28 January 2020, APEC Lunch Seminar, Kashiwa (Japan)

From supernovae to galaxies (and beyond)

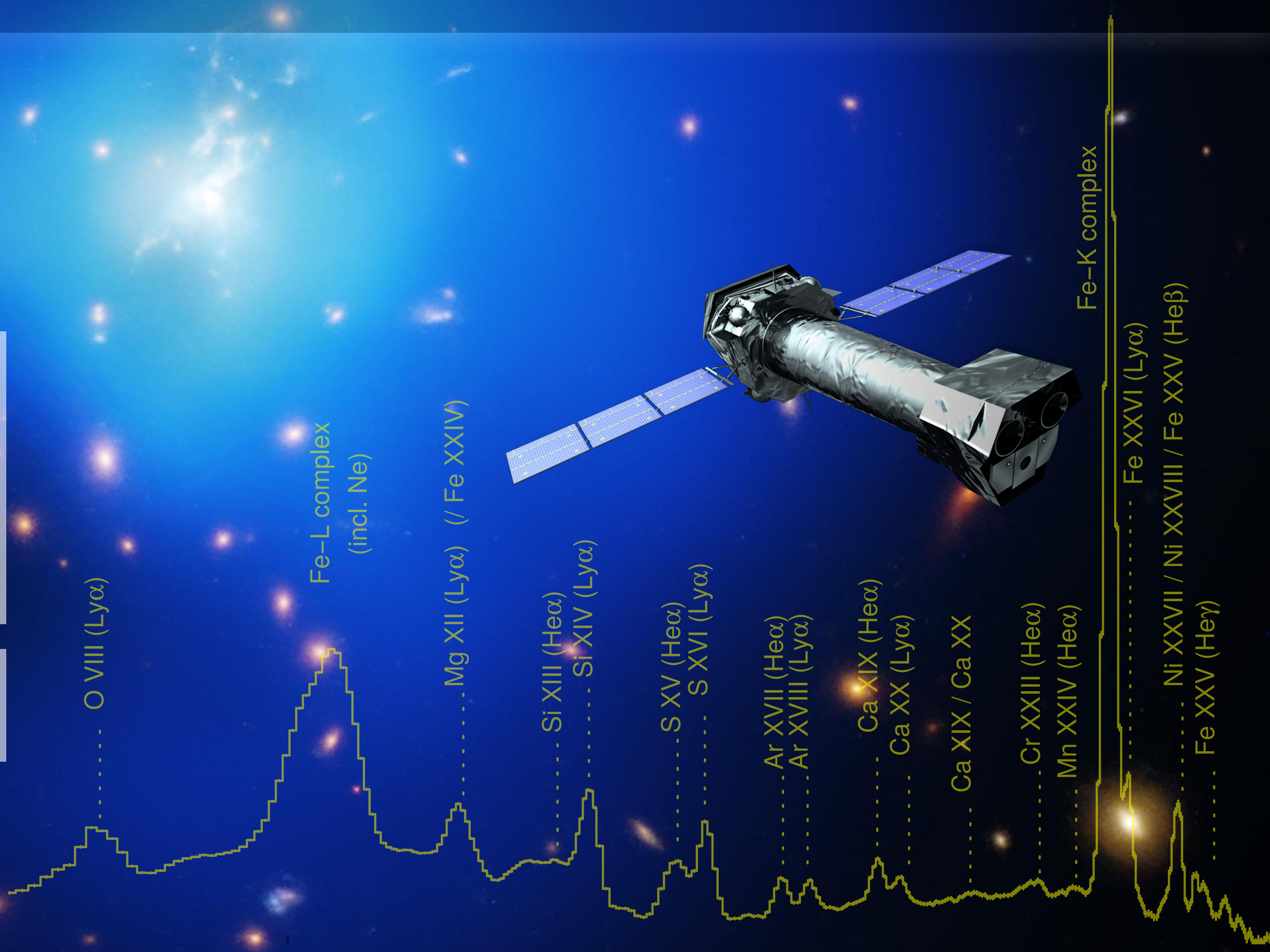
What metals in hot galactic and cluster atmospheres tell us

François Mernier

(フランソワ　メニェー)

N. Werner, N. Truong, K. Lakhchaura and the CHEERS collaboration

ESA Research Fellow, ESTEC (The Netherlands)



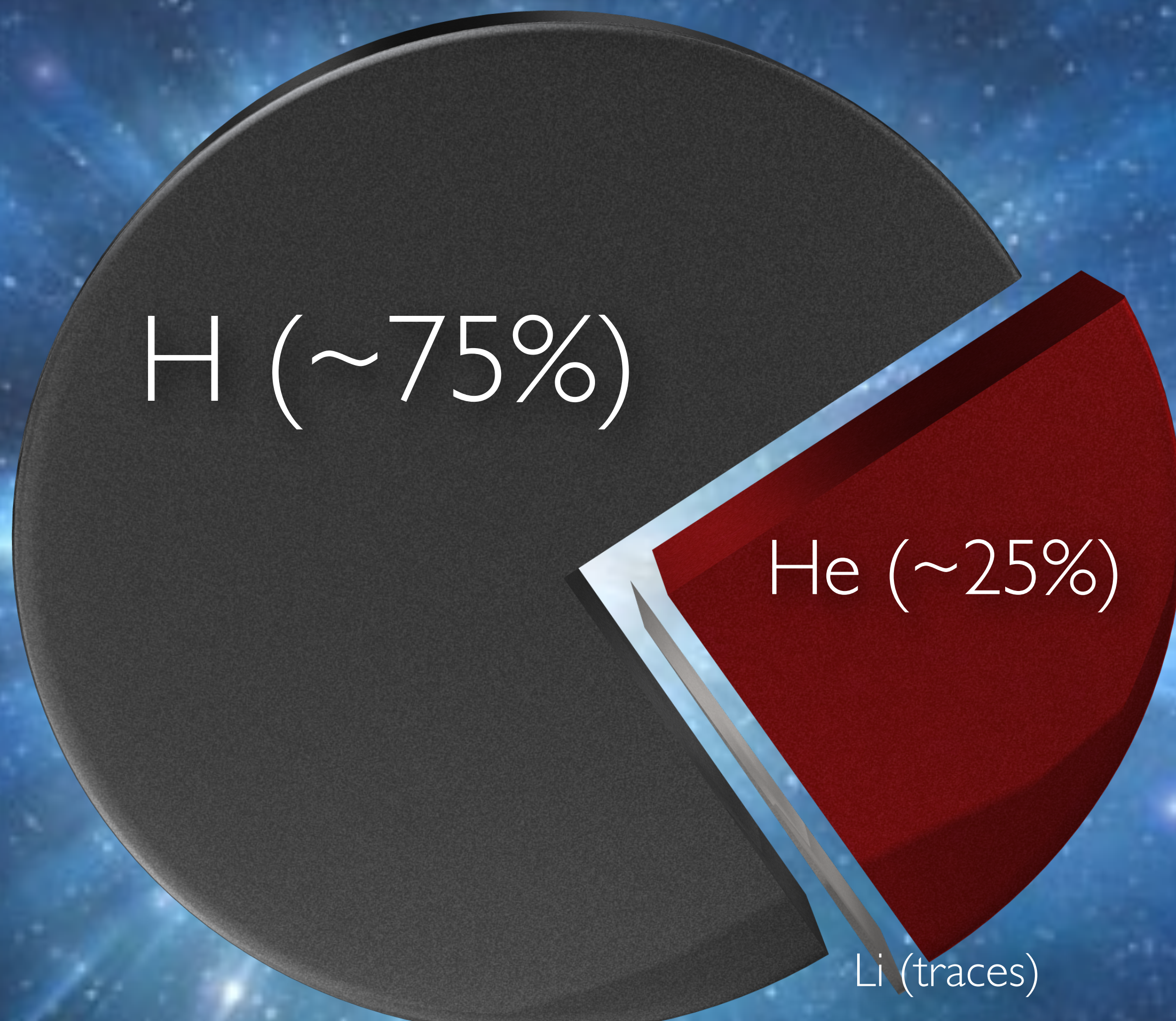
esa
European Space Agency

Introduction

The origin of chemical elements

Where do chemical elements come from?

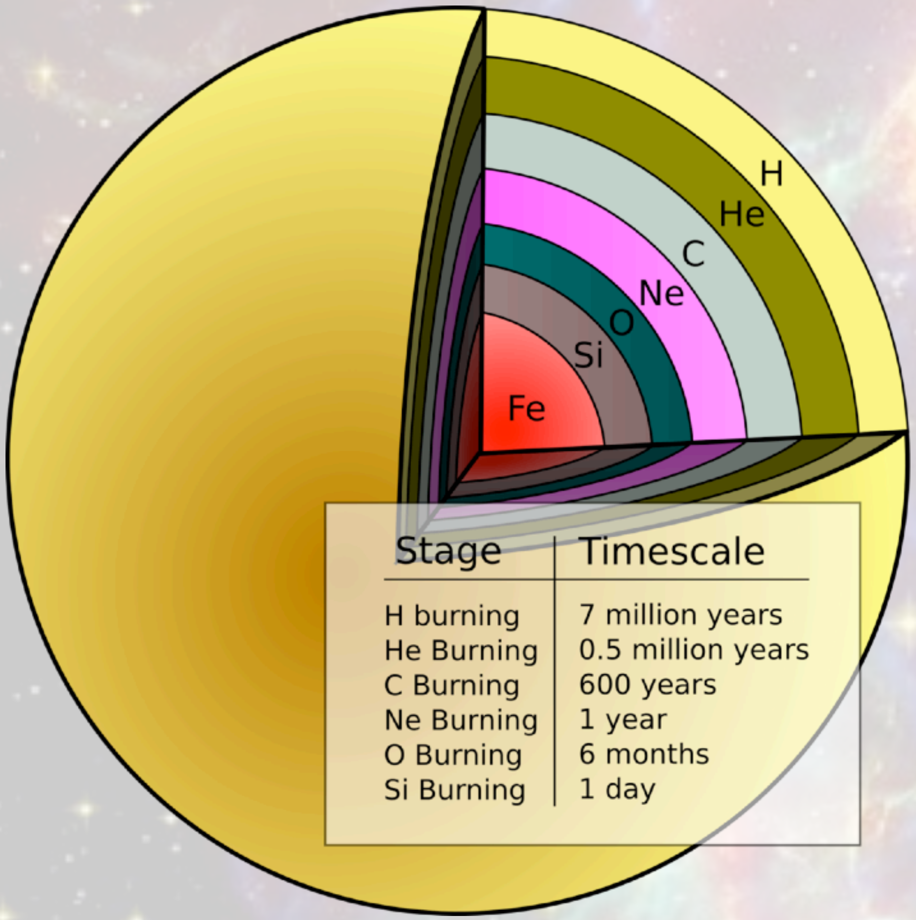
Primordial nucleosynthesis



How about heavier elements (=metals)?

The origin of chemical elements

1) Core-collapse supernovae (SNcc)



Explode (and enrich) quite fast after star formation

Produces:

➡ ***O***

➡ ***Ne***

➡ ***Mg***

➡ ***Si***

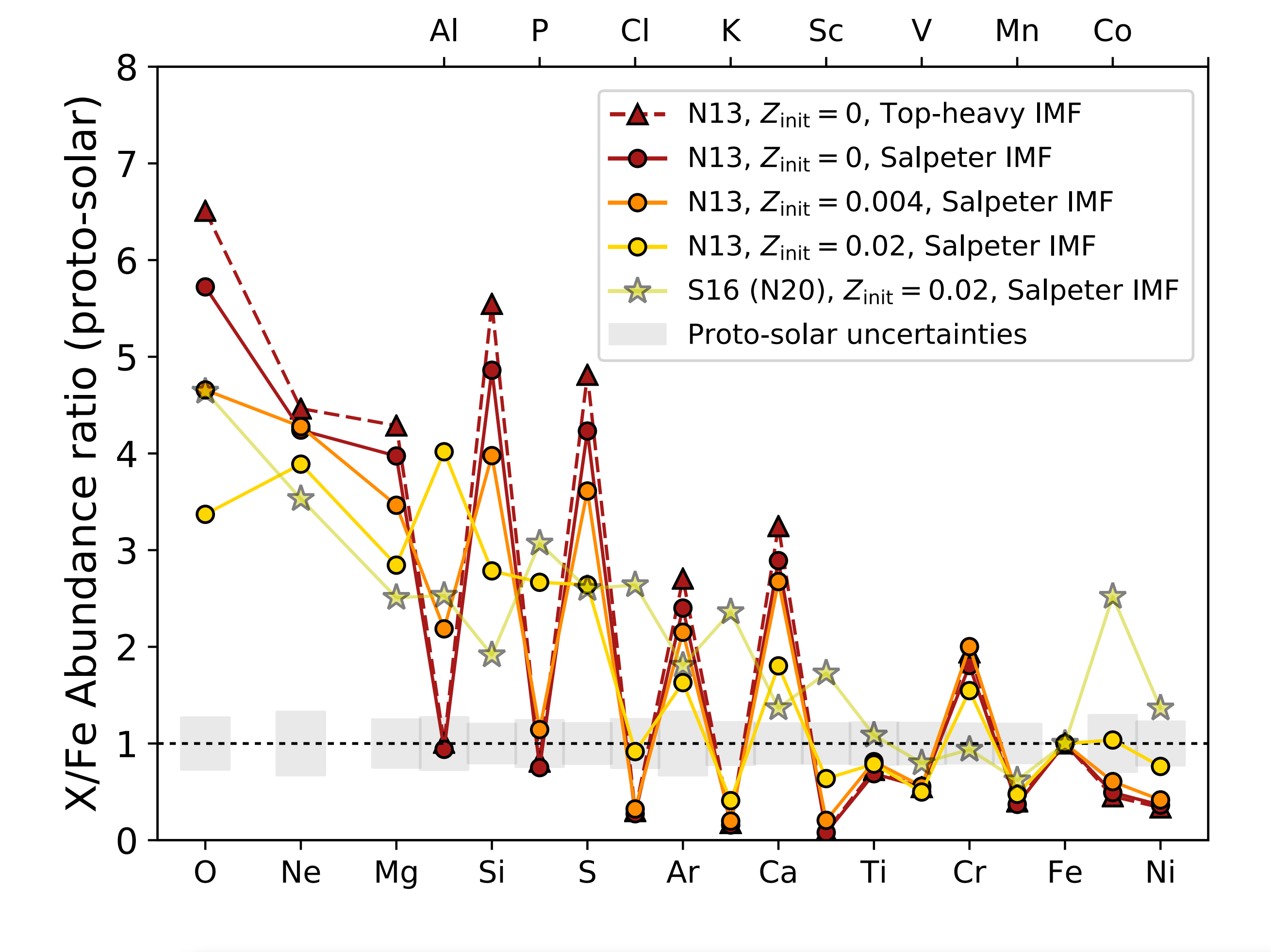
How much? Depends on:

➡ Mass of the star (➔ ***Initial mass function***)

➡ Initial metallicity of the star (Z_{init})

The origin of chemical elements

1) Core-collapse supernovae (SNcc)



Mernier et al. (2018c)
(adapted from Nomoto et al. 2013 and Sukhbold et al. 2016)

Explode (and enrich) quite fast after star formation

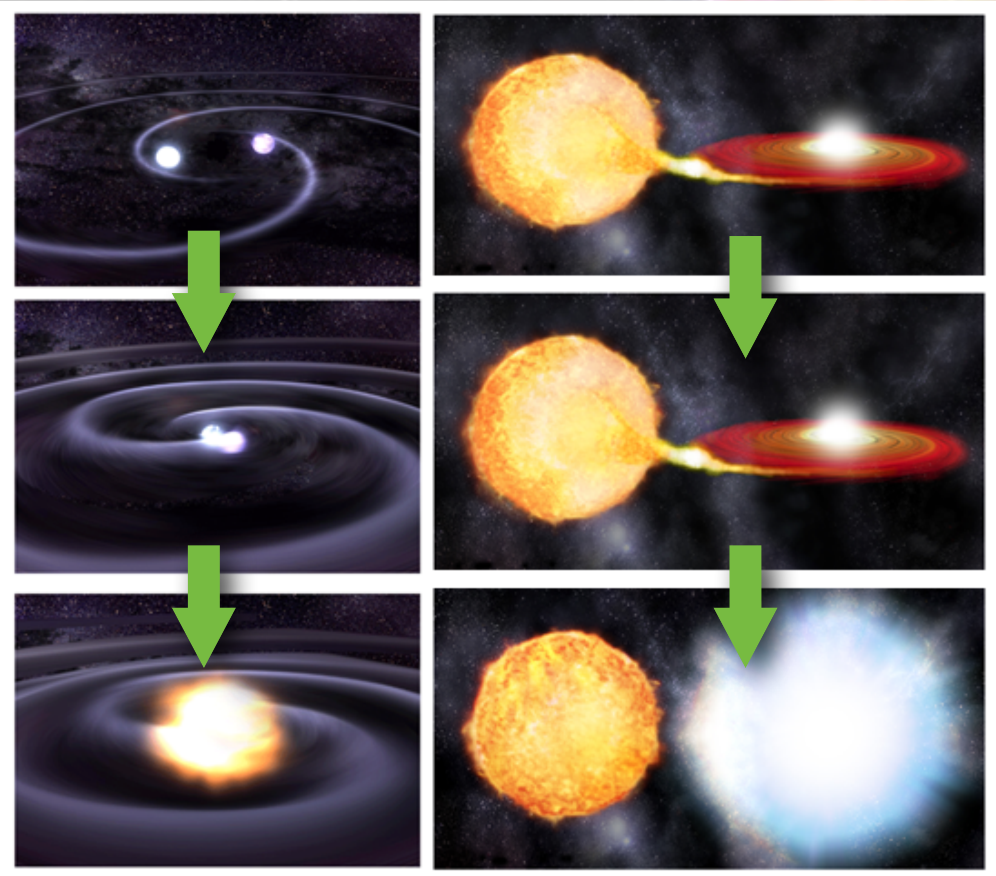
...pends on:

➔ Mass of the star (➔ ***Initial mass function***)

➔ Initial metallicity of the star ($Z_{\rm init}$)

The origin of chemical elements

2) Type Ia supernovae (SNIa)



This? ...Or this?

Time delay between star formation and SNIa explosions (?)

Produces:

- ➡ ***Si***
- ➡ ***S***
- ➡ ***Ar***
- ➡ **Ca**
- ➡ ***Fe***
- ➡ ***Ni***

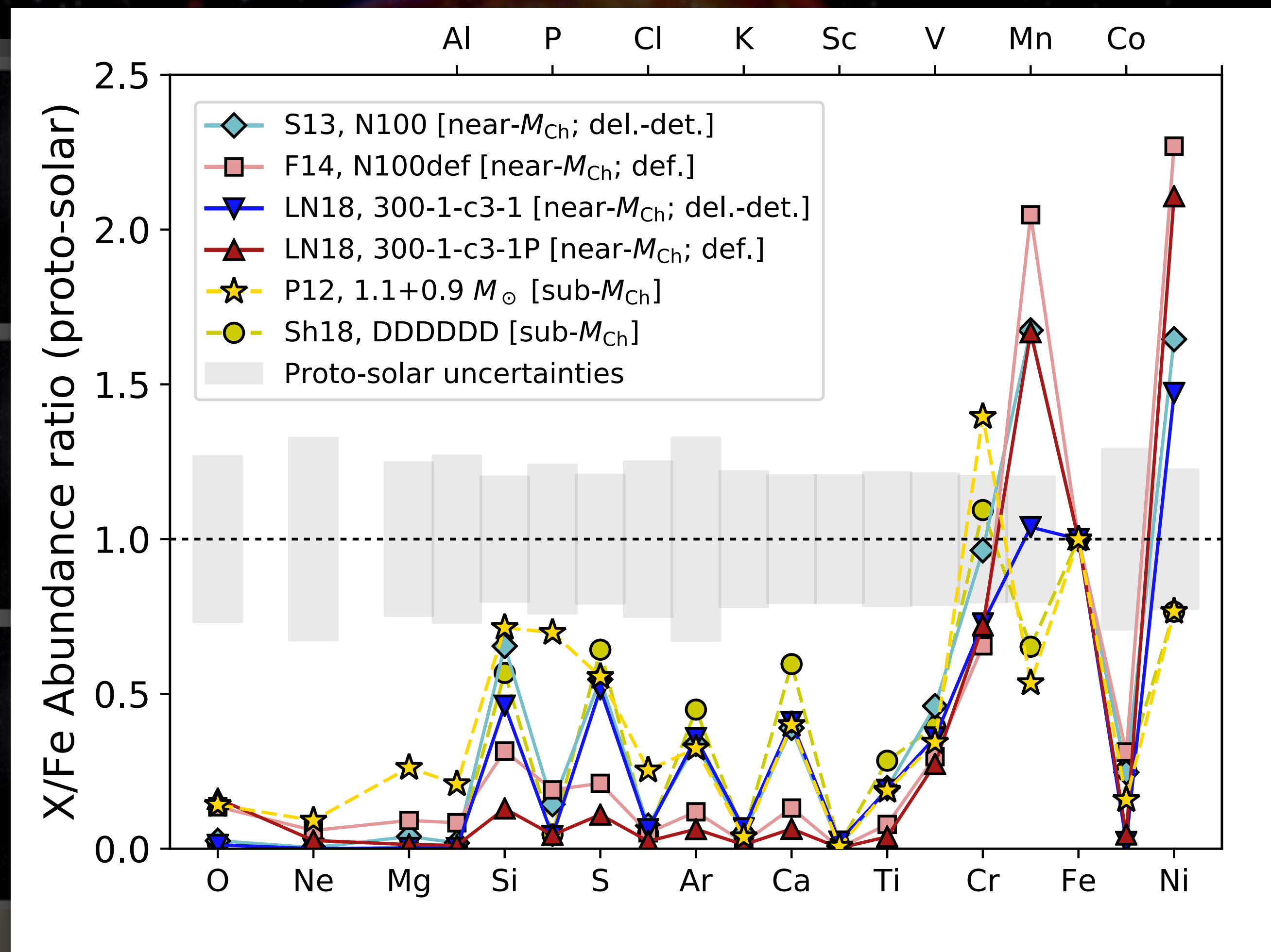
How much? Depends on:

➡ Physics of the explosion
(***deflagration*** vs. ***delayed-detonation***)

The origin of chemical elements

2) Type Ia supernovae (SNIa)

This?



Mernier et al. (2018c)
(adapted from Seitenzahl et al. 2013; Fink et al. 2014; Leung & Nomoto 2018; Pakmor et al. 2012; Shen et al. 2018)

Time delay between star formation and SNIa explosions (?)

➡ ***Ca***

➡ ***Fe***

➡ ***Ni***

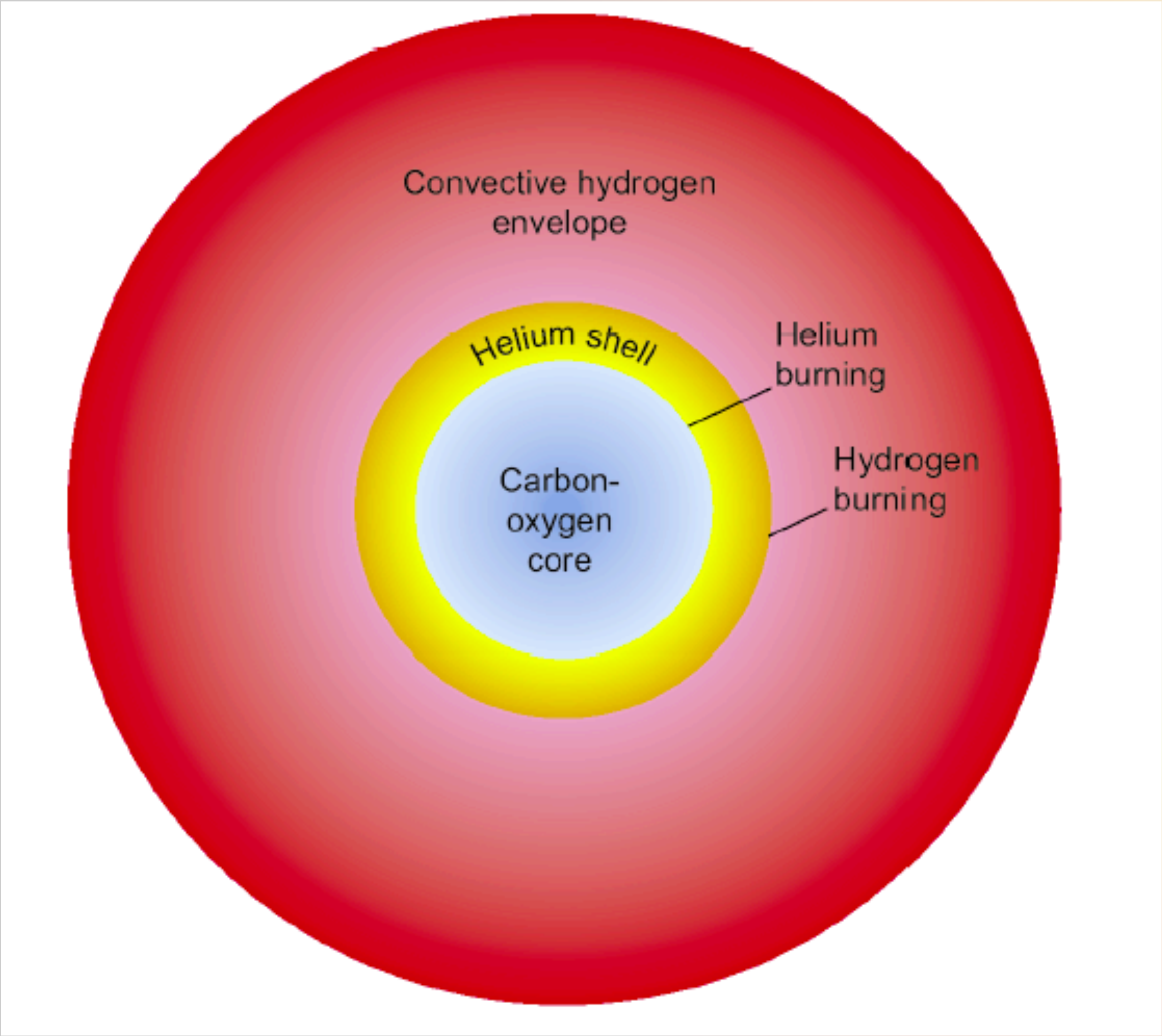
…pends on:

…e explosion

(***deflagration*** vs. ***delayed-detonation***)

The origin of chemical elements

3) Asymptotic Giant Branch stars (AGB)



Produces:

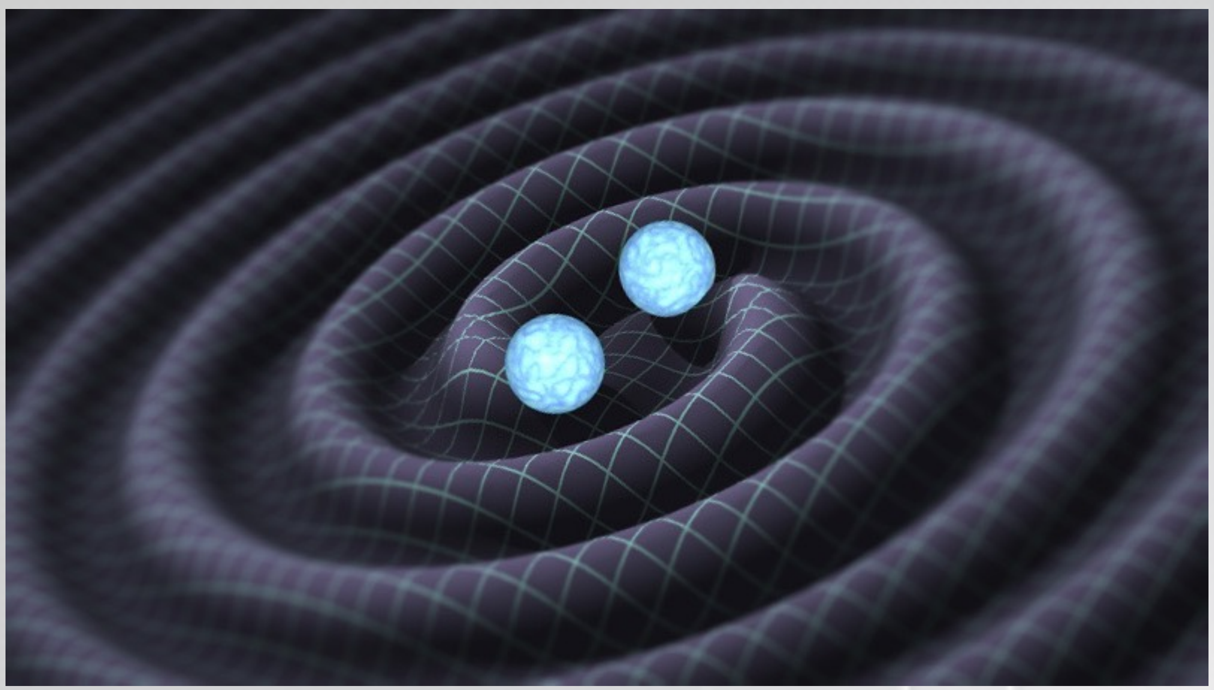
➡ ***C***

➡ ***N***

➡ traces of ***O***, ***Ne*** & ***Mg***

The origin of chemical elements

4) Merging neutron stars



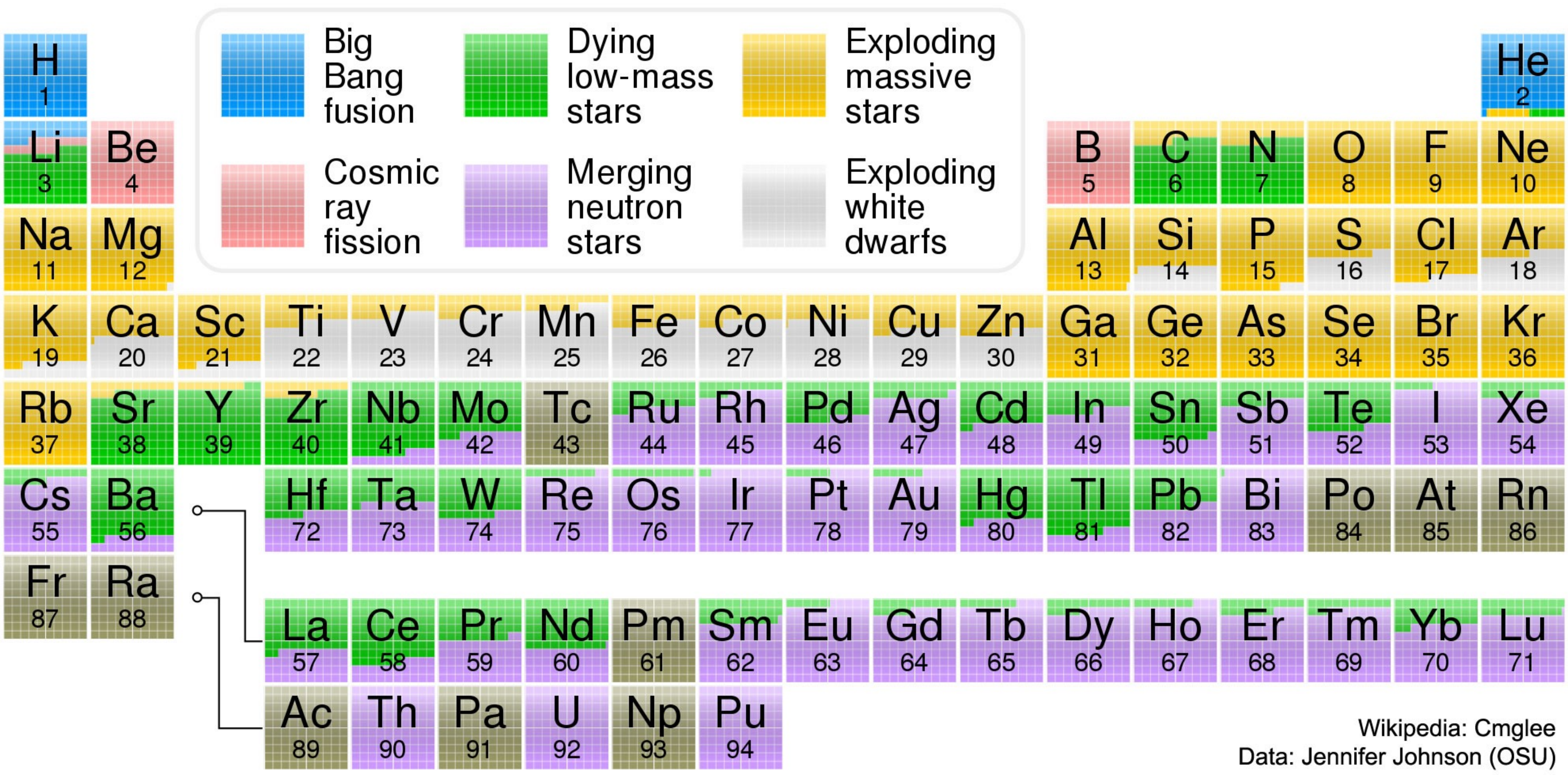
Produces:

➡ ***Heavier elements***

(Ag, Pt, Au,…)

Recently confirmed thanks to LIGO!

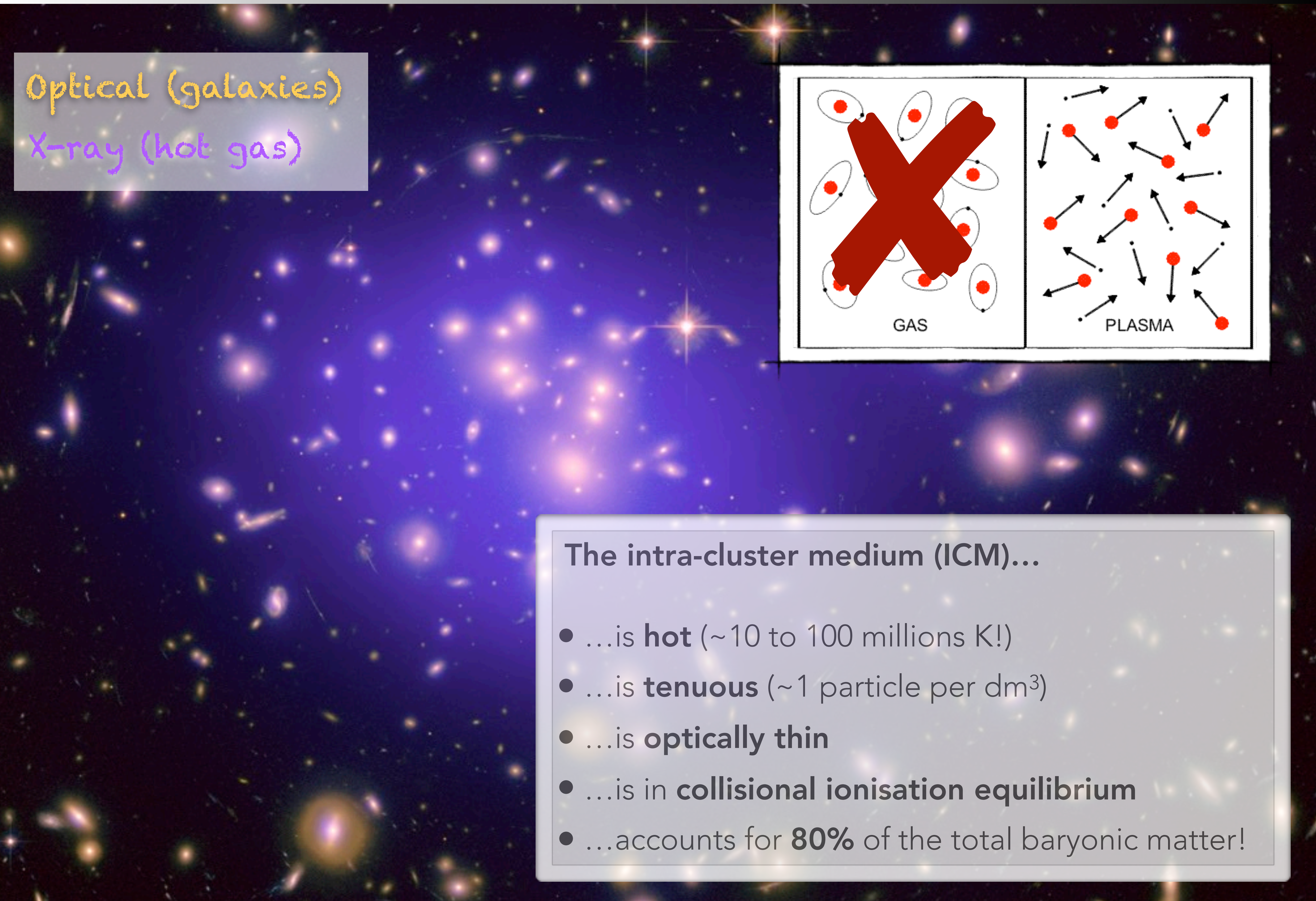
The origin of chemical elements



"We are made of star stuff!" — C. Sagan

Galaxy clusters and their hot atmospheres

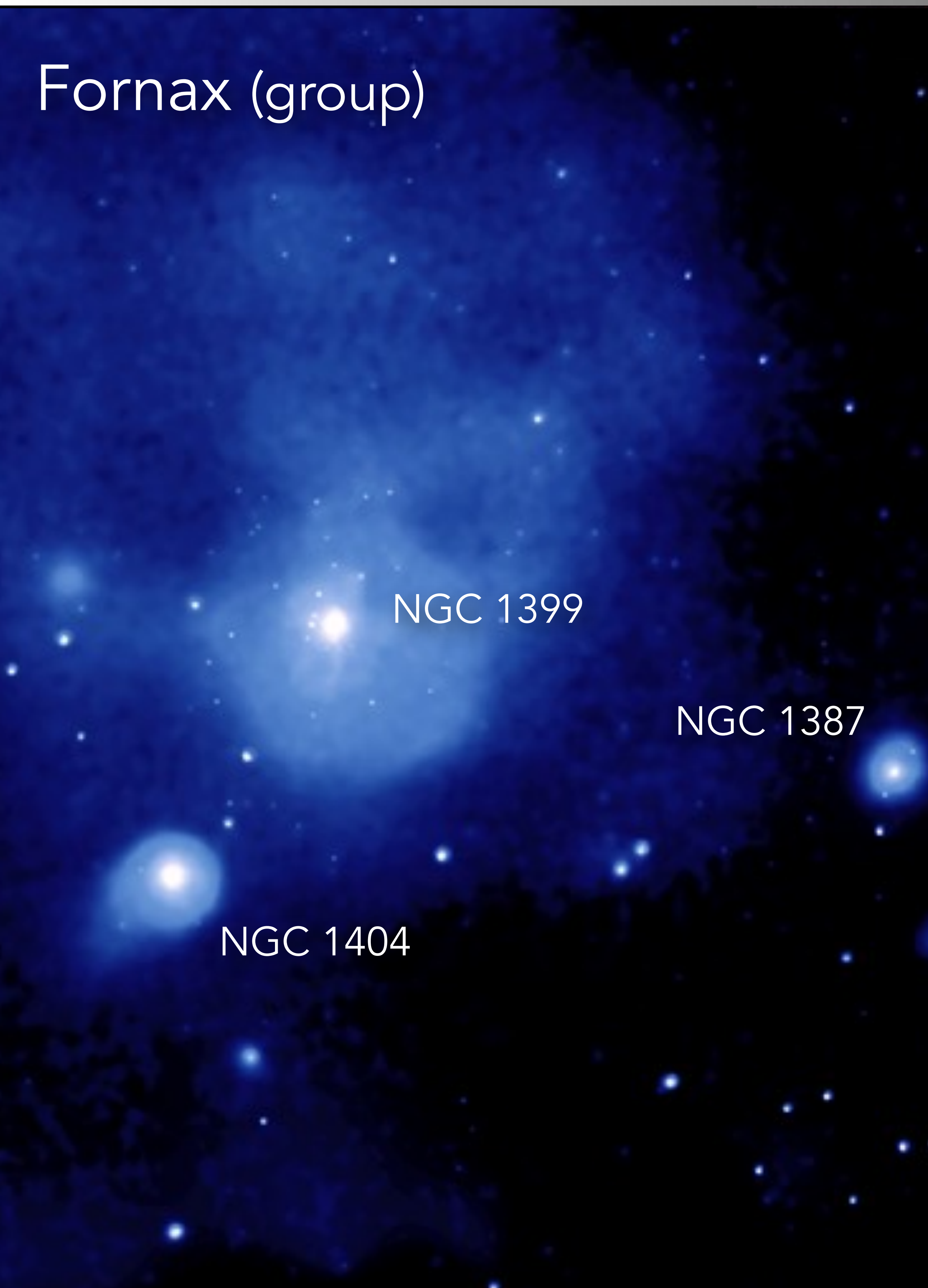
Galaxy clusters and their hot atmospheres



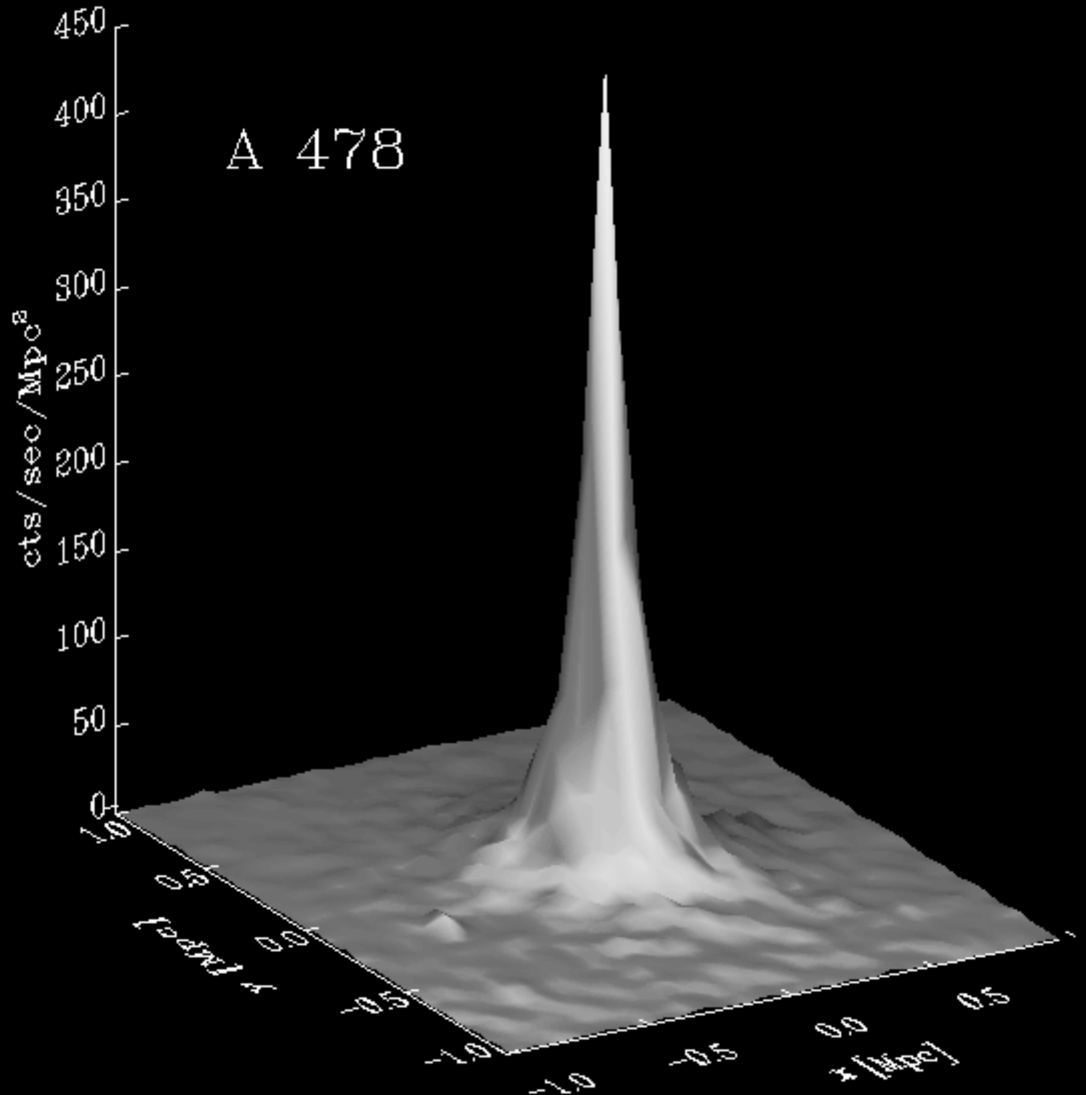
The intra-cluster medium (ICM)…

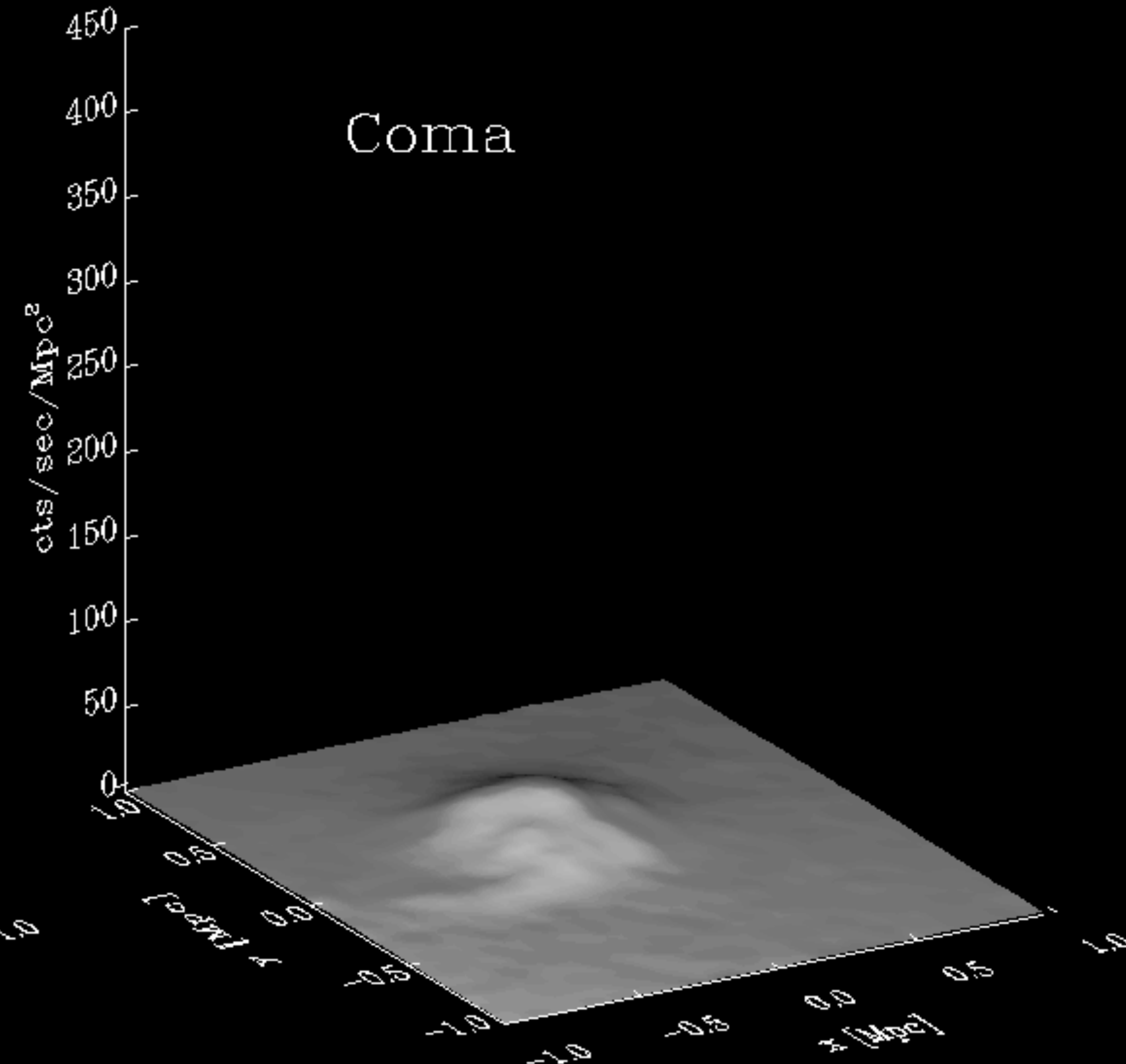
- …is **hot** (~10 to 100 millions K!)
- …is **tenuous** (~1 particle per dm^3)
- …is **optically thin**
- …is in **collisional ionisation equilibrium**
- …accounts for **80%** of the total baryonic matter!

Galaxy groups & giant elliptical galaxies

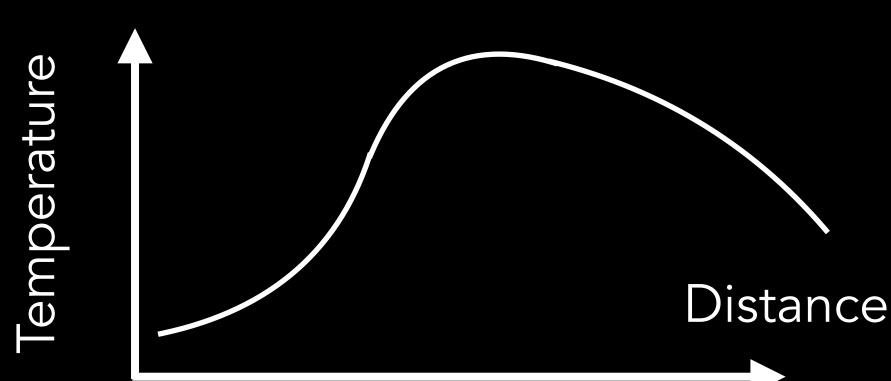


Cool-core vs. Non-cool-core systems

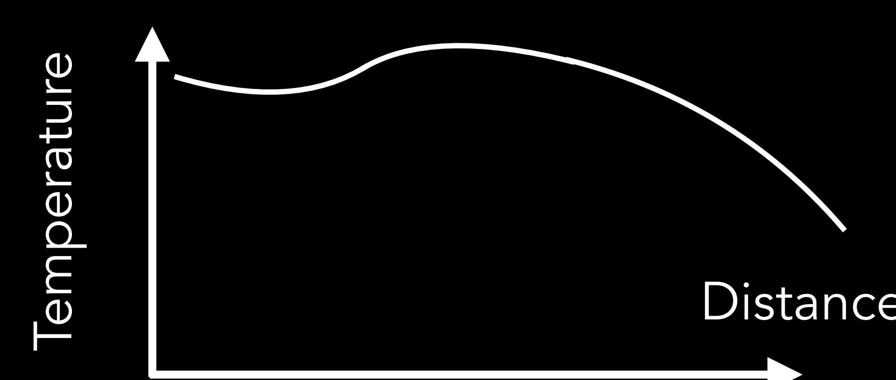




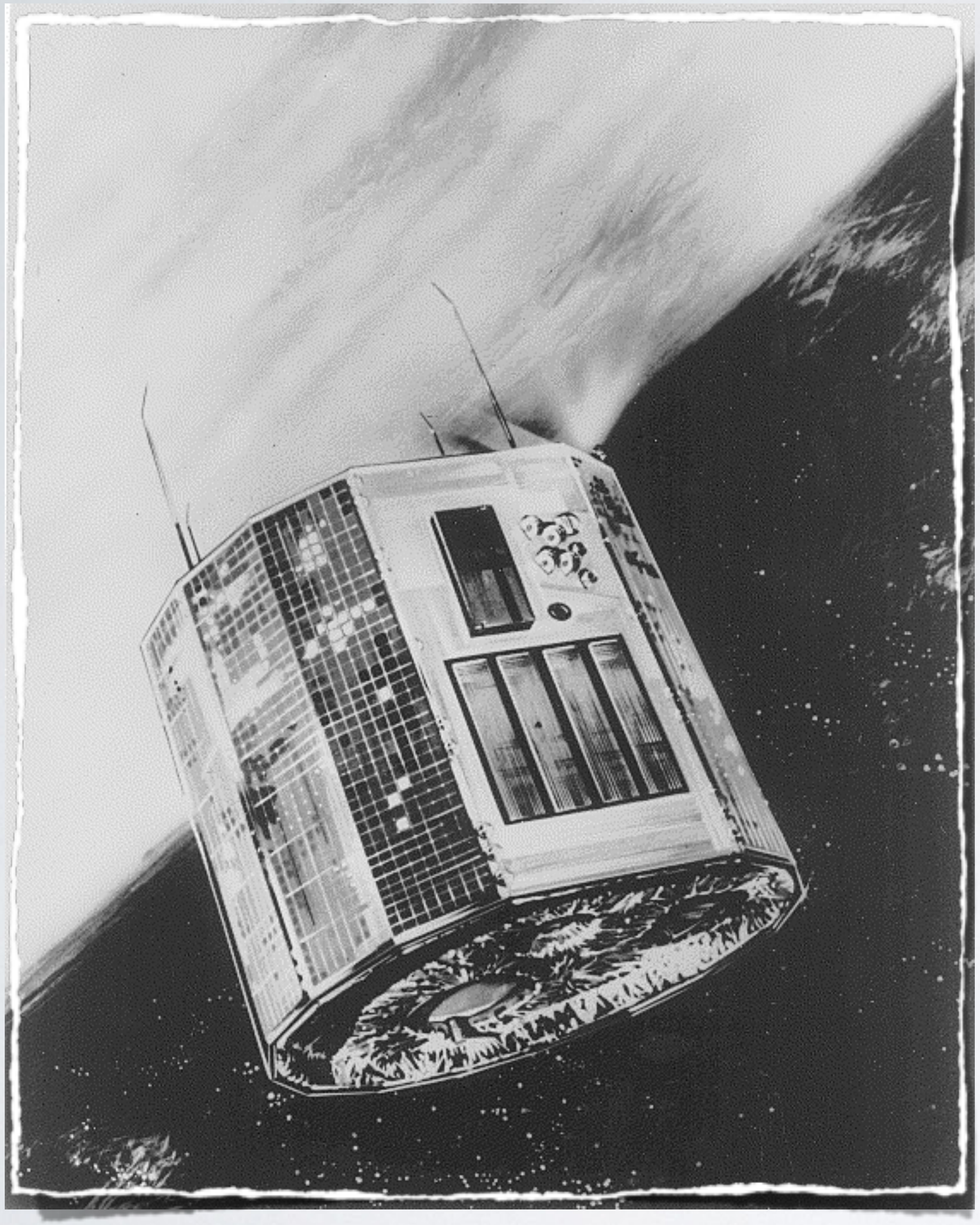
Cool-core



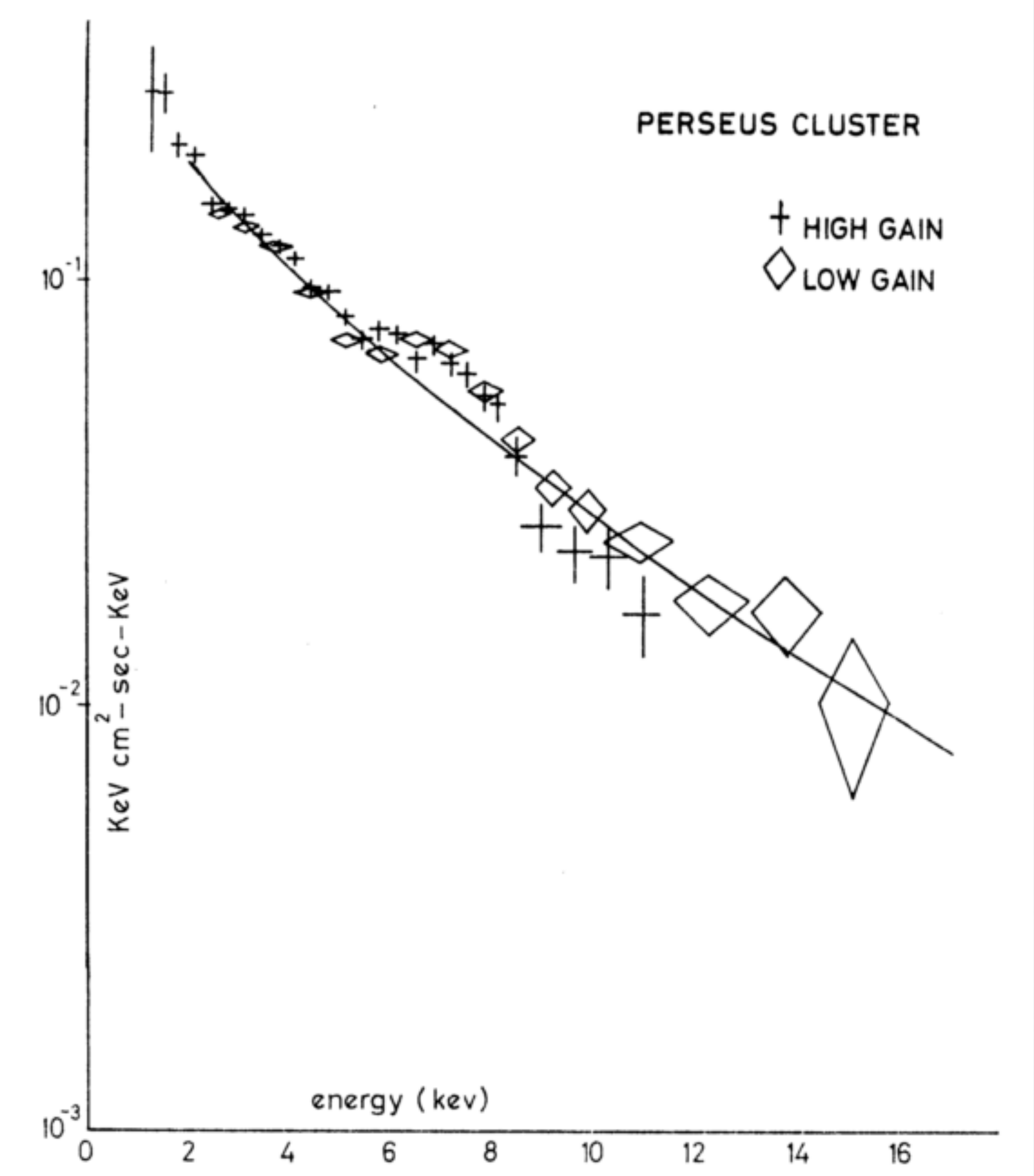
Non-cool-core



The intra-cluster medium (ICM) contains metals!



Ariel V



Mitchell et al. (1976)

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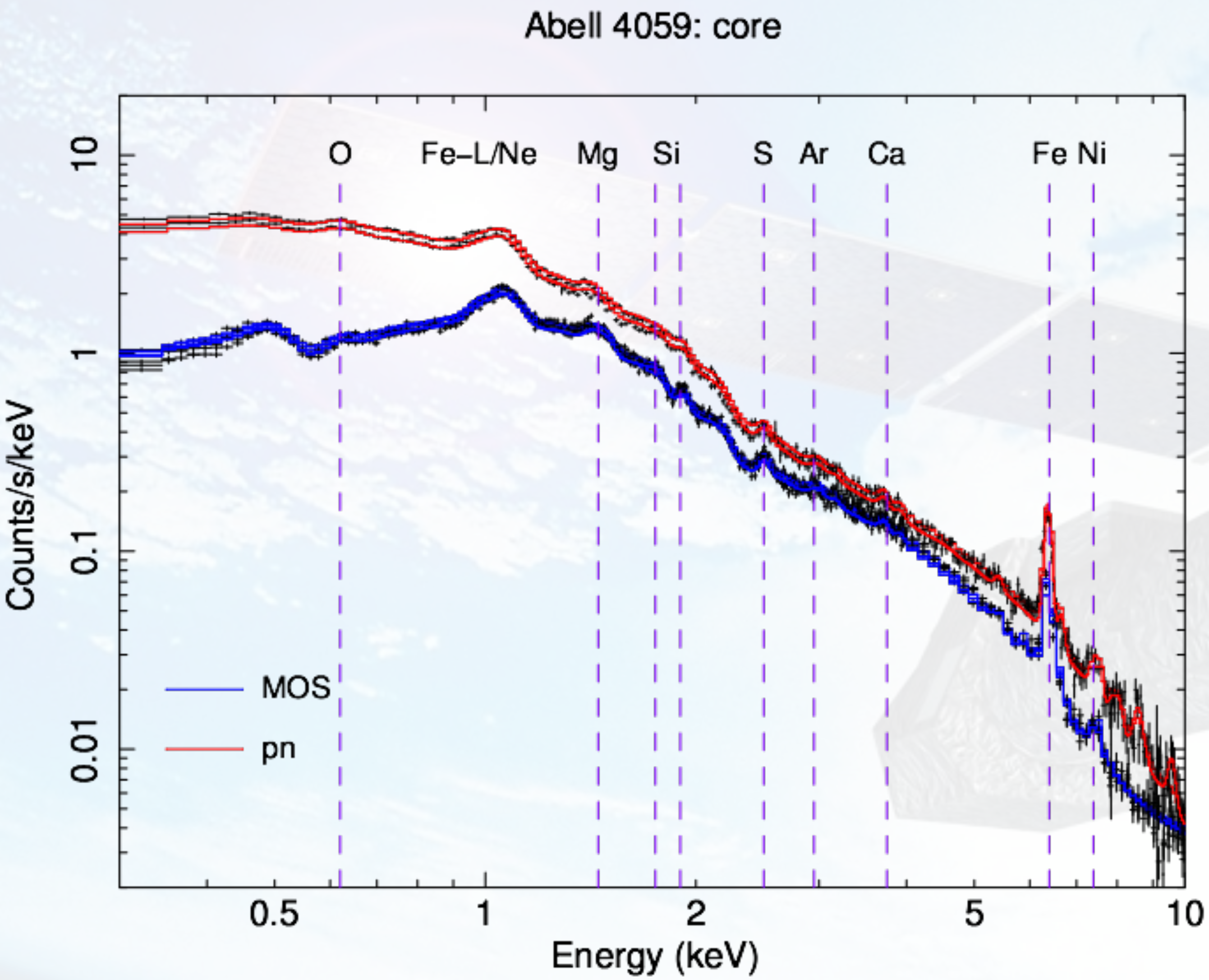
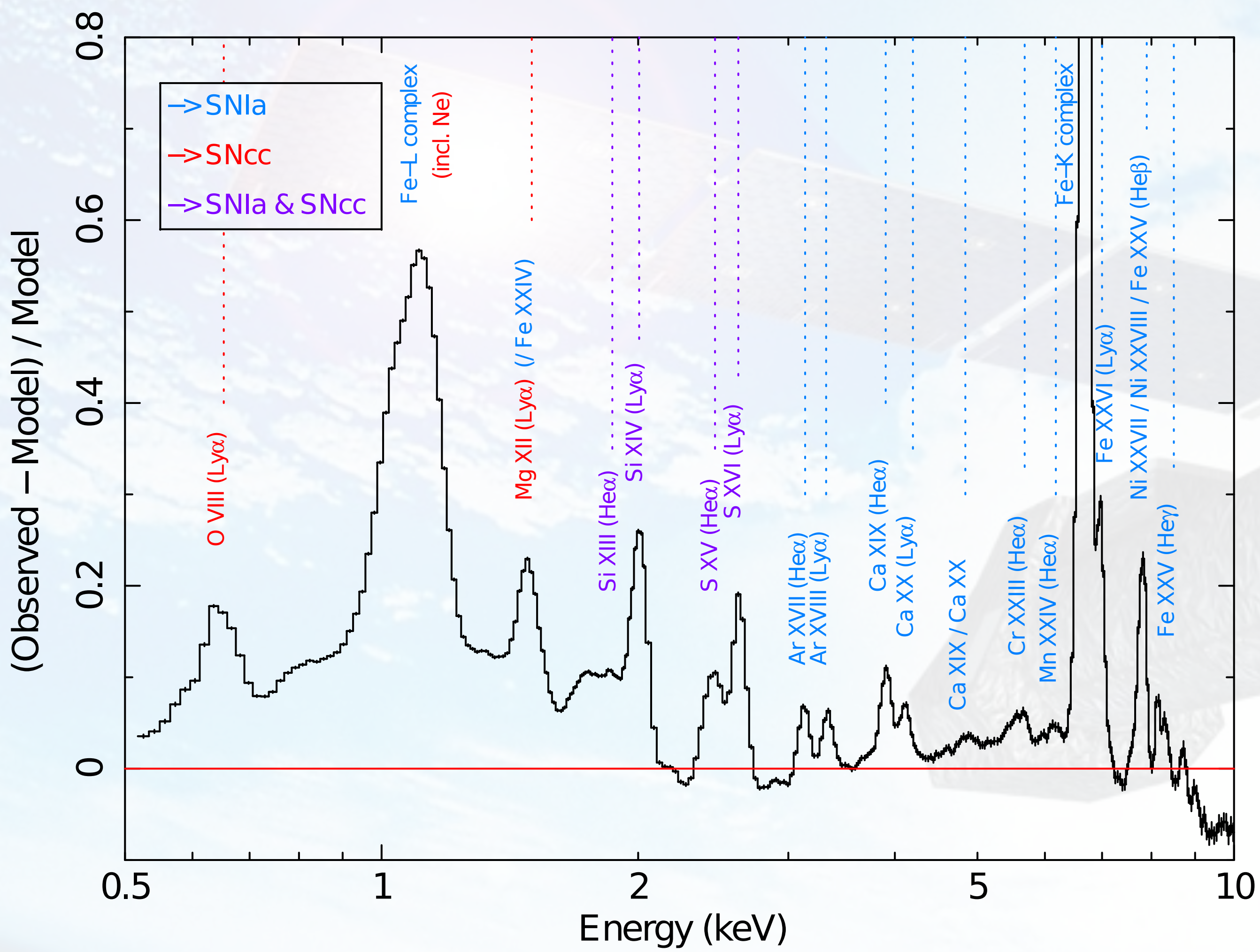


Mernier et al. (2015)

EPIC

XMM-Newton

The intra-cluster medium (ICM) contains metals!



Mernier et al. (2016a)

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XMM-Newton

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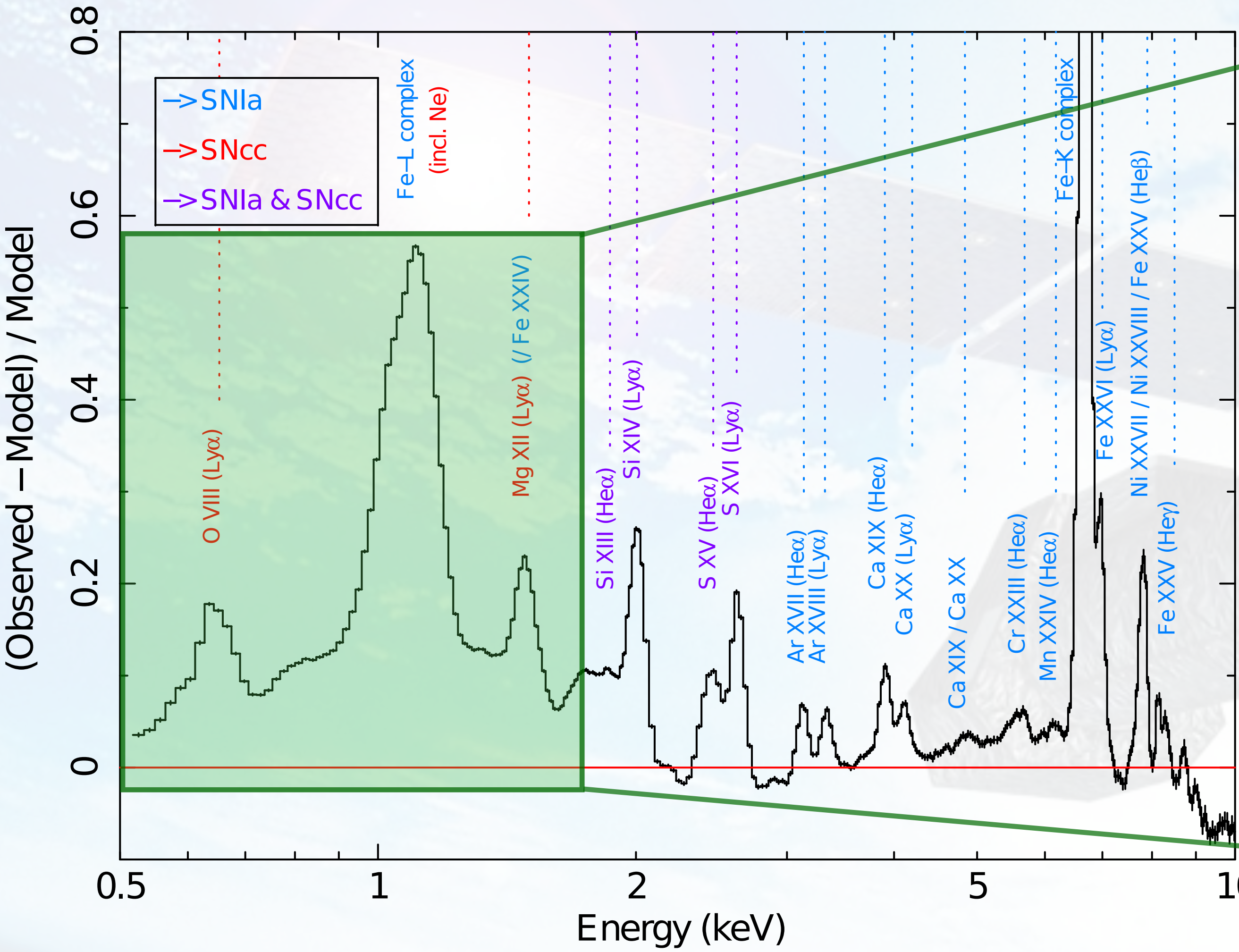
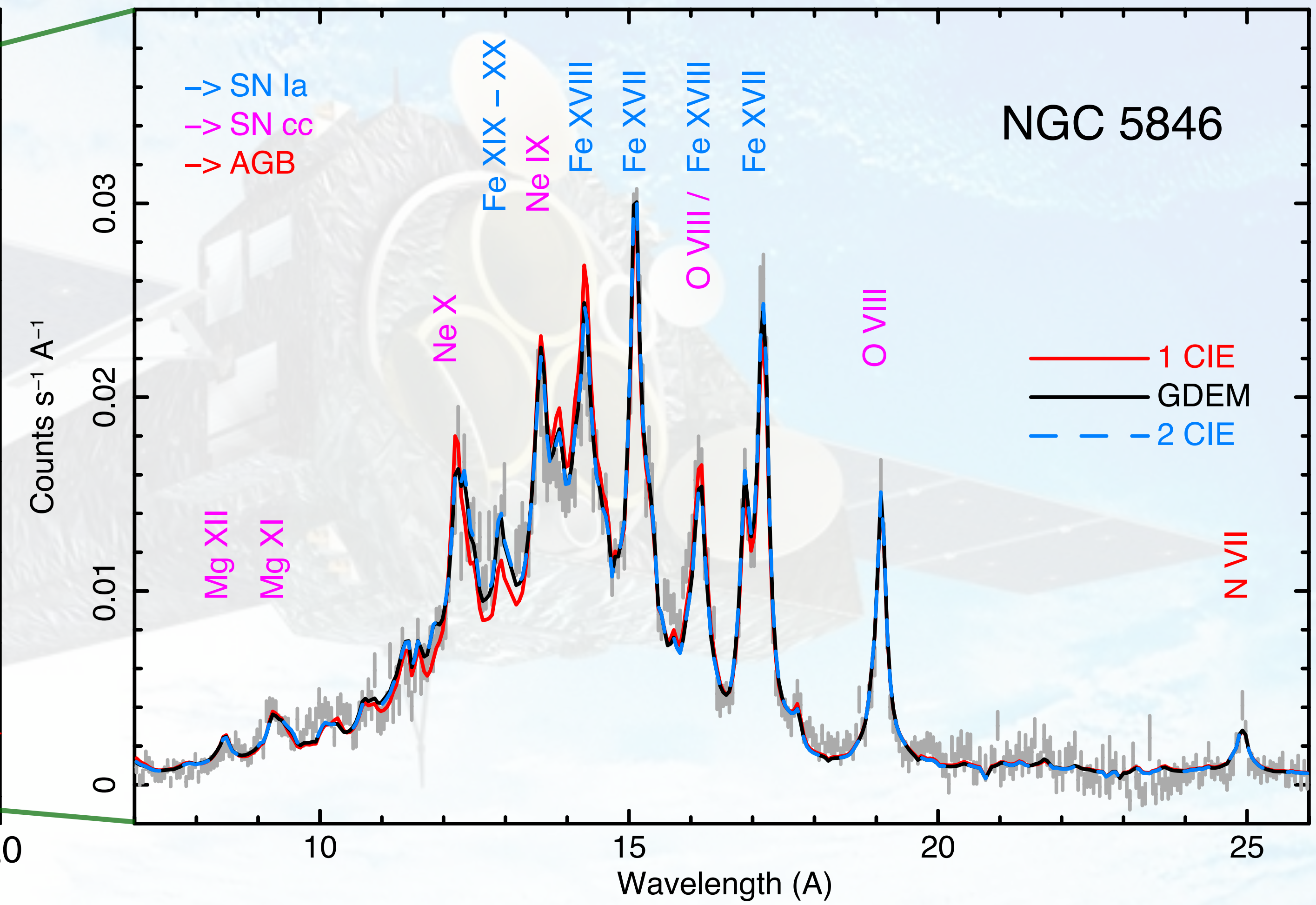


Mernier et al. (2016a)



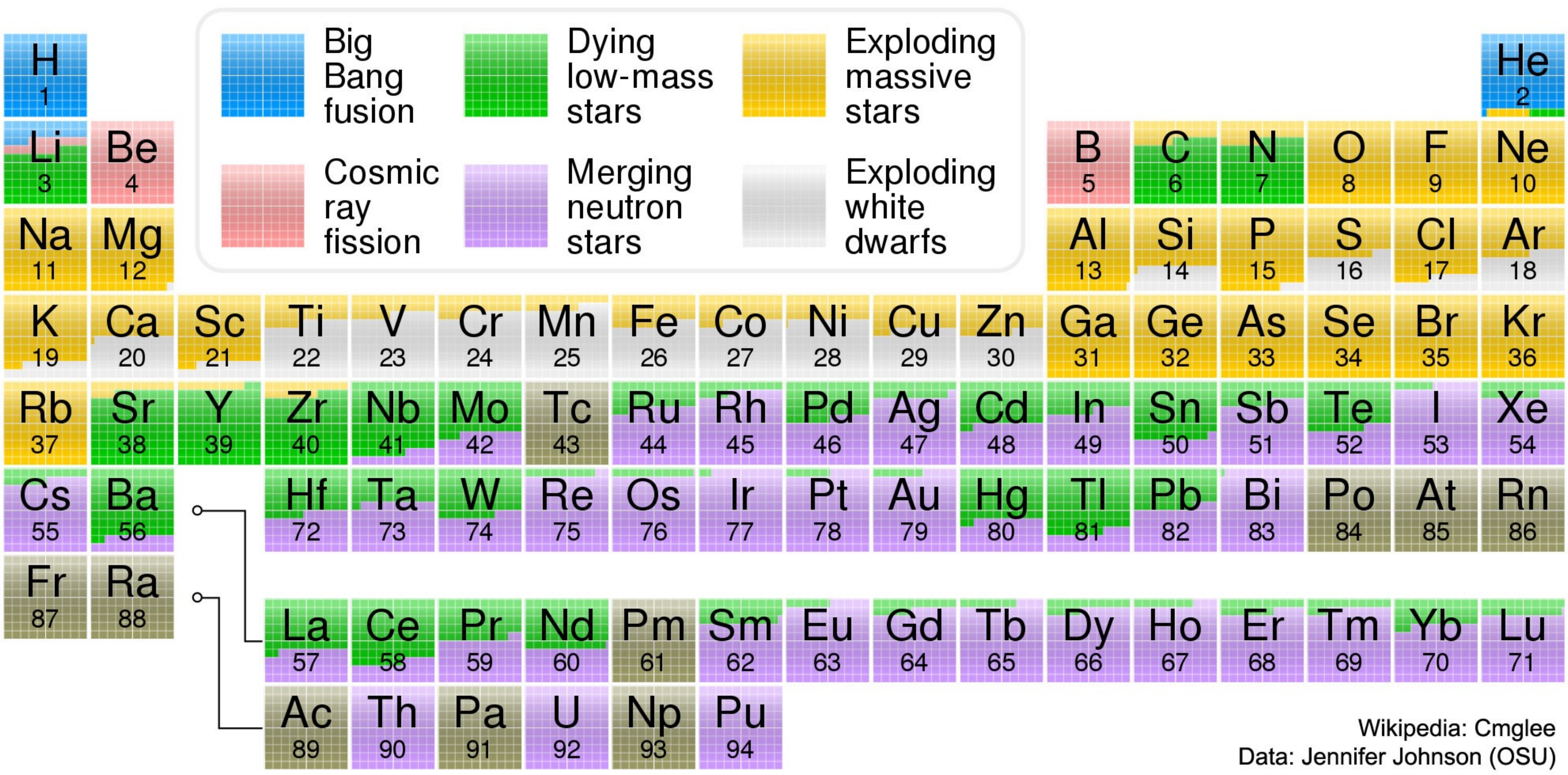
de Plaa et al. (2017)

EPIC

RGS

XMM-Newton

The origin of chemical elements



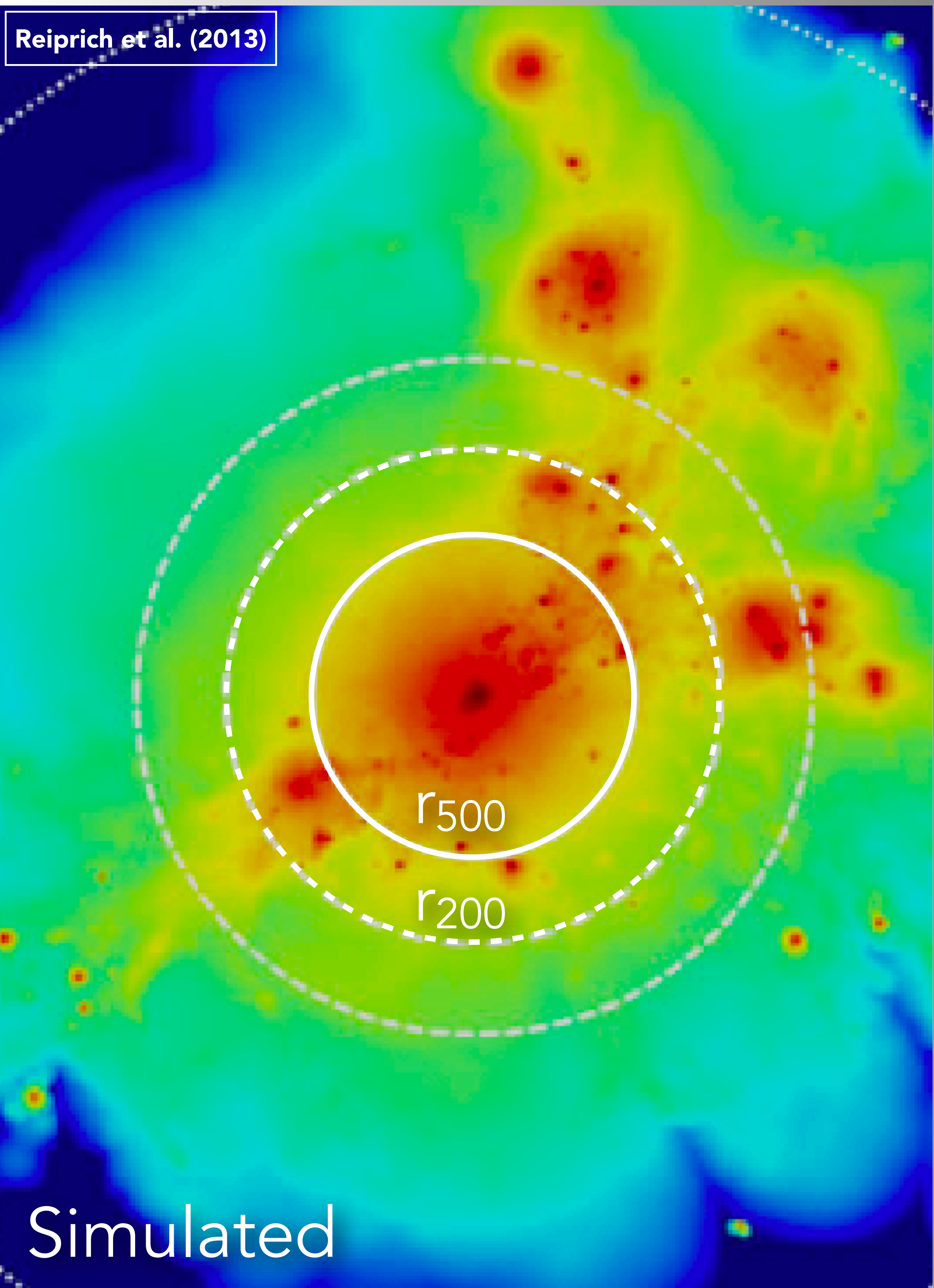
"We are made of star stuff!" — C. Sagan

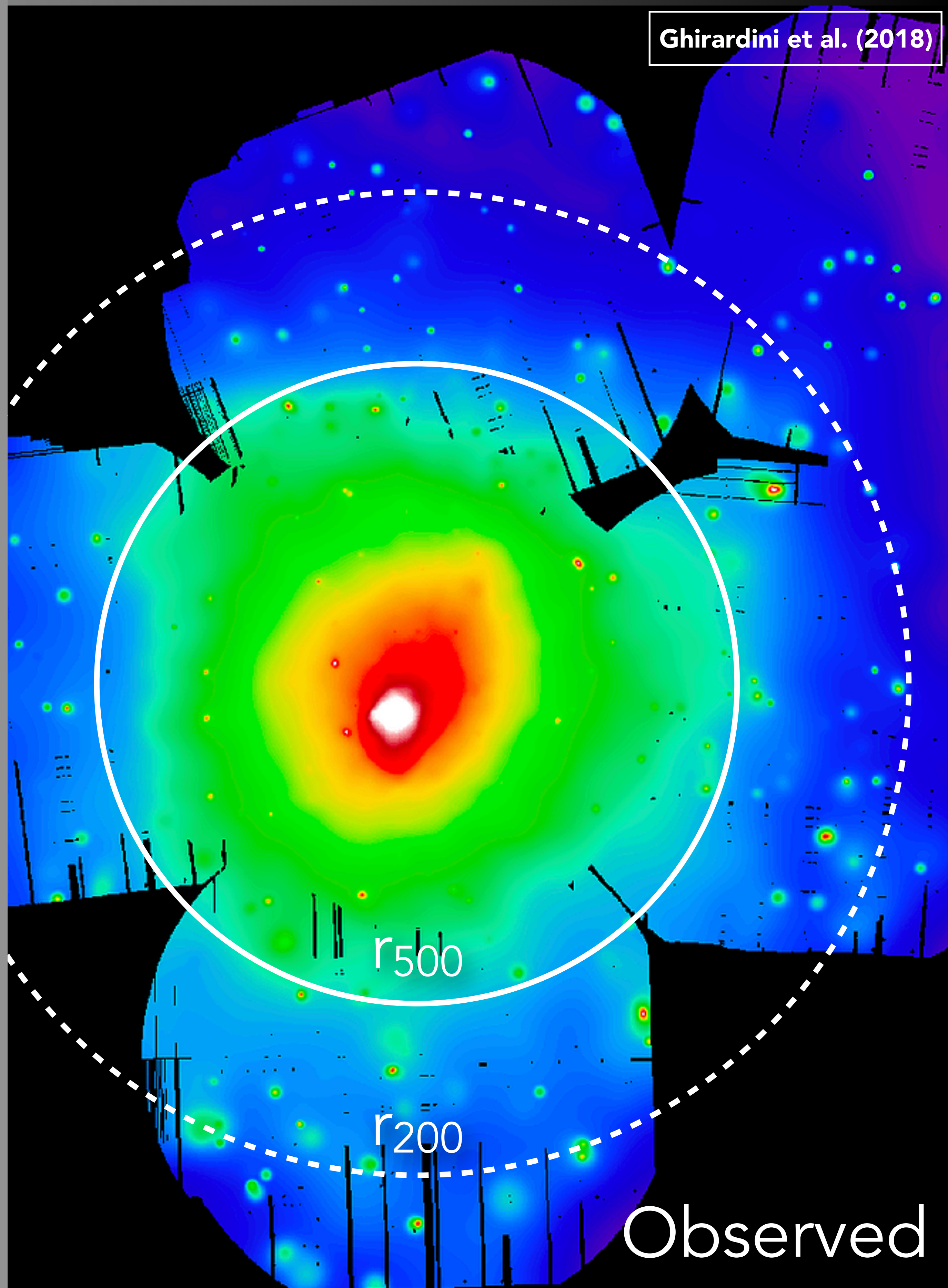
(…which is also present at the largest scales of the Universe…)

Where, ***when***, and ***how*** did these large-scale structures become chemically enriched?

☛ ***Spatial distribution*** of metals in nearby systems!

The (relaxed) ICM morphology





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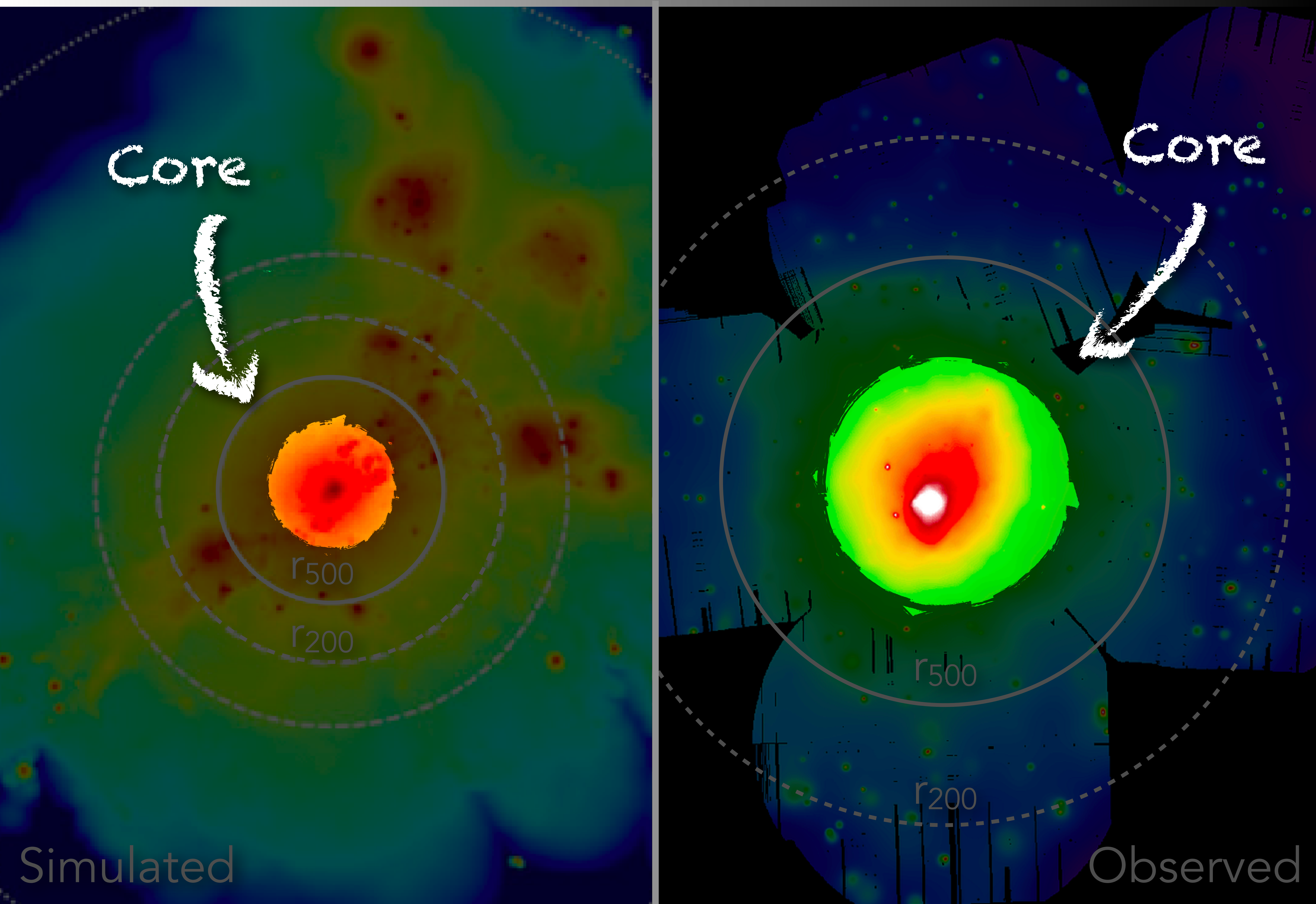

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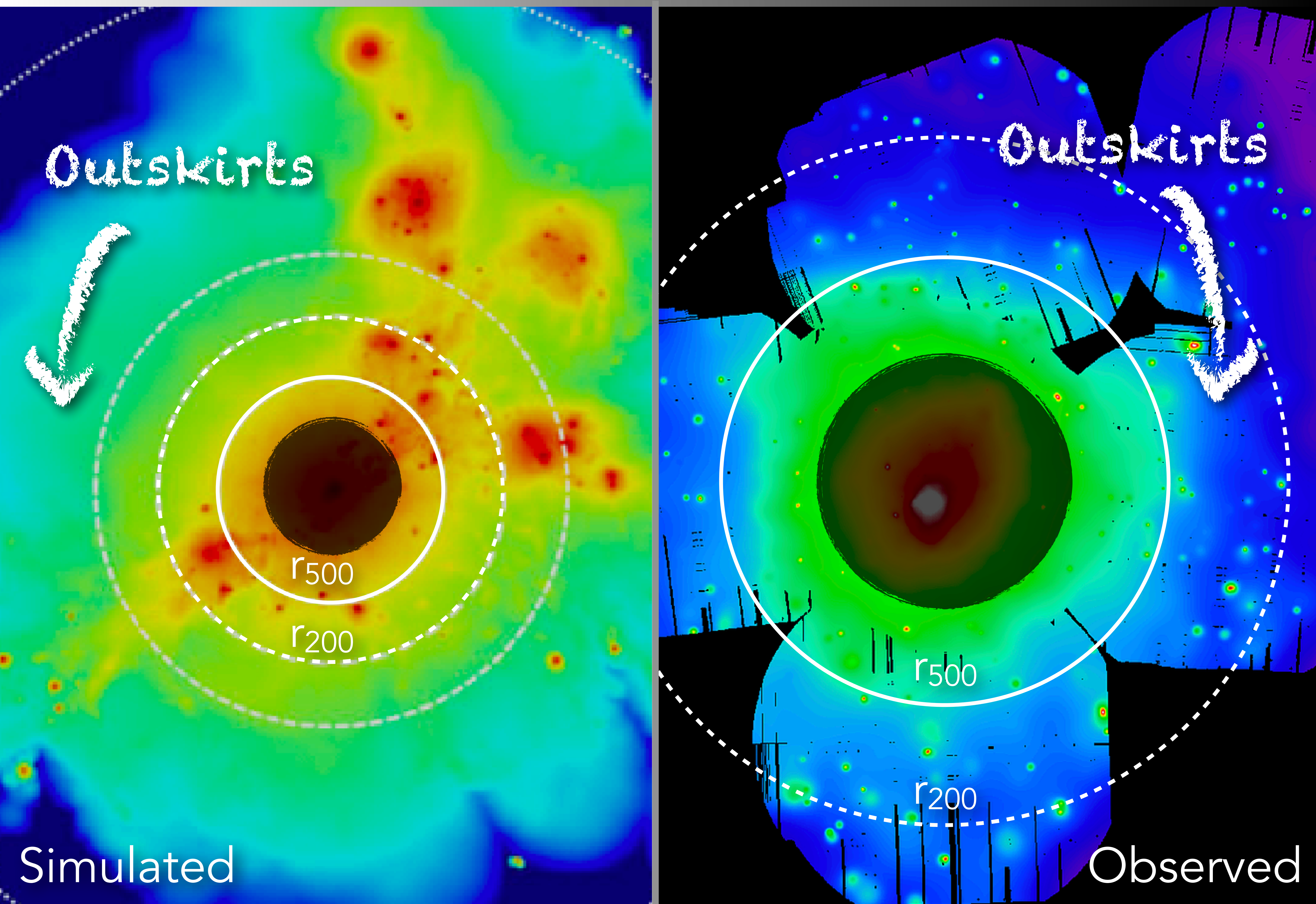
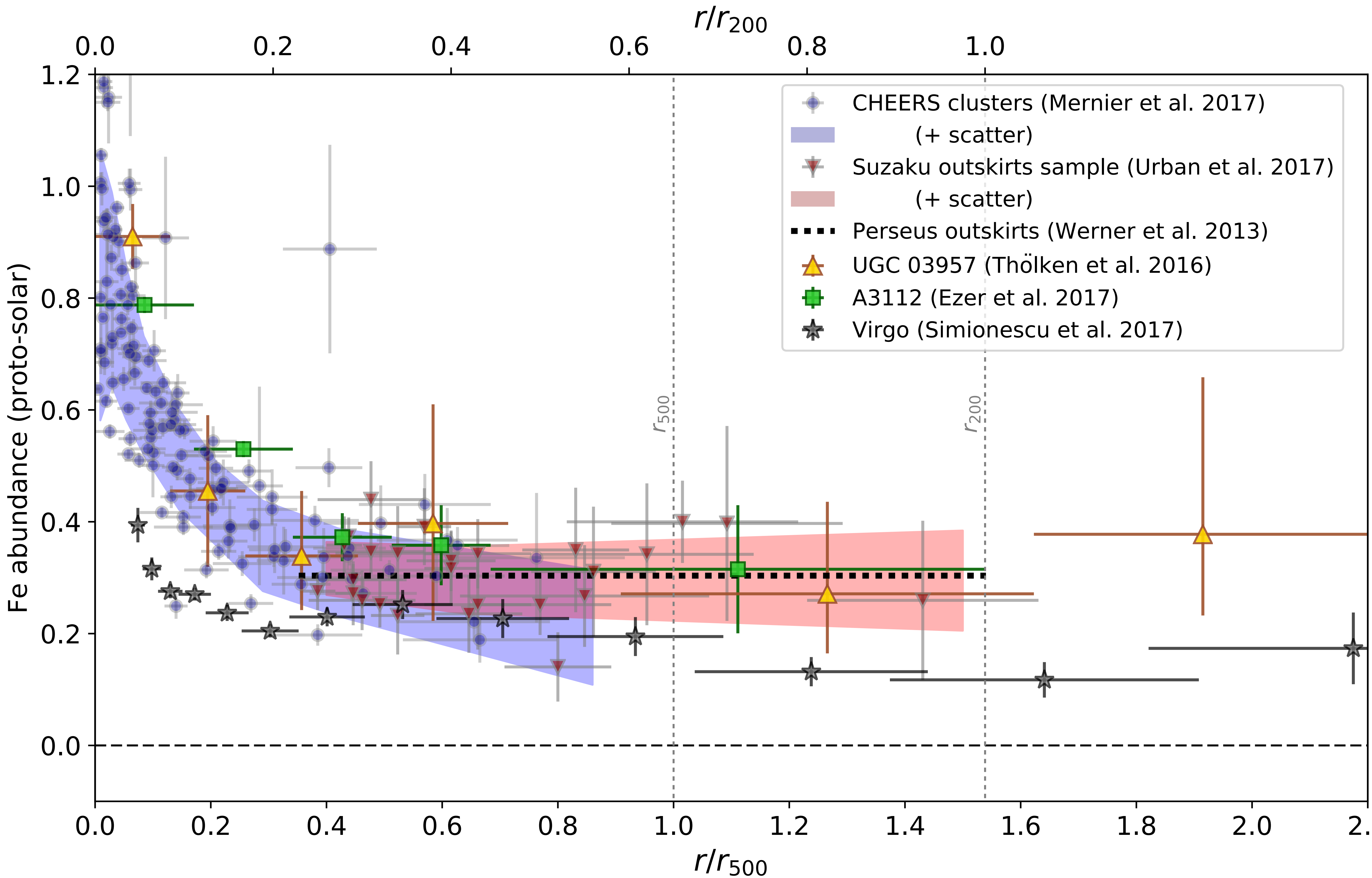


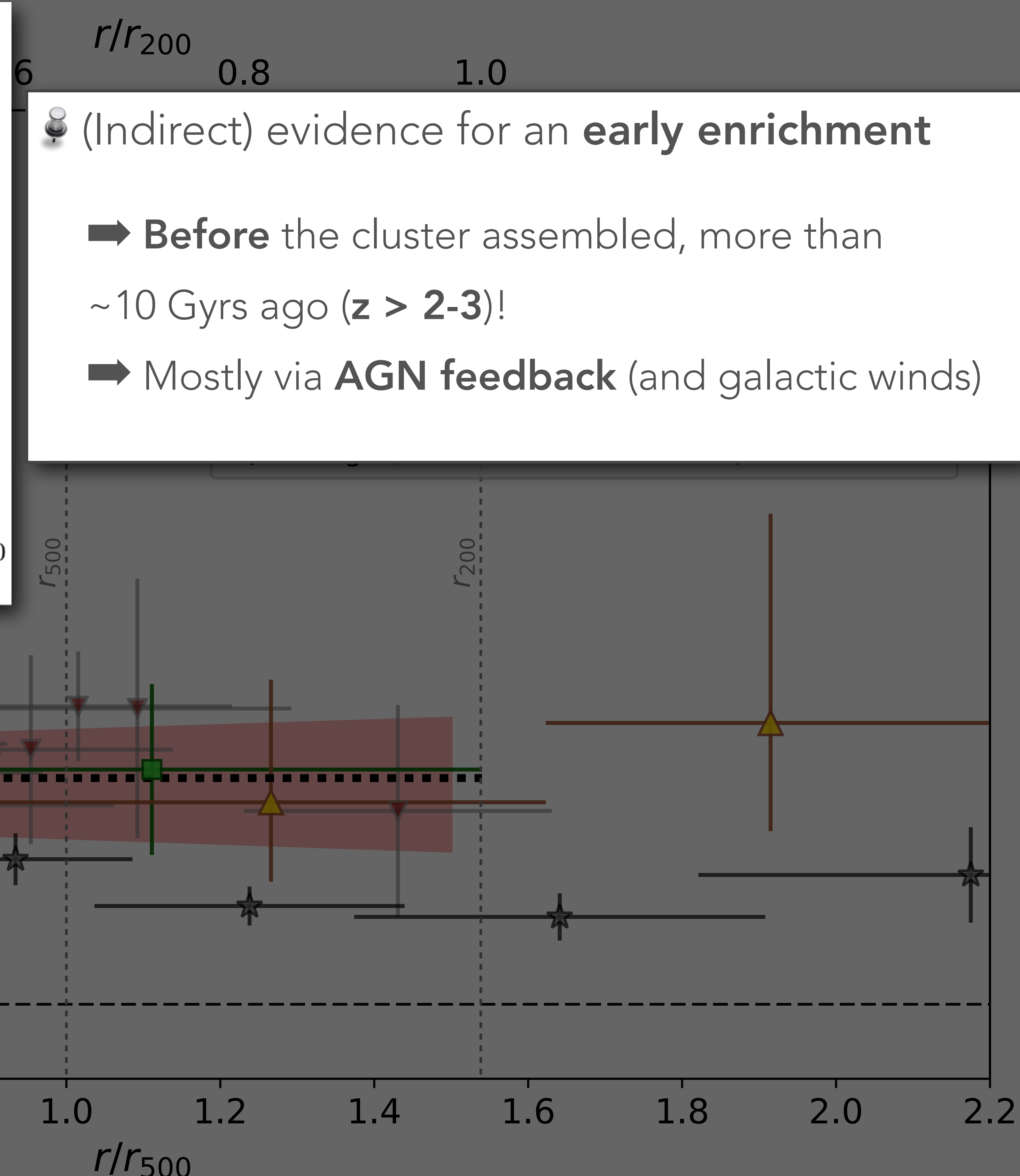
The (average) Fe profile in cool-core clusters

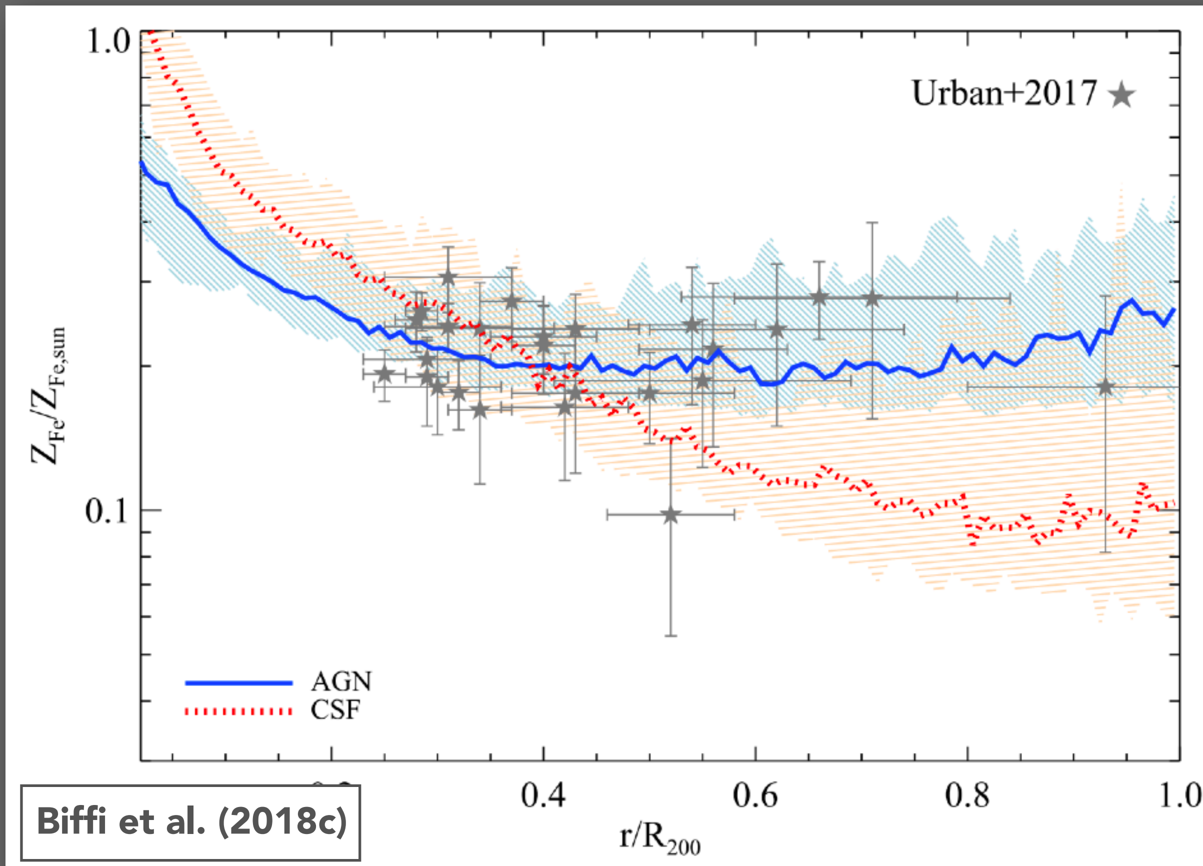


r_{500}: radius within which mass density = 500 × (critical density of the Universe)

Mernier et al. (2018c)

The (average) Fe profile in cool-core clusters





Biffi et al. (2018c)

(Indirect) evidence for an **early enrichment**

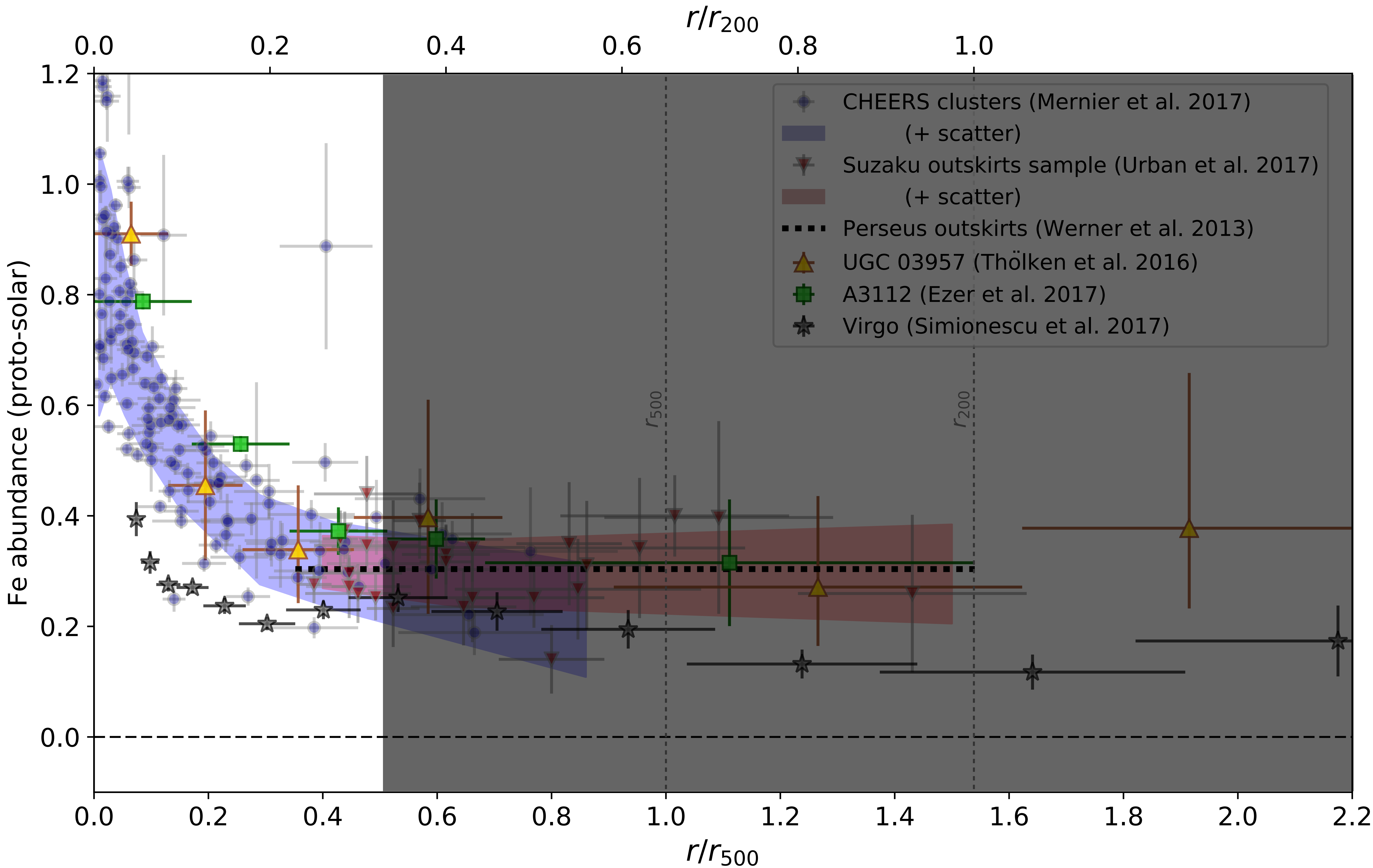
➡ **Before** the cluster assembled, more than ~10 Gyrs ago (**z > 2-3**)!

➡ Mostly via **AGN feedback** (and galactic winds)

$\boldsymbol{r_{500}}$: radius within which mass density = 500 × (critical density of the Universe)

Mernier et al. (2018c)

The (average) Fe profile in cool-core clusters



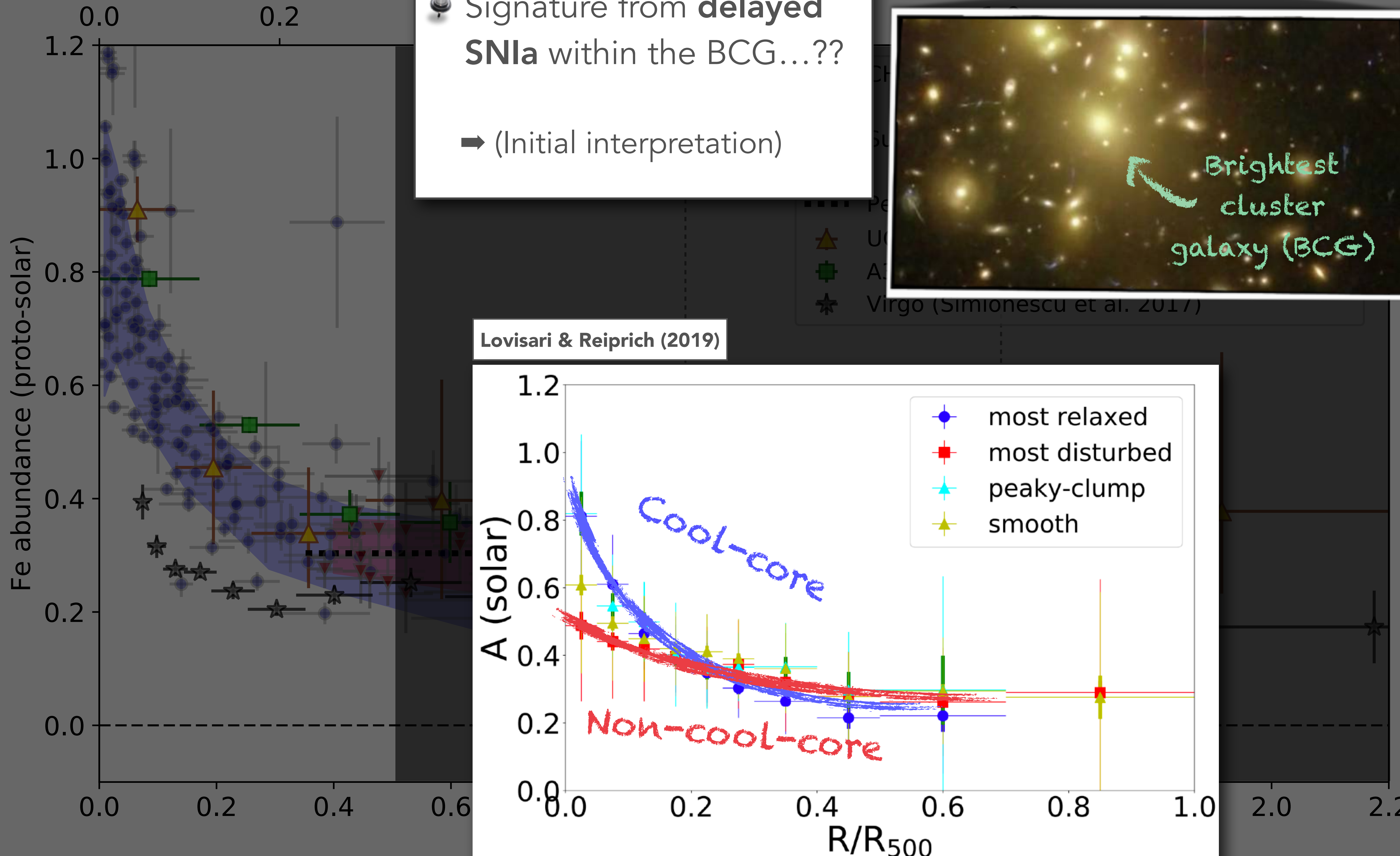
r_{500}: radius within which mass density = 500 × (critical density of the Universe)

Mernier et al. (2018c)

The (average) Fe profile in cool-core clusters

Signature from **delayed SNIa** within the BCG…??

➡ (Initial interpretation)



r_{500}: radius within which mass density = 500 × (critical density of the Universe)

Mernier et al. (2018c)

The CHEERS sample

CHEERS! (PI: J. de Plaa)

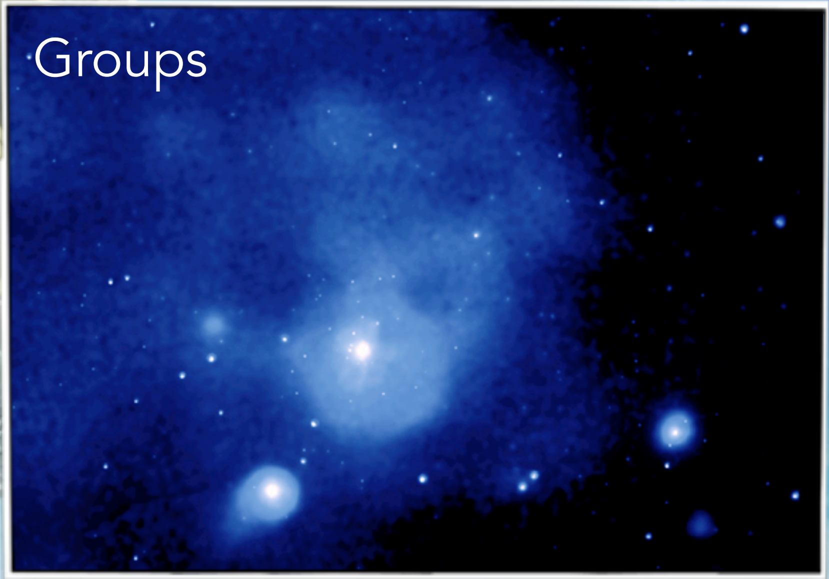
CHEERS stands for:
***CHE**mical **E**nrichment **R**gs **S**ample*

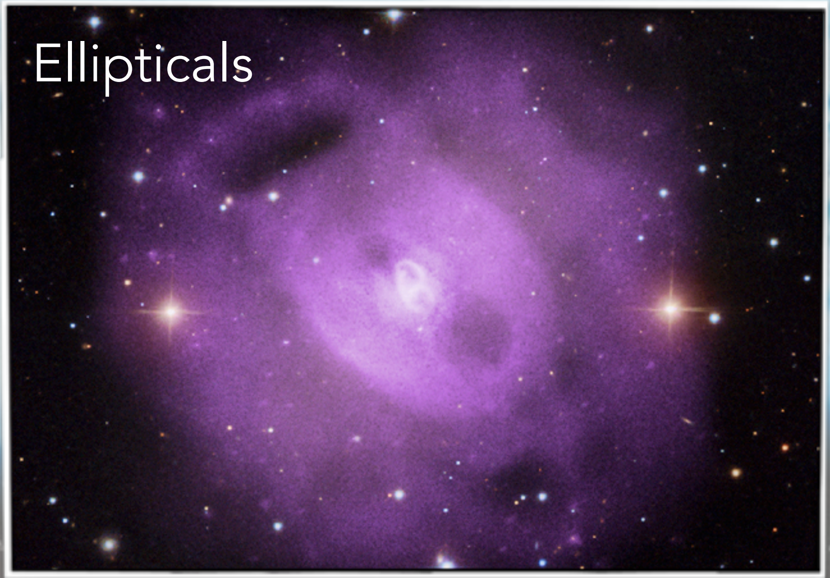
de Plaa et al. (2017)

- Cool-core galaxy **clusters**, **groups** & **ellipticals**
- O VIII line in RGS: > 5σ
- **Nearby** (z < 0.1)
- New deep observations of 11 objects (1.6 Ms)
- + archival (public) data

➡ 44 systems

➡ ~4.5 Ms
of *XMM-Newton* total net exposure





General strategy

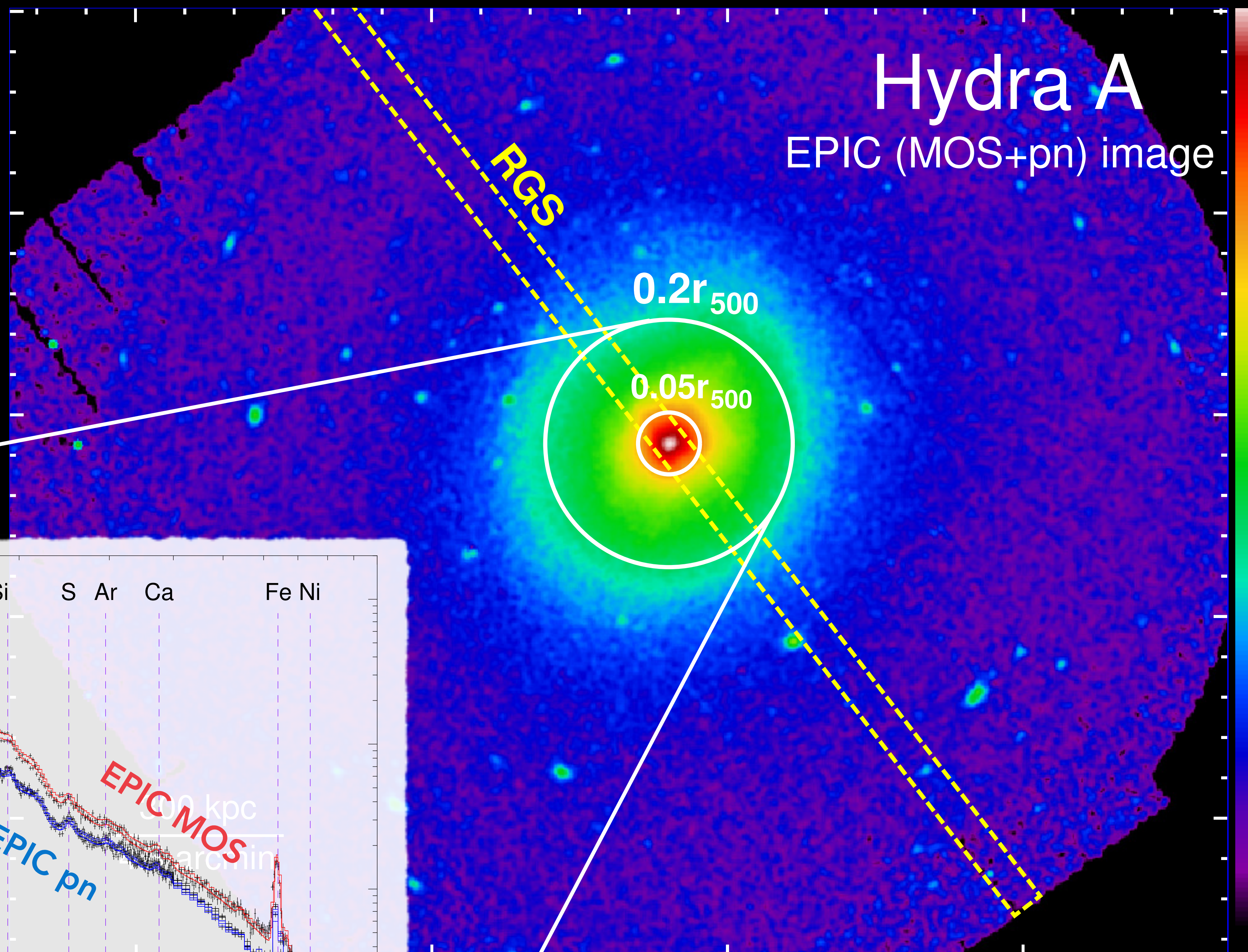
EPIC

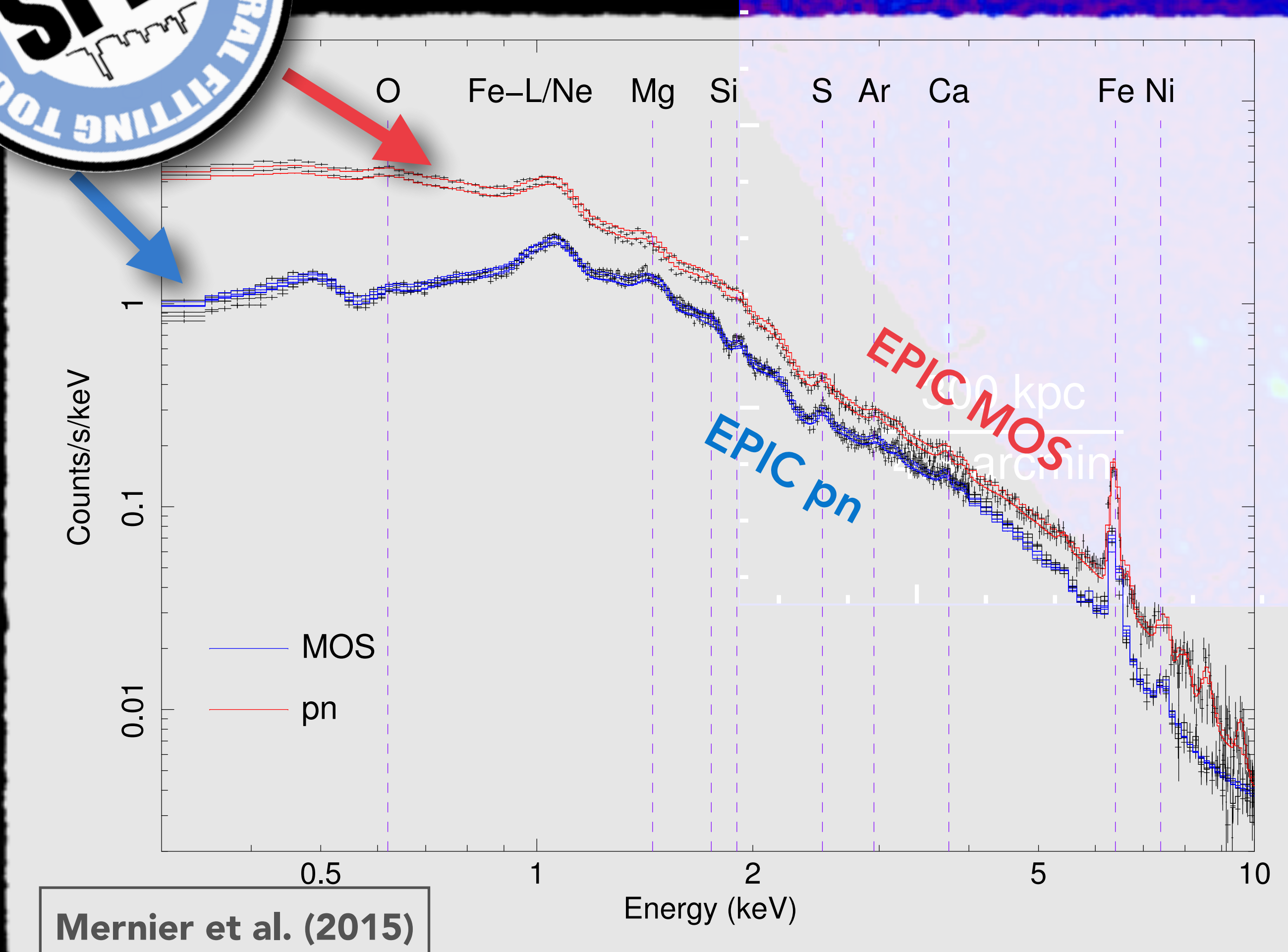
- Clusters (>1.7 keV):

  0.2 r_{500} & 0.05 r_{500}

- Groups (< 1.7 keV):

  0.05 r_{500}



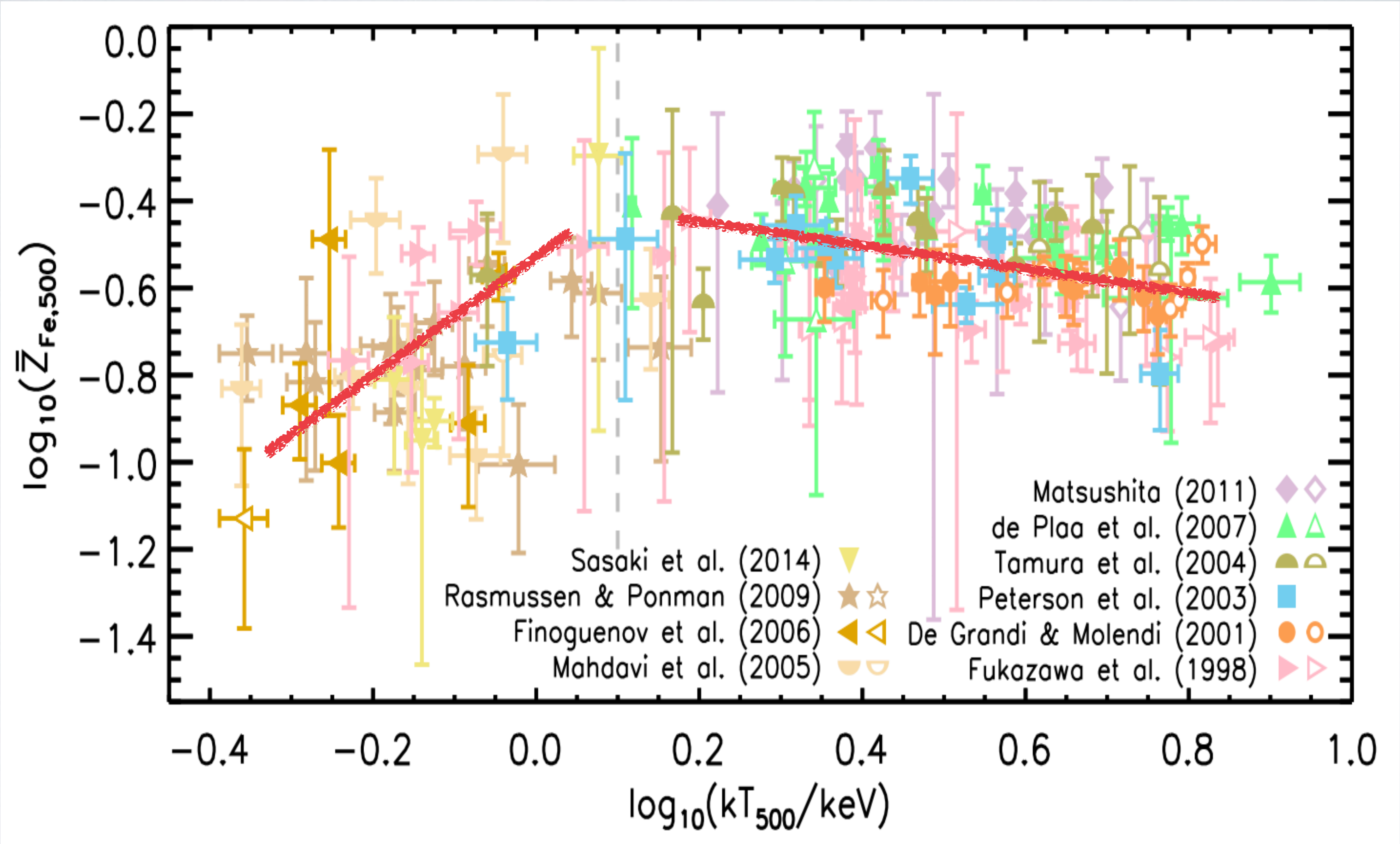


RGS

0.8 arcmin

1. Central Fe abundance (in cool-core systems)

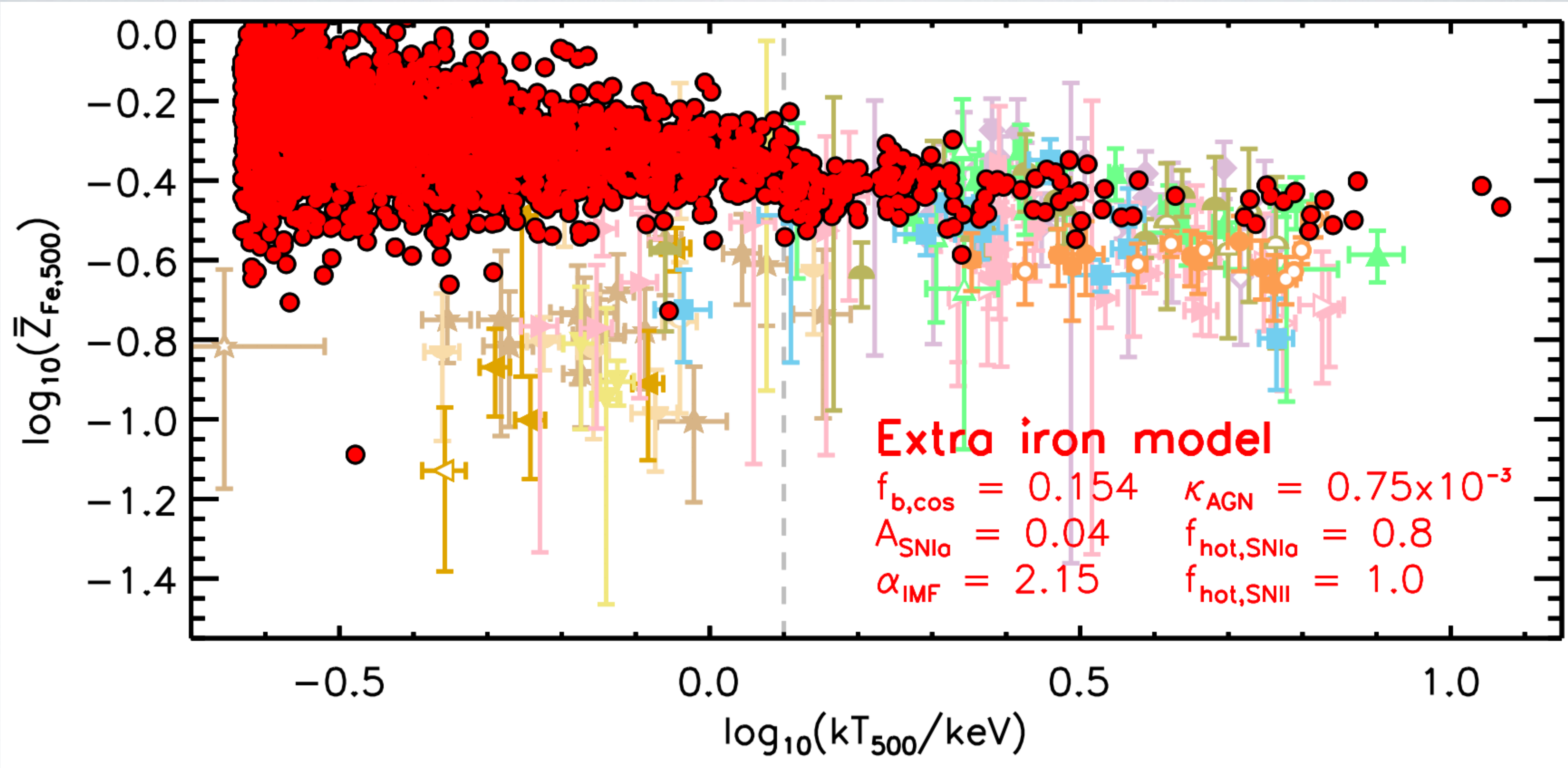
Central Fe abundance: clusters vs. groups/ellipticals



Yates et al. (2017)

- Central Fe enrichment in groups/ellipticals appears **lower** than in clusters **(Rasmussen & Ponman 2009, Sun 2012, Yates et al. 2017)**

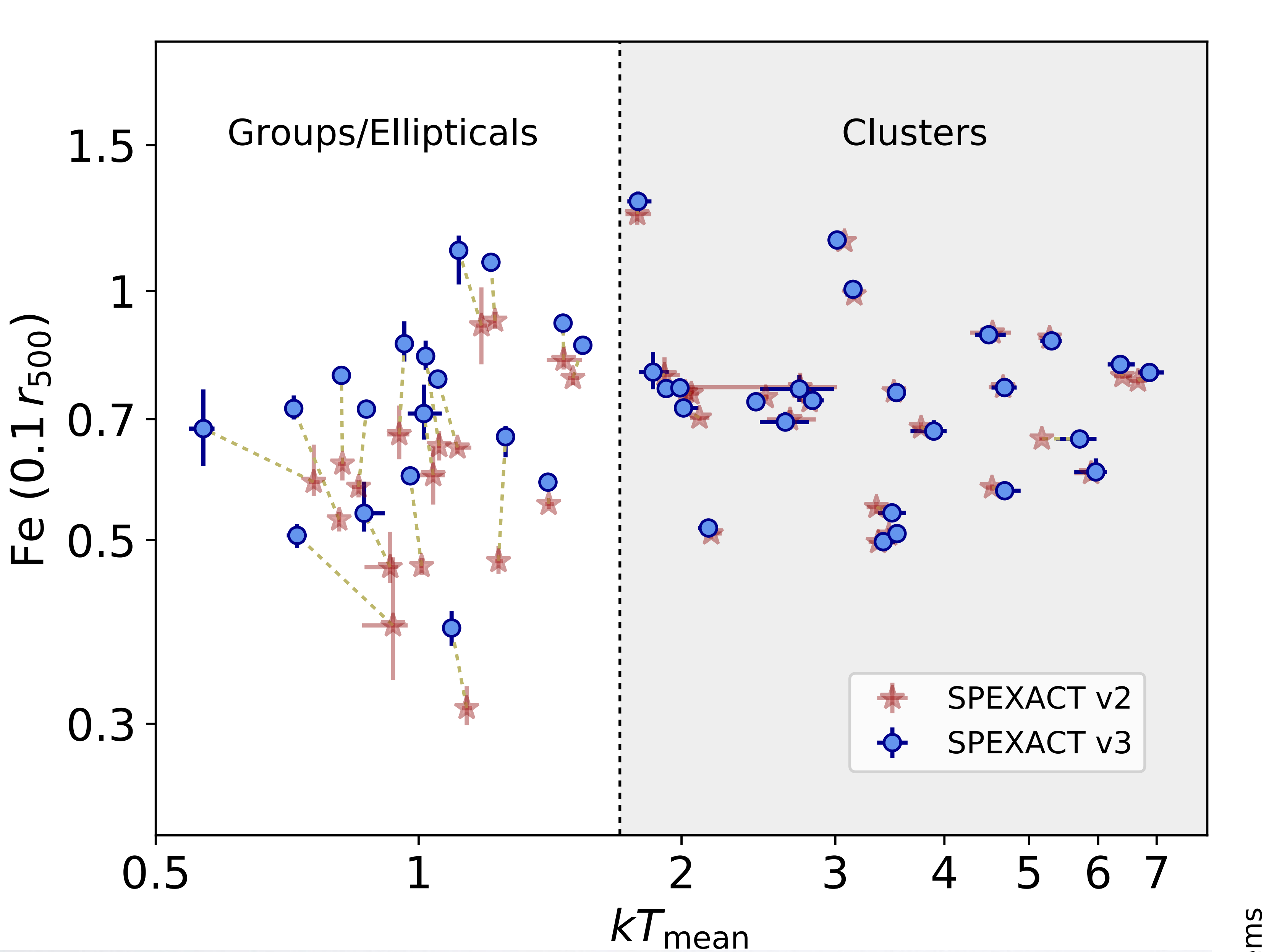
Central Fe abundance: clusters vs. groups/ellipticals



Yates et al. (2017)

- Central Fe enrichment in groups/ellipticals appears **lower** than in clusters **(Rasmussen & Ponman 2009, Sun 2012, Yates et al. 2017)**
- **Inconsistent** with theoretical expectations! **(Yates et al. 2017)**

Central Fe abundance: clusters vs. groups/ellipticals



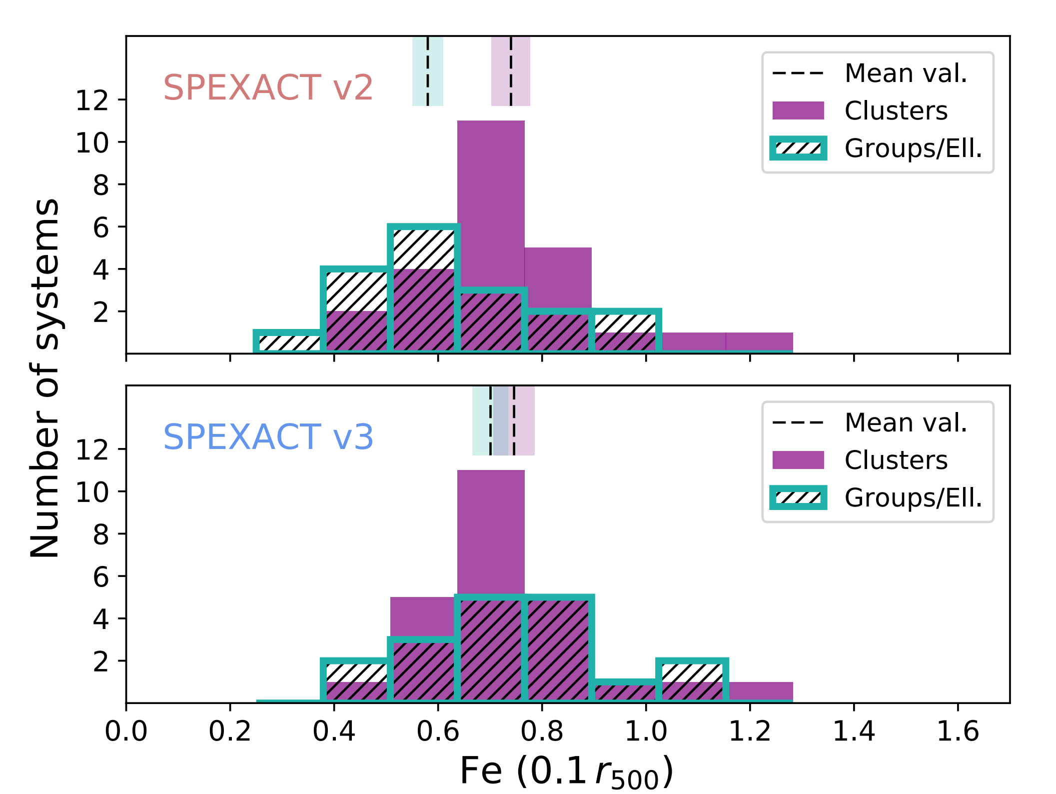
For the first time, we find **similar central Fe abundances** between:

- **clusters**
- **groups**
- **ellipticals**

(2 orders of magnitude in total mass!)

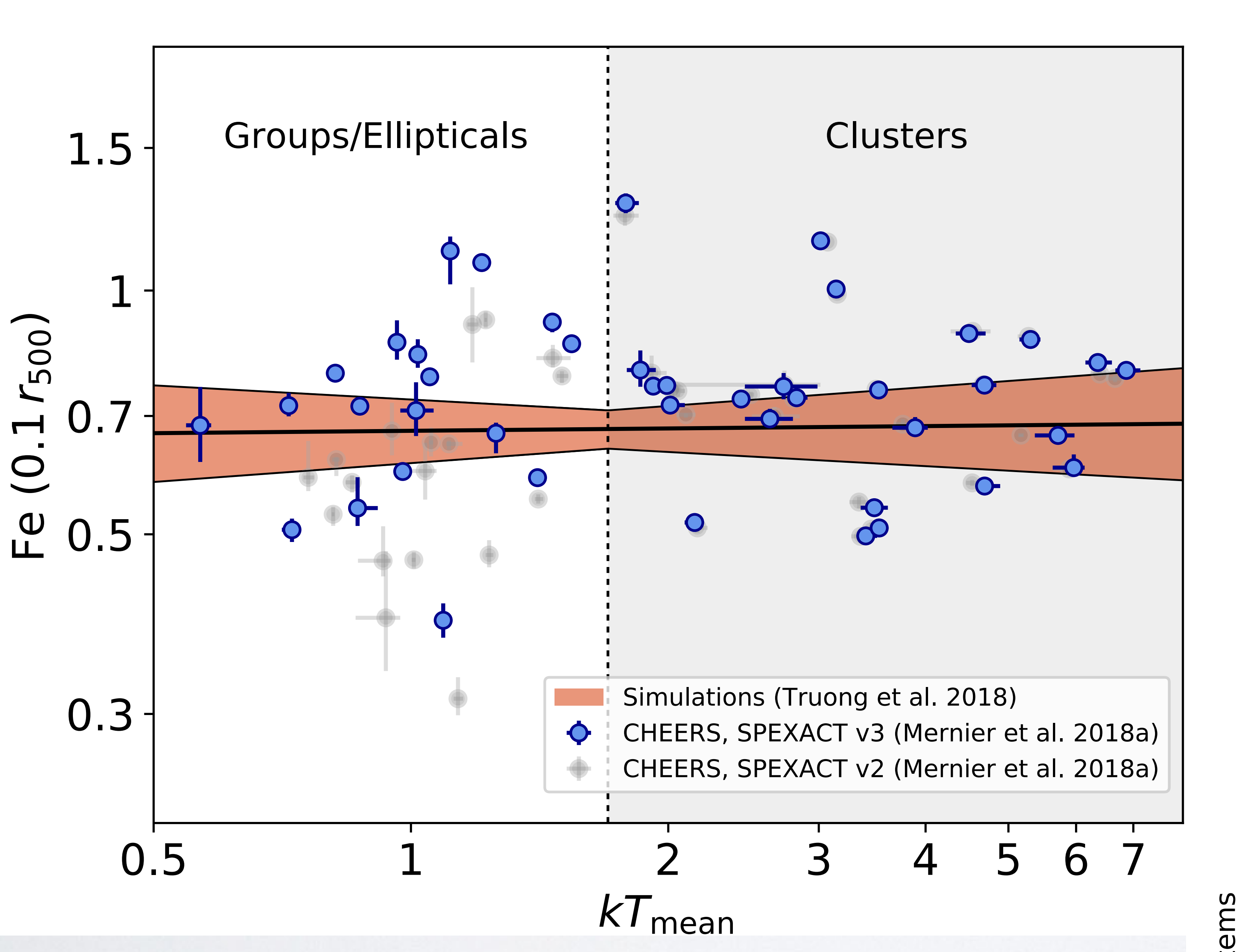
End 2016: **New SPEX release!**

SPEX v2 → SPEX v3



Mernier et al. (2018a)

Central Fe abundance: clusters vs. groups/ellipticals



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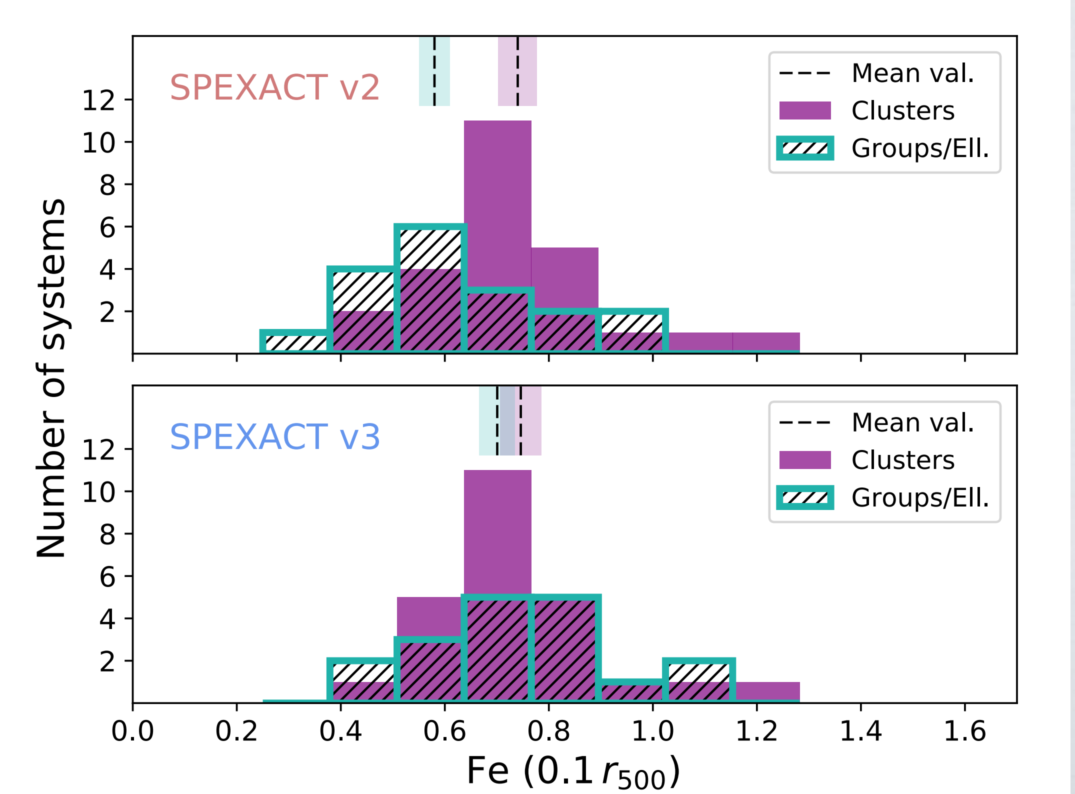


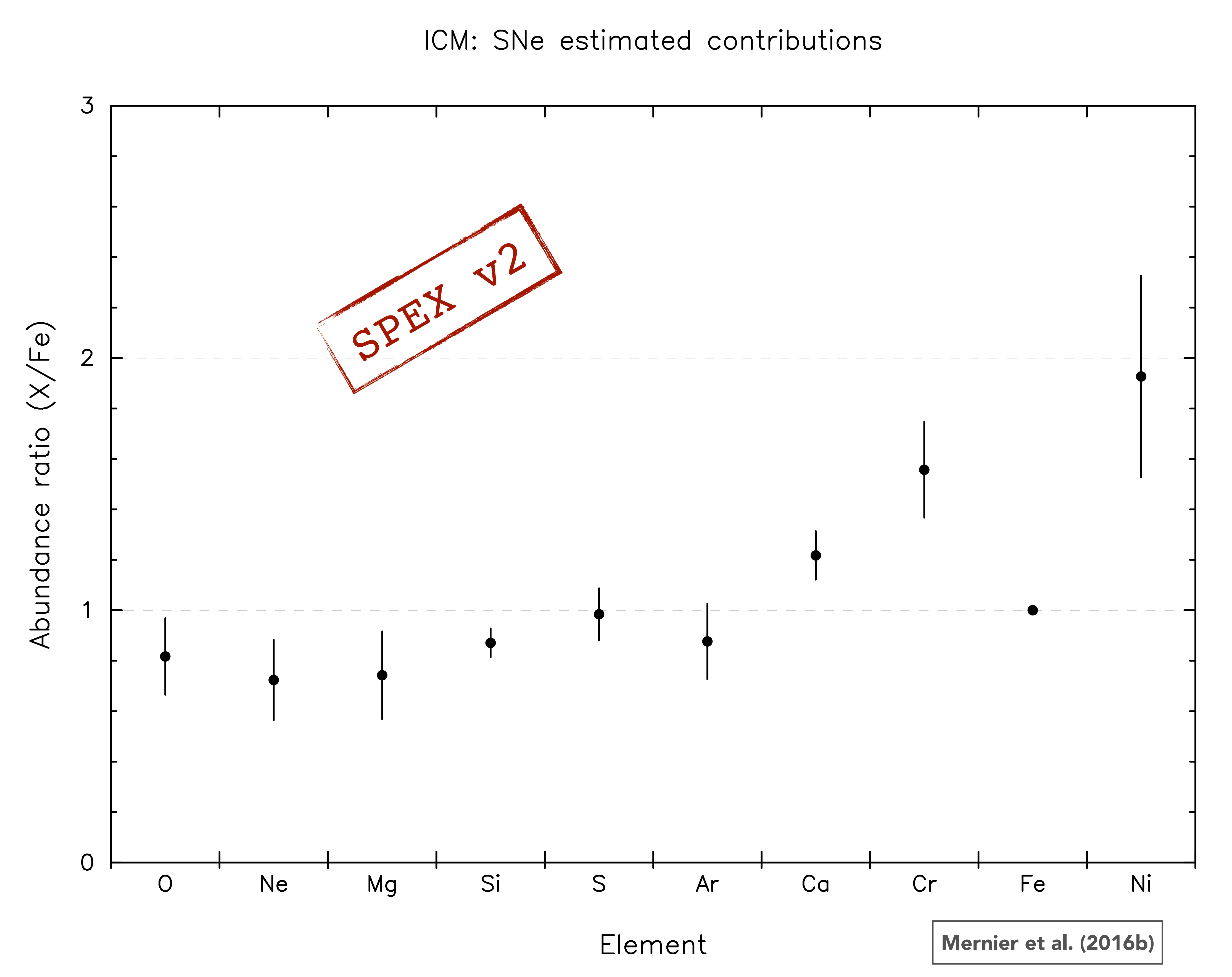
Consistent with simulations!

(see also: Truong et al. 2019)

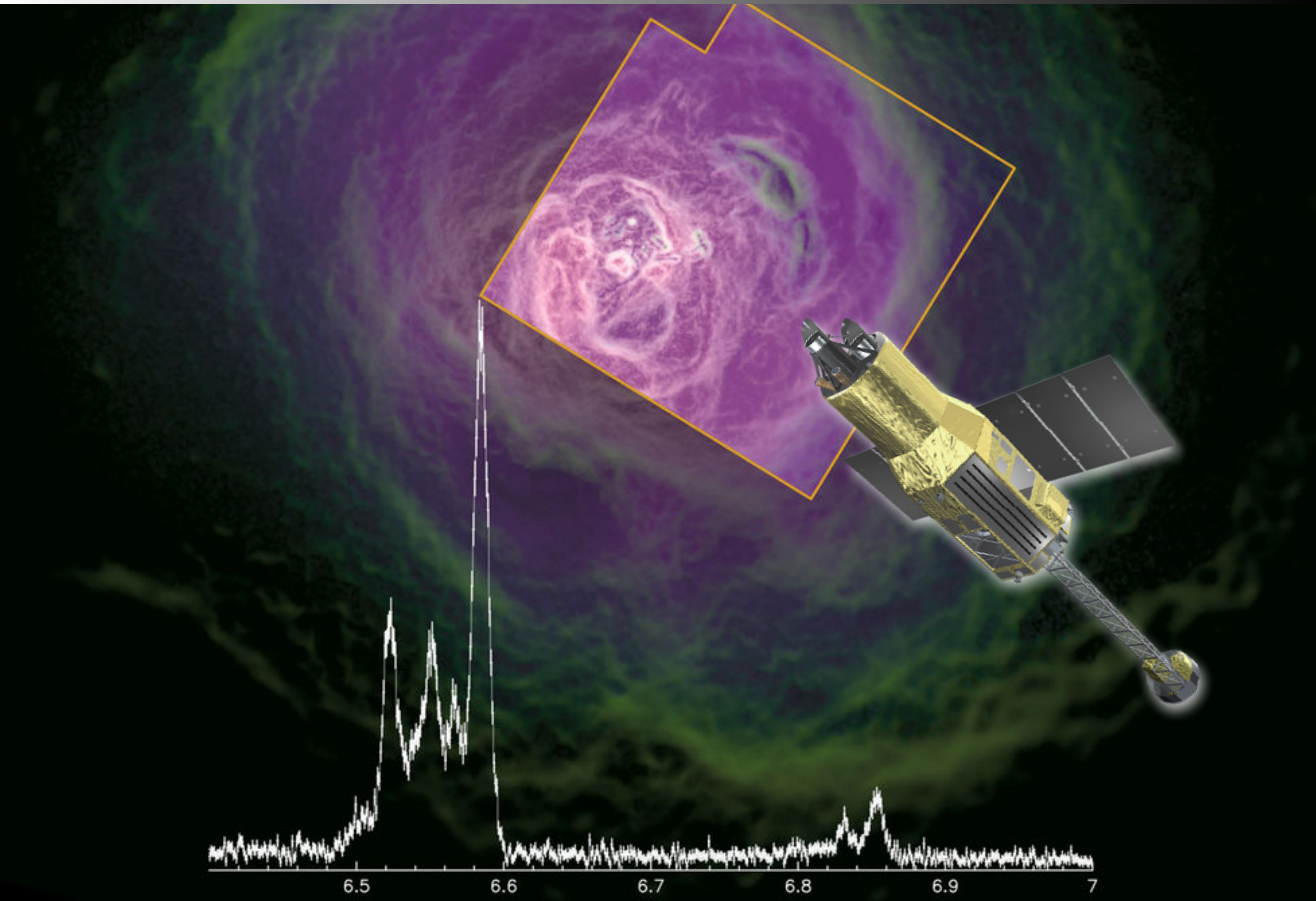
Mernier et al. (2018c)

2. Chemical composition of the ICM

Average ICM abundance pattern



Hitomi (February 2016 - March 2016)



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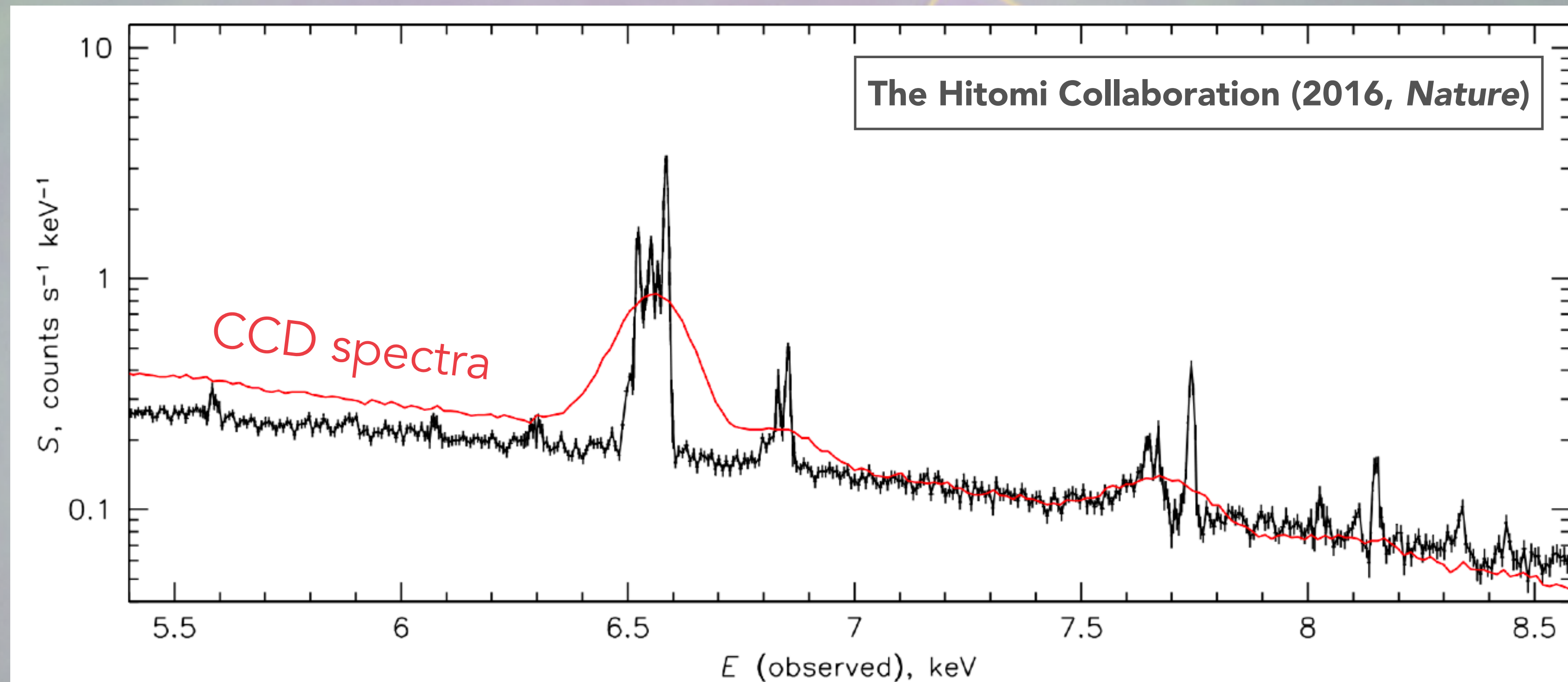
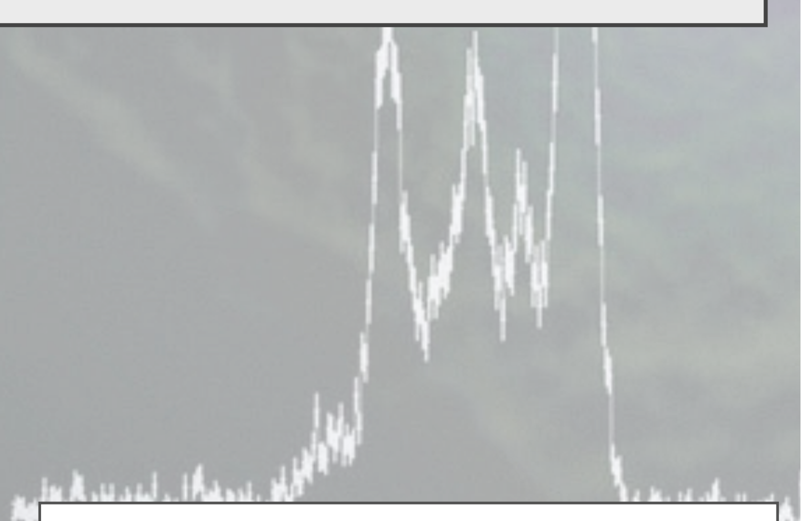
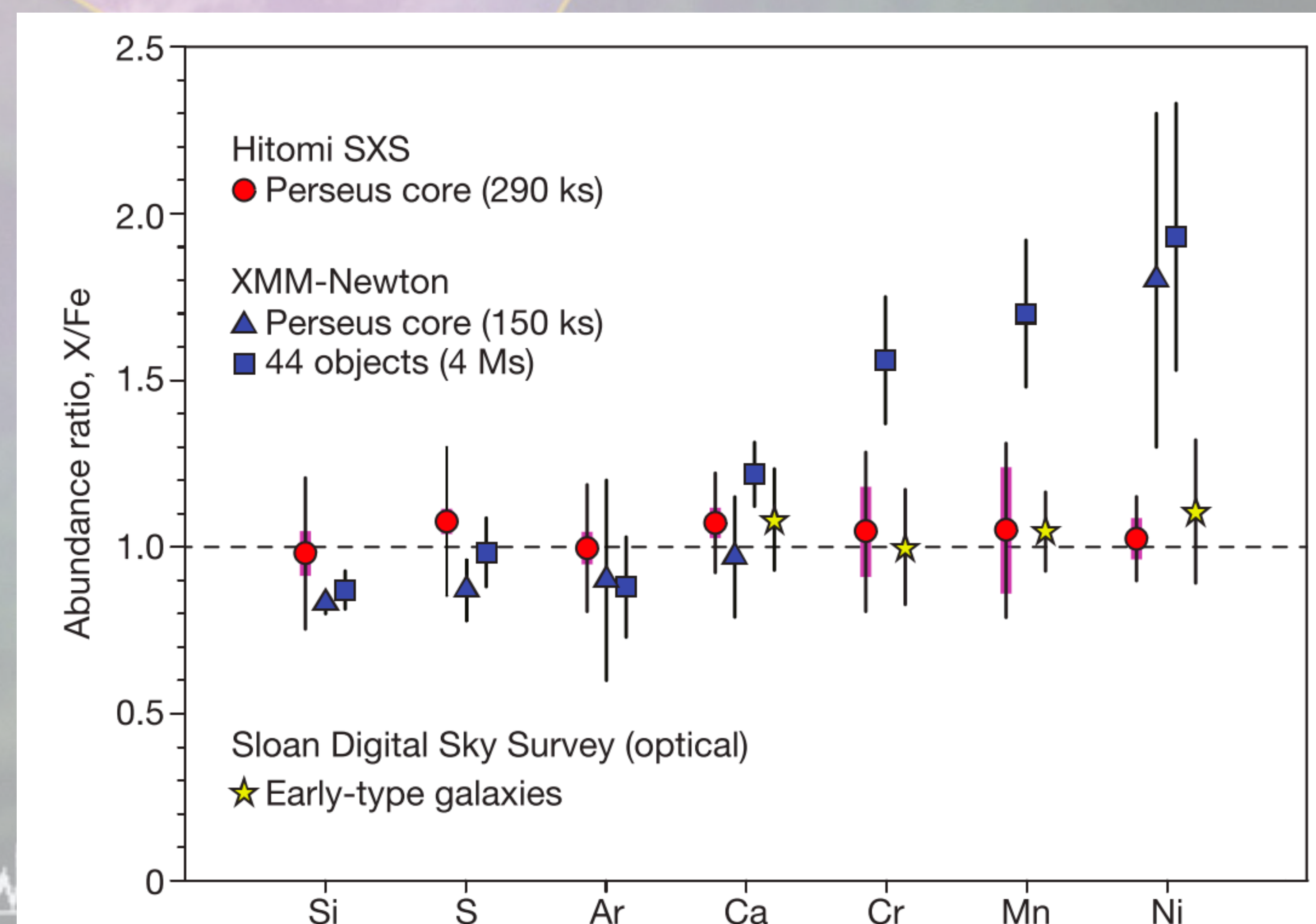


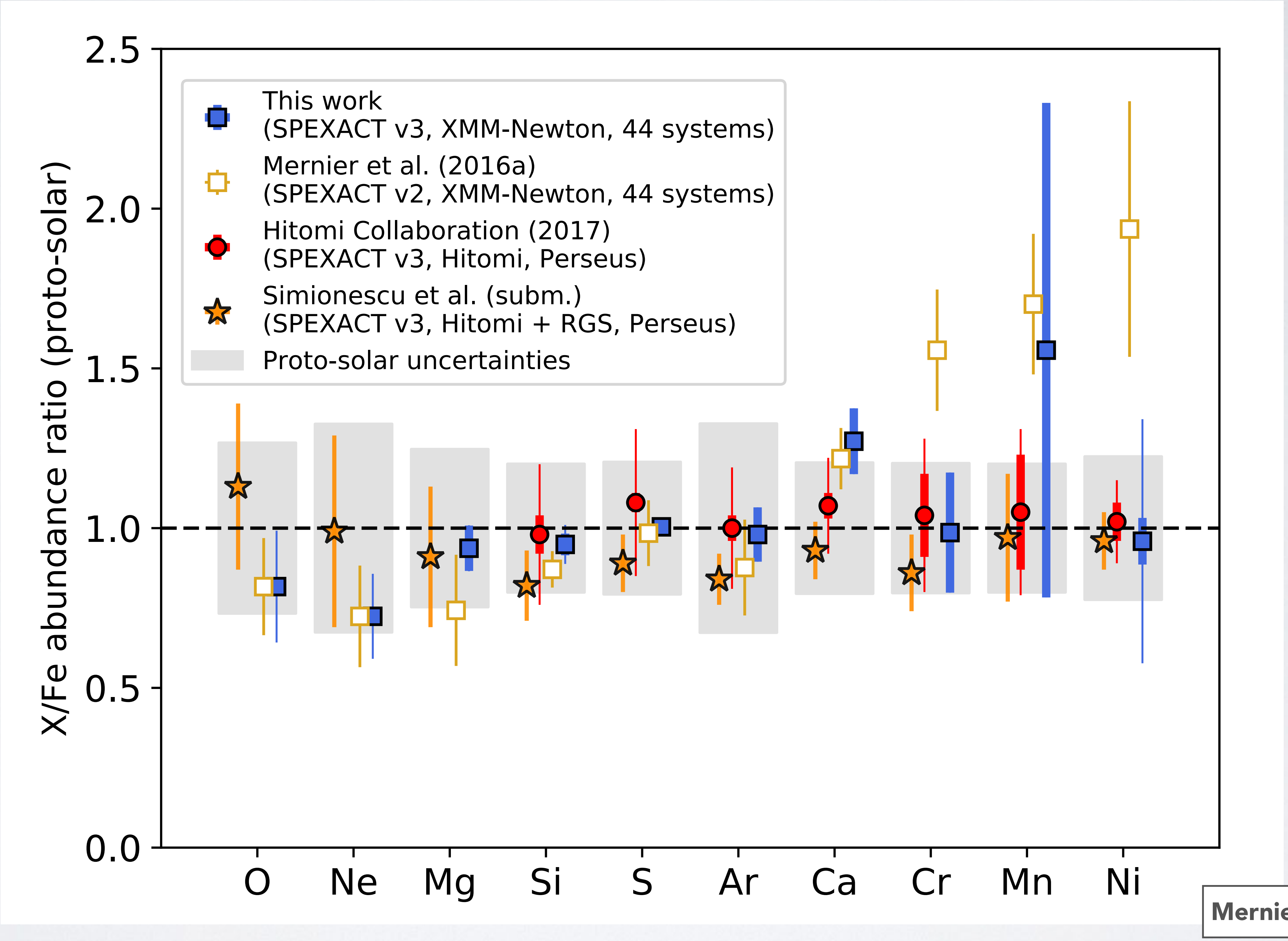
- New observatory/instrument
  - CCD ➔ ***micro-calorimeter***
- New spectral fitting code
  - SPEX v2 ➔ ***SPEX v3***



The Hitomi Collaboration (2017, *Nature*)



Enrichment in clusters vs. groups (and ellipticals)

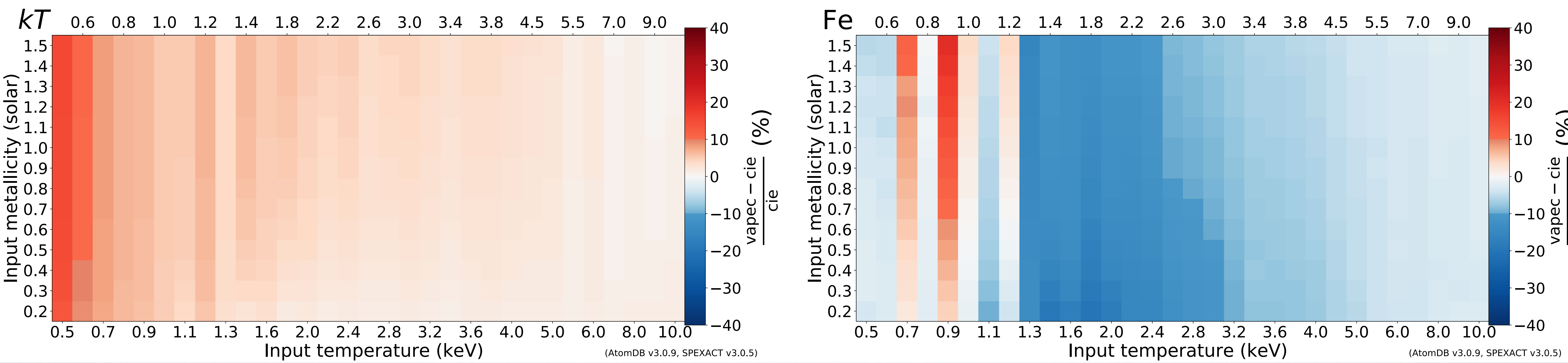


Mernier et al. (2018b)

XMM-Newton (CHEERS sample) vs. ***Hitomi*** (Perseus): all ratios are ***consistent*** **with Solar**!

Abundances measured in clusters/ groups are sensitive to **spectral codes**!

Uncertainties of spectral models: SPEX vs. apec

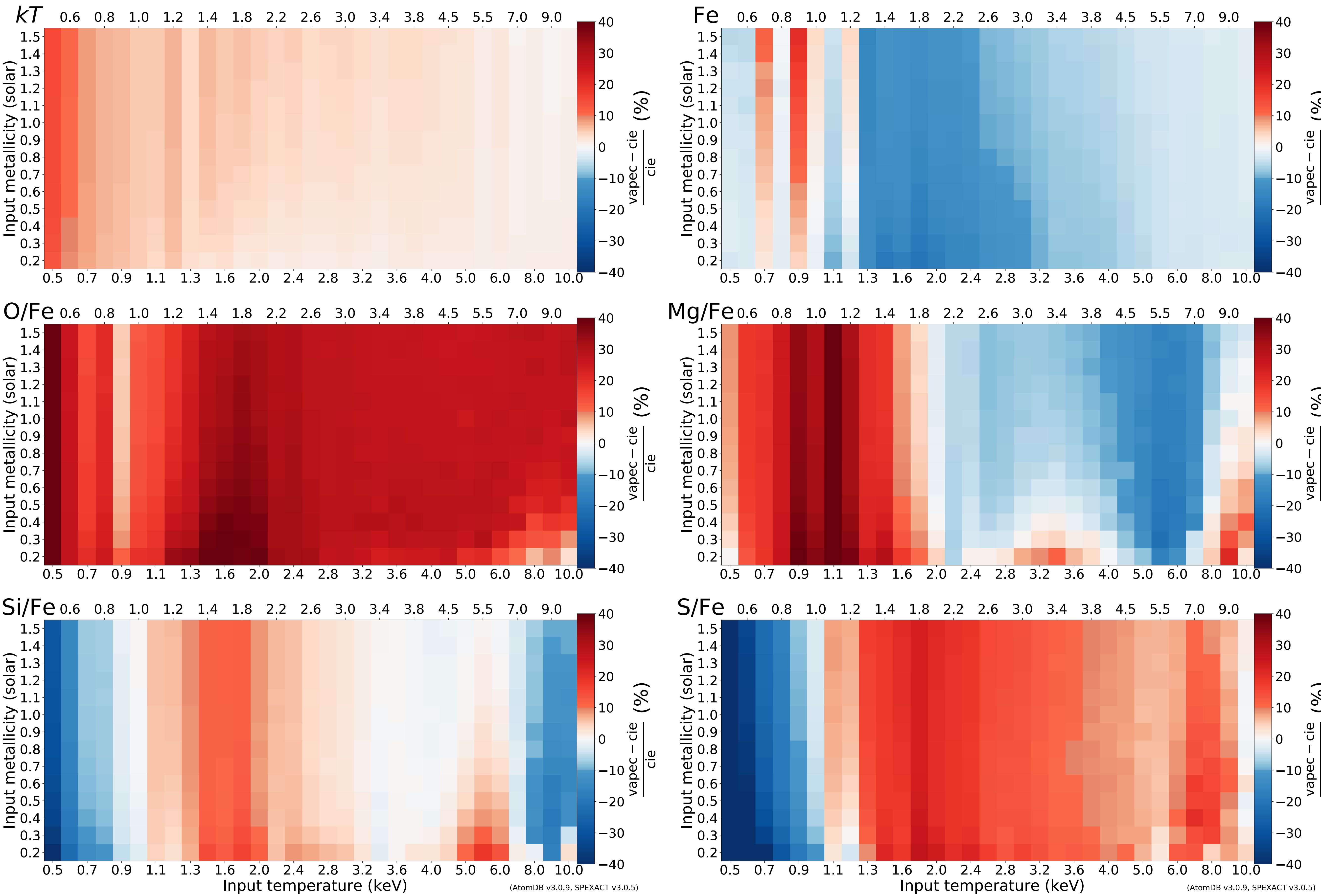


1) **Simulate** mock XMM-Newton EPIC spectra using **SPEX v3**

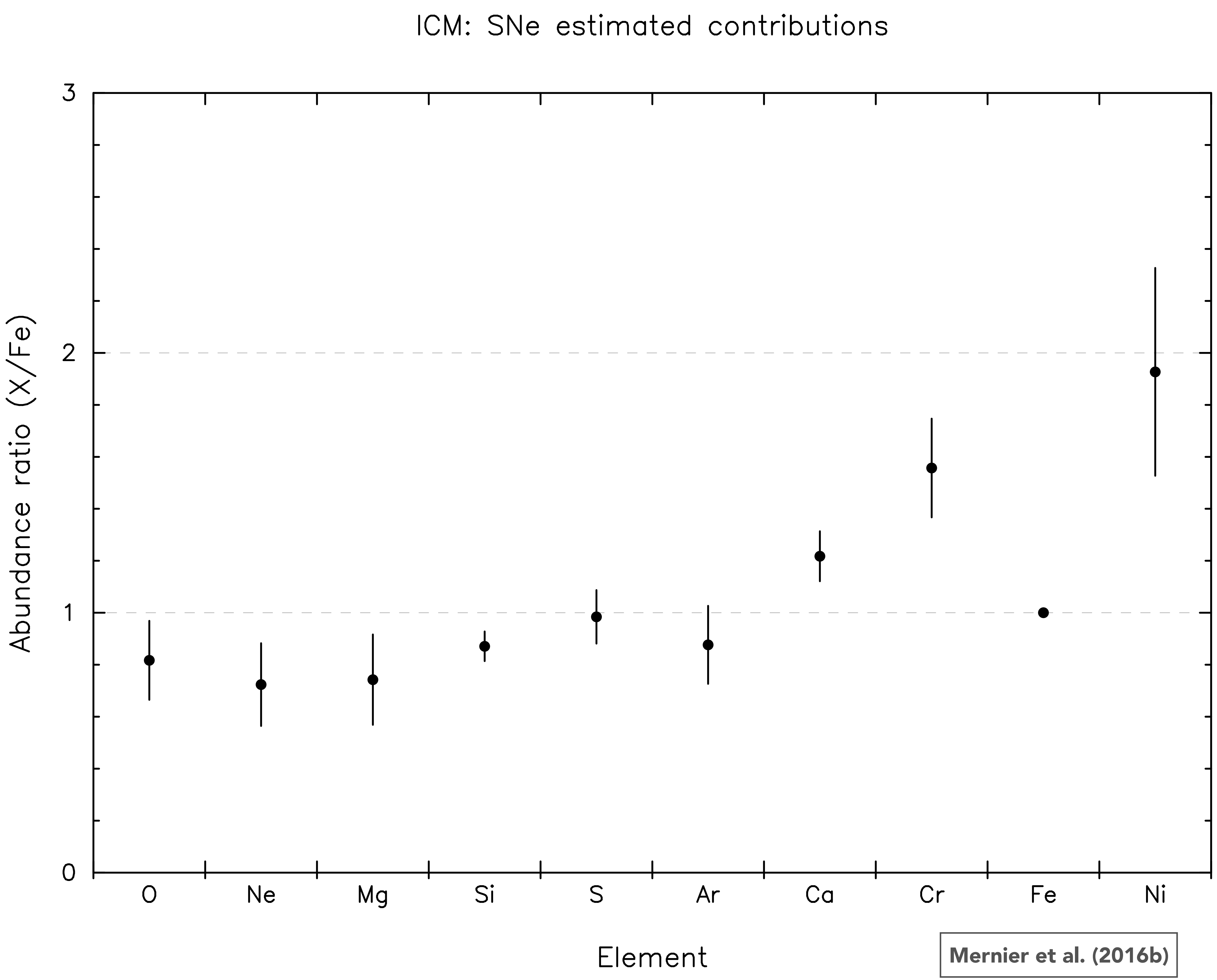
2) **Fit** these mock spectra with **apec v3.0.9 (XSPEC)**

3) **Compare** the relative differences

Uncertainties of spectral models: SPEX vs. apec



Average ICM abundance pattern



Mernier et al. (2016b)

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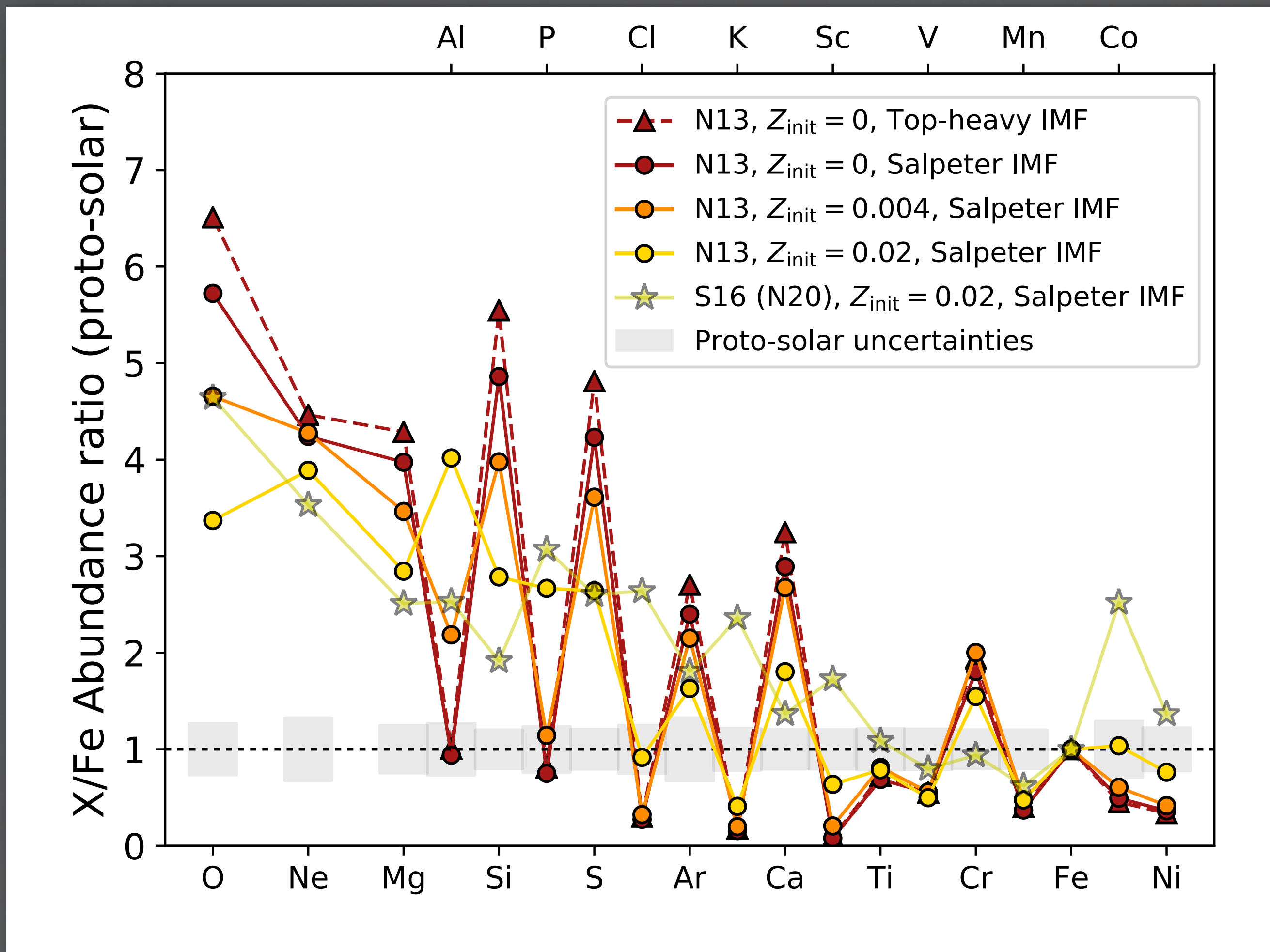
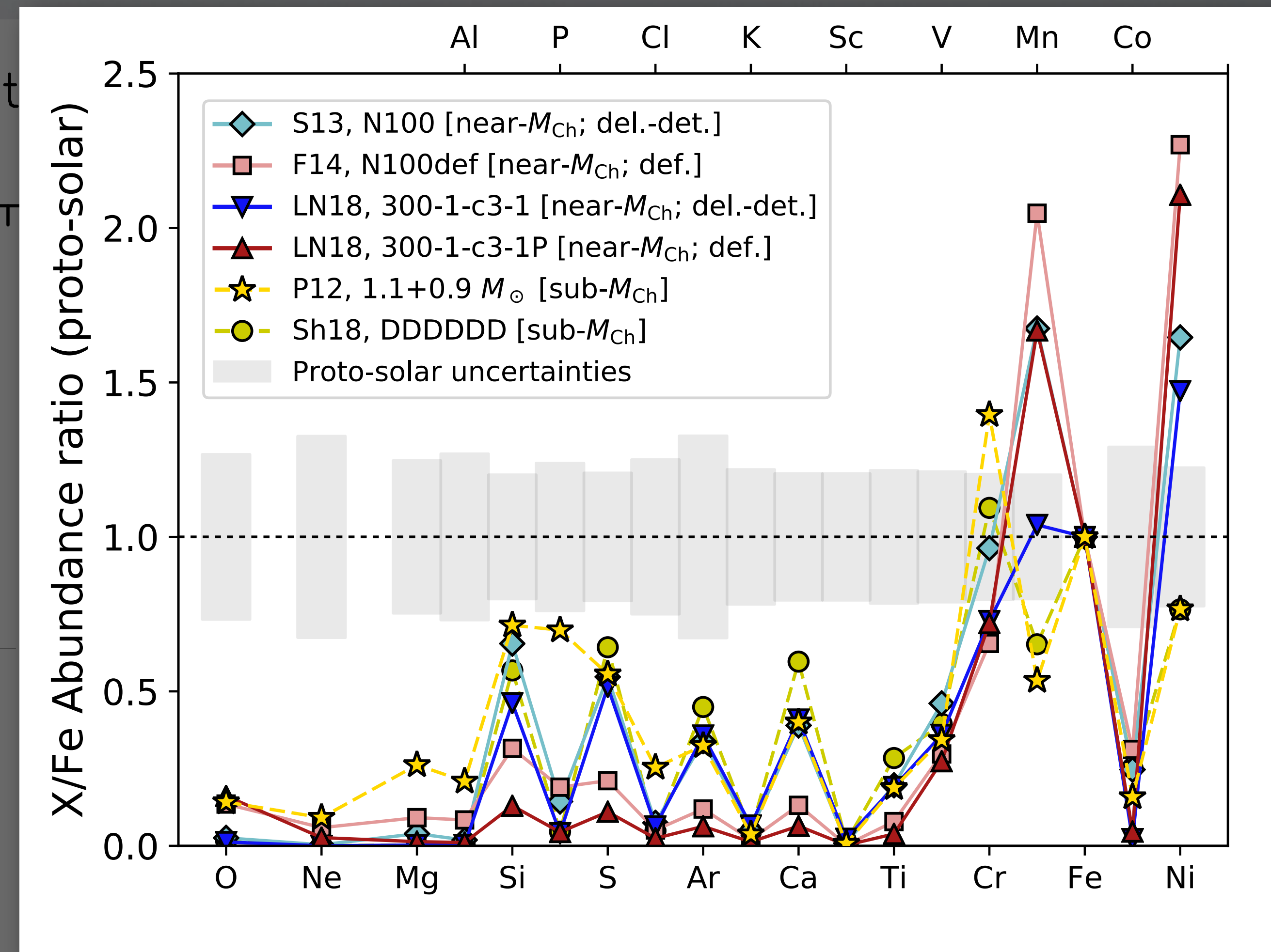


Mernier et al. (2018c)
(adapted from Nomoto et al. 2013 and Sukhbold et al. 2016)



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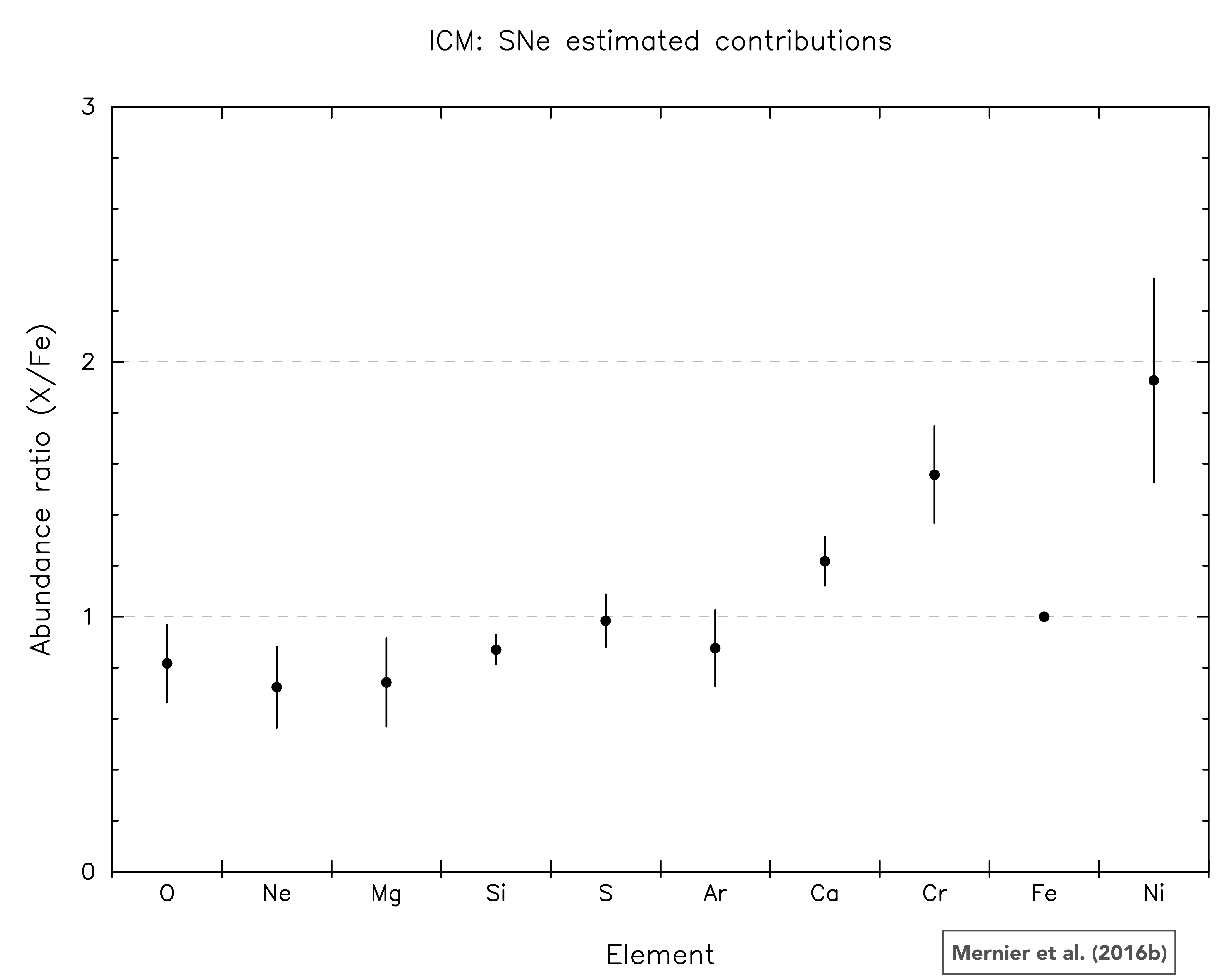

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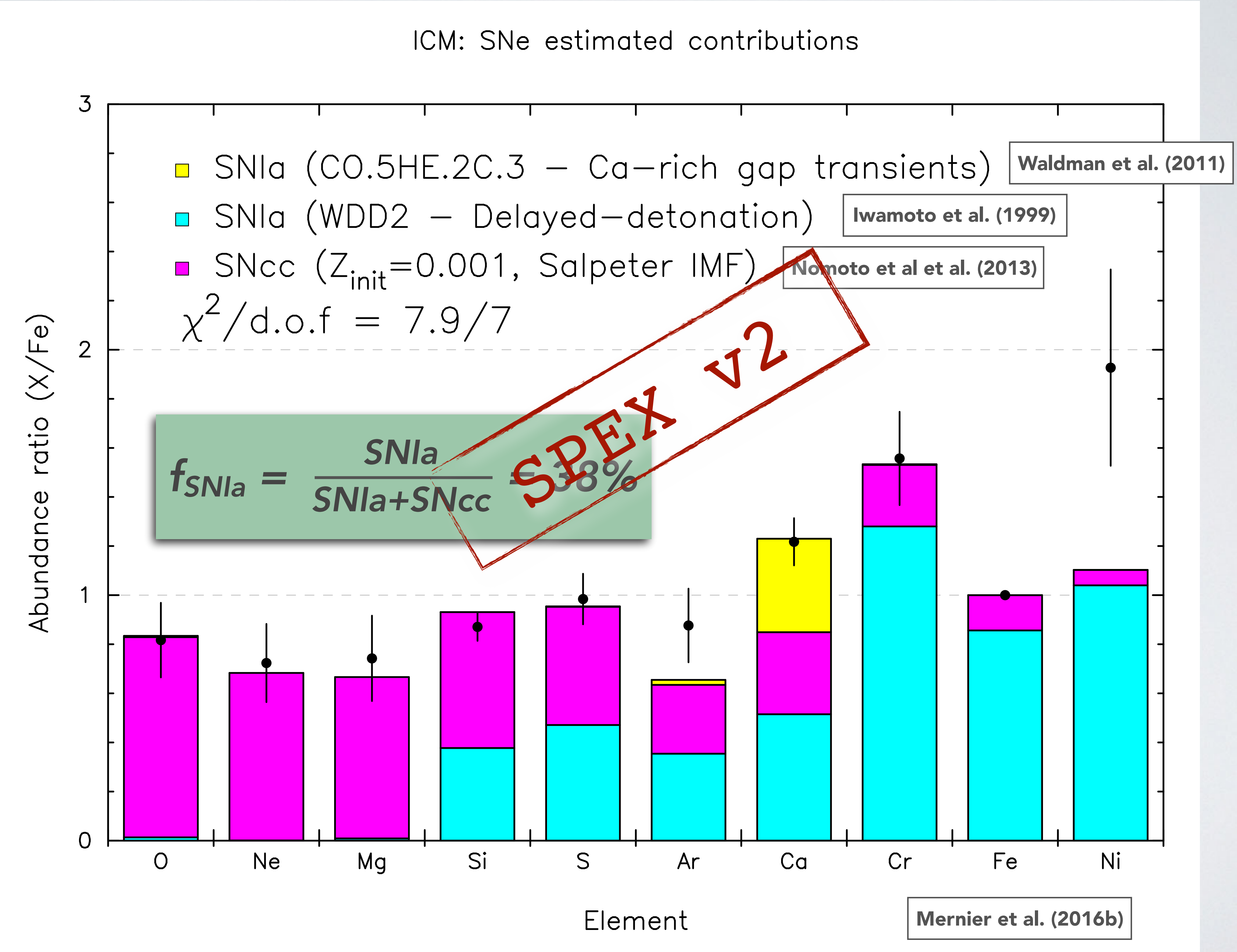

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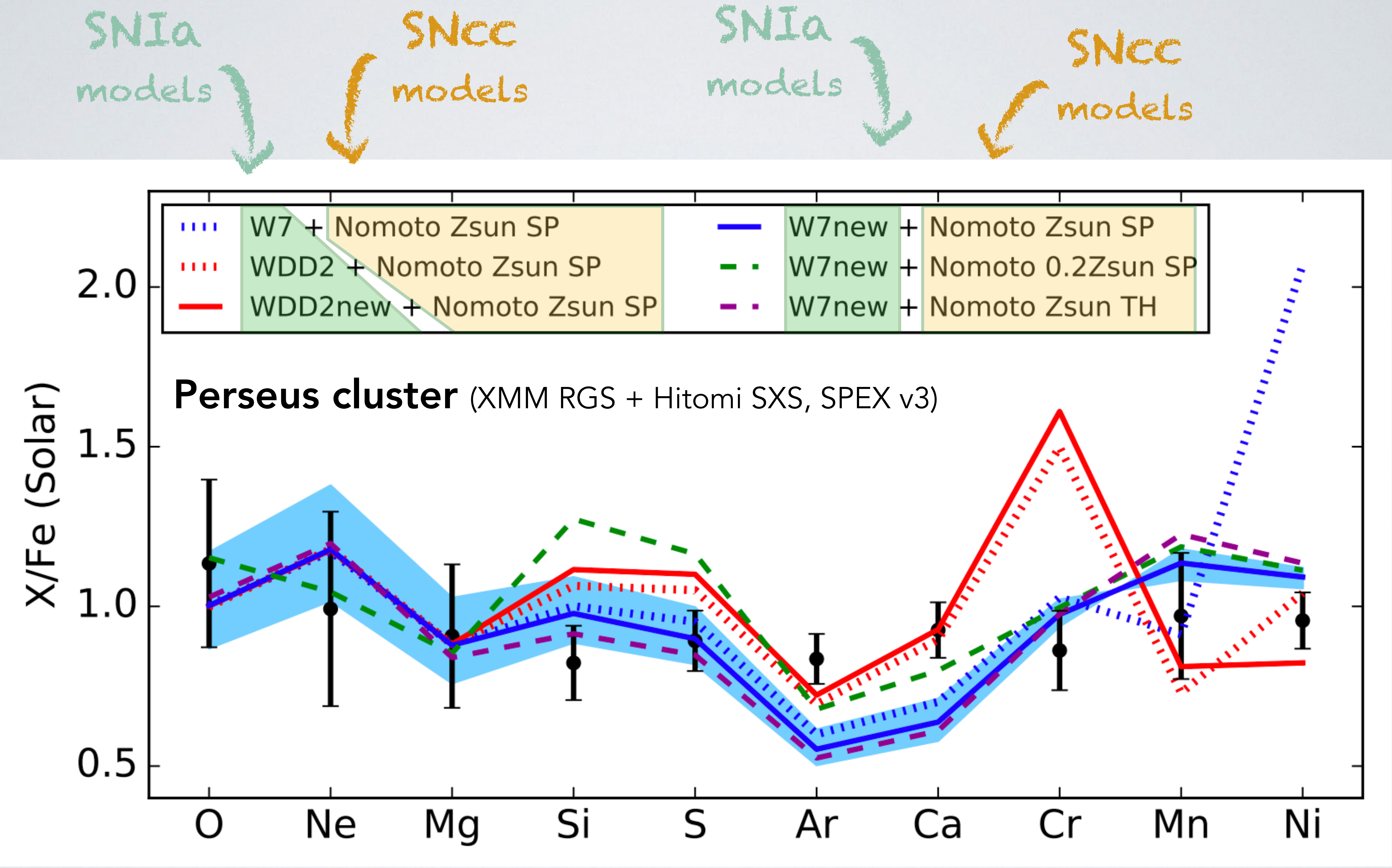
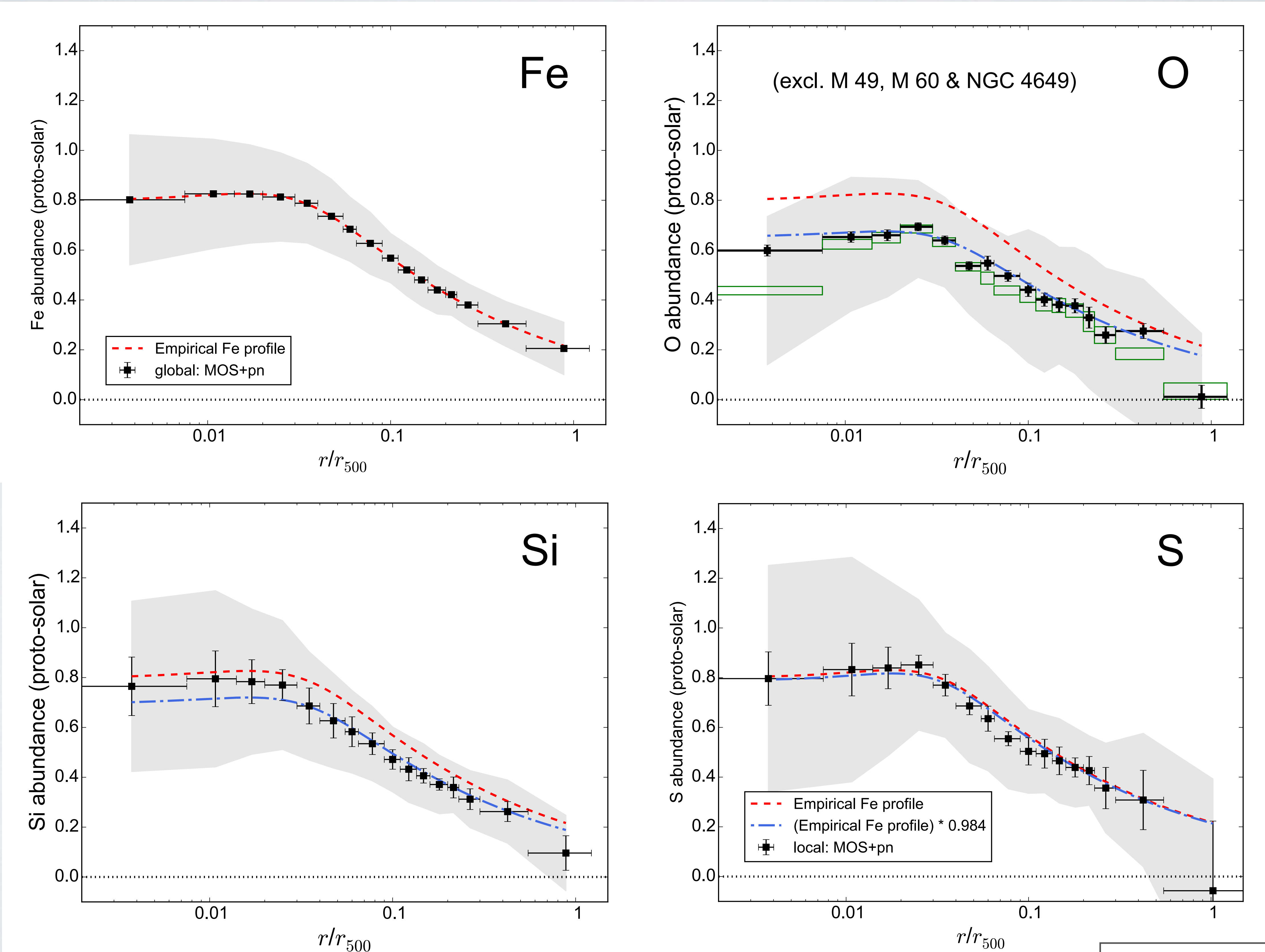


Simionescu et al. (2019)

No satisfactory combination of SNIa+SNcc models!

3. Distribution of SNIa vs. SNcc enrichment

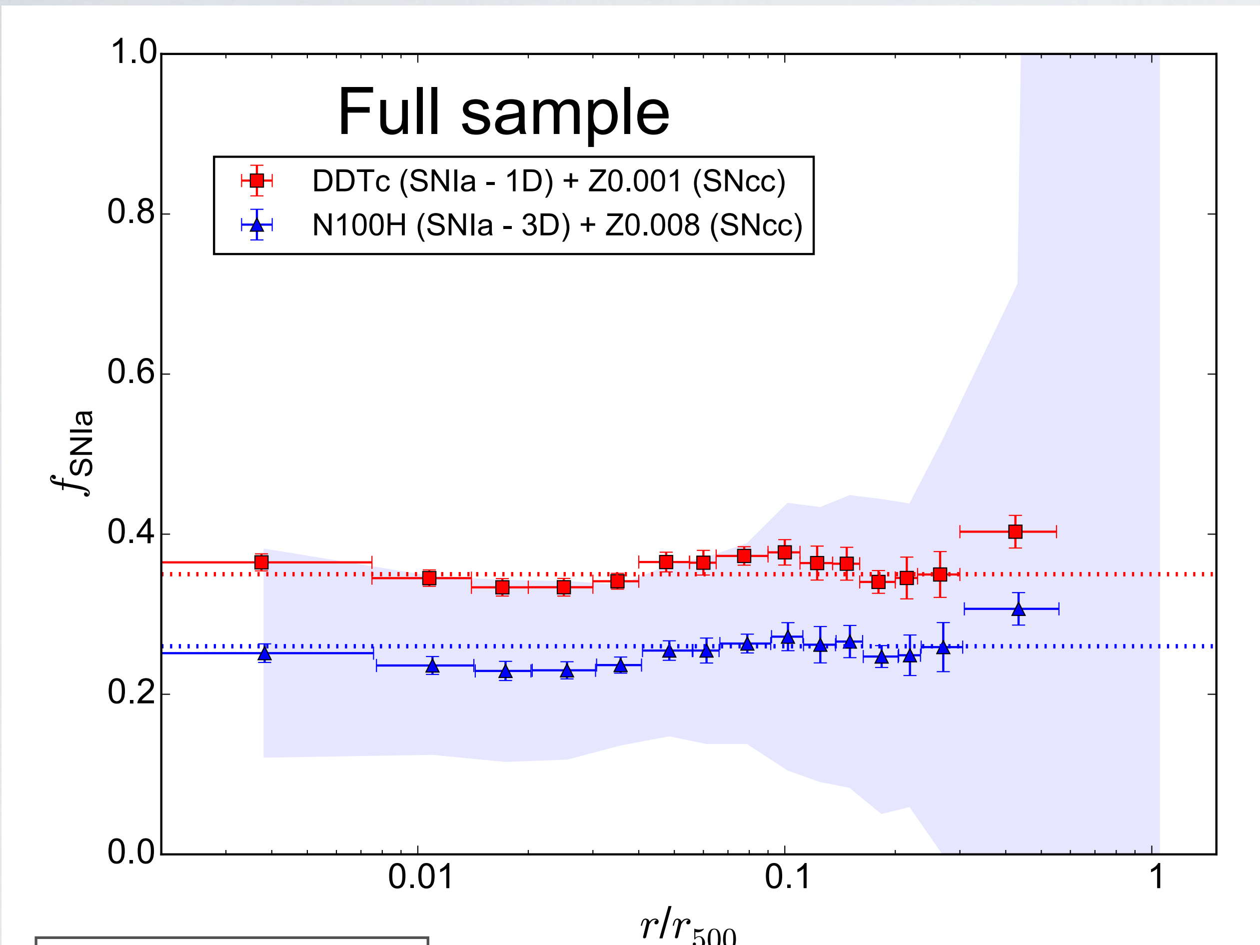
Radial distribution of the SNIa fraction



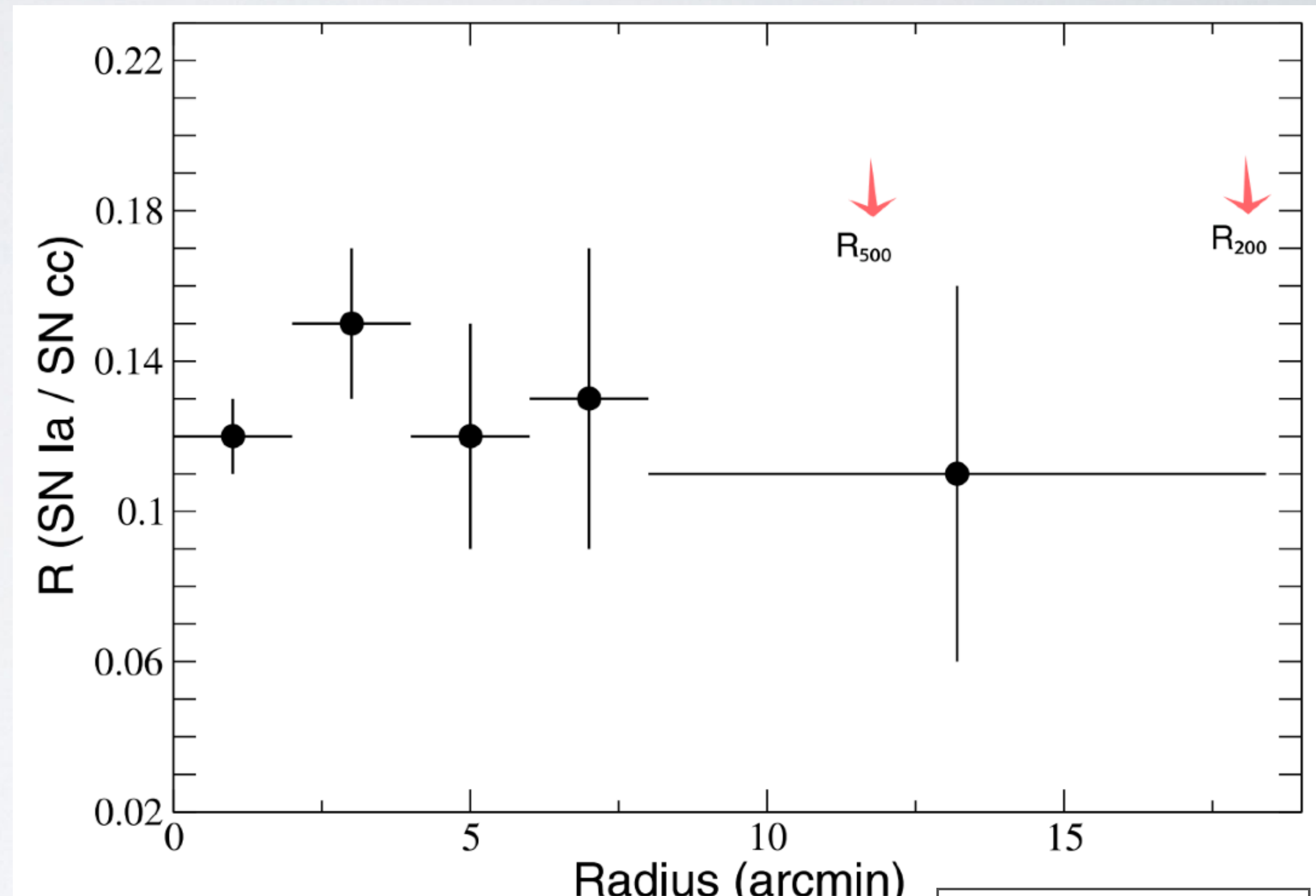
Mernier et al. (2017)

Radial distribution of the SNIa fraction

The ***relative contribution*** of SNIa vs. SNcc to the ICM enrichment is ***uniform***…



Mernier et al. (2017)



Ezer et al. (2017)

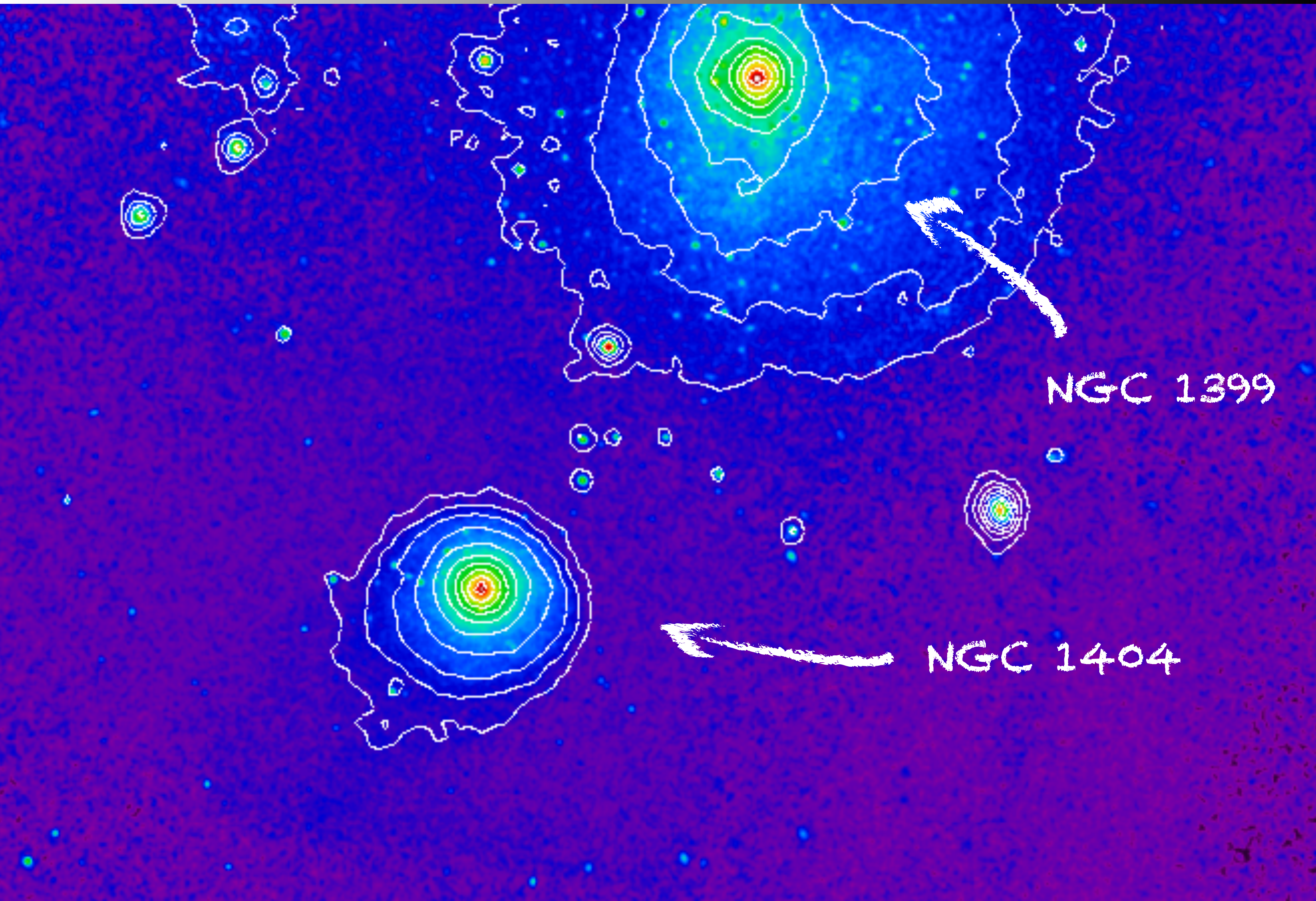
…in the core

…in the outskirts

$$f_{SNIa} = \frac{SNIa}{SNIa+SNcc}$$

3. But wait, there is more...

Radial Fe distribution in NGC 1404 (elliptical)



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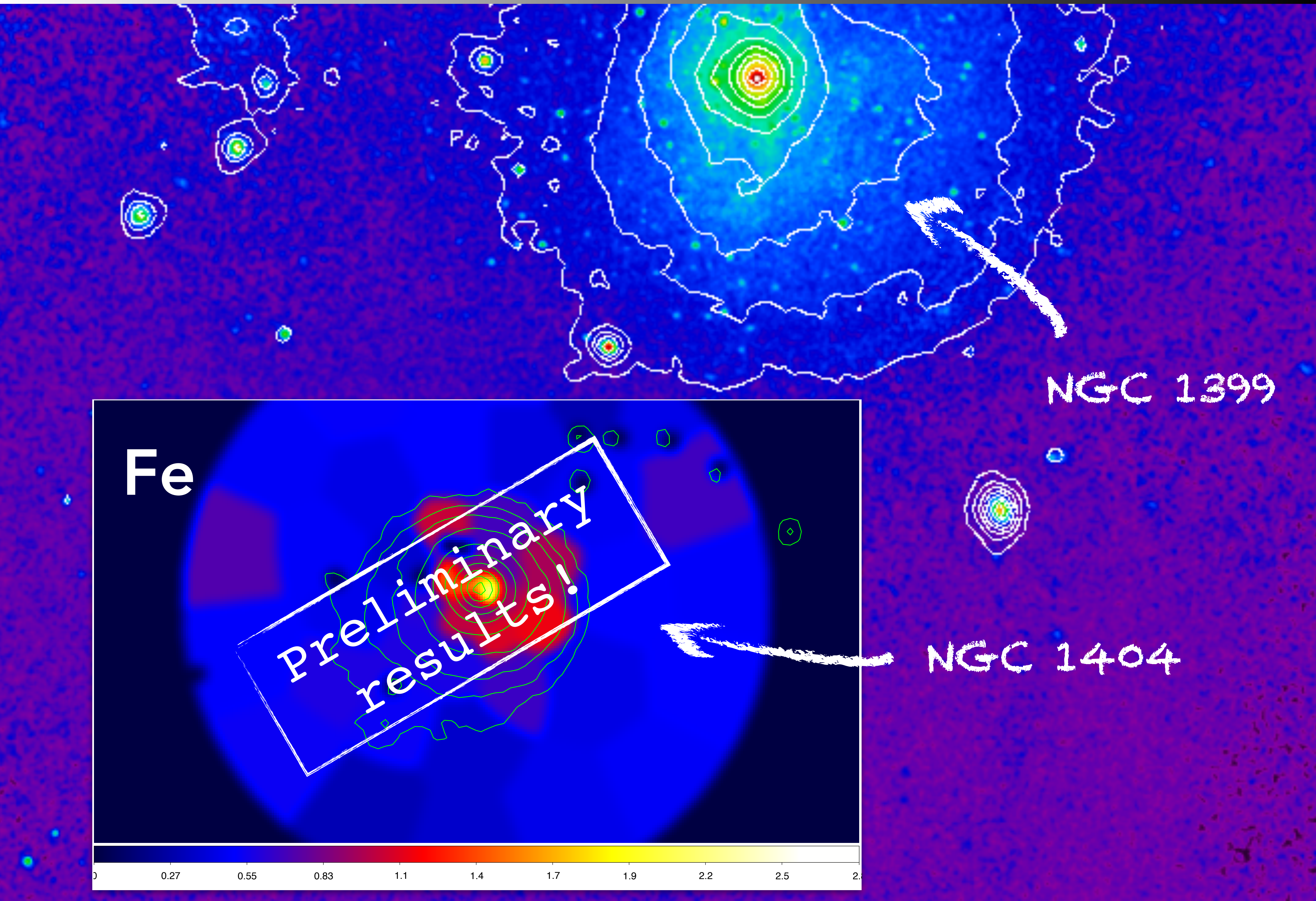
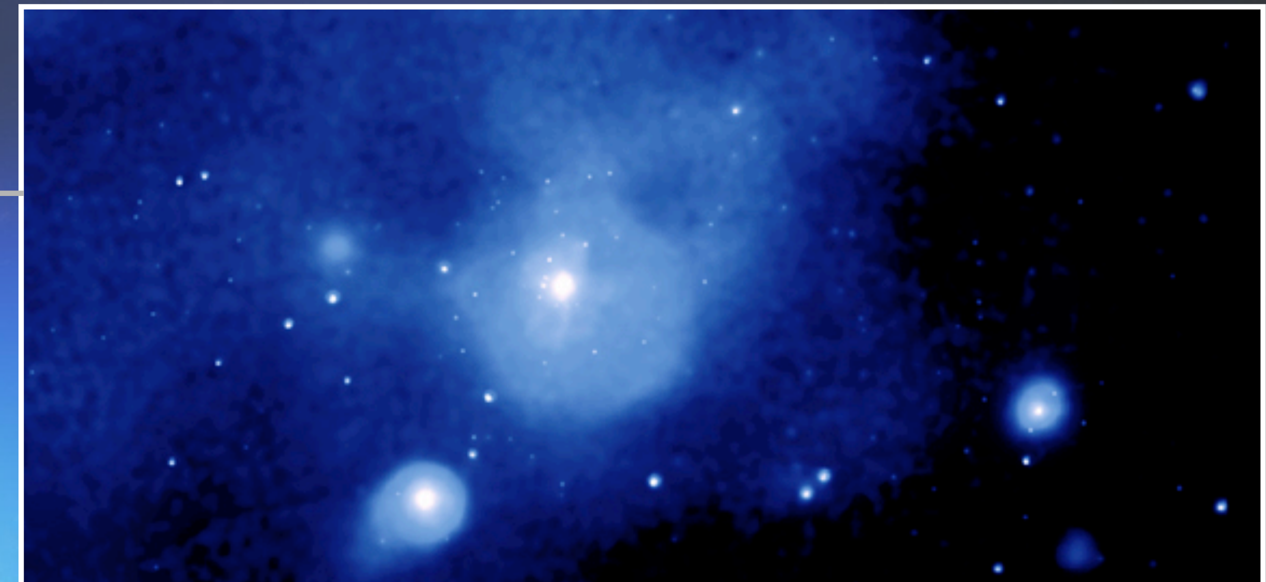
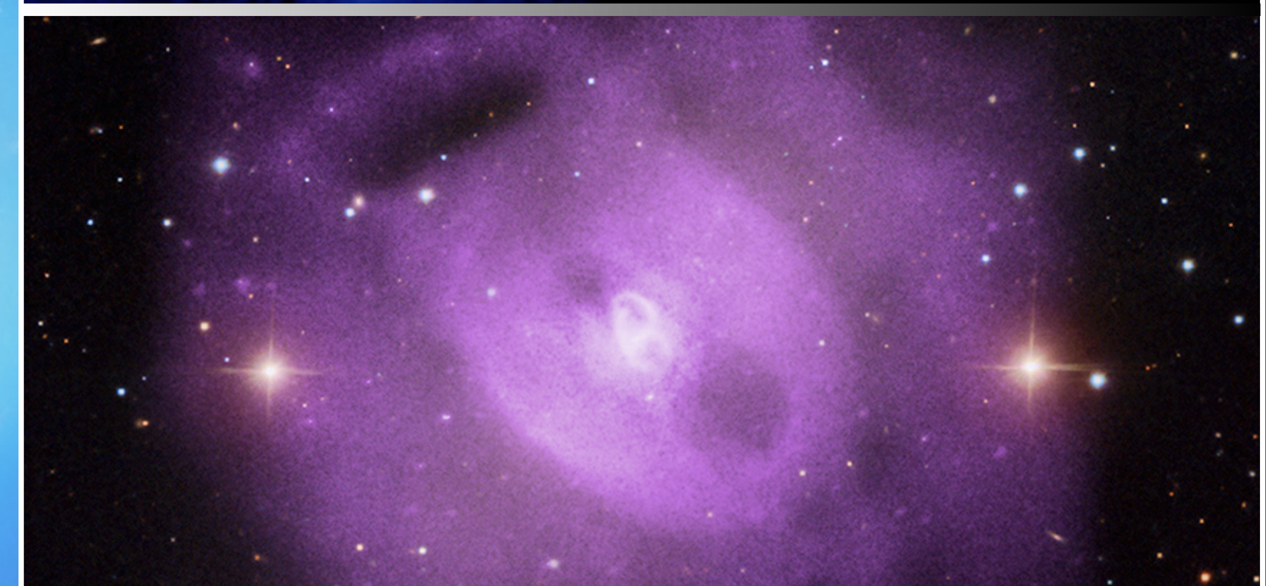
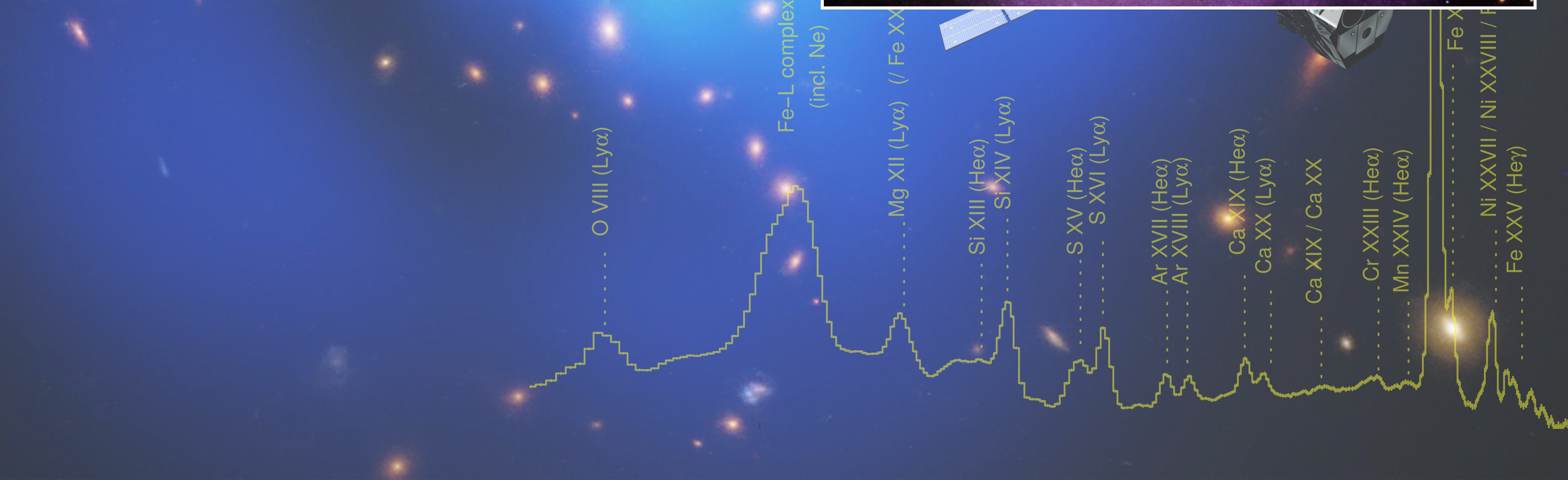


1) Central Fe abundance similar for clusters, groups, and ellipticals

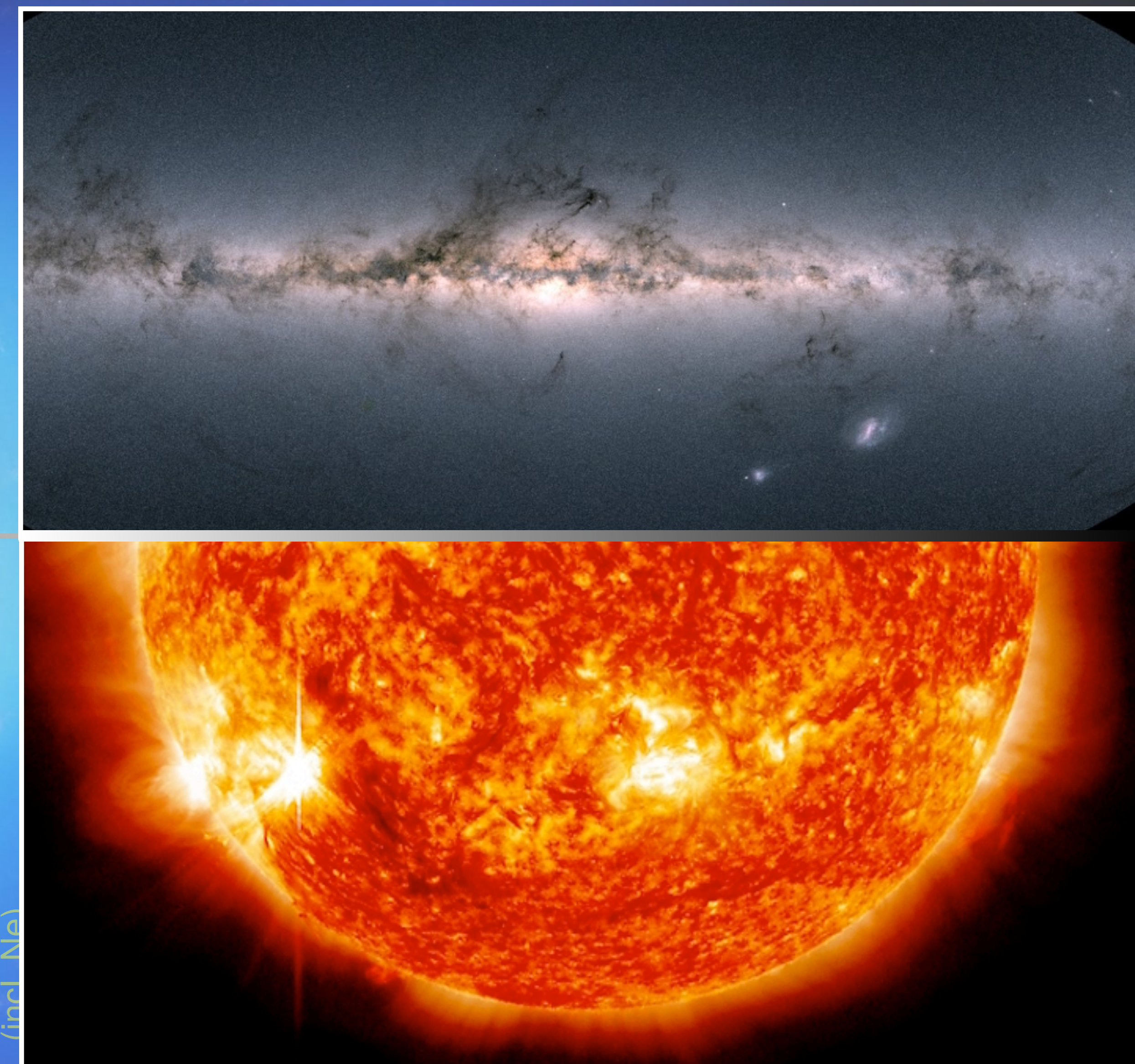


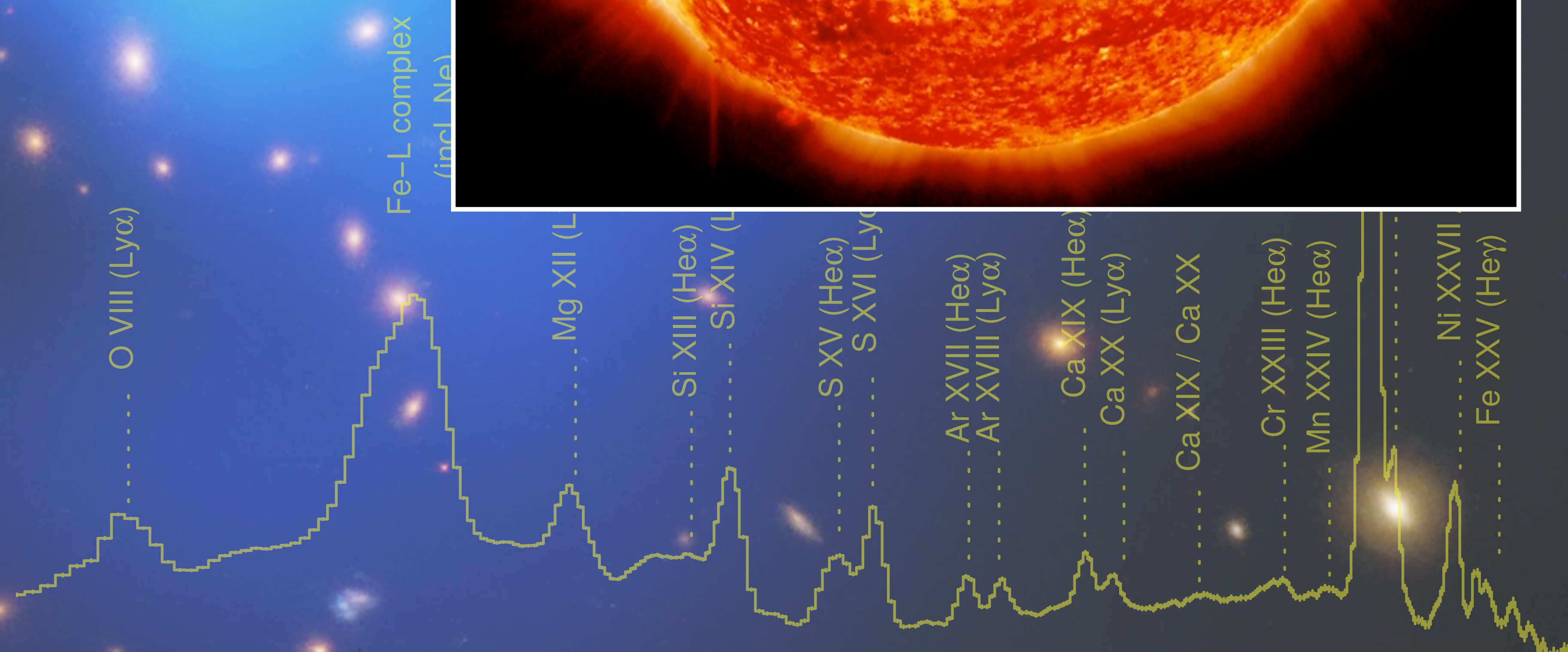




1) Central Fe abundance similar for clusters, groups, and ellipticals

2) Chemical composition of the ICM very similar to that of the Solar neighbourhood!





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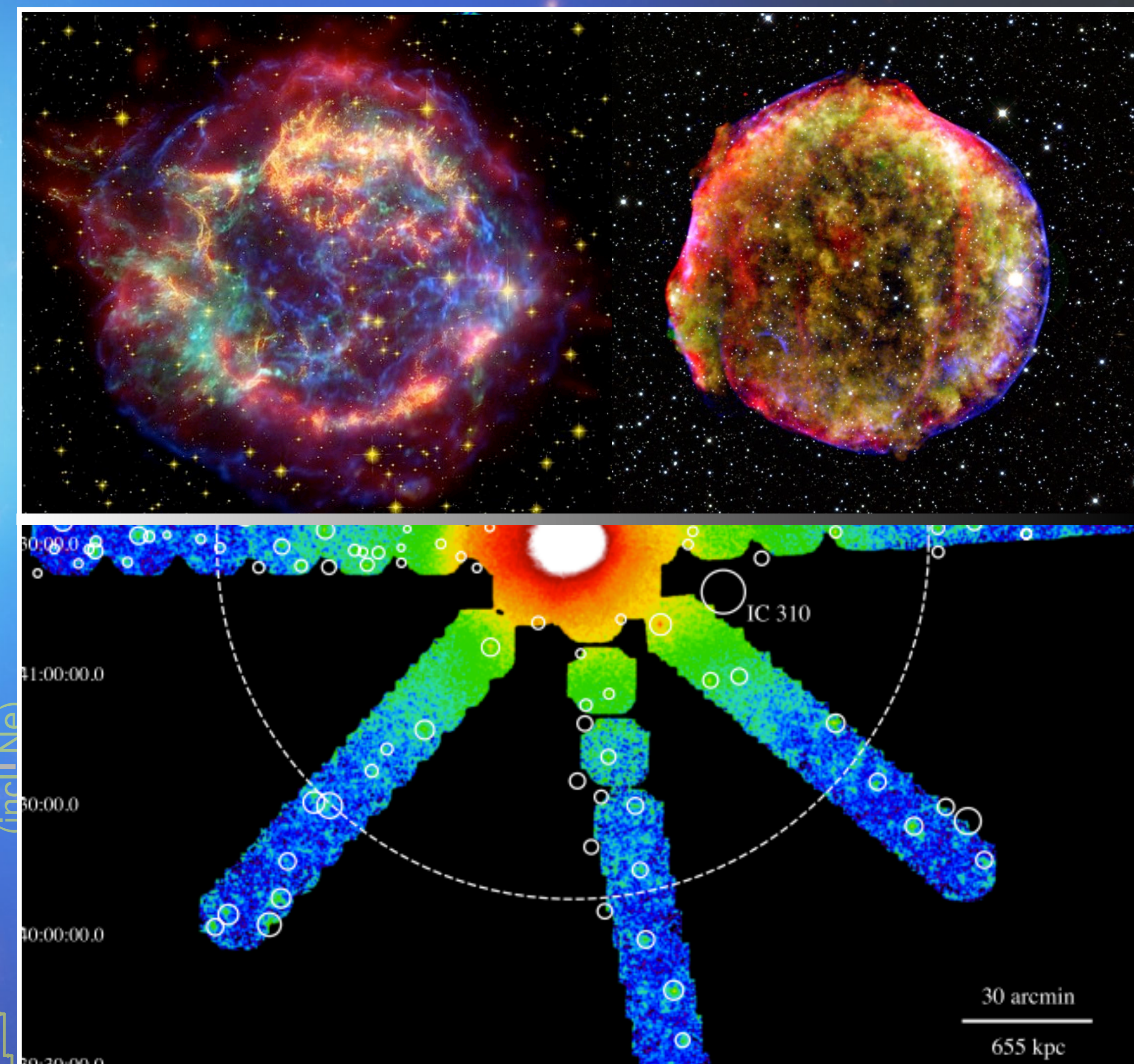
3) Relative SNIa-to-SNcc contribution similar from the core to the outskirts



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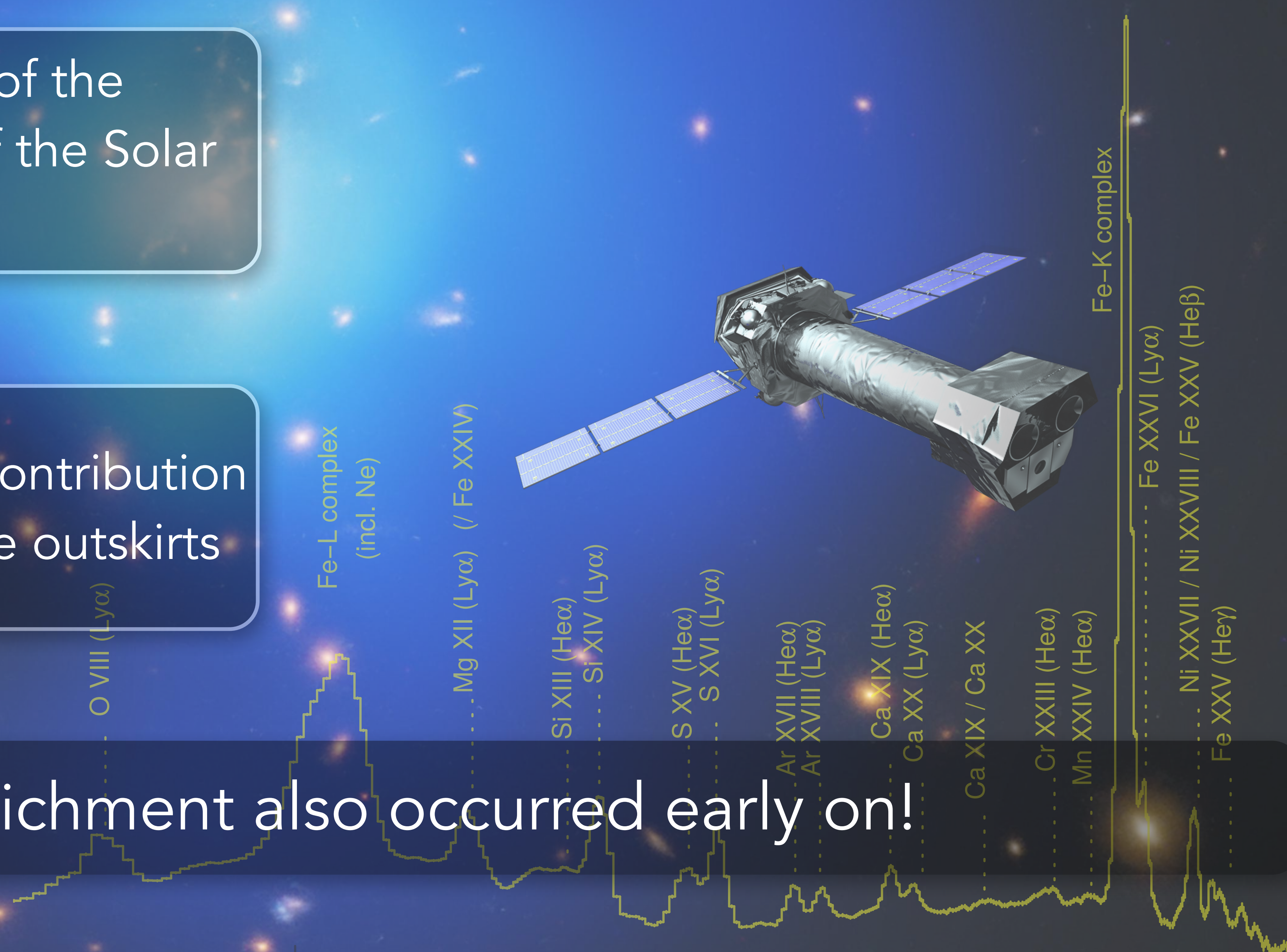
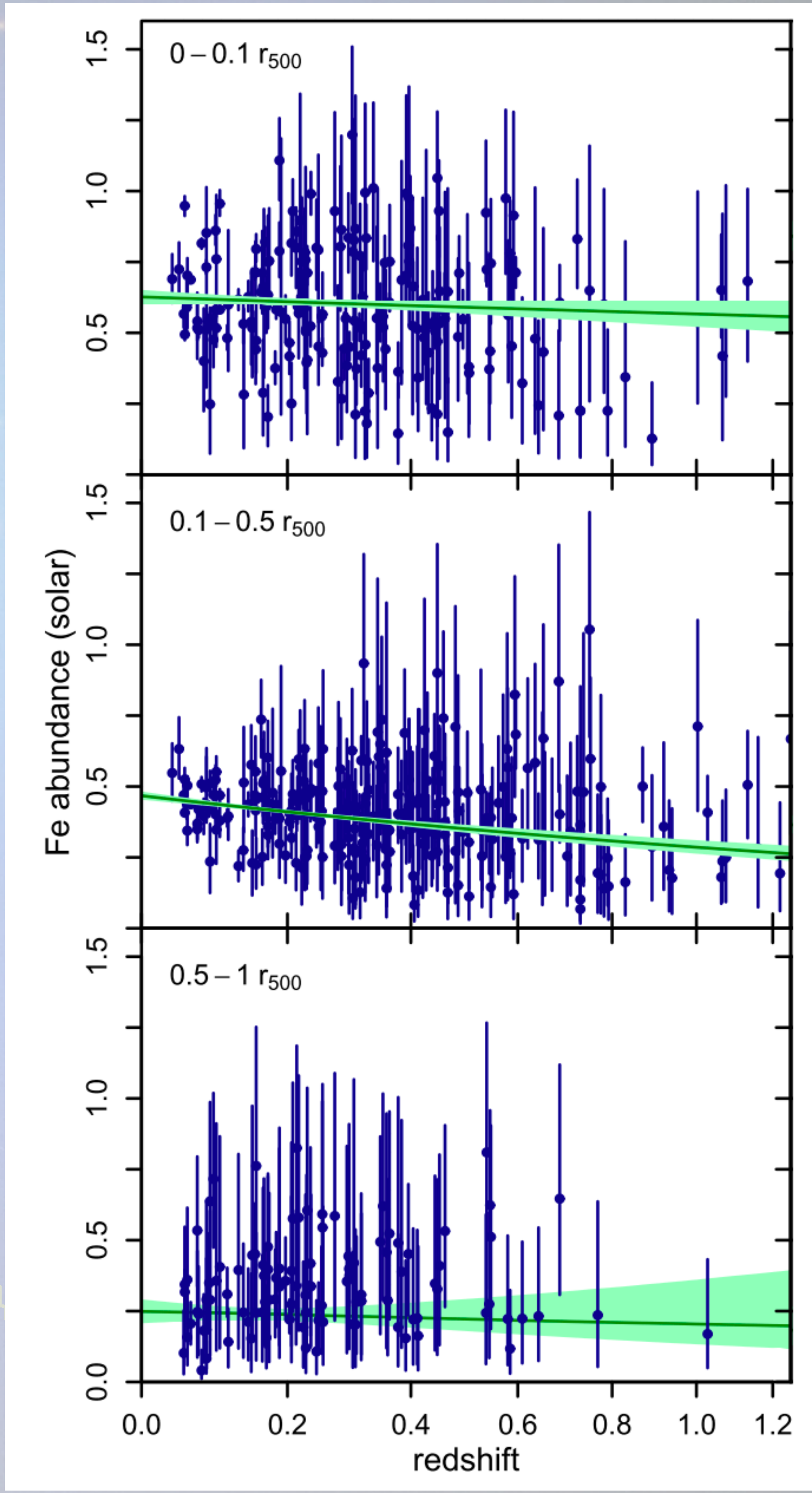


Central enrichment also occurred early on!

Chemical evolution of the ICM

Does the Fe abundance (in the core and/or the outskirts) evolve with redshift?

- Many studies, but ***contrasted results***…
- Hints towards redshift evolution:
  - **Balestra et al. (2007); Maughan et al. (2008); Anderson et al. (2009)**
- No redshift evolution (up to z~1):
  - **Mushotzky & Loewenstein (1997); Tozzi et al. (2003); Baldi et al. (2012)**
- Most recent works **(Ettori et al. 2015; Mantz et al. 2017)**:
  - ***No*** signs of evolution in the outskirts, ***small*** evolution at intermediate radii and/or in the core



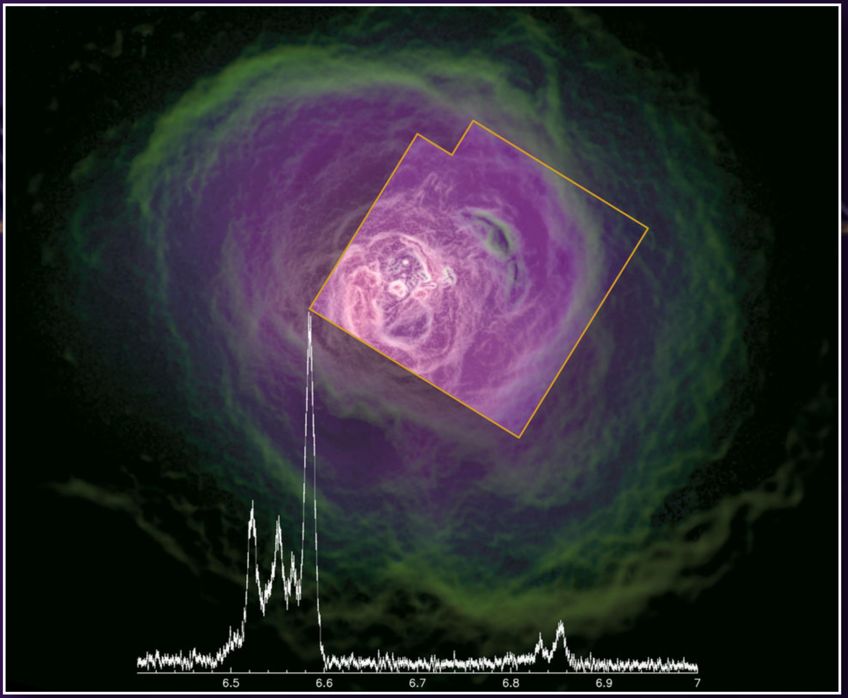
Mantz et al. (2017)

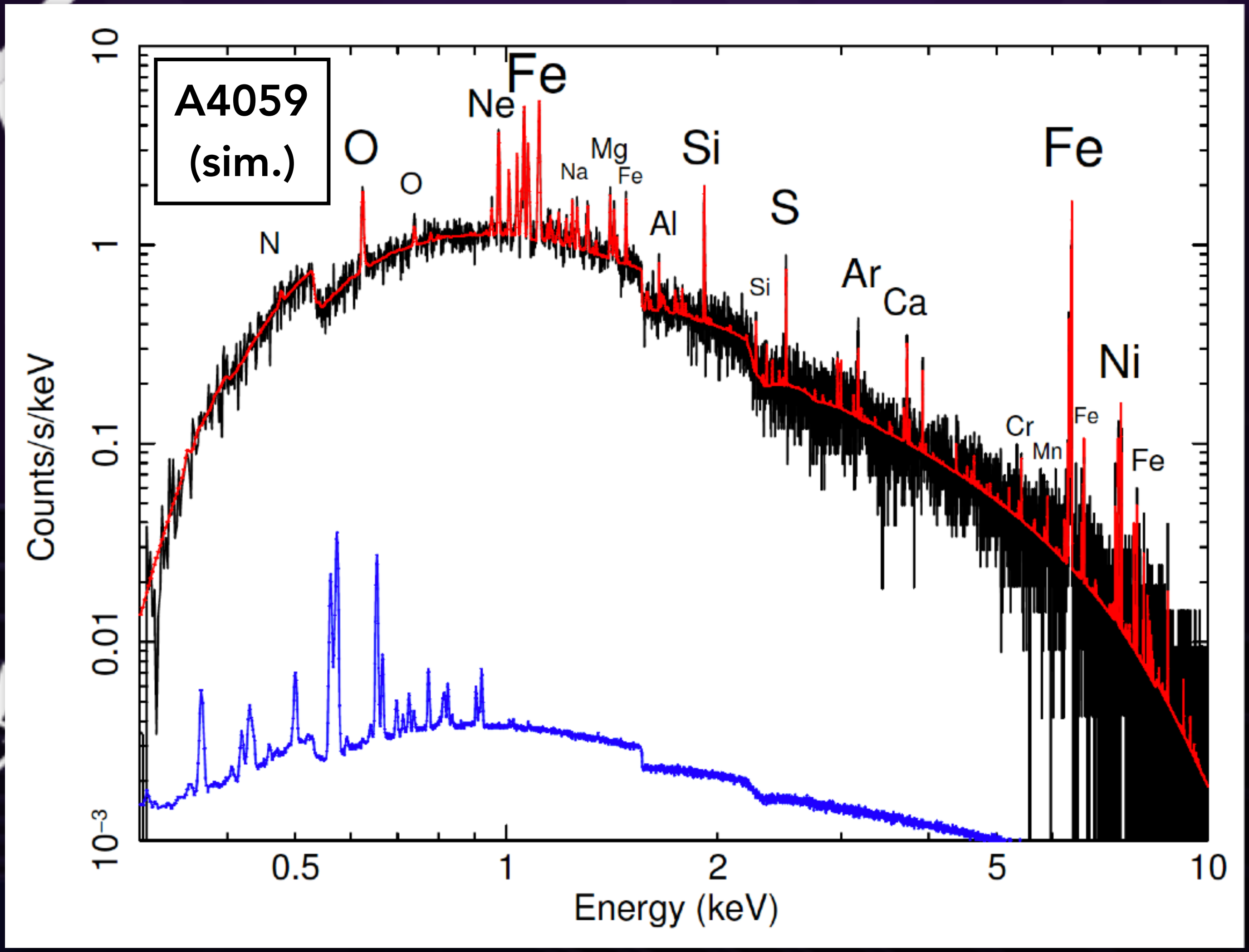
Future missions

X-Ray Imaging and Spectroscopy Mission (XRISM)

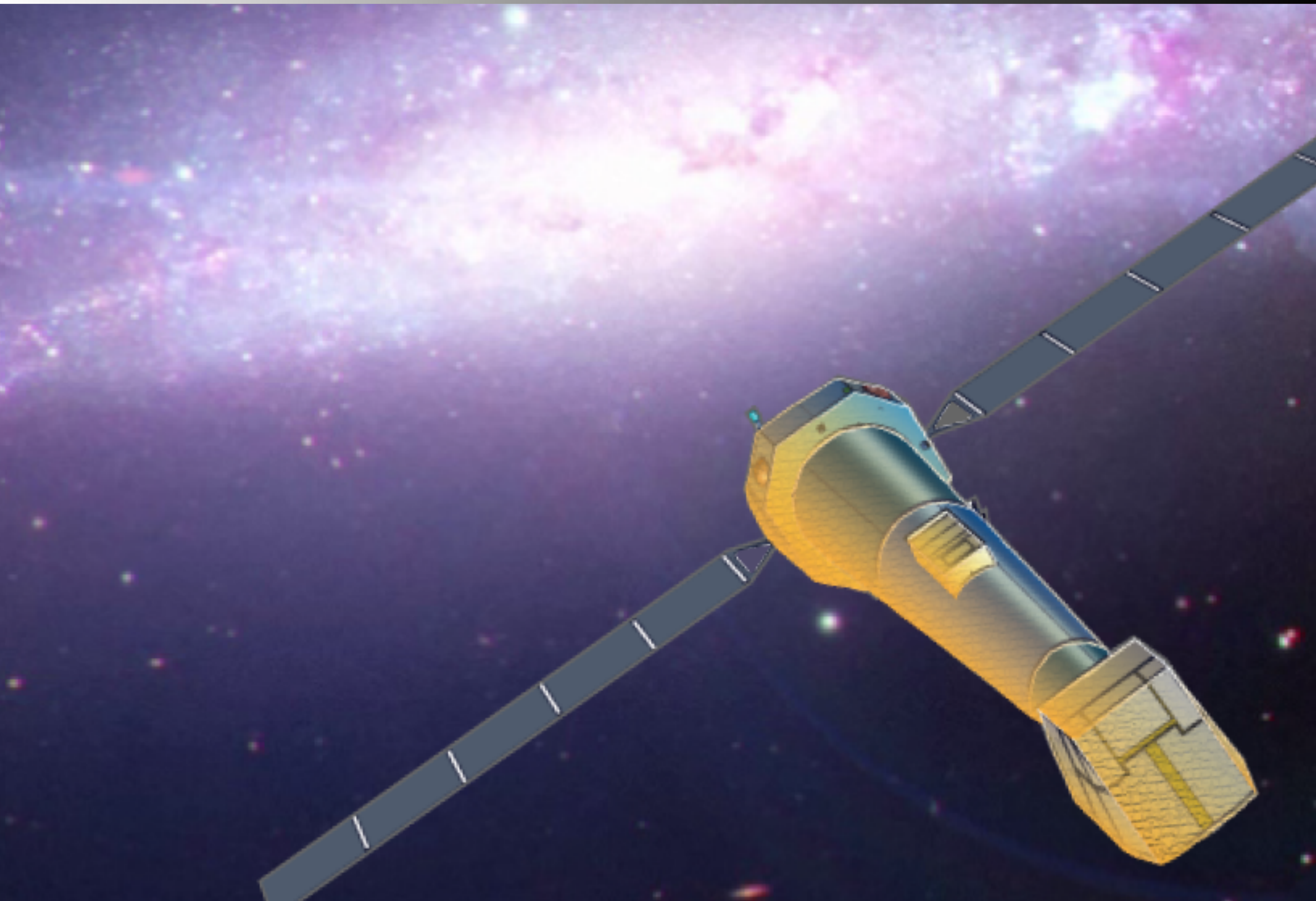
X-Ray Imaging and Spectroscopy Mission (XRISM)

- Re-flight of Hitomi
  - Demonstrated by Hitomi results!
    (see also Kitayama et al. 2014)
- Expected launch: 2022
- Dramatic improvement on abundance accuracies
- Constrains on Na and Al
  ➔ ***Initial metallicities*** of SNcc progenitors?
- Constrains on Mn and Ni
  ➔ ***Explosion*** and ***progenitors*** of SNIa?



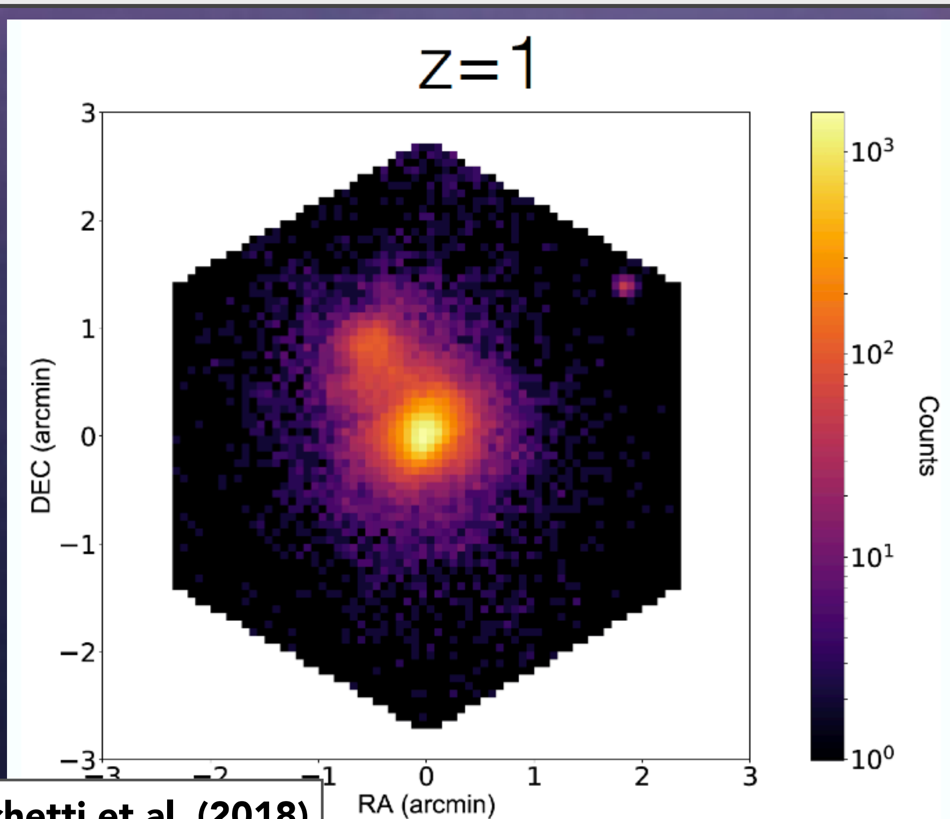


Athena

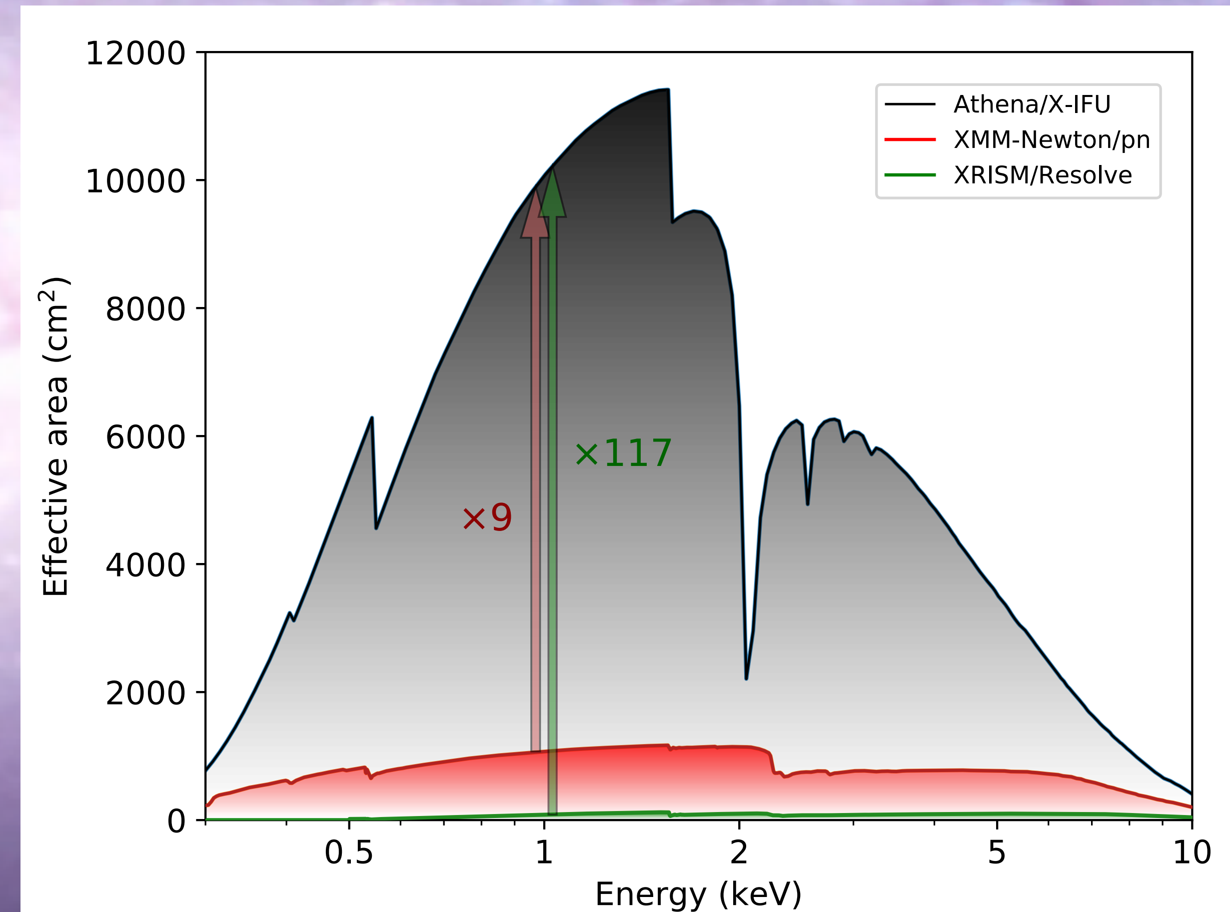


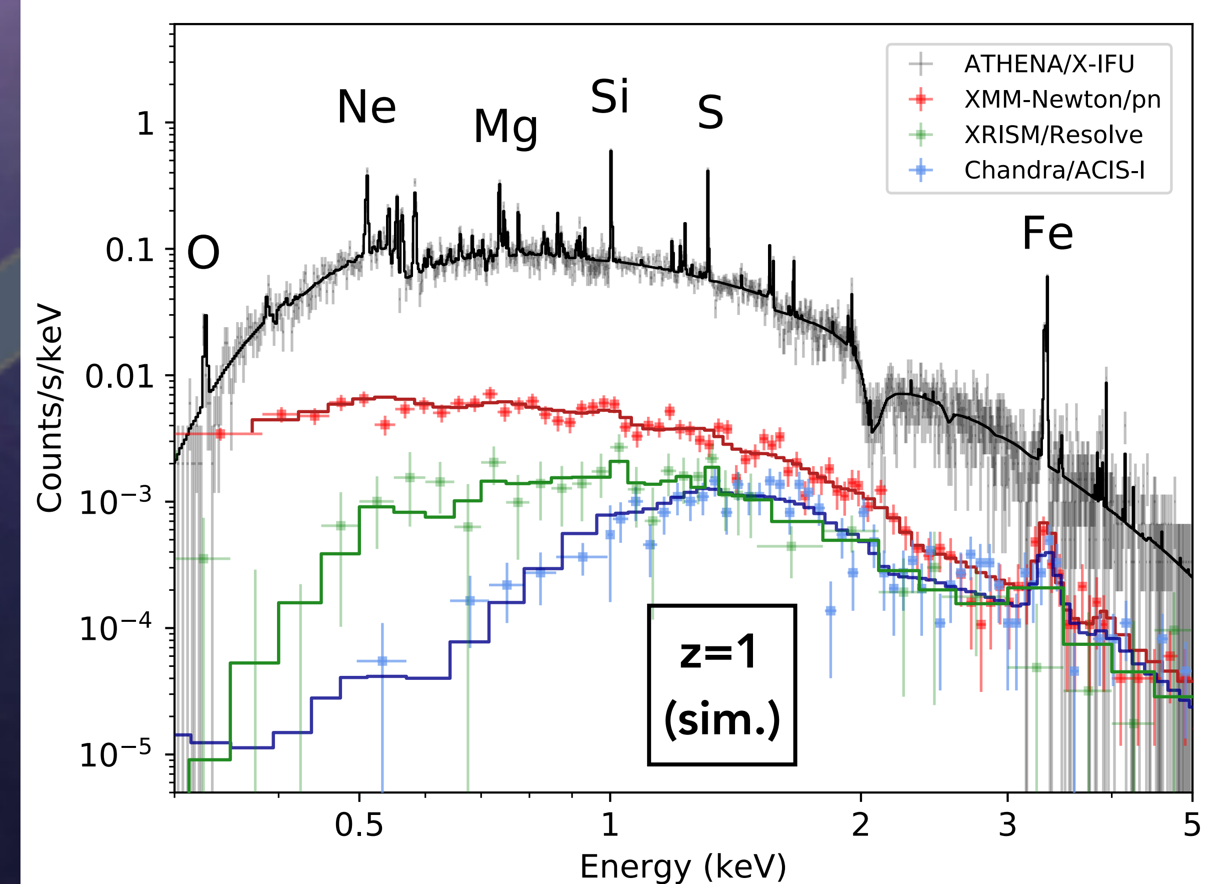
Athena

- X-IFU instrument onboard
- **Barret et al. (2013); Ettori et al. (2013); Pointecouteau et al. (2013)**
- Expected launch: ~~2028~~ ~~2030~~ 2031
- Great spectral resolution and sensitivity
- Convenient for ***redshift evolution*** of metals in the ICM



Cucchetti et al. (2018)





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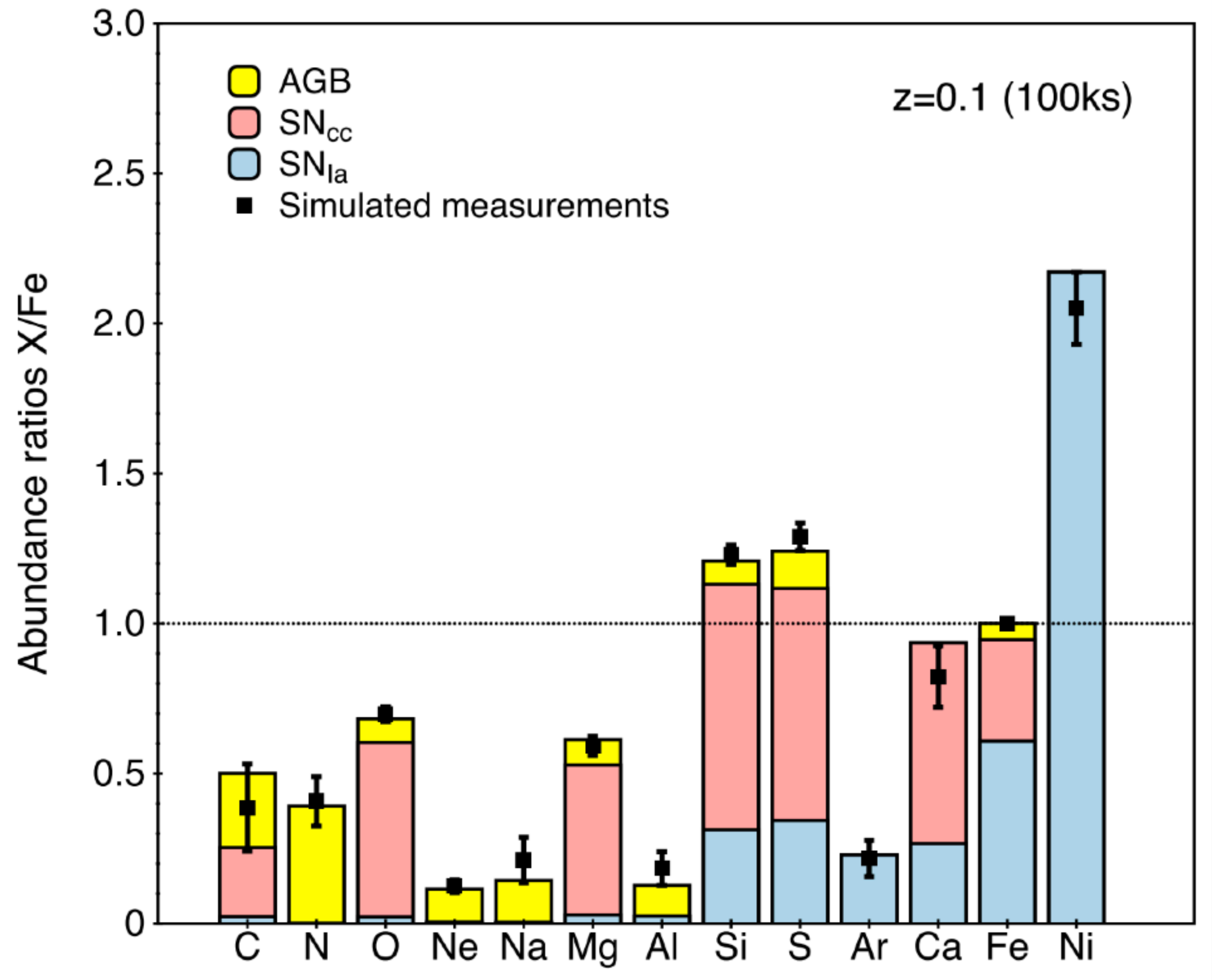

Cucchetti et al. (2018)

Improvements on

(i) Atomic codes

(ii) Nucleosynthesis yields

are required!!

Conclusion

Take home messages

Metal enrichment in hot atmospheres

Metals are found out to the **largest scales of the Universe**

The chemical enrichment is **uniform** (with system mass, ratios, distance)

➢ Clues for an **early enrichment** (>10 Gyr ago, AGN feedback)

Direct evidence for it will be revealed by **future missions** (XRISM, **Athena**)