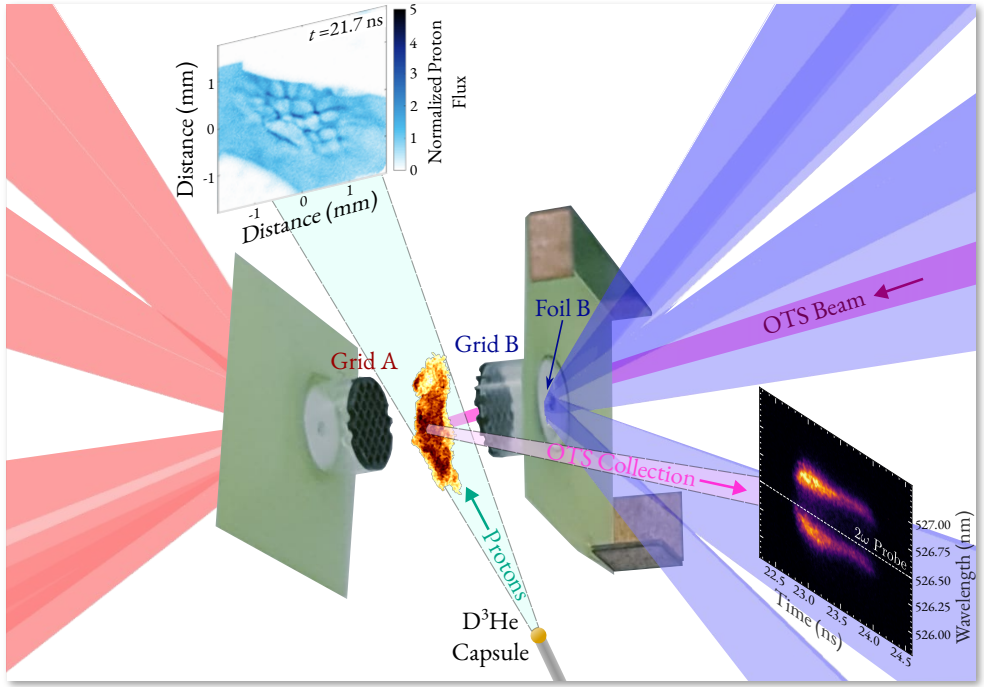
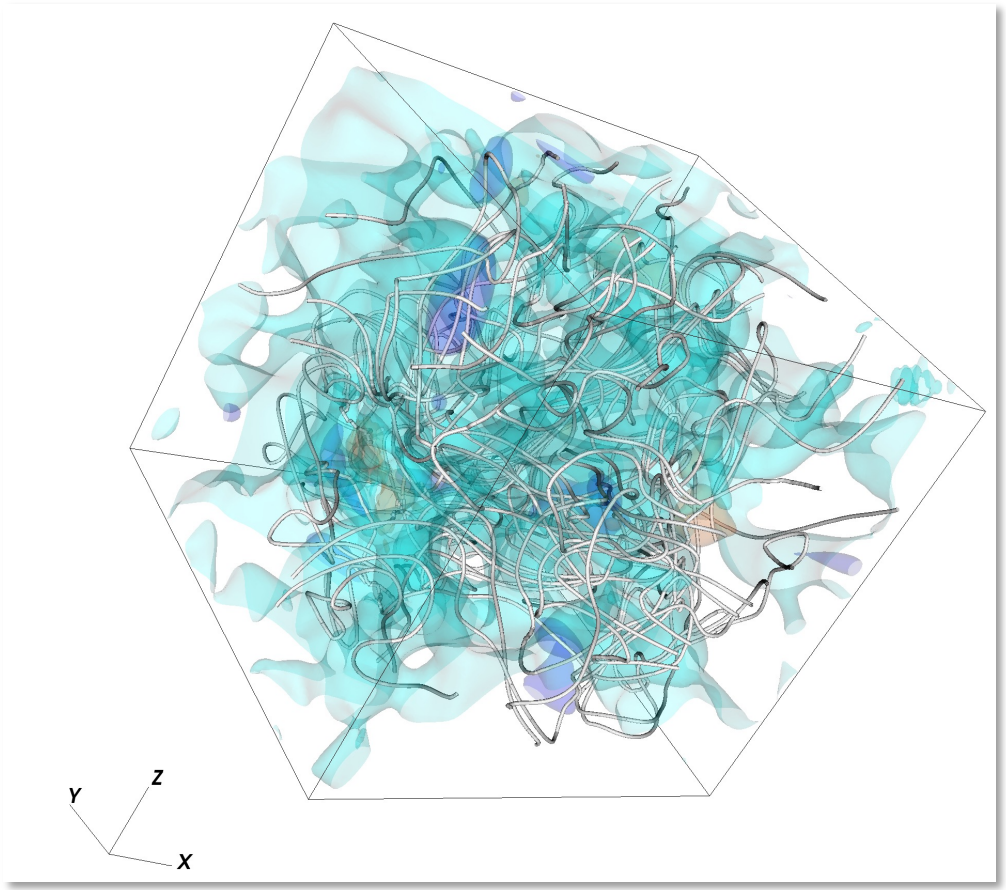
# Laboratory Experiments of Astrophysical Processes in Magnetized Turbulence




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MIPSE Seminar, September 23, 2026
University of Michigan, Ann Arbor, MI

# Acknowledgements

We acknowledge support by the U.S. DOE NNSA under Awards DE-NA0002724, DE-NA0003605, DE-NA0003934, DE-NA0004144, DE-NA0004147, and Subcontracts 630138 and C4574 with LANL; the U.S. DOE Office of Science under Award DE-SC0021990; and the NSF under Awards PHY-2033925 and PHY-2308844. We also acknowledge support from UKRI, grant number MR/W006723/1.

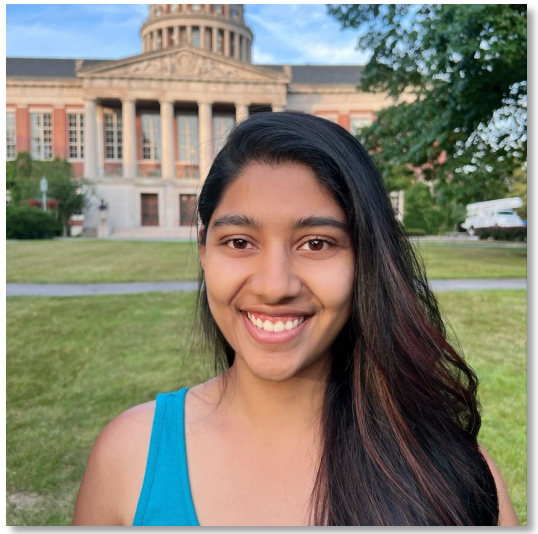
# TDYNO Team

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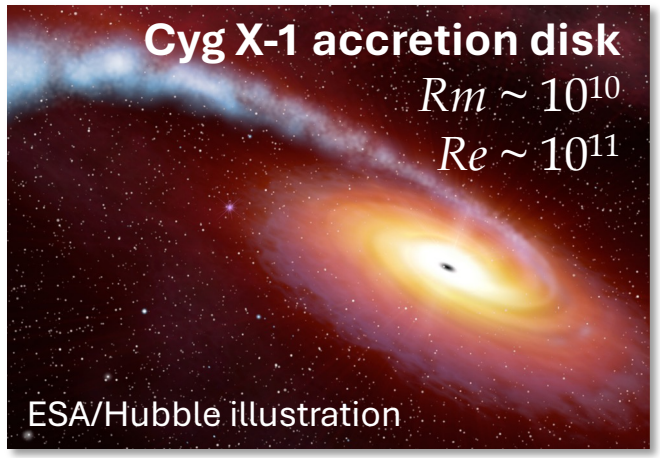
Hannah Poole,
URochester

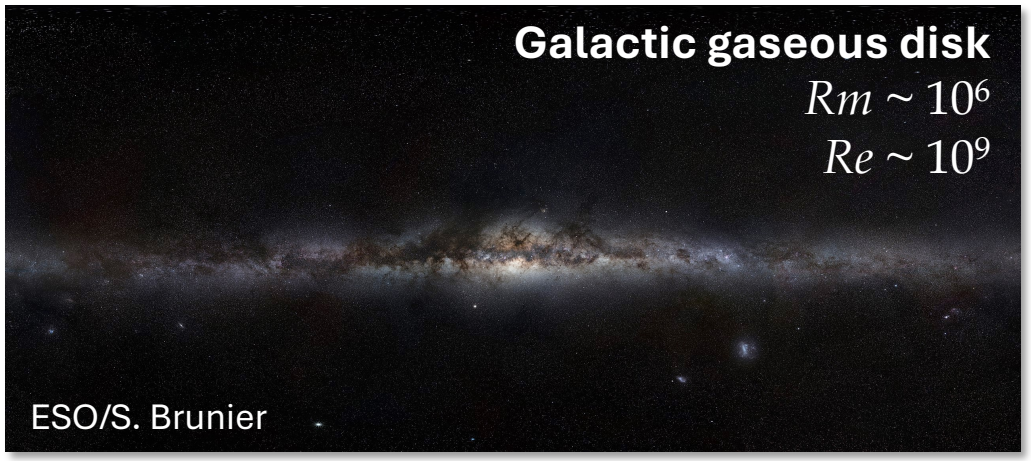
1 University of Rochester
2 University of Oxford
3 Queen's University Belfast
4 Gettysburg College
5 Lawrence Livermore National Laboratory
6 Massachusetts Institute of Technology
7 The University of Chicago

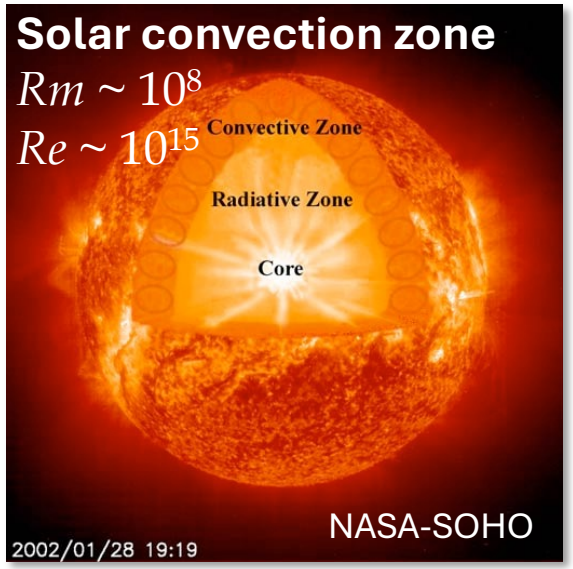


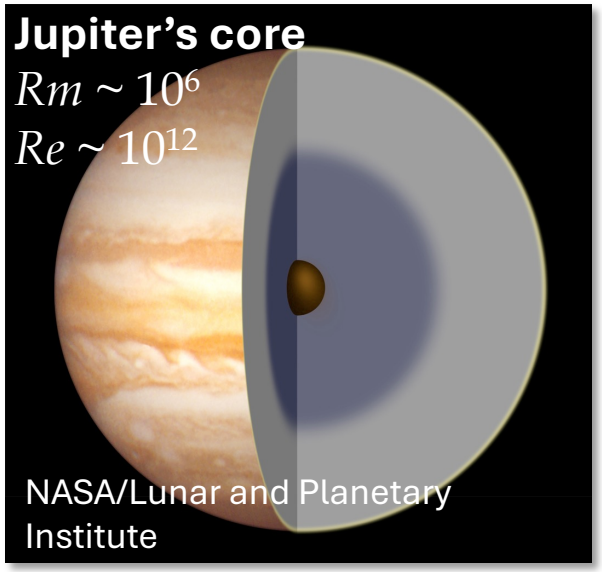
Ananya Mohapatra,
URochester

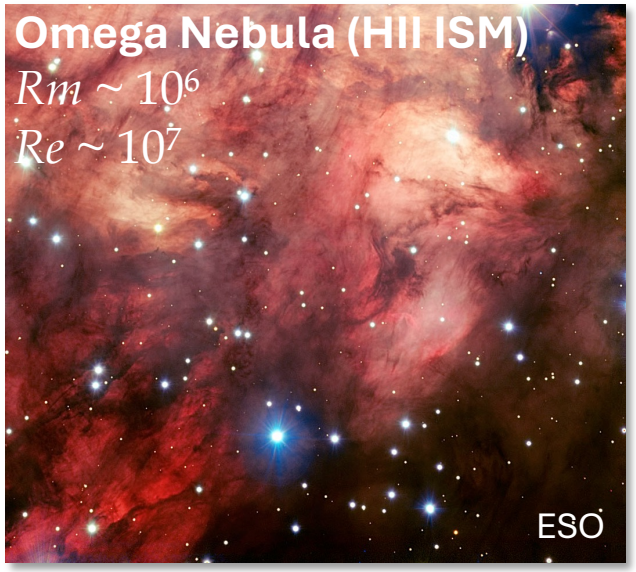
# Magnetized turbulence is ubiquitous in the Universe



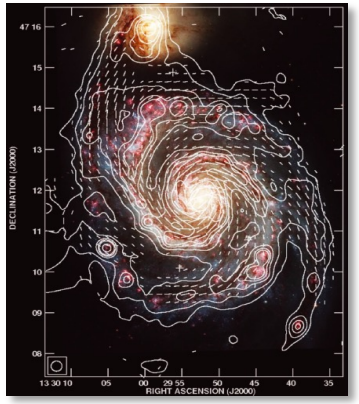

- Timescales associated with **diffusion** processes that quench fluctuations (e.g., viscosity) and decay magnetic fields (e.g., resistivity), are significantly **longer** than **advection** timescales.
- Codified in associated **Reynolds numbers**:

$$Re \equiv \frac{\tau_{\mathrm{diff},\nu}}{\tau_{\mathrm{adv}}} = \frac{\mathcal{L}u}{\nu}$$

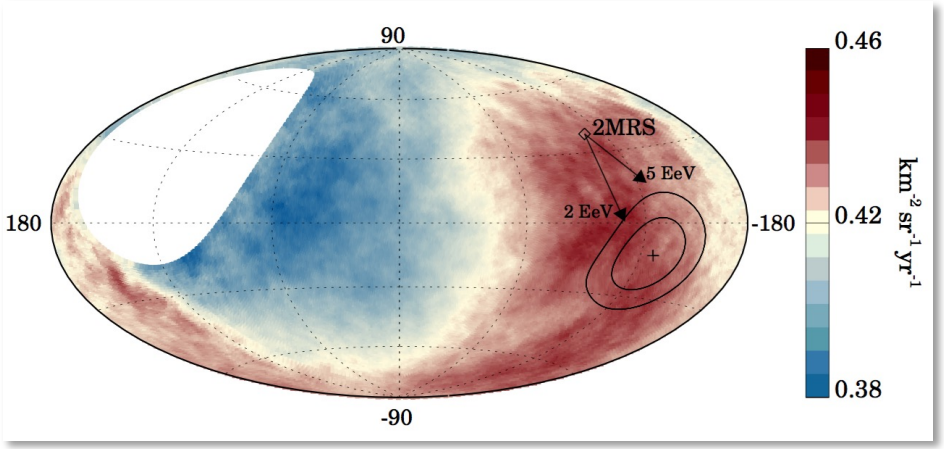
$$Rm \equiv \frac{\tau_{\mathrm{diff},\eta}}{\tau_{\mathrm{adv}}} = \frac{\mathcal{L}u}{\eta}$$

*Rm and Re estimates from Zel'dovich+ 1983

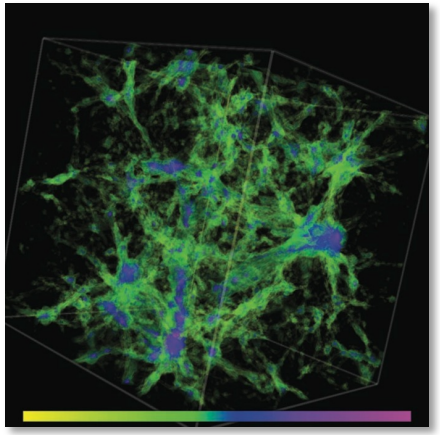
# Magnetized turbulence is a key agent in several astrophysical processes



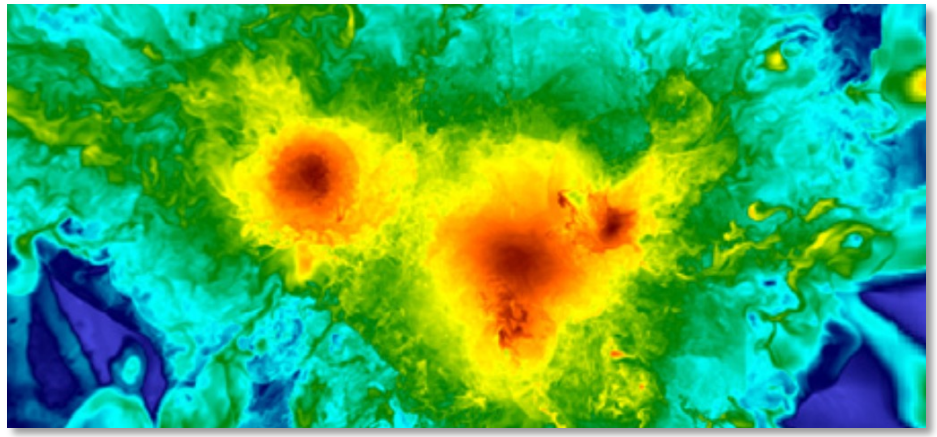

B-field vectors and optical image (Hubble) of M51




CR anisotropy (Pierre Auger Collaboration 2017



Magnetic field strength in the cosmic web (Ryu+ 2012)



Galaxy cluster merger (Miniati 2015)

- Origin of **cosmic magnetic fields** (Kulsrud+ 1997, Kulsrud & Zweibel 2008)
- **Fluctuation dynamo** (Rincon 2019, Schekochihin 2021)
- Diffusive transport and acceleration of **cosmic rays** (Jokipii 1966, Zweibel 2013)
- **Anomalous transport** in galaxy clusters – cooling flows problem (Fabian 1994, Markevitch+ 2003, Peterson & Fabian 2006, Kunz+ 2011)
- **Star formation** rate (Krumholz & McKee 2005), efficiency (Federrath & Klessen 2013), and stellar mass distribution (Padoan & Nordlund 2002)

# TDYNO Collaboration – Experimental studies of magnetized turbulence and the processes it mediates



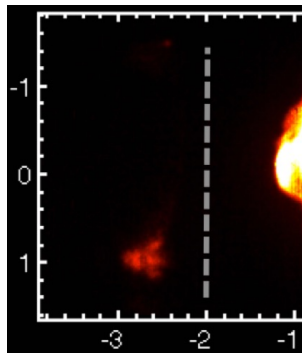


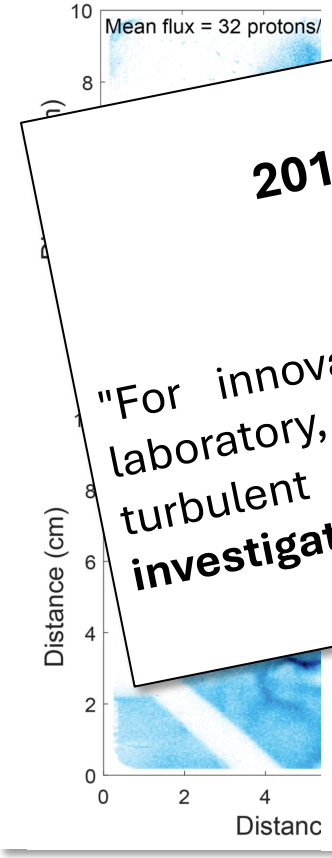
University of Rochester

UNIVERSITY OF OXFORD

- Magnetized turbulence, fluctuation dynamo, cosmic ray transport and acceleration

# The first experimental demonstration of fluctuation dynamo was achiev






## Lab experiments mimic the origin and growth of astrophysical magnetic fields

A turbulent, laser-generated plasma can amplify magnetic fields to cosmic scales.

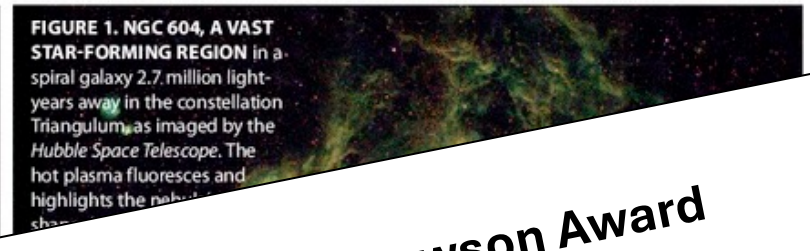


**FIGURE 1. NGC 604, A VAST STAR-FORMING REGION** in a spiral galaxy 2.7 million light-years away in the constellation Triangulum, as imaged by the *Hubble Space Telescope*. The hot plasma fluoresces and highlights the nebu

Magnetic fields permeate the space between objects throughout the universe, from galaxy clusters to galaxies to nebulae

magnetic field grows below the length scales of fluid motion. There, turbulence operates first at the smallest length scales, where it rapidly amplifies the fields. The mechanism works even in isotropic conditions.

Now Gianluca Gregori (Oxford Uni-

dynamo could be a viable mechanism for magnetic field amplification in the lab and in astrophysical settings.

### Galaxies far, far away

To sustain a dynamo, a fluid needs to be electrically conductive, and its motion cannot be too symmetric. Dynamo conditions also require that the magnetic

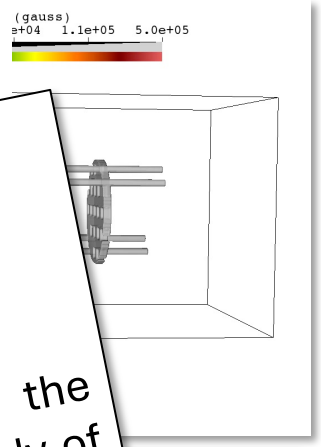
by the turbulent, high-temperature, high-velocity plasma that fills intergalactic space.

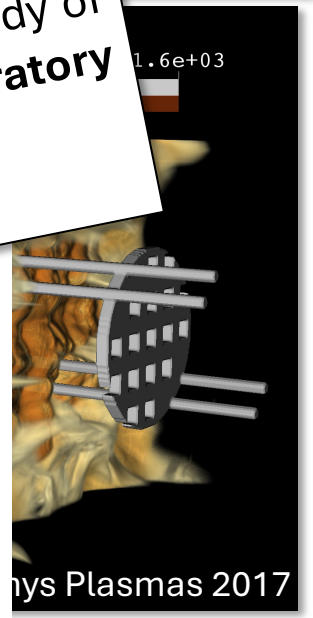
Even though conditions favorable for dynamos are common in astrophysical settings, the strong turbulence is extremely difficult to replicate in the lab. (See the article by Daniel Lathrop and Cary Forest, PHYSICS TODAY, July 2011, page 40.) Astronomical x-ray observations provide information about the temperature, density, and composition of hot plasmas in the universe. But observations cannot convey the geometry and



**2019 American Physical Society John Dawson Award for Excellence in Plasma Physics Research**

"For innovative experiments that demonstrate turbulent dynamo in the laboratory, establishing laboratory experiments as a component in the study of turbulent magnetized plasmas, and **opening a new path to laboratory investigations of other astrophysical processes**."



# The dynamo breakthrough spring boarded a concerted effort by TDYNO to study astrophysical processes mediated by turbulence

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-02953-2 OPEN

## Laboratory evidence of dynamo amplification of magnetic fields in a turbulent plasma

P. Tzeferacos[1,2], A. Rigby[1], A. F. A. Bott[1], A.R. Bell[1], R. Bingham[3,4], A. Casner[5], F. Cattaneo[2], E.M. Churazov[6,7], J. Emig[8], F. Fiuza[9], C.B. Forest[10], J. Foster[11], C. Graziani[2], J. Katz[12], M. Koenig[13], C.-K. Li[14], J. Meinecke[1], R. Petrasso[14], H.-S. Park[8], B.A. Remington[8], J.S. Ross[8], D. Ryu[15], D. Ryutov[8], T.G. White[1], B. Reville[16], F. Miniati[17], A.A. Schekochihin[1], D.Q. Lamb[2], D.H. Froula[12] & G. Gregori[1,2]

nature physics

LETTERS

https://doi.org/10.1038/s41567-018-0059-2

## Electron acceleration by wave turbulence in a magnetized plasma

A. Rigby[1*], F. Cruz[2], B. Albertazzi[3], R. Bamford[4], A. R. Bell[1], Y. Hara[7], P. M. Kozlowski[1], Y. Kuramitsu[8,9], D. Q. Lamb[10], S. Leb[...], T. Morita[7], M. Oliver[1], B. Reville[13], Y. Sakawa[7], S. Sarkar[1,14], L. O. Silva[2], R. Bingham[4,15], M. Koenig[3] and G. Gregori[1,10]

**Astrophysical shocks are commonly revealed by the non-thermal emission of energetic electrons accelerated in situ[1–3]. Strong shocks are expected to accelerate particles to very high energies[4–6]; however, they require a source of particles with velocities fast enough to permit multiple shock crossings. While the resulting diffusive shock acceleration[4] process can account for observations, the kinetic physics regulating the continuous injection of non-thermal particles is not well understood. Indeed, this injection problem is particularly acute for electrons, which rely on high-frequency plasma fluctuations to raise them above the thermal pool[7,8]. Here we show, using laboratory laser-produced shock experiments, that, in the presence of a strong magnetic field, significant electron pre-heating is achieved. We demonstrate that the key mechanism in producing these energetic electrons is through the generation of lower-hybrid turbulence via shock-reflected ions. Our experimental results are analogous to many astrophysical systems, including the interaction of a comet with the solar wind[9], a setting where electron acceleration via lower-hybrid waves is possible.**

Check for updates

## Time-resolved turbulent dynamo in a laser plasma

Archie F. A. Bott[a,b,1], Petros Tzeferacos[a,c,d,e], Laura Chen[a], Charlotte A. J. Palmer[a,f], Alexandra Rigby[a], Anthony R. Bell[a], Robert Bingham[g,h], Andrew Birkel[i], Carlo Graziani[j], Dustin H. Froula[d,e], Joseph Katz[e], Michel Koenig[k,l], Matthew W. Kunz[b], Chikang Li[i], Jena Meinecke[a], Francesco Miniati[a], Richard Petrasso[i], Hye-Sook Park[m], Bruce A. Remington[m], Brian Reville[n], J. Steven Ross[m], Dongsu Ryu[o], Dmitri Ryutov[m], Fredrick H. Séguin[i], Thomas G. White[p], Alexander A. Schekochihin[a], Donald Q. Lamb[c], and Gianluca Gregori[a,c]

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Edited by Neta A. Bahcall, Princeton University, Princeton, NJ, and approved January 14, 2021 (received for review July 27, 2020)

**Understanding magnetic-field generation and amplification in turbulent plasma is essential to account for observations of magnetic fields in the universe. A theoretical framework attributing the origin and sustainment of these fields to the so-called fluctuation dynamo was recently validated by experiments on laser facilities in low-magnetic-Prandtl-number plasmas (Pm $<1$). However, the same framework proposes that the fluctuation dynamo should operate differently when Pm $\gtrsim 1$, the regime relevant to many astrophysical environments such as the intracluster medium [...] galaxy clusters. This paper reports an experiment that create[s] laboratory Pm $\gtrsim 1$ plasma dynamo. We provide a time-resol[ved] characterization of the plasma's evolution, measuring temp[...] tures, densities, flow velocities, and magnetic fields, which all[...]**

MHD, the fluctuation dynamo can operate only if the magnetic Reynolds number $\mathrm{Rm} \equiv u_L L/\eta$—where $L$ is the length scale of driving stochastic motions, $u_\ell$ the characteristic velocity of motions at a given scale $\ell$, and $\eta$ the resistivity of the plasma—is above some critical threshold, $\mathrm{Rm}_c$ (26). The precise value of this threshold depends on the magnetic Prandtl number $\mathrm{Pm}$ of the plasma (21, 27, 28), defined by $\mathrm{Pm} \equiv \mathrm{Rm}/\mathrm{Re} = \nu/\eta$ (where $\mathrm{Re} \equiv u_L L/\nu$ is the fluid Reynolds number and $\nu$ is the kinematic

## Inefficient Magnetic-Field Amplification in Supersonic Laser-Plasma Turbulence

A. F. A. Bott[1,2,*], L. Chen,[1] G. Boutoux,[3] T. Caillaud,[3] A. Duval,[3] M. Koenig,[4,5] B. Khiar,[6] I. Lantuéjoul,[3] L. Le-Deroff[7], B. Reville[8], R. Rosch,[3] D. Ryu[9], C. Spindloe,[10] B. Vauzour,[3] B. Villette,[3] A. A. Schekochihin[1,11], D. Q. Lamb,[6] P. Tzeferacos,[1,6,12,13] G. Gregori,[1] and A. Casner[3,14]

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(Received 20 August 2020; revised 7 June 2021; accepted 17 September 2021; published 21 October 2021)

We report a laser-plasma experiment that was carried out at the LMJ-PETAL facility and realized the first magnetized, turbulent, supersonic ($\mathrm{Ma}_{\mathrm{turb}} \approx 2.5$) plasma with a large magnetic Reynolds number ($\mathrm{Rm} \approx 45$) in the laboratory. Initial seed magnetic fields were amplified, but only moderately so, and did [...] dynamically significant. A notable absence of magnetic energy at scales smaller than the outer [...]urbulent cascade was also observed. Our results support the notion that moderately supersonic, [...]ic-Prandtl-number plasma turbulence is inefficient at amplifying magnetic fields compared to [...] incompressible counterpart.

[...]/PhysRevLett.127.175002

The Astrophysical Journal, 892:114 (18pp), 2020 April 1 https://doi.org/10.3847/1538-4357/ab7a19
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## Transport of High-energy Charged Particles through Spatially Intermittent Turbulent Magnetic Fields

L. E. Chen[1], A. F. A. Bott[1], P. Tzeferacos[1,2], A. Rigby[1], A. Bell[1], R. Bingham[3,4], C. Graziani[5], J. Katz[6], M. Koenig[7,8], C. K. Li[9], R. Petrasso[9], H.-S. Park[10], J. S. Ross[10], D. Ryu[11], T. G. White[1,12], B. Reville[13], J. Matthews[1], J. Meinecke[1], F. Miniati[1], E. G. Zweibel[14], S. Sarkar[1], A. A. Schekochihin[1], D. Q. Lamb[2], D. H. Froula[6], and G. Gregori[1,2]

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*Received 2020 January 5; revised 2020 February 24; accepted 2020 February 24; published 2020 April 3*

**Abstract**

Identifying the sources of the highest energy cosmic rays requires understanding how they are deflected by the stochastic, spatially intermittent intergalactic magnetic field. Here we report measurements of energetic charged-particle propagation through a laser-produced magnetized plasma with these properties. We characterize the diffusive transport of the particles experimentally. The results show that the transport is diffusive and that, for the regime of interest for the highest energy cosmic rays, the diffusion coefficient is unaffected by the spatial intermittency of the magnetic field.

*Unified Astronomy Thesaurus concepts:* High energy astrophysics (739); Ultra-high-energy cosmic radiation (1733); Magnetic fields (994); Laboratory astrophysics (2004); Plasma astrophysics (1261); Intergalactic medium (813); Particle astrophysics (96)

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-019-09498-y OPEN

## Supersonic plasma turbulence in the laboratory

T.G. White[1,2], M.T. Oliver[1,2], P. Mabey[1,3], M. Kühn-Kauffeldt[4], A.F.A. Bott[1], L.N.K. Döhl[5], A.R. Bell[1], R. Bingham[6,7], R. Clarke[6], J. Foster[8], G. Giacinti[9], P. Graham[8], R. Heathcote[6], M. Koenig[3,10], Y. Kuramits[...], D.Q. Lamb[11], J. Meinecke[1], Th. Michel[3], F. Miniati[1], M. Notley[6], B. Reville[12], D. Ryu[13], S. Sarkar[1], Y. Sak[...], M.P. Selwood[6], J. Squire[15,16], R.H.H. Scott[6], P. Tzeferacos[11], N. Woolsey[5], A.A. Schekochihin[1] & G. Gregori[1]

The properties of supersonic, compressible plasma turbulence determine the behavior of many terrestrial and astrophysical systems. In the interstellar medium and molecular clouds, compressible turbulence plays a vital role in star formation and the evolution of our galaxy. Observations of the density and velocity power spectra in the Orion B and Perseus molecular clouds show large deviations from those predicted for incompressible turbulence. Hydrodynamic simulations attribute this to the high Mach number in the interstellar medium (ISM), although the exact details of this dependence are not well understood. Here we investigate experimentally the statistical behavior of boundary-free supersonic turbulence created by the collision of two laser-driven high-velocity turbulent plasma jets. The Mach number dependence of the slopes of the density and velocity power spectra agree with astrophysical observations, and supports the notion that the turbulence transitions from being Kolmogorov-like at low Mach number to being more Burgers-like at higher Mach numbers.

SCIENCE ADVANCES | RESEARCH ARTICLE

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## Strong suppression of heat conduction in a laboratory replica of galaxy-cluster turbulent plasmas

**Jena Meinecke[1], Petros Tzeferacos[1,2,3,4], James S. Ross[5], Archie F. A. Bott[1,6], Scott Feister[2,7], Hye-Sook Park[5], Anthony R. Bell[1,8], Roger Blandford[9], Richard L. Berger[5], Robert Bingham[8,10], Alexis Casner[11], Laura E. Chen[1], John Foster[12], Dustin H. Froula[4], Clement Goyon[5], Daniel Kalantar[5], Michel Koenig[13], Brandon Lahmann[14], Chikang Li[14], Yingchao Lu[3], Charlotte A. J. Palmer[1,15], Richard D. Petrasso[14], Hannah Poole[1], Bruce Remington[5], Brian Reville[16], Adam Reyes[3], Alexandra Rigby[1], Dongsu Ryu[17], George Swadling[5], Alex Zylstra[5,18], Francesco Miniati[1], Subir Sarkar[1], Alexander A. Schekochihin[1,19,20], Donald Q. Lamb[2], Gianluca Gregori[1,2]***

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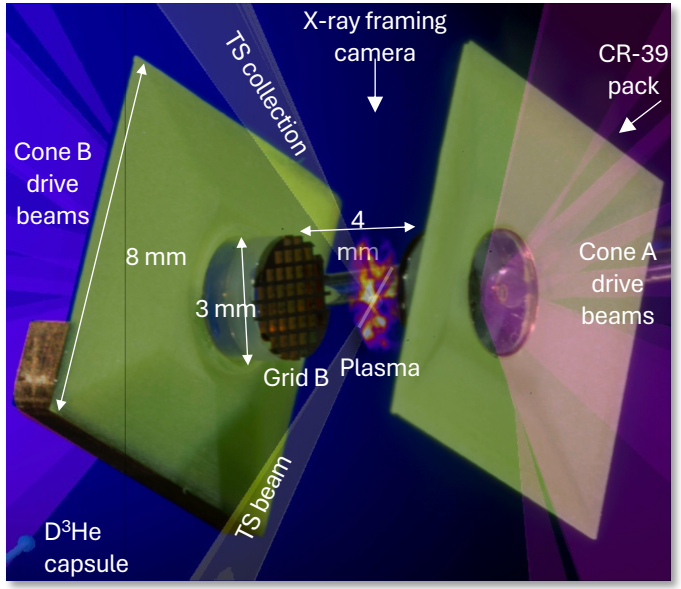
**In conventional gases and plasmas, it is known that heat fluxes are proportional to temperature gradients, with collisions between particles mediating energy flow from hotter to colder regions and the coefficient of thermal conduction given by Spitzer's theory. However, this theory breaks down in magnetized, turbulent, weakly collisional plasmas, although modifications are difficult to predict from first principles due to the complex, multiscale nature of the problem. Understanding heat transport is important in astrophysical plasmas such as those in galaxy clusters, where observed temperature profiles are explicable only in the presence of a strong suppression of heat conduction compared to Spitzer's theory. To address this problem, we have created a replica of such a system in a laser laboratory experiment. Our data show a reduction of heat transport by two orders of magnitude or more, leading to large temperature variations on small spatial scales (as is seen in cluster plasmas).**

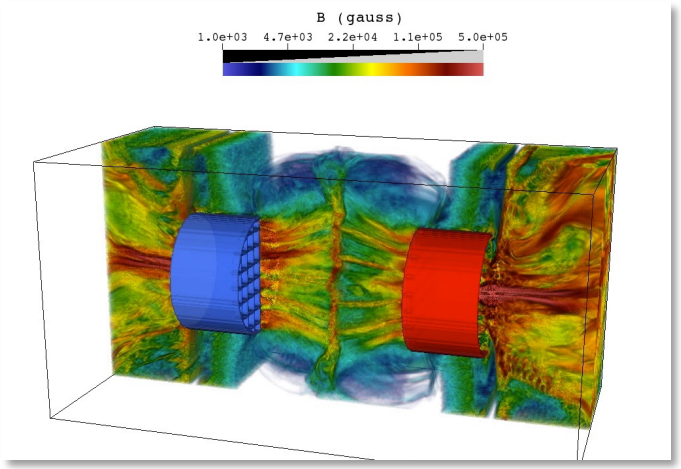
**INTRODUCTION**

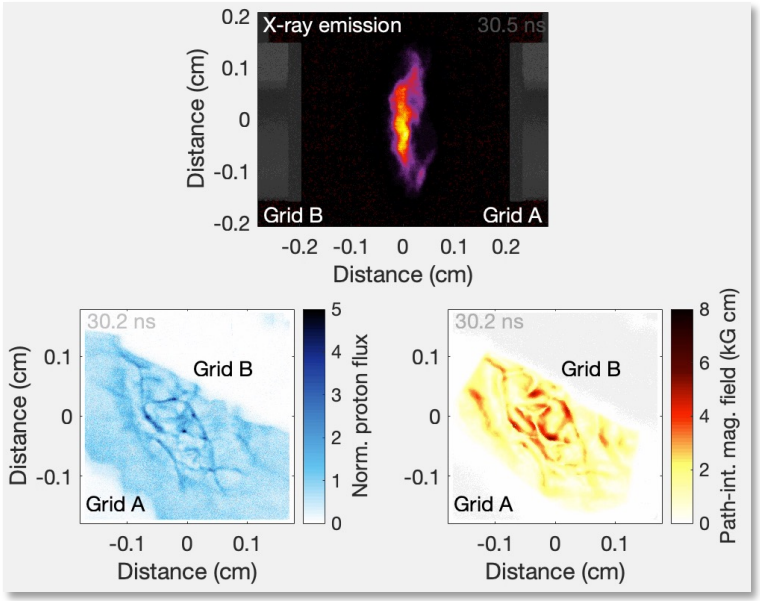
Galaxy clusters are filled with hot, diffuse x-ray emitting plasma, with a stochastically tangled magnetic field whose energy is close to equipartition with the energy of the turbulent motions (*1*, *2*). In the cluster cores, the temperatures remain anomalously high compared to what might be expected considering that the radiative cooling time is short relative to the Hubble time (*3*, *4*). While feedback from the central active galactic nuclei (AGN) (*5*–*7*) is believed to provide most of the [...] stuck in local magnetic mirrors (*12*), alignment of local temperature gradients perpendicular to magnetic fields (*13*), and plasma instabilities such as whistler waves (*14*, *15*). For these processes to occur, the electron's Larmor radius must be small compared to its Coulomb mean free path, enabling microscale changes in the electron heat transport to alter the global properties of the plasma dynamics. Numerical simulations are unable to address these issues fully (*16*, *17*), as comprehensive modeling of all the physical processes present at different scales [...]

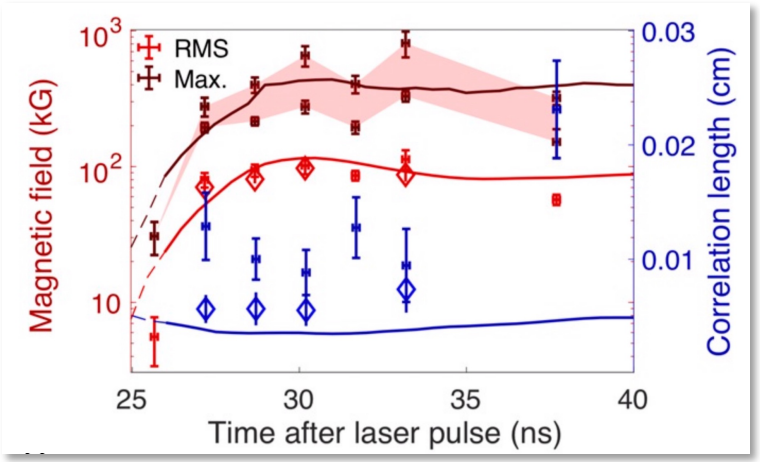
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# FLASH simulations and TDYNO Omega experiments furnish the first temporal characterization of fluctuation dynamo




RESEARCH ARTICLE | ASTRONOMY

**Time-resolved turbulent dynamo in a laser plasma**

Archie F. A. Bott, Petros Tzeferacos, Laura Chen, +24, and Gianluca Gregori. Authors Info & Affiliations

Edited by Neta A. Bahcall, Princeton University, Princeton, NJ, and approved January 14, 2021 (received for review July 27, 2020)

March 8, 2021 | 118 (11) e2015729118 | https://doi.org/10.1073/pnas.2015729118

NEWS RELEASE 11-MAR-2021

**Laser-driven experiments provide insights into the formation of the universe**

Laser-driven experiments conducted on the OMEGA laser at the University of Rochester capture for the first time in a laboratory setting the time history of the growth of magnetic fields by the "turbulent dynamo."

Peer-Reviewed Publication
UNIVERSITY OF ROCHESTER

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More on this News Release

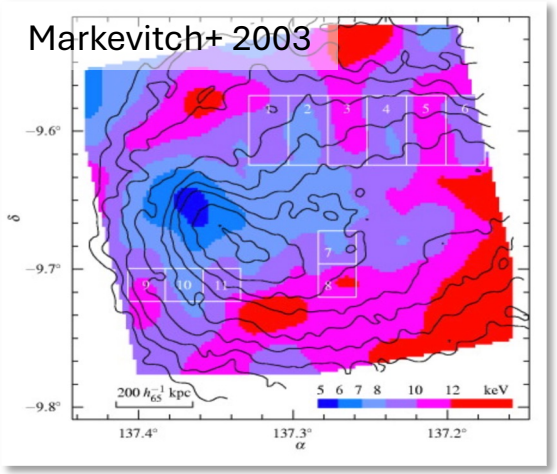
Laser-driven experiments provide insights into the

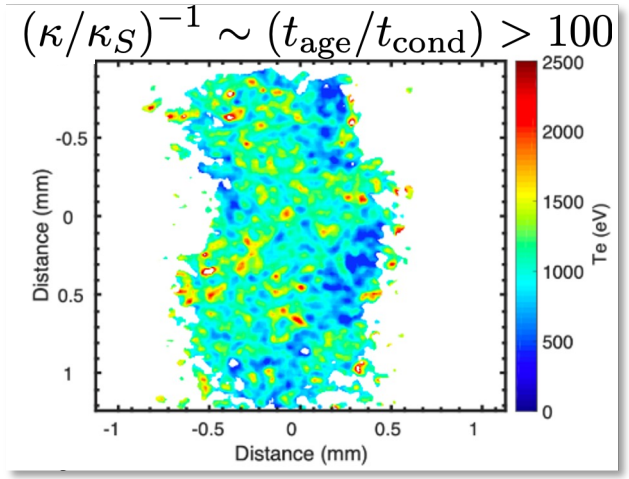


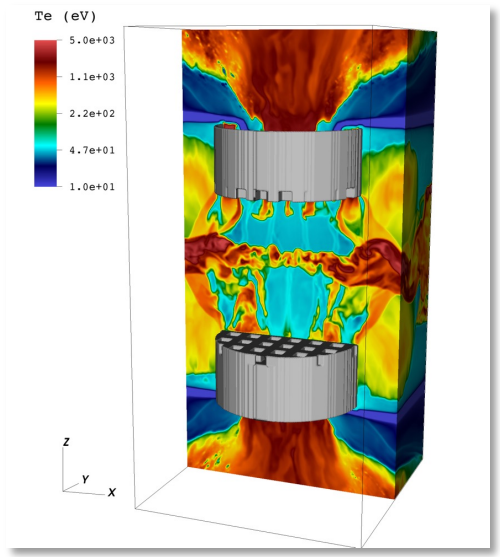
A. Bott+ Proceedings of the National Academy of Sciences 118, e2015729118 (2021)

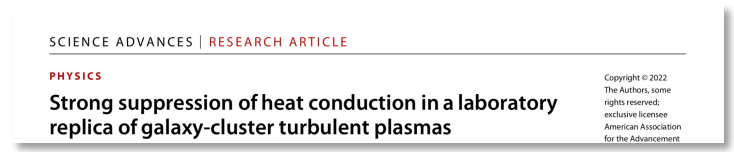
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# FLASH simulations and TDYNO NIF experiments help unravel thermal conduction suppression in galaxy clusters



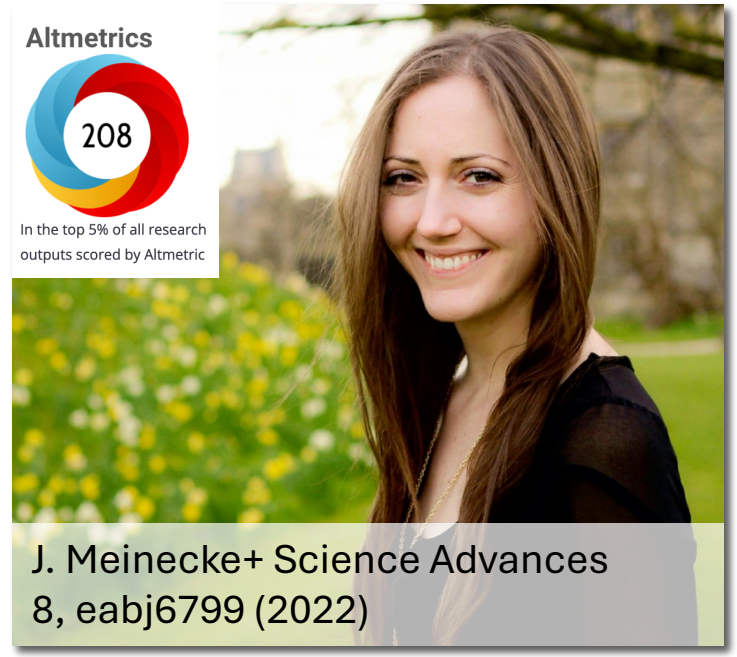



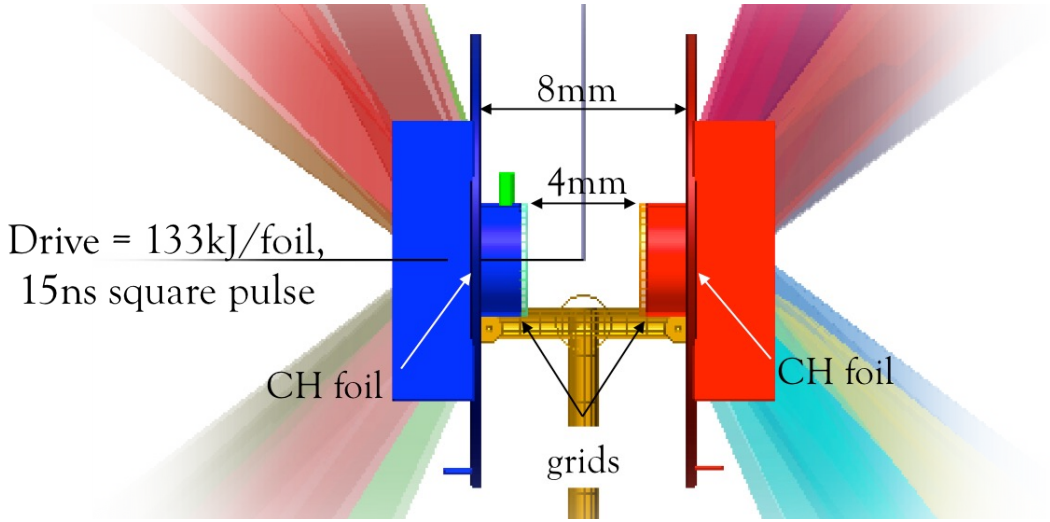



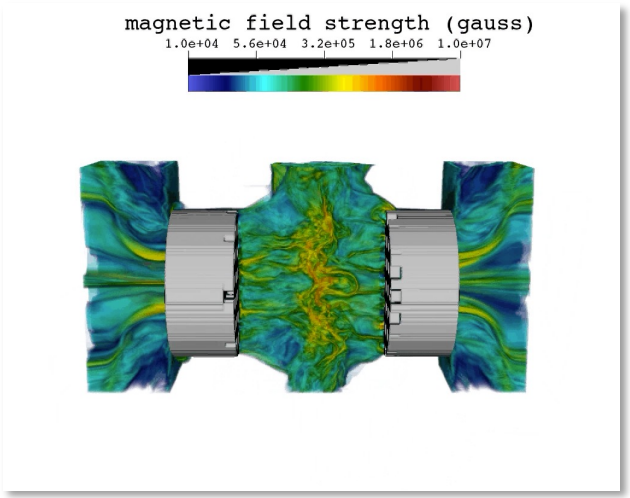







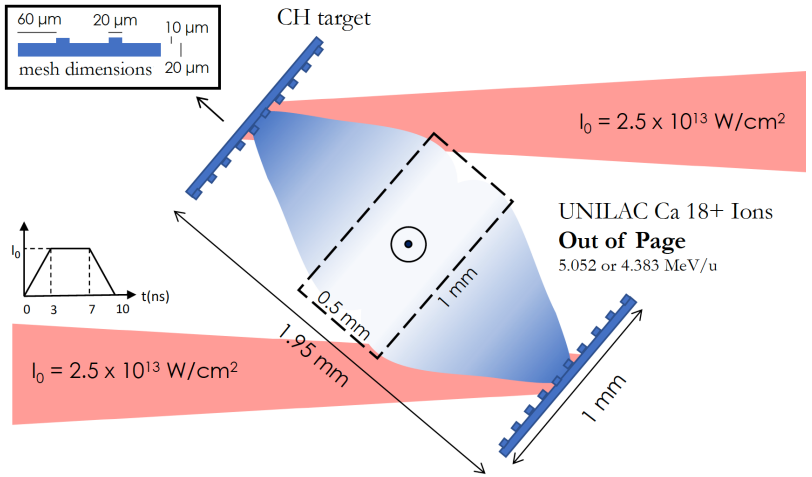


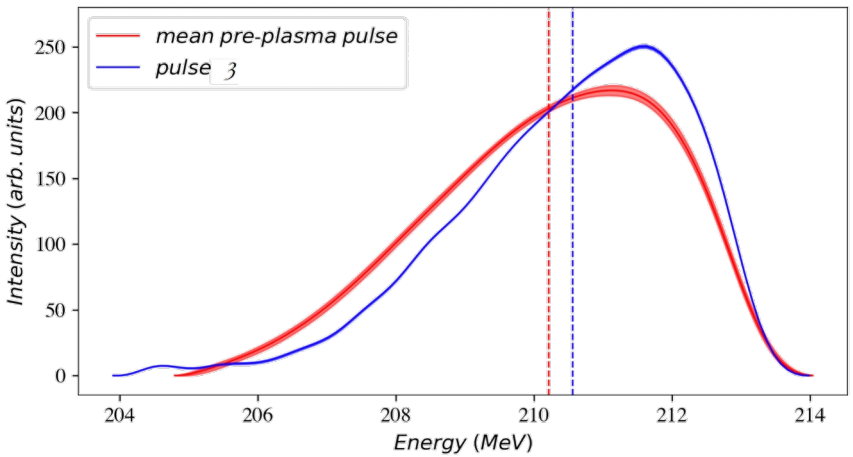



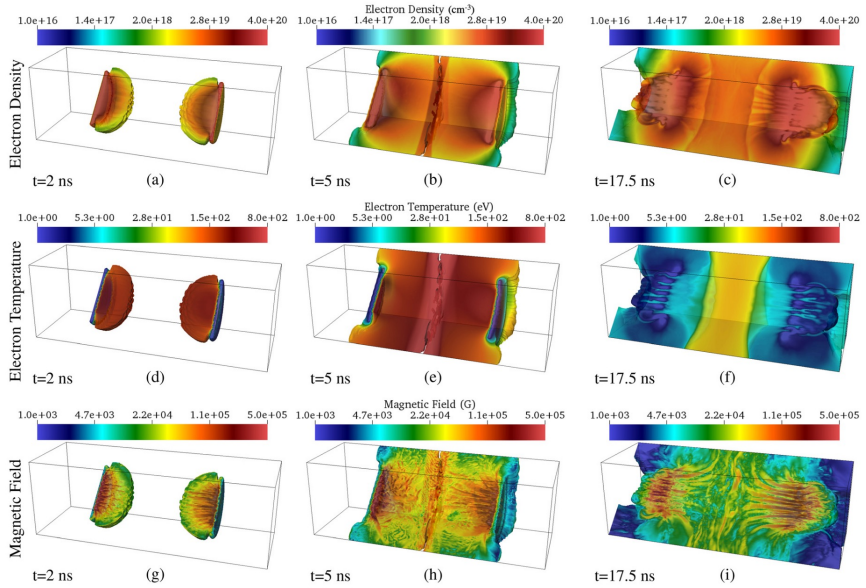




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# FLASH simulations and TDYNO GSI experiments to understand particle transport and acceleration in stochastic magnetic fields




- The UNILAC ions undergo acceleration due to the lower-hybrid drift instability with

$$|\Delta v| = \sqrt{2\frac{Z_c^2}{A_c^2}\frac{\omega_{pi}^2}{\Delta\omega}\frac{W}{nT}c_s^2\frac{L}{\nu_i}}$$

resulting in energizations of $\delta\mathcal{E} \sim 264$ keV


Physics of Plasmas ARTICLE pubs.aip.org/aip/pop

Numerical simulations of laser-driven experiments of ion acceleration in stochastic magnetic fields

Cite as: Phys. Plasmas 31, 122105 (2024); doi: 10.1063/5.0223496
Submitted: 14 June 2024 · Accepted: 8 November 2024 ·
Published Online: 4 December 2024



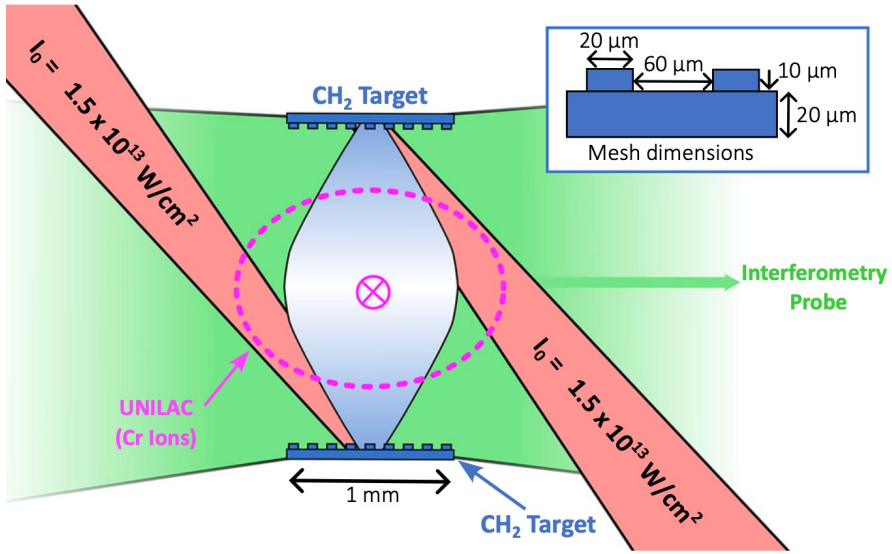
K. Moczulski,[1,a)] H. Wen,[1] T. Campbell,[2] A. Scopatz,[1] C. A. J. Palmer,[3] A. F. A. Bott,[2] C. D. Arrowsmith,[2] K. A. Beyer,[4] A. Blazevic,[5] V. Bagnoud,[5] S. Feister,[6] J. Halliday,[2,7] O. Karnbach,[2] M. Metternich,[1] H. Nazary,[2] P. Neumayer,[5] A. Reyes,[1] E. C. Hansen,[1] D. Schumacher,[5] C. Spindloe,[7] S. Sarkar,[2] A. R. Bell,[2] R. Bingham,[7,9] F. Miniati,[1] A. A. Schekochihin,[2] B. Reville,[1] D. Q. Lamb,[10] G. Gregori,[2] and P. Tzeferacos[1]

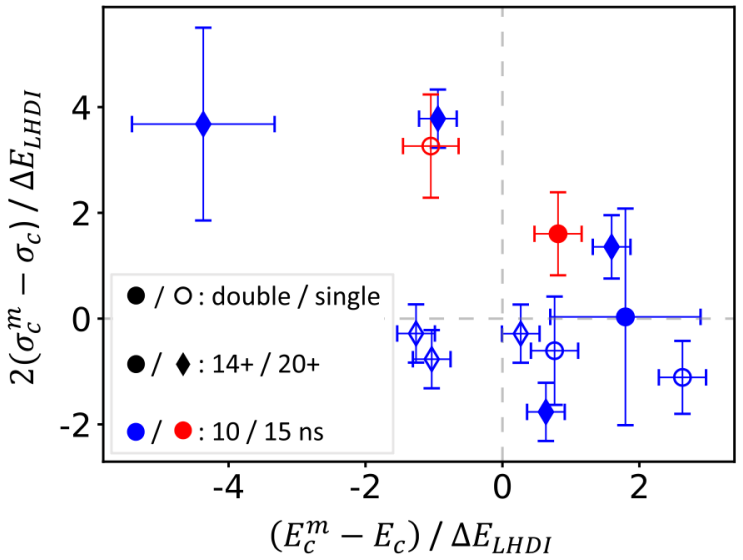


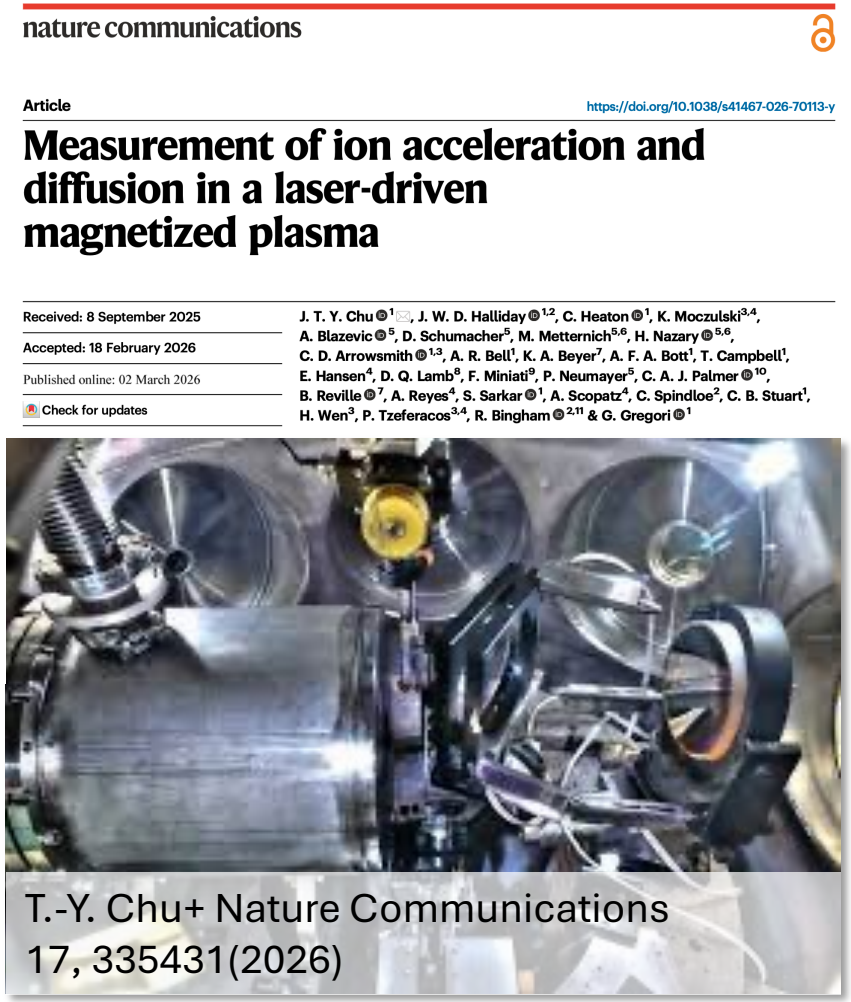

K. Moczulski+ Phys. Plasmas 31, 122105 (2024)

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# Measurement of ion acceleration and diffusion in a laser-driven magnetized plasma – GSI experiments



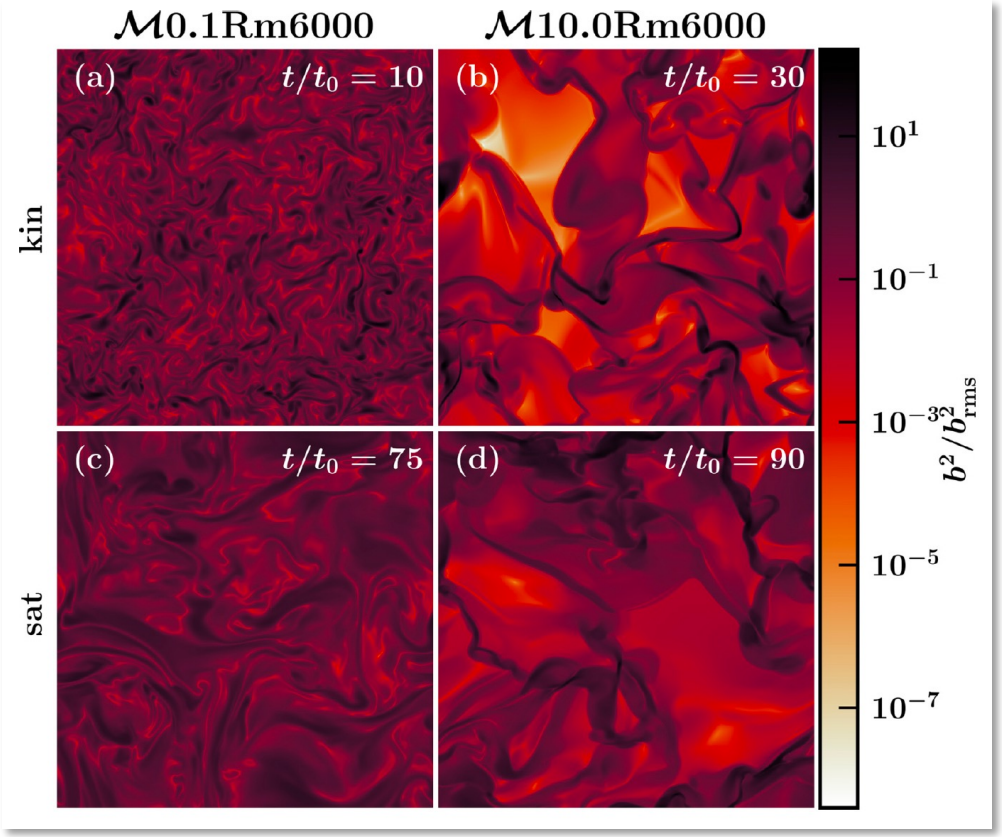



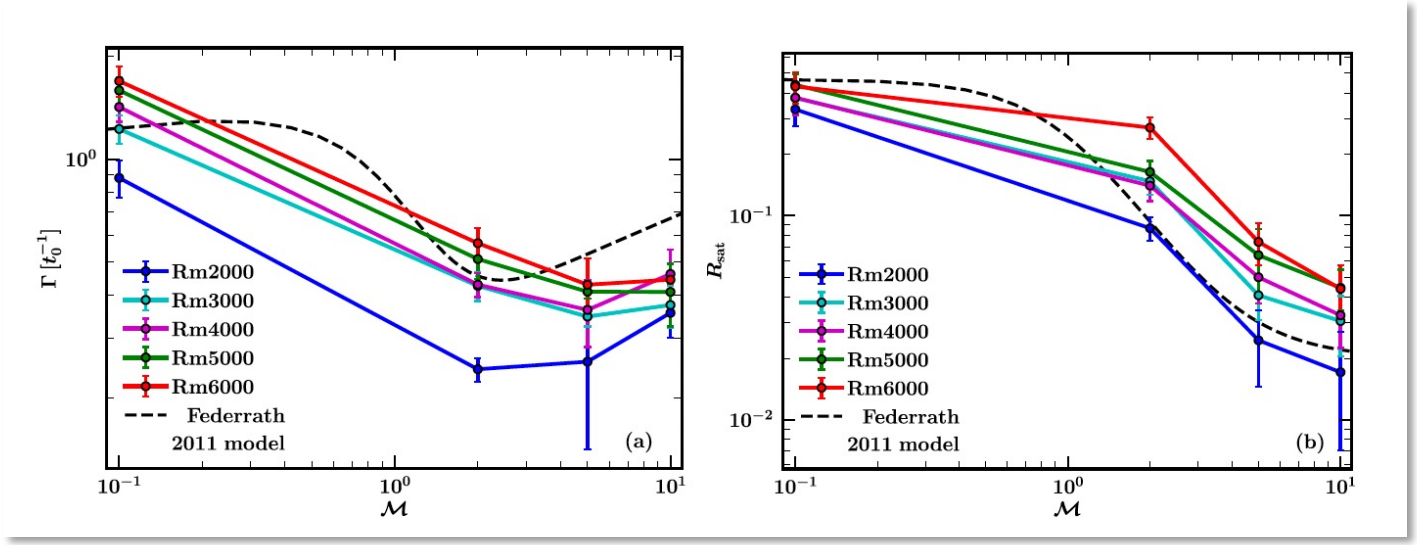




- Laser interferometry revealed the absence of strong fluid- scale turbulence.
- Acceleration and diffusion of the beam ions was driven by wave-particle interactions. A possible mechanism is particle acceleration by electrostatic, short scale length kinetic turbulence, such as the lower-hybrid drift instability.

T.-Y. Chu+ Nature Communications 17, 335431(2026)

# Fluctuation dynamo in supersonic turbulence – Theory and simulations predict a less efficient, harder to achieve dynamo



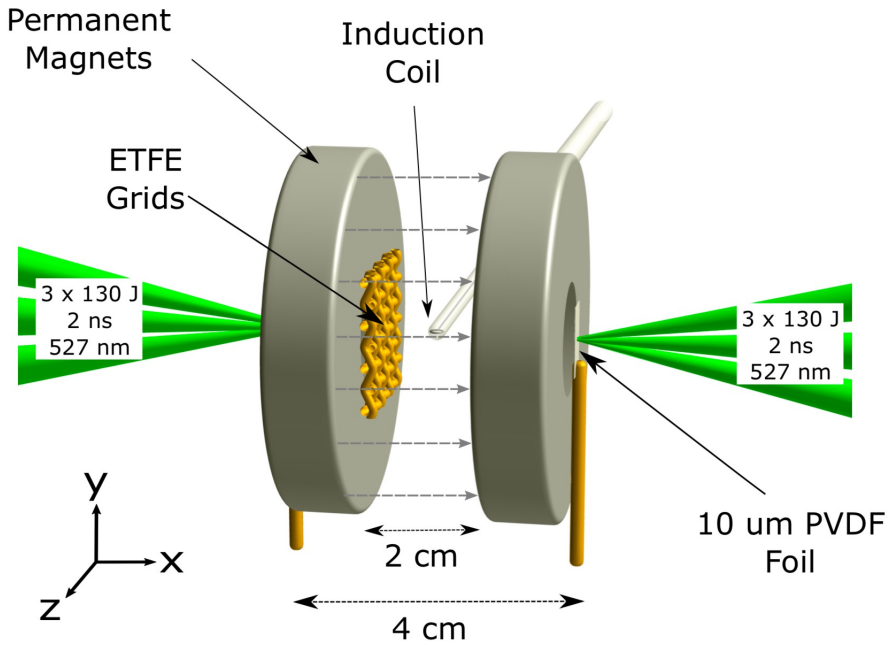



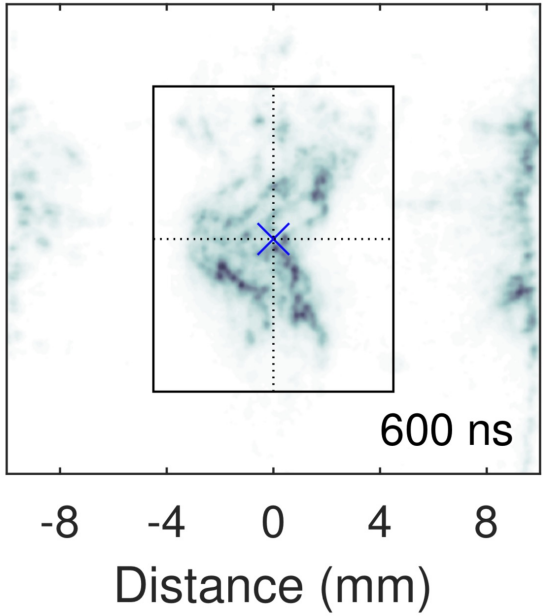

- Fluctuation dynamo in subsonic (left) and supersonic turbulence (right) (Seta & Federrath 2021)

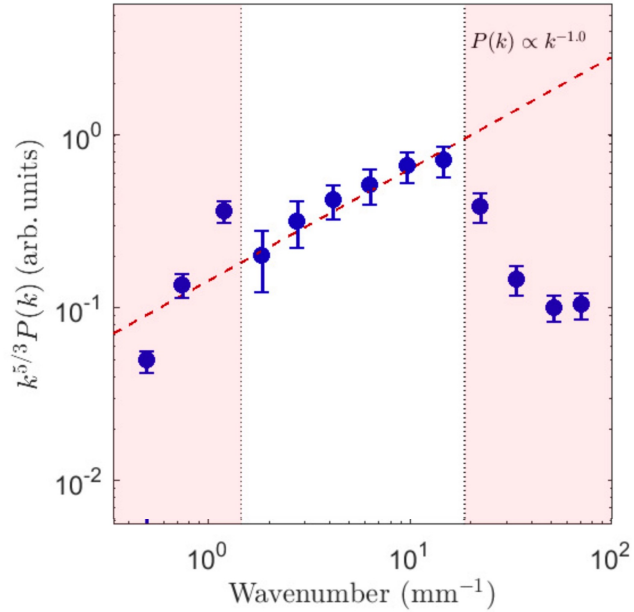
- Fluctuation dynamo is **less efficient** in supersonic turbulence than subsonic (Seta & Federrath 2021), with growth rates $\Gamma$ and saturation values $R_{sat}=E_B/E_K$ that **decrease with** $M$.

- The **critical** $Rm$ for dynamo onset is also expected to be **3x larger** than that of equivalent subsonic cases (Federrath+ 2014).

# Experiments that target supersonic magnetized turbulence at Vulcan (RAL, UK) and the Megajoule Laser (LMJ, France)

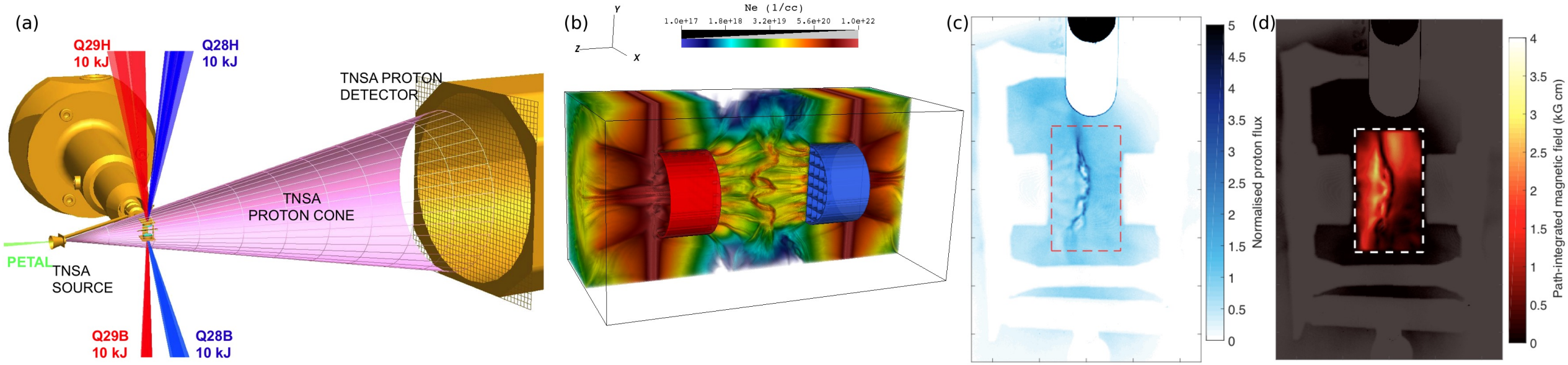



- The Vulcan experiments (White+ Nat. Commun. 2019) utilized a modified version of the TDYNO platform to investigate the statistical behavior of highly compressible hydrodynamic turbulence at large fluid Reynolds numbers ($Re \sim 10^4$).
- Using Schlieren imaging, gated optical interferometry, and spectroscopy, we measured the turbulent plasma state and showed how density and velocity power spectra **evolve from an initially Kolmogorov-like slope towards that of steady-state Burgers (1948) turbulence**.

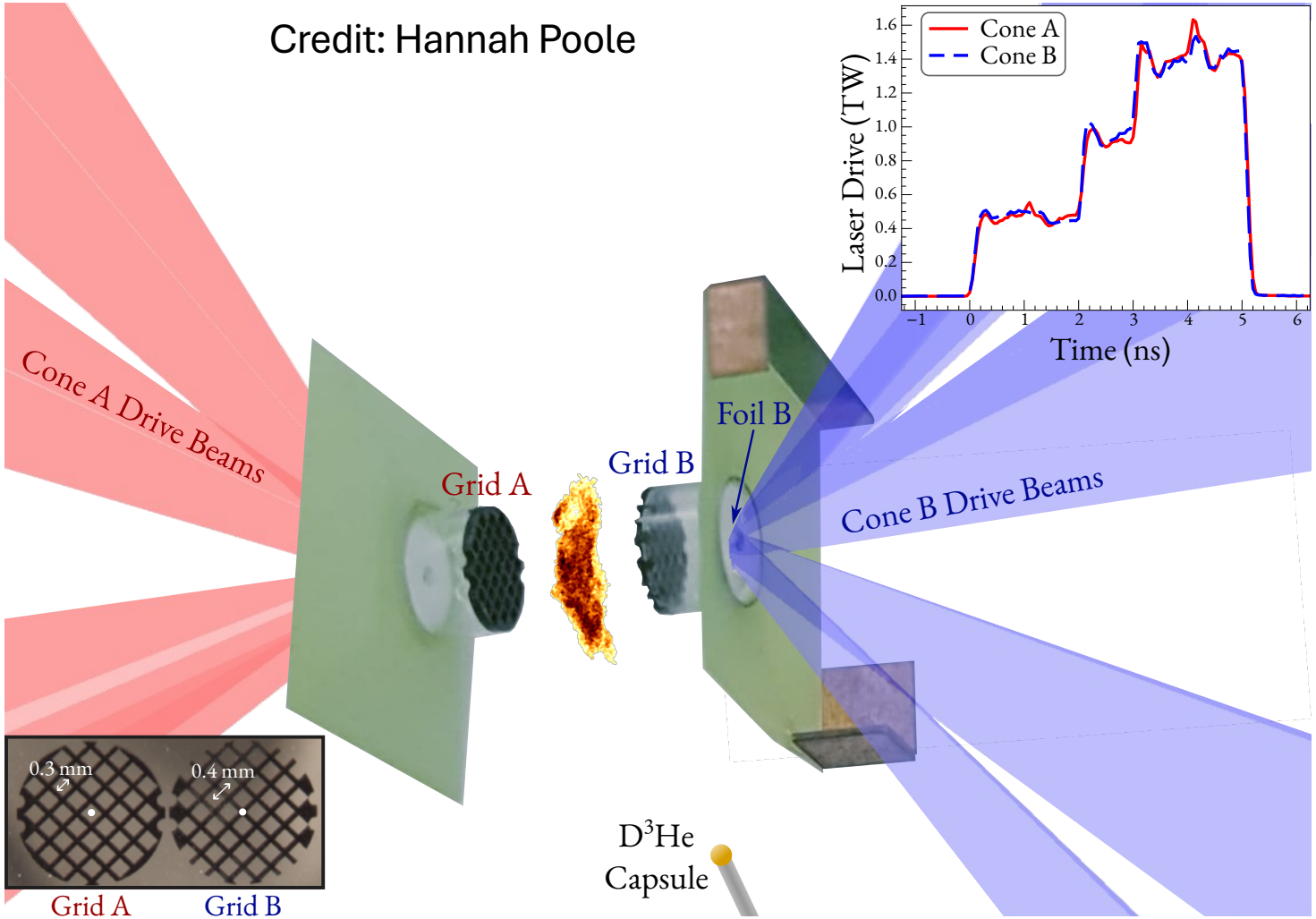
# Experiments that target supersonic magnetized turbulence at Vulcan (RAL, UK) and the Megajoule Laser (LMJ, France)




- Using FLASH simulations, we ported the TDYNO platform to LMJ and leveraged the **radiative properties** of the aluminum plasma **to decrease the sound speed** and create compressible, magnetized turbulence.
- We demonstrated the creation and modest amplification of turbulent magnetic fields (Bott+ PRL 2021), diagnosed using TNSA proton radiograph. Our results are broadly consistent with the expectation that magnetic-field amplification is **less efficient** in supersonic, low-$Pm$ turbulence, as compared to moderate-$Pm$ subsonic turbulence.

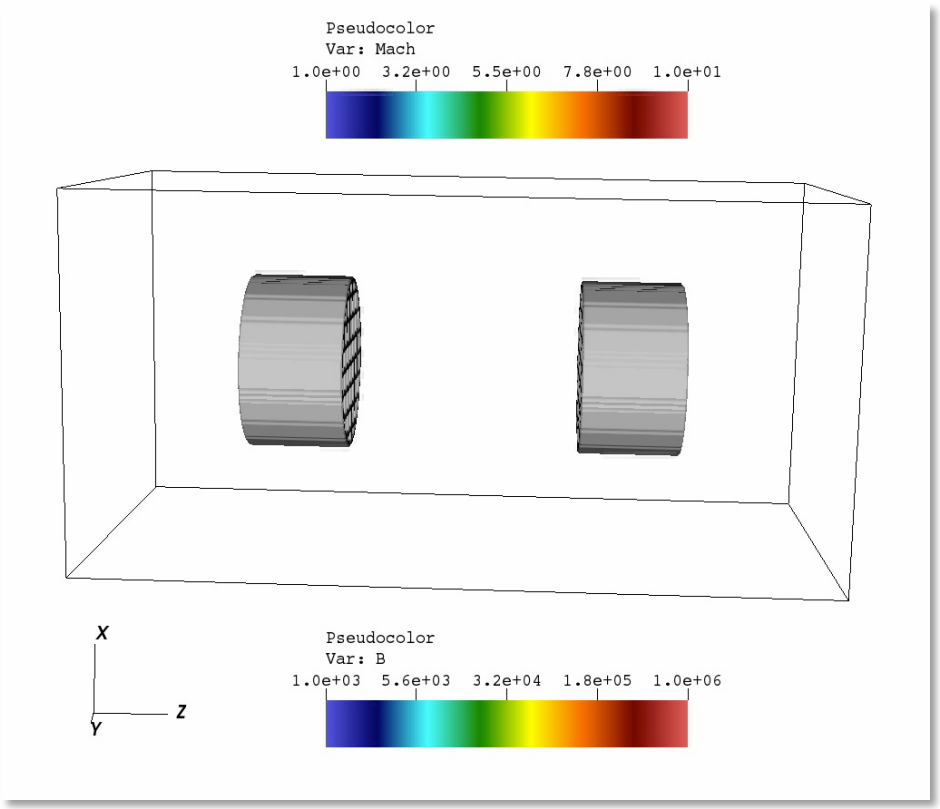
# The demonstration of supersonic turbulent dynamo is achieved by leveraging the OMEGA TDYNO platform, (1) tweaking with FLASH simulations to get the Rm & sound speed conditions just right

Credit: Hannah Poole










Need high enough $T_e$ for $Rm > Rm_C$ but low enough for $u_{turb} > Cs$: **A Goldilocks problem!**

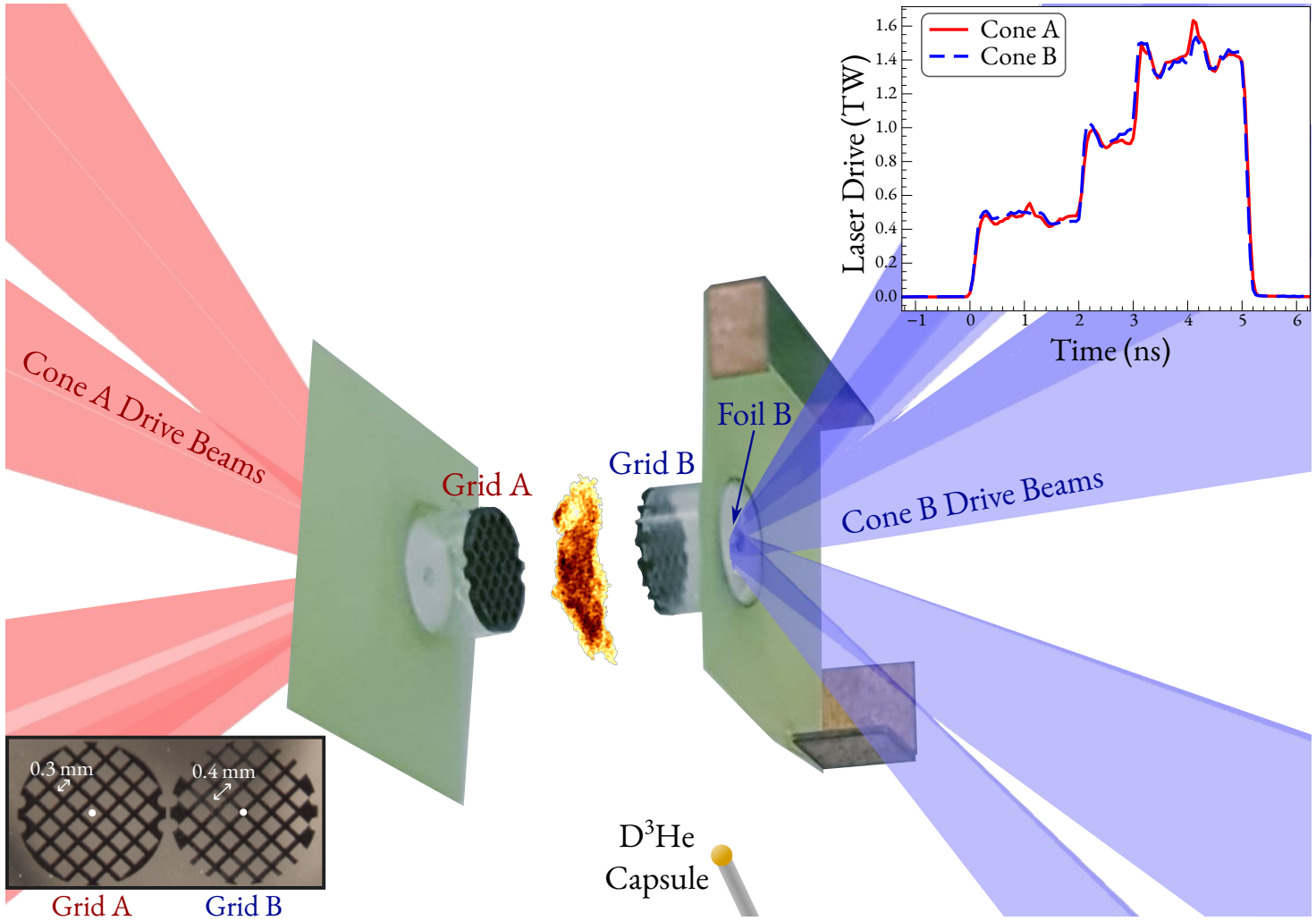
$$Cs\ (cm\ s^{-1}): 9.8 \times 10^5\ [(\langle Z \rangle + 1)\gamma_I T_e]^{1/2} \langle M \rangle^{-1/2}$$

$$\eta\ (cm^2\ s^{-1}): 3.1 \times 10^5\ Z_{\text{eff}} \log \Lambda / T_e^{3/2}$$

and $Rm \propto 1/\eta$

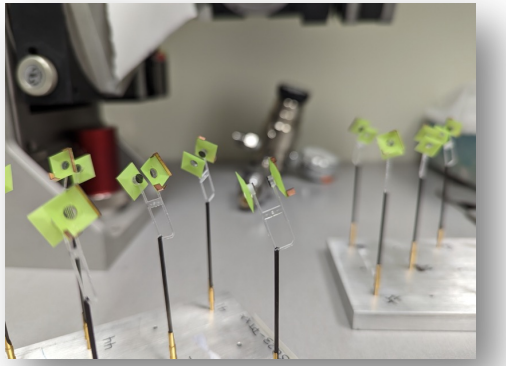
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# The demonstration of supersonic turbulent dynamo is achieved by leveraging the OMEGA TDYNO platform, (2) and with two dedicated OMEGA-60 shot days to collect the necessary data



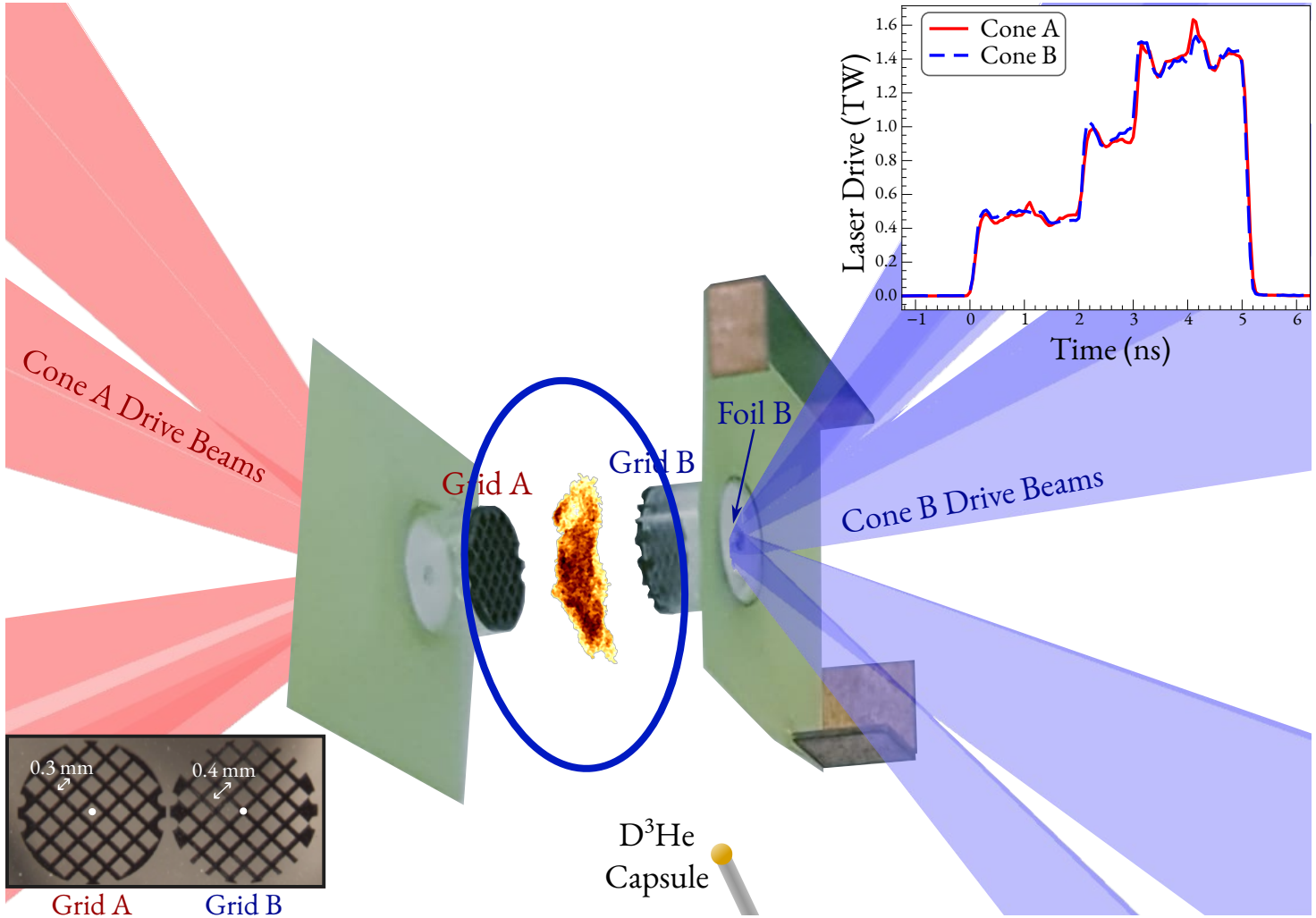



OMEGA-60 shot day, June 6 2023



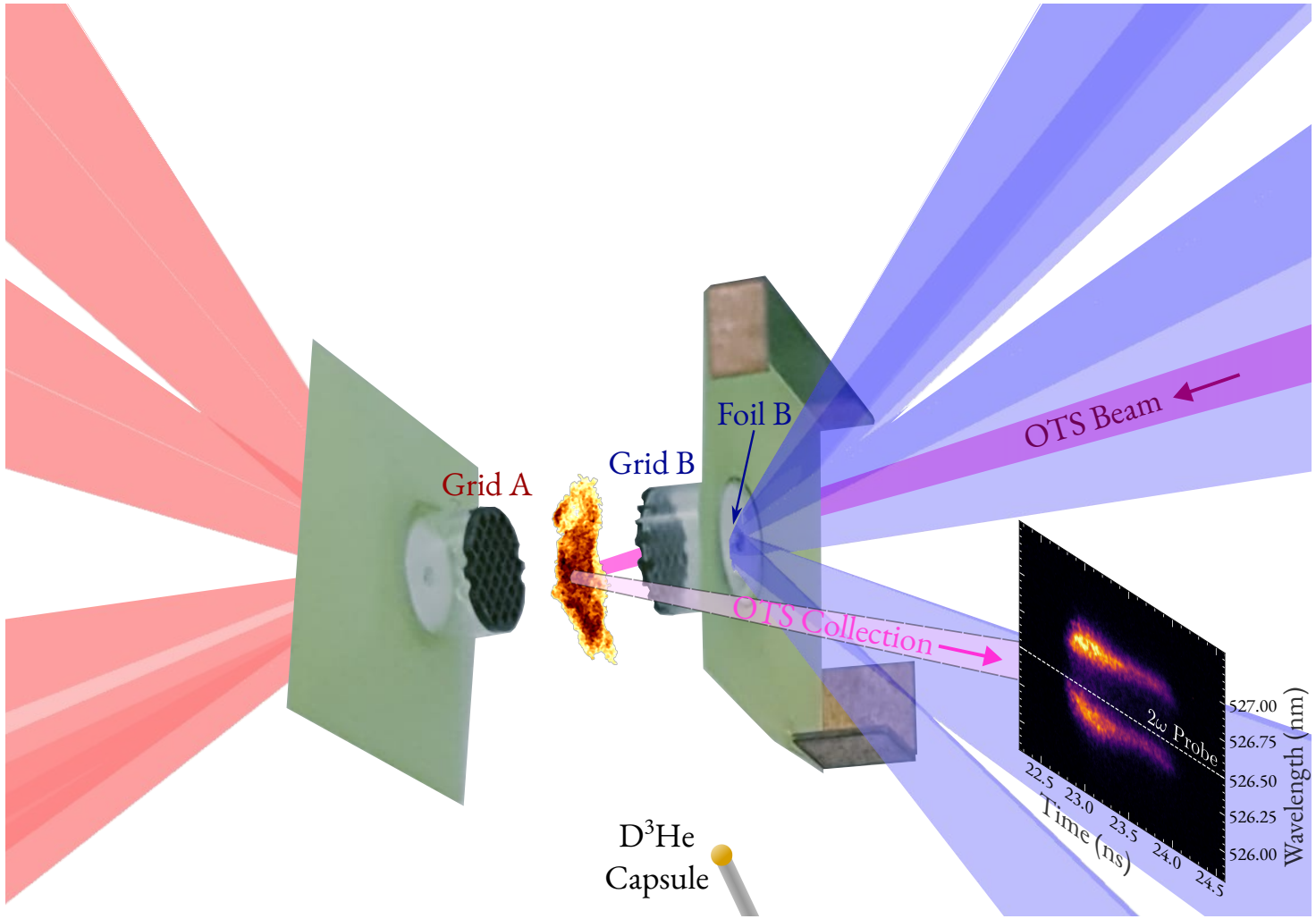


# The platform fully utilizes the rich diagnostic capabilities of the Omega Laser Facility: X-ray imaging



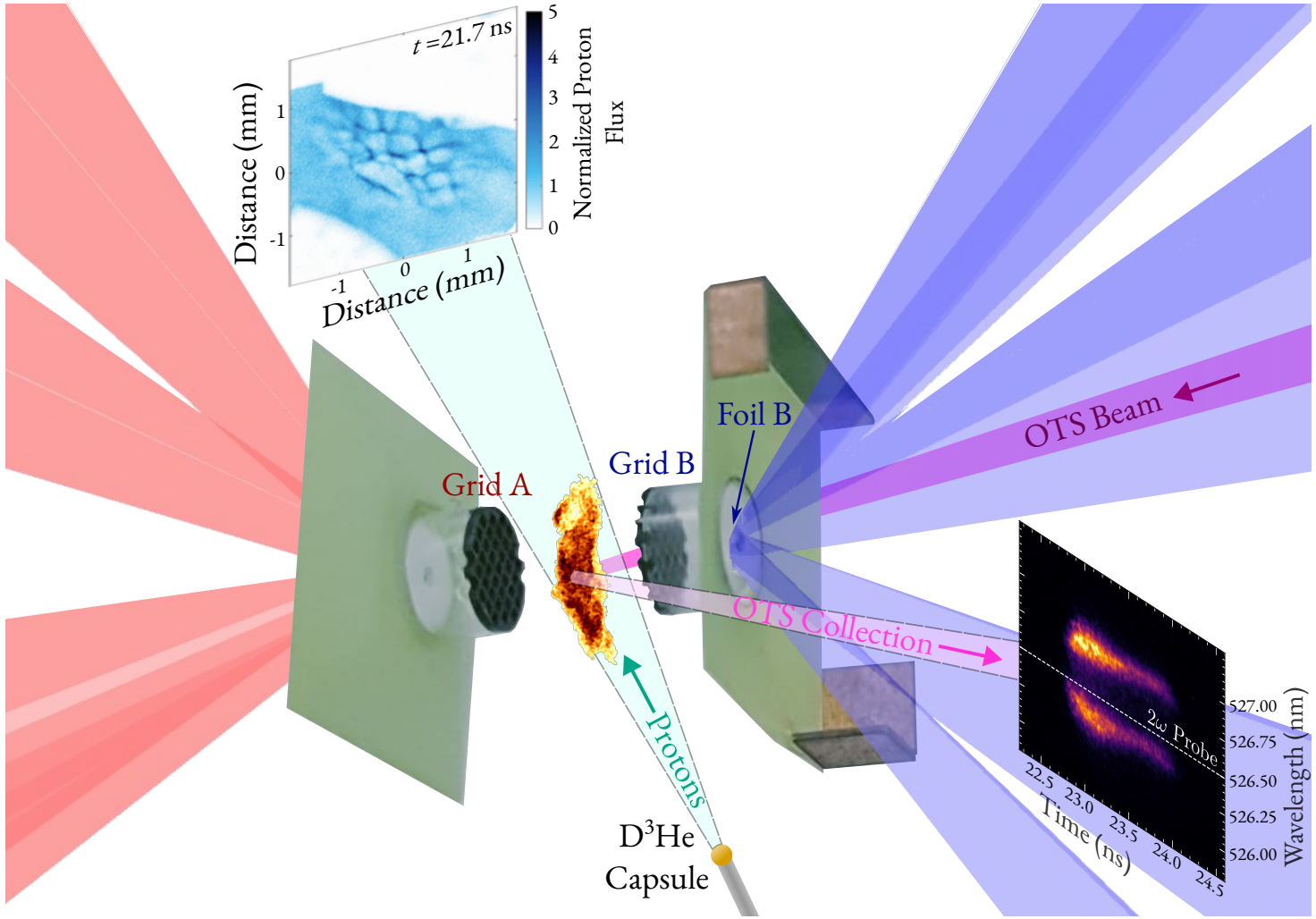

- X-ray imaging, to capture the fluctuations in intensity that can furnish **the density fluctuations in the turbulent plasma** (Tzeferacos+ 2018) and craft **the map of the electron temperature** (Meinecke+ 2022, Valenzuela-Villaseca+ 2024).

# The platform fully utilizes the rich diagnostic capabilities of the Omega Laser Facility: X-ray imaging, OTS




- X-ray imaging, to capture the fluctuations in intensity that can furnish **the density fluctuations in the turbulent plasma** (Tzeferacos+ 2018) and craft **the map of the electron temperature** (Meinecke+ 2022, Valenzuela-Villaseca+ 2024).
- Optical Thomson Scattering (OTS), to **fully characterize a small volume** in the turbulent plasma through the ion acoustic wave (IAW) and electron plasma wave (EPW) signals, including the turbulent velocity (Poole+ 2024a,b).

# The platform fully utilizes the rich diagnostic capabilities of the Omega Laser Facility: X-ray imaging, OTS, and PRAD




- X-ray imaging, to capture the fluctuations in intensity that can furnish **the density fluctuations in the turbulent plasma** (Tzeferacos+ 2018) and craft **the map of the electron temperature** (Meinecke+ 2022, Valenzuela-Villaseca+ 2024).
- Optical Thomson Scattering (OTS), to **fully characterize a small volume** in the turbulent plasma through the ion acoustic wave (IAW) and electron plasma wave (EPW) signals, including the turbulent velocity (Poole+ 2024a,b).
- Proton radiography, to image the **stochastic fluctuations** of the magnetic fields and assess their **magnitude** (Bott+ 2017).

# Temporally resolved optical Thomson scattering characterizes the turbulent plasma within the Thomson volume

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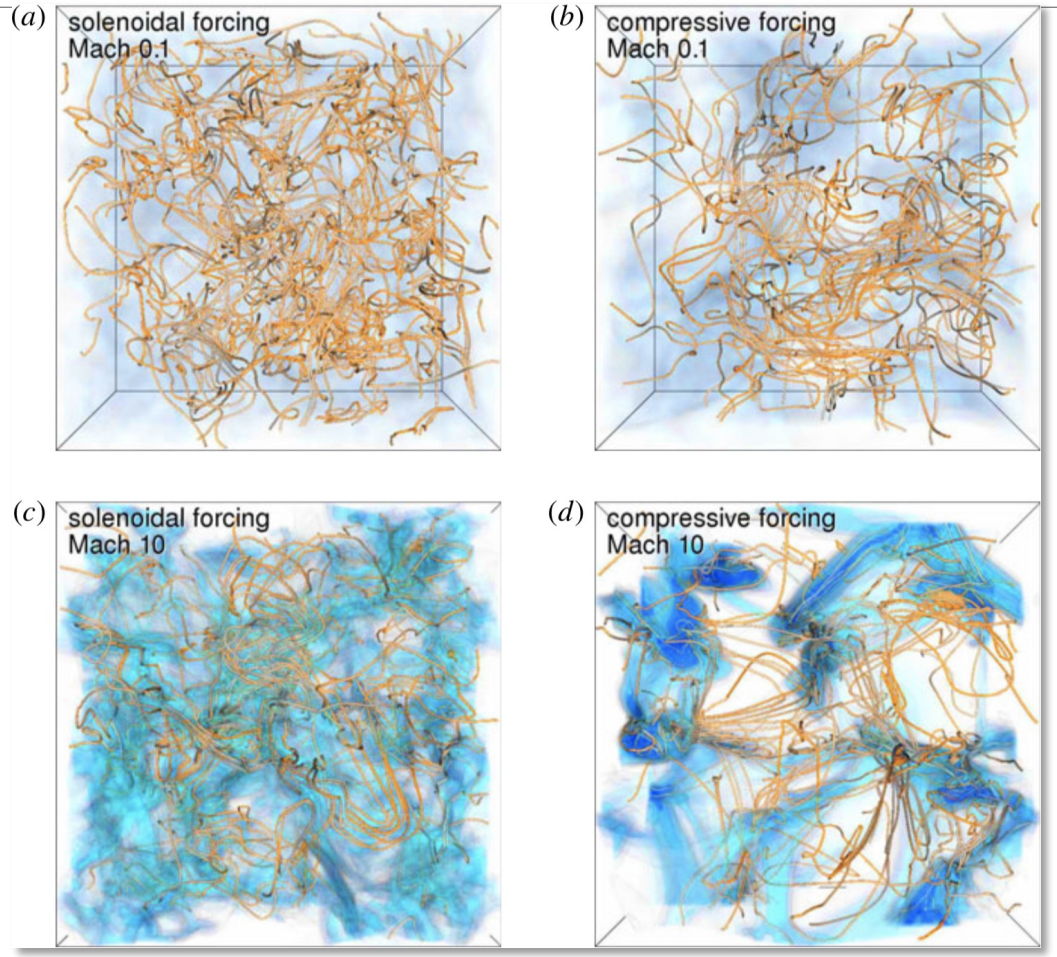
# Line-of-sight integrated density-weighted electron temperatures are inferred from X-ray emission imaging

# Line-of-sight integrated density-weighted electron temperatures are inferred from X-ray emission imaging

# Evolution of the amplification of path-integrated magnetic fields is inferred from proton radiography

# The combination of these diagnostics provides a consistent picture of fluctuation dynamo operating in a supersonic turbulent plasma!

# U.S. DOE Office of Science/FES: Driven HED turbulence to design validation TDYNO experiments (2025 PECASE Award)

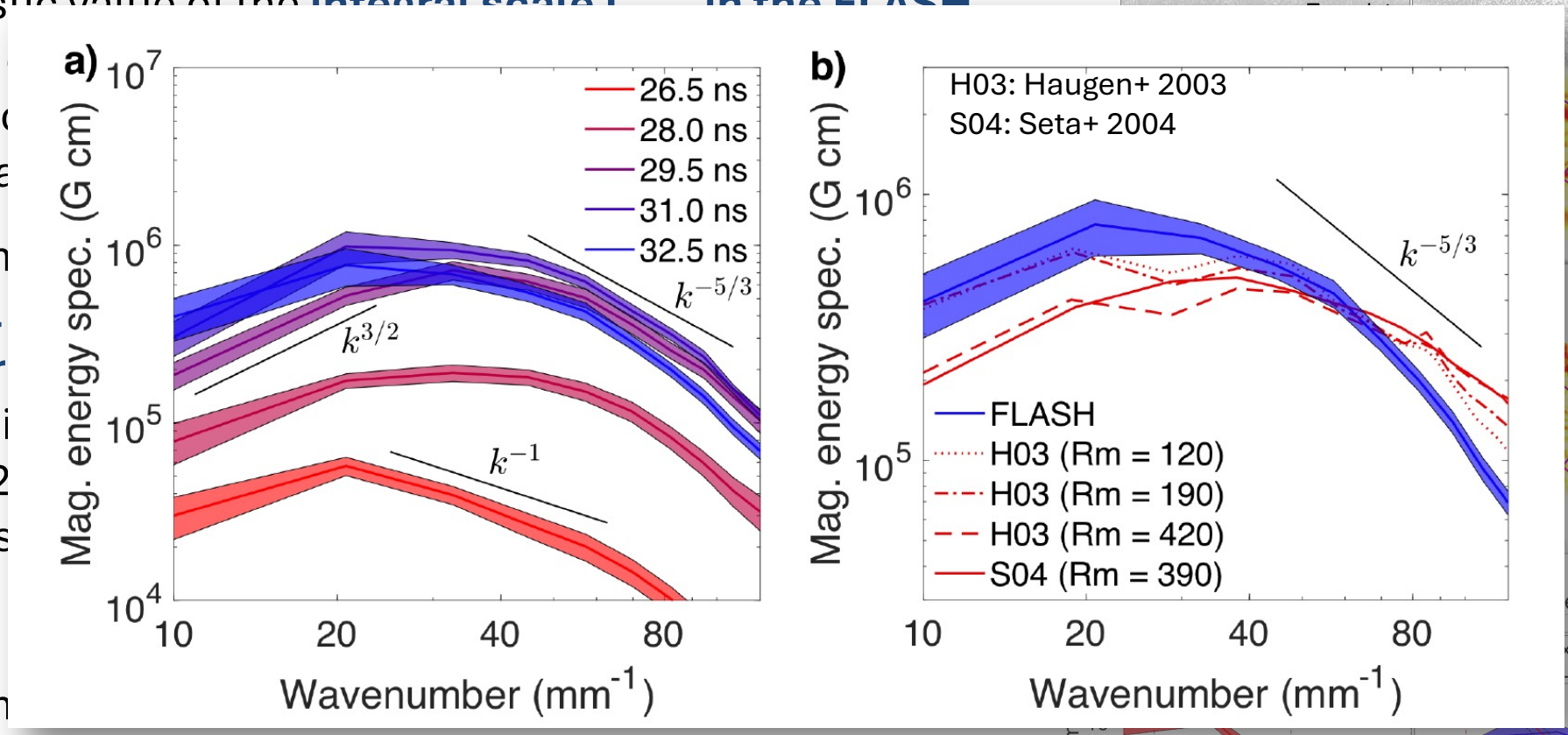



Federrath+ PRL 2011
Federrath JPP 2016

- A Department of Energy Early Career Research Program Award enables us to study high-energy-density (HED) magnetized plasma turbulence **using driven turbulence simulations with FLASH.**
- This effort holistically studies HED magnetized turbulence **in regimes where plasma physics processes are important** and go beyond the simplified approximations used in current theoretical models and numerical simulations.
- The research combines **theory, high-performance computing simulations with the FLASH code, and experiments** on our nation's **laser facilities** to establish a basis for laboratory astrophysics investigations on the nature of magnetized HED turbulence and fluctuation dynamo.

# While the resistive rad-MHD simulations of the experiments do a good job at predicting the dynamics and dynamo amplification, the integral scale of the resulting magnetic field is consistently smaller than the experiment

- The characteristic value of the **integral scale L … in the FLASH simulations is** (~0.3L, e.g., Cho … experimental va…
- Possible explan…
  - **Additional** … (e.g., **order**
  - Difference i… Federrath 2…
  - Differences… 2020)
- Intriguing, given … **observed scale of tangled magnetic fields present in the ICM** (Roh+ 2019, Vazza+2018)







Bott+ PNAS 2021

# Driven turbulence Hall MHD simulations of fluctuation dynamo

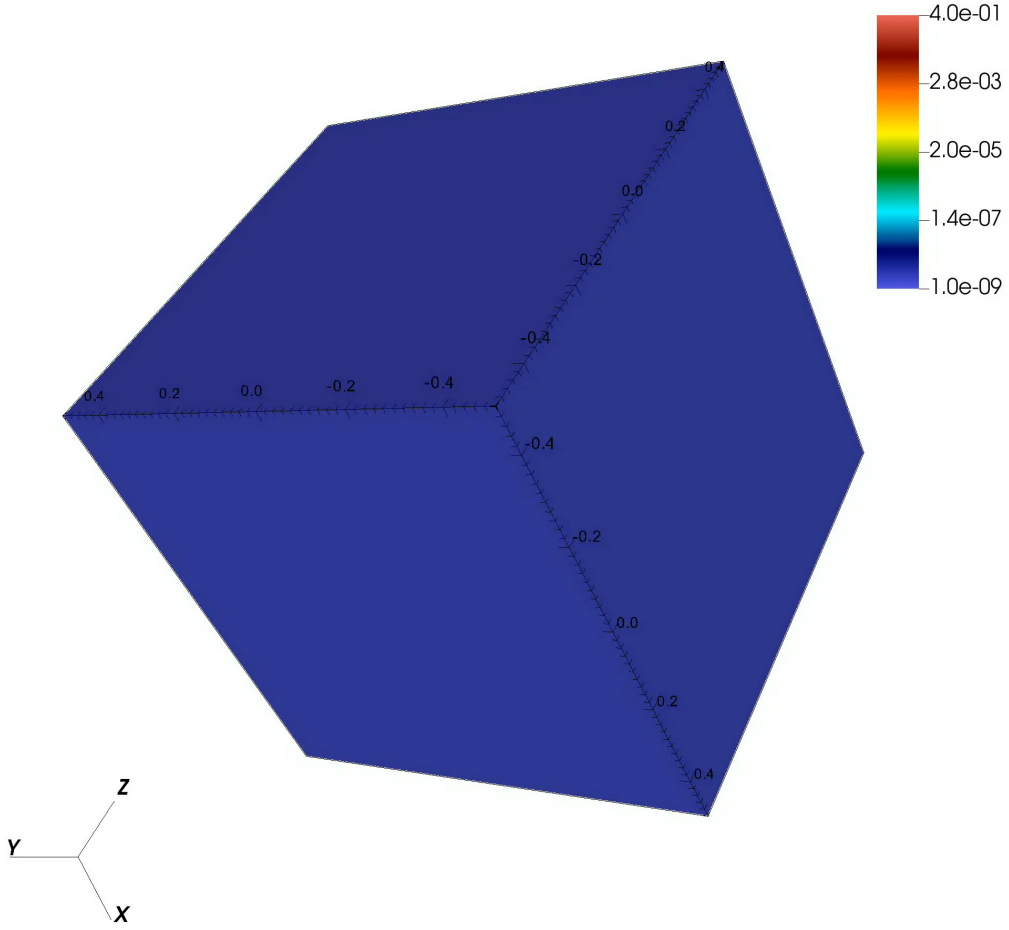
- The new **xMHD terms have been incorporated in FLASH's generalized Ohm's Law**, allow us to test these hypotheses.

$$\begin{aligned}\mathbf{E} &= -\mathbf{u}\times\mathbf{B} + \frac{\mathbf{J}}{n_e e}\times\mathbf{B} - \frac{\nabla P_e}{n_e e} \\ &+ \frac{\eta_{\parallel}}{\epsilon_0\omega_{pe}^2\tau_{ei}}\mathbf{b}(\mathbf{b}\cdot\mathbf{J}) + \frac{\eta_{\perp}}{\epsilon_0\omega_{pe}^2\tau_{ei}}\mathbf{b}\times(\mathbf{J}\times\mathbf{b}) - \frac{\eta_{\wedge}}{\epsilon_0\omega_{pe}^2\tau_{ei}}(\mathbf{b}\times\mathbf{J}) \\ &- \beta_{\parallel}\mathbf{b}(\mathbf{b}\cdot\nabla T_e) - \beta_{\perp}\mathbf{b}\times(\nabla T_e)\times\mathbf{b}) - \beta_{\wedge}(\mathbf{b}\times\nabla T_e)\end{aligned}$$

- The simulations use a 3D domain ($L$ = 1 $cm$) with uniform density and sound speed. The turbulence

**Plasma Regime at saturation** (emulating Bott+ 2021)

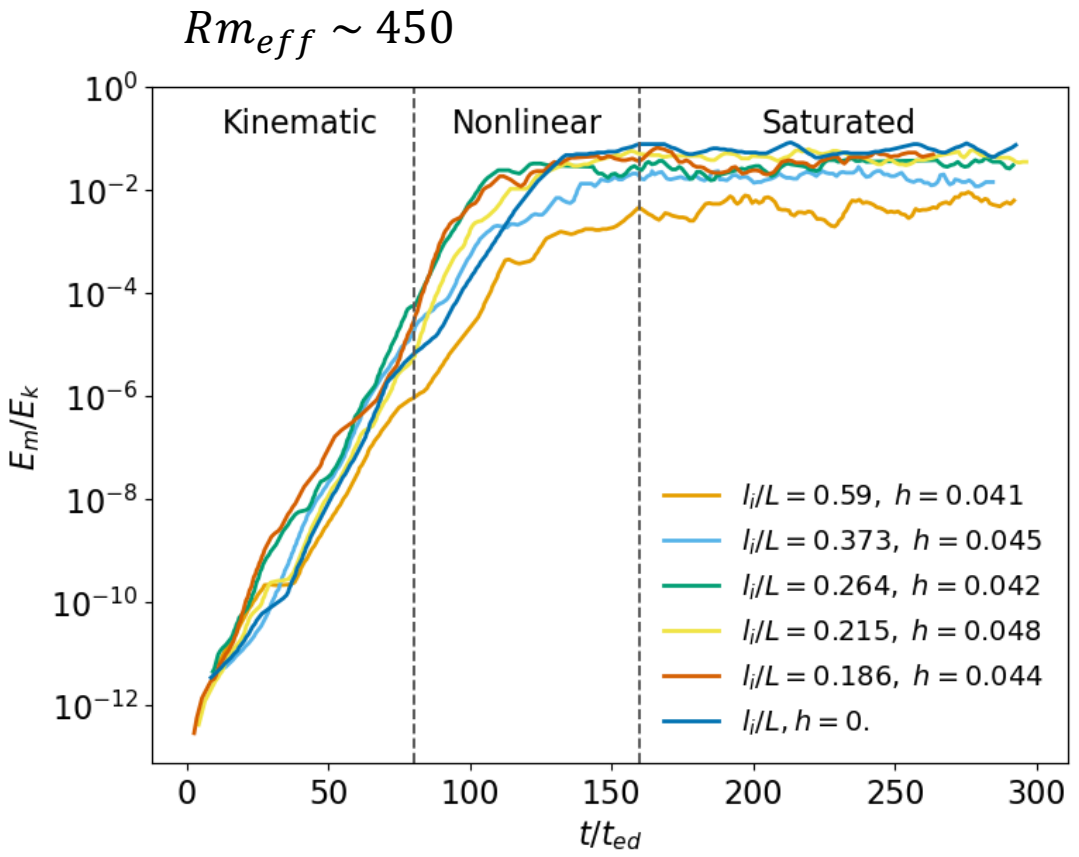
- $M \equiv \frac{u}{c_s} = 0.2 - 0.6$
- $R_e \equiv \frac{uL}{\nu} = 300 - 650$
- $R_m \equiv \frac{uL}{\eta} = 300 - 650$
- $P_m \equiv \frac{R_m}{R_e} = 1 - 2$
- $R_h \equiv \frac{1}{h} = 20 - 25$
- $h \equiv \frac{c}{\omega_{pi}L}\frac{v_A}{V_0}$ (Hall ratio)
- $l_i/L$ (Hall parameter)



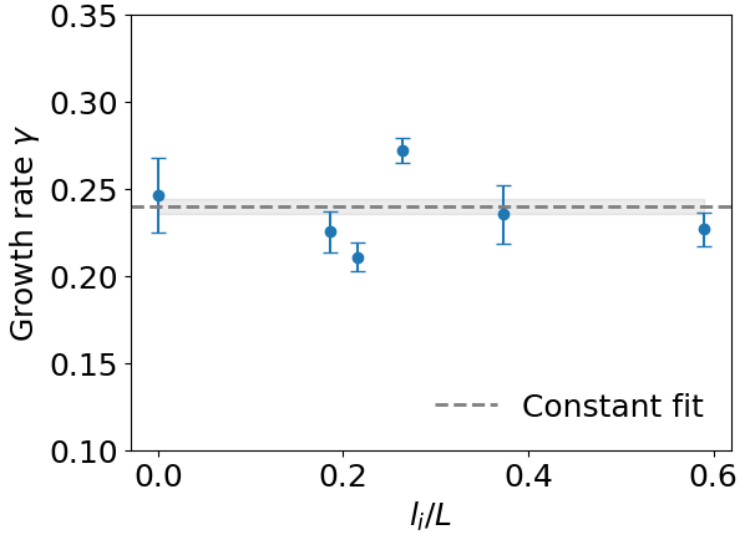


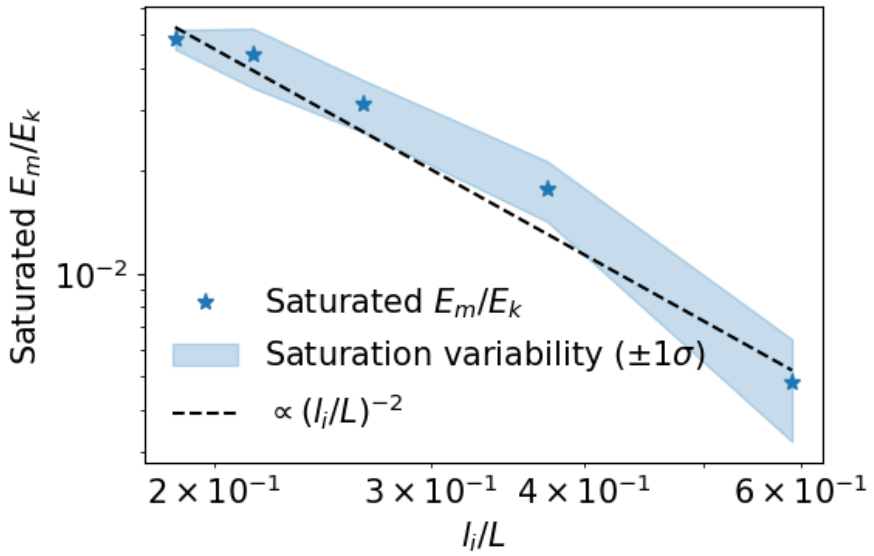

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# We observe a reduction in magnetic saturation levels with increasing ion inertial length $l_i$ (i.e., increasing Hall parameter)




- Despite different values of the Hall parameter ($l_i/L$), the Hall ratio, $h$, converges to similar values.
- Saturated $\mathbf{E_m/E_k}$ **decreases for increasing** $\boldsymbol{l_i/L}$.

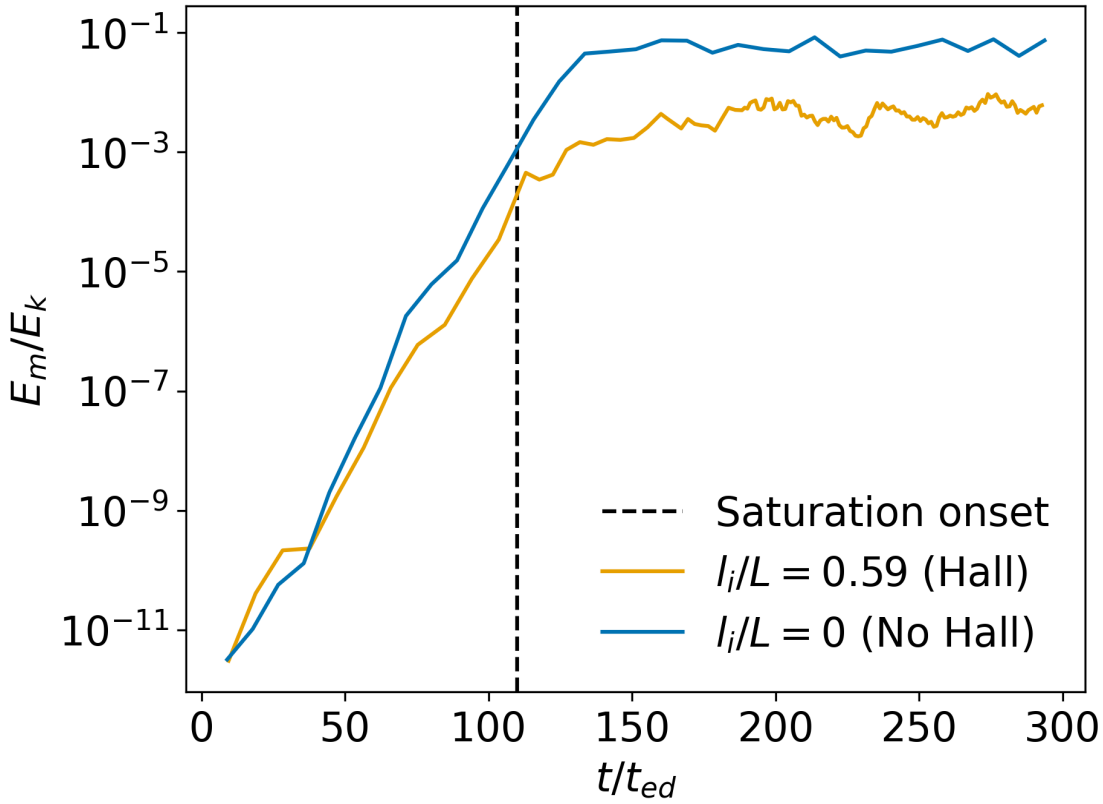


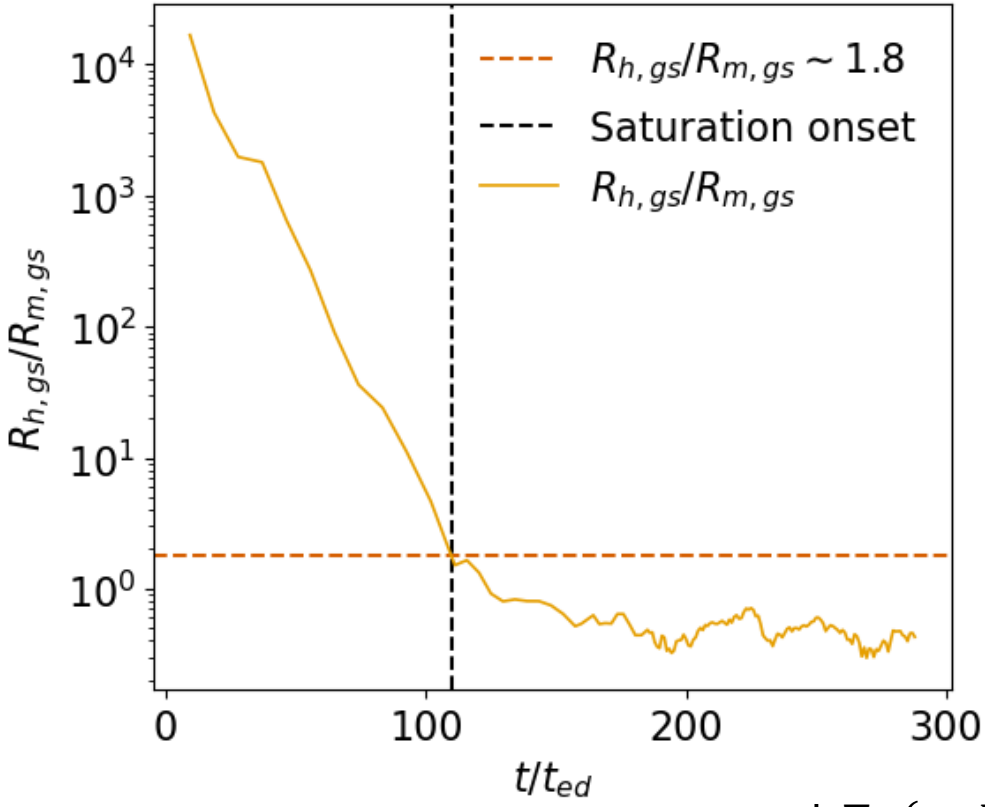




- All cases exhibit **similar exponential growth rates during the kinematic phase** before **diverging and saturating** at different energy levels.
- The saturated $E_m/E_k$ appears to **scale with the Hall parameter as** $(l_i/L)^{-2}$. The scaling can be derived by comparing the characteristic timescales of Hall-induced field-line drift with the turbulent stretching at the smallest scales.

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# The Hall effect alters the saturation level of the field when the ratio of local advection to Hall effect, $\boldsymbol{R(h,gs)}$, is comparable to the ratio of local advection to resistive diffusion, $\boldsymbol{R(m,gs)}$




- The Hall effect starts competing with resistivity and eventually determines the saturation level when $R_{h,gs} / R_{m,gs} \leq 1$. The red dashed line marks the onset of Hall dominance at $R_{h,gs}/R_{m,gs}$ =1.8, while the black dashed line represents the onset of saturation.

At the grid scale, $l = l_g$, we define

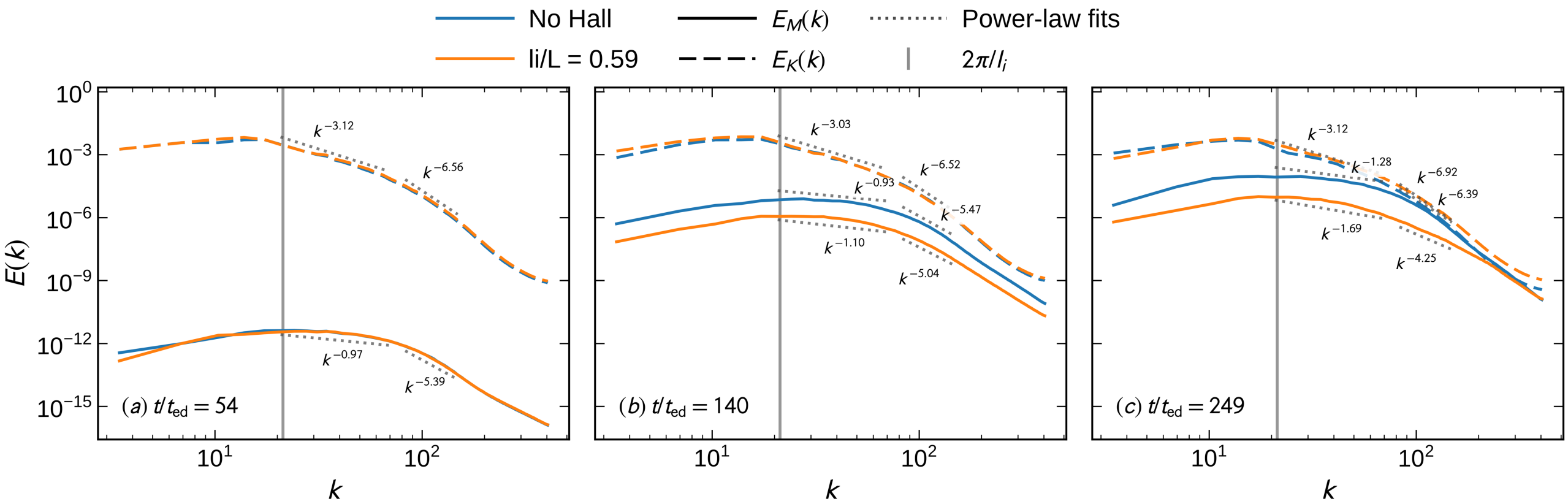
$$\boldsymbol{R_{h,gs}} = \left| \frac{\boldsymbol{\nabla \times (v \times B)}}{\nabla \times \left( \frac{\boldsymbol{J}}{ne} \times \boldsymbol{B} \right)} \right|$$

$$\boldsymbol{R_{m,gs}} = \left| \frac{\boldsymbol{\nabla \times (v \times B)}}{\eta (\boldsymbol{\nabla \times J})} \right|$$



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# The difference is also seen in the distinct magnetic energy spectrum the Hall simulation develops, compared to the no-Hall case

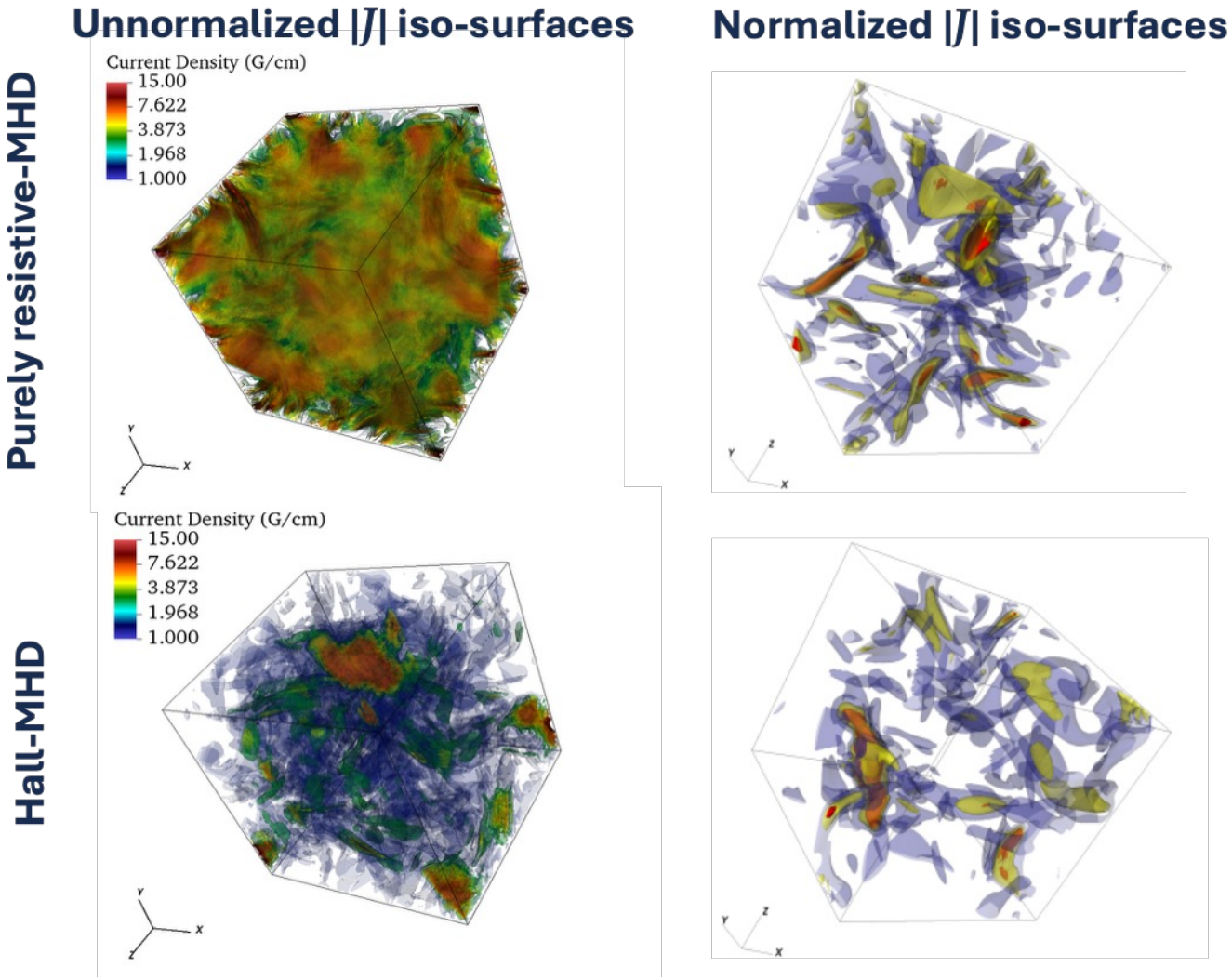


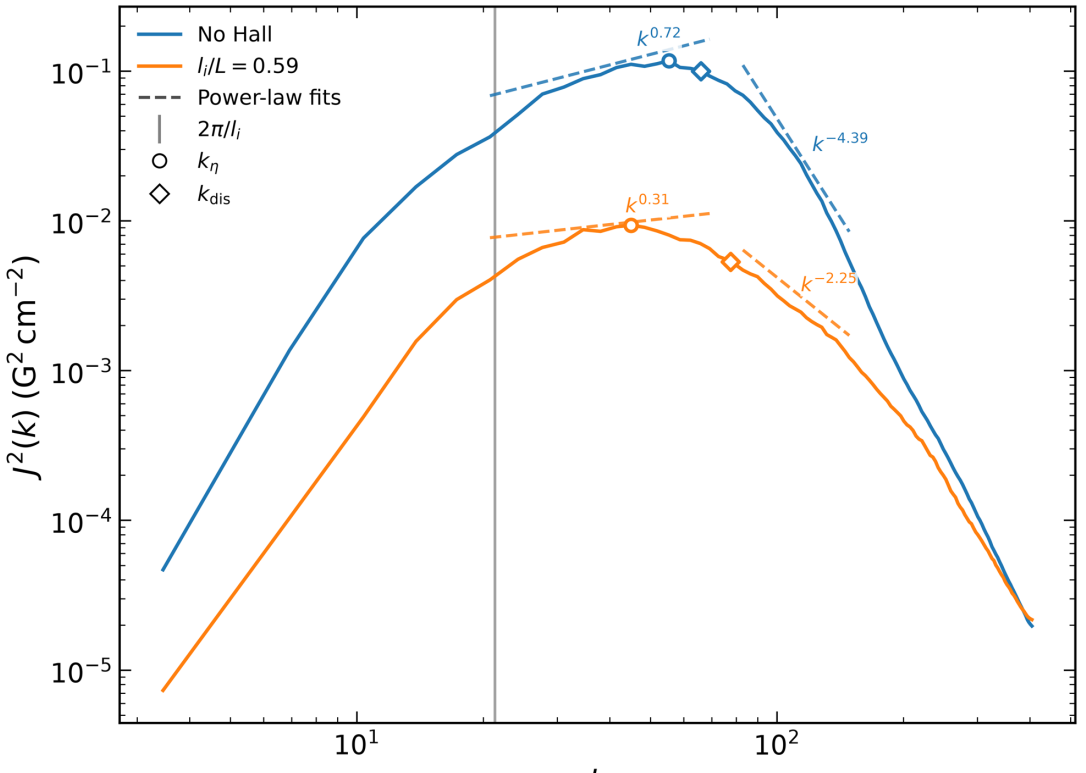

- As the turbulence evolves, the Hall case exhibits **less overall magnetic energy in the inertial range** and **more efficient energy transfer to smaller scales.** Can the Hall term explain the difference we see in the experimental results? Where does the energy peak?



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# Proton radiography formally images the MHD current and we find that Hall modifies the current density structures in the turbulence

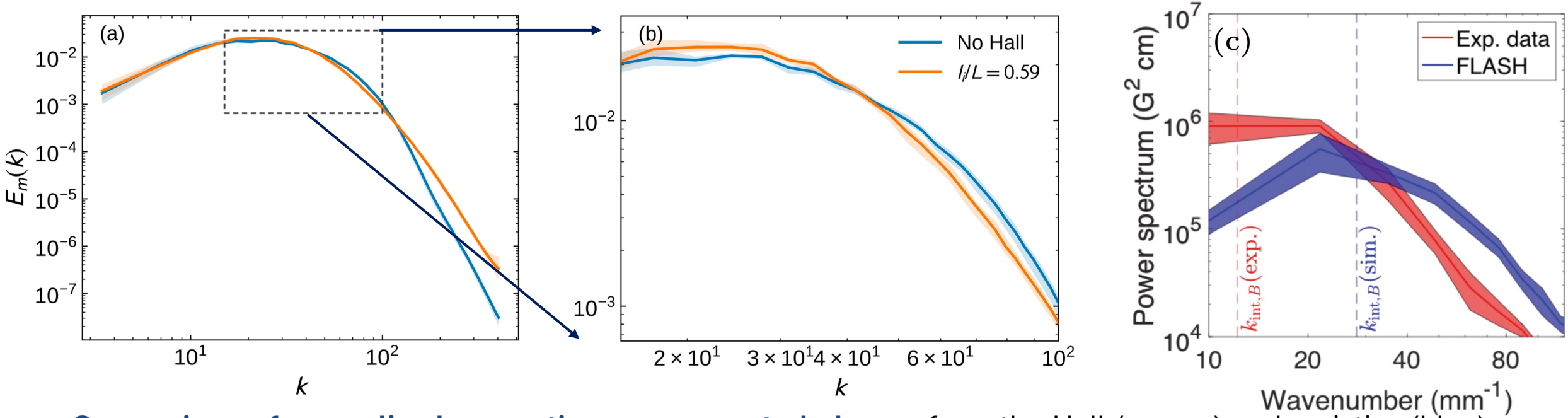



- The Hall terms **broadens the current spectrum** leading to more small-scale power and faster dissipation, resulting in thinner current sheets, with lower total current and more intermittent structures.
- The **peak current in the inertial range though, moves to lower k, i.e., larger scales.**

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# A quantitative comparison between driven turbulence FLASH simulations and the TDYNO experimental data shows that Hall physics may partially explain the discrepancy seen in the resistive MHD design simulations




- **Comparison of normalized magnetic-energy spectral shapes** from the Hall (orange) and resistive (blue) runs, with a close-up at the top of the inertial range, where the energy peaks (panel b). The Hall case has a **higher spectral peak**, indicating that a larger fraction of the available magnetic energy in the system is concentrated at that scale, compared to the resistive (no-Hall) case.
- **This behavior is consistent with the Bott+ (2021)** results (panel c), where more spectral power was located at large k in the magnetic-energy spectra from the *experimental* path-integrated magnetic field maps (in red) than what computed from *simulated* path-integrated magnetic field maps from the design FLASH simulations (in blue).

# Summary

- The advent of high-power lasers has opened **new fields of plasma physics research** and has enabled the reproduction of **astrophysical environments in the laboratory**.
- The TDYNO platform was designed with FLASH simulations to **demonstrate fluctuation dynamo in the lab for the first time**, at the Omega Laser Facility at the Laboratory for Laser Energetics. Leveraging this platform, a modified target design has realized **the generation of a supersonic turbulent interaction region.**
- The temperature and density evolution of the turbulent plasma were characterized with temporally-resolved 2ω **optical Thomson scattering** and **X-ray emission imaging**, and its magnetic field inferred from **proton radiography**.
- Combining these measurements, we have accumulated enough evidence to infer that **supersonic turbulent dynamo** has been demonstrated in a laboratory for the first time, at the Omega Laser Facility at the Laboratory for Laser Energetics.
- The experimental results motivated the development of new theories for HED magnetized turbulence **in regimes where plasma physics processes are important** and go beyond the simplified approximations used in current theoretical models and numerical simulations.
- **Fluctuation dynamo Hall MHD simulations** revealed how Hall MHD alters the attainable magnetic field strength and the shape of magnetic energy power spectrum, **uncovering a new saturation mechanism** and **explaining our TDYNO experimental findings!**

# Acknowledgements

We acknowledge support by the U.S. DOE NNSA under Awards DE-NA0002724, DE-NA0003605, DE-NA0003934, DE-NA0004144, DE-NA0004147, and Subcontracts 630138 and C4574 with LANL; the U.S. DOE Office of Science under Award DE-SC0021990; and the NSF under Awards PHY-2033925 and PHY-2308844. We also acknowledge support from UKRI, grant number MR/W006723/1.