Feedback from Active Galactic Nuclei in Galaxy Groups and Simulating Groups and the IntraGroup Medium: The Surprisingly Complex and Rich Middle Ground between Clusters and Galaxies

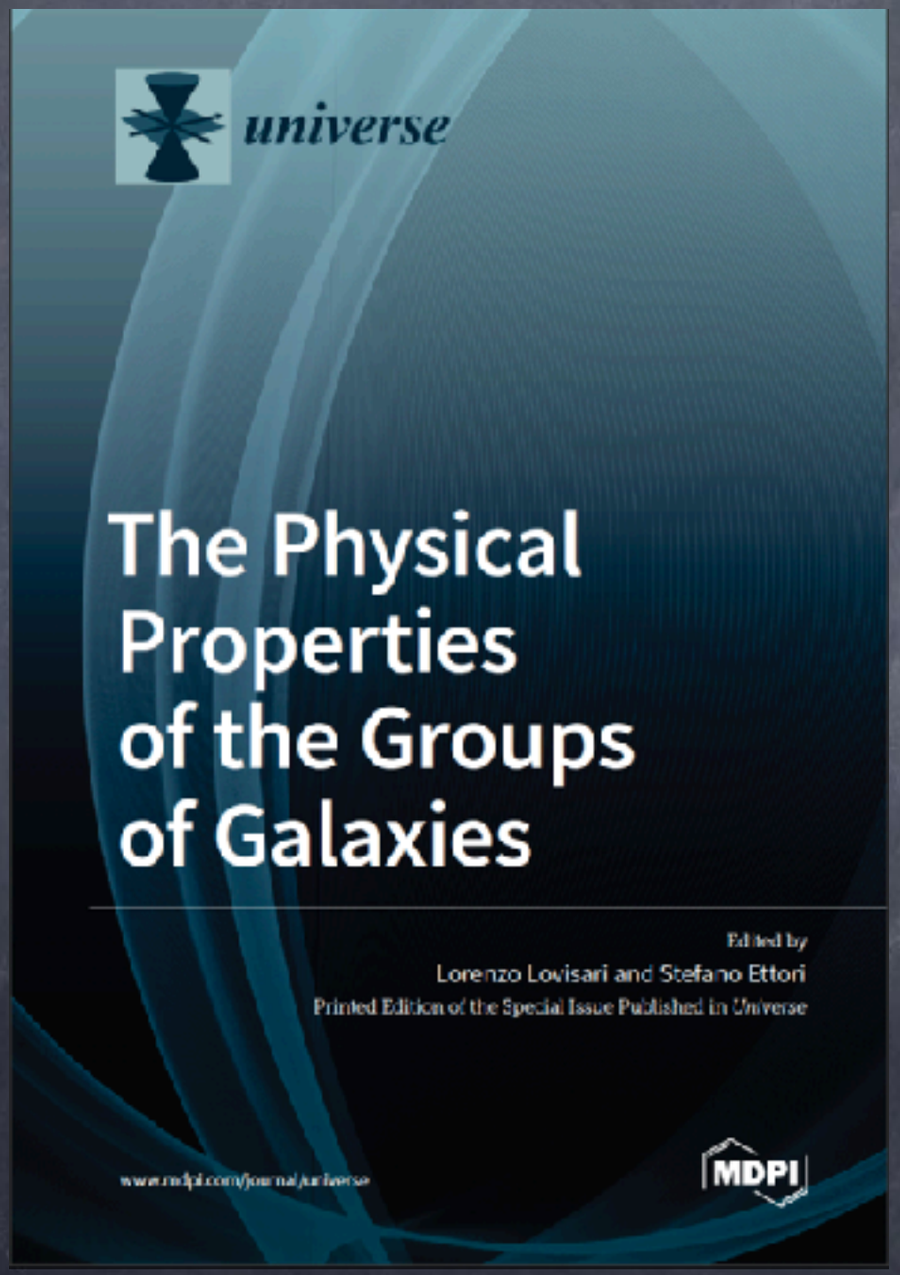
Amandine M. C. Le Brun
PSL Fellow
LUTh, Paris Observatory/PSL University

Based mostly on Eckert et al.
2021, Universe, arXiv:2106.13259

Virtual RUM 2021, September 27th 2021

The Physical Properties of the Groups of Galaxies Special Issue

Lovisari & Ettori 2021



The Physical Properties of the Groups of Galaxies Special Issue

Lovisari & Ettori 2021

Contents

All authors contributed equally to the review(s) they were involved in as indicated in authors' lists

The Physical Properties of the Groups of Galaxies Special Issue

Lovisari & Ettori 2021

universe

MDPI

Editorial

The Physical Properties of the Groups of Galaxies

Lorenzo Lovisari [1,2,*] and Stefano Ettori [1,3]

1 INAF—Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, via Piero Gobetti 93/3, 40129 Bologna, Italy; stefano.ettori@inaf.it
2 Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA
3 INFN, Sezione di Bologna, viale Berti Pichat 6/2, 40127 Bologna, Italy
* Correspondence: lorenzo.lovisari@inaf.it

Galaxy groups consist of a few tens of galaxies bound in a common gravitational potential. They dominate the number count of the halo mass function and contain a significant fraction of the overall universal baryon budget. Being less massive than clusters, the energy that is supplied by supernovae and active galactic nuclei (AGNs) to the hot intragroup medium (IGrM) can easily exceed their gravitational binding energy. Thus, it is expected that these non-gravitational mechanisms have a strong effect on the distribution of of the baryons, making galaxy groups ideal targets to constrain the mechanisms governing the cooling–heating balance. The net effect of the various feedback processes in action in the gravitational potential wells is to change the radial distribution of the energy and mass in groups, affecting the correlations between their observed properties. Therefore, they are key to our understanding of how the bulk of matter in the Universe accretes and forms hierarchical structures and how different sources of feedback affect their gravitational collapse.

Despite their crucial role in cosmic structure formation and evolution, galaxy groups have received less attention compared to massive clusters. This is in part due to the challenges (e.g., faint X-ray emission, low number of galaxies in optical, low S/N in SZ) associated with their detection, observation, and characterization. With the advent of eROSITA (launched in 2019), many thousands of galaxy groups will be detected by X-ray, complementing on-going and future optical (DES, Euclid, Vera Rubin), SZ (SPT-3G, ACT), and radio (LOFAR, MeerKAT) surveys, paving the way towards the exploitation of the next generation of X-ray instruments (onboard XRISM—expected to fly by 2023—and the ESA L2 mission Athena—expected to fly in the 2030s).

To foster progress in the field of the physical properties of galaxy groups, facilitating

check for updates

Citation: Lovisari, L.; Ettori, S. The Physical Properties of the Groups of Galaxies. *Universe* **2021**, *7*, 254. https://doi.org/10.3390/universe7080254

The Physical Properties of the Groups of Galaxies Special Issue

Lovisari & Ettori 2021

- *"Feedback from Active Galactic Nuclei in Galaxy Groups", by Eckert et al. [3]*

The formation and evolution of the physical properties in groups are a direct consequence of the interplay between galaxy evolution, the development of the intragroup medium, and feedback. Many authors have argued that feedback from SMBHs plays a crucial role in regulating the star formation rates of massive galaxies and suppressing the onset of catastrophic cooling by carving cavities and driving shocks across the medium. We review the current observational evidence for AGN feedback in nearby galaxy groups with observations at X-ray, radio, and millimeter wavelengths and describe the theoretical advances made in recent years to interpret the heating–cooling cycle.

- *"Simulating Groups and the IntraGroup Medium: The Surprisingly Complex and Rich Middle Ground between Clusters and Galaxies", by Oppenheimer et al. [4]*

The influence of the feedback processes is complex and difficult to model and to reproduce in simulations. However, cosmological simulations have enabled breakthroughs in our understanding of the gas and stellar contents of groups and of the impact of groups for cosmological parameter estimation. The review focuses on how groups process their baryons in a cosmological context, discussing the current limitations and the perspectives for improving the theoretical modeling in the near future.

- *"The Metal Content of the Hot Atmospheres of Galaxy Groups", by Gastaldello et al. [5]*

Metals play a central role in the thermodynamic balance of galaxy systems by sustaining the cooling of their environment by means of spectral line emissions. DUe to the shallower gravitational potential of groups, feedback effects leave important marks on their gas and metal contents. Therefore, the shape of the abundance profiles can be used to investigate the impact of the feedback in the IGrM. We review the status of the metal abundance measurements in the IGrM and the progress made by simulations to reproduce and interpret those measurements.

Funding: L.L. and S.E. acknowledge financial contribution from the contracts ASI-INAF Athena 2015-046-R.0, ASI-INAF Athena 2019-27-H.0, "Attività di Studio per la comunità scientifica di Astrofisica delle Alte Energie e Fisica Astroparticellare" (Accordo Attuativo ASI-INAF n. 2017-14-H.0), and from INAF "Call per interventi aggiuntivi a sostegno della ricerca di main stream di INAF".

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Agnerri, J.A.L.; Zarattini, S. Properties of Fossil Groups of Galaxies. *Universe* **2021**, *7*, 132. [CrossRef]
2. Lovisari, L.; Ettori, S.; Gaspari, M.; Giles, P.A. Scaling Properties of Galaxy Groups. *Universe* **2021**, *7*, 139. [CrossRef]
3. Eckert, D.; Gaspari, M.; Gastaldello, F.; Le Brun, A.; O'Sullivan, E. Feedback from Active Galactic Nuclei in Galaxy Groups. *Universe* **2021**, *7*, 142. [CrossRef]
4. Oppenheimer, B.D.; Babul, A.; Bahé, Y.; Butsky, I.S.; McCarthy, I.G. Simulating Groups and the IntraGroup Medium: The Surprisingly Complex and Rich Middle Ground between Clusters and Galaxies. *Universe* **2021**, *7*, 209. [CrossRef]

The Physical Properties of the Groups of Galaxies Special Issue

Lovisari et al. 2021

universe

MDPI

Review

Scaling Properties of Galaxy Groups

Lorenzo Lovisari [1,2,*,†], Stefano Ettori [1,3,†], Massimo Gaspari [4,†] and Paul A. Giles [5,†]

1 INAF—Osservatorio di Astrofisica e Scienze dello Spazio di Bologna, via Piero Gobetti 93/3, 40129 Bologna, Italy; stefano.ettori@inaf.it (S.E.); massimo.gaspari@inaf.it (M.G.)
2 Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA
3 INFN, Sezione di Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy
4 Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544, USA
5 Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, UK; P.A.Giles@sussex.ac.uk
* Correspondence: lorenzo.lovisari@inaf.it
† All authors contributed equally to this work.

Abstract: Galaxy groups and poor clusters are more common than rich clusters, and host the largest fraction of matter content in the Universe. Hence, their studies are key to understand the gravitational and thermal evolution of the bulk of the cosmic matter. Moreover, because of their shallower gravitational potential, galaxy groups are systems where non-gravitational processes (e.g., cooling, AGN feedback, star formation) are expected to have a higher impact on the distribution of baryons, and on the general physical properties, than in more massive objects, inducing systematic departures from the expected scaling relations. Despite their paramount importance from the astrophysical and cosmological point of view, the challenges in their detection have limited the studies of galaxy groups. Upcoming large surveys will change this picture, reassigning to galaxy groups their central role in studying the structure formation and evolution in the Universe, and in measuring the cosmic baryonic content. Here, we review the recent literature on various scaling relations between X-ray and optical properties of these systems, focusing on the observational measurements, and the progress in our understanding of the deviations from the self-similar expectations on groups' scales. We discuss some of the sources of these deviations, and how feedback from supernovae and/or AGNs impacts the general properties and the reconstructed scaling laws. Finally, we discuss future prospects in the study of galaxy groups.

Keywords: galaxy groups; X-ray and optical observations; intragroup medium/plasma; active galactic nuclei; hydrodynamical simulations

check for updates

Citation: Lovisari, L.; Ettori, S.; Gaspari, M.; Giles, P.A. Scaling Properties of Galaxy Groups. *Universe* 2021, 7, 139. https://doi.org/10.3390/universe7050139

Academic Editor: Francesco Shankar

Received: 31 March 2021
Accepted: 28 April 2021

The Physical Properties of the Groups of Galaxies Special Issue

Gastaldello et al. 2021

universe MDPI

Review

The Metal Content of the Hot Atmospheres of Galaxy Groups

Fabio Gastaldello [1,*], Aurora Simionescu [2,3,4], Francois Mernier [3,5], Veronica Biffi [6,7], Massimo Gaspari [8,9], Kosuke Sato [10] and Kyoko Matsushita [11]

1 Istituto di Astrofisica Spaziale e Fisica Cosmica (IASF)—Milano, National Institute of Astrophysics (INAF), via A. Corti 12, I-20133 Milano, Italy
2 SRON Netherlands Institute for Space Research, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands; a.simionescu@sron.nl (A.S.); francois.mernier@sron.nl (F.M.)
3 Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands
4 Kavli Institute for the Physics and Mathematics of the Universe (WPI), The University of Tokyo, Kashiwa, Chiba 277-8583, Japan
5 European Space Agency (ESA), European Space Research and Technology Center (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
6 INAF—Osservatorio Astronomico di Trieste, via Tiepolo 11, I-34143 Trieste, Italy; veronica.biffi@inaf.it
7 IFPU—Institute for Fundamental Physics of the Universe, via Beirut 2, I-34014 Trieste, Italy
8 INAF—Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, via Piero Gobetti 93/3, I-40129 Bologna, Italy; massimo.gaspari@inaf.it
9 Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544, USA
10 Department of Physics, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama-shi, Saitama 338-8570, Japan; kosato@phy.saitama-u.ac.jp
11 Department of Physics, Tokyo University of Science, 1-3 Kagurazaka, Shinjuku-ku, Tokyo 162-8601, Japan; matusita@rs.tus.ac.jp
* Correspondence: fabio.gastaldello@inaf.it

check for updates

Citation: Gastaldello, F.; Simionescu, A.; Mernier, F.; Biffi, V.; Gaspari, M.; Sato, K.; Matsushita, K. The Metal Content of the Hot Atmospheres of Galaxy Groups. *Universe* 2021, *7*, 168. https://doi.org/10.3390/universe7060168

Academic Editor: Francesco Shankar

Received: 31 March 2021
Accepted: 16 June 2021
Published: 24 June 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Abstract: Galaxy groups host the majority of matter and more than half of all the galaxies in the Universe. Their hot (10^7 K), X-ray emitting intragroup medium (IGrM) reveals emission lines typical of many elements synthesized by stars and supernovae. Because their gravitational potentials are shallower than those of rich galaxy clusters, groups are ideal targets for studying, through X-ray observations, feedback effects, which leave important marks on their gas and metal contents. Here, we review the history and present status of the chemical abundances in the IGrM probed by X-ray spectroscopy. We discuss the limitations of our current knowledge, in particular due to uncertainties in the modeling of the Fe-L shell by plasma codes, and coverage of the volume beyond the central region. We further summarize the constraints on the abundance pattern at the group mass scale and the insight it provides to the history of chemical enrichment. Parallel to the observational efforts, we review the progress made by both cosmological hydrodynamical simulations and controlled high-resolution 3D simulations to reproduce the radial distribution of metals in the IGrM, the dependence on system mass from group to cluster scales, and the role of AGN and SN feedback in producing the observed phenomenology. Finally, we highlight future prospects in this field, where progress will be driven: both by a much richer sample of X-ray emitting groups identified with eROSITA, and by a revolution in the study of X-ray spectra expected from micro-calorimeters onboard XRISM and ATHENA.

Keywords: galaxies: abundances; galaxies: clusters: intracluster medium; X-rays: galaxies

1. Introduction

Two major astrophysical discoveries have provided key answers to the fundamental question of the origin of the chemical elements in the past century: the discovery that stellar nucleosynthesis is responsible for the production of all the heavy elements from

The Physical Properties of the Groups of Galaxies Special Issue

Aguerri & Zarattini 2021

universe

MDPI

Review

Properties of Fossil Groups of Galaxies

J. Alfonso L. Aguerri [1,2,*†] and Stefano Zarattini [3,4,†]

1 Instituto de Astrofísica de Canarias, C/Vía Láctea s/n, E-38200 La Laguna, Spain; jalfonso@iac.es
2 Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Spain
3 Dipartimento di Fisica e Astronomia "G. Galilei", Università di Padova, Vicolo dell'Osservatorio 3, I-35122 Padova, Italy
4 INAF—Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 2, I-35122 Padova, Italy
* Correspondence: stefano.zarattini@unipd.it
† These authors contributed equally to this work.

Abstract: We review the formation and evolution of fossil groups and clusters from both the theoretical and the observational points of view. In the optical band, these systems are dominated by the light of the central galaxy. They were interpreted as old systems that had enough time to merge all the M^* galaxies within the central one. During the last two decades, many observational studies were performed to prove the *old and relaxed* state of fossil systems. The majority of these studies that spans a wide range of topics including halos global scaling relations, dynamical substructures, stellar populations, and galaxy luminosity functions seem to challenge this scenario. The general picture that can be obtained by reviewing all the observational works is that the fossil state could be transitional. Indeed, the formation of the large magnitude gap observed in fossil systems could be related to internal processes rather than an old formation.

Keywords: fossil galaxy groups; galaxy clusters; galaxy groups; X-ray and optical observations; hydrodynamical simulations

check for updates

Citation: Aguerri, J. A. L.; Zarattini, S. Properties of Fossil Groups of Galaxies. *Universe* 2021, *7*, 132. https://doi.org/10.3390/universe7050132

Academic Editor: Francesco Shankar

Received: 26 March 2021
Accepted: 28 April 2021

1. Introduction

The Lambda cold dark matter scenario (ΛCDM) predicts that structures in the Universe form following a hierarchical evolution: small objects collapsed first under their self-gravity and are then merged continuously to build larger structures. In this scenario, galaxy formed first, then merged in small groups and the process continues until the creation of massive galaxy clusters [1,2].

Ponman and Bertram [3] firstly suggested, while studying compact groups, that this

The Physical Properties of the Groups of Galaxies Special Issue

Oppenheimer et al. 2021

universe

MDPI

Review

Simulating Groups and the IntraGroup Medium: The Surprisingly Complex and Rich Middle Ground between Clusters and Galaxies

Benjamin D. Oppenheimer [1,2,*], Arif Babul [3], Yannick Bahé [4], Iryna S. Butsky [5] and Ian G. McCarthy [6]

1 CASA, Department of Astrophysical and Planetary Sciences, University of Colorado, 389 UCB, Boulder, CO 80309, USA
2 Harvard Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
3 Department of Physics and Astronomy, University of Victoria, Victoria, BC V8W 2Y2, Canada; babul@uvic.ca
4 Leiden Observatory, Leiden University, P.O. Box 9513, 2300 RA Leiden, The Netherlands; bahe@strw.leidenuniv.nl
5 Astronomy Department, University of Washington, Seattle, WA 98195, USA; ibutsky@uw.edu
6 Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK; i.g.mccarthy@ljmu.ac.uk
* Correspondence: benjamin.oppenheimer@colorado.edu

Abstract: Galaxy groups are more than an intermediate scale between clusters and halos hosting individual galaxies, they are crucial laboratories capable of testing a range of astrophysics from how galaxies form and evolve to large scale structure (LSS) statistics for cosmology. Cosmological hydrodynamic simulations of groups on various scales offer an unparalleled testing ground for astrophysical theories. Widely used cosmological simulations with ~$[100\ \mathrm{Mpc}]^3$ volumes contain statistical samples of groups that provide important tests of galaxy evolution influenced by environmental processes. Larger volumes capable of reproducing LSS while following the redistribution of baryons by cooling and feedback are the essential tools necessary to constrain cosmological parameters. Higher resolution simulations can currently model satellite interactions, the processing of cool ($T \approx 10^{4-5}$ K) multi-phase gas, and non-thermal physics including turbulence, magnetic fields and cosmic ray transport. We review simulation results regarding the gas and stellar contents of groups, cooling flows and the relation to the central galaxy, the formation and processing of multi-phase gas, satellite interactions with the intragroup medium, and the impact of groups for cosmological parameter estimation. Cosmological simulations provide evolutionarily consistent predictions of these observationally difficult-to-define objects, and have untapped potential to accurately model their gaseous, stellar and dark matter distributions.

check for updates

Citation: Oppenheimer, B.D.; Babul, A.; Bahé, Y.; Butsky, I.S.; McCarthy, I.G. Simulating Groups and the IntraGroup Medium: The Surprisingly Complex and Rich Middle Ground between Clusters and Galaxies. *Universe* **2021**, *7*, 209. https://doi.org/10.3390/universe7070209

Academic Editors: Lorenzo Lovisari and Stefano Ettori

Received: 9 April 2021
Accepted: 2 June 2021

Keywords: black holes; galaxy groups; galaxy surveys; intragroup medium/plasma; hydrody-

The Physical Properties of the Groups of Galaxies Special Issue

Eckert et al. 2021

universe

MDPI

Review

Feedback from Active Galactic Nuclei in Galaxy Groups

Dominique Eckert [1,*,†], Massimo Gaspari [2,3,†], Fabio Gastaldello [4,†], Amandine M. C. Le Brun [5,†] and Ewan O'Sullivan [6,†]

1 Department of Astronomy, University of Geneva, Ch. d'Ecogia 16, CH-1290 Versoix, Switzerland
2 INAF—Osservatorio di Astrofisica e Scienza dello Spazio di Bologna, Via Piero Gobetti 93/3, I-40129 Bologna, Italy; massimo.gaspari@inaf.it
3 Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544, USA
4 IASF—Milano, INAF, Via A. Corti 12, I-20133 Milano, Italy; fabio.gastaldello@inaf.it
5 LUTh, UMR 8102 CNRS, Observatoire de Paris, PSL Research University, Université Paris Diderot, 5 Place Jules Janssen, 92190 Meudon, France; amandine.le-brun@obspm.fr
6 Center for Astrophysics, Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA; eosullivan@cfa.harvard.edu
* Correspondence: Dominique.Eckert@unige.ch
† All authors contributed equally to this work.

Abstract: The coevolution between supermassive black holes and their environment is most directly traced by the hot atmospheres of dark matter halos. The cooling of the hot atmosphere supplies the central regions with fresh gas, igniting active galactic nuclei (AGN) with long duty cycles. Outflows from the central engine tightly couple with the surrounding gaseous medium and provide the dominant heating source preventing runaway cooling by carving cavities and driving shocks across the medium. The AGN feedback loop is a key feature of all modern galaxy evolution models. Here, we review our knowledge of the AGN feedback process in the specific context of galaxy groups. Galaxy groups are uniquely suited to constrain the mechanisms governing the cooling–heating balance. Unlike in more massive halos, the energy that is supplied by the central AGN to the hot intragroup medium can exceed the gravitational binding energy of halo gas particles. We report on the state-of-the-art in observations of the feedback phenomenon and in theoretical models of the heating-cooling balance in galaxy groups. We also describe how our knowledge of the AGN feedback process impacts galaxy evolution models and large-scale baryon distributions. Finally, we discuss how new instrumentation will answer key open questions on the topic.

Keywords: black holes; galaxy groups; elliptical galaxies; intragroup medium/plasma; active nuclei; X-ray observations; hydrodynamical and cosmological simulations

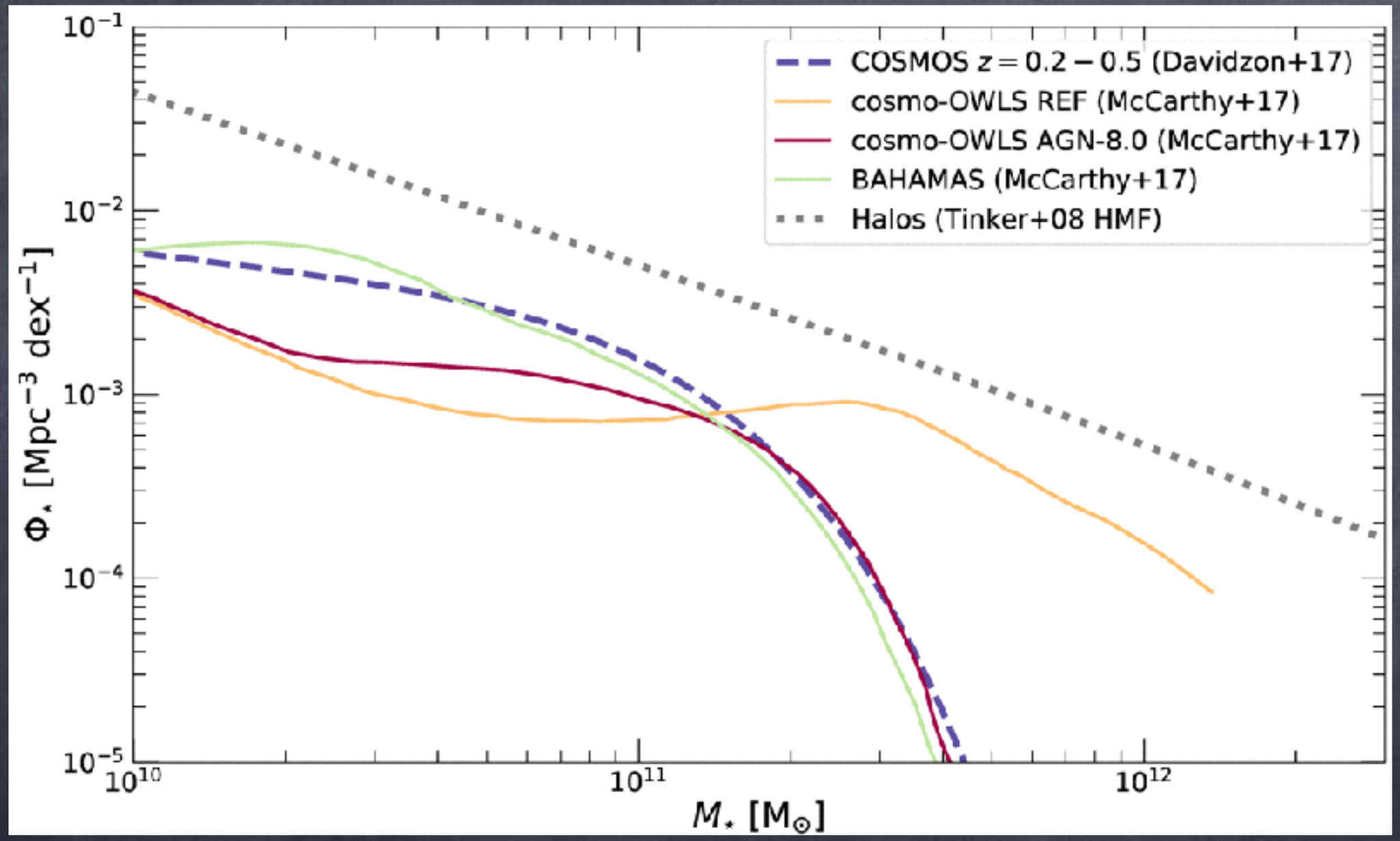
check for updates

Citation: Eckert, D.; Gaspari, M.; Gastaldello, F.; Le Brun, A.M.C.; O'Sullivan, E. Feedback from Active Galactic Nuclei in Galaxy Groups. *Universe* **2021**, *7*, 142. https://doi.org/10.3390/universe7050142

Academic Editor: Francesco Shankar

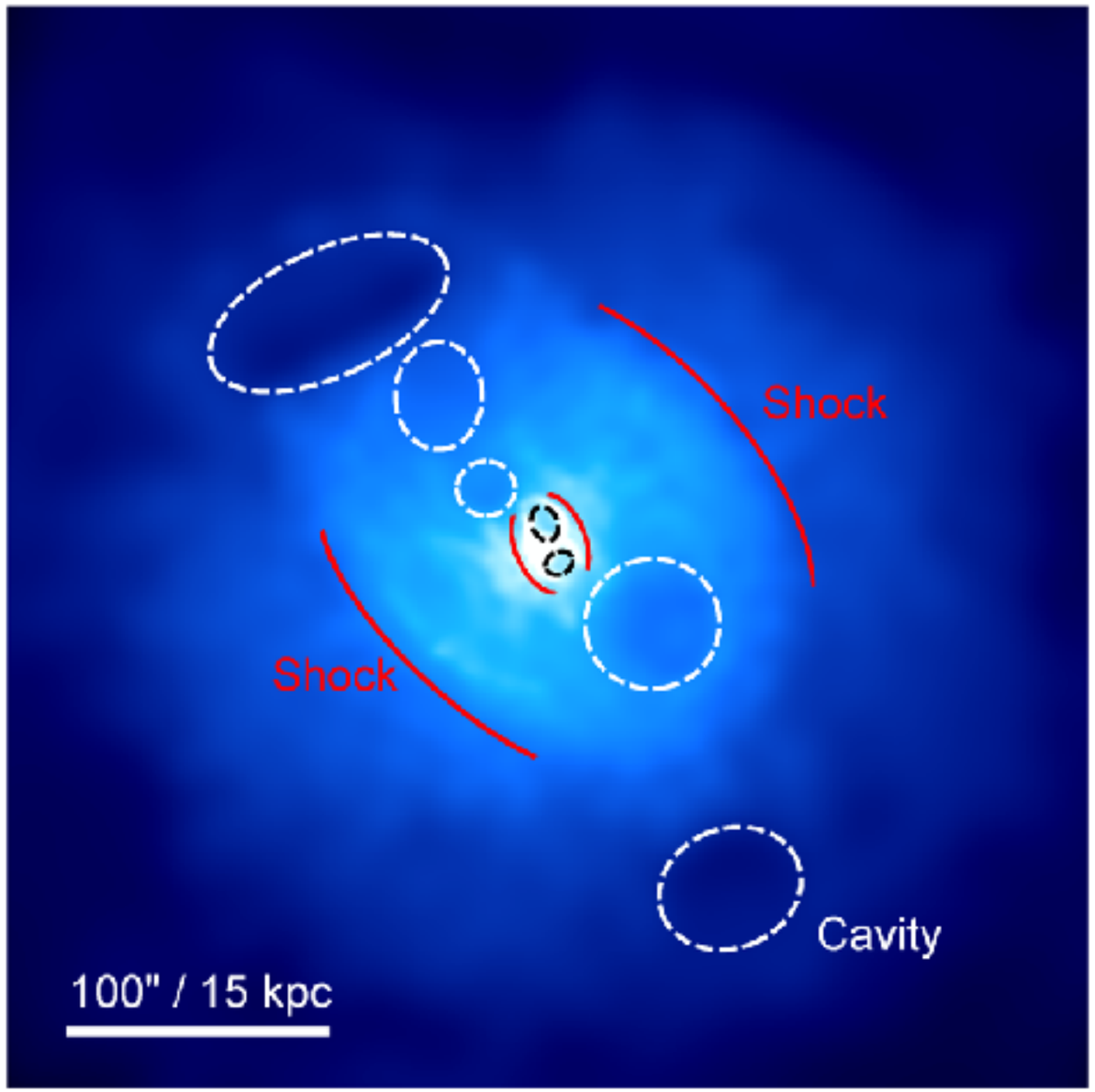
Received: 31 March 2021
Accepted: 29 April 2021

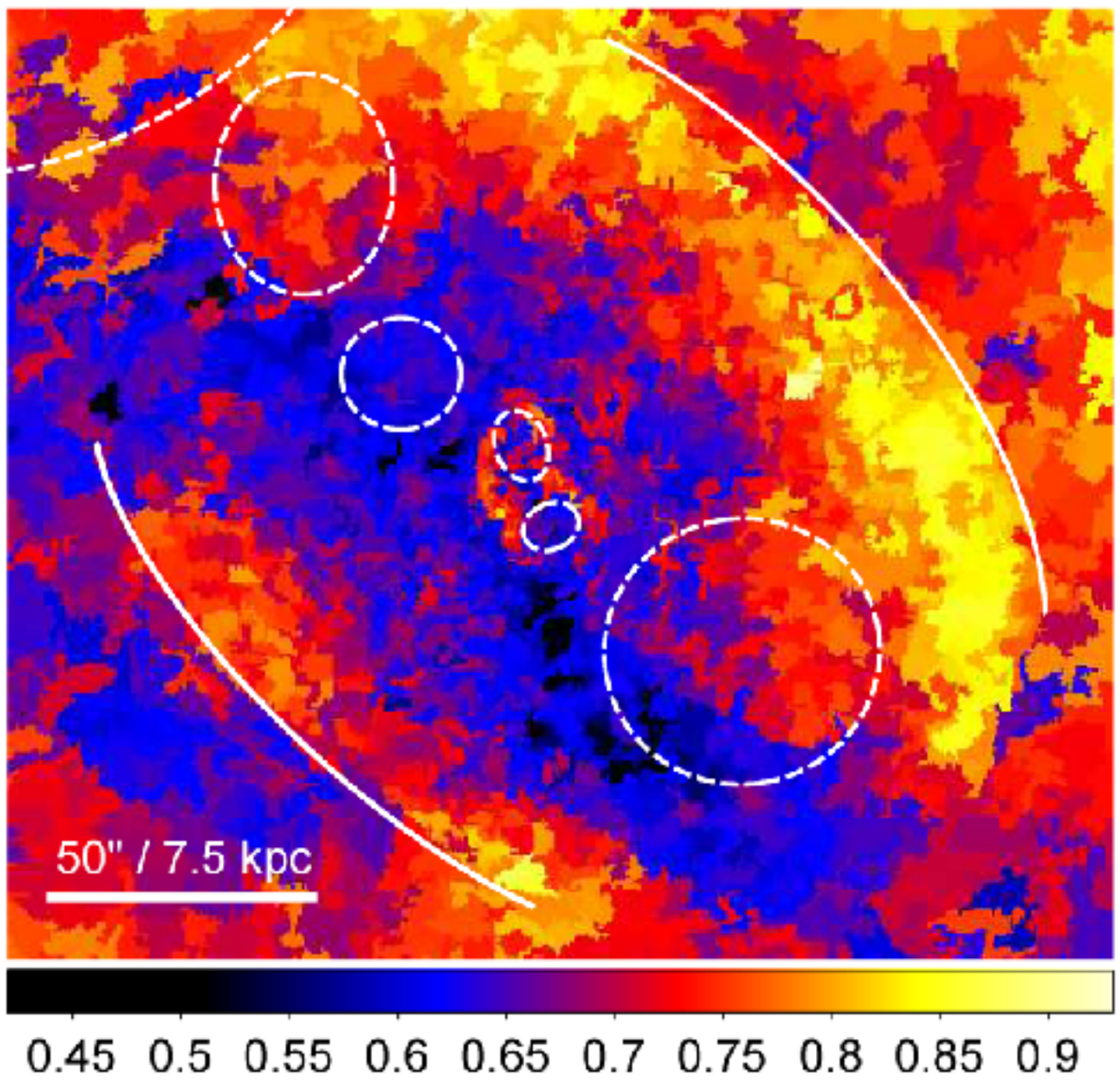
AGN feedback in groups review



Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

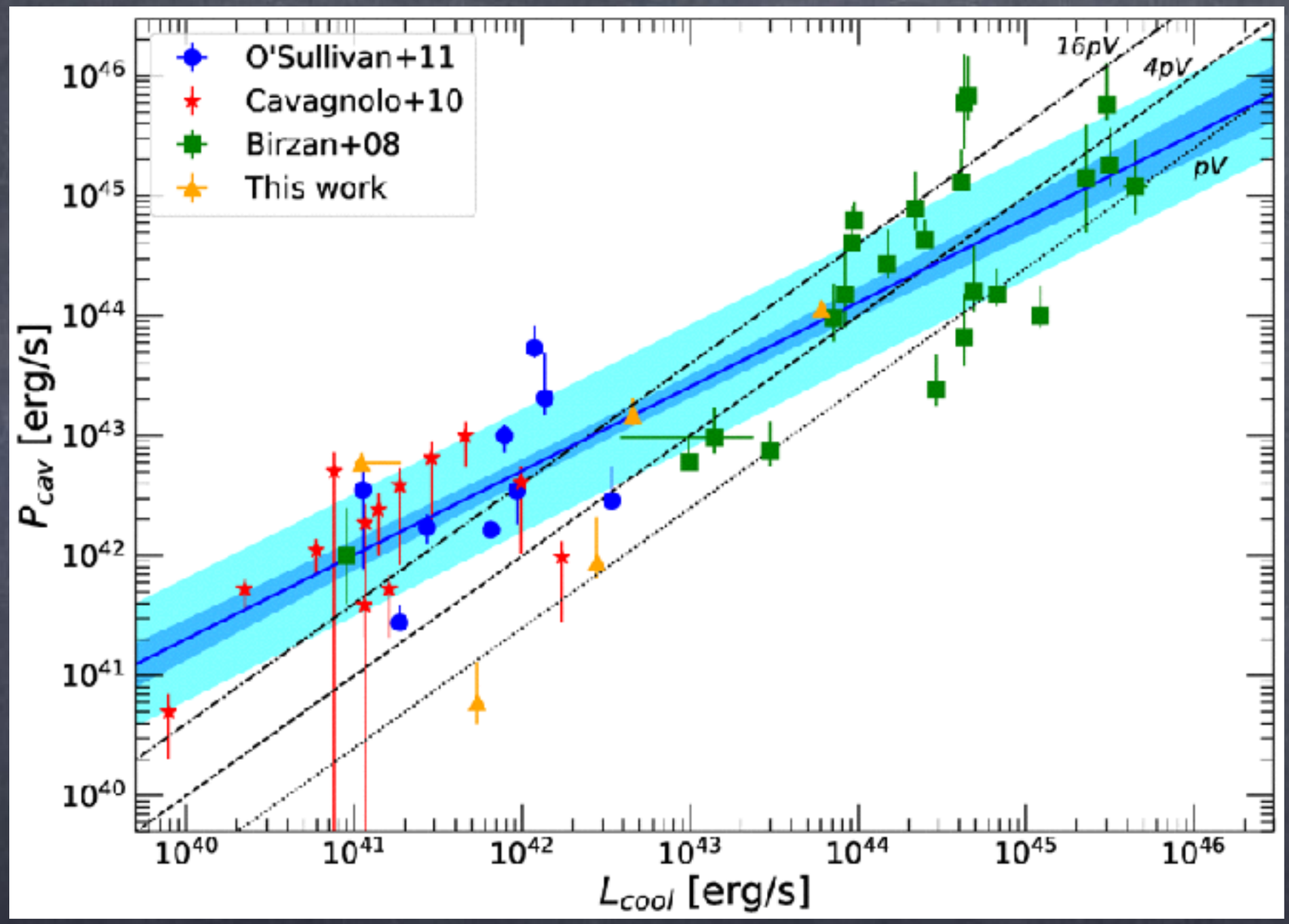
AGN feedback in groups review





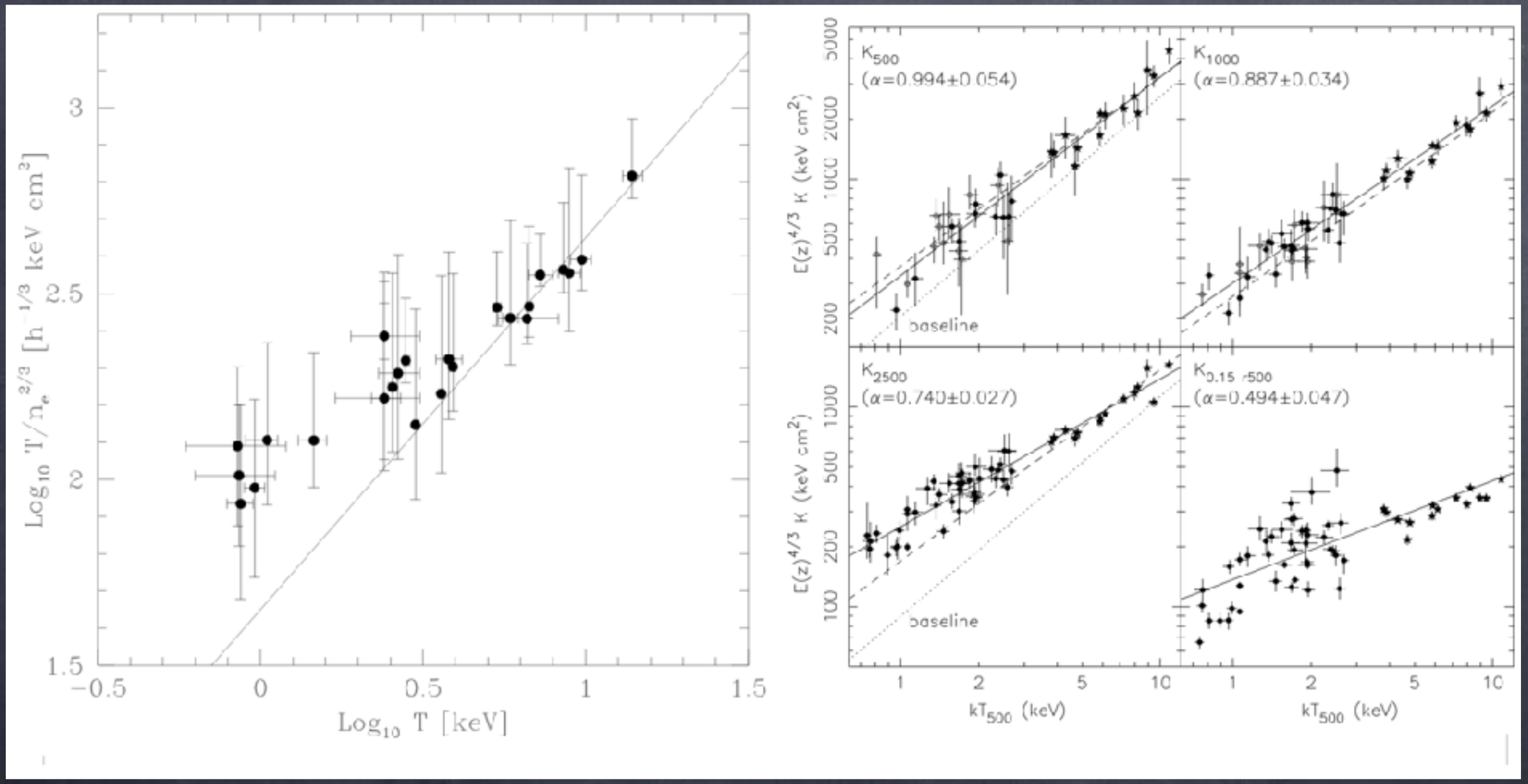
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



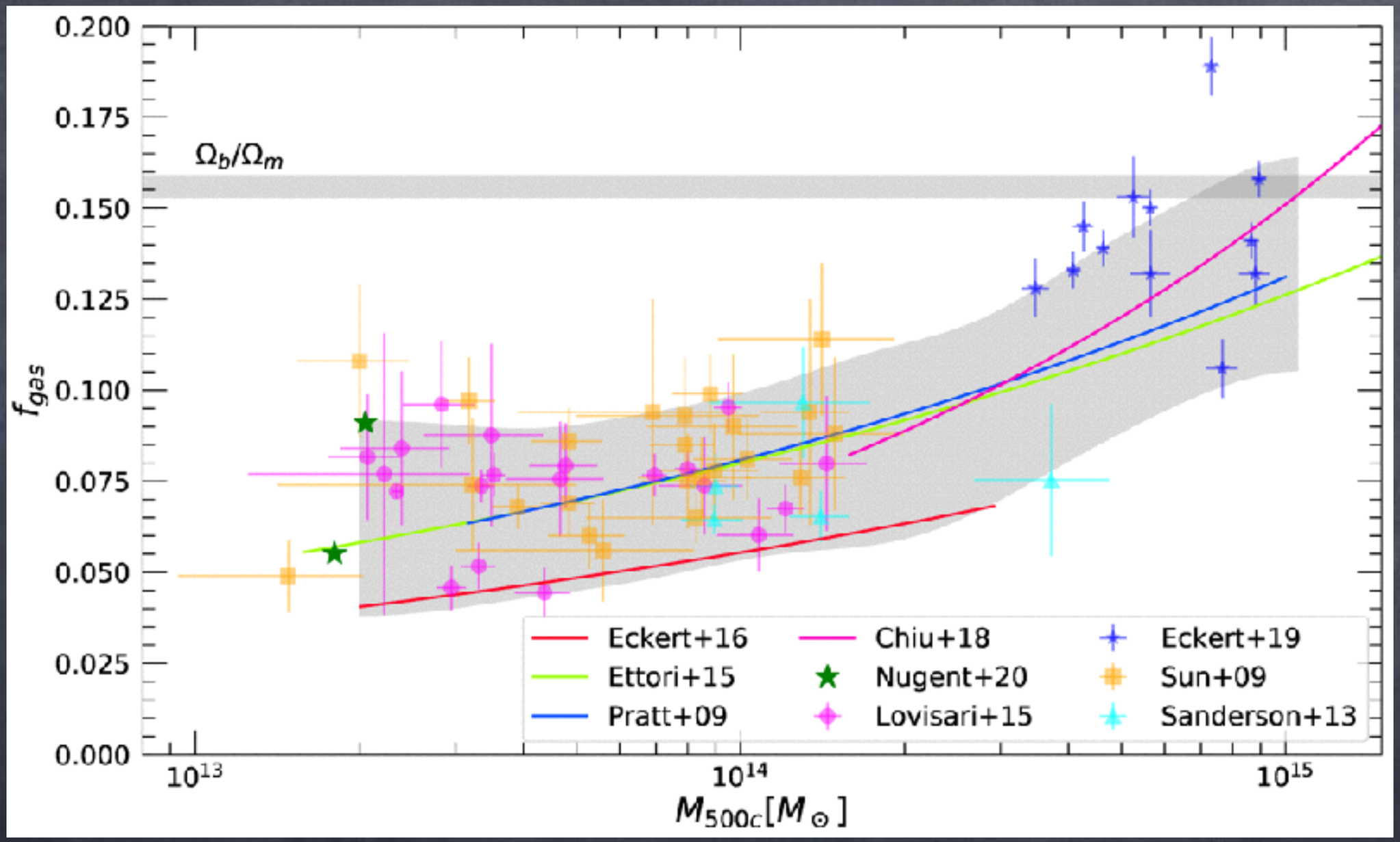
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



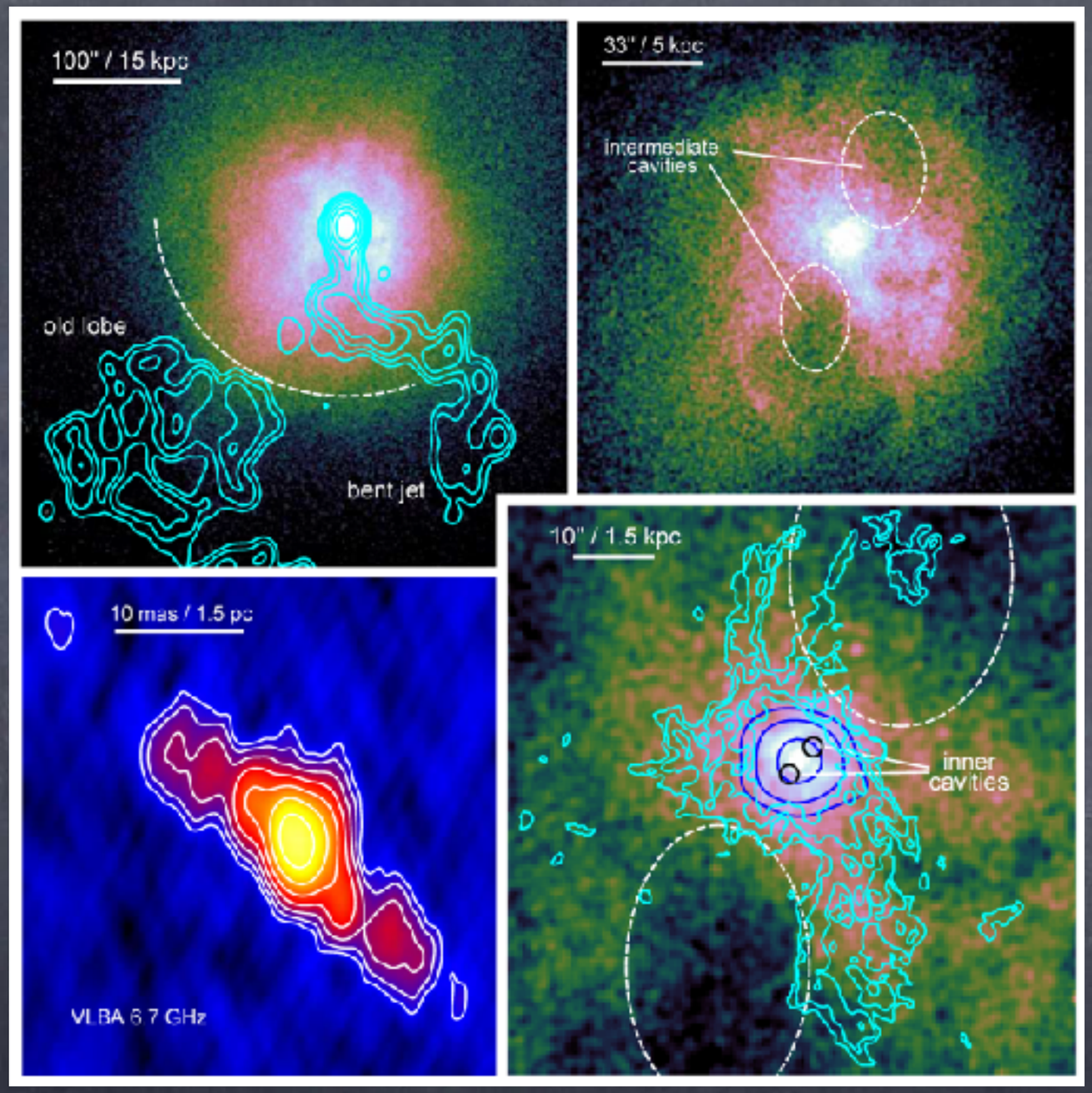
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



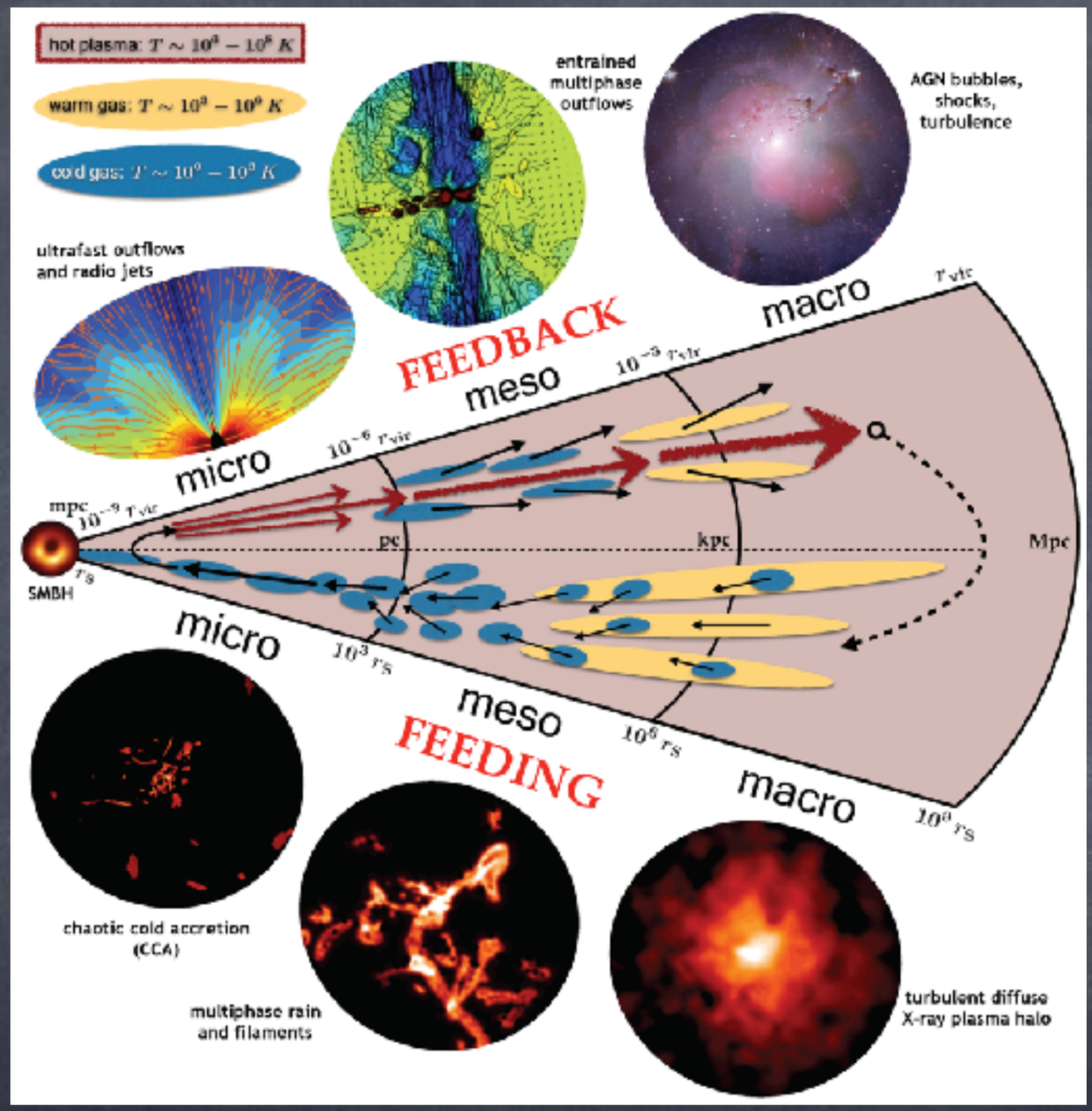
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



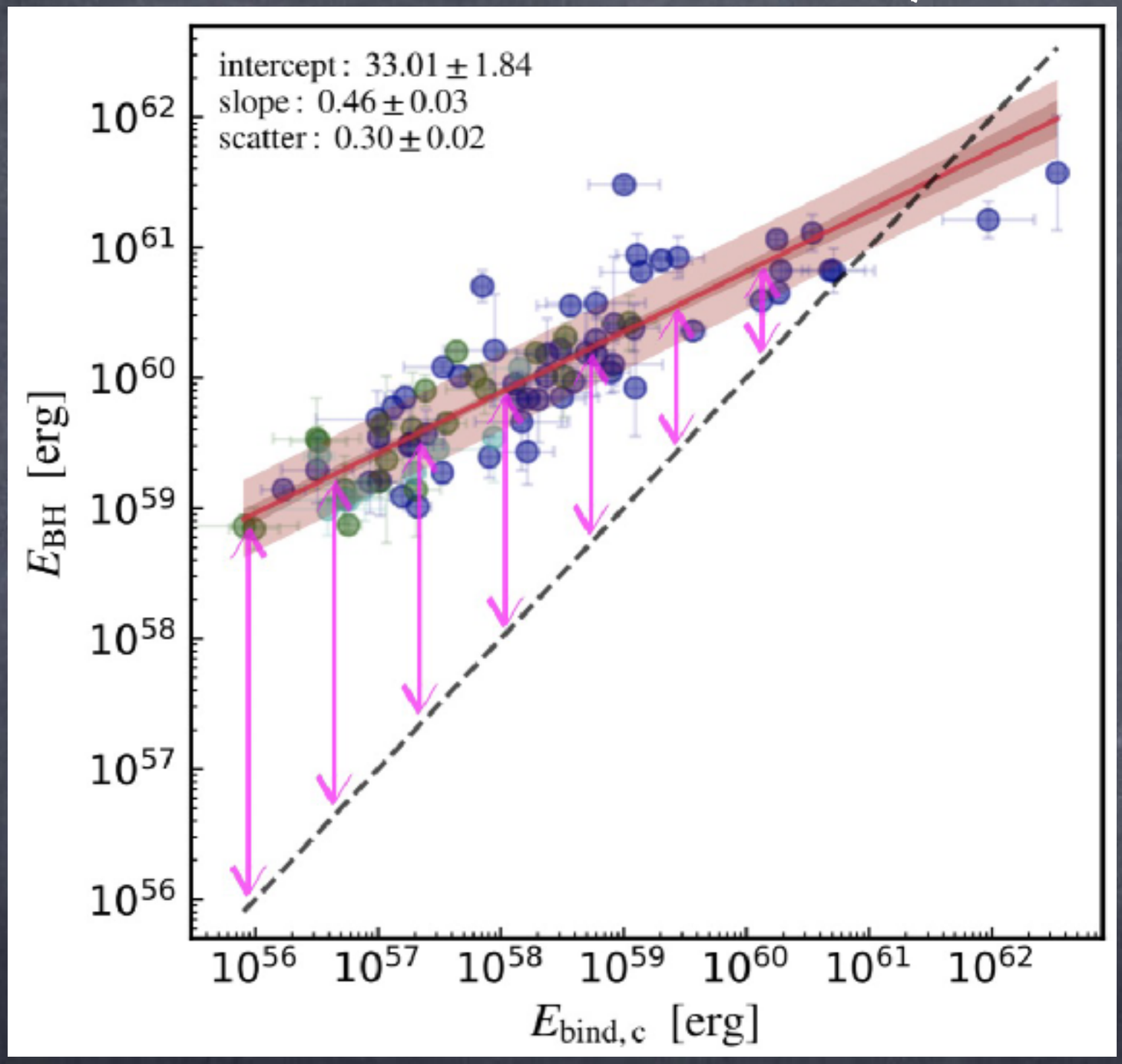
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



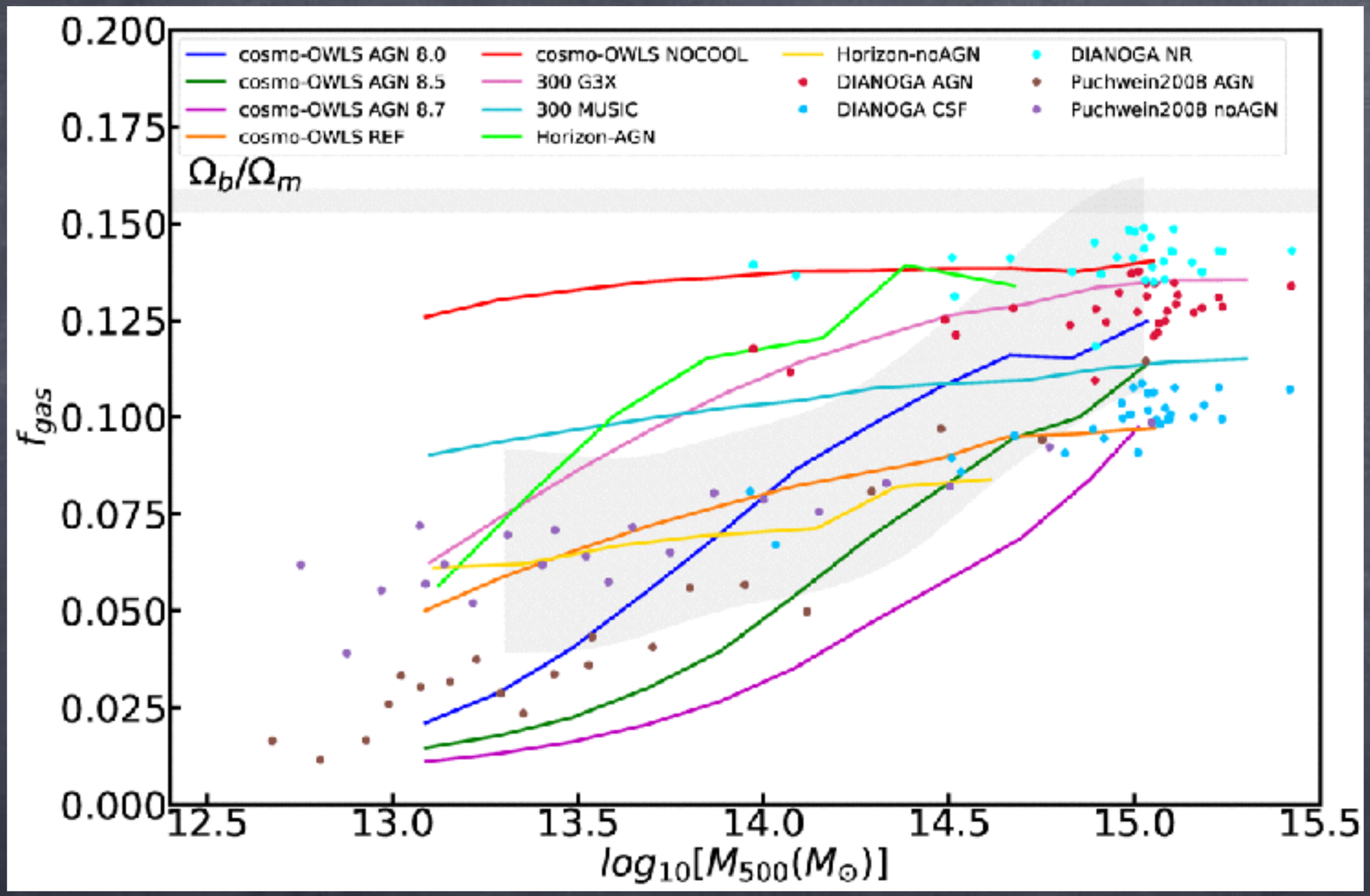
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



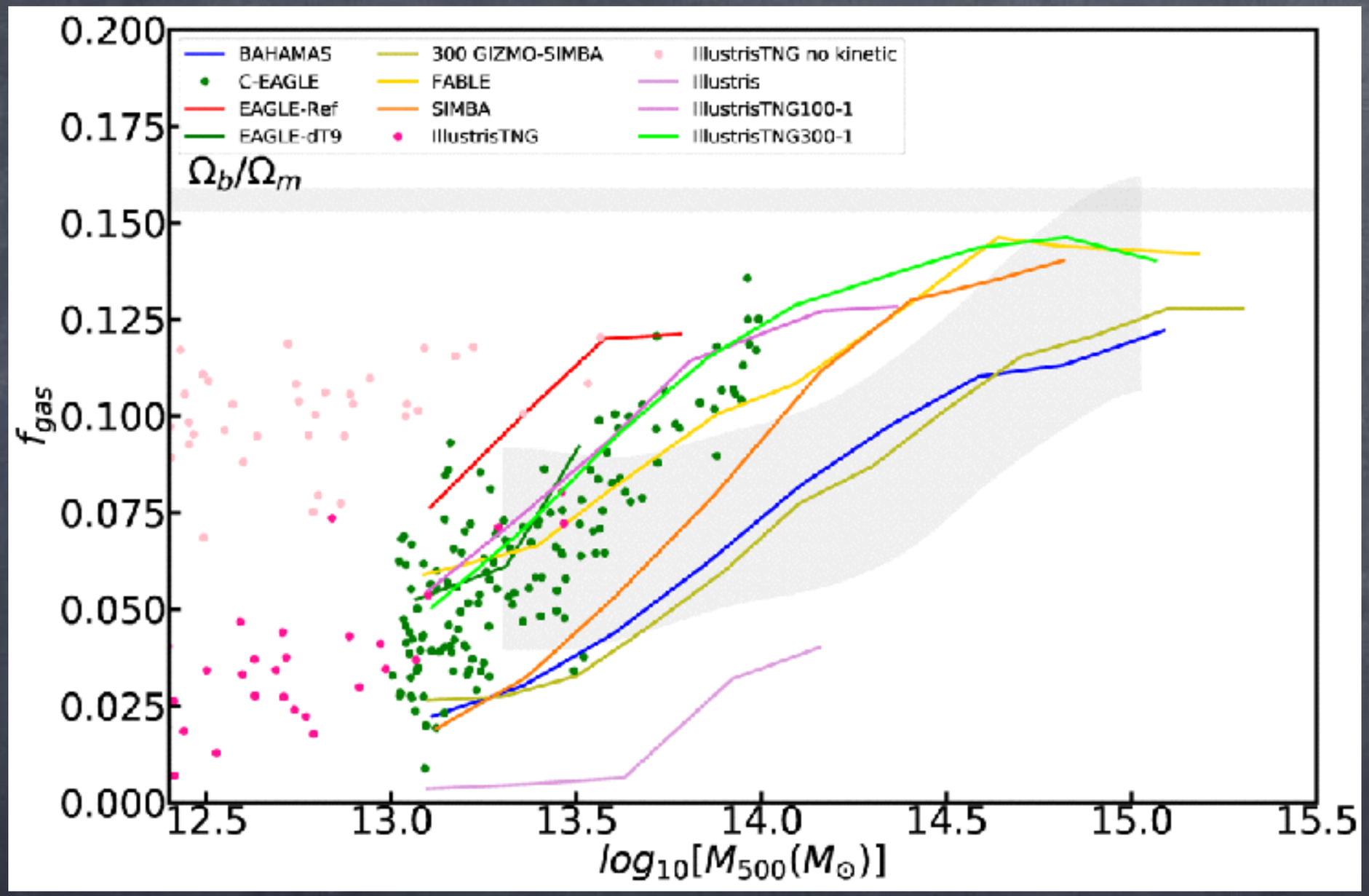
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



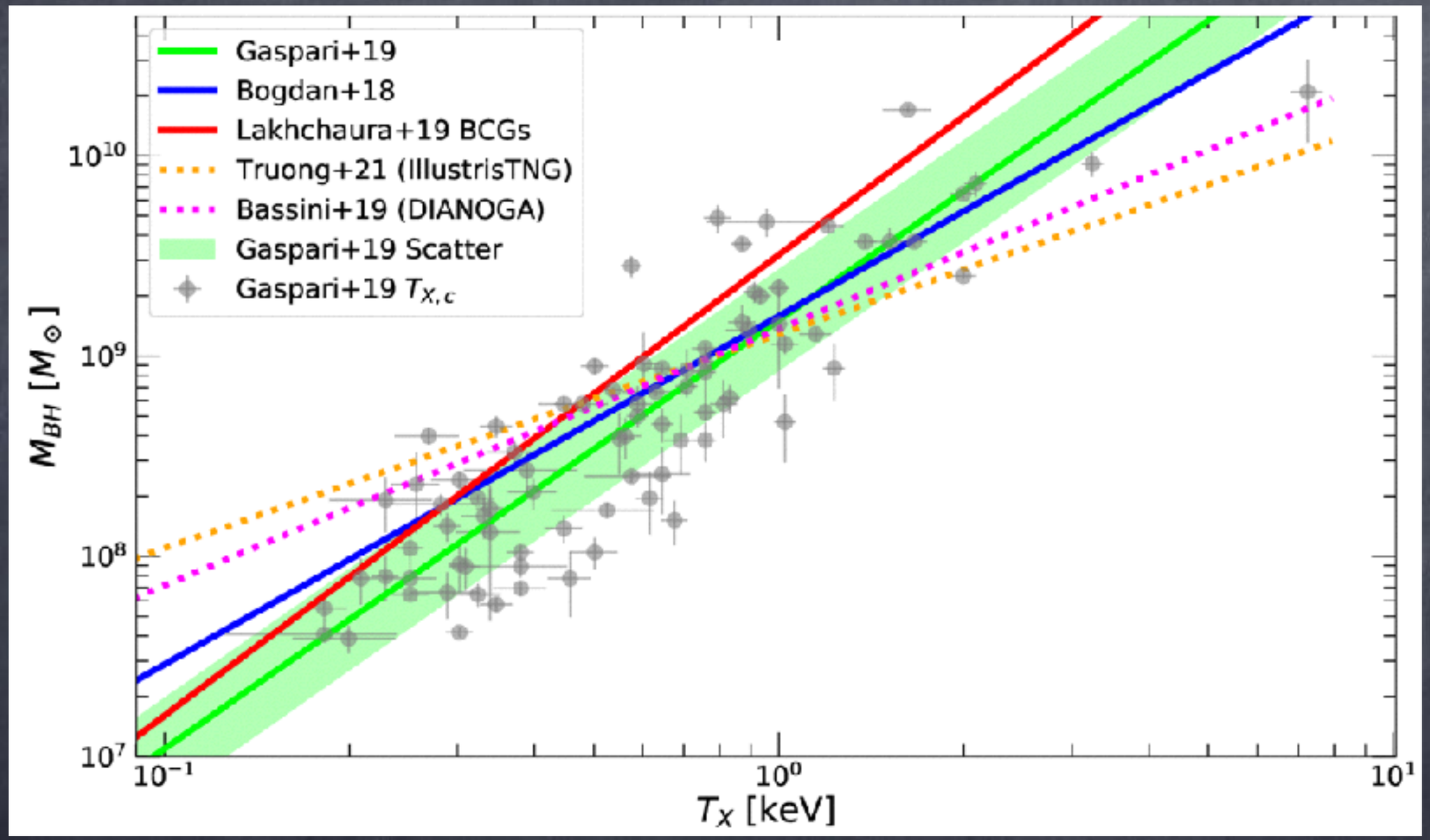
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



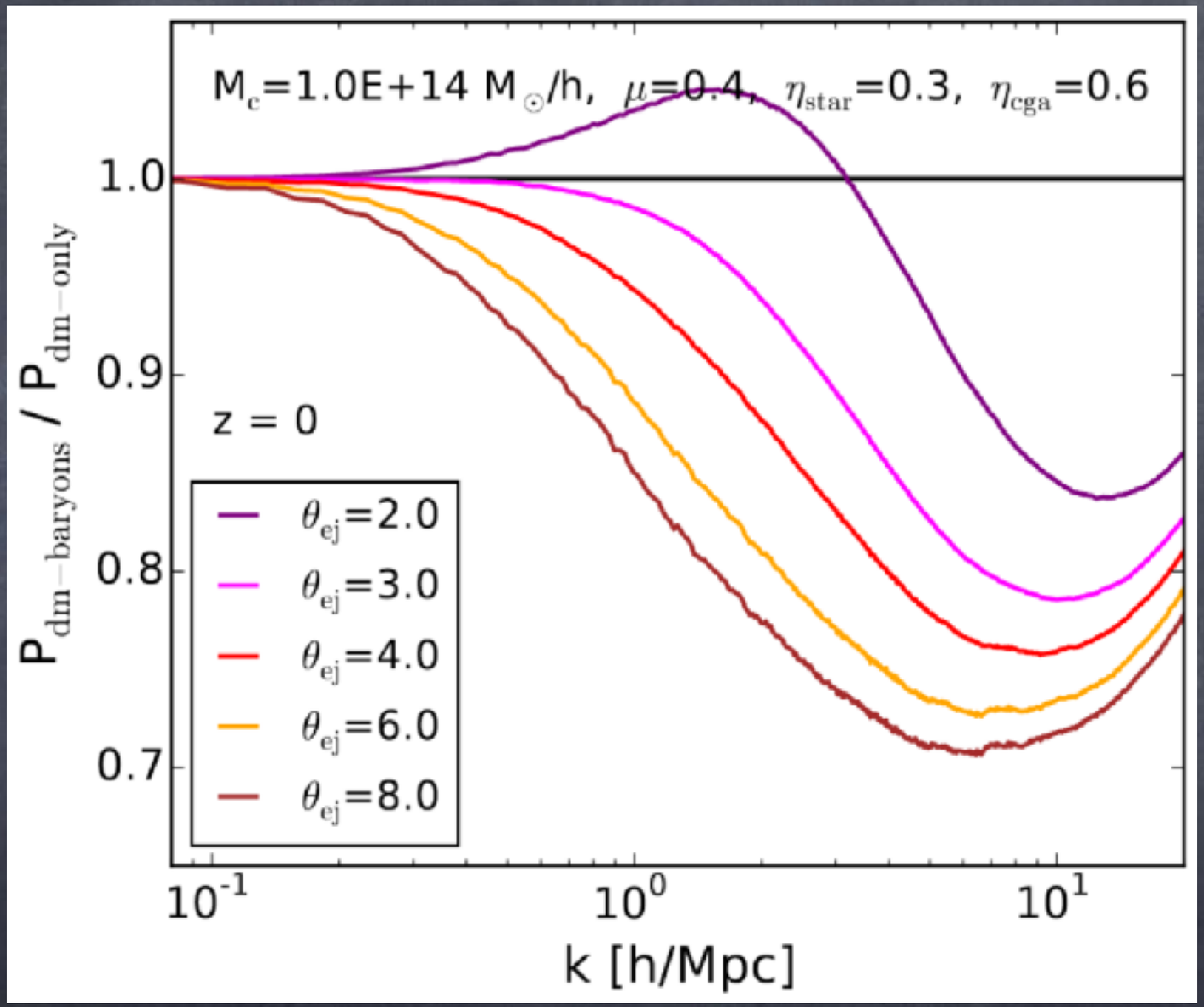
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



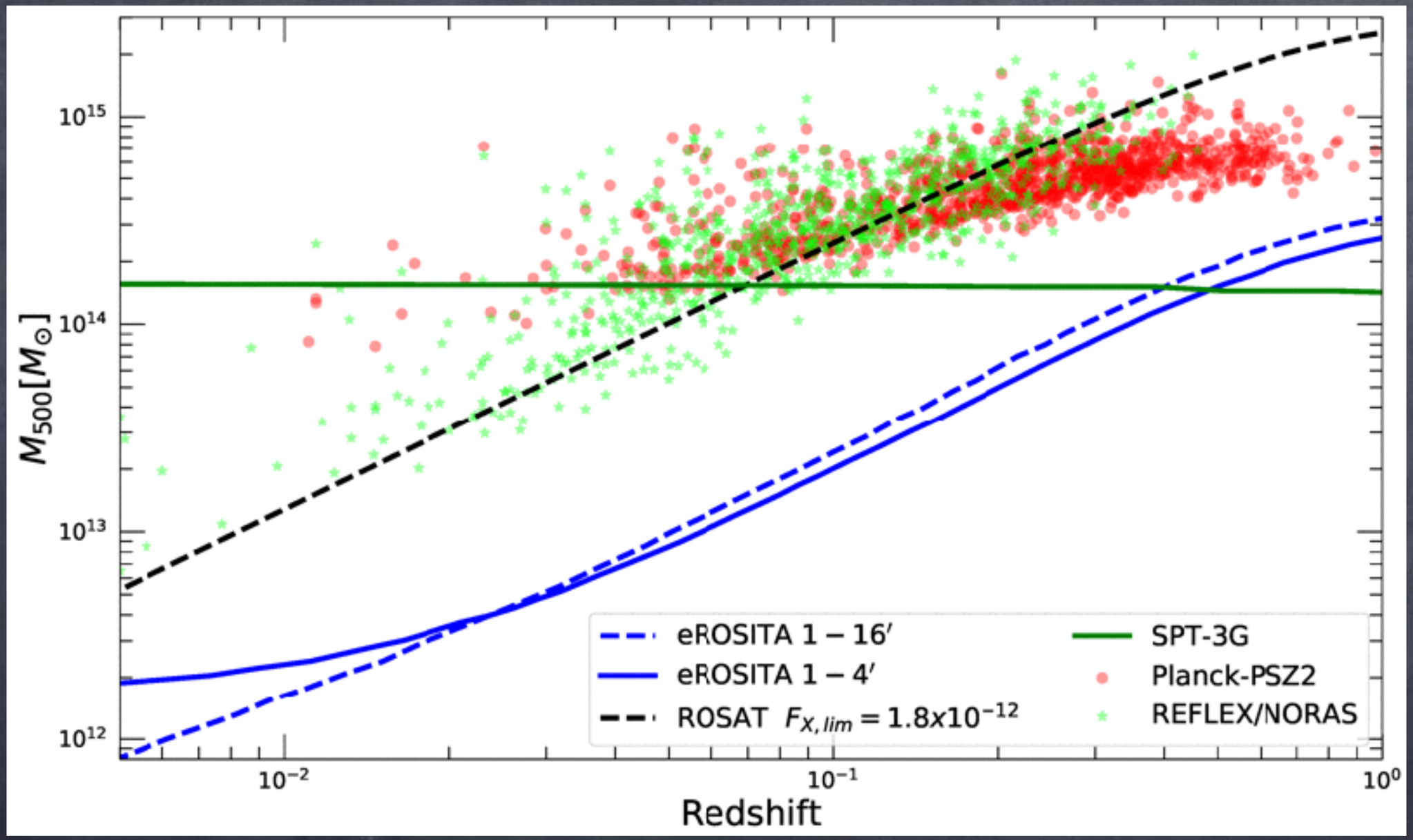
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



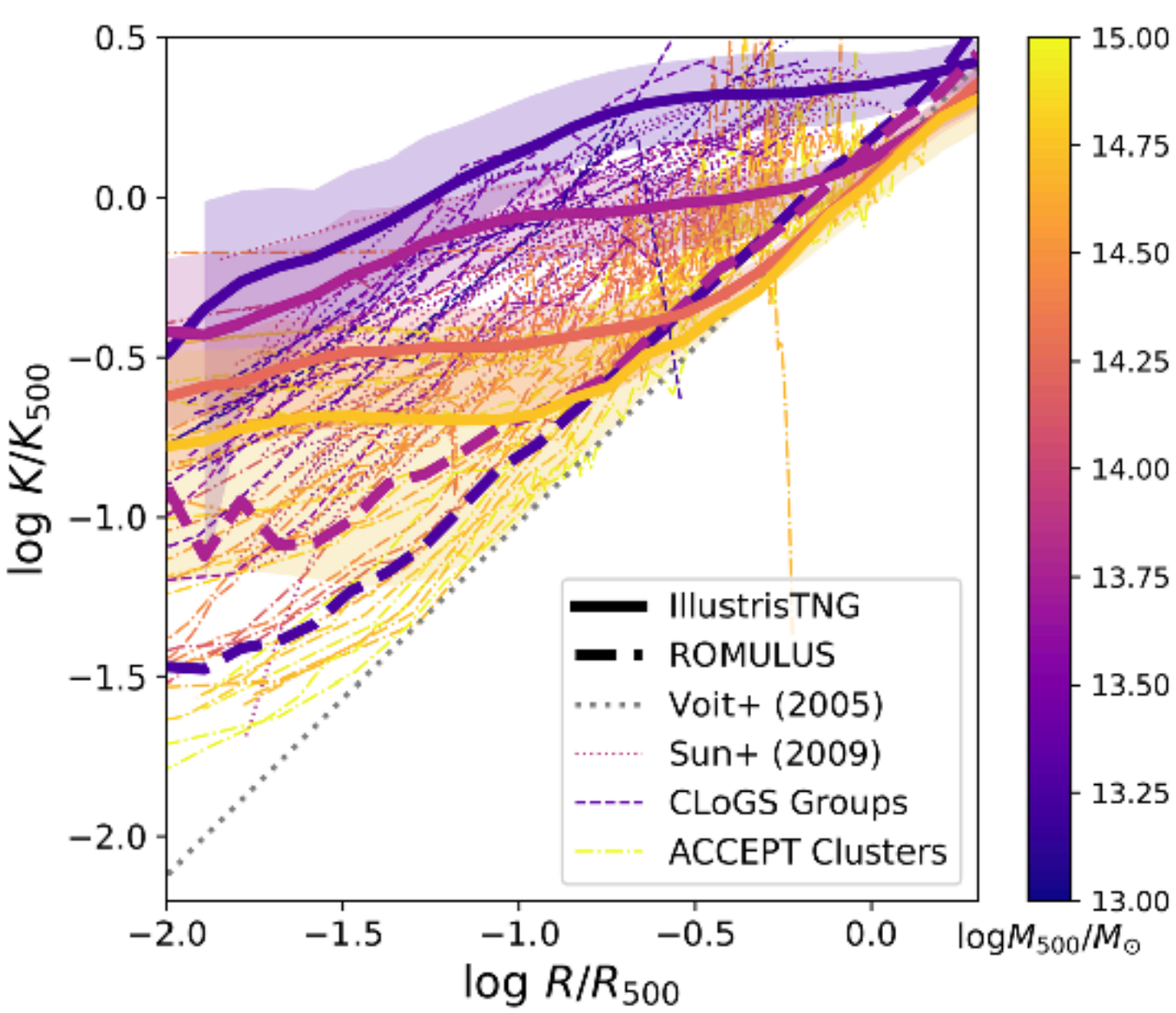
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

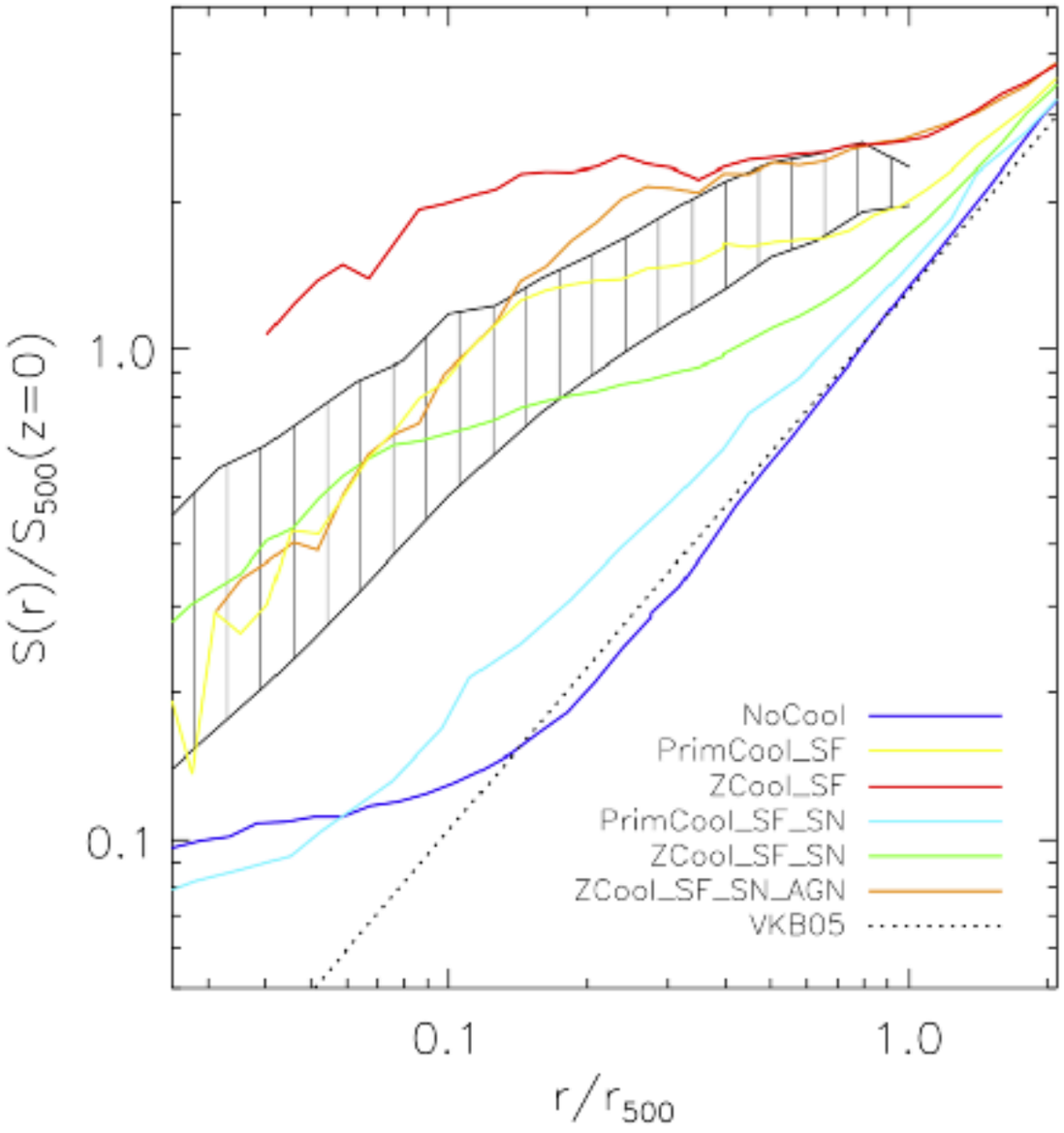
AGN feedback in groups review



Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

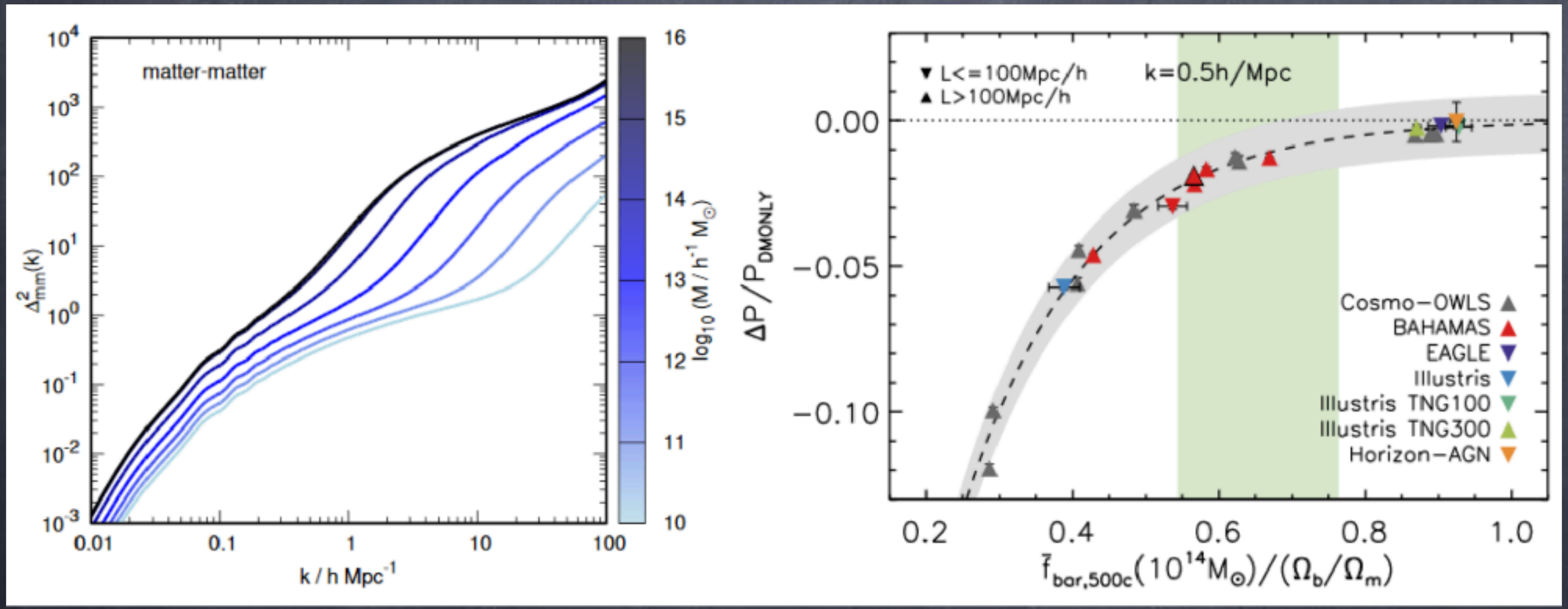
Simulating Groups and the IntraGroup Medium review





Oppenheimer, Babul, Bahé, Butsky & McCarthy 2021, Universe, 7, 209 (arXiv:2106.13257)

Simulating Groups and the IntraGroup Medium review



Oppenheimer, Babul, Bahé, Butsky & McCarthy 2021, Universe, 7, 209 (arXiv:2106.13257)

Take-home messages

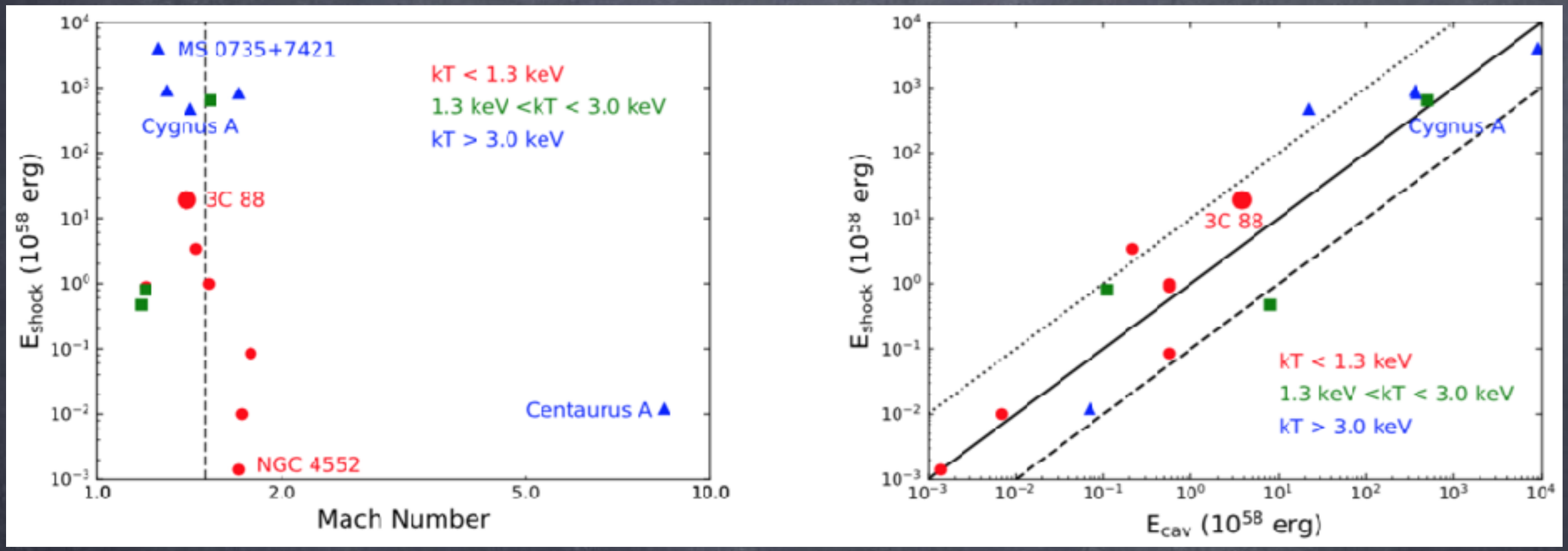
- All references are clickable links
- Groups more than intermediate scale between clusters and halos hosting individual galaxies: ideal targets for constraining cooling-heating mechanisms
- Key to our understanding of structure formation
- Influence of feedback processes complex and difficult to model and reproduce in simulations despite recent breakthroughs in understanding through cosmological simulations
- Simulations now facing important challenge of producing realistic galaxy populations and gas properties

Galaxy groups are best astrophysical laboratories for studying impact of various feedback mechanisms as managed to retain enough hot gas to allow for study of impact of feedback on IGrM, while representing transitional regime for galaxy stellar properties.

Thank you!

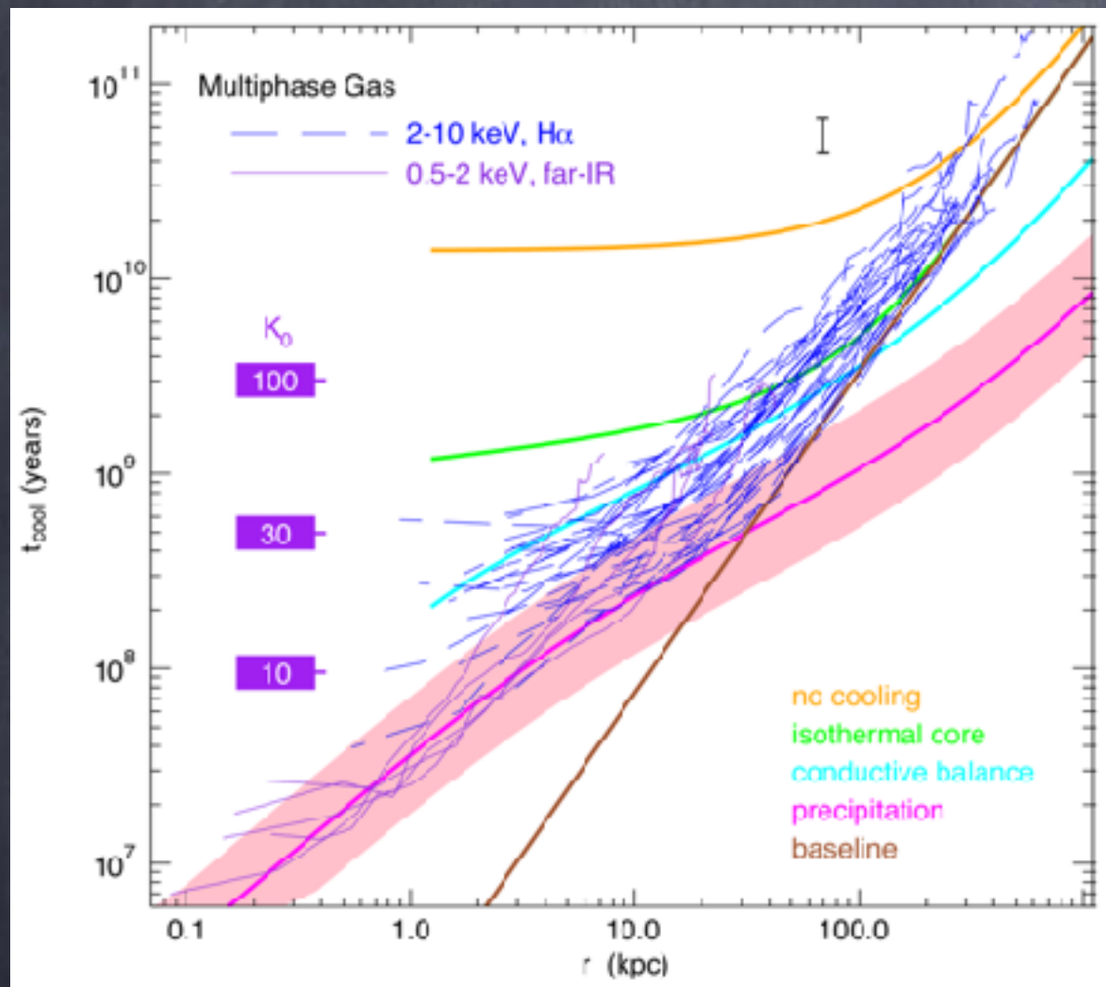
Backup slides

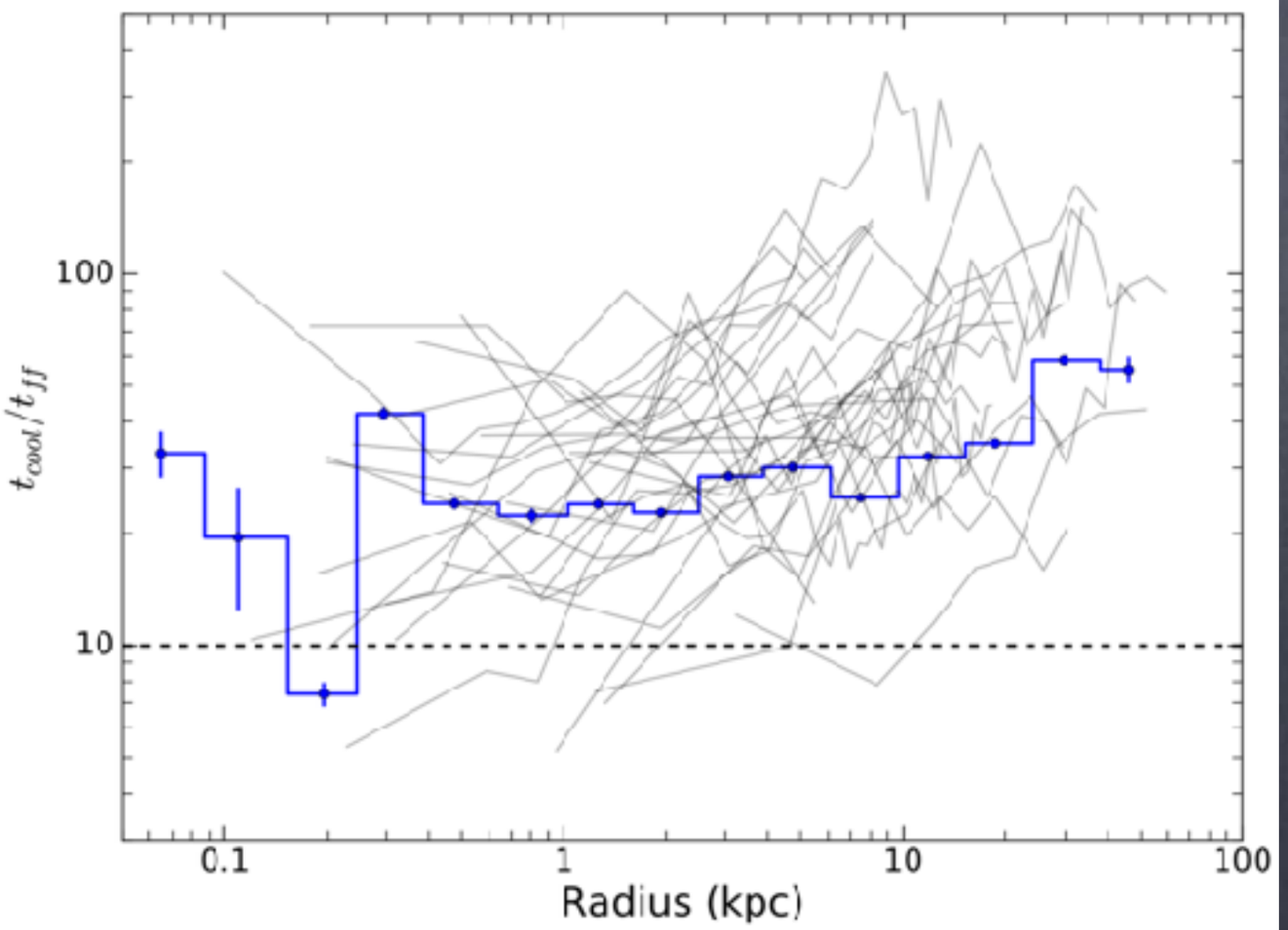
AGN feedback in groups review



Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

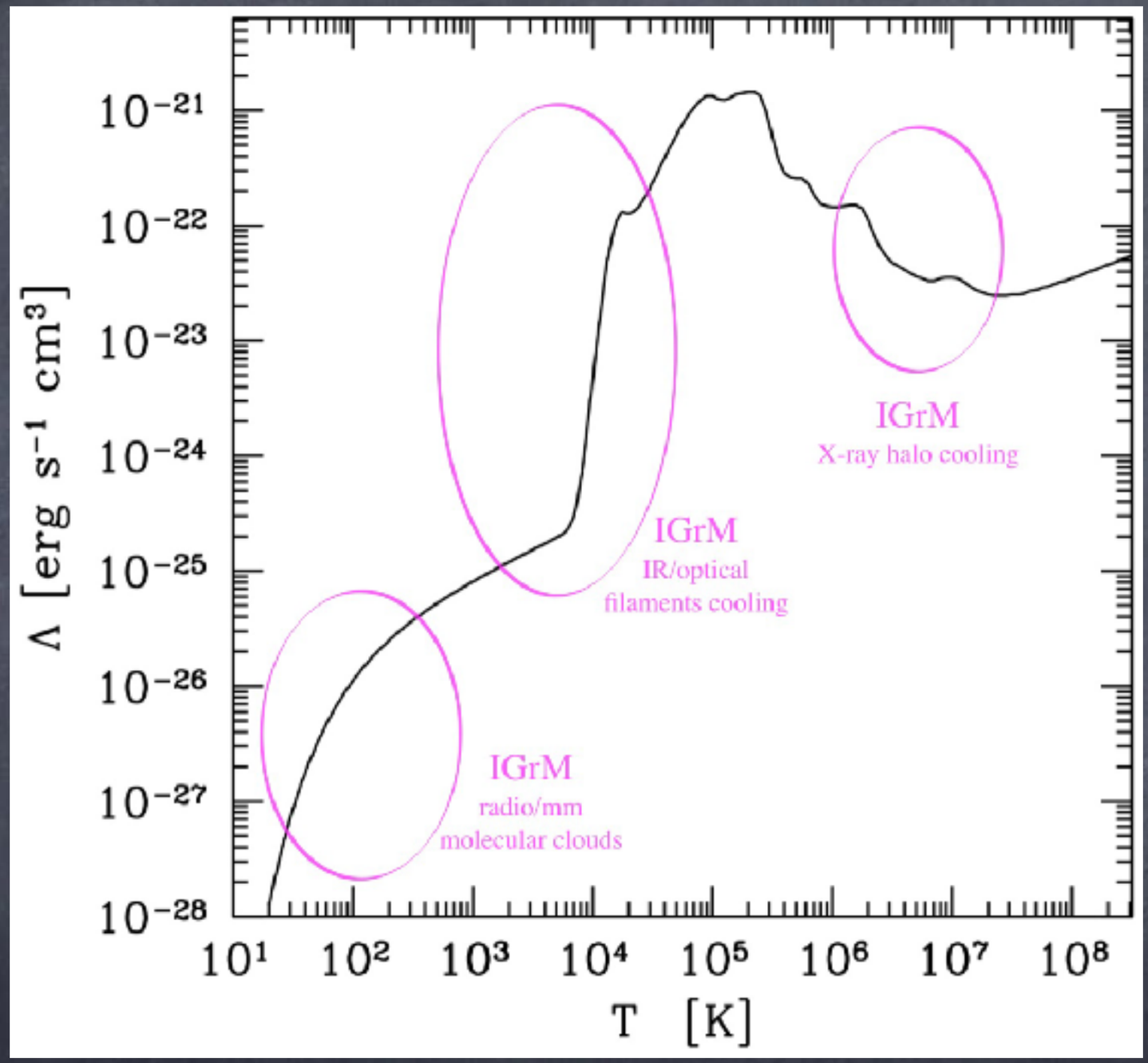
AGN feedback in groups review





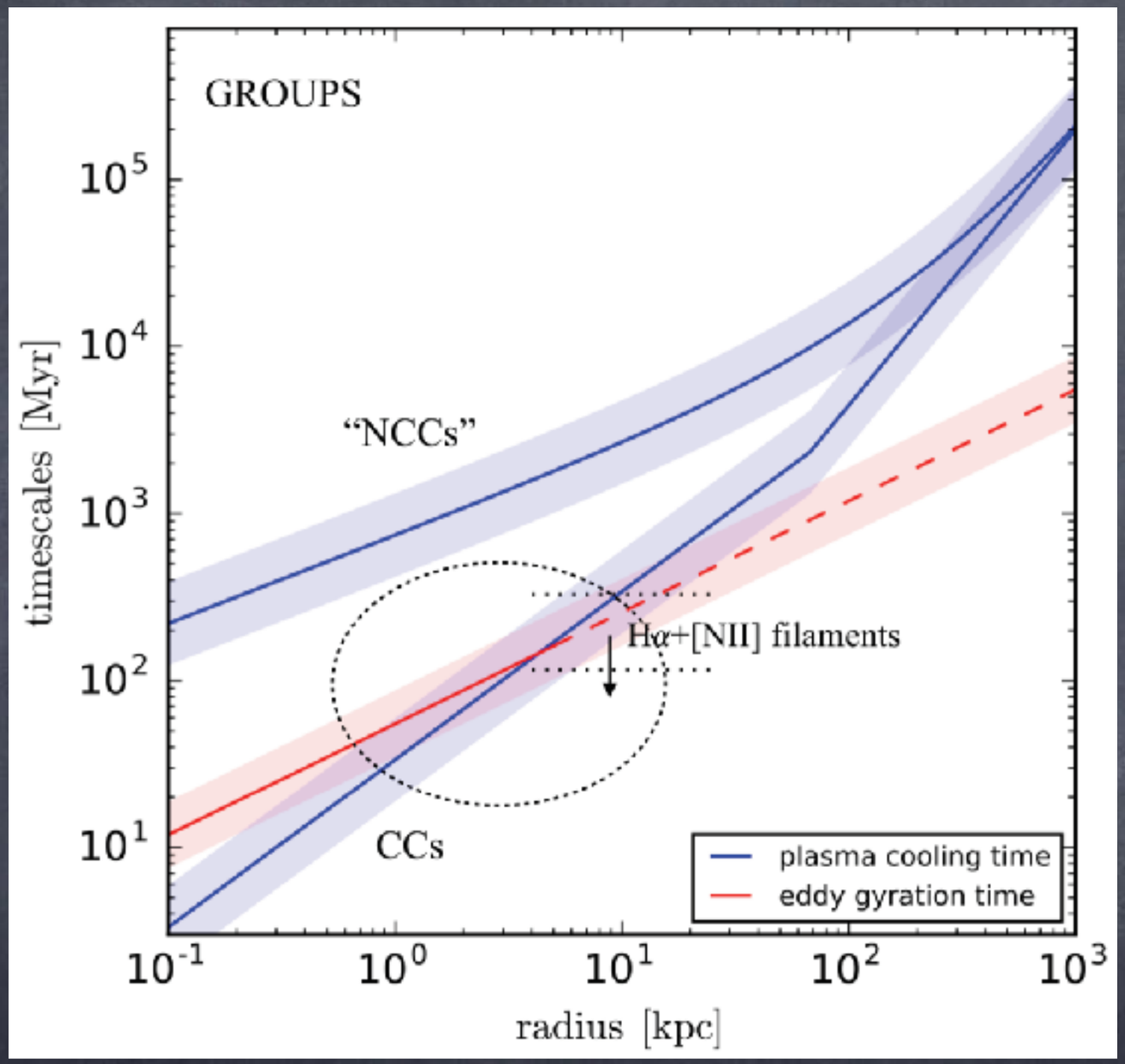
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



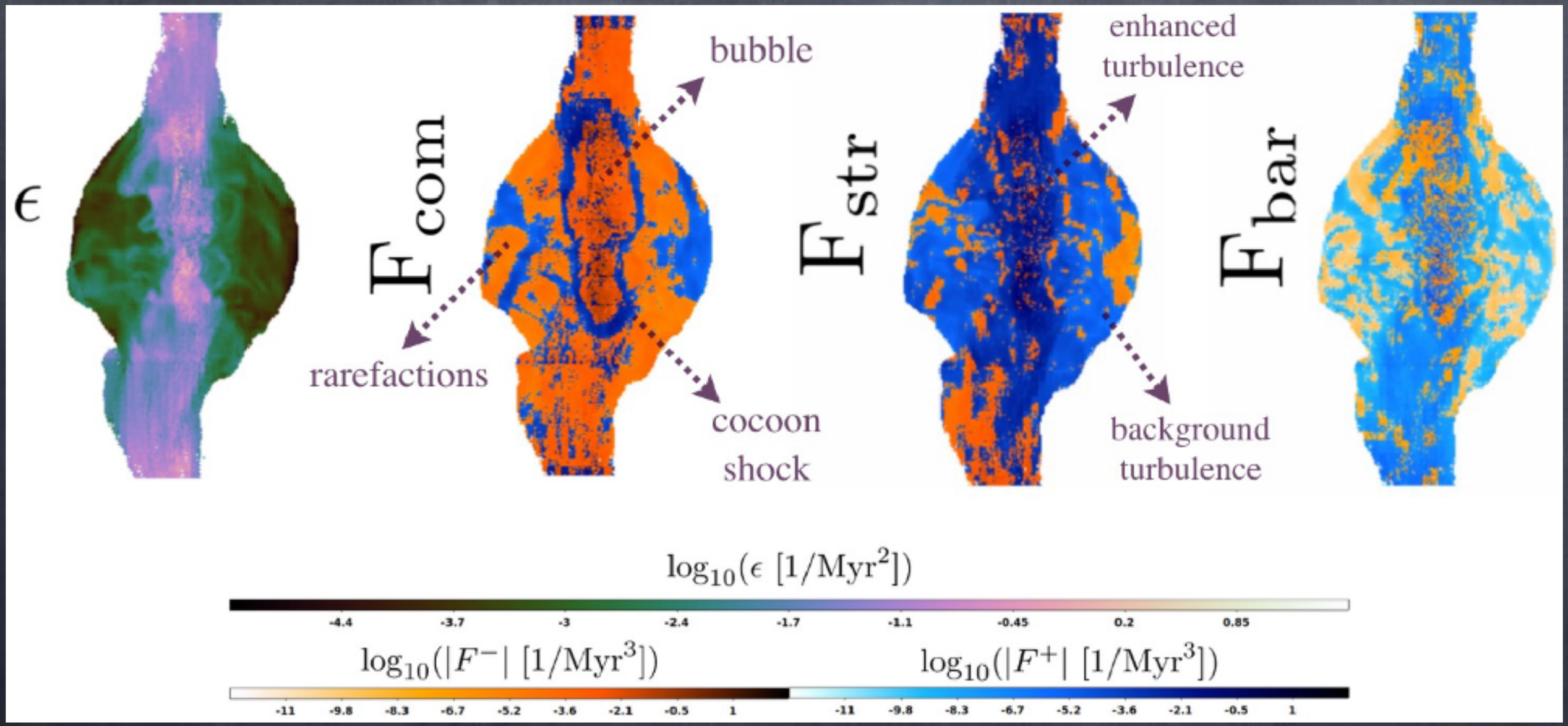
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



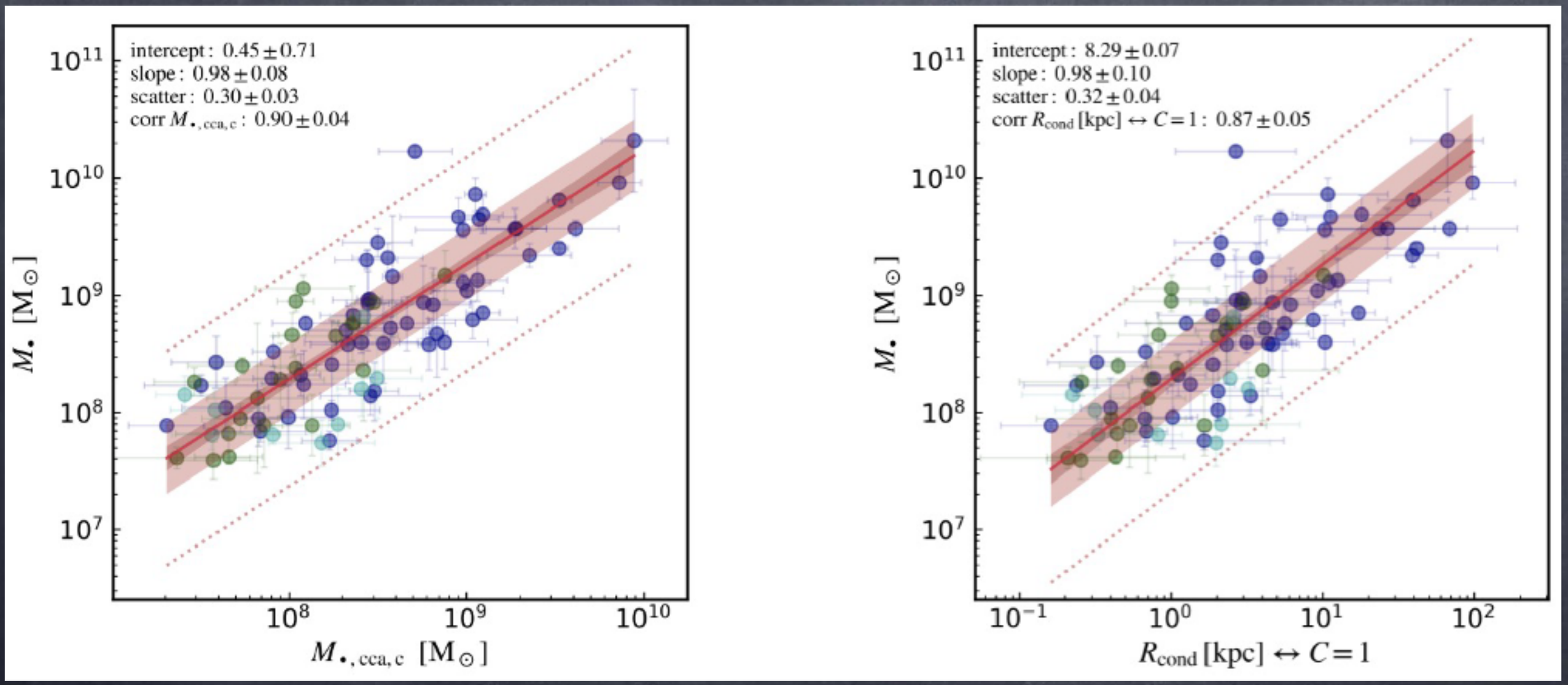
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



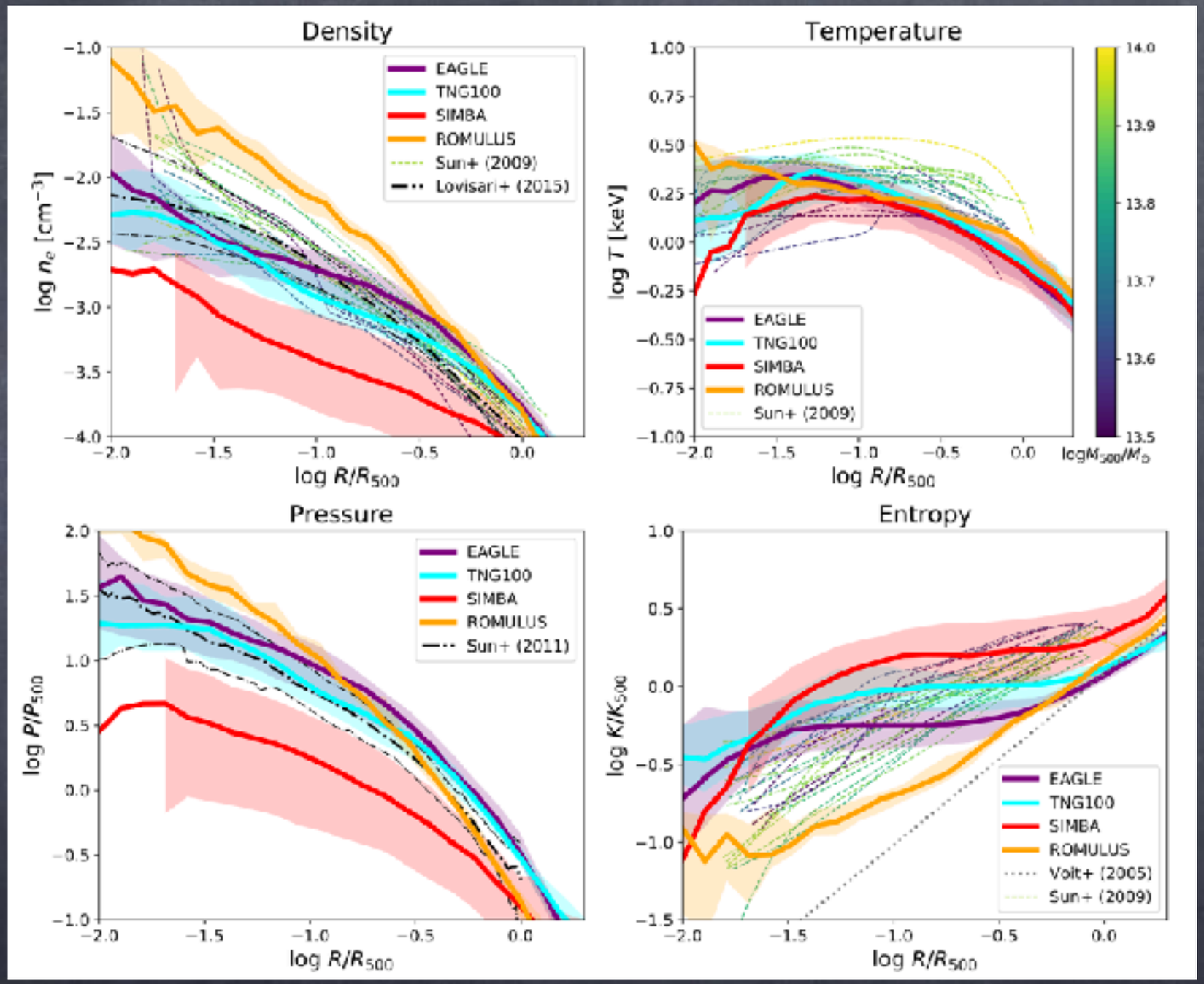
Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

AGN feedback in groups review



Eckert, Gaspari, Gastaldello, Le Brun & O'Sullivan 2021, Universe, 7, 142 (arXiv:2106.13259)

Simulating Groups and the IntraGroup Medium review



Oppenheimer, Babul, Bahé, Butsky & McCarthy 2021, Universe, 7, 209 (arXiv:2106.13257)