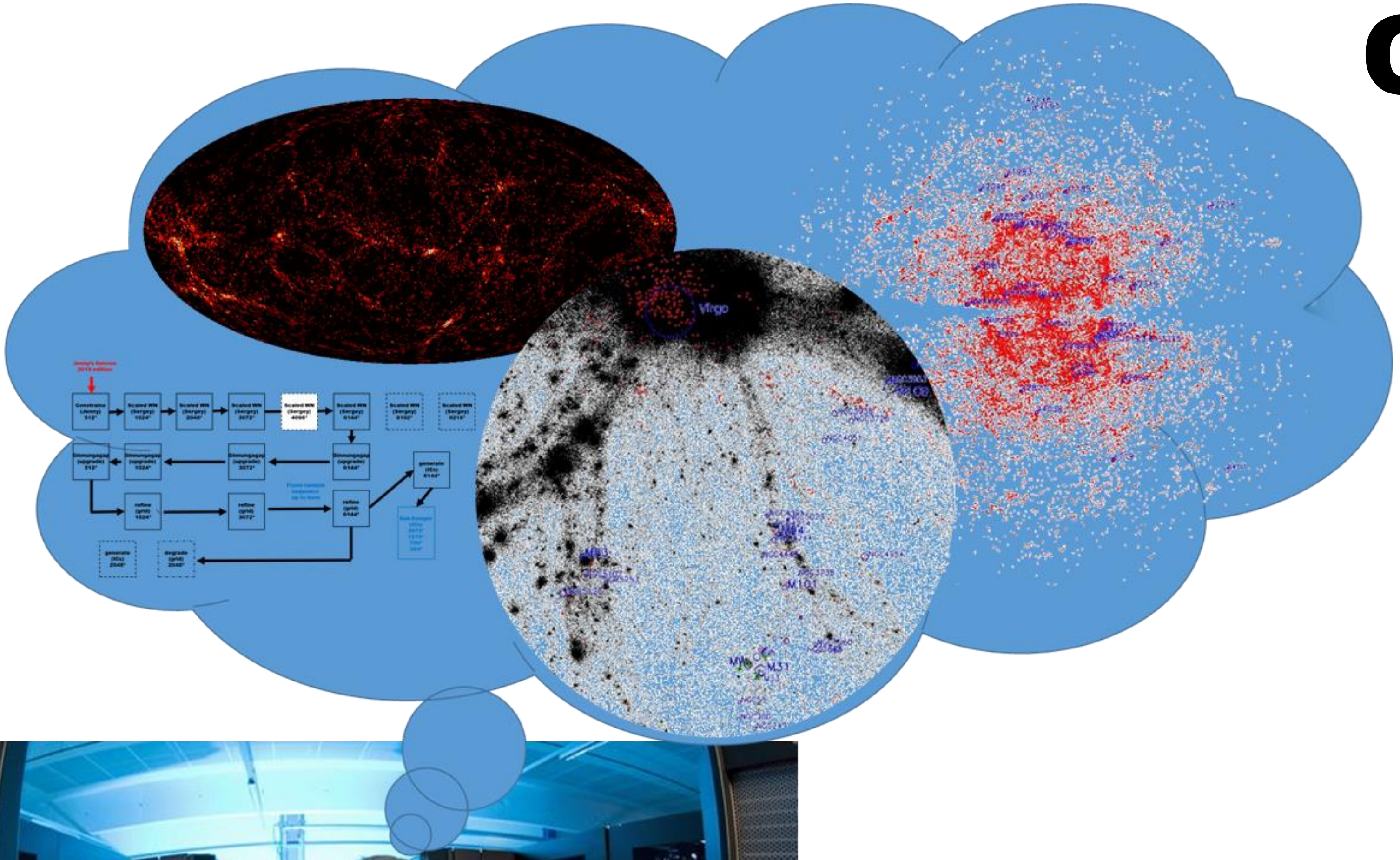
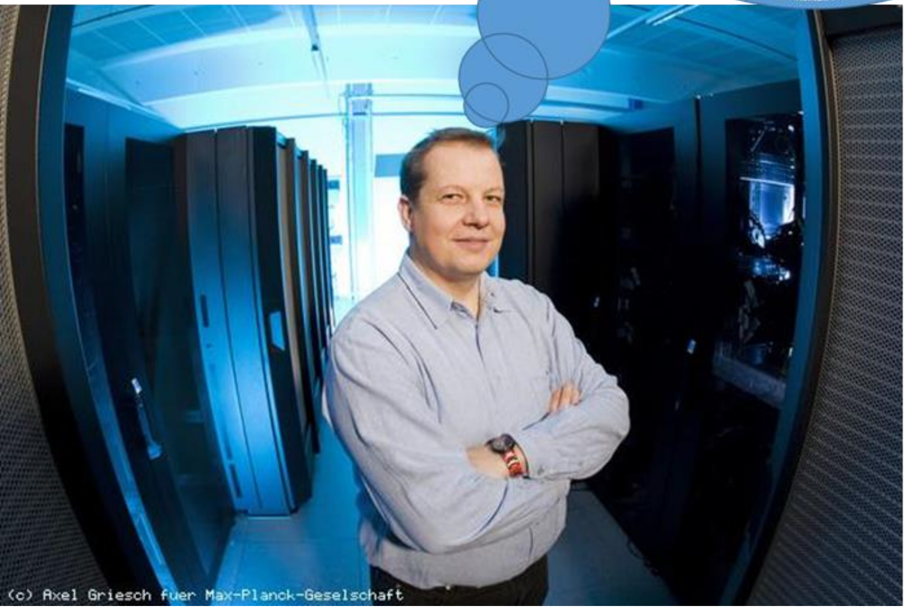
CRs & Magnetic Fields in the Local Universe

Klaus Dolag*
USM/LMU

* 道樂

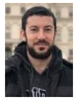




ACME
SPACE
TUM LMU ORIGINS Excellence Cluster
erc European Research Council
COMPLEX
LOCALIZATION
anr agence nationale de la recherche
DFG Deutsche Forschungsgemeinschaft German Research Foundation

 L. Sala

 E. Hernandez

 T. Marin

 F. Groth

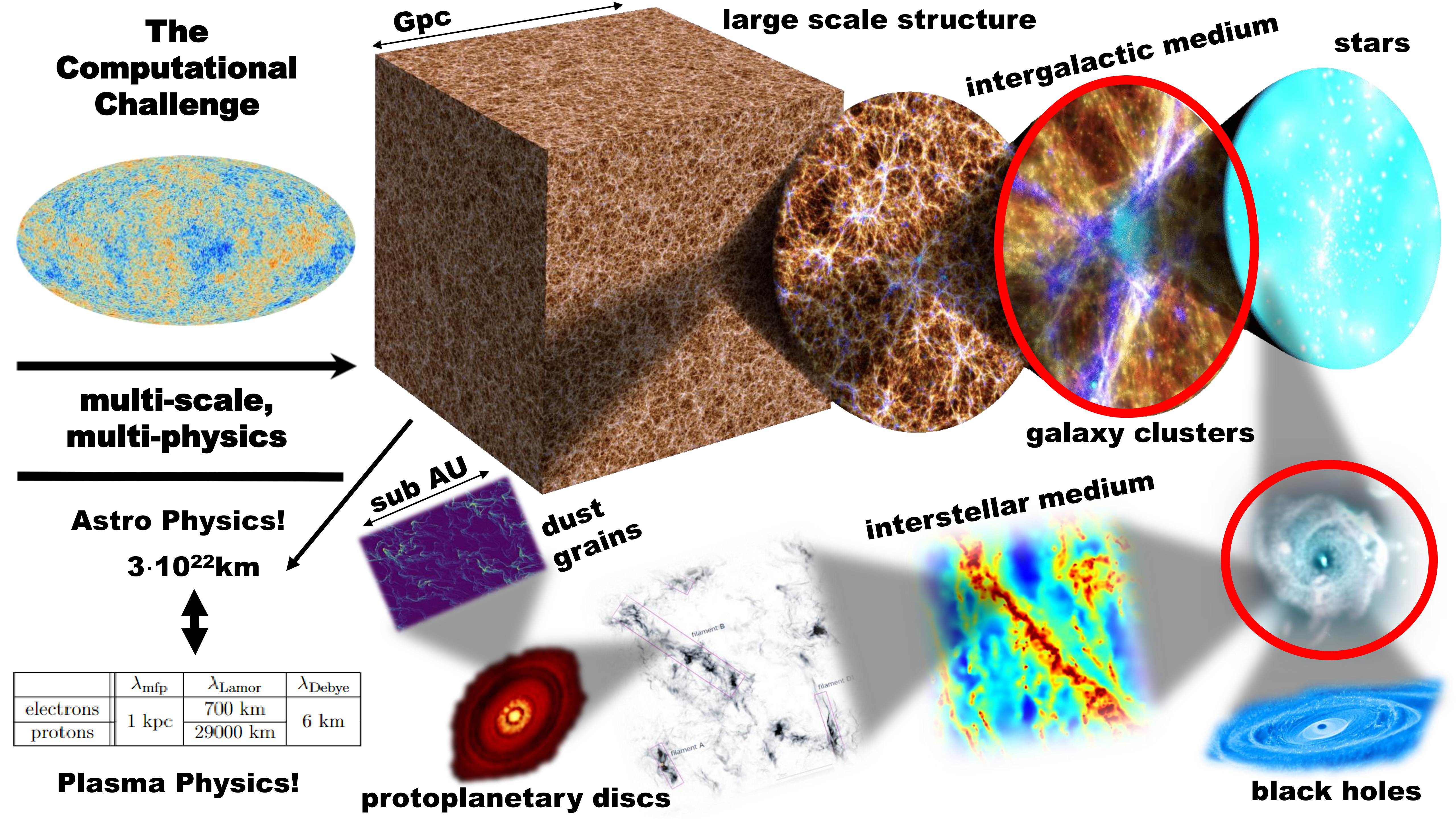
 U. Steinwandel

 I. Khabibullin

 L. Böss

 B. Seidel

Intro I: The big picture



The Computational Challenge
multi-scale, multi-physics
Astro Physics!
3·10²²km
Plasma Physics!
λmfp
λLamor
λDebye
electrons
protons
1 kpc
700 km
29000 km
6 km
Gpc
large scale structure
intergalactic medium
stars
galaxy clusters
sub AU
dust grains
interstellar medium
protoplanetary discs
black holes

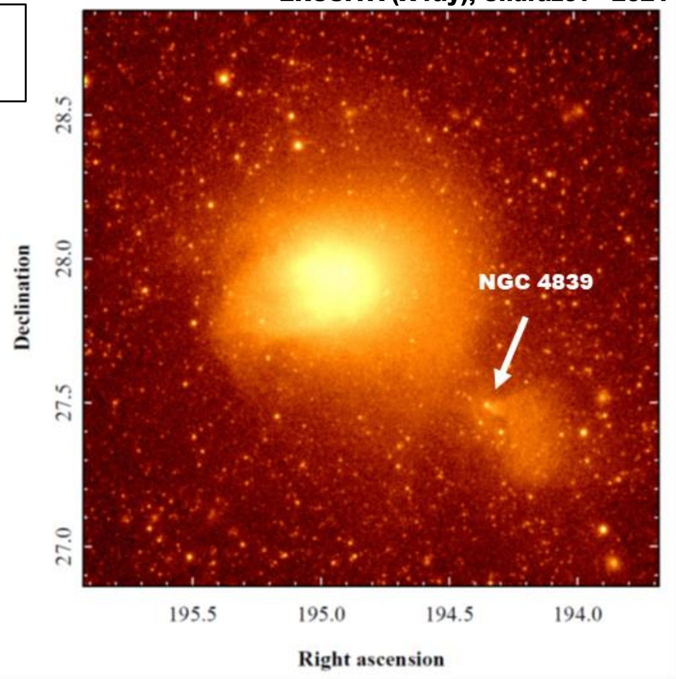
Intro II: The intra cluster medium (ICM)

ICM is the hot Atmosphere of Massive Galaxies

- **Measured in large details**
  X-ray (temperature, velocities)
  SZ (pressure)

EROSITA (X-ray), Churazov+ 2021

Coma

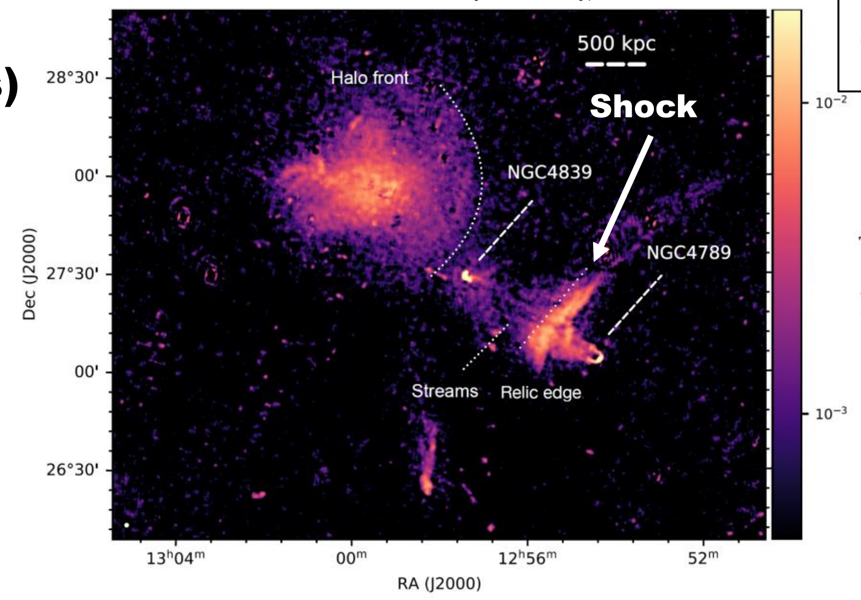


Density: 10^{2} to 10^{-3} part/cm³
Temperature: 10keV to 0.1keV

ICM is the hot Atmosphere of Massive Galaxies

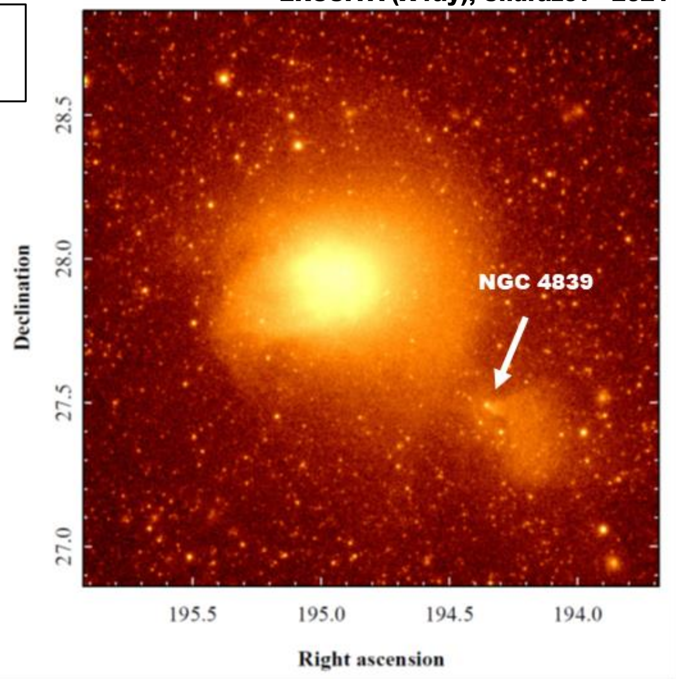
- ❑ **Measured in large details**
  X-ray (temperature, velocities)
  SZ (pressure)
- ❑ **Non-thermal components give additional insights (magnetic fields, CRs)**

LOFAR (144 MHz), Bonafede+ 2020

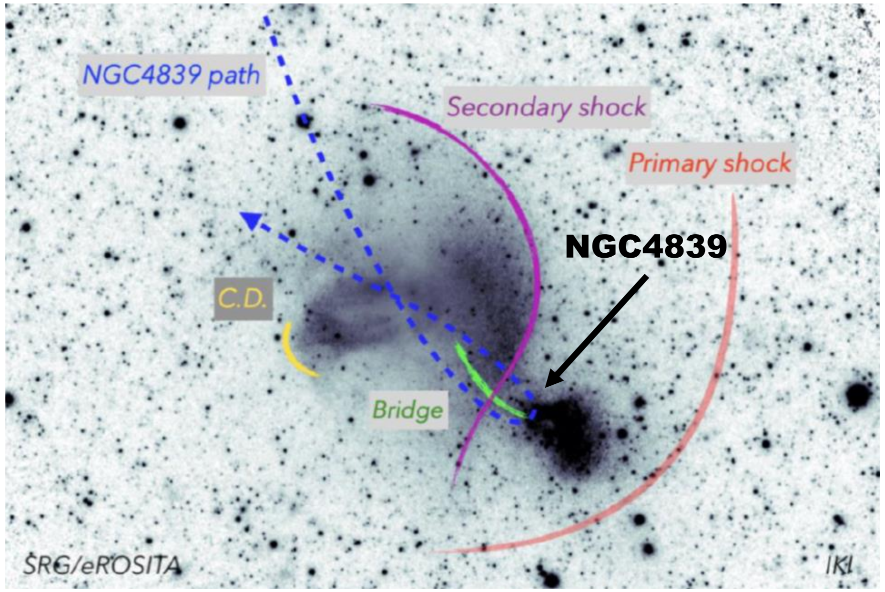


Coma

EROSITA (X-ray), Churazov+ 2021



Magnetic field: μG to nG
CR electrons: GeV



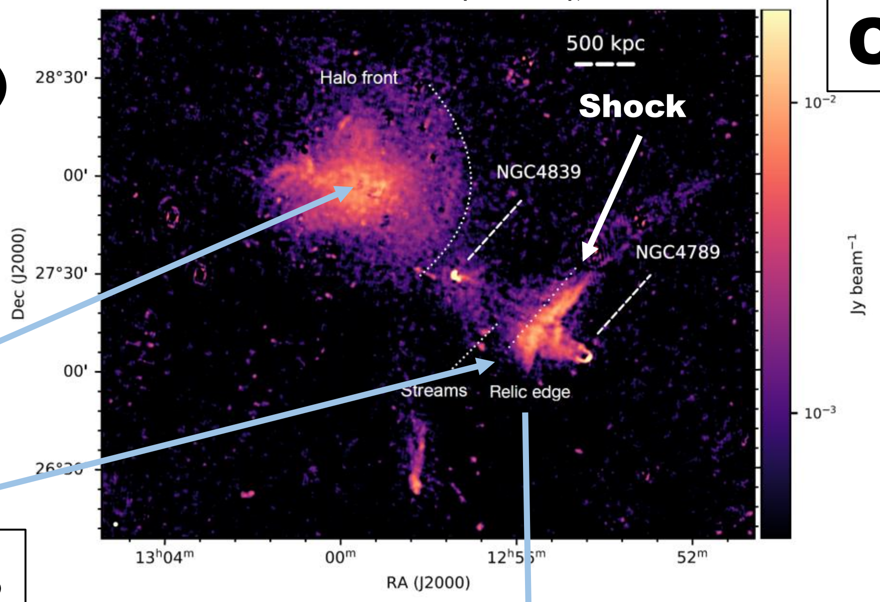
ICM is the hot Atmosphere of Massive Galaxies

- ❑ Measured in large details
  X-ray (temperature, velocities)
  SZ (pressure)
- ❑ Non-thermal components give additional insights (magnetic fields, CRs)

Turbulence

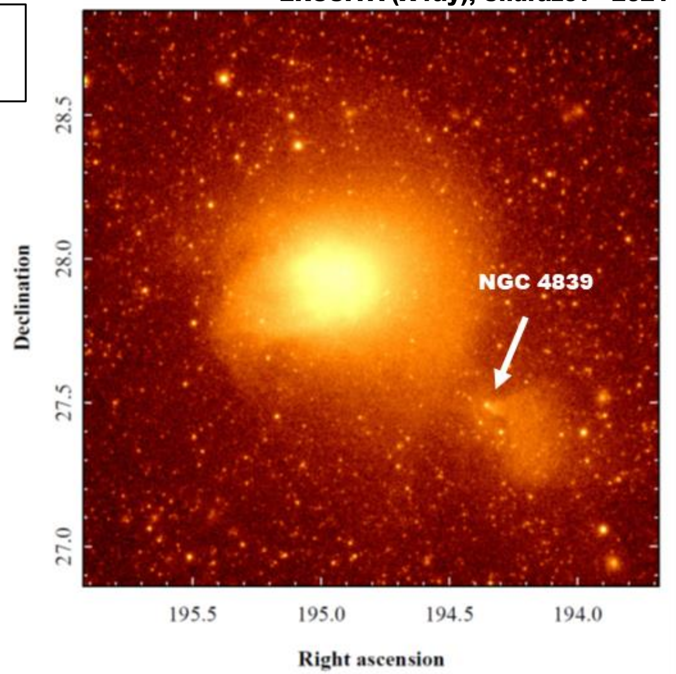
Shocks

LOFAR (144 MHz), Bonafede+ 2020



Coma

EROSITA (X-ray), Churazov+ 2021



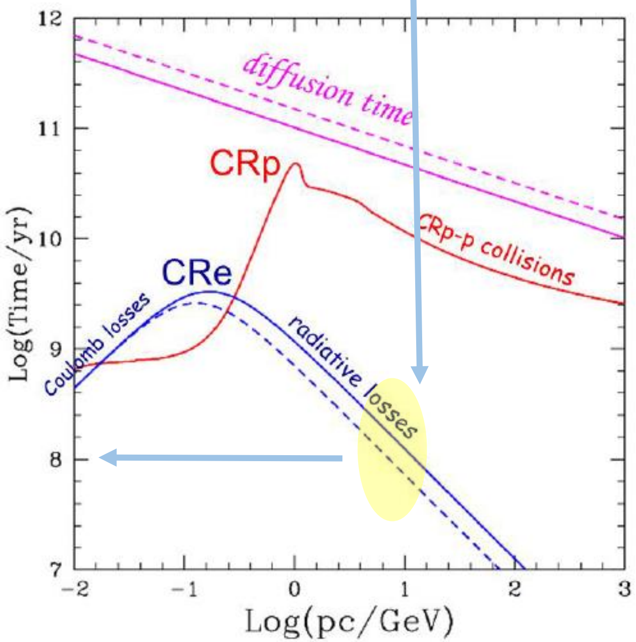
Short cooling time of CRe:

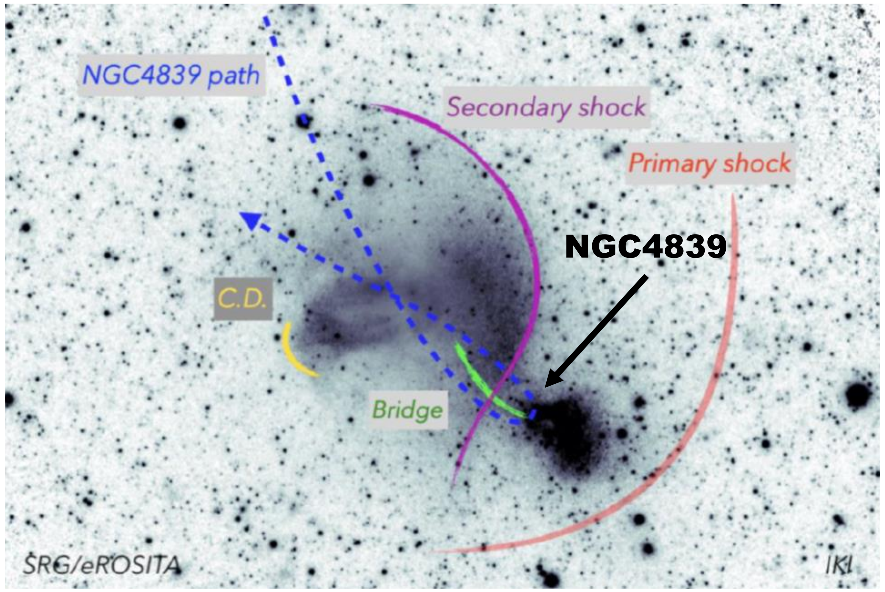
- ❑ test shocks on 10th of kpc
- ❑ test turbulence (re-acceleration)

Long cooling time of CRp:

- ❑ can be dynamically important

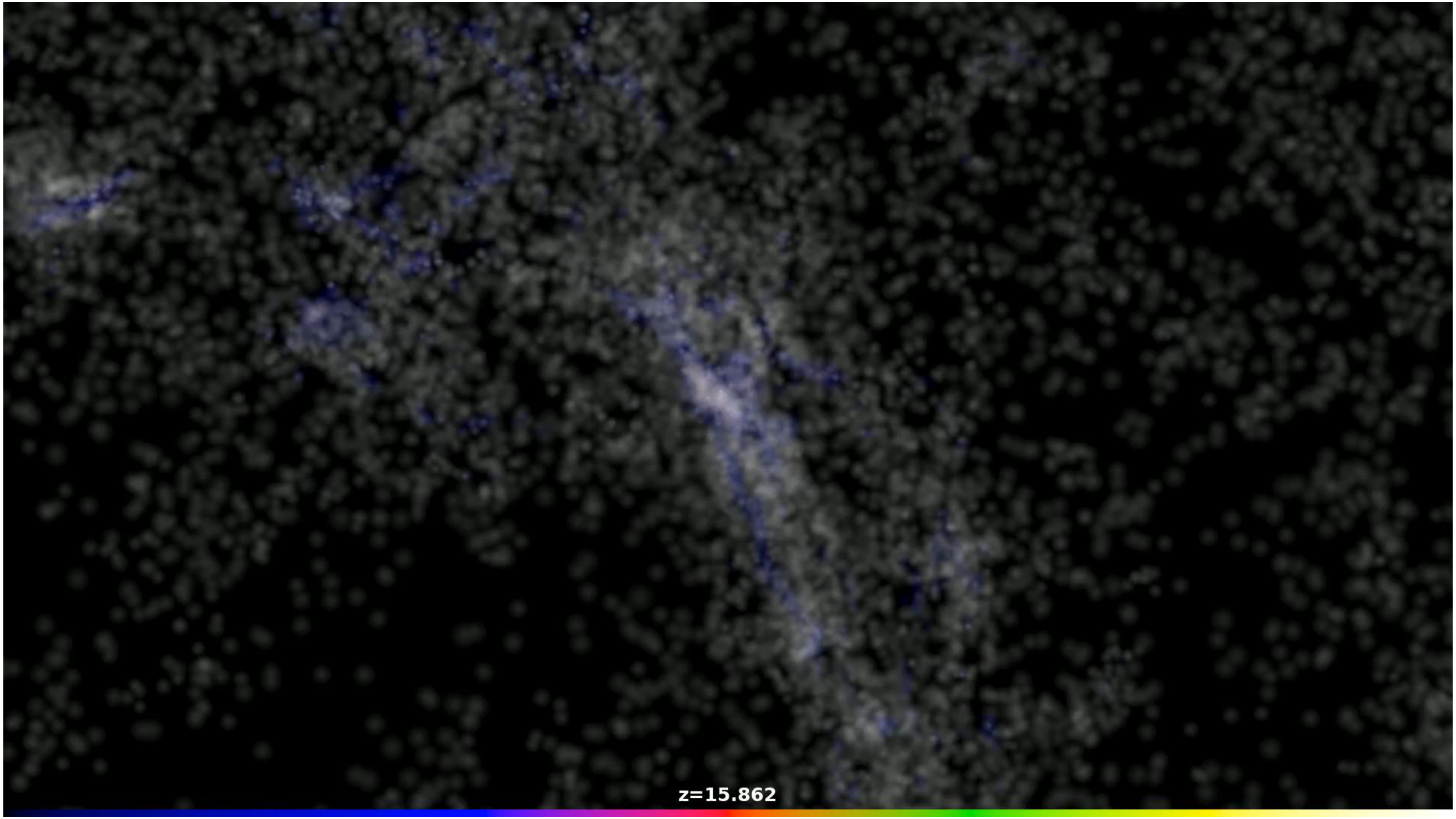
Both couple to B-Field





Simulations I: Galaxy cluster formation

Simulating Galaxy Clusters and the ICM



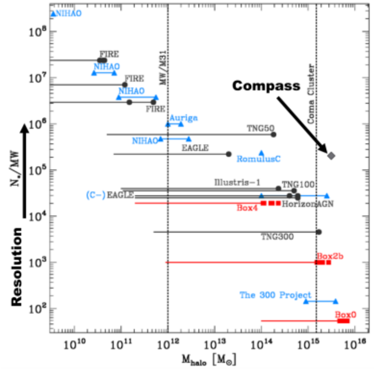
Mach number: 2 3 4 >5

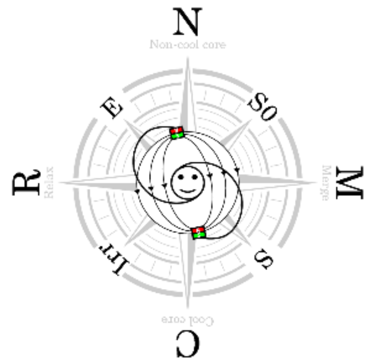
Galaxy Clusters:

M ~ 2x10^{15}M$_{sol}$

almost 10^{9} part in R$_{vir}$
~ 90.000 galaxies
~ 250.000 timesteps

$\varepsilon_{gas/stars}$ ~ 240 pc/h





C·O·M·P·A·S·S

Cosmic Rays: The need for a Fokker-Planck solver!

L. Böss

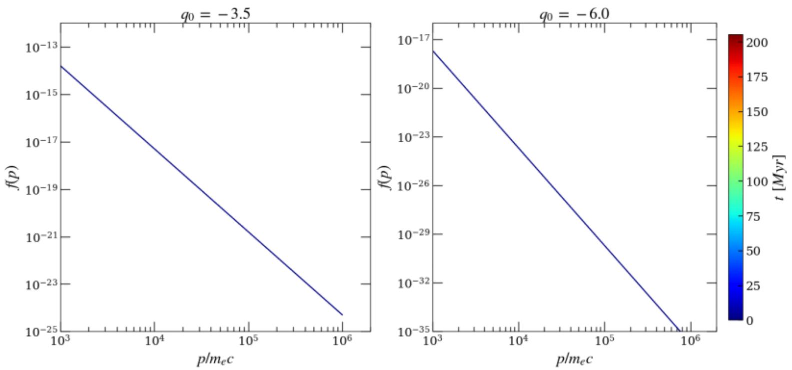
$$\underbrace{\frac{\partial f}{\partial t}}\;+\;\underbrace{\mathbf{u}\cdot\nabla f}_{\text{spatial convection}}\;-\;\underbrace{\nabla\left(\boldsymbol{\kappa}\nabla f\right)}_{\text{spatial diffusion}}\;=$$

$$\underbrace{\frac{1}{3}\left(\nabla\cdot\mathbf{u}\right)p\frac{\partial f}{\partial p}}_{\text{momentum convection}}+\underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left[b_\ell f+D_p\frac{\partial f}{\partial p}\right]\right)}_{\text{momentum diffusion + continuous losses}}-\underbrace{\frac{f(p,\mathbf{x},t)}{t_c(p,\mathbf{x})}}_{\text{catastrophic losses}}+\underbrace{j(p,\mathbf{x})}_{\text{source term}}$$

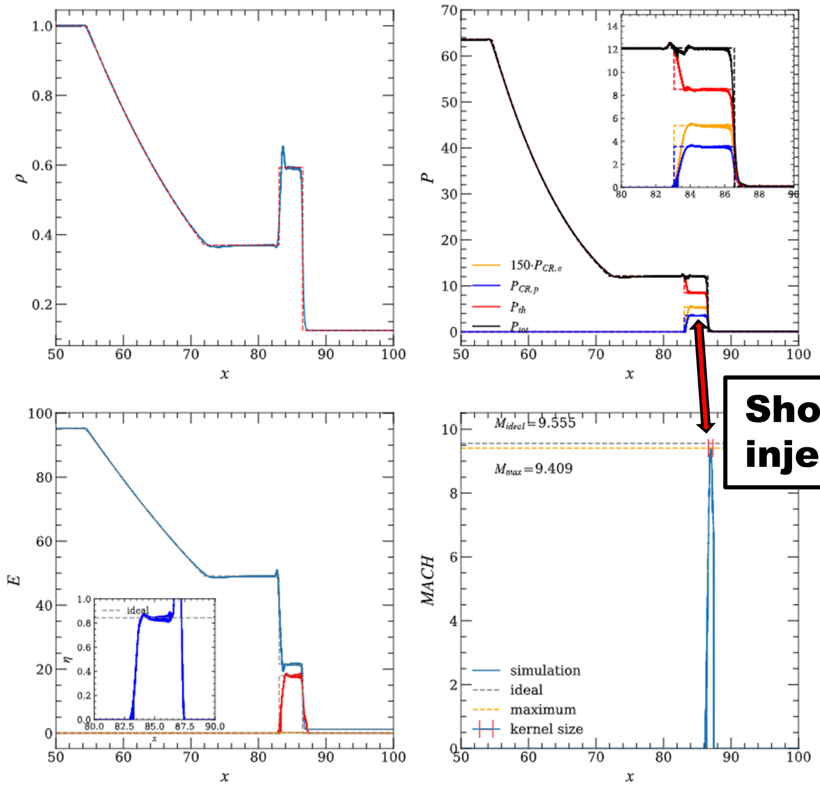
Turbulence

- **Shocks**
- **SFR**
- **AGN**

Cooling of CRe

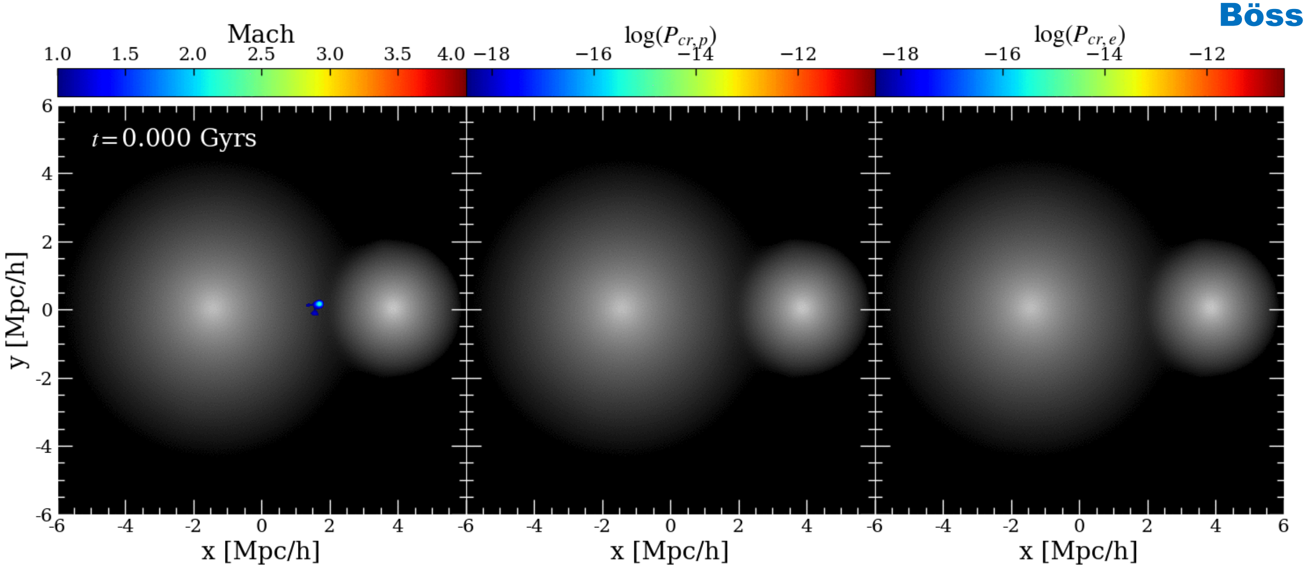


Every resolution element in a simulation has to additionally evolve a sampled distribution function of CR(e,p)!



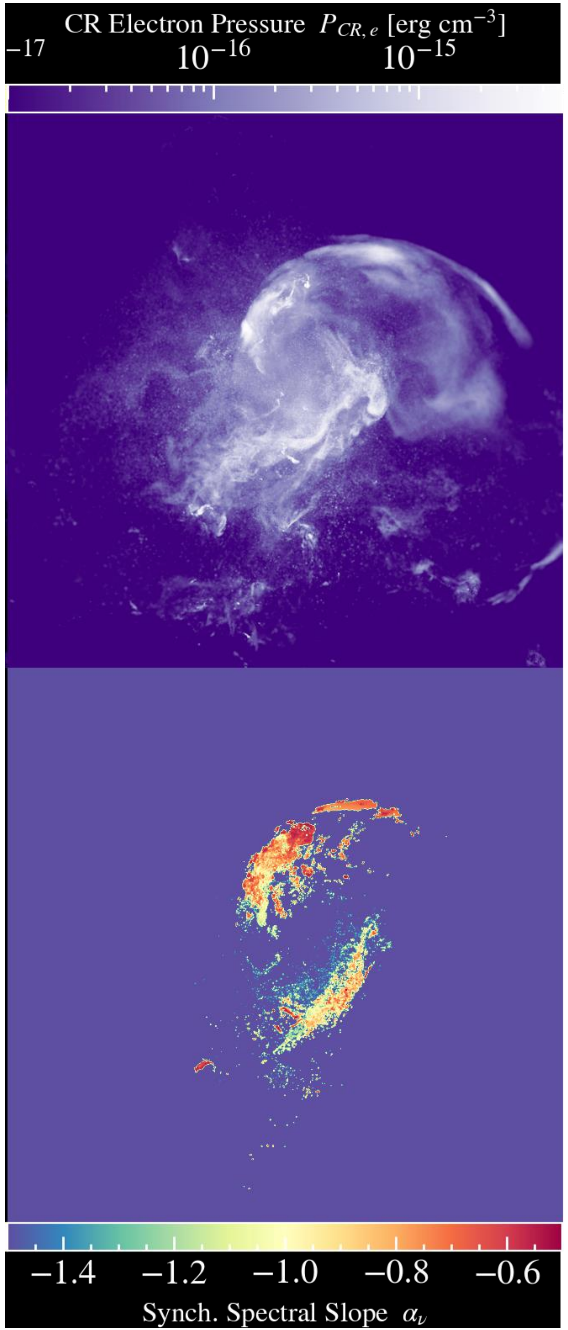
Shock injection

Böss et al. 2022



Radio Relics

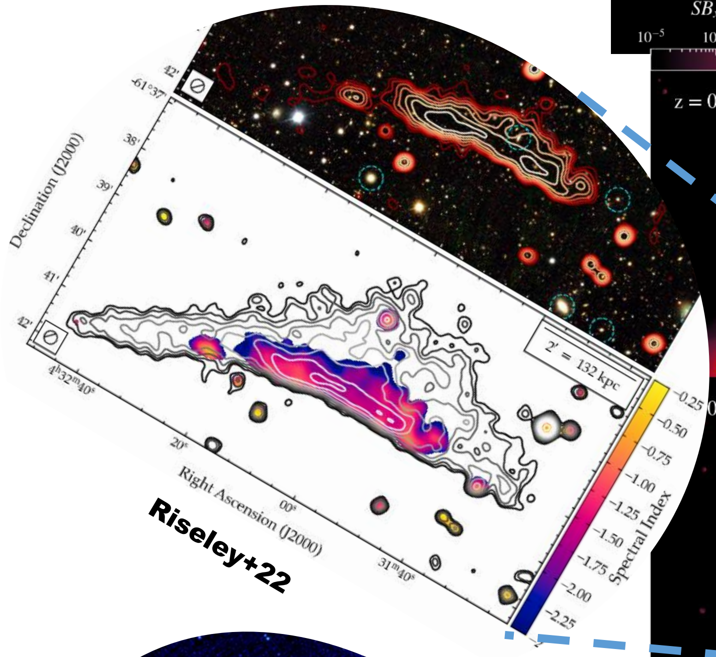
L. Böss



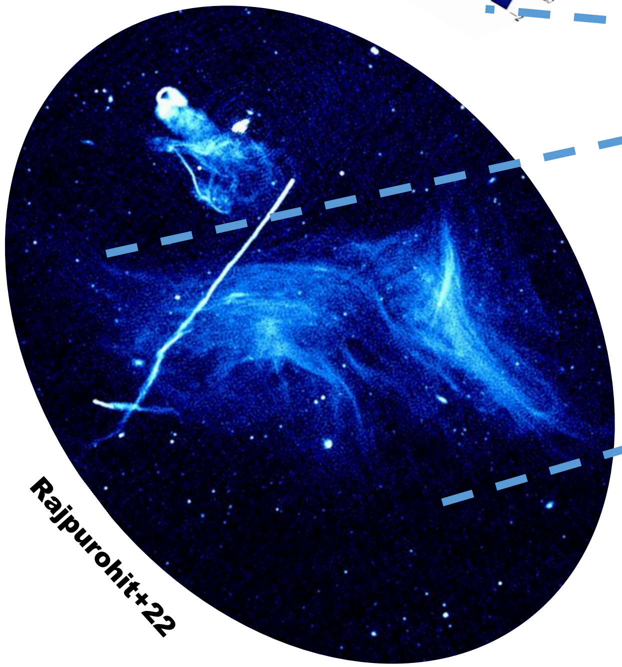
Böss+ 2024

Wrong way Radio Relics!

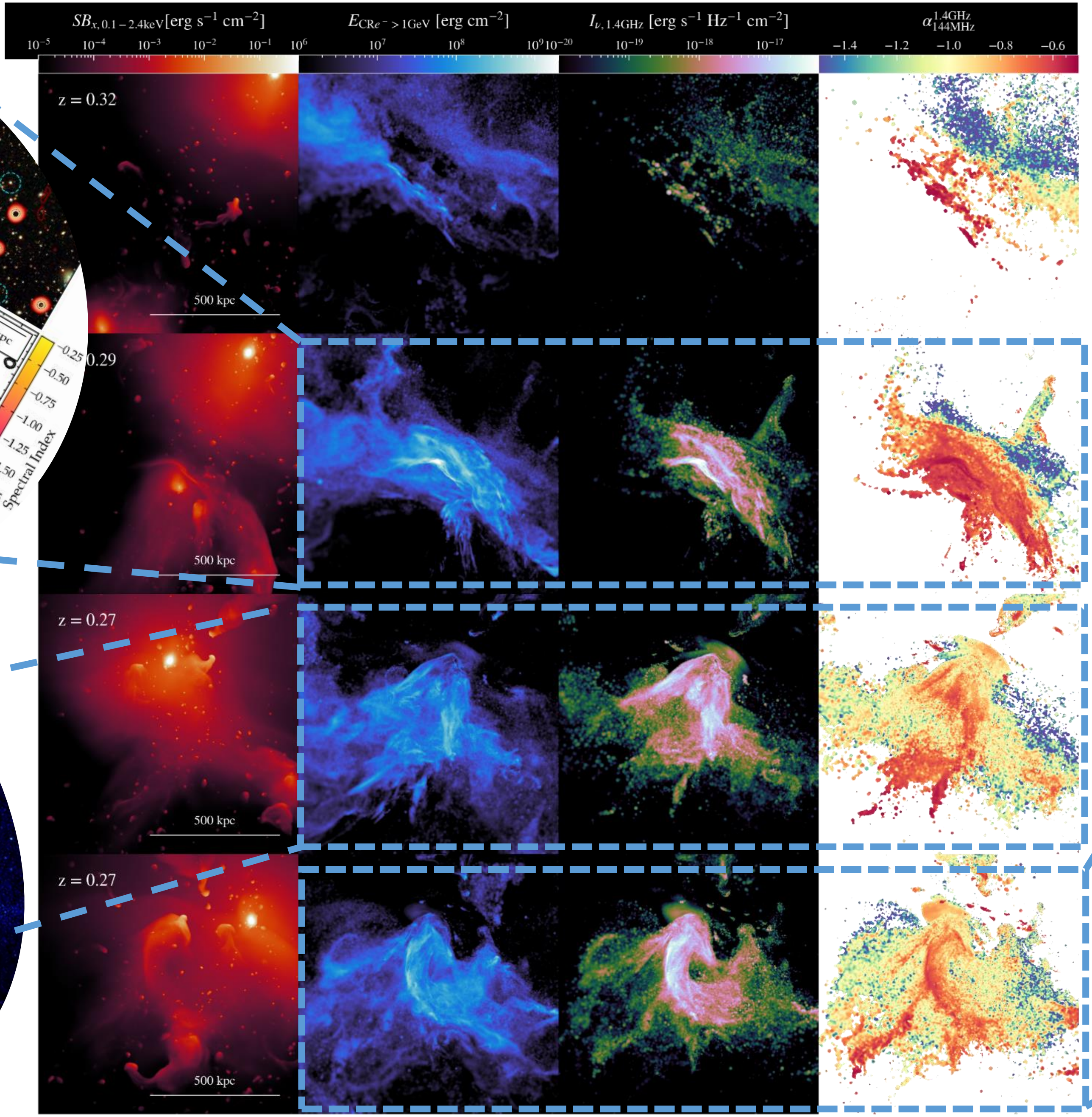
L. Böss



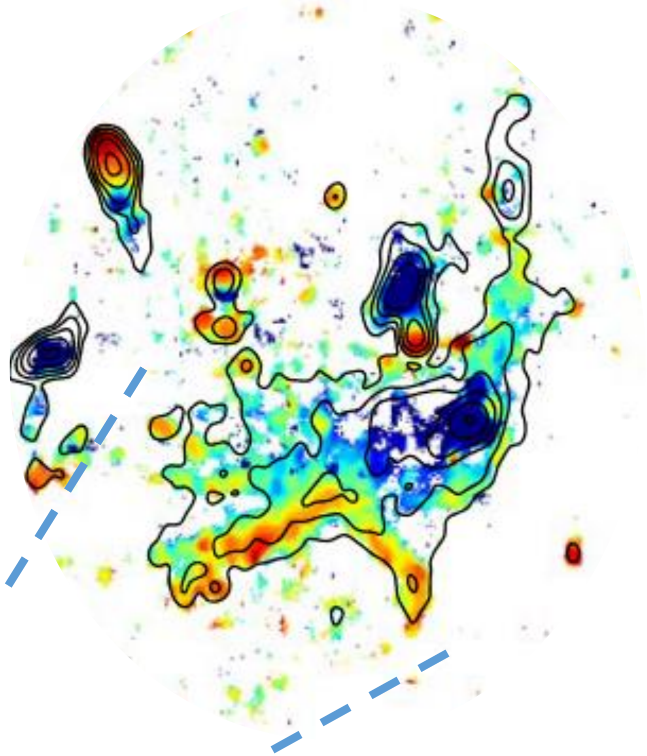
Riseley+22



Rajpurohit+22



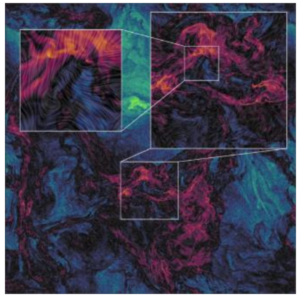
Di Gennaro+18

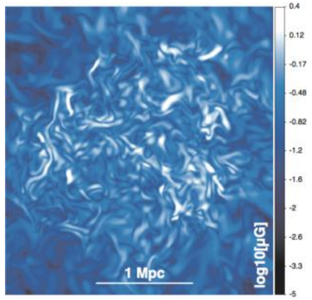


Böss+ 2024

Simulations of turbulent dynamo in the ICM

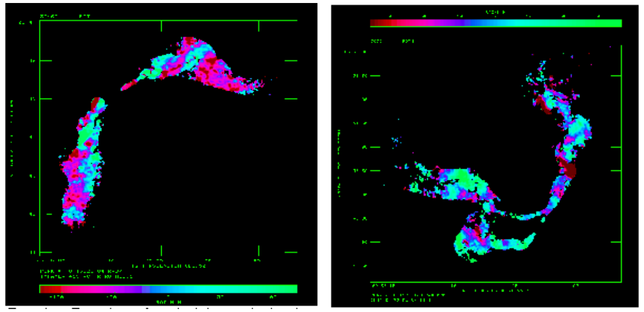
"Towards cosmological simulations of the magnetized intracluster medium with resolved Coulomb collision scale"



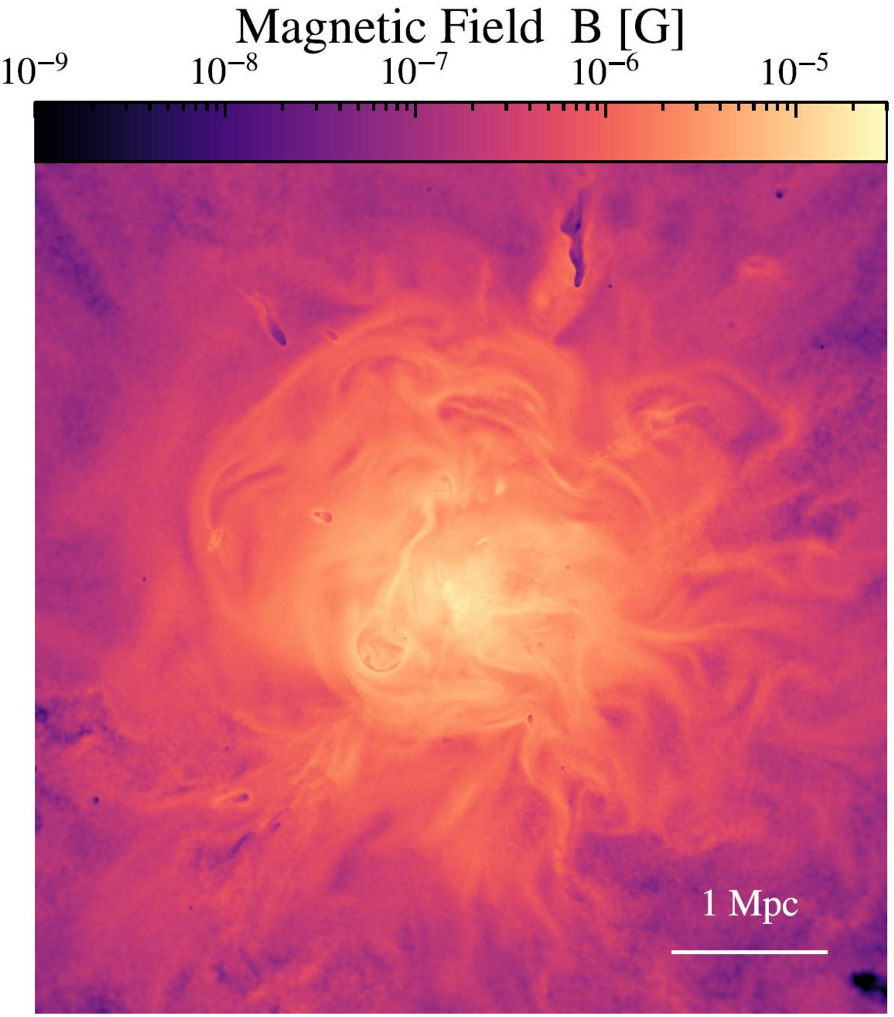


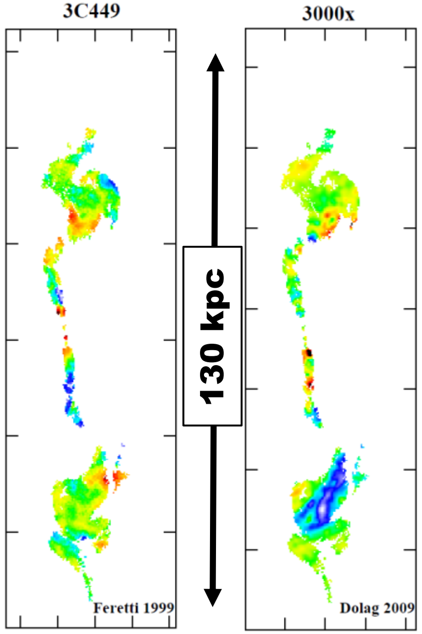
Vazza+ 2018

Eilek & Owen 2000

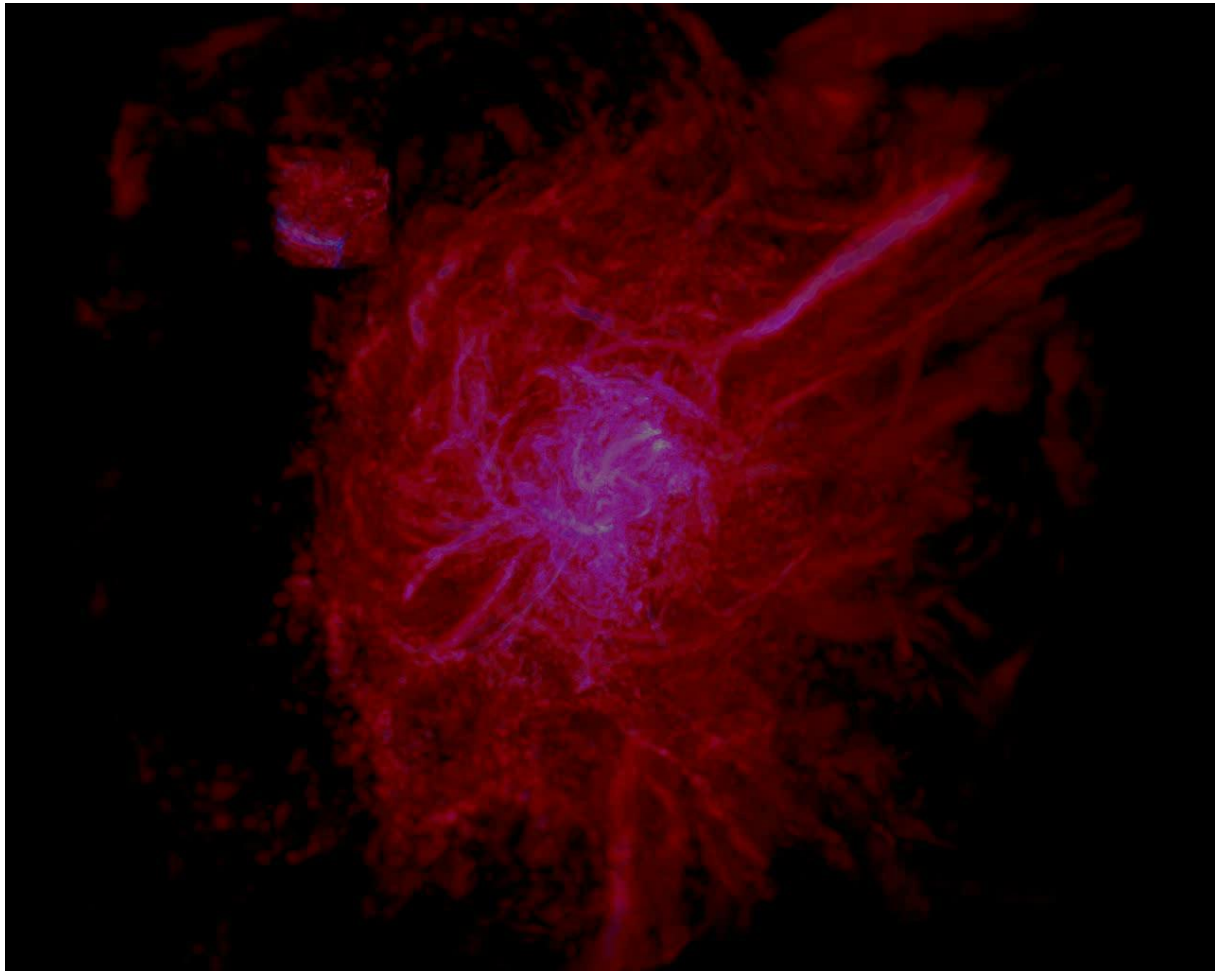


Beattie & Federrath 2023





KD+ 2009



Steinwandel+ 2023

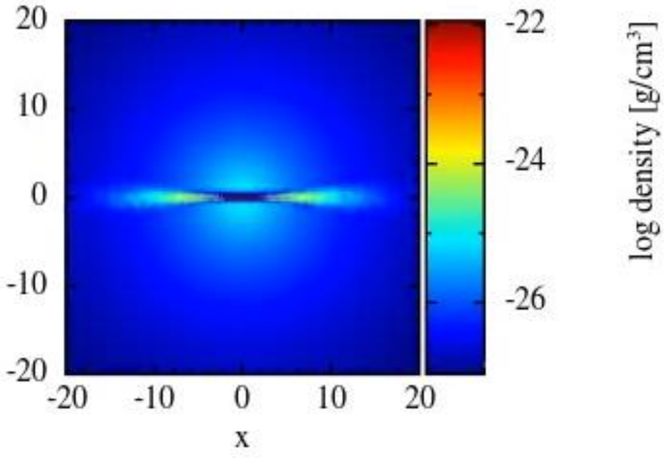
Simulations II: Magnetic Fields in Galaxies

Dynamo in Galaxies

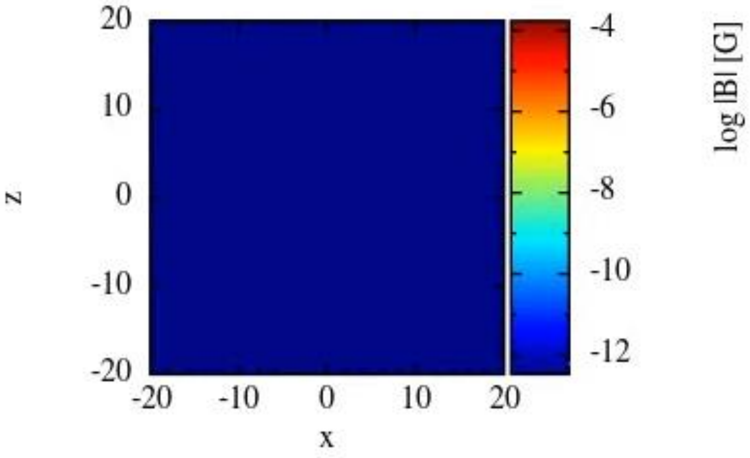
A turbulent dynamo amplifying B is common prediction of all simulations ...

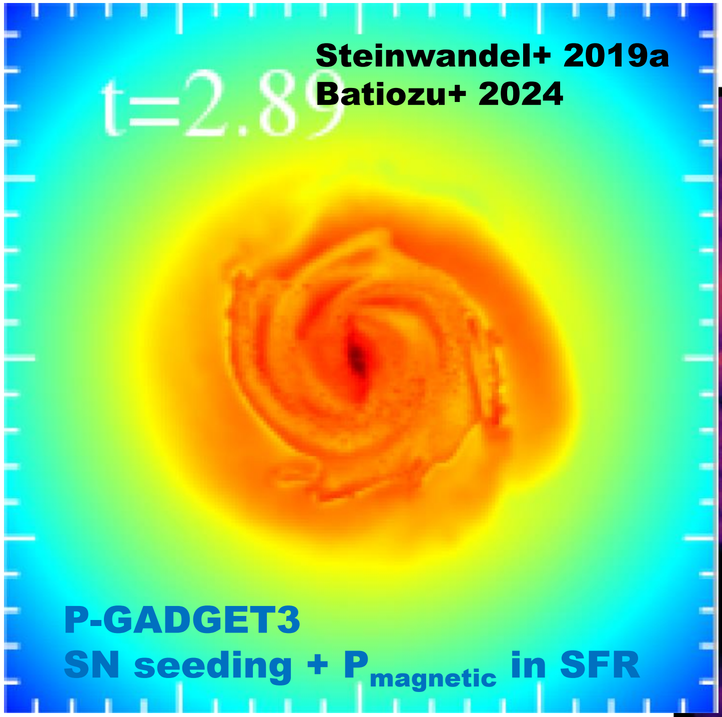
Ulrich Steinwandel

density

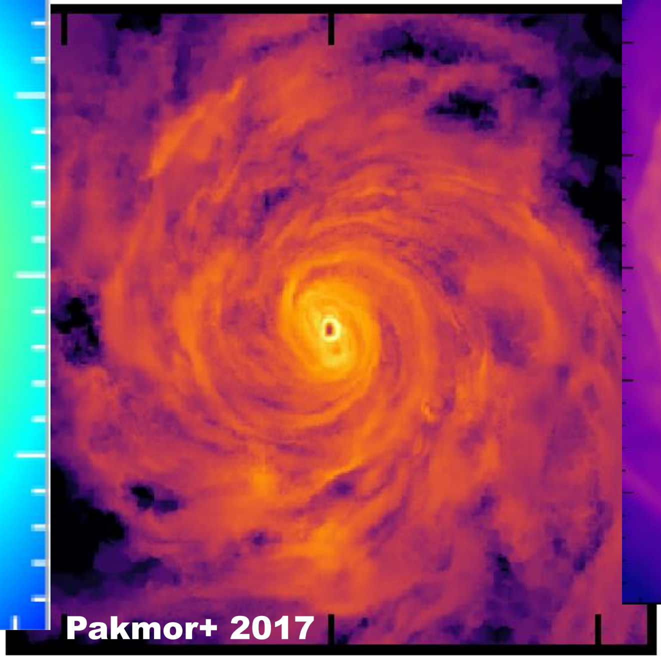


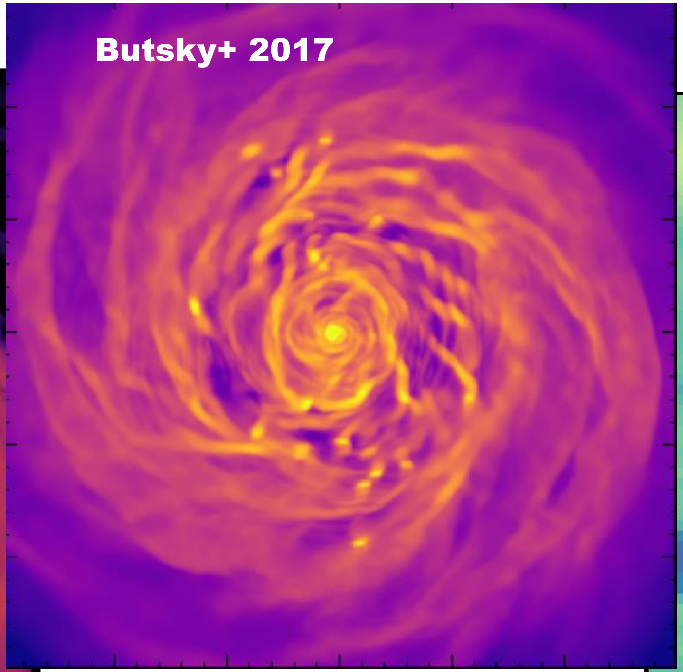
magnetic field





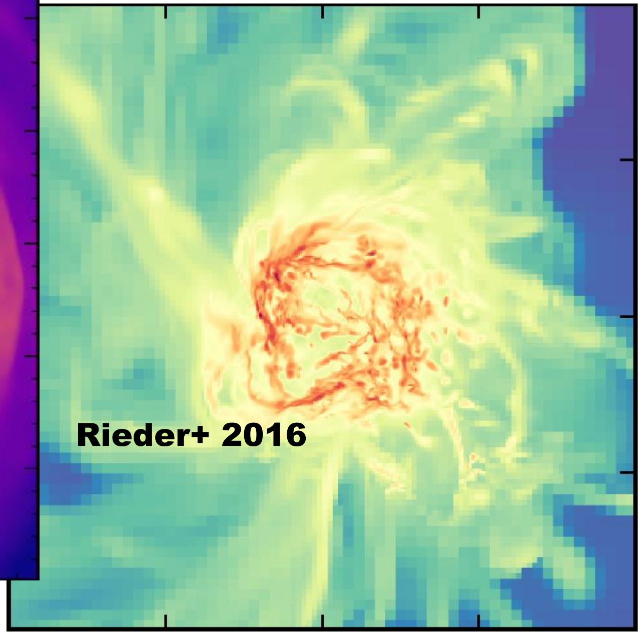
AREPO, primordial B



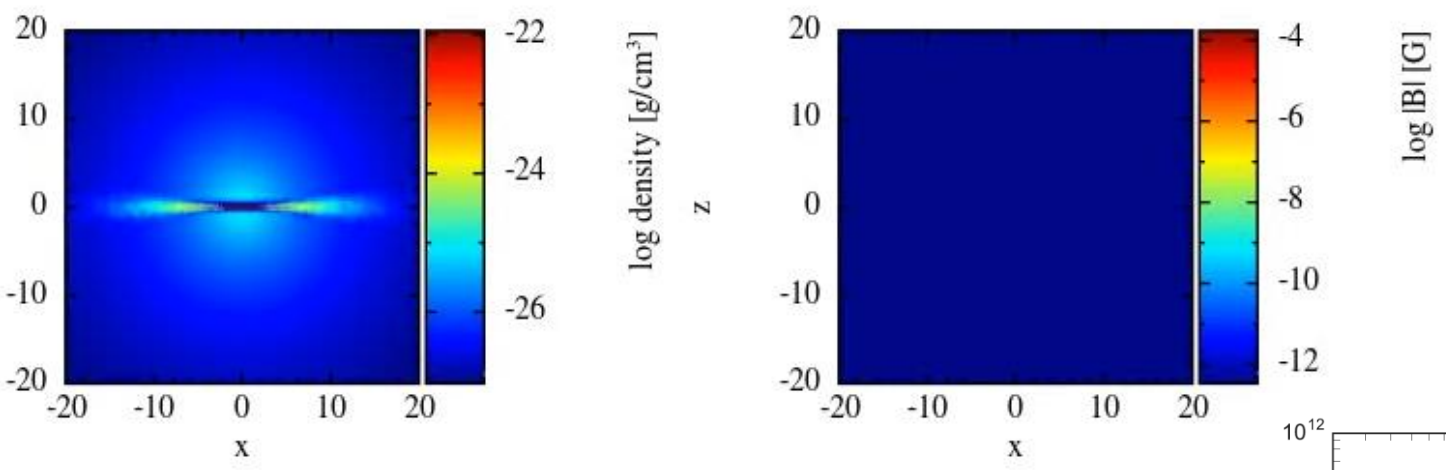


ENZO, primordial B

RAMSES, SN seeding



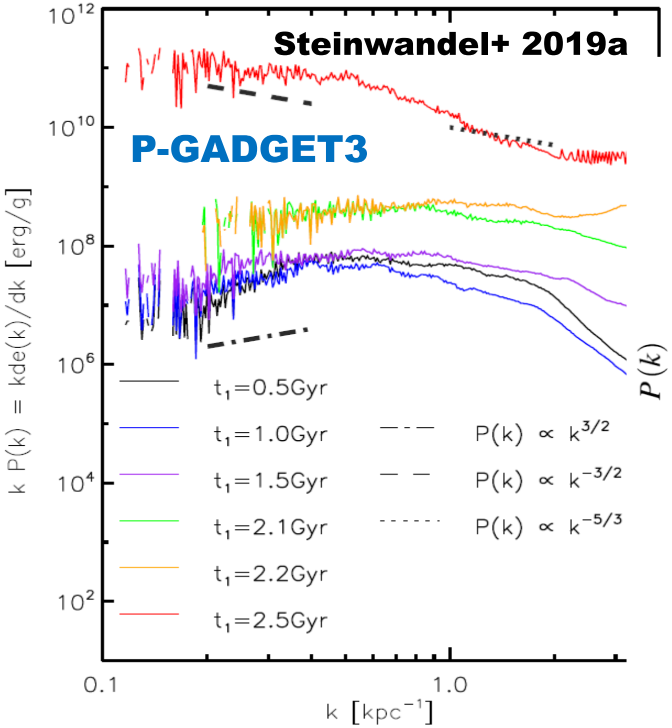
Dynamo in Galaxies

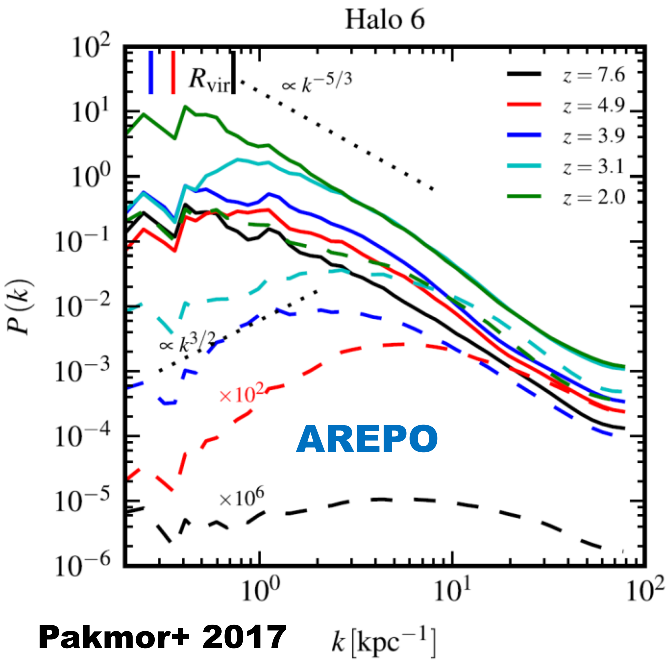


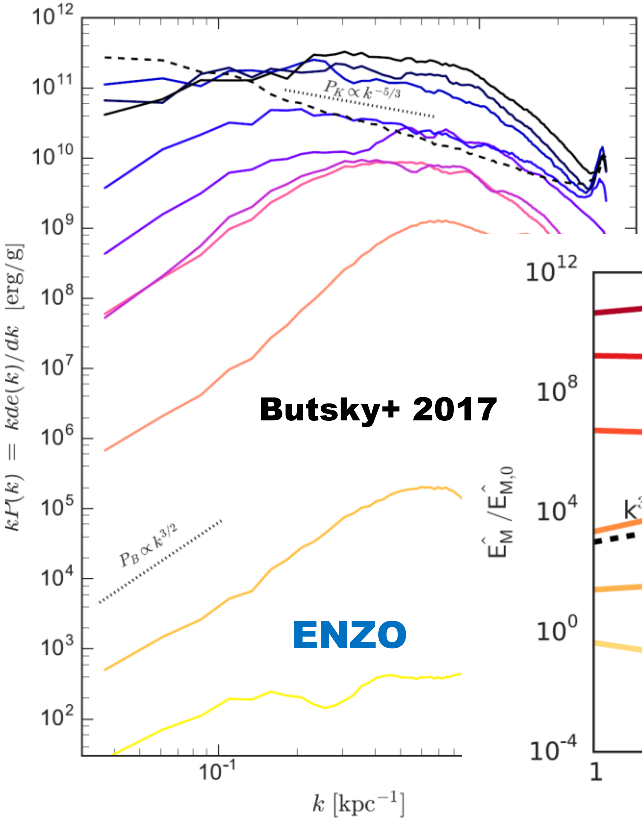
A turbulent dynamo amplifying B is common prediction of all simulations ...

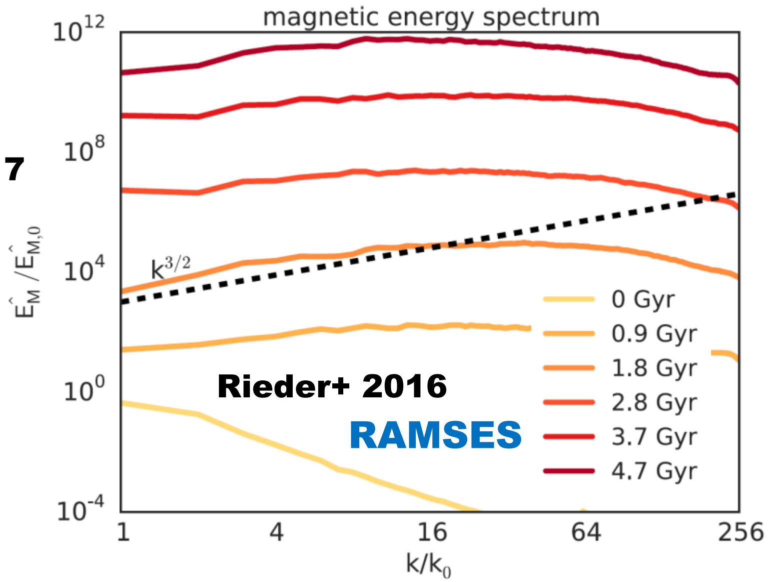
... typically proven by calculating a simple power spectrum ...

Ulrich Steinwandel







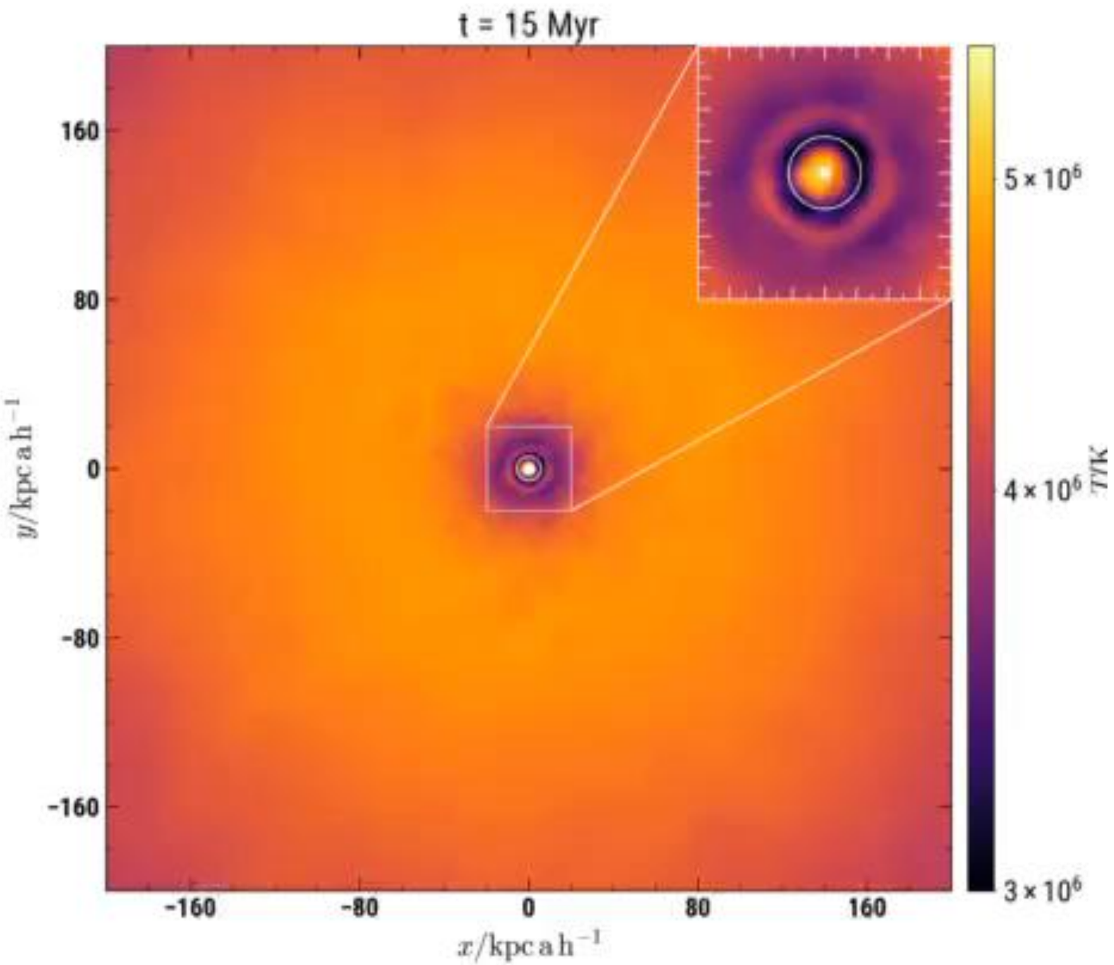


AGN in Galaxies

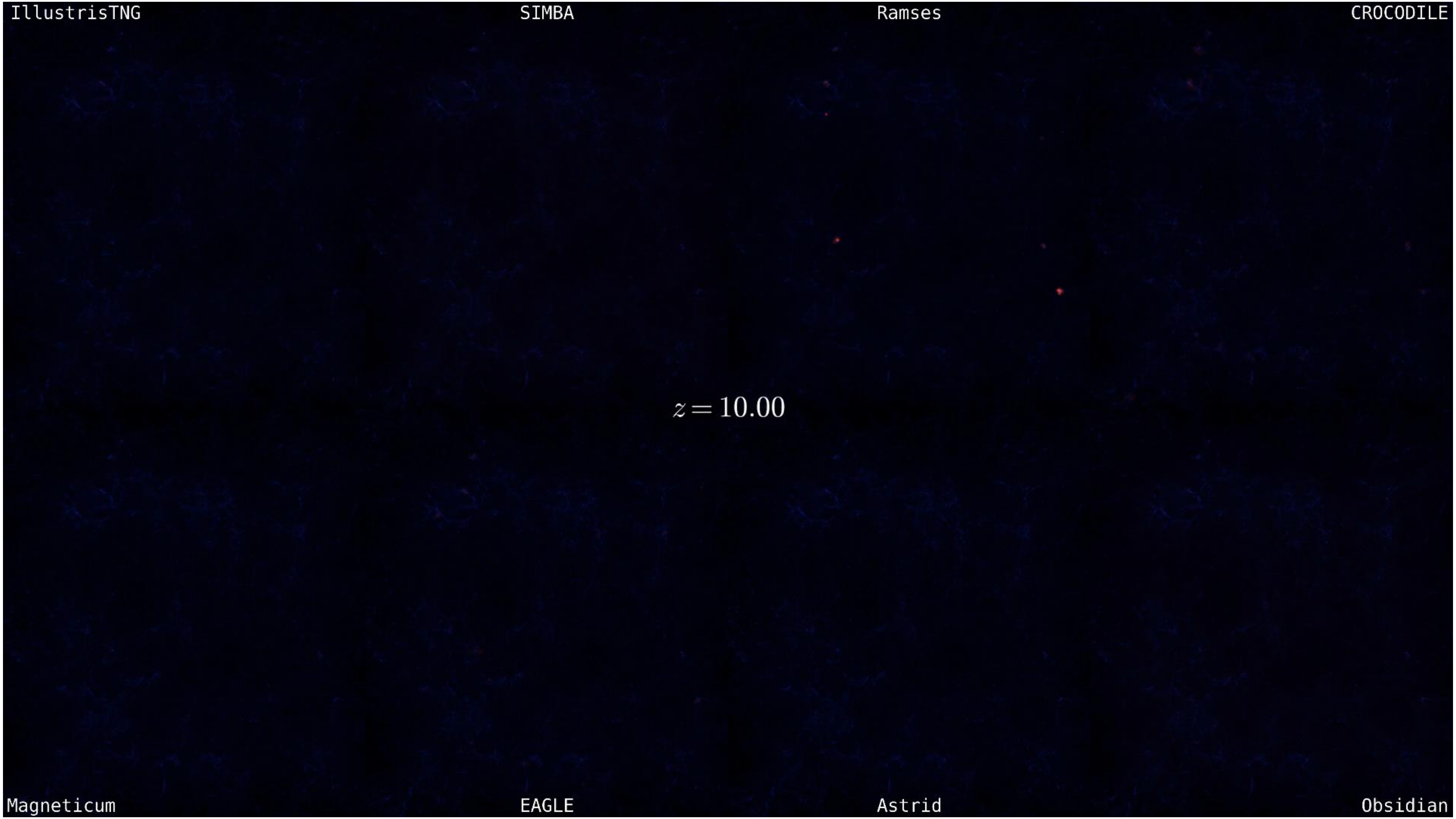
Modelling of the BH evolution with a sub-grid model which also follows the spin evolution. So far still only thermal feedback.

Luca Sala

Idealized galaxy cluster



Massive galaxy forming in cosmological context

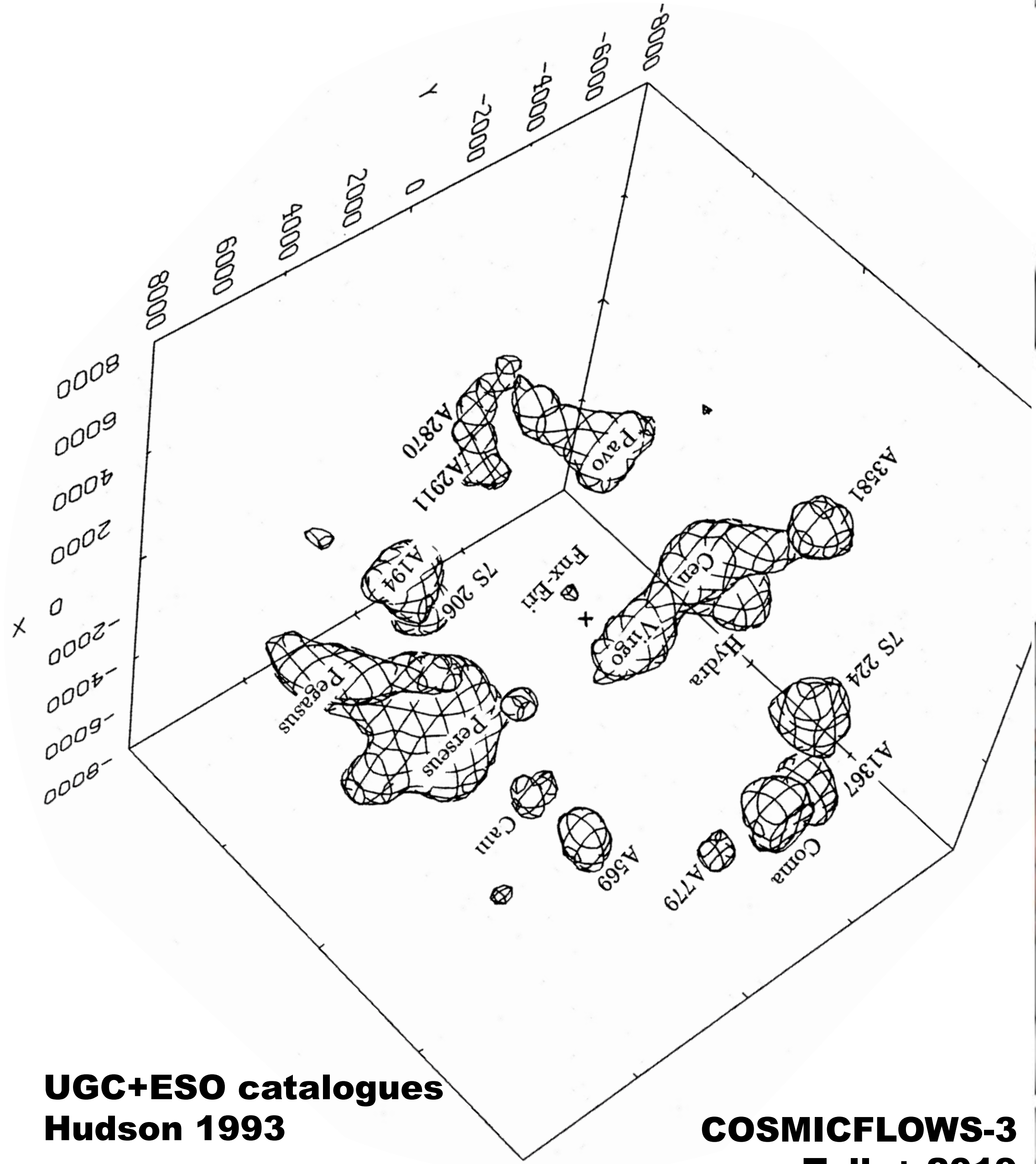


Francisco Villaescusa-Navarro (CAMELS, www.camels-simulations.org)

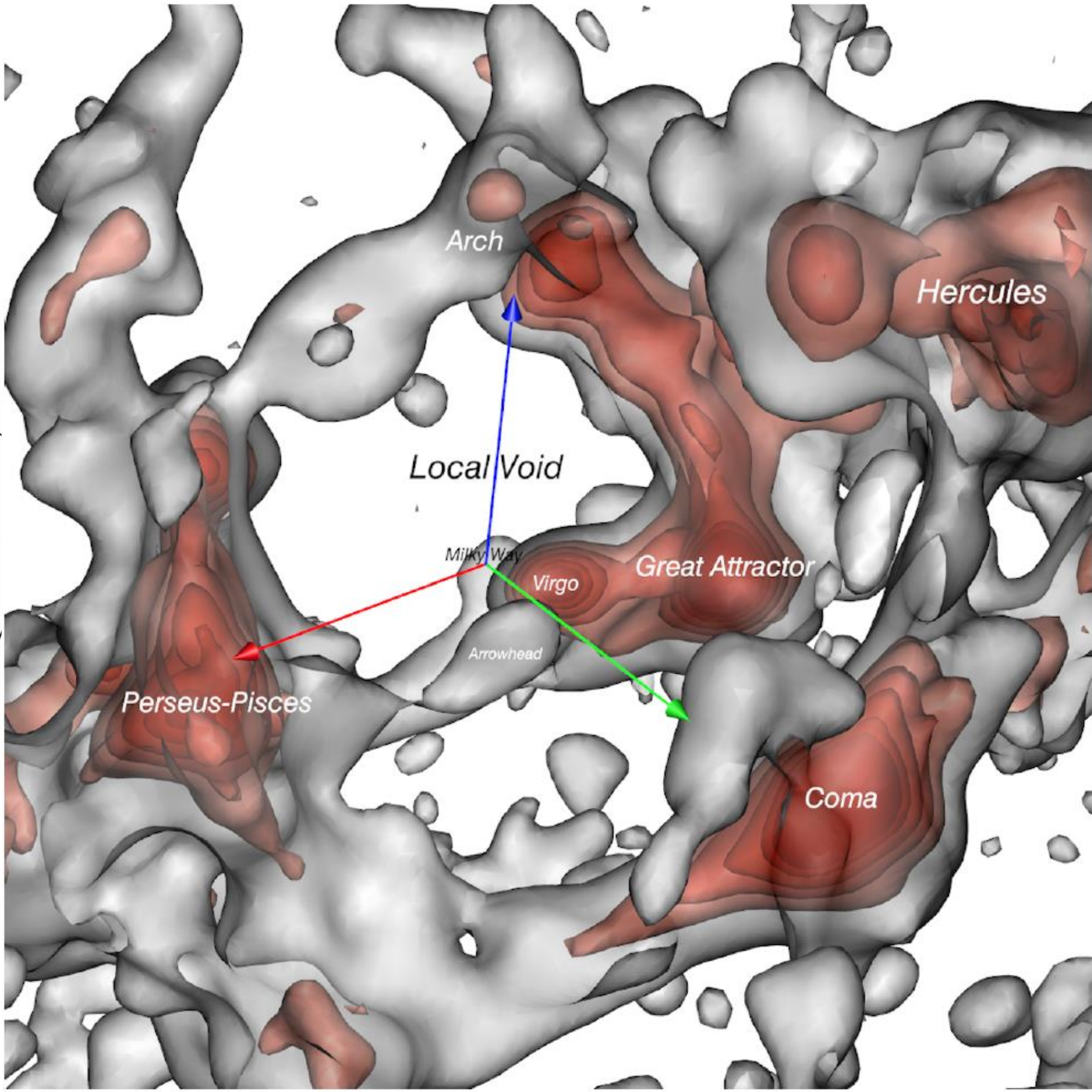
https://users.flatironinstitute.org/~fvillaescusa/Movies/Miscellaneous/

Intro III: The Local Universe

The Local Universe



UGC+ESO catalogues
Hudson 1993

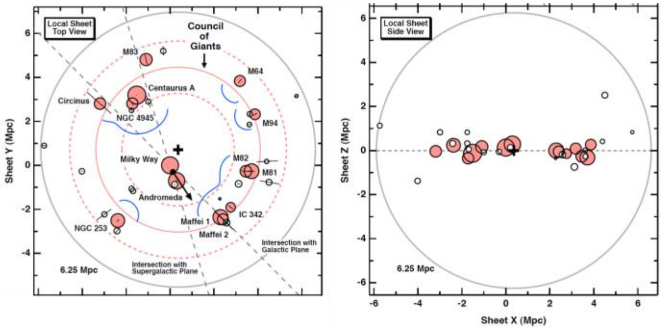


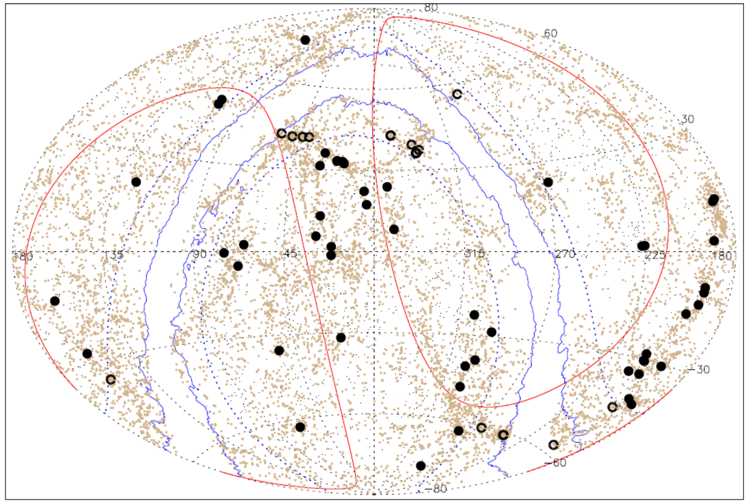
COSMICFLOWS-3
Tully+ 2019

Local Universe Features

A Council of Giants

McCall 2014





The Cosmic Large-Scale Structure in X-rays (CLASSIX) Cluster Survey II: Unveiling a pancake structure with a 100 Mpc radius in the local Universe ⋆

Hans Böhringer[1,2], Gayoung Chon[1], Joachim Trümper[2]

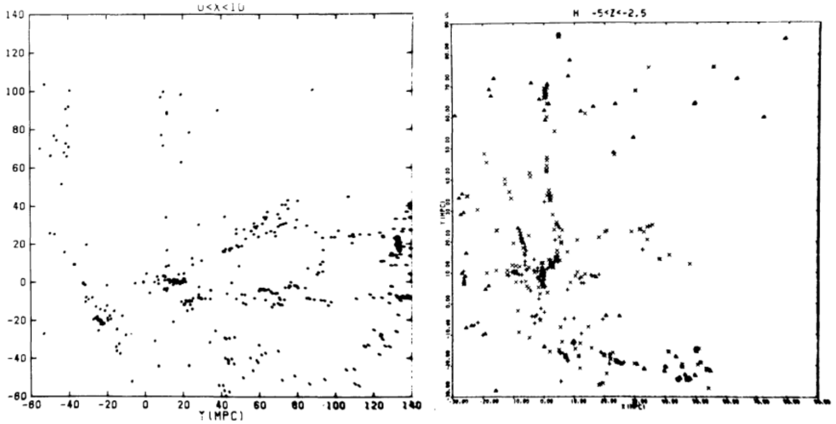
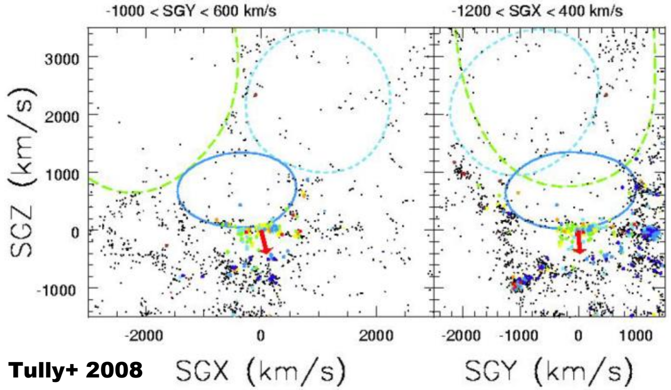


Figure 4. Thin slices through the Local Supercluster, in SG coordinates, corresponding to Hubble constant 100.

Our Peculiar Motion Away from the Local Void



Tully+ 2008

See also Reviews:
Flin 1986
Rubin 1989
Lahav+ 2000
Peebles 2022

NEIGHBORING SUPERCLUSTERS AND THEIR ENVIRONS

J. Einasto[1] and R.H. Miller[2]
[1]Tartu Astrophysical Observatory
[2]European Southern Observatory

Einasto & Miller 1983

Recently finished redshift surveys make it possible to study the large-scale environment of superclusters and their mutual relationship.

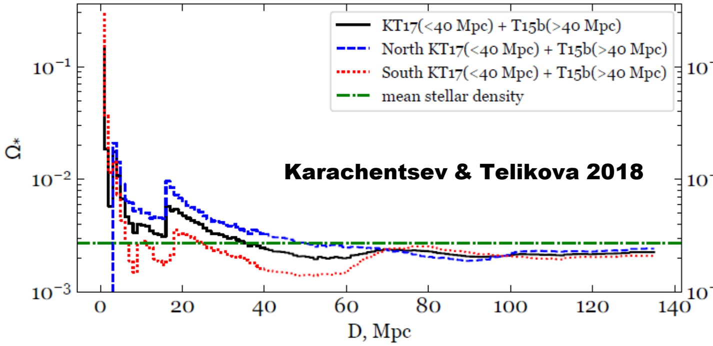
Figure 1 shows the distribution of nearby clusters in the sky in supergalactic coordinates at two redshift intervals. Nearby clusters in the distance interval 75 to 150 Mpc form a belt around us which is close to the supergalactic equator; its inclination is only 20°. The following superclusters belong to this belt: Ursa Major-Lynx (Giovanelli and Haynes 1982), Coma, Hydra-Centaurus, Pavo-Corona Australes, and Perseus-Pisces. Coordinates and redshifts for a number of previously unknown southern clusters have been derived by Dr. H. Corwin and Dr. M. Tarenghi (Einasto et al. 1982).

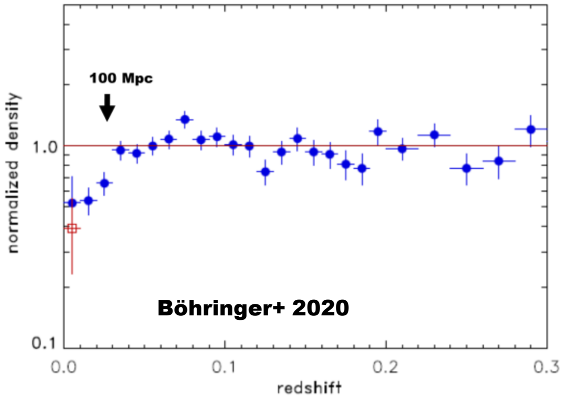
Clusters in the distance interval 150 to 250 Mpc are found at much higher supergalactic latitudes. Clusters in this distance interval form a number of superclusters: Hercules, Ursa Major-Leo, Pegasus and several southern superclusters.

All these superclusters belong to cells which can be called the Northern Local Cell and the Southern Local Cell (Einasto et al. 1982). Nearby superclusters form together with our Local Supercluster a disk about 250 Mpc in diameter and 50 Mpc thick, which is located between both local cells. The Hercules supercluster is located between the Northern Local Cell and The Bootes cell, studied by Kirsher et al. (1981). The Perseus-Pisces and Pegasus superclusters are located between the Northern Local Cell and the Perseus cell.

Observational evidence for a local underdensity in the Universe and its effect on the measurement of the Hubble Constant ⋆

Stellar and dark matter density in the Local Universe

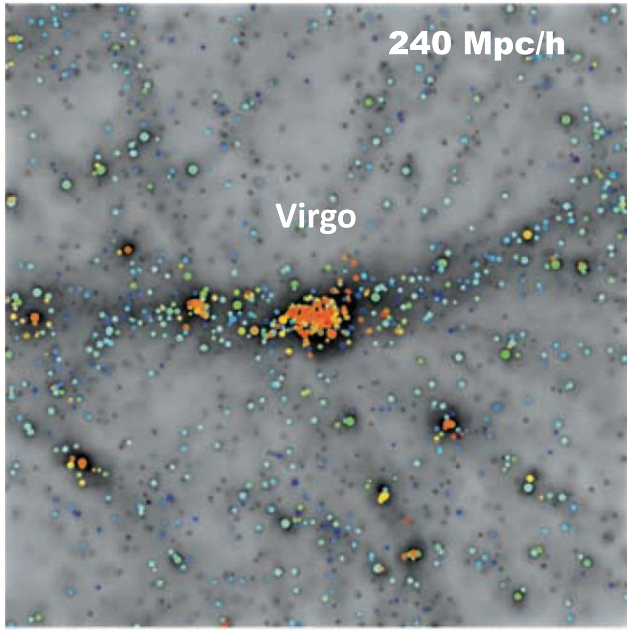




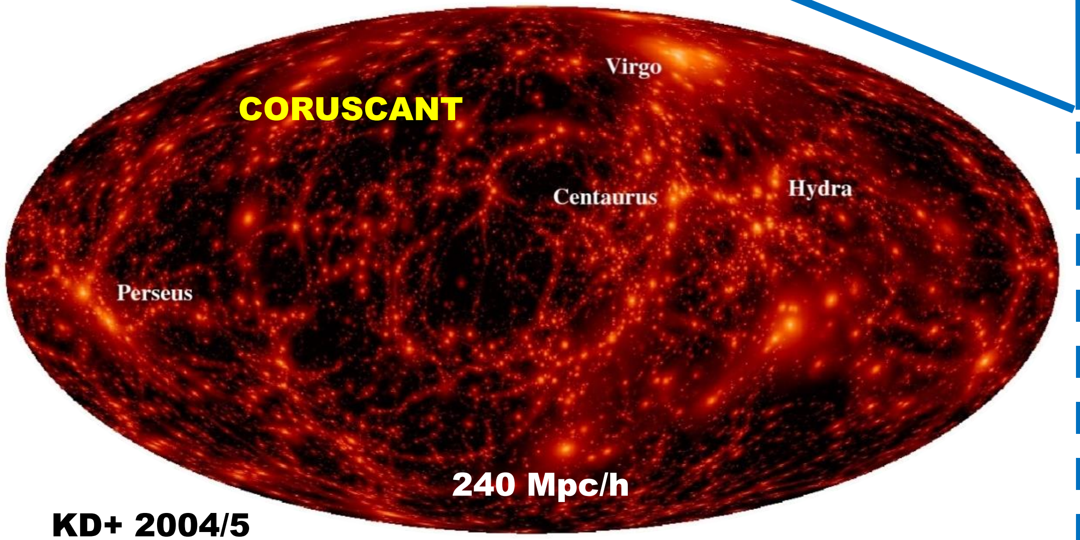
Simulations III: Towards the Local Universe

Local Universe Simulations

Density based (redshift surveys)

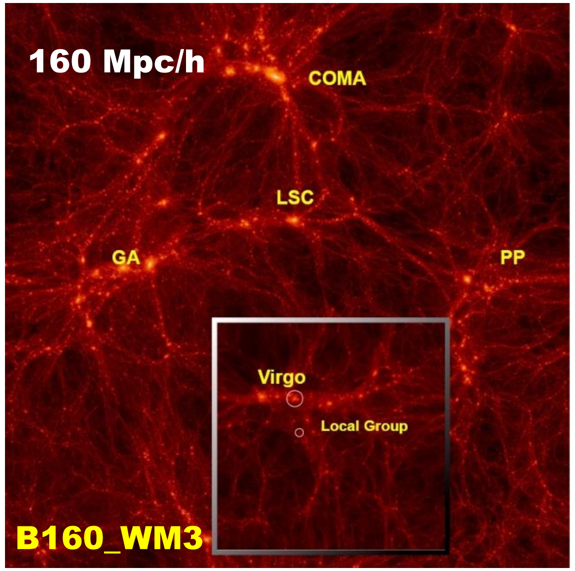


Mathis+ 2002



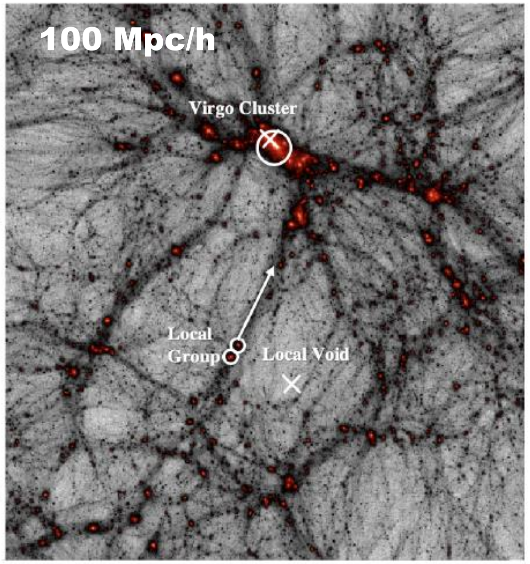
KD+ 2004/5

Hybrid approach

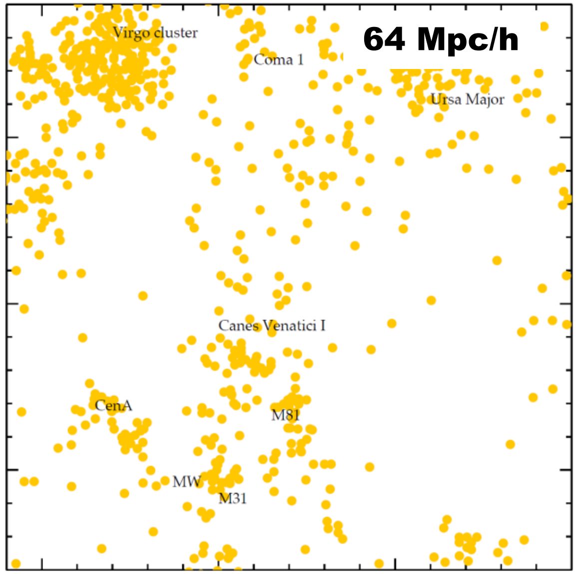


Klypin+ 2003 / Gottlöber+ 2010

Velocity based
(peculiar velocity derived from distance measures)



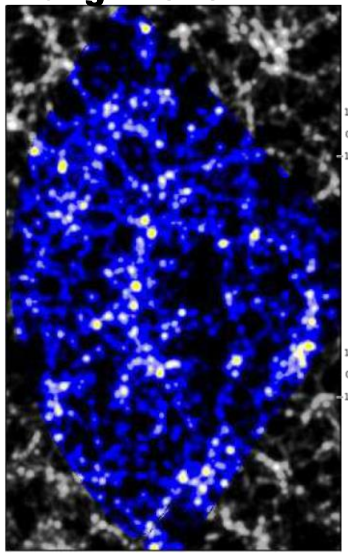
Liebeskind+ 2016+

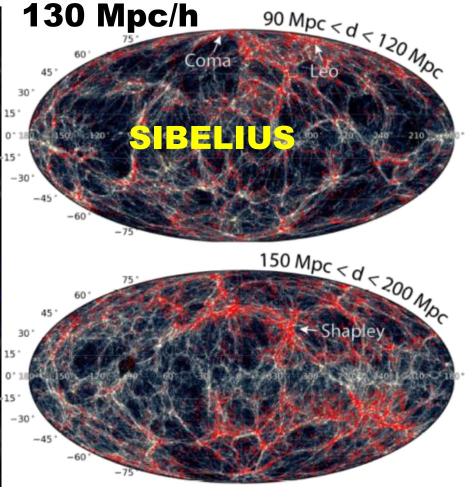


Ocvirk+ 2020, Sorce+ 2022

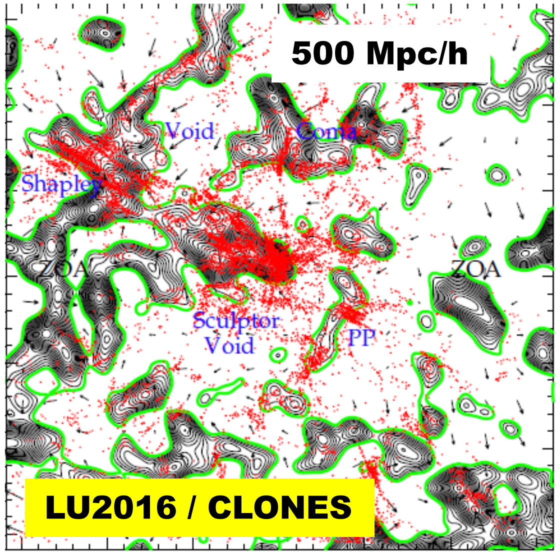
Bayesian forward modelling

Wang+ 2016





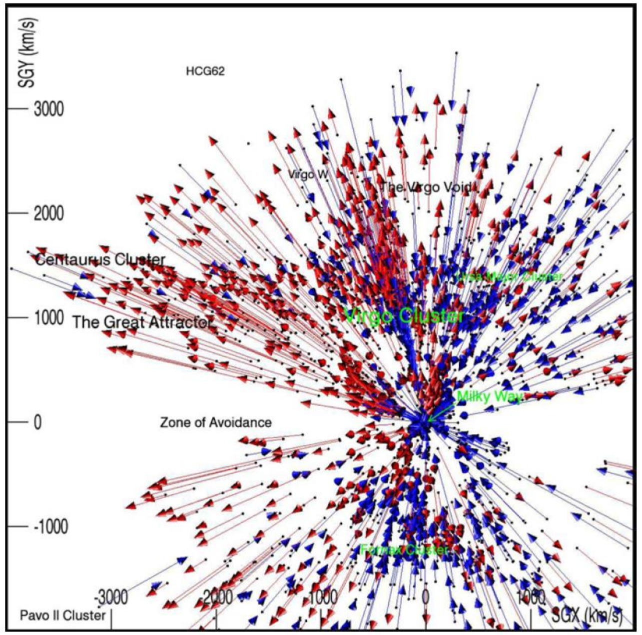
McAlpine 2022

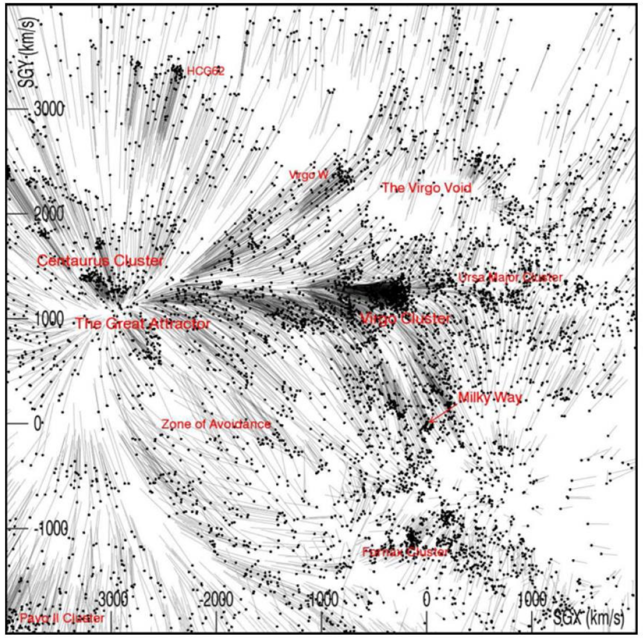


Sorce 2016, 2018

Some details what is done to obtain ICs

Here, details are worked out / improved continuously over last decade. Especially through contributions by J. Sorce.



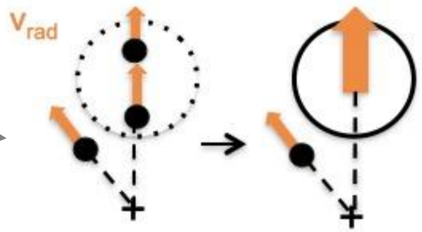


Method

- Radial peculiar velocity catalog
- Grouping
- Minimization of biases
- Wiener filtering
- Reverse Zel'dovich Approximation
- Constrained realization
- Constrained initial conditions

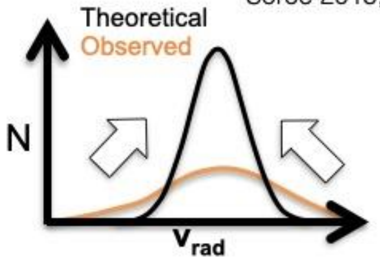
Sorce & Tempel 2017,2018

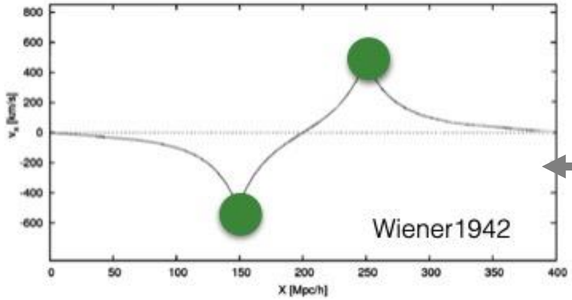
Obtaining linear component of the velocity field.



Sorce 2015, 2018

Bias minimization
Malmquist bias & lognormal errors

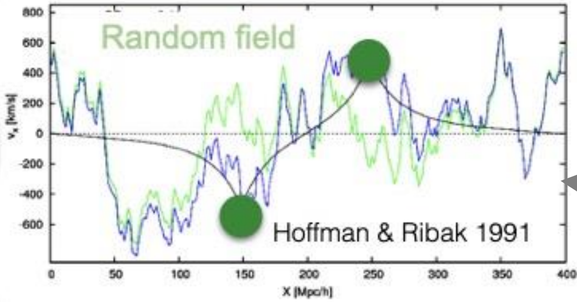




Reconstruct the displacement field

Doumler+2013 Sorce+2014

Relocating constrains



Combine with random realization for missing structures.

Sorce2018, Sorce et al. 2021, etc.

Slice kindly provided by J. Sorce

Simulating the LOcal Web

Box of 500 Mpc/h

Several hundreds of dark matter only test simulations

Two production runs:

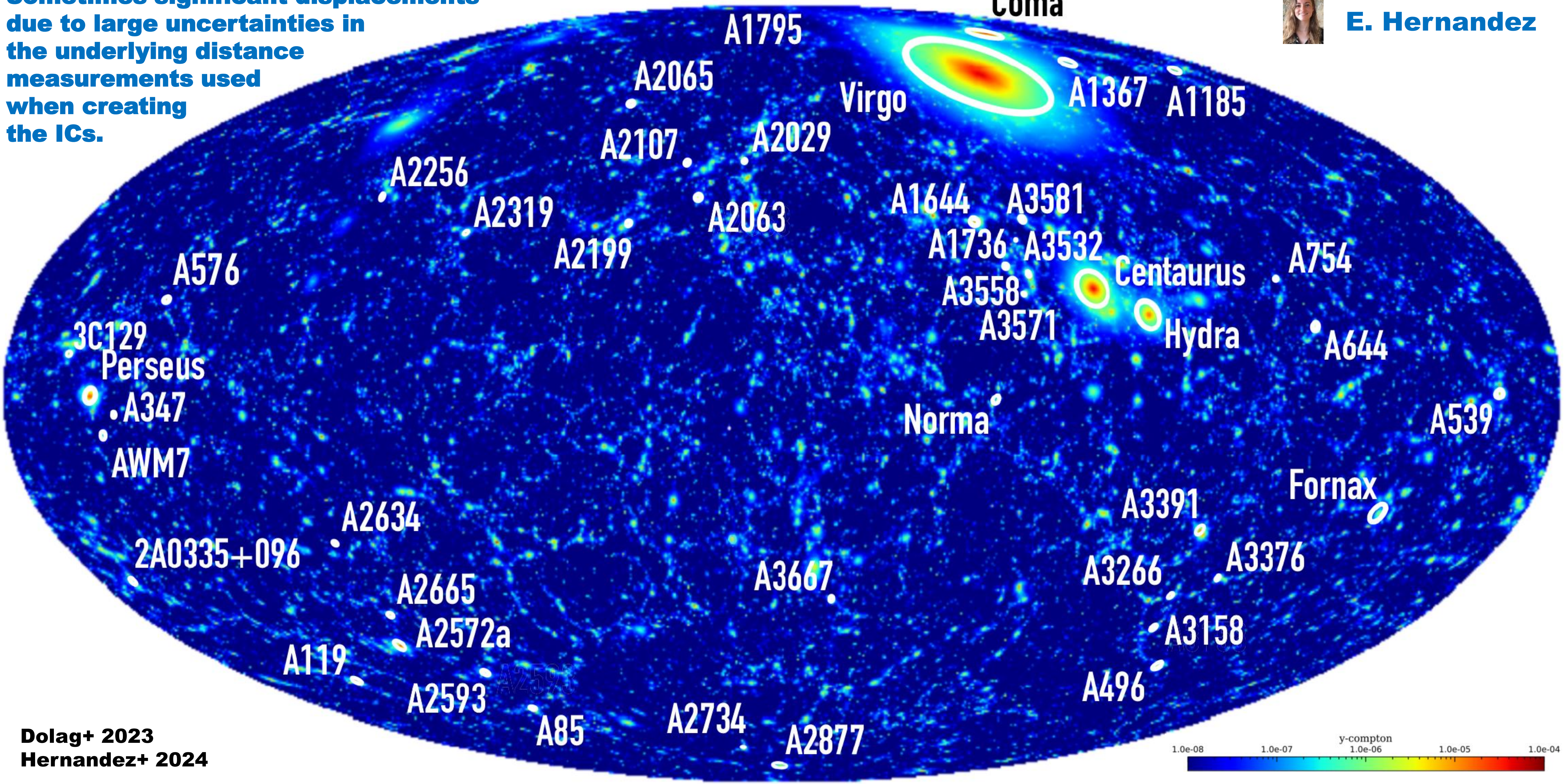
- **2×1536^3 full galaxy formation physics, including AGN (AGN)** (Dolag+ 2023)
- **2×3072^3 non radiative MHD with cosmic rays (MHD+CRs)** (Böss+ 2024)

The SLOW simulation

Cross identified more than 45 Clusters between simulations and observational catalogues (like CLASSIX, PLANCK, …)

Sometimes significant displacements due to large uncertainties in the underlying distance measurements used when creating the ICs.

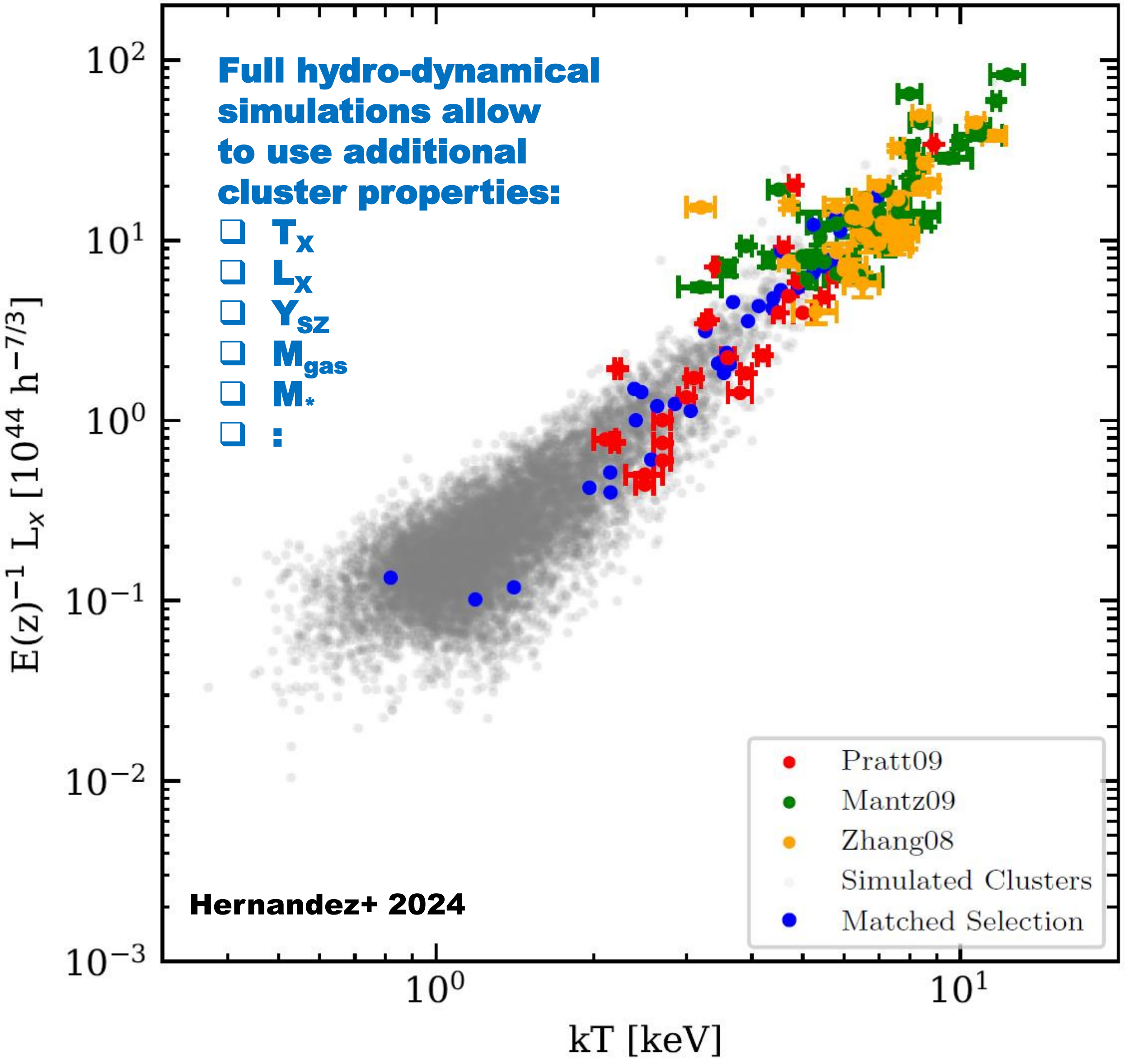
E. Hernandez

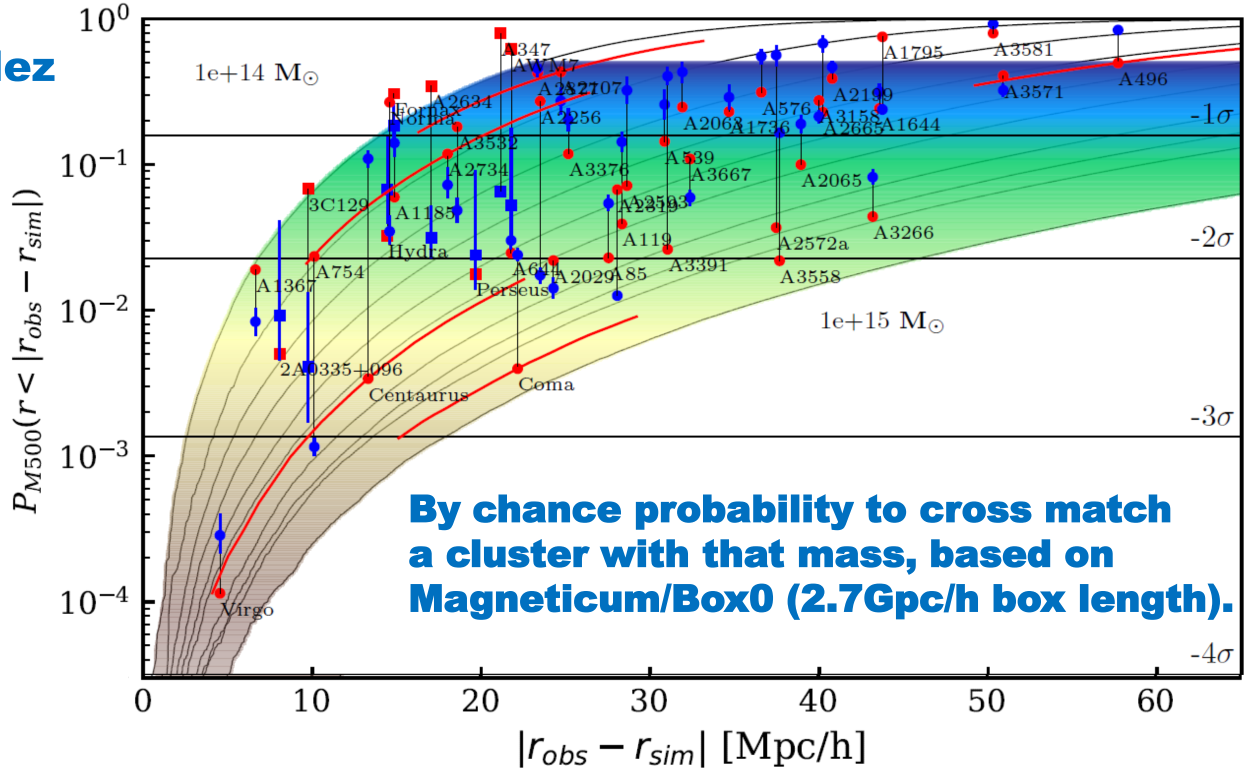


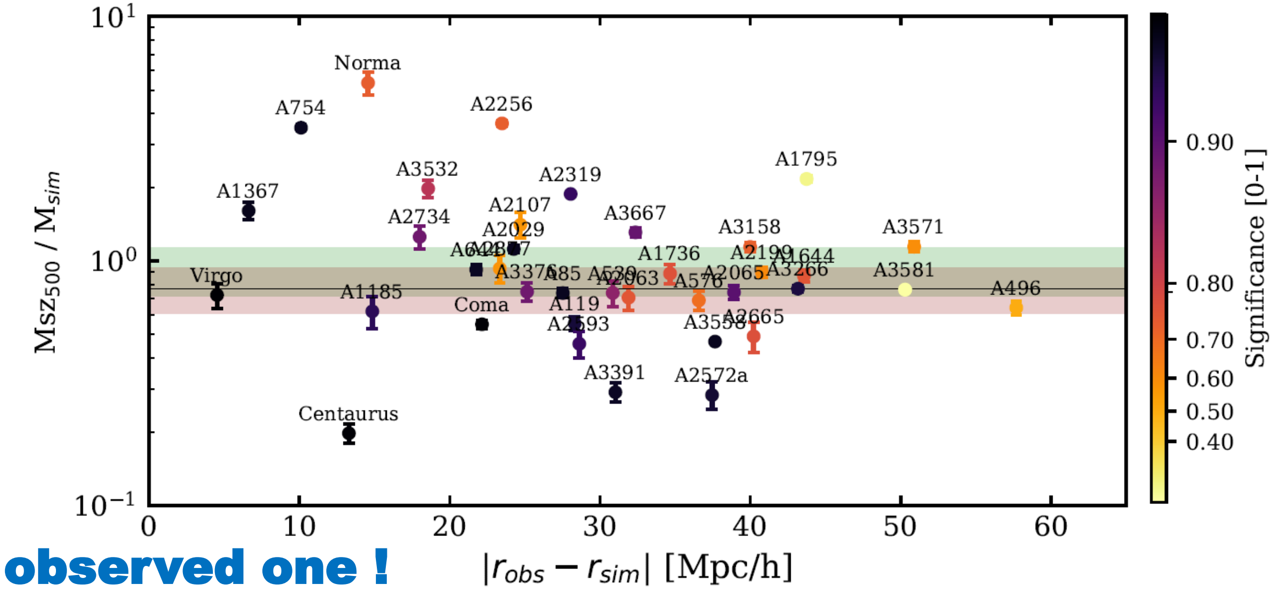
Dolag+ 2023
Hernandez+ 2024

The SLOW simulation

E. Hernandez

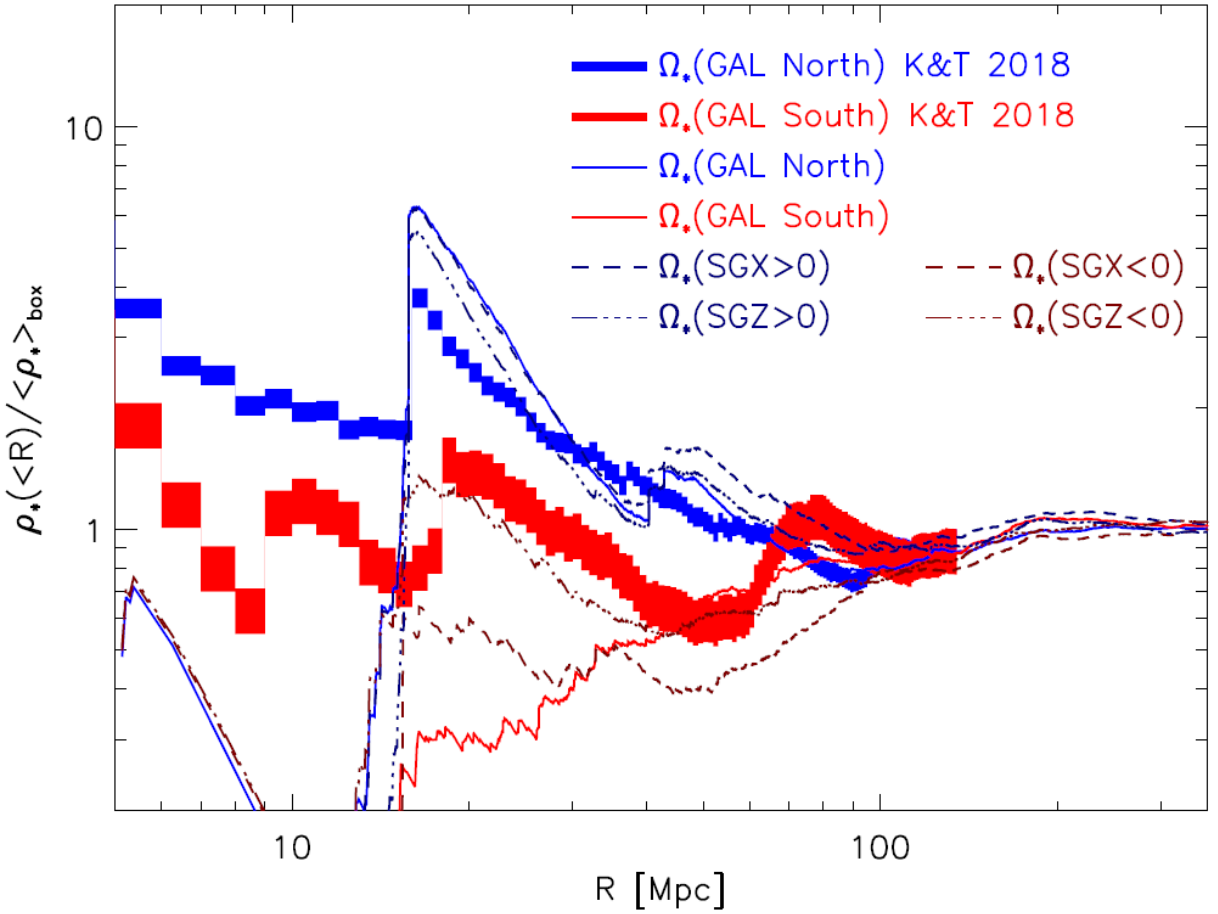


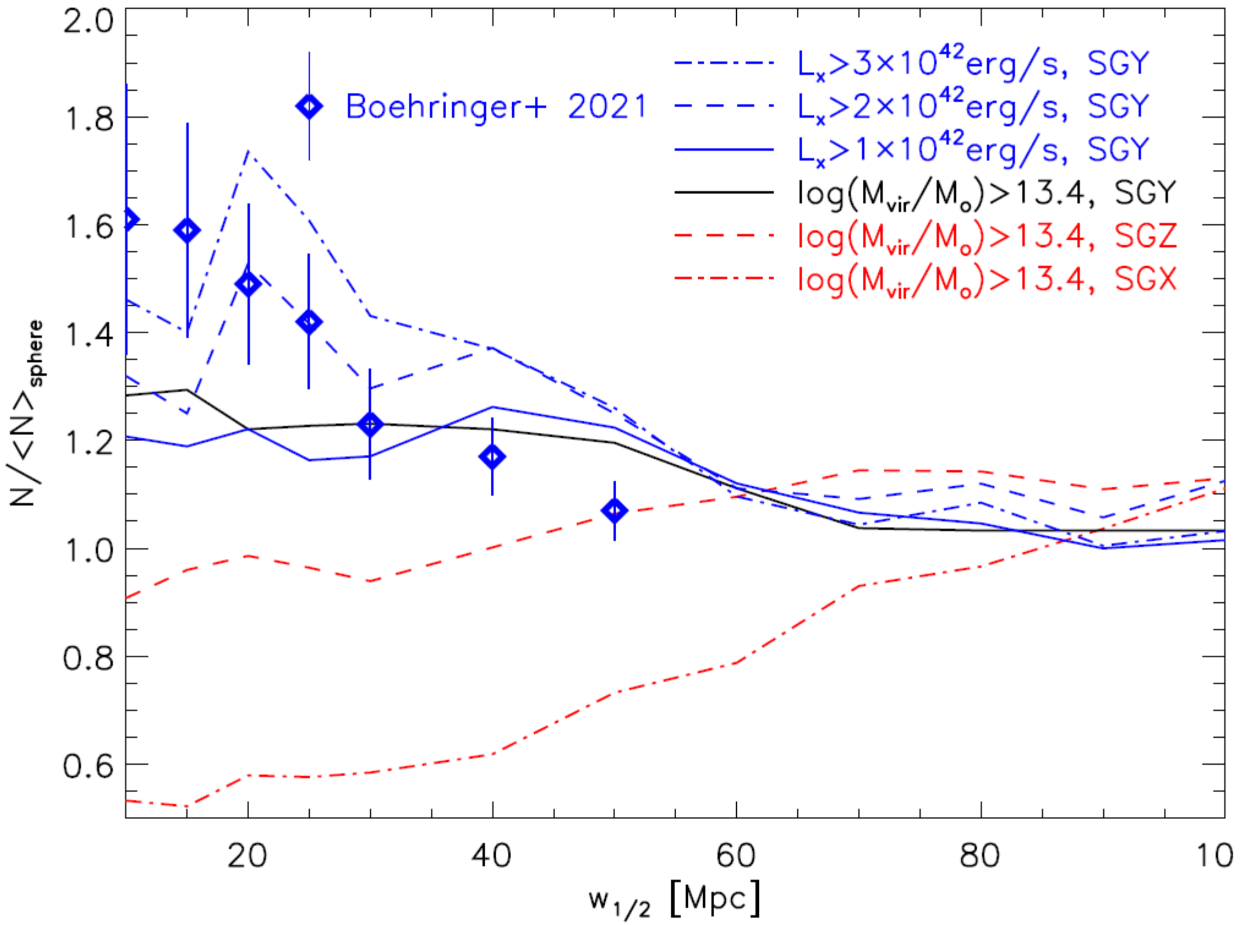




- ❑ **On average, the simulated mass matches the observed one !**
- ❑ **The ratio of observed to simulation mass indicate a hydrostatic mass bias (1-b) ~ 0.87 ...**

The SLOW simulation: matter distribution and tracers



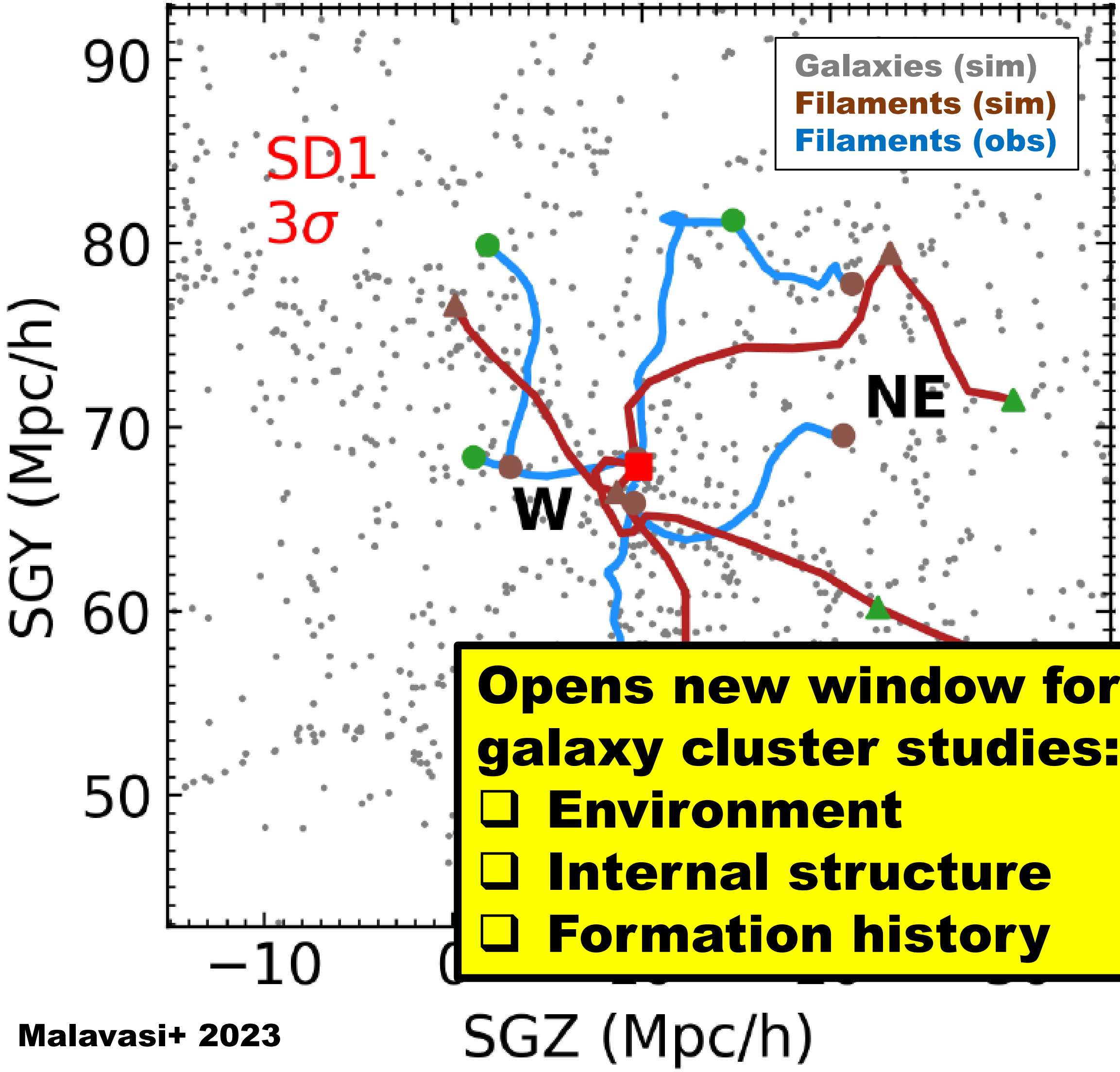


- ❑ **Pancake like structure traced by clusters reproduced**
- ❑ **Density structures and north/south split in galaxies reproduced at large R**
- ❑ **Density in stars closer than 20 Mpc not well represented**

What can we learn?

The SLOW/CLONES simulation

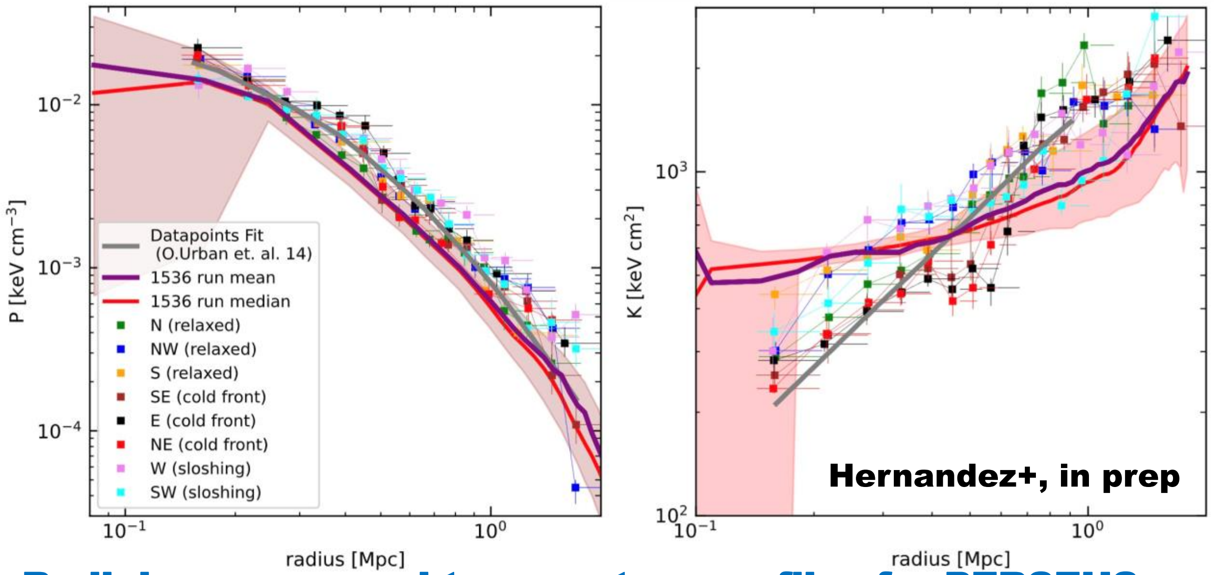
Filaments detected using DISPERSE in a zoom-in simulation of Coma from CLONES (DM only, RAMSES) compared with the ones detected in DSS.



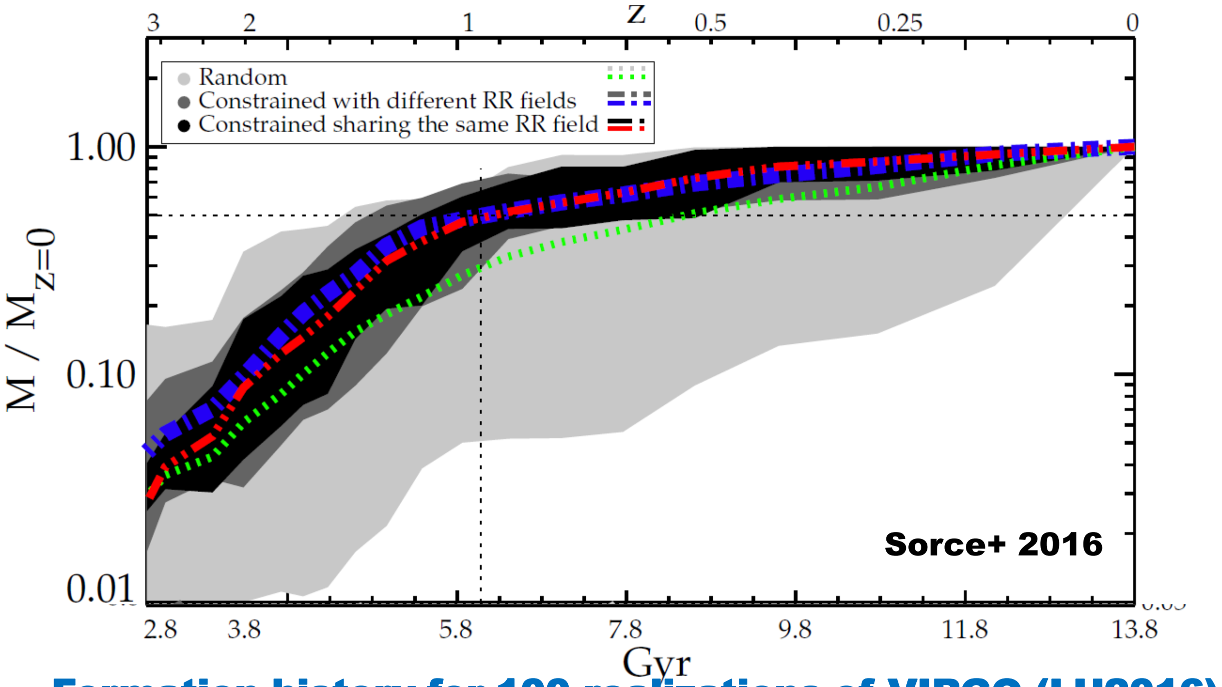
Opens new window for galaxy cluster studies:

- ❑ **Environment**
- ❑ **Internal structure**
- ❑ **Formation history**

Malavasi+ 2023



Radial pressure and temperature profiles for PERSEUS (SLOW, AGN1576 run) compared to X-ray observations.



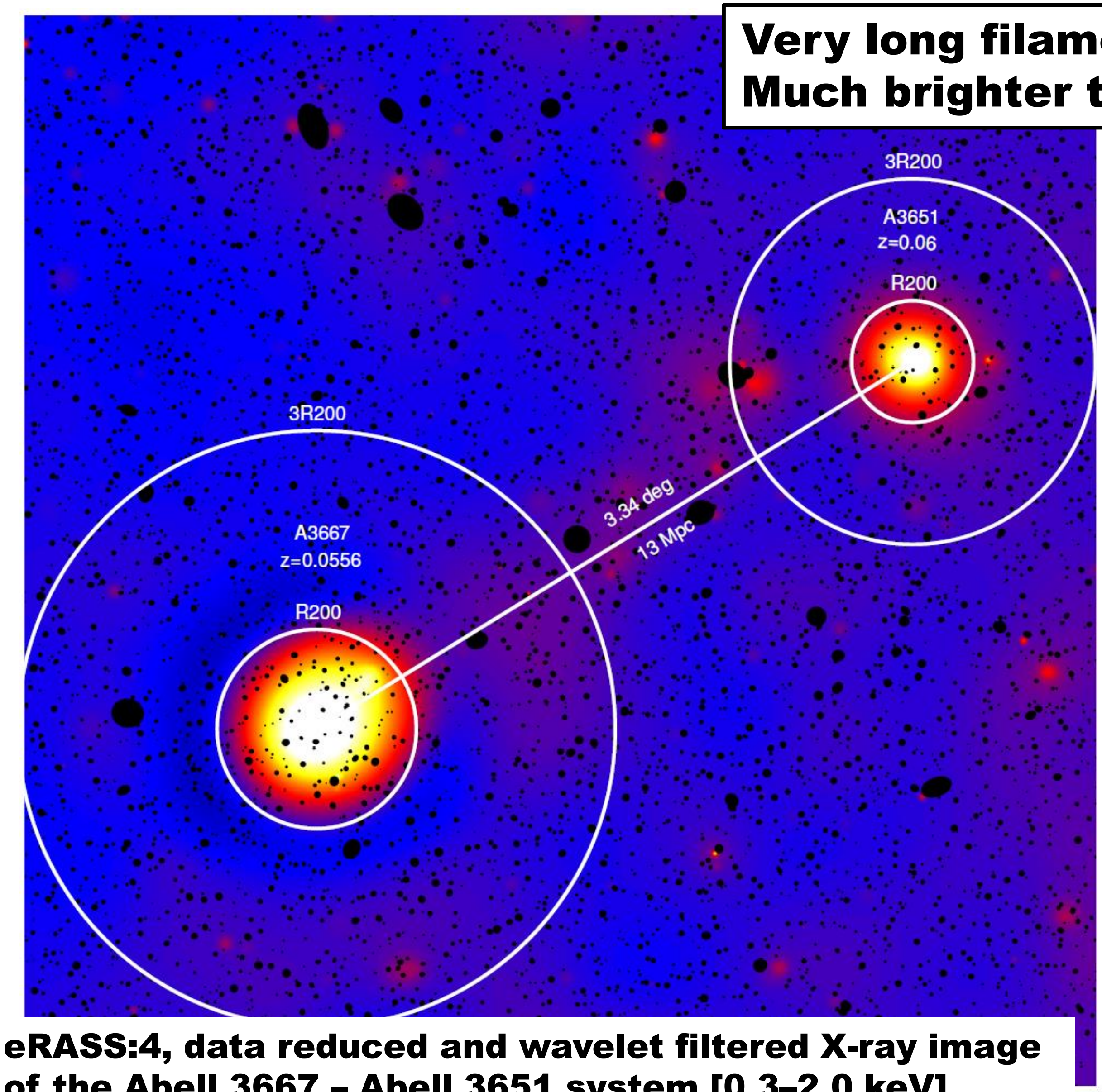
Formation history for 100 realizations of VIRGO (LU2016) compared to randomly selected haloes with equal mass.

An eROSITA filament with a counterpart in SLOW?

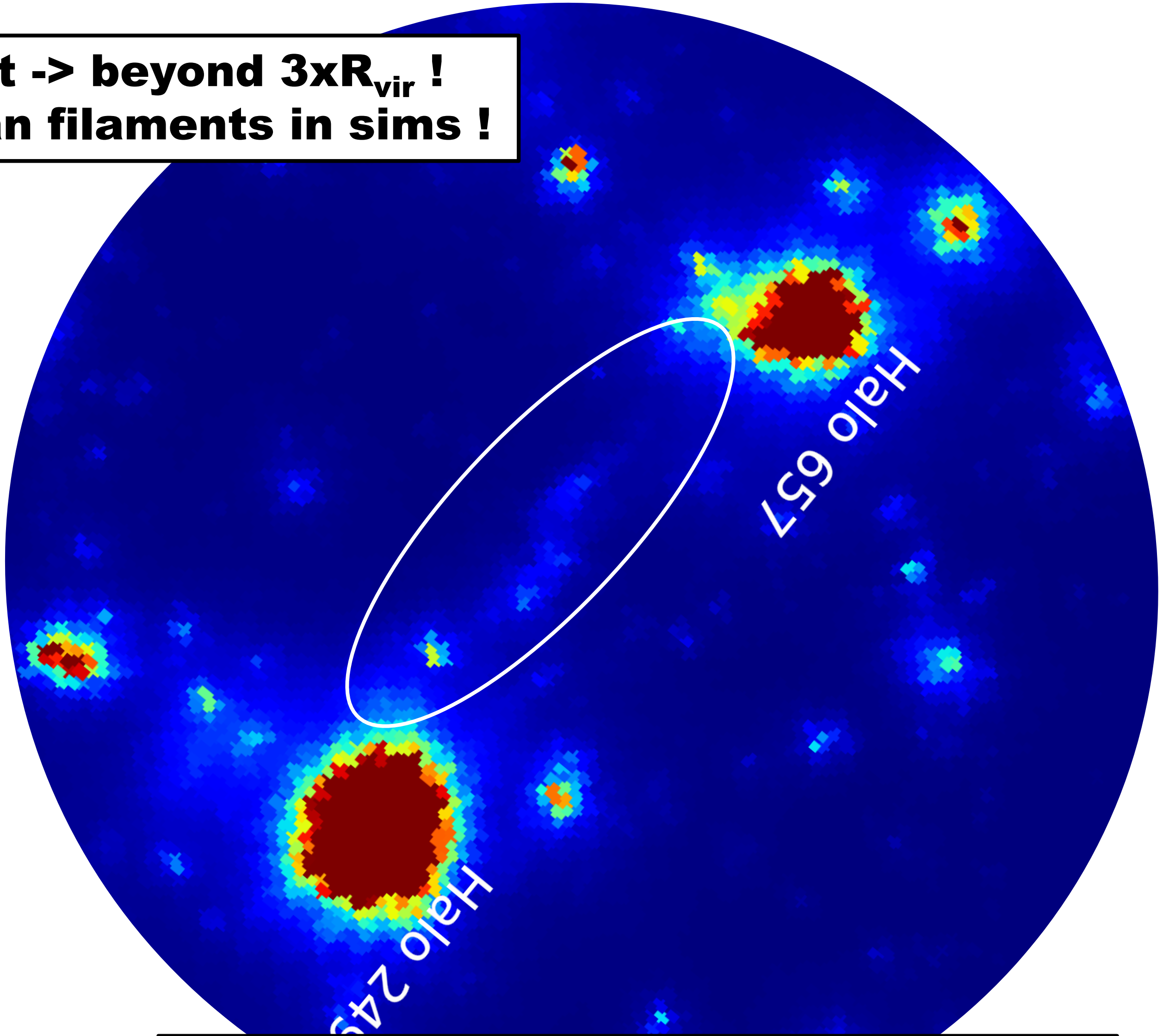
Filament between the cross identified clusters in SLOW

B. Seidel

Very long filament -> beyond 3xR_{vir} !
Much brighter than filaments in sims !

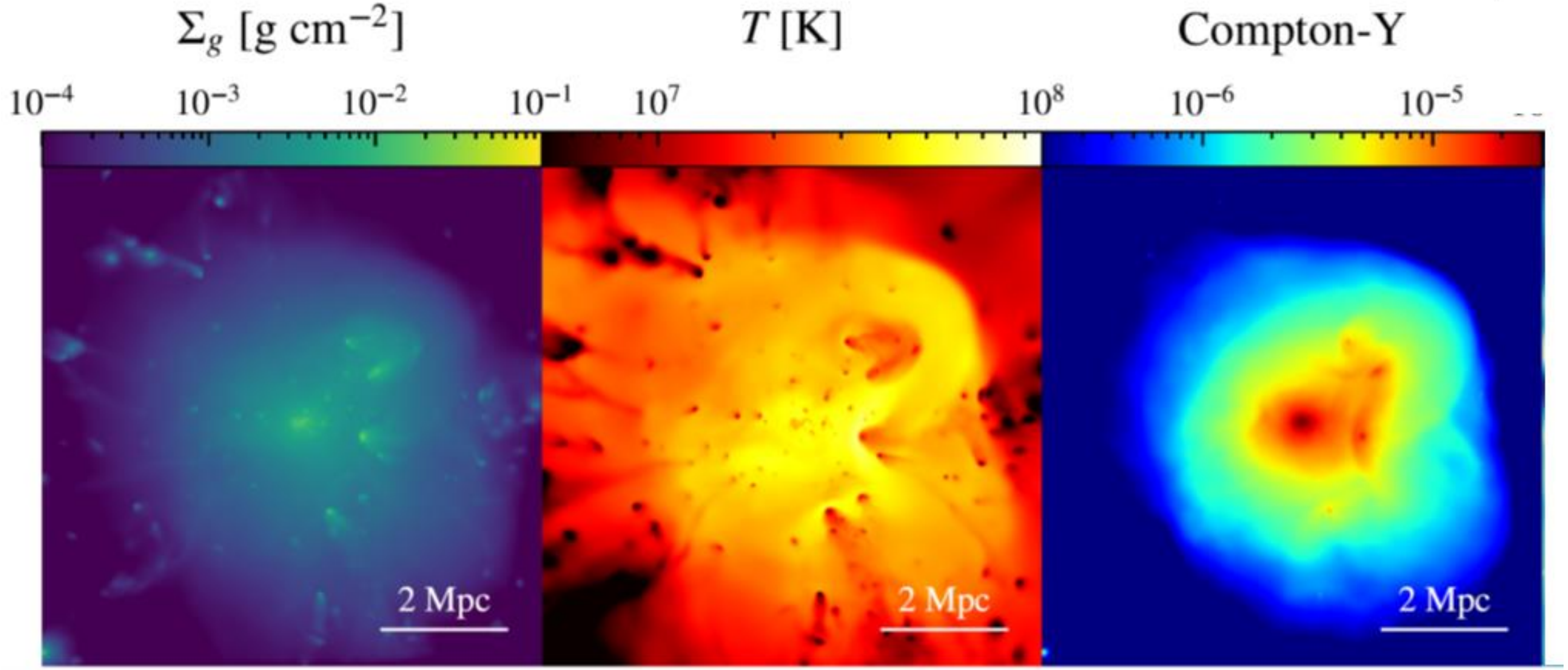


eRASS:4, data reduced and wavelet filtered X-ray image of the Abell 3667 – Abell 3651 system [0.3–2.0 keV]
Dietl+ 2024

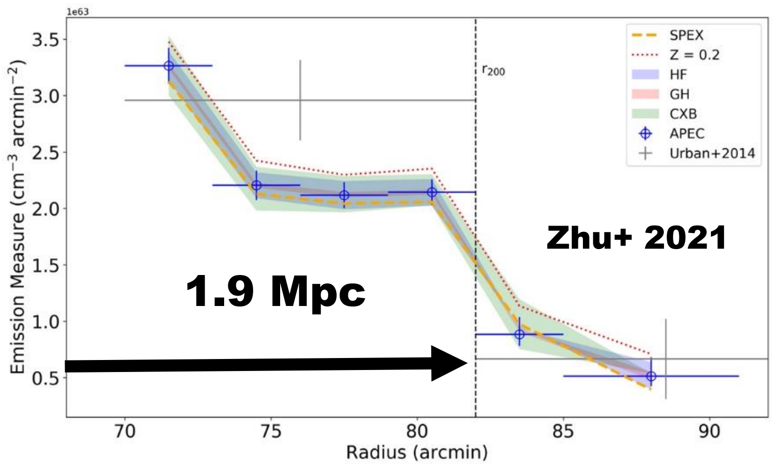


1) **The clusters will not merge!**
2) **Filament is bright as it is a merged structure out of 2 filaments!**

Perseus Cluster?



L. Böss

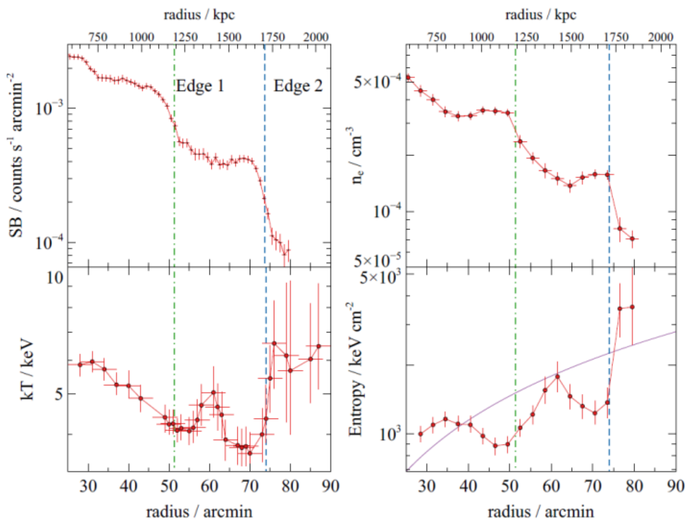


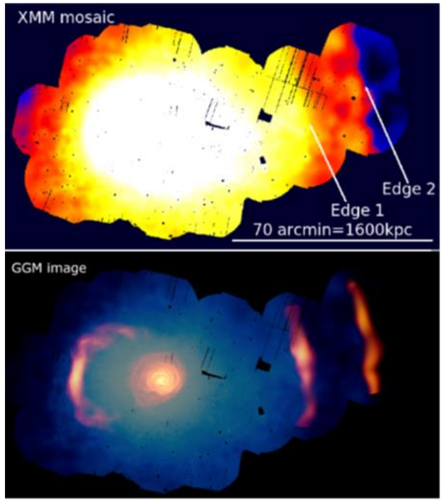
Contact Discontinuity (CD) at R=1.7Mpc observed in Perseus.

- **Suggested to be sloshing**

►**but Timescale would be 8 Gyr !**

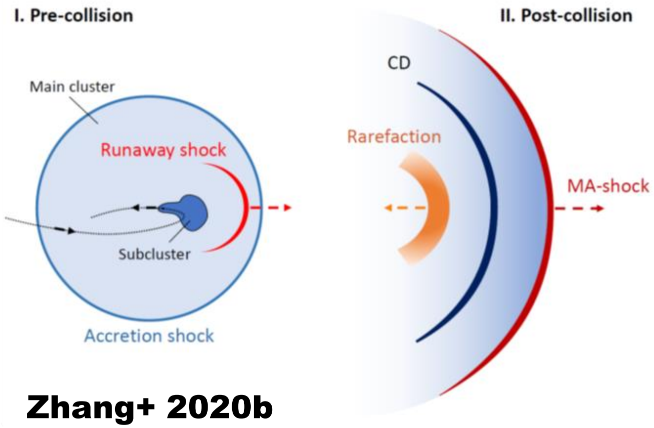
►**Can be more naturally created through collision of shocks !**



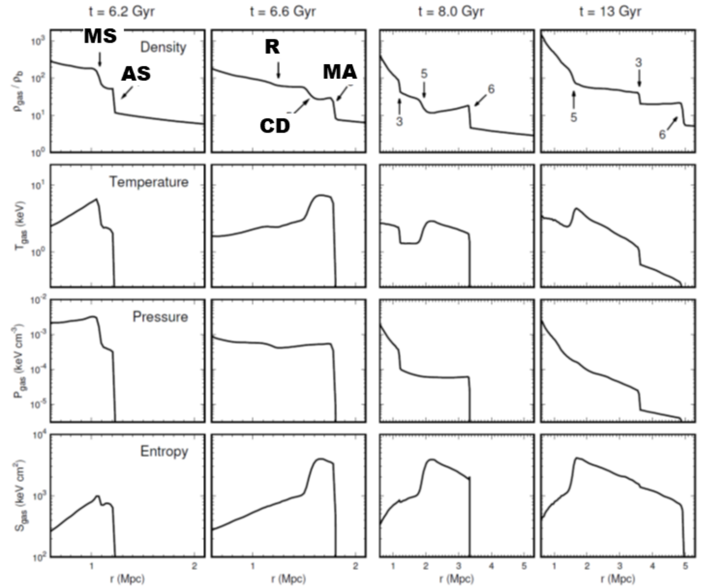


Walker+ 2020

Idealized model



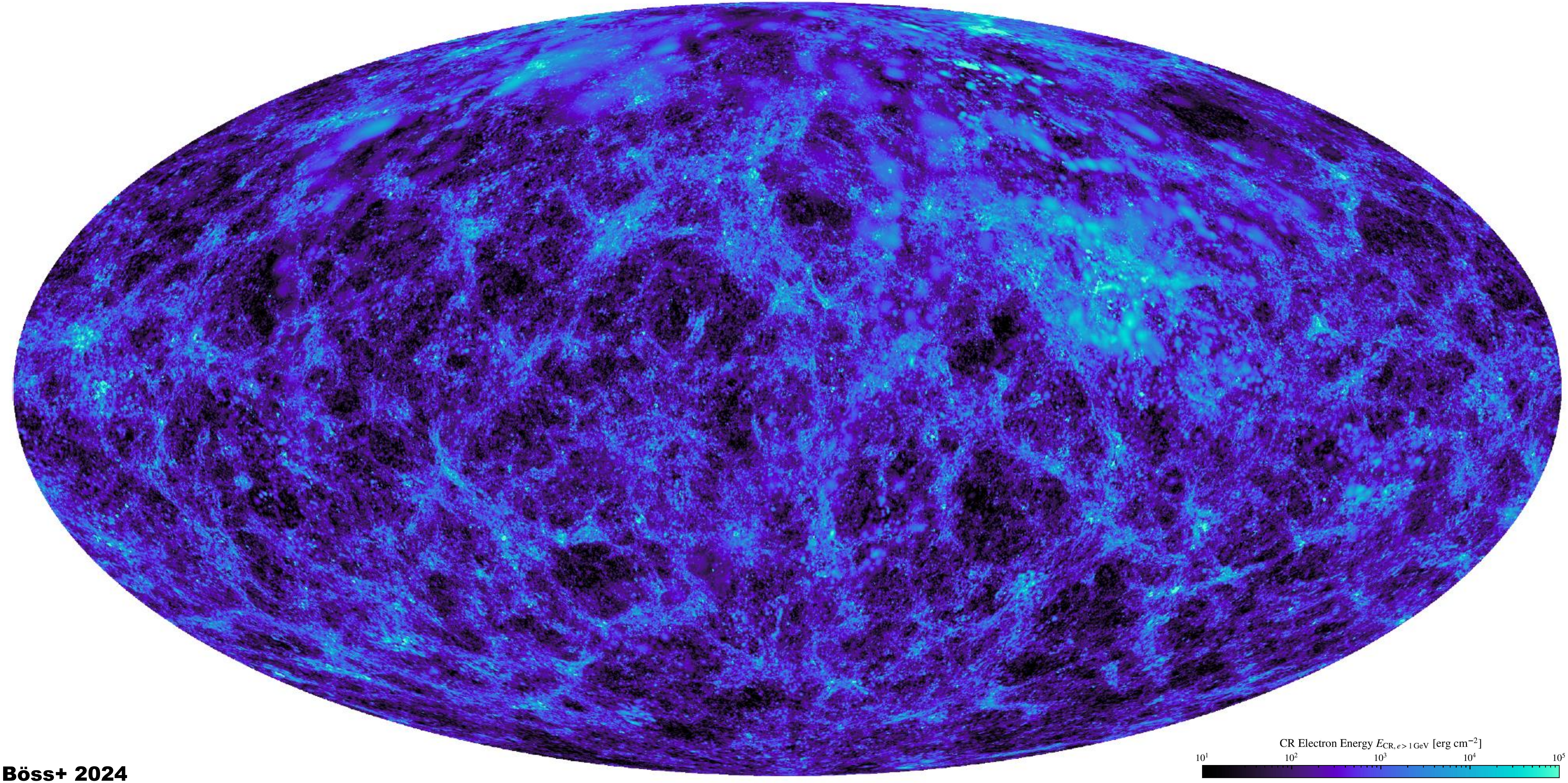
Zhang+ 2020b



Magnetic Fields and Radio Emission

Simulationg the LOcal Web (SLOW)

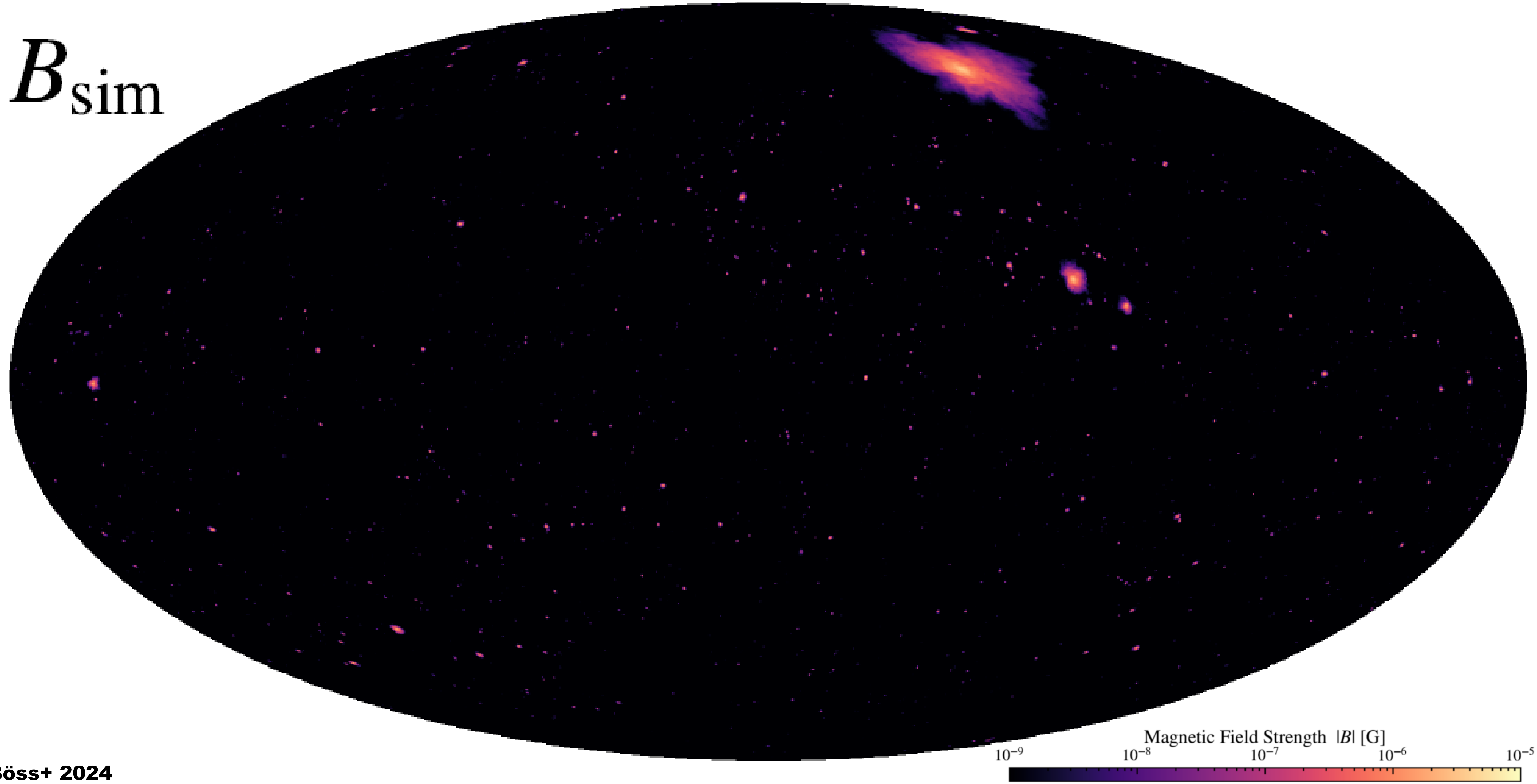
L. Böss



Böss+ 2024

Simulationg the LOcal Web (SLOW)

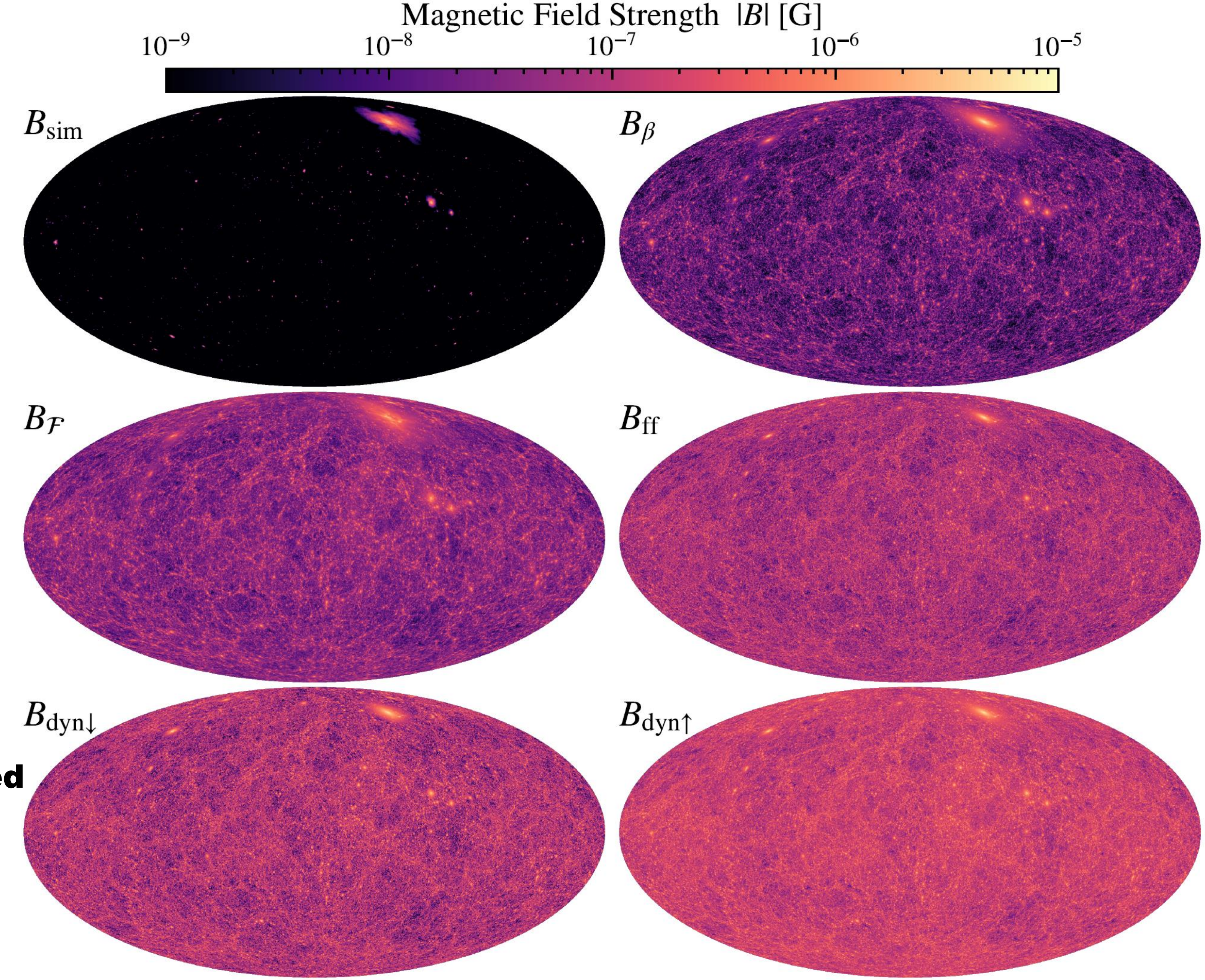
L. Böss



Böss+ 2024

Simulationg the LOcal Web (SLOW)

L. Böss



Primordial, simulation

B scaled as β = 50

B scaled with turbulent pressure

B scaled as frozen in

B scaled as saturated dynamo, with cut in voids

B scaled as saturated dynamo

Böss+ 2024

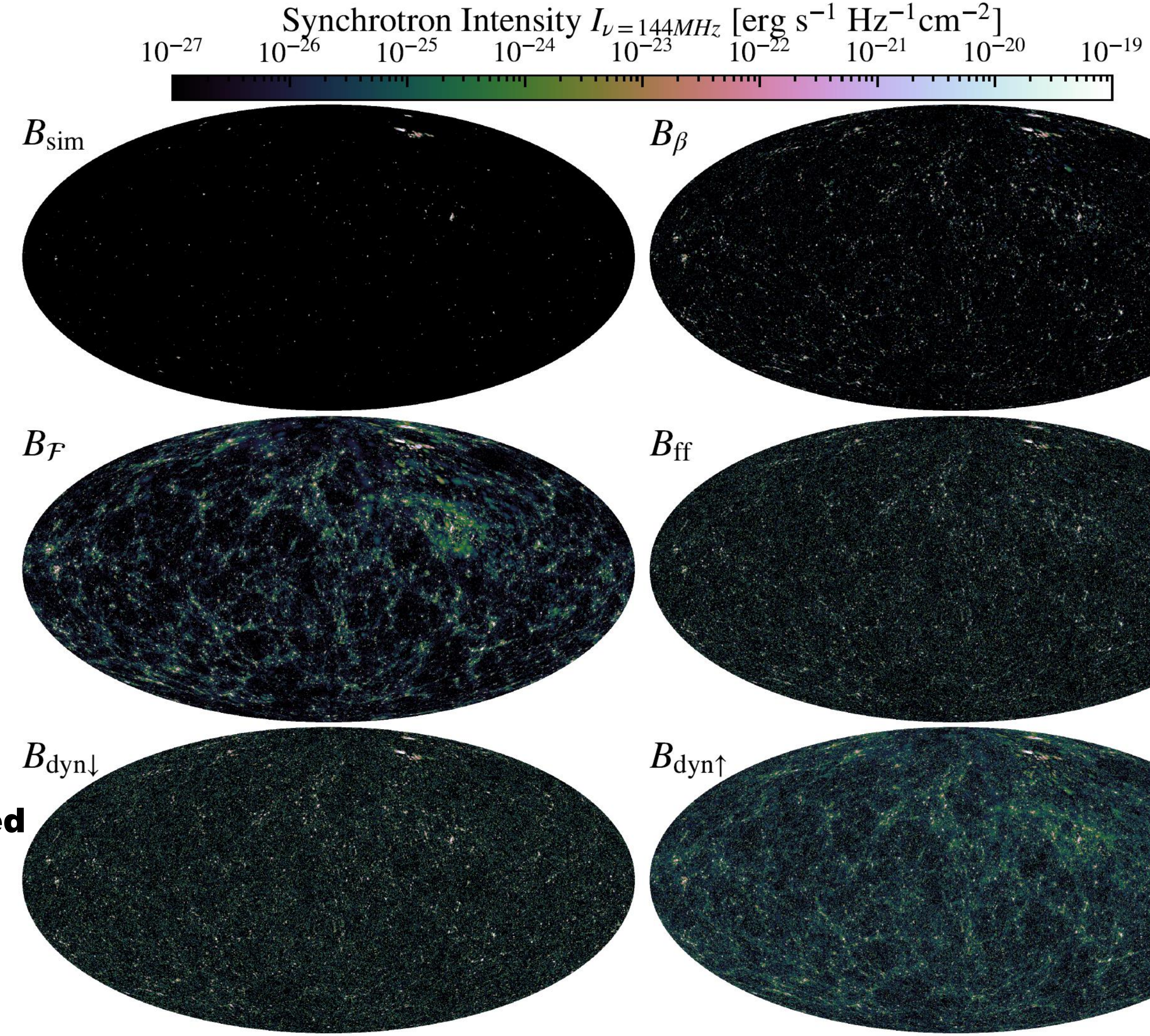
Simulationg the **LO**cal **W**eb (SLOW)

L. Böss

Primordial, simulation

B scaled with turbulent pressure

B scaled as saturated dynamo, with cut in voids



B scaled as β = 50

B scaled as frozen in

B scaled as saturated dynamo

Böss+ 2024

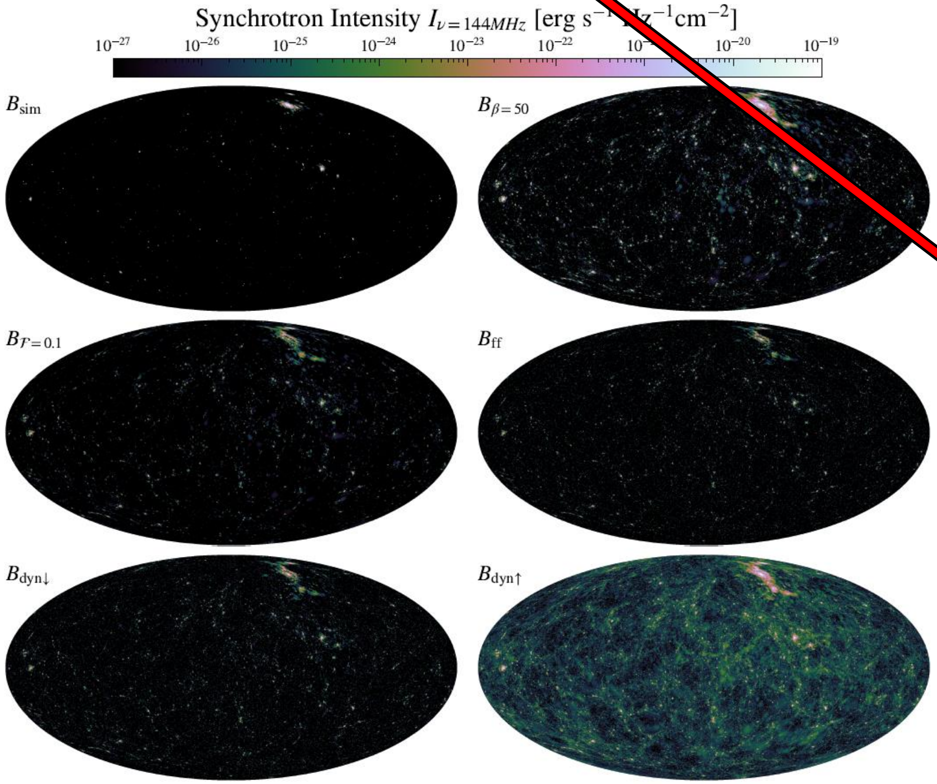
Simulationg the LOcal Web (SLOW)

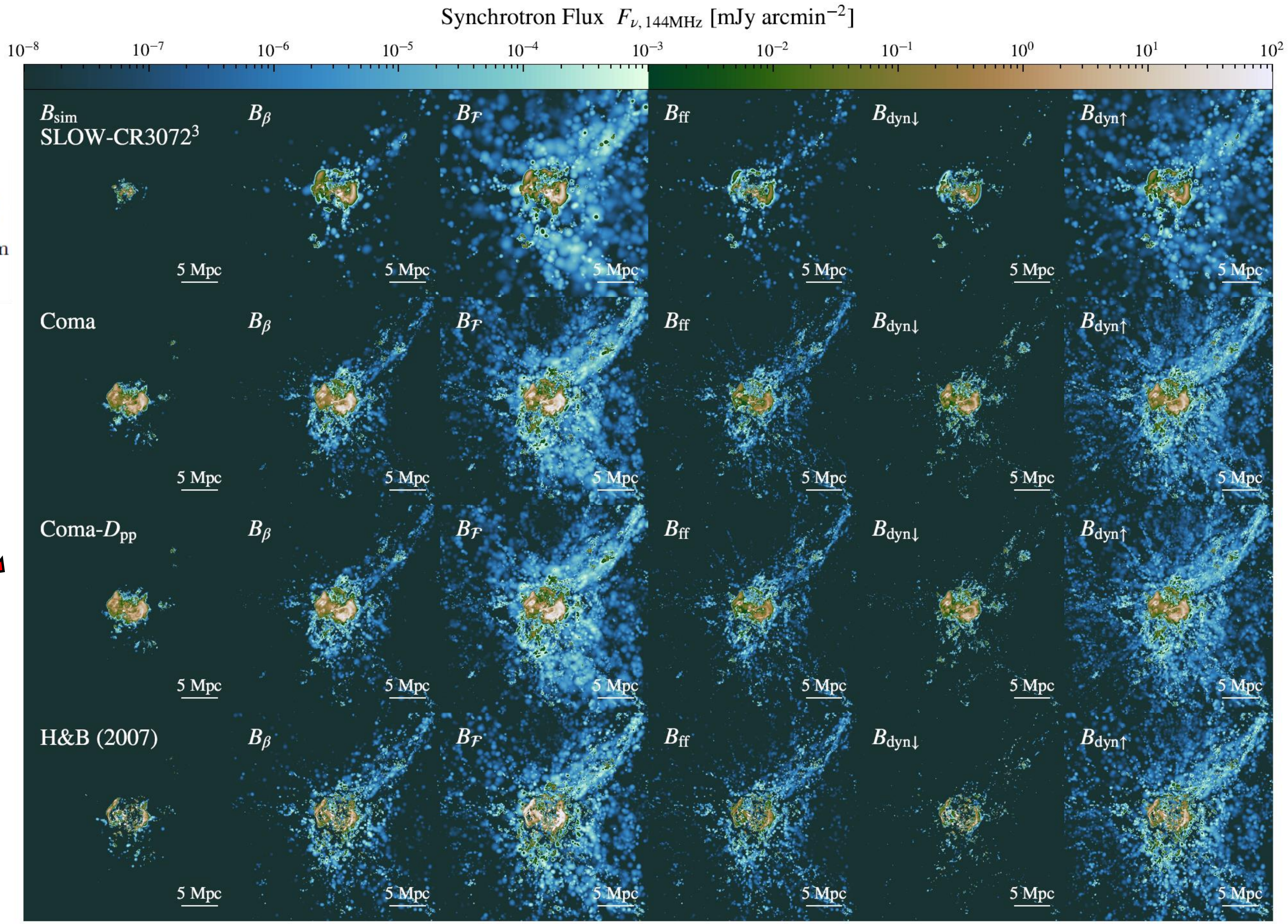
L. Böss

- **Shocks**
- SFR
- AGN

$$\underbrace{\frac{\partial f}{\partial t}}\; + \underbrace{\mathbf{u}\cdot\nabla f}_{\text{spatial convection}} - \underbrace{\nabla\left(\boldsymbol{\kappa}\nabla f\right)}_{\text{spatial diffusion}} =$$

$$\underbrace{\frac{1}{3}\left(\nabla\cdot\mathbf{u}\right)p\frac{\partial f}{\partial p}}_{\text{momentum convection}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left[b_\ell f + D_p\frac{\partial f}{\partial p}\right]\right)}_{\text{momentum diffusion + continuous losses}} - \underbrace{\frac{f(p,\mathbf{x},t)}{t_c(p,\mathbf{x})}}_{\text{catastrophic losses}} + \underbrace{j(p,\mathbf{x})}_{\text{source term}}$$





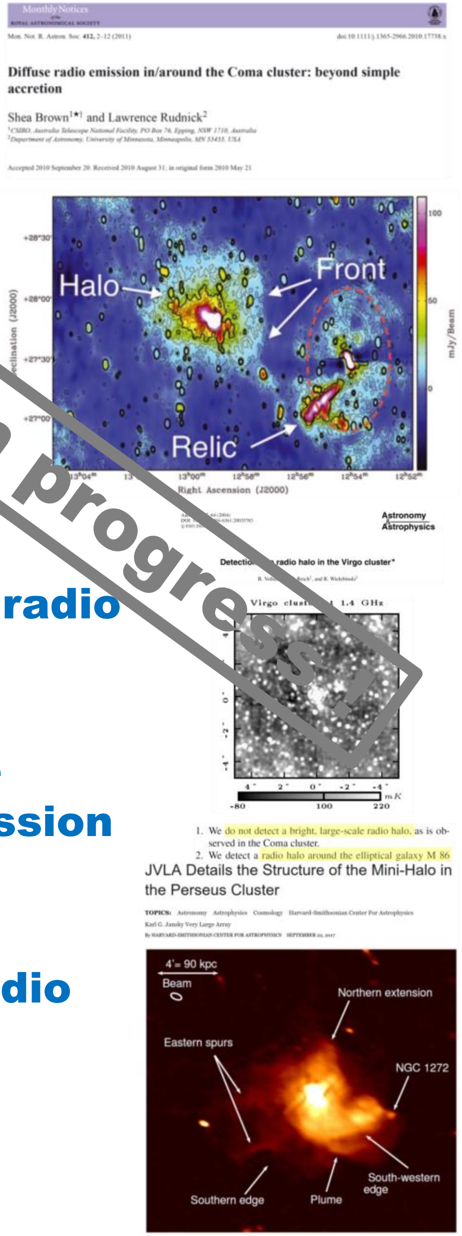
Böss+ 2024

Coma in shining in radio in SLOW

$$\underbrace{\frac{\partial f}{\partial t} + \mathbf{u}\cdot\nabla f}_{\text{spatial convection}} - \underbrace{\nabla(\boldsymbol{\kappa}\nabla f)}_{\text{spatial diffusion}} = \underbrace{\frac{1}{3}(\nabla\cdot\mathbf{u})\,p\frac{\partial f}{\partial p}}_{\text{momentum convection}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left[b_\ell f + D_p\frac{\partial f}{\partial p}\right]\right)}_{\text{momentum diffusion + continuous losses}} - \underbrace{\frac{f(p,\mathbf{x},t)}{t_c(p,\mathbf{x})}}_{\text{catastrophic losses}} + \underbrace{j(p,\mathbf{x})}_{\text{source term}}$$

L. Böss

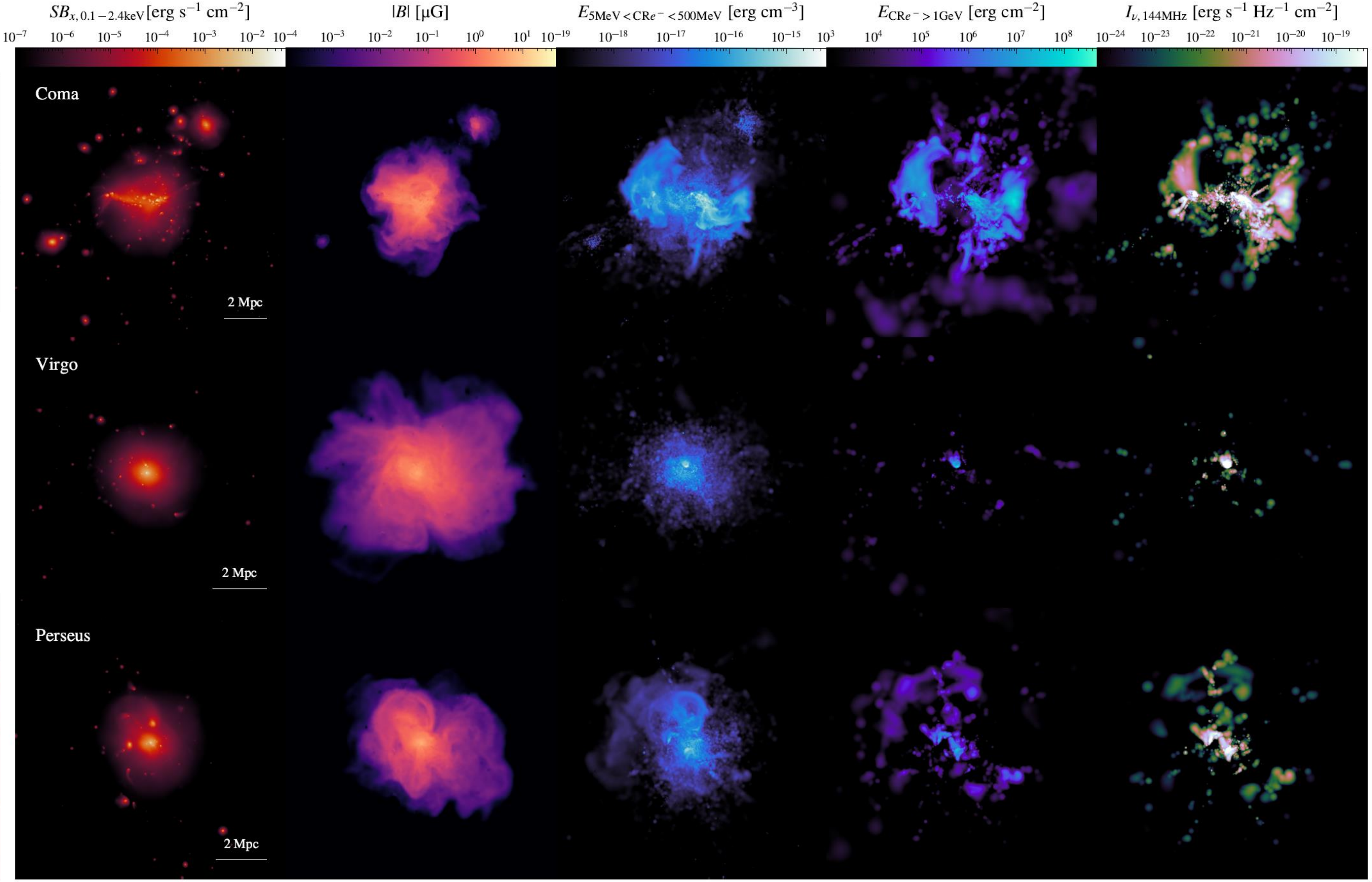
- ❑ **2x3072³ non radiative (MHD+CRs)**



Coma:
-> extended radio emission!

Virgo:
-> no diffuse radio emission

Perseus:
-> only very central radio emission



Böss+ 2024

Connecting to Galaxies

Radio shocks on galaxy scale ?

Discovery of a new extragalactic circular radio source with ASKAP: ORC J0102–2450

Bärbel S. Koribalski,[1,2★] Ray P. Norris,[2,1] Heinz Andernach,[3] Lawrence Rudnick,[4] Stanislav Shabala,[5] Miroslav Filipović,[2] and Emil Lenc[1]
[1]Australia Telescope National Facility, CSIRO Astronomy and Space Science, P.O. Box 76, Epping, NSW 1710, Australia
[2]School of Science, Western Sydney University, Locked Bag 1797, Penrith, NSW 2751, Australia
[3]Departmento de Astronomía, Universidad de Guanajuato, Callejón de Jalisco s/n, Guanajuato, C.P. 36023, GTO, Mexico
[4]Minnesota Institute for Astrophysics, University of Minnesota, 116 Church St. SE, Minneapolis, MN 55455, USA
[5]School of Natural Sciences, University of Tasmania, Private Bag 37, Hobart 7001, Australia

Koribalski+ 2022

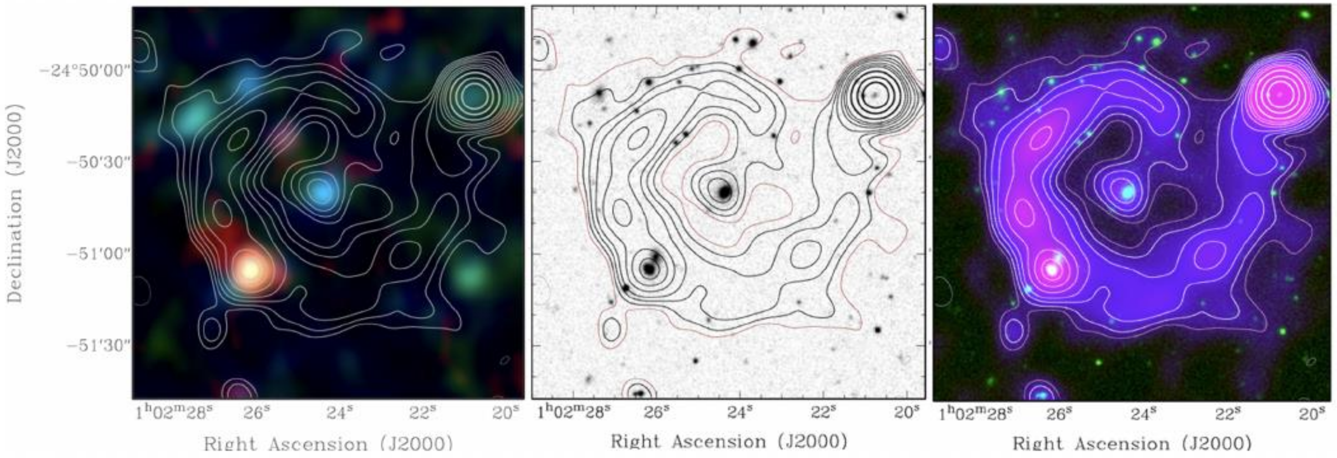


Figure 2. ASKAP radio continuum contours of ORC J0102–2450 overlaid onto a WISE RGB colour image (red: 12μm (W3), green: 4.6μm (W2), and 3.4μm (W1)

source name		discovery telescope	central host galaxy	galaxy redshift	ring diameter [arcsec]	[kpc]	spectral index	Ref.
ORC J2103–6200	(ORC 1)	ASKAP	WISE J210258.15–620014.4	0.55	80	510	-1.17 ± 0.04	Norris et al. 2021a
ORC J1555+2726	(ORC 4)	GMRT	WISE J155524.65+272633.7	0.39	70	370	-0.92 ± 0.18	Norris et al. 2021a
ORC J0102–2450	(ORC 5)	ASKAP	DES J010224.33–245039.5	0.27	70	300	-0.8 ± 0.2	this paper

Ring like features beyond R_{vir} (300 kpc – 500 kpc) in several (5) galaxies found!

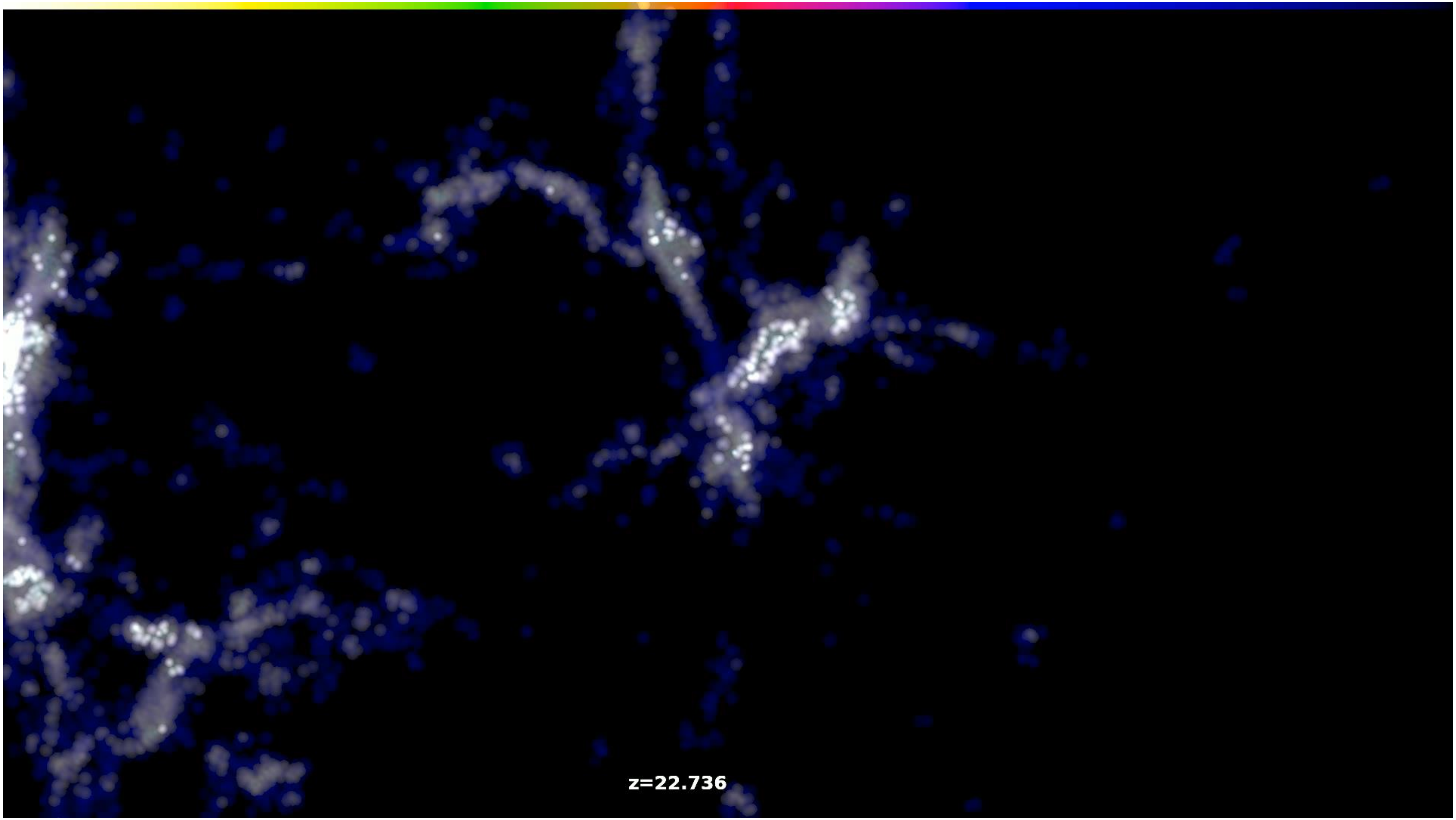
Suggested to be AGN or star-burst winds, but could be just merger shocks ?

ORC centre galaxies
(from DES DR9 via the *legacyserver.org/viewer* – not to scale)

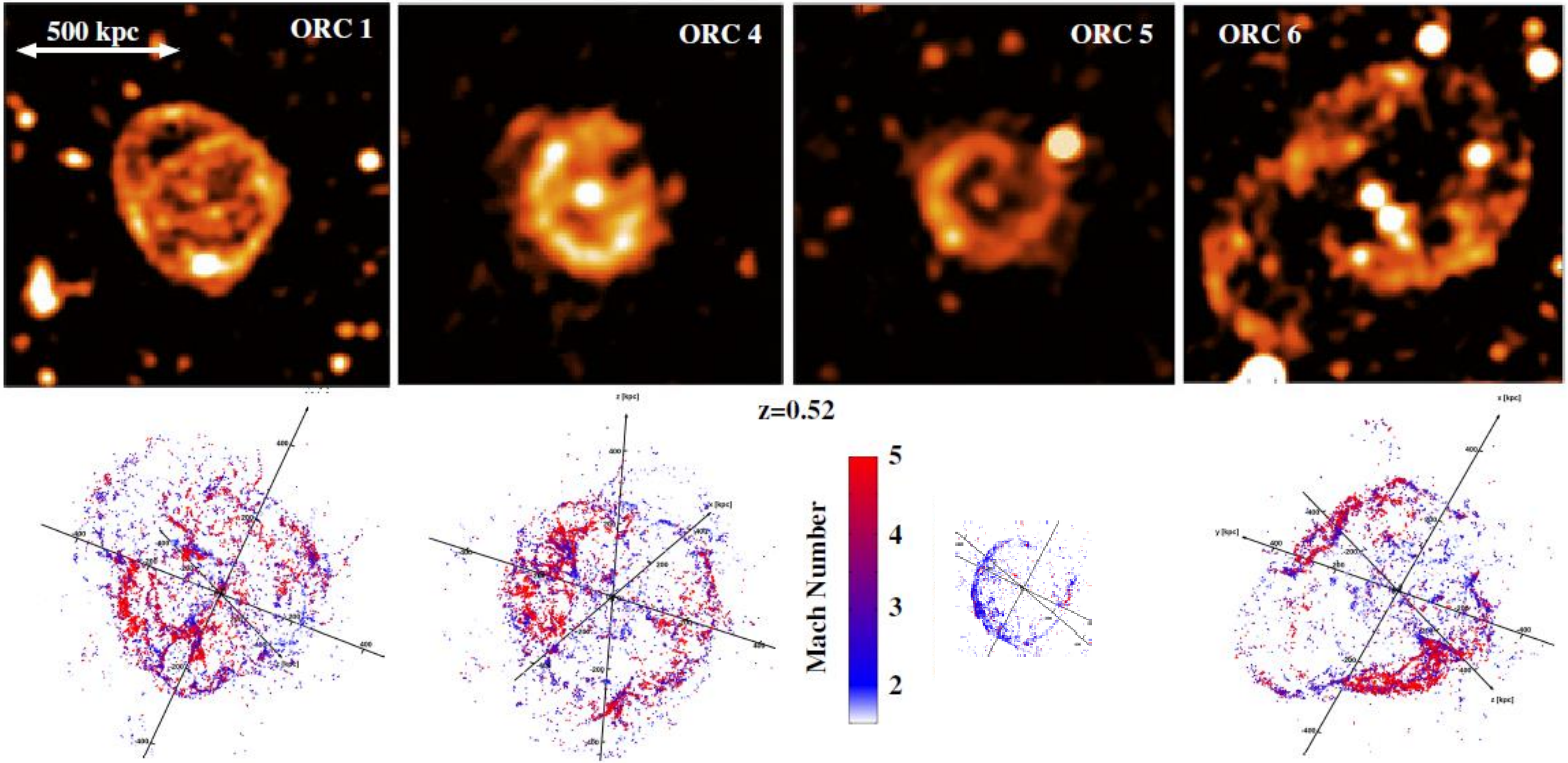
ORC 1 ORC 4 ORC 5

$M_* \sim 10^{11}\ M_{sol}$

Shocks in the simulated galaxy

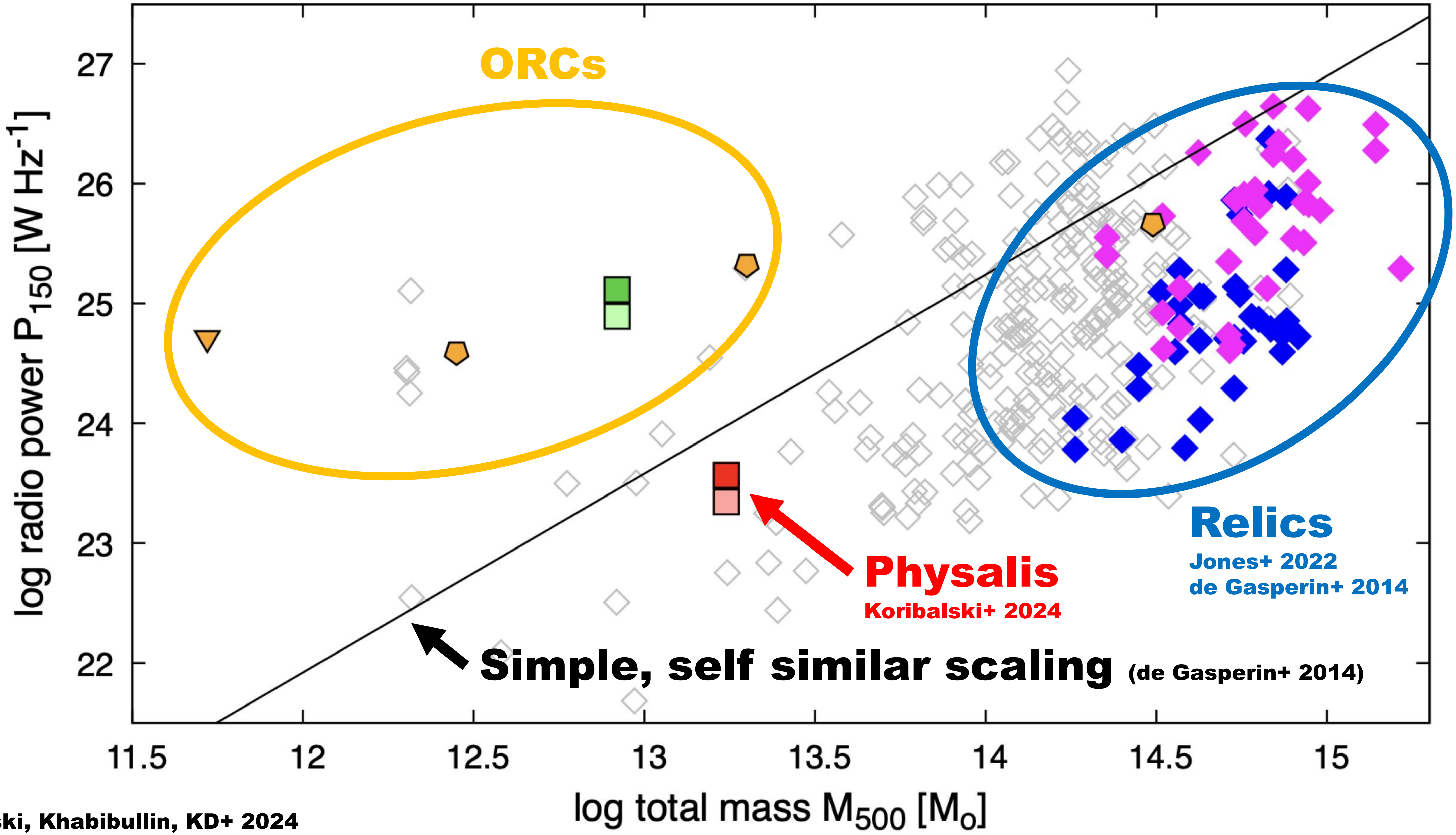


Shock structures are matching the observed ORCs



KD+ 2022

Shock structures linking galaxy clusters to galaxies

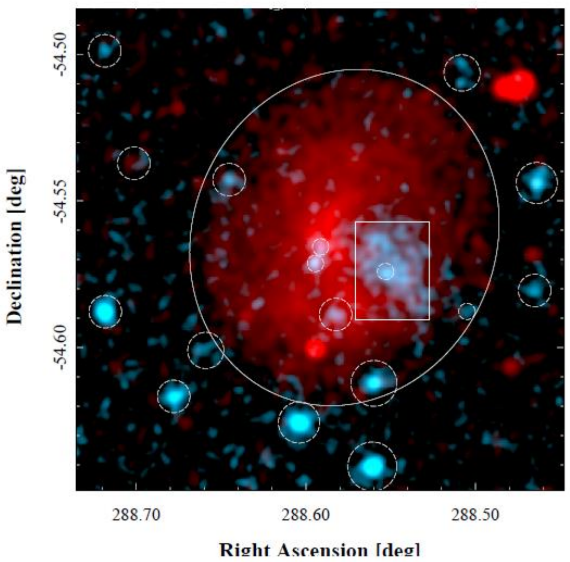


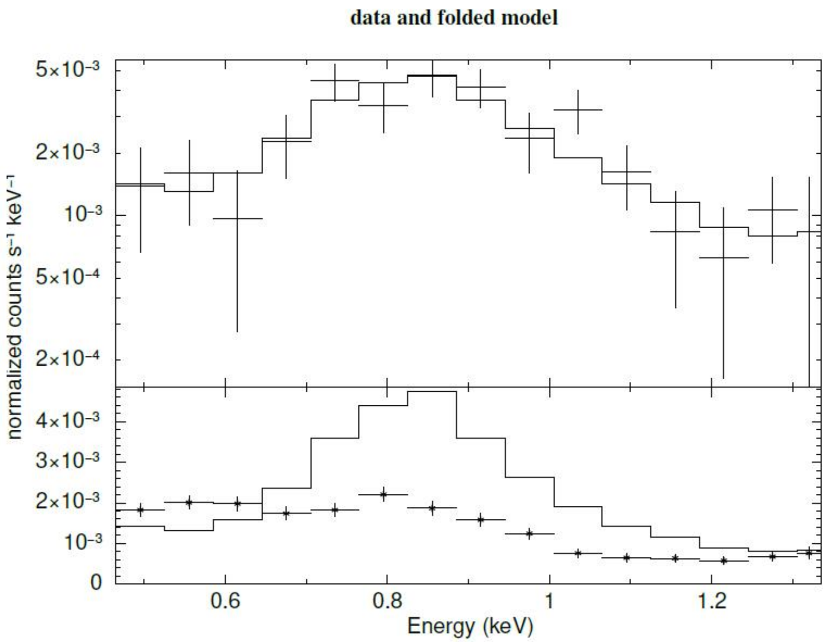
Koribalski, Khabibullin, KD+ 2024

The Physalis system, an early stage of an ORC?

I. Khabibullin

ASKAP / XMM

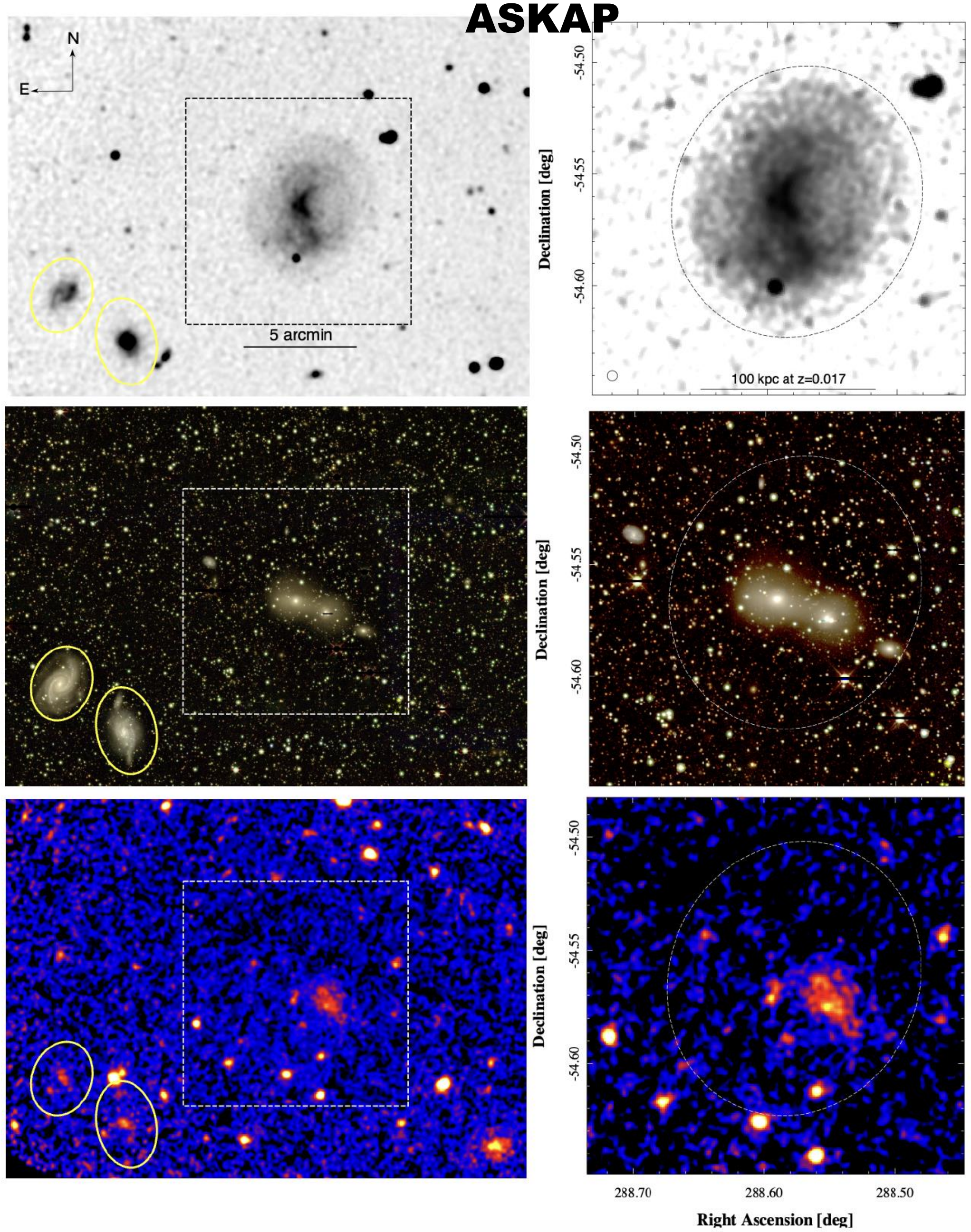




ASKAP

DESI

XMM



ESO 184-G042 and LEDA 418116

D = 75 Mpc (z = 0.017)

log stellar mass [$M_\odot$] ~ 11.1 and 10.7

$P_{th} \approx 3\times10^{-12}$ erg cm^{-3}

$E_{tot} \sim 2 \times 10^{59}$ erg ← **Energy involved**

$t_{cool} \sim 4 \times 10^{8}$ yr ← **Timescale involved**

Similar than in clusters, radio plasma is anti-correlated with thermal plasma (but reversed!).

Koribalski, Khabibullin, KD+ 2024

The Physalis system in simulations?

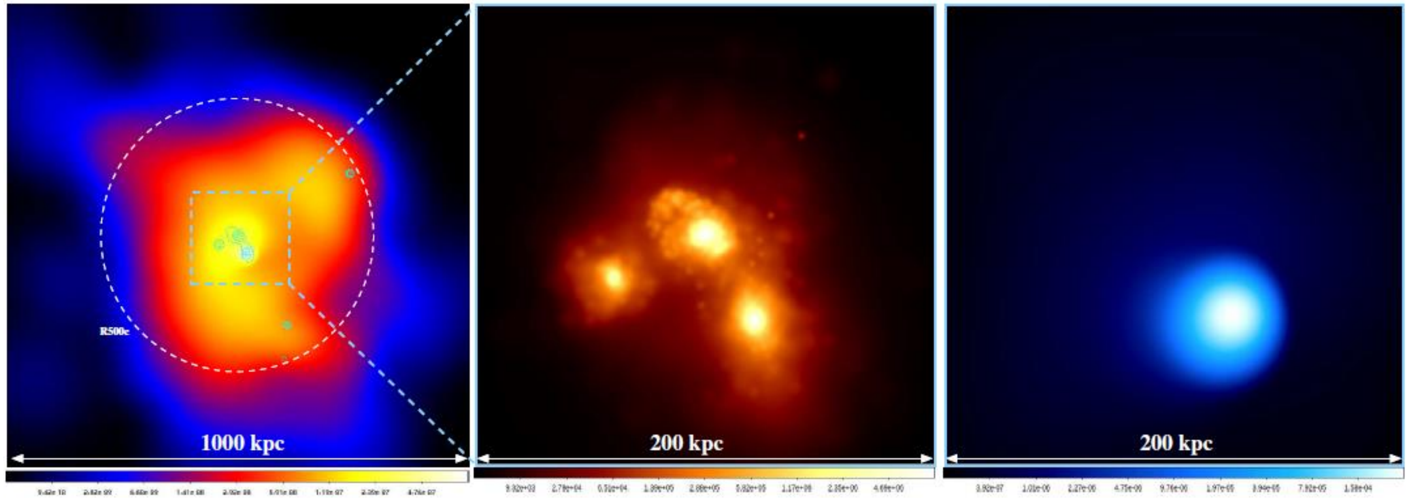
I. Khabibullin

Magneticum Box2b/hr (640 h^{-1}cMpc)
$10^{13} < M_{vir} < 3 \times 10^{13}$
-> ~26000 haloes

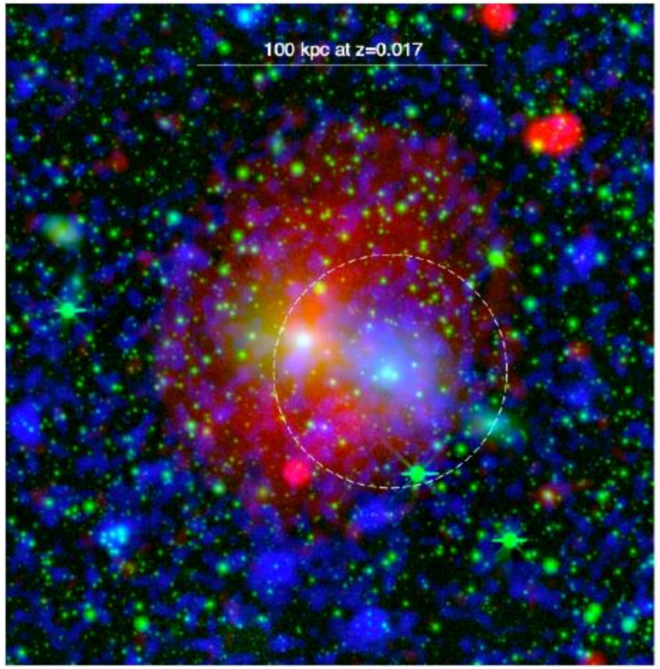
Forcing two massive galaxies with D < 70kpc and more hot gas associated to the galaxy with the lower stellar mass

-> 10 Haloes

Closer inspection, only 1 Halo shows a good match:



ASKAP / XMM / DESI



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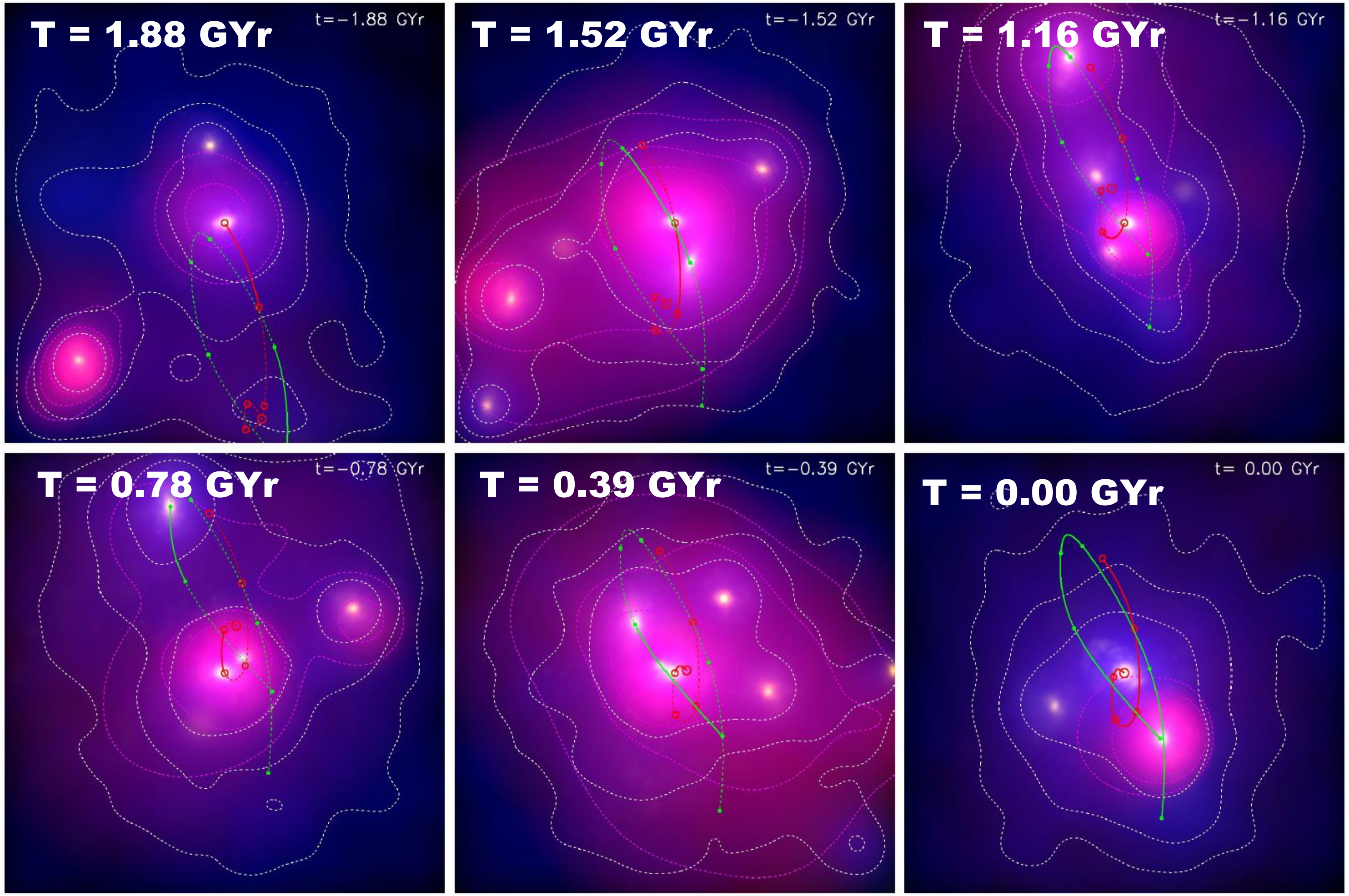
Koribalski, Khabibullin, KD+ 2024

The Physalis system, what to learn from it?

I. Khabibullin

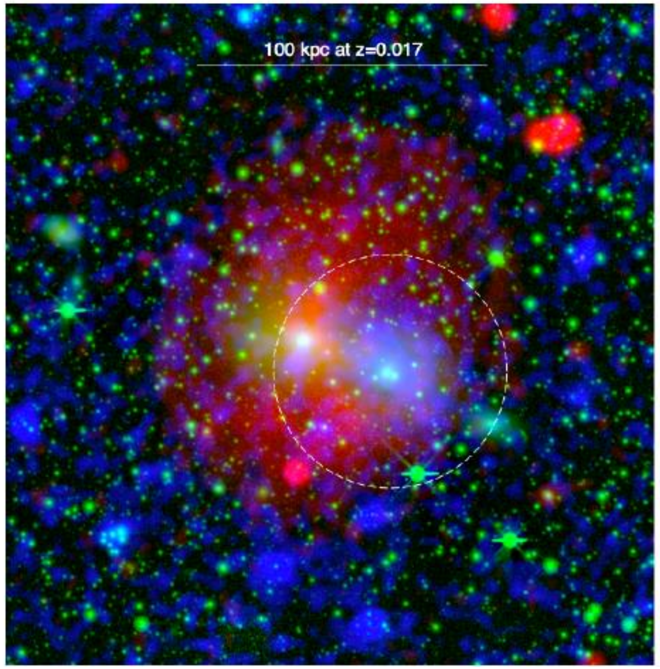


DM (blue)

X-ray (red)

SDSS-K (white)

ASKAP / XMM / DESI



ESO 184-G042 and LEDA 418116
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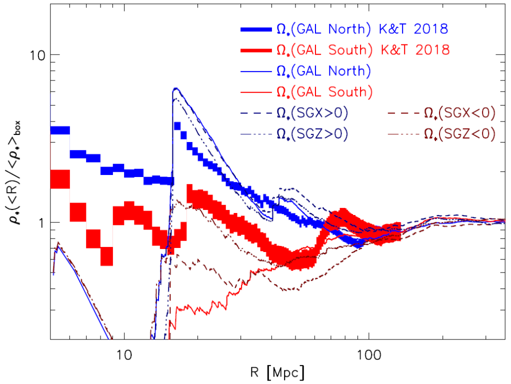
$E_{tot} \sim 2 \times 10^{59}$ erg
$t_{cool} \sim 4 \times 10^{8}$ yr

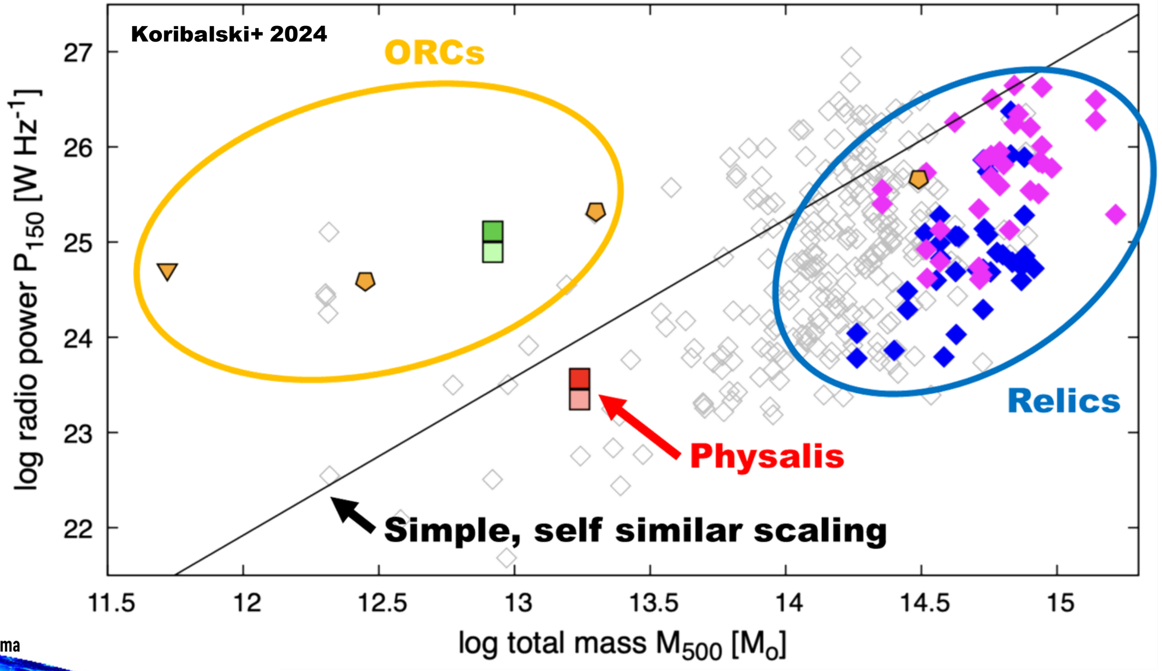
In the last 0.49 GYr the BH grows (by accretion) significantly ~$10^8 M_\odot$, releasing an energy of 10^{59} erg and displaces the IGrM from the radio emitting region showing that AGN and shocks could produce ORCs!

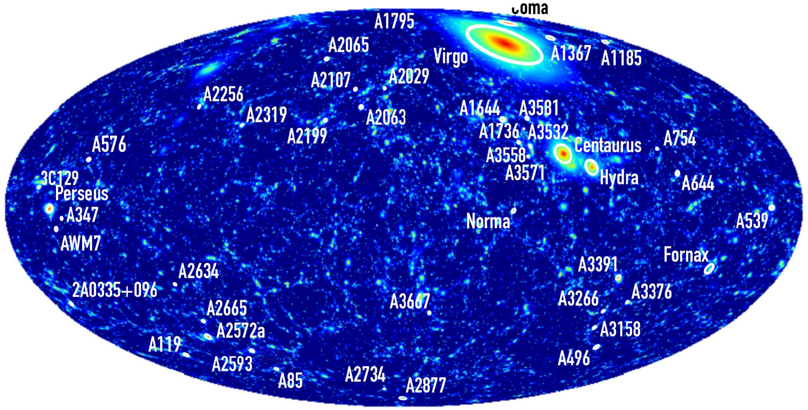
Koribalski, Khabibullin, KD+ 2024

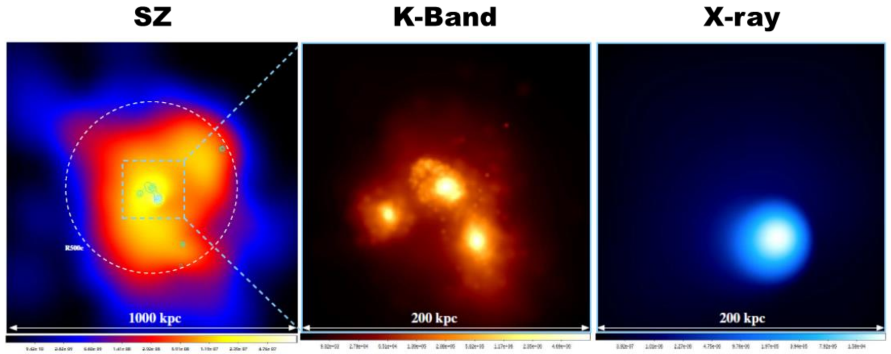
Conclusions

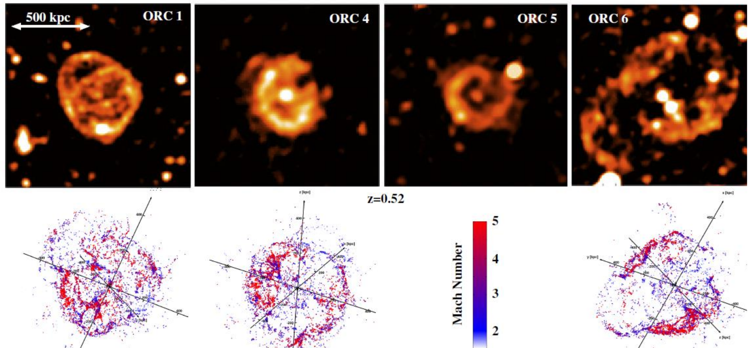
Distribution of matter











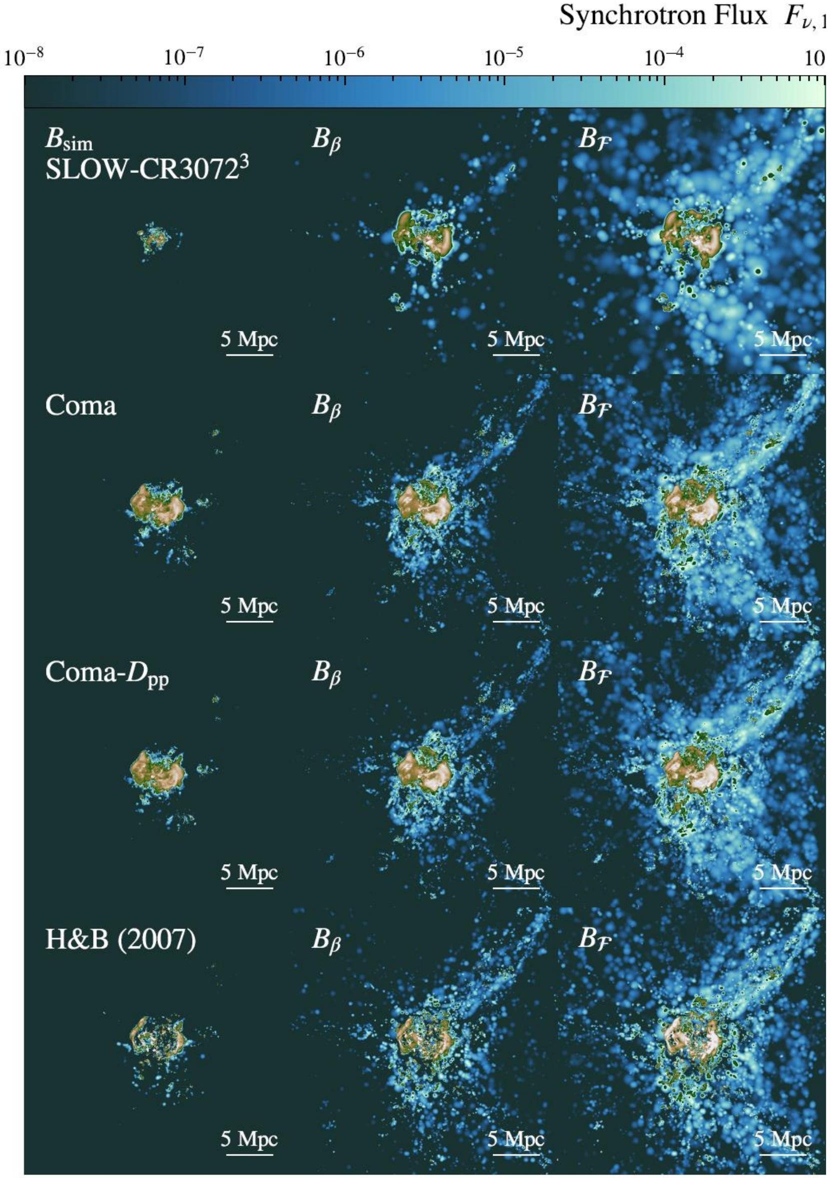
Dolag+ 2022

Current generation of constrained simulations allow to obtain unique insights into the local structures.

- ➢ **First steps to make the Local Universe a cos,mic magnetic field and CR lab**

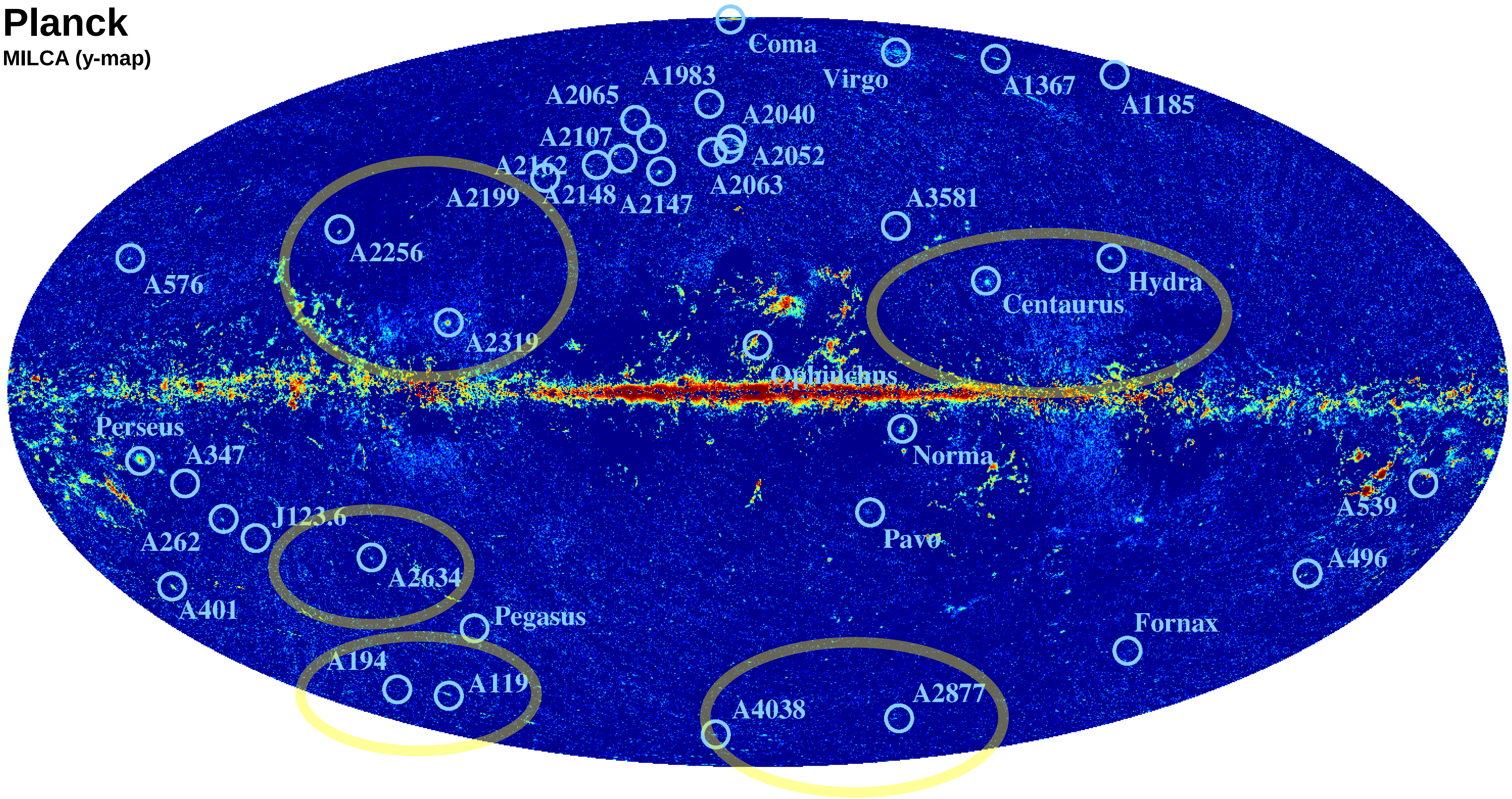
Bridging galaxies to clusters give new insights how non-thermal emission is linked to structure formation.

Böss+ 2024



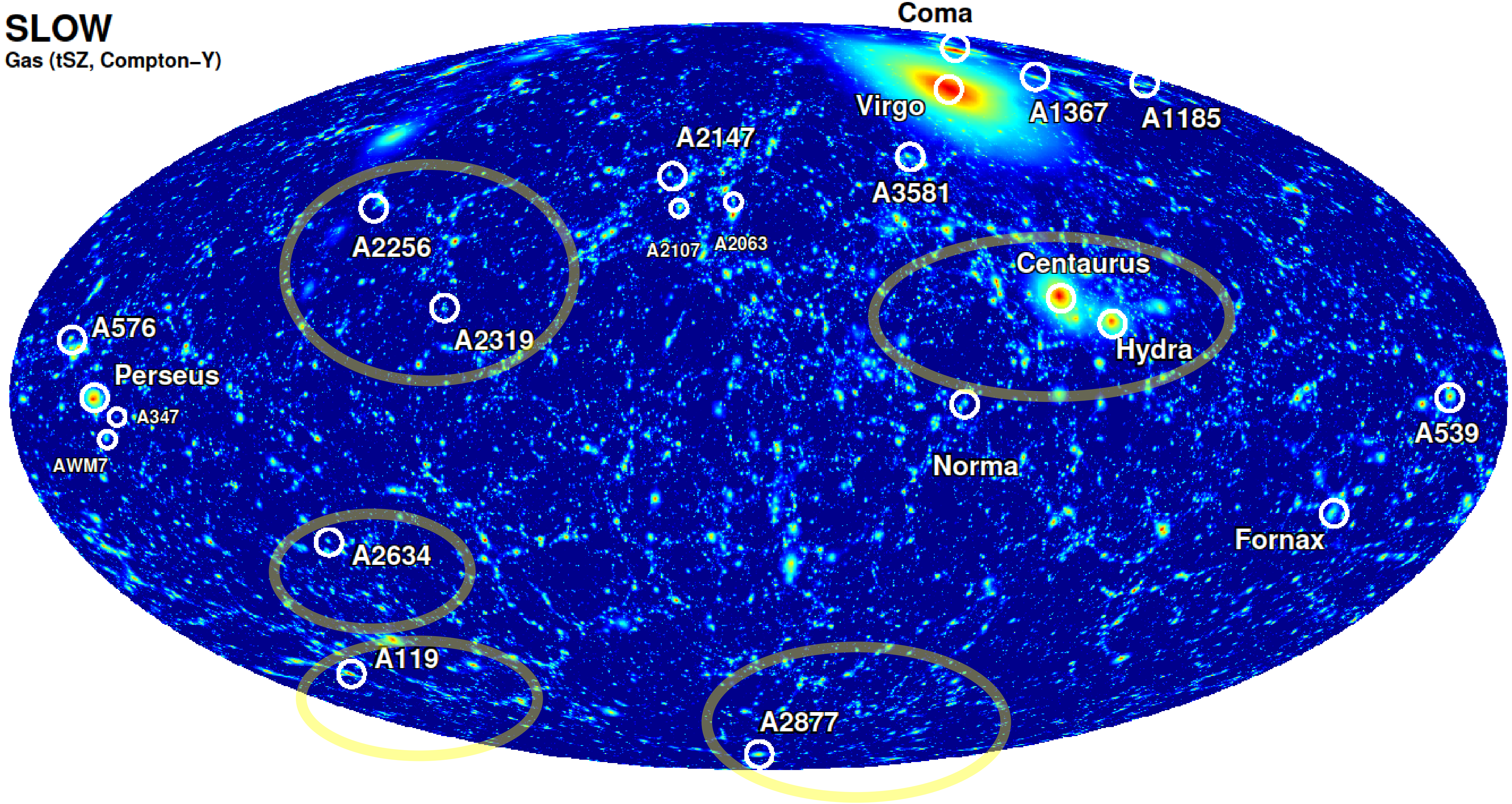
Matter distribution and tracers

Matching against the SLOW simulations



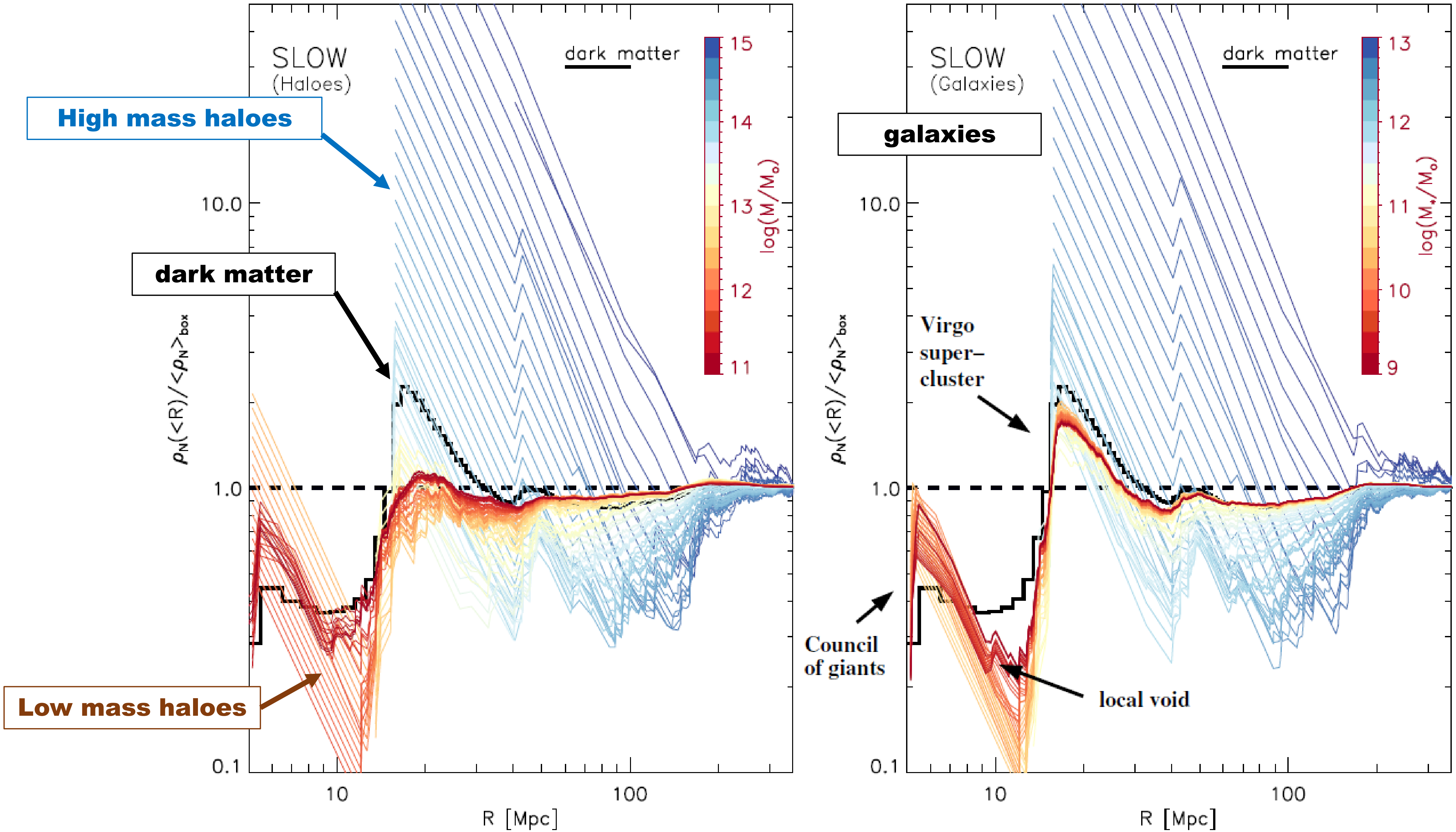
Some twist in sky positions by residuals in velocity bias/reconstruction

Matching against the SLOW simulations

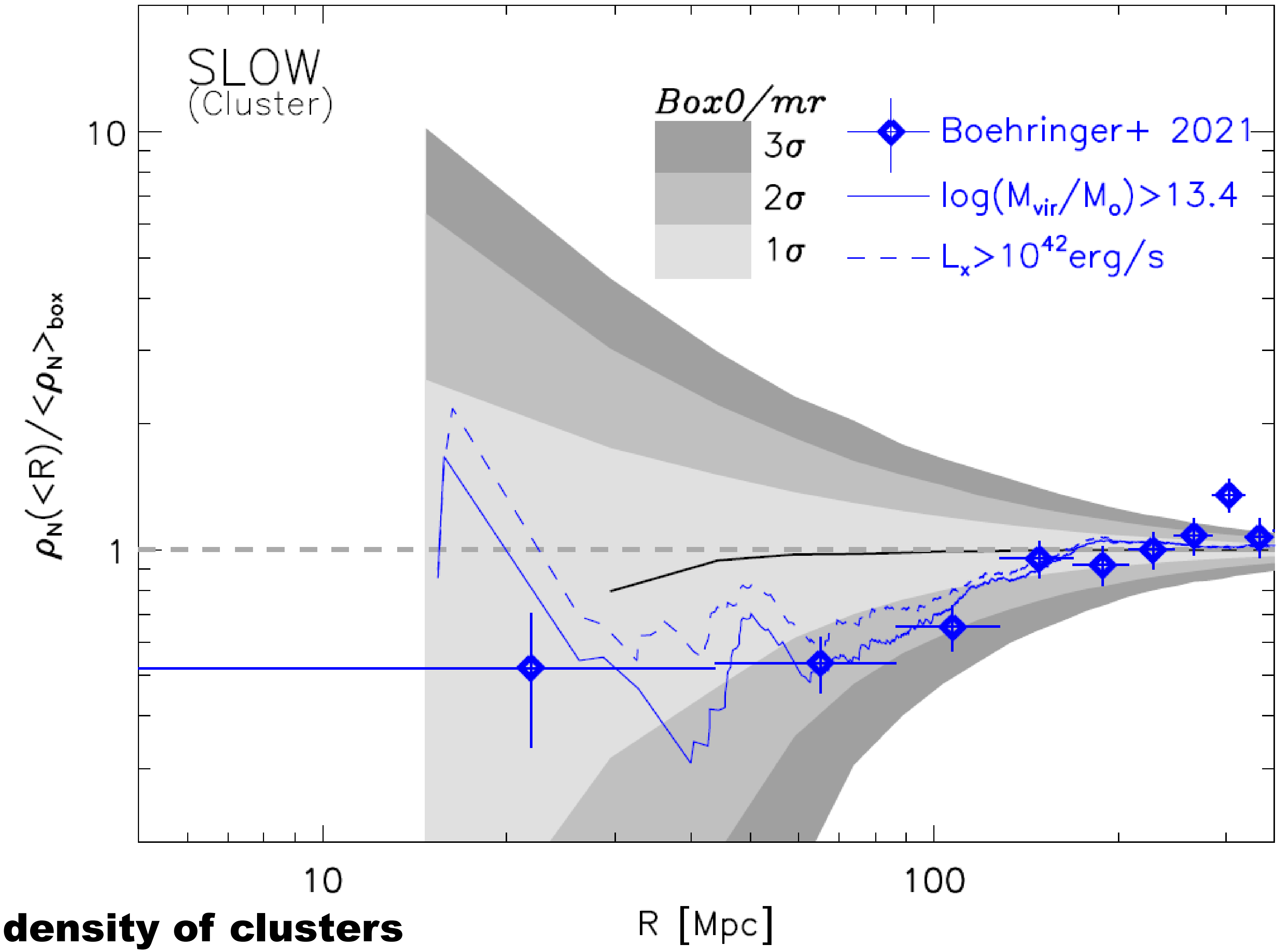


Some twist in sky positions by residuals in velocity bias/reconstruction

The SLOW simulation: matter distribution and tracers

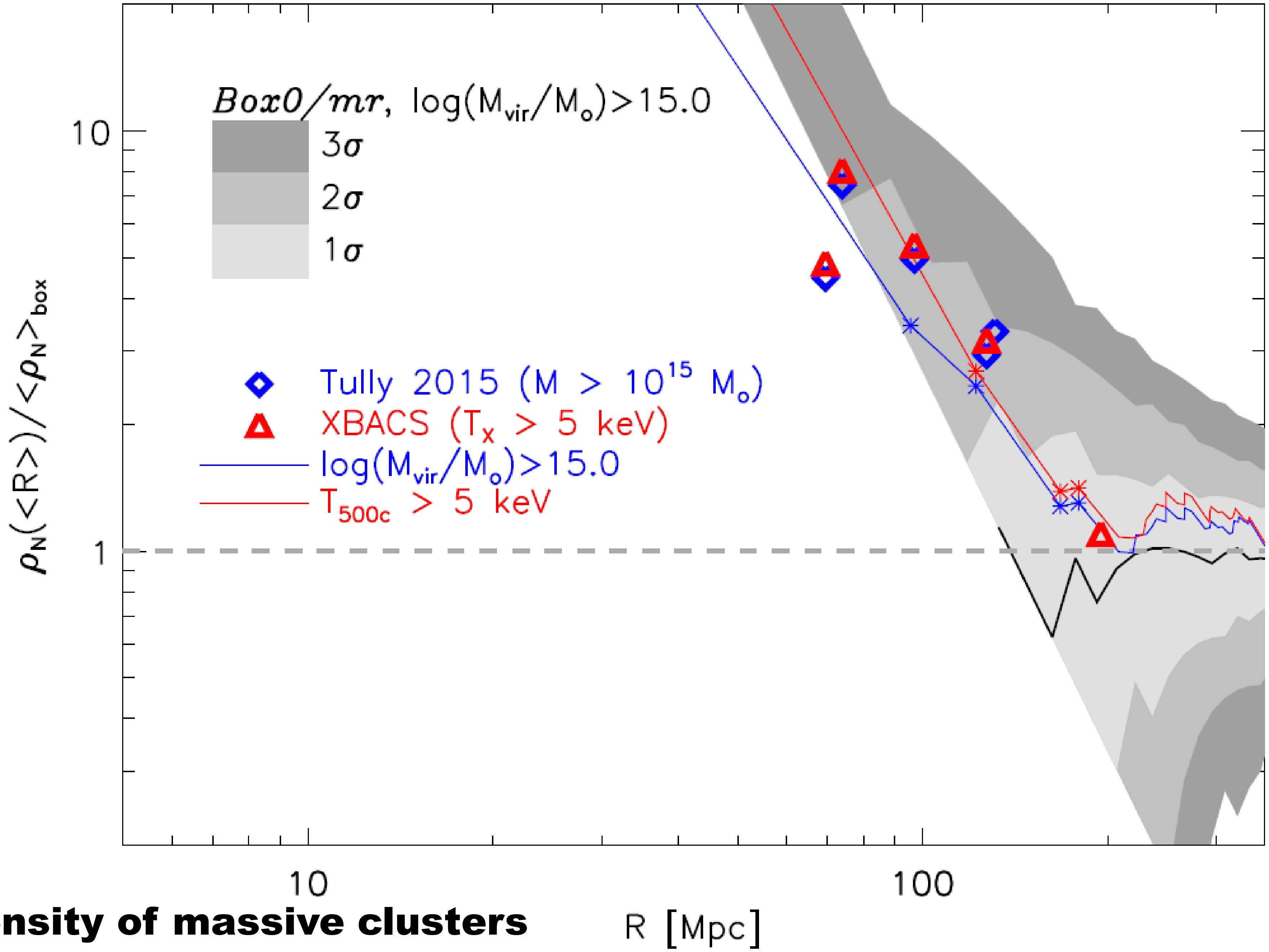


The SLOW simulation: matter distribution and tracers



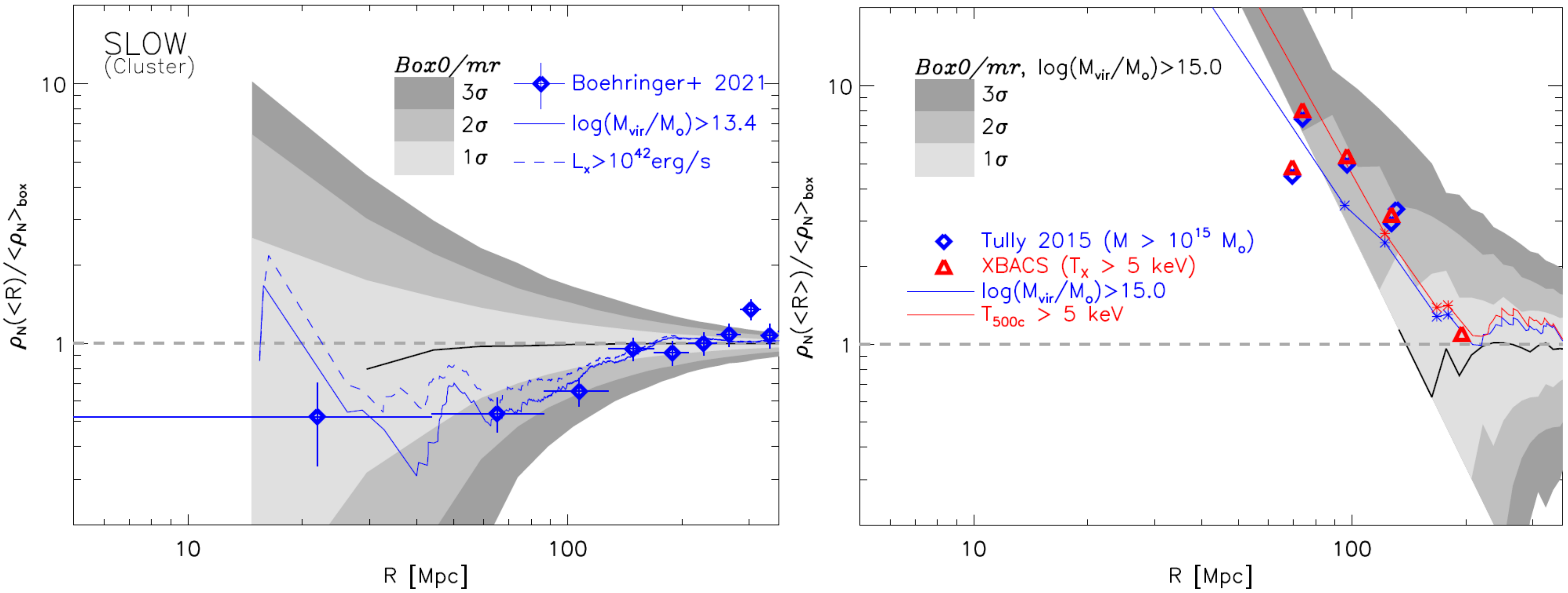
local under density of clusters

The SLOW simulation: matter distribution and tracers



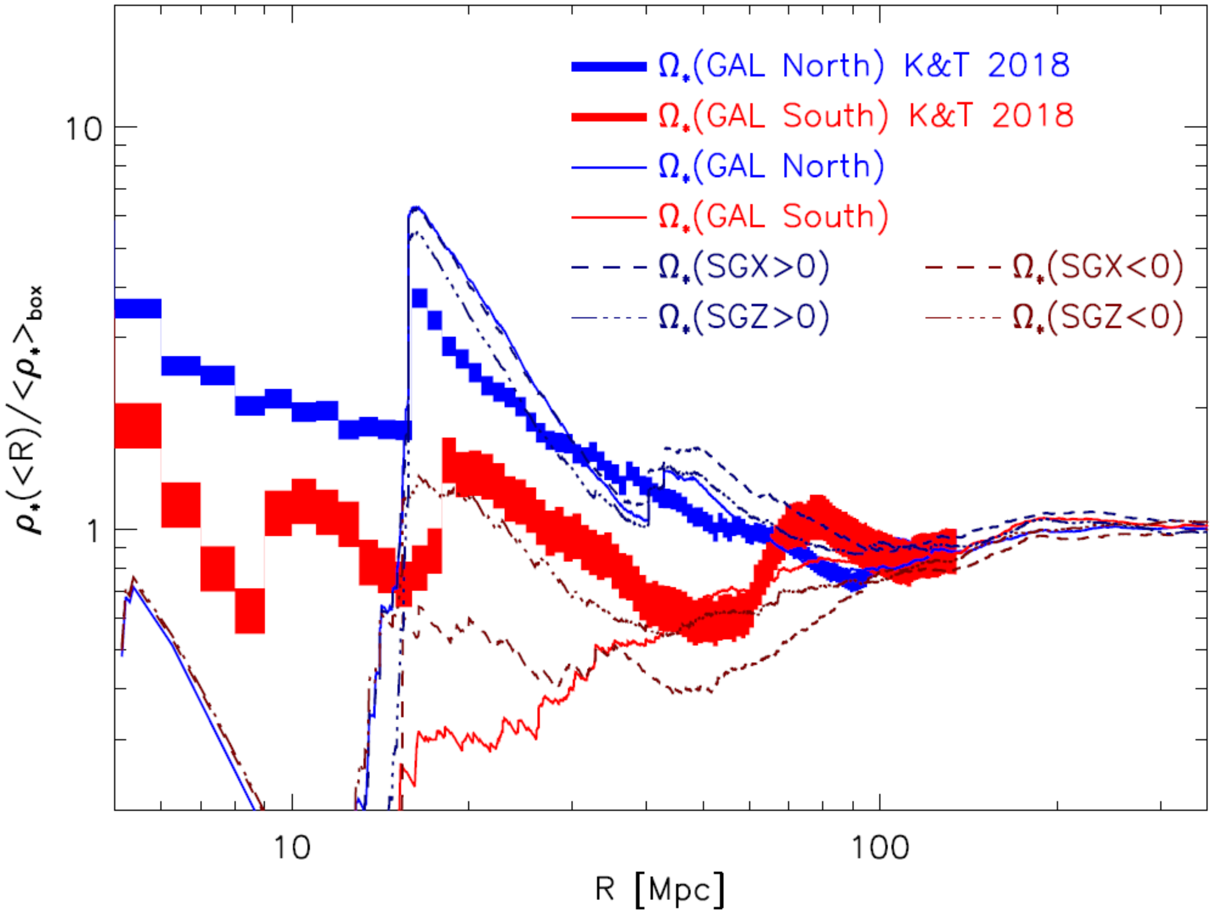
local over density of massive clusters

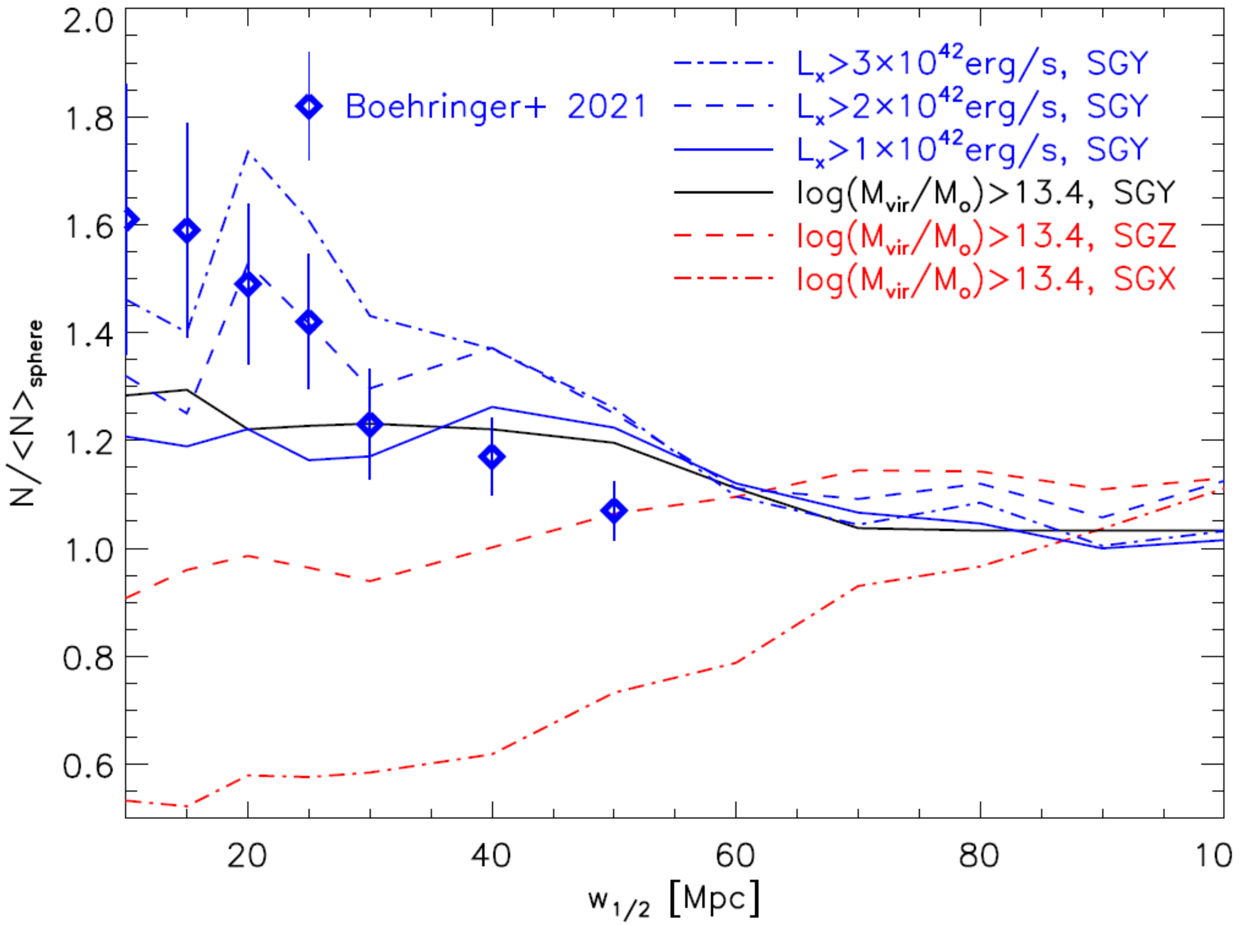
The SLOW simulation: matter distribution and tracers



Only 44 out of 15635 regions from Box0 are matching (>3σ !)

The SLOW simulation: matter distribution and tracers

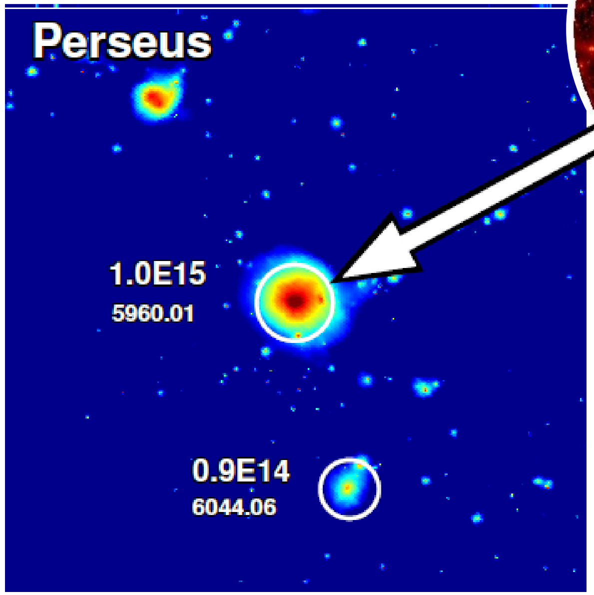


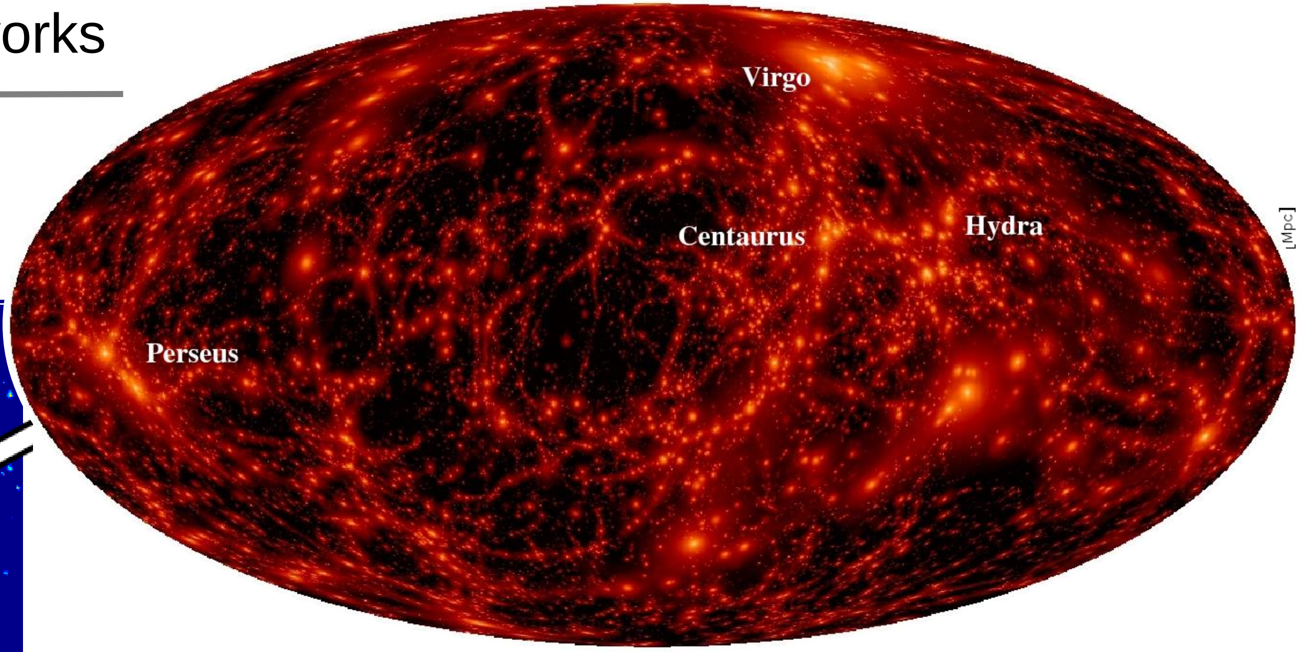


- ❑ **Pancake like structure traced by clusters reproduced**
- ❑ **Density structures and north/south split in galaxies reproduced at large R**
- ❑ **Density in stars closer than 20 Mpc not well represented**

Comparing to previous work

Comparison to previous works

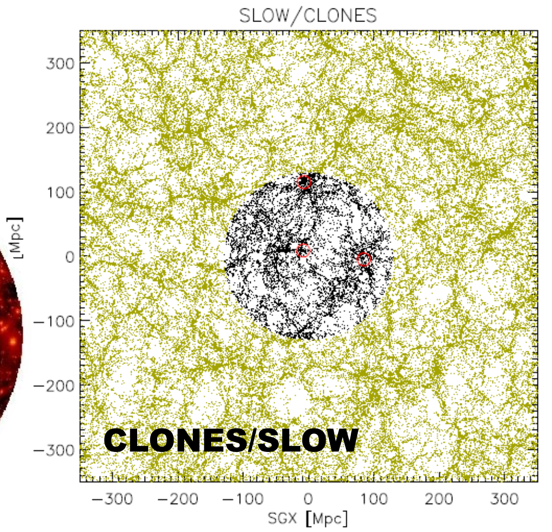


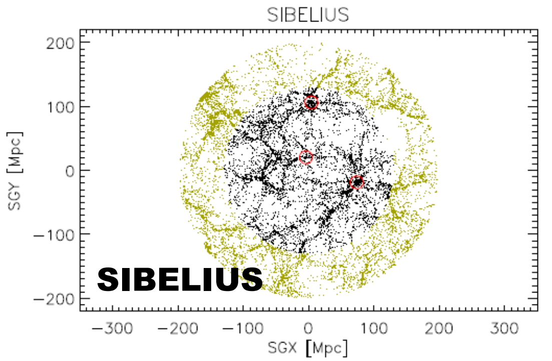


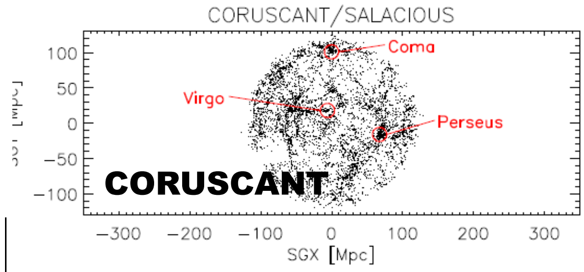
- **Virgo: Too low mass CORUSCANT/SIBELIUS**
- **Perseus: Too massive in SIBELIUS**
- **Perseus: Two massive halos in CORUSCANT**
- **Coma: Too low mass in CORUSCANT**

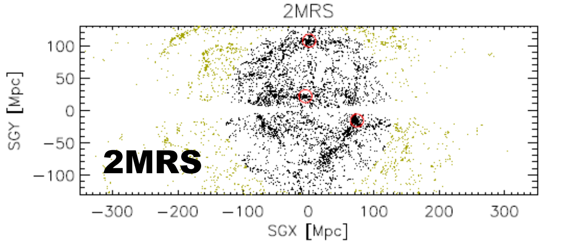
Note that the mass of structures for velocity based methods is a much more independent test than for density based methods.

Cluster	distance $v_{\rm CMB}$ [km/s]	2MRS $M_{\rm dyn}/1.12$ $[M_\odot]$	PLANCK $1.7\times M^{SZ}_{500c}$ $[M_\odot]$	LU2016 $M_{\rm vir}$ $[M_\odot]$	SLOW/CLONES $v_{\rm rad}$ [km/s]	SLOW/CLONES $M_{\rm vir}$ $[M_\odot]$	CORUSCANT $M_{\rm vir}$ $[M_\odot]$	SIBELIUS $1.2\times M_{200c}$ $[M_\odot]$
Coma	7264	1.4×10^{15}	1.2×10^{15}		8316	1.8×10^{15}	7.6×10^{14}	1.5×10^{15}
Perseus	5155	1.5×10^{15}			6343	1.0×10^{15}	1.3×10^{15}	3.3×10^{15}
Virgo	1636	6.3×10^{14}	8.1×10^{14}	$(6.5\pm1)\times10^{14}$	1434	9.8×10^{14}	5.5×10^{14}	4.3×10^{14}

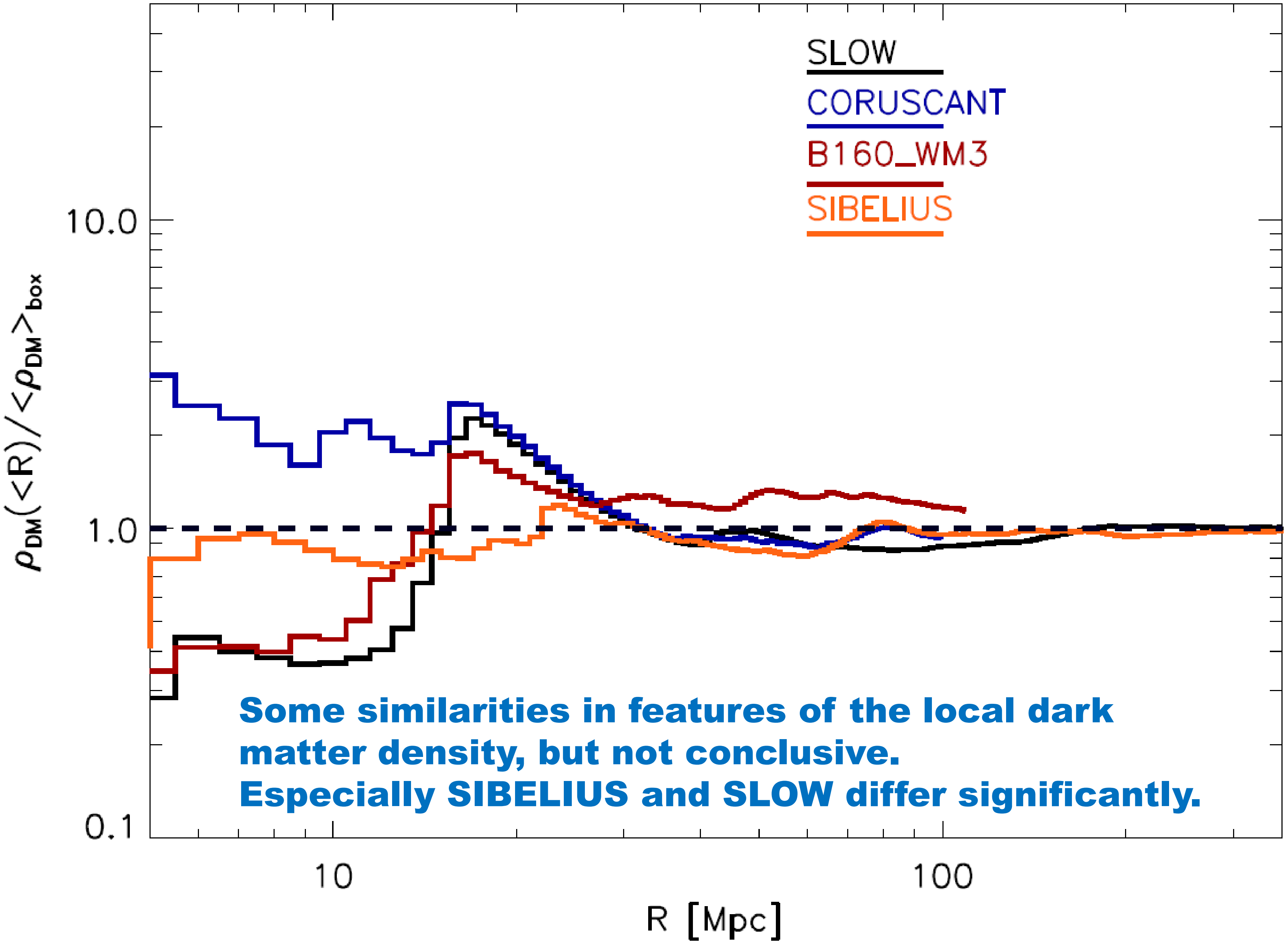


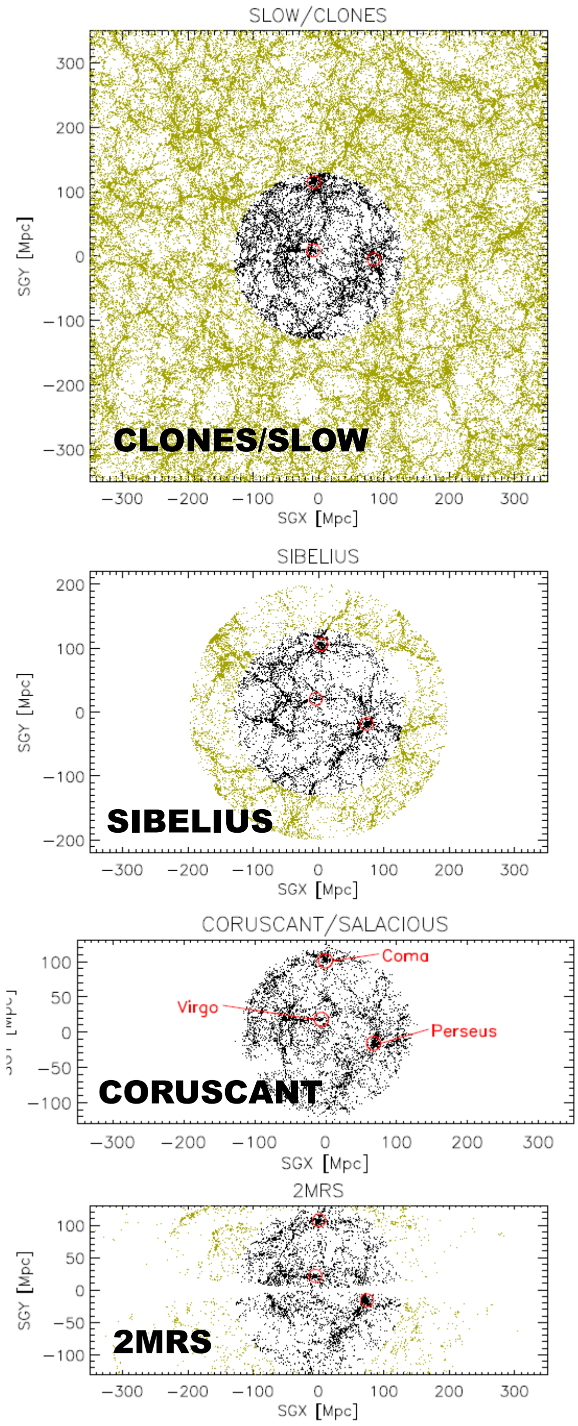






Comparison to previous works



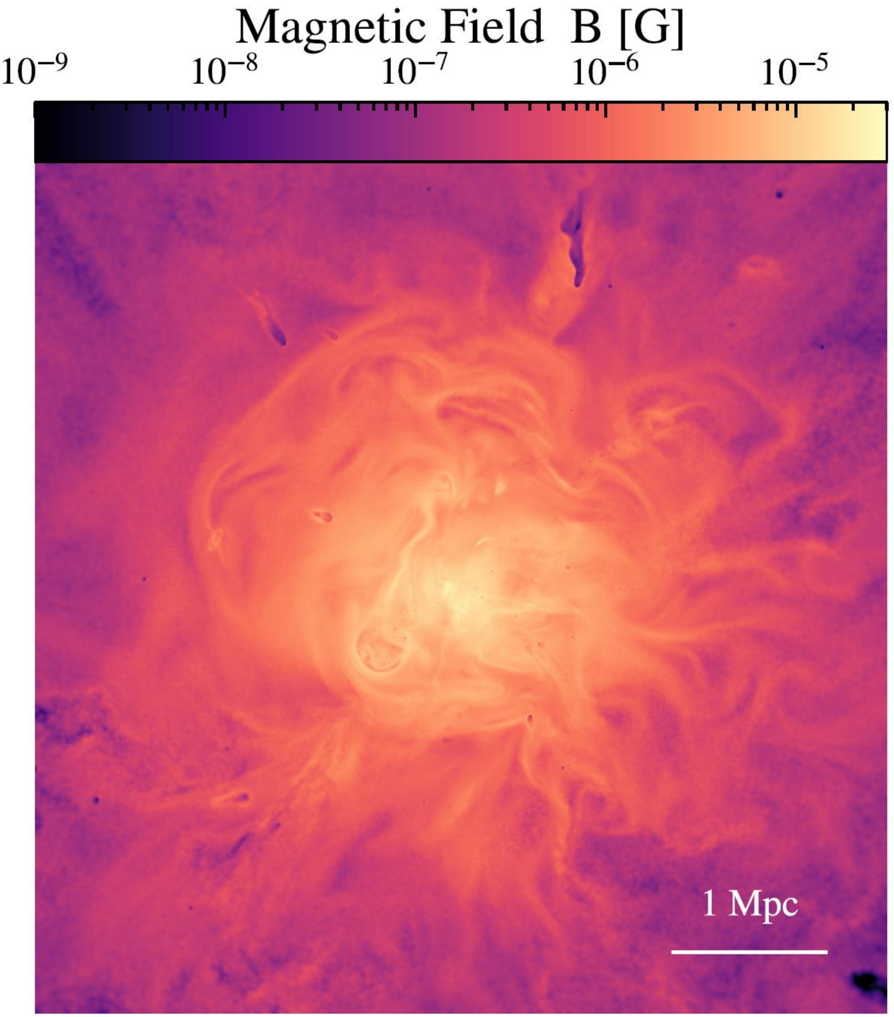


Towards Plasma Physics in the ICM

Simulations of turbulent dynamo in the ICM

U. Steinwandel

"Towards cosmological simulations of the magnetized intracluster medium with resolved Coulomb collision scale"



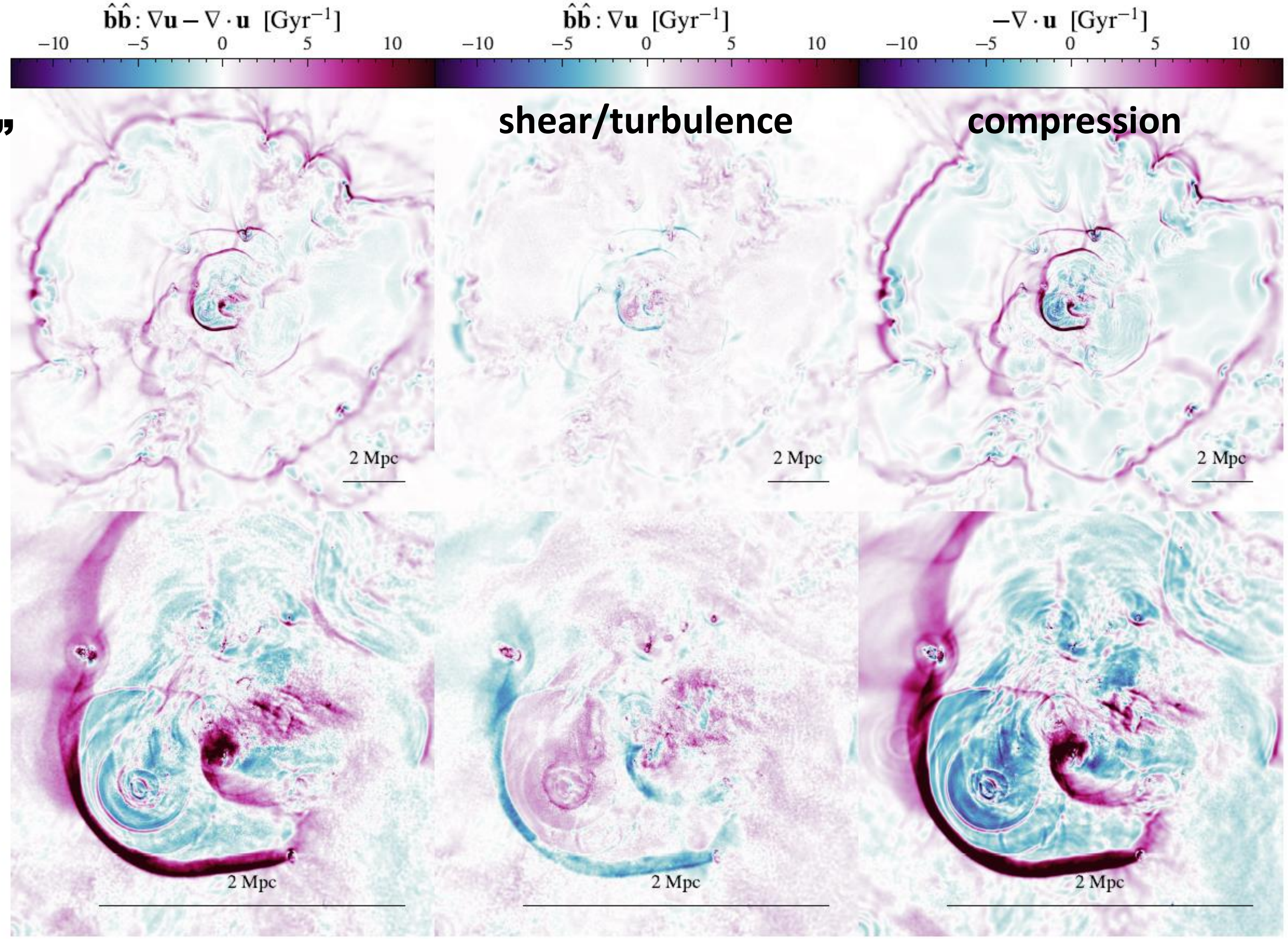
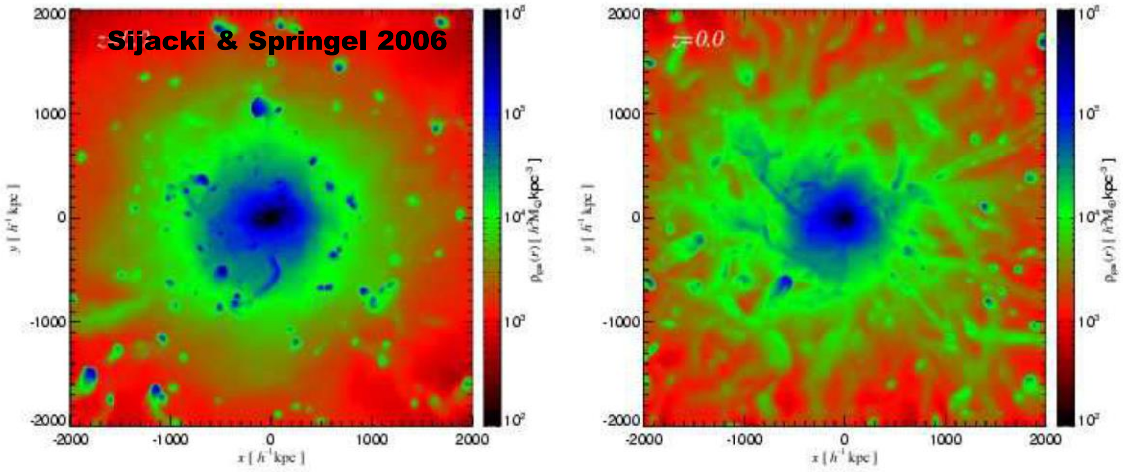


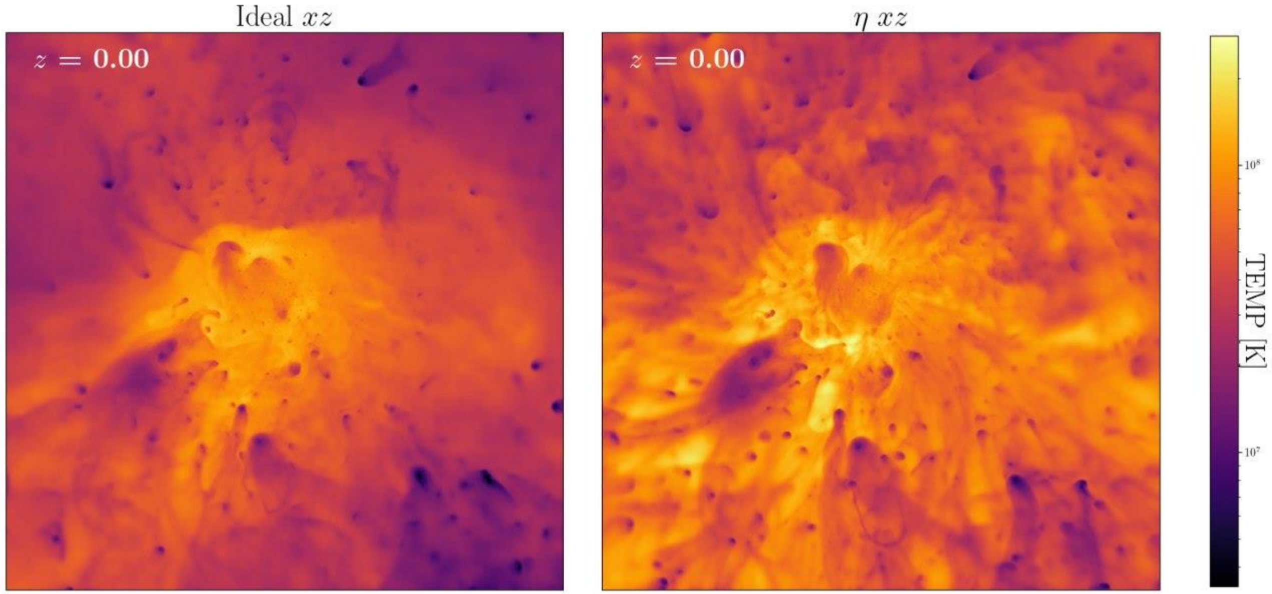
Figure 10. Total rate of change of the magnetic field (left), shearing/turbulent rate of change of the magnetic field (center), and compressive rate of change of the magnetic field (right). The top row shows the whole simulation domain, while the bottom panel is focusing on the field structure around a cold front that forms right at redshift zero through a sub-structure that is penetrating the cluster center.

Steinwandel+ 2023

Plasma Physics: Essential for mixing and multiphase nature of ICM

Effect of viscosity?





Marin-Gilabert+ 2022/24

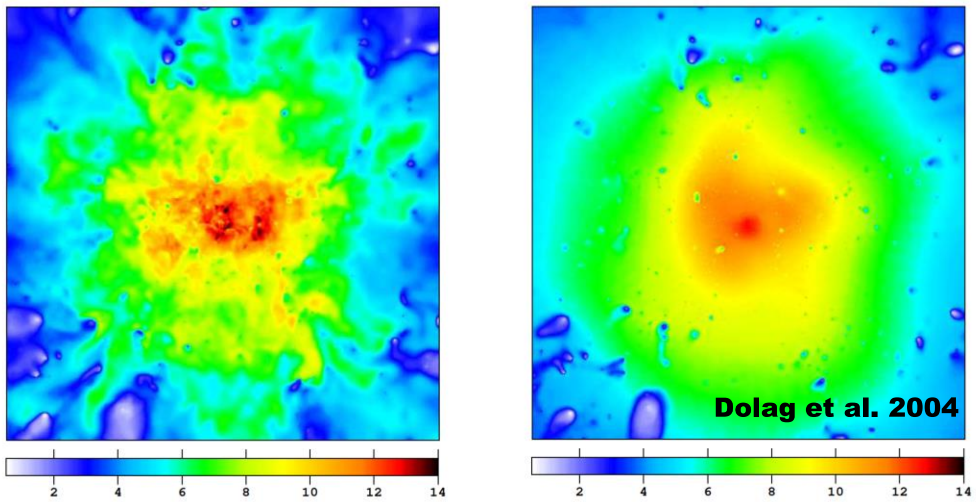
mach number — size of galaxies

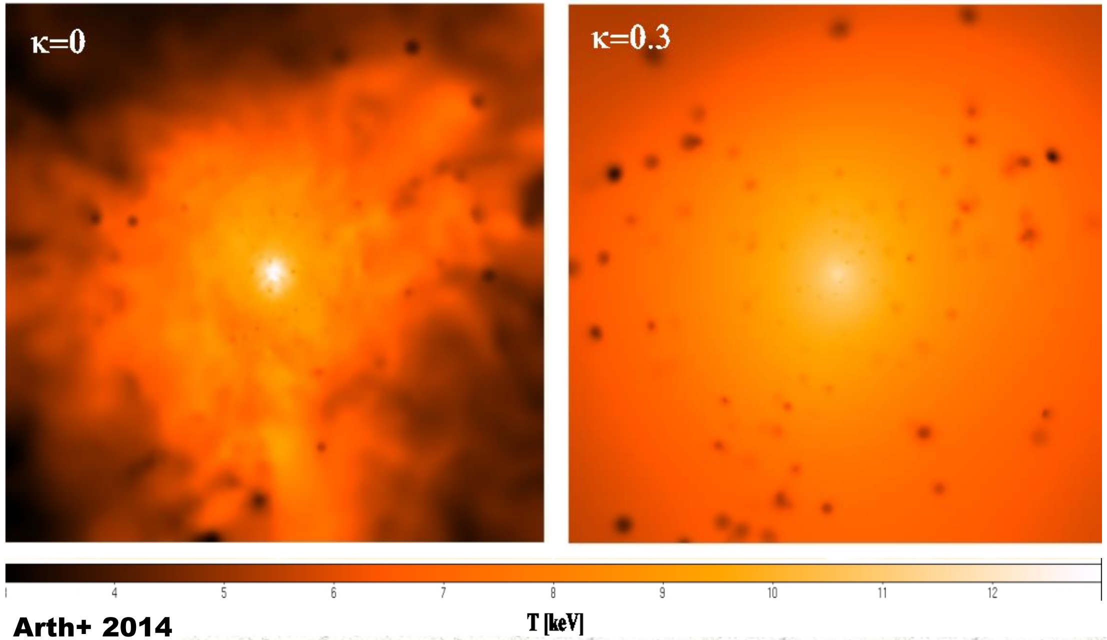
$Re \approx 3M\left(\frac{l}{\lambda_i}\right)$

l ~ λ_i !!!

ion mean free path: $\lambda_e = \lambda_i \approx 23\,\mathrm{kpc}\left(\frac{T_g}{10^8\,\mathrm{K}}\right)^2\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)^{-1}$

Effect of thermal conduction?

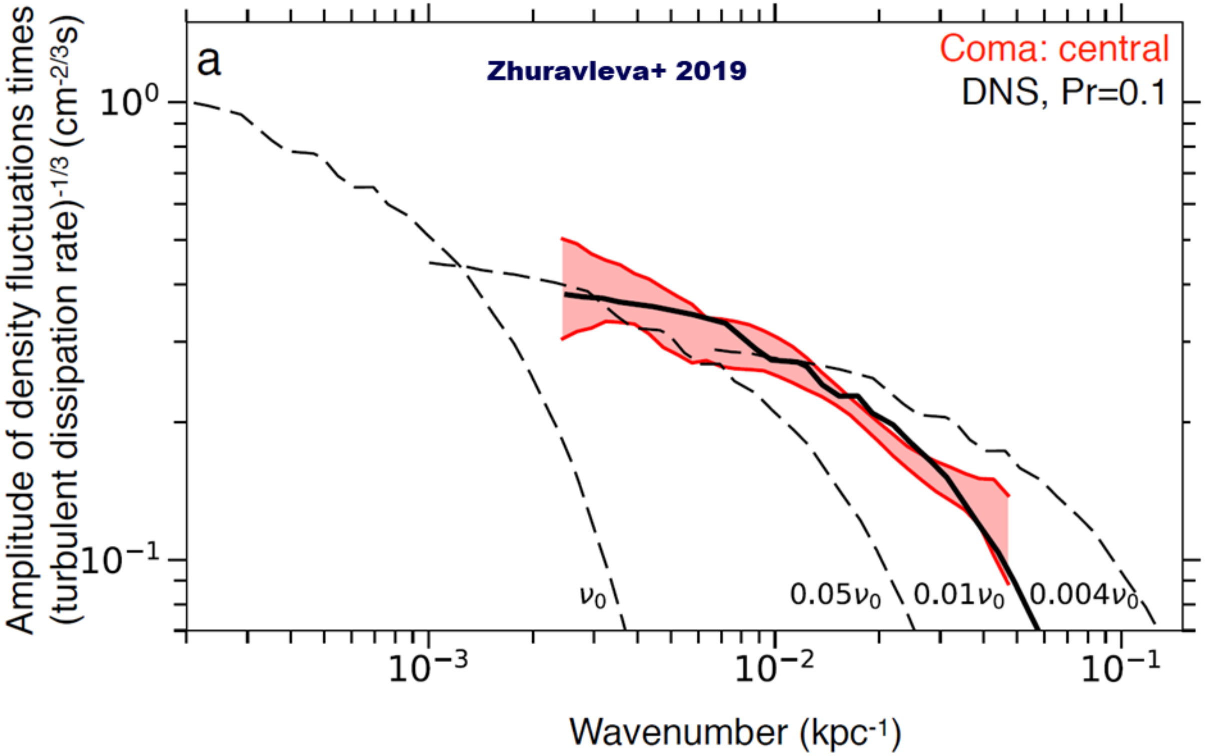




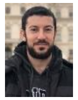
Arth+ 2014

$$\kappa = 1.31 n_e \lambda_e k \left(\frac{kT_e}{m_e}\right)^{1/2} \approx 4.6\times10^{13}\left(\frac{T_e}{10^8\,\mathrm{K}}\right)^{5/2}\left(\frac{\ln\Lambda}{40}\right)^{-1} \mathrm{erg\,s^{-1}\,cm^{-1}\,K^{-1}}.$$

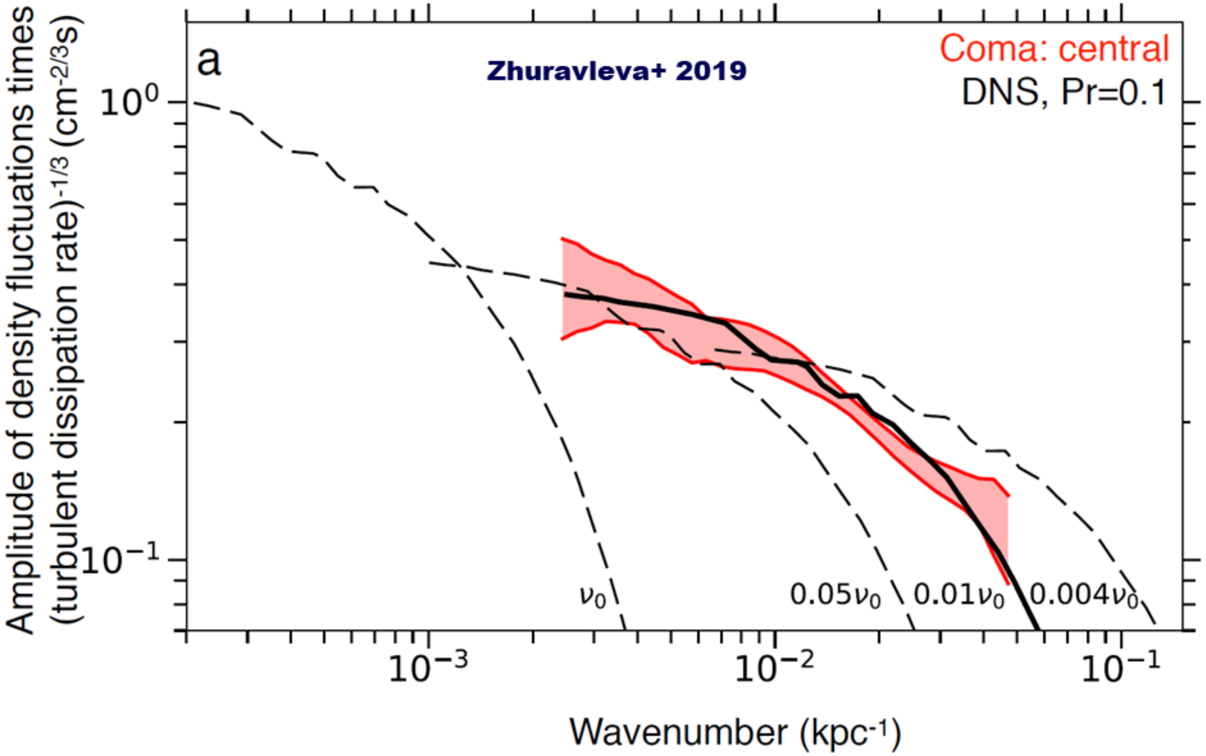
Density fluctuations to measure viscosity

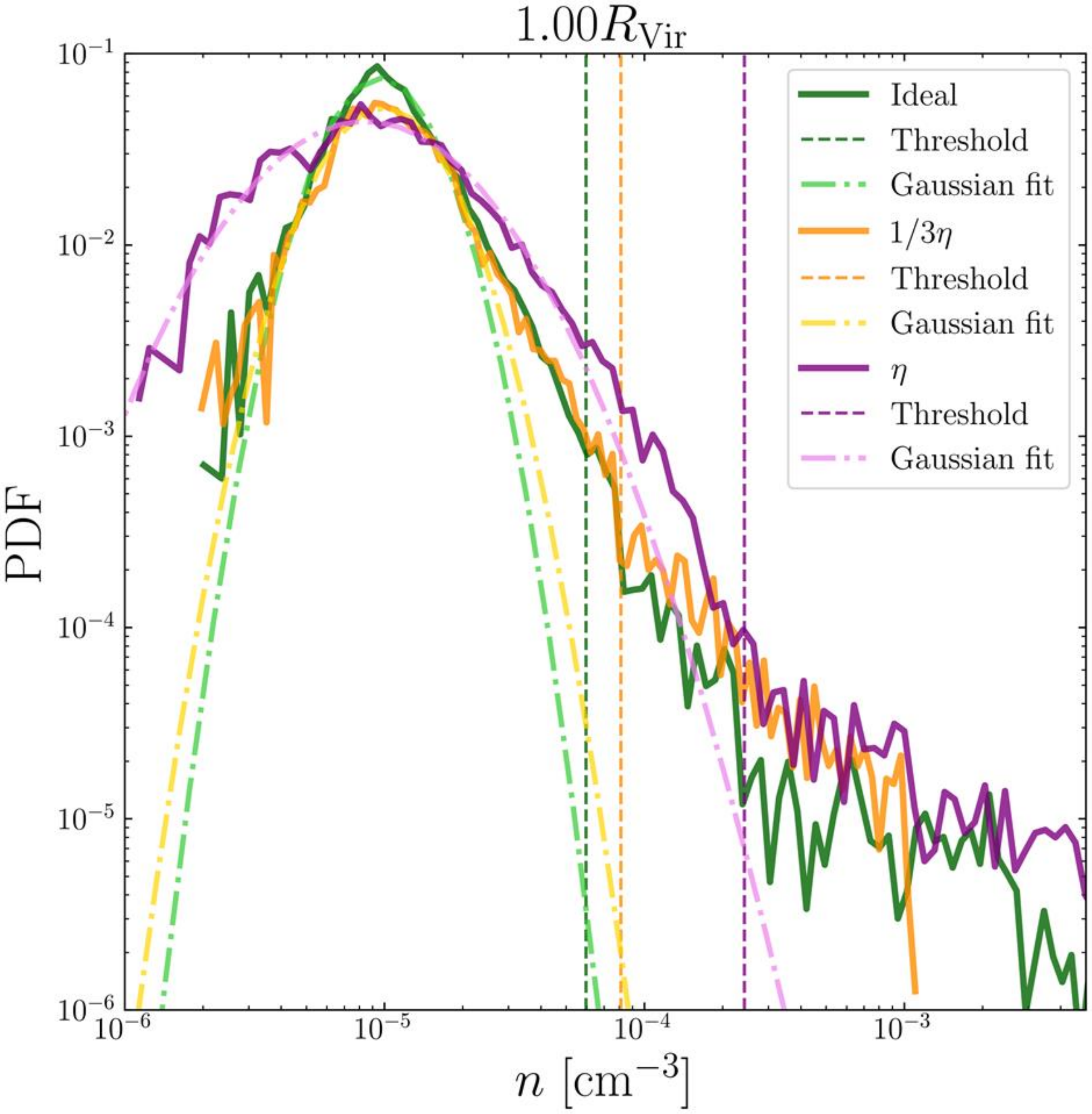


Density fluctuations to measure viscosity



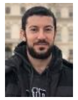
T. Marin





Marin-Glabert+ 2024

Density fluctuations to measure viscosity



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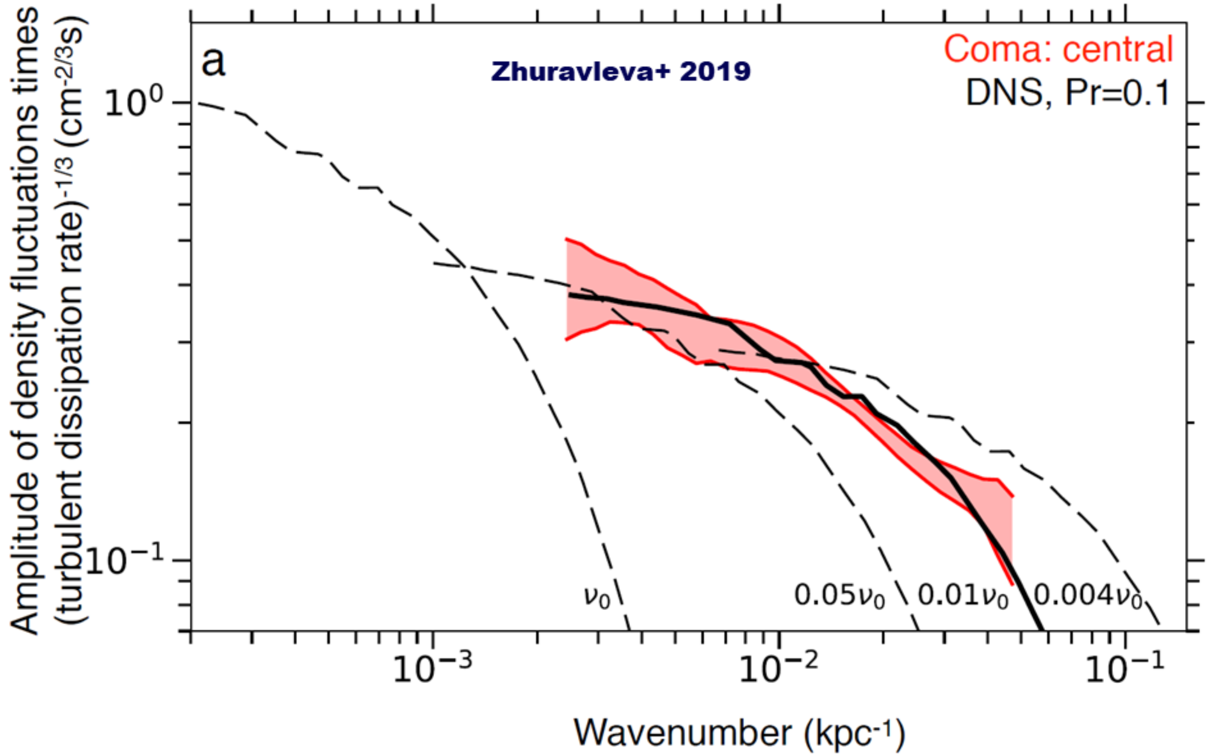
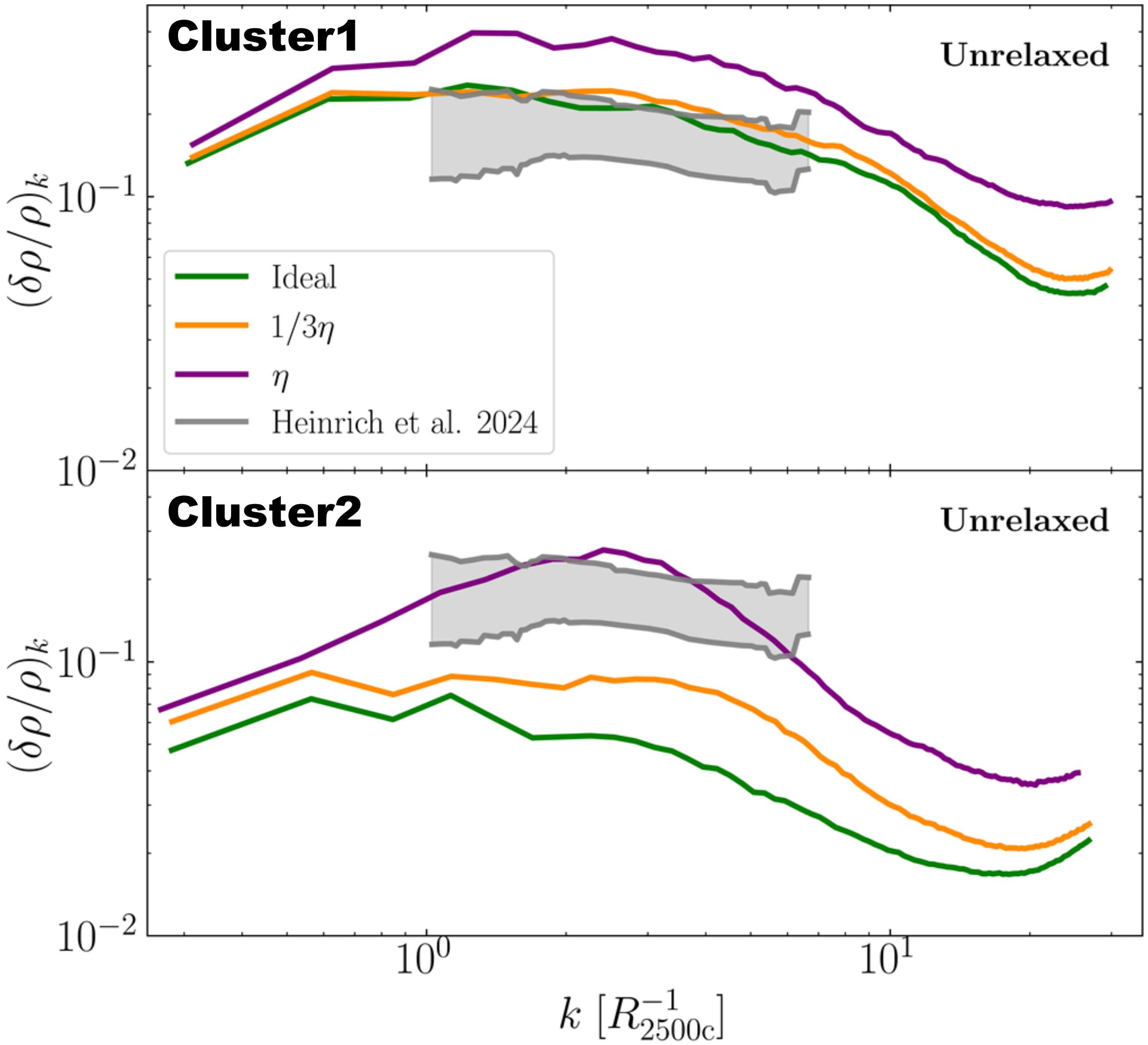
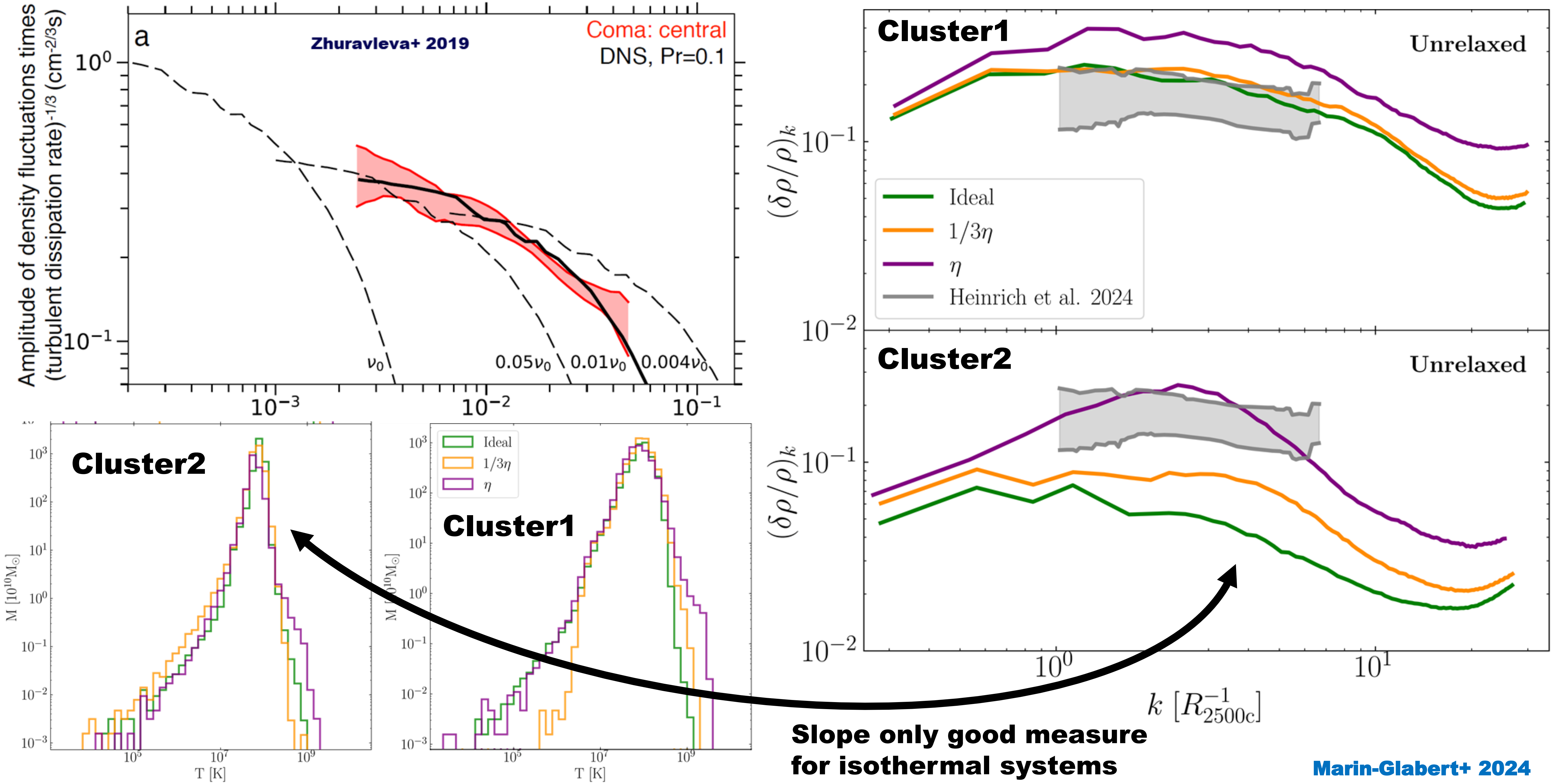




Marin-Glabert+ 2024

Density fluctuations to measure viscosity

T. Marin



Slope only good measure for isothermal systems

Marin-Glabert+ 2024