Laser experiments probing cosmic ray transport in the laboratory

(*a journey with Subir*)

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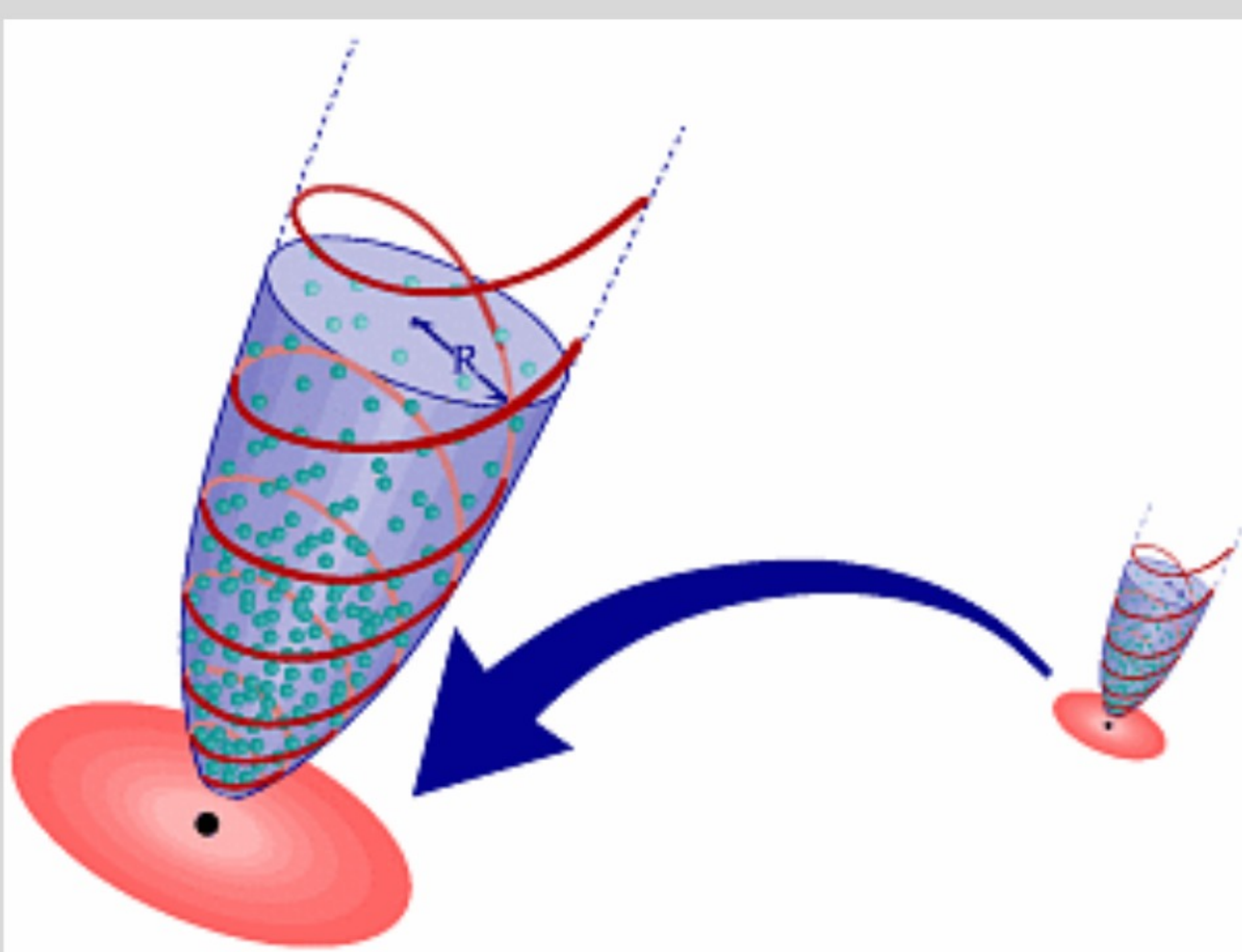
What is laboratory astrophysics?

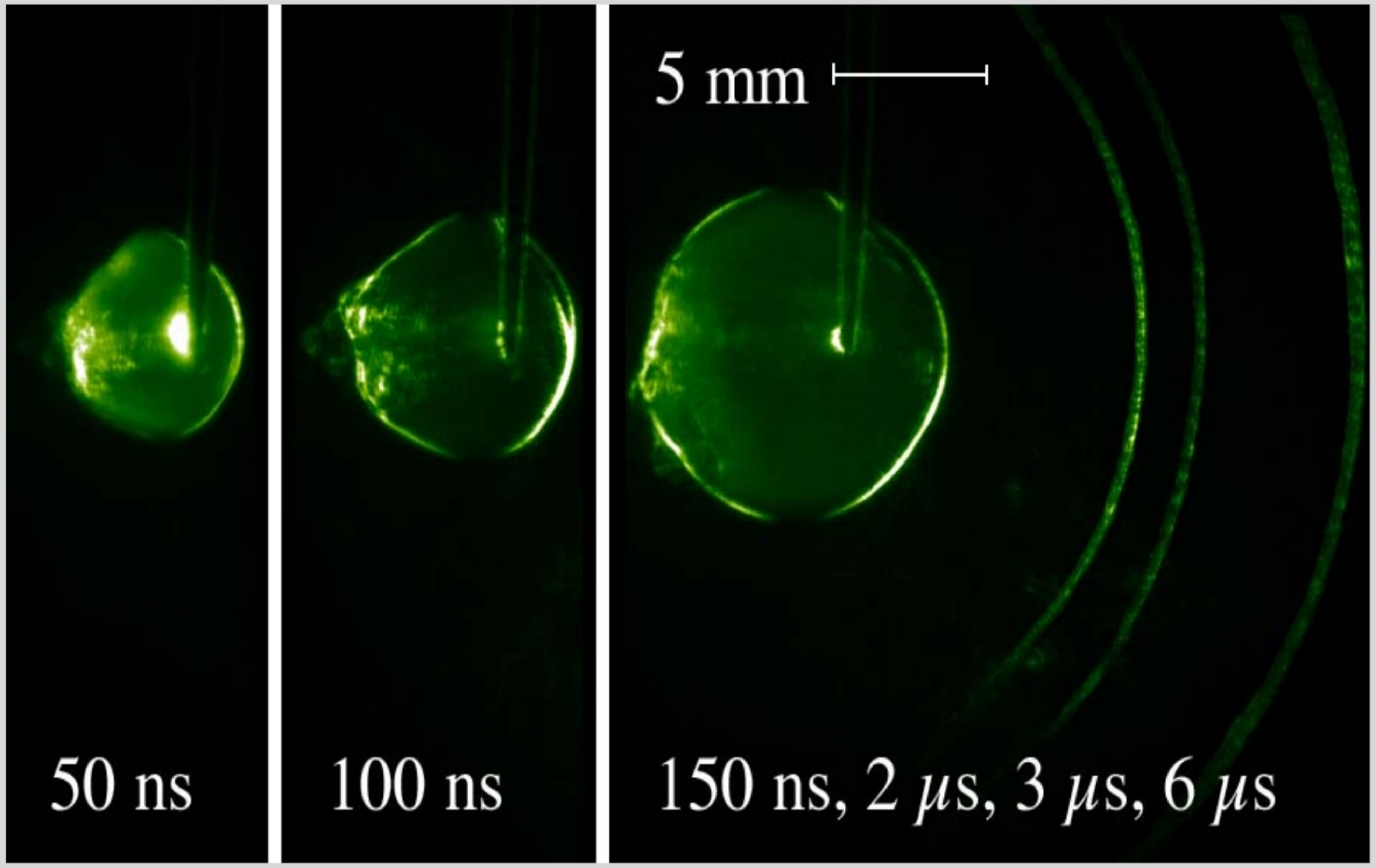
- Research in astrophysics/astronomy is usually done in two different ways:
  - Observations with telescopes or satellites;
  - Numerical simulations.
- Laboratory astrophysics provides a different approach whereby astrophysical problems are studied in a laboratory on Earth.
- *Syntactic isomorphism*: **two systems are described by the same mathematical equations through a mapping that assigns different physical interpretations to the same mathematical objects.**



$$\frac{\partial U}{\partial t} + \nabla \cdot F(U) = 0$$

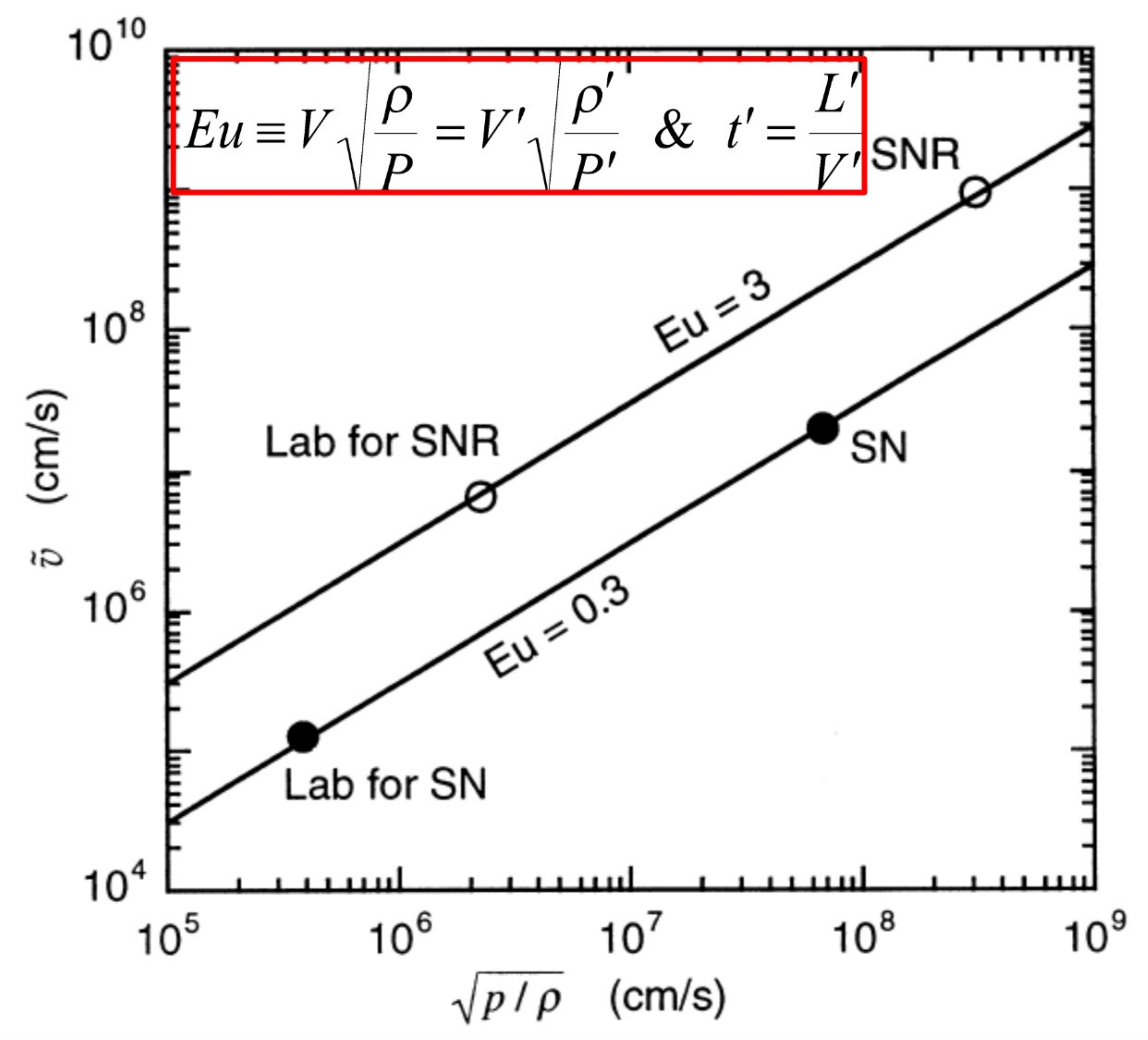
$$\left.\begin{array}{l} \ell, u, \rho \\ \tau = \ell / u \\ p = \rho u^2 \end{array}\right\} \xrightarrow[\text{transform}]{\text{self-similar}} \left\{\begin{array}{l} \ell', u', \rho' \\ \tau' = \dfrac{\ell'/\ell}{u'/u}\tau \\ p' = \dfrac{\rho'}{\rho}\left(\dfrac{u'}{u}\right)^2 p \end{array}\right.$$

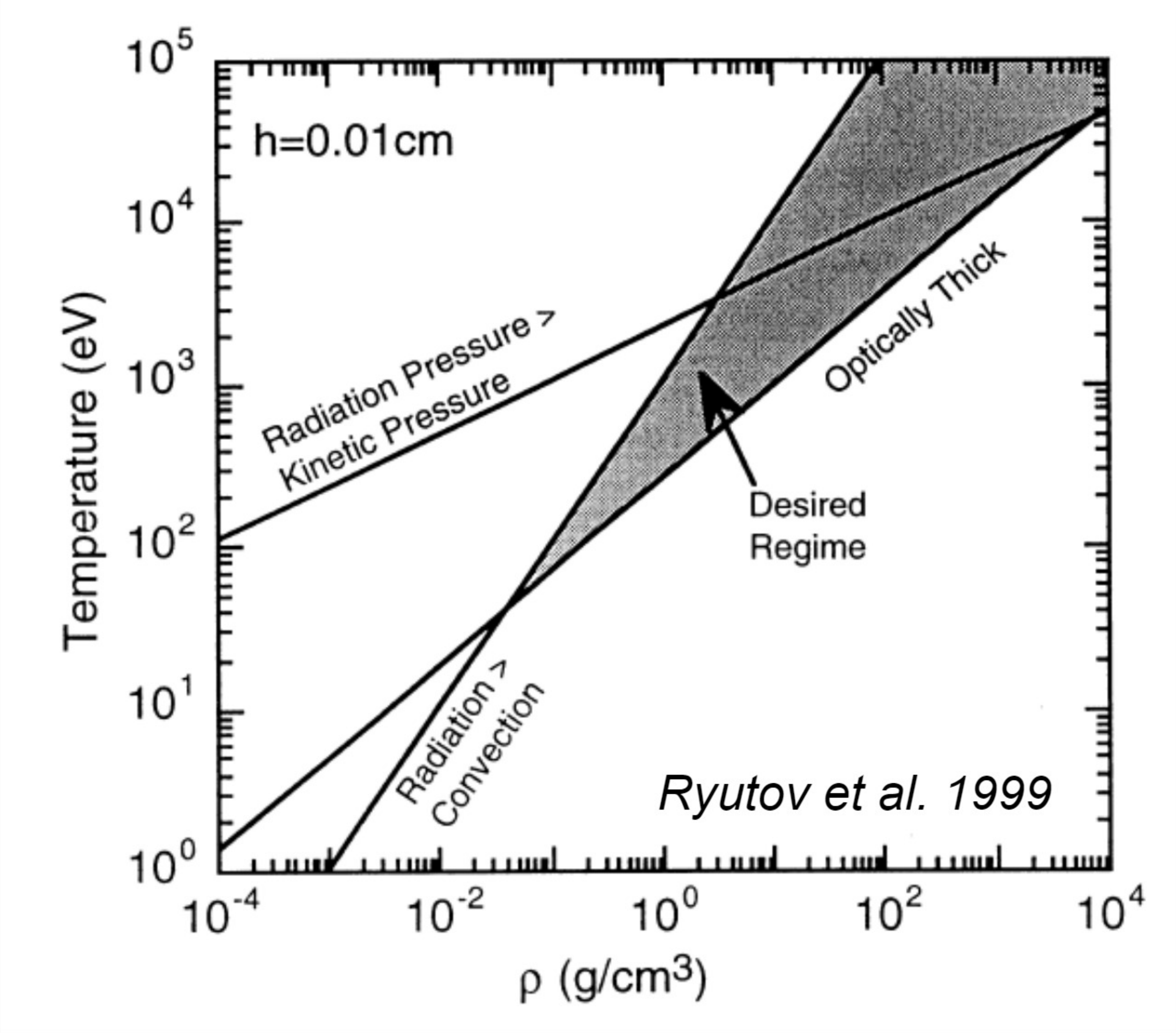
Laboratory astrophysics as new way to study astrophysical objects



- The requirement for *syntactic isomorphism* is that in both the laboratory and the astrophysical systems, viscosity, heat dissipation, and electrical resistivity can be neglected.
- Laboratory experiments can be complementary to observations (we can measure the property of the plasma in details) and offer a mean to directly validate numerical simulations as well as reach spatial and temporal scales not accessible by state-of-art calculations.

Scaling relations put at work





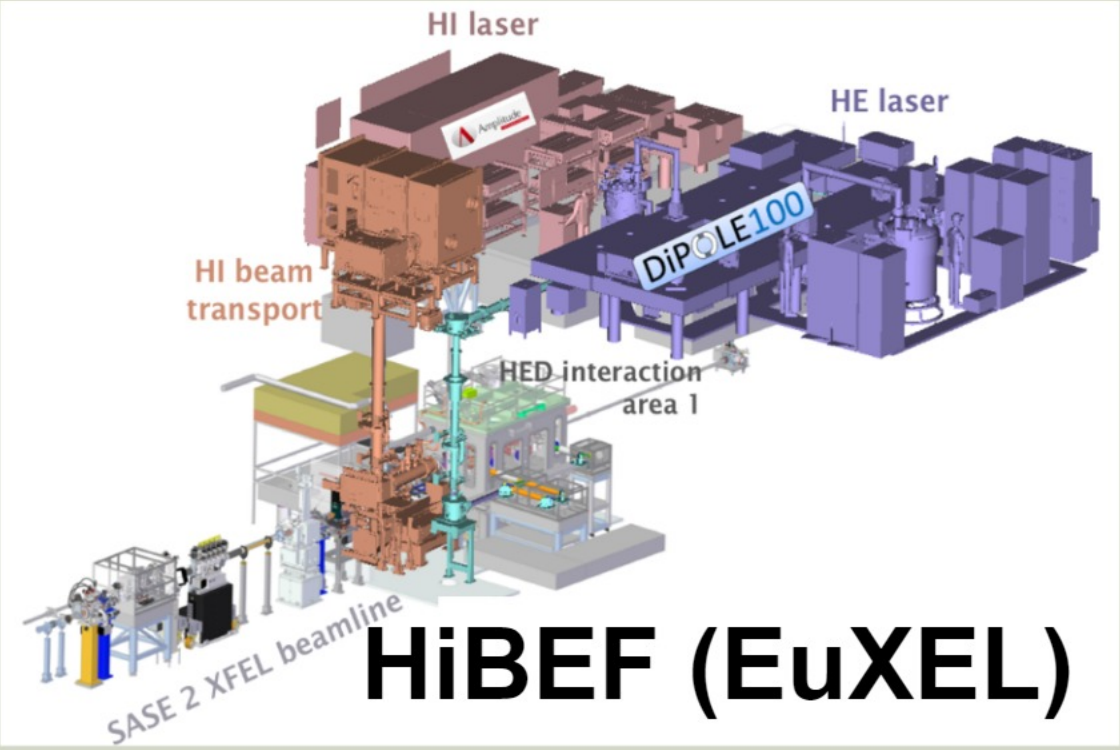
- In practice, at a given spatial scale, laboratory experiments require large temperatures and large densities.
- This implies large energy densities (>100 GPa); hence the need to drivers that can achieve these extreme conditions.

Facilities for laboratory astrophysics

High-power lasers

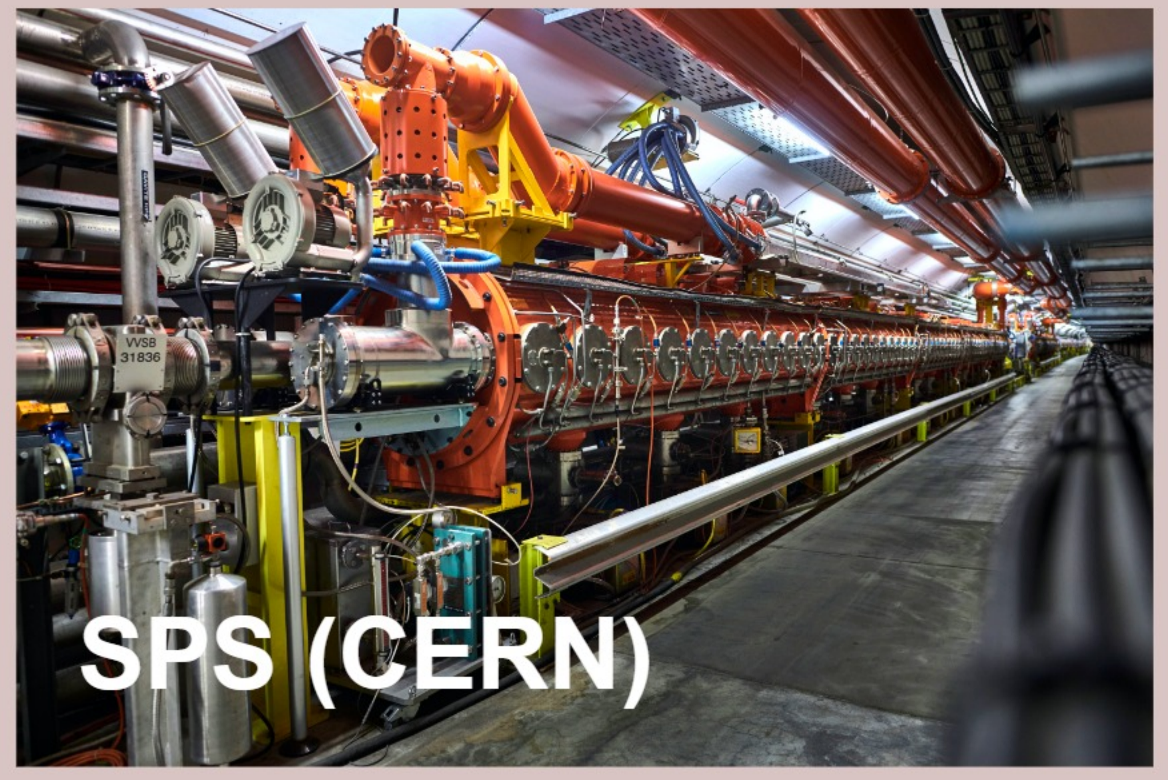
- Many systems available worldwide.
- High-intensity lasers are the new frontier.
- Access extreme pressures and extreme fields (from planetary science to QED).

X-ray FELs



- HiBEF consortium (at EuXFEL) is commissioning a multi-purpose facility (XFEL, High-rep rate optical laser, High-intensity laser, Pulse magnet).
- Similar facility is been planned for MEC-U.

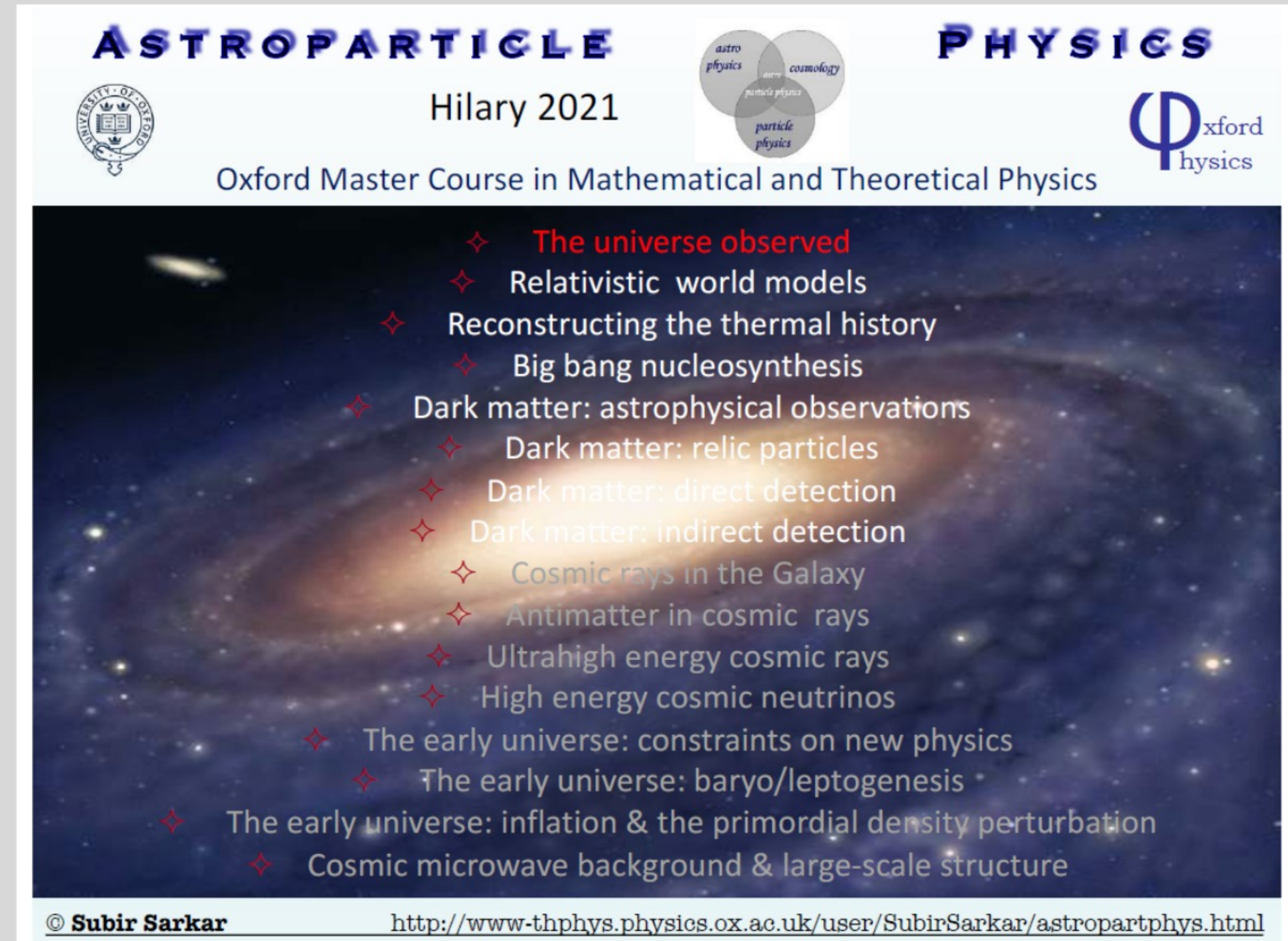
Particle accelerators



- Use particle physics facilities in a very different mode.
- FACET (at SLAC) and now HiRadMat (at CERN) are flagship facilities in these efforts.

Combination of different facilities is bringing new perspectives

But, of course, experiments are useless if you don't know astrophysics...



- In 2014 I attended Subir's course on Astroparticle Physics.
- And this is when I started to know Subir and discussed the experiments we were doing at that time (on plasma turbulence) and relate them to cosmic ray acceleration.
- I am going to showcase what I have been doing with Subir since 2014 on turbulence and particle acceleration.
- But, this is not all...we also worked on axions, laboratory GRBs, Unruh radiation...

Fermi acceleration is a universal process for particle energization

- The presence of energetic particles in the Universe is now a century-old problem, with measurements of the cosmic ray (CR) spectrum extending beyond 10^{20} eV.
- Although many different processes may result in CR acceleration, the consensus is that turbulence plays an essential role in energizing particles.
- Fast particles collide with moving magnetized clouds (*Fermi, 1949*). Particles can gain or lose energy, but head-on collisions (gain) are slightly more probable.
- The evolution of the protons as they escape the plasma is governed by a diffusion equation (*Kaplan, 1955; Blandford & Eichler, 1987*).

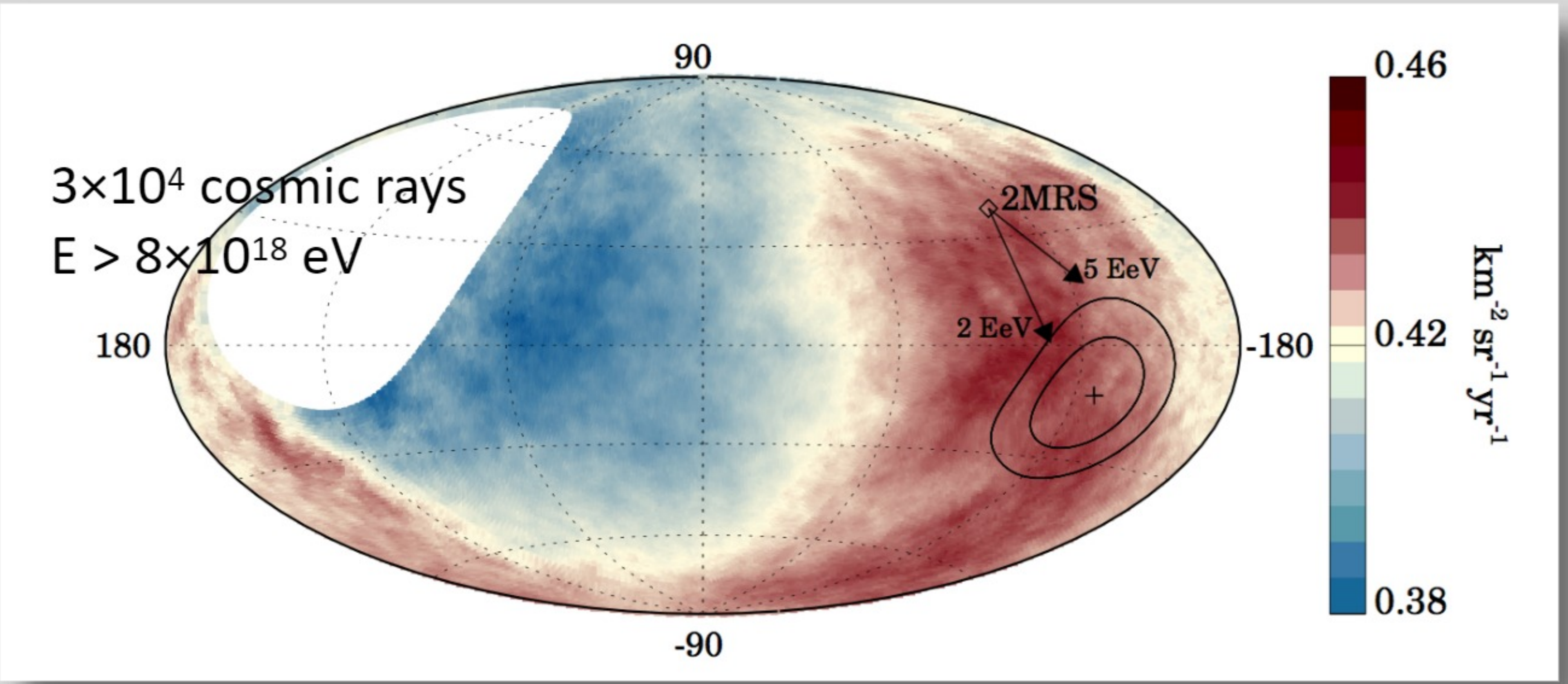
$$\frac{\partial f}{\partial t} = \boxed{-\frac{1}{p^2}\frac{\partial}{\partial p}\left(-p^2 \mathcal{D}_{pp}\frac{\partial f}{\partial p}\right)} - \frac{f}{\tau_{esc}} + \frac{I_0 \delta(p-p_0)\delta(t-t_0)}{4\pi p^2}$$

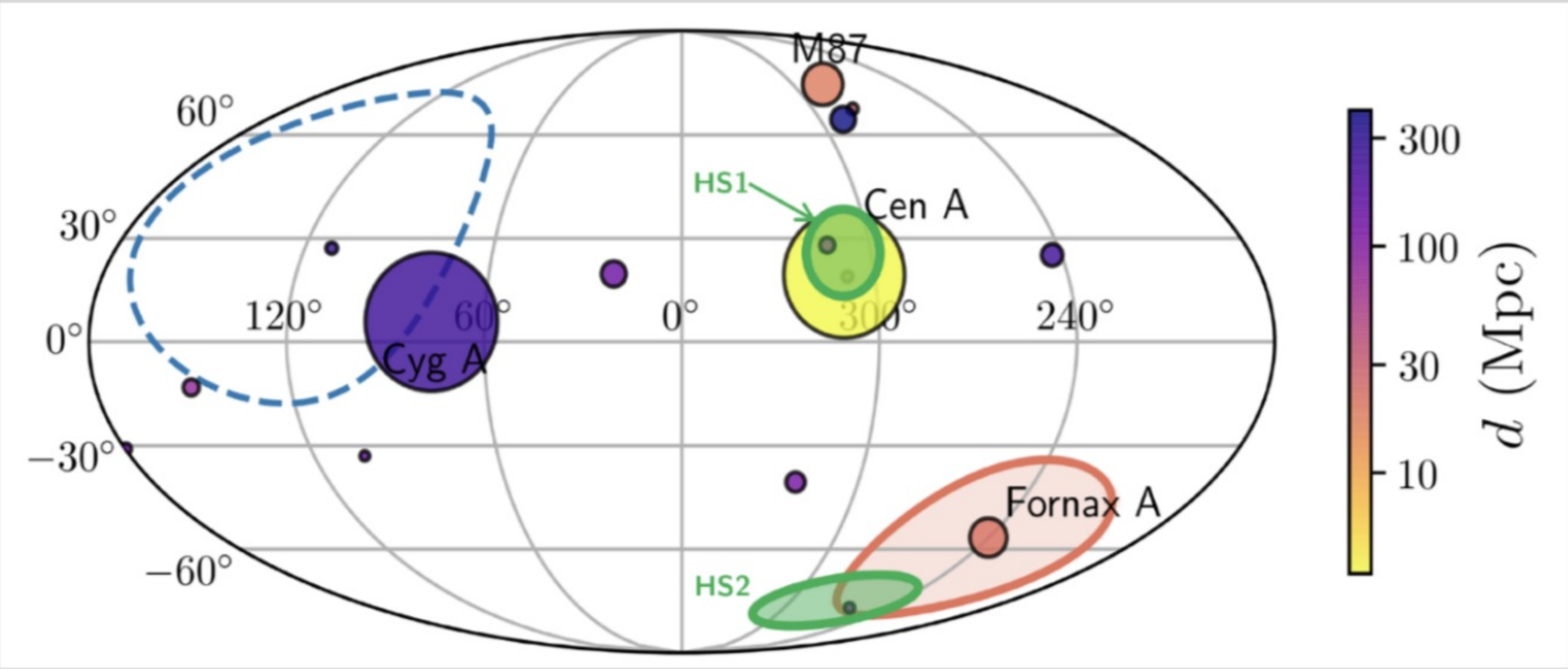
Neglecting adiabatic losses and assuming impulsive injection

- This equation can be solved analytically (*Cowsik & Sarkar, 1984; Mertsch, 2011; Beyer et al. 2018*).

How cosmic rays (CRs) are observed on Earth depends on the extragalactic magnetic fields

The Pierre Auger Collaboration,
Science (2017)

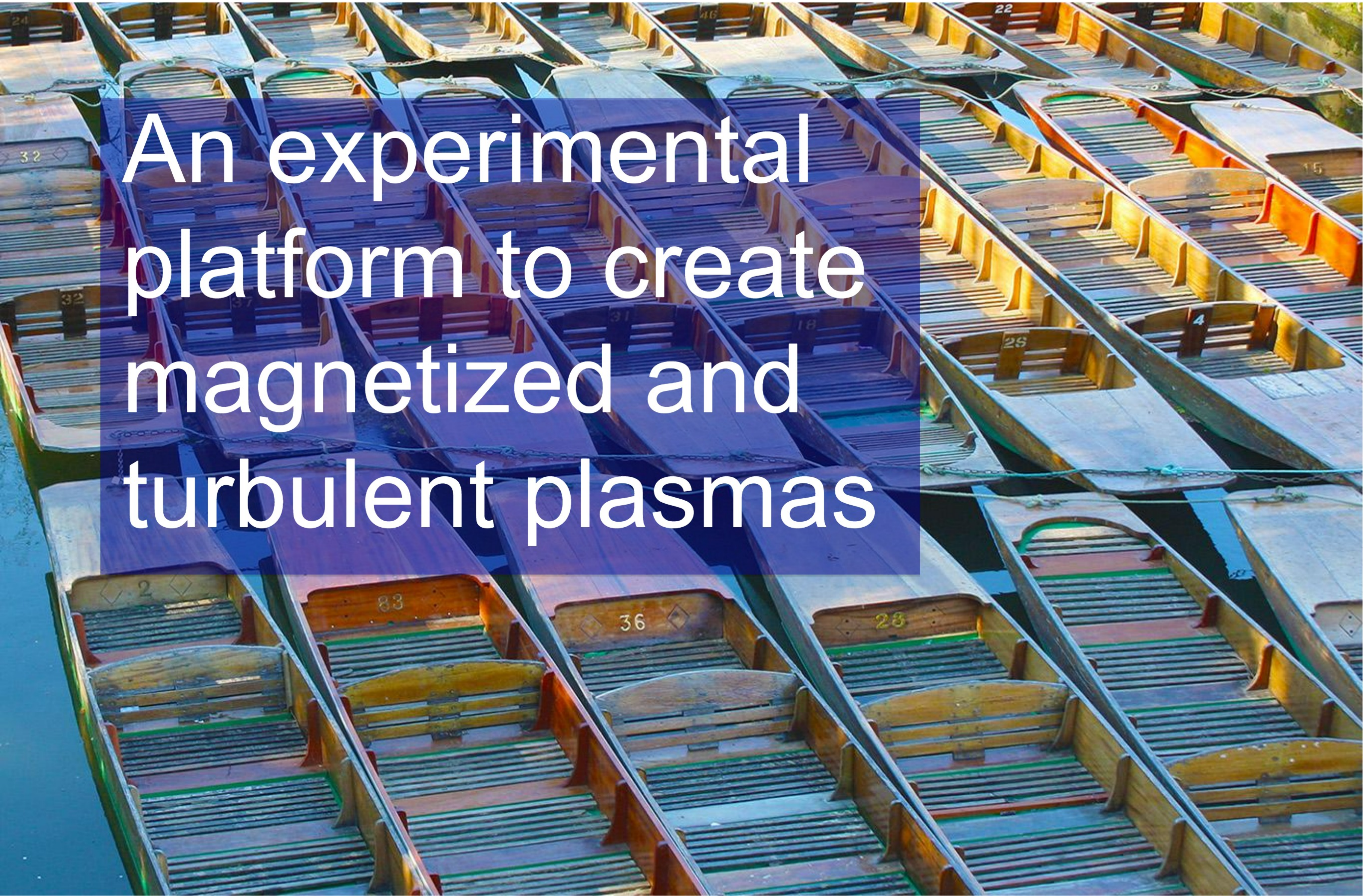




Matthews et al. (2018)

- 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*).

An experimental platform to create magnetized and turbulent plasmas

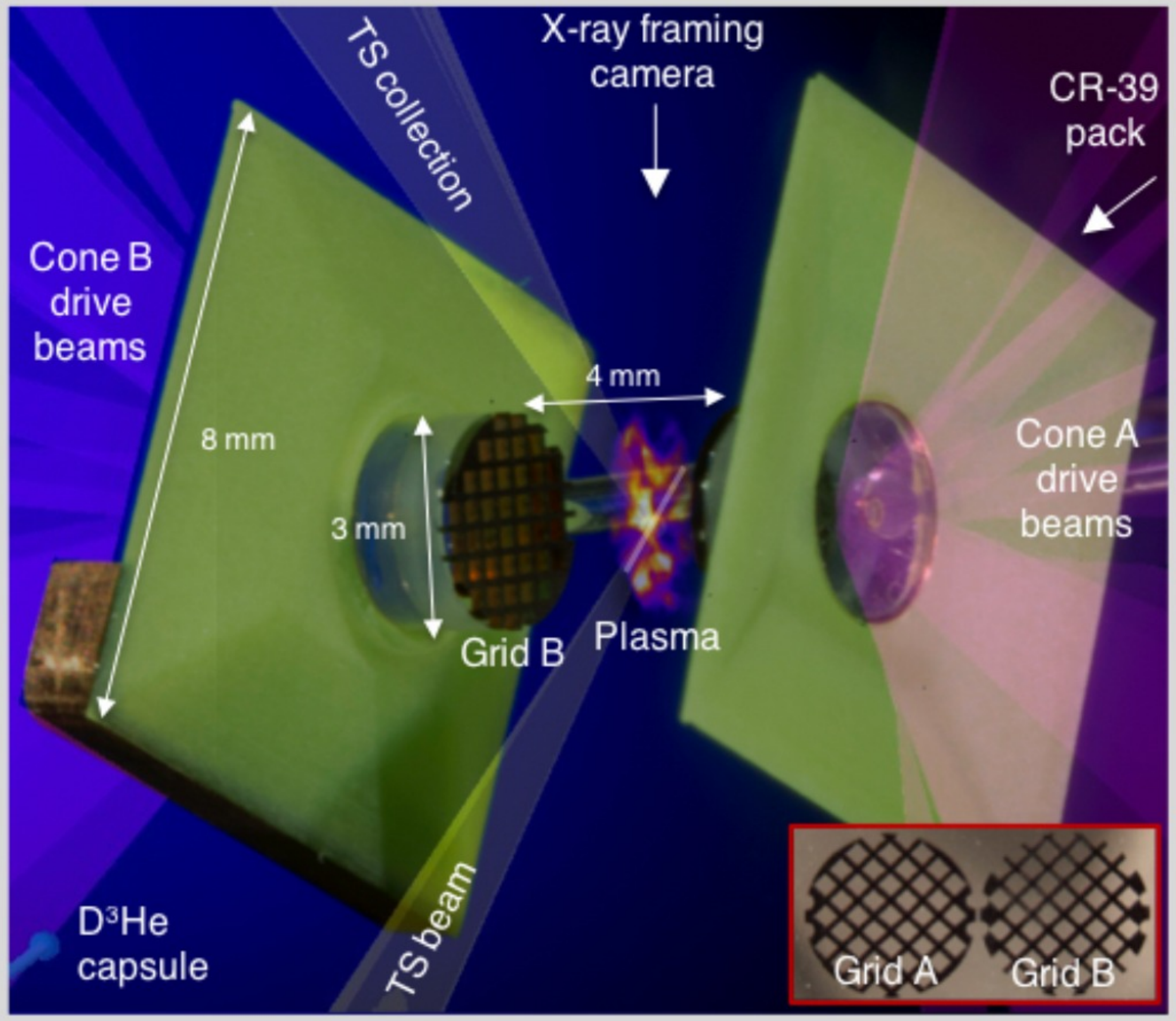


Experiment uses colliding flows and grids to create strong turbulence

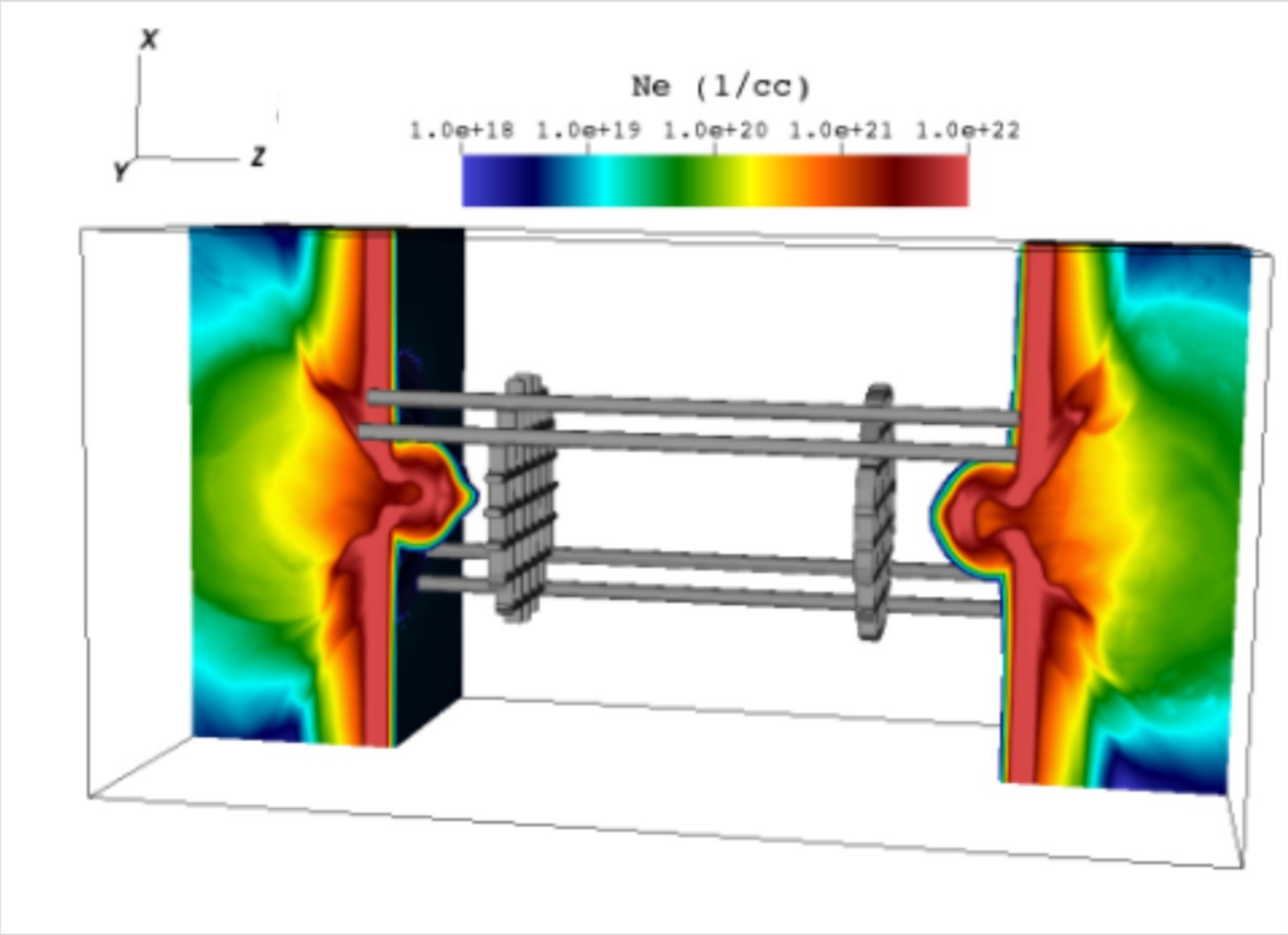
→We use experiments to create colliding jets of plasmas
- Plasma flows are created by firing two sets of laser beams
- Flow initially destabilized by interaction with a grid

→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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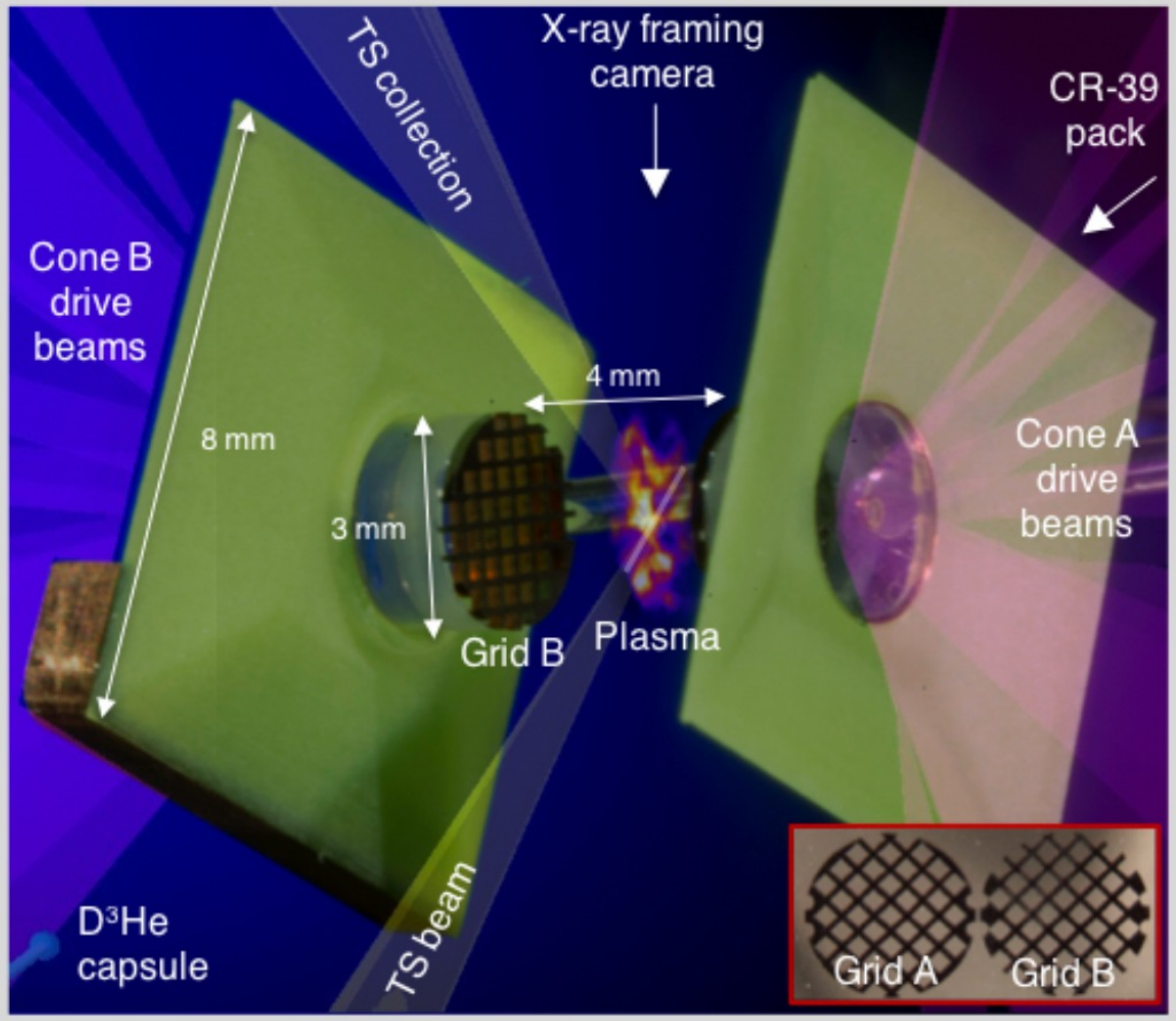

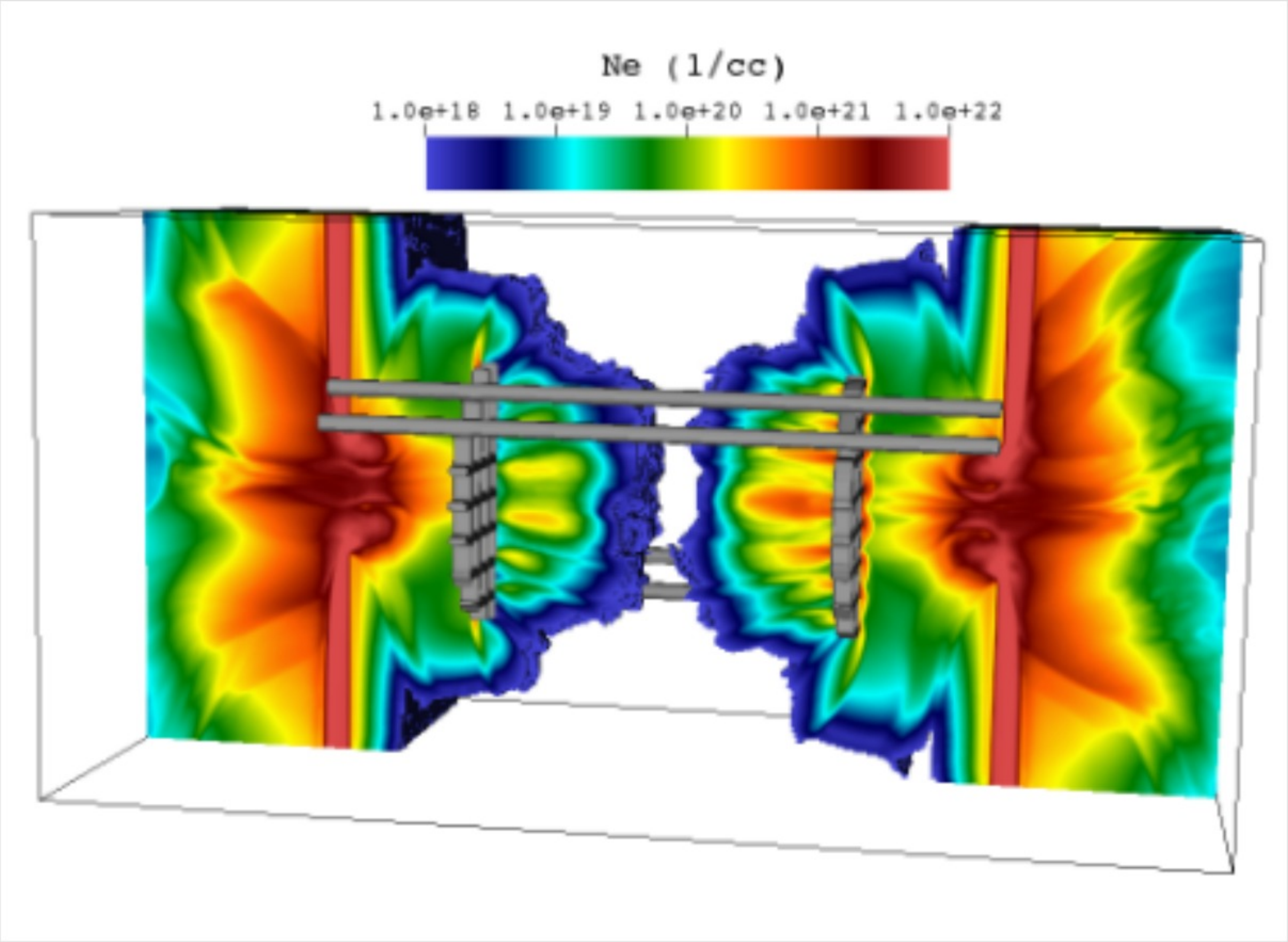

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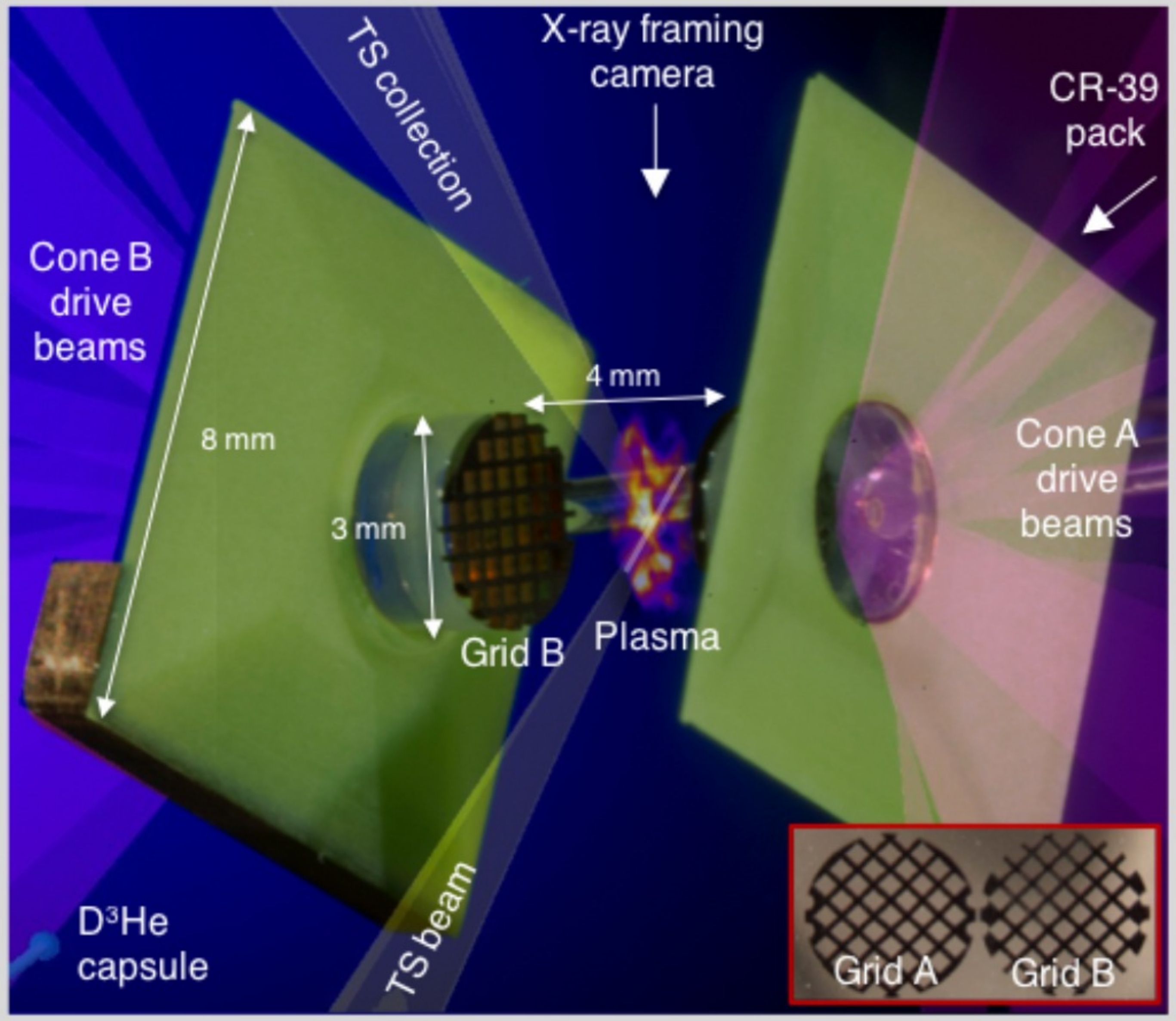
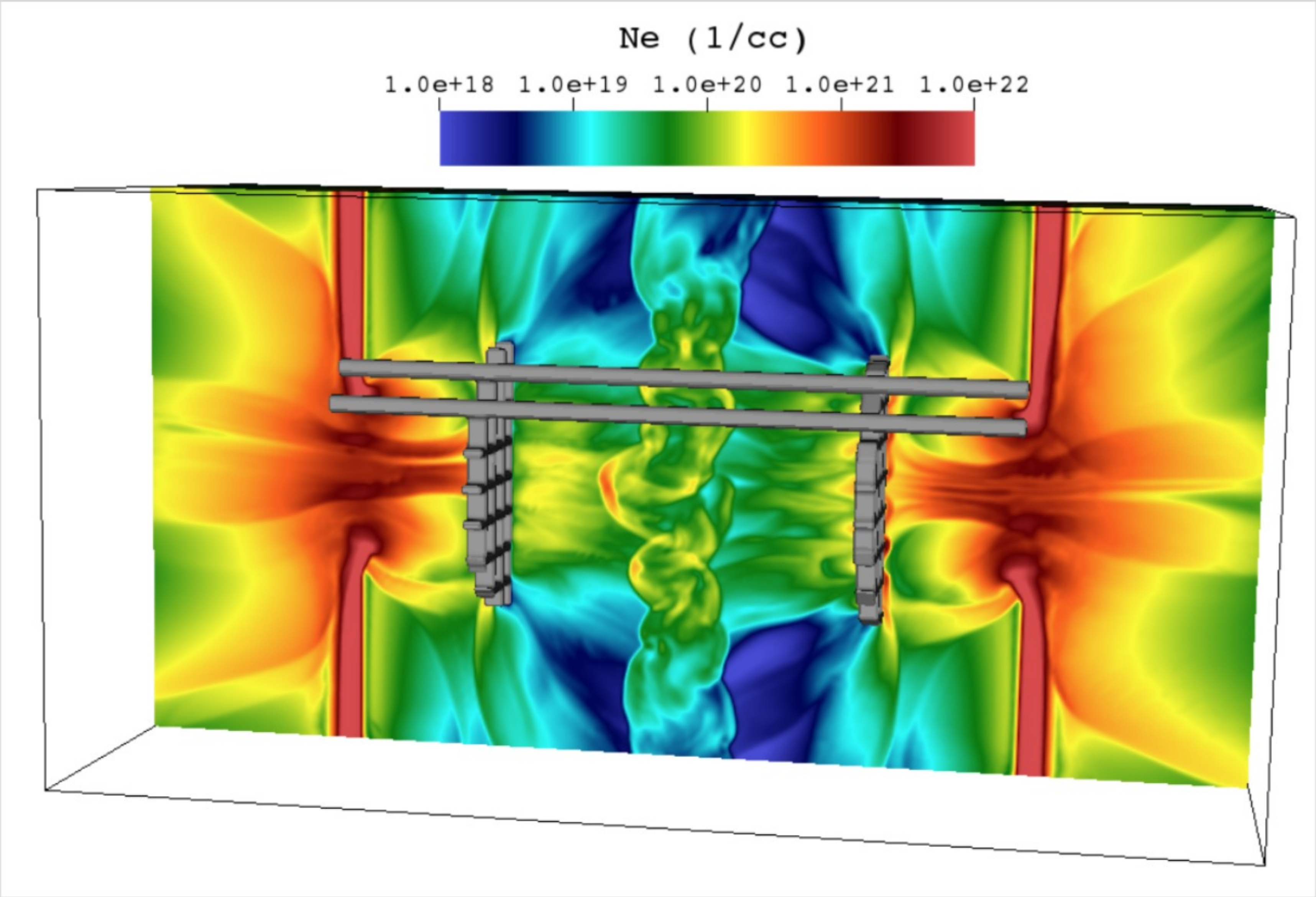
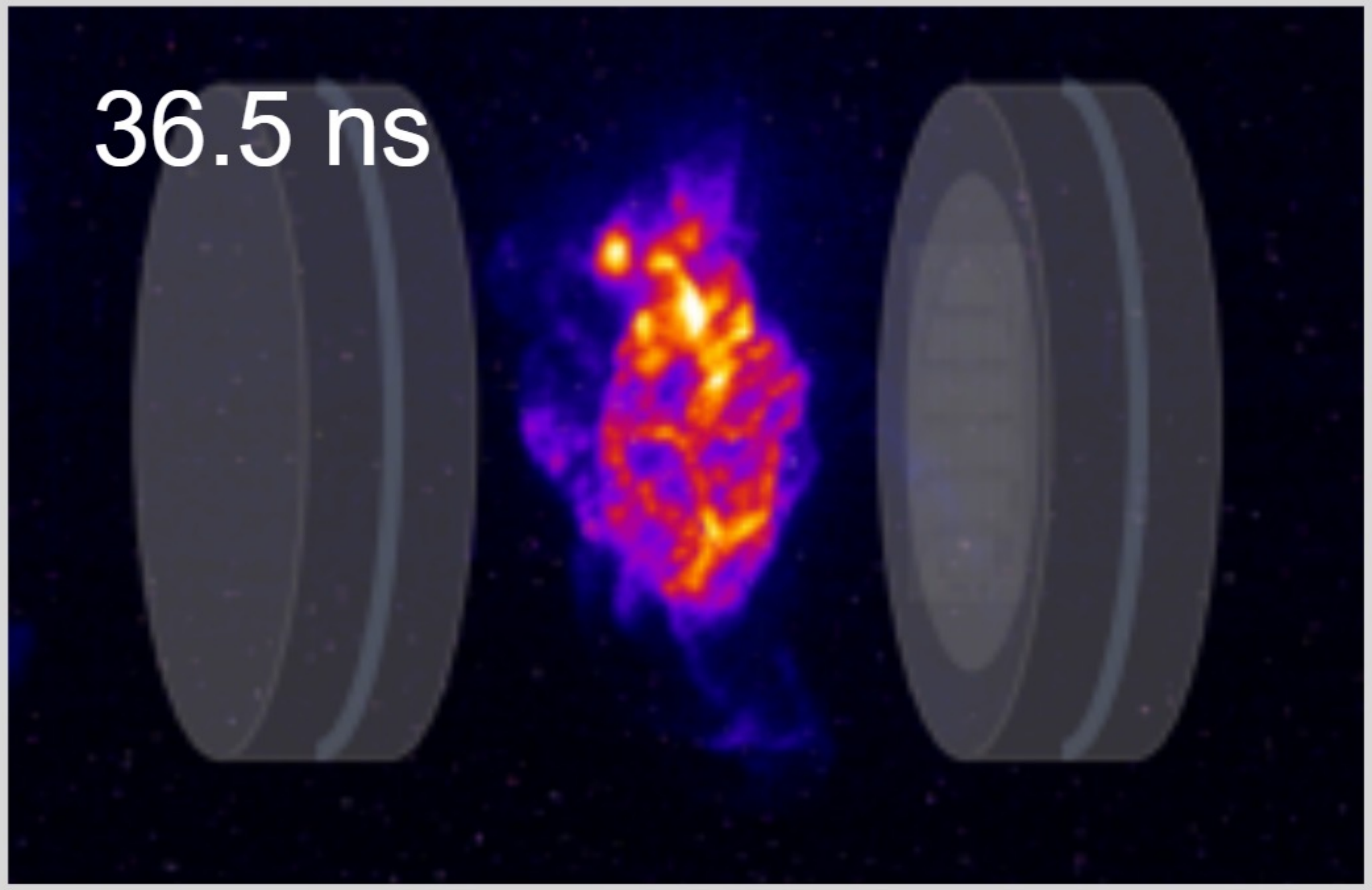
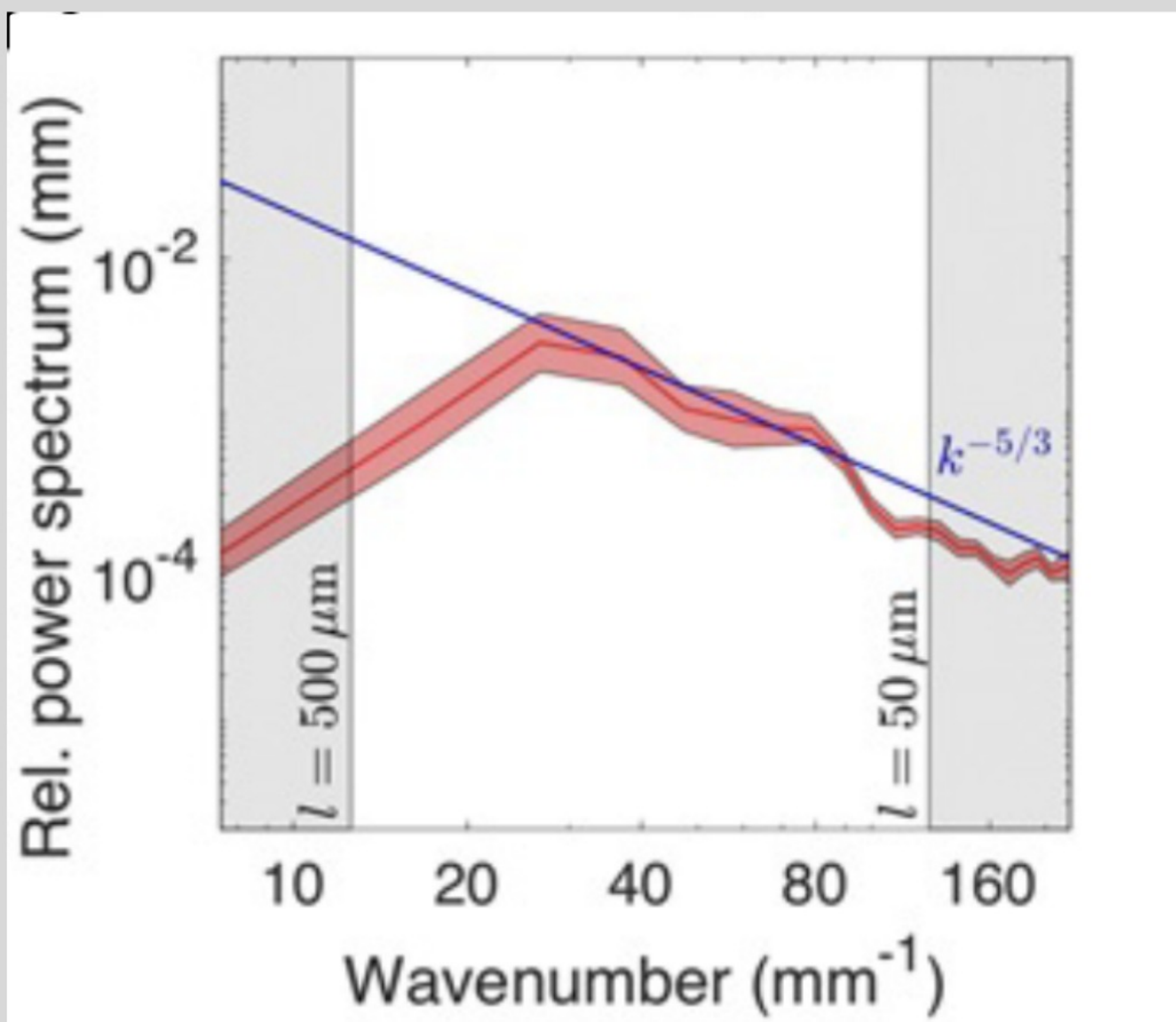




Tzeferacos et al. Nature Comm. (2018)

X-ray emission is used to determine power spectrum of turbulence

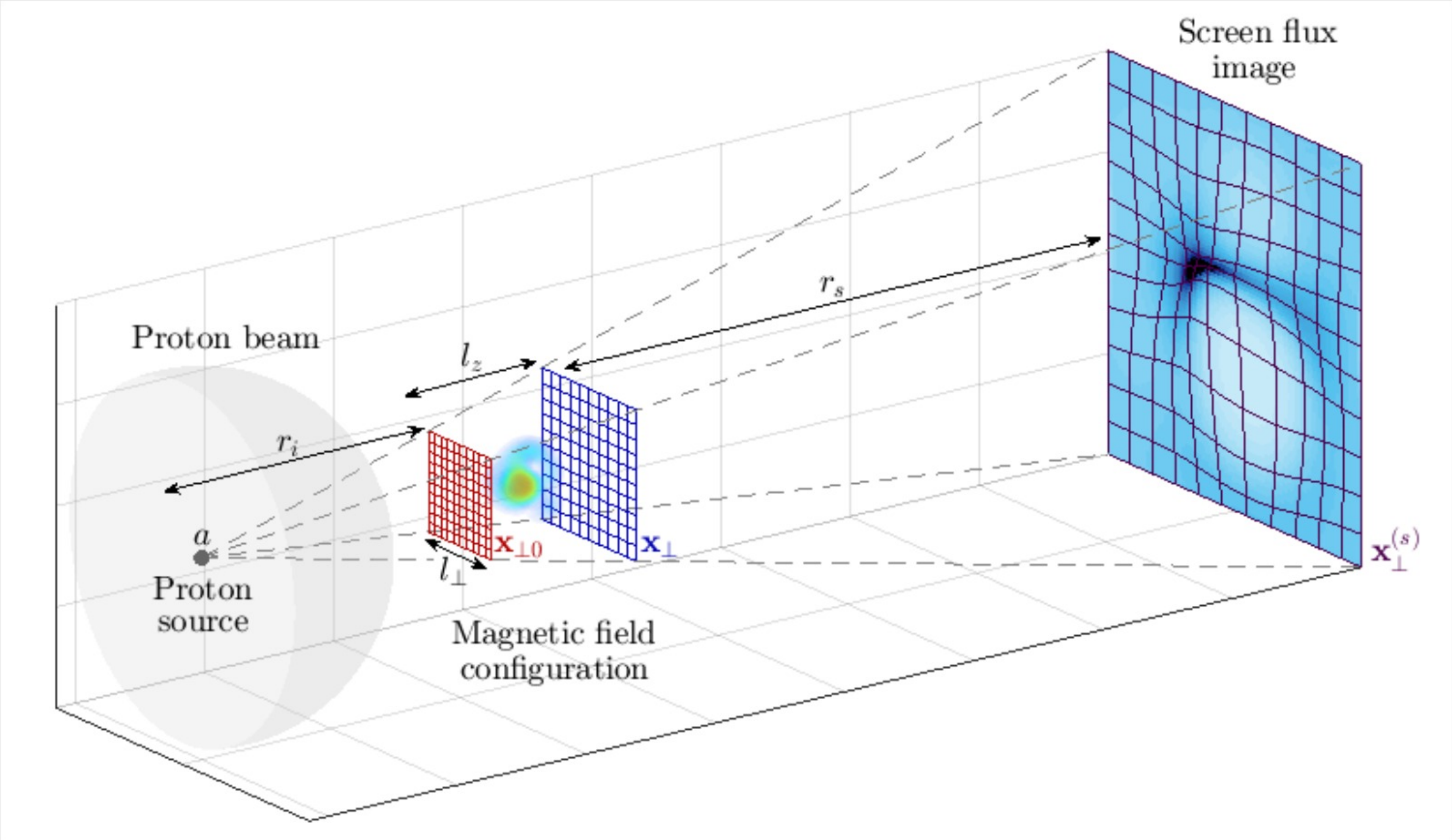




Bott et al. PNAS (2021)

- Assume an optically thin plasma so that fluctuation of X-ray emission depends on density variations.
- The 2D Fourier transform of the intensity fluctuations can thus be related to the 3D spectrum of the density fluctuations.
- Density fluctuations exhibit a Kolmogorov power law.
- There is strong indication density and velocity fluctuations have the same spectrum (Zhuravleva et al. 2015).

Magnetic fields are measured by proton radiography



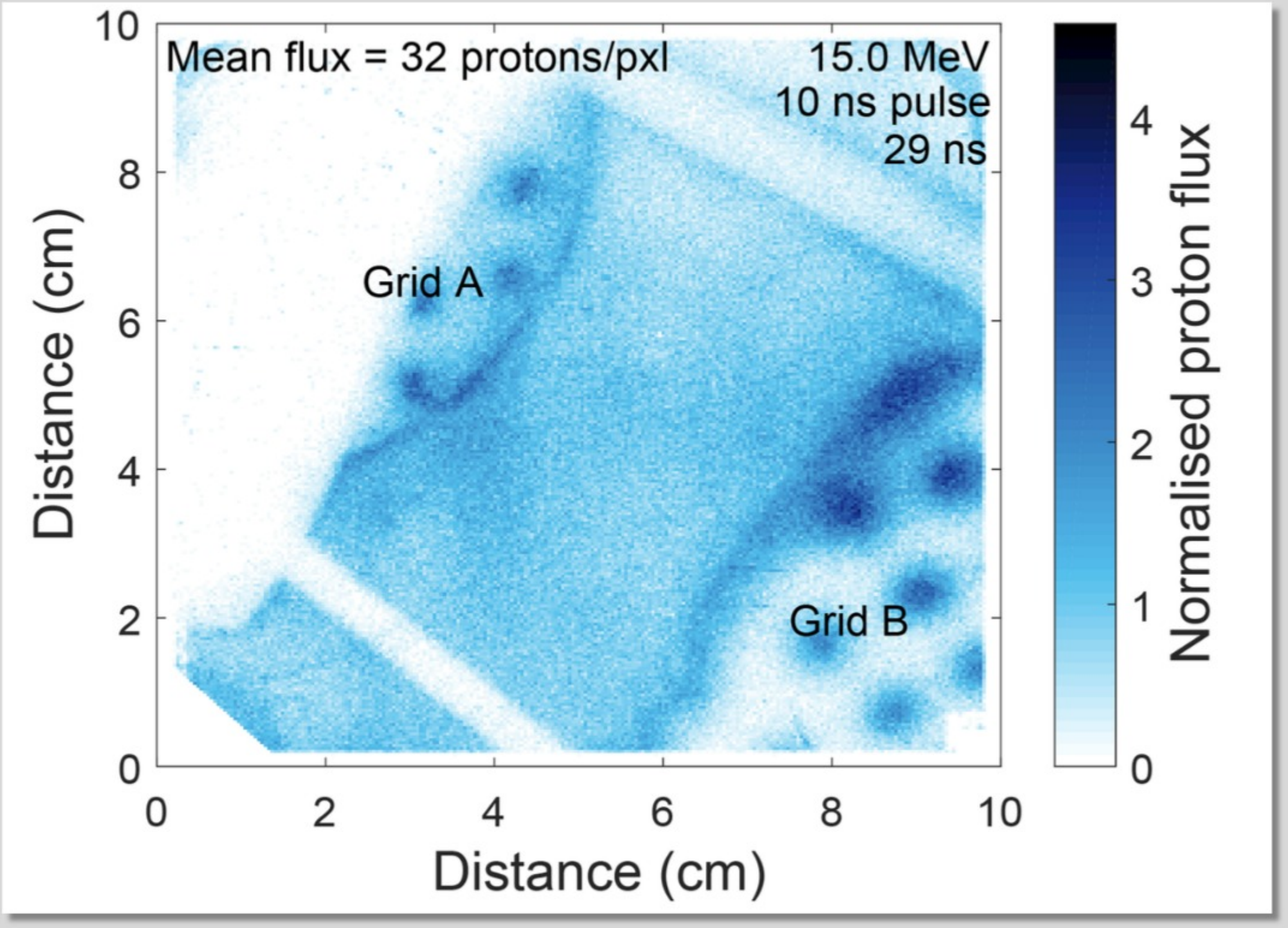
→ We use 3.3 MeV and 15 MeV protons to map the magnetic field structures in the plasma

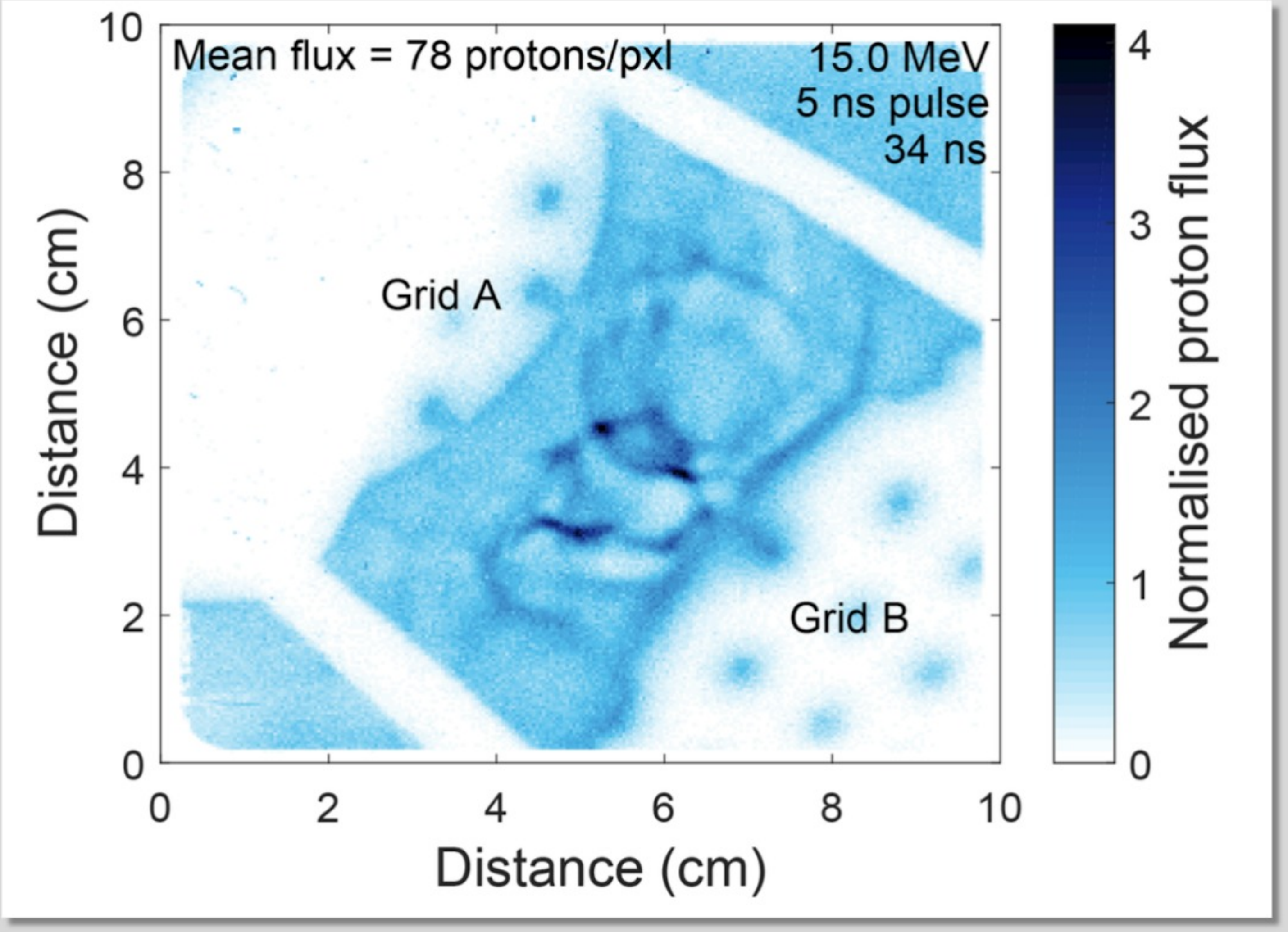
→ Proton deflections are a measurement of the path-integrated magnetic field

→ 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*)

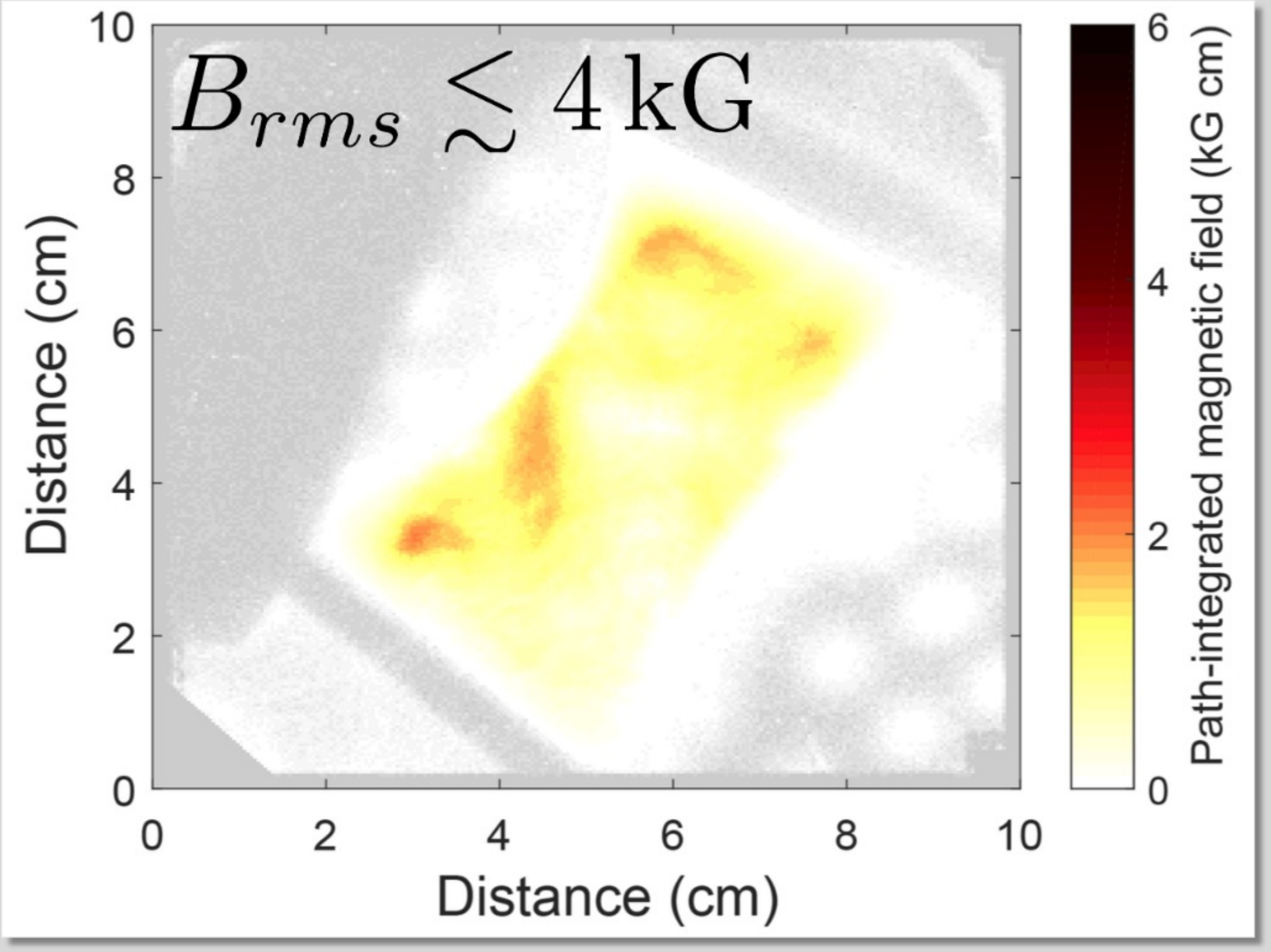
Magnetic fields are measured by proton radiography

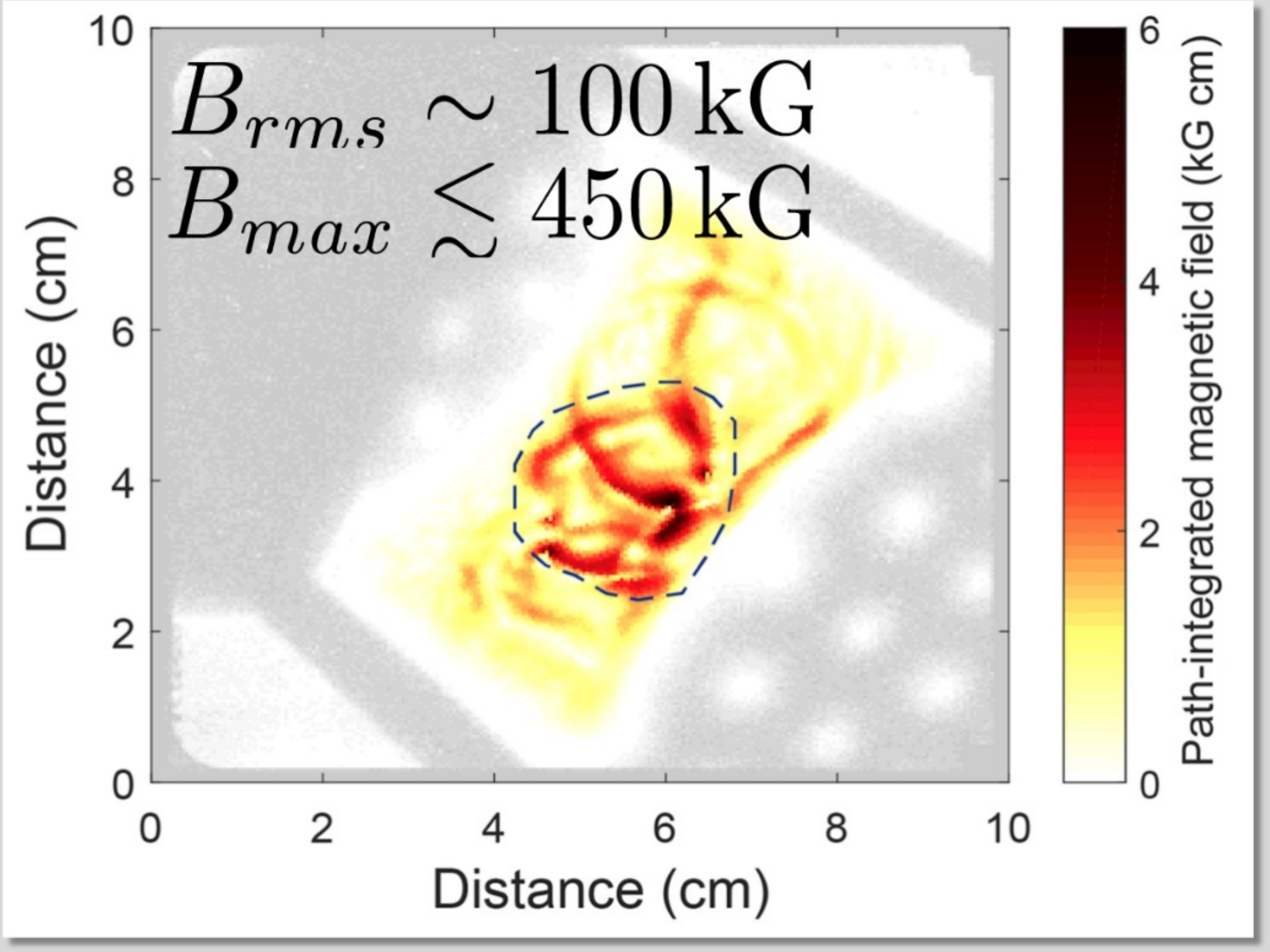




- → No structures appear in the images before the collision.
- → Filaments are seen after the collision.

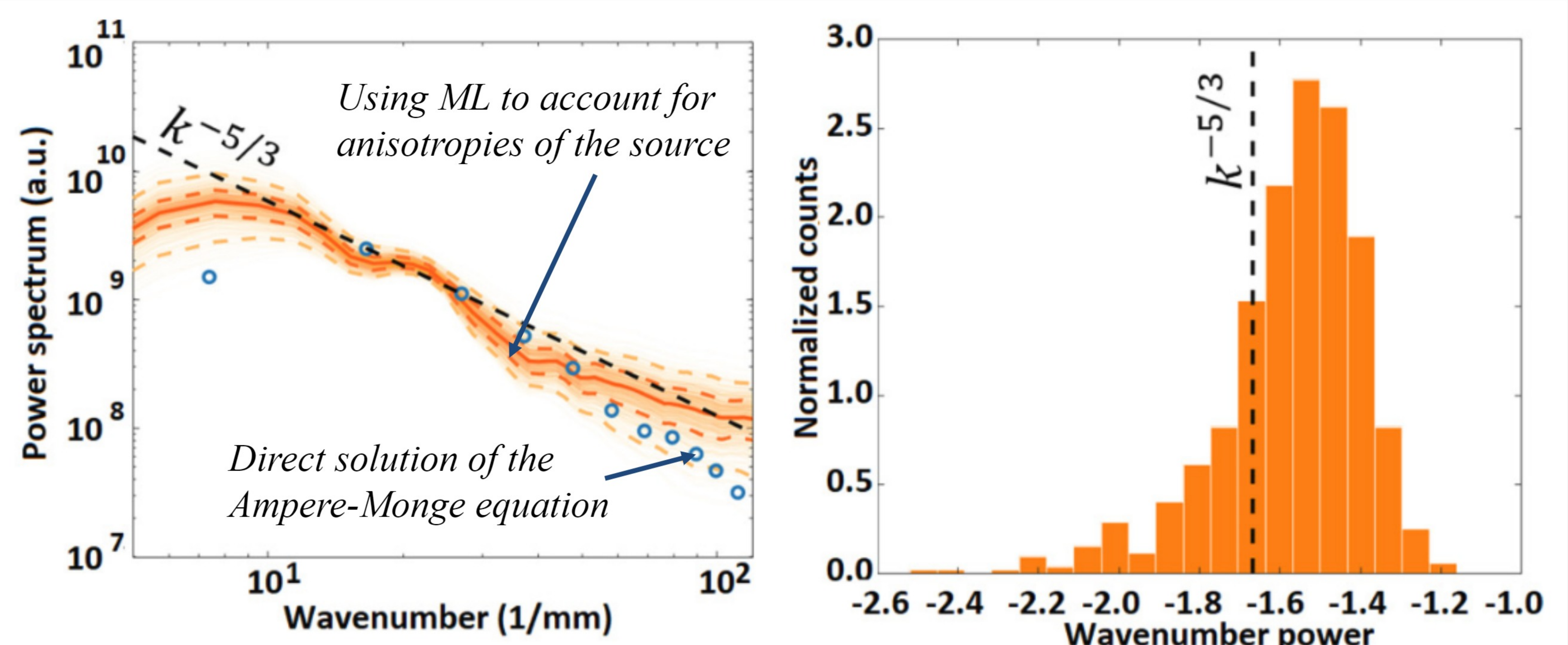
The inferred magnetic field is significantly amplified by the turbulence





- ➜ 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).

Magnetic field spectra are also retrieved from the experimental data



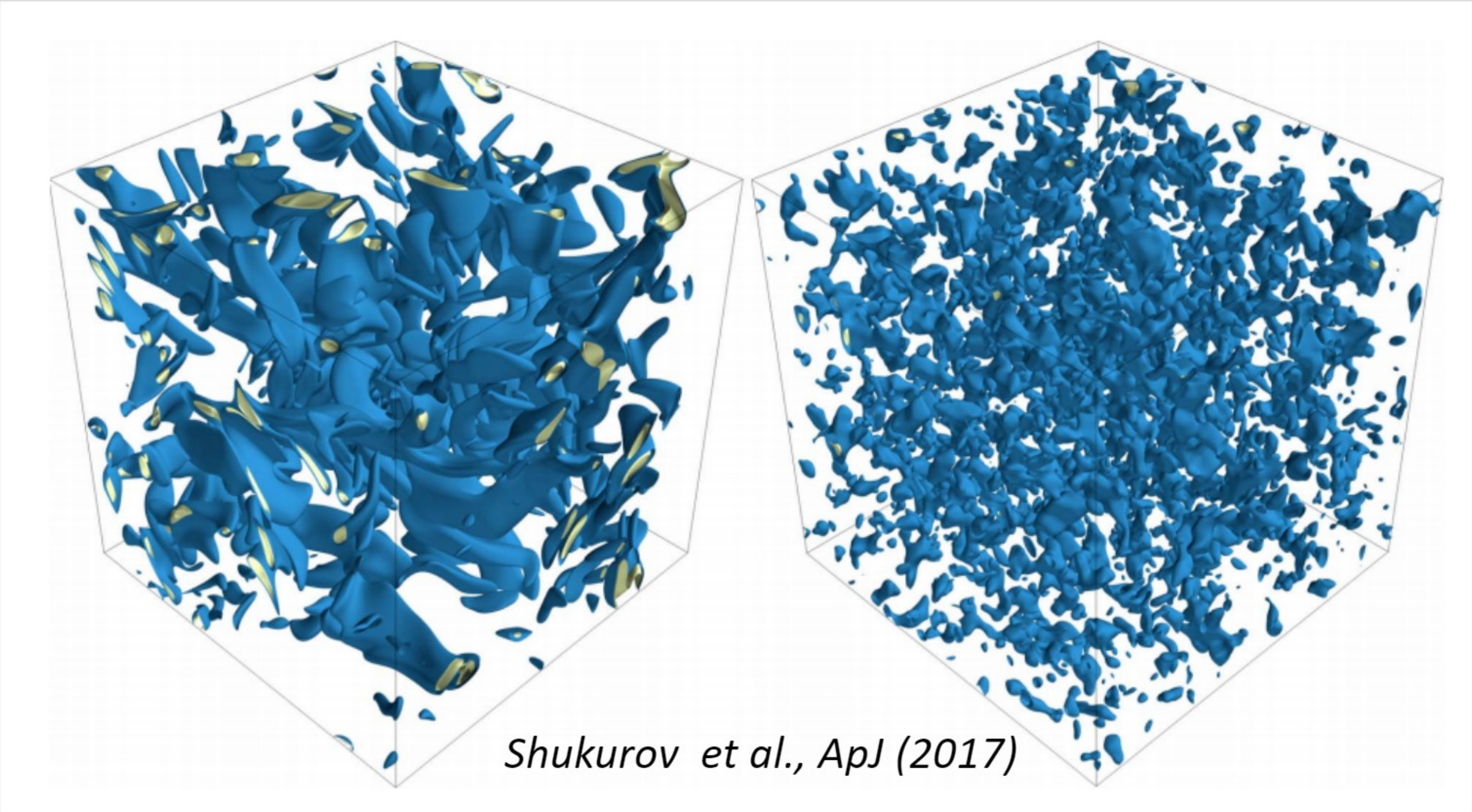
Kasim et al. PRE (2019)

→ We have used regression and Bayesian analysis to determine the best fit and distribution of magnetic field power spectra.

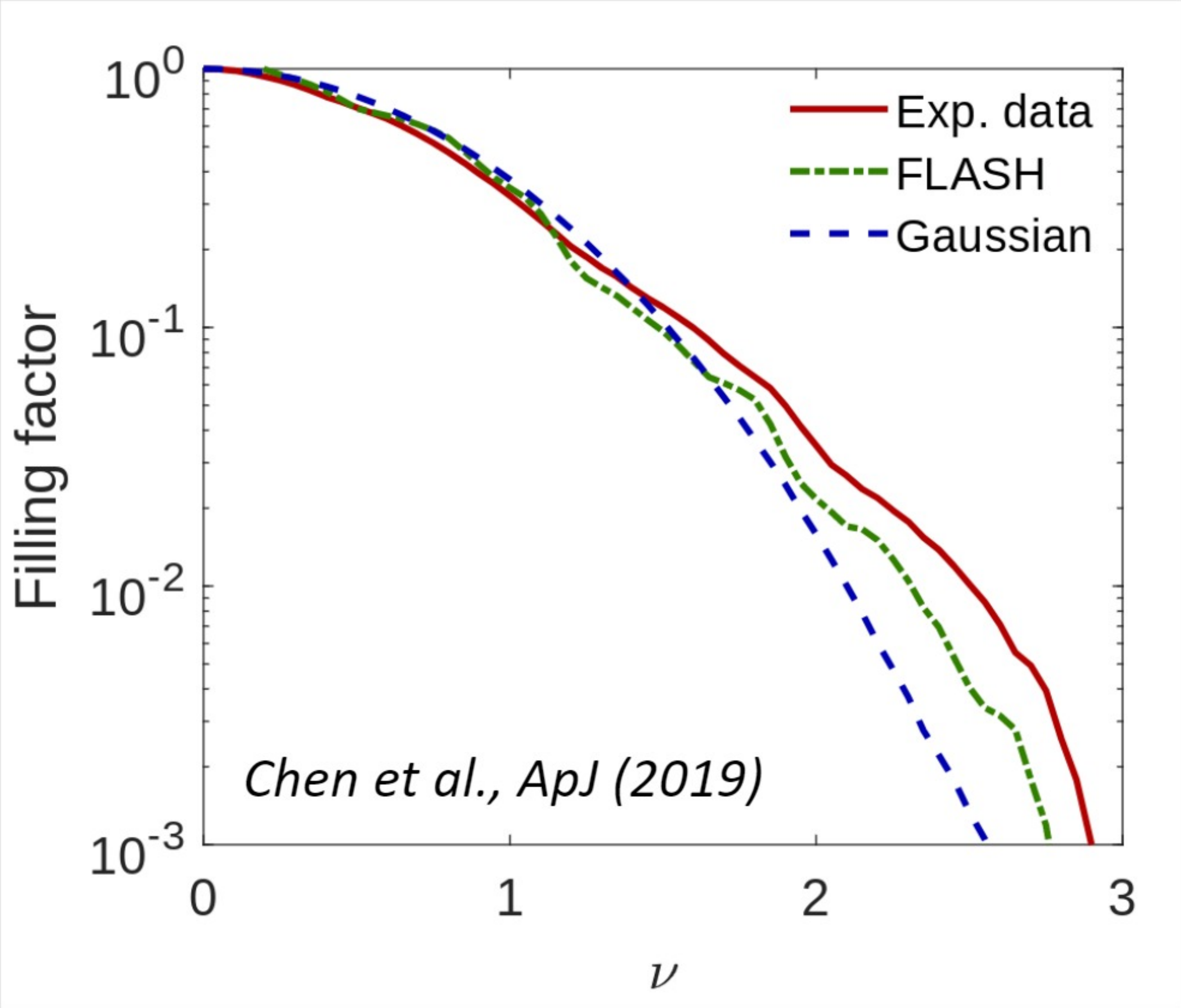
→ Measured spectra slopes are consistent with MHD numerical simulations.

Magnetic fields in the experiments are not volume-filling

Non Gaussian **Gaussian**



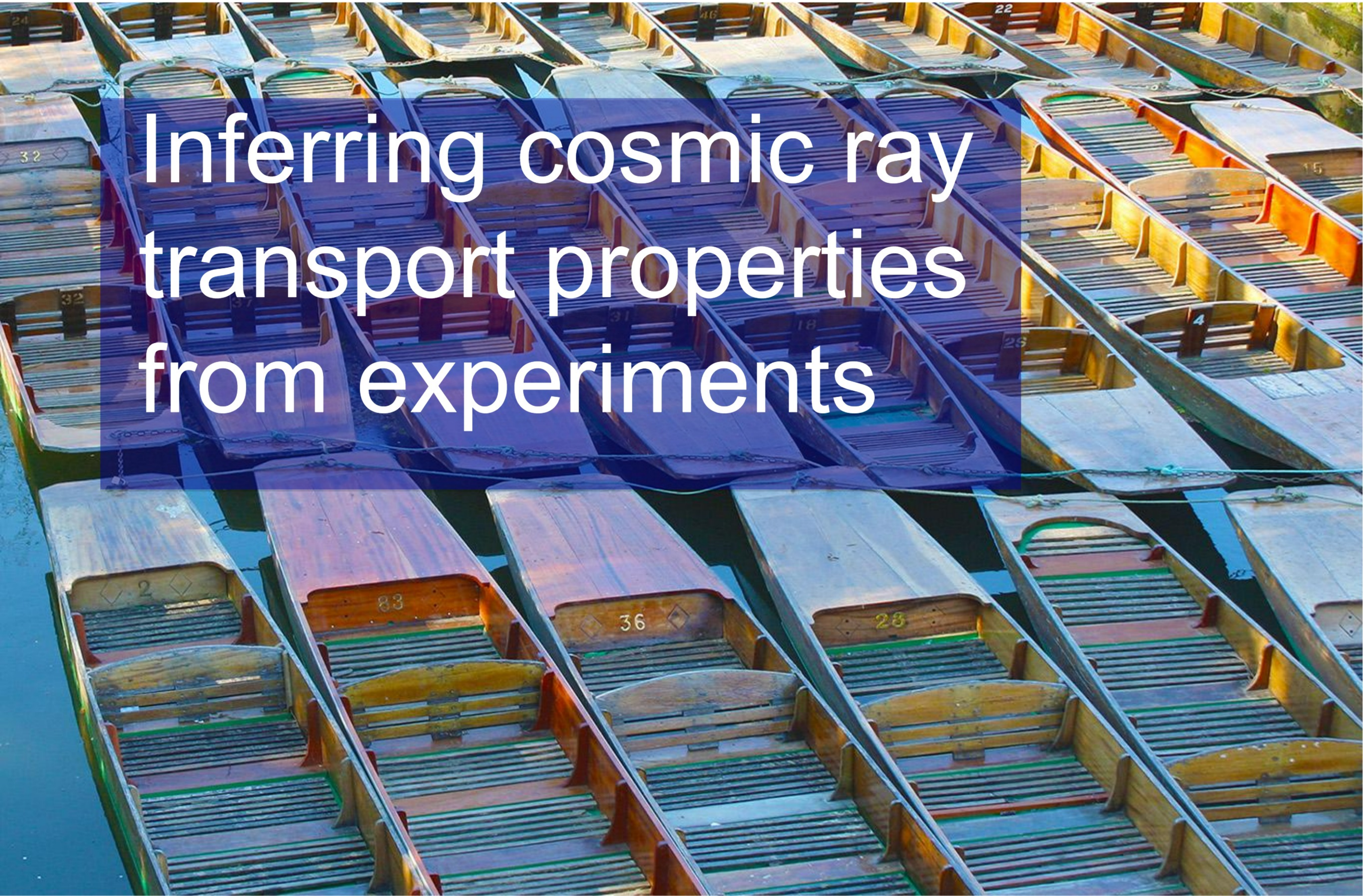
Shukurov et al., ApJ (2017)



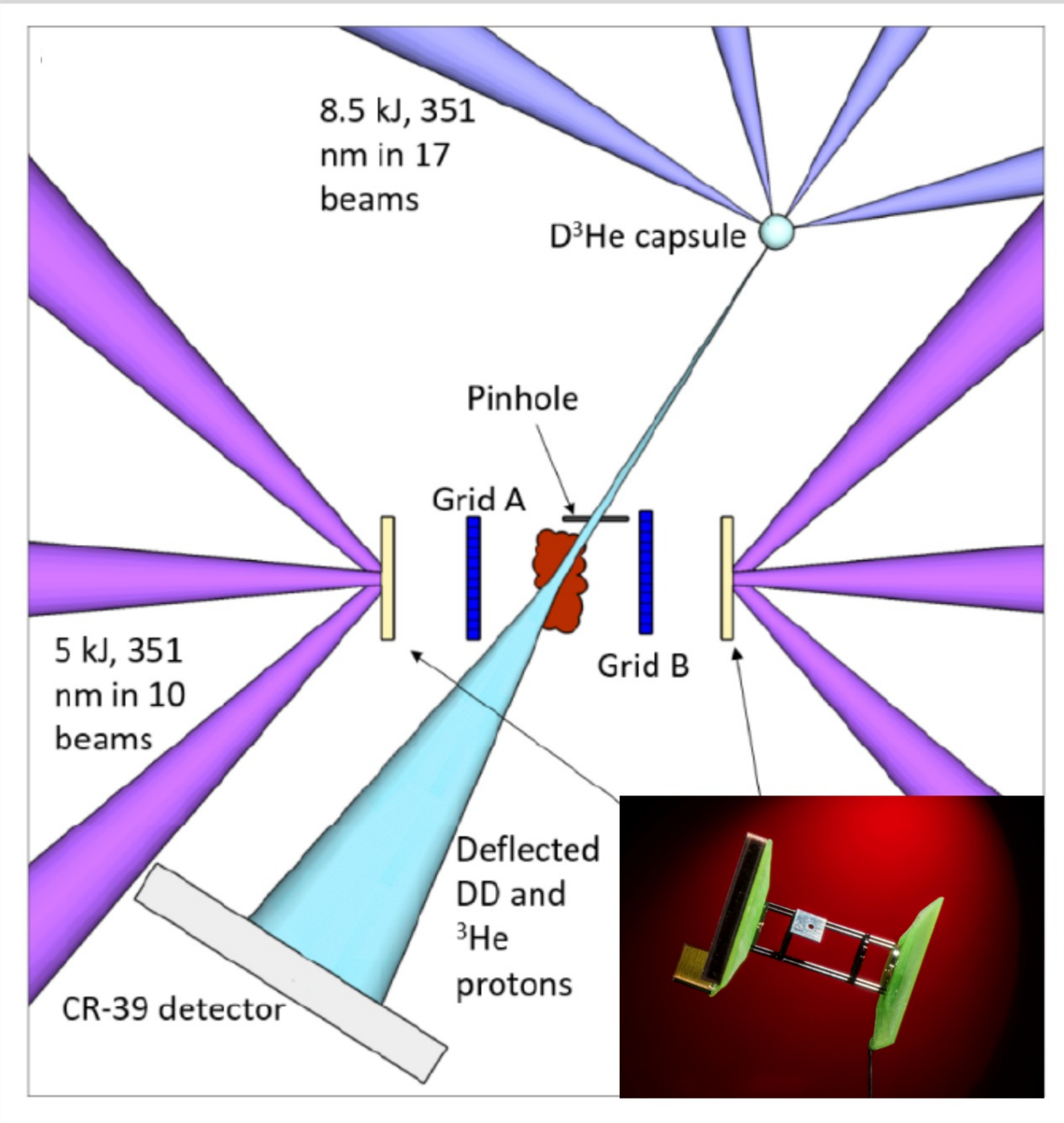
Chen et al., ApJ (2019)

- ➔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

Inferring cosmic ray transport properties from experiments



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



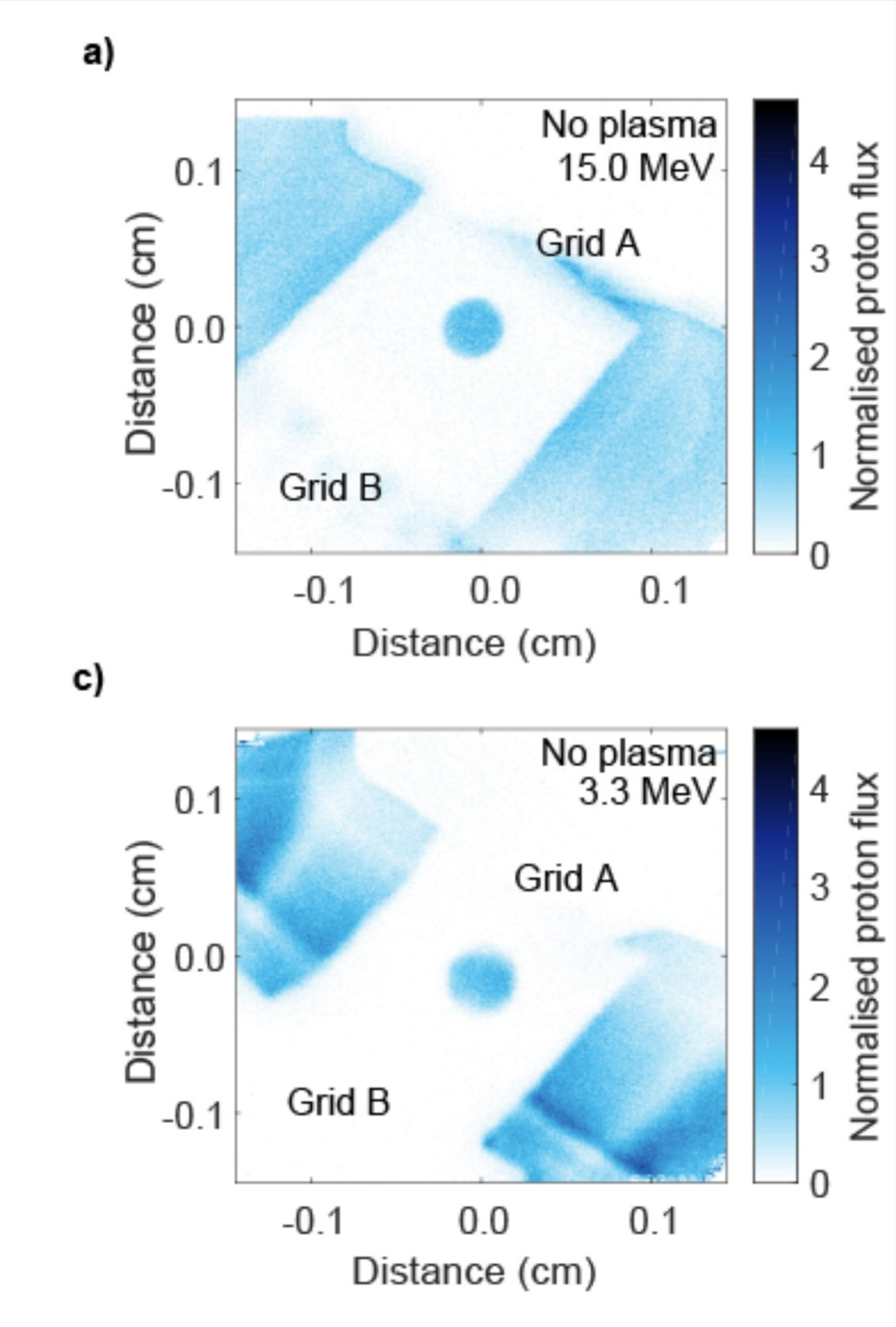
Chen et al. ApJ 2020

- 3 MeV and 15 MeV produced by DD and D^3He 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:

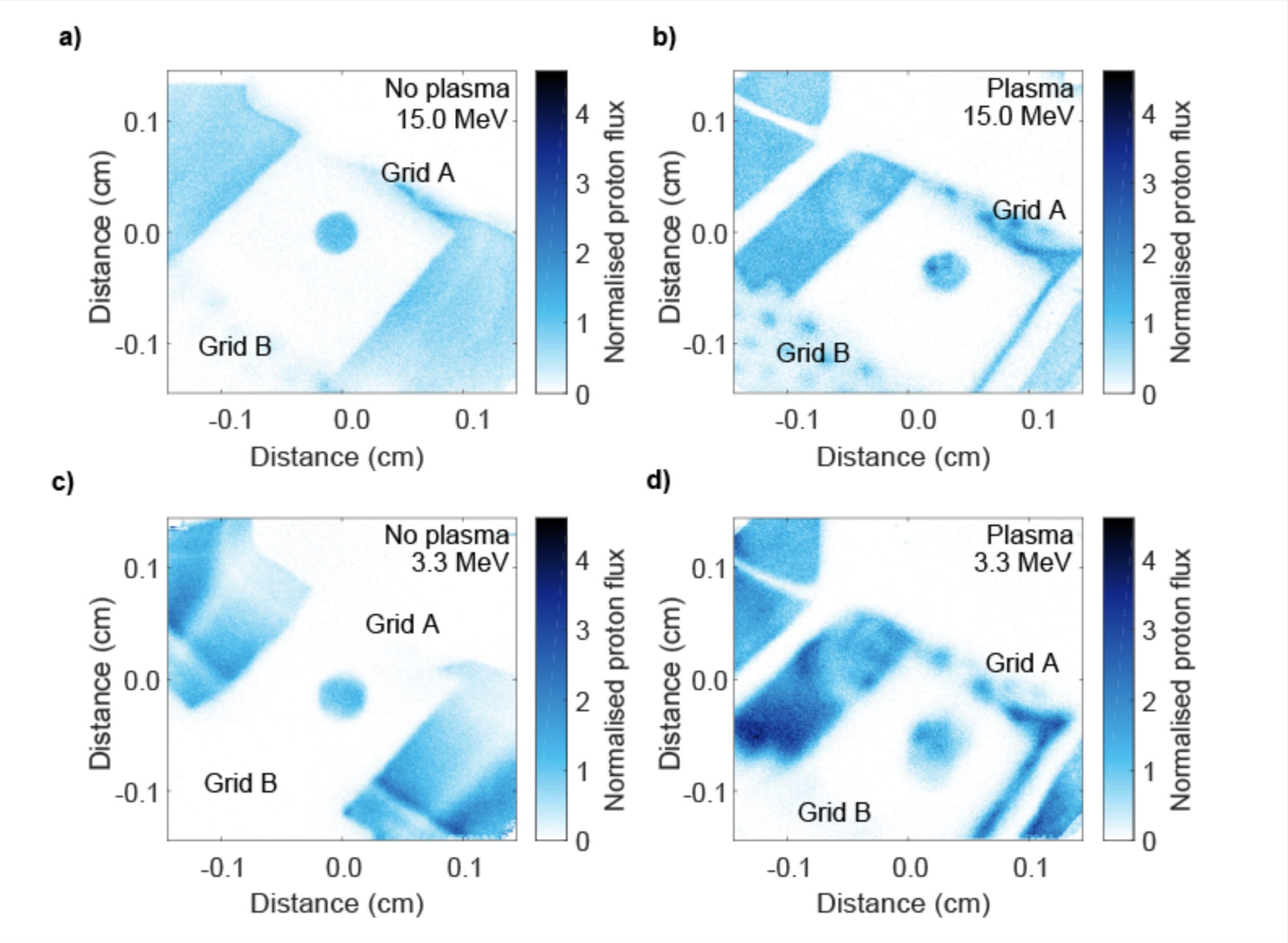
An analogue for Ultra High Energy Cosmic Rays (UHECR)!

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

We use our experimental platform to study proton transport through plasma



Significant broadening of the proton beam is observed



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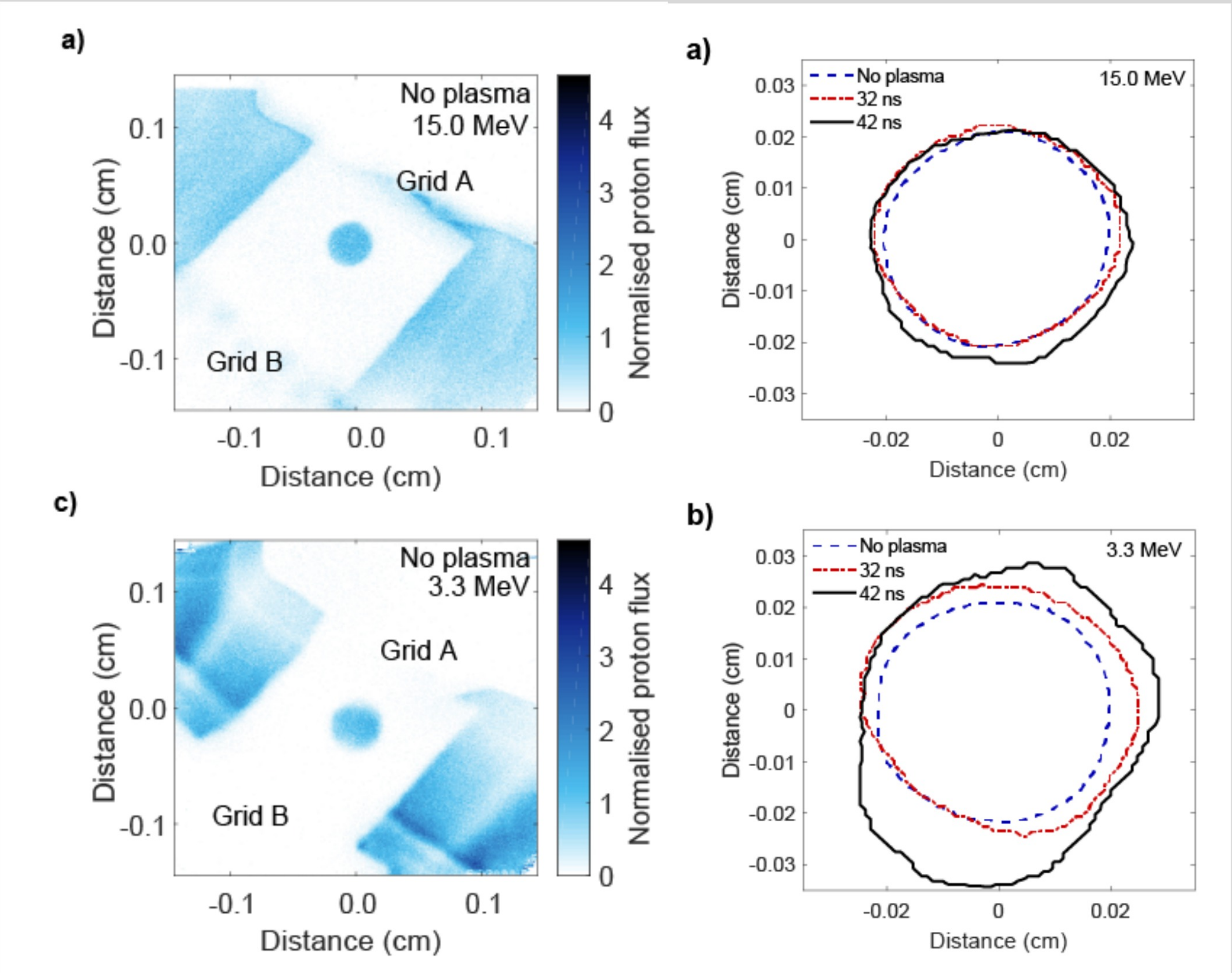
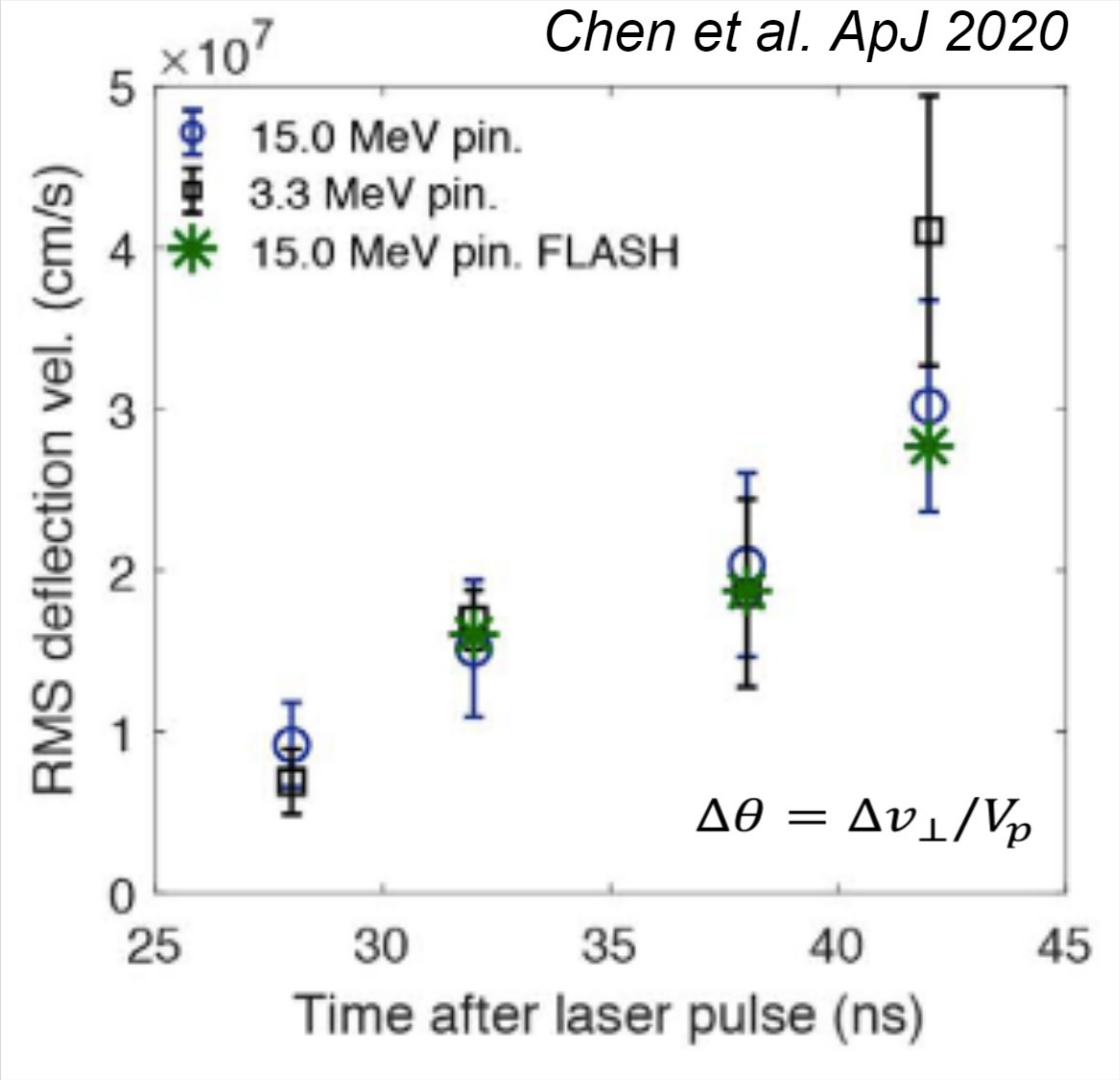


Deflections are due to stochastic magnetic fields



- 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

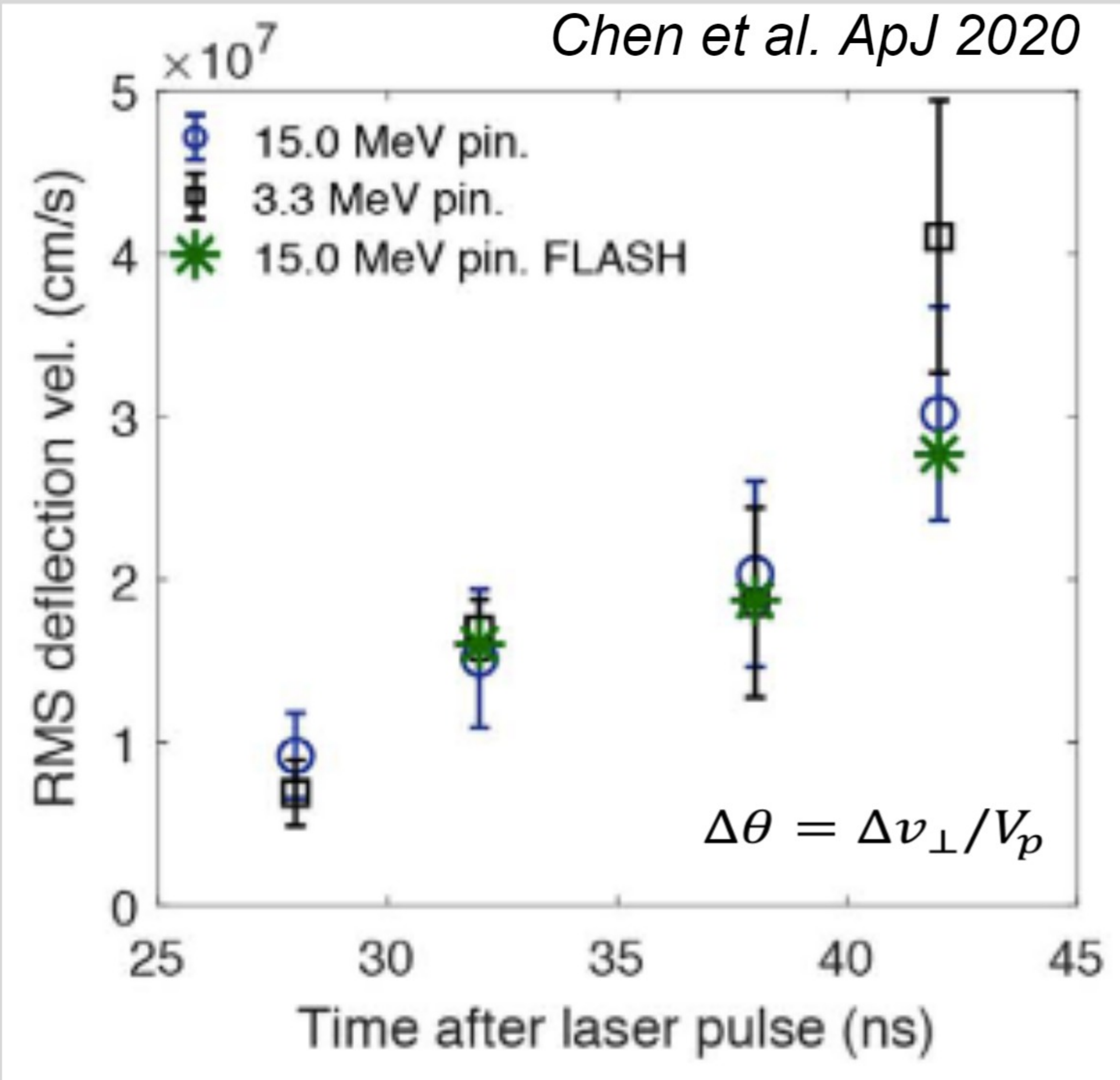
→ From the measured deflection velocity, we can estimate the angular scattering coefficient in velocity space

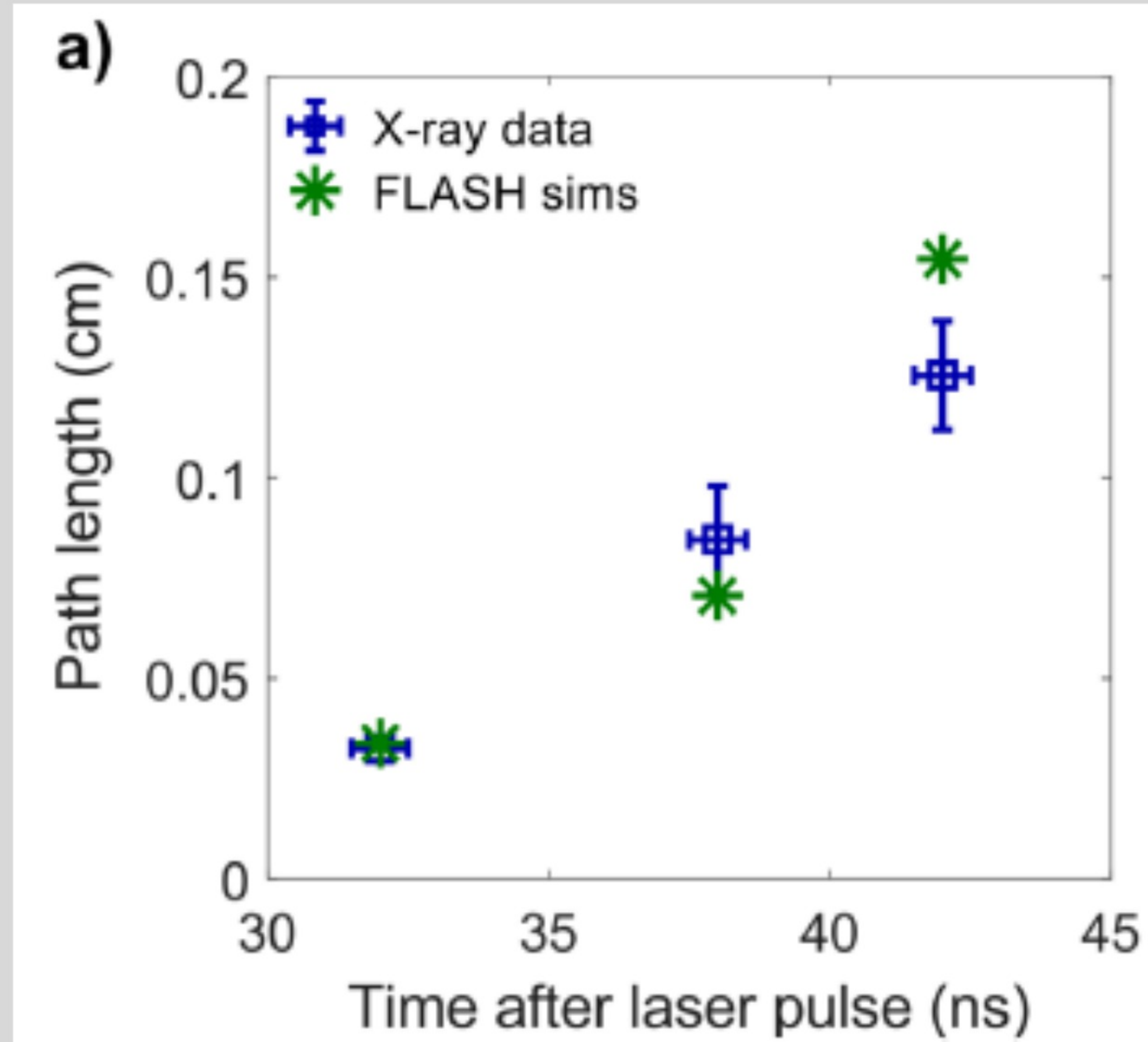
$$\nu = \frac{(\Delta v_\perp / V_p)^2}{\tau}$$

Transit time through the plasma

$$\tau = \ell_i / V_p$$

Scattering coefficient is measured directly from experimental data





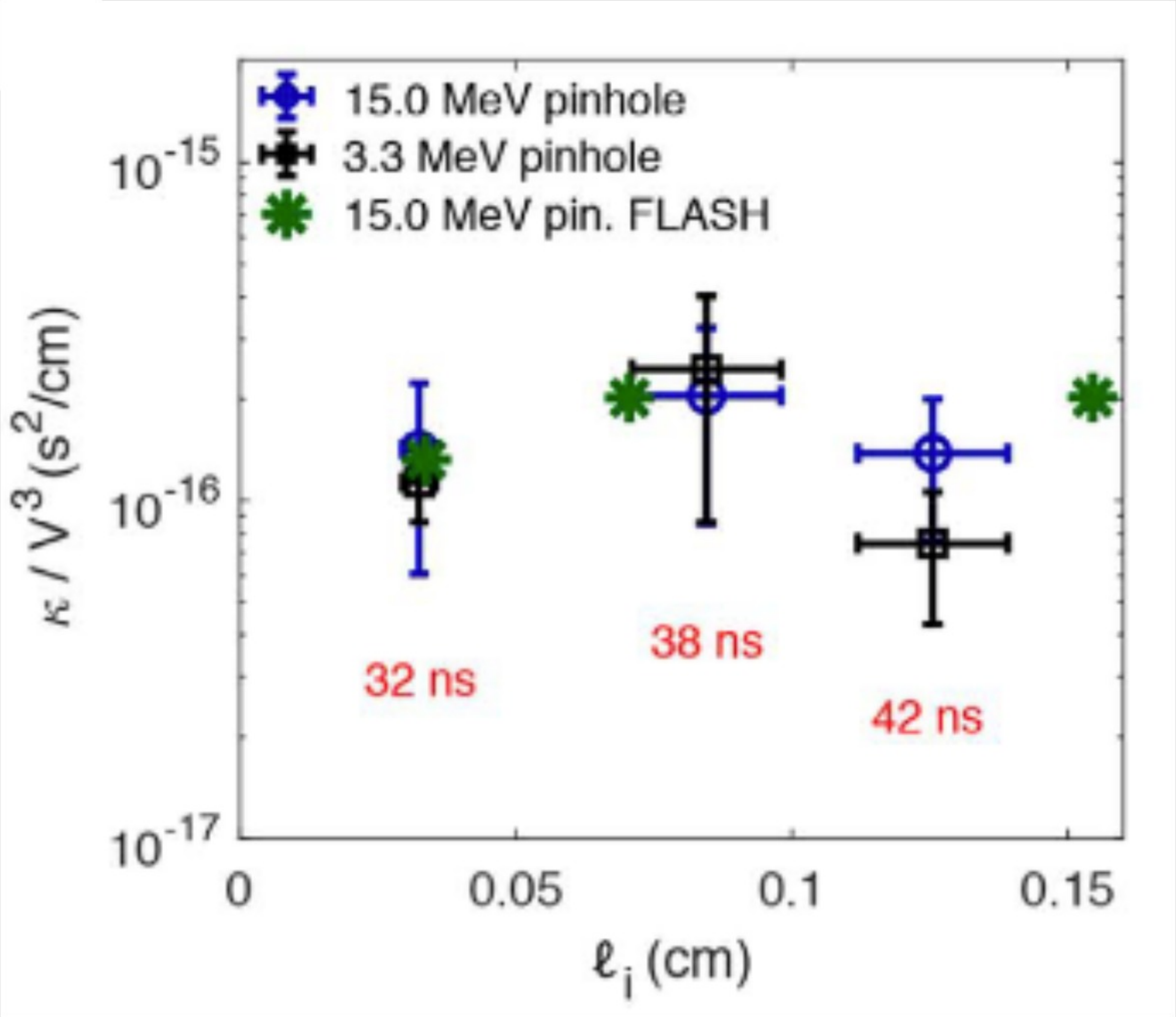
→ From the measured deflection velocity, we can estimate the angular scattering coefficient in velocity space

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

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:

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

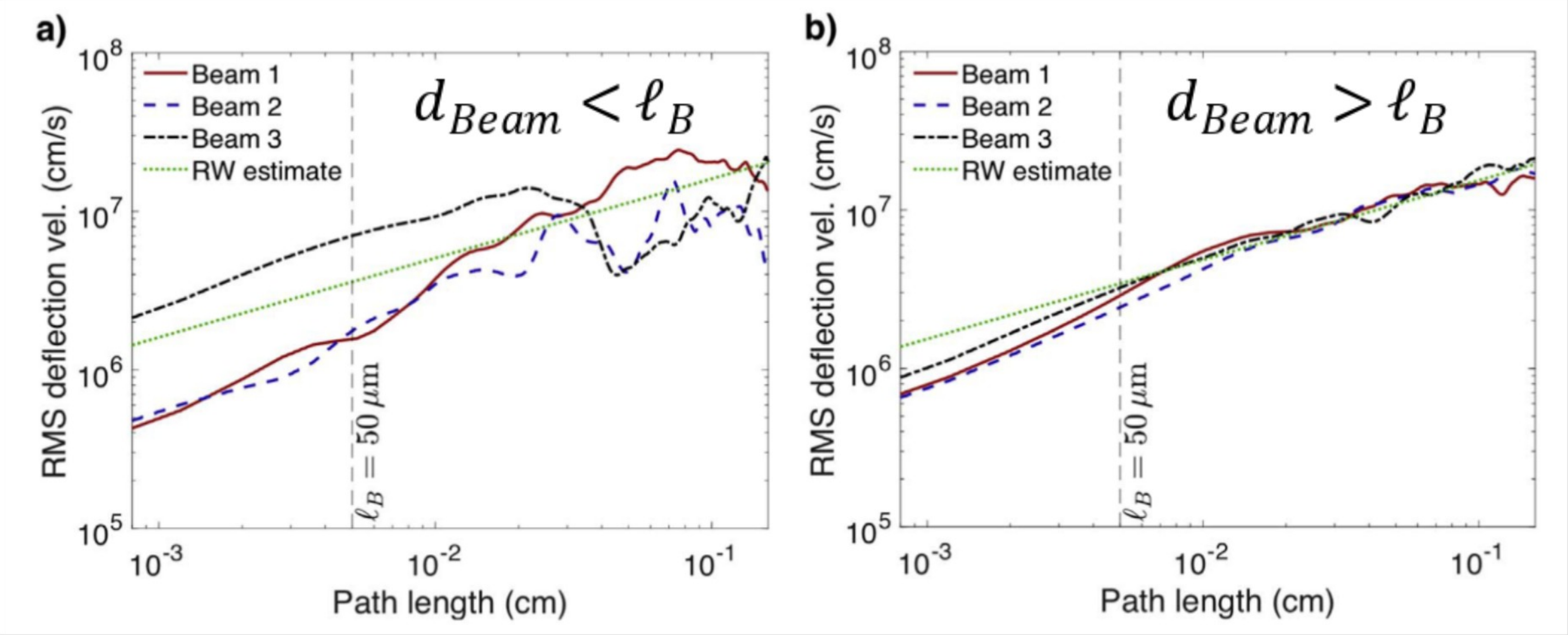
→ Since κ/V^3 is constant, it means that:

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

→ 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.

CR mean-free path depends only on Larmor radius

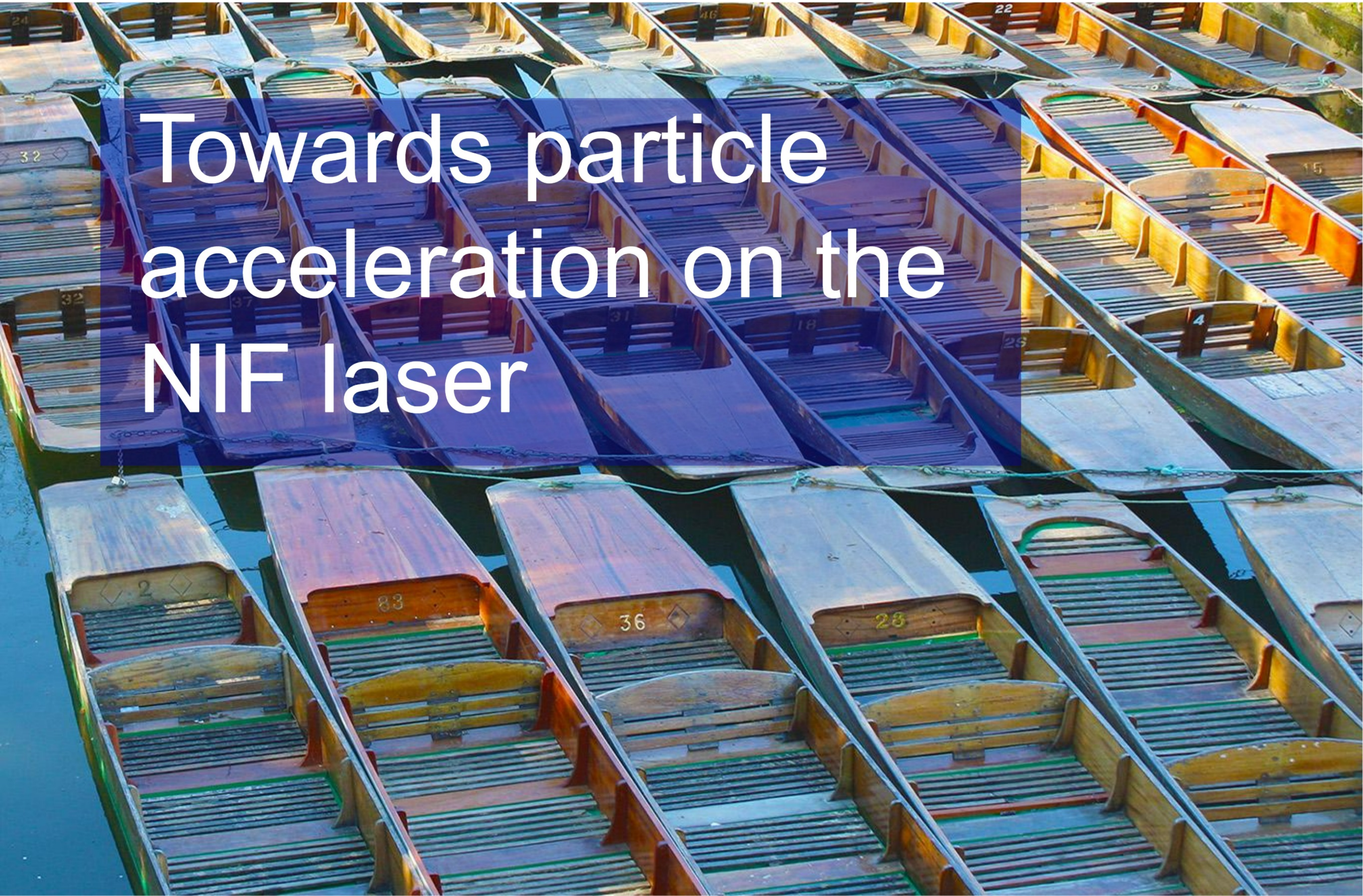


- → For correlated random walks, the diffusion coefficient is modified as (*Shukurov et al. 2017*):

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

- → Since $\Delta\theta \ll 1$ in the experiment, we expect diffusion coefficient to be proportional to r_g^2.
- → CR diffusion is independent of the structure of turbulence: in the experiment we have k^{-1} and in *Subedi et al.* $k^{-3/2}$.
- → Perhaps due to the fact that the transverse CR beam has a size larger than the correlation length of the field.

Towards particle acceleration on the NIF laser

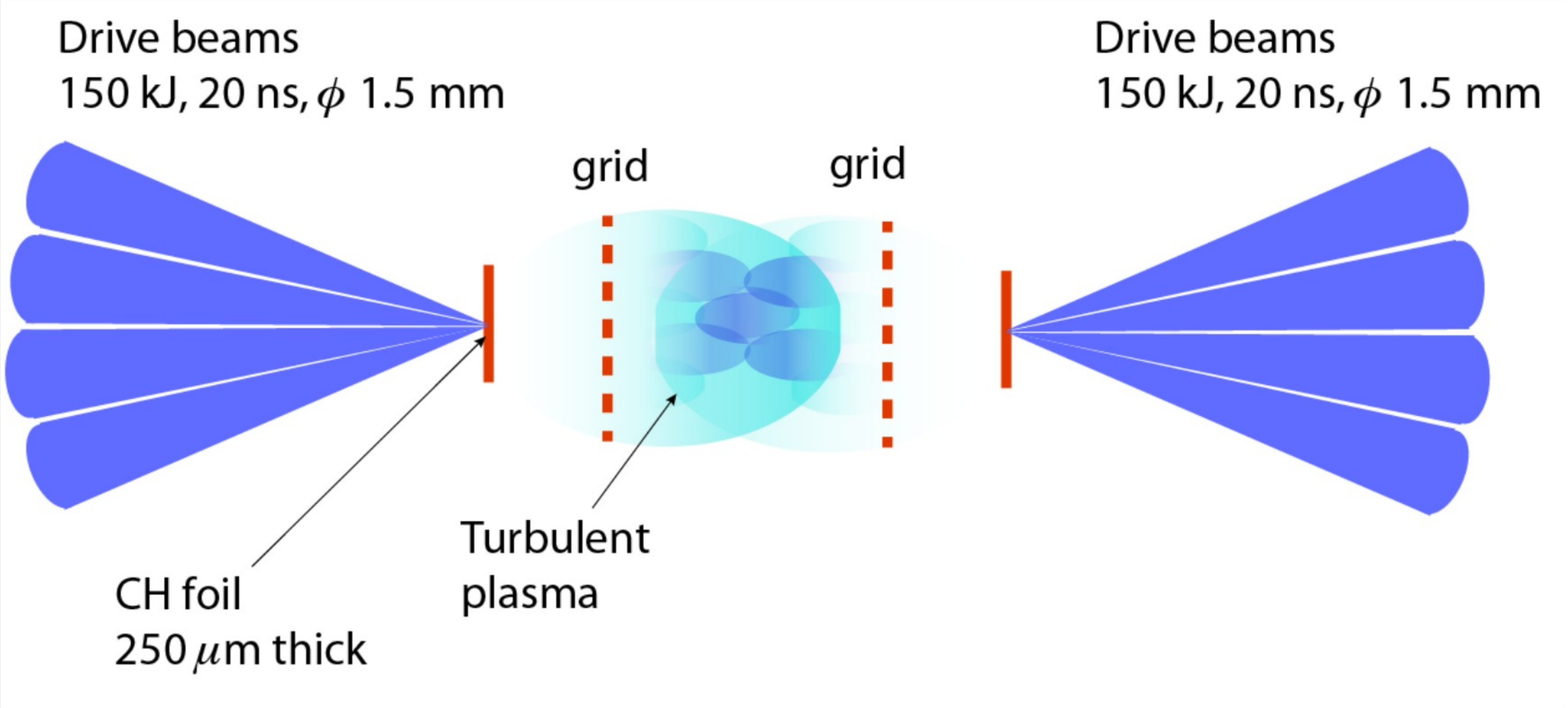


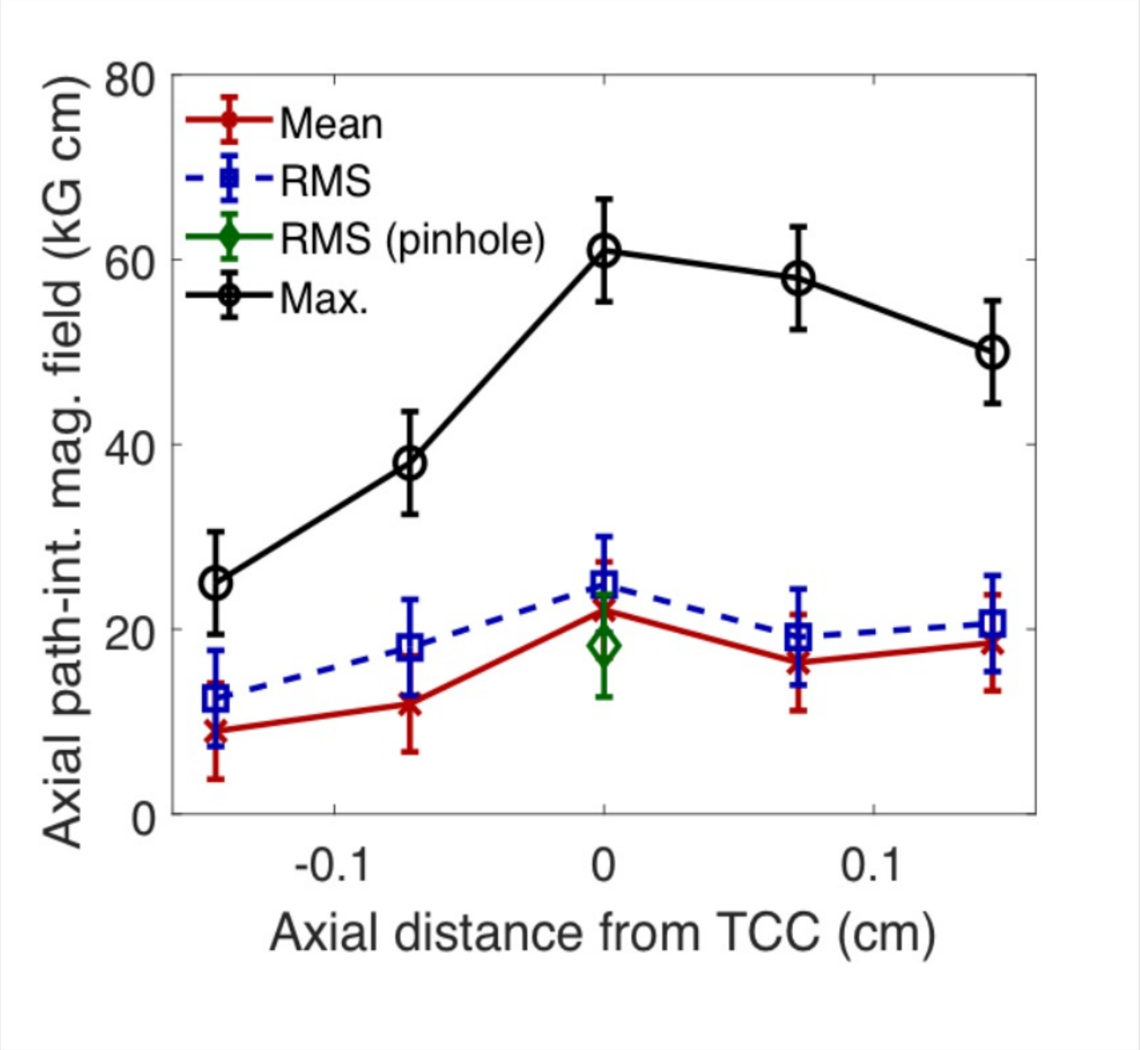
NIF is needed if we want to measure energy gain/loss by the charged particles

→ Measurement on the smaller laser facility (OMEGA) give a spatial diffusion coefficient $\kappa \sim 10^7$ cm^2/s.

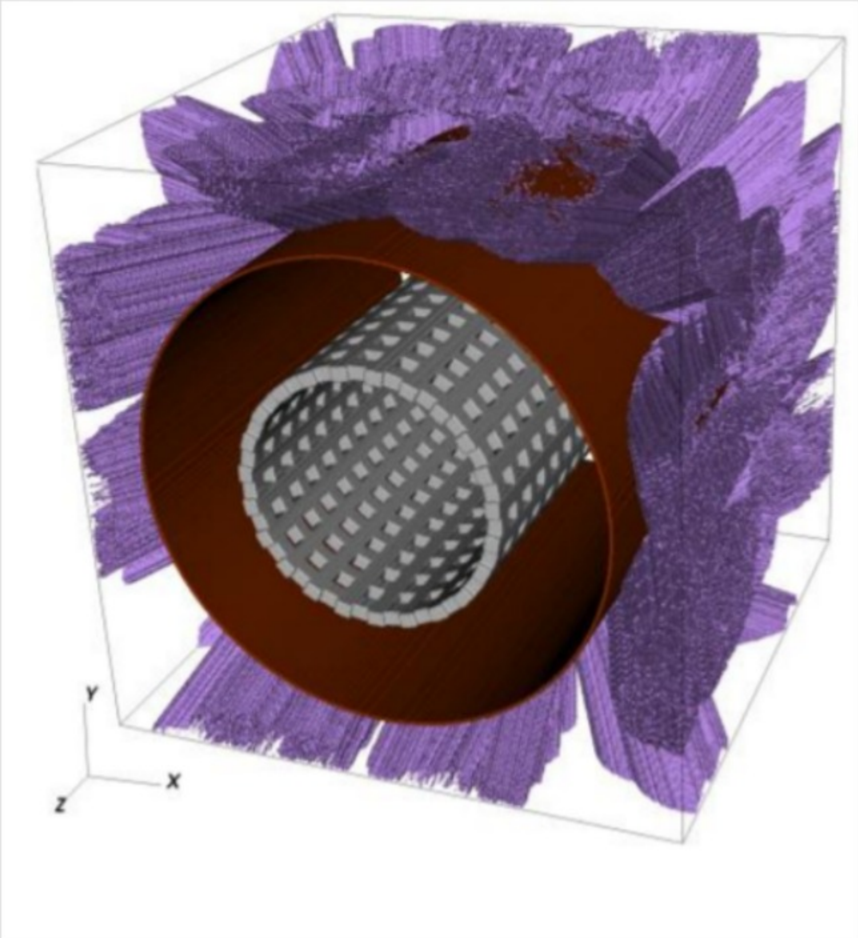
→ This implies a momentum diffusion coefficient $\mathcal{D}_{pp} = p^2 u^2/\kappa$, and a stochastic energy gain per scattering $\Delta E/E \sim (u/V_p)\Delta\theta \sim 3 \times 10^{-5}$. This is too small to be measurable.

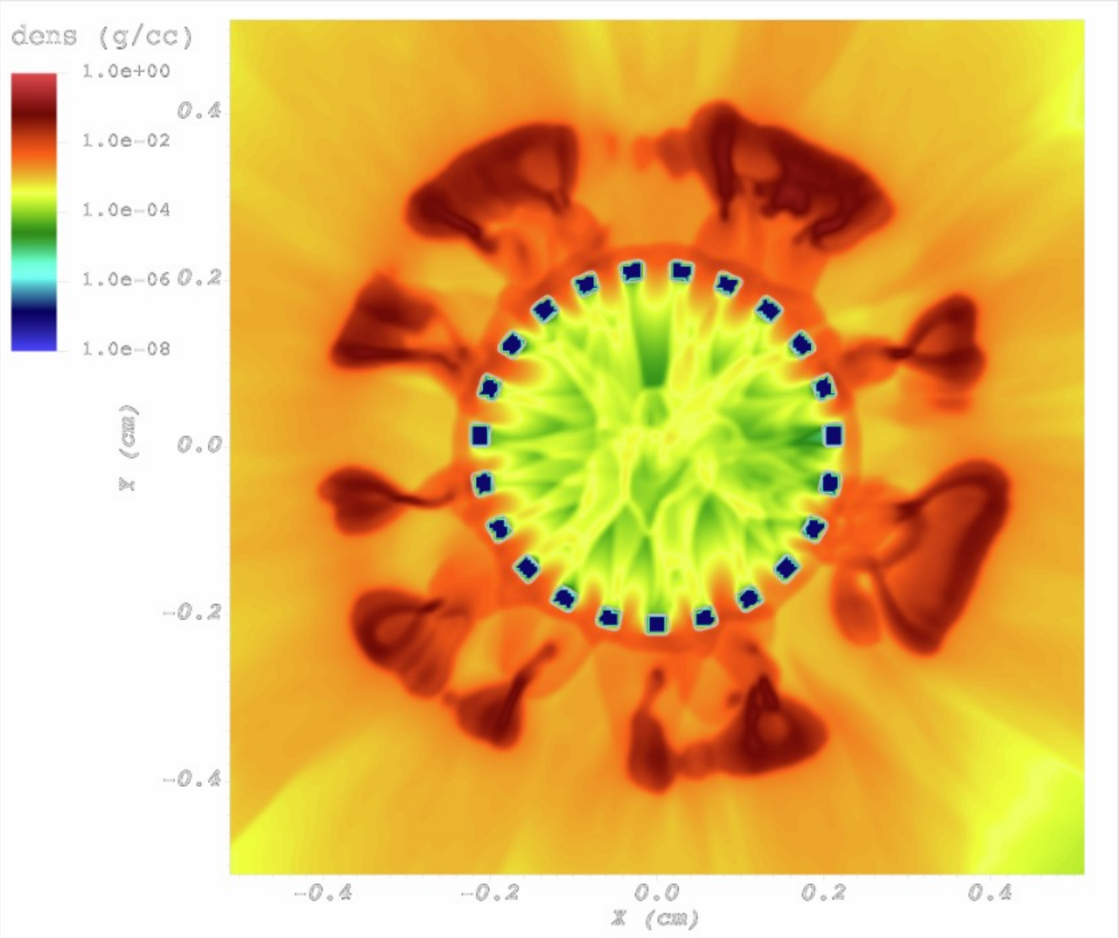
→ On NIF we can get 10x increase in the magnetic energy just by employing the same platform, but this is still insufficient.



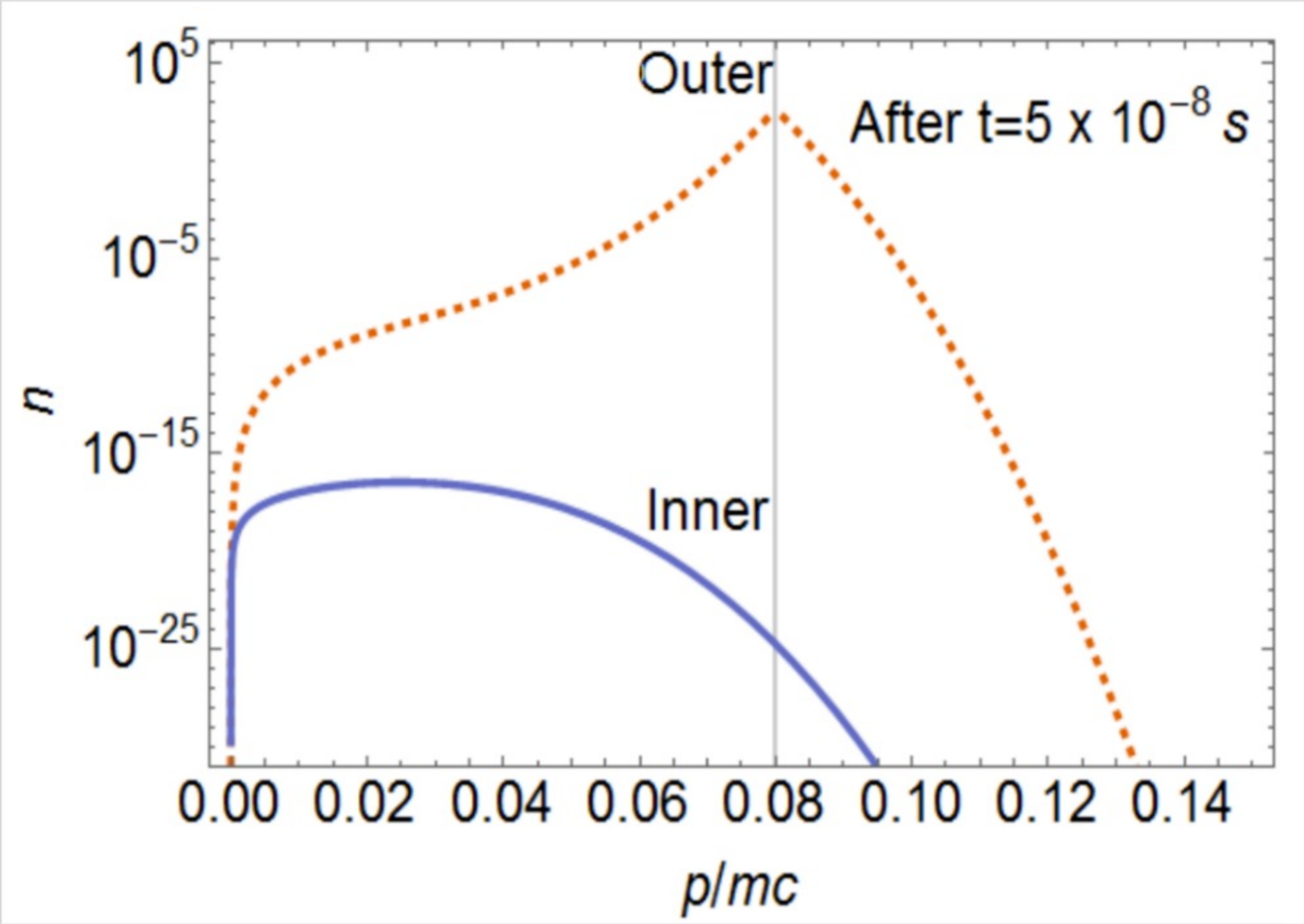


We are now developing a modified platform to test CR acceleration in the laboratory





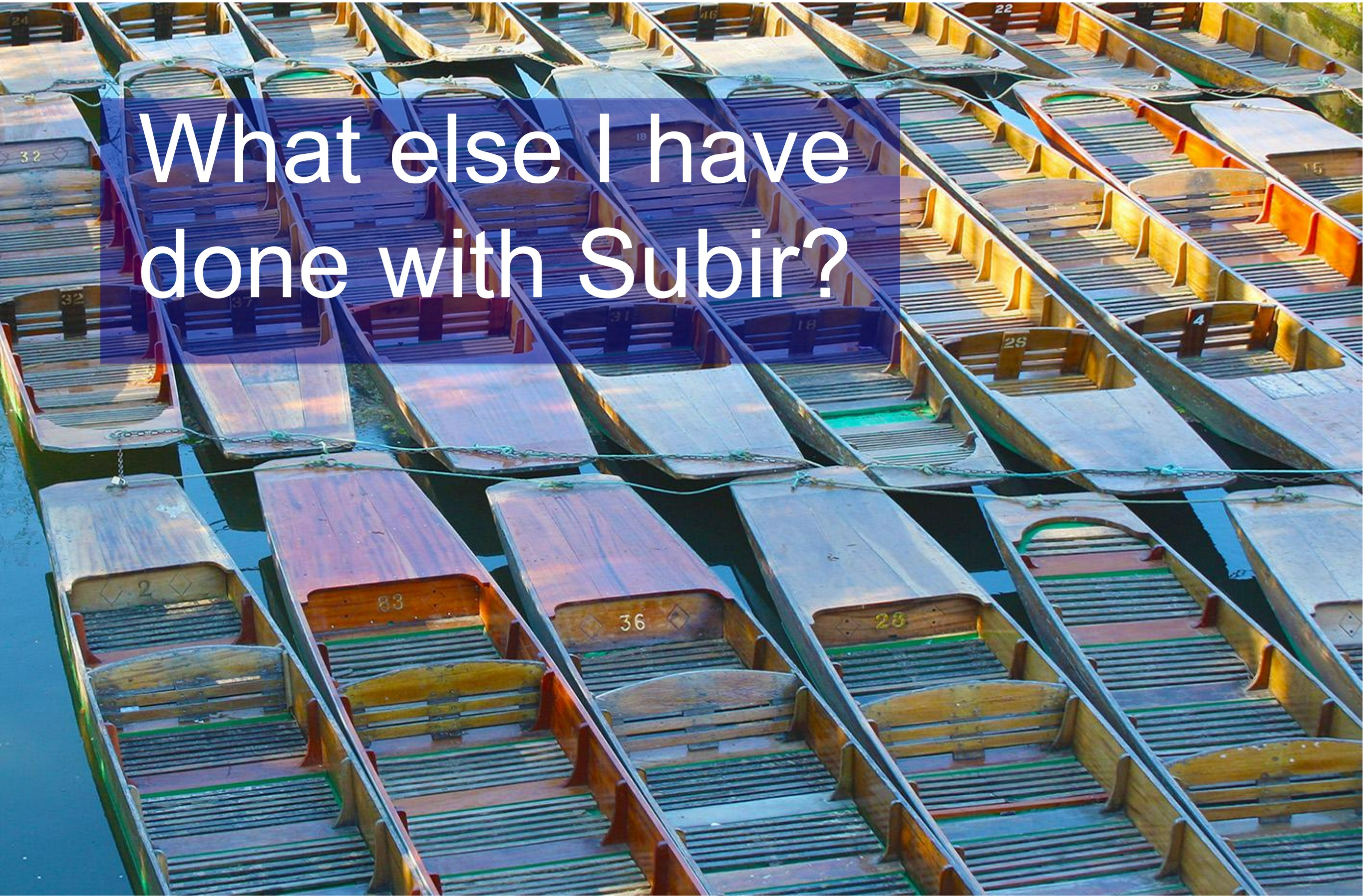
expected proton spectrum



- Converging geometry allows for strong turbulence, large magnetic fields over a long path (the axis of the cylinder) - expected energy broadening up to ΔE ~ 1 MeV and energy gain up to ~ 300 KeV (*Beyer et al. 2018*)
- Propose to measure proton energy gain with two independent approaches:
    - Self-generated DD protons from plasma (using deuterium-doped foils)
    - Protons from travelling across the turbulent plasma

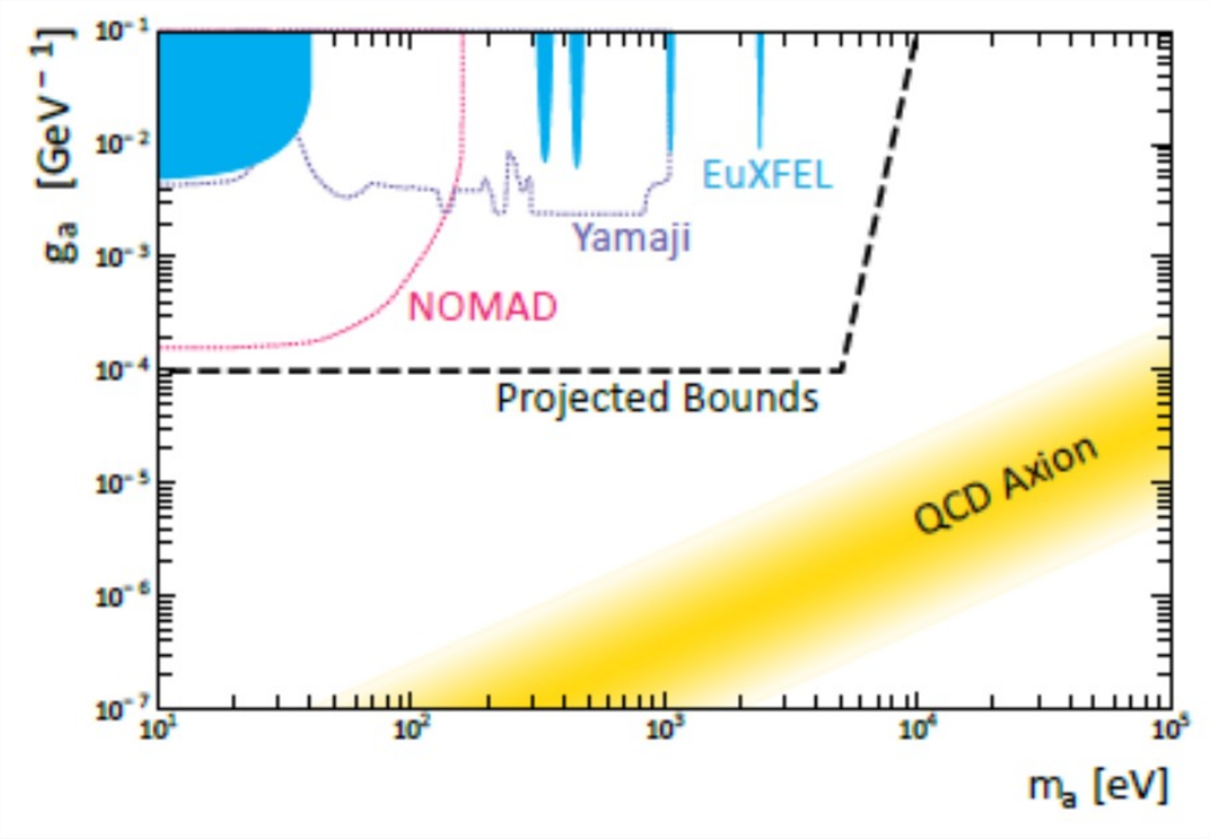
Oxford Physics

What else I have done with Subir?



I am enjoying a lot of discussions with Subir

- → Generation of the largest pair-plasma in the world at CERN (>10^{13} pairs).
- → Beams with energy >100 MeV used to mimic gamma-ray bursts.



- → Experiments at X-ray FELs to look for >eV axions.
- → First experiment performed a few months ago extends current bounds.

While I truly expect you will be spending time on warmer (less rainy) climates, I hope you will still continue these collaborations which I am enjoying so much.

Thank you Subir!

Thanks to all collaborators

- A Rigby, L Chen, T Campbell, C Arrowsmith, J Meinecke, F Miniati, S Sarkar, A Schekochihin, H Poole, M Kasim, S Vinko, BT Huffman, G Gregori (U Oxford)
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- P Tzeferacos, D Froula, J Katz, K Moczulski, B Boni, JL Shaw, A Scopatz (LLE)
- B Albertazzi, M Koenig (LULI)
- A Blazevic, P Neumayer, D Schumacher, M Metternich, H Nazary, V Bagnoud (GSI)
- T White (U Nevada Reno)
- F Cruz, P Bilbao, L Silva (IST Lisbon)
- S Ross, J Emig, D Ryutov, B Remington, H-S Park (LLNL)
- C-K Li, R Petrasso (MIT)
- D Ryu (Unist)
- S Lebedev (Imperial College)
- A Bott (Princeton)
- C Palmer (QUB)
- N Shukla (CINECA, Italy)
- JT Gudmundsson (University of Iceland)
- B Reville, E Churazov, K Beyer (MPI)
- C Forest, E Zweibel (U Wisconsin)
- S Feister (CSU Channel Island)
- J Foster, T Hodge, S Richardson (AWE)
- N Charitonidis, P Simon (CERN)
- A Casner (CEA)
- F Fiuza, R Blandford (Stanford)
- B Bingham, R Bamford, AR Bell, C Spindloe, M Oliver , T Davenne, R MGM Trines, (RAL)