2019.06.12-14, XMM-Newton 2019 Science Workshop, ESAC, Madrid, Spain

An X-ray view of the hot circum-galactic medium (CGM)

Jiang-Tao Li

Assistant Research Scientist
Department of Astronomy, University of Michigan, Ann Arbor
jiangtal@umich.edu

Image credit: Li Jiang-Tao, Bregman Joel N., Wang Q. Daniel, Crain Robert A., Anderson Michael E., and ESA

Outline

- 1. What we know about the hot CGM?
- 2. What we still don't know?
- 3. What could we do with future X-ray missions?

1.0. Key science related to the hot CGM

Mass/baryon/metal and energy budget of galaxies

How much mass/baryon/metal and energy are expected v.s. How much are detected

Other key science:

How the CGM is connected to the star formation?

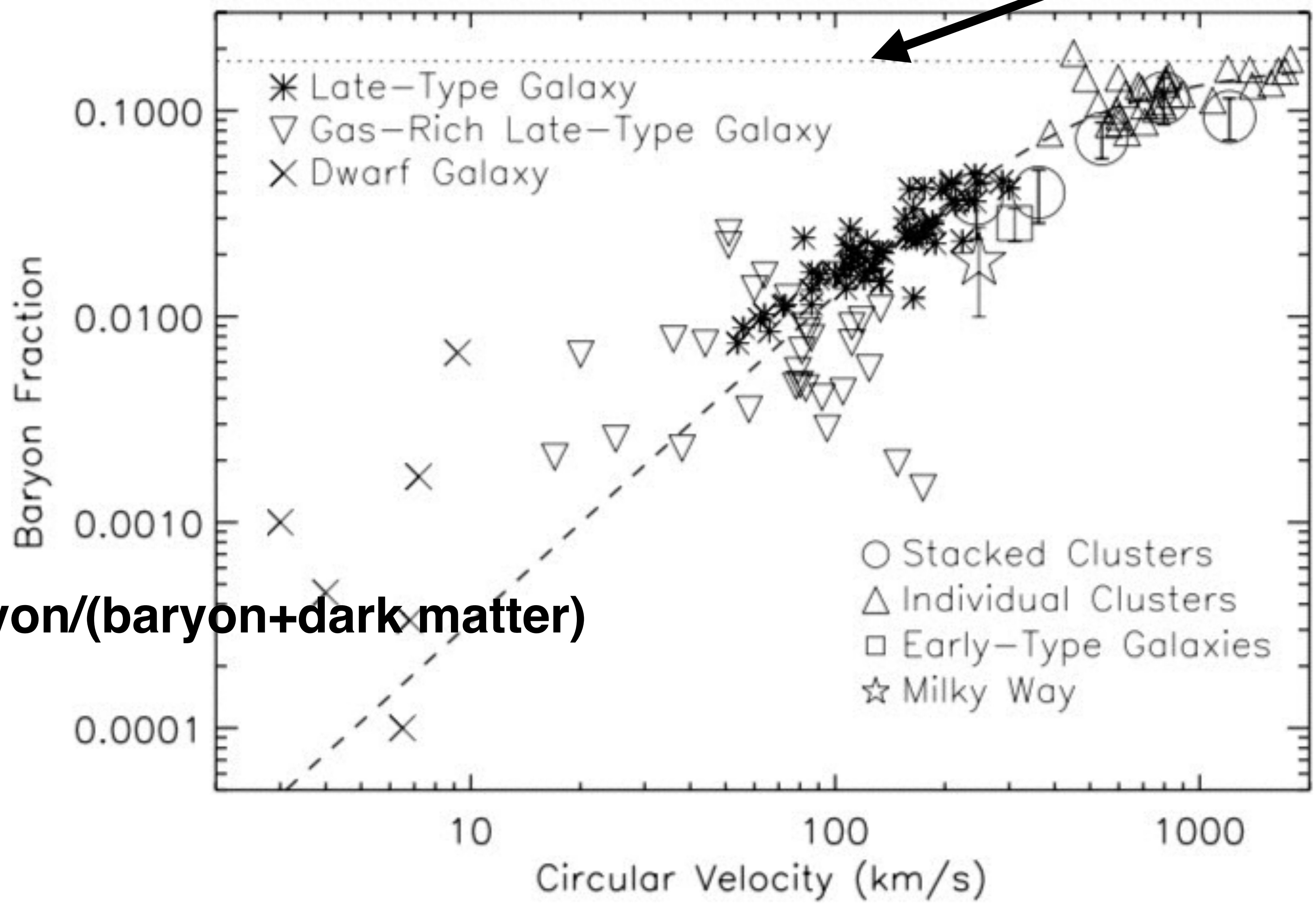
How the galaxies coevolve with their ecosystem?

……

1.0. Key science related to the hot CGM

Mass/baryon/metal budget of galaxies

cosmic baryon fraction



= baryon/(baryon+dark matter)

Dai et al., 2010, ApJ, 719, 119

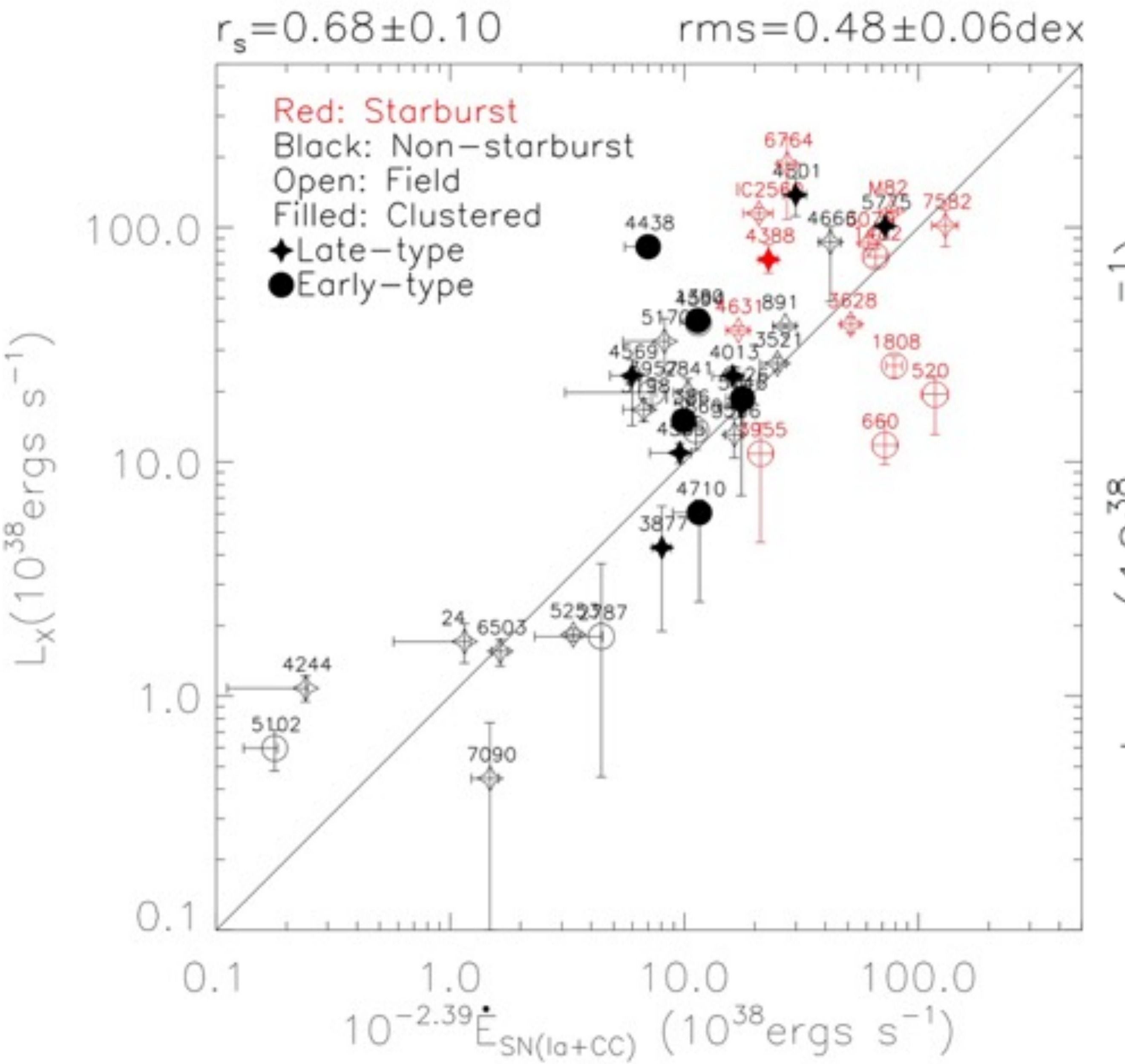
A review of the **missing baryon problem** (**Bregman, 2007, ARA&A, 45, 221; Bregman et al., 2018, ApJ, 862, 3**).

Energy budget of galaxies

Energy detected in different phases of the CGM

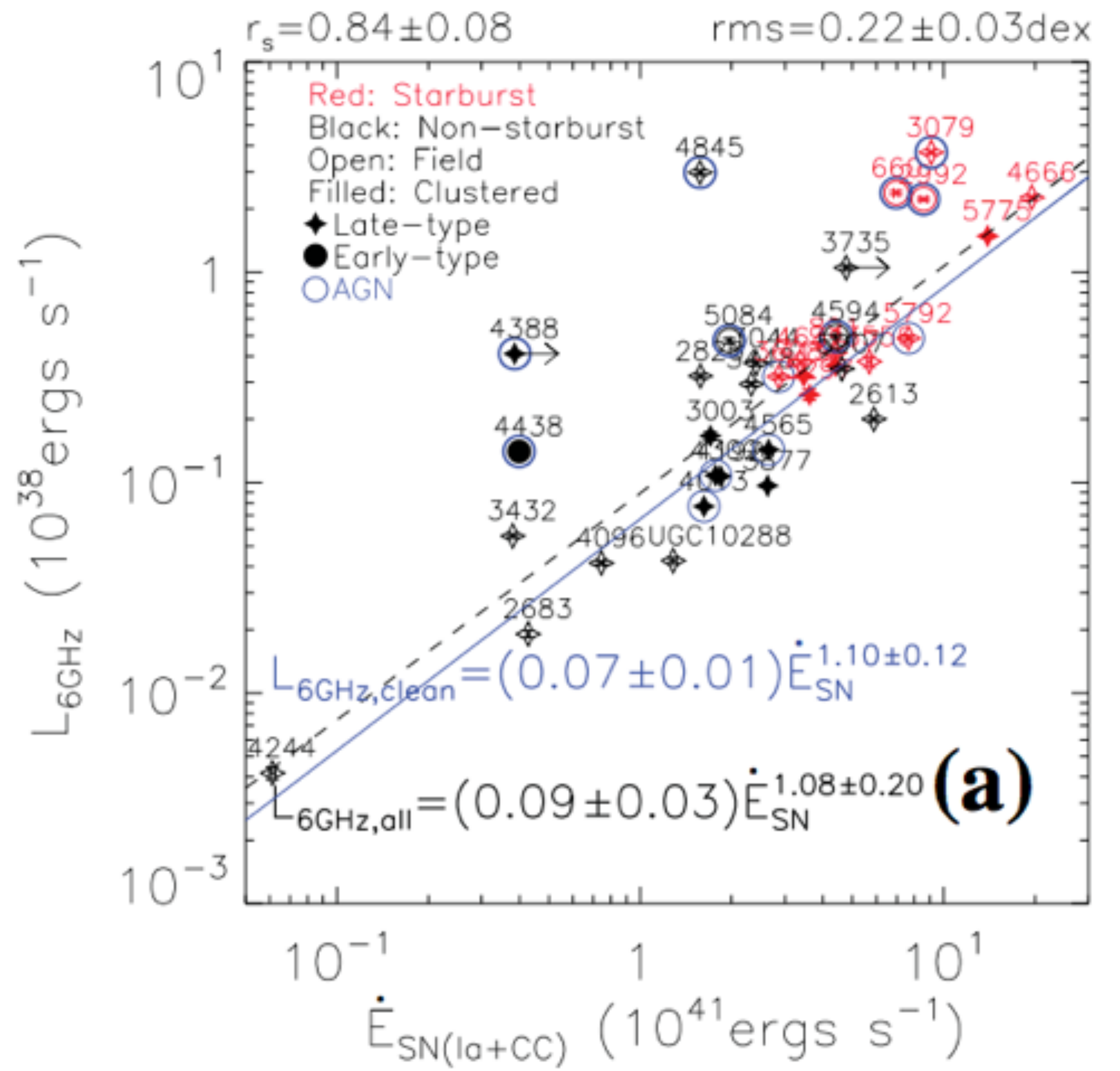
X-ray

Li & Wang, 2013, MNRAS, 435, 3071



Radio

Li et al., 2016, MNRAS, 456, 1723



Expected supernovae energy injection rate

Energy budget of galaxies

Energy sources:

~~(1) AGN~~

~~(2) Gravitational energy of the infall gas in the dark matter halo~~

~~(3) Radiation from young stars~~

~~(4) Young stellar wind~~

(5) Supernovae: Type Ia+ core collapsed (CC)

……

Converted to:

Inside the galaxy (in the ISM):

~~(1) IR continuum reprocessed by dust~~

~~(2) UV, optical, IR line emission reprocessed by cool gas~~

……

Out of the galaxy (in the CGM):

(1) Thermal energy of hot gas (radiated via X-ray) **~1%E_{SN}**

(2) Kinetic energy of global motion of hot gas (pressure driven adiabatic expansion) **<1%E_{SN}**

(3) Turbulent energy of small scale motion of hot gas **<0.1%E_{SN}**

(4) Kinetic energy of cold gas outflow **<1%E_{SN}**

(5) Radiative cooling of cool gas (peaked in UV emission lines) **~5%E_{SN}**

(6) Cosmic ray (CR) **~5%E_{SN}**

(7) Large scale magnetic field **<5%E_{SN}**

……

Total energy detected in the CGM: E_{CGM}<20%E_{SN}

Based on current observations! (e.g., Li & Wang 2013, MNRAS, 435, 3071; Li et al. 2016, MNRAS, 456, 1723)

1.1. Astronomy: Extended diffuse soft X-ray emission is ubiquitous around nearby galaxies

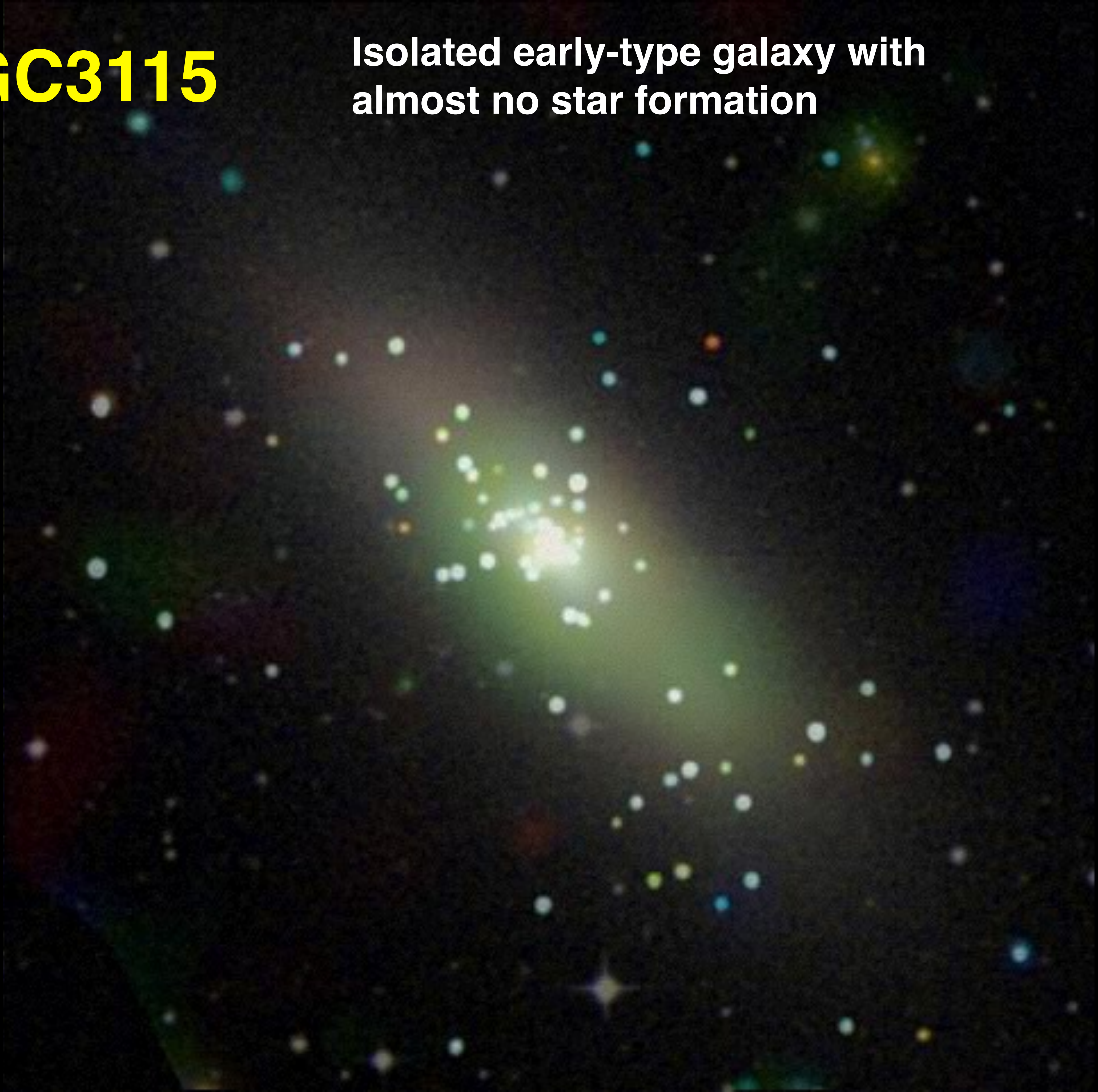
M82 Starburst in the nuclear region

NGC891

Star formation region spread over the disk

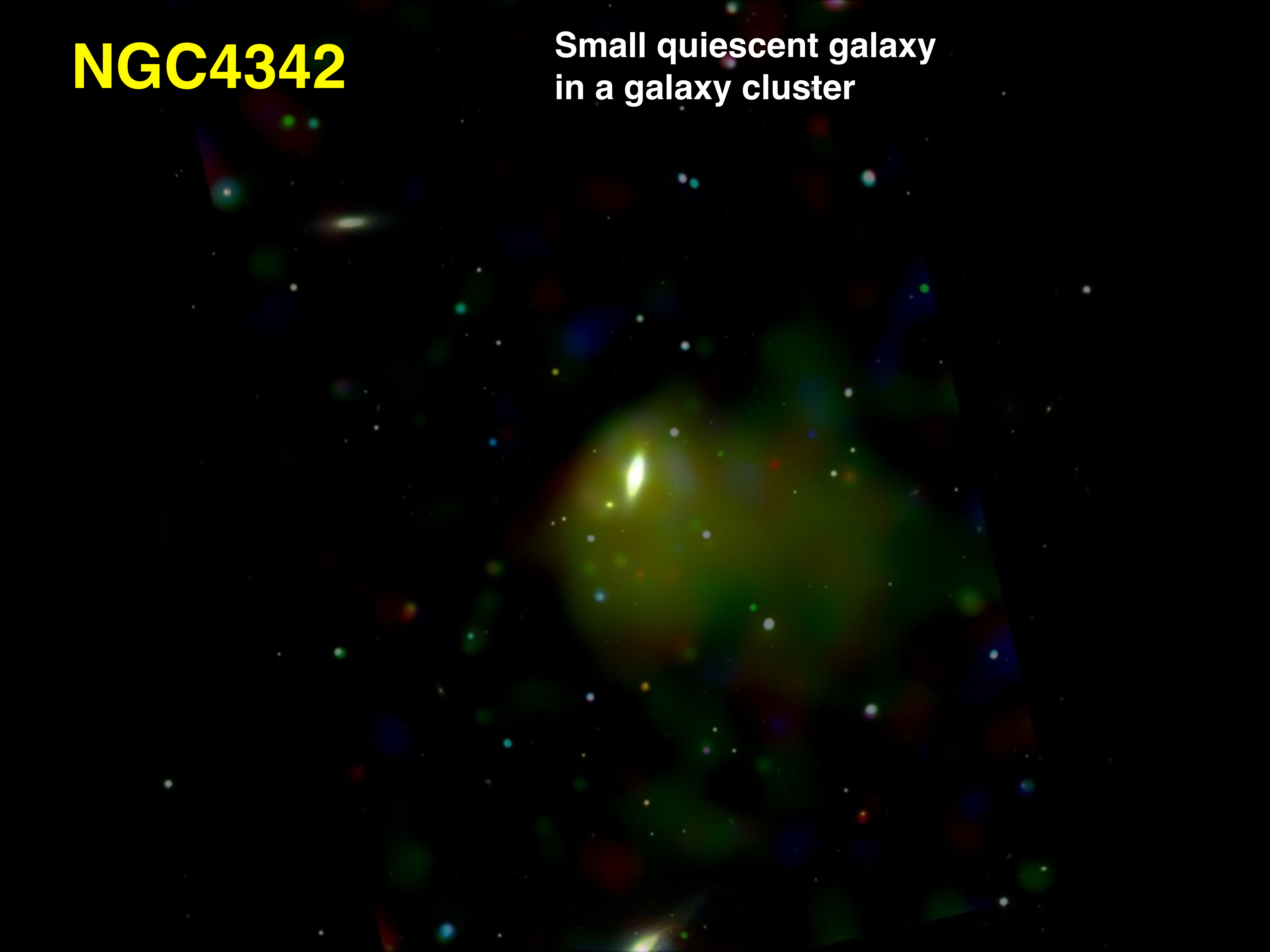
NGC3115

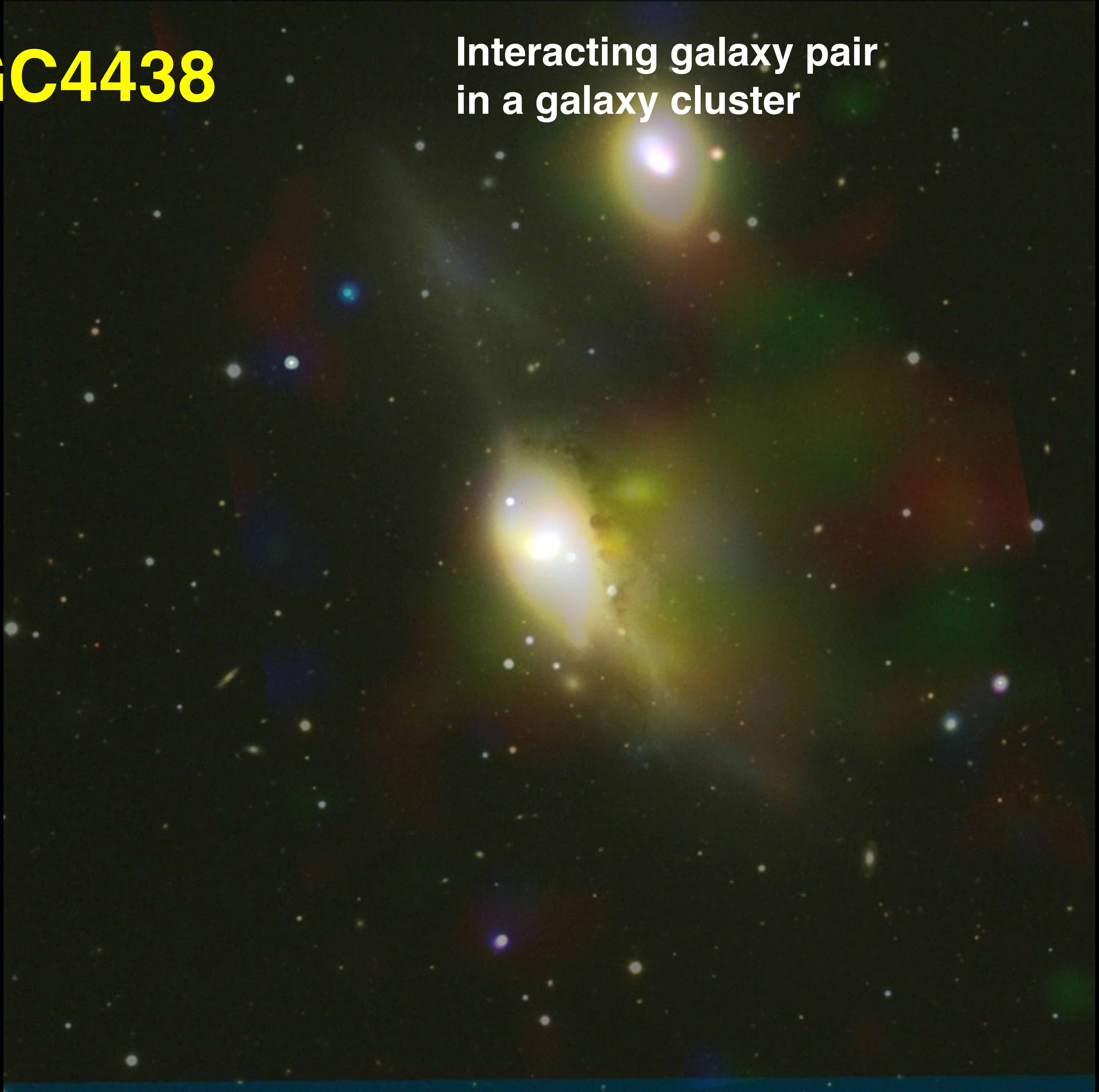
Isolated early-type galaxy with almost no star formation

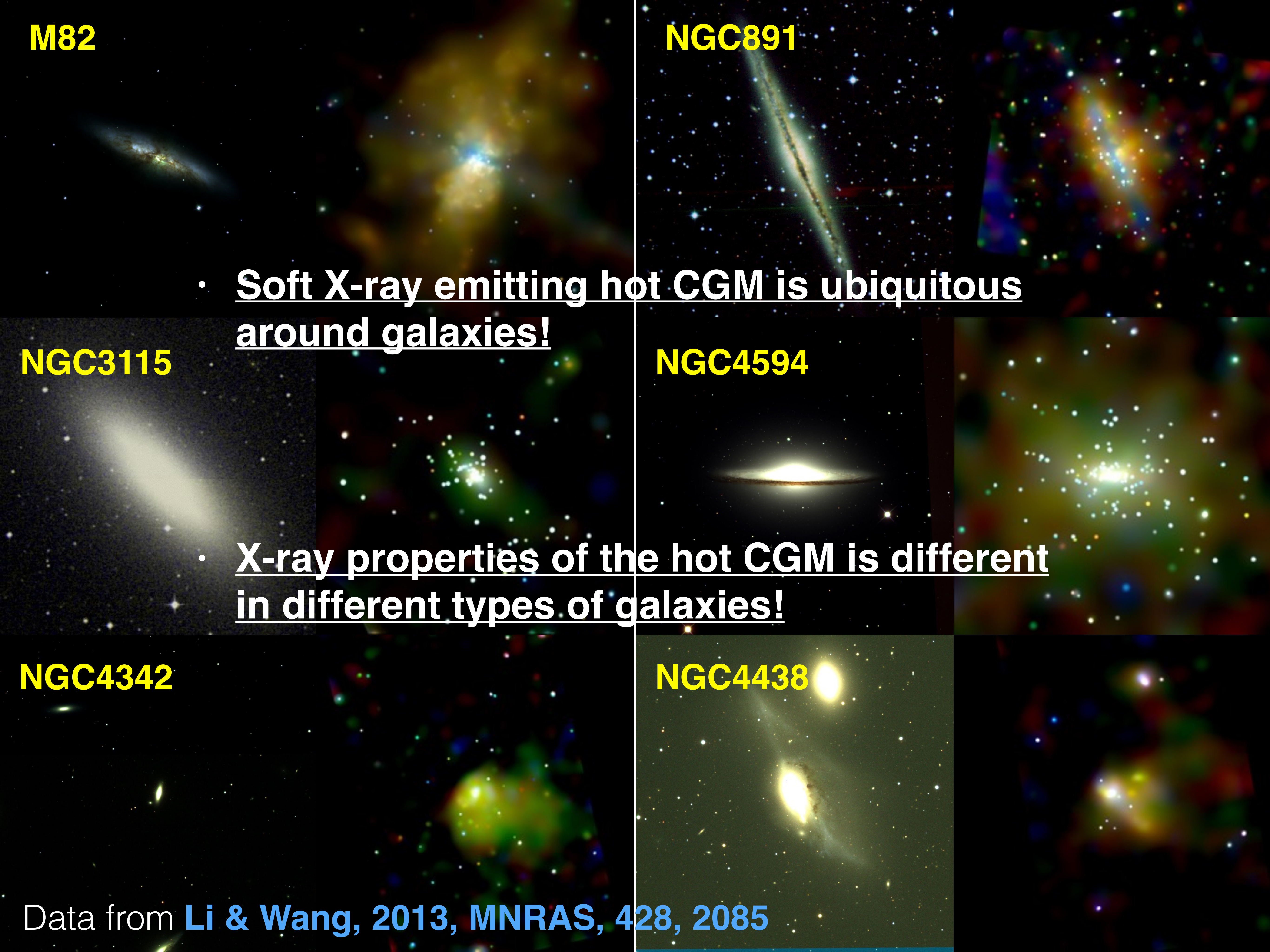


NGC4594

Isolated early-type galaxy with almost no star formation


NGC4342
Small quiescent galaxy
in a galaxy cluster


NGC4438
Interacting galaxy pair
in a galaxy cluster



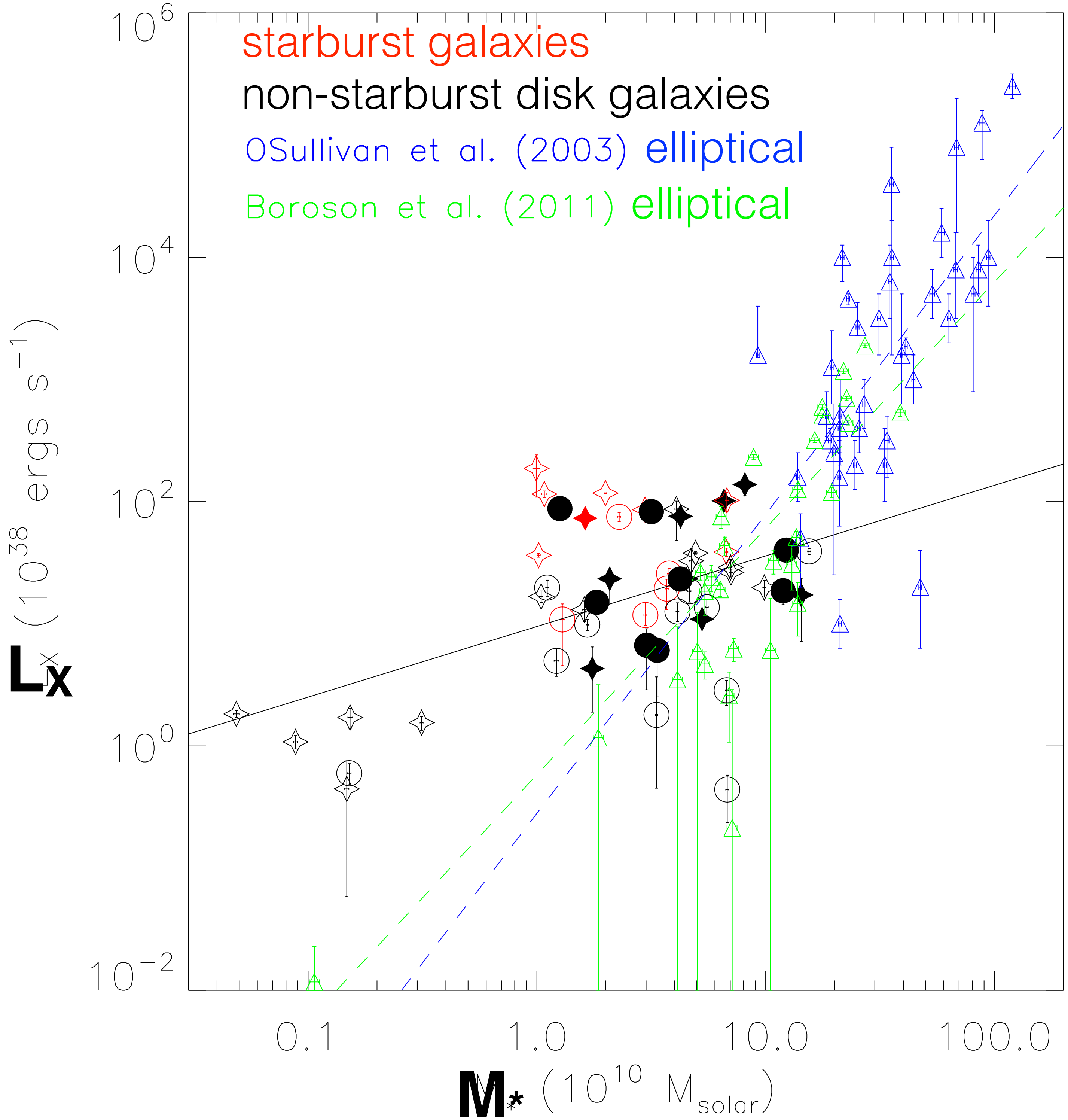
- Soft X-ray emitting hot CGM is ubiquitous around galaxies!
- X-ray properties of the hot CGM is different in different types of galaxies!

Data from Li & Wang, 2013, MNRAS, 428, 2085

1.2. Statistics: X-ray properties of the CGM are different in different types of galaxies

disk galaxies

elliptical galaxies



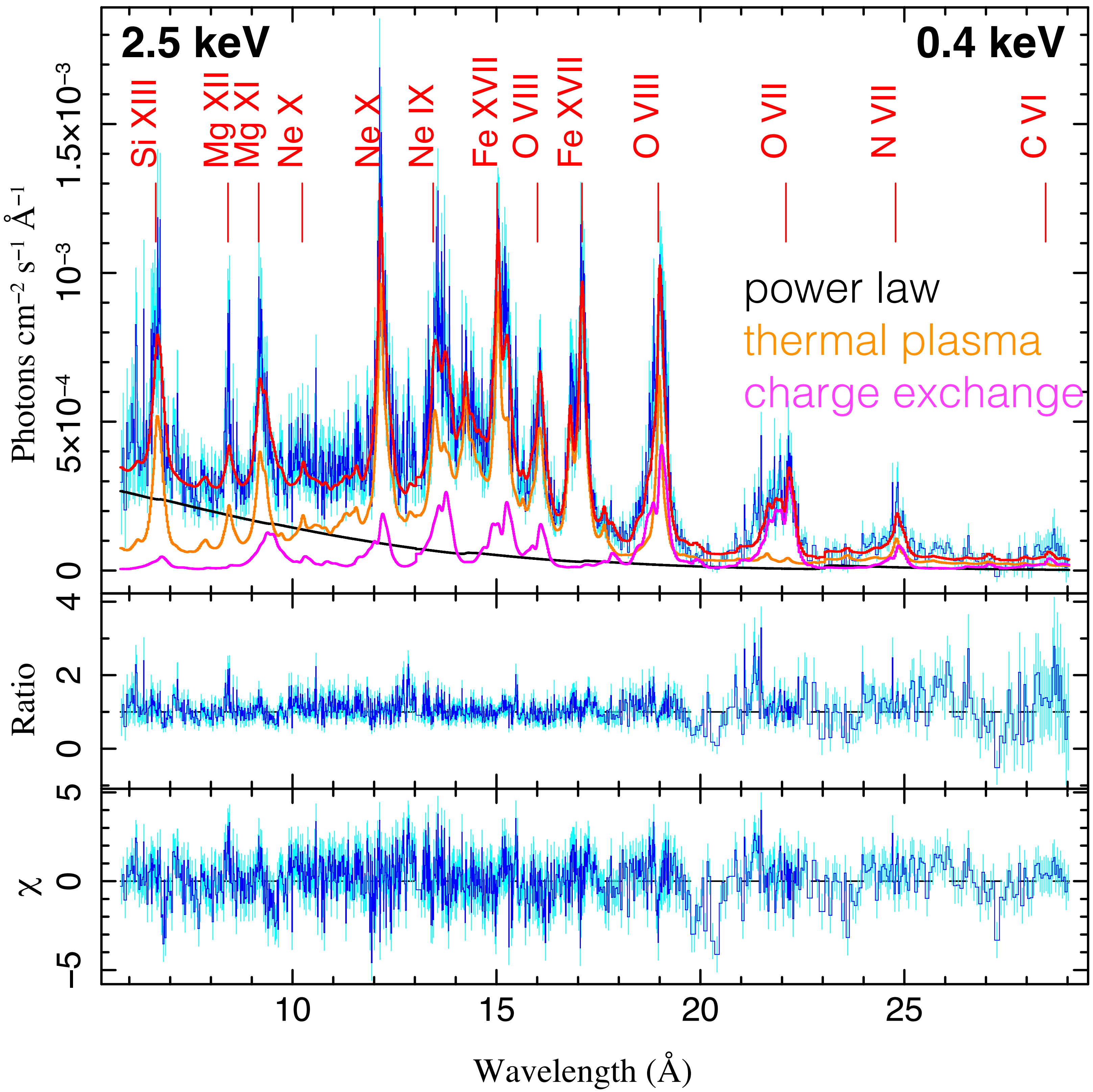
Sample still small. Cannot well determine relationships for different subsamples.

Li & Wang, 2013, MNRAS, 435, 3071; O'Sullivan03, Strickland04, Tullmann06, Humphrey06, Boroson11, Mineo12, Bogdan15, Kim15,18, Wang16, etc.

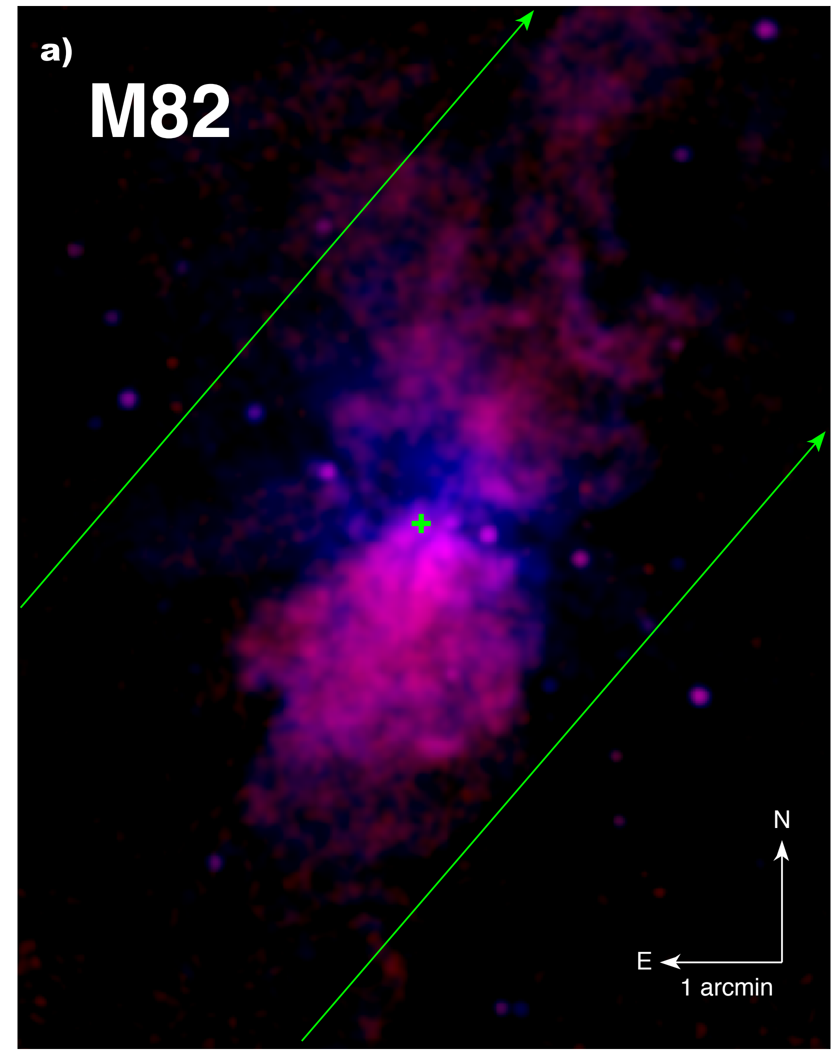
Outline

- **1. What we know about the hot CGM?**
- **2. What we still don’t know?**
- **3. What could we do with future X-ray missions?**

2.1. Physics: What is the physical, chemical, and dynamical properties of the hot CGM?

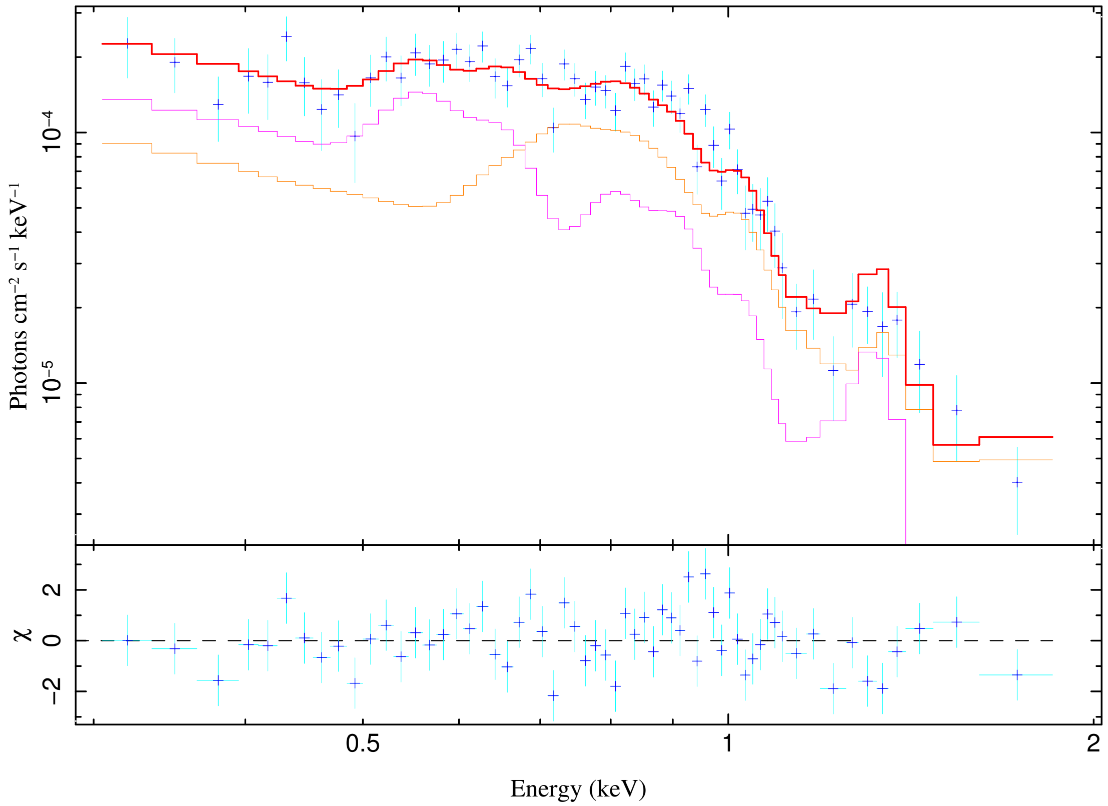


Zhang et al., 2014, ApJ, 794, 61

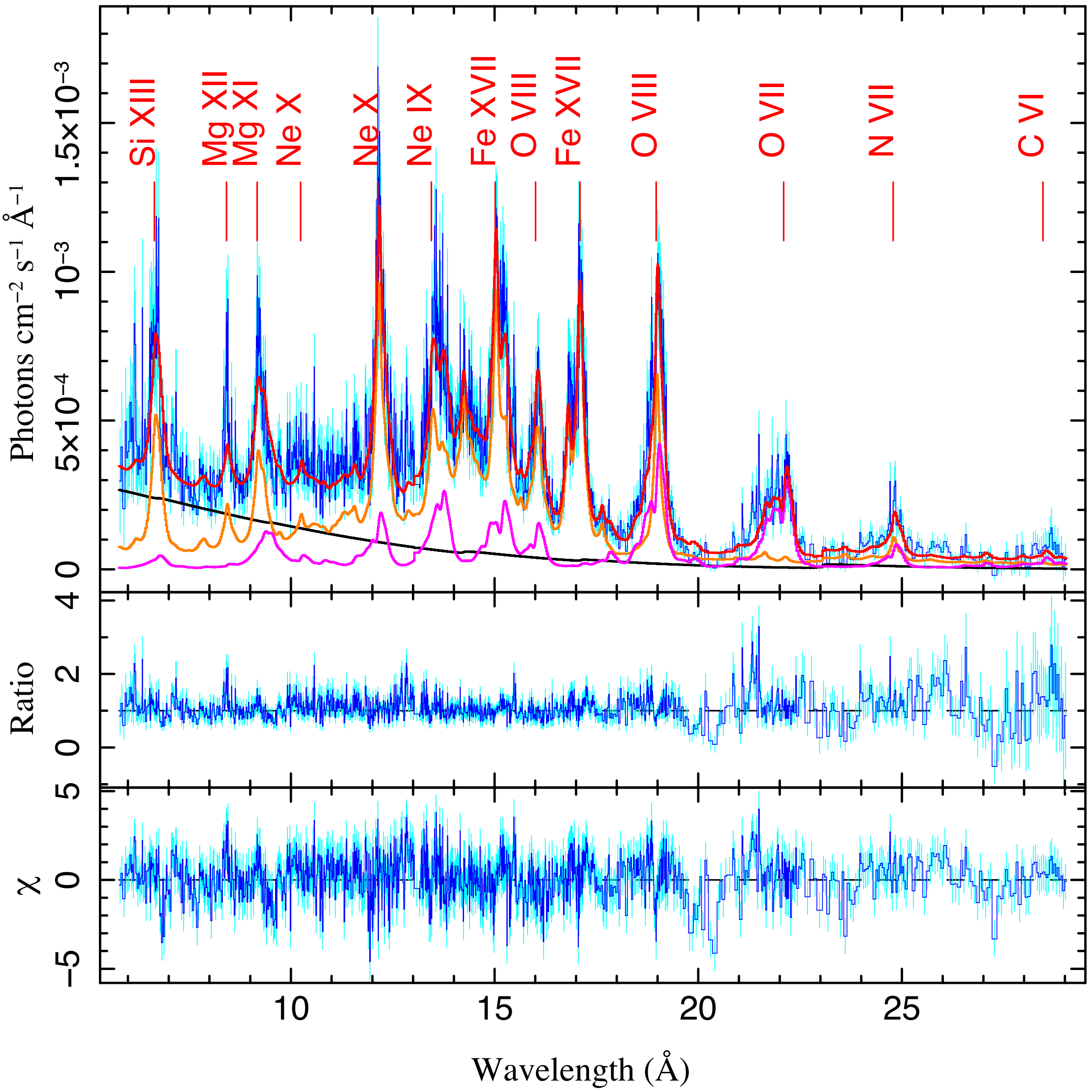


Grating X-ray spectra.

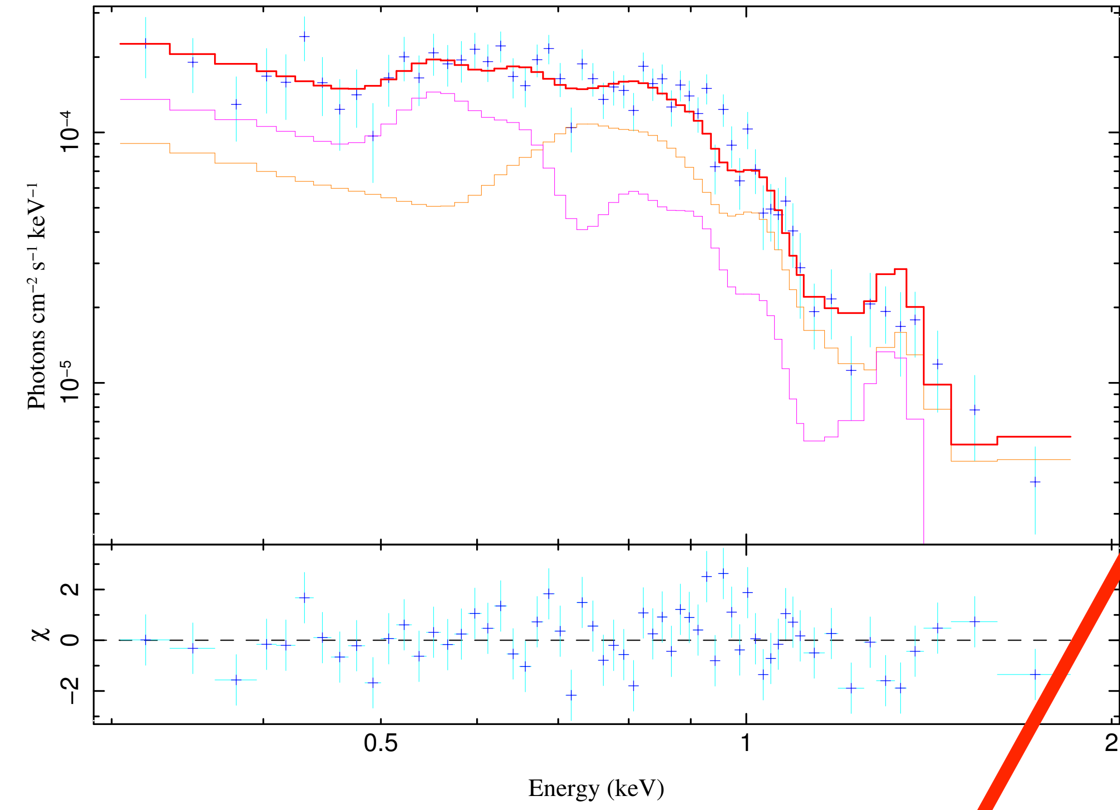
Soft X-ray emission dominated by **strong emission lines** from different components.



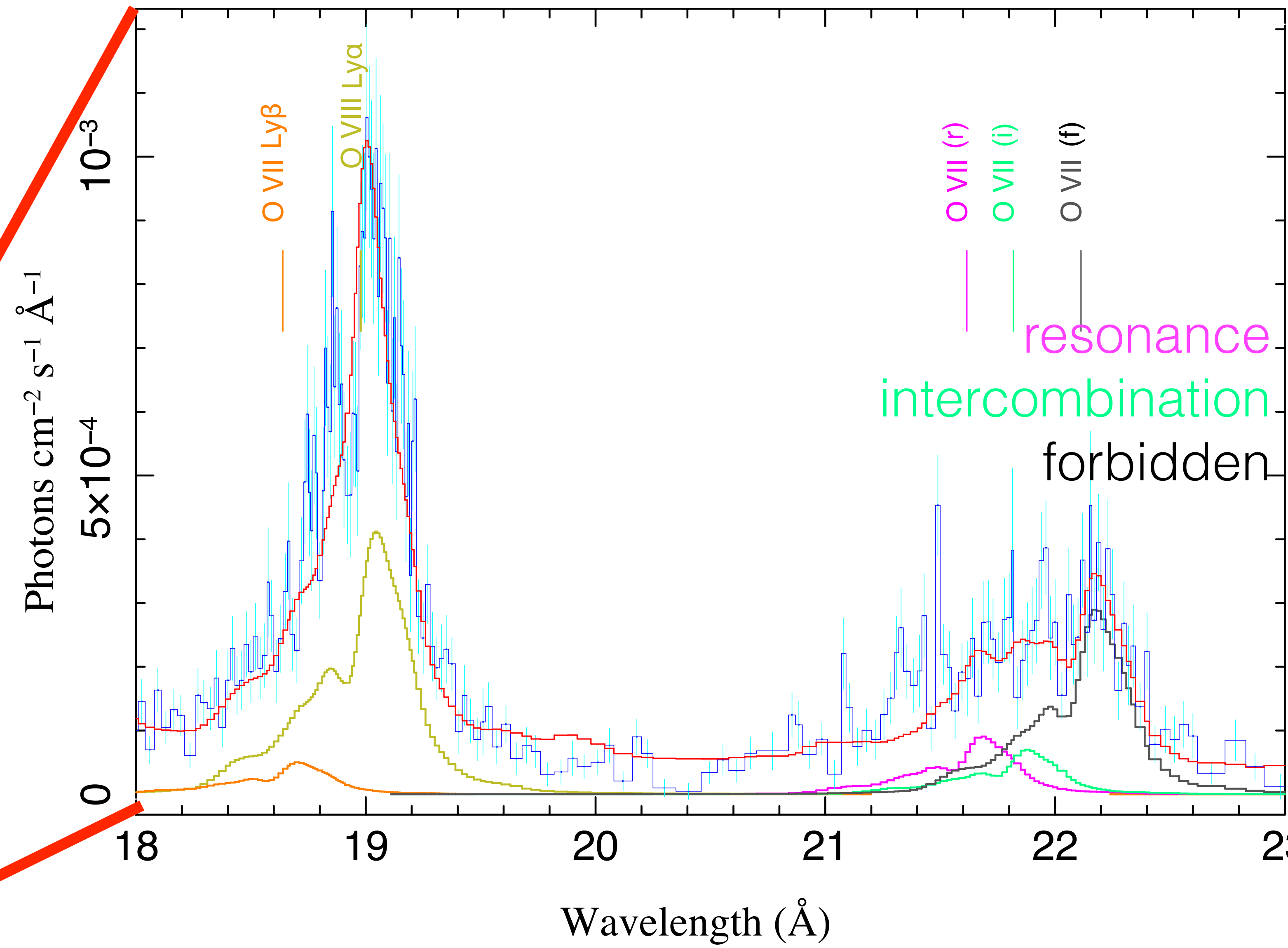
CCD imaging spectra

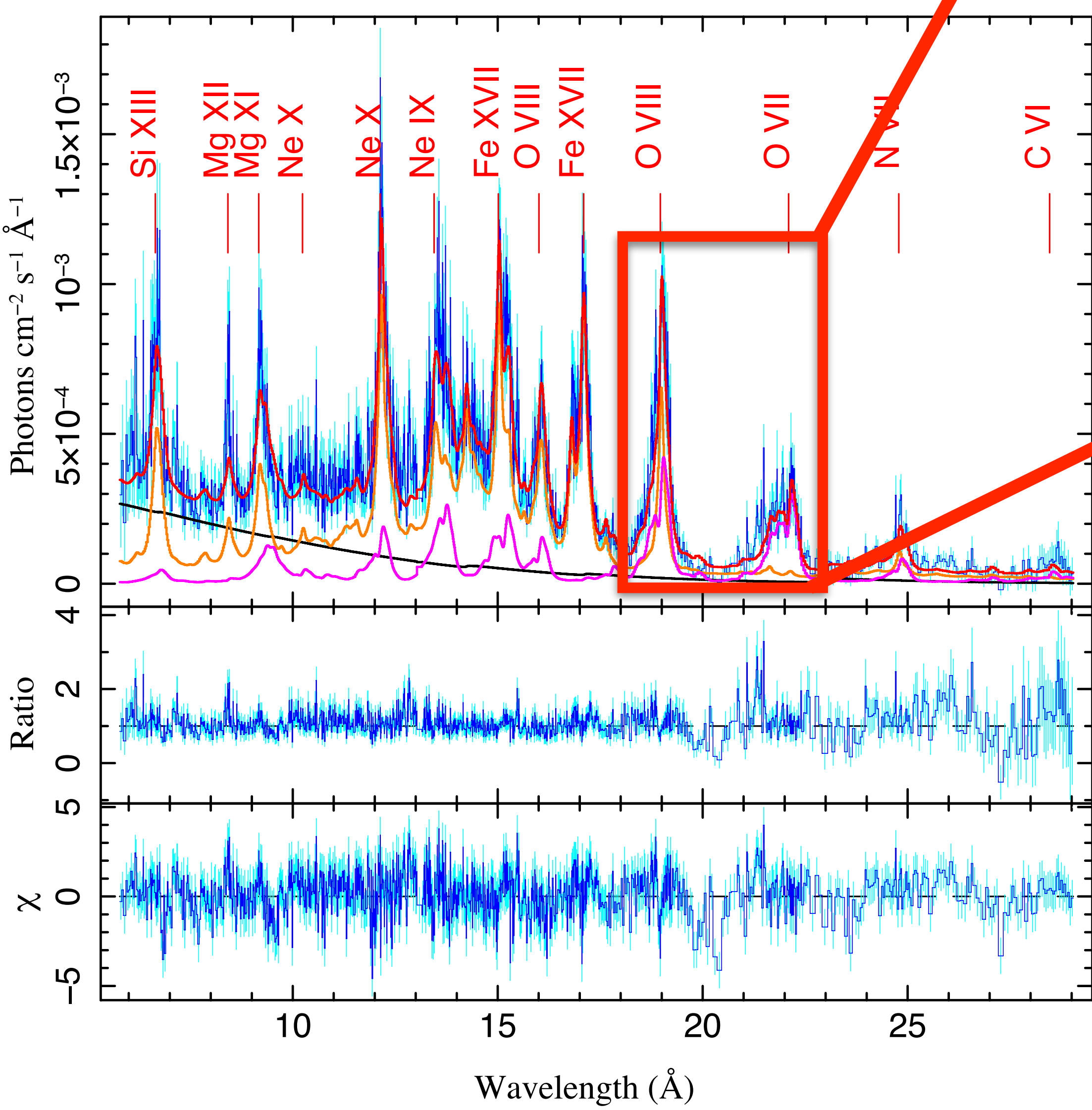


grating spectra



CCD imaging spectra



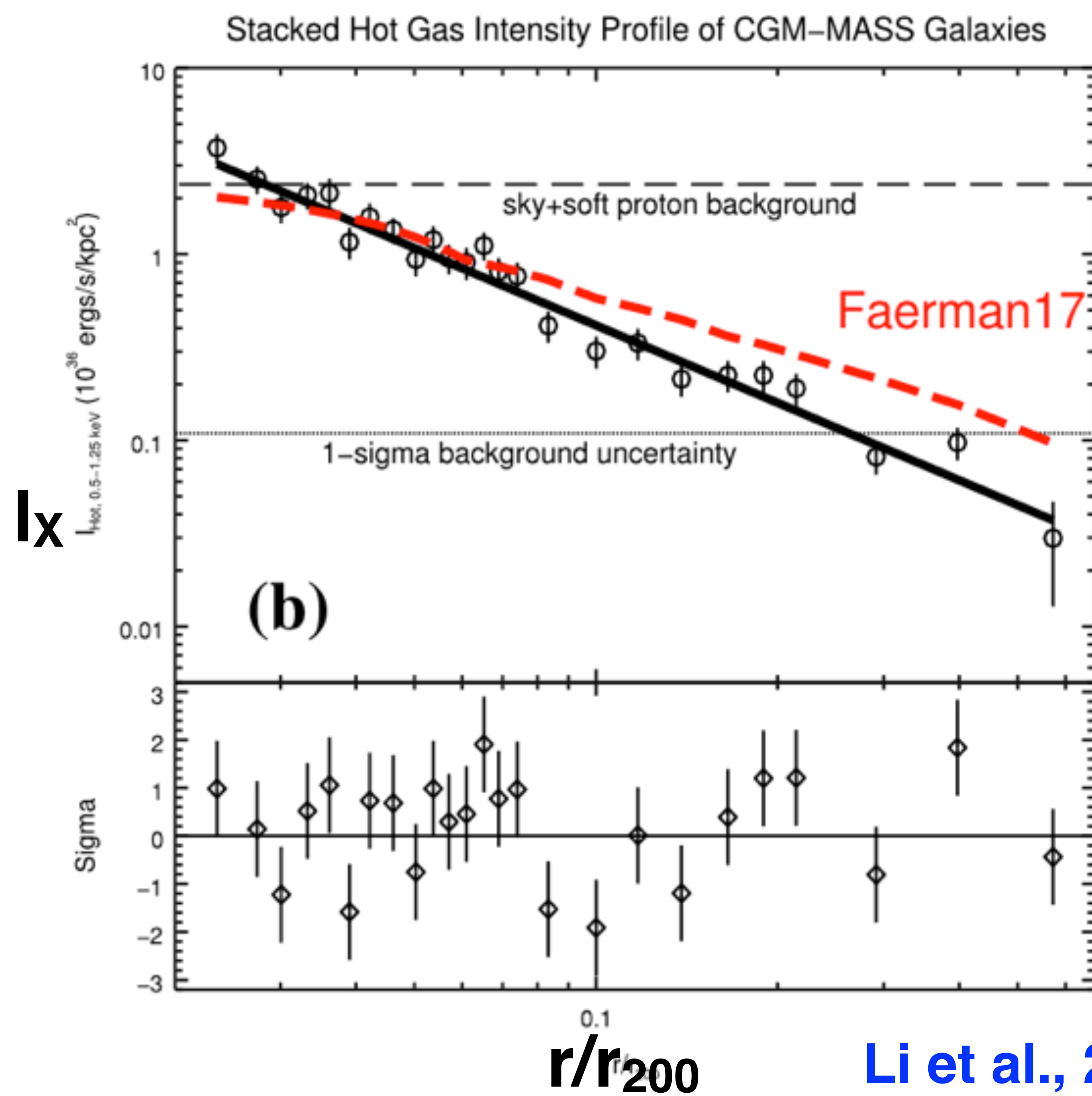


87% of the OVII 22Å and 54% of the OVIII 19Å emissions are produced by charge exchange (CX), instead of thermal plasma!

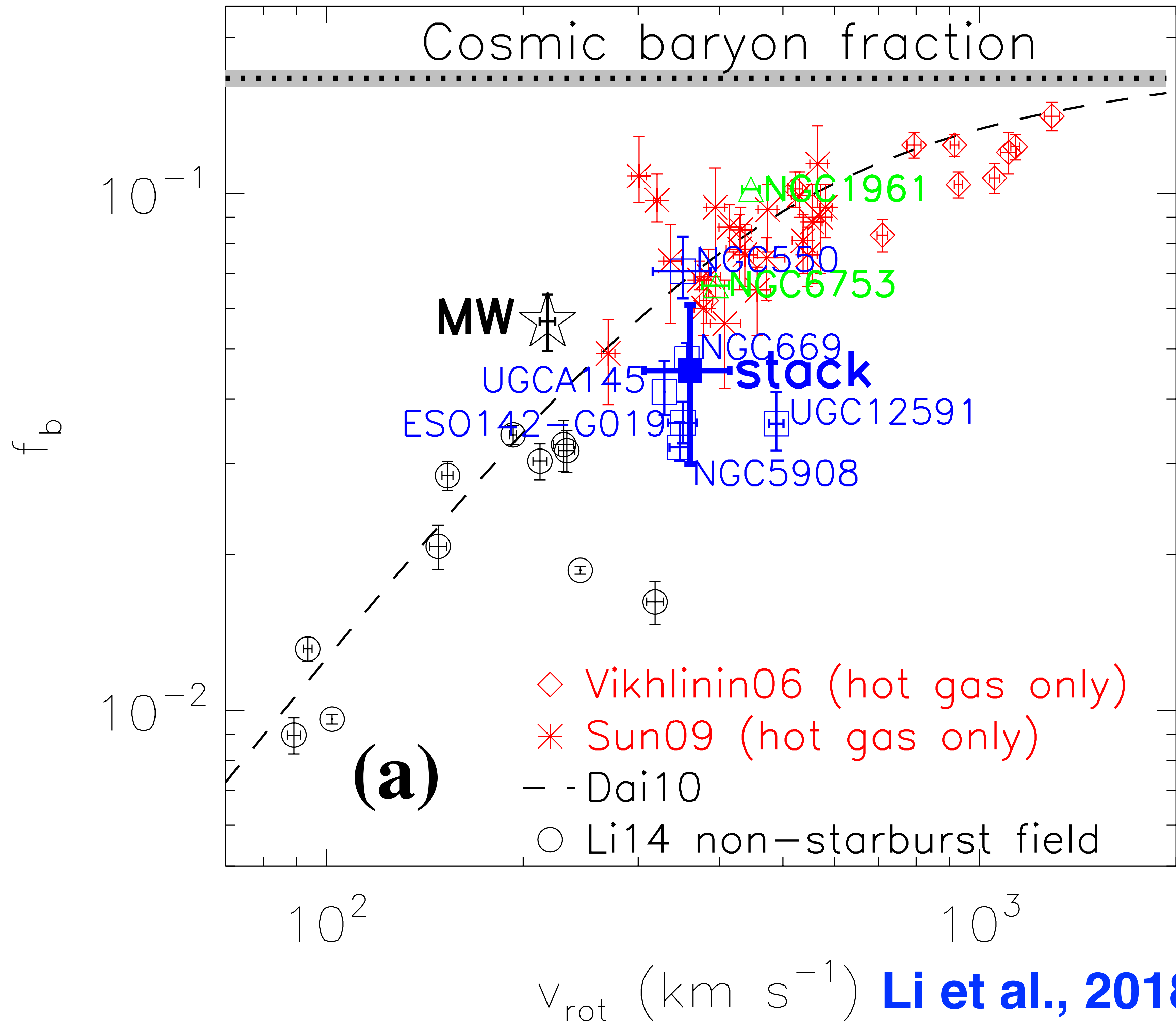
grating spectra

2.2. Cosmology: What is the total mass/baryon/metal and energy content of the hot CGM?

An example on the hot baryon content



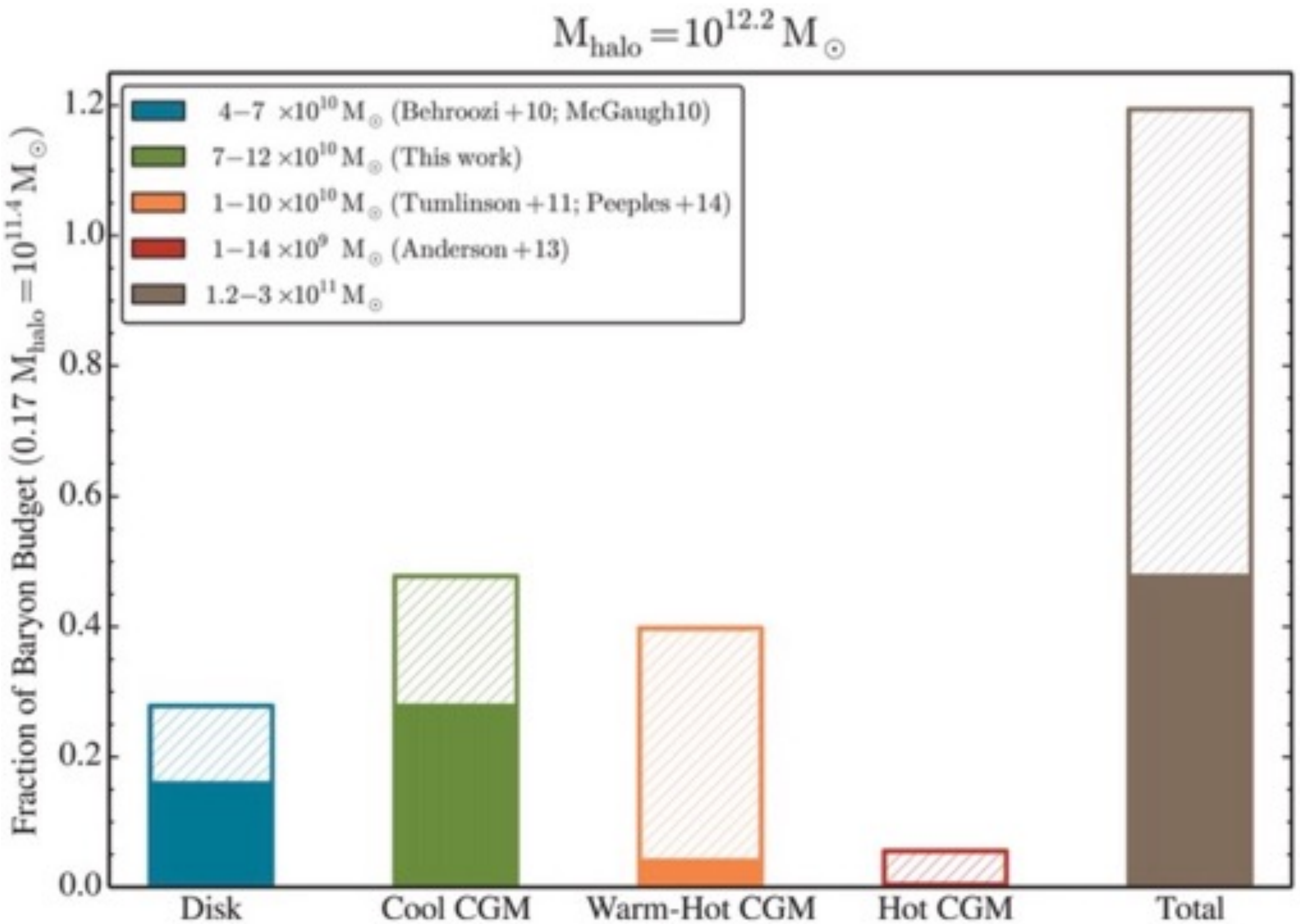
Li et al., 2018, ApJL, 855, 24



Li et al., 2018, ApJL, 855, 24

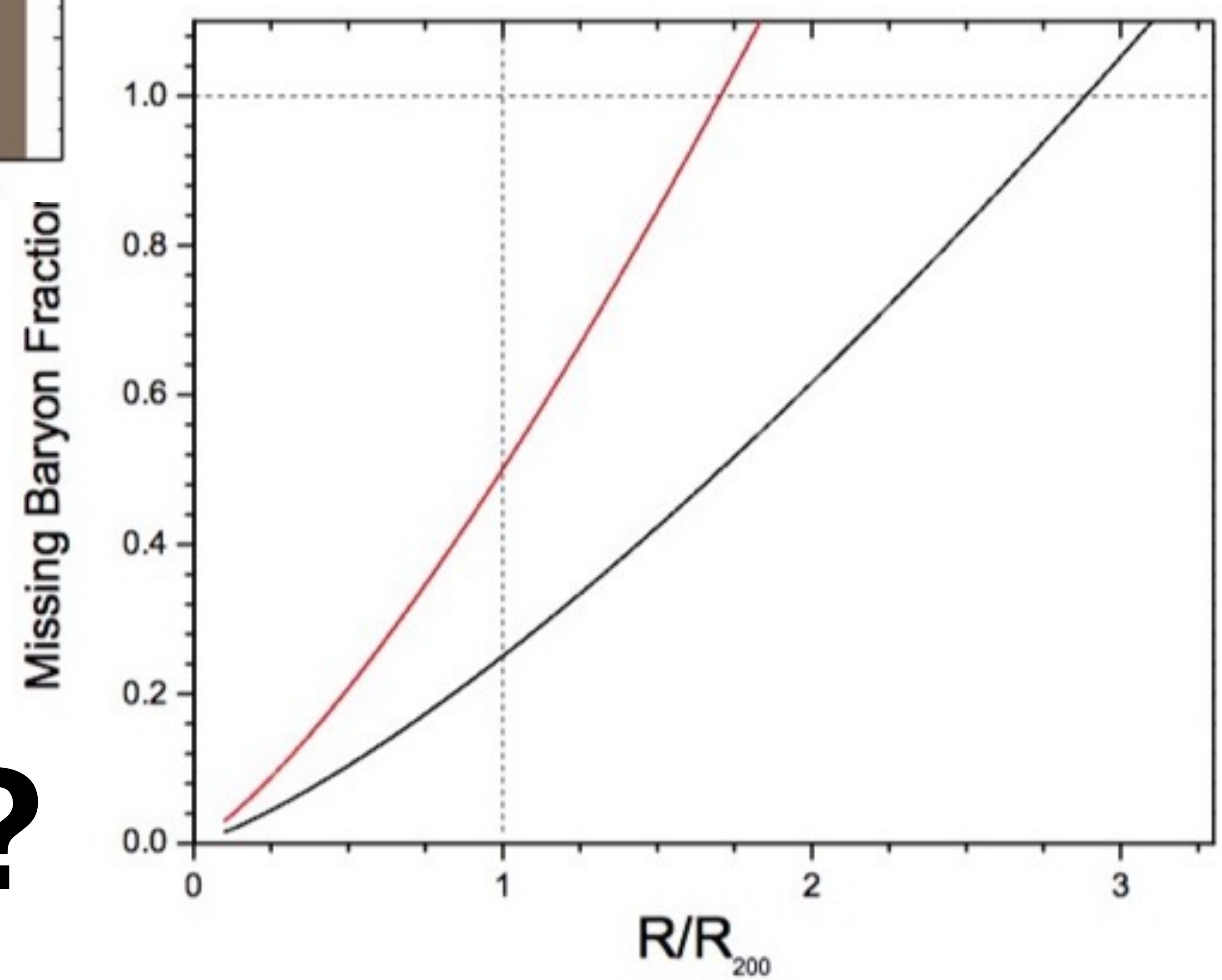
- ~26% of the expected baryons are detected in stars and the hot CGM.

Where are the missing baryons?



COS-Halos (**Werk et al. 2014, ApJ, 792, 8**)

Bregman et al., 2018, ApJ, 862, 3



Different phase or different place?

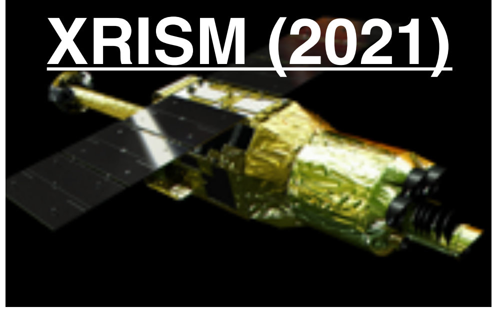
Outline

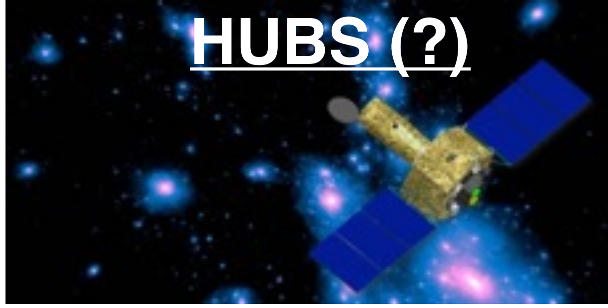
- 1. What we know about the hot CGM?
- 2. What we still don’t know?
- 3. What could we do with future X-ray missions?

eROSITA

- **Larger sample** to study the dependence of CGM properties on **various** galaxy properties for **various** types of galaxies.

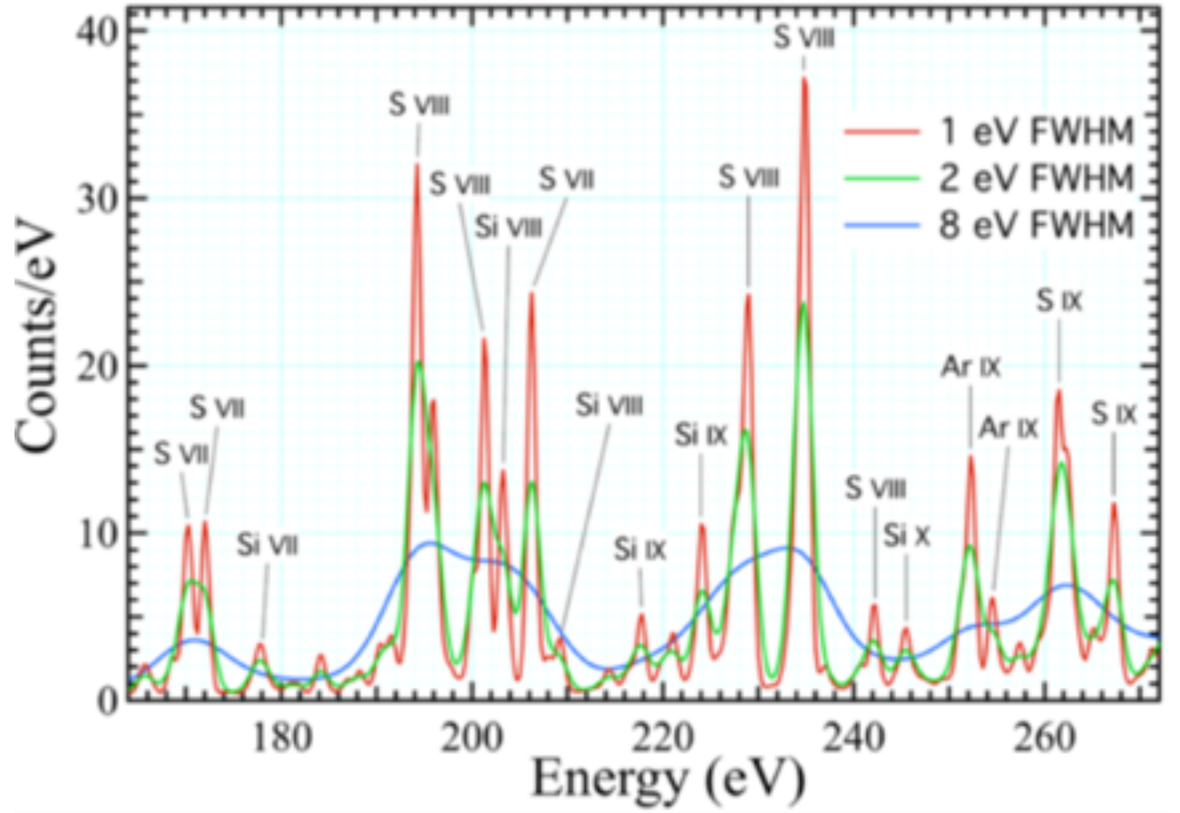
- **High resolution spectra** (E/ΔE>500; **microcalorimeter** for imaging spectroscopy or **grating** for absorption line studies) for the study of the **physical**, **chemical**, **dynamical** states, and total **energy budget** of the hot CGM.

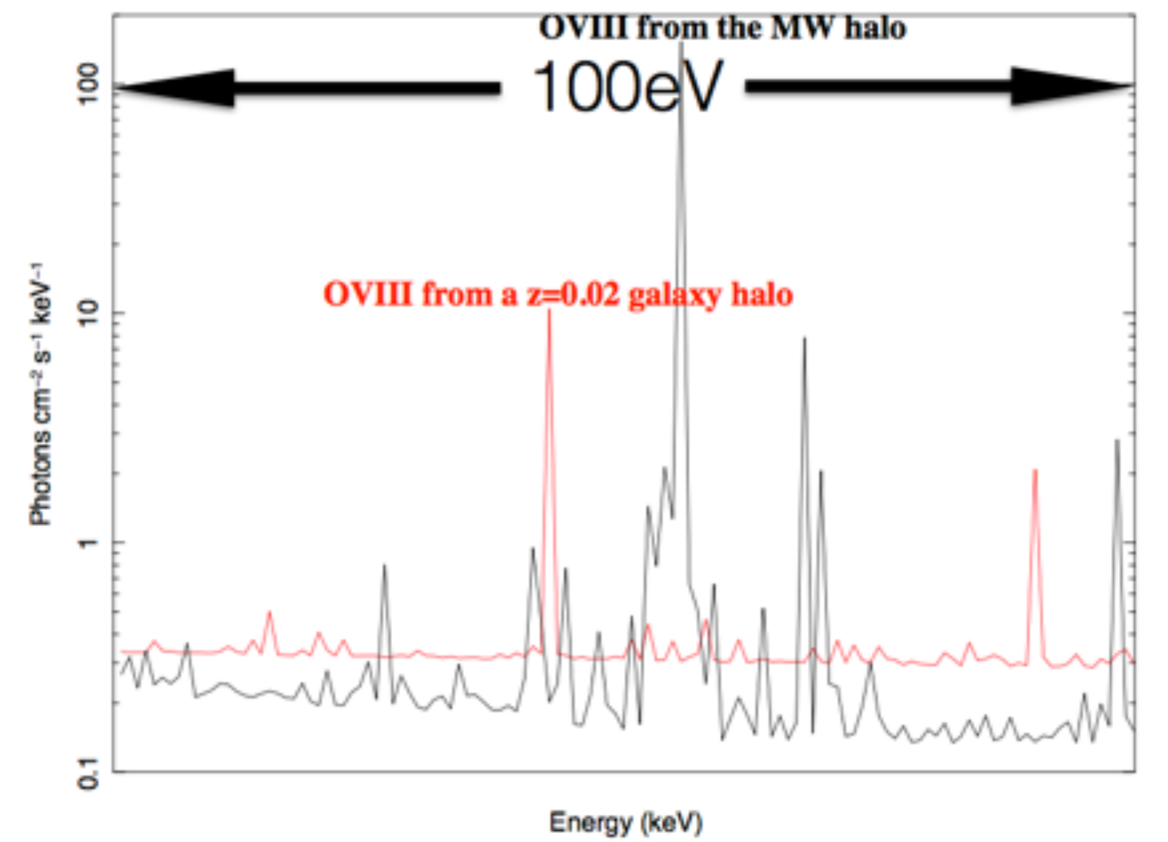




Other mission concepts of focusing X-ray telescopes: **AXIS**, **Super DIOS**

- **Larger sample** to study the dependence of CGM properties on **various** galaxy properties for **various** types of galaxies.
- **High resolution spectra** (E/ΔE>500; **microcalorimeter** for imaging spectroscopy or **grating** for absorption line studies) for the study of the **physical**, **chemical**, **dynamical** states, and total **energy budget** of the hot CGM.
- **Deep narrow-band imaging** and/or **stacking of large sample** to probe the radial distribution, outermost extension, total **mass/baryon/metal and energy content of the hot CGM**.





Hot Universe Baryon Surveyor (HUBS)

PI: Prof. Wei Cui, Tsinghua University

May 16, 201

HUBS Concept

- A TES spectrometer optimized for soft X-rays
  - Energy range: 0.1-2 keV
  - 60x60 pixel array, with 2 eV energy resolution
  - 12x12 central sub-array with smaller pixels, optimized for absorption line spectroscopy with sub-eV resolution below 1 keV
- High throughput X-ray optics with large FoV
  - Effective area: $A_{eff} > 500\ cm^2$

Name	d (Mpc)	v (km/s)	r_{virial} (deg)	ΔE (eV) @0.6keV
NGC 891	10	530	1.5	1
M87 (Virgo Cluster)	16	1280	(4)	2.5
Fornax Cluster	20	1340	1.9	2.7
NGC 5908	50	3300	0.5	6.5
Perseus Cluster	75	5400	1.3	10
Coma Cluster	100	6900	1.5	14

For detecting **absorption lines** from bright **point-like** sources, the instrumental figure-of-merit (FoM) is:

$$FoM = RA_{eff}$$

Mission	Instrument	Technology	R@0.6 keV	A_{eff} @0.6 keV (cm^2)	FoM x1000	EW limit (mA)
Chandra	LETG/ACIS -S	Grating	600	10	6	48
XRISM	Resolve	Calorimeter	100	70	7	44
XMM-Newton	RGS	Grating	500	45	22.5	25
HUBS	XQSC	Calorimeter	600	500	300	6.8
Athena	X-IFU	Calorimeter	240	5000	1200	3.4
Arcus		Grating	2500	900	2250	2.5
Lynx		Grating	>5000	>4000	>20000	<0.8

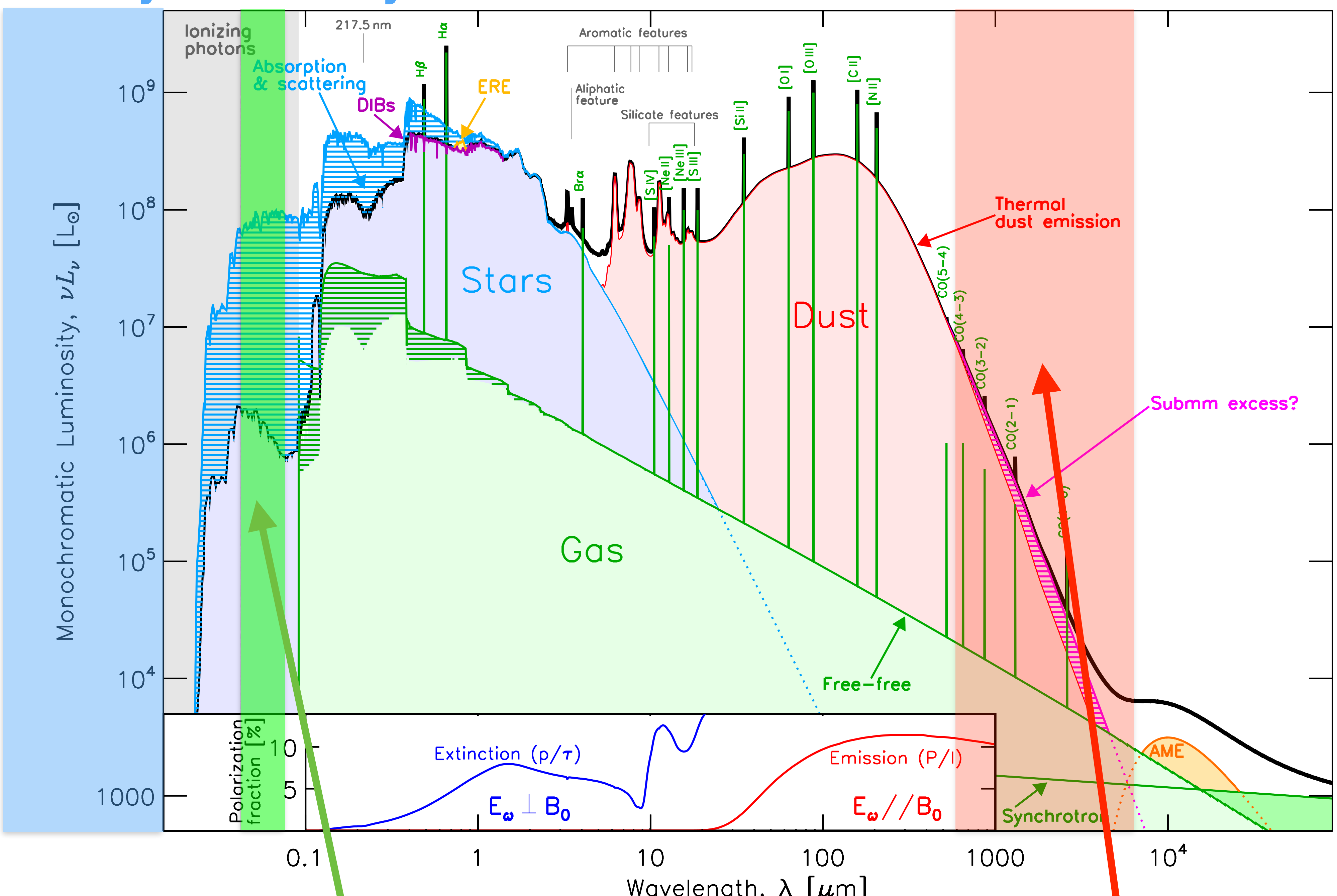
For detecting **emission lines** from **extended sources**, the instrumental figure-of-merit (FoM) is:

$$FoM = RA_{eff}\Omega_{FOV}$$

Mission	Instrument	Technology	R@0.6 keV	A_{eff} @0.6 keV (cm^2)	Ω_{FOV} (deg^2)	FoM
XARM	XRISM	Calorimeter	100	70	0.0023	22
Athena	X-IFU	Calorimeter	240	5000	0.0069	8280
Lynx		Calorimeter	200	10000	0.0069	13800
HUBS	XQSC	Calorimeter	300	500	1	150000

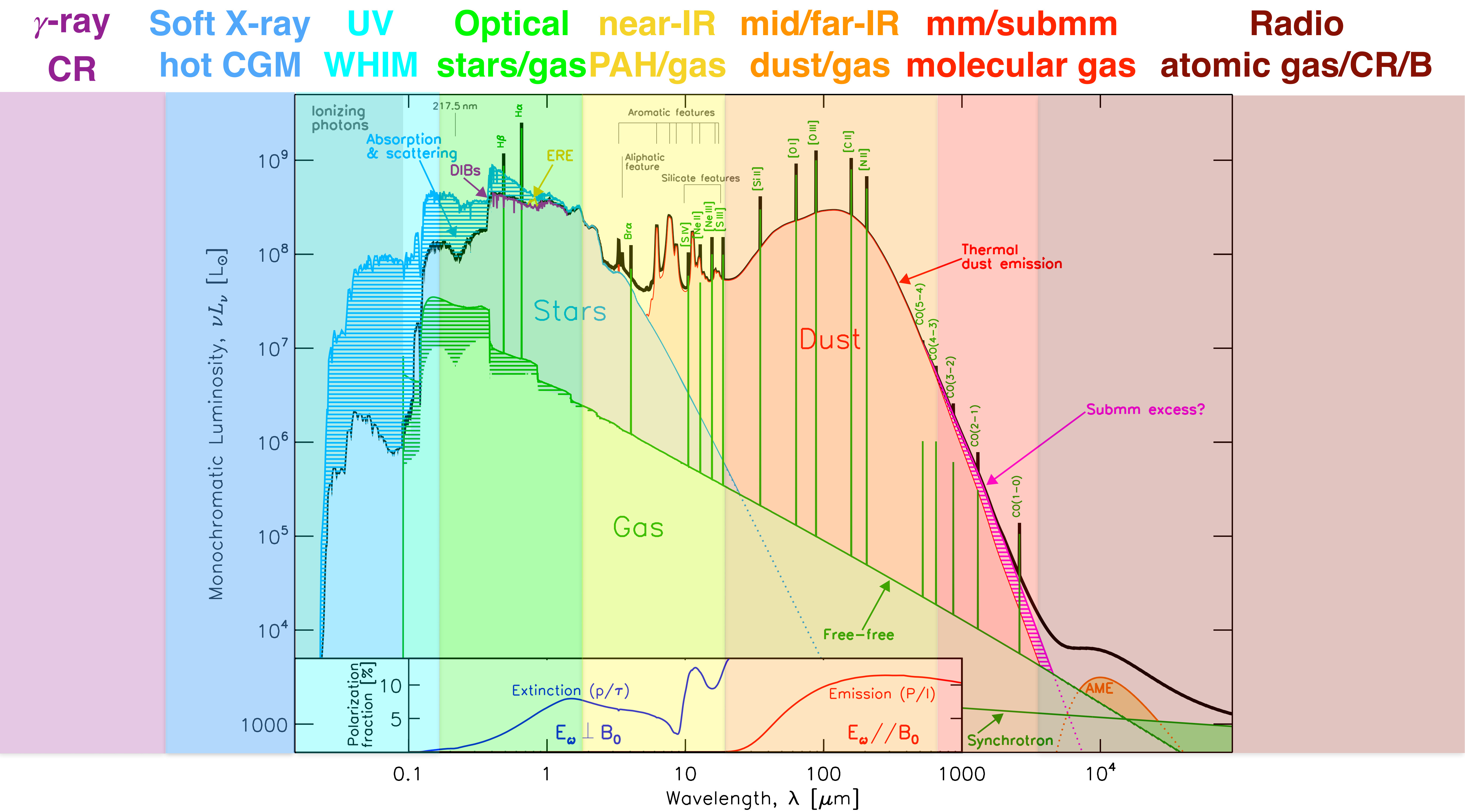
SED of a galaxy from UV to high frequency radio
(Galliano F., et al., 2018, ARA&A, 56, 673)

I only focused on the hot CGM traced by soft X-ray



But the hot CGM is also traced by the SZ (Sunyaev–Zeldovich) signal and some UV emission lines from high ions (Mg X, Ne VIII, etc.)

Multi-wavelength survey of the multi-phase CGM



Summary

<u>What we know and what we don't know?</u>

- Extended soft X-ray emission is ubiquitous around galaxies. **Astronomy** 😄
- CGM X-ray properties depend on the galaxy properties in different ways for different types of galaxies. **Statistics** 😩
- Soft X-ray emission is dominated by various emission lines tracing different physical processes. **Physics** 😱
- The total mass/baryon/metal and energy content of the hot CGM is still poorly constrained. **Cosmology** 😱

Thank you very much!

<u>What is the future?</u>

- **Larger sample** for **statistical analysis of different types of galaxies**.
- **High resolution spectra** for the study of the **physical**, **chemical**, **dynamical** states of the hot CGM.
- **Deep narrow-band imaging** and **stacking of large galaxy sample** probing the radial distribution, outermost extension, total **mass/baryon/metal and energy content of the hot CGM**.