DRAGONS Team

The Eventful Lives of Galaxy Clusters: from Violent Proto-Clusters to Present-day Monsters

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First Structures, Paris, 04.09.2023

LMU USM

CAST Computational Astrophysics Group Munich University Observatory

Galaxy Cluster @ z ≈ 0

Virgo Cluster

Estimated $M_{tot} = 1.2 \times 10^{15}\ M_{\odot}$

Coma Cluster

Estimated $M_{tot} > 2 \times 10^{15}\ M_{\odot}$

Galaxy Cluster @ z ≈ 0.3-0.4

Image credit: NASA, ESA, and M. Montes (University of New South Wales, Sydney, Australia)

Cluster Abell 2744
Estimated $M_{tot} = 2 \times 10^{15}\ M_{\odot}$

Cluster MCS J0416.1–2403
Estimated $M_{tot} = 1.1 \times 10^{15}\ M_{\odot}$

Image credit: NASA, ESA, and J. Lotz, M. Mountain, A. Koekemoer, and the HFF Team (STScI).

Galaxy Cluster @ z ≈ 1

Cluster MOO J1142+1527
Estimated $M_{tot} = 1 \times 10^{15}\ M_{\odot}$

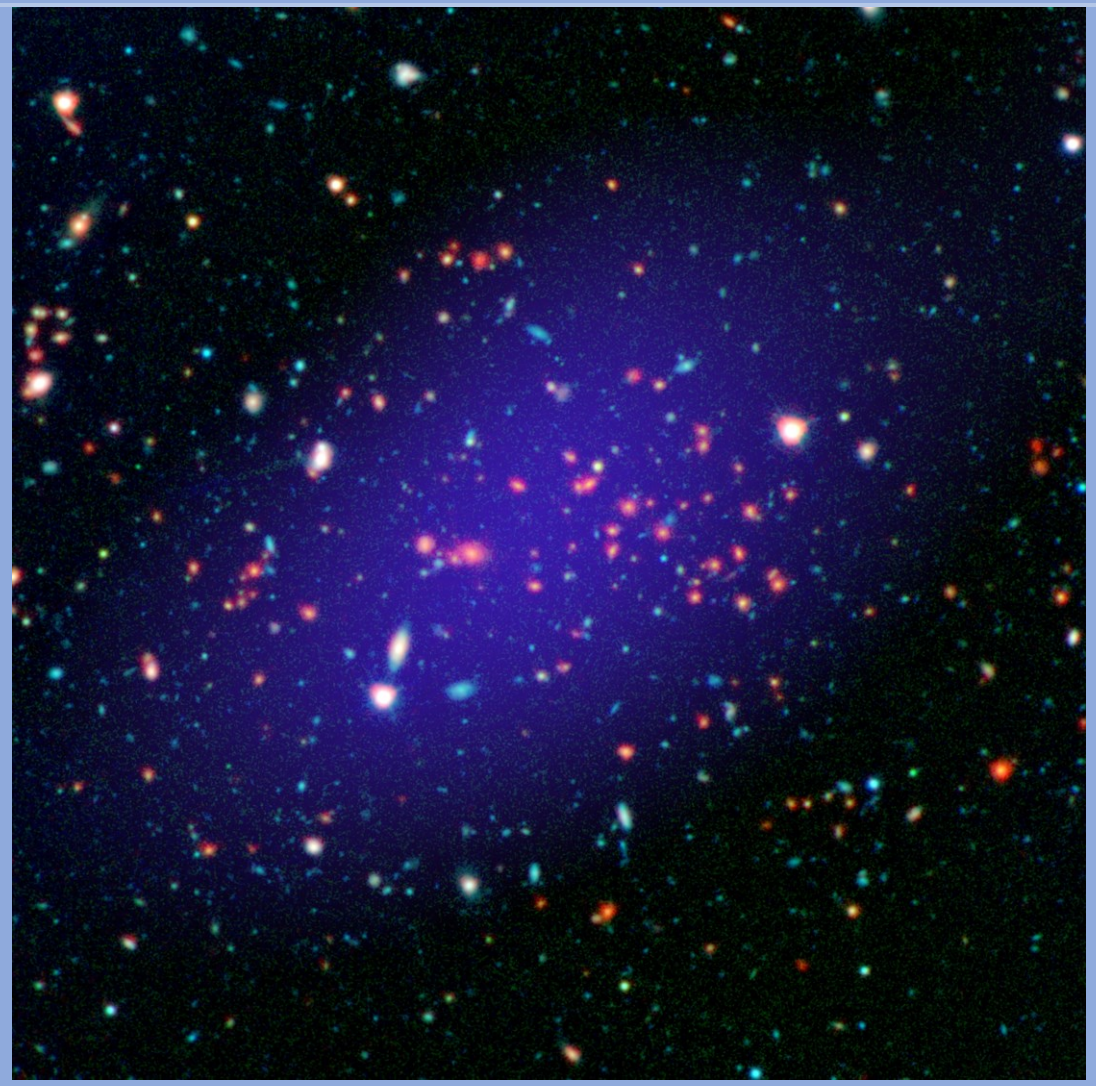
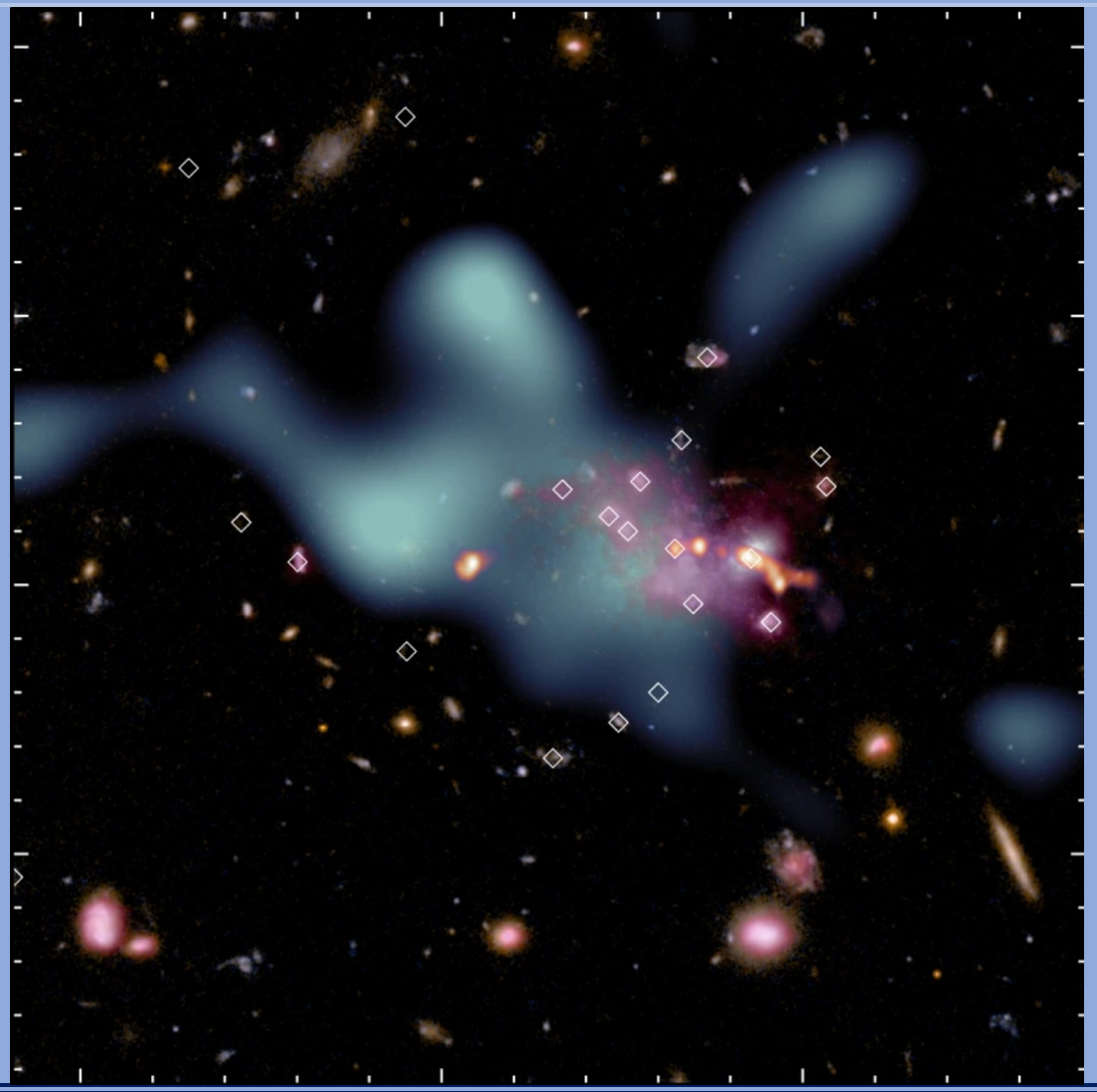


Image credit: NASA/JPL-Caltech/Gemini/CARMA

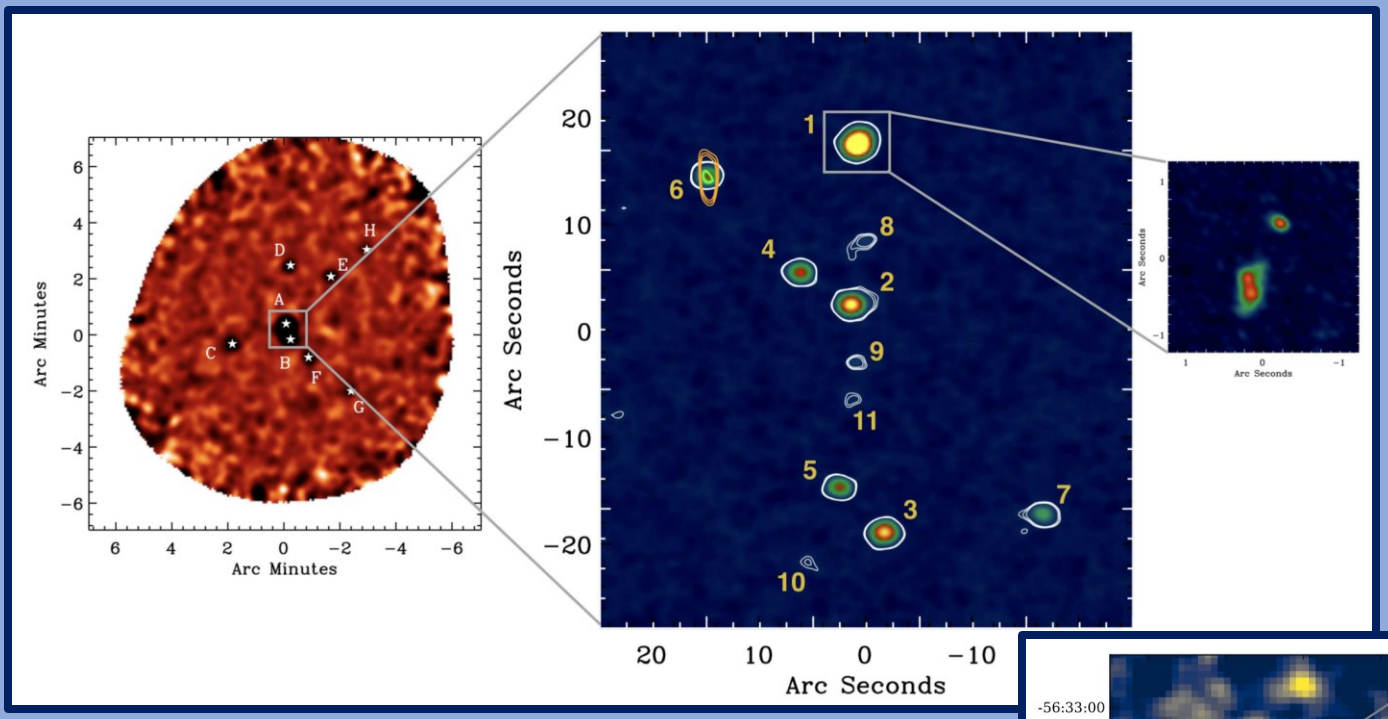
Galaxy Cluster @ z ≈ 2

Spiderweb Protocluster
Estimated $M_{tot} \approx 4 \times 10^{13}\ M_{\odot}$



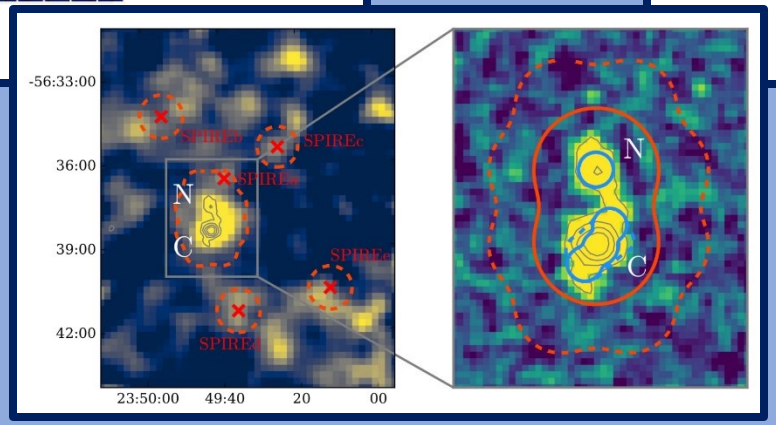
DiMascolo+2023

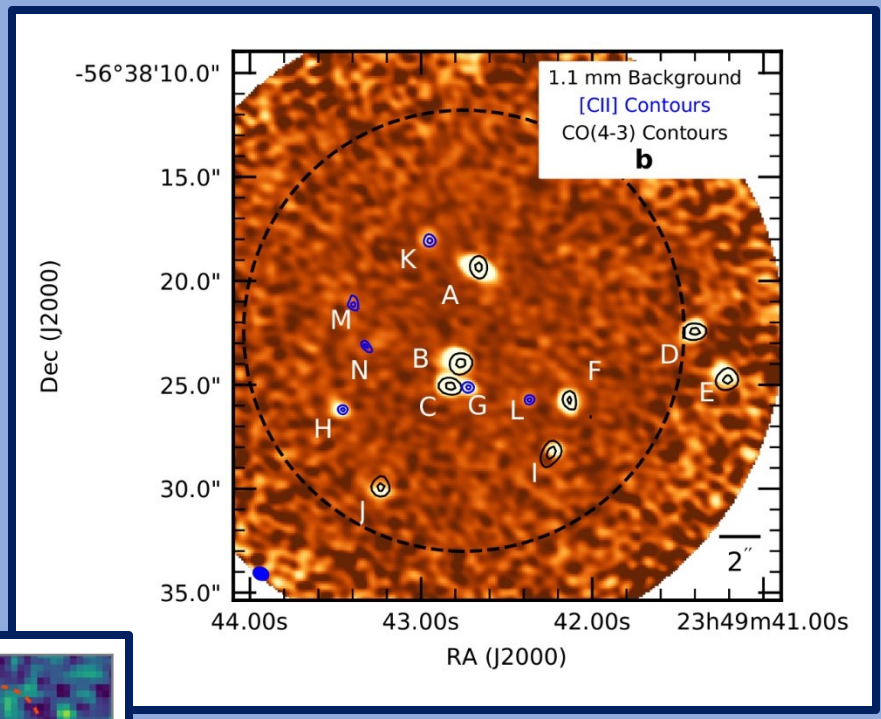
Protoclusters @ z ≈ 4.2



Estimated $M_{tot} = 4.4 \times 10^{13}\ M_{\odot}$

Oteo et al., 2018





Estimated $M_{tot} = 1.16 \times 10^{13}\ M_{\odot}$

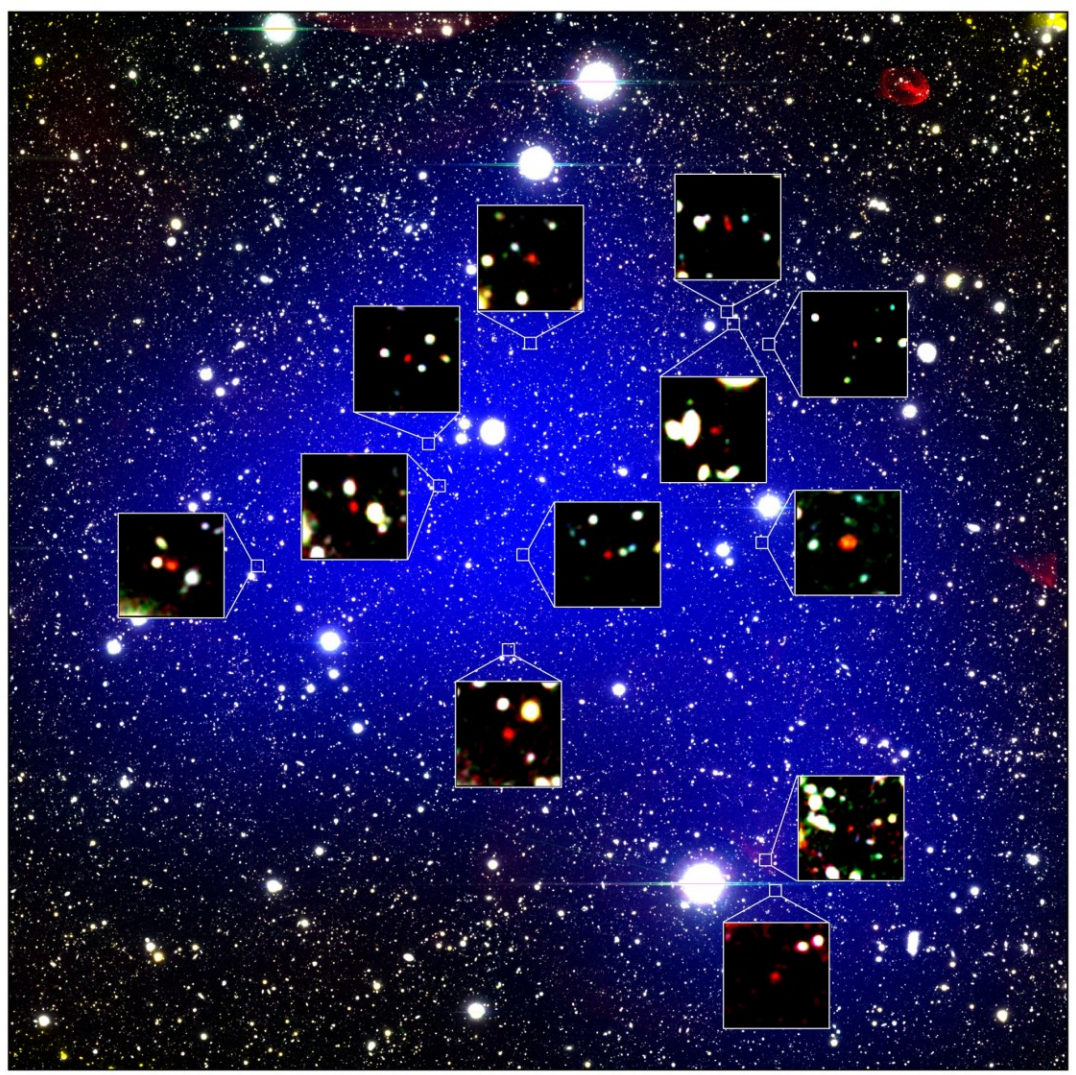
Miller et al., 2018

Estimated $M_{tot} = 9 \pm 5\ \times 10^{12}\ M_{\odot}$

Hill et al., 2020

Galaxy Cluster @ z ≈ 6

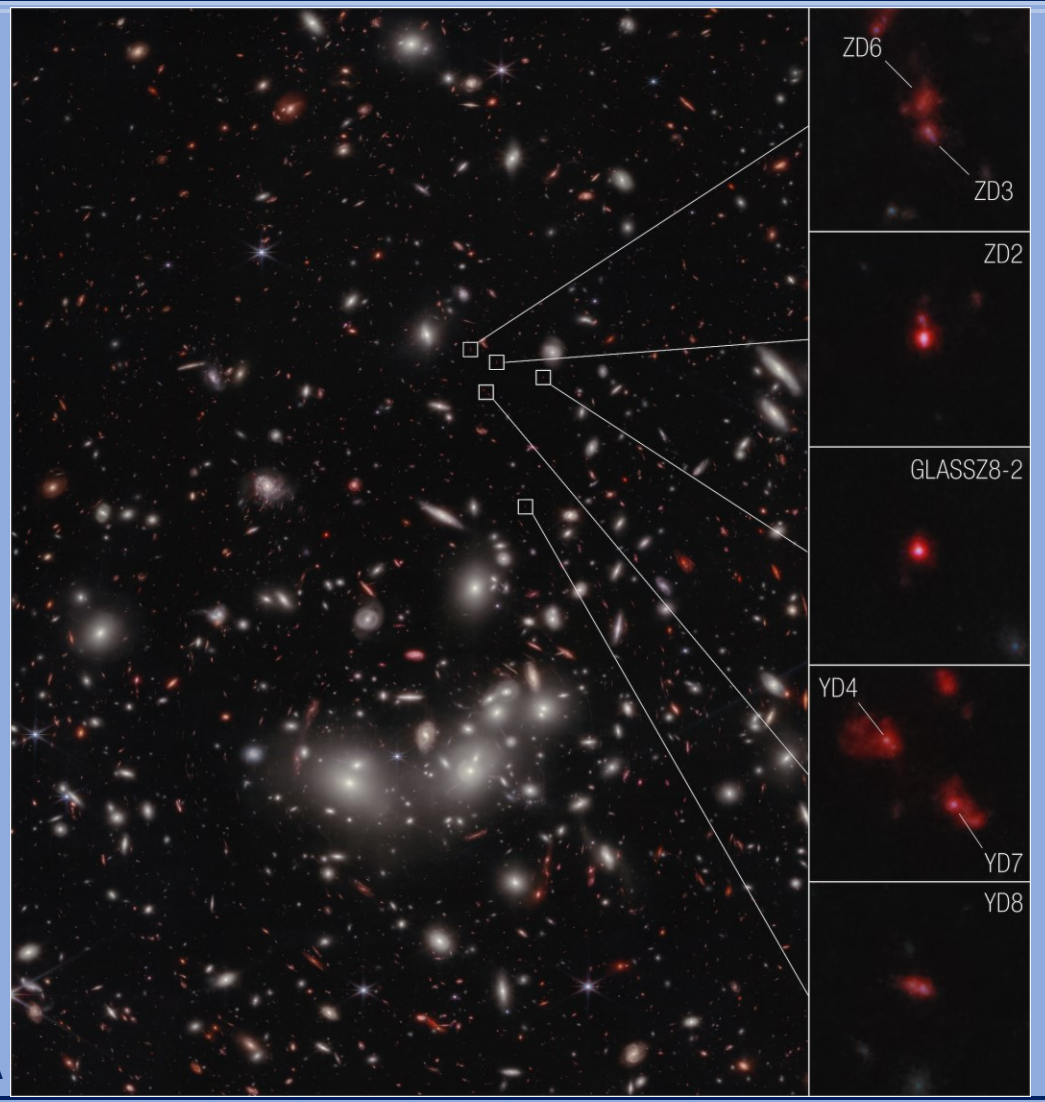
Protocluster z66OD
Estimated $M_{tot} \approx 3 \times 10^{14}\ M_{\odot}$



Credit: NAOJ/Harikane+2019

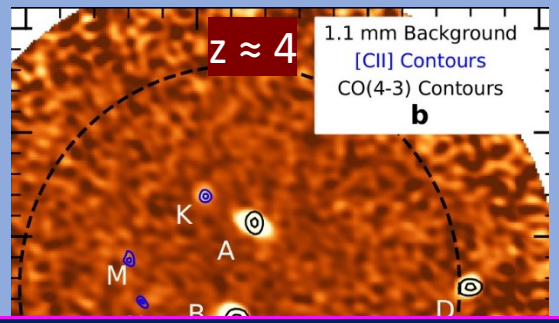
Protocluster @ z ≈ 7.88

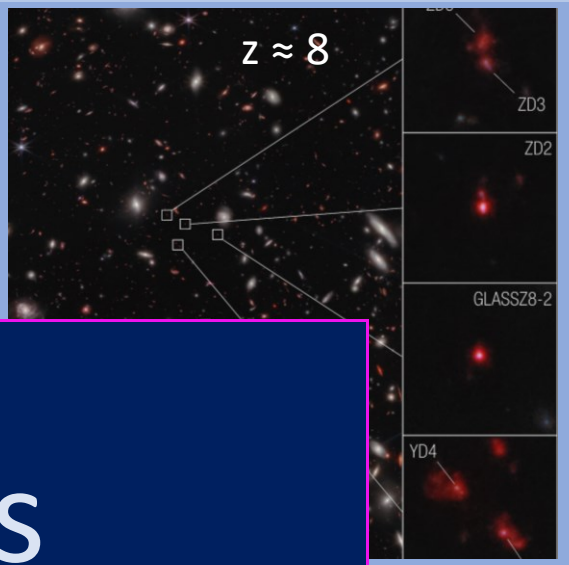
Behind Cluster Abell 2744
Estimated $M_{tot} = 4 \times 10^{11}\ M_{\odot}$



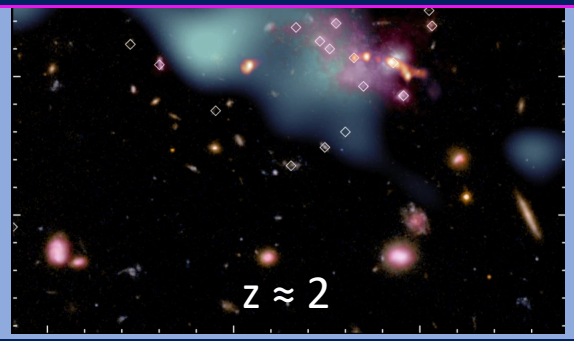
Morishita et al., 2023; image credit: ESA/NASA/STScI/CSA

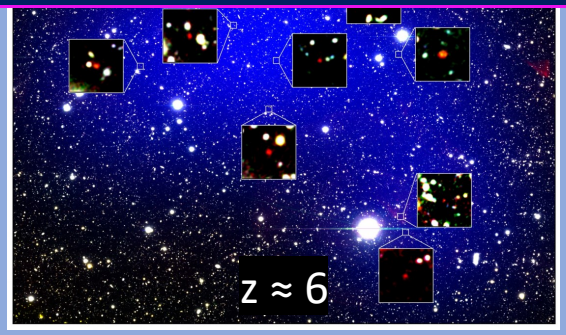
How do we bring them together?



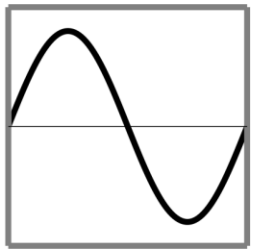


Cosmological Simulations





Modes in Cosmological Simulations



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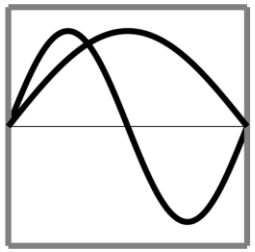

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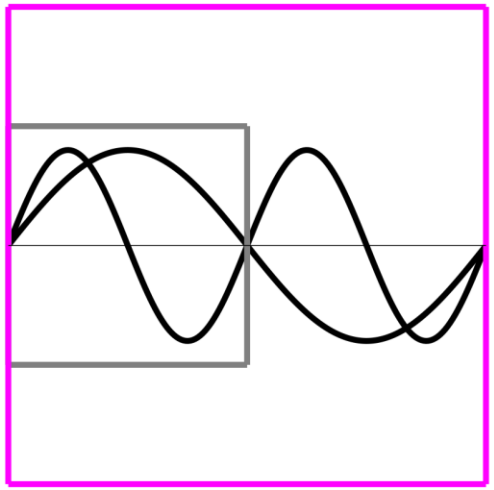

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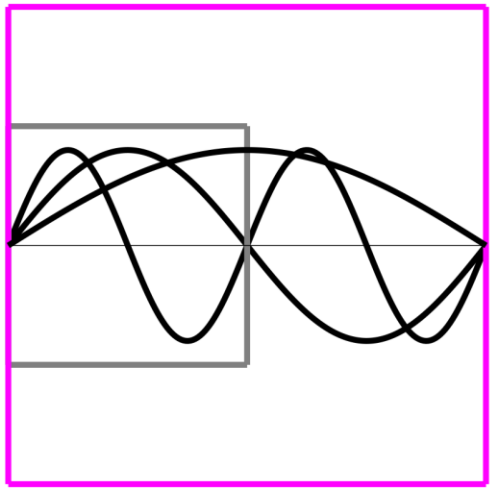

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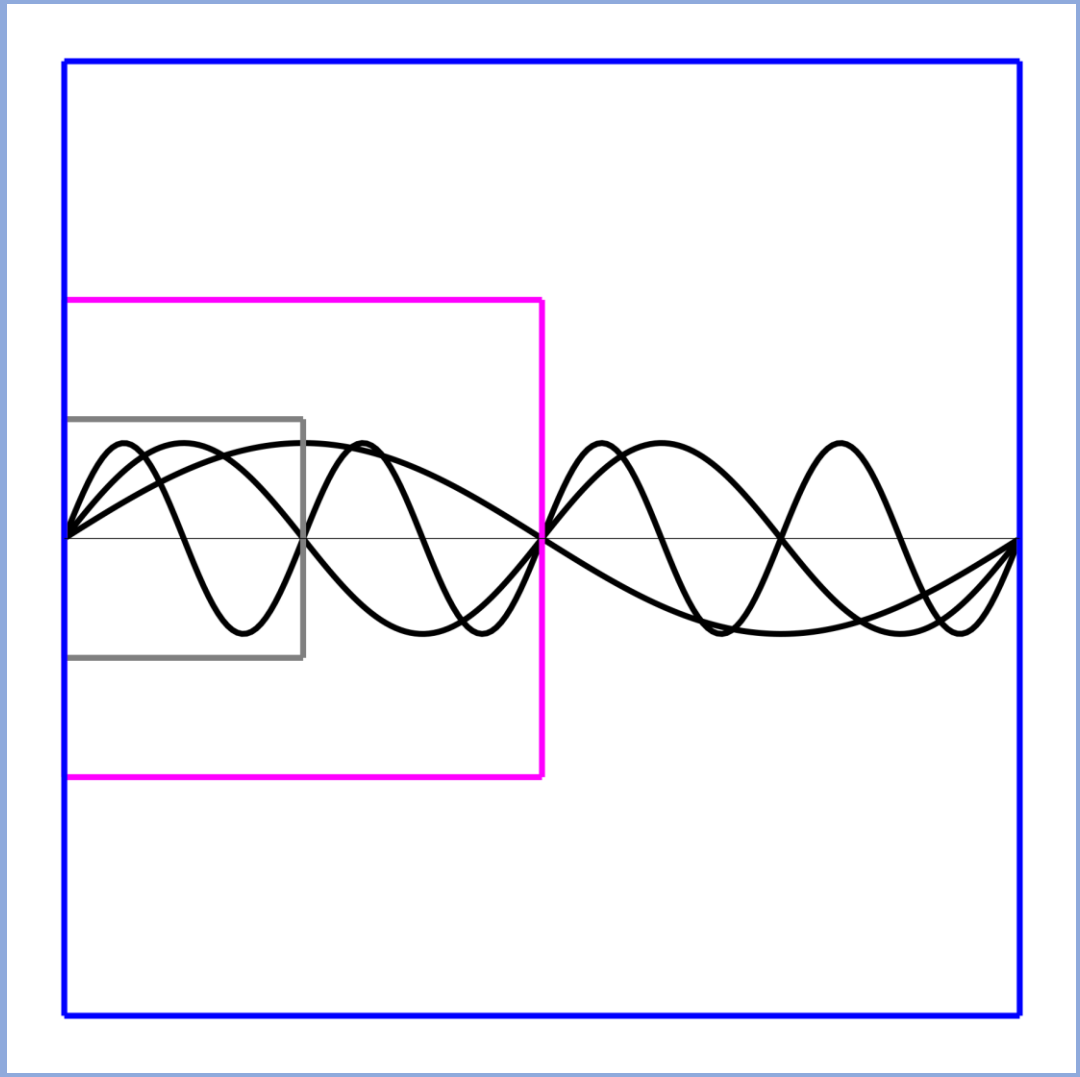

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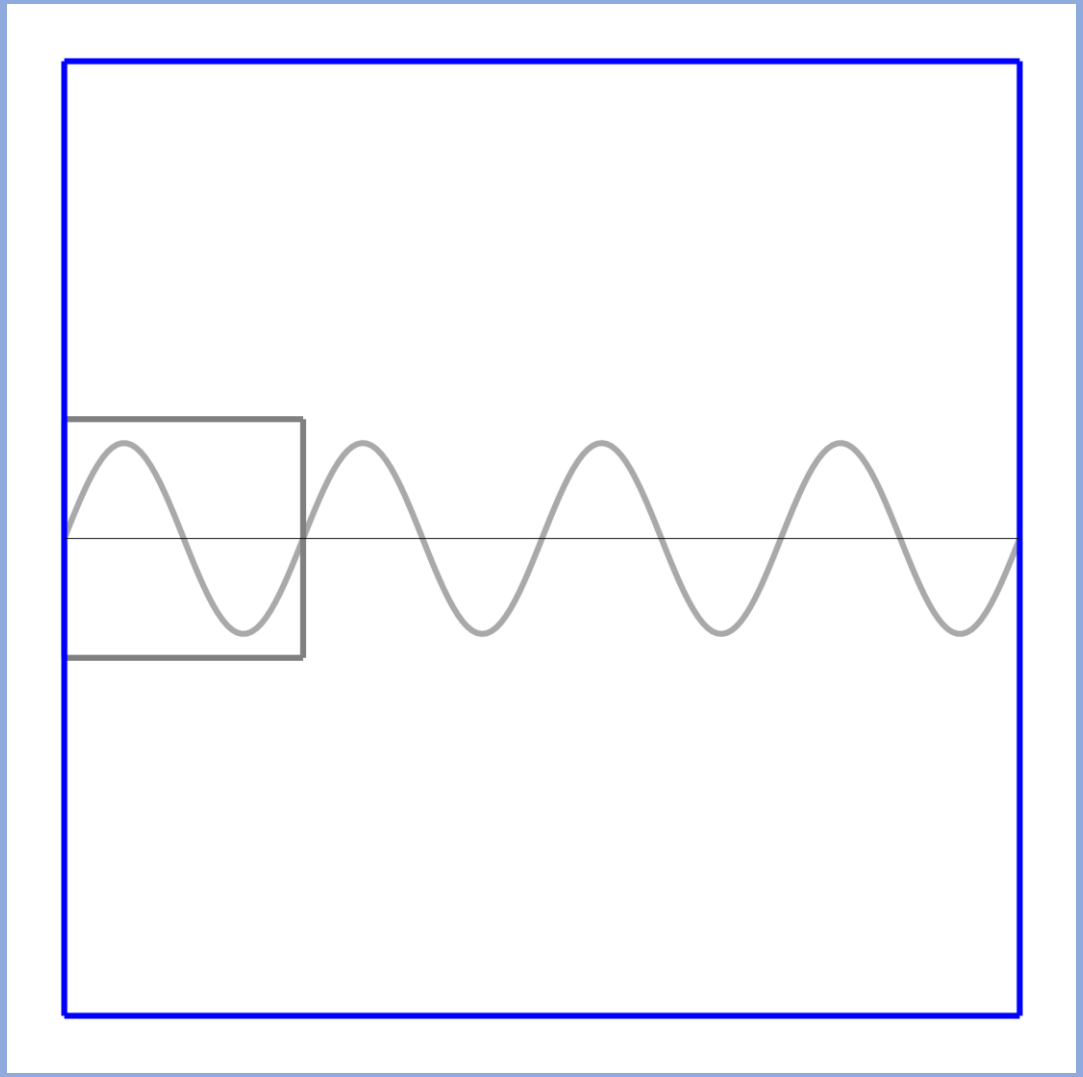

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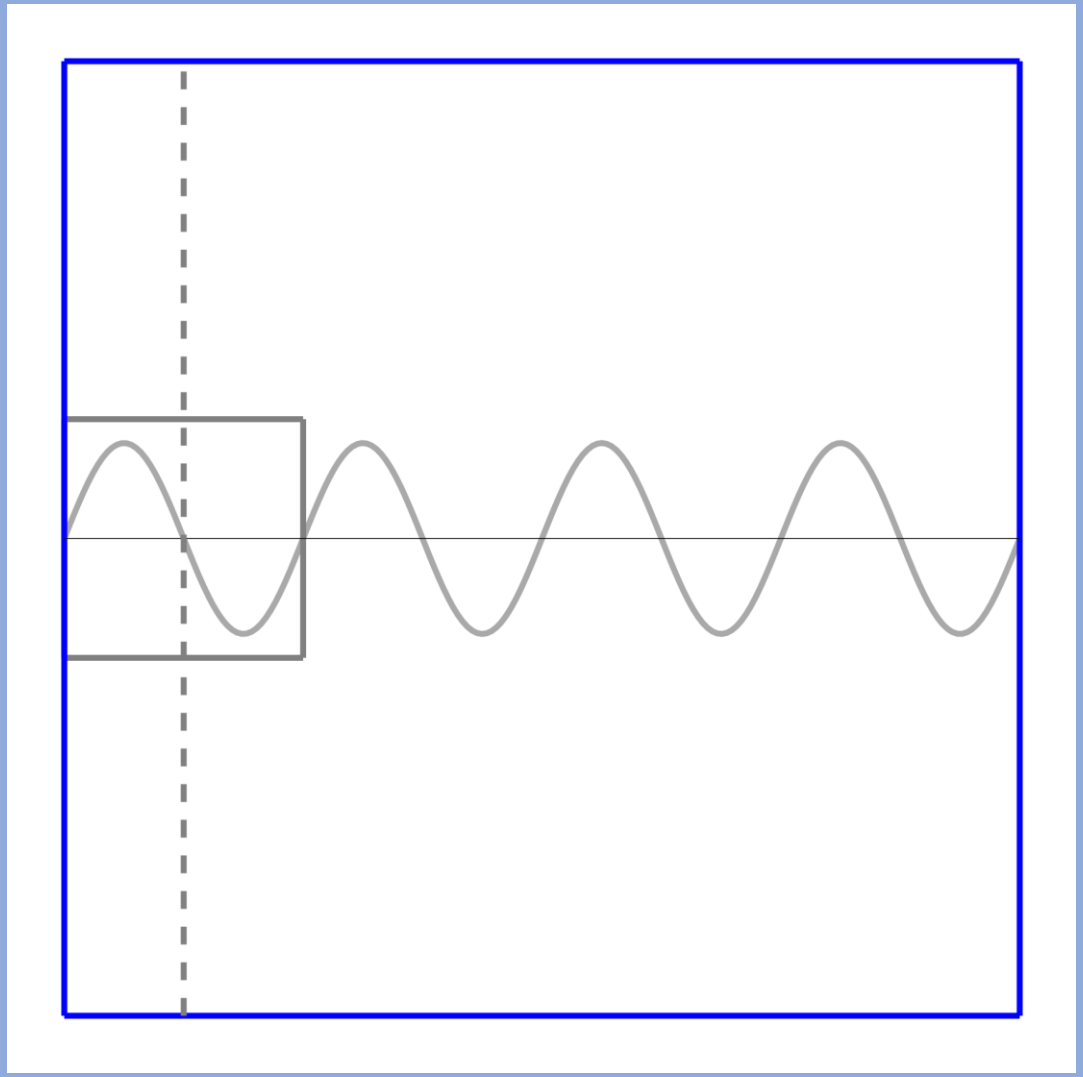

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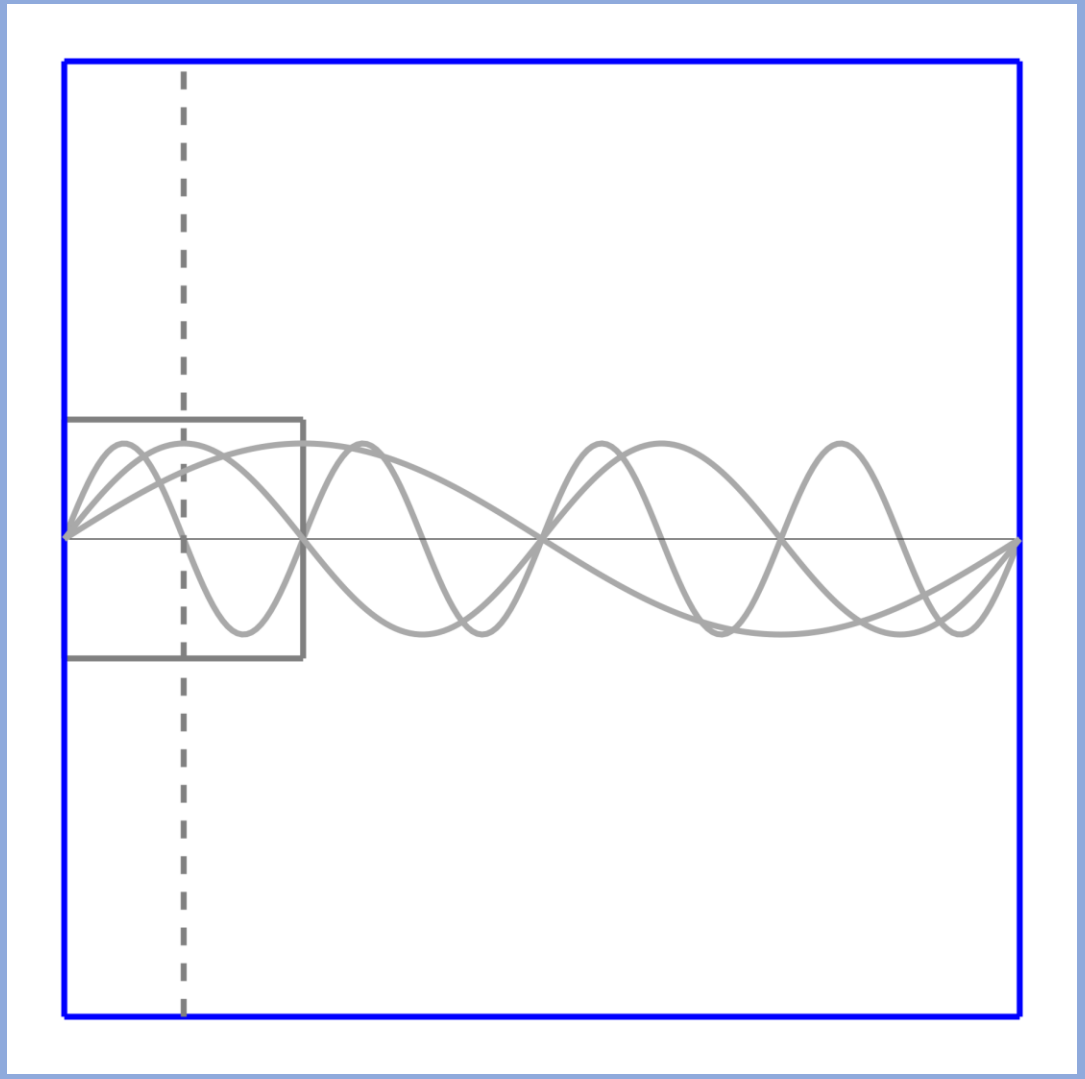

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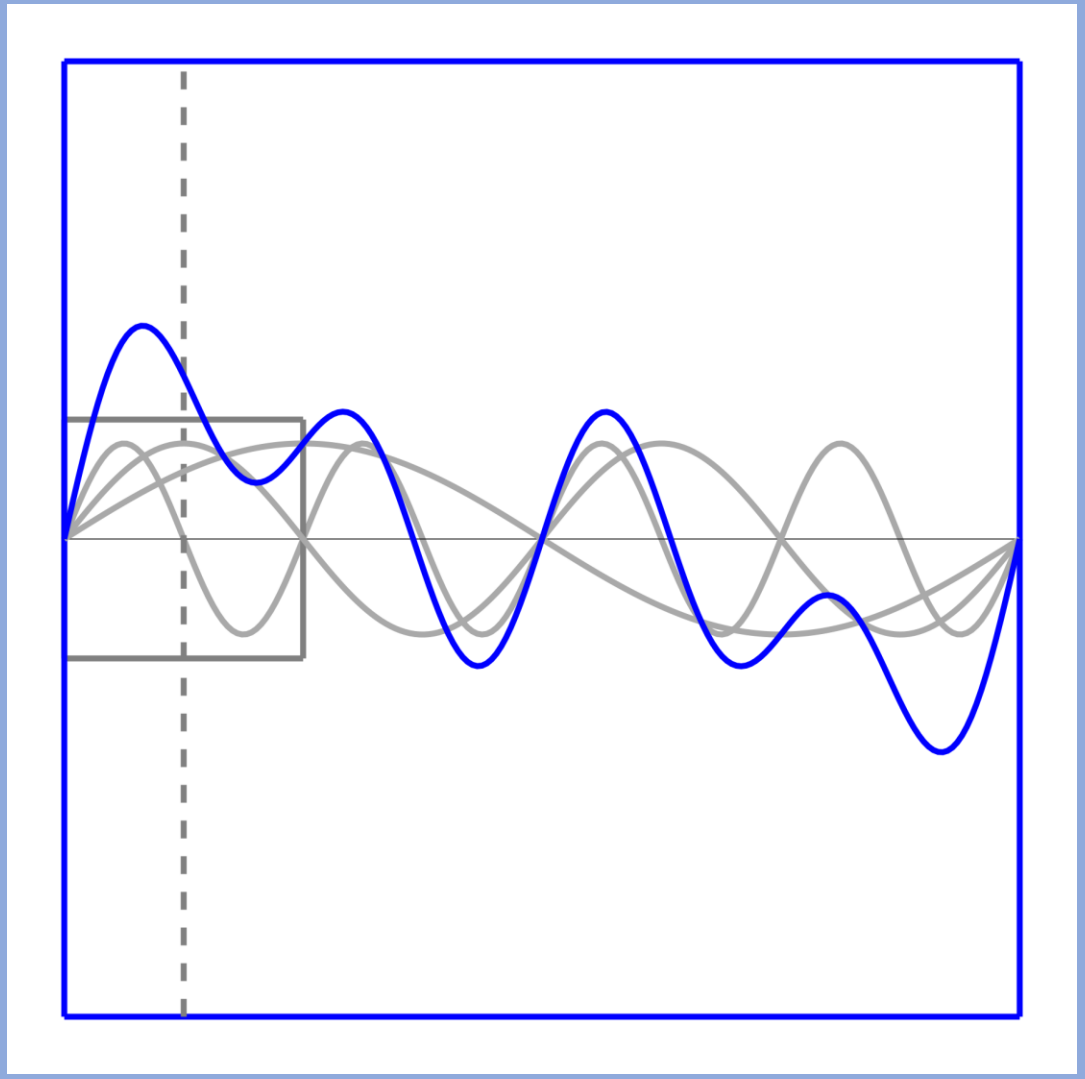

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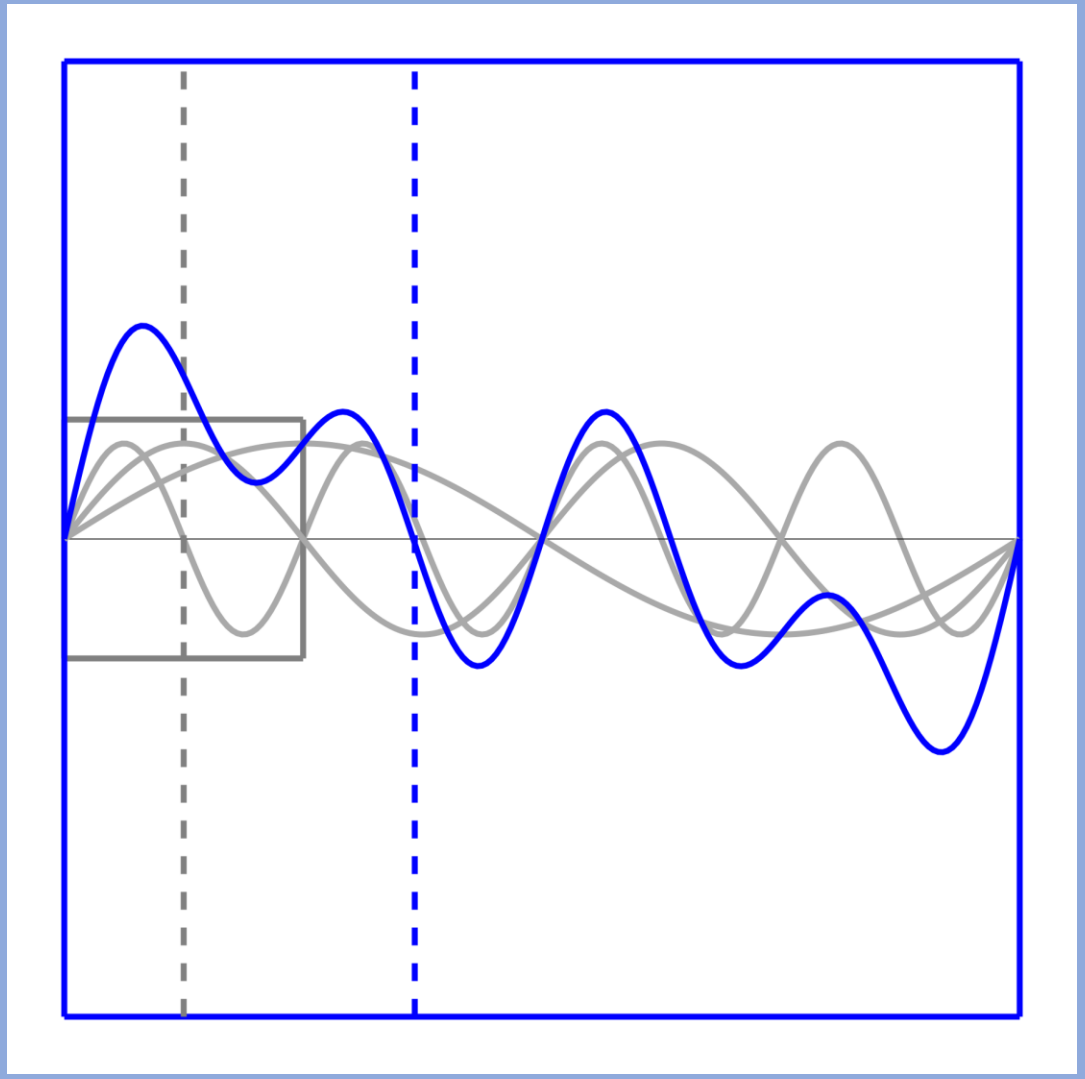
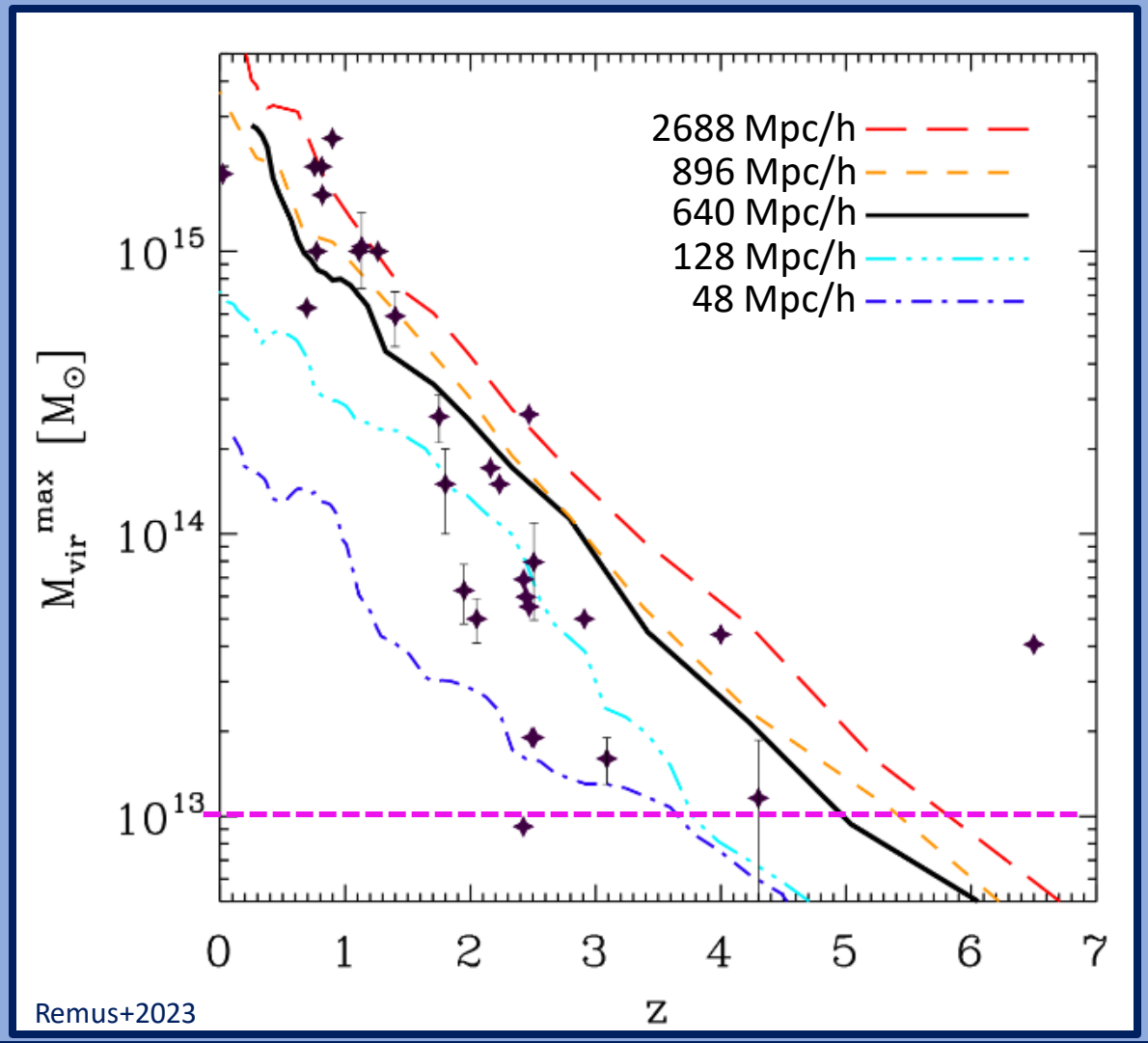
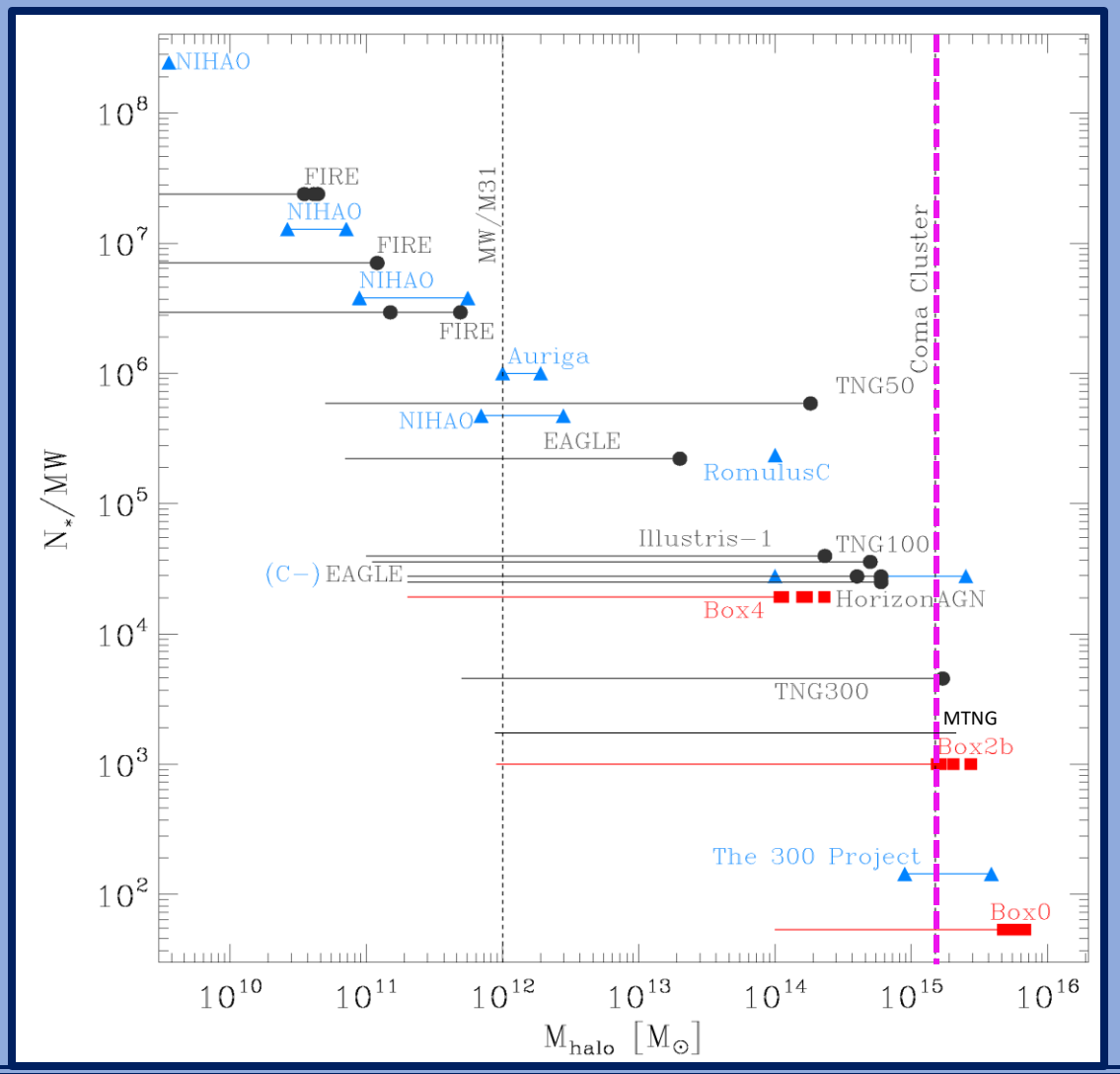


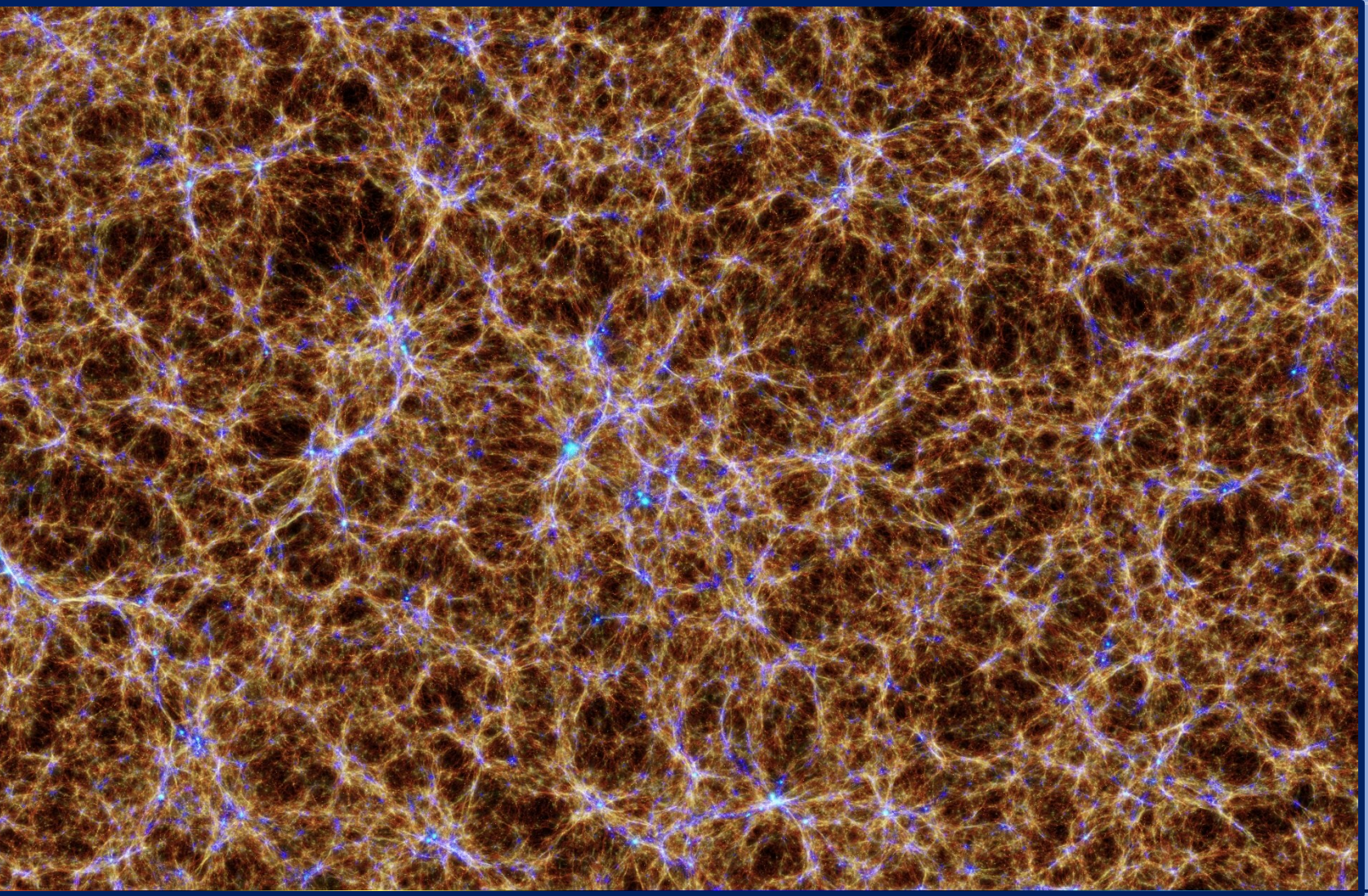
Simulations: Size vs Resolution



Remus+2023



Currently Available Large Volume Cosmological Simulations



Magneticum Box2b-Simulation:
640 Mpc/h,
$m_{DM}\ (M_\odot/h) = 6.9{\cdot}10^8$ Dolag+2016

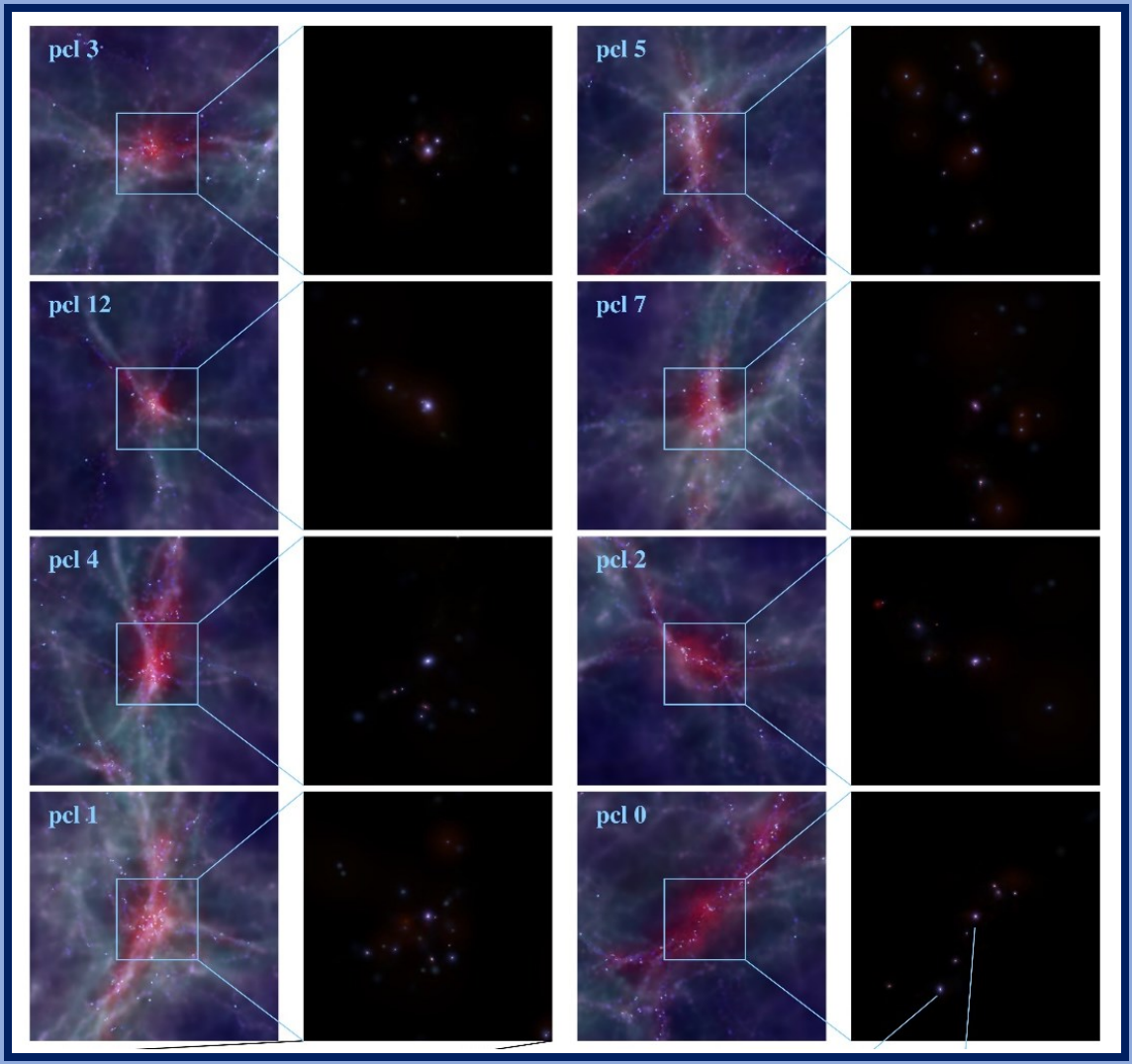
MilleniumTNG-Simulation:
500 Mpc/h,
$m_{DM}\ (M_\odot/h) = 1.7{\cdot}10^8$ Pakmor+2022

Millenium-Simulation:
500 Mpc/h,
$m_{DM}\ (M_\odot/h) = 8{\cdot}10^8$ Springel+2005

Bahamas-Simulation:
400 Mpc/h,
$m_{DM}\ (M_\odot/h) = 3.85{\cdot}10^9$ McCarthy+2017

TNG300:
300 Mpc/h,
$m_{DM}\ (M_\odot/h) = 6{\cdot}10^7$ Springel+2018

Identifying Protocluster

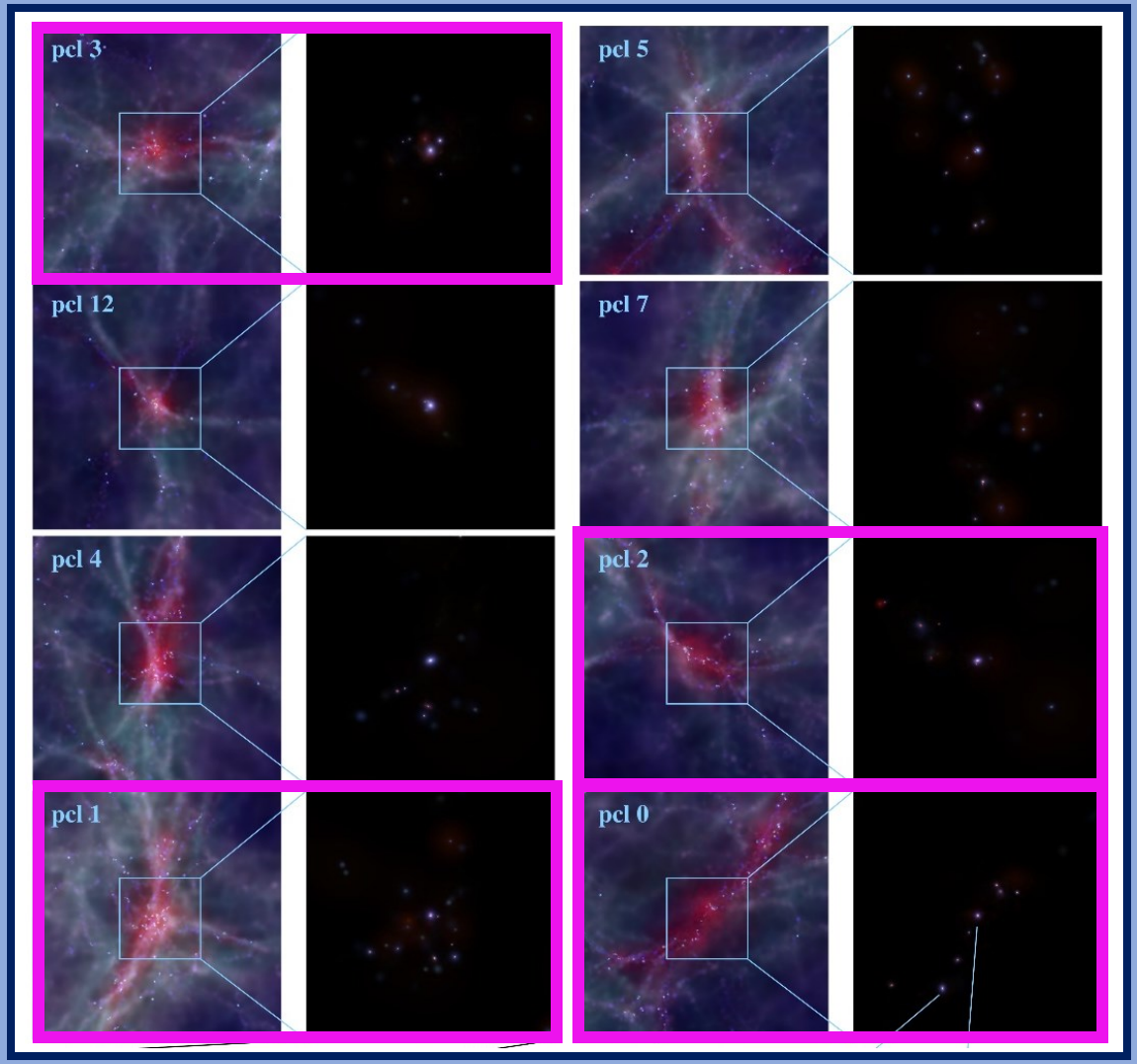


Different selection criteria:

- Most massive M_{vir}
- Most massive M_{BCG}
- Richest N_{gal}
- Most starforming

Remus et al., 2023

Identifying Protocluster



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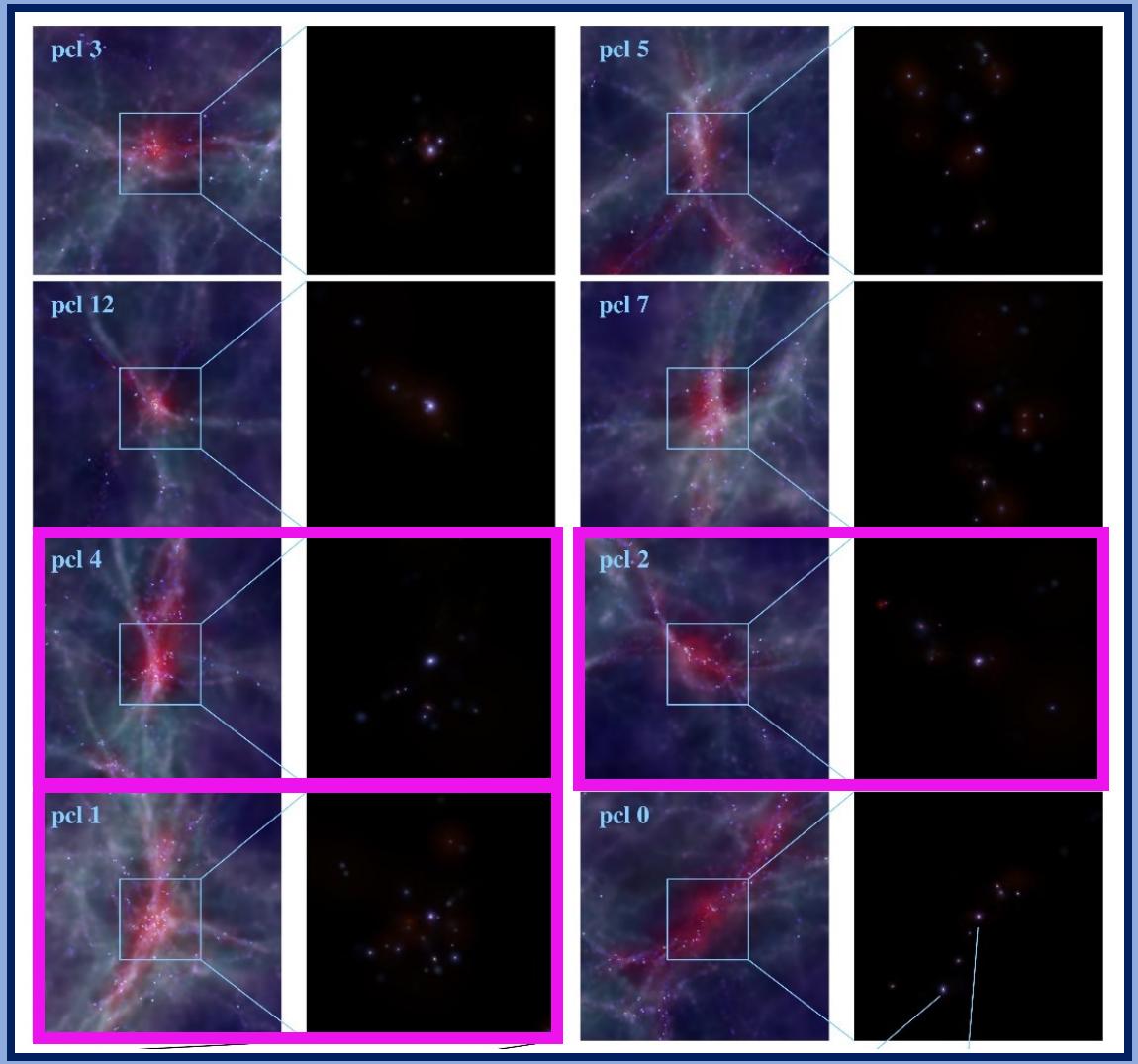

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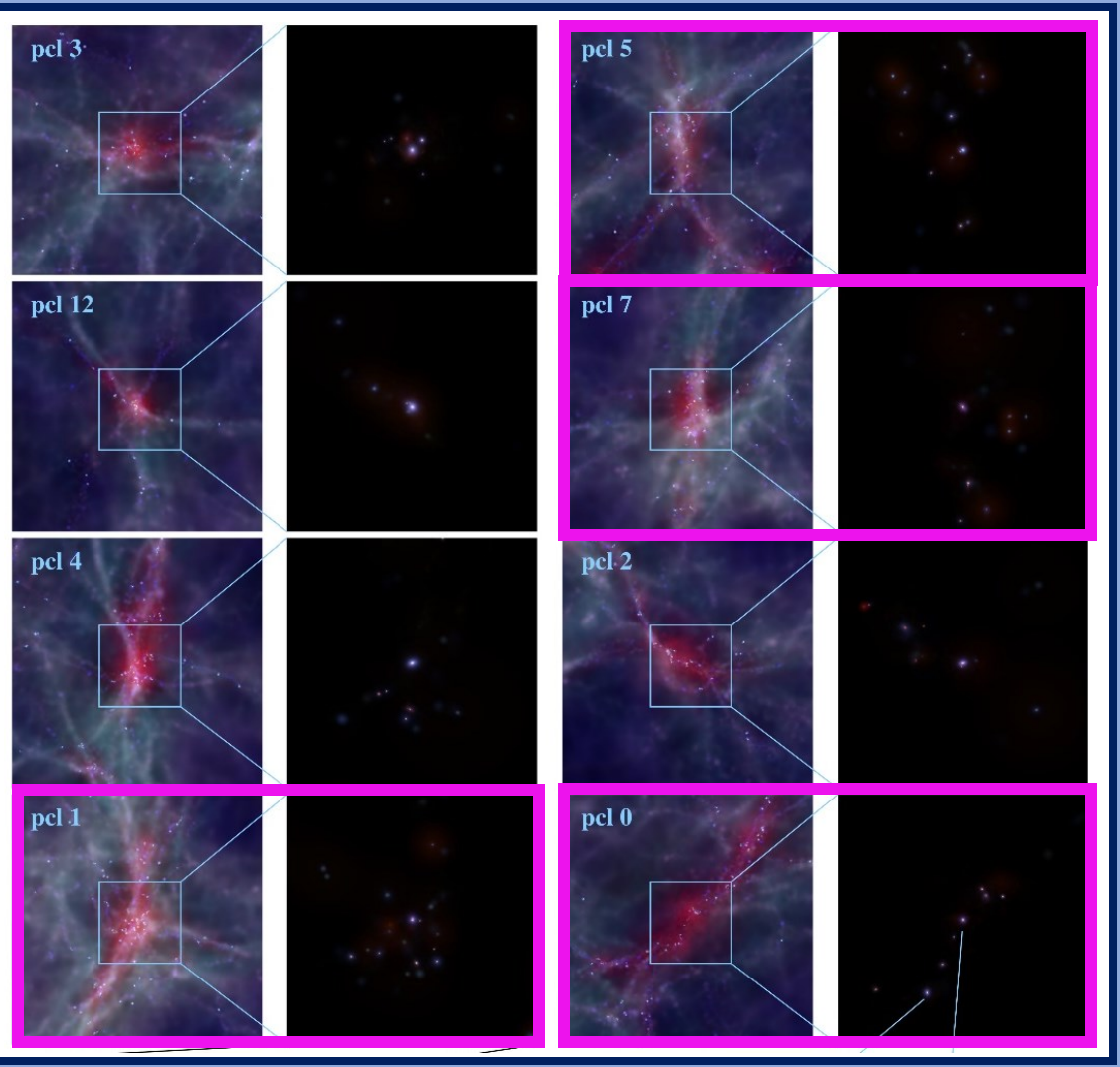

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Remus et al., 2023

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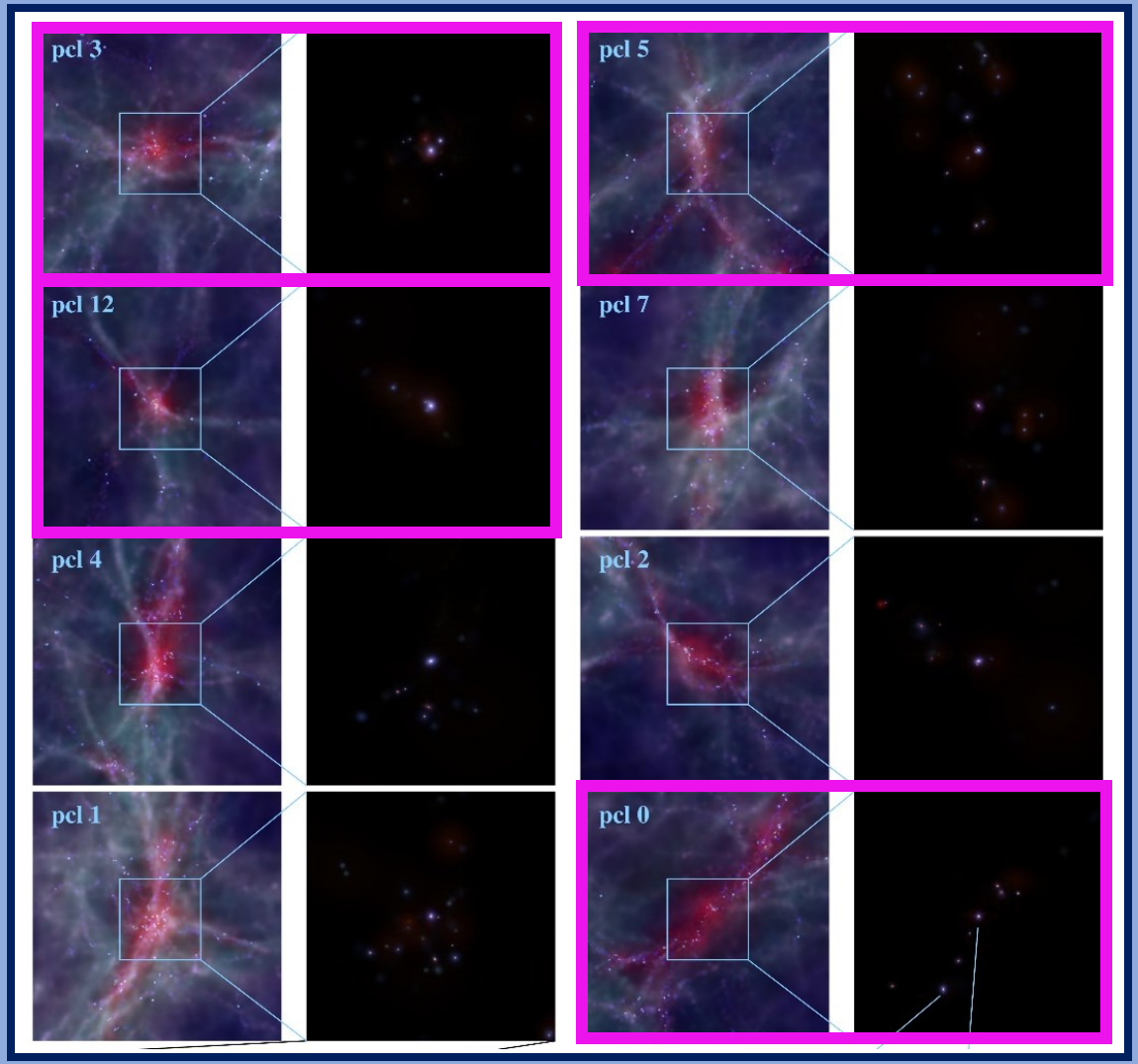

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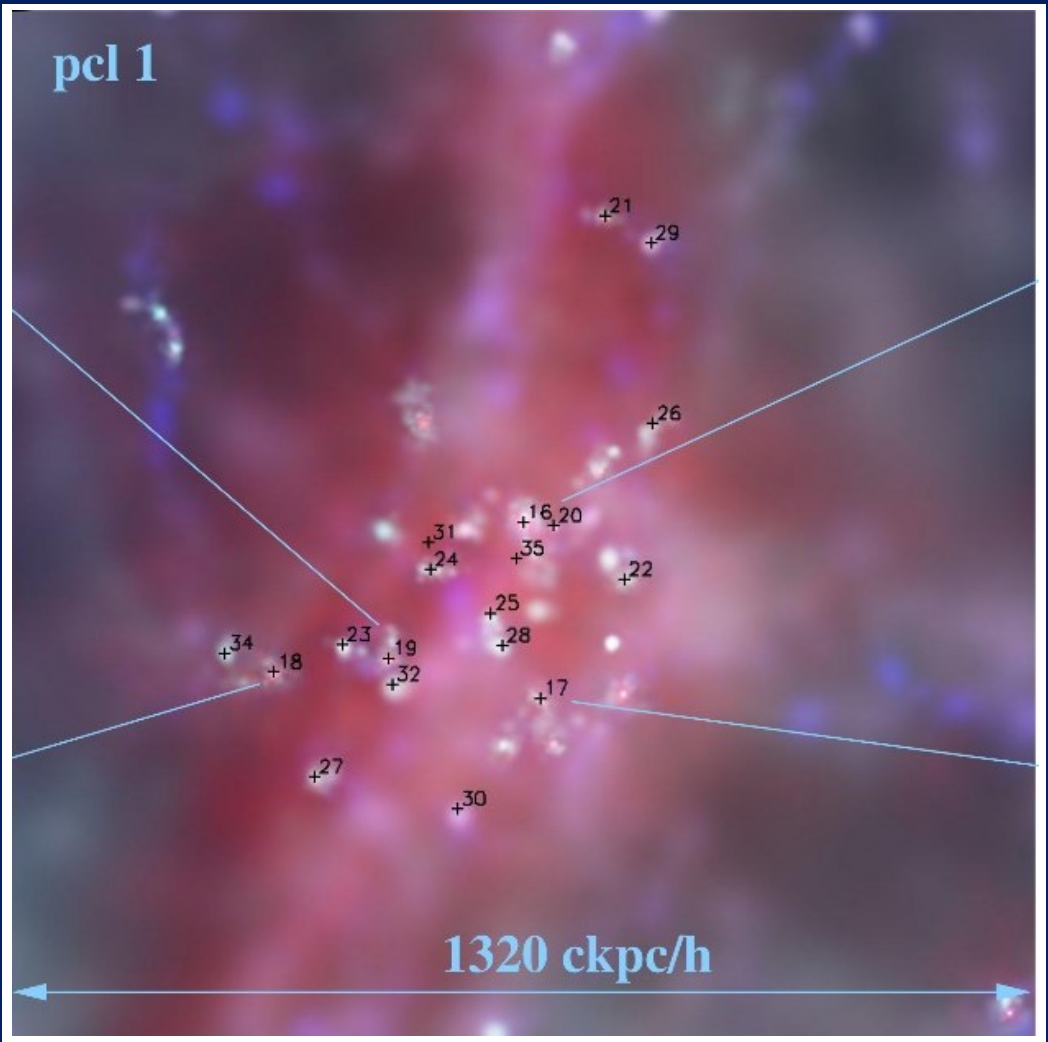
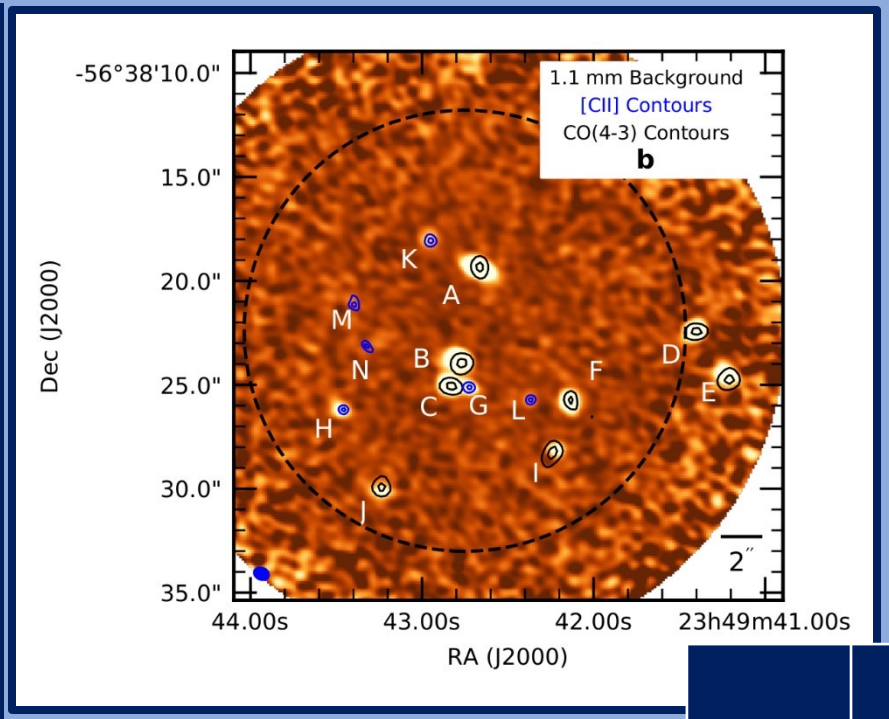
- Most massive M_{BCG}
- Richest N_{gal}
- Most starforming

Remus et al., 2023

Example Comparison



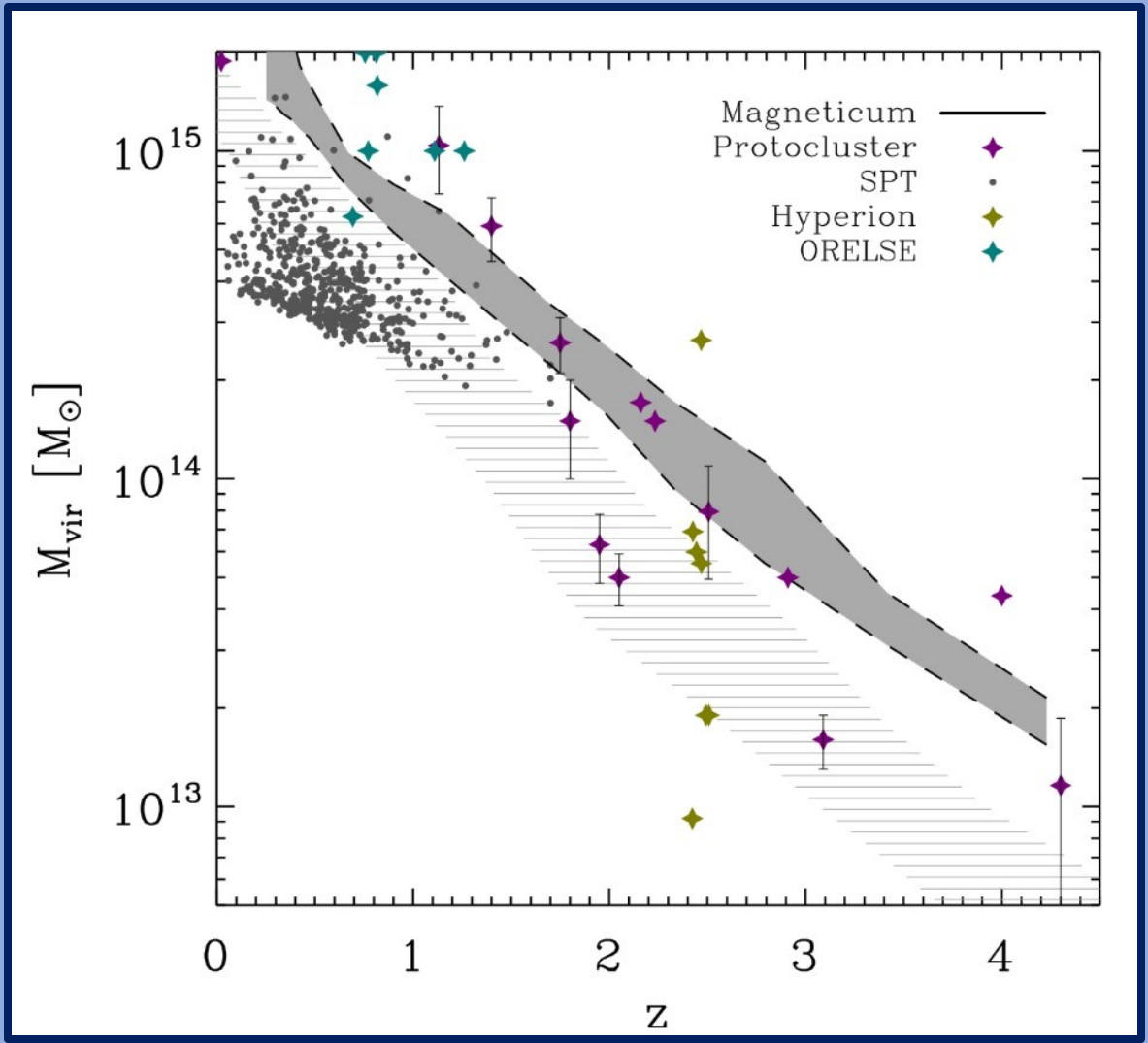
Remus et al., 2023



Miller et al., 2018

	PT2349-56	PCl1
M_{BCG}	$3.2\ x\ 10^{11} M_{\odot}$	$5.7\ x\ 10^{11} M_{\odot}$
N_{gal}	14	19
M_{*}	$1.2\ x\ 10^{12} M_{\odot}$	$1.0 x\ 10^{12} M_{\odot}$

Protocluster Evolution

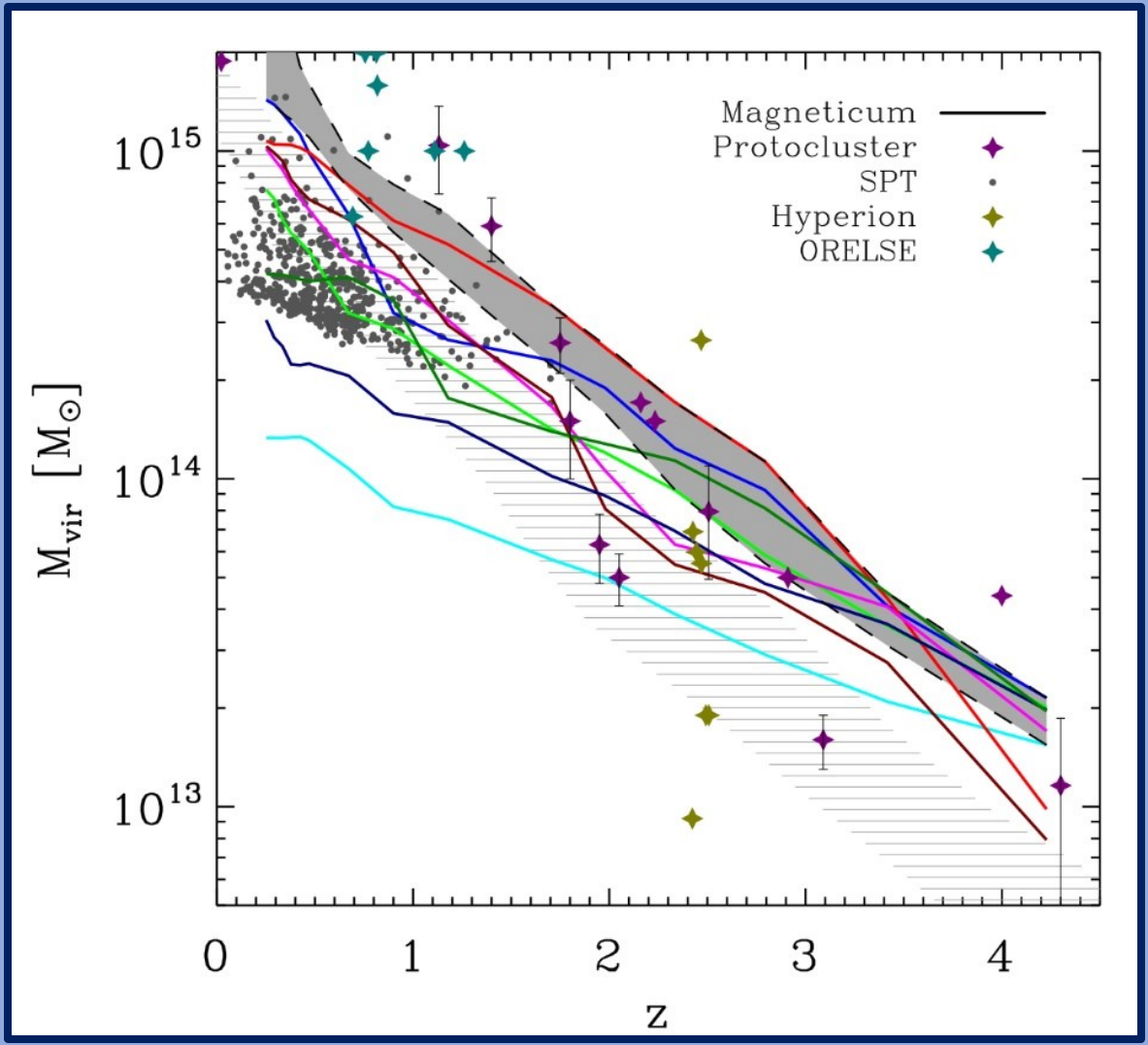


Shade: Magneticum Most Massive at each redshift, Remus+2023

Striped: Millenium prediction, Chiang+2013

Remus et al., 2023

Protocluster Evolution

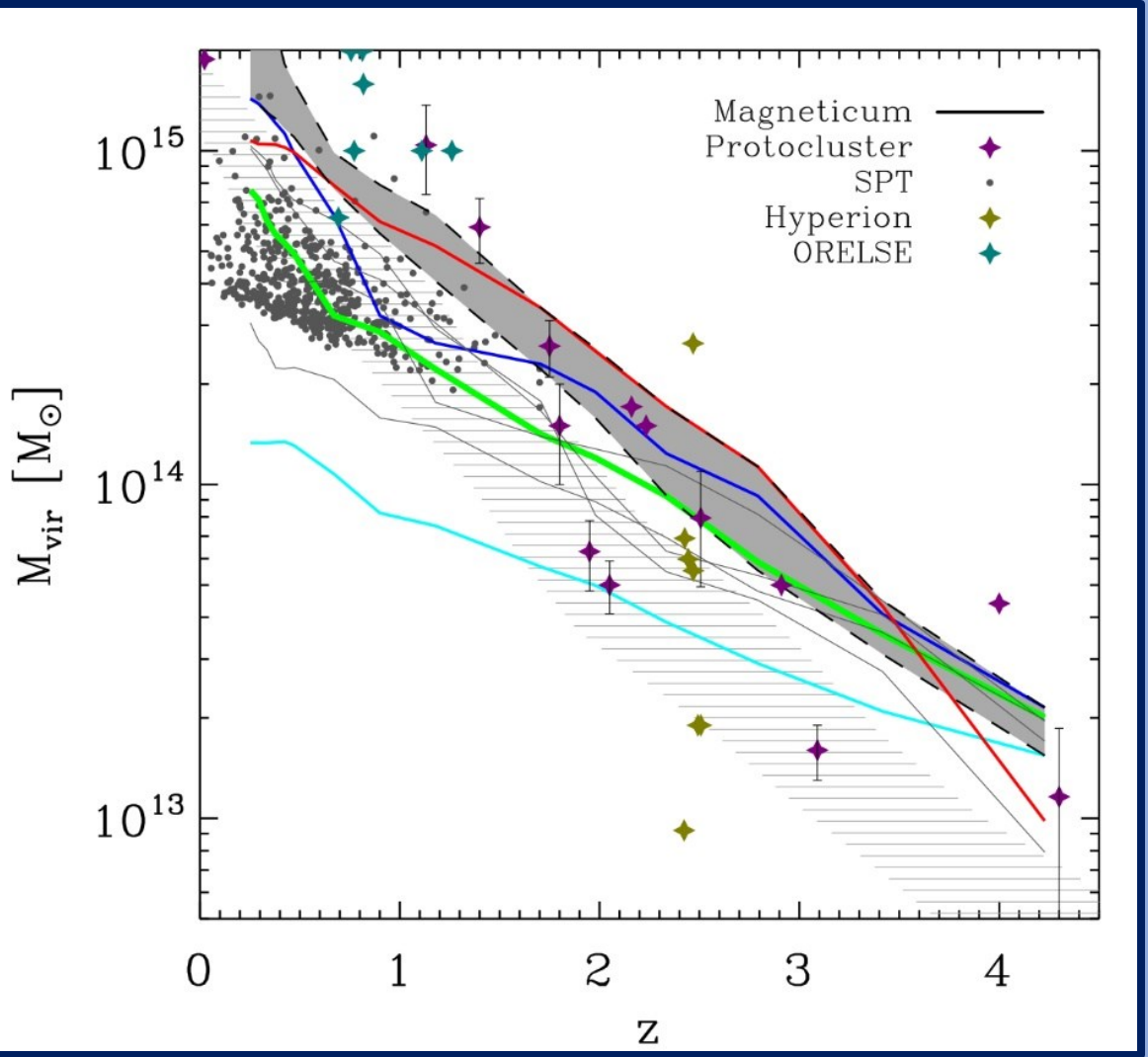


Remus et al., 2023

Colored lines: Tracked Protoclusters

Shade: Magneticum Most Massive at each redshift, Remus+2023
Striped: Millenium prediction, Chiang+2013

Protocluster Evolution

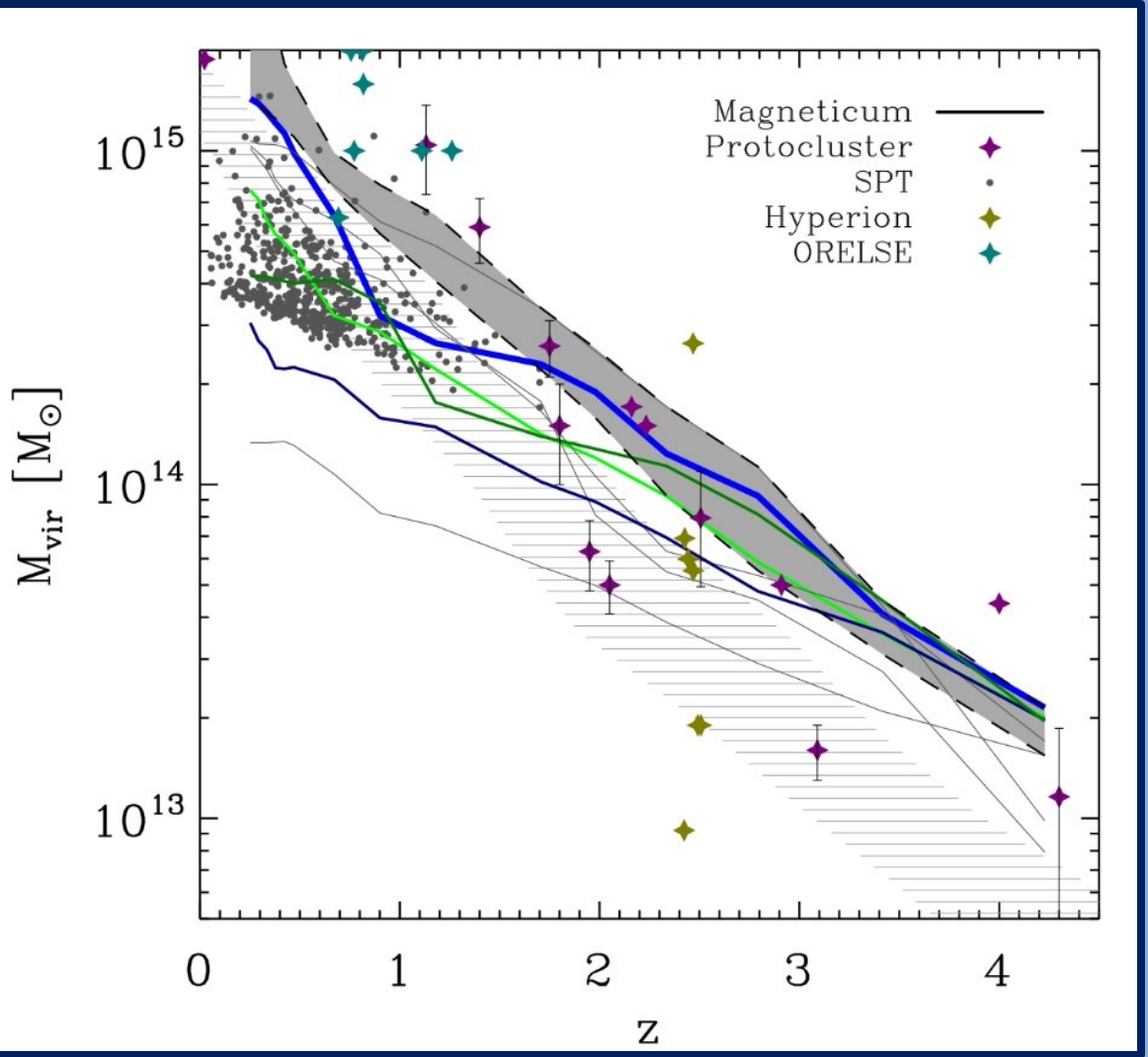


Protoclusters: Most Star Forming

Shade: Magneticum Most Massive at each redshift
Striped: Millenium prediction, Chiang et al., 2013

Remus et al., 2023

Protocluster Evolution

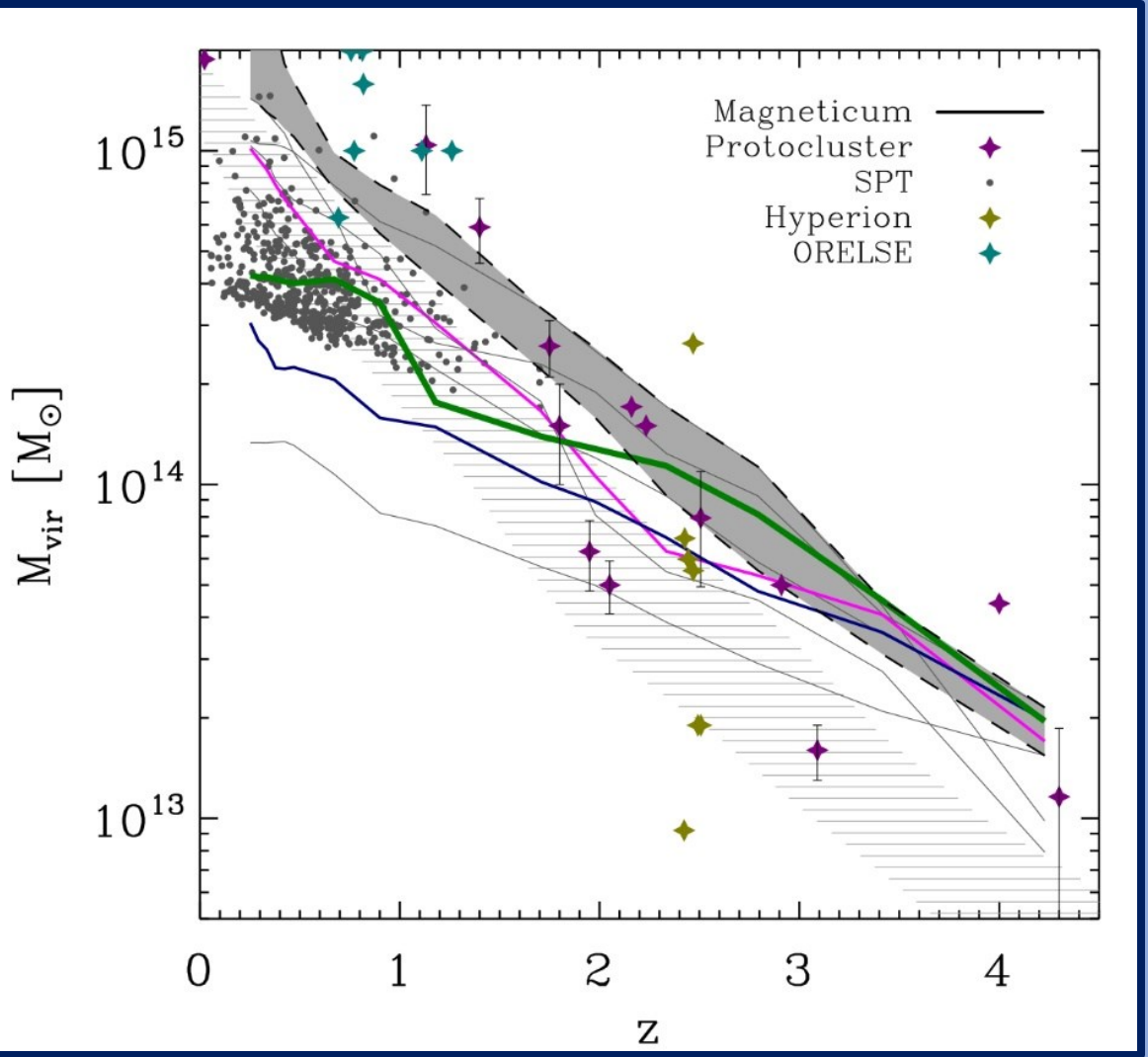


Protoclusters: Highest Total Mass

Shade: Magneticum Most Massive at each redshift
Striped: Millenium prediction, Chiang et al., 2013

Remus et al., 2023

Protocluster Evolution

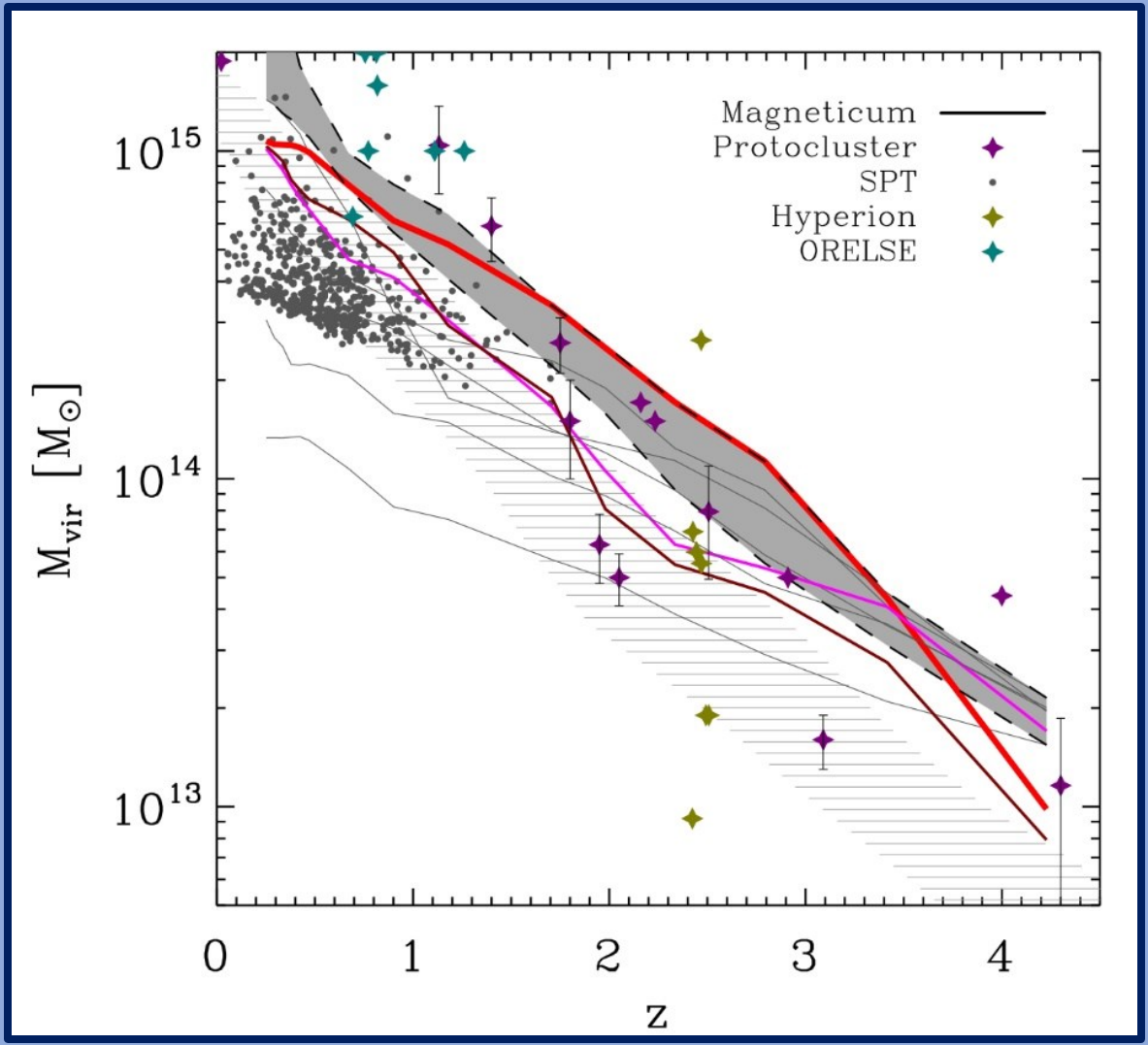


Protoclusters: Most Massive BCG

Shade: Magneticum Most Massive at each redshift
Striped: Millenium prediction, Chiang et al., 2013

Remus et al., 2023

Protocluster Evolution

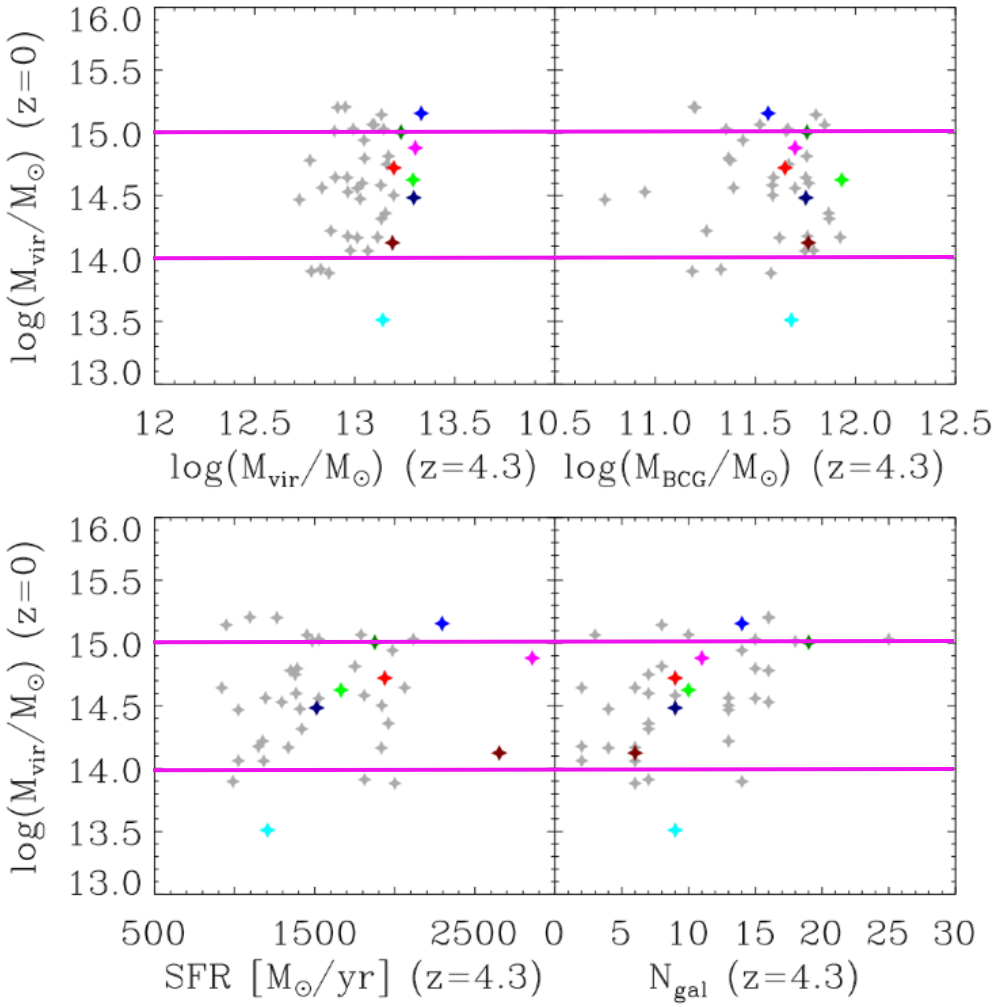


Protoclusters: Richest Cluster

Shade: Magneticum Most Massive at each redshift
Striped: Millenium prediction, Chiang et al., 2013

Remus et al., 2023

Protocluster Evolution



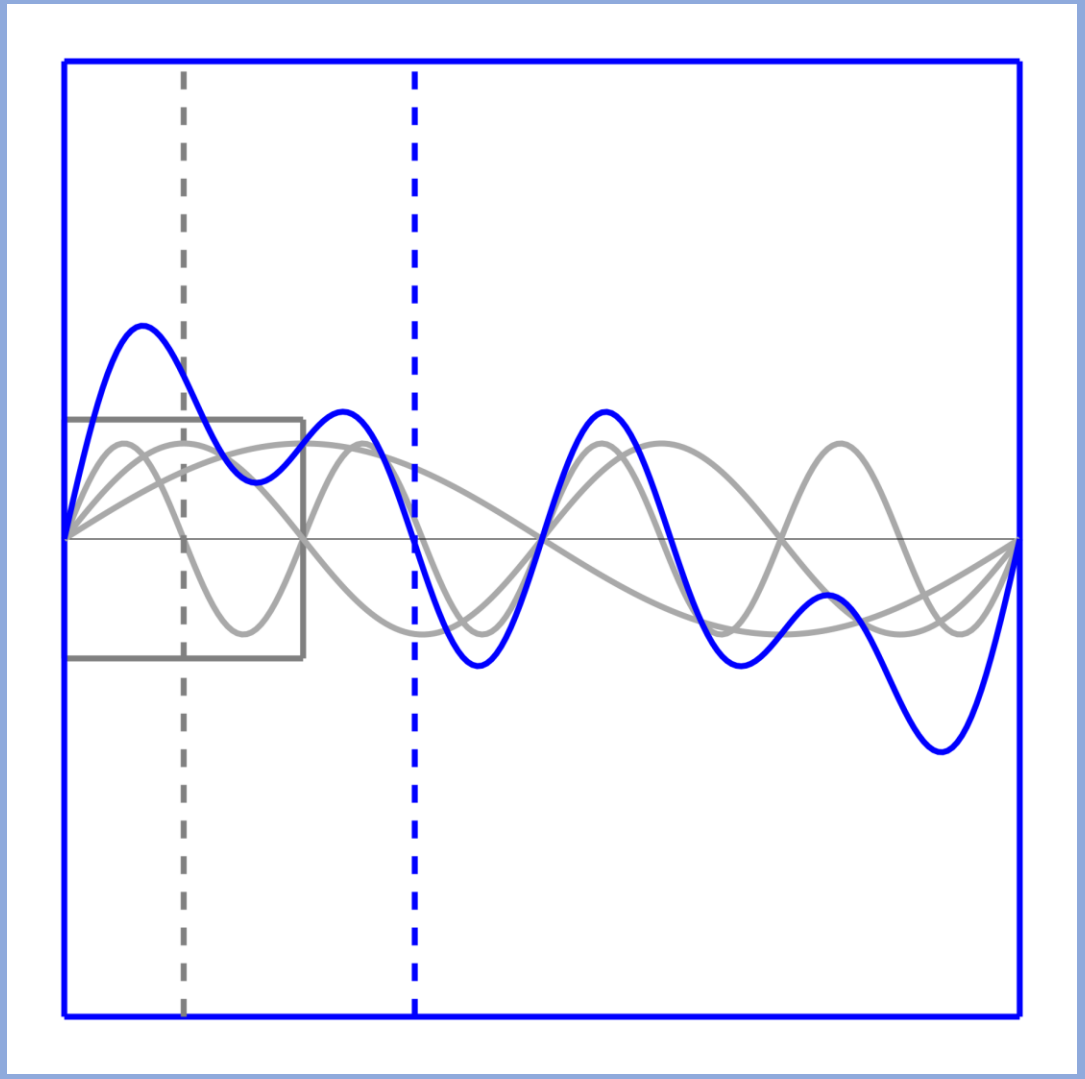
Neither total mass nor BCG mass or star formation rate at z=4.3 are a good measure of what to become.

Not All Protoclusters become actual clusters at z=0! (see also Kimmig et al, 2023)

Best indicator: Number of galaxies

Remus et al., 2023

Remember: Modes in Cosmological Simulations



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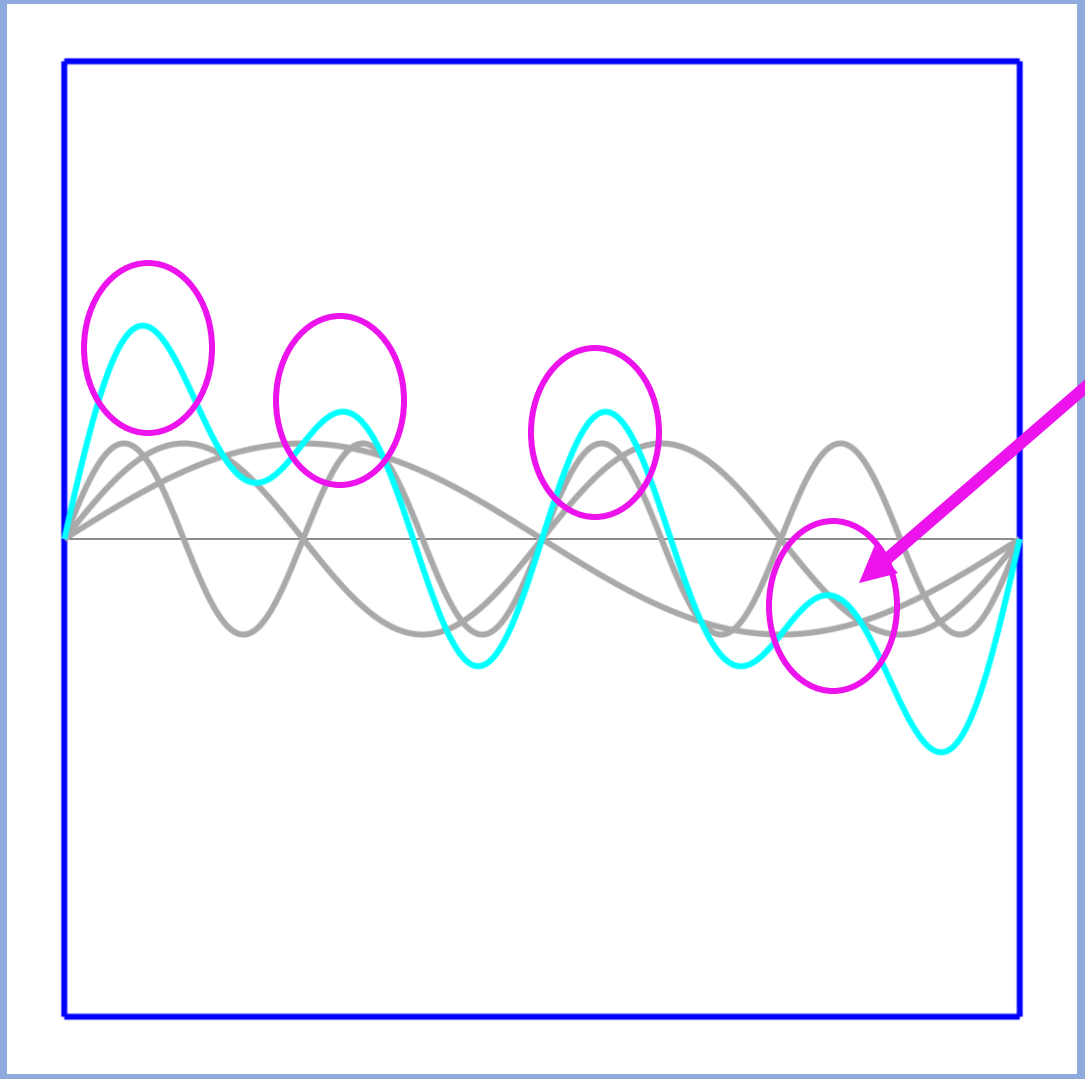
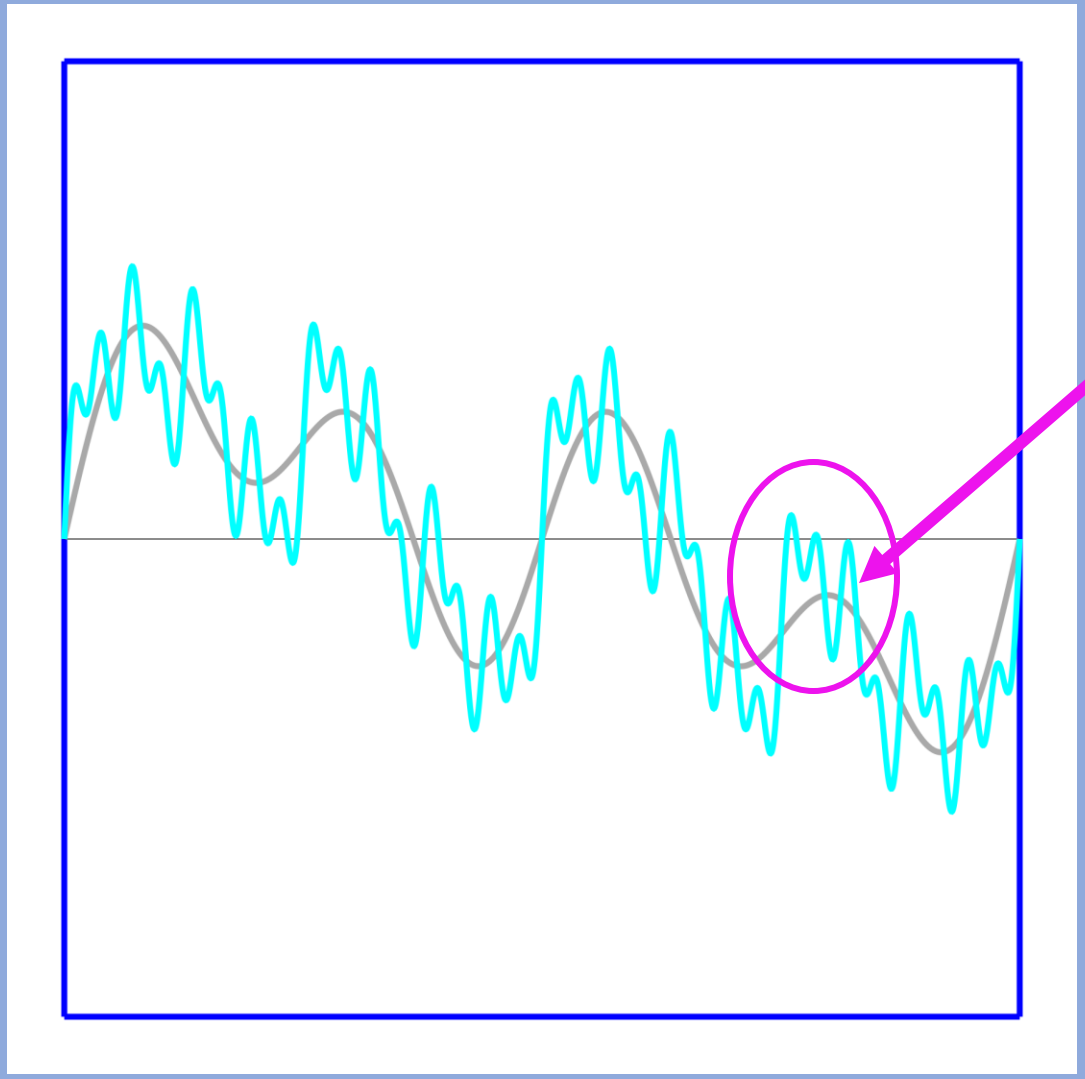


High-z overdensity,
BUT
global underdensity!

Halo will starve!

Remember: Modes in Cosmological Simulations



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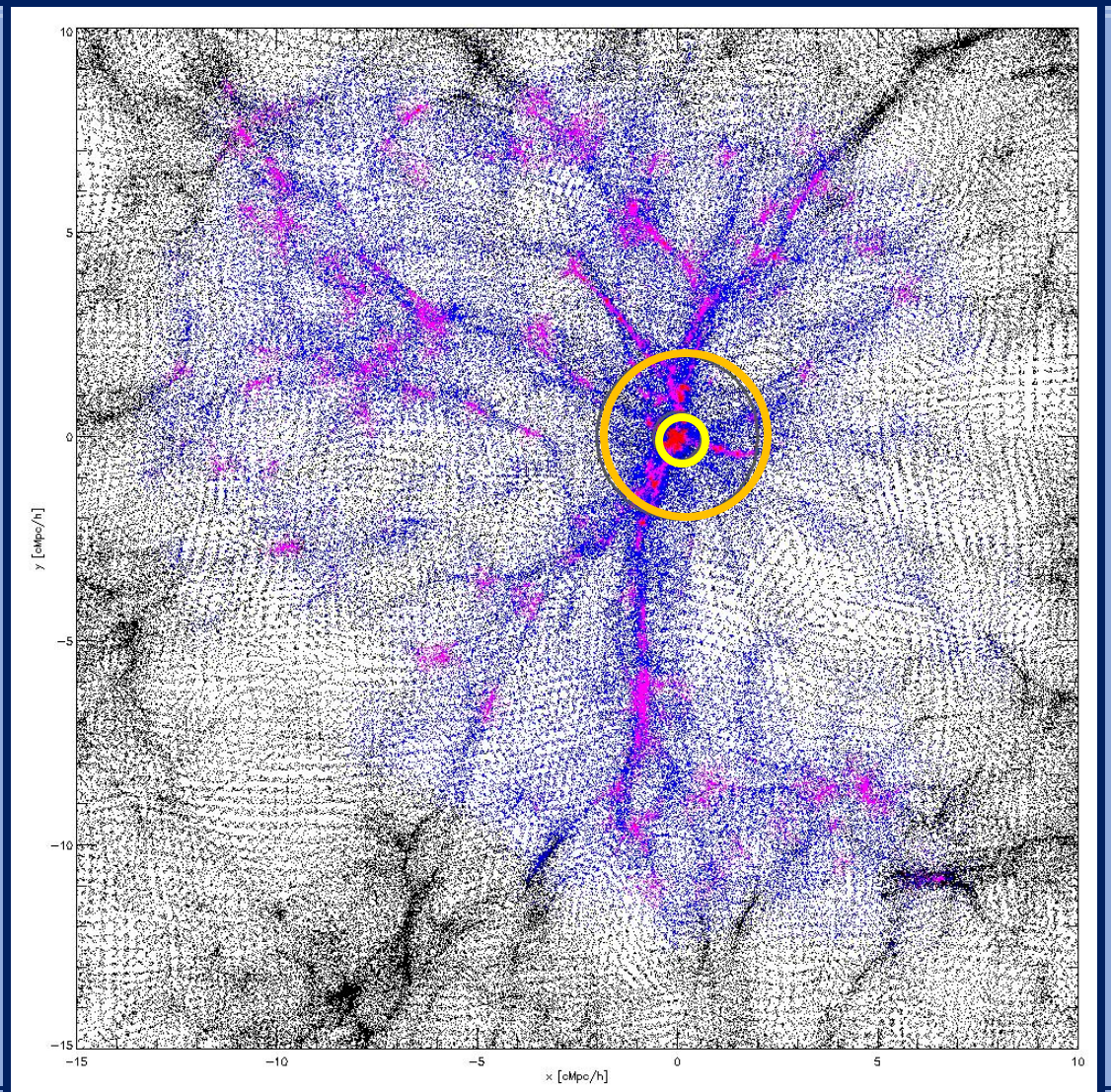
Protocluster: Map the Web

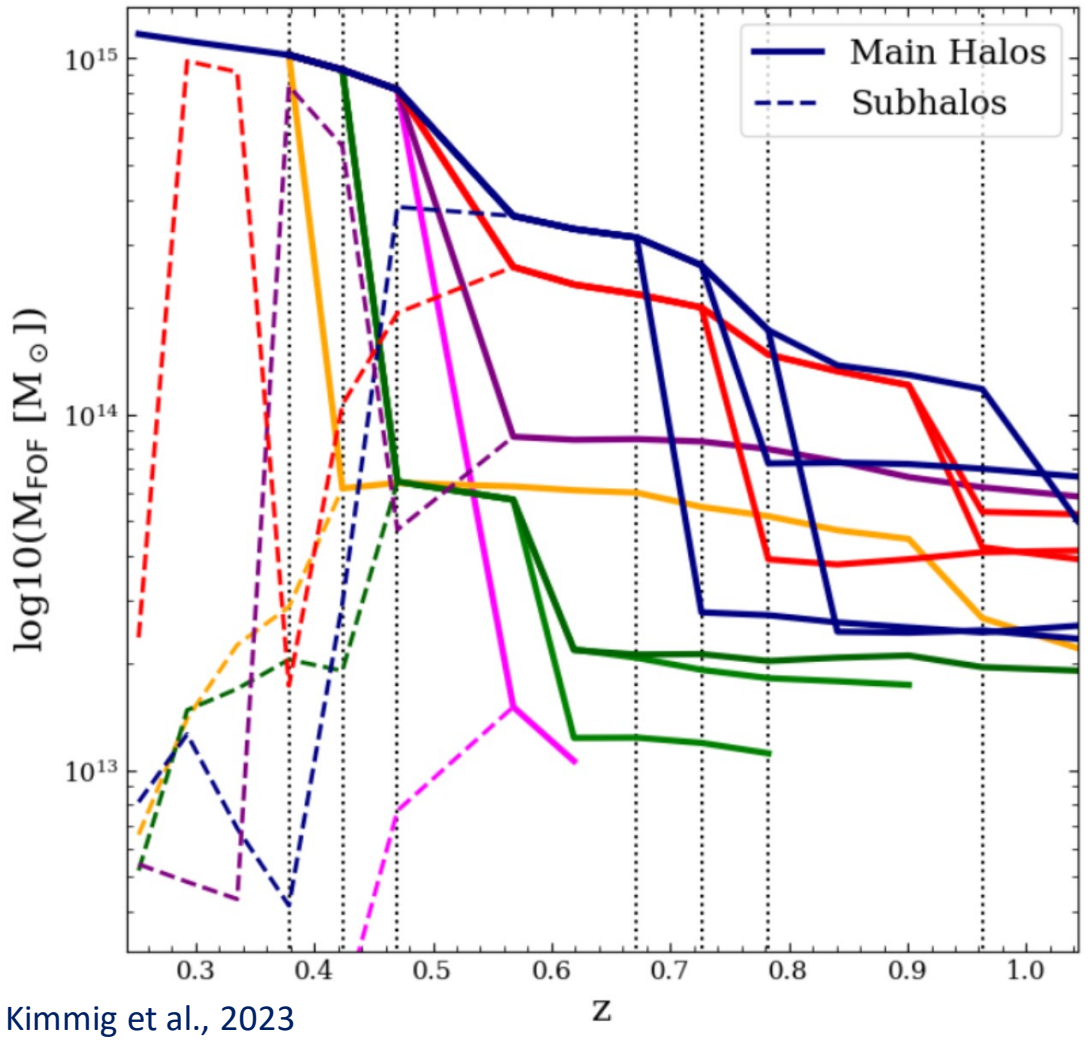


Number Member Galaxies ≙ Cosmic Web Tracing

R_{vir} @ z = 4.3
R_{vir} @ z = 0

Remus et al., 2023

Protocluster Late Assembly

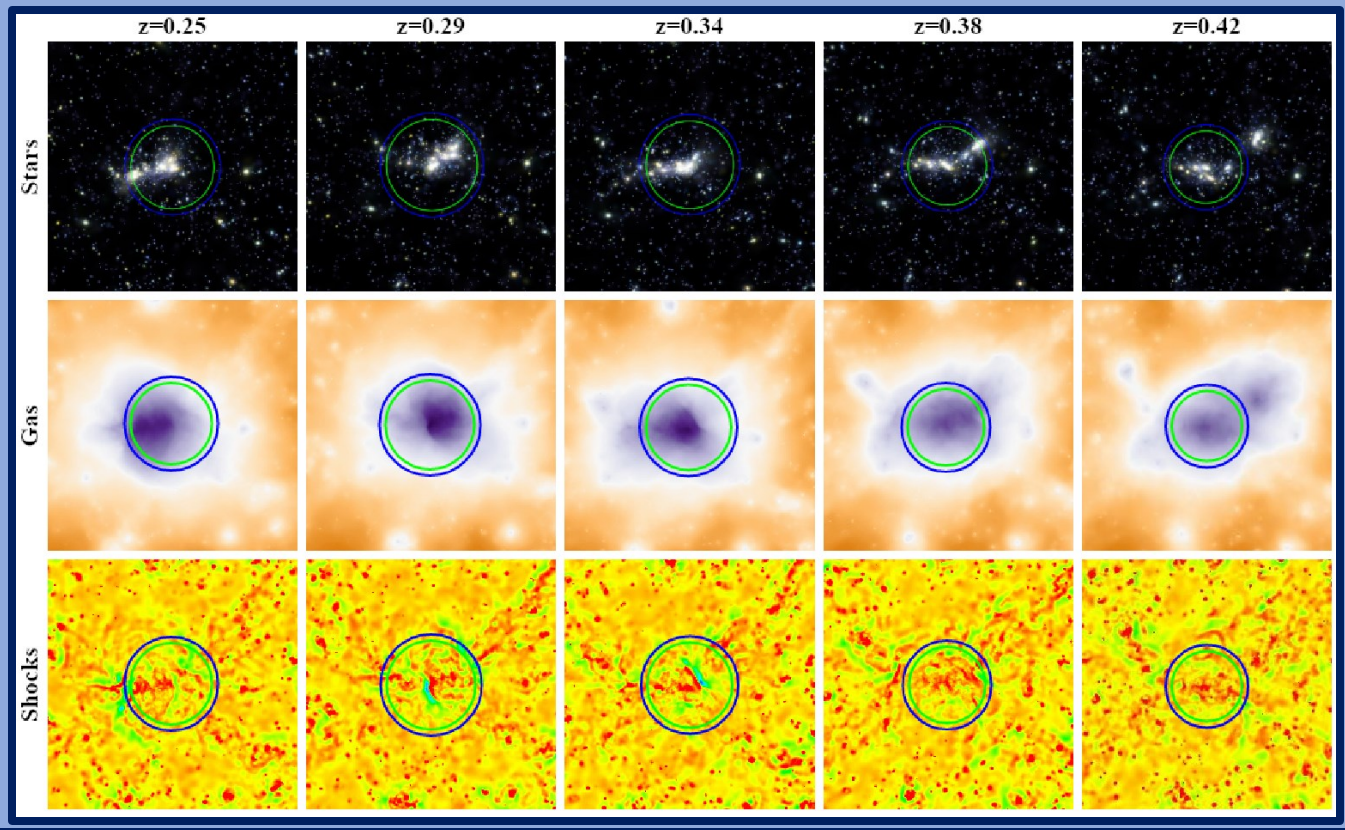


Kimmig et al., 2023

Simulated Counterpart to Abell2744:

Some of the most massive Galaxy Clusters have not even reached Cluster Mass at z=1

(Kimmig et al., 2023)



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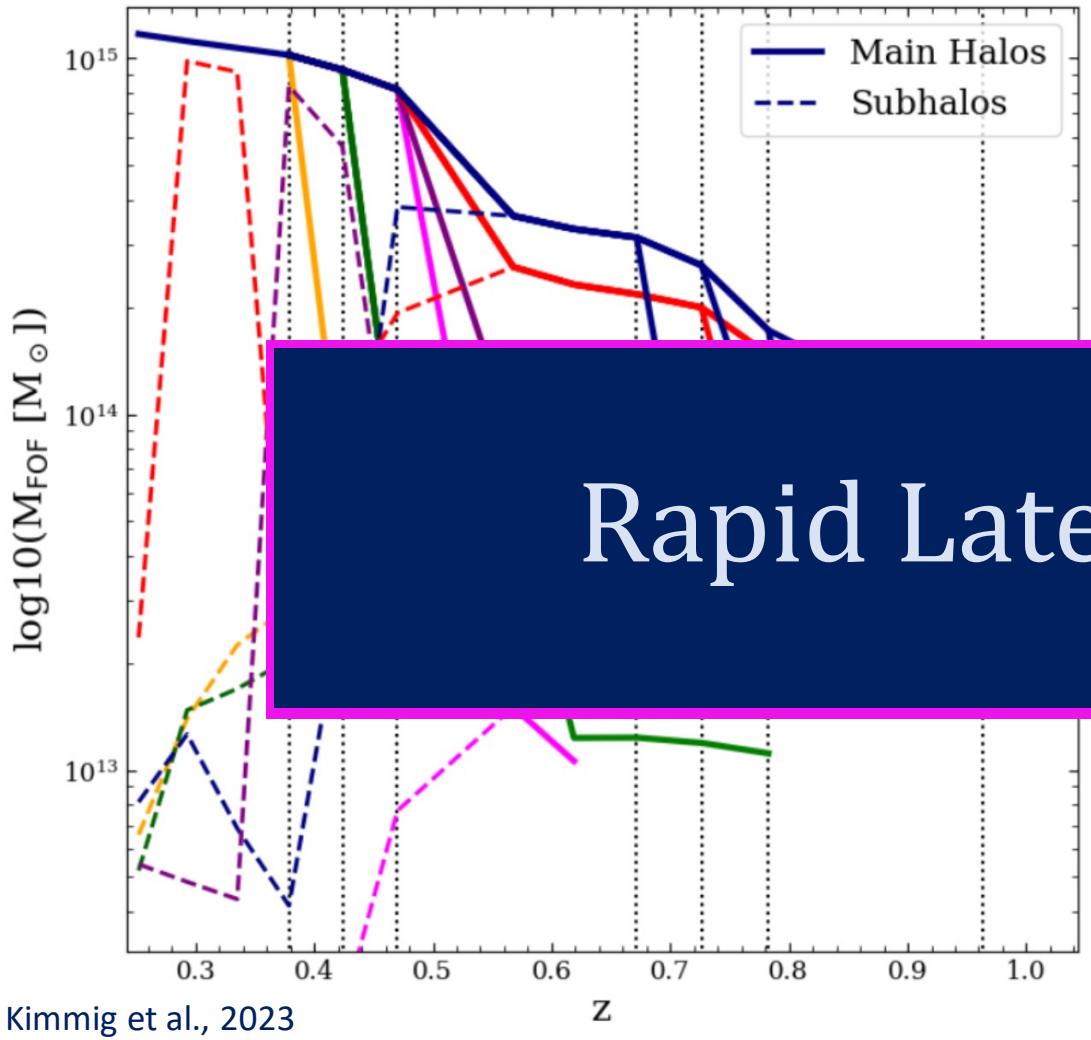

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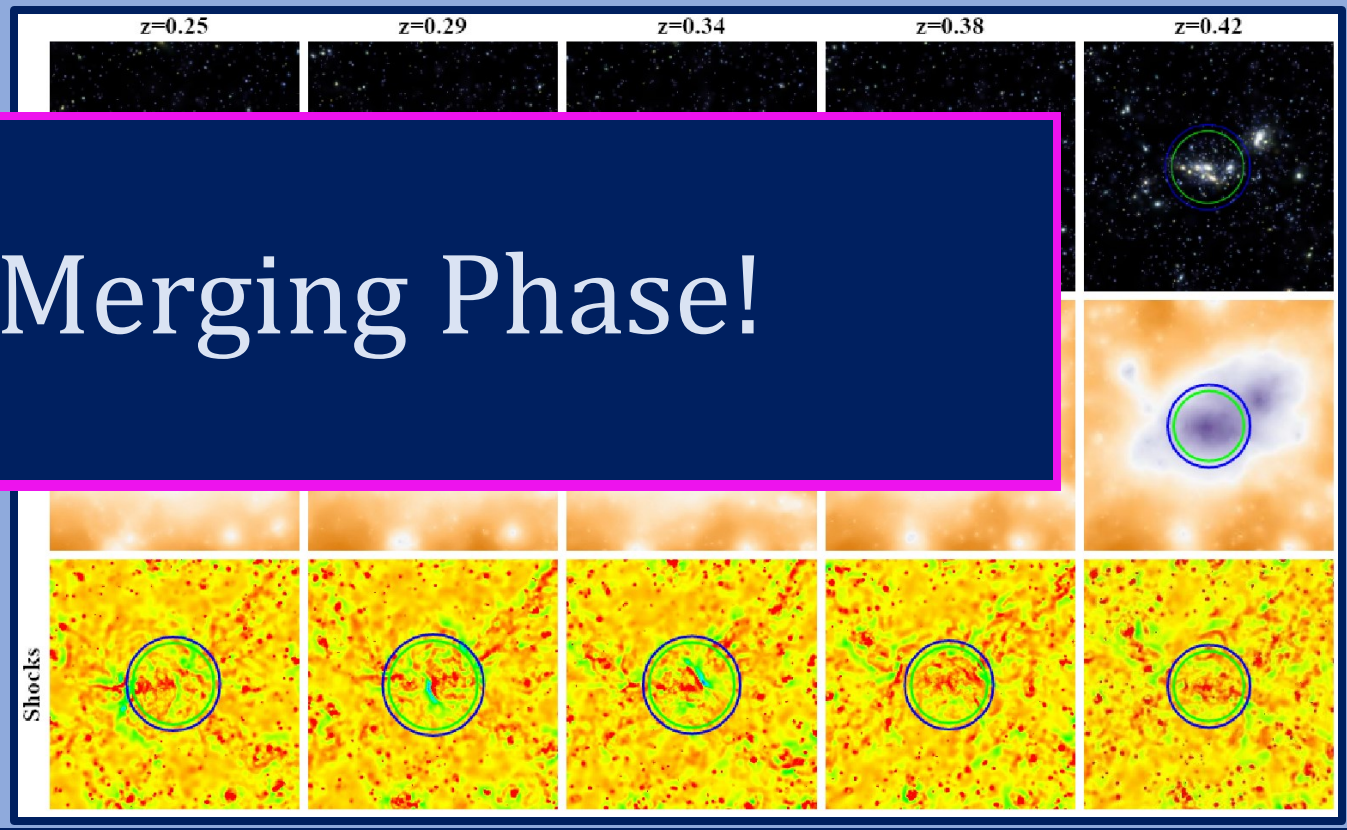
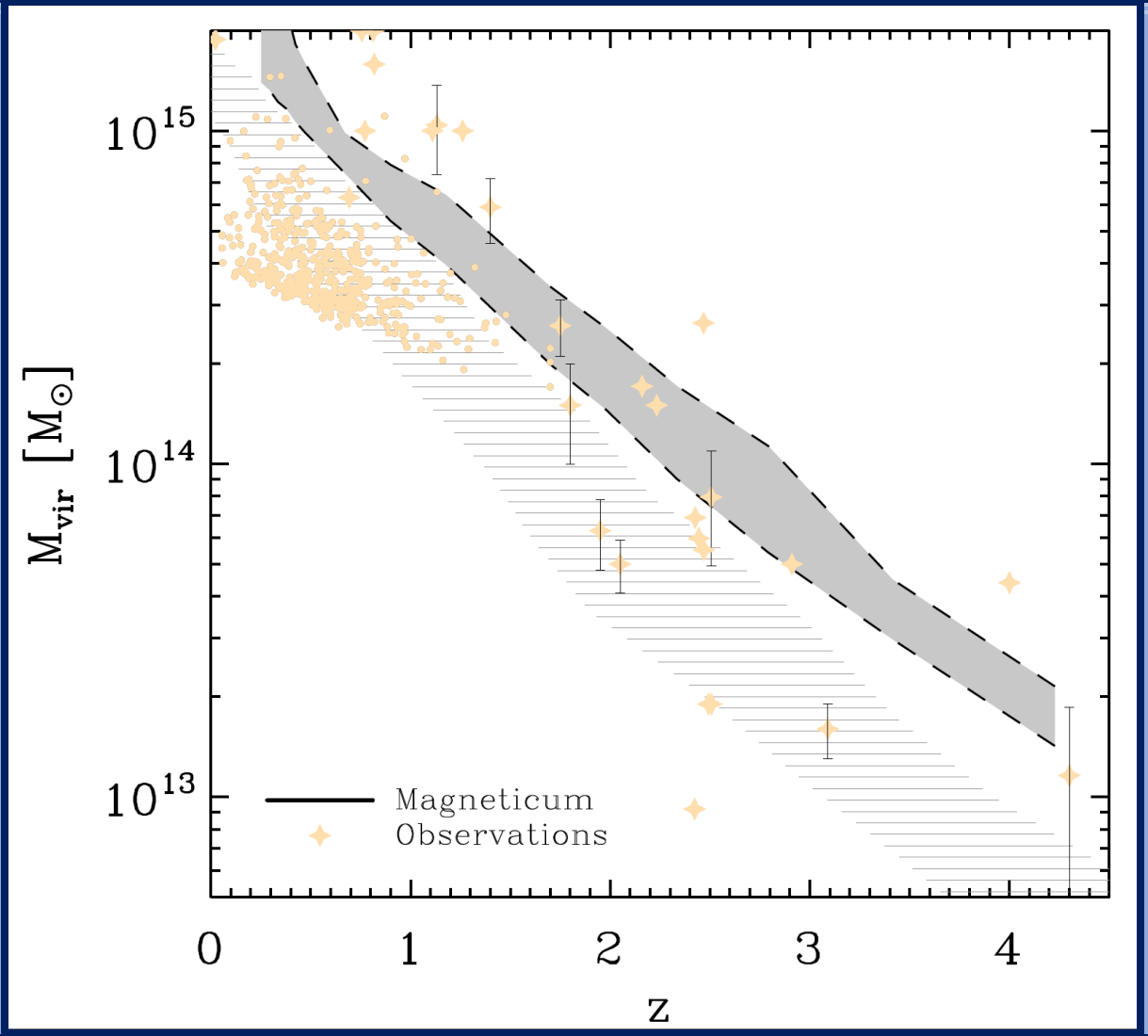


Rapid Late Merging Phase!

Protocluster: Going Local

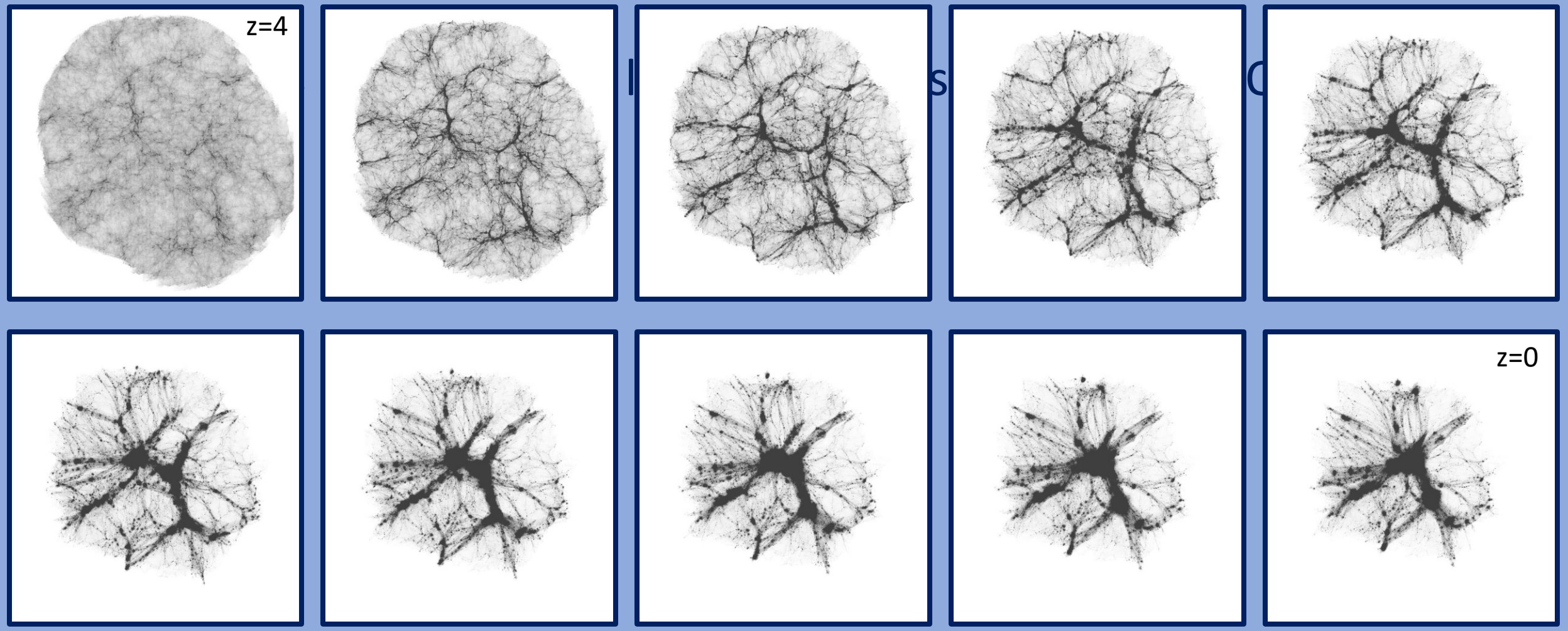
Local Universe Simulation: Initial conditions constrained by observations of the local flow field (Tully+2013), method by Sorce+2017



CLONES Simulations: Local Universe Simulations Sorce+2018

SLOW Simulations: Local Universe Box Simulation (Dolag+2023)

Protocluster: Going Local – COMA cluster

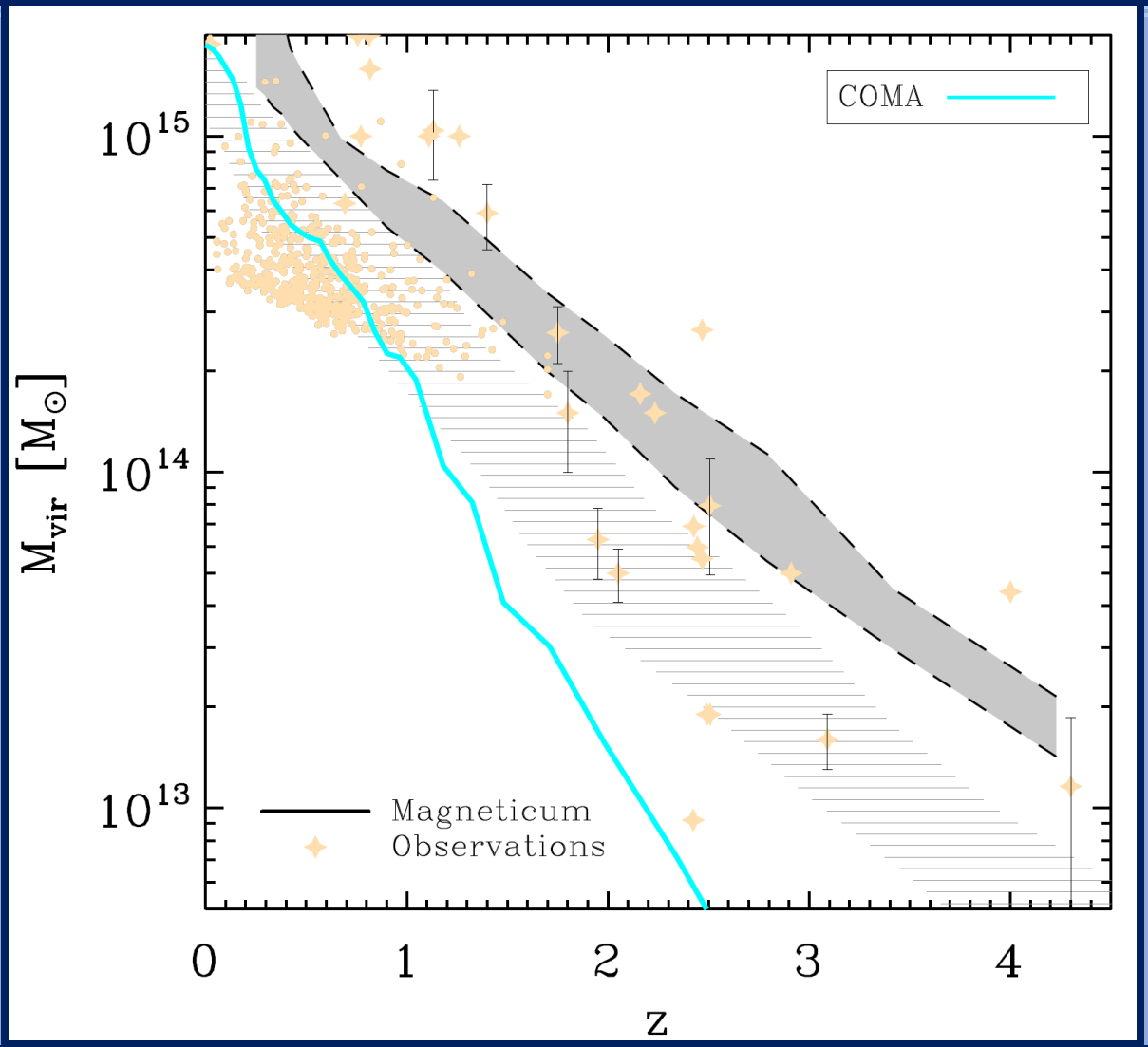


Pictures Curtesy of Benjamin Seidel

Protocluster: Going Local

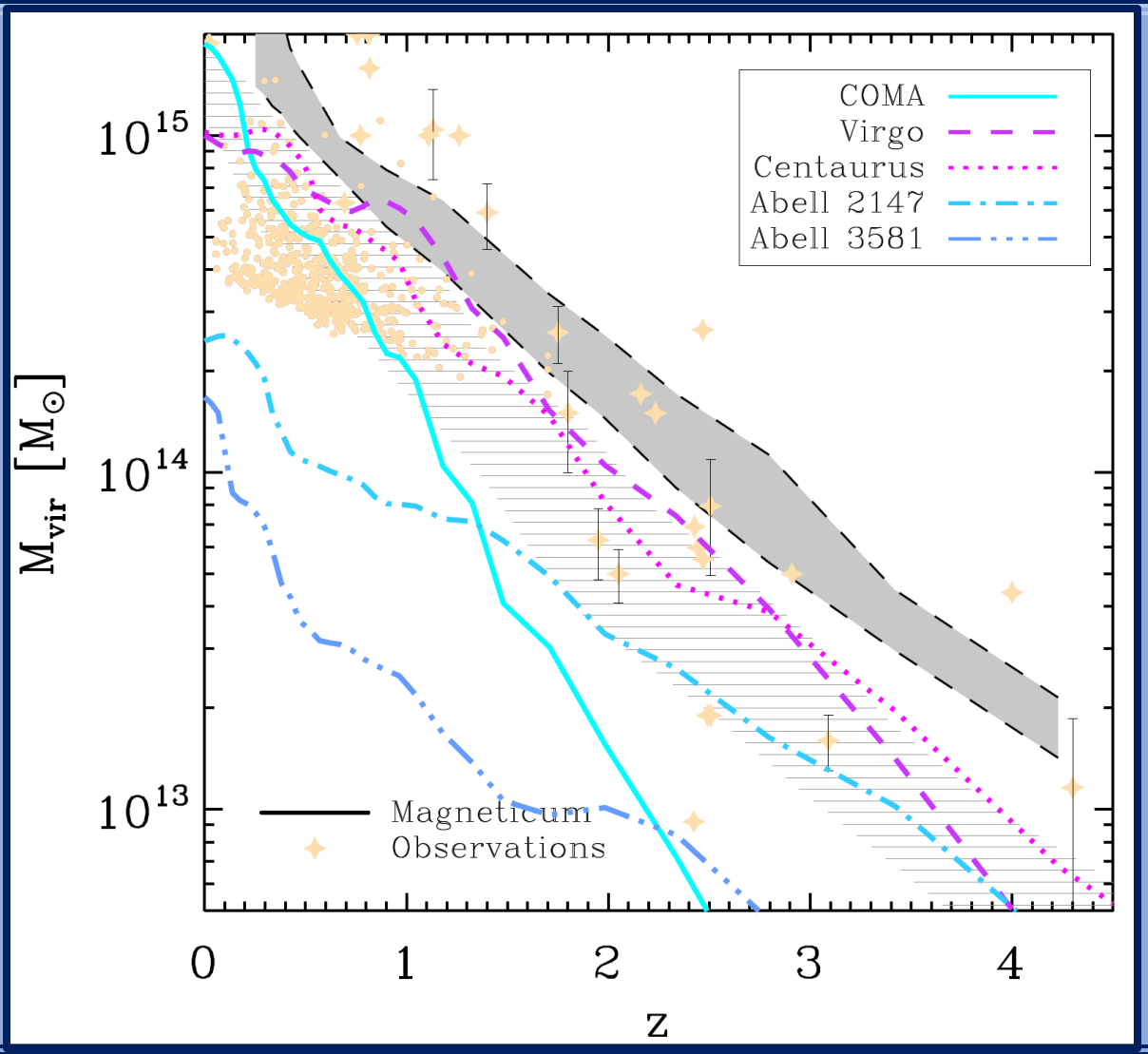
Estimated main progenitor:
$M_{vir} = 6 - 7 \times 10^{11}\ M_{\odot}$
$M_{*} = 5 - 6 \times 10^{10}\ M_{\odot}$

➡ It's a galaxy!!!



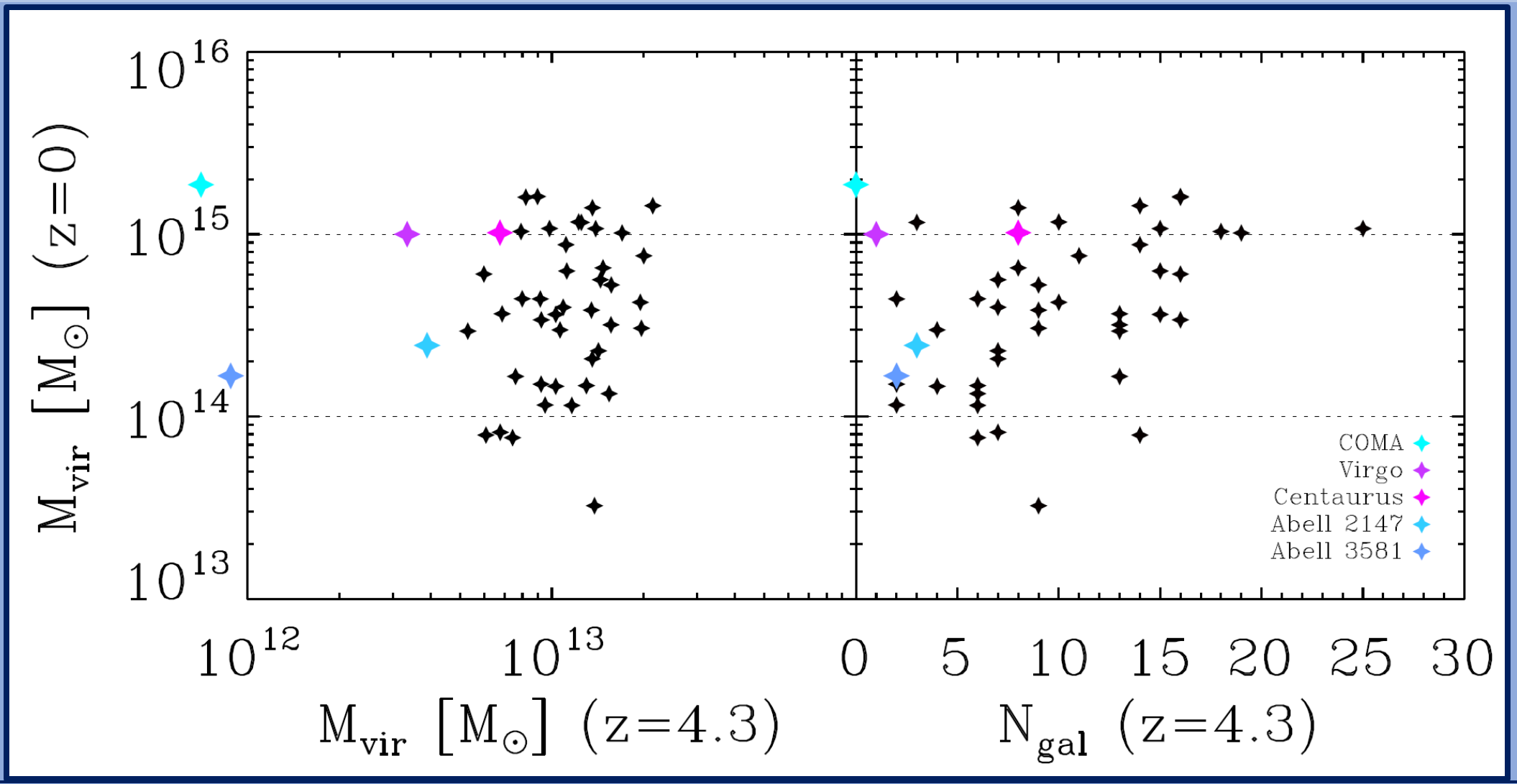
See also Malavasi+2023 for more details on the COMA cluster CLONE

Protocluster: Going Local

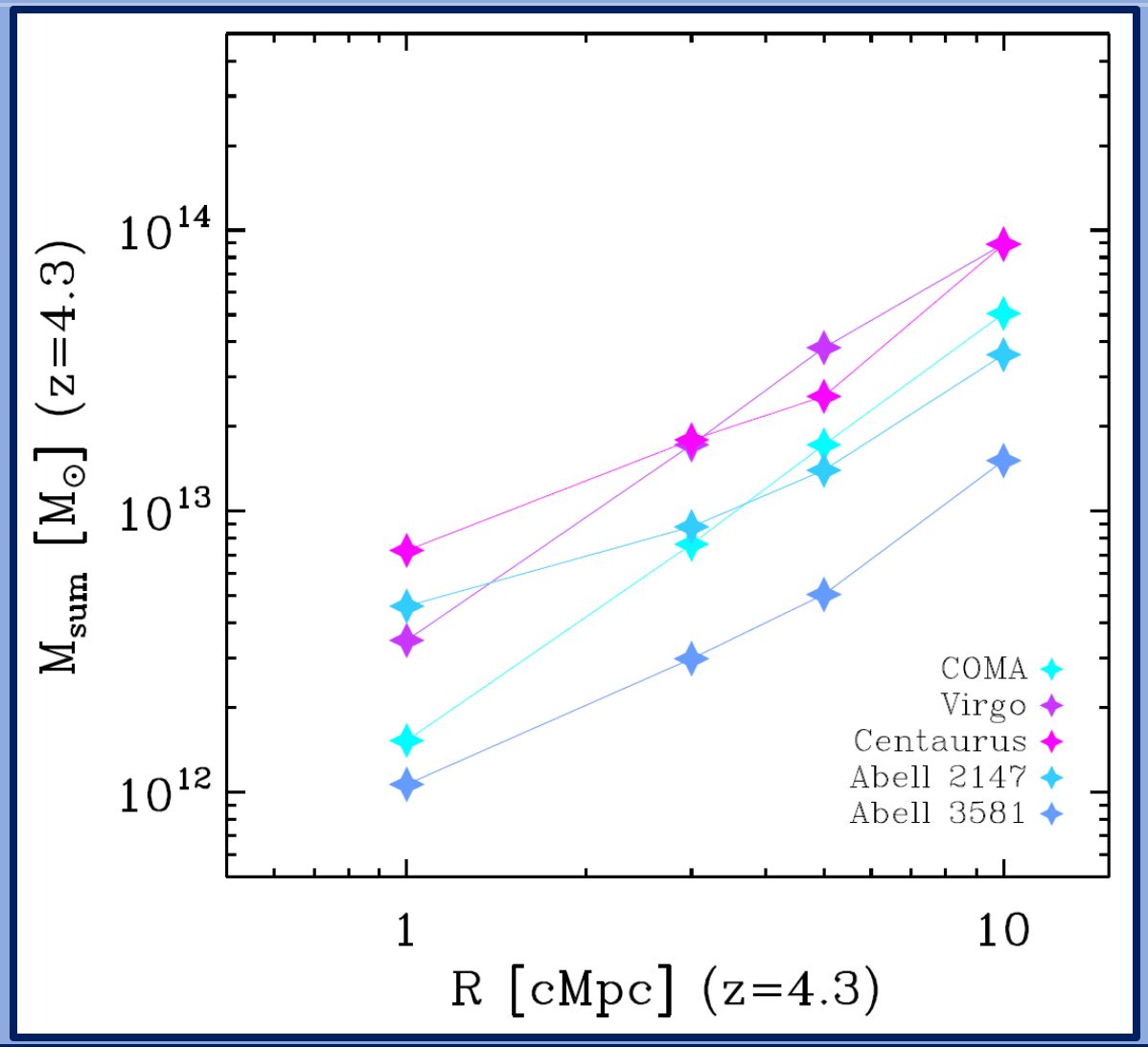


See also Sorce+2017, 2019 for more details on the Virgo-Cluster CLONE

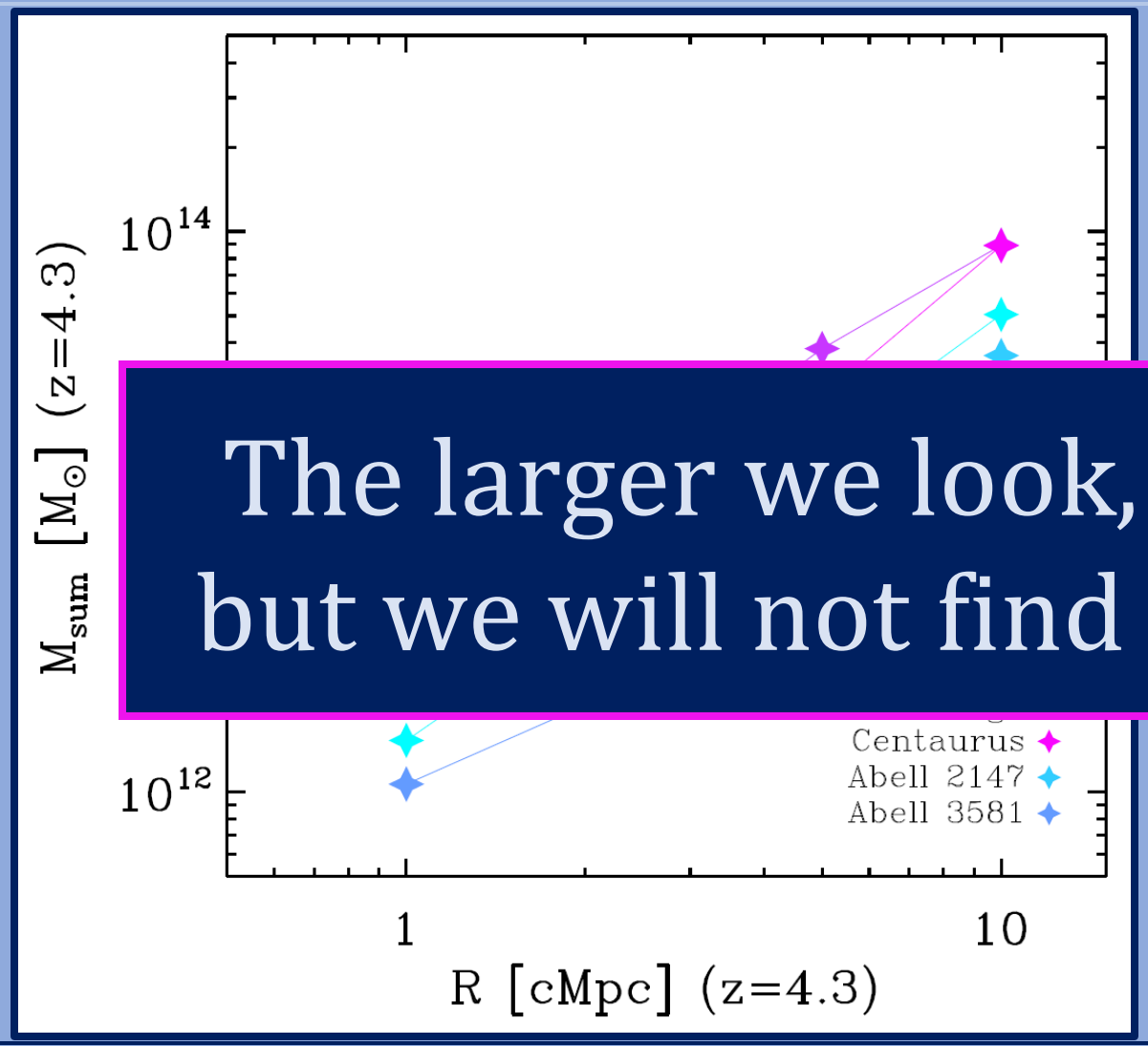
Protocluster: Going Local

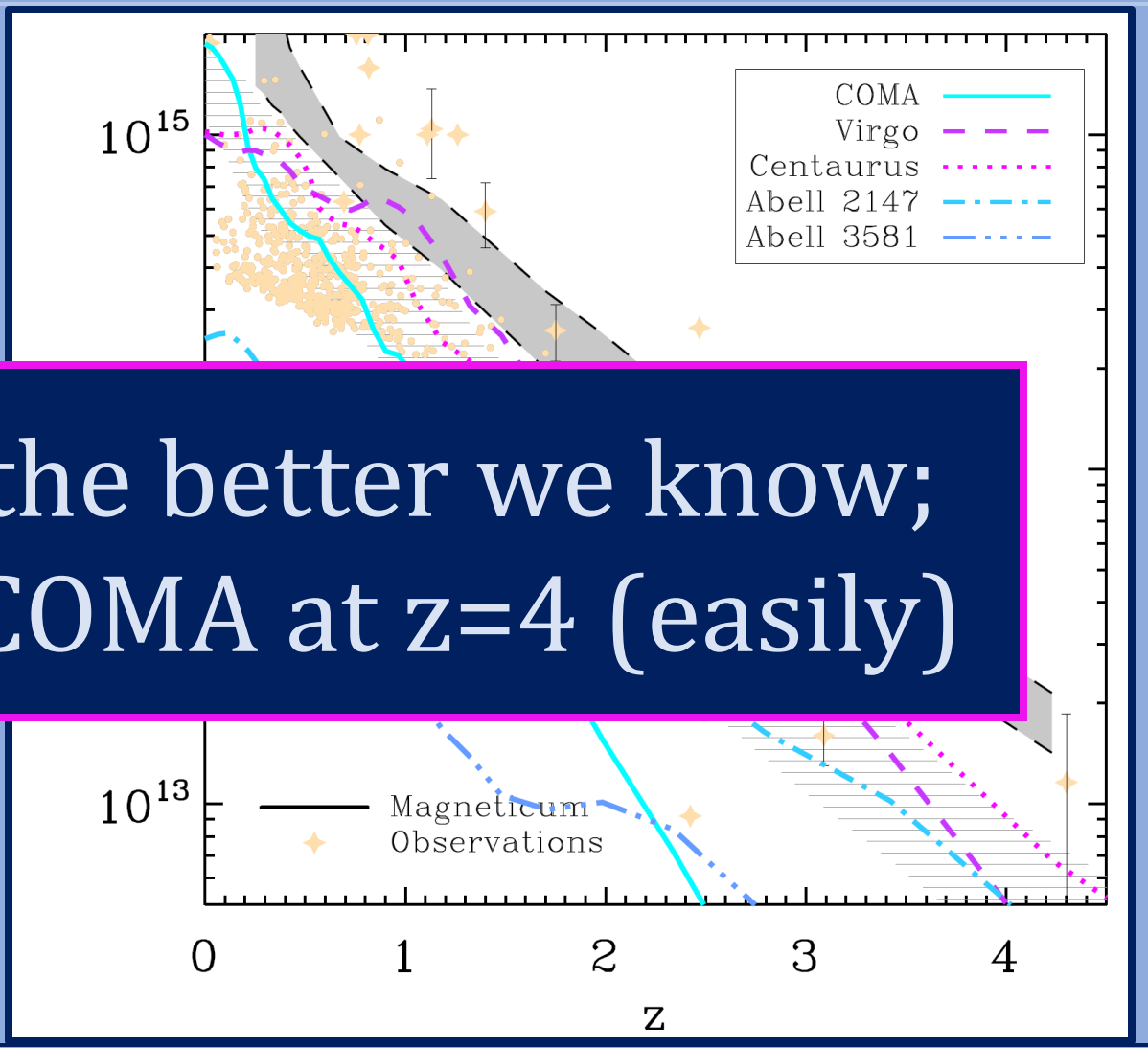


Protocluster: Going Local



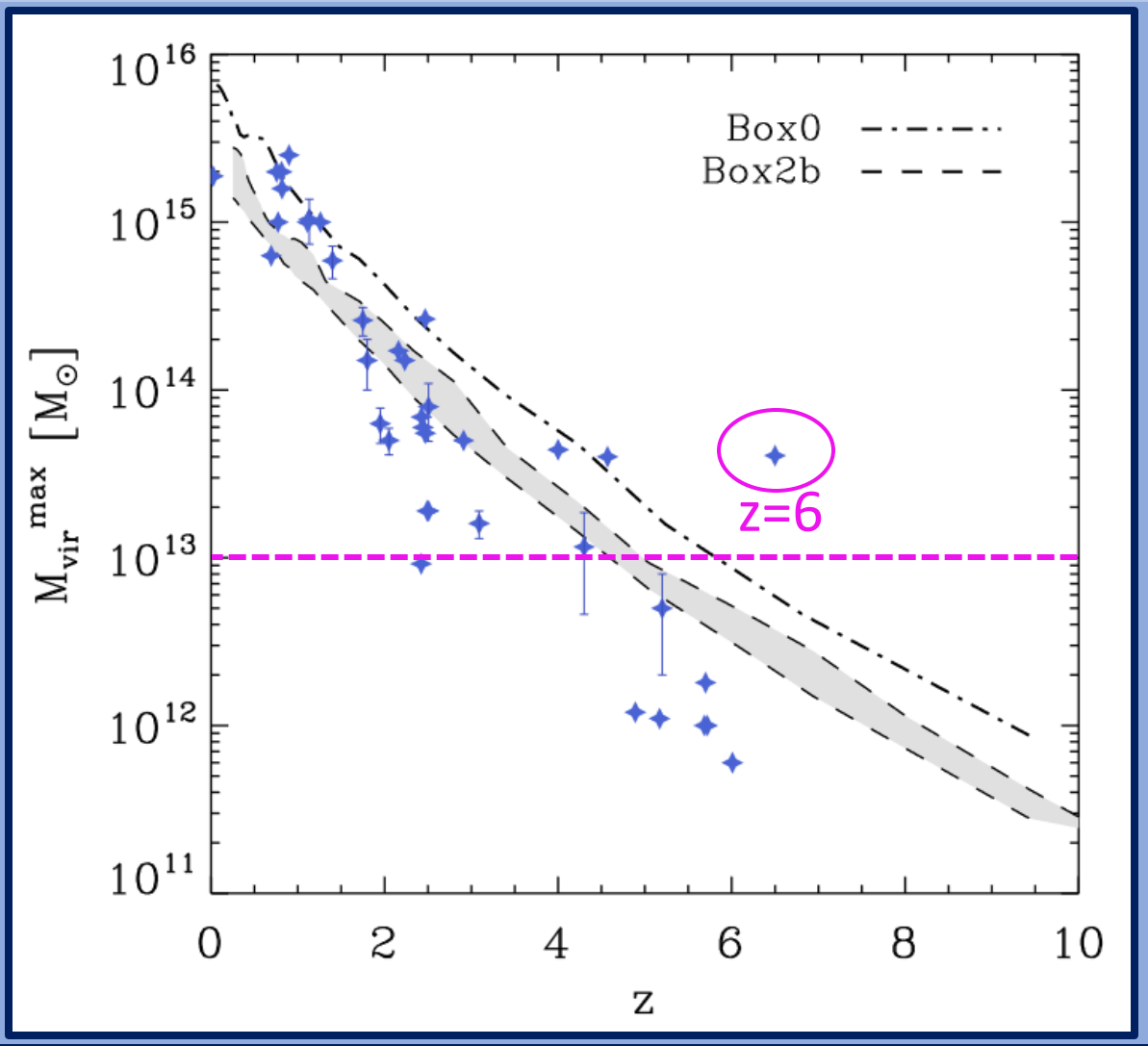
Protocluster: Going Local





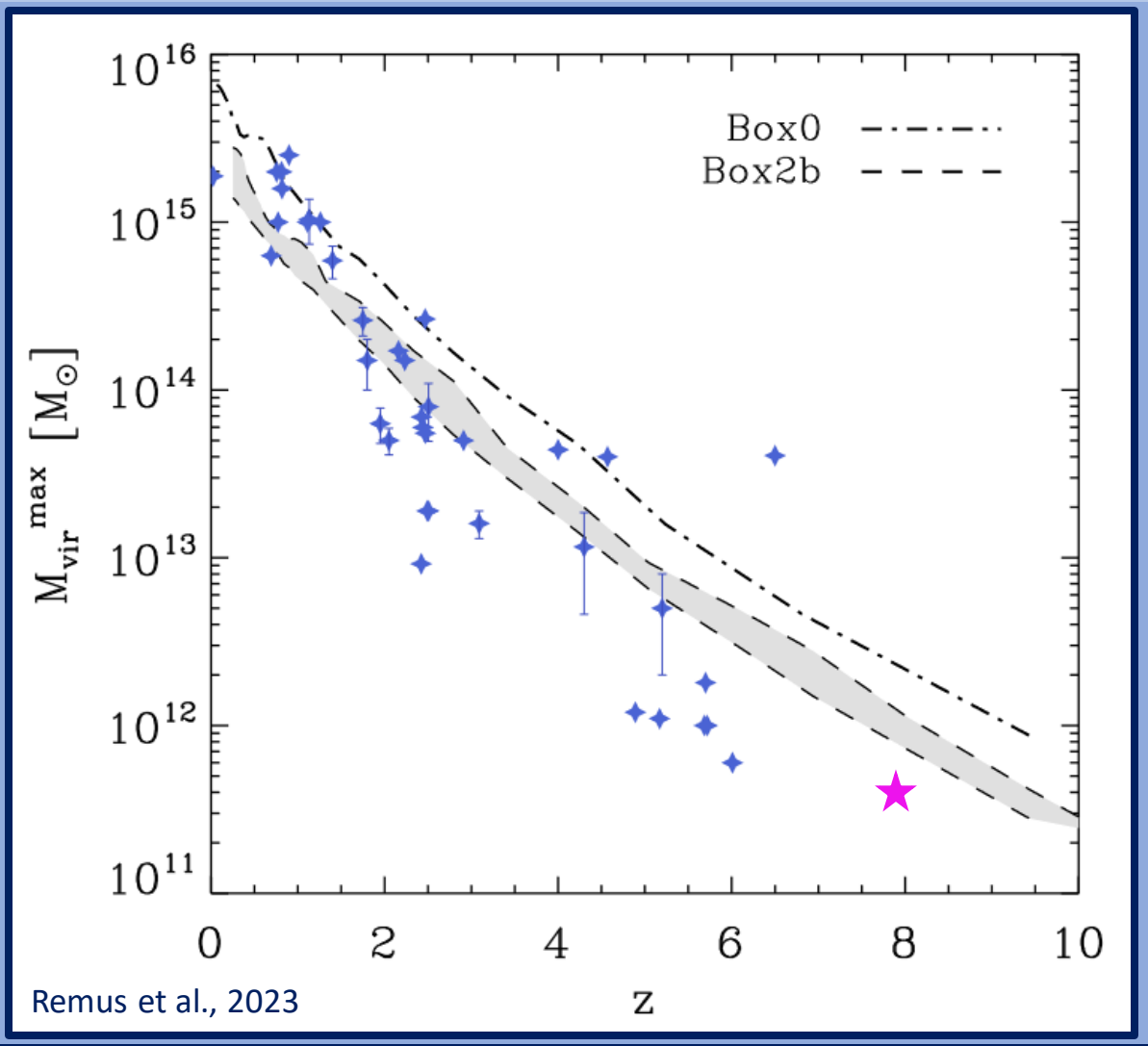
The larger we look, the better we know; but we will not find COMA at z=4 (easily)

Protocluster: How High can we Go?



Remus et al., 2023

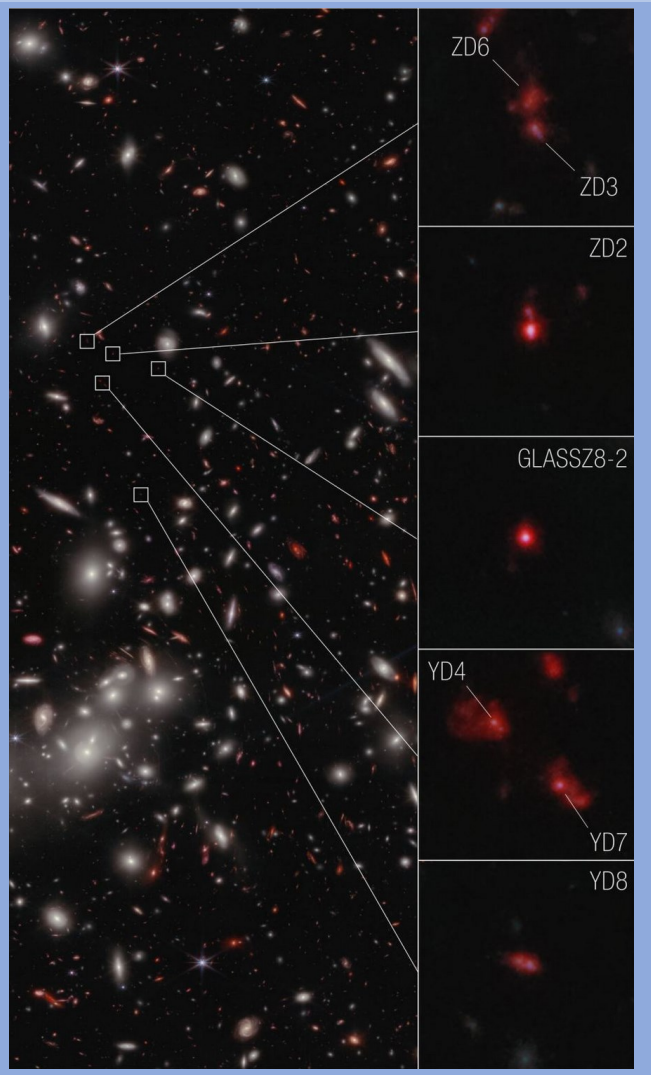
Protocluster: How High can we Go?



Remus et al., 2023

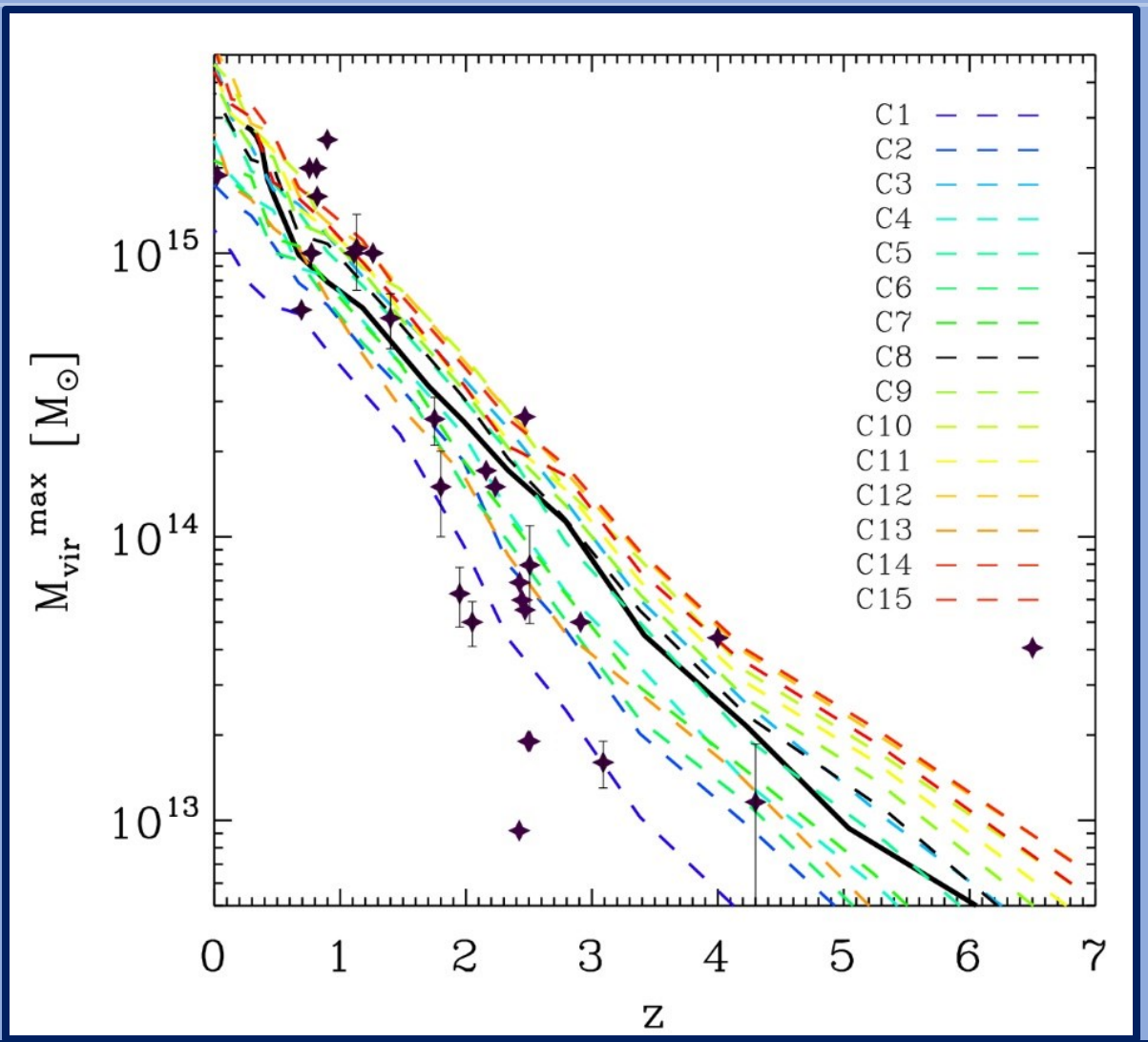
z=7.88

$M_{tot} = 4 \cdot 10^{11} M_\odot$

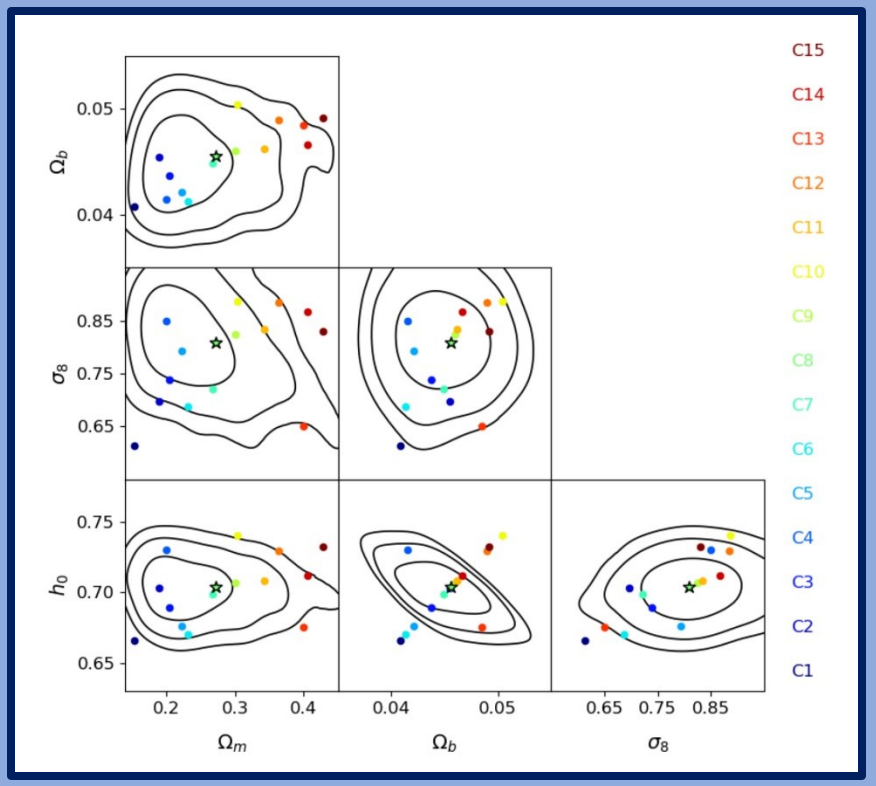


Morishita+2023; image credit: ESA/NASA/STScI/CSA

Protocluster for Cosmology

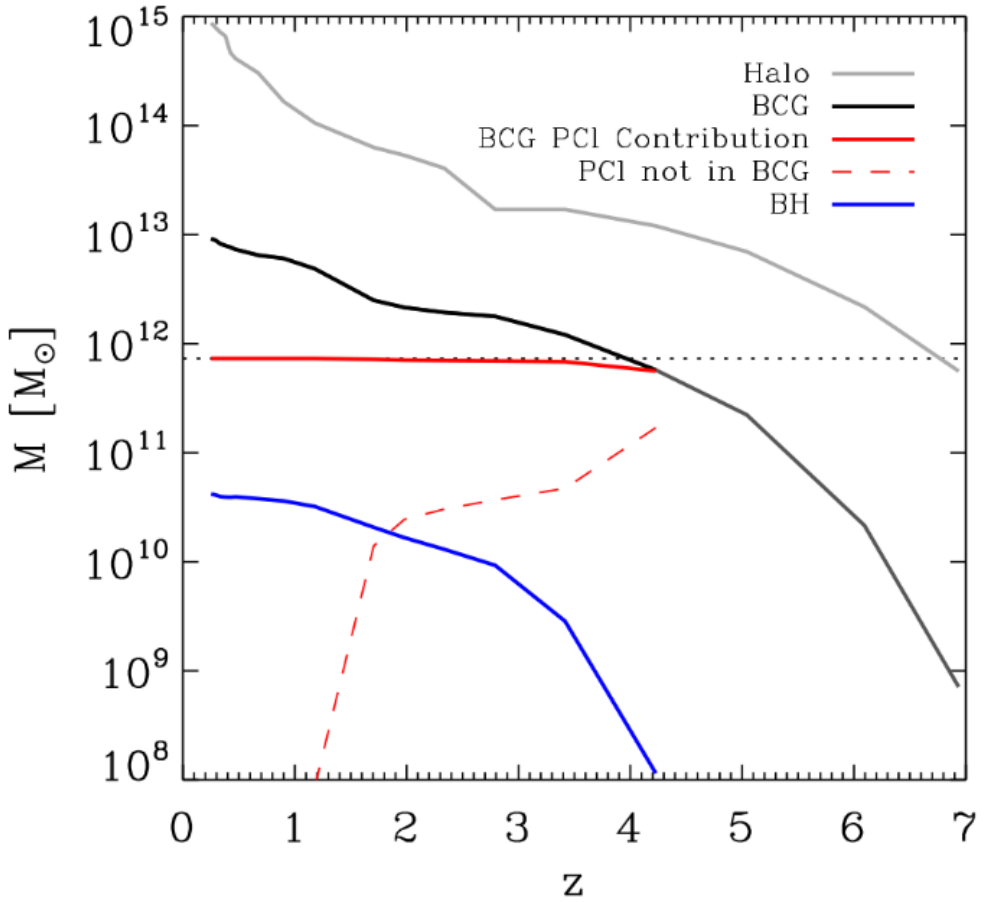


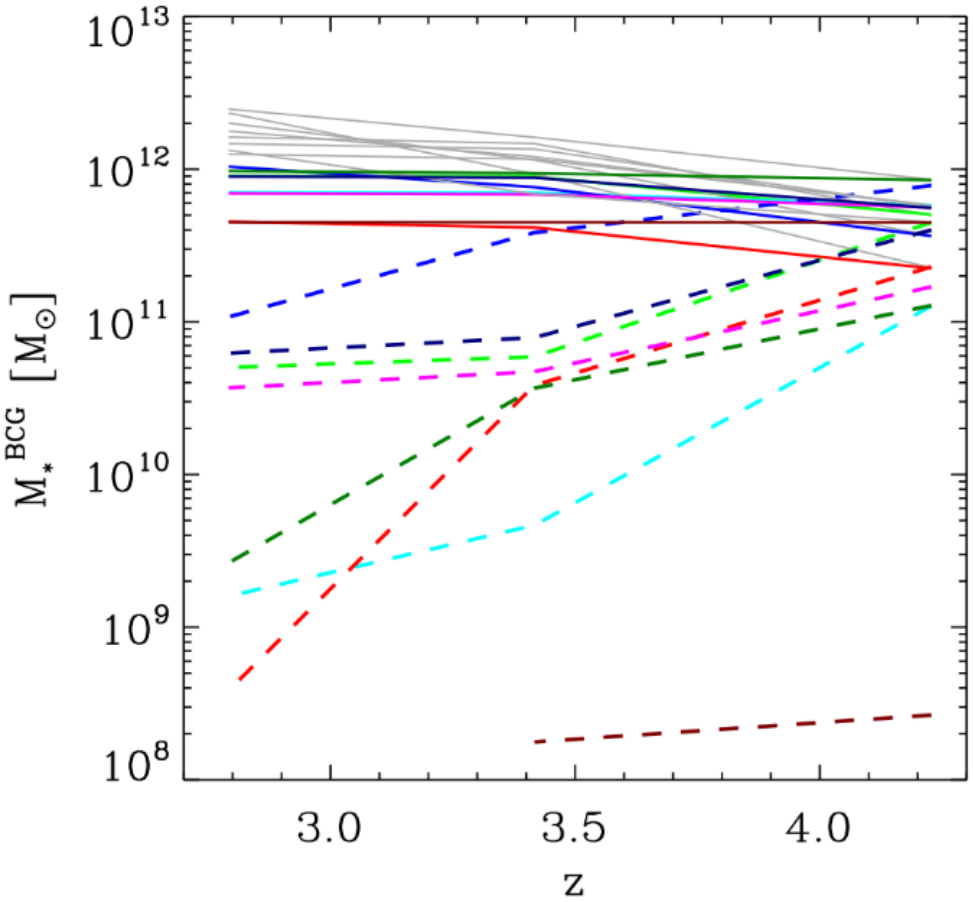
σ_8 most important for slope of M_{vir}-z relation.



Remus et al., 2023

Galaxies in Protocluster: BCG Formation



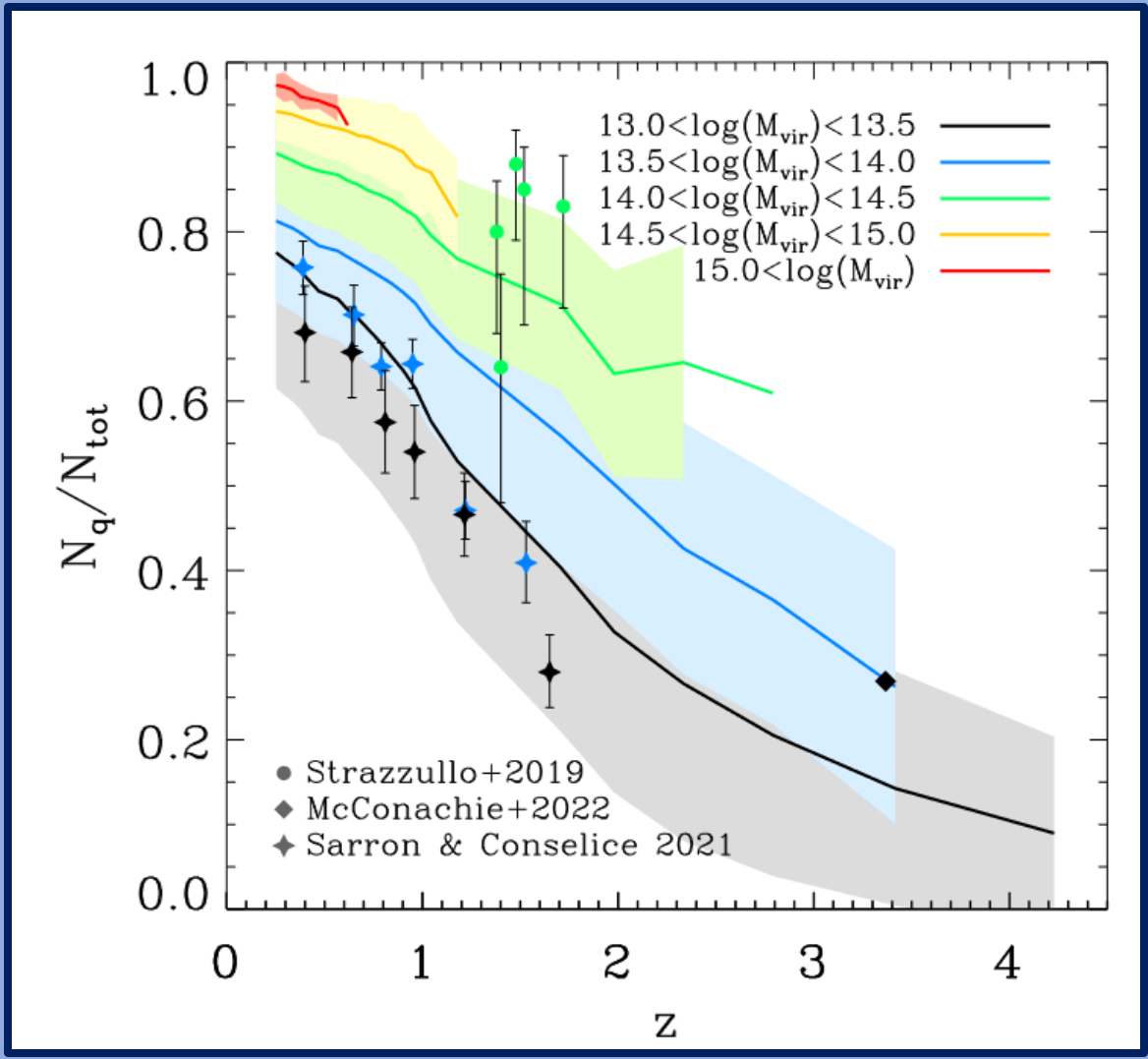


Remus et al., 2023

See also Rennehan et al., 2019 for BCG formation in Simulations

But also see his talk!

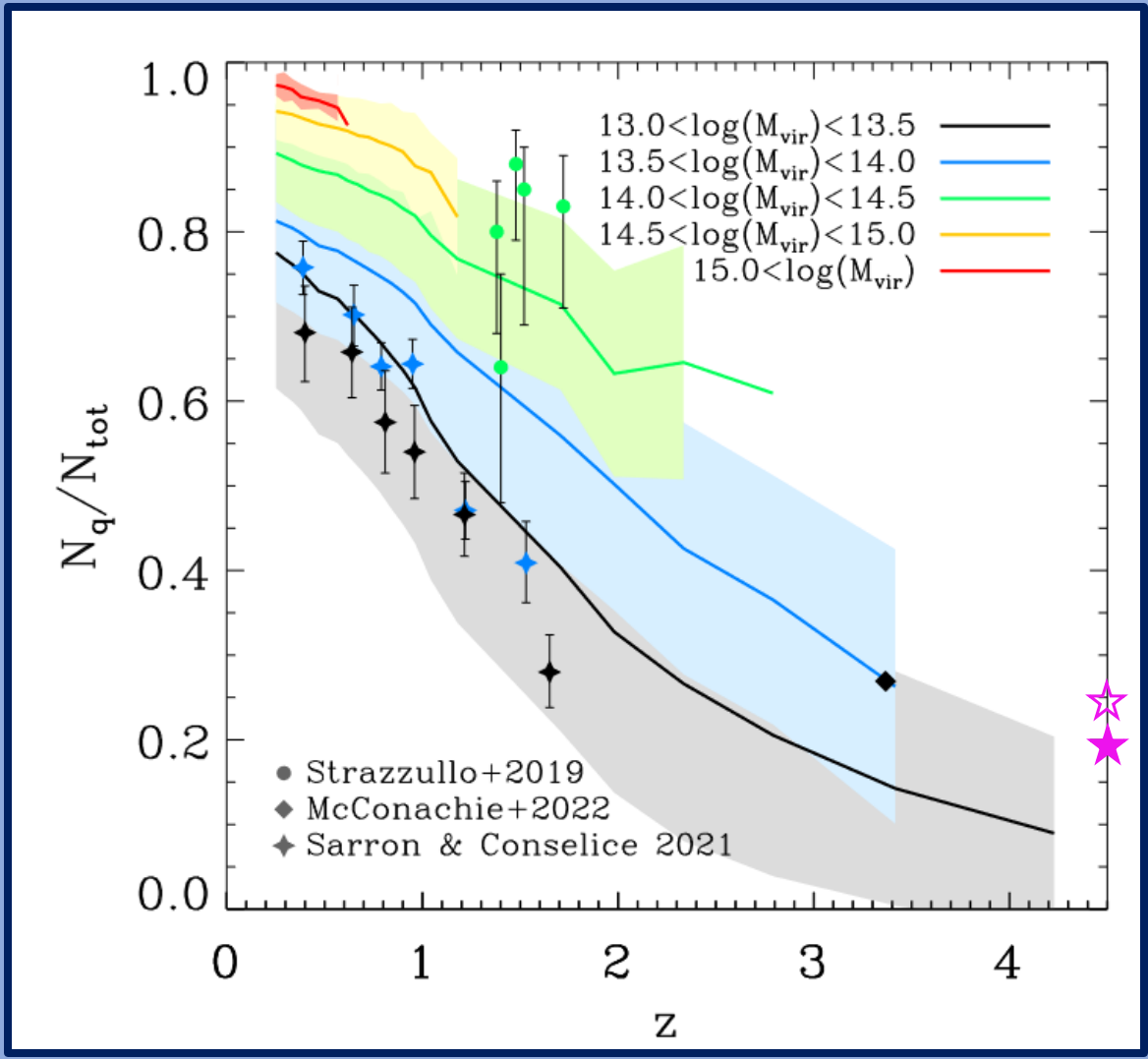
Protocluster Quenched Fractions



See also talks by Veronica Strazzullo, Florian Sarron, and Alan McConachie, but also by Syeda Lammim Ahad for simulation approaches and Devontae Baxter for Modelling

Remus et al., 2023

Protocluster Quenched Fractions

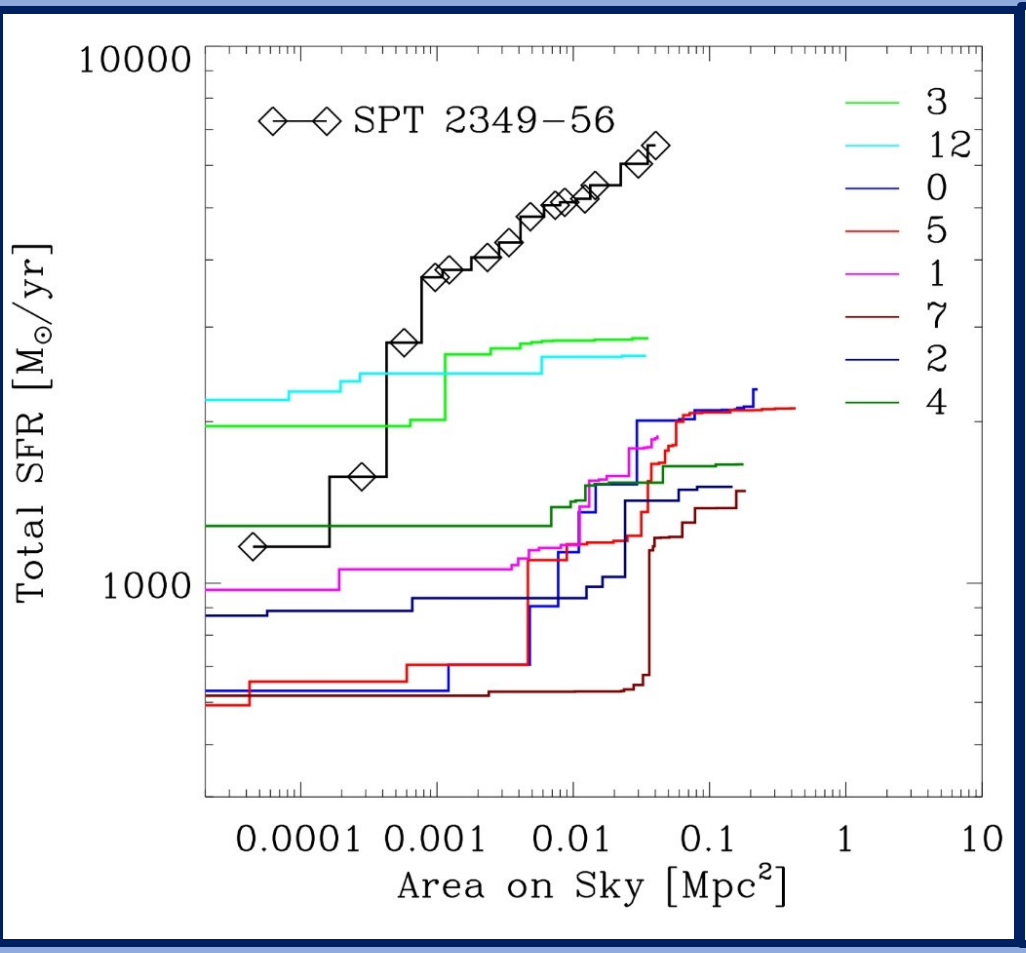


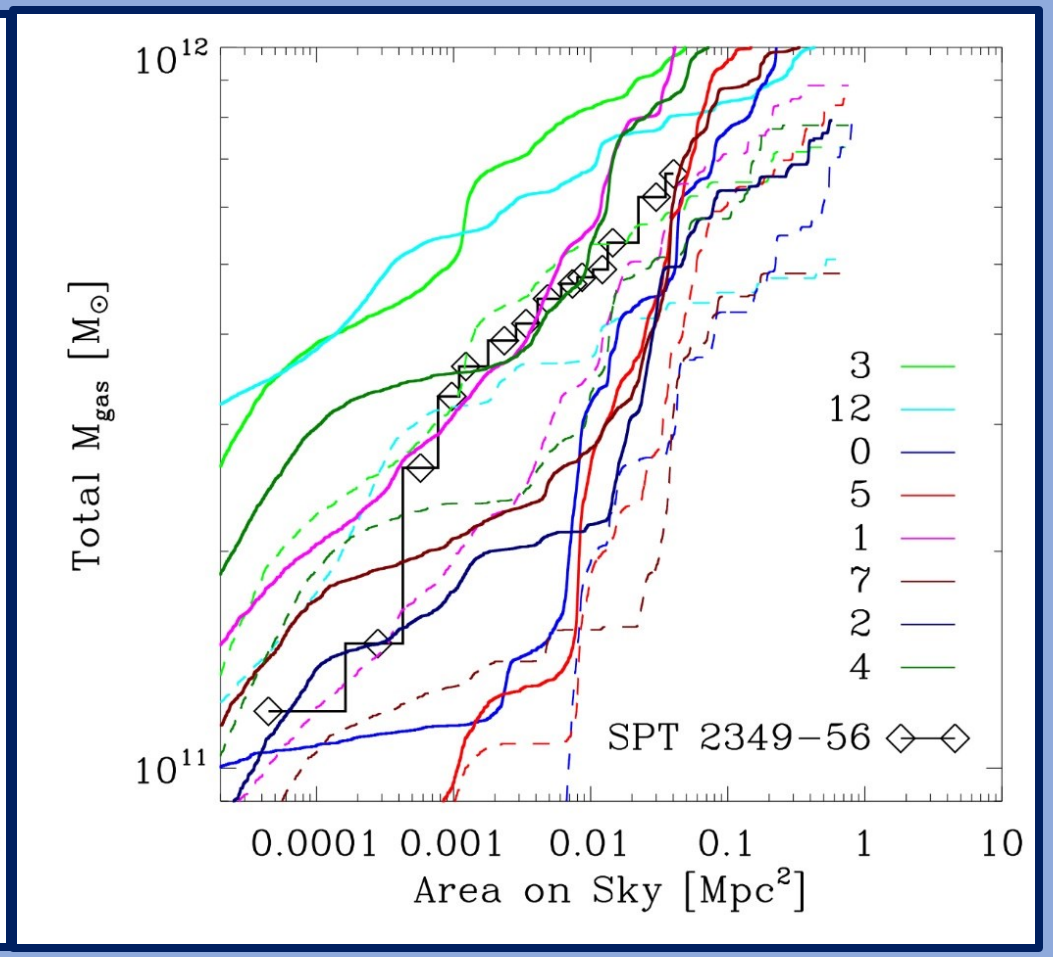
See also talks by Veronica Strazzullo, Florian Sarron, and Alan McConachie, but also by Syeda Lammim Ahad for simulation approaches and Devontae Baxter for Modelling

Quenched Galaxy in a Group at z=4.5 (Kakimoto+2023): 1 out of 5 (4) galaxies quenched, expected group mass about $M_{group} = 10^{13} M_{\odot}$

Remus et al., 2023

What still is a problem?



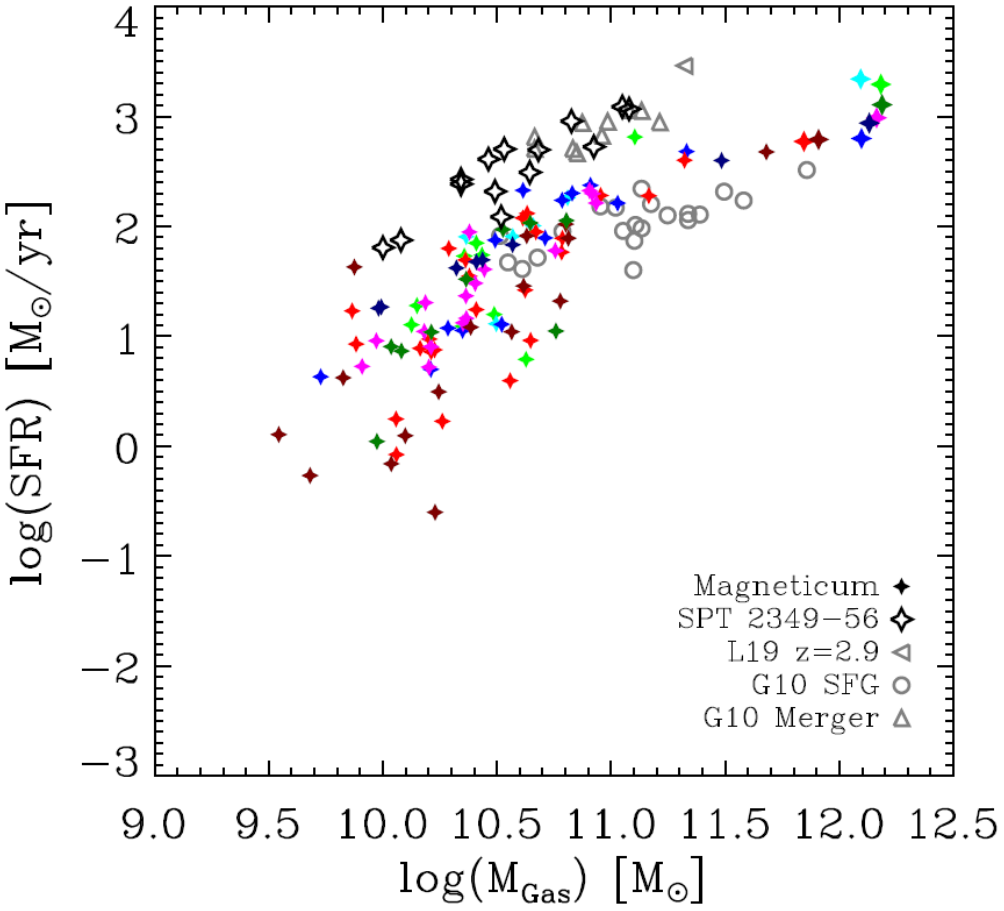


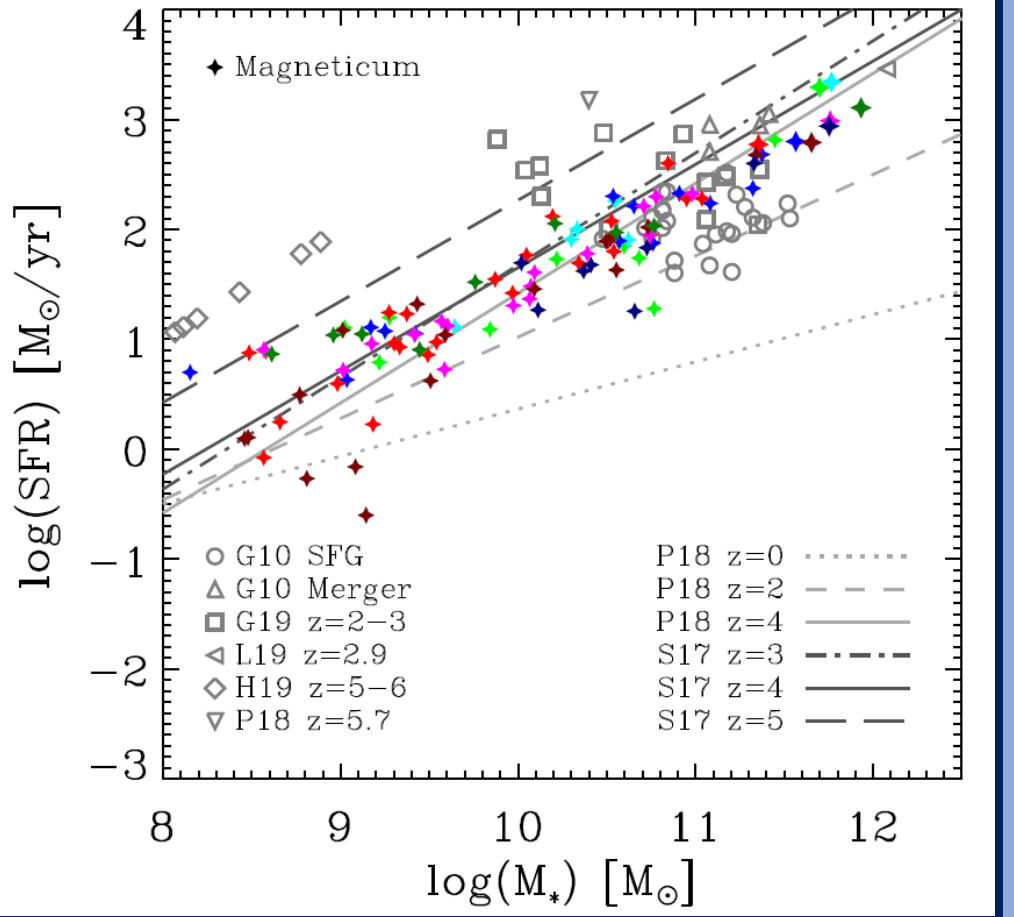
Remus et al., 2023

SPT 2349-56: Miller et al., 2018

See also talks by Michela Esposito and Laya Ghodsi this afternoon

What still is a problem?

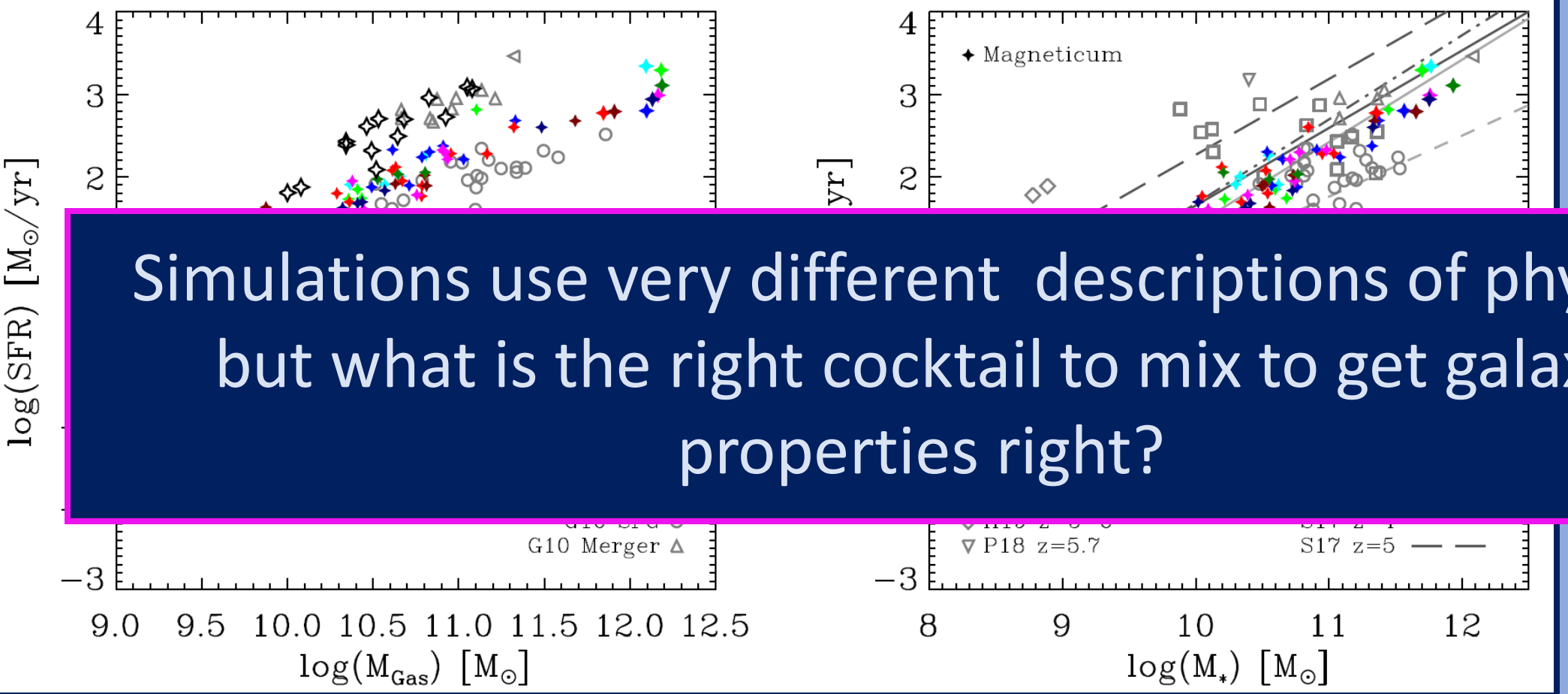




SPT 2349-56:
Miller et al., 2018

Remus et al., 2023

What still is a problem?



Simulations use very different descriptions of physics, but what is the right cocktail to mix to get galaxy properties right?

SPT 2349-56:
Miller et al., 2018

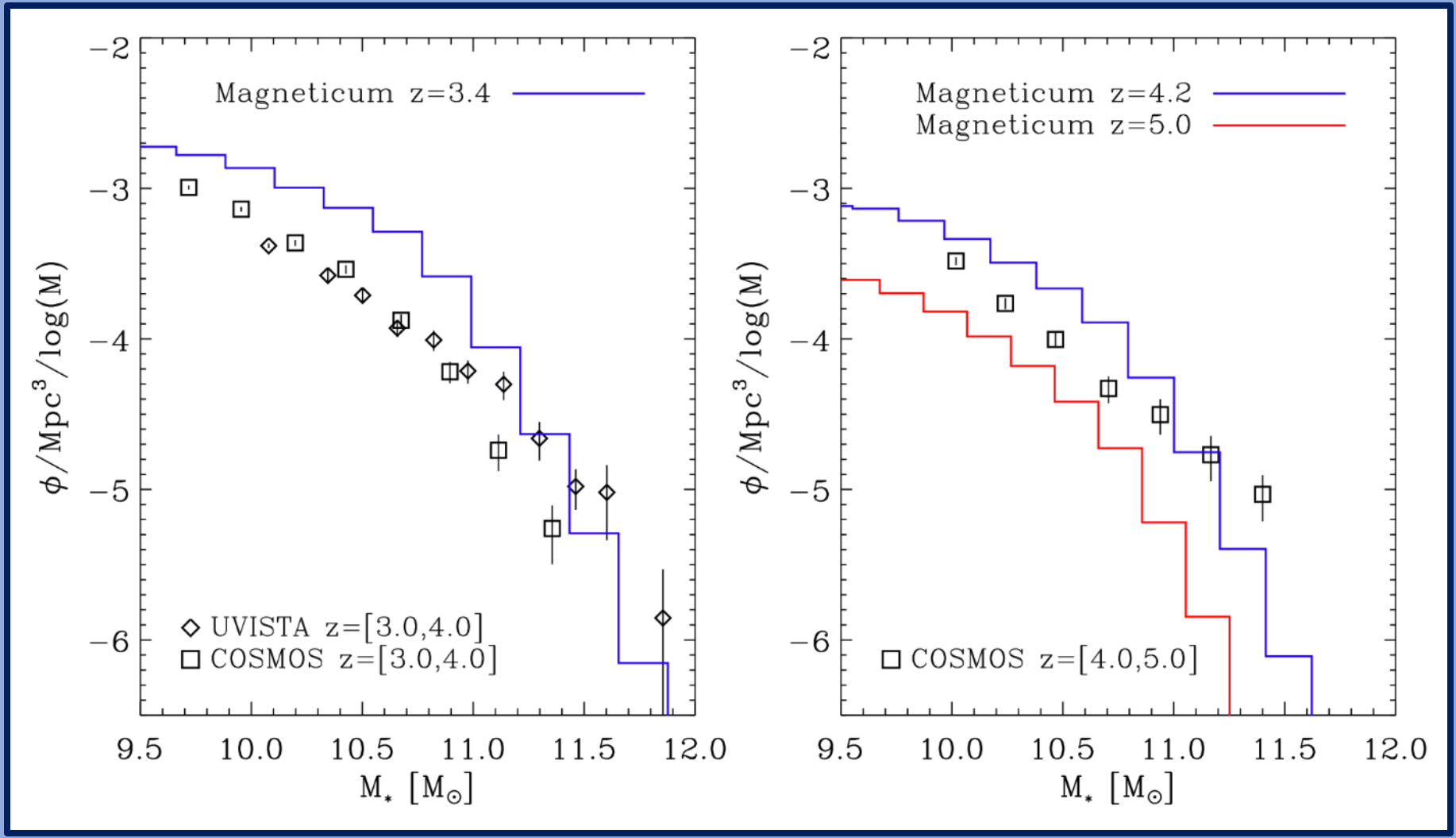
Remus et al., 2023

(Proto)-Cluster Evolution – a Summary

- Connecting Protoclusters to present-day clusters is not a linear mapping.
  - Only about 25% of protoclusters are massive clusters at z=0!
  - About 10% never even reach a mass of $10^{14}\ M_{\odot}$
- From our local massive clusters, none would be found to be a protocluster at z>4. Coma, for example, would be a MW-like galaxy.
- Neither mass nor star formation properties of protoclusters are good measure of what to become, but the number of galaxies is – cosmic web tracing! The larger the observed area, the better.
- Global galaxy properties of protoclusters are reproduced successfully by simulations (gas mass, stellar mass, kinematics of gas and stars, phase-space properties, metallicities and enrichment of the halo).
- Onset of environmental quenching starts at about z=4, but only efficient below z=1.5
- Star-formation receipt are assuming continuous star formation

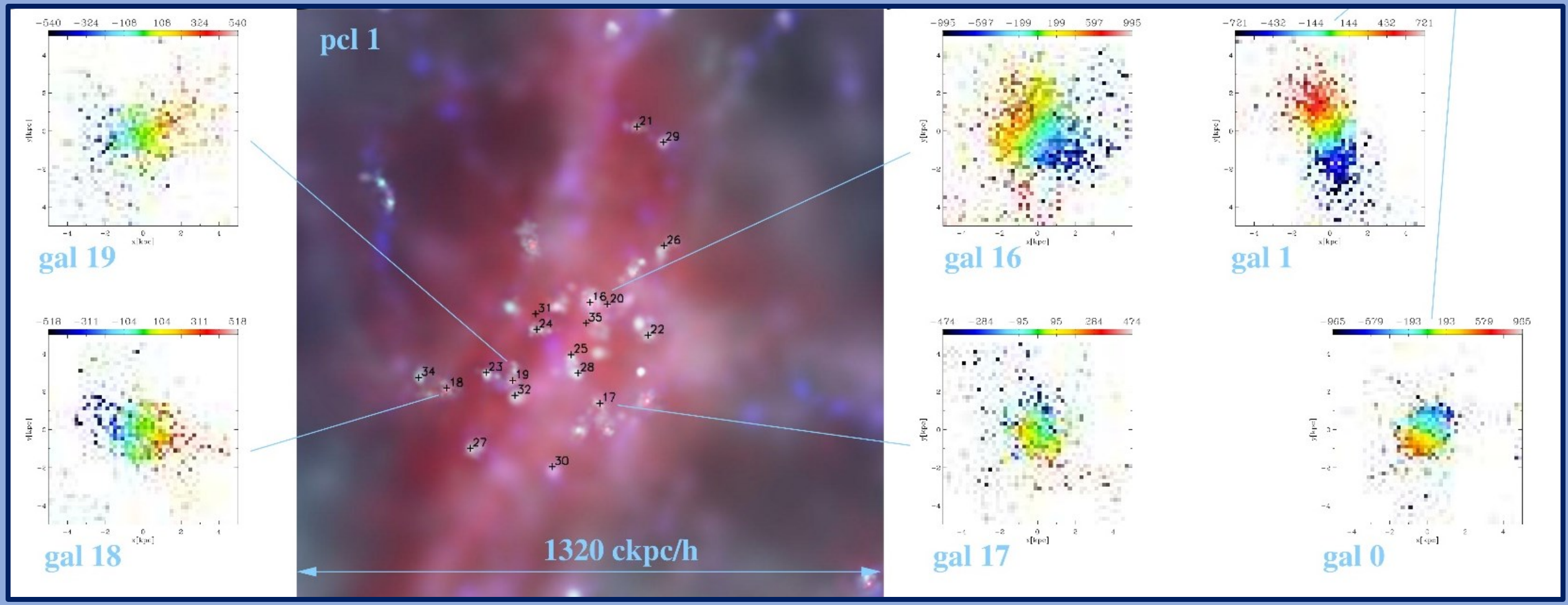
→ Star- and Gasmass work, but extreme star formation rates are not captured! Star formation is more bursty than predicted by simulations.

Protocluster in Magneticum: Mass Function



Remus et al., 2023

Protocluster in Magneticum: Rotation



Remus et al., 2023