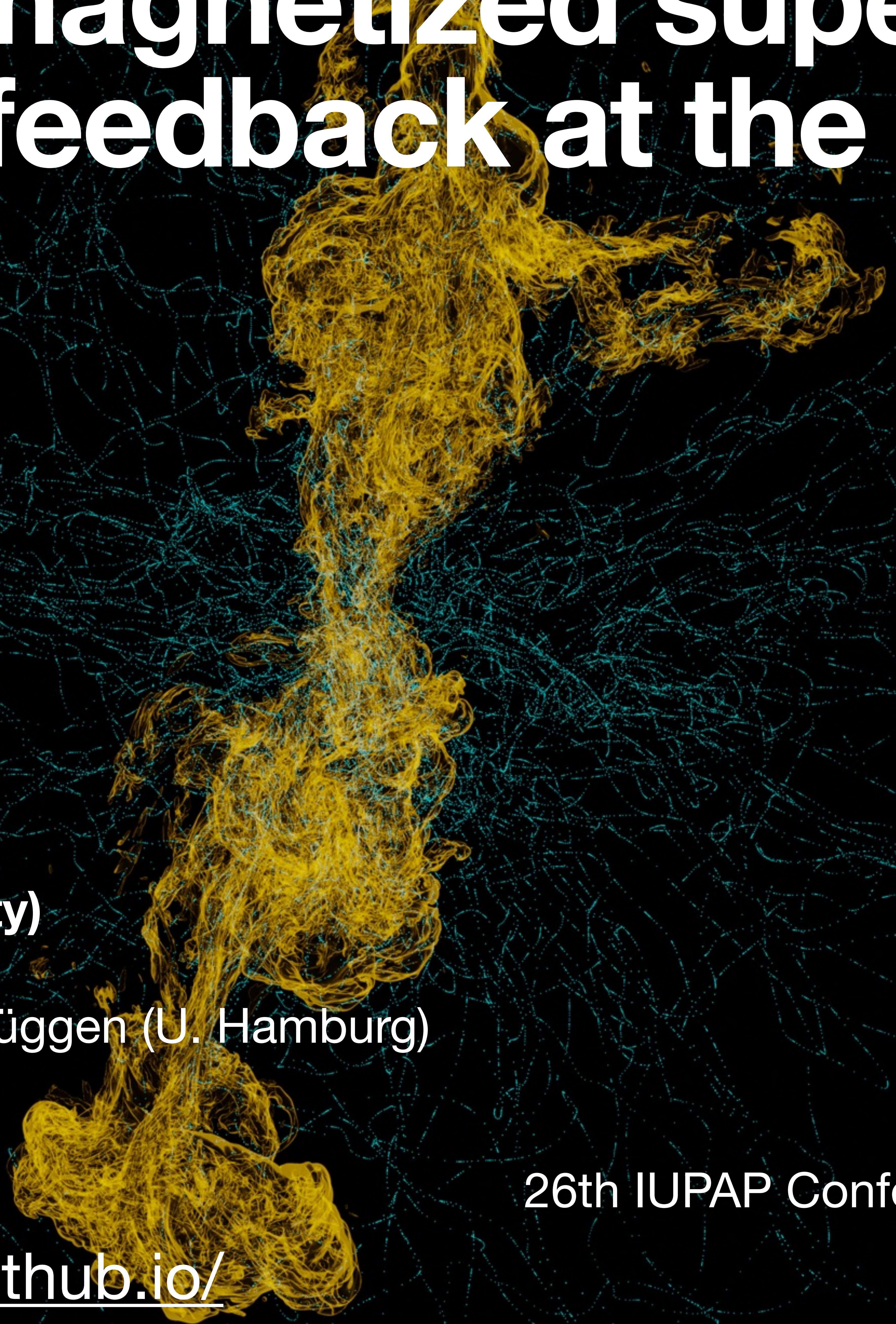
Simulating magnetized supermassive black hole feedback at the exascale



Brian O'Shea (Michigan State University)
Ben Wibking, Mark Voit (MSU)
Martin Fournier, Philipp Grete, Marcus Brüggen (U. Hamburg)
Forrest Glines (MSU->LANL->NVIDIA)
Deovrat Prasad (Cardiff)

https://xmagnet-simulations.github.io/

26th IUPAP Conference of Computational Physics
Oak Ridge National Laboratory
November 5, 2025

What are we talking about?

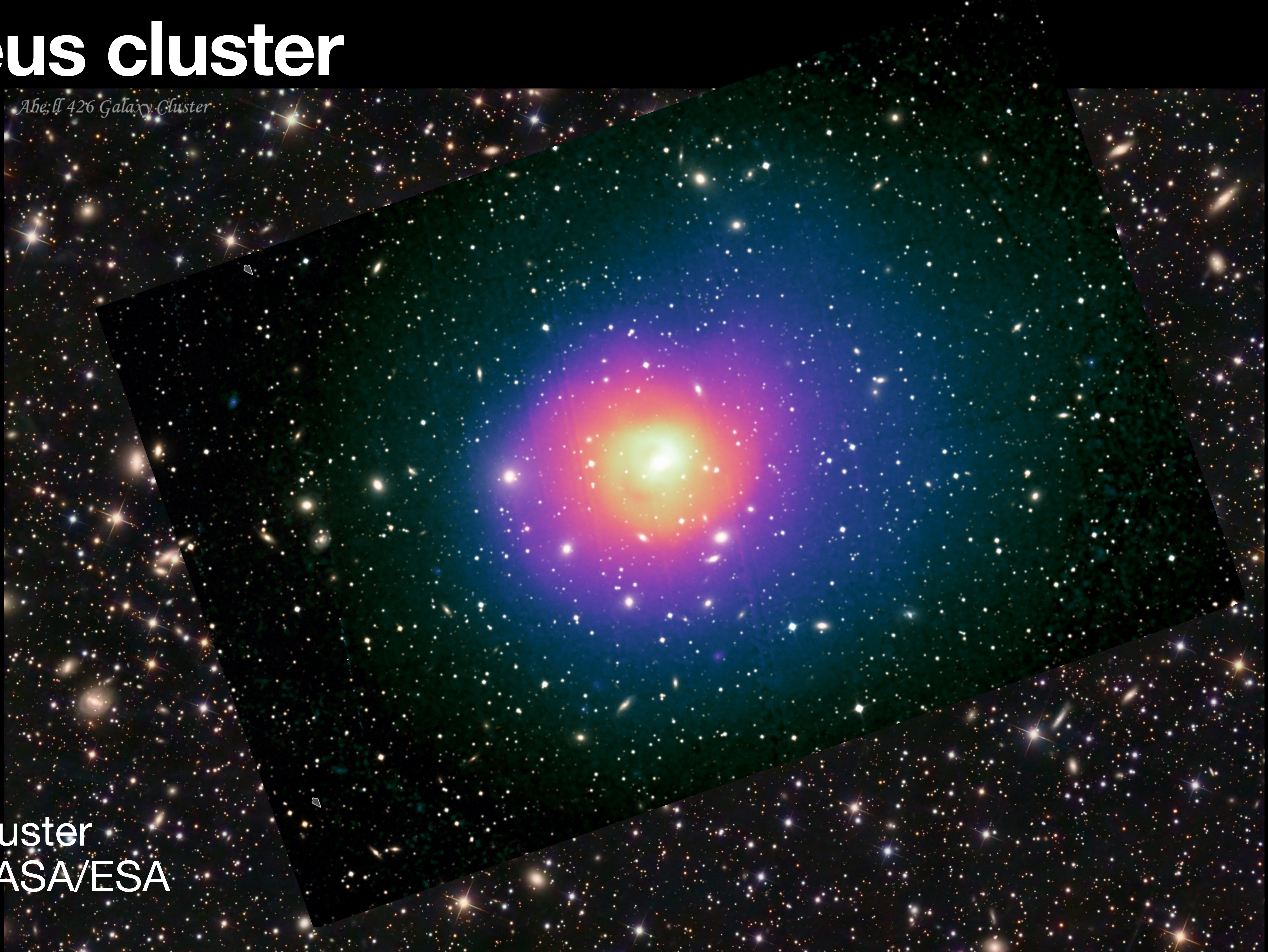
1. What are galaxy clusters, and how do we simulate them?
2. What are the technical challenges in doing so?
3. What interesting things can we learn about galaxy clusters?

What is a galaxy cluster?

Perseus cluster

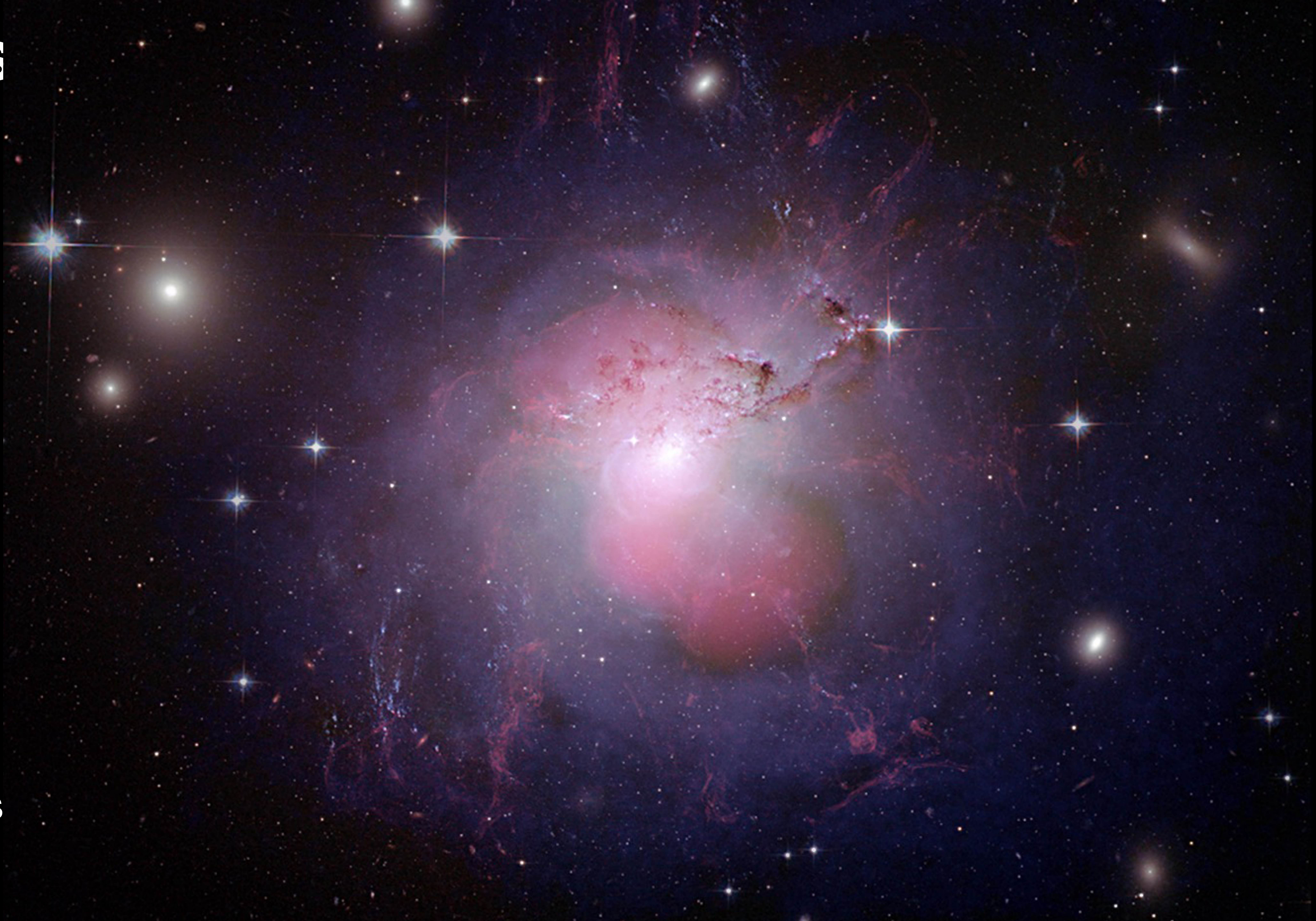
Perseus cluster
Images: NASA/ESA

Perseus cluster

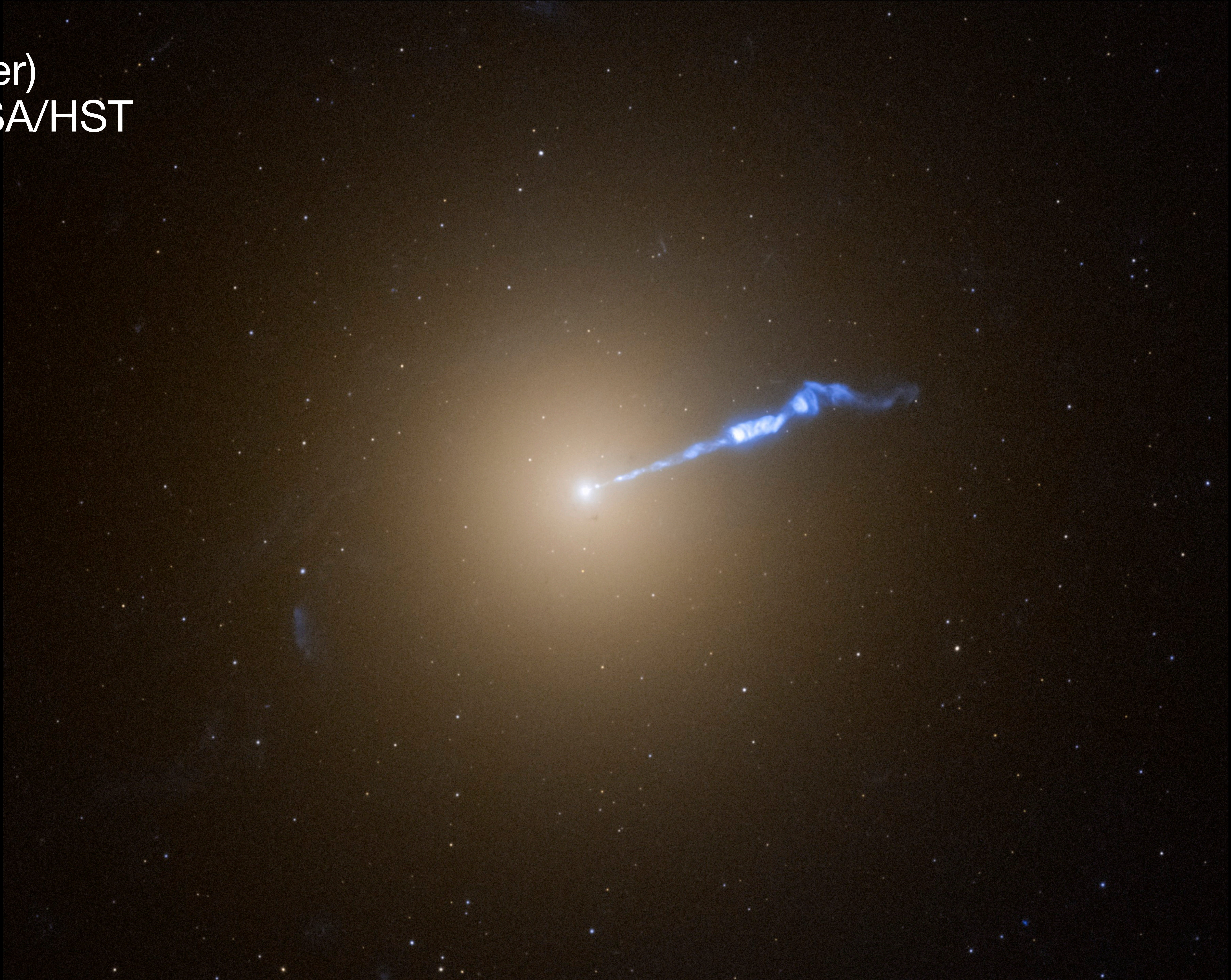


Perseus cluster
Images: NASA/ESA

Pers



Perseus
Images:



M87 galaxy
(Virgo cluster)
Image: NASA/HST


M87 galaxy
(Virgo cluster)
Image: NASA/HST


M87 galaxy
(Virgo cluster)
Image: NASA/HST
M87*
Image: Event Horizon Telescope

Why are galaxy clusters interesting?

1. They’re useful for cosmology!
2. Very extreme astrophysical systems - useful for understanding galaxy evolution (more on that later)
3. They are plasma physics laboratories!

Wl

1.

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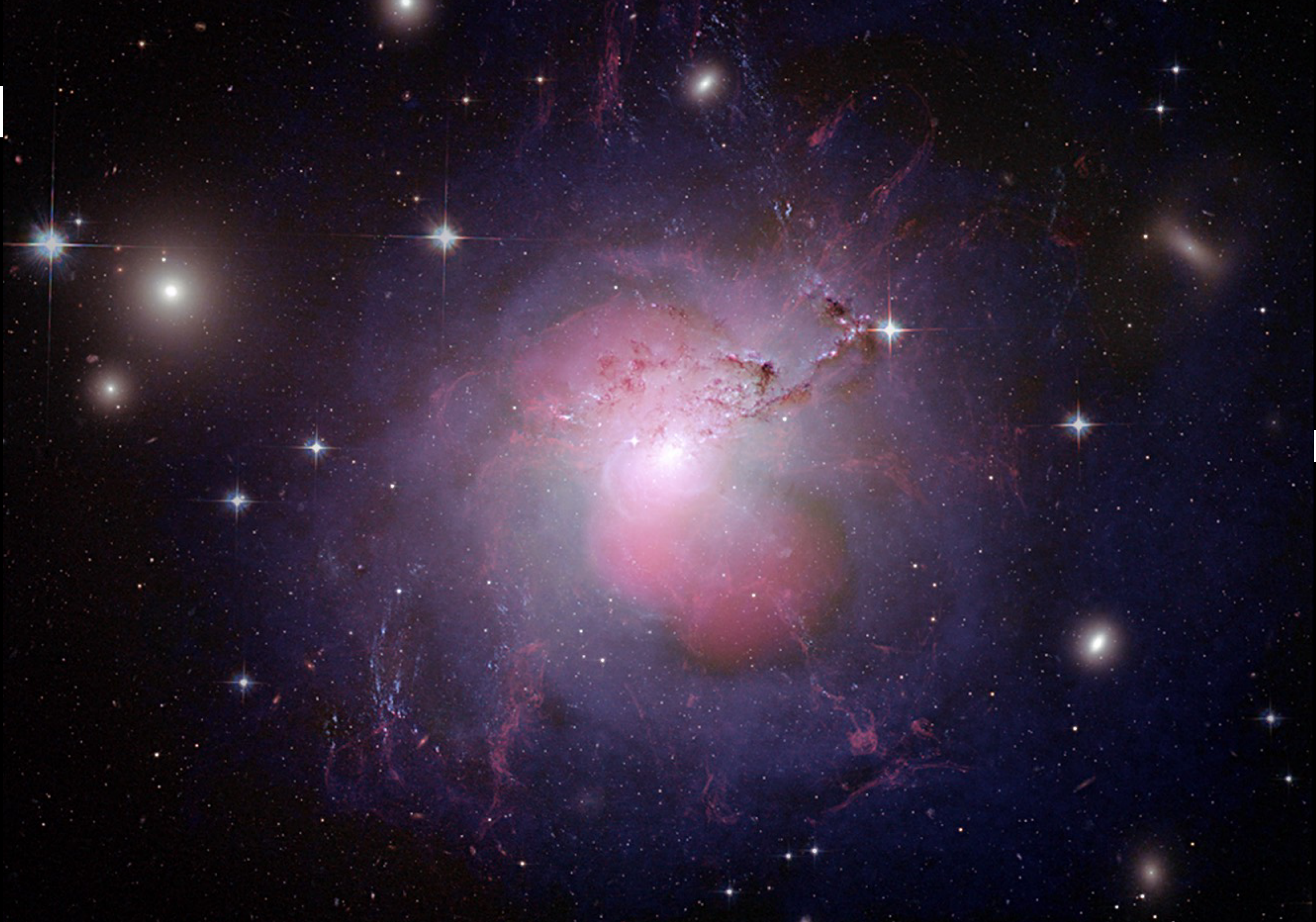
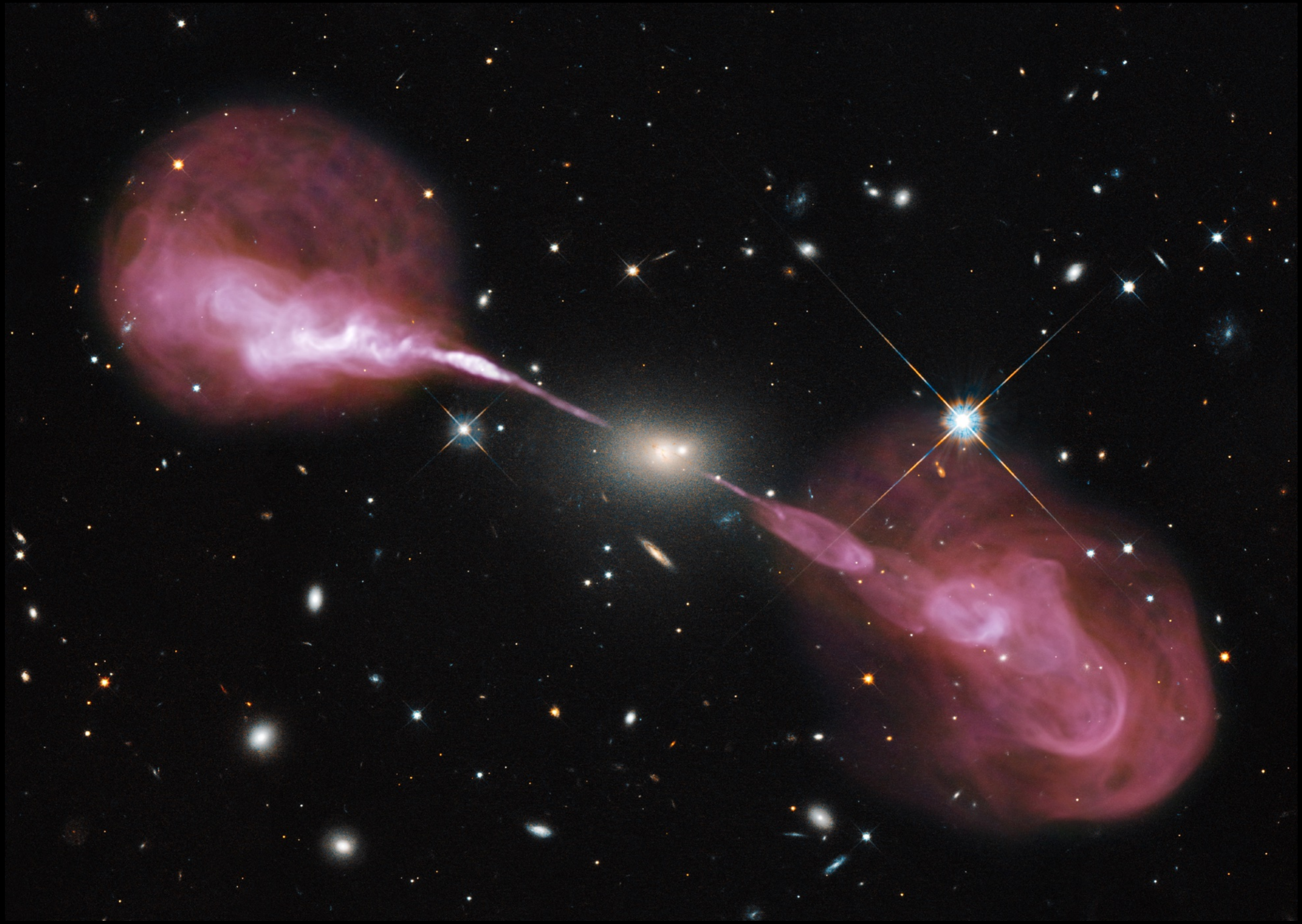


An aside: plasma physics and the universe

- Plasmas are ubiquitous in the universe
- Understanding these plasmas are crucial to making accurate predictions and interpreting observations
- Astrophysical plasmas inform us about terrestrial plasma physics (e.g., fusion energy) and vice versa!



Hercules A galaxy
Optical: Hubble Space Telescope
Radio: Very Large Array

A puzzle: galaxies (and groups, and clusters) regulate themselves!

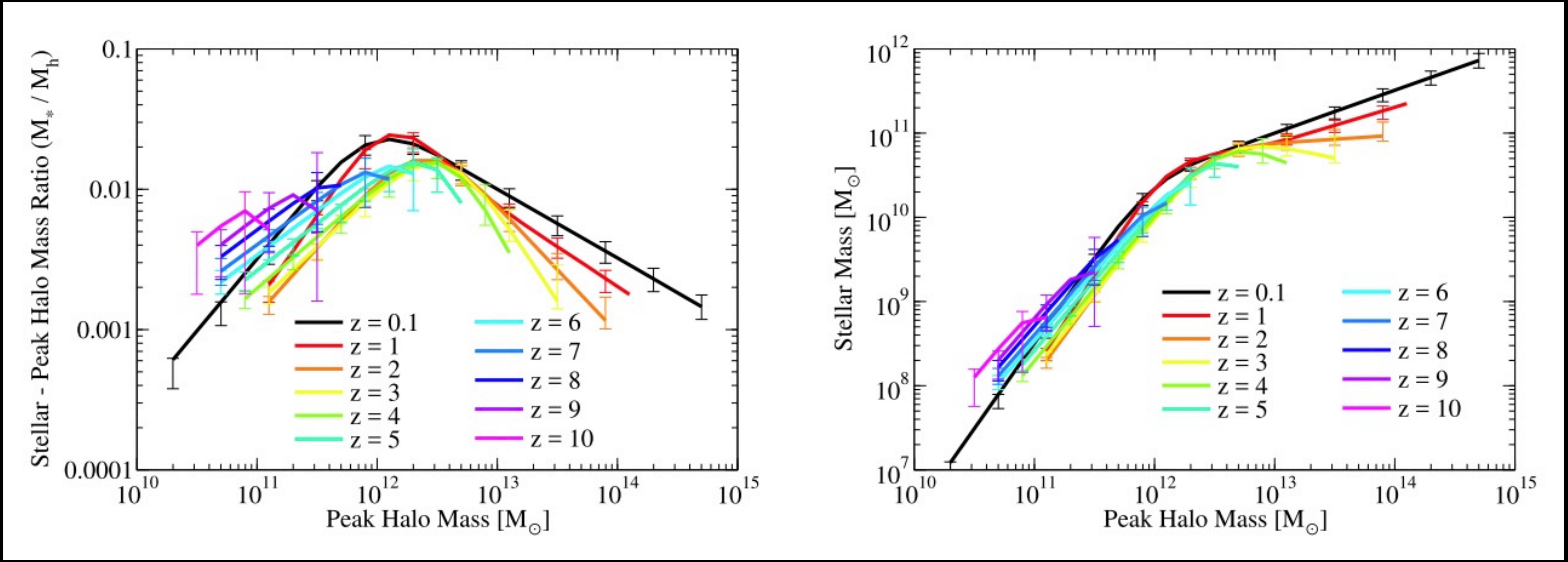


Fig. 9 from Behroozi et al. 2019, MNRAS, 488, 3143-3194

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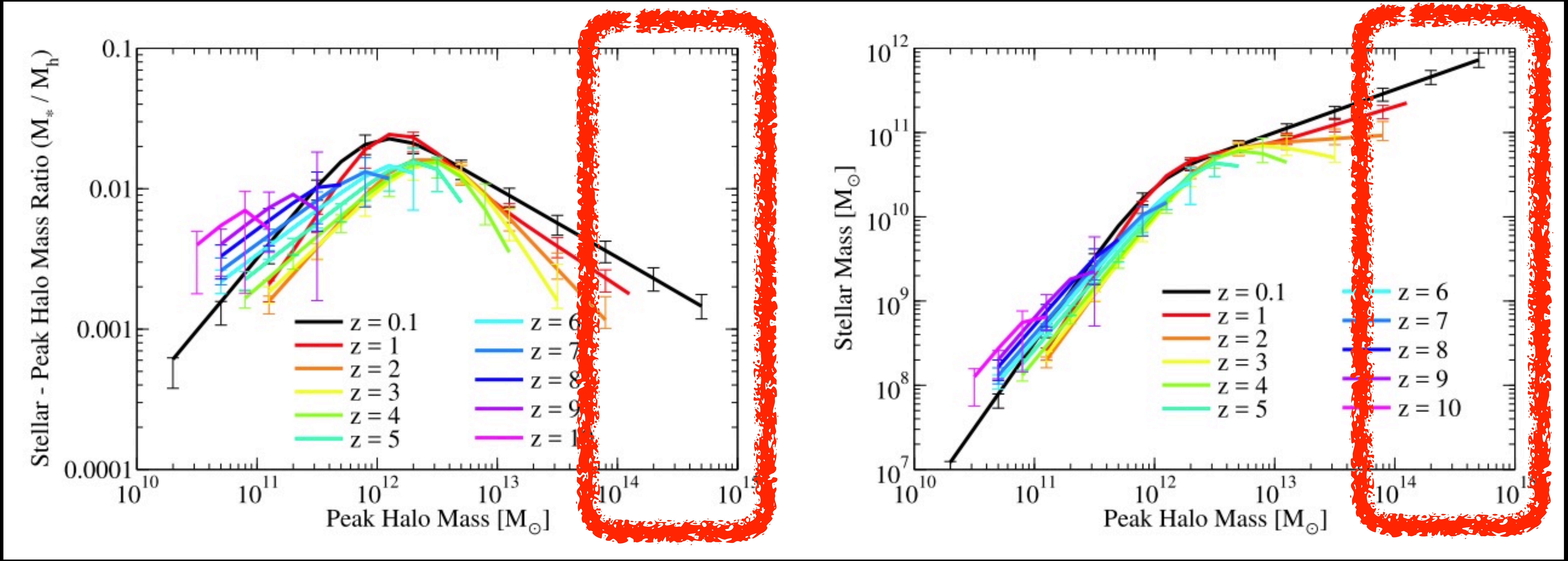

Fig. 9 from Behroozi et al. 2019, MNRAS, 488, 3143-3194

Galaxy cluster self-regulation is AGN-driven!

- Many galaxy clusters have very short plasma cooling times*, yet the systems are stable. How?
- active galactic nuclei (i.e., jets from supermassive black holes) feedback seems to be the solution! ($\dot{E}_{AGN} \simeq \dot{E}_{cool}$)
- How is energy from the AGN injected, redistributed, thermalized?
- How does this energy deposition (at scales of $L \sim 100$ kpc) regulate black hole accretion (at scales of $L \ll 1$pc)?

X-Ray, radio, optical composite image of the core of the Perseus Cluster;
Courtesy of NASA, ESA, and L. Frattare (STScI);

Why is simulating a galaxy cluster hard?

Relevant scales:

- Mass of Perseus cluster: 6×10^{14} Msun (1.2×10^{45} kg)
- Radius of Perseus cluster: ~2.2 Mpc (6.7×10^{22} m)
- Sound-crossing time of Perseus cluster: ~ 3 Gyr
- Radius of Perseus central galaxy: ~20 kpc (6.1×10^{20} m)
- Mass/Radius/light crossing time of Perseus galaxy supermassive black hole: 8×10^{8} Msun / 2.4×10^{12} m / 3 hours

Why is simulating a galaxy cluster hard?

Relevant physics:

- Cosmology (expansion of universe)
- Gravity
- Magnetohydrodynamics (if the scales are large enough)
- Thermal radiative loss
- Star formation and stellar feedback (i.e, supernovae)
- Black hole formation, evolution, and feedback
- Non-thermal radiative emission (e.g., synchrotron emission)
- More complex plasma physics (cosmic rays, thermal conduction, viscosity, …)

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What tools do we use?

International Journal of
HIGH PERFORMANCE
COMPUTING APPLICATIONS

Research Paper

Parthenon—a performance portable block-structured adaptive mesh refinement framework

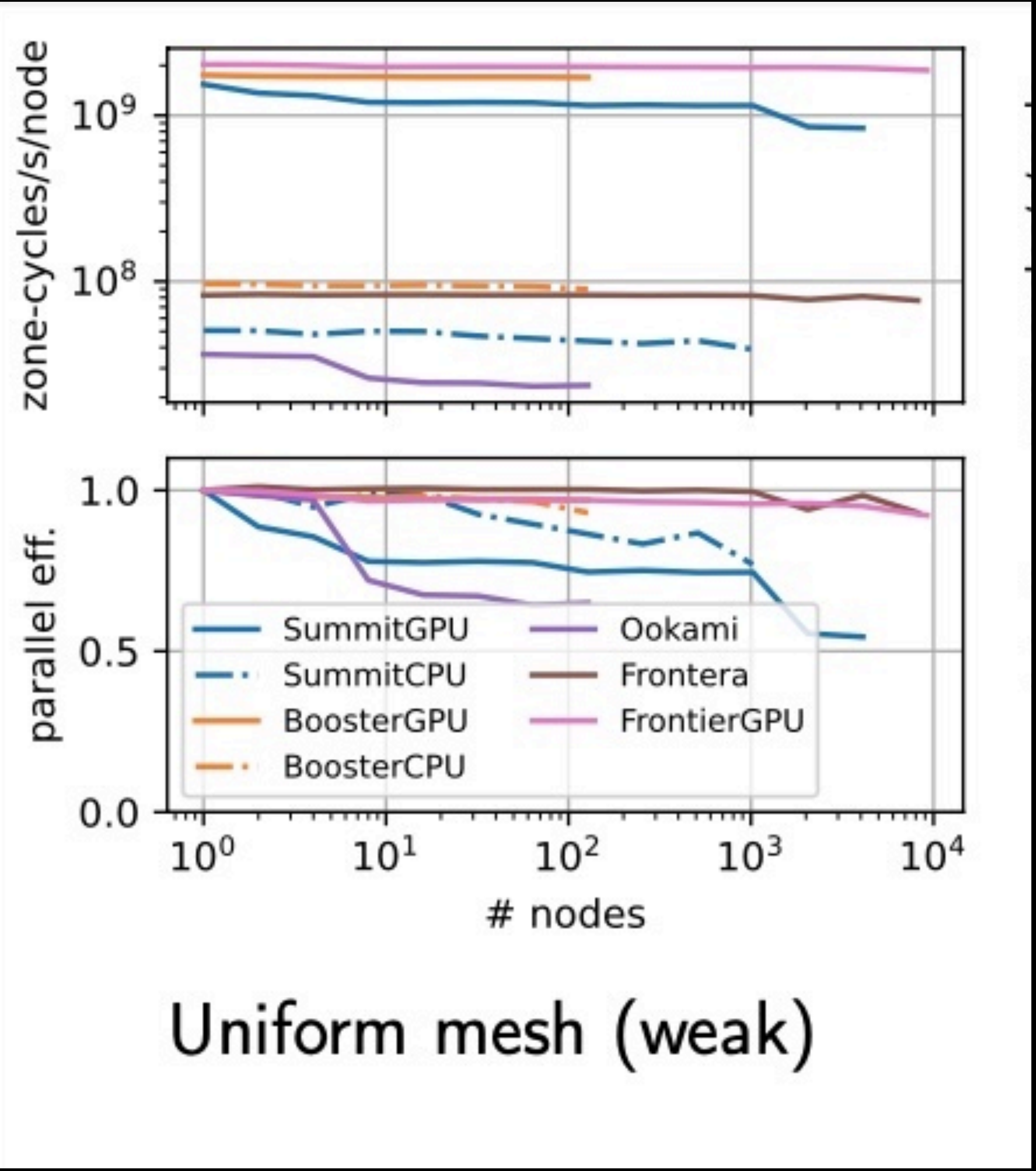
The International Journal of High Performance Computing Applications
2023, Vol. 37(5) 465–486

DOI: 10.1177/10943420221143775
journals.sagepub.com/home/hpc
Sage

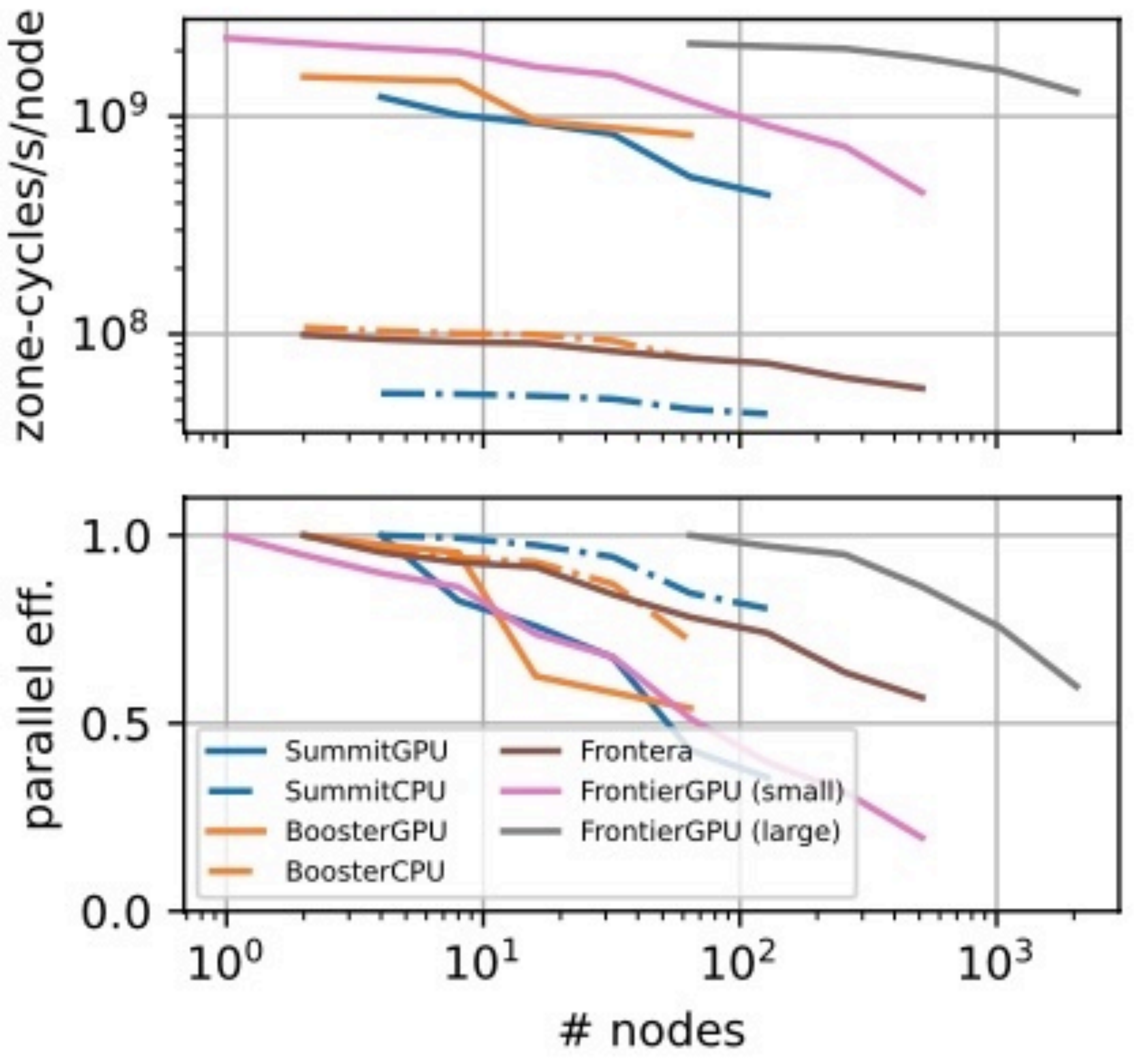
Philipp Grete[1,2], Joshua C Dolence[3,4], Jonah M Miller[3,4], Joshua Brown[5,6], Ben Ryan[3,4], Andrew Gaspar[5], Forrest Glines[2], Sriram Swaminarayan[5], Jonas Lippuner[3,4], Clell J Solomon[7], Galen Shipman[5], Christoph Junghans[5], Daniel Holladay[5], James M Stone[8] and Luke F Roberts[3]

Get it at https://github.com/parthenon-hpc-lab/parthenon !

Parthenon scaling (hydro mini-app)

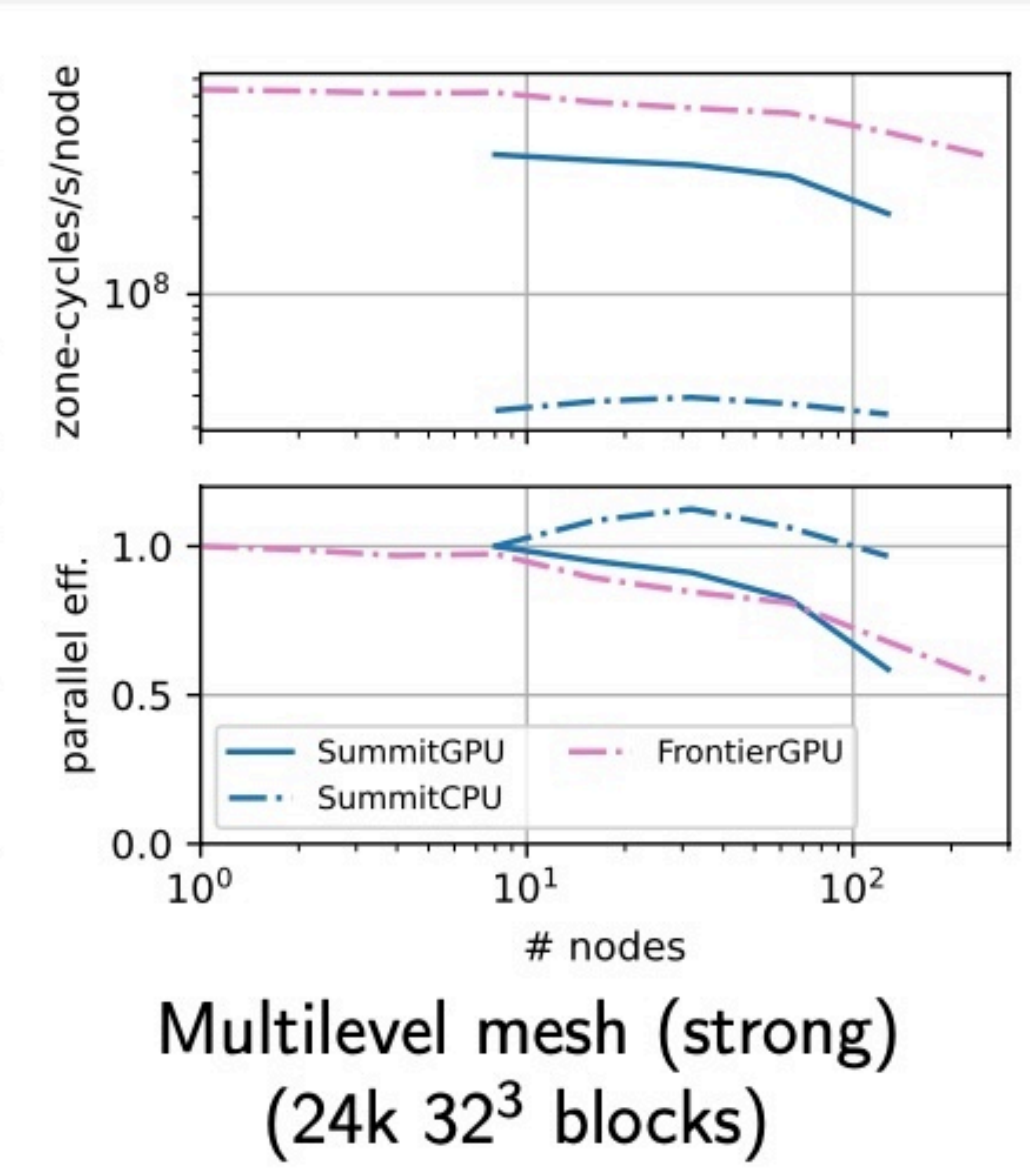


Parthenon scaling
(hydro mini-app)

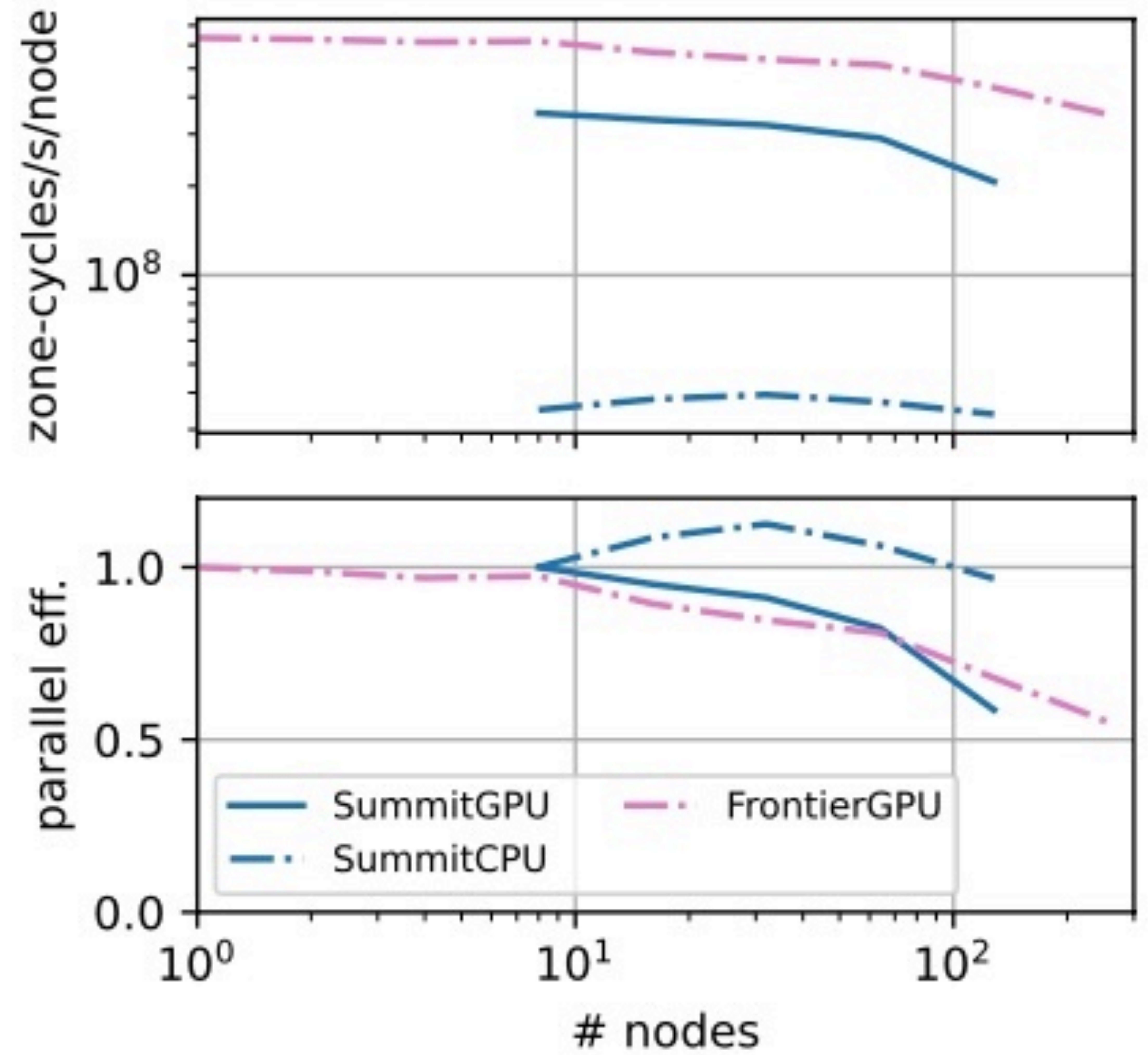


Uniform mesh (strong)

Parthenon scaling
(hydro mini-app)



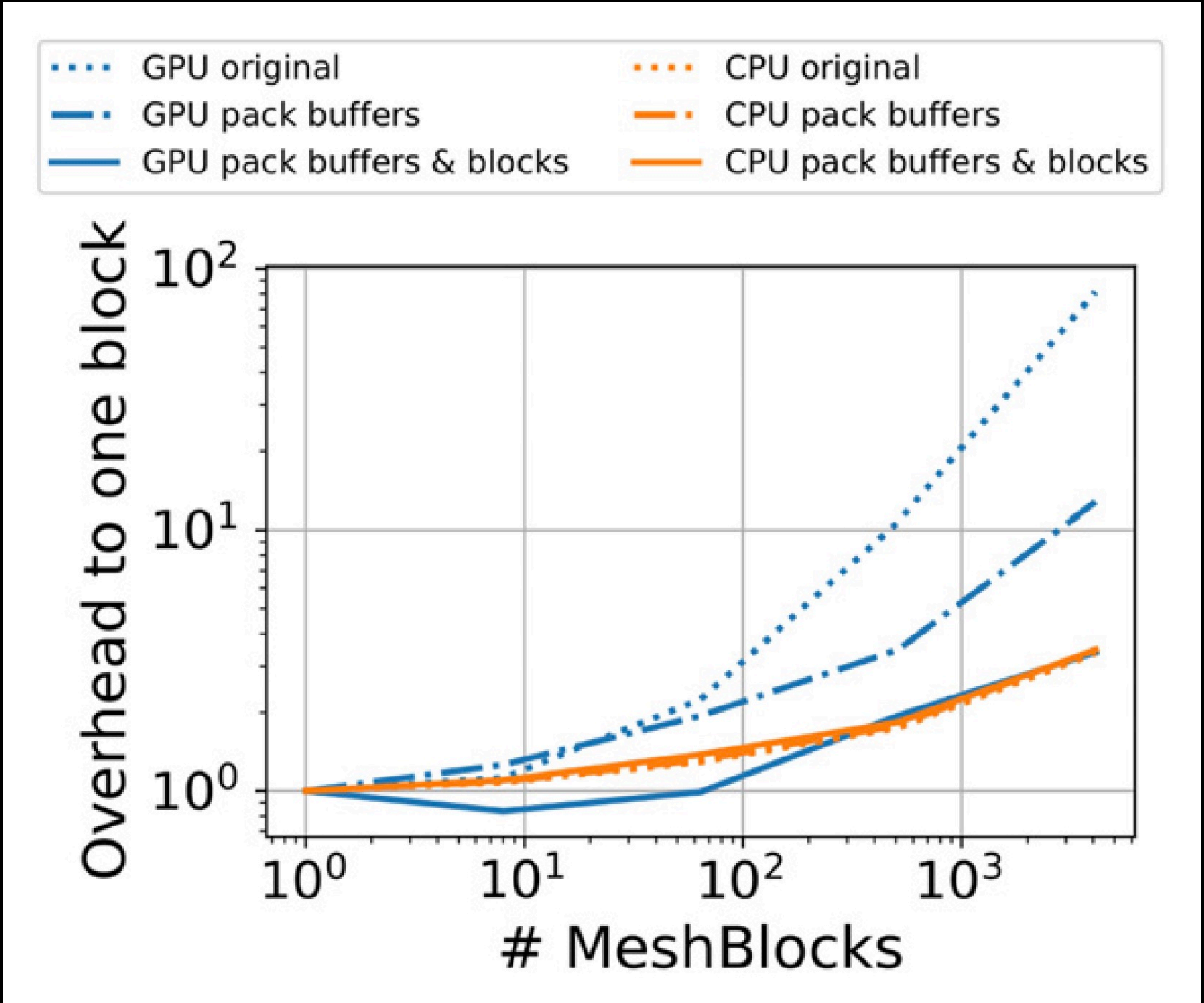
Parthenon scaling
(hydro mini-app)



Multilevel mesh (strong)
(24k 32^3 blocks)

92% weak scaling efficiency on 73,728 GPUs!

>50% strong scaling efficiency for 100x increase in resources!



GPU original
CPU original
GPU pack buffers
CPU pack buffers
GPU pack buffers & blocks
CPU pack buffers & blocks
Overhead to one block
10^2
10^1
10^0
10^0
10^1
10^2
10^3
MeshBlocks

AthenaPK: Parthenon + Athena++

- Based on Parthenon
- Finite volume (magneto)hydrodynamics with various integrators, reconstruction methods, Rieman solvers
- Diffusion processes (conduction, viscosity, resistivity)
- Optically thin radiative losses
- Tracer particles
- Static and adaptive mesh refinement
- Many problem generators!

Download it at https://github.com/parthenon-hpc-lab/athenapk !

The xMAGNET Project: Exascale MHD simulations of AGN feedback in galaxy groups and clusters

https://xmagnet-simulations.github.io/

Grete et al. 2025, ApJ, 988, 155 (Project overview)

Fournier et al. 2025, A&A, 698, 121 (Velocity structure functions in multiphase gas)

Prasad et al. 2025, ApJ, submitted (arXiv:250817508; Behavior of massive galaxy groups)

DOE INCITE program (2023-24; award AST146)

What questions are we addressing?

- How do AGN within galaxies and clusters regulate the thermal state of the multiphase and magnetized IGrM/ICM?
- Where is the energy from magnetized AGN jets dissipated in the IGrM and ICM, and through what mechanism(s)?
- How does the IGrM/ICM become magnetized, and what is the structure of the magnetic fields?
- How does magnetized plasma turbulence in the galaxy group/cluster compare to more idealized experiments, and what can this tell us about turbulence in general?
- How do the "cold" and "hot" phases of the IGrM/ICM relate to each other, both mechanistically and in observations?
- How does our numerical treatment of AGN jets impact our results?

IGrM = Intragroup medium   ICM = Intracluster medium

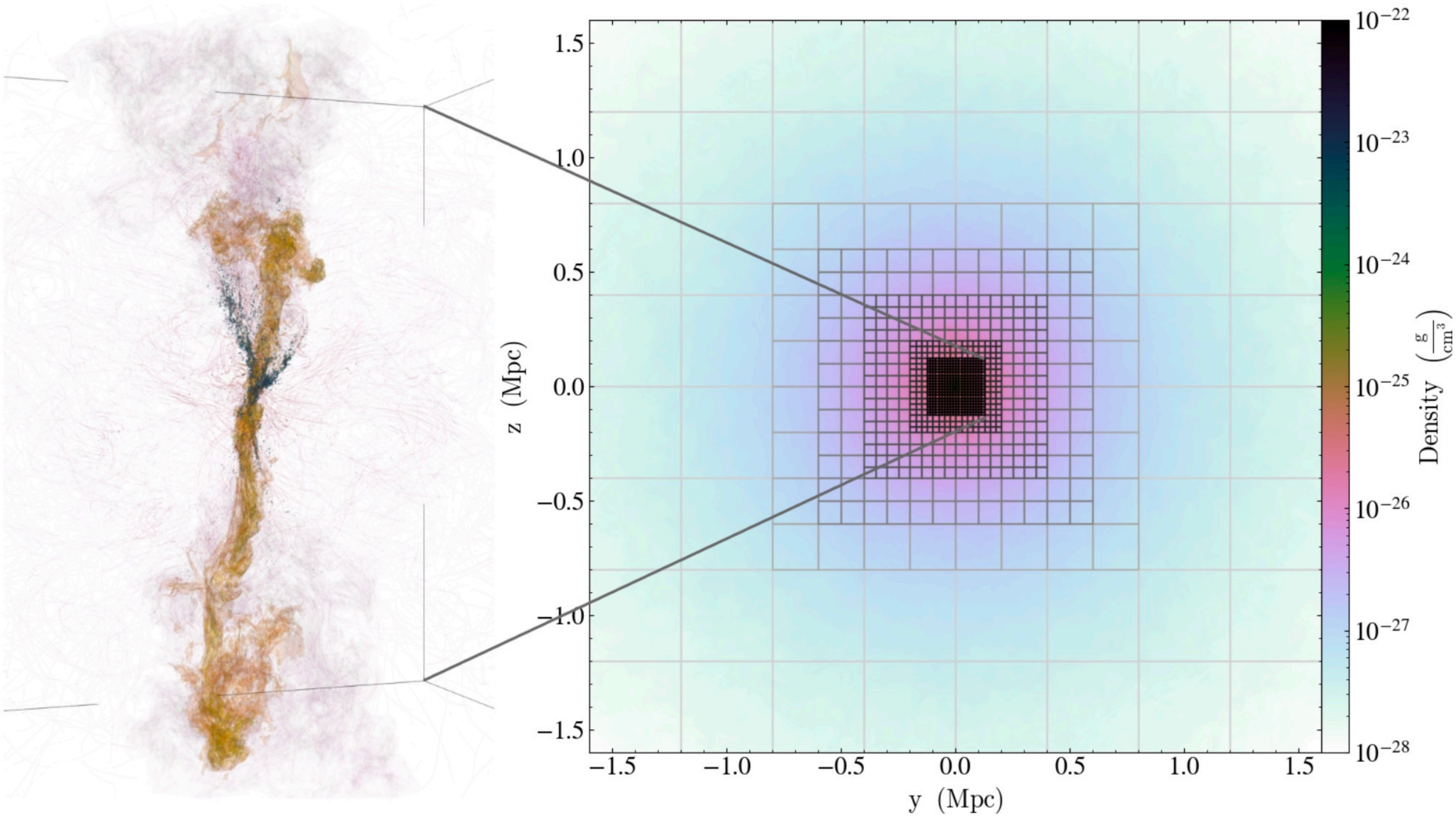
Simulation setup

Isolated galaxy cluster (Perseus analog)

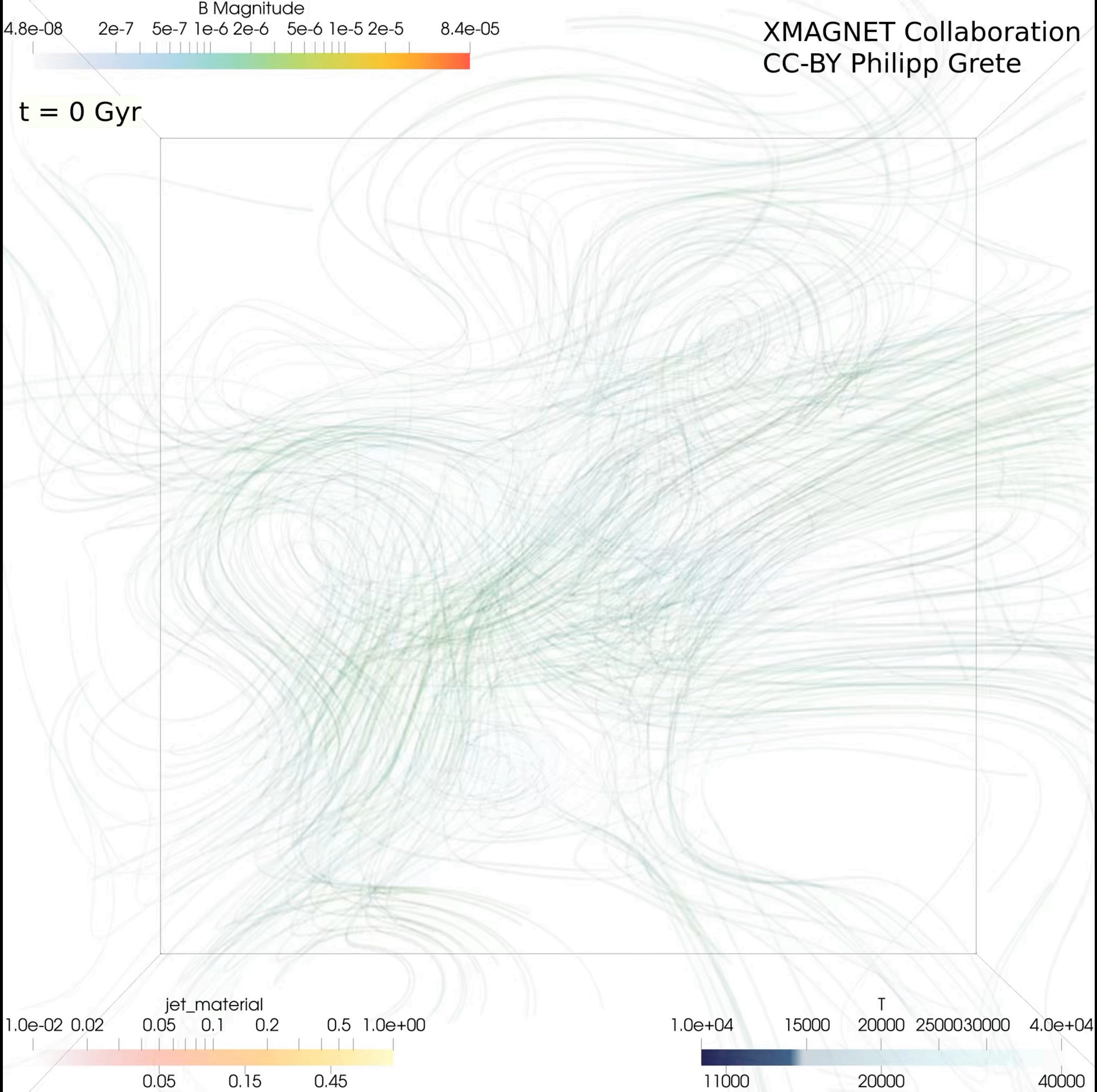
- Static gravitational potential (DM halo + BCG + black hole)
- Gas in initial hydrostatic equilibrium with realistic entropy profile and short central cooling time
- initial perturbations in density, magnetic field
- Static, telescoping mesh: central [200 kpc]^3 covered at 100 pc resolution (2,048^3 uniform grid)

- Evolution:
  - Ideal MHD + radiative cooling (+1 hydro simulation)
  - Thermal, kinetic, magnetic AGN feedback triggered by accretion of cold gas in black hole region
  - Run for 4 Gyr (many cooling times) - millions of time steps!

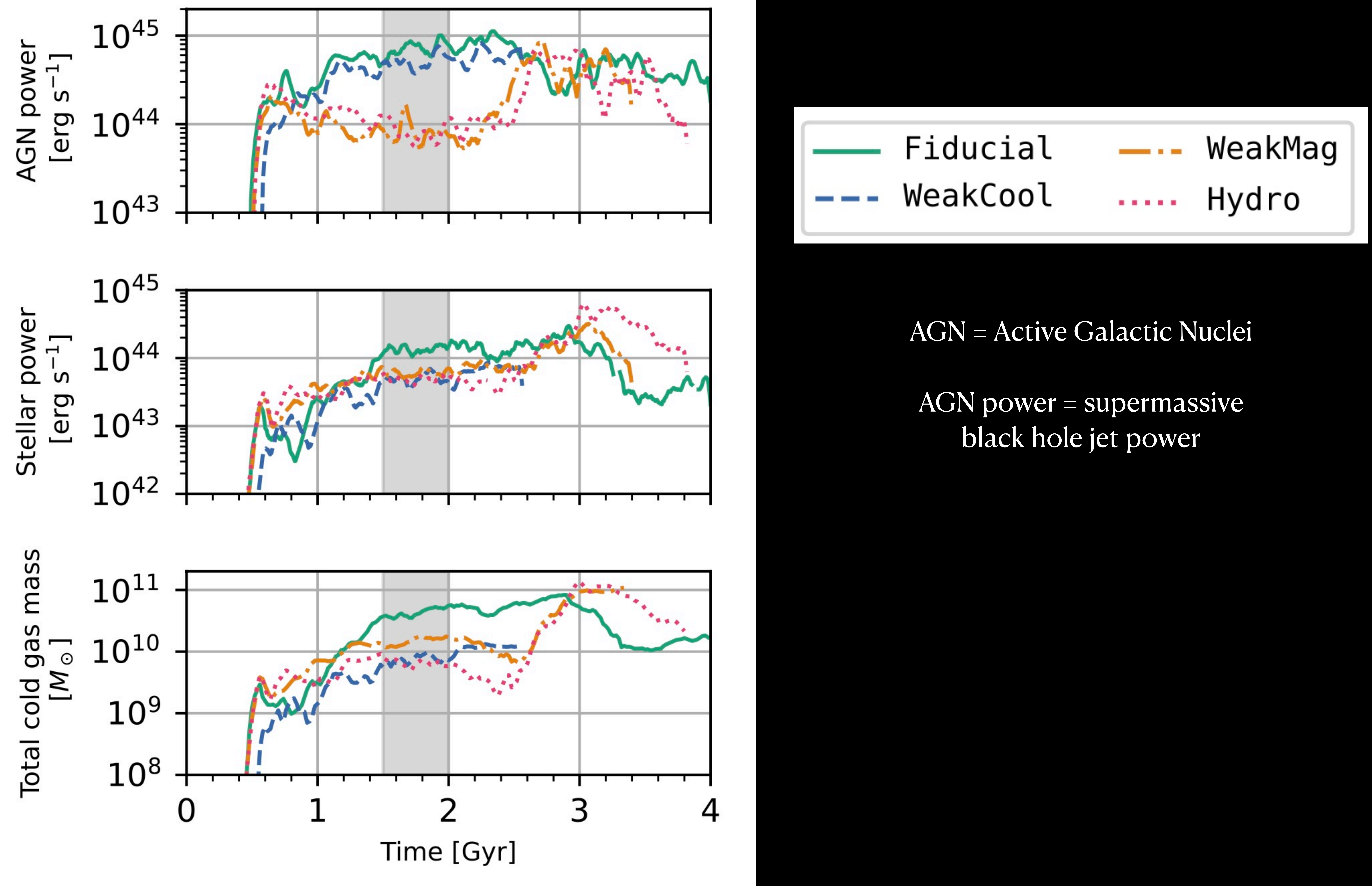
Simulations run with AthenaPK on Frontier @ OLCF, supported by DOE INCITE allocation AST146



z (Mpc)
y (Mpc)
Density $\left(\frac{g}{cm^3}\right)$
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}



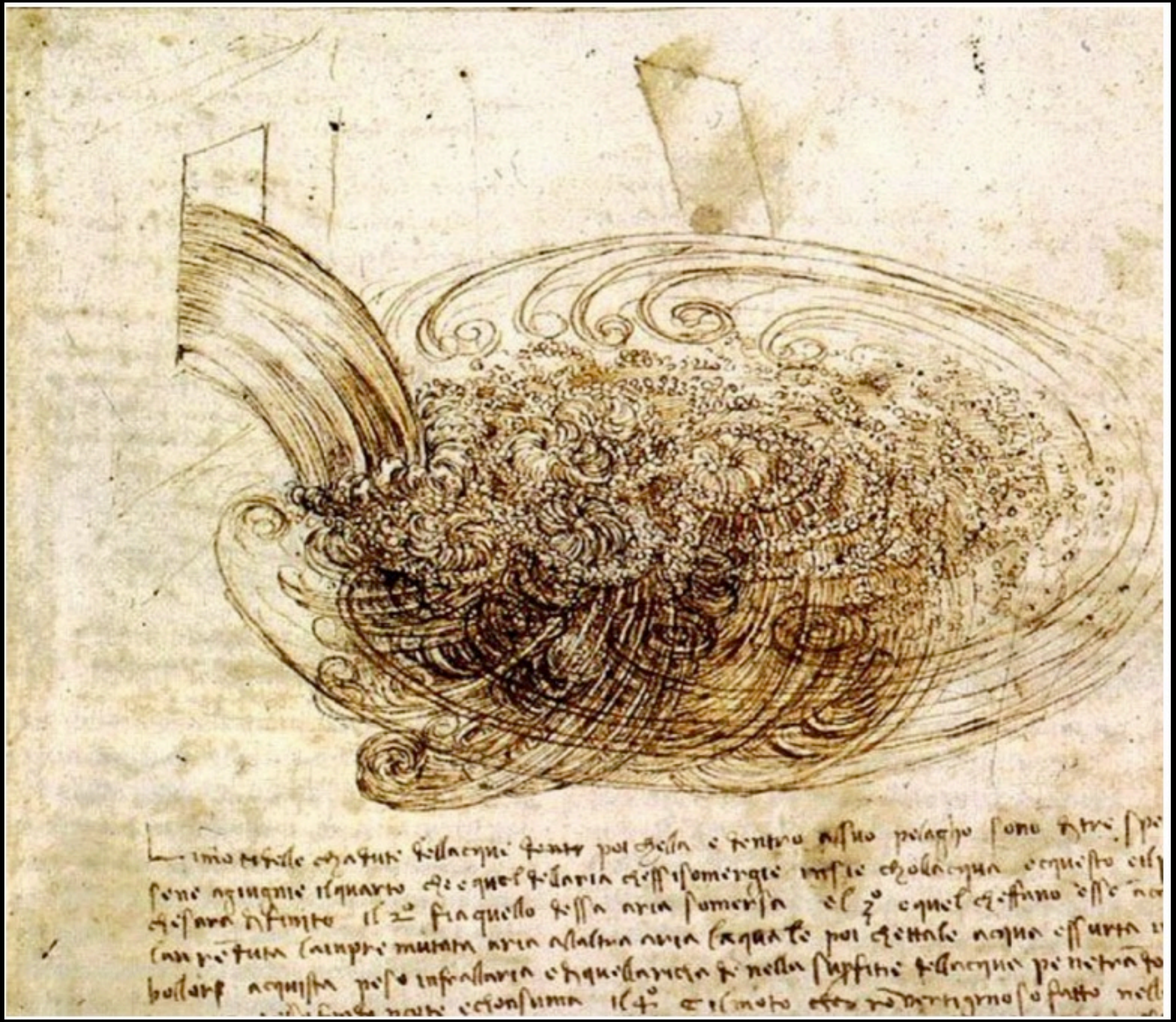
B Magnitude
4.8e-08 2e-7 5e-7 1e-6 2e-6 5e-6 1e-5 2e-5 8.4e-05
XMAGNET Collaboration
CC-BY Philipp Grete
t = 0 Gyr
jet_material
1.0e-02 0.02 0.05 0.1 0.2 0.5 1.0e+00
0.05 0.15 0.45
T
1.0e+04 15000 20000 2500030000 4.0e+04
11000 20000 40000



AGN = Active Galactic Nuclei

AGN power = supermassive black hole jet power

A brief aside on turbulence

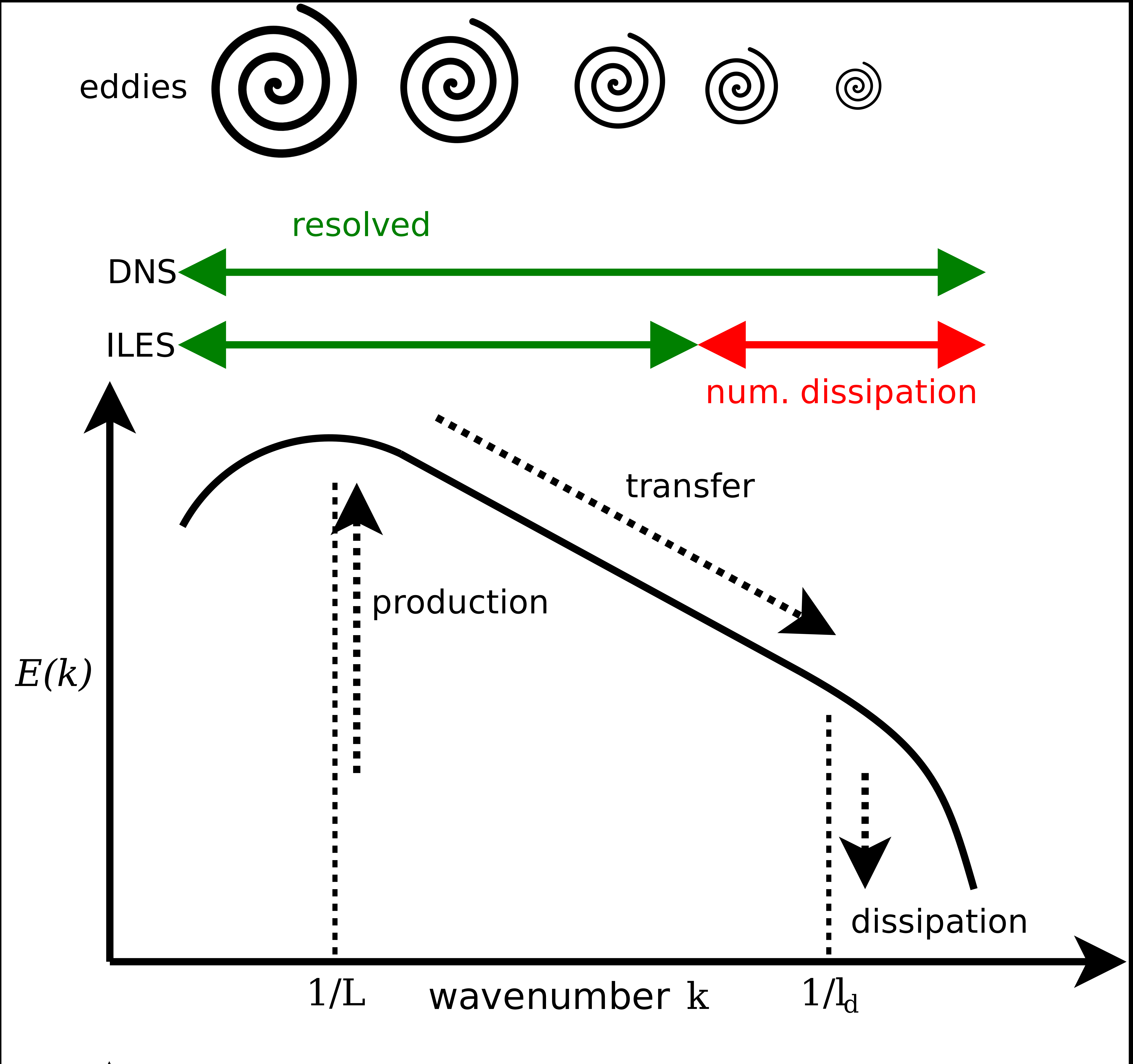


Leonardo da Vinci “Studies of water”
(c. 1510-12). c/o Royal Collection Trust

Hydrodynamic turbulence

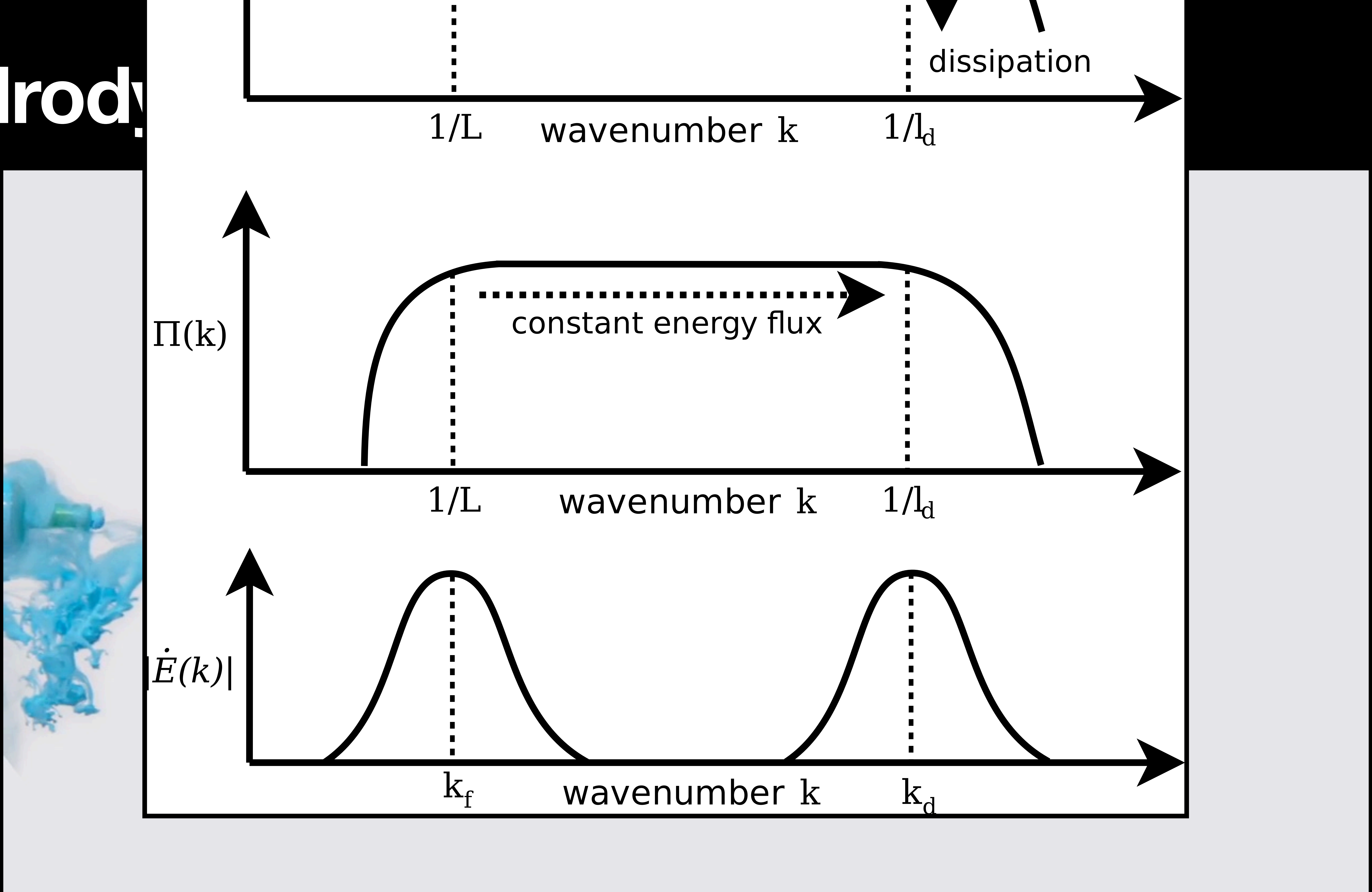
Clip from The Slo-Mo Guys, YouTube, 2015

Hydrody


eddies
resolved
DNS
ILES
num. dissipation
transfer
production
$E(k)$
dissipation
1/L
wavenumber k
$1/l_d$

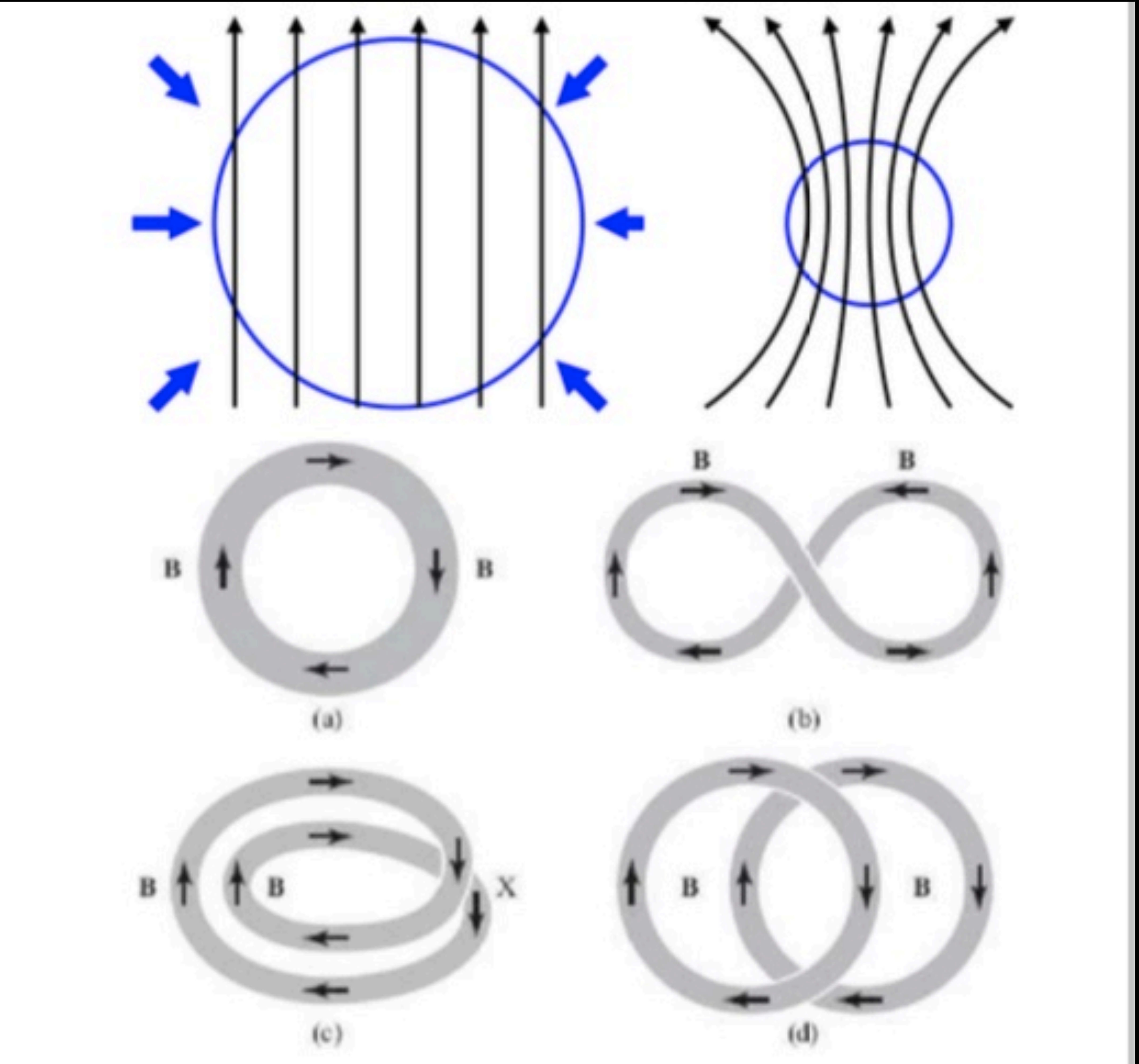
5

Hydrody

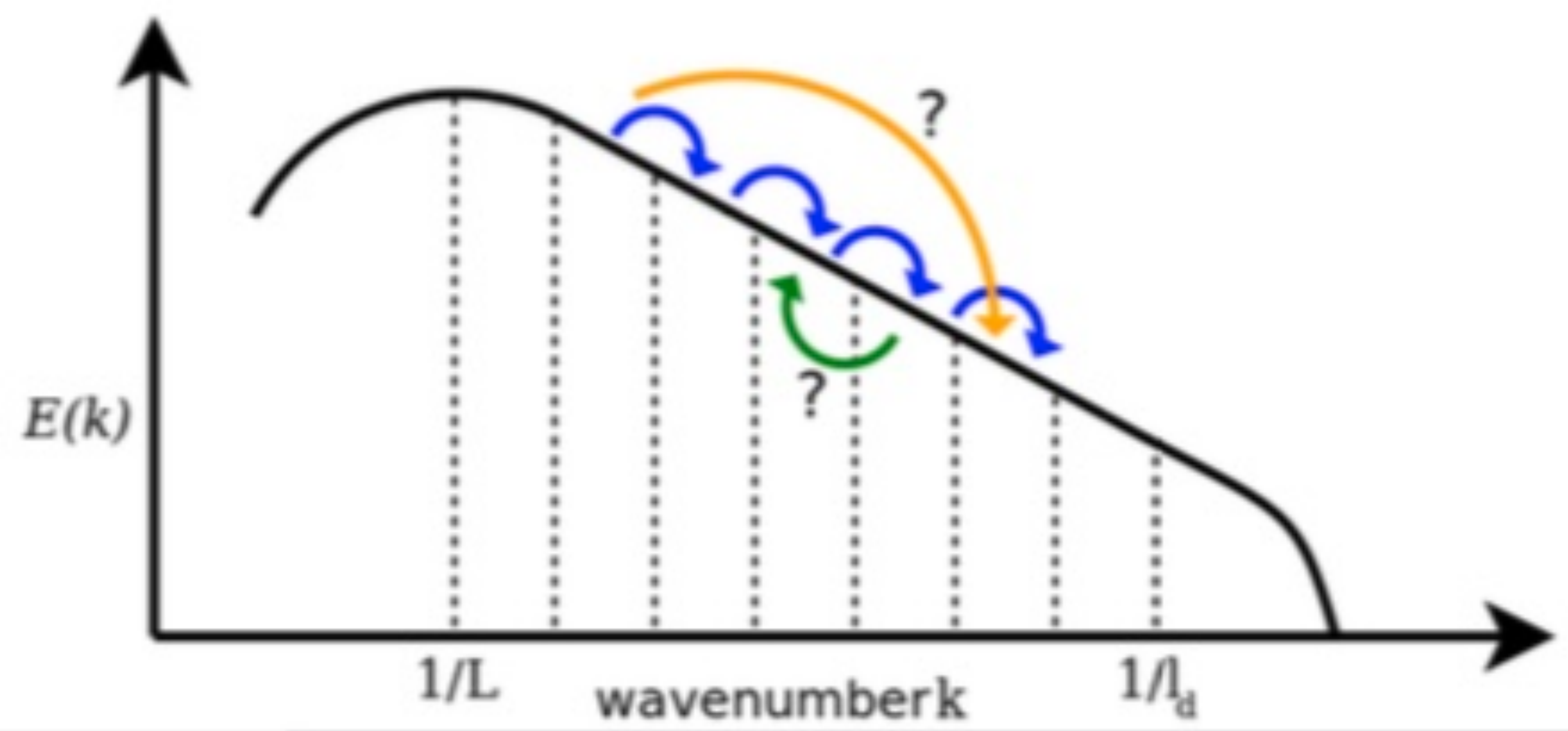


Clip from The Slo-Mo Guys, YouTube, 2015

Complexity from magnetic fields



[Dynamo image credit: Vainshtein & Zel'dovich '72]



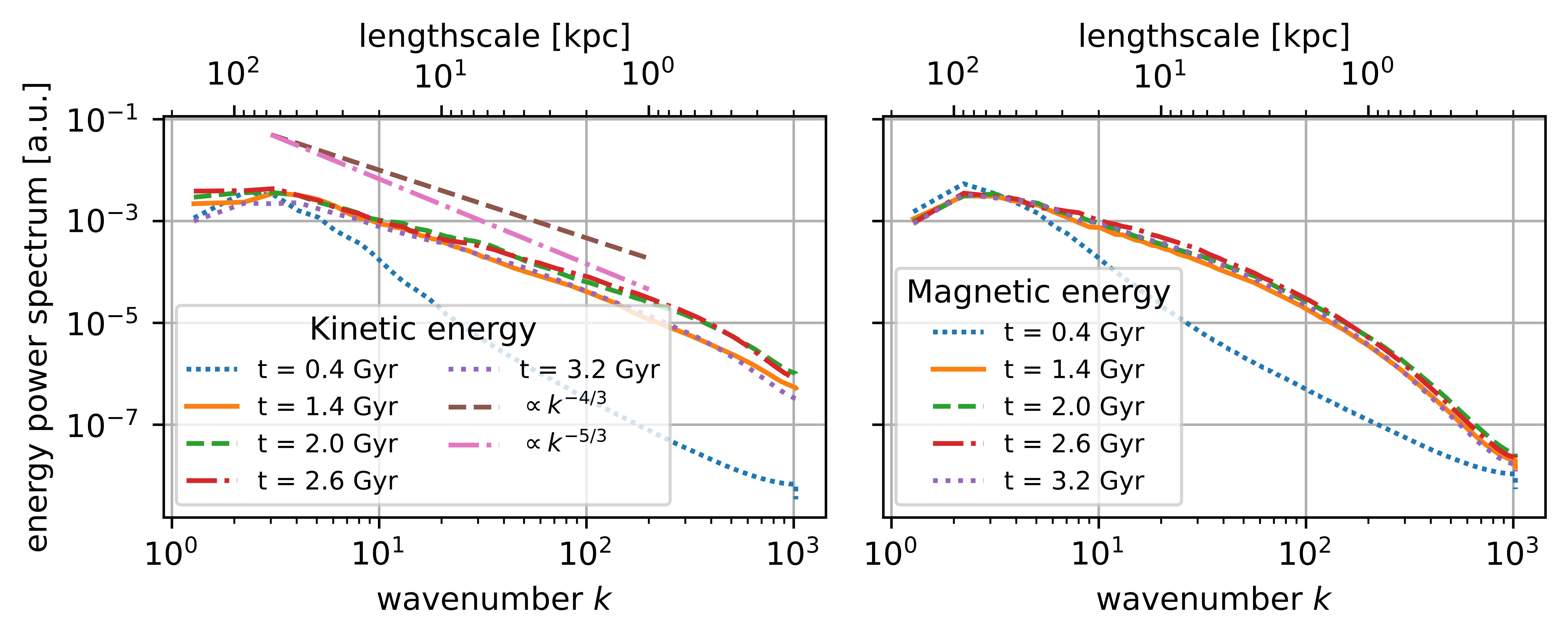
Energy transfer:

Energy cascade

Inverse transfer

Nonlocal transfer

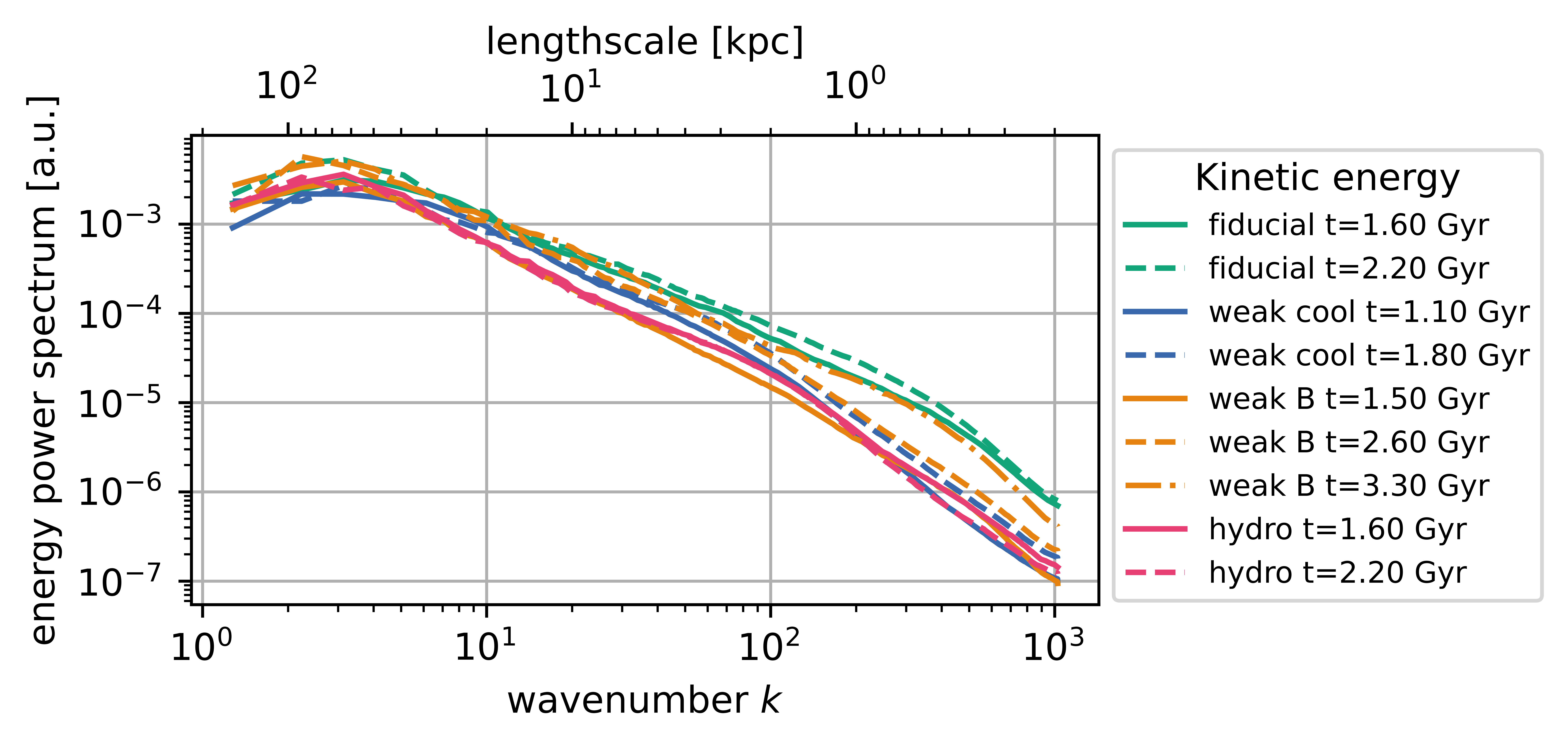
Comparison (fiducial run)



Recall 1 kpc ~ 3,300 light years

From Grete et al. 2025

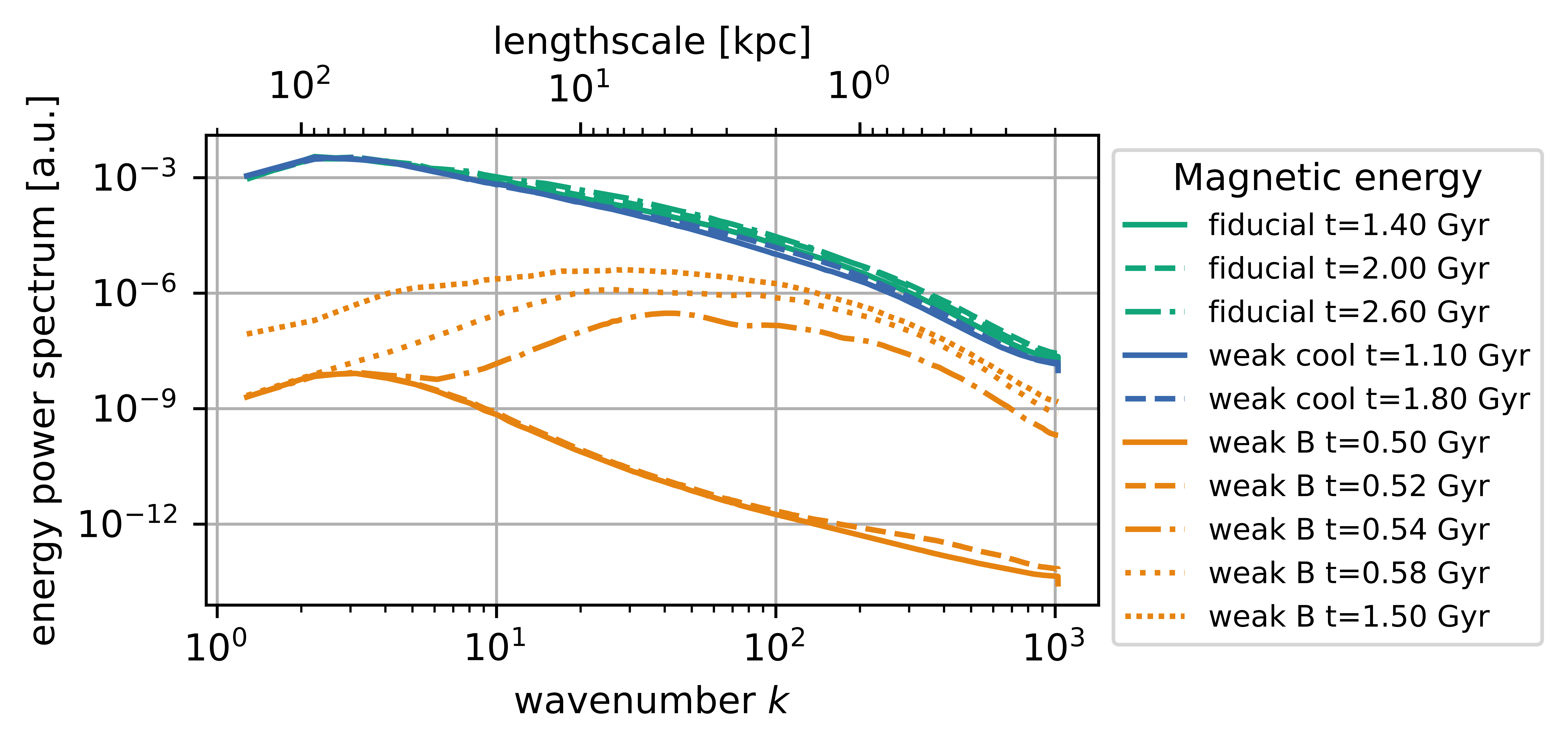
Kinetic energy spectra



Note: spectra measured within central [200 kpc]3 region

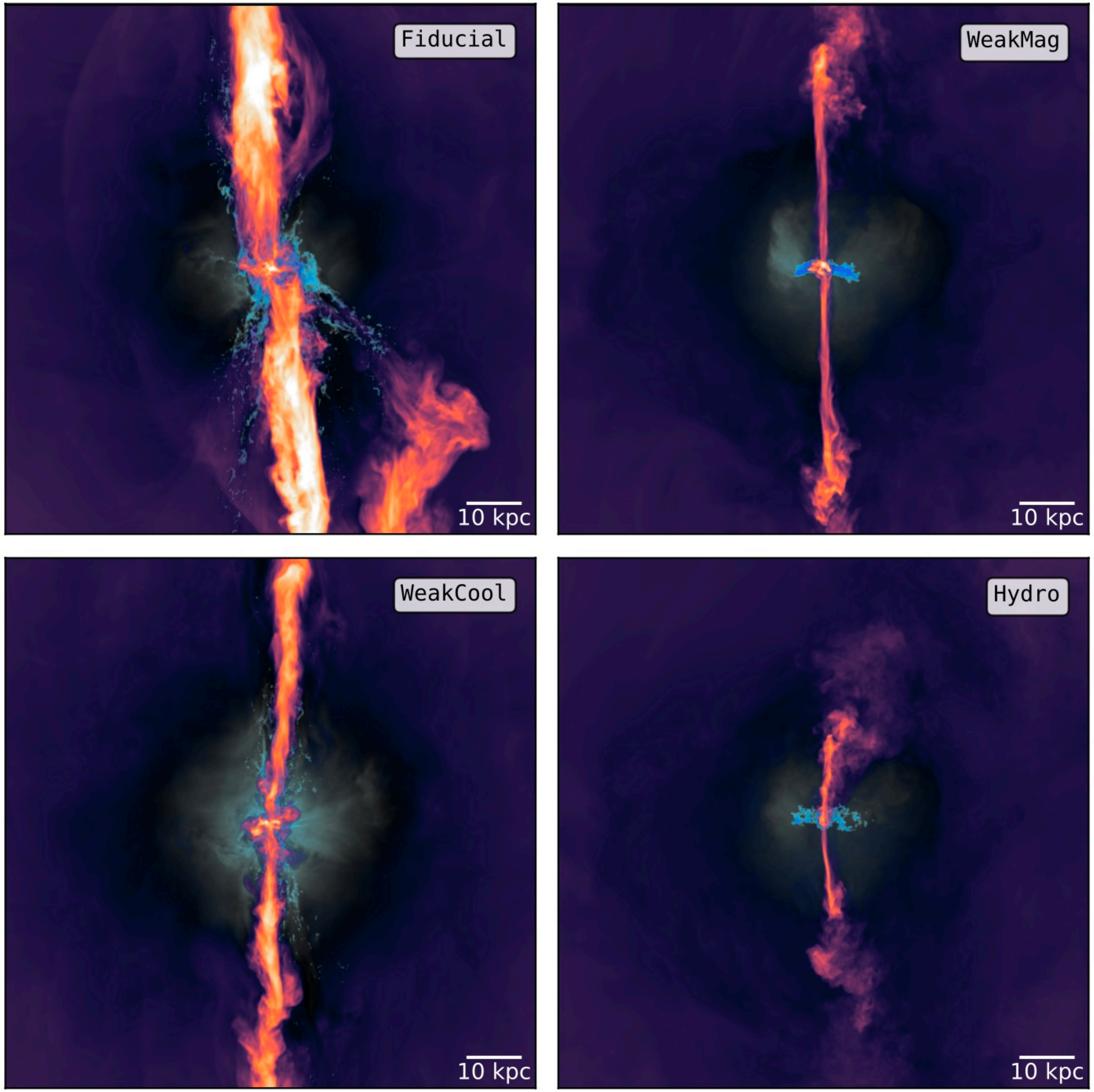
From Grete et al. 2025

Magnetic energy spectra

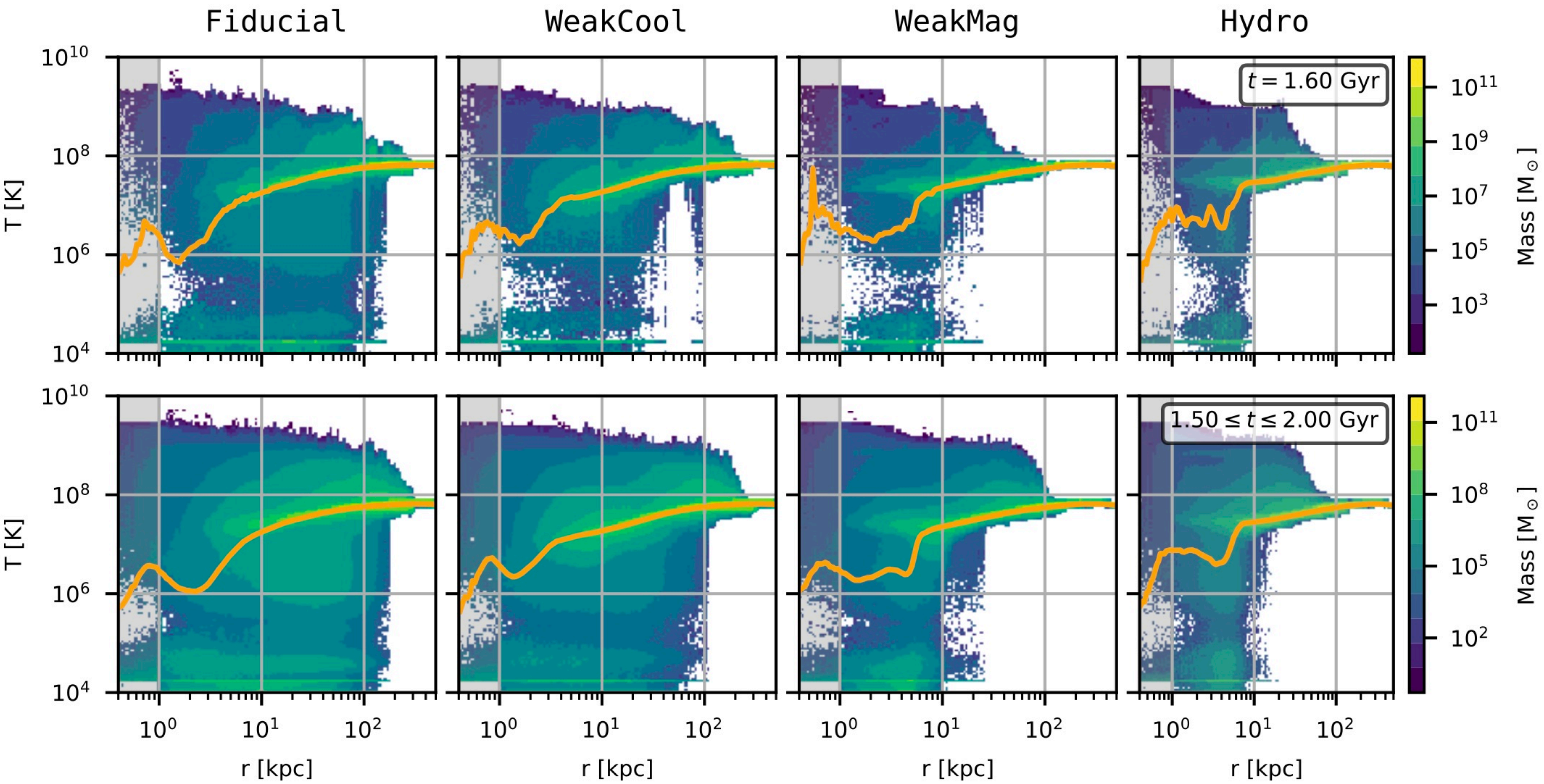


Note: spectra measured within central [200 kpc]^3 region

From Grete et al. 2025

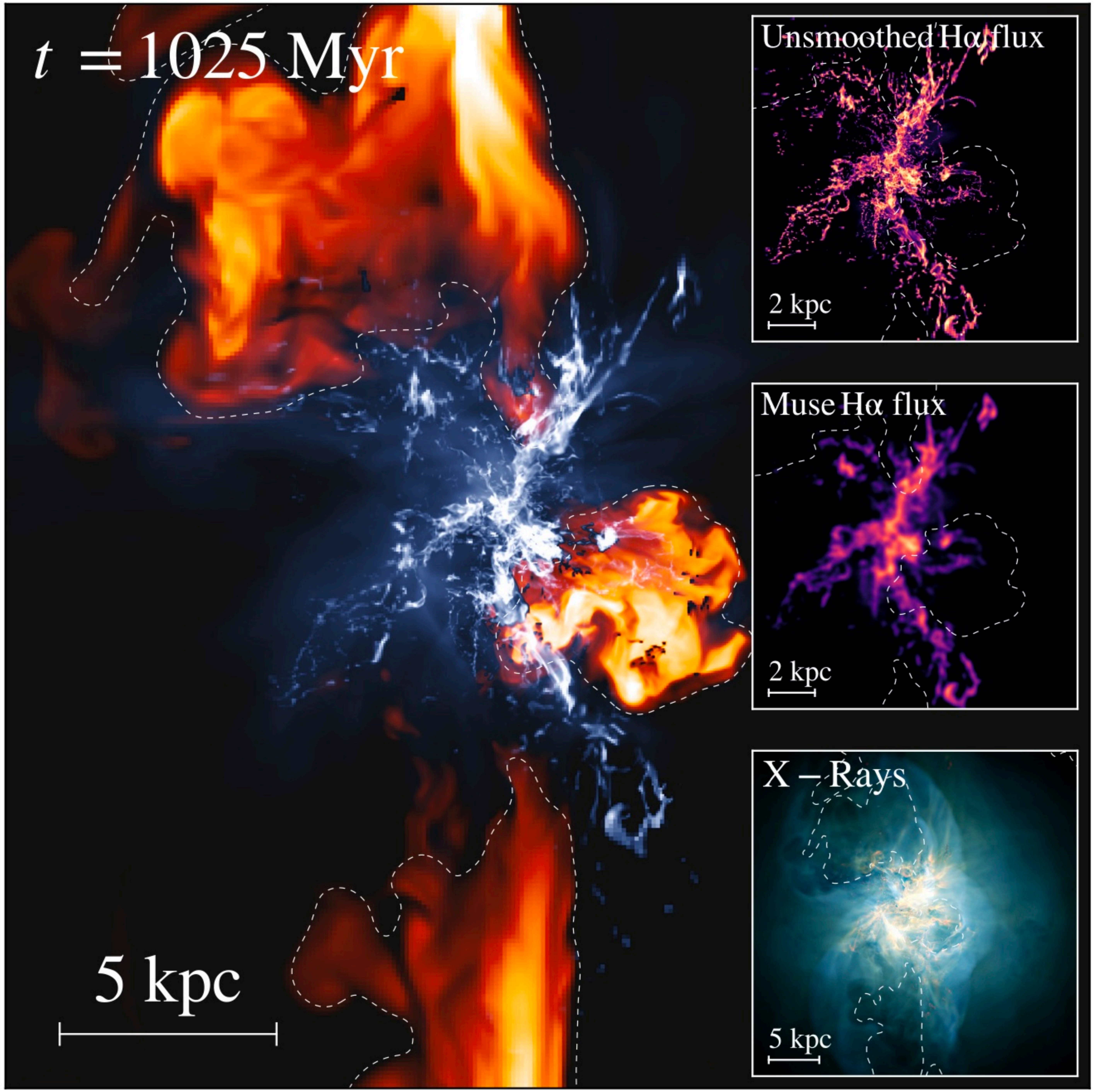


From Grete et al. 2025

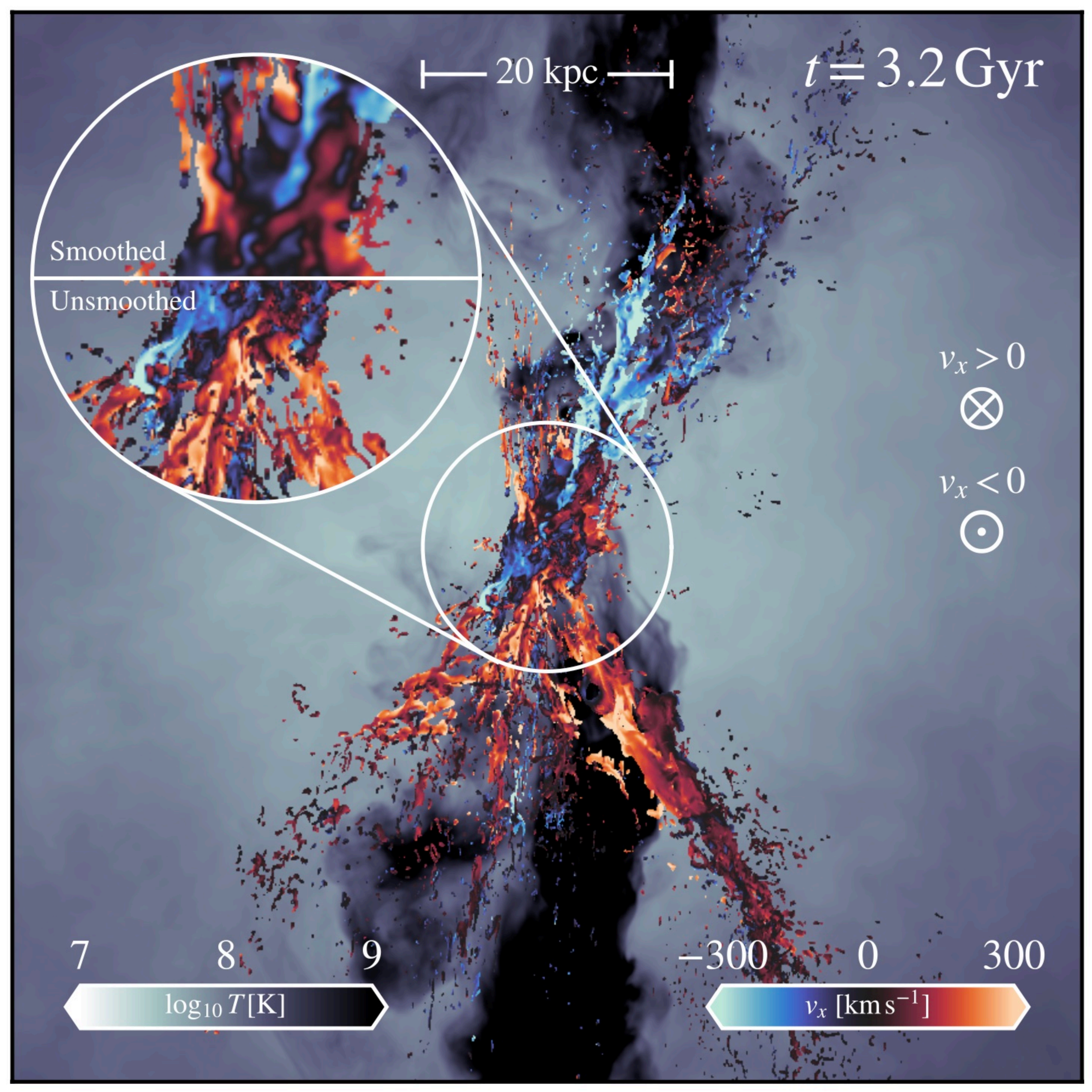


From Grete et al. 2025

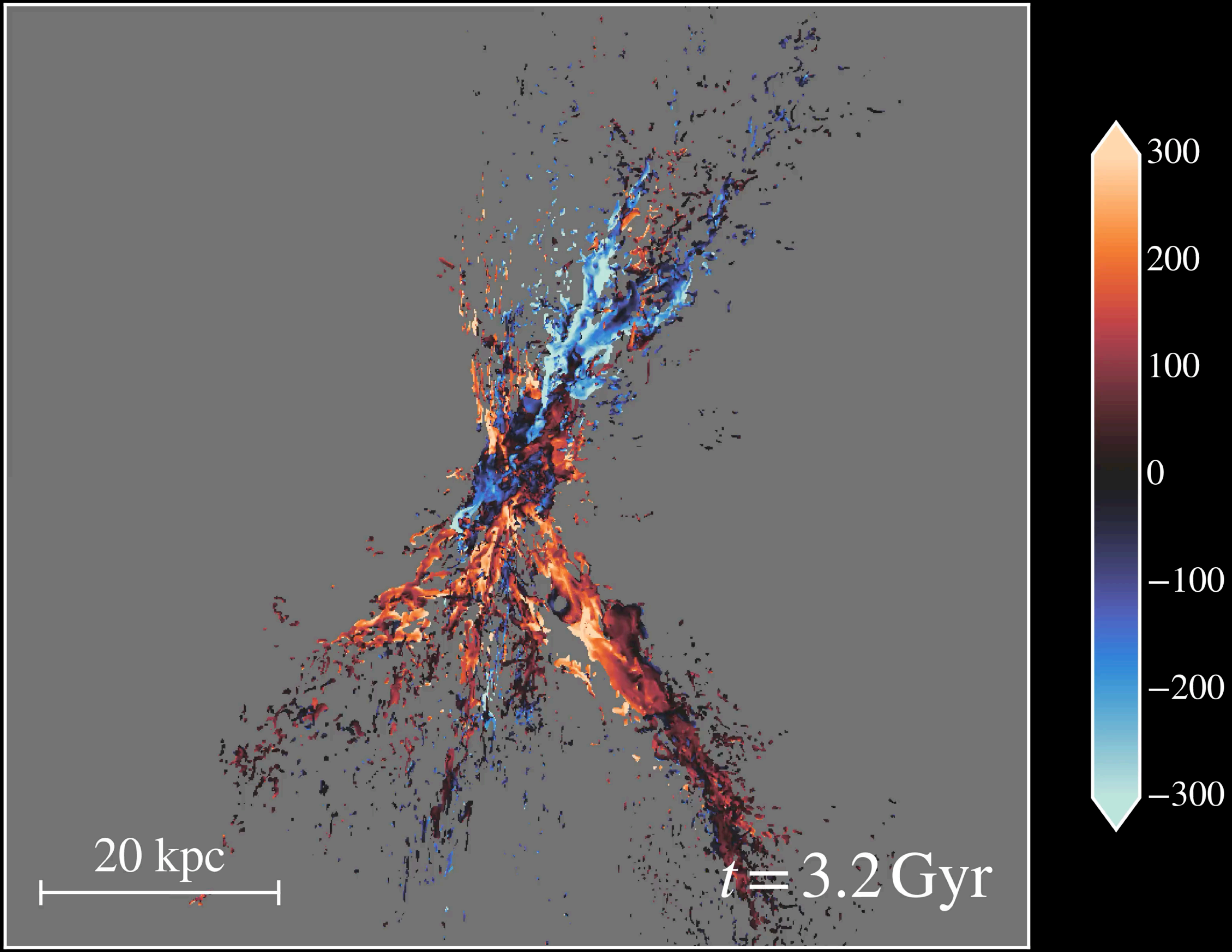
NGC 1275
Images: NASA/ESA, VLA



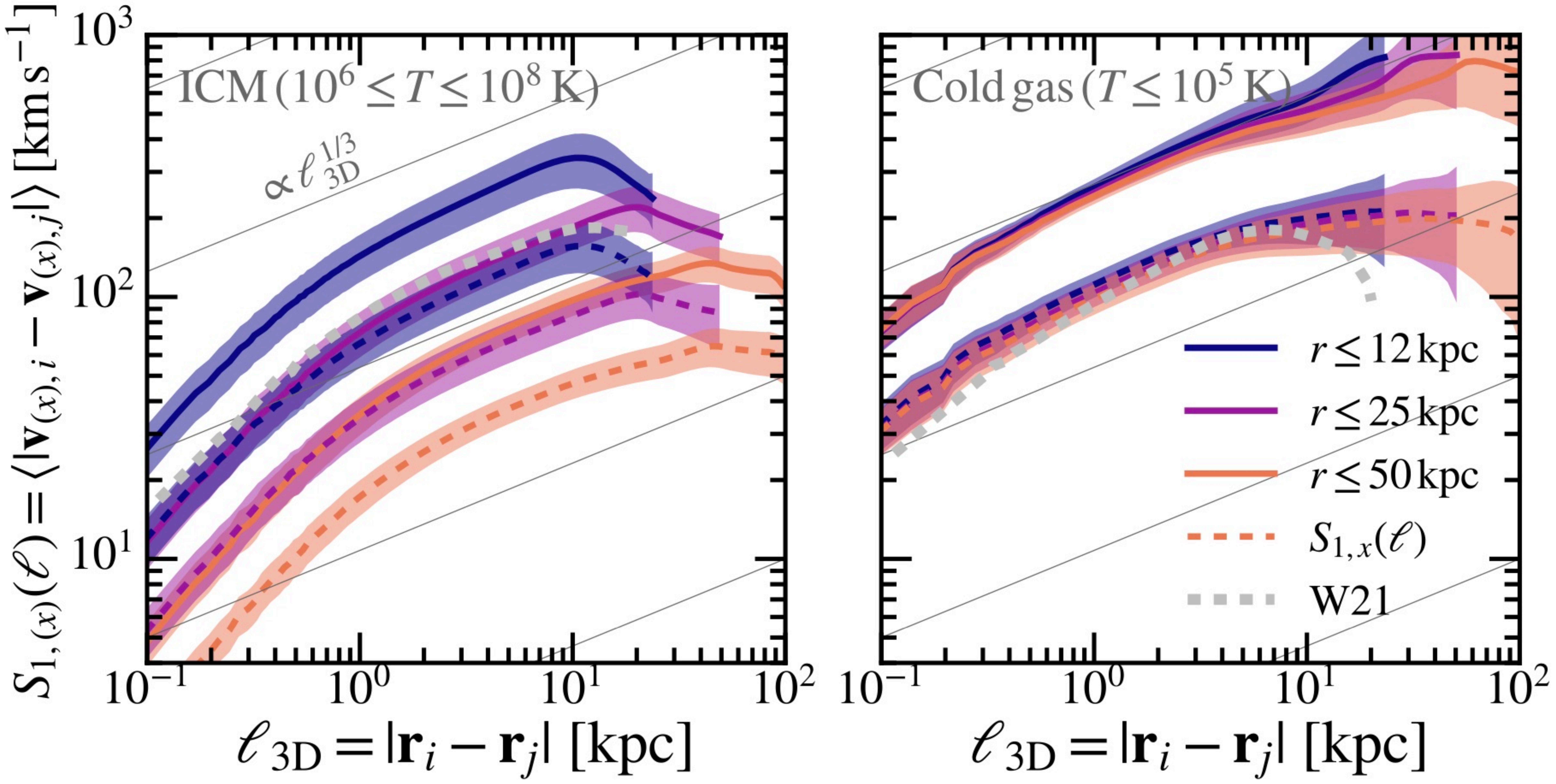
From Fournier et al. 2024



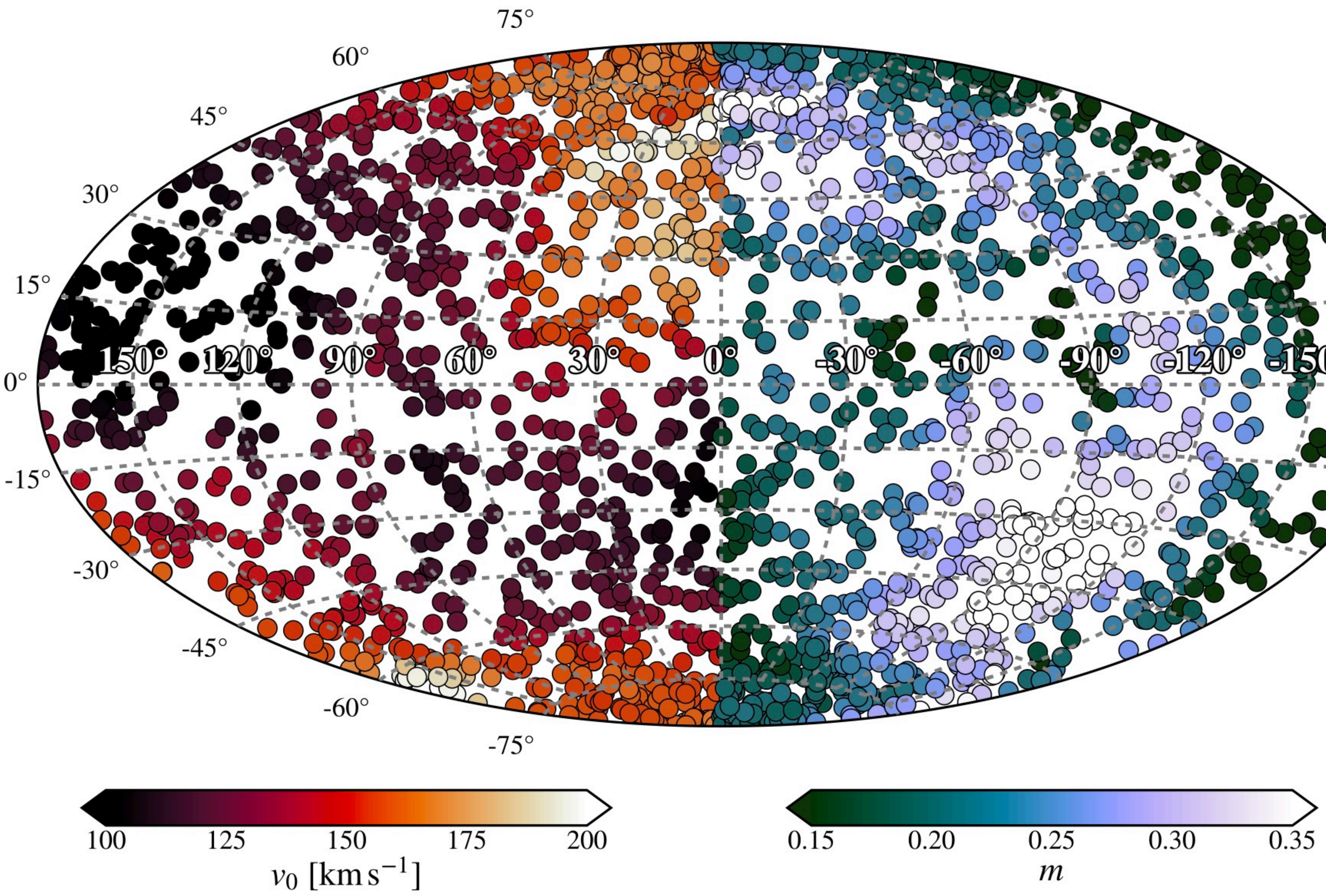
From Fournier
et al. 2025



From Fournier
et al. 2025



From Fournier et al. 2025



From Fournier et al. 2025

So, what should you take away from this talk?

- Galaxy clusters are the most massive self-gravitating structures in the universe, and are interesting laboratories for astrophysics and plasma physics!
- We can simulate them, but it’s challenging due to the dynamic range and physics required.
- We have begun to learn how:
  - Galaxy clusters regulate themselves with AGN feedback
  - Magnetized turbulence is ubiquitous in the cluster and an important energy dissipation mechanism
  - Multiphase gas forms in filaments and has complex structure

Papers, movies, images, etc. at https://xmagnet-simulations.github.io/
My email address: oshea@msu.edu