Generation and characterization of scaled magnetic turbulence in the laboratory

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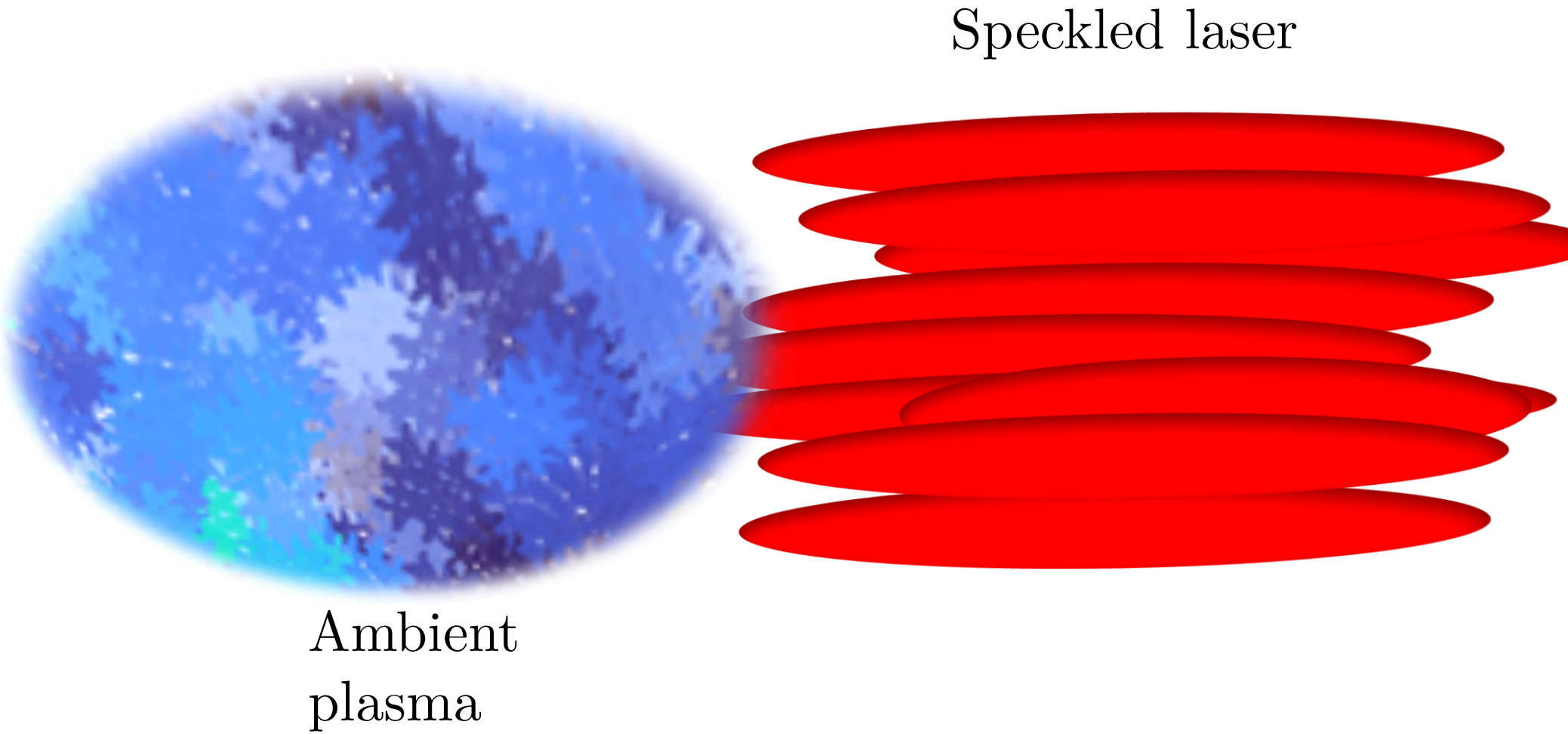
KPAP

April 20, 2026

New method to produce very large volume of magnetic turbulence



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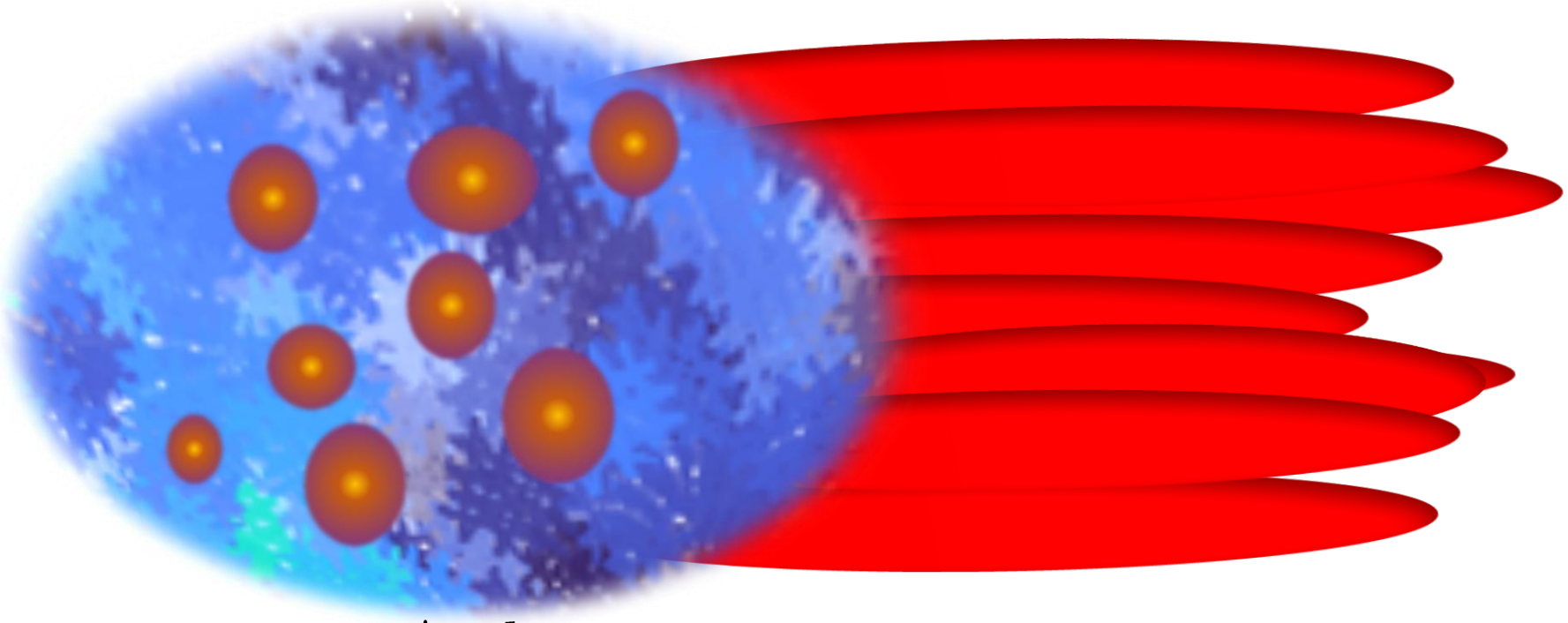
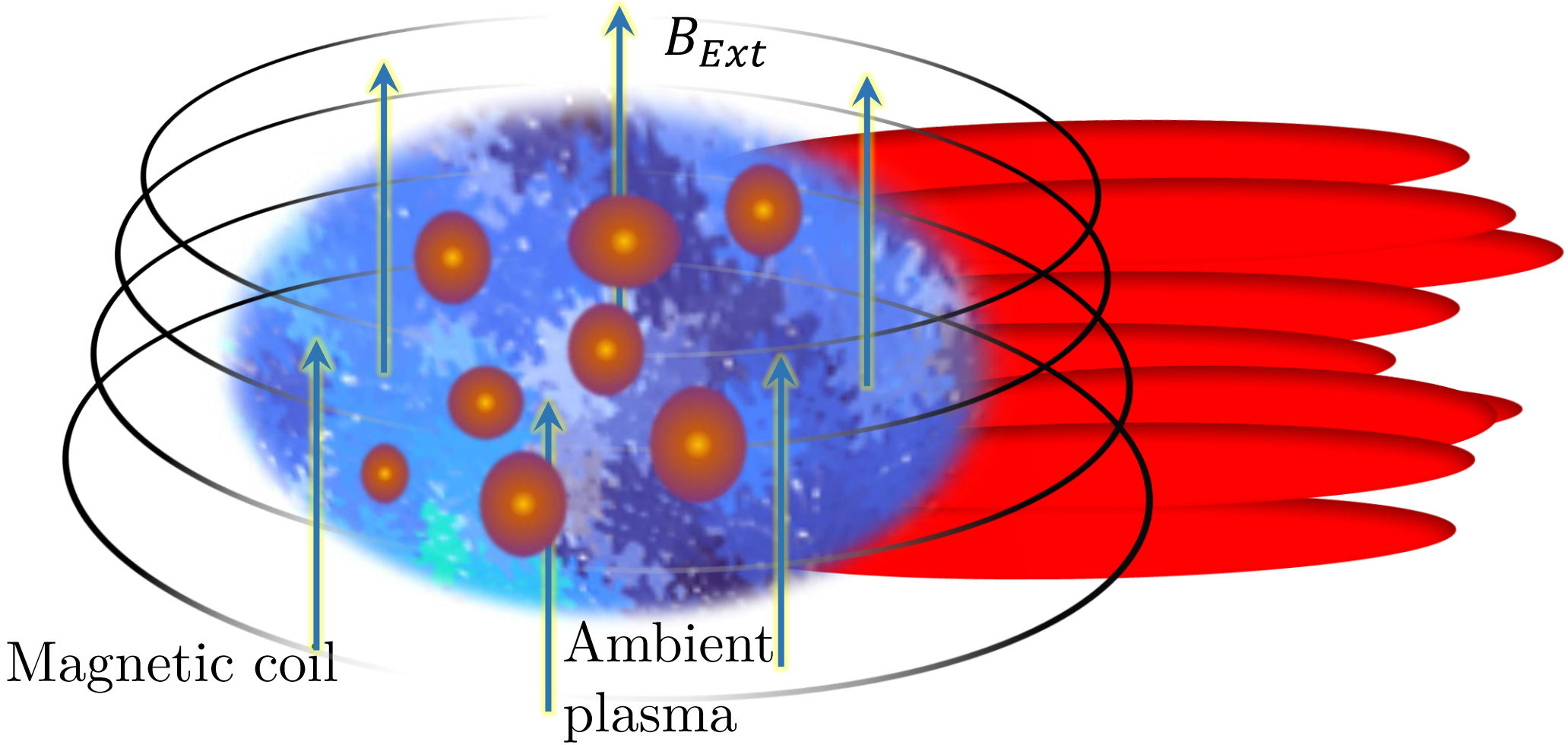


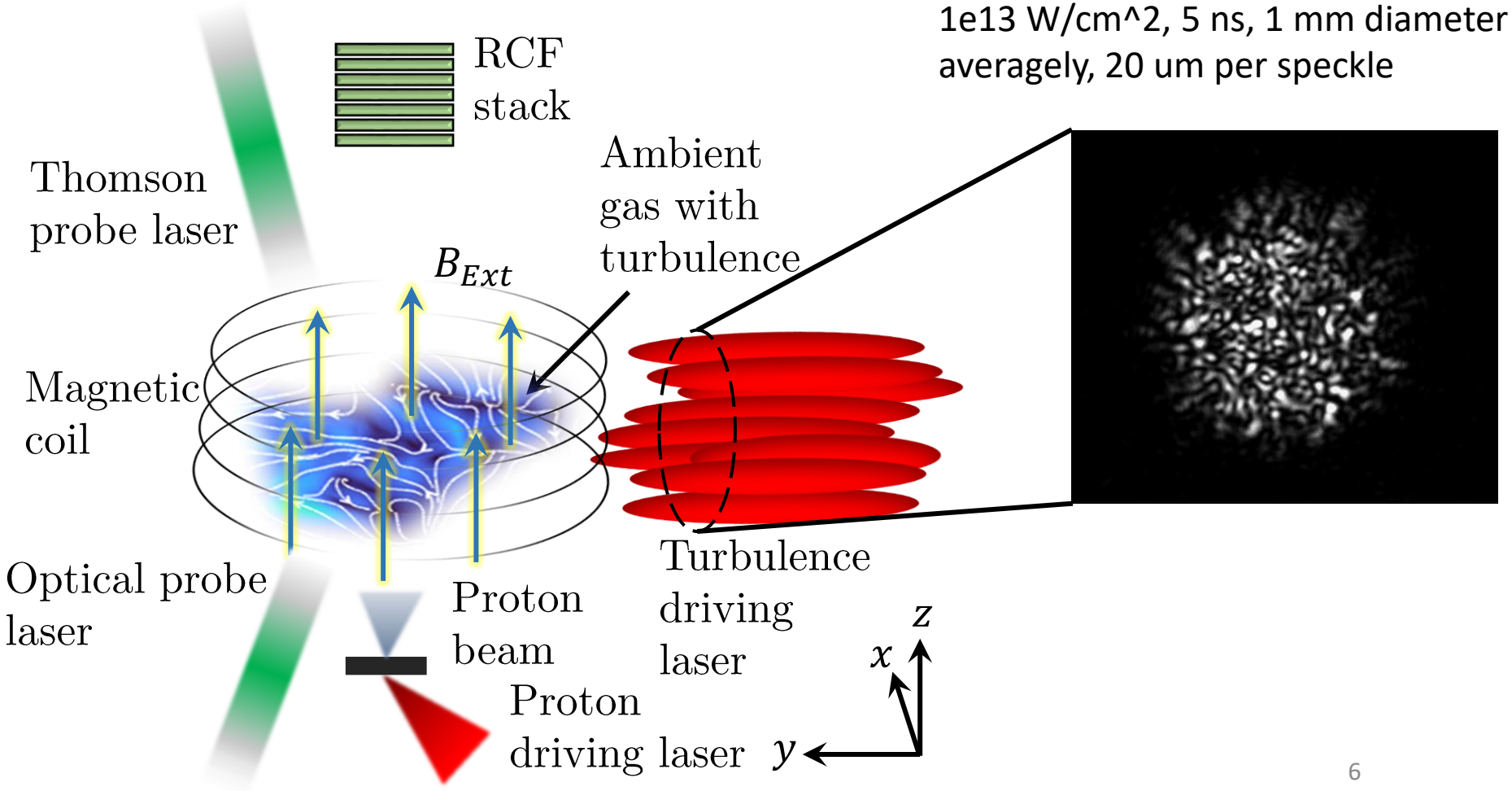
Ambient plasma

New method to produce very large volume of magnetic turbulence



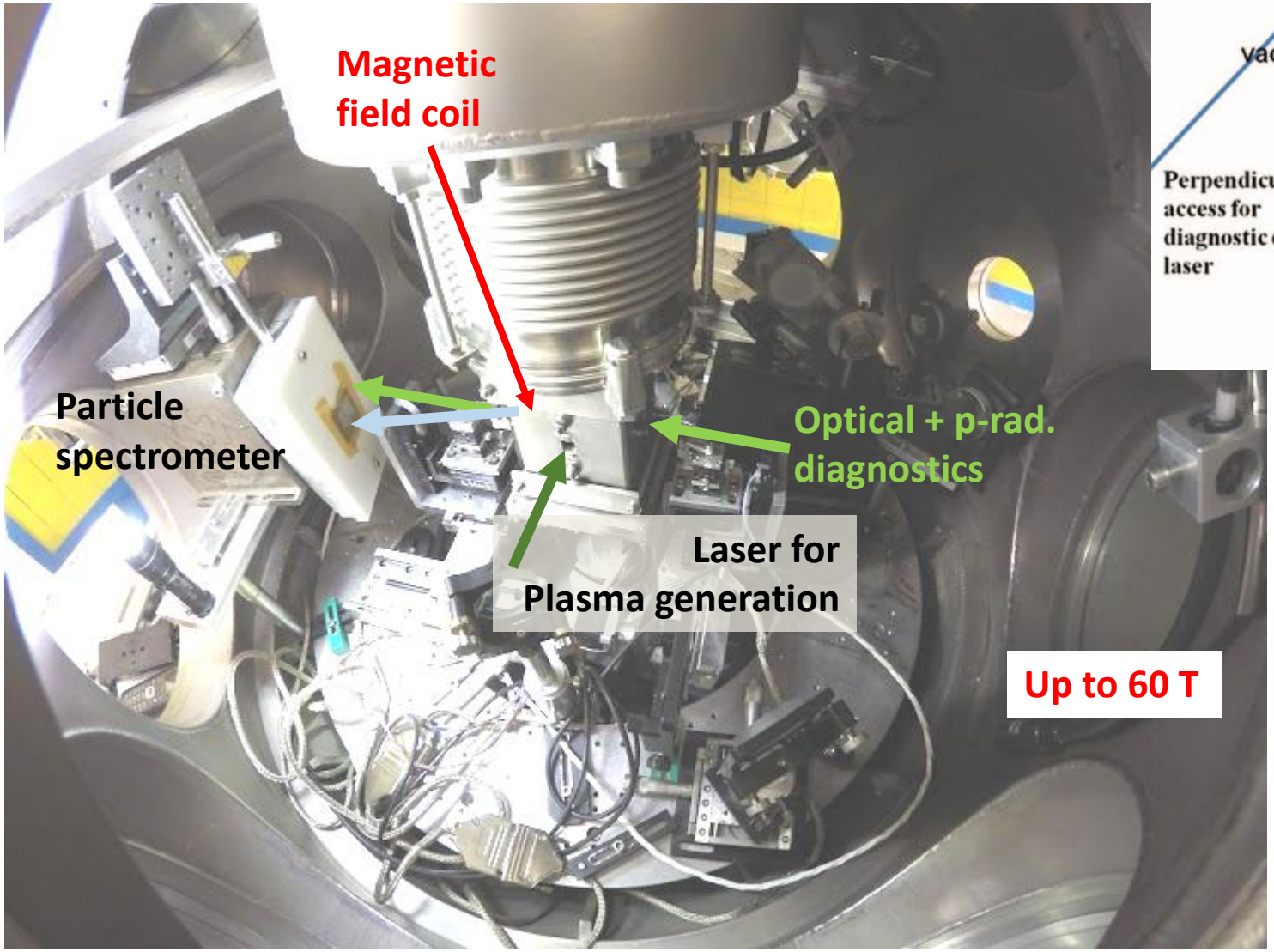
Localized heating allows to randomize the magnetic field

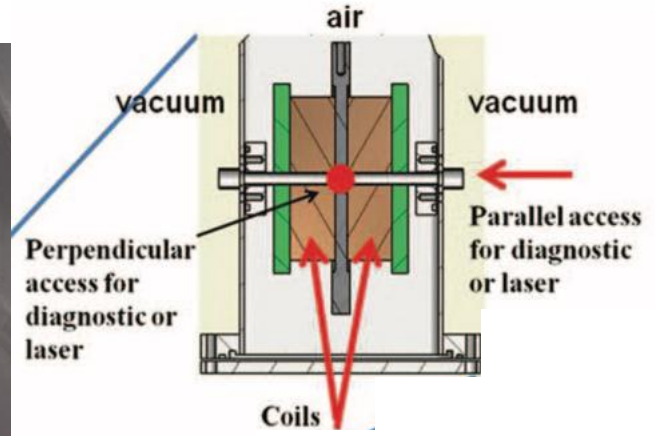
Concept= distord the lines of an existing guide-field



1e13 W/cm^2, 5 ns, 1 mm diameter averagely, 20 um per speckle

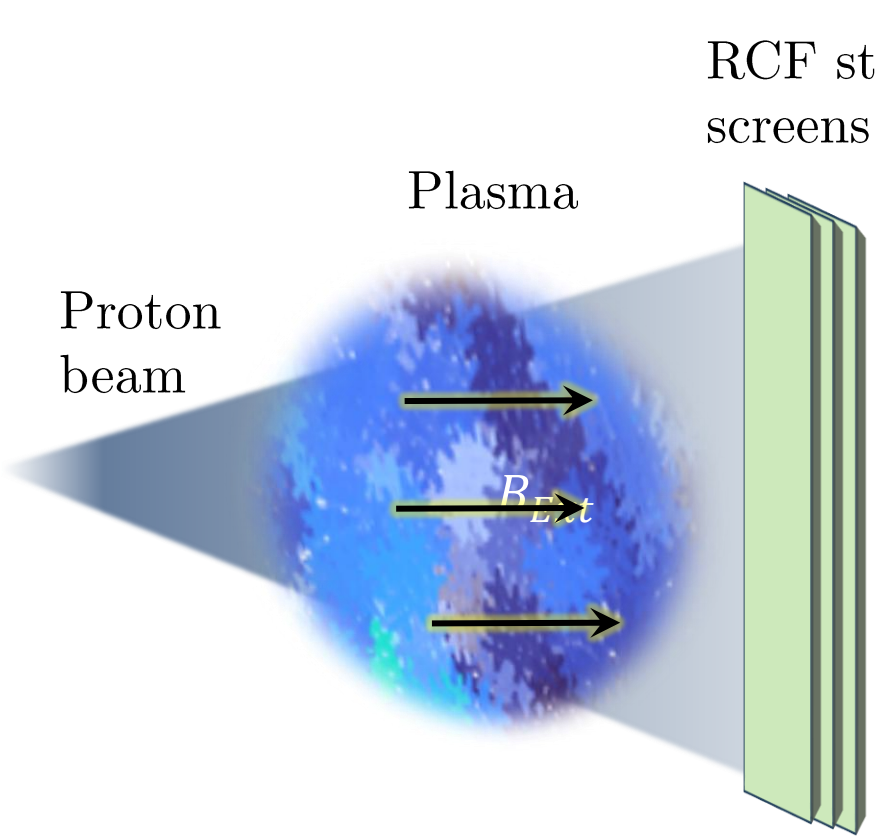
Relies on external, large-volume magnetization device

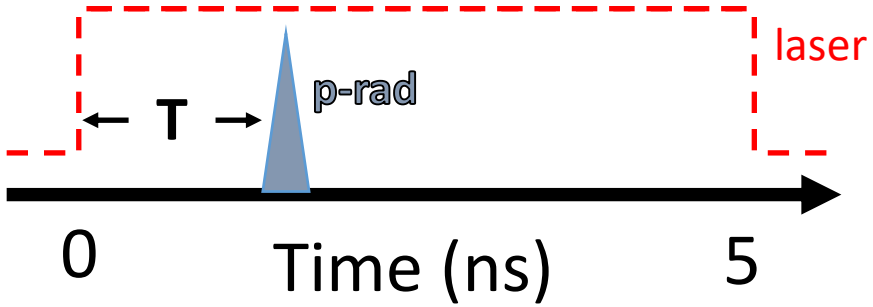




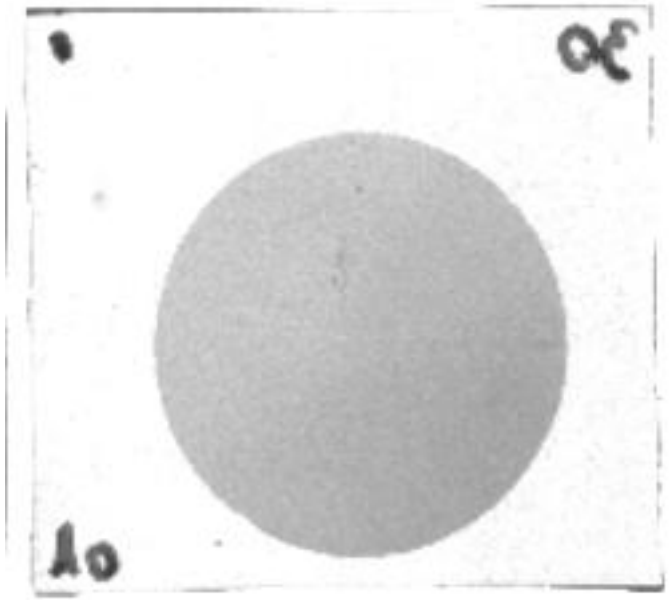
[B. Albertazzi et al., Rev. Sci. Inst. 84, 043505 (2013)]

Characterisation of the B-field disturbance



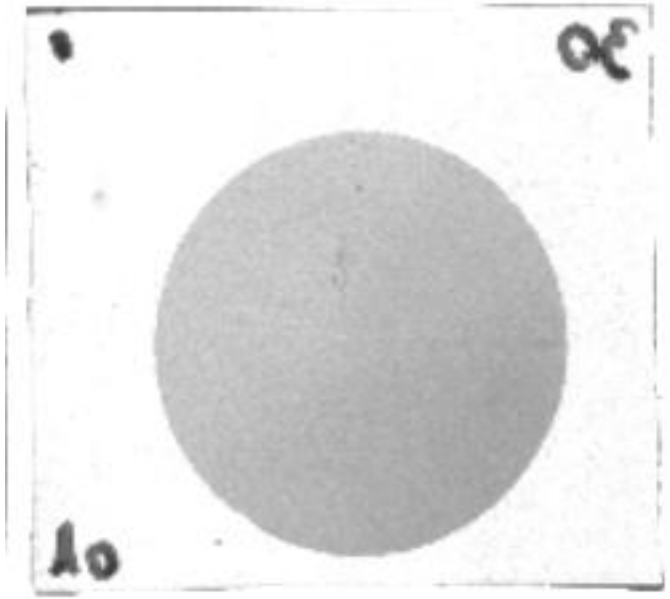


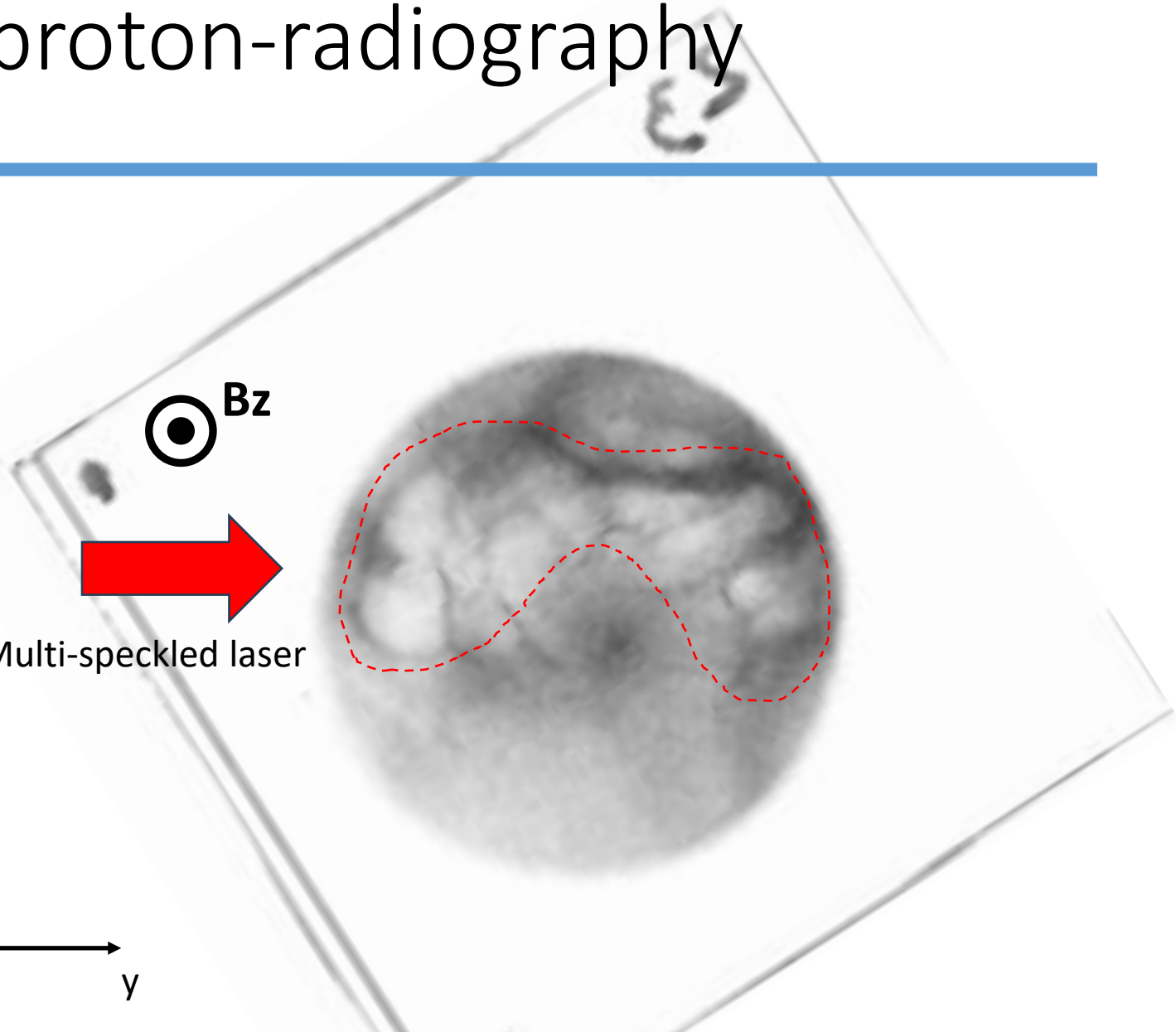
w/o laser, or w/o B-field



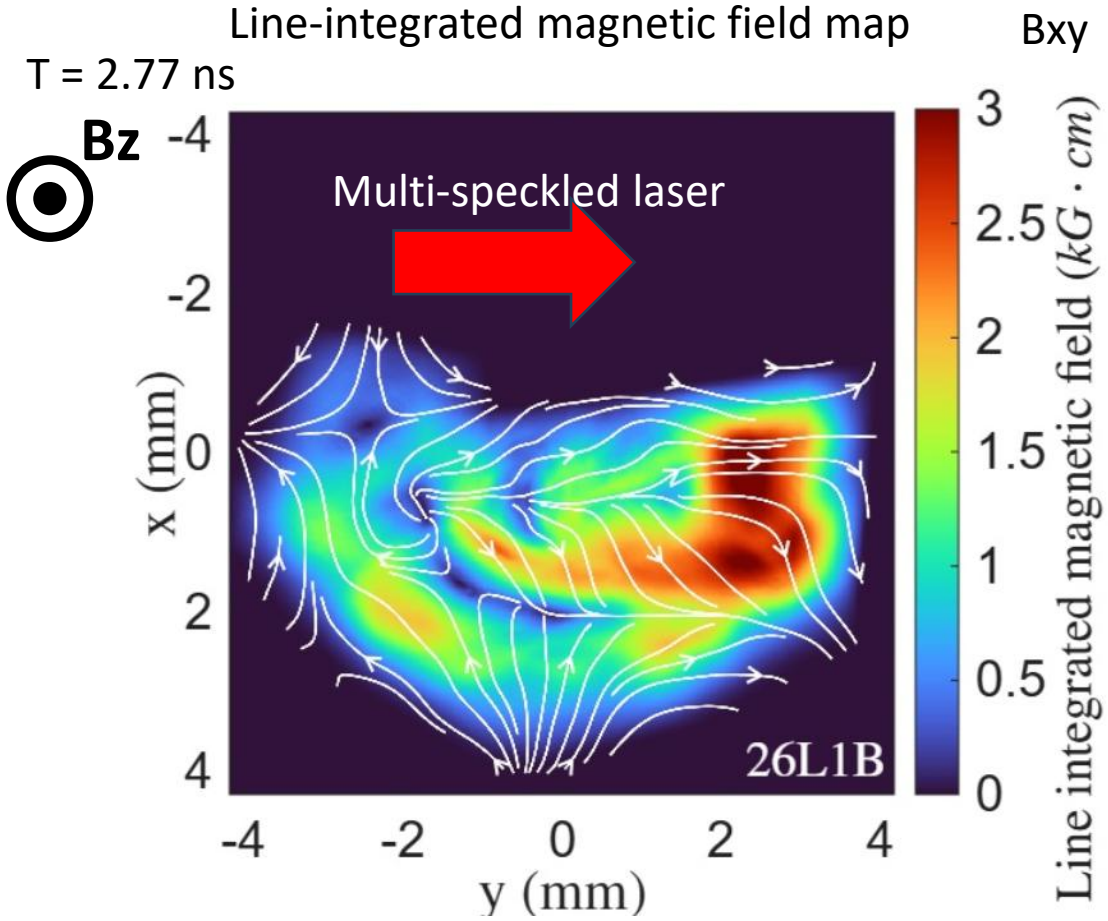
Characterisation of the B-field disturbance using proton-radiography

w/o laser, or w/o B-field





Quantitative characterization aligns with solar wind turbulence

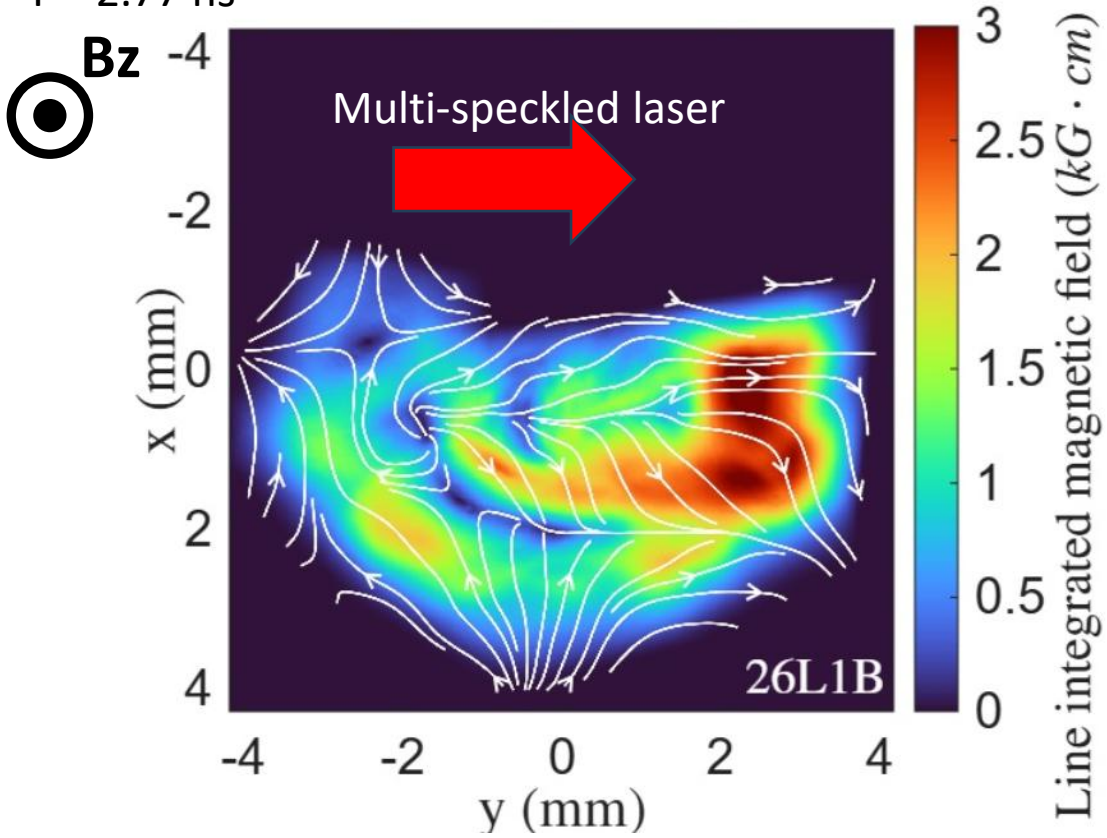


Quantitative characterization aligns with solar wind turbulence

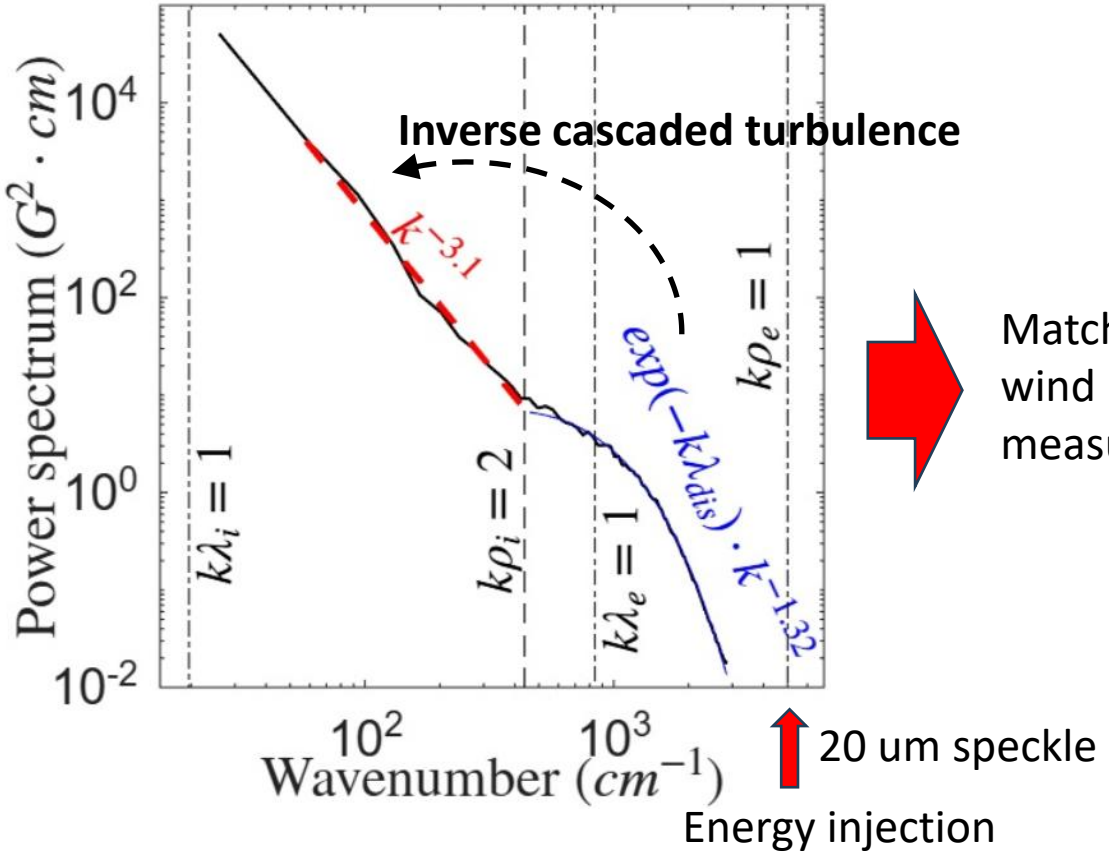
Line-integrated magnetic field map

Bxy

T = 2.77 ns



Magnetic field fluctuations spectrum



Matches solar wind measurements

Temporal dynamics of the analyzed B-field maps (B_{xy}) using the PROBLEM code (A. Bott)

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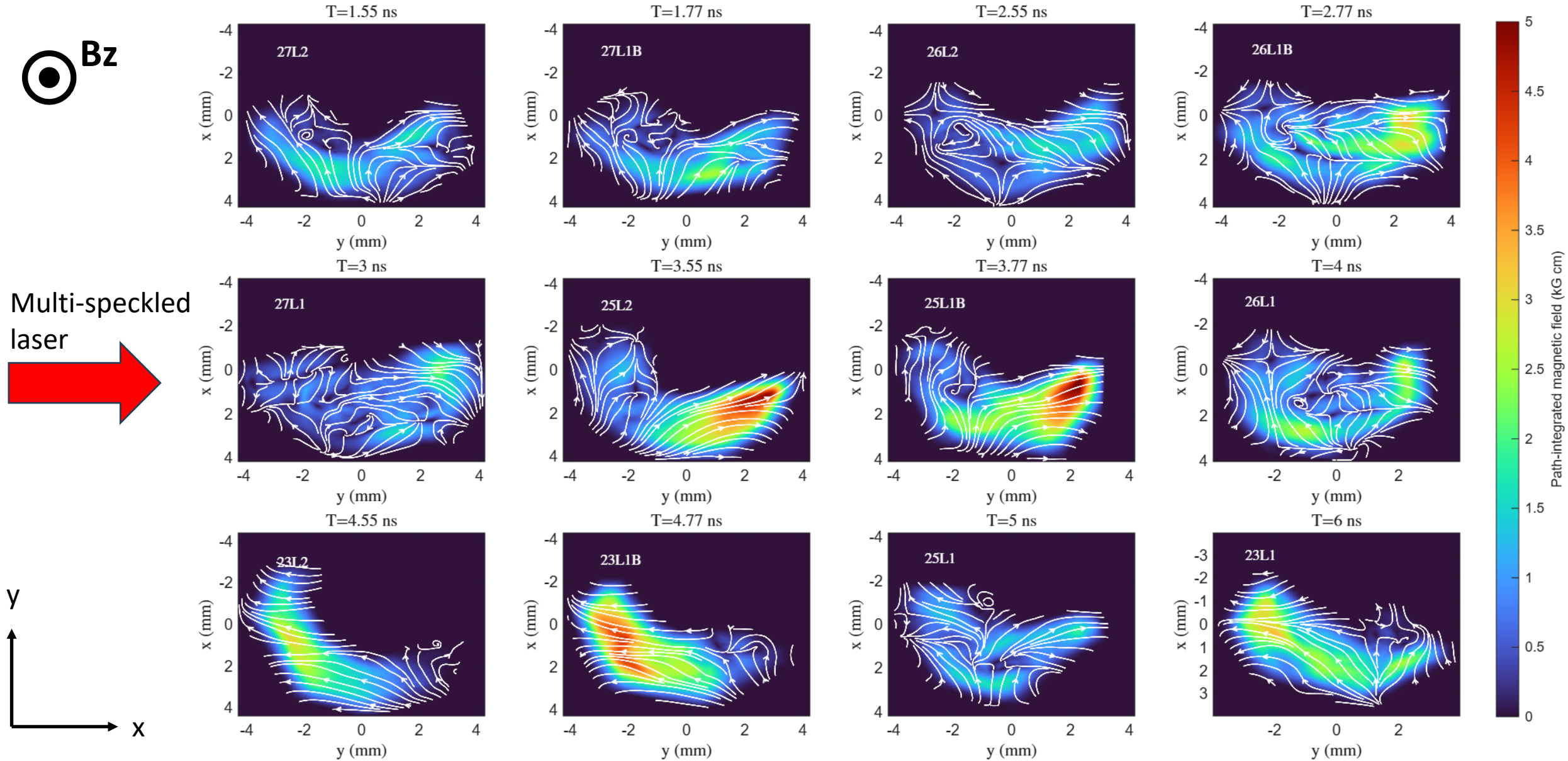
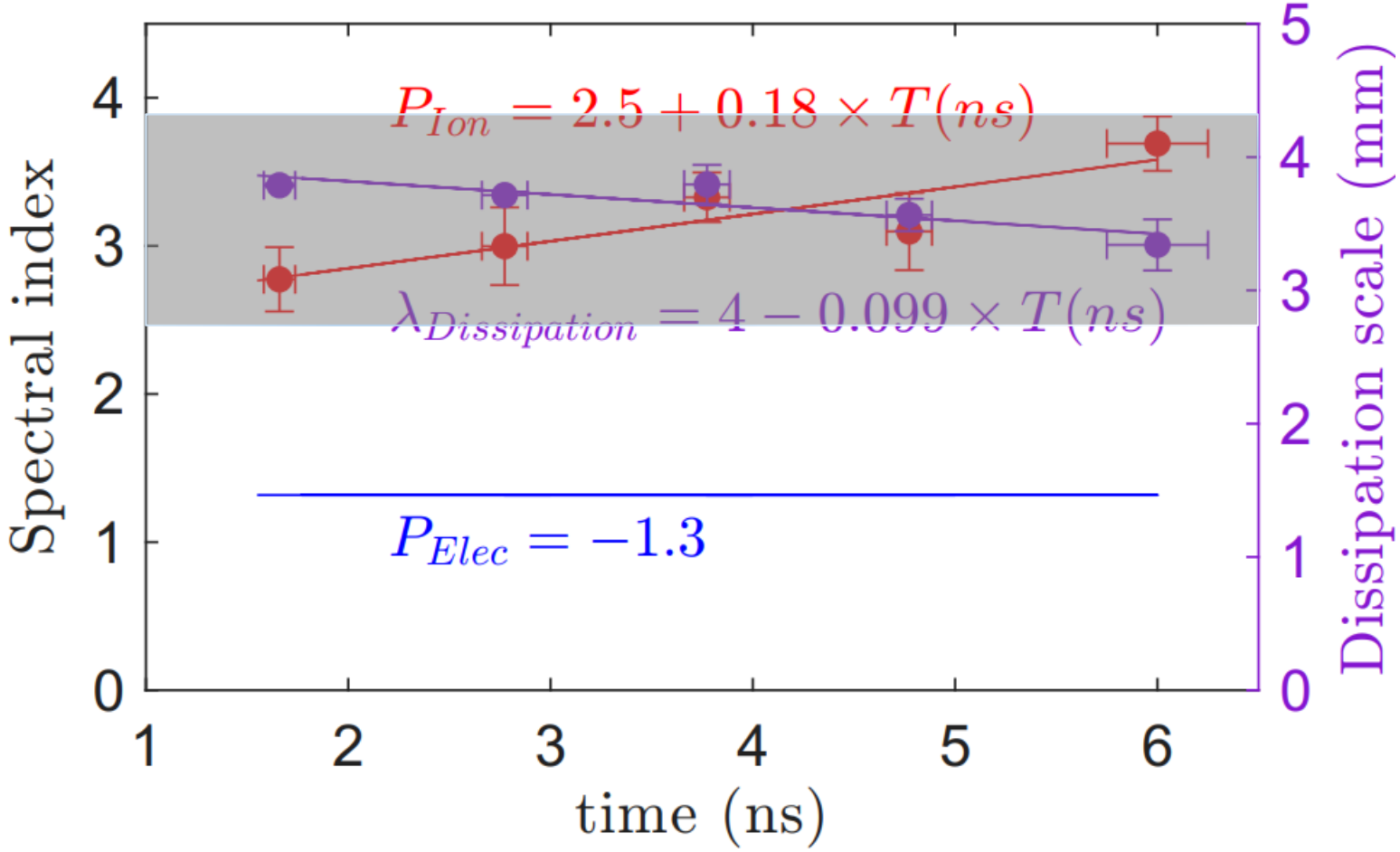
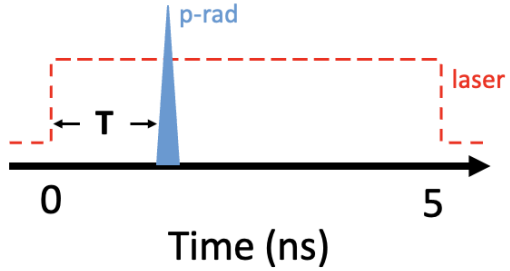


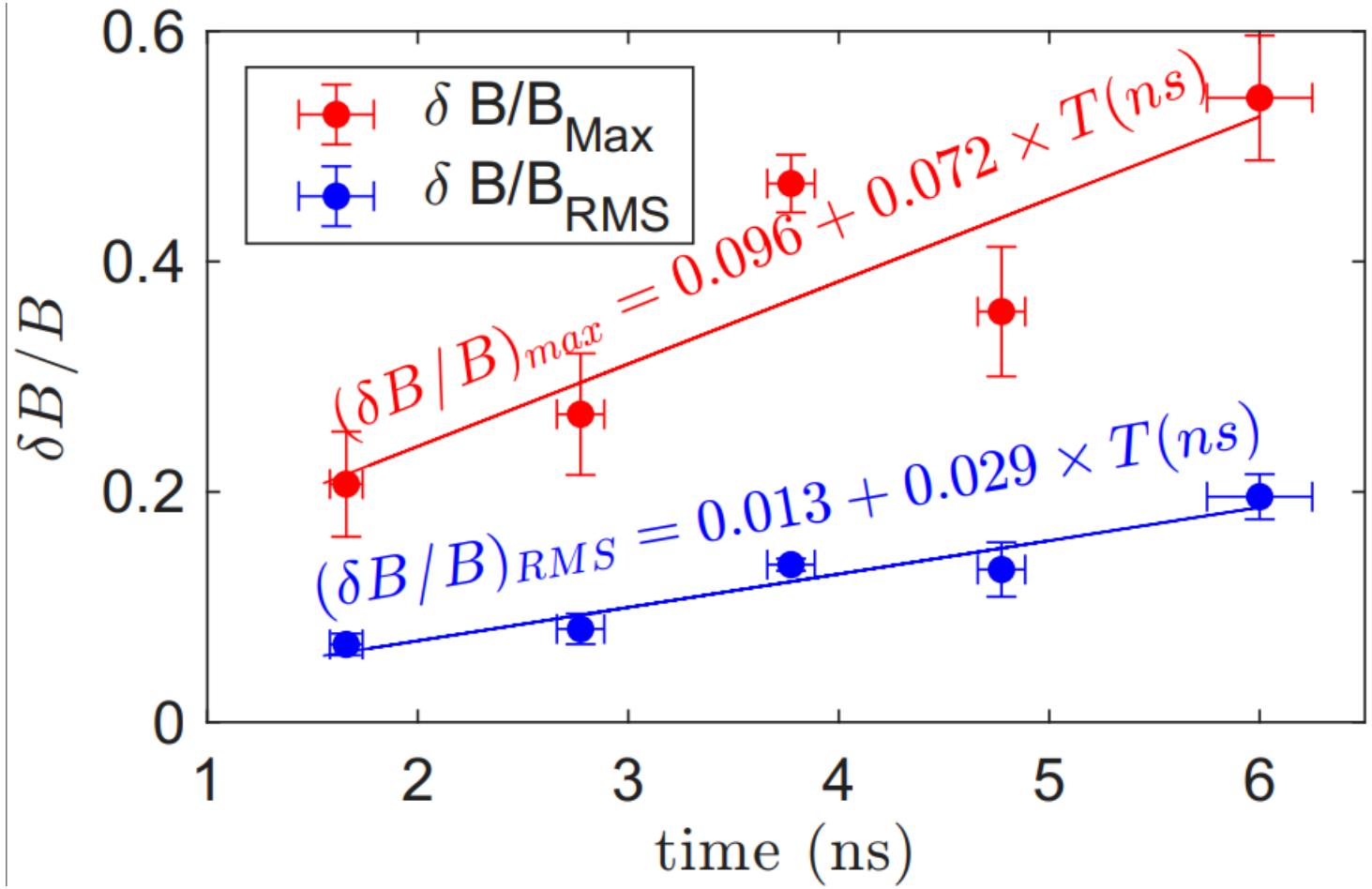
Evolution of the power spectra indexes over time

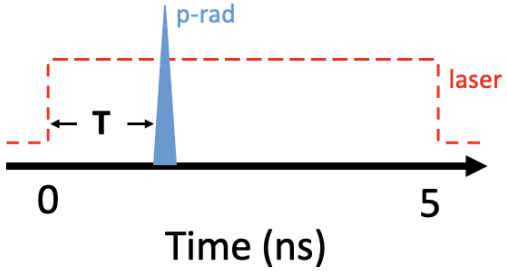




Solar wind observations
(at the Ion scale)

Evolution of the **amplitude** of the fluctuations over time

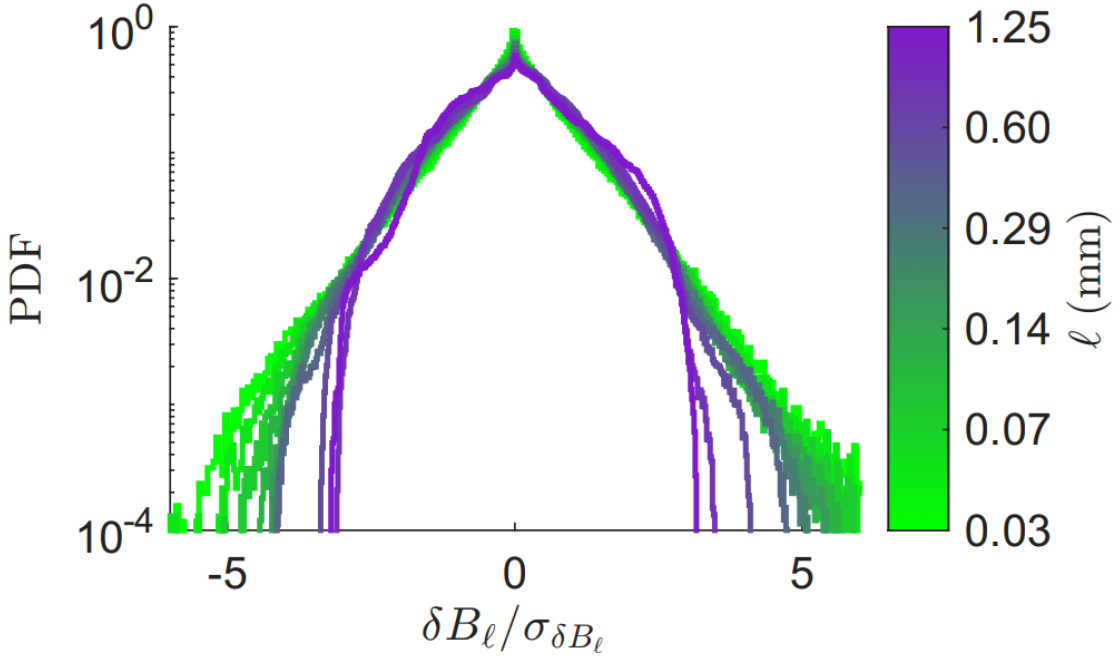




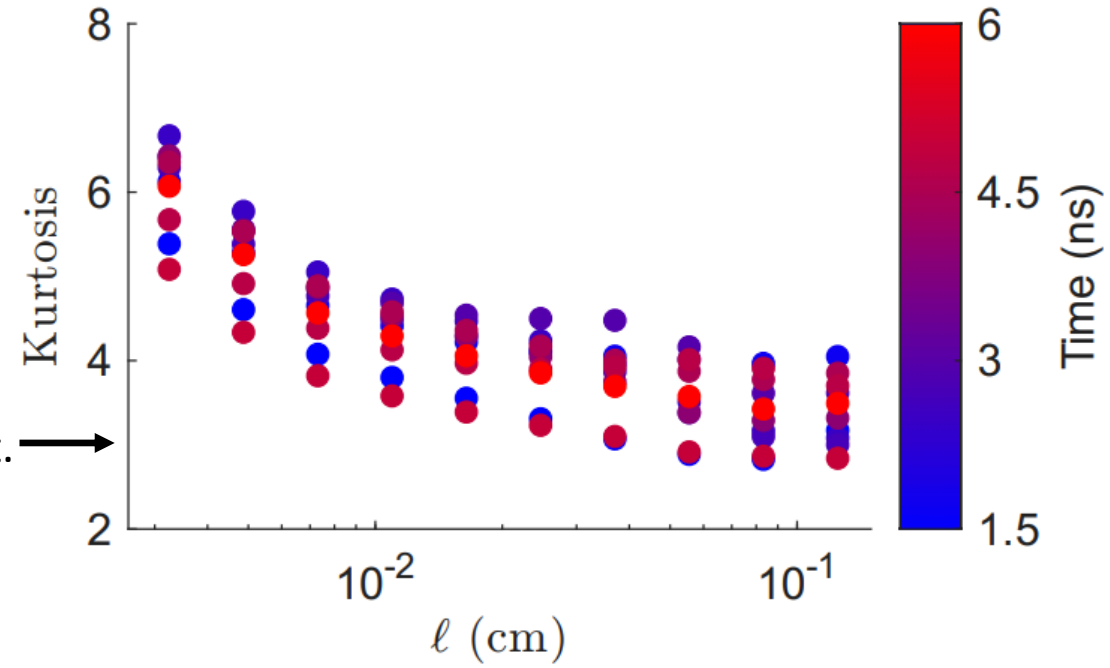
With further evidence of **intermittency** in the turbulence

$$\delta B_\ell = \left(\vec{B}(\vec{r}+\vec{\ell}) - \vec{B}(\vec{r})\right) \cdot \frac{\vec{\ell}}{\ell}$$

T = 2.77 ns



Normal dist.

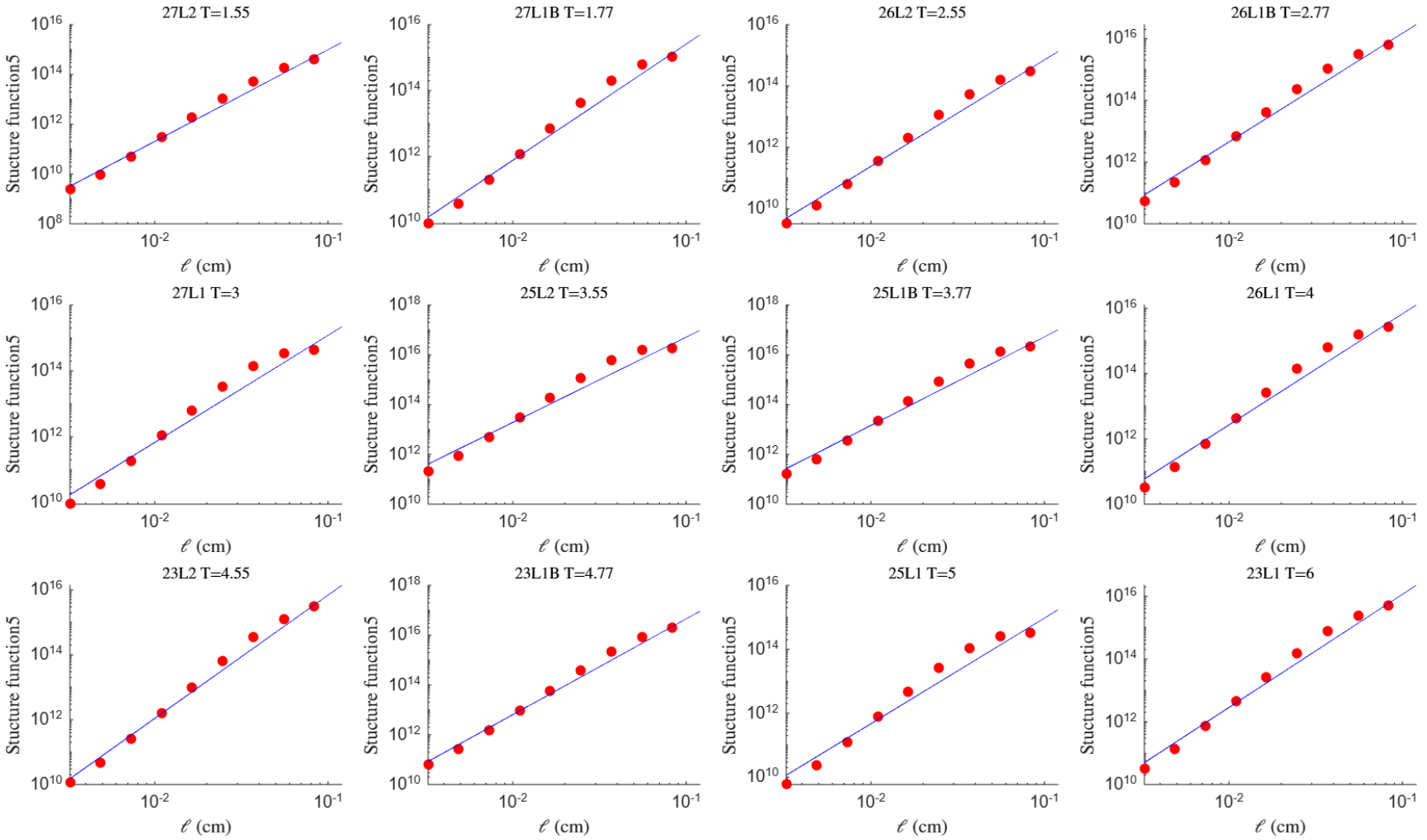


Another characterization of intermittency: structure functions

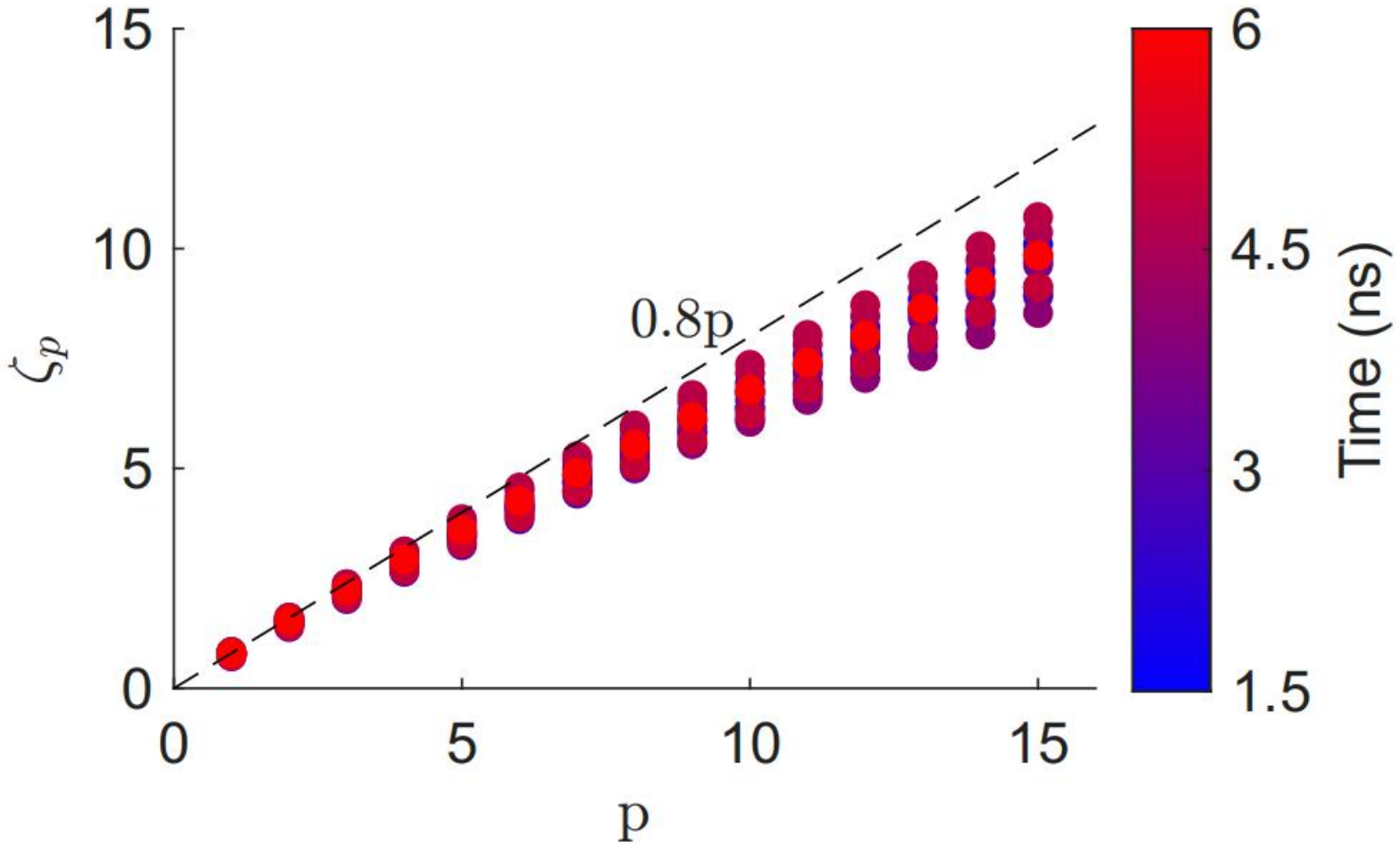
$S(p,\ell)=\text{mean}\left(\left|\delta B_\ell(\vec{\ell})\right|^p\right)$

$S(p,\ell)\sim\ell^{\zeta_p}$

Fits for p=5



Obvious deviation from uniform turbulence



Deviation from linearity

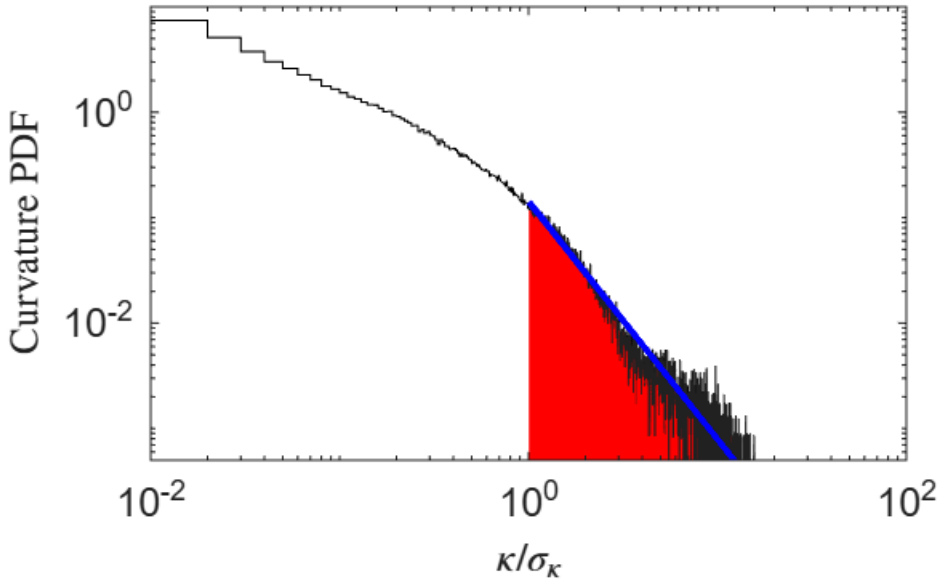
Evidence of intermittency

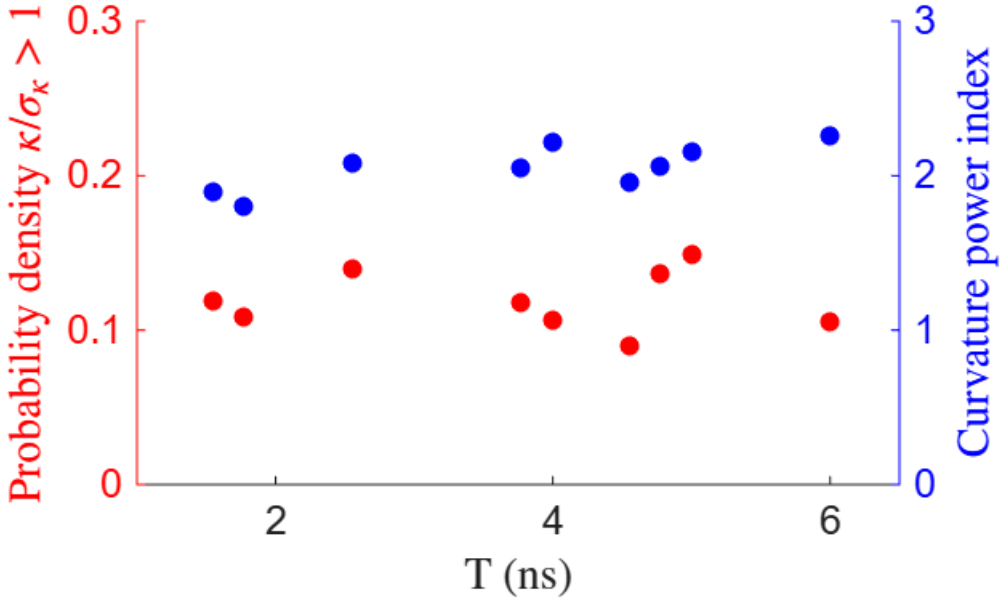
Steady state of intermittency

Magnetic field curvature in the **intermittent** turbulence

$$\vec{\kappa} = \frac{(\vec{\nabla}\times\vec{B})\times\vec{B}}{B^2} = \frac{(\vec{B}\cdot\vec{\nabla})\vec{B}}{B^2}$$

T = 2.77 ns





Summary of laboratory capabilities

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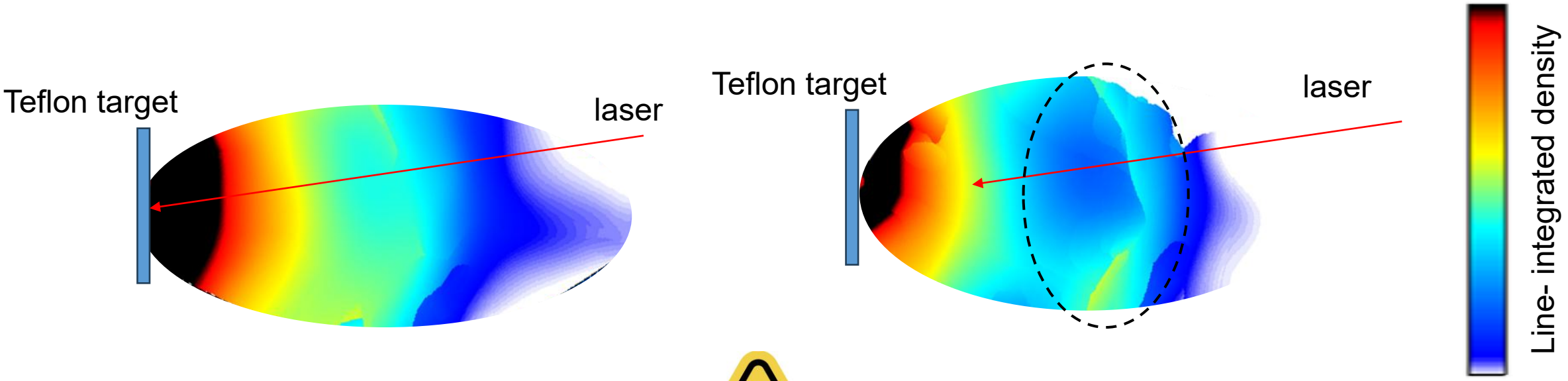
Laboratory intermittent plasma with:

- Turbulence amplitude $\frac{\delta B}{B_0} \sim 0.5$ (still growing in time)
- **Spectral index ~3** at ion scales
- Dissipation scale $\lambda_{dissipation} = 3\ mm, \frac{\lambda_{dissipation}}{\lambda_{e\ inertial}} = 3.3$
- Electron Larmor radius $\rho_e = 0.2\ mm\ \frac{\rho_e}{\lambda_{e\ inertial}} = 0.16$
- Ion Larmor radius $\rho_i = 4.5\ mm\ \frac{\rho_i}{\lambda_{i\ inertial}} = 0.09$
- Electron inertial length $\lambda_{e\ inertial} = 1.2\ mm$
- Ion inertial length $\lambda_{i\ inertial} = 50.9\ mm$
- **System size** $= 10\ mm$

When sending a shock through the turbulent zone, density characterization shows strong impact of added magnetic turbulence

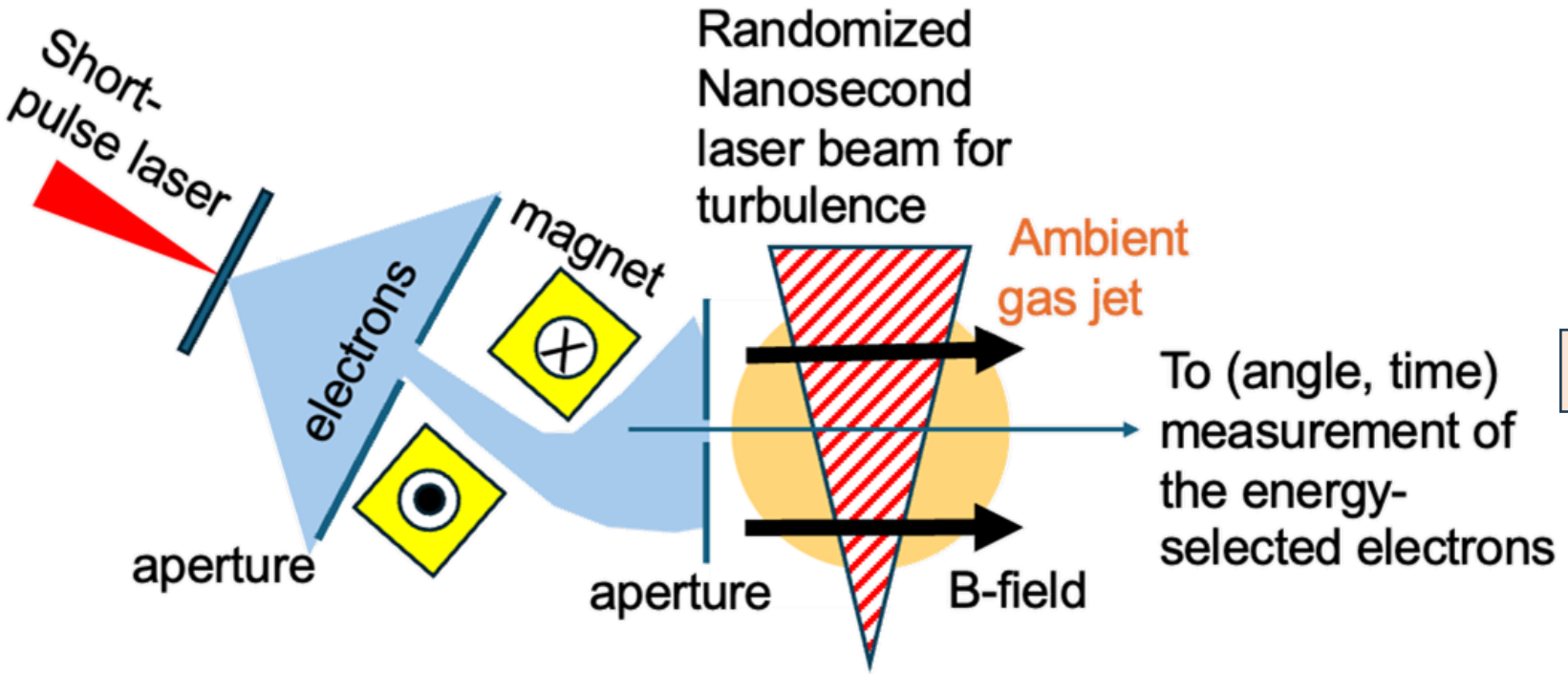
Experimental measurements
(optical interferometry)



Mach number: $M \sim 3.1$

Ongoing analysis

Cosmic-ray transport via laser-driven magnetic turbulence



Measurements of: **diffusion time** and **perpendicular diffusion**

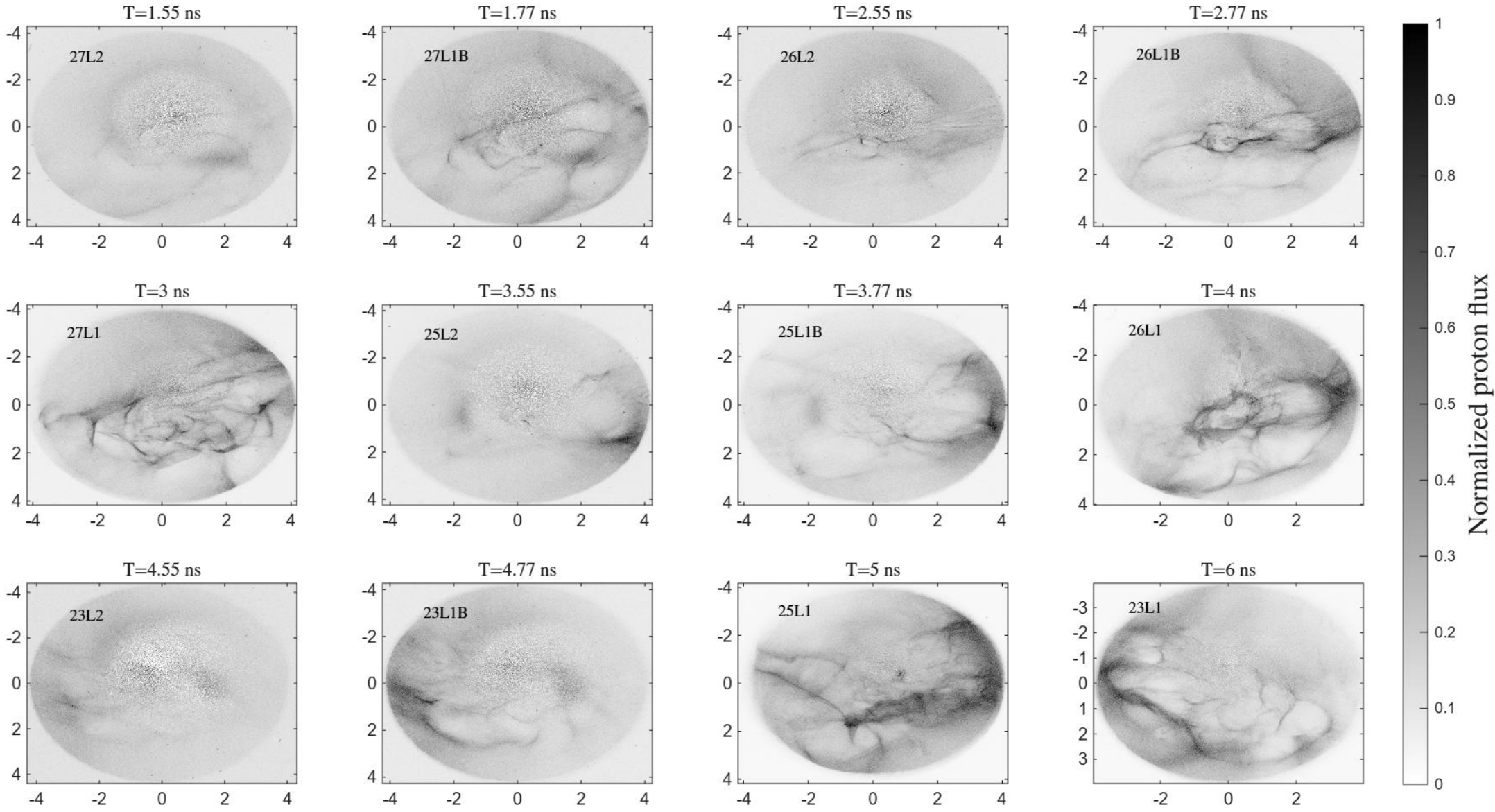
Ongoing experiment

Conclusion & Prospects

- We developed a new way of generating large volumes of magnetized turbulence
- It quantitatively matches space plasma turbulence (power-law & intermittency)
- Future:
  - Compare with simulations using Athena
  - Extend the heating to test saturation, or different scales of injection
  - Model shock interaction with turbulence in the ambient
  - Model cosmic-ray transport

Temporal dynamics

Multi-speckled laser



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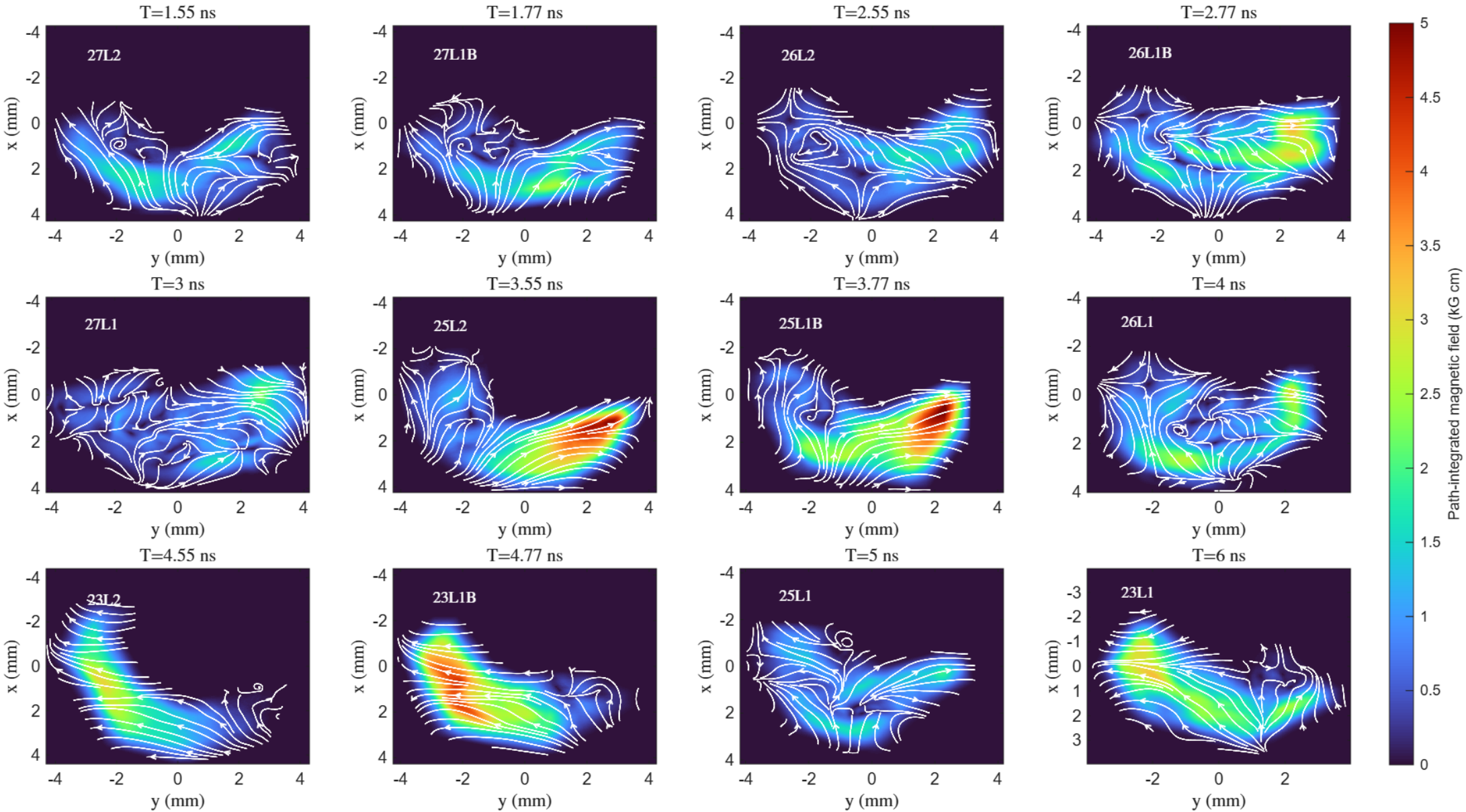

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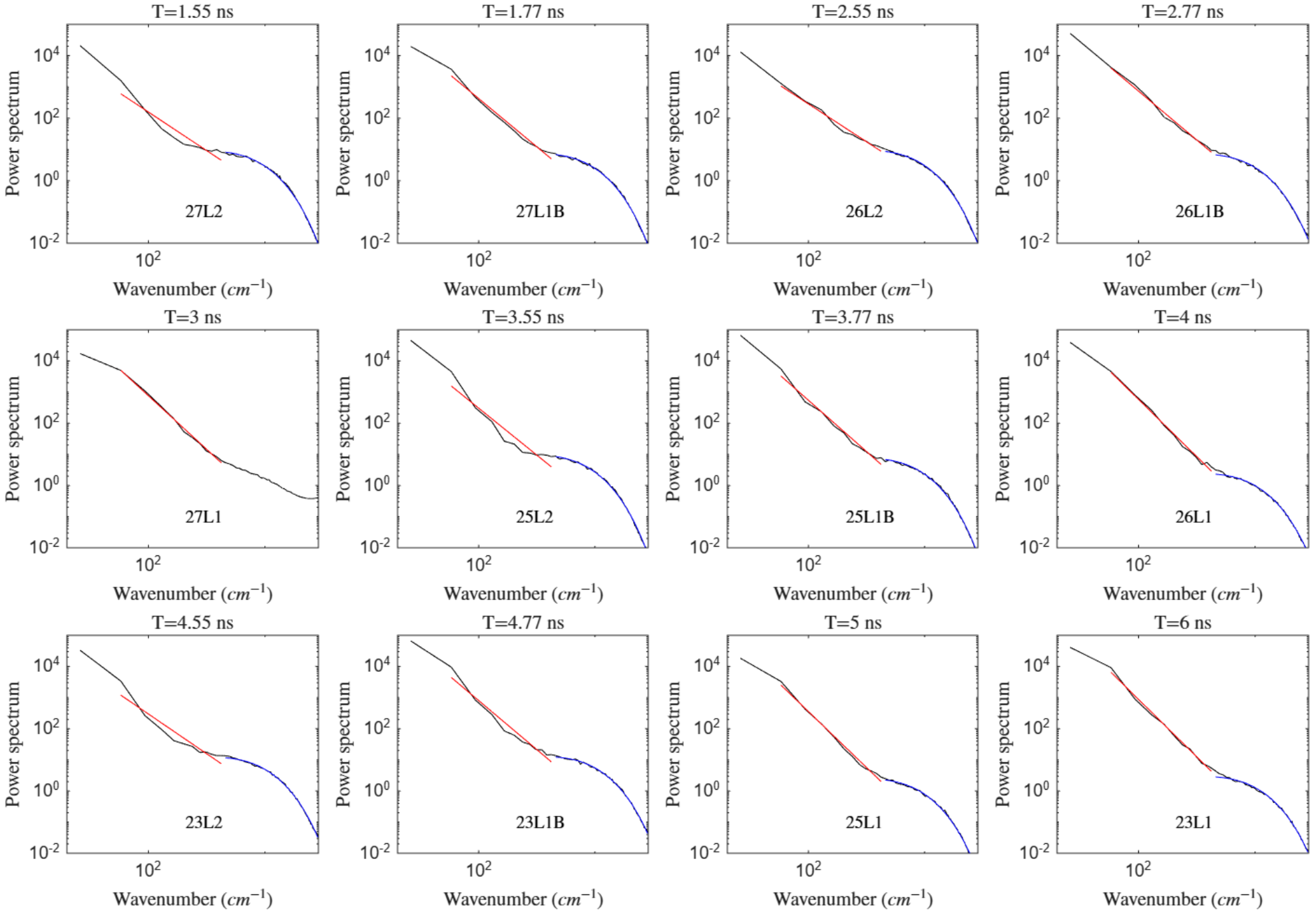
Very stable & reproducible over time



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Density measurement

Multi-speckled laser