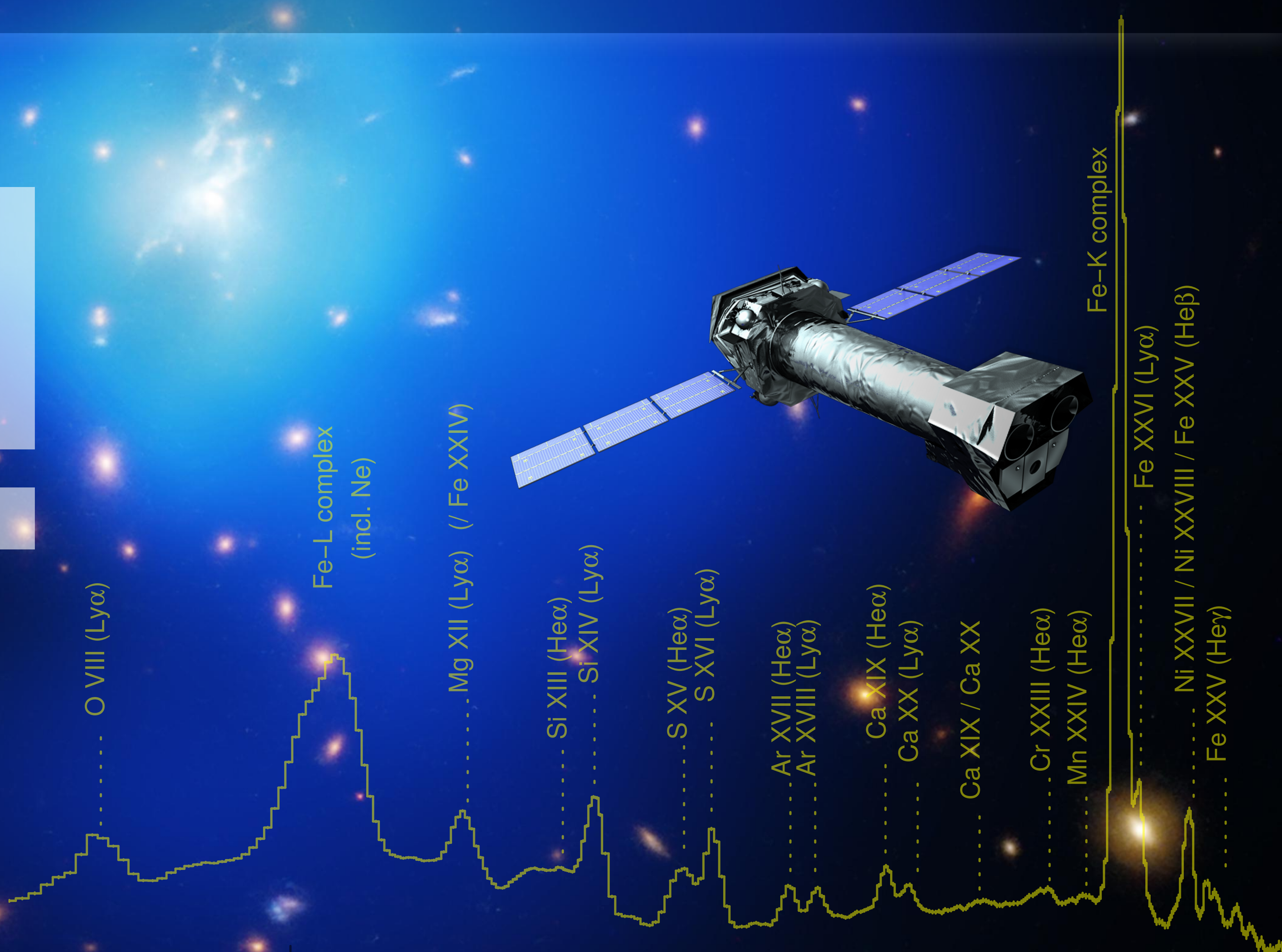
6 March 2019, *Physics of The Intra-Cluster Medium: Theory and Computation*, Budapest (Hungary)

Chemical enrichment of the atmospheric gas in clusters, groups, and massive galaxies

François Mernier

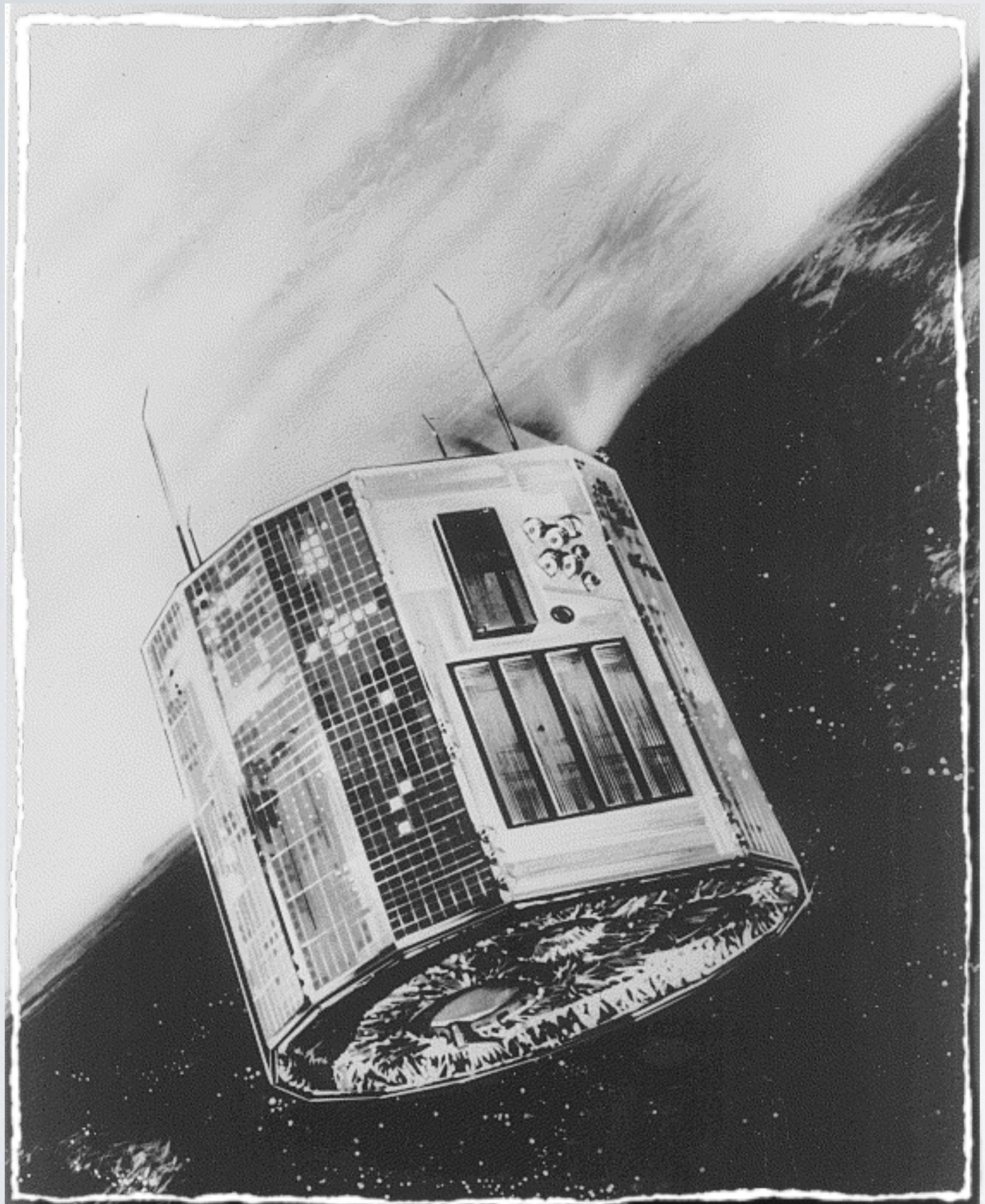
N. Werner, N. Truong, and the CHEERS collaboration

MTA-Eötvös University, Budapest

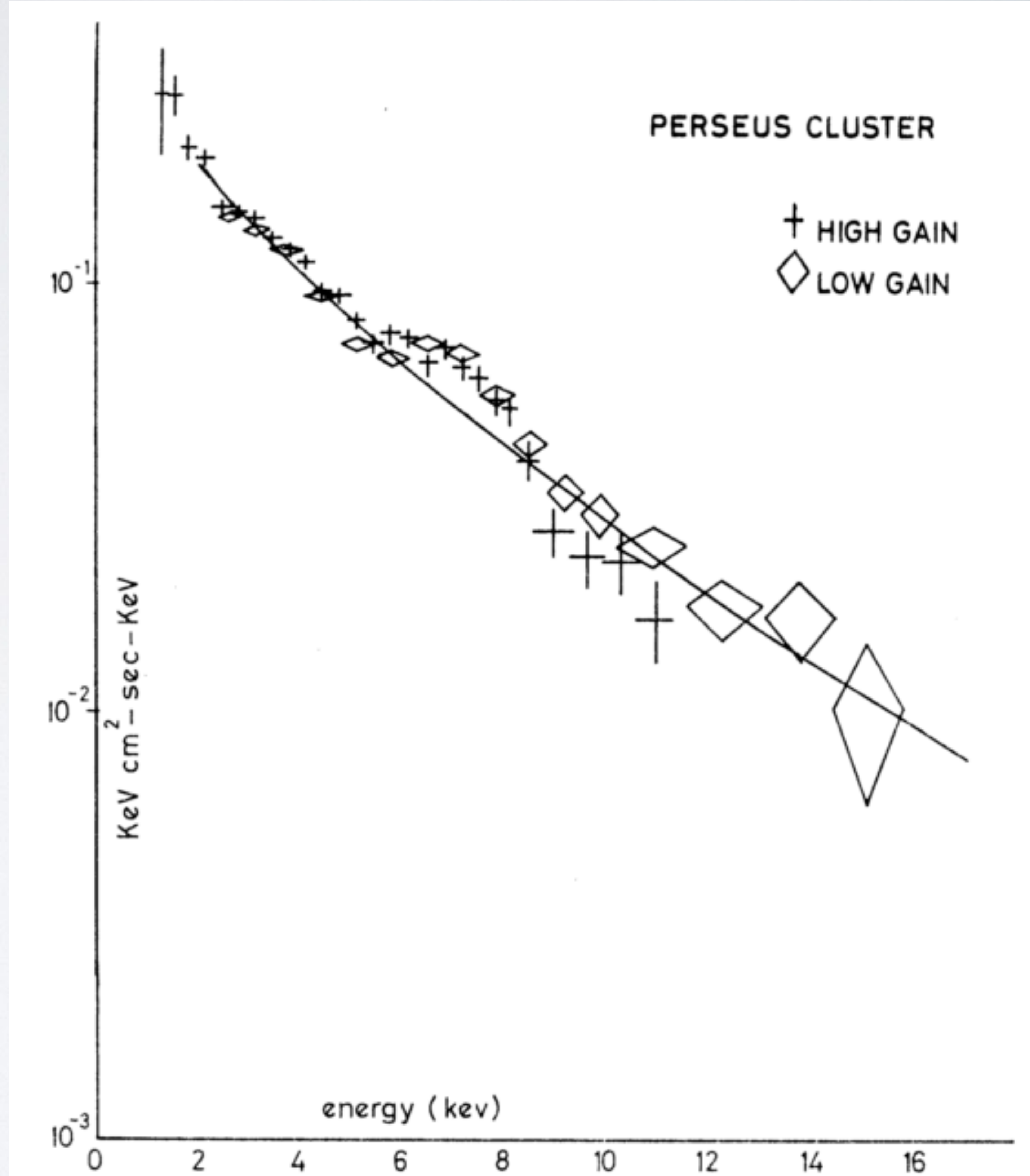


SRON Netherlands Institute for Space Research

The intra-cluster medium (ICM) contains metals!

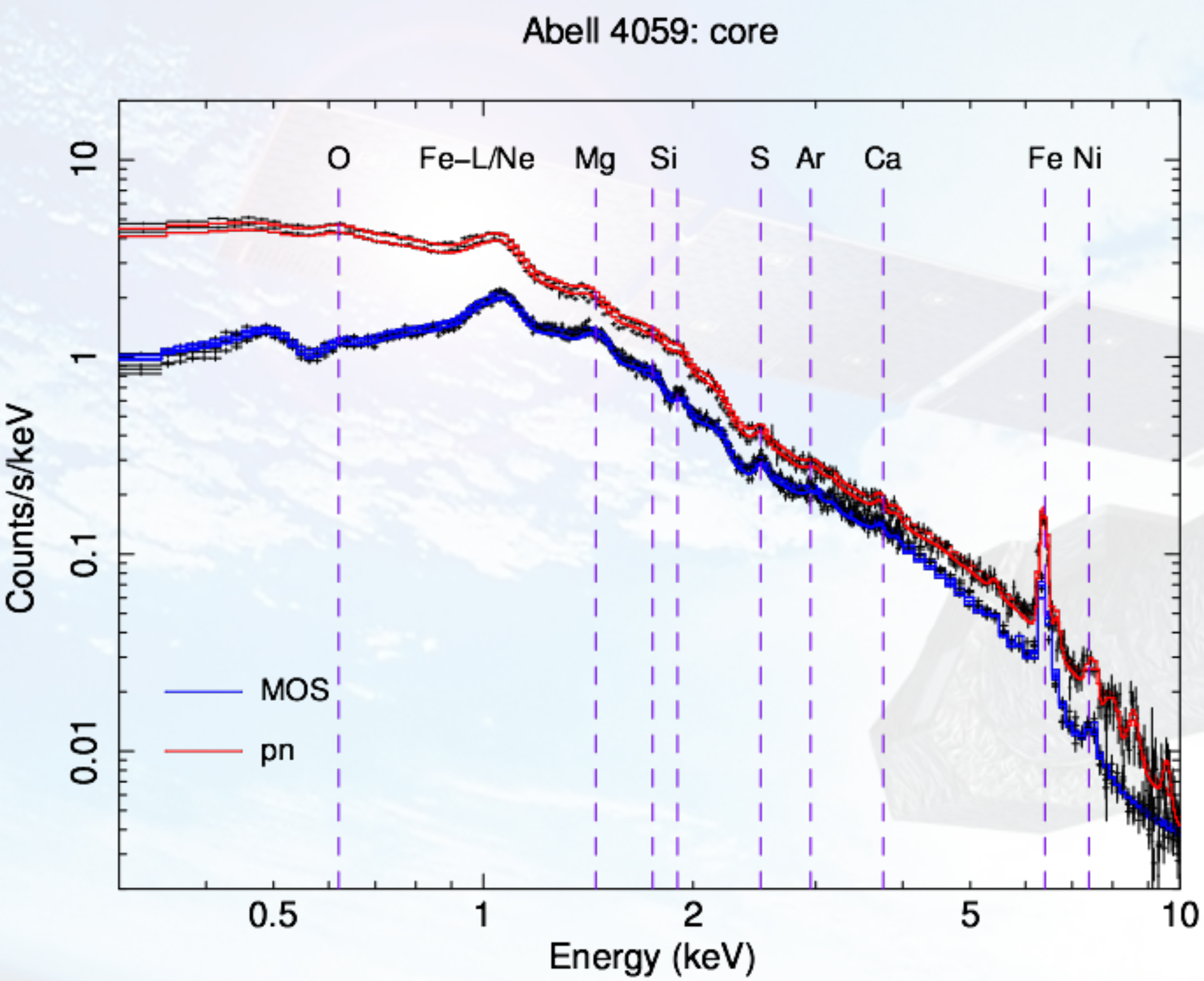


Ariel V



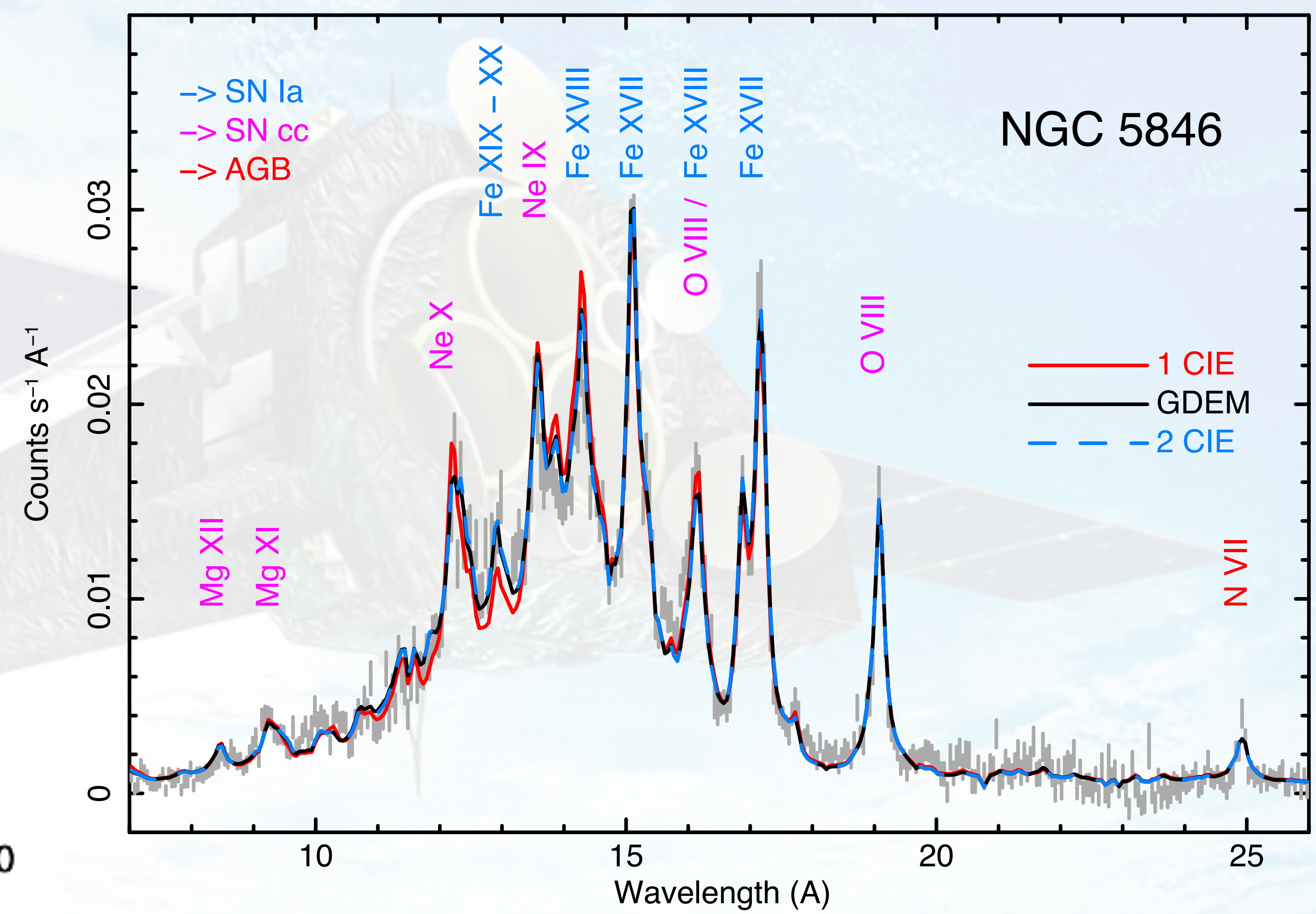
Mitchell et al. (1976)

The intra-cluster medium (ICM) contains metals!



Mernier et al. (2015)

EPIC

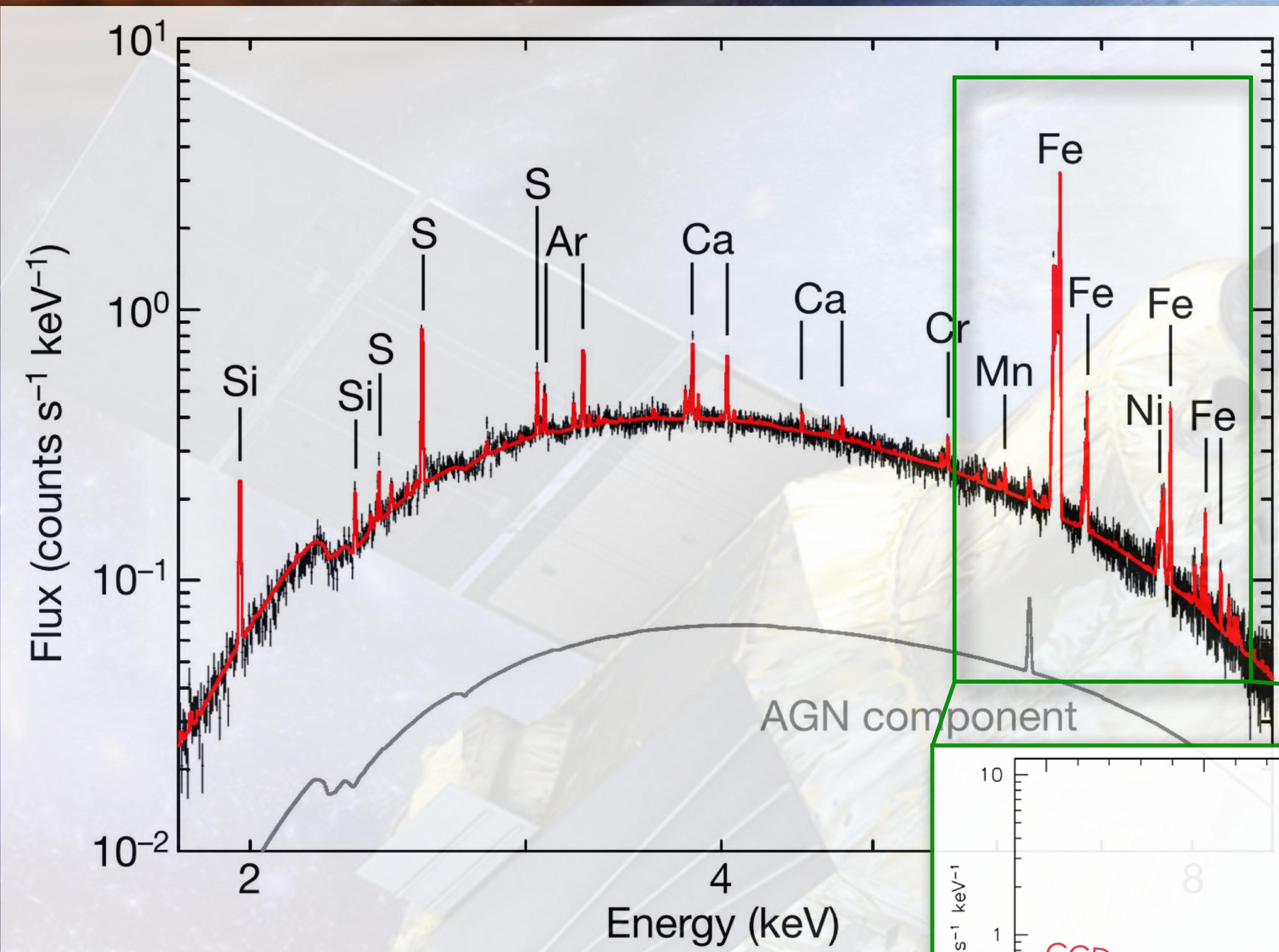


de Plaa et al. (2017)

RGS

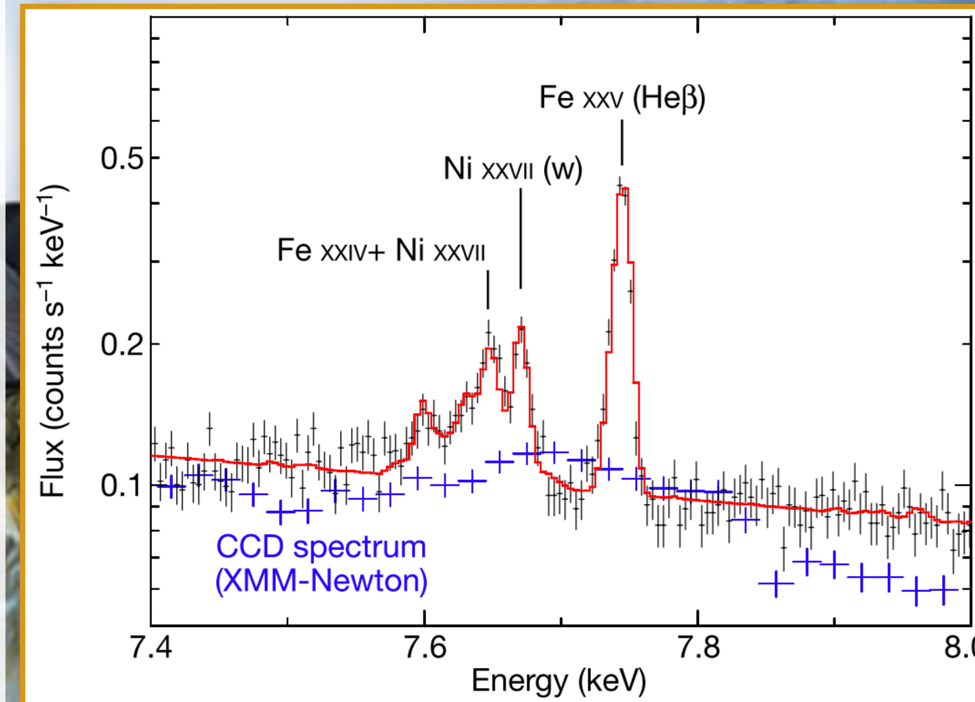
XMM-Newton

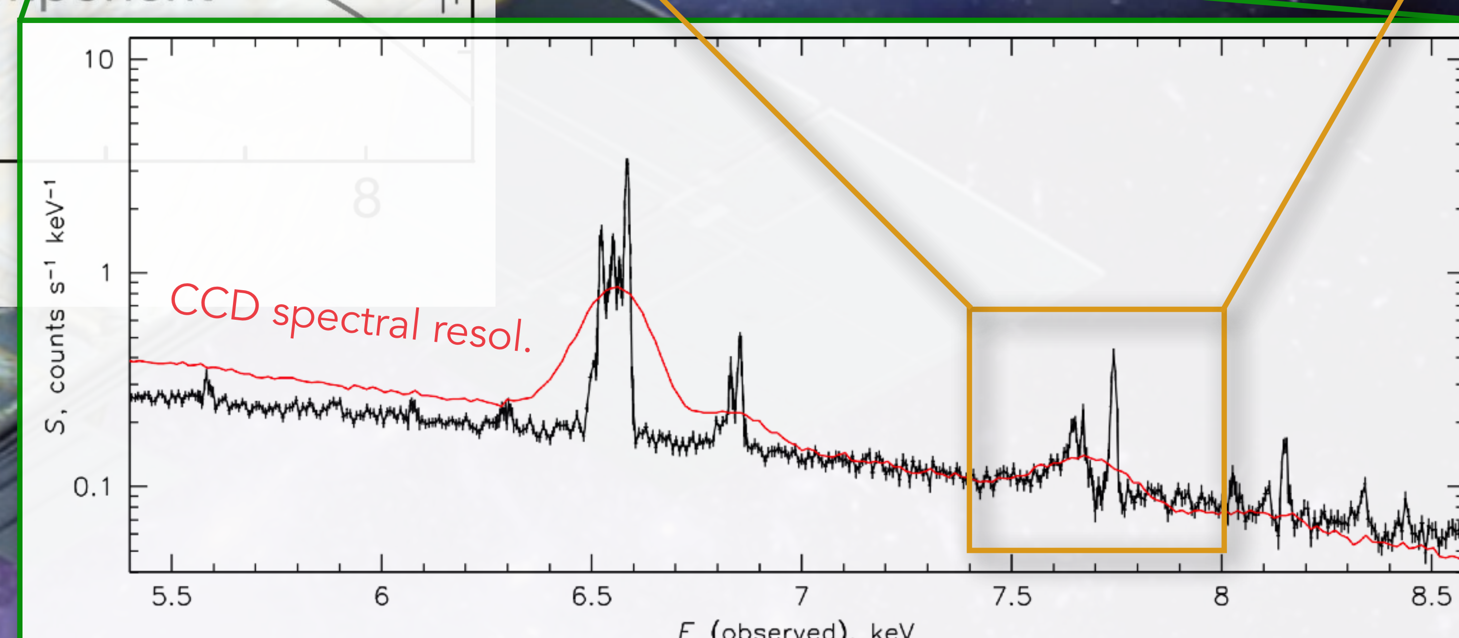
The intra-cluster medium (ICM) contains metals!



Hitomi Collaboration (2017, *Nature*)

Hitomi Collaboration (2017, *Nature*)





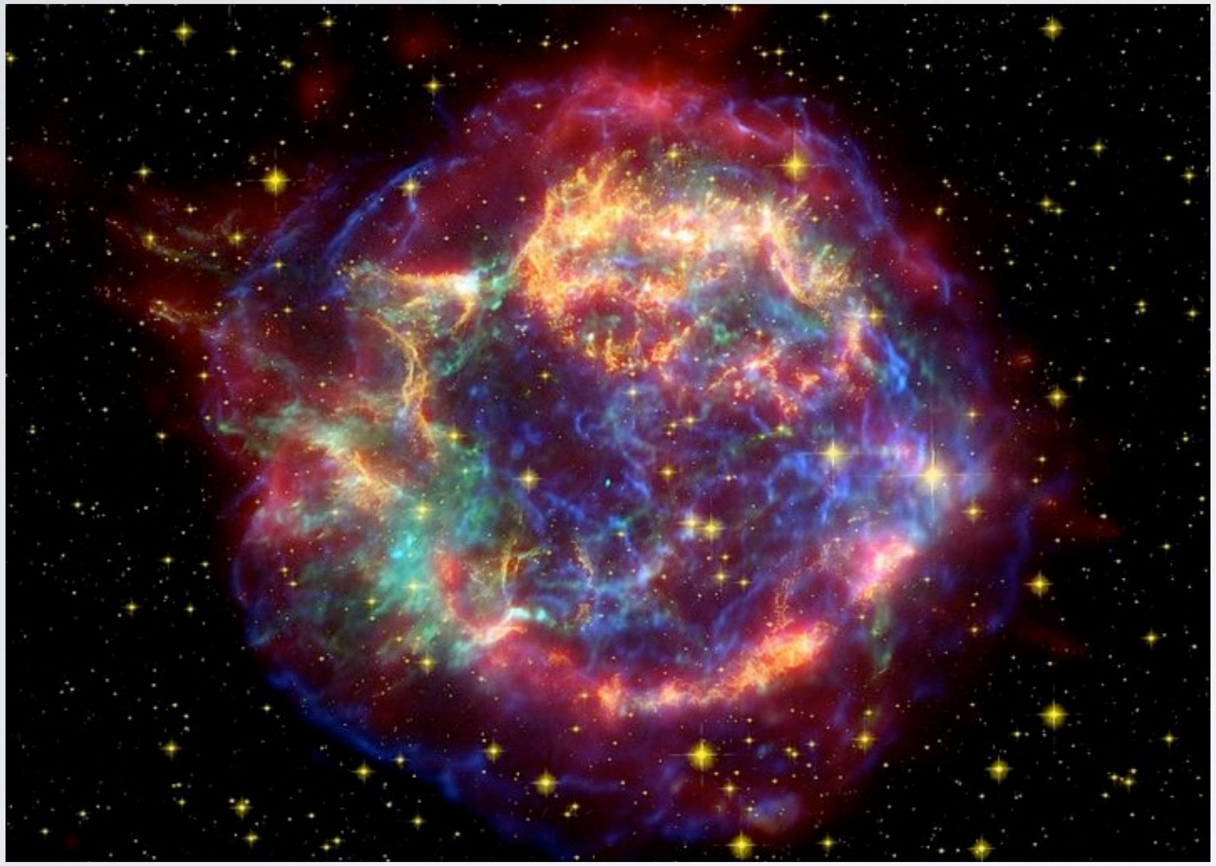
Hitomi Collaboration (2016, *Nature*)

SXS

Hitomi

The origin of (heavy) chemical elements

Core collapse supernovae (SNcc)

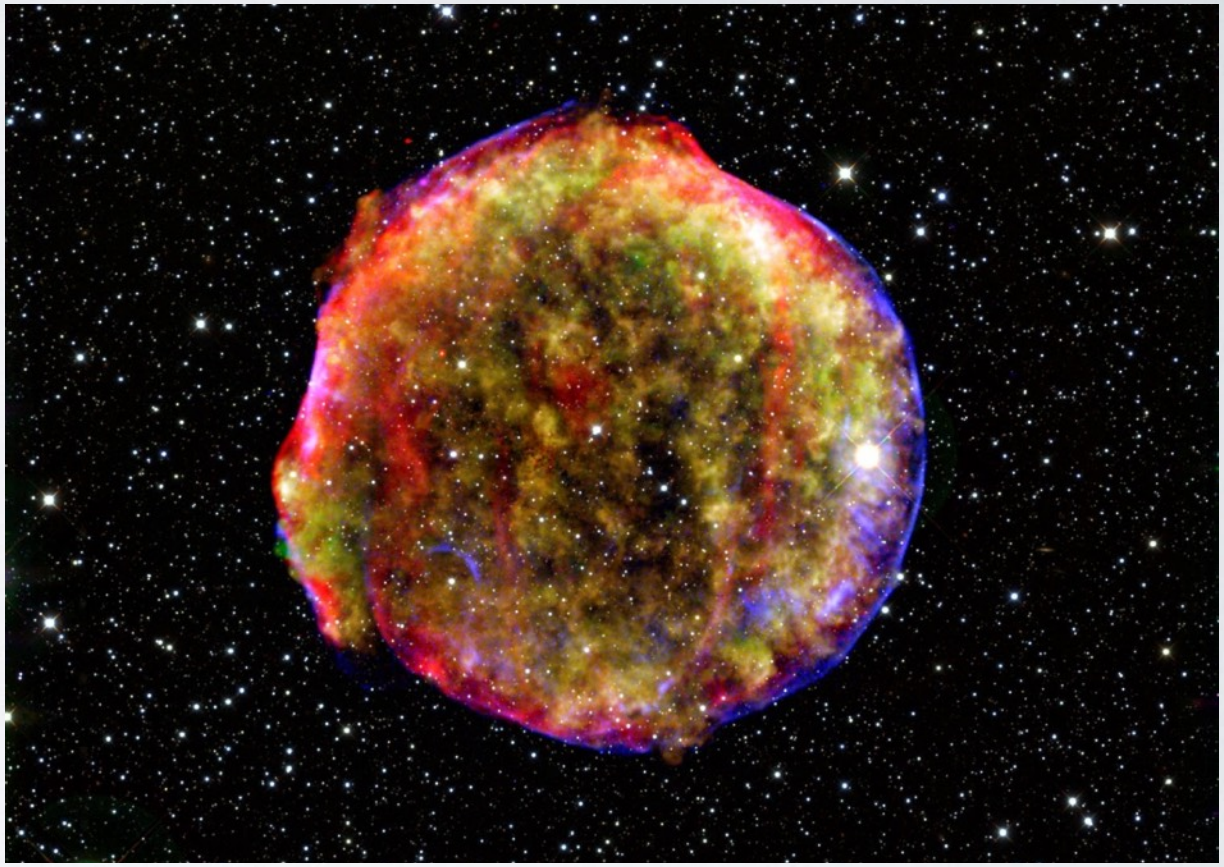


Produce:

➡ O, Ne, Mg, Si, S

Explode (and enrich) quite fast after star formation

Type Ia supernovae (SNIa)



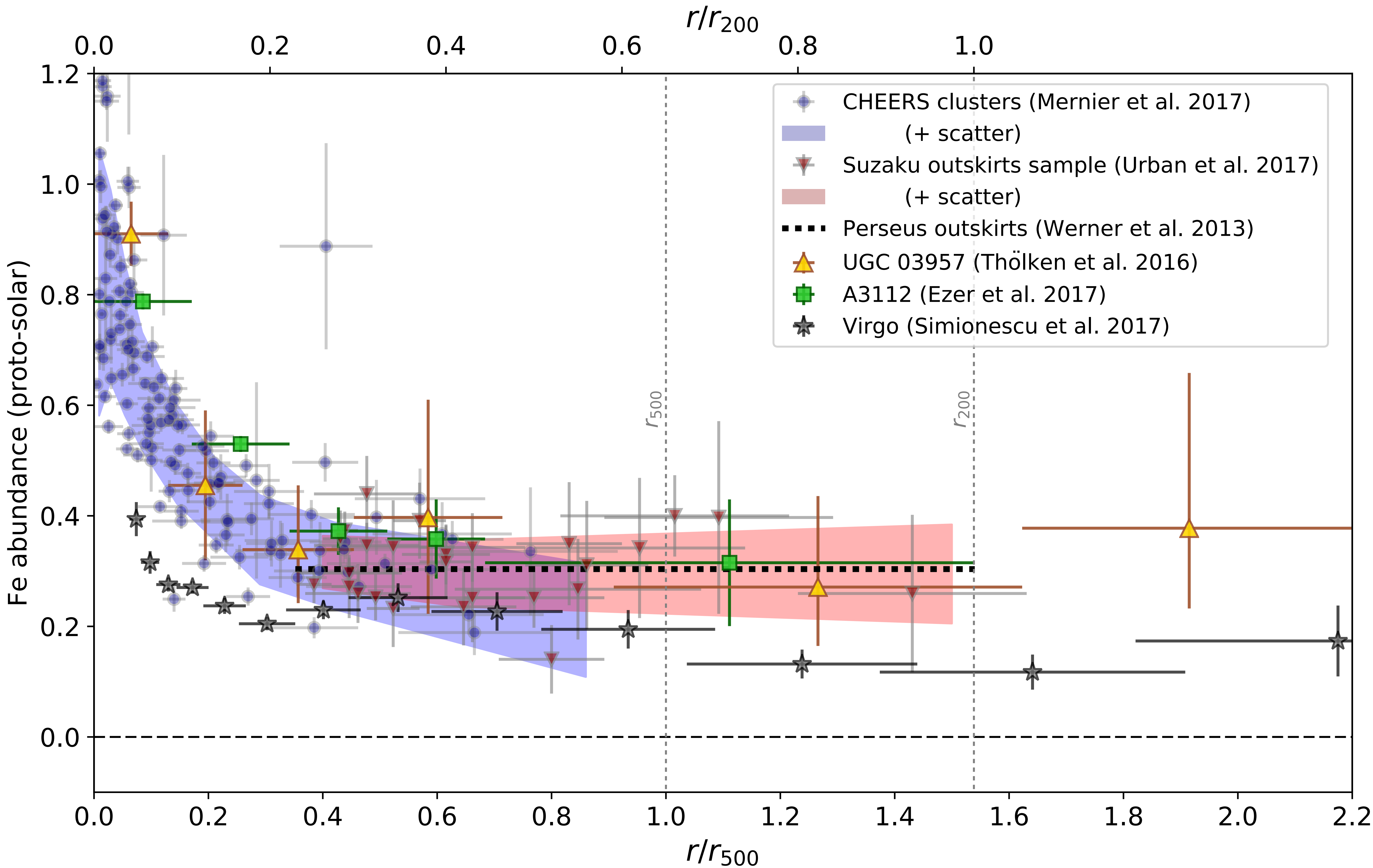
Produce:

➡ Si, S, Ar, Ca, Fe, Ni

Time delay between star formation and SNIa explosions (?)

The ***spatial distribution*** of metals through the ICM provides valuable information on the ***chemical enrichment history*** of galaxy clusters!

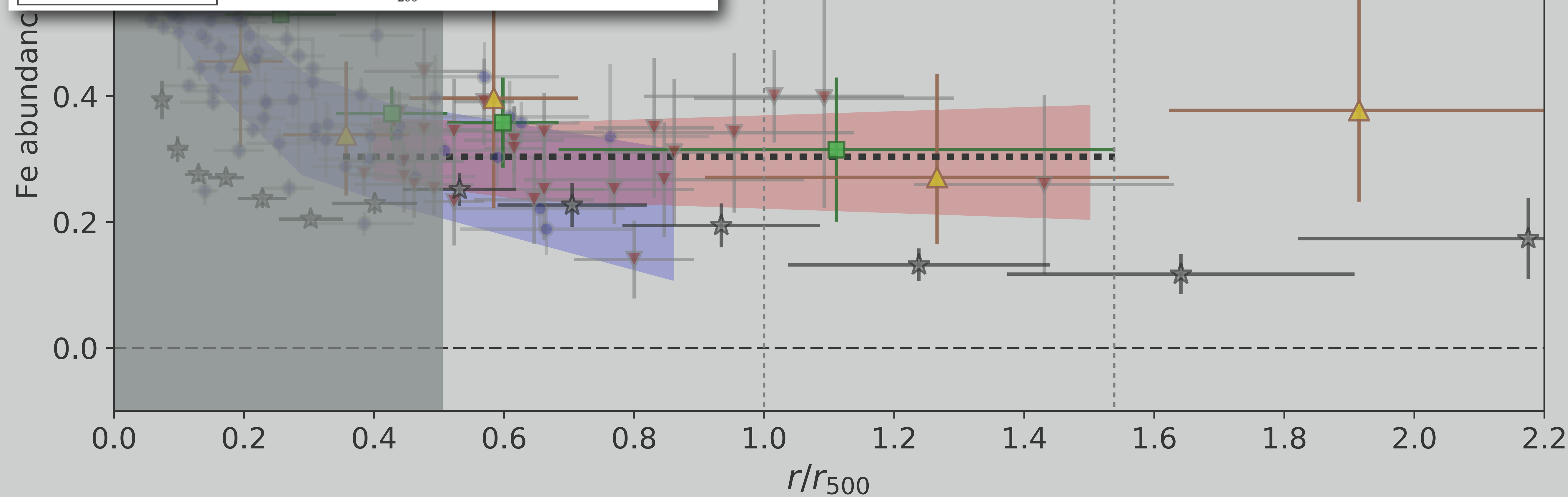
The (average) Fe profile in cool-core clusters

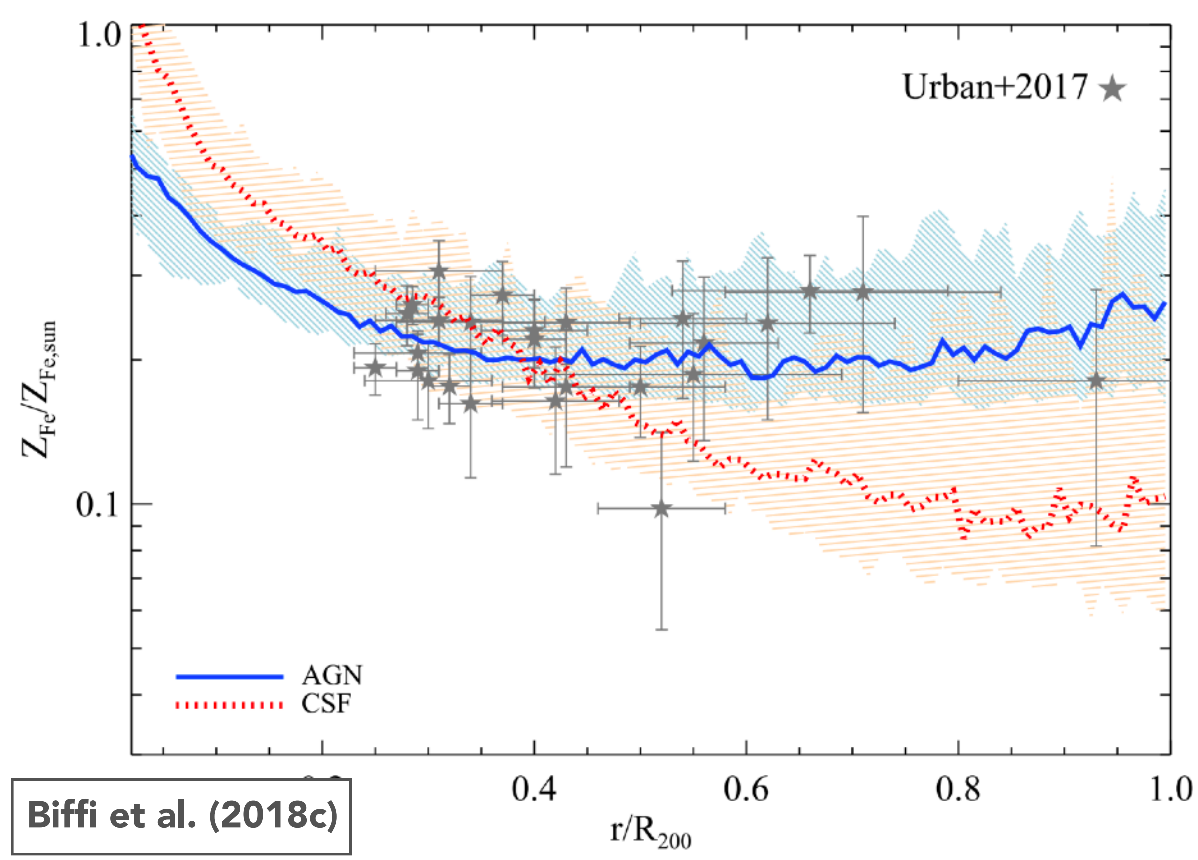


r_{500}: radius within which mass density = 500 × (critical density of the Universe)

Mernier et al. (2018c)

The (average) Fe profile in cool-core clusters





Biffi et al. (2018c)

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

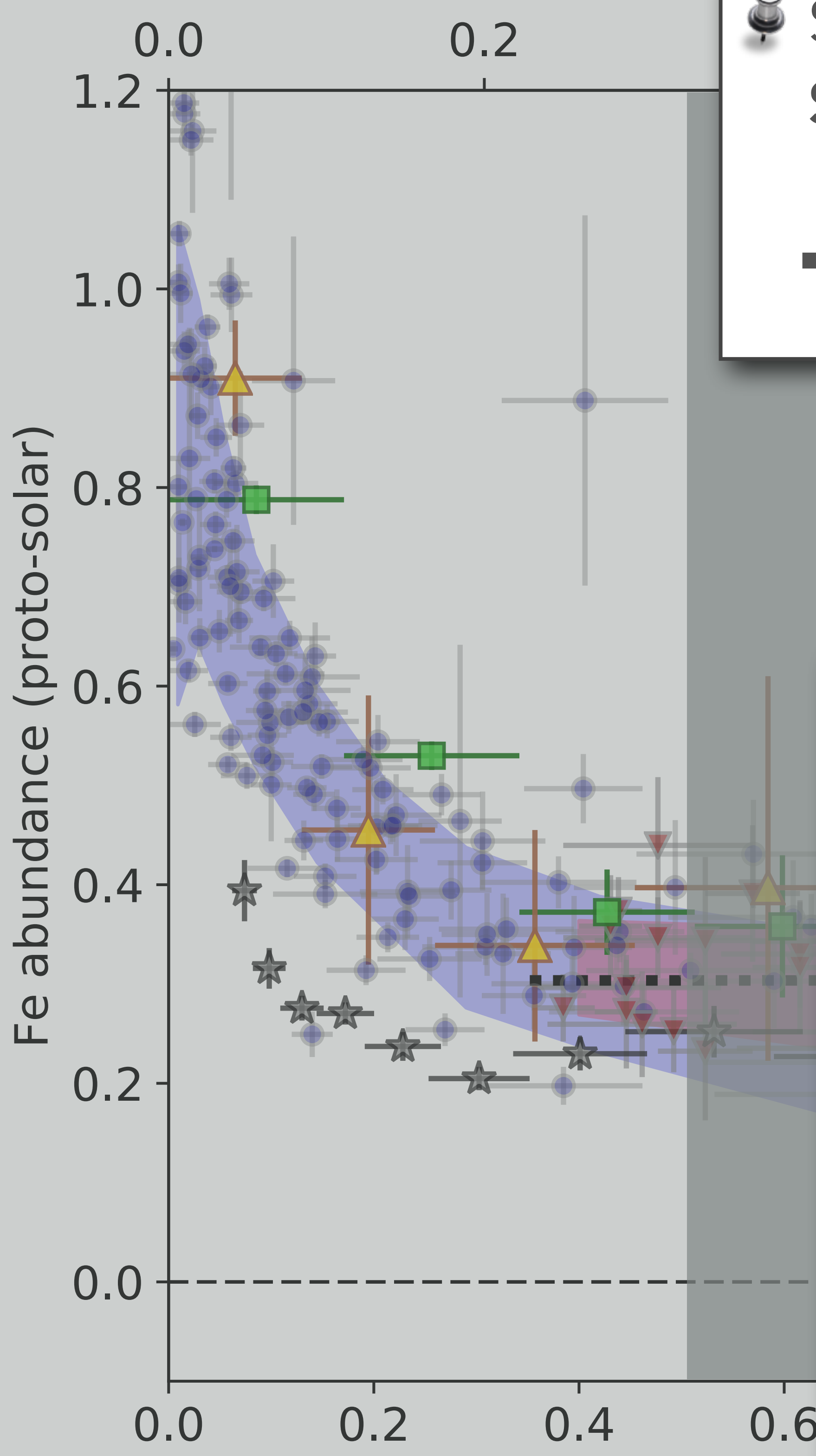
➡ **Before** the cluster assembled, more than ~10 Gyrs ago (**z > 2-3**)!

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

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

Mernier et al. (2018c)

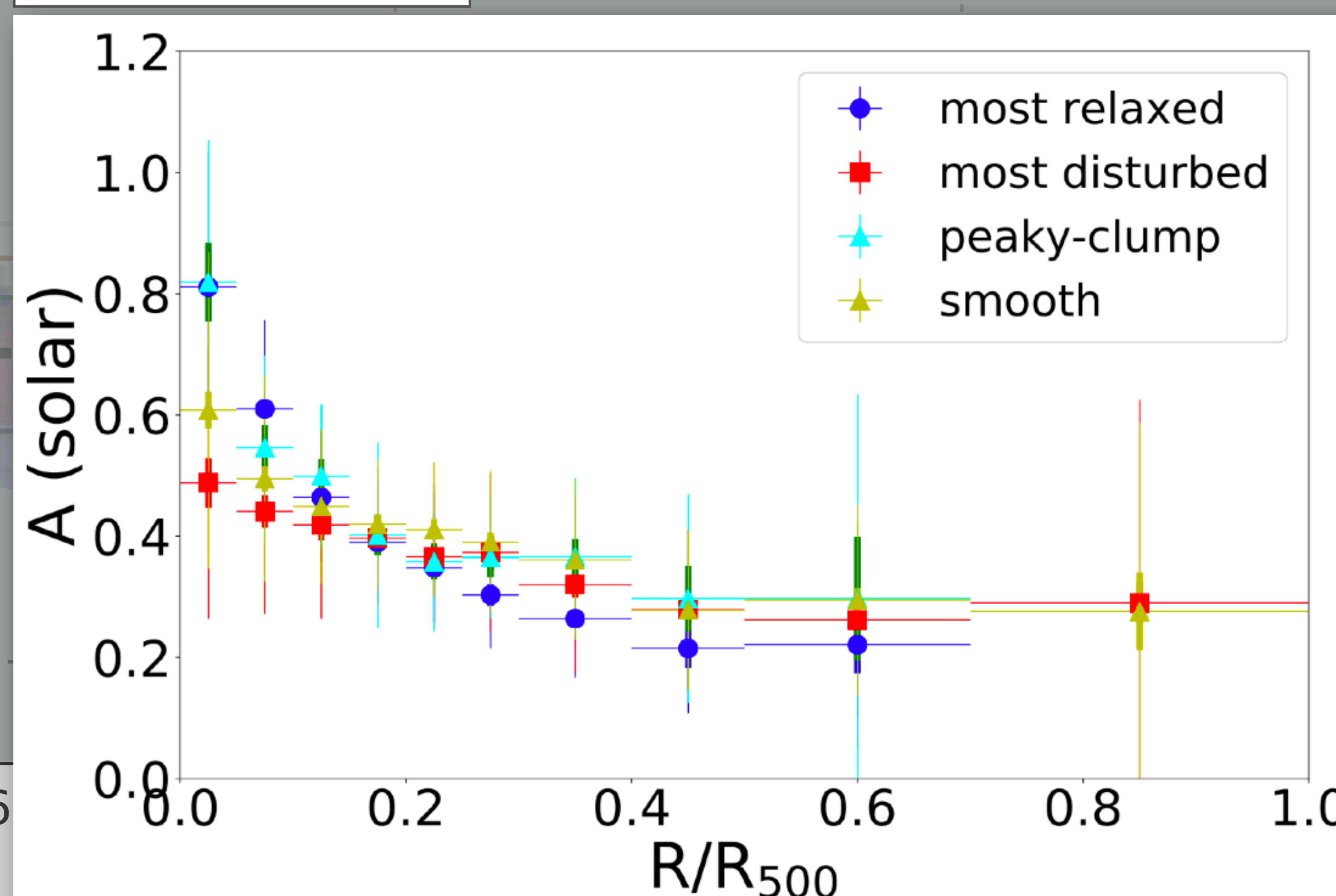
The (average) Fe profile in cool-core clusters



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

➡ (Initial interpretation)

Lovisari & Reiprich (2019)



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

Mernier et al. (2018c)

CHEERS! (PI: J. de Plaa)

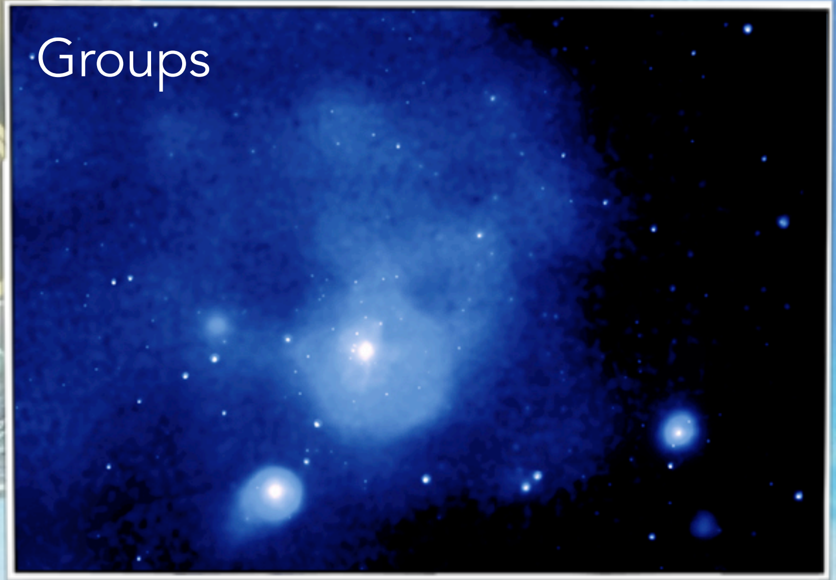
CHEERS stands for:
CHE*mical* ***E****nrichment* ***R****gs* ***S****ample*

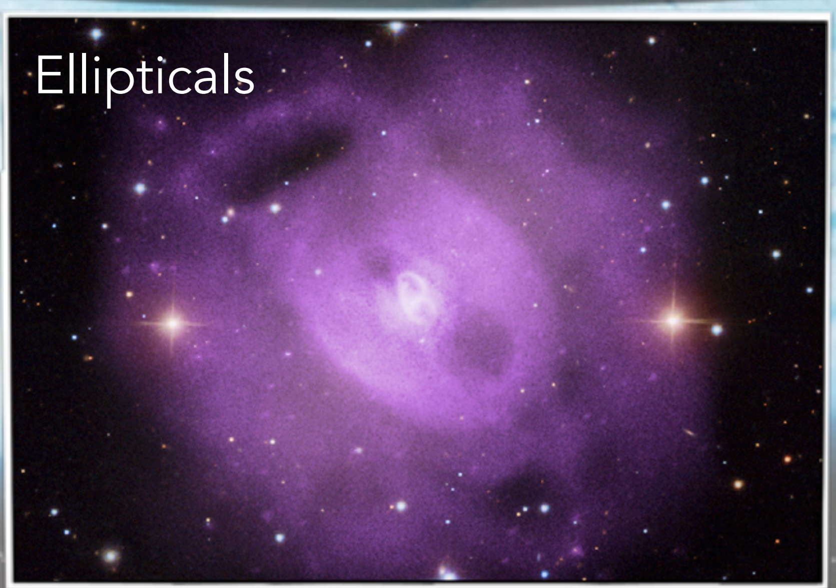
de Plaa et al. (2017)

- 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

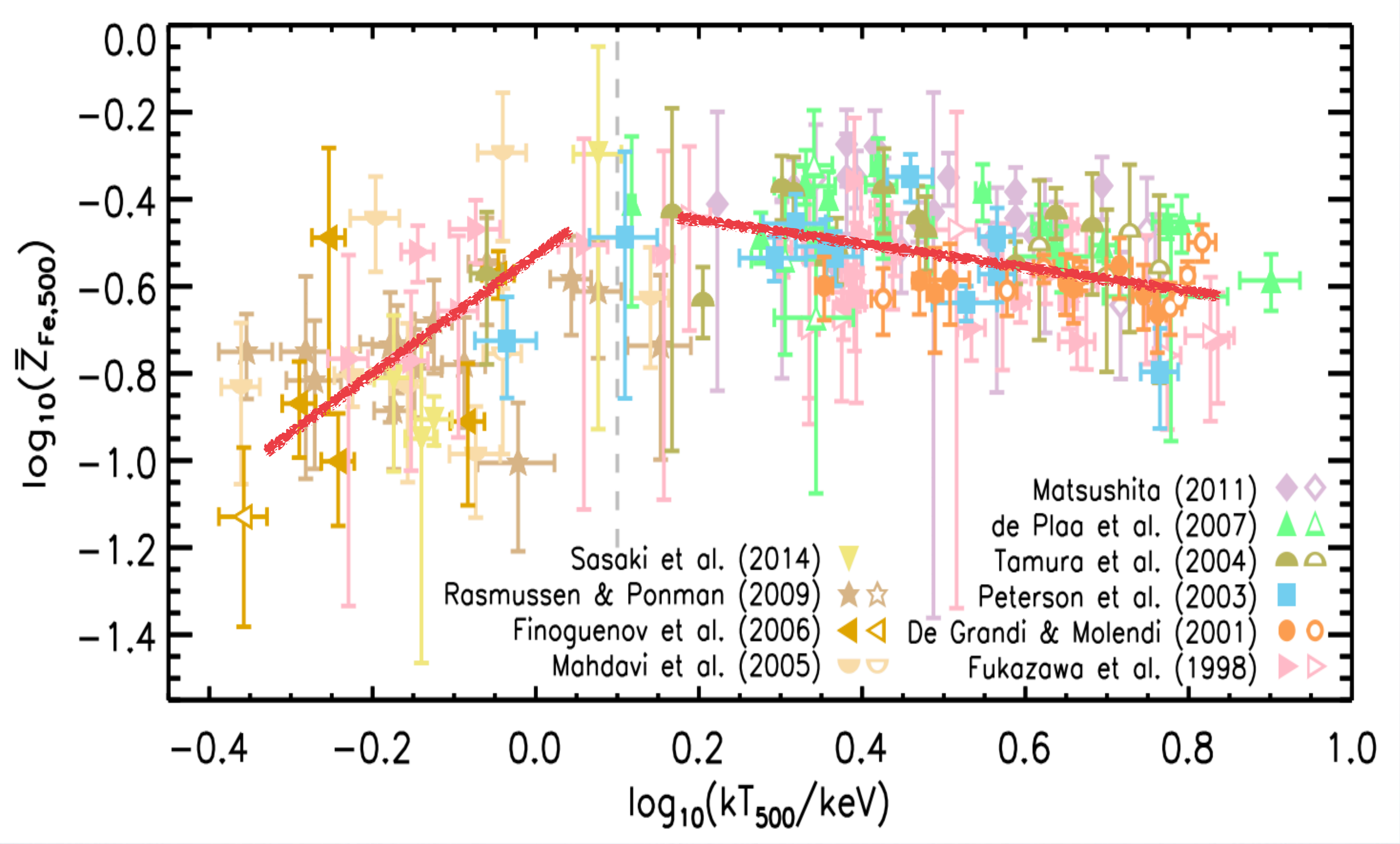
➡ ~4.5 Ms of *XMM-Newton* total net exposure





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

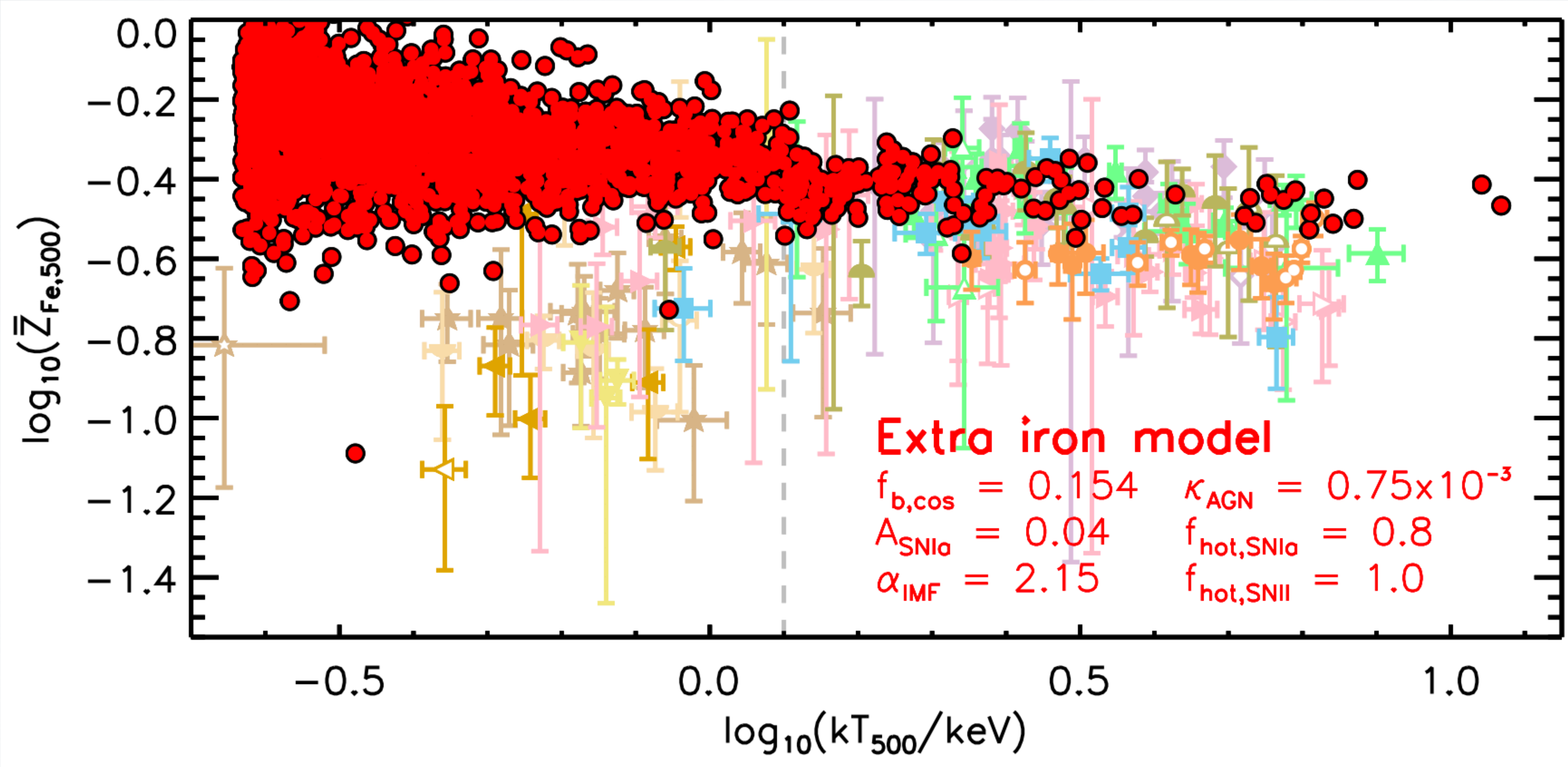
Central Fe abundance: clusters vs. groups/ellipticals



Yates et al. (2017)

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

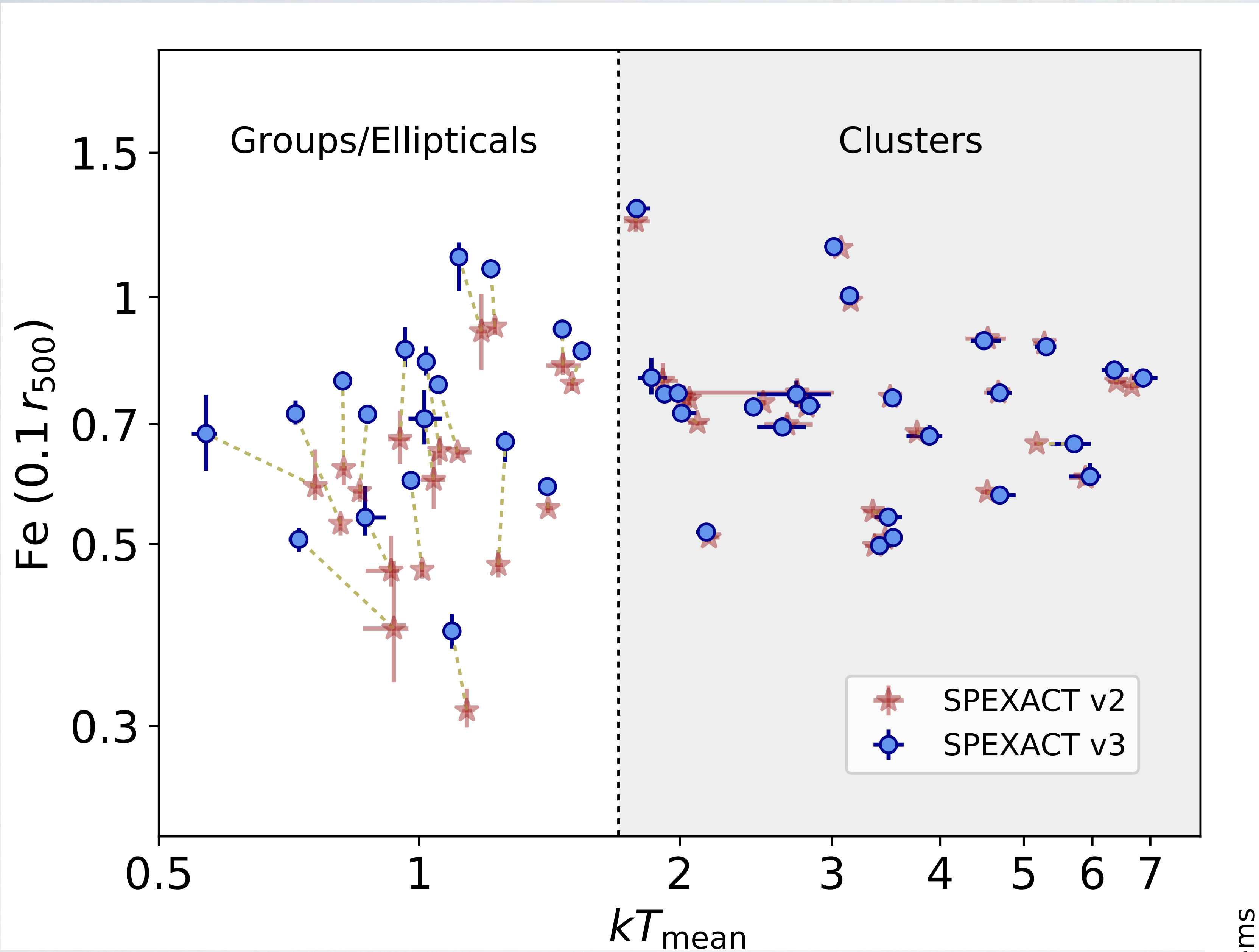
Central Fe abundance: clusters vs. groups/ellipticals



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



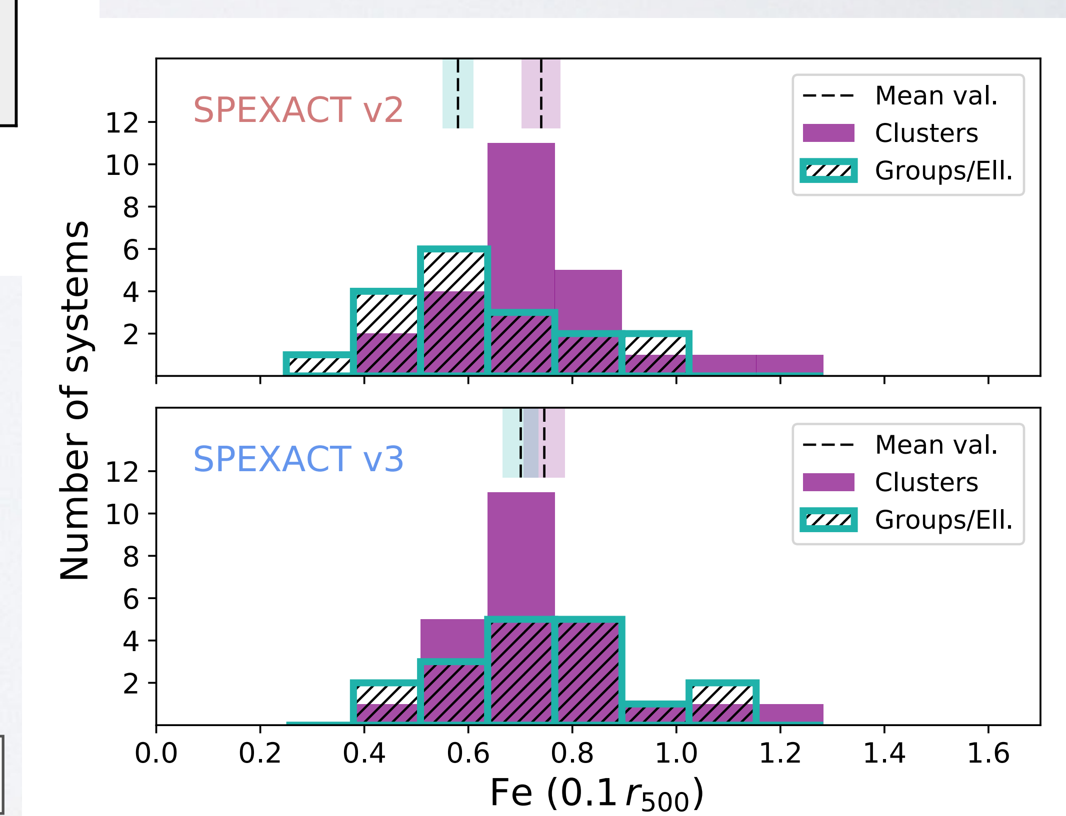
For the first time, we find **similar central Fe abundances** between:

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

(2 orders of magnitude in total mass!)

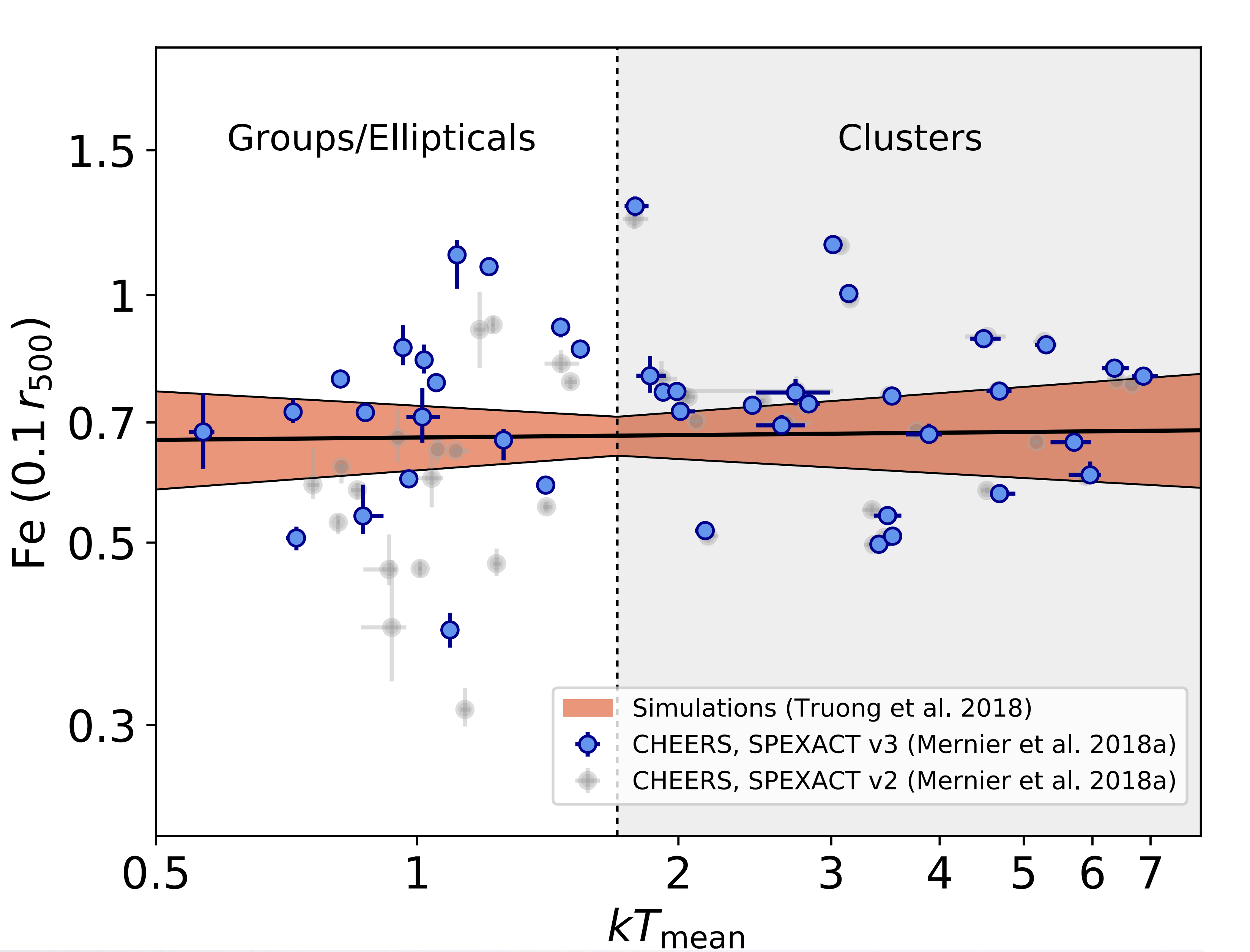
End 2016: **New SPEX release!**

SPEX v2 → SPEX v3



Mernier et al. (2018a)

Central Fe abundance: clusters vs. groups/ellipticals



Mernier et al. (2018c)

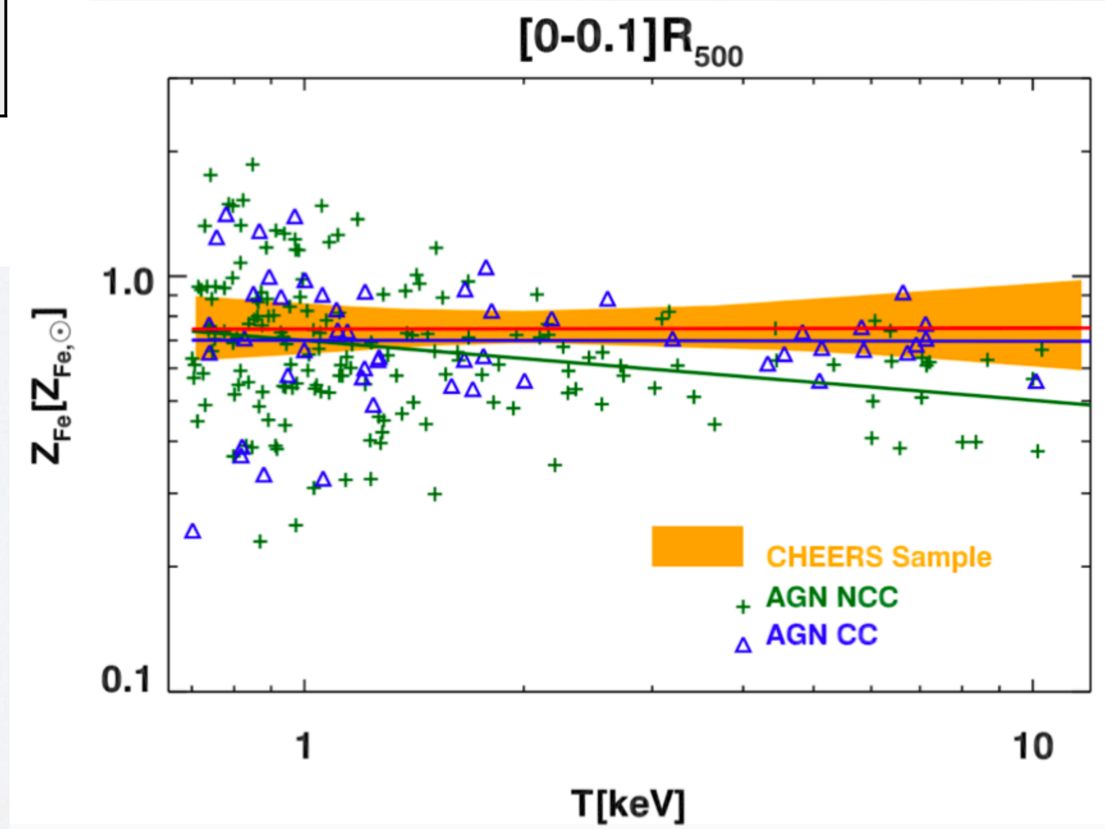
For the first time, we find **similar central Fe abundances** between:

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

(2 orders of magnitude in total mass!)

Consistent with simulations!

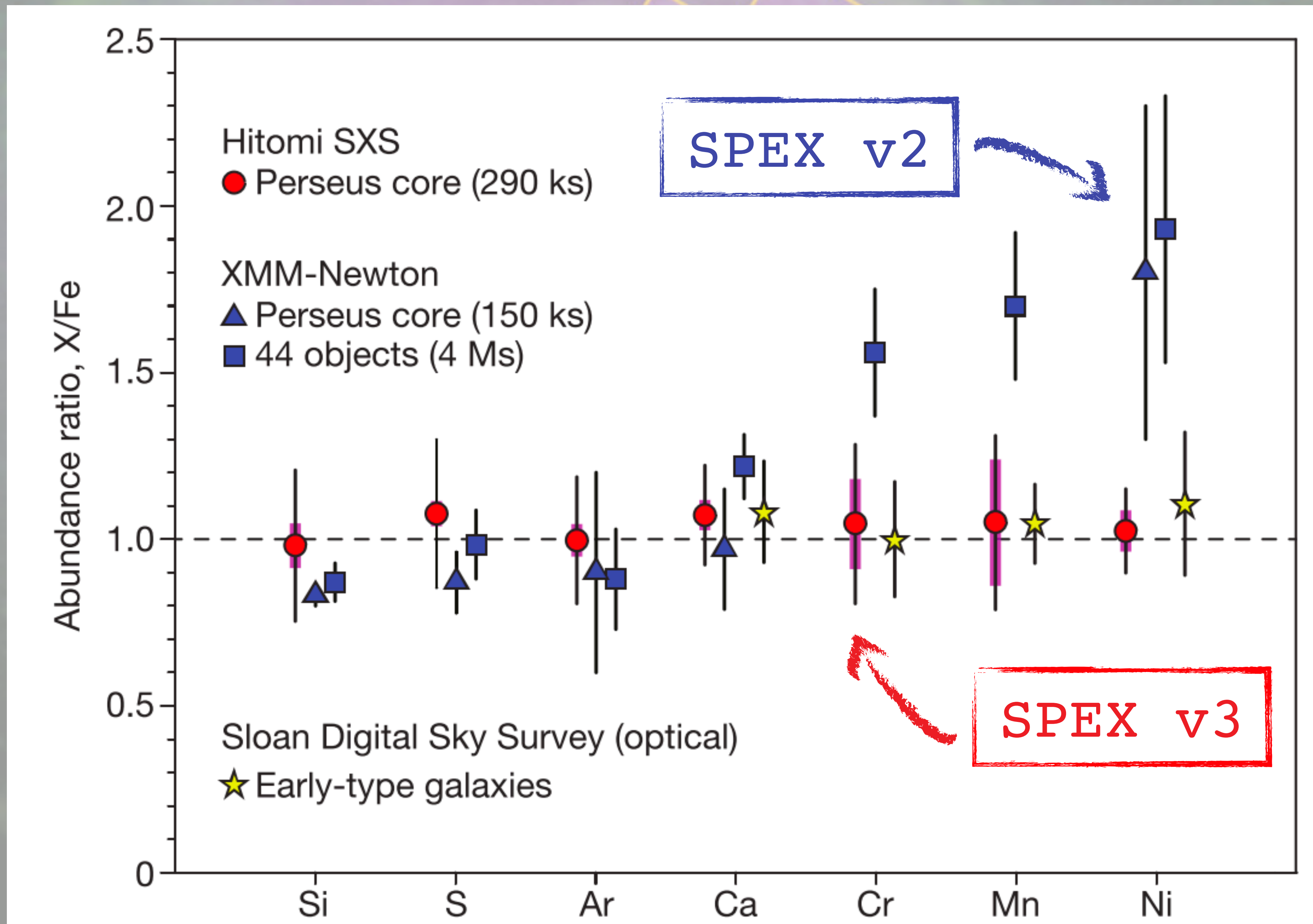
see: **Truong et al. (2019)**



Truong et al. (2019)

2. Chemical composition of the ICM

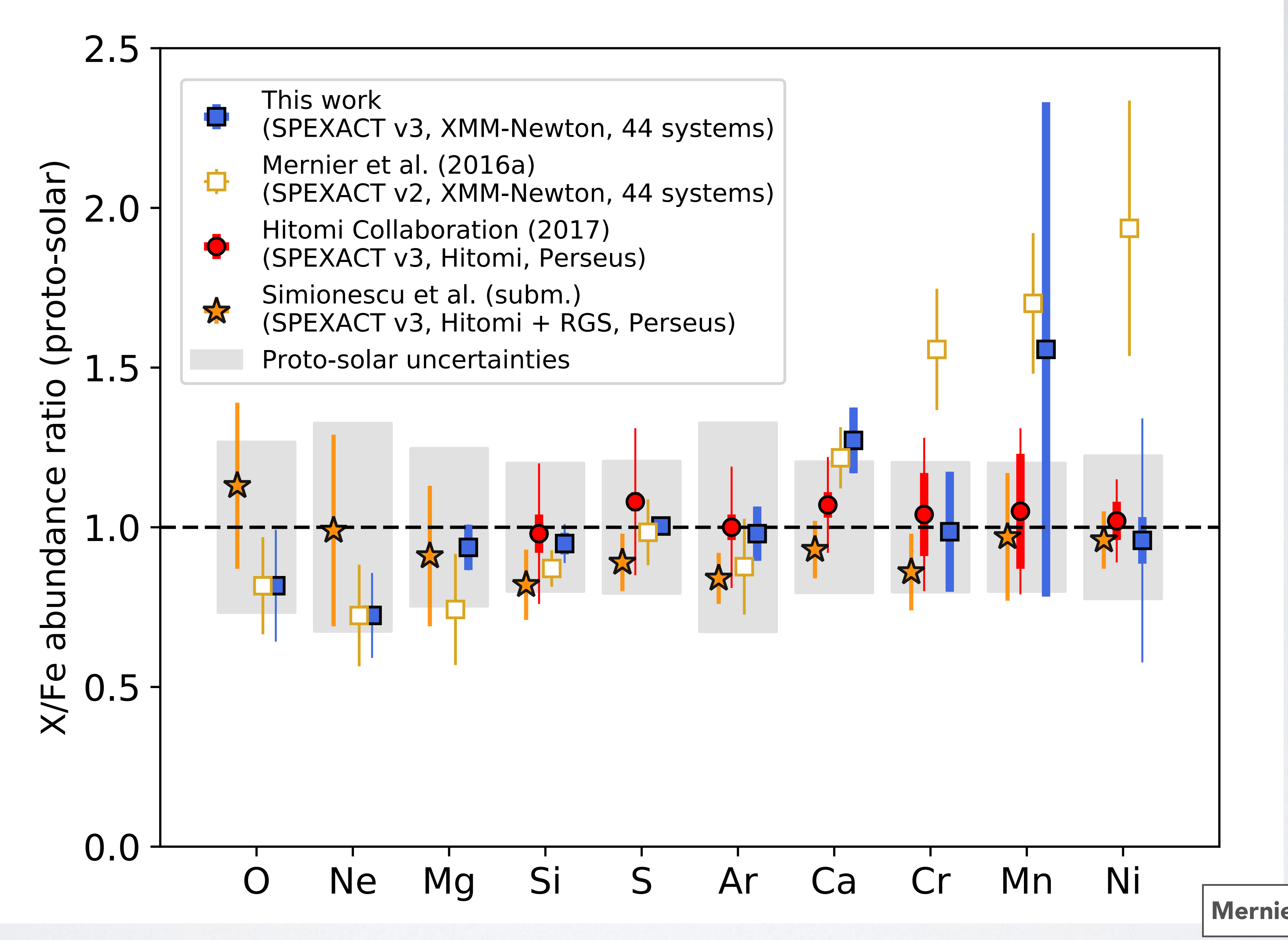
Hitomi (February 2016 - March 2016)



The Hitomi Collaboration (2017, *Nature*)

see also: **Simionescu et al. (2019)**

Chemical composition of the ICM



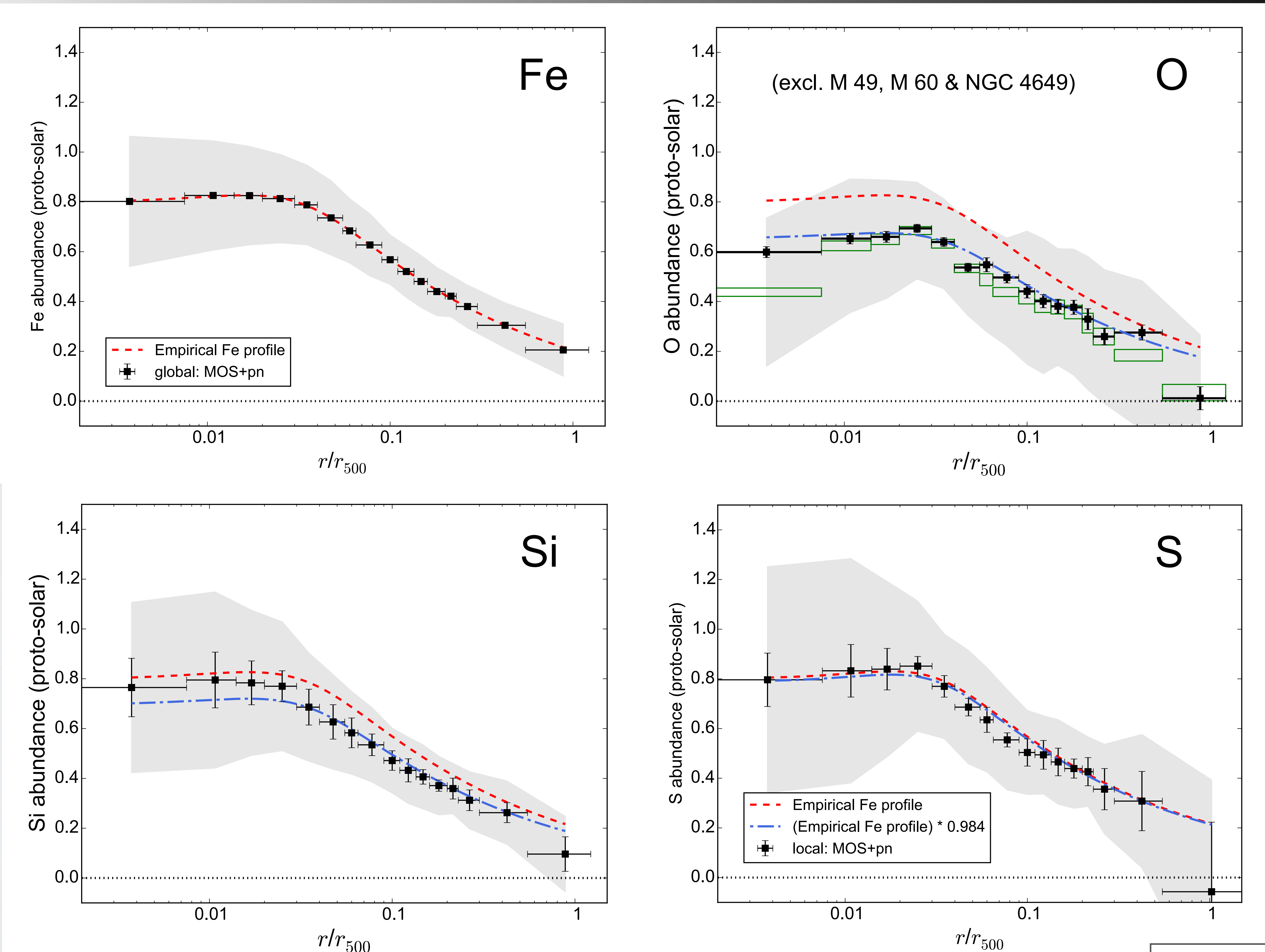
Mernier et al. (2018b)

All abundance ratios measured with XMM-Newton EPIC (CHEERS sample) are ***consistent*** with Hitomi (Perseus)!

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

3. Distribution of SNIa vs. SNcc enrichment

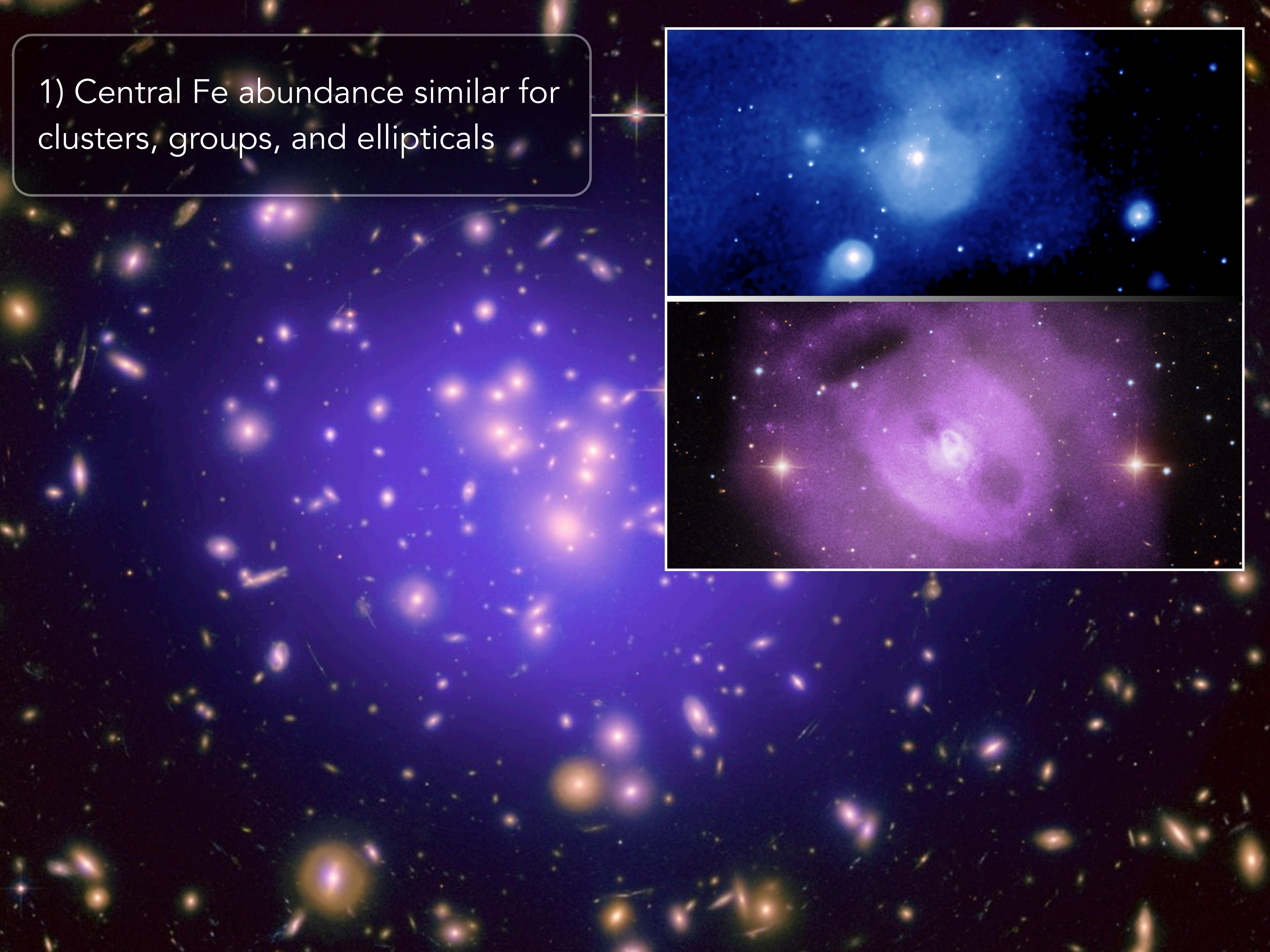
Radial distribution of the SNIa fraction



Mernier et al. (2017)

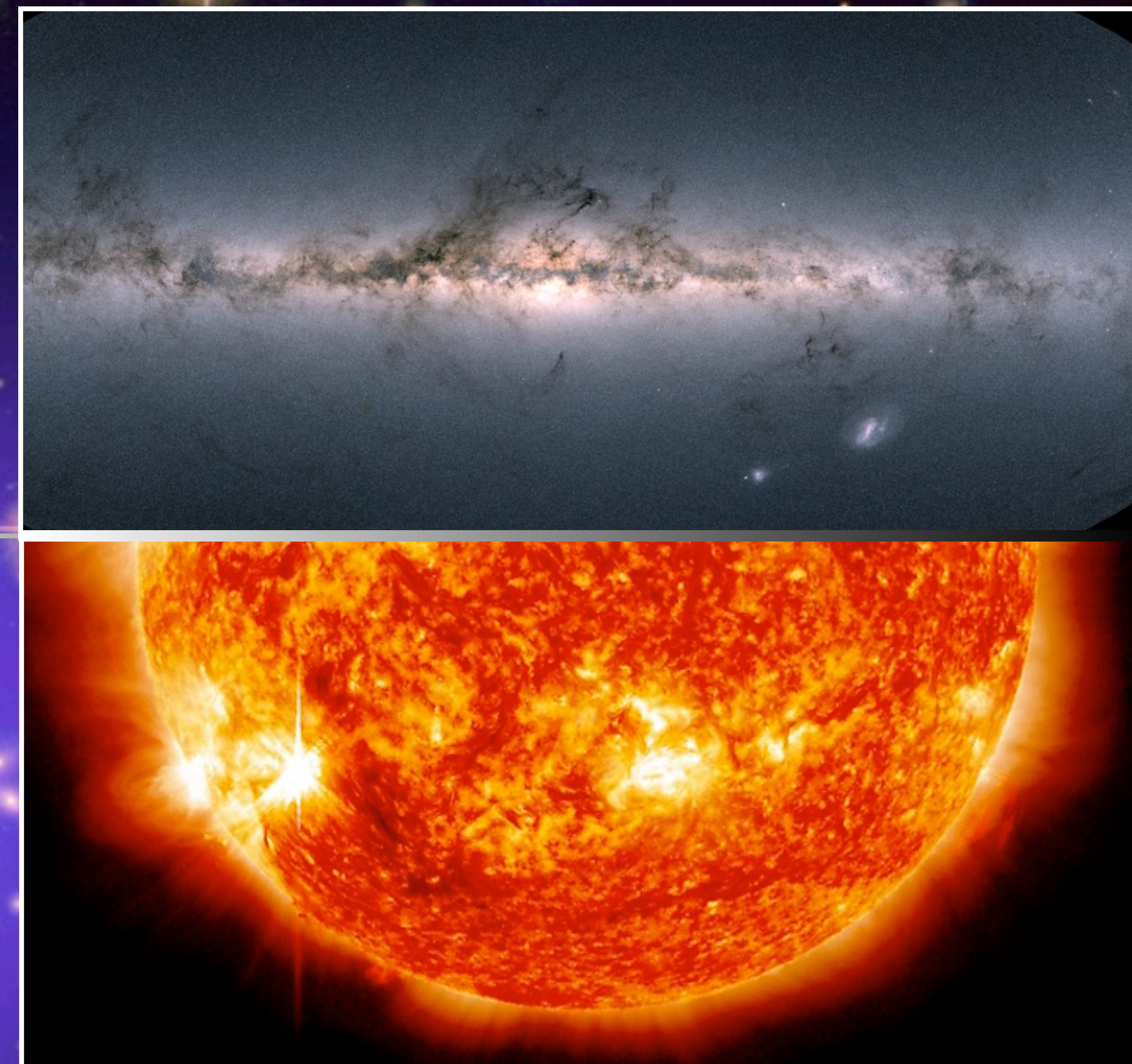
see also: **Simionescu et al. (2015), Ezer et al. (2017)**

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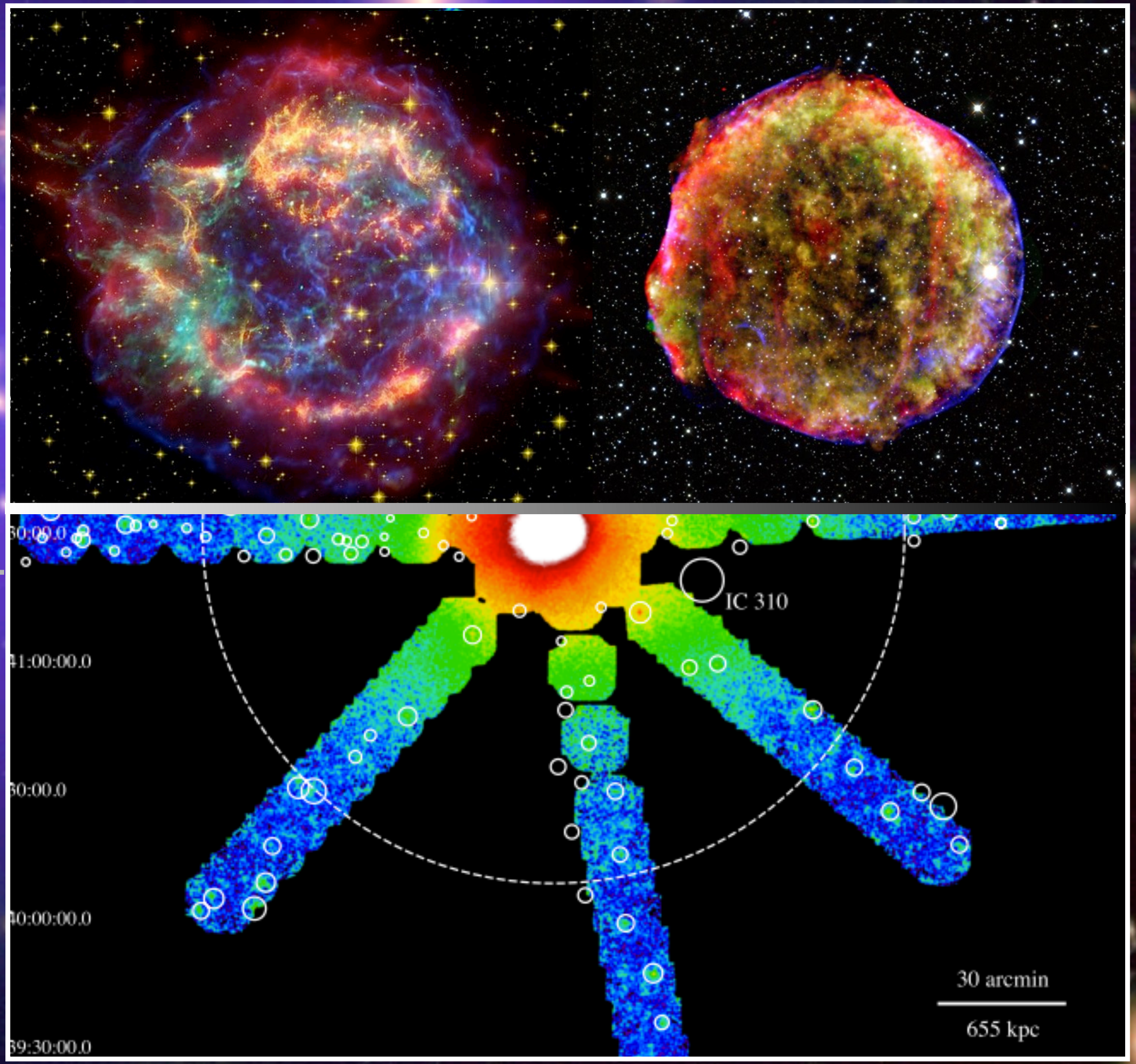
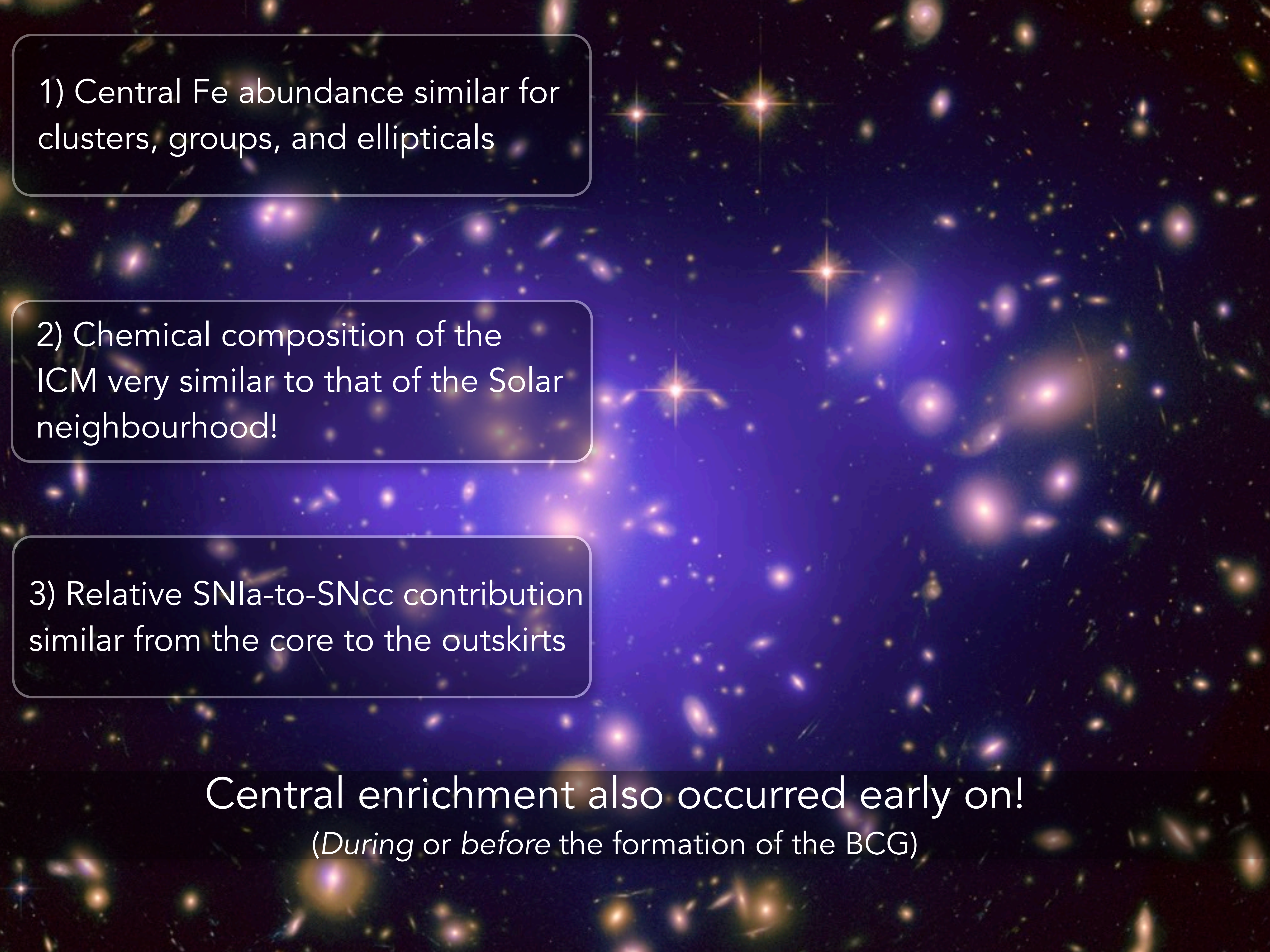
2) Chemical composition of the ICM very similar to that of the Solar neighbourhood!

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





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

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

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

Central enrichment also occurred early on!

(*During* or *before* the formation of the BCG)

Recent reviews…

Space Sci Rev (2018) 214:123
arXiv:1811.01955

Space Sci Rev (2018) 214:129
arXiv:1811.01967

Space Sci Rev (2018) 214:123
https://doi.org/10.1007/s11214-018-0557-7

CrossMark

Enrichment of the Hot Intracluster Medium: Numerical Simulations

V. Biffi[1,2] · F. Mernier[3,4,5] · P. Medvedev[6]

Received: 6 July 2018 / Accepted: 1 November 2018

Abstract The distribution of chemical elements in the hot intracluster medium (ICM) retains valuable information about the enrichment and star formation histories of galaxy clusters, and on the feedback and dynamical processes driving the evolution of the cosmic baryons. In the present study we review the progresses made so far in the modelling of the ICM chemical enrichment in a cosmological context, focusing in particular on cosmological hydrodynamical simulations. We will review the key aspects of embedding chemical evolution models into hydrodynamical simulations, with special attention to the crucial assumptions on the initial stellar mass function, stellar lifetimes and metal yields, and to the numerical limitations of the modelling. At a second stage, we will overview the main simulation results obtained in the last decades and compare them to X-ray observations of the ICM enrichment patterns. In particular, we will discuss how state-of-the-art simulations are able to reproduce the observed radial distribution of metals in the ICM, from the core to the outskirts, the chemical diversity depending on cluster thermo-dynamical properties,

Space Sci Rev (2018) 214:129
https://doi.org/10.1007/s11214-018-0565-7

CrossMark

Enrichment of the Hot Intracluster Medium: Observations

F. Mernier[1,2,3] · V. Biffi[4,5] · H. Yamaguchi[6] ·
P. Medvedev[7] · A. Simionescu[3,6,8] · S. Ettori[9,10] ·
N. Werner[1,11,12] · J.S. Kaastra[3,13] · J. de Plaa[3] · L. Gu[14,3]

Received: 6 July 2018 / Accepted: 15 November 2018

Abstract Four decades ago, the firm detection of an Fe-K emission feature in the X-ray spectrum of the Perseus cluster revealed the presence of iron in its hot intracluster medium (ICM). With more advanced missions successfully launched over the last 20 years, this discovery has been extended to many other metals and to the hot atmospheres of many other galaxy clusters, groups, and giant elliptical galaxies, as evidence that the elemental bricks of life—synthesized by stars and supernovae—are also found at the largest scales of the

Clusters of Galaxies: Physics and Cosmology
Edited by Andrei Bykov, Jelle Kaastra, Marcus Brüggen, Maxim Markevitch, Maurizio Falanga and Frederik Bernard Stefan Paerels

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1 Lendület Hot Universe Research Group, MTA-Eötvös University, Pázmány Péter sétány 1/A,

Fe-L complex

6 March 2019, *Physics of The Intra-Cluster Medium: Theory and Computation*, Budapest (Hungary)

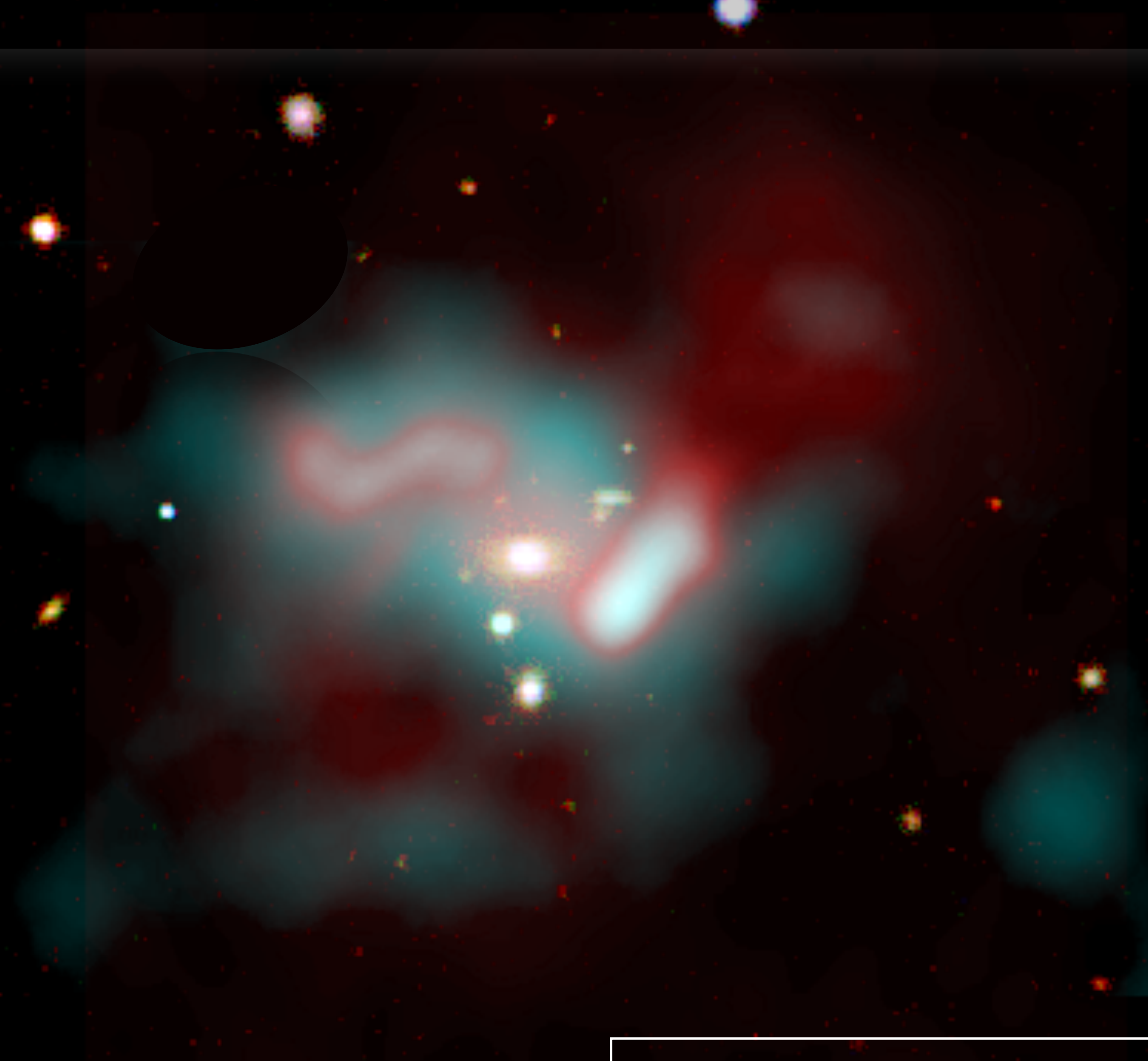
Magnetic fields and extraordinarily bright radio emission in the X-ray faint galaxy group MRC 0116+111

François Mernier

N. Werner, J. Bagchi, A. Simionescu, H Böhringer, S. W. Allen, and J. Jacob

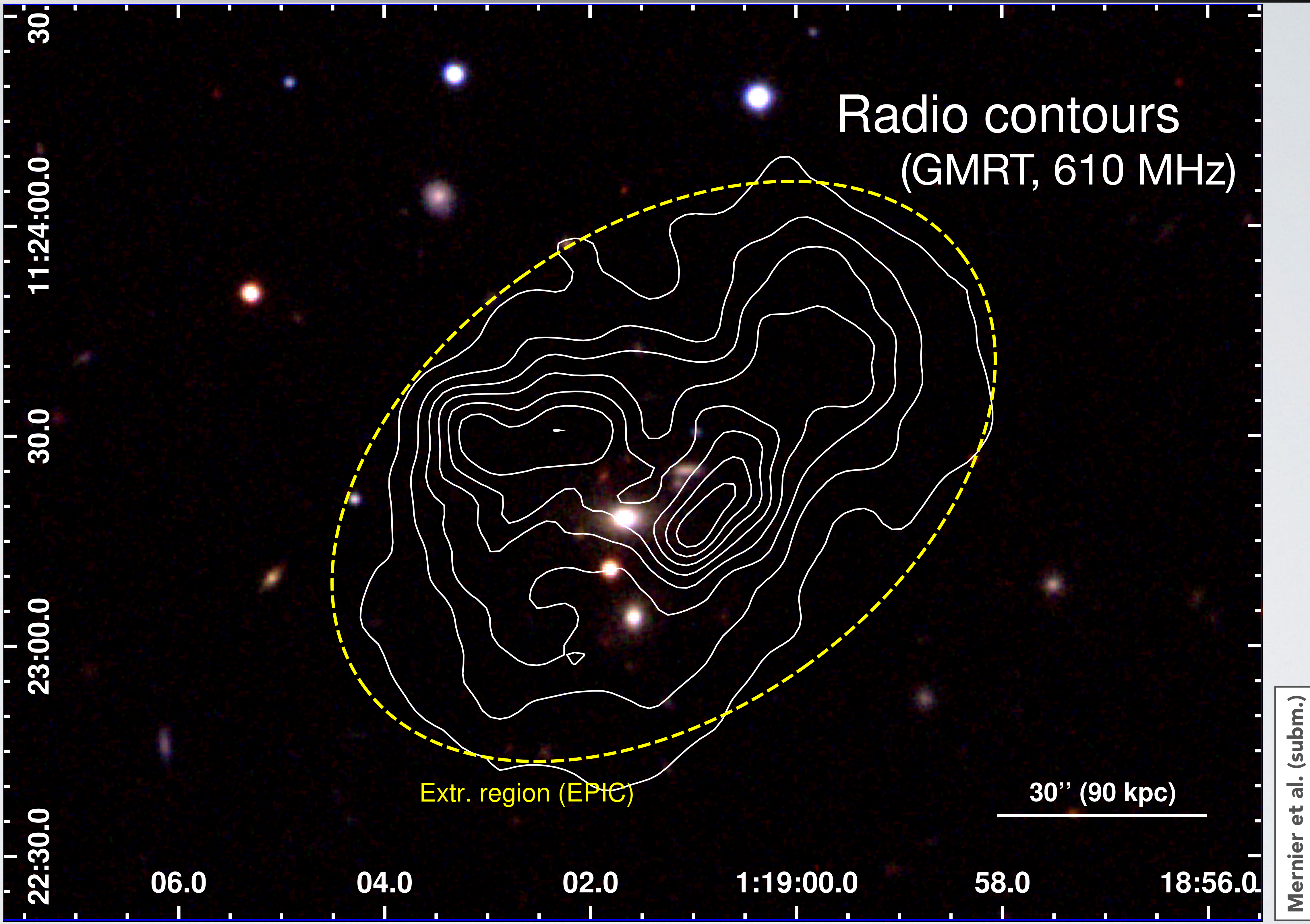
MTA-Eötvös University, Budapest

Netherlands Institute for Space Research



arXiv:1902.09560

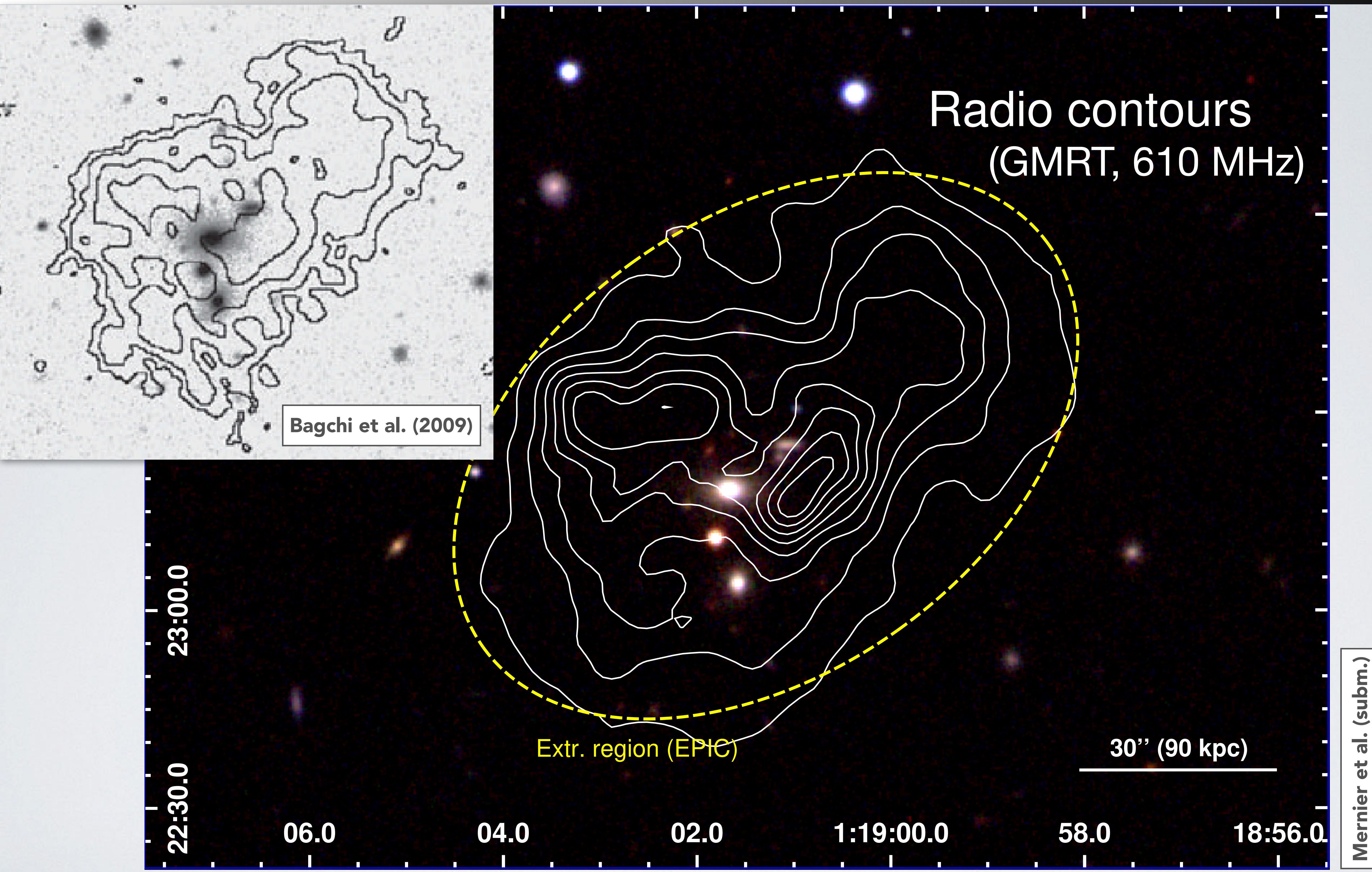
MRC 0116+111



Nearby (z=0.132), poor galaxy group

Radio study: **Bagchi et al. (2009)**

MRC 0116+111



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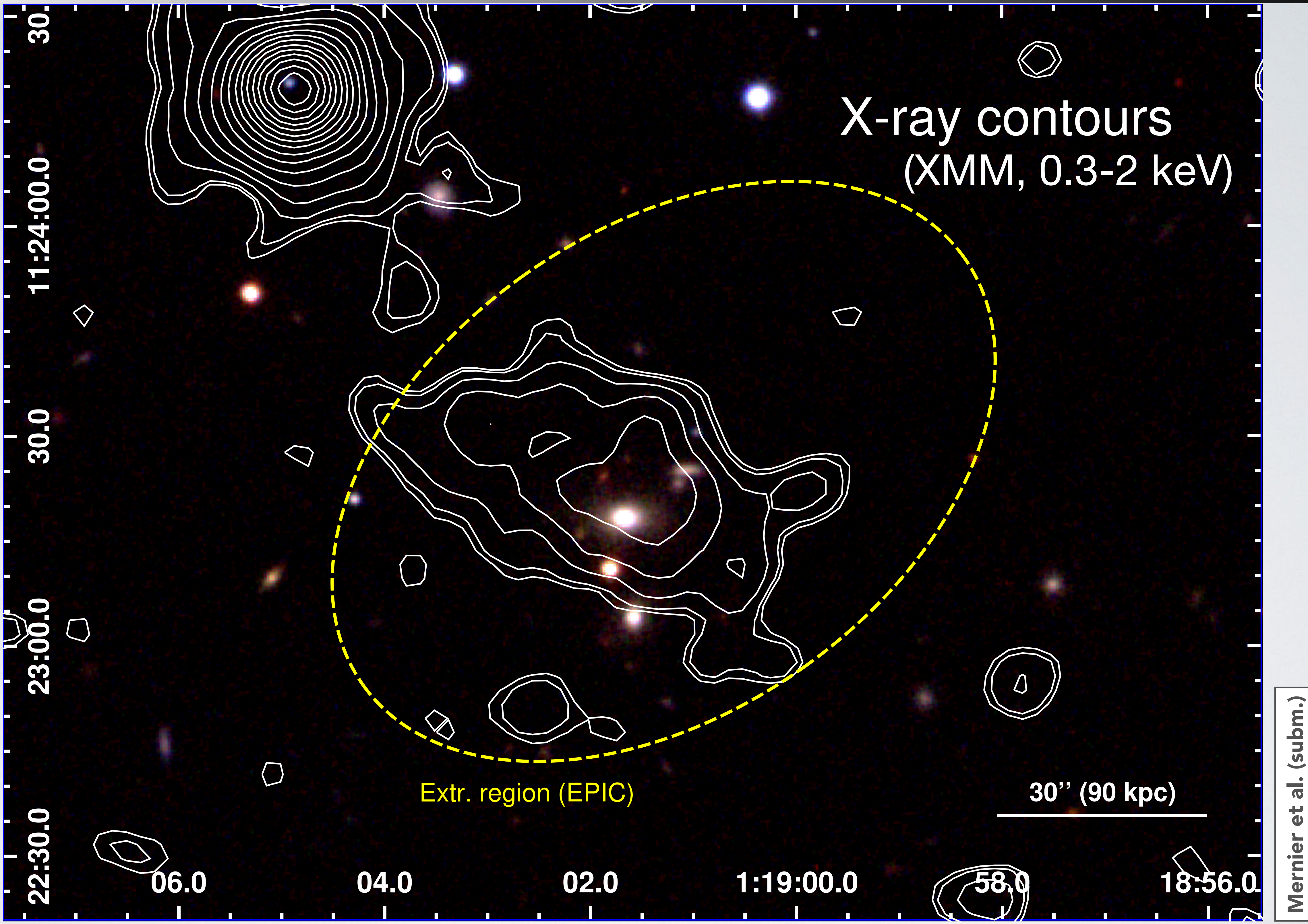
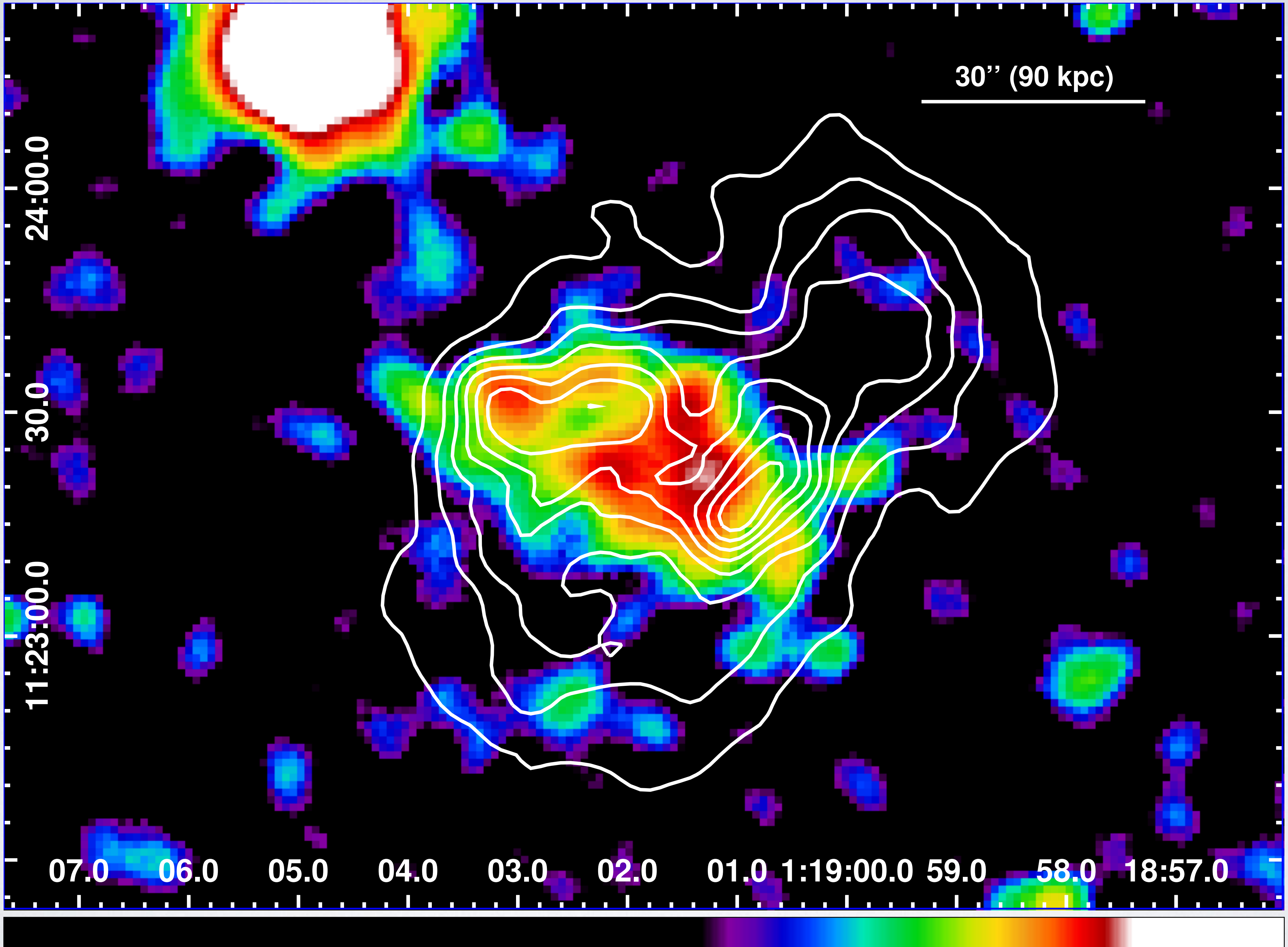
MRC 0116+111



XMM-Newton observation: ~30 ks of cleaned EPIC exposure

MRC 0116+111



Mernier et al. (subm.)

Radio emission **3x** more extended than X-ray emission!

Constrain the volume-averaged magnetic field

Ideal target to search for **Inverse-Compton** (IC) X-ray emission!

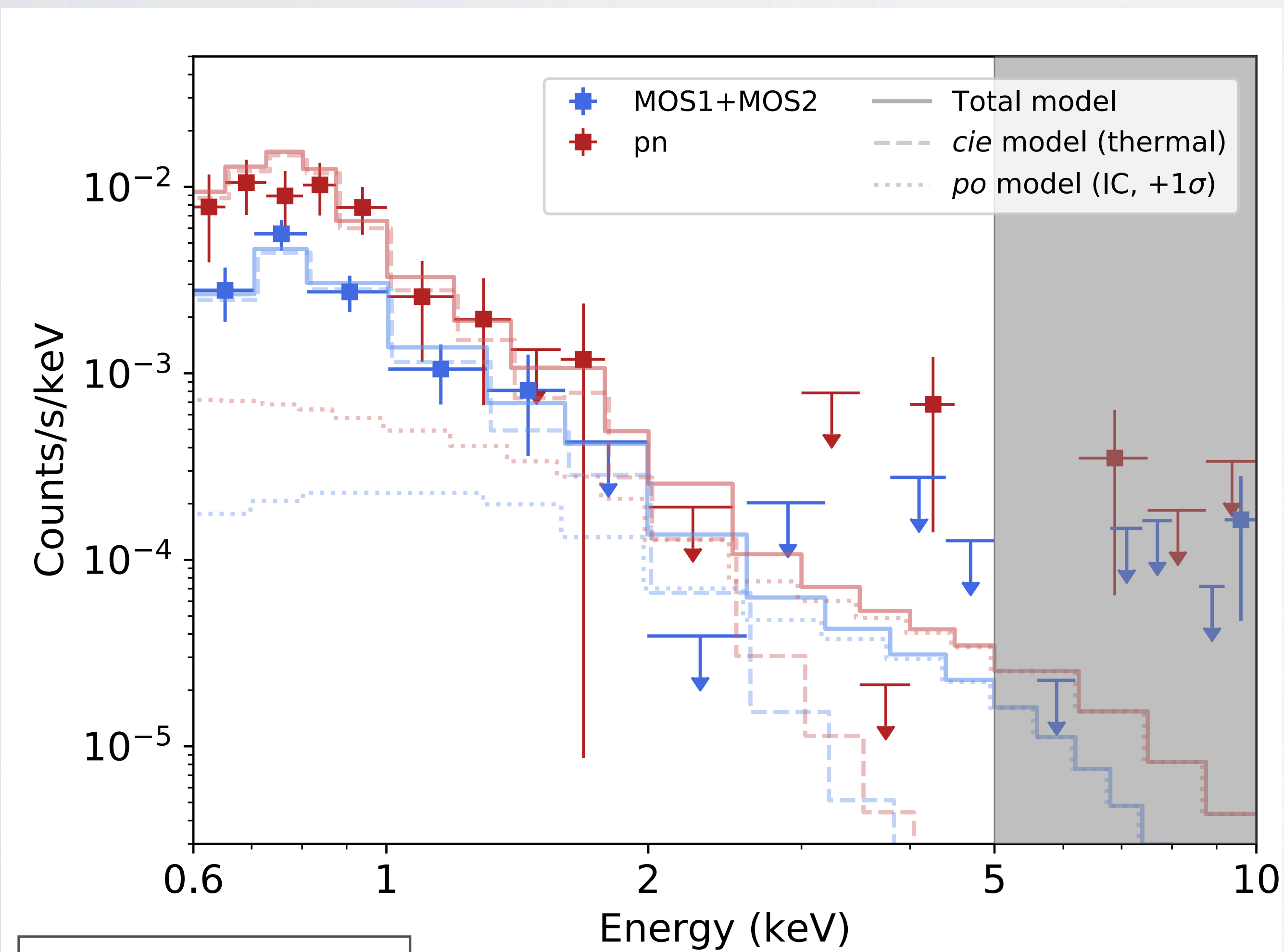
Assuming a power-law distributed electron population:

$$N(\gamma) = N_0 \gamma^{-p}$$

One gets…

$$f_r(\nu_{\rm syn}) \equiv \frac{dW_{\rm syn}}{d\nu_{\rm syn} dt} = \frac{4\pi N_0 e^3 B^{\frac{p+1}{2}}}{m_e c^2} \left(\frac{3e}{4\pi m_e c} \right)^{\frac{p-1}{2}} a(p)\, \nu_{\rm syn}^{-\frac{p-1}{2}}$$

$$f_x(\nu_{\rm IC}) \equiv \frac{dW_{\rm IC}}{d\nu_{\rm IC} dt} = \frac{8\pi^2 N_0 r_0^2}{c^2} h^{-\frac{p+3}{2}} (kT_{\rm CMB})^{\frac{p+5}{2}} F(p)\, \nu_{\rm IC}^{-\frac{p-1}{2}}$$



Mernier et al. (subm.)

Upper limit on IC flux

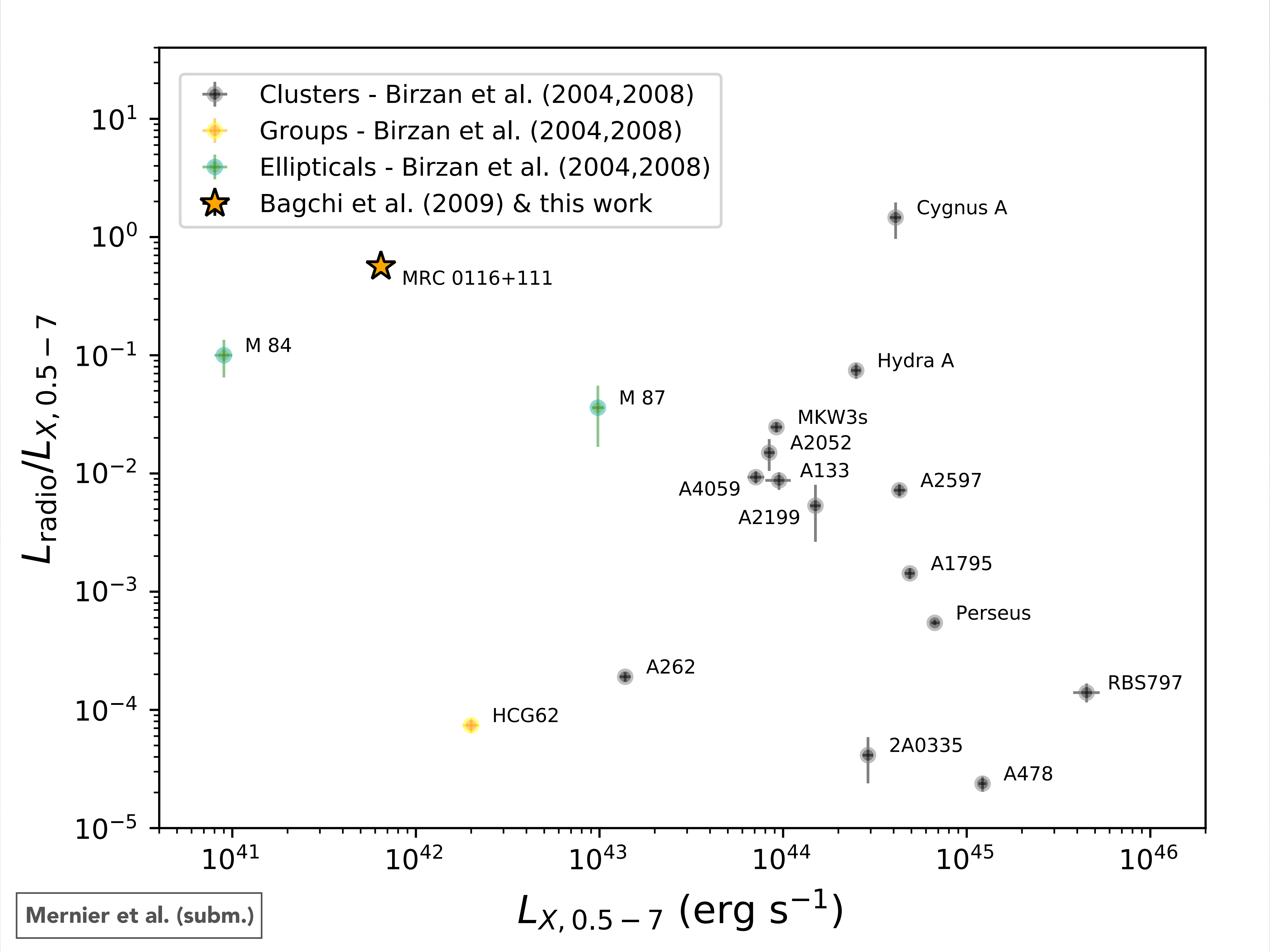
➡ **Lower limit on (volume-averaged) magnetic field!**

➡ **B > 4.3 μG**

Highest B measurement with this method so far

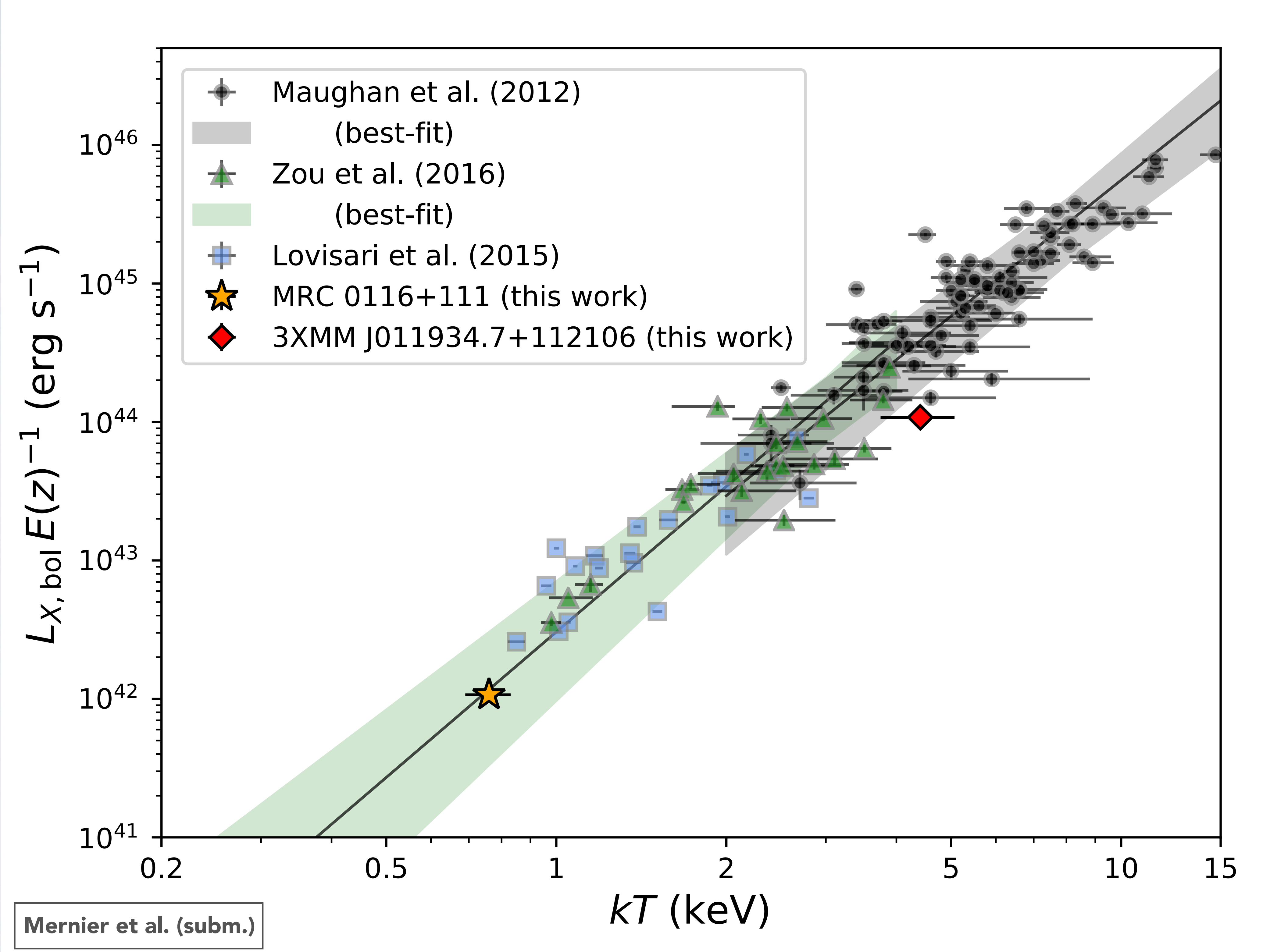
(Comparable to radio measurements assuming equipartition)

An extremely bright radio-to-X-ray diffuse source(!)



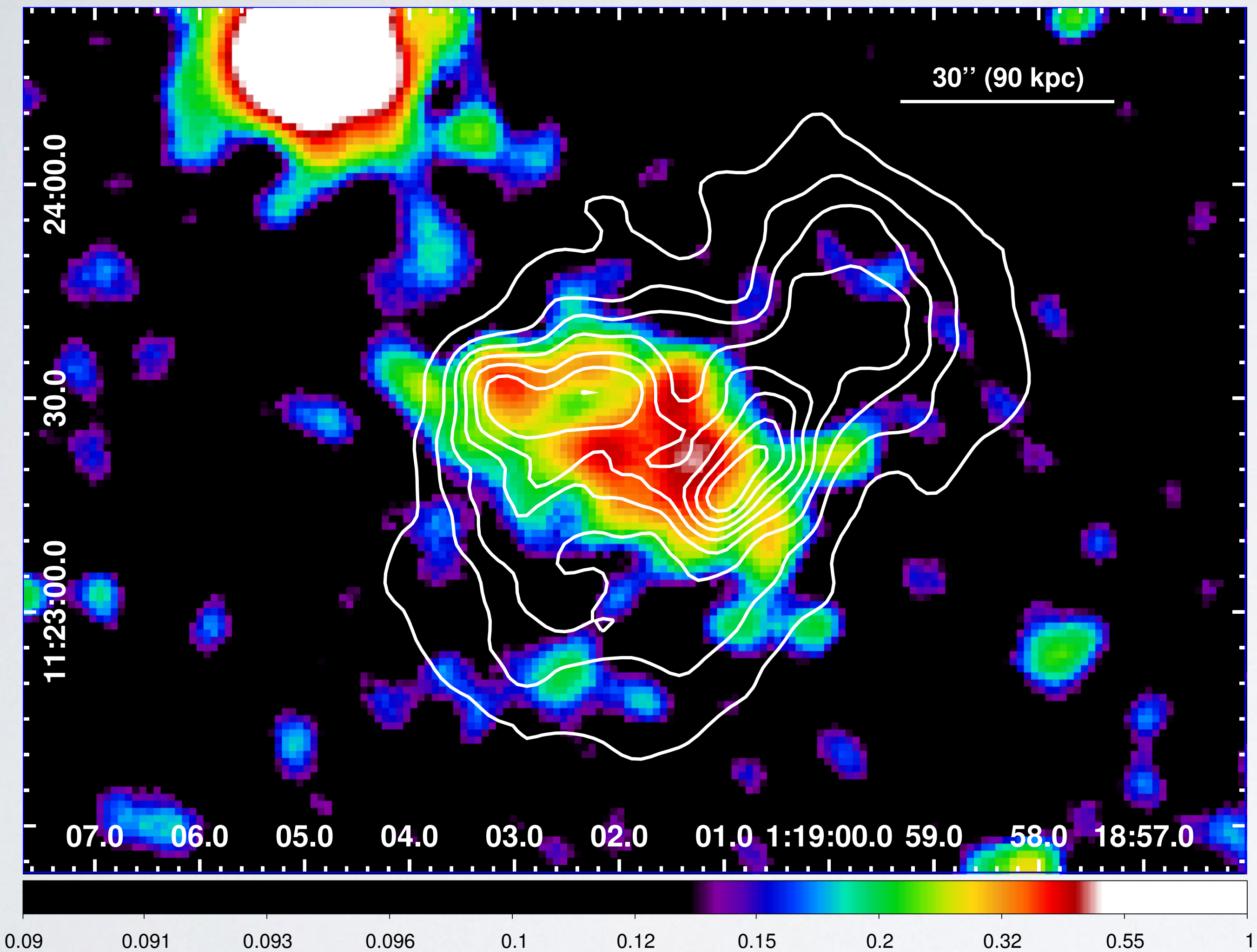
Extreme past AGN outburst(s)?

An extremely bright radio-to-X-ray diffuse source(!)

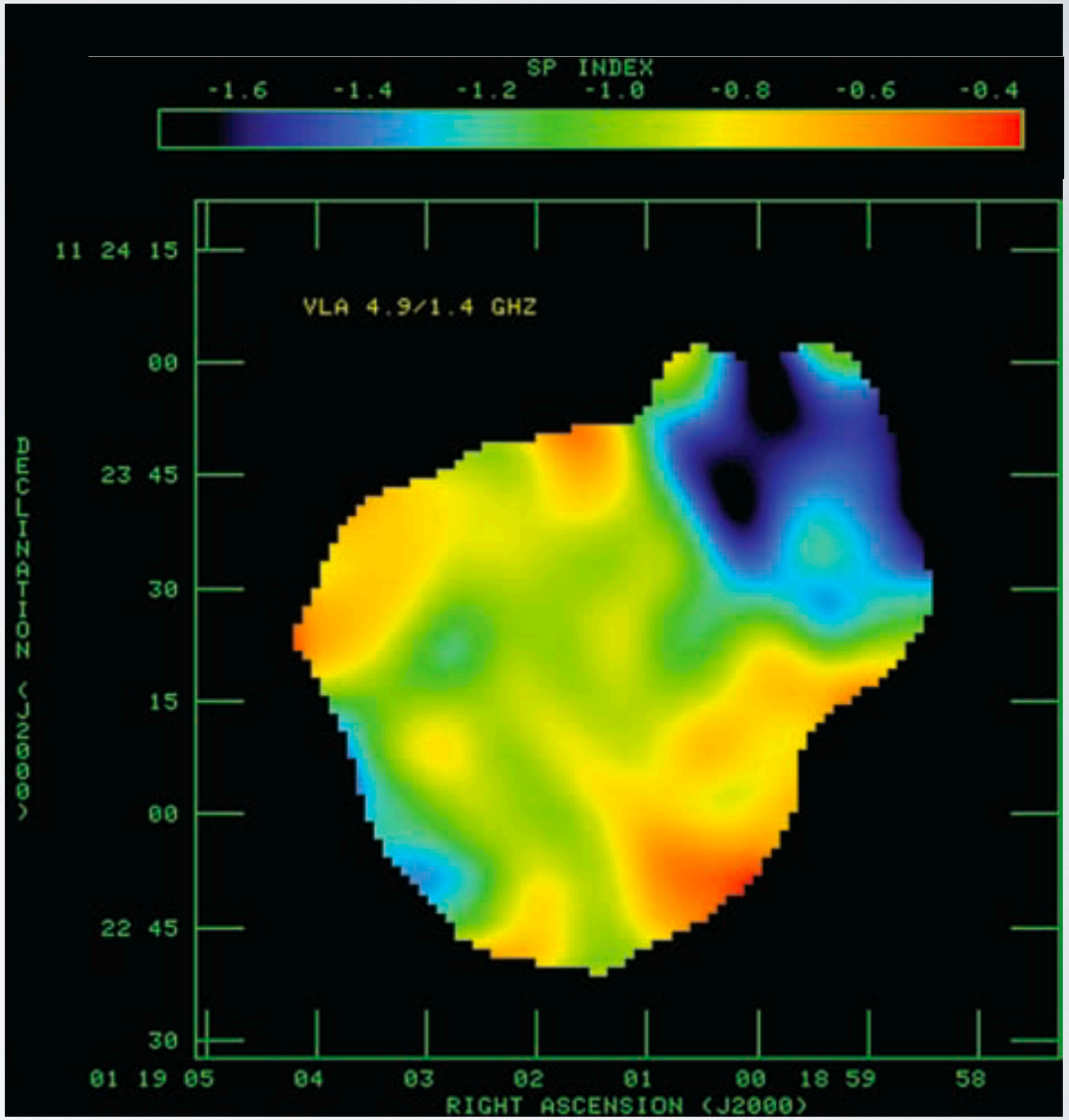


No dramatic gas heating / baryons removal

An extremely bright radio/X-ray diffuse source(!)



Mernier et al. (subm.)



Bagchi et al. (2009)

…but turbulence re-accelerating electrons?

Take home messages

Chemical enrichment in the ICM

Central enrichment…

- Invariant in **mass** of the system (clusters vs. groups vs. ellipticals)!
- Invariant in **SNIa vs. SNcc** contribution
- Similar to **Solar composition**!

  → **Early central enrichment** (~BCG formation), unrelated to present stellar population

arXiv:1902.09560

MRC 0116+111

- Volume-averaged magnetic field: **> 4.3 μG**
- (Among the) highest L_{radio}/L_X diffuse, extragalactic source known!
- Spectacular AGN feeback (L_X and kT unaffected, turbulence?)