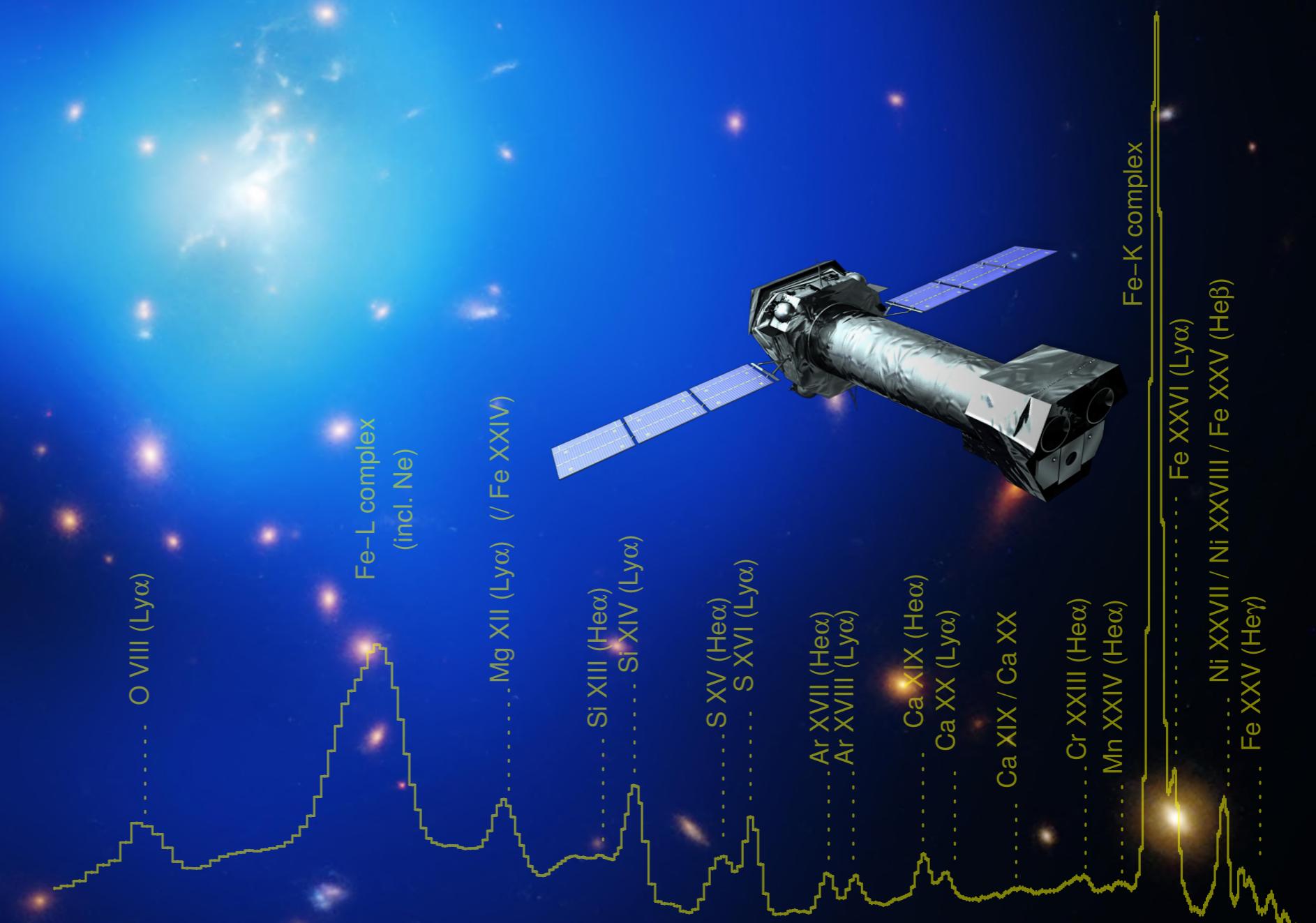


Clusters of galaxies... ...and the surprises of their spectacular hot atmospheres

François Mernier

MTA-Eötvös University,
Budapest

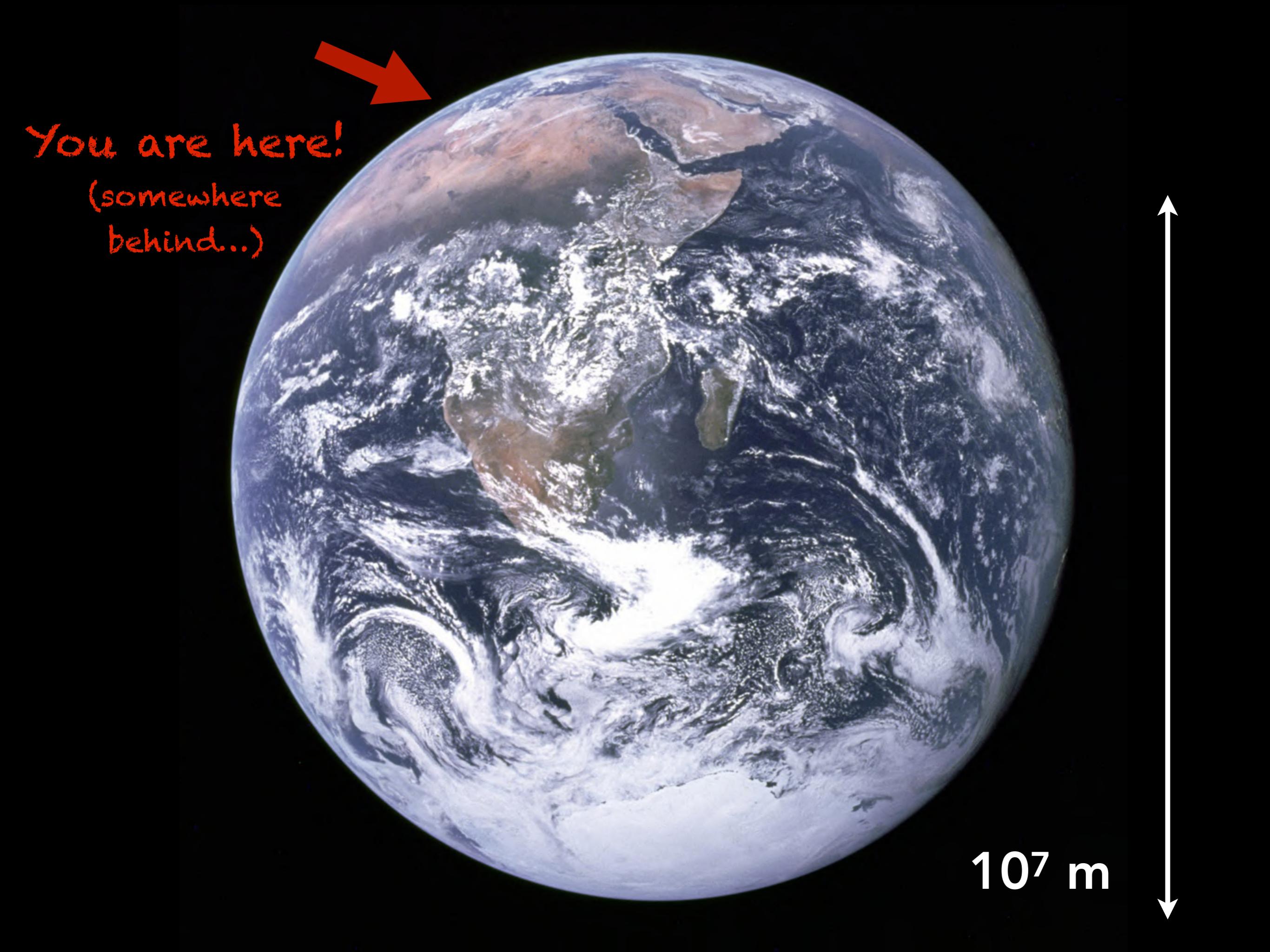


mernier@caesar.elte.hu -



Wallon Super





You are here!
(somewhere
behind...)

10^7 m

You are here!

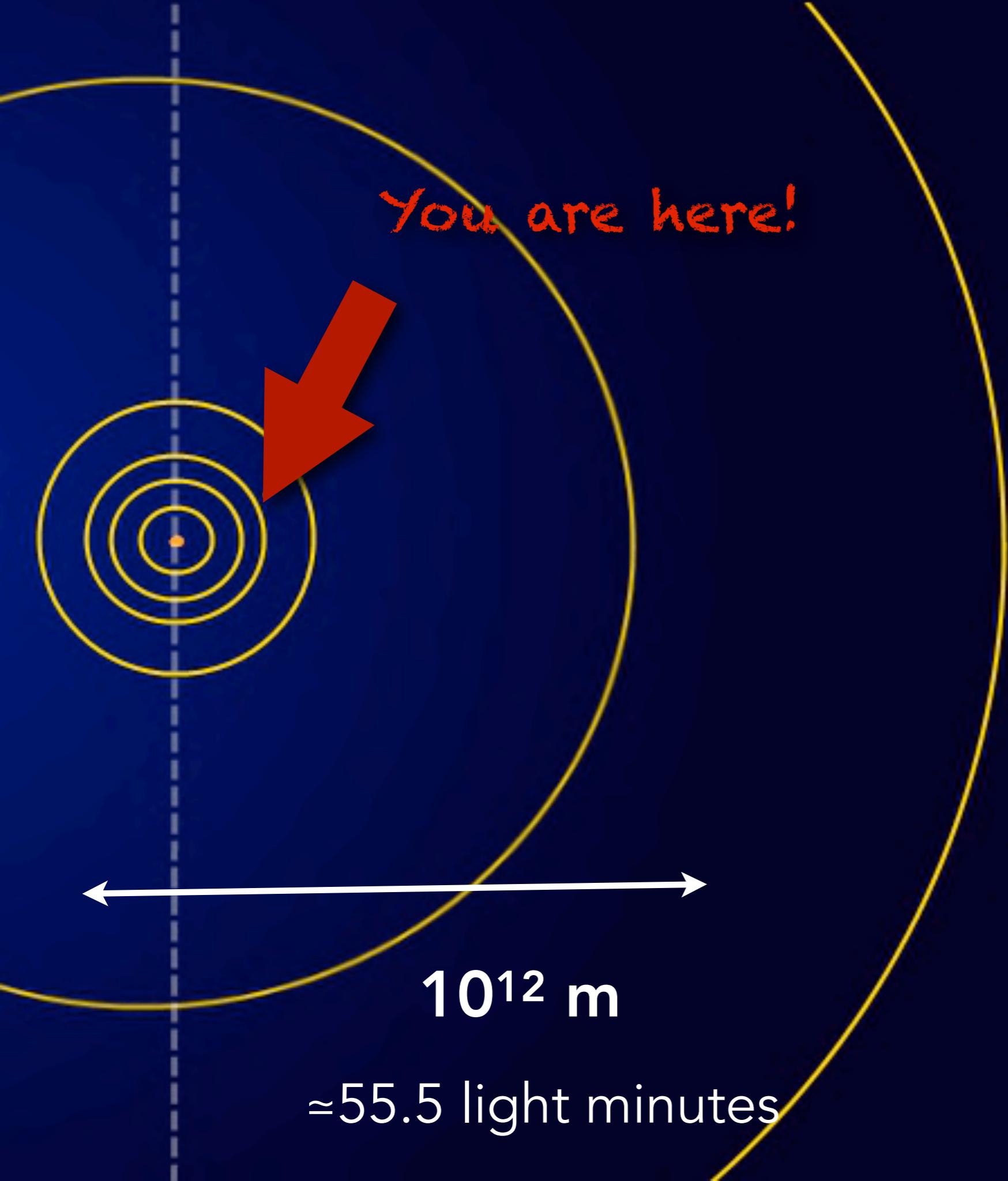


(and this is the Moon)



10^9 m

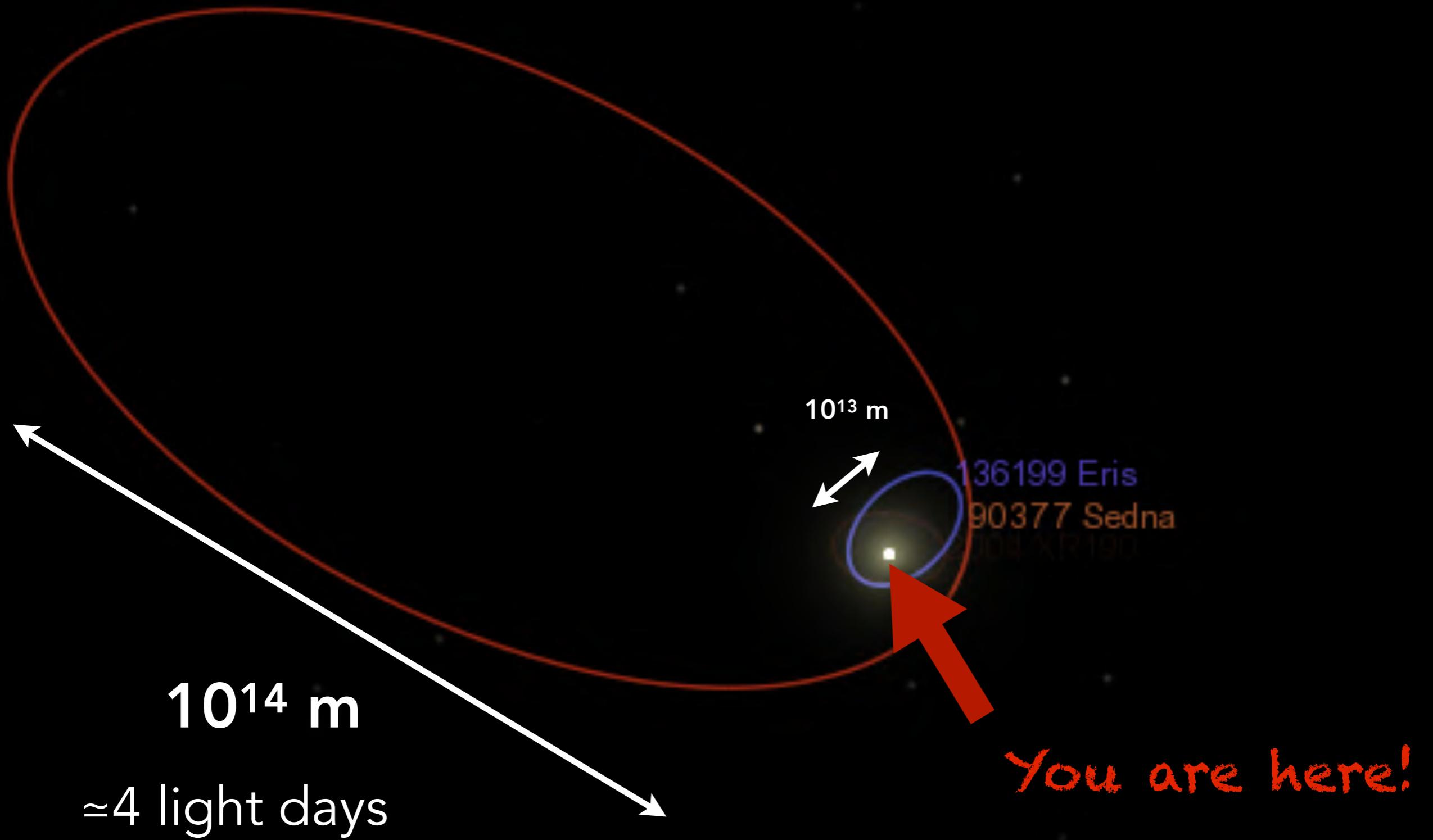
\approx 3.3 light seconds

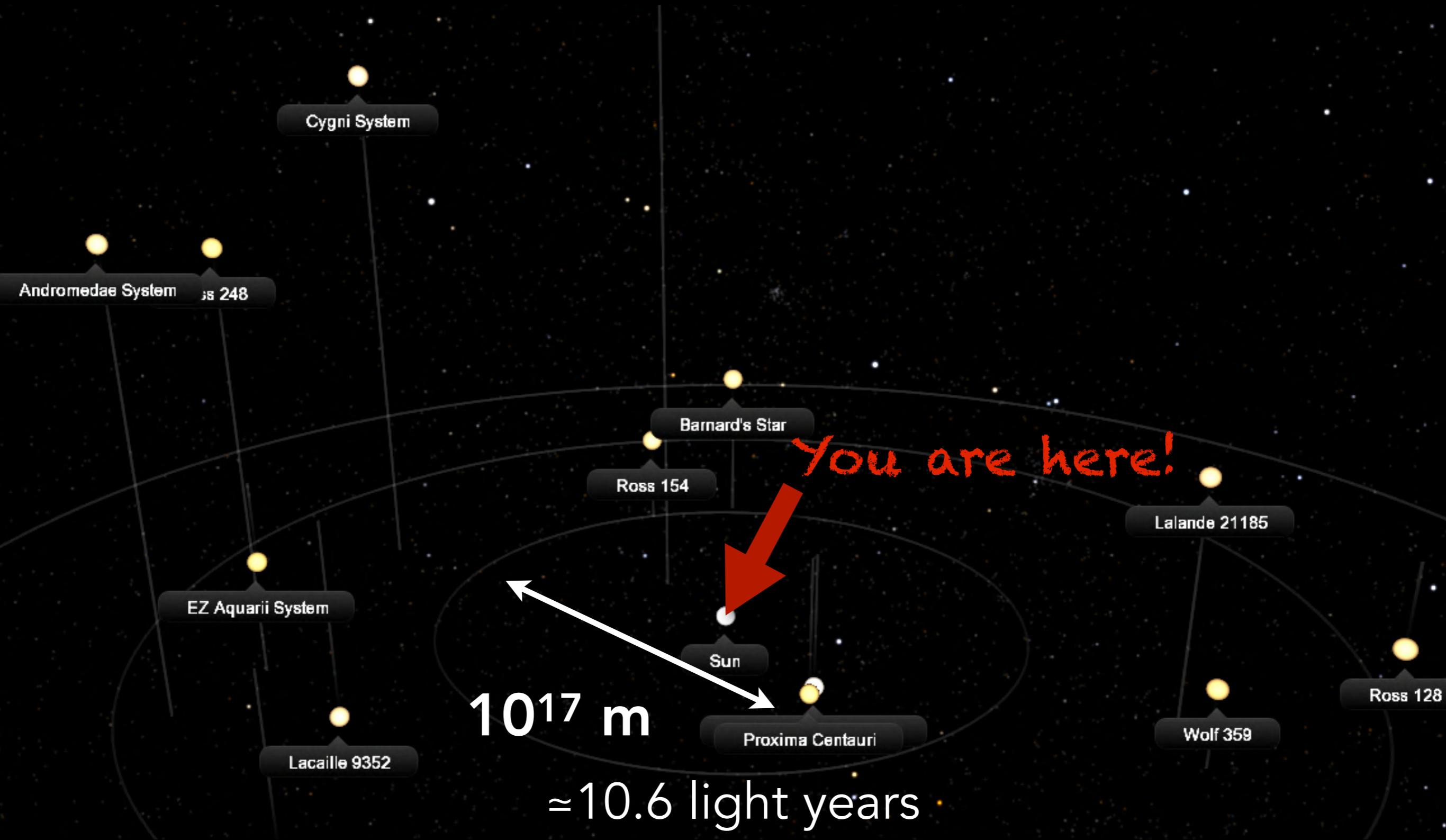


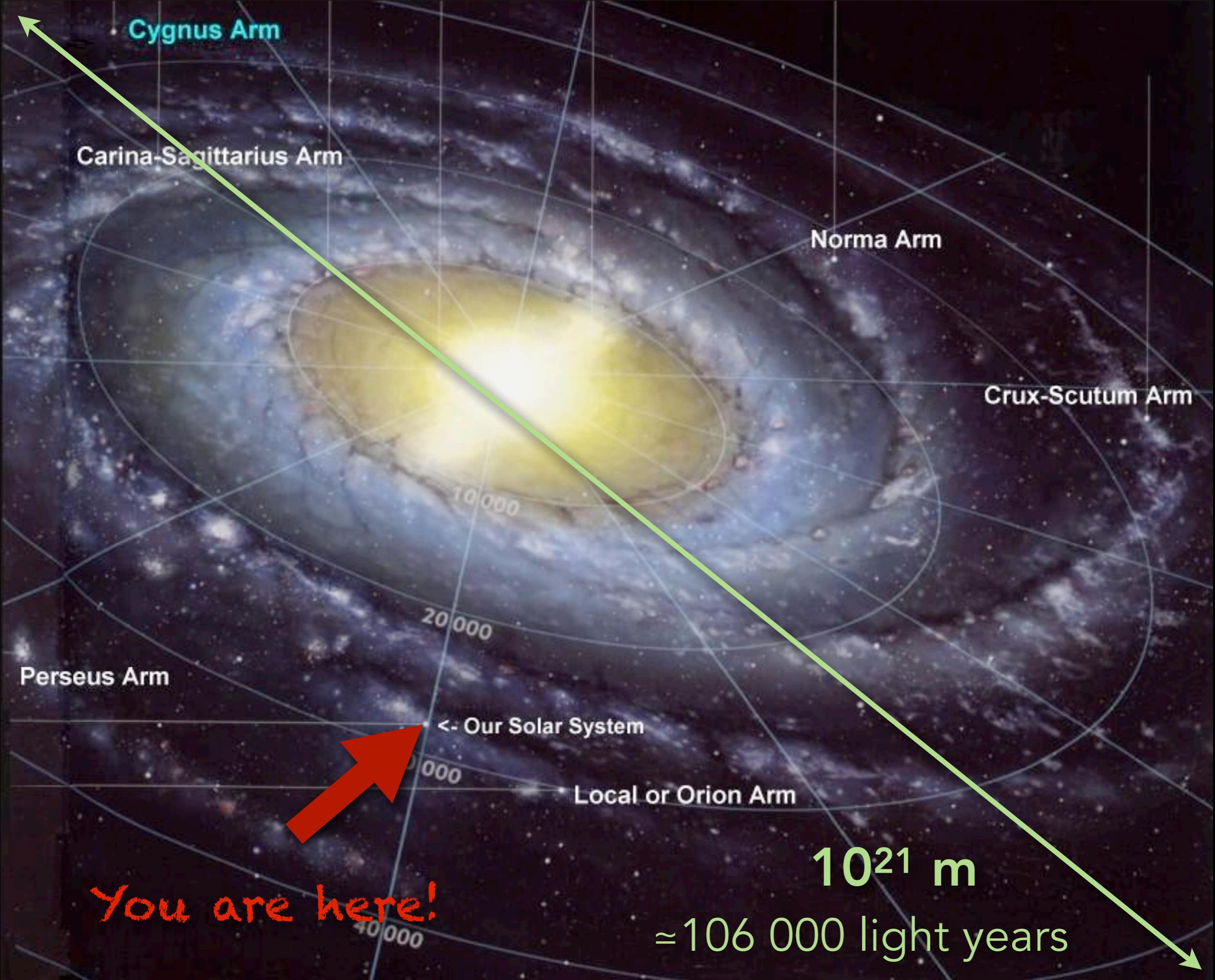
You are here!

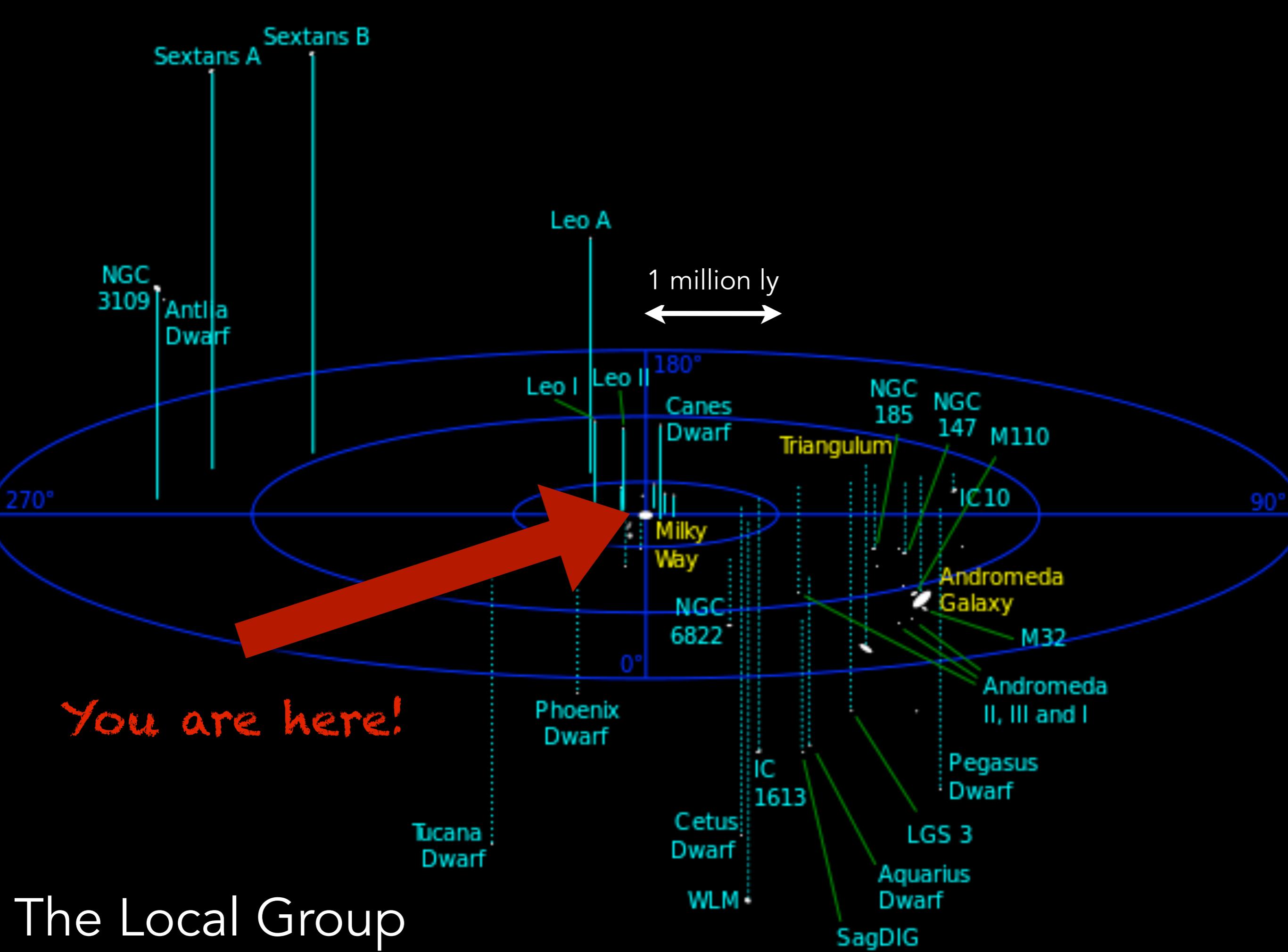
10^{12} m

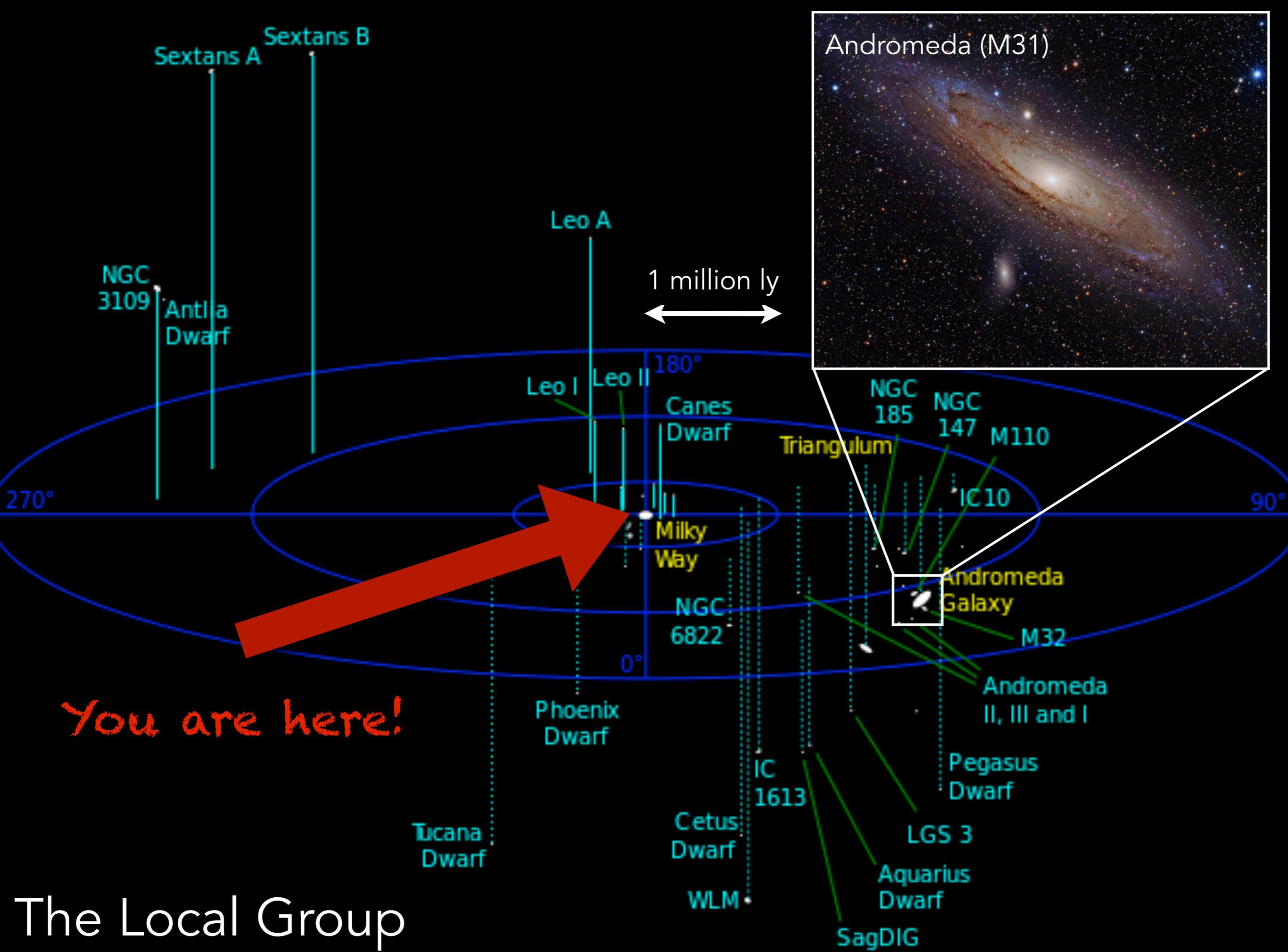
$\approx 55.5 \text{ light minutes}$

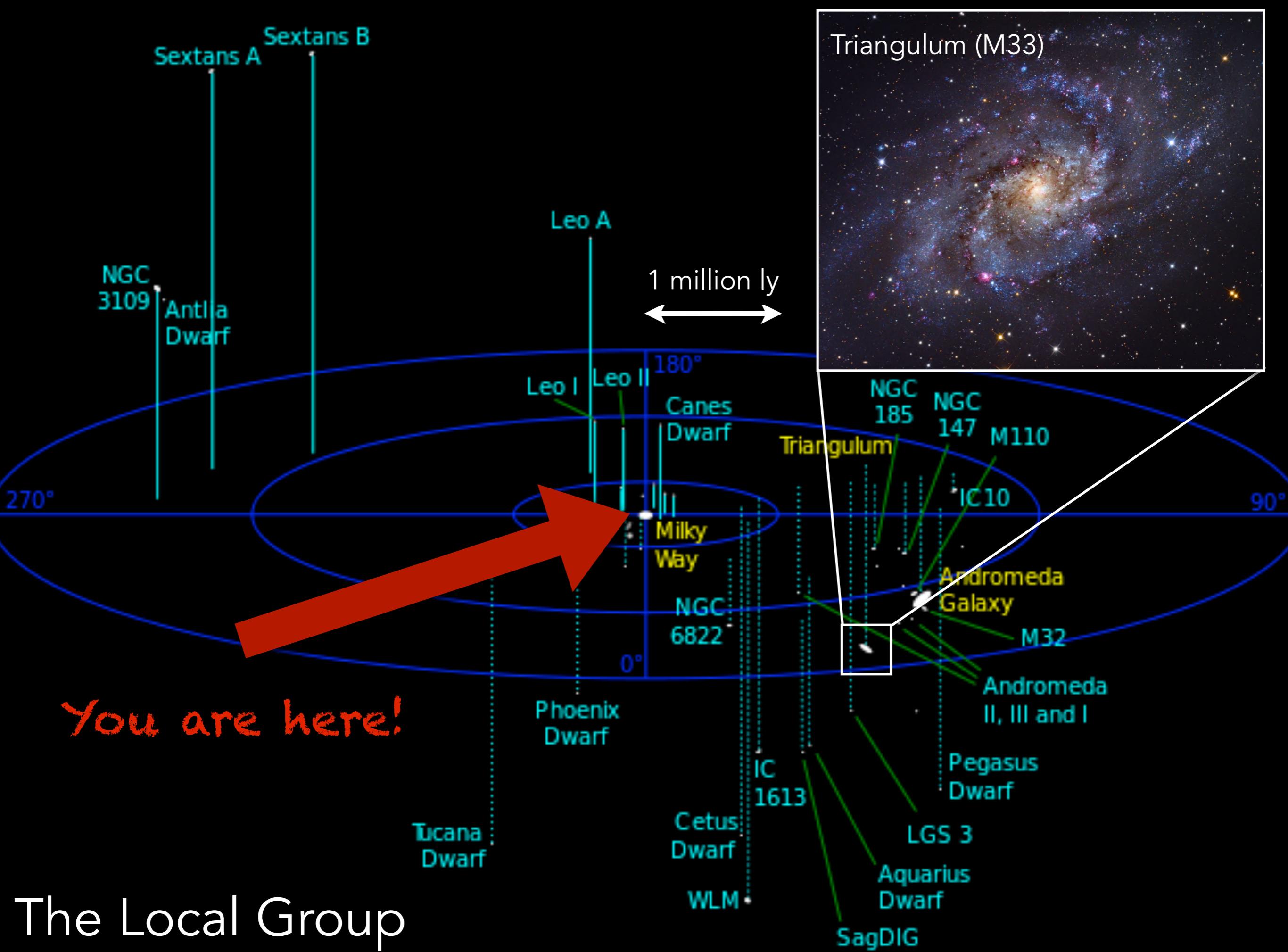


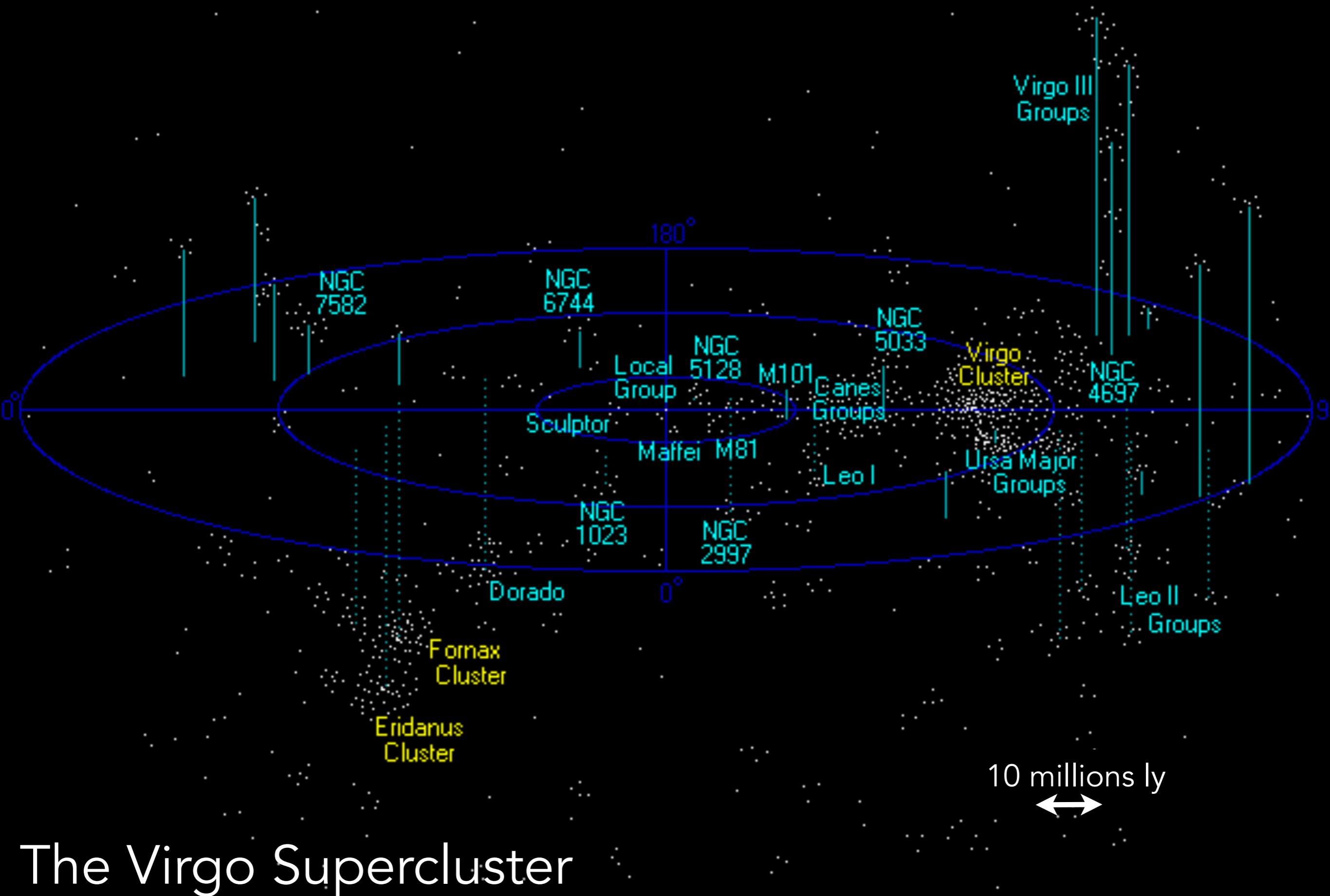


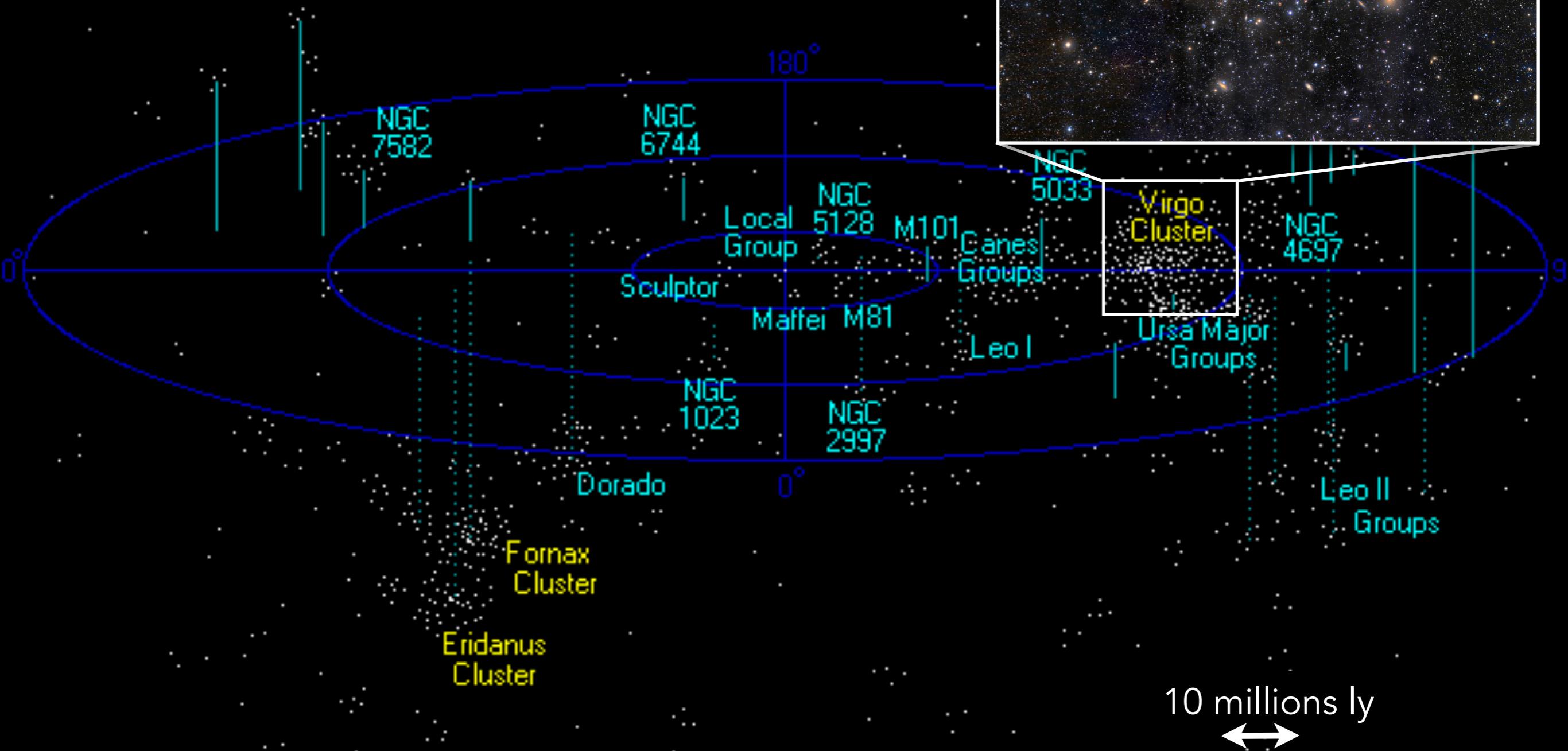




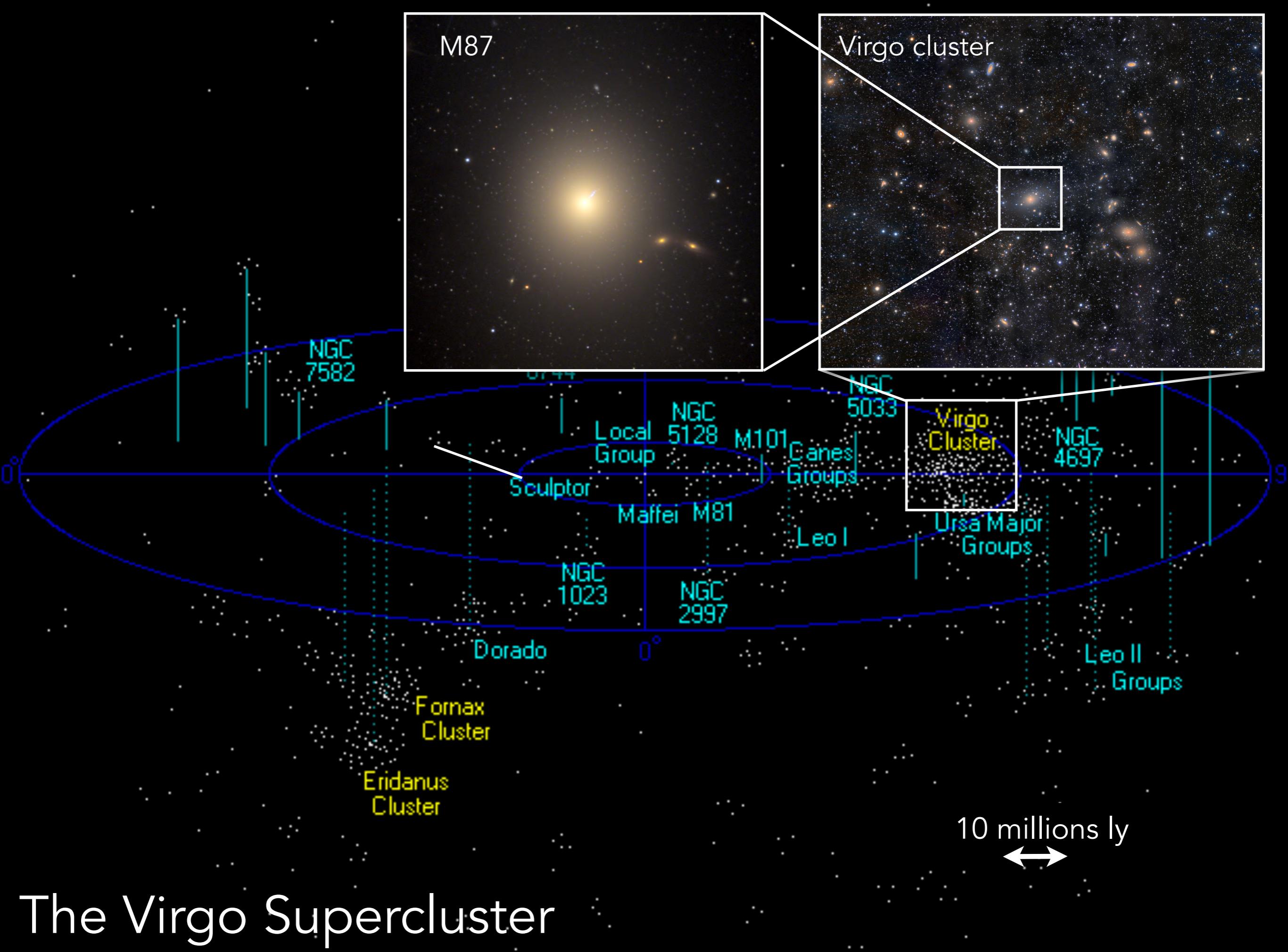


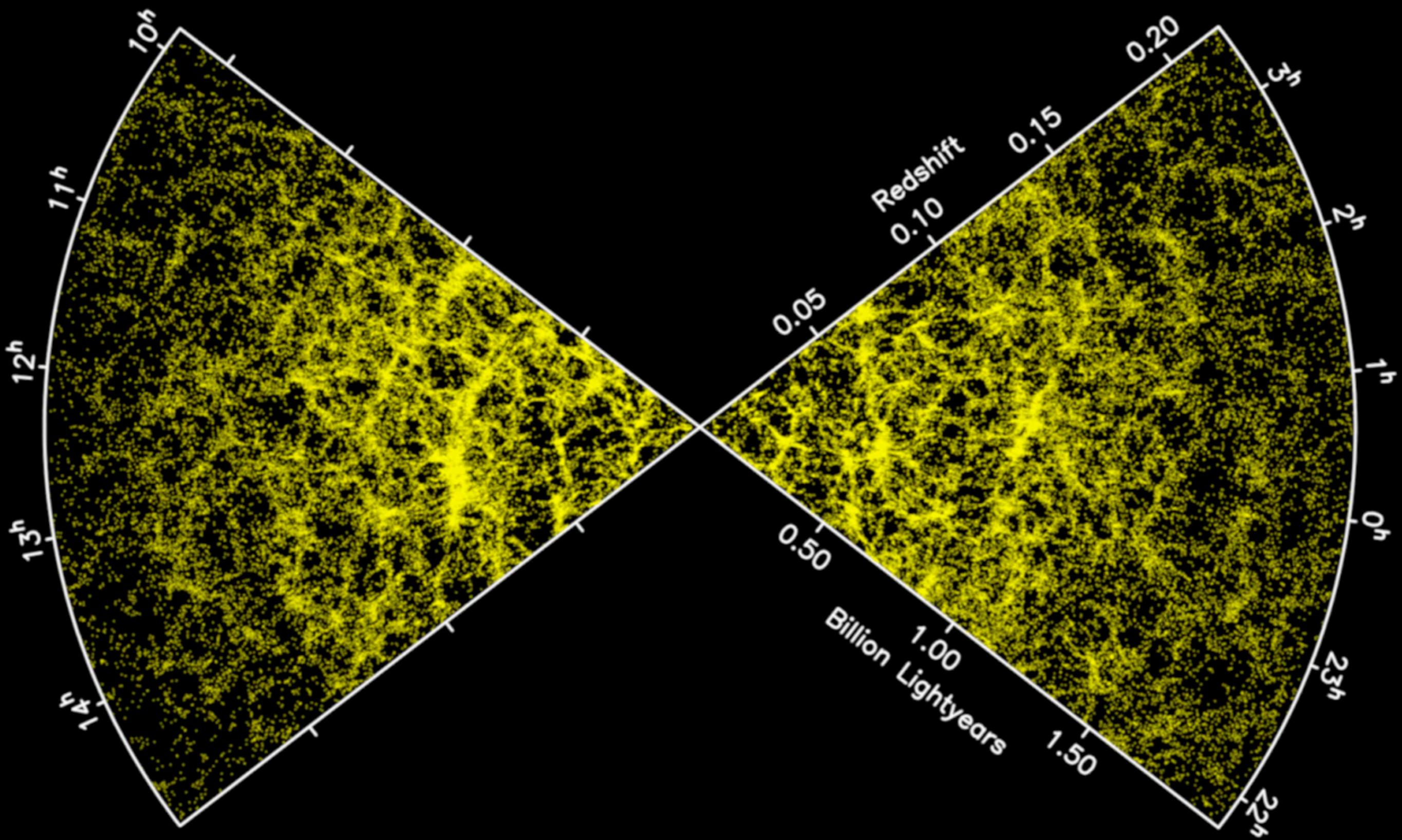






The Virgo Supercluster





The large scale structure of the universe



Abell 2199 (429 000 000 light years)

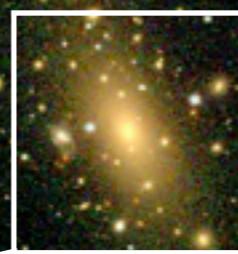


• Abell 2029 (1.1 billion light years)

Abell 2029 (1.1 billion light years)

[65.468 41.580 40.612]

5.000 Mpc



$z = 2.249$

Object0038



Abell 1689 (2.2 billion light years)

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 electromagnetic 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 helpful, as when radiation is used to kill cancer cells, and other times not, as when we get sunburned.

Seeing Beyond our Atmosphere

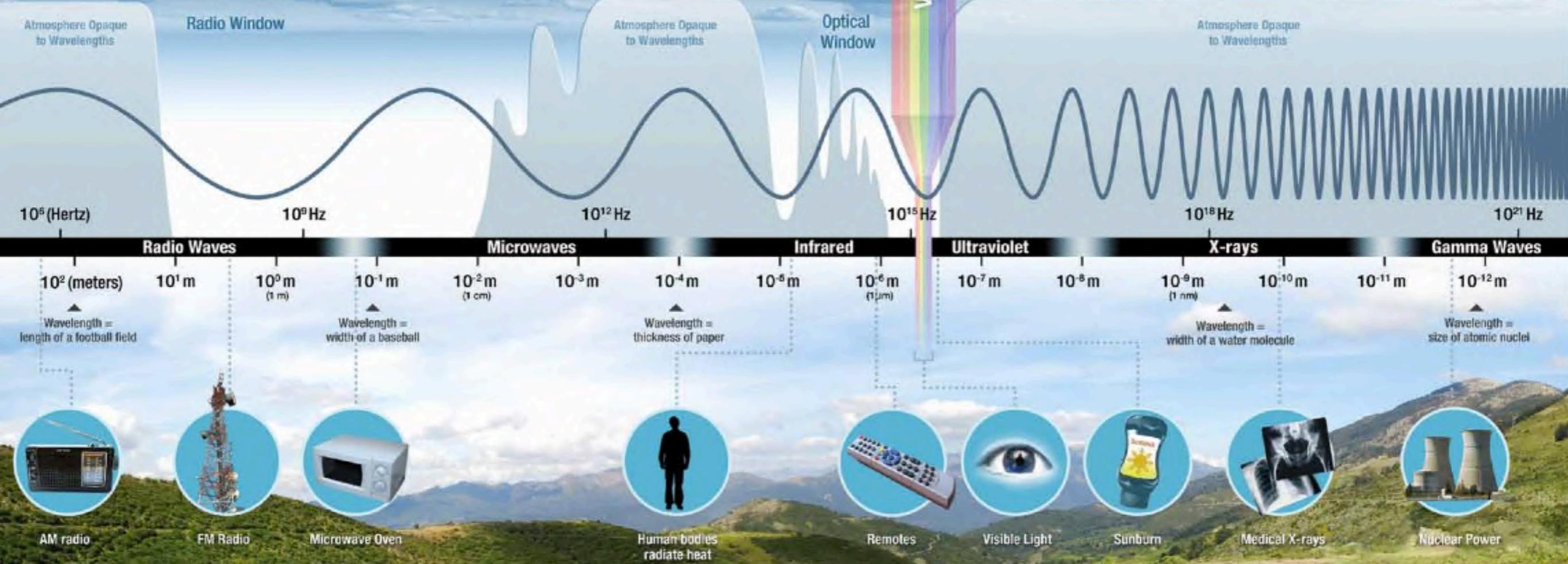
NASA spacecraft, such as RHESSI, provide scientists with a unique vantage point, helping them “see” at higher-energy wavelengths that are blocked by the Earth's protective atmosphere.



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 visible 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.



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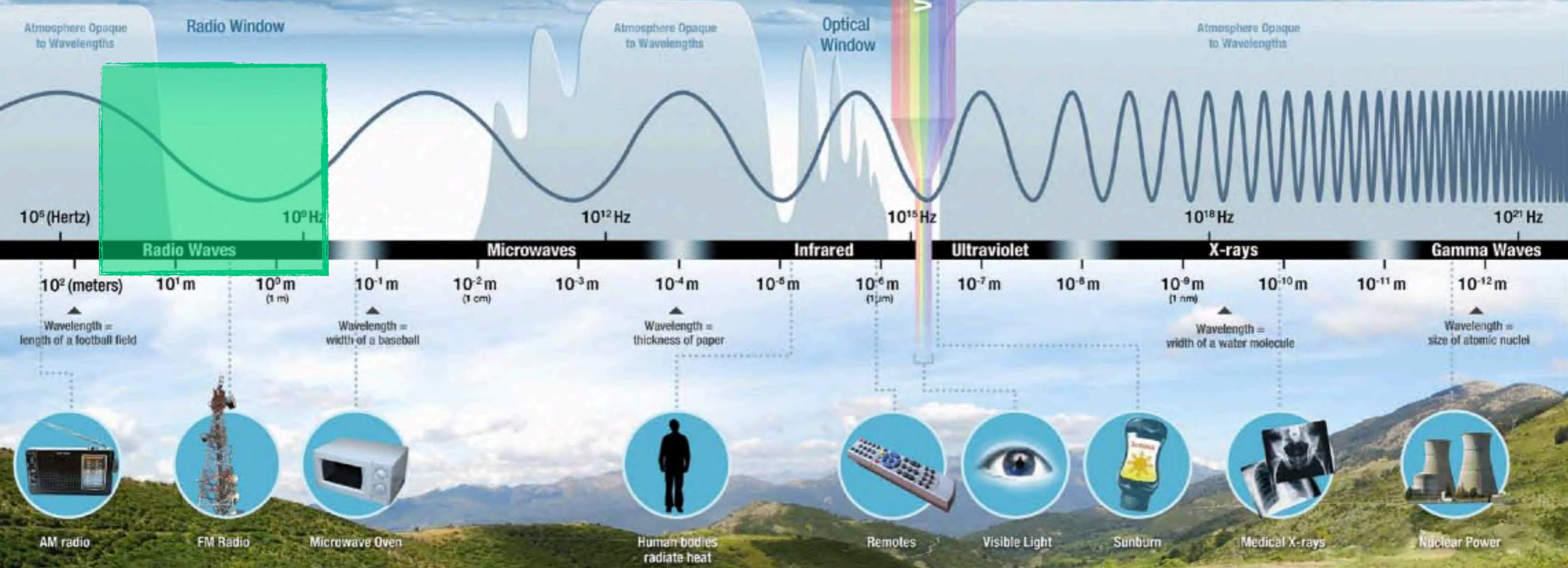
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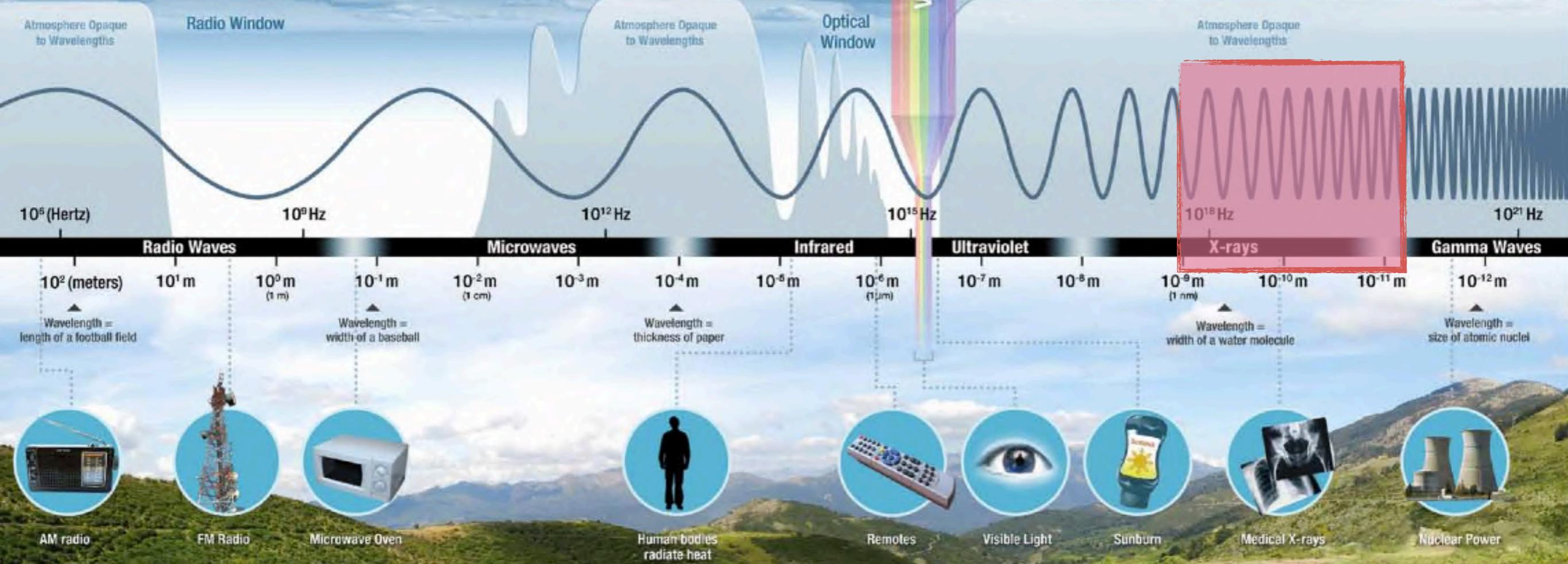
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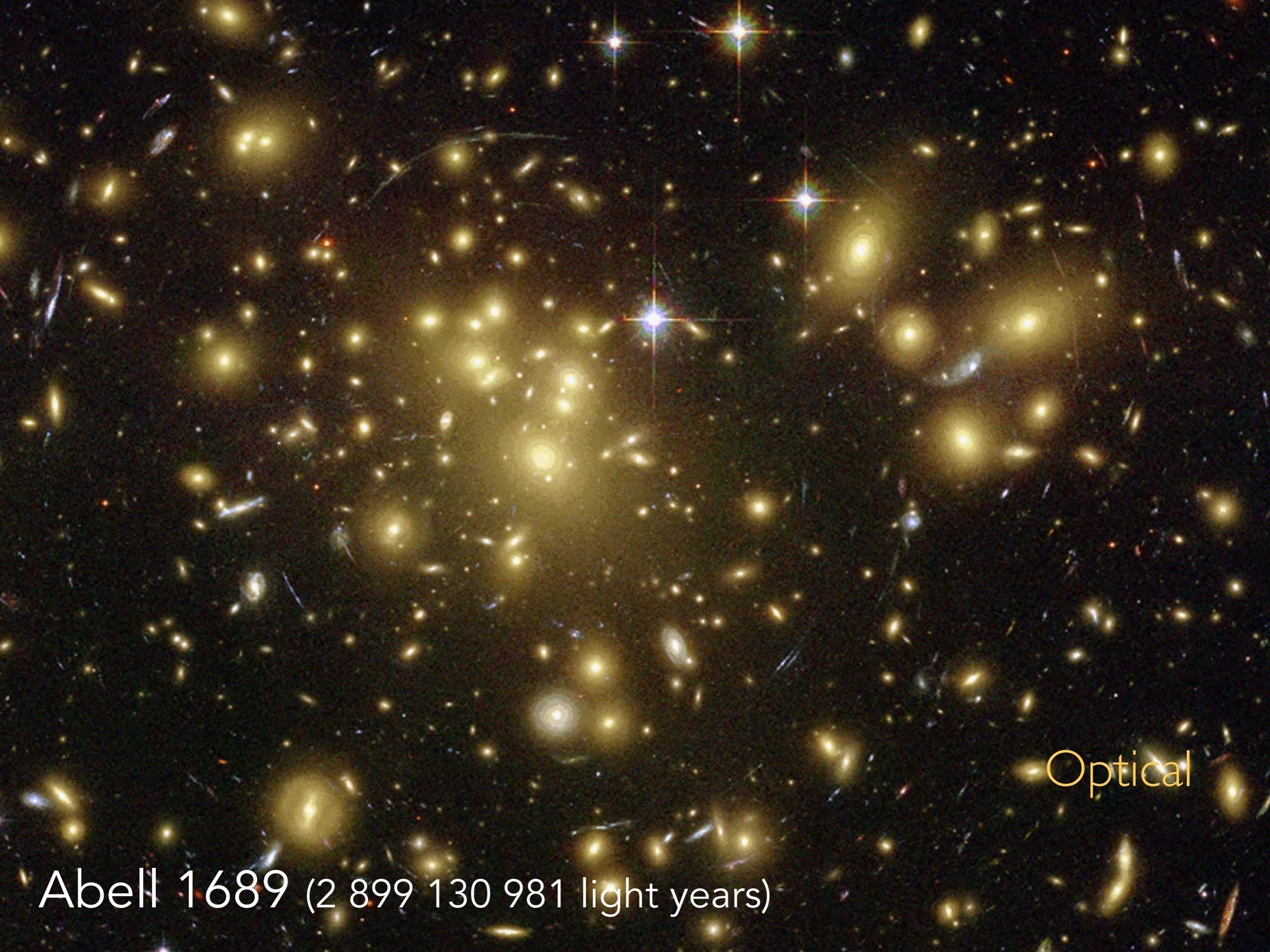


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Abell 1689 (2 899 130 981 light years)

Optical

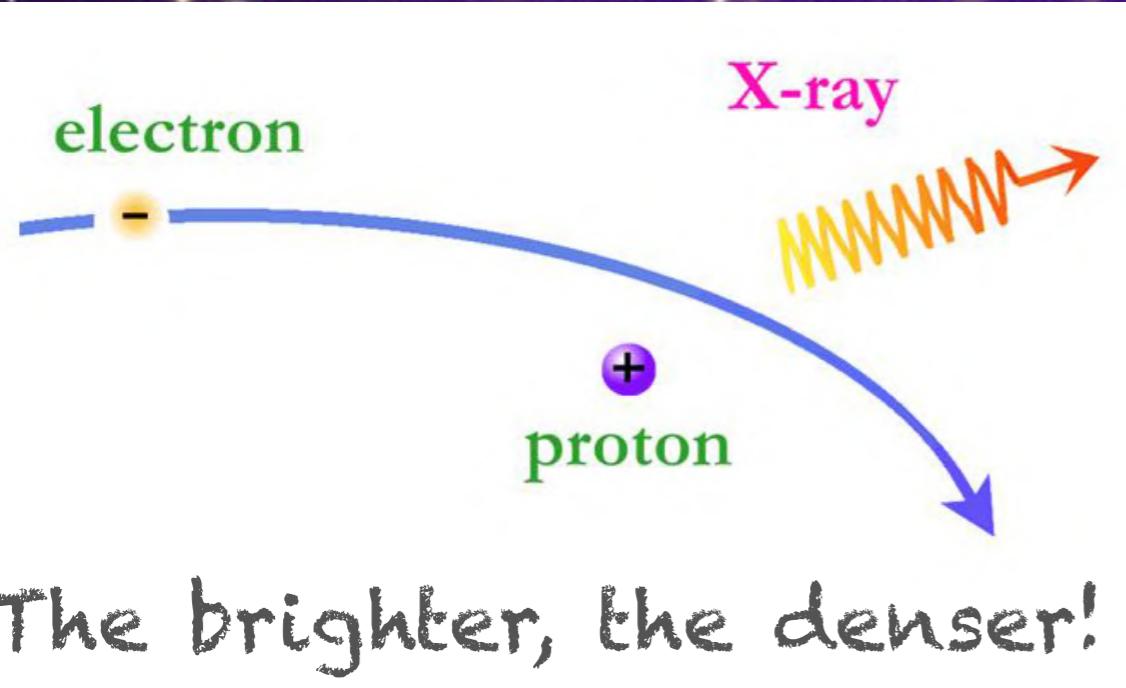
X-rays

Abell 1689 (2 899 130 981 light years)

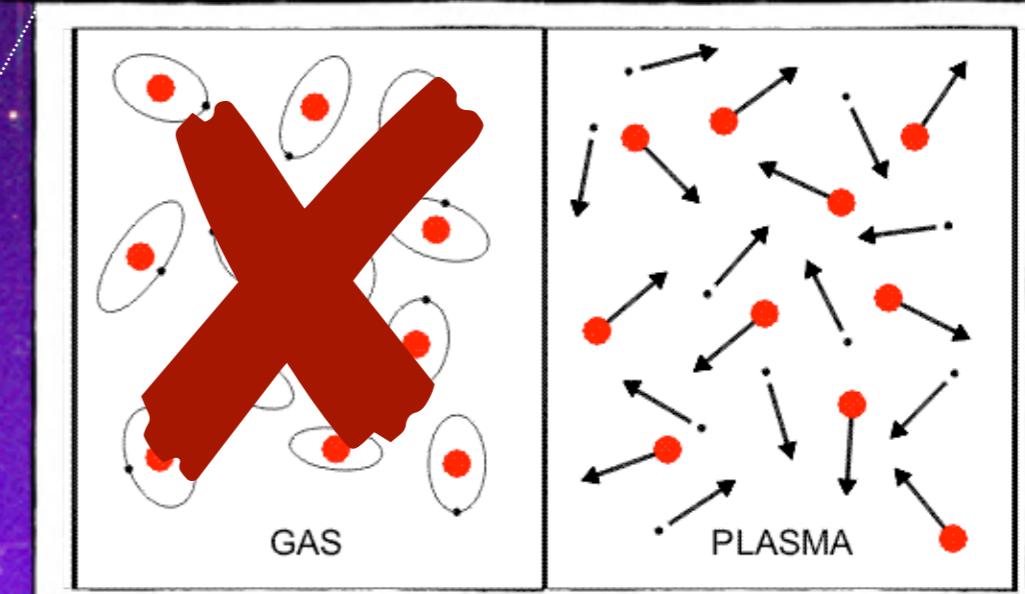


X-rays

Optical

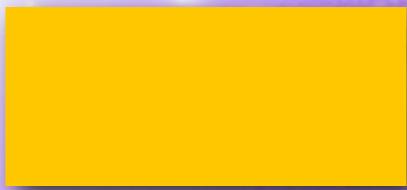


The brighter, the denser!



Hot atmospheres... are hot!
(~10 to 100 million °C)

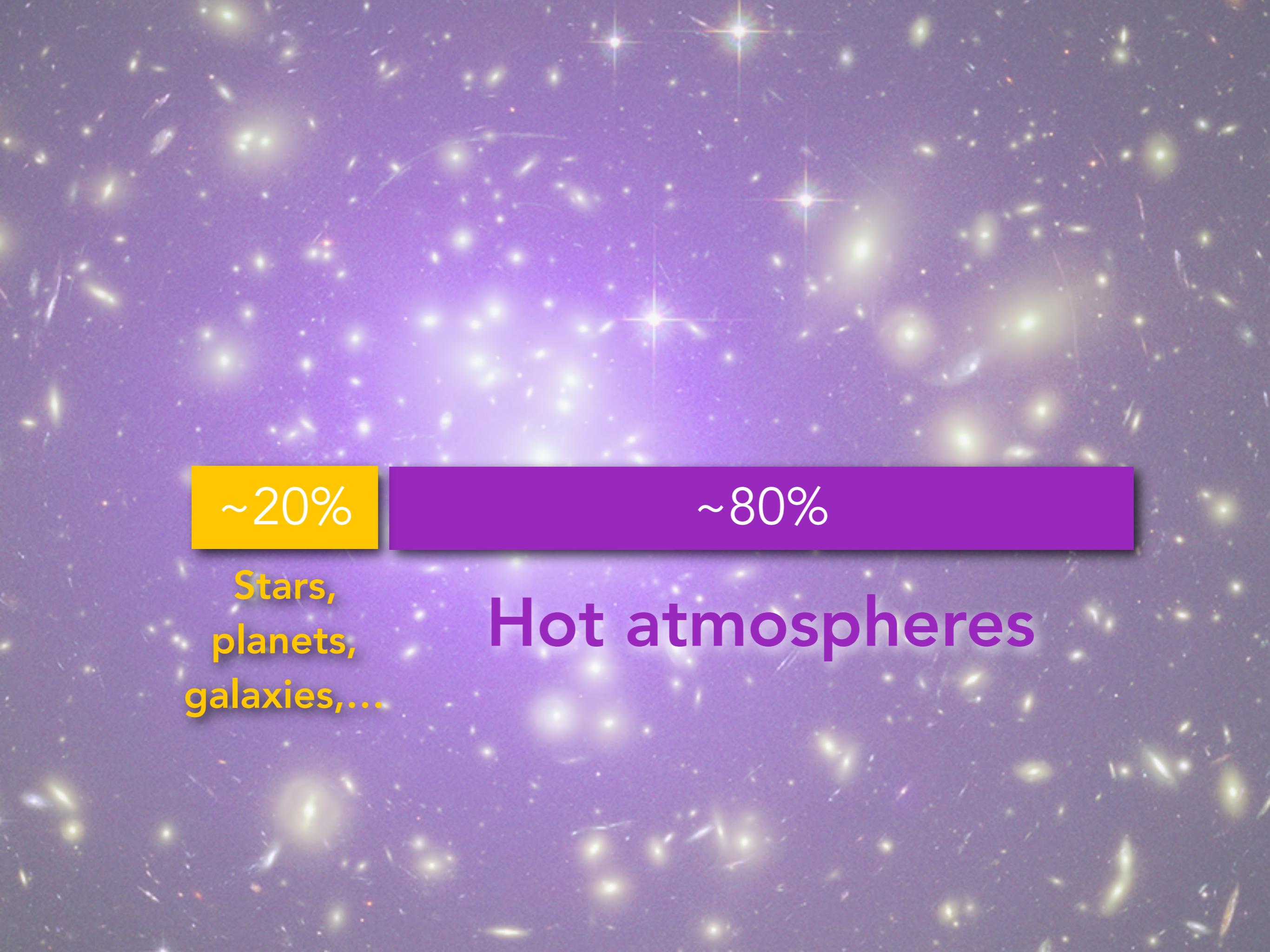
X-rays
Optical



Stars,
planets,
galaxies,...



Stars,
planets,
galaxies,...



~20%

~80%

Stars,
planets,
galaxies,...

Hot atmospheres



\sim 15%

\sim 85%

Stars,
planets,
galaxies,... Hot
atmospheres

Dark matter



Fornax cluster (62 million light years)

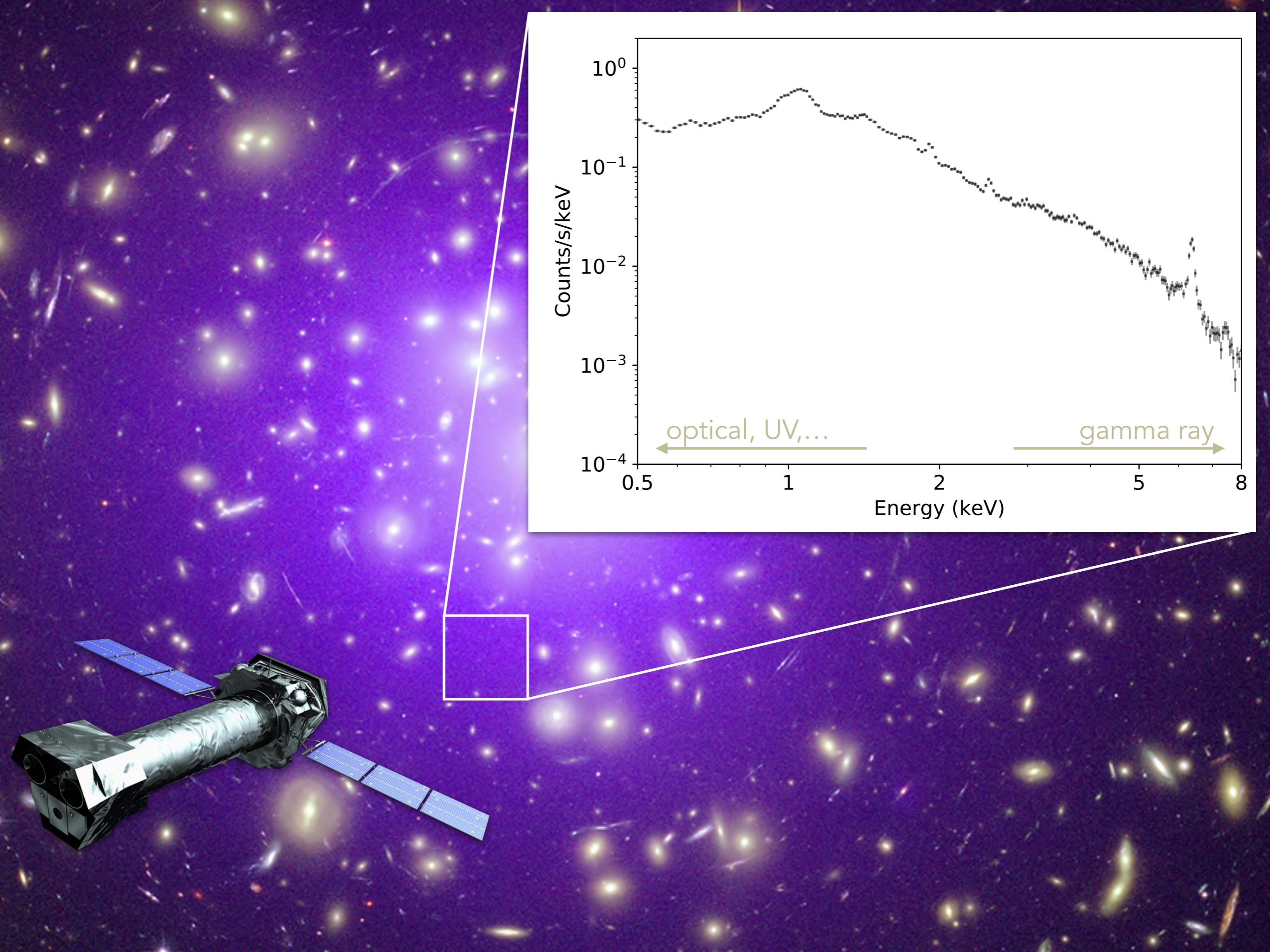


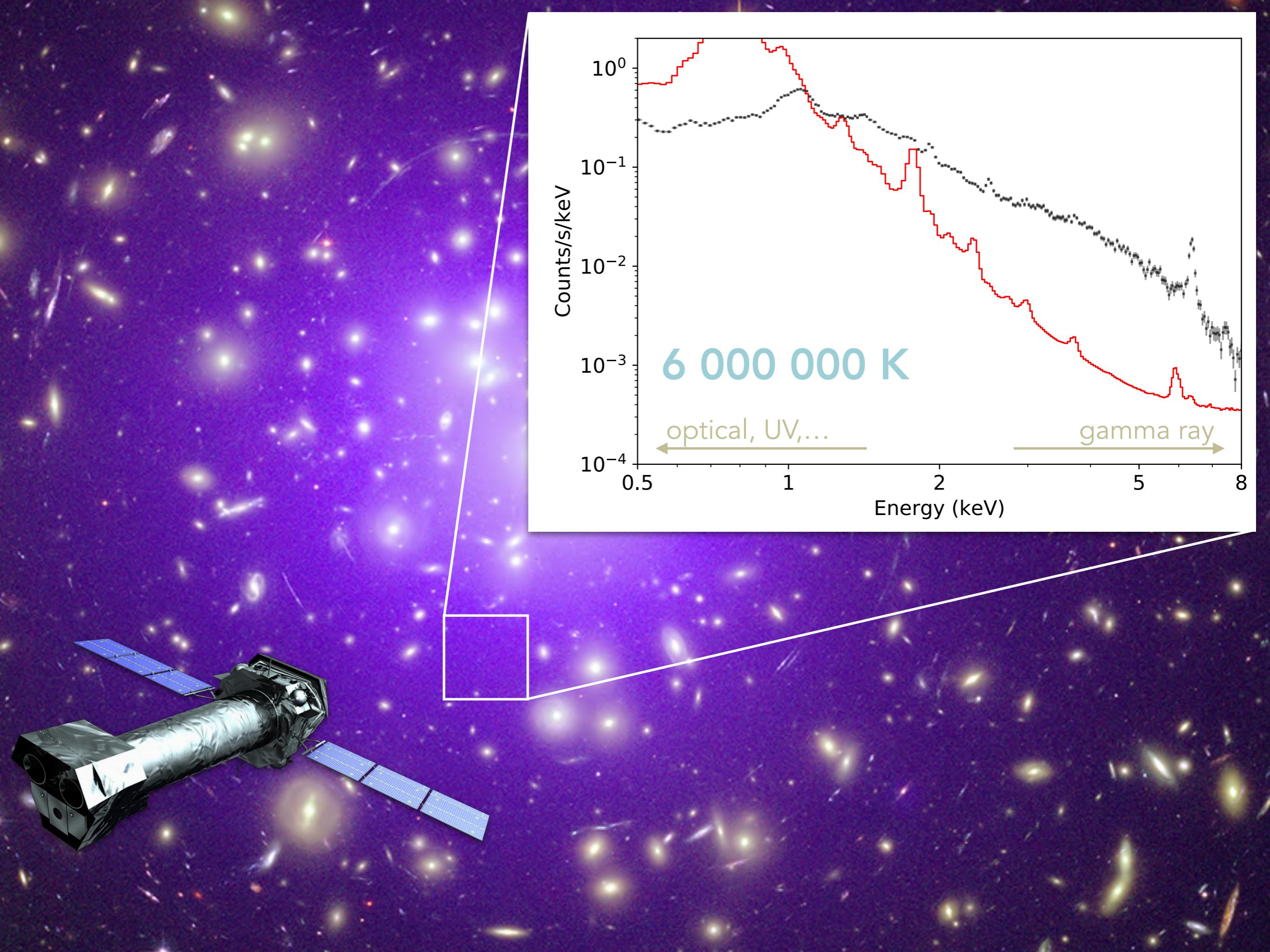
Hot atmospheres are studied in Budapest (ELTE)!

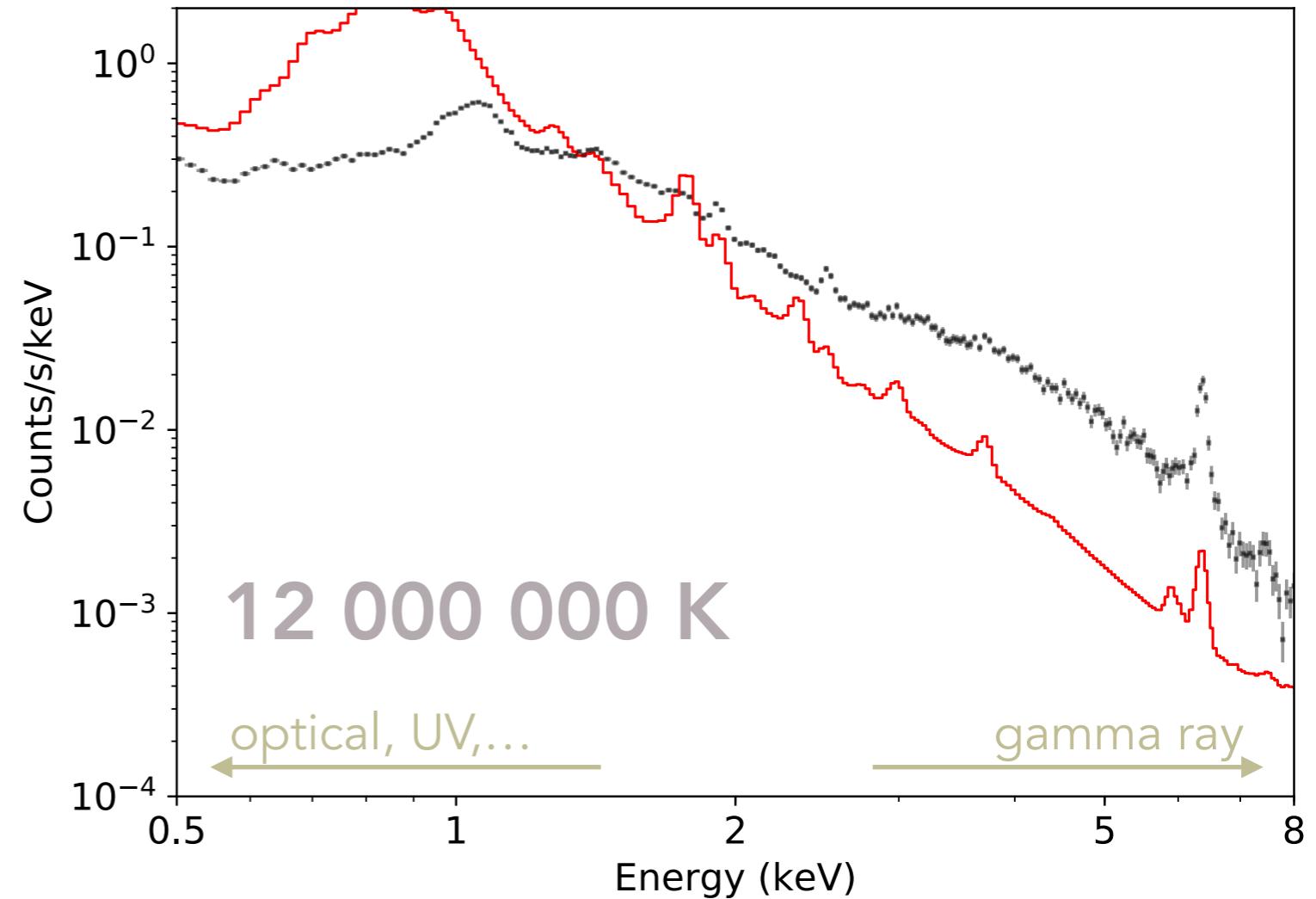
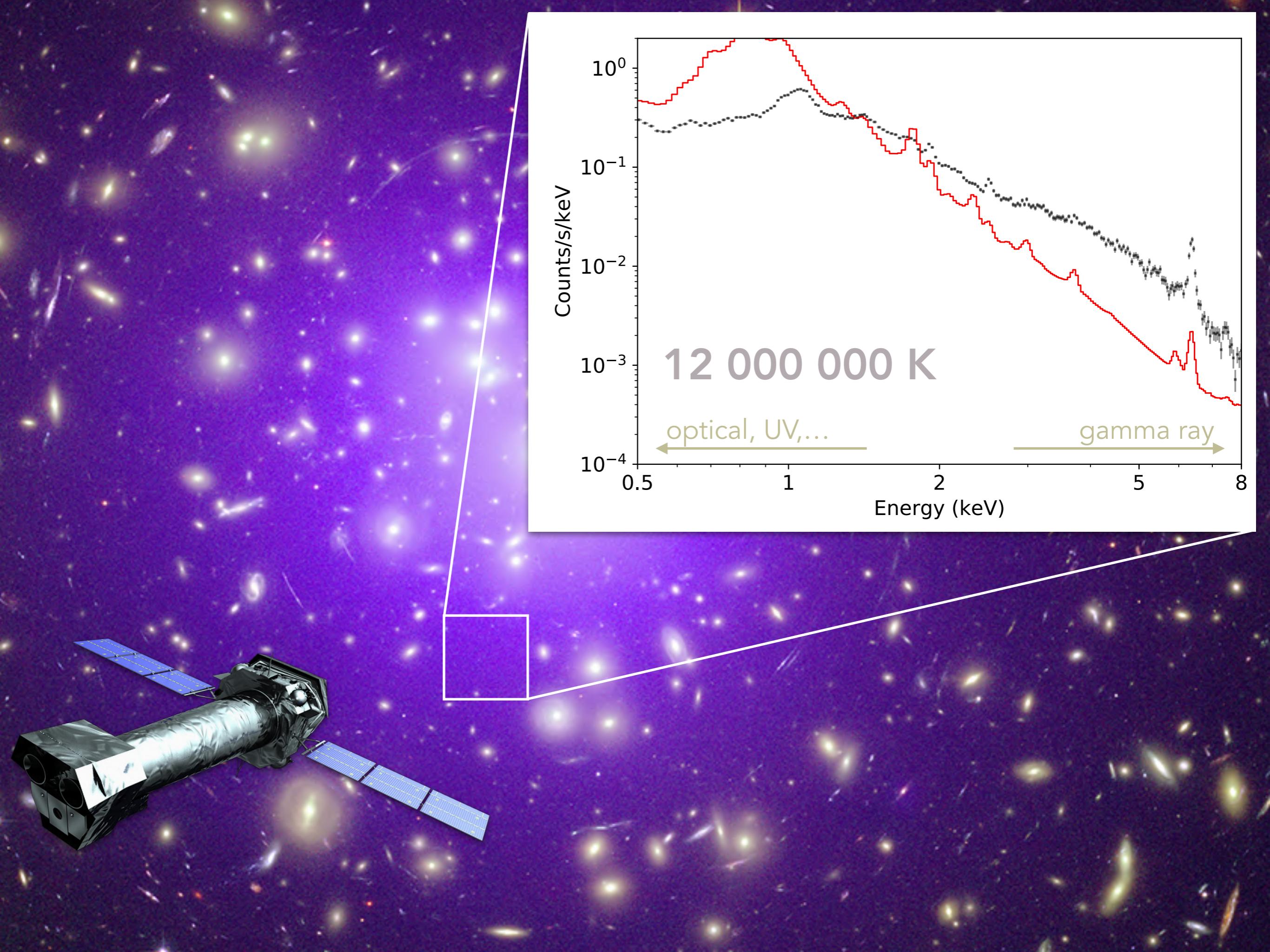
- **Temperature** (Kiran Lakhchaura, Norbert Werner)
- **Chemical composition** (François Mernier, Norbert Werner)
- **Cosmological simulations** (Nhut Truong)

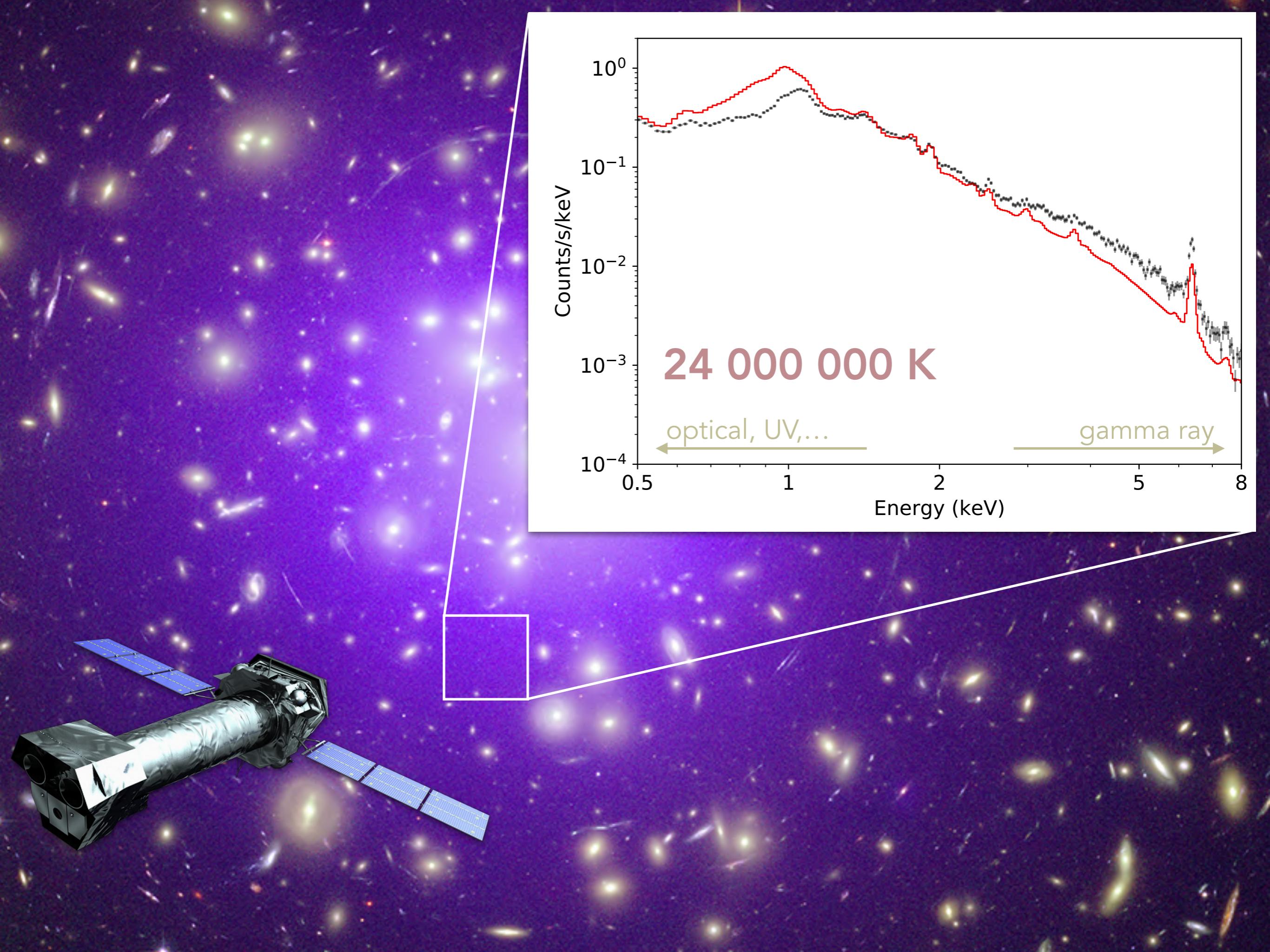
1. Temperature

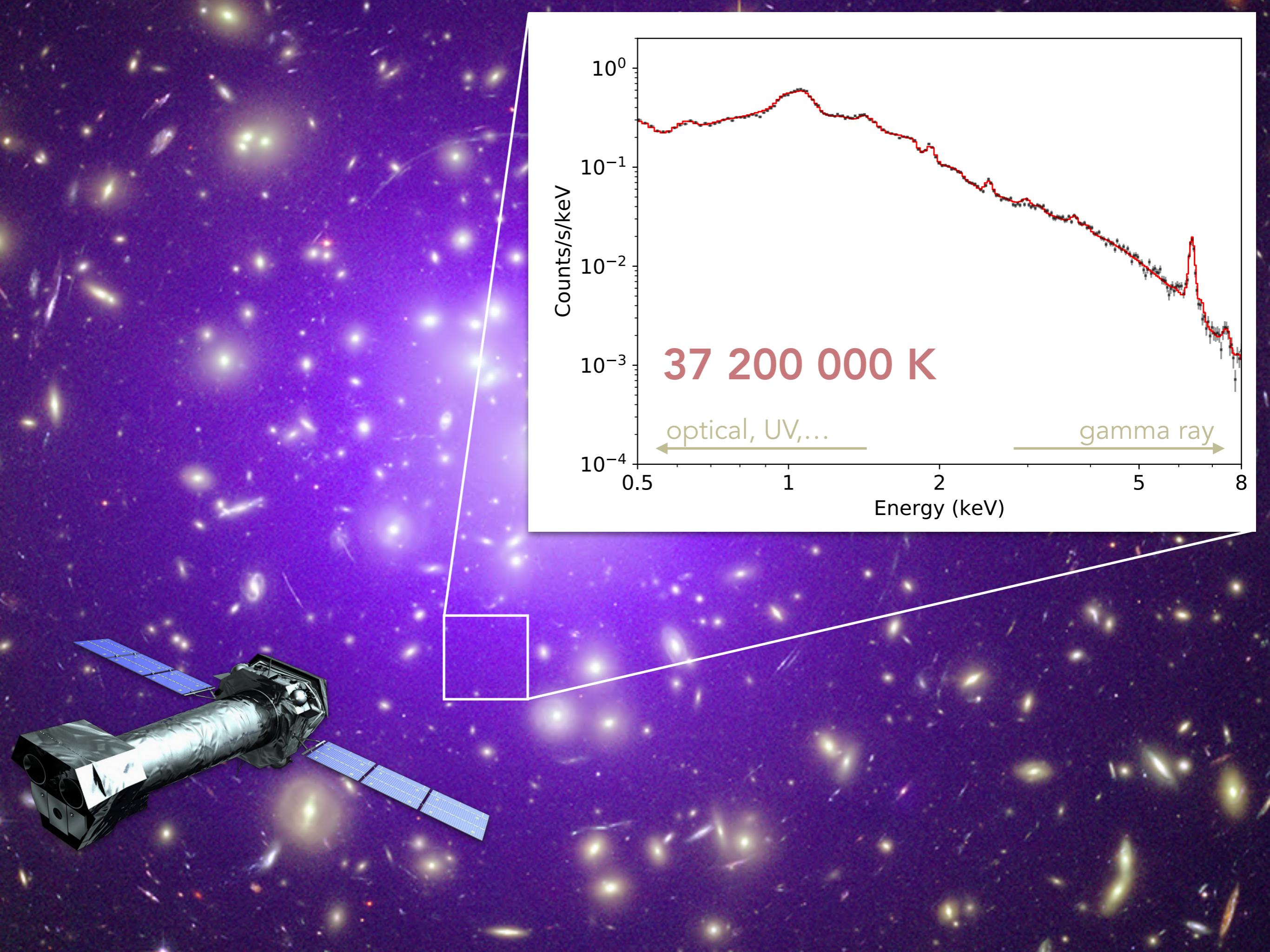


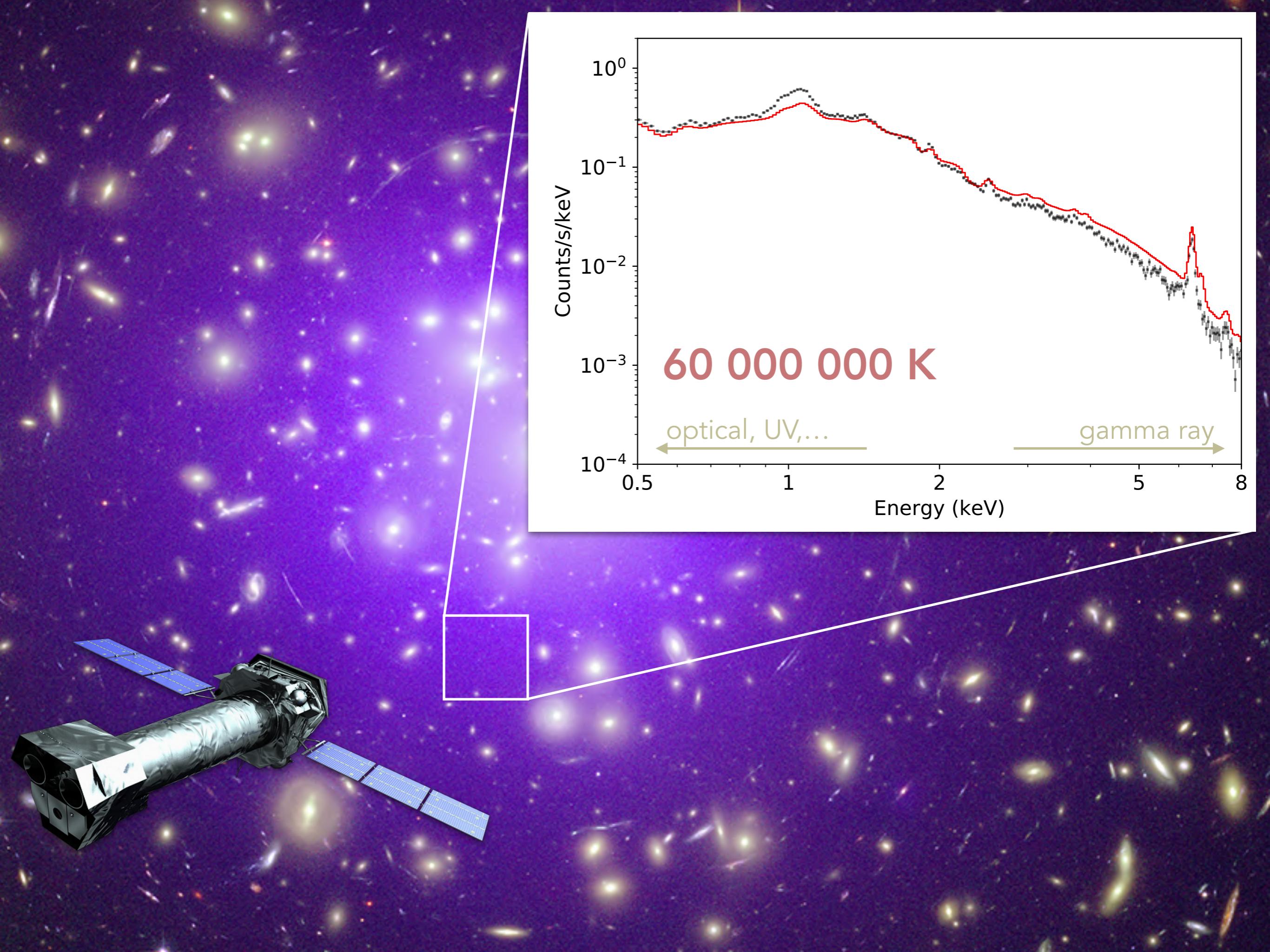


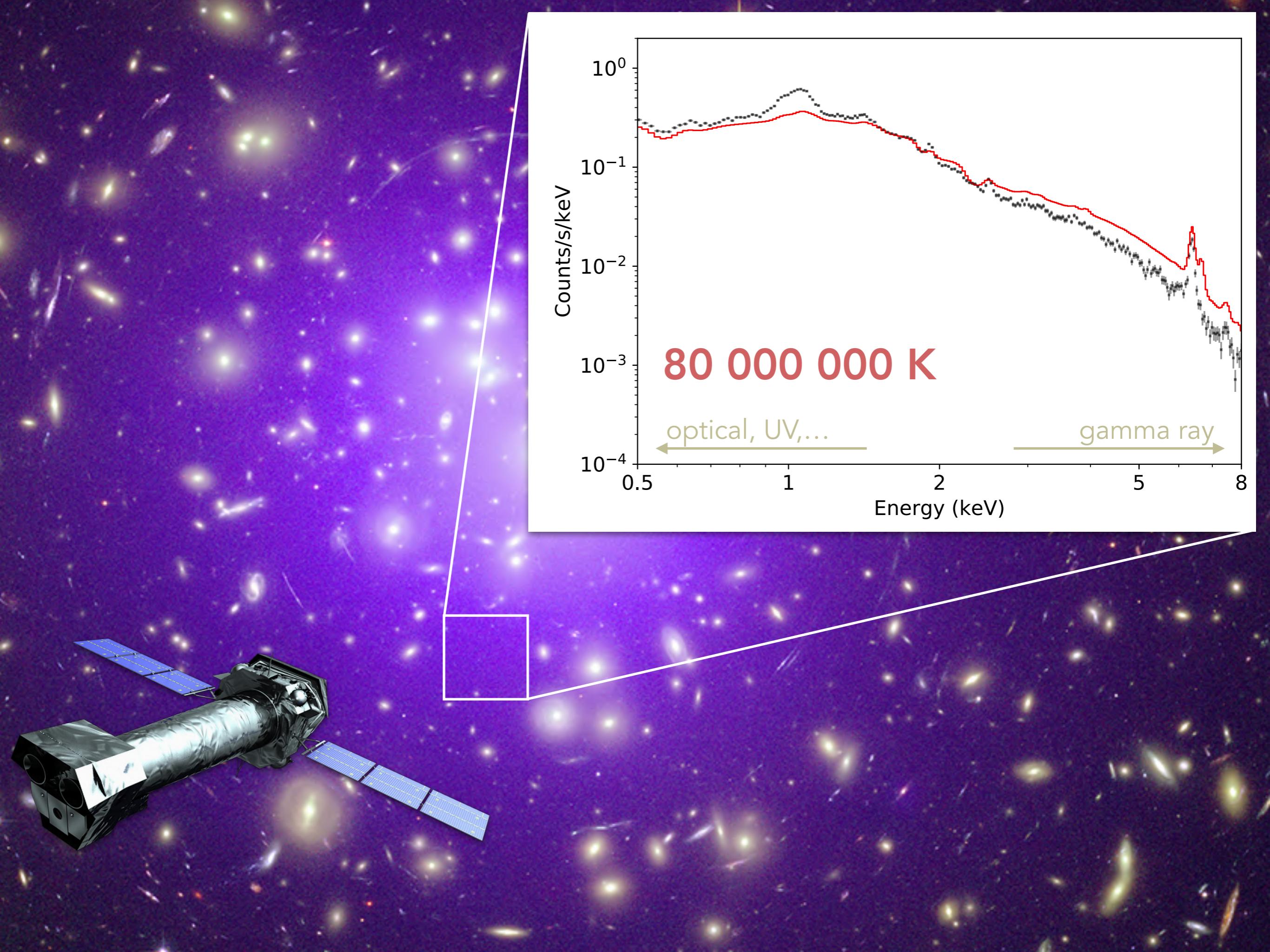


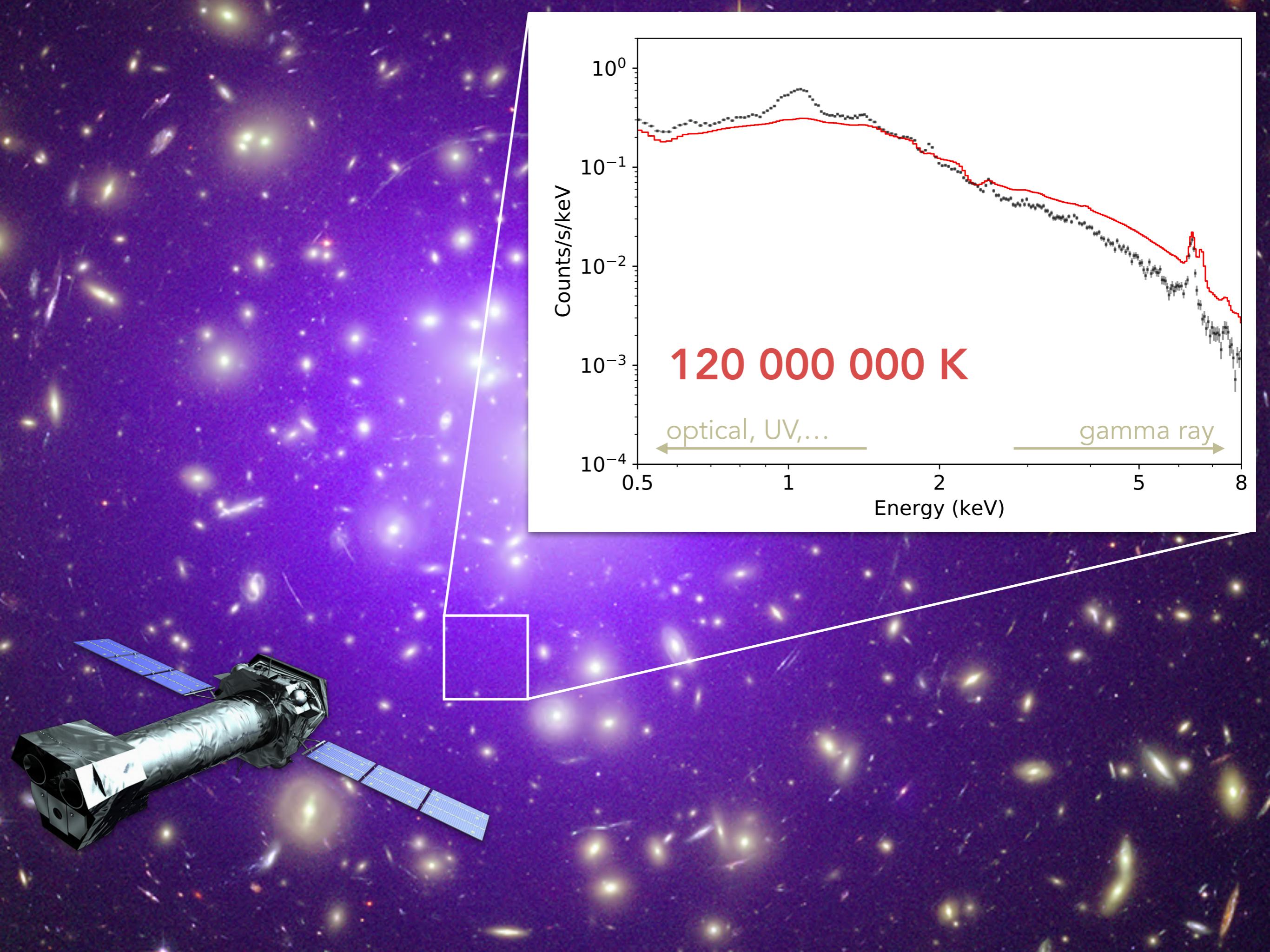


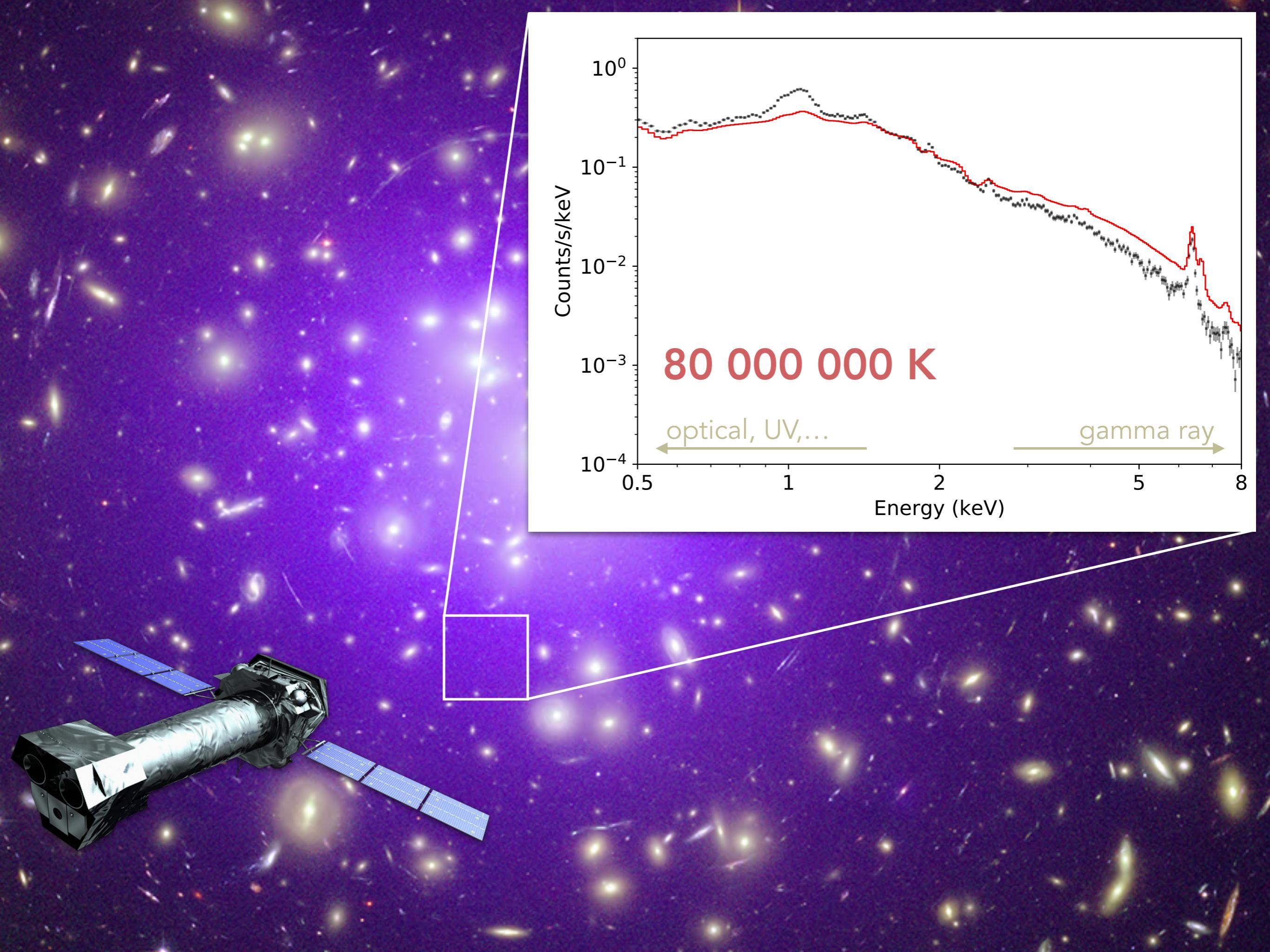


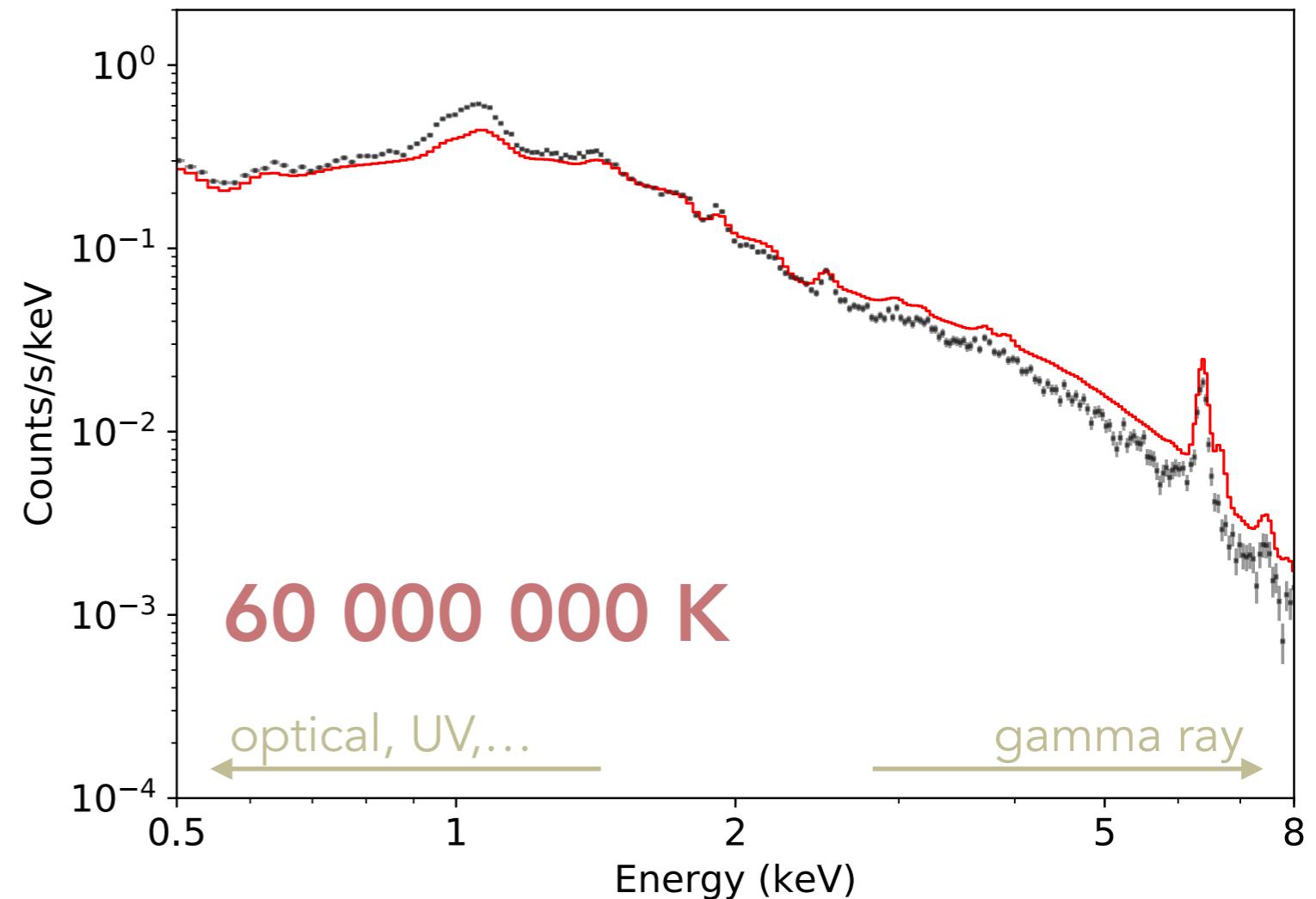
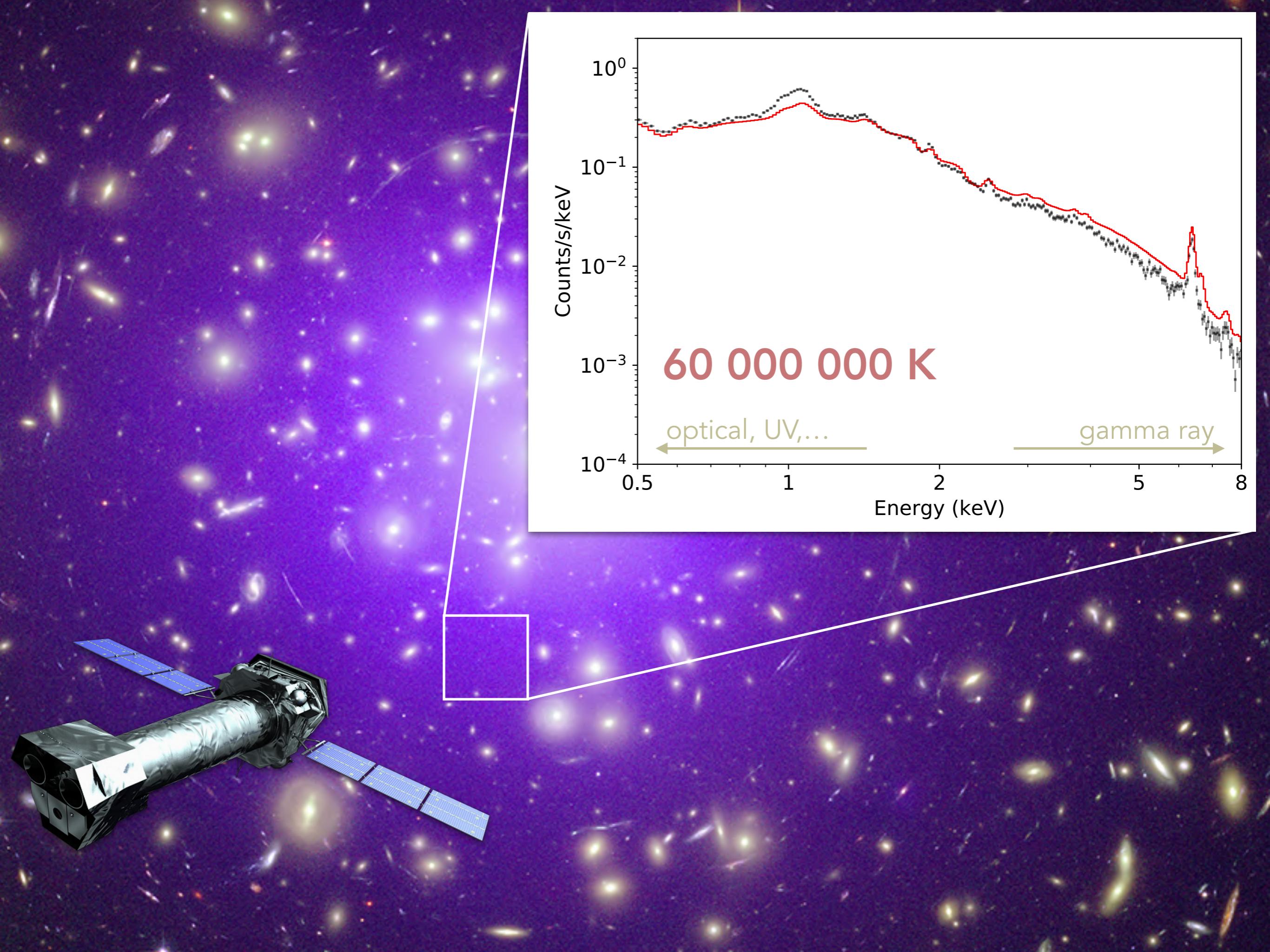


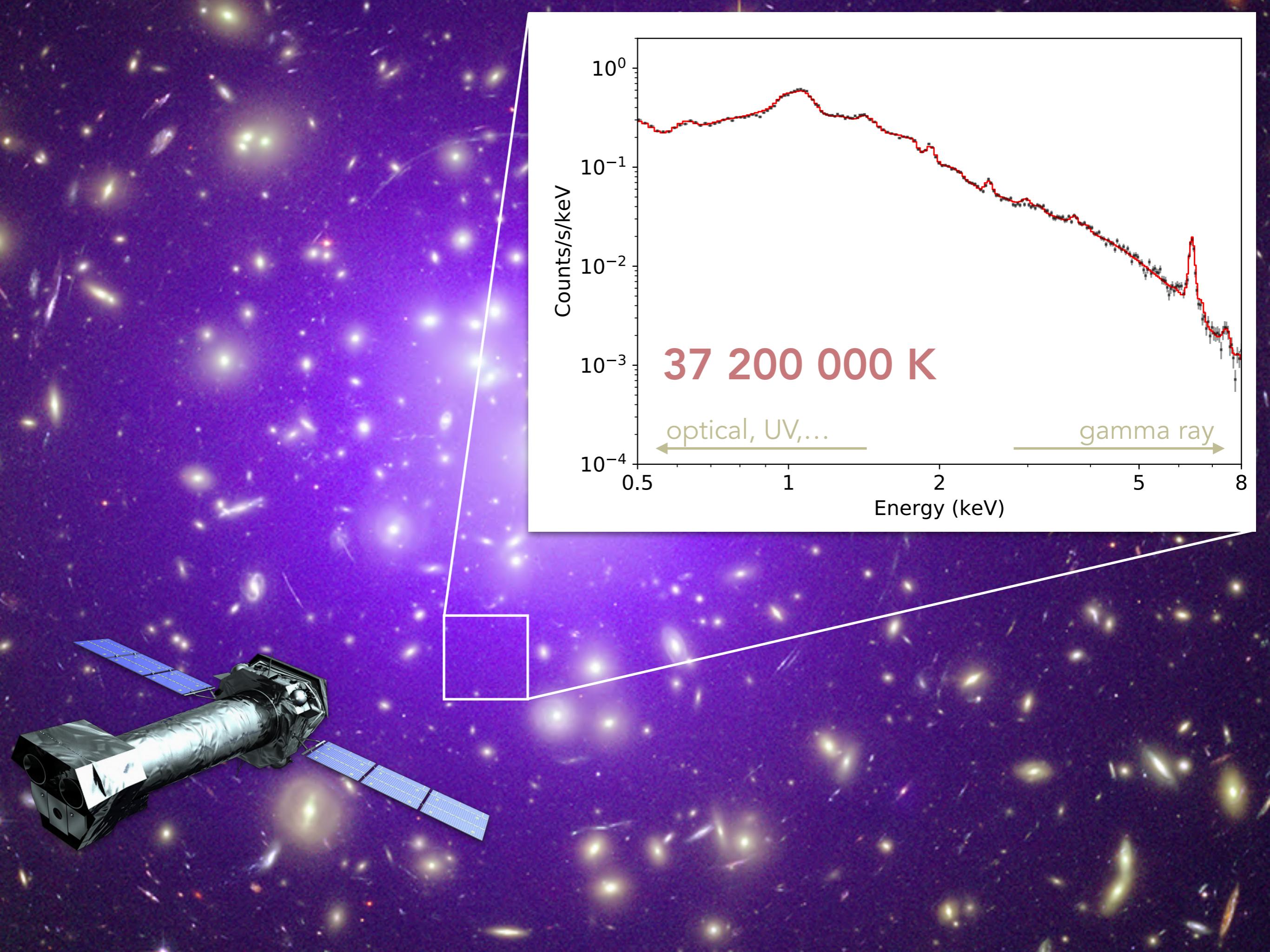


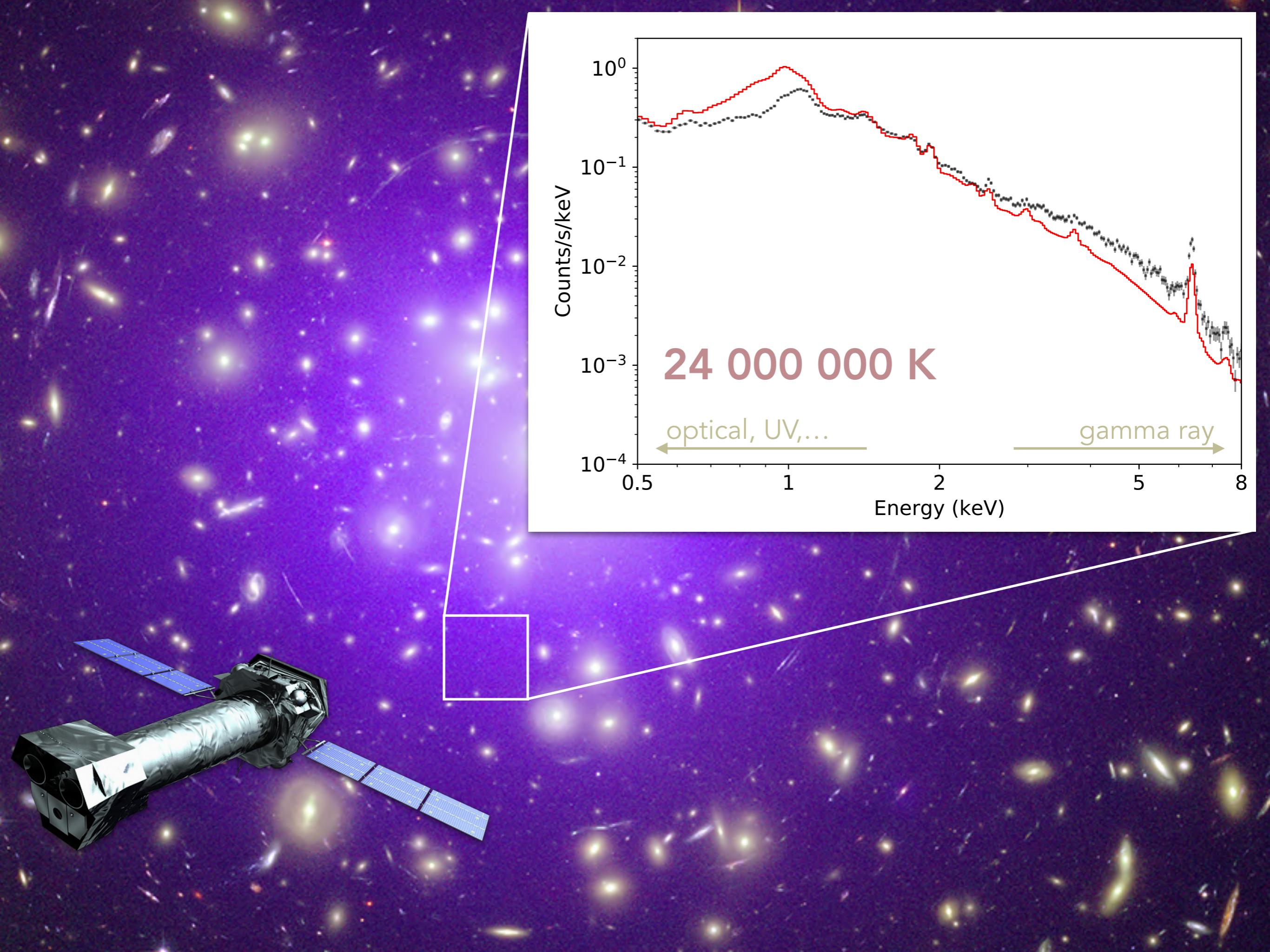


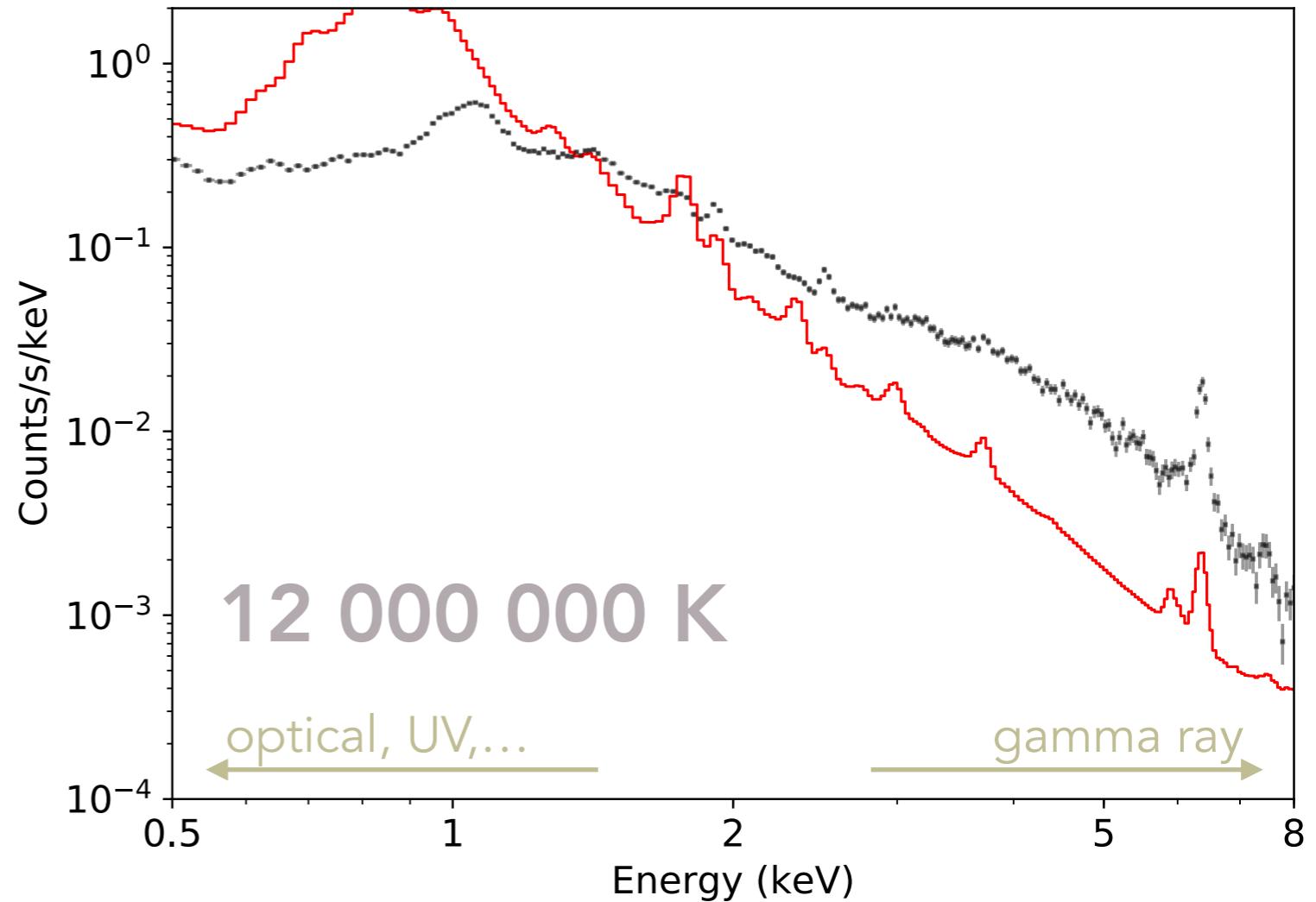
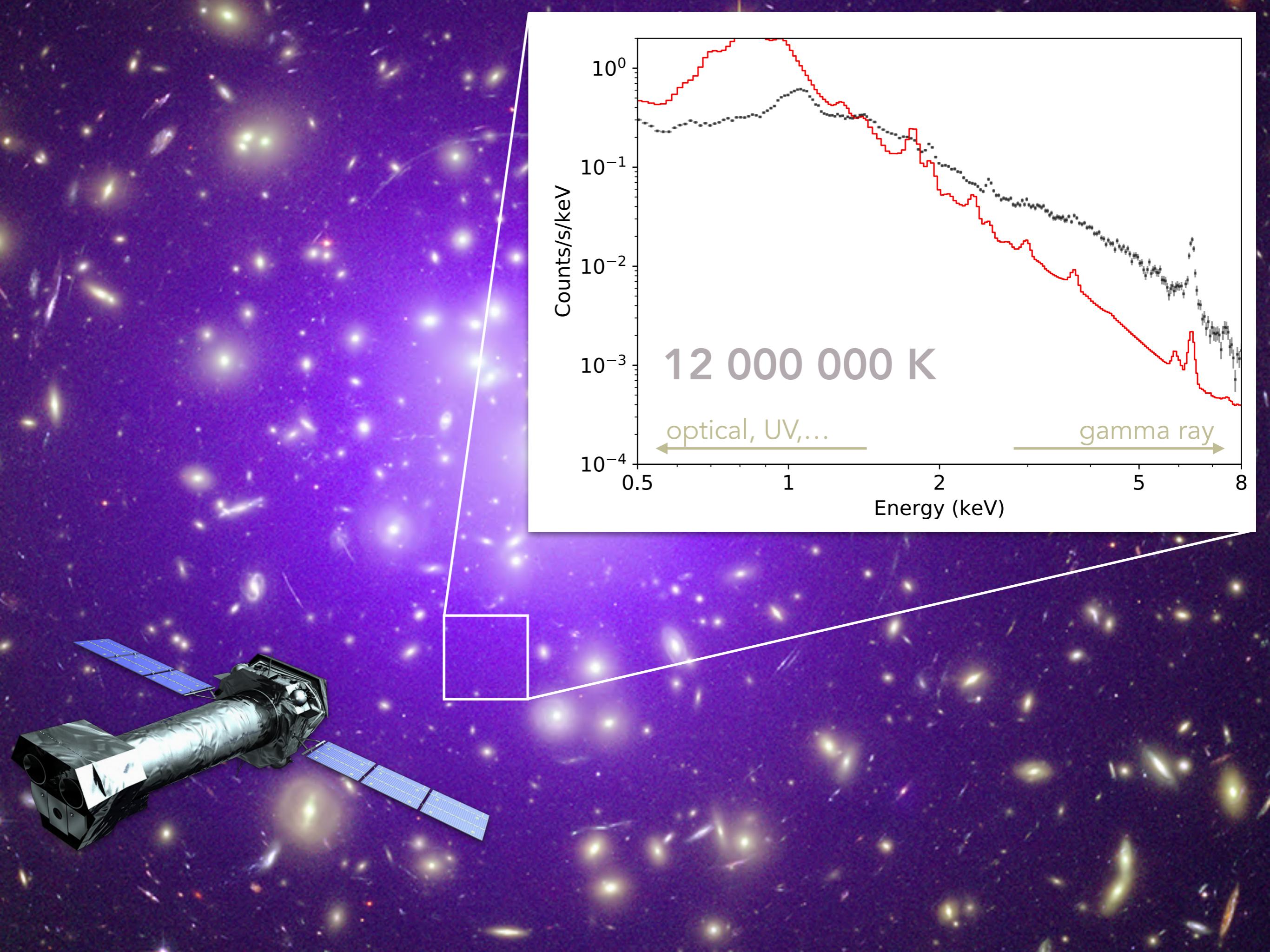


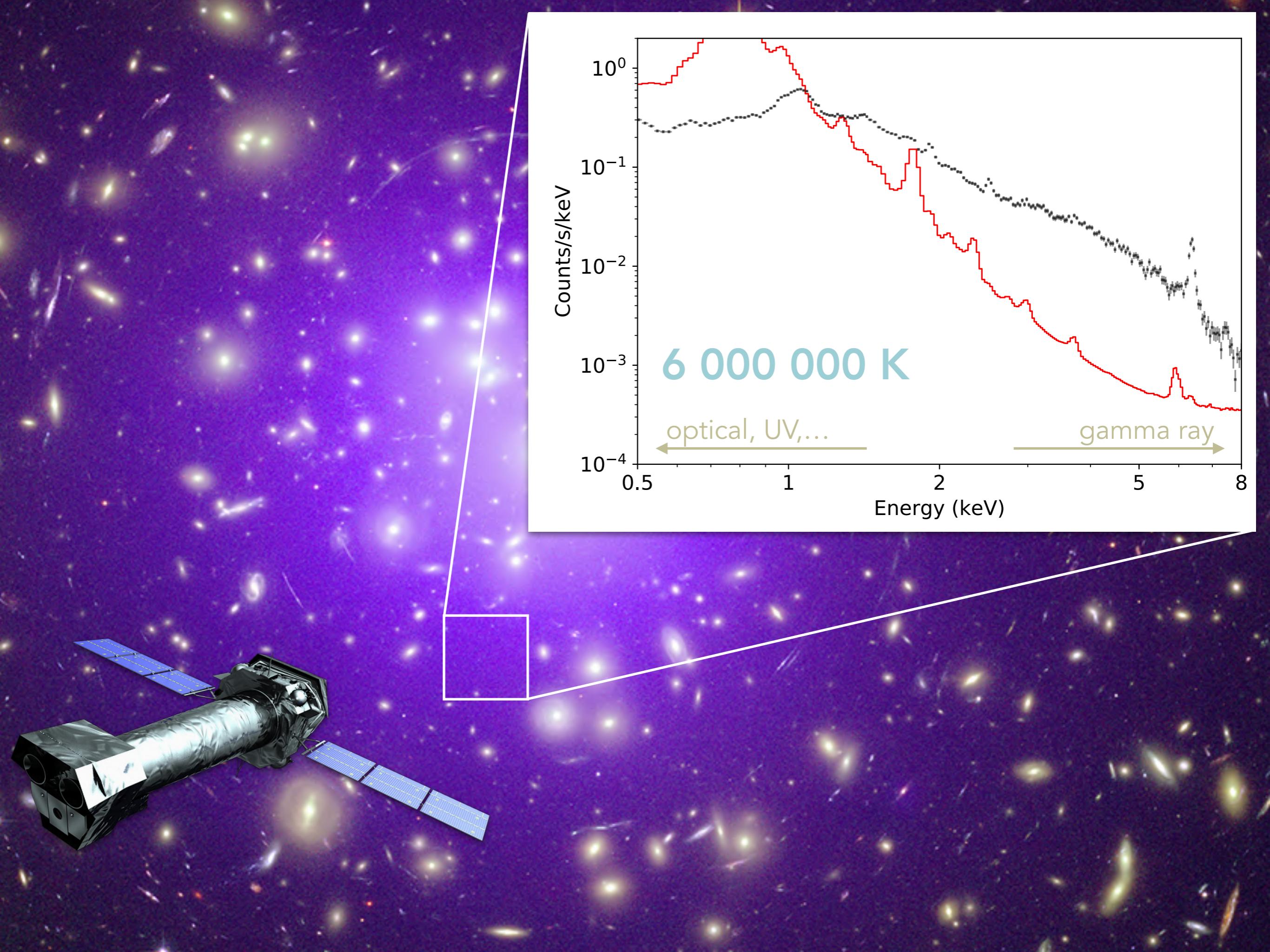


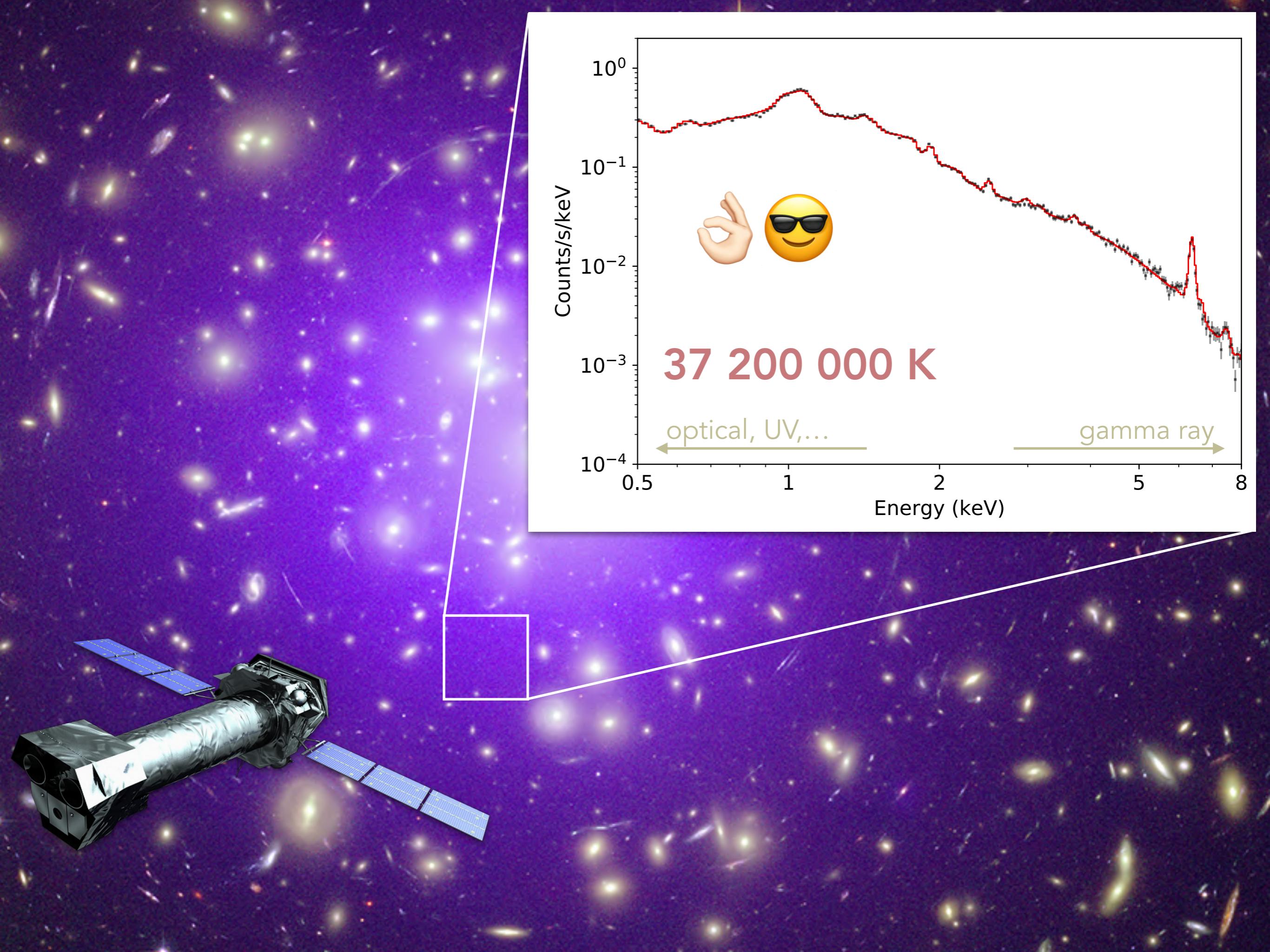


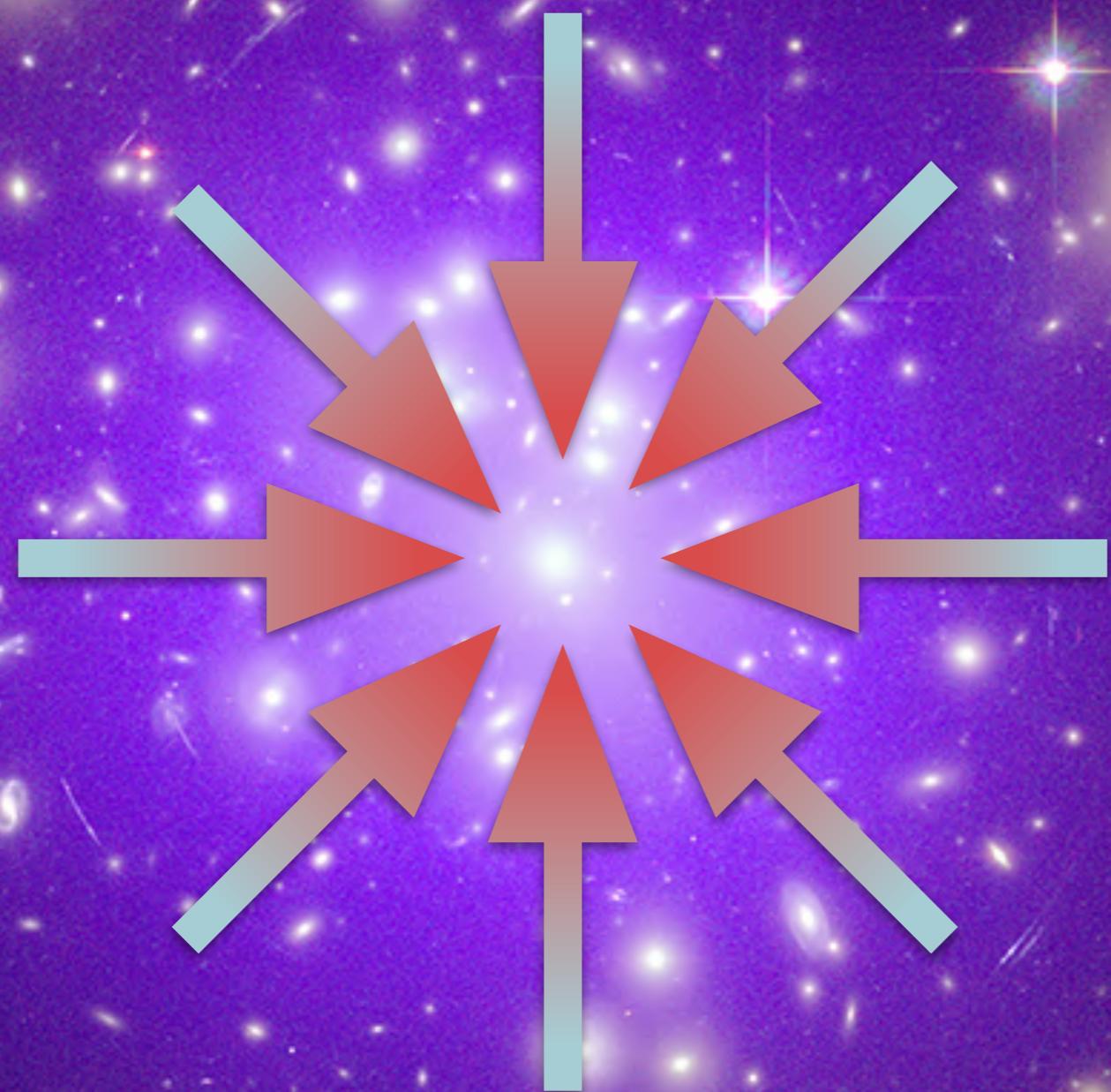




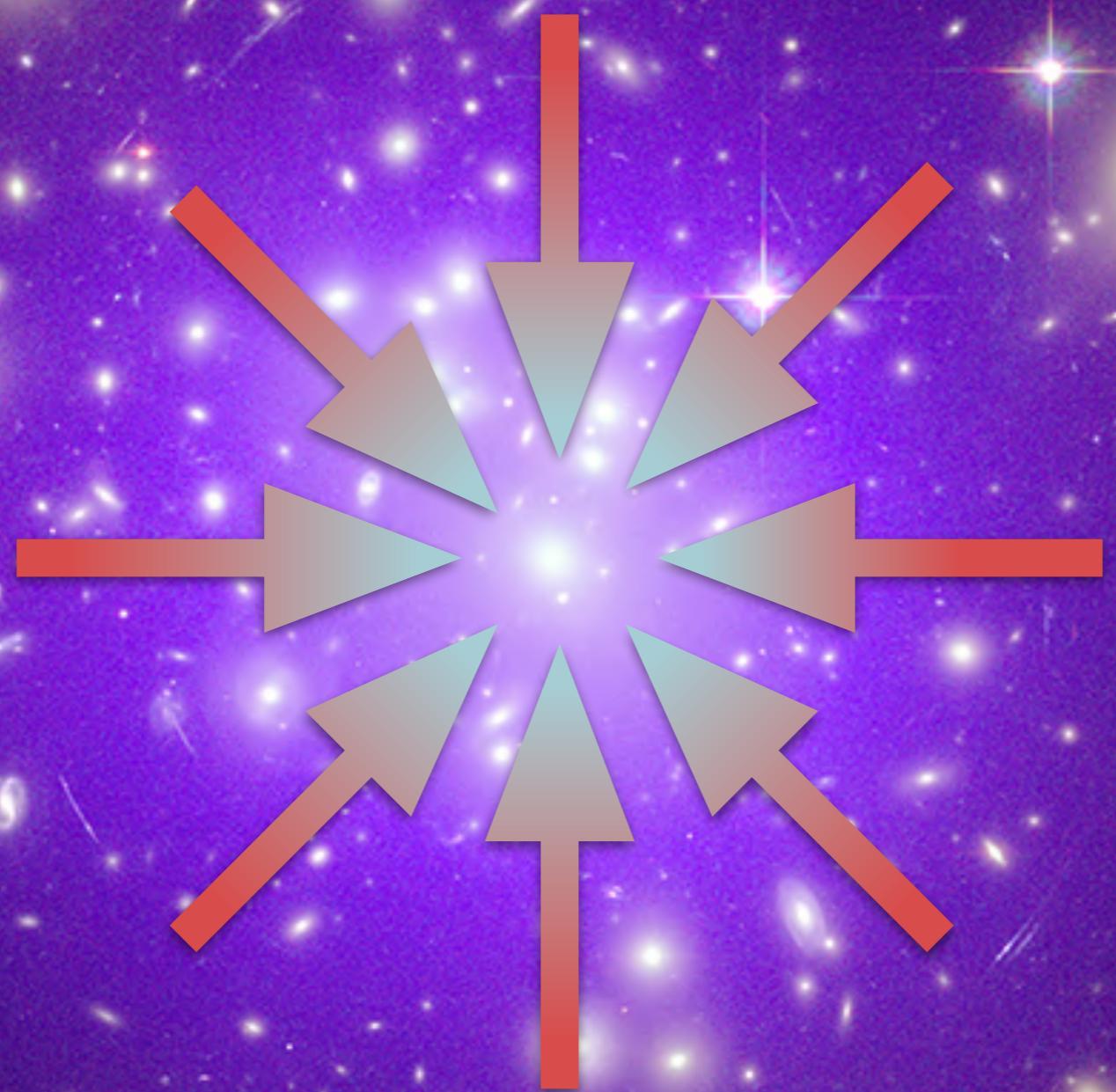




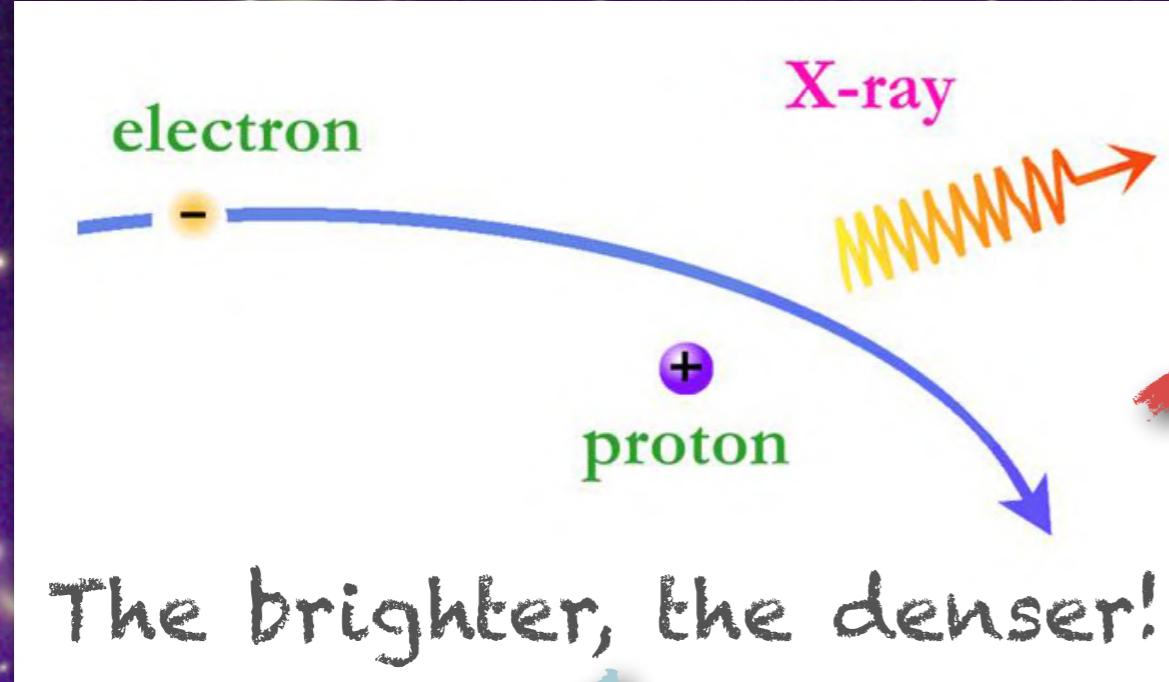




hotter...?



...or cooler?



The brighter, the denser!

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



The gas cools down!

$$\downarrow PV = kRT \downarrow$$

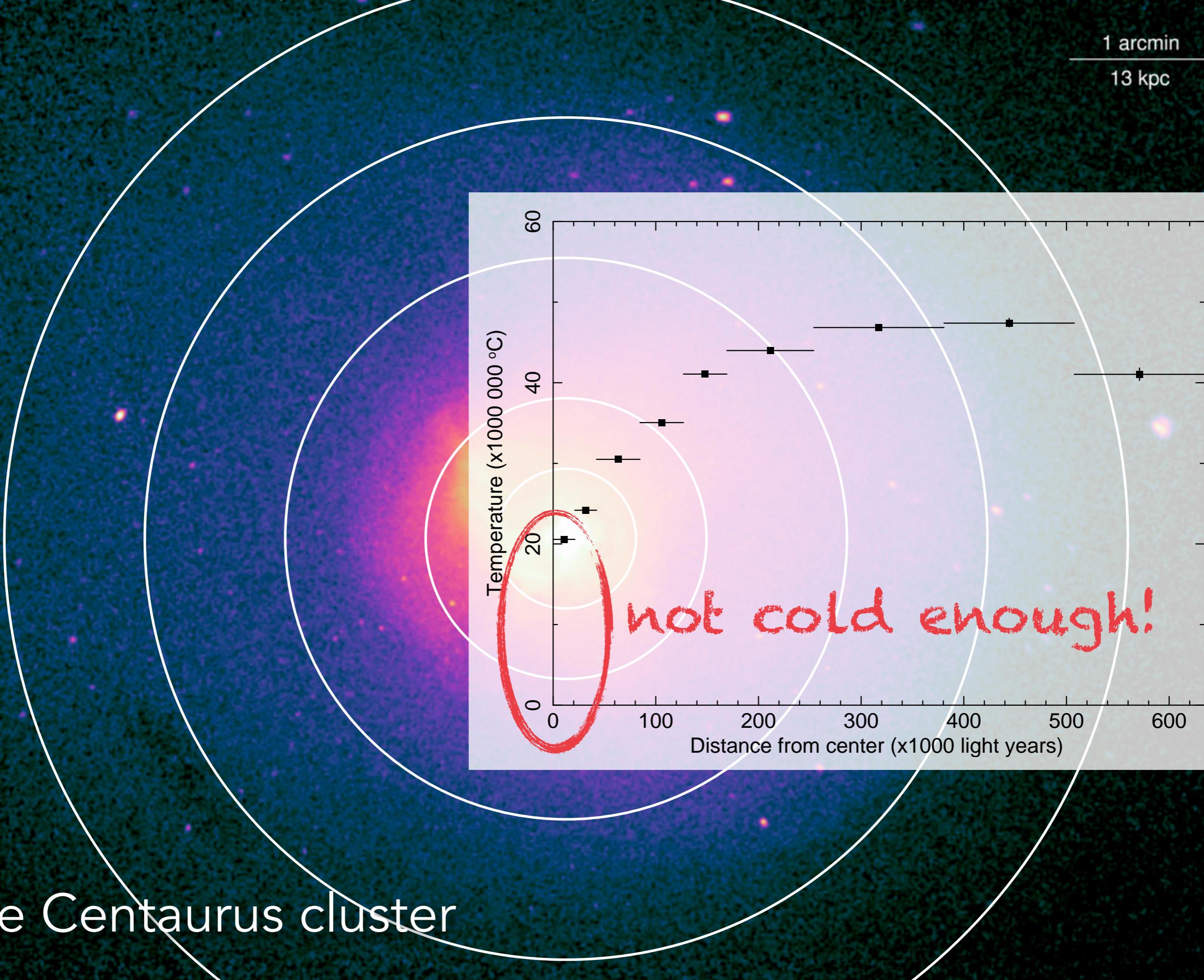
The surrounding gas "falls" in the centre...

The central pressure drops!



1 arcmin
13 kpc

The Centaurus cluster



The Centaurus cluster

Central cluster galaxies should look like this...



...but they look like this.

A wide-field image of the universe, showing a dense distribution of galaxies. In the center, a large, bright yellow/orange galaxy with a distinct spiral structure is visible. To its left, a smaller blue and white spiral galaxy is partially visible. The background is filled with numerous smaller, fainter galaxies of various shapes and colors, including red, orange, and blue. The overall scene is a representation of the vastness and diversity of the observable universe.

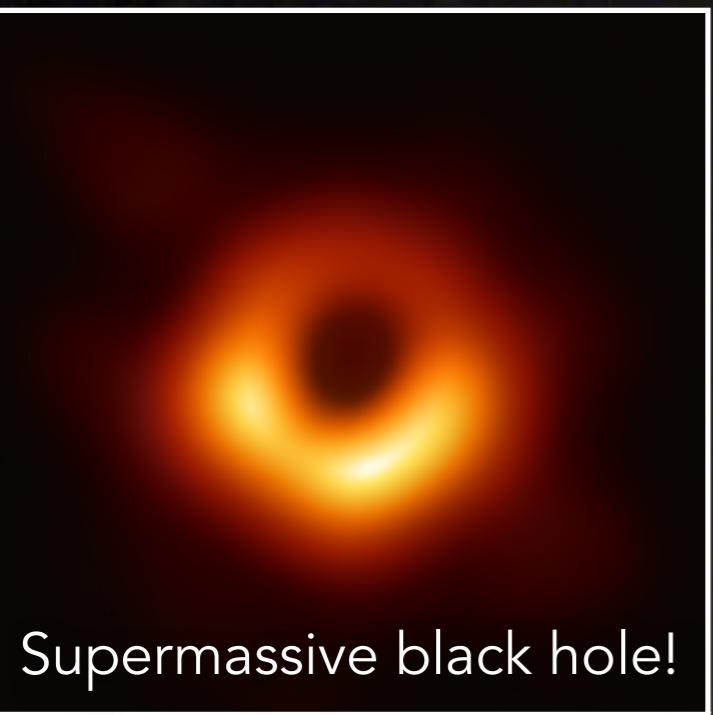
...but they look like this.

What prevents the hot gas from cooling?

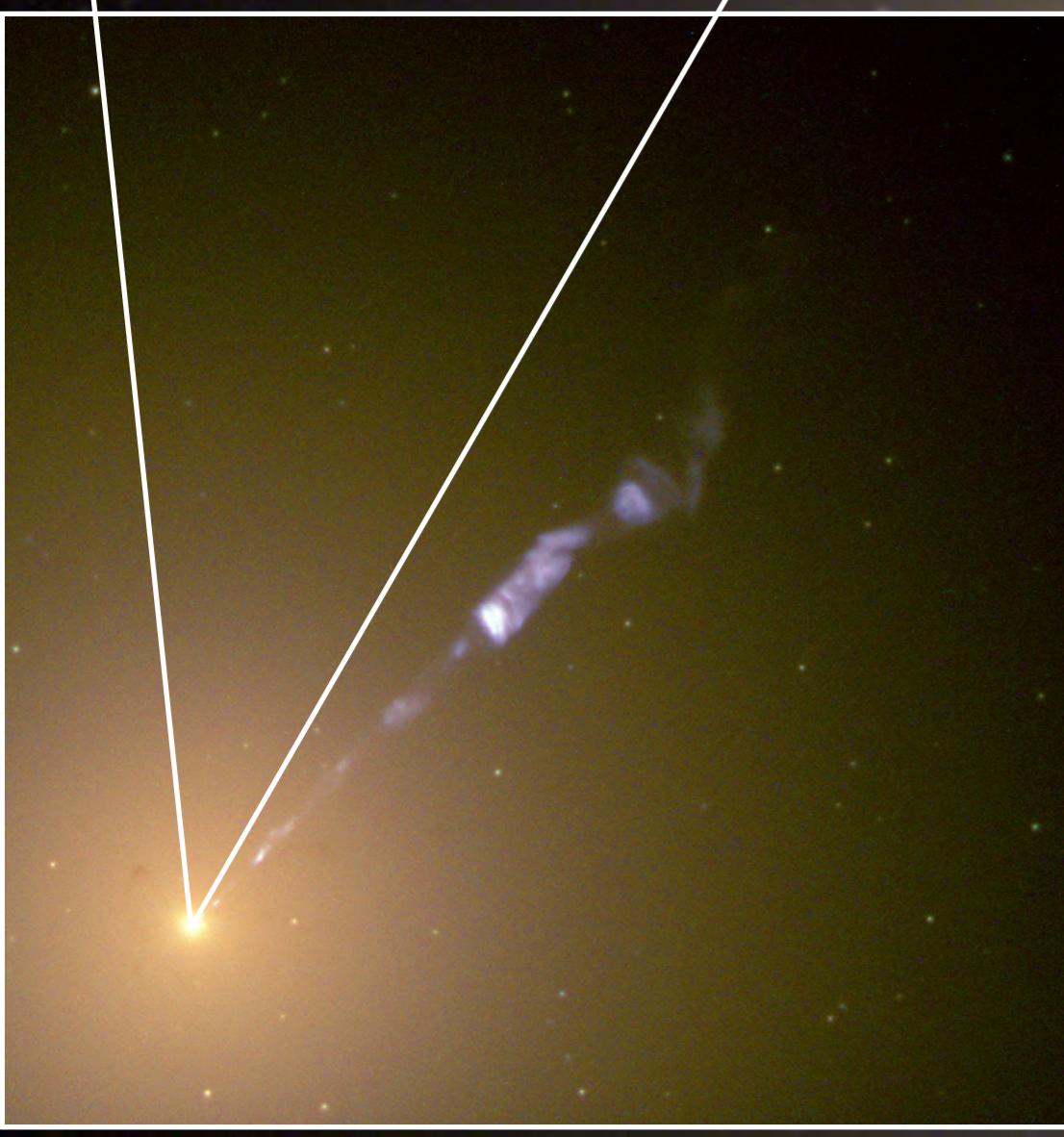
M87



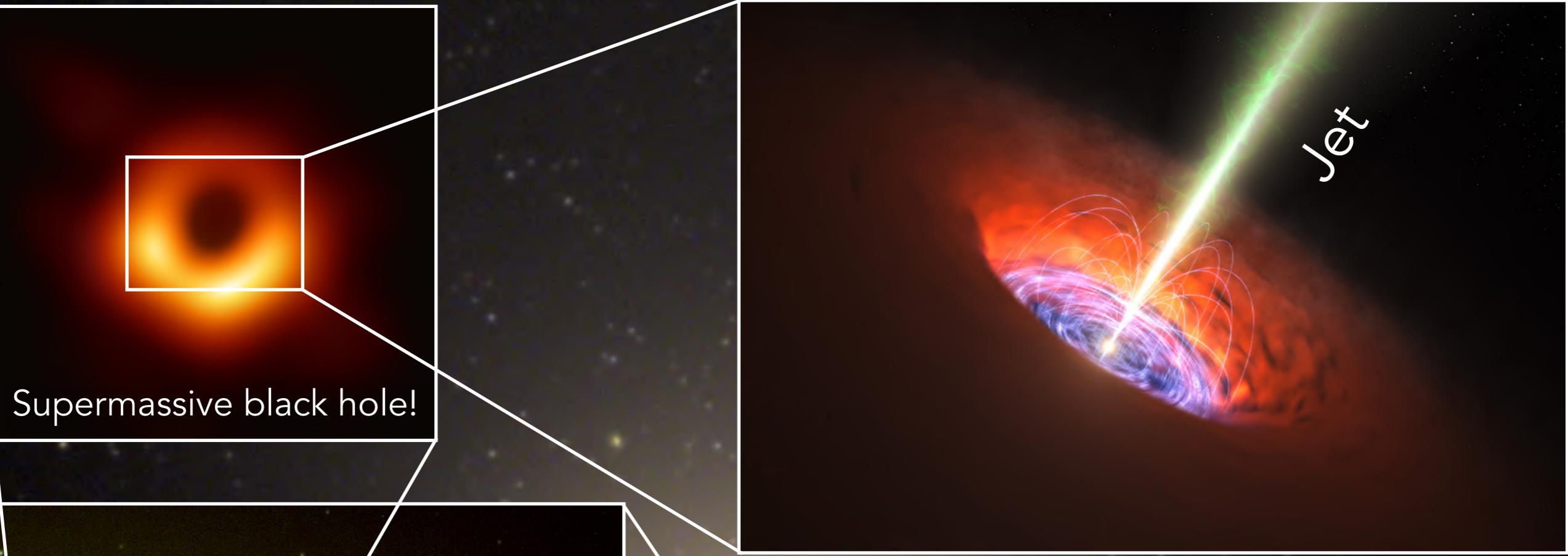
M87



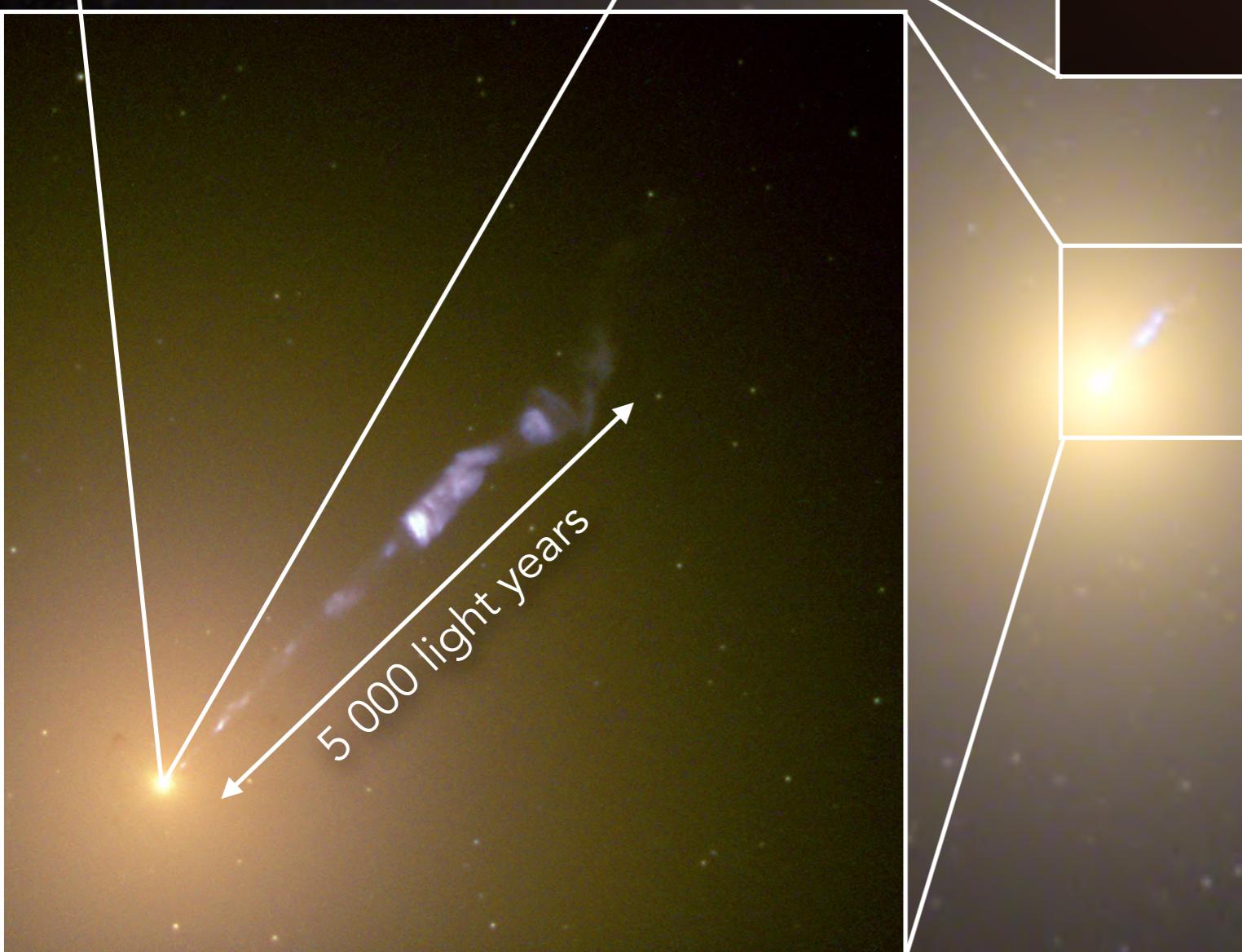
Supermassive black hole!



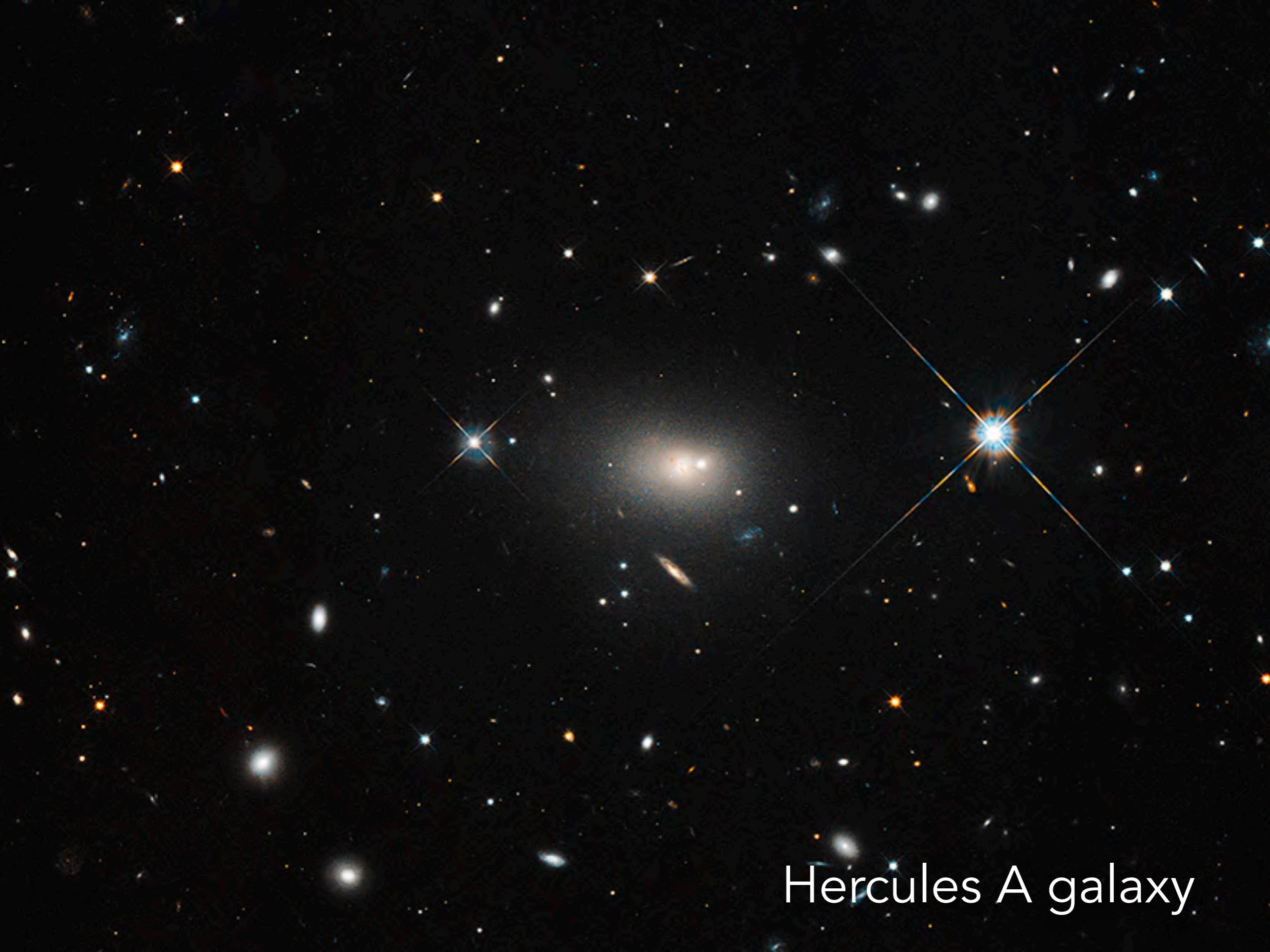
M87



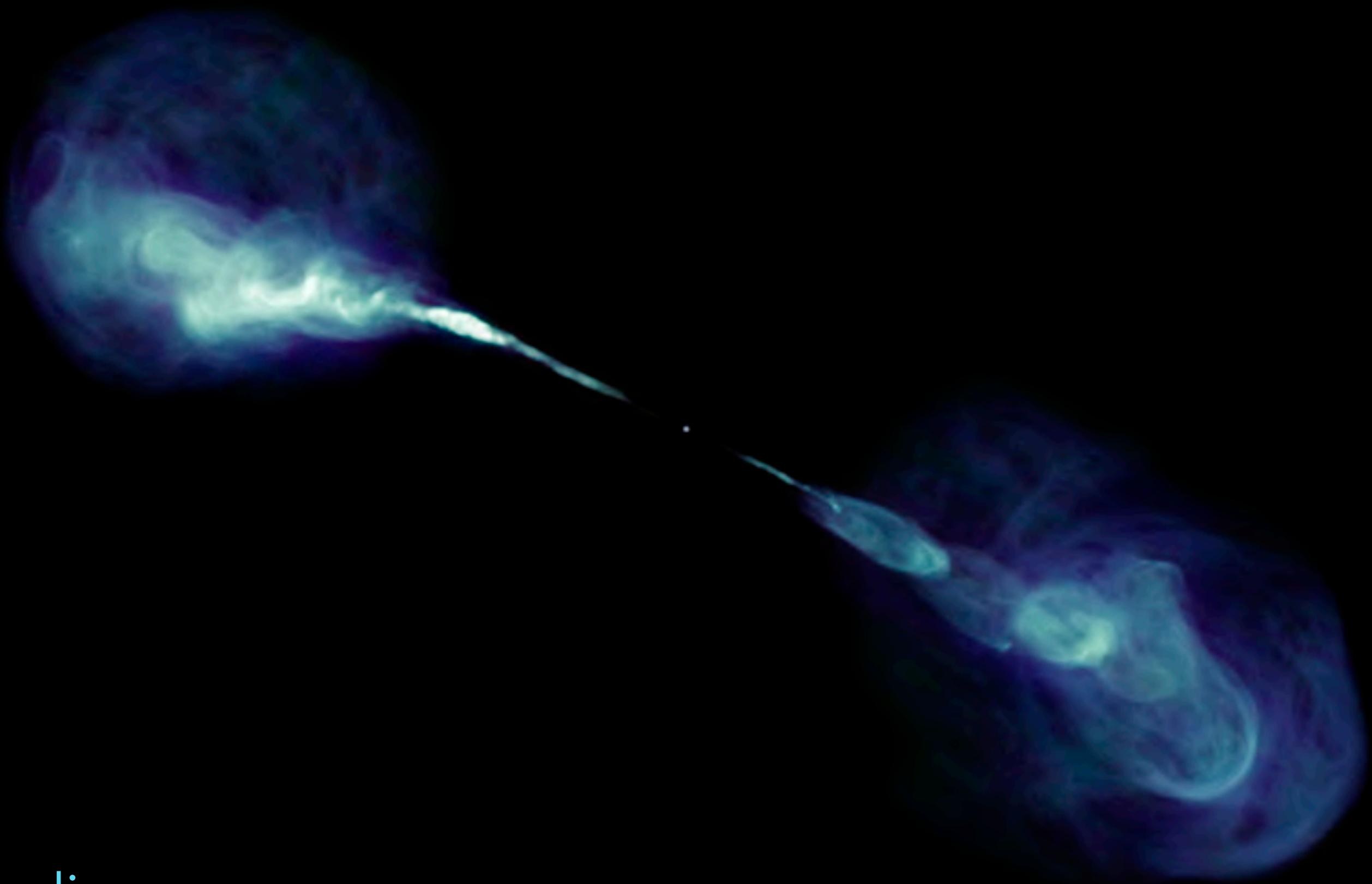
Supermassive black hole!



M87



Hercules A galaxy



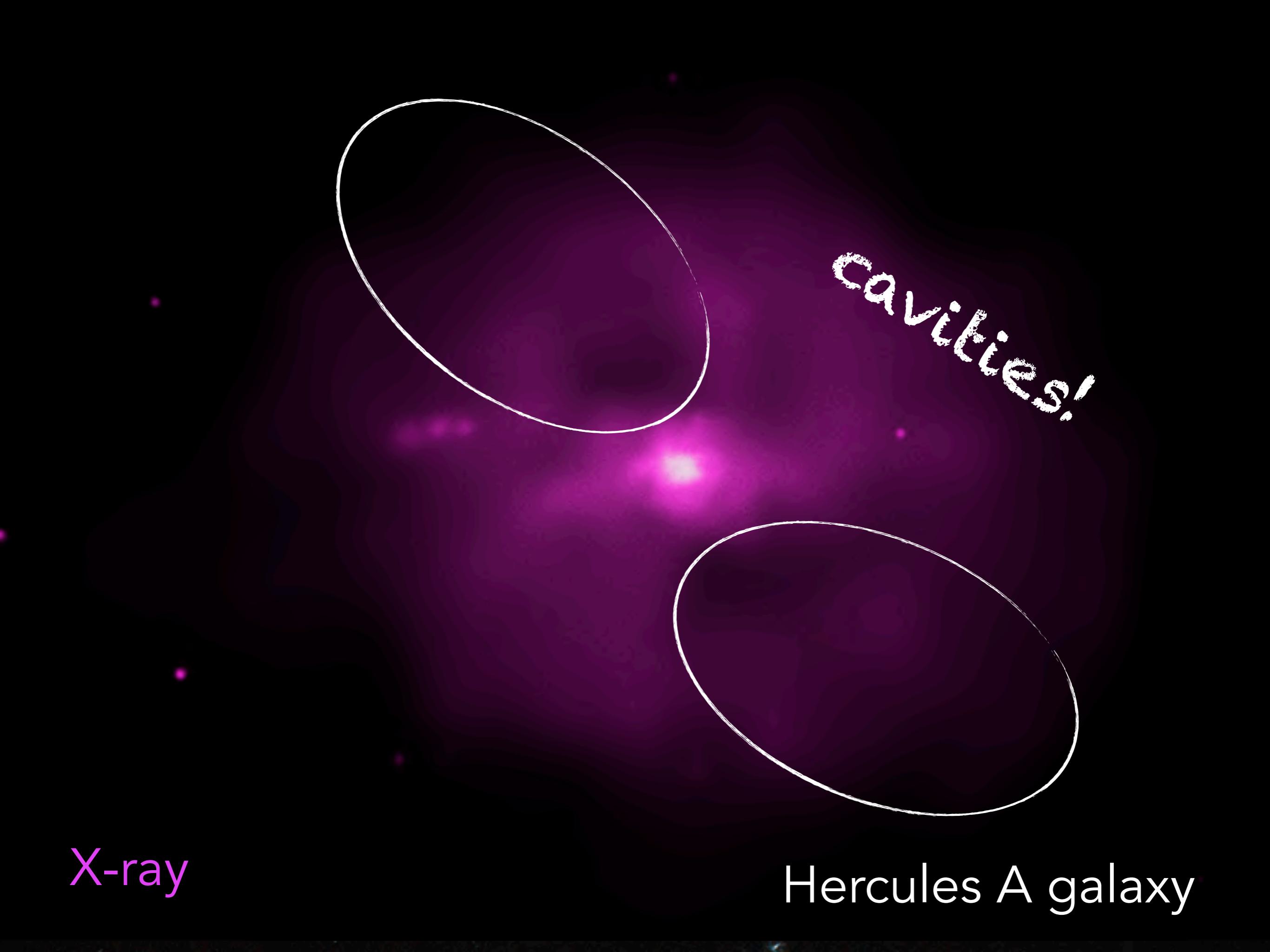
Radio

Hercules A galaxy



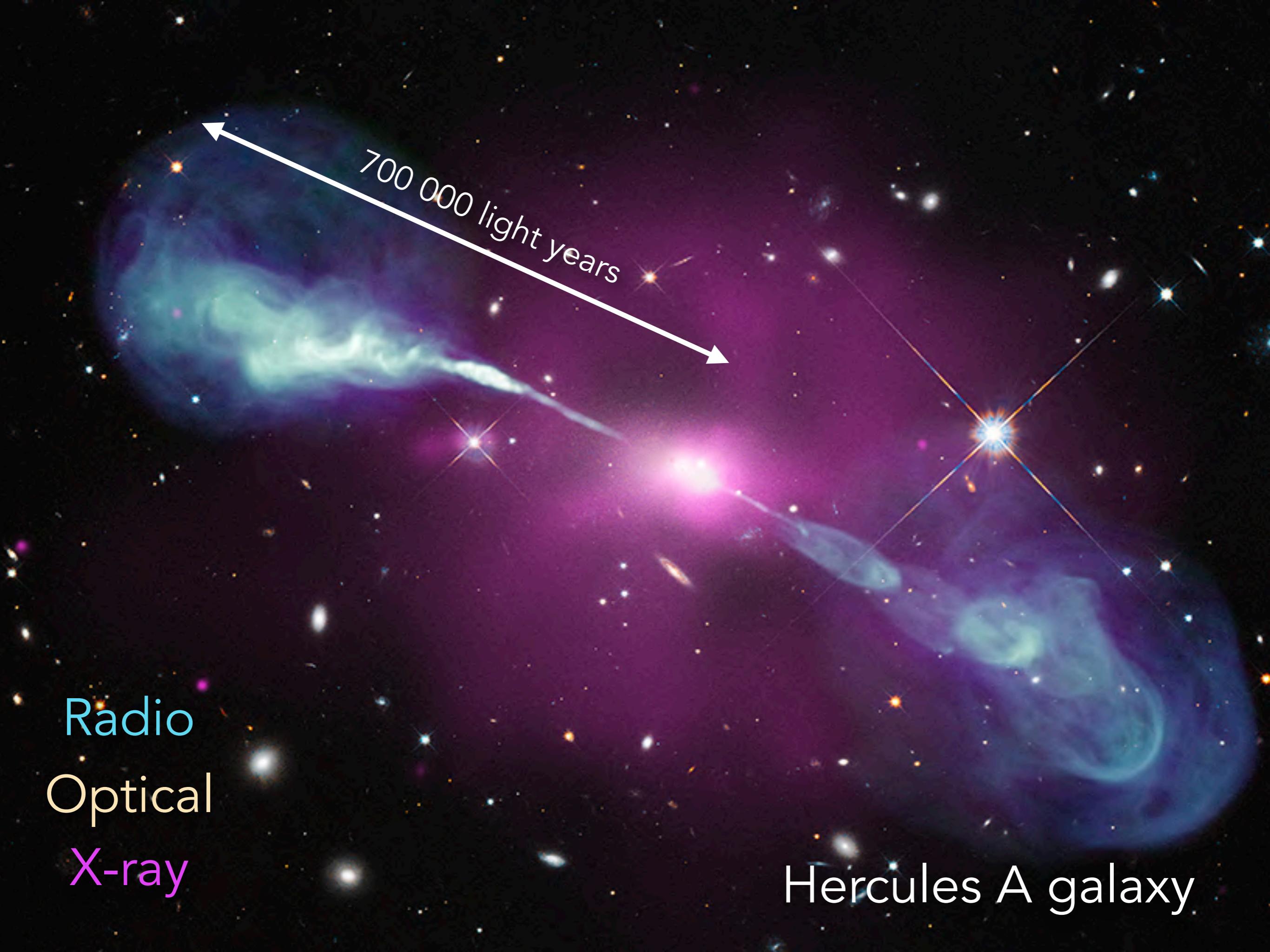
X-ray

Hercules A galaxy



X-ray

Hercules A galaxy



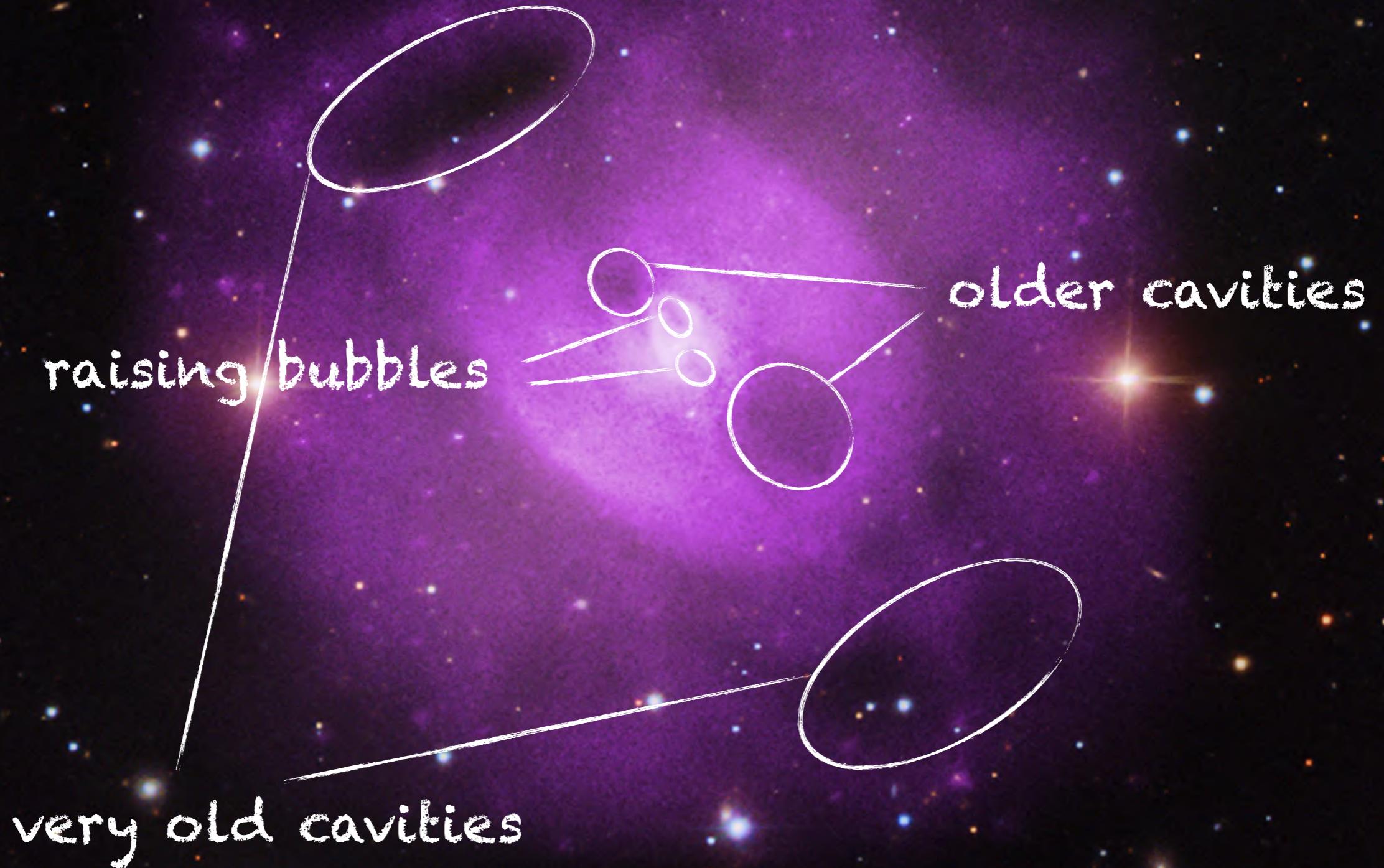
Radio
Optical
X-ray

Hercules A galaxy

700 000 light years



NGC 5813

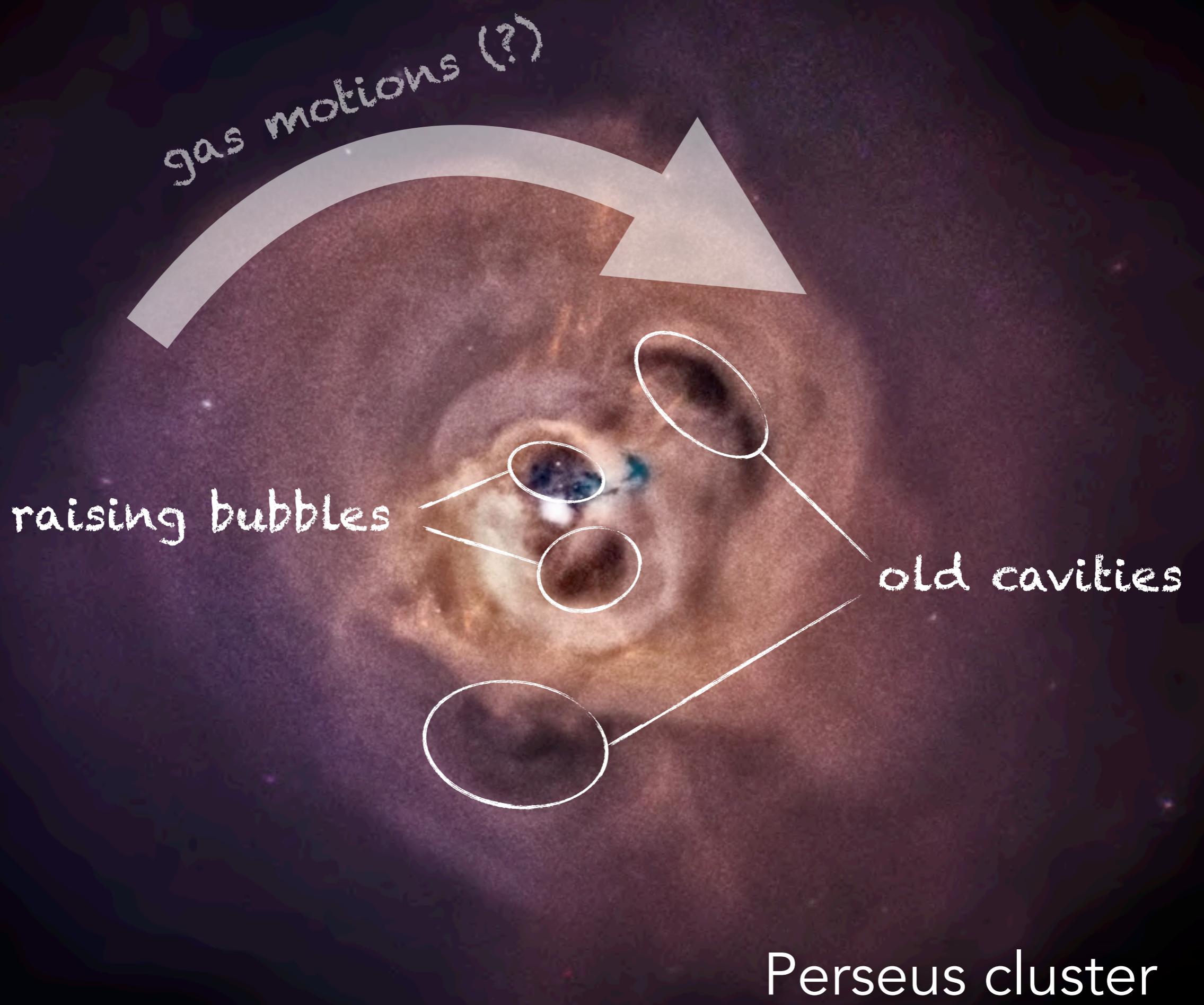


NGC 5813



A composite image of the Perseus galaxy cluster, showing X-ray emission in red, optical light in green, and radio emission in blue. The cluster's core is dominated by a central elliptical galaxy with a bright, multi-colored nucleus. The surrounding gas is shown in shades of red and orange, with blue filaments indicating magnetic fields or young star-forming regions.

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)

Radio
Optical
X-ray

MS 0735.6+7421 (2.6 billion light years)

1 000 000 light years



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

We don't know (yet)...

2. Chemical composition

Periodic Table of the Elements

Hydrogen (H)

Helium (He)

State of matter (color of name)

- GAS
- LIQUID
- SOLID
- UNKNOWN

Subcategory in the metal-metalloid-nonmetal trend (color of background)

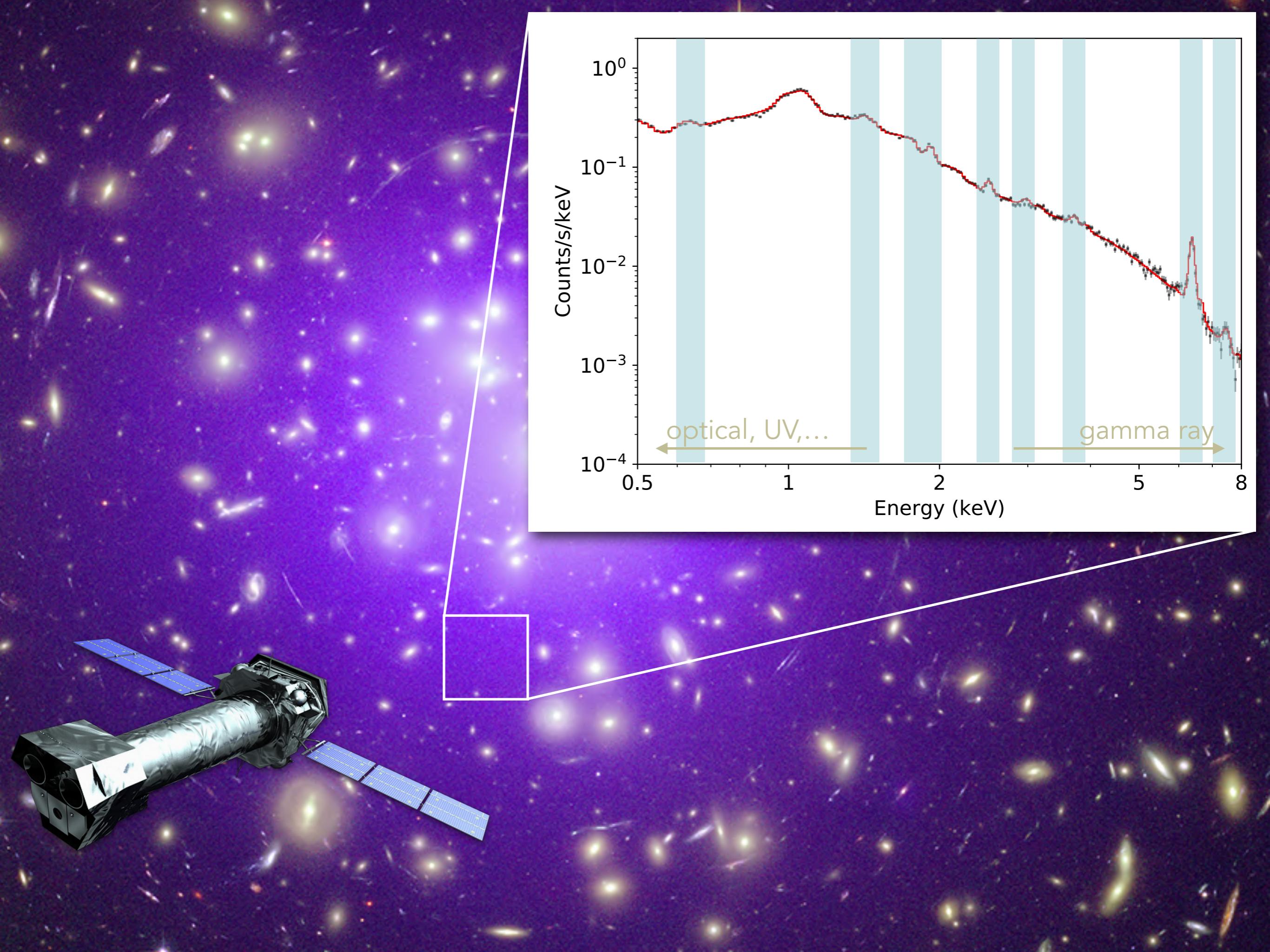
- Alkali metals
- Alkaline earth metals
- Transition metals
- Lanthanides
- Actinides
- Post-transition metals
- Metalloids
- Reactive nonmetals
- Noble gases

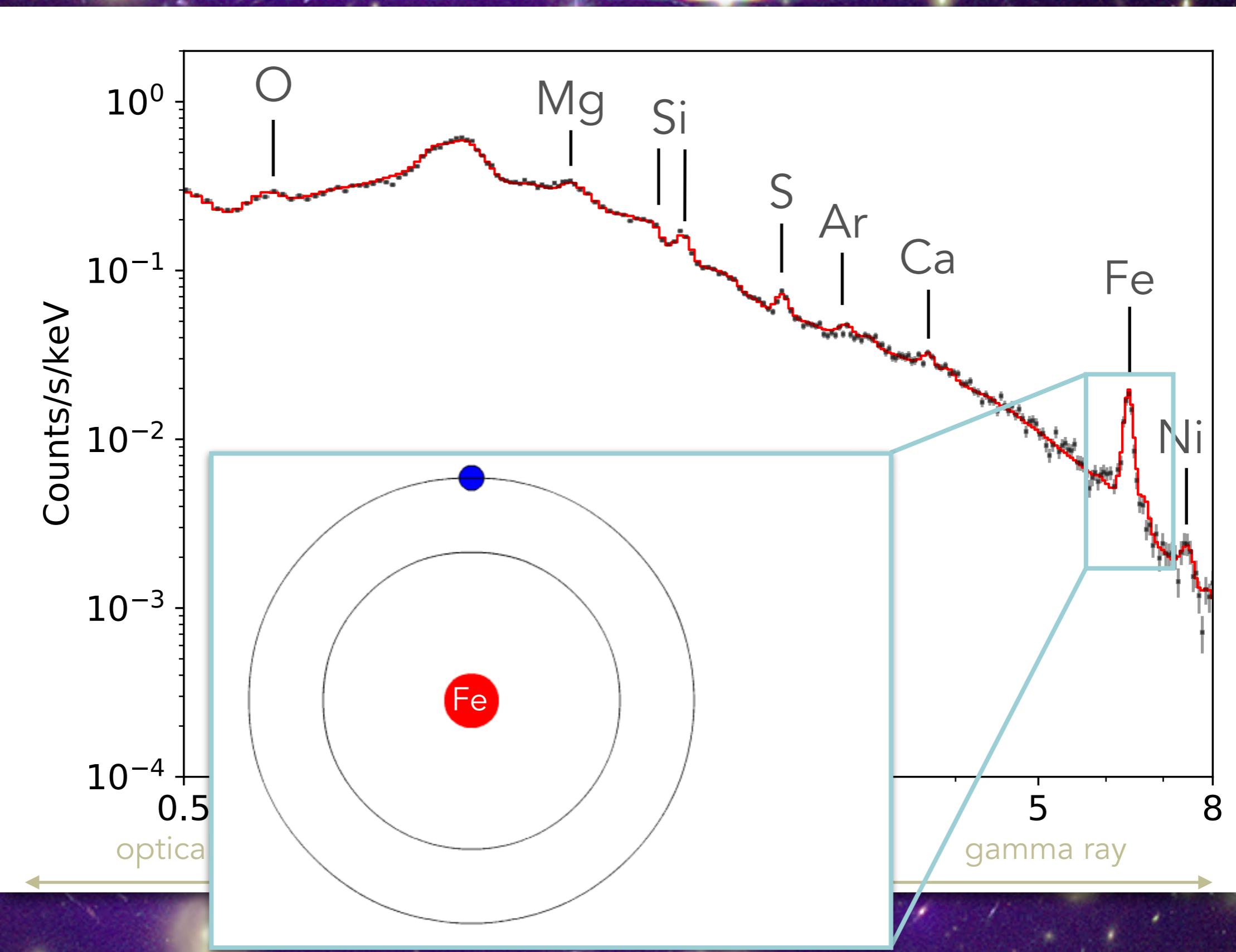
Unknown chemical properties

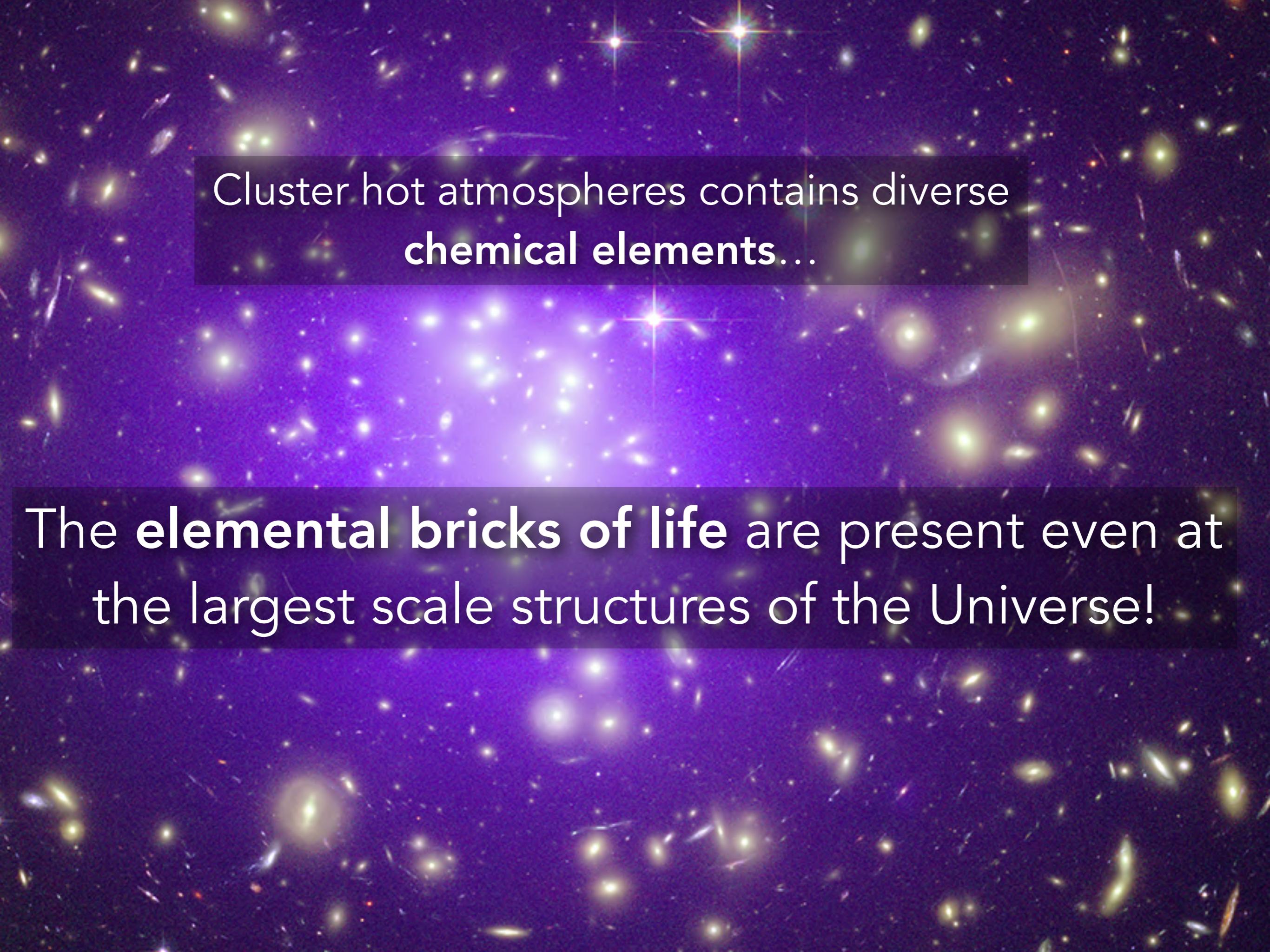
1 IA	2 IIA	3 IIIA	4 IVB	5 VB	6 VIB	7 VIIA	8 VIIIB	9	10	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VI	17 VIIA	18 VIII				
H Hydrogen 1.008 1	Li Lithium 6.94 2-1	Be Beryllium 9.01 2-1	N Sodium 22.9897 2-8-1	Mg Magnesium 24.305 2-8-2	Sc Scandium 44.95908 2-8-2	Ti Titanium 47.867 2-8-2	V Vanadium 50.915 2-8-2	Cr Chromium 51.996 2-8-2	Mn Manganese 54.938 2-8-2	Fe Iron 55.845 2-8-2	Co Cobalt 58.931 2-8-2	Ni Nickel 58.693 2-8-2	Cu Copper 63.546 2-8-1	Zn Zinc 65.38 2-8-2	Ga Gallium 69.723 2-8-3	Ge Germanium 72.630 2-8-4	As Arsenic 74.922 2-8-5	S Sulfur 32.06 2-8-4	O Oxygen 16.00 2-5	F Fluorine 18.998 2-7	Ne Neon 20.183 2-8
K Potassium 39.09 2-8-8-1	Ca Calcium 40.078 2-8-2	Sc Scandium 44.95908 2-8-2	Ti Titanium 47.867 2-8-2	V Vanadium 50.915 2-8-2	Cr Chromium 51.996 2-8-2	Mn Manganese 54.938 2-8-2	Fe Iron 55.845 2-8-2	Co Cobalt 58.931 2-8-2	Ni Nickel 58.693 2-8-2	Cu Copper 63.546 2-8-1	Zn Zinc 65.38 2-8-2	Ga Gallium 69.723 2-8-3	Ge Germanium 72.630 2-8-4	As Arsenic 74.922 2-8-5	S Sulfur 32.06 2-8-4	O Oxygen 16.00 2-5	F Fluorine 18.998 2-7	Ne Neon 20.183 2-8			
Rb Rubidium 85.4478 2-8-8-1	Sr Strontium 87.62 2-8-8-2	Y Yttrium 88.90584 2-8-8-2	Zr Zirconium 91.224 2-8-8-10-2	Nb Niobium 91.9637 2-8-8-10-1	Mo Molybdenum 95.95 2-8-10-1	Tc Technetium (98) 2-8-10-12	Ru Ruthenium 101.07 2-8-10-1	Rh Rhodium 102.91 2-8-10-1	Pd Palladium 104.42 2-8-10-1	Ag Silver 107.87 2-8-10-1	Cd Cadmium 112.41 2-8-10-10-2	In Indium 114.82 2-8-10-10-3	Sn Tin 118.71 2-8-10-10-4	Sb Antimony 121.76 2-8-10-10-5	Te Tellurium 121.60 2-8-10-10-6	I Iodine 126.90 2-8-10-10-7	Xe Xenon 131.29 2-8-10-10-8				
Cs Cesium 132.9154576 2-8-8-8-1	Ba Barium 137.327 2-8-8-8-2	Lanthanides 57-71	Hf Hafnium 178.49 2-8-10-10-2	Ta Tantalum 180.94788 2-8-10-10-2	W Tungsten 183.84 2-8-10-10-2	Re Rhenium 186.21 2-8-10-10-2	Os Osmium 190.23 2-8-10-10-2	Ir Iridium 192.22 2-8-10-10-2	Pt Platinum 195.08 2-8-10-10-2	Au Gold 196.97 2-8-10-10-2	Hg Mercury 200.59 2-8-10-10-2	Tl Thallium 204.38 2-8-10-10-3	Pb Lead 207.2 2-8-10-10-4	Bi Bismuth 208.98 2-8-10-10-5	Po Polonium (209) 2-8-10-10-6	At Astatine (210) 2-8-10-10-7	Rn Radon (222) 2-8-10-10-8				
Fr Francium (229) 2-8-10-10-8-1	Ra Radium (226) 2-8-10-10-8-2	Actinides 89-103	Rf Rutherfordium (267) 2-8-10-10-10-2	Db Dubnium (268) 2-8-10-10-10-2	Sg Seaborgium (269) 2-8-10-10-10-2	Bh Bohrium (290) 2-8-10-10-10-2	Hs Hassium (270) 2-8-10-10-10-2	Mt Meitnerium (278) 2-8-10-10-10-2	Ds Darmstadtium (280) 2-8-10-10-10-2	Rg Roentgenium (282) 2-8-10-10-10-2	Cn Copernicium (285) 2-8-10-10-10-2	Nh Nihonium (284) 2-8-10-10-10-3	Fl Flerovium (289) 2-8-10-10-10-4	Mc Moscovium (290) 2-8-10-10-10-5	Lv Livermorium (293) 2-8-10-10-10-6	Ts Tennessine (294) 2-8-10-10-10-7	Og Oganesson (294) 2-8-10-10-10-8				

La Lanthanum 138.91 2-8-10-10-2	Ce Cerium 140.12 2-8-10-10-2	Pr Praseodymium 140.91 2-8-10-10-2	Nd Neodymium 144.24 2-8-10-10-2	Pm Promethium (145) 2-8-10-10-2	Sm Samarium 150.36 2-8-10-10-2	Eu Europium 151.96 2-8-10-10-2	Gd Gadolinium 157.25 2-8-10-10-2	Tb Terbium 158.93 2-8-10-10-2	Dy Dysprosium 162.59 2-8-10-10-2	Ho Holmium 164.93 2-8-10-10-2	Er Erbium 166.93 2-8-10-10-2	Tm Thulium 168.93 2-8-10-10-2	Yb Ytterbium 173.05 2-8-10-10-2	Lu Lutetium 174.97 2-8-10-10-2
Ac Actinium (227) 2-8-10-10-8-2	Th Thorium 232.04 2-8-10-10-8-2	Pa Protactinium 231.04 2-8-10-10-8-2	U Uranium 238.03 2-8-10-10-8-2	Np Neptunium (237) 2-8-10-10-8-2	Pu Plutonium (240) 2-8-10-10-8-2	Am Americium (243) 2-8-10-10-8-2	Cm Curium (247) 2-8-10-10-8-2	Bk Berkelium (247) 2-8-10-10-8-2	Cf Californium (250) 2-8-10-10-8-2	Es Einsteinium (252) 2-8-10-10-8-2	Fm Fermium (257) 2-8-10-10-8-2	Md Mendelevium (258) 2-8-10-10-8-2	No Nobelium (259) 2-8-10-10-8-2	Lr Lawrencium (266) 2-8-10-10-8-2





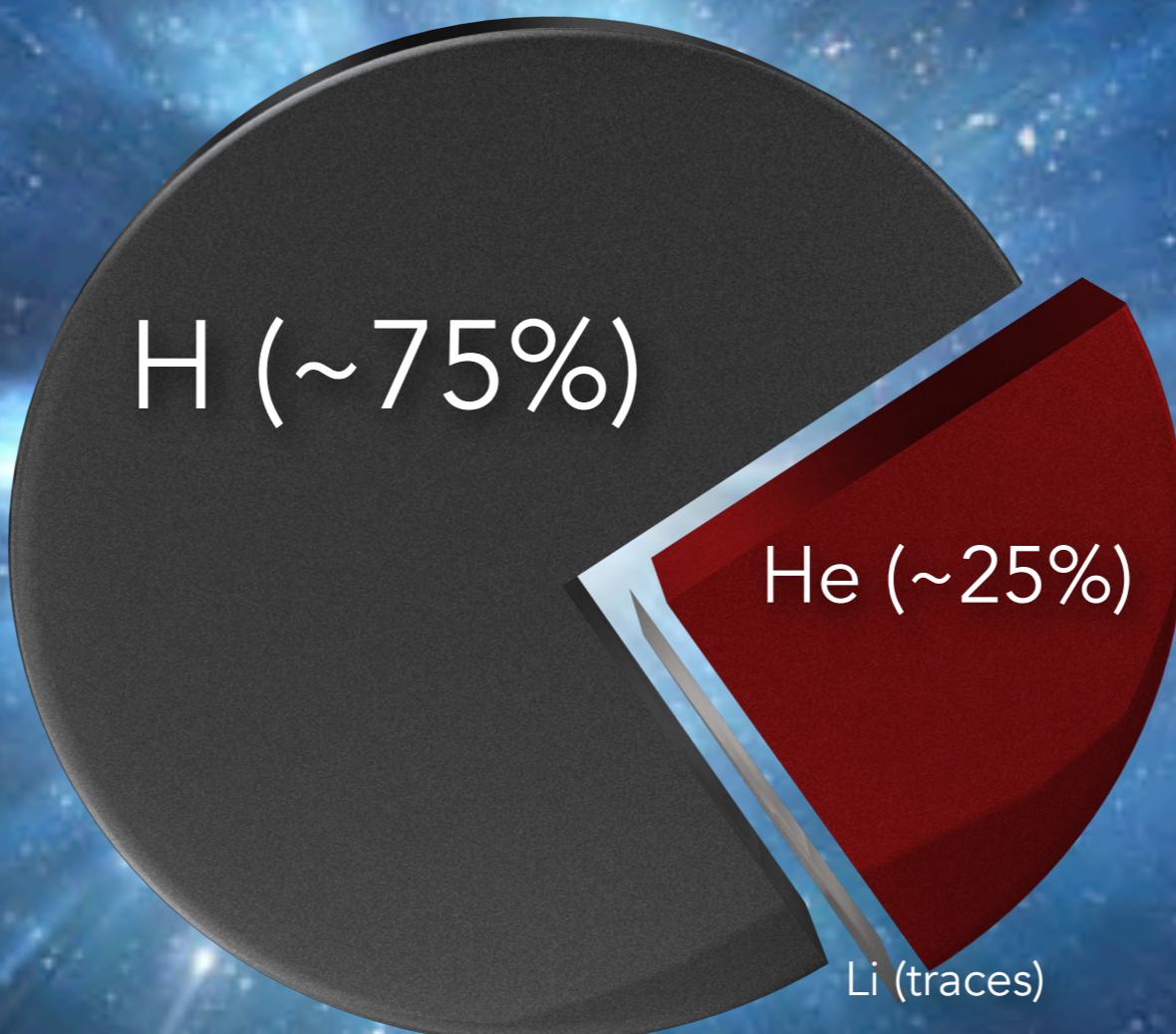




Cluster hot atmospheres contains diverse
chemical elements...

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

Primordial nucleosynthesis

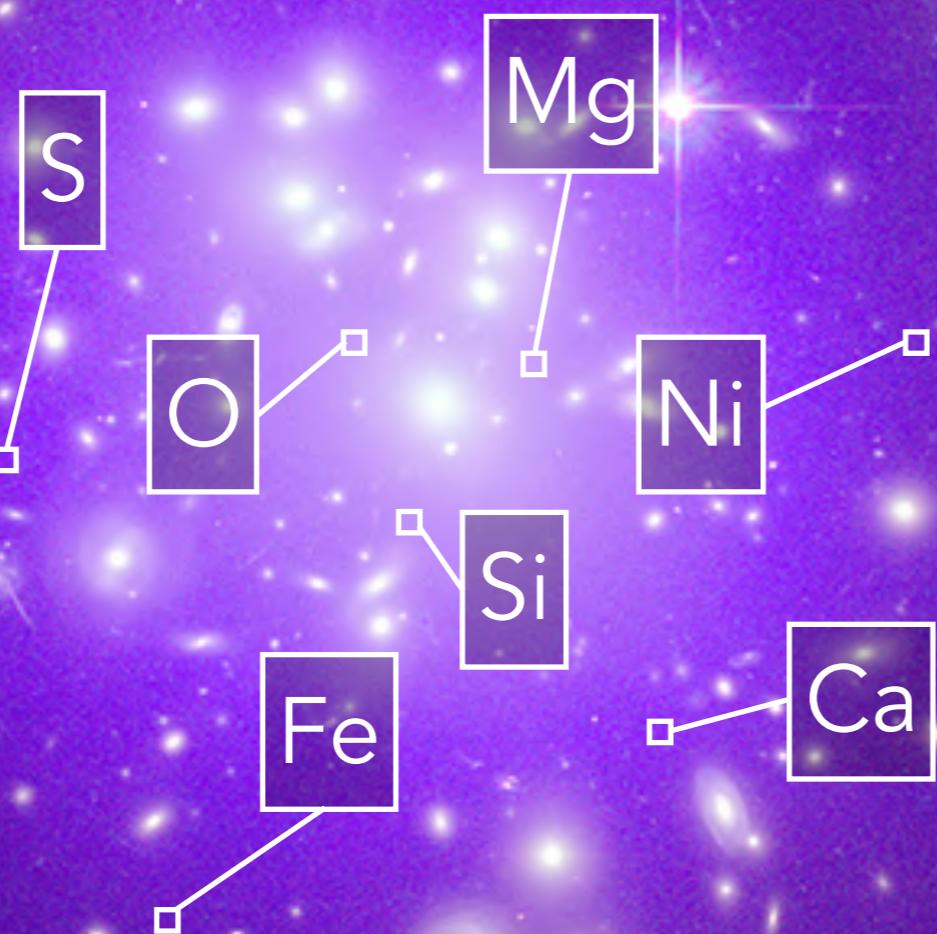


Big Bang

The background of the slide features a deep space scene with a central, luminous nebula. The nebula is composed of intricate, wispy clouds of gas and dust, primarily in shades of red, orange, yellow, green, and blue. It is set against a dark, almost black, background that is speckled with numerous small, yellow and white stars of varying sizes.

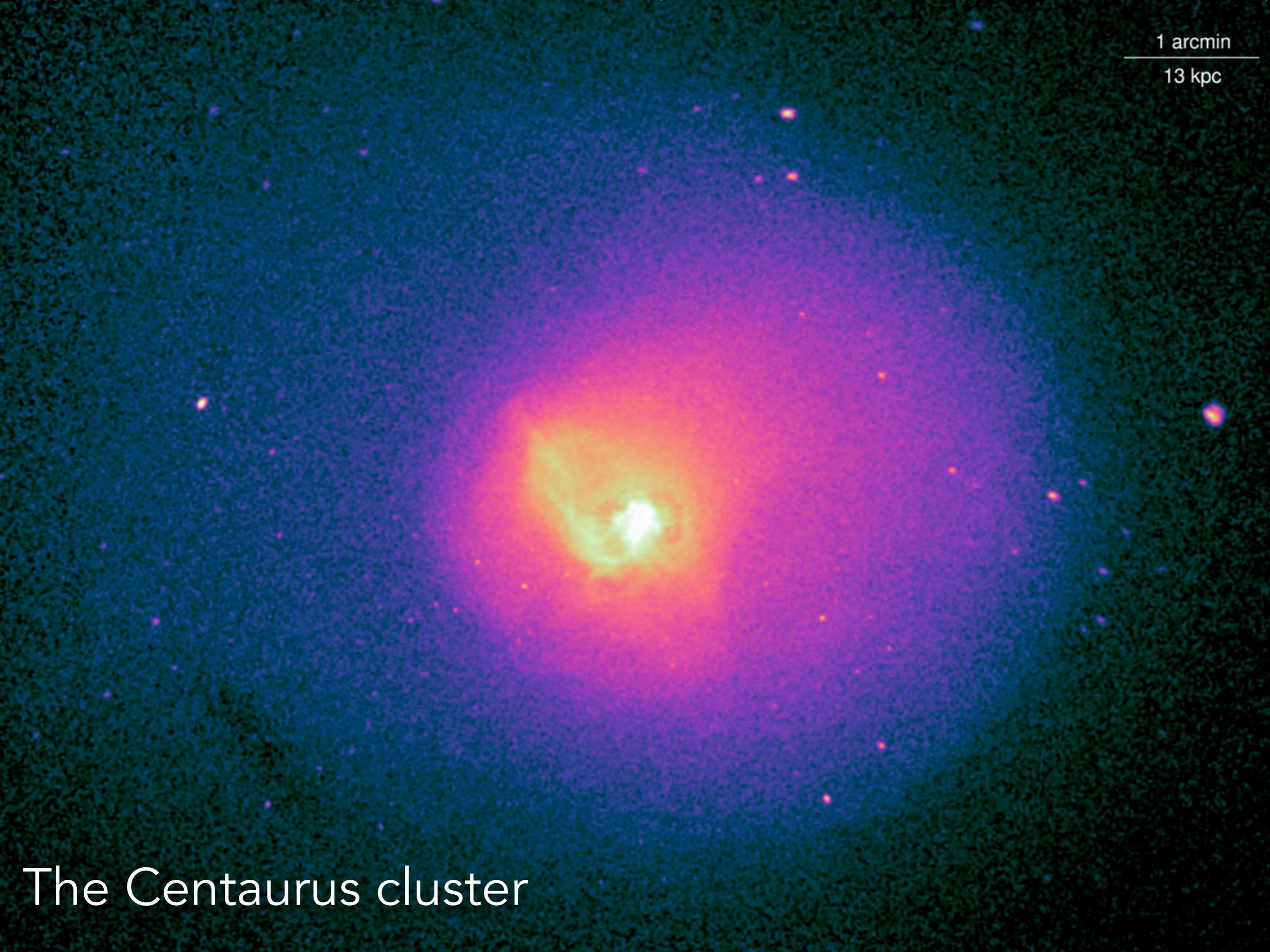
Exploding stars (supernovae) are the only way to produce elements other than H and He...

“We are made of starstuff.” - Carl Sagan





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



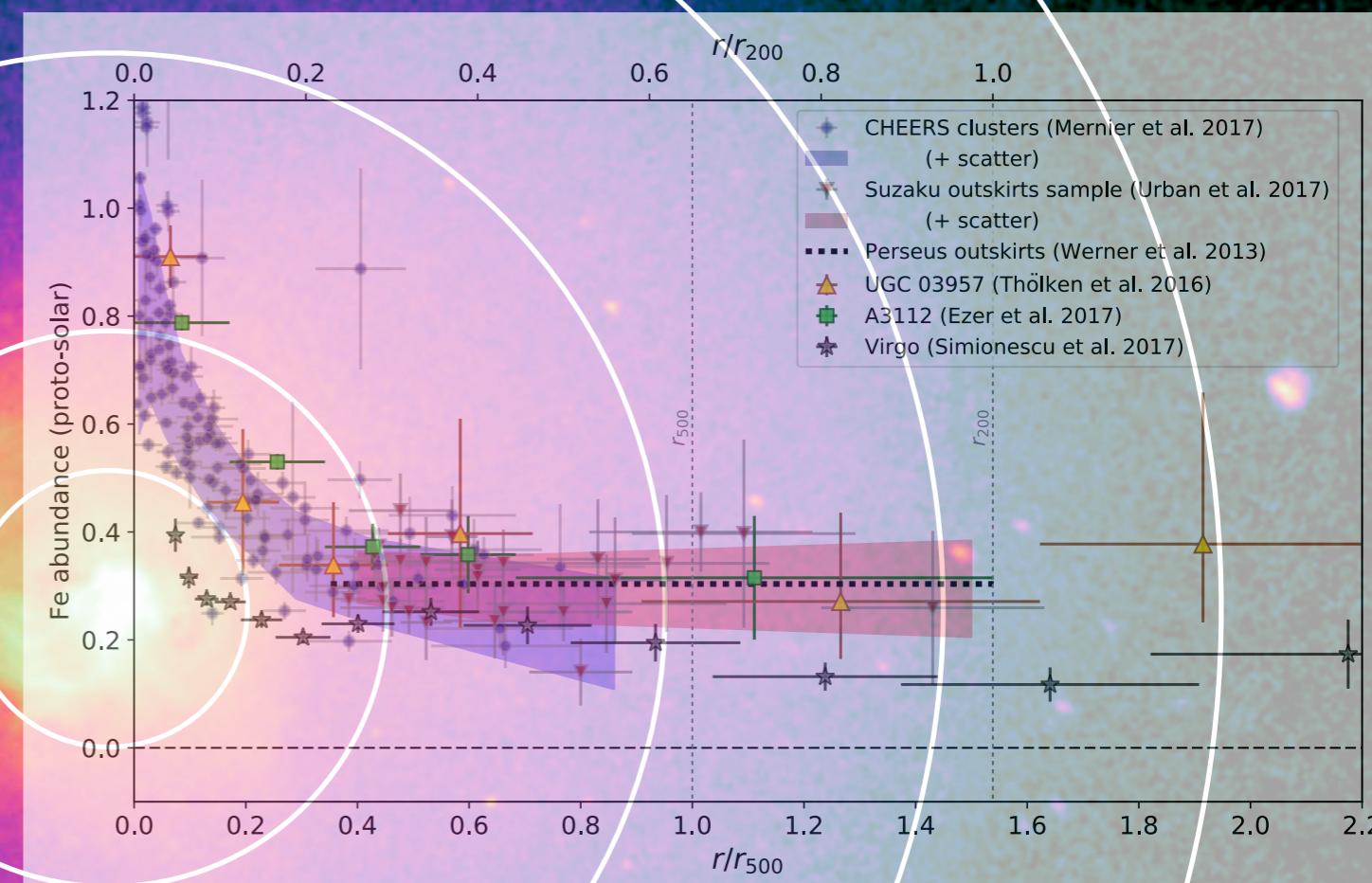
1 arcmin
13 kpc

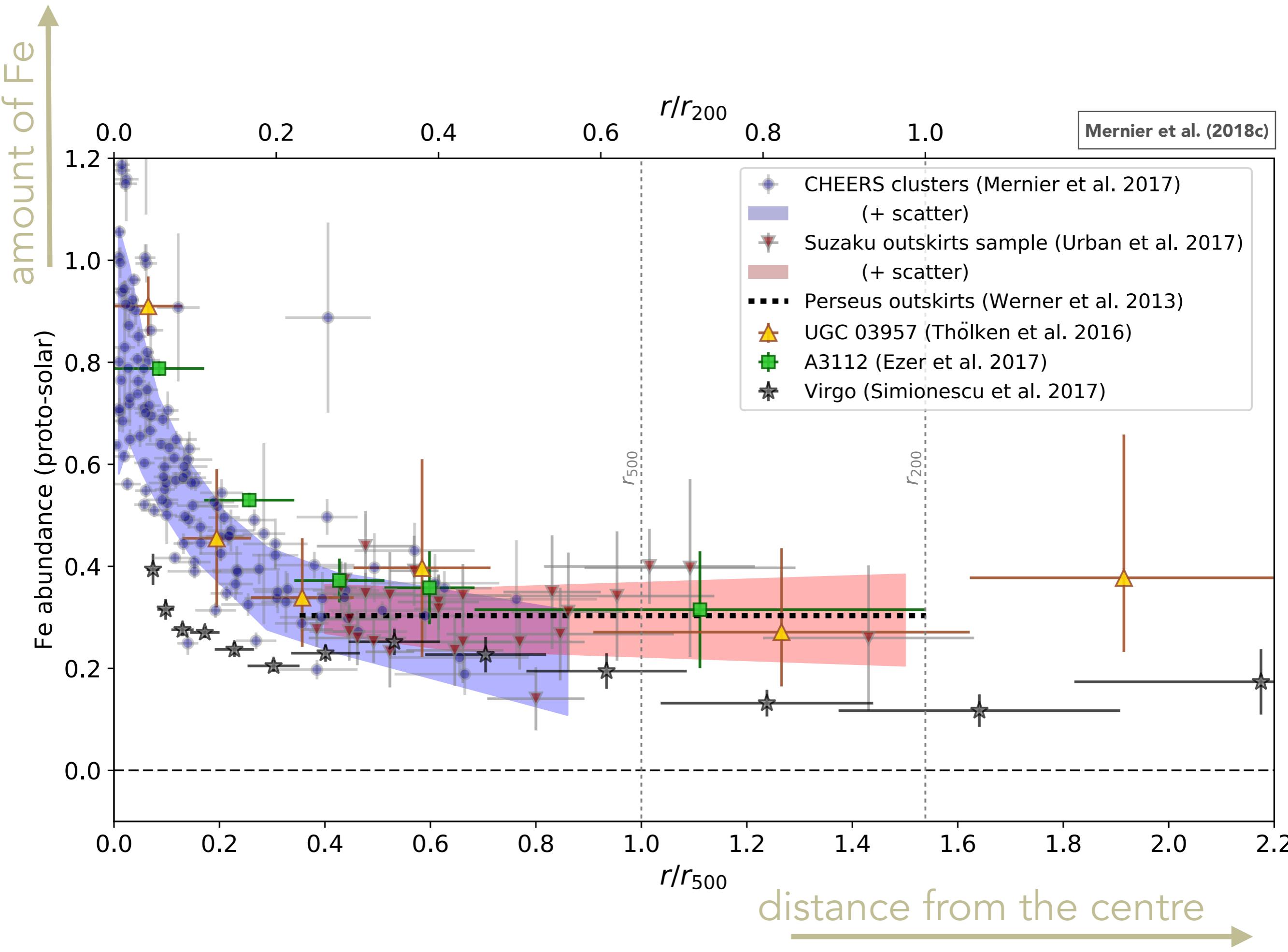
The Centaurus cluster

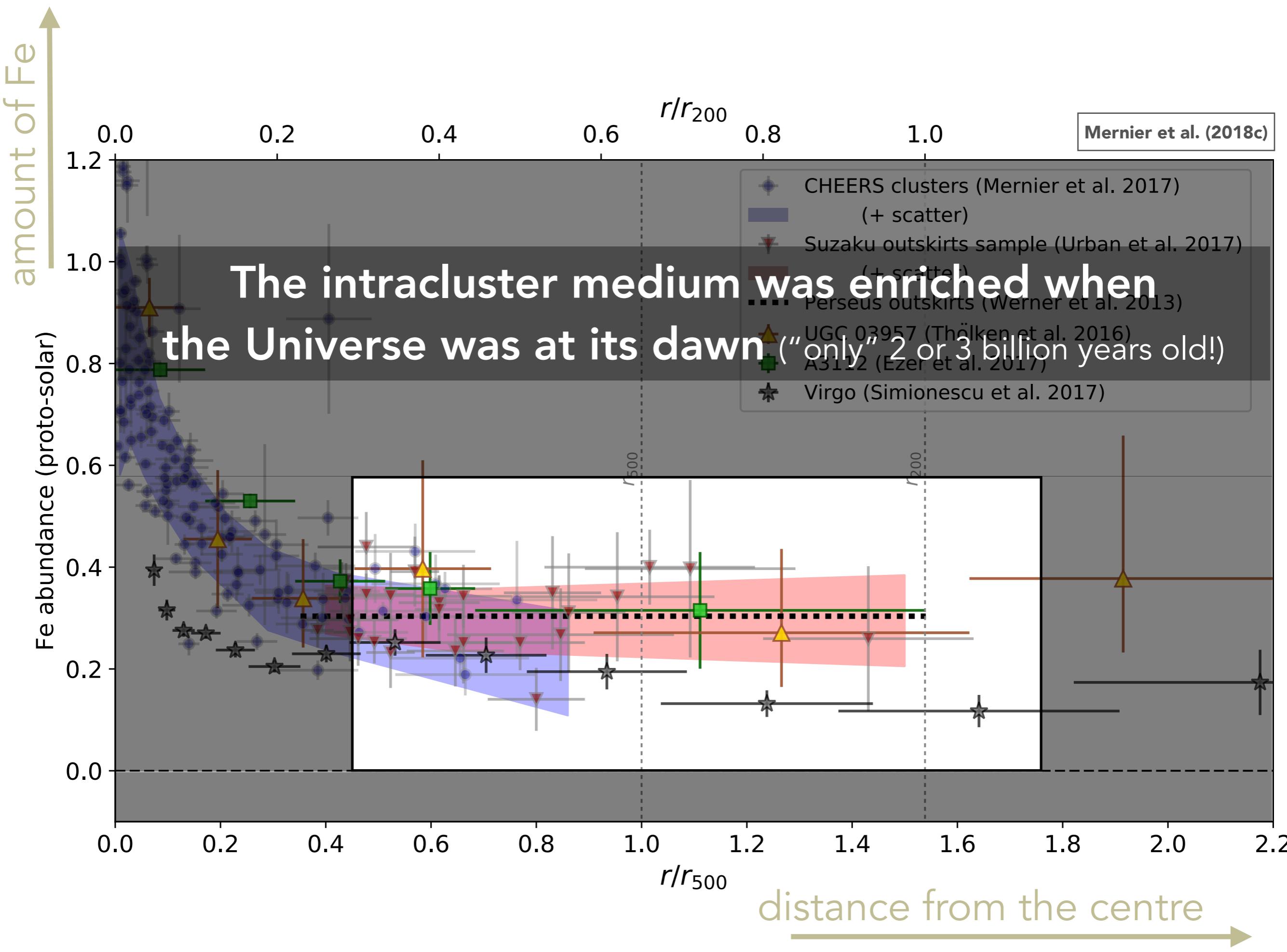
1 arcmin

13 kpc

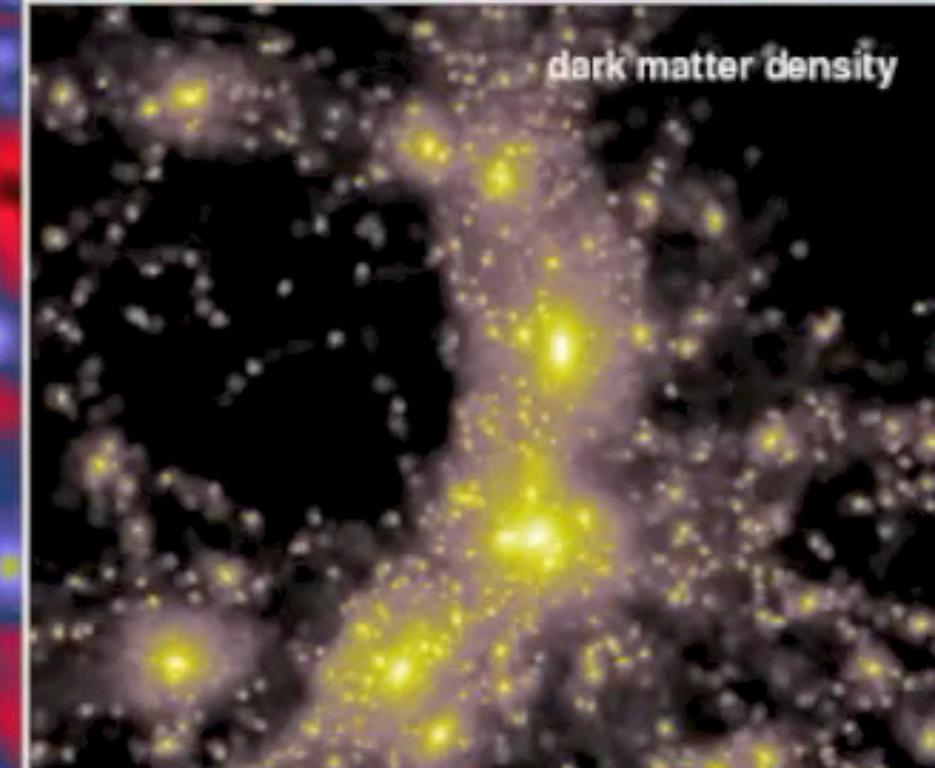
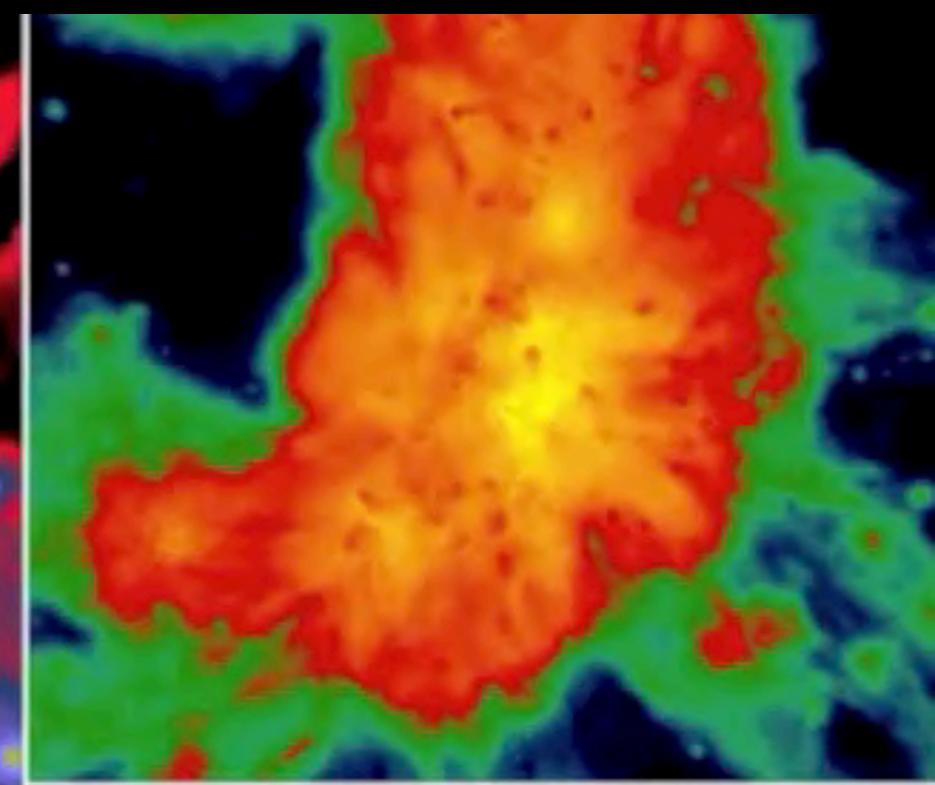
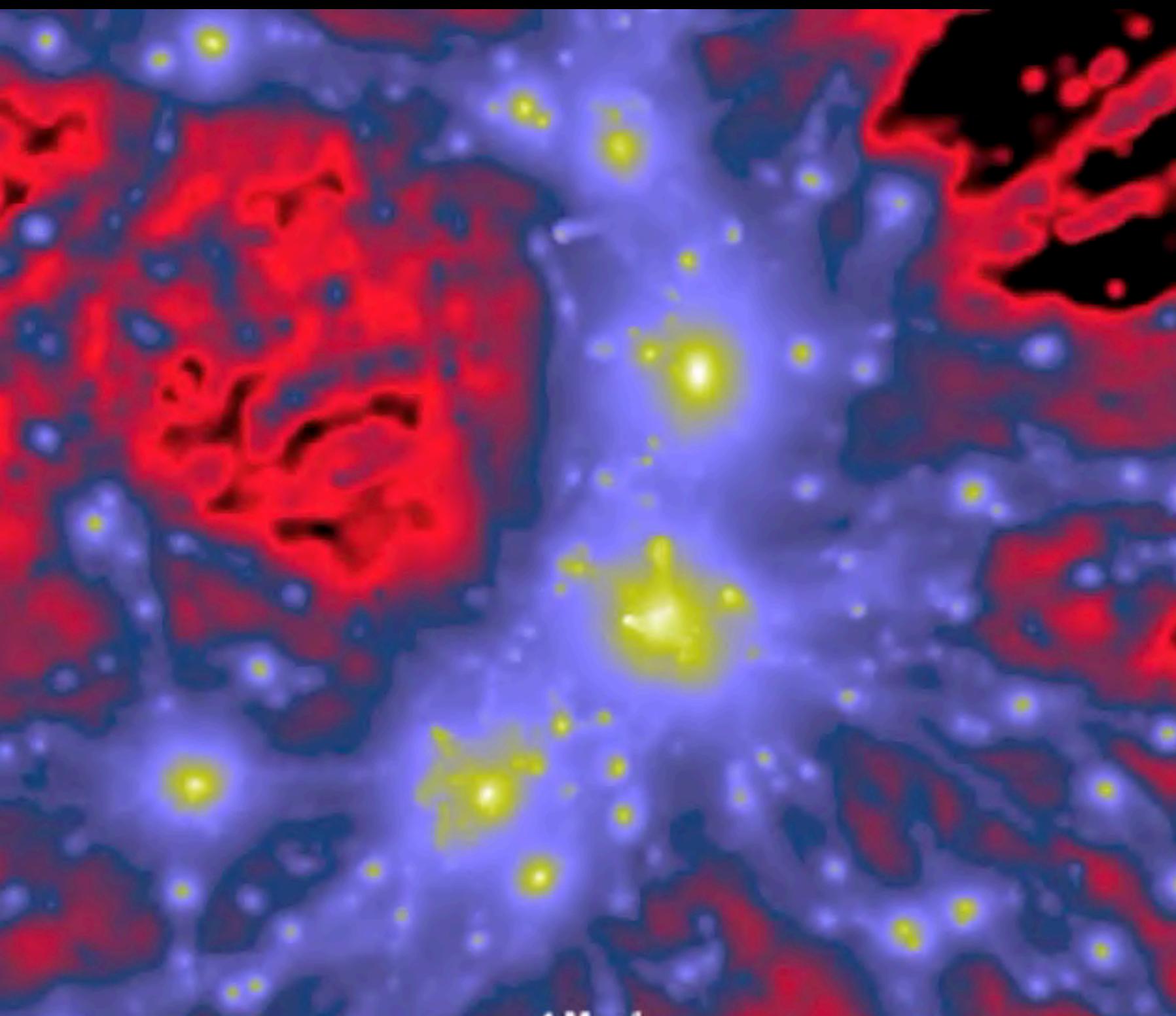
The Centaurus cluster

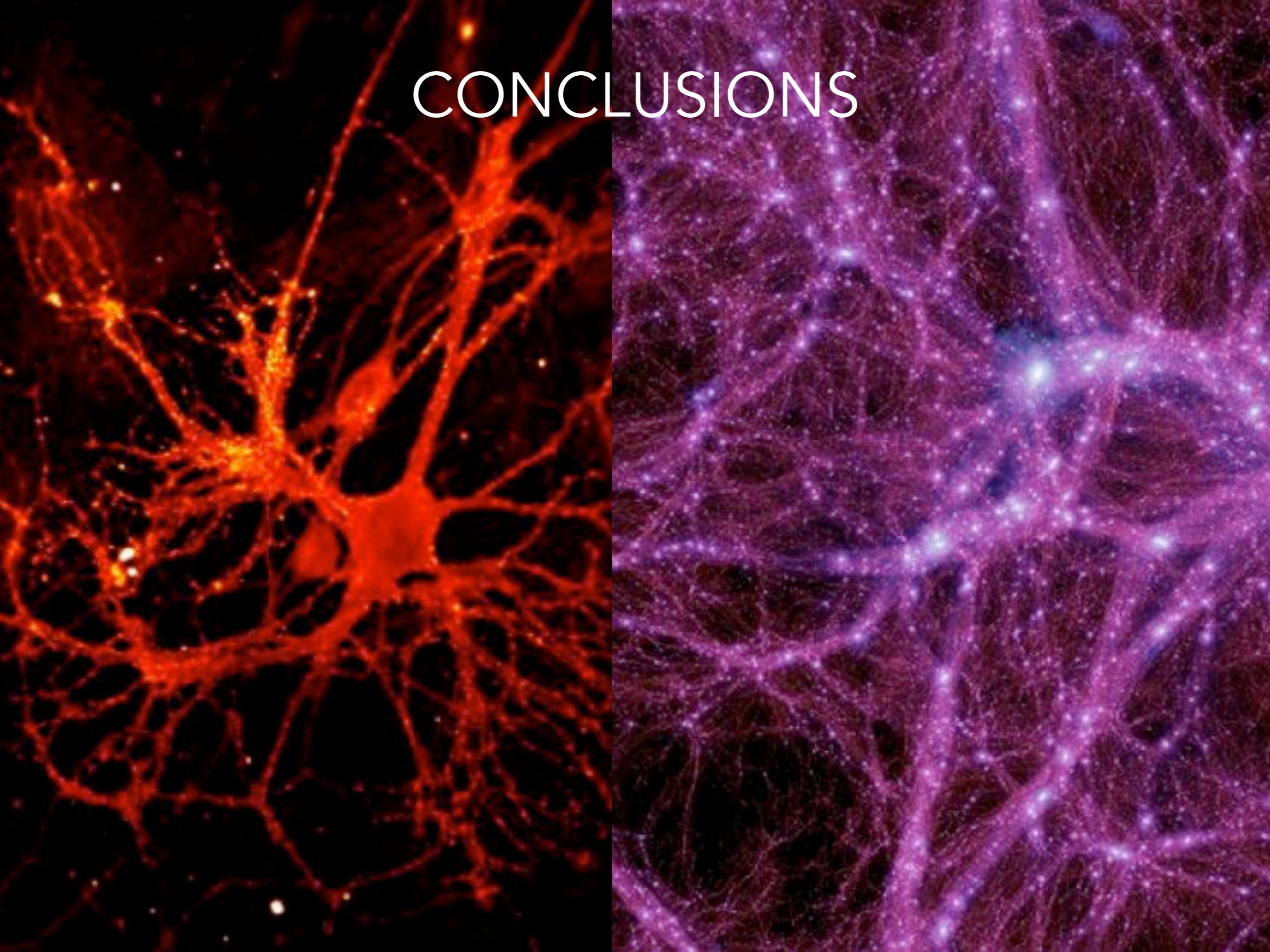






3. Cosmological simulations





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!