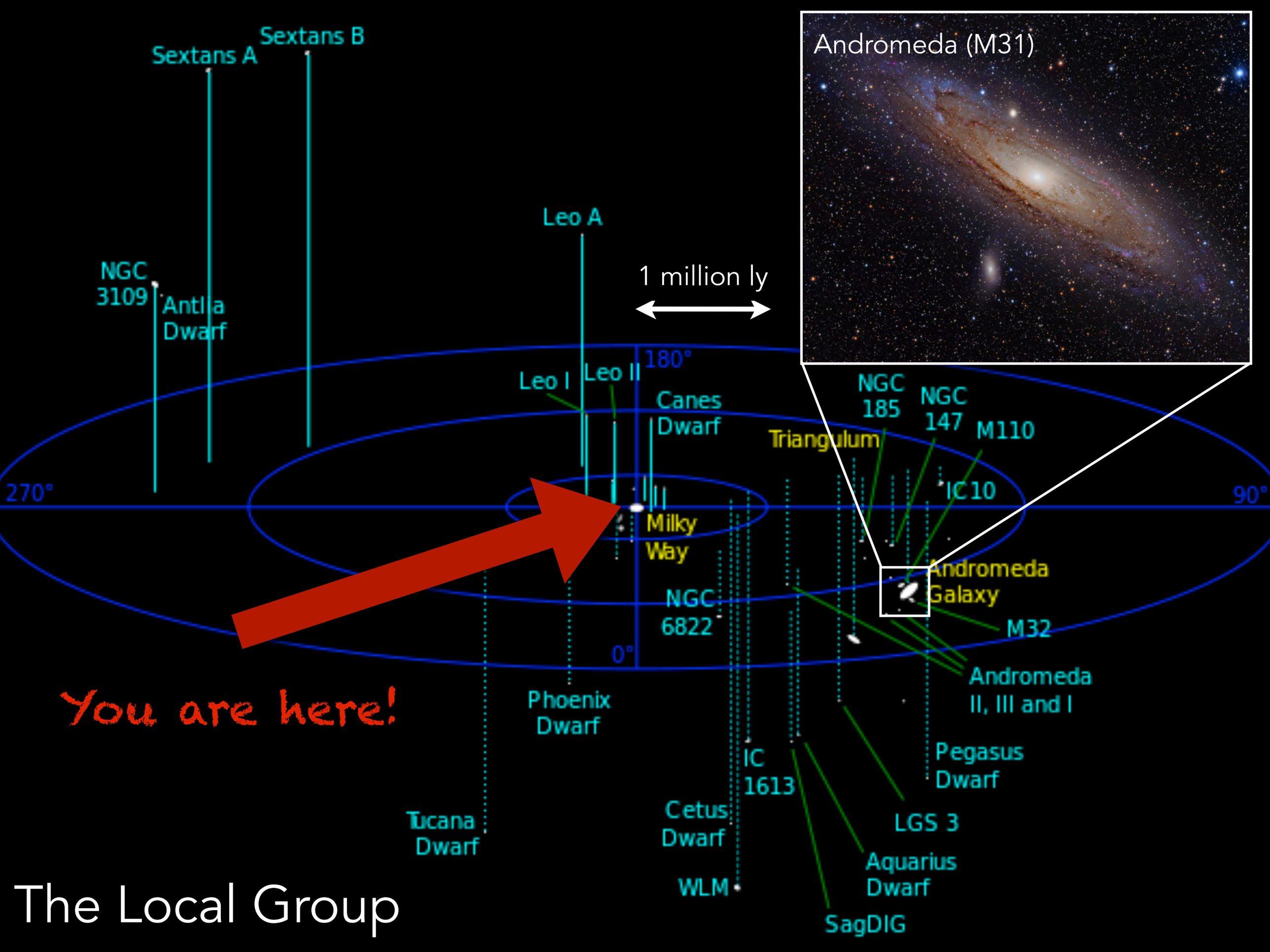
Lacaille 9352

≃10.6 light years

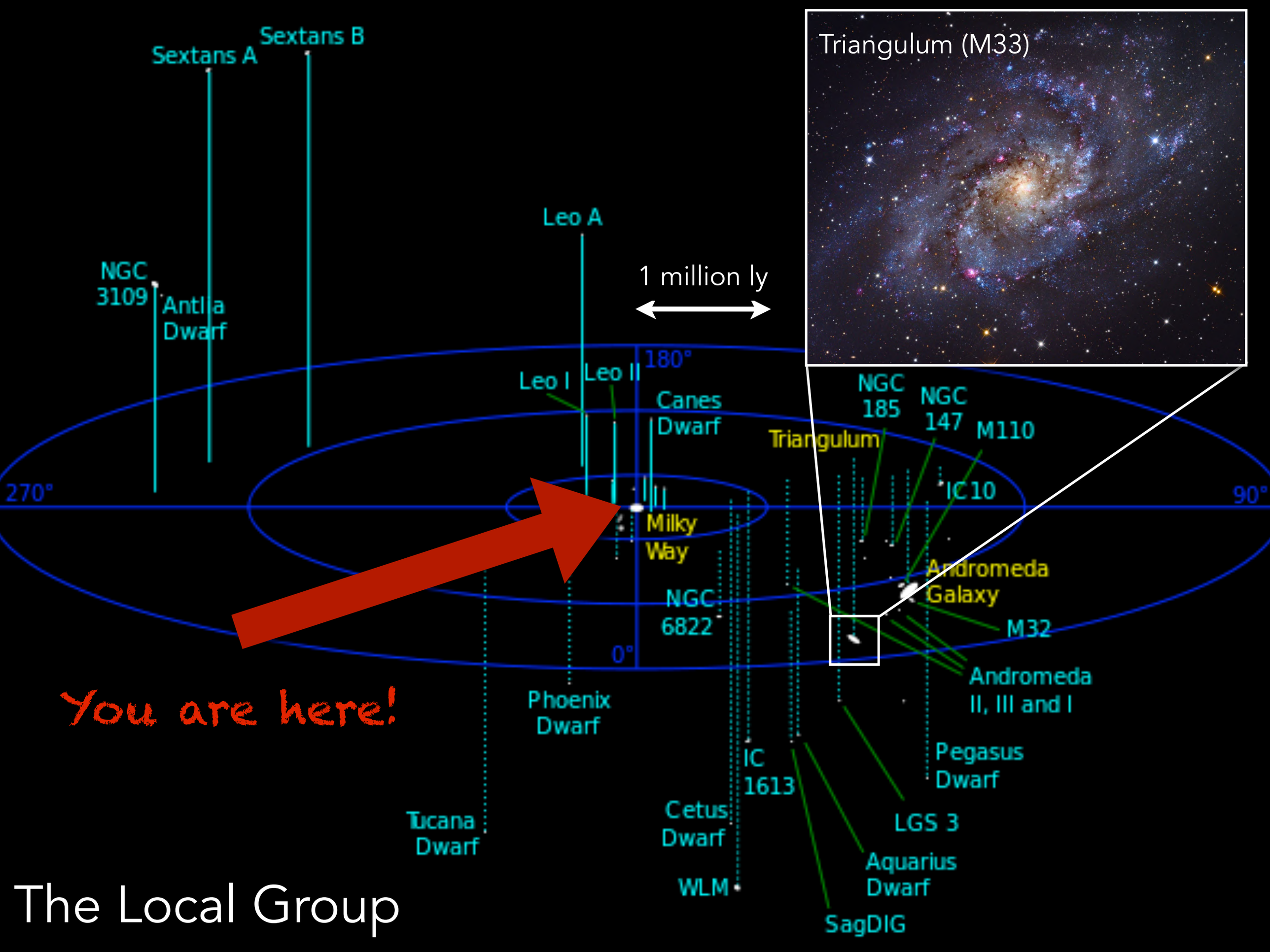

Cygnus Arm
Carina-Sagittarius Arm
Norma Arm
Crux-Scutum Arm
10 000
20 000
Perseus Arm
<- Our Solar System
000
Local or Orion Arm
You are here!
40 000
10^21 m
≃106 000 light years

The Local Group

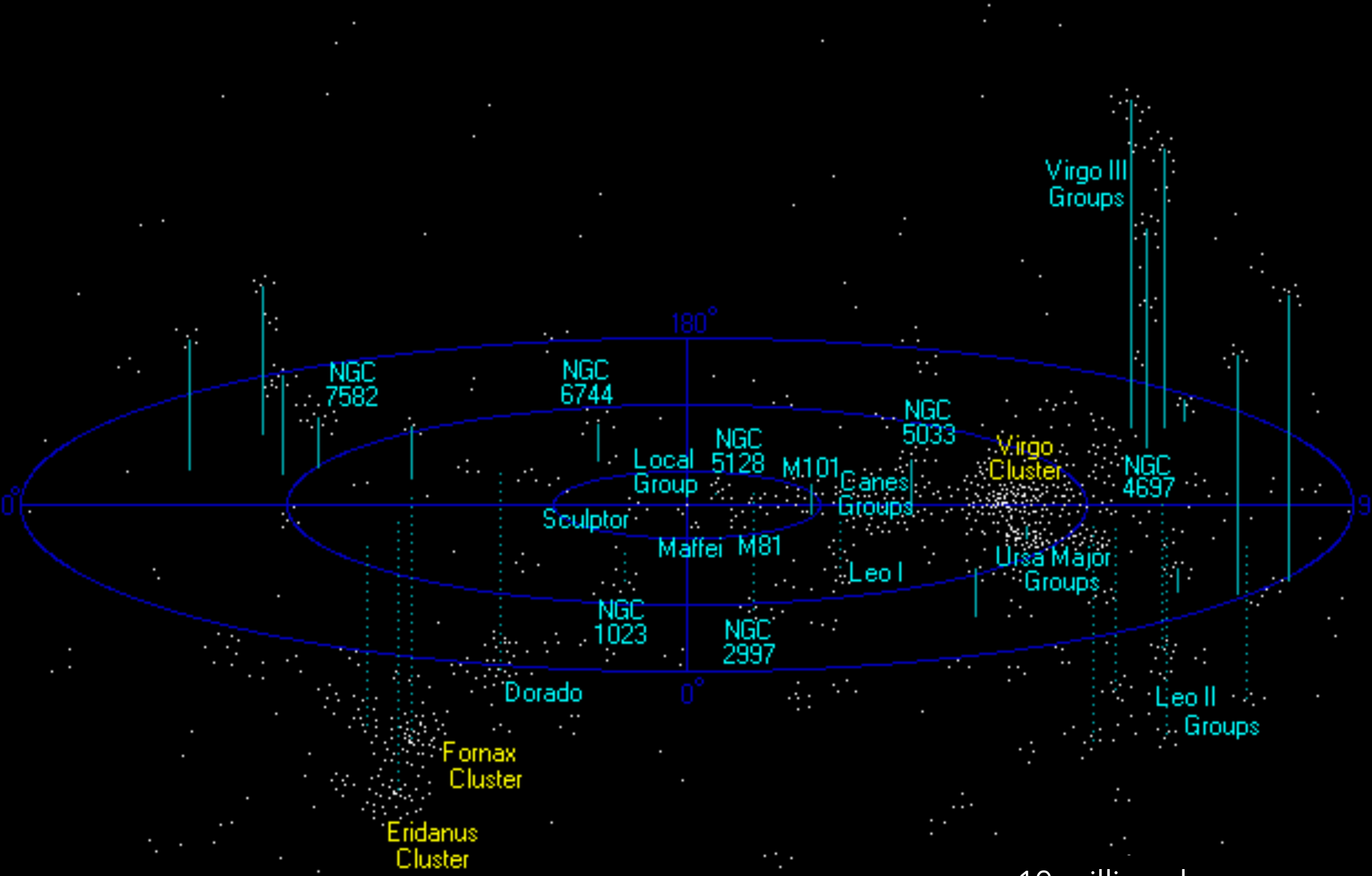




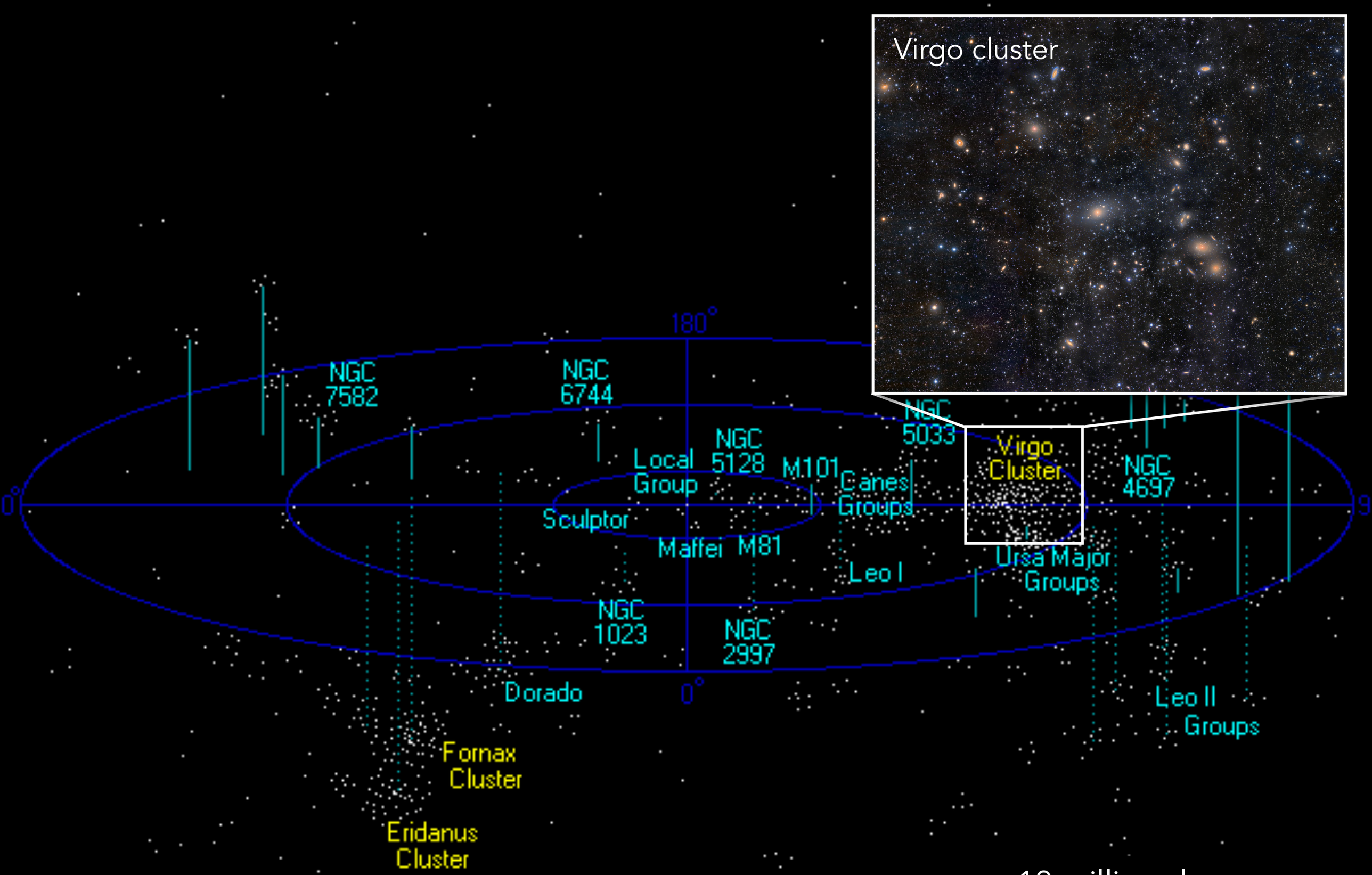
The Local Group



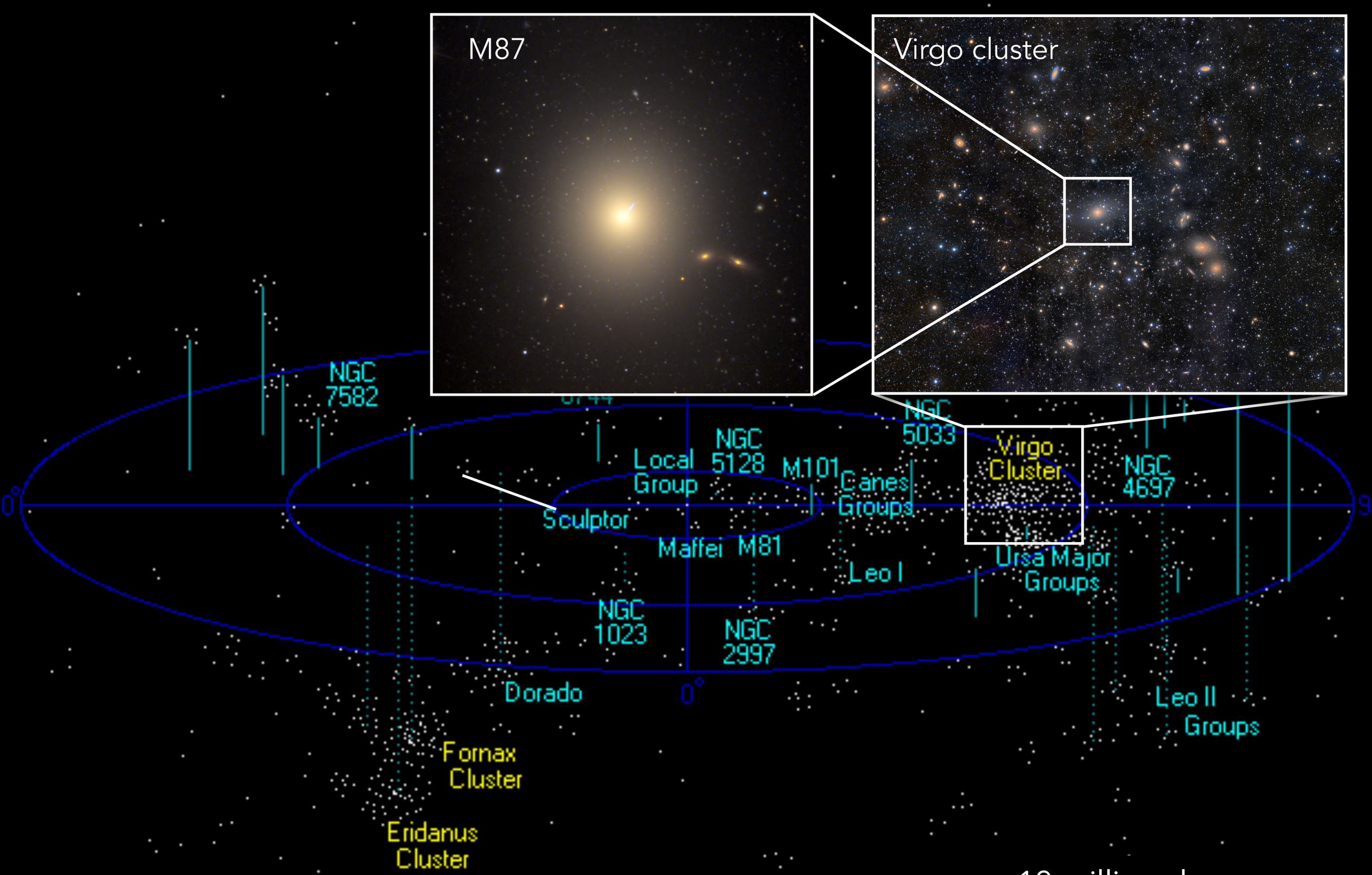
The Local Group



The Virgo Supercluster

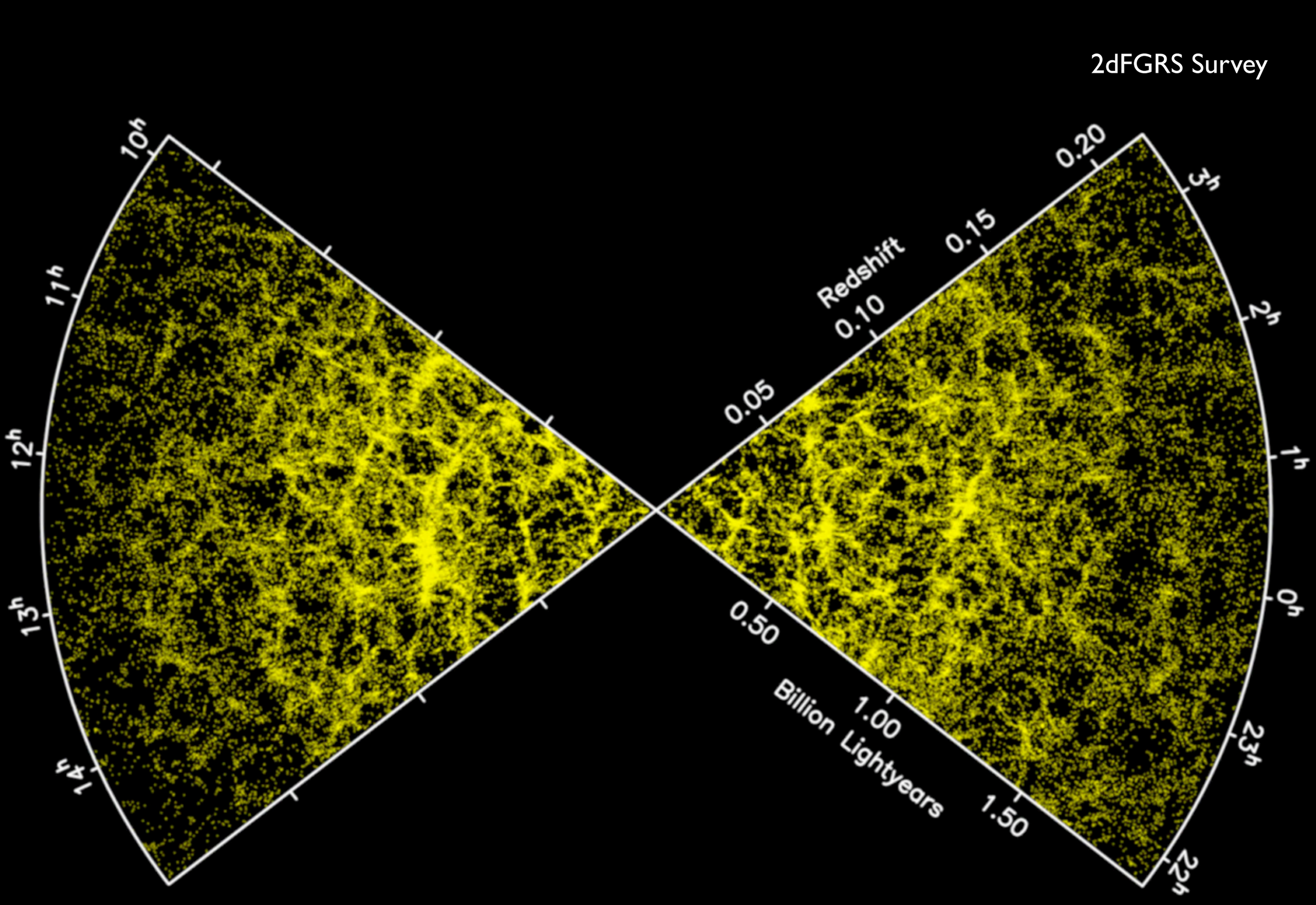


The Virgo Supercluster



The Virgo Supercluster

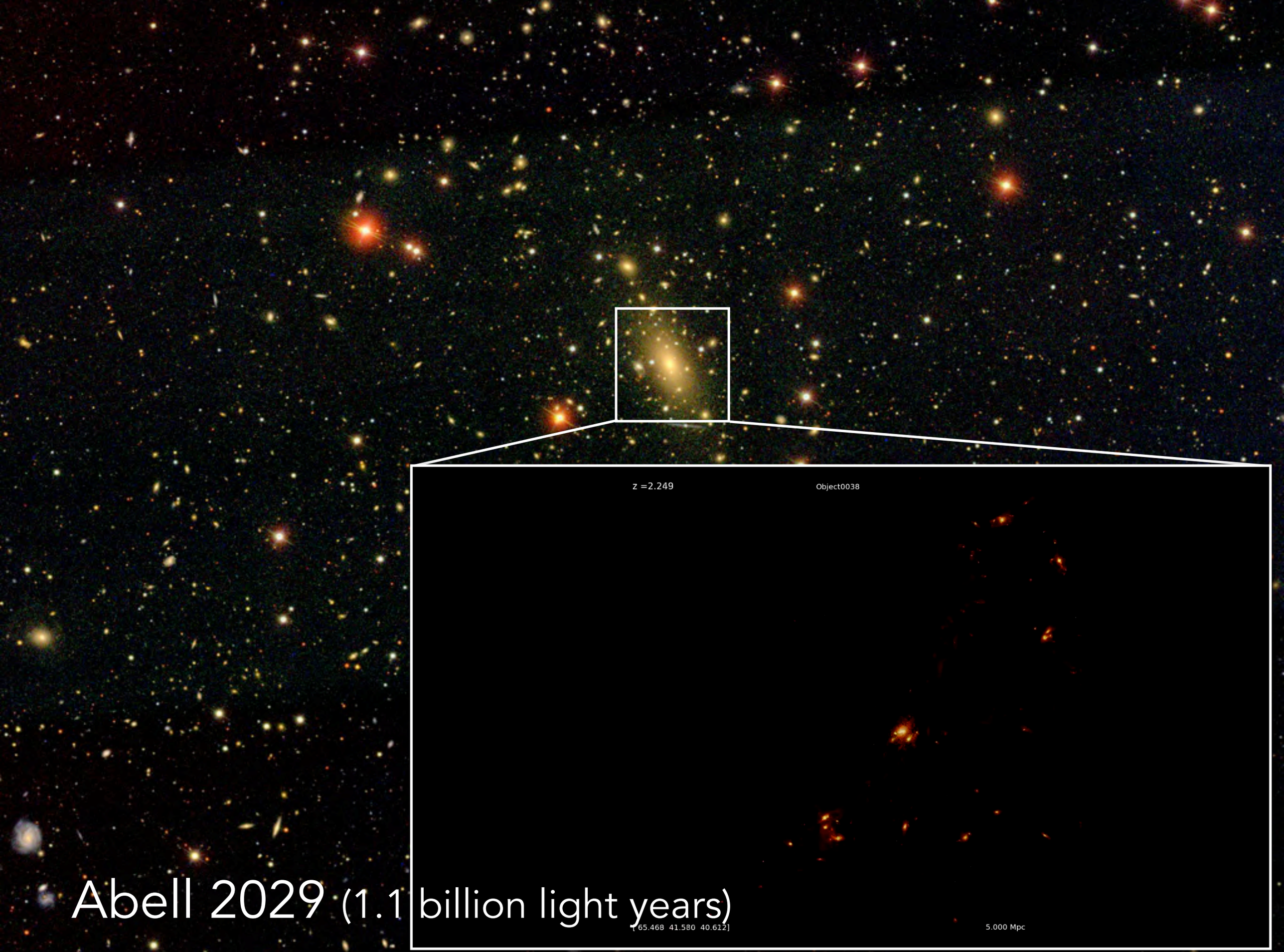
2dFGRS Survey



The large scale structure of the universe

Abell 2199 (429 000 000 light years)

Abell 2029 (1.1 billion light years)

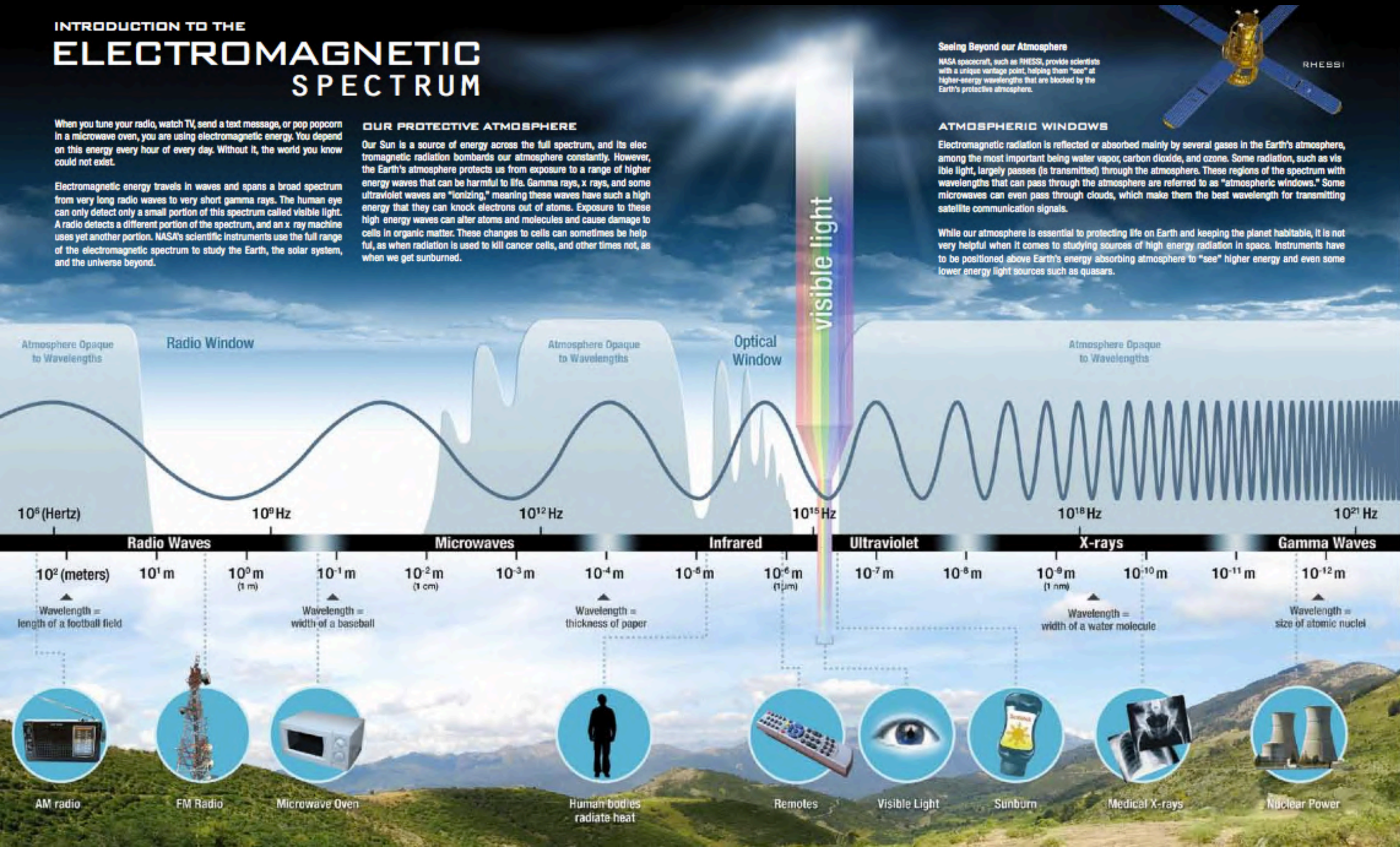


Abell 2029 (1.1 billion light years)

Abell 1689 (2.2 billion light years)

Light emits at optical “colors”…

…but also in infrared, radio, …and X-ray!



Light emits at optical “colors”…

…but also in infrared, radio, …and X-ray!

INTRODUCTION TO THE

ELECTROMAGNETIC SPECTRUM

When you tune your radio, watch TV, send a text message, or pop popcorn in a microwave oven, you are using electromagnetic energy. You depend on this energy every hour of every day. Without it, the world you know could not exist.

Electromagnetic energy travels in waves and spans a broad spectrum from very long radio waves to very short gamma rays. The human eye can only detect only a small portion of this spectrum called visible light. A radio detects a different portion of the spectrum, and an x ray machine uses yet another portion. NASA's scientific instruments use the full range of the electromagnetic spectrum to study the Earth, the solar system, and the universe beyond.

OUR PROTECTIVE ATMOSPHERE

Our Sun is a source of energy across the full spectrum, and its elec tromagnetic radiation bombards our atmosphere constantly. However, the Earth's atmosphere protects us from exposure to a range of higher energy waves that can be harmful to life. Gamma rays, x rays, and some ultraviolet waves are "ionizing," meaning these waves have such a high energy that they can knock electrons out of atoms. Exposure to these high energy waves can alter atoms and molecules and cause damage to cells in organic matter. These changes to cells can sometimes be help ful, as when radiation is used to kill cancer cells, and other times not, as when we get sunburned.

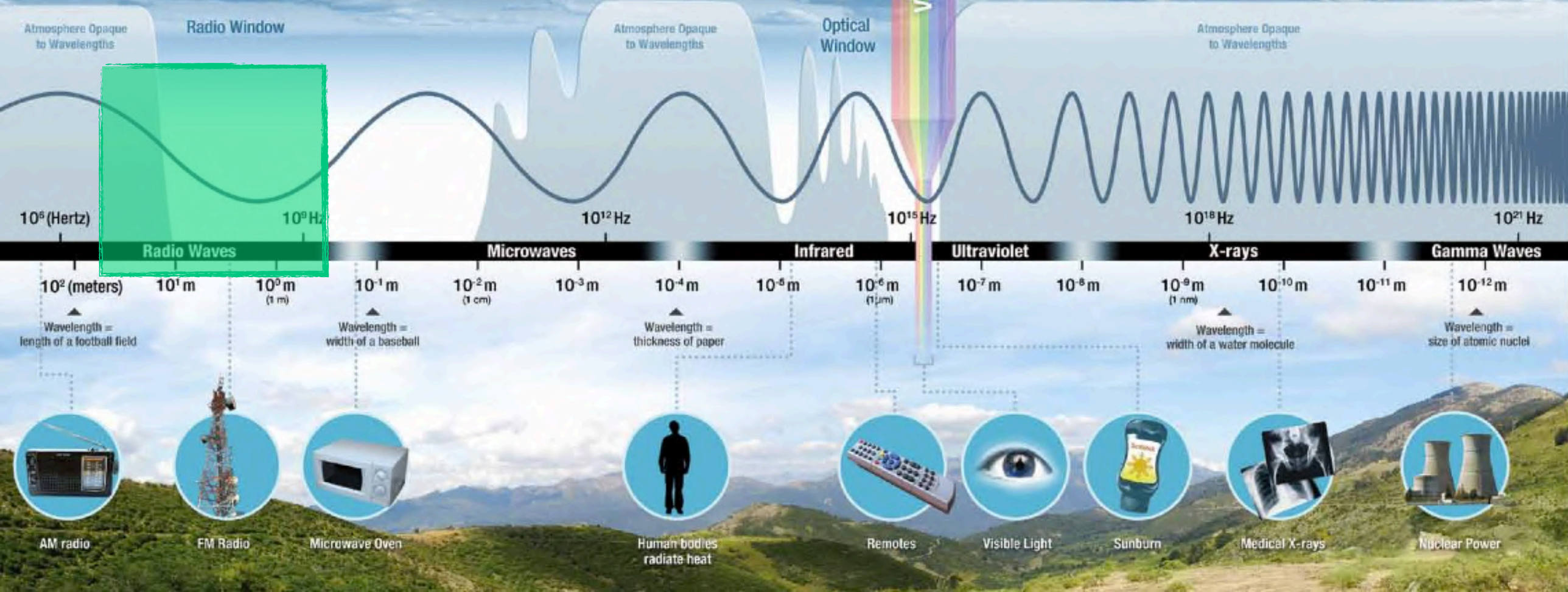
Seeing Beyond our Atmosphere

NASA spacecraft, such as RHESSI, provide scientists with a unique vantage point, helping them "see" at higher-energy wavelengths that are blocked by the Earth's protective atmosphere.

ATMOSPHERIC WINDOWS

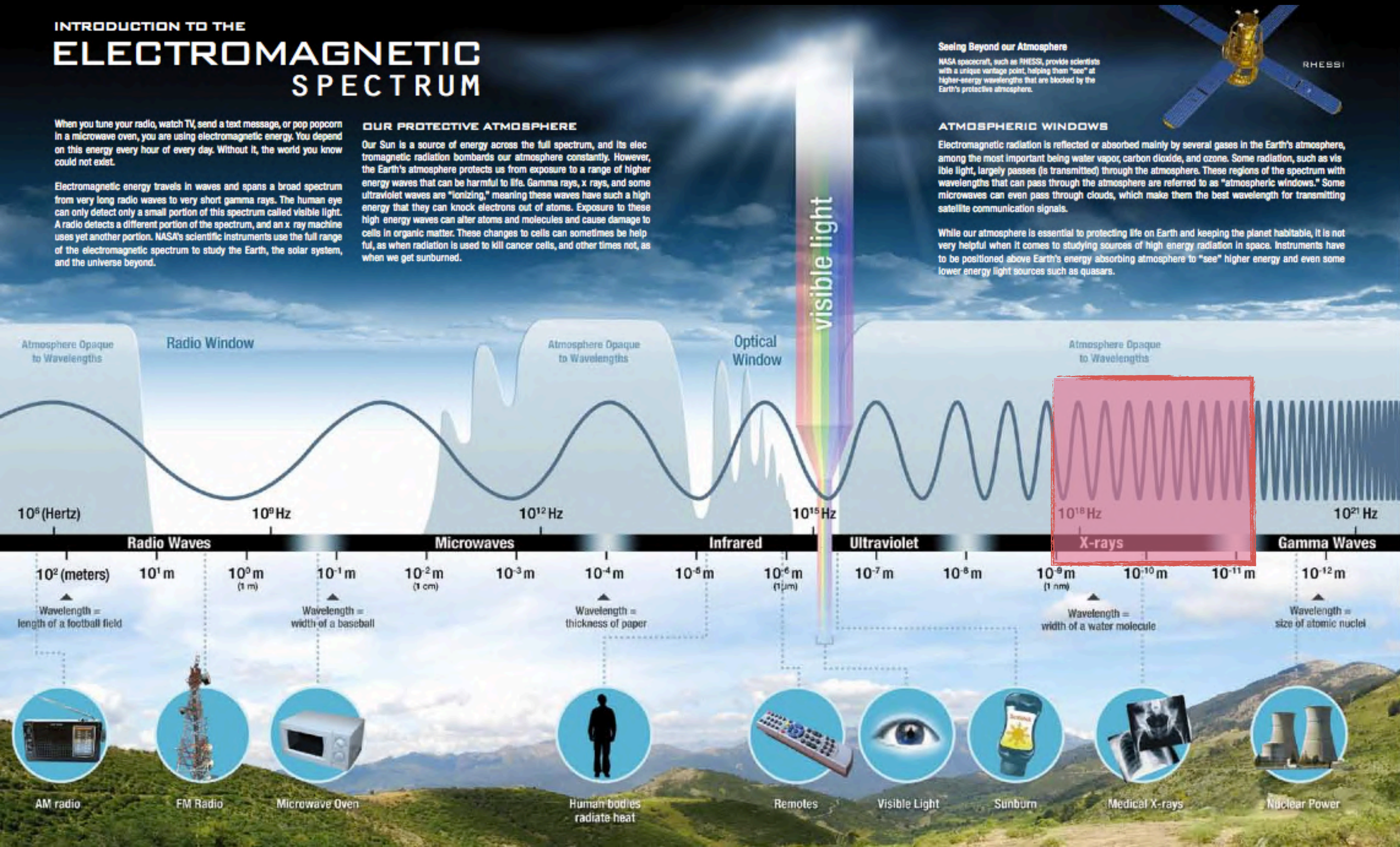
Electromagnetic radiation is reflected or absorbed mainly by several gases in the Earth's atmosphere, among the most important being water vapor, carbon dioxide, and ozone. Some radiation, such as vis ible light, largely passes (is transmitted) through the atmosphere. These regions of the spectrum with wavelengths that can pass through the atmosphere are referred to as "atmospheric windows." Some microwaves can even pass through clouds, which make them the best wavelength for transmitting satellite communication signals.

While our atmosphere is essential to protecting life on Earth and keeping the planet habitable, it is not very helpful when it comes to studying sources of high energy radiation in space. Instruments have to be positioned above Earth's energy absorbing atmosphere to "see" higher energy and even some lower energy light sources such as quasars.



Light emits at optical “colors”…

…but also in infrared, radio, …and X-ray!



Optical

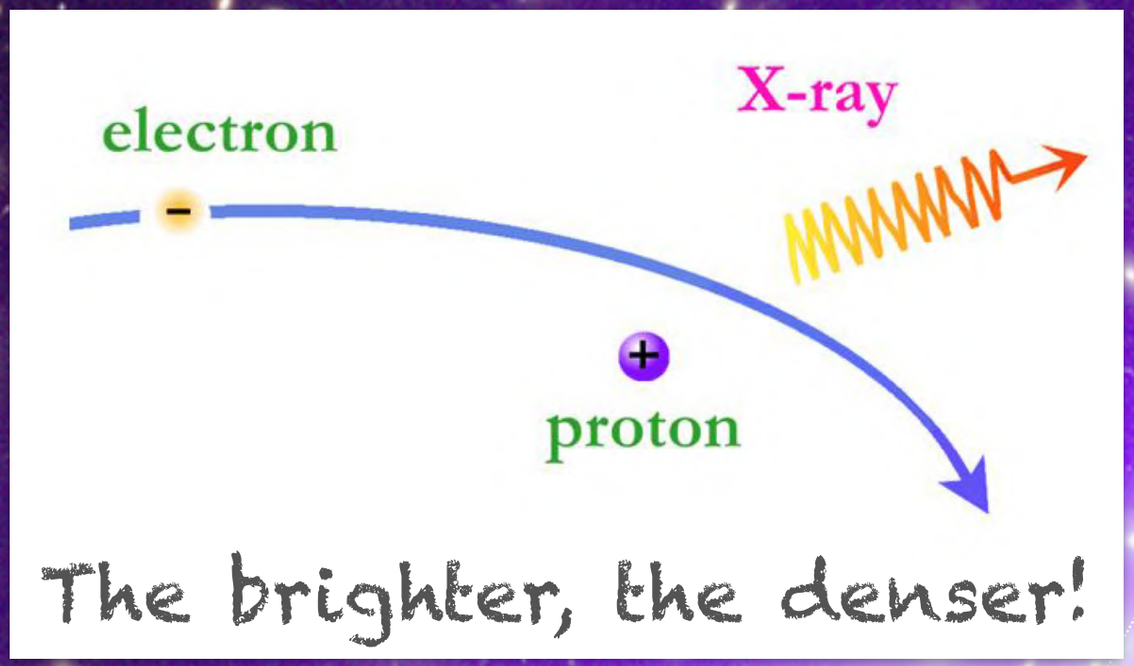
Abell 1689 (2 899 130 981 light years)

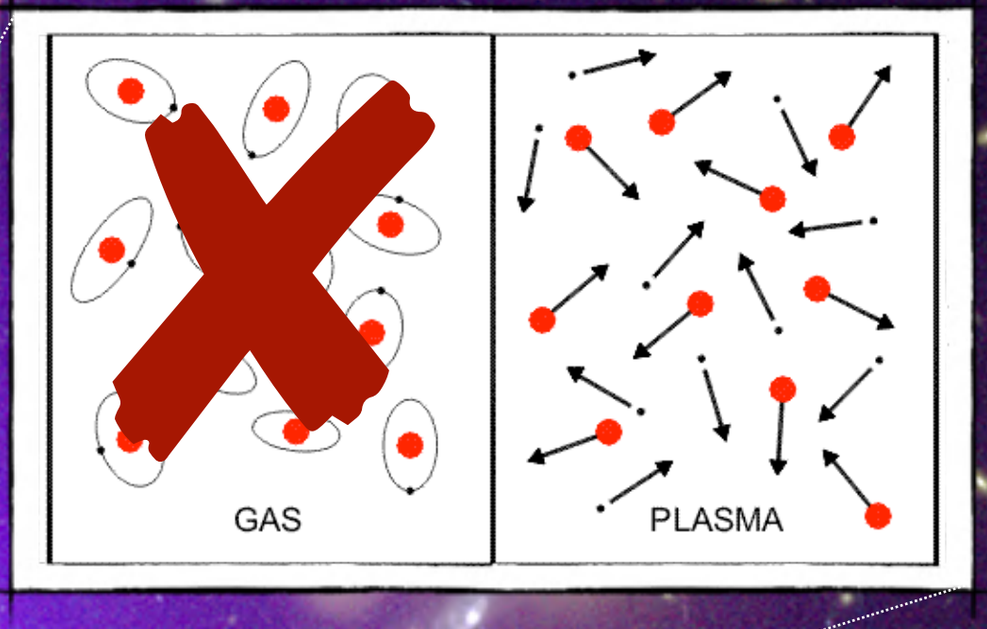
X-rays

Abell 1689 (2 899 130 981 light years)

X-rays

Optical





X-rays

Optical

Hot atmospheres… are hot!

(~10 to 100 million ºC)

Stars,
planets,
galaxies,…

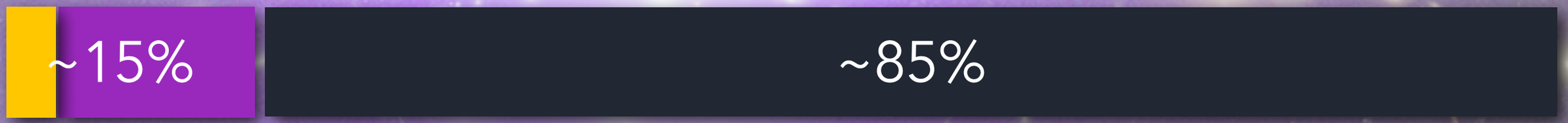
Stars,
planets,
galaxies,…

~20%

~80%

Stars, planets, galaxies,…

Hot atmospheres



Stars, planets, galaxies,…

Hot atmospheres

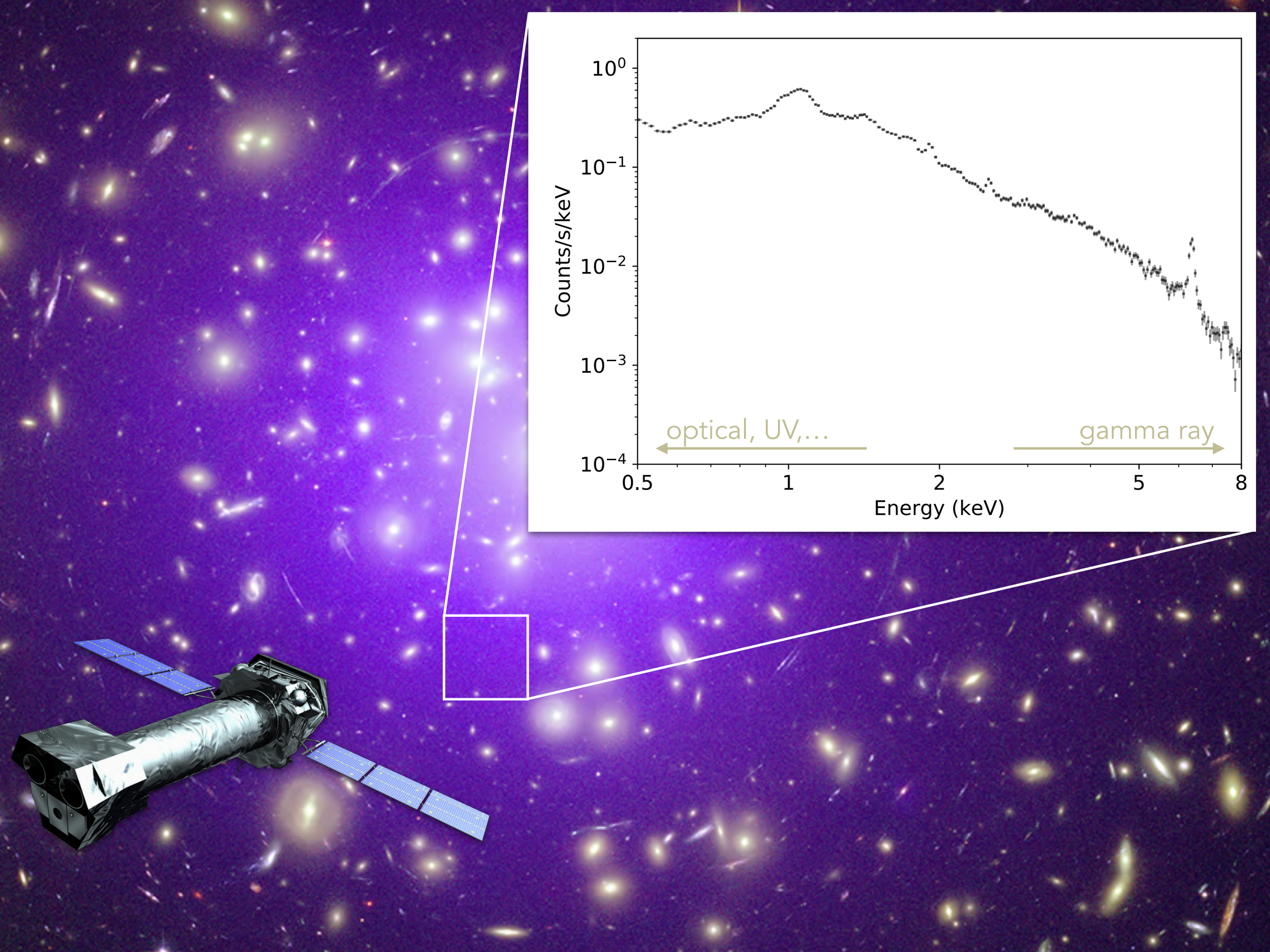
Dark matter

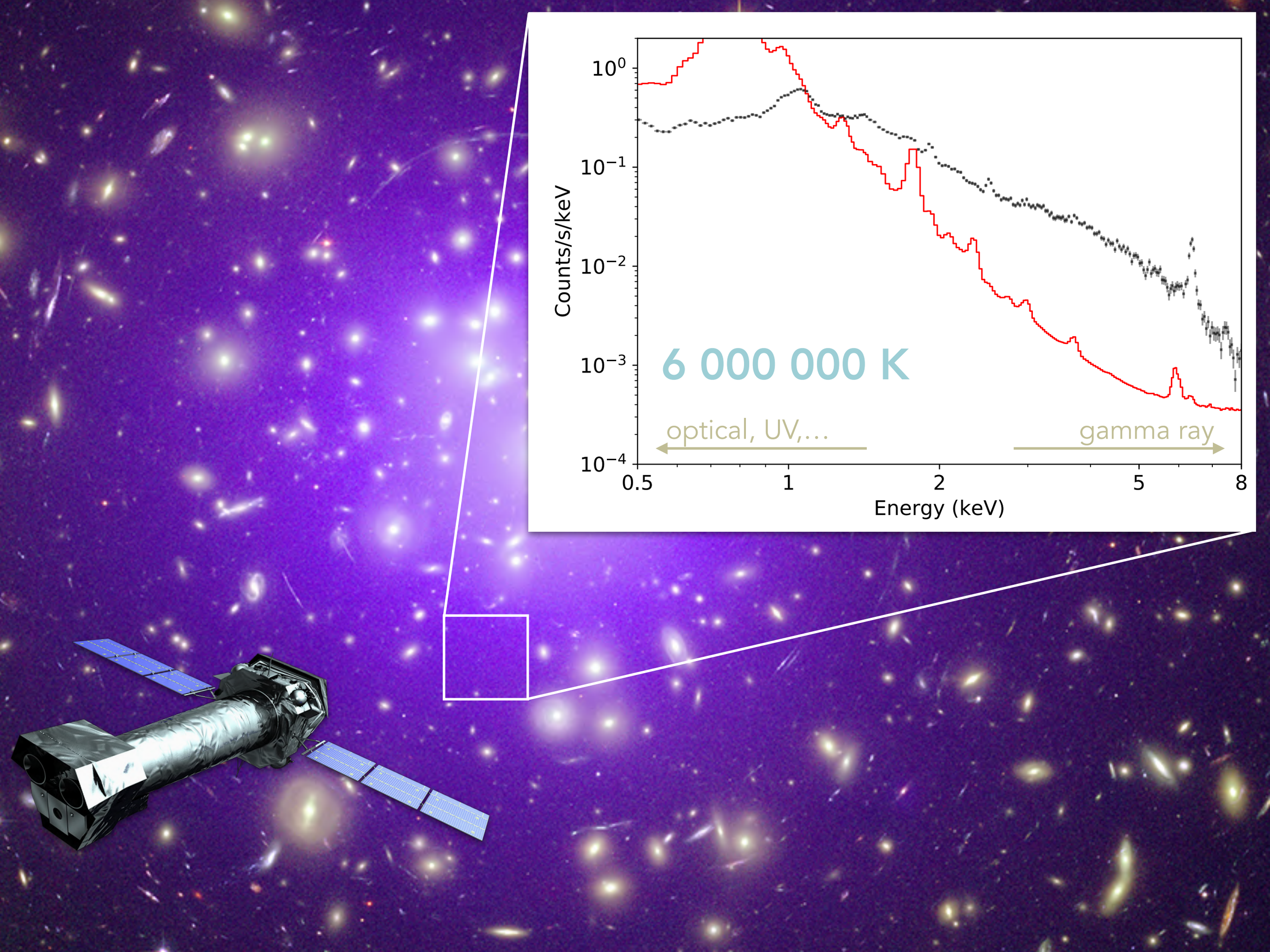
Fornax cluster (62 million light years)

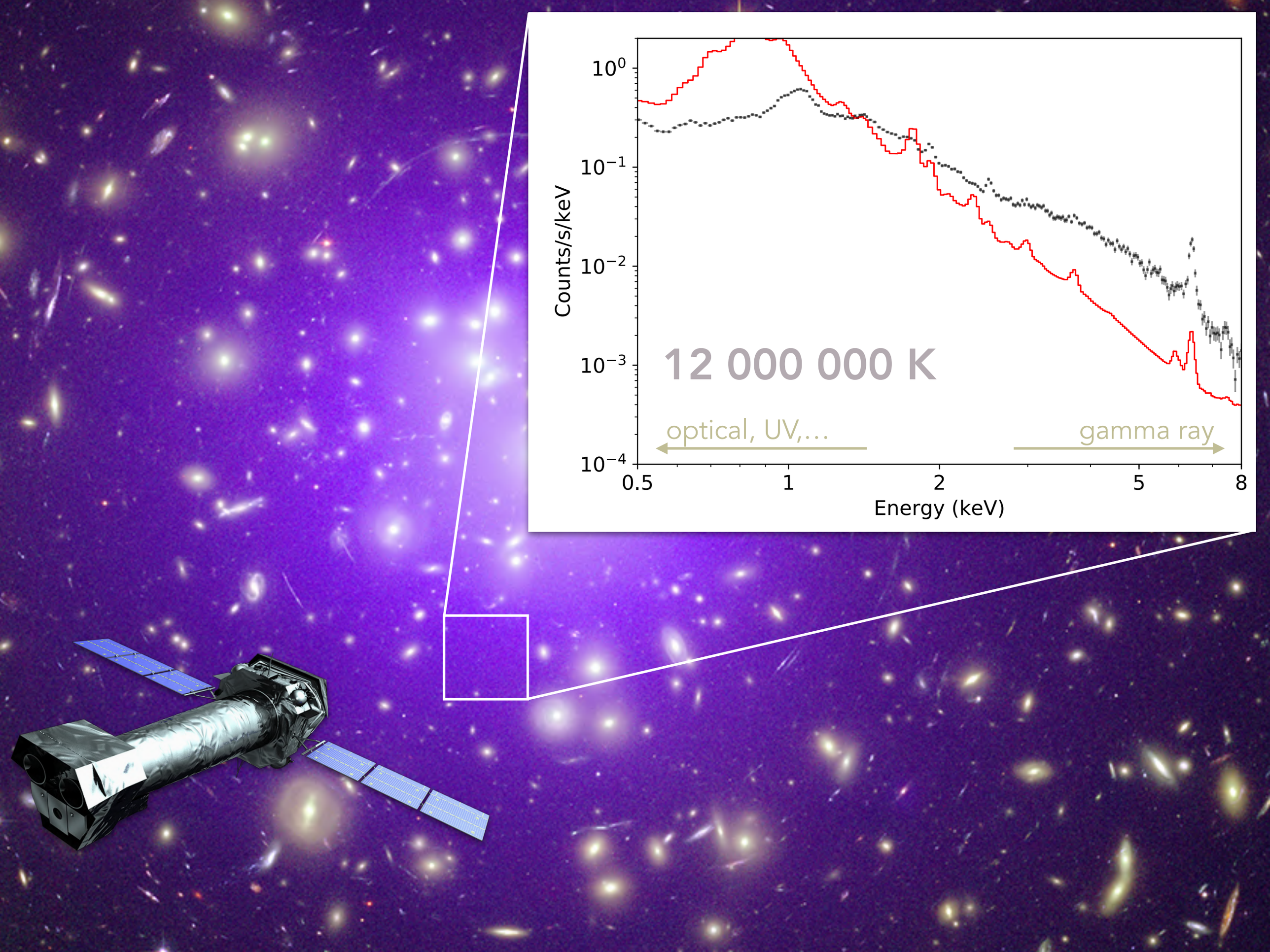
Hot atmospheres are studied in Budapest (ELTE)!

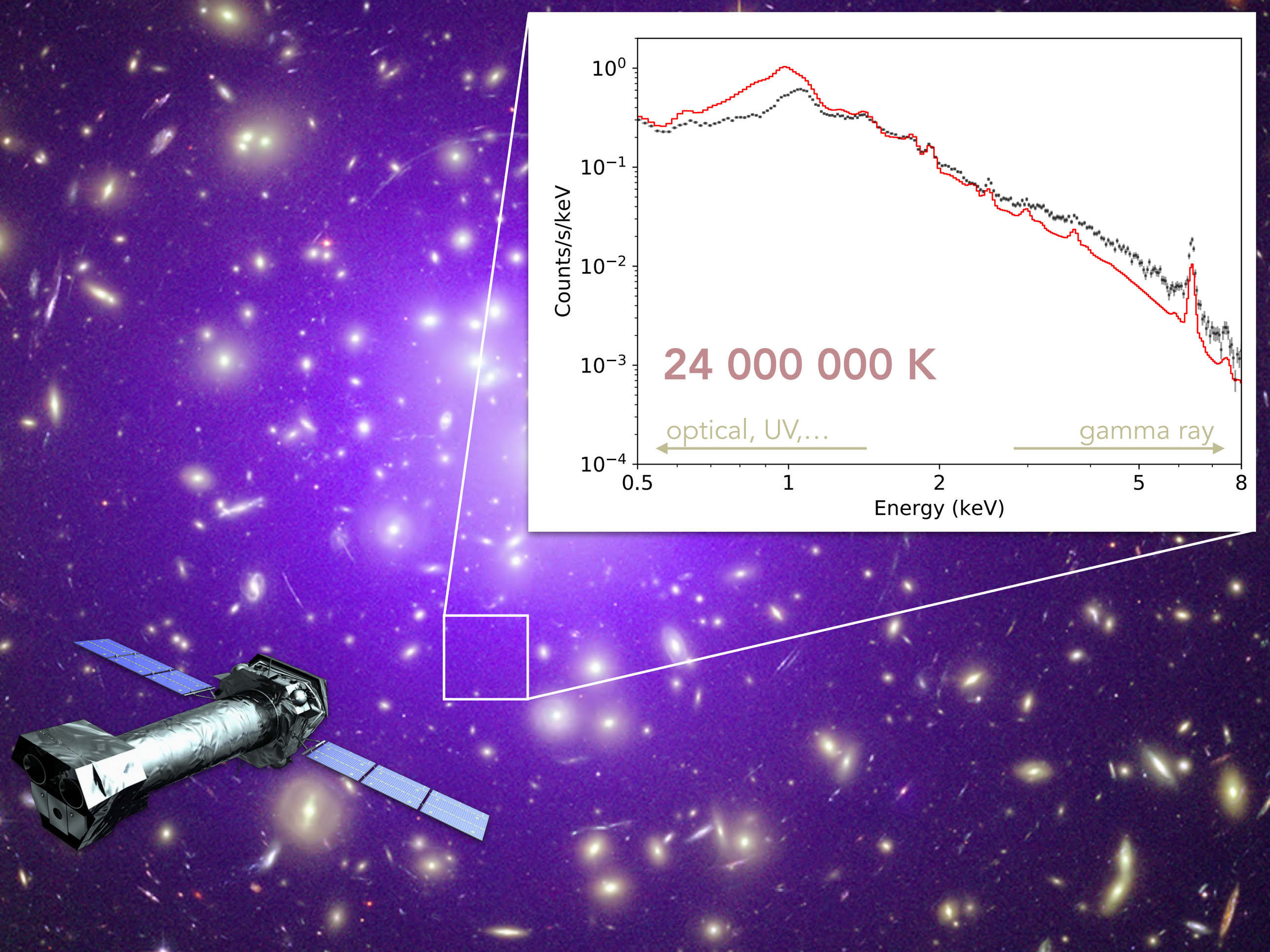
- **Temperature** (Kiran Lakhchaura, Norbert Werner)
- **Chemical composition** (François Mernier, Norbert Werner)
- **Cosmological simulations** (Nhut Truong)

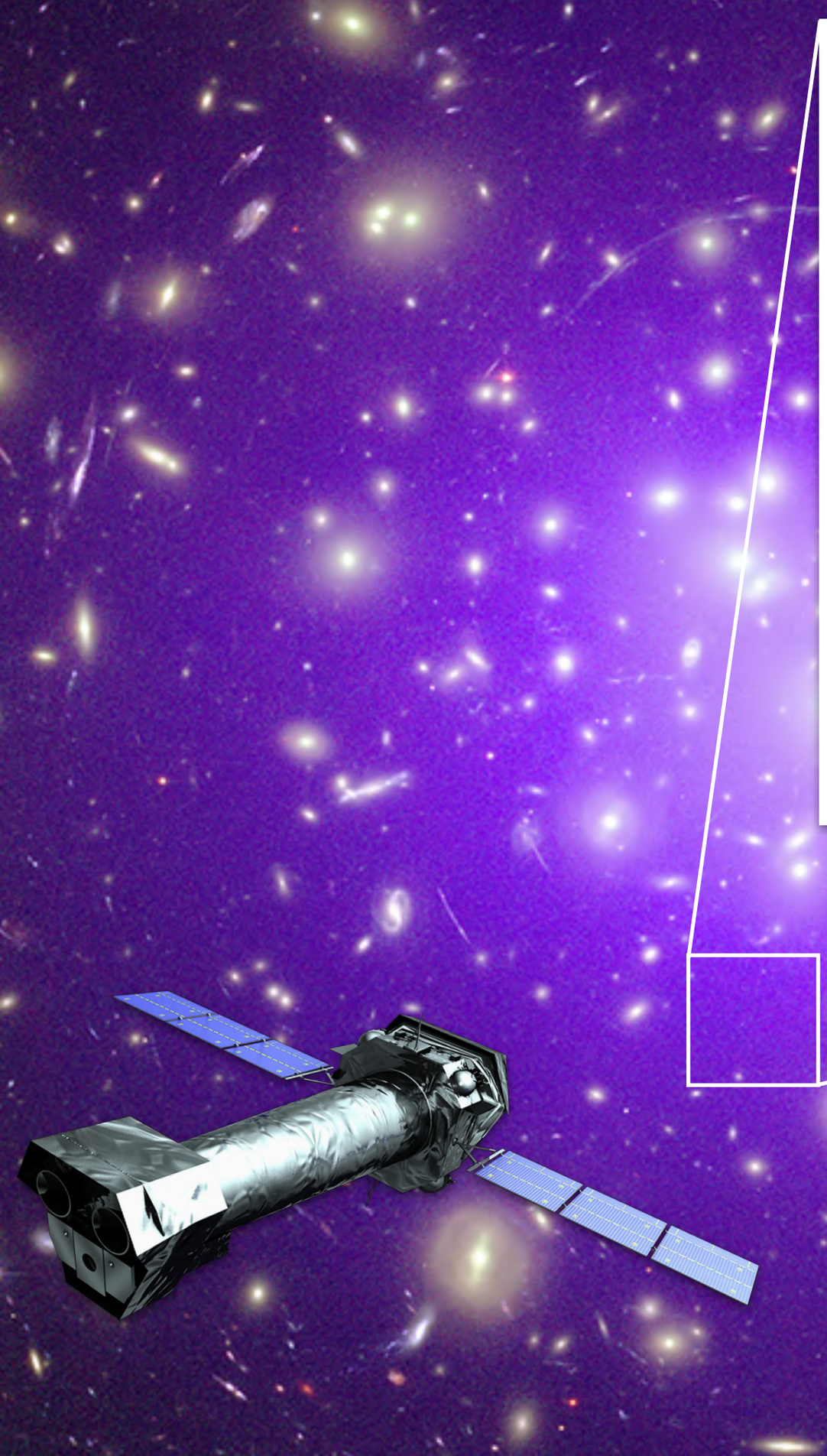
1. Temperature

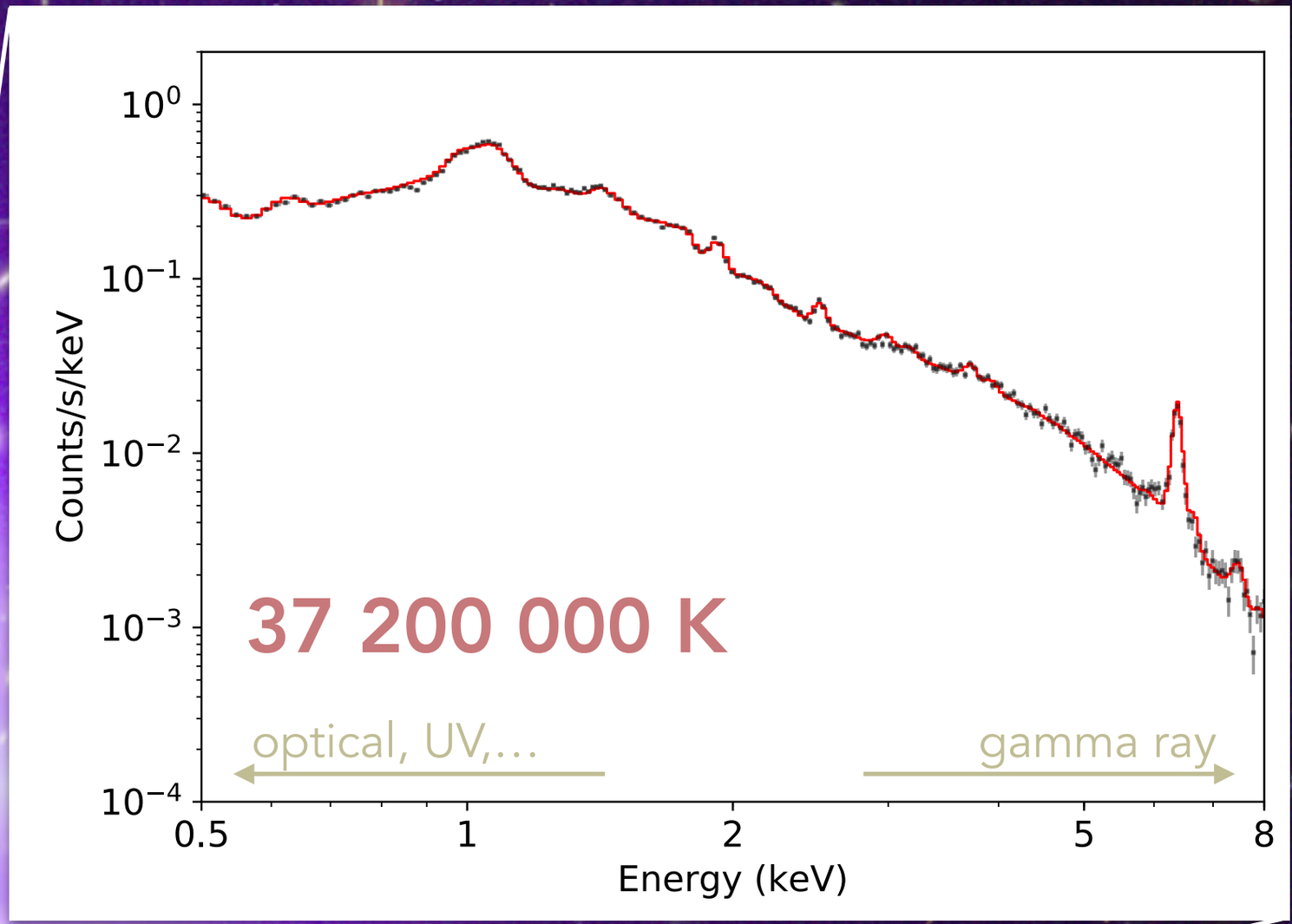

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)

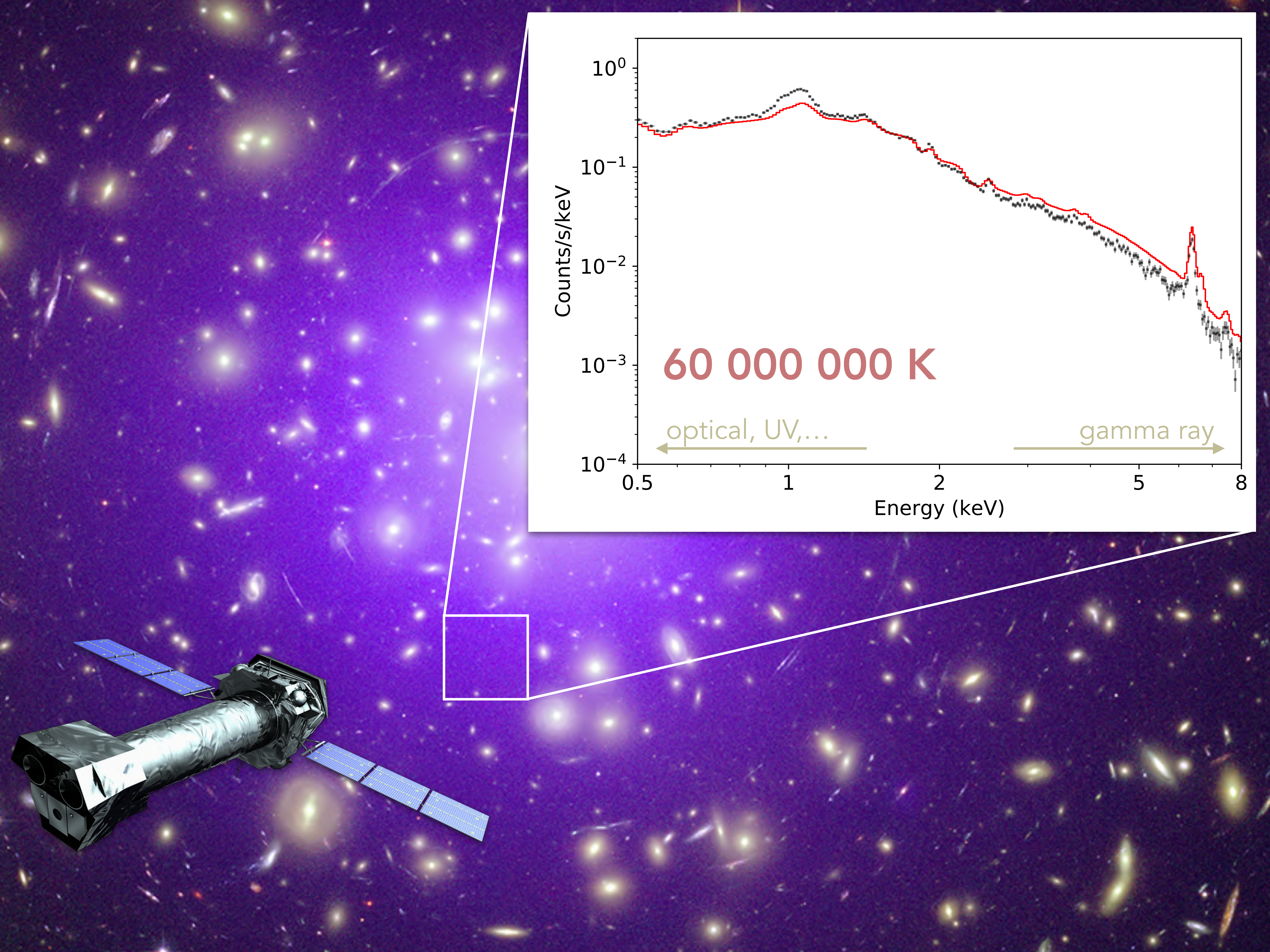

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
6 000 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)

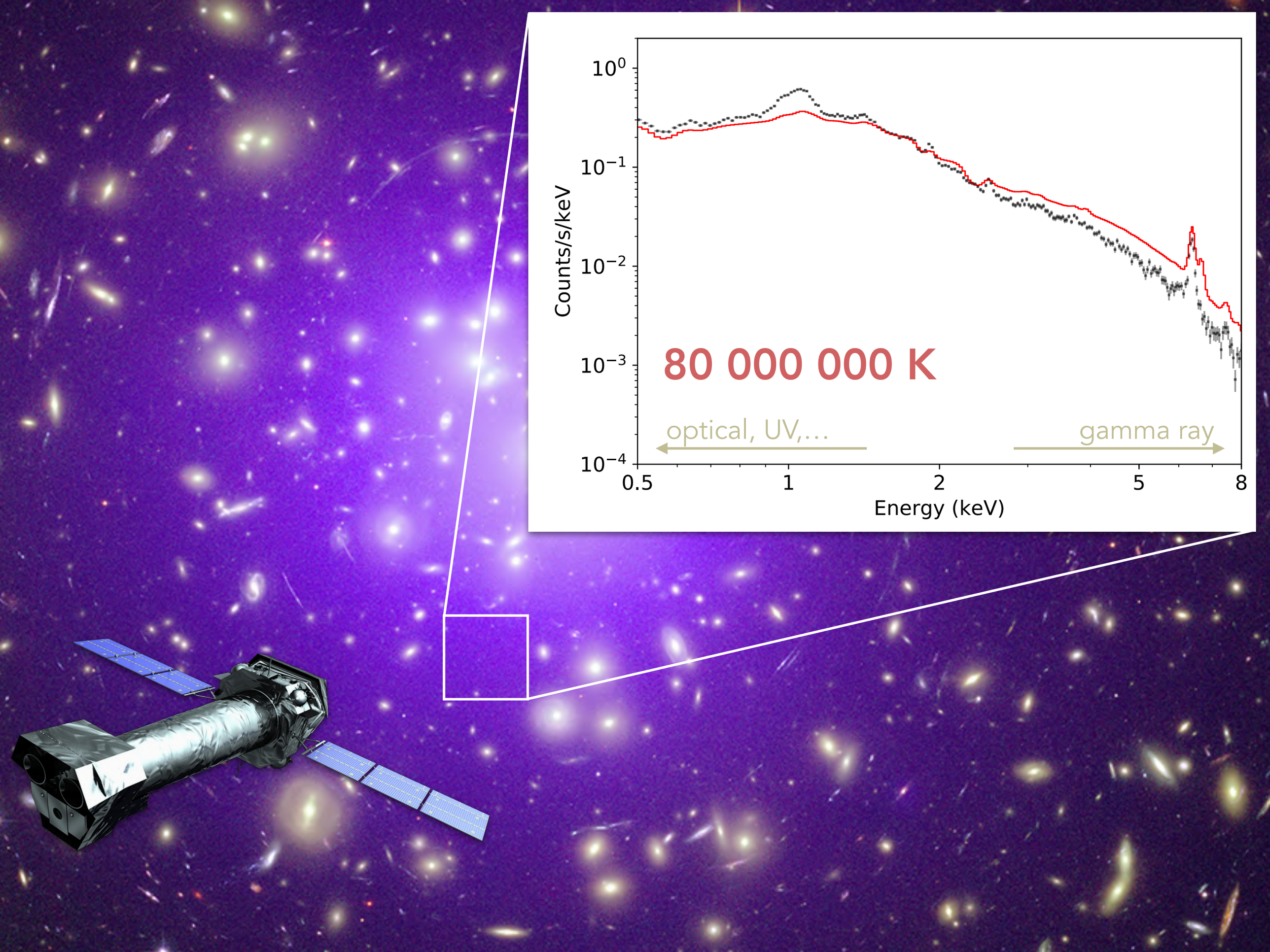

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
12 000 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)

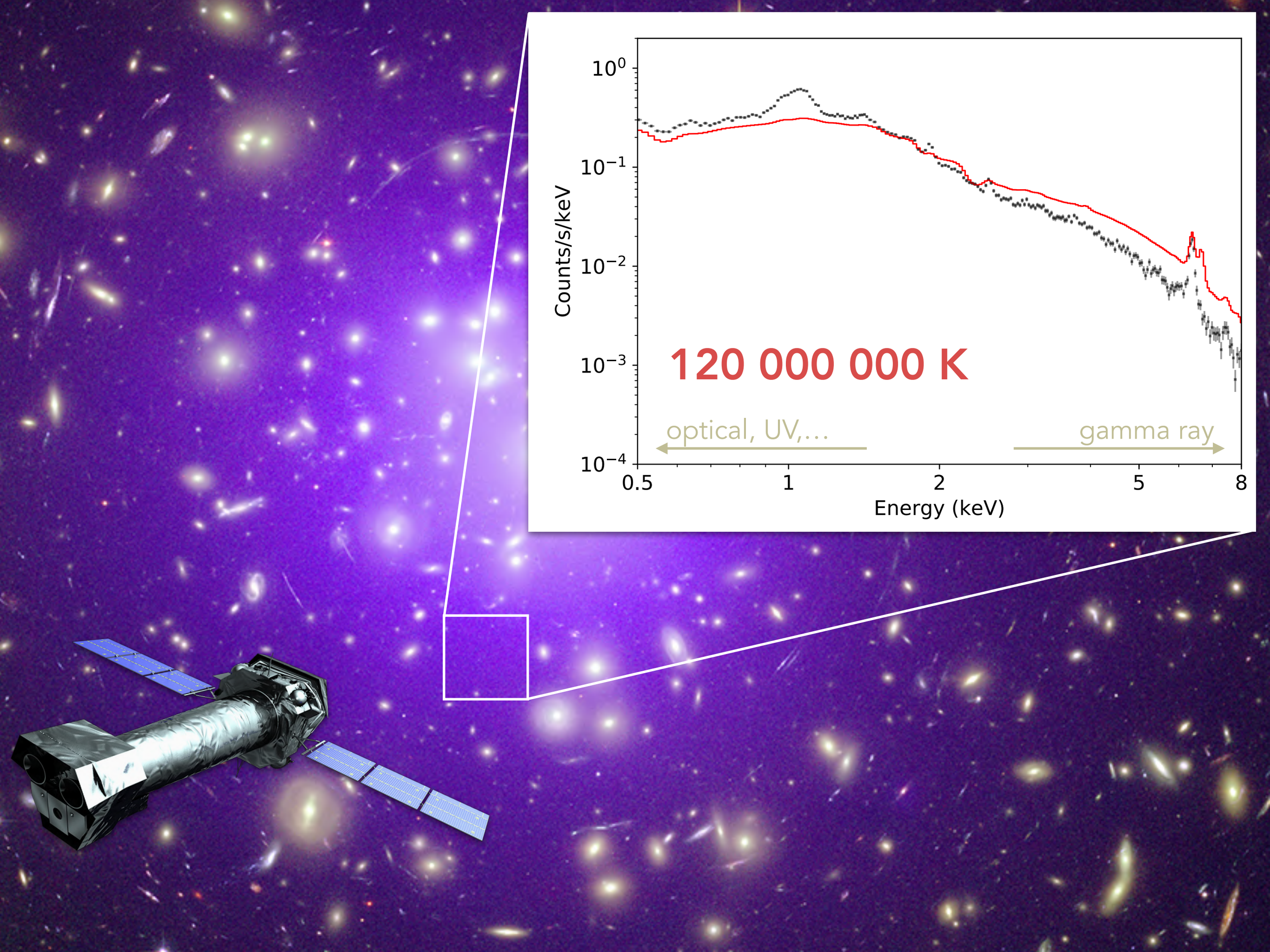

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
24 000 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)

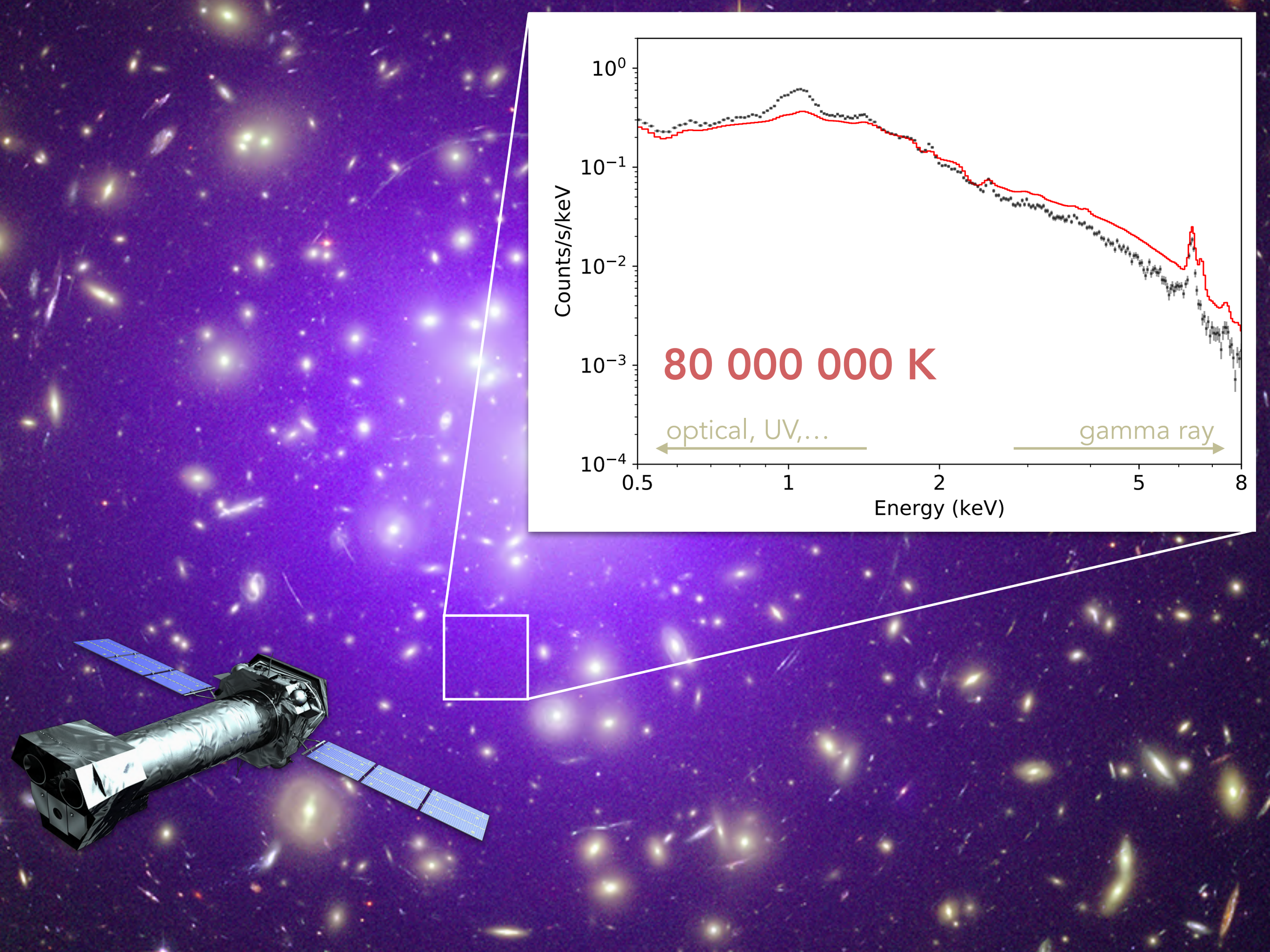


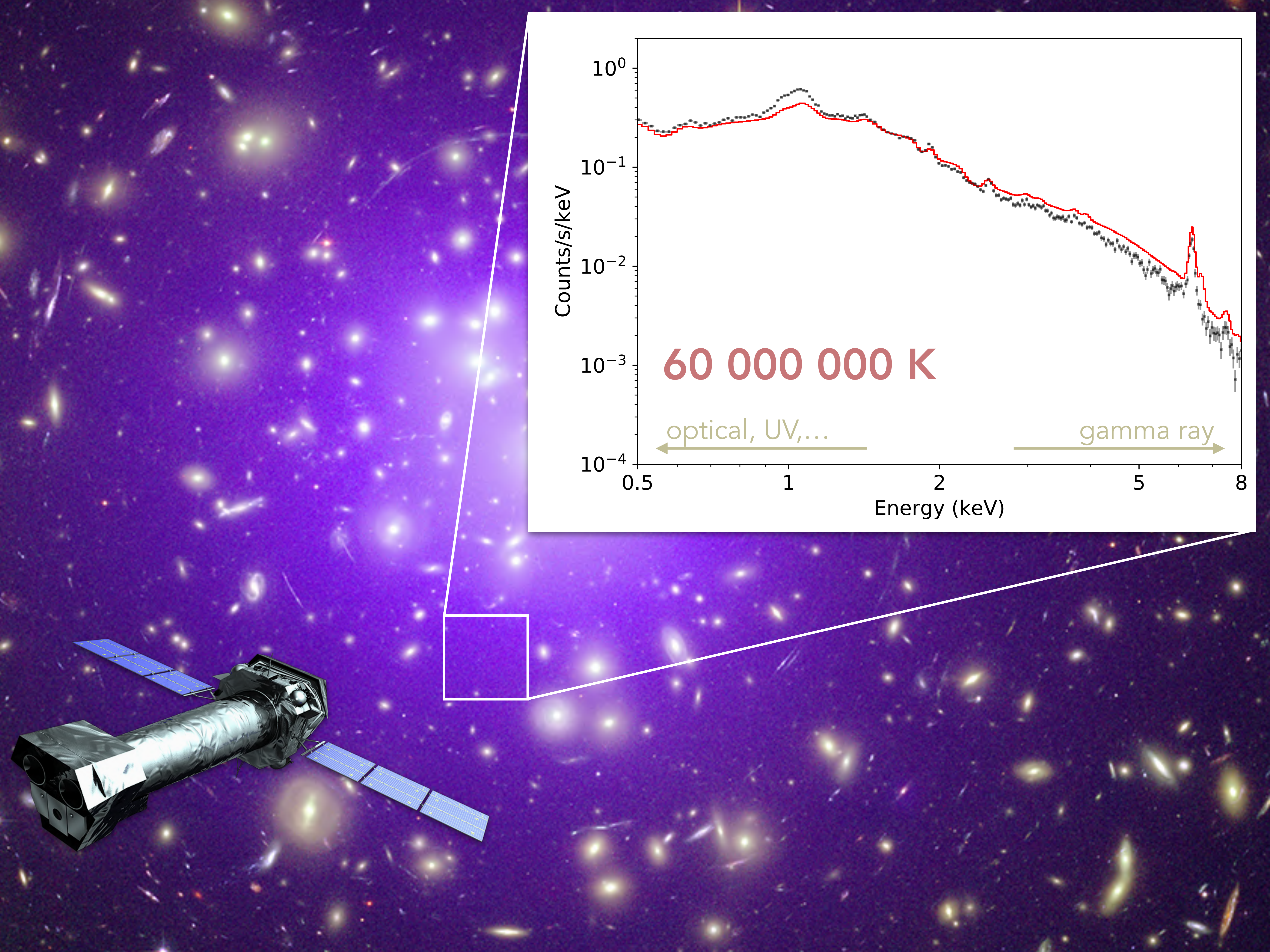

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Counts/s/keV
37 200 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)


Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
60 000 000 K
optical, UV,...
gamma ray
0.5
1
2
5
8
Energy (keV)

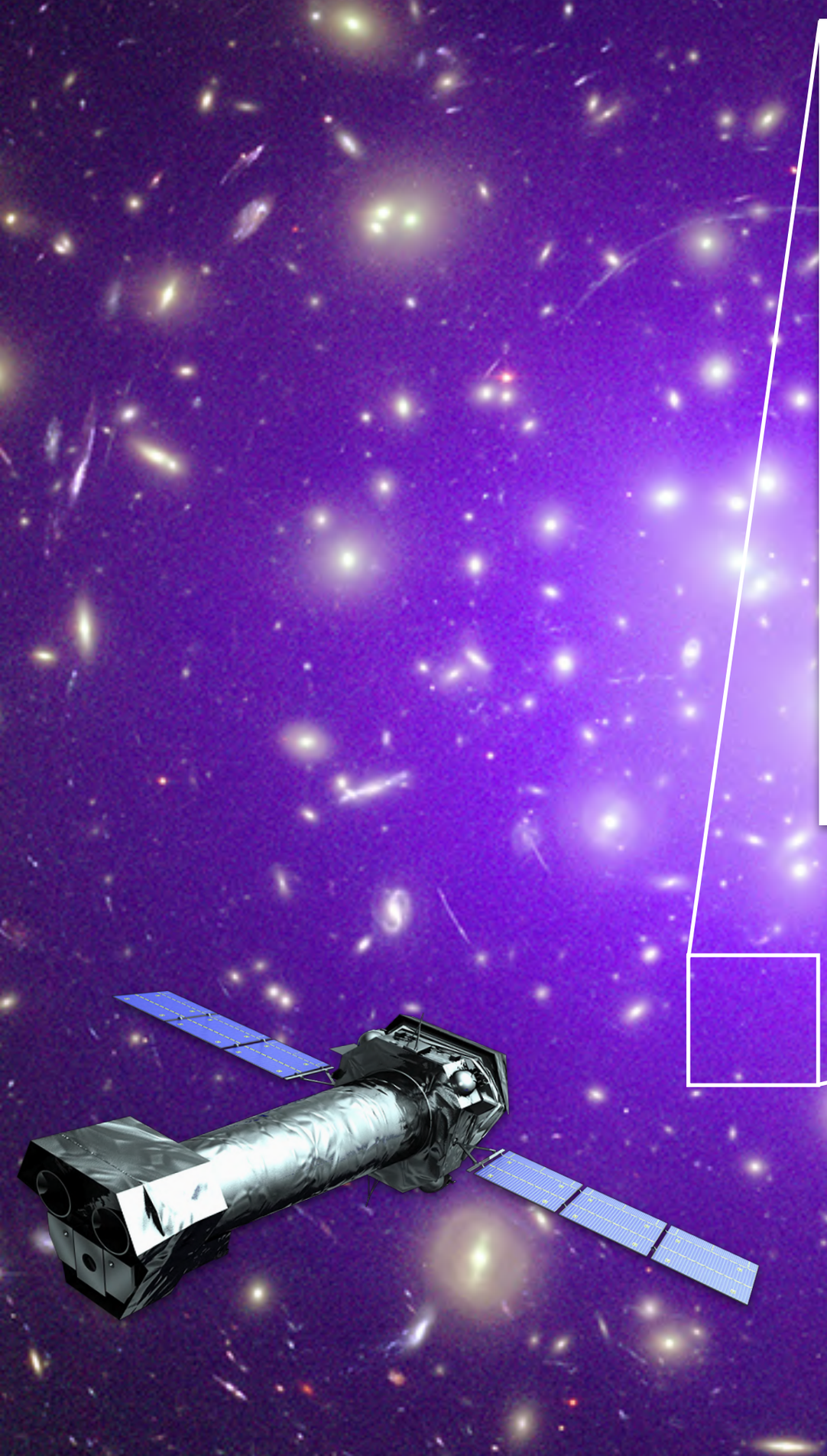

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1
2
5
8
Energy (keV)
80 000 000 K
optical, UV,…
gamma ray

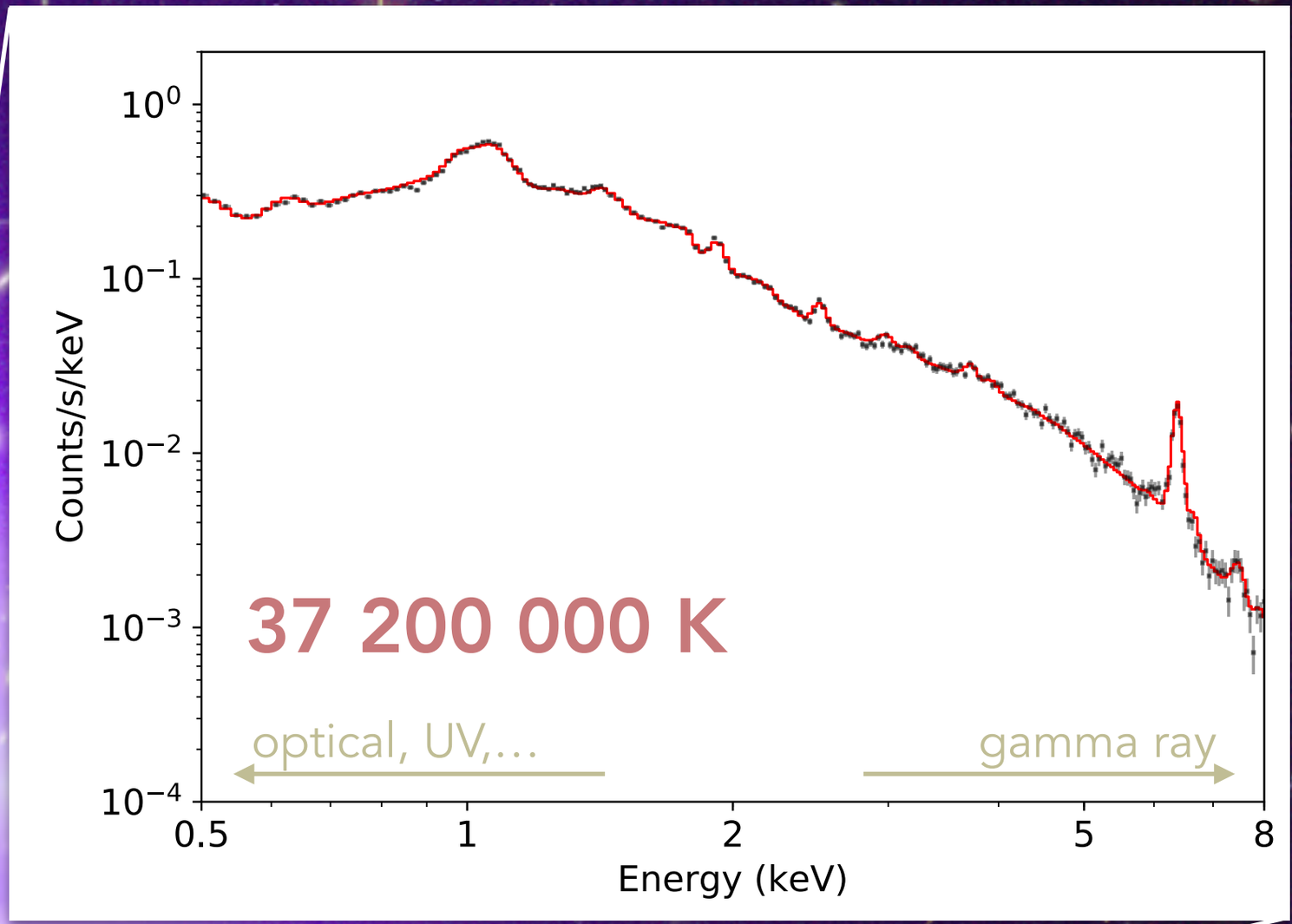

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
120 000 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)

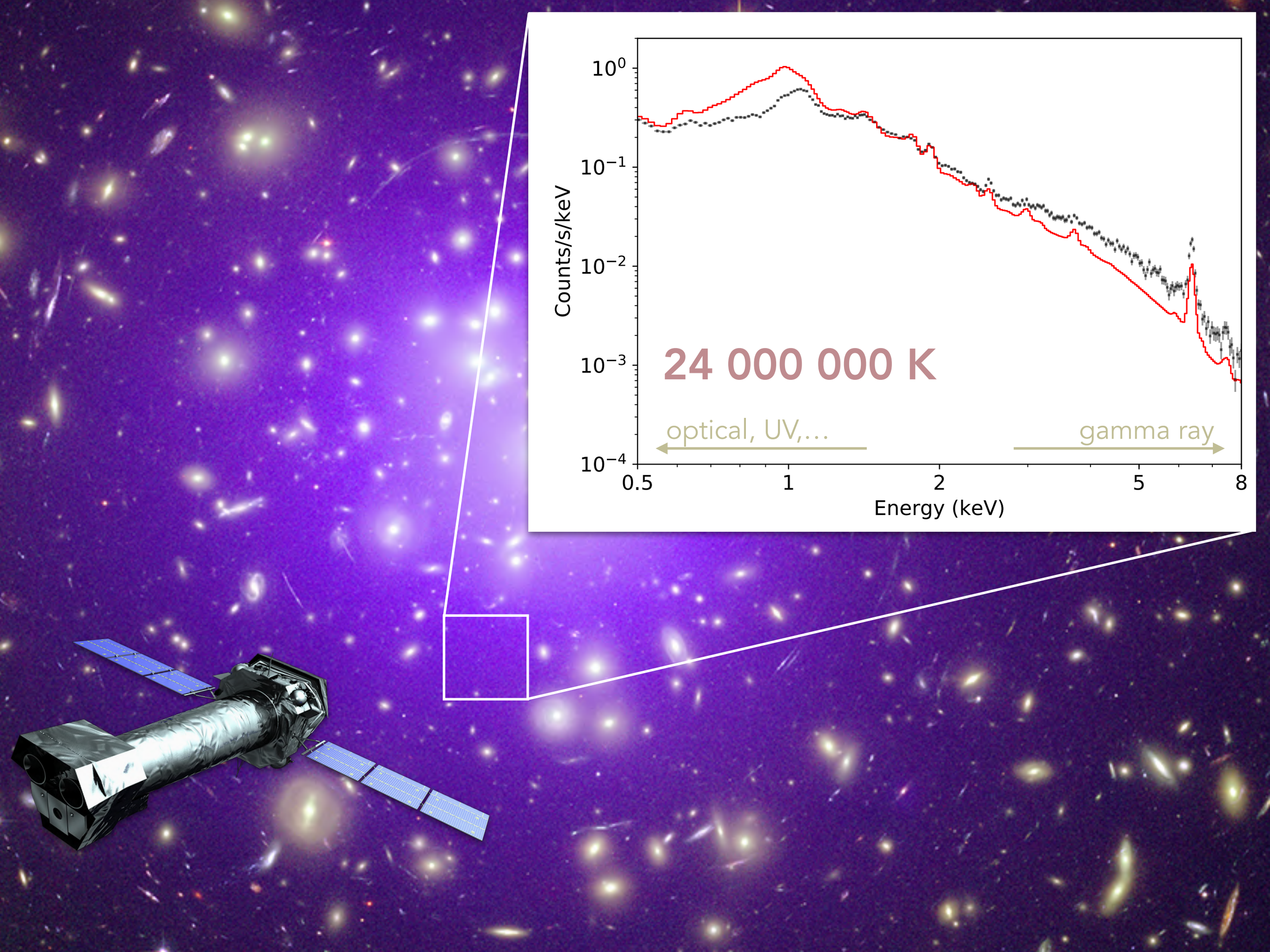

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1
2
5
8
Energy (keV)
80 000 000 K
optical, UV,…
gamma ray

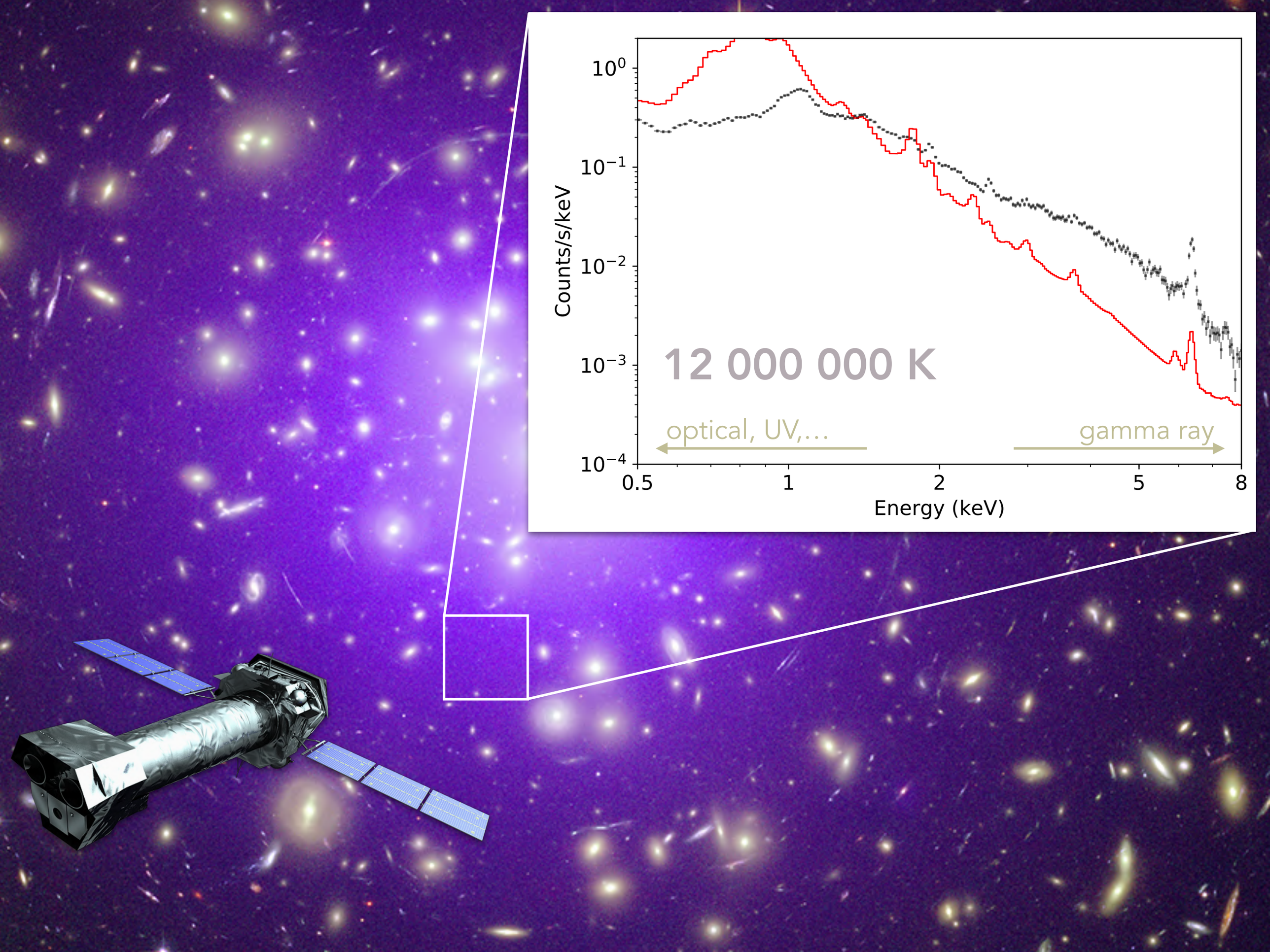


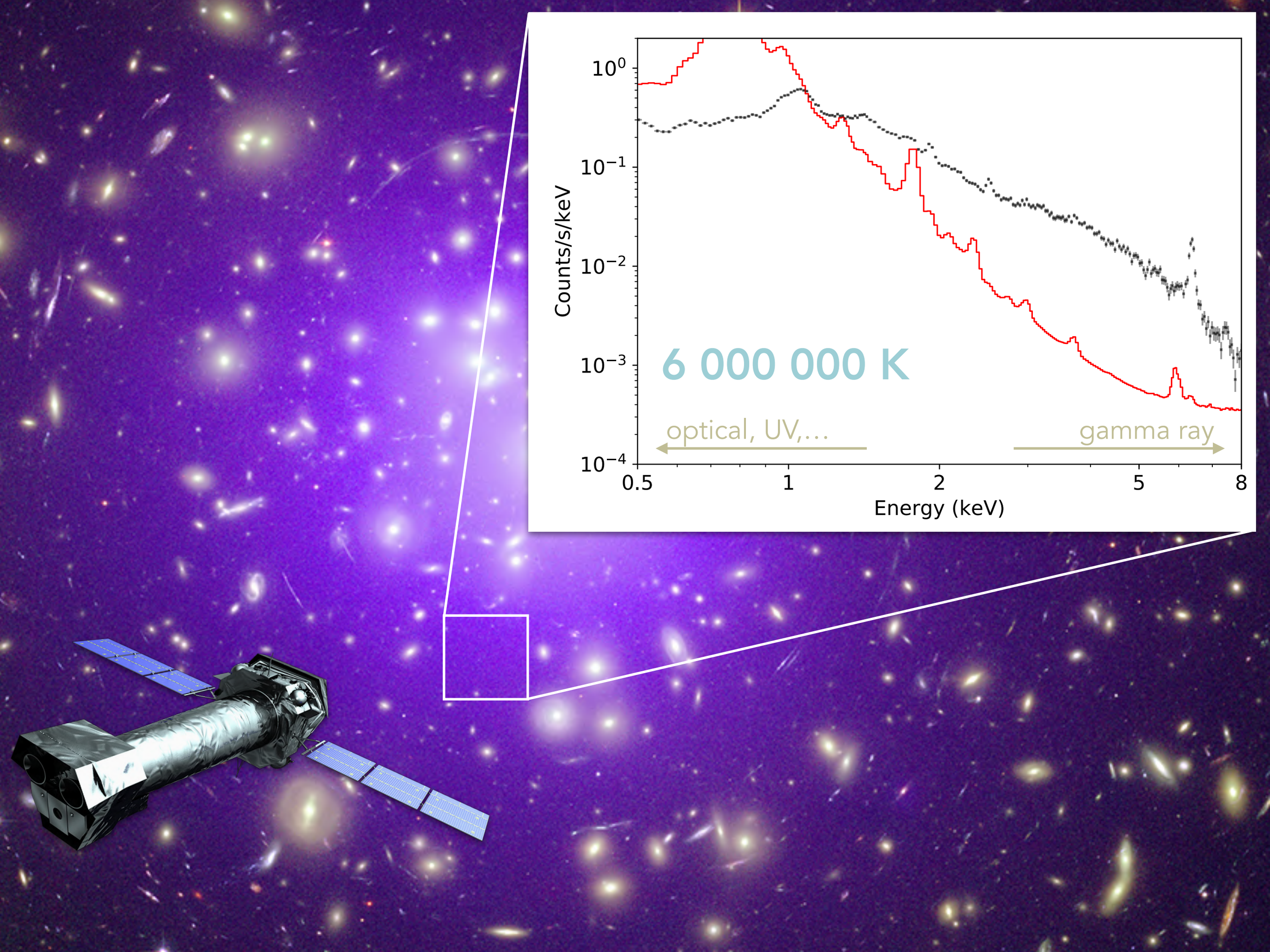
Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
60 000 000 K
optical, UV,...
gamma ray
0.5
1
2
5
8
Energy (keV)

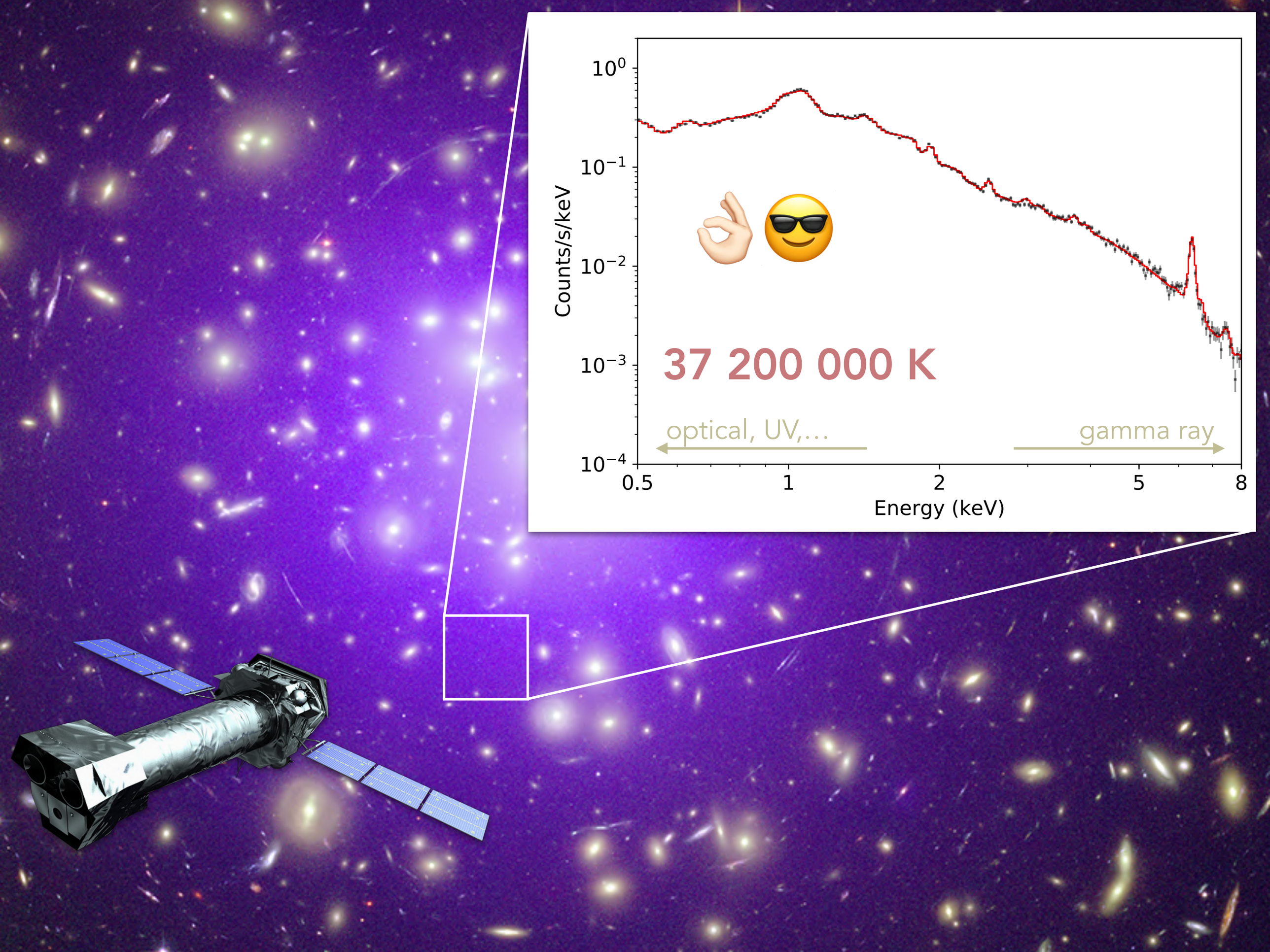


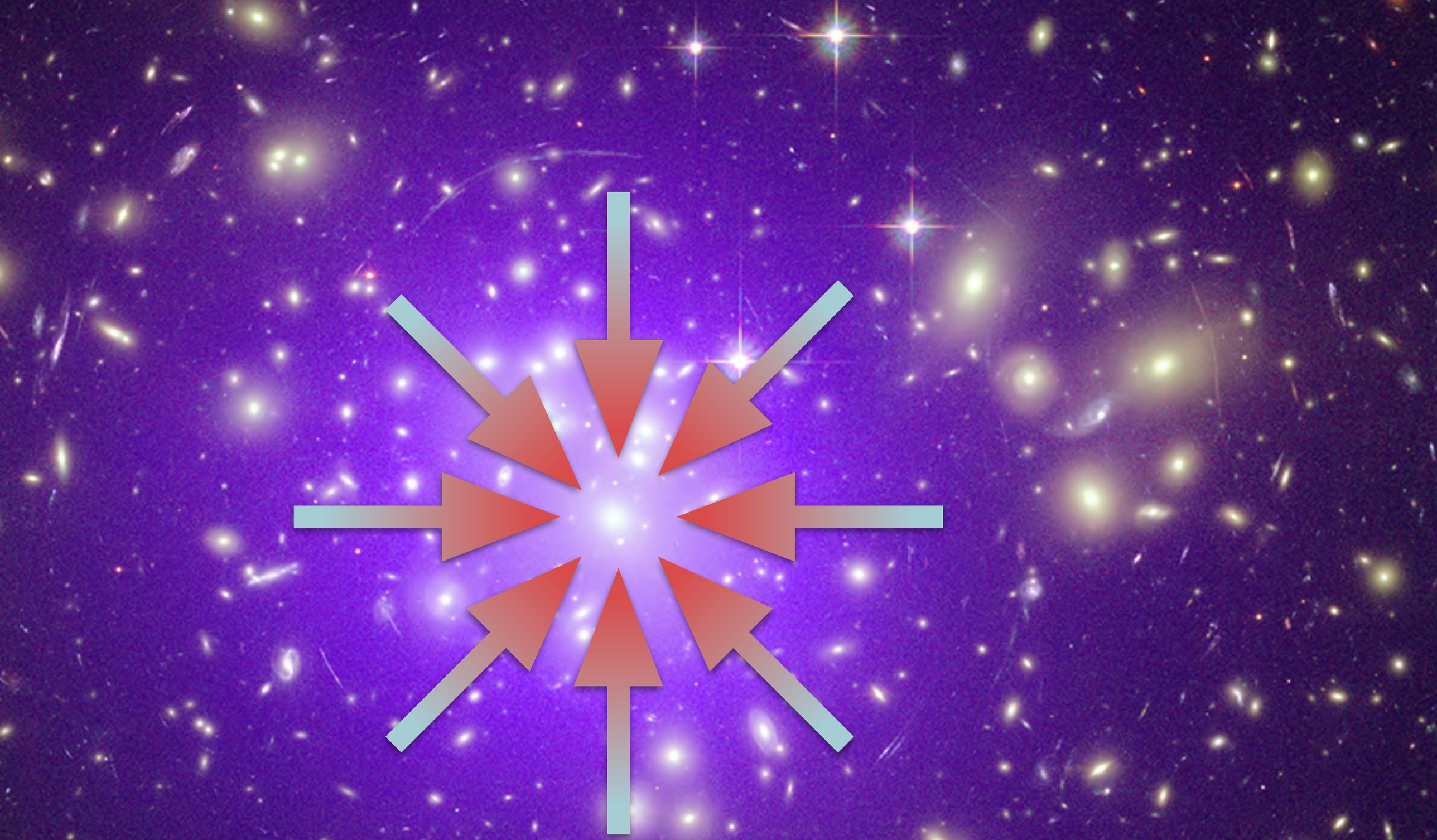

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Counts/s/keV
37 200 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)


Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
24 000 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)

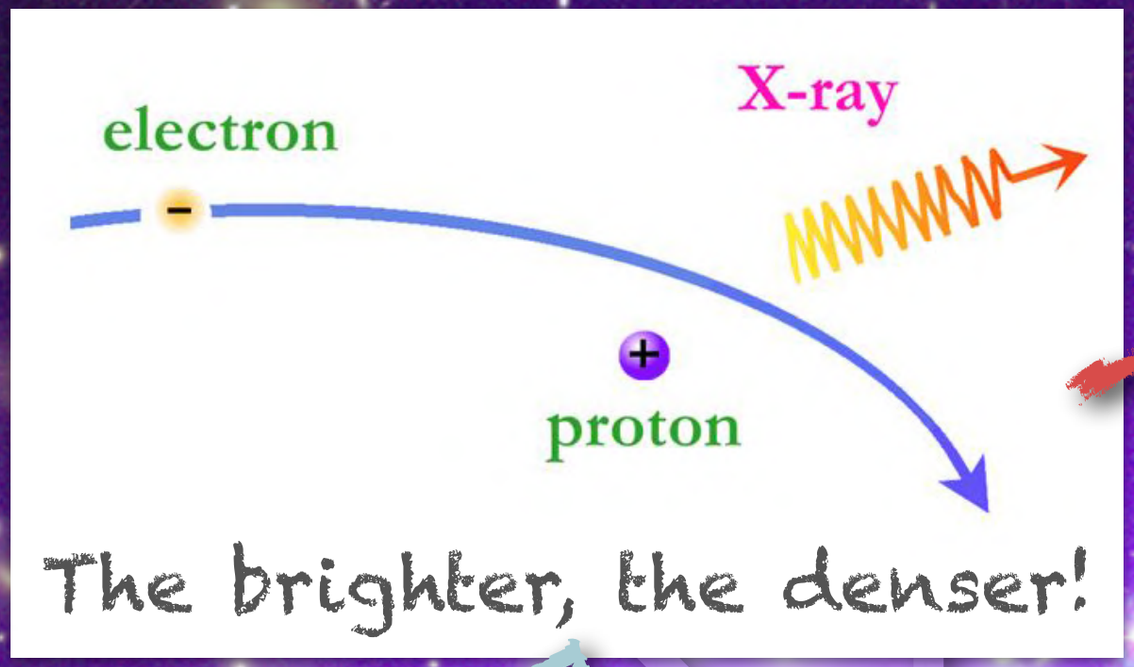

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
12 000 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)


Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
6 000 000 K
optical, UV,…
gamma ray
0.5
1
2
5
8
Energy (keV)


Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1
2
5
8
Energy (keV)
37 200 000 K
optical, UV,…
gamma ray


hotter...?

...or cooler?



The brighter, the denser!

When a X-ray photon escapes, the gas is losing energy...

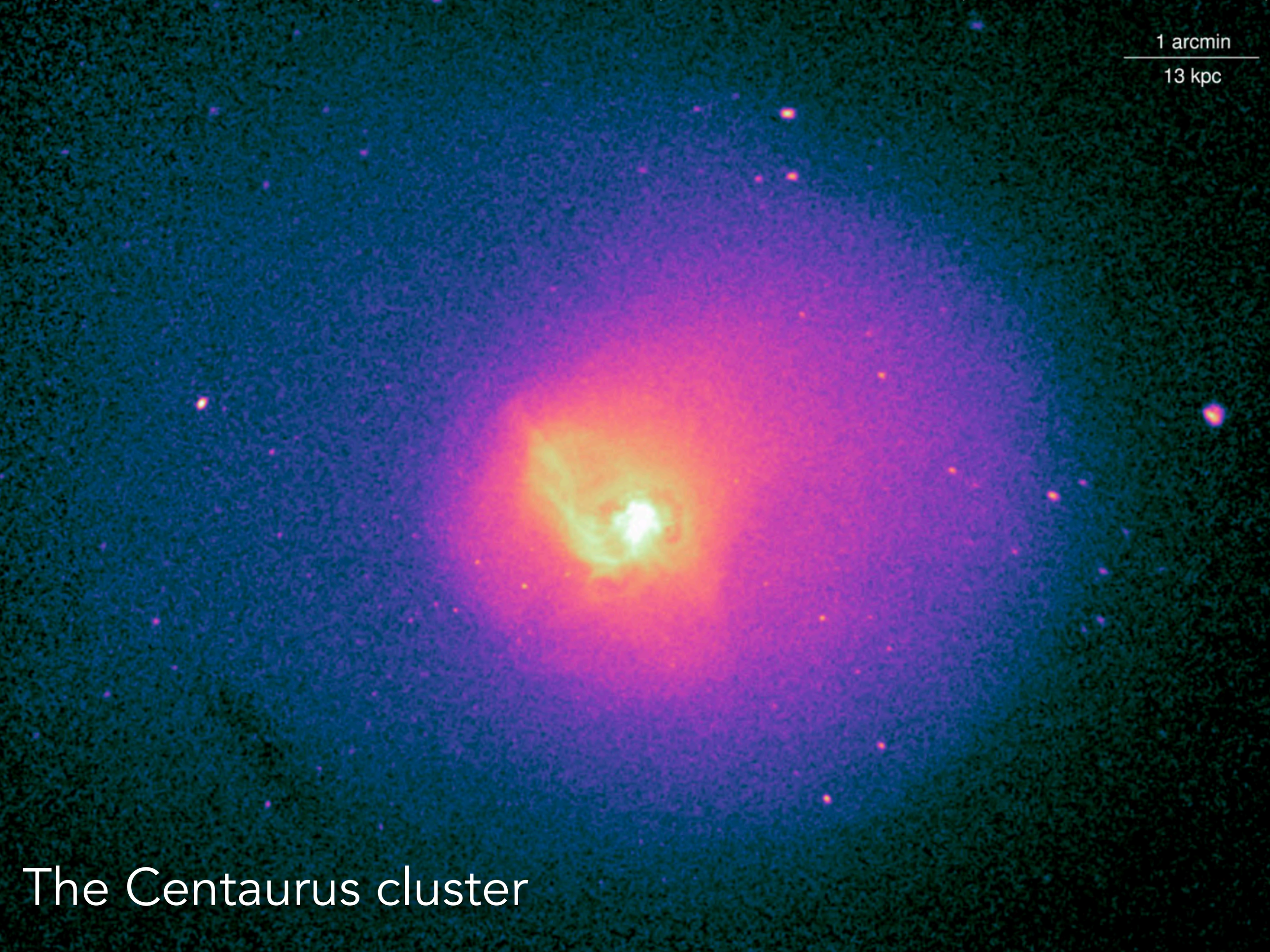
The gas cools down!

$PV = nRT$

The central pressure drops!

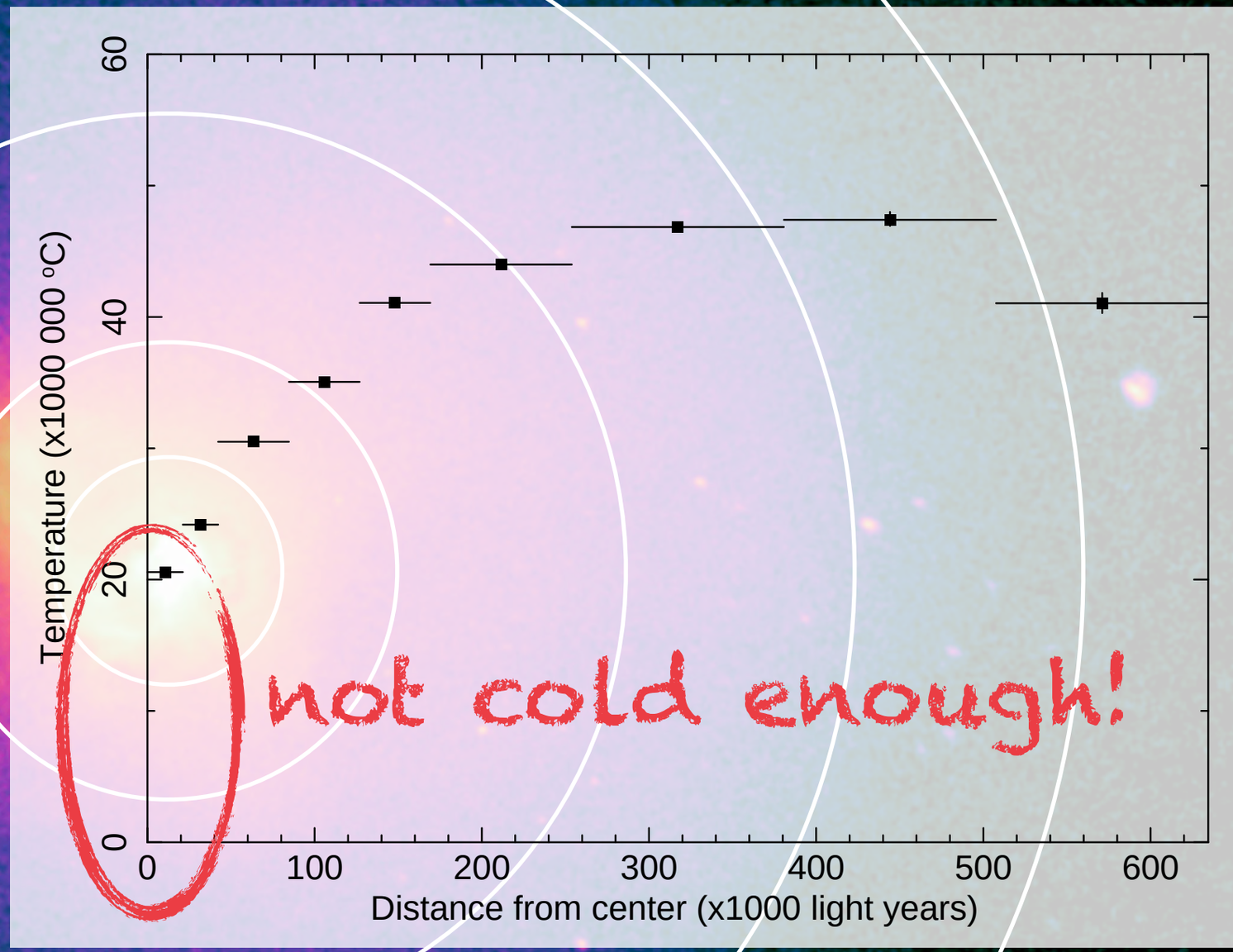
The surrounding gas "falls" in the centre...

Make the gas dense again!



The Centaurus cluster

1 arcmin
13 kpc



The Centaurus cluster

- Central cluster galaxies should look like this…

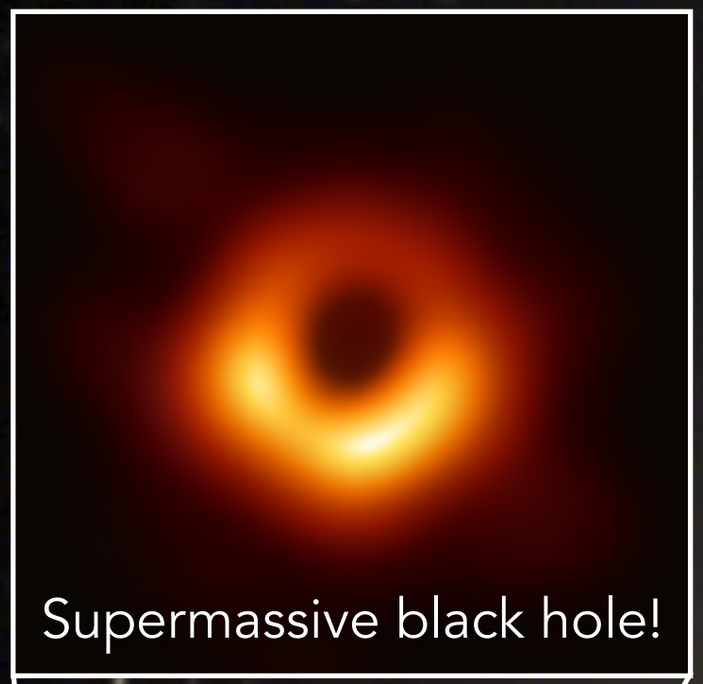
…but they look like this.

…but they look like this.

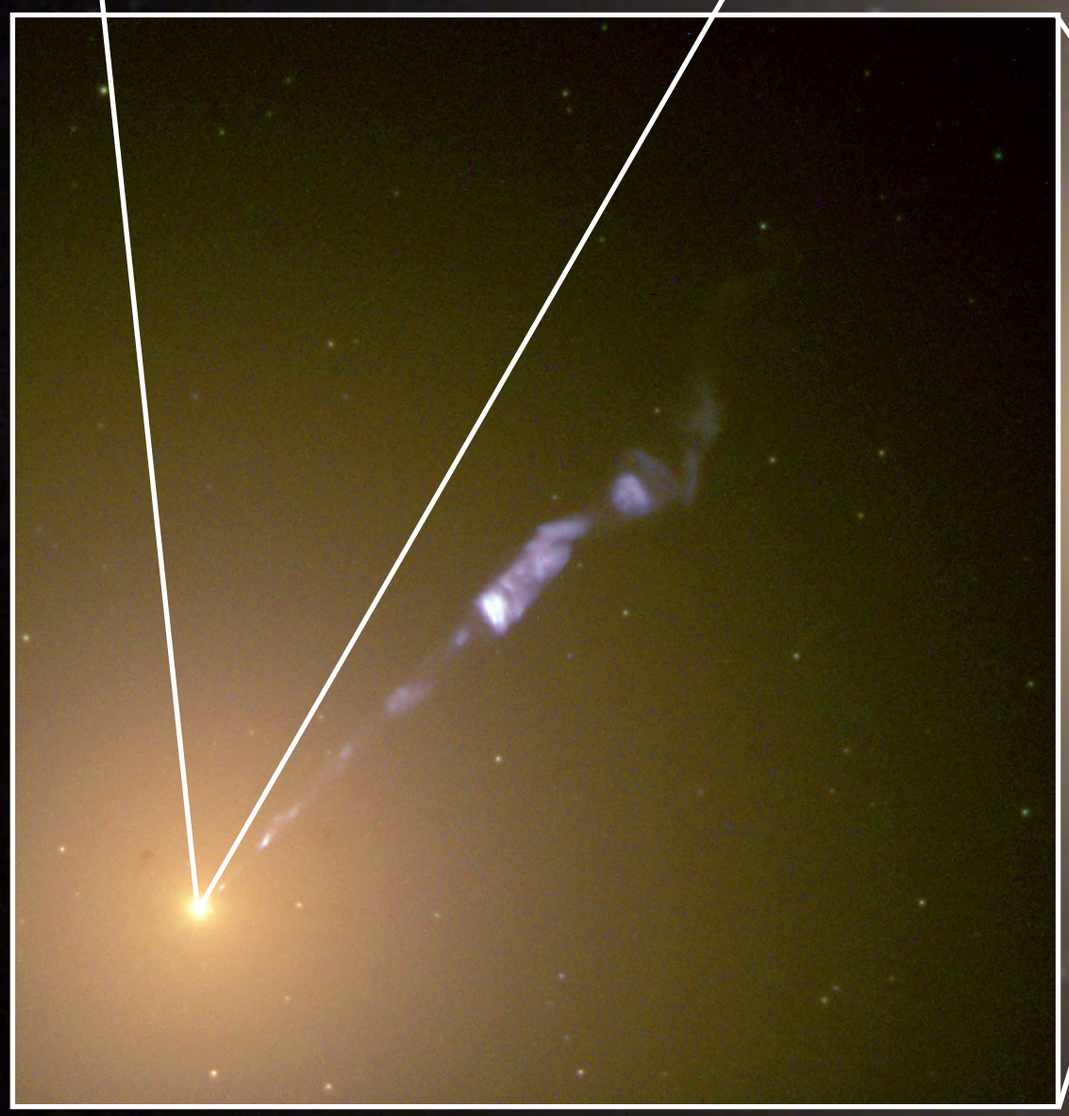
What prevents the hot gas from cooling?


M87

M87



Supermassive black hole!



M87

Supermassive black hole!

Jet

5 000 light years

M87

Hercules A galaxy

Radio

Hercules A galaxy

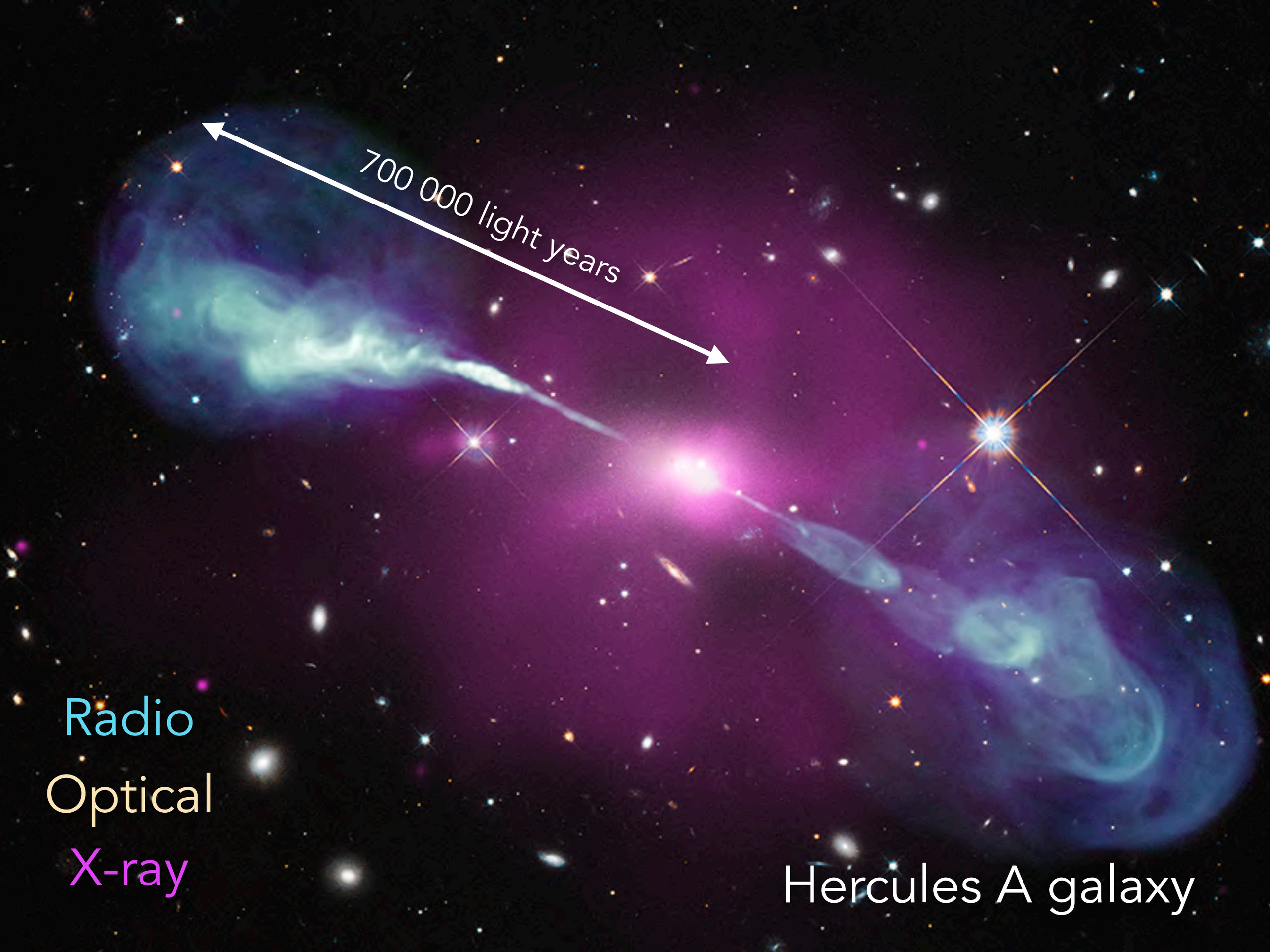
X-ray

Hercules A galaxy

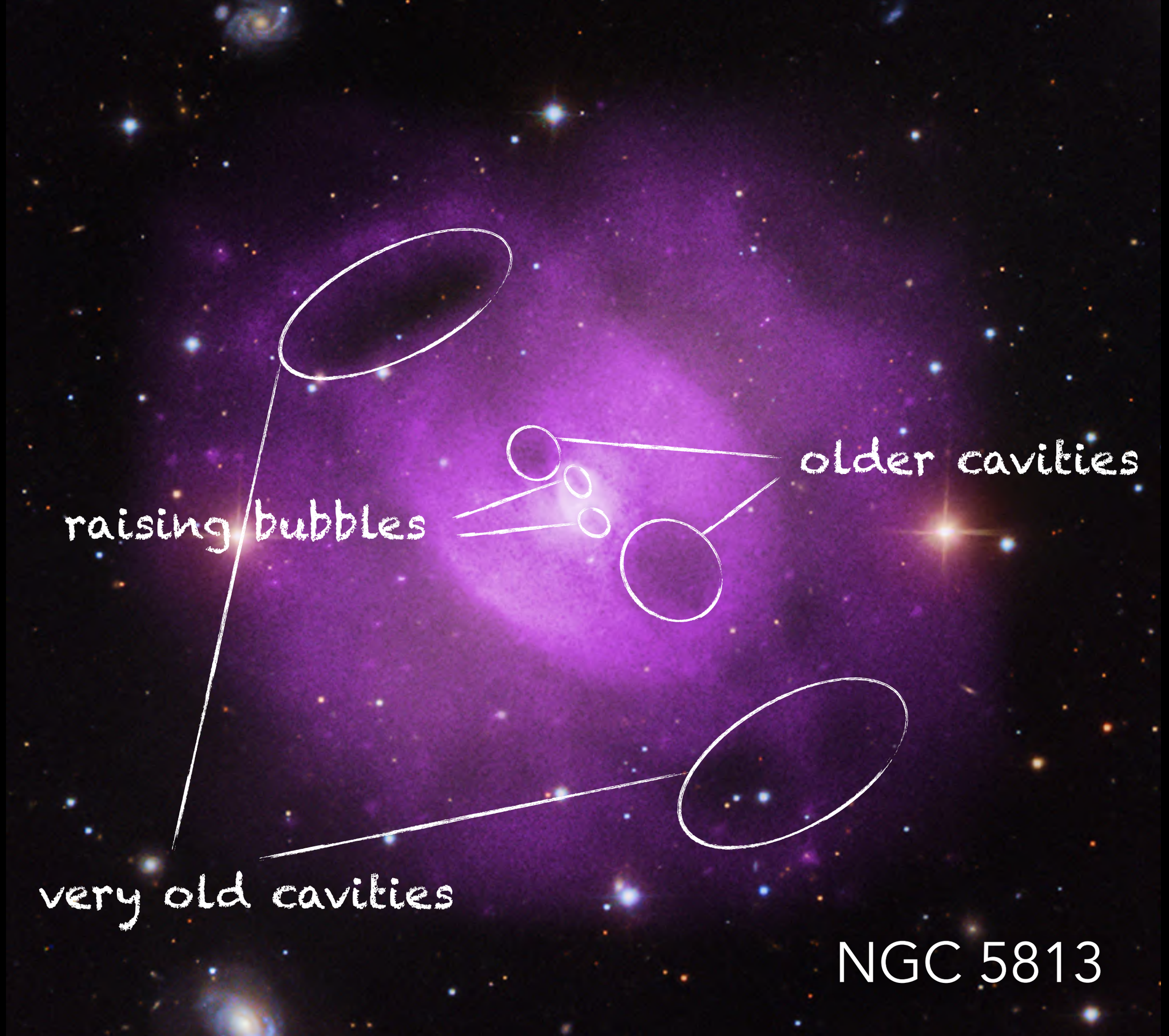
cavities!

X-ray

Hercules A galaxy


700 000 light years
Radio
Optical
X-ray
Hercules A galaxy


NGC 5813


raising bubbles
older cavities
very old cavities
NGC 5813

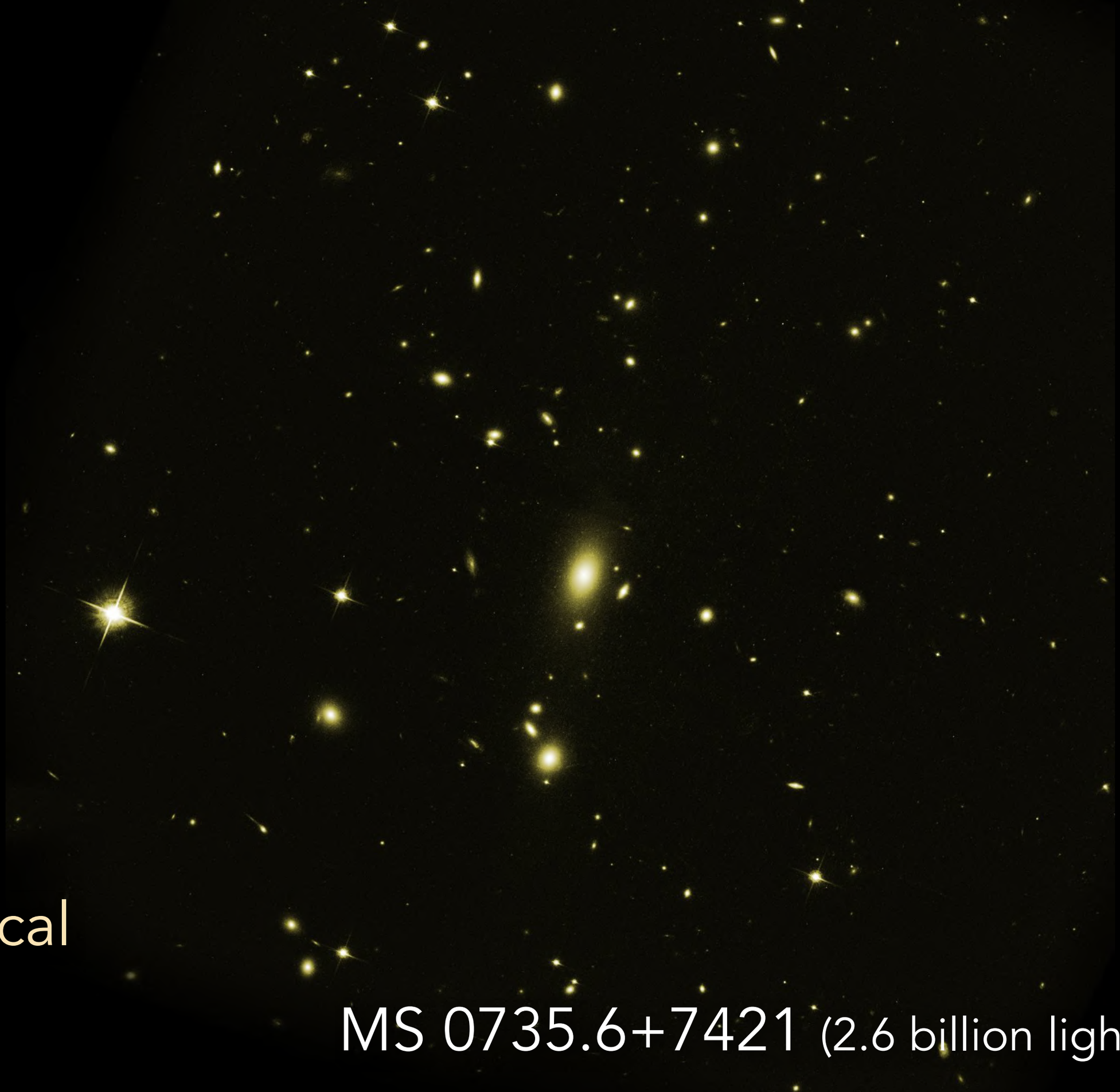
Perseus cluster

gas motions (?)

raising bubbles

old cavities

Perseus cluster

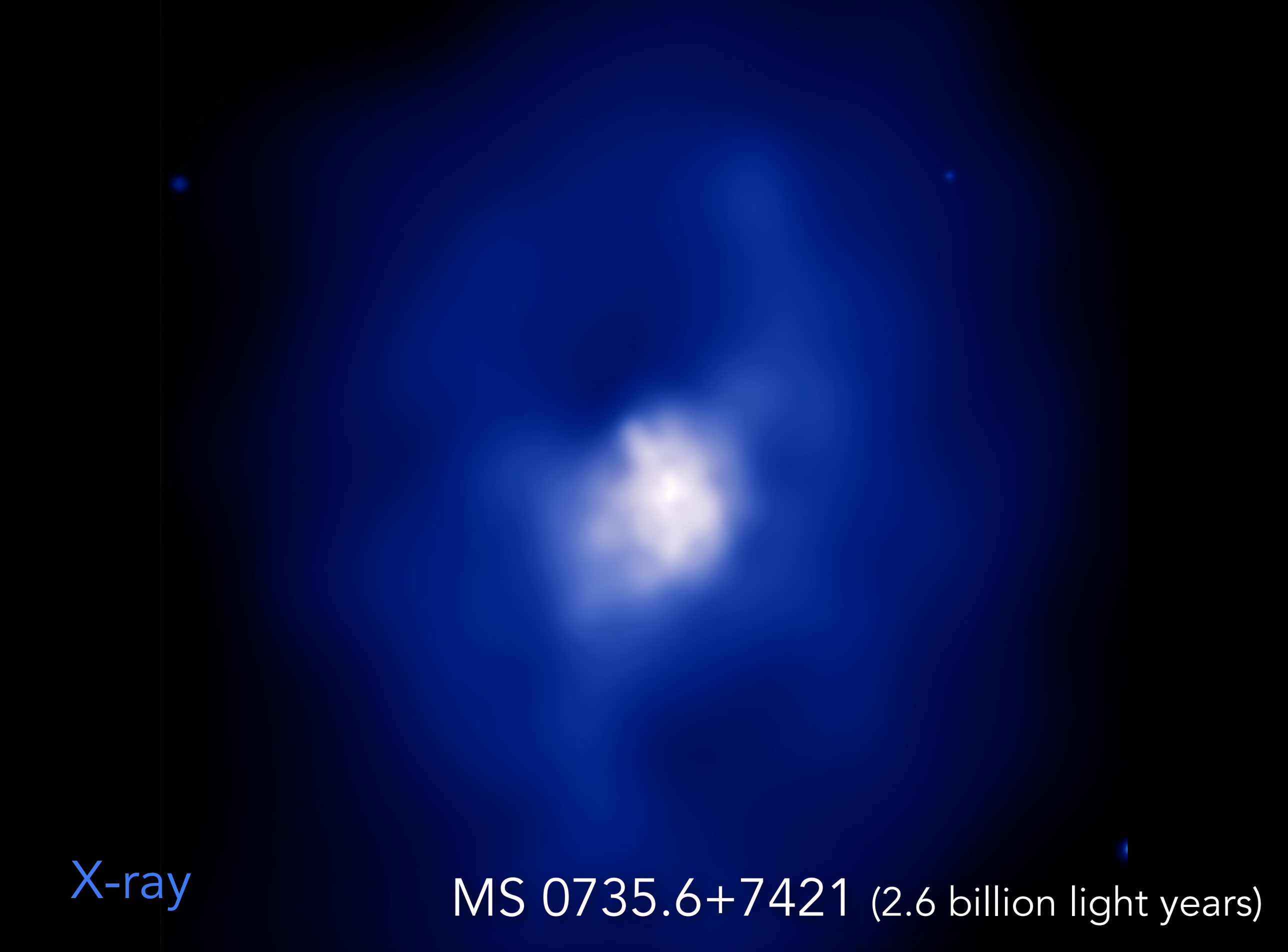


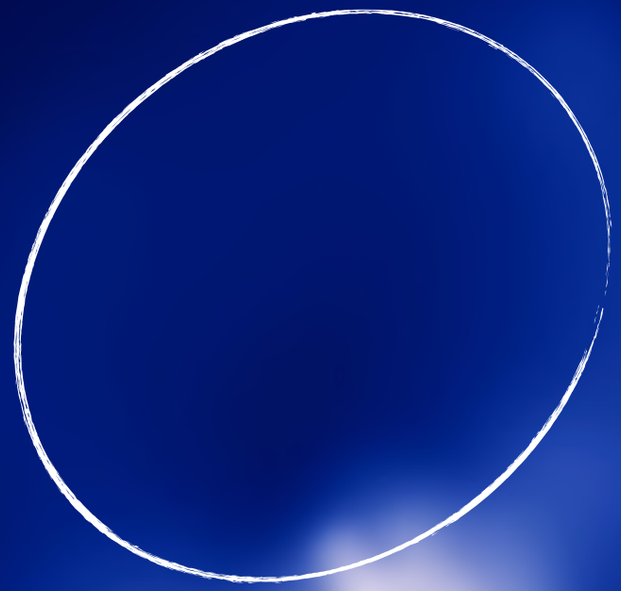
Optical

MS 0735.6+7421 (2.6 billion light years)

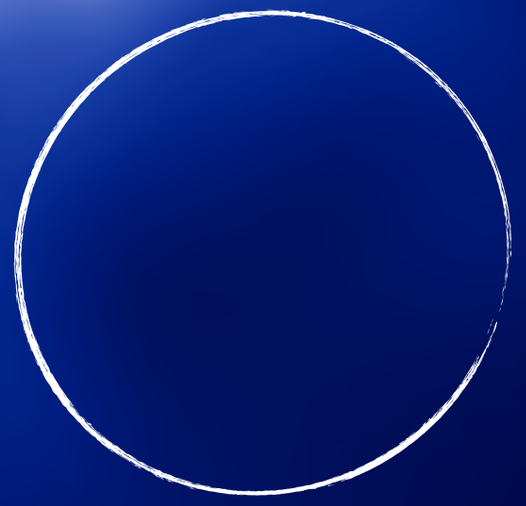
Radio

MS 0735.6+7421 (2.6 billion light years)


X-ray
MS 0735.6+7421 (2.6 billion light years)

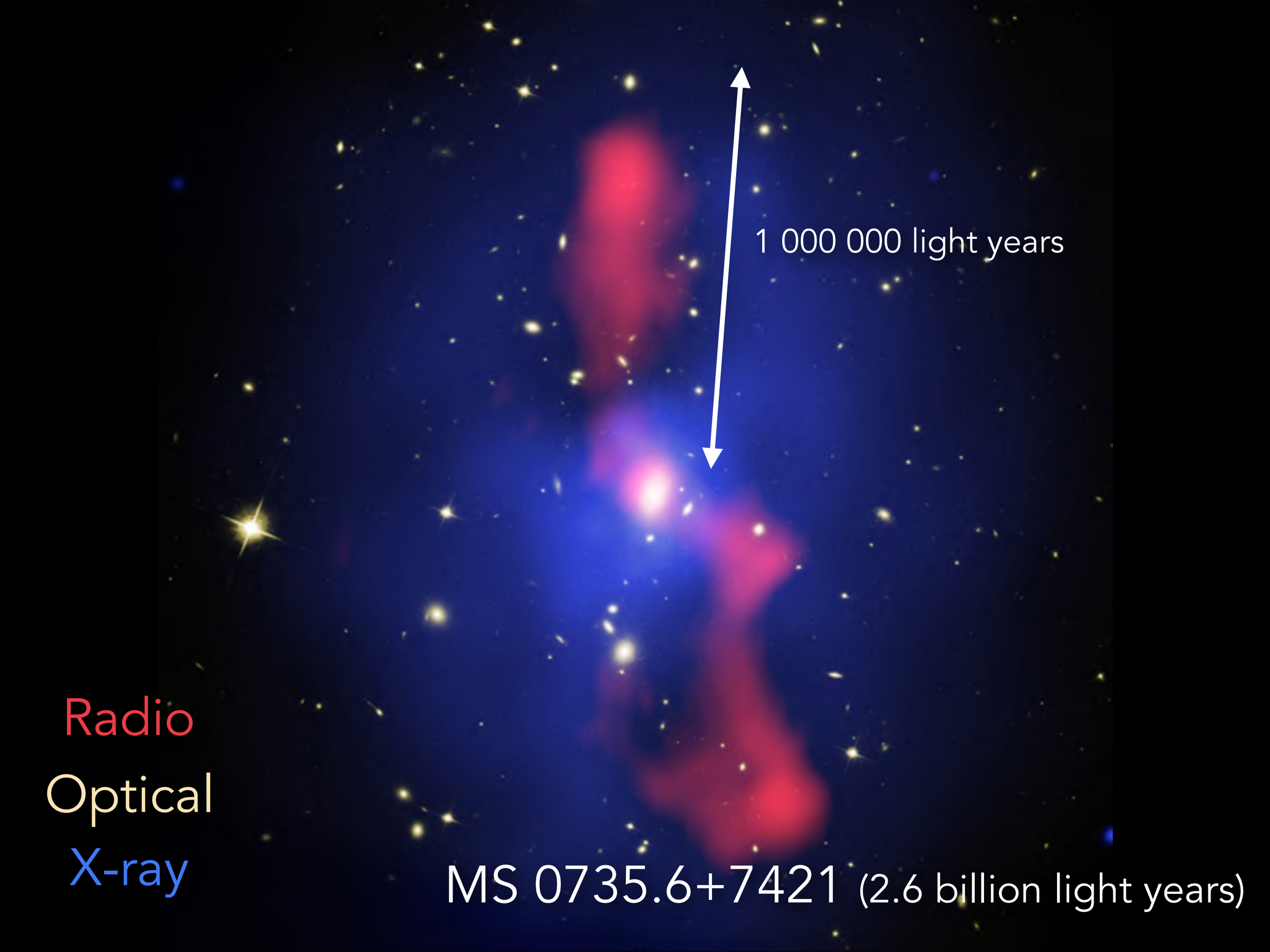


cavities!



X-ray

MS 0735.6+7421 (2.6 billion light years)

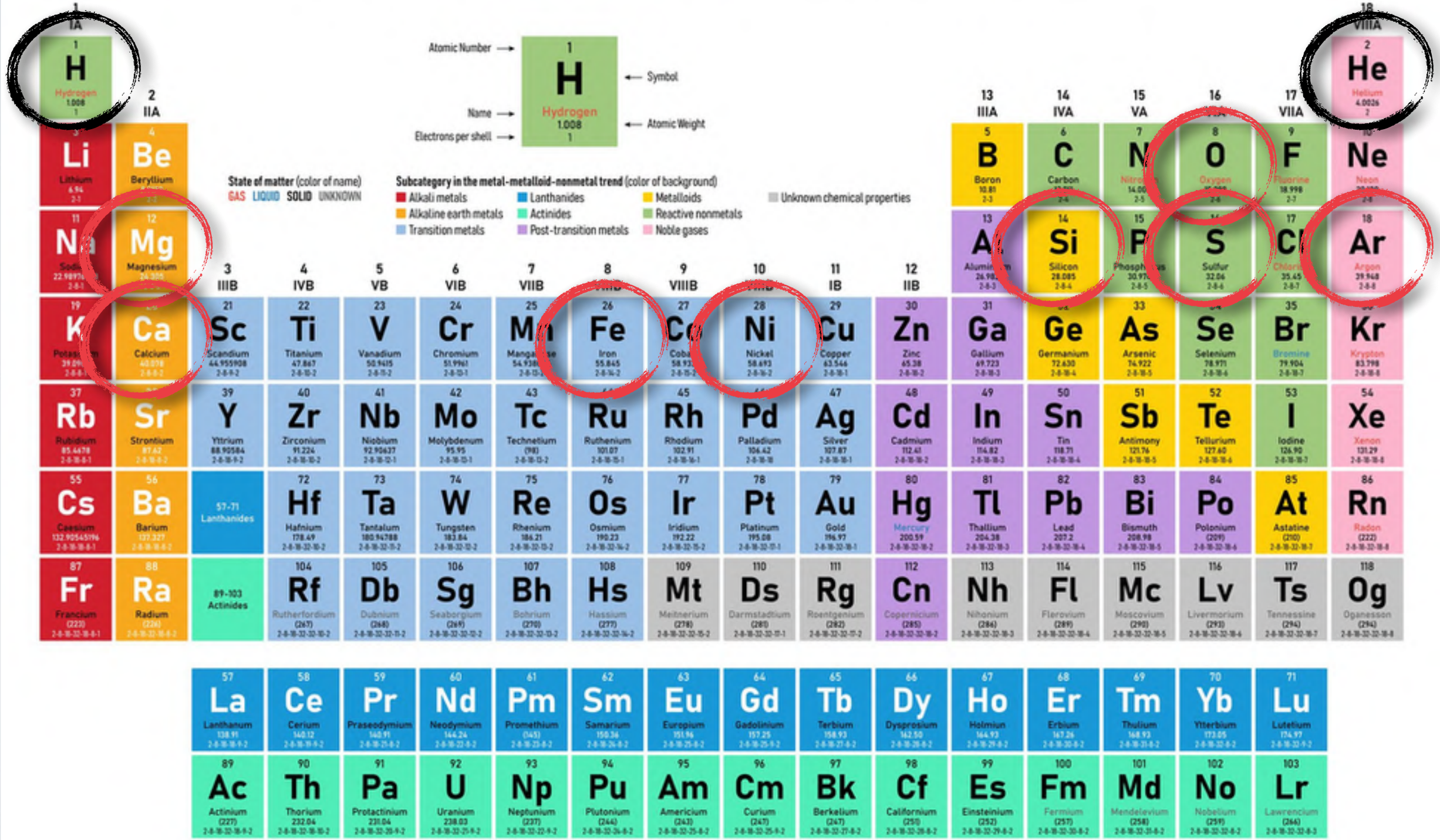

1 000 000 light years
Radio
Optical
X-ray
MS 0735.6+7421 (2.6 billion light years)

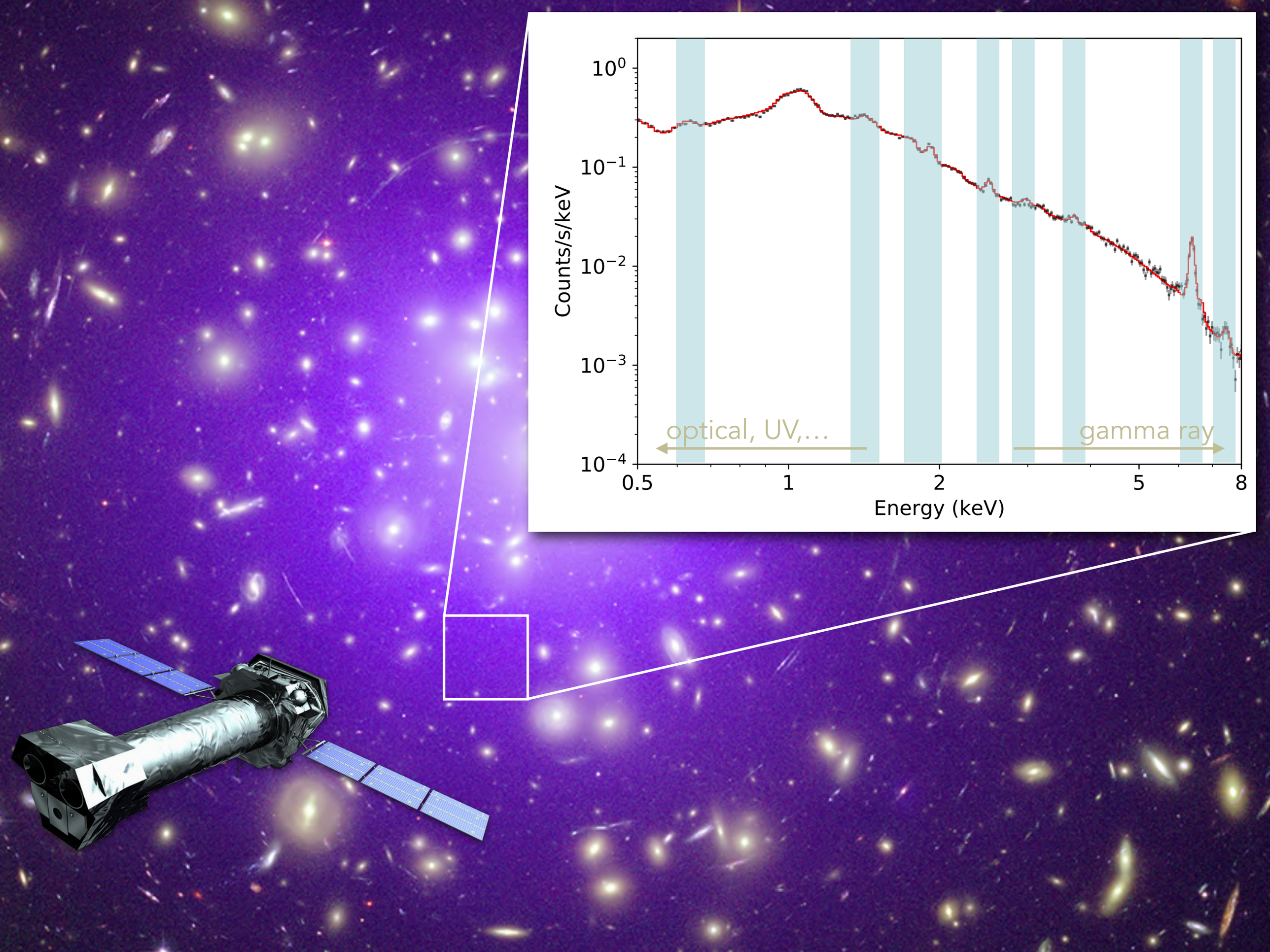
But how exactly jets/cavities (re)heat the gas?

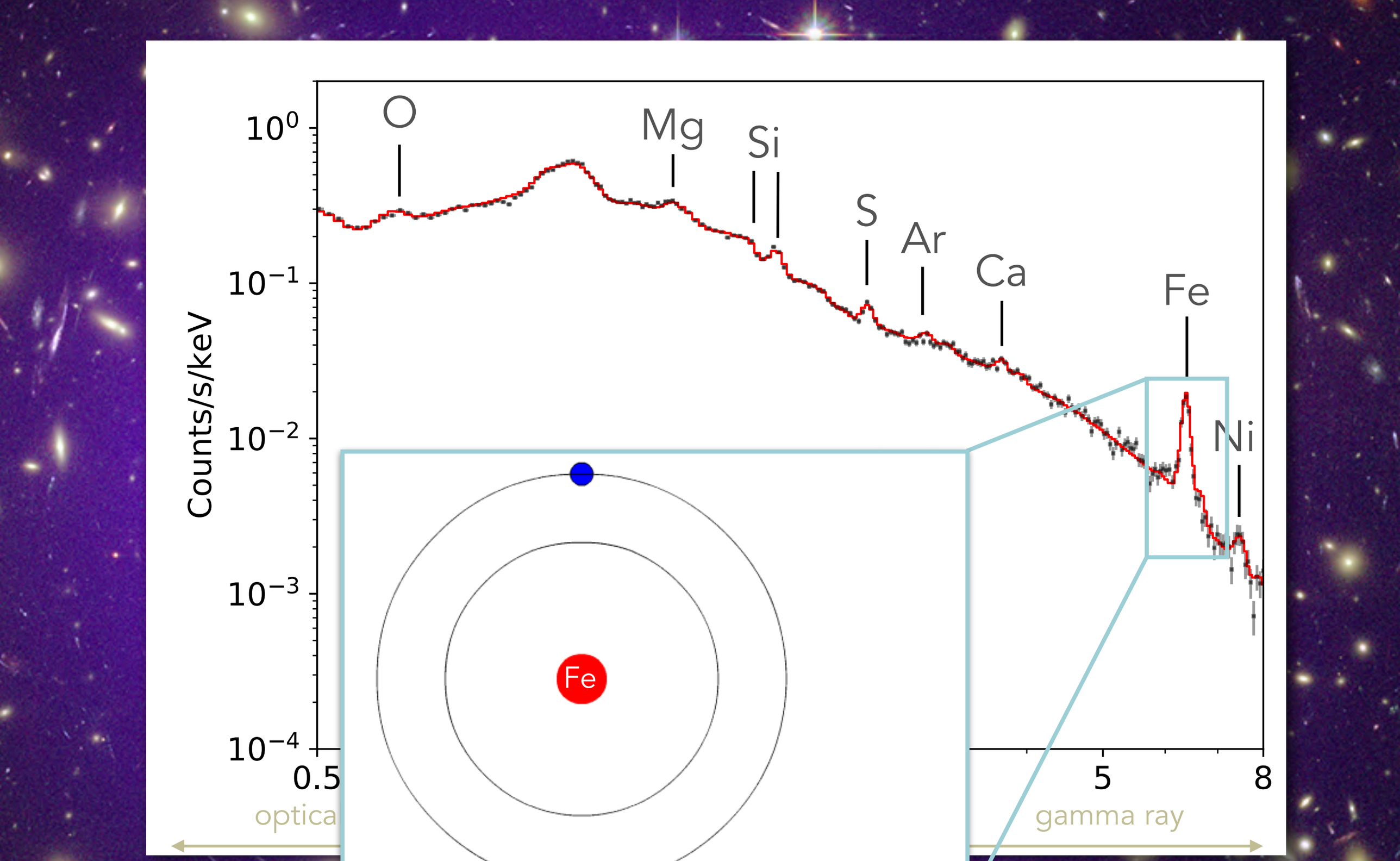
We don’t know (yet)…

2. Chemical composition

Periodic Table of the Elements



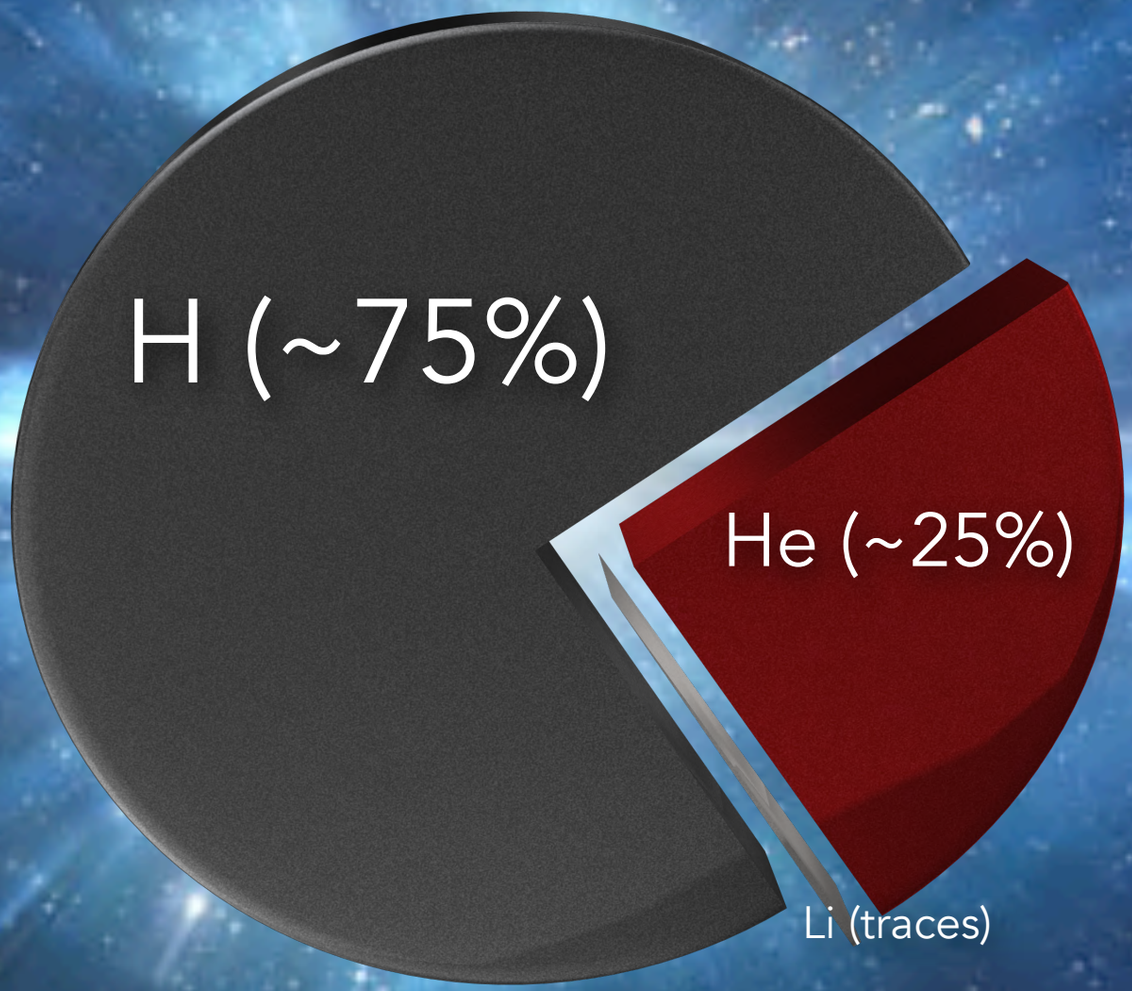

Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1
2
5
8
Energy (keV)
optical, UV,…
gamma ray


O
Mg
Si
S
Ar
Ca
Fe
Ni
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Counts/s/keV
0.5
5
8
optica
gamma ray
Fe

Cluster hot atmospheres contains diverse **chemical elements**…

The **elemental bricks of life** are present even at the largest scale structures of the Universe!

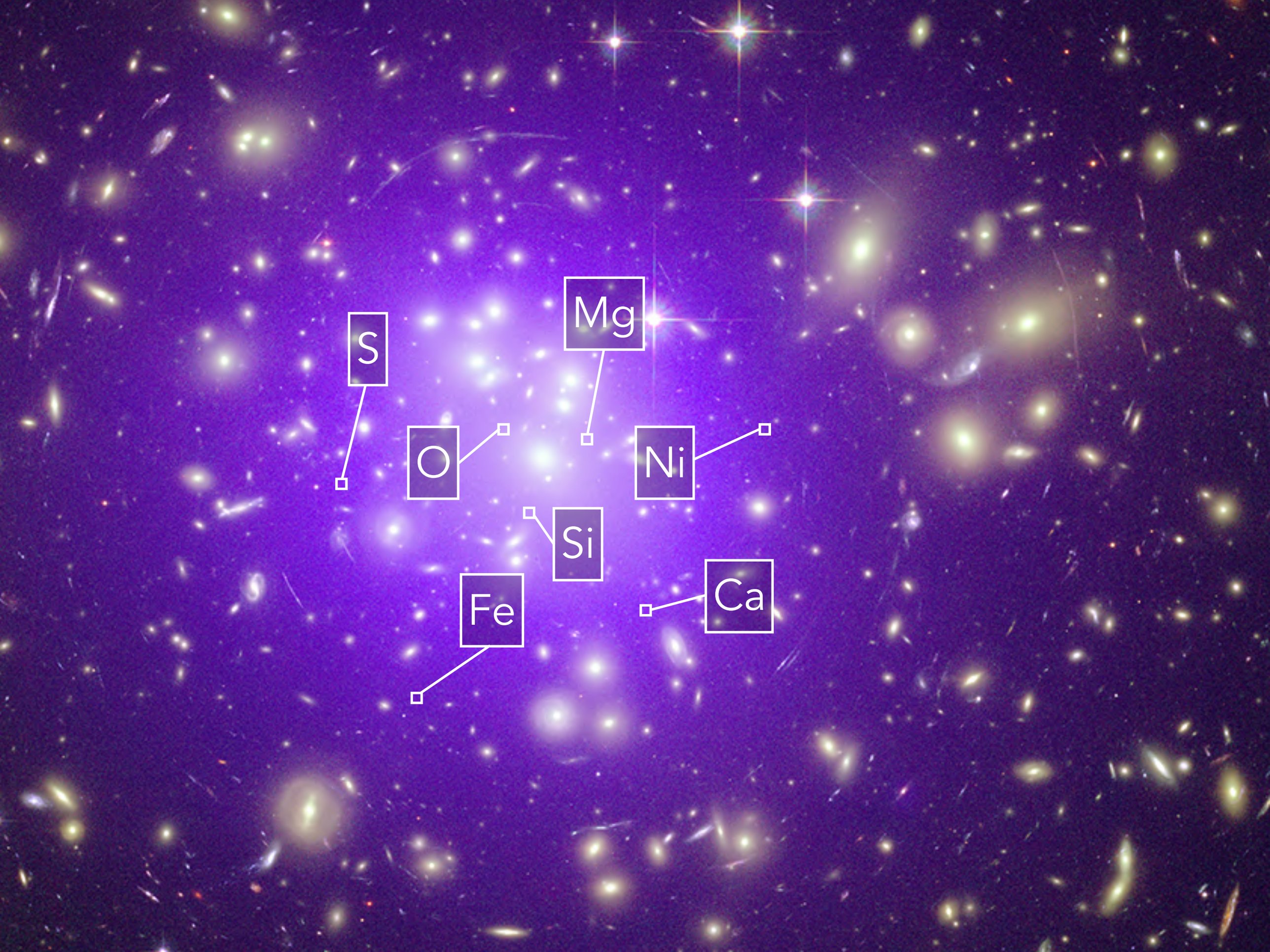
Primordial nucleosynthesis



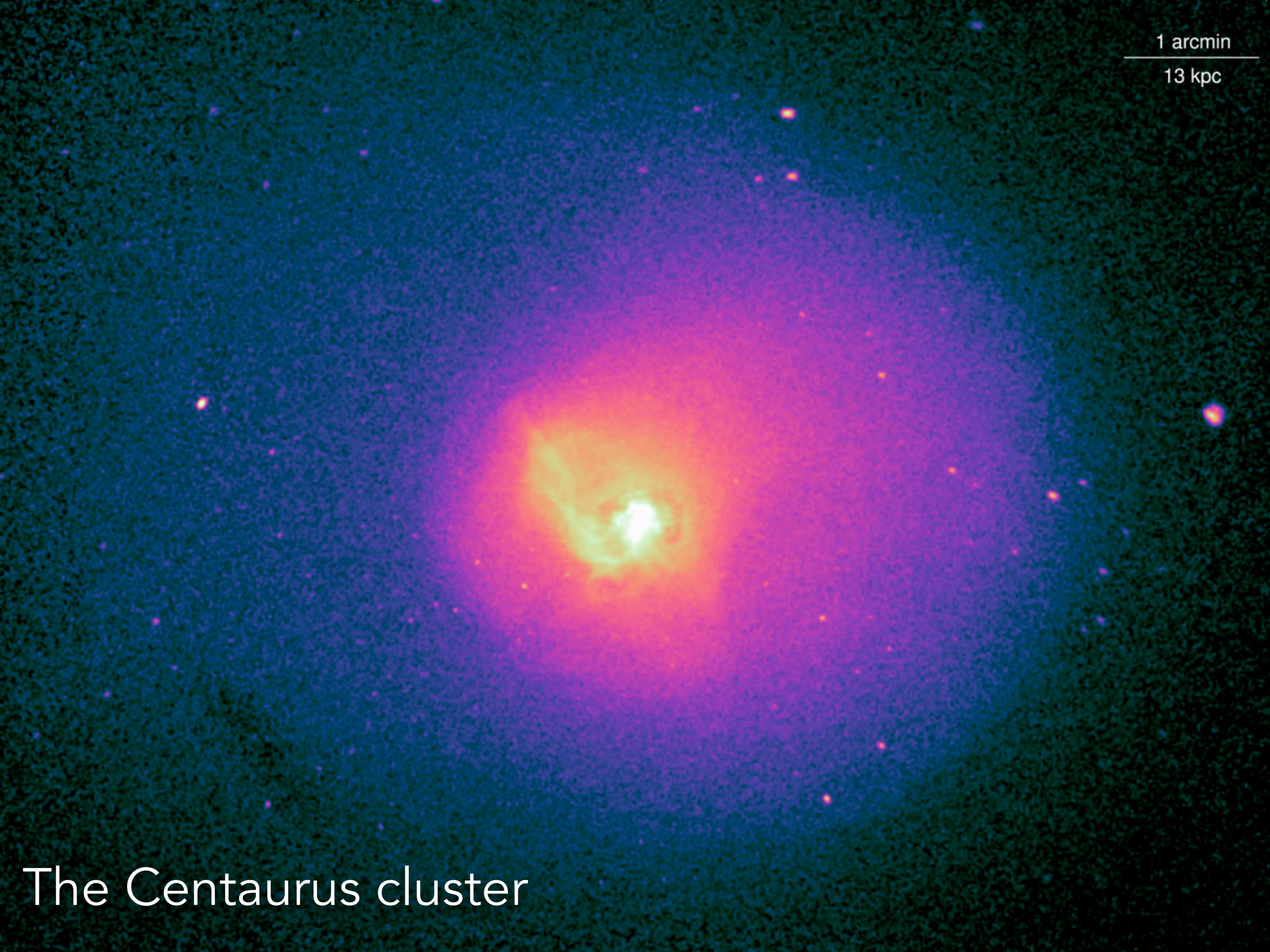
Big Bang

Exploding stars (supernovae) are the only way to produce elements other than H and He…

"We are made of starstuff." **- Carl Sagan**

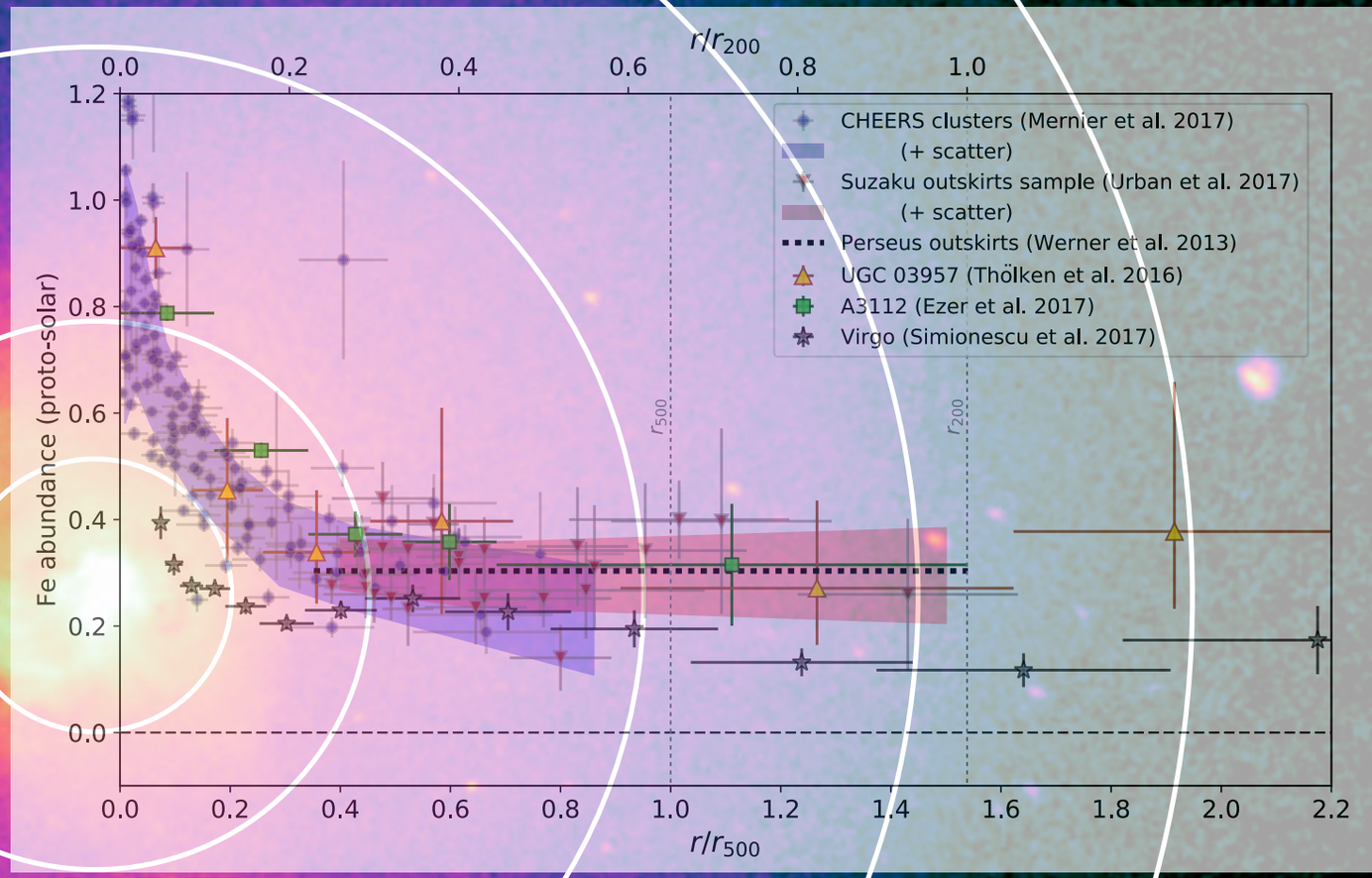

S
Mg
O
Ni
Si
Fe
Ca

How and ***when*** did exploding stars eject their products outside of their galaxies?



The Centaurus cluster

1 arcmin
13 kpc



The Centaurus cluster

amount of Fe

r/r_{200}

Mernier et al. (2018c)

CHEERS clusters (Mernier et al. 2017)
(+ scatter)
Suzaku outskirts sample (Urban et al. 2017)
(+ scatter)
Perseus outskirts (Werner et al. 2013)
UGC 03957 (Thölken et al. 2016)
A3112 (Ezer et al. 2017)
Virgo (Simionescu et al. 2017)

r_{500}

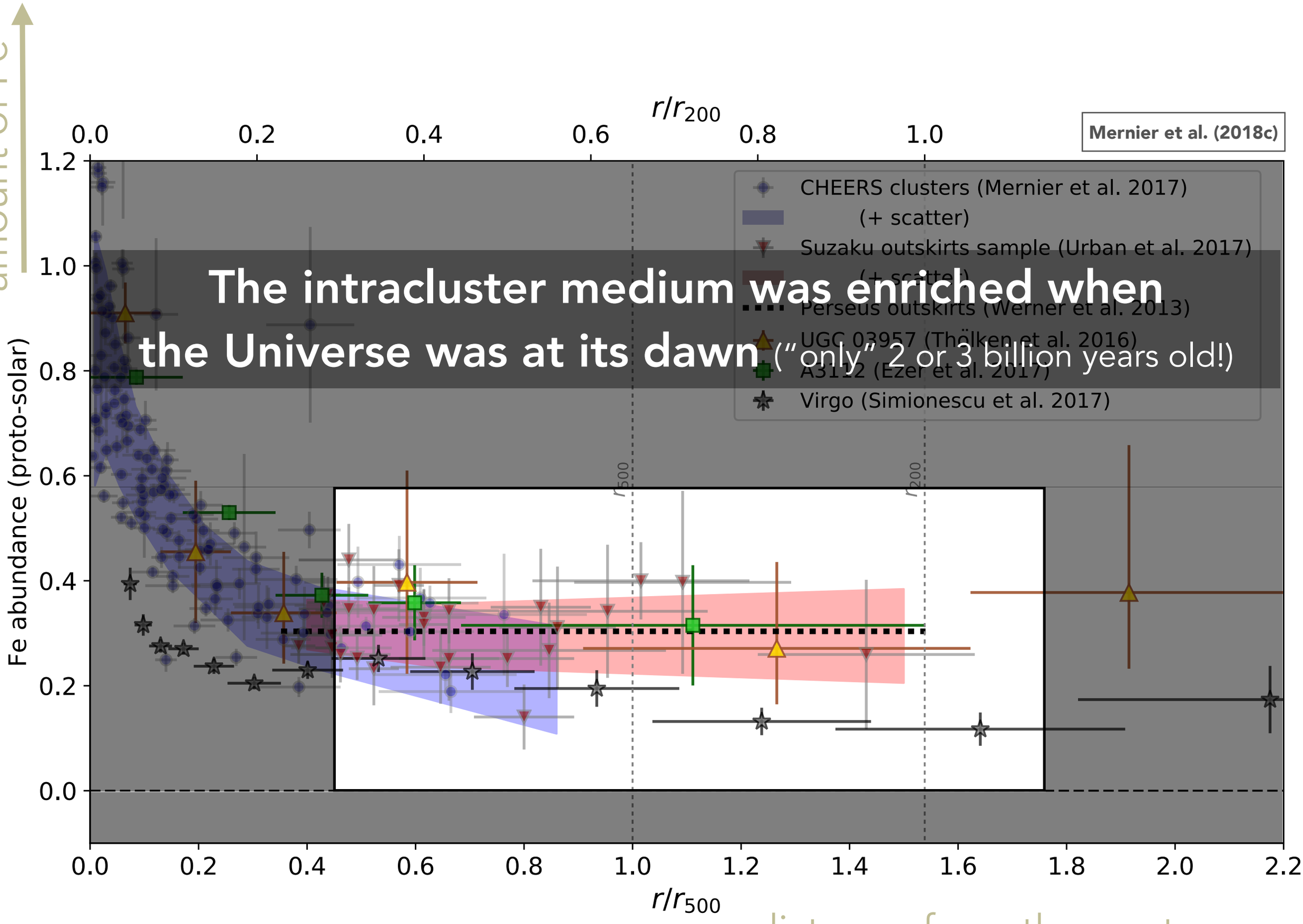
r_{200}

Fe abundance (proto-solar)

r/r_{500}

distance from the centre

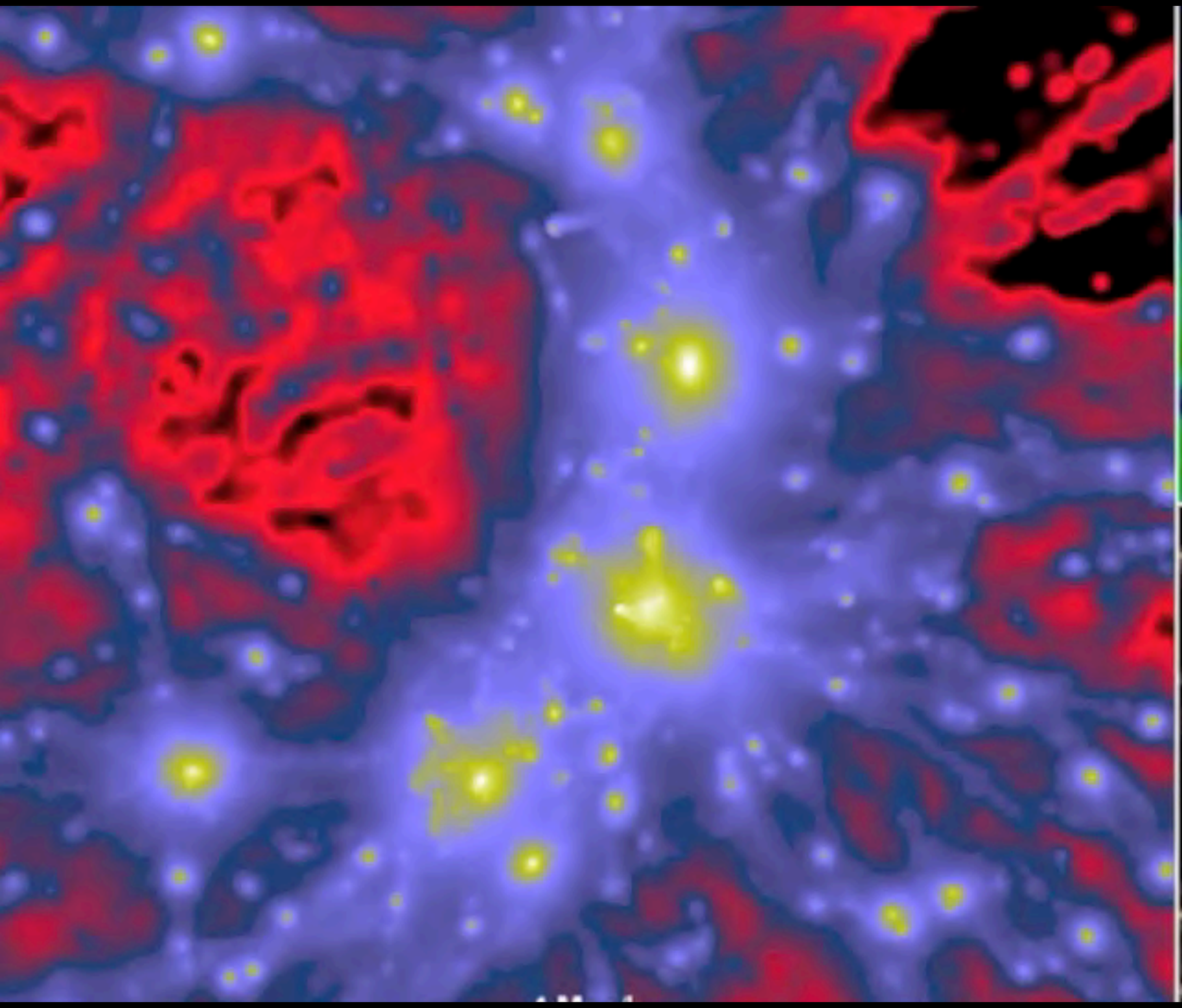
amount of Fe

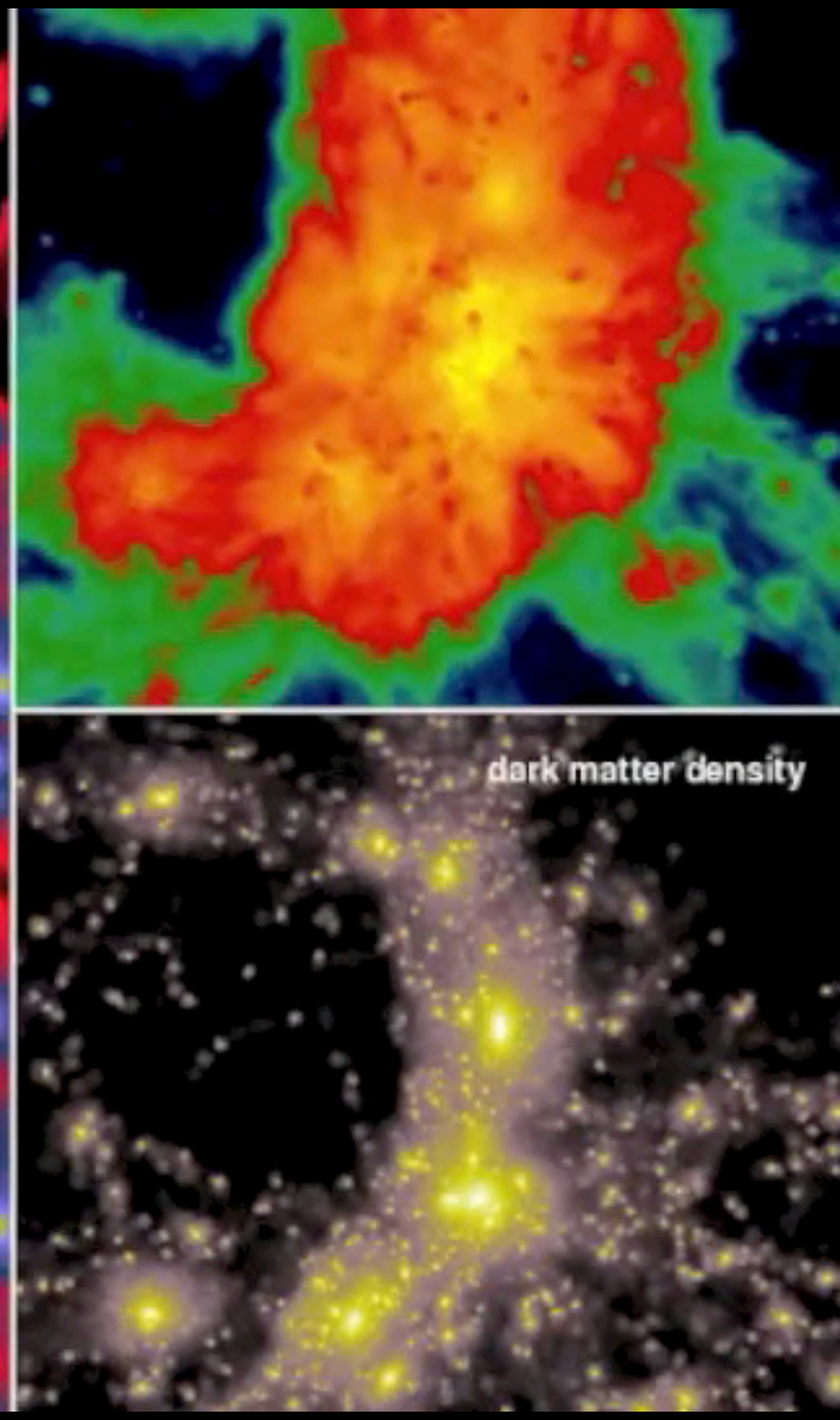


The intracluster medium was enriched when the Universe was at its dawn ("only" 2 or 3 billion years old!)

distance from the centre

3. Cosmological simulations




dark matter density

CONCLUSIONS

CONCLUSIONS

- Clusters of galaxies are the largest structures of our Universe
- Their evolution is impacted by cosmology and gravity,… *LARGE SCALES*
- …but also by stars and supermassive black holes! *SMALL SCALES*

Optical light (seen by our eyes) does ***not*** reveal all the mysteries of our Universe!

Planets, stars, galaxies,... are only a ***tiny*** part of it!