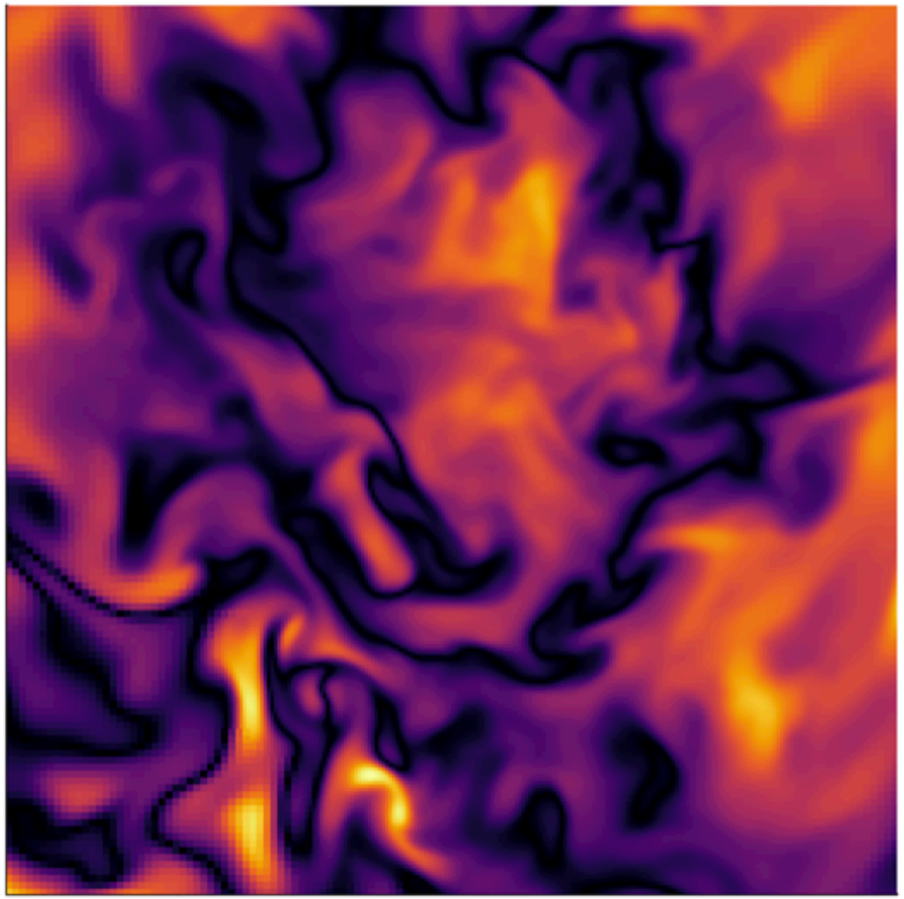
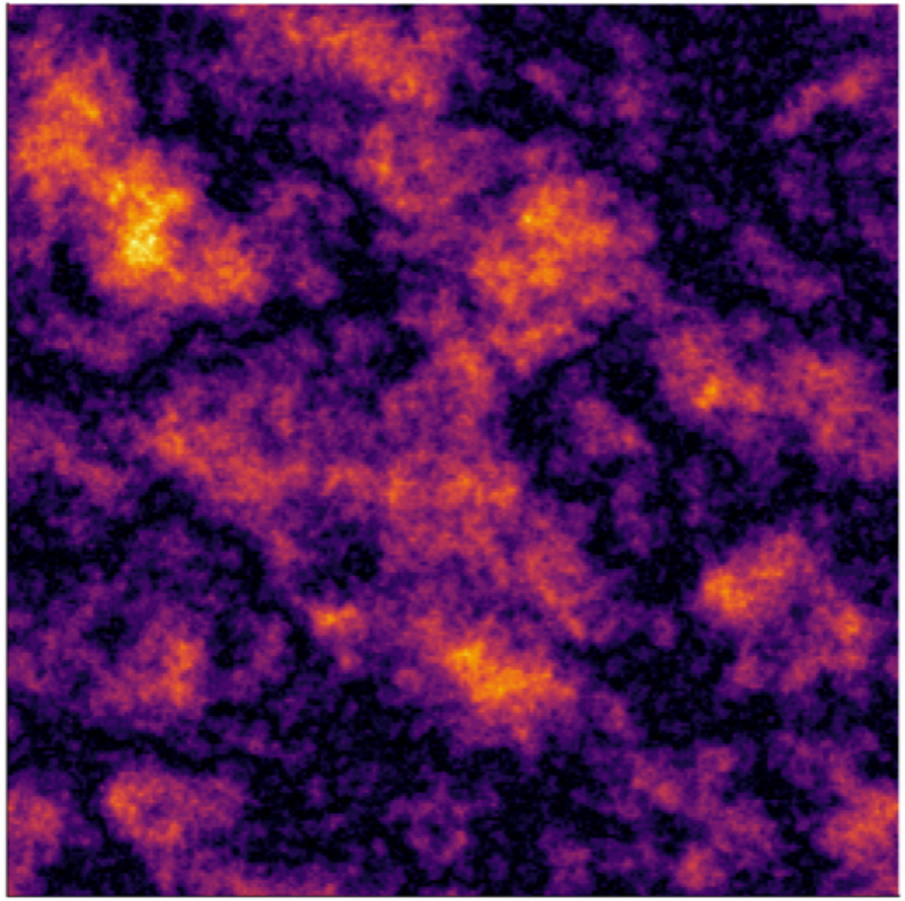
On the interpretation of XRISM X-ray measurements of turbulence in the intracluster medium: a comparison with cosmological simulations

Franco Vazza





based on Vazza & Brunetti https://arxiv.org/pdf/2507.04727

THE XRISM SATELLITE

- **JAXA+NASA+ESA X-ray telescope launched in late 2023**
- **success after long history of “unlucky” satellites for X-ray spectroscopy: AstroE (2000), Suzaku(2006), Hitomi (2016)..**
- **unprecedented spectral resolution (5-7eV), limited ang. resolution (30”) and FOV (3’)**
- **ideal to measure (finally!) turbulence in the intracluster medium via X-ray spectroscopy**

THE XRISM SATELLITE

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XRISM Reveals Low Nonthermal Pressure in the Core of the Hot, Relaxed Galaxy Cluster A2029

XRISM Collaboration, Marc Audard[1], Hisamitsu Awaki[2], Ralf Ballhausen[3,4,5], Aya Bamba[6], Ehud Behar[7], Rozenn Boissay-Malaquin[4,5,8], Laura Brenneman[9], Gregory V. Brown[10], Lia Corrales[11], Elisa Costantini[12], Renata Cumbee[4], Maria Diaz Trigo[13], Chris Done[14], Tadayasu Dotani[15], Ken Ebisawa[15], Megan E. Eckart[10], Dominique Eckert[1], Satoshi Eguchi[16], Teruaki Enoto[17], Yuichiro Ezoe[18], Adam Foster[9], Ryuichi Fujimoto[15], Yutaka Fujita[18], Yasushi Fukazawa[19], Kotaro Fukushima[15], Akihiro Furuzawa[20], Luigi Gallo[21], Javier A. García[4,22],

Advance access publication date:

XRISM Observation of the Ophiuchus Galaxy Cluster: Quiescent Velocity Structure in the Dynamically Disturbed Core

Yutaka Fujita[1,*] Kotaro Fukushima[2] Kosuke Sato[3] Yasushi Fukazawa[4] and Marie Kondo[5]

[1]Department of Physics, Graduate School of Science, Tokyo Metropolitan University, 1-1 Minami-Osawa, Hachioji-shi, Tokyo 192-0397
[2]Institute of Space and Astronautical Science, JAXA, 3-1-1 Yoshinodai, Chuo-ku, Sagamihara, Kanagawa 252-5210

Mapping the Perseus Galaxy Cluster with XRISM

Gas Kinematic Features and their Implications for Turbulence

Congyao Zhang[*1,2], Irina Zhuravleva[2], Annie Heinrich[2], Elena Bellomi[3], Nhut Truong[4,5,6], John ZuHone[3], Eugene Churazov[7,8], Megan E. Eckart[9], Yutaka Fujita[10], Julie Hlavacek-Larrondo[11], Yuto Ichinohe[12], Maxim Markevitch[5], Kyoko Matsushita[13], François Mernier[14], Eric D. Miller[15], Koji Mori[16], Hiroshi Nakajima[17], Anna Ogorzalek[18,5,6], Frederick S. Porter[5], Ayşegül Tümer[4,5,6], Shutaro Ueda[19,20,21], and Norbert Werner[1]

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ApJ Letters accepted

Comparing XRISM cluster velocity dispersions with predictions from cosmological simulations: are feedback models too ejective?

XRISM Collaboration:

Marc Audard, Hisamitsu Awaki, Ralf Ballhausen, Aya Bamba, Ehud Behar, Rozenn Boissay-Malaquin, Laura Brenneman, Gregory V. Brown, Lia Corrales, Elisa Costantini, Renata Cumbee, Maria Diaz Trigo, Chris Done, Tadayasu Dotani, Ken Ebisawa, Megan E. Eckart, Dominique Eckert, Satoshi Eguchi, Teruaki Enoto, Yuichiro Ezoe, Adam Foster, Ryuichi Fujimoto, Yutaka Fujita, Yasushi Fukazawa, Kotaro Fukushima, Akihiro Furuzawa, Luigi Gallo, Javier A. García, Liyi Gu, Matteo Guainazzi, Kouichi Hagino, Kenji Hamaguchi, Isamu Hatsukade, Katsuhiro Hayashi, Takayuki Hayashi, Natalie Hell, Edmund Hodges-Kluck,

XRISM-Subaru views of Abell 754: Energetic ICM Motions Revealed by XRISM/Resolve

Yuki Omiya[1], Nobuhiro Okabe[2,3,4], Kazuhiro Nakazawa[5,1], Naomi Ota[6], Yuto Ichinohe[7], Shutaro Ueda[8,9] and Nhan T. Nguyen-Dang[6]

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XRISM Forecast for the Coma Cluster: Stormy, with a Steep Power Spectrum

XRISM Collaboration, Marc Audard[1], Hisamitsu Awaki[2], Ralf Ballhausen[3,4,5], Aya Bamba[6], Ehud Behar[7], Rozenn Boissay-Malaquin[4,5,8], Laura Brenneman[9], Gregory V. Brown[10], Lia Corrales[11], Elisa Costantini[12],

THE XRISM VIEW OF THE COMA CLUSTER

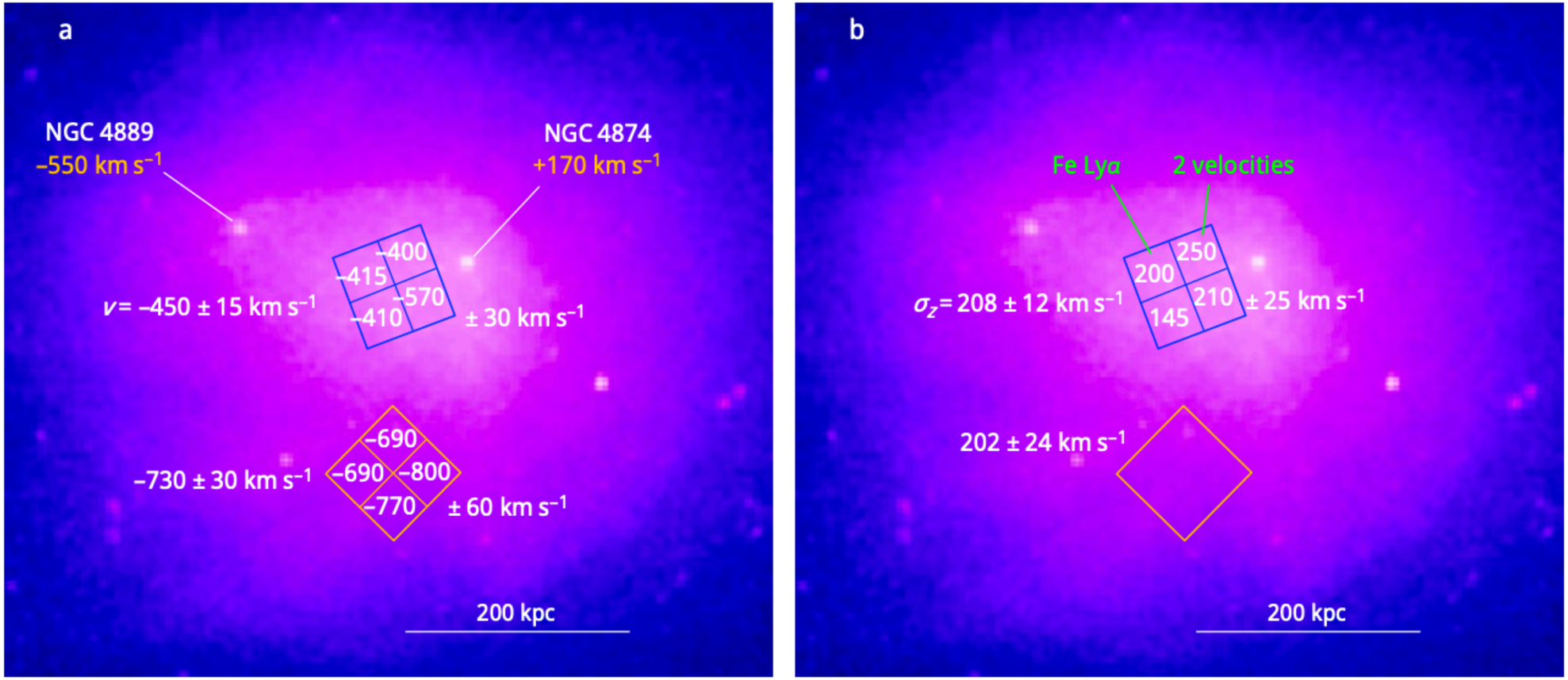

Figure 3. *XRISM* Resolve measurements of (*a*) the LOS velocities relative to the mean velocity of cluster member galaxies and (*b*) LOS velocity dispersion, overlaid on the *XMM-Newton* image. Uncertainties are statistical 1σ. The values to the left of the fields represent the entire $3' \times 3'$ field, while the values inside the FOV pertain to the $1.5'$ quadrants, for which the relatively small PSF smearing effect is not included. The two brightest galaxies are marked along with their relative LOS velocities. Green labels mark the quadrants discussed in §§3.2–3.3.

THE XRISM VIEW OF THE COMA CLUSTER

Abstract

The XRISM Resolve microcalorimeter array measured the velocities of hot intracluster gas at two positions in the Coma galaxy cluster: $3' \times 3'$ squares at the center and at $6'$ (170 kpc) to the south. We find the line-of-sight velocity dispersions in those regions to be $\sigma_z = 208 \pm 12\,\mathrm{km\,s^{-1}}$ and $202 \pm 24\,\mathrm{km\,s^{-1}}$, respectively. The central value corresponds to a 3D Mach number of $M = 0.24 \pm 0.015$ and a ratio of the kinetic pressure of small-scale motions to thermal pressure in the intracluster plasma of only $3.1\% \pm 0.4\%$, at the lower end of predictions from cosmological simulations for merging clusters like Coma, and similar to that observed in the cool core of the relaxed cluster A2029. Meanwhile, the gas in both regions exhibits high line-of-sight velocity differences from the mean velocity of the cluster galaxies, $\Delta v_z = 450 \pm 15\,\mathrm{km\,s^{-1}}$ and $730 \pm 30\,\mathrm{km\,s^{-1}}$, respectively. A small contribution from an additional gas velocity component, consistent with the cluster optical mean, is detected along a sight line near the cluster center. The combination of the observed velocity dispersions and bulk velocities is not described by a Kolmogorov velocity power spectrum of steady-state turbulence; instead, the data imply a much steeper effective slope (i.e., relatively more power at larger linear scales). This may indicate either a very large dissipation scale, resulting in the suppression of small-scale motions, or a transient dynamic state of the cluster, where large-scale gas flows generated by an ongoing merger have not yet cascaded down to small scales.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Coma Cluster (270); Intracluster medium (858); High resolution spectroscopy (2096)

The two brightest galaxies are marked along with their relative LOS velocities. Green labels mark the quadrants discussed in §§5.2–5.3.

THE XRISM VIEW OF THE COMA CLUSTER

A) VERY LARGE DISSIPATION SCALE (>100KPC)

OR

B) TURBULENCE FROM ONGOING MERGER WHICH HAS NOT CASCADED DOWN TO SMALL SCALES

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THE XRISM VIEW OF THE COMA CLUSTER

A) VERY LARGE DISSIPATION SCALE

(>100KPC)

OR

B) TURBULENCE FROM ONGOING MERGER

WHICH HAS NOT CASCADED DOWN TO

SMALL SCALES

ACCORDING TO OUR WORK:

PROBABLY NOTHING OF THIS

nt with the cluster optical mean, is detected along
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Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Coma Cluster (270); Intracluster medium (858); High resolution spectroscopy (2096)

- **WHY SHOULD CLUSTERS OF GALAXIES BE TURBULENT ?**
- **WHY SHOULD TURBULENCE FOLLOW SOME SPECIFIC LAW?**
- **WHAT XRISM MEASURED AND WHAT WE THINK IT MEANS**

WHY SHOULD CLUSTERS OF GALAXIES BE TURBULENT?

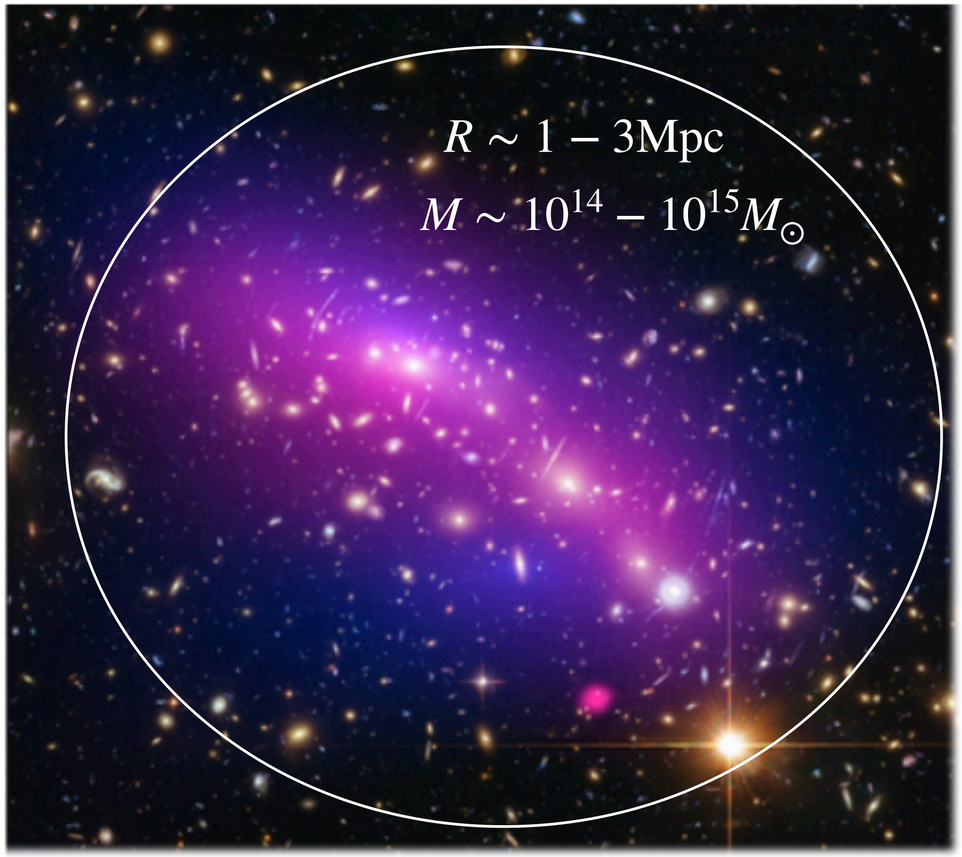
WHY SHOULD CLUSTERS OF GALAXIES BE TURBULENT?

they are:

WHY SHOULD CLUSTERS OF GALAXIES BE TURBULENT?

they are:

"the largest gravitationally bound structures in the Universe"



$\sim 84\,\%$ dark matter

$\sim 16\,\%$ ordinary matter

$(\sim 1\,\%$ stars)

(approximate) virialisation:

$$2E_k = U \rightarrow \sigma_v^2 \sim \frac{GM}{R_{\mathrm{vir}}} \sim \frac{5k_bT}{3\mu m_p} \sim 10^3 \mathrm{km/s}$$

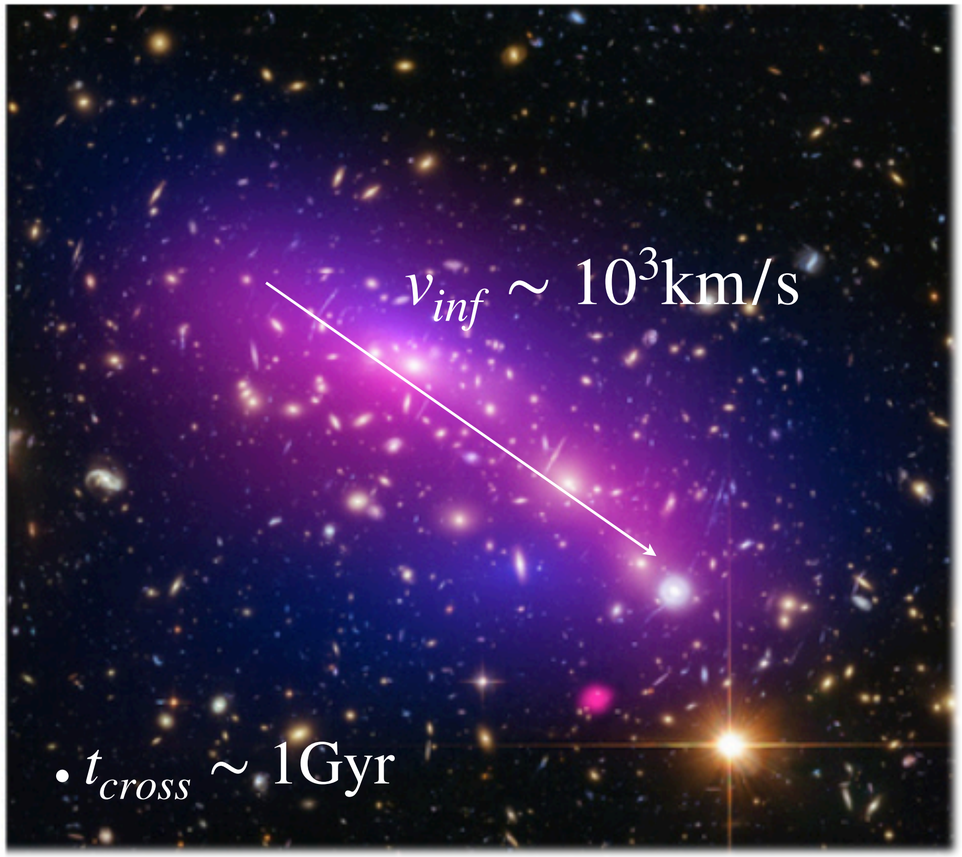
$$R_{\mathrm{vir}} = \sqrt{GM/\sigma_v^2} \sim 1 - 3\mathrm{Mpc}$$

→ large

WHY SHOULD CLUSTERS OF GALAXIES BE TURBULENT?

they are:

"formed by the most energetic events in the Universe (cluster mergers)"



$E_k \sim U \sim 10^{64}$erg

$P_{\rm kin} \sim E_k / t_{\rm cross} \lesssim 10^{46}$erg/s

A fraction $\sim 10\,\% P_{kin}$ is channeled into turbulence, cosmic rays and B-field

→ evolving

WHY SHOULD CLUSTERS OF GALAXIES BE TURBULENT?

they are……. *“the most perfect plasma laboratory in the Universe”*

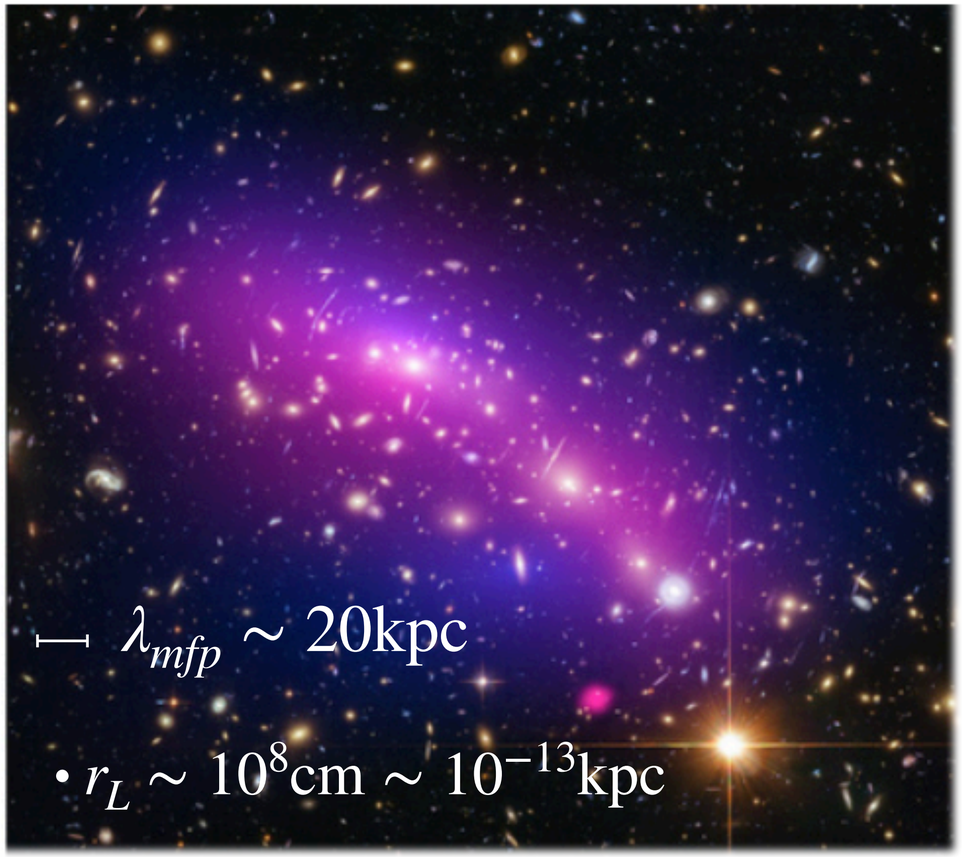
λ_{mfp} collisional mean free path ($\sim 20\mathrm{kpc}$)

r_L gyroradius of protons ($\sim 10^{-13}\mathrm{kpc}$)

$$r_L \ll \lambda_{\mathrm{mfp}} \ll R_{\mathrm{vir}}$$

the dynamics of the intracluster medium is ruled by collective plasma processes.

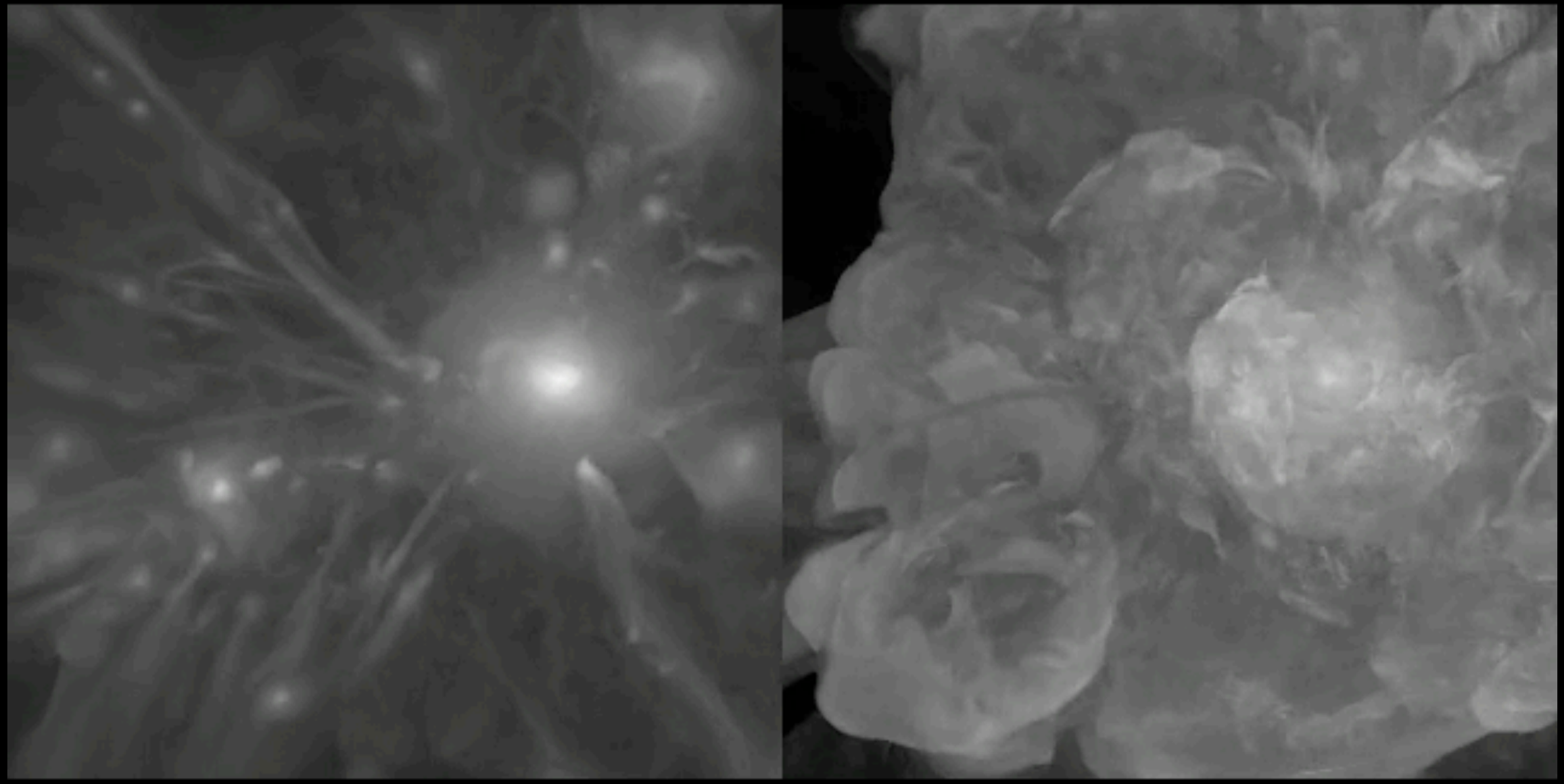
If turbulence is injected on $\sim R_{vir}$ scales, it can develop over a huge dynamical range



→ turbulent

gas density

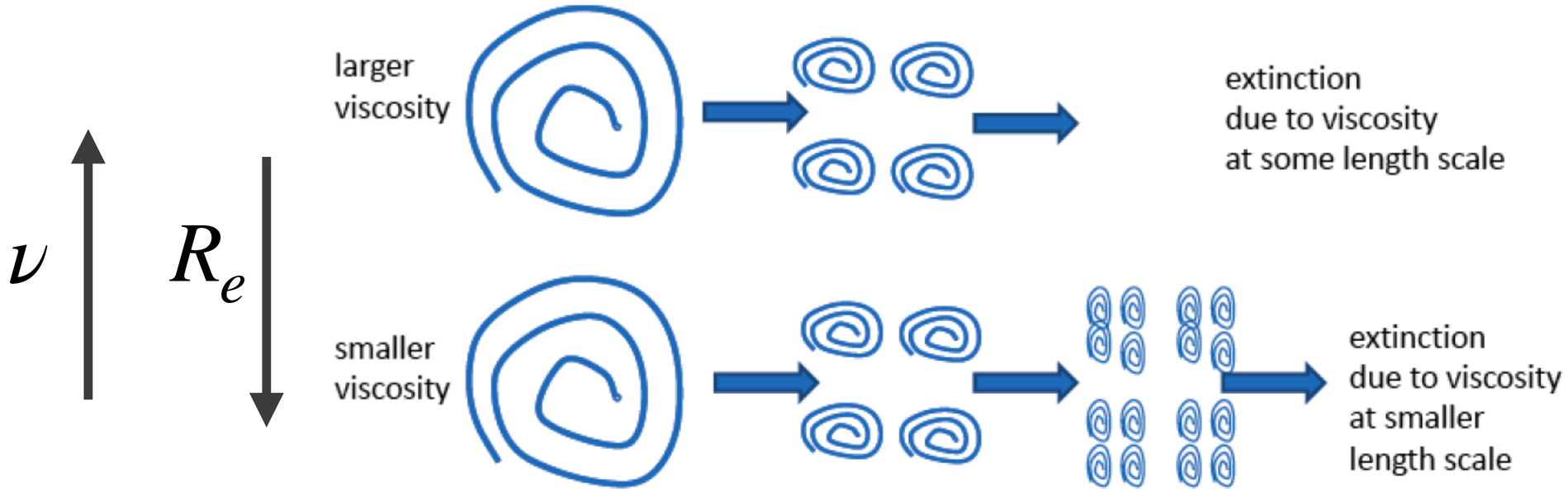
gas temperature



WHY SHOULD TURBULENCE FOLLOW SOME SPECIFIC LAW?

- A turbulent flow is composed by eddies of different size (λ) and internal velocity dispersion v_λ. Eddies "process" their energy on a $\tau_\lambda \sim \lambda / v_\lambda$ timescale, and reorganize into smaller eddies producing a "cascade" of kinetic energy.

- the energy "goes" from the largest scales (L) of the motion to smaller scales ($\sim \lambda_{\rm visc}$) at which the viscosity dissipates the kinetic energy (into microscopic random motions, i.e. "heating")



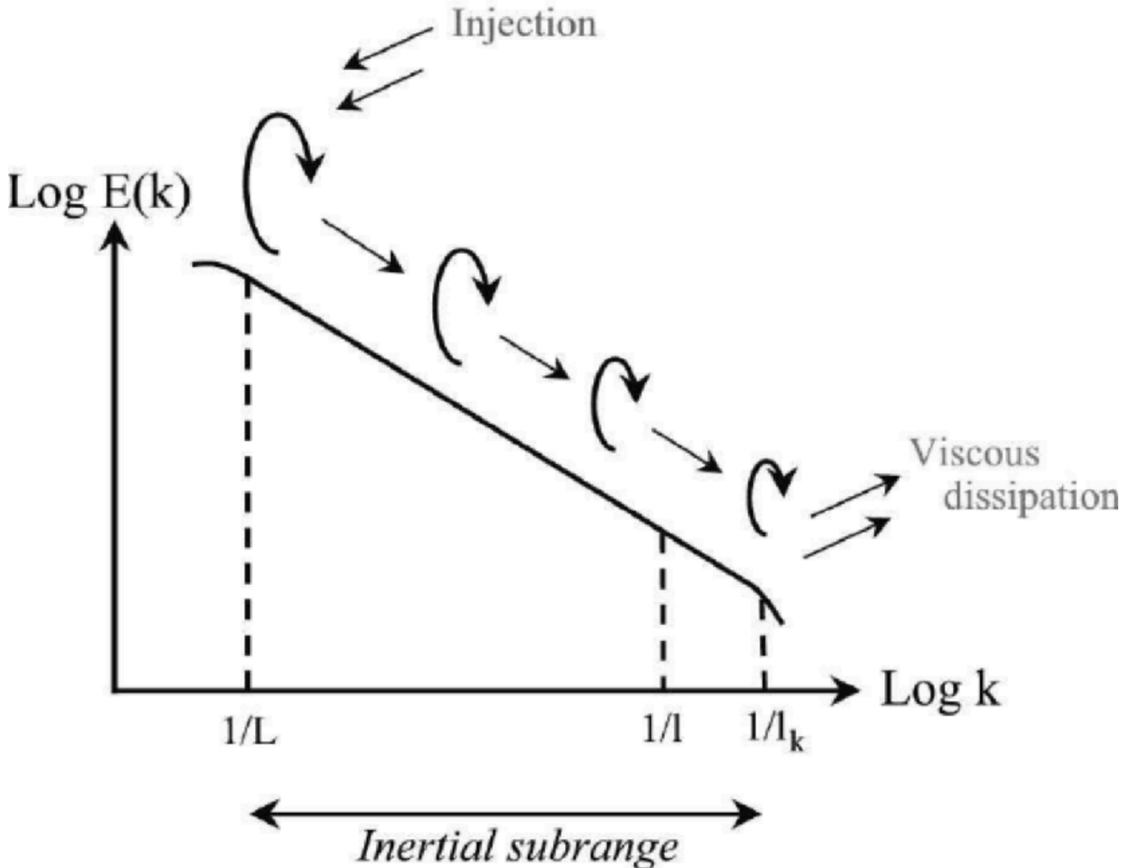
- If kinetic energy is conserved, the flow of kinetic energy across scales follows: $\epsilon = \frac{v_\lambda^2}{\tau_\lambda} = \frac{v_\lambda^3}{\lambda} = \text{constant}$

WHY SHOULD TURBULENCE FOLLOW SOME SPECIFIC LAW?

The process is more naturally described in Fourier space - as a continuous distribution of waves with frequency $k = 2\pi/\lambda$.

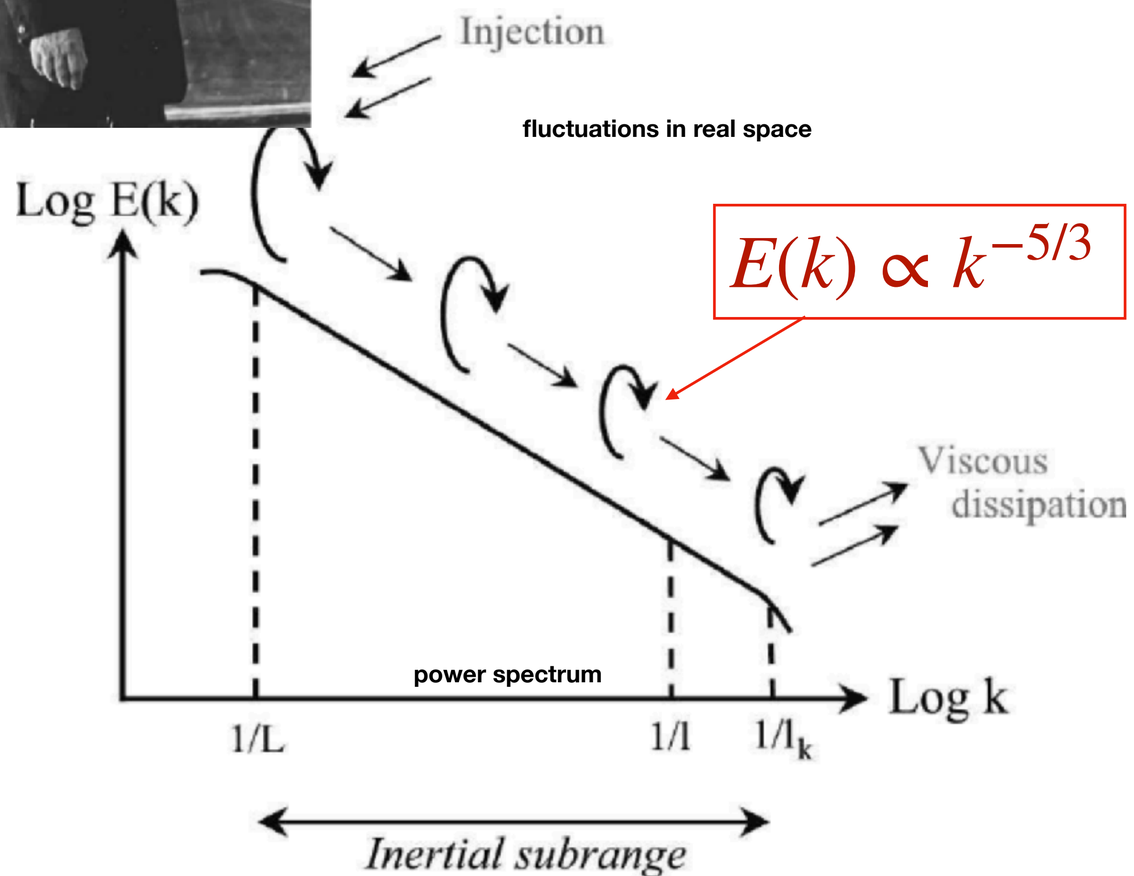
The power spectrum $E(k)$ describes the energy of flucutations as a function of scale and its integral gives the total kinetic energy:

$$\int_{k_{\text{inj}}}^{k_{\text{visc}}} E(k)dk = \frac{\langle \Delta v \rangle^2}{2}$$



FULLY DEVELOPED TURBULENCE - K41 MODEL

In 1941, through "dimensional analysis" A. Kolmogorov demonstrated that the only allowed form for the power spectrum is: $E(k) \propto \epsilon^{2/3} k^{-5/3}$ if the flow is a) stationary, b) incompressible and c) homogenous.



Demonstration:

$\Delta v^2 \propto E(k)dk$ implies this possible combination of dimensions:

$$[\frac{\mathrm{cm}^2}{\mathrm{s}^2}] = \epsilon^{\alpha} \cdot (\mathrm{kdk})^{\beta} = [\frac{\mathrm{m}^{2\alpha}}{\mathrm{s}^{3\alpha}} \cdot \frac{1}{\mathrm{m}^{\beta+1}}]$$

in which α and β are unknown. But we now have a system of two equations:

$$\begin{cases} 2 = 2\alpha - \beta - 1 & \text{for [m]} \\ 2 = 3\alpha & \text{for [s]} \end{cases}$$

With solution $\alpha = 2/3$ and $\beta = -5/3$.

So $E(k) \propto \epsilon^{2/3} k^{-5/3}$.

This is the famous "Kolmogorov's 5/3 law"

TURBULENCE IN ASTROPHYSICAL ENVIRONMENTS

Thus "Kolmogorov's 5/3 law" has been observed virtually everywhere in astrophysics: from $\sim 10^3$ kmto $\sim$ Mpc scales.

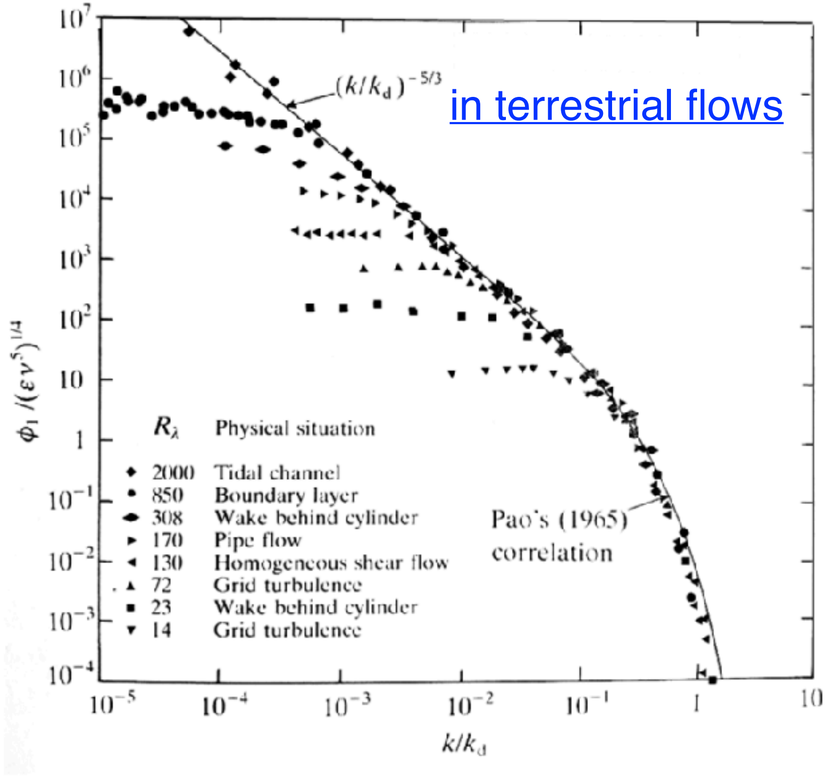
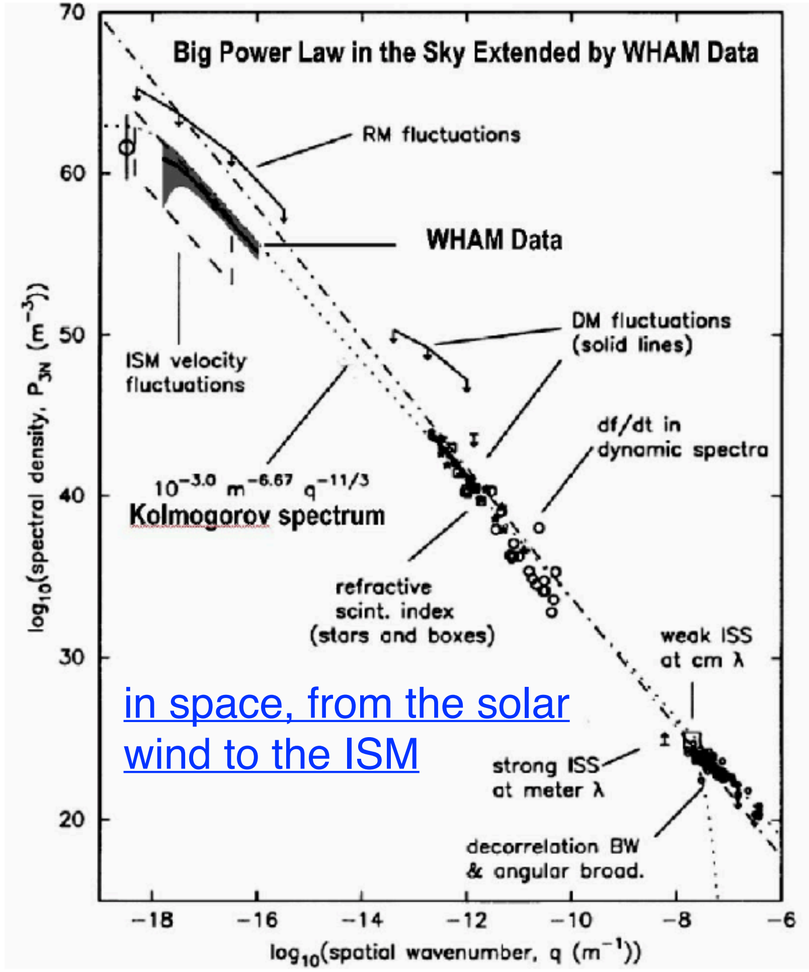


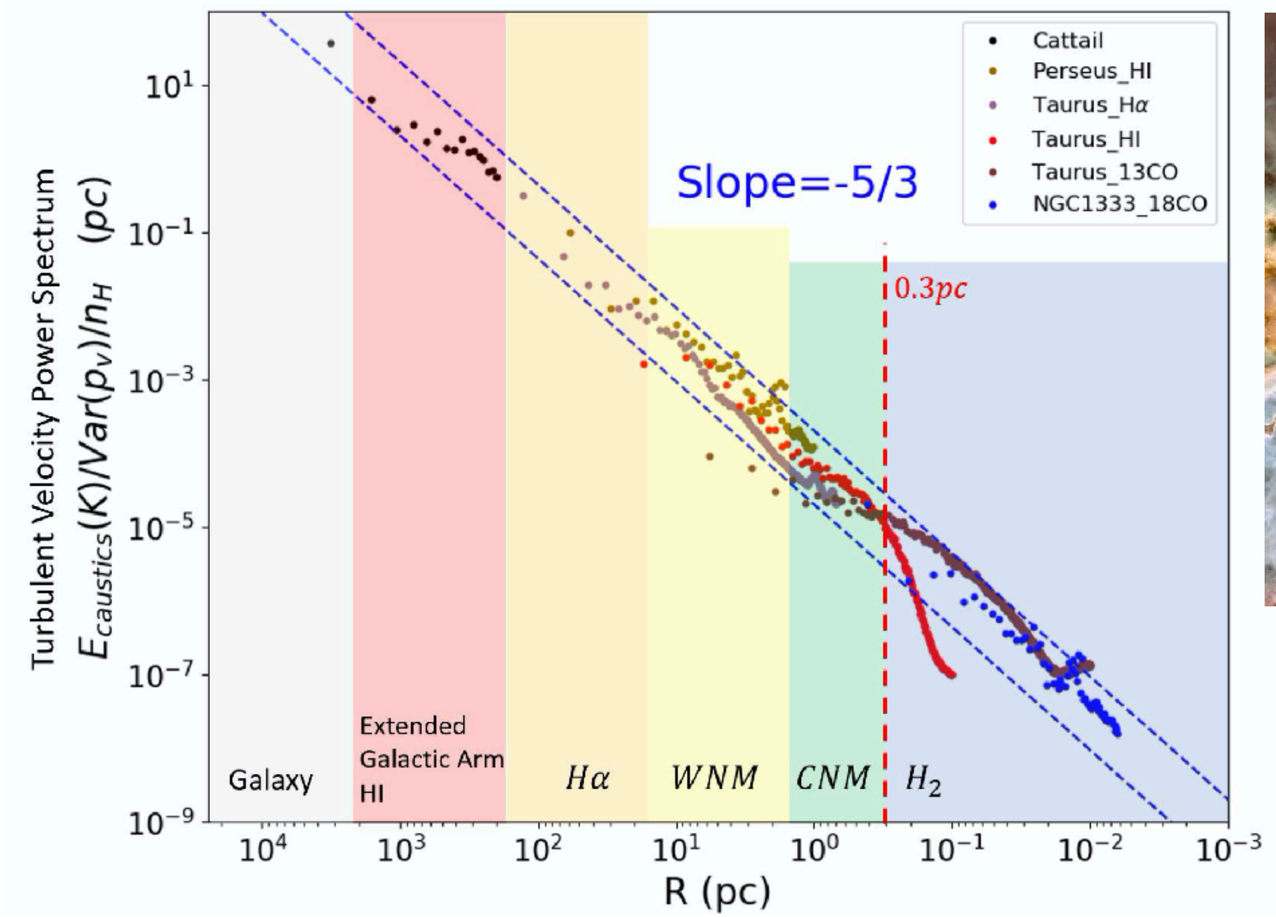
Figure 1. Measured one-dimensional energy spectra for a wide range of Reynolds numbers and physical situations showing the asymptotic effect of scaling on Kolmogorov (1941) variables. Image reproduced from Figure 2.4 of Reference [6].

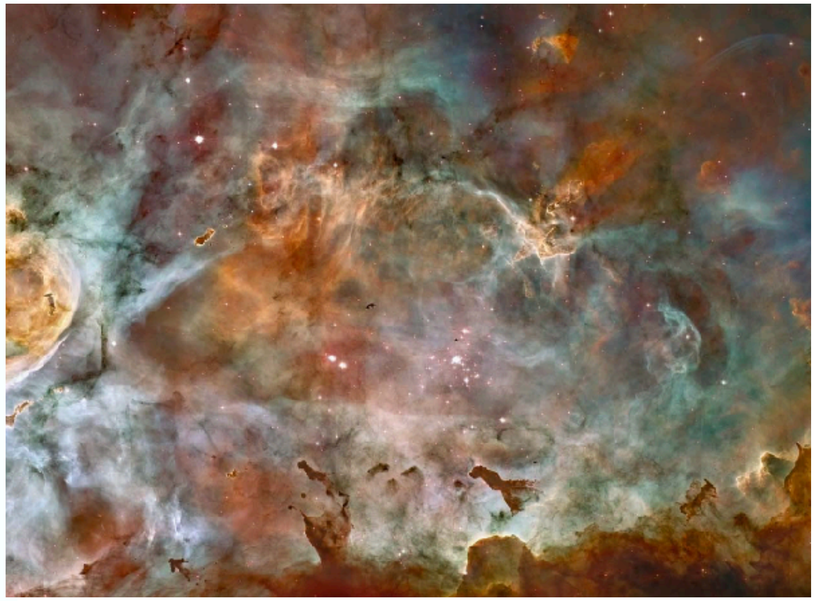


Big power law in the sky from [45] extended to scale of parsecs using WHAM data. From [46].

TURBULENCE IN ASTROPHYSICAL ENVIRONMENTS

Turbulent velocity power spectrum for a compilation of probes of the ISM dynamics:
supersonic ($\sigma_v \geq c_s$) & magnetised ($\sigma_v \sim v_A$) turbulence



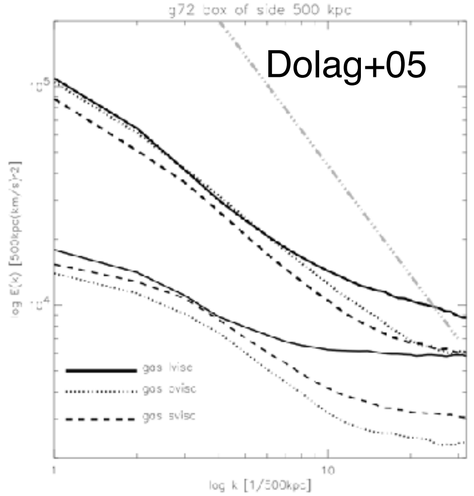


- NOT the same single injection
- …still close to a global Kolmogorov spectrum

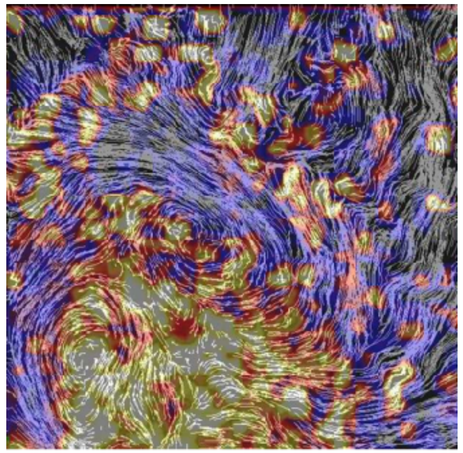
(SIMULATED) TURBULENCE IN THE ICM

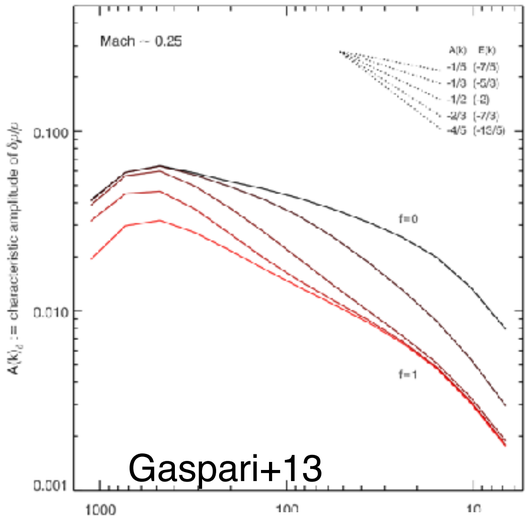
literature of the last ~ 20 years:

- turbulence close to Kolomogorov (slightly steeper)
- turbulent pressure $\sim 5-30\,\%$ thermal depending on dynamical state AND "filtering" methods



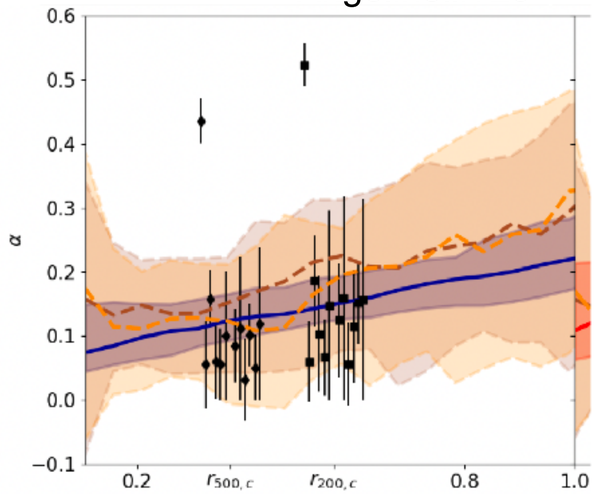
Dolag+05



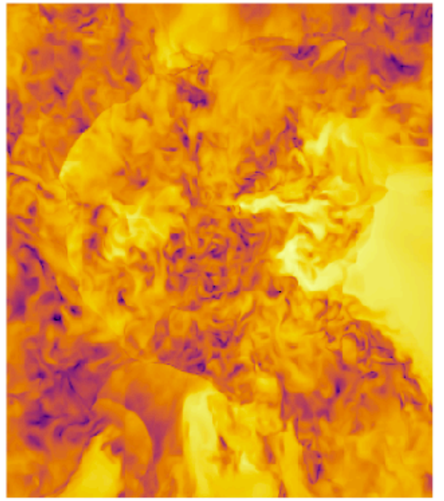


Gaspari+13

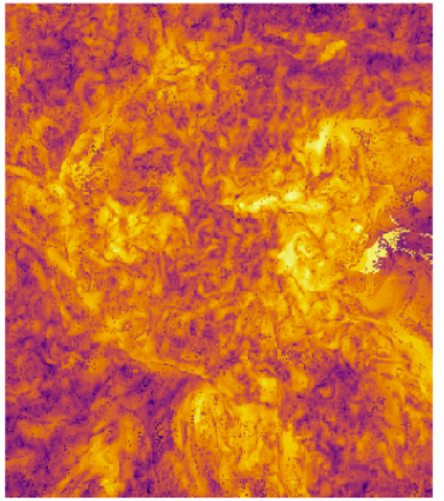
Angelinelli+20

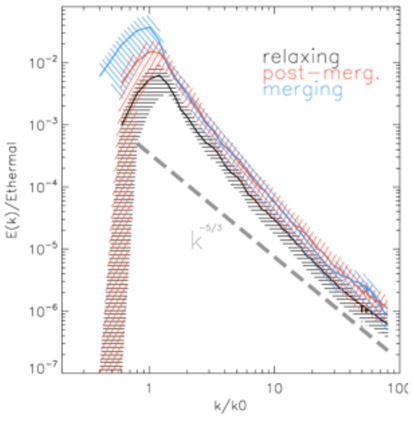


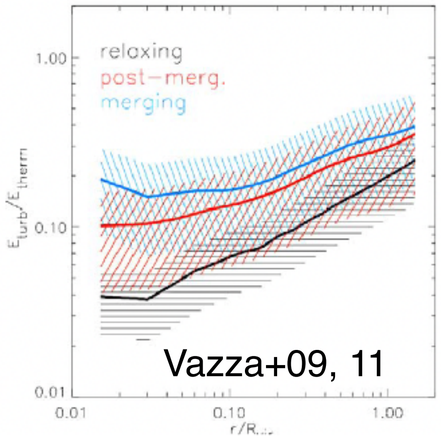
Velocity field

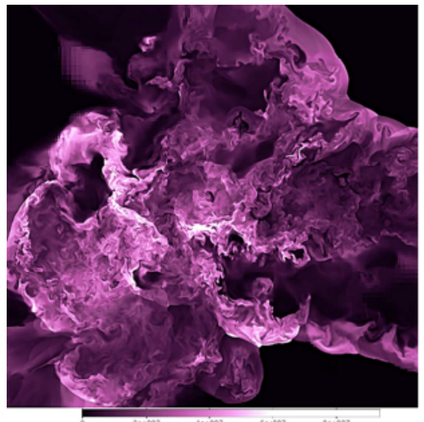


Turbulent velocity field, tolerance: $f = 0.77$









see also Iapchino+08, Ryu+08, Lau+09, Vazza+12,17,18;

Valdarnini+19, Mohapatra+22; Groth+24, Valles-Perez+24…

(SIMULATED) TURBULENCE IN THE ICM

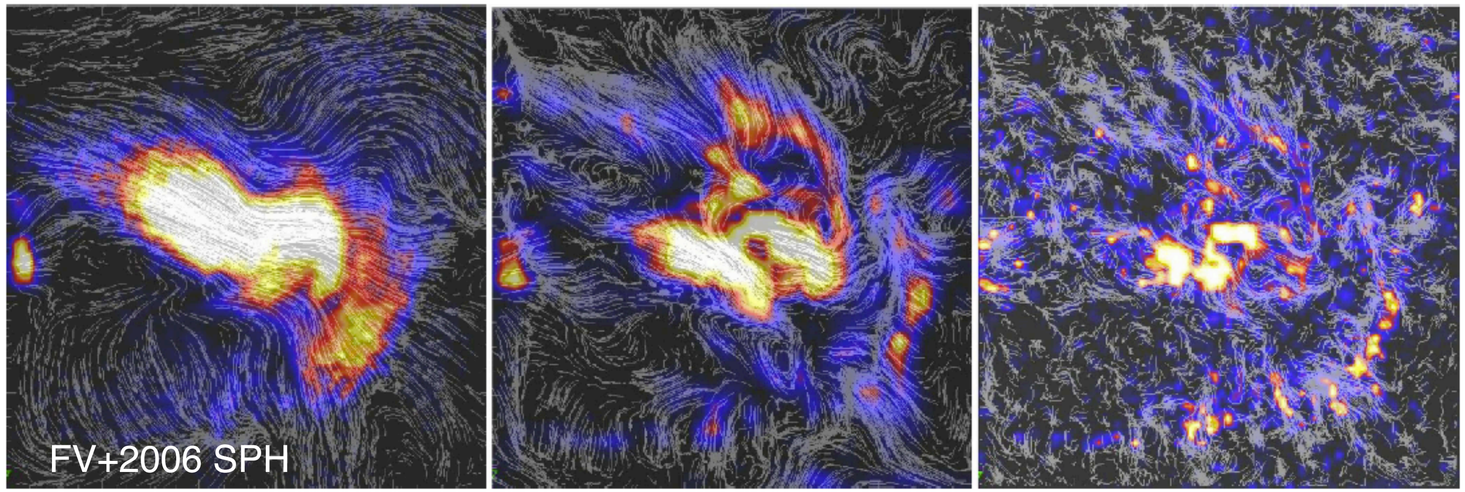
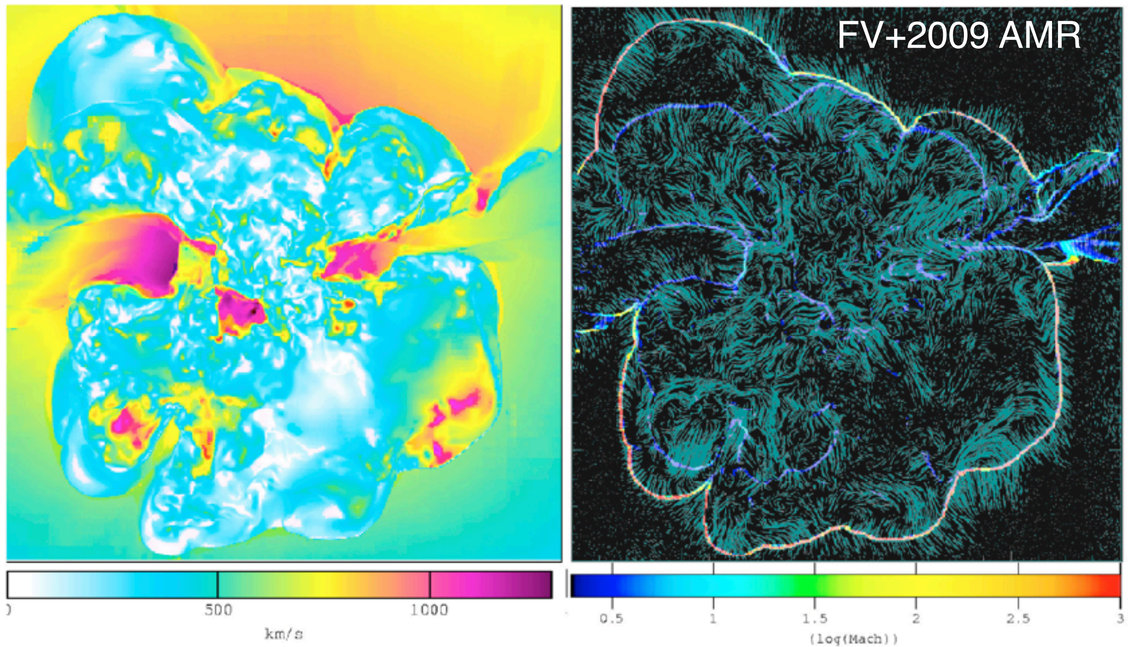
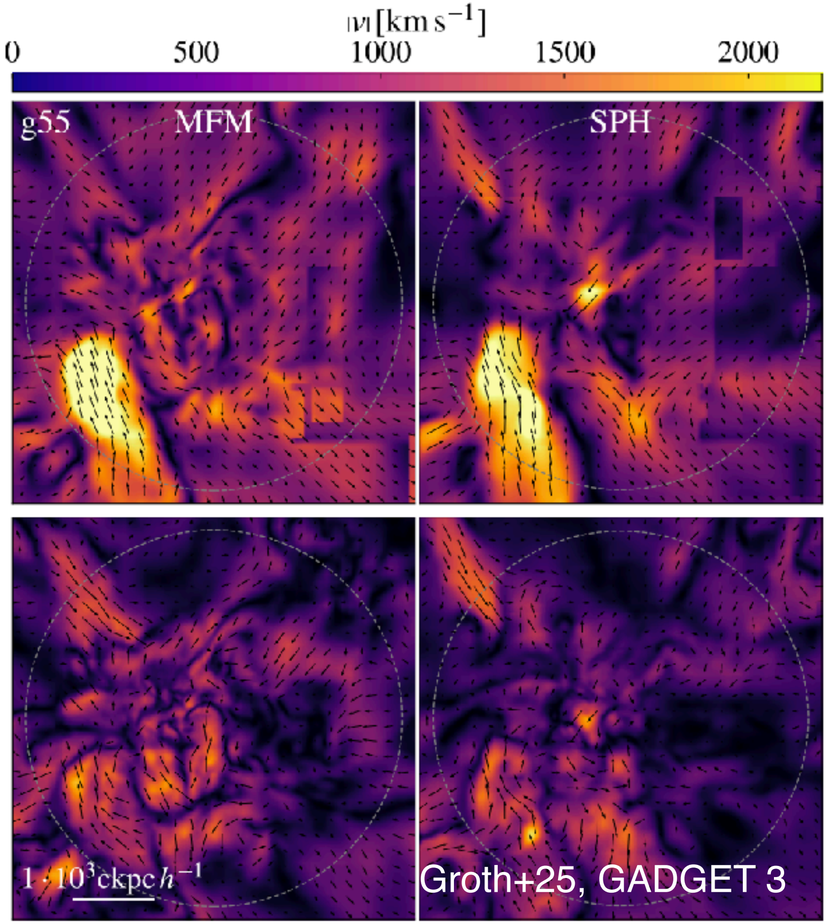


Figure 1. Two-dimensional maps for the central $\sim(1.3\,\mathrm{Mpc})^2$ region of the most massive cluster of our sample. A subcluster 10 times less massive is being accreted (entering from the left). The streamlines on the left depict the velocity defined with respect to the centre of mass velocity; on the right they depict the local velocity residuals for two different resolutions of the algorithm: $l \sim 32\,\mathrm{kpc}$ (centre) and $l \sim 16\,\mathrm{kpc}$ (right). The overlayed colour maps show the kinetic energy of gas particles for each of the velocity fields.

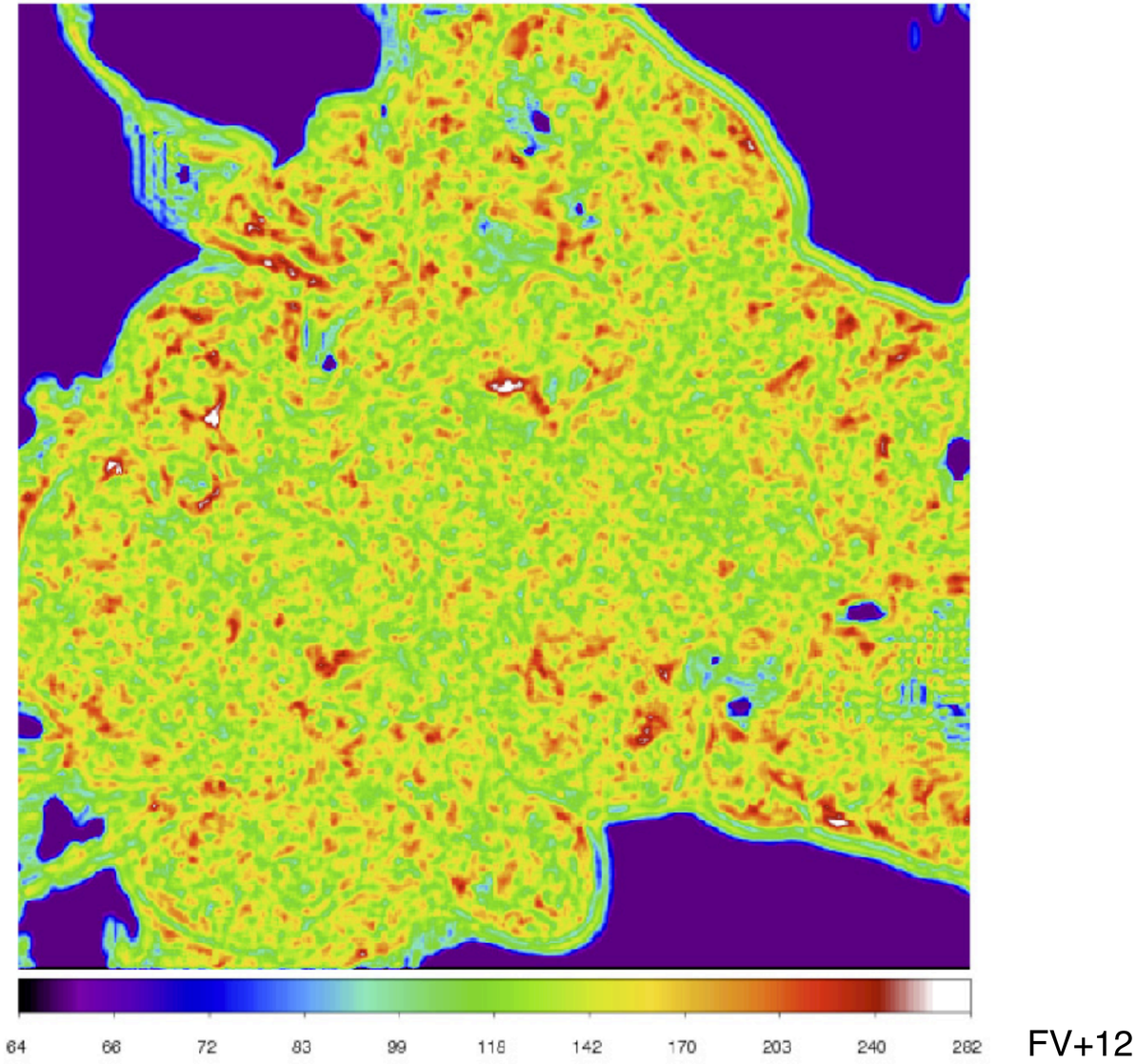


SIMULATIONS

- a lot of turbulent motions injected by multiple accretion events



(SIMULATED) TURBULENCE IN THE ICM



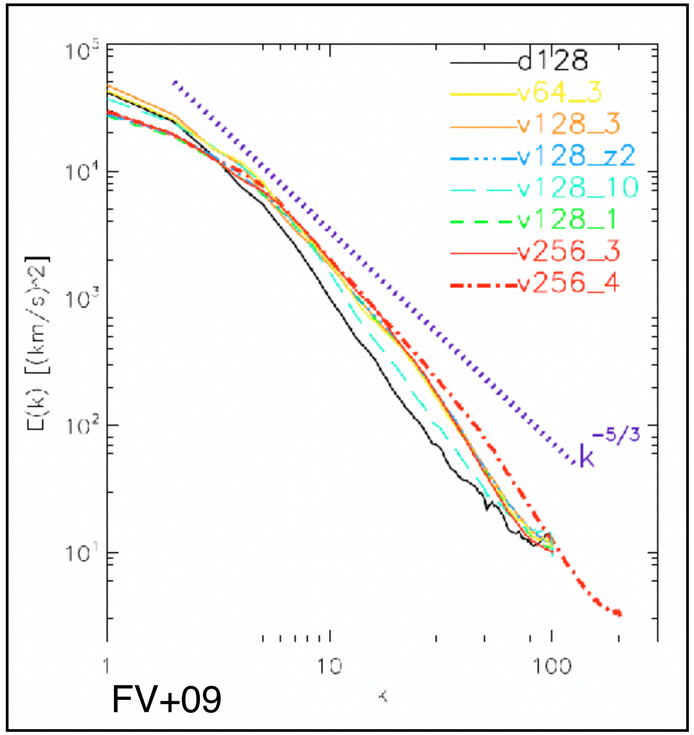
FV+12

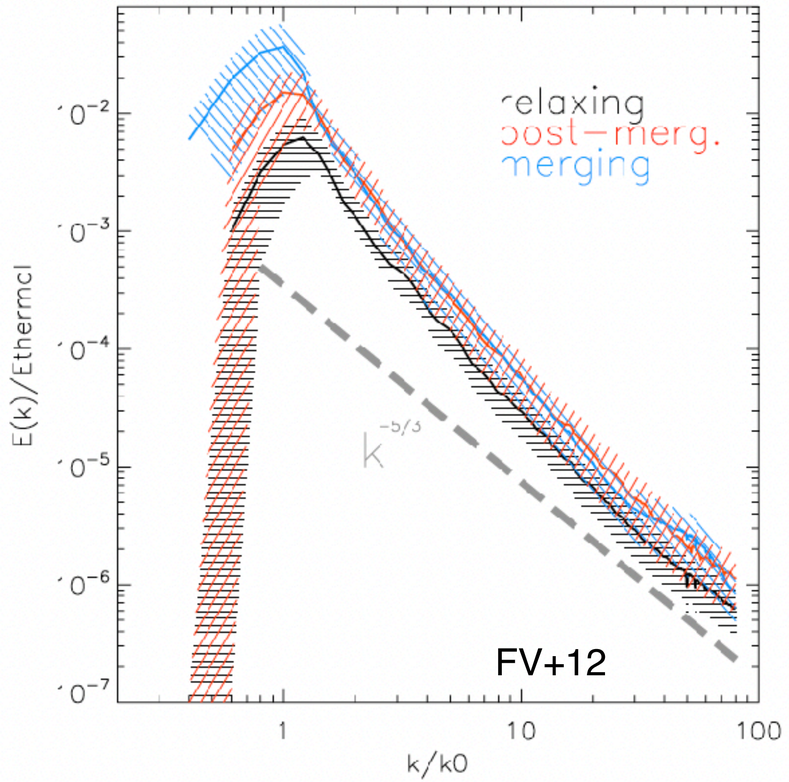
Fig. 7. Two-dimensional slice showing the distribution of coherence scales (in kpc) for a velocity field of the same region as in Fig. 5.

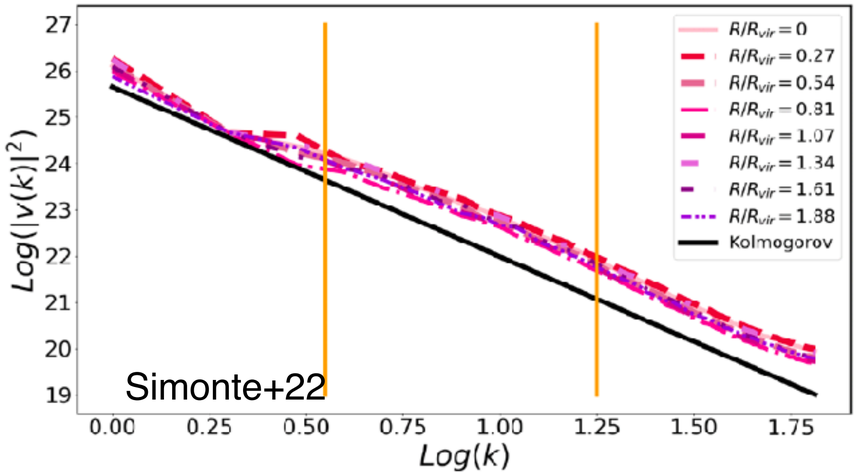
SIMULATIONS

- a lot of turbulent motions injected by multiple accretion events
- **there is no single injection episode nor a single injection scale - but rather A DISTRIBUTION OF INJECTIONS (AND CASCADES)**

(SIMULATED) TURBULENCE IN THE ICM







SIMULATIONS

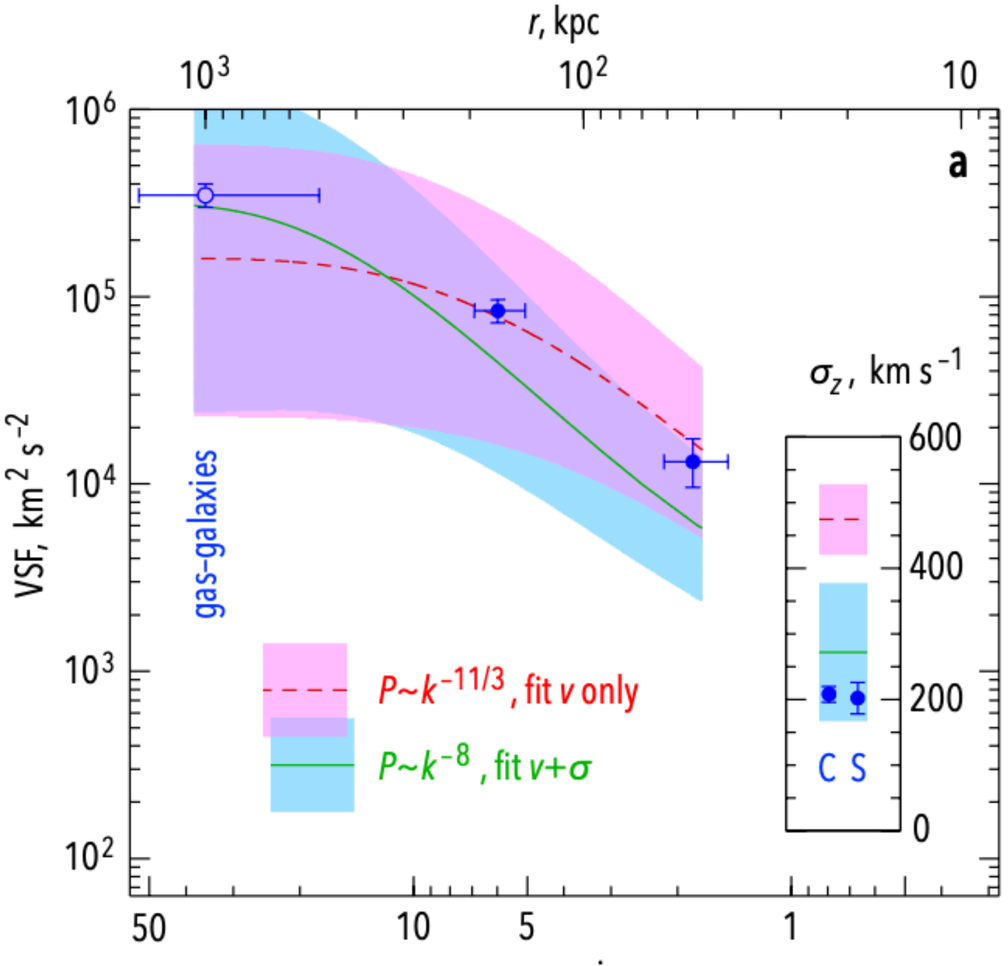
- a lot of turbulent motions injected by multiple accretion events
- there is no single injection episode nor a single injection scale - but rather A DISTRIBUTION OF INJECTIONS (AND CASCADES)

- **Velocity power spectra close to Kolmogorov ($P_v(k) \propto k^{-5/3}$) to a good approximation…but NOT the classical stationary and single injection model!**
- **if $P_v(k)$ is measured in small volumes ($\leq 300^3 \mathrm{kpc}^3$) it gets close to Kolmogorov, but when the $P_v(k)$ for the entire cluster is steeper ($\propto k^{-2}$): stratification, shocks..**

(BACK TO) THE XRISM VIEW OF THE COMA CLUSTER

KEY FINDINGS:

- velocity structure function much steeper than Kolmogorov
- relatively low velocity dispersion ($\sigma \leq 250$ km/s) resulting into a low turbulent pressure support ($\leq 3\,\%$ of total)



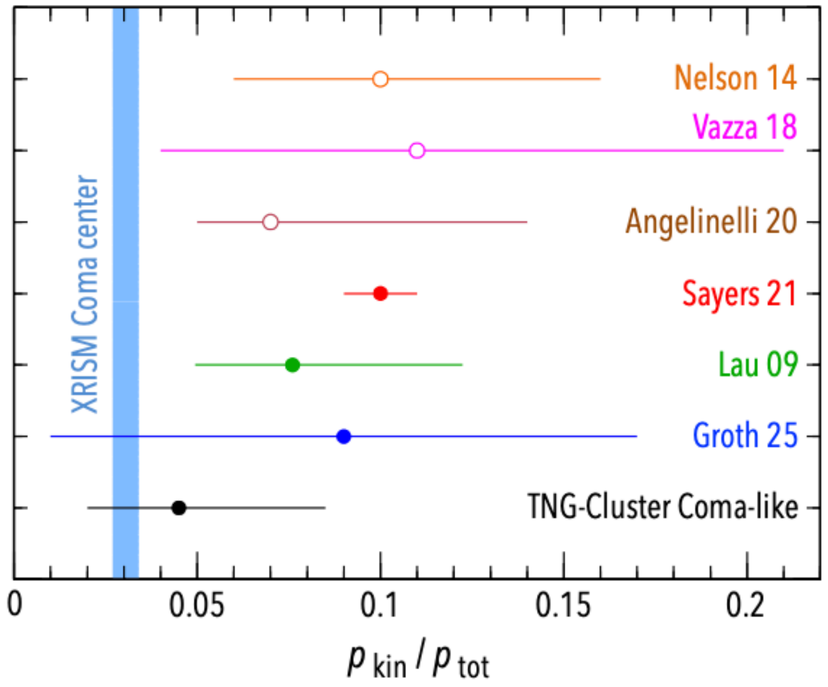
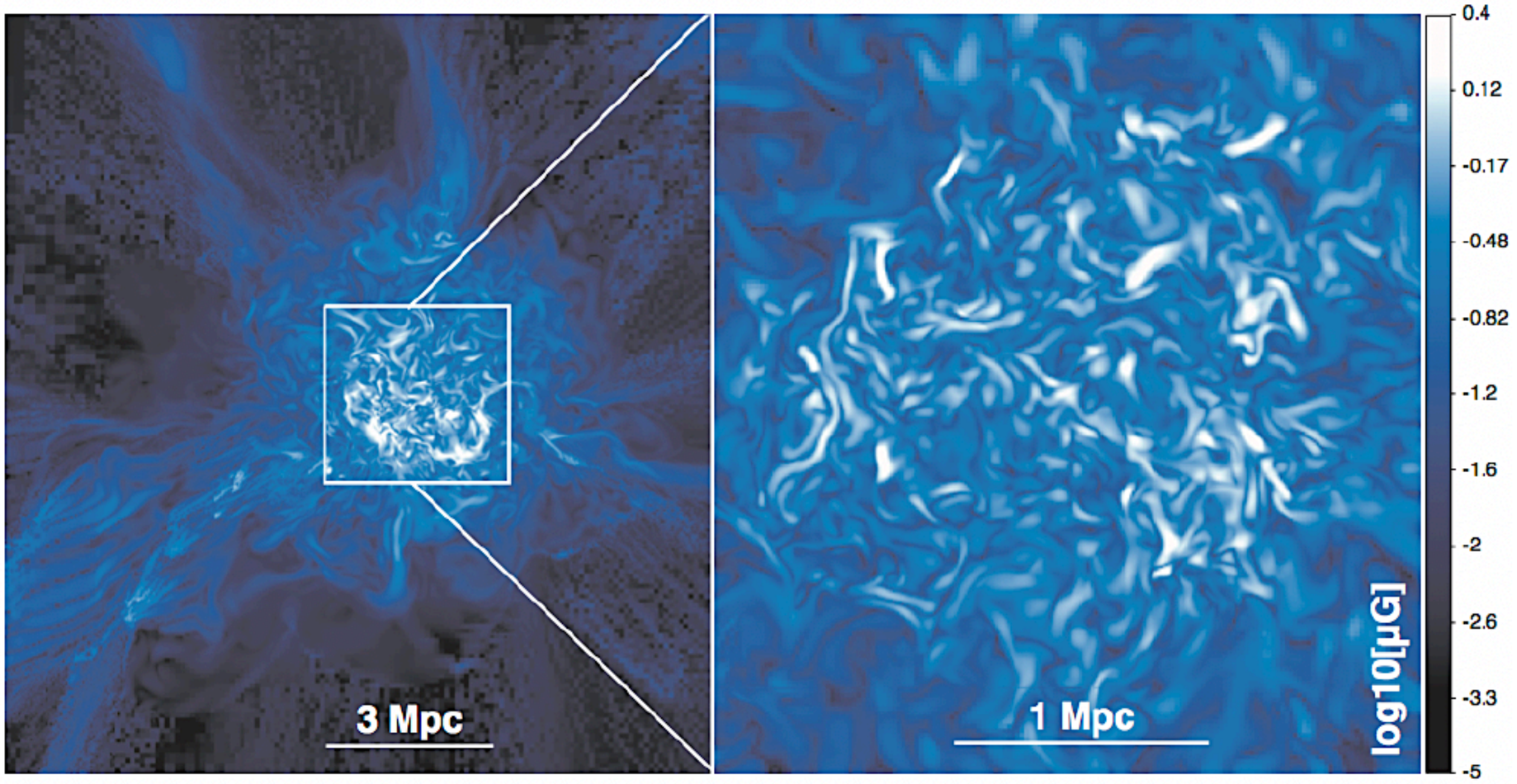


Figure 6. The *XRISM* value of $p_{\rm kin}/p_{\rm tot}$ for Coma, derived from the central line width, is compared with predictions from several cosmological simulations. Open symbols represent all clusters, while filled symbols select only the disturbed Coma-like clusters. For TNG-Cluster, there is an additional selection based on cluster mass and weighting by X-ray emission measure (see Appendix B). The horizontal intervals show the $16^{\rm th}-84^{\rm th}$ percentiles of the simulated cluster populations. The measured value is at the low end of the predictions.

XRISM COLLAB. 2025

THE XRISM VIEW OF THE COMA CLUSTER

Re-analysis of a $\sim 10^{15} M_{\odot}$ Coma-like cluster (produced in 2018)



- same mass as Coma
- similar density and entropy profiles
- good match to the RM profile of real Coma

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COSMOLOGICAL MHD SIMULATIONS

(Ideal) MHD equations on a comoving grid.

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\nabla \cdot (\rho \mathbf{v}) = 0$$

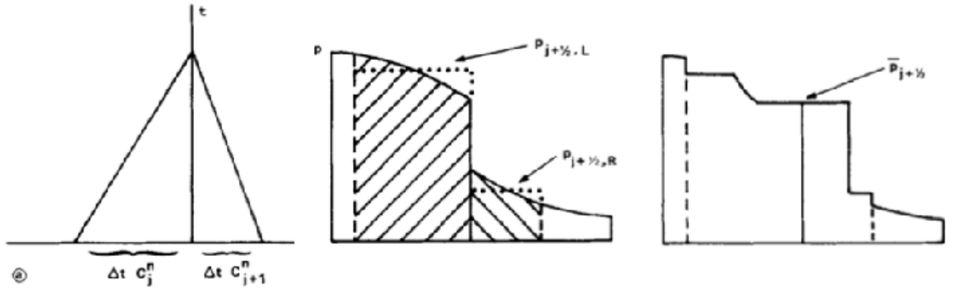
$$\frac{\partial \rho \mathbf{v}}{\partial t} + \frac{1}{a}\nabla \cdot (\rho \mathbf{v}\mathbf{v} + \bar{p} - \mathbf{B}\mathbf{B}) = -\frac{\dot{a}}{a}\rho \mathbf{v} - \frac{1}{a}\rho \nabla \Phi$$

$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla \cdot [\mathbf{v}(\bar{p} + E) - \mathbf{B}(\mathbf{B} \cdot \mathbf{v})] = -\frac{\dot{a}}{a}(\rho v^2 + \frac{2}{\gamma - 1}p + \frac{B^2}{2}) - \frac{\rho}{a}\mathbf{v} \cdot \nabla \Phi$$

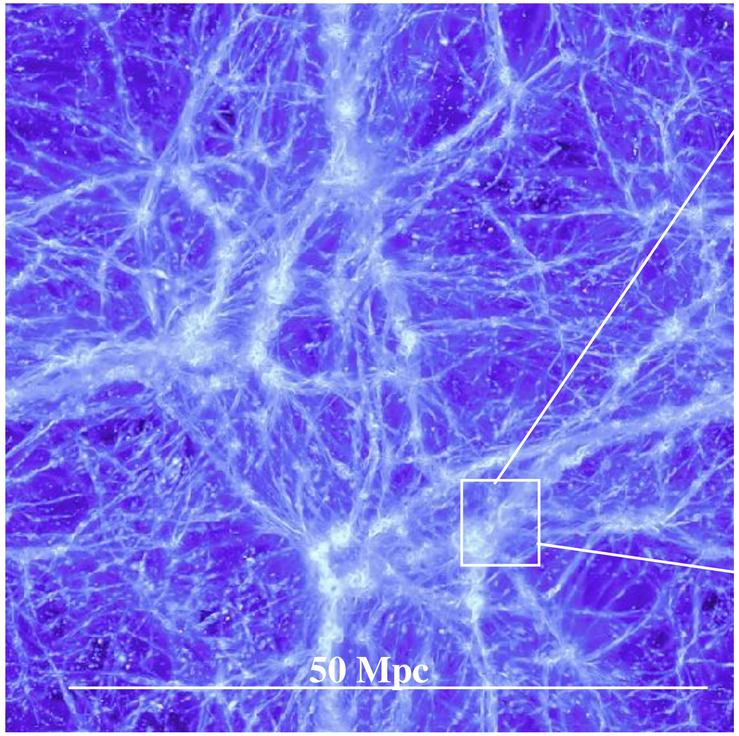
$$\frac{\partial \mathbf{B}}{\partial t} - \frac{1}{a}\nabla \times (\mathbf{v} \times \mathbf{B}) = -\frac{\dot{a}}{2a}\mathbf{B}$$

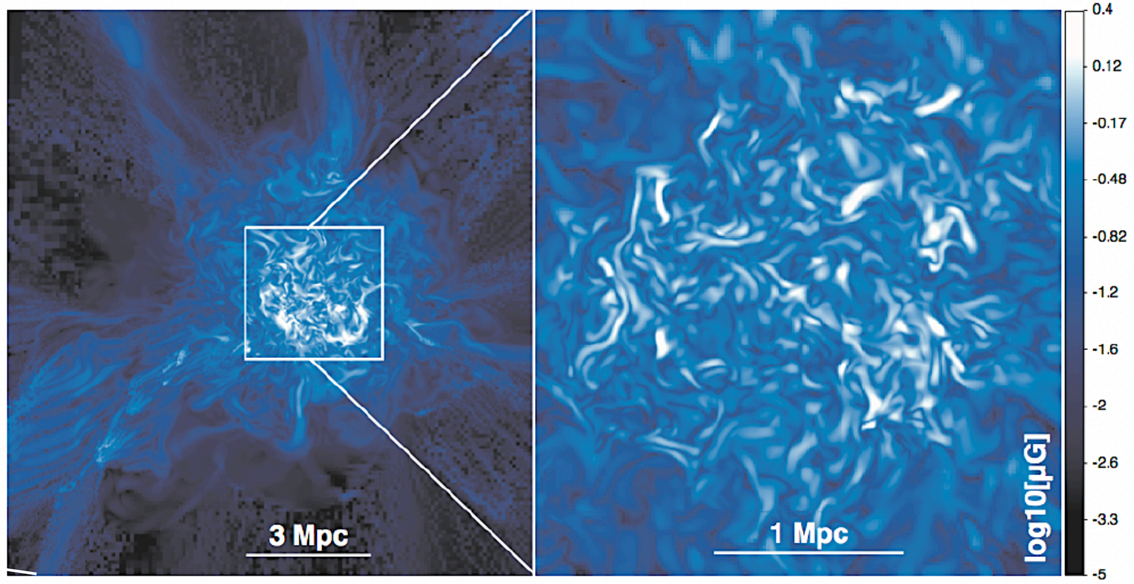
(+ source terms from star/AGN feedback)

Ideal for discontinuities (shocks), turbulence and hydro-MHD phenomena.



Large volumes: statistics and lightcones → comparison with radio surveys

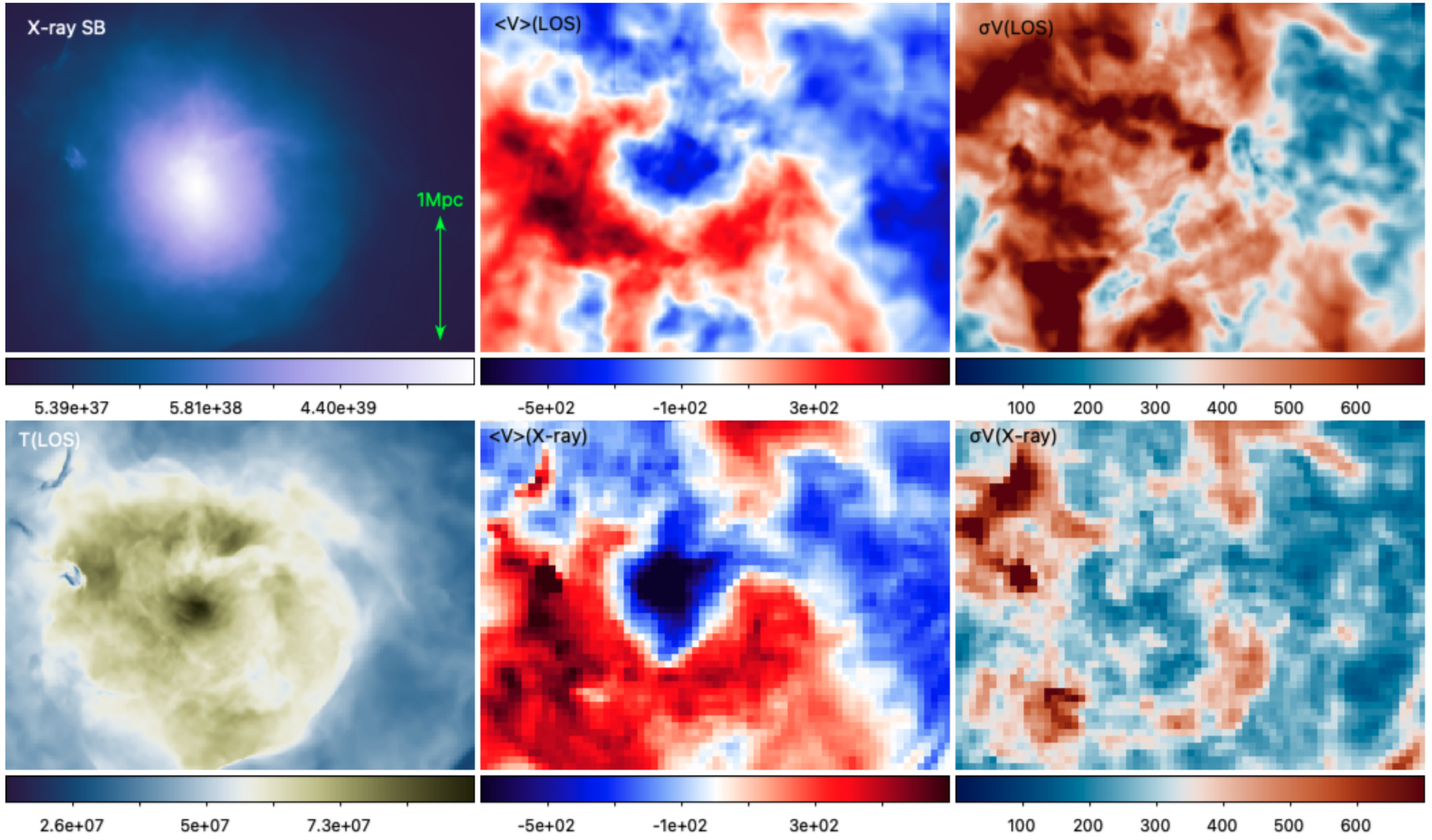




zoomed sims: plasma physics →
comparison with single objects

THE XRISM VIEW OF THE COMA CLUSTER

Re-analysis of a $\sim 10^{15} M_{\odot}$ Coma-like cluster (produced in 2018)



LOS average velocity and velocity dispersion

X-ray weighted LOS average velocity and velocity dispersion within 90^2 kpc^2 FOV as in XRISM

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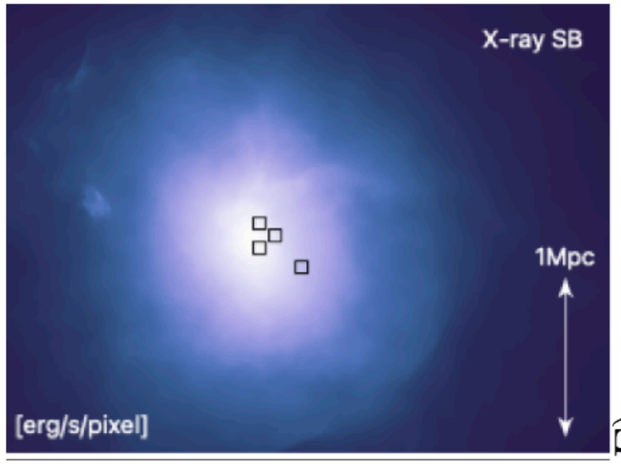
THE XRISM VIEW OF THE COMA CLUSTER

Simulated Iron Line broadening for 4 different FOVs in the cluster centre



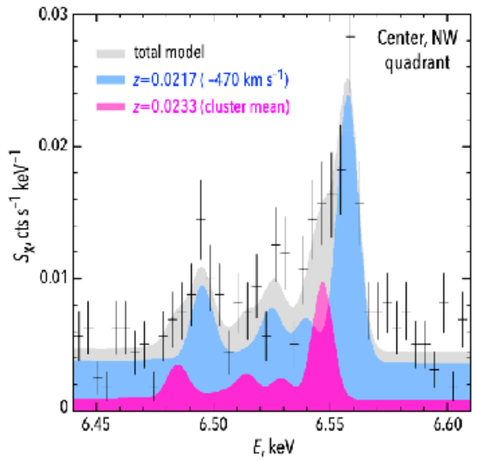
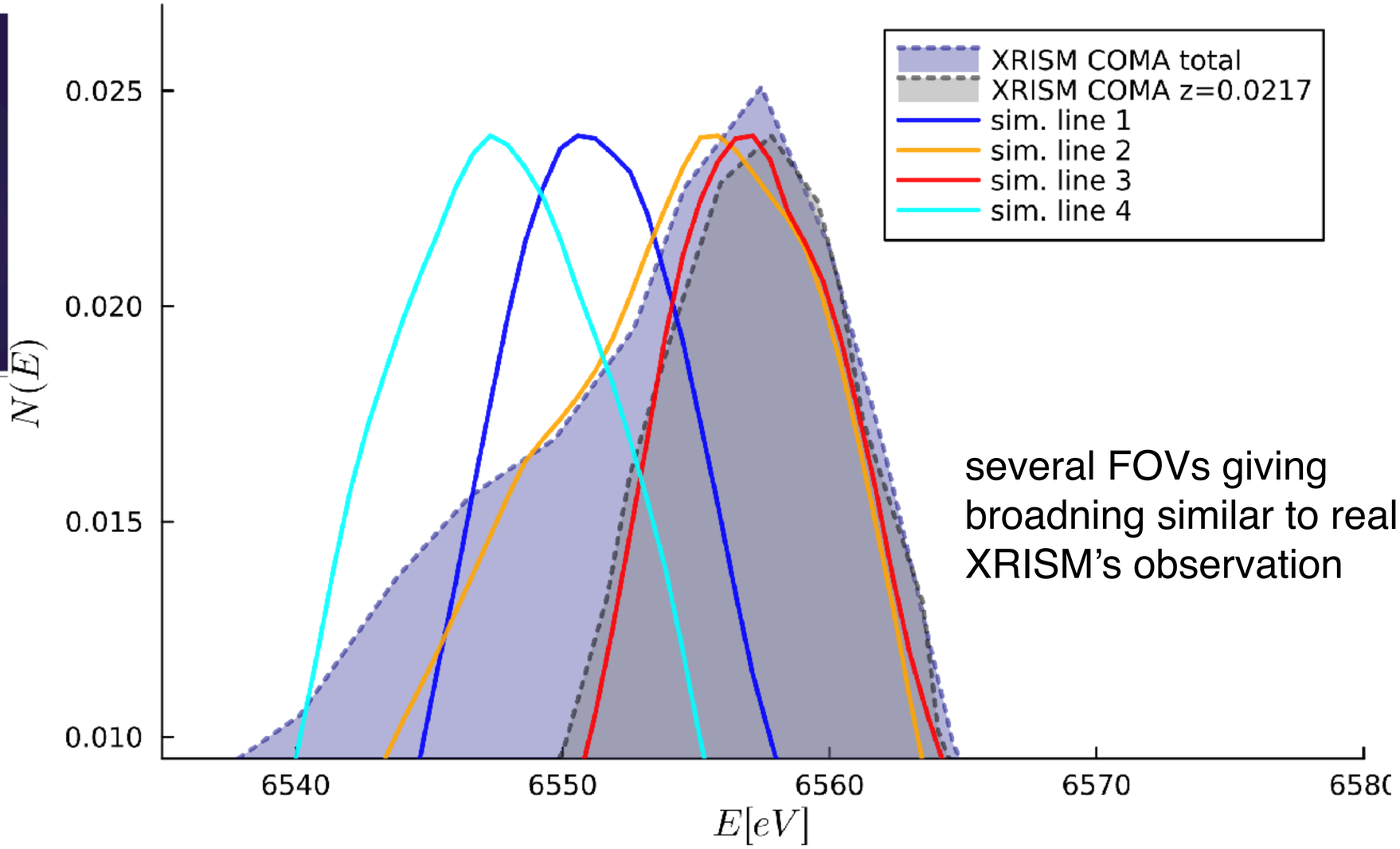


Figure 4. The spectrum for the NW quadrant of the Center field (the one with the highest velocity dispersion, see Fig. 3*b*). Only the Fe-Heα line complex is displayed, binned by 4 eV. Two velocity components are needed to model the line profile. The main component (blue) is blueshifted from the cluster mean by 470 km s^{-1}, while the additional component (magenta) is at the cluster optical mean velocity and contributes $22 \pm 7\%$ of the emission measure.



several FOVs giving broadning similar to real XRISM's observation

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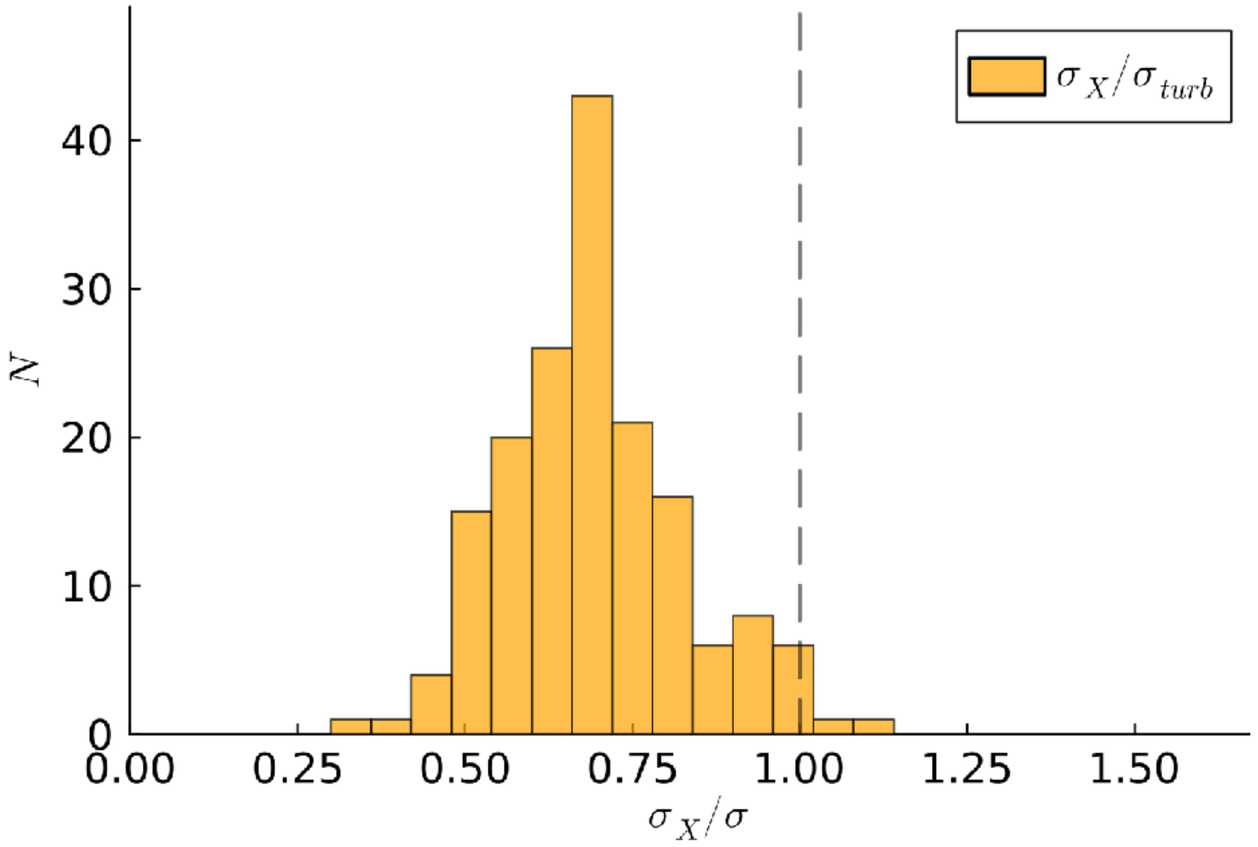
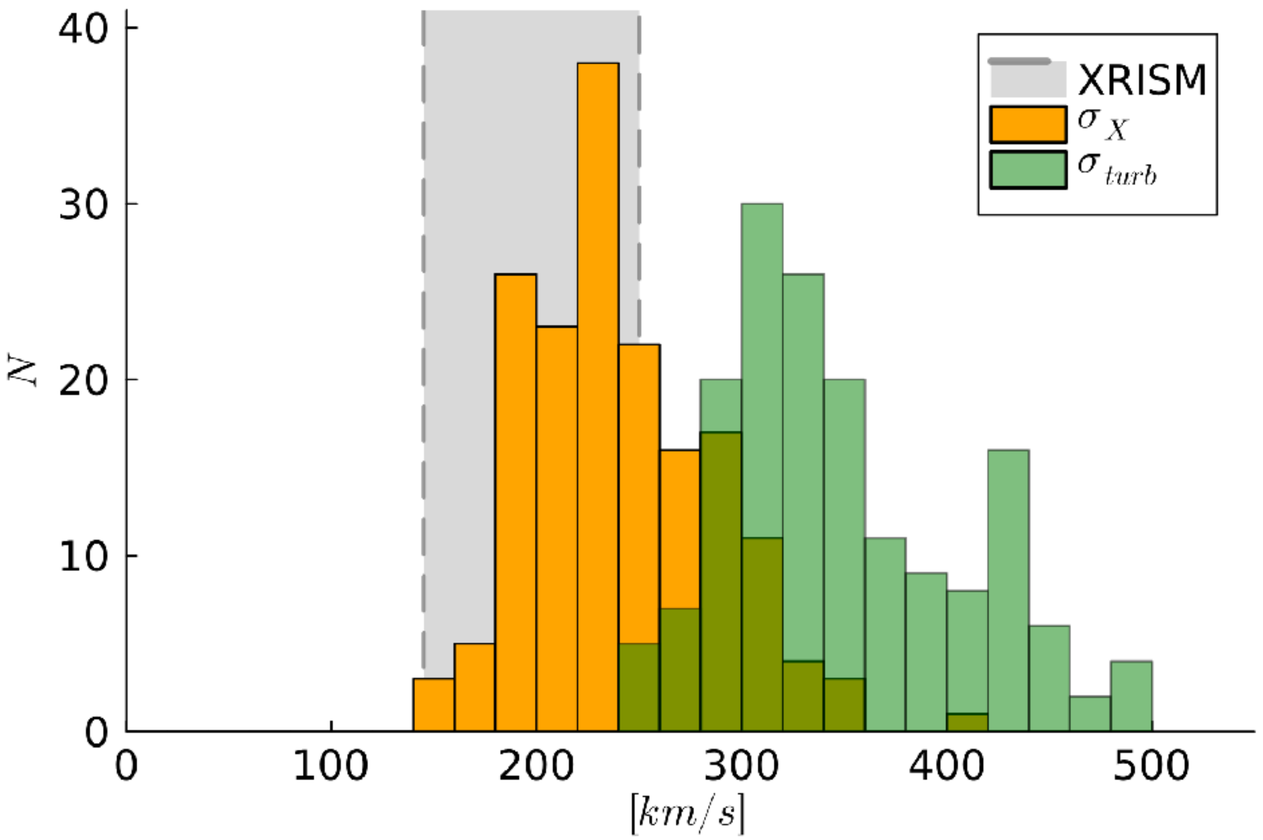
THE XRISM VIEW OF THE COMA CLUSTER

Ratio between the X-ray weighted velocity dispersion and the true (energy weighted) velocity dispersion along all LOS within $r \leq 500$ kpc





X-ray weighted σs well in line with XRISM observations, but the true ones are $\sim 30 - 50\,\%$ higher

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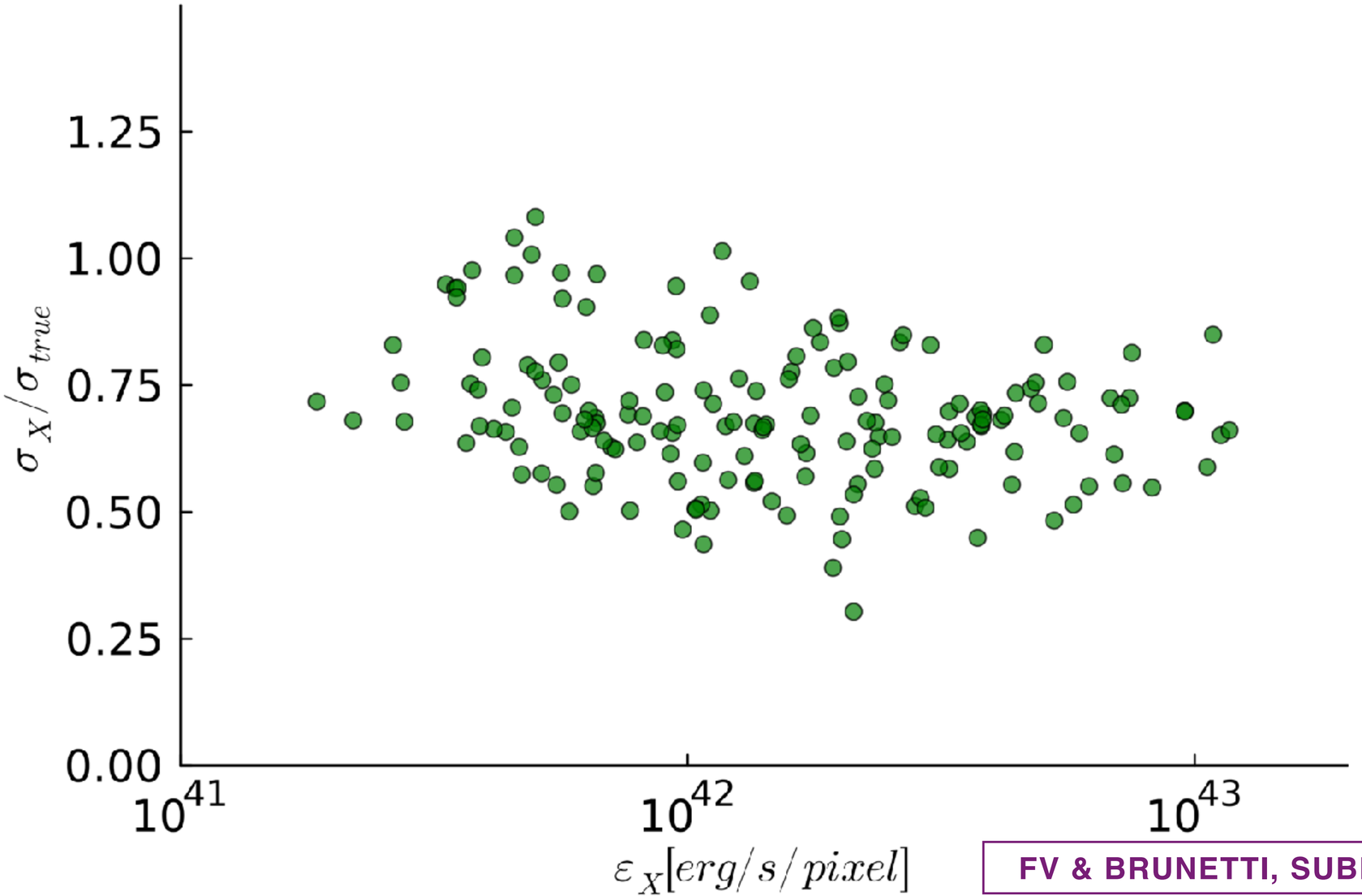
THE XRISM VIEW OF THE COMA CLUSTER

Ratio between the X-ray weighted velocity dispersion and the true (energy weighted) velocity dispersion along all LOS within $r \leq 500$ kpc

Ratio btw X-ray and true velocity dispersion has a very scattered trend with X-ray emission

(→ no obvious correction term to offer)



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THE XRISM VIEW OF THE COMA CLUSTER

The true isotropic turbulent support is $\sim 5-15\,\%$ depending on the filtering scale, while the X-ray estimate is biased low: $\sim 3\,\%$

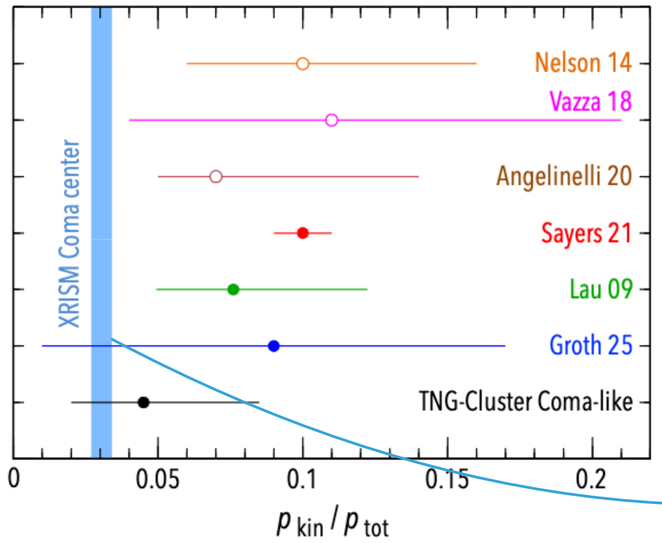
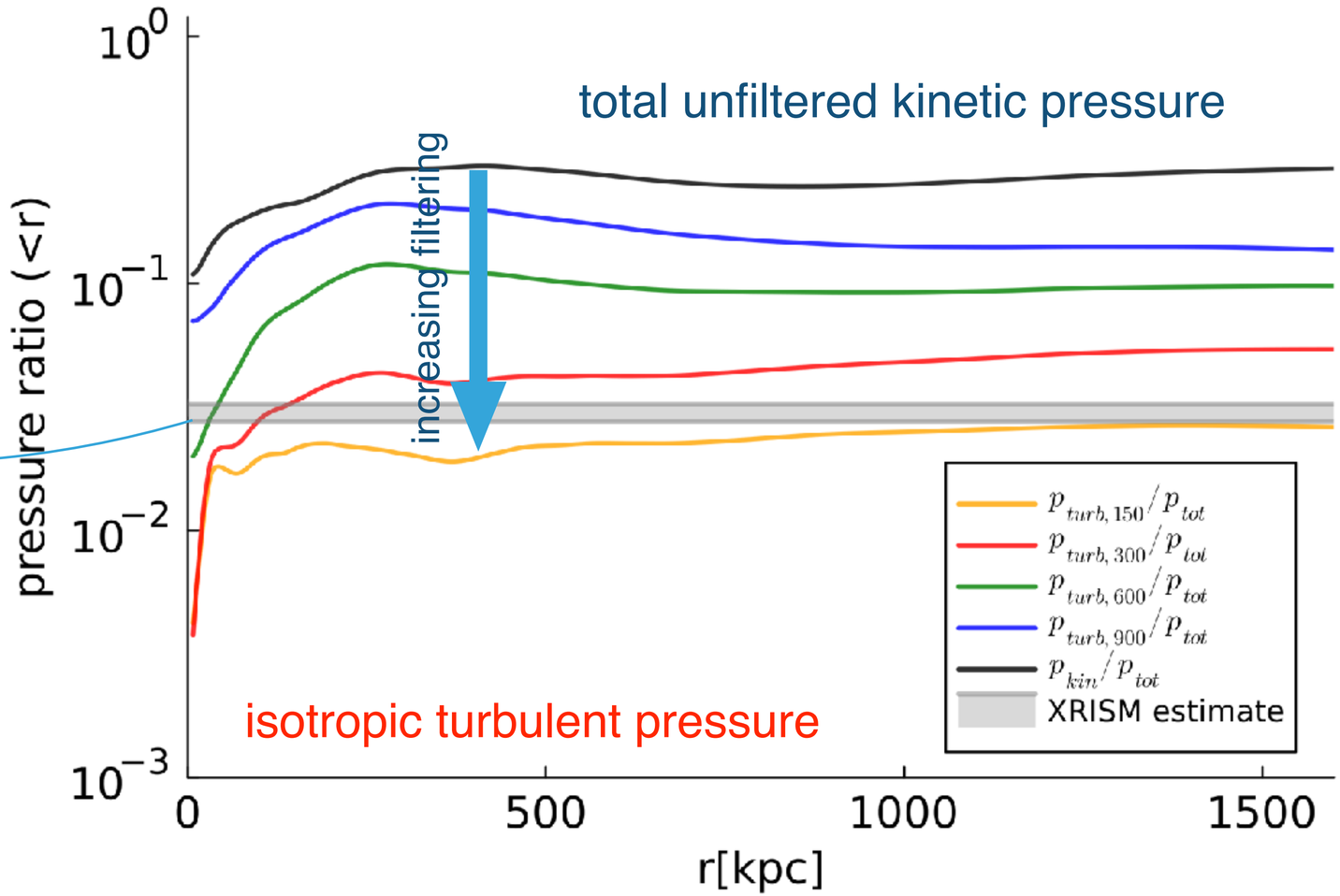


Figure 6. The *XRISM* value of $p_{\rm kin}/p_{\rm tot}$ for Coma, derived from the central line width, is compared with predictions from several cosmological simulations. Open symbols represent all clusters, while filled symbols select only the disturbed Coma-like clusters. For TNG-Cluster, there is an additional selection based on cluster mass and weighting by X-ray emission measure (see Appendix B). The horizontal intervals show the $16^{\rm th}-84^{\rm th}$ percentiles of the simulated cluster populations. The measured value is at the low end of the predictions.



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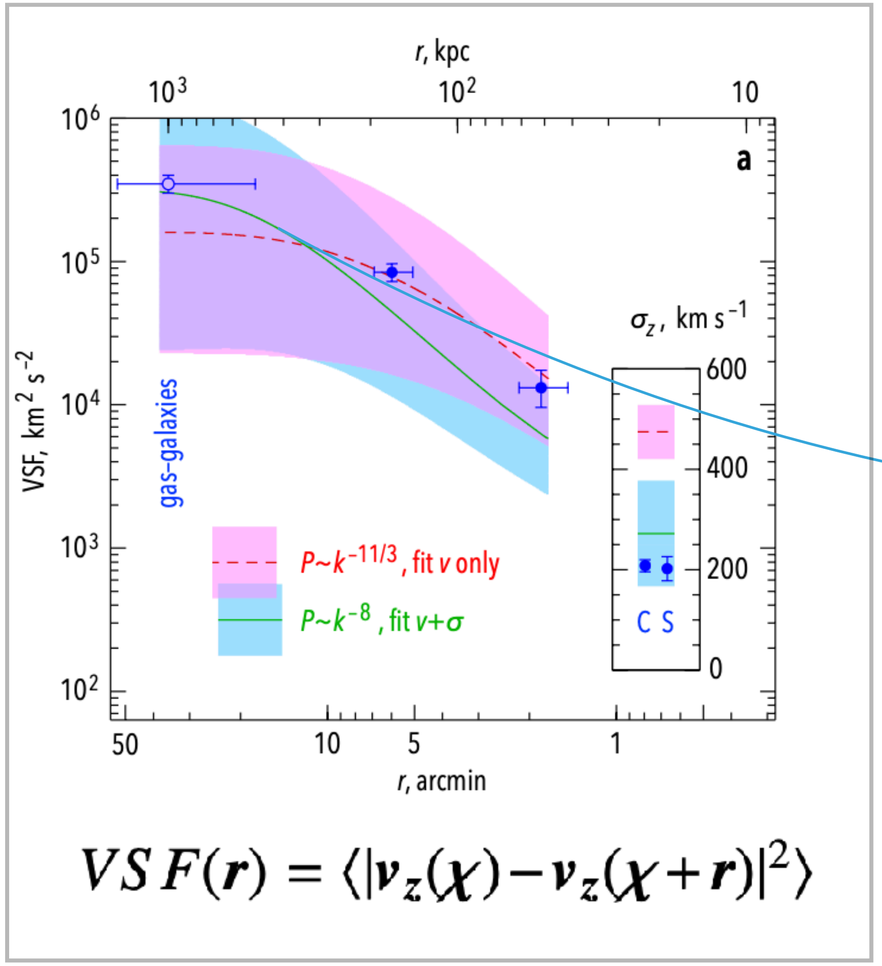
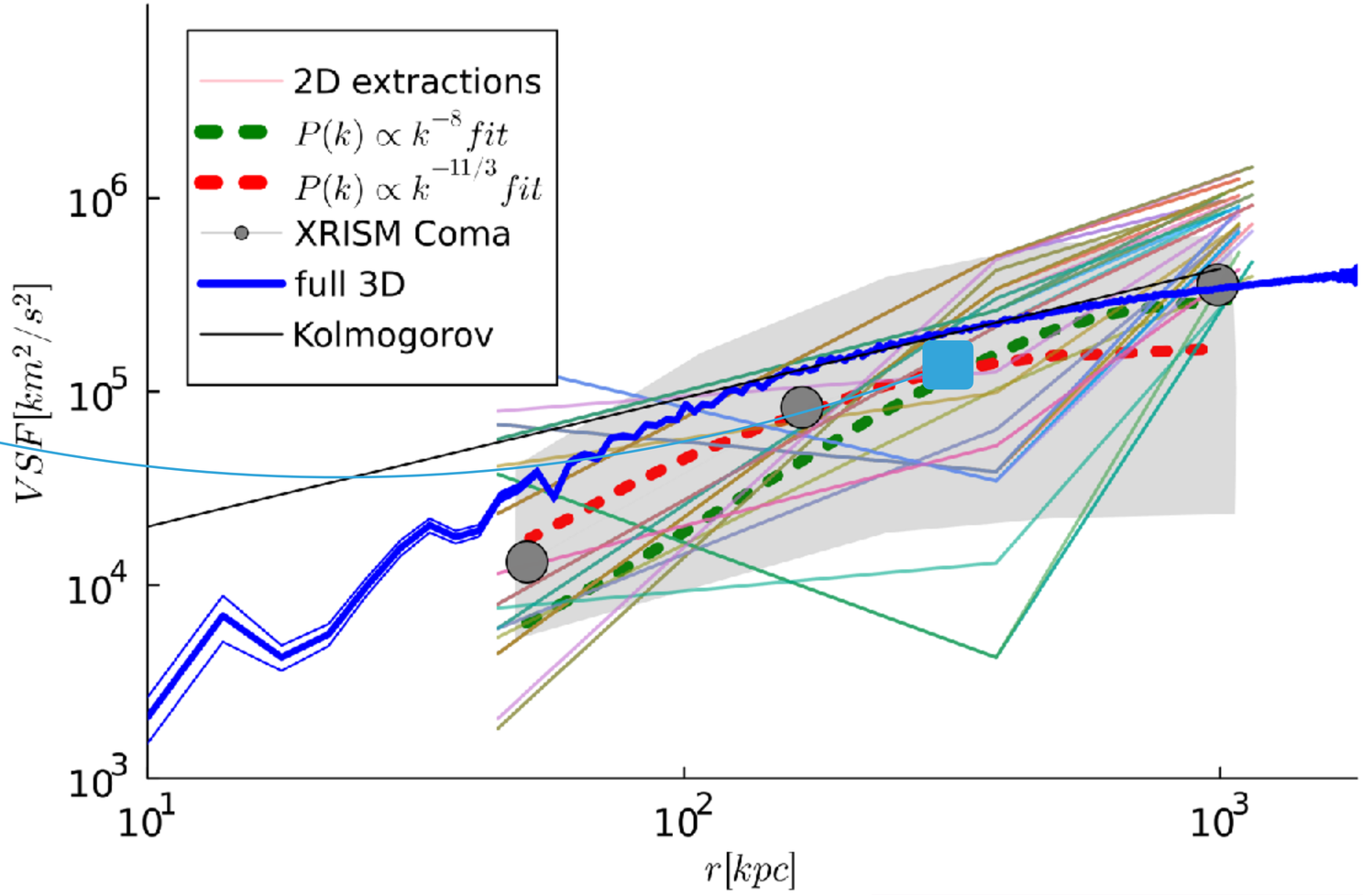
IS X-RAY SPECTROSCOPIC TURBULENCE CONSISTENT WITH MODELS?

The 3D velocity structure function is ∼ Kolmogorov for more than a decade in scale.

VSFs reconstructed using a few LOS are similar to XRISM, but in general little reliable



$$VSF(r) = \langle |v_z(\chi) - v_z(\chi + r)|^2 \rangle$$



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SO..WHAT IS HAPPENING?

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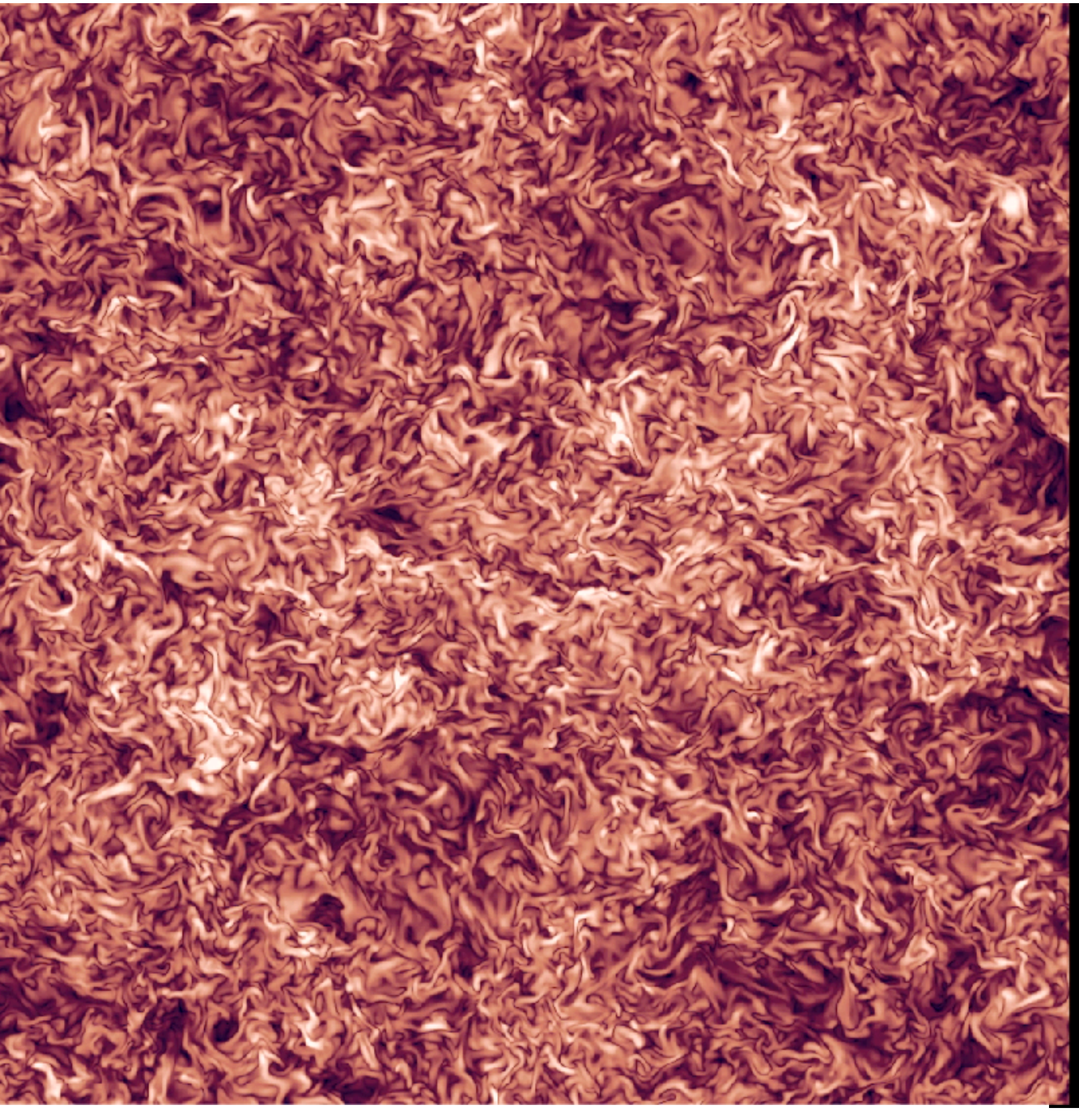
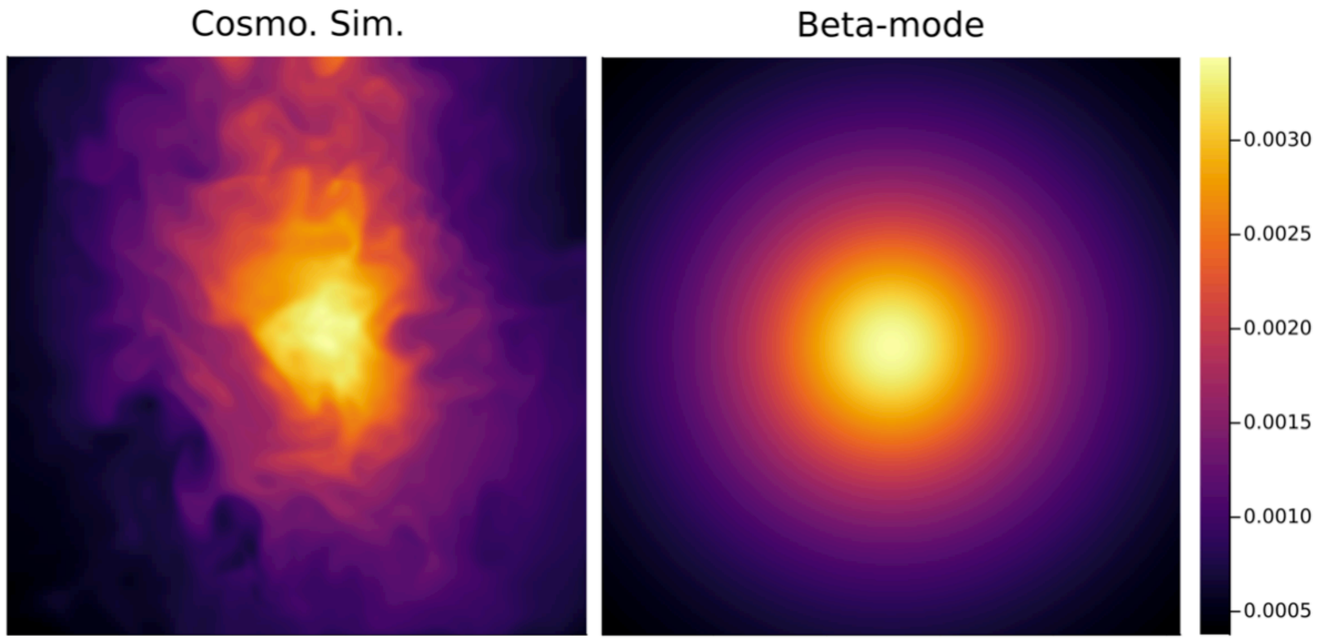
IDEALISED VS CLUSTER TURBULENCE

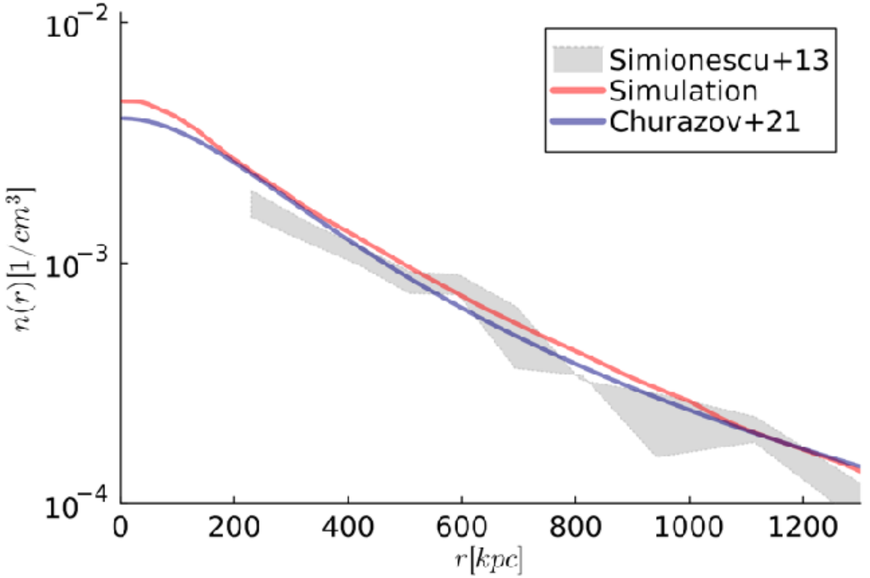


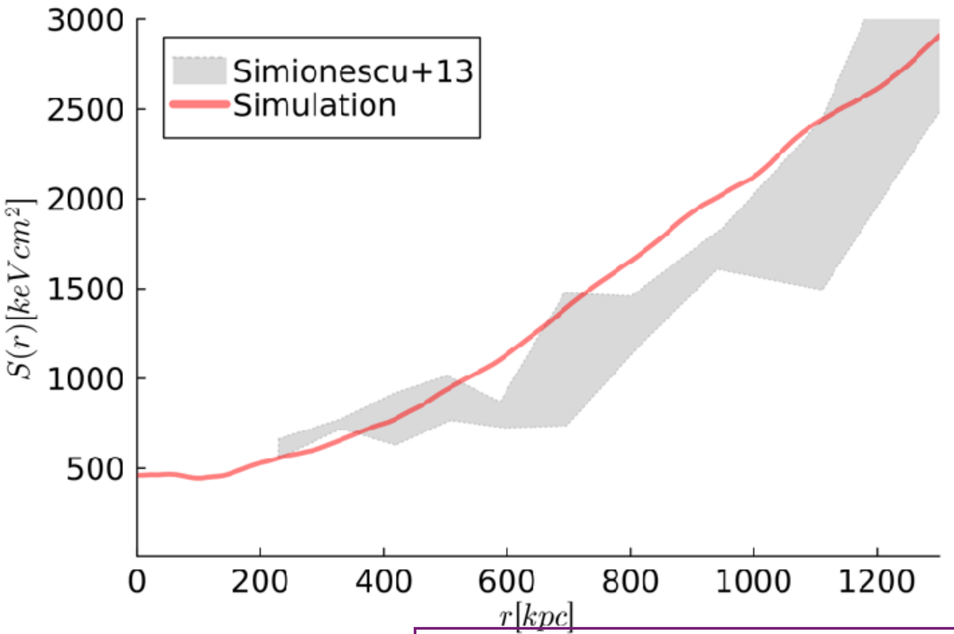
stationary turbulence forcing in an idealised "turbulent in the box" setup $R_e \sim 512$

turbulence in the central region of a cluster simulated in cosmology $R_e \sim 500$

SO..WHAT IS HAPPENING?







Fully cosmological simulated cluster vs analytical $\beta-$model

spherical cluster model taiolred to reproduce Coma

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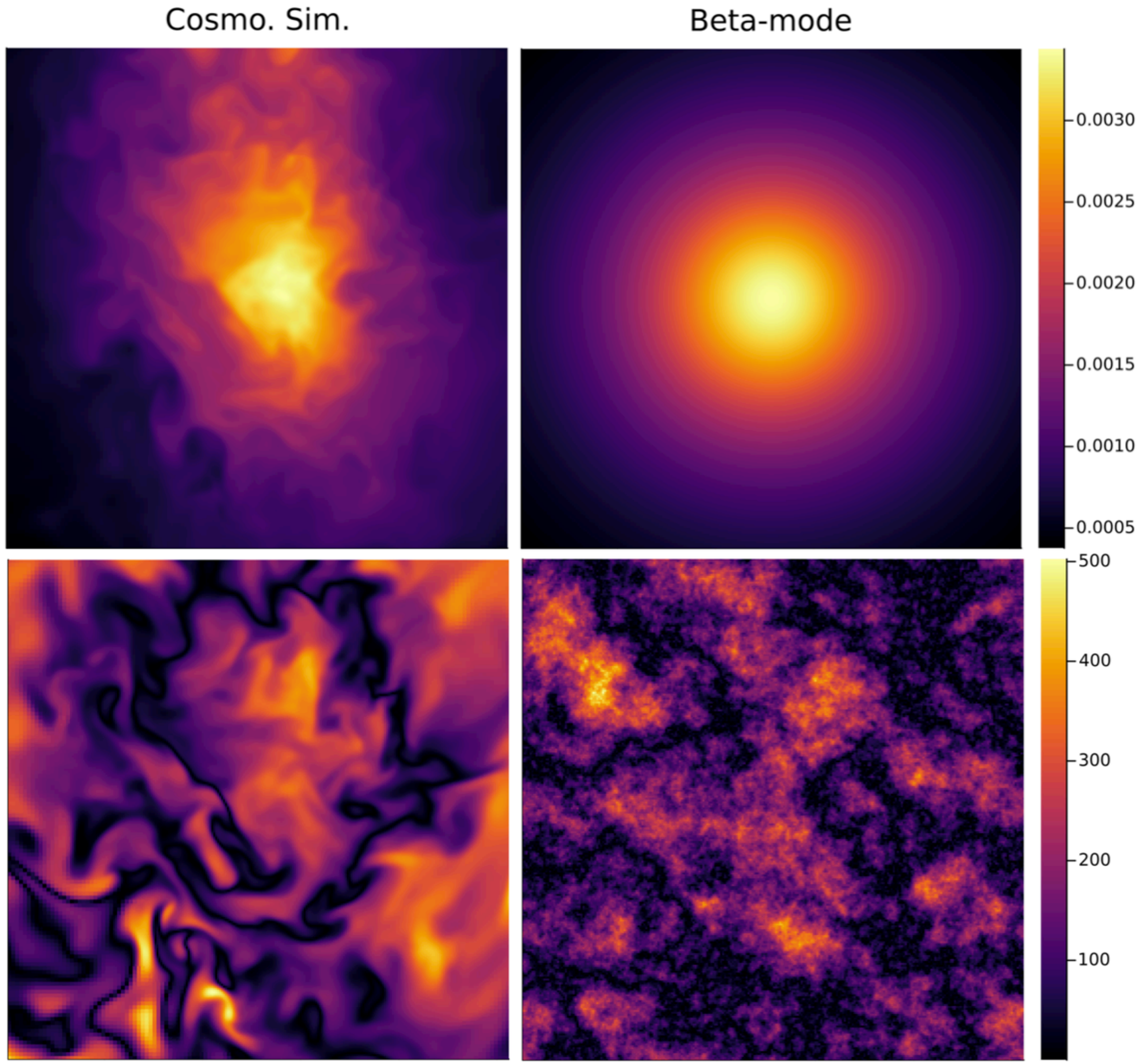
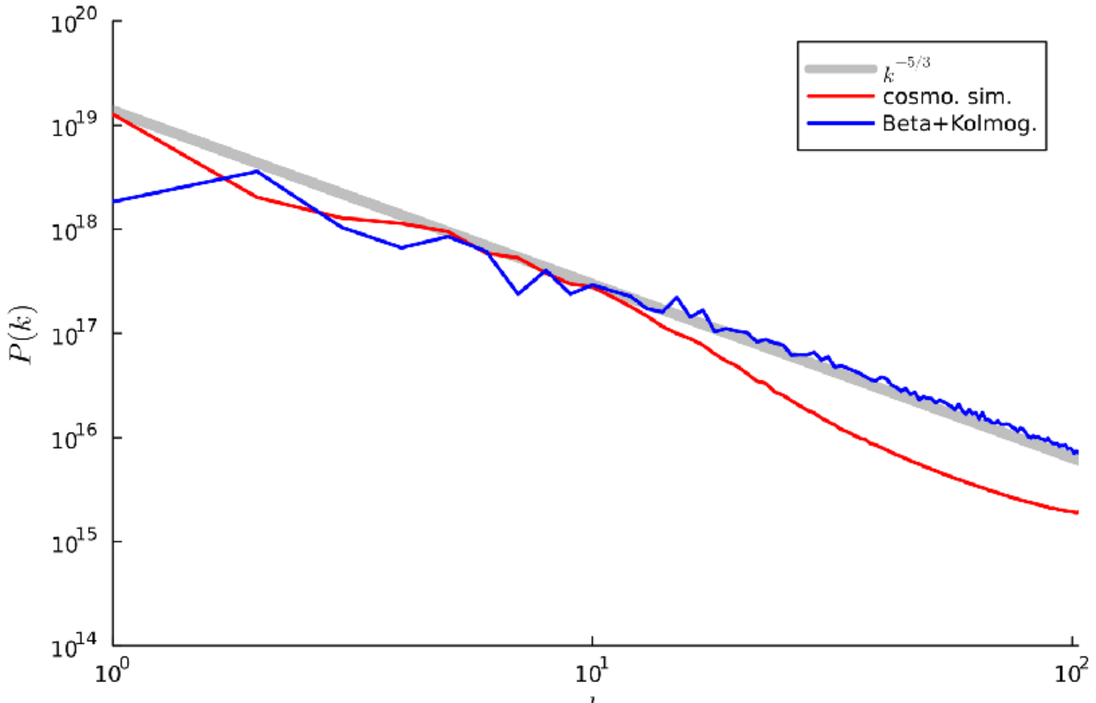
SO..WHAT IS HAPPENING?





3D velocity field from the simulation vs analytically generated random velocity field drawn from a Kolmogorov spectrum, with identical kinetic energy

$$\int E(k)dk = E_{kin}$$

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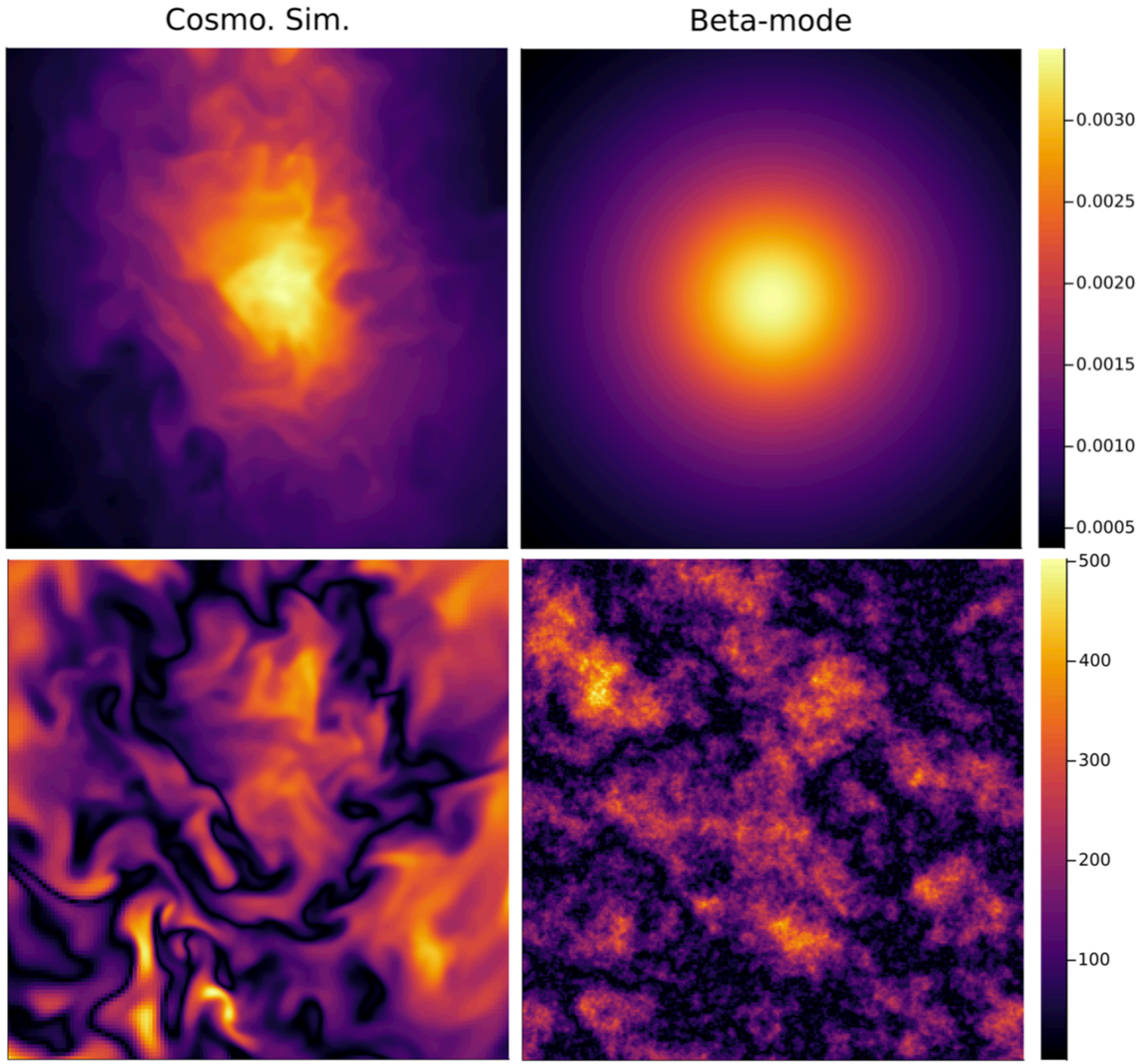
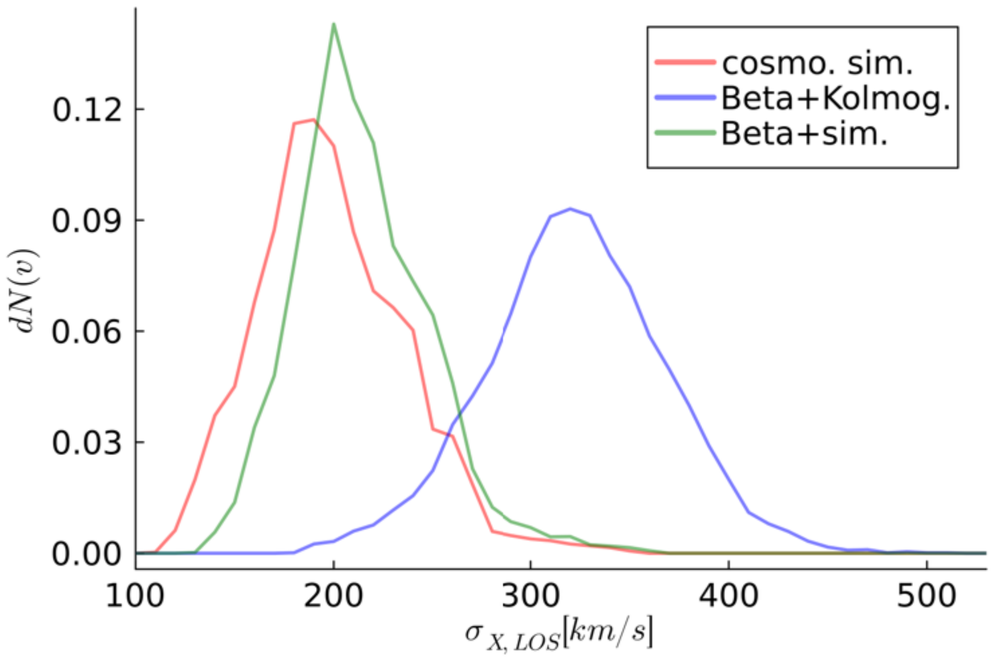
SO..WHAT IS HAPPENING?





- distribution of $\sigma_{X,LOS}$: the simulated ones are ~60% of the analytical ones.
- why? intermittency (=less filling factor) of realistic ICM turbulence

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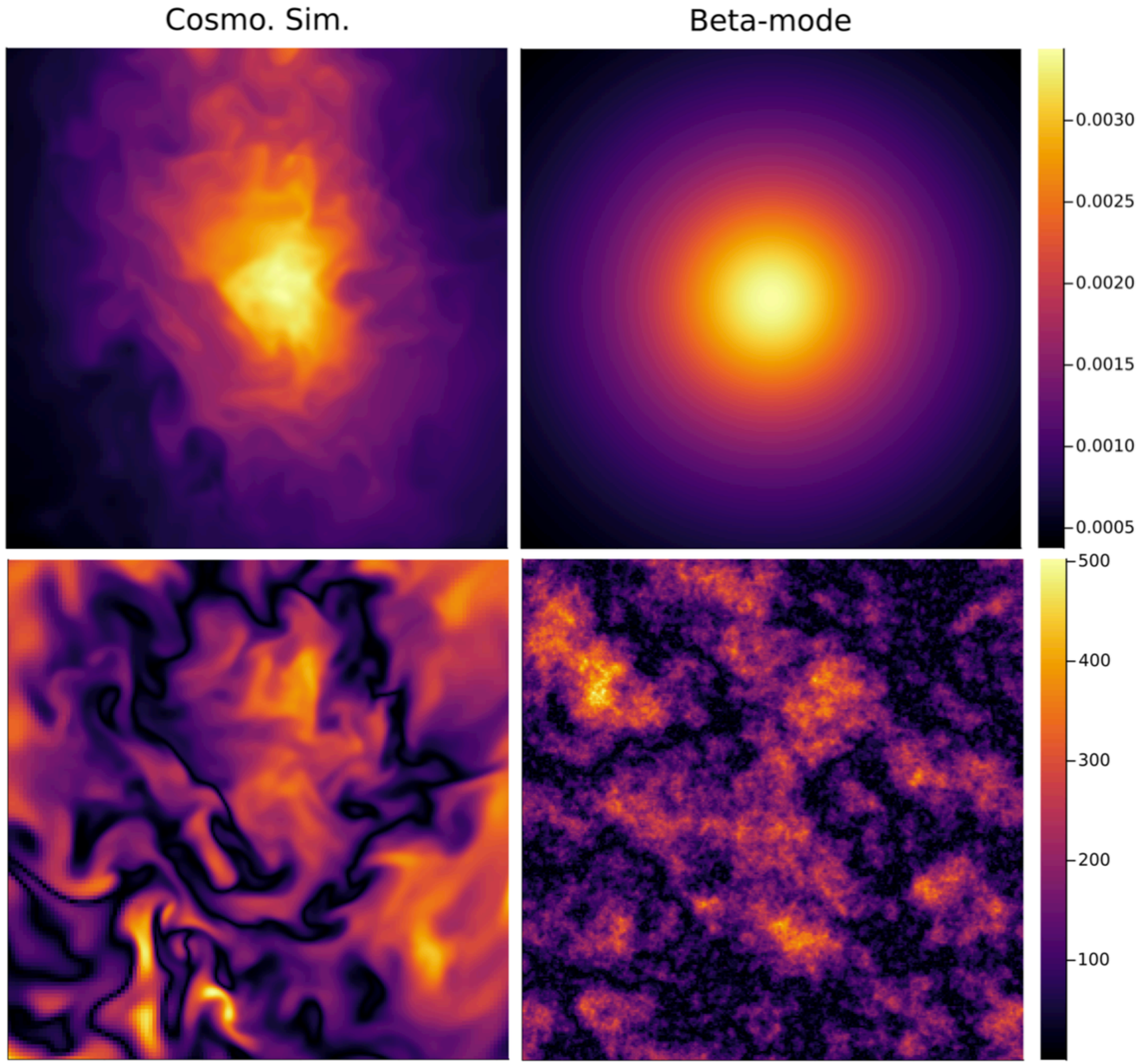
SO..WHAT IS HAPPENING?



Key message:

if turbulence in the ICM is anything like the one in (any) cosmological simulation, the same distribution of $\sigma_{X,LOS}$ corresponds to a higher (~ 2 at least) turbulent kinetic energy.

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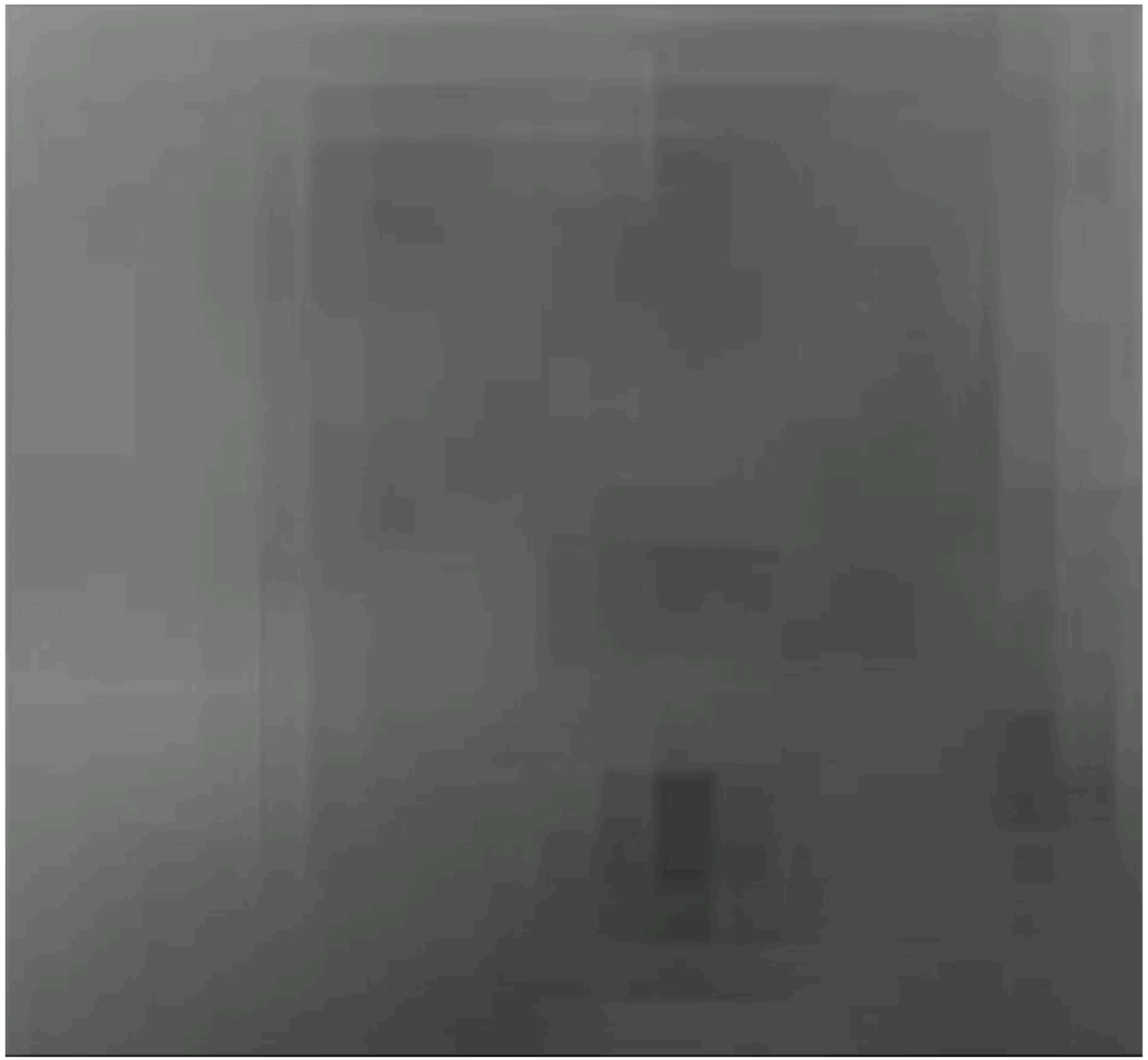
SO..WHAT IS HAPPENING?



Key message: if turbulence in the ICM is anything like the one in (any) cosmological simulation:

- the same total kinetic energy gives a ~ 2 smaller $\sigma_{X,LOS}$ compared to homogenous Kolmogorov turbulence
- a given $\sigma_{X,LOS}$ corresponds to a ~ 2 higher kinetic energy compared to homogenous Kolmogorov turbulence

Multiple and intermittent driving events create a patchy and intermittent turbulent flow

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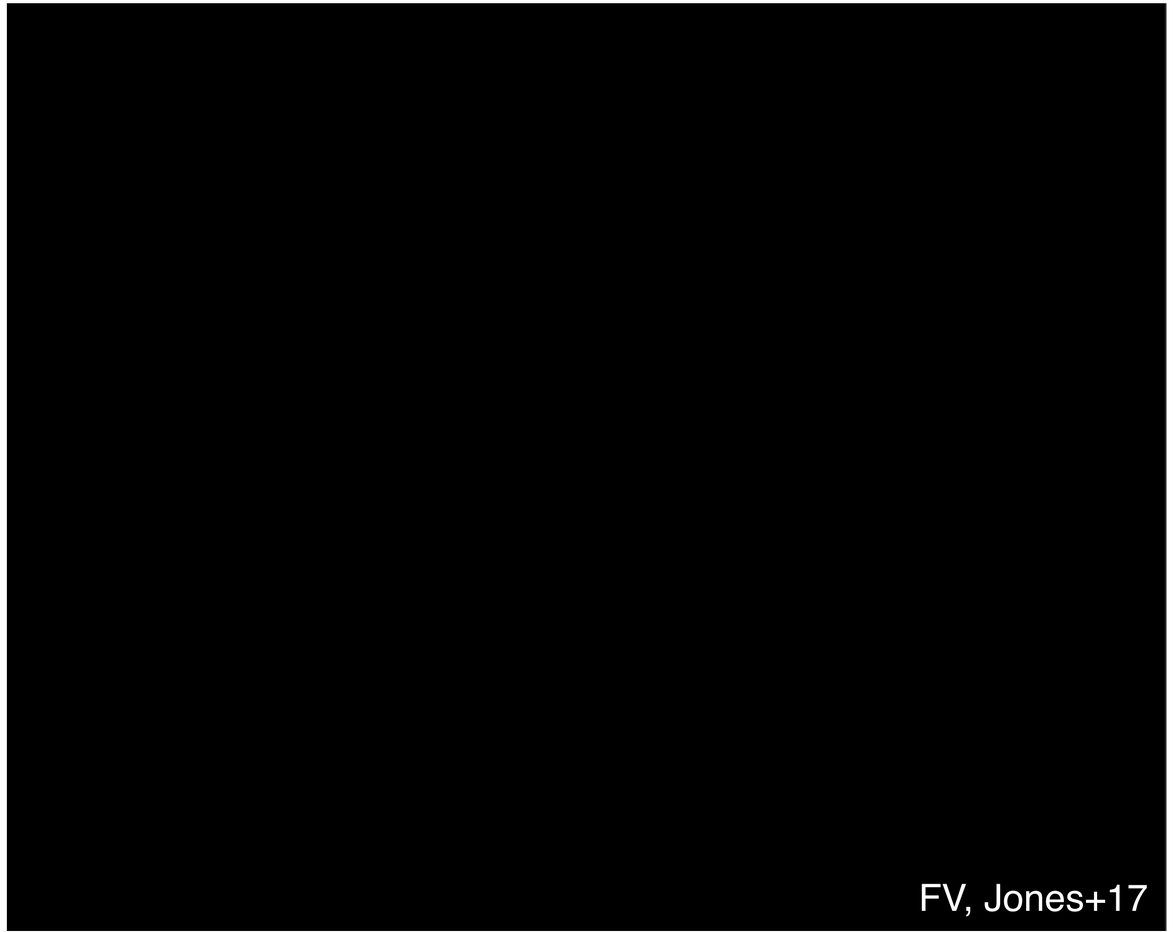
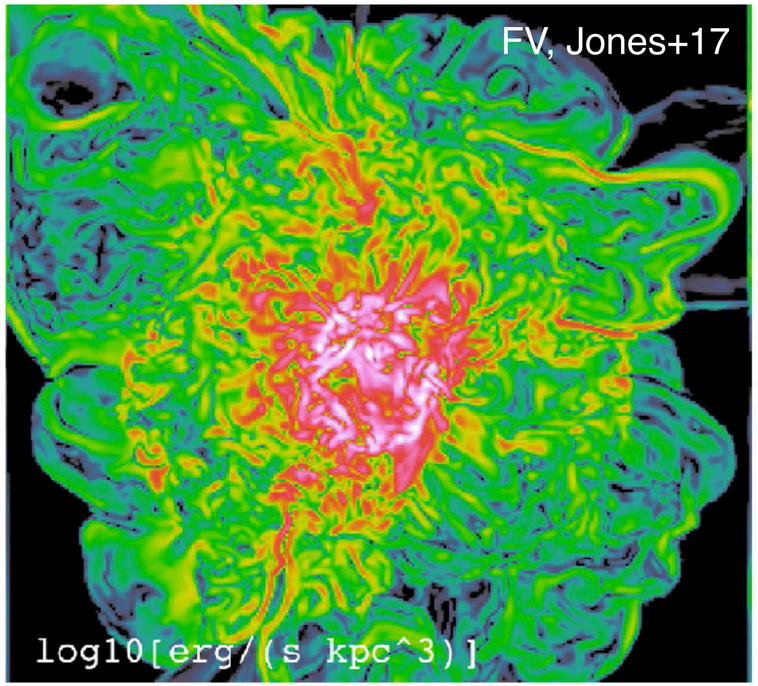
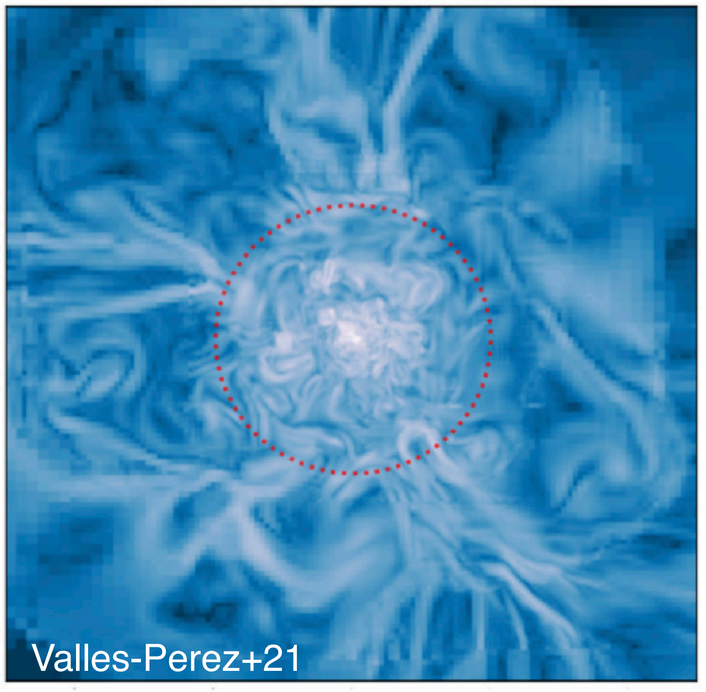
INTERMITTENCY IS KEY

from Kowal, Lazarian & Bersnyak (2007) in ISM context

> Instead, fluctuations tend to get increasingly sparse in time and space at smaller scales. This property is called intermittency. Note that power-law scaling does not guarantee scale invariance or the absence of intermittency.
>
> Intermittency is an essential property of astrophysical fluids.





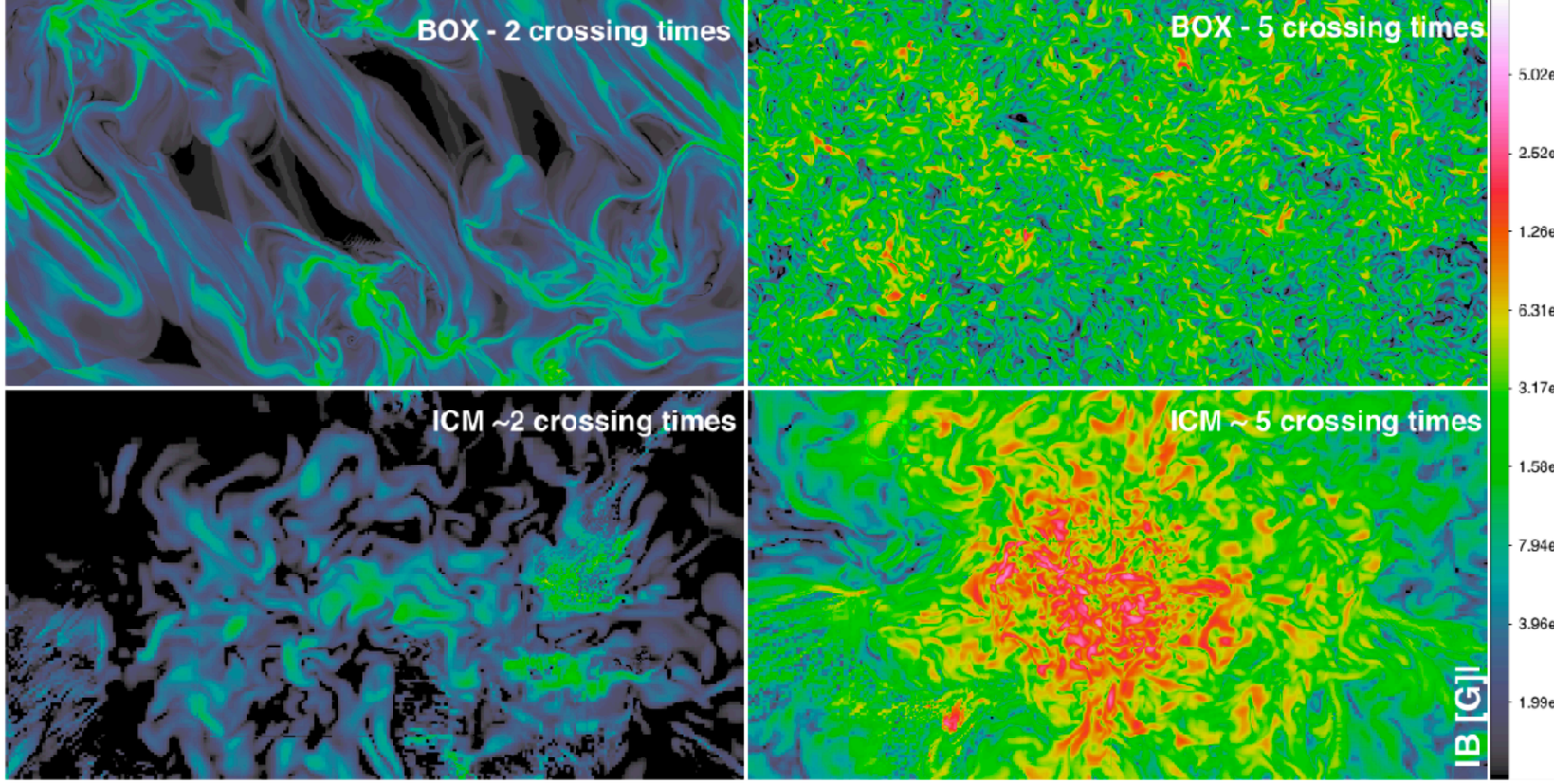


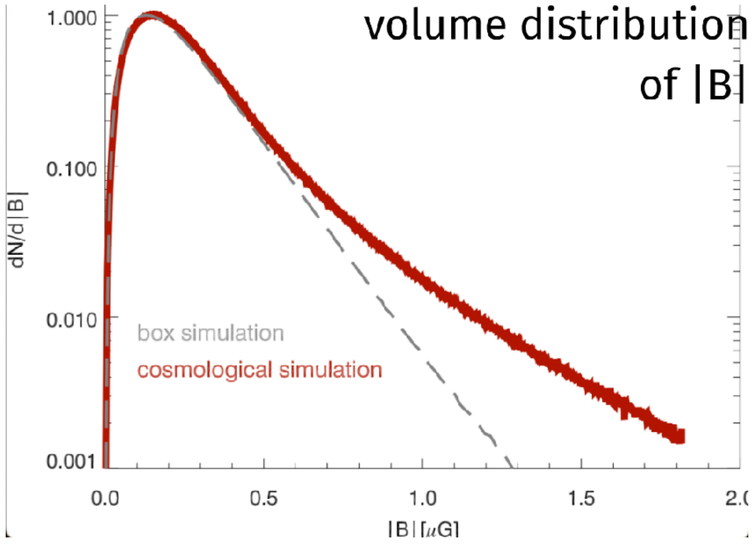
Side note:

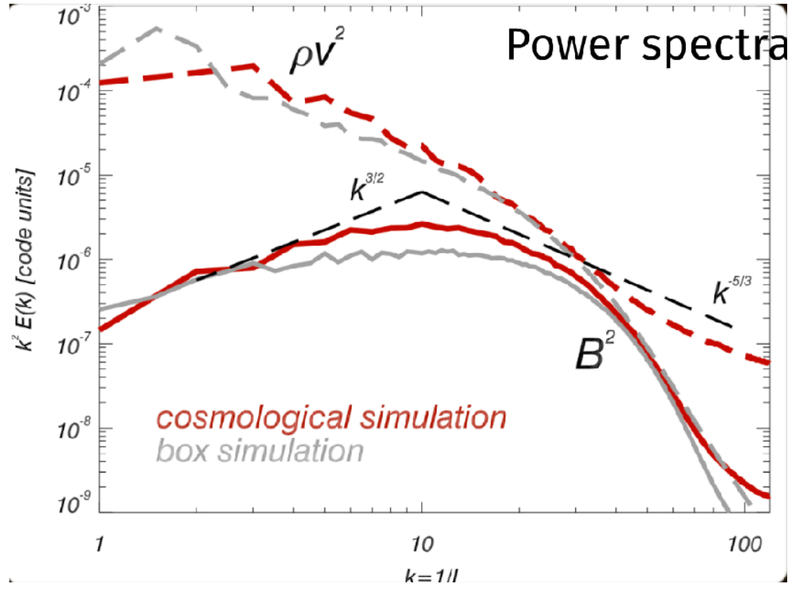
we already reported the same effects in dyamically simulated **magnetic fields** vs turbulence in a box simulations:

in the more complex ICM, more intermittency of B-flucutations even if with the same power spectra

(FV+18 MNRAS)







IS XRISM TURBULENCE COMPATIBLE WITH SIMULATIONS?

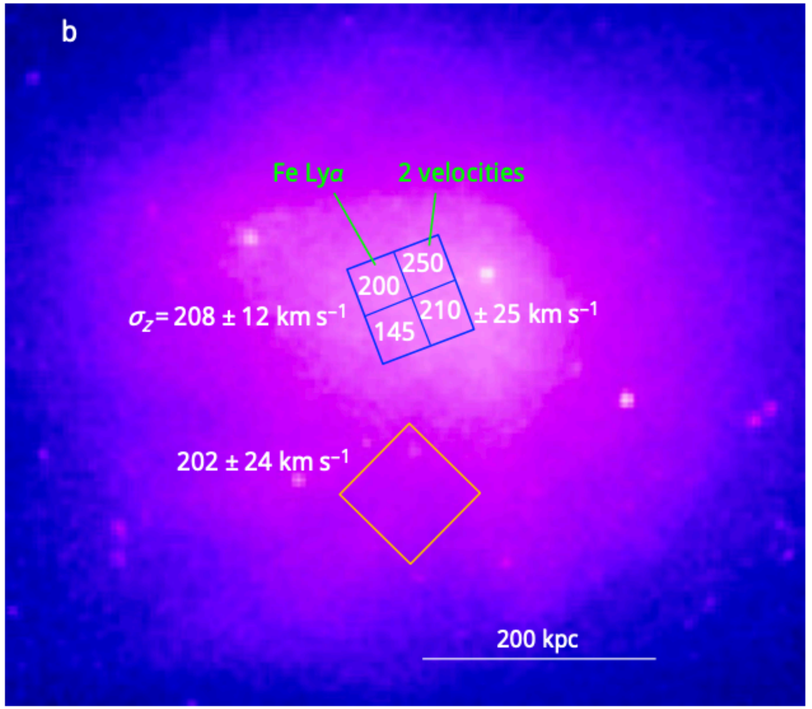
Bottom line:

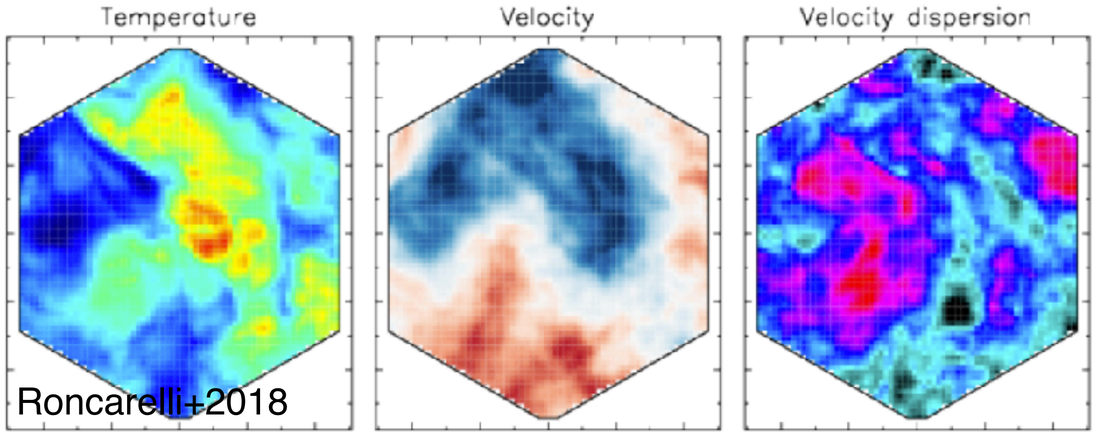
- <u>YES</u>

- the “boring” hydro-MHD view of the simulated ICM well explains XRISM observations of Coma: turbulence in the ICM is patchy, intermittent and non-stationary

- inverting the information from biased X-ray spectroscopic measurements from limited FOV is not easy..

- future? the situation should improve with (New)ATHENA in ∼2030





THANKS