Simulating the evolution of Magnetic Fields and CRs in large scale structures

Klaus Dolag

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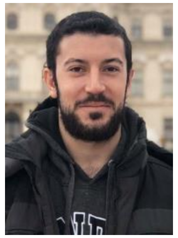

Ludwig Böss, Tirso Marin, Frederick Groth & Ulrich Steinwandel

COMPLEX
European Research Council
ORIGINS Excellence Cluster
C2PAP
LMU Ludwig-Maximilians-Universität München
anr agence nationale de la recherche
DFG Deutsche Forschungsgemeinschaft
German Research Foundation
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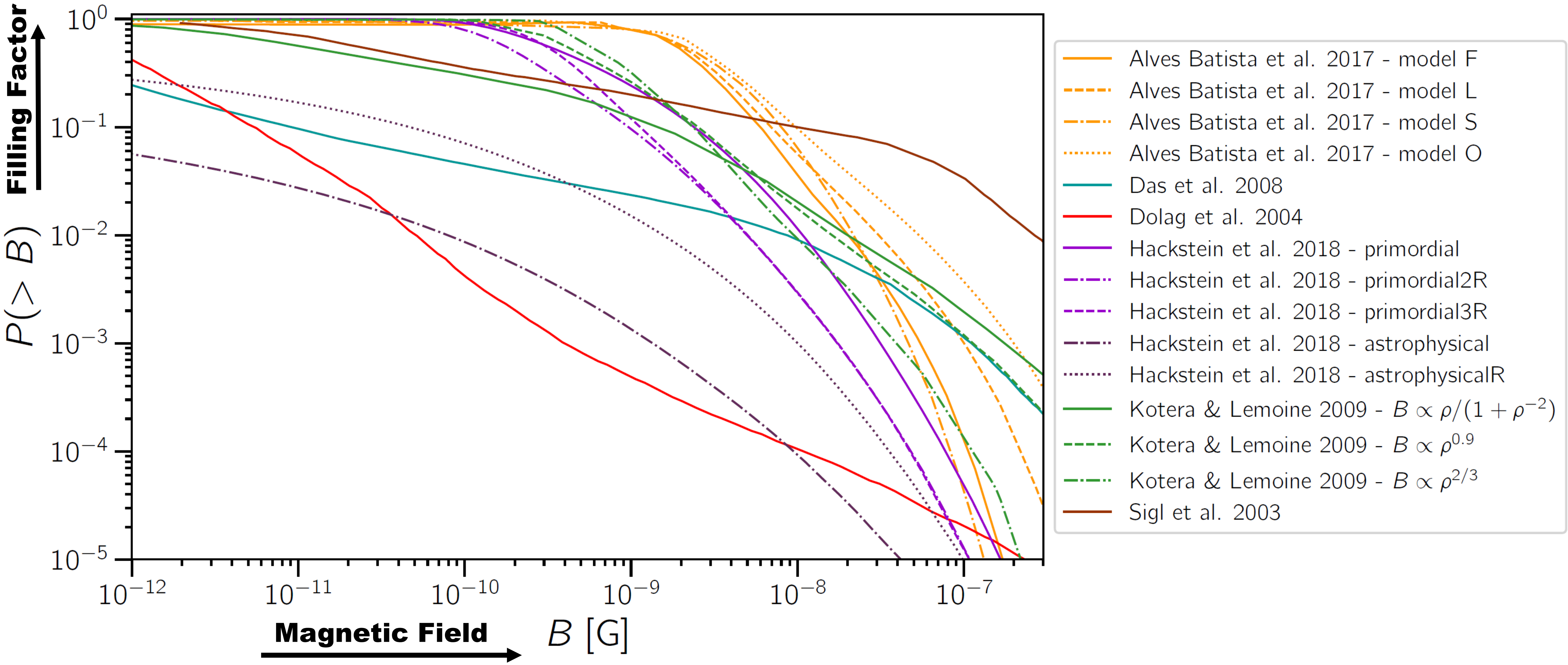
AHEAD 2020
Innovative Training Networks
Marie Curie Actions
BiD4BESt

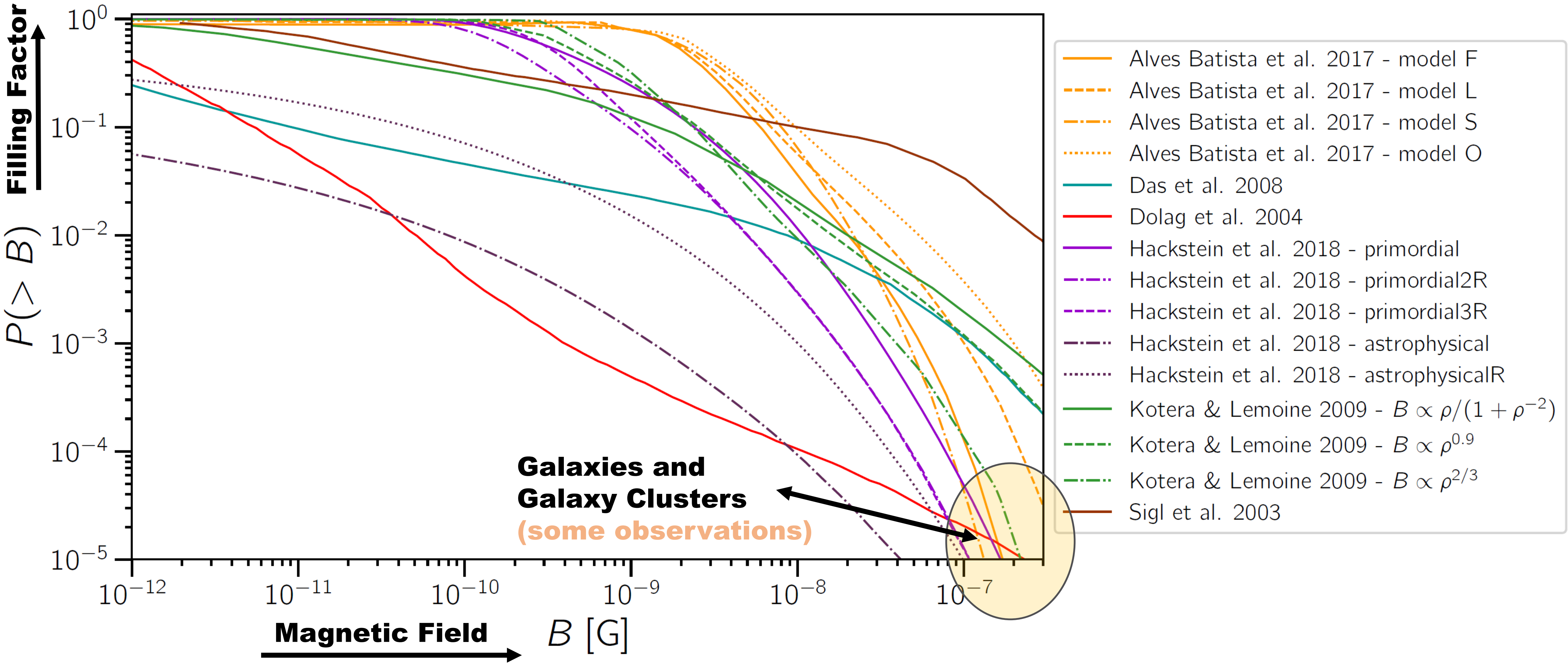
Motivation

Magnetic Fields, mostly unknown !



***Open Questions in Cosmic-Ray Research at Ultrahigh Energies,* Batista et al. 2019 (F. Oikonomou & K. Fang)**

Magnetic Fields, mostly unknown !



Open Questions in Cosmic-Ray Research at Ultrahigh Energies, **Batista et al. 2019**
(F. Oikonomou & K. Fang)

What Galaxy Clusters tell us

ICM is the hot Atmosphere of Massive Galaxies

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

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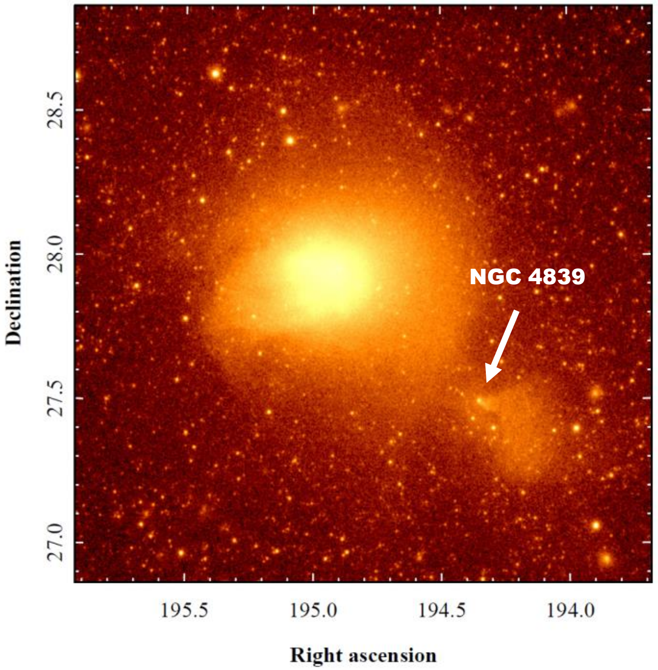
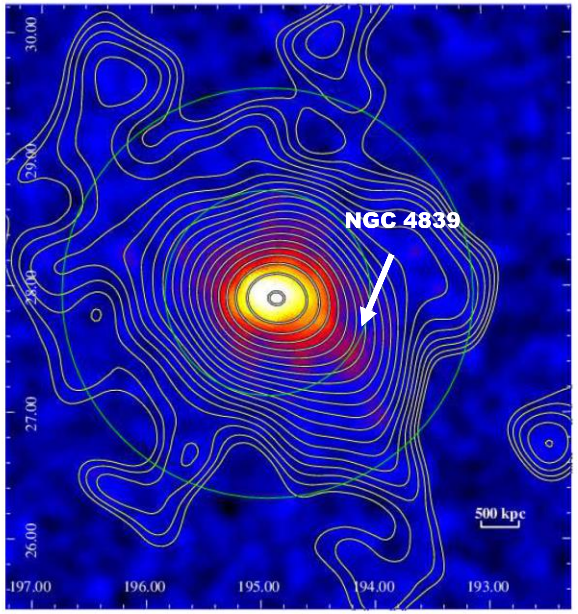
EROSITA (X-ray), Churazov+ 2021





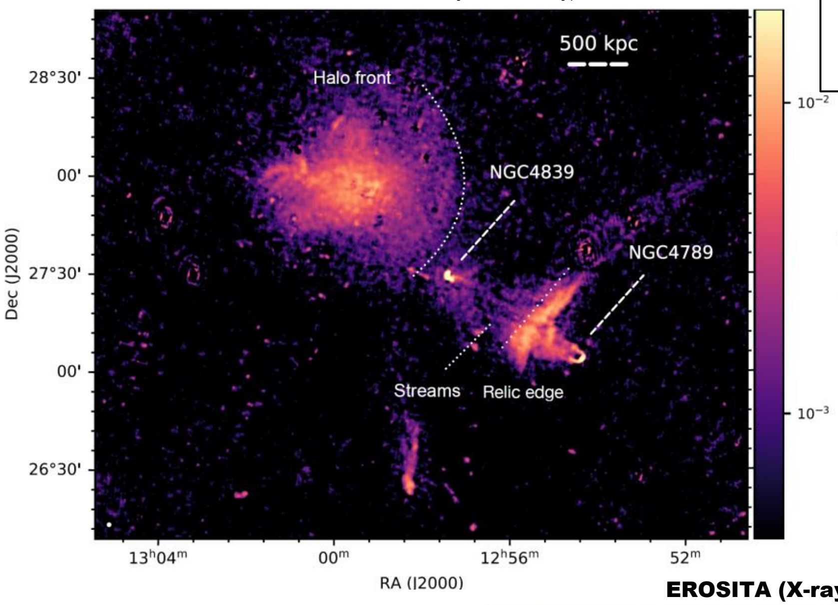
PLANCK (SZ), Planck 2012

ICM is the hot Atmosphere of Massive Galaxies

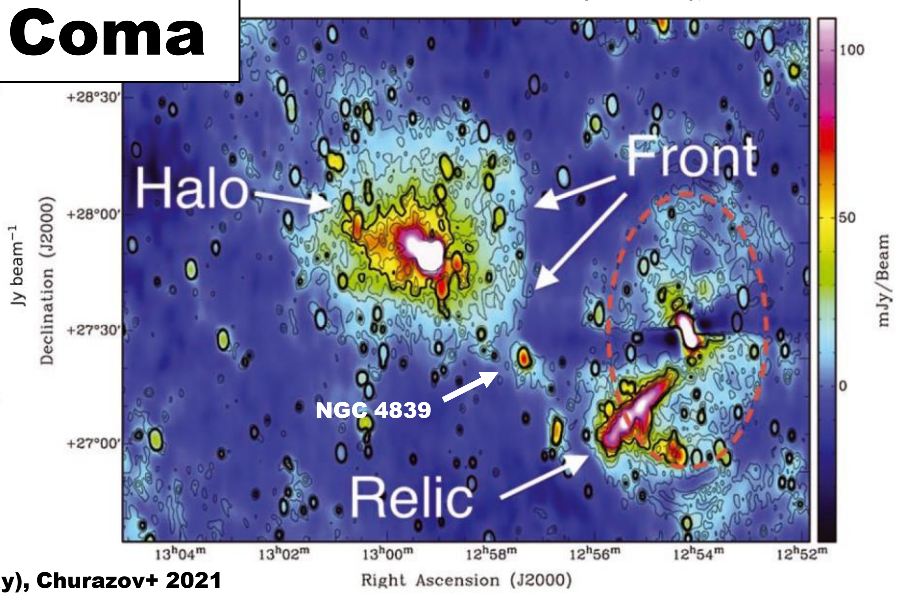
- ❑ **Measured in large details**
  X-ray (temperature, velocities)
  SZ (pressure)
- ❑ **Non-thermal components give additional insights (magnetic fields, CRs)**

Coma

LOFAR (144 MHz), Bonafede+ 2020



GMRT (352 MHz), Brown+ 2011



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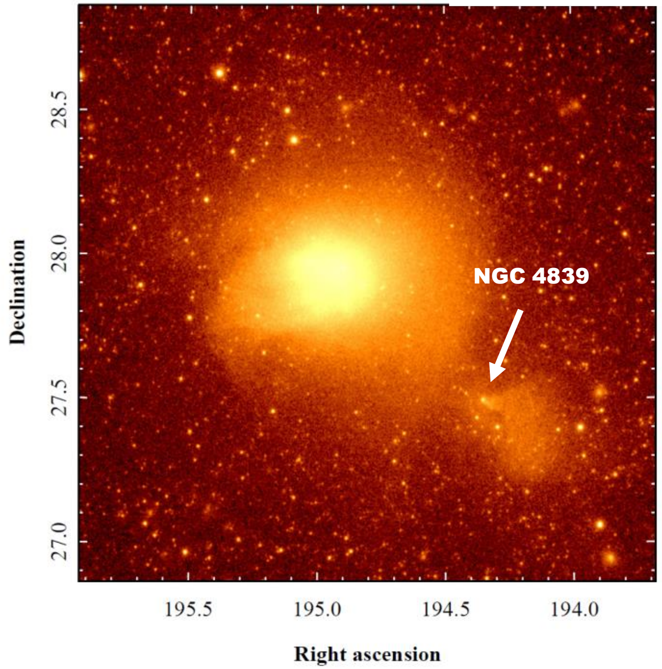
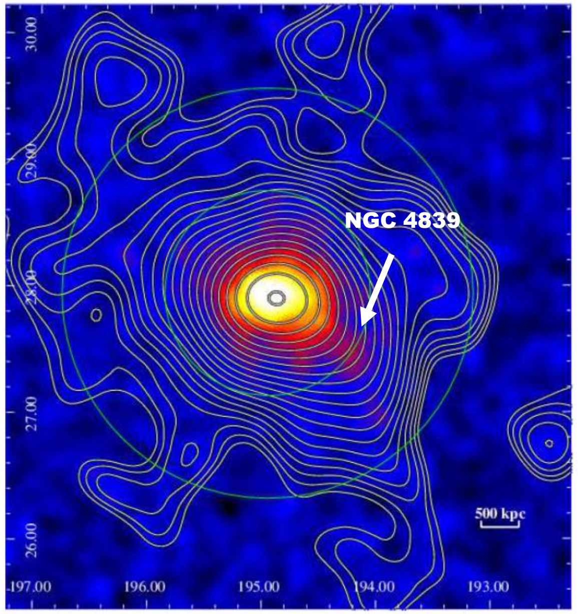




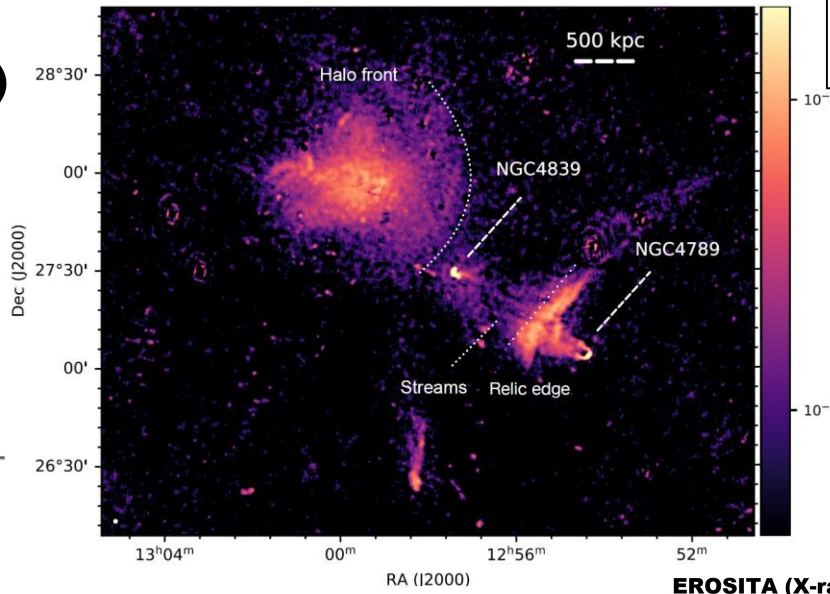
PLANCK (SZ), Planck 2012

ICM is the hot Atmosphere of Massive Galaxies

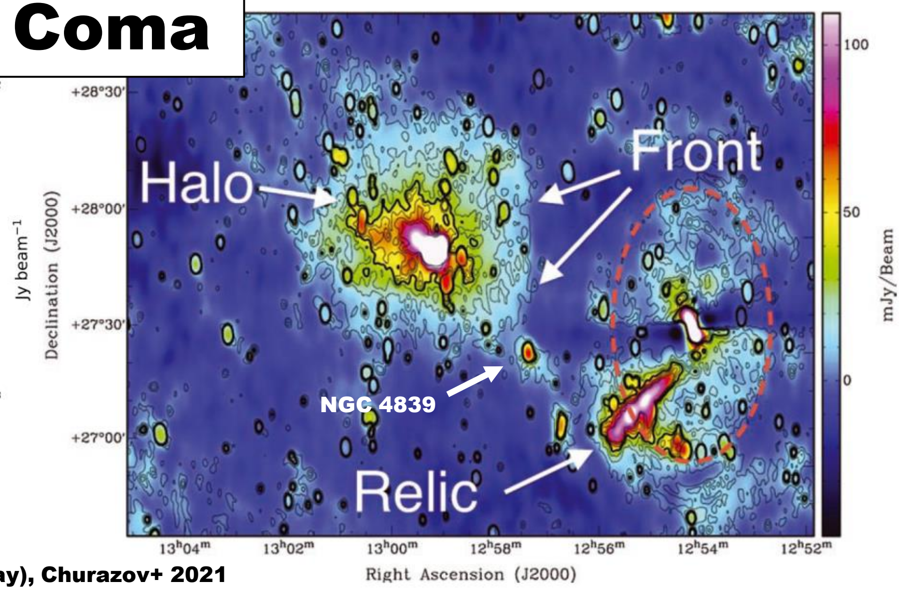
- ❑ **Measured in large details**
  X-ray (temperature, velocities)
  SZ (pressure)
- ❑ **Non-thermal components give additional insights (magnetic fields, CRs)**
- ❑ **Closed system (chemical imprint)**

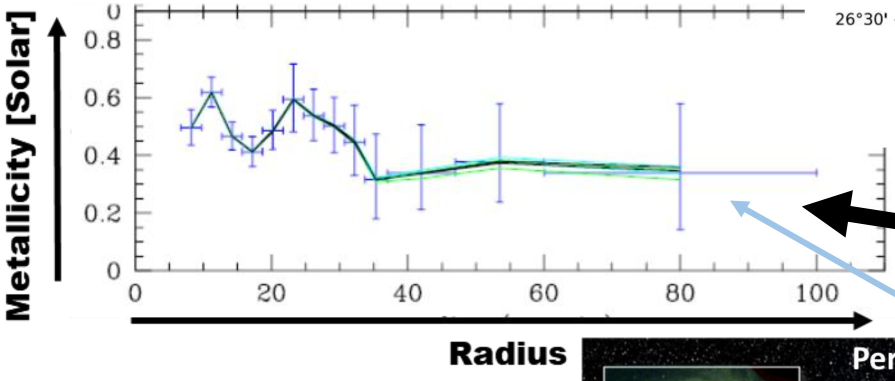
Coma

LOFAR (144 MHz), Bonafede+ 2020

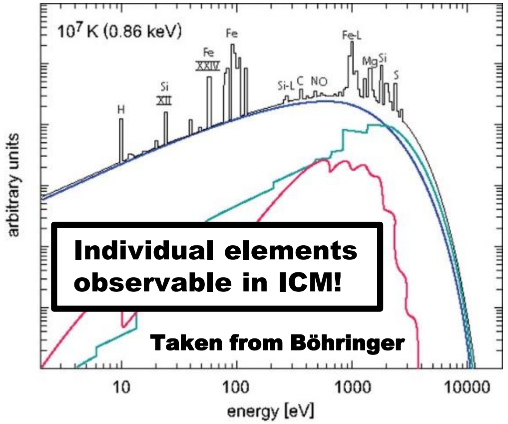


GMRT (352 MHz), Brown+ 2011



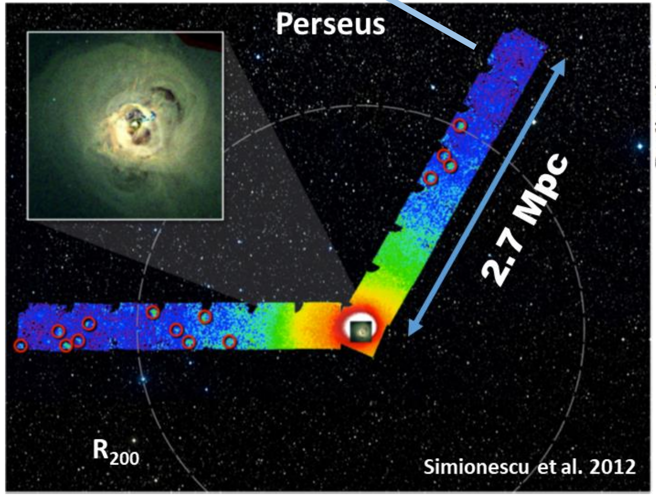


All ICM within R_{vir} contains at least 10% stellar debris!

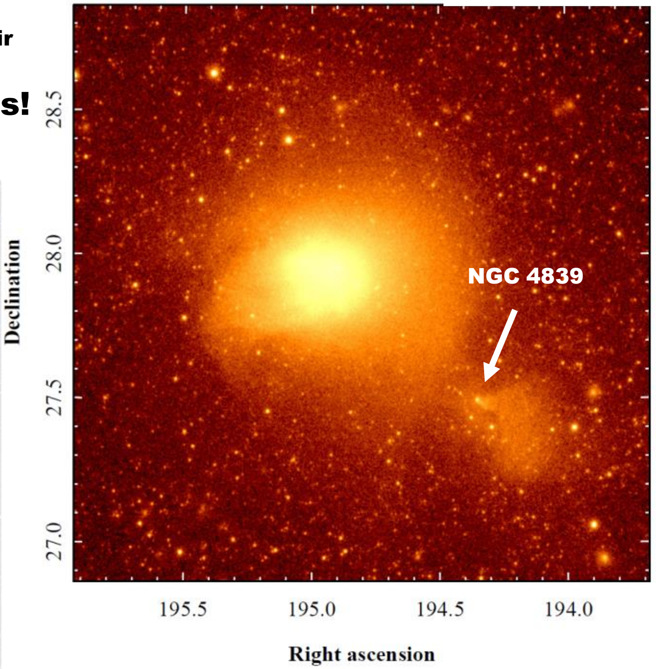


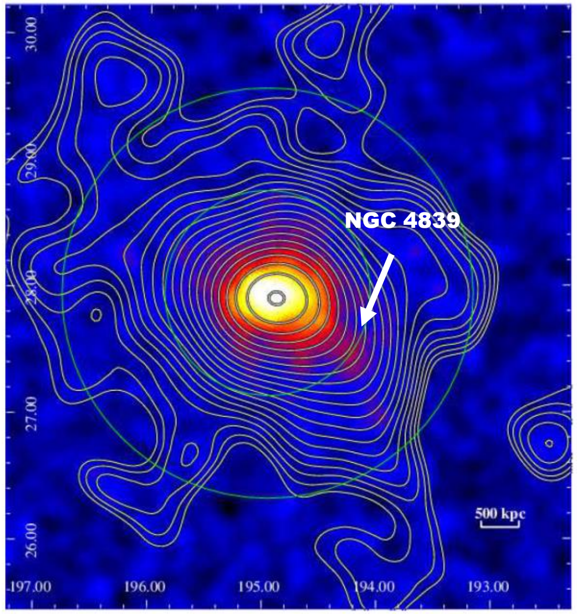
Individual elements observable in ICM!

Taken from Böhringer



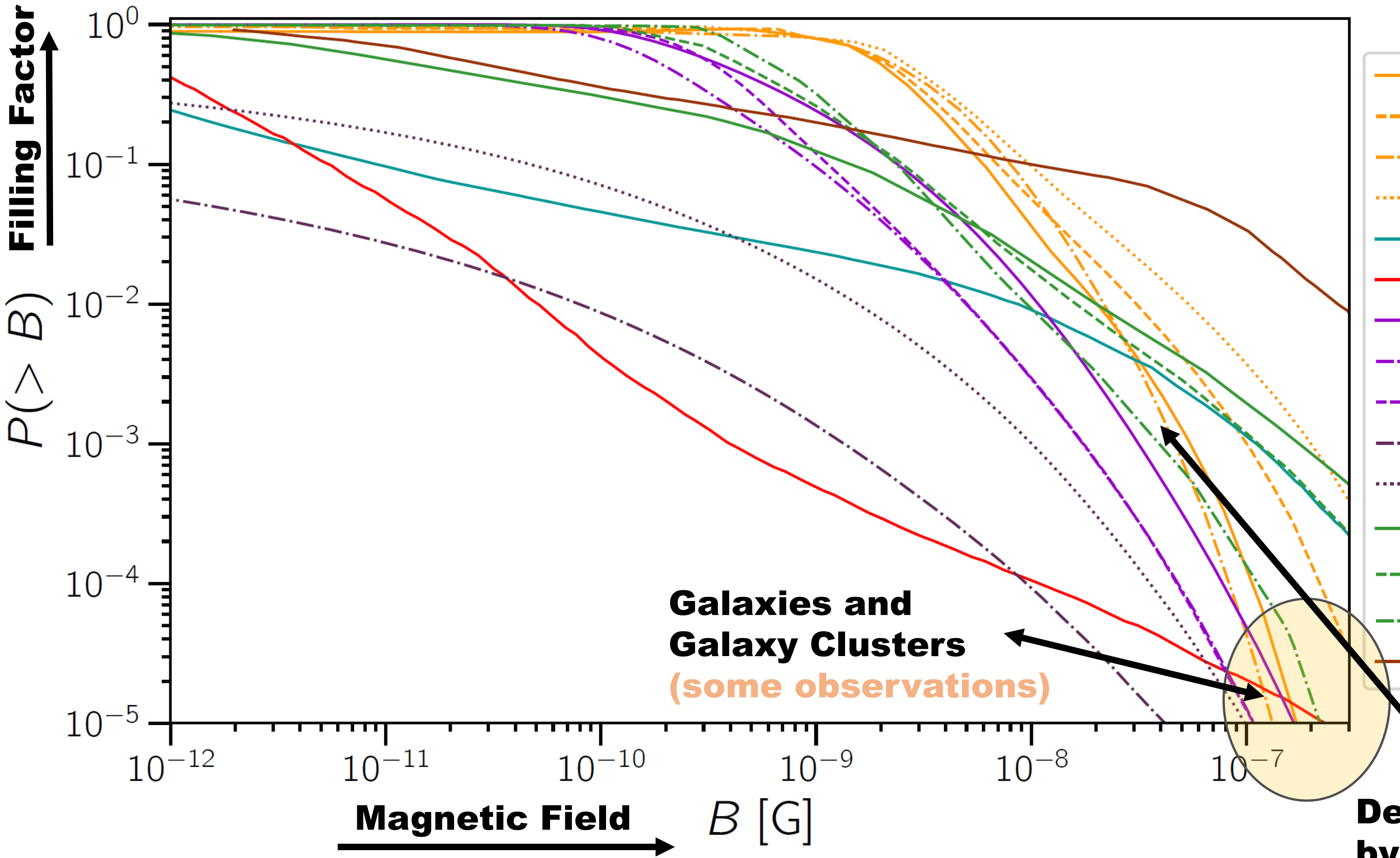
EROSITA (X-ray), Churazov+ 2021

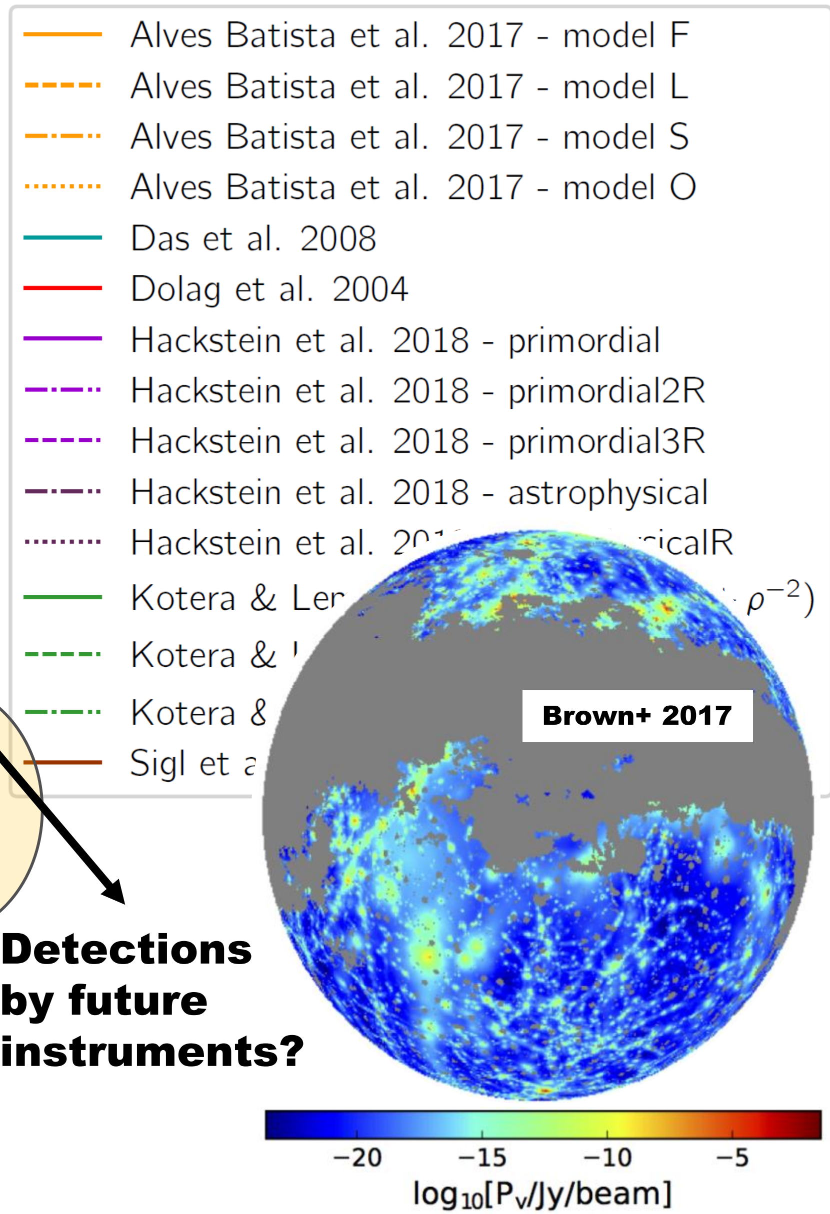




PLANCK (SZ), Planck 2012

Magnetic Fields, mostly unknown !





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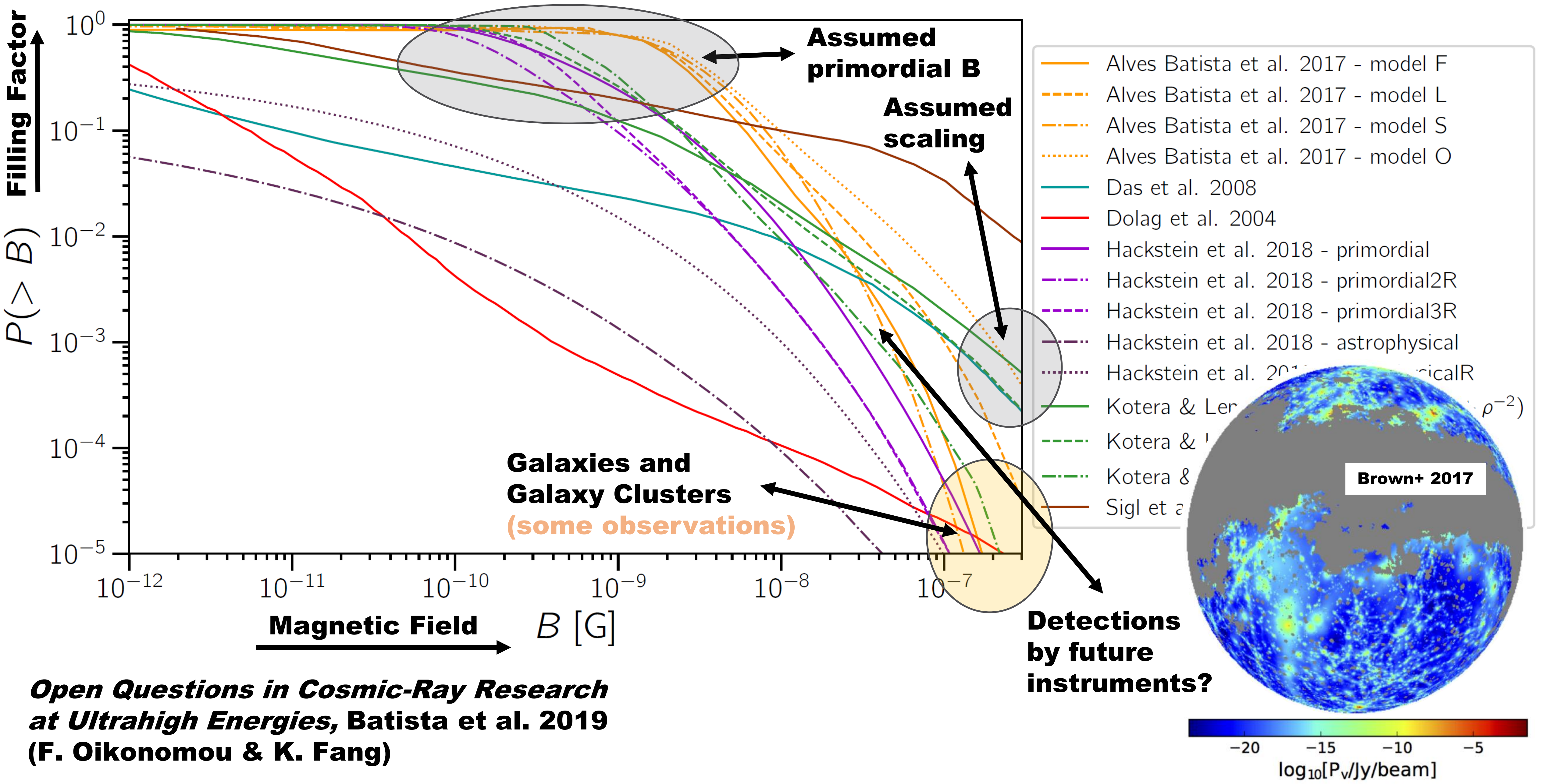

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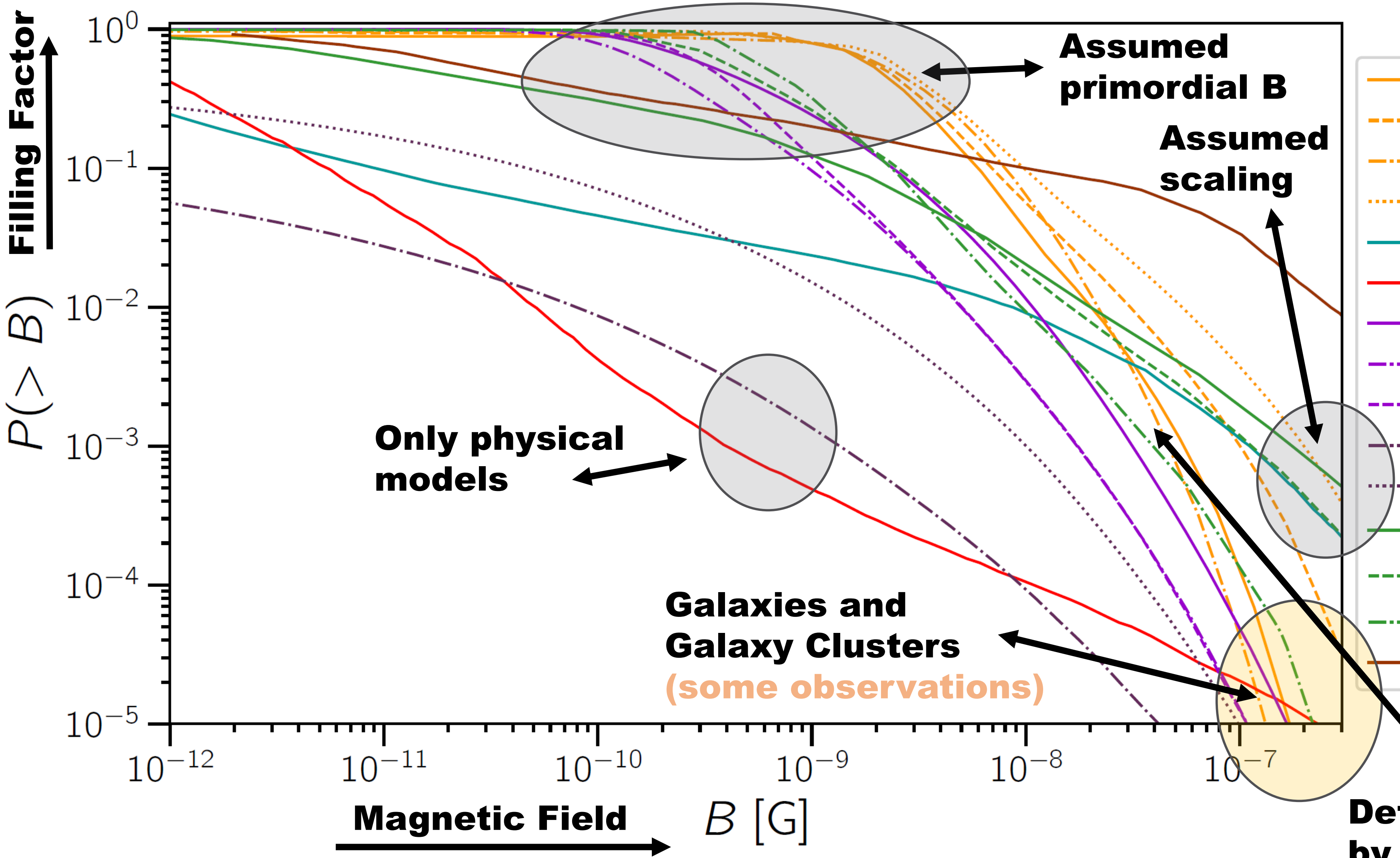

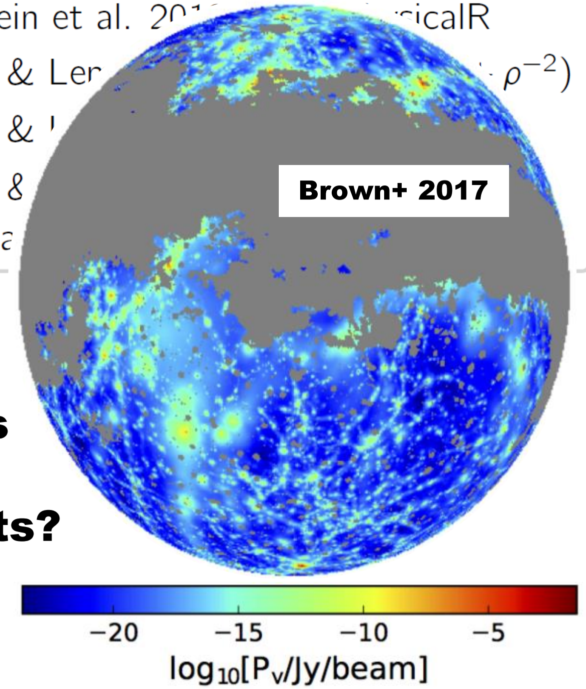

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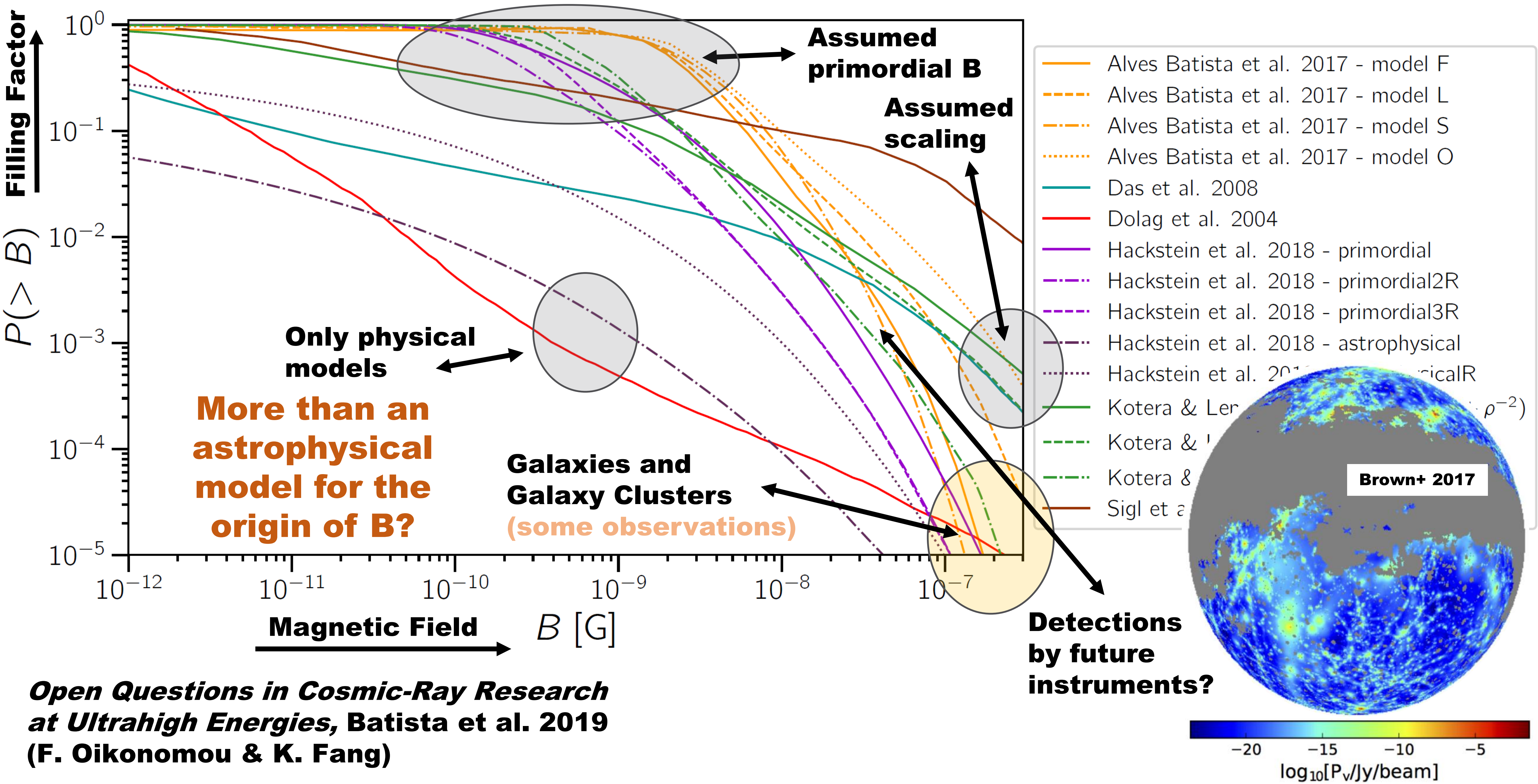

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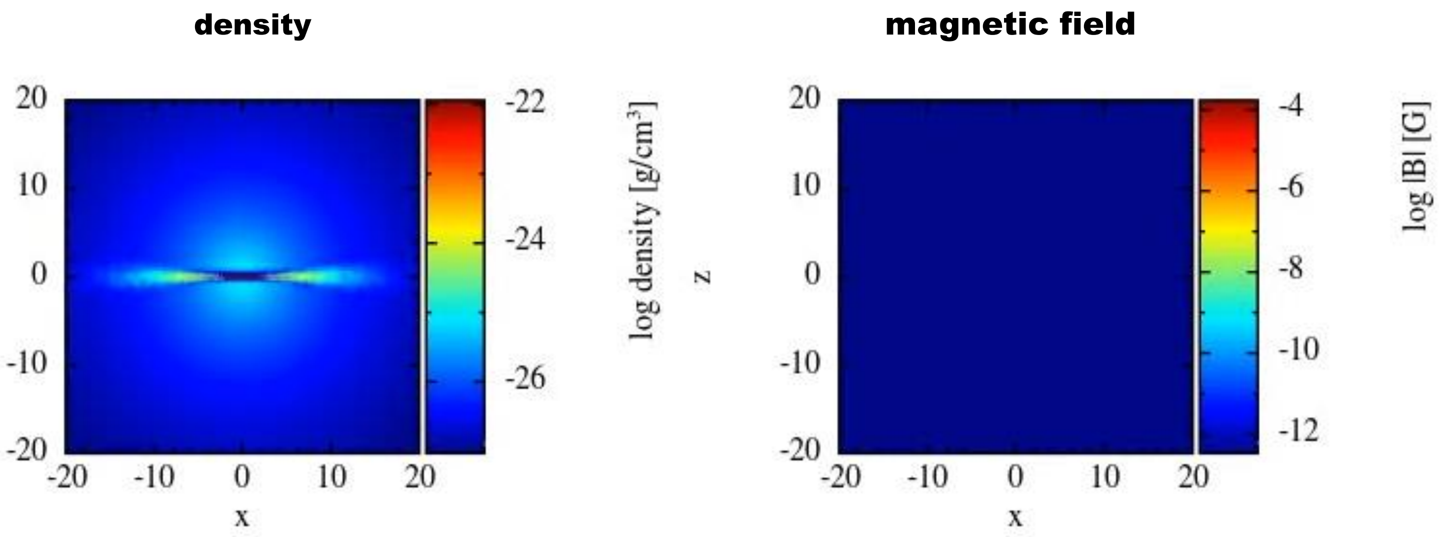
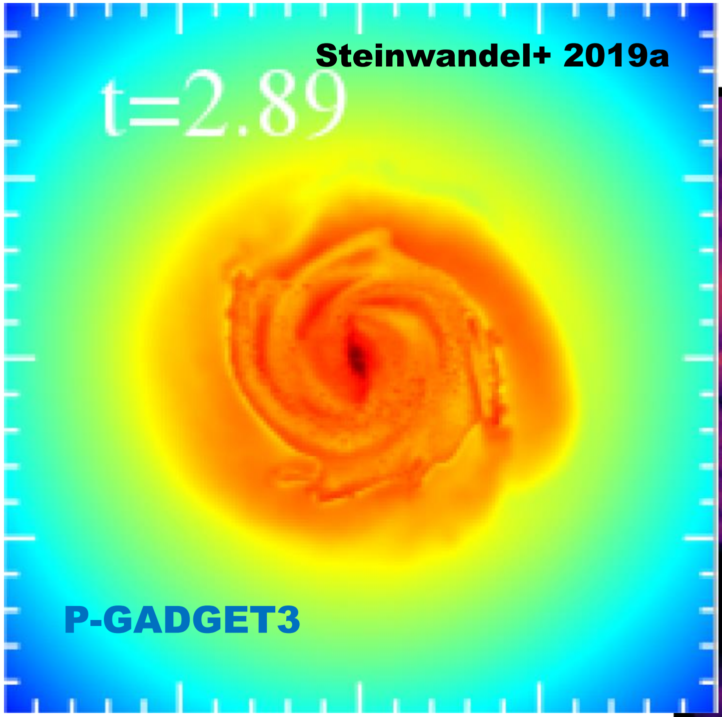
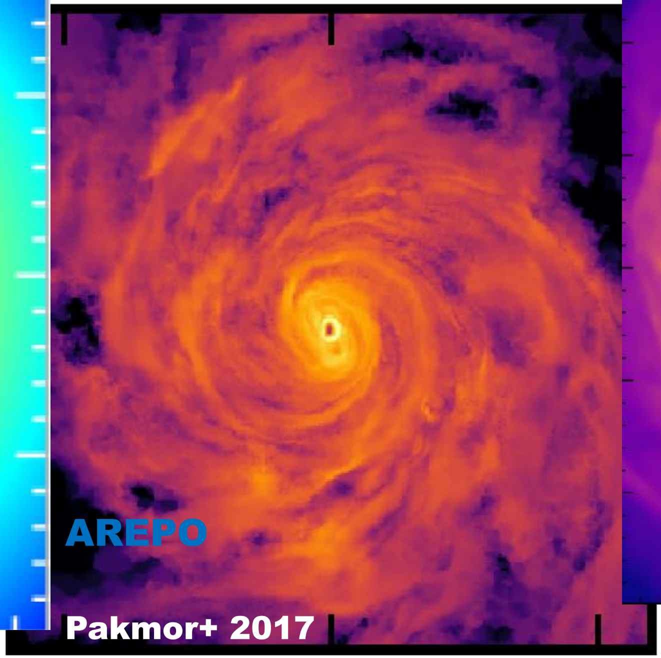
Dynamo in Galaxies

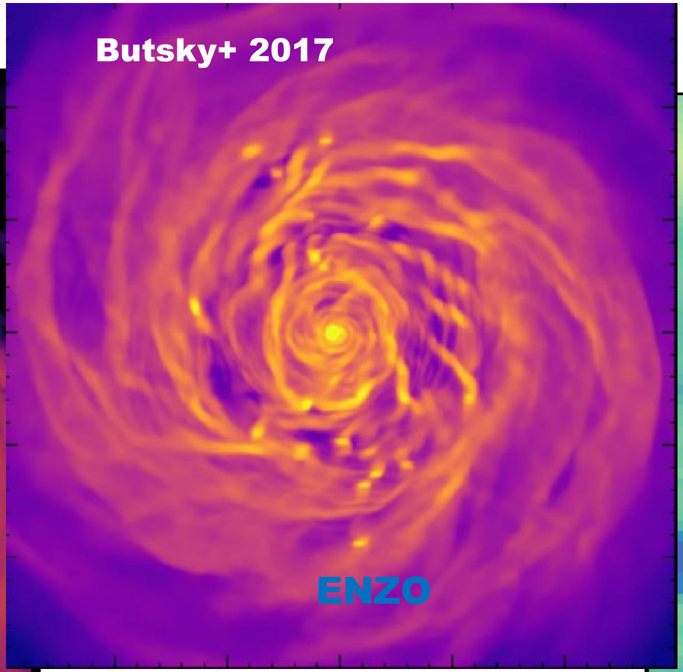
A turbulent dynamo amplifying B is common prediction of all simulations …

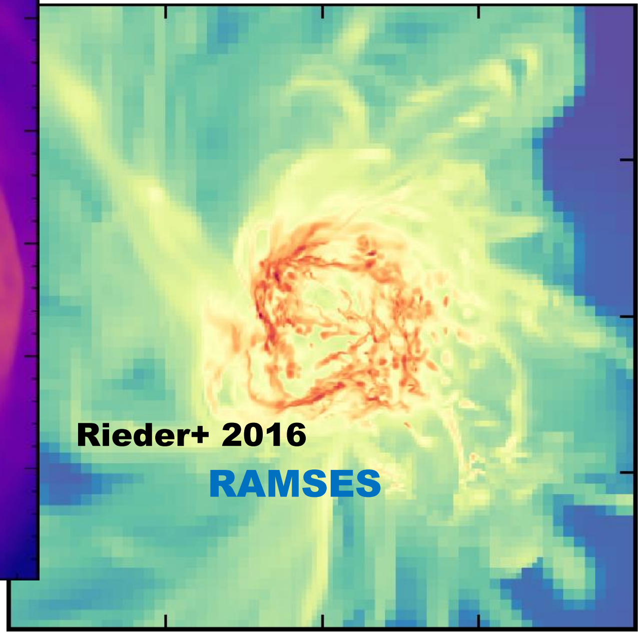
Ulrich Steinwandel





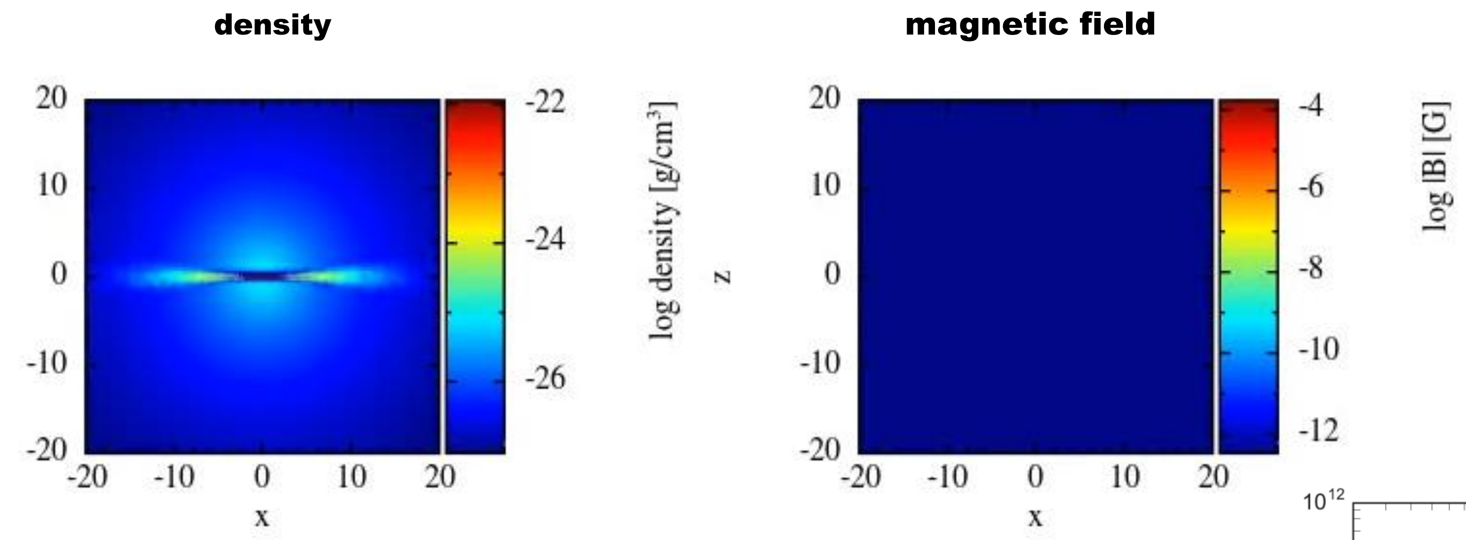




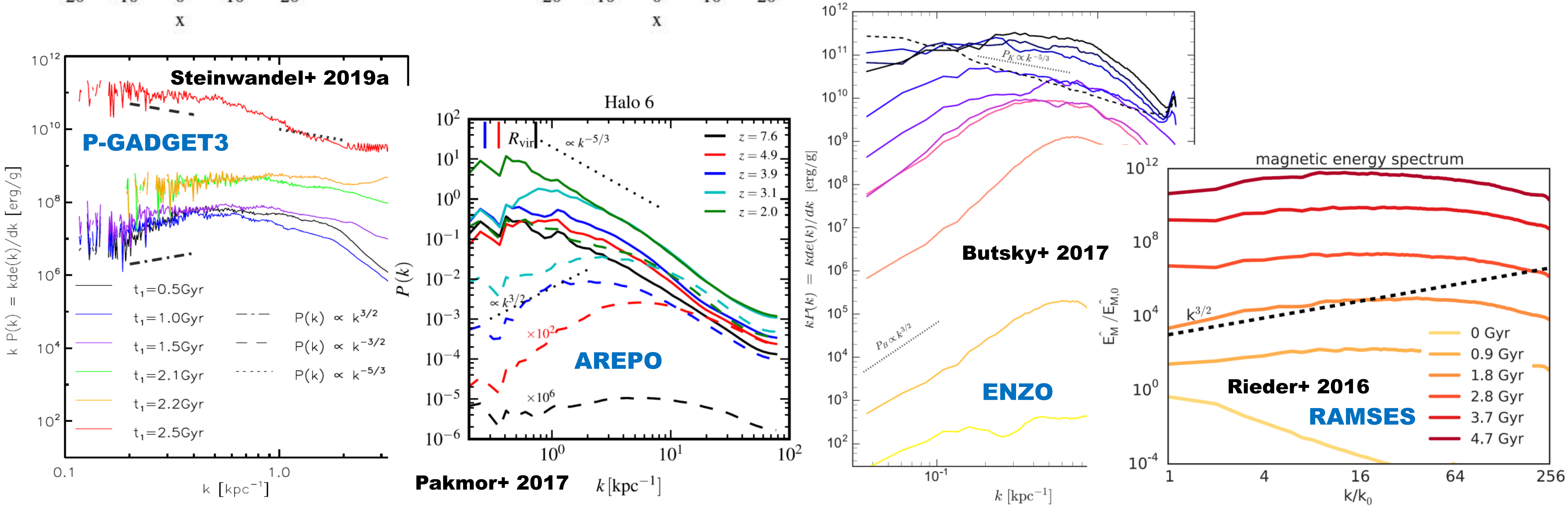


Dynamo in Galaxies

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



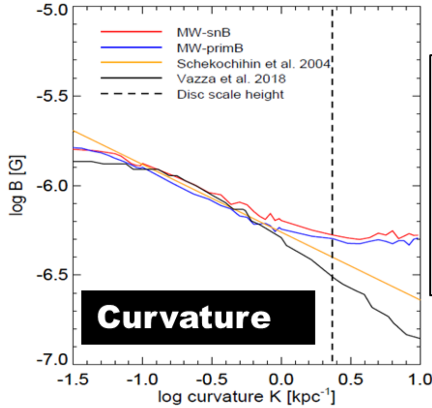
Ulrich Steinwandel



Dynamo in Galaxies

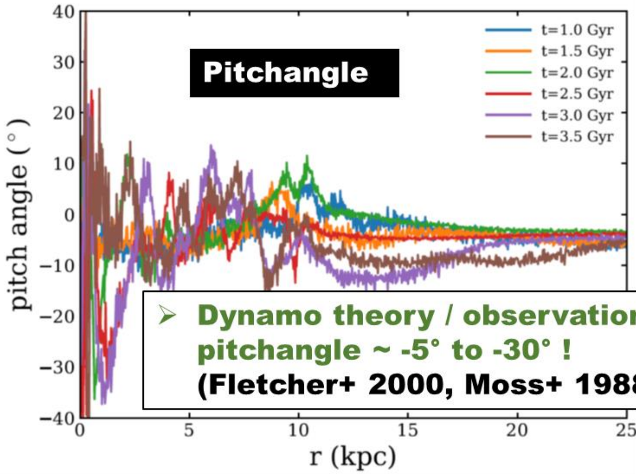
... but first to prove the different dynamo actions far beyond simple power spectrum ...

Ulrich Steinwandel

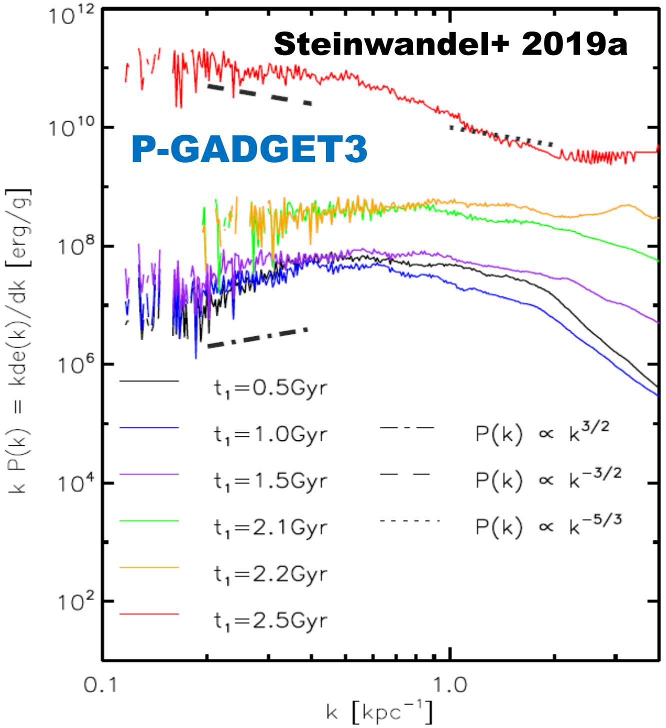


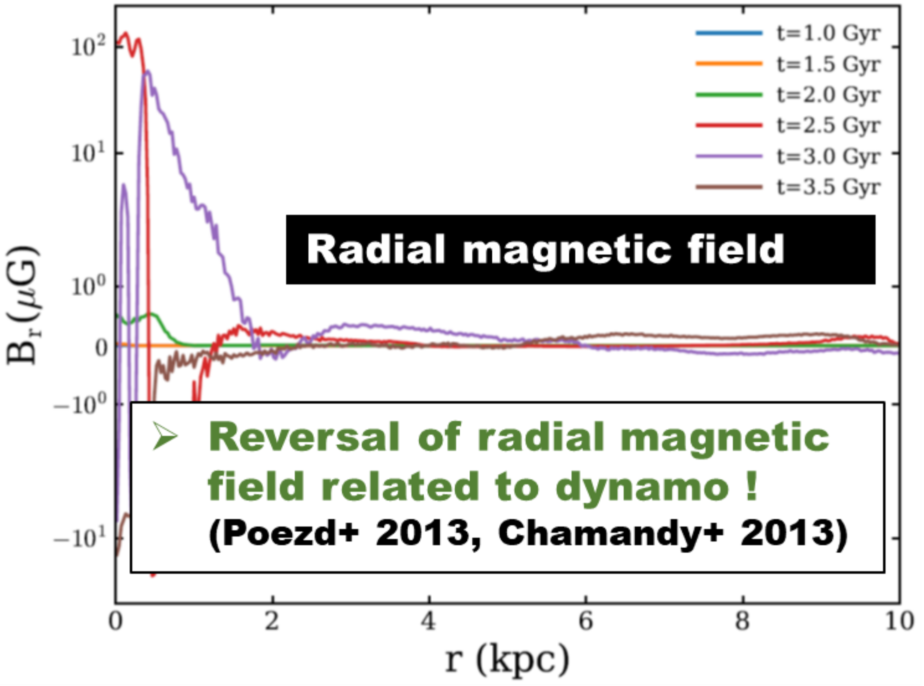
- **Evidence for small scale turbulent dynamo via magnetic field lines' curvature !**
  (e.g. Vazza+ 2018)
- **The curvature of the field lines follows the predictions from dynamo theory !**
  (e.g. Schekochihi+ 2004)

Steinwandel+ 2019b

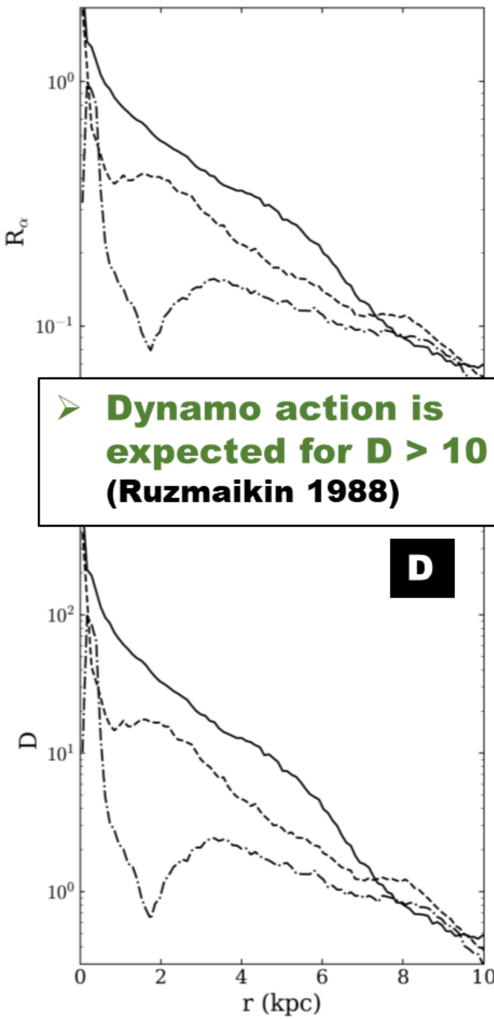


- **Dynamo theory / observations: pitchangle ~ -5° to -30° !**
  (Fletcher+ 2000, Moss+ 1988)





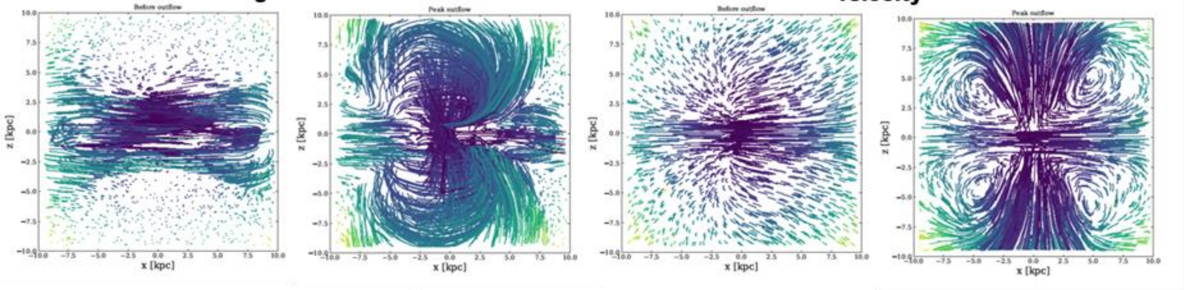
- **Reversal of radial magnetic field related to dynamo !**
  (Poezd+ 2013, Chamandy+ 2013)



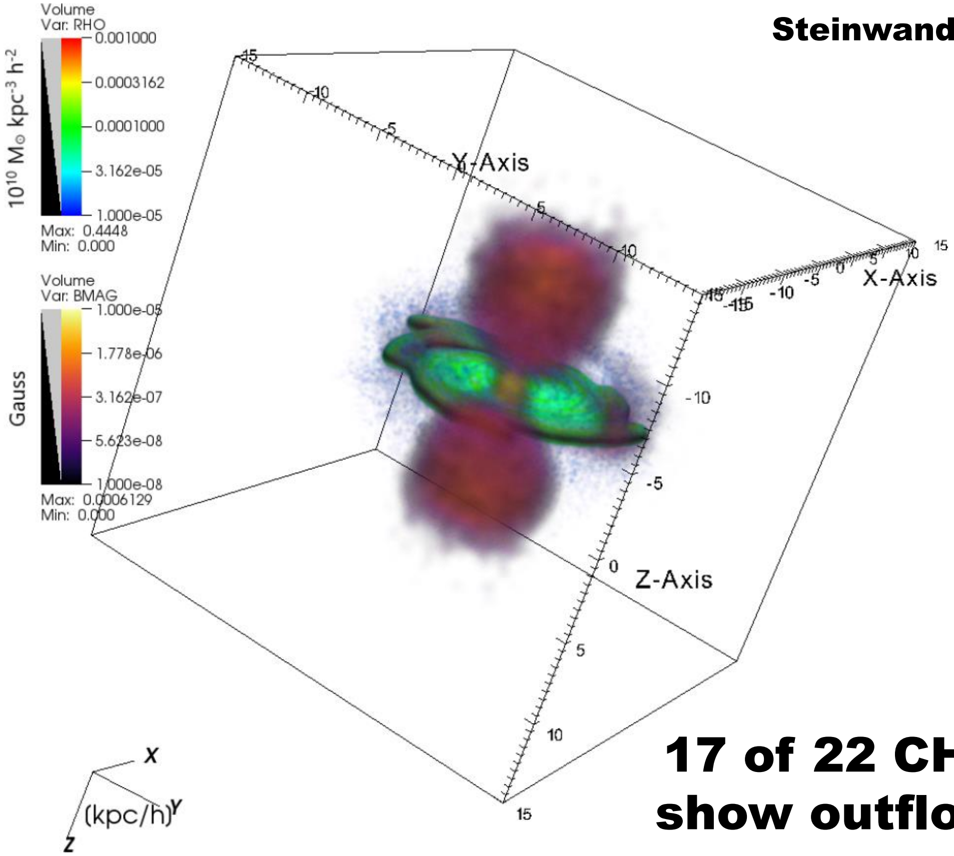
- **Dynamo action is expected for D > 10 !**
  (Ruzmaikin 1988)

Dynamo/outflows in Galaxies

First MHD galaxy simulation with fully resolved, two phase dynamo and magnetic driven outflows, triggered by bar instability !



Steinwandel+ 2020



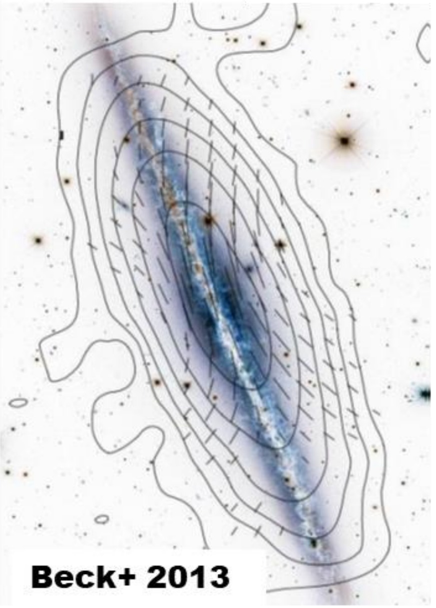
17 of 22 CHANG-ES* Galaxies show outflow + bar !

(*) Krause+ 2020

… and first to find a B driven galactic outflow! (interplay between bar / dynamo!)

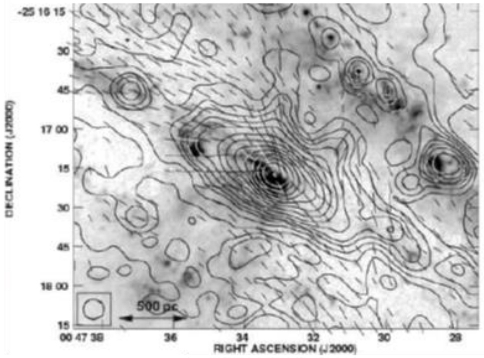
Ulrich Steinwandel

NGC891



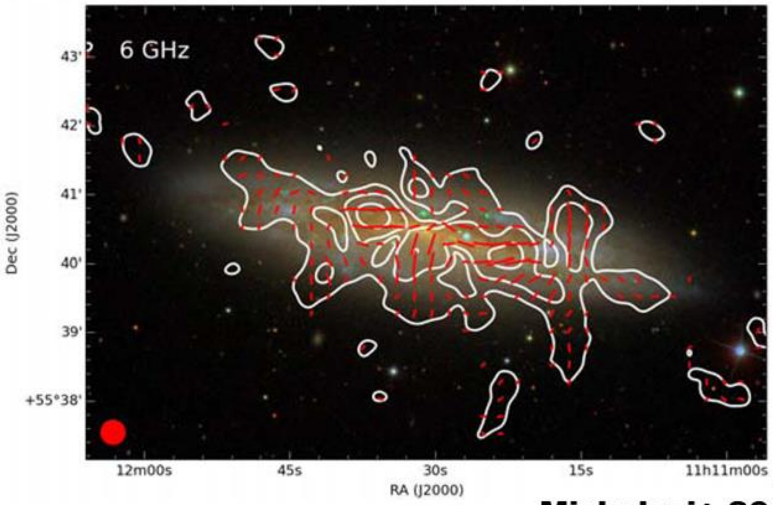
Beck+ 2013

NGC253



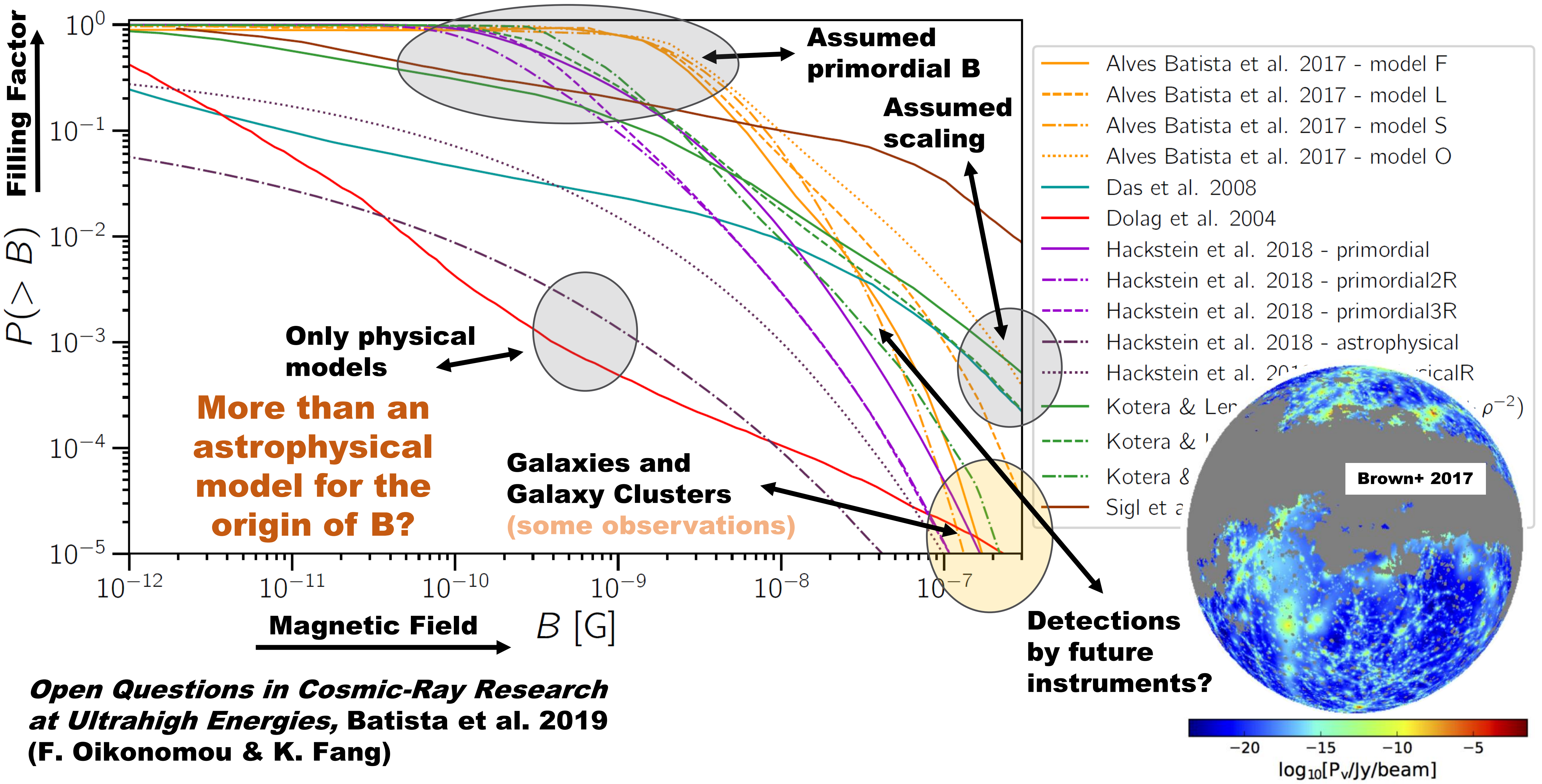
Heesen+ 2011

NGC3556



Miskolczi+ 2019

Magnetic Fields, mostly unknown !



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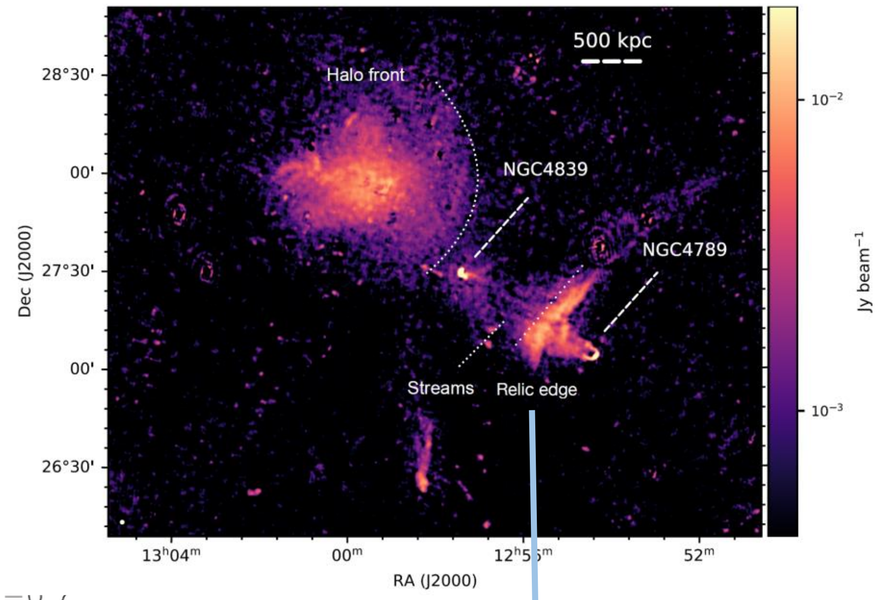
Magnetic Field
and
CRs in Galaxy Cluster

What do CR (electrons) tell us?

Short cooling time of CRe:

- ❑ test shocks on 10th of kpc

LOFAR (144 MHz), Bonafede+ 2020



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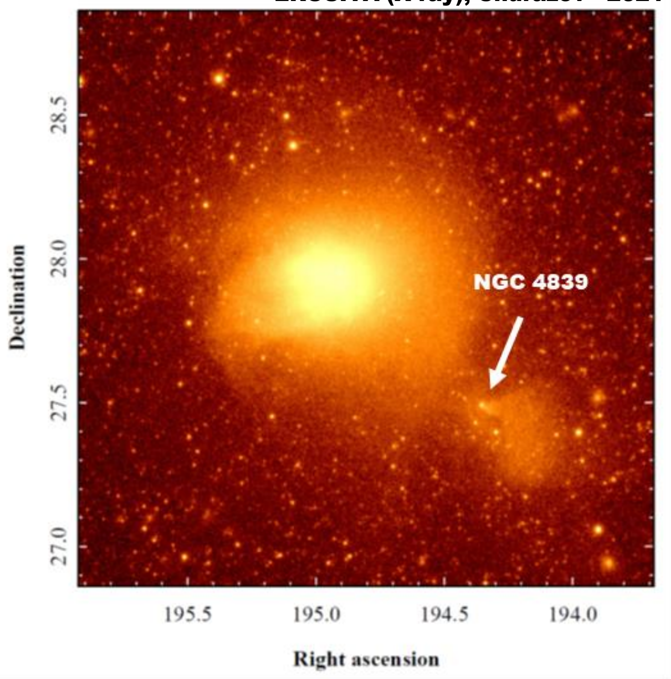
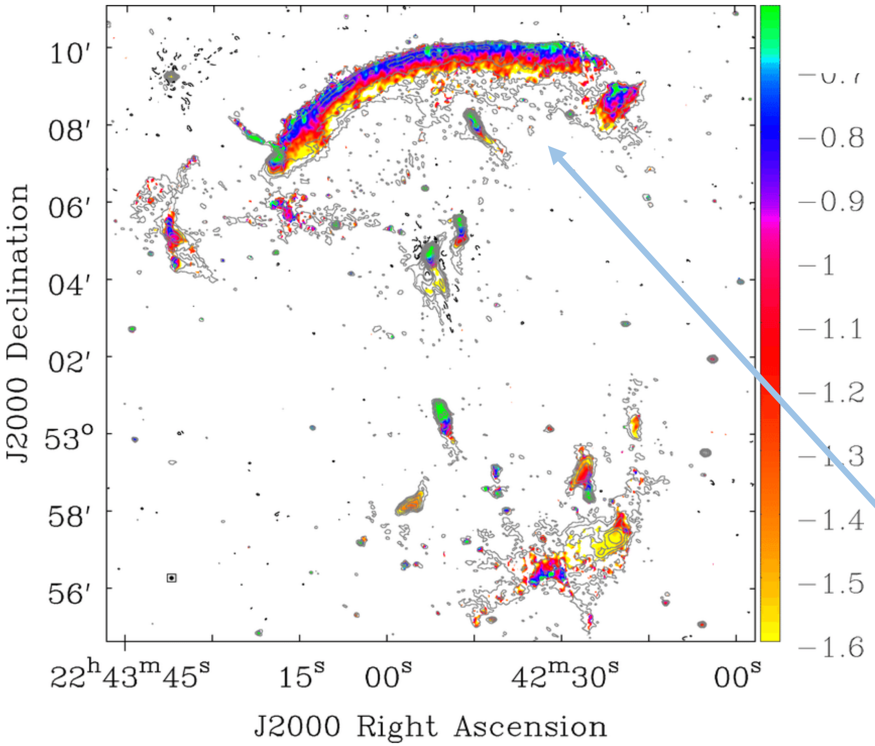
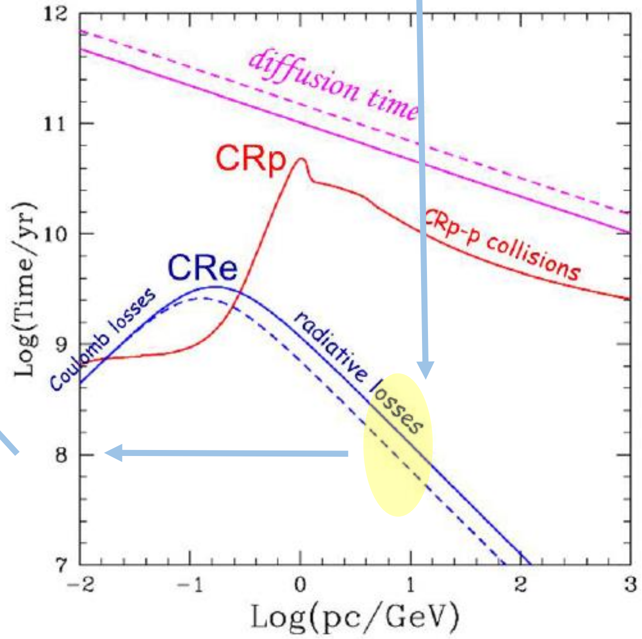


Shocks



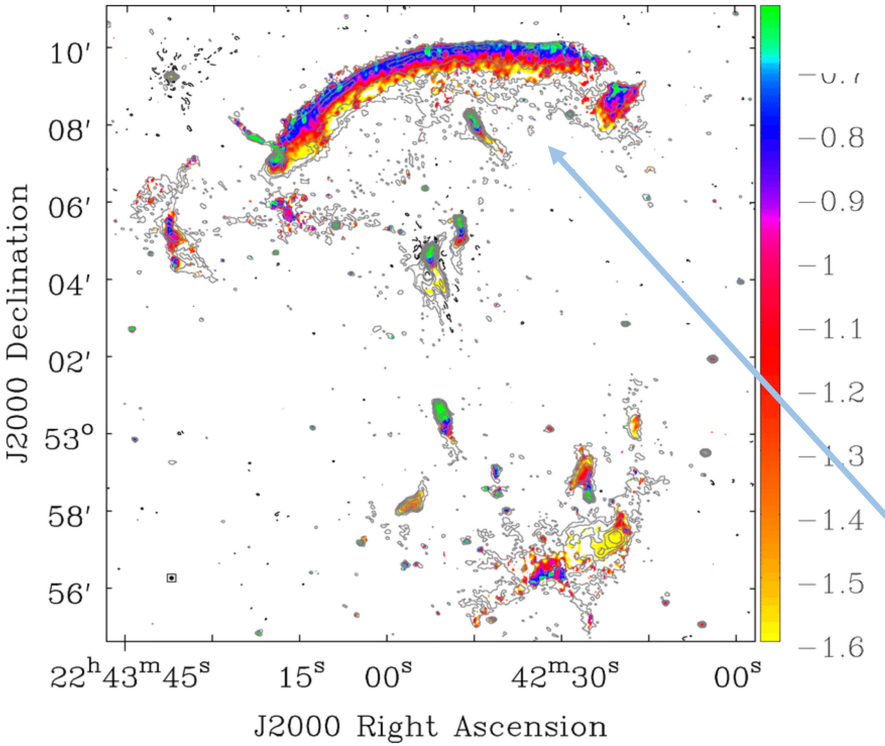


What do CR (electrons) tell us?

Short cooling time of CRe:

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

Shocks



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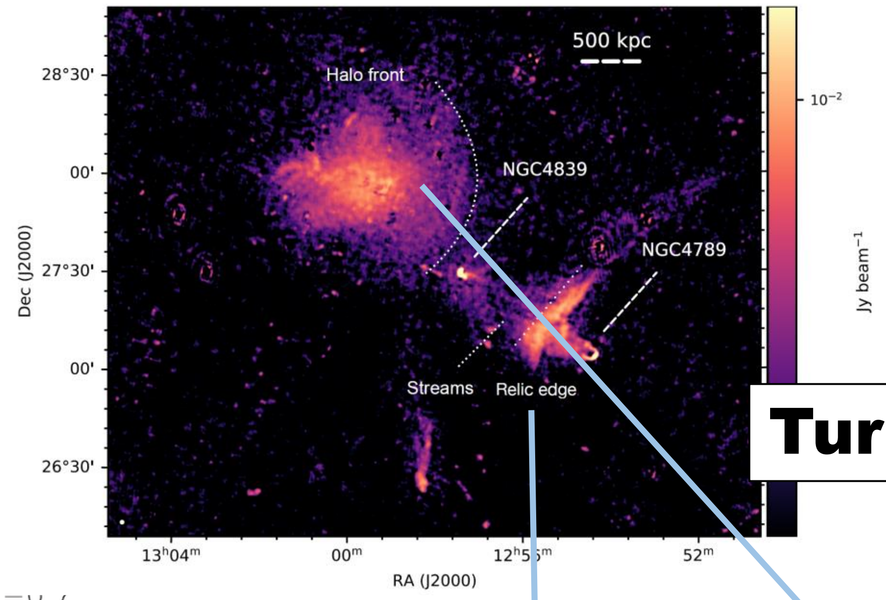
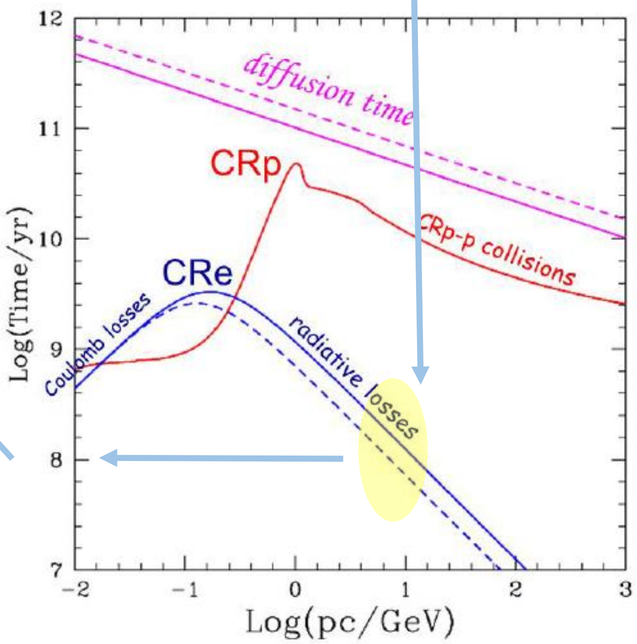
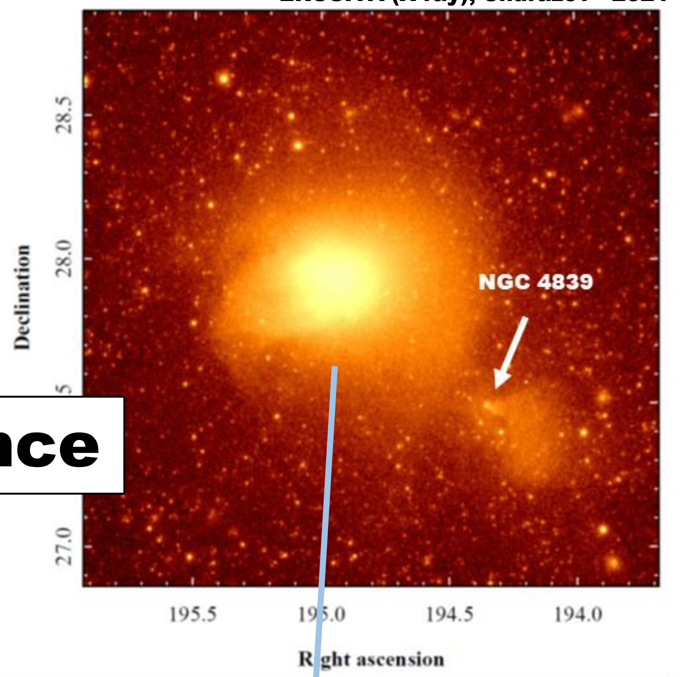


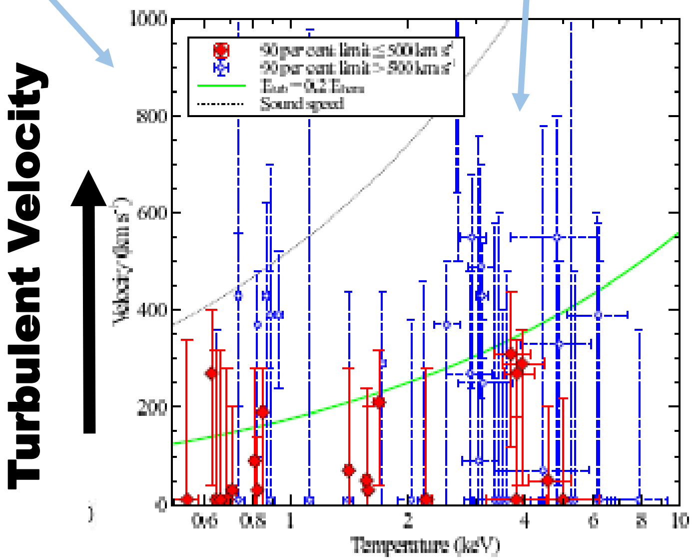


Turbulence

EROSITA (X-ray), Churazov+ 2021

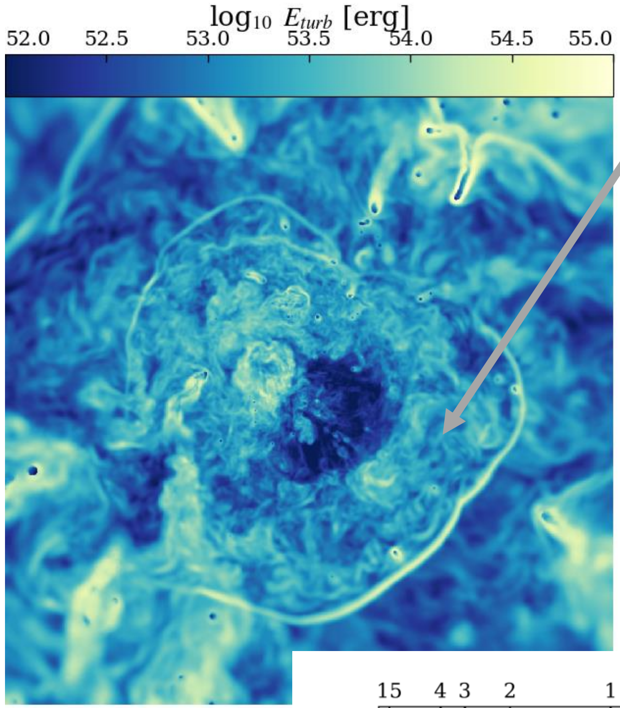


Sanders & Fabian 2013



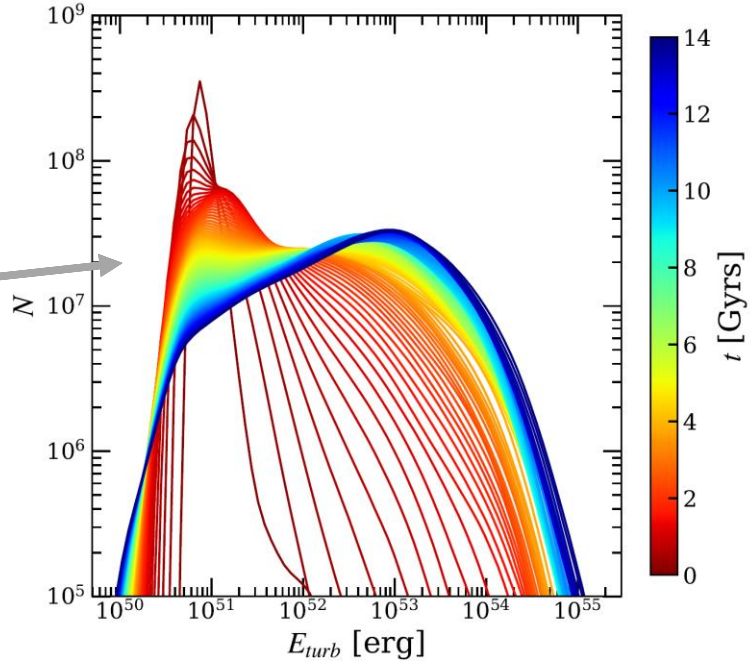
Numerical Challenges

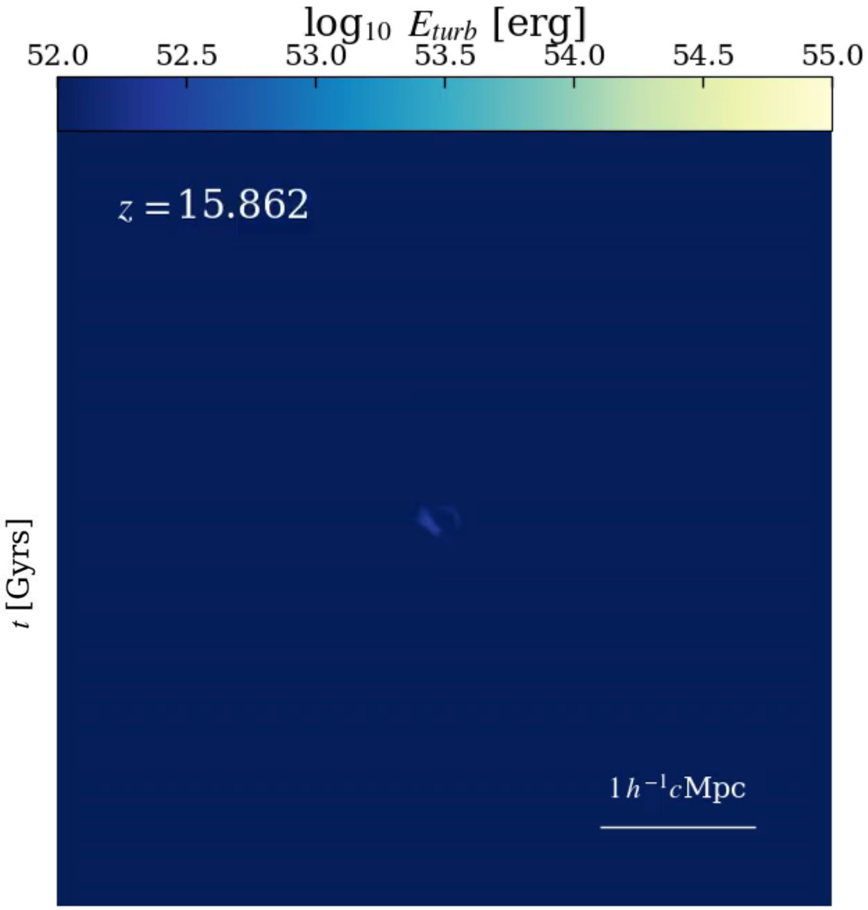
Do simulations reproduce Turbulence?

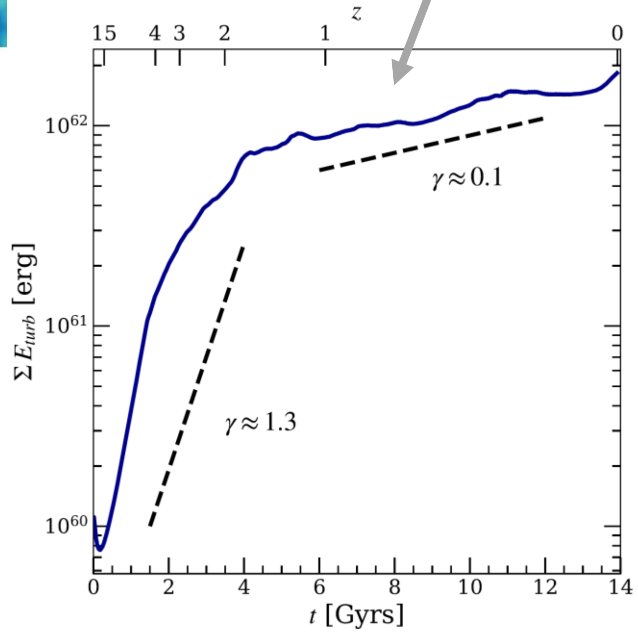


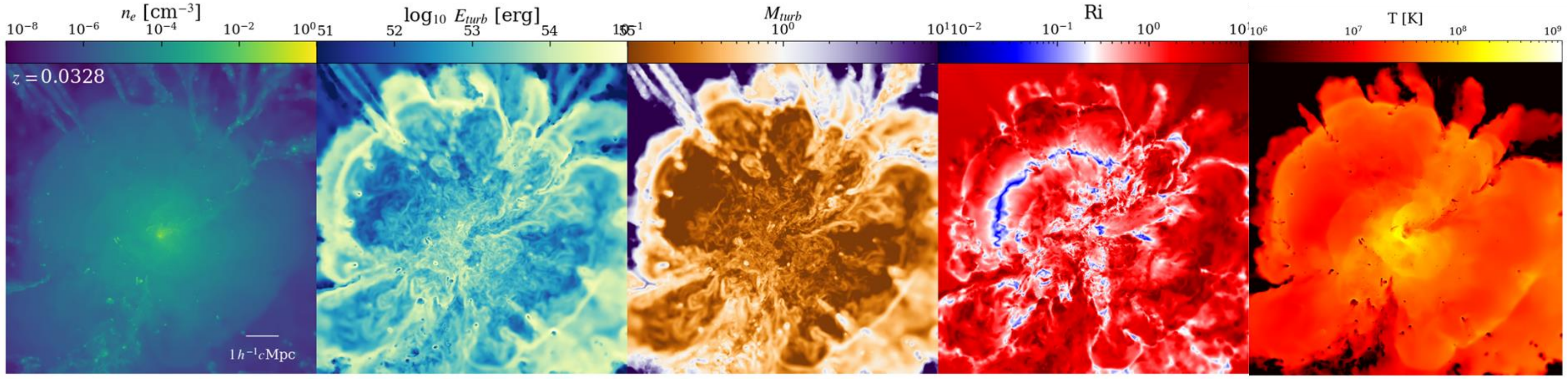
Injection of turbulence behind the shocks!

Turbulence only grows with time!



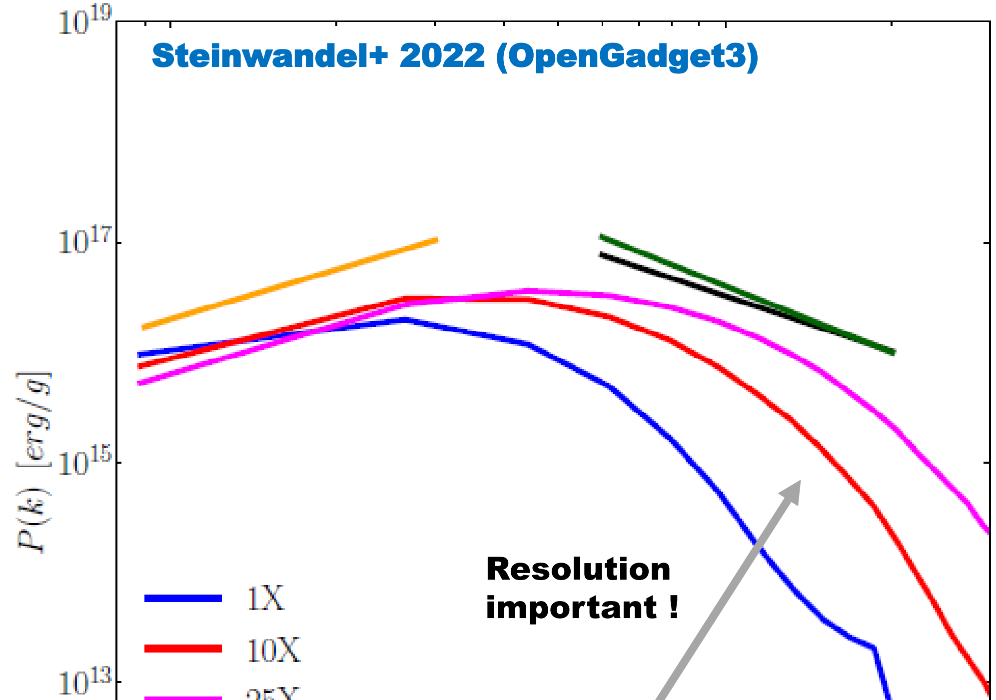




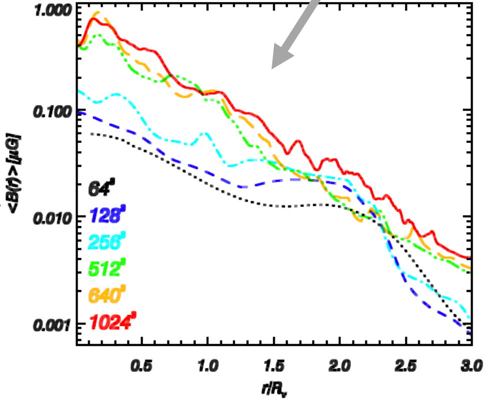


Ludwig Böss

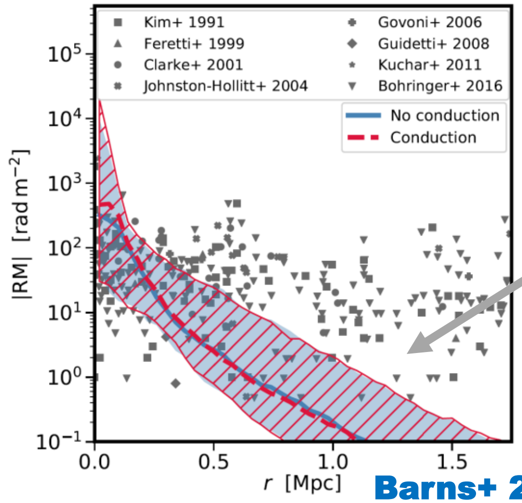
Simulations of turbulent dynamo in the ICM



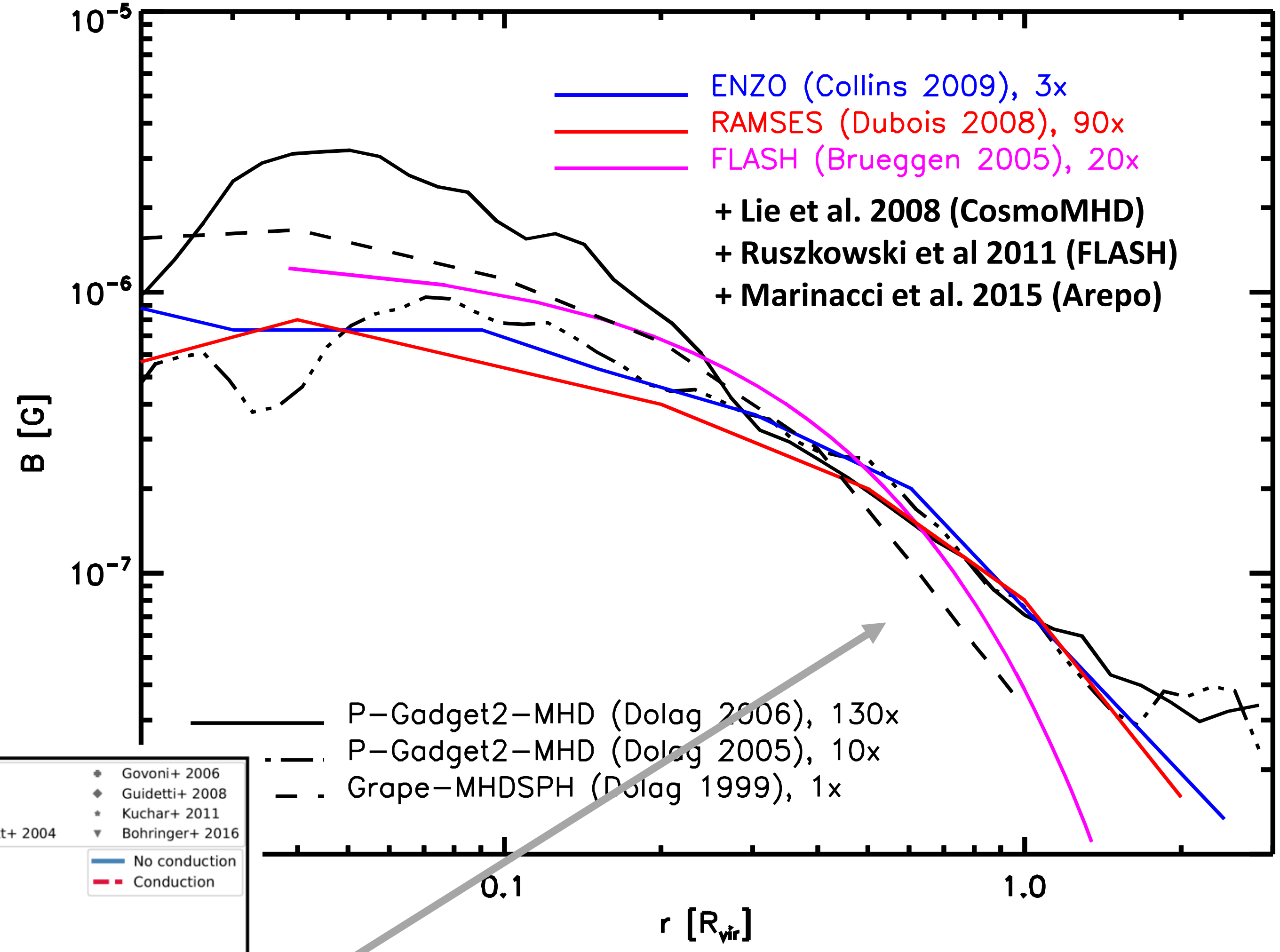
Resolution important !



Vazza et al. 2014 (ENZO)

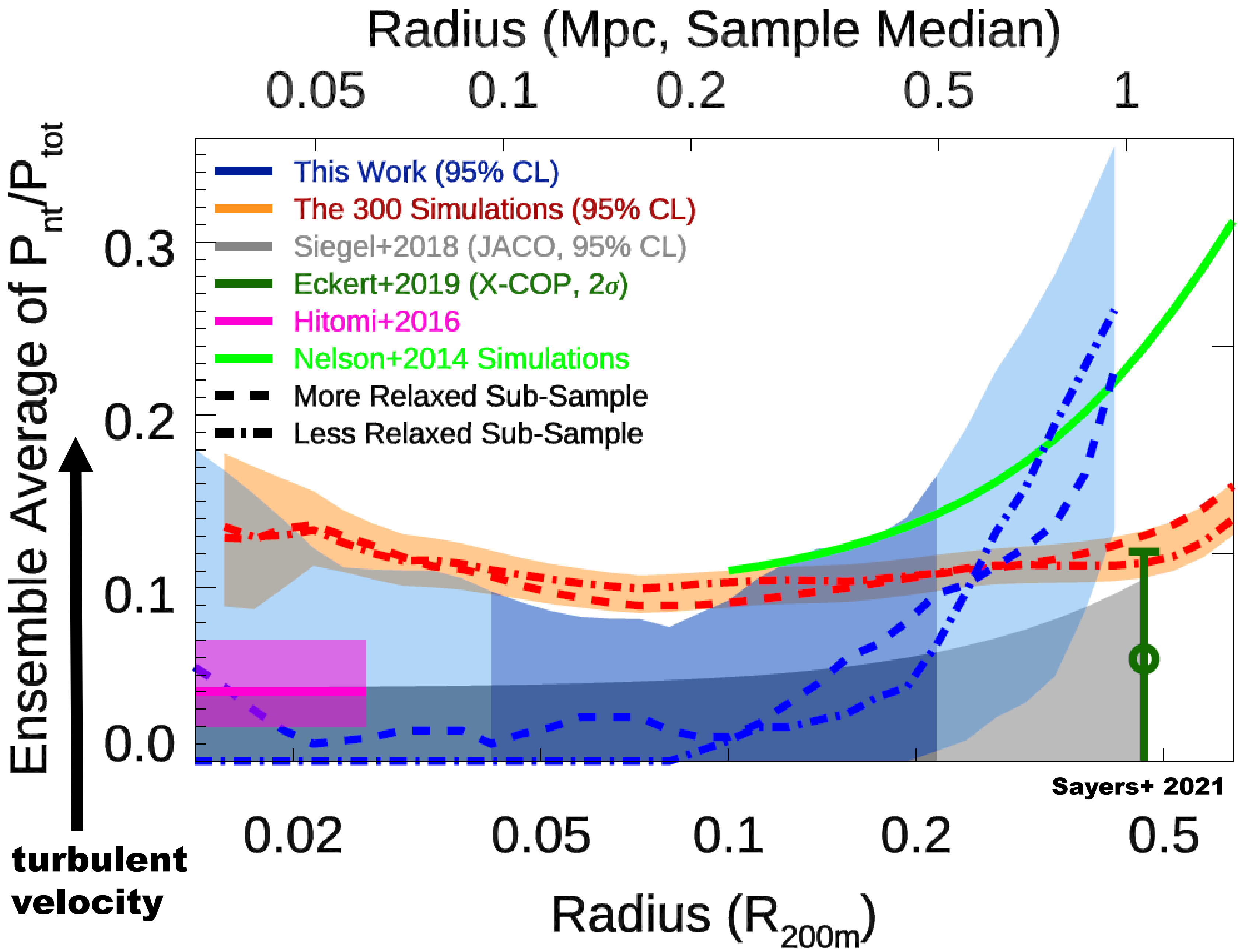


Barns+ 2019 (AREPO)



Profile too steep !

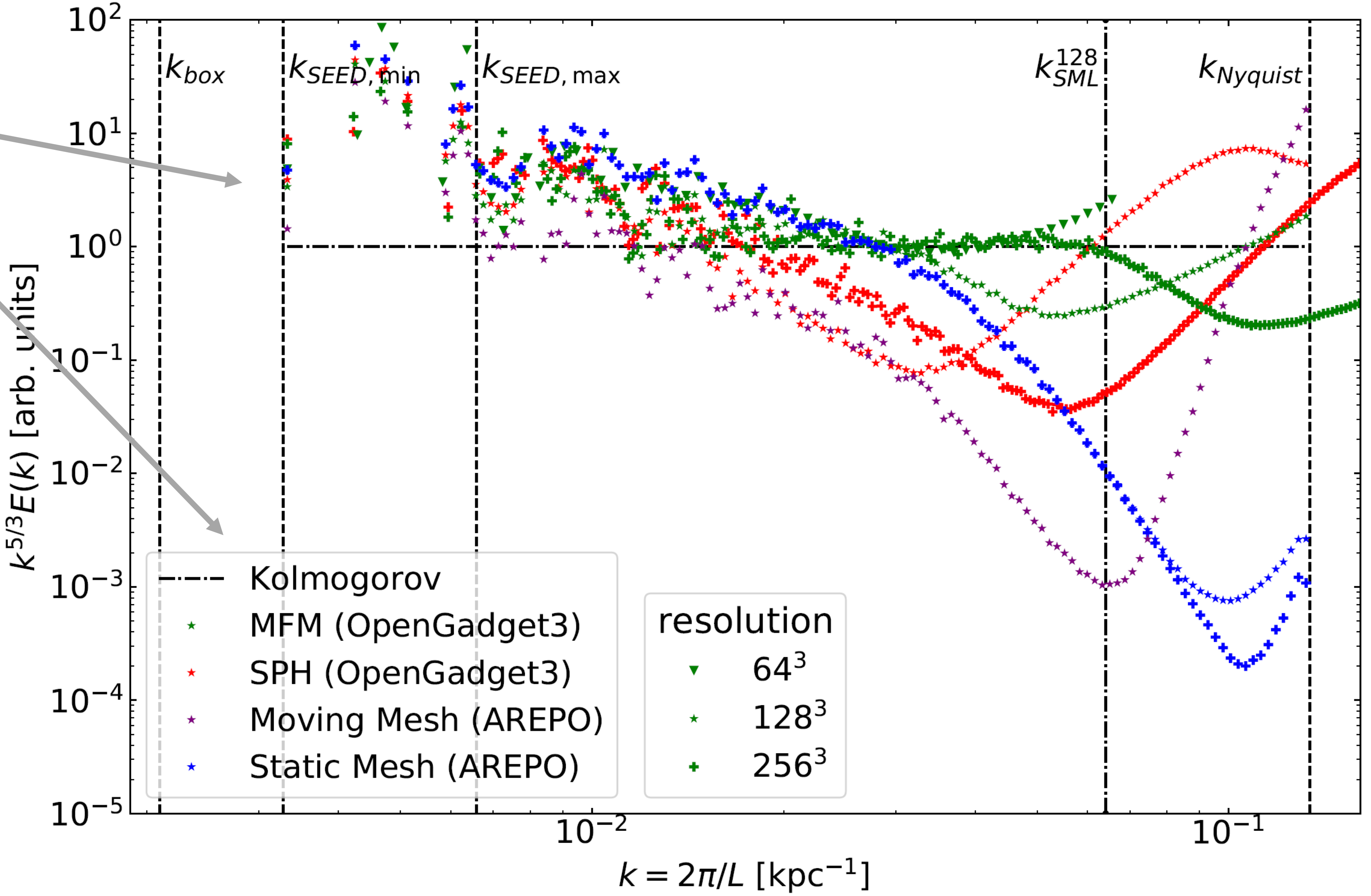
Observational inferred Turbulence in Galaxy Clusters



Simulations seems not to produce “relaxed” systems …

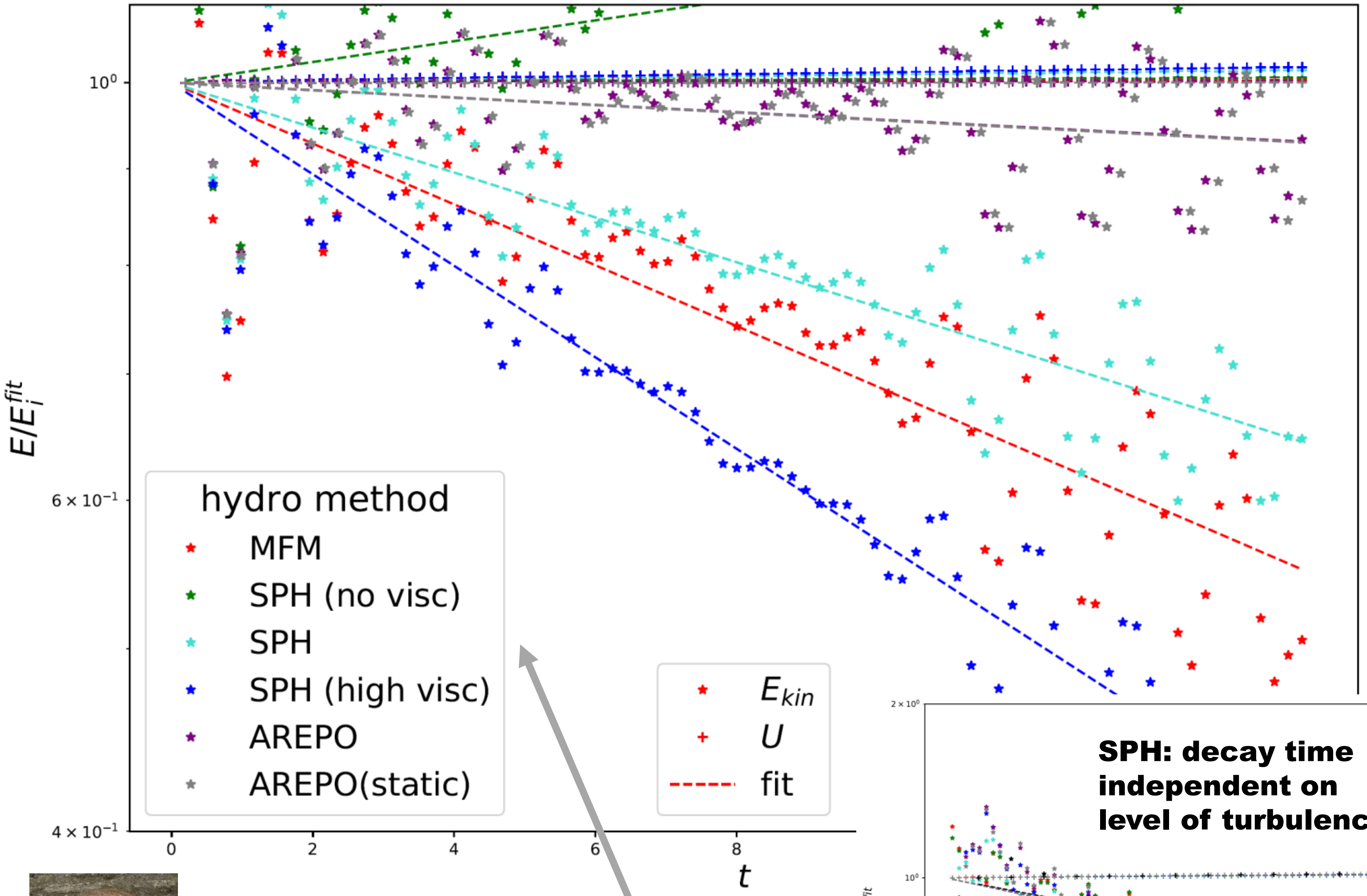
Decaying Turbulence in Simulations and different methods (I)

- IC: $\rho = const$, seed ≈ 70 large scale modes.
- $X = E_{turb}/E_{therm} = 0.3$, such that $\mathcal{M} \approx 0.07$
- Go down to $X = 10^{-4}$ or $\mathcal{M} \lesssim 0.004$
- Use different hydro methods/codes for calculation.

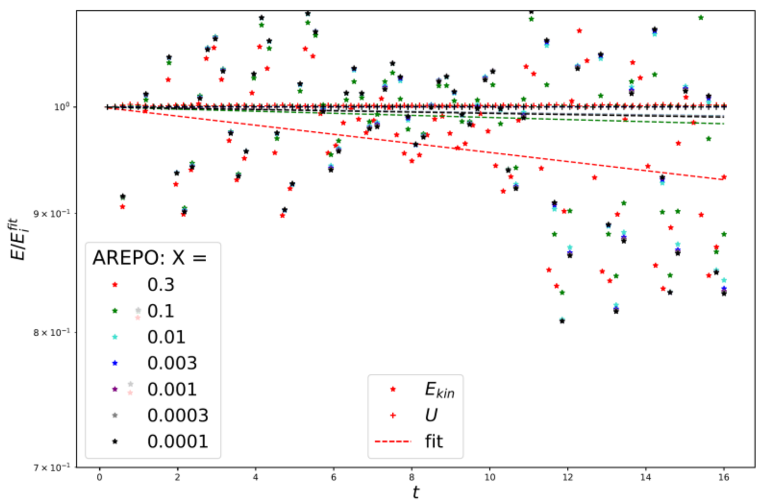


Frederick Groth

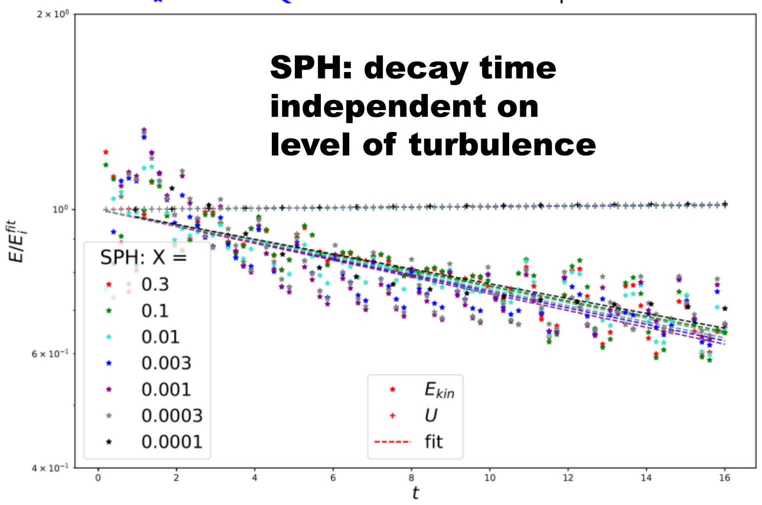
Decaying Turbulence in Simulations and different methods (II)



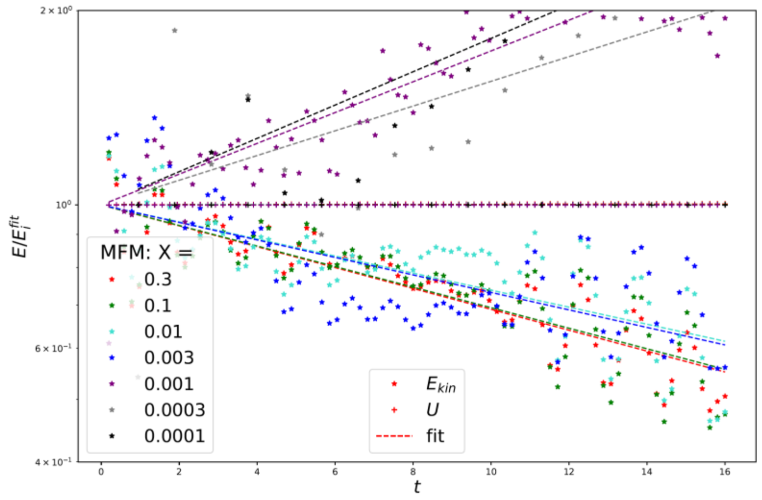
SPH: but depending on artificial viscosity!



AREPO: No decay of turbulent energy!



SPH: decay time independent on level of turbulence



MFM: decay time similar to SPH for X>0.003 but then numerical artefacts!

Frederick Groth

Effect of viscosity?

mach number

size of galaxies

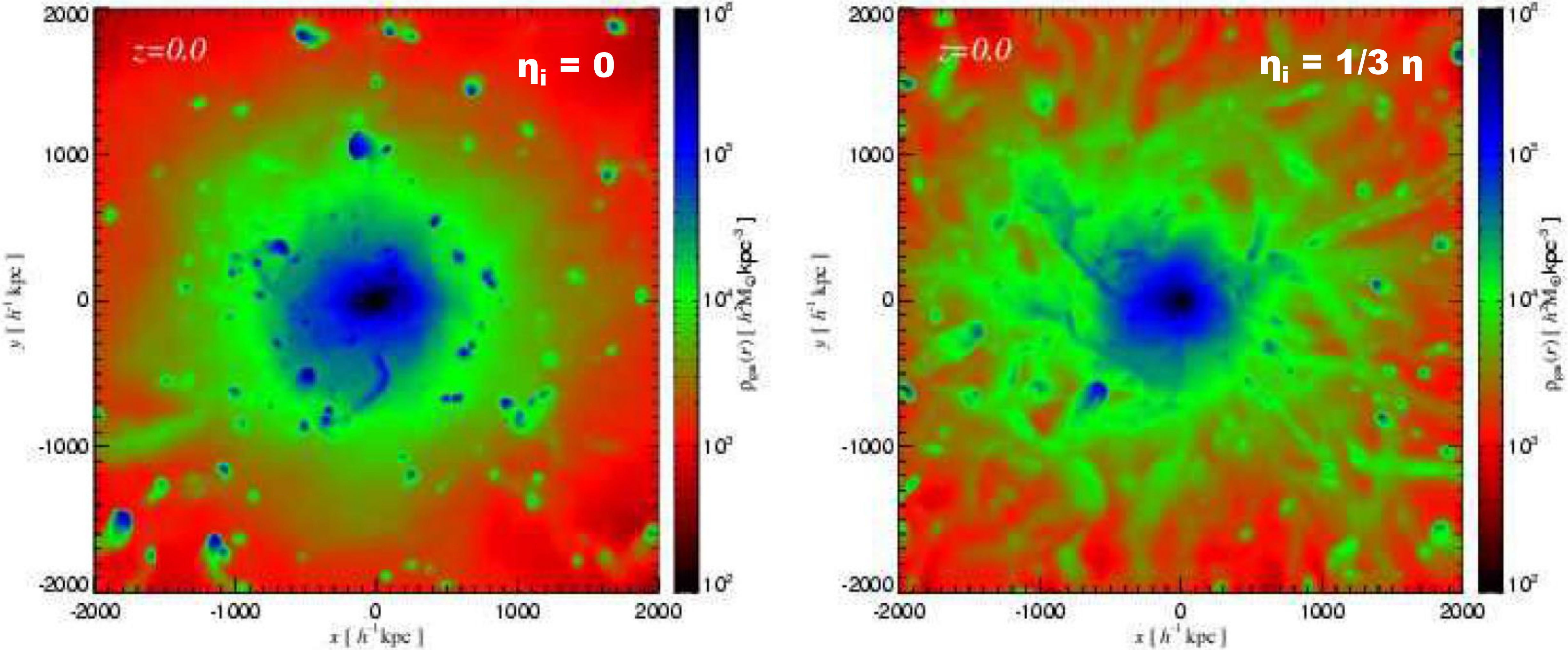
$$Re \approx 3M\left(\frac{l}{\lambda_i}\right)$$

$l \sim \lambda_i$!!!

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

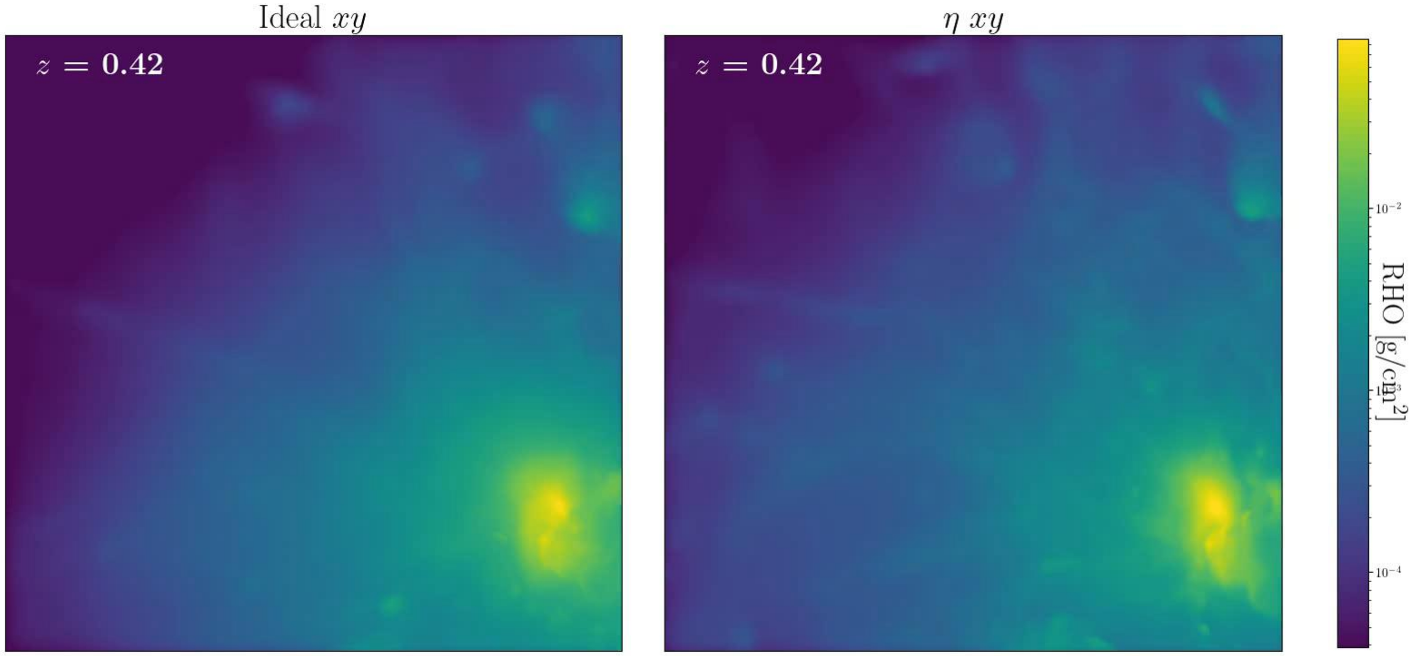
$$\eta \approx \frac{1}{3} m_i n_i \langle v_i \rangle_{rms} \lambda_i$$
$$\approx 5500\,\mathrm{gm\,cm^{-1}\,s^{-1}}\left(\frac{T_e}{10^8\,K}\right)^{5/2}\left(\frac{\ln\Lambda}{40}\right)^{-1}$$

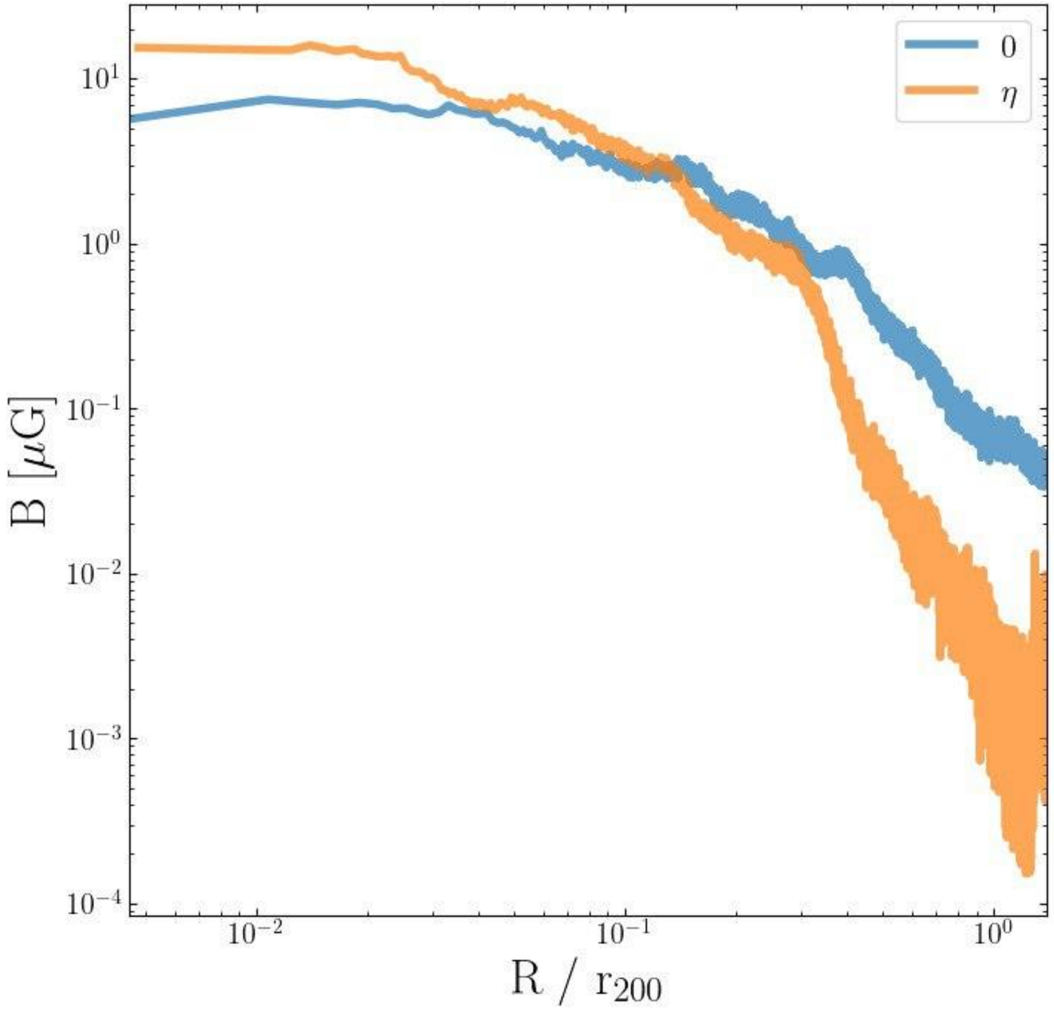
ICM density maps for simulations
Without (left) and with (right) viscosity



Sijacki & Springel 2006

Role of viscosity in Simulations and different methods (I)



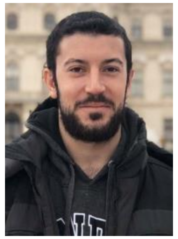


$$\sigma_{\alpha\beta}\Big|_i = \eta \left(\frac{\partial v_\alpha}{\partial x_\beta}\Big|_i + \frac{\partial v_\beta}{\partial x_\alpha}\Big|_i - \frac{2}{3}\delta_{\alpha\beta}\frac{\partial v_\gamma}{\partial x_\gamma}\Big|_i \right) + \zeta\delta_{\alpha\beta}\frac{\partial v_\gamma}{\partial x_\gamma}\Big|_i$$

0

Shear viscosity

Bulk viscosity



Tirso Marin

$$\eta = 0.406\,\frac{m_i^{1/2}(k_B\,T_i)^{5/2}}{(Z\,e)^4\ln\Lambda}$$

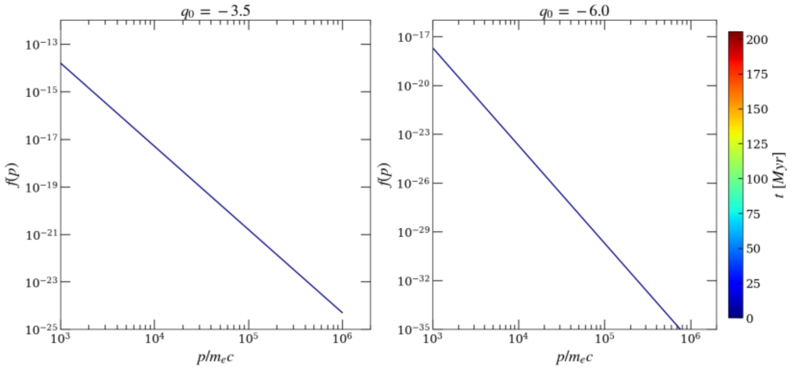
For a fully ionized plasma

Developing a Fokker-Planck solver for CRs

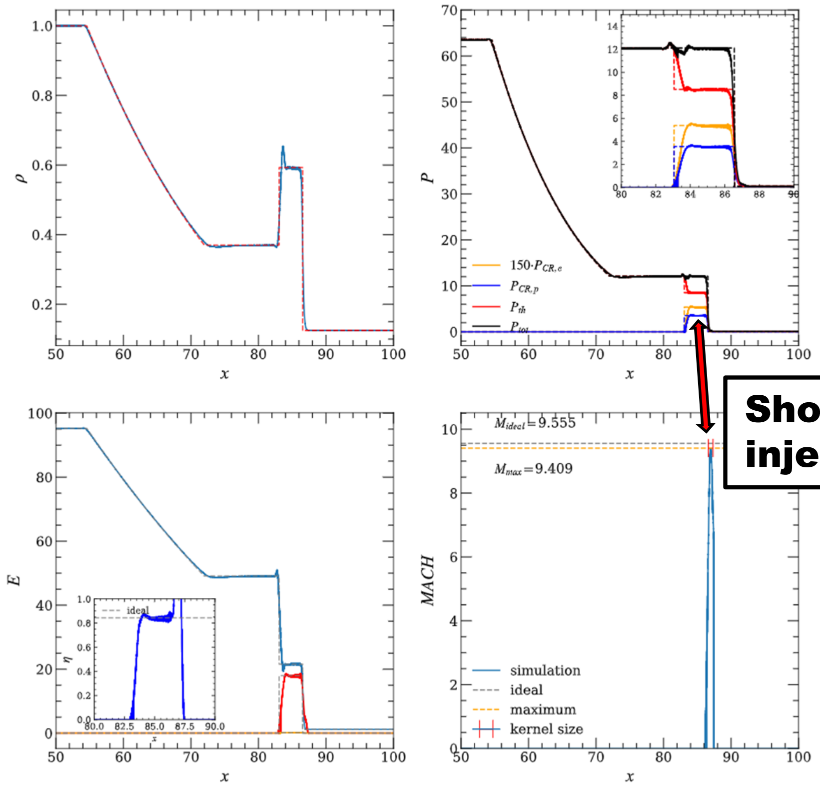
$$\underbrace{\frac{\partial f}{\partial t} + \mathbf{u}\cdot\nabla f}_{\text{spatial convection}} - \underbrace{\nabla\left(\boldsymbol{\kappa}\nabla f\right)}_{\text{spatial diffusion}} = \underbrace{\frac{1}{3}\left(\nabla\cdot\mathbf{u}\right)p\frac{\partial f}{\partial p}}_{\text{momentum convection}}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

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

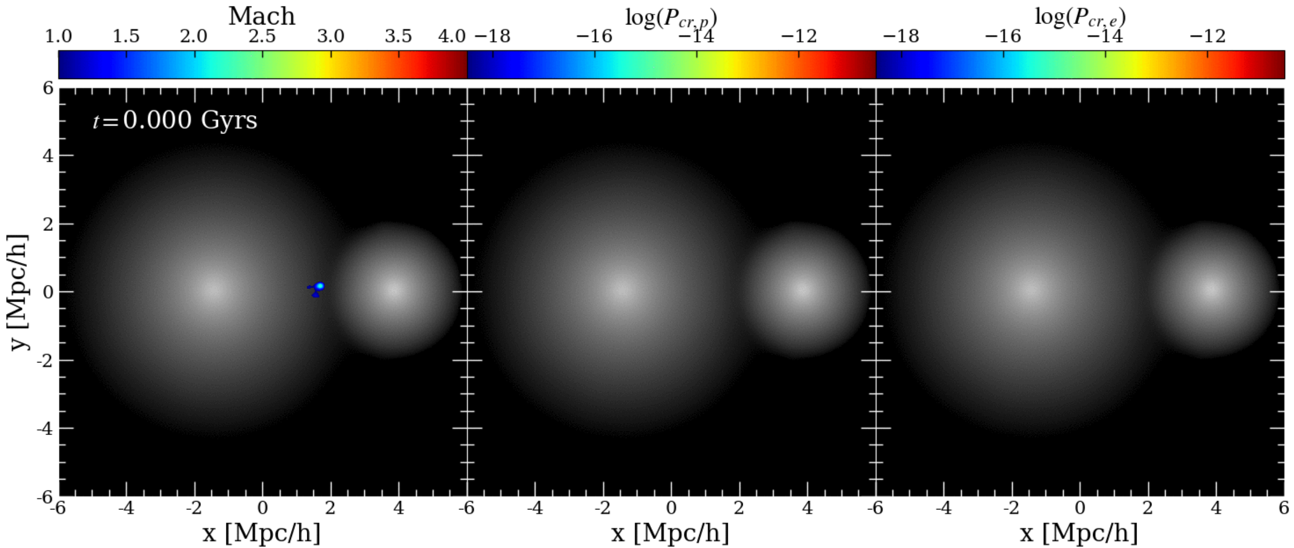
Cooling of CRe



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

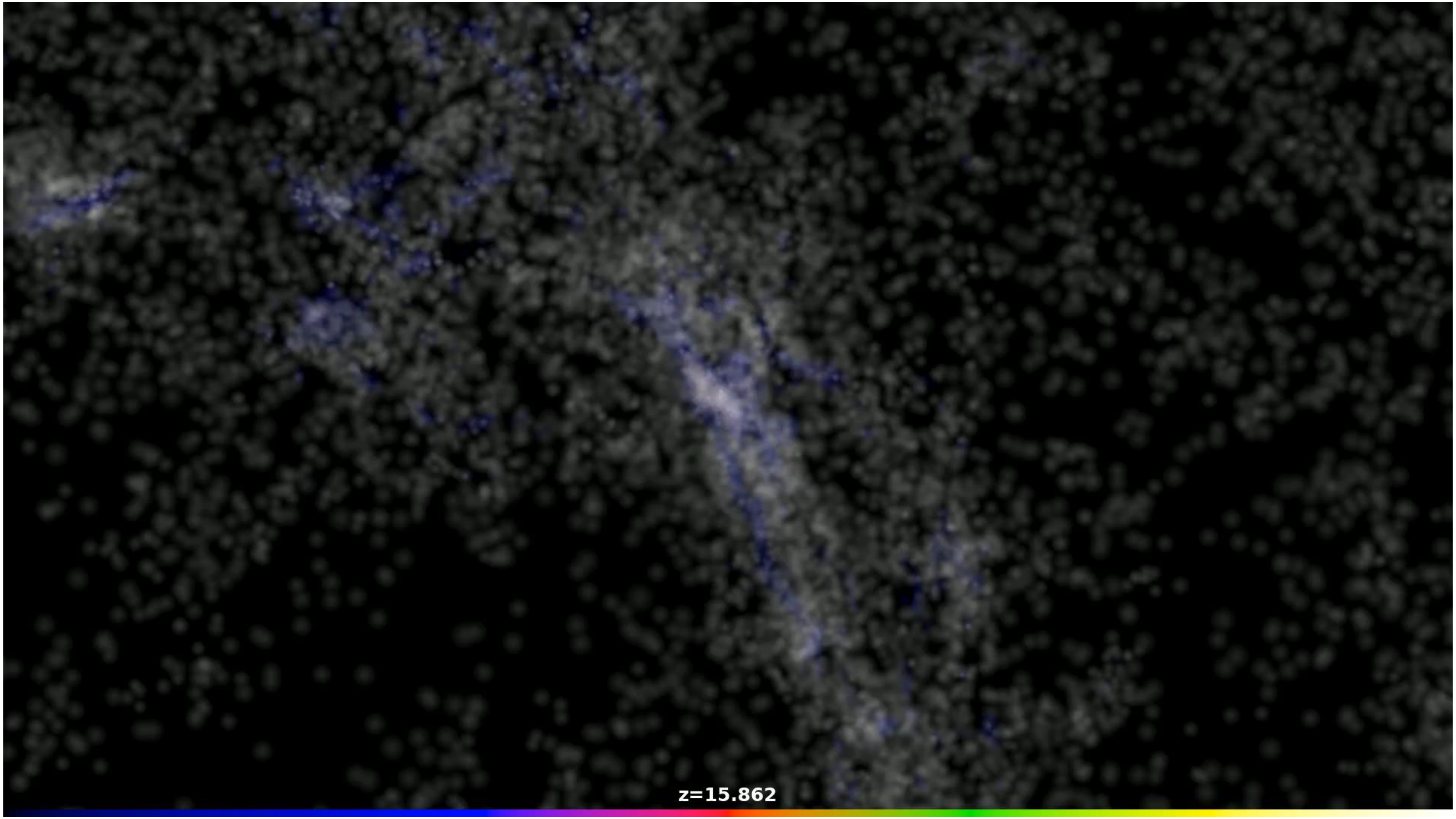


Shock injection



Shocks in Galaxy Clusters

Galaxy clusters, the hot atmosphere of massive galaxies



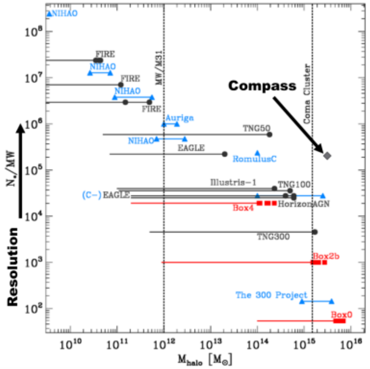
Mach number: 2 3 4 >5

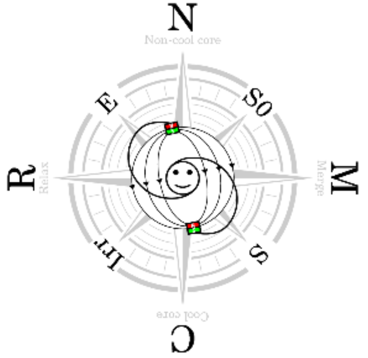
Galaxy Clusters:

M ~ 2x$10^{15}$$M_{sol}$

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

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



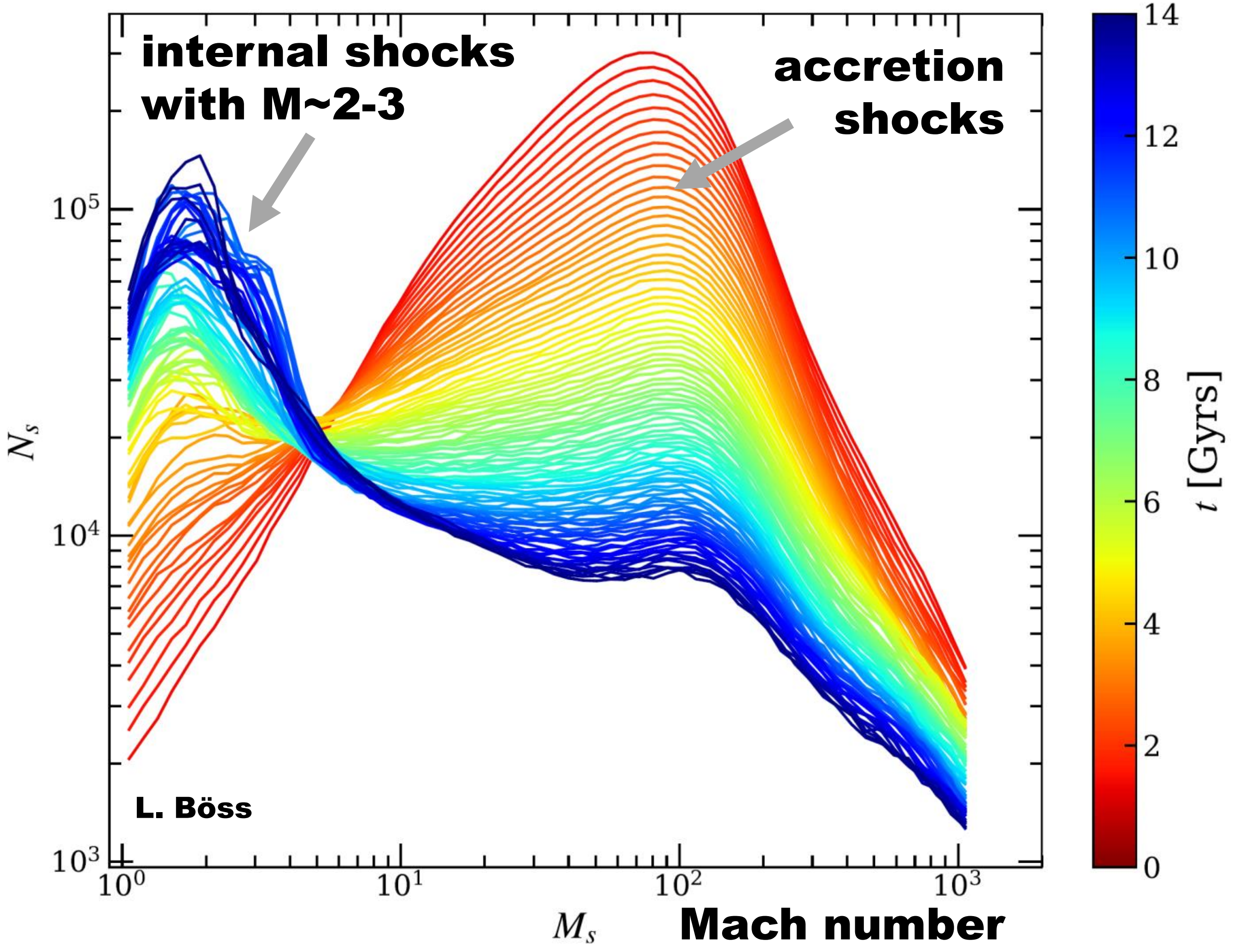


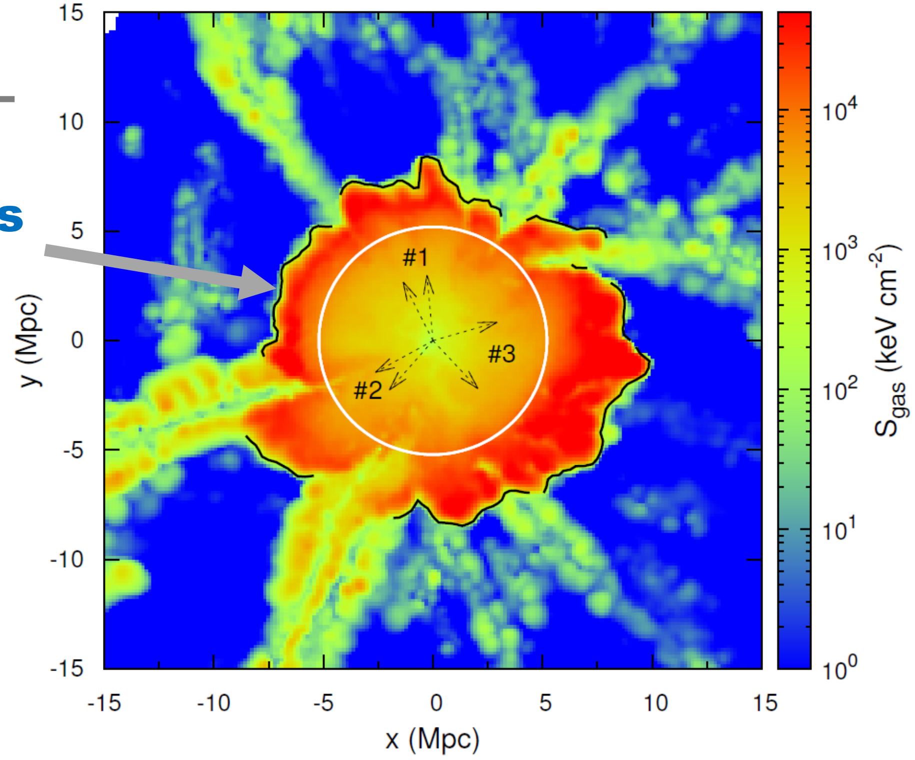
C·O·M·P·A·S·S

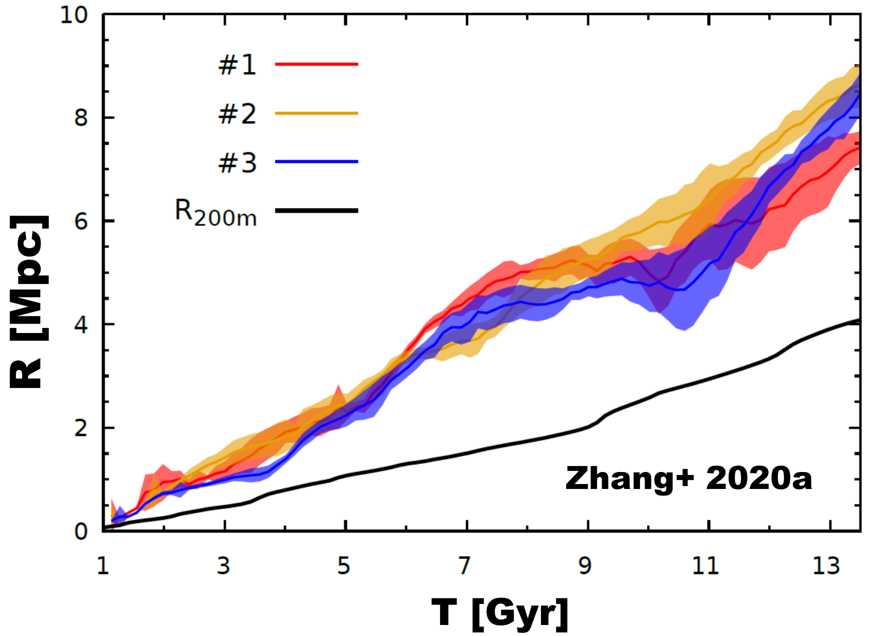
Can we still learn something from this?

When clusters form, they are heated by internal shocks!

Virial shock is pushed back through collisions with internal shocks!

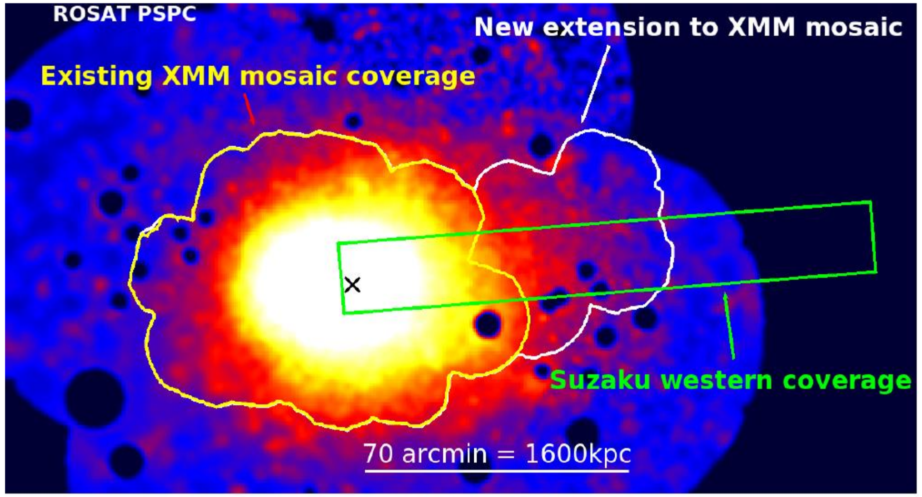


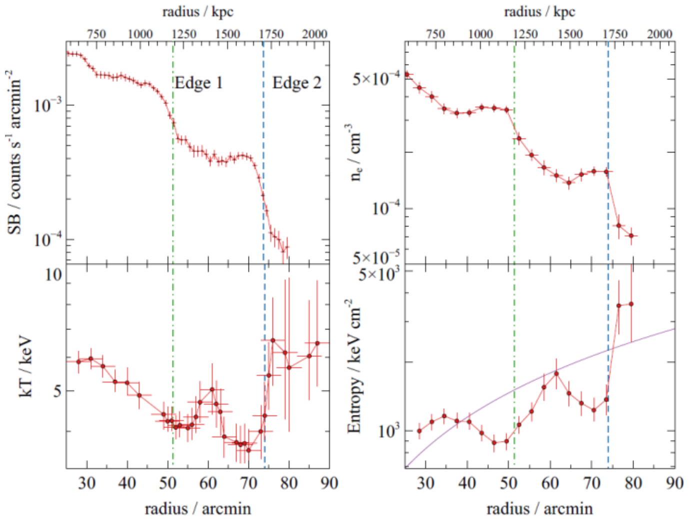




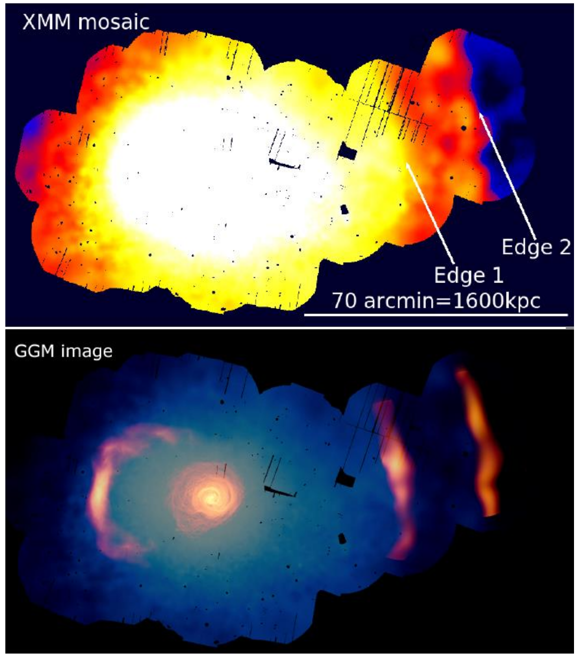
Or even explain some observations?

Perseus Cluster



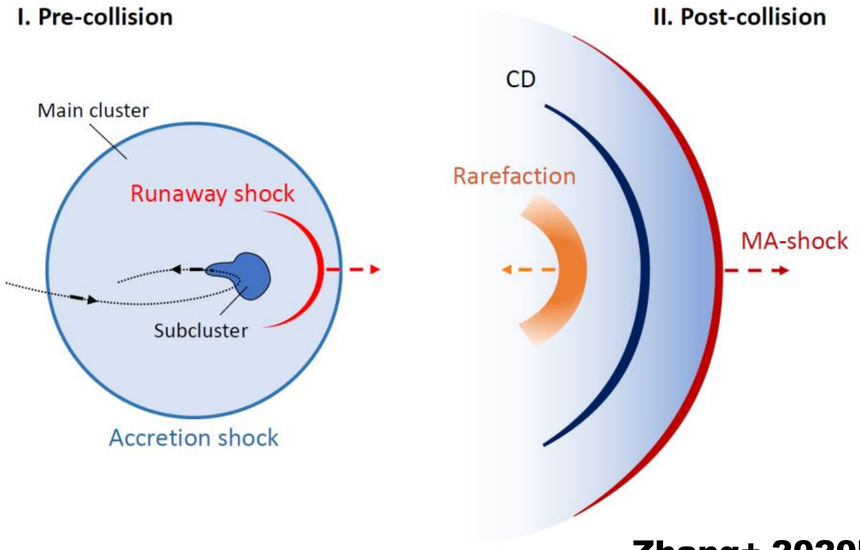


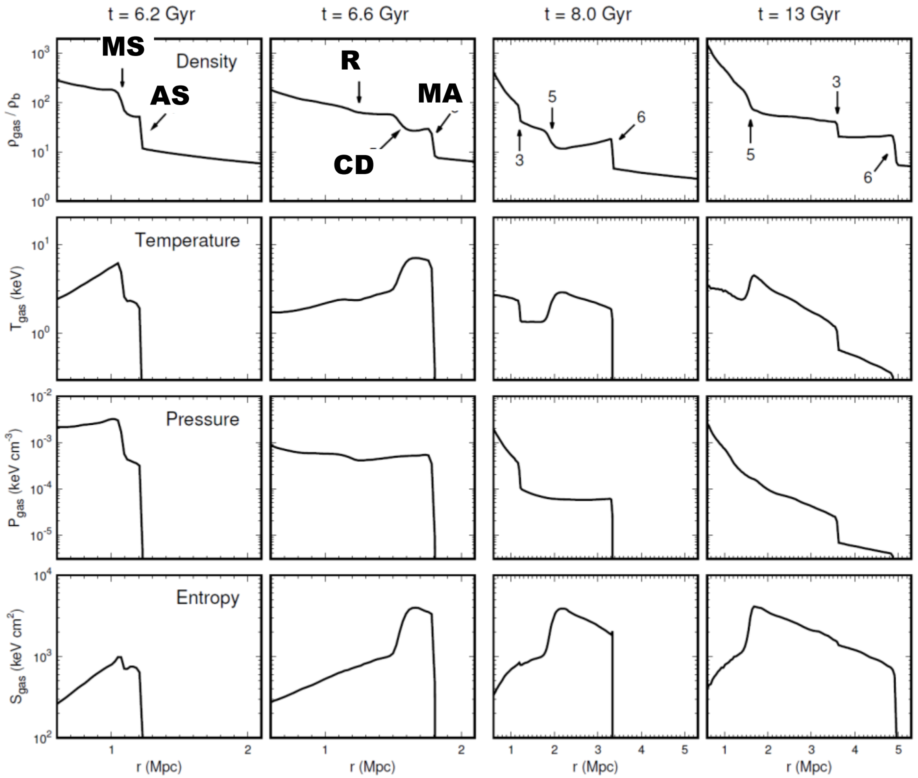
Contact Discontinuity (CD) at R=1.7Mpc observed in Perseus.
▪ Suggested to be sloshing
►but Timescale would be 8 Gyr !
►Can be more naturally created through collision of shocks !



Walker+ 2020

Idealized model

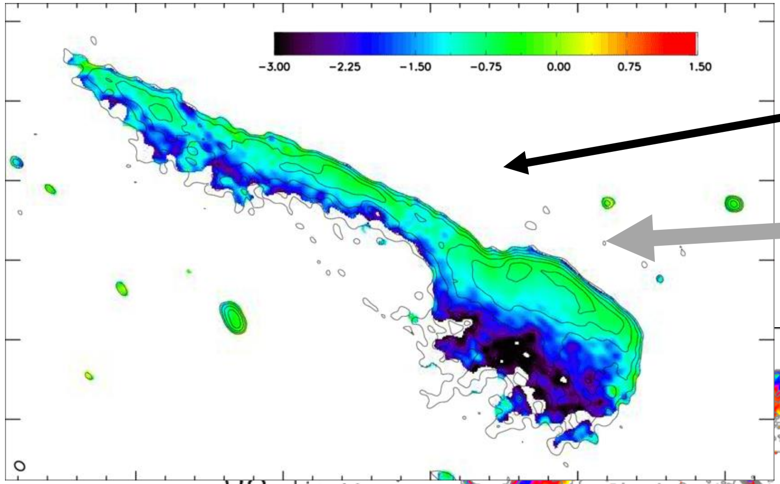




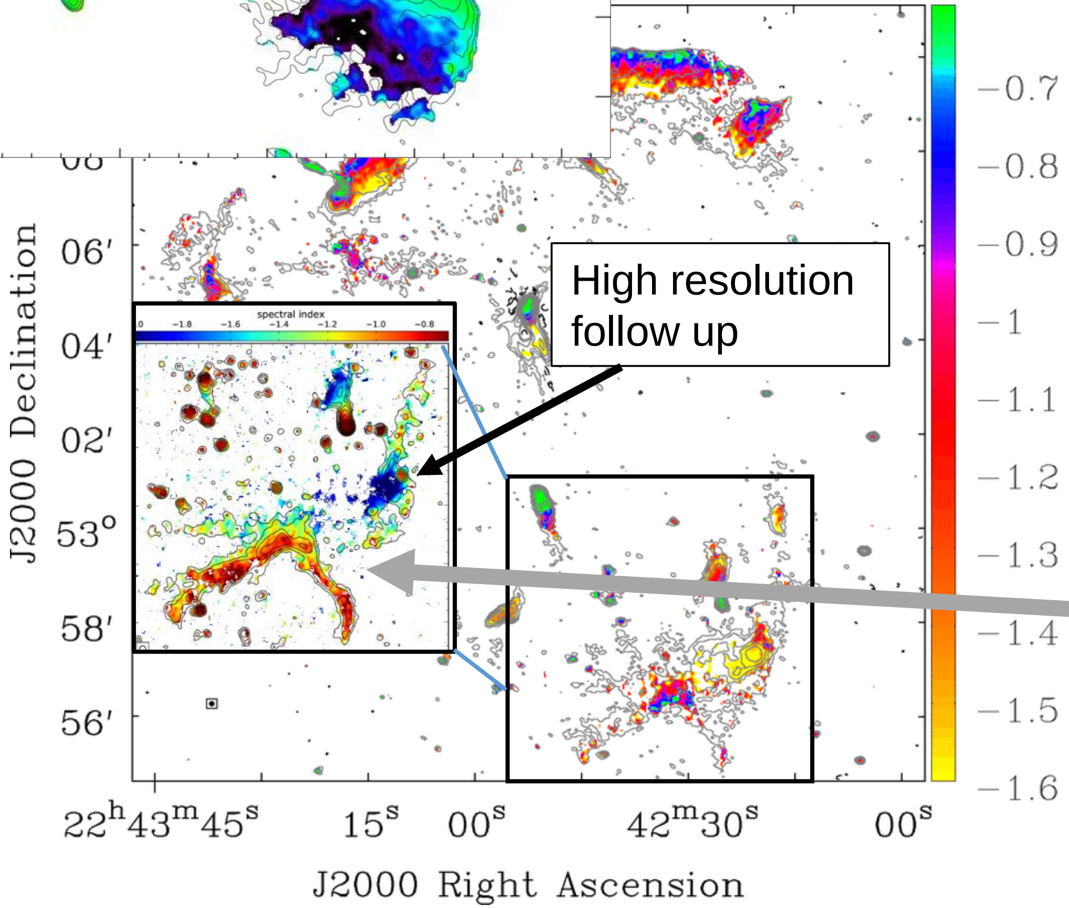
Zhang+ 2020b

Are the simulations matching the observed morphologies?

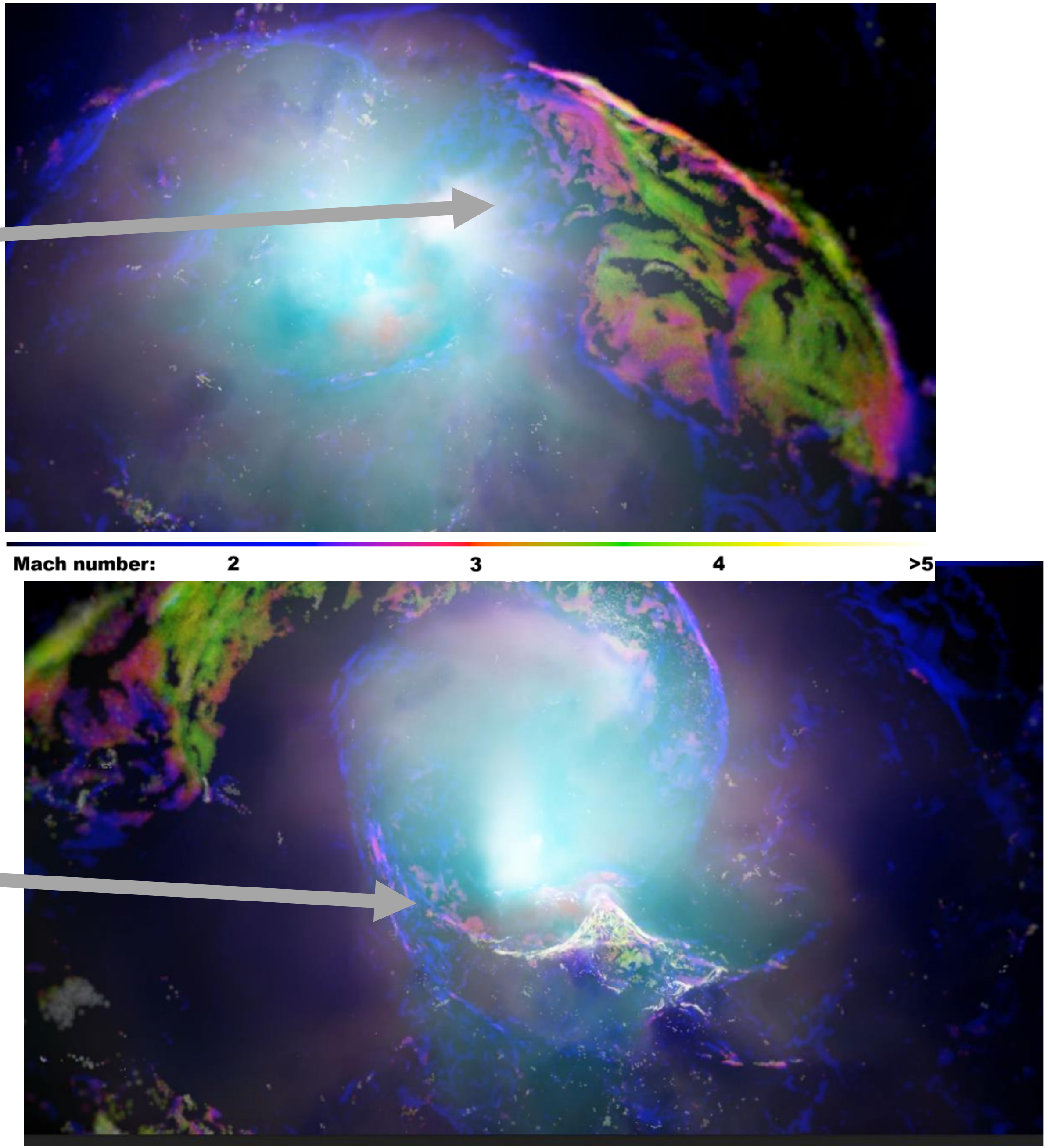
Examples for more complex shock structures observed:



Almost 2Mpc long, but not curved!

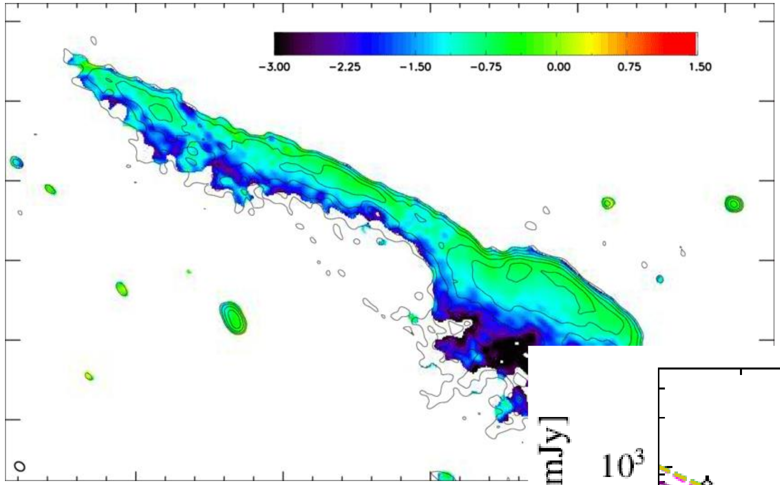


High resolution follow up

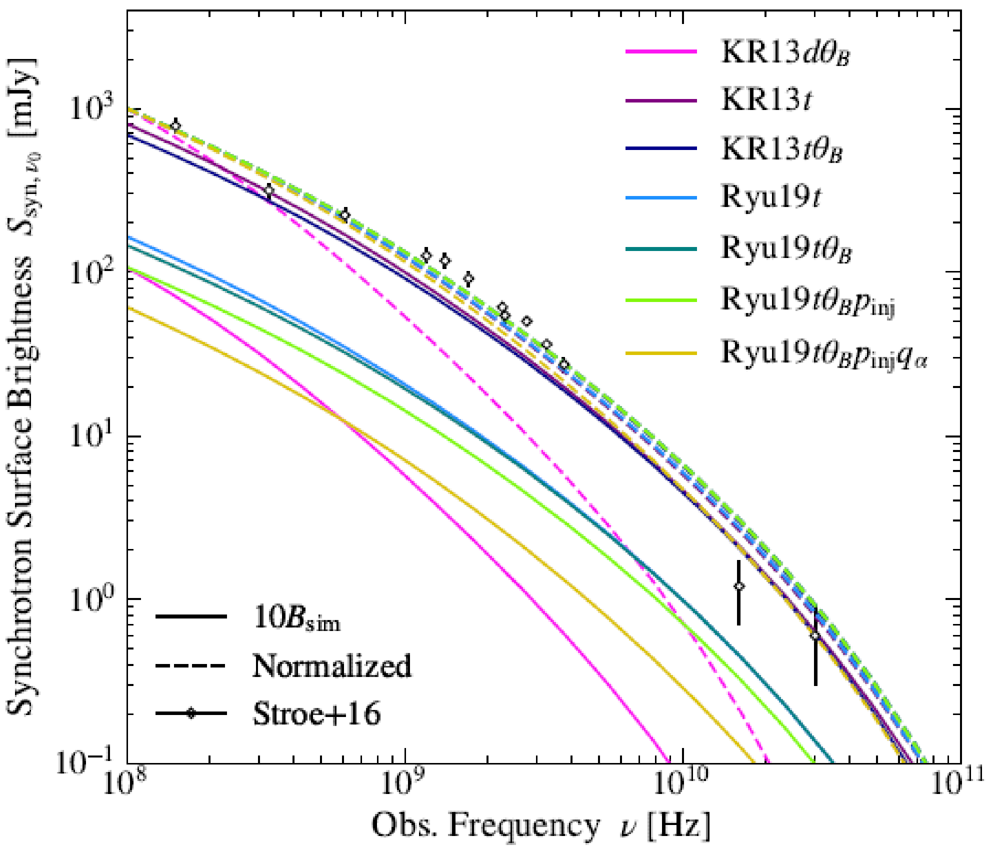


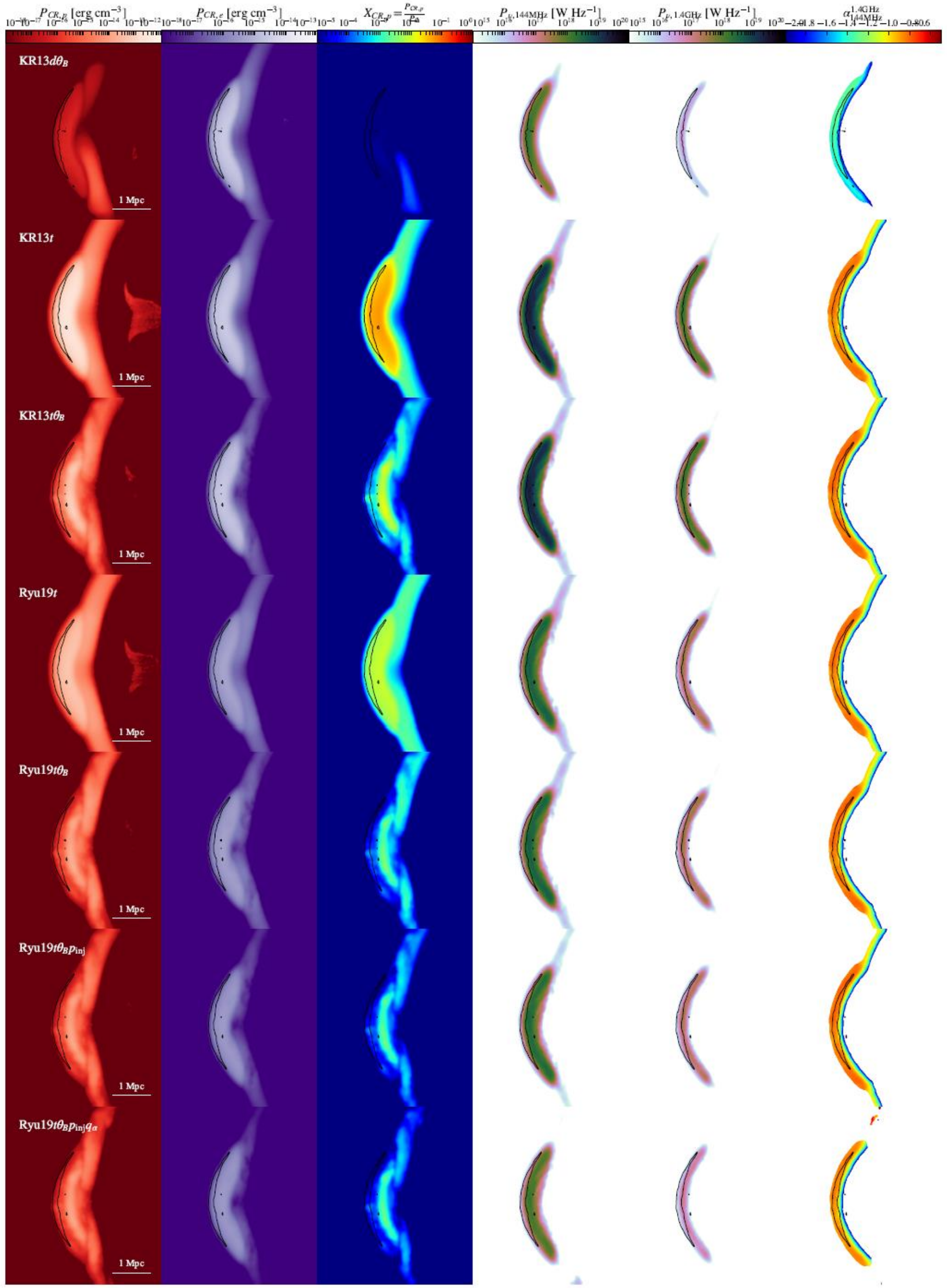
What to choose for the (re-)acceleration efficiency?

Spectral index steepening and acceleration efficiency



Böss+ 2022





Ludwig Böss

The new Frontier for 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

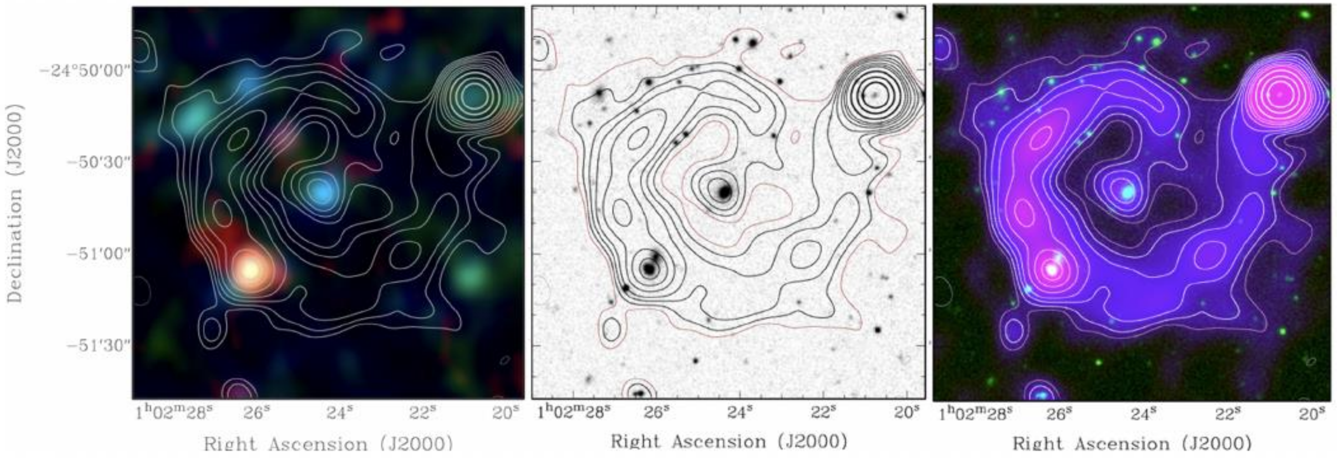


Figure 2. ASKAP radio continuum contours of ORC J0102–2450 overlaid onto a WISE RGB colour image (red: 12μm (W3), green: 4.6μm (W2), and 3.4μm (W1)

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, but could be just merger shocks ?

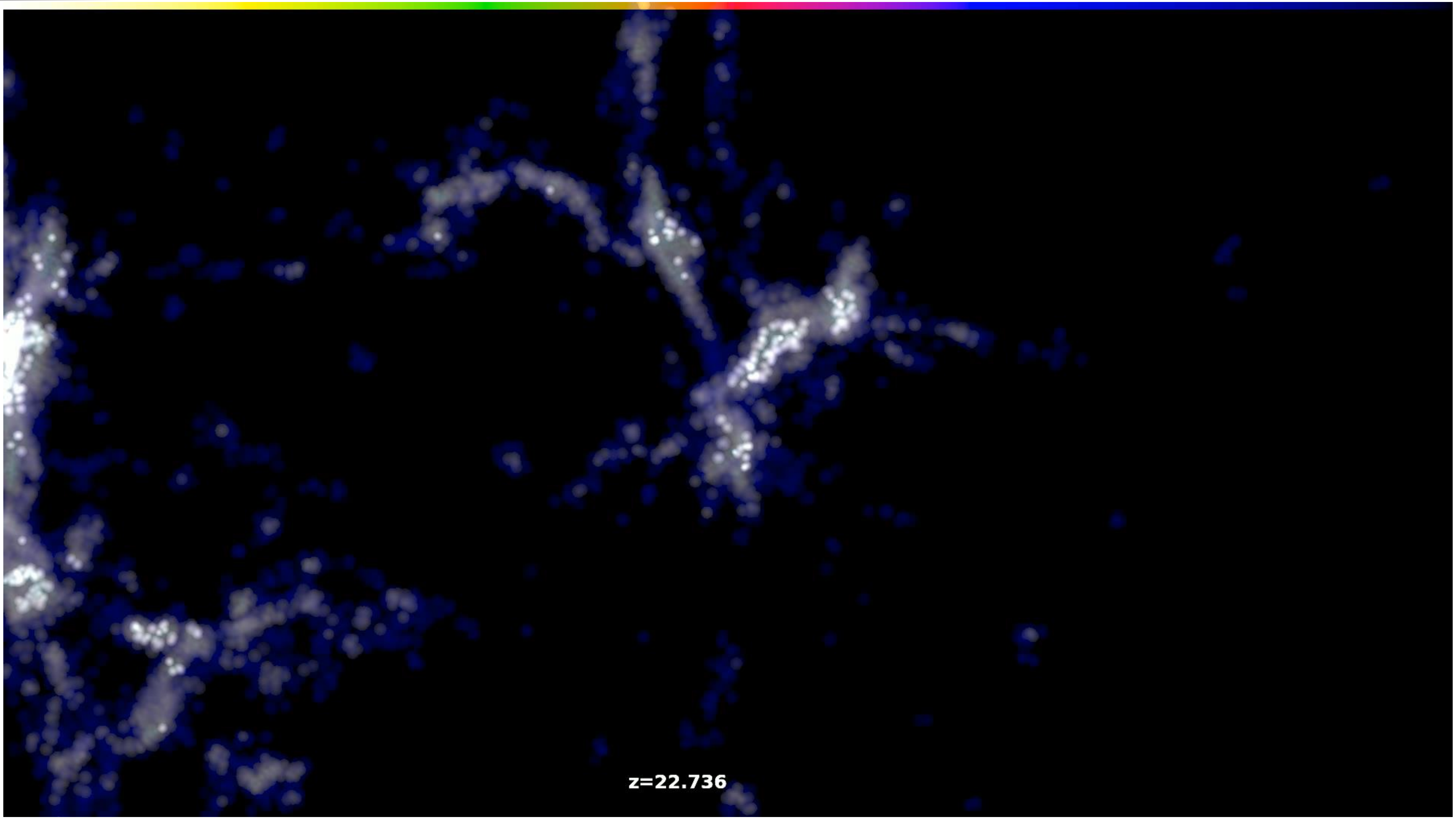
ORC centre galaxies

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

ORC 1 ORC 4 ORC 5

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

Are galaxies different (MW like halo at 25000x)



1300h^{-1}ckpc

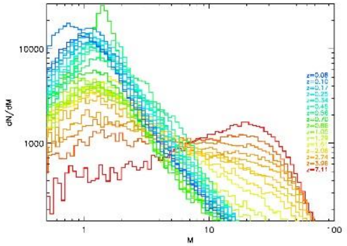
R_{vir}

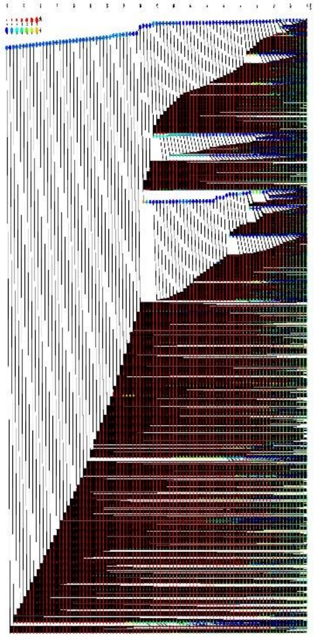
MW like Galaxy:

M ~ 1.2x$10^{12}M_{sol}$

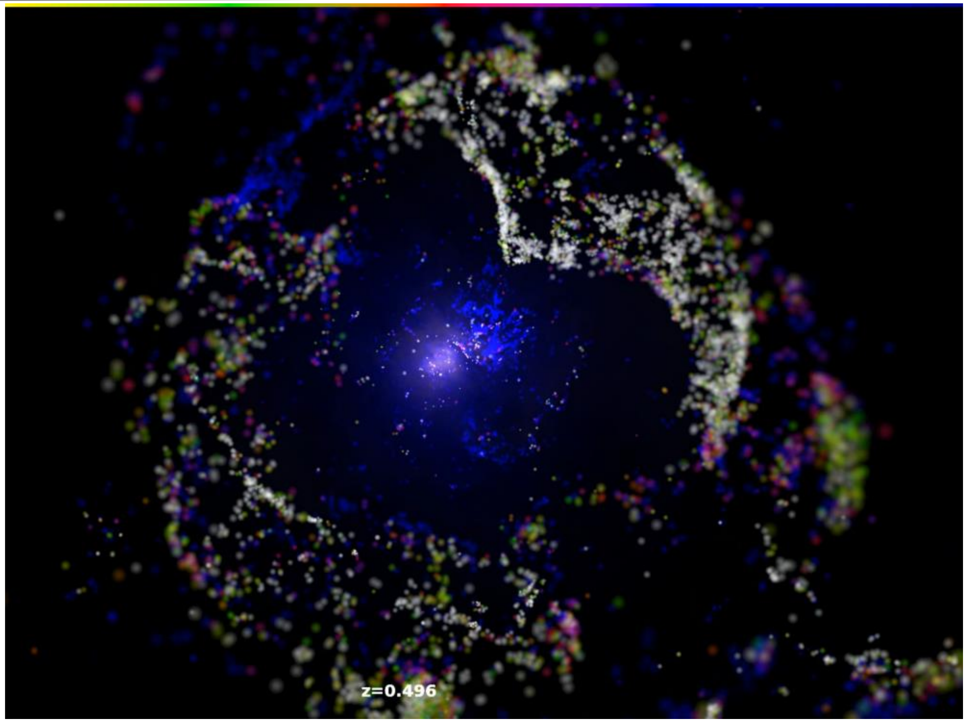
~ 4x10^{7} part in R_{vir}
~ 2.300 sat galaxies
~ 10^{7} timesteps (??)

$\varepsilon_{gas/stars}$ ~ 110 pc/h





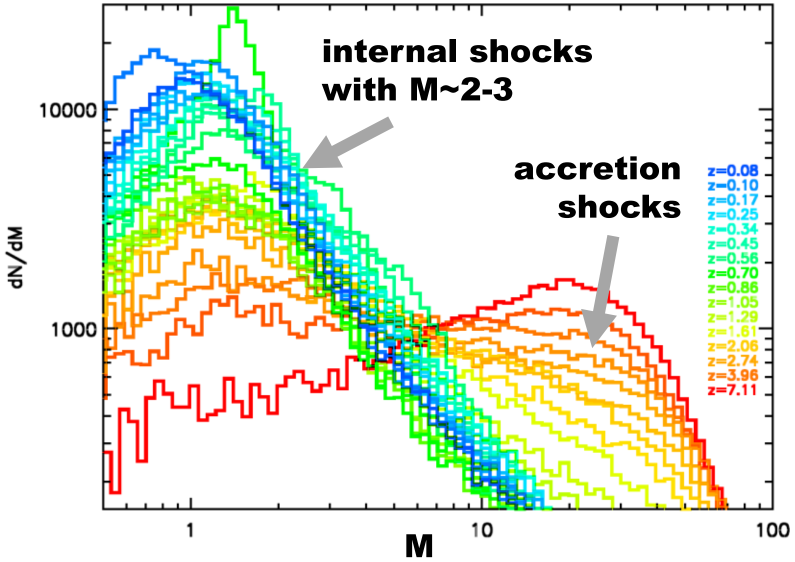
Shocks in the simulated galaxy



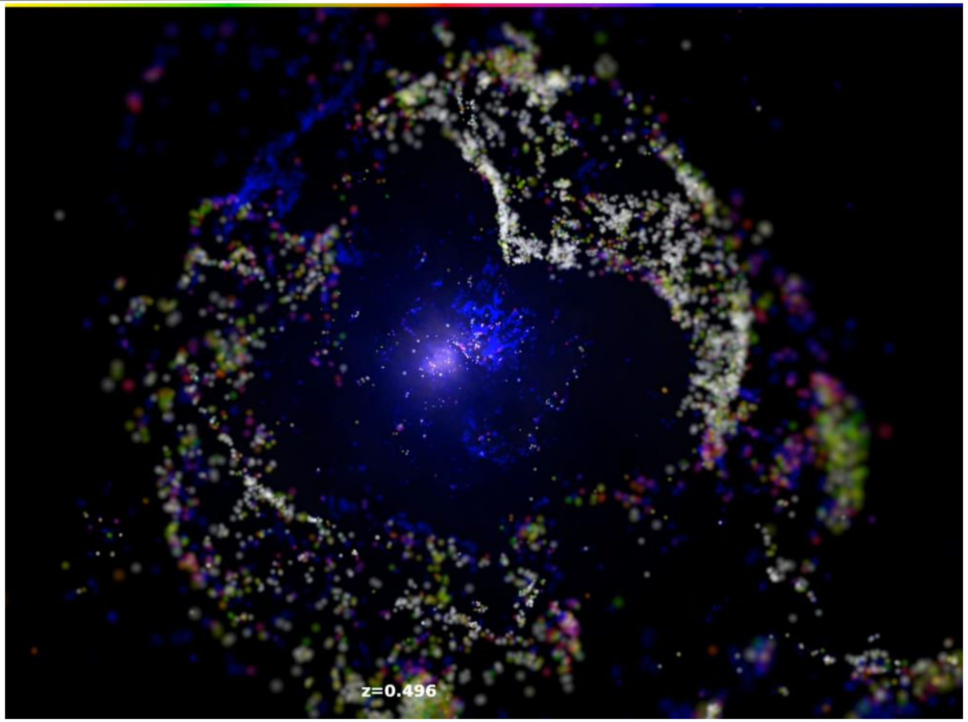
Simulated Galaxy

$M_{vir} \sim 1.2 \times 10^{12} M_{sol}$

several shocks



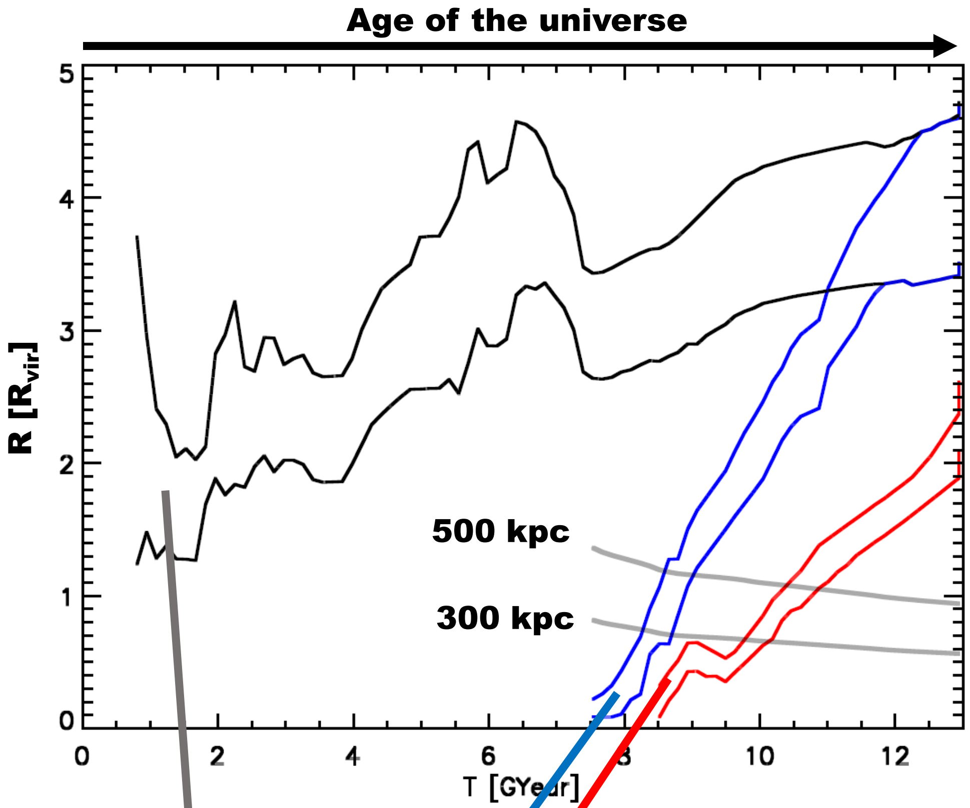
Shocks in the simulated galaxy

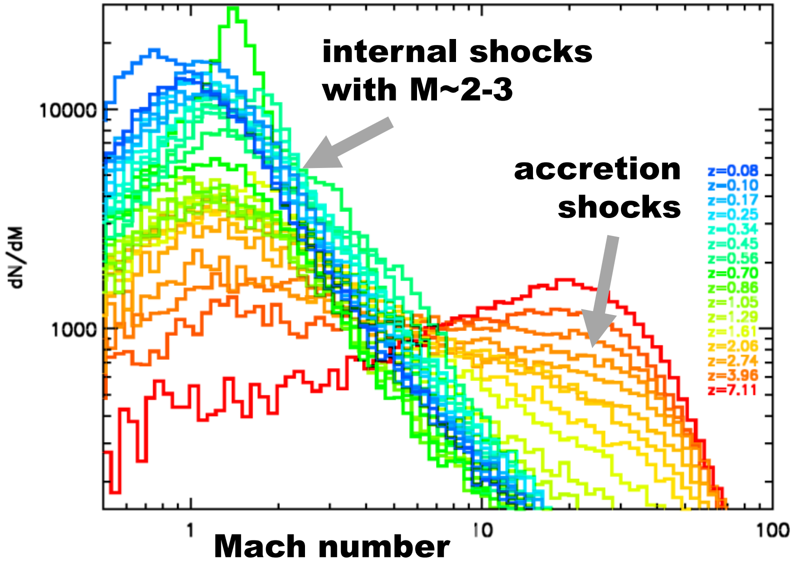


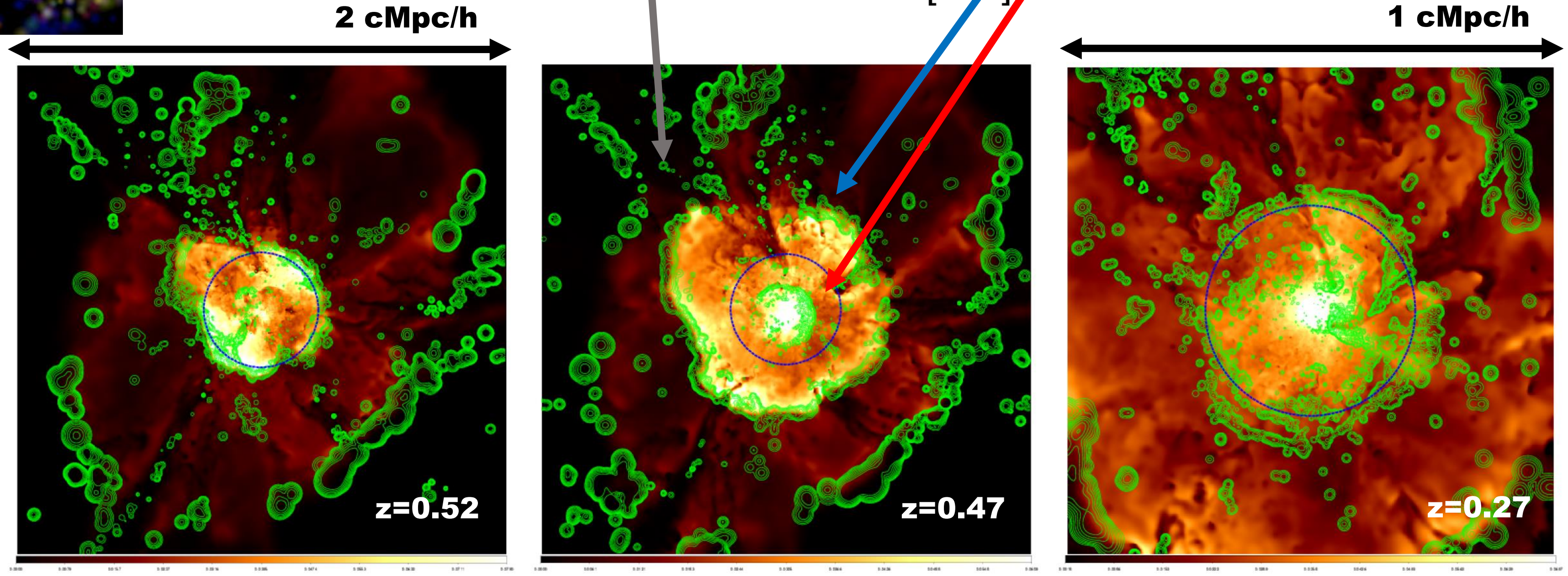
Simulated Galaxy

$M_{vir} \sim 1.2 \times 10^{12} M_{sol}$

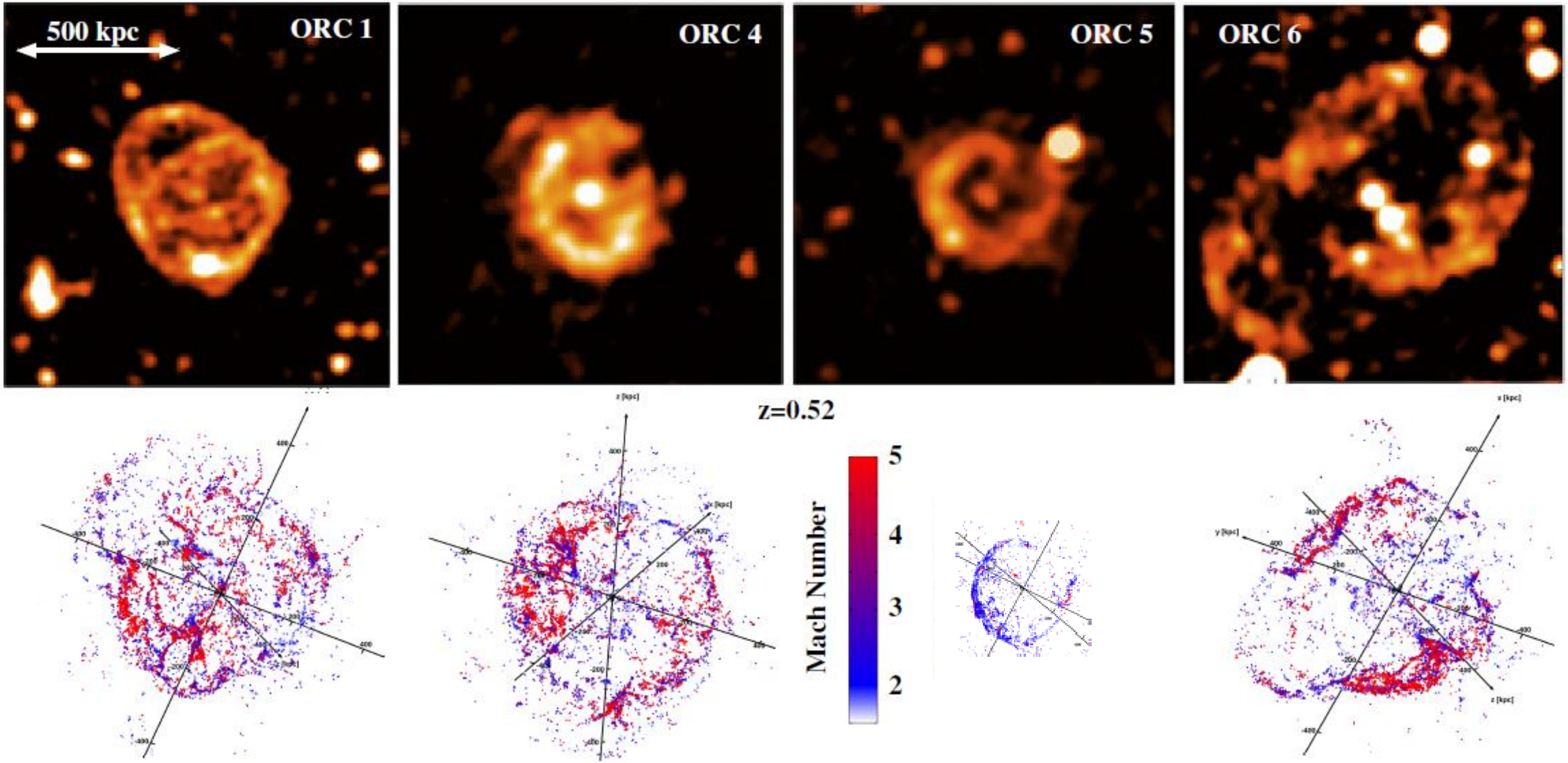
several shocks





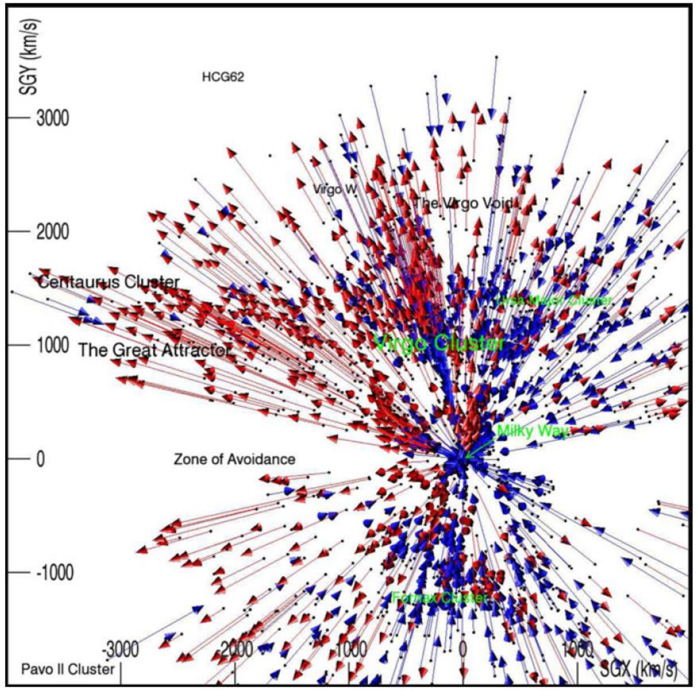


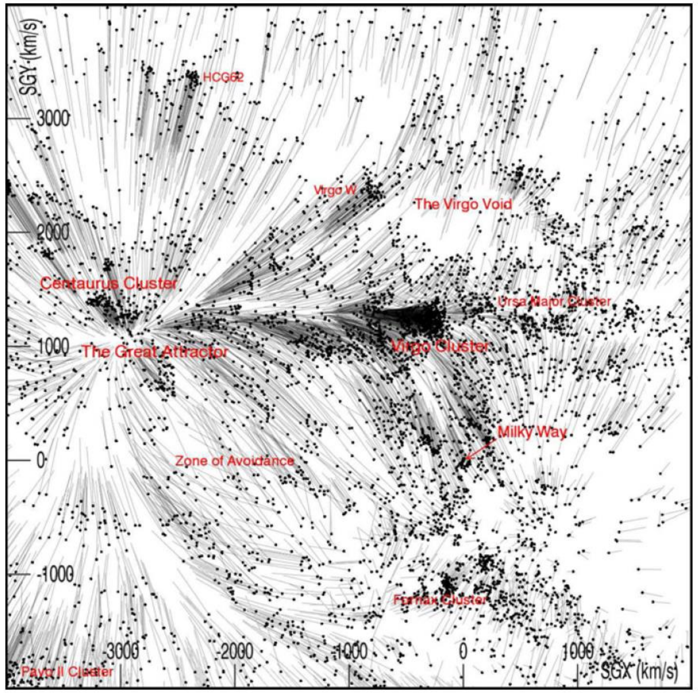
Shock structures are matching the observed ORCs



Dolag+ 2022

Towards our Local Universe



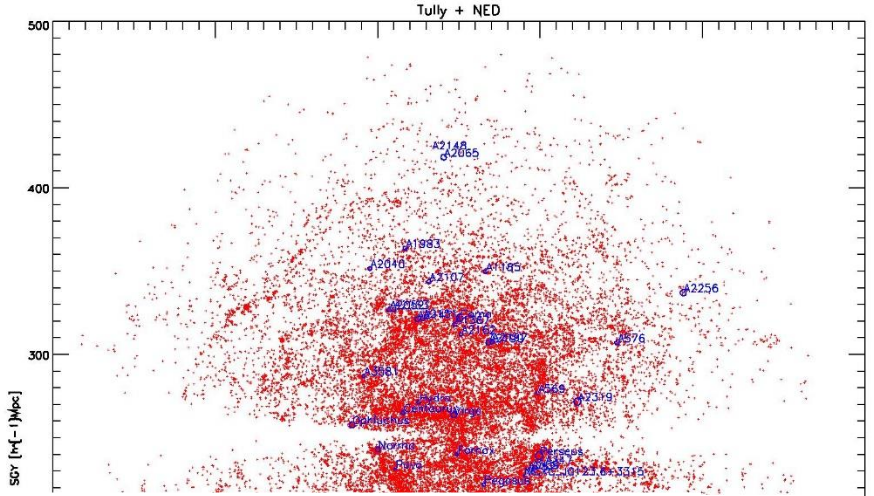


Distribution of local galaxies

Distance measures allow to obtain peculiar velocities

Wiener filter allows to re-construct velocity field

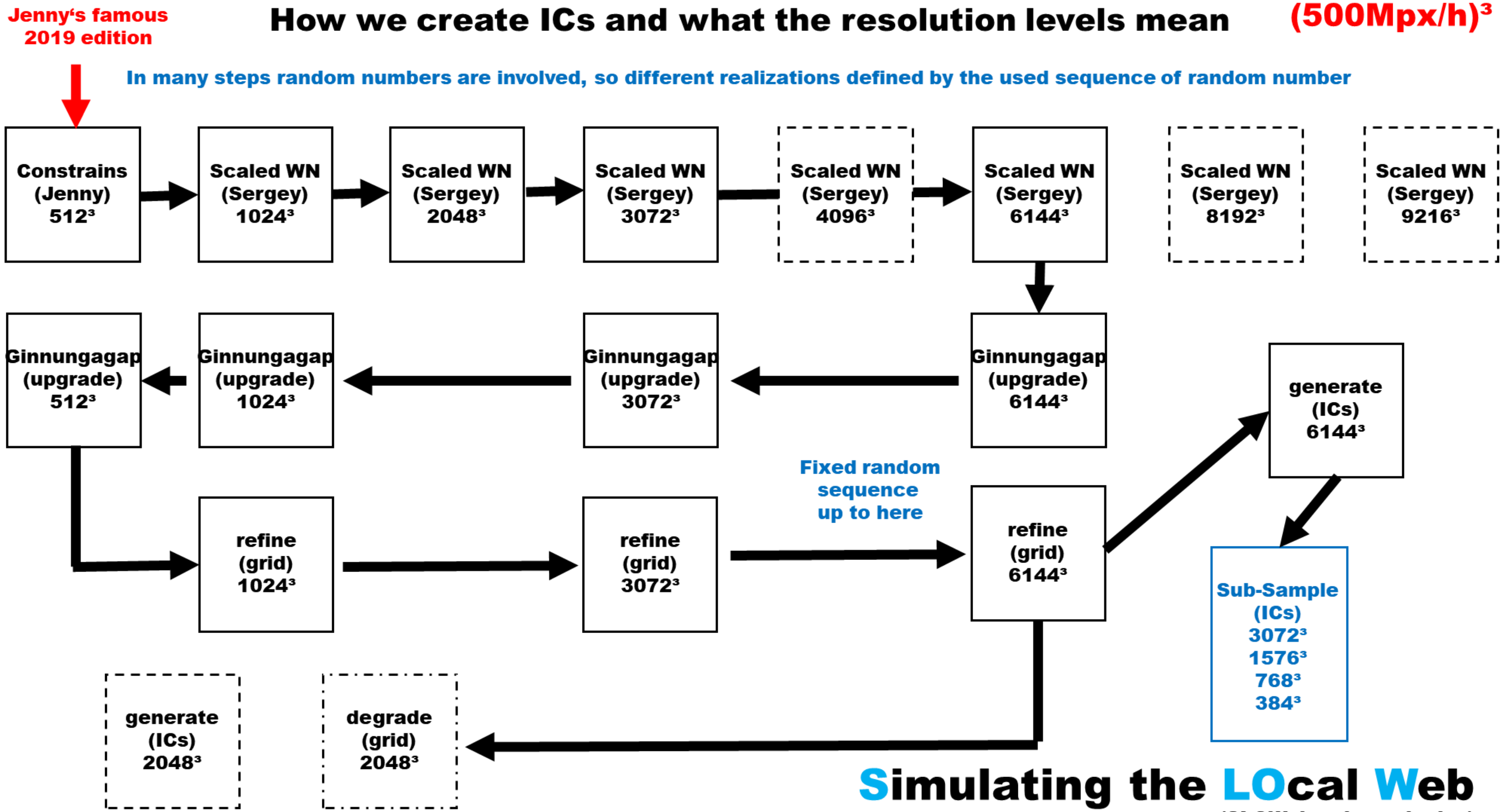
-> Constrained initial conditions



How we create ICs and what the resolution levels mean

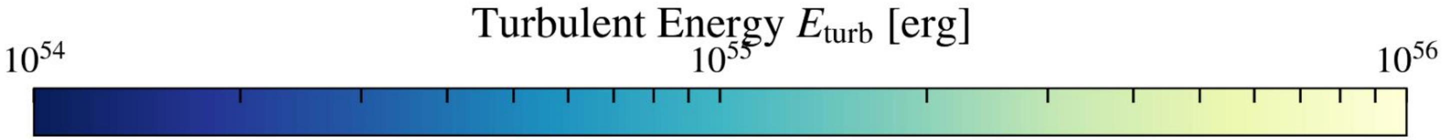
(500Mpx/h)³

In many steps random numbers are involved, so different realizations defined by the used sequence of random number

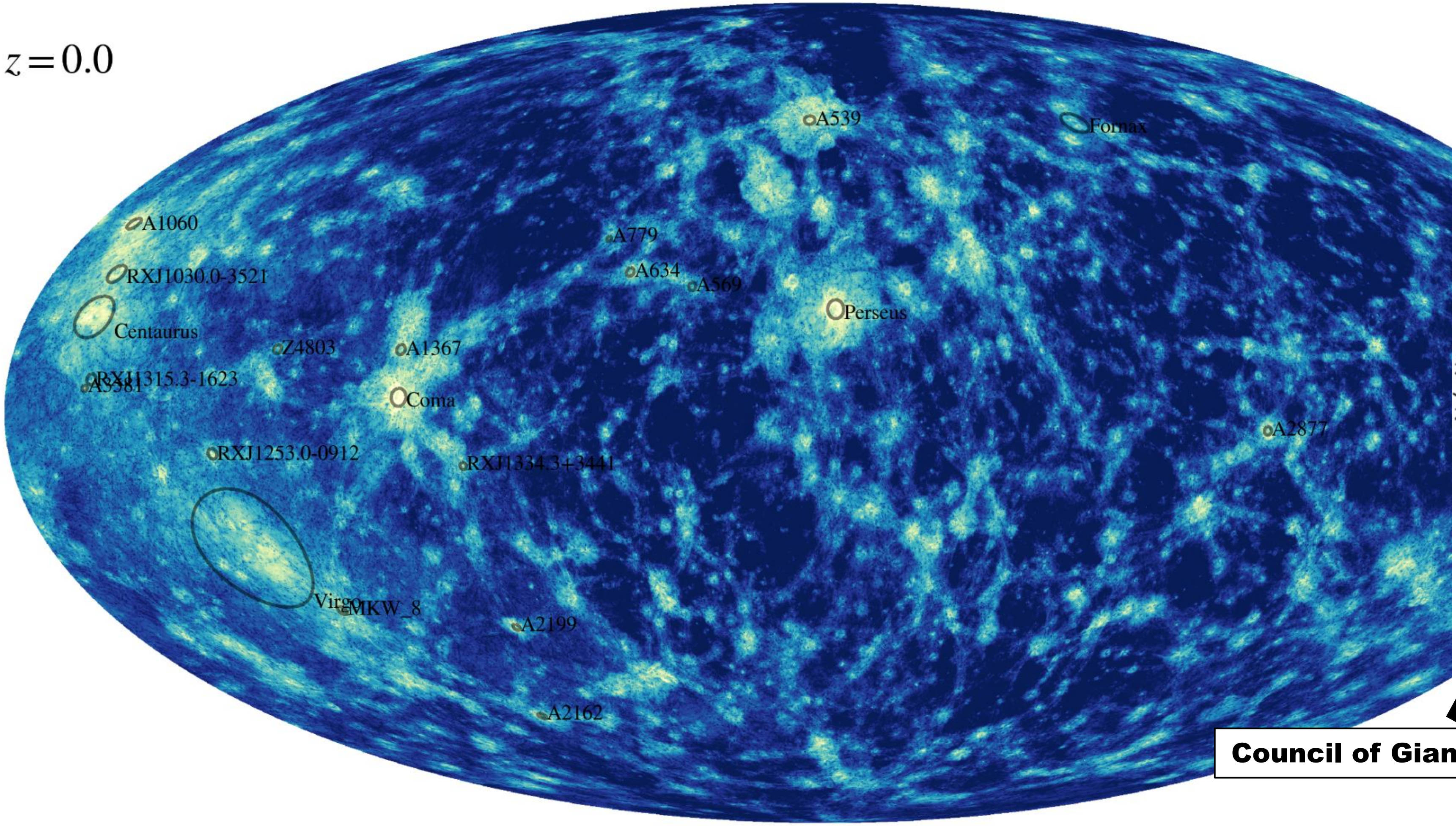


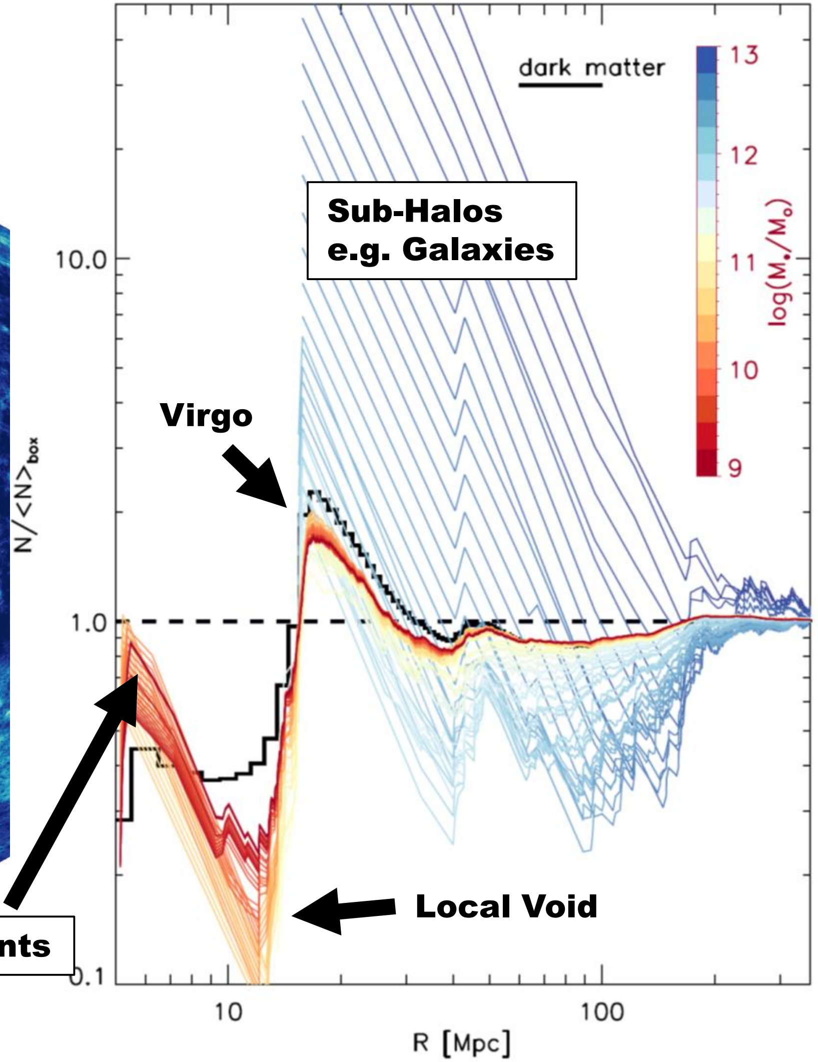
Simulating the LOcal Web
(SLOW dancing galaxies)

Prominent Structures in our Environment

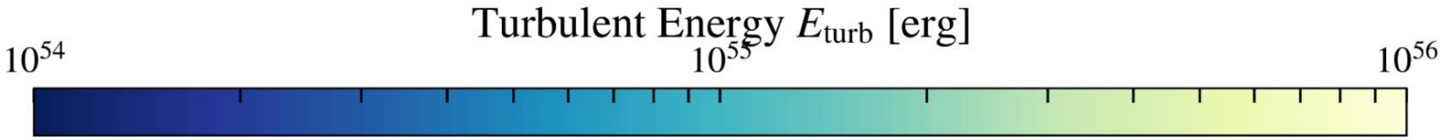


Simulating the **REAL** Universe

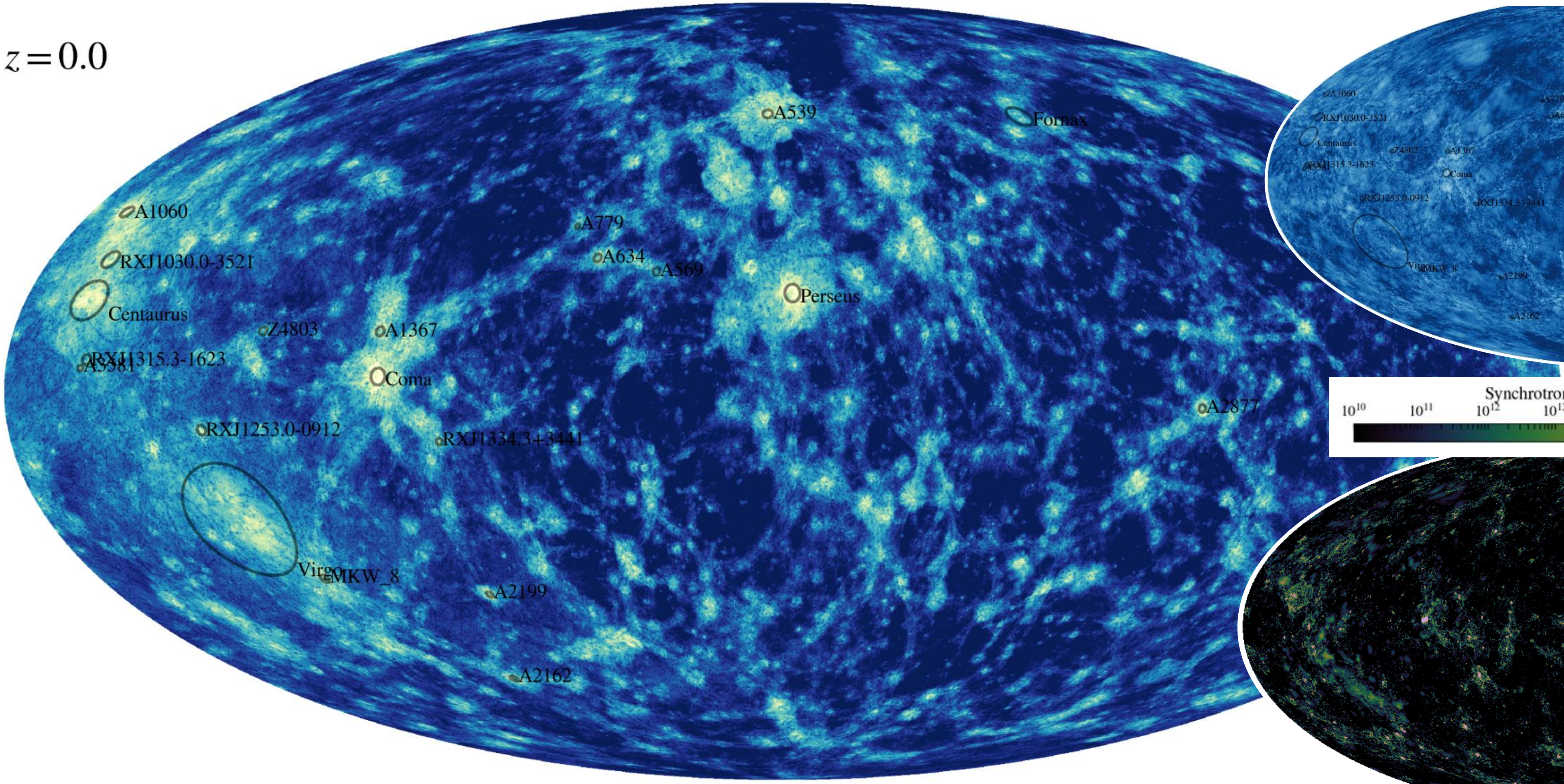


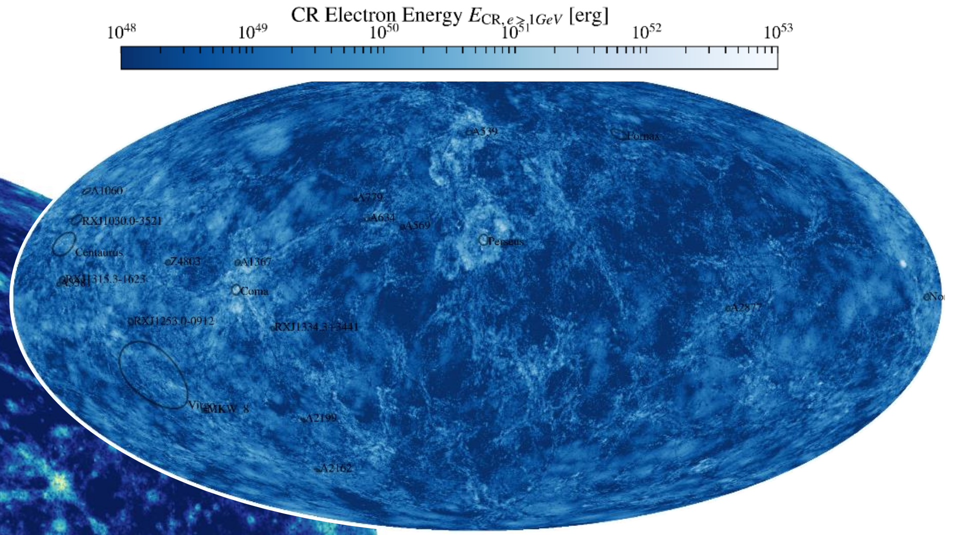


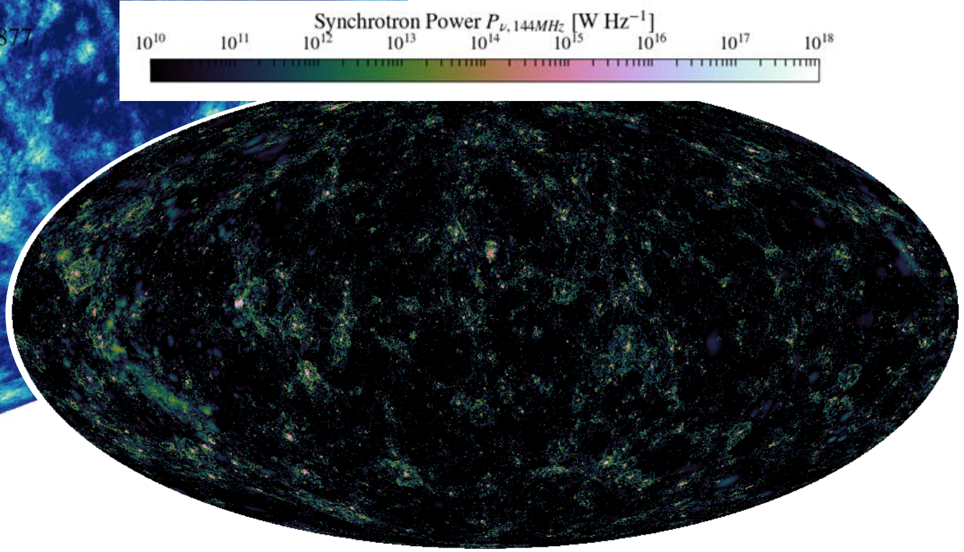
Prominent Structures in our Environment



Simulating the REAL Universe



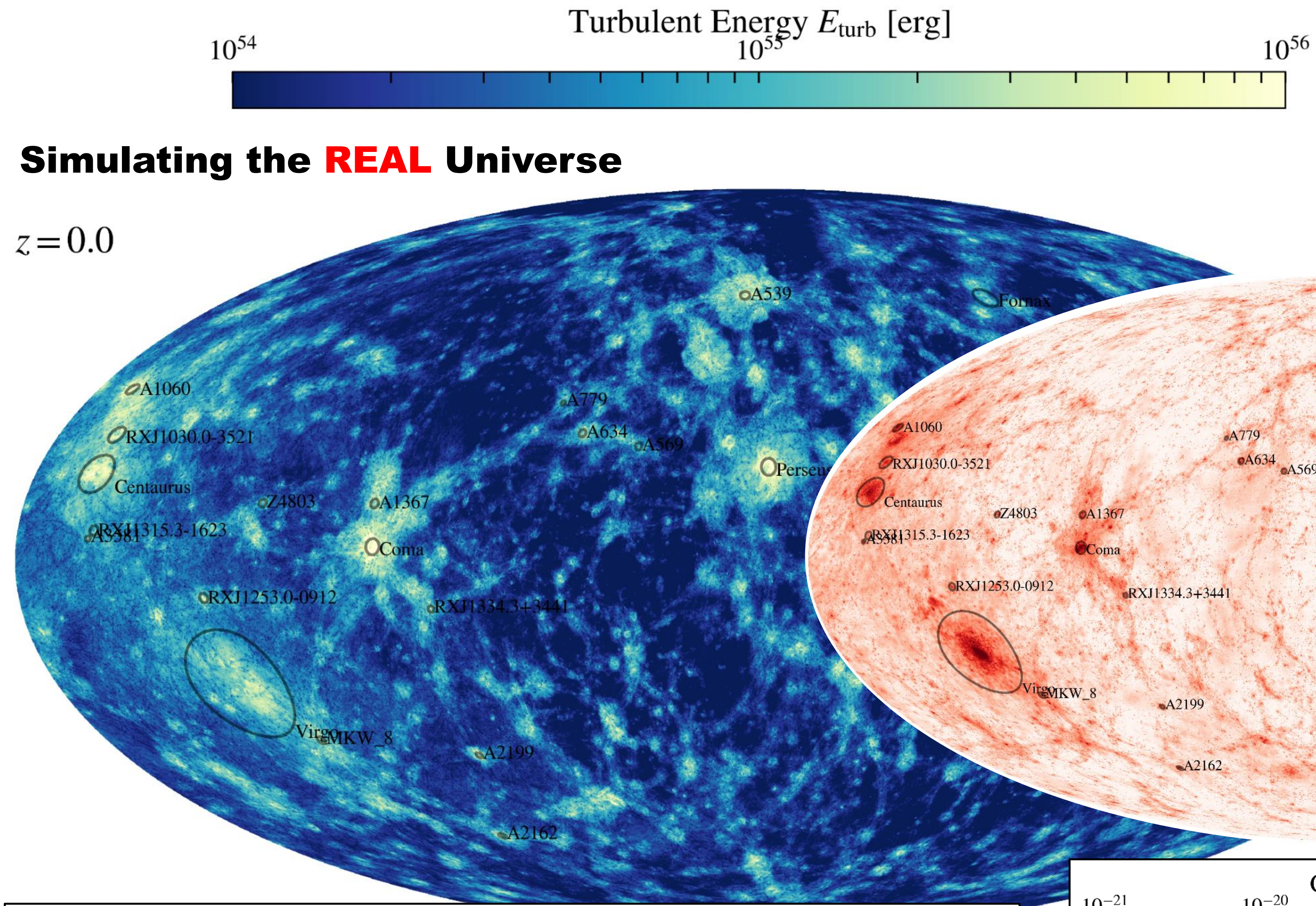


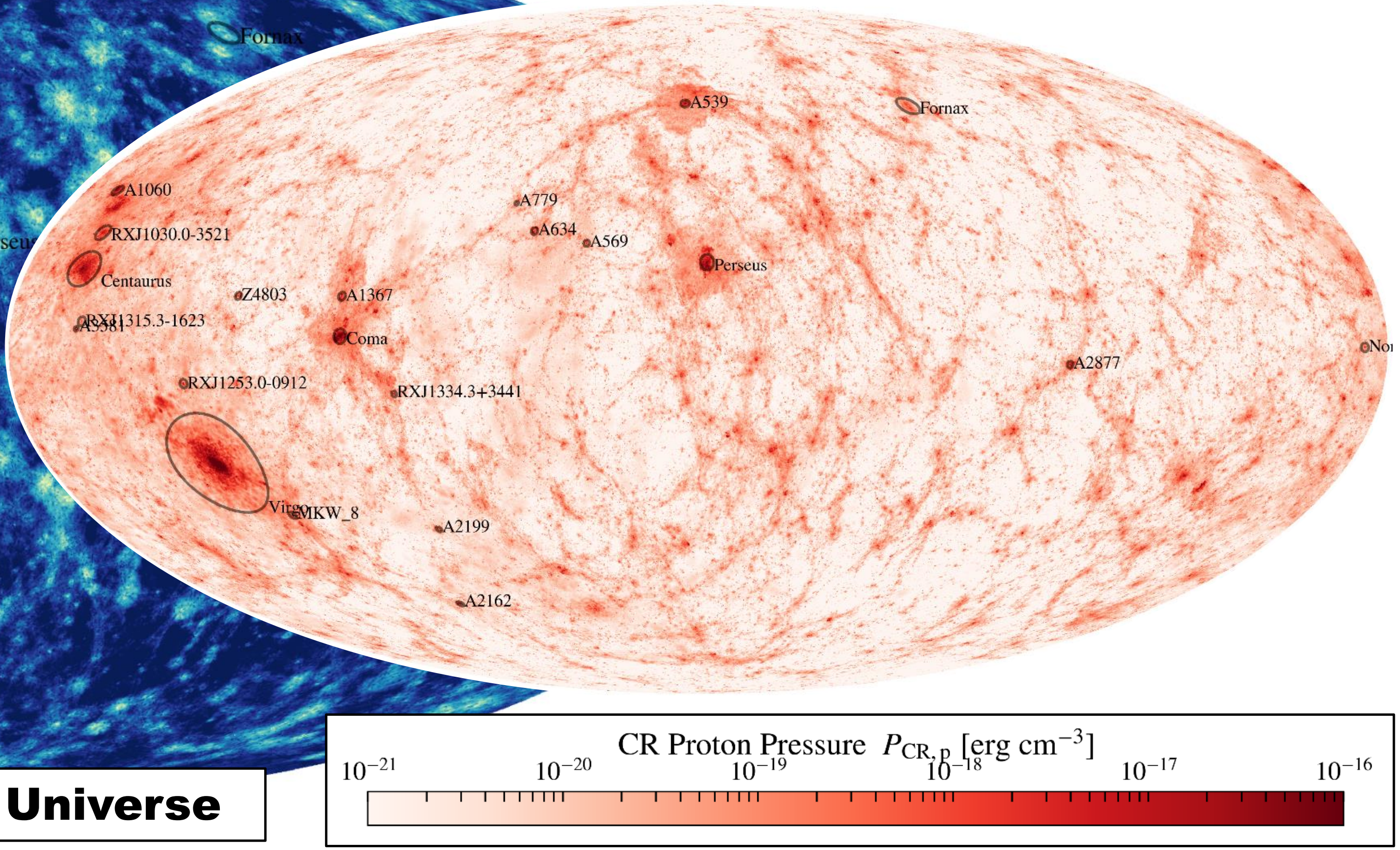


Prominent Structures in our Environment

Ludwig Böss

Simulating the **REAL** Universe

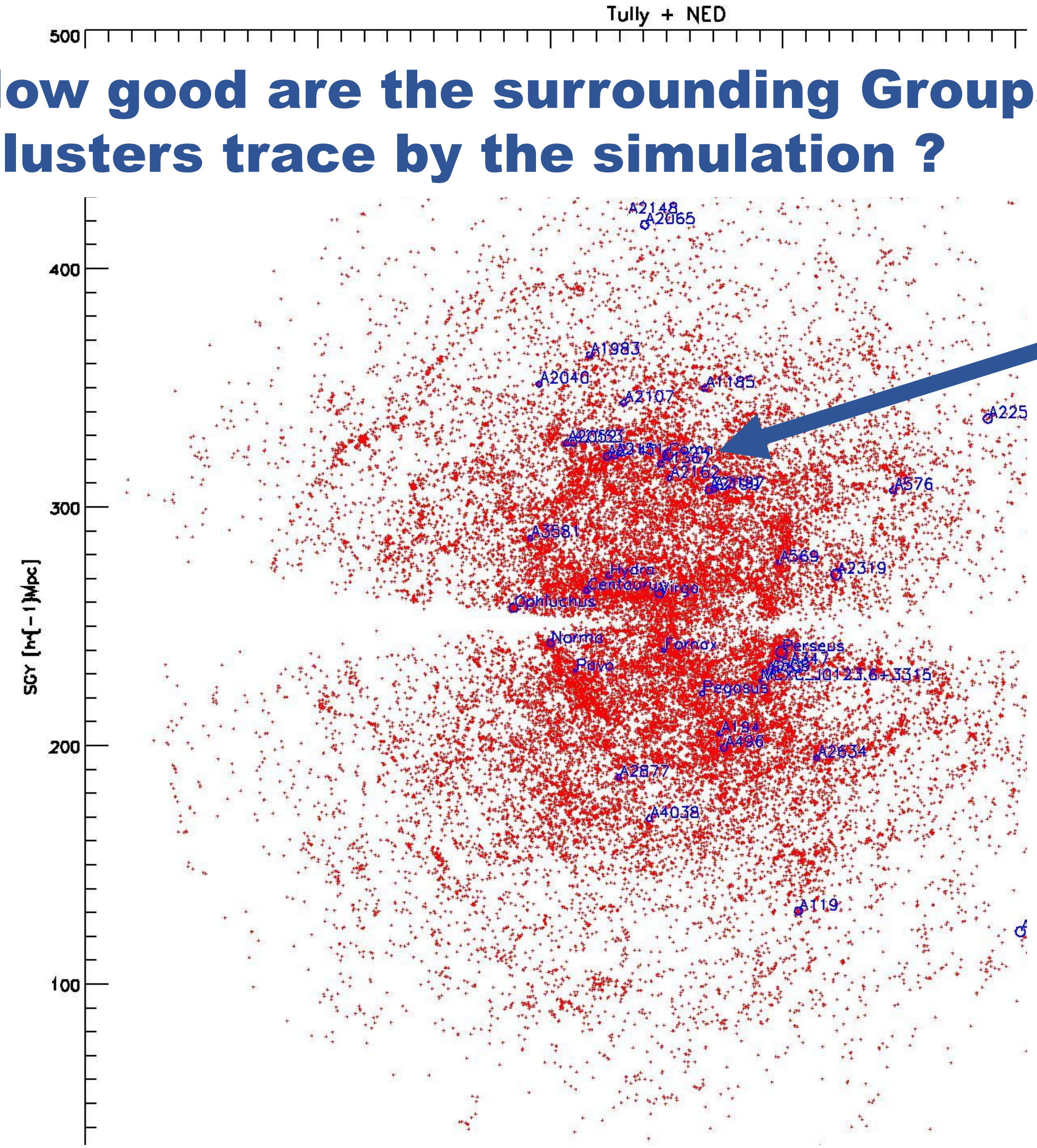


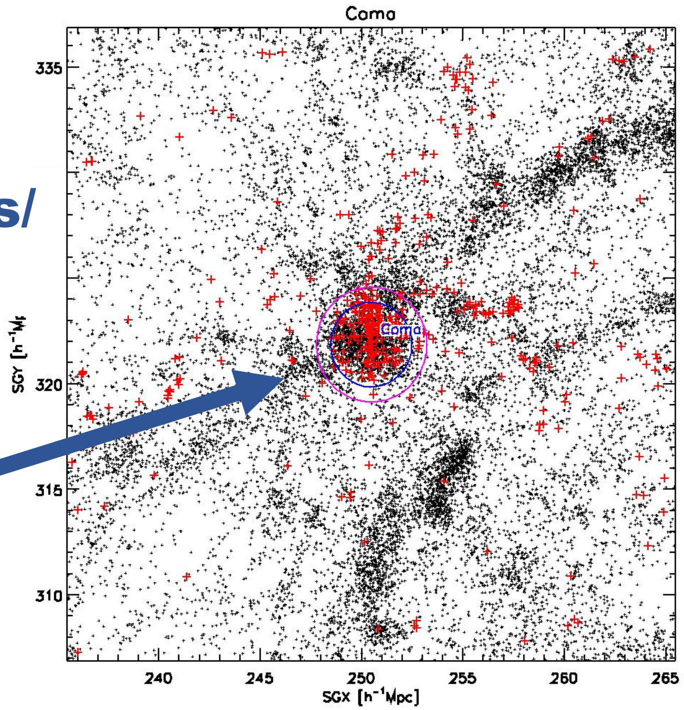


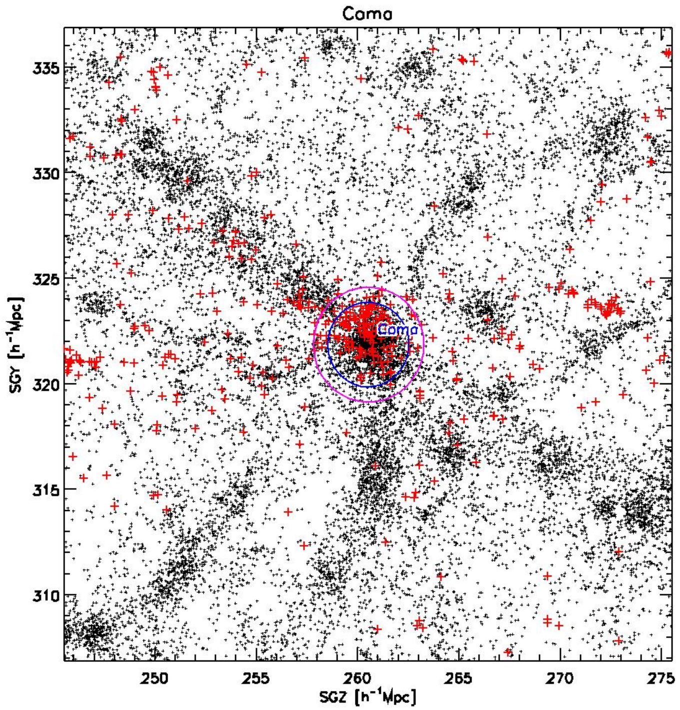
Multi Messenger Particles in the Local Universe

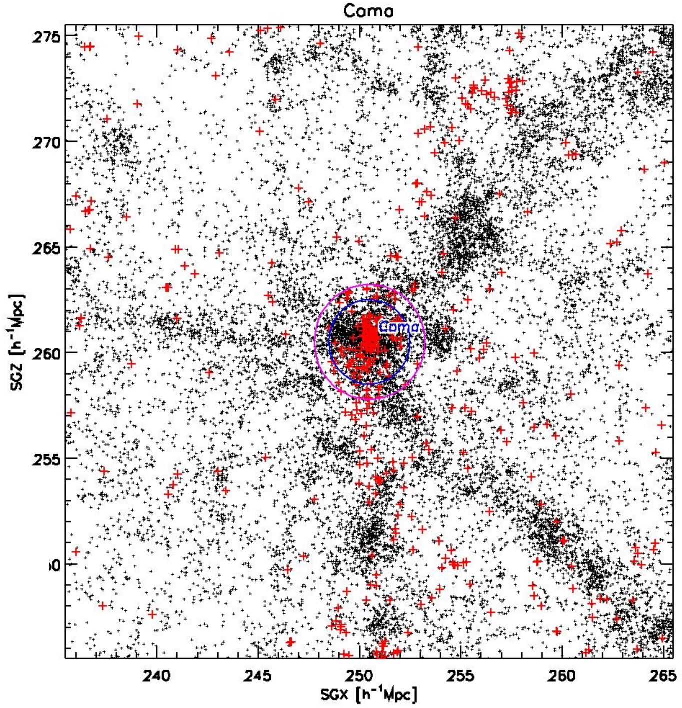
SLOW 1.0_9100, 3072^3 Coma

How good are the surrounding Groups/ Clusters trace by the simulation ?









How good are the surrounding 2MASS galaxies trace by the simulation?

R_{vir} **Obs**

R_{vir} **Sim**

\+ **2MASS Galaxis**

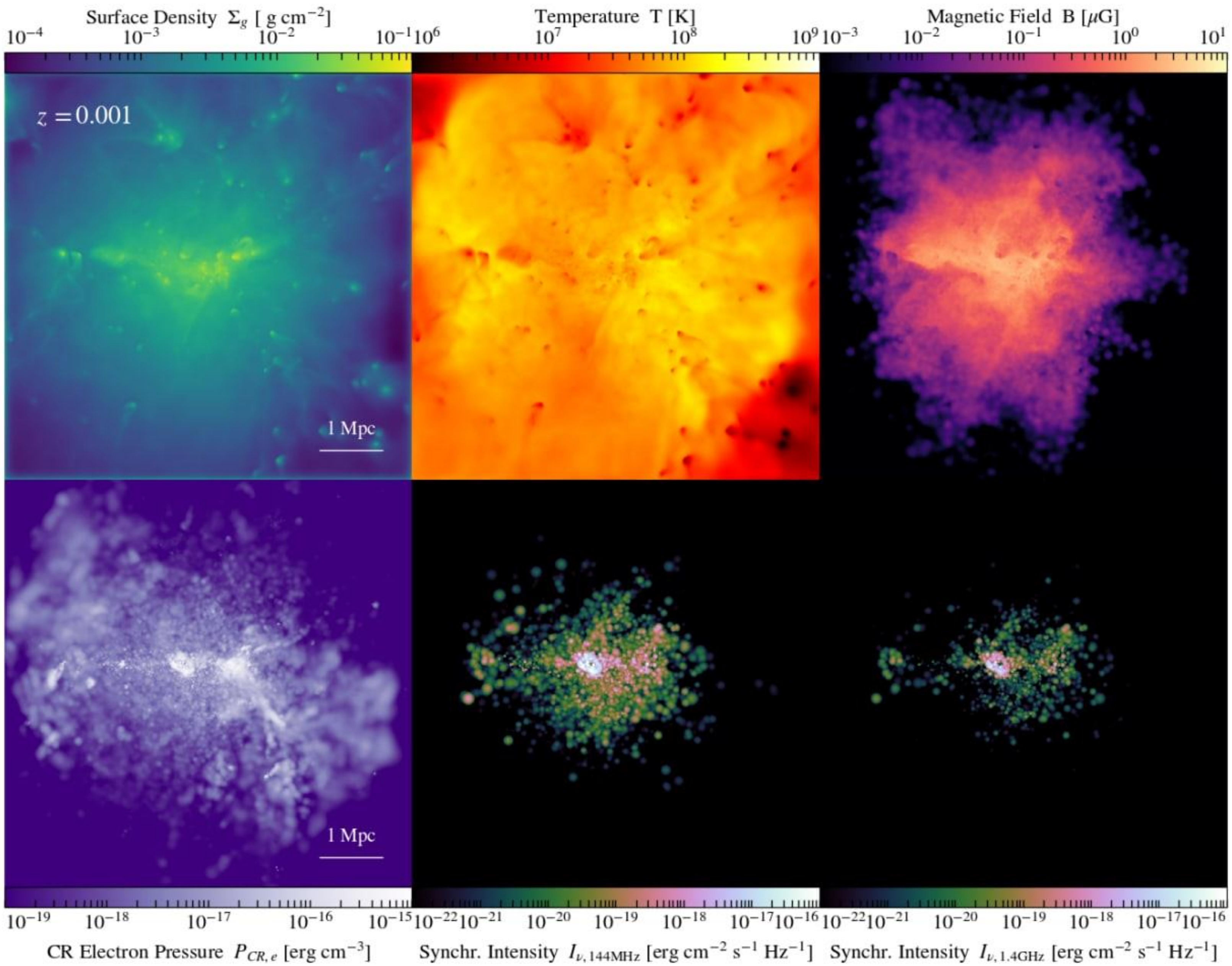
• **Sim Galaxies**

Compare the mass !

Filaments in Coma (N. Malavasi+ 2022)

SLOW 2.0_9100, 3072^3

Coma (MHD+CRs)



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Mon. Not. R. Astron. Soc. **412,** 2–12 (2011) doi:10.1111/j.1365-2966.2010.17738.x

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

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[2]*Department of Astronomy, University of Minnesota, Minneapolis, MN 55455, USA*

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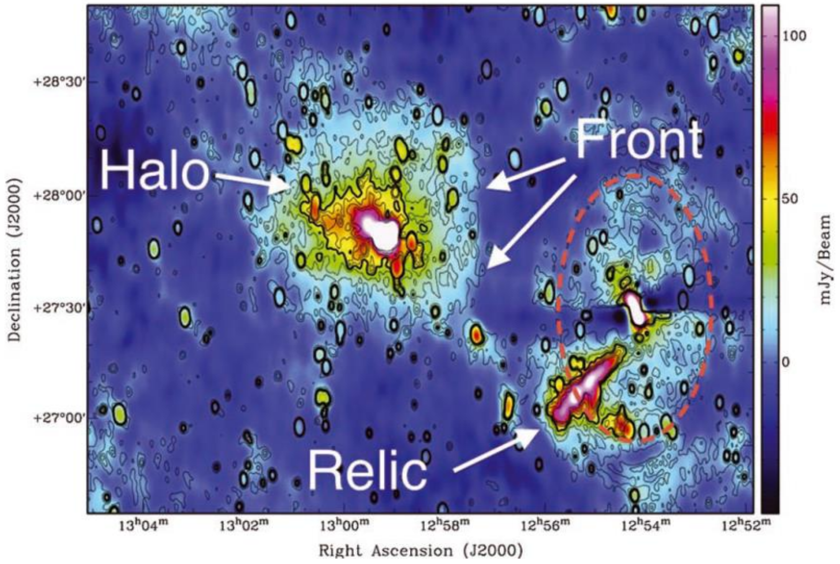
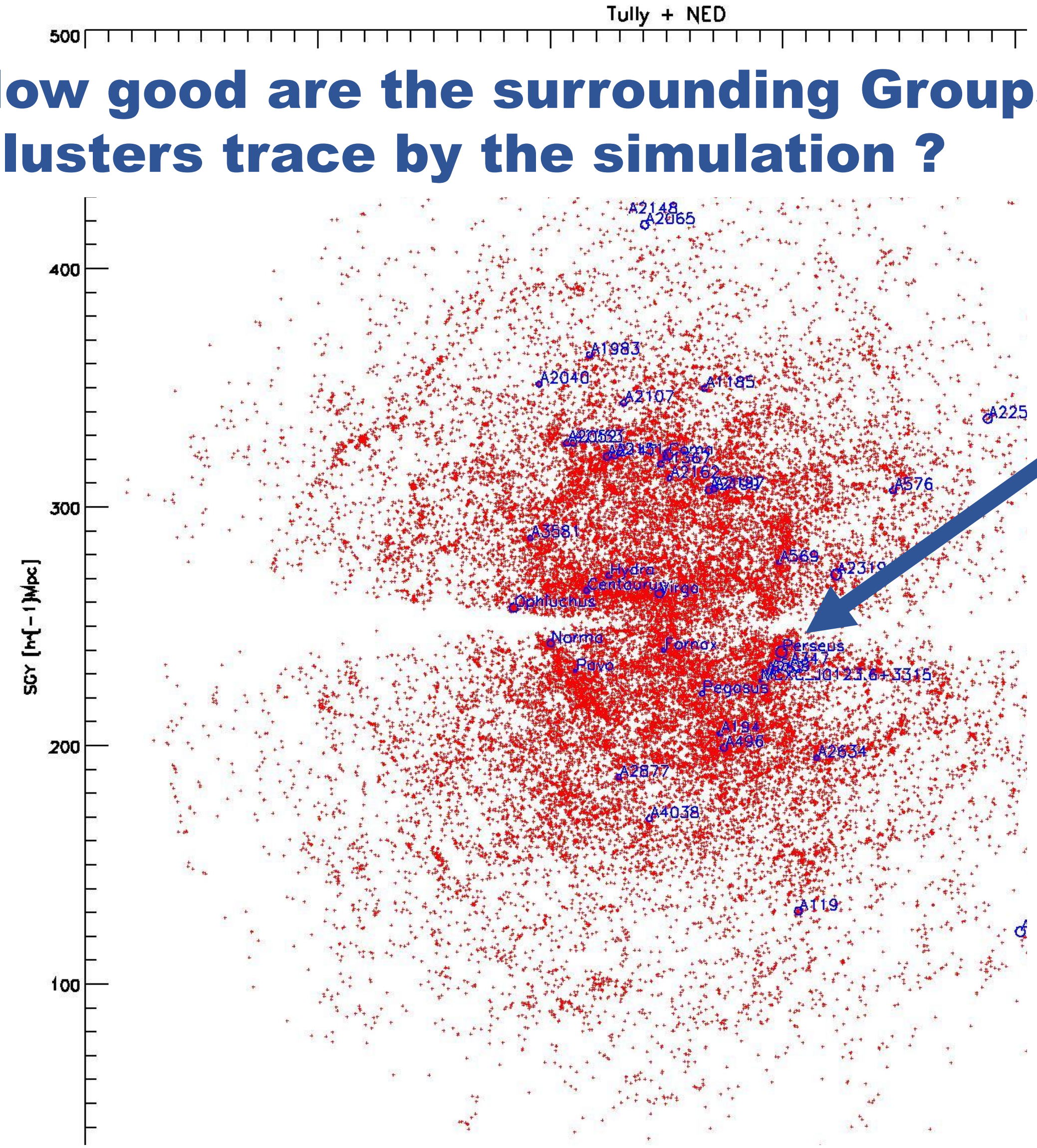


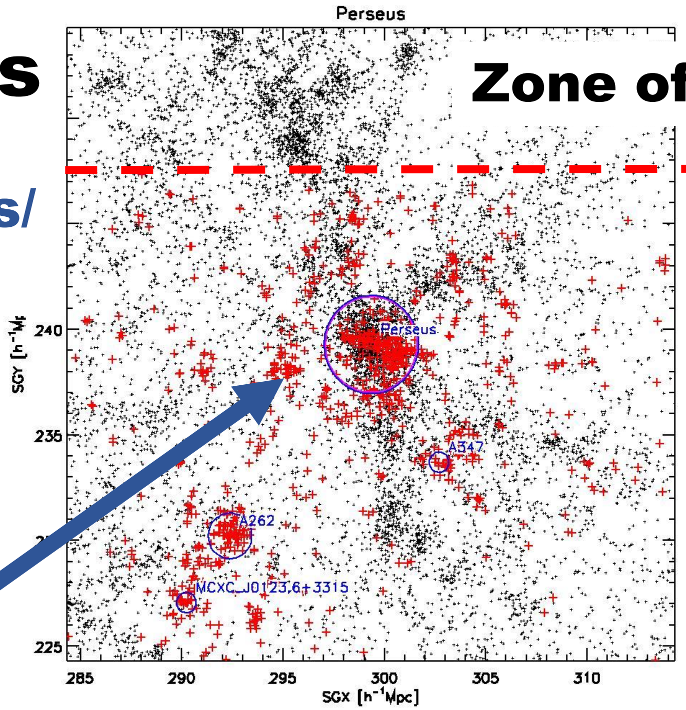
Giant radio halo!

SLOW 1.0_9100, 3072³

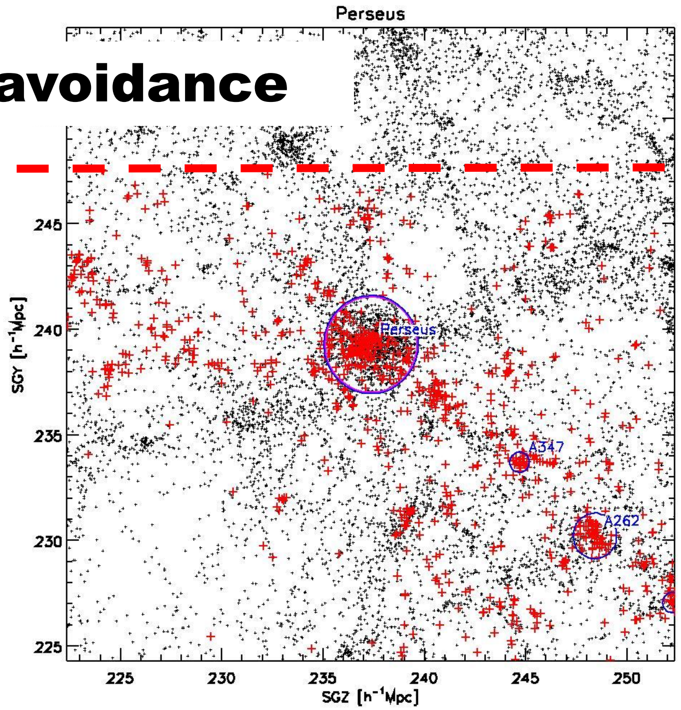
Perseus

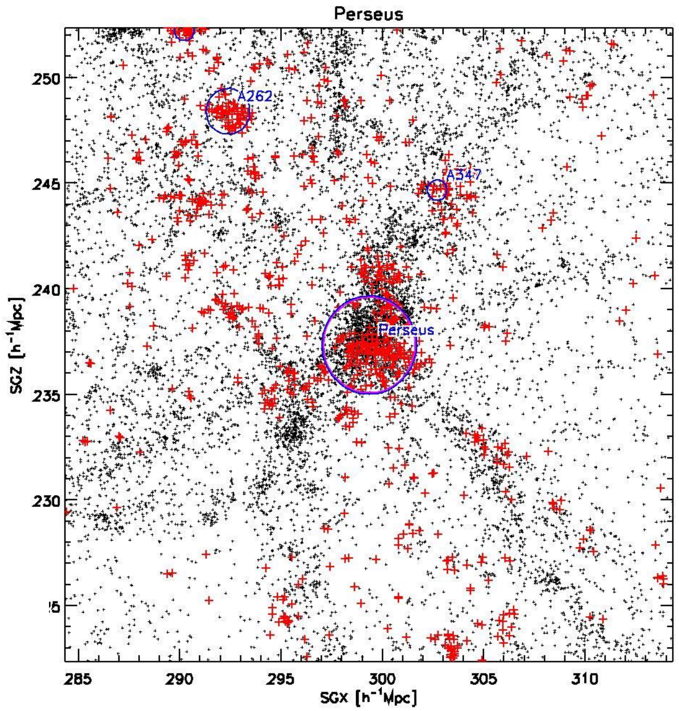
How good are the surrounding Groups/ Clusters trace by the simulation ?





Zone of avoidance





R_{vir} **Obs**

R_{vir} **Sim**

\+ **2MASS Galaxis**

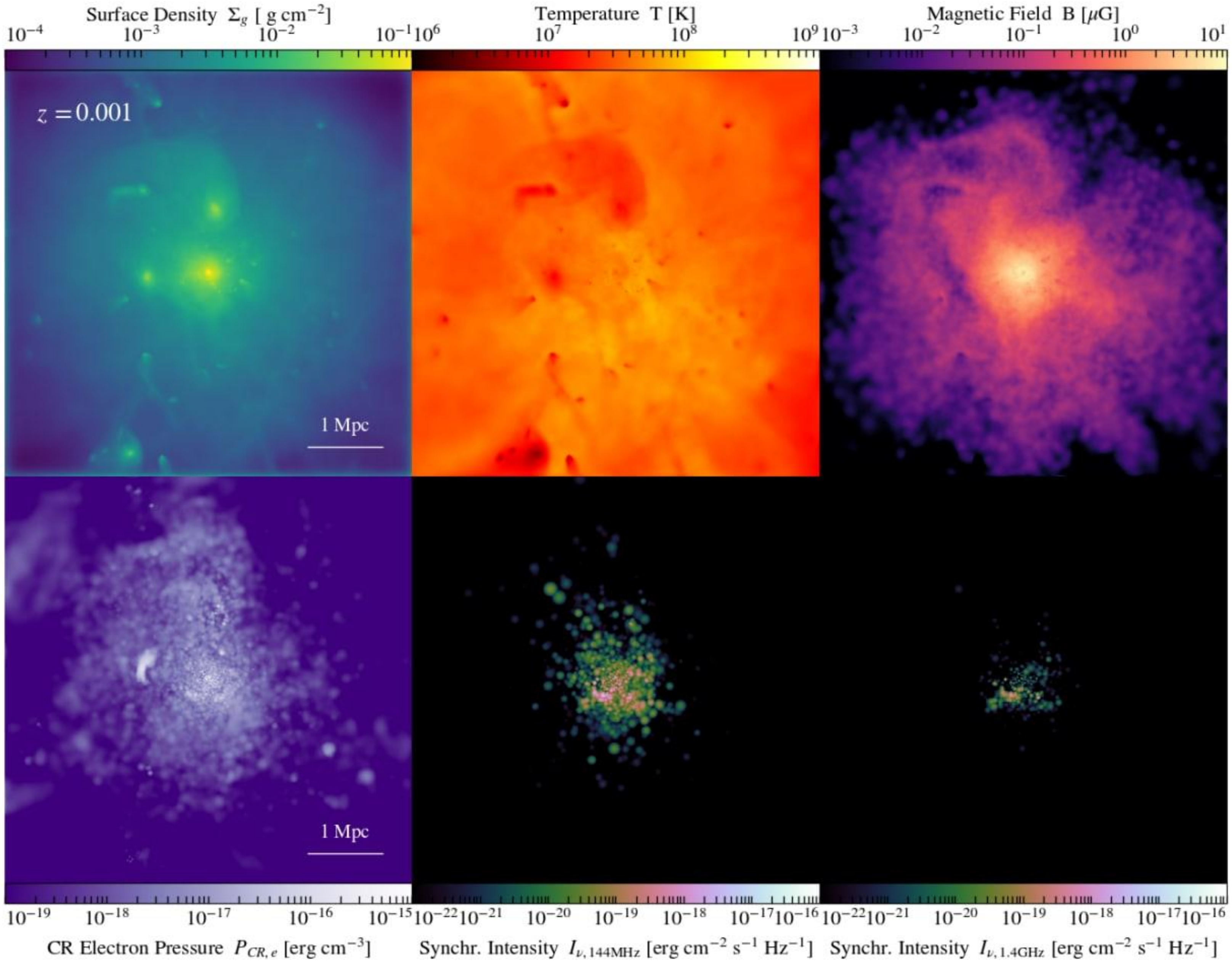
• **Sim Galaxies**

Compare the mass !

How good are the surrounding 2MASS galaxies trace by the simulation?

SLOW 2.0_9100, 3072³

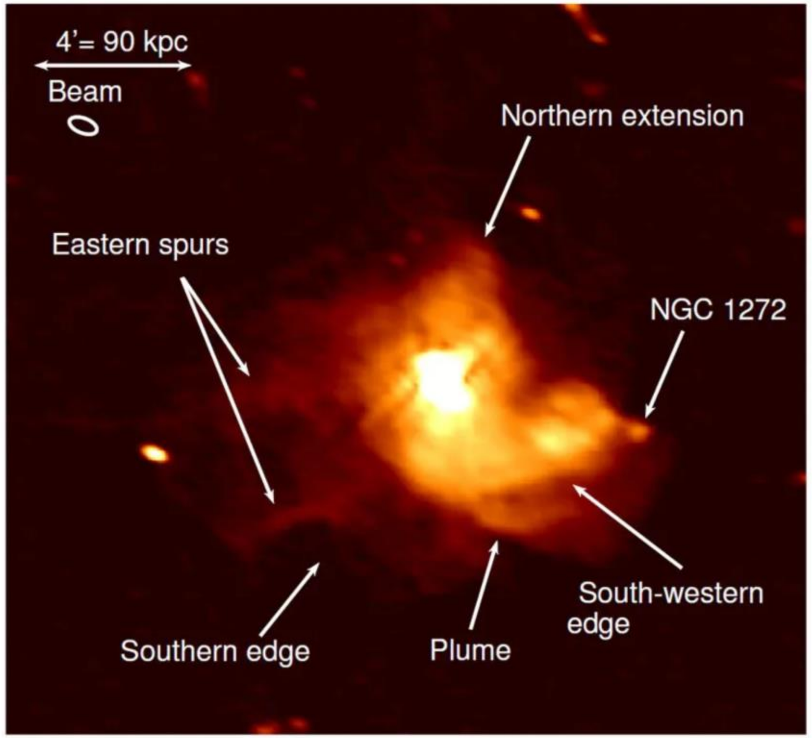
Perseus (MHD+CRs)



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

TOPICS: Astronomy Astrophysics Cosmology Harvard-Smithsonian Center For Astrophysics Karl G. Jansky Very Large Array

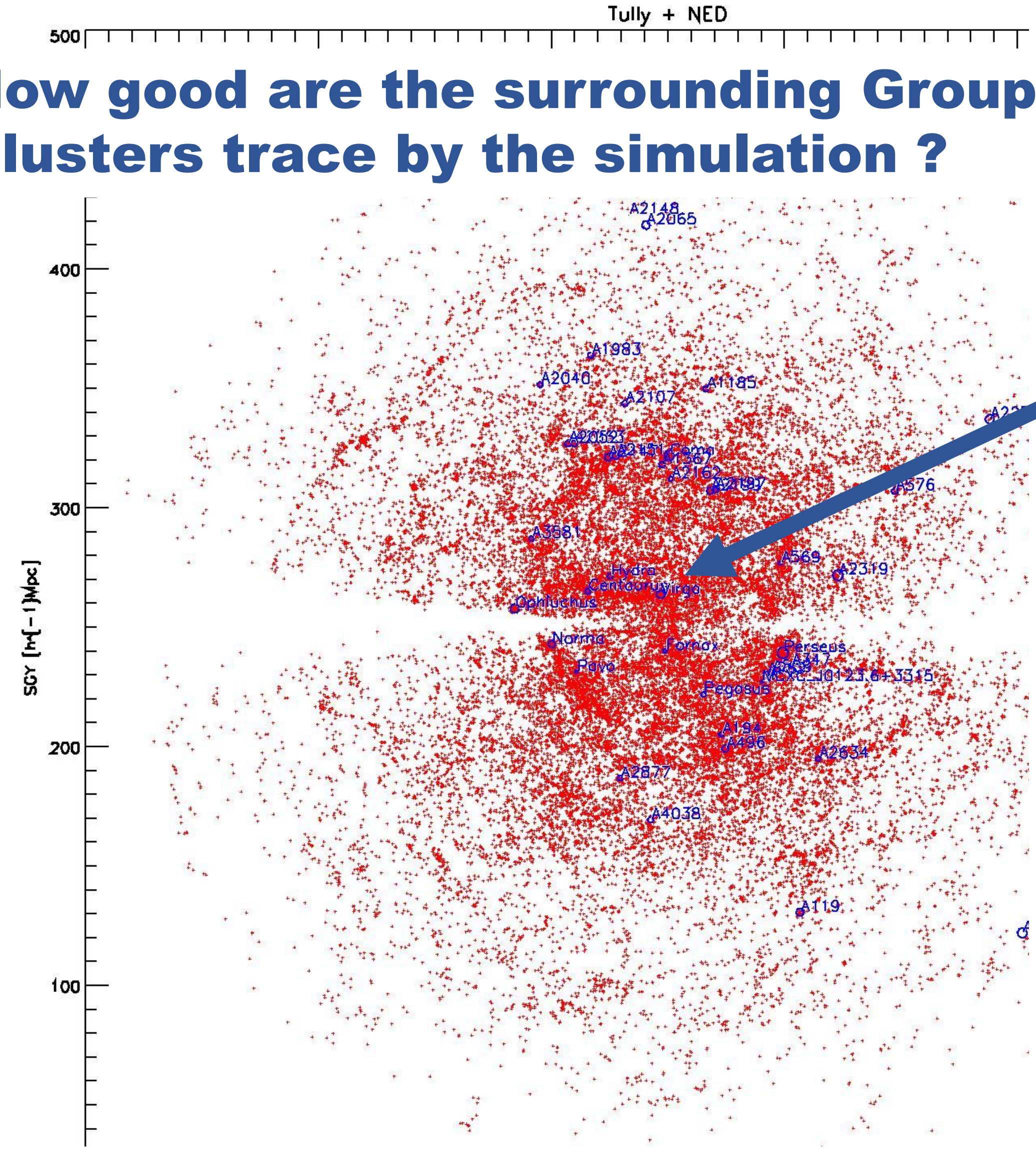
By HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS SEPTEMBER 22, 2017

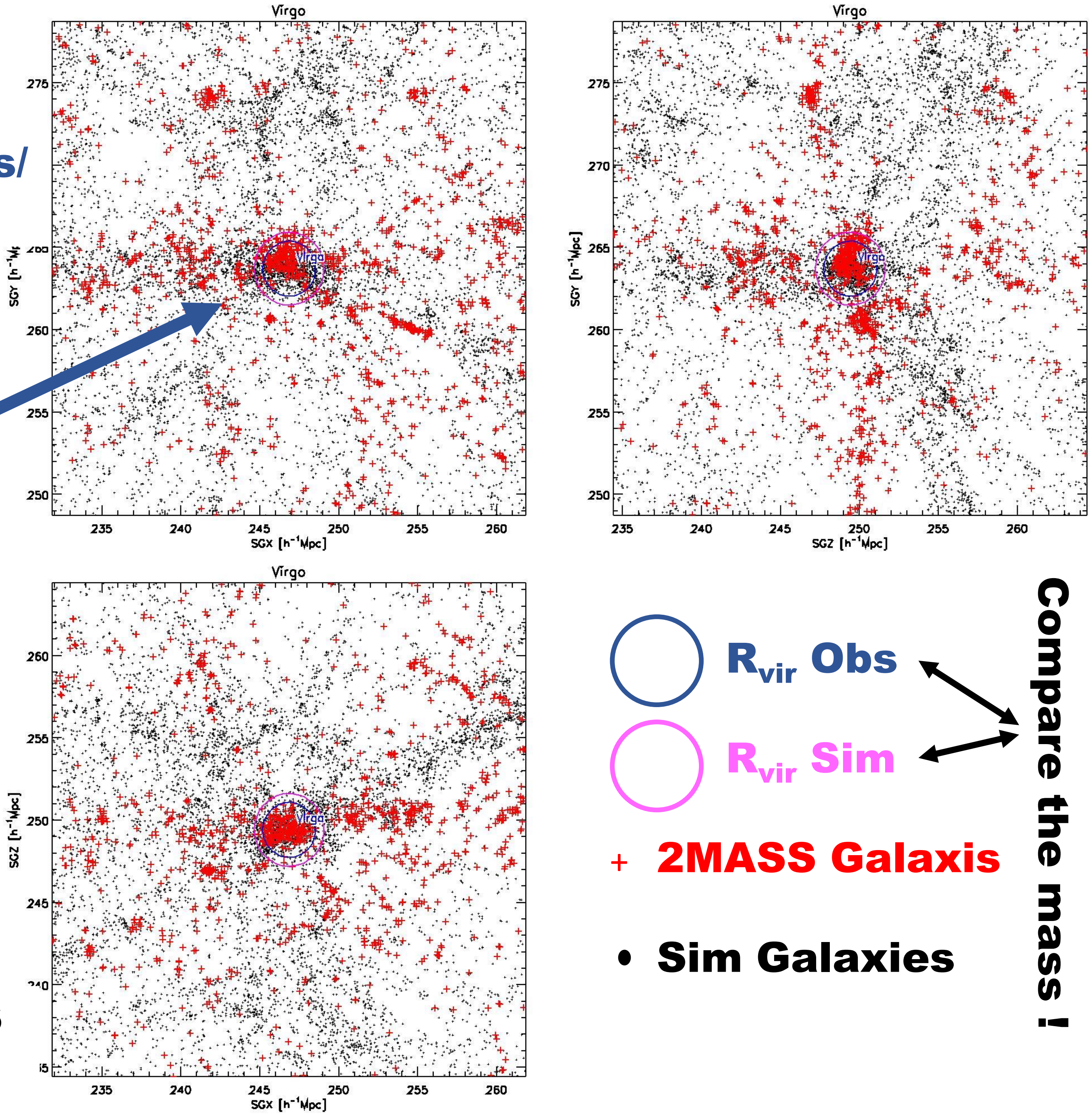


radio mini halo!

SLOW 1.0_9100, 3072^3 Virgo

How good are the surrounding Groups/ Clusters trace by the simulation ?





How good are the surrounding 2MASS galaxies trace by the simulation?

R_{vir} Obs

R_{vir} Sim

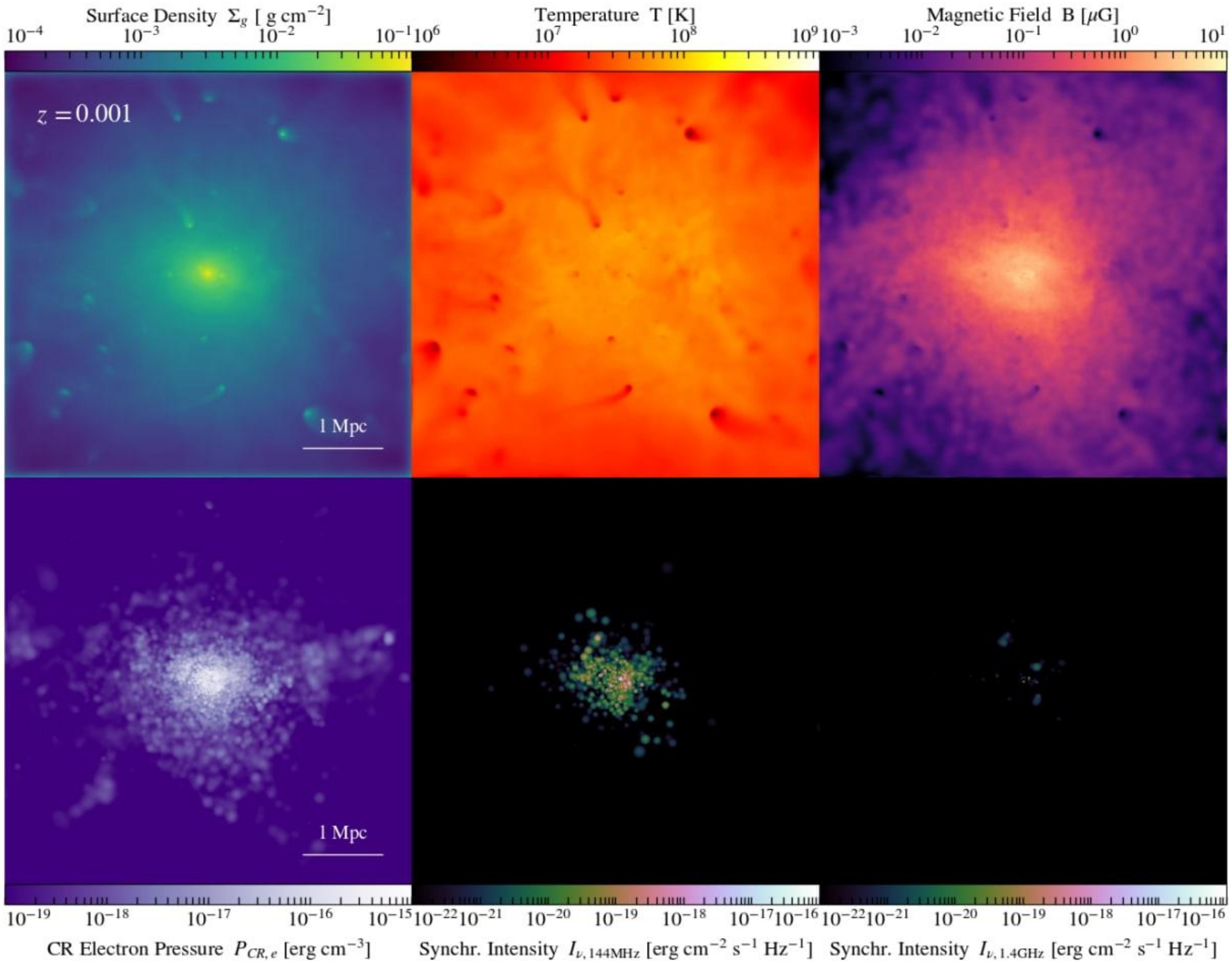
+ 2MASS Galaxis

• Sim Galaxies

Compare the mass !

SLOW 2.0_9100, 3072³

Virgo (MHD+CRs)



A&A 423, 57–64 (2004)
DOI: 10.1051/0004-6361:20035783
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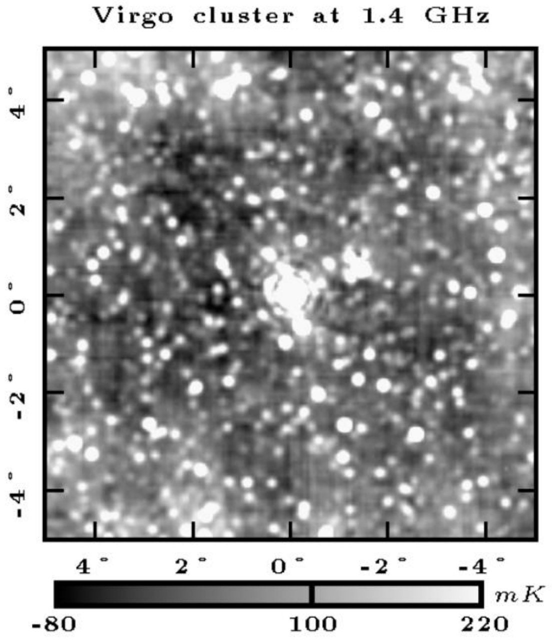
Astronomy & Astrophysics

Detection of a radio halo in the Virgo cluster★

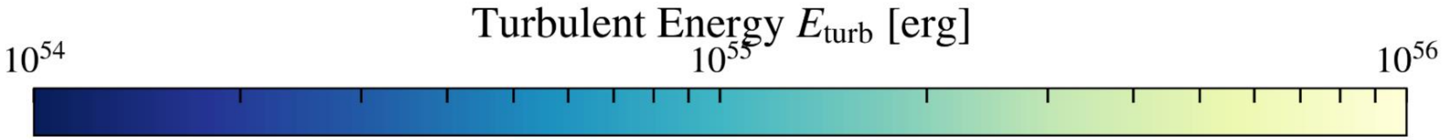
B. Vollmer[1,2], W. Reich[2], and R. Wielebinski[2]



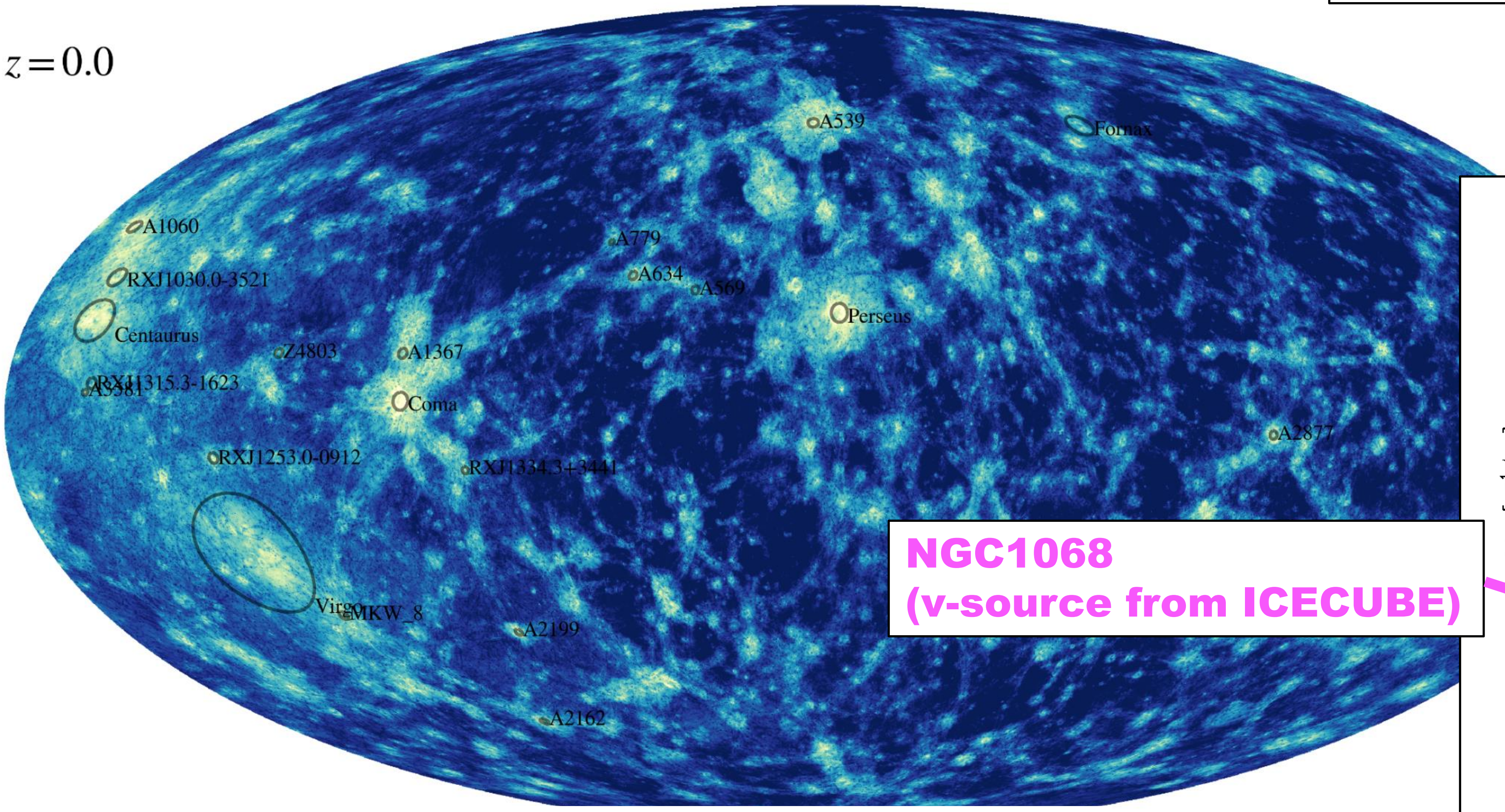
1. We do not detect a bright, large-scale radio halo, as is observed in the Coma cluster.
2. We detect a radio halo around the elliptical galaxy M 86 with an estimated radial extent of ∼2° and an estimated total flux density of 5 ± 1.5 Jy.

No radio emission!

Prominent Structures in our Environment



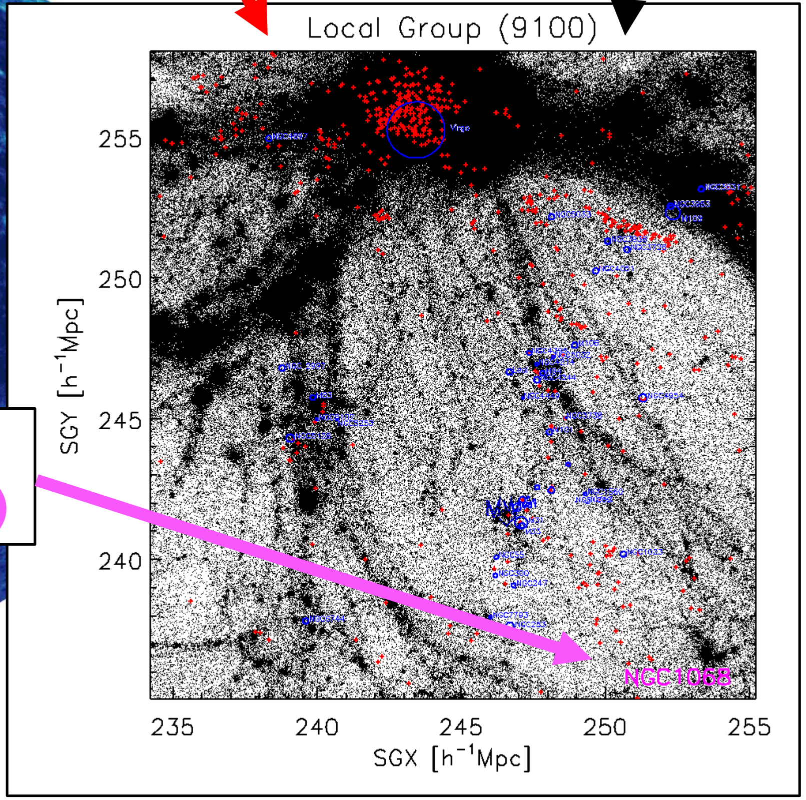
Simulating the REAL Universe



Galaxies from 2MRS

Simulation

NGC1068
(ν-source from ICECUBE)



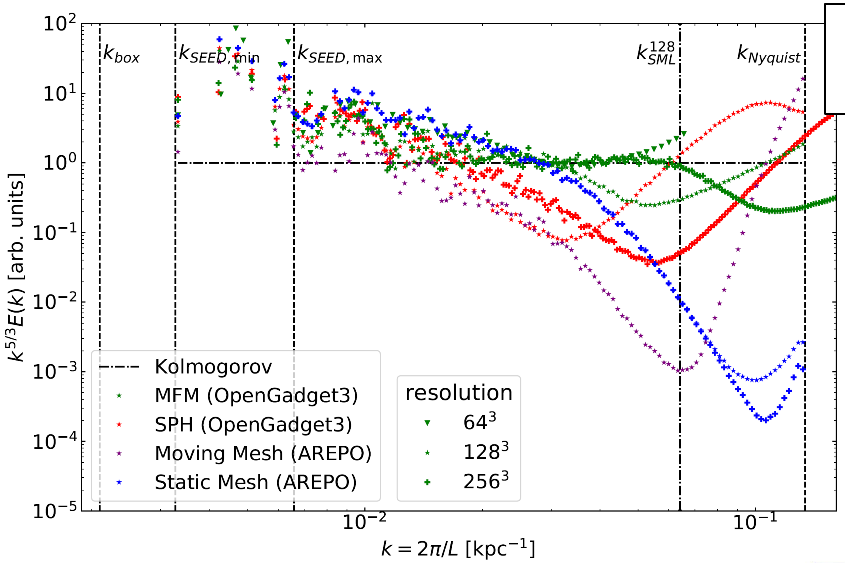
Multi Messenger Particles in the Local Universe

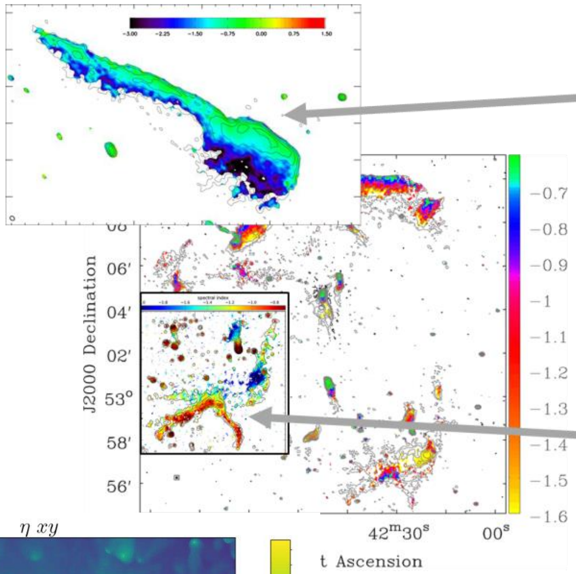
The End

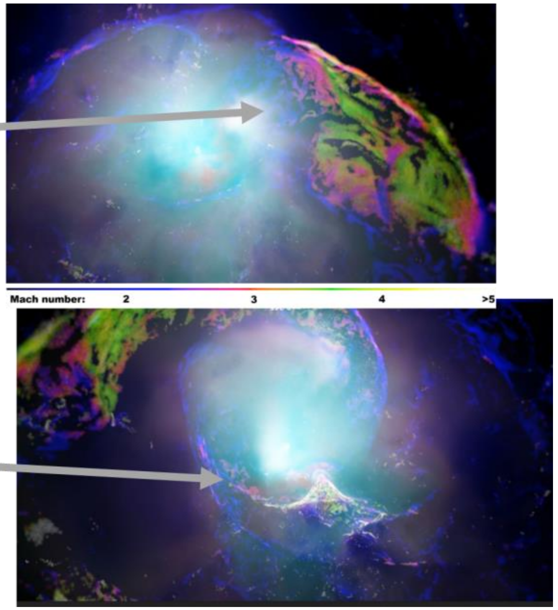
Conclusions:

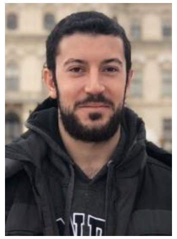
MFM, SPH & AREPO: Different behavior for strongly subsonic, decaying turbulence!

SPH: low intrinsic viscosity, still sizeable dissipation, capturing effects of physical viscosity well!

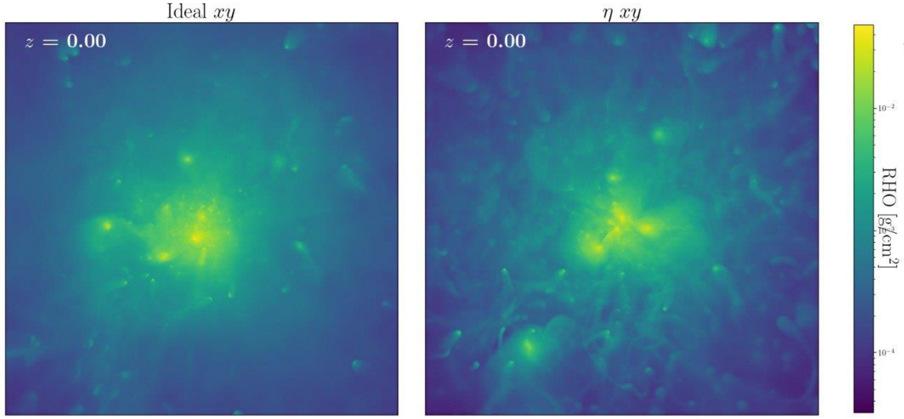




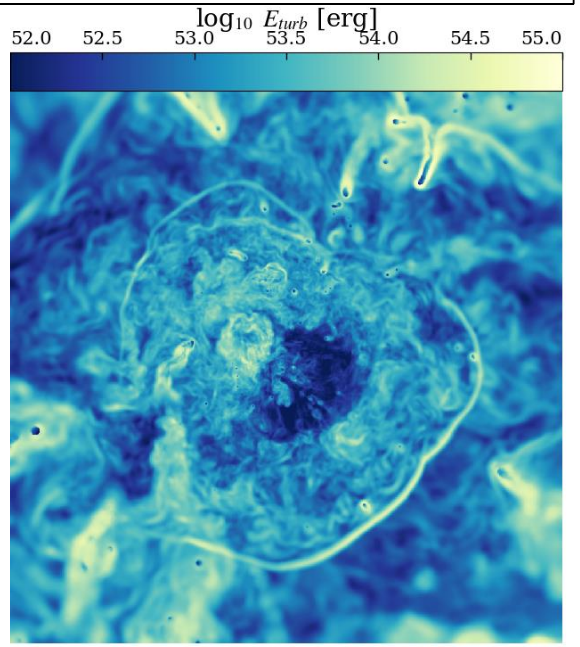


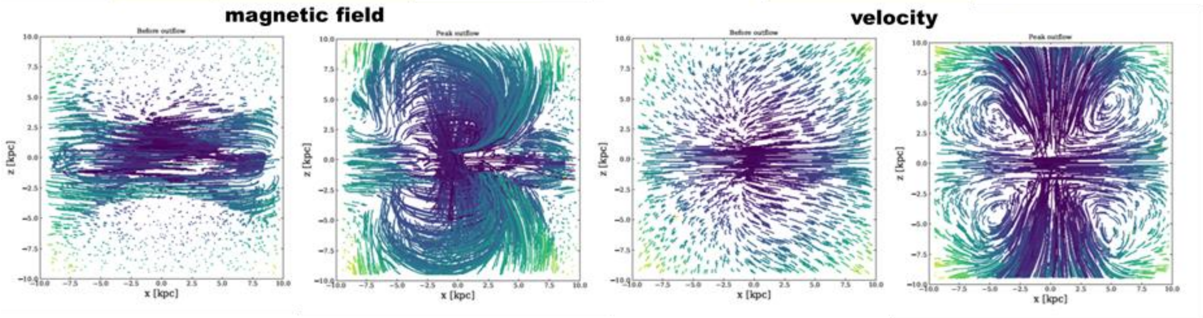
Ludwig Böss **Tirso Marin** **Frederick Groth** **Ulrich Steinwandel**

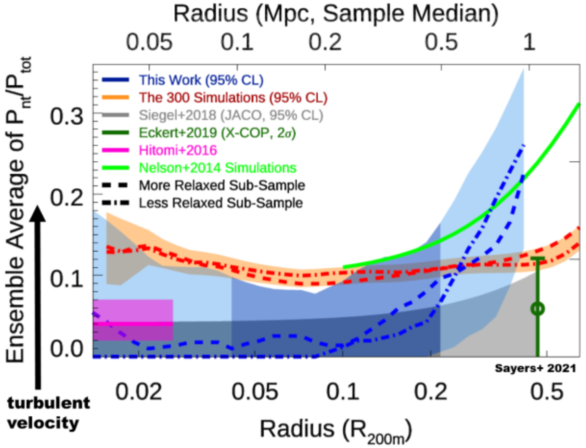


Do we capture Turbulence within ICM correctly??

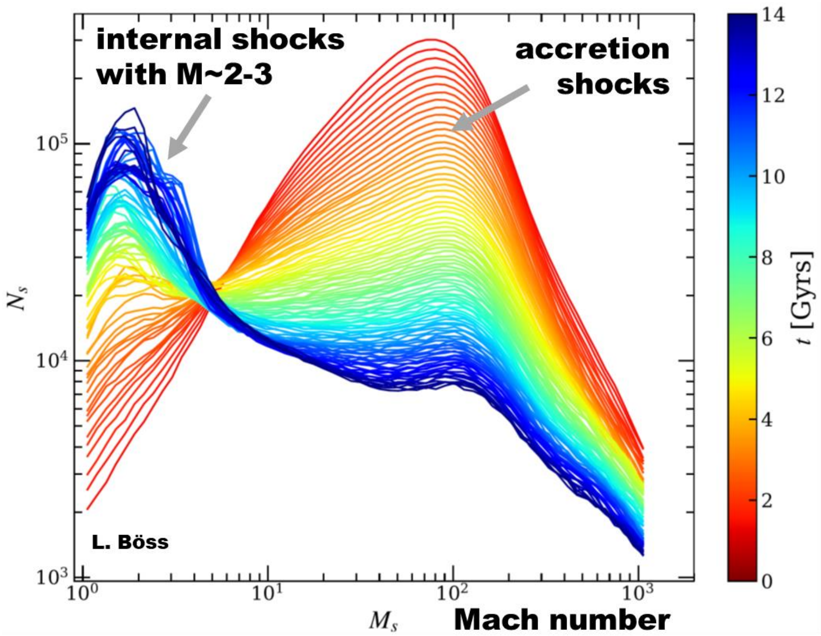


First MHD galaxy simulation with fully resolved, two phase dynamo and magnetic driven outflows, triggered by bar instability !



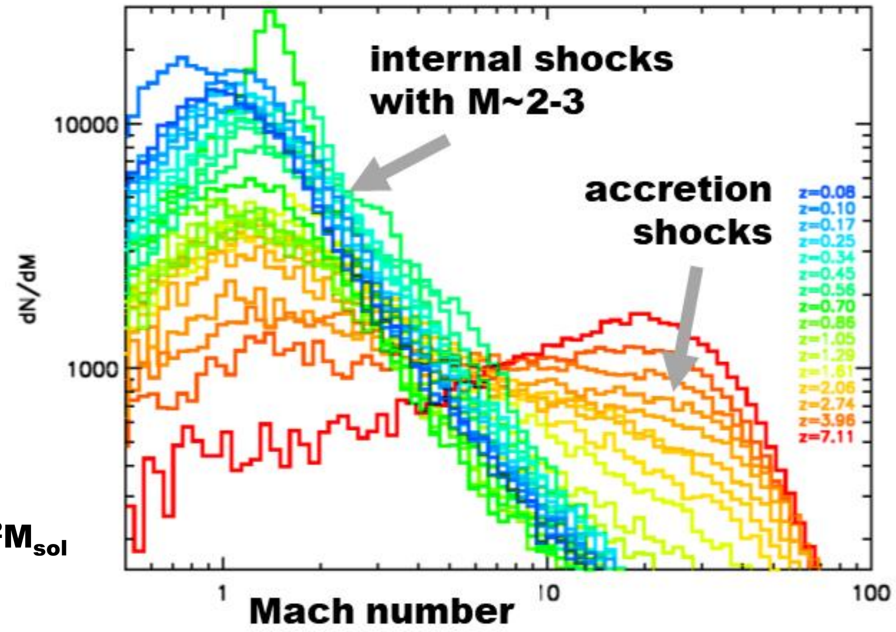


Conclusions



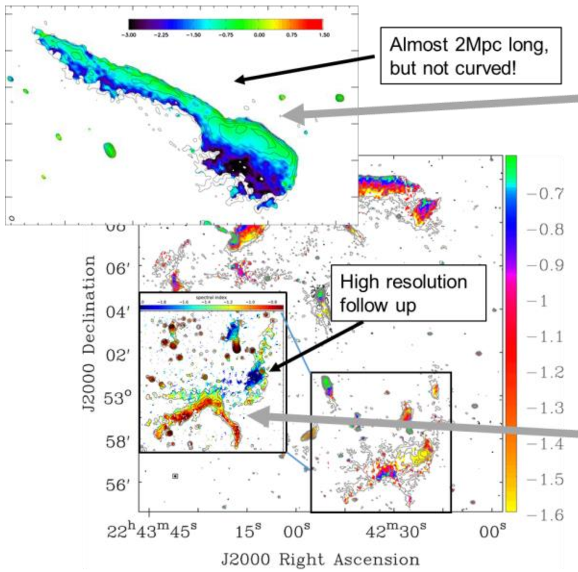
Galaxy Cluster
$M \sim 2 \times 10^{15} M_{sol}$

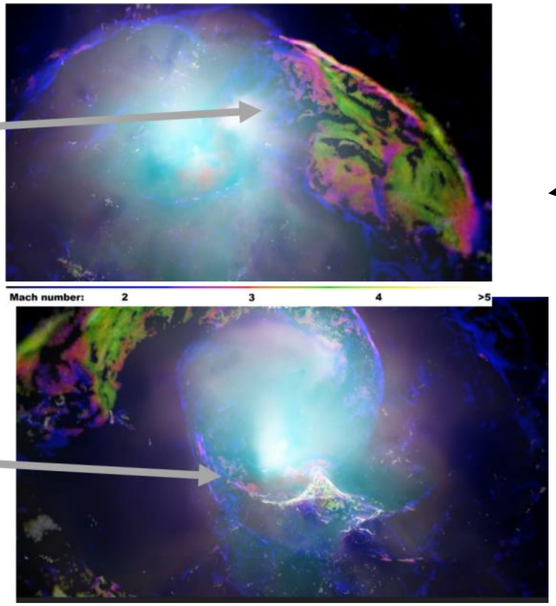
Galaxy
$M \sim 1.2 \times 10^{12} M_{sol}$



BUT:
Shocks
vs.
Feedback
vs.
AGN?

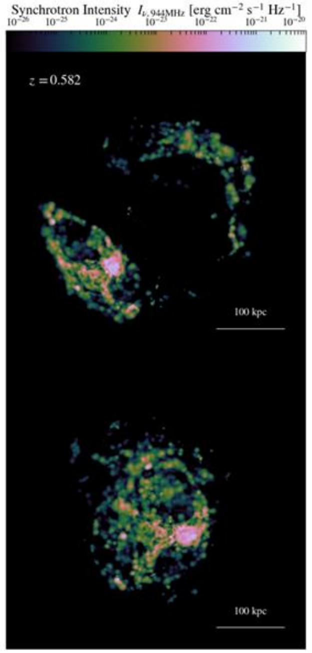
Examples for more complex shock structures observed:

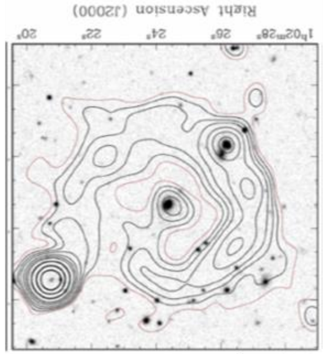




??

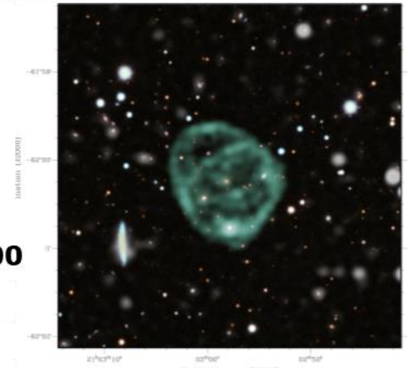
ASKAP / MeerKAT measures shocks in galaxies?





ORC J0102-2450

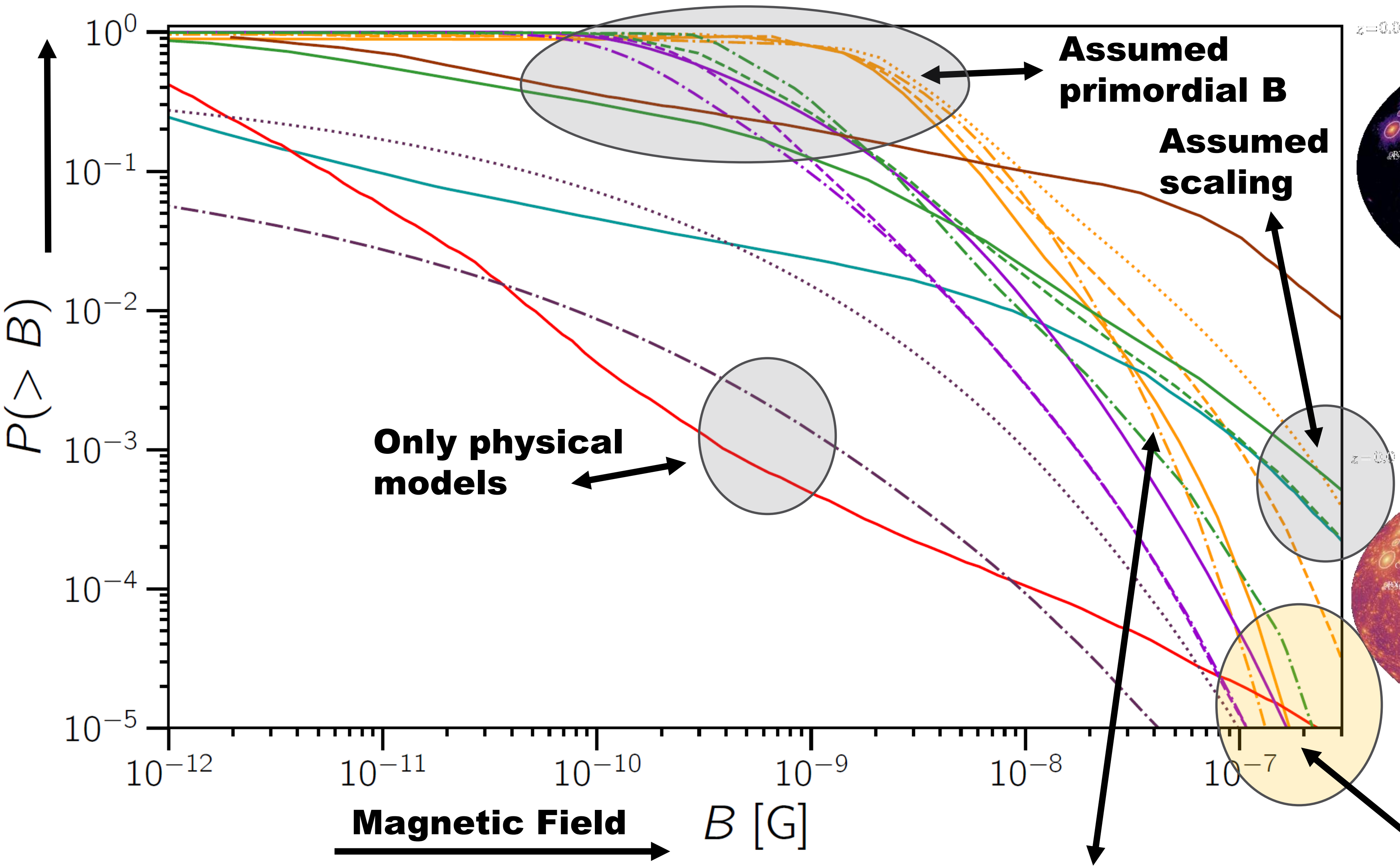
Koribalski+ 2022

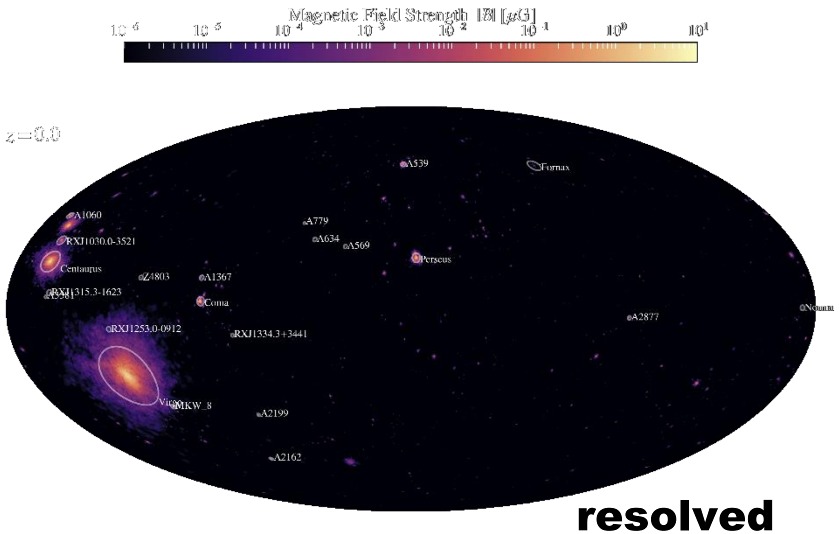


ORC J2103-6200

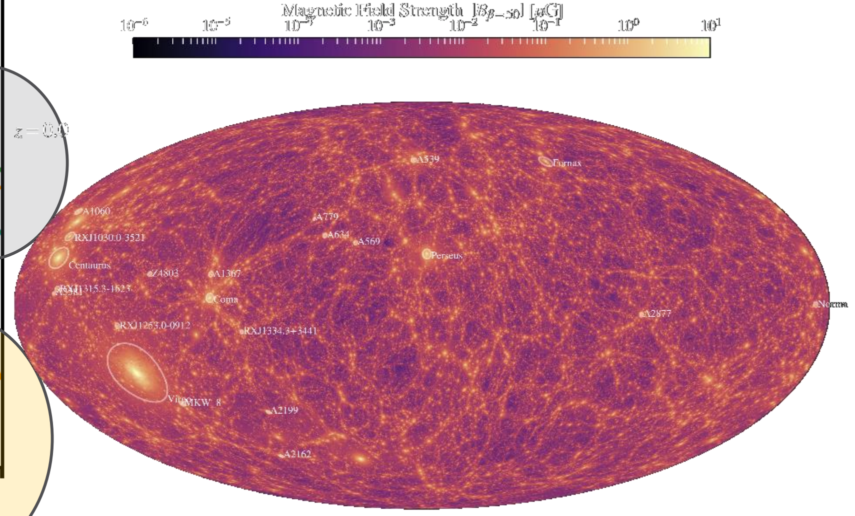
Norris+ 2022

Conclusions





resolved



Assumed scaling !

Detections by future instruments?

Galaxies and Galaxy Clusters (some observations)

Open Questions in Cosmic-Ray Research at Ultrahigh Energies, **Batista et al. 2019 (F. Oikonomou & K. Fang)**