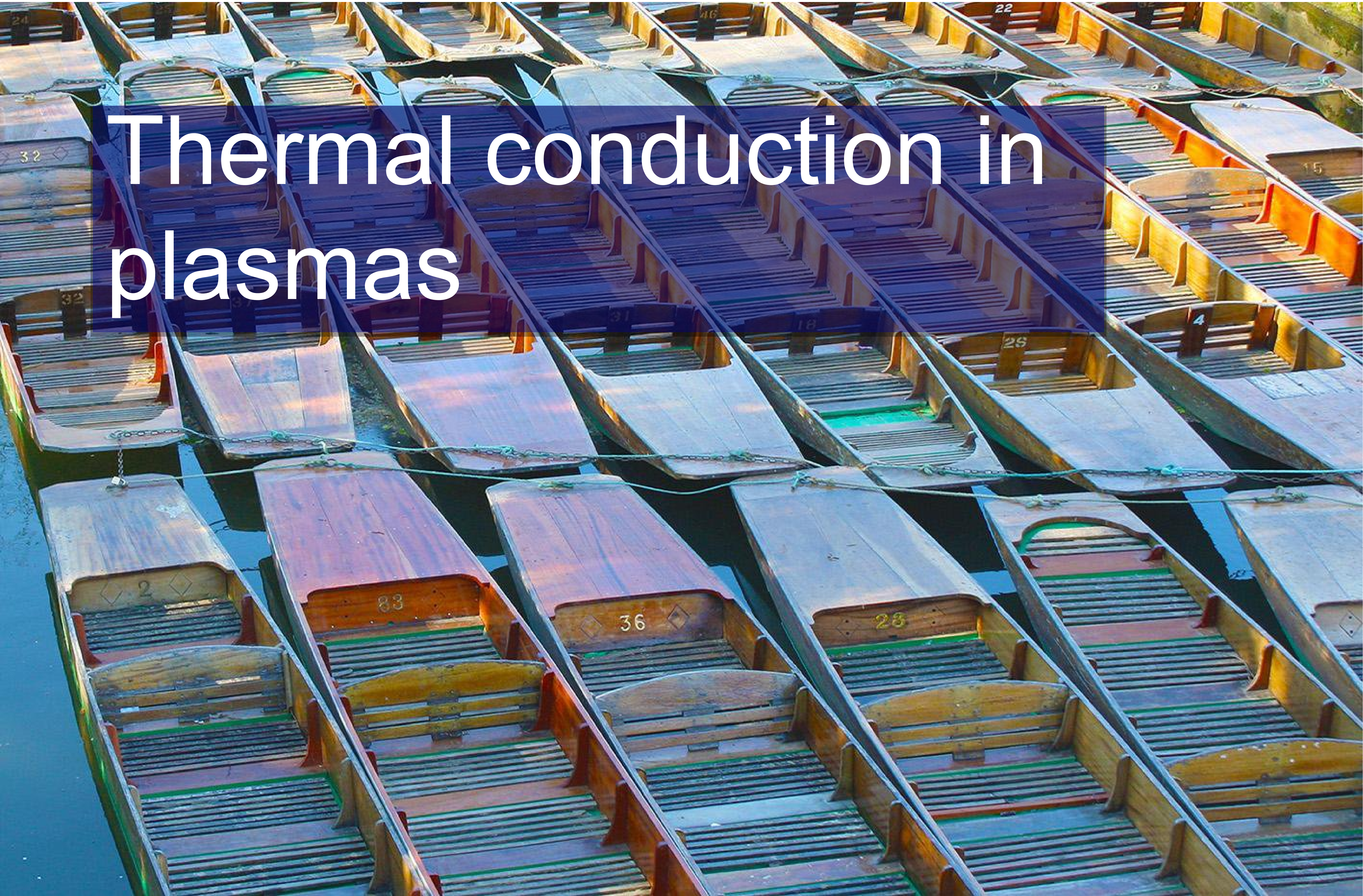
Strong suppression of heat conduction in laboratory and astrophysical plasmas

Gianluca Gregori (University of Oxford)

21 July 2022



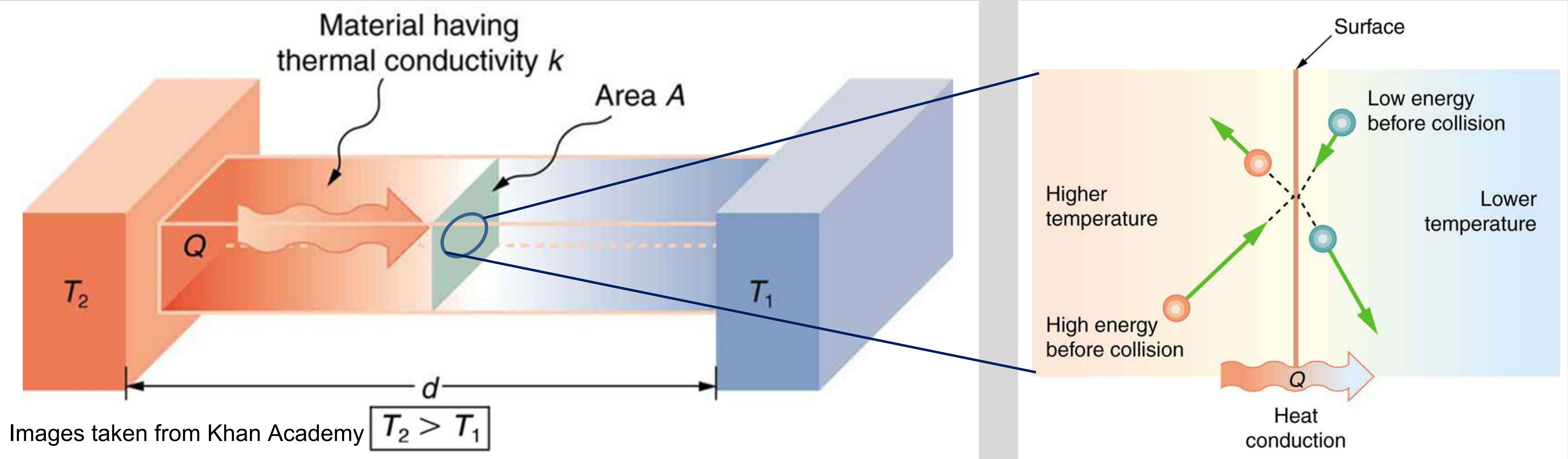
Thermal conduction in plasmas

Classical (Spitzer) thermal conduction in plasmas relies on Coulomb collisions

- In a classical (collisional) plasma electron collisions mediate the heat transport. The heat flux is given by Fick's law

$$Q = \frac{(4\pi\,\epsilon_0)^2 (k_B T)^{5/2}}{{m_e}^{1/2} e^4} \nabla(k_B T)$$

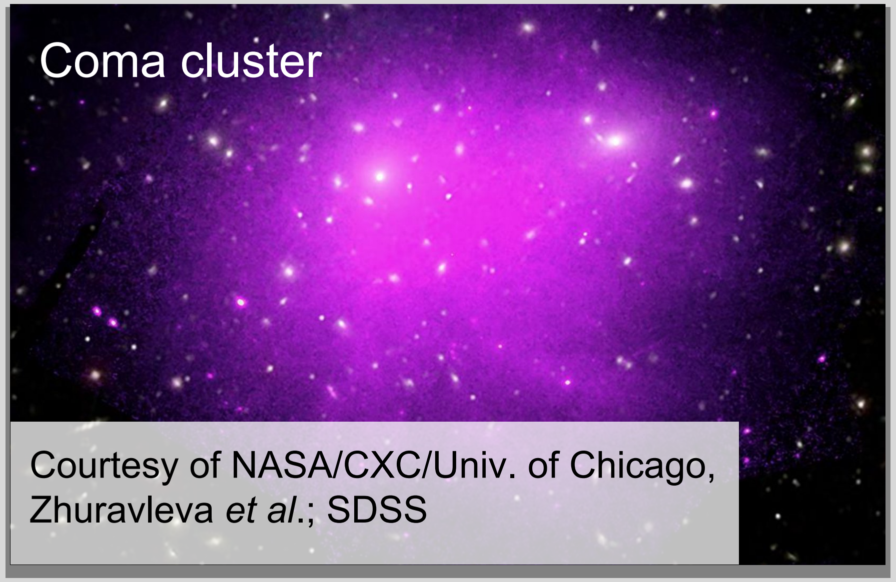
- This model assumes the electrons to be in equilibrium, with a Maxwell-Boltzmann distribution, and with no magnetic fields.
- In several laboratory and astrophysical conditions, the above assumptions do not hold, and conduction does not always take a Fick's law form.



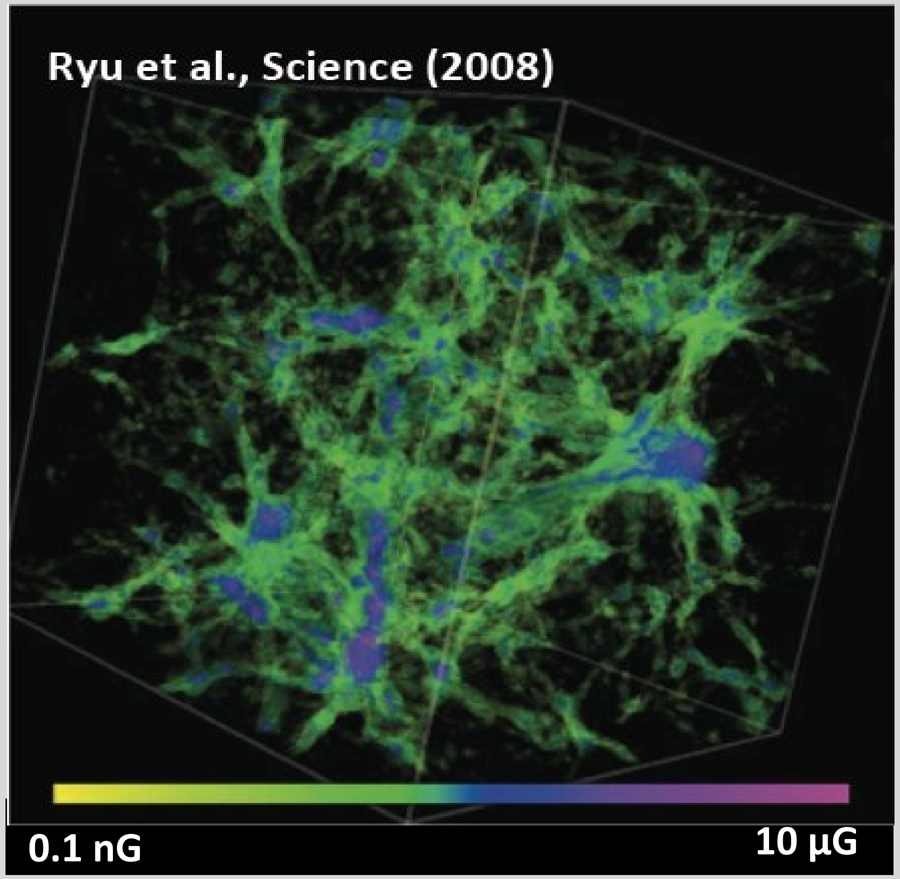
Images taken from Khan Academy

Thermal transport is a challenge in many astrophysical systems

- Galaxy clusters are diffuse, turbulent magnetized plasmas.
- In cluster cores, the temperatures remain anomalously high compared to what might be expected, given that the cooling time is short relative to the Hubble time.
- While feedback from the central active galactic nuclei is believed to provide most of the heating, there has been a long debate as to whether conduction of heat from the bulk to the core might help the core reach observed temperatures.
- ***Thermal conduction in magnetized, weakly collisional plasmas is a longstanding problem in plasma physics.***

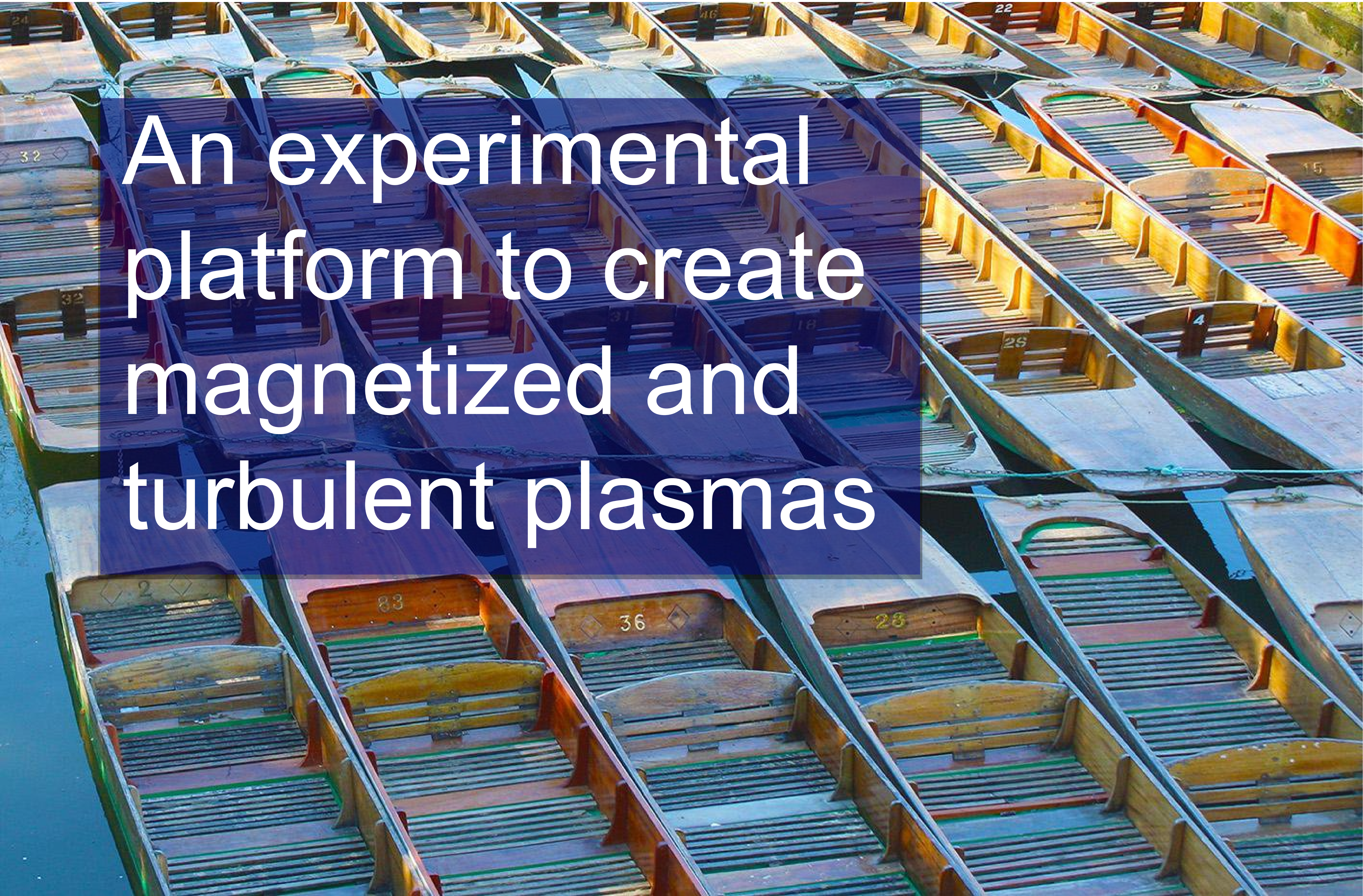

Coma cluster

Courtesy of NASA/CXC/Univ. of Chicago, Zhuravleva *et al.*; SDSS


Ryu et al., Science (2008)

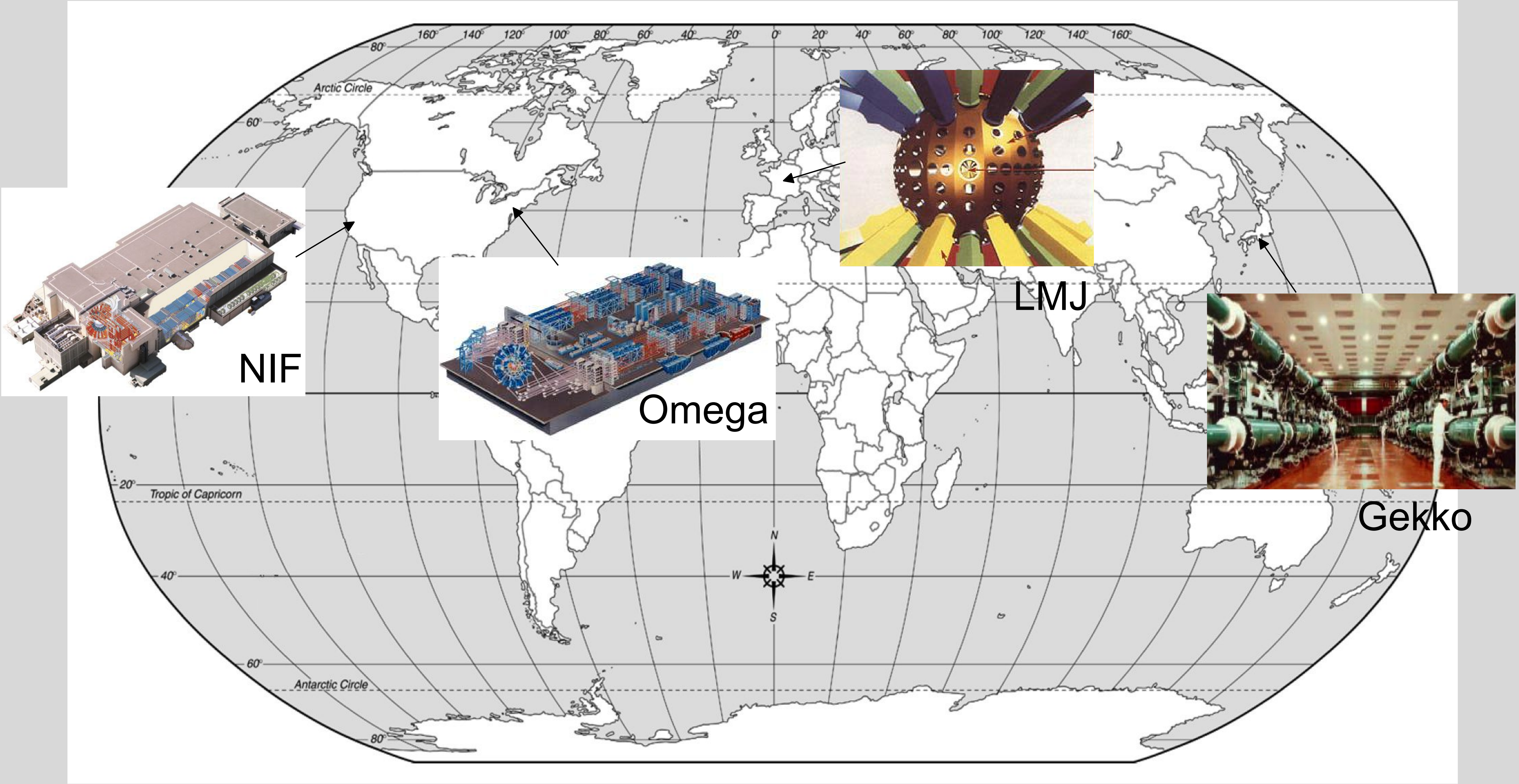
100 Mpc

An experimental platform to create magnetized and turbulent plasmas



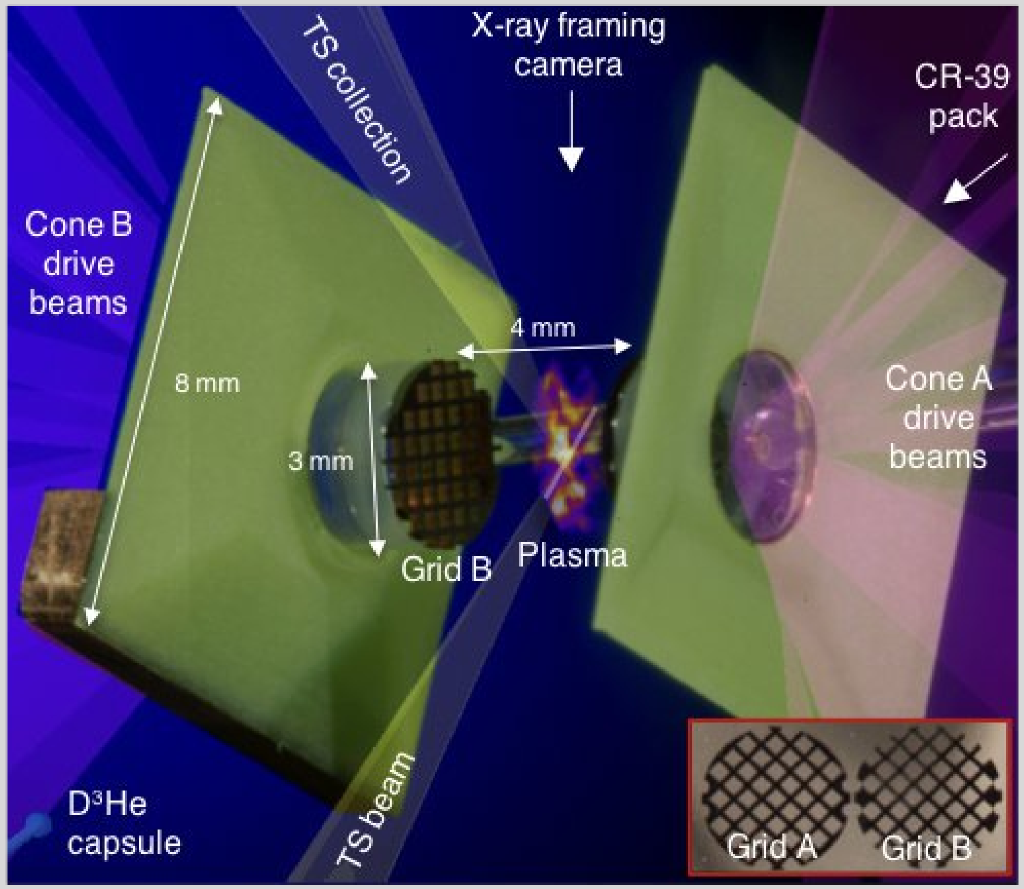
We have used several large laser facilities around the world

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

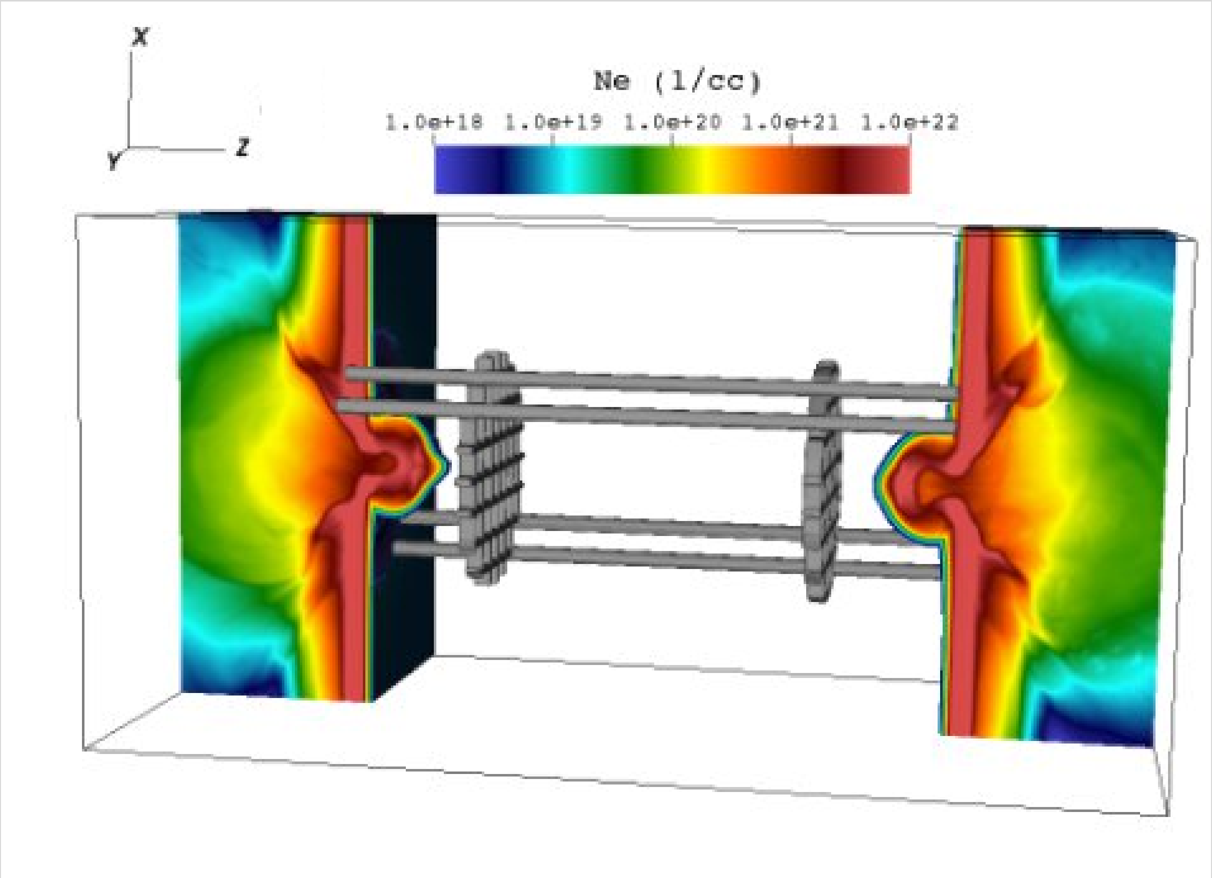


Experiment uses colliding flows and grids to create strong turbulence

- ➜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)



Numerical simulations done with the MHD code FLASH (including laser package and non-ideal EOS)

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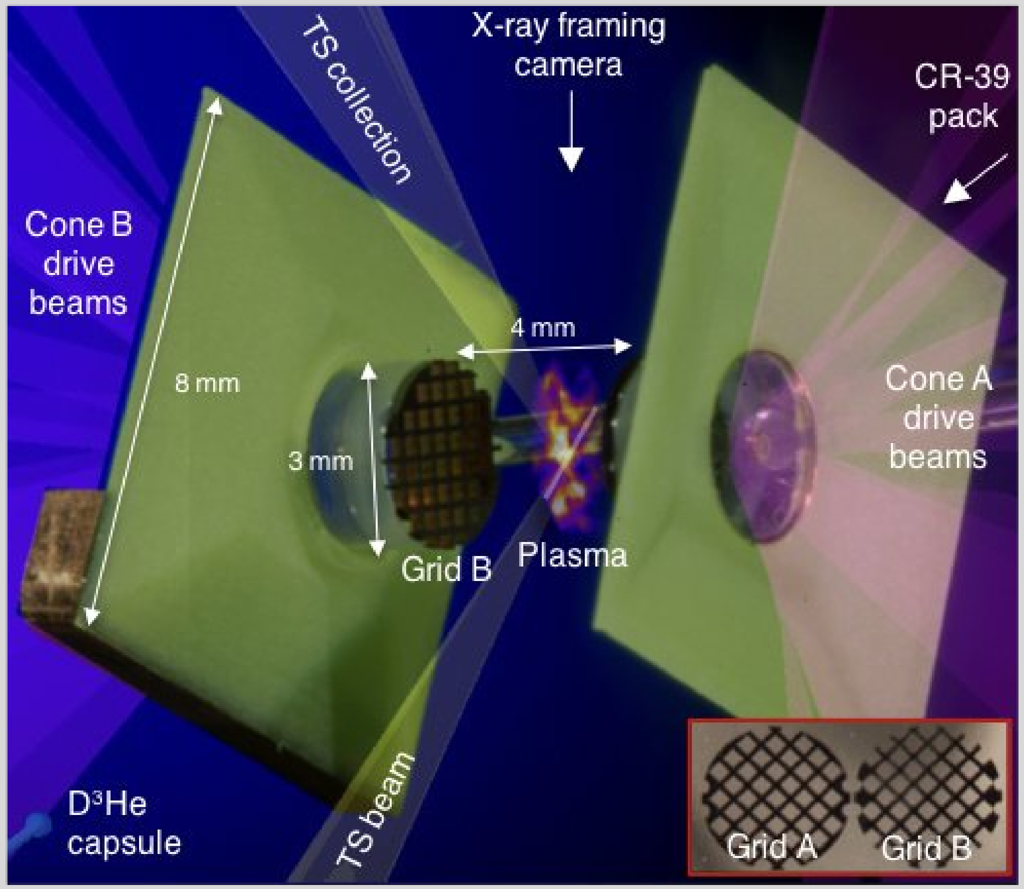

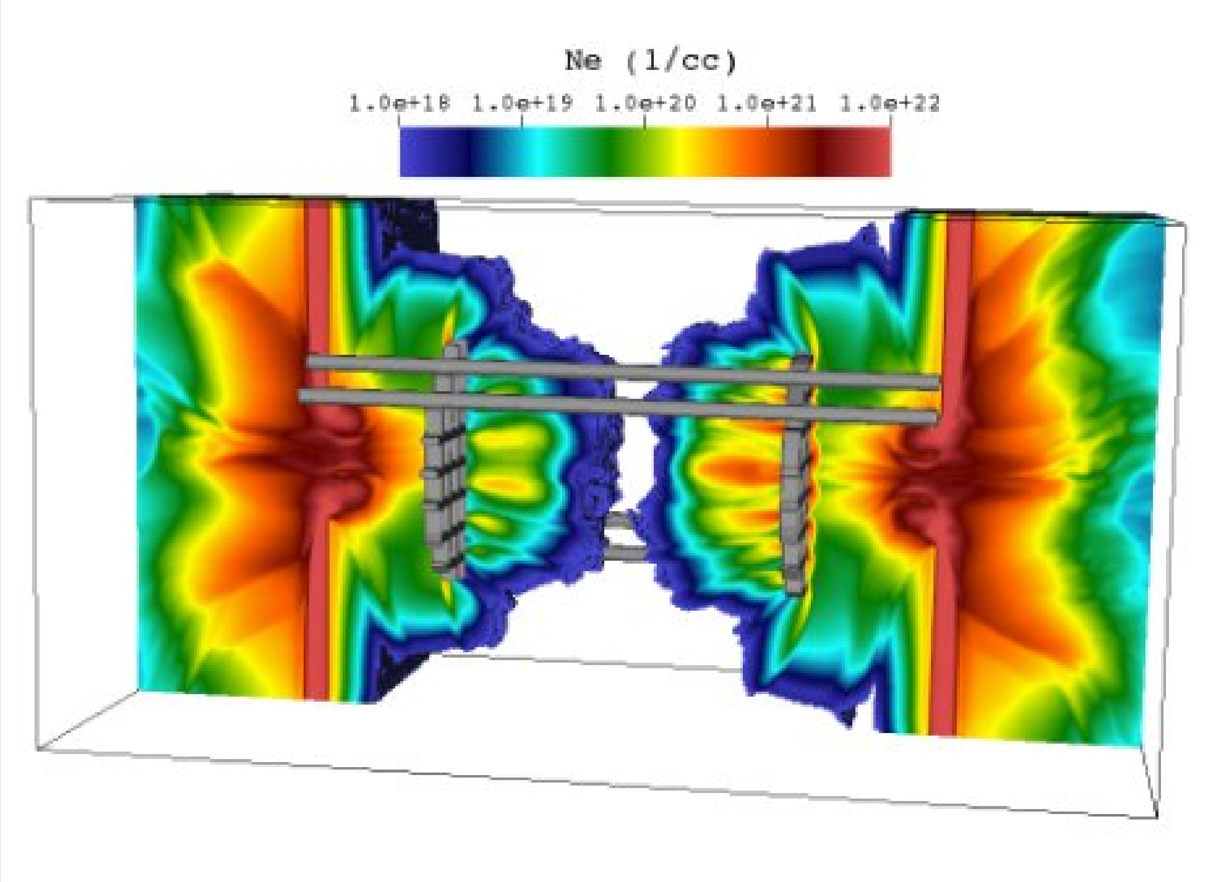

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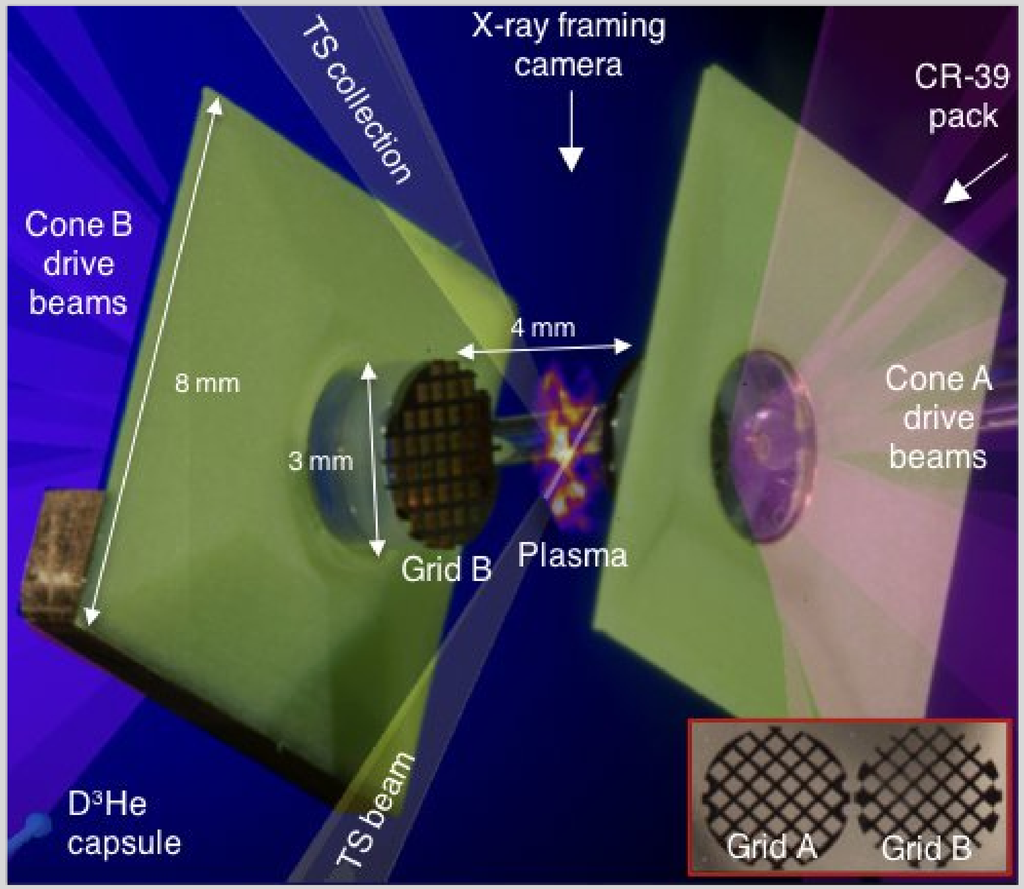
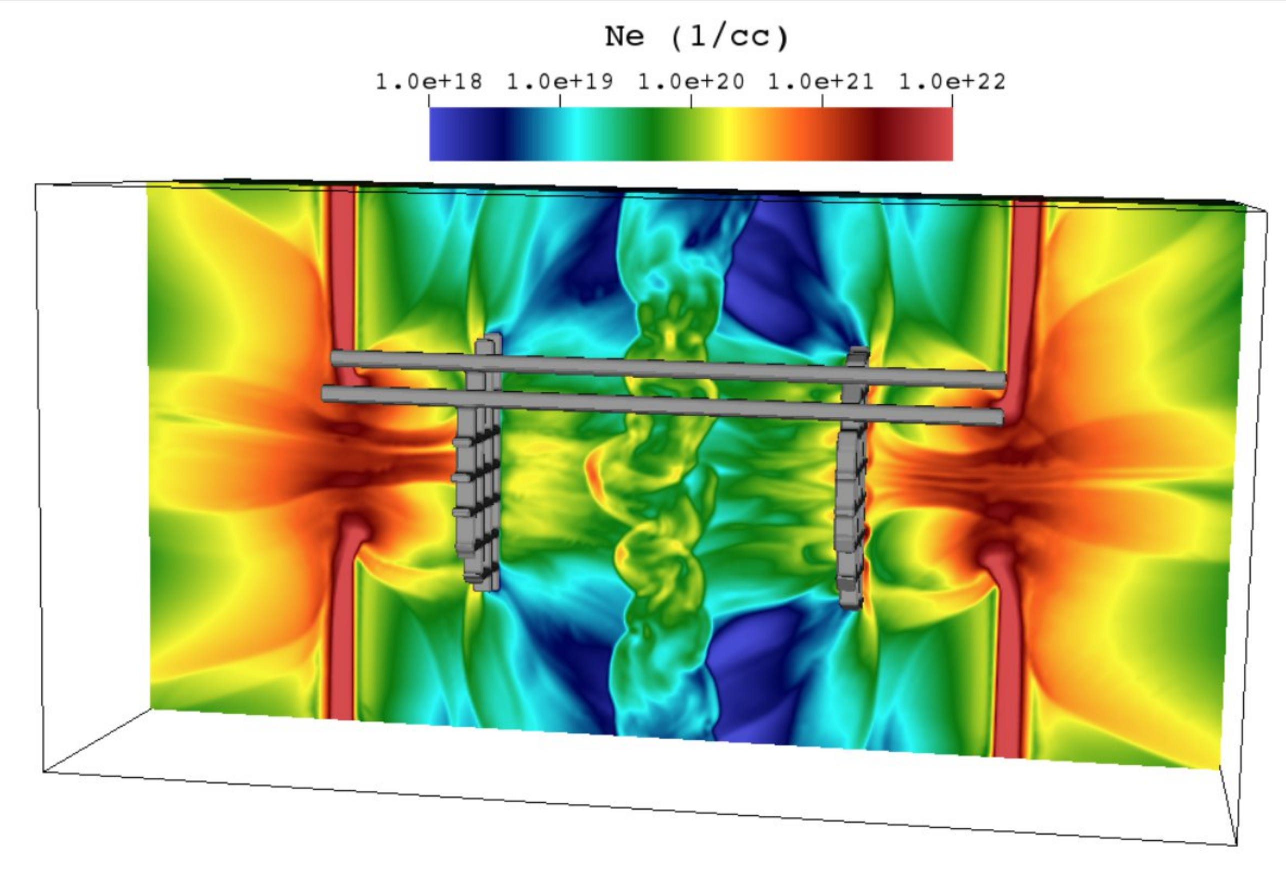
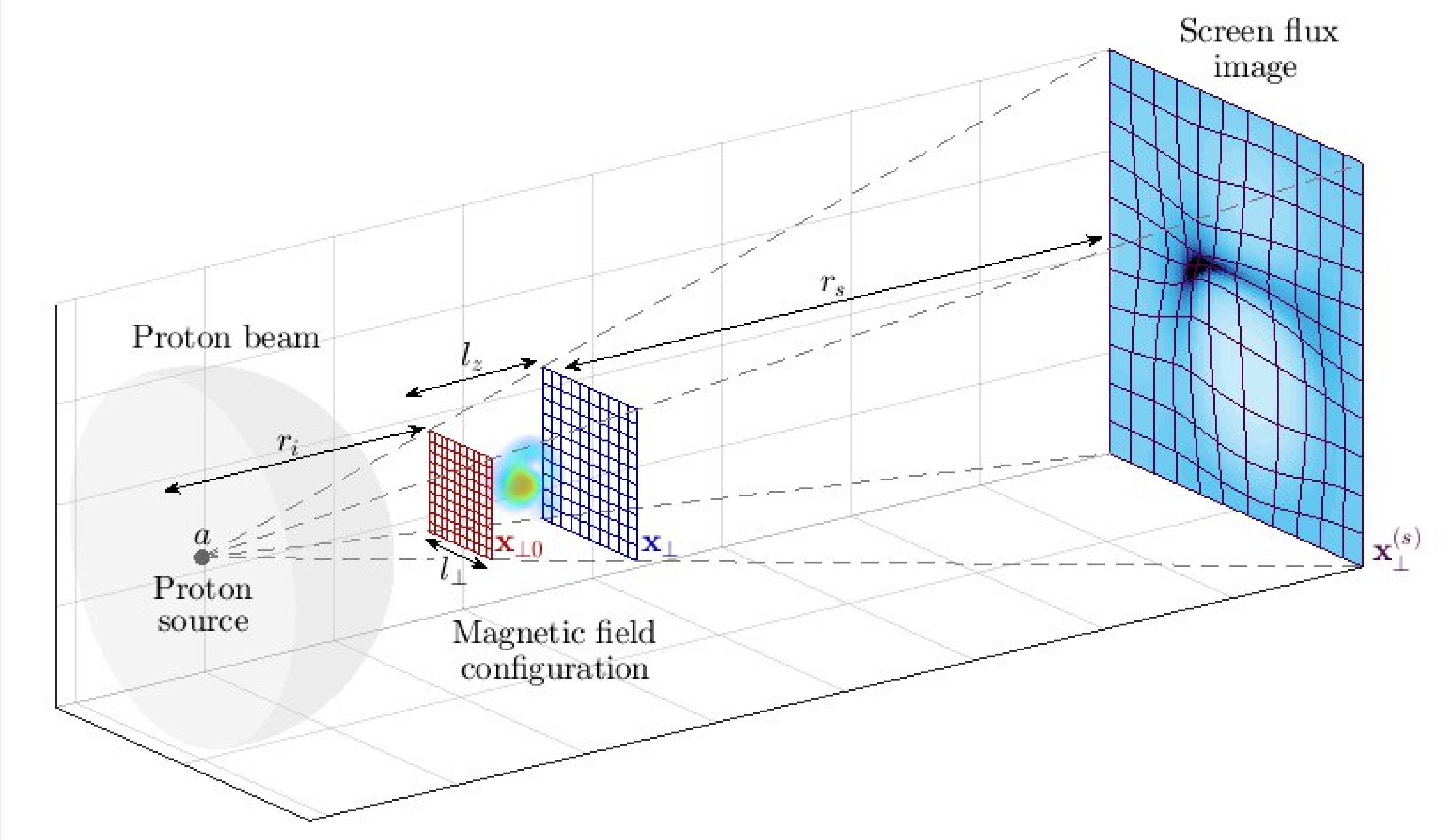




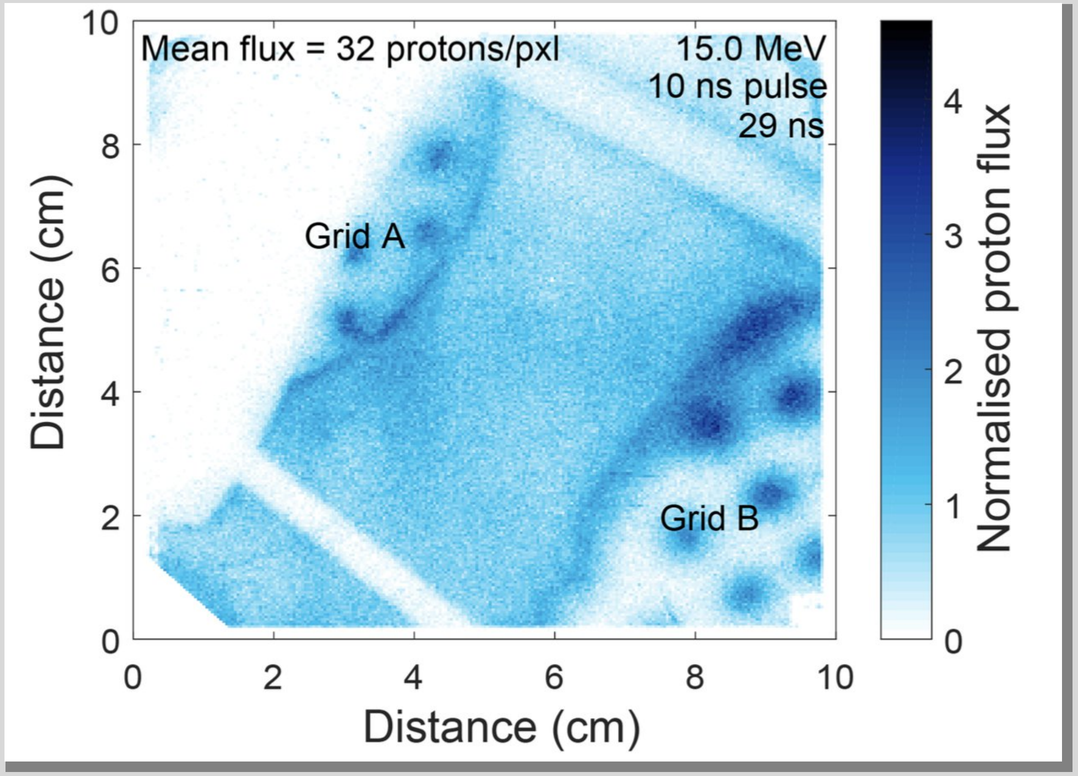
Tzeferacos et al. Nature Comm. (2018)

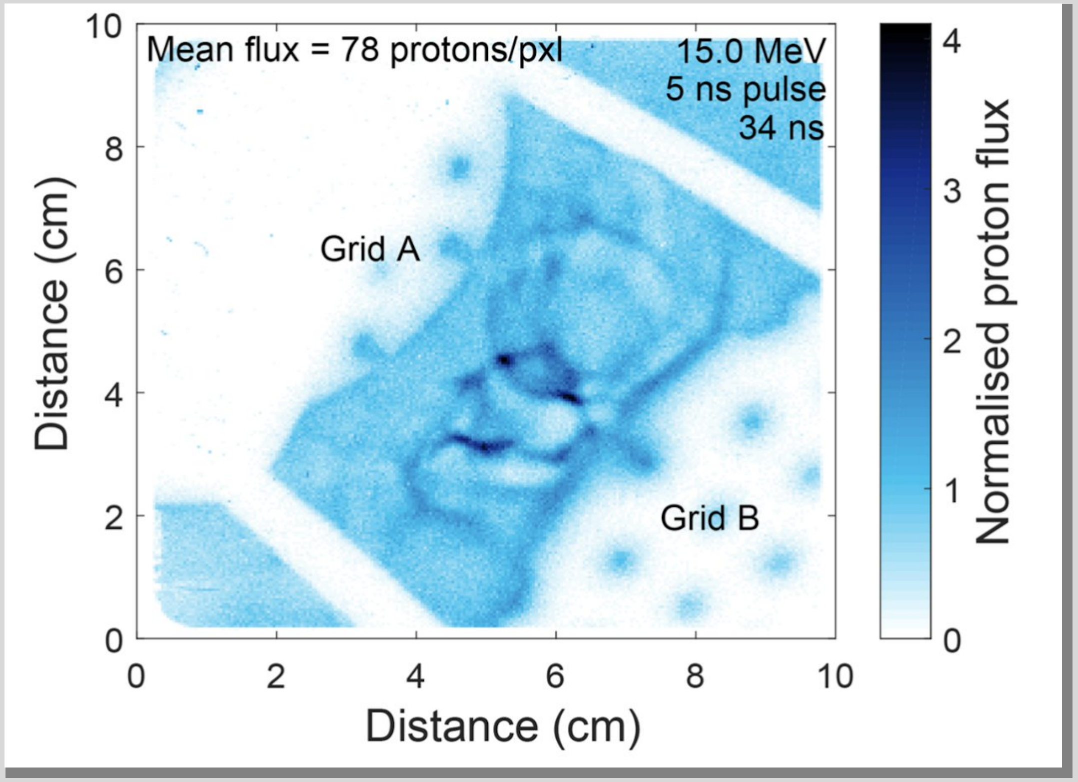
Magnetic fields are measured by proton radiography



- We use 3.3 MeV and 15 MeV protons to map the magnetic field structures in the plasma
- Proton deflections are a measurement of the path-integrated magnetic field
- How to obtain the (path-integrated) magnetic field:
    - Solution of the Ampere-Monge equation (*Bott et al., 2017*)
    - Optimal regression analysis with Bayesian inference (*Kasim et al., 2019*)

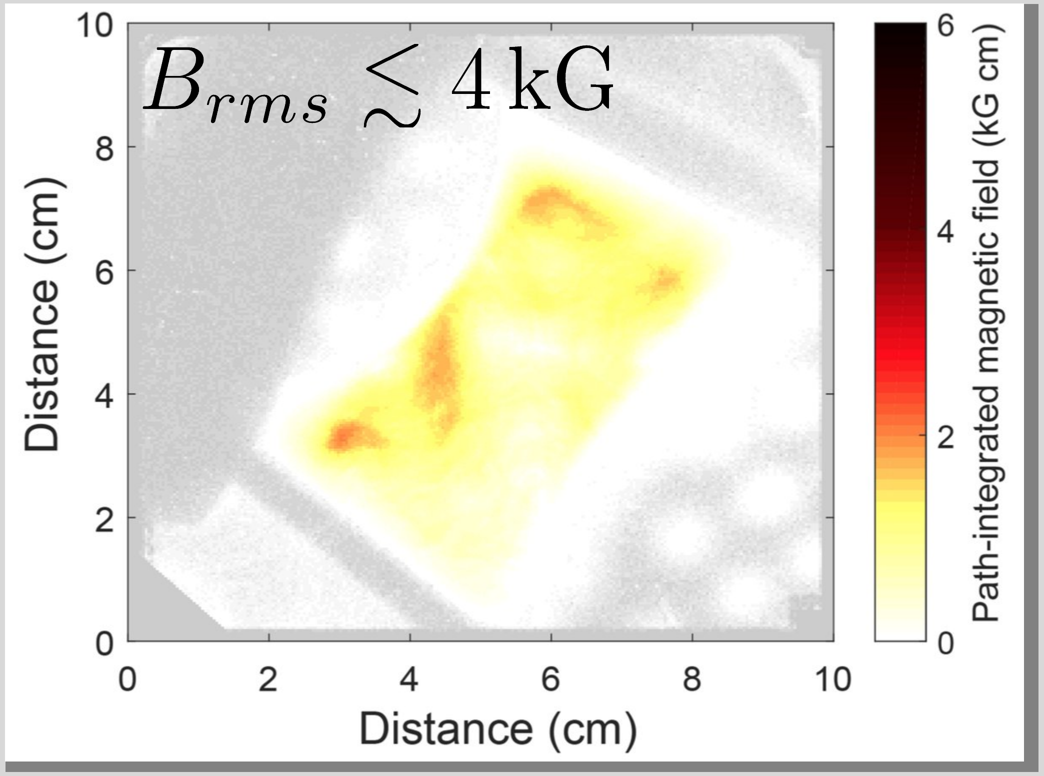
Magnetic fields are measured by proton radiography

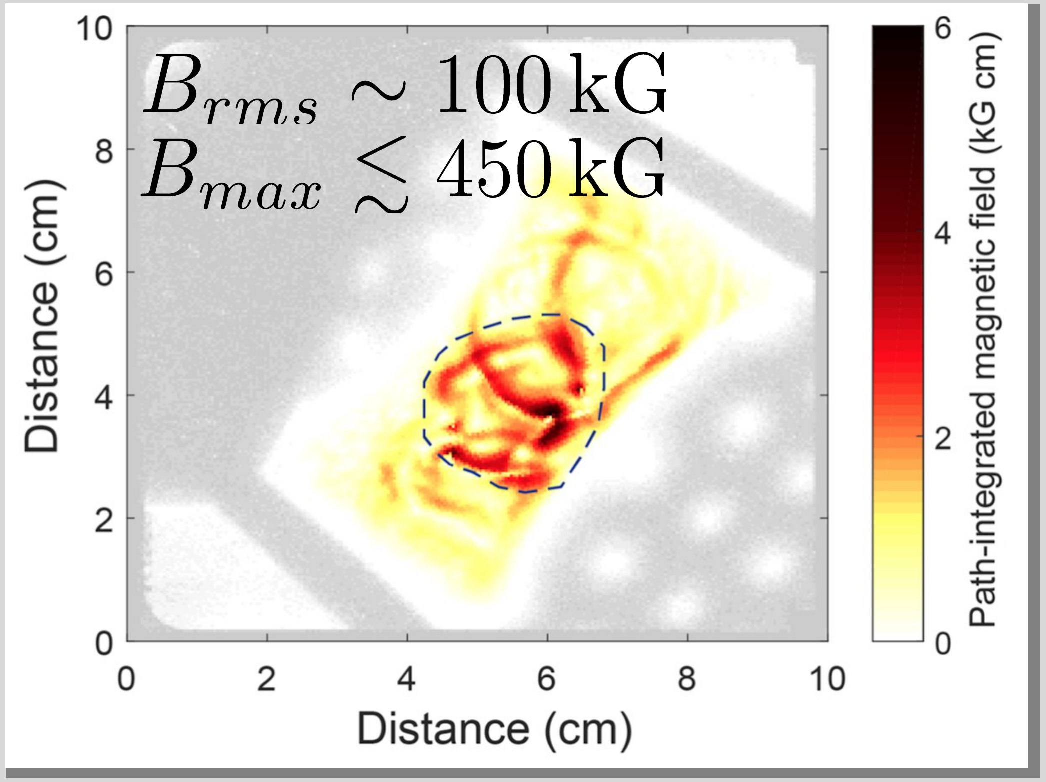




- ➜ No structures appear in the images before the collision.
- ➜ Filaments are seen after the collision.

The inferred magnetic field is significantly amplified by the turbulence



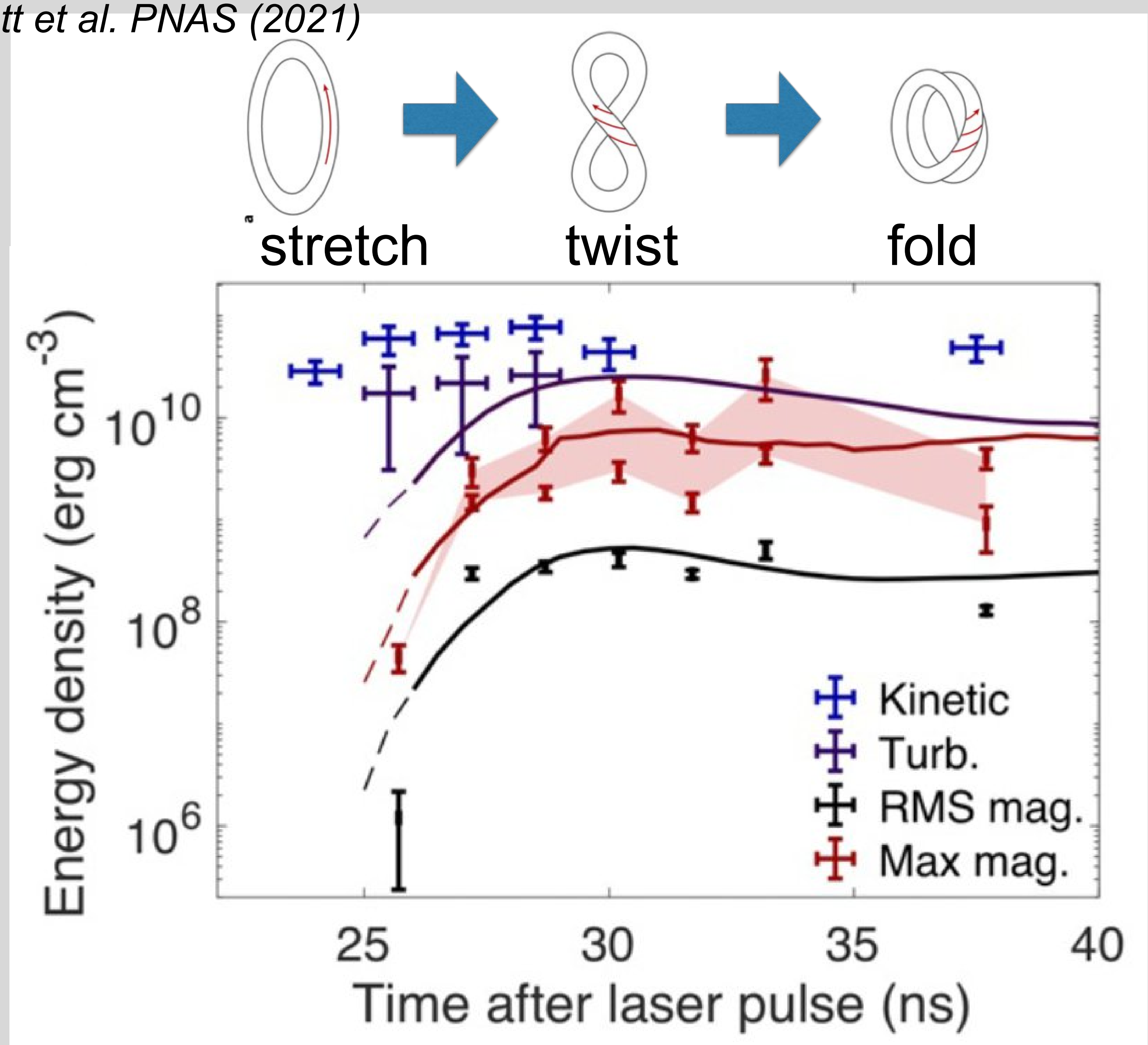


- ➜ An initial (seed) magnetic field is present in the plasma before the collision.

- ➜ A much stronger field is observed after the collision, when turbulence is stronger.
- ➜ Our analysis suggests **25x** amplification of the RMS field and peaks of **450 kG** (near saturation).

Omega conditions are in the regime where turbulent dynamo can be excited

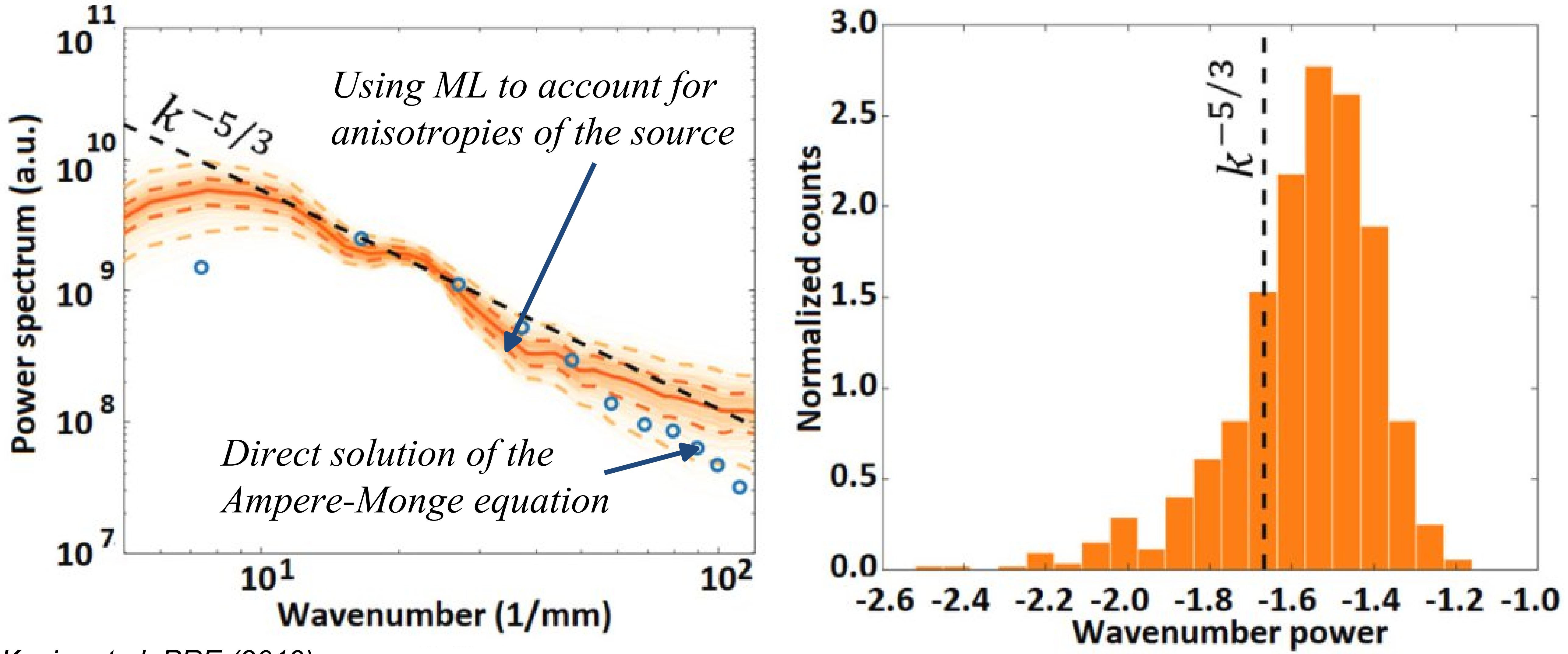
Bott et al. PNAS (2021)



	Experiment
v	100 km/s
T_e	450 eV
n_e	~10^{20} cm^{-3}
M	1
Re	1200
Rm	600
Pm	<1

- Dynamo can only be excited for Rm > a few hundred (plasma must be a very good conductor).
- We have achieved magnetic Reynolds number much larger that the threshold value for turbulent dynamo action.
- The measured magnetic field is in dynamical equipartition between fluid motions.

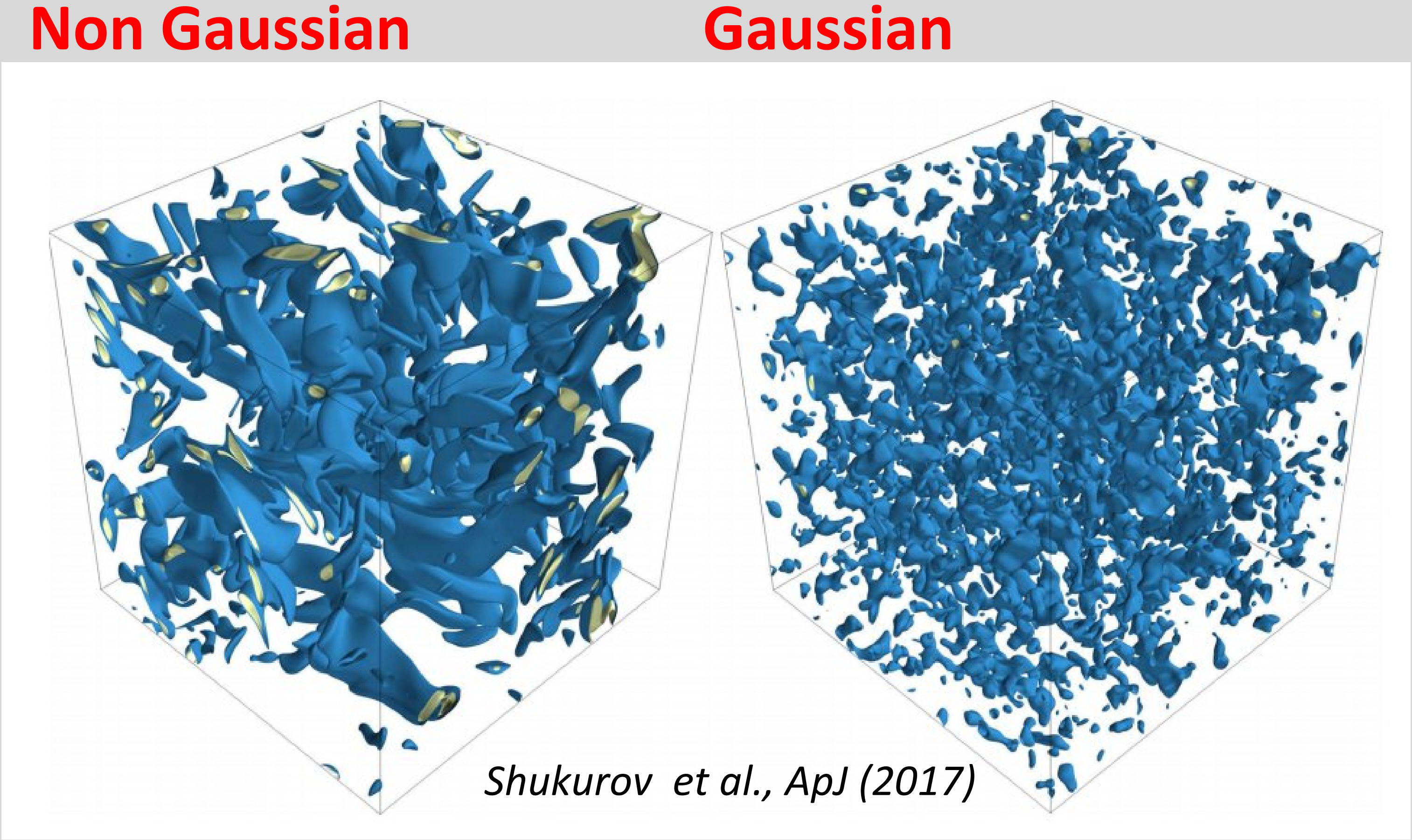
Magnetic field spectra are retrieved using machine learning



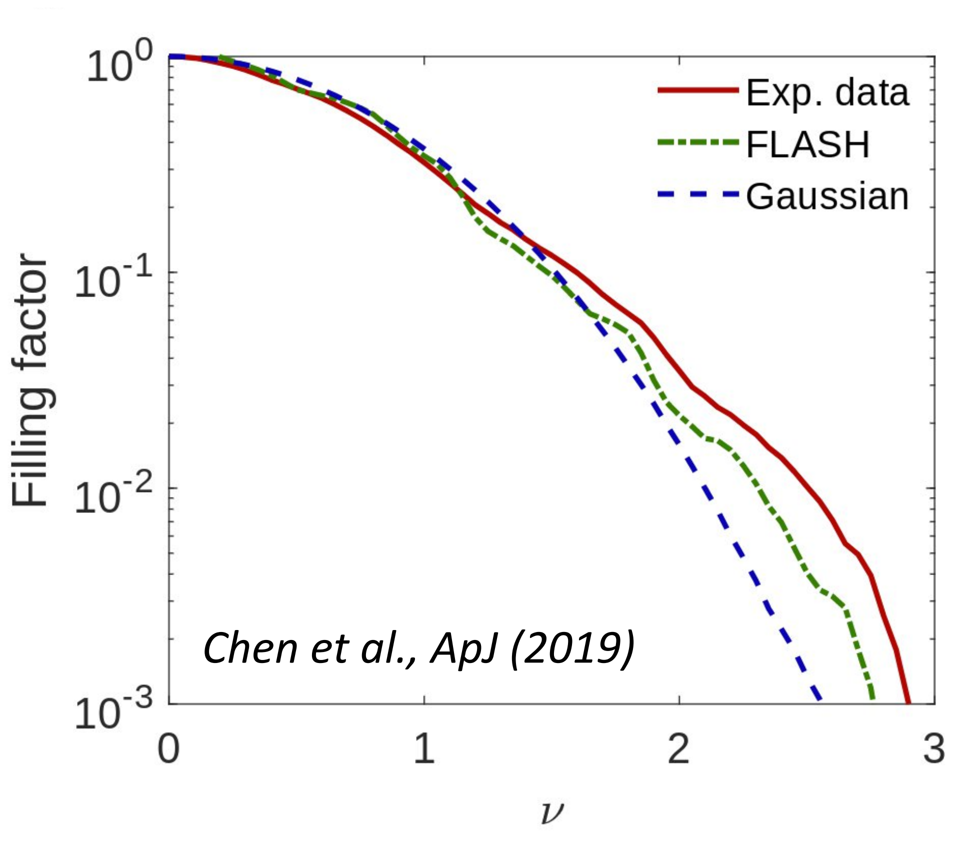
Kasim et al. PRE (2019)

- ➜ We have used regression and Bayesian analysis to determine the best fit and distribution of magnetic field power spectra.
- ➜ Measured spectra slopes are consistent with MHD numerical simulations.

Magnetic fields in the experiments are not volume-filling

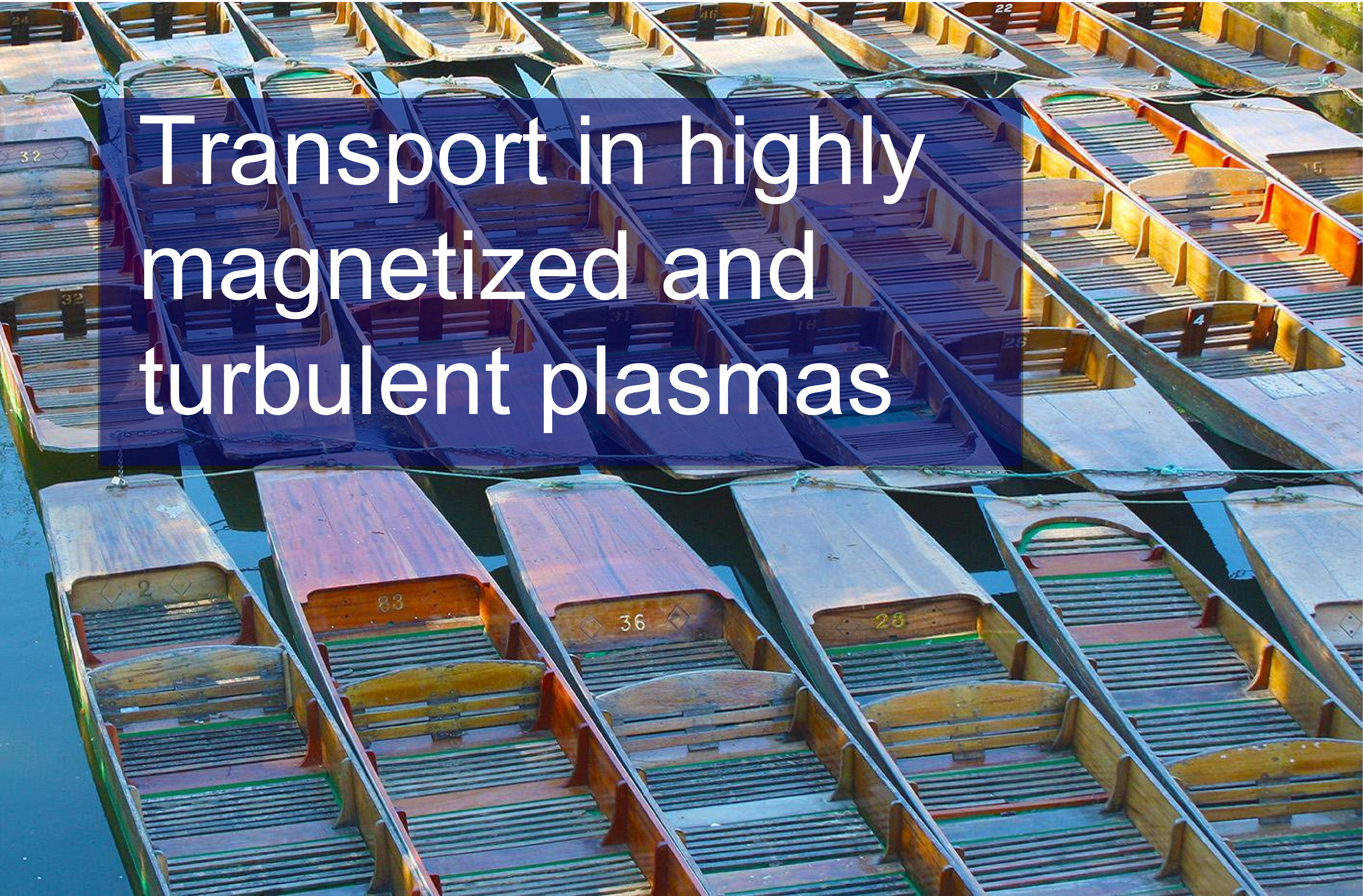


Shukurov et al., ApJ (2017)



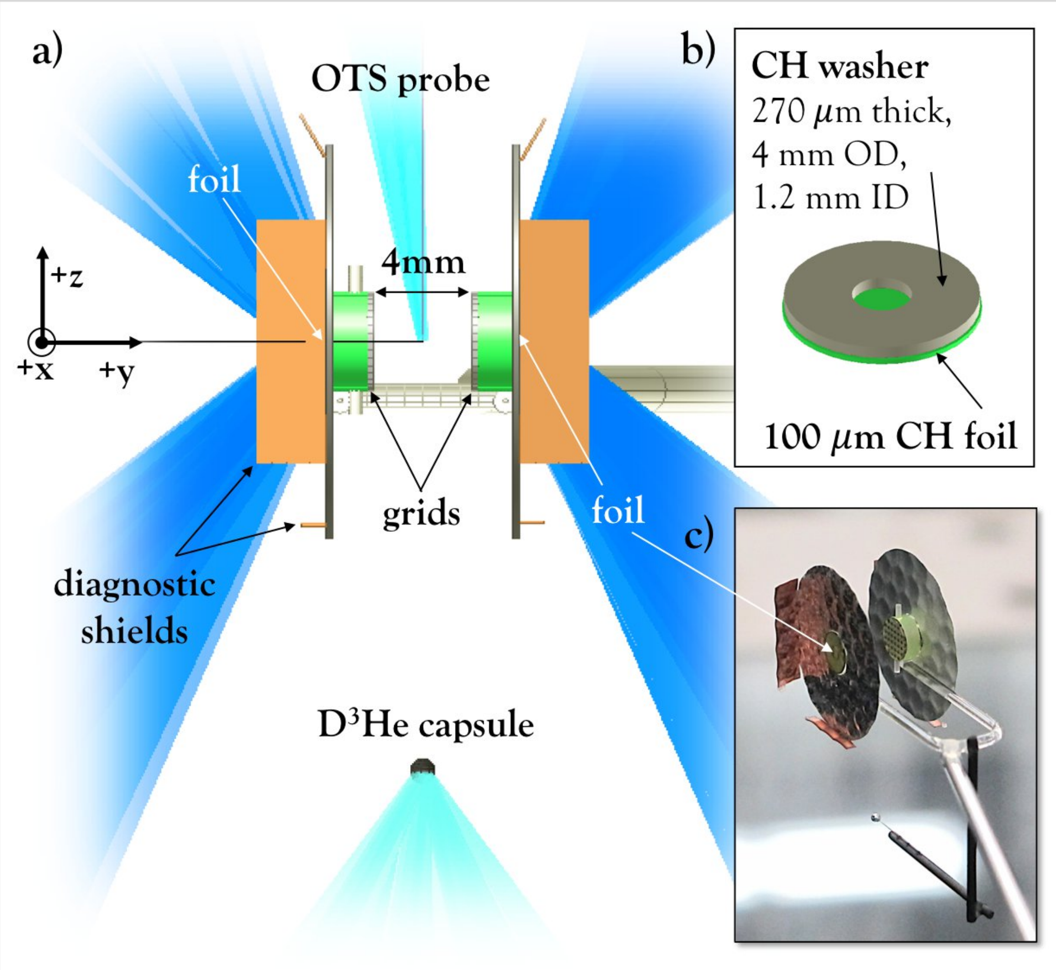
Chen et al., ApJ (2019)

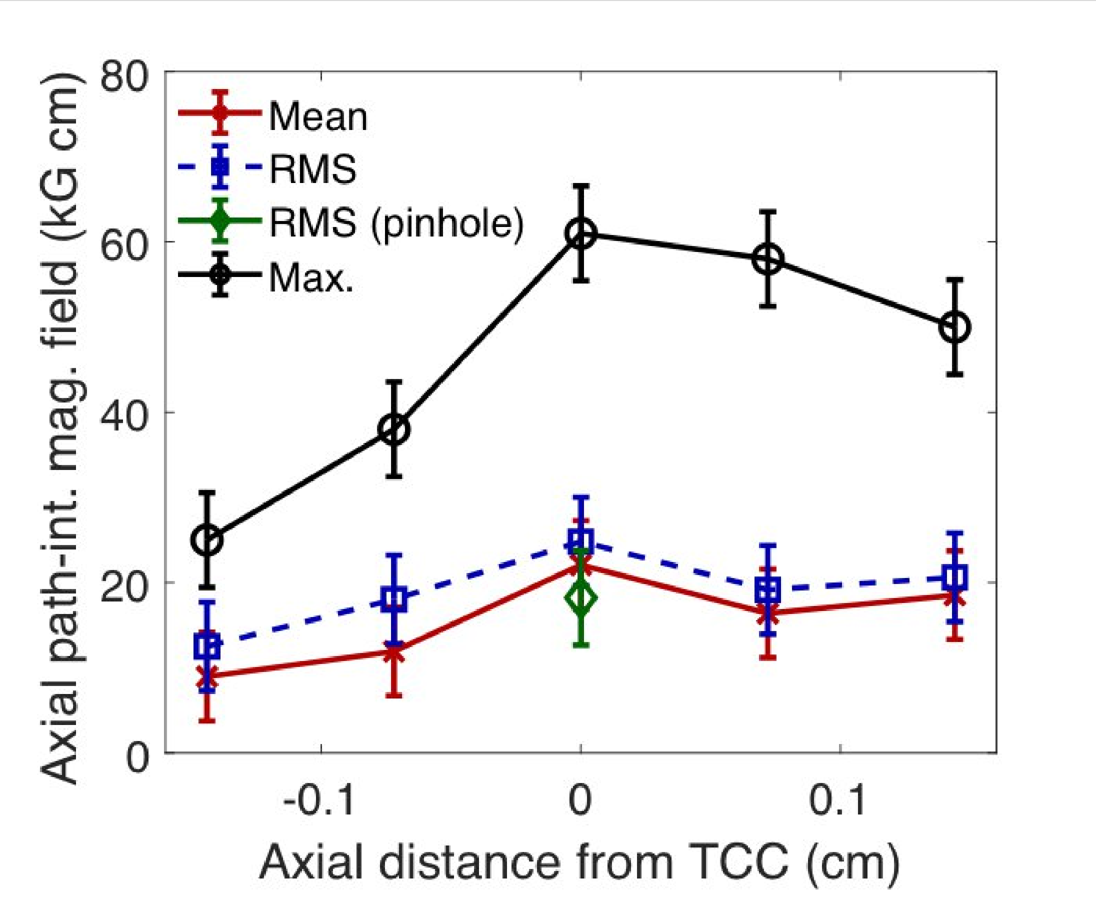
- The fractional volume with magnetic fields $B > \nu B_{rms}$ shows a non-Gaussian behavior (expected since MHD turbulence in intermittent).
- Magnetic field spatial distribution shows islands of large field strength surrounded by regions of weak field.
- On these experiments, $r_g > \lambda_e$, therefore we don't expect the structure of the magnetic field to affect thermal conduction.



Transport in highly magnetized and turbulent plasmas

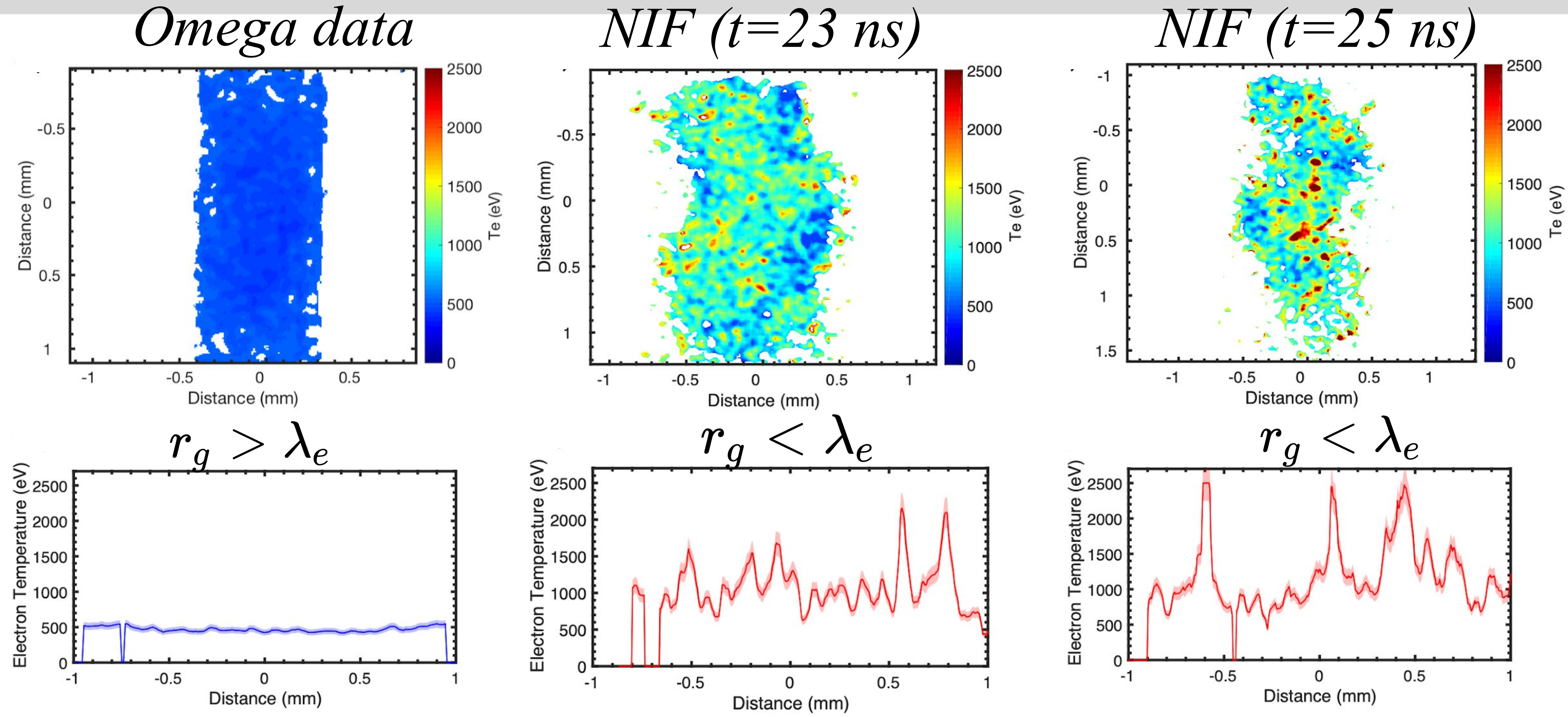
NIF experiments show a significant increase in magnetic field turbulence





- ➜ At the National Ignition Facility (NIF) laser we observe about 10x increase in magnetic field values compared to Omega experiments.
- ➜ Increase in magnetic field is due to larger laser drive and faster flow motions.
- ➜ The larger magnetic field starts to affect the plasma transport properties (thermal conduction).

We measure the 2d temperature maps of the interaction region



Omega data

NIF (t=23 ns)

NIF (t=25 ns)

$r_g > \lambda_e$

$r_g < \lambda_e$

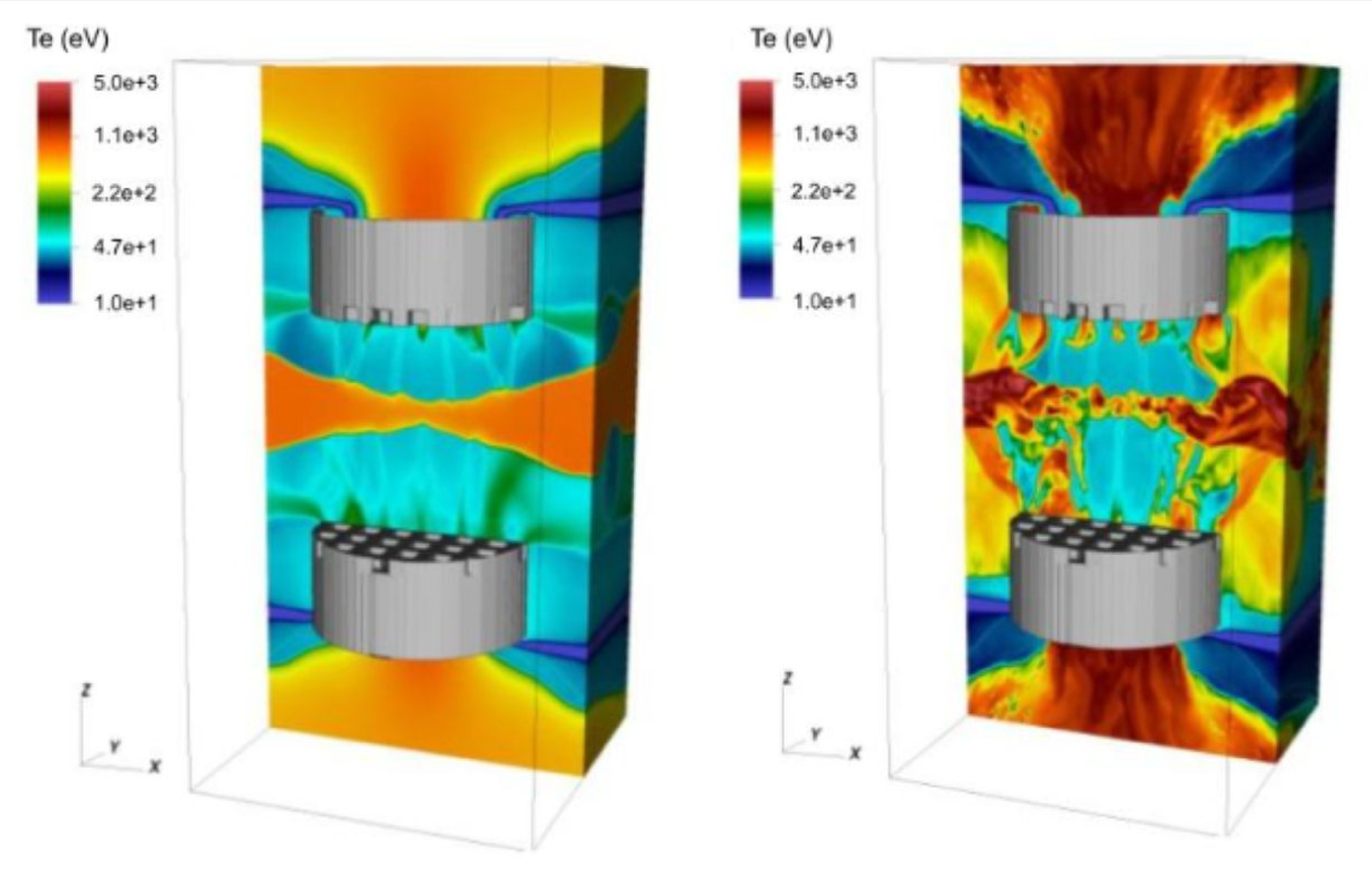
$r_g < \lambda_e$

Meinecke et al. arXiv:2105.08461 (2021)

- ➜ On NIF we observe a significant scatter in the temperature distribution with hot spots surrounded by regions of cooler plasma.
- ➜ On Omega, instead, the temperature is very uniform all across the interaction region.
- ➜ The size of the observed hot spots is limited by instrument resolution.

3D MHD simulations of the interaction region

FLASH
with thermal
Conduction



FLASH
No thermal
Conduction

- ➜ NIF data revealed highly-structured temperature profile when the Larmor radius, r_g ($\sim 0.1\ \mu m$) is smaller than the electron Coulomb mean free path, λ_e.($\sim 1\ \mu m$).
- ➜ FLASH simulations with thermal conduction off shows significant structures in the temperature profiles.

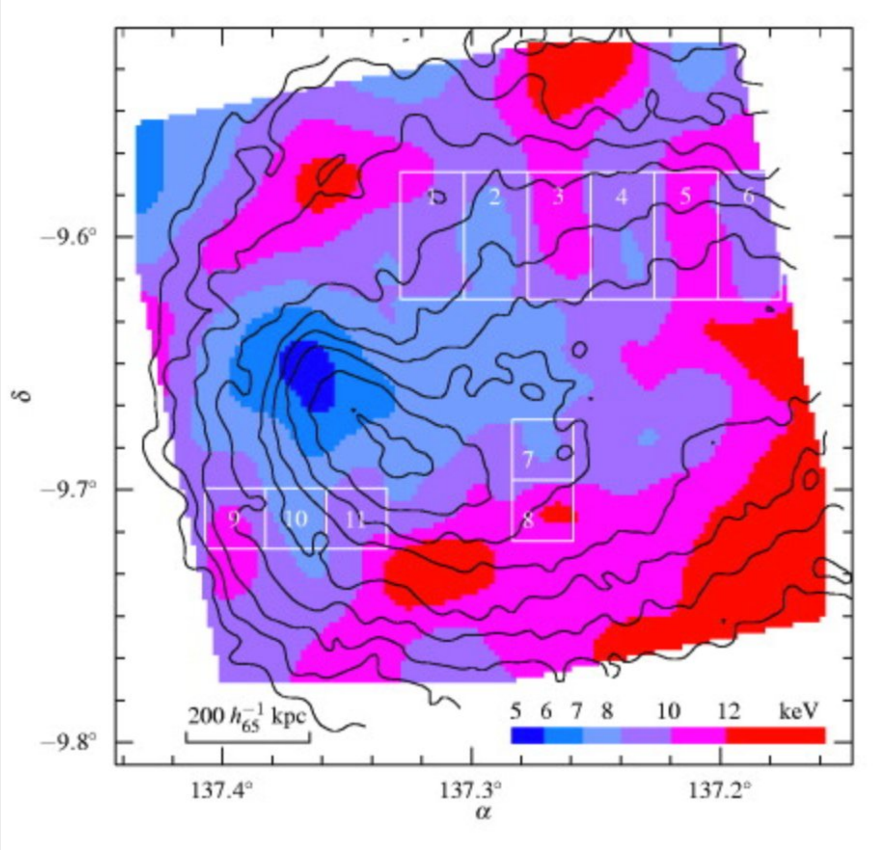
Data is consistent with a strong suppression of heat conduction

Quantity	NIF t = 23ns	NIF t = 25ns	Omega t = 18ns
$n_e(\mathrm{cm}^{-3})$	7e20	5e20	1e20
T_e (keV)	1.4	1.6	0.4
$l_T(\mu m)$	50	50	200
L (mm)	1	1	0.5
$Z_{\rm eff}$	5.7	5.7	5.3
$t_{\rm cond}$ (ps)	27	14	1324
$t_{\rm age}$ (ns)	1.7	1.6	1.6
$\frac{t_{\rm age}}{t_{\rm cond}}$	63	114	1.2

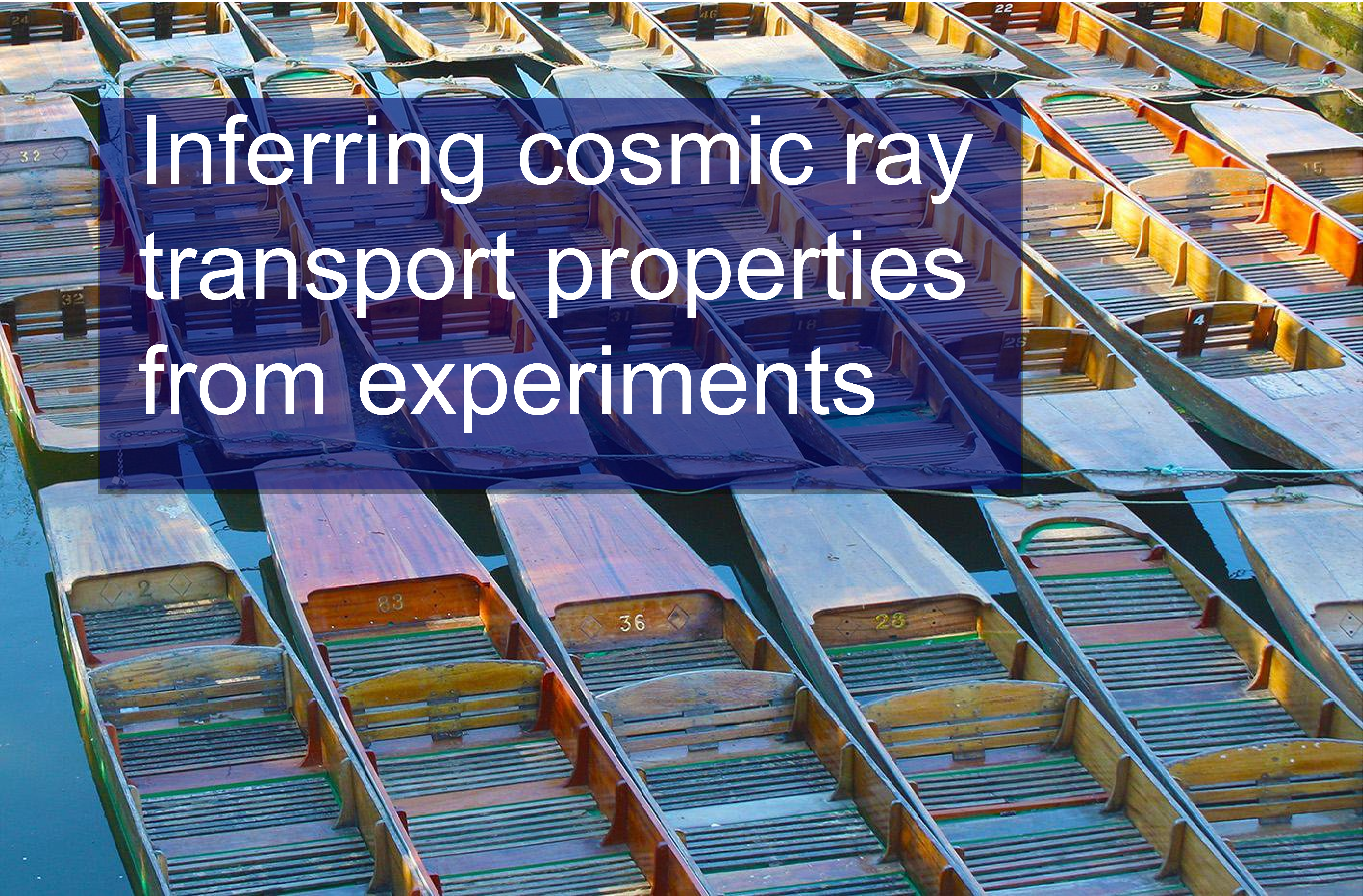
$$t_{\rm cond} \sim k_B n_e \ell_T^2/\kappa_S$$
$$t_{\rm age} \sim L/c_s$$
$$\Rightarrow (\kappa/\kappa_S)^{-1} \sim (t_{\rm age}/t_{\rm cond})$$

- ➜ An estimate for heat conduction suppression is obtained by comparing the conduction time-scale with the time required for the turbulent structures to persists.
- ➜ Our estimates suggest 100x reduction of heat conduction in the NIF experiments.

- ➜ These conditions are, in fact, very similar to what we would expect to see in cluster of galaxies (Markevitch et al., ApJ 2003; Baldi et al. ApJ 2009).

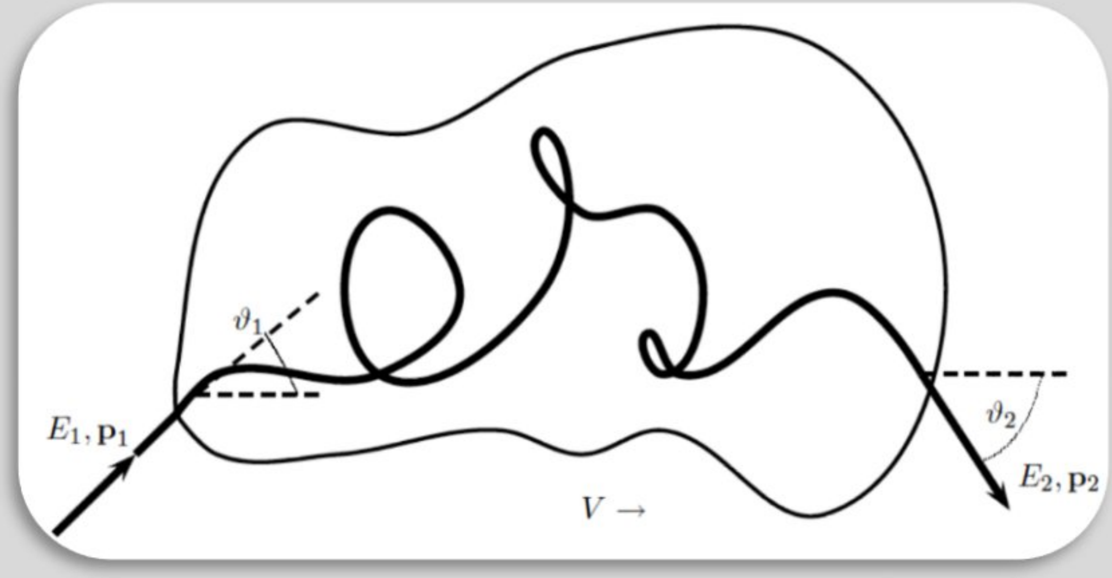


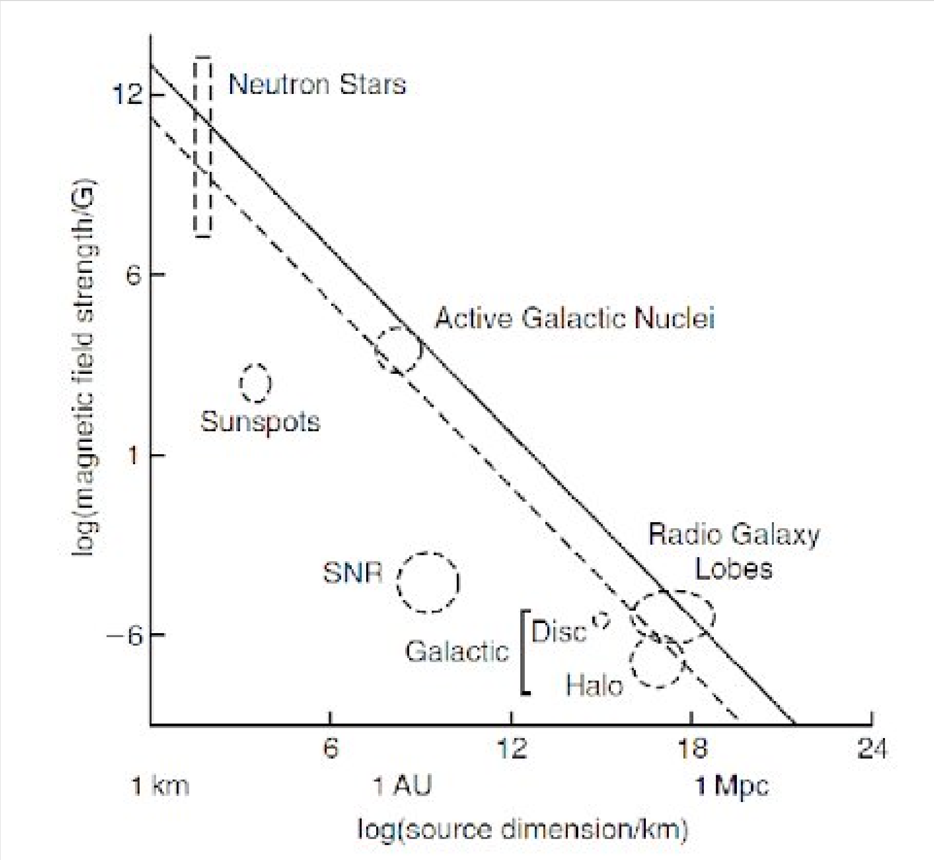
Projected temperature map of A754 overlaid with CHANDRA x-ray image at 0.8-5 keV (Markevitch et al., ApJ 2003)



Inferring cosmic ray transport properties from experiments

Cosmic ray acceleration requires the presence of a turbulent plasma





Protheroe (2004)

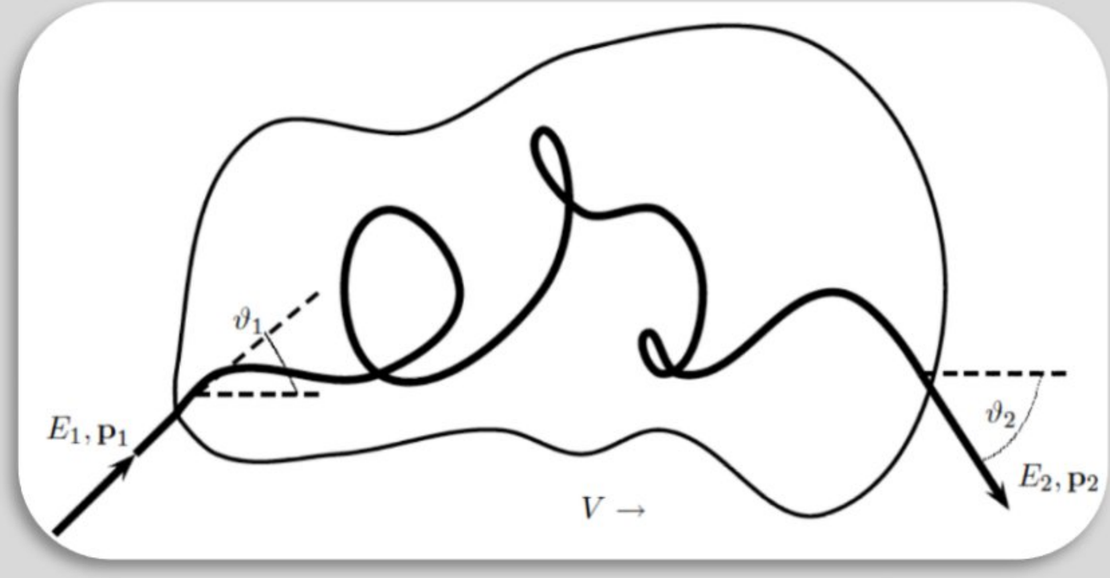
- Fast particles collide with moving magnetized clouds (*Fermi, 1949*). Particles can gain or lose energy, but head-on collisions (gain) are slightly more probable.

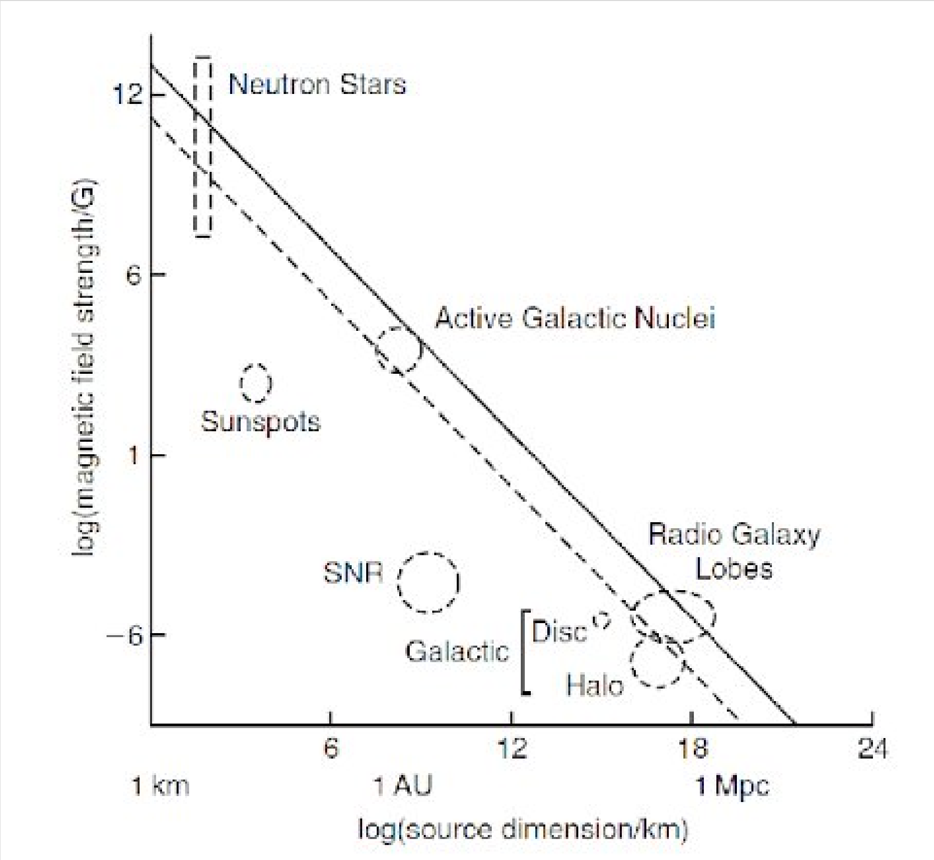
- First-order ‘Diffusive Shock Acceleration’ (*Blandford & Ostriker 1978; Bell 1978*) is very efficient, however in several astrophysical contexts, second-order Fermi is more relevant (*Petrosian, SSR 173:535, 2012*).

- 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

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





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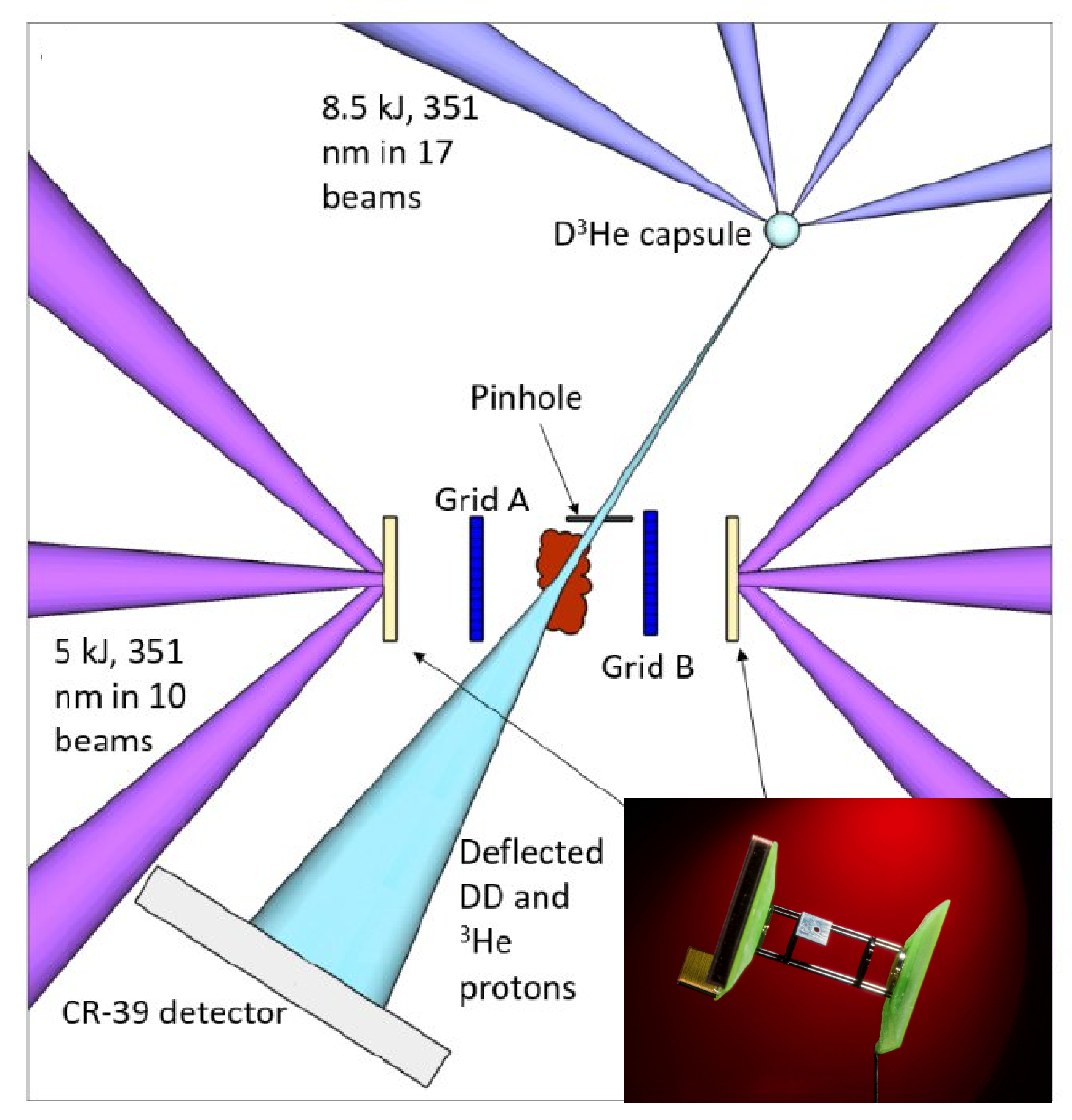
- The evolution of CRs as they are accelerated in the plasma is governed by a diffusion equation (*Kaplan, 1955; Cowsik & Sarkar, 1984; Blandford & Eichler, 1987*).
- ***In addition to astrophysical sources, laboratory plasmas can also potentially accelerate particle***

Simulating Ultra High Energy Cosmic Rays (UHECR) with fusion protons



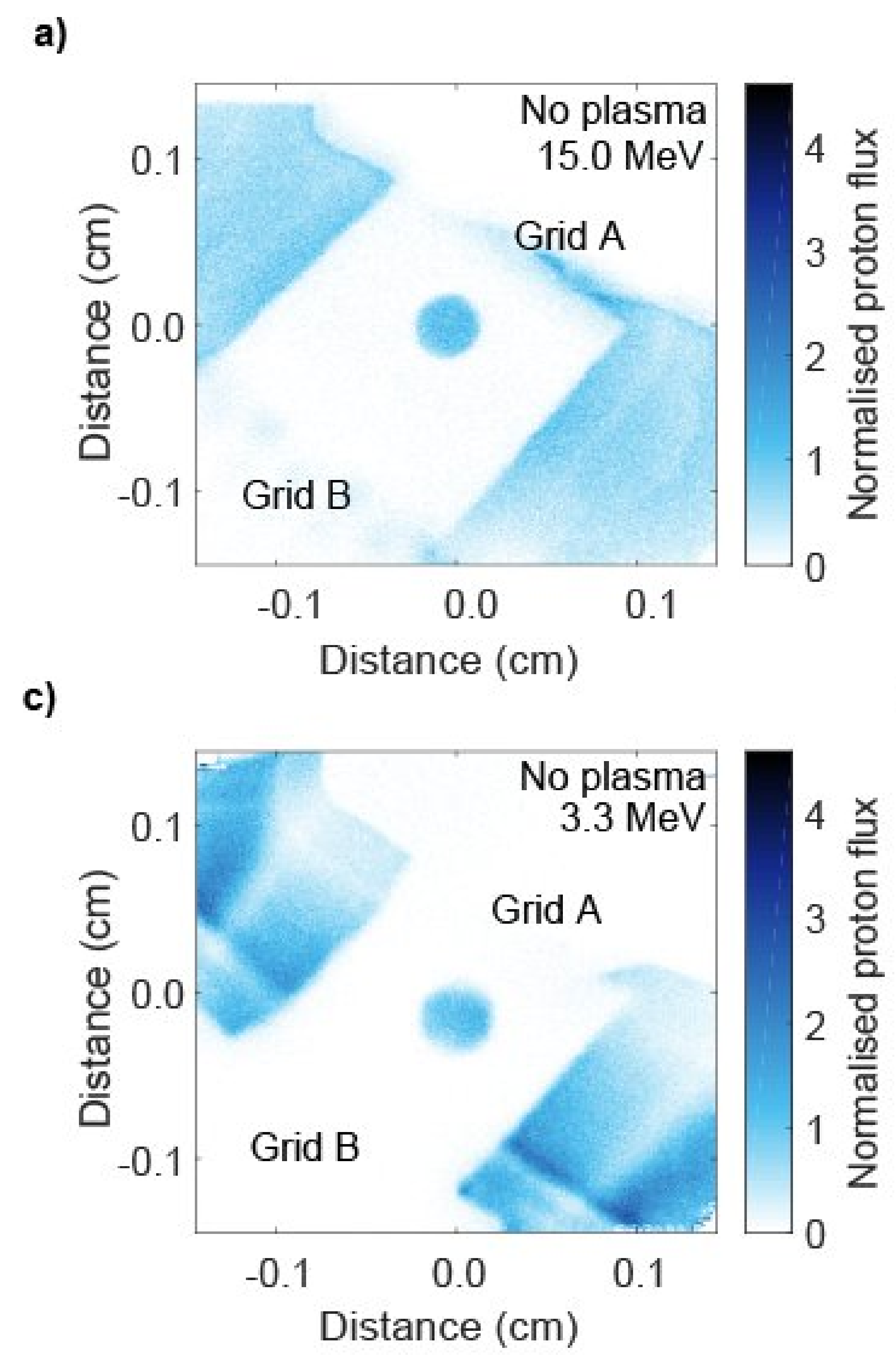
Chen et al. ApJ 2020

- 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:

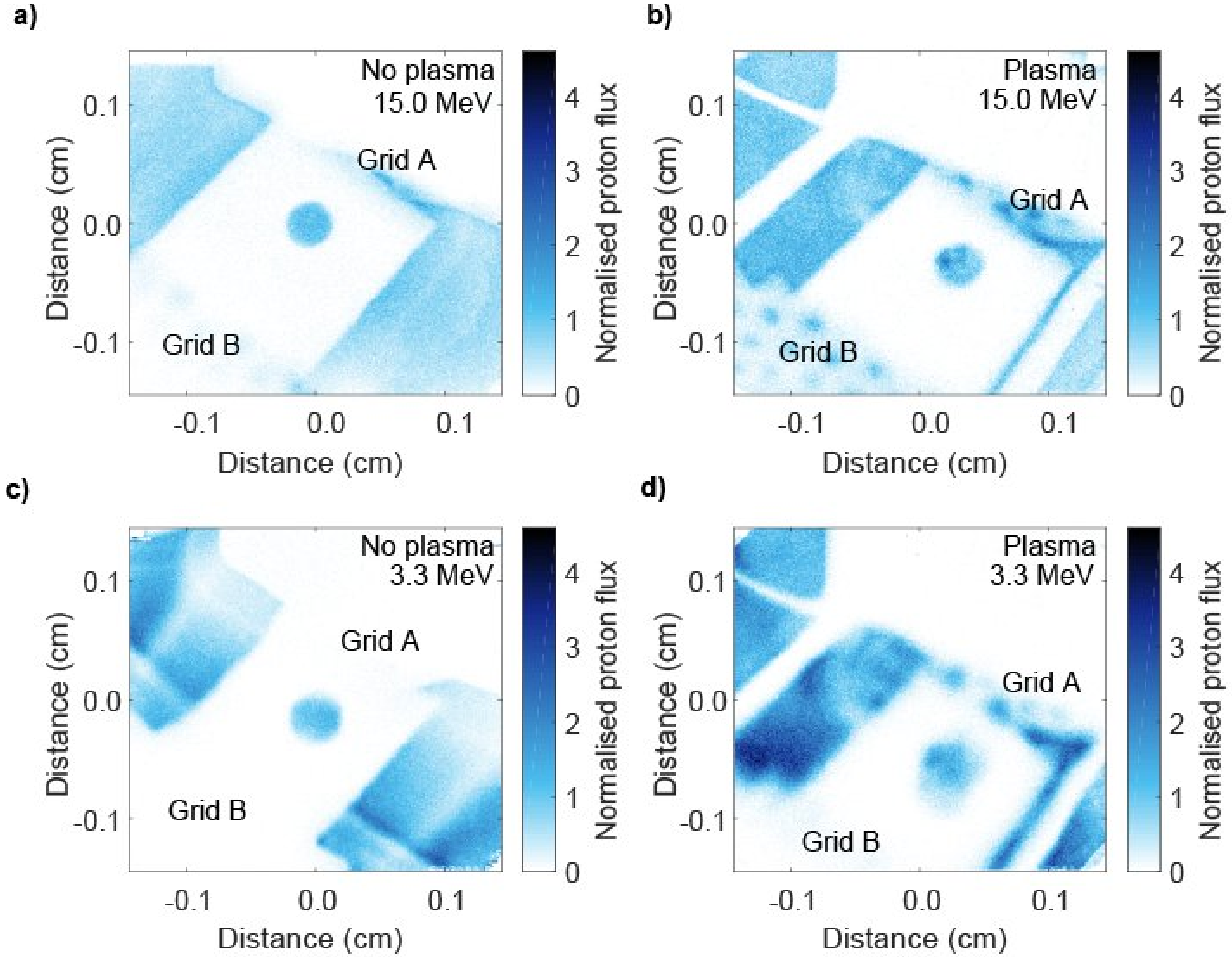
An analogue for Ultra High Energy Cosmic Rays (UHECR)!

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

We use our experimental platform to study proton transport through plasma



Significant broadening of the proton beam is observed



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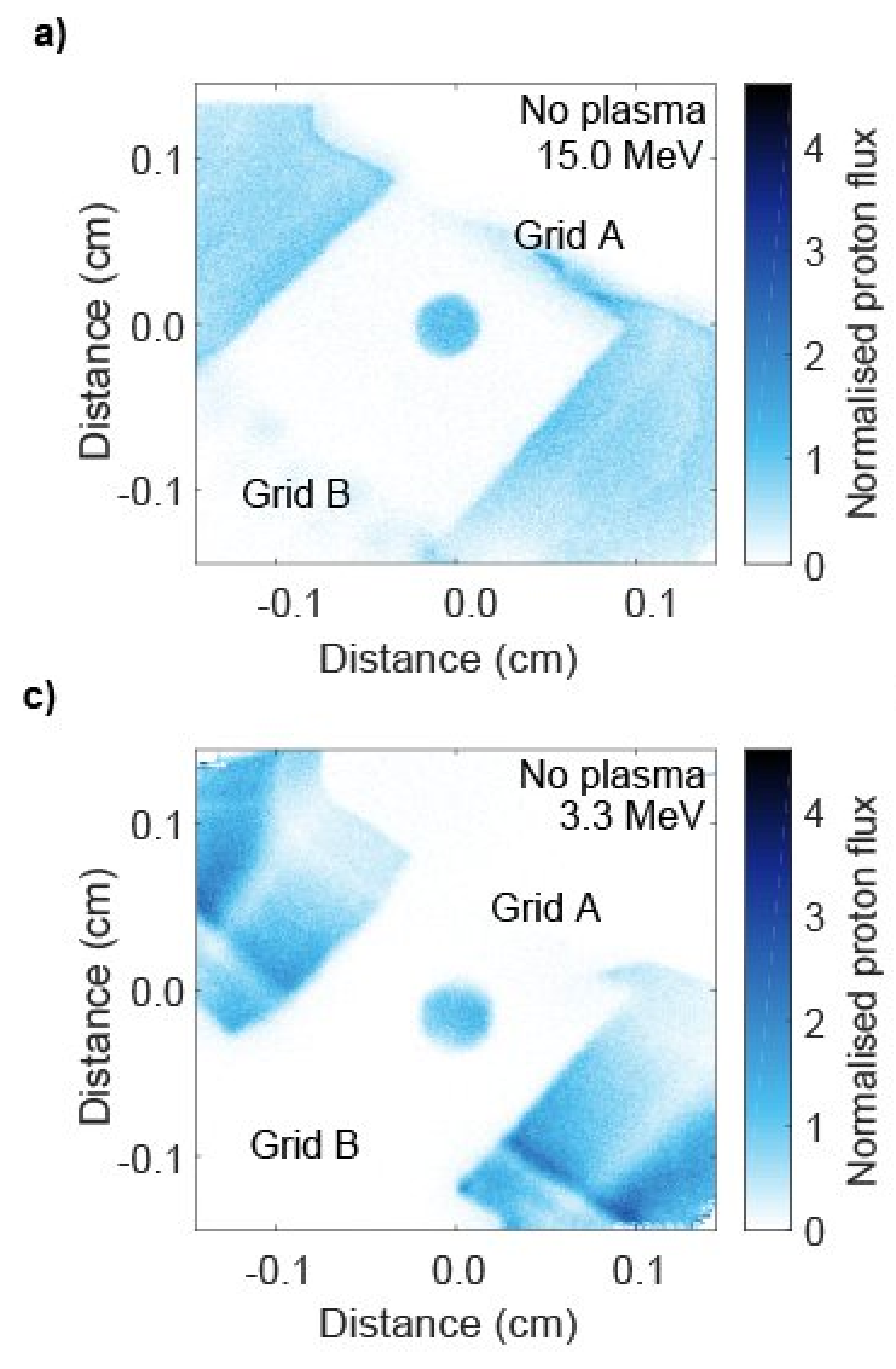
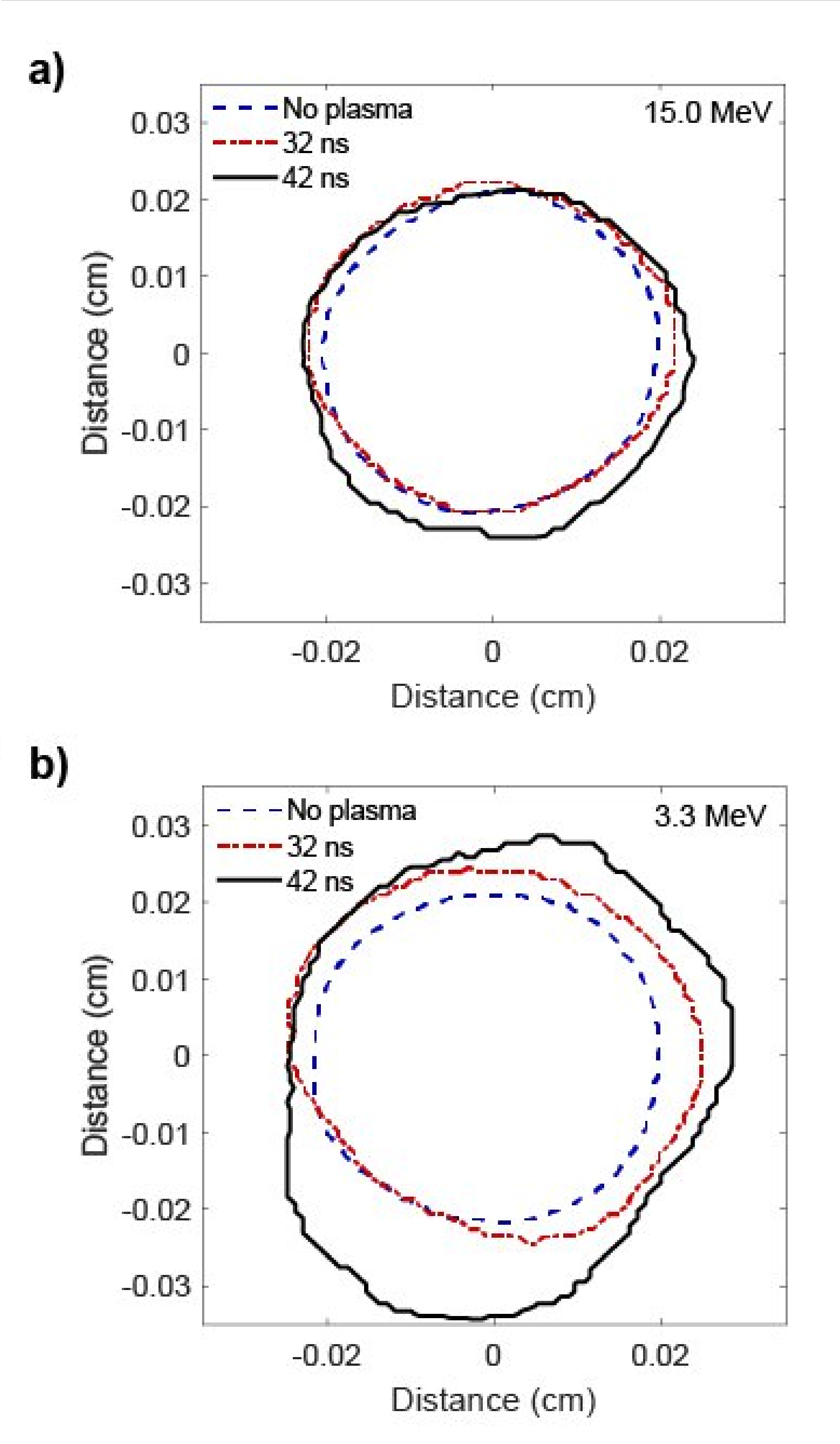
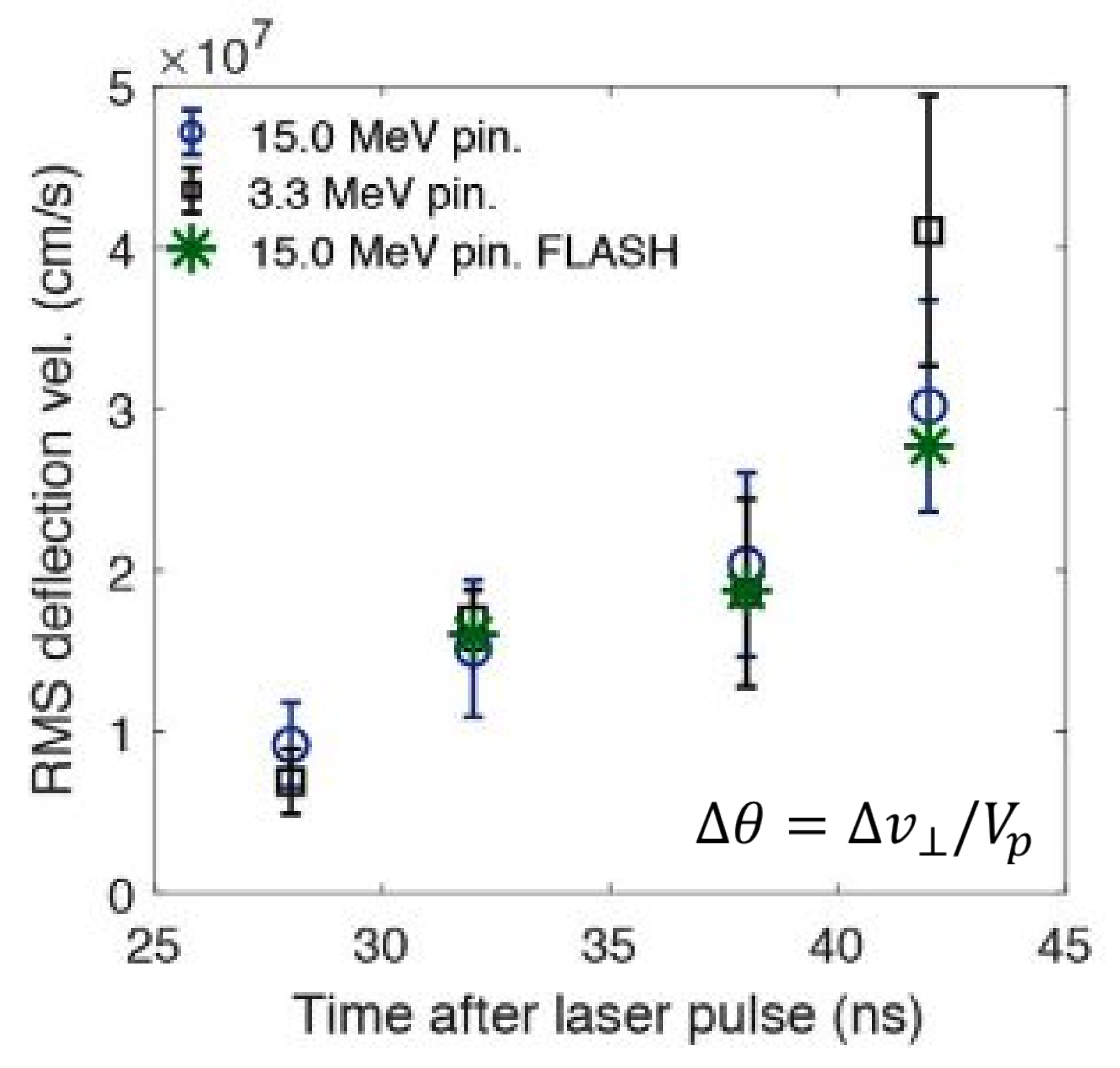




Deflections are due to stochastic magnetic fields



- 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

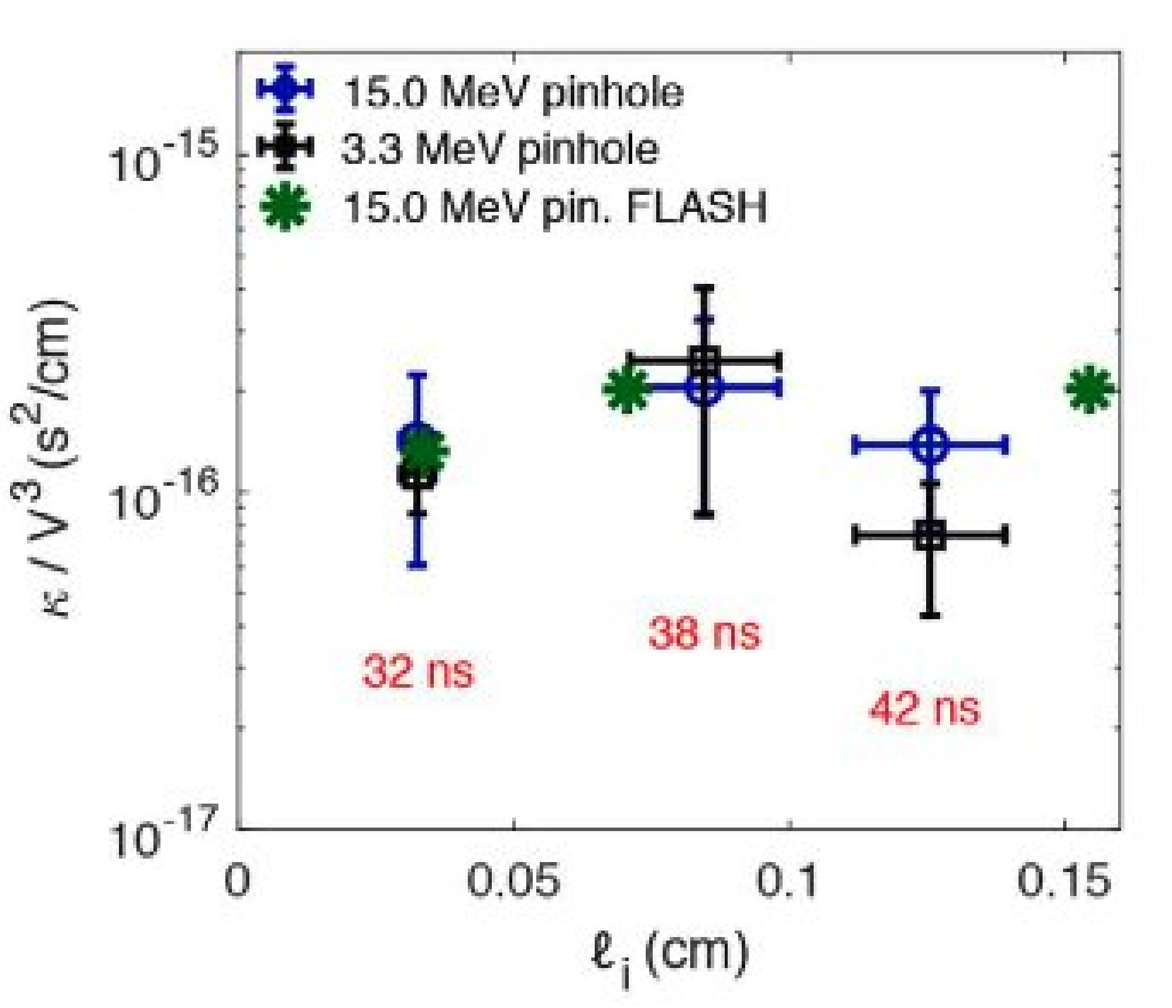
➜ From the measured deflection velocity, we can estimate the angular scattering coefficient in velocity space

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

Transit time through the plasma

$$\tau = \ell_i / V_p$$

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:

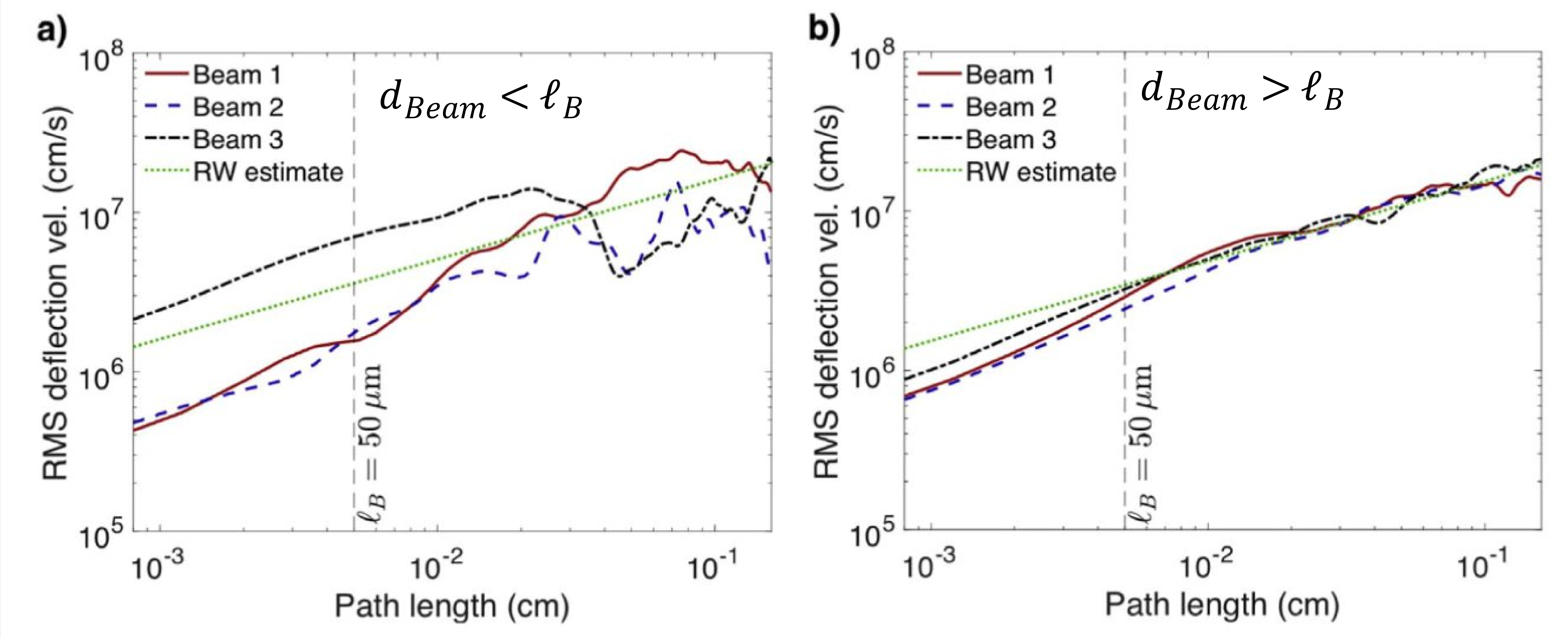
$$\kappa = \frac{V_p^2}{\nu} = \frac{\ell_i V_p^3}{(\Delta v_\perp)^2}$$

- ➜ 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*).
- ➜ This may seems surprising given that the magnetic field is not Gaussian.

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

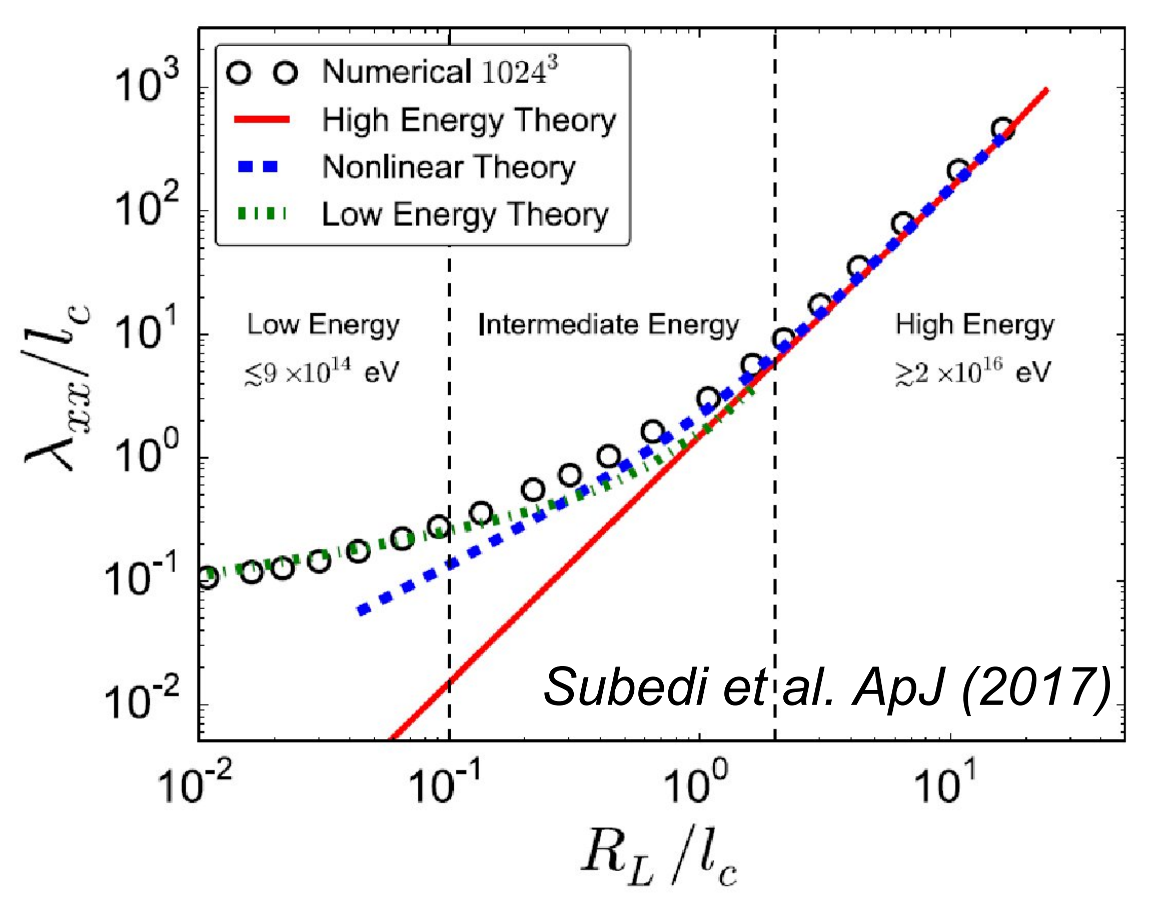


- ➜ Since κ/V^3 is constant, it means that:

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

- ➜ This implies **normal (Markovian) spatial diffusion** (*Tsytovich 1977, Salchi 2009, Subedi et al. 2017*).
- ➜ This is because the proton beam transverse size is much larger than the correlation length of the magnetic field turbulence.

Experimental data are consistent with simple theory of UHECR diffusion

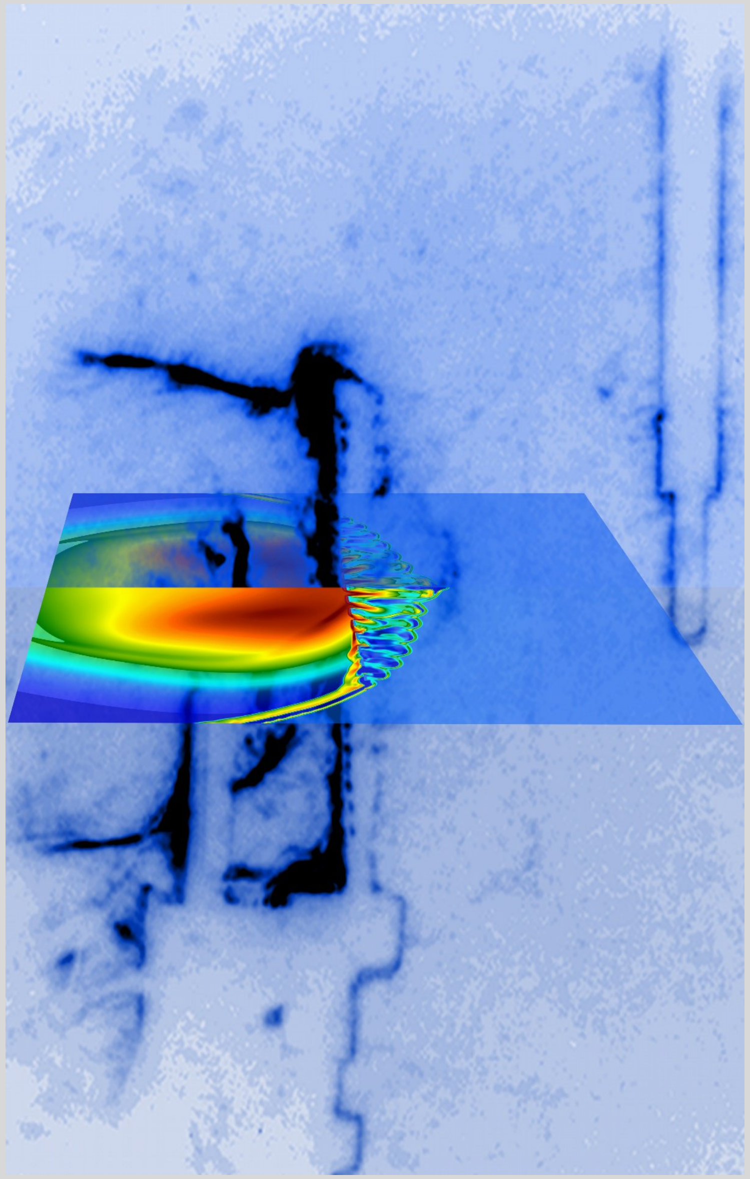


Subedi et al. ApJ (2017)

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

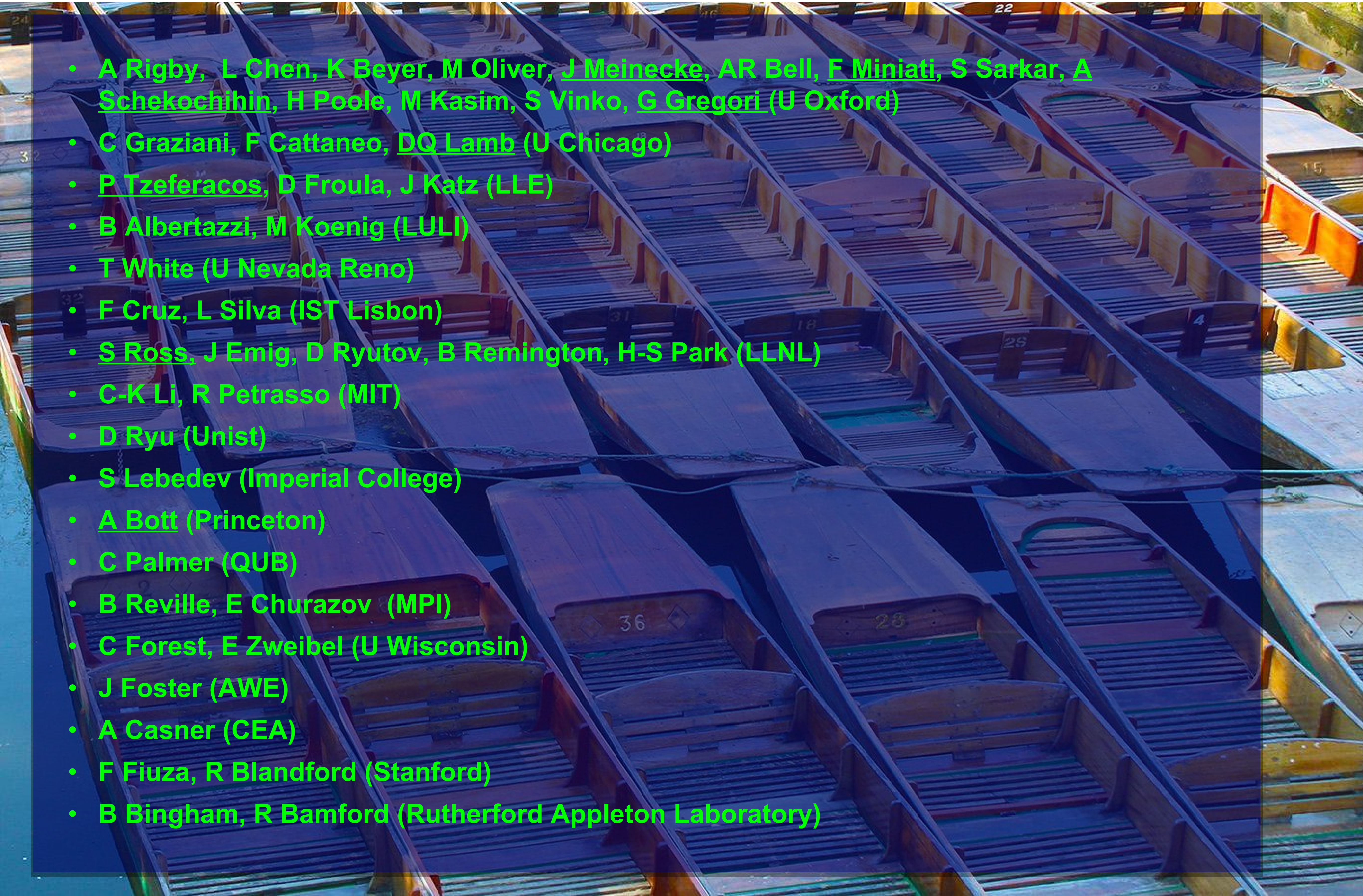
- ➜ Protons in the experiment have a ratio ℓ_c/r_g that is the same as that of 10 EeV UHECR interacting with the Galactic magnetic field.
- ➜ In this high energy regime, the experiment shows that the mean free path depends only on the Larmor radius - consistent with numerical simulations.
- ➜ This is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

Summary



- We have developed a platform to study transport processes in turbulent and magnetized plasmas.
- Results from NIF show very different temperature maps than what observed on Omega.
- NIF results are consistent with a reduction in heat conduction by a significant factor (~100x), as seen in laboratory and astrophysical plasmas.
- We have developed a new ML tool that can be used to extract transport models from the data.
- 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 all collaborators



- A Rigby, L Chen, K Beyer, M Oliver, J Meinecke, AR Bell, F Miniati, S Sarkar, A Schekochihin, H Poole, M Kasim, S Vinko, G Gregori (U Oxford)
- C Graziani, F Cattaneo, DQ Lamb (U Chicago)
- P Tzeferacos, D Froula, J Katz (LLE)
- B Albertazzi, M Koenig (LULI)
- T White (U Nevada Reno)
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Thank you for your attention!

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