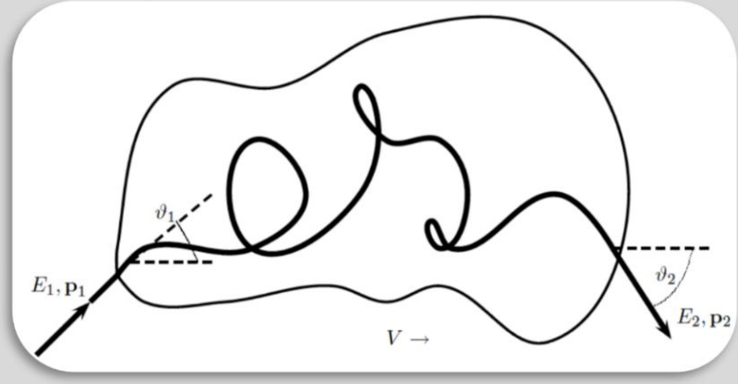
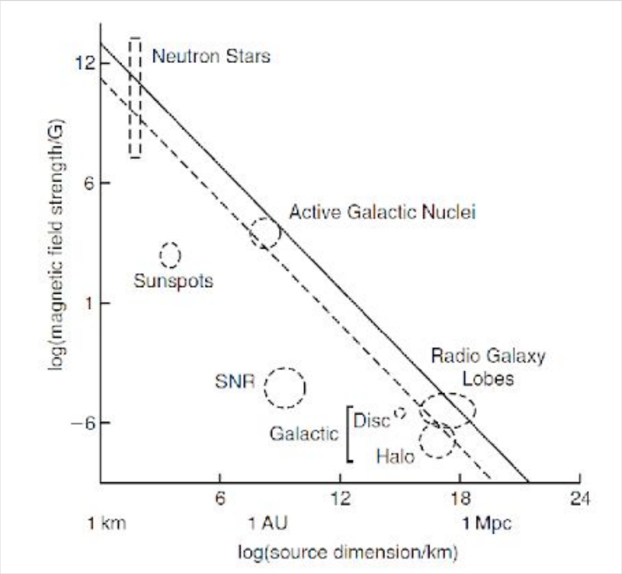
Experimental analogue of cosmic ray transport with a laser-produced turbulent plasma

Gianluca Gregori

Bologna, May 8th 2019

Cosmic ray acceleration requires the presence of a turbulent plasma

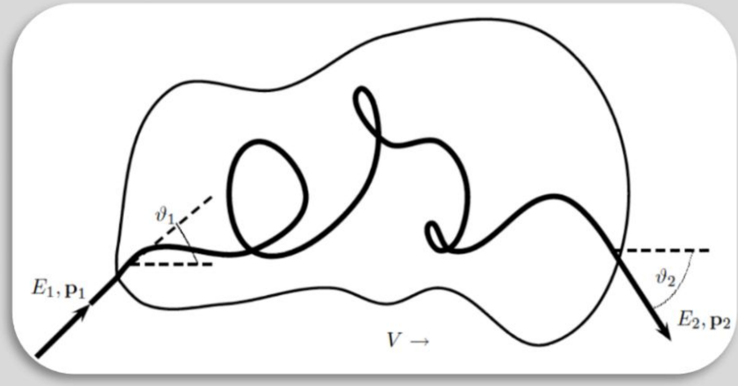


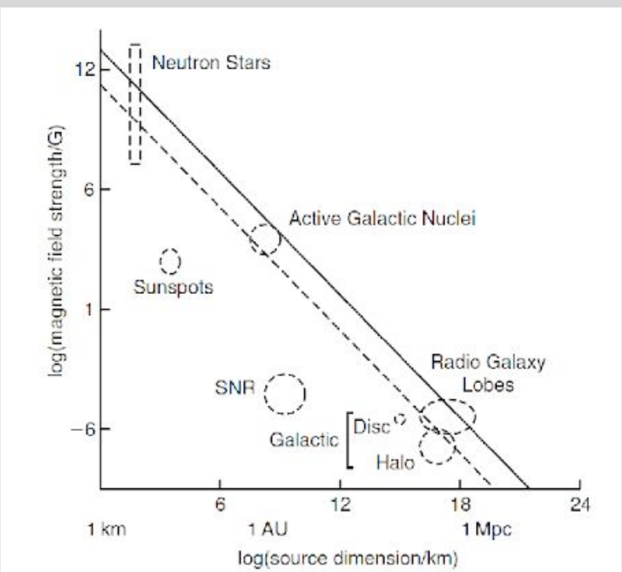


Protheroe (2004)

- Fast particles collide with moving magnetized clouds (*Fermi, 1949*). Particles can gain or lose energy, but head-on collisions (gain) are slightly more probable
- First-order 'Diffusive Shock Acceleration' (*Blandford & Ostriker 1978; Bell 1978*) is very efficient, however in several astrophysical contexts, second-order Fermi is more relevant (*Petrosian, SSR 173:535, 2012*)
- The evolution of CRs as they are accelerated in the plasma is governed by a diffusion equation (*Kaplan, 1955; Cowsik & Sarkar, 1984; Blandford & Eichler, 1987*)

Cosmic ray acceleration requires the presence of a turbulent plasma





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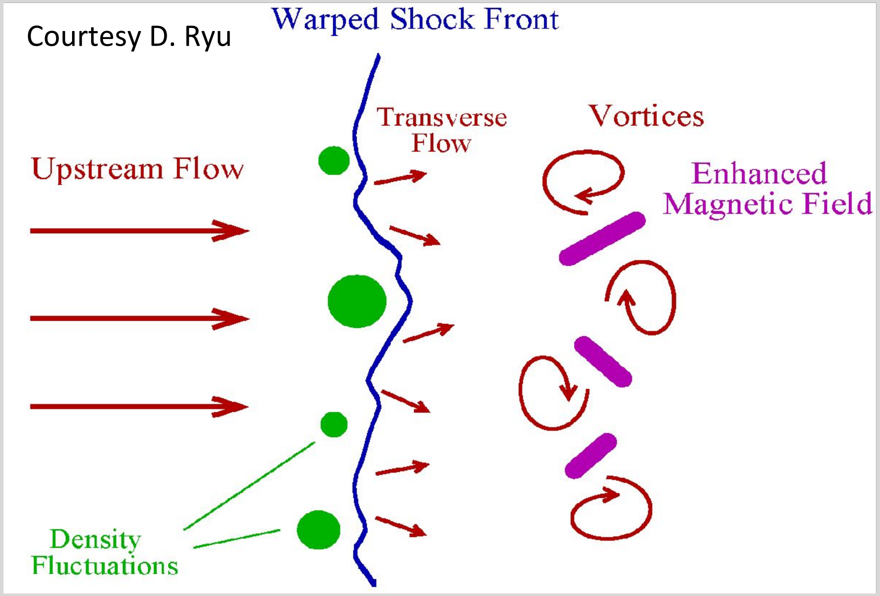
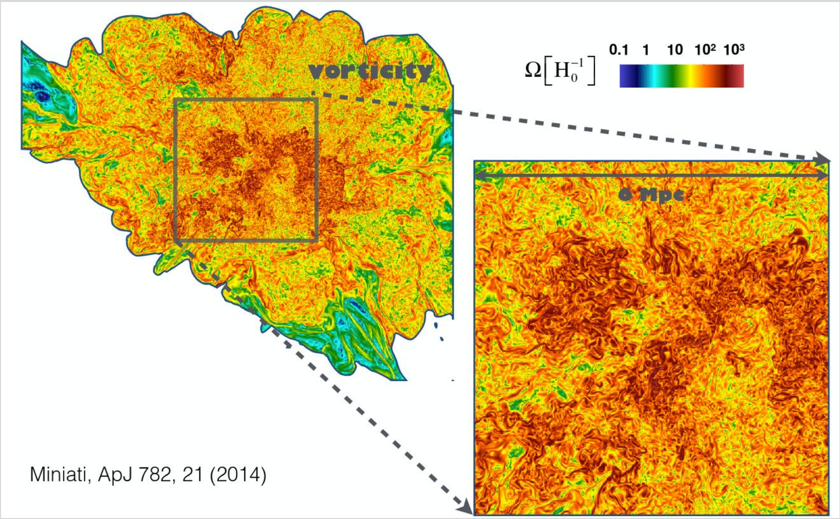
- ***In addition to astrophysical sources, laboratory plasmas can also potentially accelerate particle***

Turbulence is driven by accretion shocks in galaxy clusters

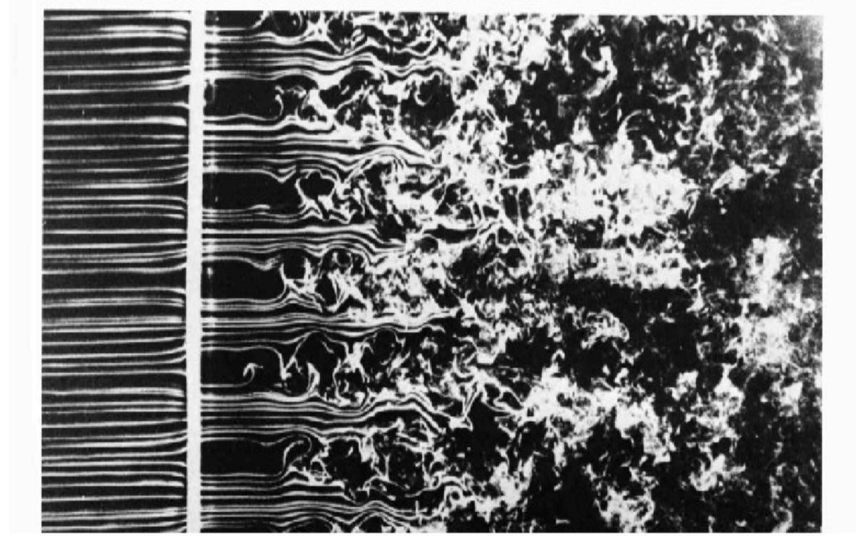


Vorticity



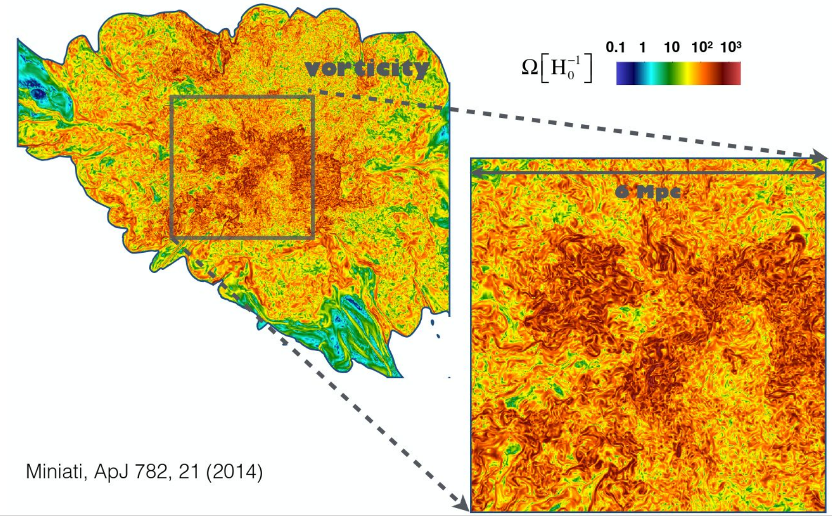
- ➜ The overall state of the Universe is akin to that of a turbulent and magnetized fluid
- ➜ Shocks inject vorticity into the intra-cluster medium
- ➜ Assume there are tiny magnetic fields generated before structure formation
- ➜ Magnetic fields are then amplified to dynamical strength and coherence length by turbulent motions

Turbulence is driven by accretion shocks in galaxy clusters



Van Dyke, Album of Fluid motion

Vorticity



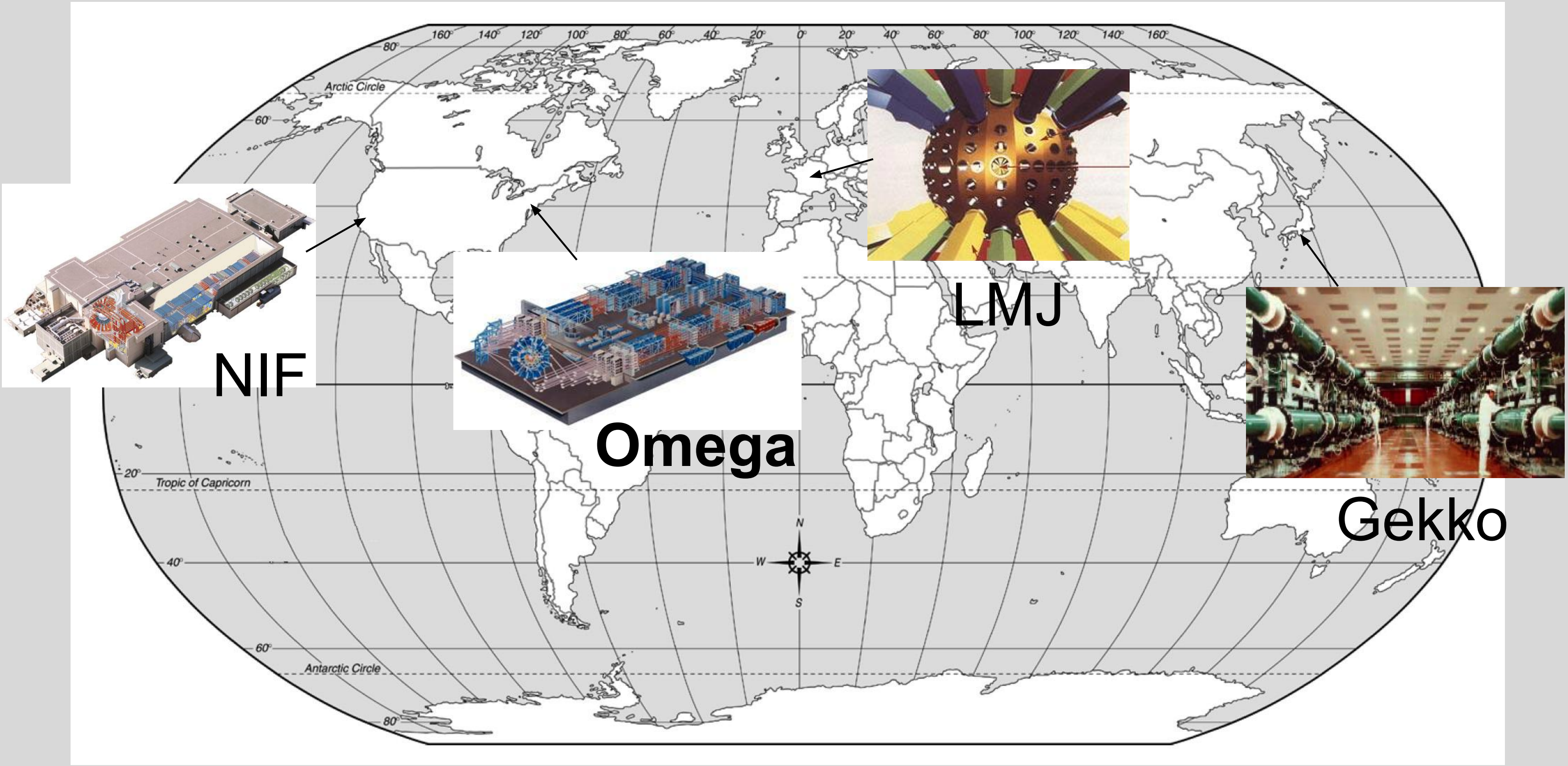
Miniati, ApJ 782, 21 (2014)

➜ The overall state of the Universe is akin to that of a turbulent and magnetized fluid

➜ Laboratory experiments can produce turbulent fluids. More challenging is to generate **turbulent and magnetized plasmas**

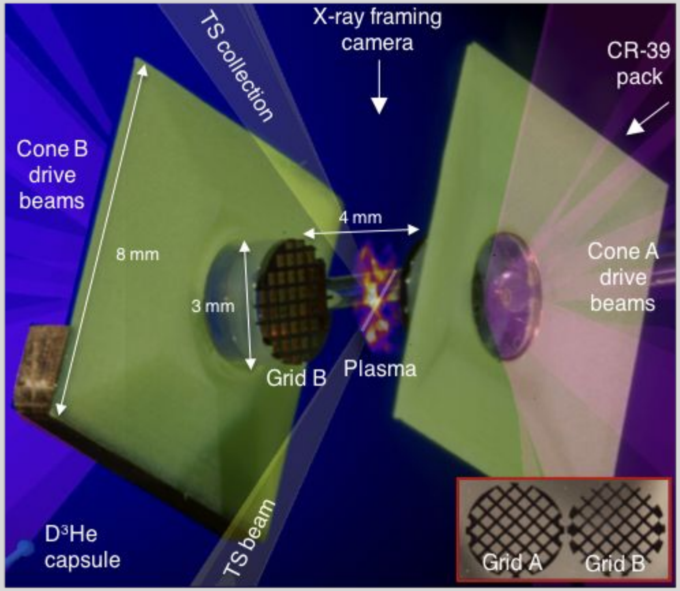
We study magnetized turbulence and particle acceleration using laser facilities

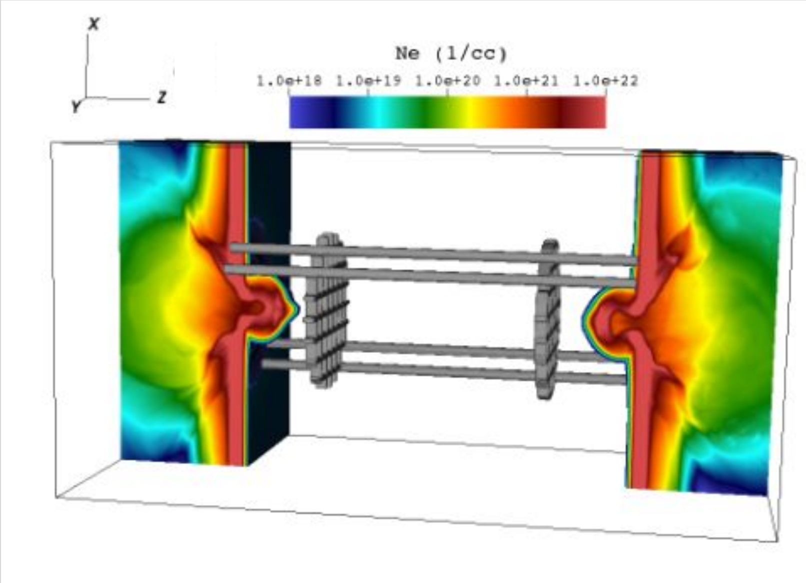
Nanosecond pulses (10^{-9} s)
Mega-joules energy
Petawatt peak powers (10^{15} W)



Experiment uses colliding flows and grids to create strong turbulence

- ➜ We use experiments to create colliding jets of plasmas
  - — Plasma flows are created by firing two sets of laser beams
  - — Flow initially destabilized by interaction with a grid
- ➜ In the collision region, strong turbulence is generated
- ➜ At the same time, magnetic fields are amplified by turbulent dynamo





Tzeferacos et al. Nature Comm. (2018)

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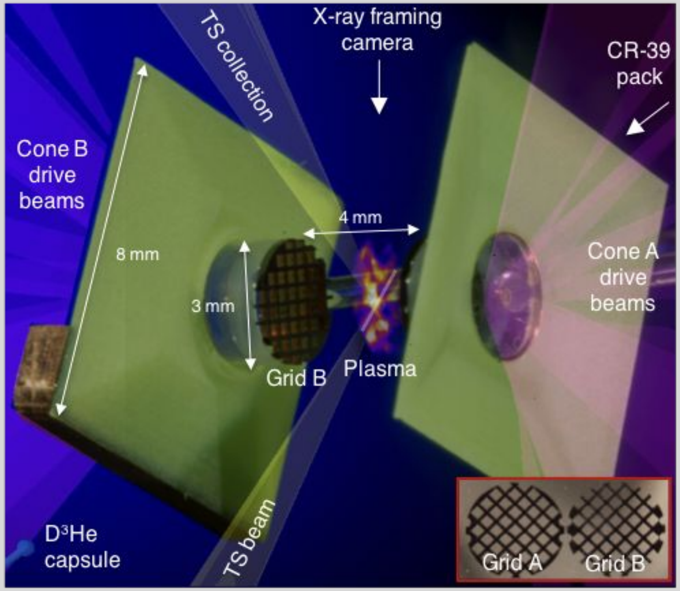

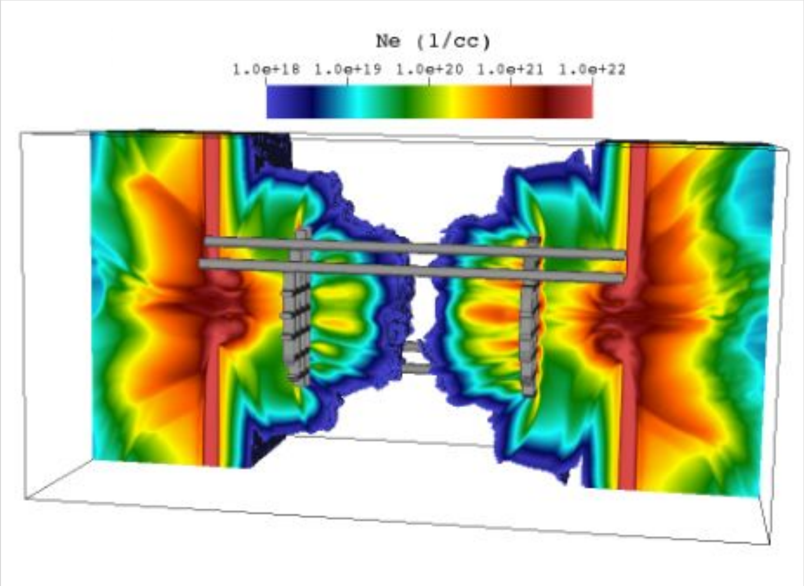

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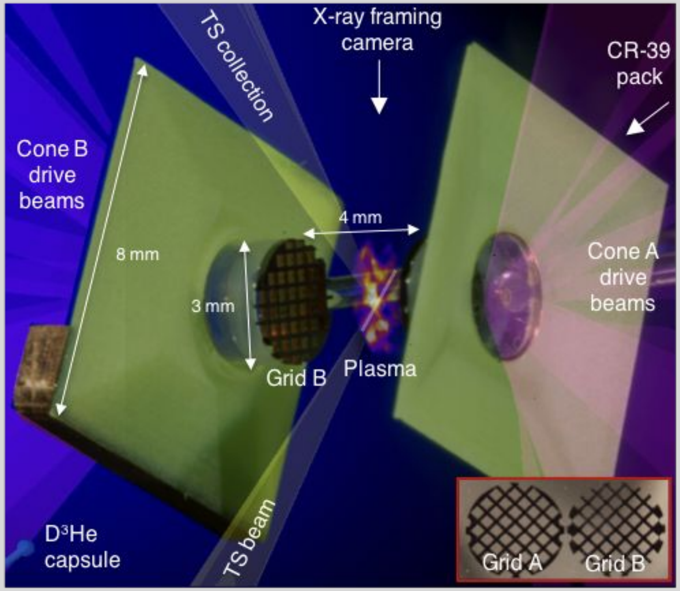
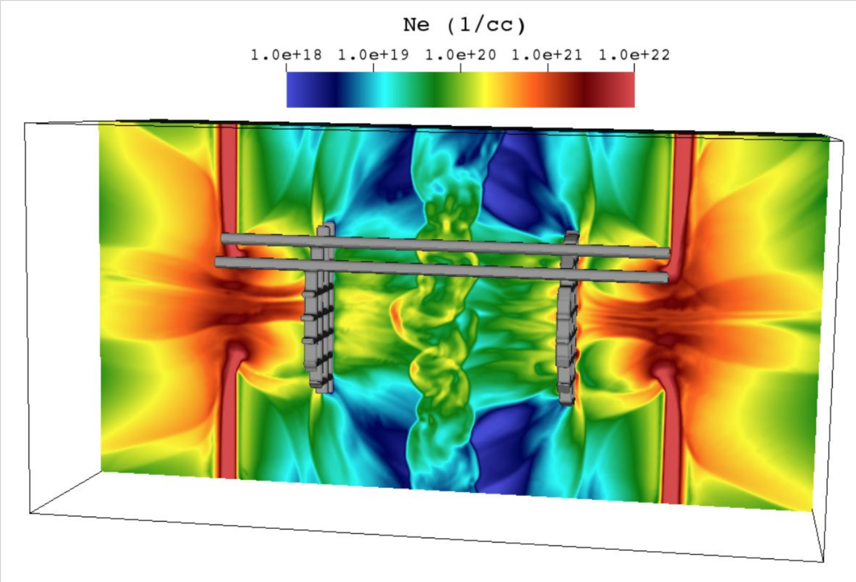
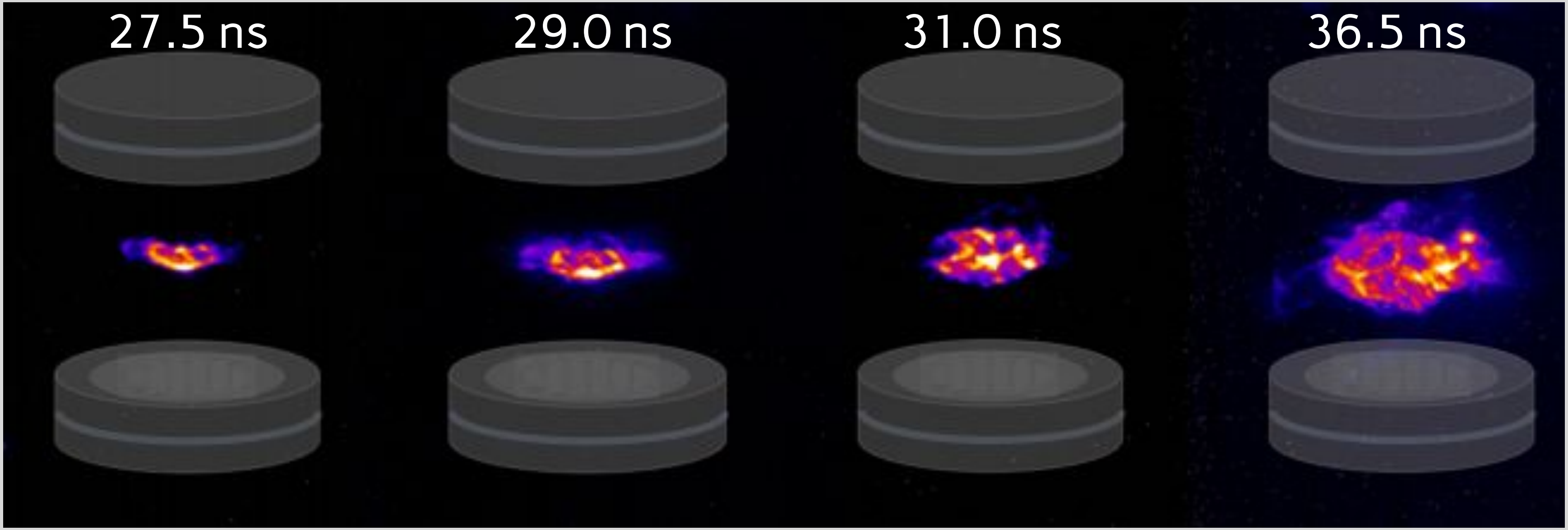




Tzeferacos et al. Nature Comm. (2018)

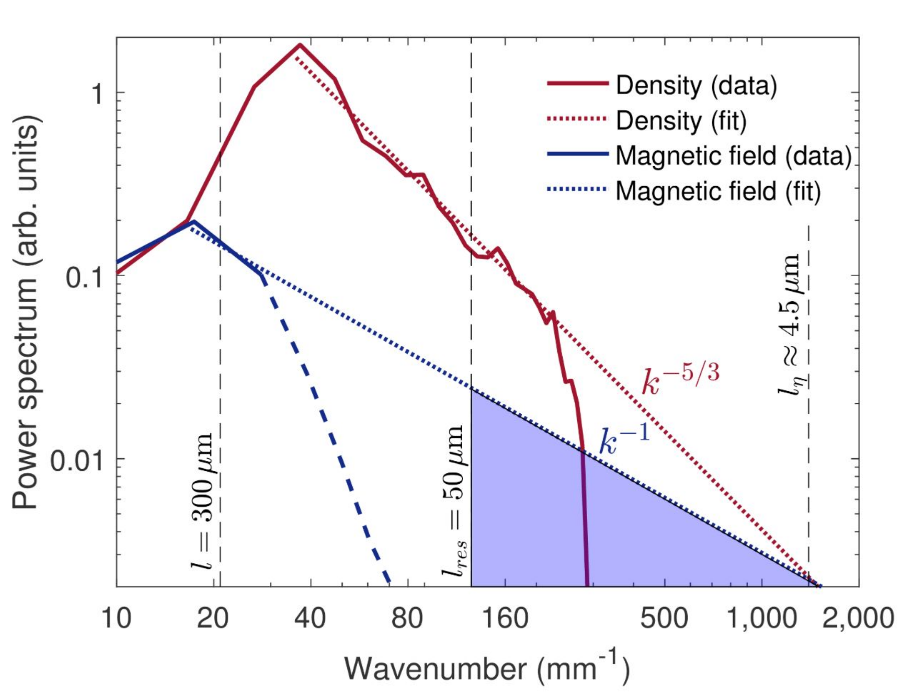
Several plasma diagnostics characterize the properties of turbulence and fields

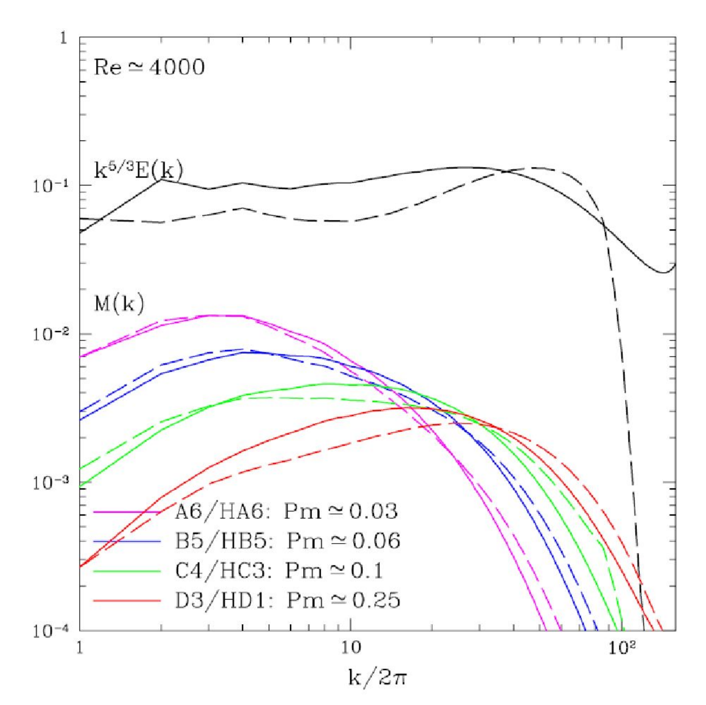


- ➜ **X-ray emission** used to on determine density variations (for subsonic flows, spectrum of density fluctuation is the same as that of kinetic energy)
- ➜ **Faraday rotation** used to determine magnetic field intensity
- ➜ **Proton deflectometry** used to measure magnetic field spectrum
- ➜ **Thomson-scattering** used to measure plasma temperature, fluid velocity and turbulent velocity

We have measured the properties of the turbulence in the plasma

Schekochihin et al. (2007)





- ➜ Density/velocity power spectrum is consistent with Kolmogorov's $k^{-5/3}$ power-law
- ➜ Magnetic field power spectrum is consistent with k^{-1} power-law (predicted for dynamo produced magnetic fields)

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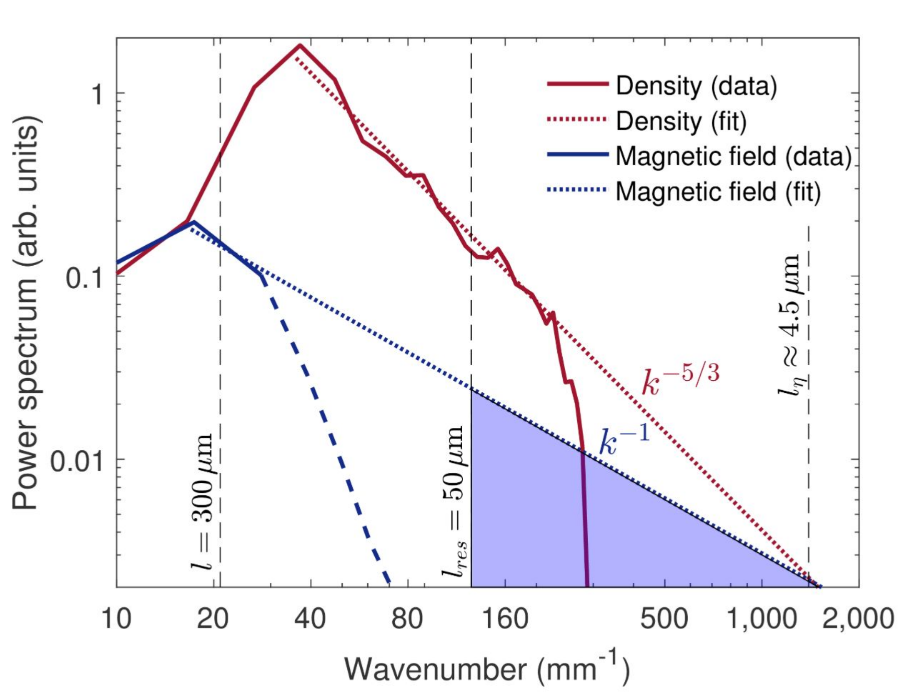
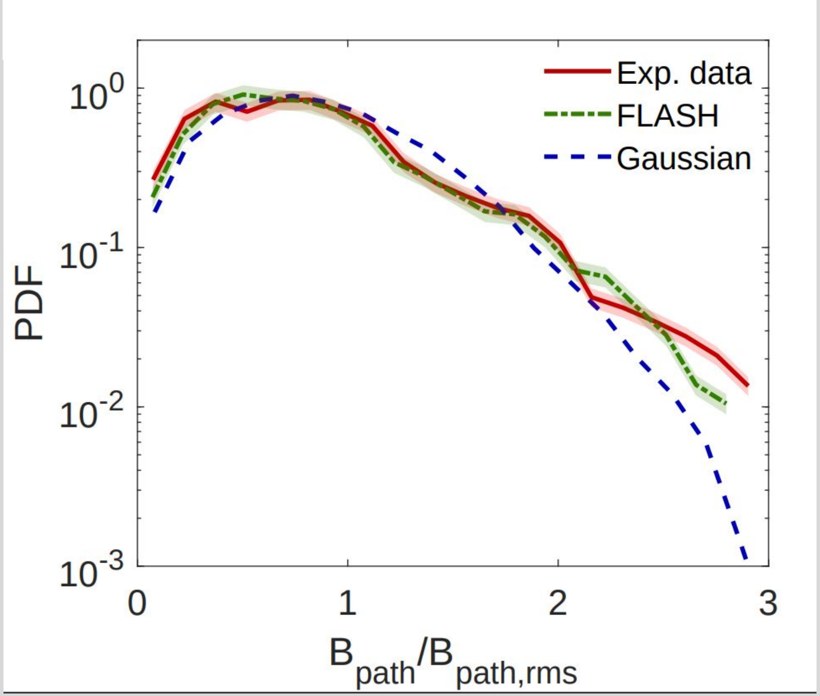
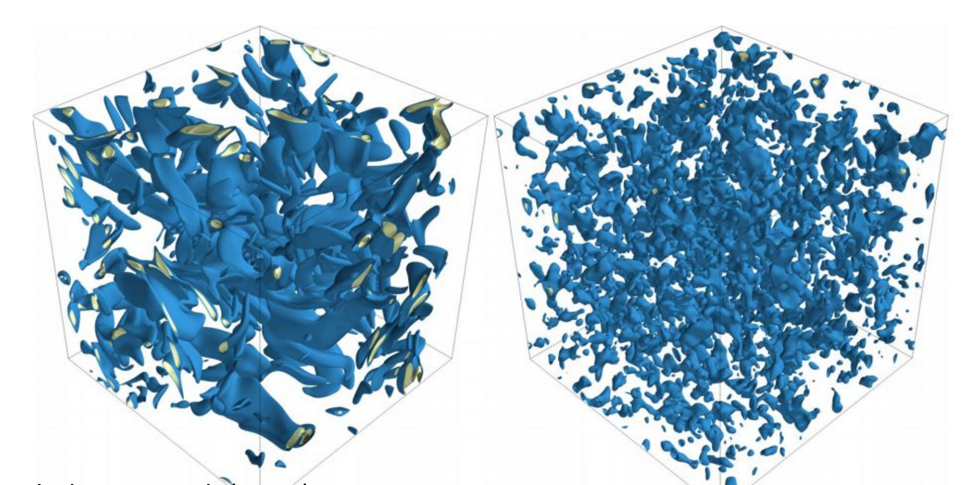




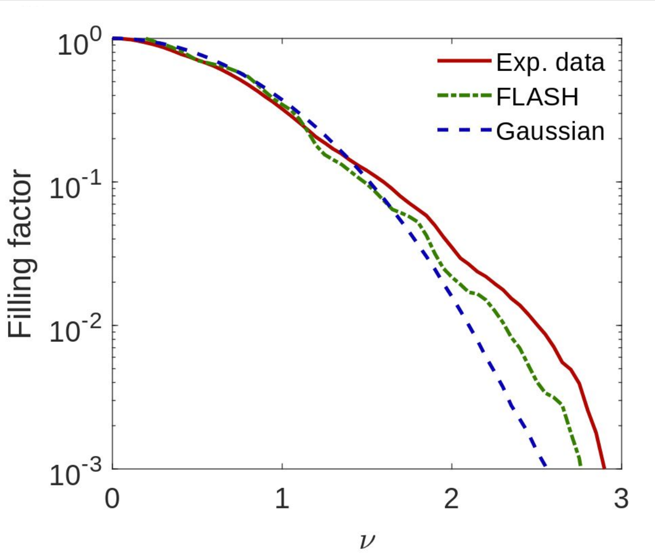
- ➜ Density/velocity power spectrum is consistent with Kolmogorov's $k^{-5/3}$ power-law
- ➜ Magnetic field power spectrum is consistent with k^{-1} power-law (predicted for dynamo produced magnetic fields)
- ➜ The magnetic field probability distribution function is **not Gaussian**
- ➜ Good agreement with numerical predictions (FLASH code)

Magnetic fields in the experiments are not volume-filling

Non Gaussian **Gaussian**



Shukurov et al. (2017)

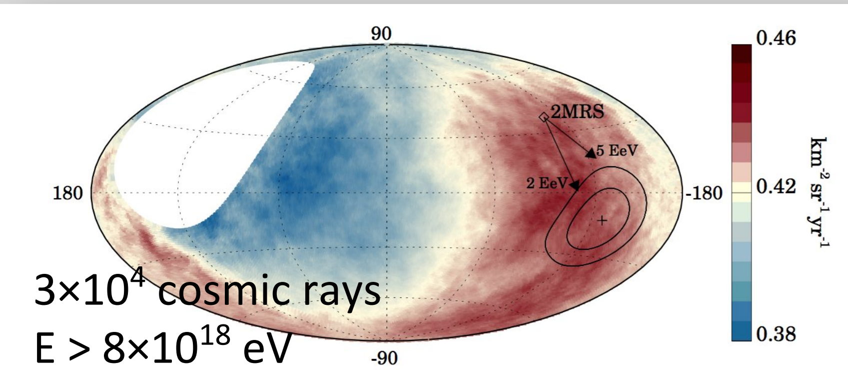


- ➜ The fractional volume with magnetic fields $B > \nu B_{rms}$ shows a non-Gaussian behaviour
- ➜ Magnetic field spatial distribution shows islands of large field strength surrounded by regions of weak field
- ➜ Spatially intermittent magnetic fields are believed to be more representative of the ISM/IGM B-field distribution

Magnetic fields and CR's observed on Earth

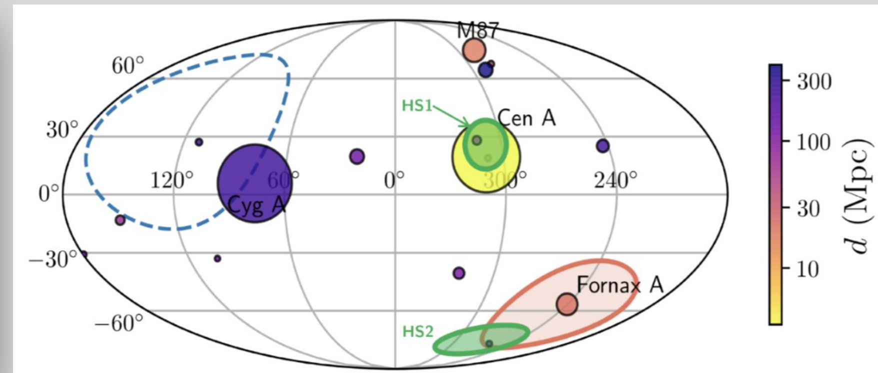
The Pierre Auger Collaboration, Science (2017)

$$\frac{\partial f}{\partial t} + \mathbf{u} \cdot \nabla f = \frac{\partial}{\partial u_i} D_{ij} \frac{\partial f}{\partial u_j}$$



$3{\times}10^4$ cosmic rays

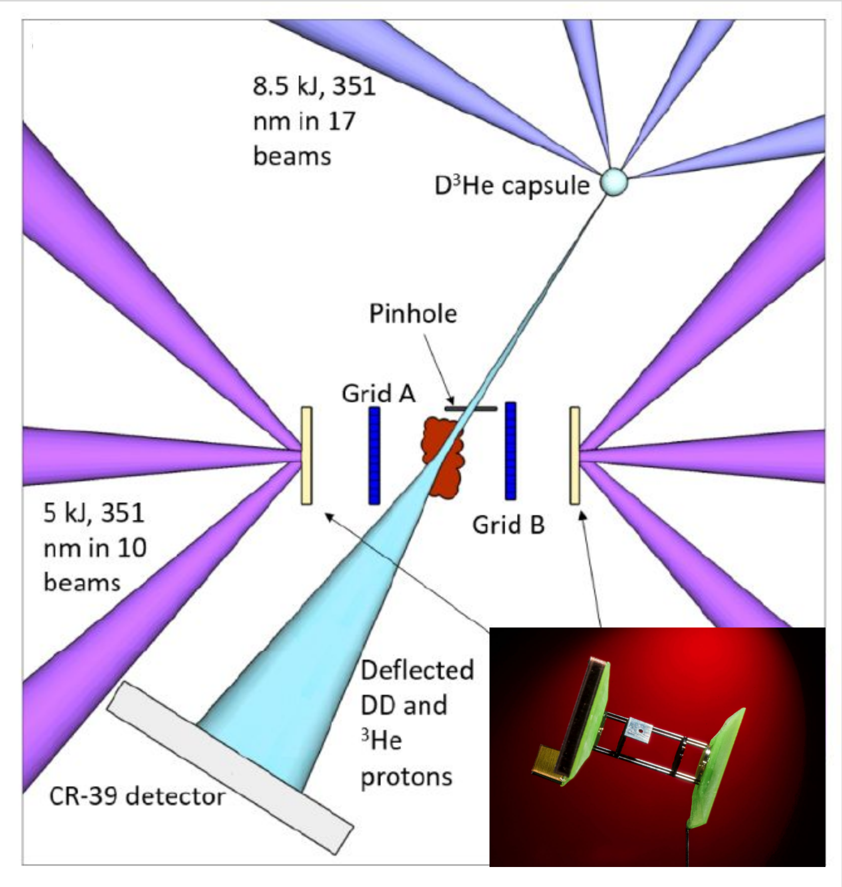
$E > 8{\times}10^{18}$ eV



Matthews et al. (2018)

- Extragalactic CRs will traverse the magnetic fields present in the IGM
- The spectral distribution of the turbulent fields and the particle energy (gyroradius vs. the correlation length of the fields) determine how CRs will diffuse through cosmic plasma (*Jokipii 1966, Subedi et al. 2017*), setting their mean free path and the diffusion coefficient (*Batchelor 1953*)
- Spatial super- ,sub-, or normal diffusion? (*Jokipii & Parker 1969, Reville et al. 2008, Lazarian & Yan 2014*)

Simulating UHECR with fusion protons



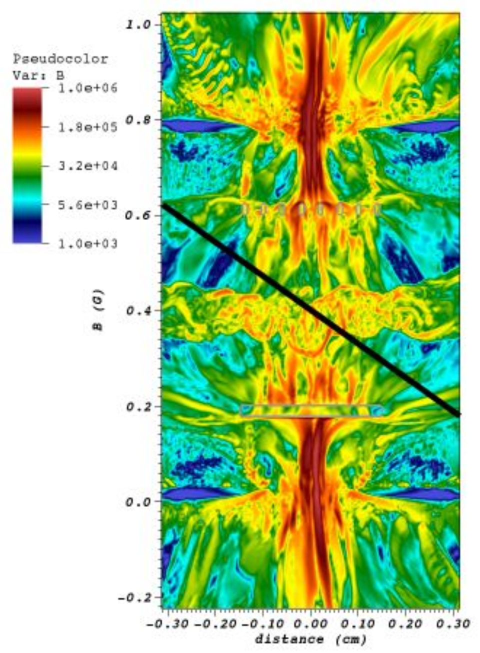
Chen et al. arXiv 1808.04430 (2018)

- ➜ 3 MeV and 15 MeV produced by DD and D^{3}He fusion reactions
- ➜ 300 μm pinhole used to collimate proton beam
- ➜ As protons pass through the turbulent plasma they acquire transverse deflections (diffusion)
- ➜ Larmor radius of these protons much larger than magnetic field correlation length:

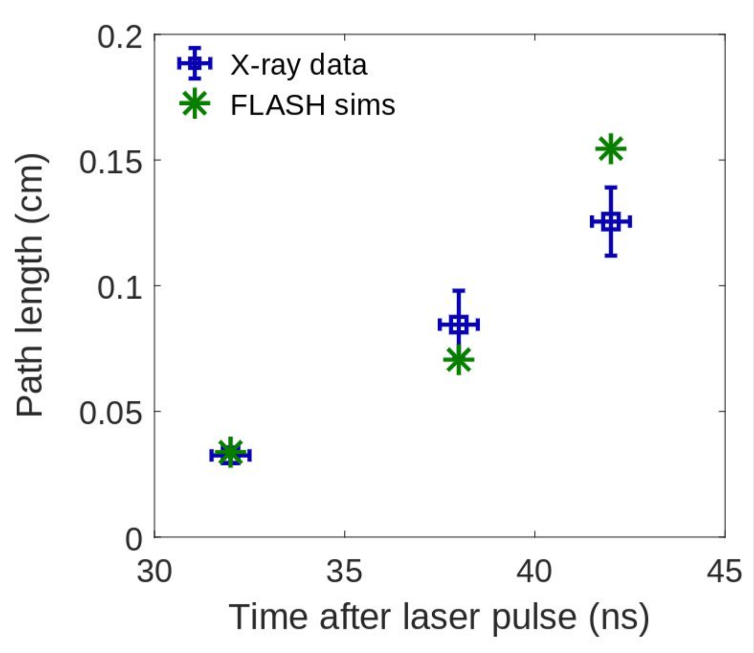
$$r_g/\ell_c > 10^3$$

An analogue for Ultra High Energy Cosmic Rays (UHECR)!

Many possible mechanisms for magnetic field generation



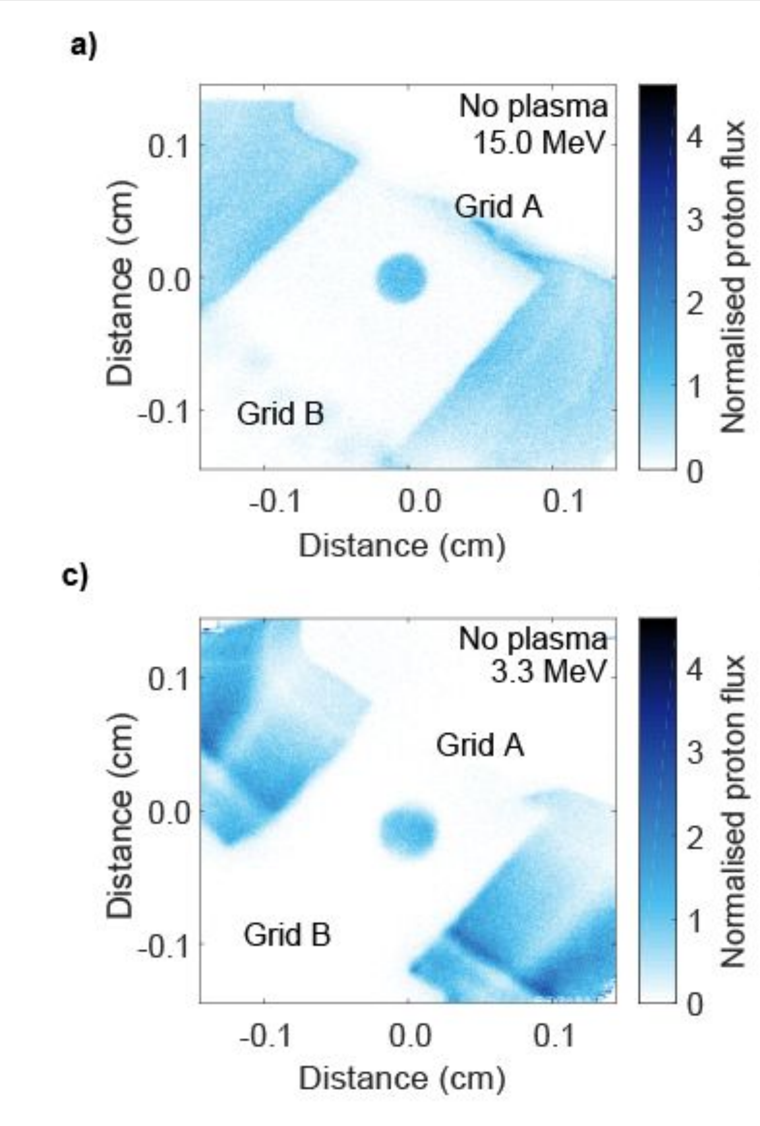
Proton path



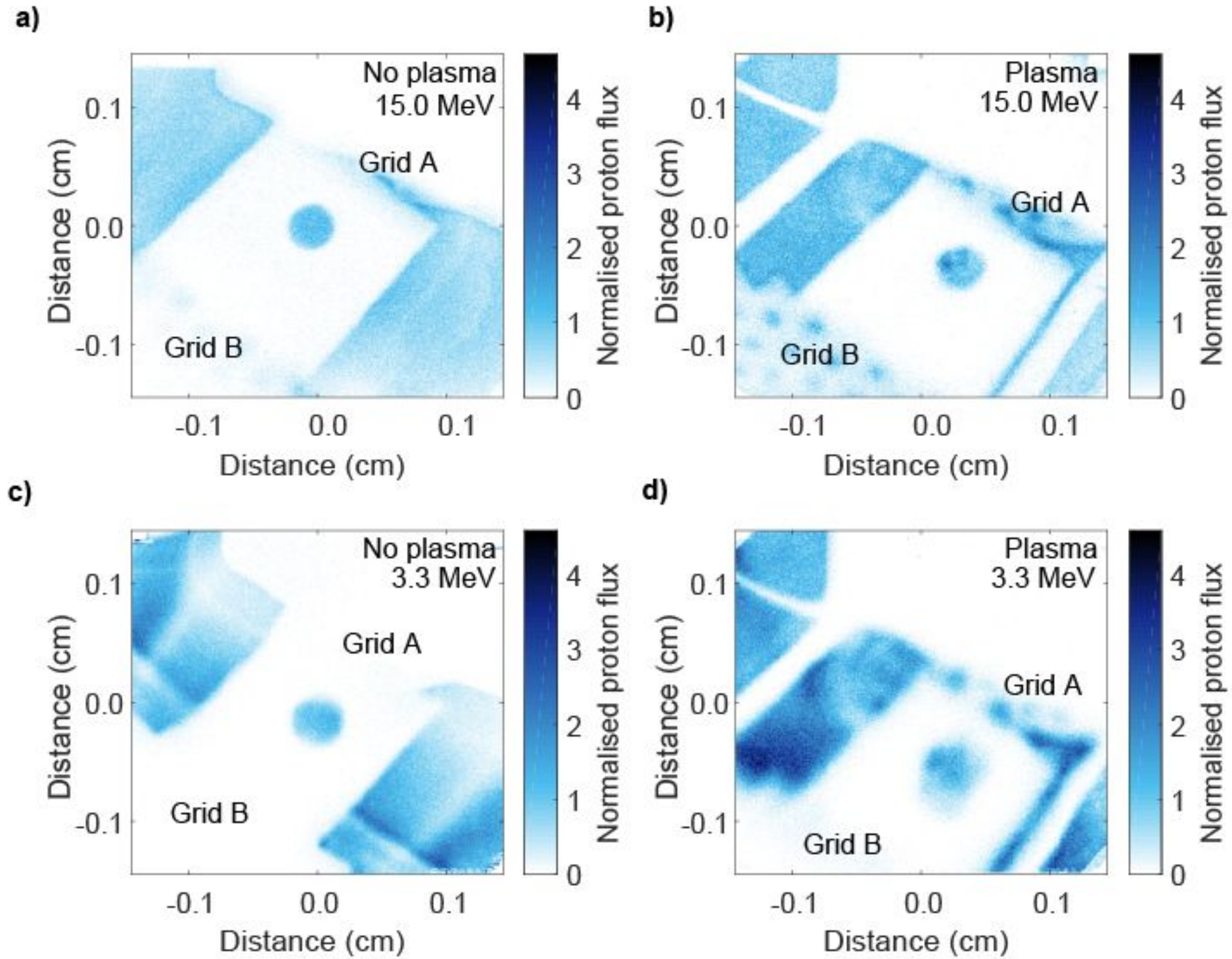
- The proton path length is accurately evaluated in the simulations (direct measurement) and the experiment (FWHM of the interaction region from X-ray imaging)

- Interaction length: ℓ_i~0.5–1.5 mm

We use our experimental platform to study proton transport through plasma



Significant broadening of the proton beam is observed



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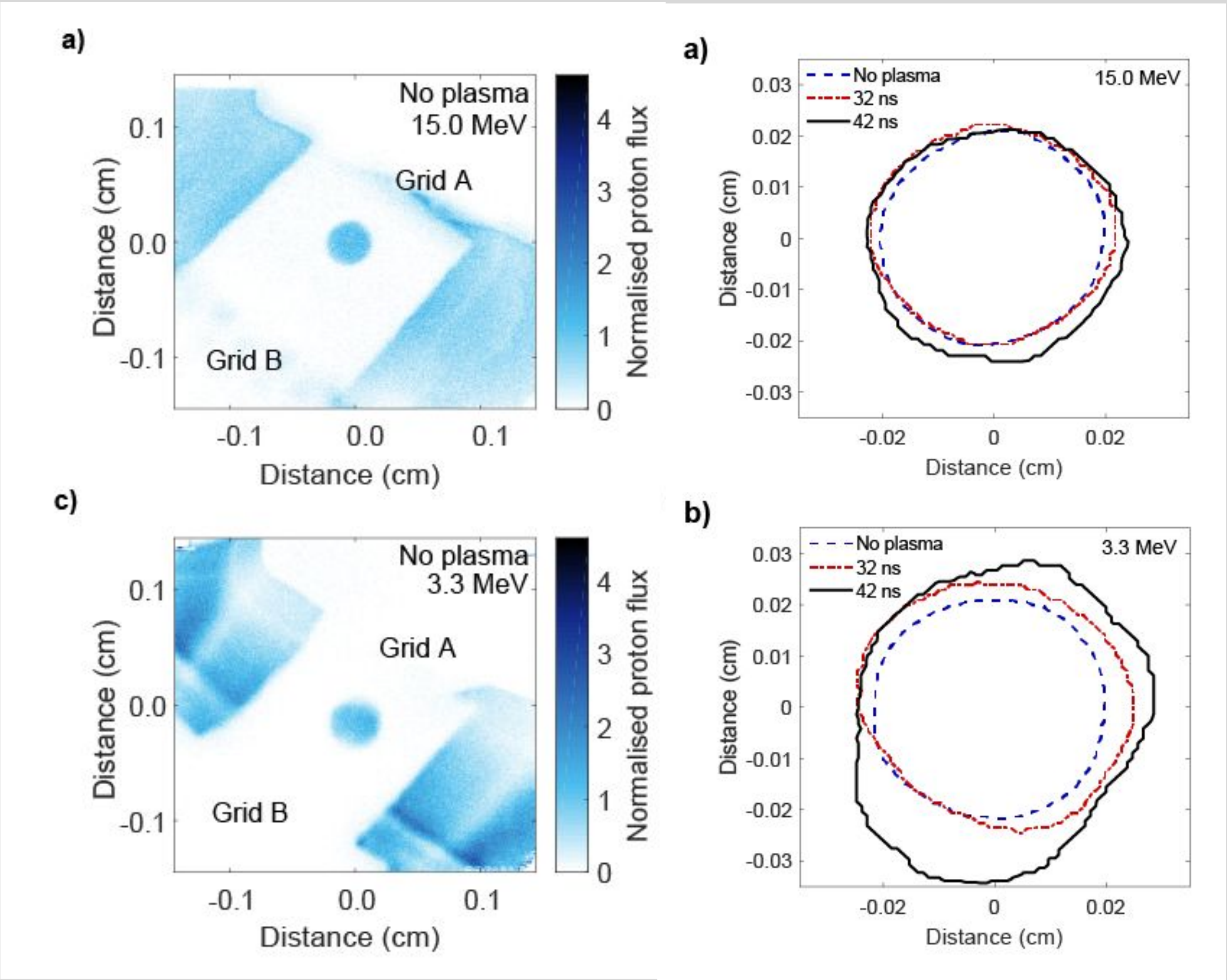
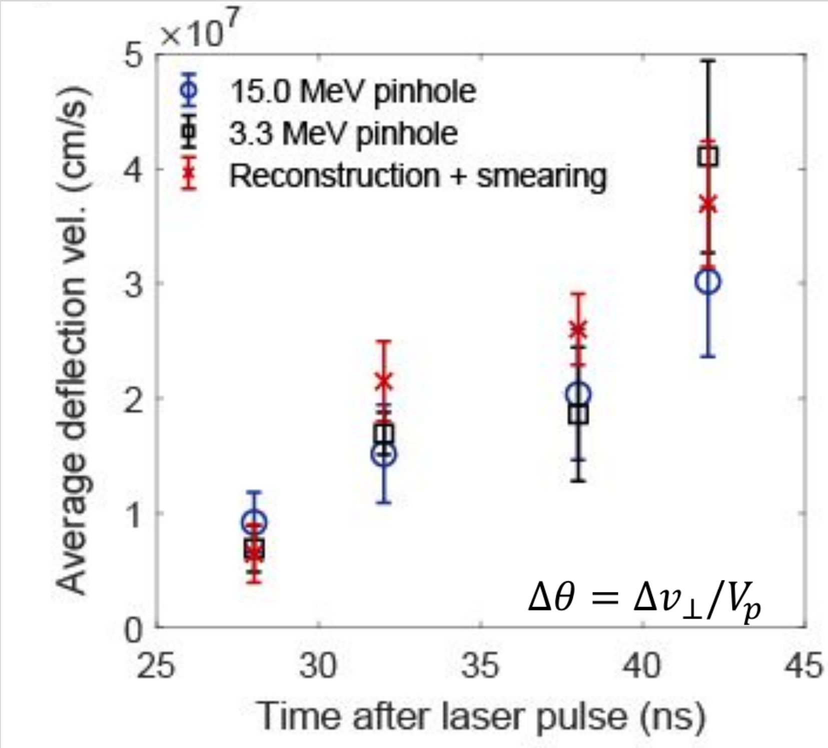


Deflections are due to stochastic magnetic fields



- The protons of the beam obtain a transverse velocity

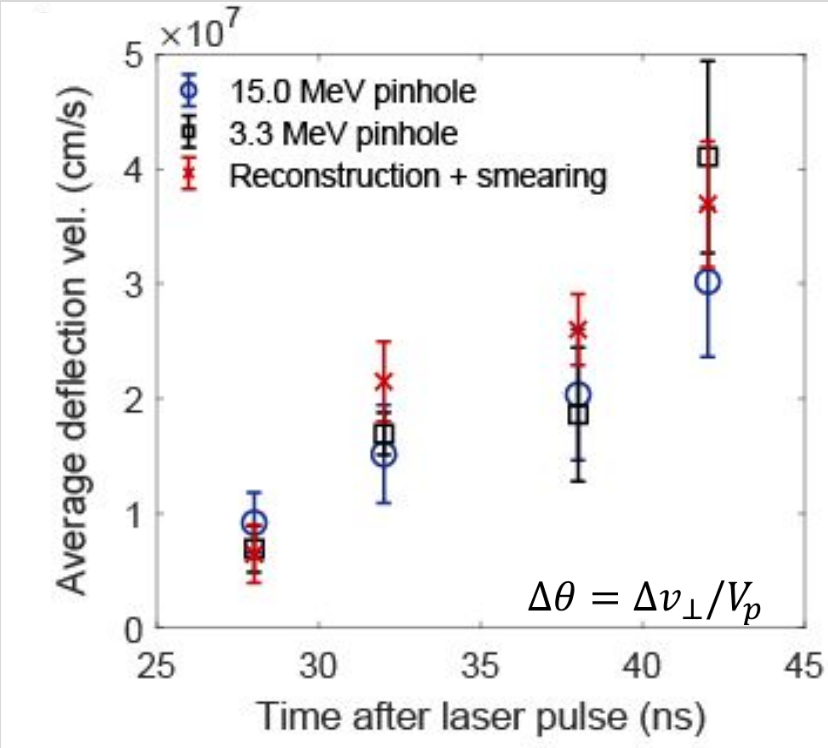
$$\Delta v_\perp = \frac{e}{m_p V_p} \int_0^{\ell_i} E(z)dz$$

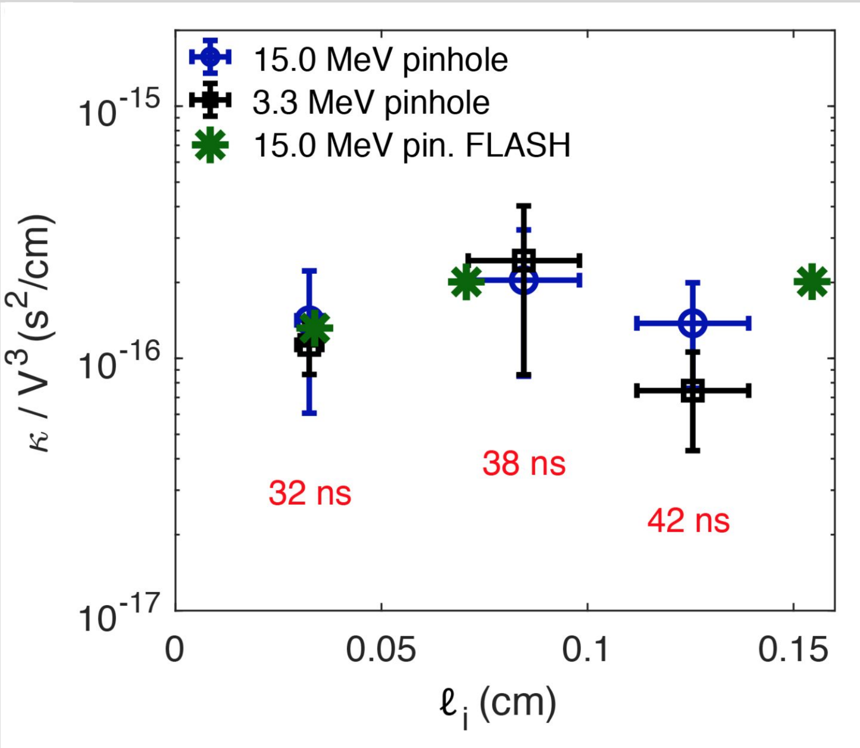
- The electric field is given by the generalized Ohm's law
- The transverse velocity is independent of the proton energy: deflections are due to B-fields

➜ From the measured deflection velocity, we can estimate the angular scattering coefficient in velocity space

$$\nu = \frac{(\Delta v_\perp / V_p)^2}{\tau} \qquad \tau = \ell_i / V_p$$

For an infinite, isotropic plasma we can estimate the diffusion coefficient

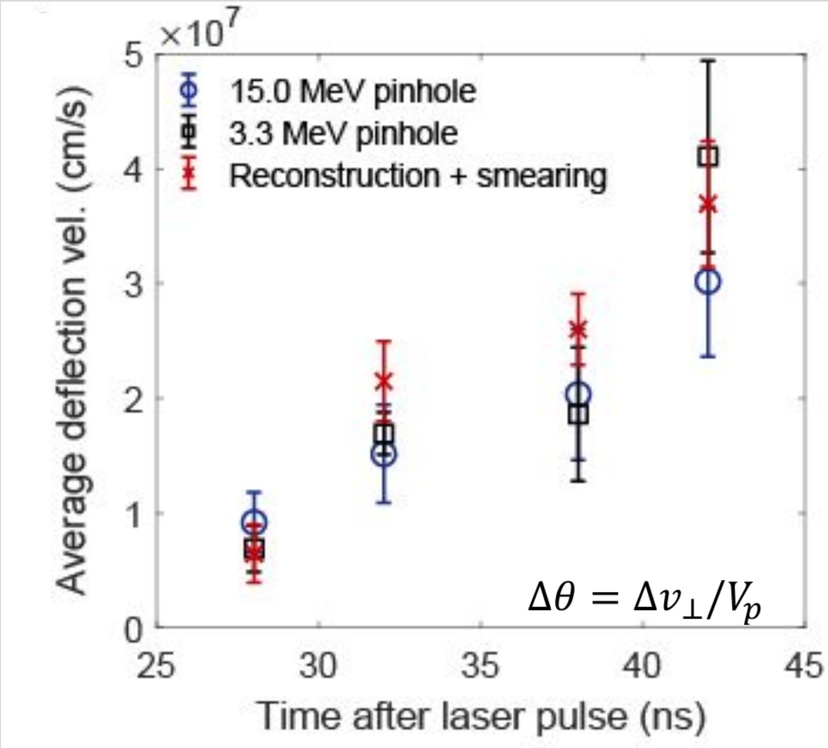


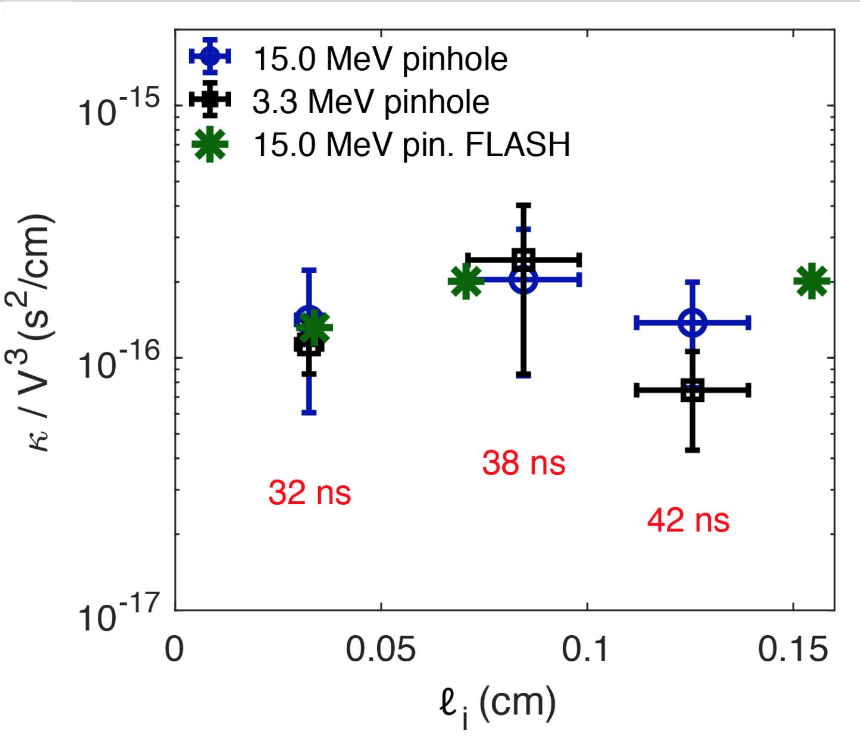


➜ If we had an infinite isotropic plasma, the derived scattering rate implies a diffusion coefficient

$$\kappa = \frac{V_p^2}{\nu} = \frac{\ell_i V_p^3}{(\Delta v_\perp)^2}$$

Deflections are due to stochastic magnetic fields



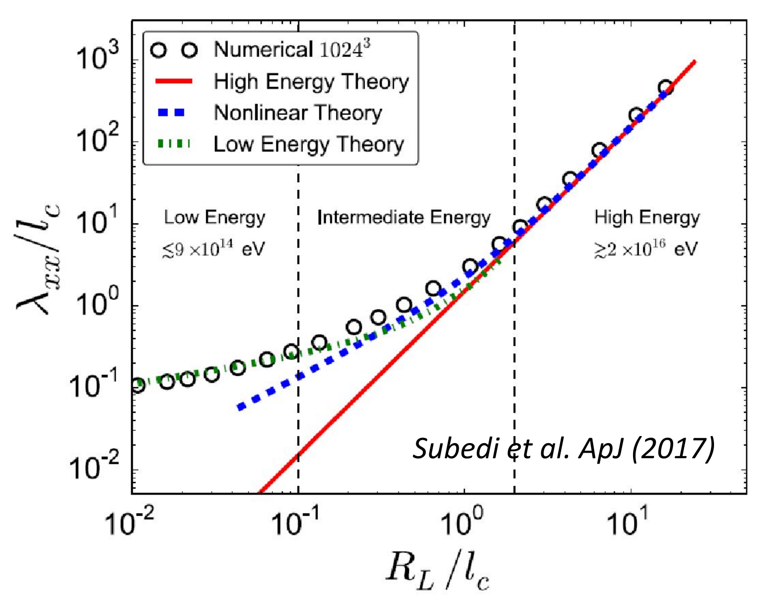


➜ Since κ/V^3 is constant, it means that

$$(\Delta v_\perp)^2 \propto \ell_i \propto \tau$$

➜ This implies **normal (Markovian) spatial diffusion** (*Tsytovich 1977, Salchi 2009, Subedi et al. 2017*)

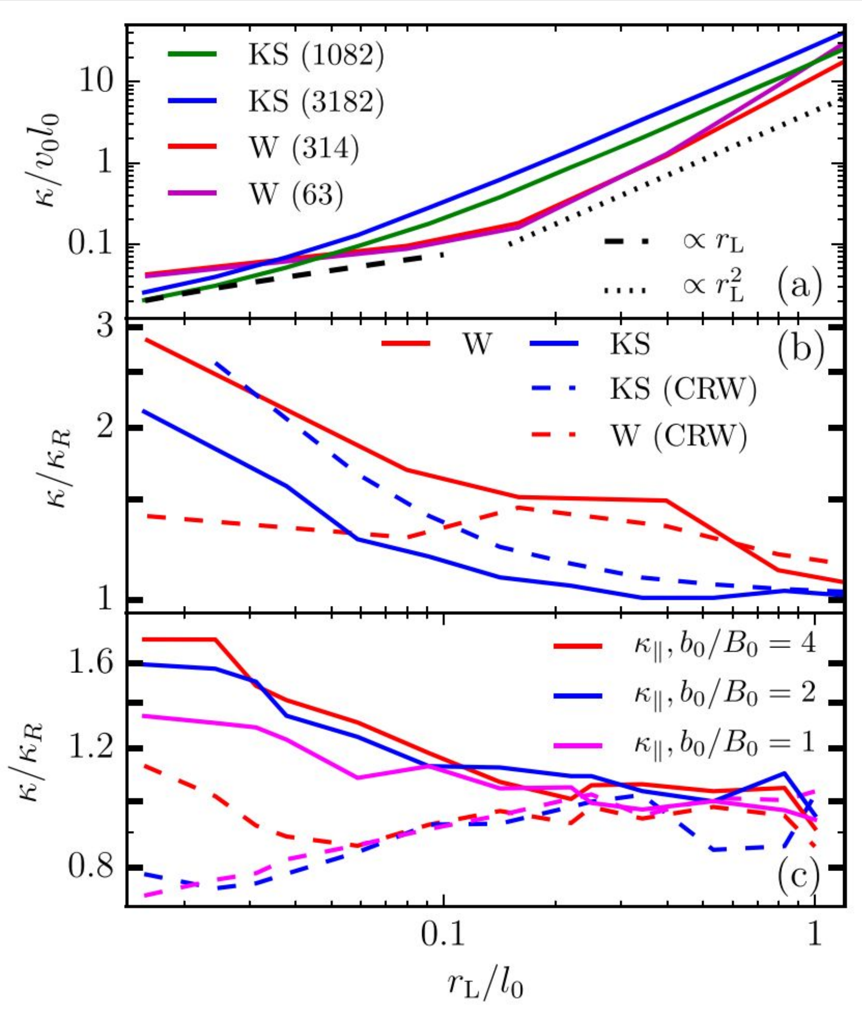
Experimental data are consistent with simple theory of UHECR diffusion



$$\lambda/\ell_c \sim (V_p/\nu)/\ell_c \propto (r_g/\ell_c)^2$$

- ➜ Protons in the experiment have a ratio ℓ_c/r_g that is the same as that of 10 EeV UHECR interacting with the Galactic magnetic field
- ➜ In this high energy regime, the experiment shows that the mean free path depends only on the Larmor radius - consistent with numerical simulations
- ➜ This is independent of the structure of turbulence: in the experiment we have k^{-1} and in *Subedi et al.* $k^{-3/2}$

Intermittency of the magnetic field is not important for UHECR diffusion



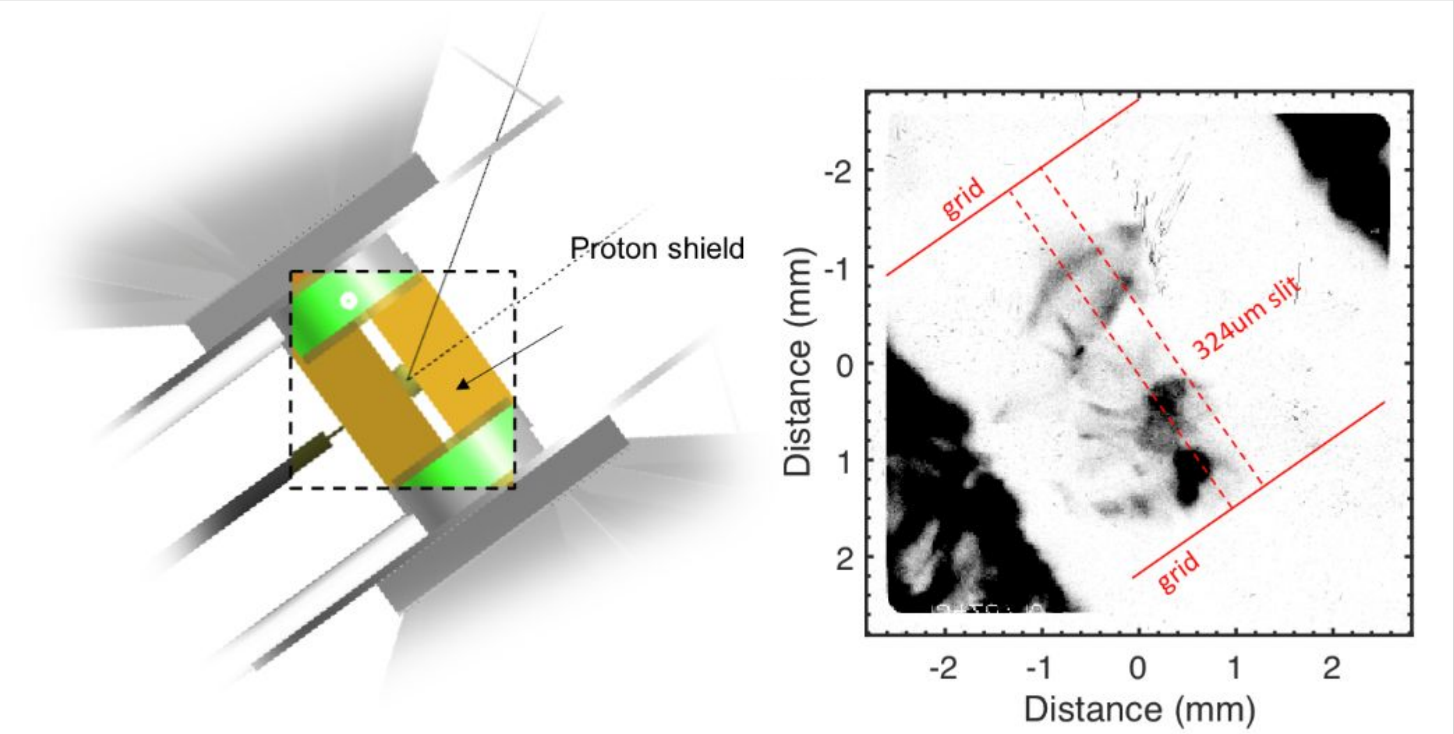
Shukurov et al. (2017)

- In the Auger data we see a strong anisotropy of CR arrival directions above 8 EeV (intermittency?)
- For correlated random walks, the diffusion coefficient is modified as (*Shukurov et al. 2017*):

$$\kappa = \frac{\ell_i V_p^3}{(\Delta v_\perp)^2}\left[1 + \frac{2\langle\cos\Delta\theta\rangle}{1-\langle\cos\Delta\theta\rangle}\right]$$

- Since $\Delta\theta \ll 1$ in the experiment, we expect diffusion coefficient to be $\propto r_g^2$

On NIF we expect to reach conditions where intermittency is important



➜ At the National Ignition Facility (NIF) laser, turbulence reaches equipartition at much larger values of the magnetic field

➜ Proton deflections are **not** in the small angle regime (as seen in the data)

➜ Expect significant departures from normal diffusion (*work in progress*)

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Summary

- The interplay between charged particles and turbulent magnetic fields is crucial to understanding how CRs propagate through space
- We have designed a novel experimental platform at Laser Facilities to study astrophysical processes in magnetized turbulence
- Collimation of fusion protons enabled us to create an experimental analogue of UHECR transport in magnetized turbulence
- We fully characterized the proton diffusion in the experiments, recovering deflection velocities, angular scattering coefficients, spatial diffusion coefficients, and mean free paths that are consistent with normal diffusion and a random walk picture
- The experiments validated theoretical tools and simulations used in analyzing the propagation of UHECRs through the IGM

Thanks to a fantastic team!

L.E. Chen[1], P. Tzeferacos[2], A.F.A. Bott[1], A. Rigby[1], A.R. Bell[1], R. Bingham[3,4], C. Graziani[2],

J. Katz[5], M. Koenig[6], C.K. Li[7], R. Petrasso[7], H.-S. Park[8], J.S. Ross[8], D. Ryu[9],

D. Ryutov[8], T.G. White[1,10], B. Reville[11], J. Matthews[2], J. Meinecke[1], F. Miniati[1], E.G. Zweibel[12], S. Sarkar[1], A.A. Schekochihin[1], D.H. Froula[5], D.Q. Lamb[2], and G. Gregori[1,2]

[1]U Oxford [2]U Chicago [3]RAL [4]U Strathclyde [5]LLE-U Rochester [6]LULI [7]MIT [8]LLNL [9]UNIST [10]U Nevada-Reno [11]MPIK Heidelberg [12]U Wisconsin-Madison