The XMAGNET Exascale MHD simulations of SMBH feedback in galaxy groups and clusters

Philipp Grete
Hamburg Observatory
in collaboration with B. O'Shea, F. Glines, D. Prasad, B. Wibking, M. Fournier, M. Brüggen, and the Parthenon community

18th Potsdam Thinkshop

Universität Hamburg
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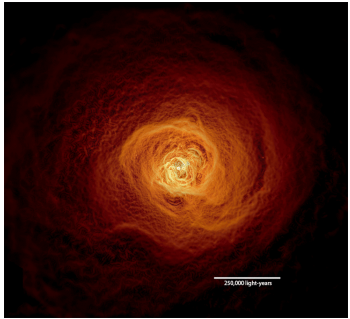
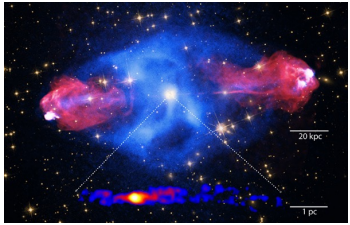
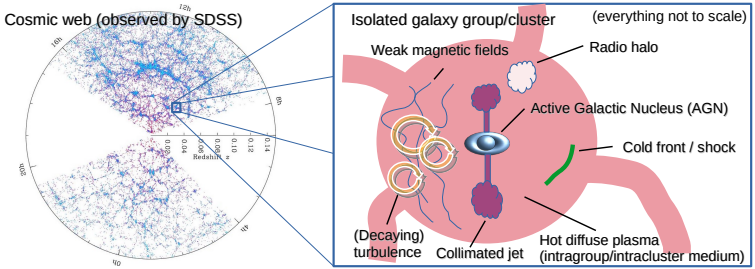
Motivation







- AGN feedback cycle and the self-regulation of galaxies within groups and clusters
- How is energy deposited and redistributed?

$\Rightarrow$ Need to bridge/resolve many scales

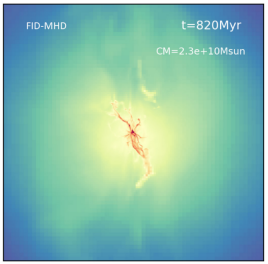
[Top left: NASA/Walker+. Bottom left: Cygnus A in radio (red, by VLA), X-ray (blue, Chandra), Optical (by Hubble) Inset in radio (by VLBI)]

XMAGNET project

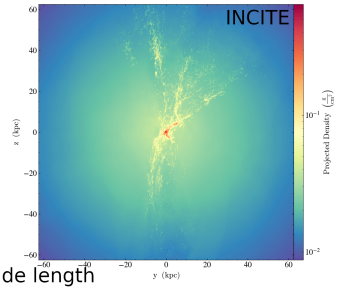
[XMAGNET collab. Grete+ arXiv:2502.13213]

e**X**ascale simulations of **M**agnetized **AGN** feedback focusing on **E**nergetics and **T**urbulence

- Supported by DOE INCITE grant
- Simulation setup using AthenaPK
  - isolated galaxy groups and clusters
  - static gravitational potential
  - accretion of cold gas
  - triggers AGN feedback



Wang+21



125kpc side length

XMAGNET project

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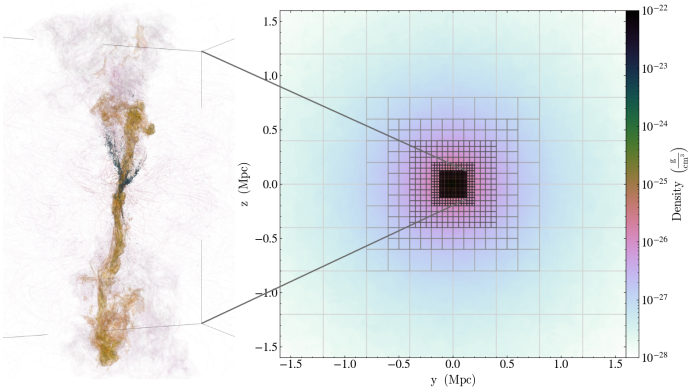
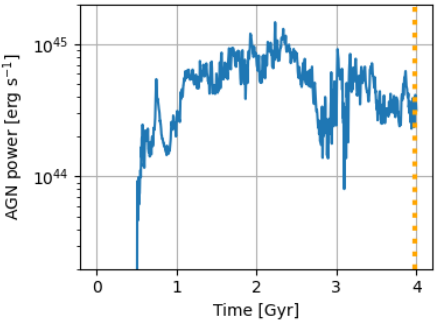
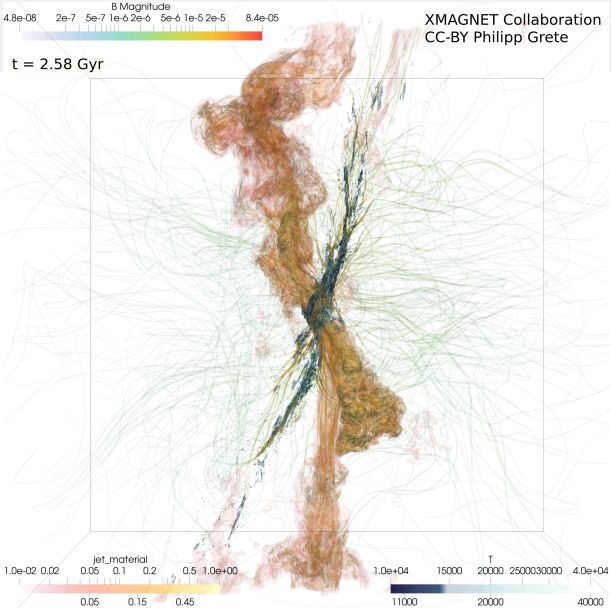
- Simulation setup using AthenaPK
  - isolated galaxy groups and clusters
  - static gravitational potential
  - accretion of cold gas
  - triggers AGN feedback
- 6 levels mesh refinement. Center:
  - $[256\,\mathrm{kpc}]^3$ covered by 2560^3 cells
  - no multi-level artifacts
  - $\Delta_x = 100\,\mathrm{pc} \leftrightarrow$ effective mass resolution $\approx 10^3 M_\odot \frac{n}{0.1\,\mathrm{cm}^{-3}}$
  - but data analysis is tough



XMAGNET in motion

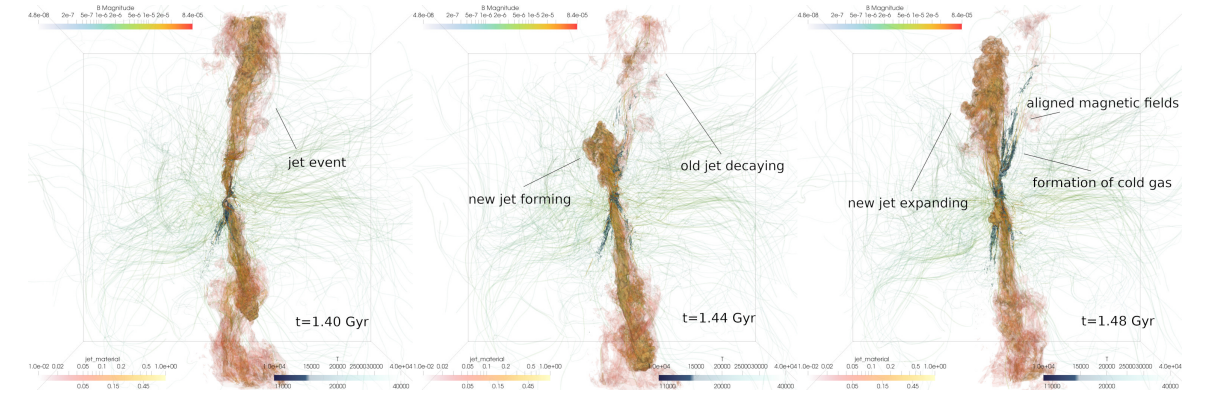
- Perseus-like initial conditions
- Evolved for 4 Gyr
- System is self-regulating





AGN duty cycles

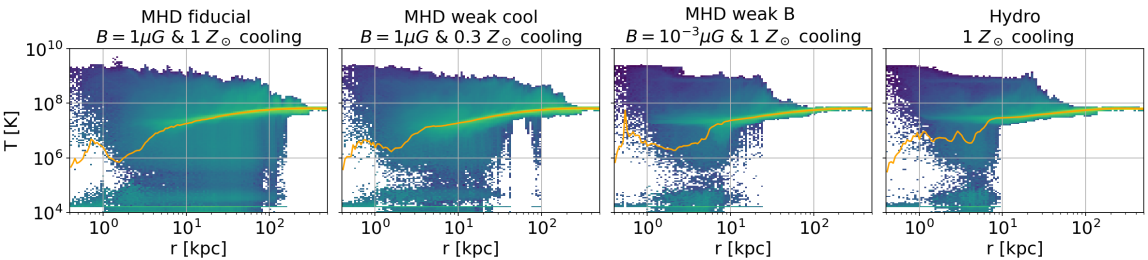
[XMAGNET collab. Grete+ arXiv:2502.13213]



Impact of magnetic fields and cooling

[XMAGNET collab. Grete+ arXiv:2502.13213]

- Temperature vs. radius phase plot at *fixed* time

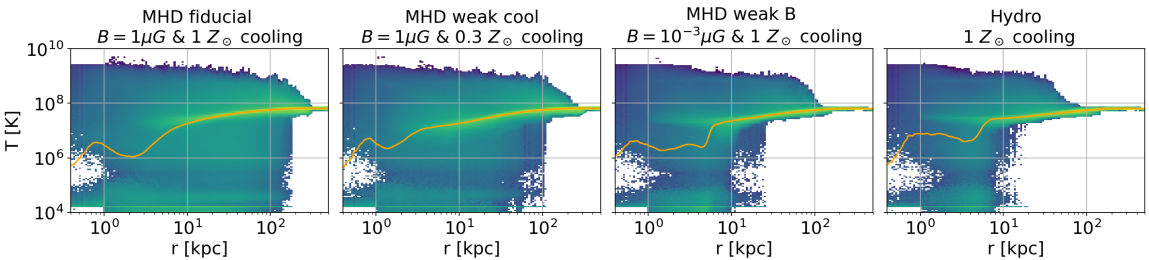


- Magnetic fields facilitate the *presence* of cold gas at larger radii
- Strength of cooling less important

Impact of magnetic fields and cooling

[XMAGNET collab. Grete+ arXiv:2502.13213]

- Temperature vs. radius phase plot at *averaged* over 500 Myr



- Magnetic fields facilitate the *presence* of cold gas at larger radii
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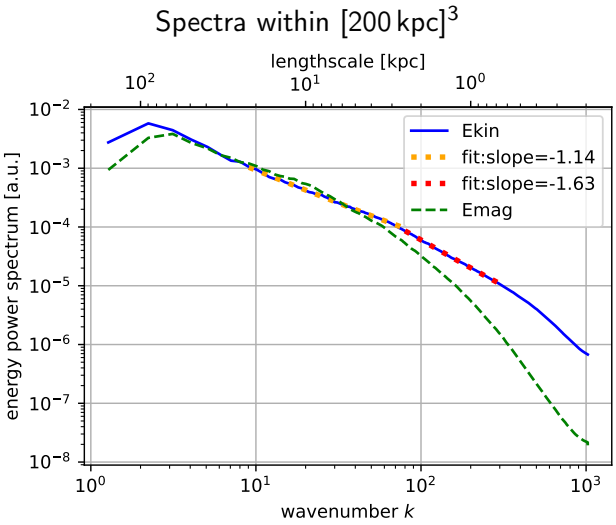
Energy spectra in simulations

[XMAGNET collab. Grete+ arXiv:2502.13213]

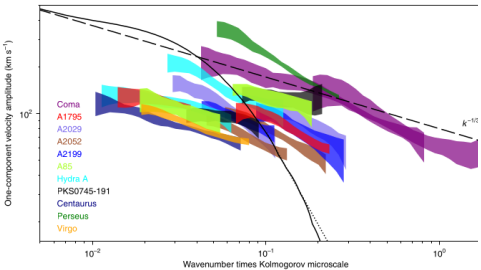
- Kinetic energy spectrum shows multiple breaks
  - "Kolmogorov" scaling around injection scale
  - Flatter on intermediate scales



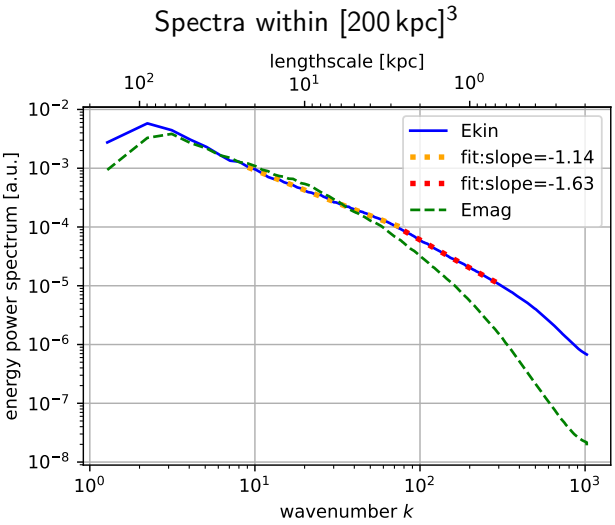
Energy spectra in simulations and observations

[XMAGNET collab. Grete+ arXiv:2502.13213]

- Kinetic energy spectrum shows multiple breaks
  - "Kolmogorov" scaling around injection scale
  - Flatter on intermediate scales
- Tied to interpretation of observations

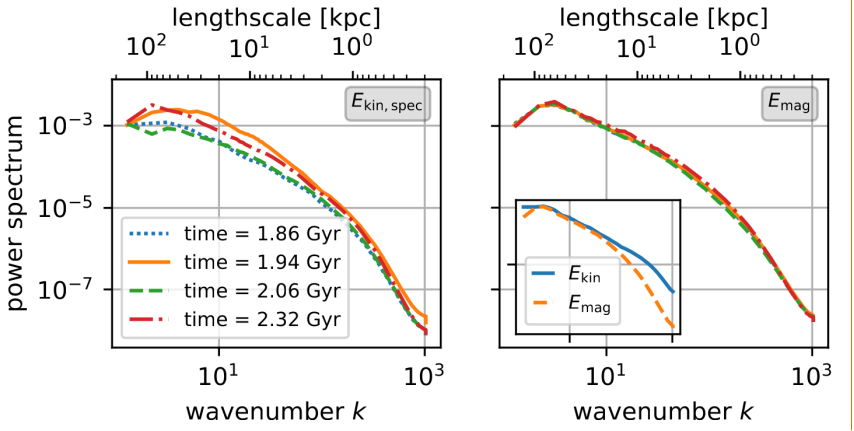


[Zhuravleva+ Nature 2019]



Energy spectra at various times

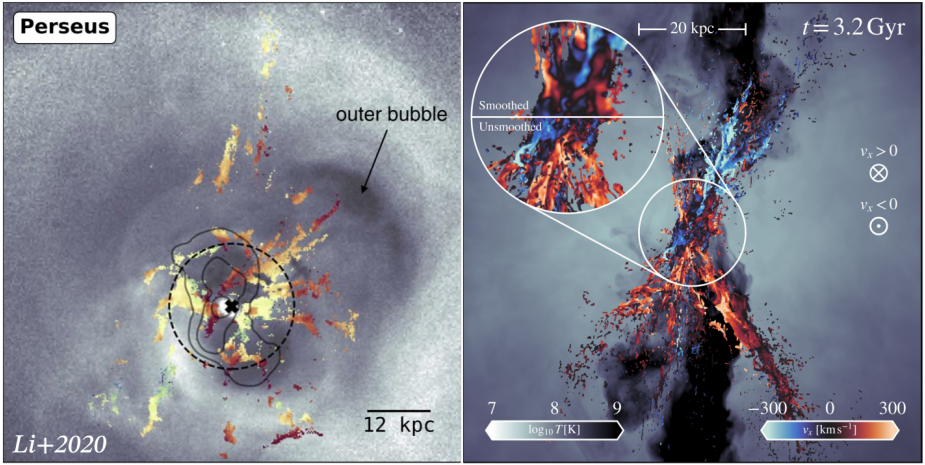
[XMAGNET collab. Grete+ arXiv:2502.13213]



- Kinetic energy spectra/slopes vary with time
- Magnetic energy spectra approx. constant

(Observable) multiphase kinematics

[XMAGNET collab. Fournier, PG+ arXiv:2502.19486]

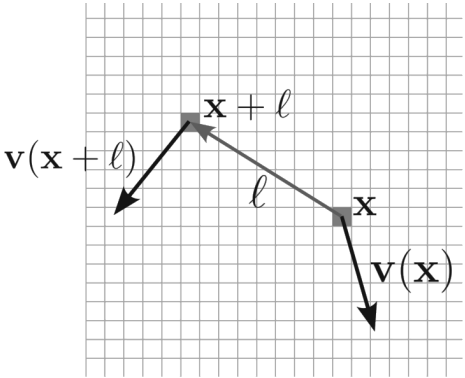


Work by Martin Fournier

Velocity structure functions theory

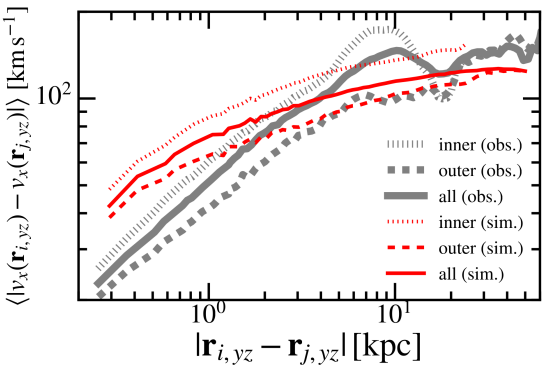
[XMAGNET collab. Fournier, PG+ arXiv:2502.19486]

- Amplitude of (average) fluctuations versus distance
- Can be done
  - in 2D and 3D
  - separate for hot and cold phase
- For incompressible, isotropic, hydrodynamic turbulence equivalent to power spectrum



Velocity structure functions in practice

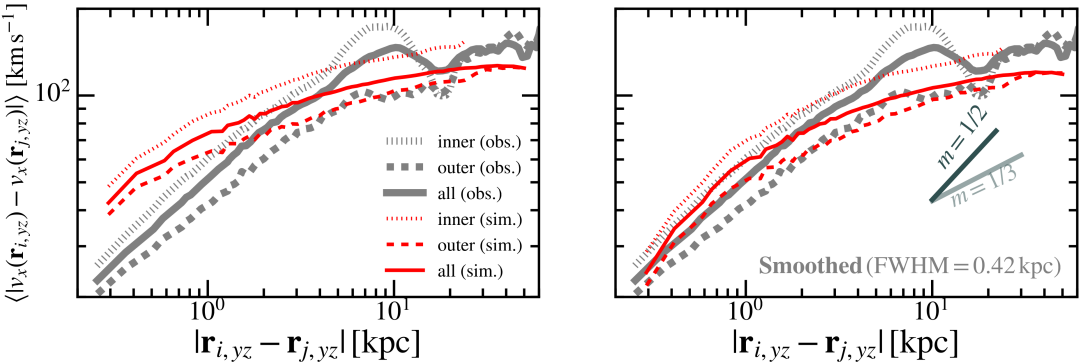
[XMAGNET collab. Fournier, PG+ arXiv:2502.19486]



- Projected 2D structure functions of the cold phase
- Observations (gray) from Li+20
  - Slope ($m \approx 1/2$) steeper than Kolmogorov
- Simulation consistent with Kolmogorov *(but there is no reason to it!)*
- Tension between obs. and sim.

Velocity structure functions in practice

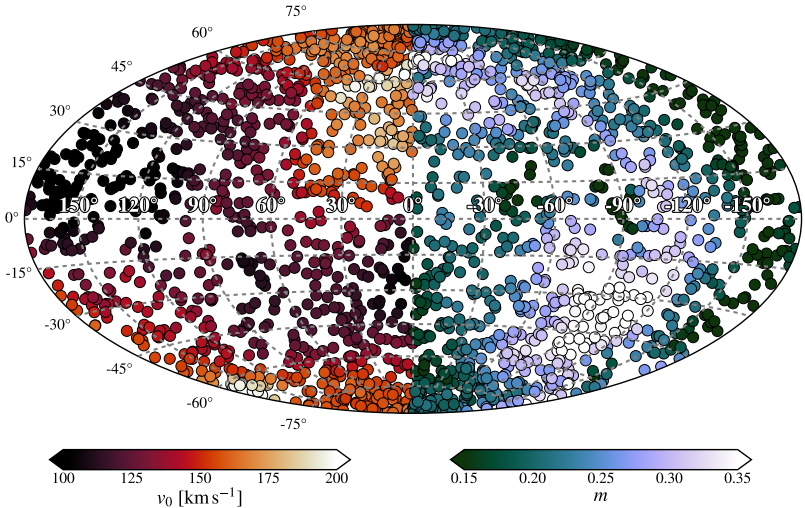
[XMAGNET collab. Fournier, PG+ arXiv:2502.19486]



Good agreement when taking atmospheric seeing into account

VSF – Impact of viewing angle

[XMAGNET collab. Fournier, PG+ arXiv:2502.19486]

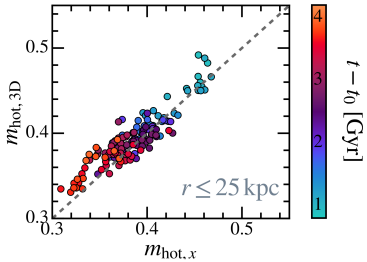


- Amplitude (left) and slope (right) at various viewing angles

$\Rightarrow$ It depends!

VSF – Tracing phases

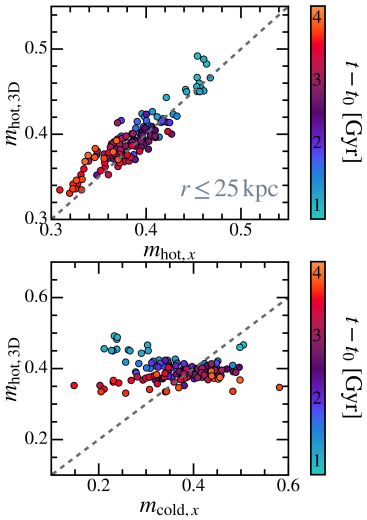
[XMAGNET collab. Fournier, PG+ arXiv:2502.19486]



- 3D VSF of hot phase traces 2D projected VSF of the hot phase

VSF – Tracing phases

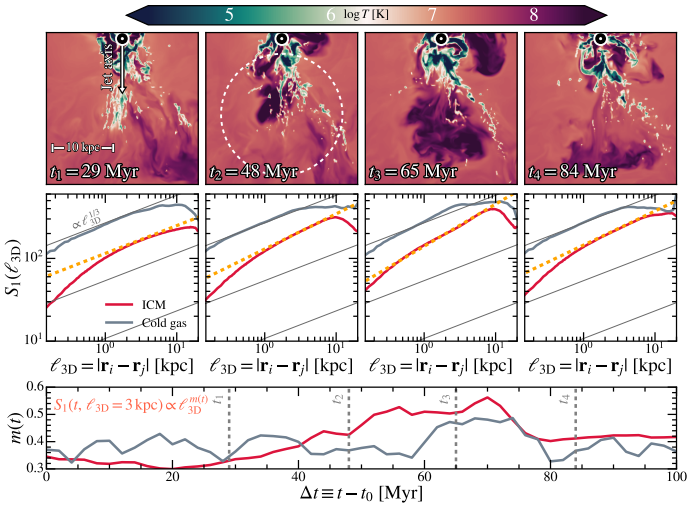
[XMAGNET collab. Fournier, PG+ arXiv:2502.19486]



- 3D VSF of hot phase traces 2D projected VSF of the hot phase
- Hot and cold phase VSF do not trace each other (in the ICM with jet feedback)

VSF – Temporal variations

[XMAGNET collab. Fournier, PG+ arXiv:2502.19486]



- VSF depend on dynamical state, see also Wang+21

Conclusions

- e**X**ascale simulations of **M**agnetized **AGN** feedback focusing on **E**nergetics and **T**urbulence

⇒ Magnetic fields matter for multiphase structure

⇒ Good agreement between obs. and sim. cold phase VSF

⇒ (Observable) kinematics vary with viewing angle and time

- Exascale (GPU) computing is here!
- Simulation powered by AthenaPK and Parthenon

⇒ Bridging computational scales with 70000+ GPUs