Cosmological magnetic fields and particle acceleration in the laboratory

Gianluca Gregori

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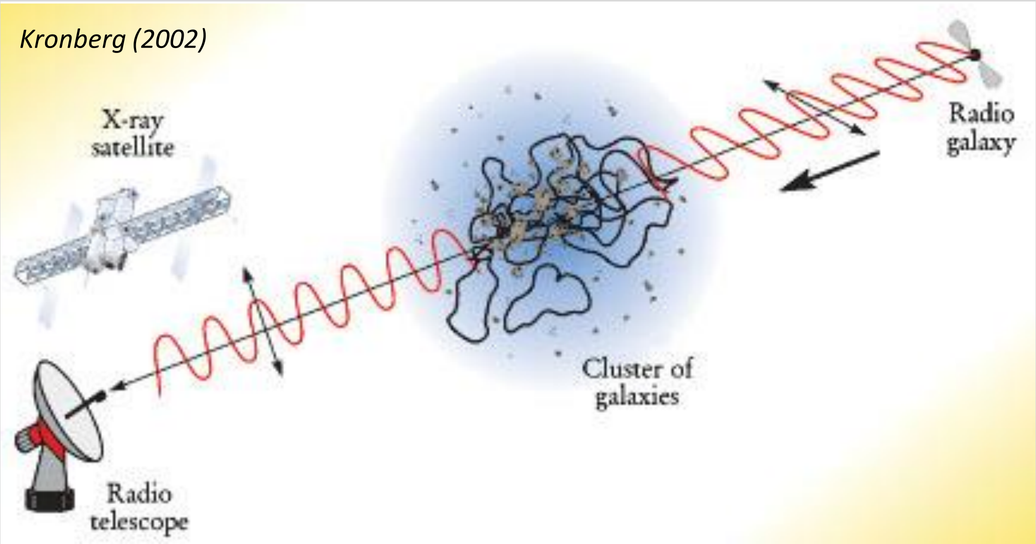
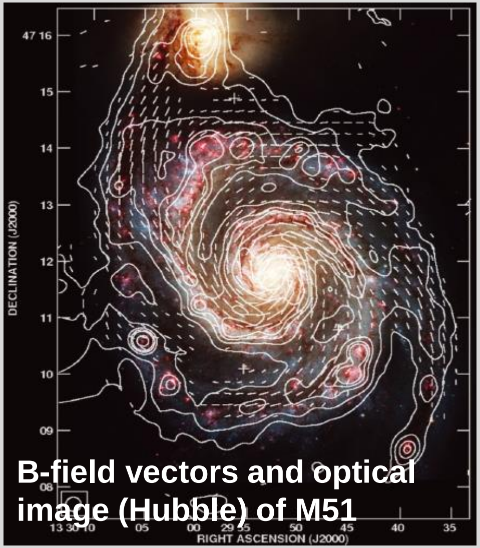
TeVPA

Magnetic fields are measured in galaxies and cluster of galaxies





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

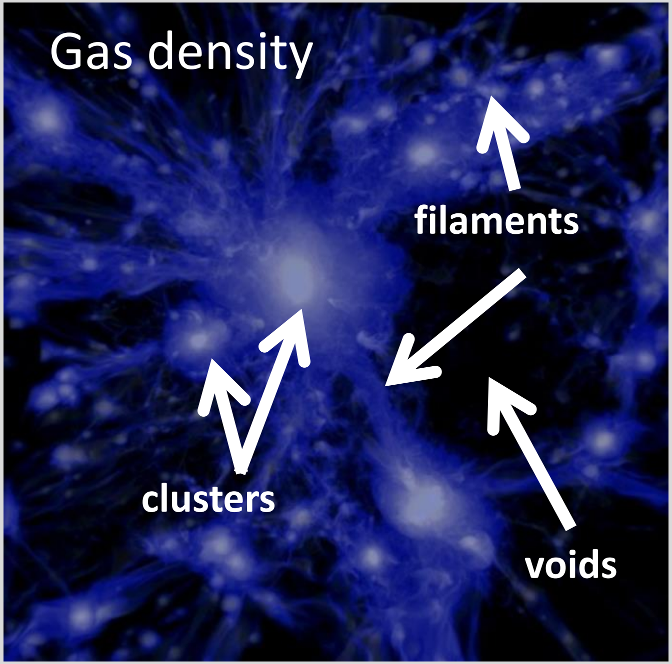
→Faraday rotation and synchrotron emission are used to measure magnetic fields in galaxies and clusters.

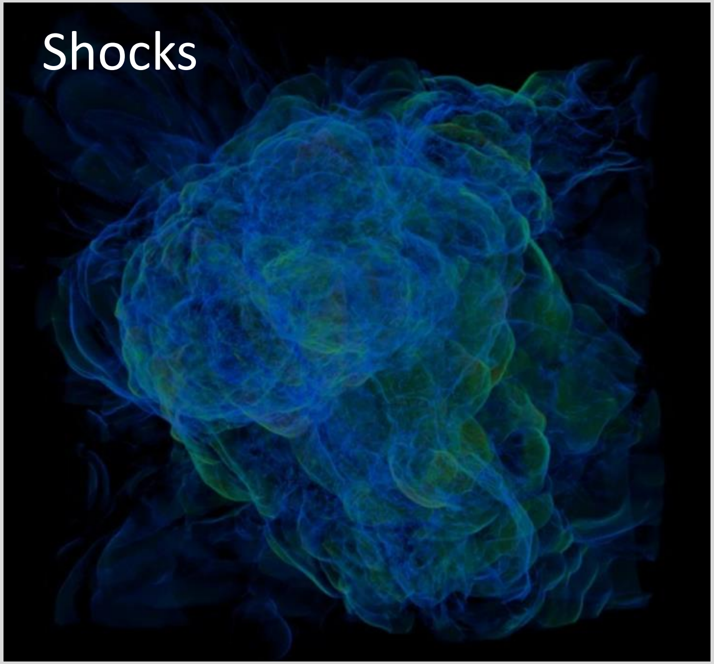
→The Universe is ubiquitously magnetized:

- Clusters and galaxies (a few μG)
- filaments (a few nG)
- voids (≈0.1 fG)

→**Primordial processes produce a magnetic seed $\sim 10^{-21}$ G (much smaller than observed values)**

A large fraction of the luminous matter in the Universe is in a turbulent state

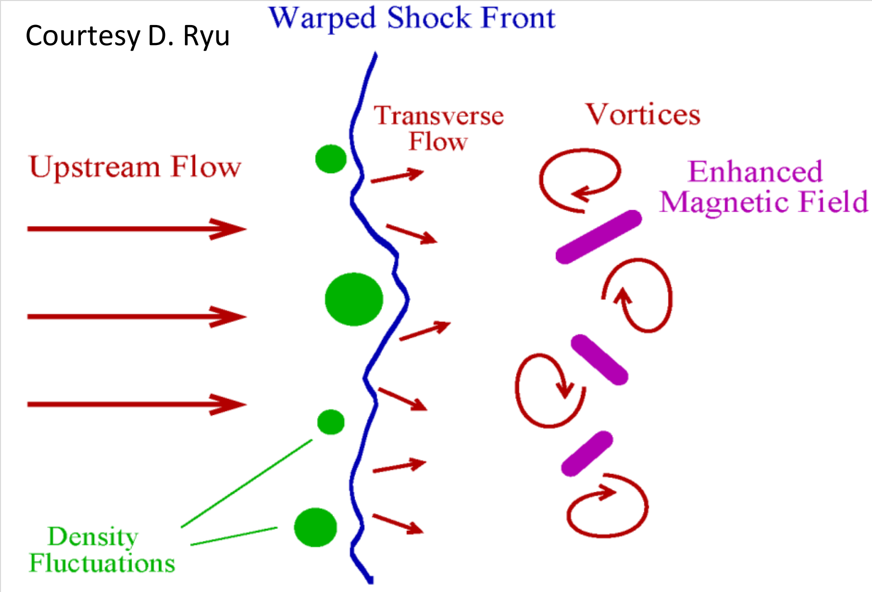


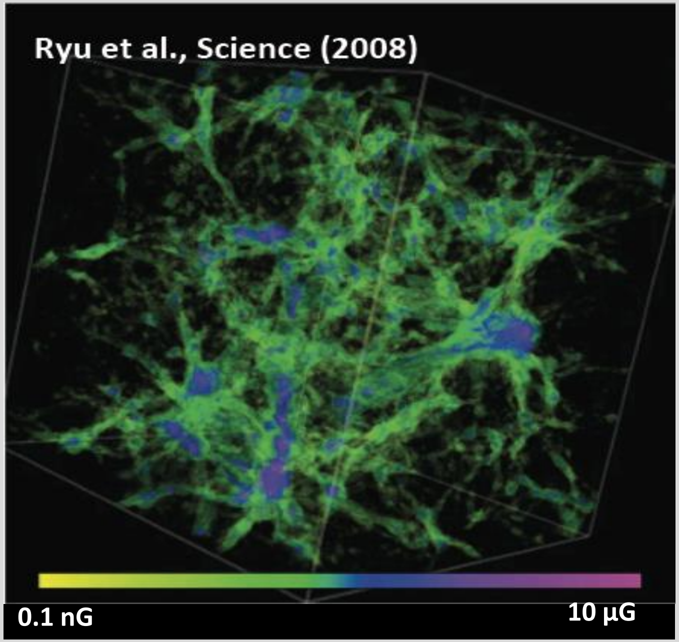


Courtesy of F Miniati (ETH)

→ Structure formation results in a hierarchical web made of clusters, filaments and voids
→ Shocks inject vorticity into the intra-cluster medium
→ The overall state of the Universe is that of a turbulent fluid

The standard model of cosmic generation of magnetic fields invokes MHD turbulence





100 Mpc

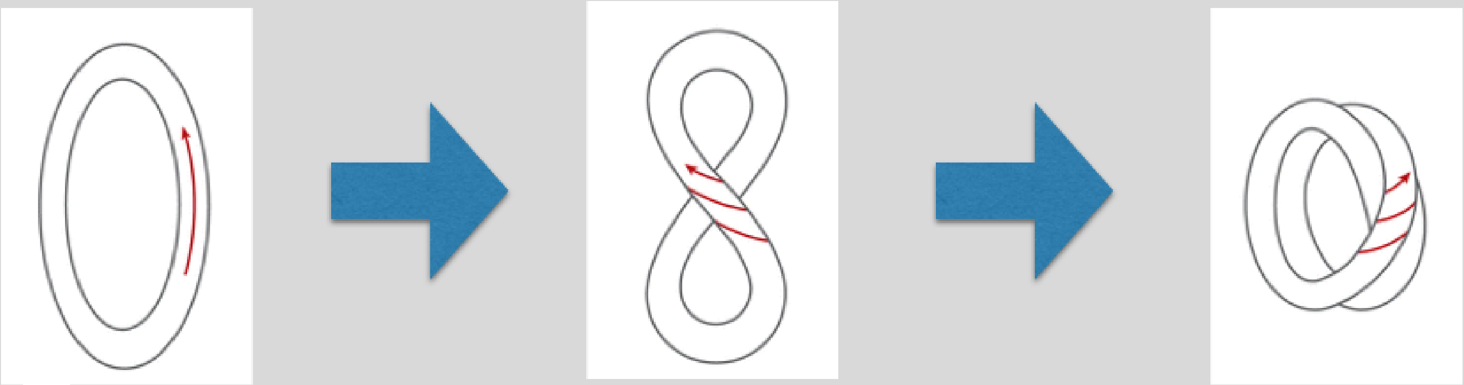
→Assume there are tiny magnetic fields generated before structure formation

→Magnetic field are then amplified to dynamical strength and coherence length by turbulent motions

→It follows directly from the induction equation:

$$\frac{d\boldsymbol{B}}{dt} = \boldsymbol{u} \cdot \nabla \boldsymbol{B} \;\Rightarrow B \sim B_0 \exp(ut/L)$$

The dynamo mechanism: stretch, twist and fold



In the kinematic regime the magnetic energy grows exponentially (at a rate set by the eddy-turnover time $\tau_L = L/u$)

However:
cosmological numerical models of MHD dynamo in the ICM typically achieve only modest magnetic field amplification, by factors of order $\approx 10^3$ (e.g., Xu et al. 2012)

We need experiments!

Laboratory experiments to study field amplification

Laboratory experiments are a viable tool to study complex processes such as dynamo

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

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

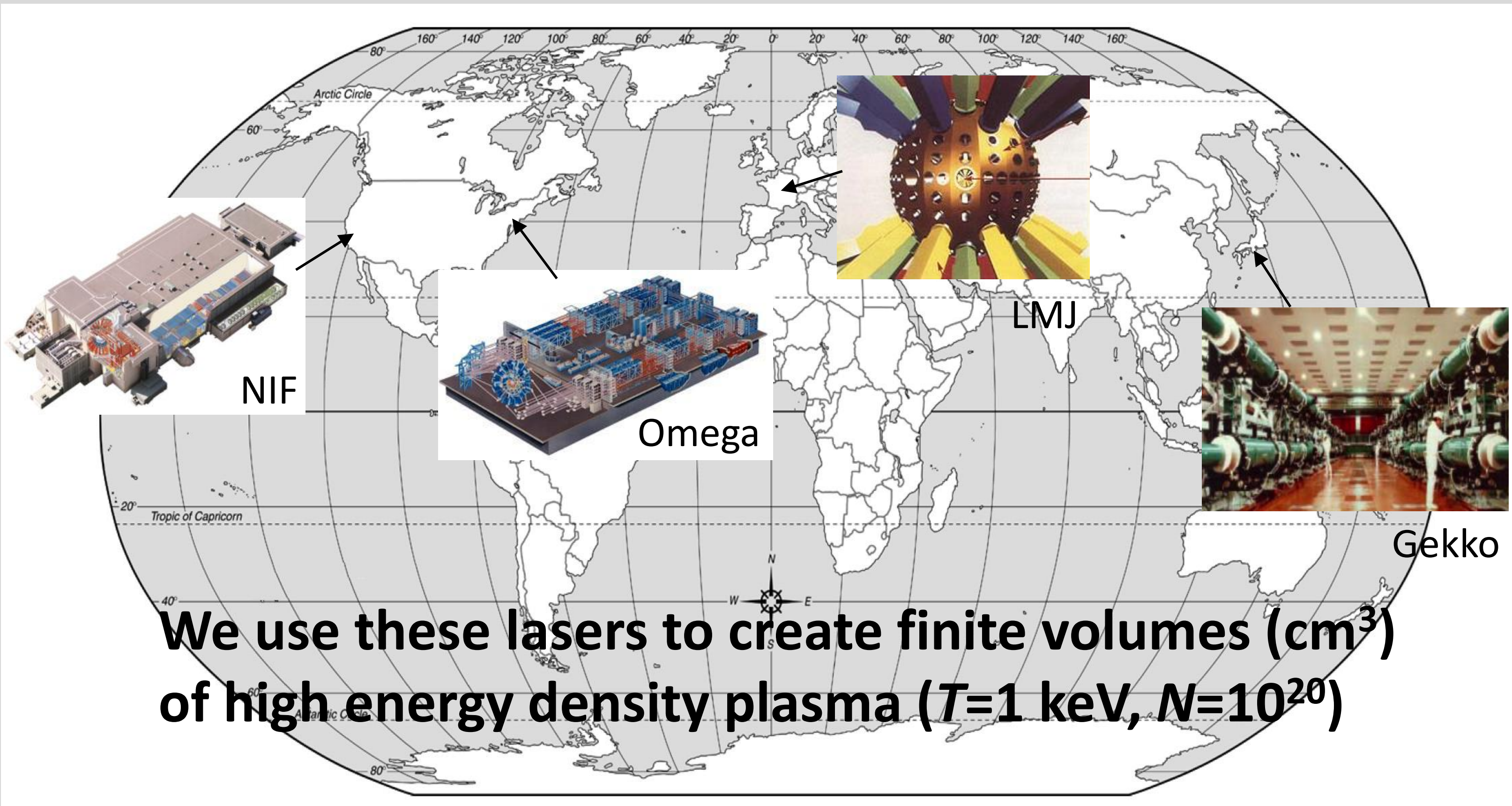
→ Equations of ideal MHD have no intrinsic scale, hence a similarity relation exists

→ This requires that particle localization, Reynolds number, Peclet number, magnetic Reynolds number are all large in both the astrophysical and laboratory systems

→ *Can be complementary to astrophysical observations and numerical simulations*:
- Compared to observations, experiments allow detailed measurements of the plasma properties
- Experiments can achieve conditions unattainable in simulations (beyond linear regimes, larger scales, etc.)
- The difficulty, so far, remained in achieving Reynolds numbers large enough for dynamo to be operative
- **The full range of parameters (highest energies, temperatures, etc.) are not accessible in experiments**

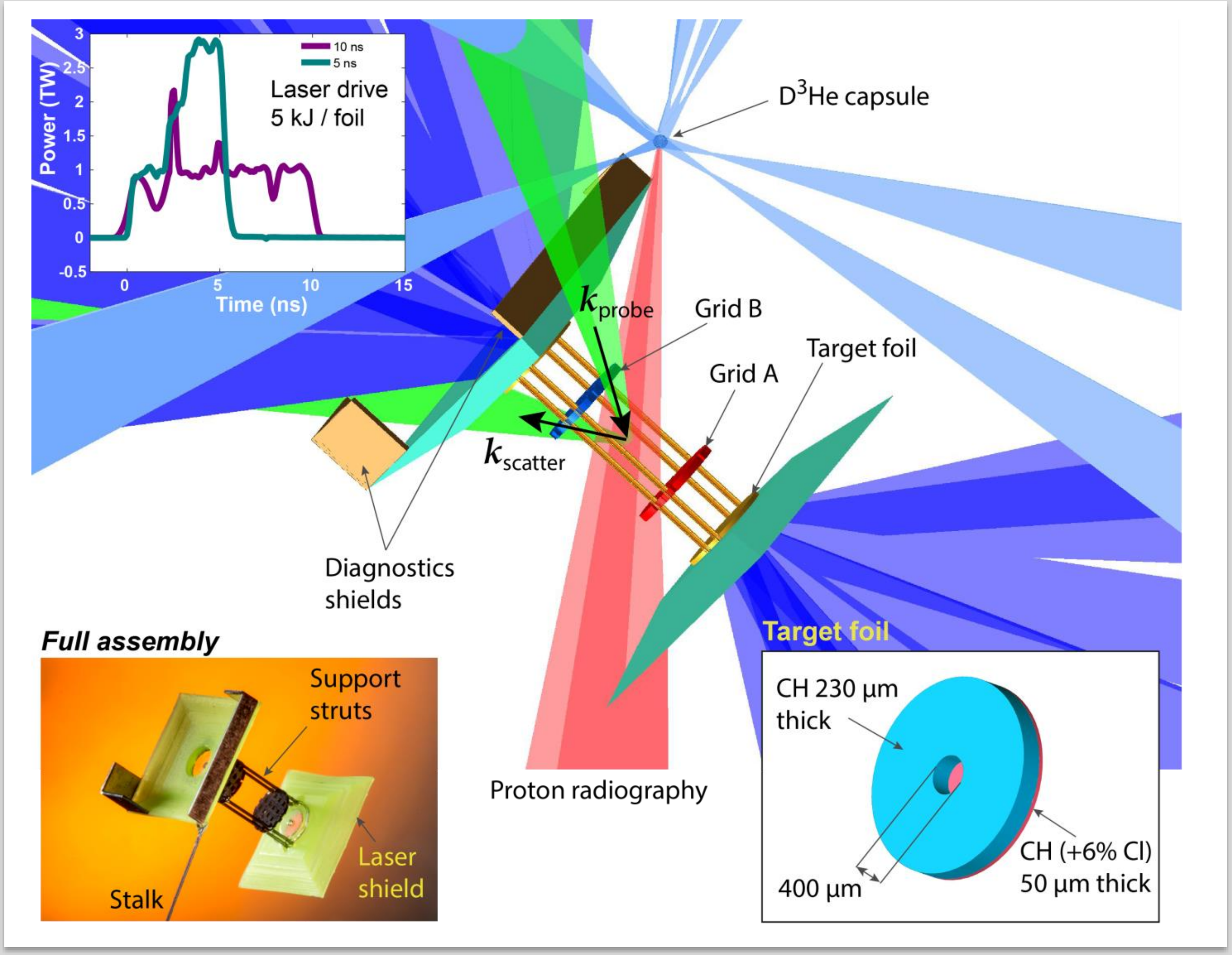
Experiments are done on laser facilities

Nanosecond pulses (10^{-9} s)
Mega-joules energy
Petawatt peak powers (10^{15} W = 2 million nuclear power plants)

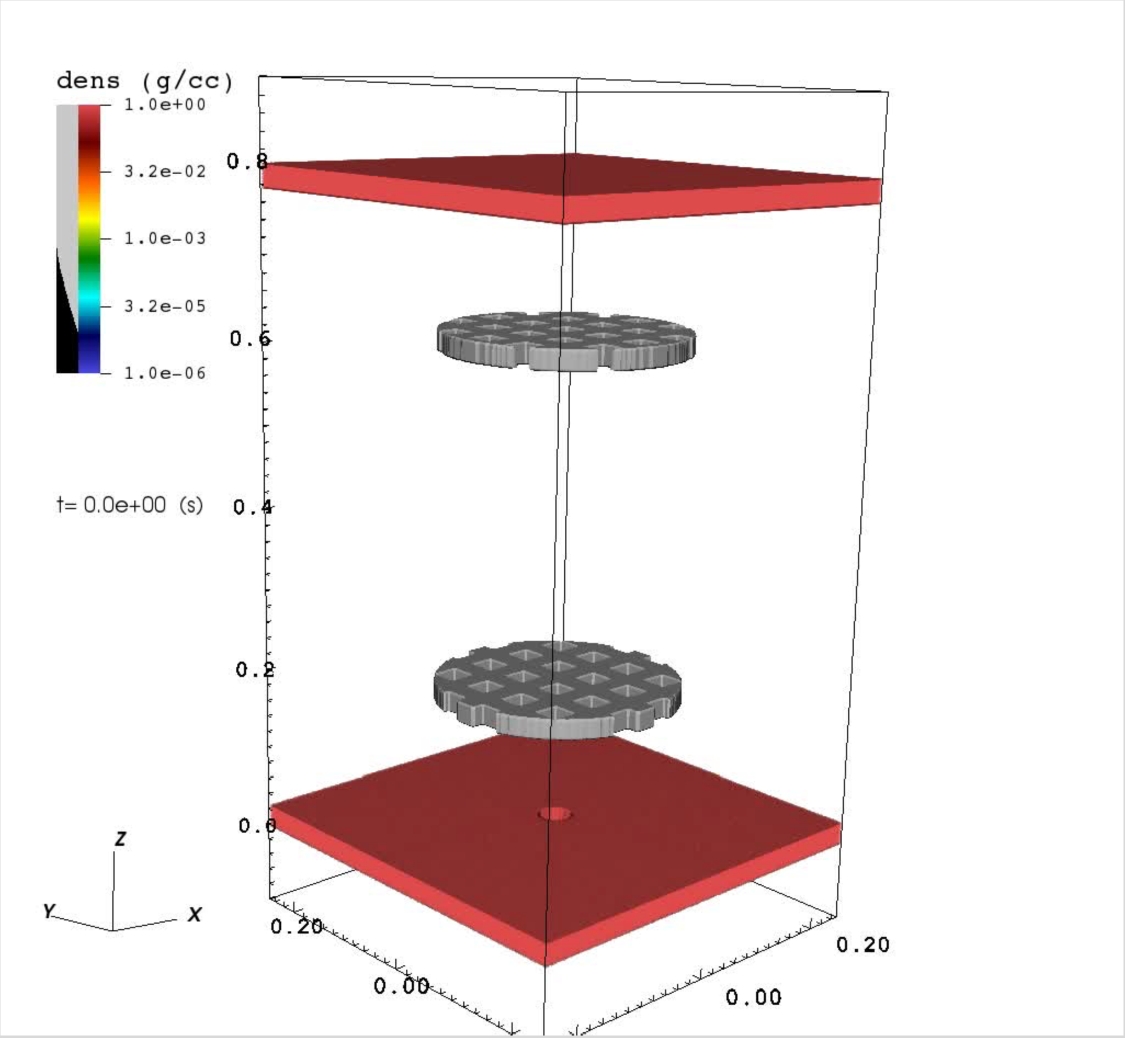


We use these lasers to create finite volumes (cm^3) of high energy density plasma (T=1 keV, N=10^{20})

Experiment uses colliding flows and grids to create strong turbulence

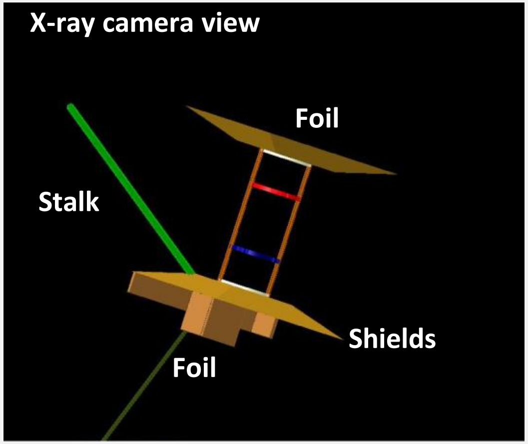


Experiment uses colliding flows and grids to create strong turbulence



Multiple diagnostics are used to monitor the plasma properties and magnetic fields

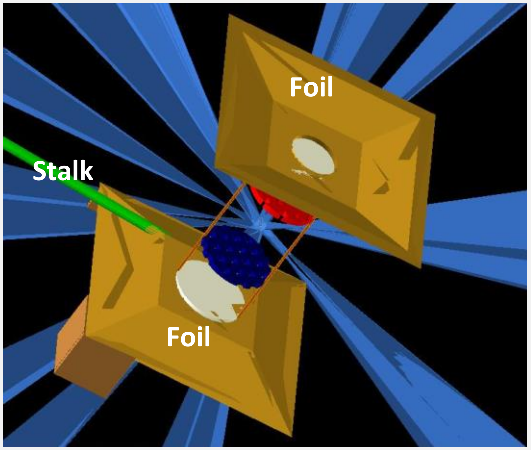
X-ray imaging



→Time resolved x-ray images provides will be used to infer density fluctuation spectrum

→Use similar analysis approach as the one to analyze x-ray maps from galaxy cluster

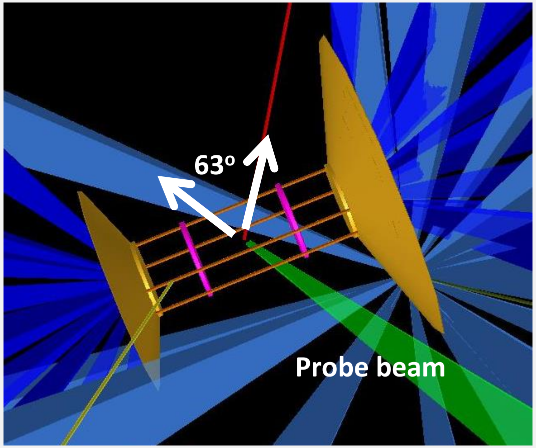
Proton radiography



→Proton radiography images map the magnetic field topology

→Provides estimate of the magnetic field produced by turbulence

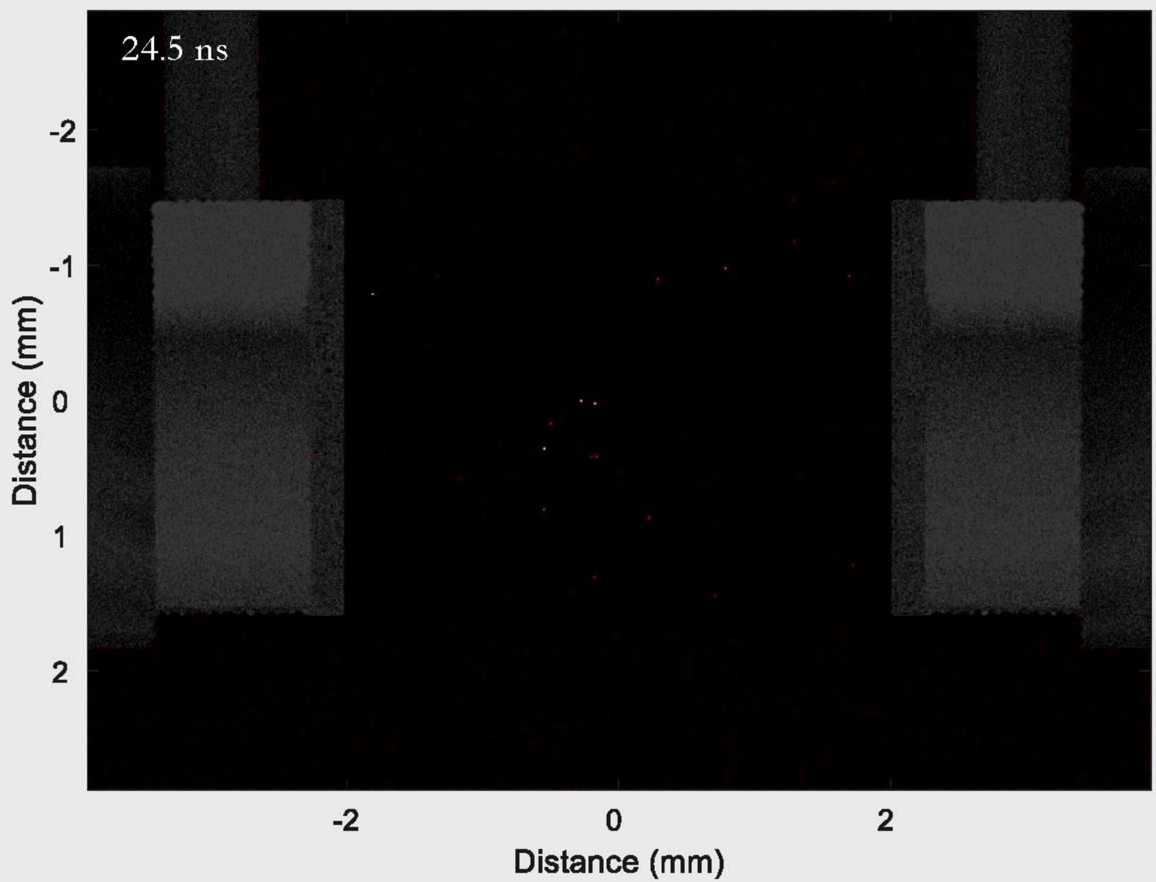
Thomson scattering



→Local, time-resolved, temperature measurement at the center of the interaction region

→Modified to include Faraday Rotation capabilities

Experimental results show colliding plasma creating turbulence



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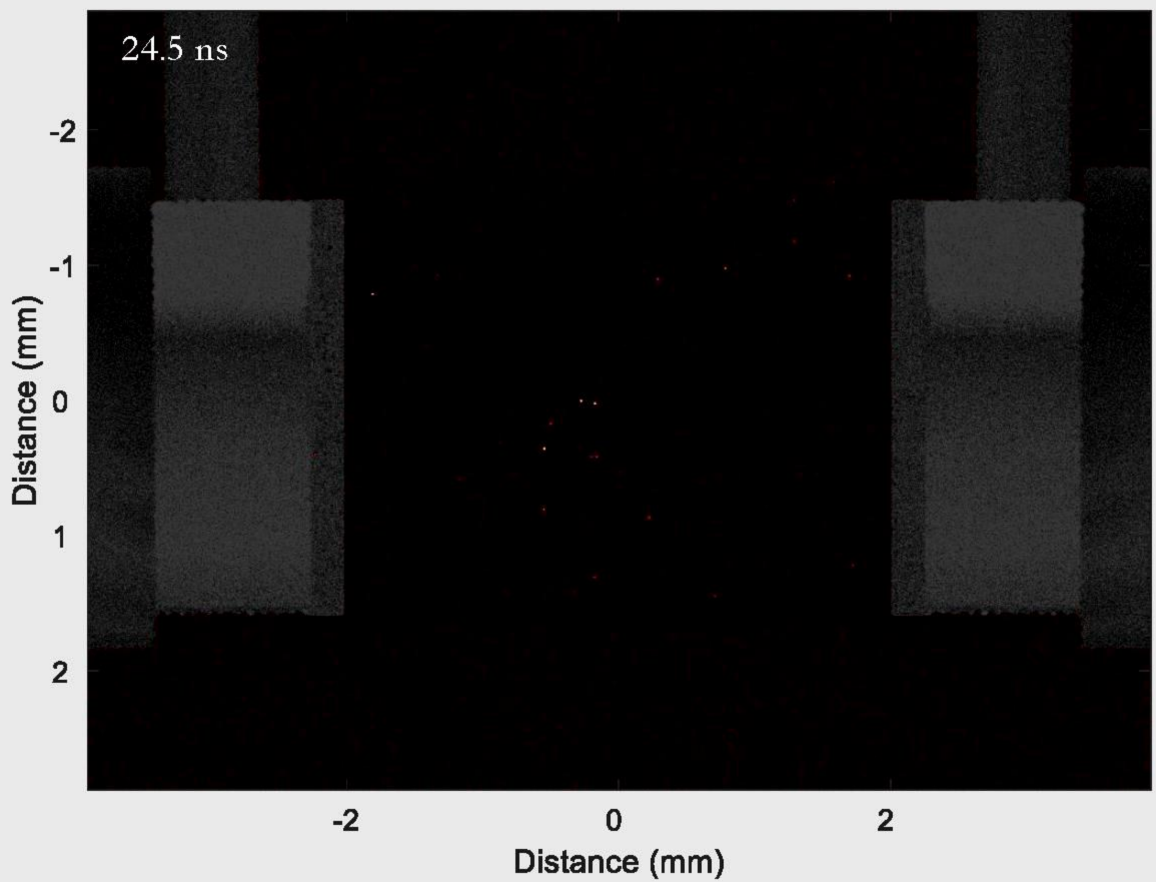
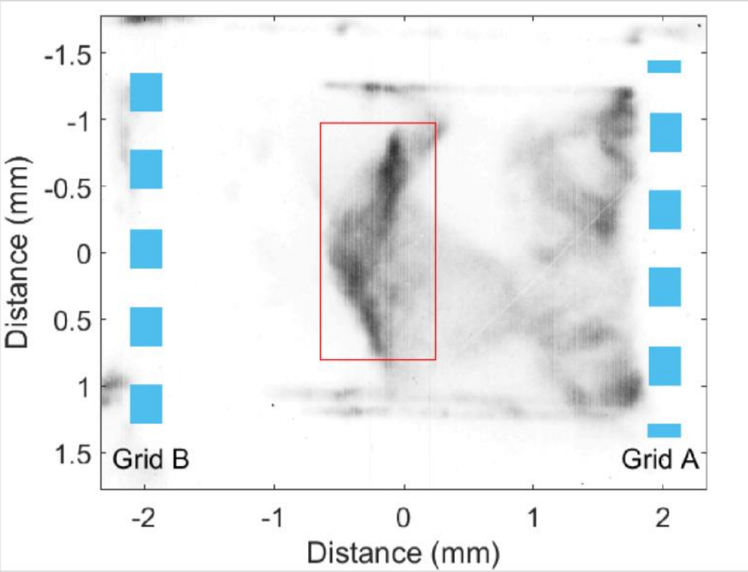
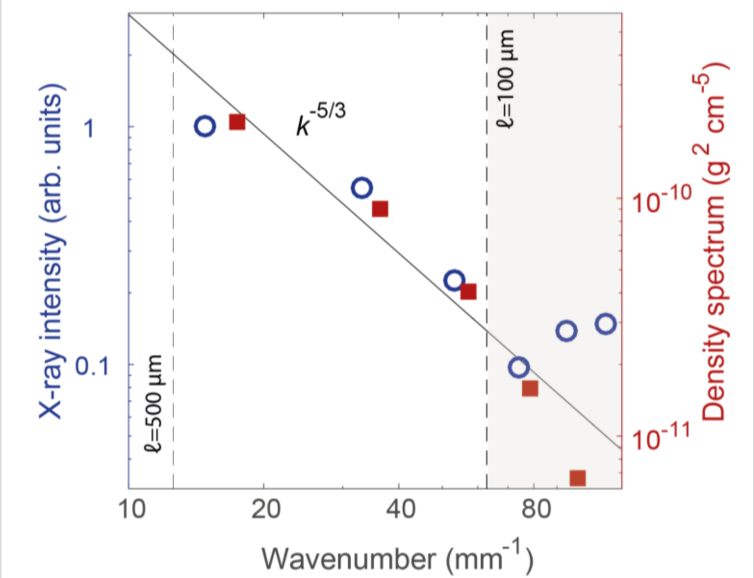


X-ray emission is used to determine power spectrum of density fluctuations





→ Assume an optically thin plasma with Planck opacity $\kappa_P \sim \kappa_0 \rho^\alpha T^\beta$

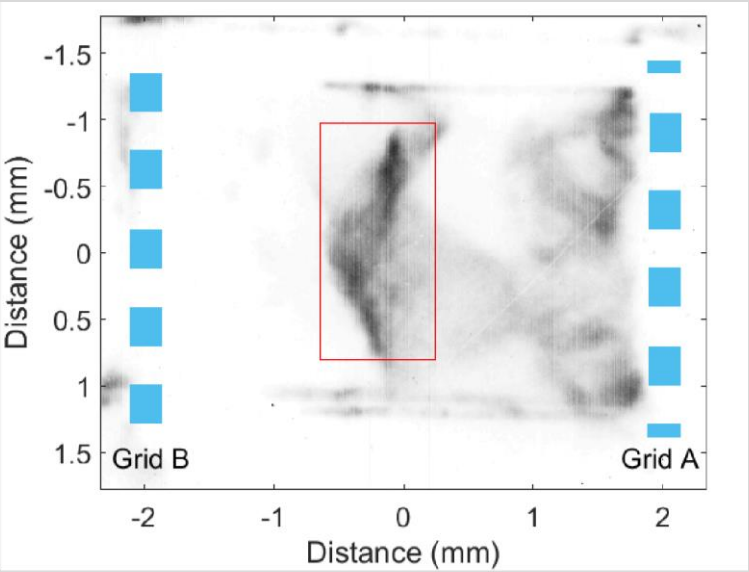
→ Fluctuation of X-ray emission depends on density variations

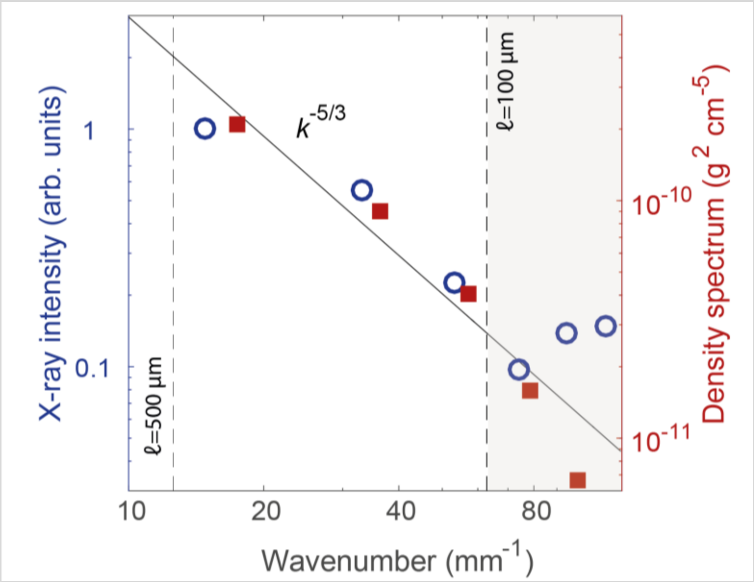
$$\frac{\delta I}{I_0} \sim a_{\alpha,\beta} \int \frac{\delta n}{n_0} dz + b_{\alpha,\beta} \int \left(\frac{\delta n}{n_0}\right)^2 dz + \cdots$$

→ If $\frac{\delta n}{n_0} < \left(\frac{\ell_n}{L}\right)^{1/2} \sim 1$ then the quadratic term can be neglected

→ The 2D Fourier transform of the intensity fluctuations can thus be related to the 3D spectrum of the density fluctuations

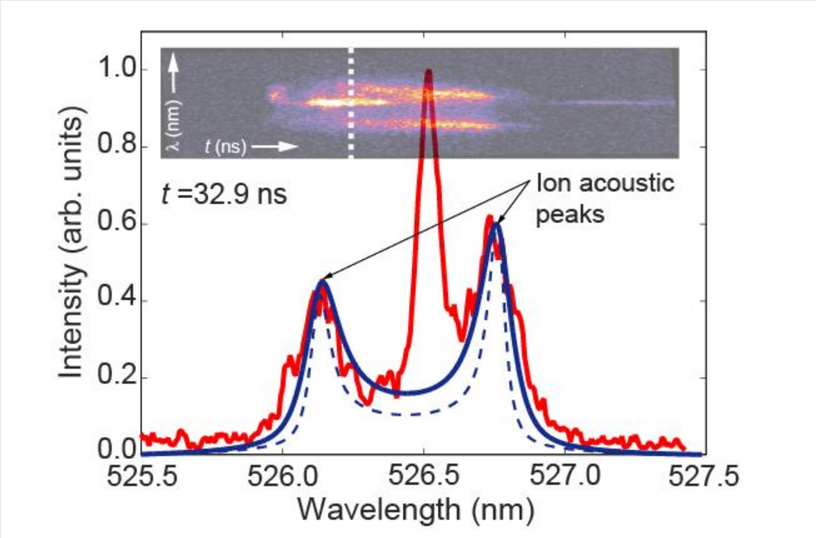
X-ray emission is used to determine power spectrum of density fluctuations

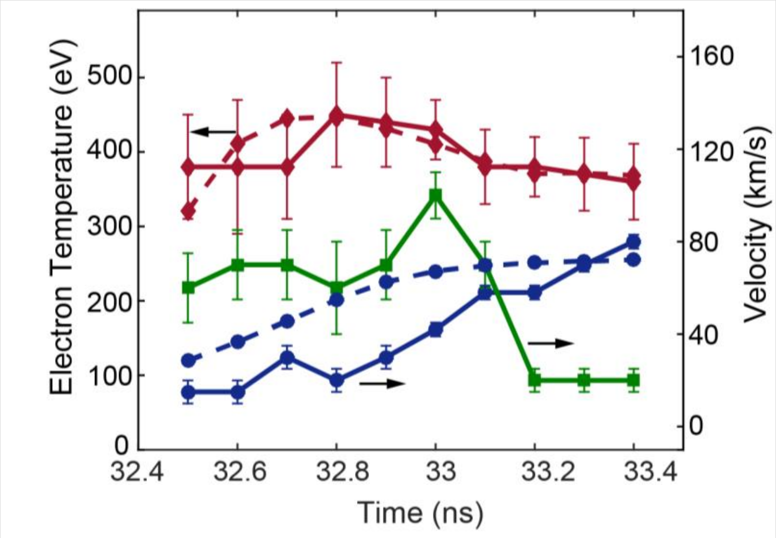




- → Density fluctuations exhibit a Kolmogorov power law
- → There is strong indication density and velocity fluctuations have the same spectrum (Zhuravleva et al. 2015)
- → Assuming Kolmogorov spectrum for the motions, velocities at different scales in the inertial range are related by $u_L \sim \left(L u_\ell^3/\ell\right)^{1/3}$

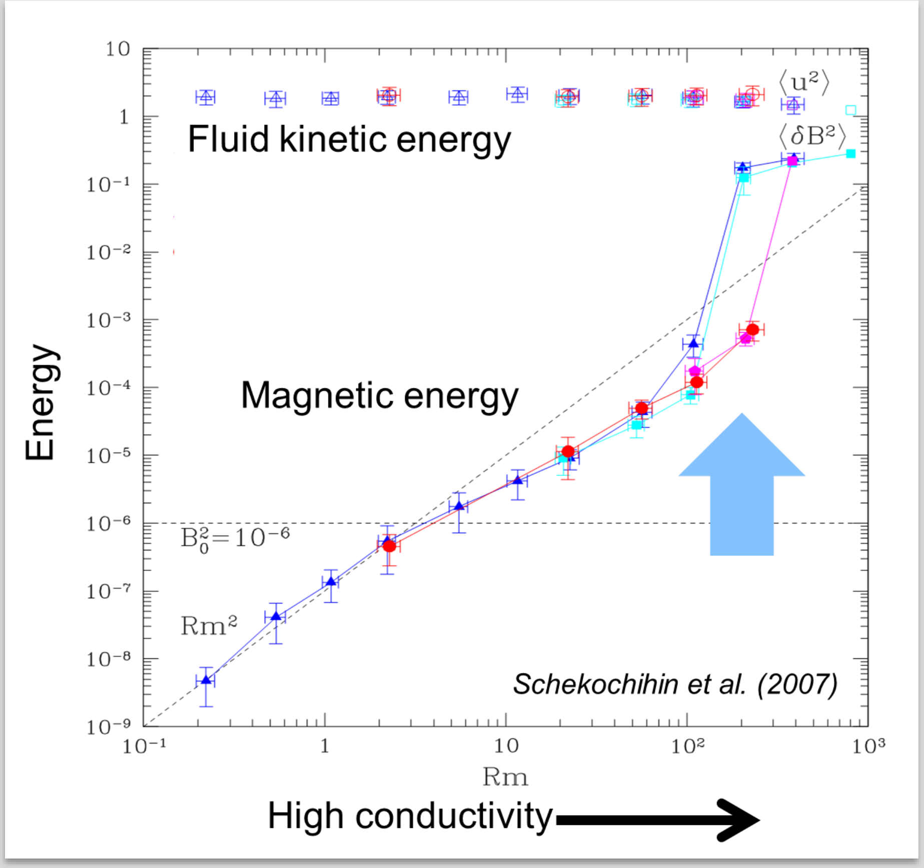
Optical Thomson scattering gives detailed information of the plasma velocities





- → ***Bulk velocity of the flows from global shift of the scattering features***
  - Before the collision, $U \approx 150 - 200$ km/s
  - After the collision, $U \approx 20 - 80$ km/s
- → ***Sound velocity from separation of ion-acoustic waves***
  - Before the collision, $T_e \approx 250$ eV
  - After the collision, $T_e \approx 400 - 500$ eV
- → ***Additional broadening due to turbulent velocity***
  - At the scale of the Thomson scattering probe (50 μm), $u_\ell \sim 50$ km/s
  - This gives a velocity of 100 km/s at the outer scale

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

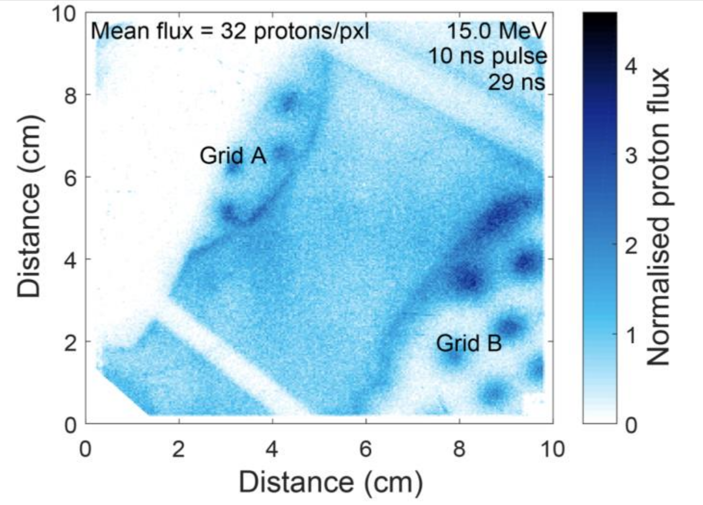


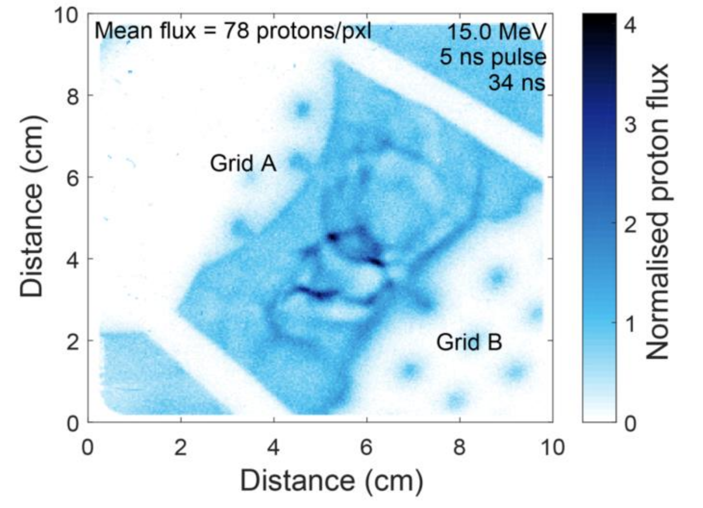
	Experiment
v	100 km/s
T_e	450 eV
n_e	~10^{20} cm^{-3}
M	1
Re	600
Rm	700
Pm	1

→ We have achieved magnetic Reynolds number much larger that the threshold value for turbulent dynamo action

→ Expect to reach dynamical equipartition between fluid motions and magnetic field

Proton deflections track magnetic fields in turbulent plasma (*caustics*)

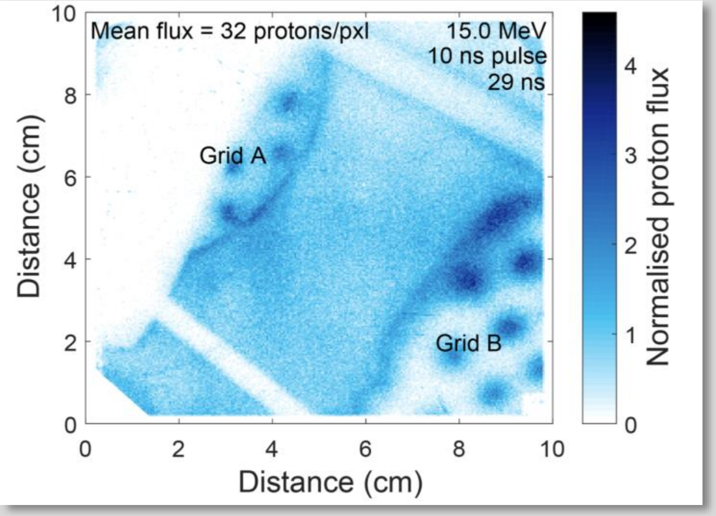




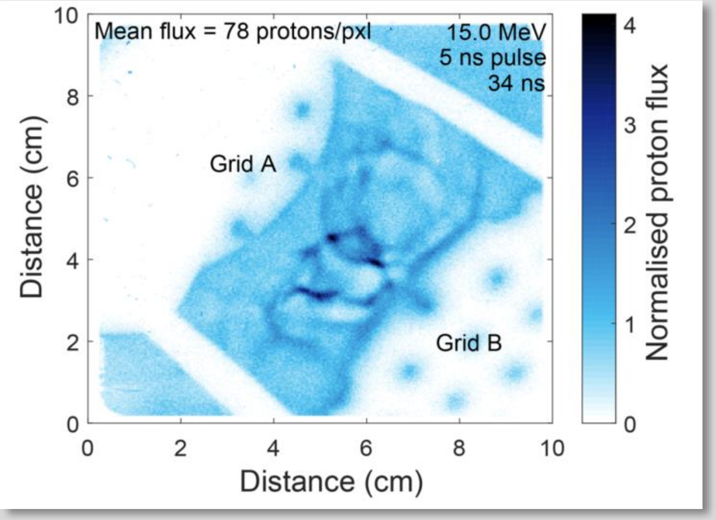
- → No structures appear in the images before the collision, but filaments are seen after the collision
- → Proton deflections are a measurement of the path-integrated magnetic field

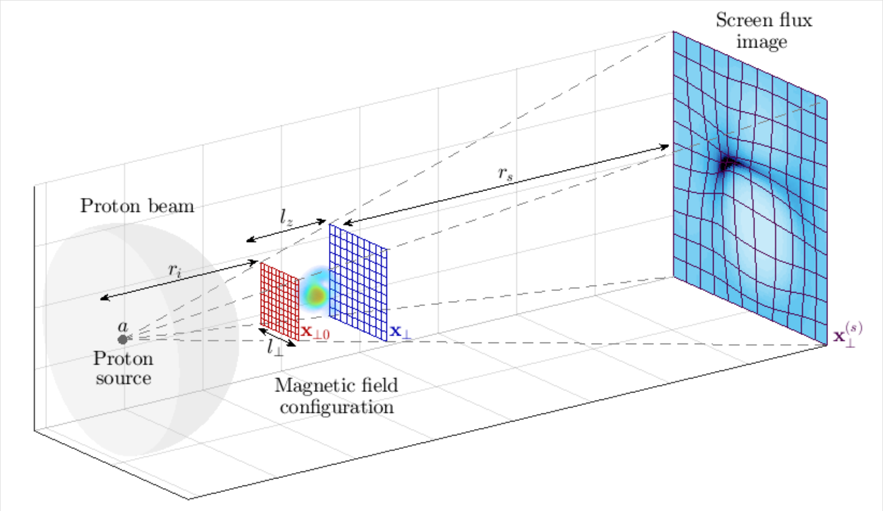
$$|\mathbf{B}| \sim \frac{1}{\ell_n} \int_0^{\ell_n} \mathbf{B}_\perp dl$$

Proton deflections track magnetic fields in turbulent plasma (*caustics*)

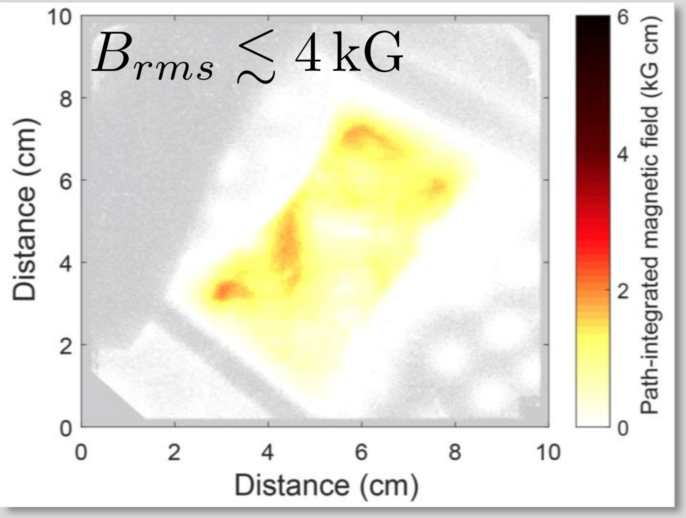


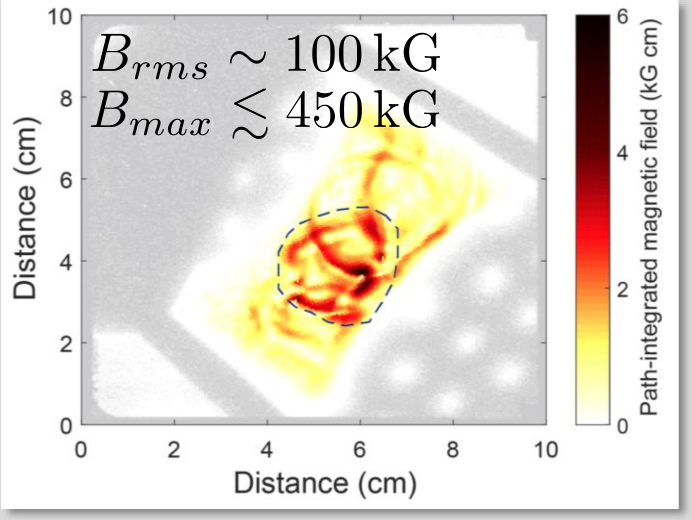
→ Non-linear reconstruction of the magnetic field from the proton deflections is possible (*Bott et al. arXiv 1708.01738*)





Magnetic field reconstruction from 15 MeV proton deflections

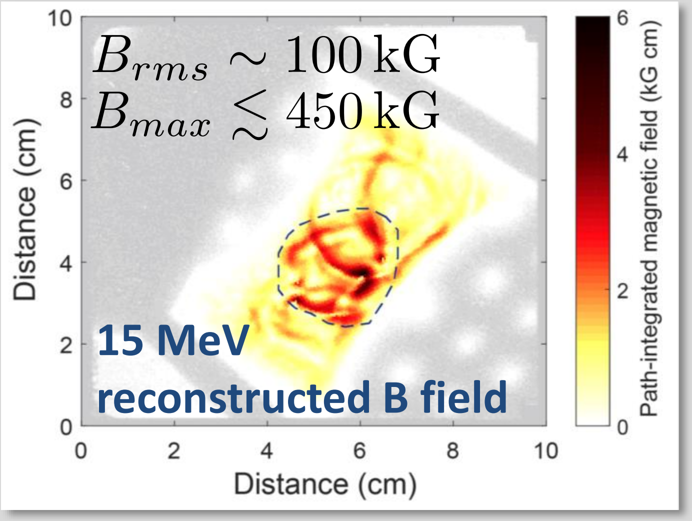




→ No structures appear in the images before the collision, but filaments are seen after the collision

→ Our analysis suggests **25x** amplification of the RMS field and peaks of **450 kG** (near saturation)

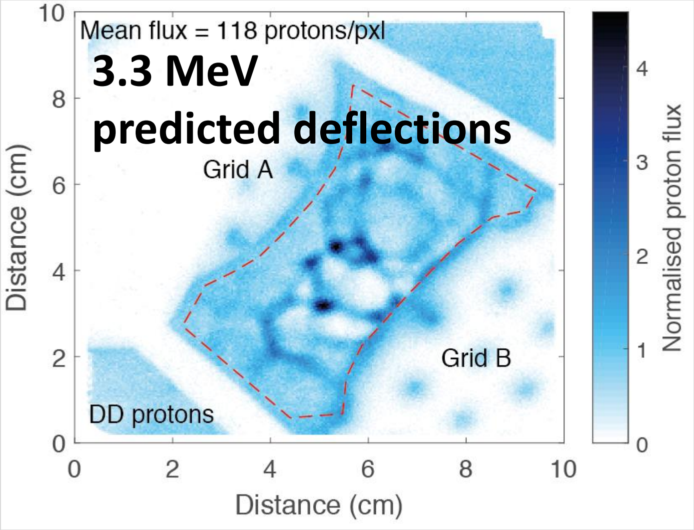
Validation of magnetic field reconstruction algorithm

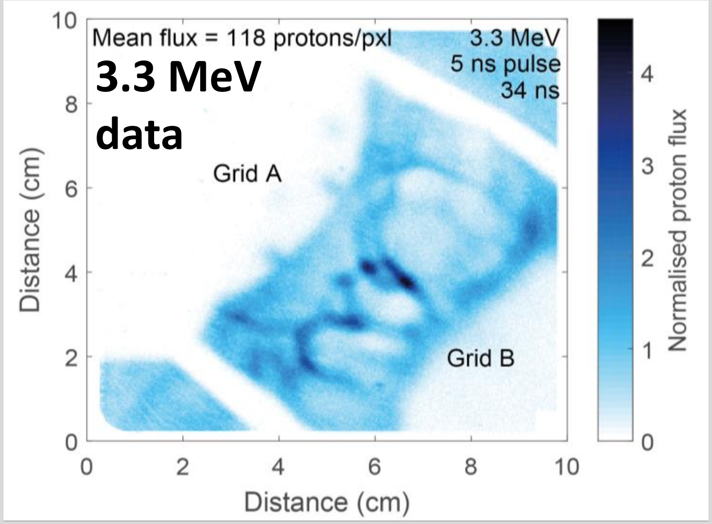


→ Our analysis suggests **25x** amplification of the RMS field and peaks of **450 kG** (near saturation)

→ Predicted and actual 3.3 MeV proton deflections are very similar

→ **But** lines in data are more diffuse





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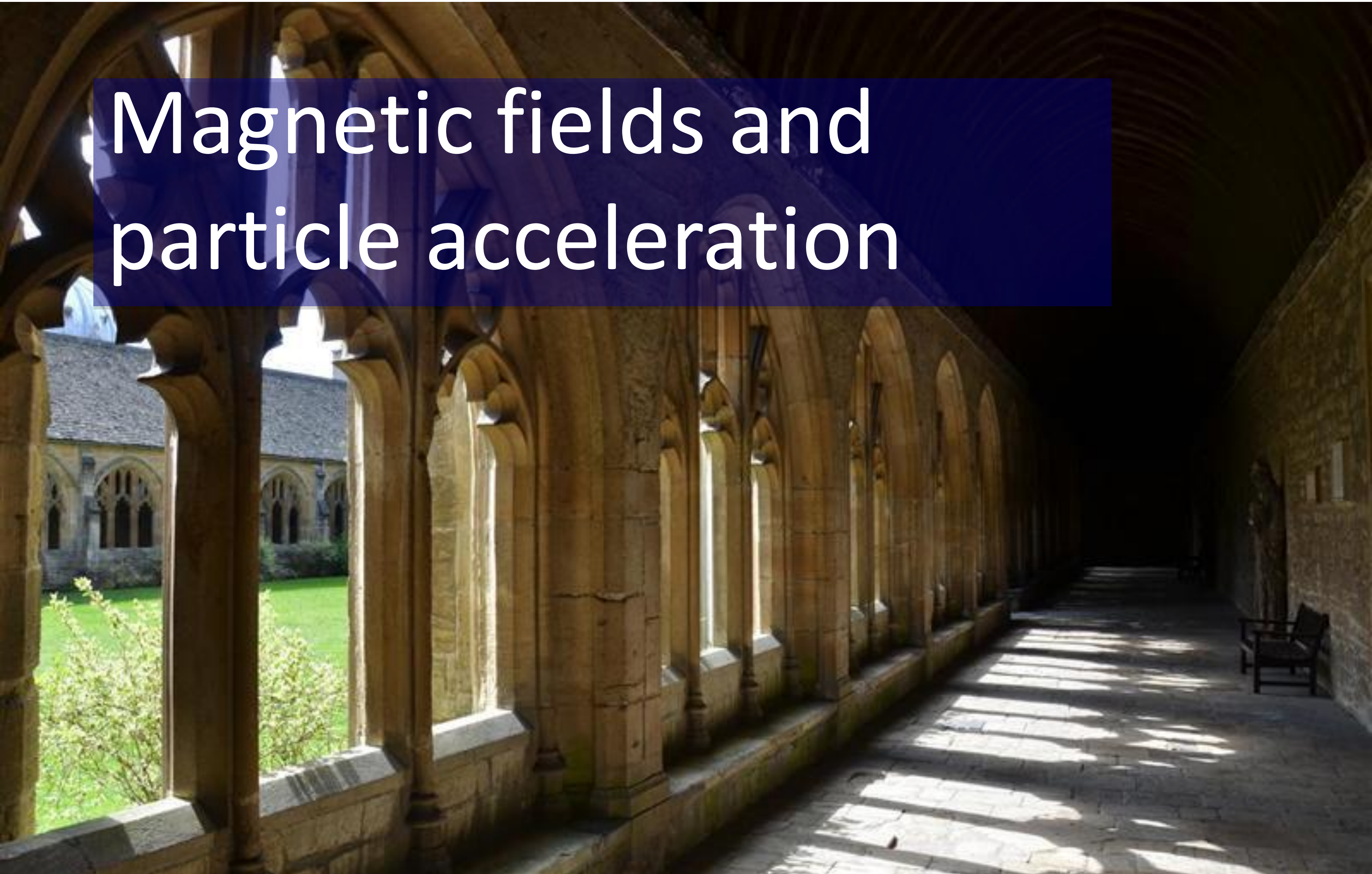
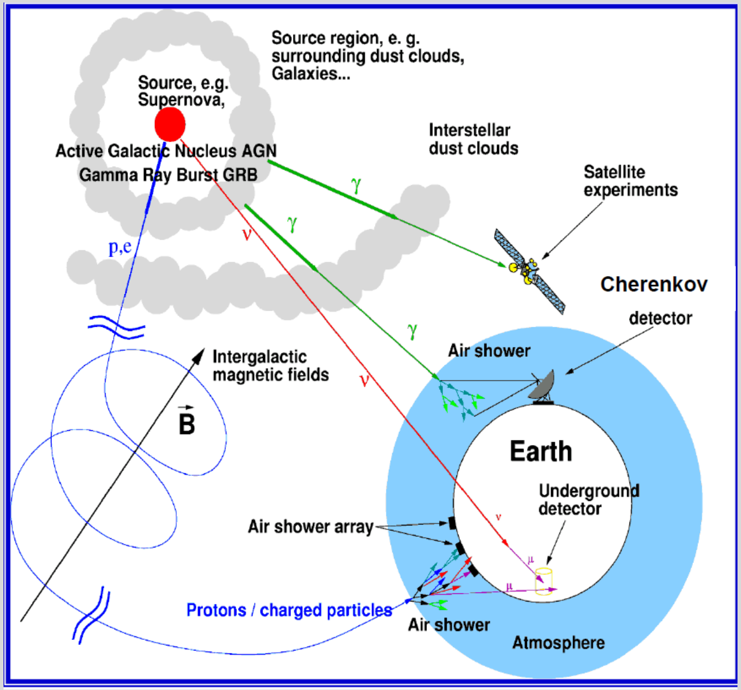
Magnetic fields and particle acceleration

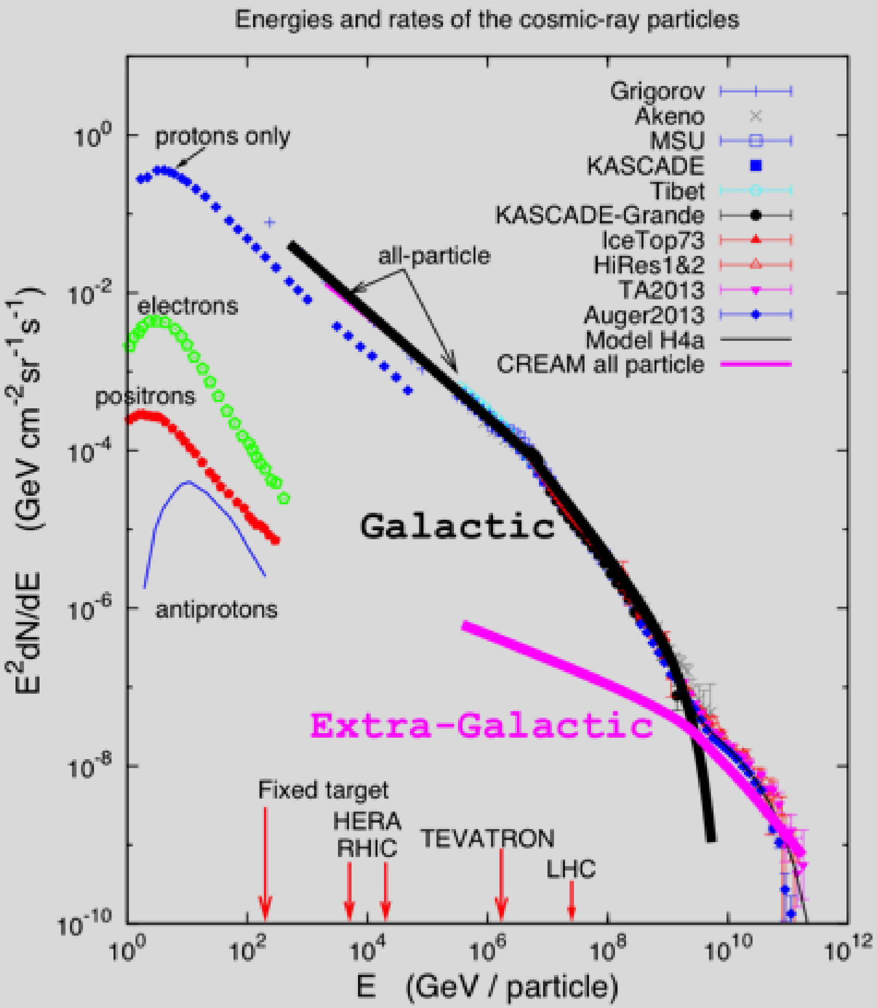


Very high energy particles (Cosmic Rays) observed on Earth

→ CRs are in apparent defiance of thermodynamics

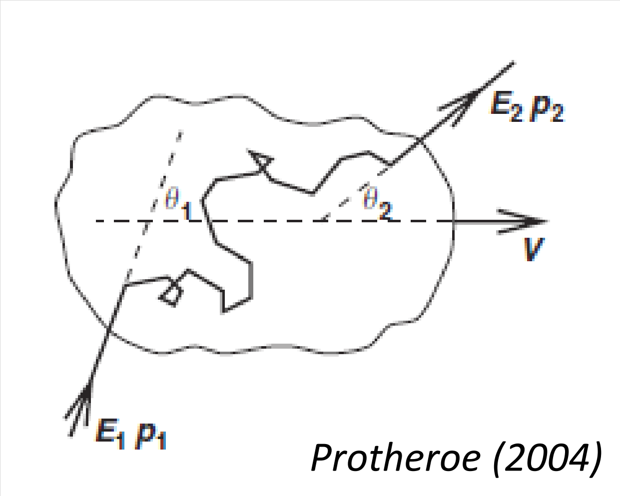


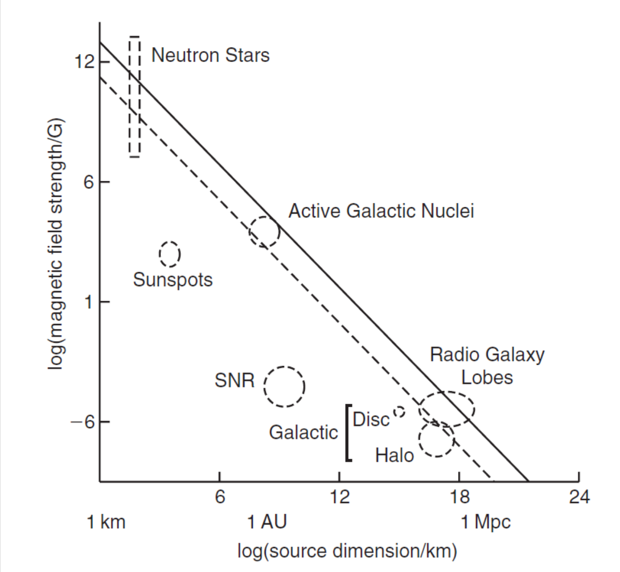
Wagner (2004)



http://masterclass.icecube.wisc.edu

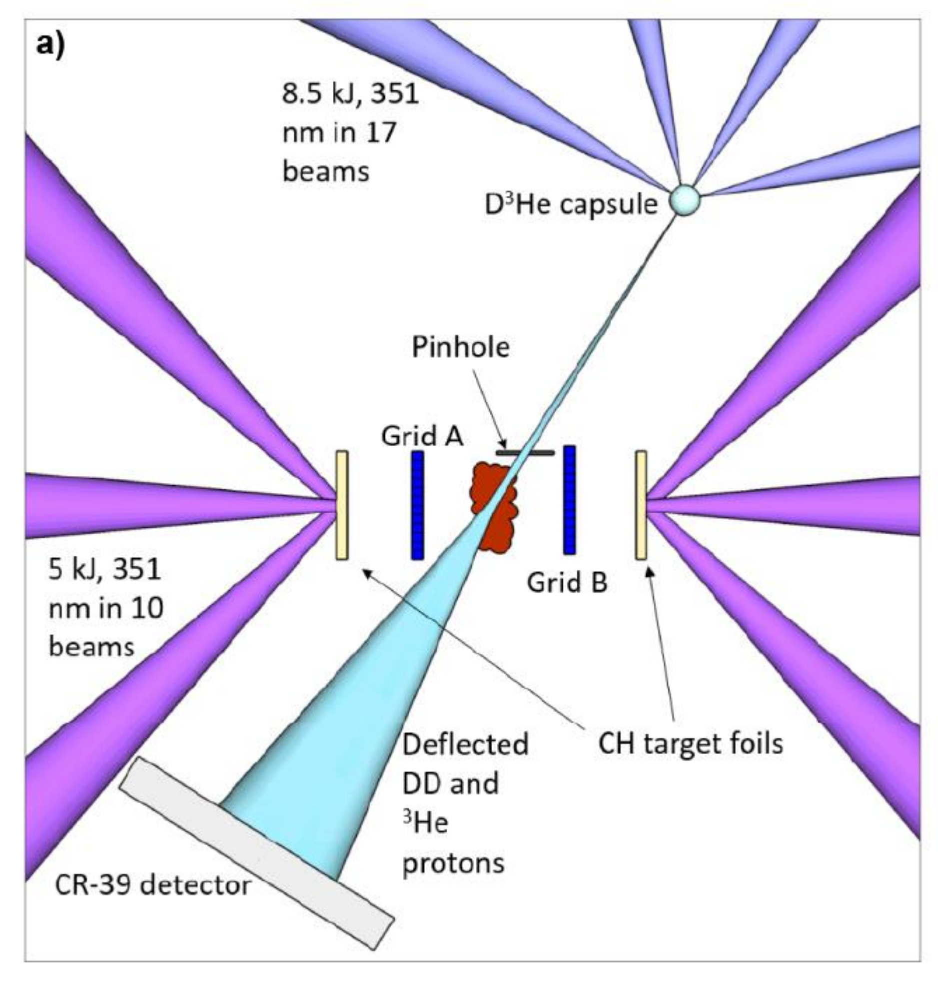
Fermi acceleration is a universal process for particle energization





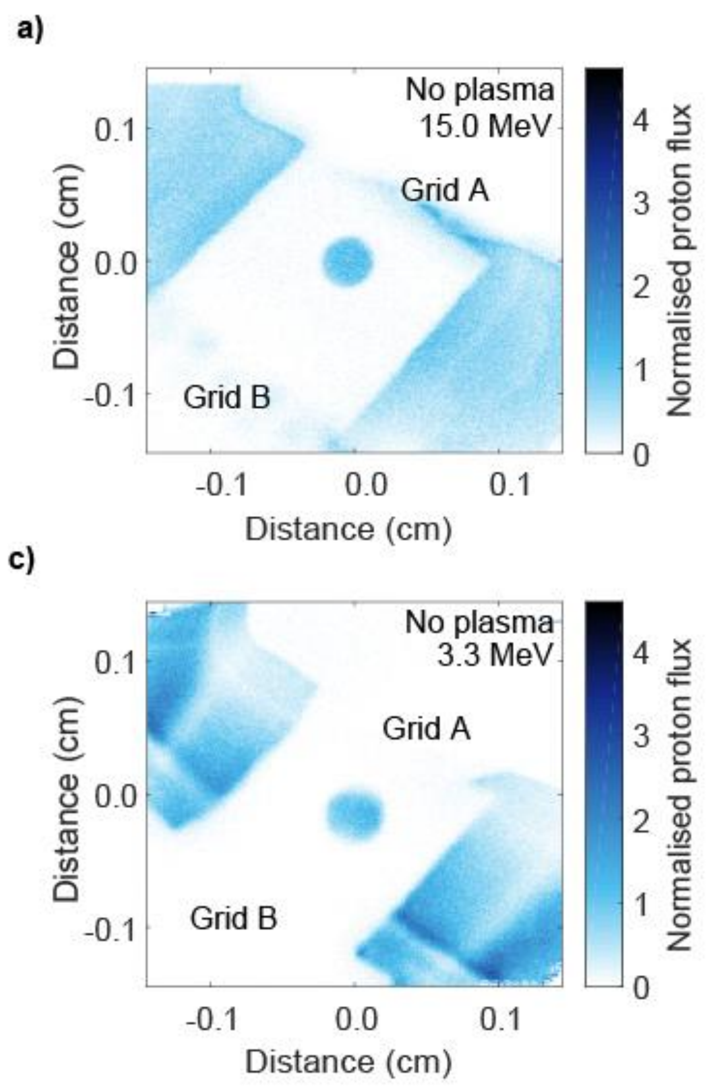
- Fast particles collide with moving magnetized clouds (*Fermi, 1949*). Particles can gain or lose energy, but head-on collisions (gain) are slightly more probable
- The evolution of CRs as they are accelerated in the plasma is governed by a diffusion equation (*Kaplan, 1955; Cowsik & Sarkar, 1984; Blandford & Eichler, 1987*)
- *In addition to astrophysical sources, laboratory plasmas can also potentially accelerate particle*

We use the dynamo platform to study proton diffusion through plasma



- → High energy protons produced by capsule implosion are collimated with a pinhole
- → As they pass through the turbulent plasma they acquire transverse deflections (diffusion)

We use the dynamo platform to study proton diffusion through plasma



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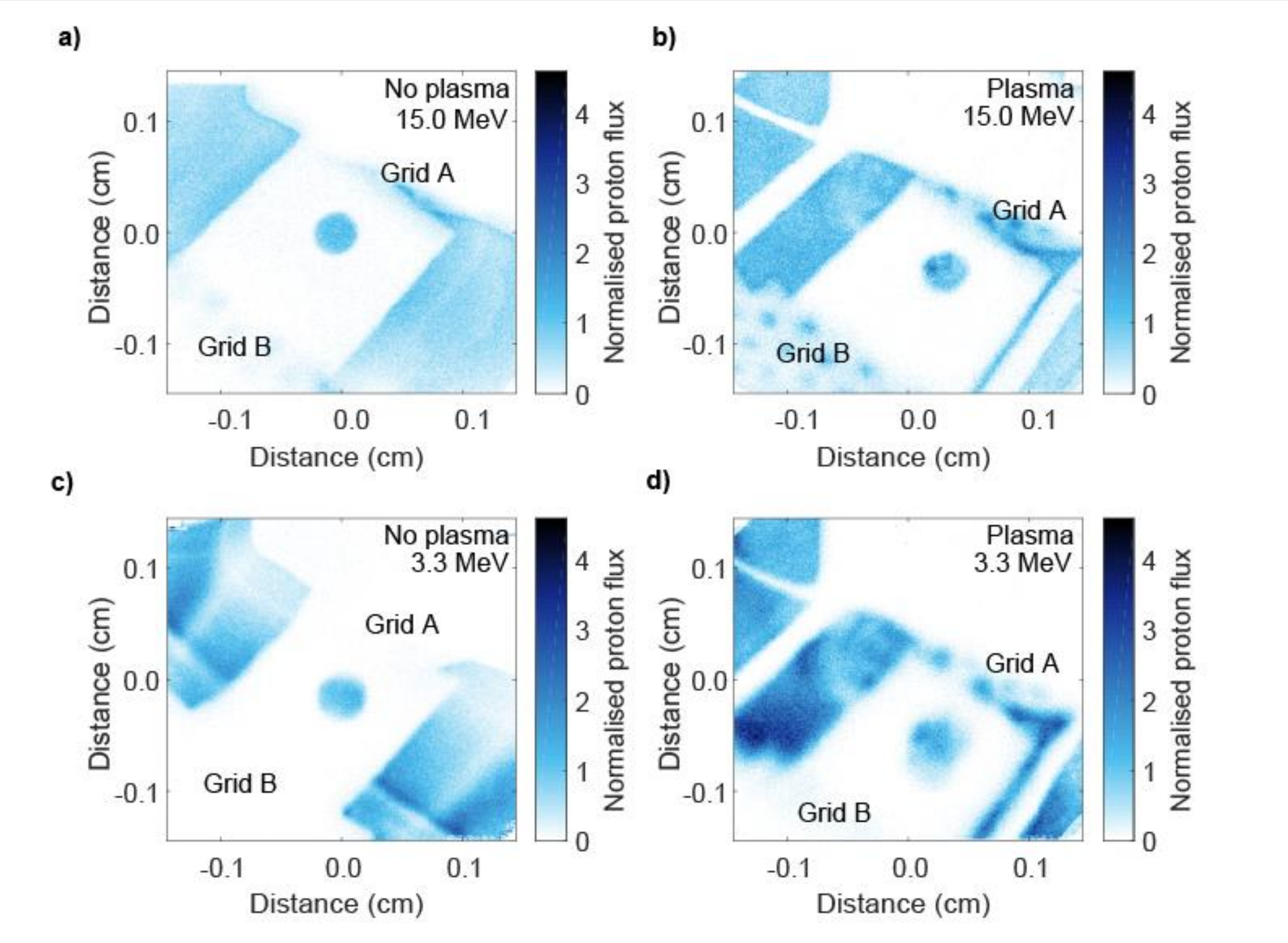
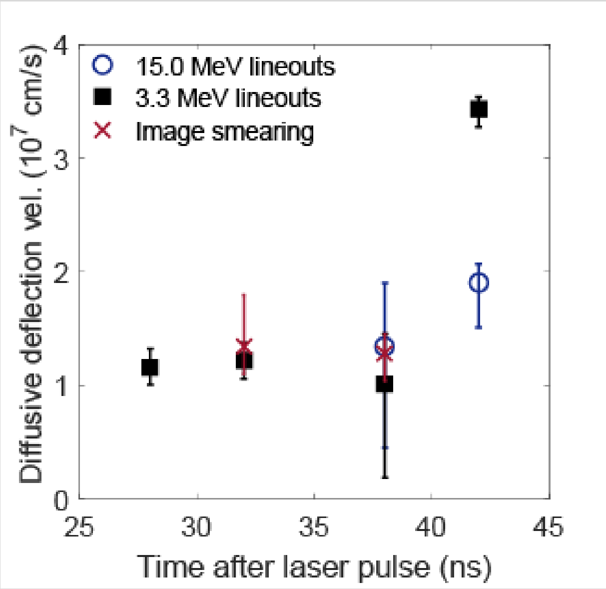
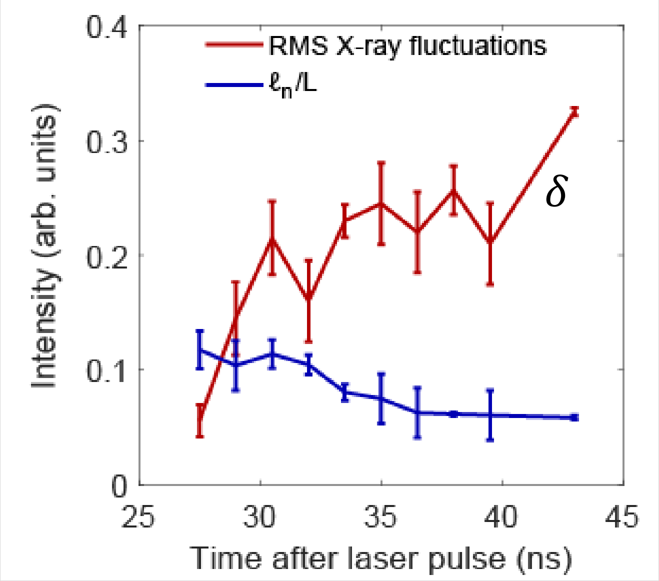


We use the dynamo platform to study proton diffusion through plasma





$$\Delta v_\perp = \frac{e}{m_p V_p}\int_0^L E(z)dz \sim \frac{eE\ell_n}{m_p V_p}\left(\frac{L}{\ell_n}\right)^{1/2} \qquad \Delta\theta = \Delta v_\perp / v$$

→ The proton deflection at later times is determined by the electric fields in the plasma

→ The electric field is given by the generalized Ohm's law:

$$\boldsymbol{E} = -\mathbf{V}_\mathrm{p} \times \boldsymbol{B} - \frac{\eta}{\mu_0}\nabla \times \boldsymbol{B} - \boldsymbol{E}_{te}$$

Preliminary analysis shows deflections are due to baroclinic electric fields

$$\boldsymbol{E} = -\mathbf{V}_{\mathrm{p}} \times \boldsymbol{B} - \frac{\eta}{\mu_0} \nabla \times \boldsymbol{B} - \boldsymbol{E}_{te}$$

→ This term gives a smaller velocity deflection independent on the proton energy (does not agree with data at later times)

→ The second term is always small since the magnetic Reynolds number is large. That is, resistive diffusion is negligible

→ The thermoelectric (baroclinic) field is largest at the resistive scale: $E_{te} = \frac{\nabla P_e}{e n_e} \sim \frac{1}{(1-\delta)} \frac{T}{\lambda_\mu}$

→ This gives for the 3.3 MeV protons $\Delta v_\perp \sim 2 \times 10^7$ cm/s, in agreement with data

→ The predicted acceleration is $\Delta W \sim E_{te} (L \ell_n)^{1/2} \sim 100$ keV

Thanks to all collaborators

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Summary

- Magnetic fields are ubiquitous in the Universe. Their strength suggest turbulent dynamo is operative
- Laser-plasma experiments have reached the conditions were turbulent dynamo could be initiated, and we have seen large amplification
- Turbulent magnetic fields are associated to particle acceleration and CR's
- We have measured the diffusion of protons through the turbulent plasma
- Laboratory laser-based platforms offer the ability to directly test theory of particle acceleration