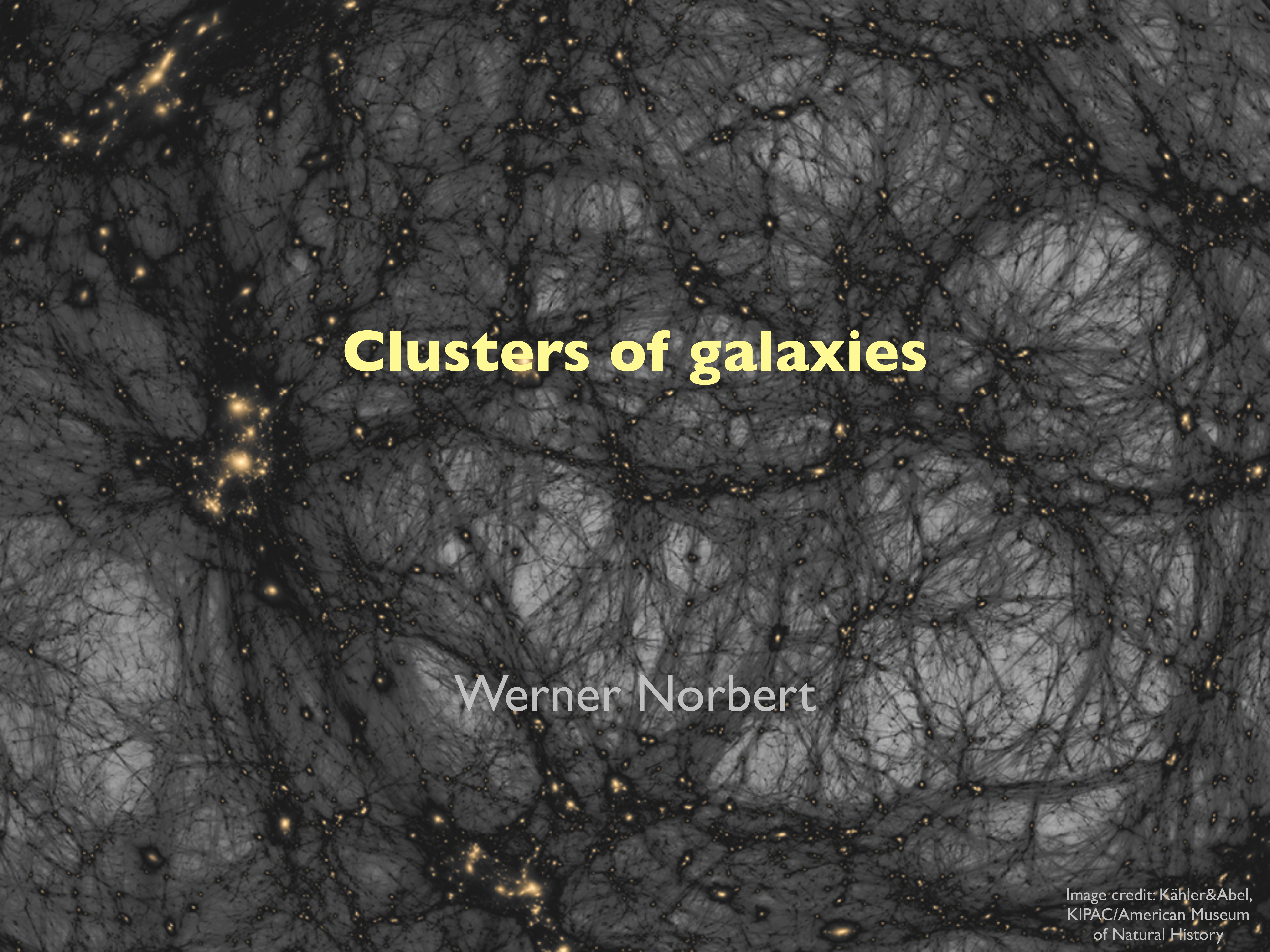
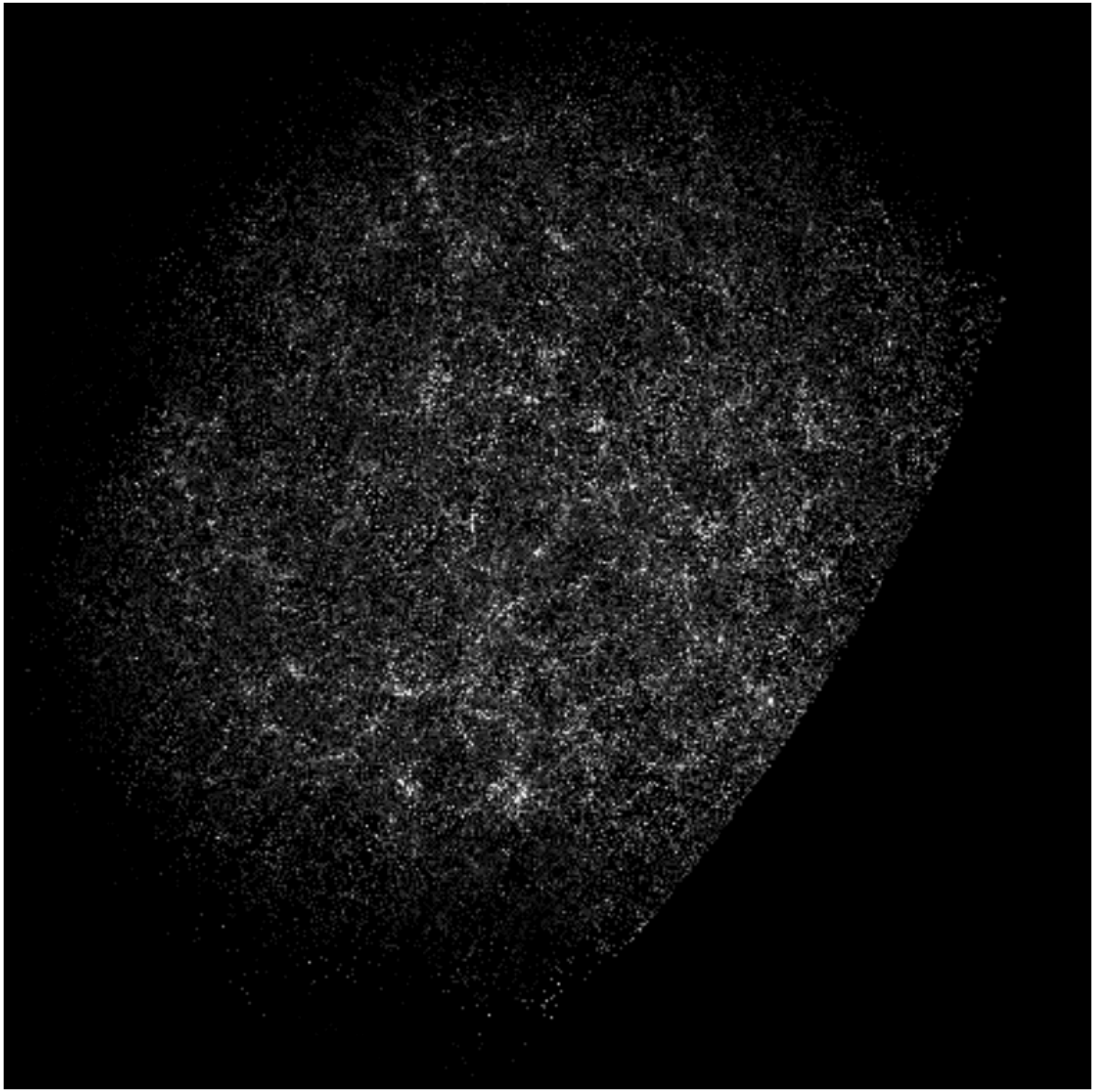


Clusters of galaxies

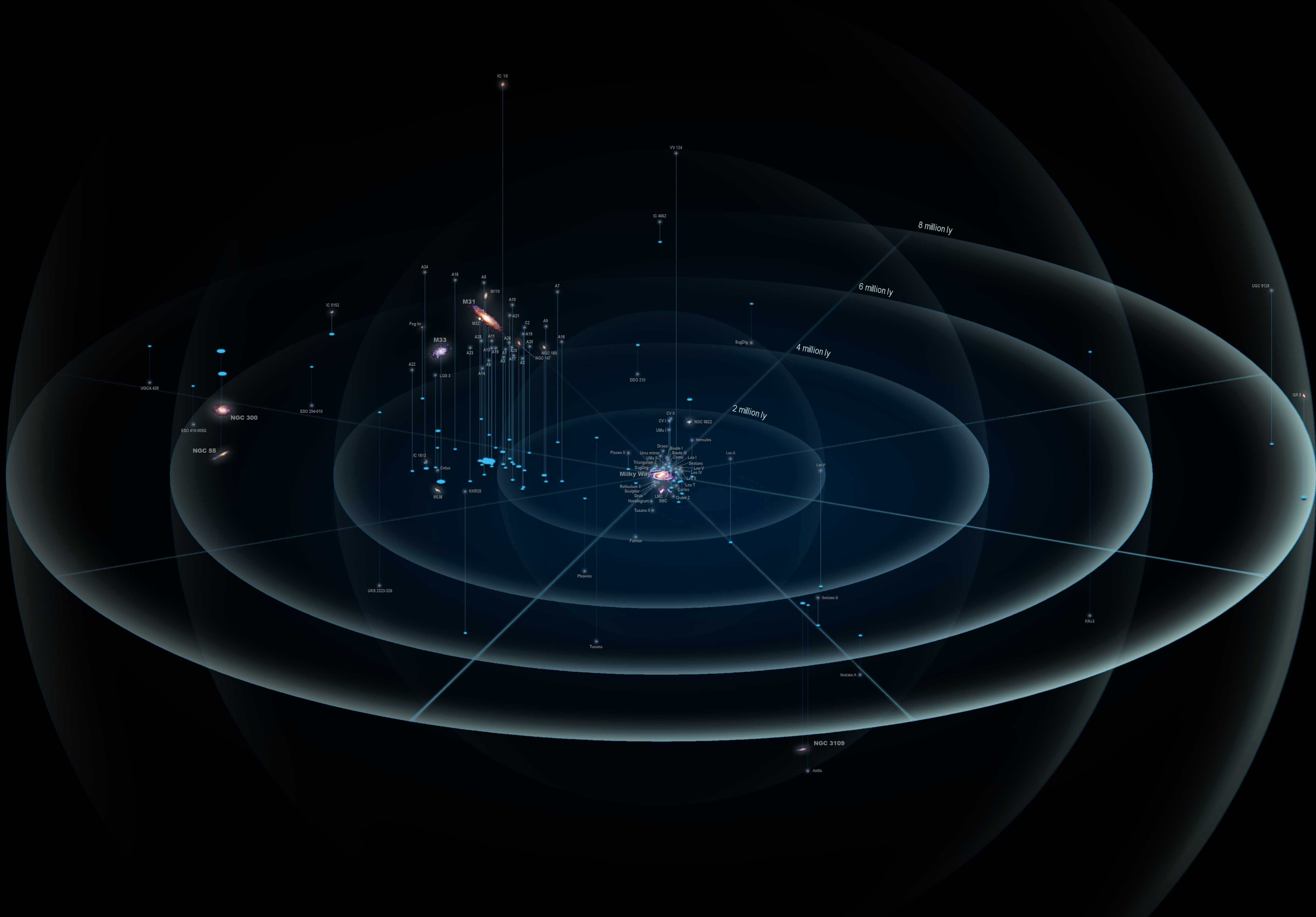
Werner Norbert

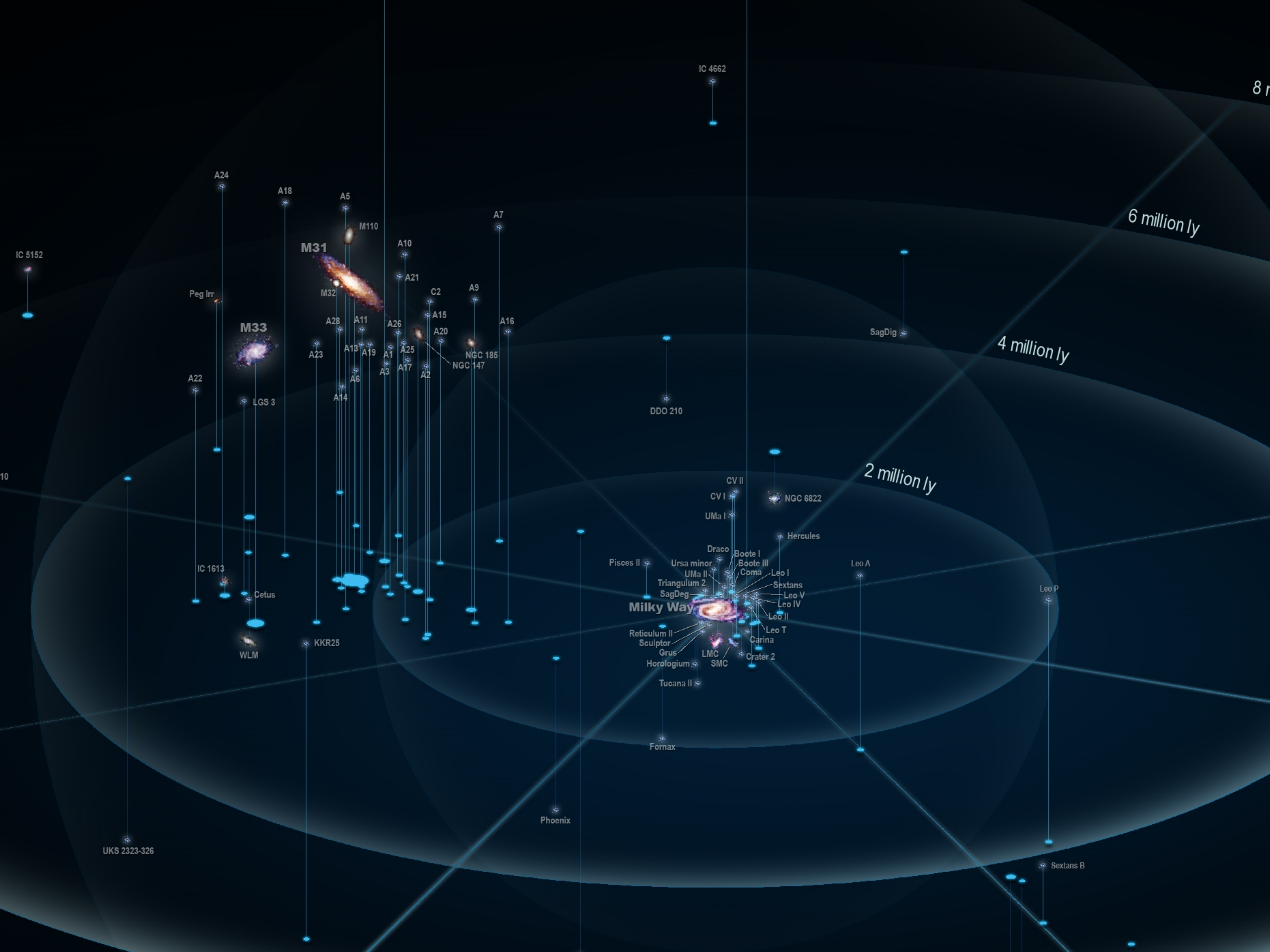
Image credit: Kähler&Abel,
KIPAC/American Museum
of Natural History



The distribution of galaxies in the Northern sky, as compiled in the Lick catalog. This catalog contains the galaxy number counts for “pixels” of $10' \times 10'$ each. It is clearly seen that the distribution of galaxies on the sphere is far from being homogeneous. Instead it is distinctly structured (text book by Schneider)

Local Group and nearest galaxies





8 m
IC 4662
6 million ly
4 million ly
2 million ly
A24
A18
A5
M110
A7
A10
M31
IC 5152
A21
M32
C2
A9
Peg Irr
A15
A28
A11
A26
M33
A20
A16
SagDig
A13
A19
A1
A25
NGC 185
A23
A17
NGC 147
A3
A2
A6
A22
A14
LGS 3
DDO 210
CV II
CV I
NGC 6822
UMa I
Hercules
Draco
Boote I
Pisces II
Ursa minor
Boote III
Leo A
UMa II
Coma
Leo I
IC 1613
Triangulum 2
Sextans
Leo P
Cetus
SagDeg
Leo V
Milky Way
Leo IV
Leo II
Leo T
Reticulum II
Carina
WLM
KKR25
Sculptor
Grus
LMC
Crater 2
Horologium
SMC
Tucana II
Fornax
Phoenix
UKS 2323-326
Sextans B

The Local group of galaxies

- ~100 galaxies (most of the dwarfs)
- large members: Milky Way, M31 (Andromeda galaxy), M33 (Triangulum galaxy)
- Mass of ~3×10^{12} solar masses
- diameter of 3 Mpc
- binary distribution

Abell (Optical) Cluster Catalog

- Palomar Sky Survey using the 48 inch Schmidt telescope (+ the 48 inch telescope in Australia)
- Abell (1958) catalog of 1682 clusters on the northern sky
- Abell, Corwin, & Olowin (1989) – catalog on the south
- In total 4073 objects

Abell (Optical) Cluster Catalog

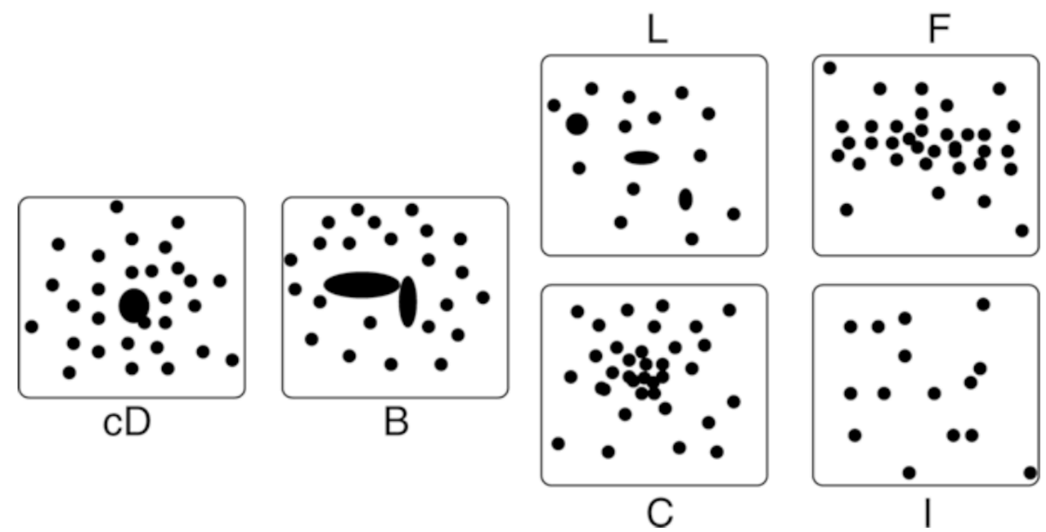
- *Richness Criterion:* a cluster contains at least 50 members with $m_3 < m < m_3 + 2$.
- *Richness classes:* based on the number of galaxies in this range.
- *Compactness Criterion:* Only galaxies within an angular radius of 1.7arcmin/ z get counted. That corresponds to a physical radius of 1.5 h^{-1} Mpc. The redshifts were estimated based on the apparent magnitude m_{10} galaxy
- *Distance Criteria:* Lower redshift limit (z = 0.02) to force clusters onto one (6 x 6 degree) POSS photo plate. Upper limit due to mag limit of POSS, which matches z of about 0.2.
- Later surveys (e.g. based on SDSS such as maxBCG) take into account the colors of the galaxies (multi-color photometry reduces spurious detections because the cores of clusters are dominated by red early-type galaxies)

Abell (Optical) Cluster Catalog

Table 4.1. Definitions of the richness classes of Abell clusters and the numbers of clusters within Abell's complete northern sample of 1682 clusters. N is the number of galaxies in the cluster between magnitudes m_3 and $m_3 + 2$ (Abell 1958, Bahcall 1988).

Richness Class R	N	Number of clusters in the complete northern sample
(0)[a]	(30 – 49)	($\geq 10^3$)
1	50 – 79	1224
2	80 – 129	383
3	130 – 199	68
4	200 – 299	6
5	300 or more	1

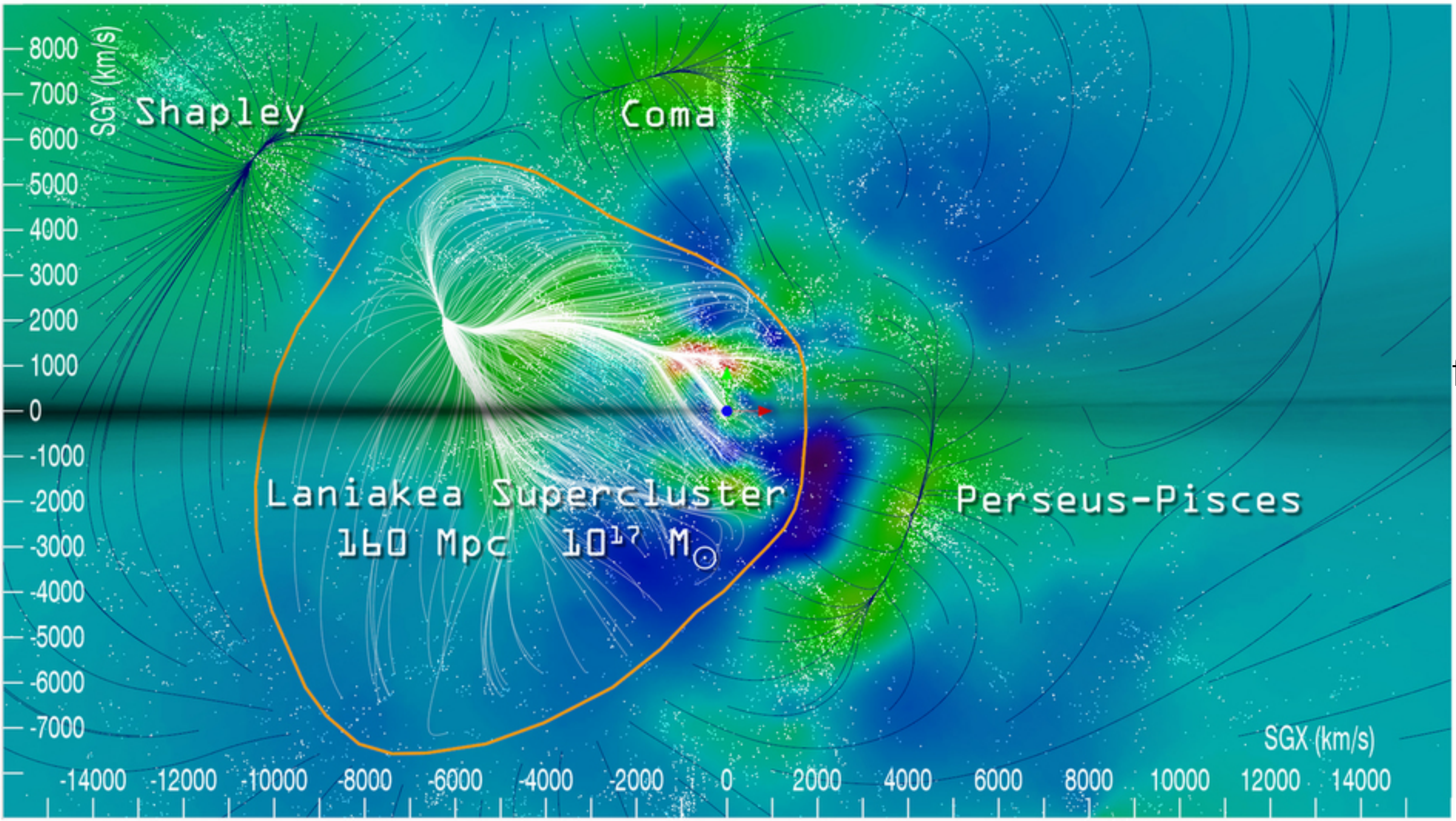
[a] The sample is not complete for richness class zero.



Clusters and groups of galaxies

- Clusters of galaxies ~10^{14} — 10^{15} Solar masses
- Groups of galaxies ~10^{12} — 10^{14} Solar masses
- Clusters are the most massive gravitationally bound objects in the Universe and they were the last structures to form
- First identified in optical surveys galaxy surveys

Laniakea Supercluster

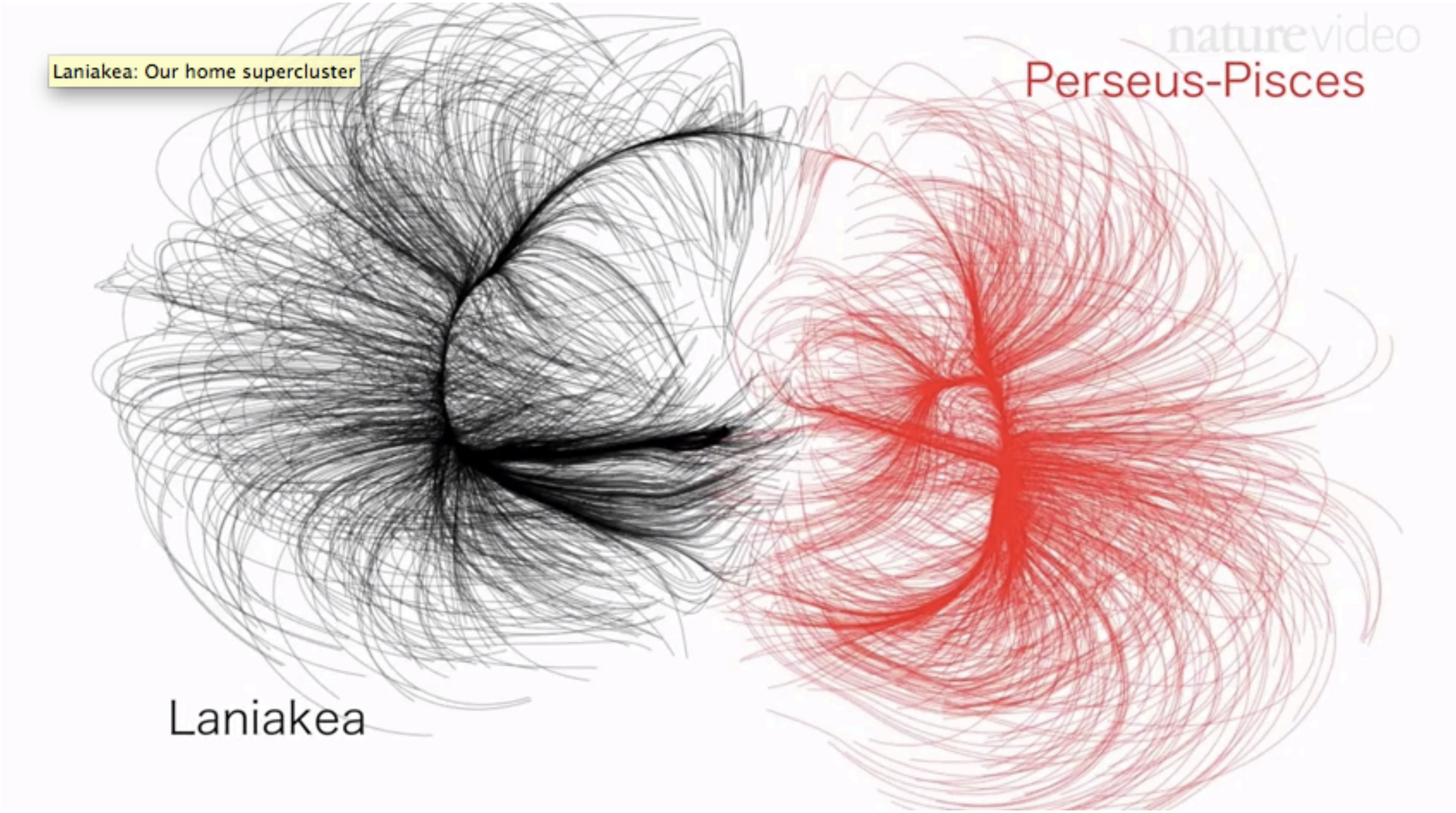


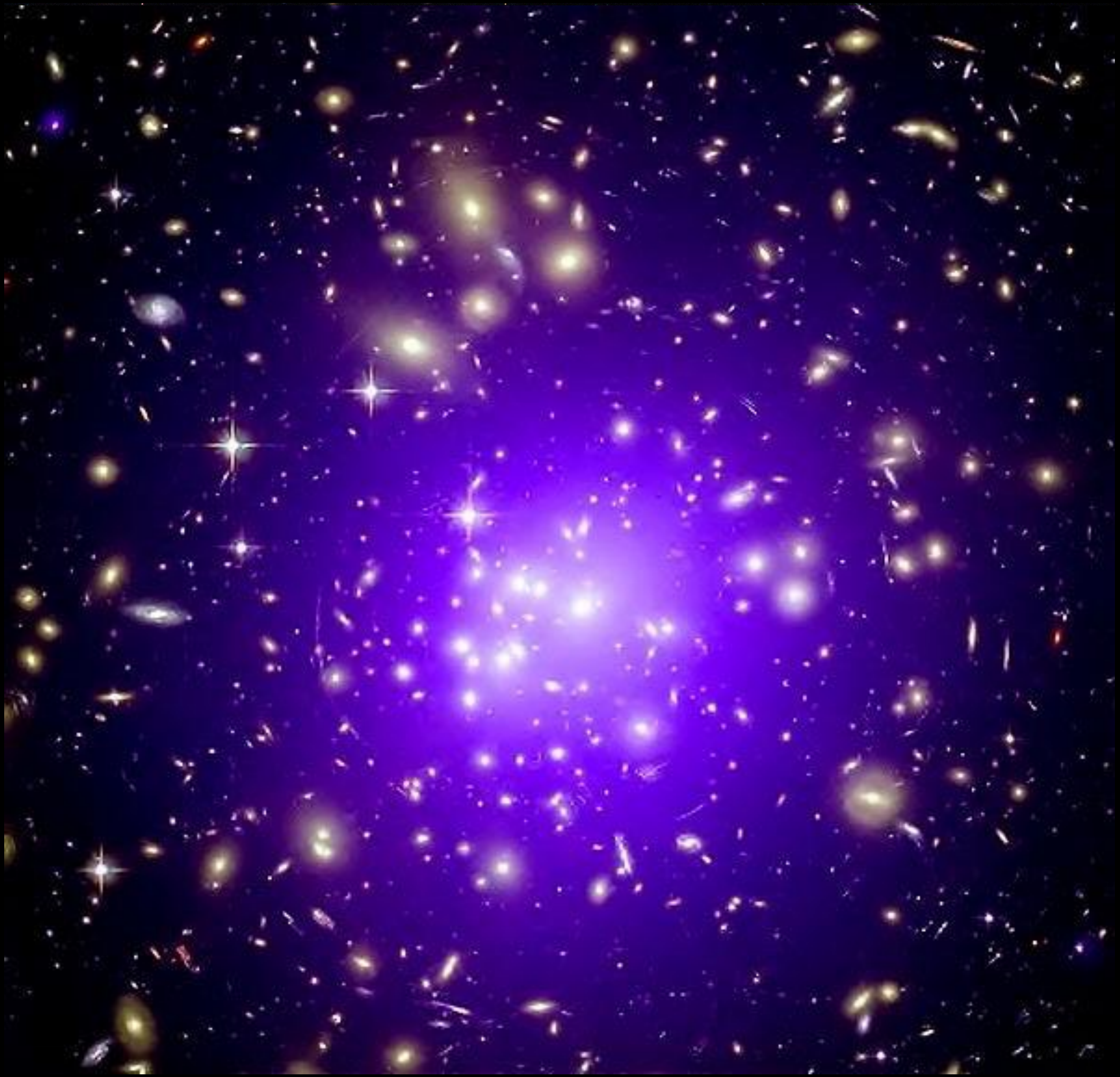
If the distance to each galaxy from Earth is directly measured, then the peculiar velocity can be derived from the subtraction of the mean cosmic expansion, the product of distance times the Hubble constant, from observed velocity. The peculiar velocity is the line-of-sight departure from the cosmic expansion and arises from gravitational perturbations

Where peculiar velocity flows diverge, as water does at watershed divides, we trace the surface of divergent points that surrounds us. Within the volume enclosed by this surface, the motions of galaxies are inward after removal of the mean cosmic expansion. These volumes are called Superclusters.

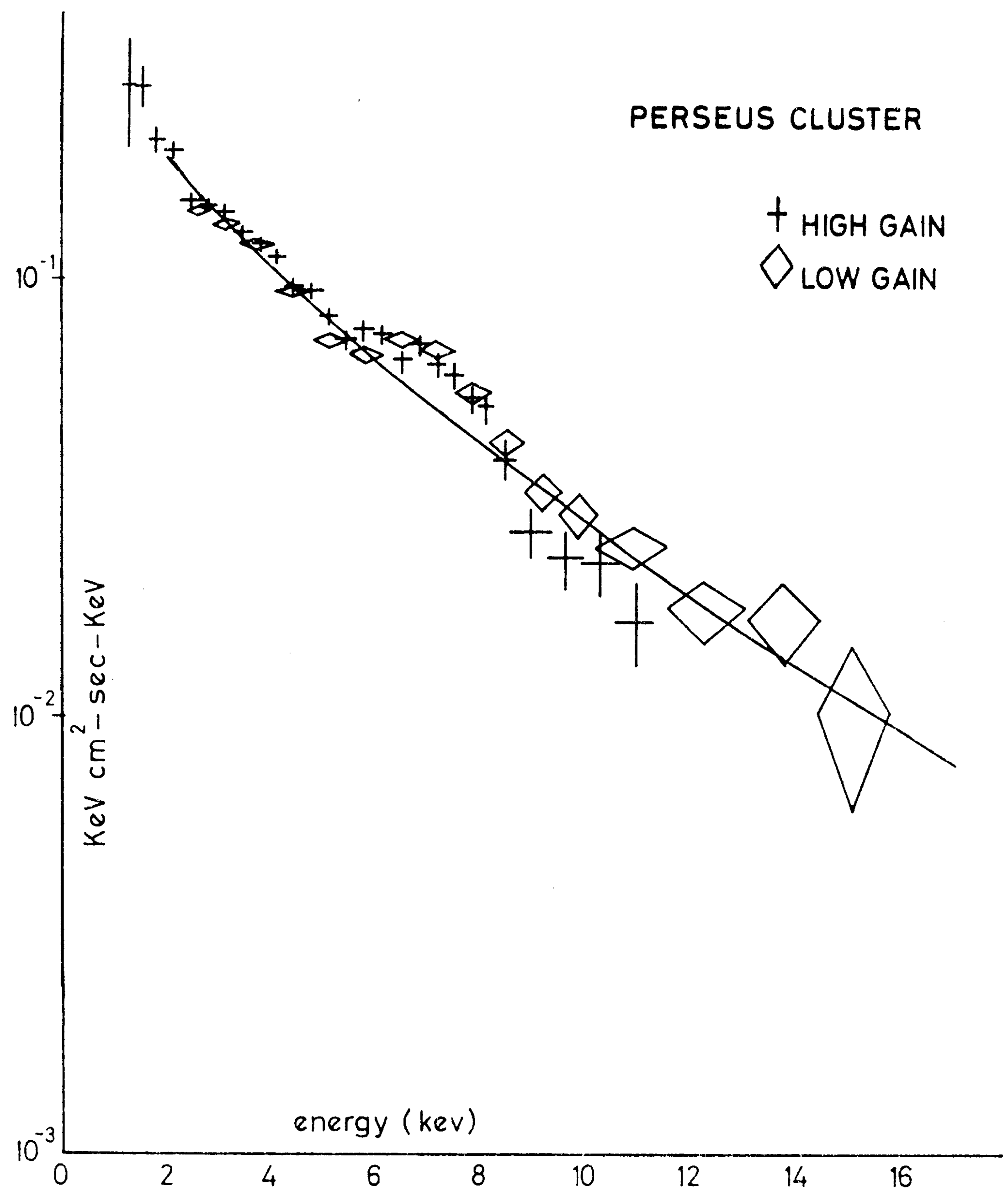
Tully et al. 2014


YOU ARE HERE

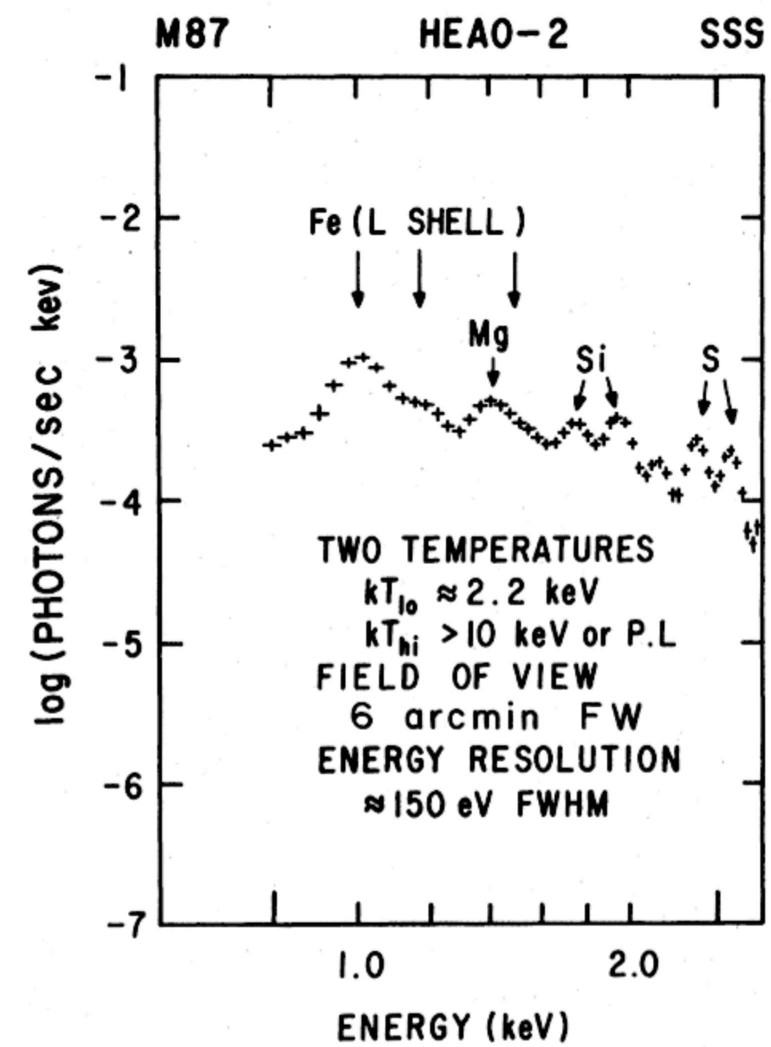

Laniakea: Our home supercluster
naturevideo
Perseus-Pisces
Laniakea



Thermal plasma



Ariel 5
Mitchell et al. 1976



Einstein
Lea et al. 1982

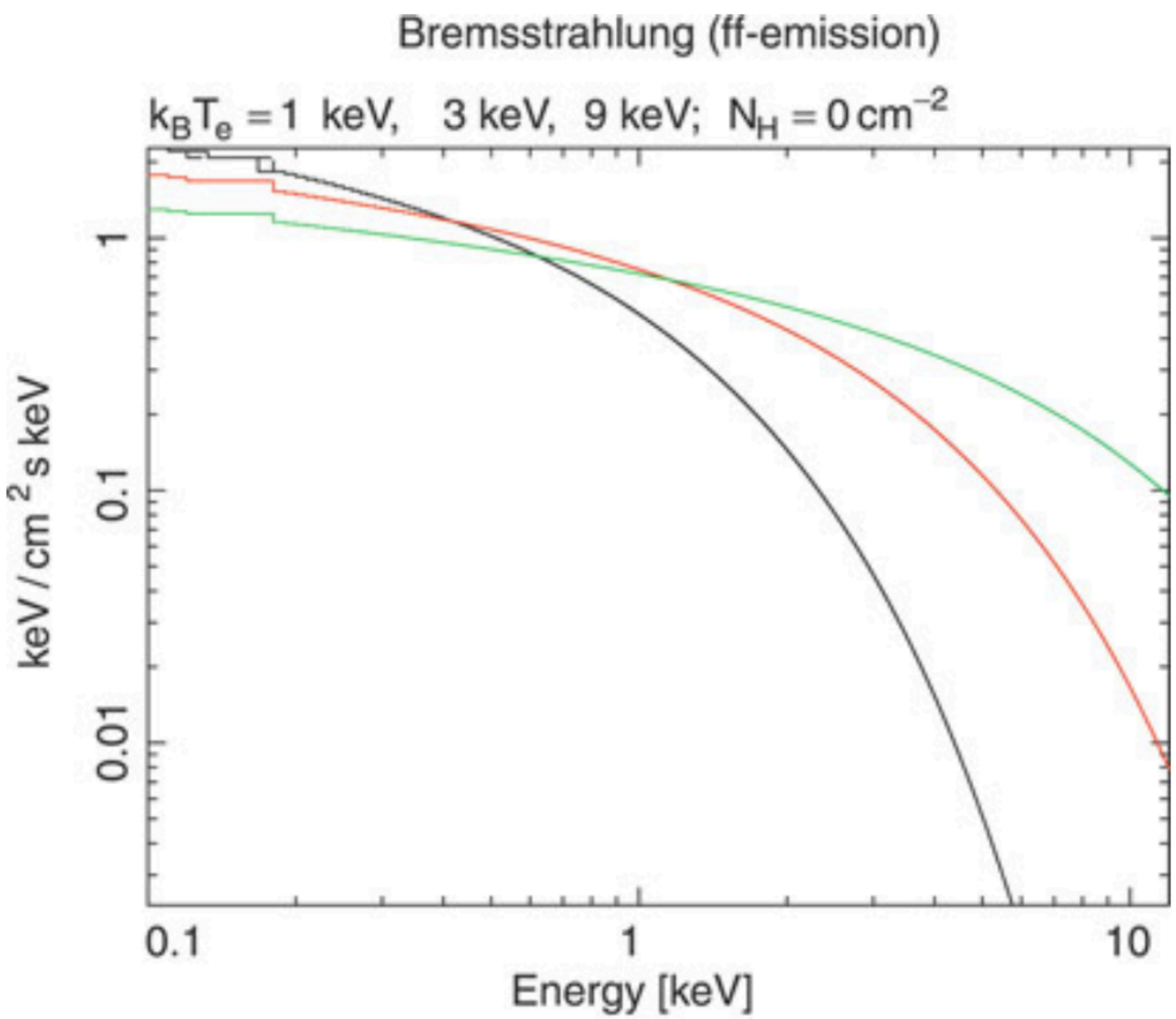
low densities n=10^{-1}-10^{-5} cm^{-3}, high temperatures T=5x10^6-10^8 K

bremsstrahlung (free-free), recombination (free-bound), de-excitation (bound-bound)

collisional ionization equilibrium

electron and ion temperatures in equilibrium

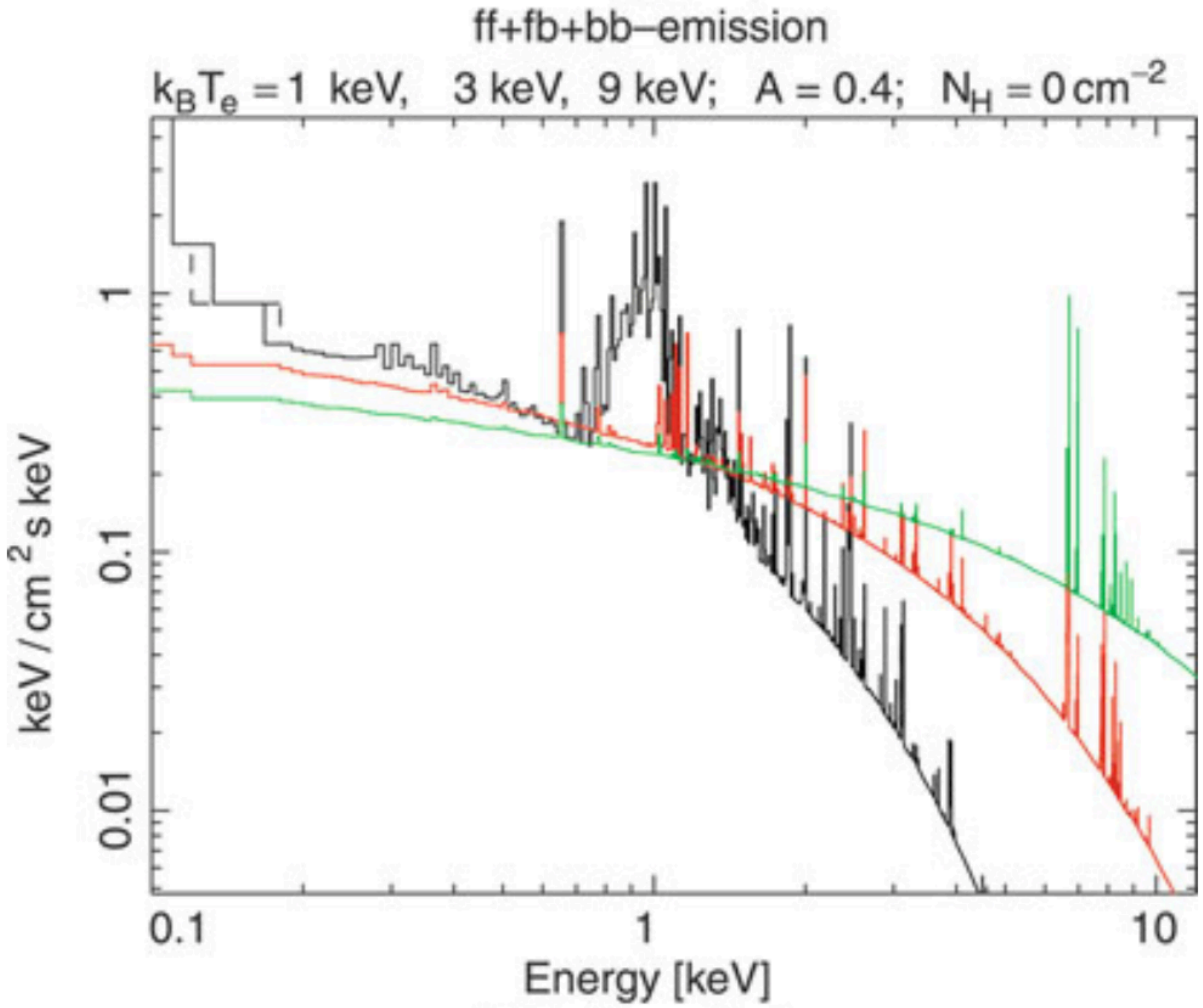
shape of spectrum entirely determined by kT and chemical abundances



$$\epsilon_\nu^{\rm ff} = \frac{32\pi Z^2 e^6 n_{\rm e} n_{\rm i}}{3 m_{\rm e} c^3}\sqrt{\frac{2\pi}{3k_{\rm B} T m_{\rm e}}}\, {\rm e}^{-h_{\rm P}\nu/k_{\rm B}T}\, g_{\rm ff}(T,\nu)$$

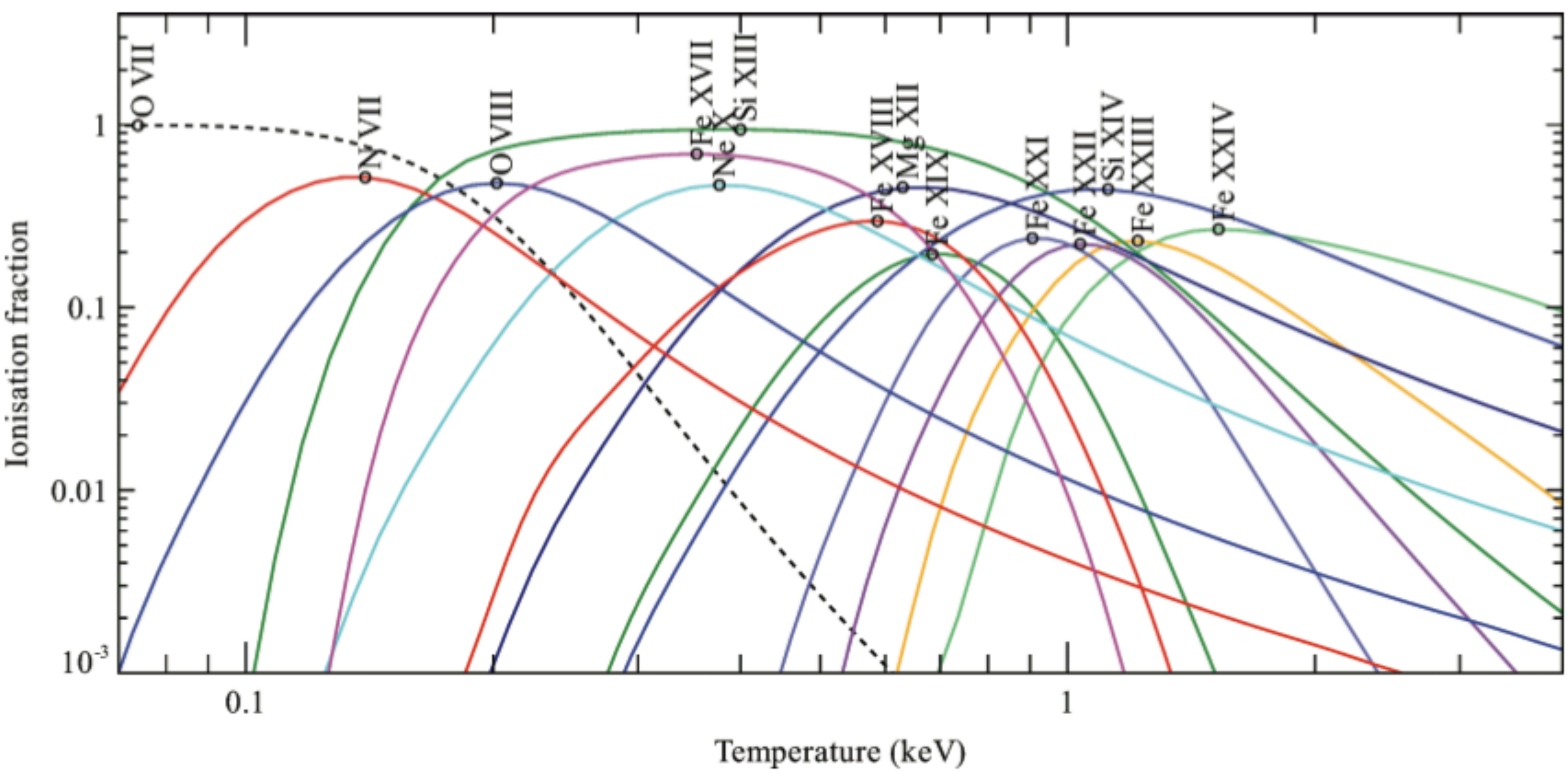
$$\epsilon^{\rm ff} = \int_0^\infty {\rm d}\nu\, \epsilon_\nu^{\rm ff} \approx 3.0\times 10^{-27}\sqrt{\frac{T}{1{\rm K}}}\left(\frac{n_{\rm e}}{1\,{\rm cm}^{-3}}\right)^2 {\rm erg\,cm^{-3}s^{-1}}$$

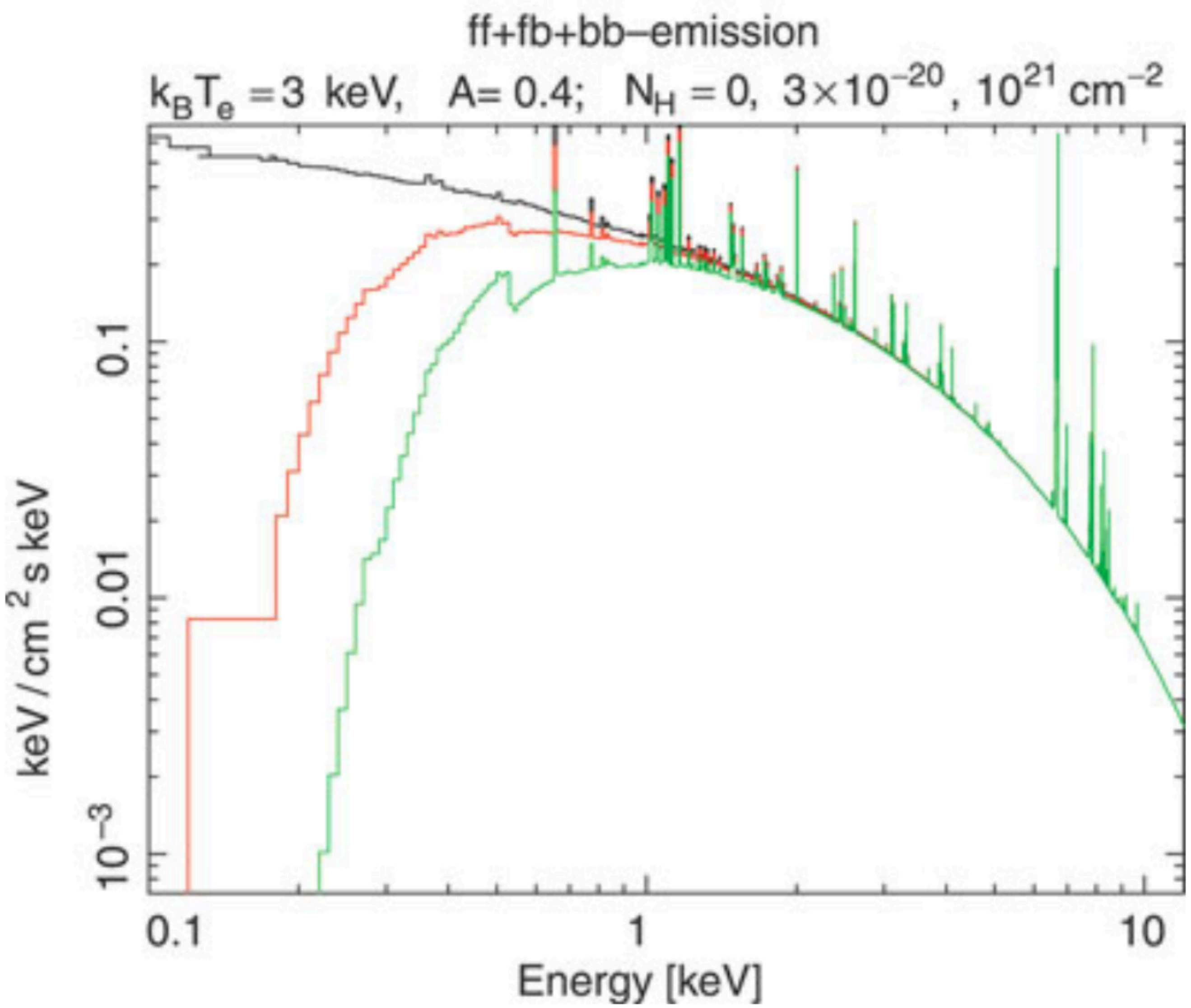
$$g_{\rm ff} \approx \frac{3}{\sqrt{\pi}}\ln\left(\frac{9k_{\rm B}T}{4h_{\rm P}\nu}\right)$$



$$\epsilon \approx 6.2 \times 10^{-19} \left(\frac{T}{1\,\mathrm{K}}\right)^{-0.6} \left(\frac{n_\mathrm{e}}{1\,\mathrm{cm}^{-3}}\right)^2 \mathrm{erg\,cm^{-3}\,s^{-1}} \;.$$

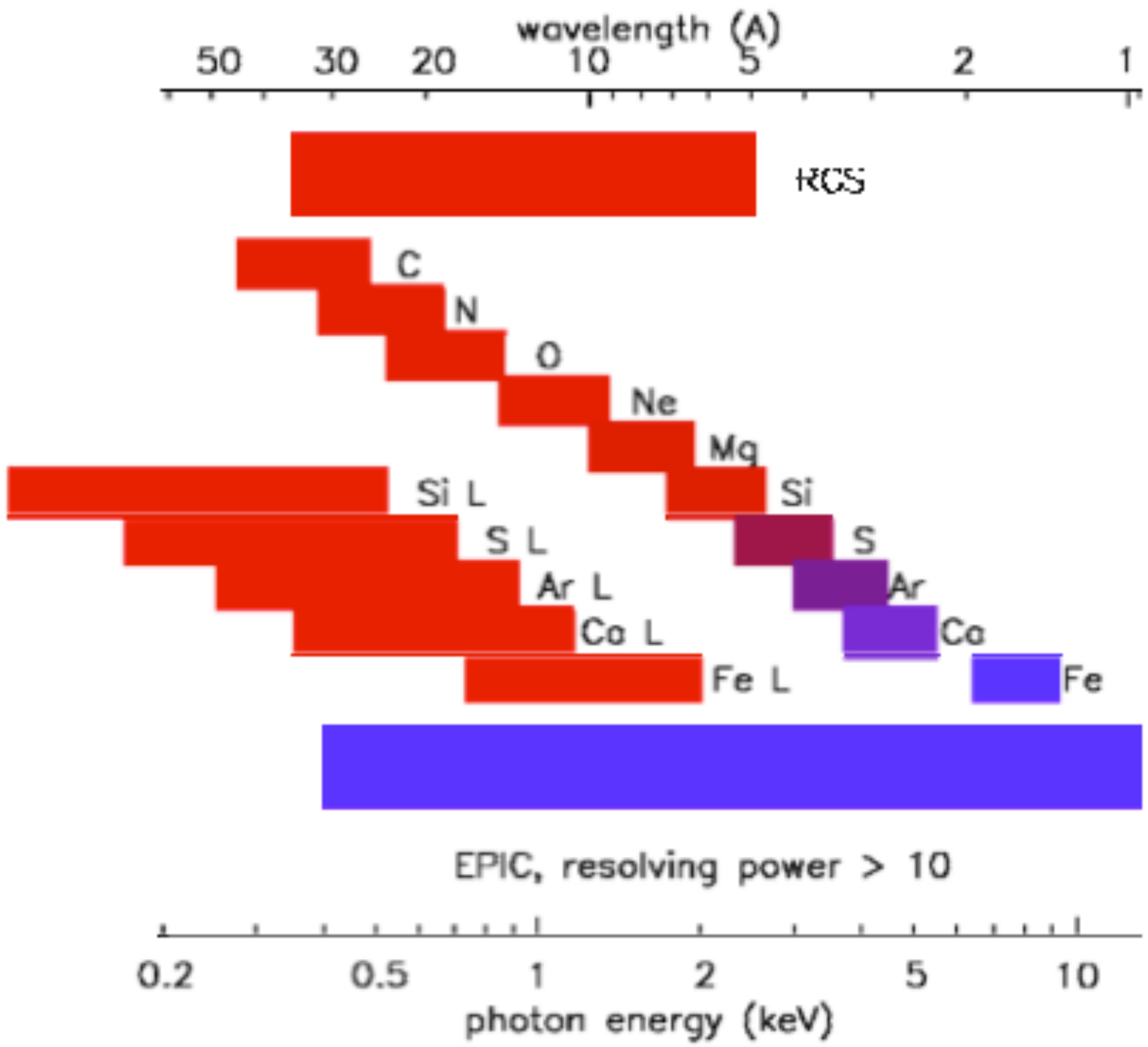
Lines and temperatures

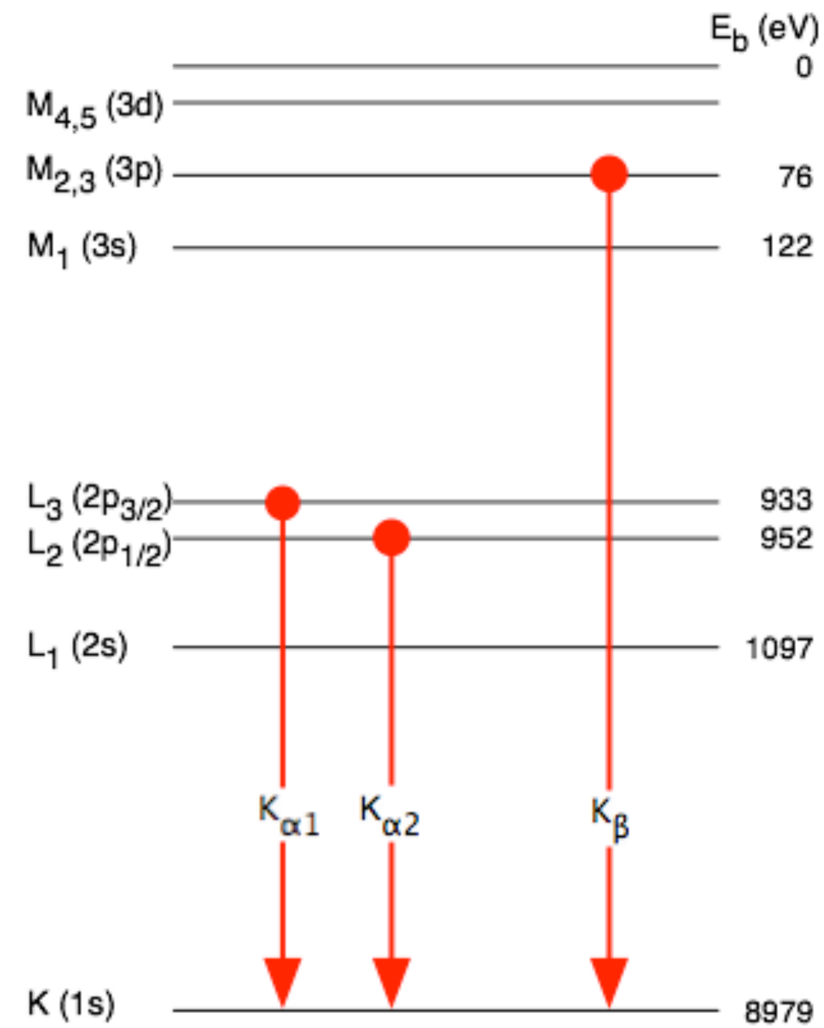




ff+fb+bb−emission
$k_B T_e = 3$ keV, A= 0.4; $N_H = 0,\ 3\times10^{-20},\ 10^{21}\ cm^{-2}$
keV / cm ^{2} s keV
0.1
0.01
10^{-3}
0.1
1
10
Energy [keV]

Which elements, where?

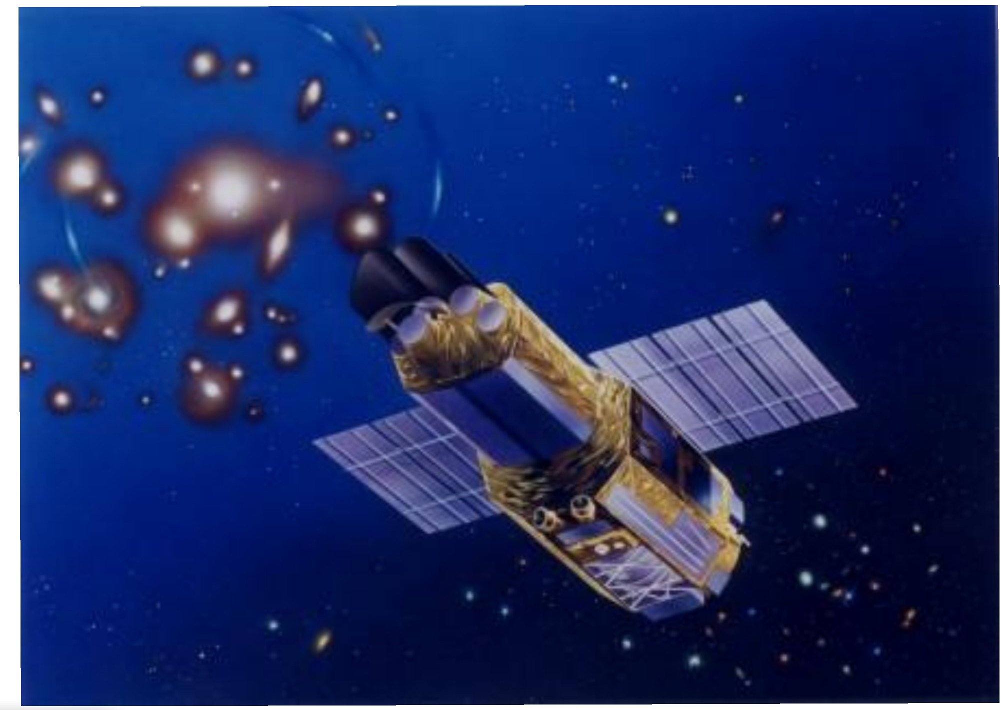




X-ray lines between neutral fluorescent n=2-1, and H-like n=1-∞ (think of the Bohr model!)

X-ray observatories

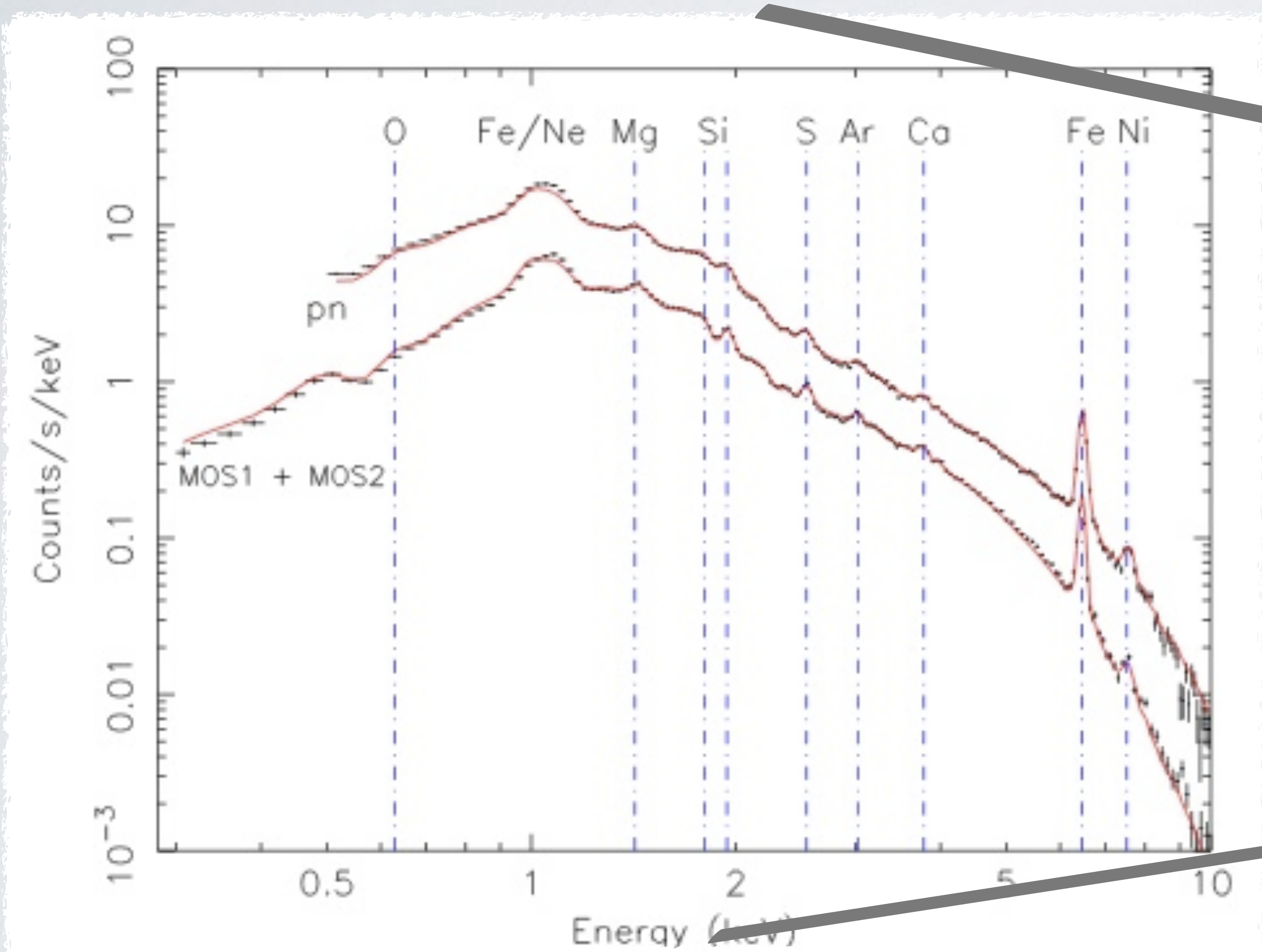
XMM-Newton



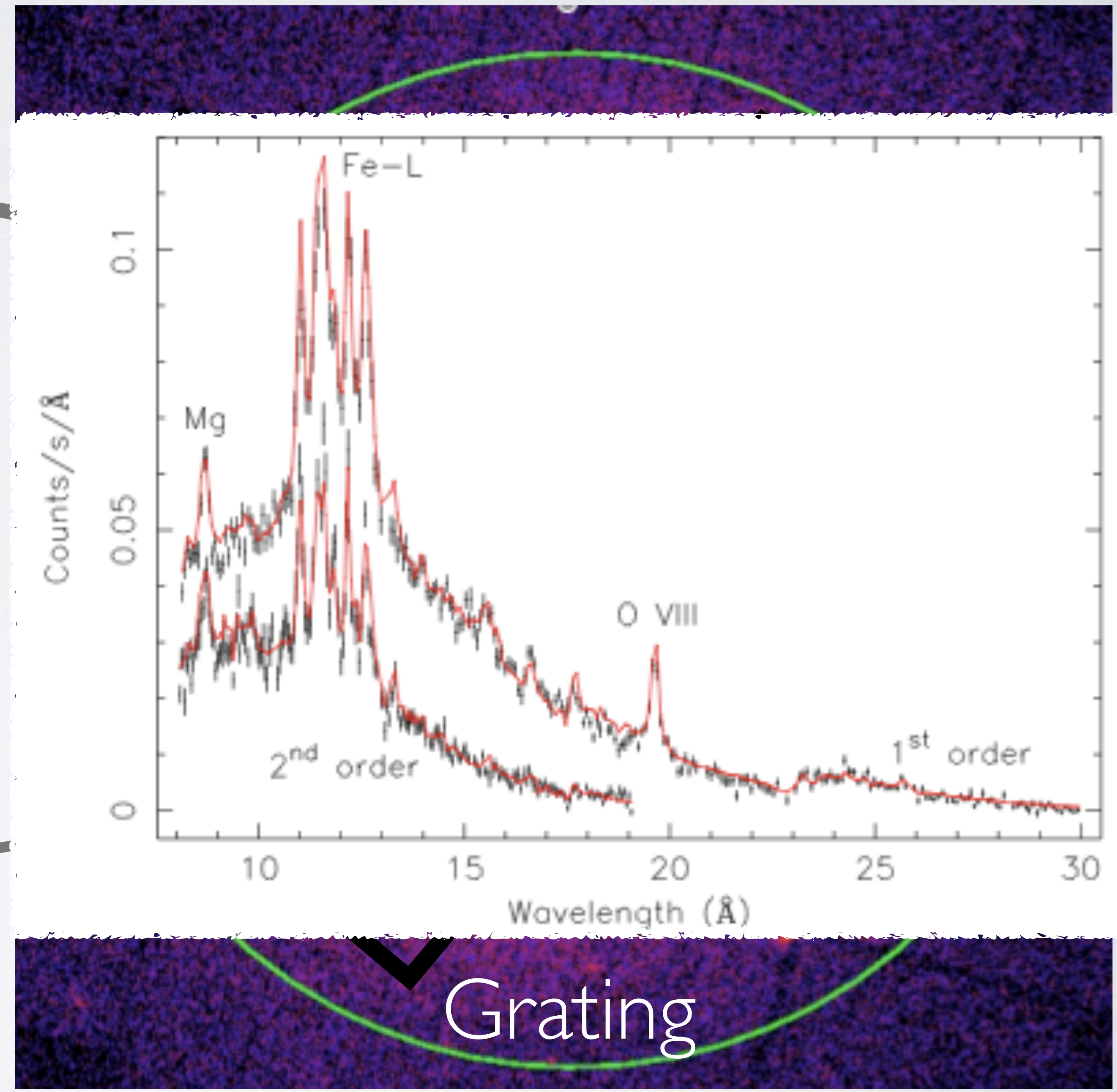
Suzaku

Chandra

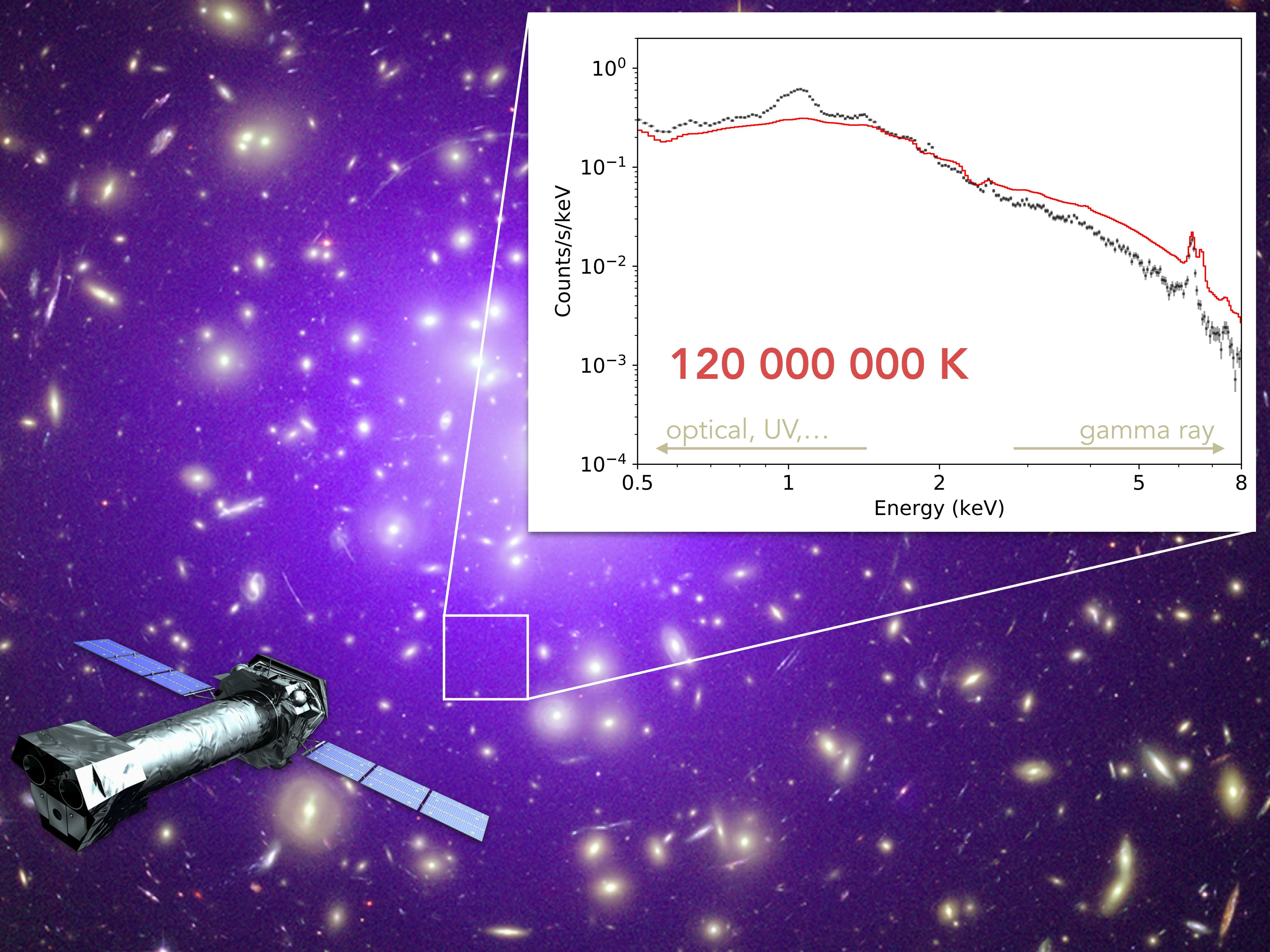
X-RAY SPECTRA OF HOT DIFFUSE PLASMA



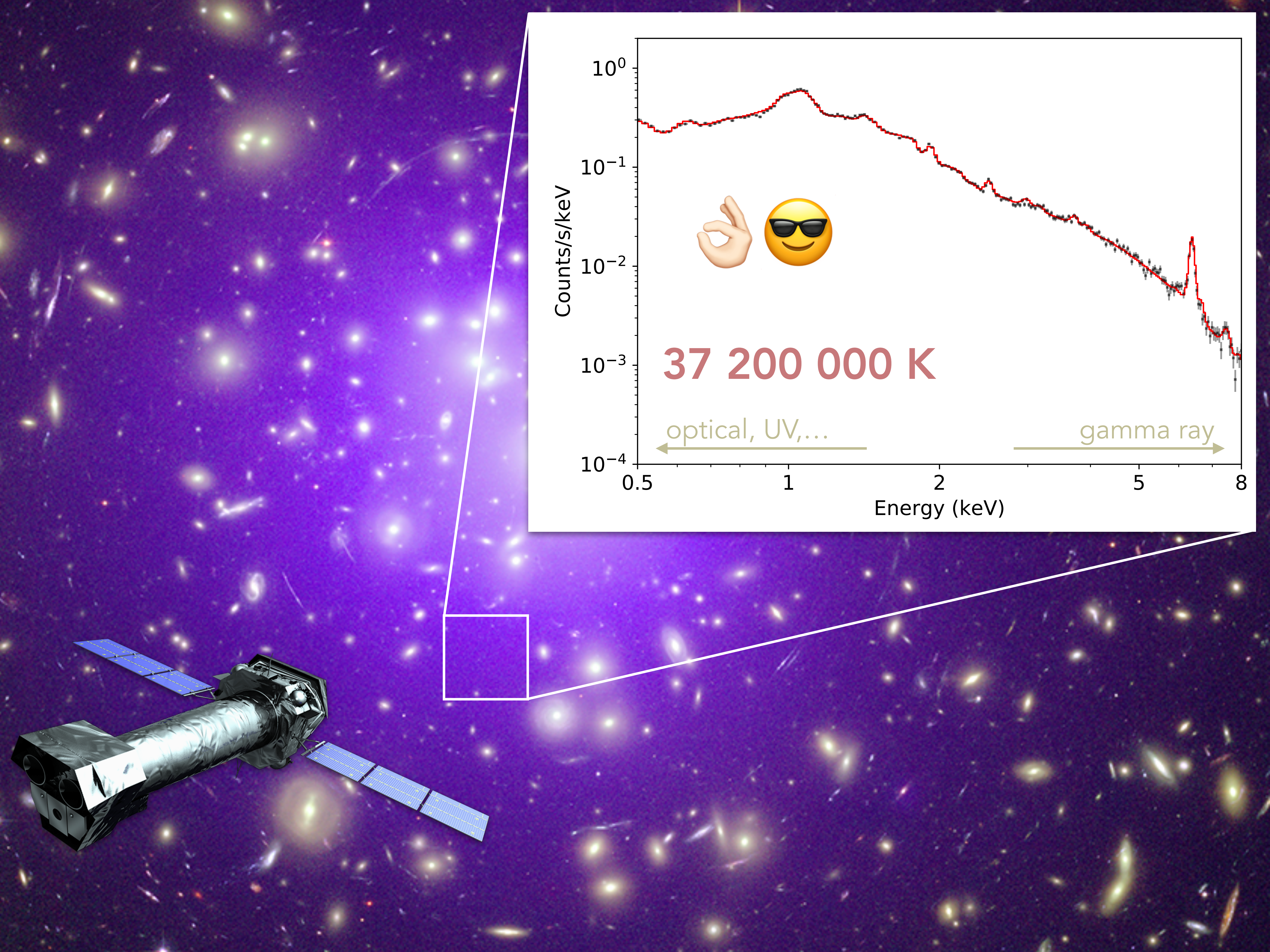
CCD



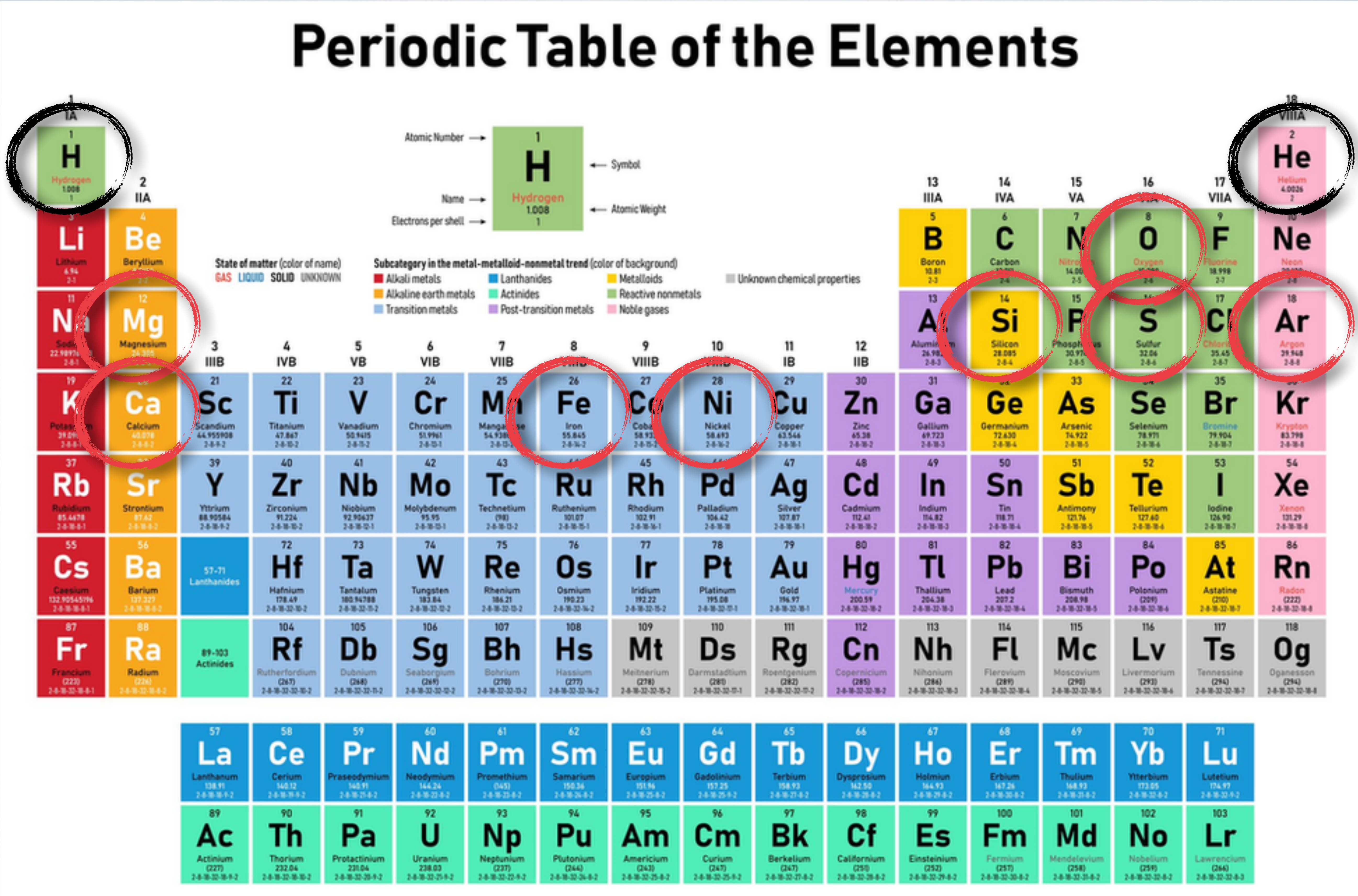
Grating



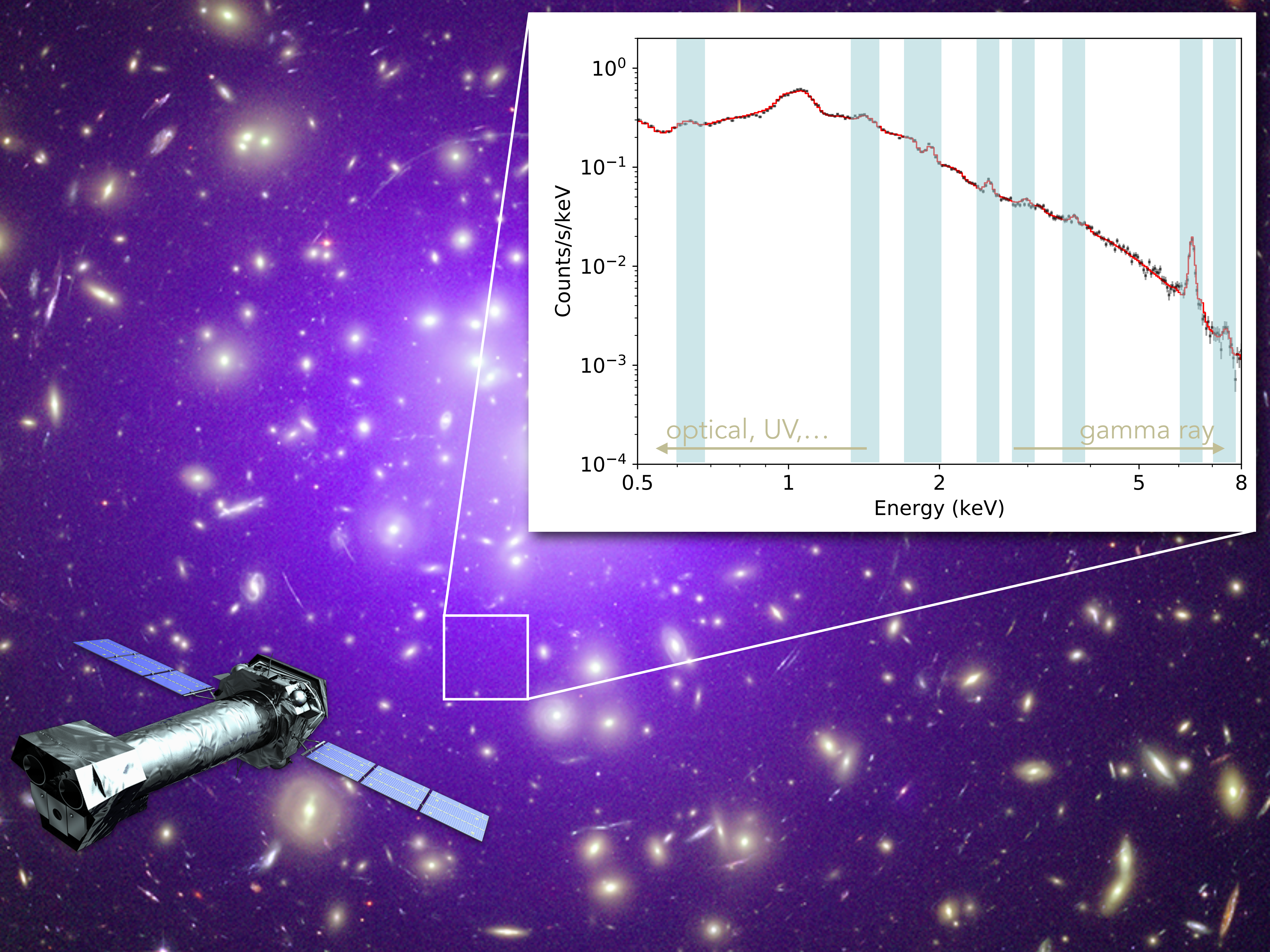
Counts/s/keV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
120 000 000 K
optical, UV,...
gamma ray
0.5
1
2
5
8
Energy (keV)



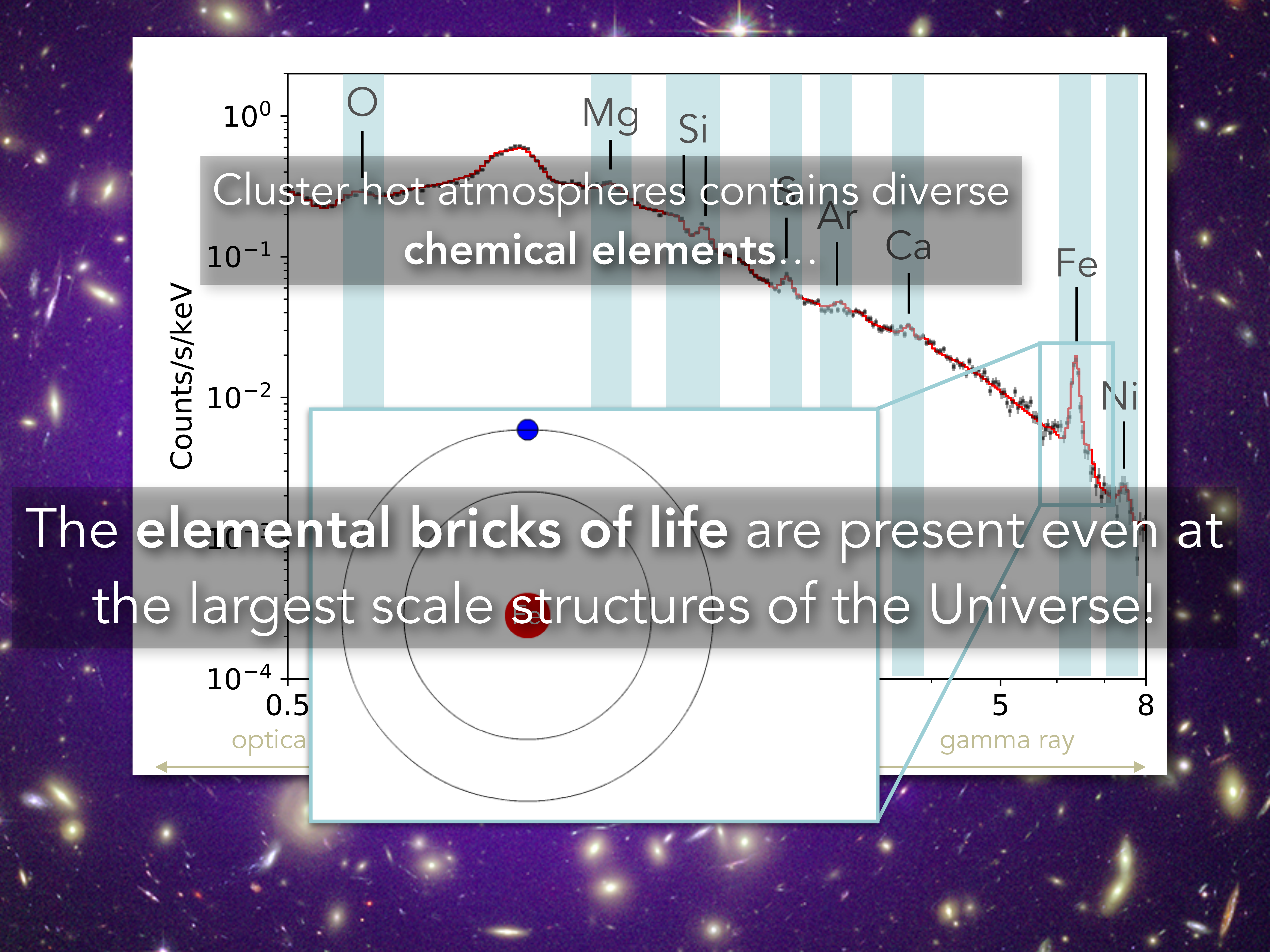
Counts/s/keV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
37 200 000 K
optical, UV,...
gamma ray
0.5
1
2
5
8
Energy (keV)



Periodic Table of the Elements
Atomic Number
Symbol
Name
Atomic Weight
Electrons per shell
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 IIIB
4 IVB
5 VB
6 VIB
7 VIIB
8 VIIIB
9 VIIIB
10 VIIIB
11 IB
12 IIB
13 IIIA
14 IVA
15 VA
16 VIA
17 VIIA
18 VIIIA
1 H Hydrogen
2 He Helium
3 Li Lithium
4 Be Beryllium
5 B Boron
6 C Carbon
7 N Nitrogen
8 O Oxygen
9 F Fluorine
10 Ne Neon
11 Na Sodium
12 Mg Magnesium
13 Al Aluminium
14 Si Silicon
15 P Phosphorus
16 S Sulfur
17 Cl Chlorine
18 Ar Argon
19 K Potassium
20 Ca Calcium
21 Sc Scandium
22 Ti Titanium
23 V Vanadium
24 Cr Chromium
25 Mn Manganese
26 Fe Iron
27 Co Cobalt
28 Ni Nickel
29 Cu Copper
30 Zn Zinc
31 Ga Gallium
32 Ge Germanium
33 As Arsenic
34 Se Selenium
35 Br Bromine
36 Kr Krypton
37 Rb Rubidium
38 Sr Strontium
39 Y Yttrium
40 Zr Zirconium
41 Nb Niobium
42 Mo Molybdenum
43 Tc Technetium
44 Ru Ruthenium
45 Rh Rhodium
46 Pd Palladium
47 Ag Silver
48 Cd Cadmium
49 In Indium
50 Sn Tin
51 Sb Antimony
52 Te Tellurium
53 I Iodine
54 Xe Xenon
55 Cs Caesium
56 Ba Barium
57-71 Lanthanides
72 Hf Hafnium
73 Ta Tantalum
74 W Tungsten
75 Re Rhenium
76 Os Osmium
77 Ir Iridium
78 Pt Platinum
79 Au Gold
80 Hg Mercury
81 Tl Thallium
82 Pb Lead
83 Bi Bismuth
84 Po Polonium
85 At Astatine
86 Rn Radon
87 Fr Francium
88 Ra Radium
89-103 Actinides
104 Rf Rutherfordium
105 Db Dubnium
106 Sg Seaborgium
107 Bh Bohrium
108 Hs Hassium
109 Mt Meitnerium
110 Ds Darmstadtium
111 Rg Roentgenium
112 Cn Copernicium
113 Nh Nihonium
114 Fl Flerovium
115 Mc Moscovium
116 Lv Livermorium
117 Ts Tennessine
118 Og Oganesson
57 La Lanthanum
58 Ce Cerium
59 Pr Praseodymium
60 Nd Neodymium
61 Pm Promethium
62 Sm Samarium
63 Eu Europium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
67 Ho Holmium
68 Er Erbium
69 Tm Thulium
70 Yb Ytterbium
71 Lu Lutetium
89 Ac Actinium
90 Th Thorium
91 Pa Protactinium
92 U Uranium
93 Np Neptunium
94 Pu Plutonium
95 Am Americium
96 Cm Curium
97 Bk Berkelium
98 Cf Californium
99 Es Einsteinium
100 Fm Fermium
101 Md Mendelevium
102 No Nobelium
103 Lr Lawrencium

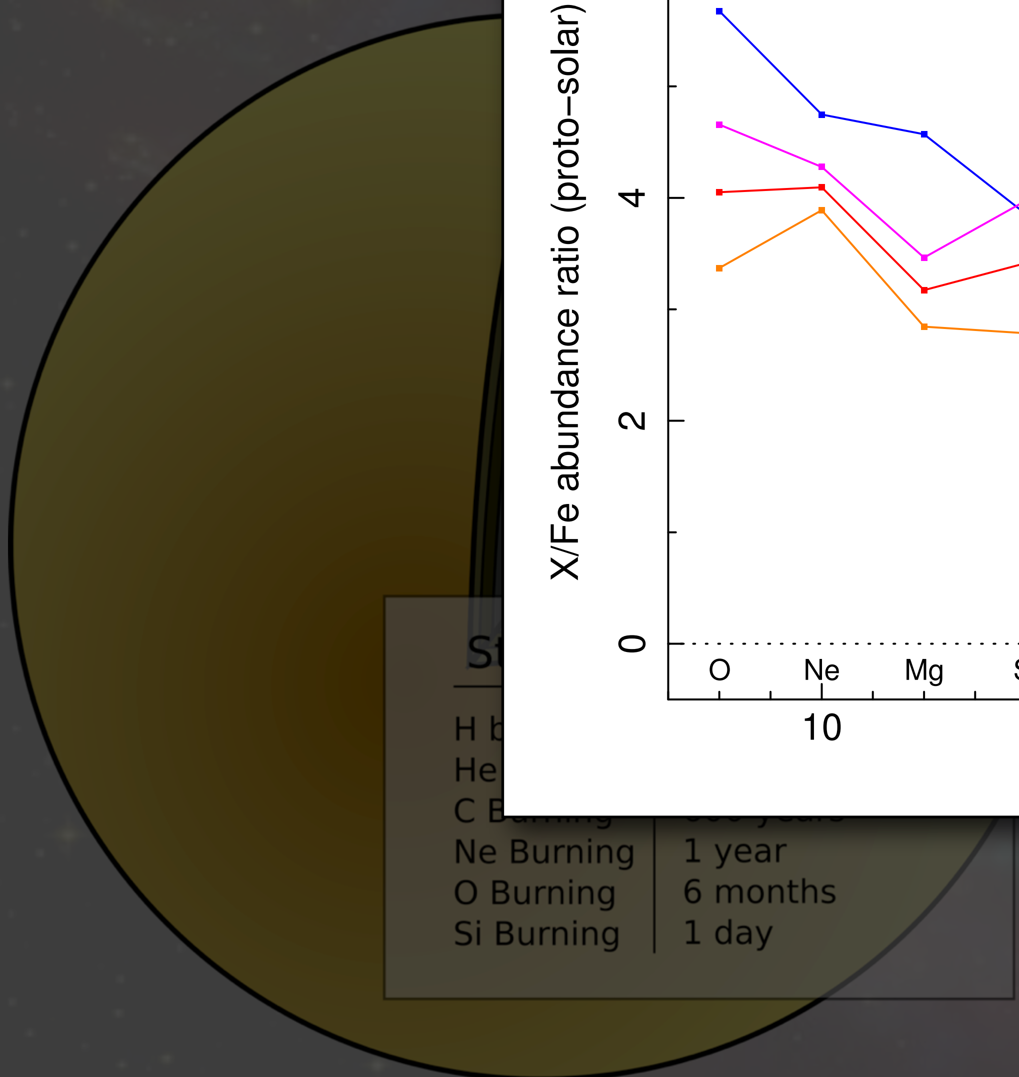


Counts/s/keV
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1
2
5
8
Energy (keV)
optical, UV,...
gamma ray

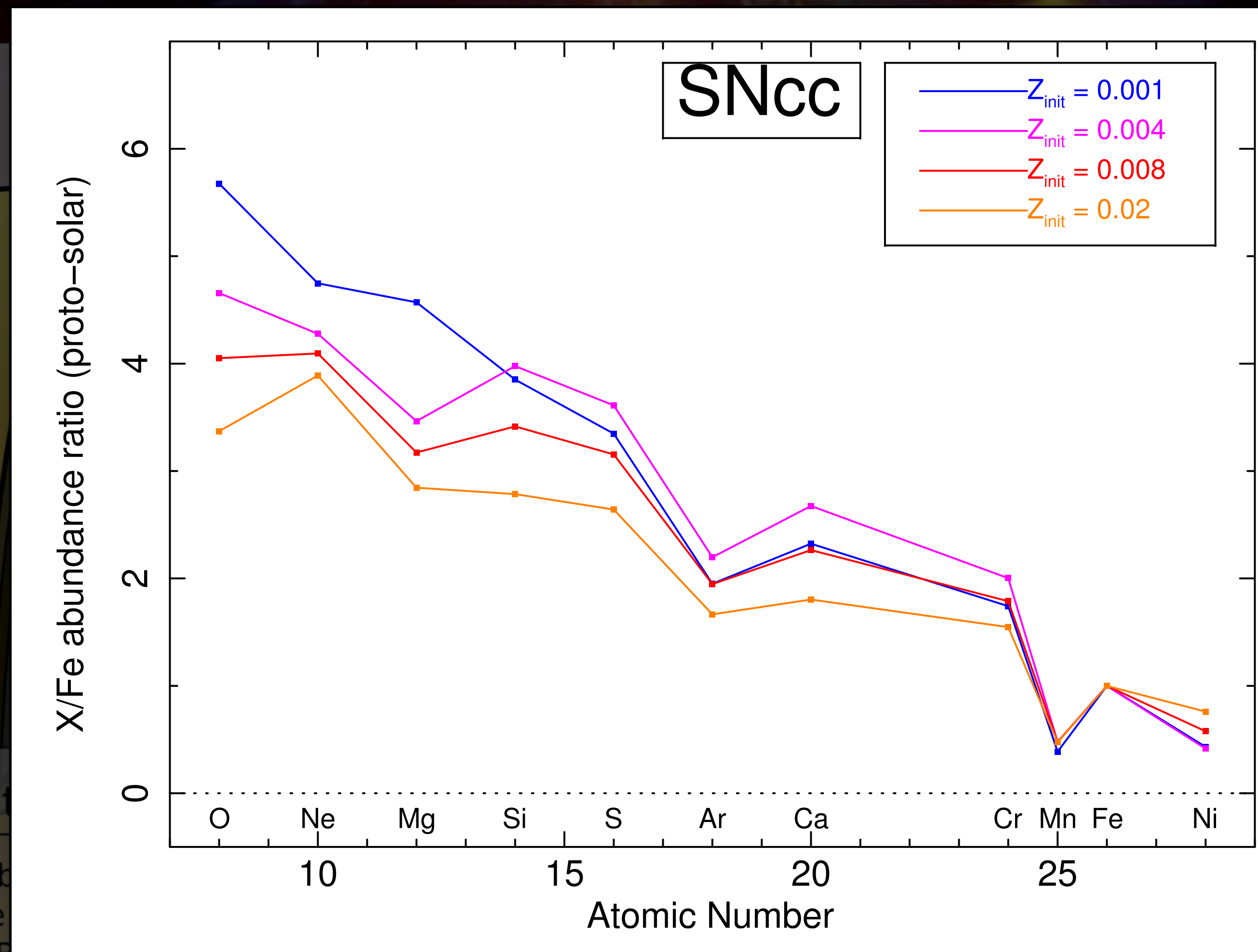


Cluster hot atmospheres contains diverse **chemical elements**…
The **elemental bricks of life** are present even at the largest scale structures of the Universe!
Counts/s/keV
10^{0}
10^{-1}
10^{-2}
10^{-4}
O
Mg
Si
Ar
Ca
Fe
Ni
0.5
5
8
gamma ray

The origin of chemical elements

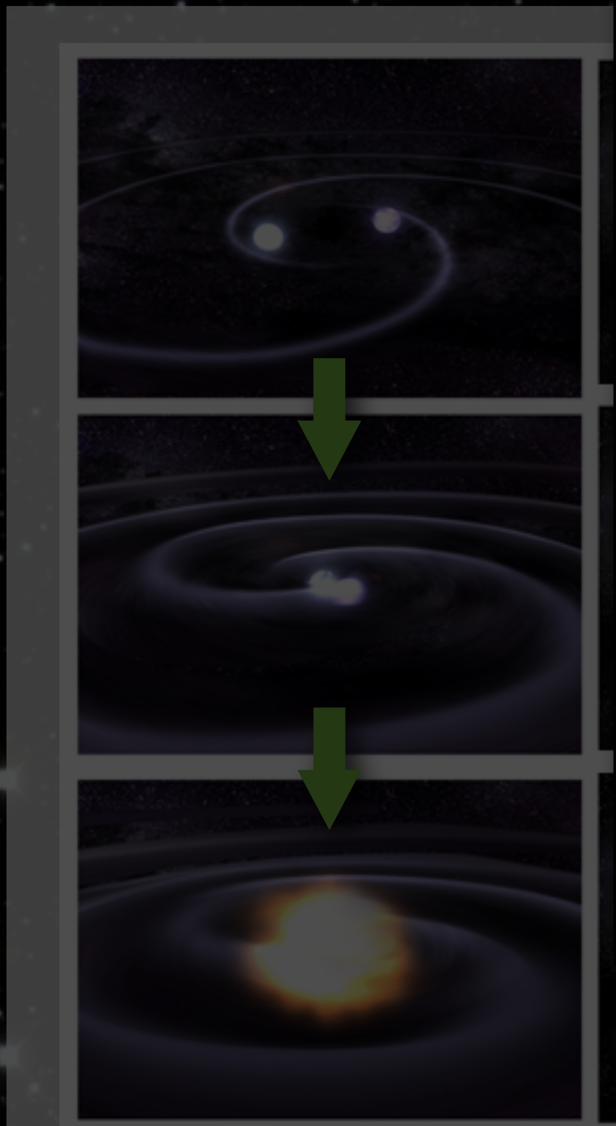


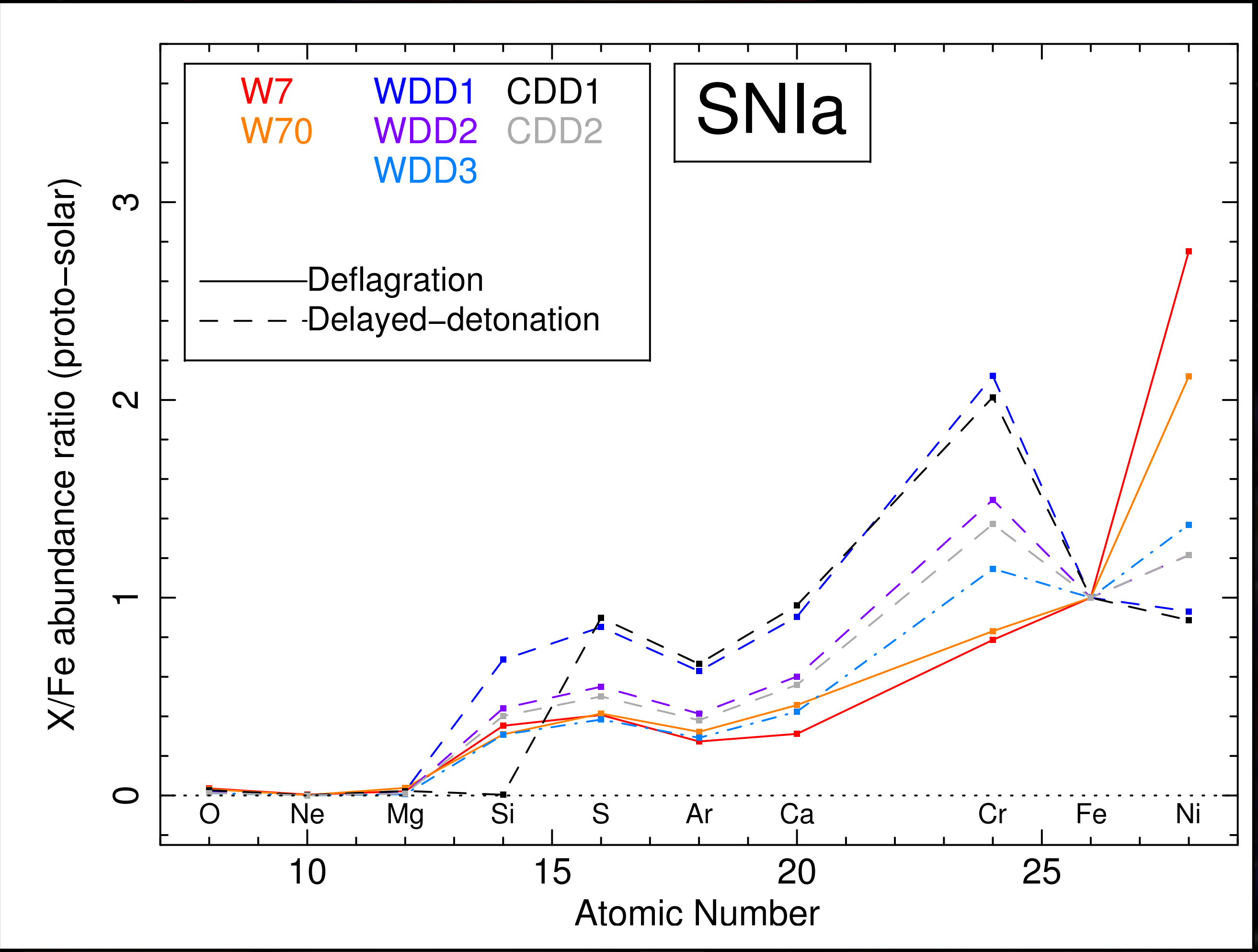
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day



see Nomoto et al. (2013)

The origin of chemical elements

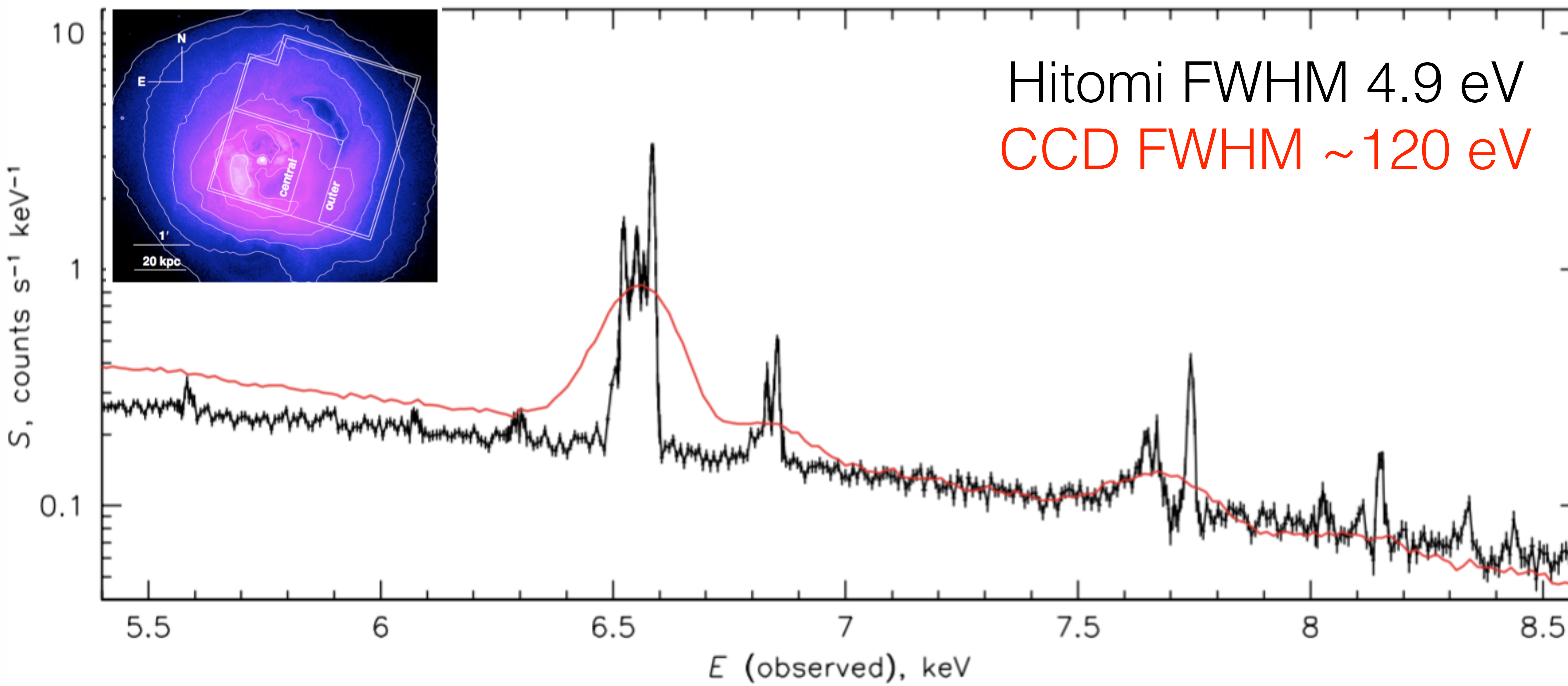




see Iwamoto et al. (1999)

Hitomi (ASTRO-H) Observation

X-ray spectrum of the core of the Perseus cluster



Hitomi collaboration, Nature, 2016

Hitomi (ASTRO-H) Observation

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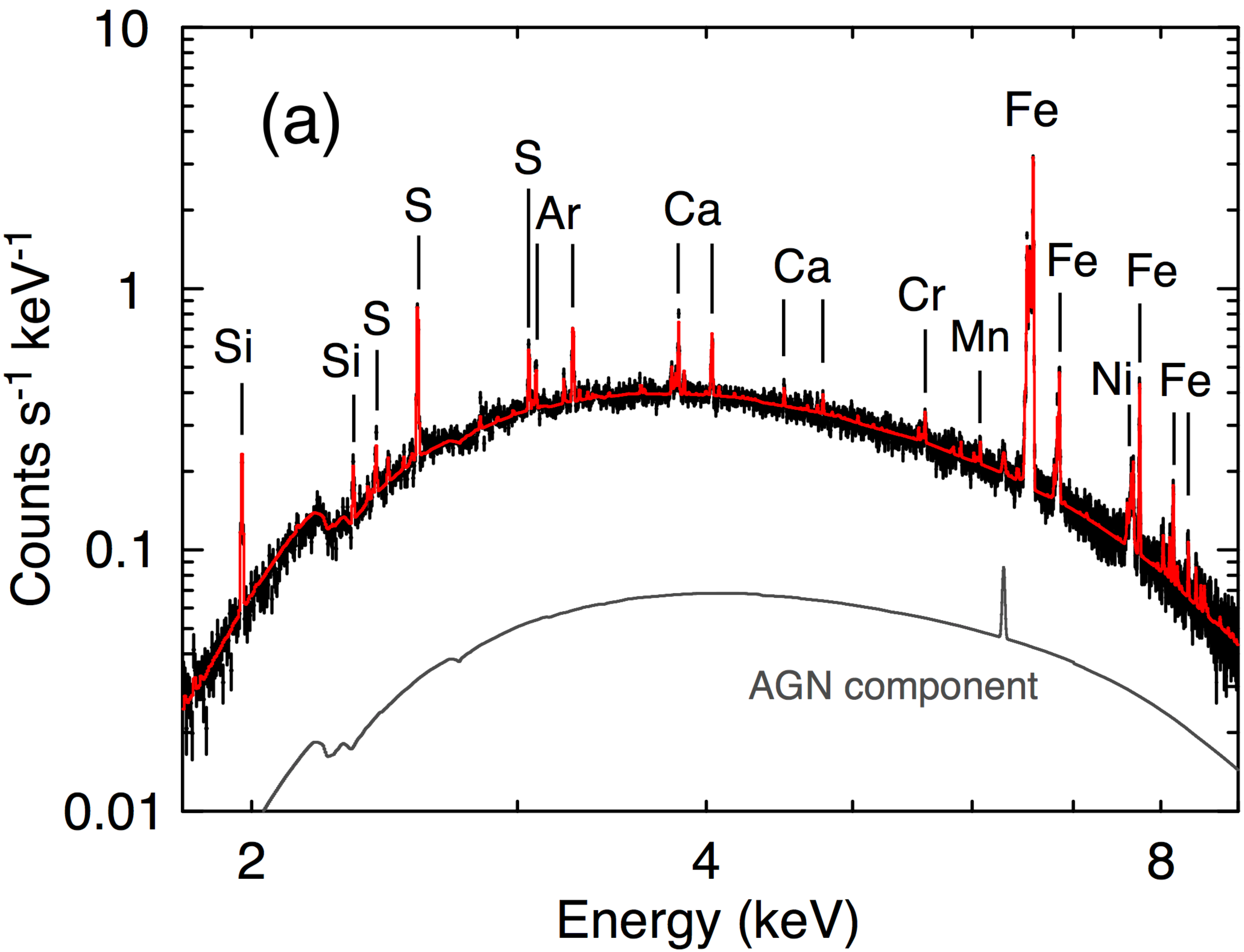
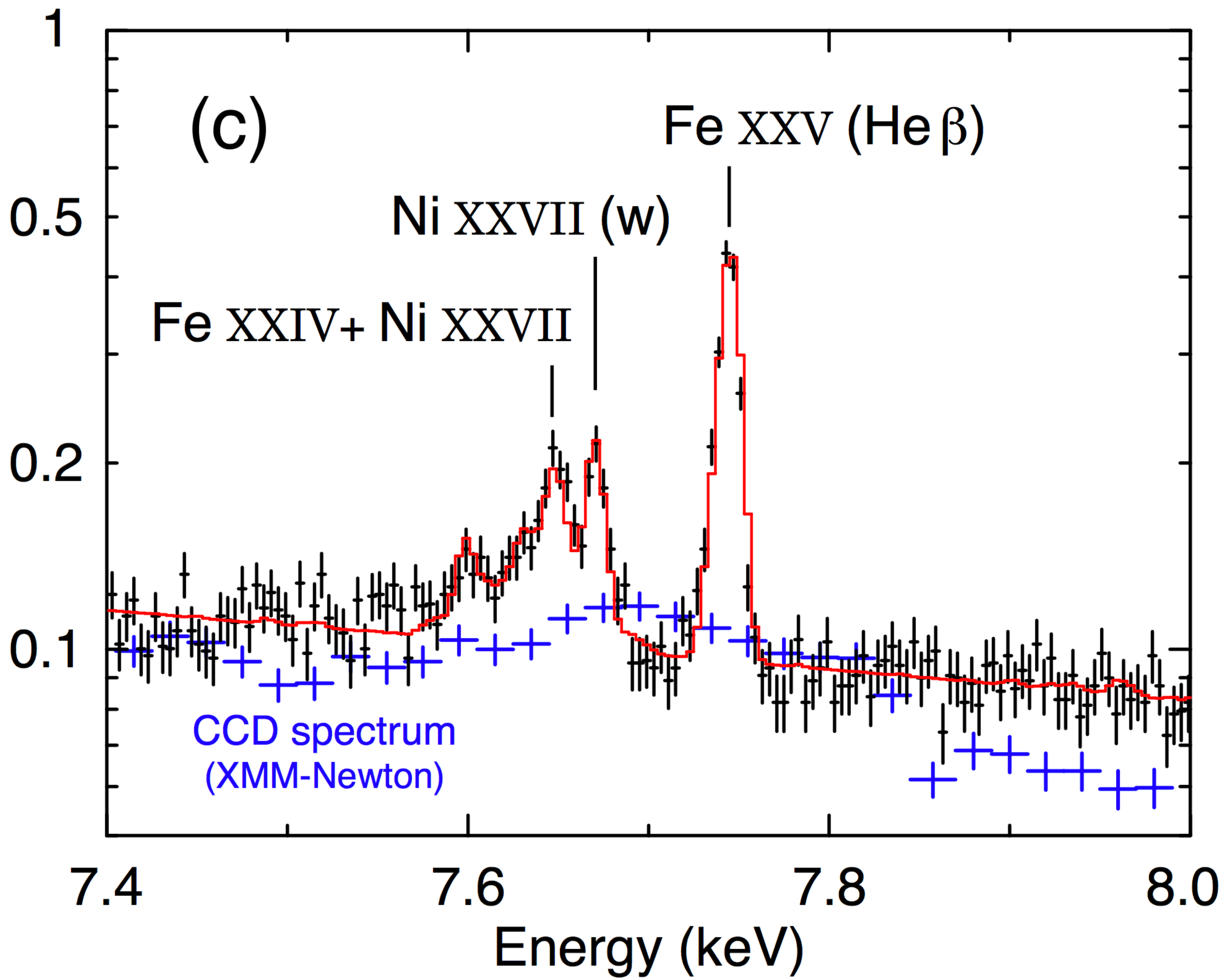


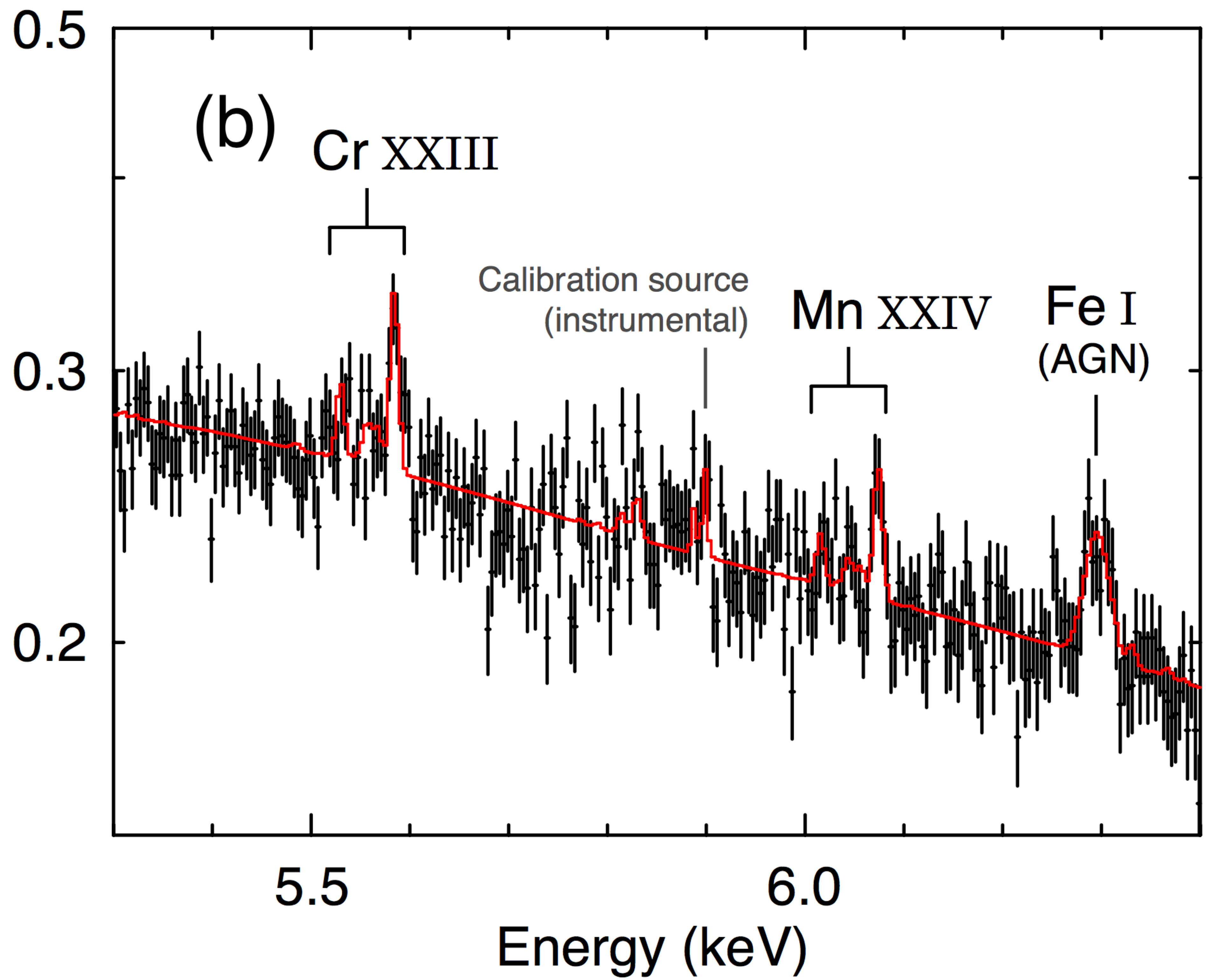
Hitomi collaboration, Nature, 2017

Resolving the Ni lines



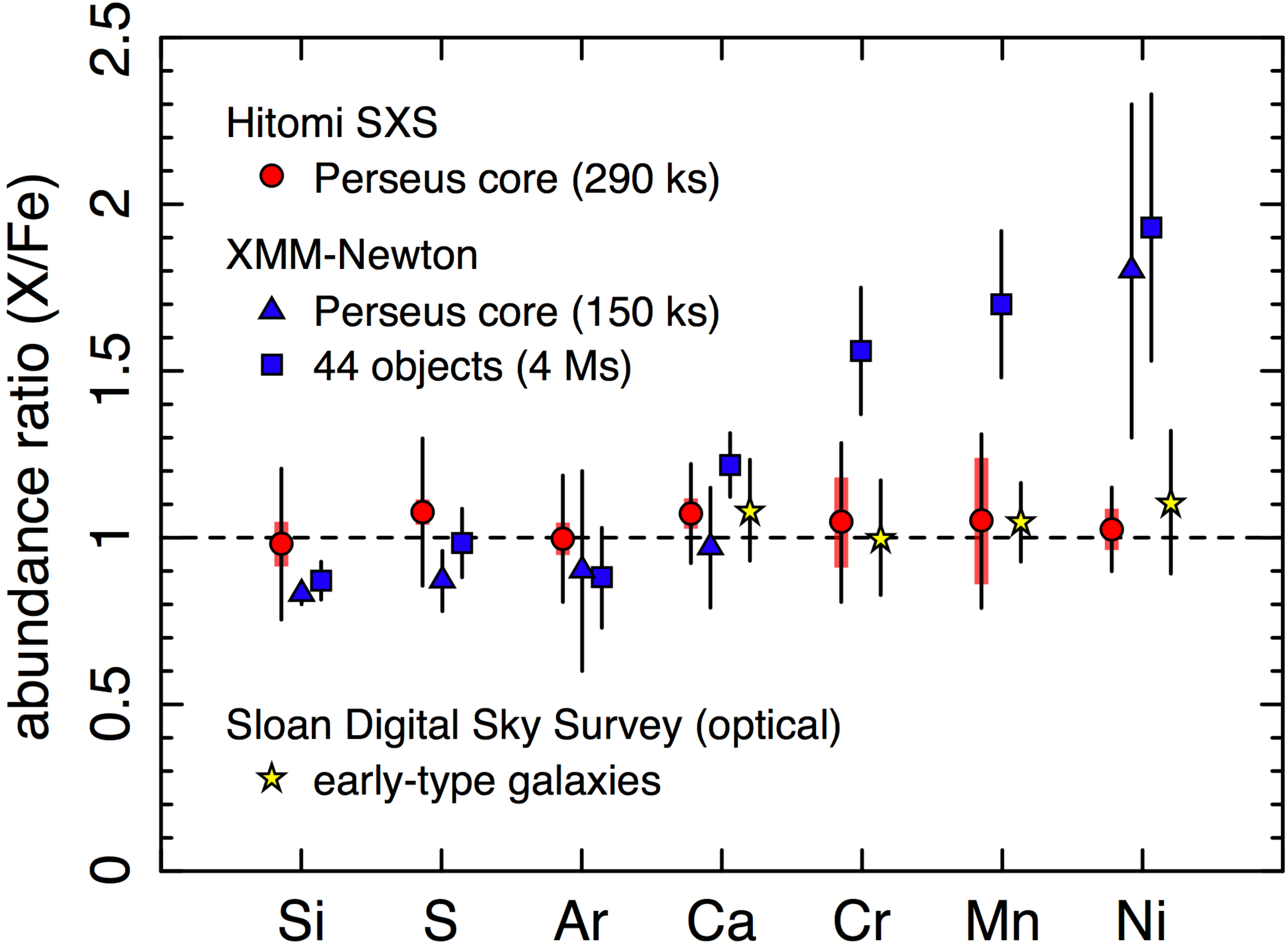
Hitomi collaboration, Nature, 2017

Detecting rare elements



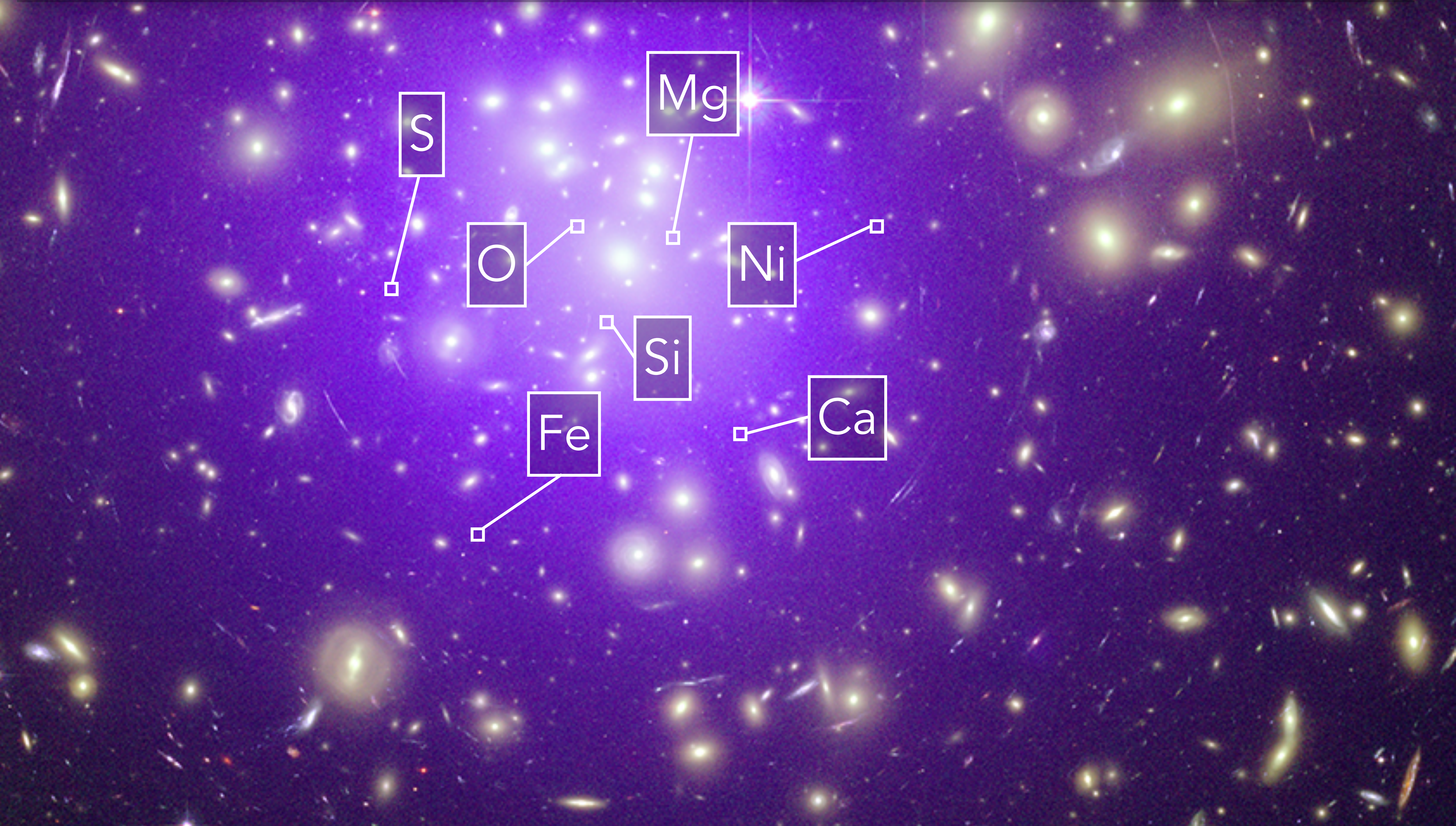
Hitomi collaboration, Nature, 2017

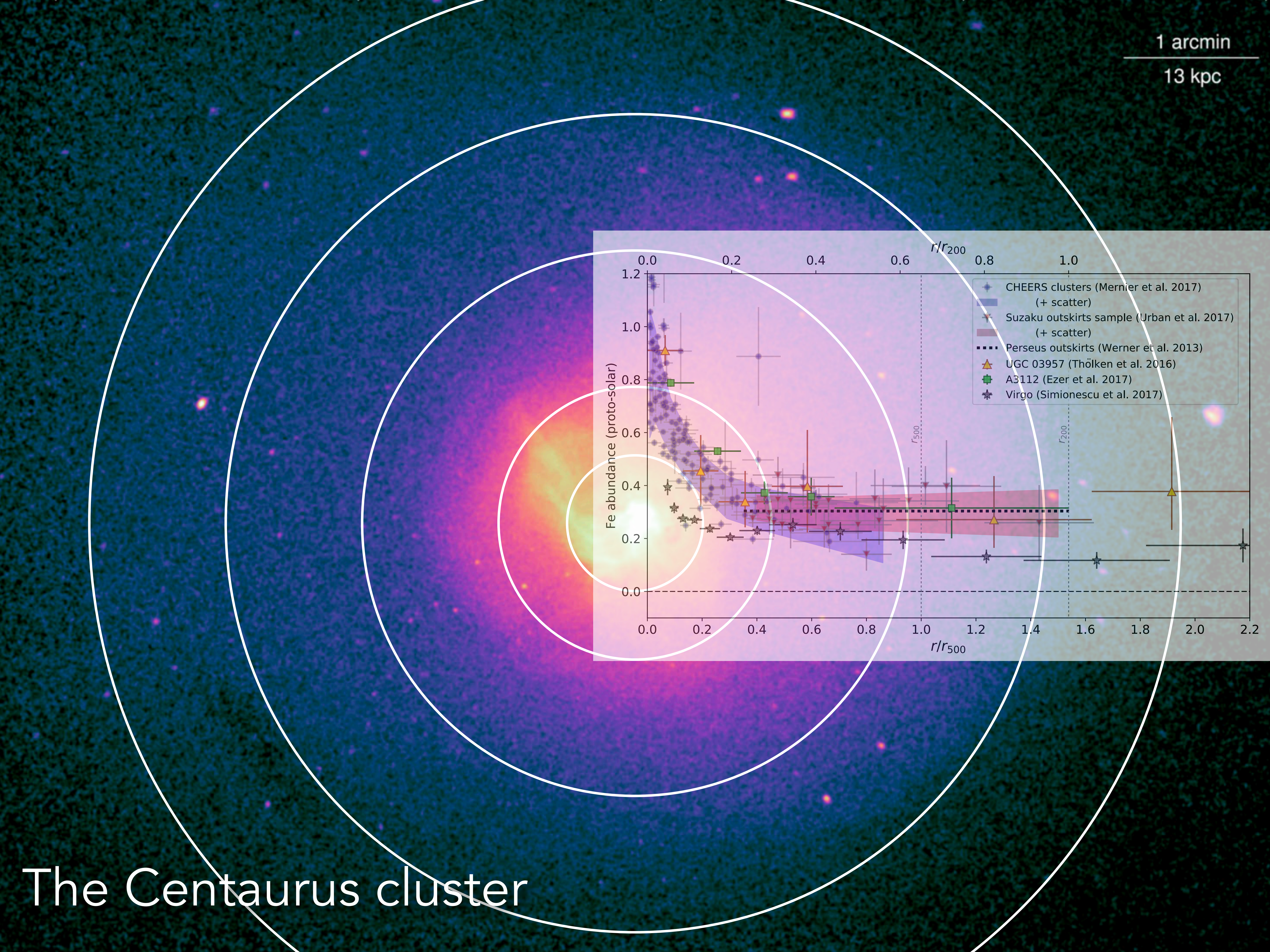
Measured abundance ratios are Solar



Hitomi collaboration, Nature, 2017

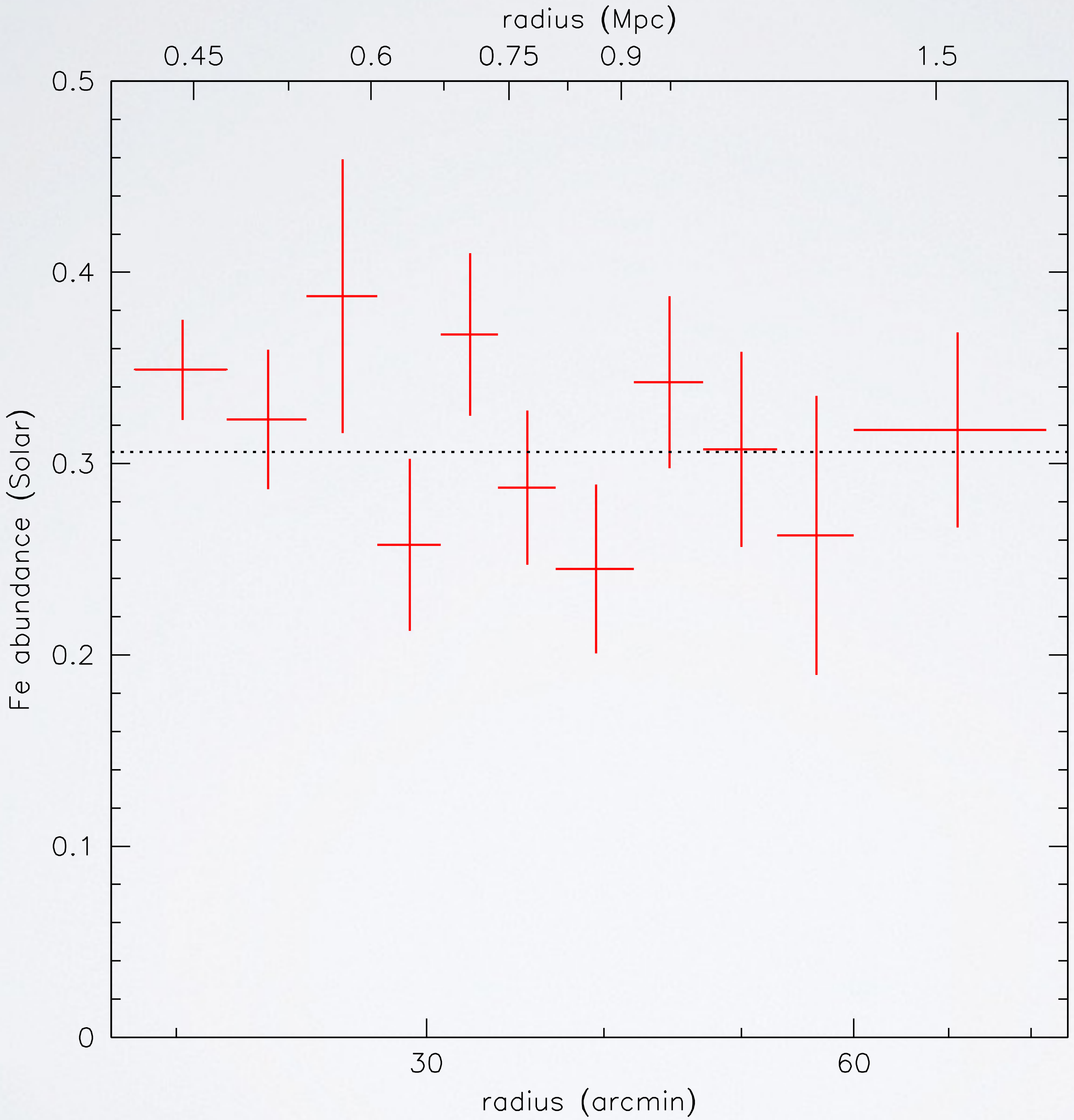
How **and** ***when*** **did exploding stars eject their products outside of their galaxies?**





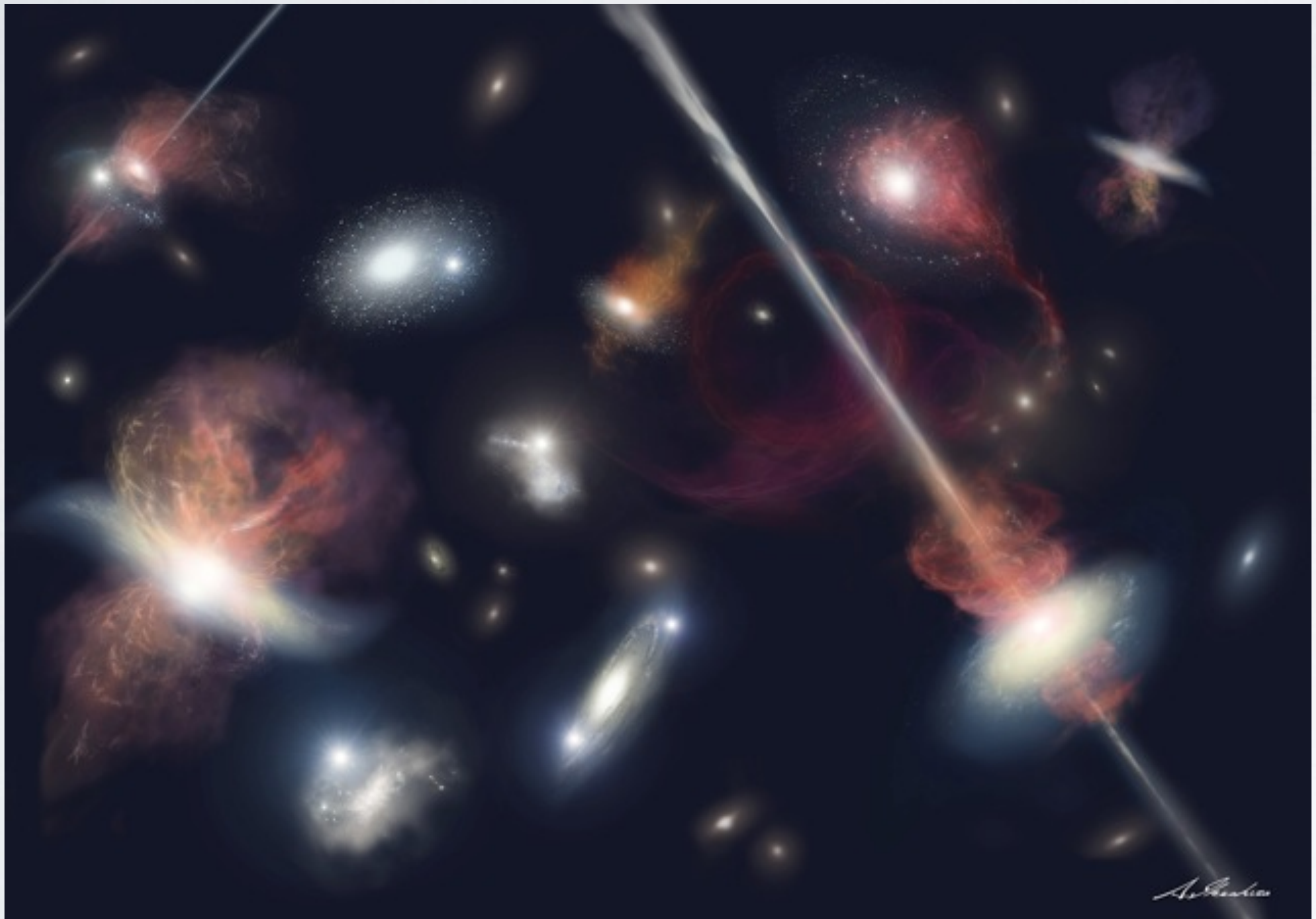
1 arcmin
13 kpc
r/r200
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Fe abundance (proto-solar)
CHEERS clusters (Mernier et al. 2017)
(+ scatter)
Suzaku outskirts sample (Urban et al. 2017)
(+ scatter)
Perseus outskirts (Werner et al. 2013)
UGC 03957 (Thölken et al. 2016)
A3112 (Ezer et al. 2017)
Virgo (Simionescu et al. 2017)
r500
r200
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
r/r500
The Centaurus cluster

METALLICITY PROFILE OF THE PERSEUS CLUSTER

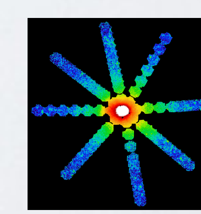


Werner et al. 2013

THE TURBULENT YOUNG UNIVERSE



- 10-12 billion years ago galaxies formed stars at very high rates, resulting in many supernova explosions
- at the same time, black holes grew fast by accreting matter
- combined energy of these processes produced winds blowing material out of galaxies



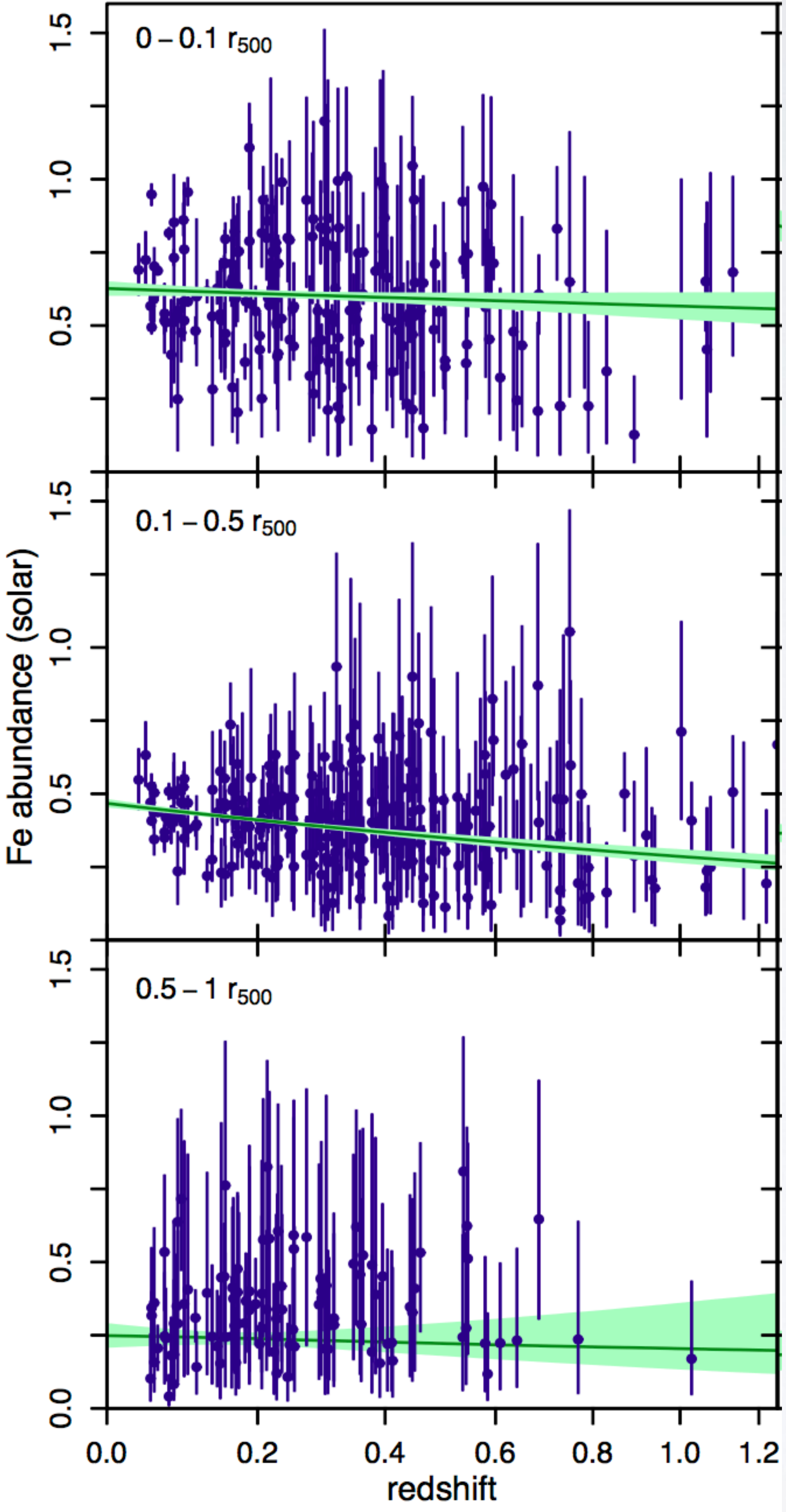
in billions of years

-13.8 | -12 | -10 | -8 | -6 | -4 | -2

Big Bang

galactic winds

clusters form

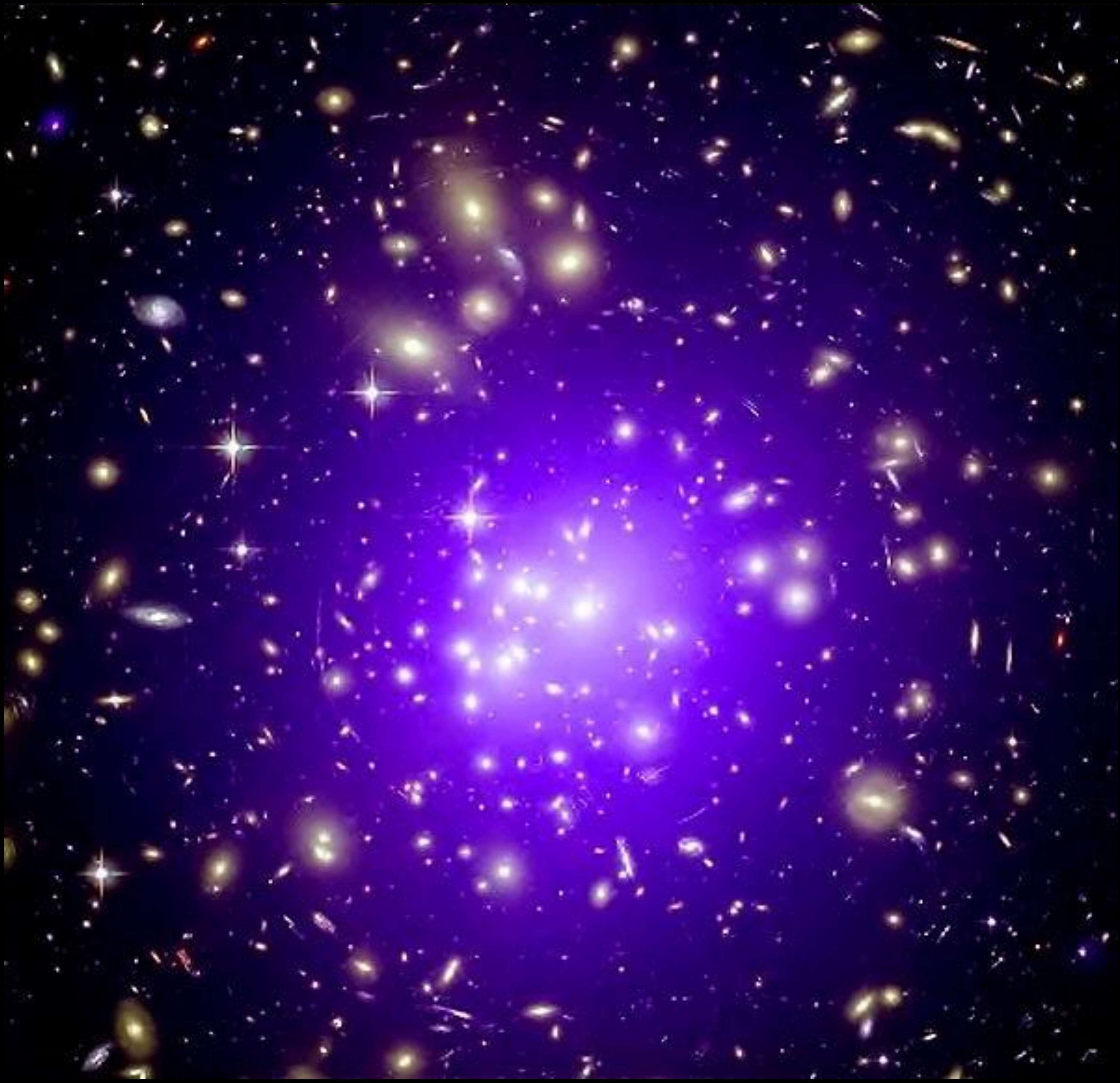


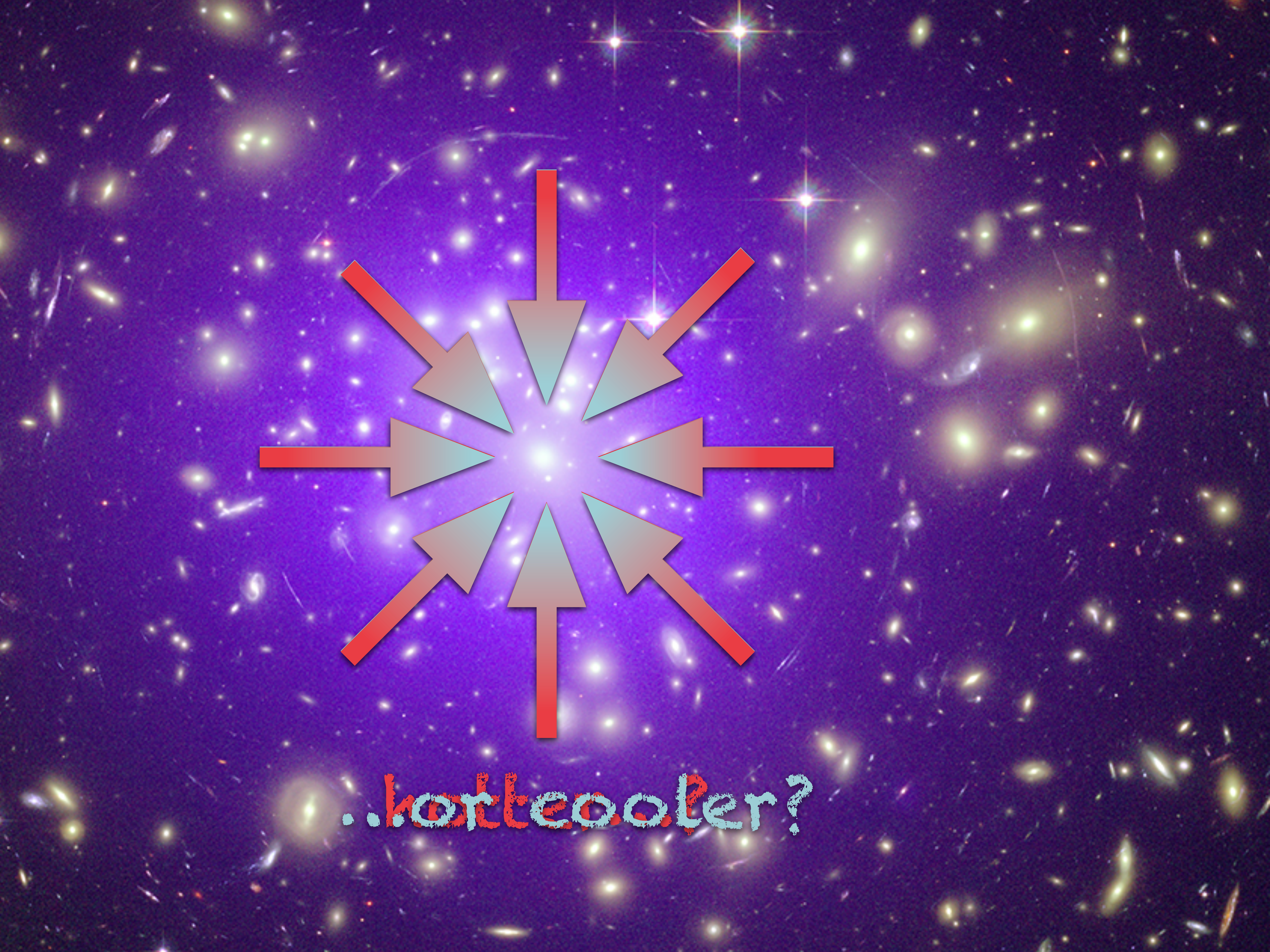
REDSHIFT EVOLUTION OF METALS

- Large scatter but no evolution in the core
- No evolution in the outskirts
- Evolution at intermediate radii, where mixing with the core might be gradually increasing the metallicity

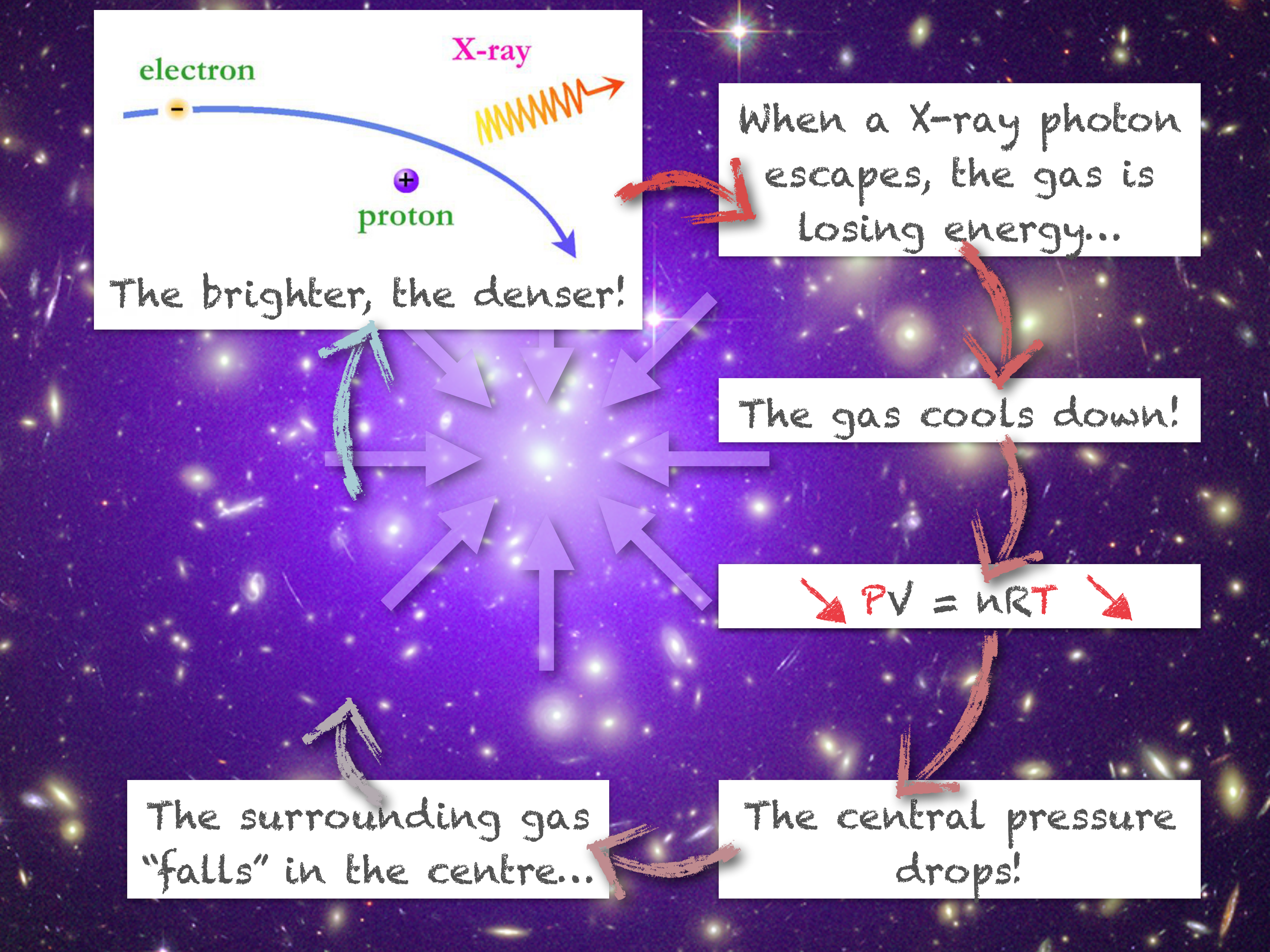
Mantz et al. 2017

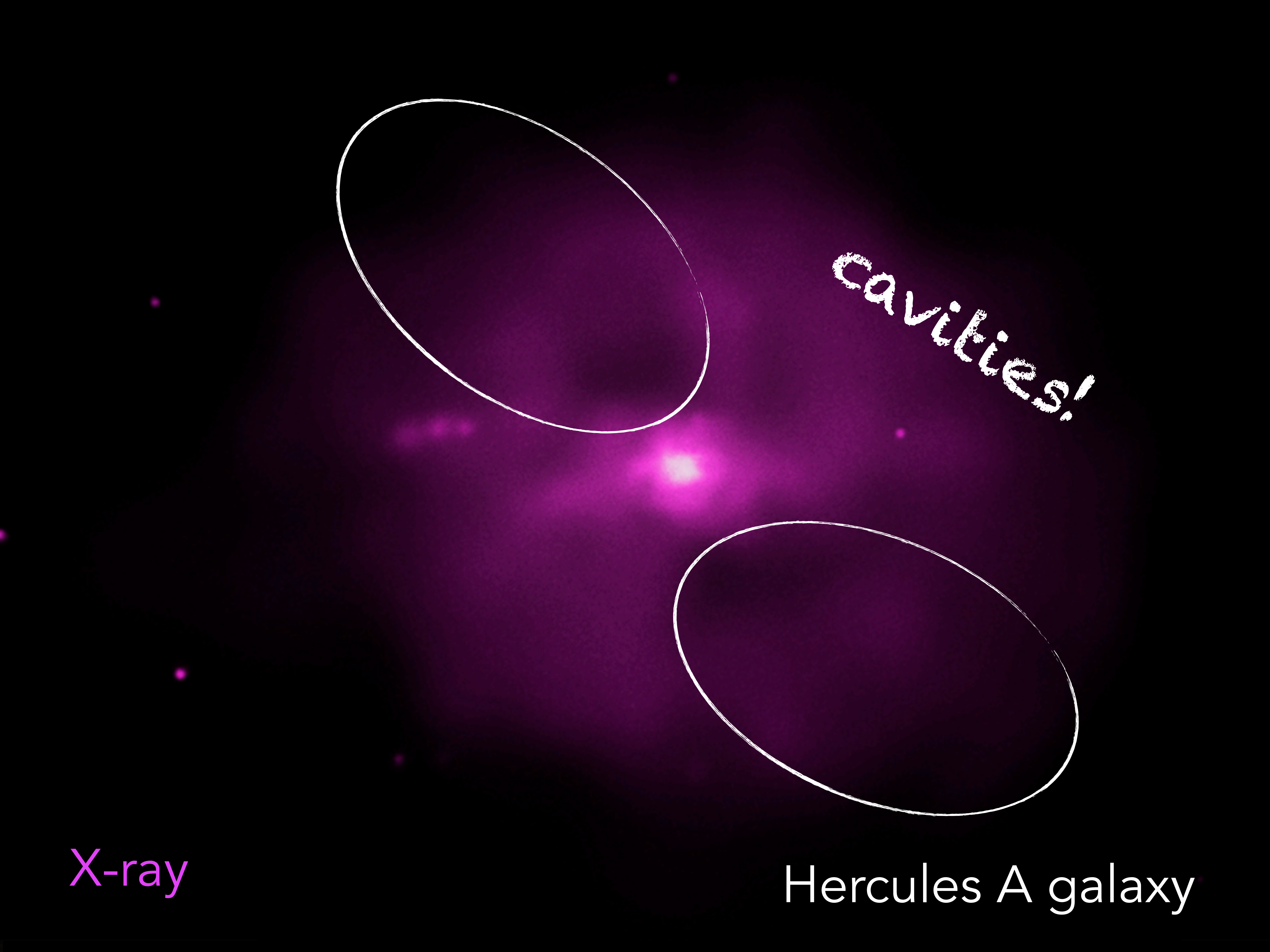
GALACTIC WINDS AND AGN OUTFLOWS WERE THE SPOON MIXING THE METALS

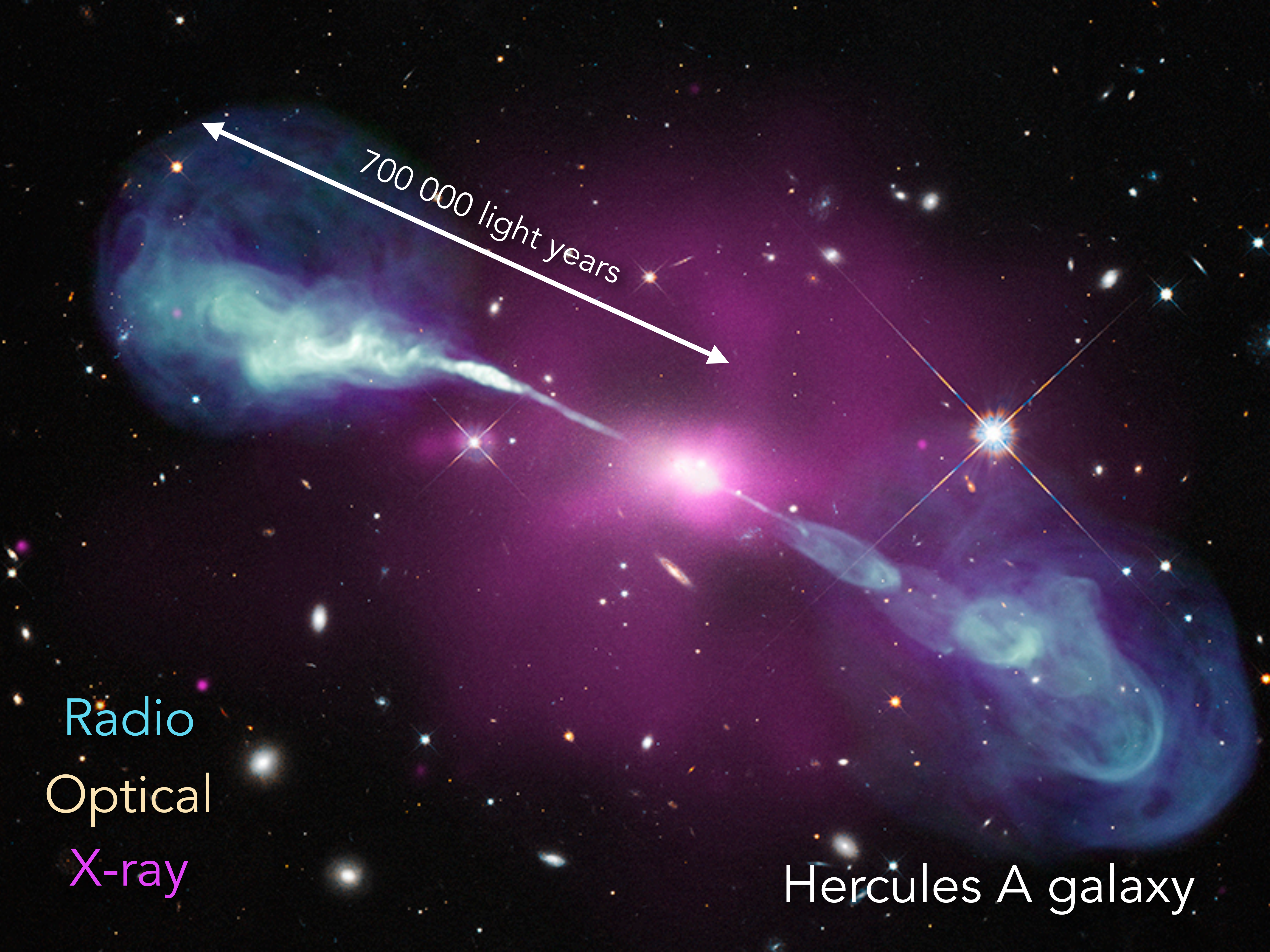


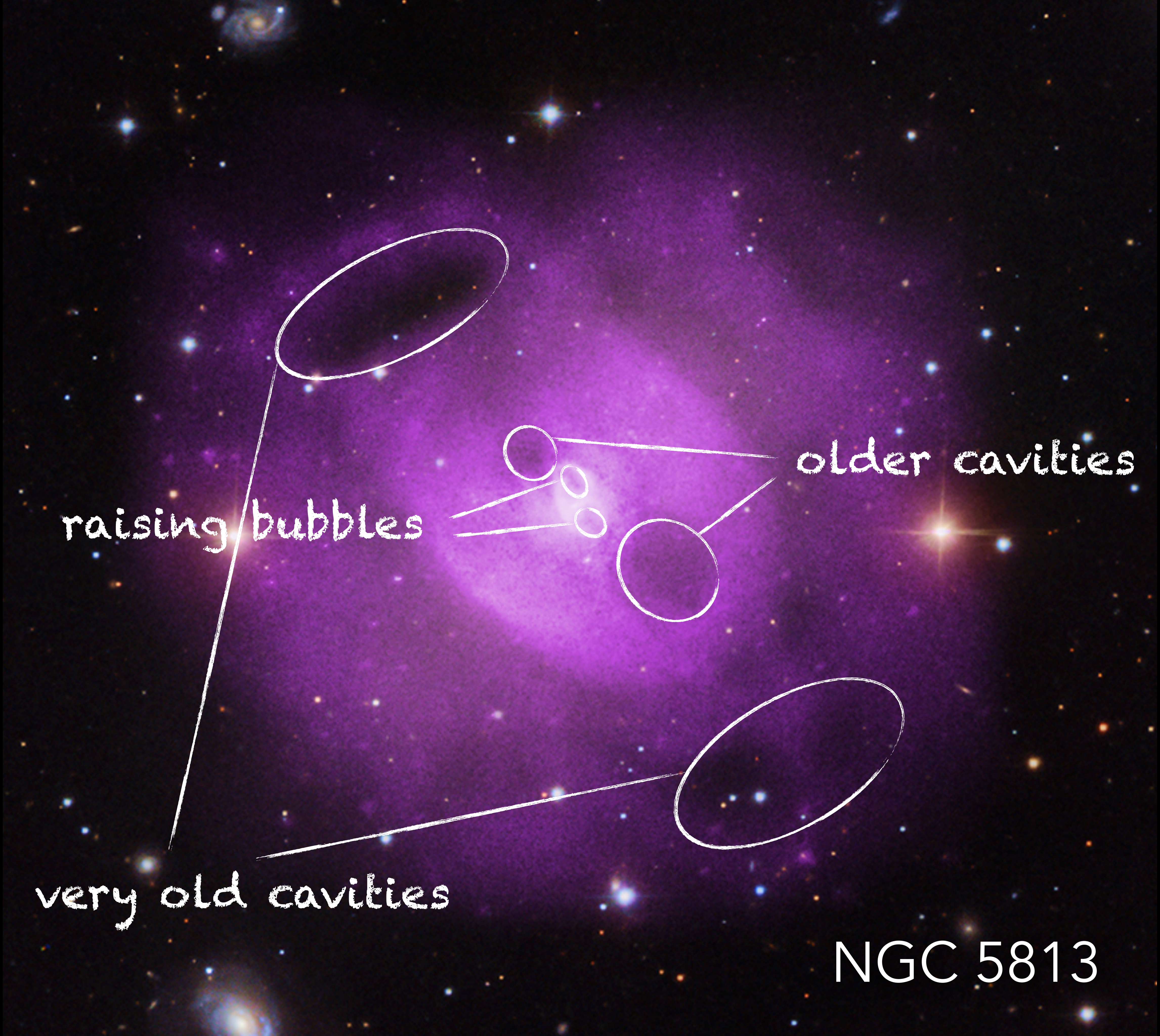


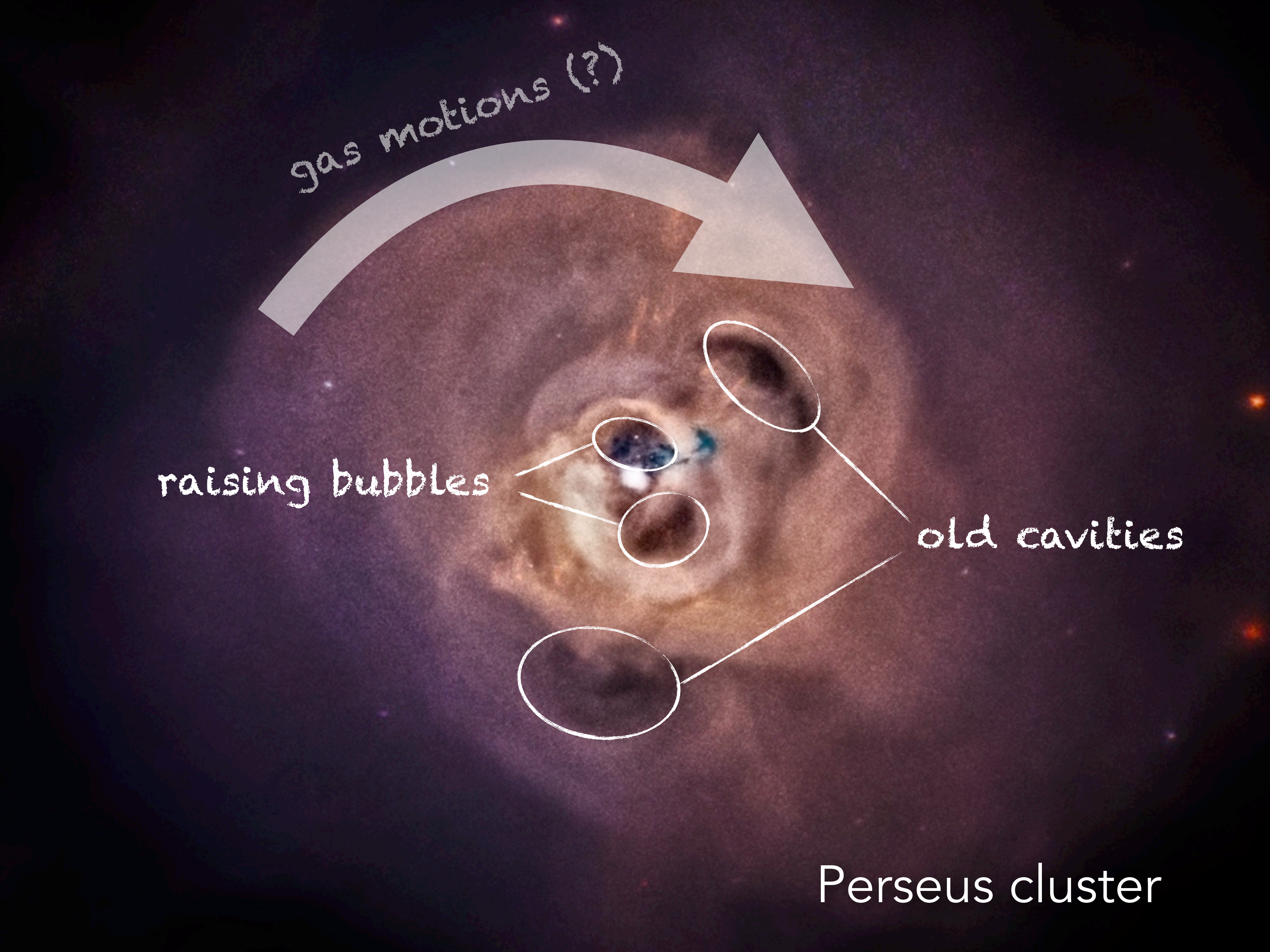
..hotter
..cooler?


electron
X-ray
proton
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...

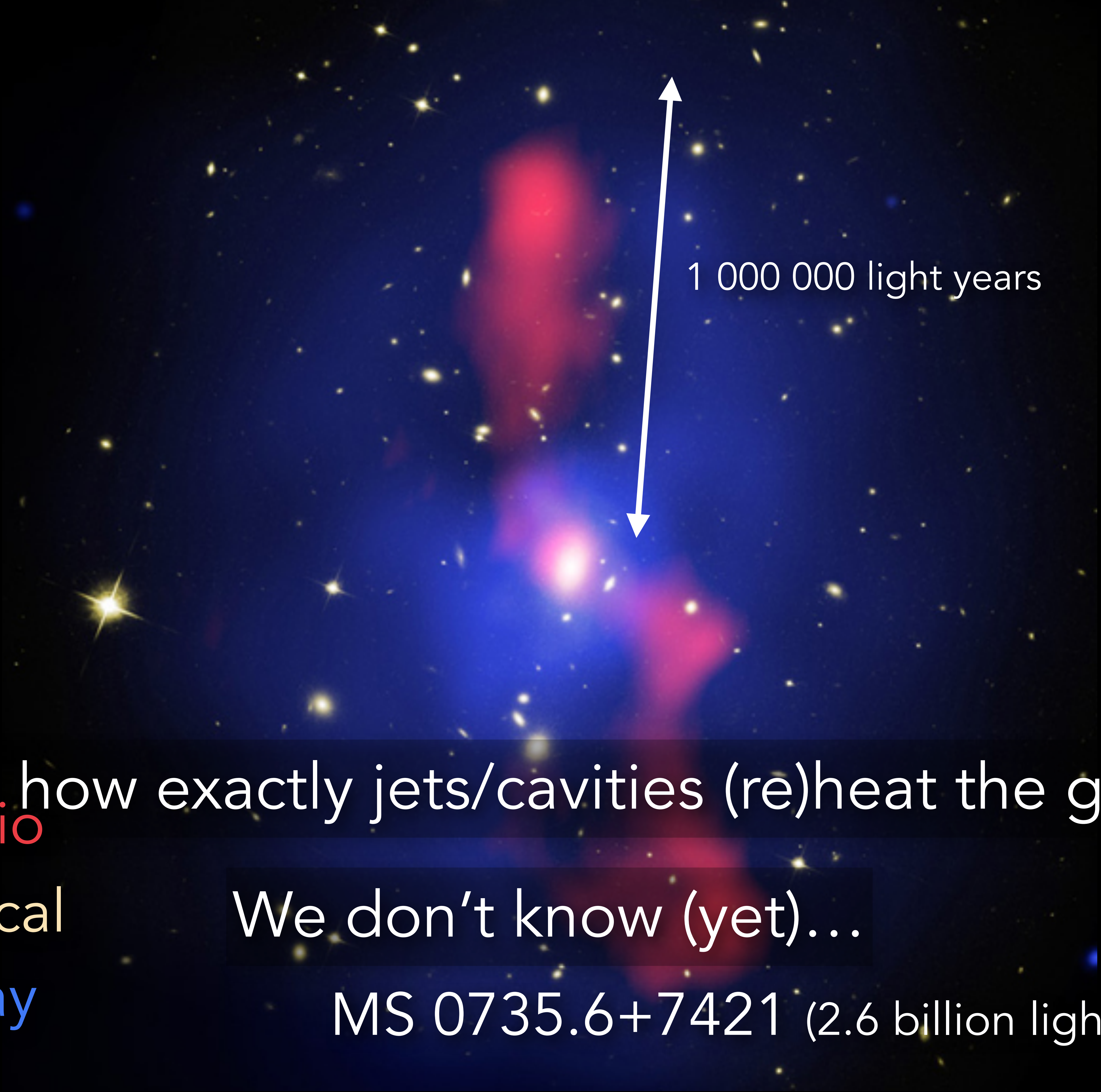

cavities!
X-ray
Hercules A galaxy


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


older cavities
raising bubbles
very old cavities
NGC 5813

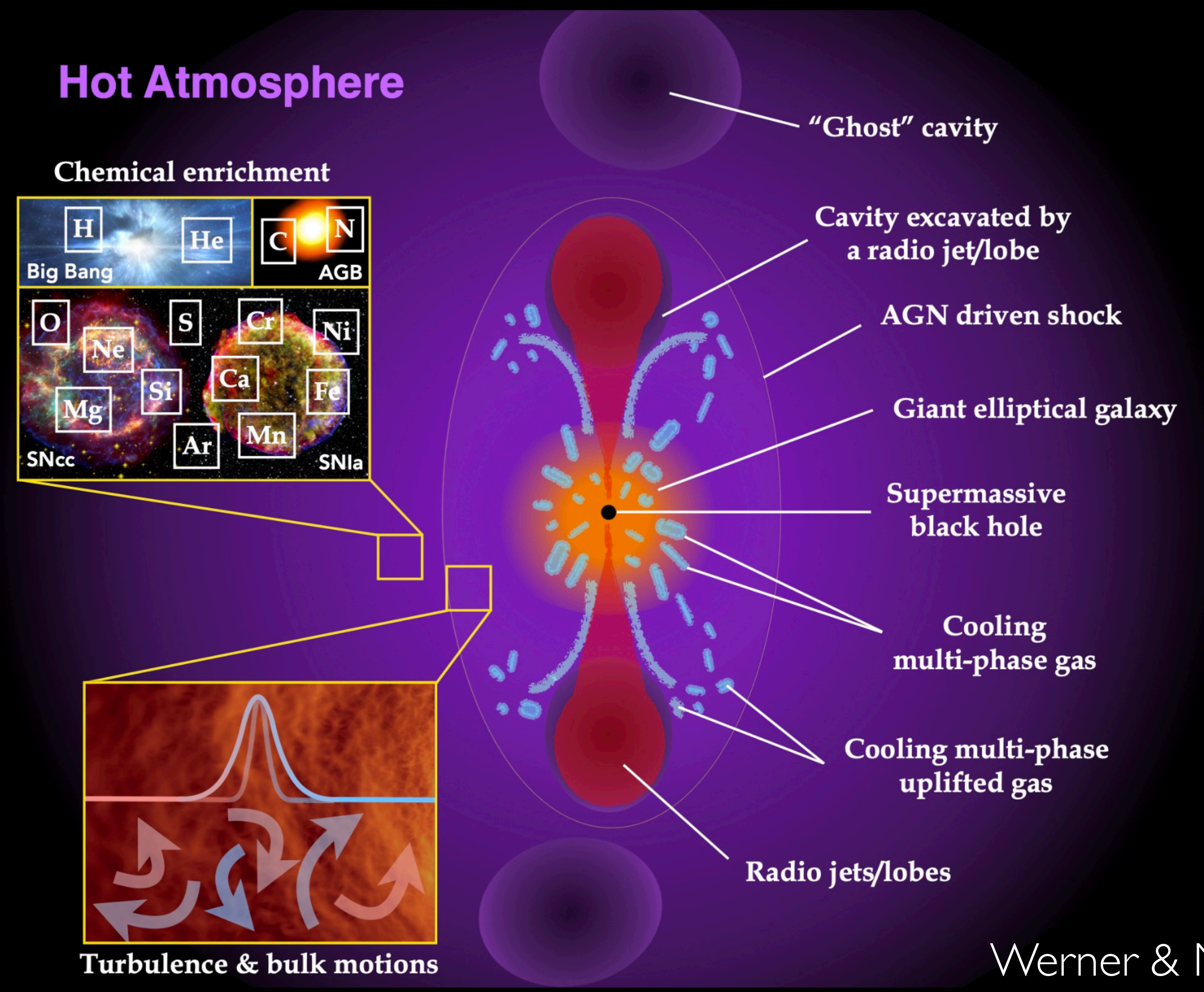

gas motions (?)
raising bubbles
old cavities
Perseus cluster


cavities!
Radio
Optical
X-ray
MS 0735.6+7421 (2.6 billion light years)

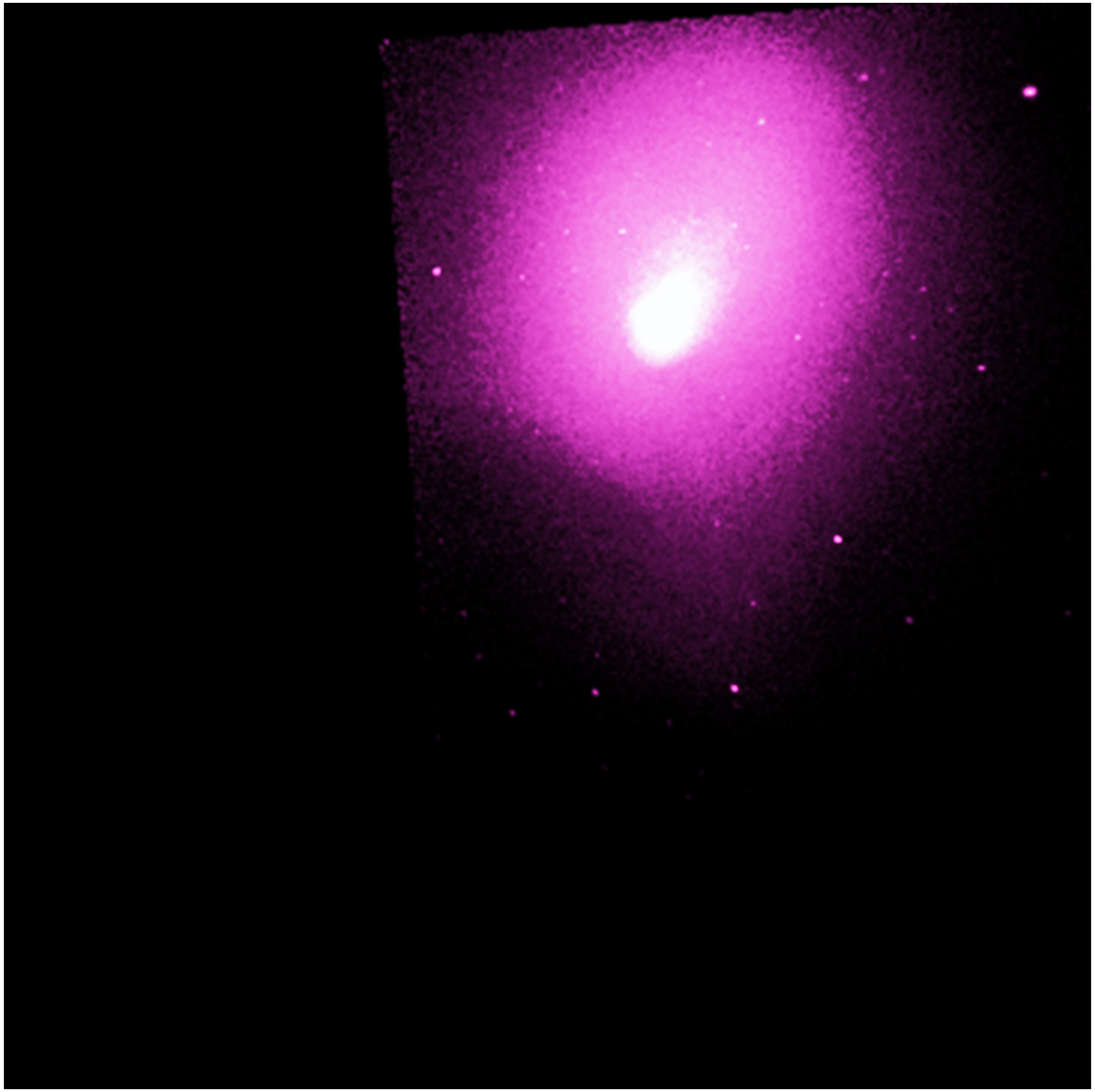


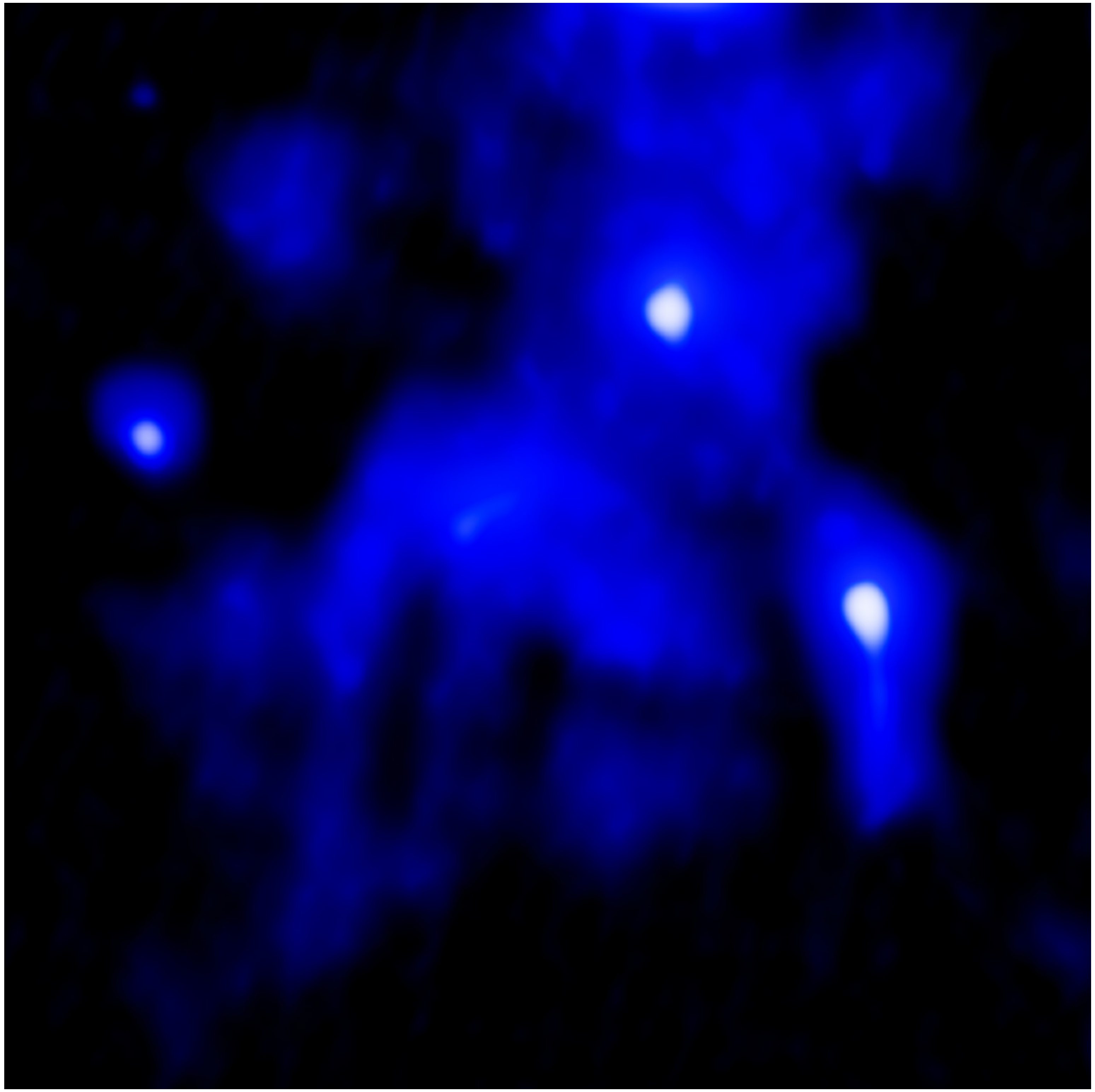
But how exactly jets/cavities (re)heat the gas?

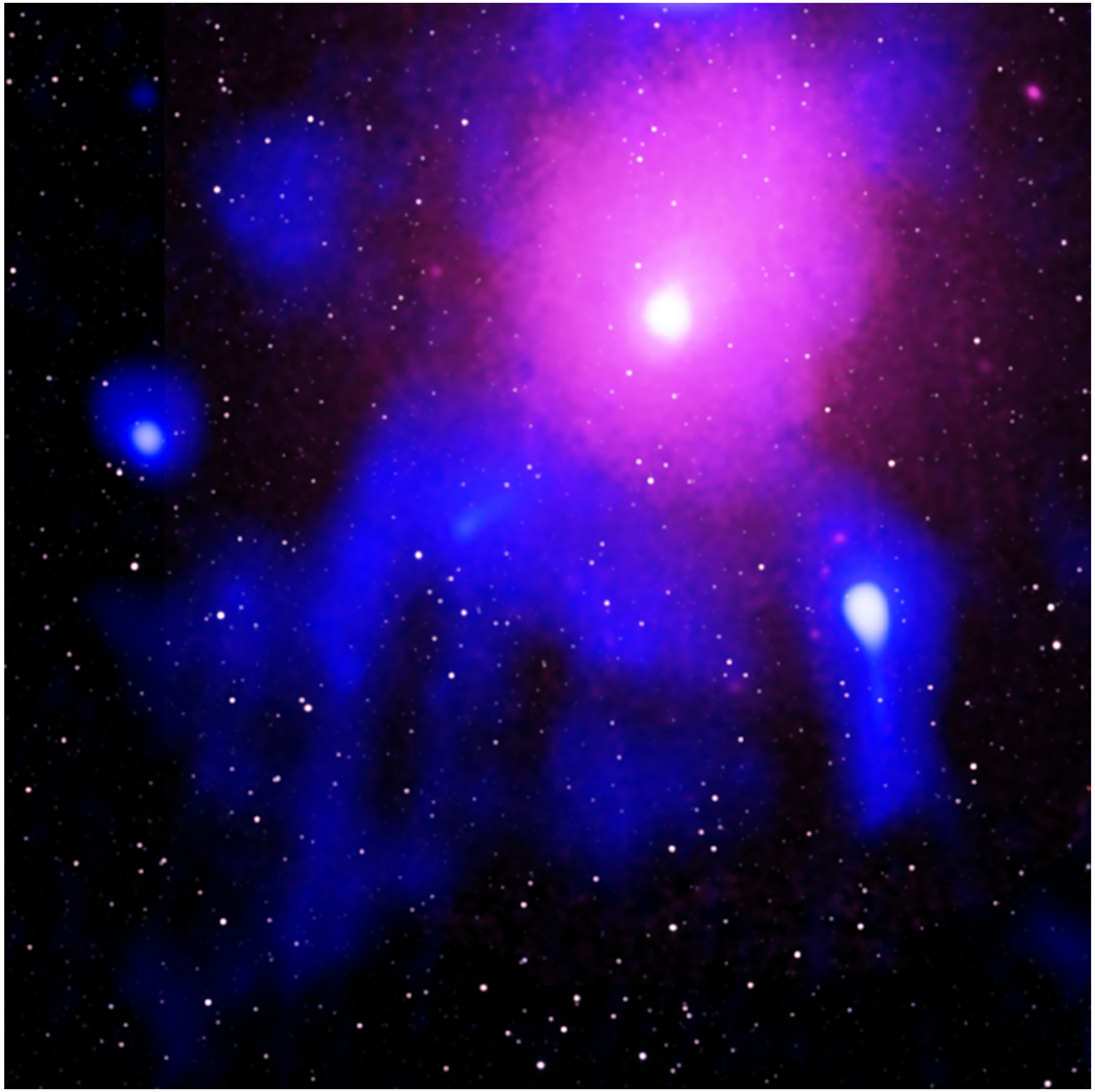
We don’t know (yet)…

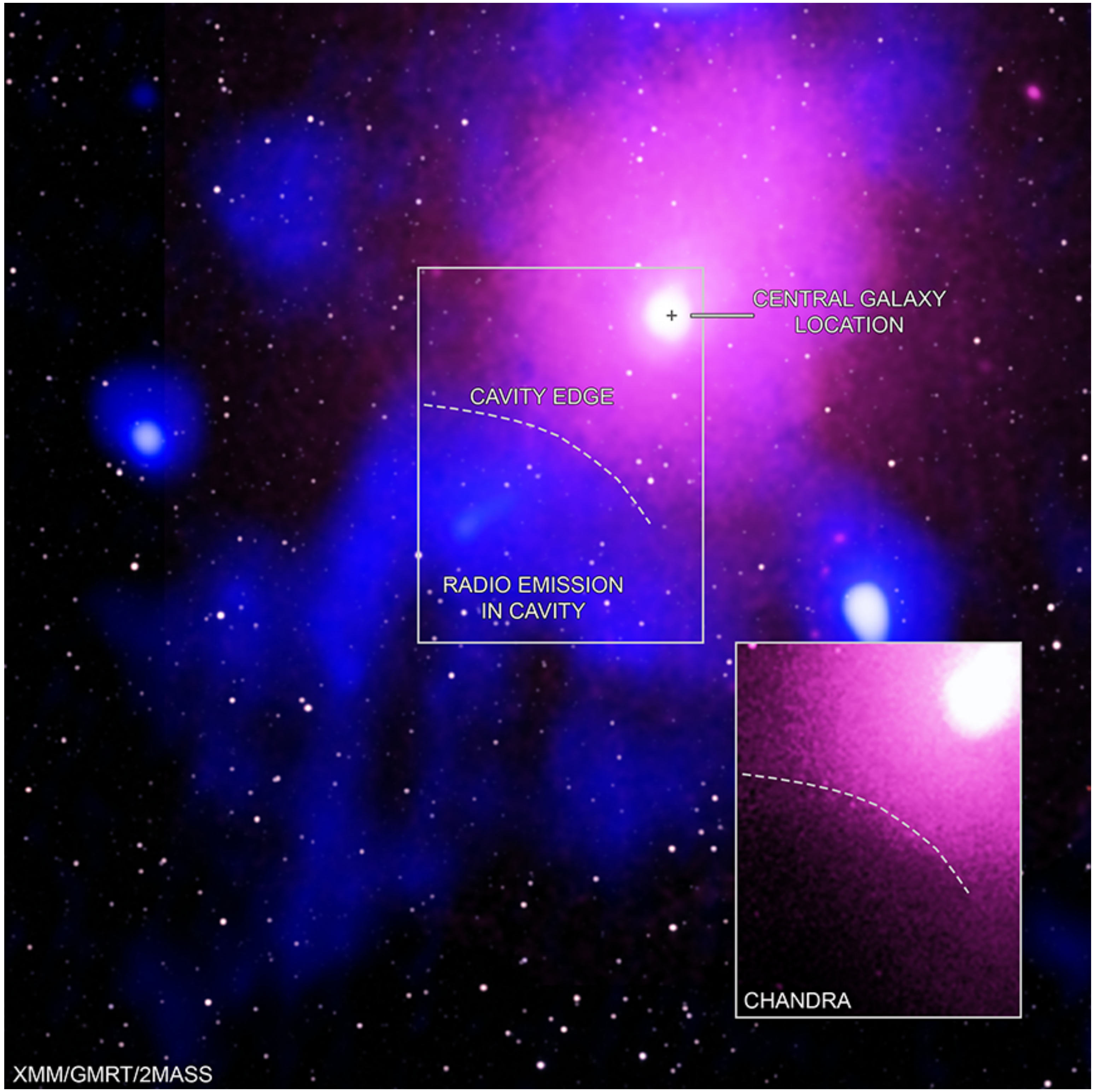


Werner & Mernier 2020

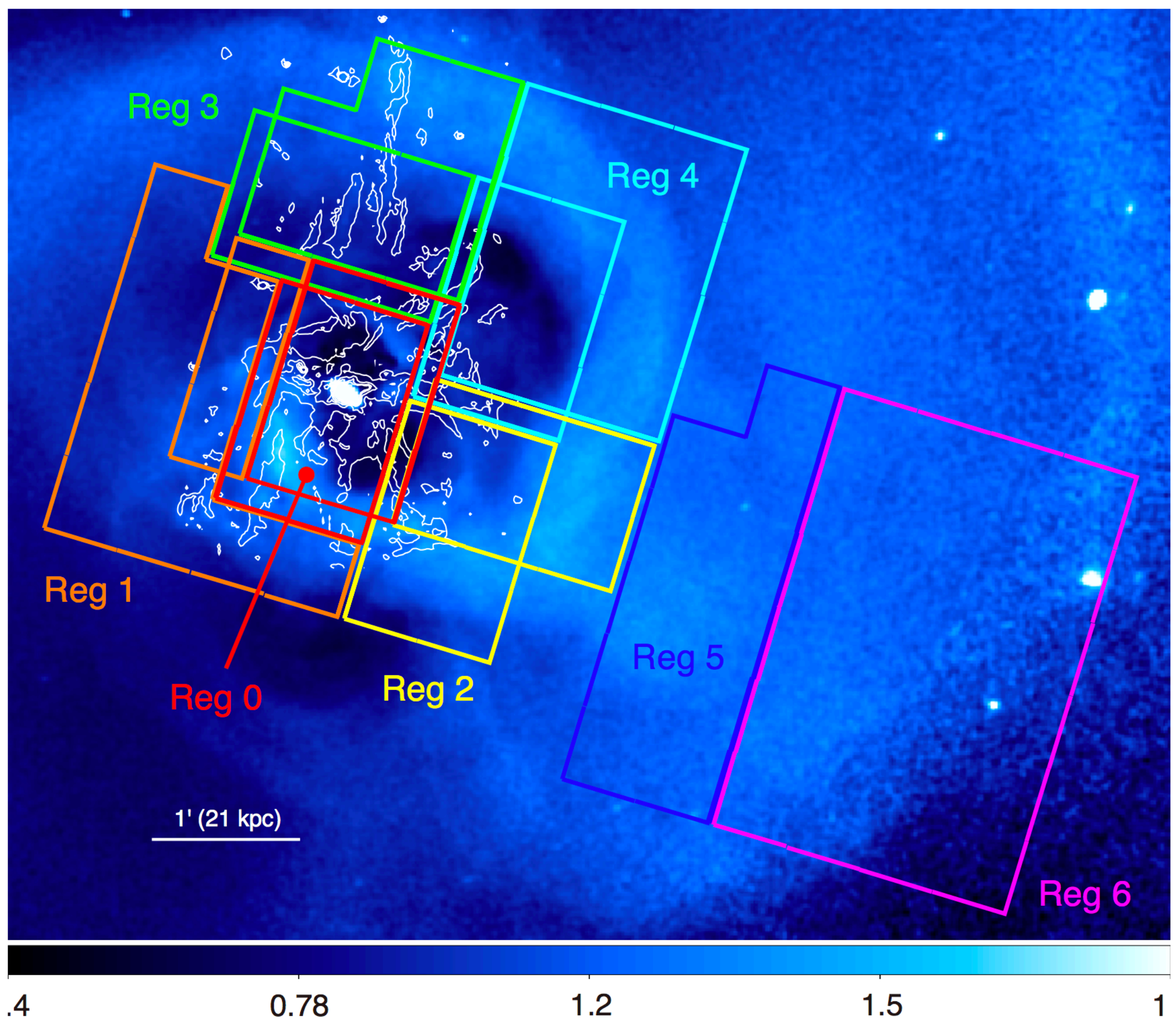




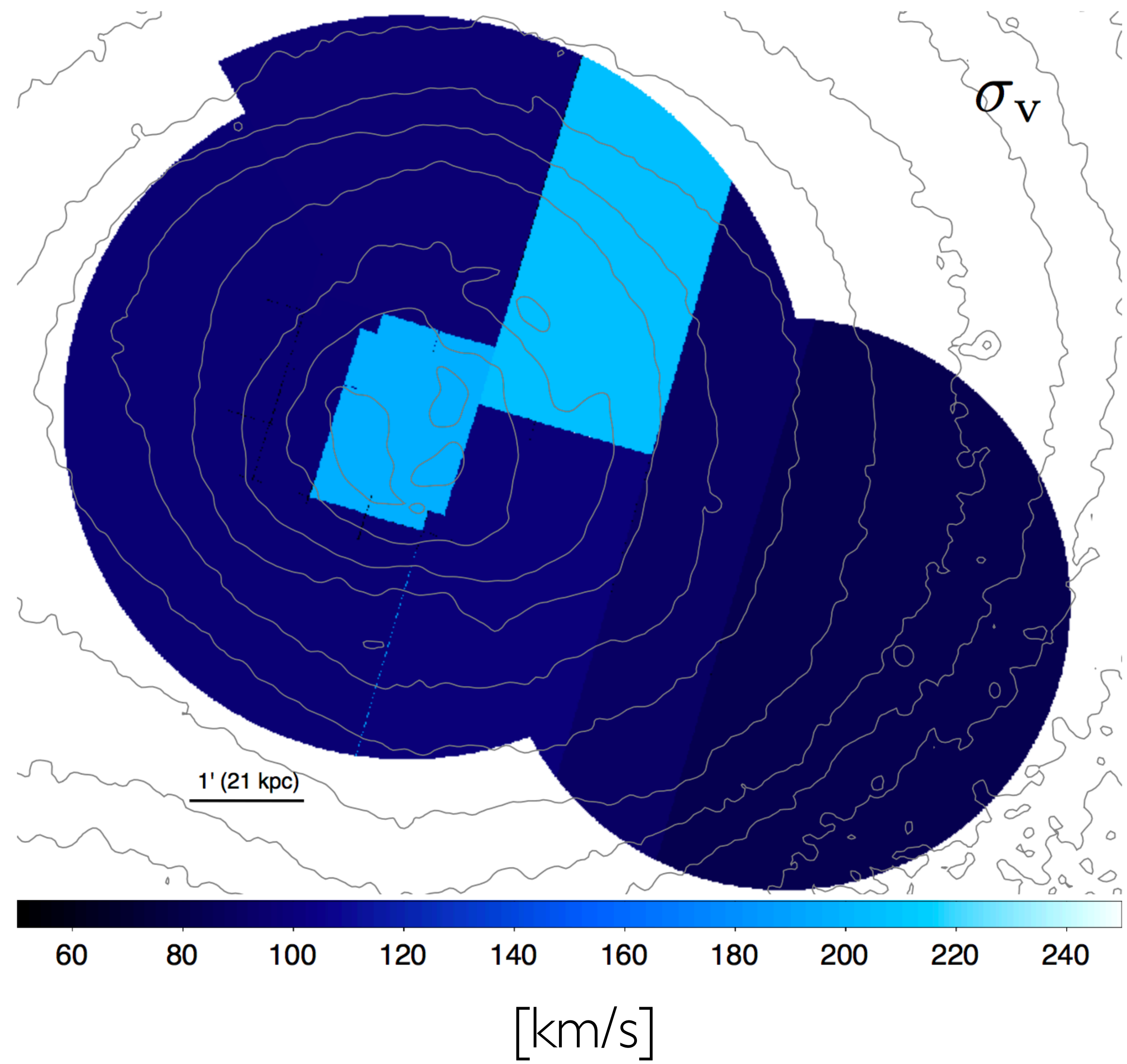



CENTRAL GALAXY LOCATION
CAVITY EDGE
RADIO EMISSION IN CAVITY
CHANDRA
XMM/GMRT/2MASS

First Direct Velocity Measurements



line broadening

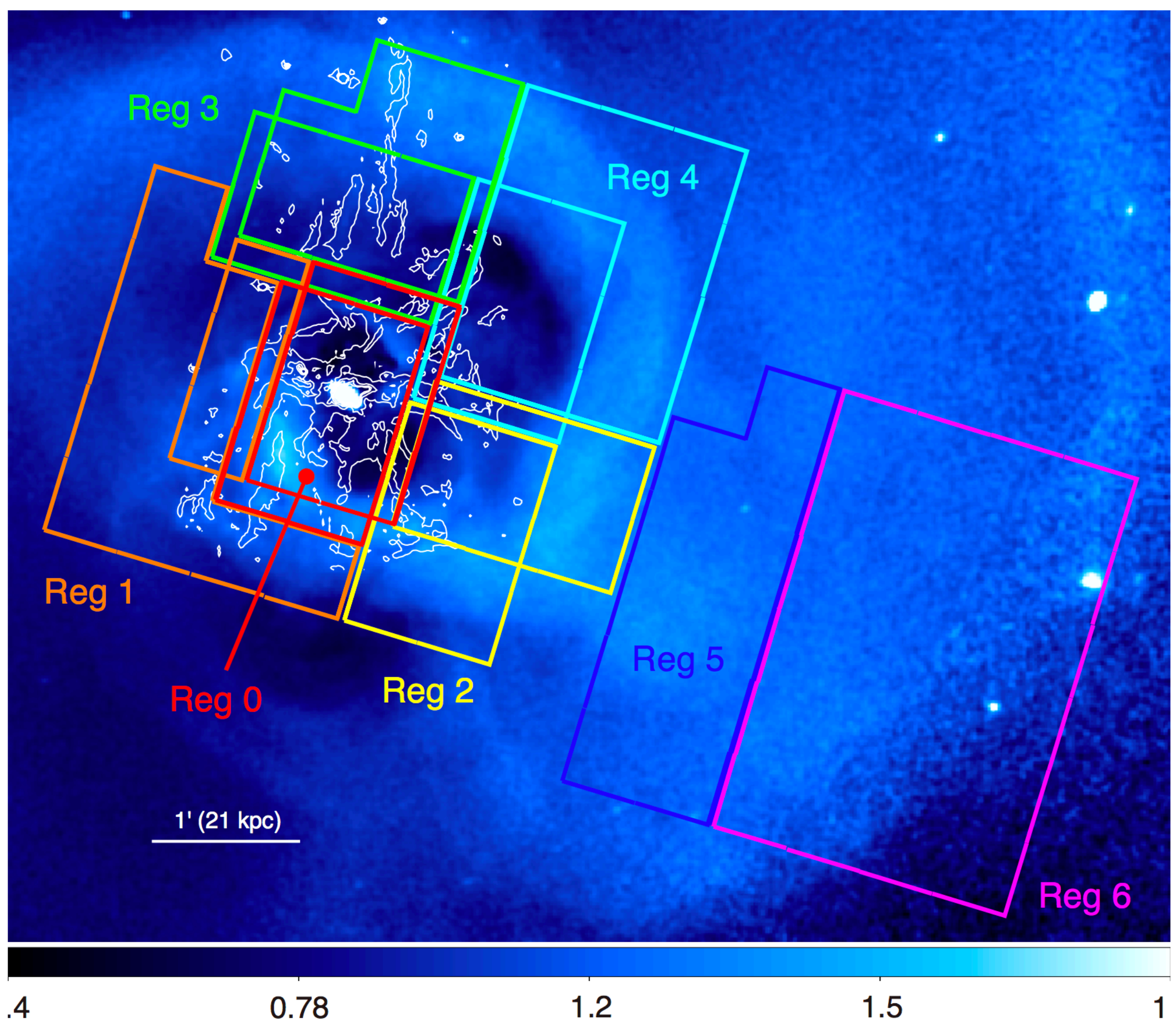


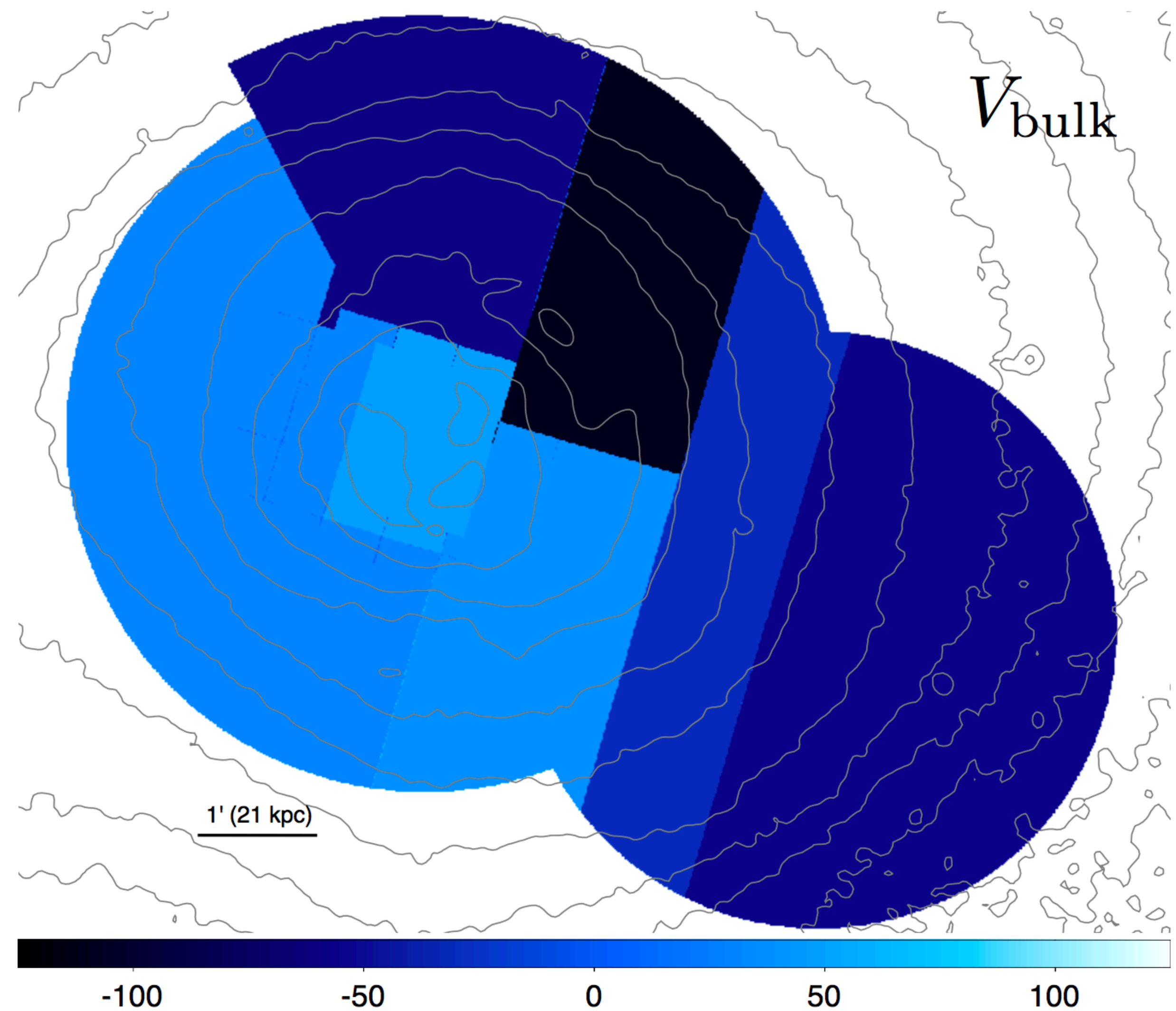
E_{turb}/E_{therm} ~ 2–6%

[on behalf of the Hitomi collaboration, PASJ 2018]

First Direct Velocity Measurements

line shifts

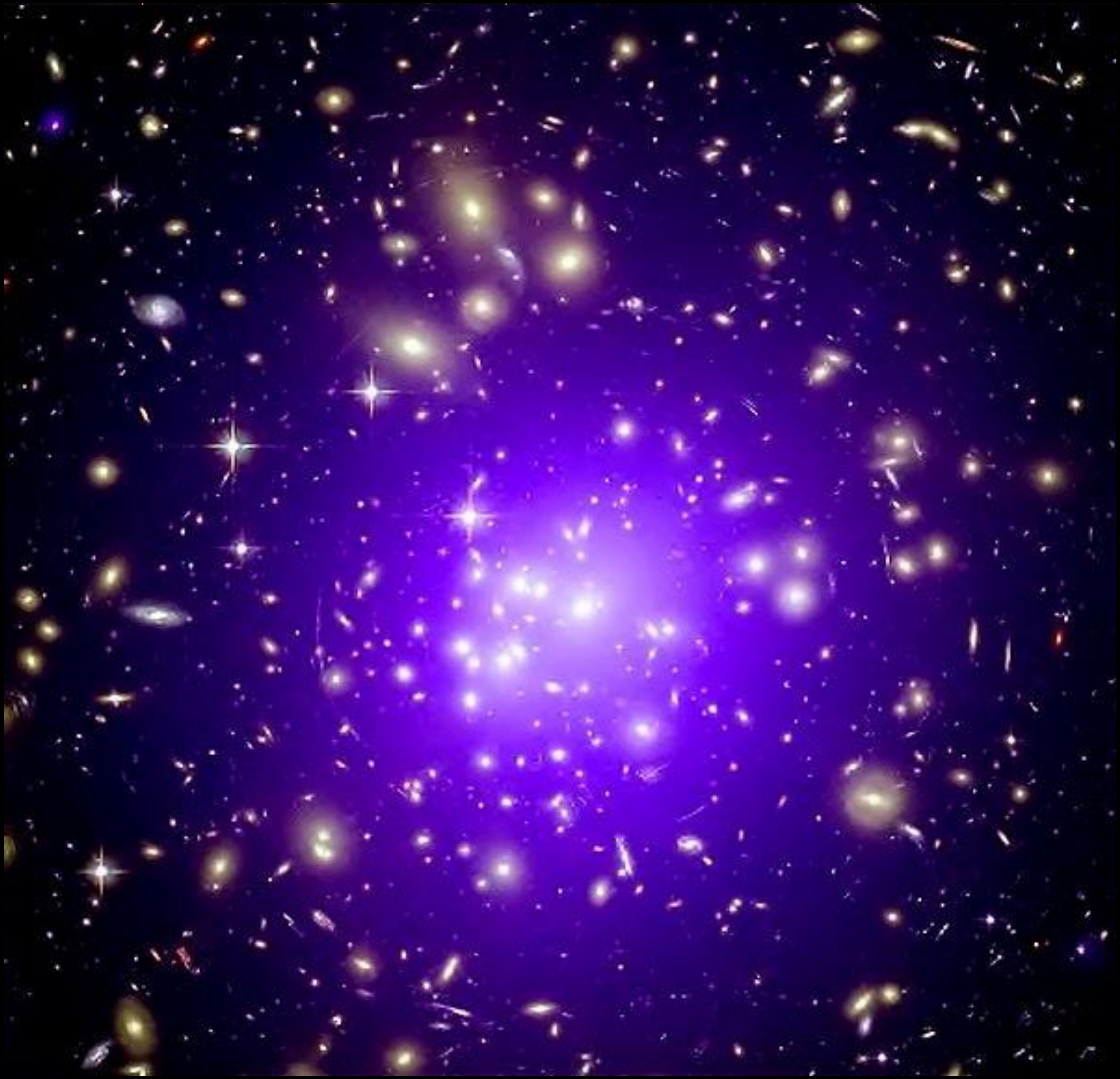




[km/s]

$$\frac{\epsilon_{\mathrm{kin}}}{\epsilon_{\mathrm{therm}}} = \frac{\mu m_{\mathrm{p}}(3\sigma_{\mathrm{v}}^2 + V_{\mathrm{bulk}}^2)}{3kT} \sim 0.02 - 0.07$$

[on behalf of the Hitomi collaboration, PASJ 2018]



X-ray measurements of the masses of clusters of galaxies

$$\nabla P = -\rho_{\mathrm{g}} \nabla \Phi$$

Gravitational force is balance by the pressure force

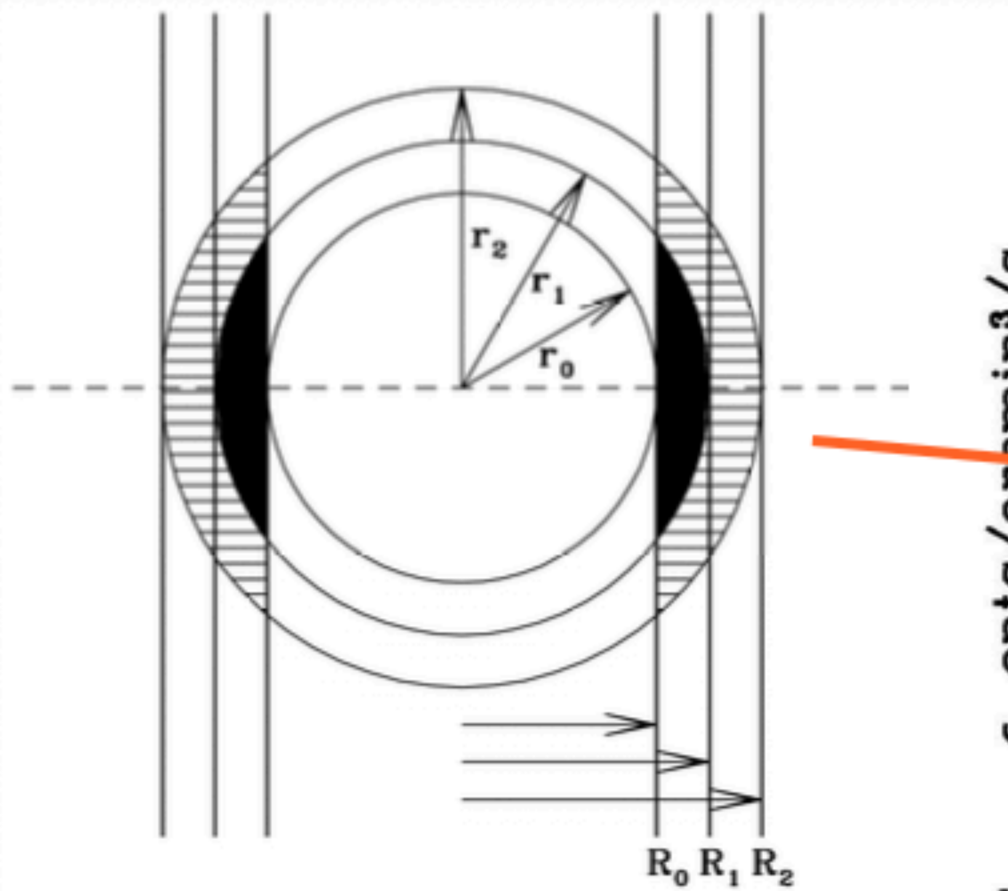
$$\frac{1}{\rho_{\mathrm{g}}} \frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{\mathrm{d}\Phi}{\mathrm{d}r} = -\frac{GM(r)}{r^2}$$

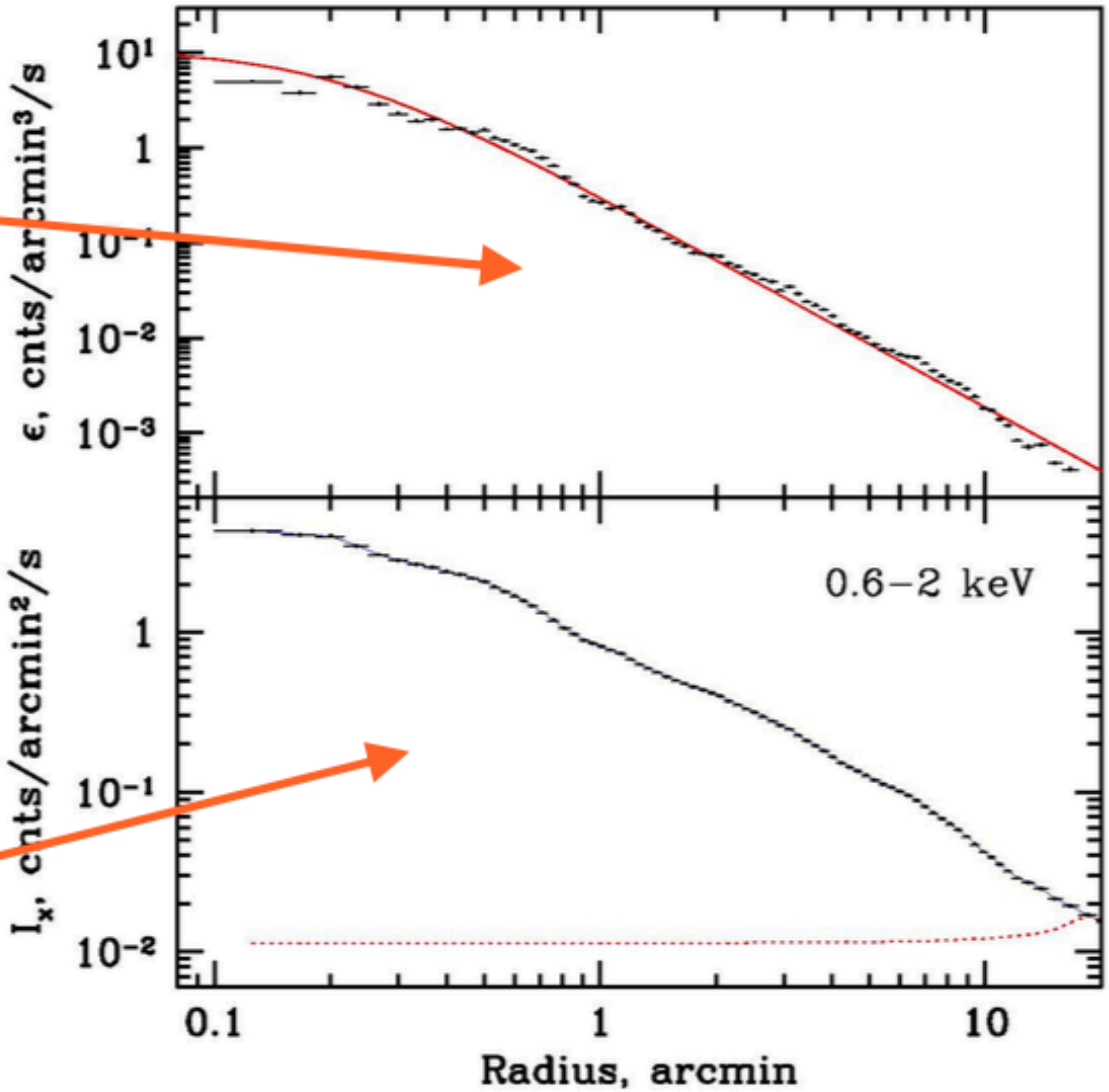
$$P = nk_{\mathrm{B}}T = \rho_{\mathrm{g}} k_{\mathrm{B}} T/(\mu m_{\mathrm{p}})$$

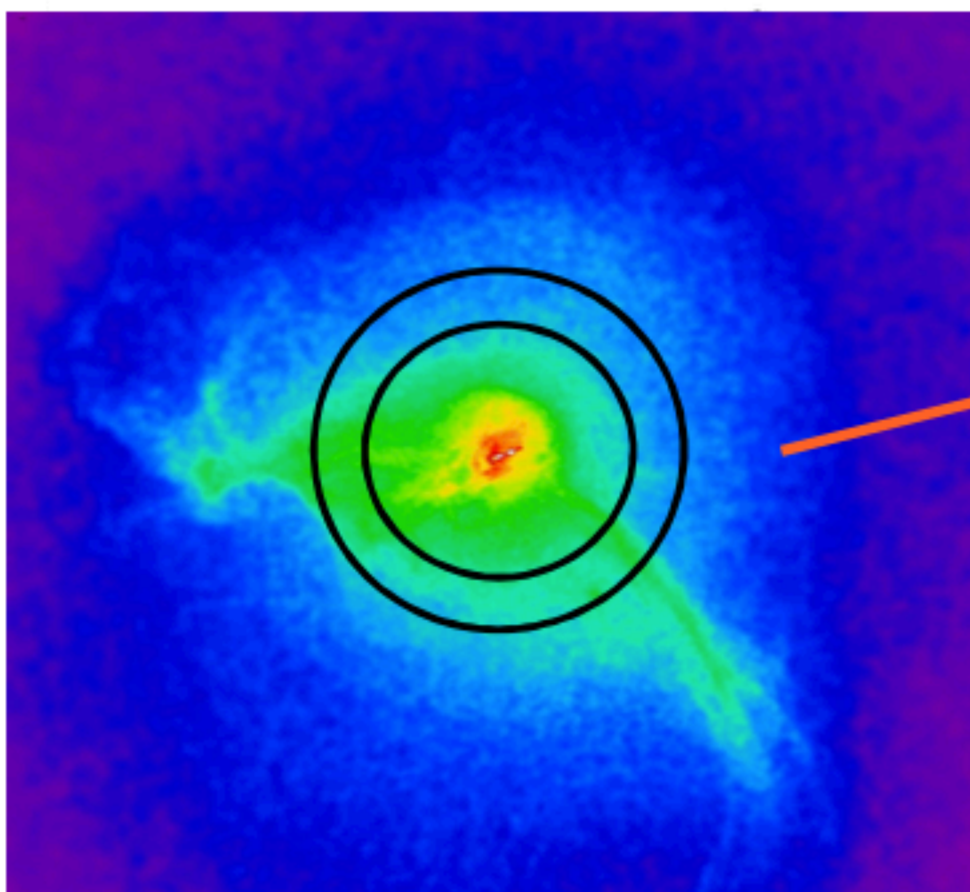
μ is the mean molecular mass.
For ionized intracluster plasma μ~0.63

$$M(r) = -\frac{k_{\mathrm{B}} T r^2}{G \mu m_{\mathrm{p}}} \left(\frac{\mathrm{d} \ln \rho_{\mathrm{g}}}{\mathrm{d}r} + \frac{\mathrm{d} \ln T}{\mathrm{d}r} \right)$$

Deprojection of X-ray data



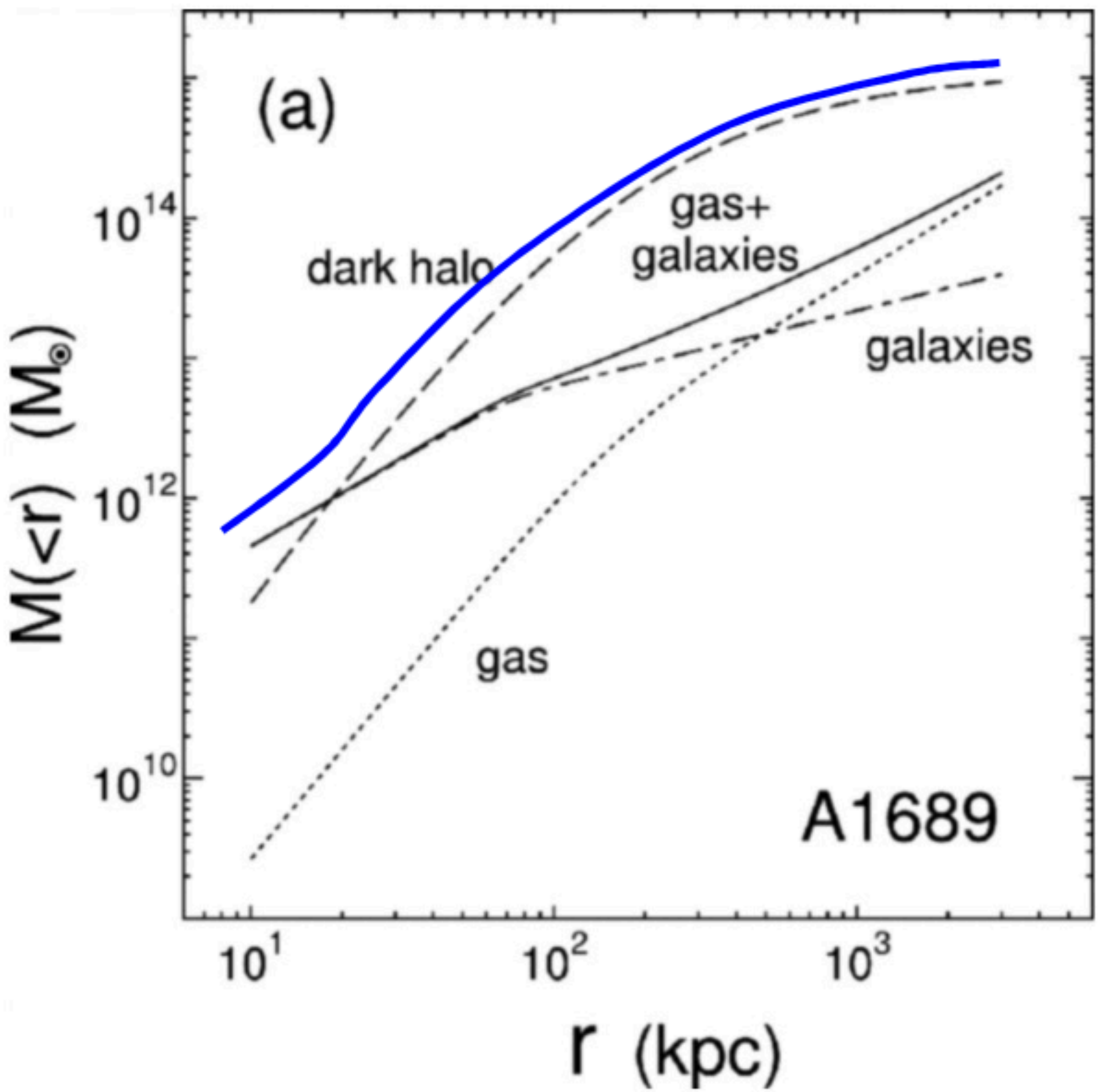




Repeat the same exercise at all energies

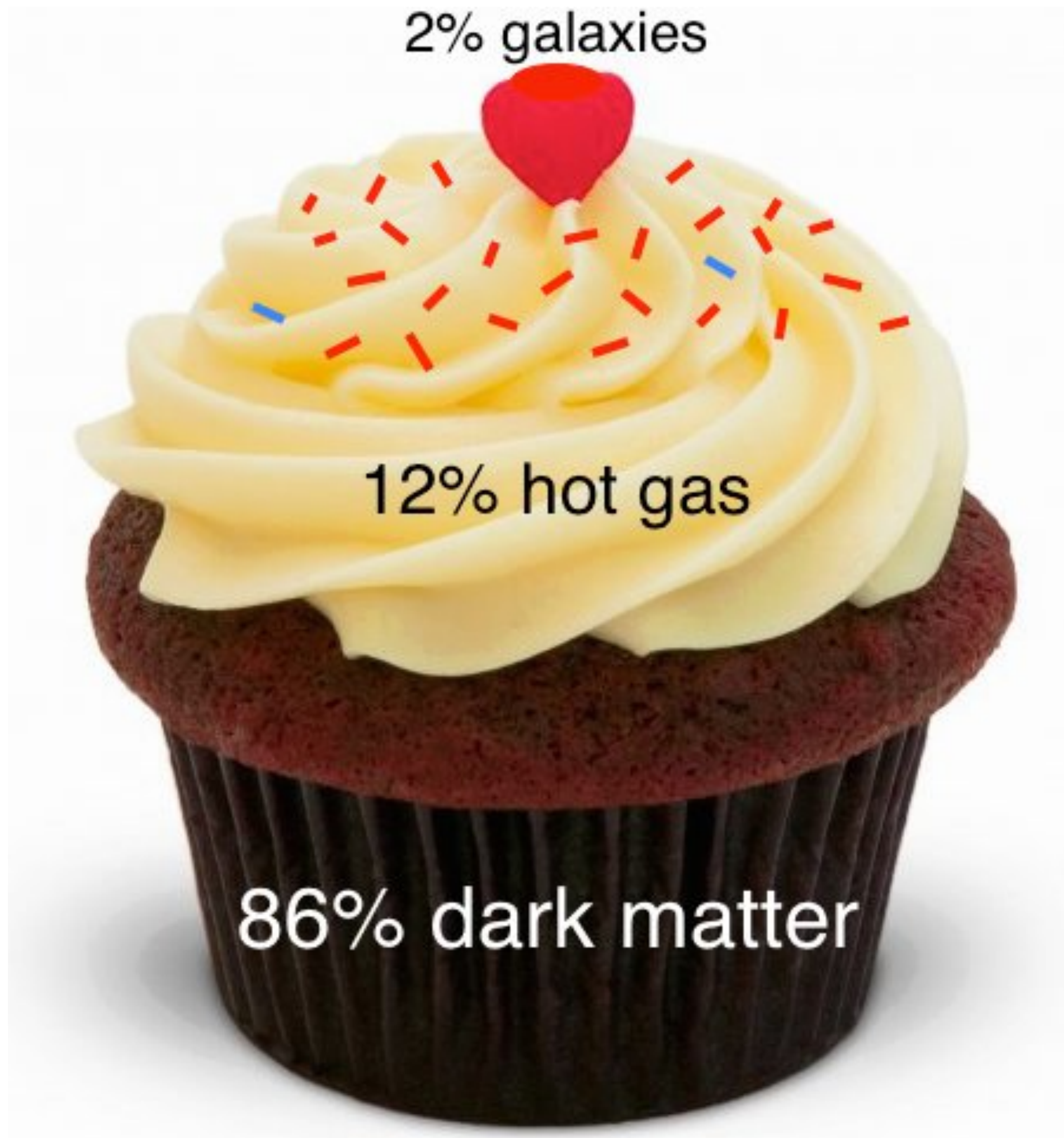
$\varepsilon(r,E)=n(r)^2S(E,T(r))$

Mass profile of a real cluster



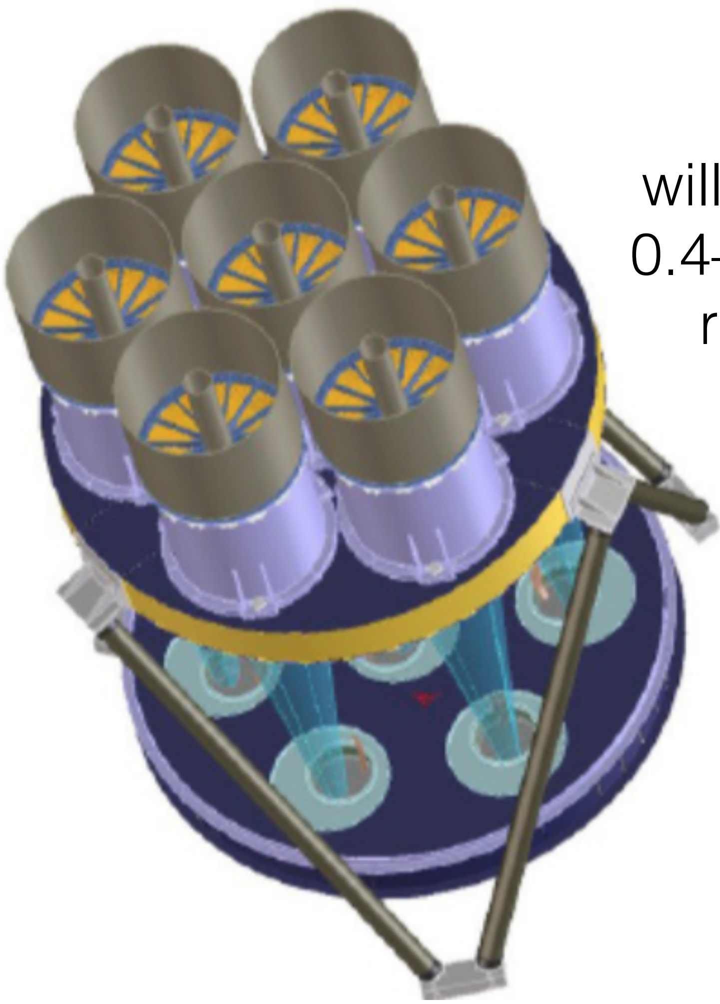
DM : 80-85%
Gas : 12-15%
Stars : 2-5%

Clusters of galaxies as cupcakes



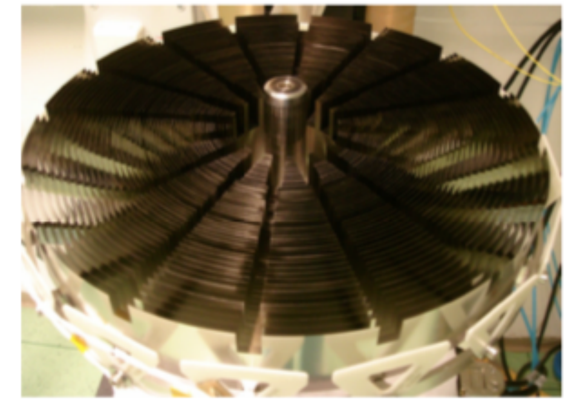
A. Mantz

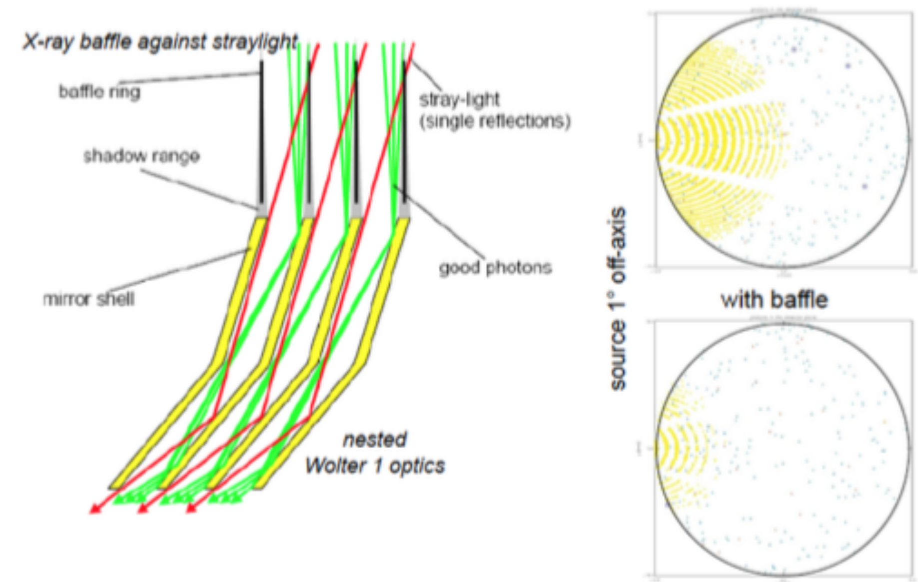
eRosita on Spectrum-Roentgen-Gamma



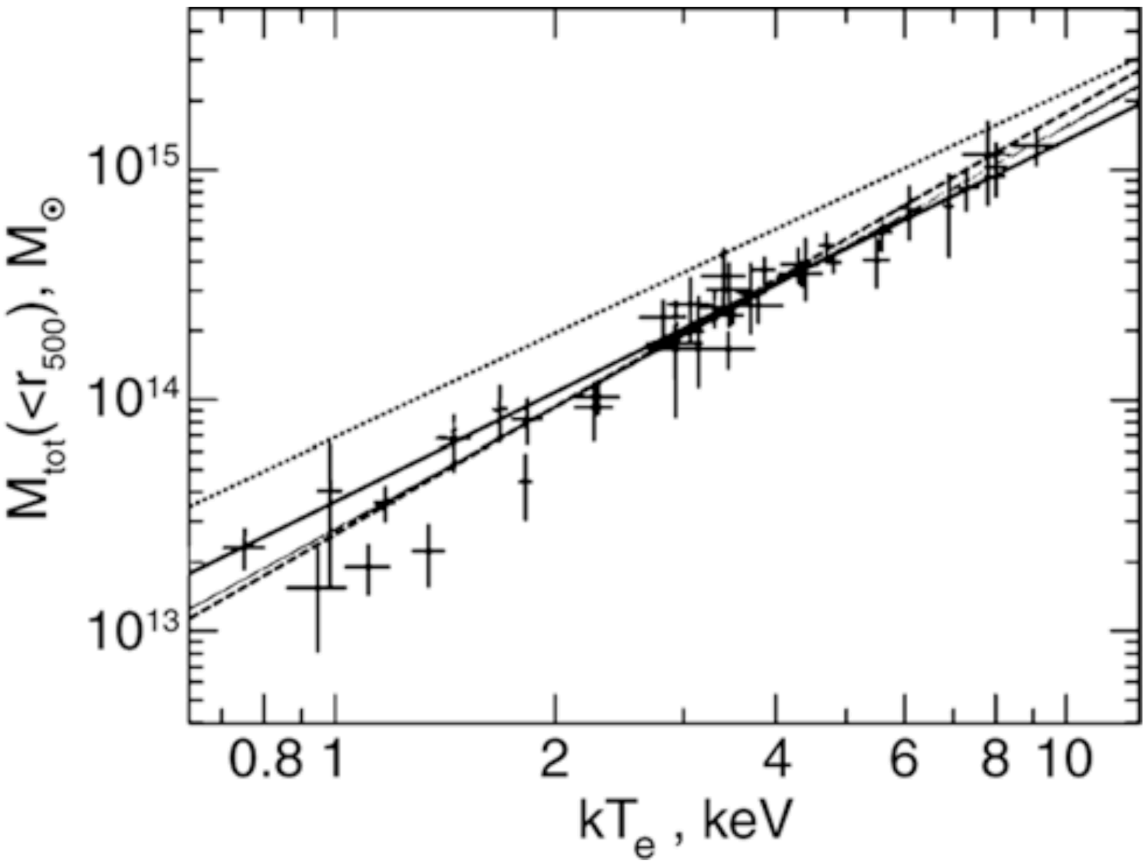
7 telescopes each made of
54 nested mirror shells

will survey the whole sky in the
0.4—10 keV band at the spatial
resolution of XMM-Newton





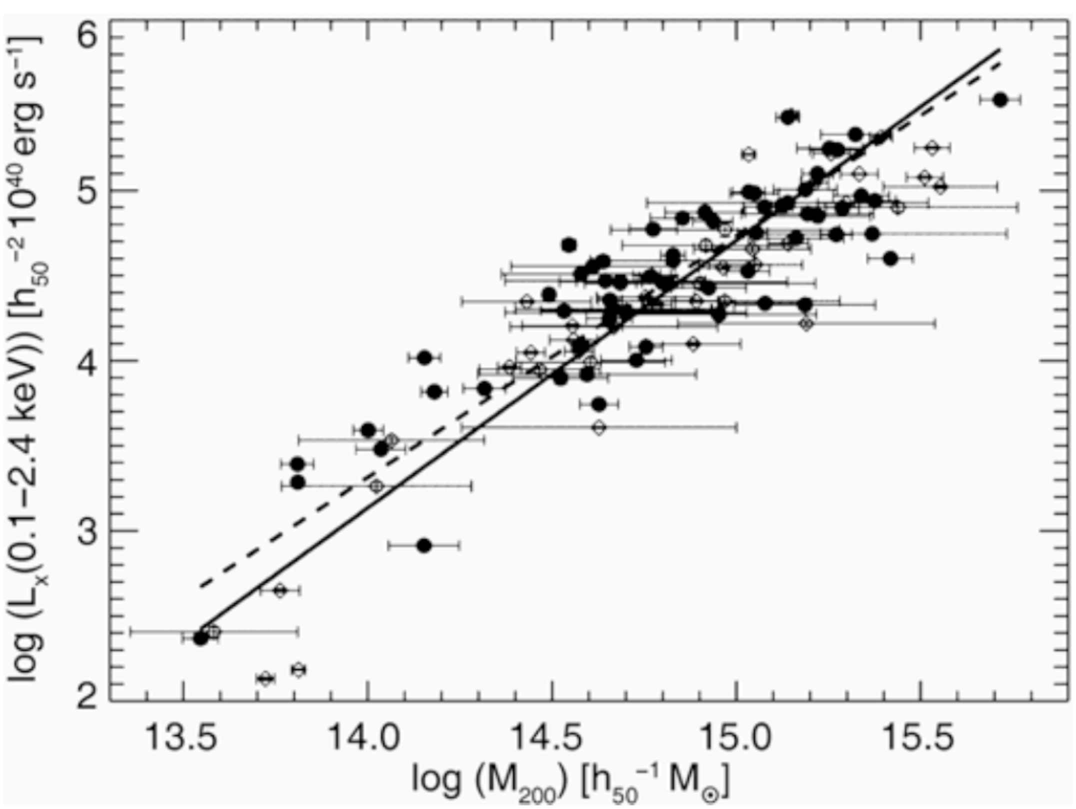
- detect the hot intergalactic medium of 50-100 thousand galaxy clusters
- detect up to 3 Million new, distant active galactic nuclei
- study the physics of galactic X-ray emitting pre-main sequence stars, supernova remnants and X-ray binaries.



The X-ray temperature T specifies the thermal energy per gas particle, which is proportional to the binding energy for a cluster in virial equilibrium

$$T \propto M/r$$

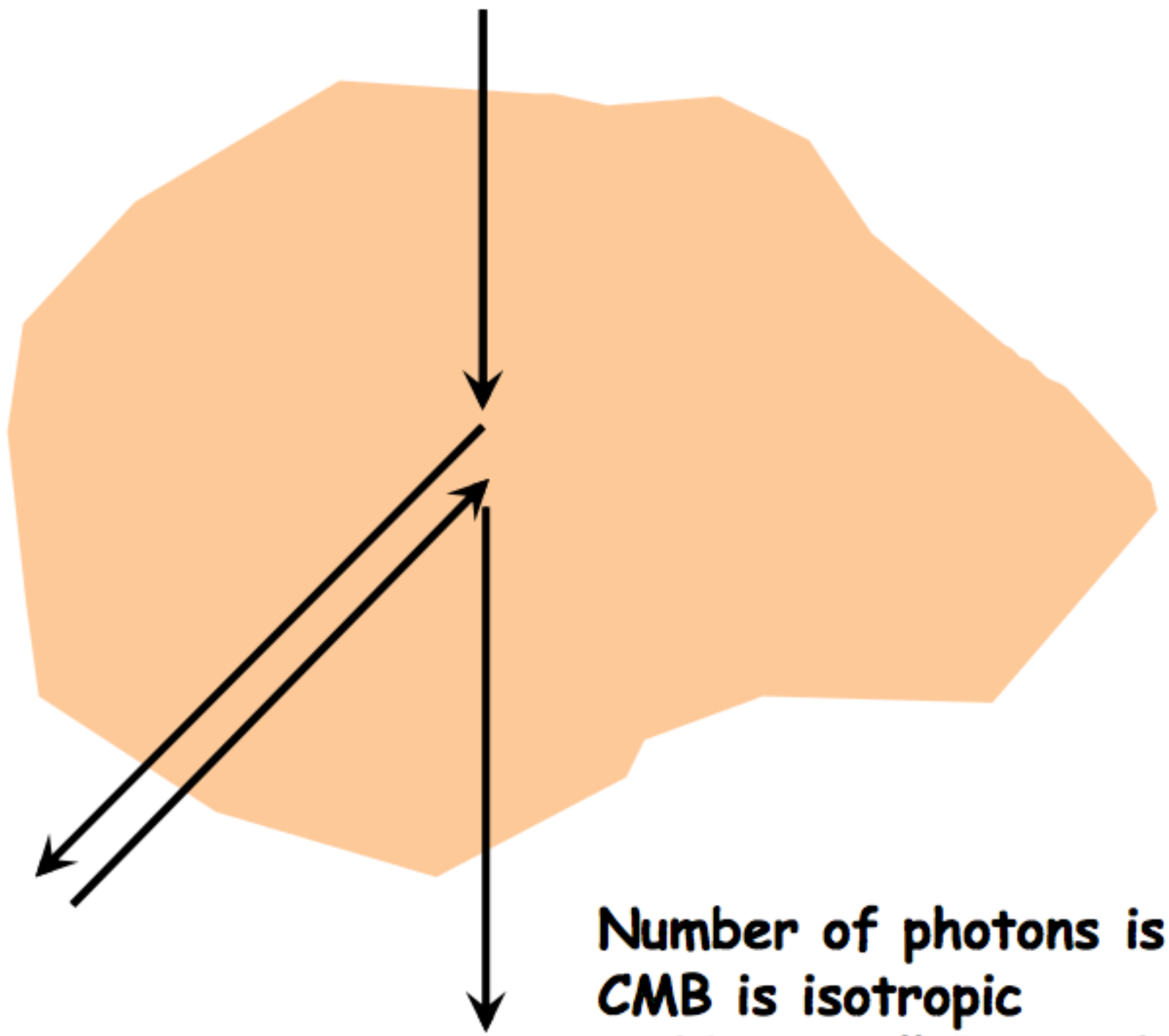
r radius within which the matter of the cluster is virialized. The virial radius is defined such that within a sphere of radius $r_{\rm vir}$, the average mass density of the cluster is about 200 times as high as the critical density of the Universe. The mass within $r_{\rm vir}$ is called the virial mass $M_{\rm vir}$



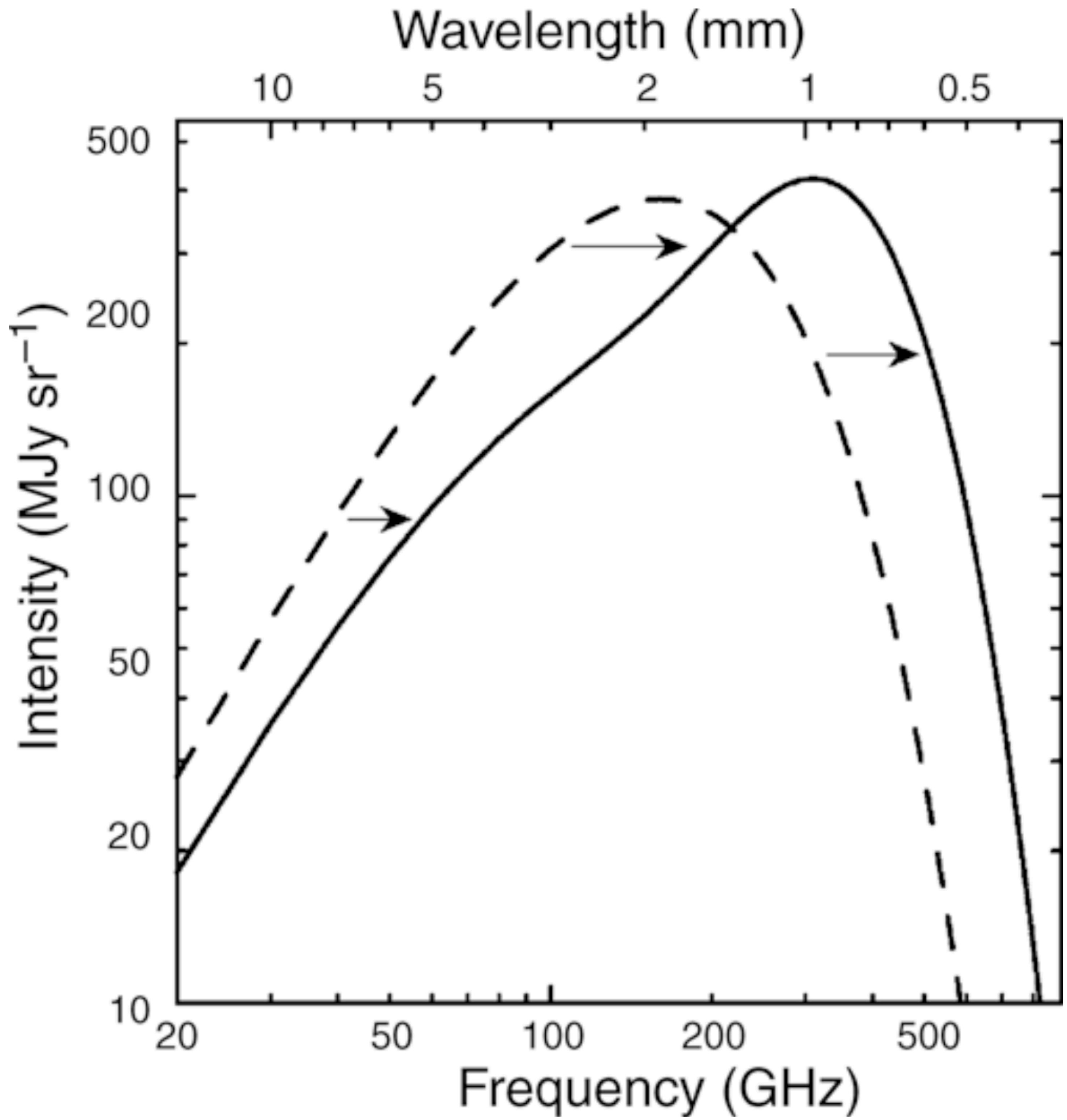
$$M_{\rm vir} = \frac{4\pi}{3}\,\Delta_{\rm c}\,\rho_{\rm cr}\,r_{\rm vir}^3$$

$$T \propto \frac{M_{\rm vir}}{r_{\rm vir}} \propto r_{\rm vir}^2 \propto M_{\rm vir}^{2/3}$$

$$\frac{d\sigma}{d\Omega} = \frac{3}{8}\sigma_T\left(1+\cos^2\theta\right) \quad \text{[electron at rest, } h\nu << m_e c^2\text{]}$$



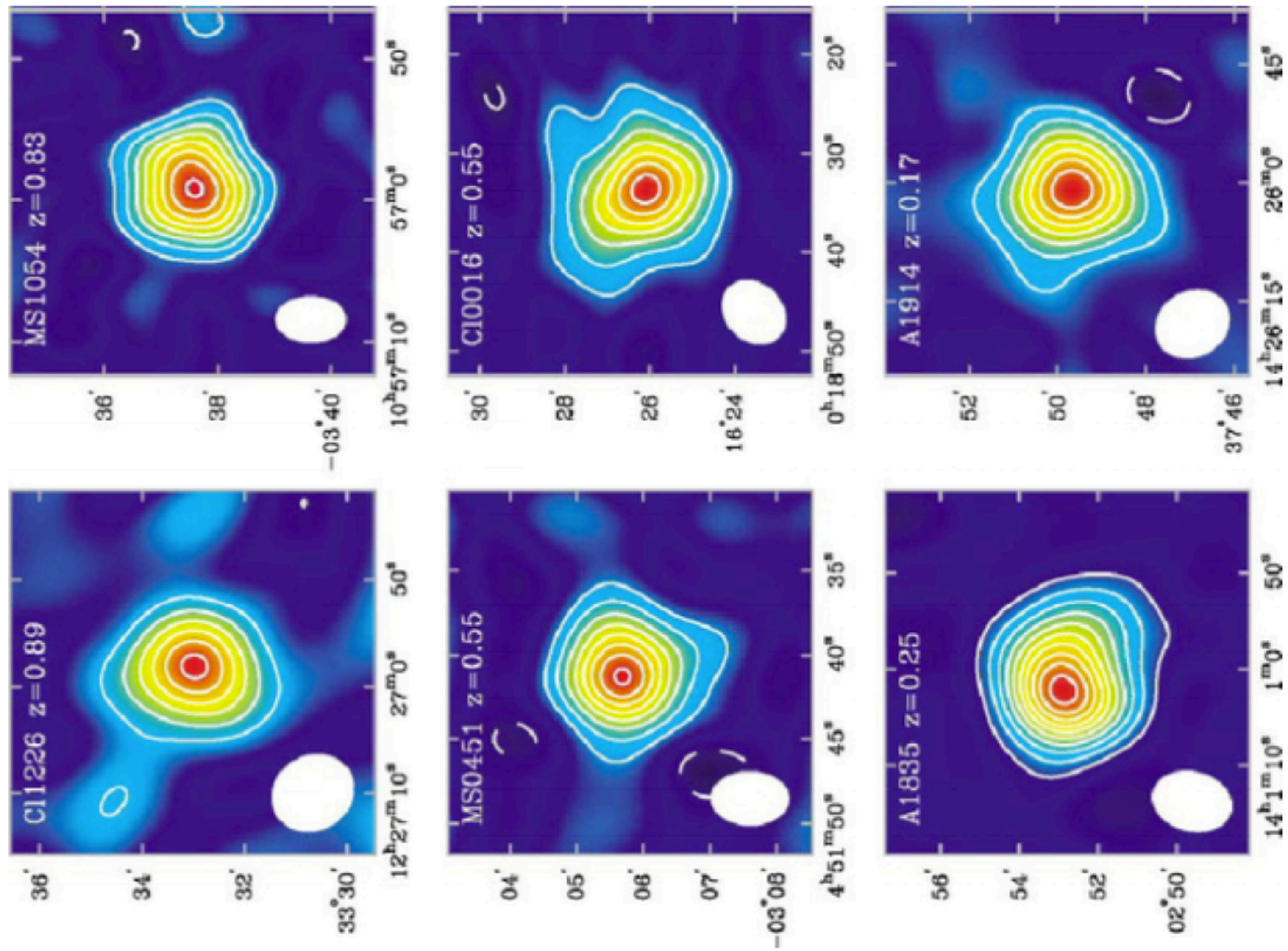
Number of photons is conserved
CMB is isotropic
⇒ No signal! [in number of photons]
⇒ Spectrum?



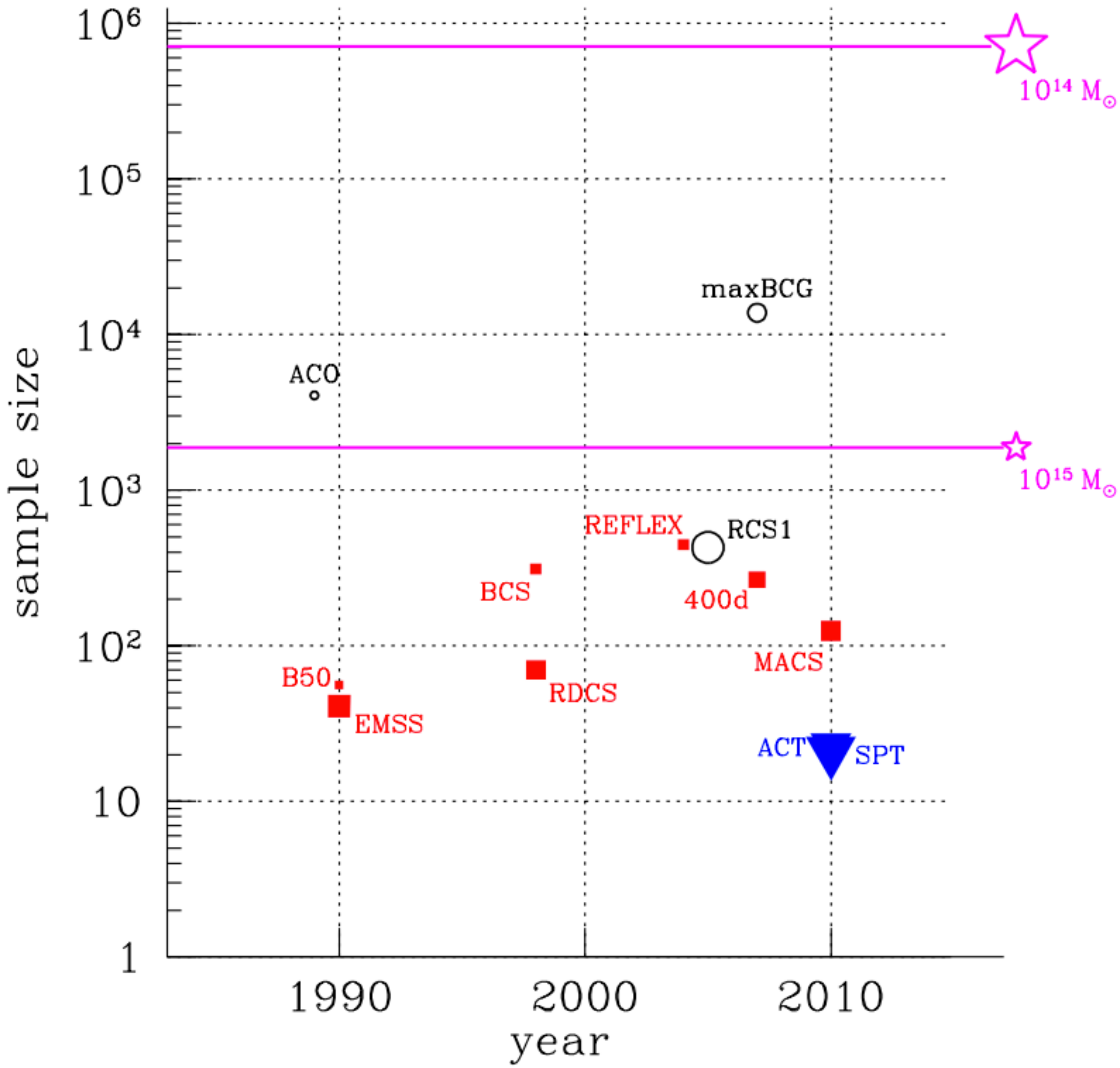
$$\frac{\Delta I_\nu^{\mathrm{RJ}}}{I_\nu^{\mathrm{RJ}}} = -2y \qquad \boxed{y = \int \mathrm{d}l \, \frac{k_{\mathrm{B}} T_{\mathrm{g}}}{m_{\mathrm{e}} c^2} \, \sigma_{\mathrm{T}} \, n_{\mathrm{e}}} \quad \text{with} \quad \sigma_{\mathrm{T}} = \frac{8\pi}{3} \left(\frac{e^2}{m_{\mathrm{e}} c^2} \right)^2$$

SZE signal is independent on redshift

Distant cluster, z,
brightness temperature attenuated by (1+z),
but the CMB temperature was (1+z) times higher



Cluster surveys



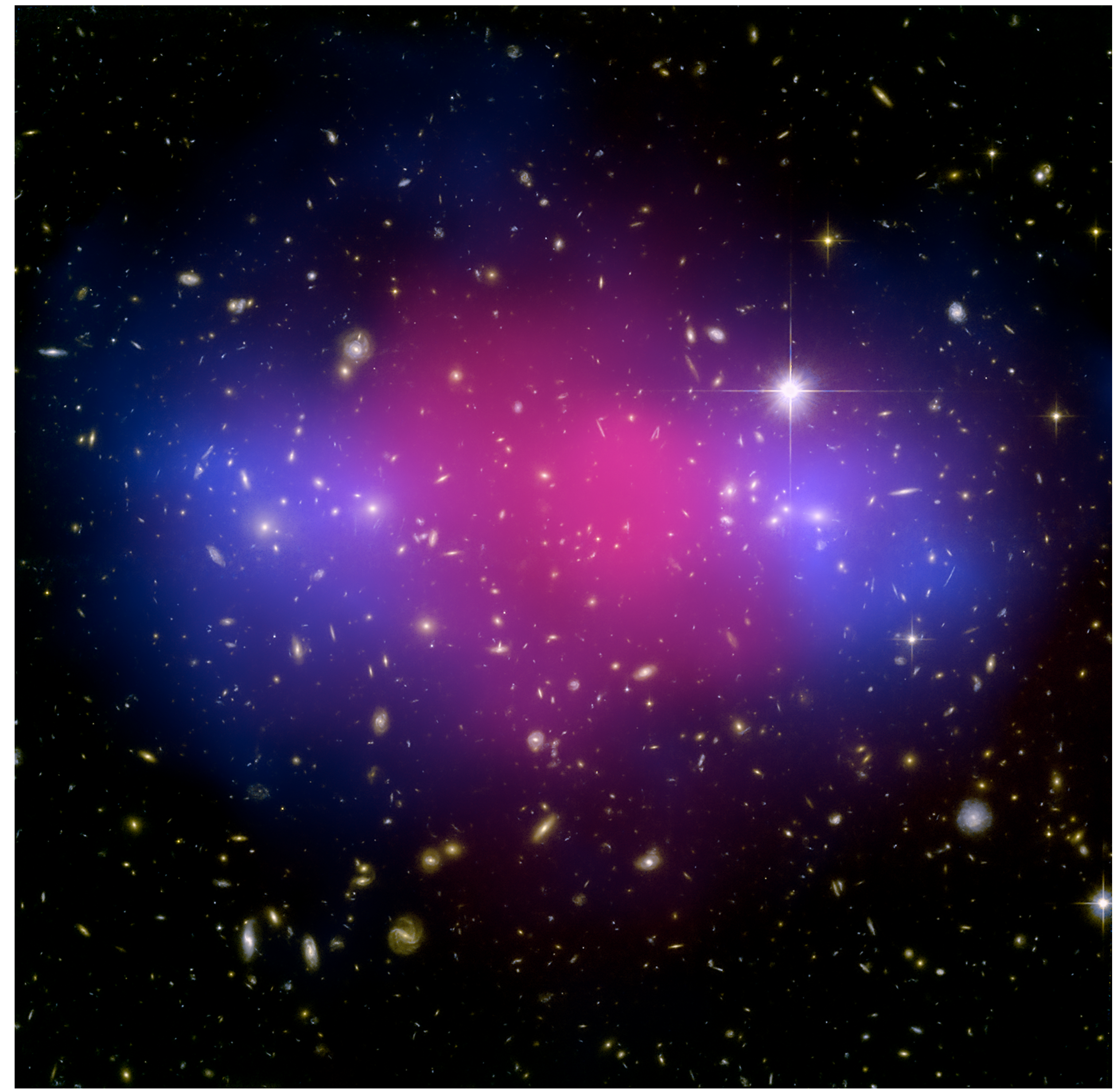
optical surveys

X-ray surveys

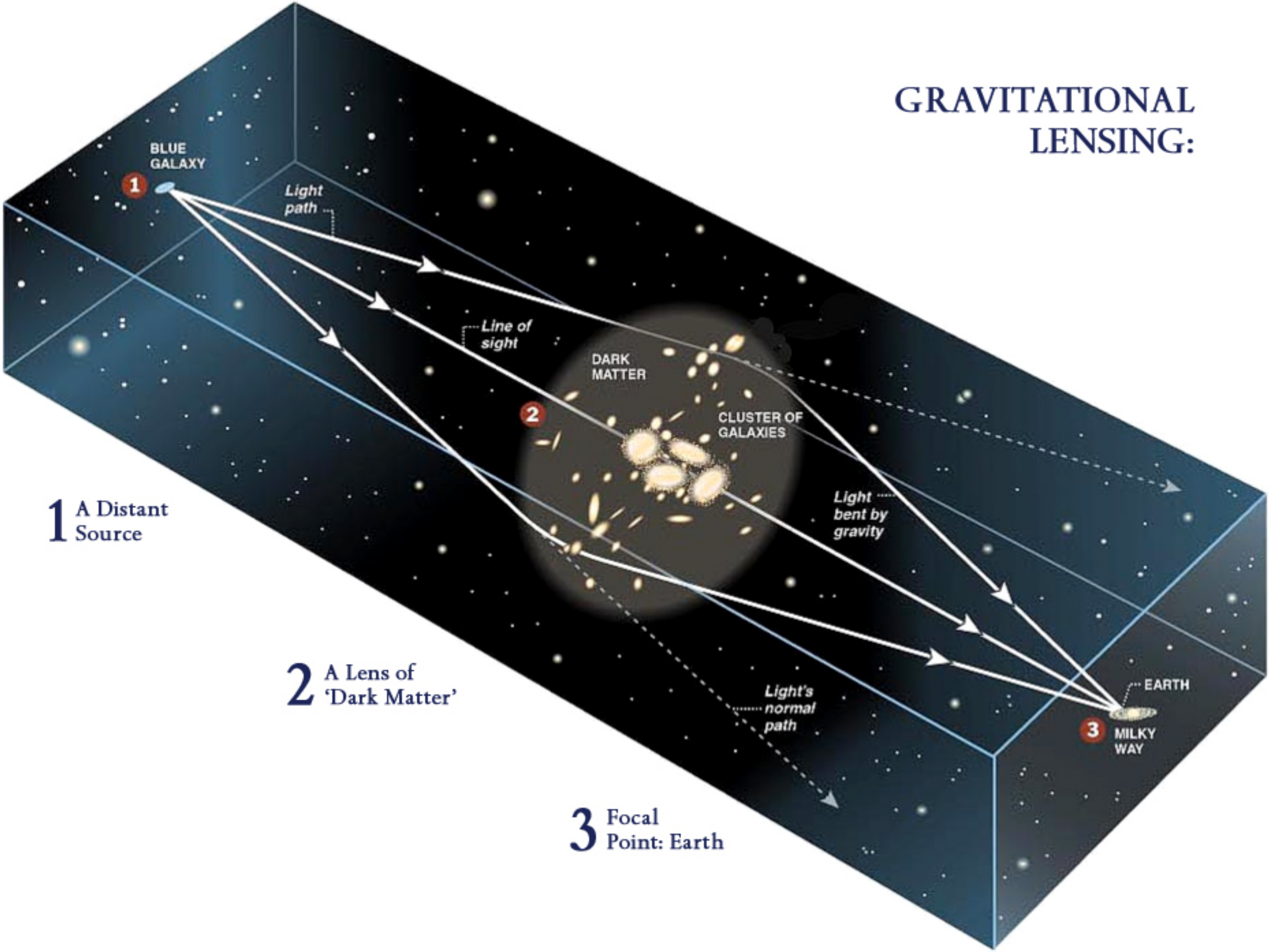
SZ surveys

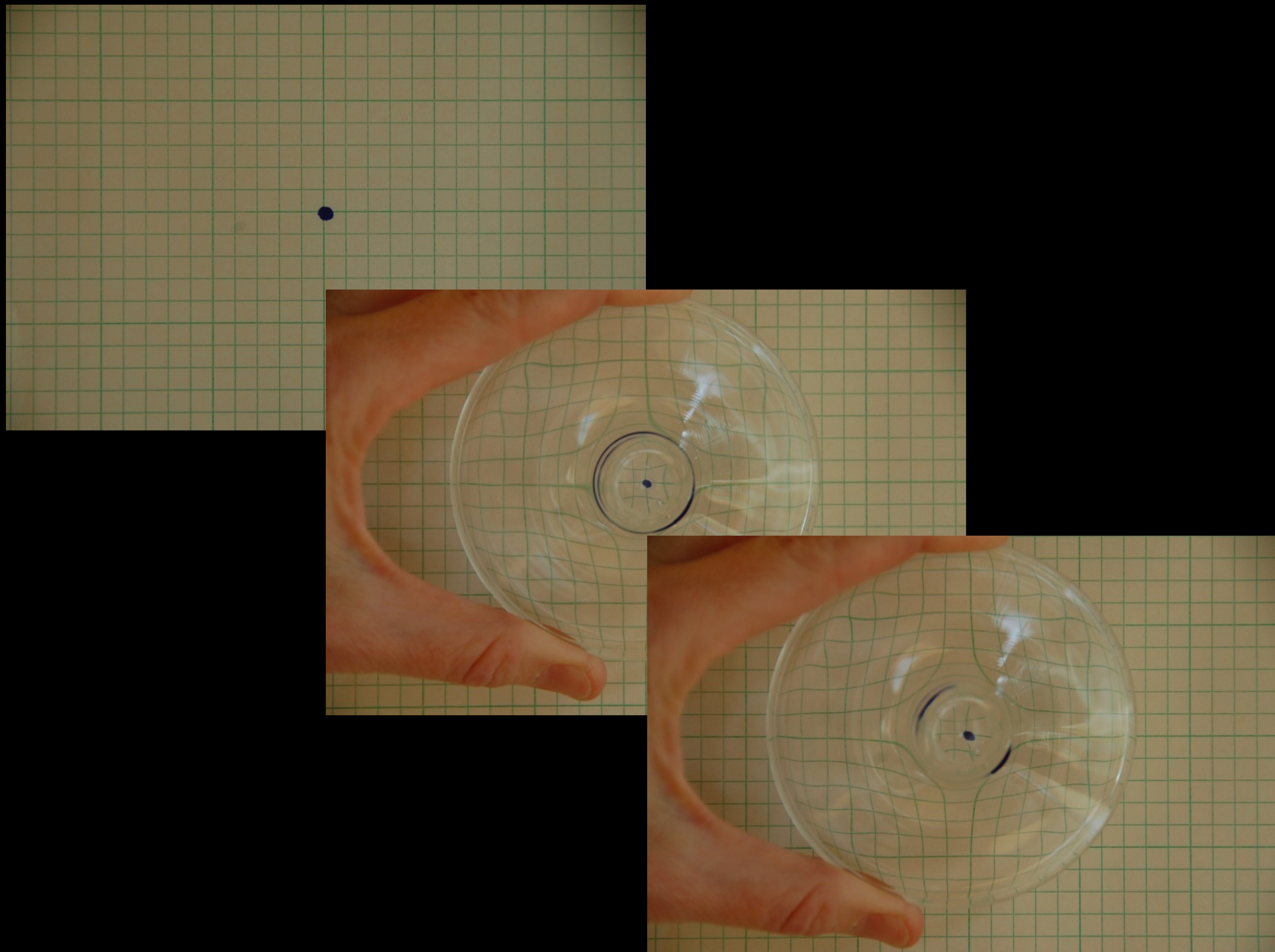
Fundamental physics with clusters of galaxies:

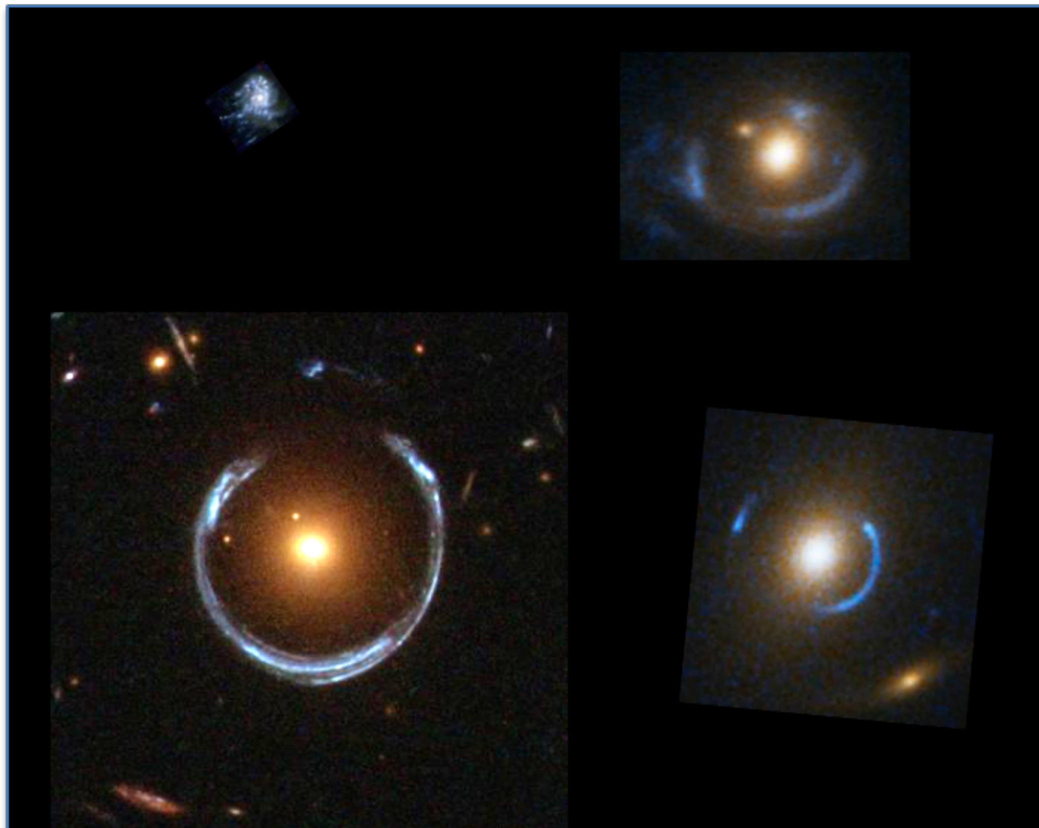
Dark Matter



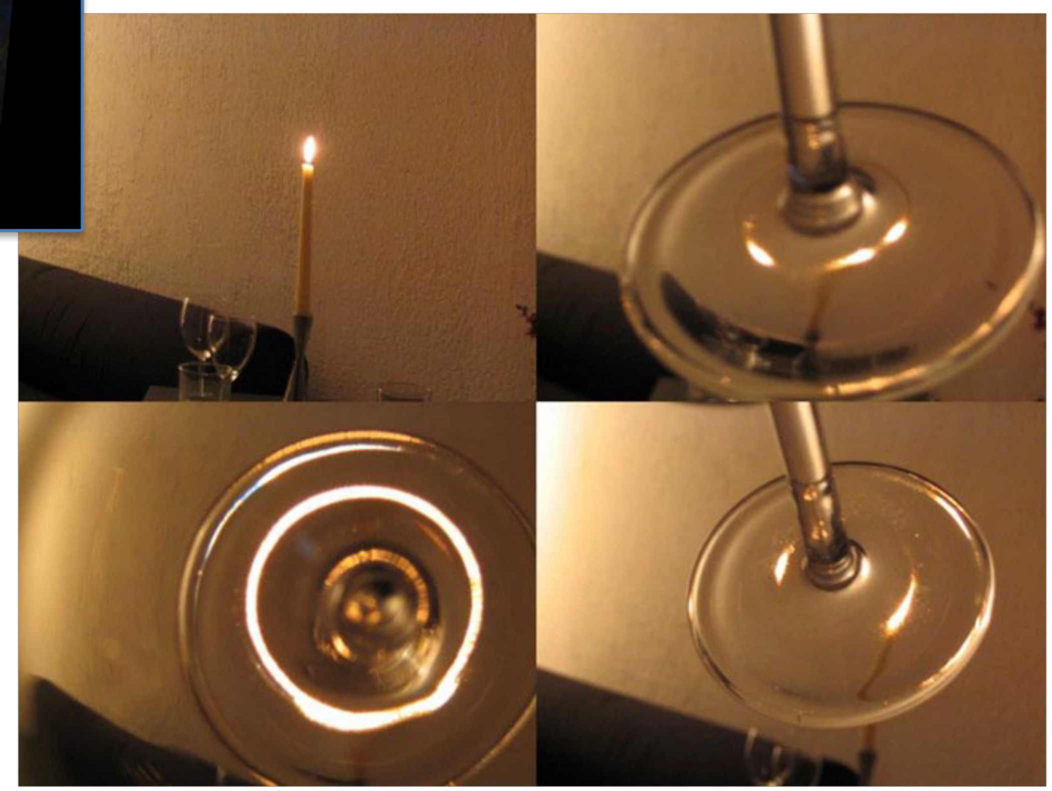
GRAVITATIONAL LENSING:



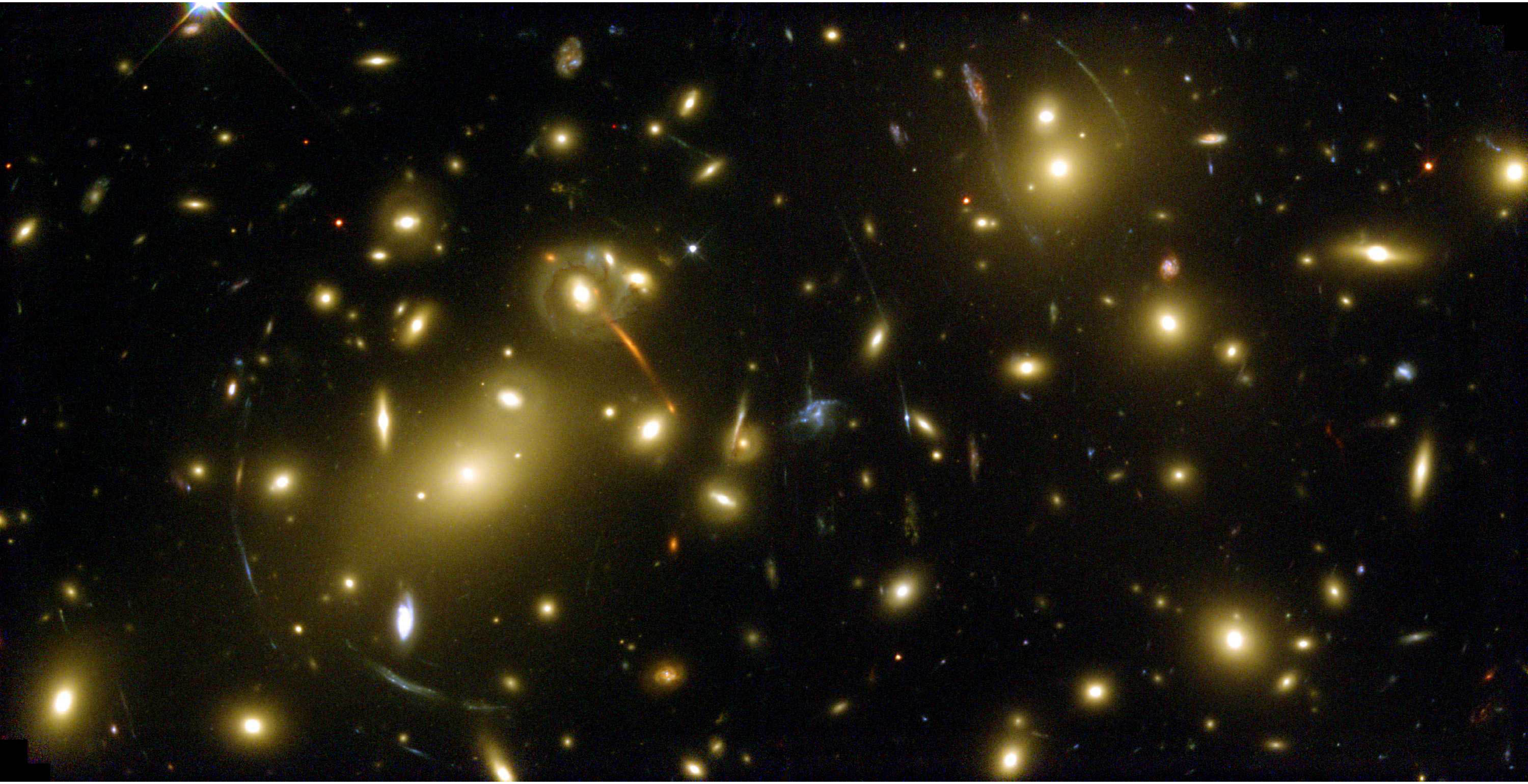


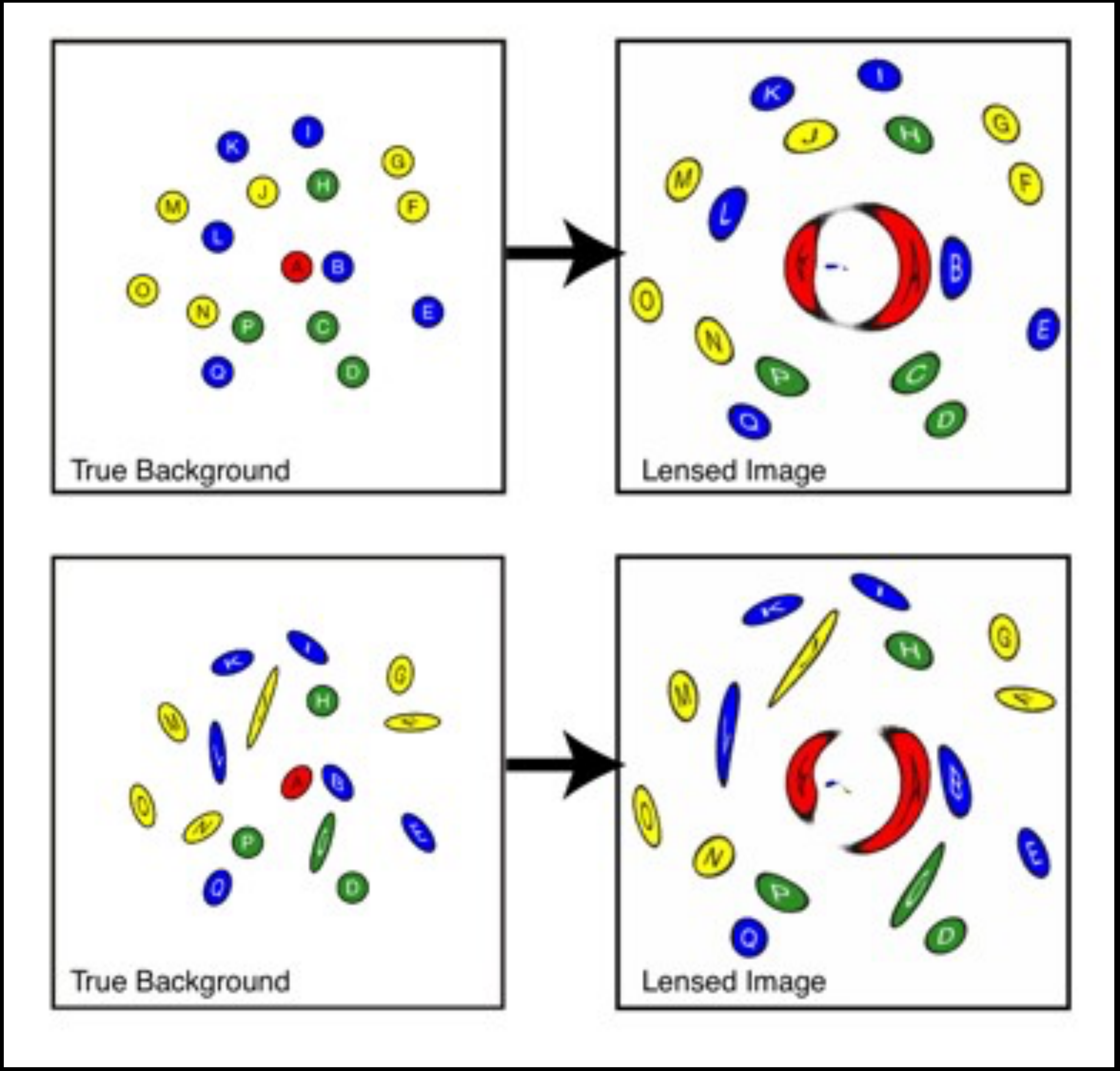


“Gravitational lensing” – using a light source

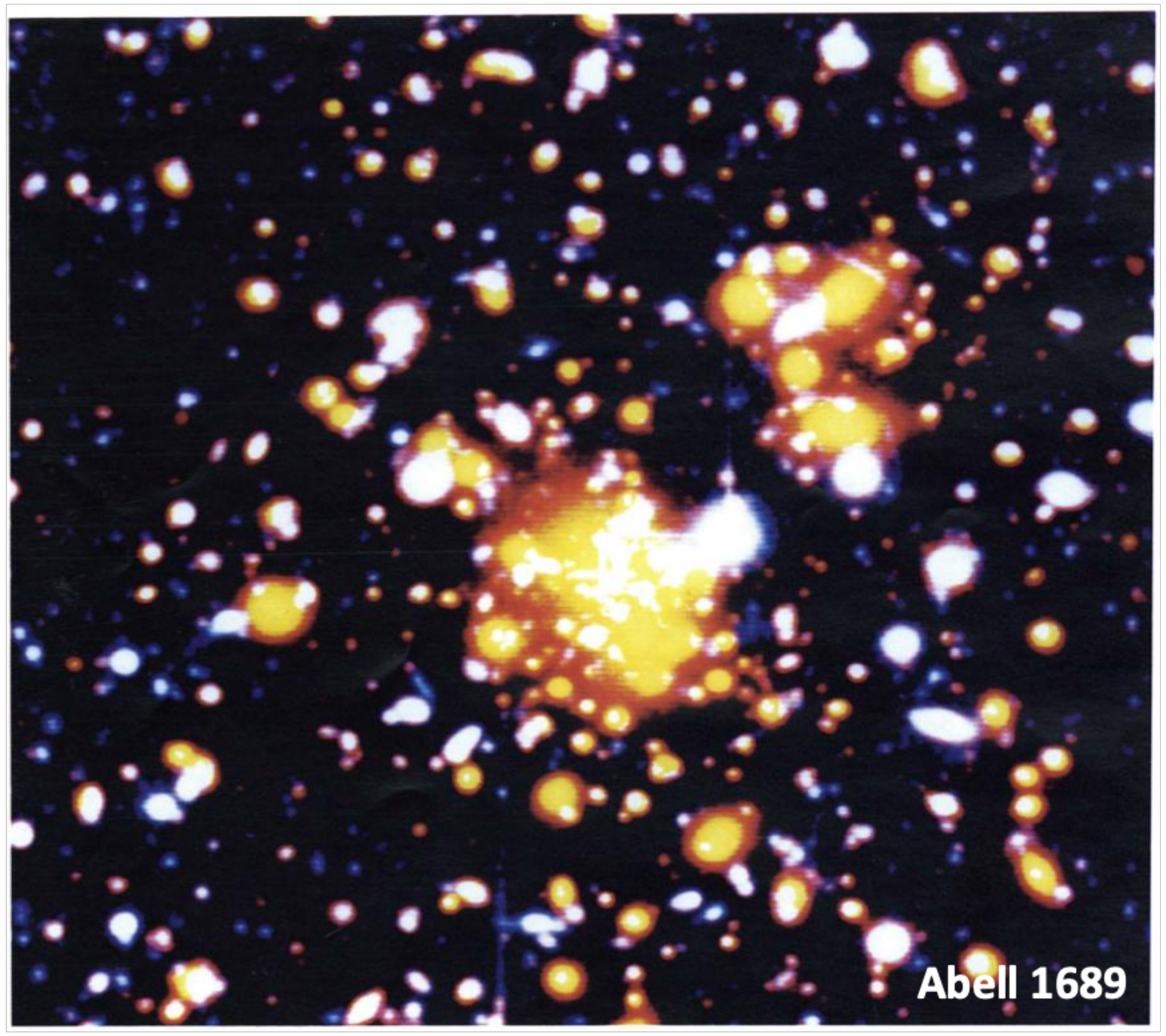


Credit: Phil Marshall



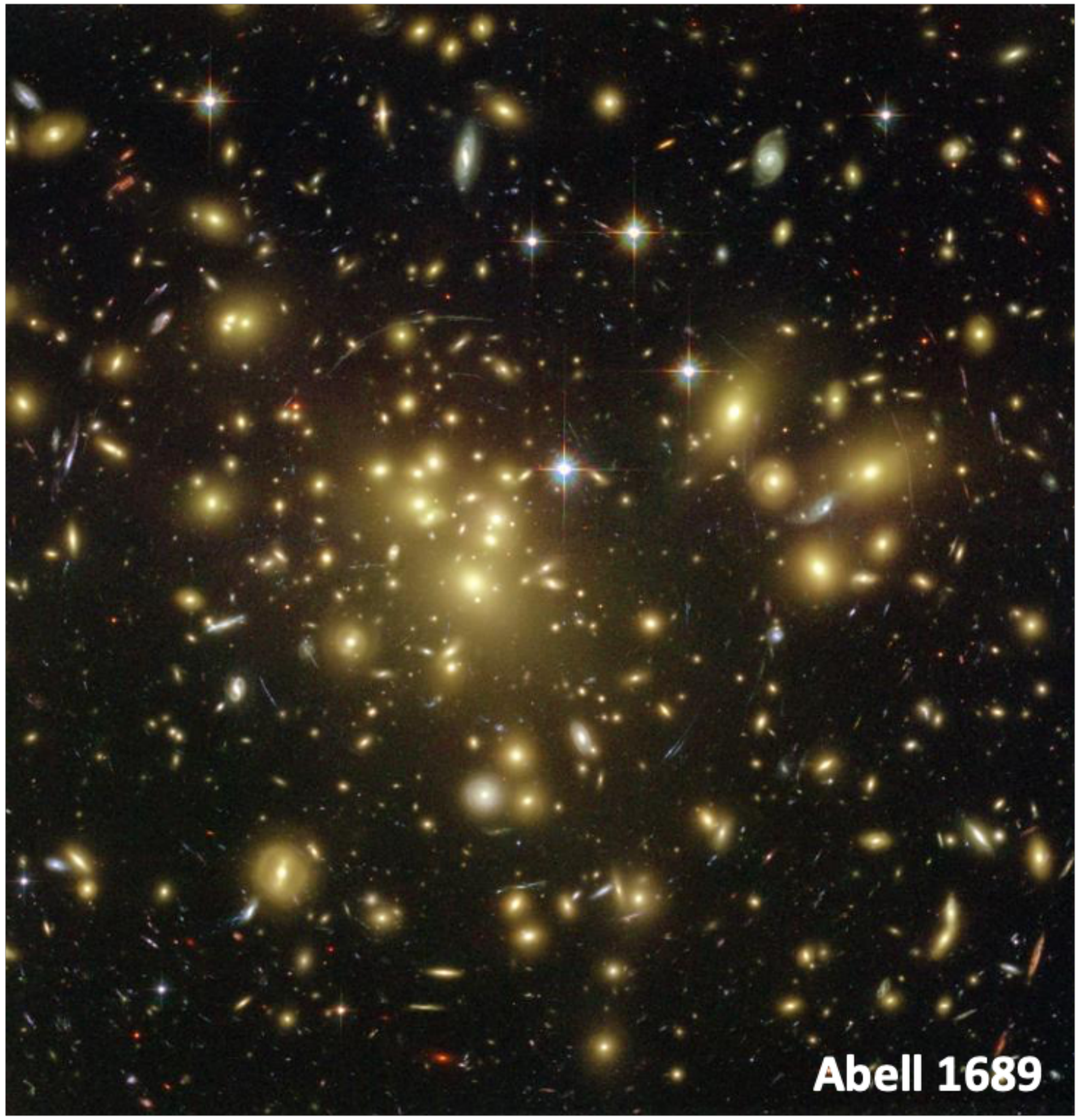

True Background
Lensed Image
True Background
Lensed Image

Weighing clusters with weak gravitational lensing

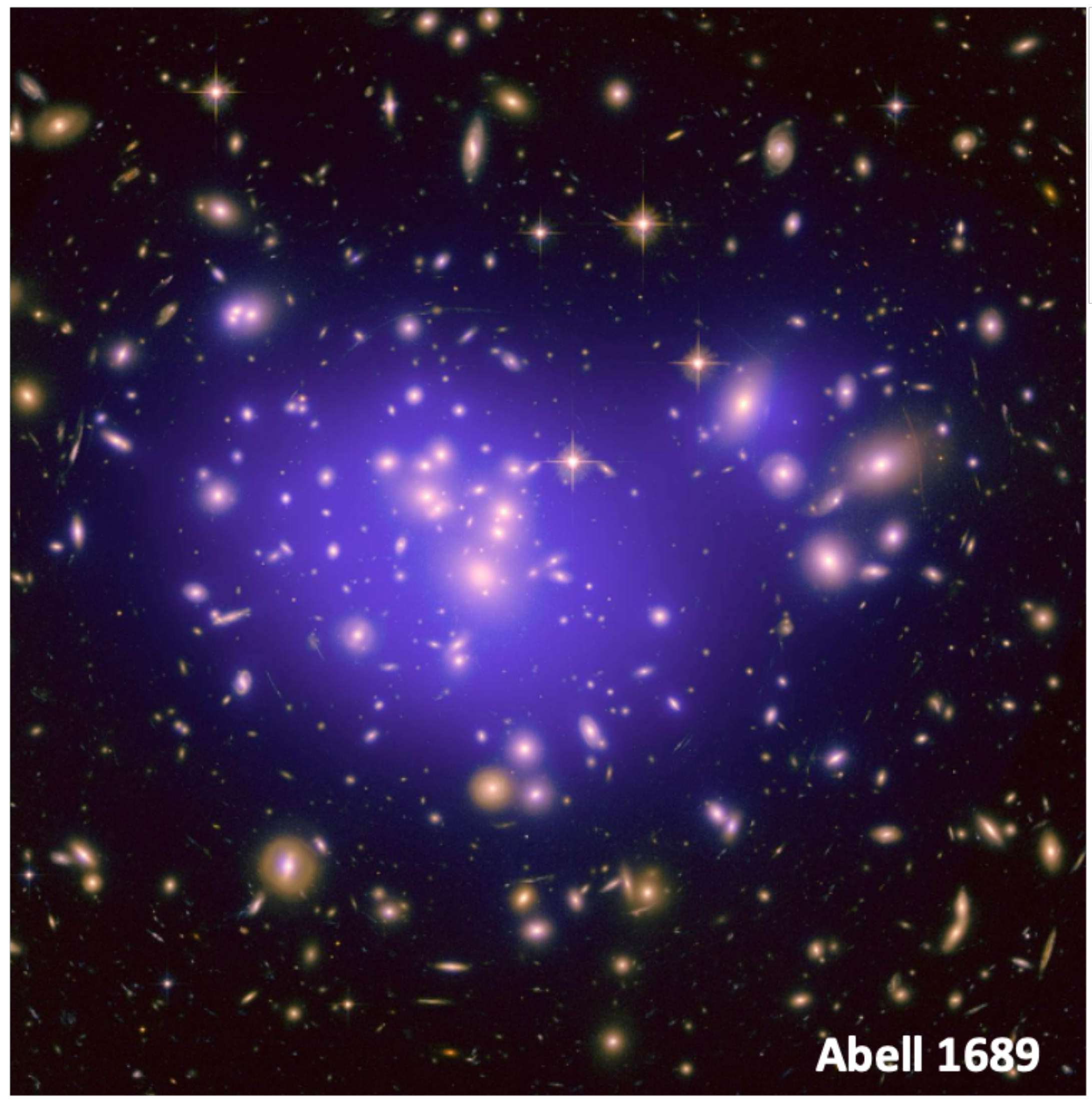


Tyson et al. (1990)

A lot of improvement over the past decade



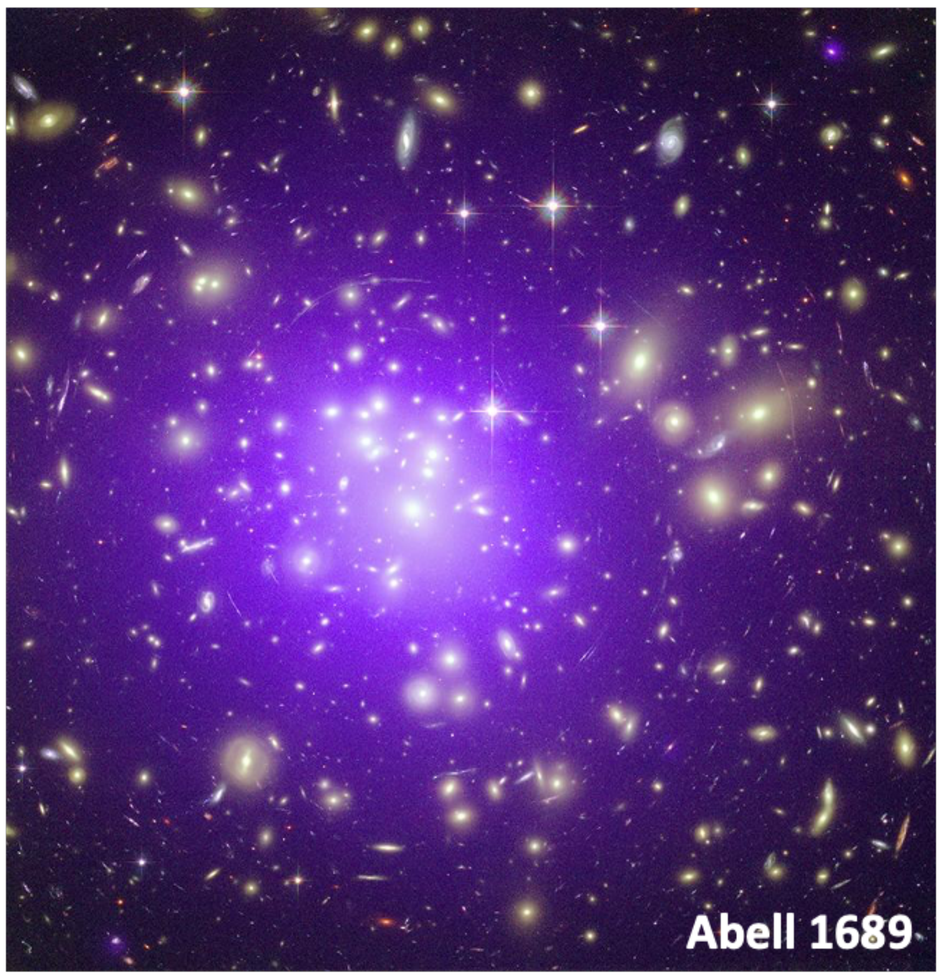
Much higher resolution mass maps



NASA, ESA, E. Jullo (JPL/LAM), P. Natarajan (Yale) and J-P. Kneib (LAM)

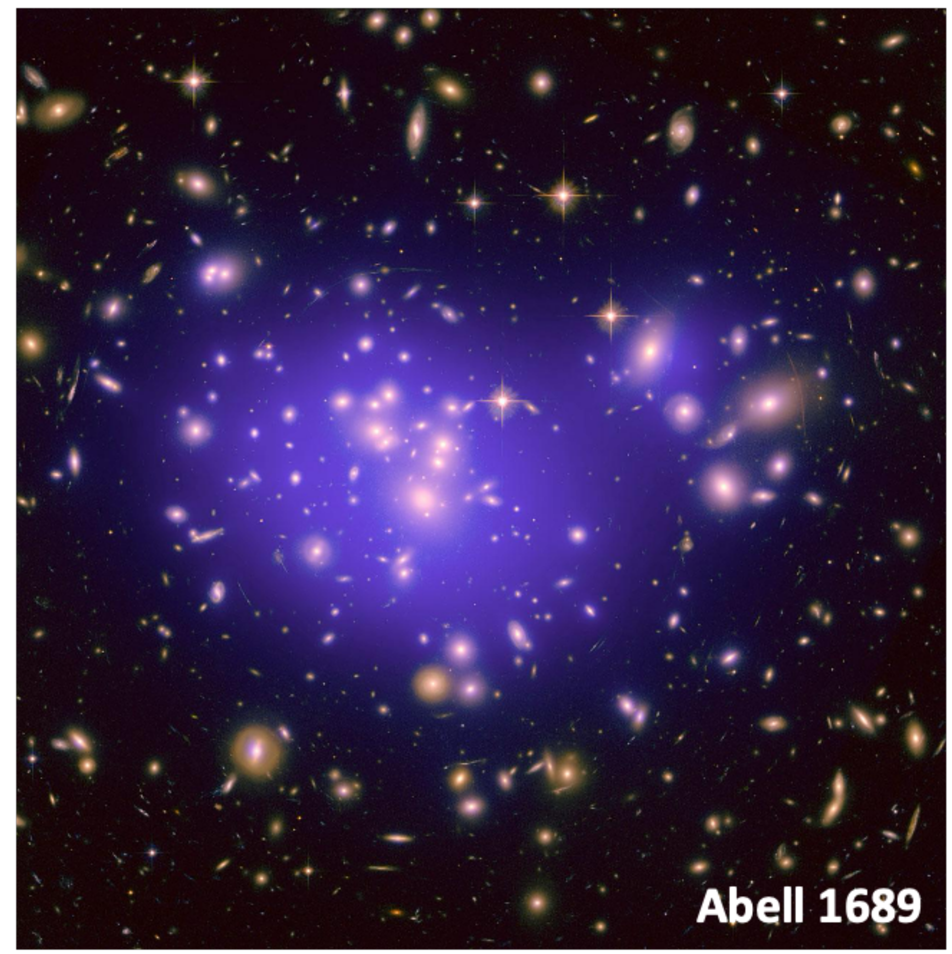
For some clusters the X-ray plasma and dark matter distributed similarly

X-ray Plasma



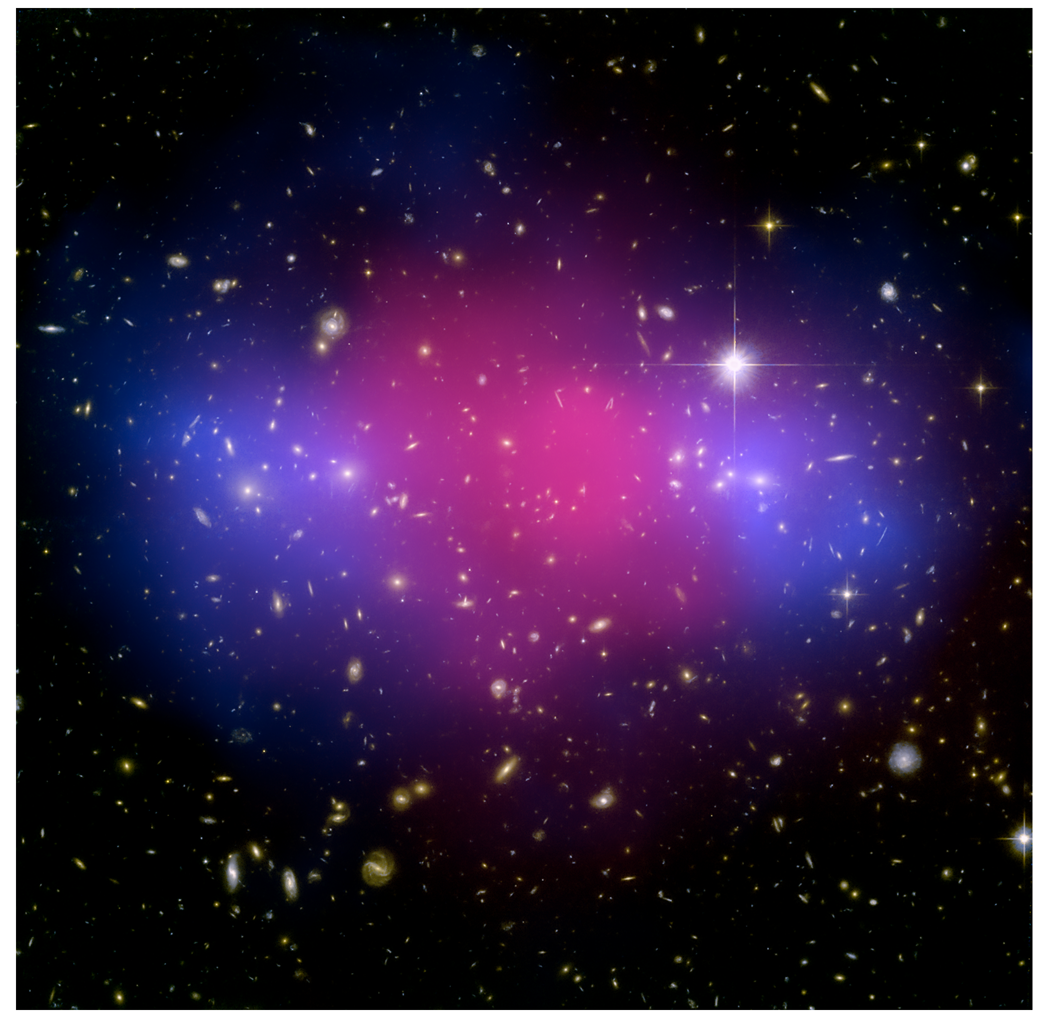
X-ray: NASA/CXC/MIT/E.-H Peng et al; Optical: NASA/STScI

Dark Matter

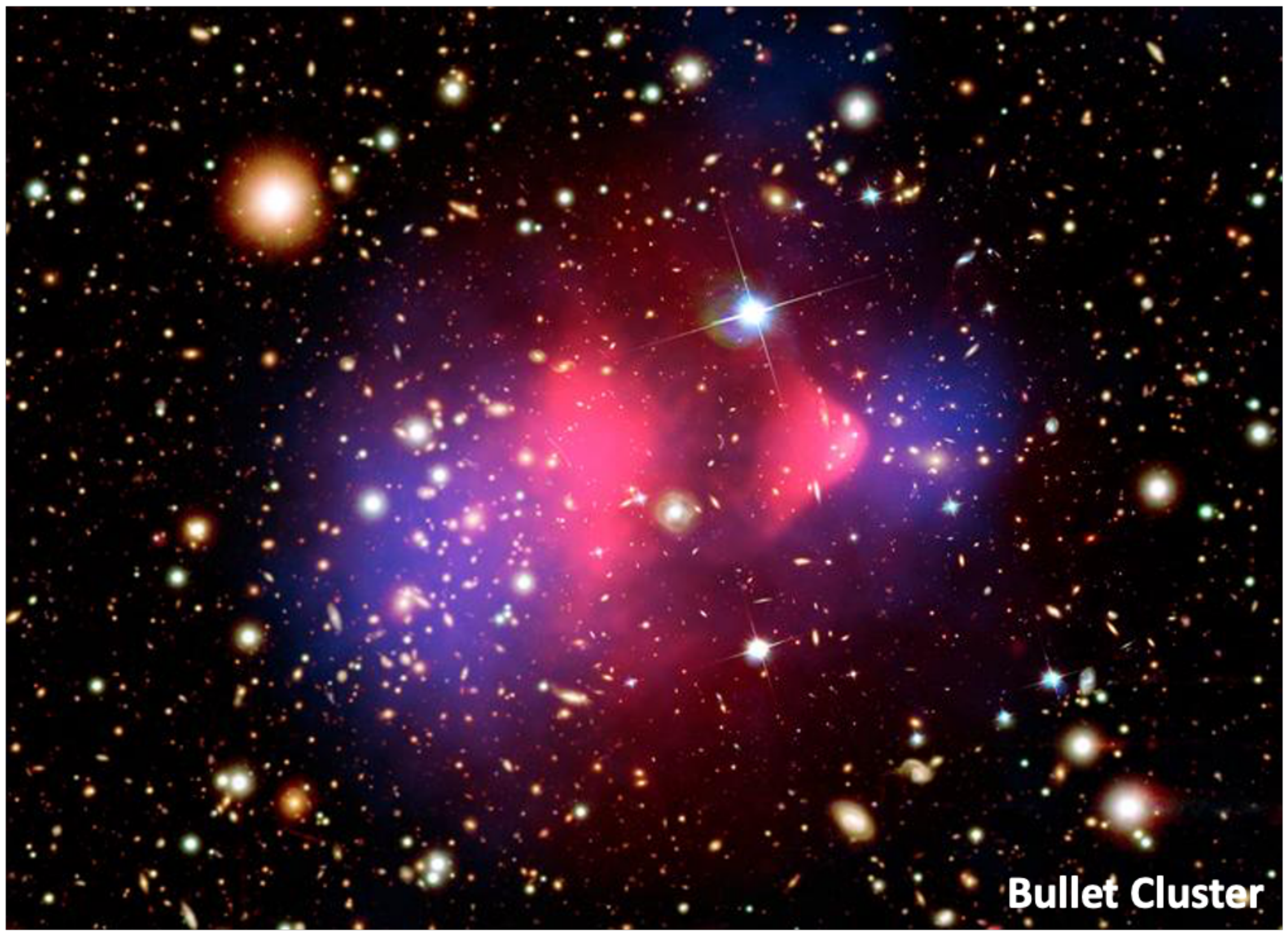


NASA, ESA, E. Jullo (JPL/LAM), P. Natarajan (Yale) and J-P. Kneib (LAM)

Merging clusters are an exception

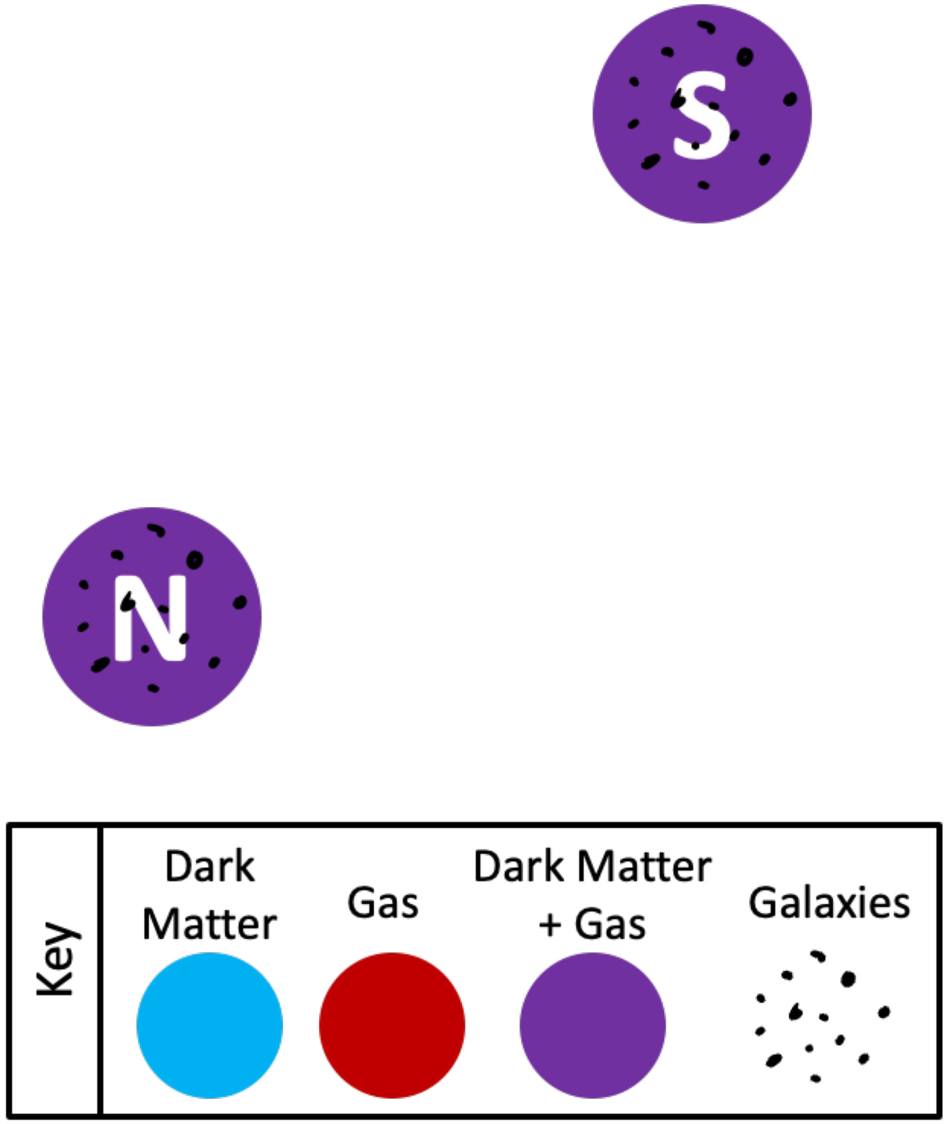


Merging galaxy clusters are an exception

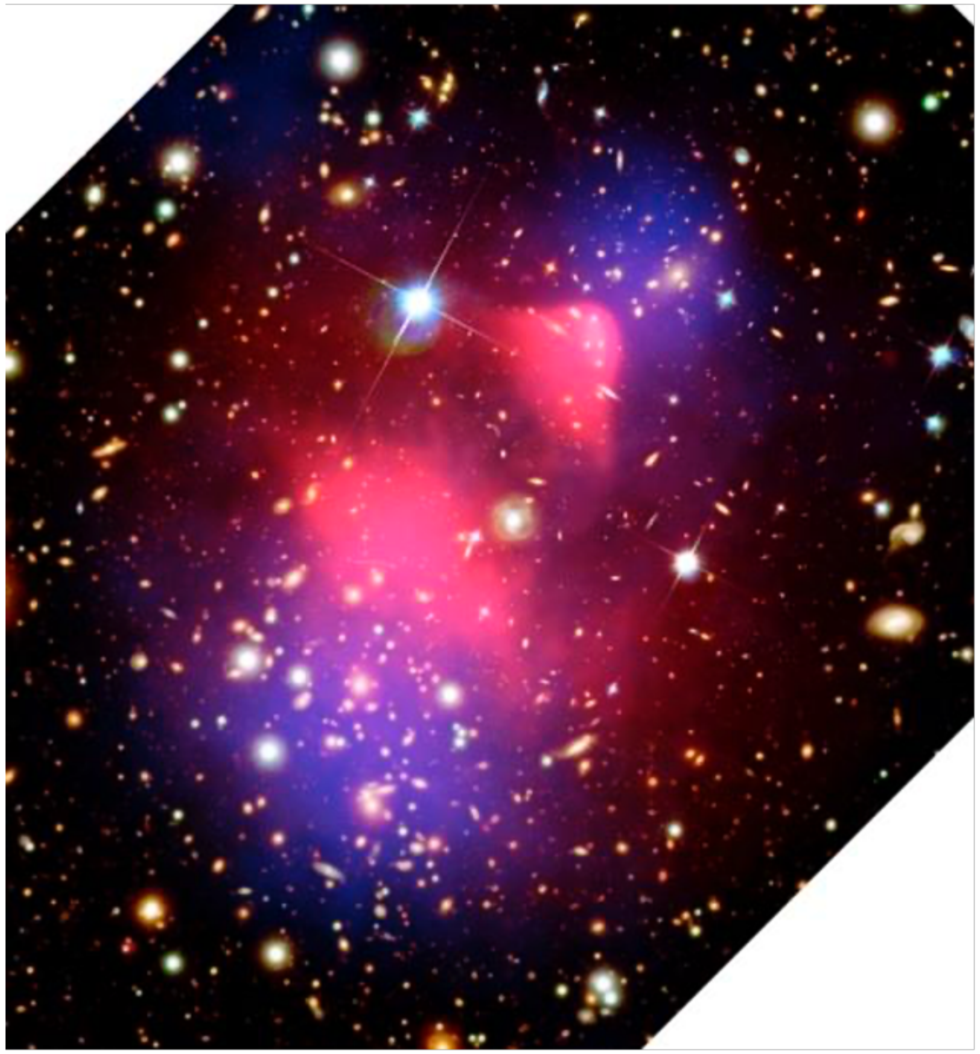


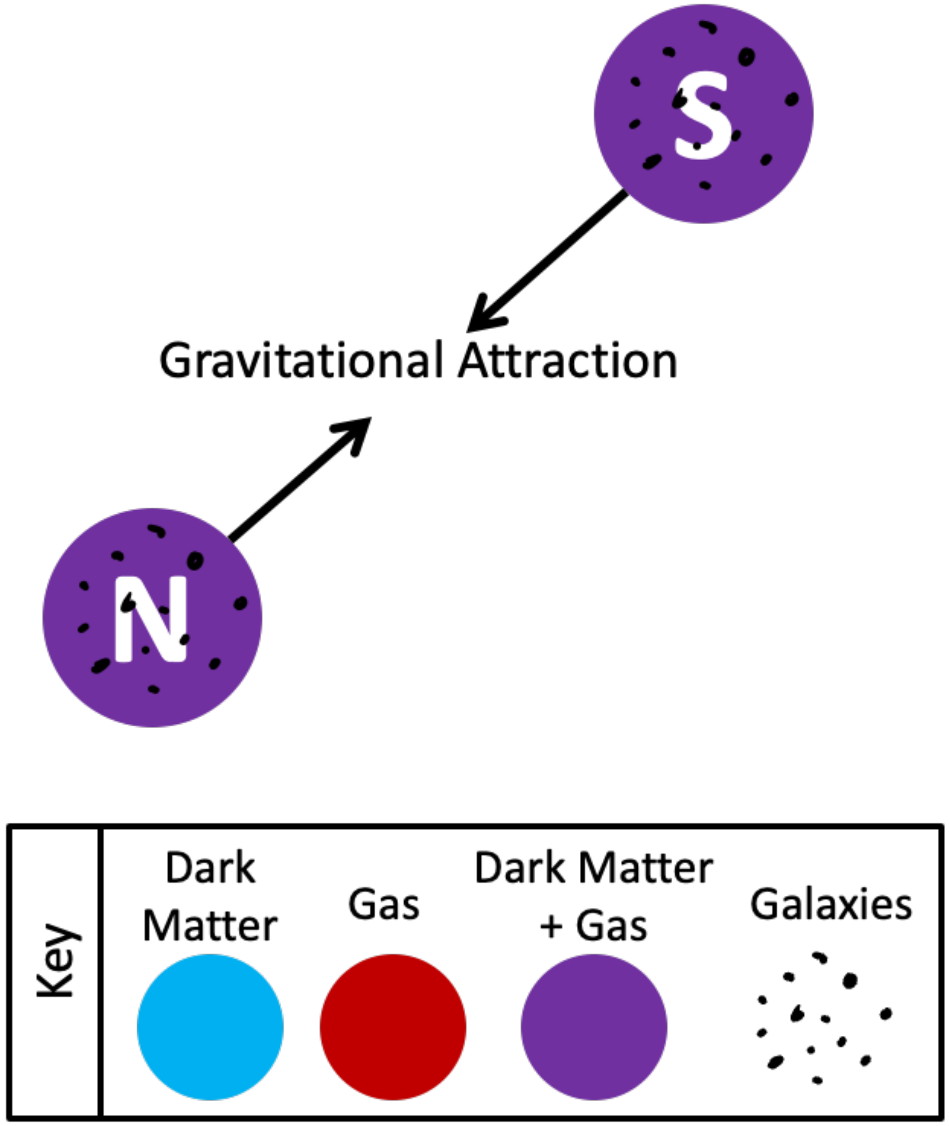
X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

Merger Scenario

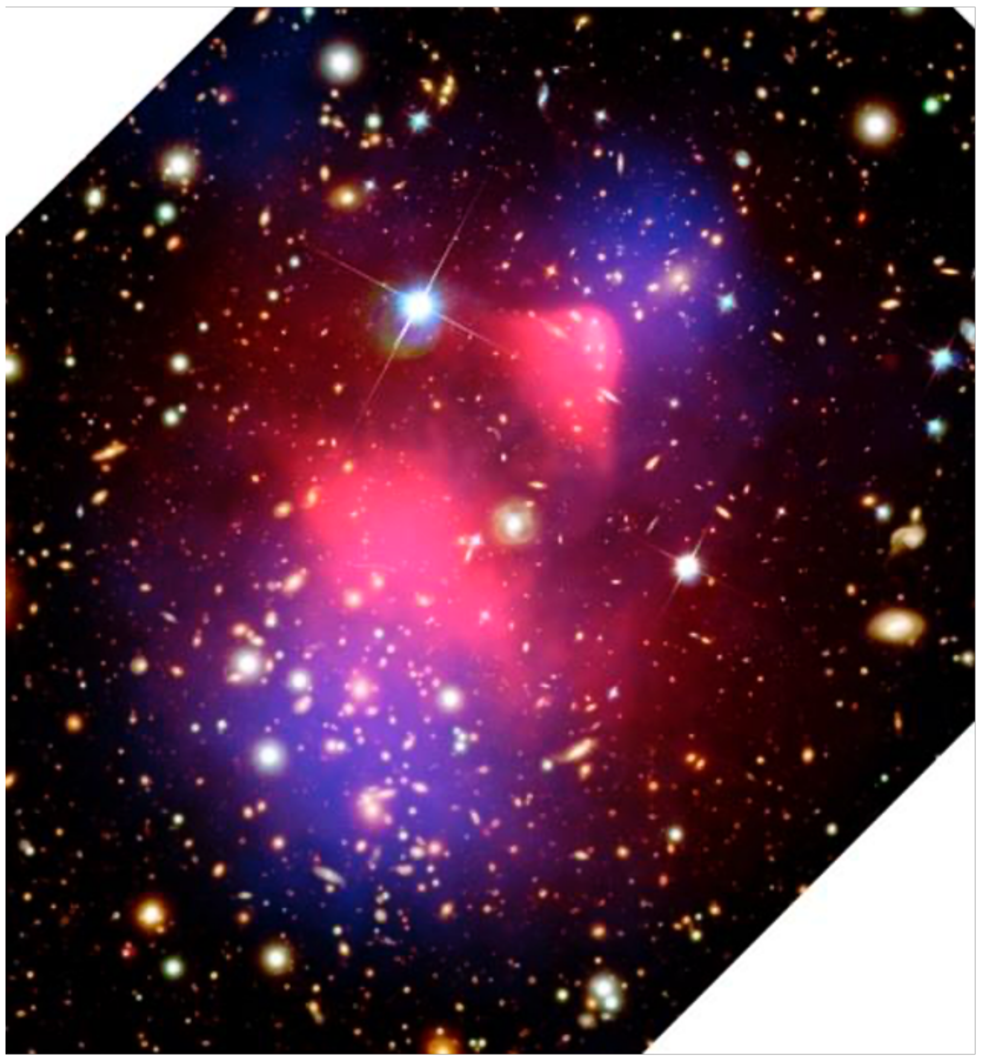


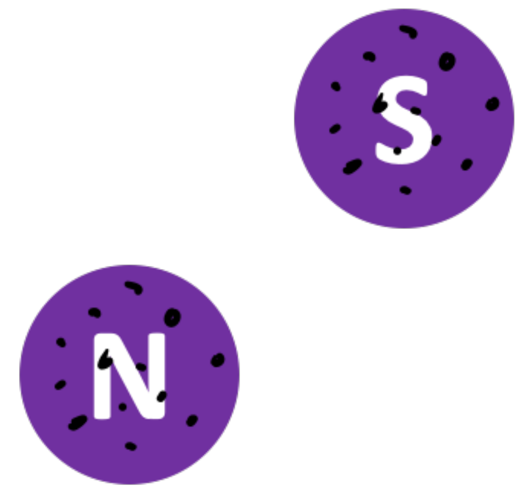
Merger Scenario

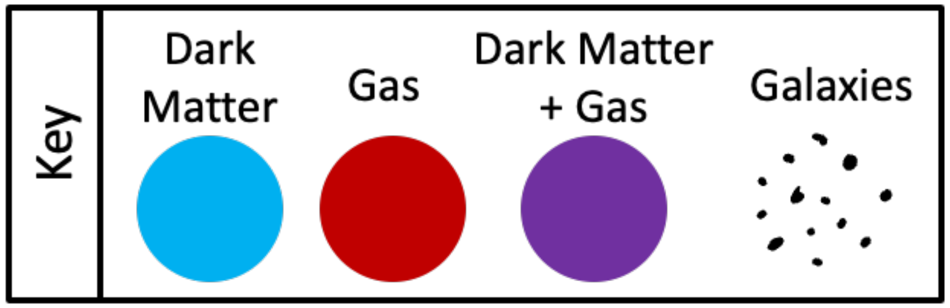




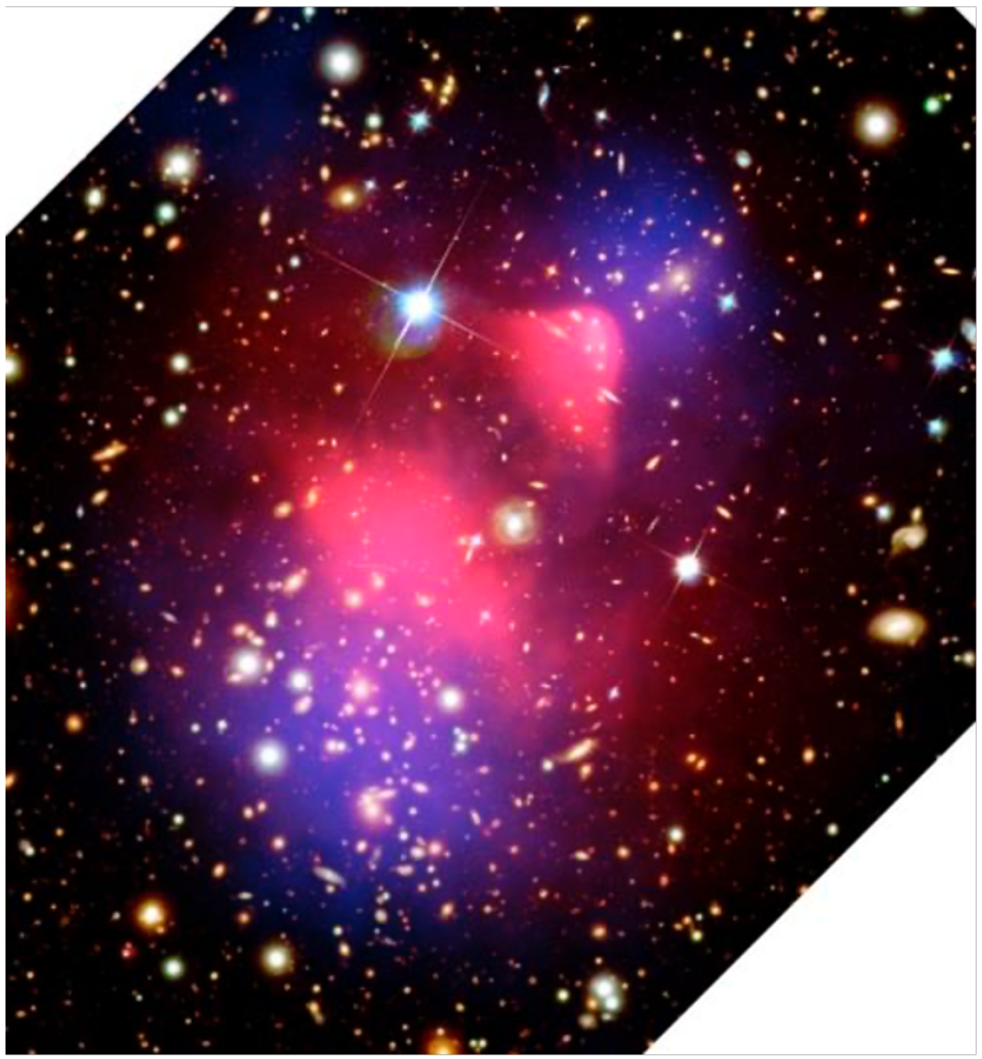
Merger Scenario

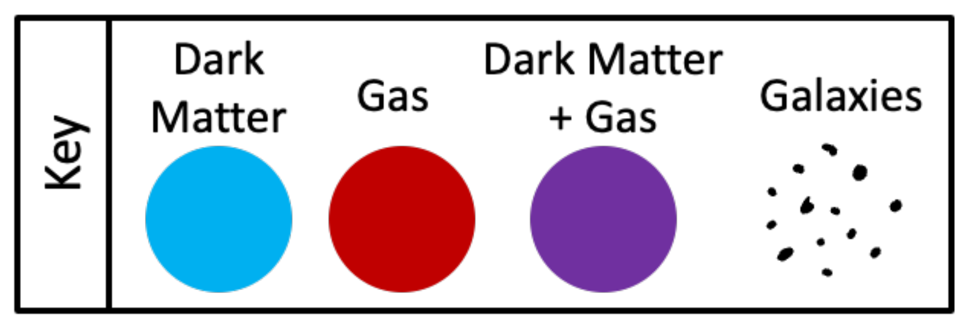




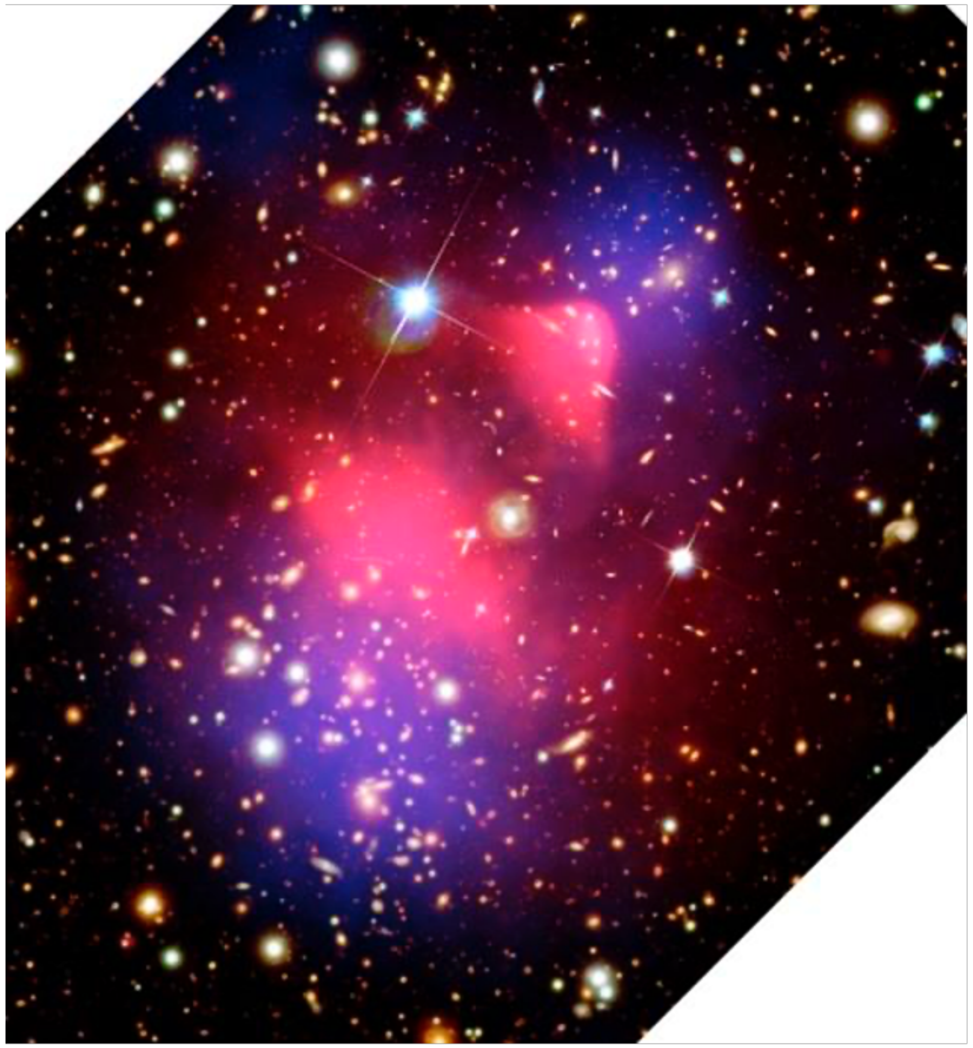


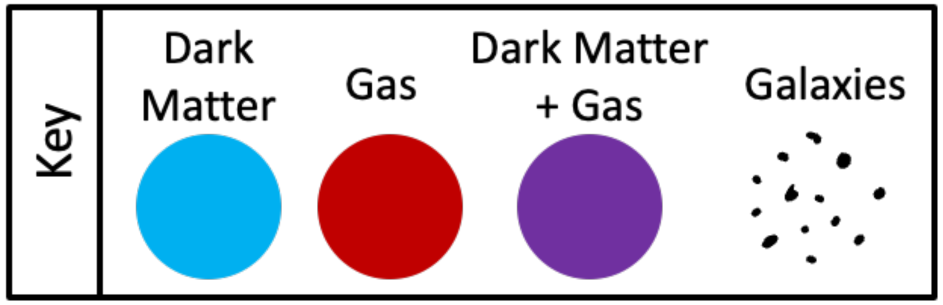
Merger Scenario



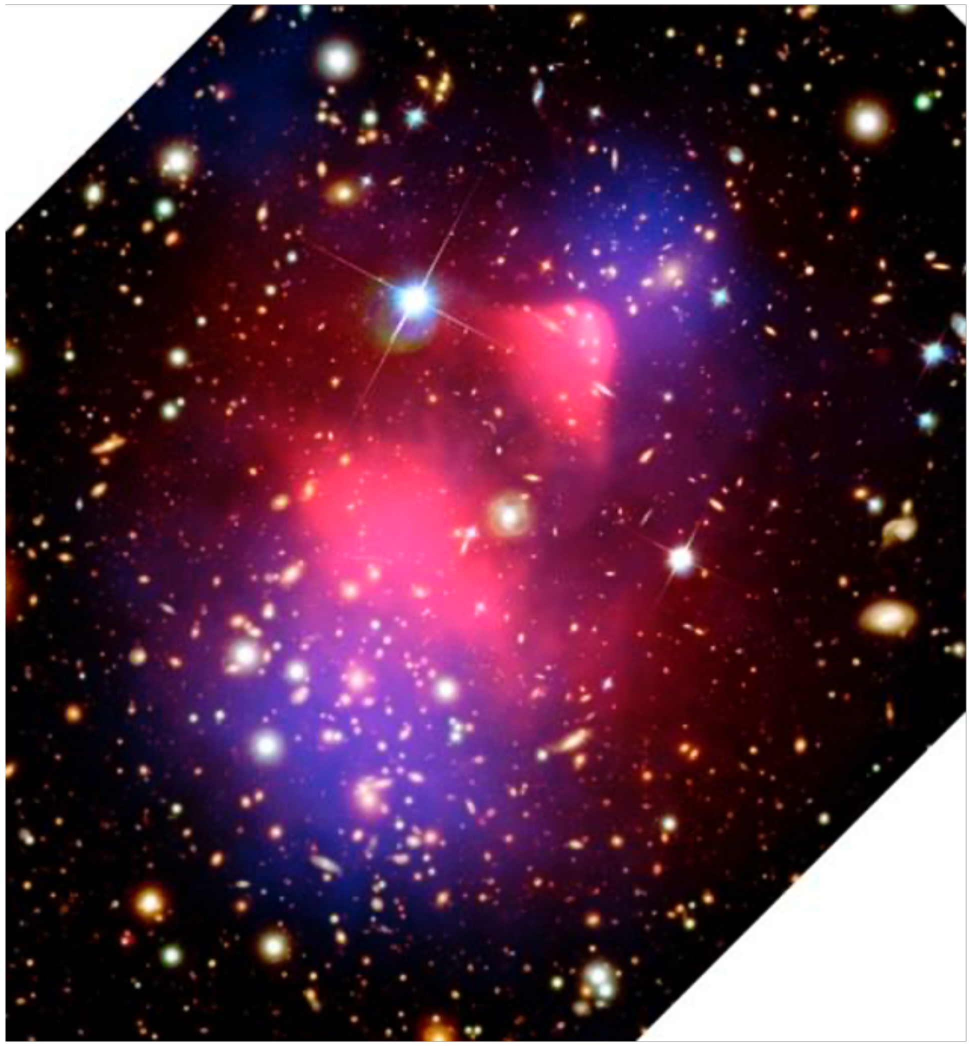


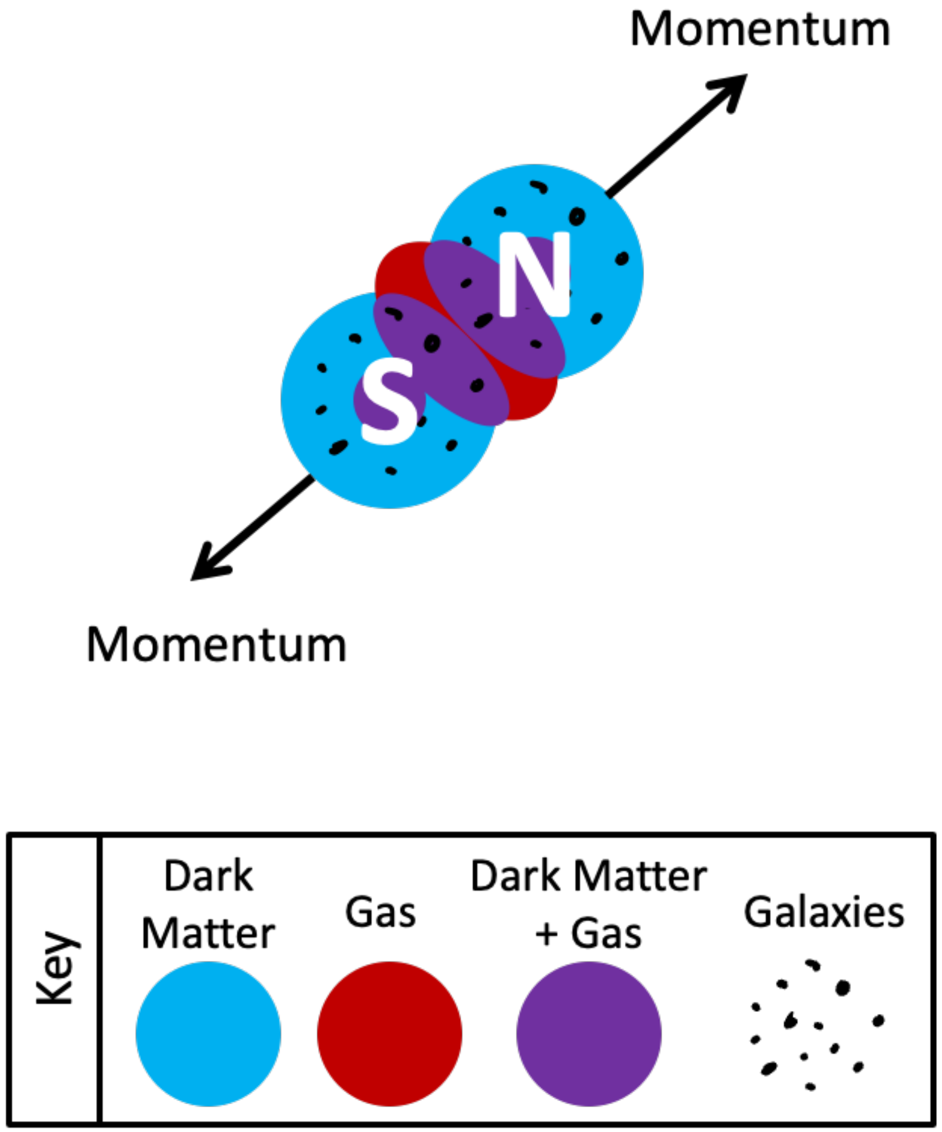
Merger Scenario





Merger Scenario





Merger Scenario