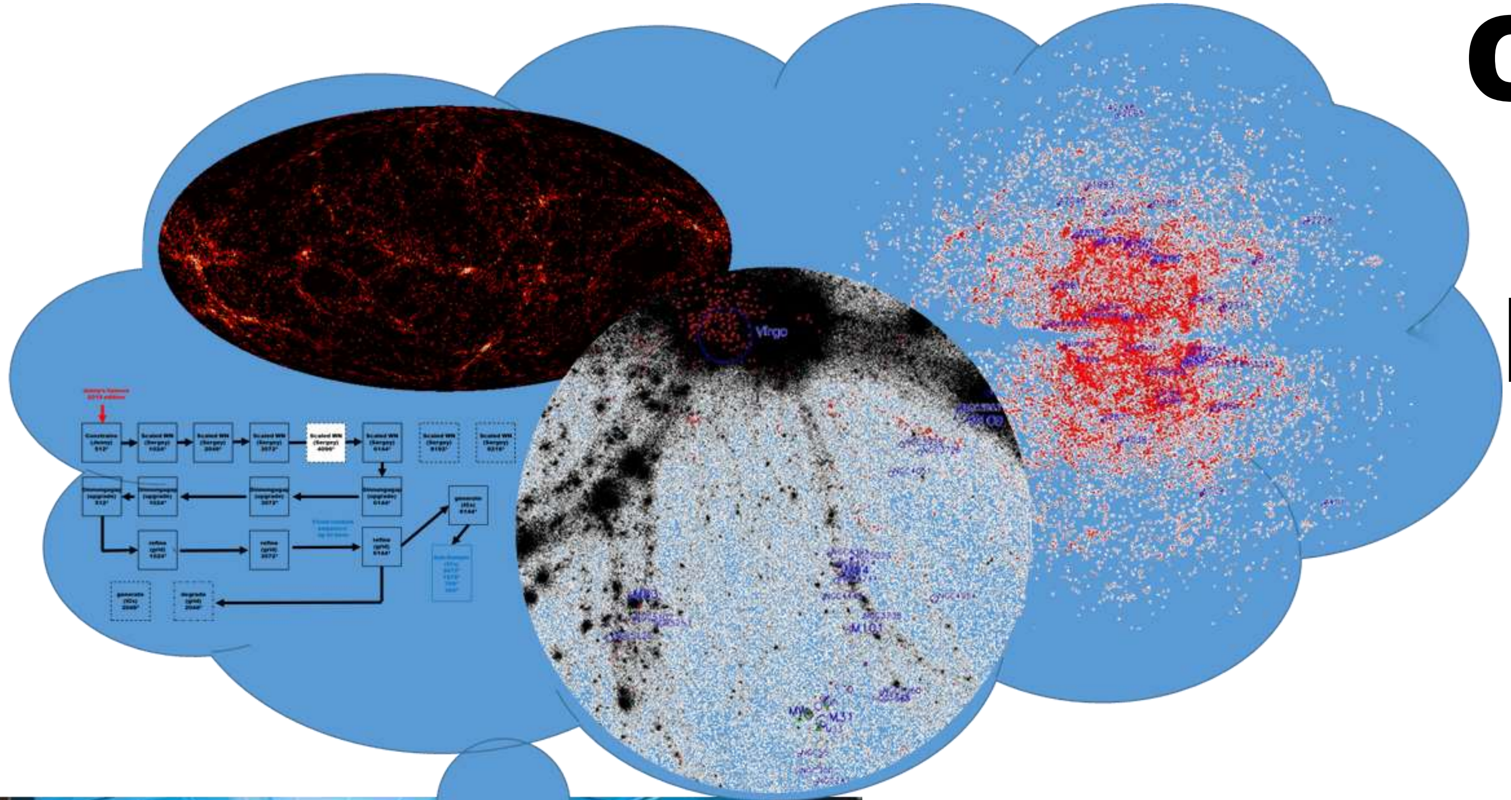
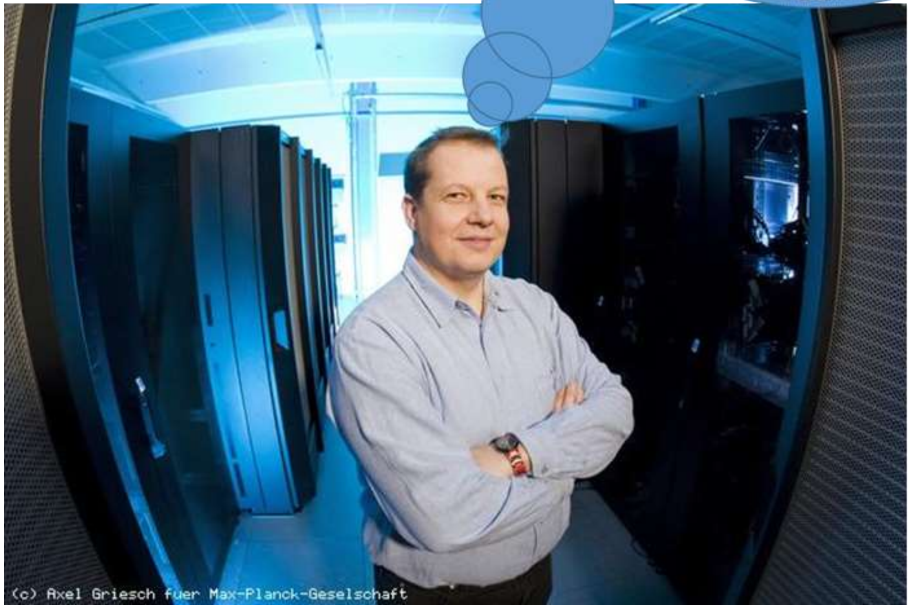
CRs & Magnetic Fields in the Local Universe

Klaus Dolag*
USM/LMU

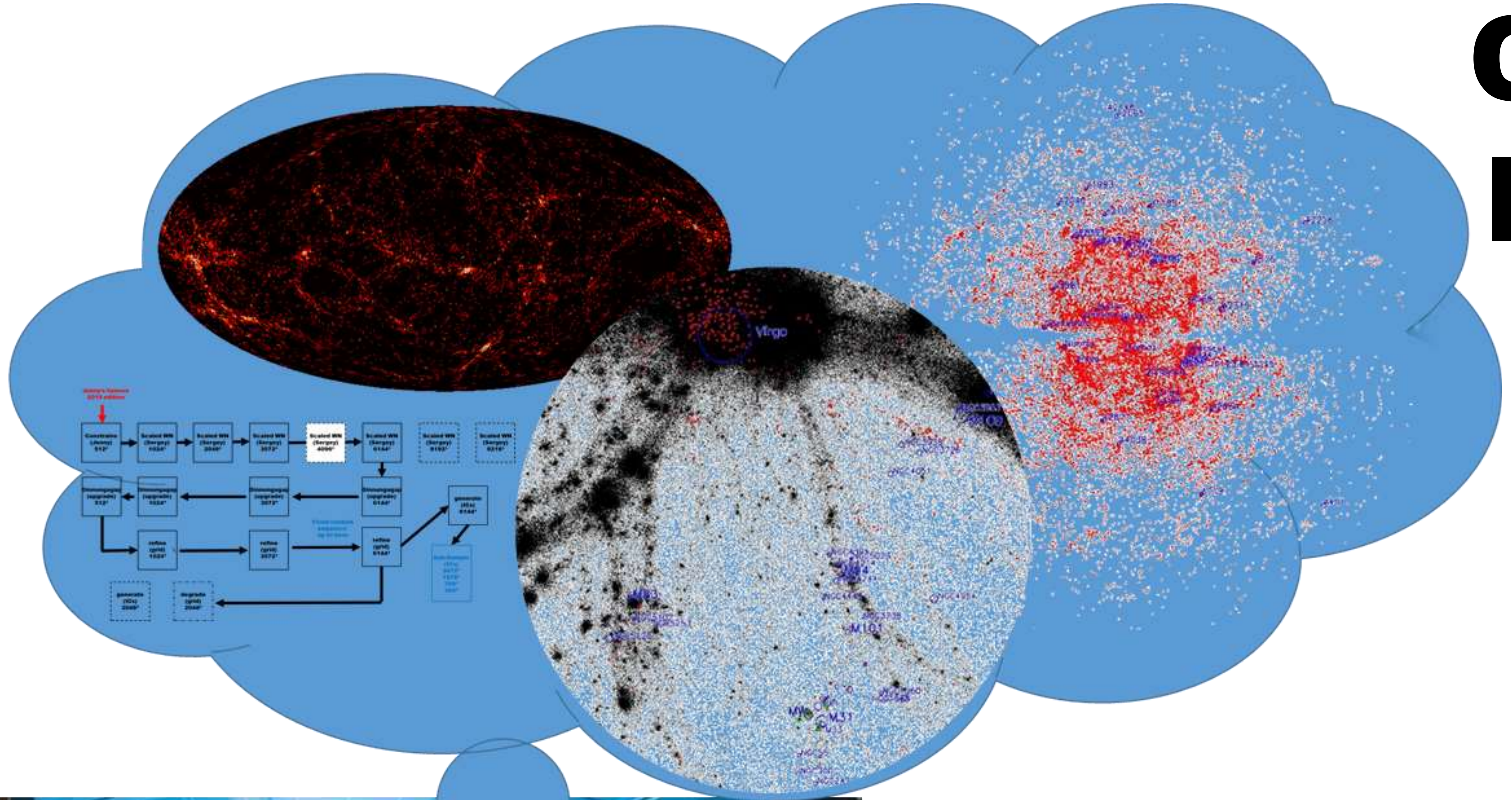
* 道楽





SPACE
ORIGINS Excellence Cluster
erc
COMPLEX
LOCALIZATION
anr agence nationale de la recherche
DFG Deutsche Forschungsgemeinschaft

 **E. Hernandez**
 **U. Steinwandel**
 **T. Marin**
 **I. Khabibullin**
 **F. Groth**
 **L. Böss**
 **B. Seidel**



Can we use the Local Universe as Plasma Physics lab?

Klaus Dolag*
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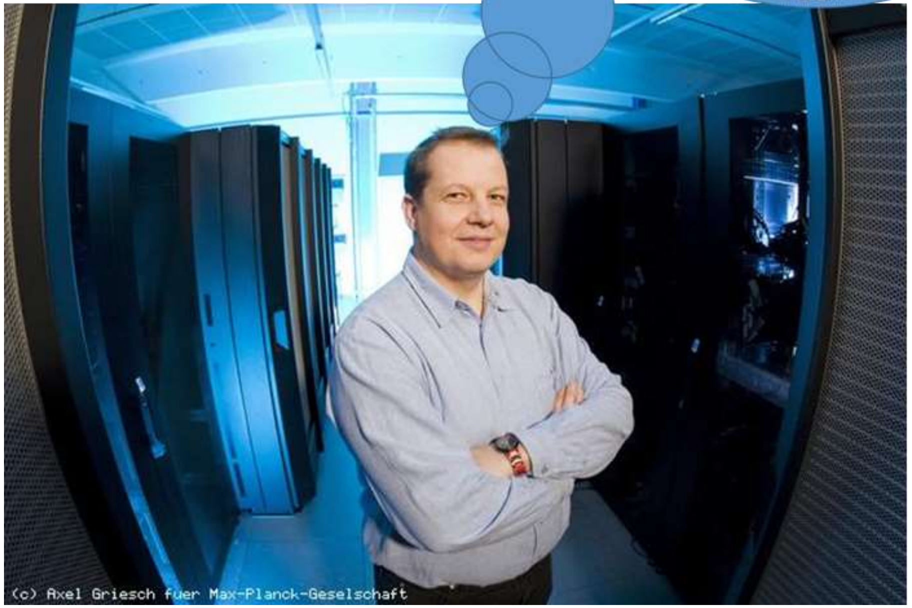

SPACE — TUM LMU ORIGINS Excellence Cluster — erc European Research Council COMPLEX — LOCALIZATION — anr agence nationale de la recherche — DFG Deutsche Forschungsgemeinschaft

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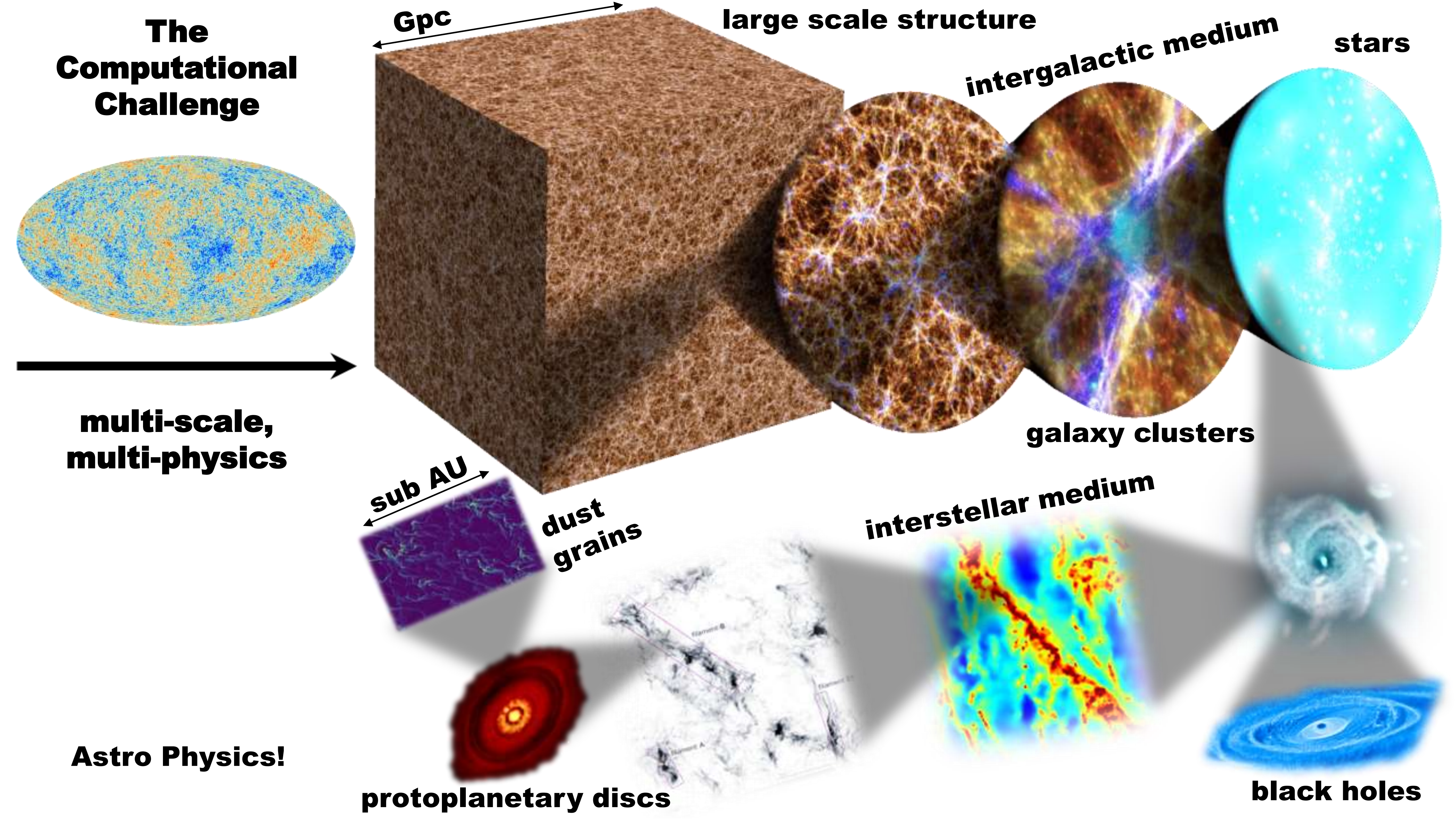
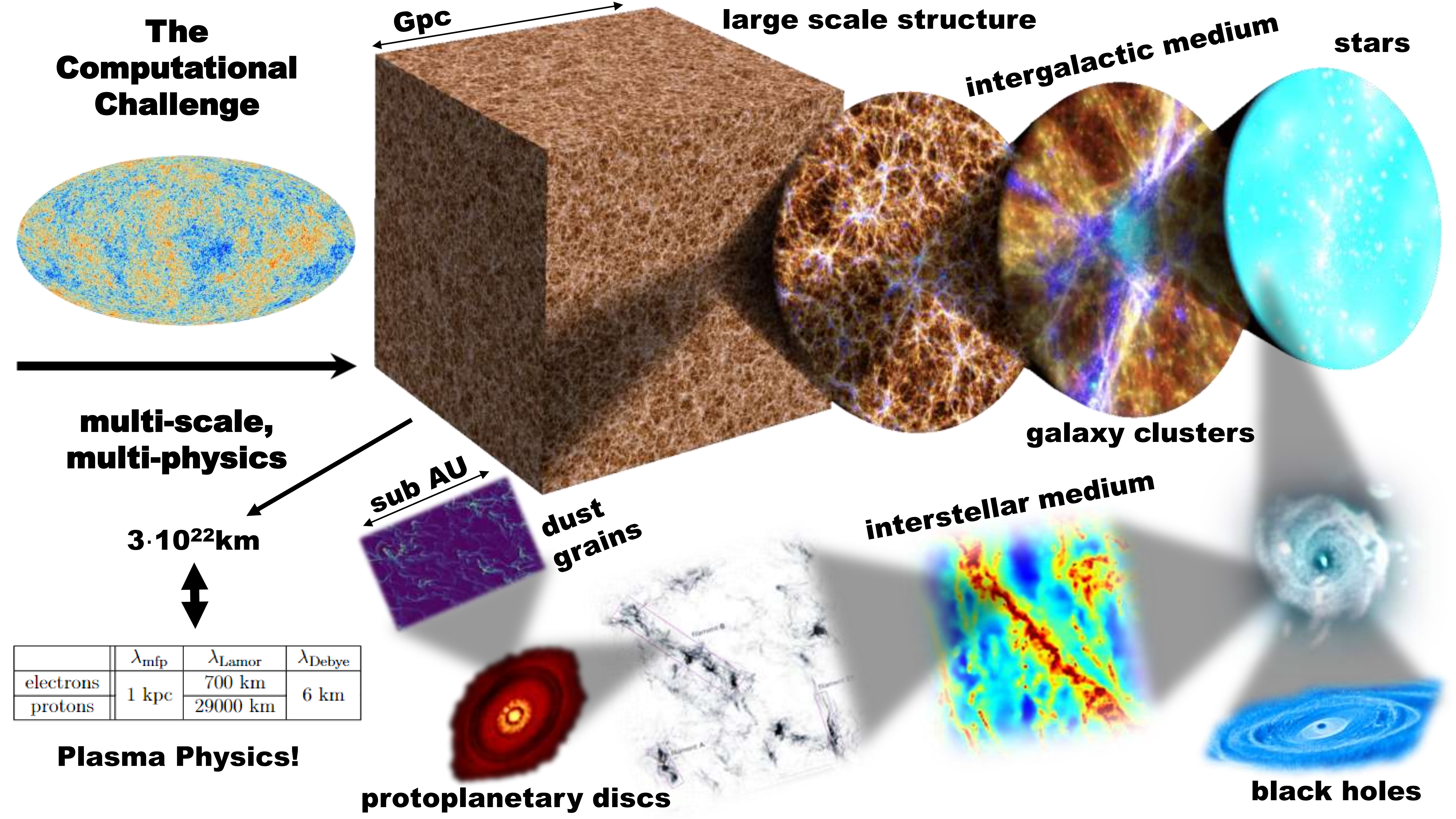
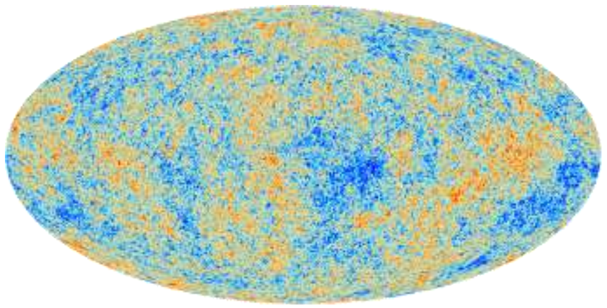
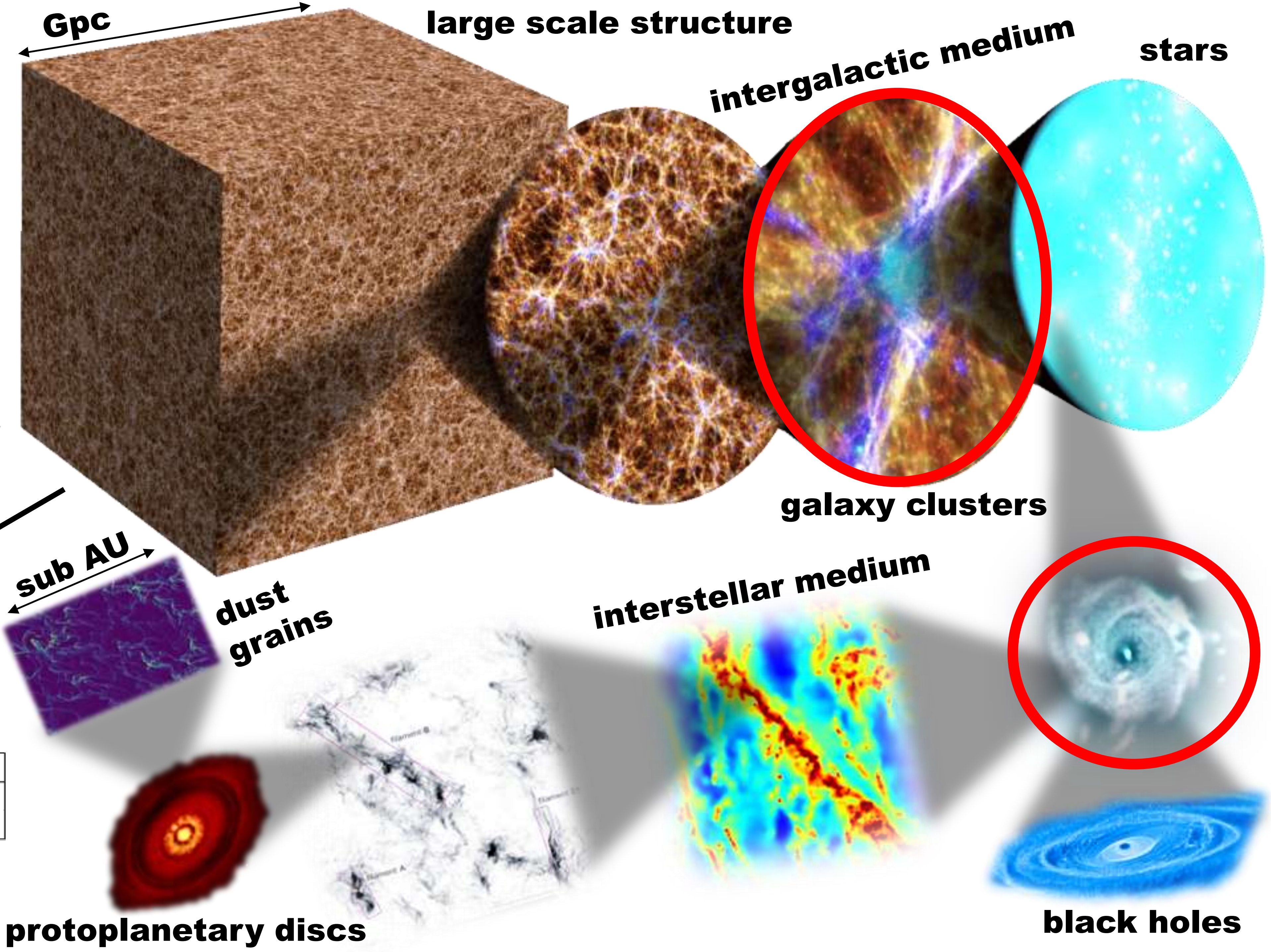
Intro I: The big picture


The Computational Challenge
multi-scale, multi-physics
Astro Physics!
Gpc
large scale structure
intergalactic medium
stars
galaxy clusters
sub AU
dust grains
interstellar medium
protoplanetary discs
black holes


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

The Computational Challenge





multi-scale, multi-physics

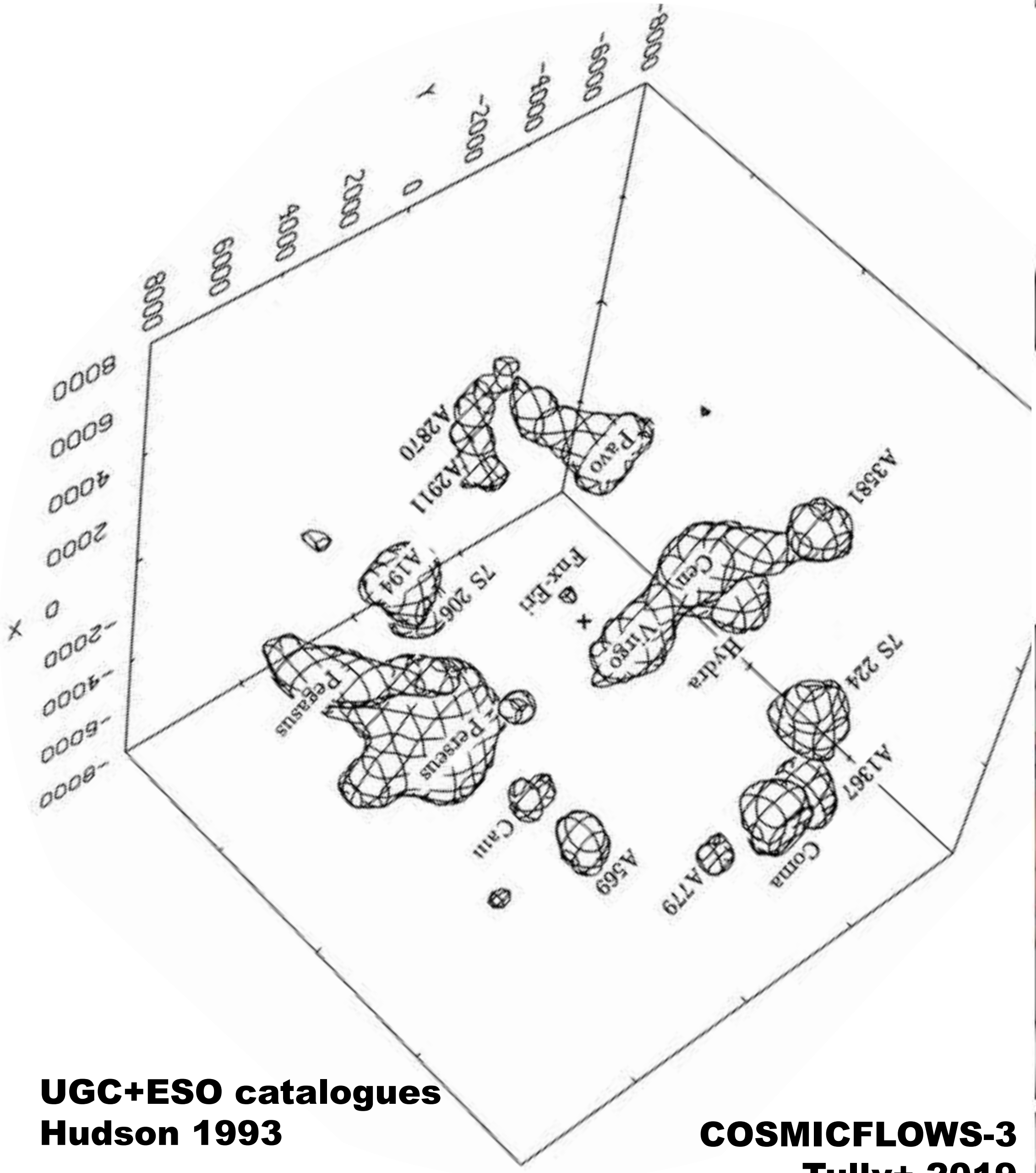
$3 \cdot 10^{22}$km

	λ_{mfp}	λ_{Lamor}	λ_{Debye}
electrons	1 kpc	700 km	6 km
protons		29000 km	

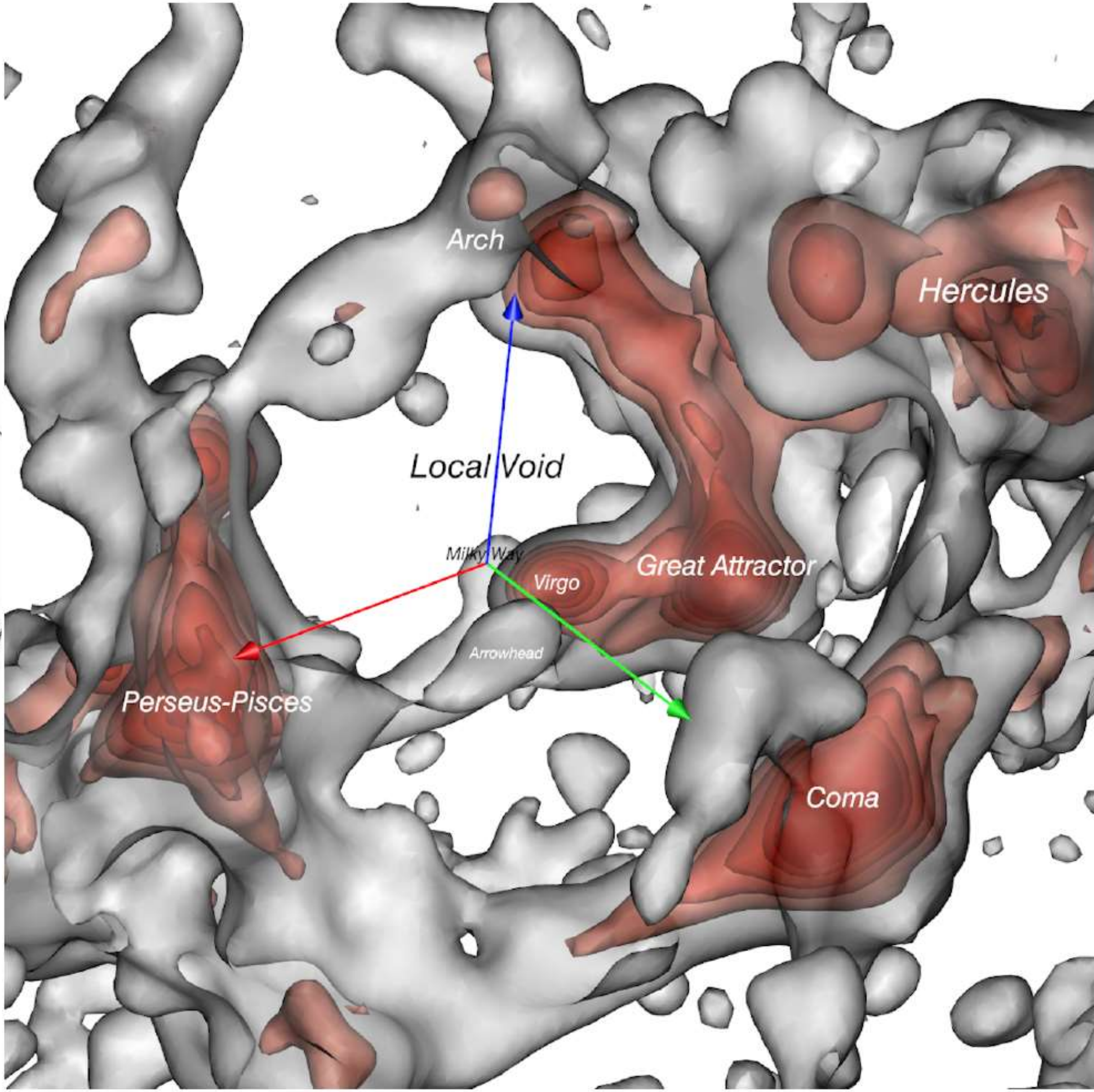
Plasma Physics!

Intro II: The Local Universe

The Local Universe



UGC+ESO catalogues
Hudson 1993



COSMICFLOWS-3
Tully+ 2019

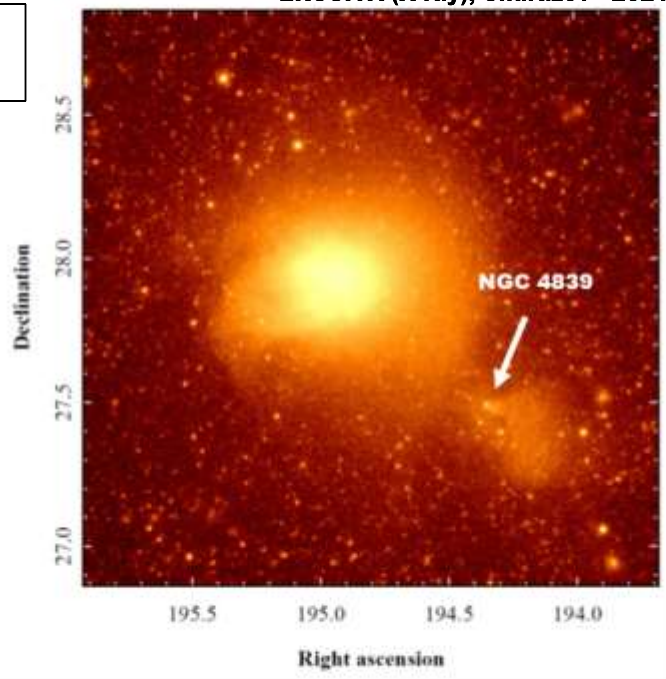
Intro III: The intra cluster medium (ICM)

ICM is the hot Atmosphere of Massive Galaxies

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

EROSITA (X-ray), Churazov+ 2021

Coma

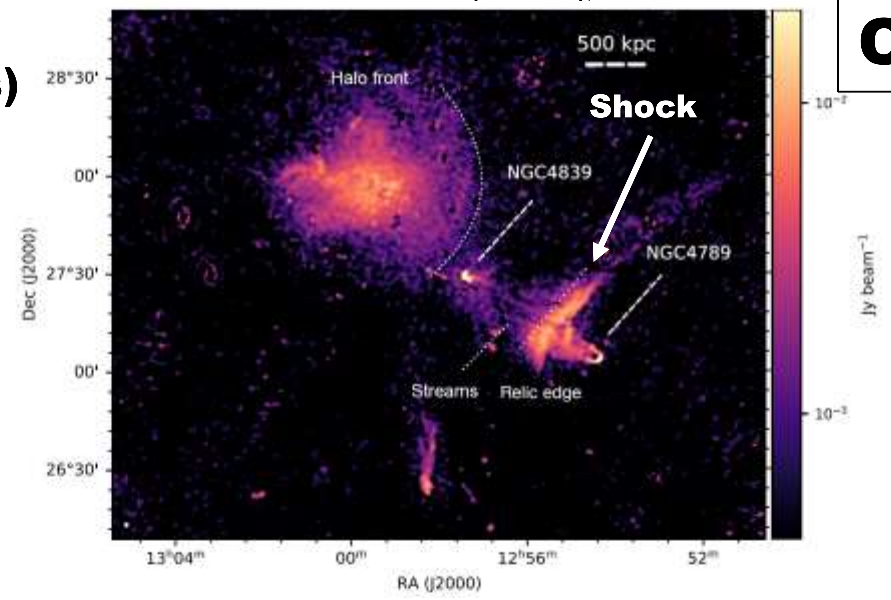


Density: 10^2 to 10^{-3} part/cm³
Temperature: 10keV to 0.1keV

ICM is the hot Atmosphere of Massive Galaxies

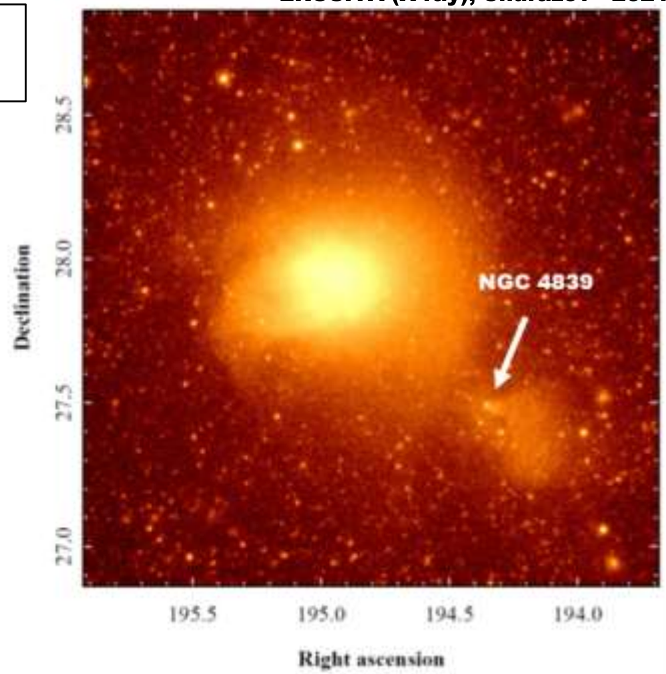
- ❑ **Measured in large details**
  X-ray (temperature, velocities)
  SZ (pressure)
- ❑ **Non-thermal components give additional insights (magnetic fields, CRs)**

LOFAR (144 MHz), Bonafede+ 2020

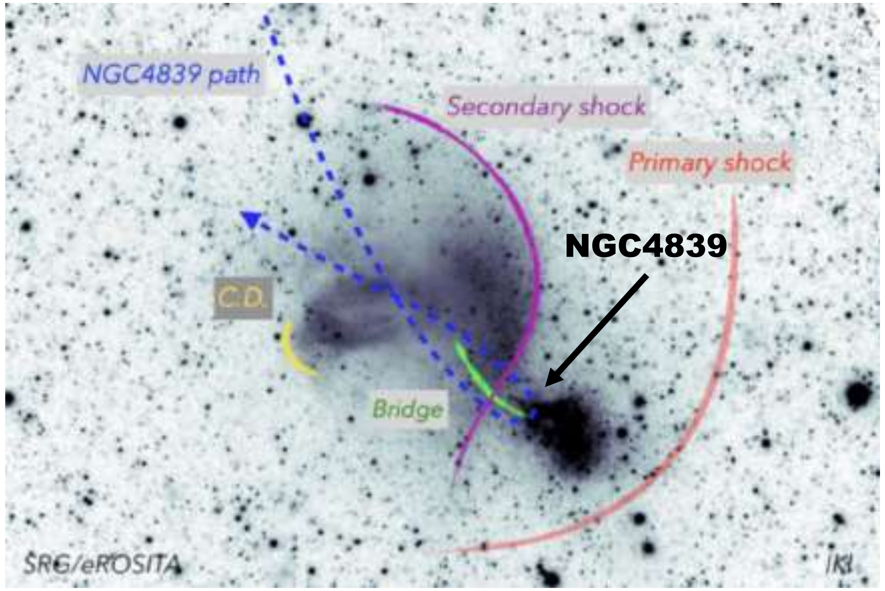


Coma

EROSITA (X-ray), Churazov+ 2021



Magnetic field: μG to nG
CR electrons: GeV



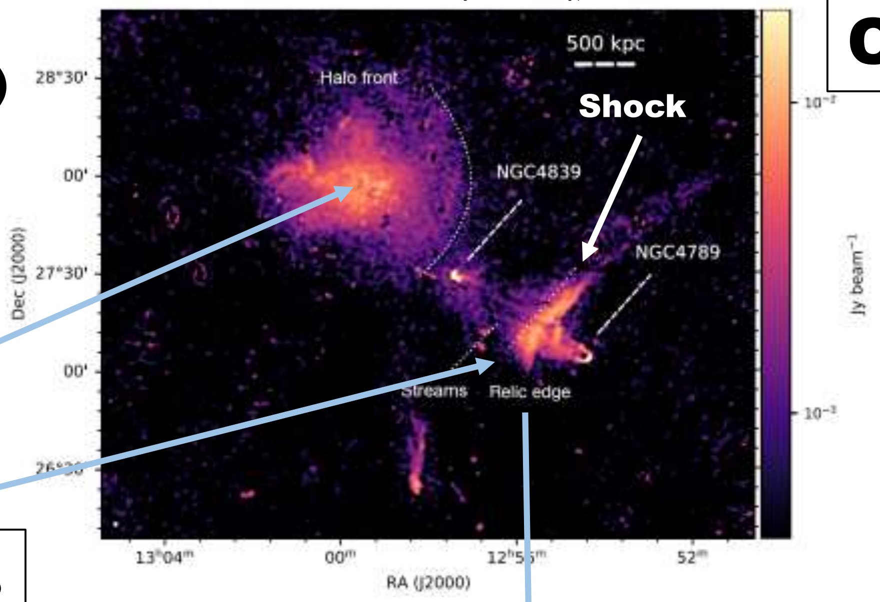
ICM is the hot Atmosphere of Massive Galaxies

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

Turbulence

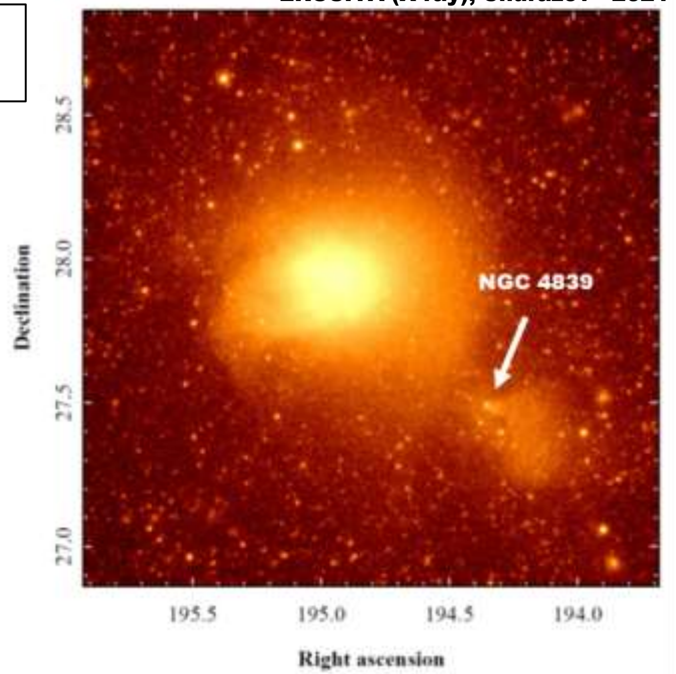
Shocks

LOFAR (144 MHz), Bonafede+ 2020



Coma

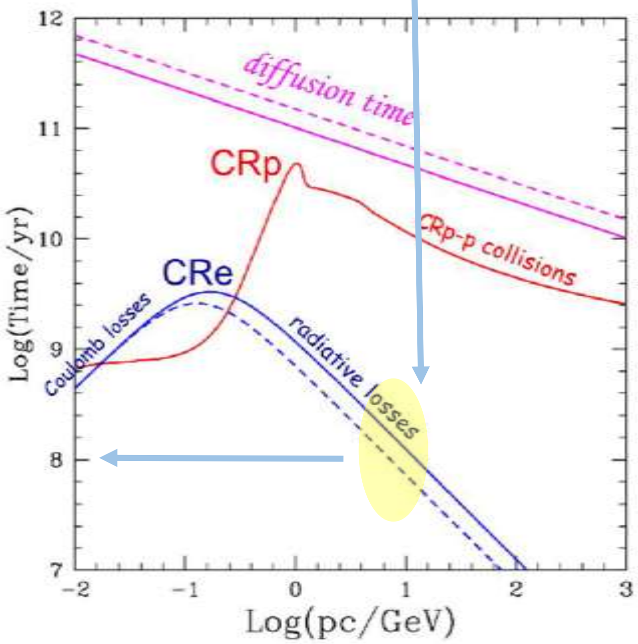
EROSITA (X-ray), Churazov+ 2021

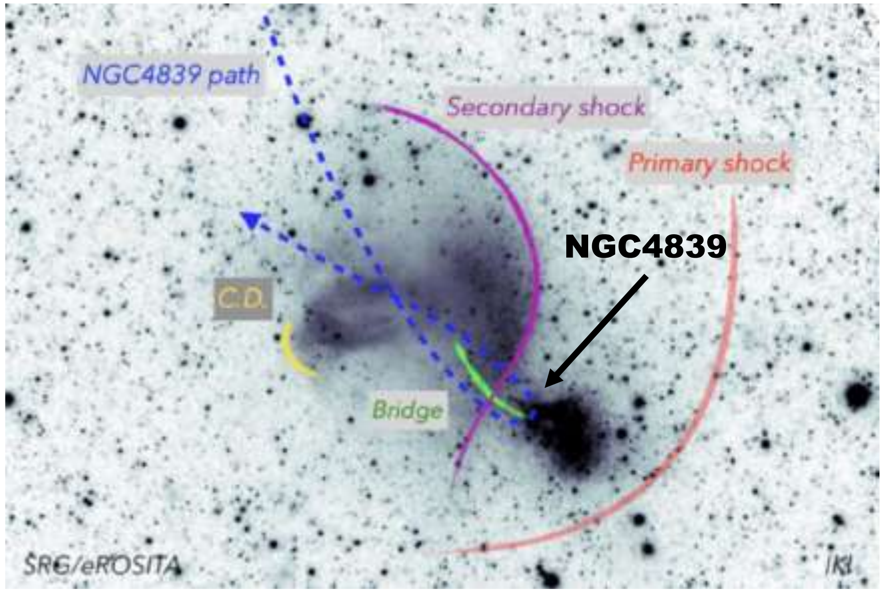


Short cooling time of CRe:
- ❑ test shocks on 10th of kpc
- ❑ test turbulence (re-acceleration)

Long cooling time of CRp:
- ❑ can be dynamically important

Both couple to B-Field





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

L. Böss

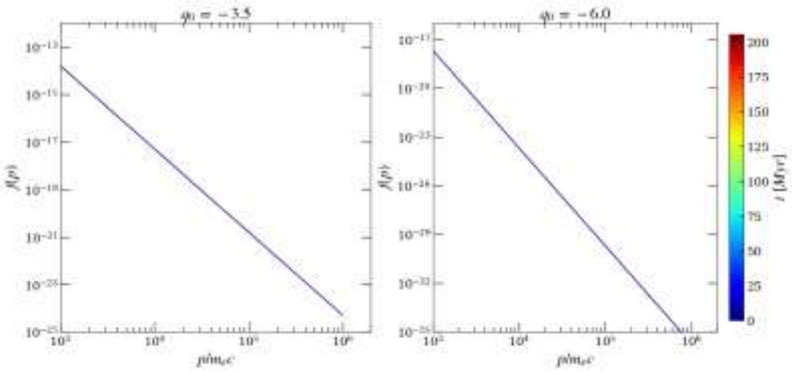
$$\underbrace{\frac{\partial f}{\partial t}}\; + \underbrace{\mathbf{u}\cdot\nabla f}_{\text{spatial convection}} - \underbrace{\nabla\left(\boldsymbol{\kappa}\nabla f\right)}_{\text{spatial diffusion}} =$$

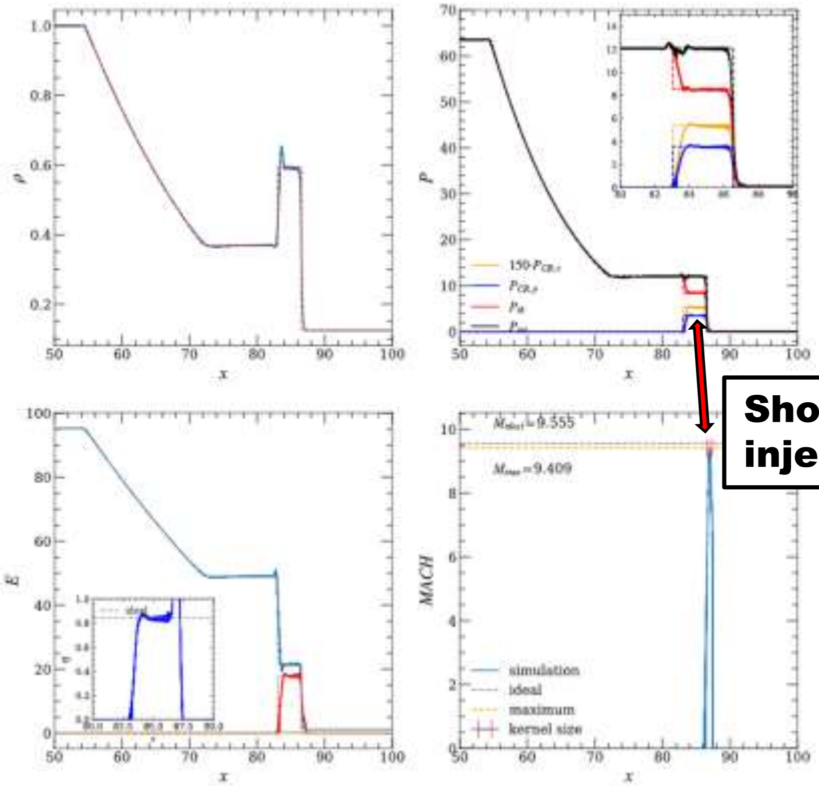
$$\underbrace{\frac{1}{3}\left(\nabla\cdot\mathbf{u}\right)p\frac{\partial f}{\partial p}}_{\text{momentum convection}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left[b_\ell f + D_p\frac{\partial f}{\partial p}\right]\right)}_{\text{momentum diffusion + continuous losses}} - \underbrace{\frac{f(p,\mathbf{x},t)}{t_c(p,\mathbf{x})}}_{\text{ca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

Turbulence

- **Shocks**
- SFR
- AGN

Cooling of CRe

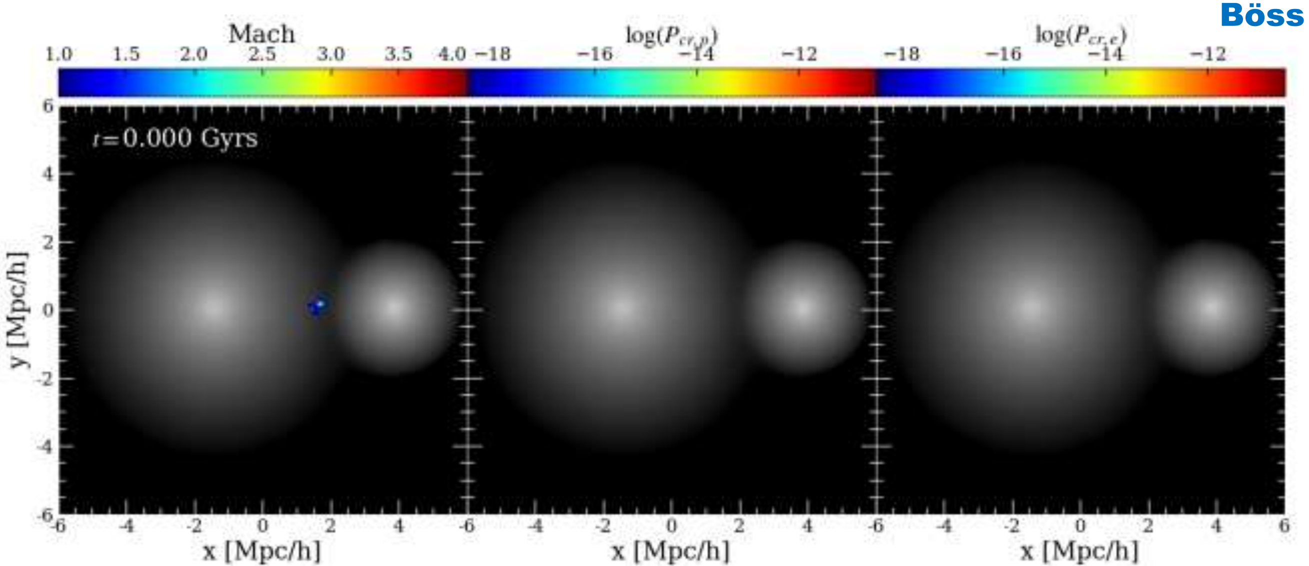




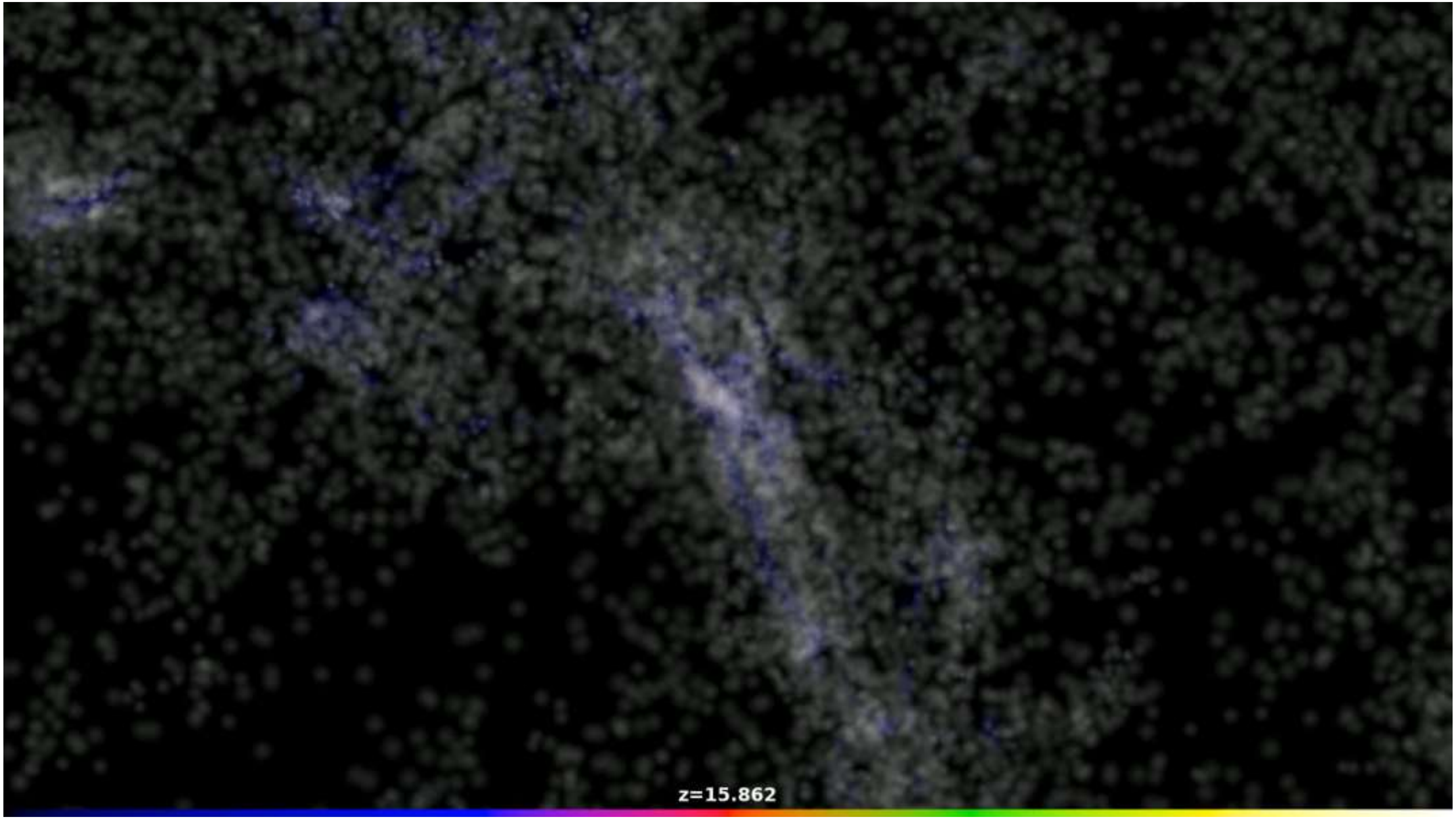
Shock injection

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

Böss et al. 2022



Simulating Galaxy Clusters and the ICM



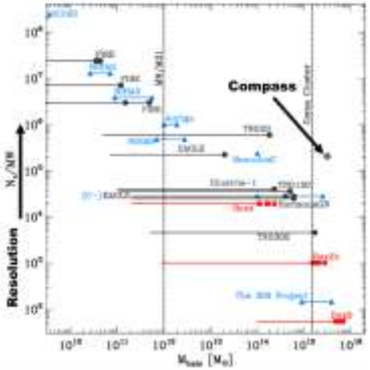
Mach number: 2 3 4 >5

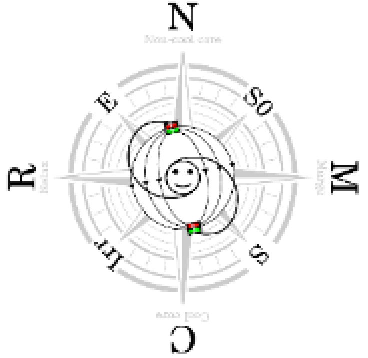
Galaxy Clusters:

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

almost 10^9 part in R_{vir}
~ 90.000 galaxies
~ 250.000 timesteps

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

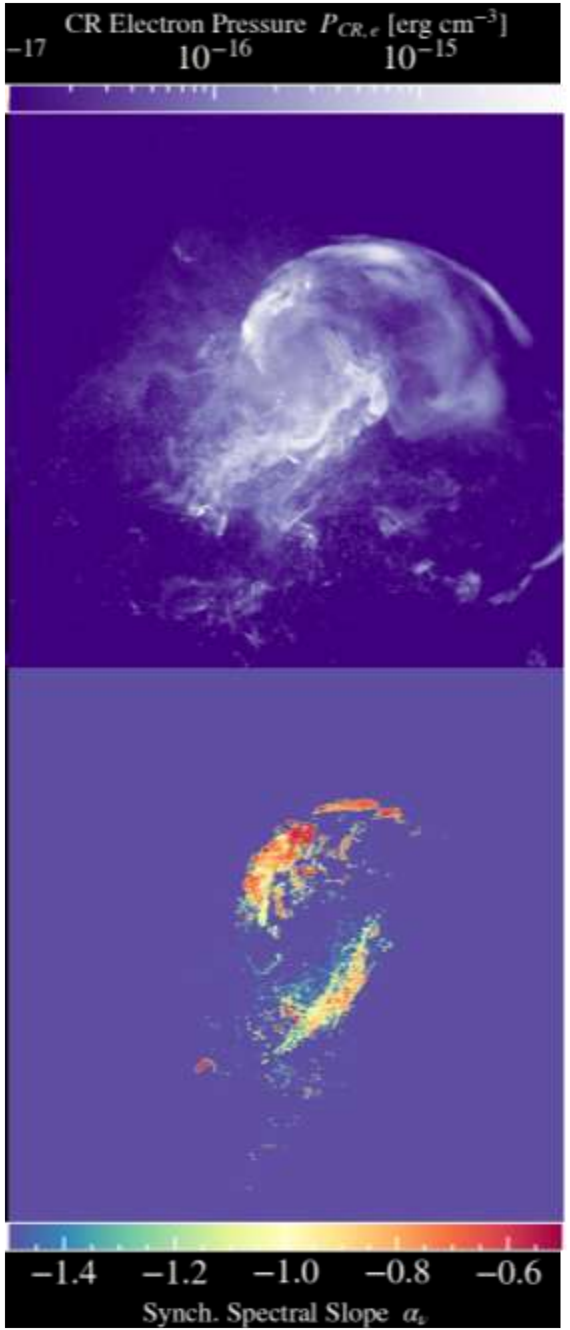




C·O·M·P·A·S·S

Radio Relics

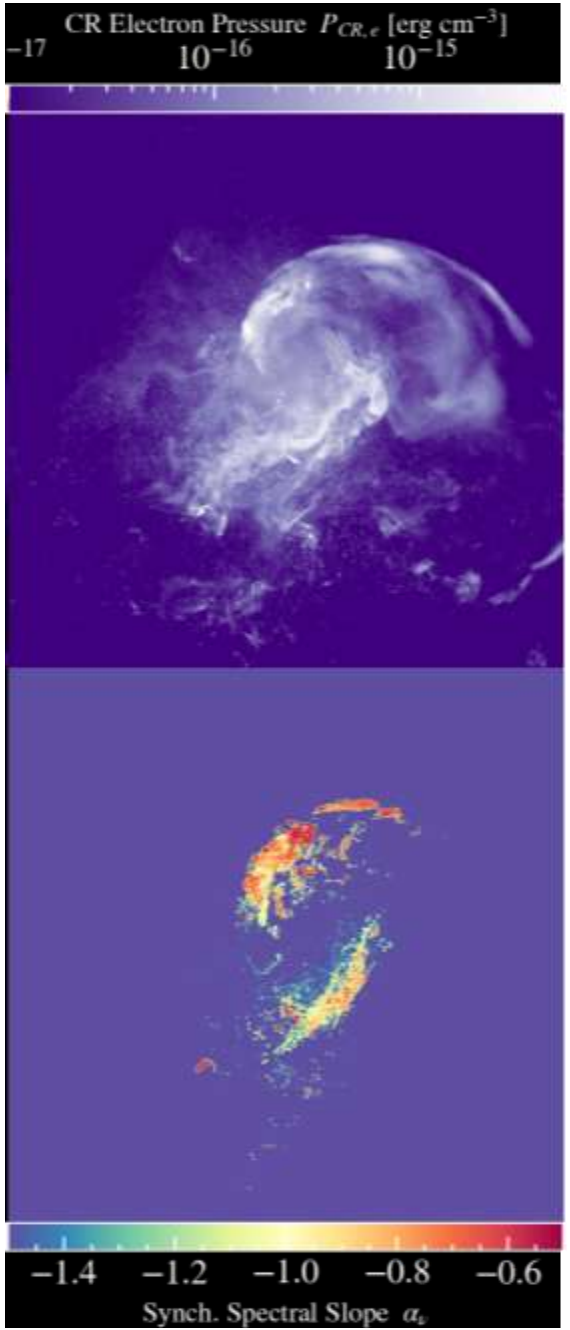

L. Böss



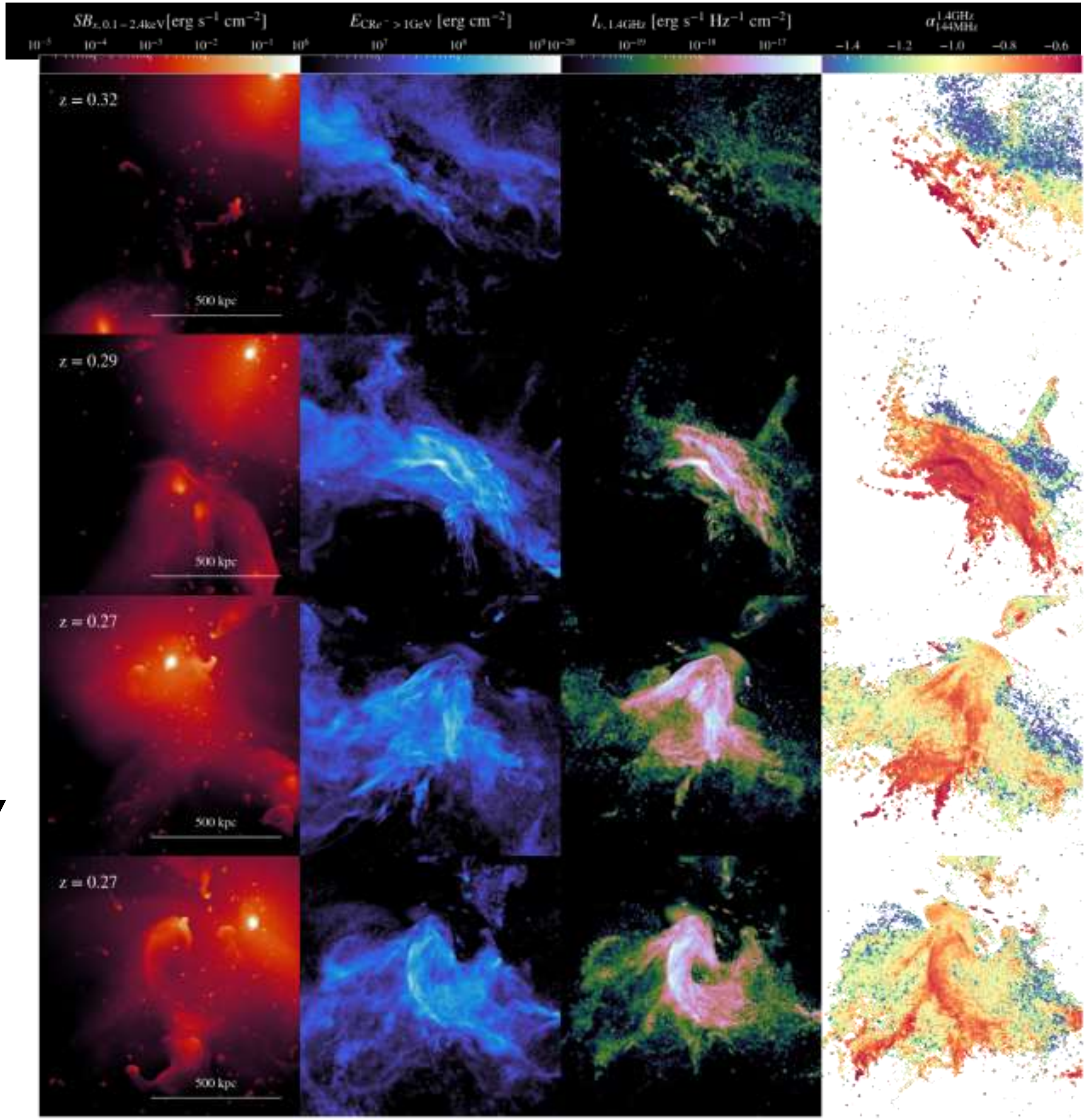
Böss+ 2024

Wrong way Radio Relics?

L. Böss



Time

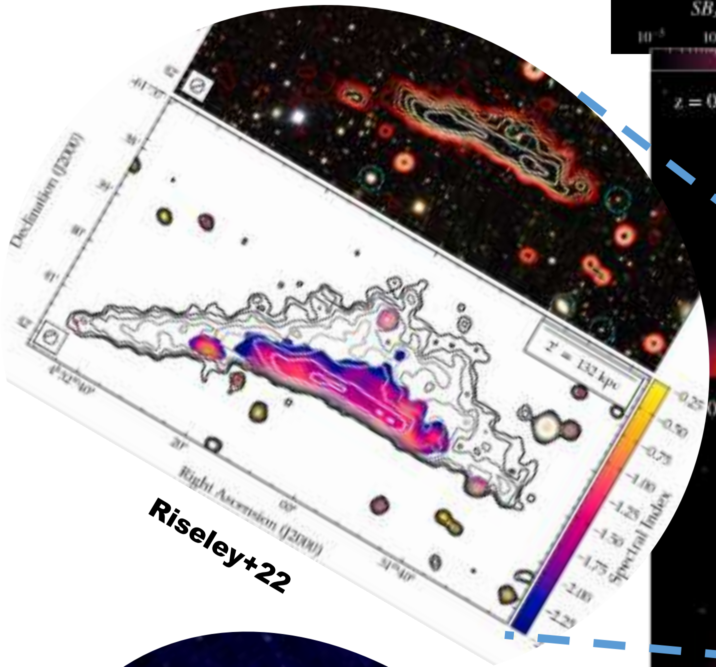


Rotation

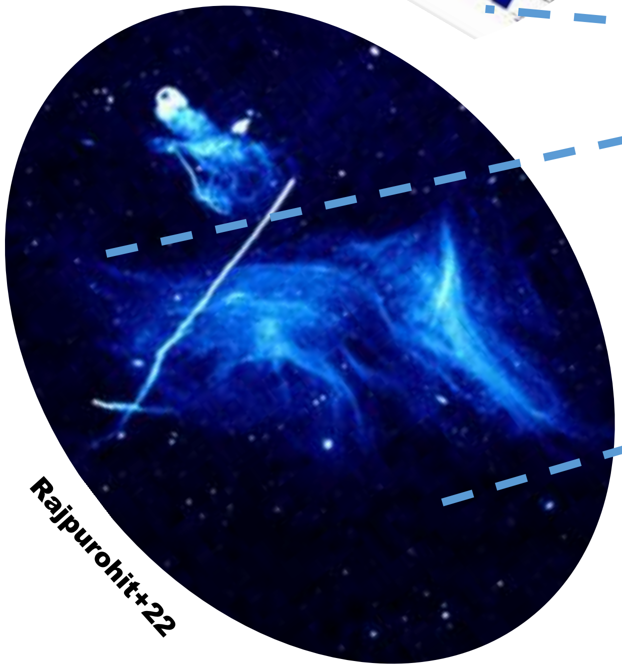
Böss+ 2024

Wrong way Radio Relics!

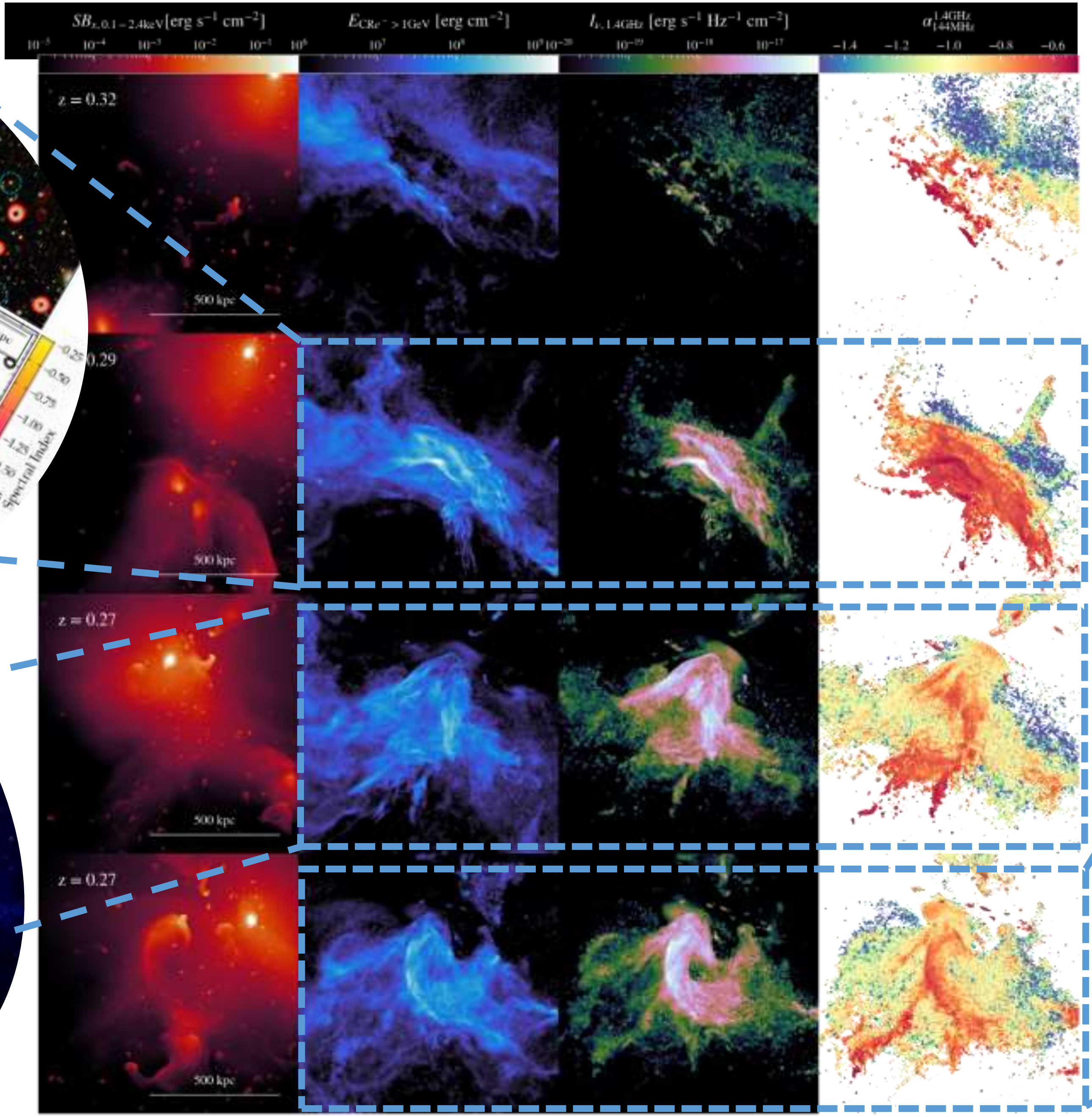
L. Böss



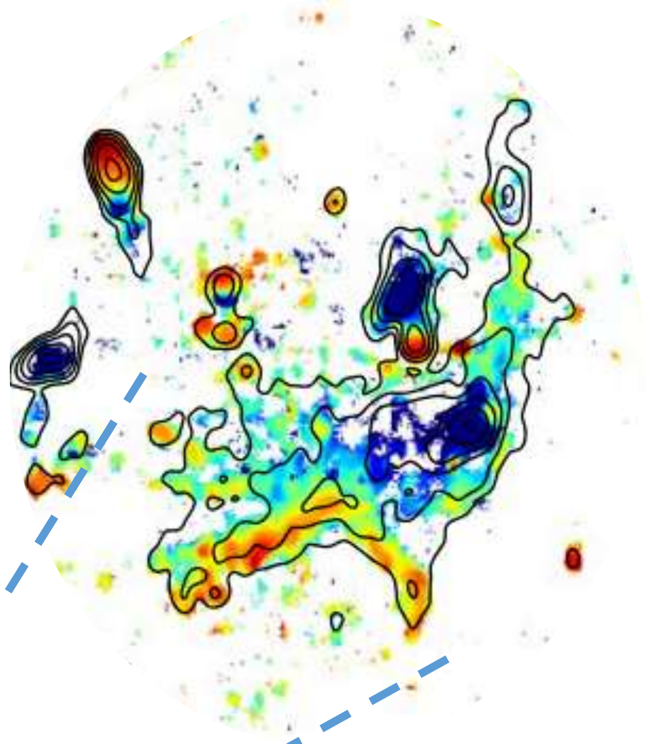
Riseley+22



Rajpurohit+22



Di Gennaro+18

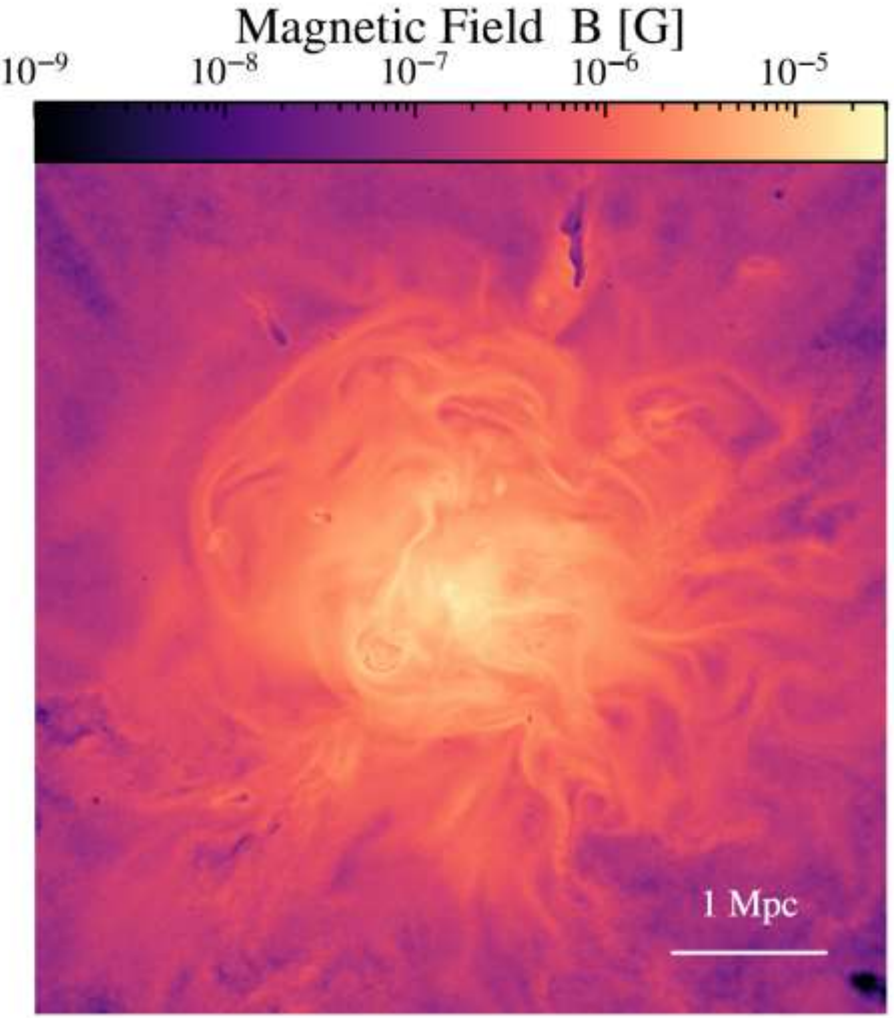


Böss+ 2024

Simulations of turbulent dynamo in the ICM

U. Steinwandel

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



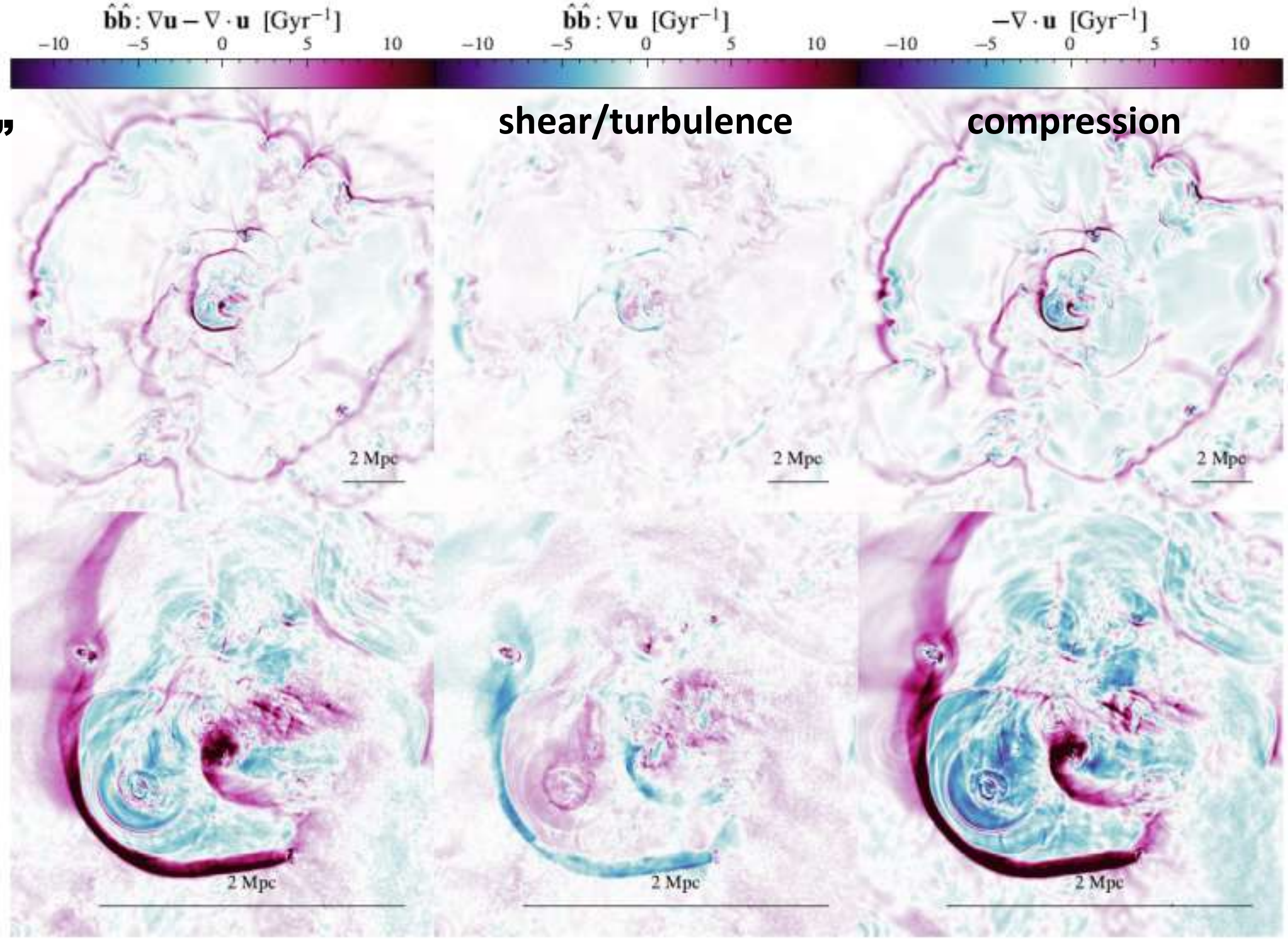


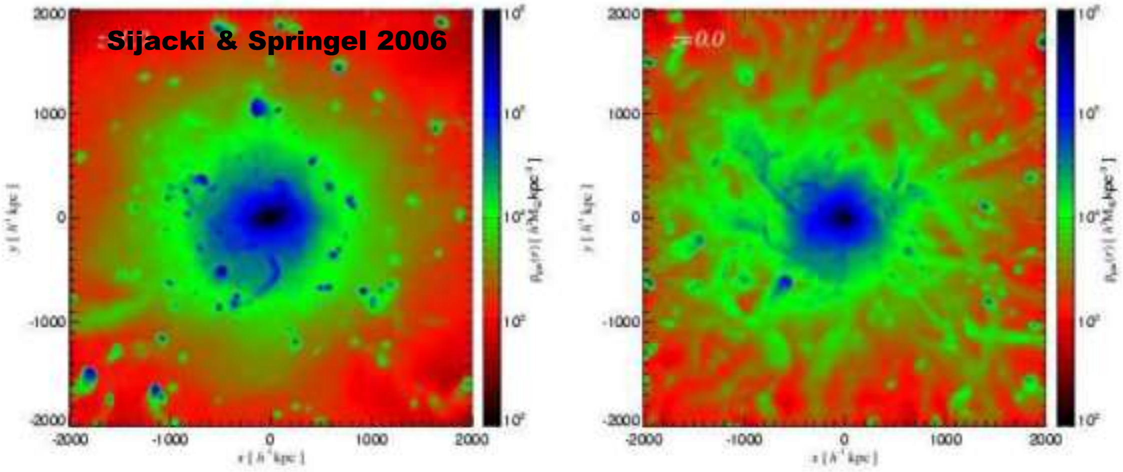
Figure 10. Total rate of change of the magnetic field (left), shearing/turbulent rate of change of the magnetic field (center), and compressive rate of change of the magnetic field (right). The top row shows the whole simulation domain, while the bottom panel is focusing on the field structure around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

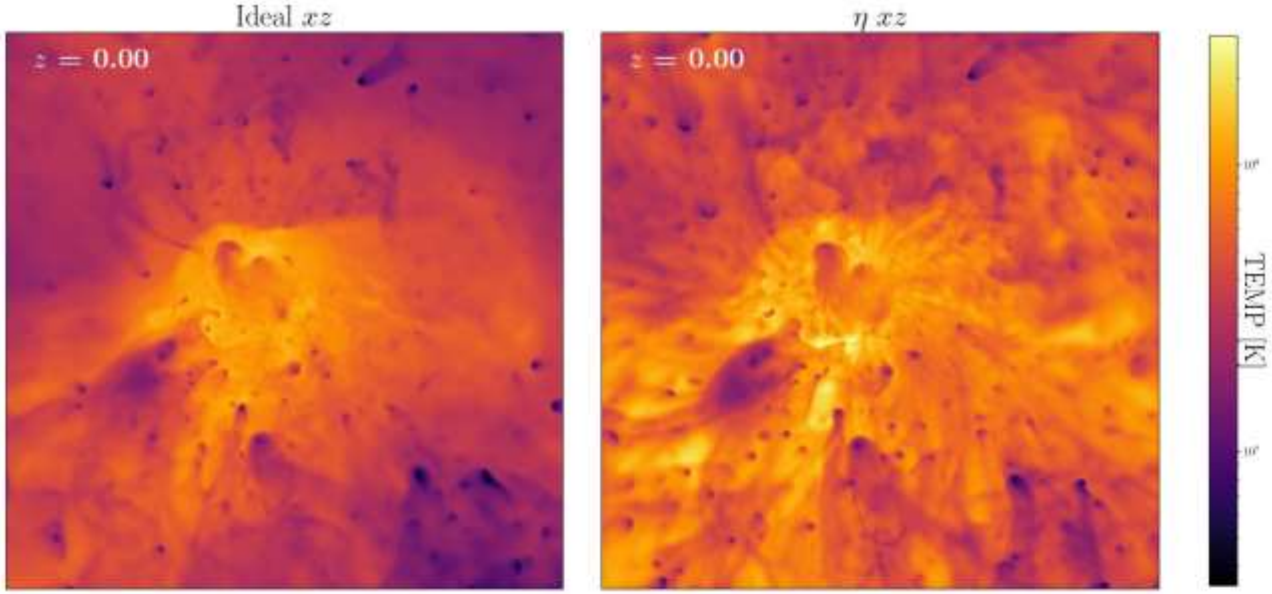
Steinwandel+ 2023

Towards Plasma Physics in the ICM

Plasma Physics: Essential for mixing and multiphase nature of ICM

Effect of viscosity?





Marin-Gilabert+ 2022/24

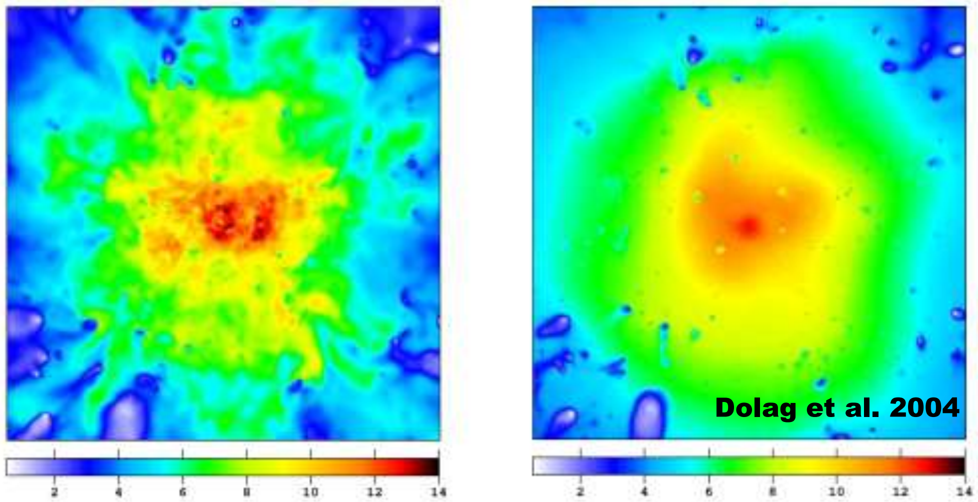
mach number → size of galaxies

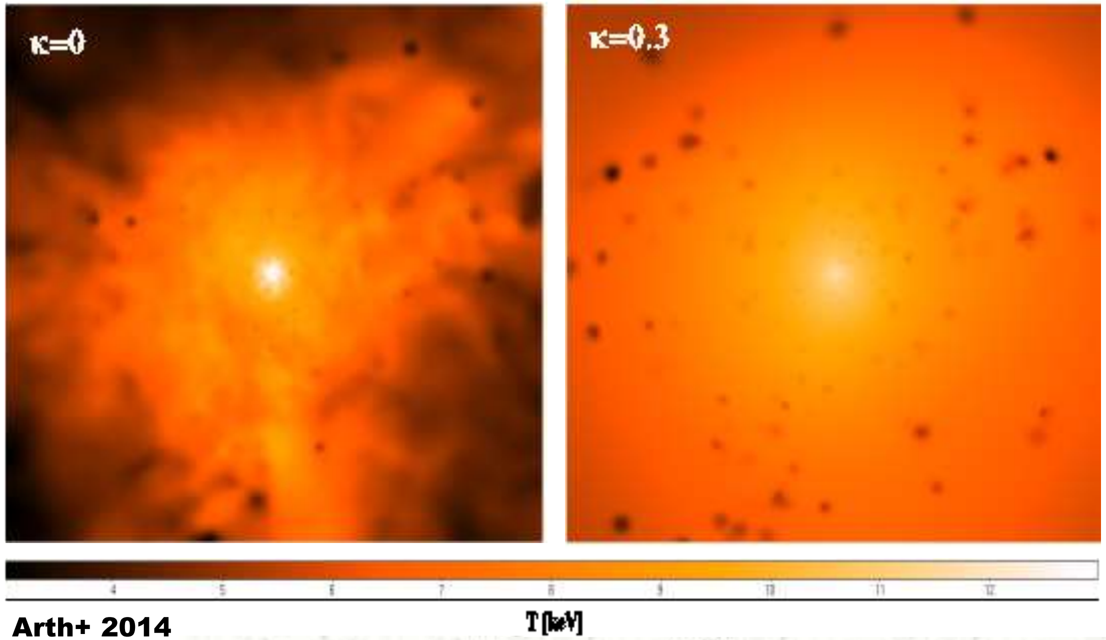
$Re \approx 3M\left(\frac{l}{\lambda_i}\right)$

$l \sim \lambda_i$!!!

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?

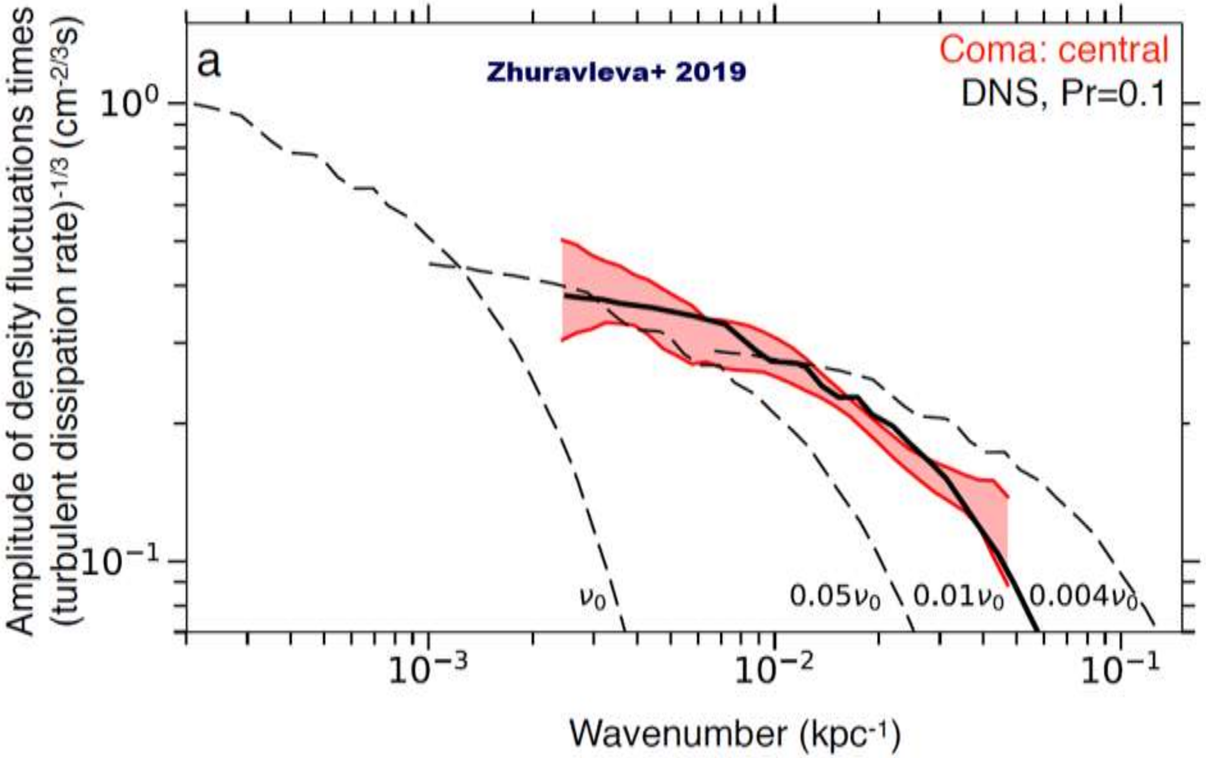




Arth+ 2014

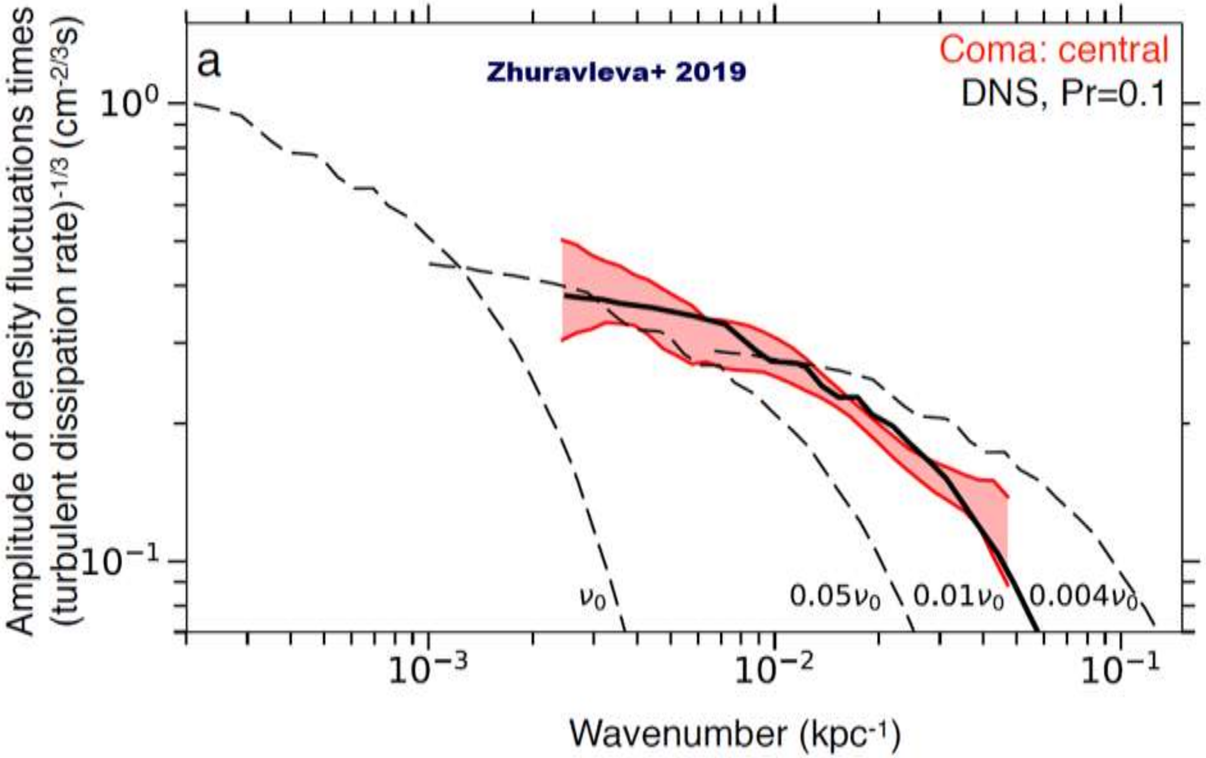
$$\kappa = 1.31 n_e \lambda_e k\left(\frac{kT_e}{m_e}\right)^{1/2} \approx 4.6\times10^{13}\left(\frac{T_e}{10^8\,\mathrm{K}}\right)^{5/2}\left(\frac{\ln\Lambda}{40}\right)^{-1} \mathrm{erg\,s^{-1}\,cm^{-1}\,K^{-1}}.$$

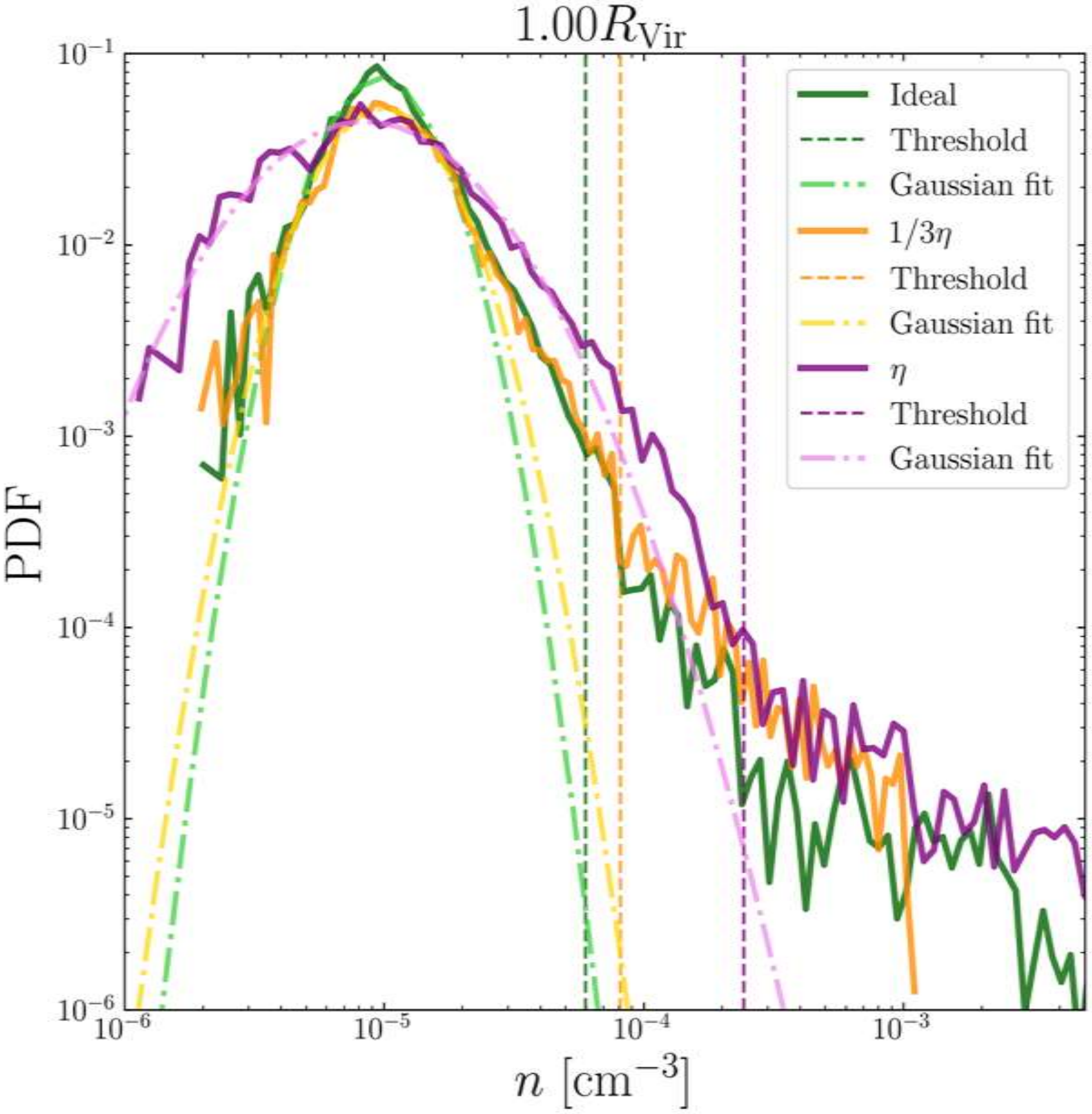
Density fluctuations to measure viscosity



Density fluctuations to measure viscosity

T. Marin

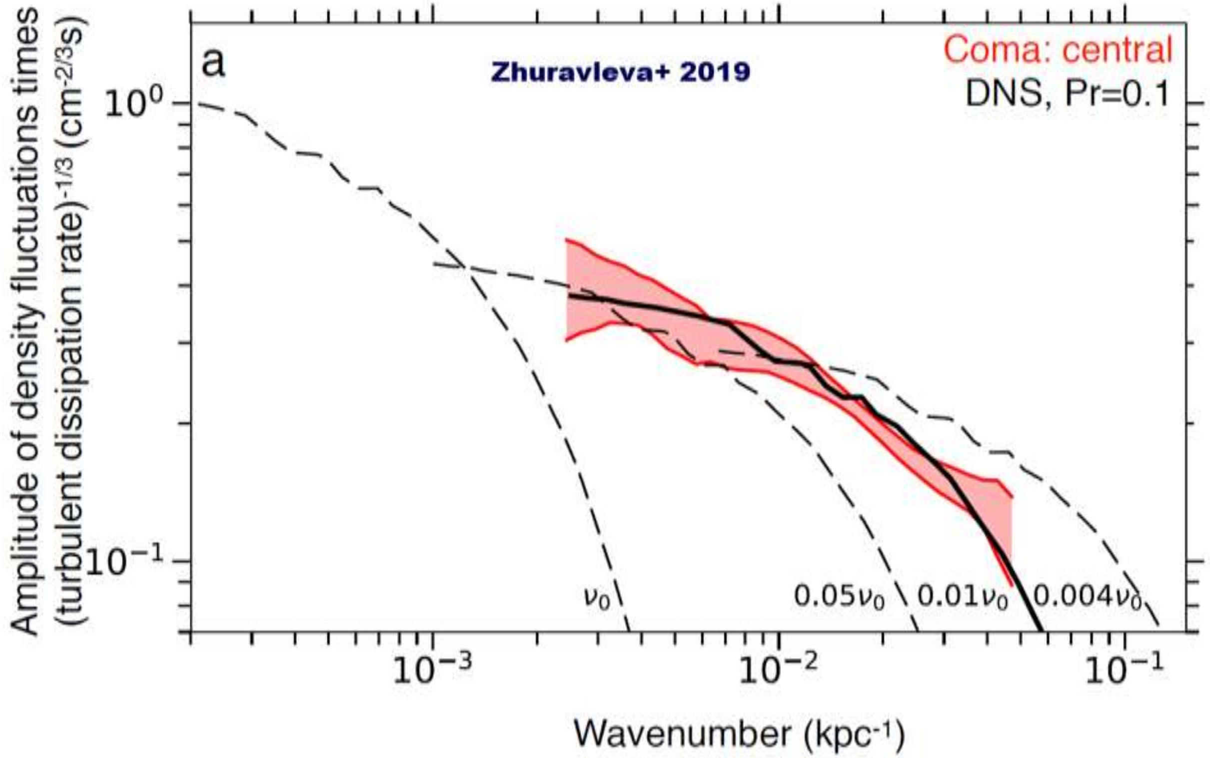


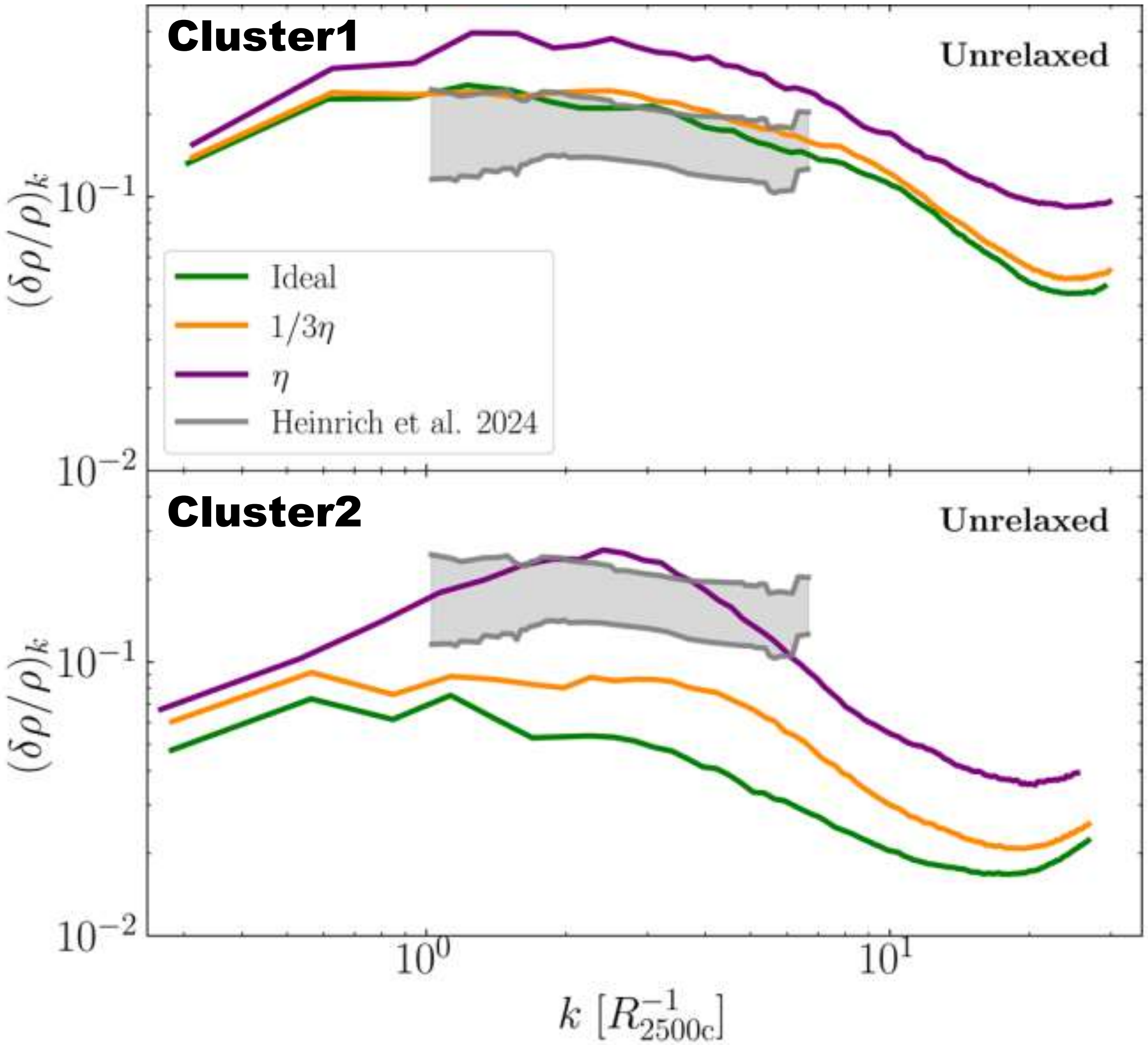


Marin-Glabert+ 2024

Density fluctuations to measure viscosity

T. Marin

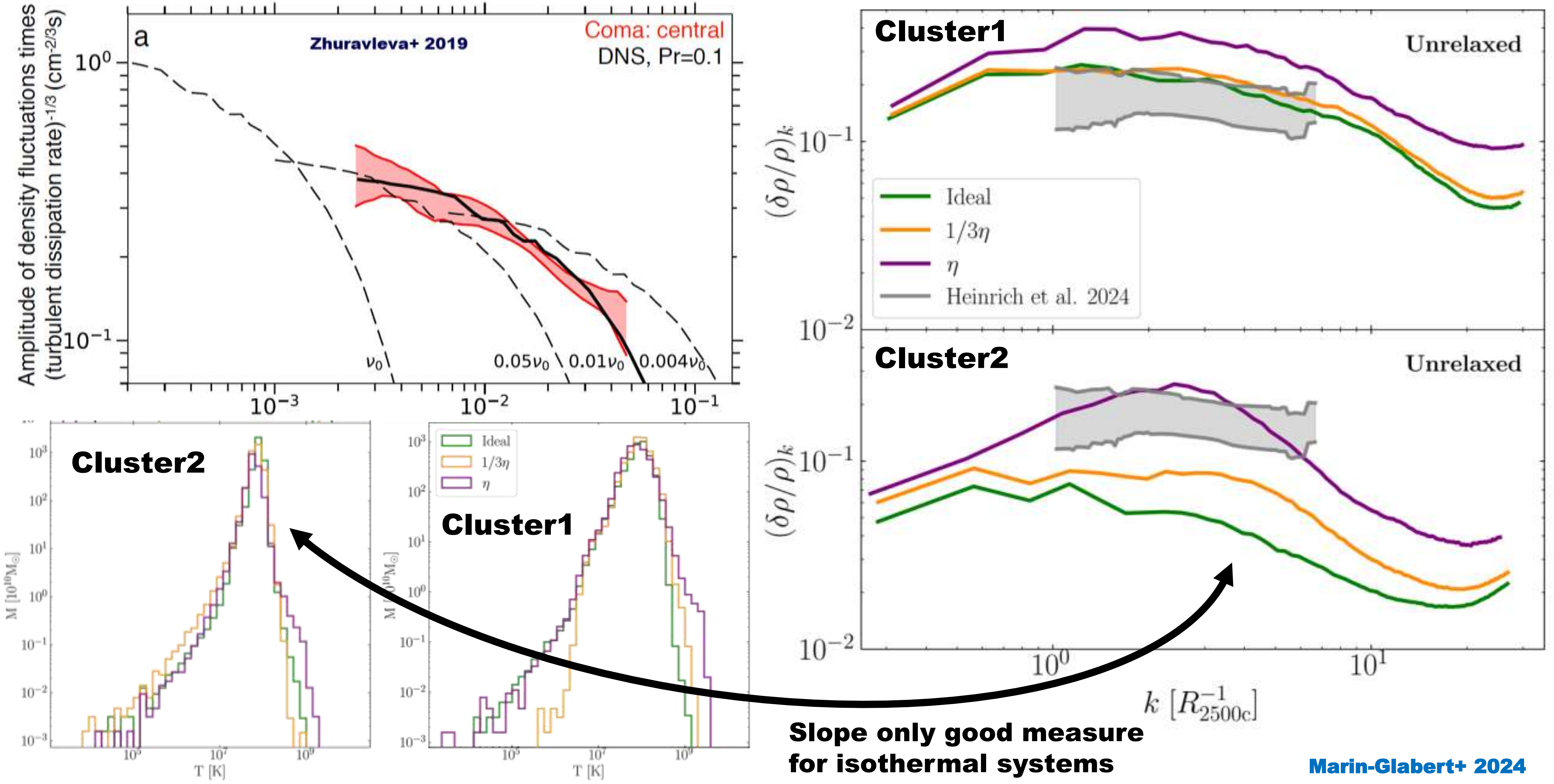




Marin-Glabert+ 2024

Density fluctuations to measure viscosity

T. Marin



Slope only good measure for isothermal systems

Marin-Glabert+ 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

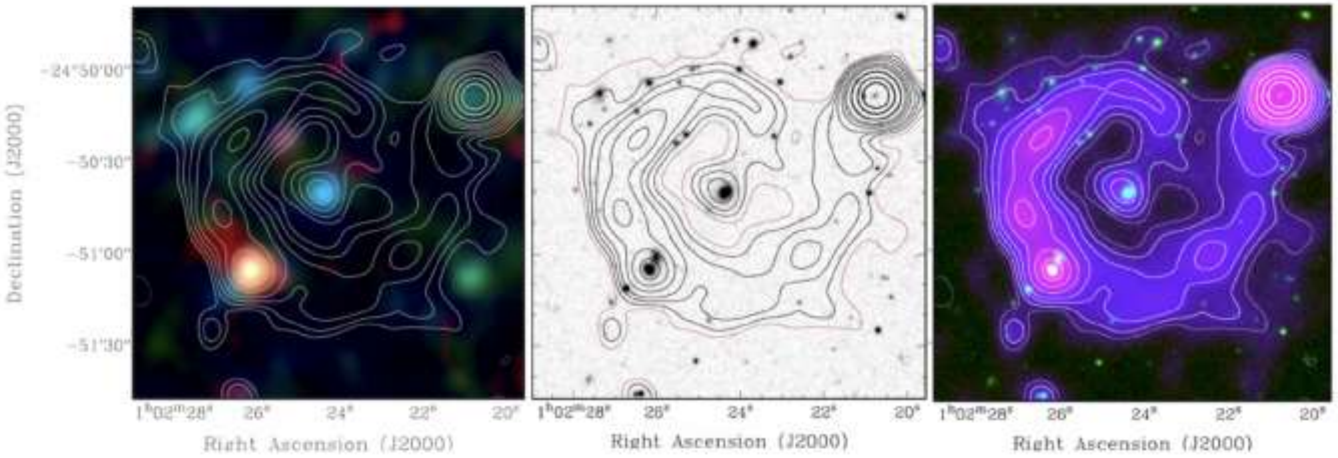


Figure 2. ASKAP radio continuum contours of ORC J0102–2450 overlaid onto a WISE RGB colour image (red: 12μm (W3), green: 4.6μm (W2), and 3.4μm (W1)

source name		discovery telescope	central host galaxy	galaxy redshift	ring diameter [arcsec]	ring diameter [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!

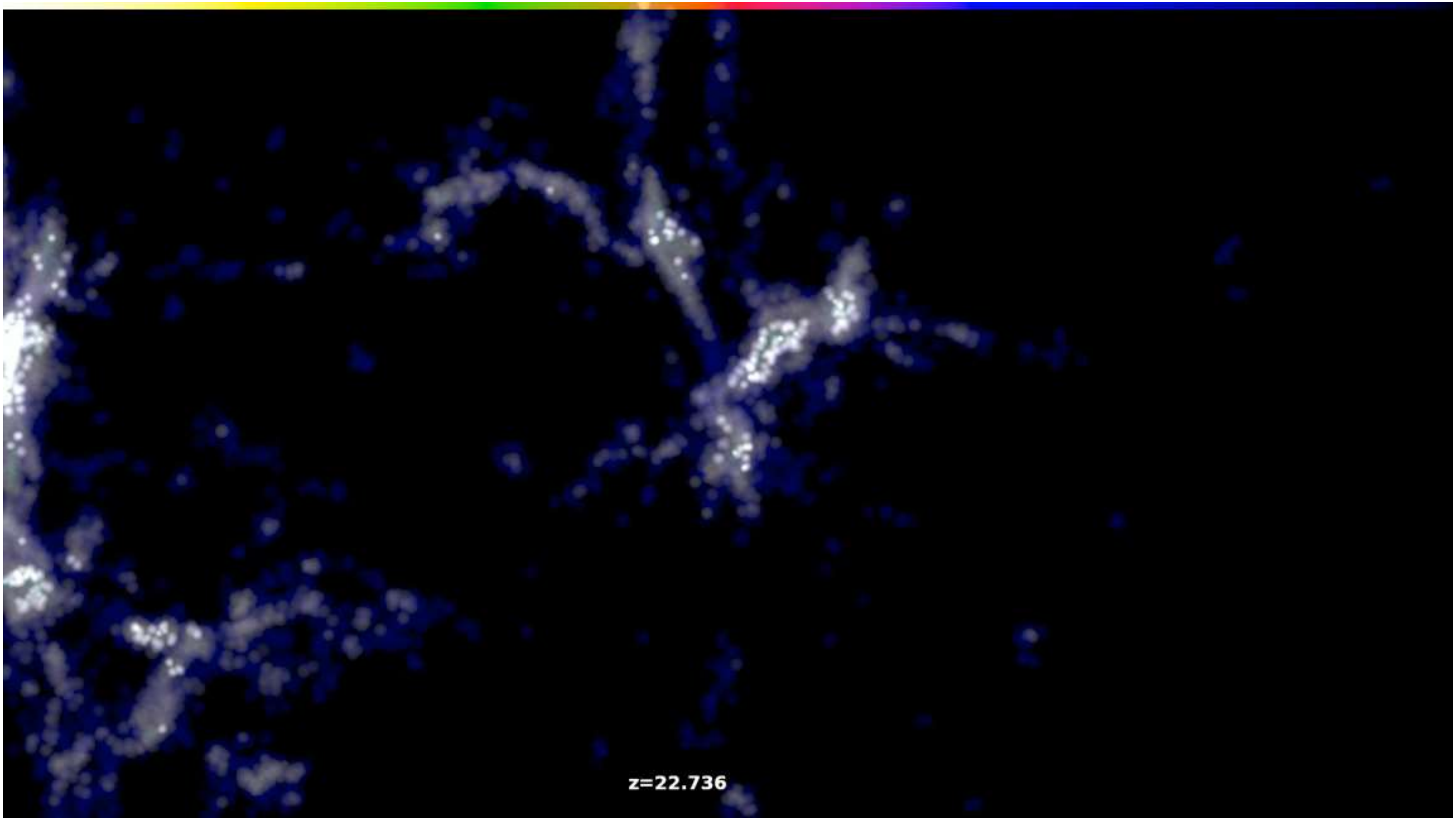
Suggested to be AGN or star-burst winds, but could be just merger shocks ?

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

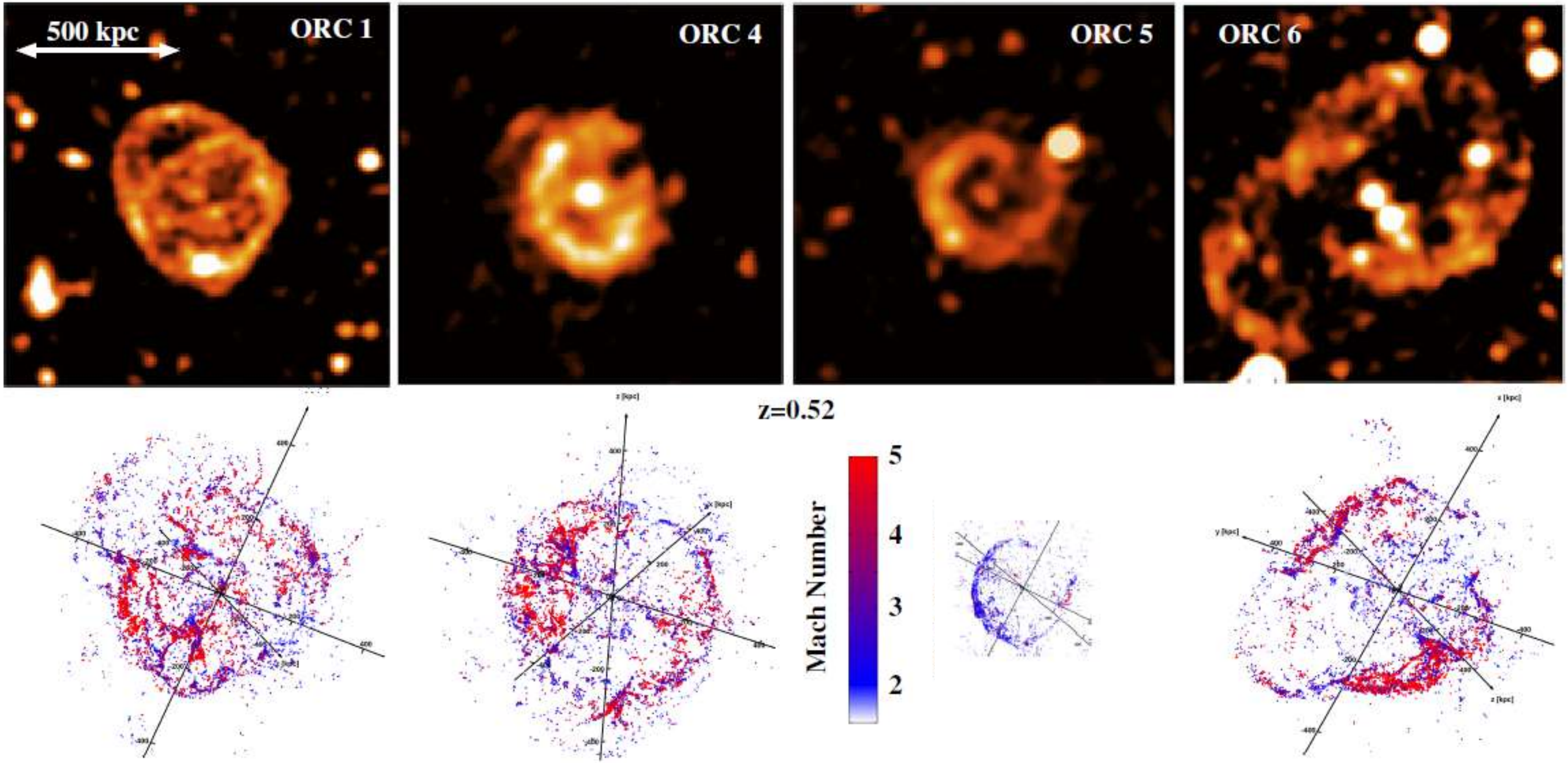
ORC 1 ORC 4 ORC 5

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

Shocks in the simulated galaxy

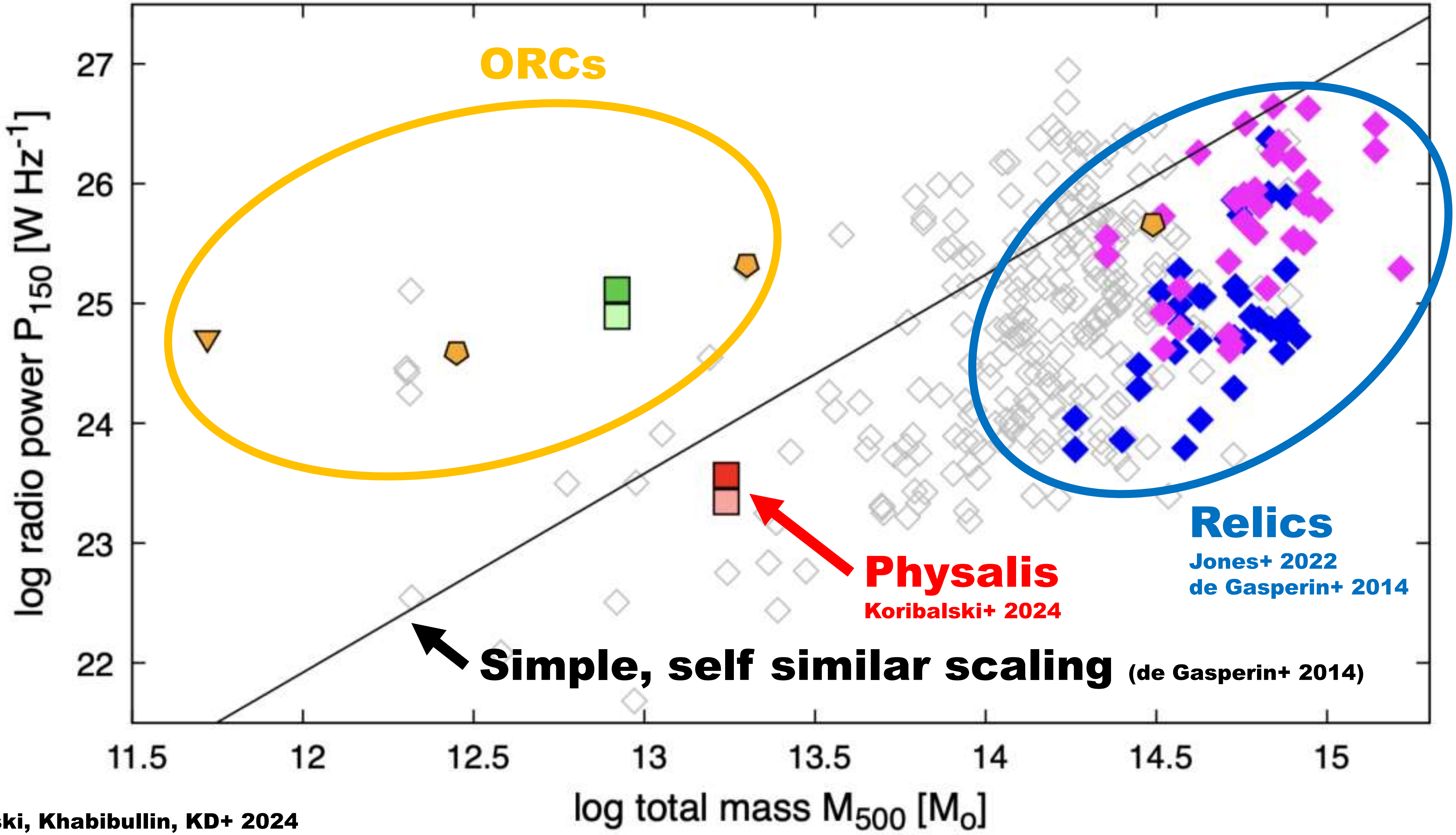


Shock structures are matching the observed ORCs



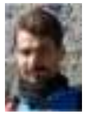
KD+ 2022

Shock structures linking galaxy clusters to galaxies



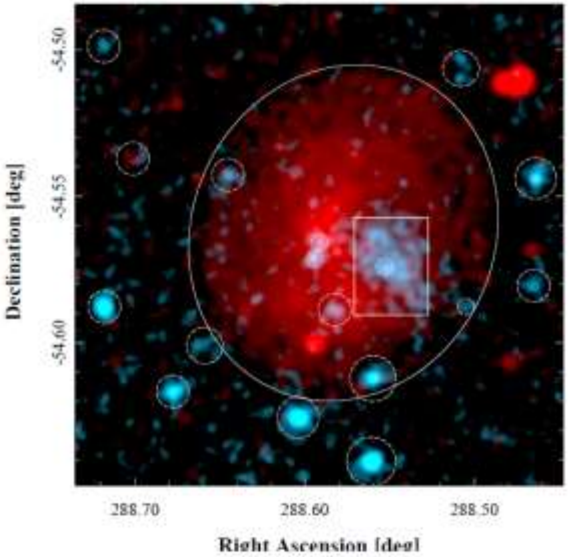
Koribalski, Khabibullin, KD+ 2024

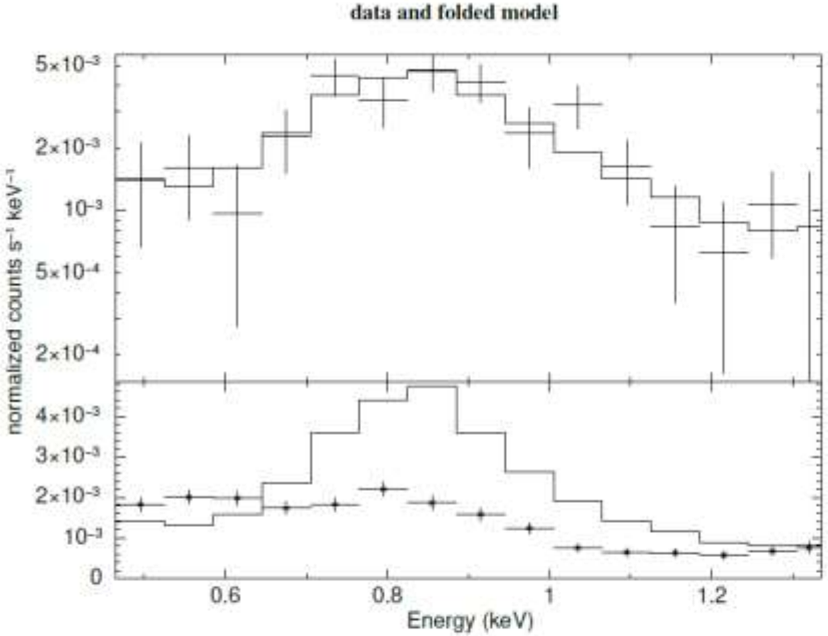
The Physalis system, an early stage of an ORC?



I. Khabibullin

ASKAP / XMM





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}

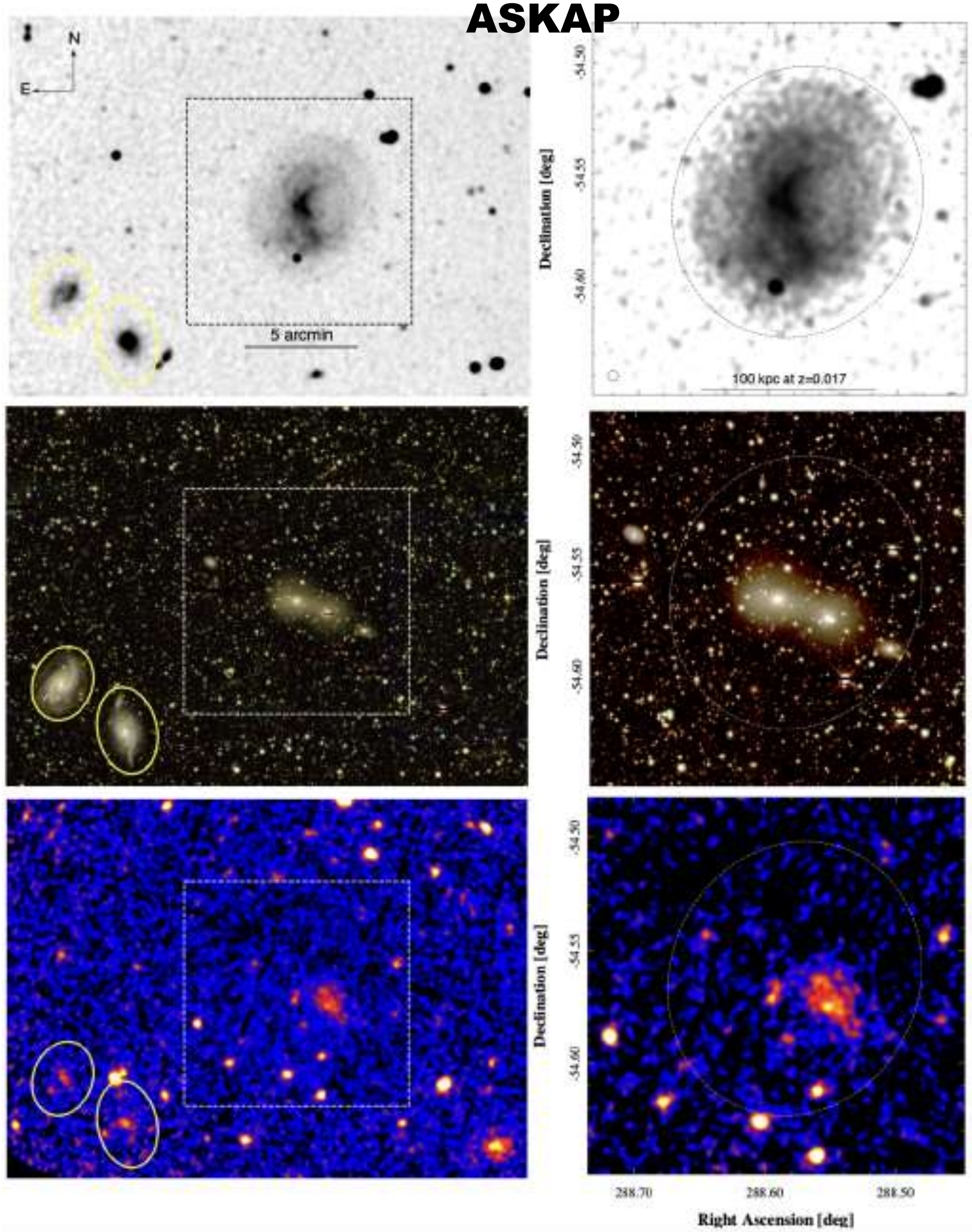
$E_{tot} \sim 2\times10^{59}$ erg ← **Energy involved**

$t_{cool} \sim 4\times10^{8}$ yr ← **Timescale involved**

ASKAP

DESI

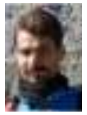
XMM



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

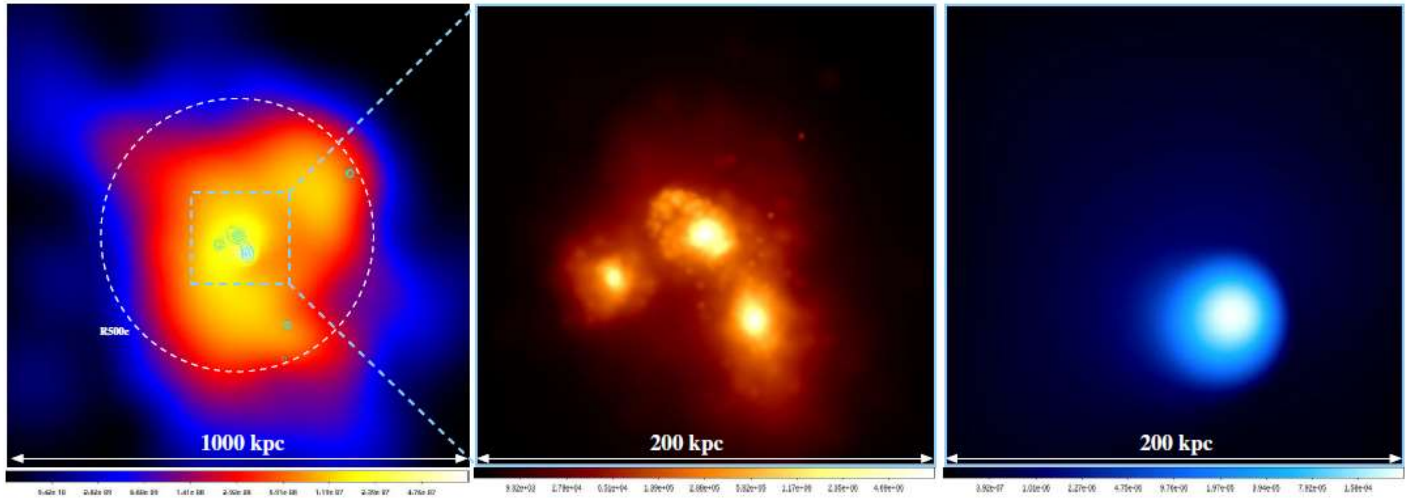
Magneticum Box2b/hr (640 h^{-1}cMpc)
$10^{13} < M_{vir} < 3x10^{13}$
-> ~26000 haloes

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

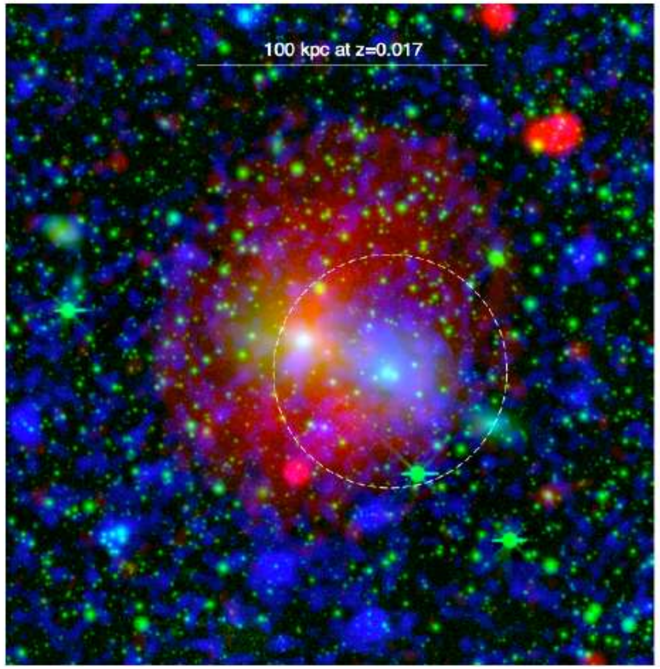
-> 10 Haloes

Closer inspection, only 1 Halo shows a good match:

SZ **K-Band** **X-ray**



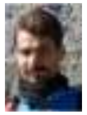
ASKAP / XMM / DESI



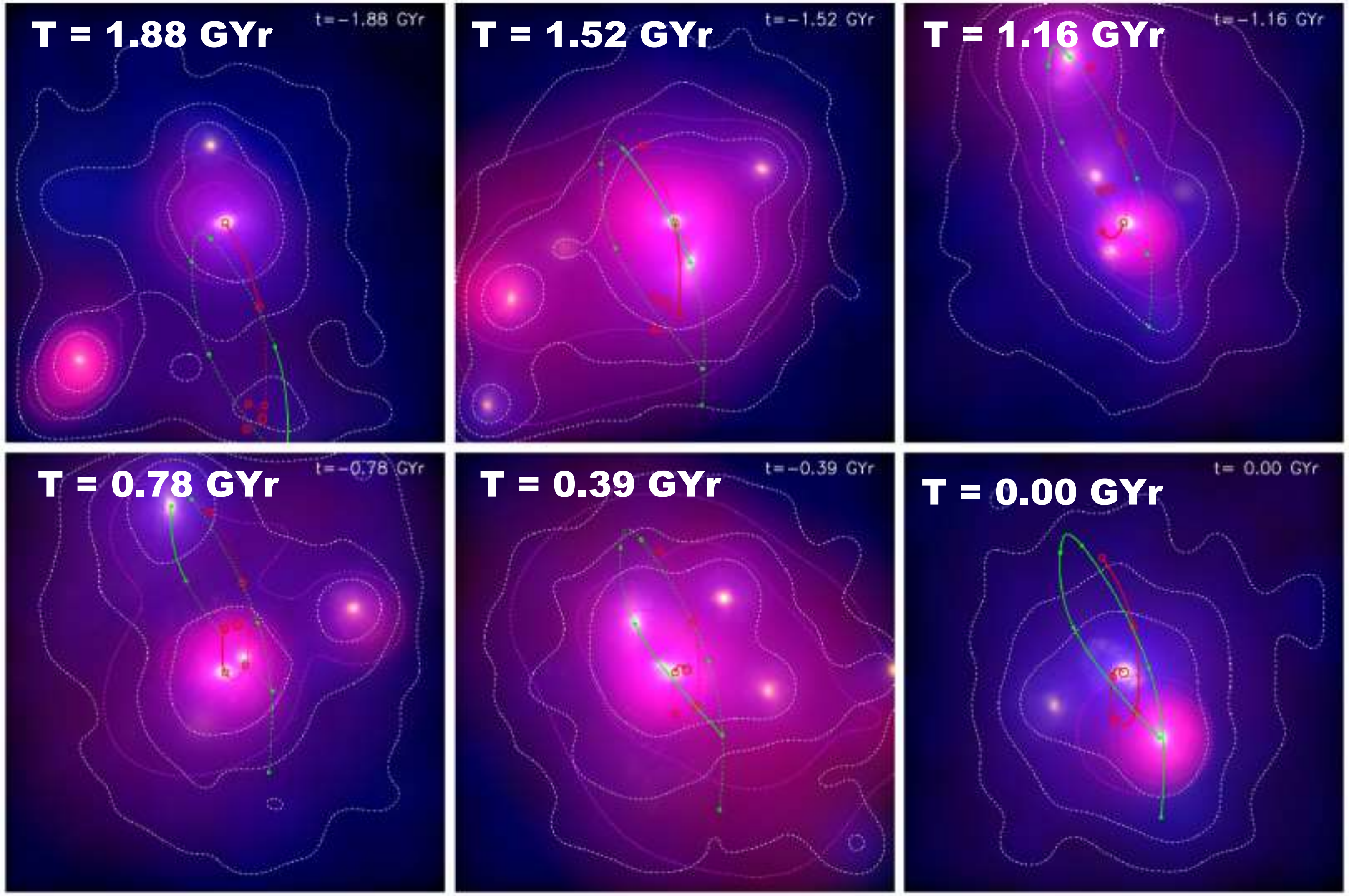
ESO 184-G042 and LEDA 418116
D = 75 Mpc (z = 0.017)
log stellar mass [$M_\odot$] ~ 11.1 and 10.7
$P_{th} \approx 3 \times 10^{-12}$ erg cm^{-3}
$E_{tot} \sim 2 \times 10^{59}$ erg
$t_{cool} \sim 4 \times 10^{8}$ yr

Koribalski, Khabibullin, KD+ 2024

The Physalis system, what to learn from it?



I. Khabibullin

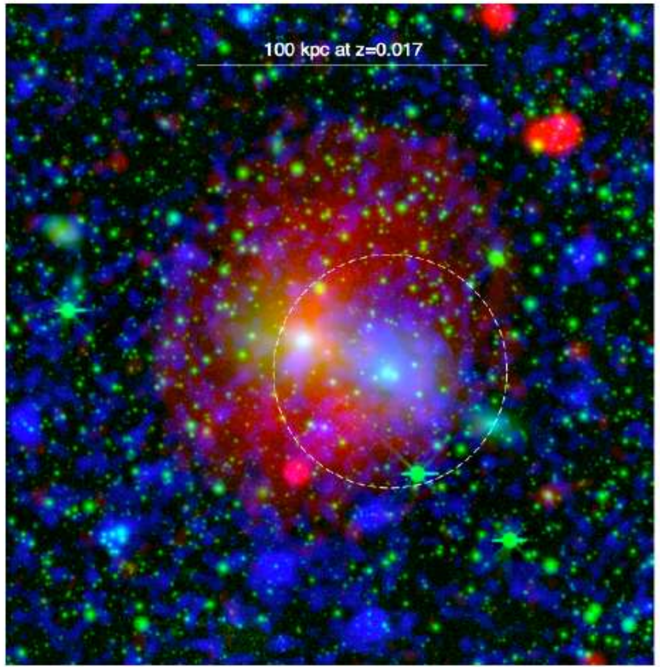


DM (blue)

X-ray (red)

SDSS-K (white)

ASKAP / XMM / DESI



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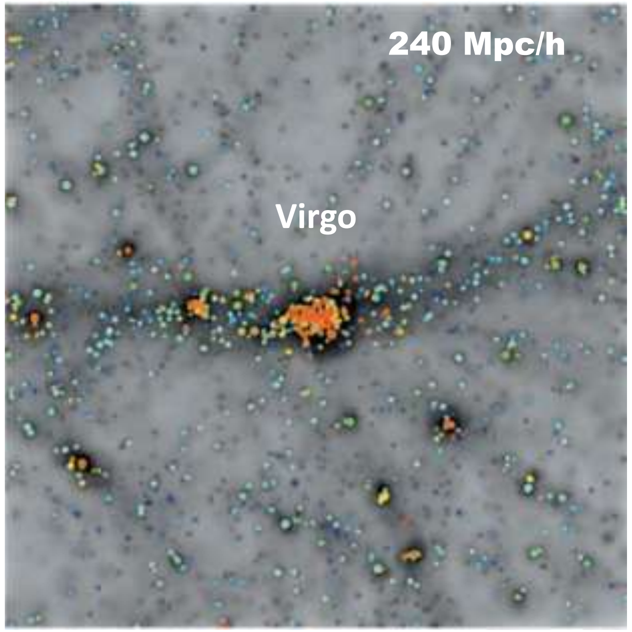
In the last 0.49 GYr the BH grows (by accretion) significantly ~$10^8 M_\odot$, releasing an energy of 10^{59} erg and displaces the IGrM from the radio emitting region showing that AGN and shocks could produce ORCs!

Koribalski, Khabibullin, KD+ 2024

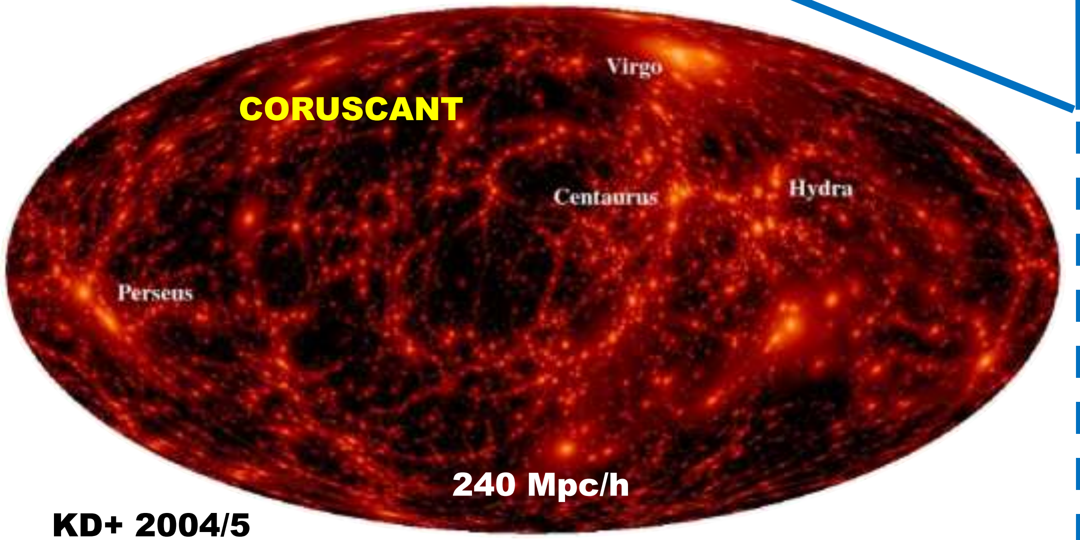
Towards a the Local Universe Lab

Local Universe Simulations

Density based (redshift surveys)

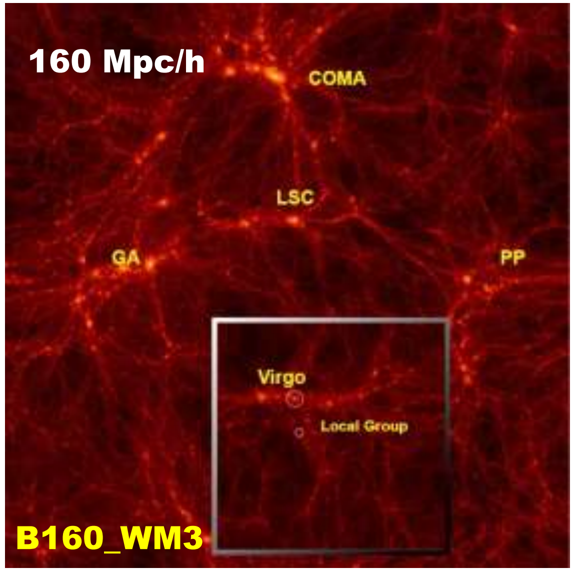


Mathis+ 2002



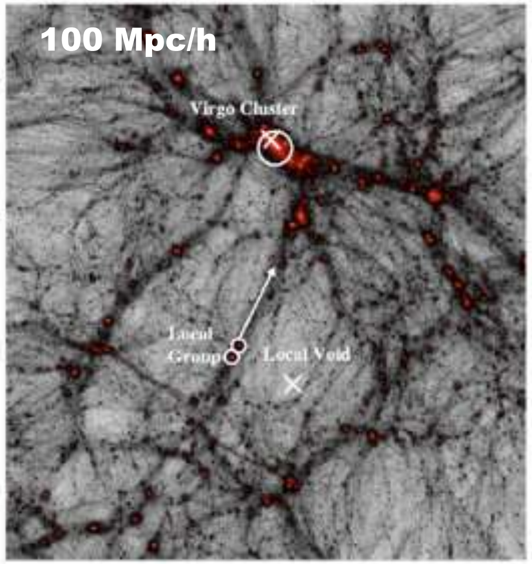
KD+ 2004/5

Hybrid approach

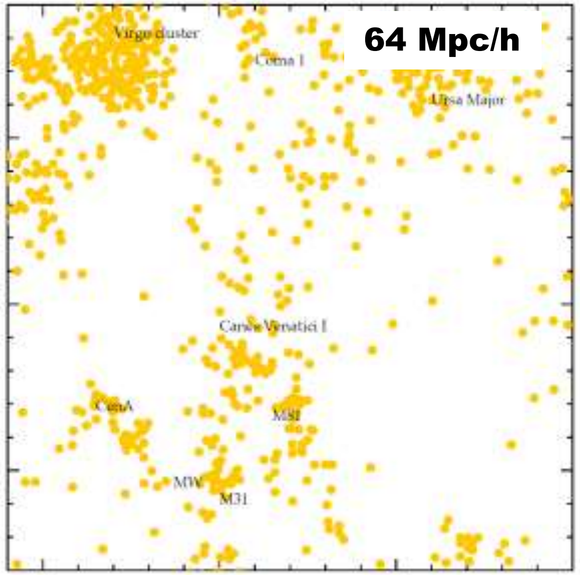


Klypin+ 2003 / Gottlöber+ 2010

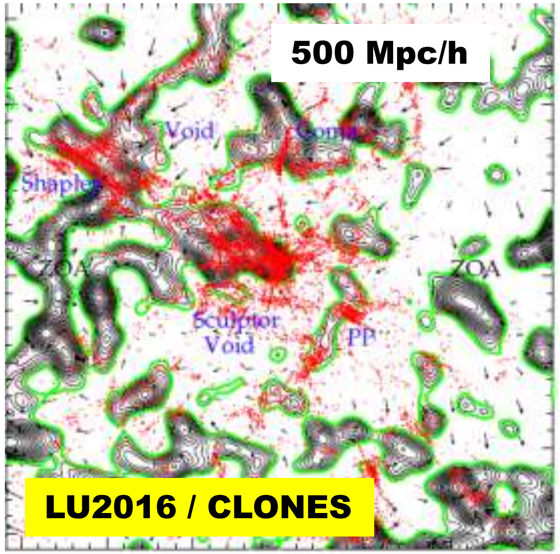
Velocity based
(peculiar velocity derived from distance measures)



Liebeskind+ 2016+



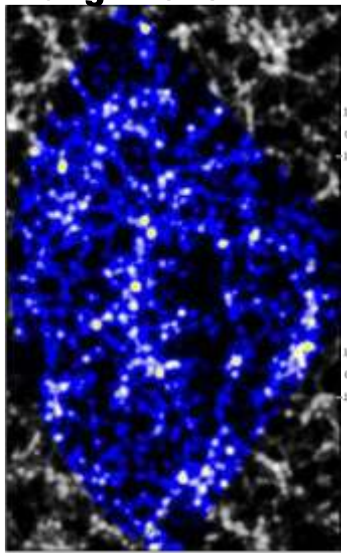
Ocvirk+ 2020, Sorce+ 2022

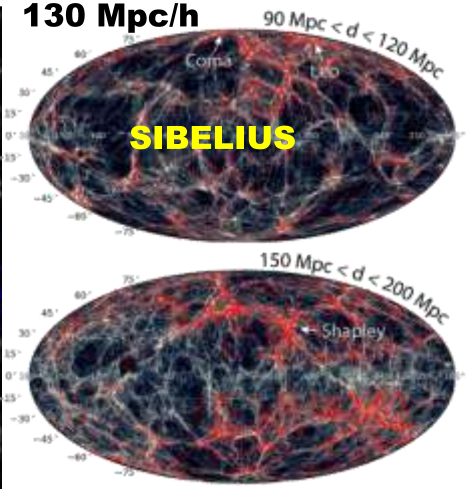


Sorce 2016, 2018

Bayesian forward modelling

Wang+ 2016

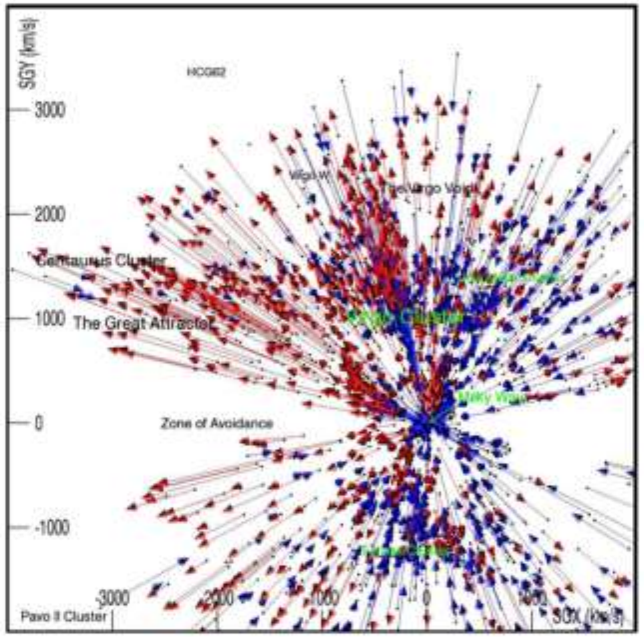


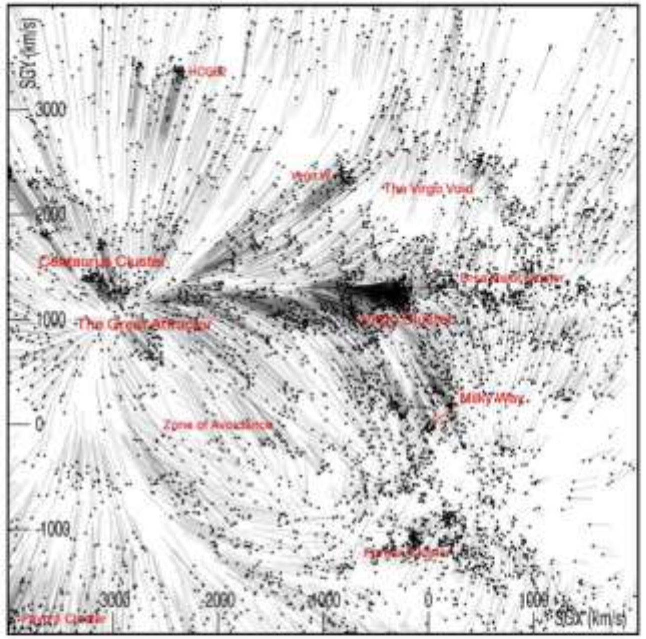


McAlpine 2022

Some details what is done for ICs

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



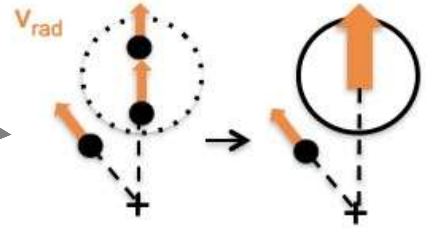


Method

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

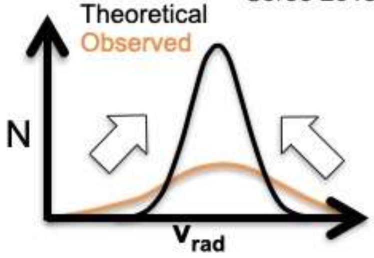
Sorce & Tempel 2017,2018

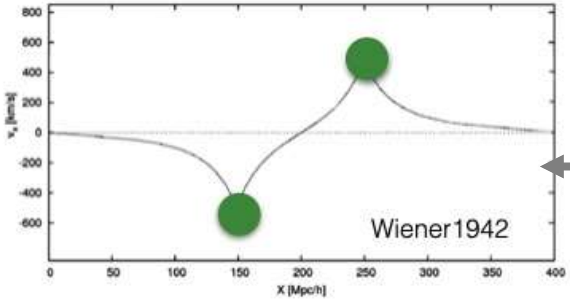
Obtaining linear component of the velocity field.



Sorce 2015, 2018

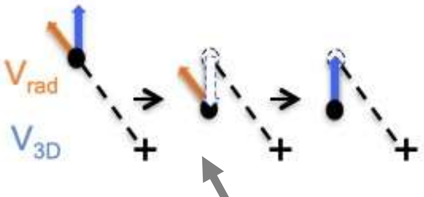
Bias minimization
Malmquist bias & lognormal errors



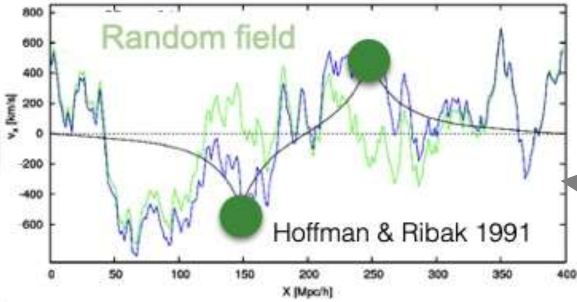


Reconstruct the displacement field

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:

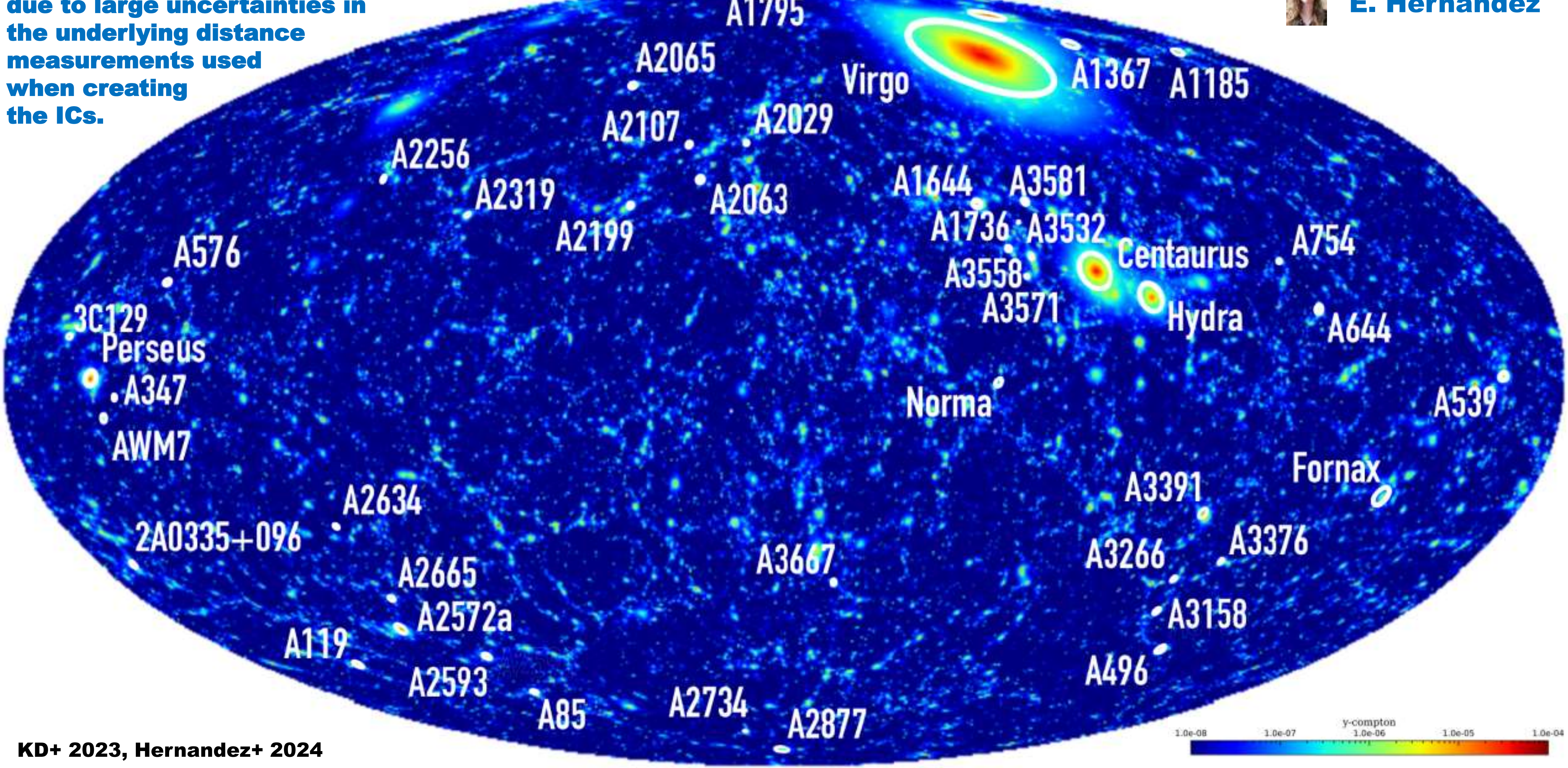
- **$2x1536^3$ full galaxy formation physics, including AGN (AGN)**
- **$2x3072^3$ non radiative MHD with cosmic rays (MHD+CRs)**

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



KD+ 2023, Hernandez+ 2024

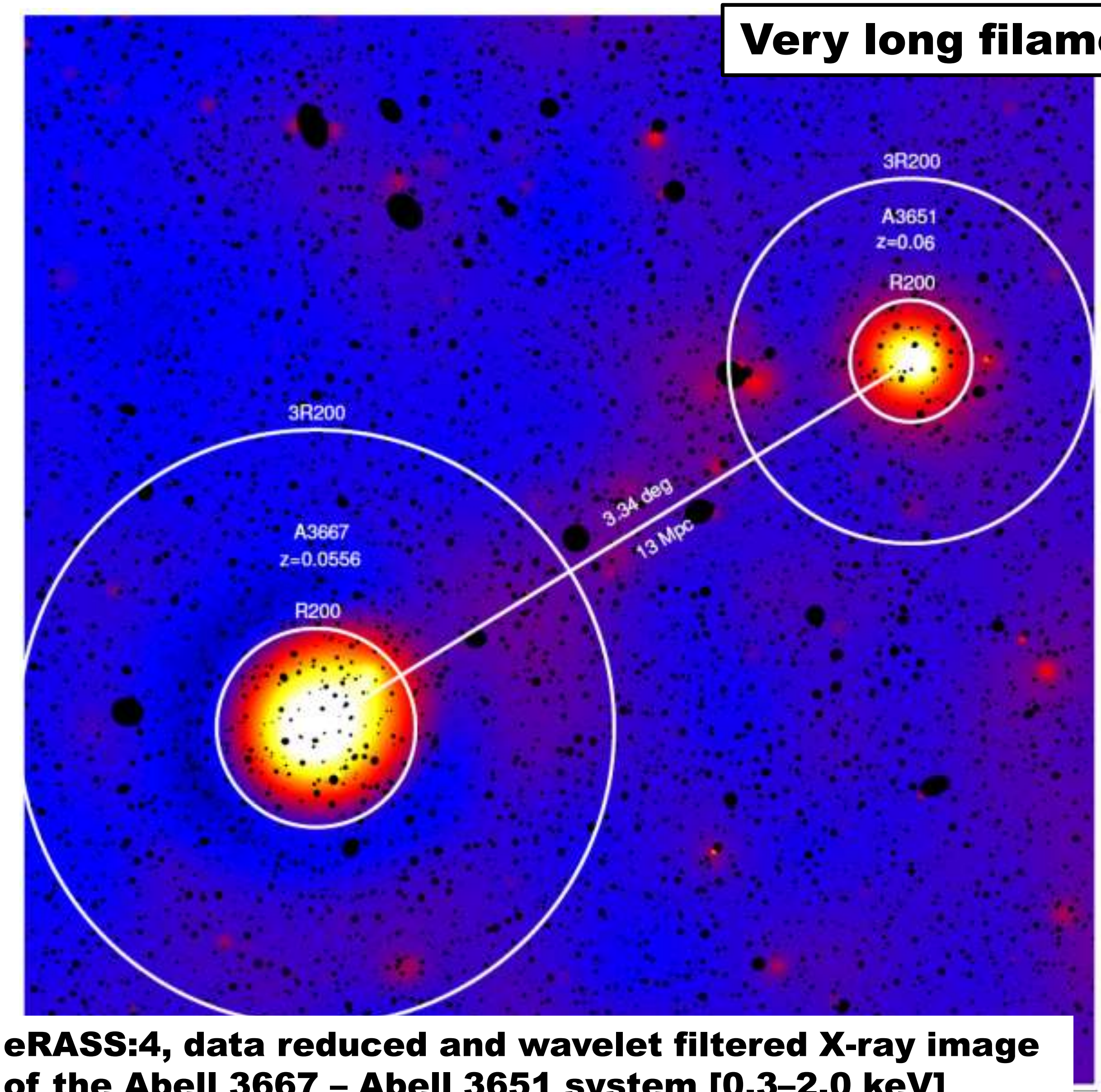
What can we learn?

An eROSITA filament with a counterpart in SLOW?

Filament between the cross identified clusters in SLOW

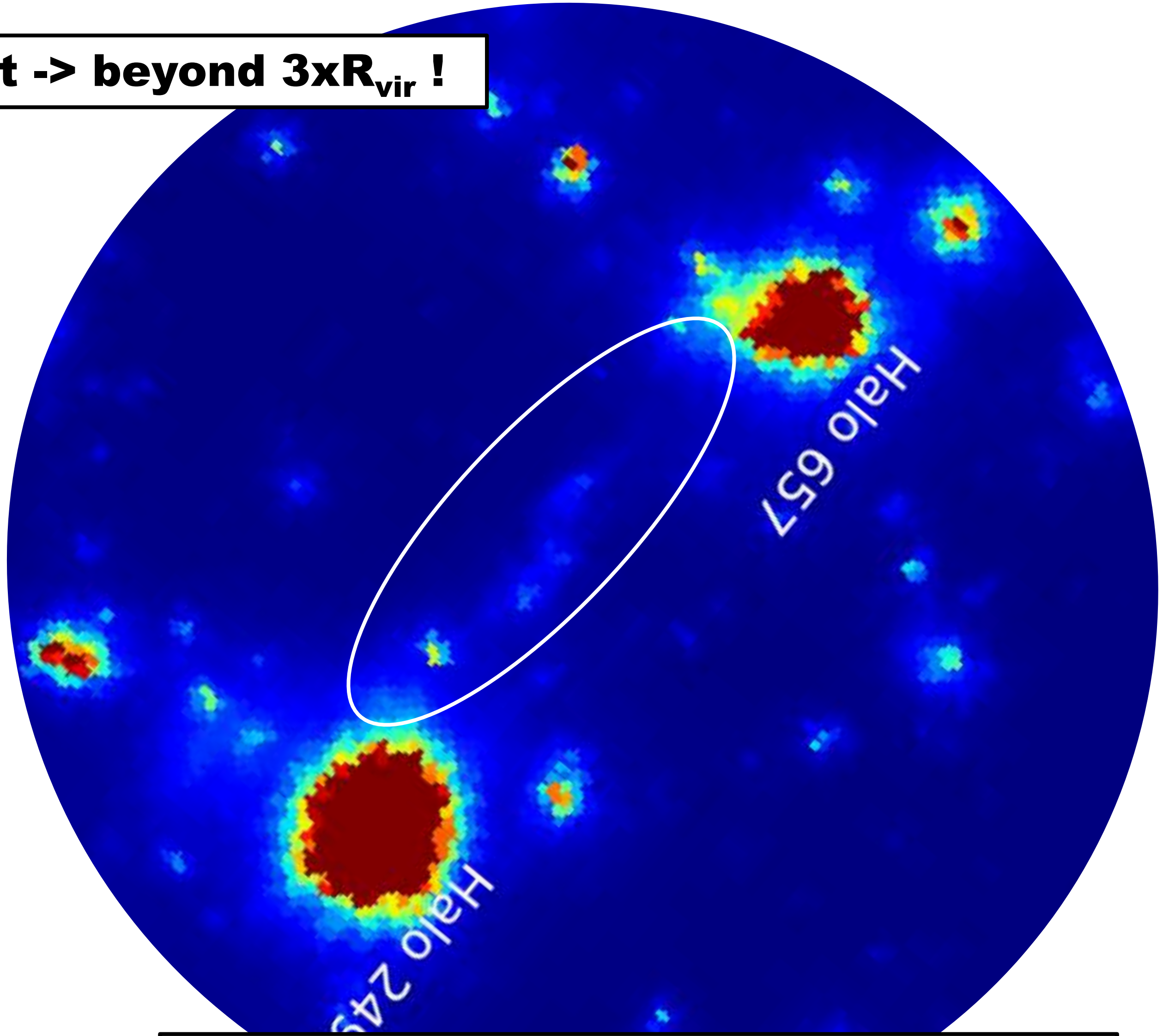
B. Seidel

Very long filament -> beyond $3xR_{vir}$!



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!**

Now we can finally test Plasma Physics (?)

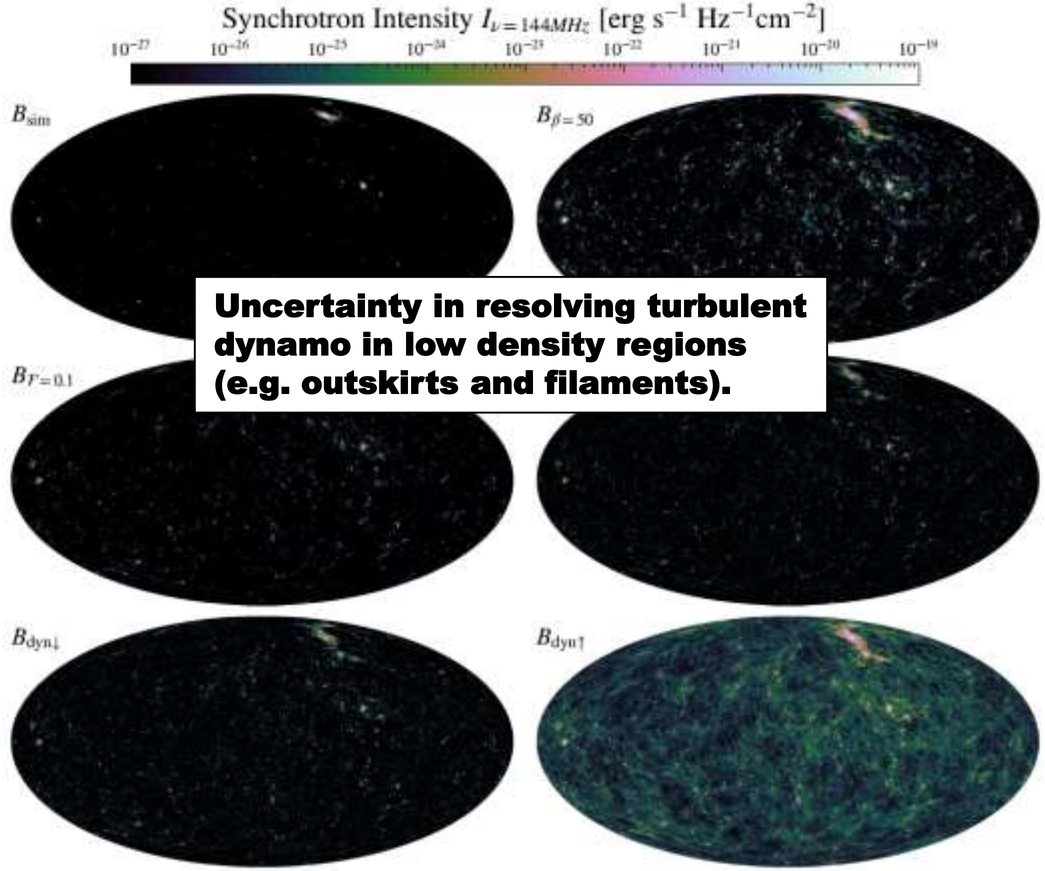
Coma in shining in radio in SLOW

- 2x3072³ non radiative (MHD+CRs)

- **Shocks**
- SFR
- AGN

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

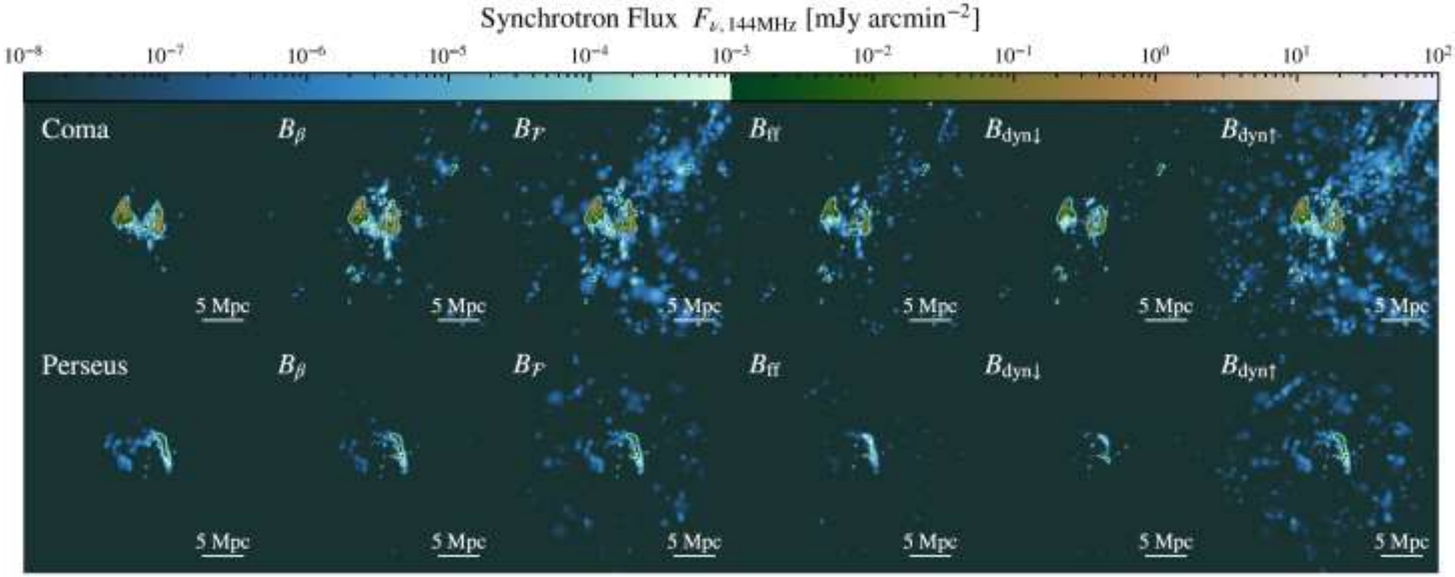
$$\underbrace{\frac{1}{3}\left(\nabla\cdot\mathbf{u}\right)p\frac{\partial f}{\partial p}}_{\text{momentum convection}} + \underbrace{\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2\left[b_\ell f + D_p\frac{\partial f}{\partial p}\right]\right)}_{\substack{\text{momentum diffusion}\\ +\text{ continuous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

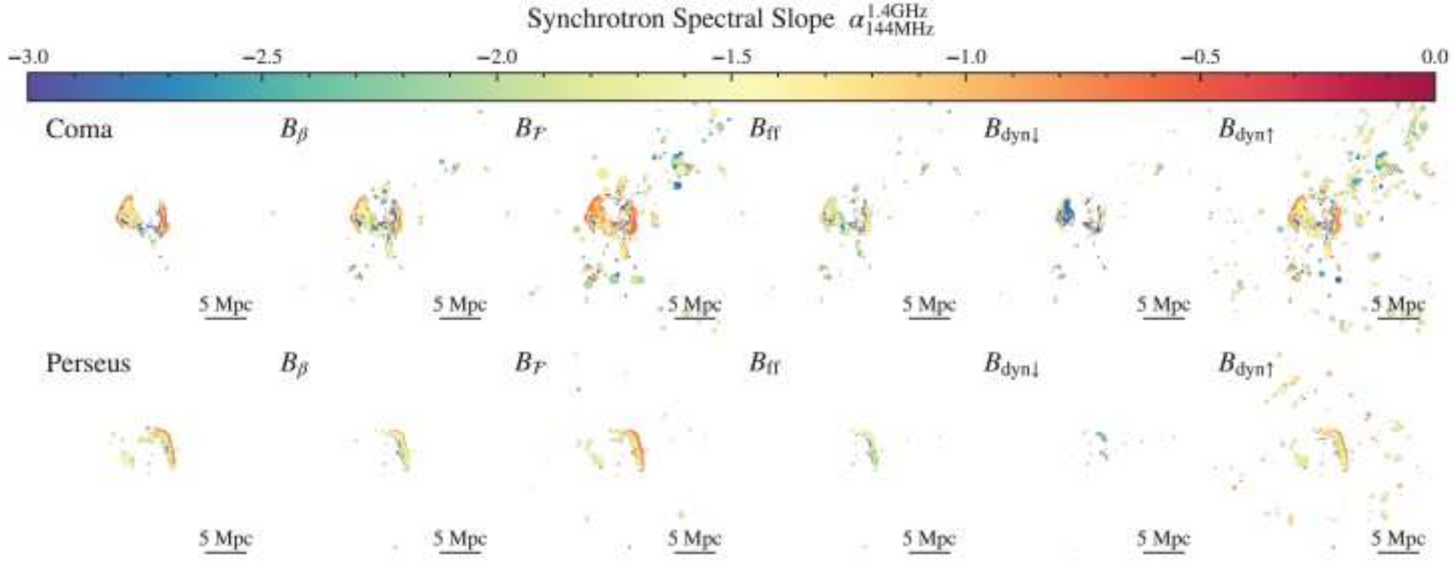


Uncertainty in resolving turbulent dynamo in low density regions (e.g. outskirts and filaments).

Predicted radio emission of Coma and Perseus for different magnetic field models.

L. Böss





Coma in shining in radio in SLOW

L. Böss

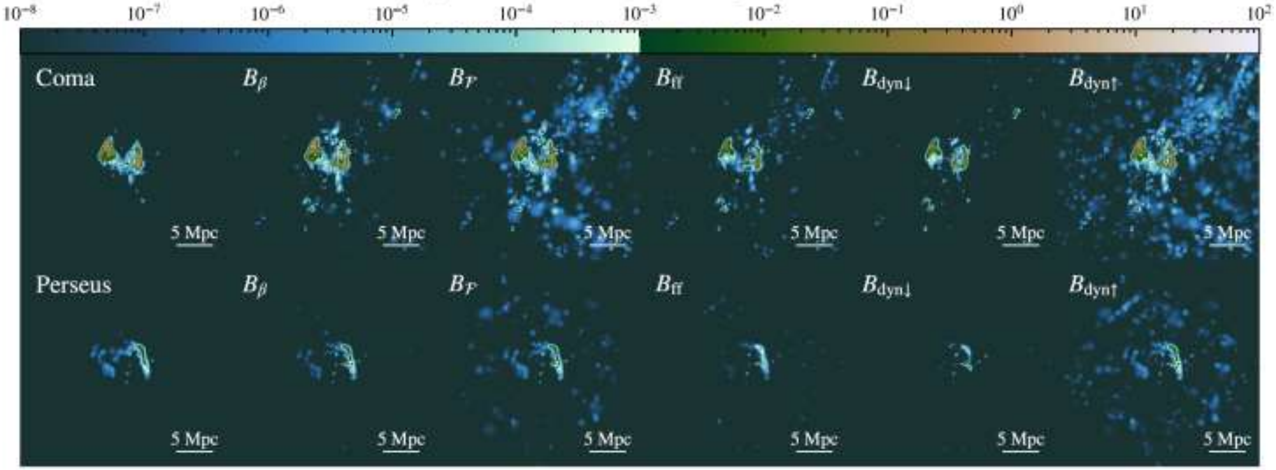
- ❑ **2x3072³ non radiative (MHD+CRs)**

- **Shocks**
- SFR
- AGN

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

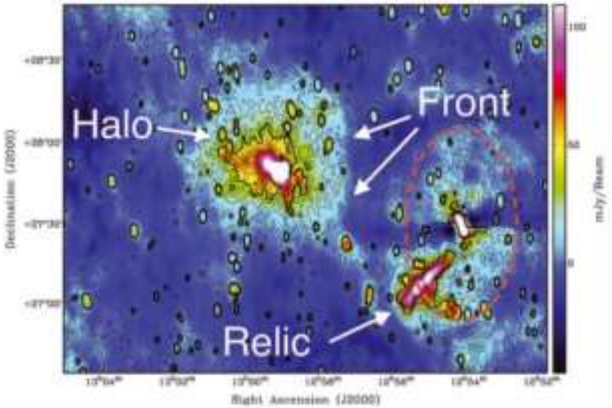
Coma:
-> extended radio emission!
Perseus:
-> only very central radio emission
Virgo:
-> no diffuse radio emission

Predicted radio emission from turbulent re-acceleration for Coma, Perseus and Virgo very Promising!

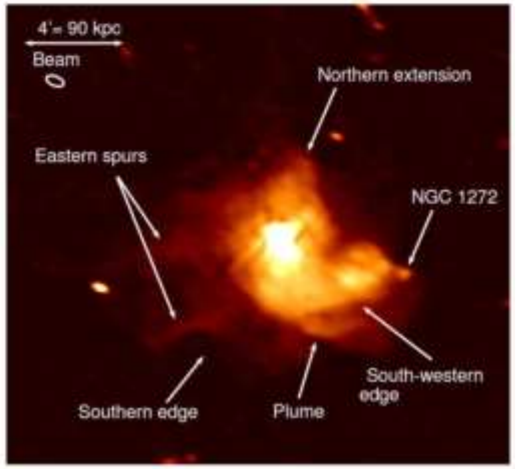


Diffuse radio emission in/around the Coma cluster: beyond simple accretion

Shea Brown and Lawrence Rudnick

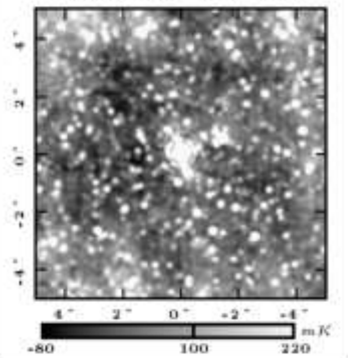


JVLA Details the Structure of the Mini-Halo in the Perseus Cluster



Astronomy & Astrophysics

Detection of a radio halo in the Virgo cluster

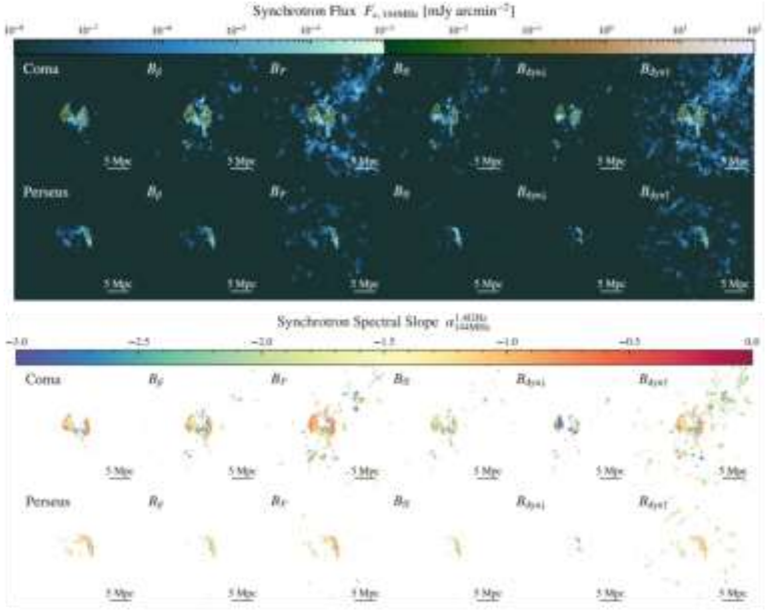


1. We do not detect a bright, large-scale radio halo, as is observed in the Coma cluster.
2. We detect a radio halo around the elliptical galaxy M 86 with an estimated radial extent of ~2° and an estimated total flux density of 5 ± 1.5 Jy.

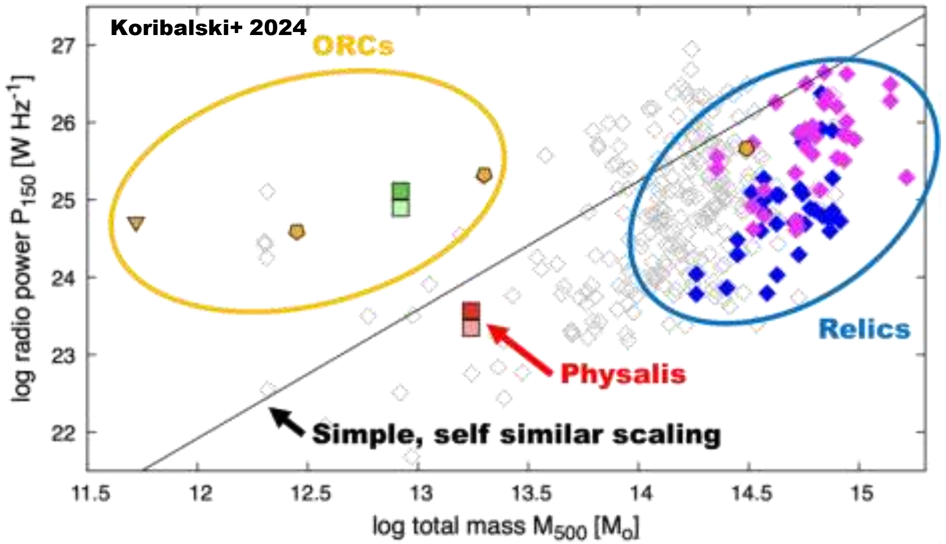
Conclusions

Plasma Physics is a key element for proper modeling of the thermal and non thermal properties within the ICM in galaxy clusters !

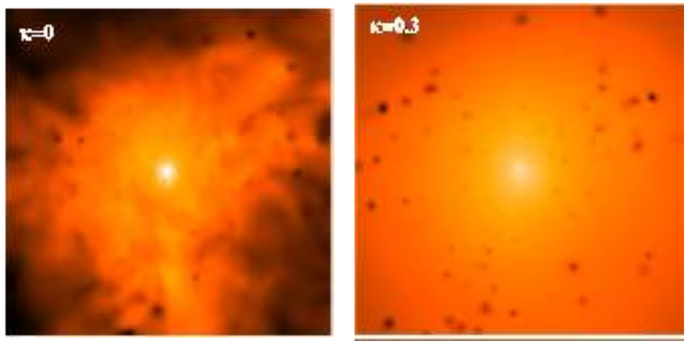
Bridging galaxies to galaxy clusters give new insights how non-thermal emission is linked to structure formation and might challenge Plasma Physics!



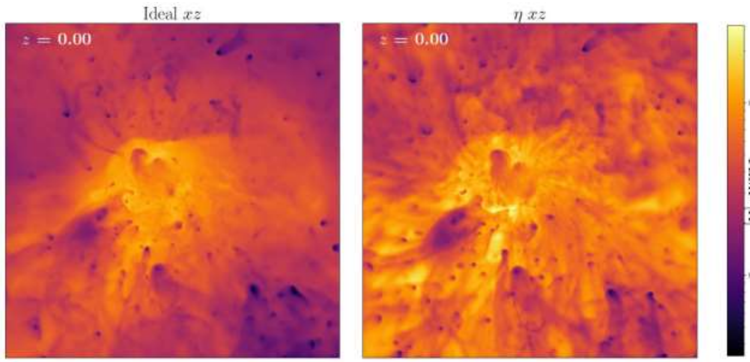
Böss+ 2024



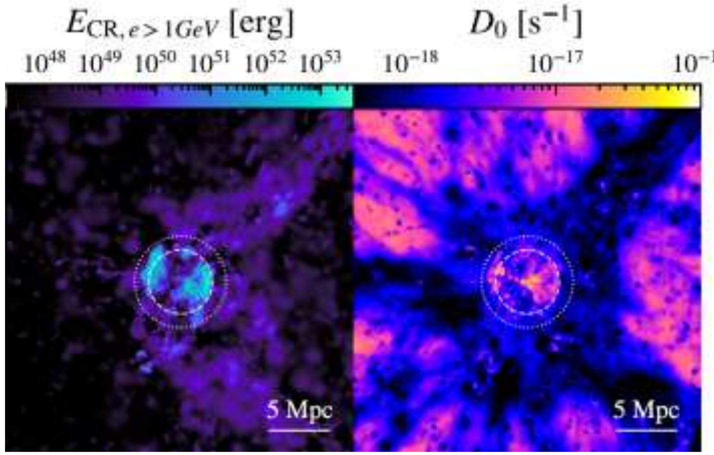
Heat transport



Viscosity



CR acceleration



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

- **First steps to make the Local Universe a Plasma Physics lab!**