Particle acceleration in shocks: from simulations to observations via laboratory experiments

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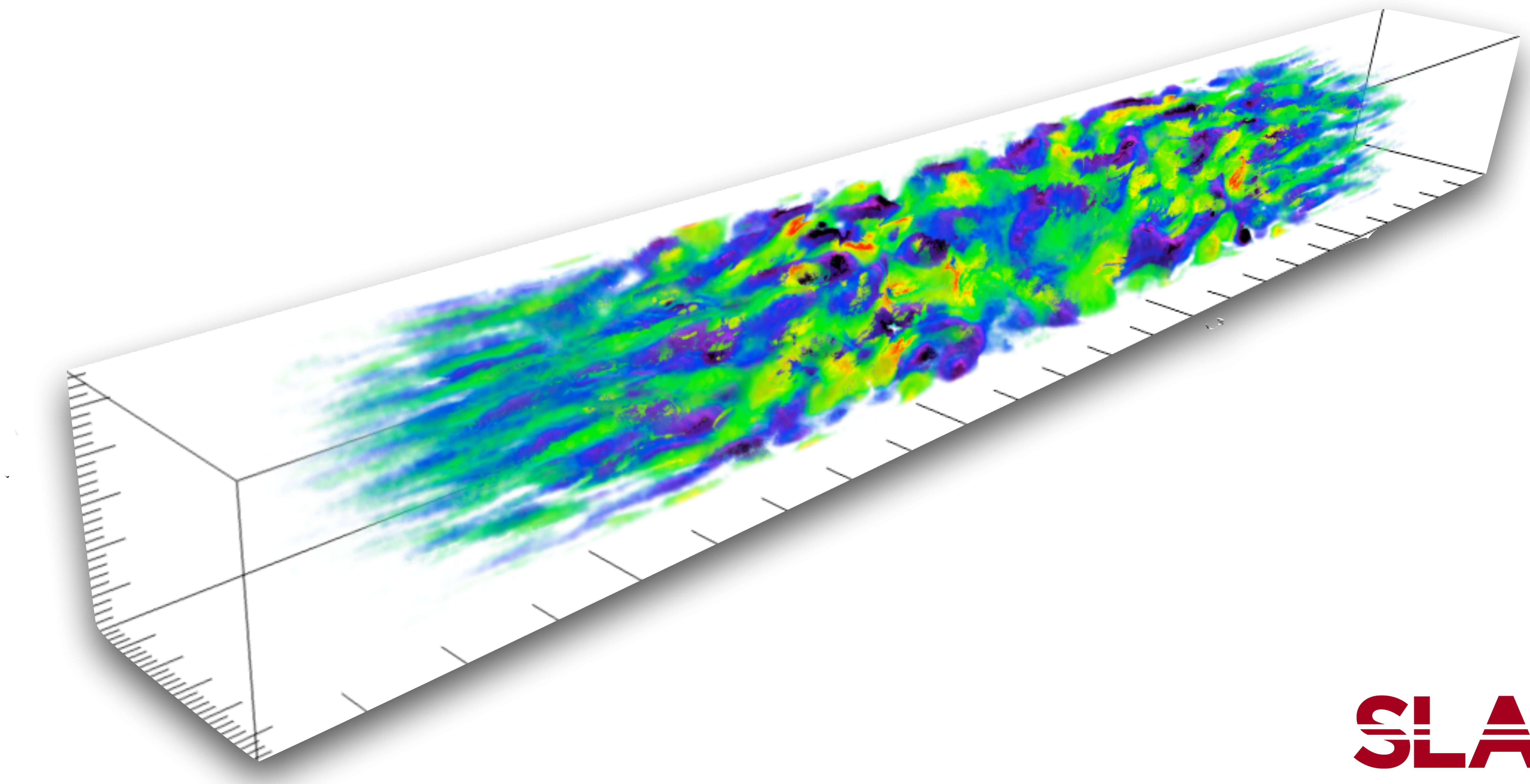

U.S. DEPARTMENT OF ENERGY
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SLAC NATIONAL ACCELERATOR LABORATORY

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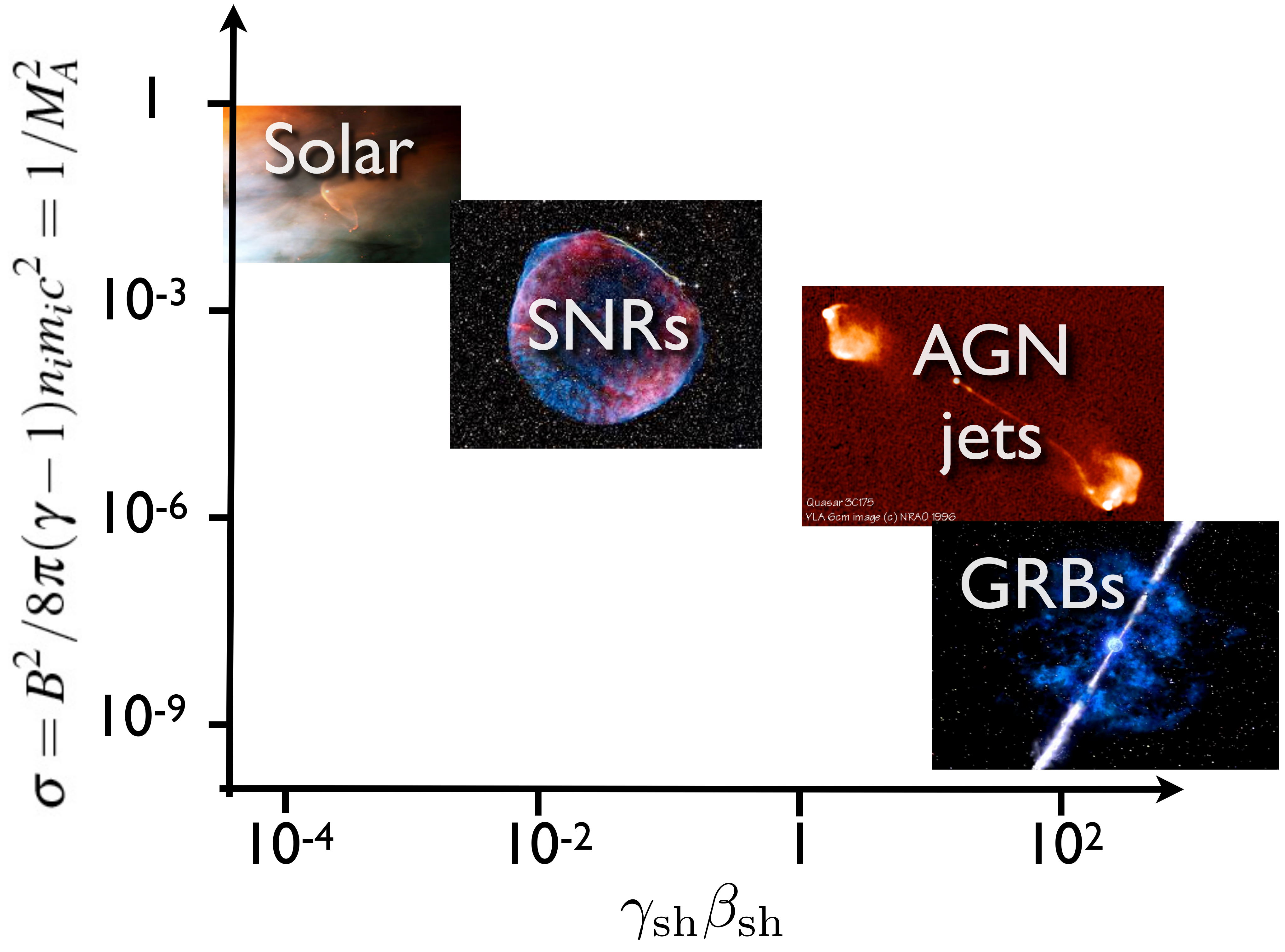
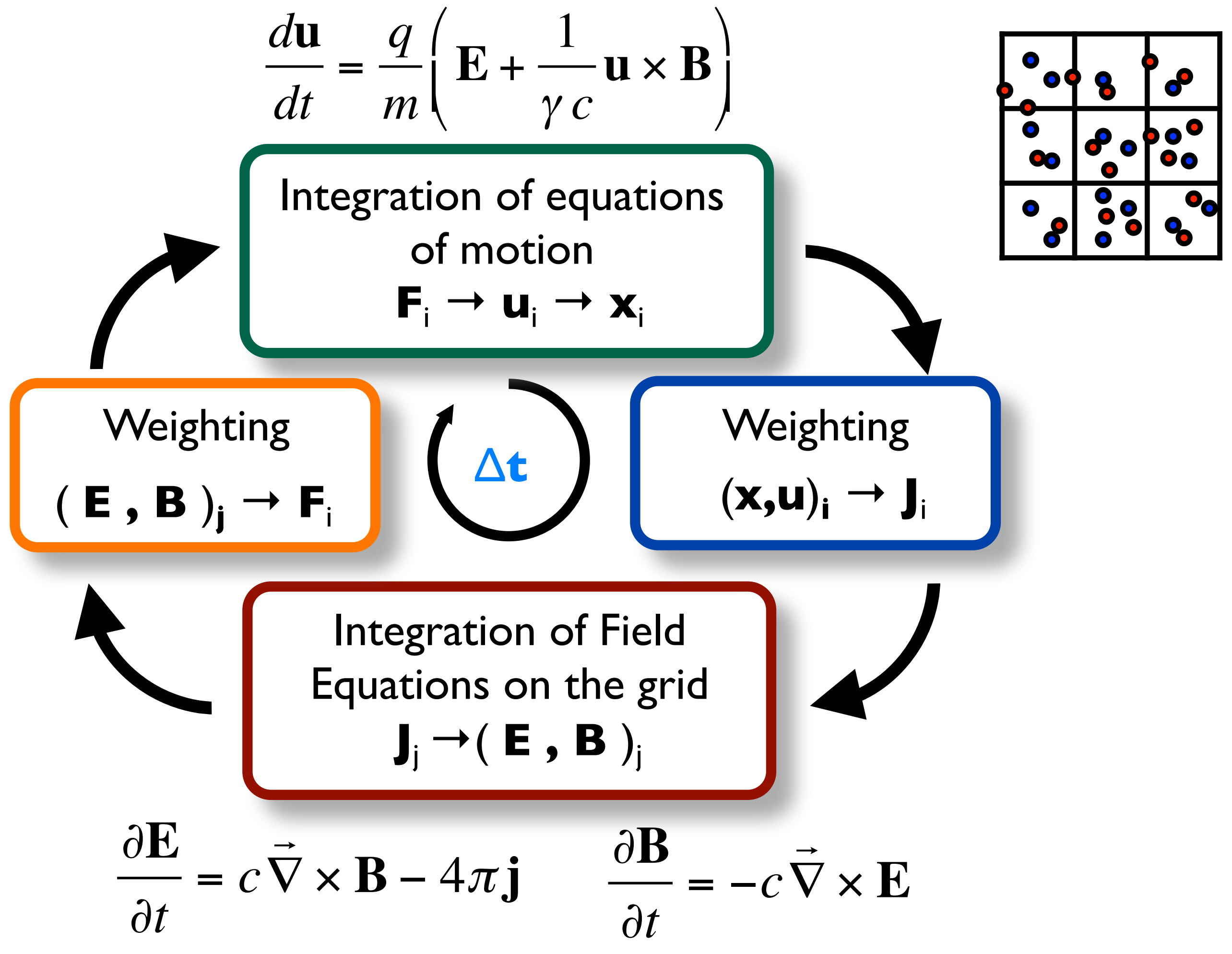
Shock microphysics is important to understand particle acceleration

- Astrophysical shocks are efficient accelerators of both electrons and protons (cosmic rays)
- Theory of diffusive shock acceleration (DSA) is well established*
- However, injection of particles at the shock and magnetic field amplification is not fully understood and impact overall efficiency and maximum energy
- Observations (in particular, multi-wavelength) provide critical constrains on models for acceleration but shock microphysics is still not resolved
- Spacecraft measurements provide important characterization of microphysics but mostly for low Mach # shocks (M_{sh} < 10)



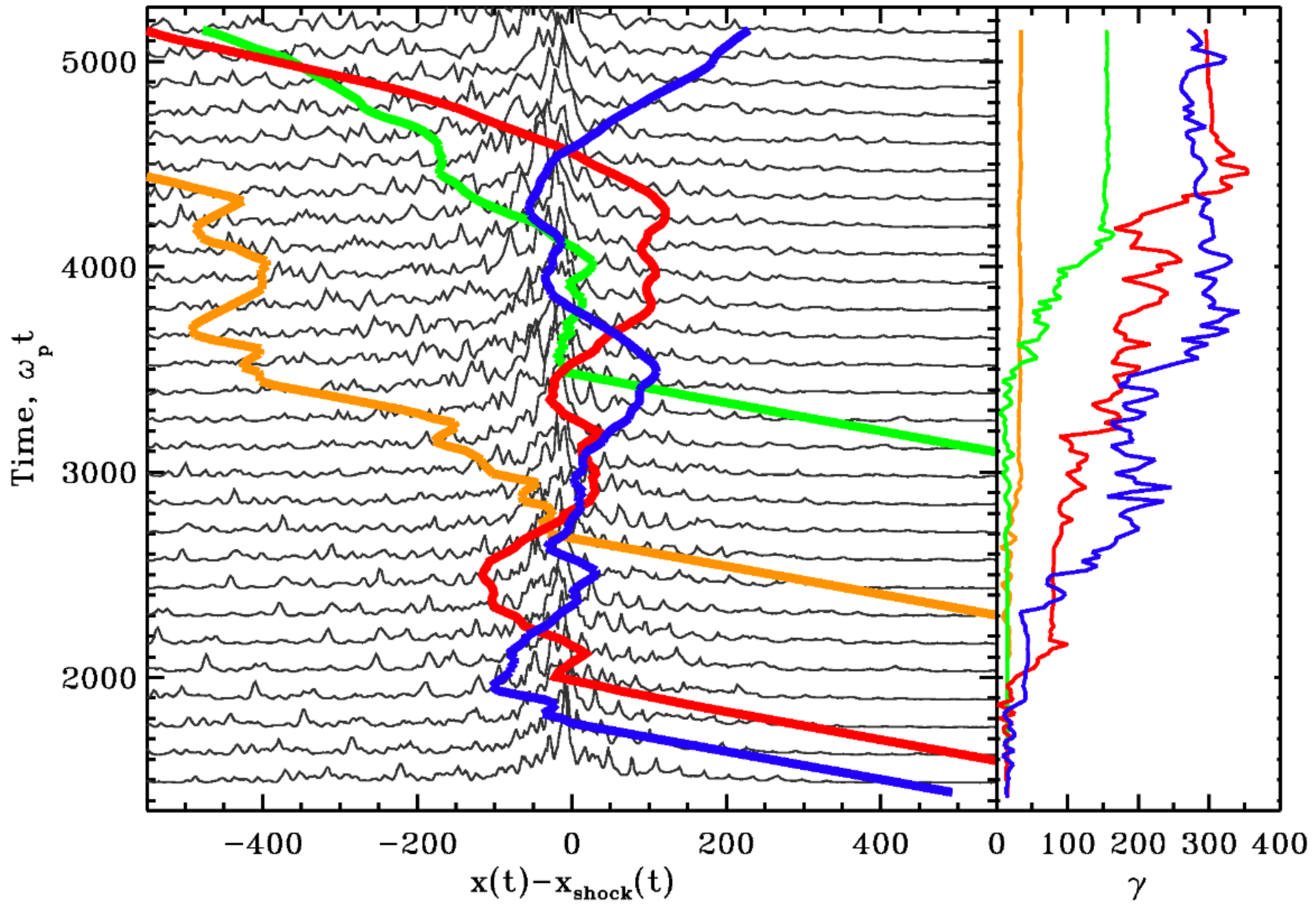
* Krymskii 1977, Axford, Leer, Skadron 1977, Bell 1978, Blandford & Ostriker 1978, Drury 1983

Kinetic simulations are important to study injection physics at the shock

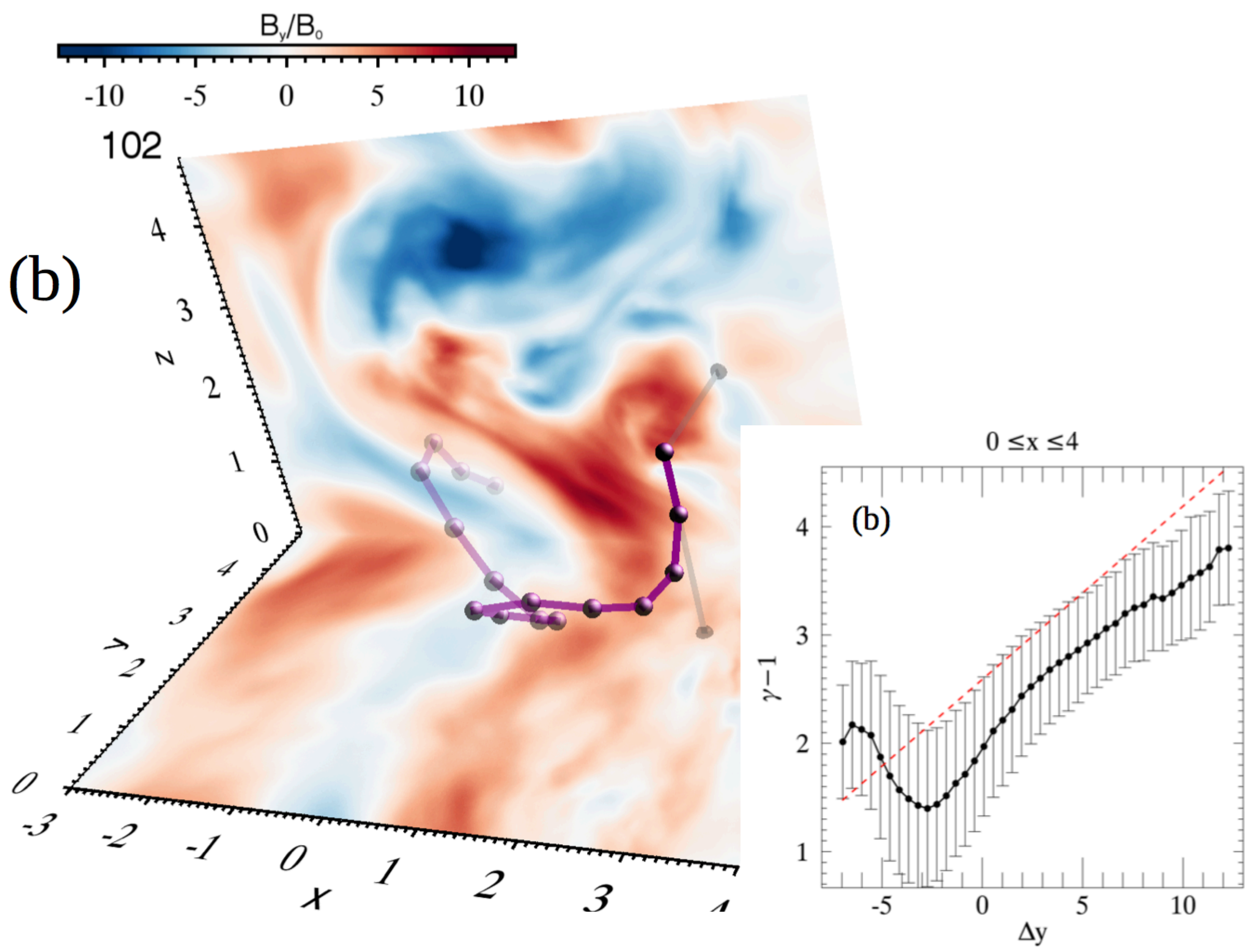


- Particle-in-cell (PIC) simulations have been established over the last decades as critical tool to study acceleration in electromagnetic shocks
- For high-M_A shocks role of ambient field might be reduced and self-generated waves/magnetic turbulence (Weibel, Buneman, Bell…) control injection at shock structure

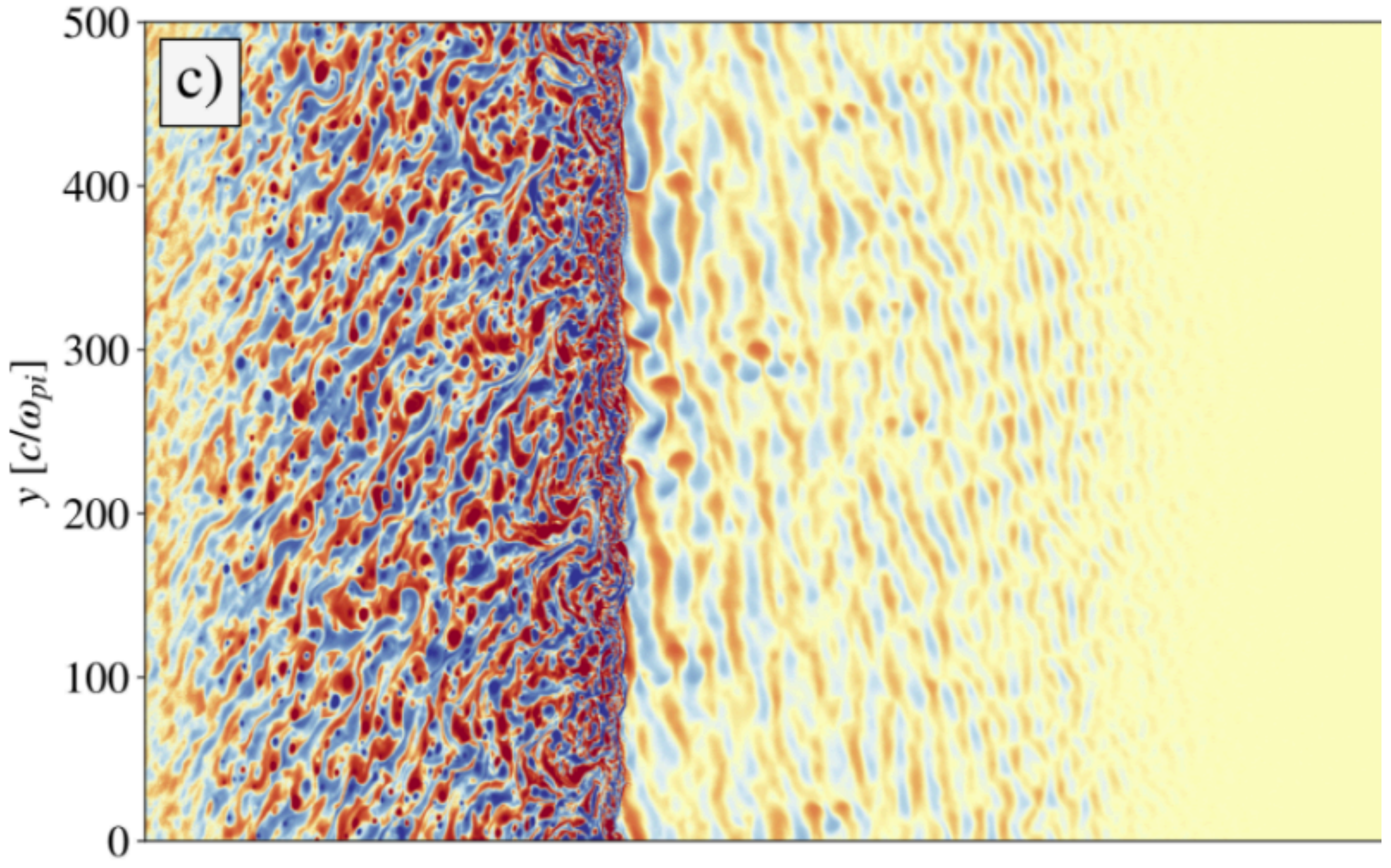
Acceleration in relativistic Weibel shocks [1]



Stochastic SDA in Weibel turbulence in perpendicular shocks [2]



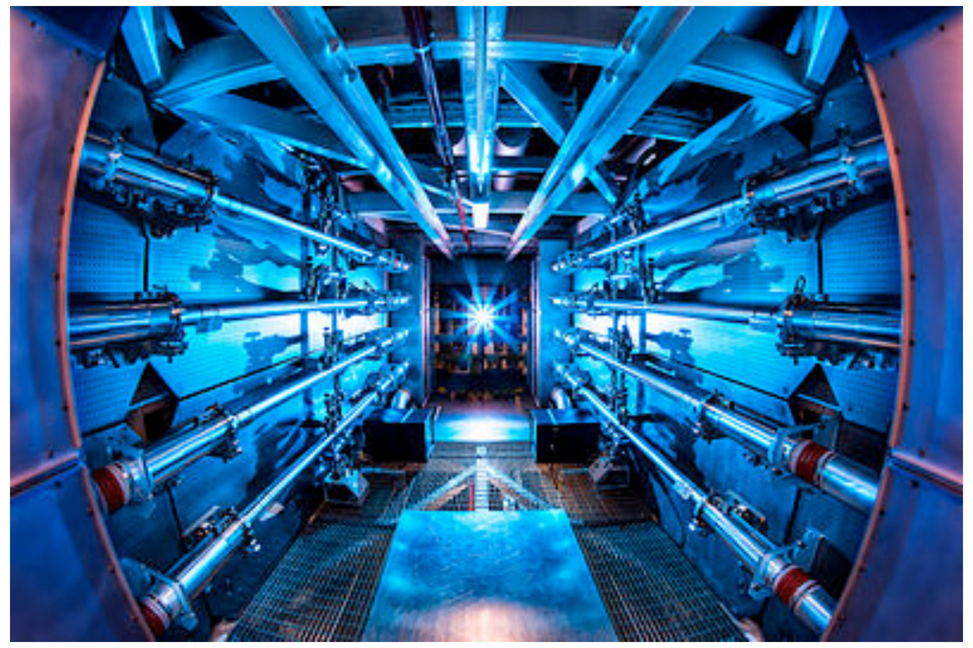
Injection by Bell waves in parallel shocks [3]



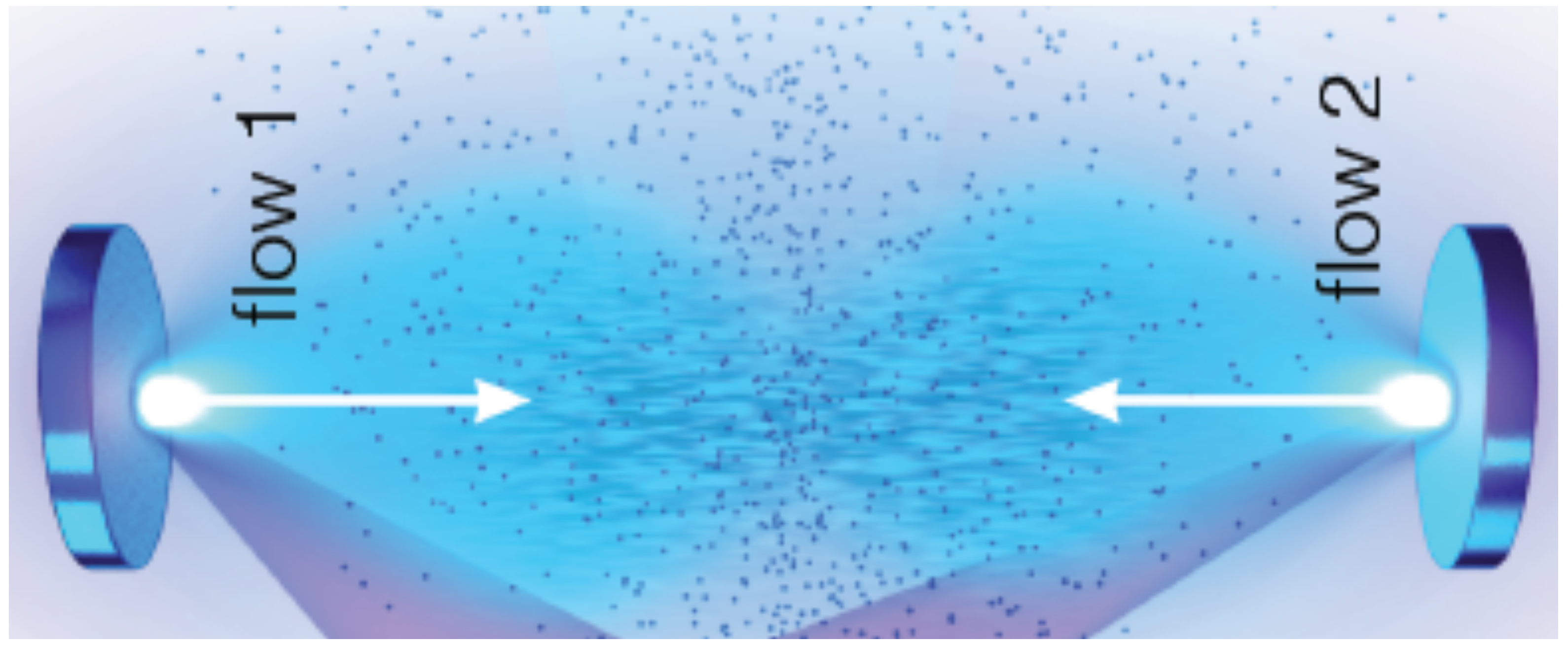
[1] Spitkovsky ApJL 2008; [2] Matsumoto et al. PRL 2017; [3] P. Crumley et al., MNRAS 2019

Laboratory experiments can complement studies of particle acceleration

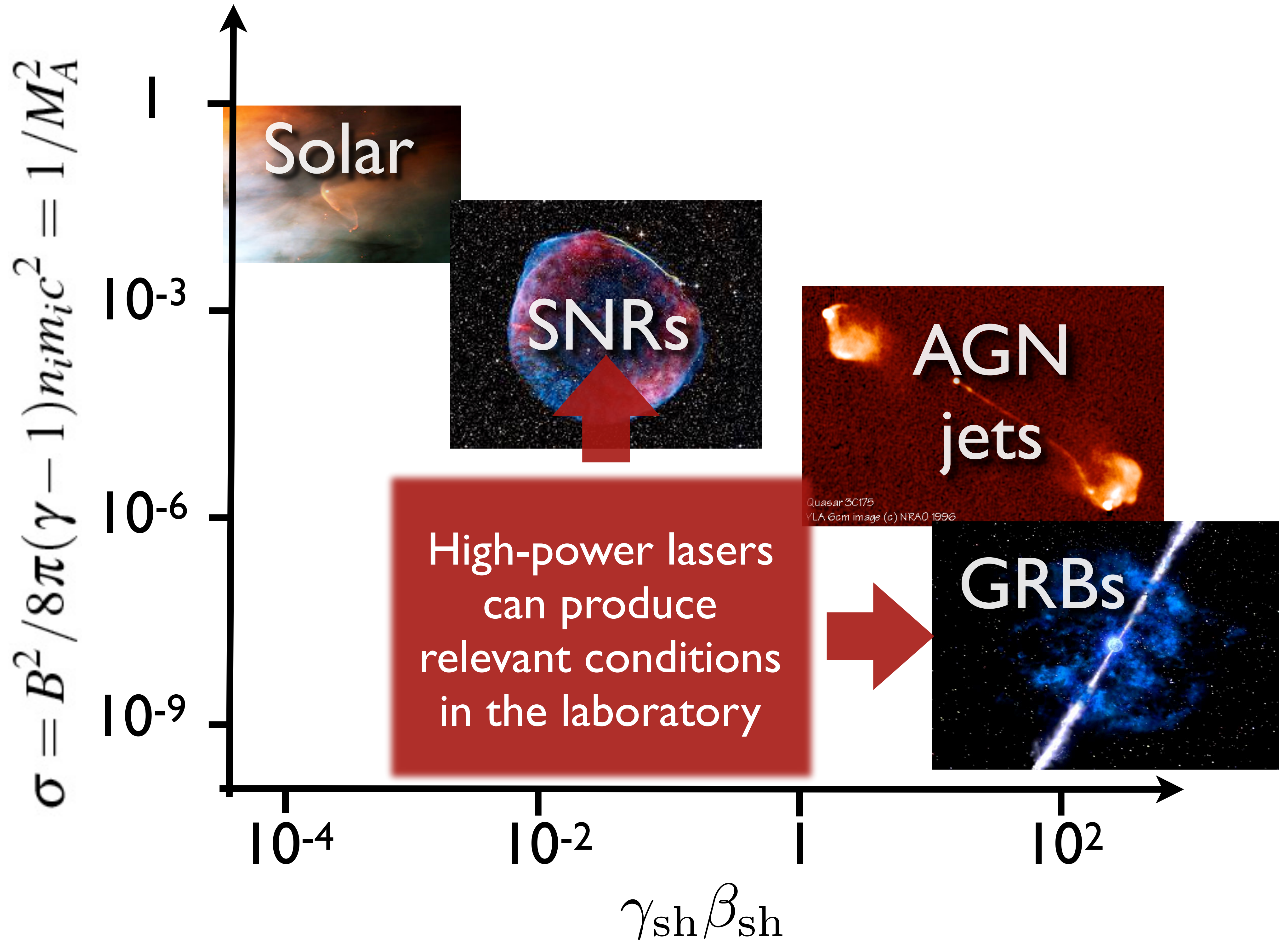
- Significant experimental studies of ion-acoustic shocks since 60s
- Only now it is becoming possible to drive energetic enough plasma flows with lasers to produce electromagnetic shocks (L_{system} > 100 c/ω_{pi} and λ_{mfp} >> L_{system})
- Controlled study of shock structure and particle acceleration for different plasma conditions (including high M_{sh})
- Benchmark numerical tools that are being used to develop injection models



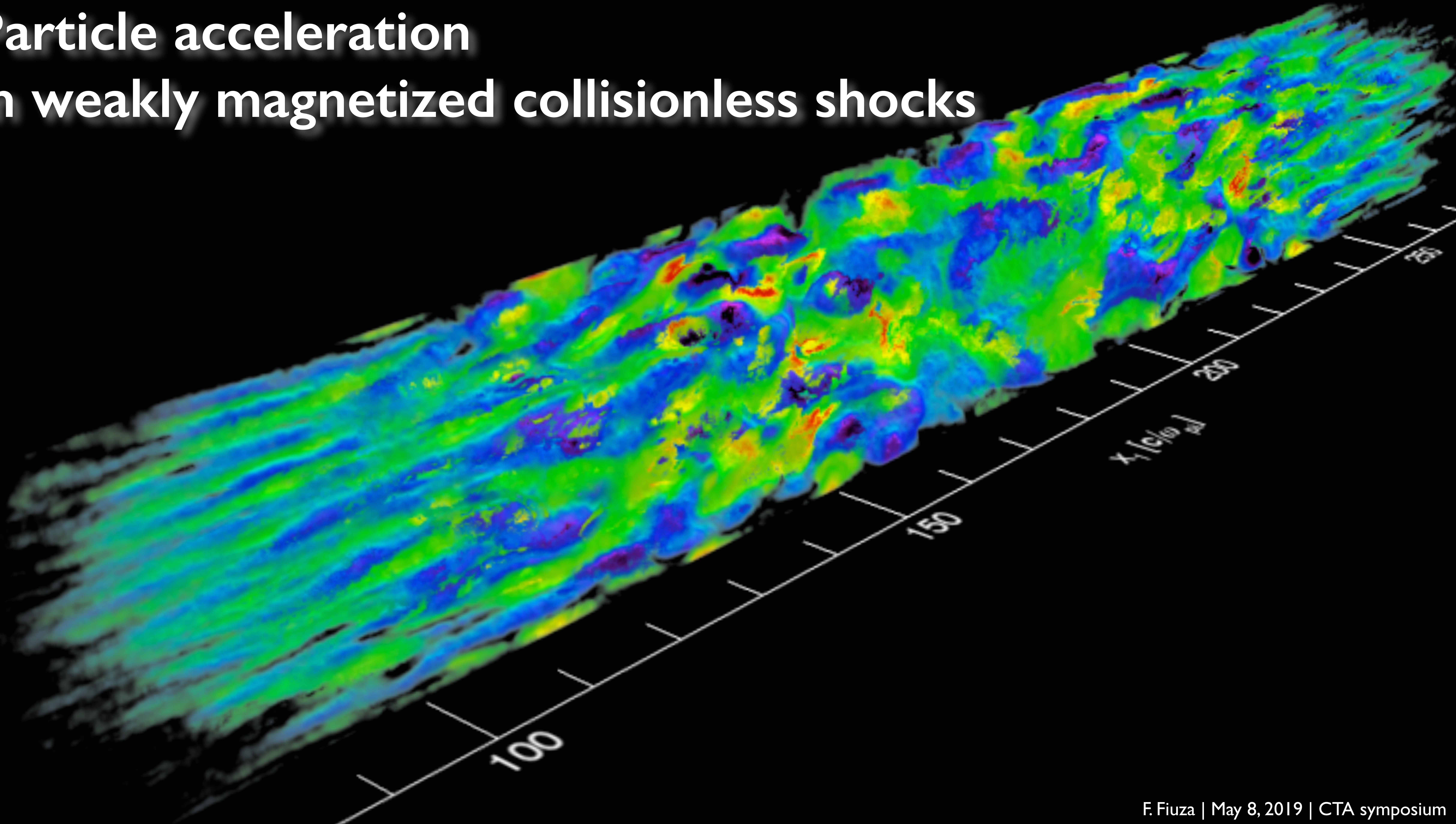
National Ignition Facility



Cartoon of laser-driven counter-streaming plasma experiments

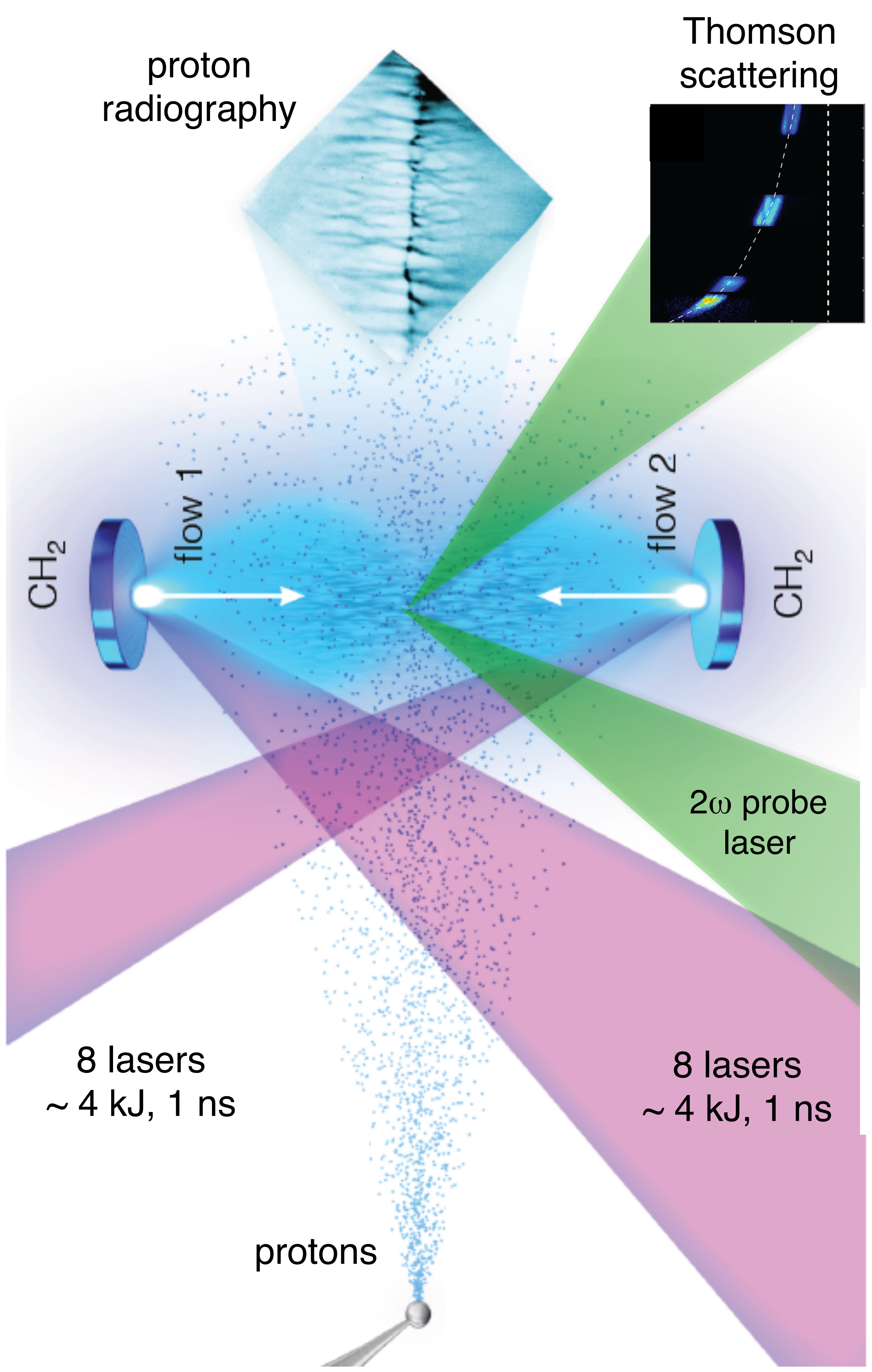


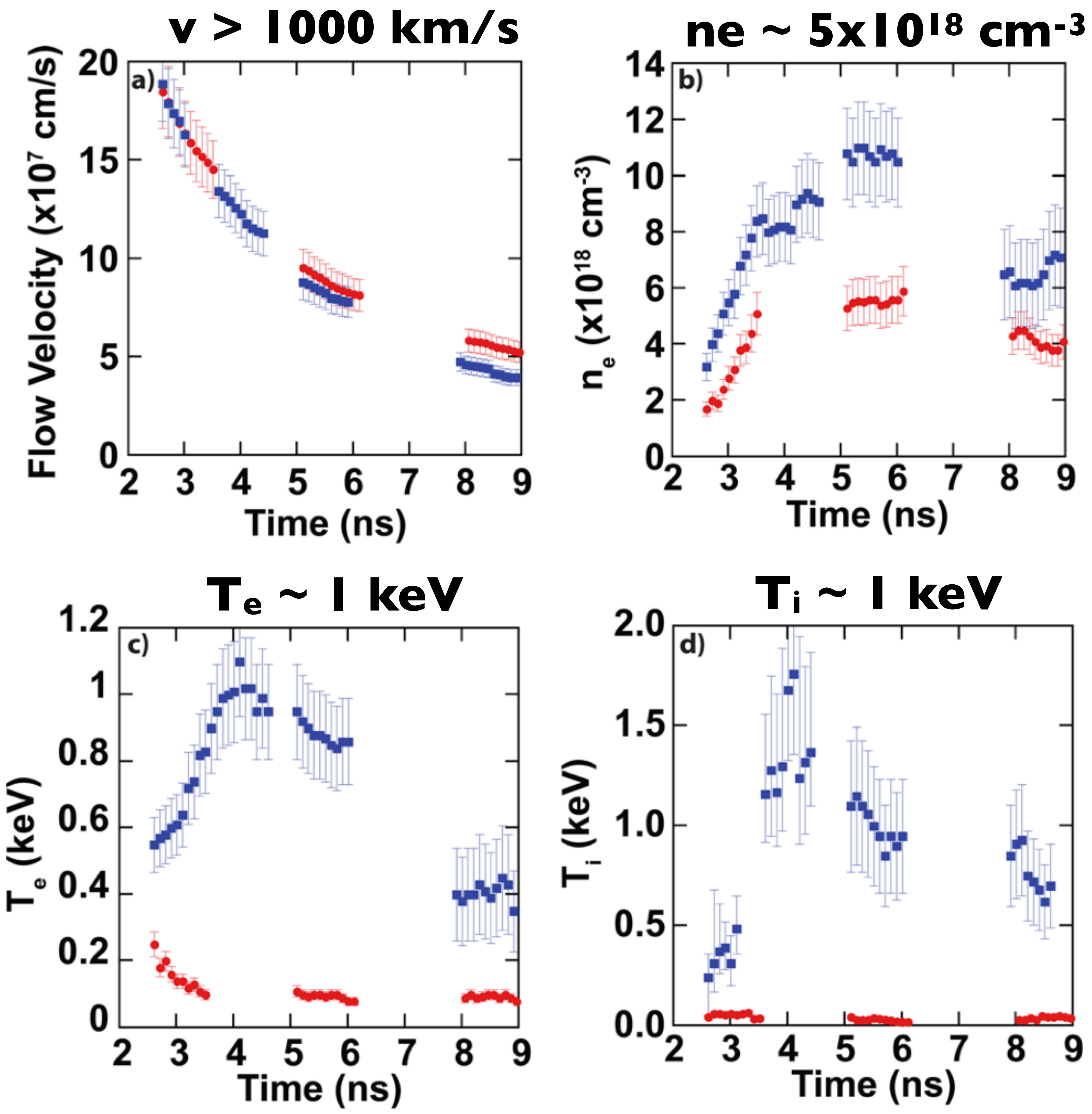
Particle acceleration in weakly magnetized collisionless shocks



Formation of collisionless shocks in weakly magnetized plasmas

High Mach # plasma flows can be created in the lab by laser irradiation

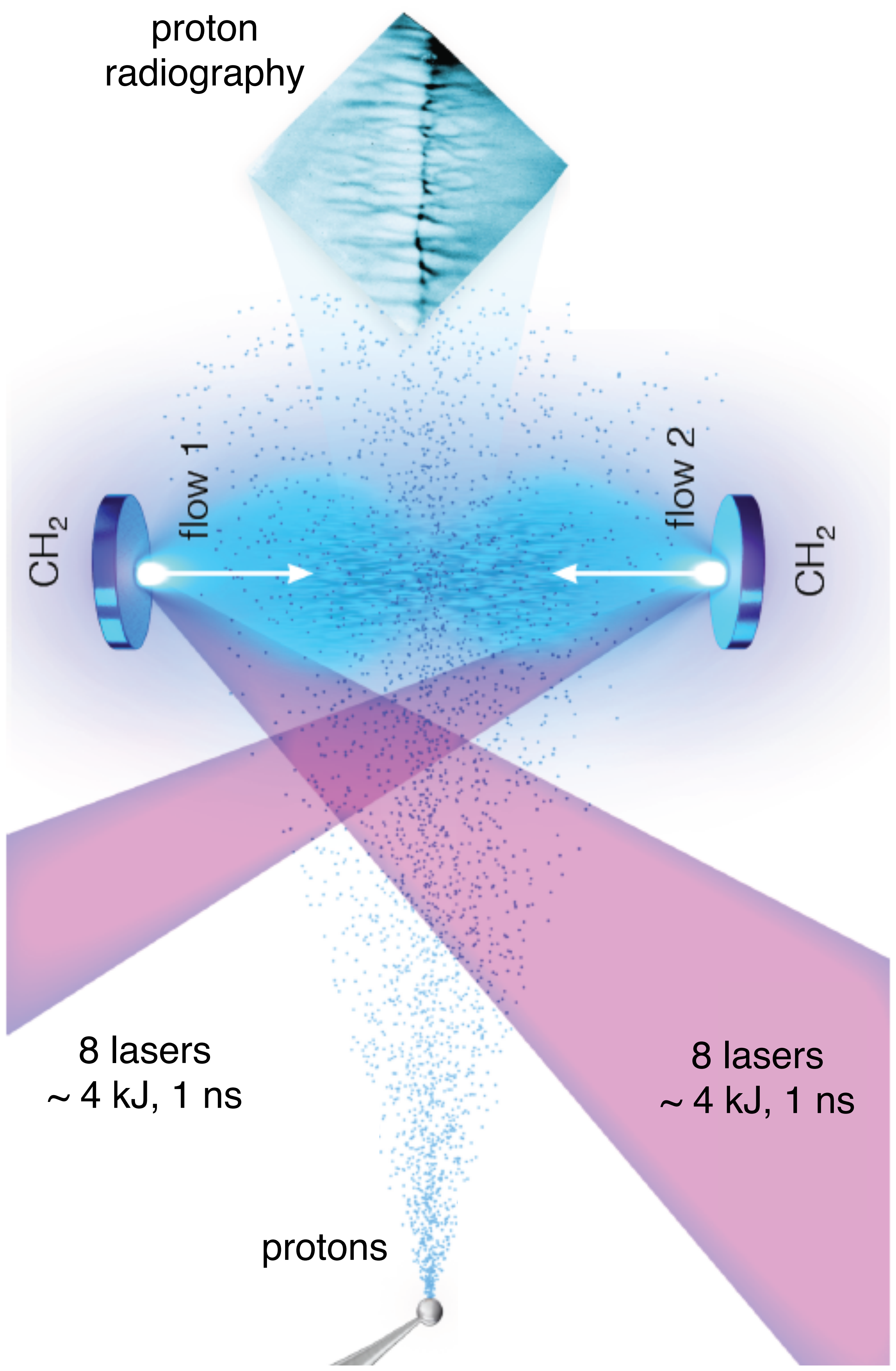


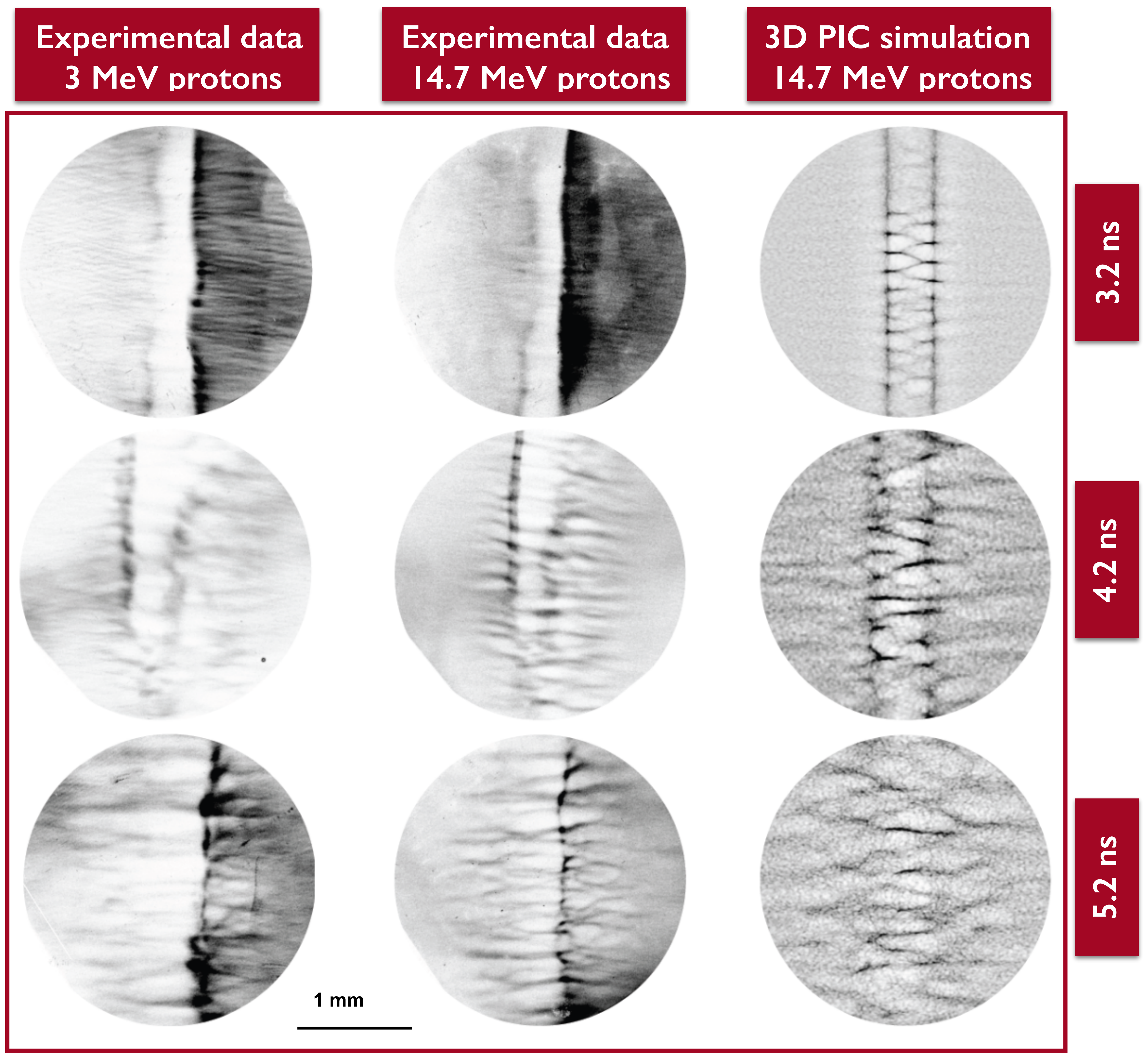


Collisionless interaction with $\lambda_{mfp} > 10\ L_{system}$

S. Ross et al., Phys. Plasmas (2012)

B-field amplification by the ion Weibel instability observed

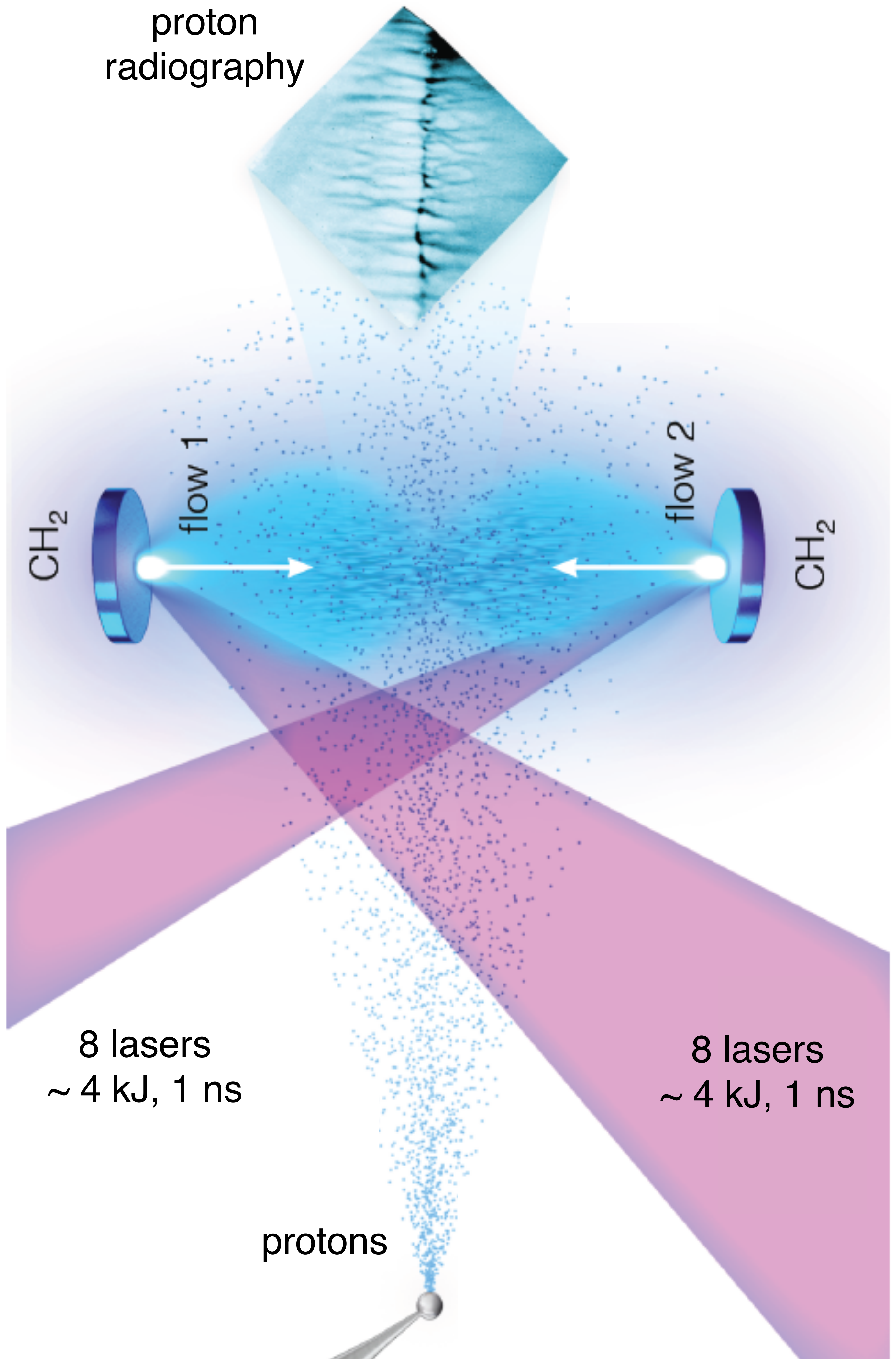


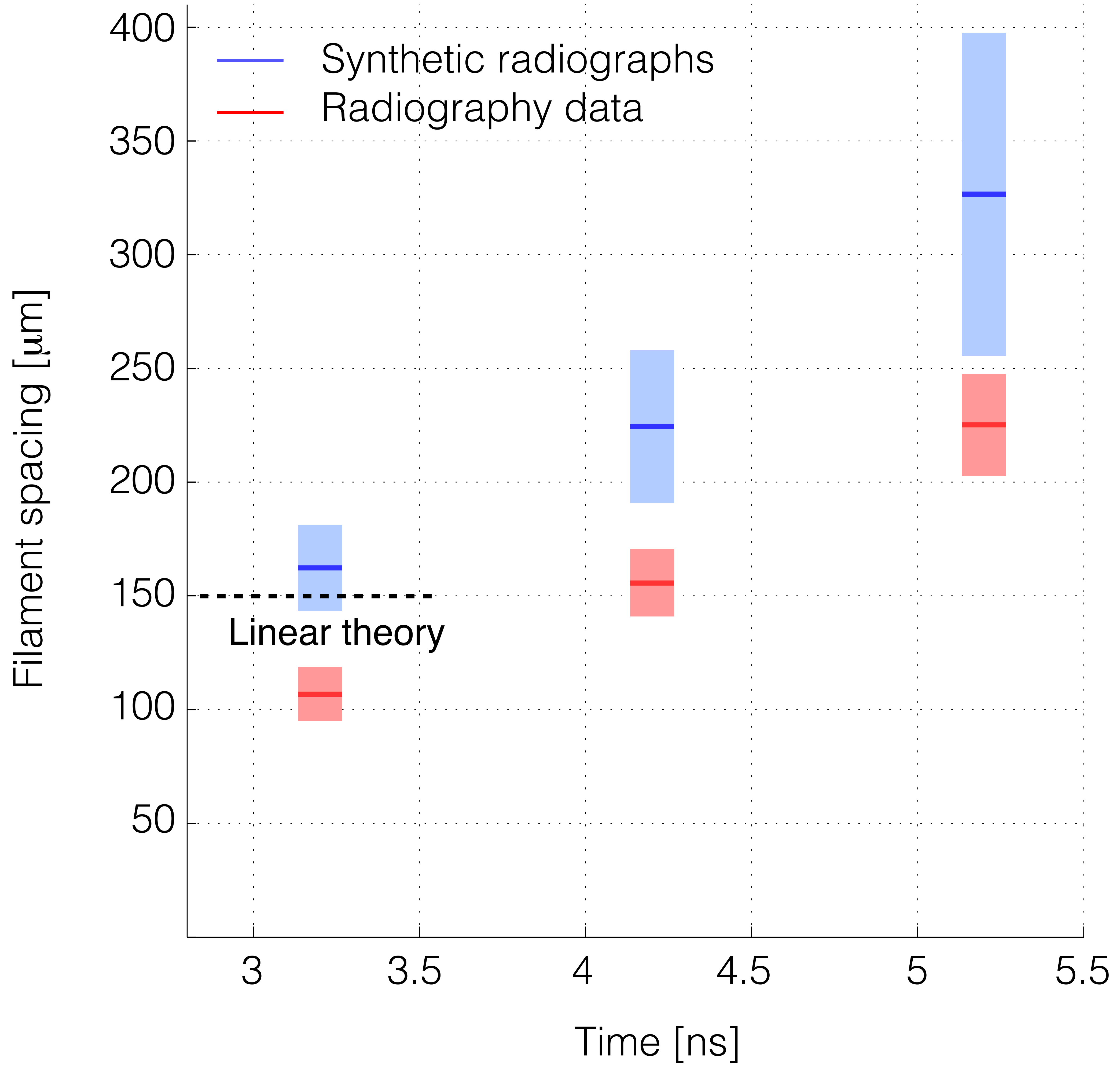


Relative proton deflection at 3 MeV vs. 14.7 MeV indicates B-field dominate over E-field

C. Huntington, F. Fiuza *et al.* Nat. Physics 11, 173 (2015); see also W. Fox et al., PRL 111, 225002 (2013)

B-field amplification by the ion Weibel instability observed

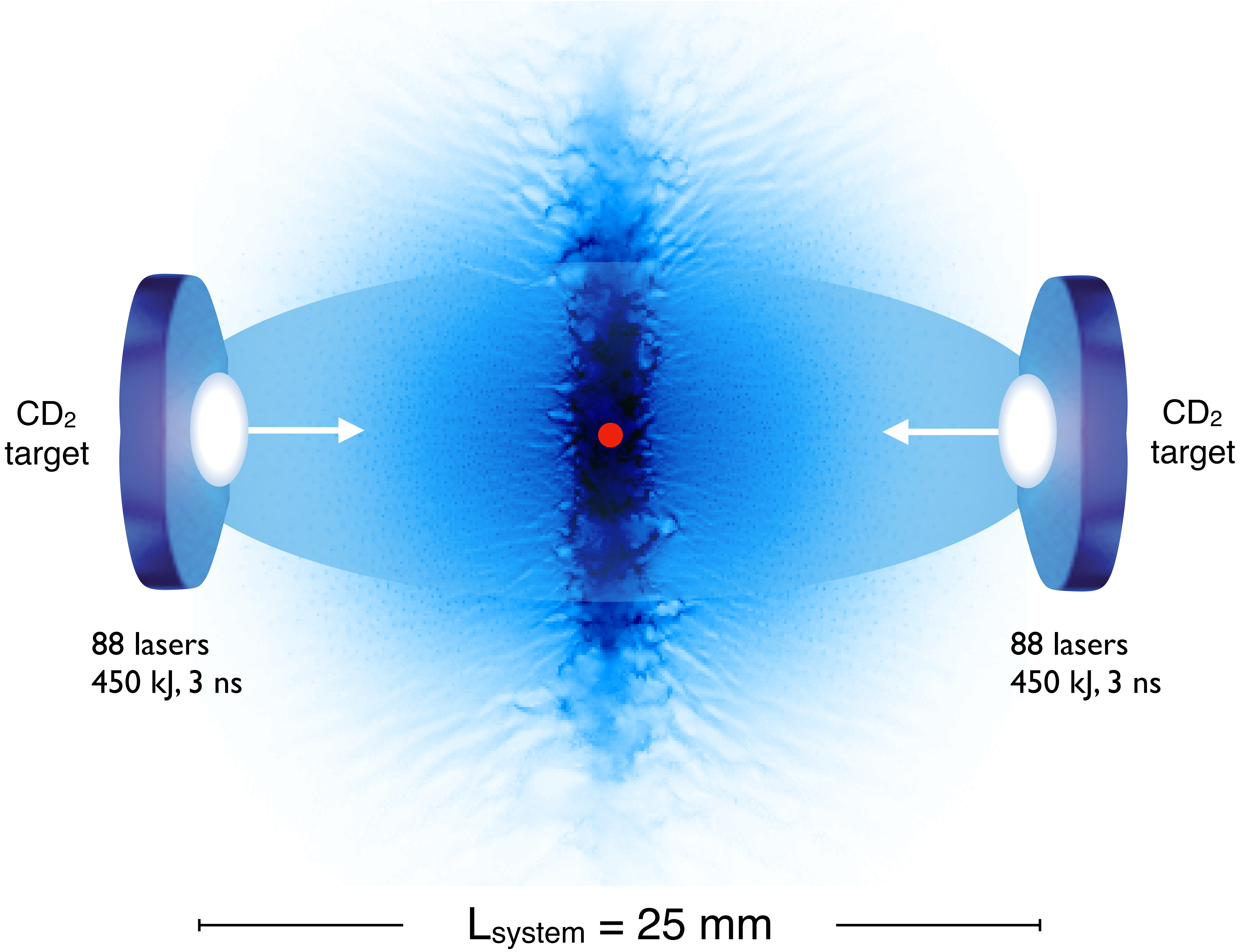




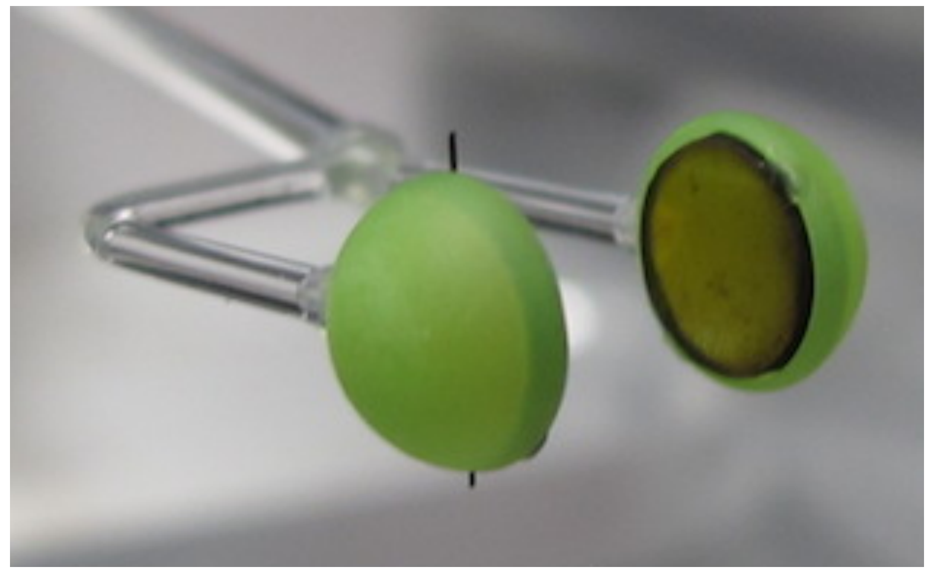
C. Huntington, F. Fiuza *et al*. Nat. Physics 11, 173 (2015); see also W. Fox et al., PRL 111, 225002 (2013)

Platform to study shock formation and particle acceleration at NIF

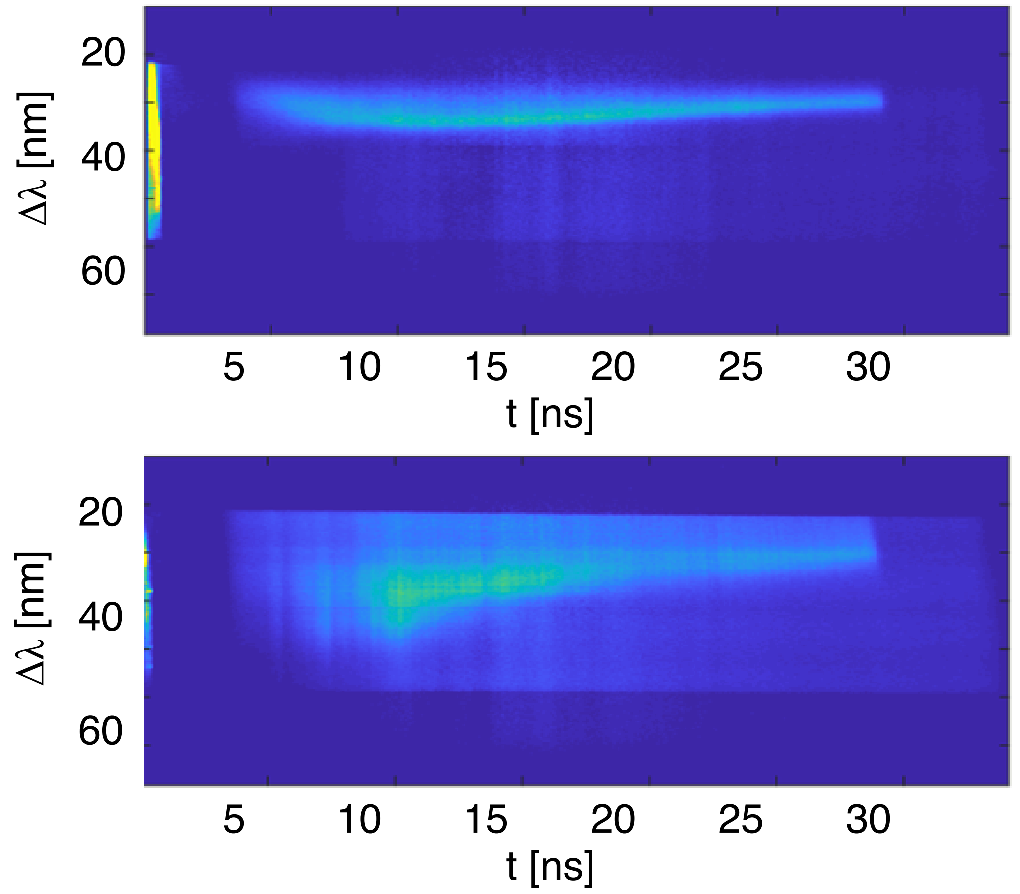
NIF laser system delivers ~ 1MJ in 190 beams



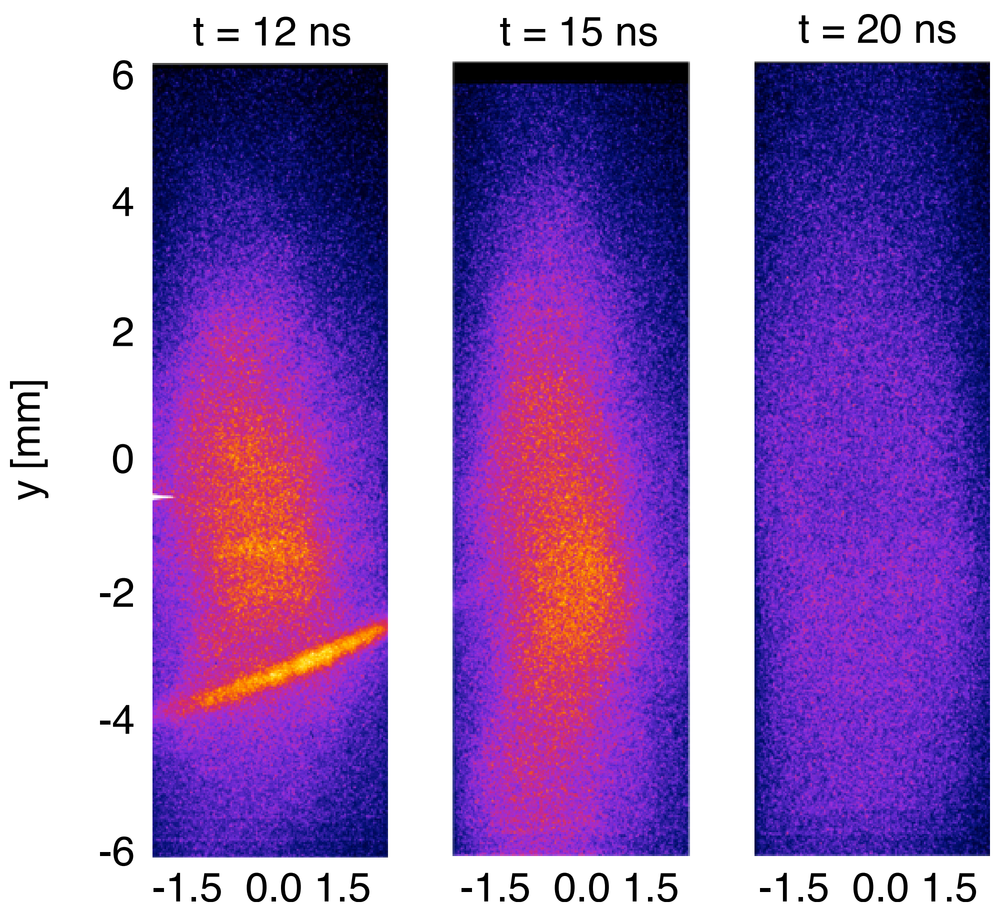
CD2 targets



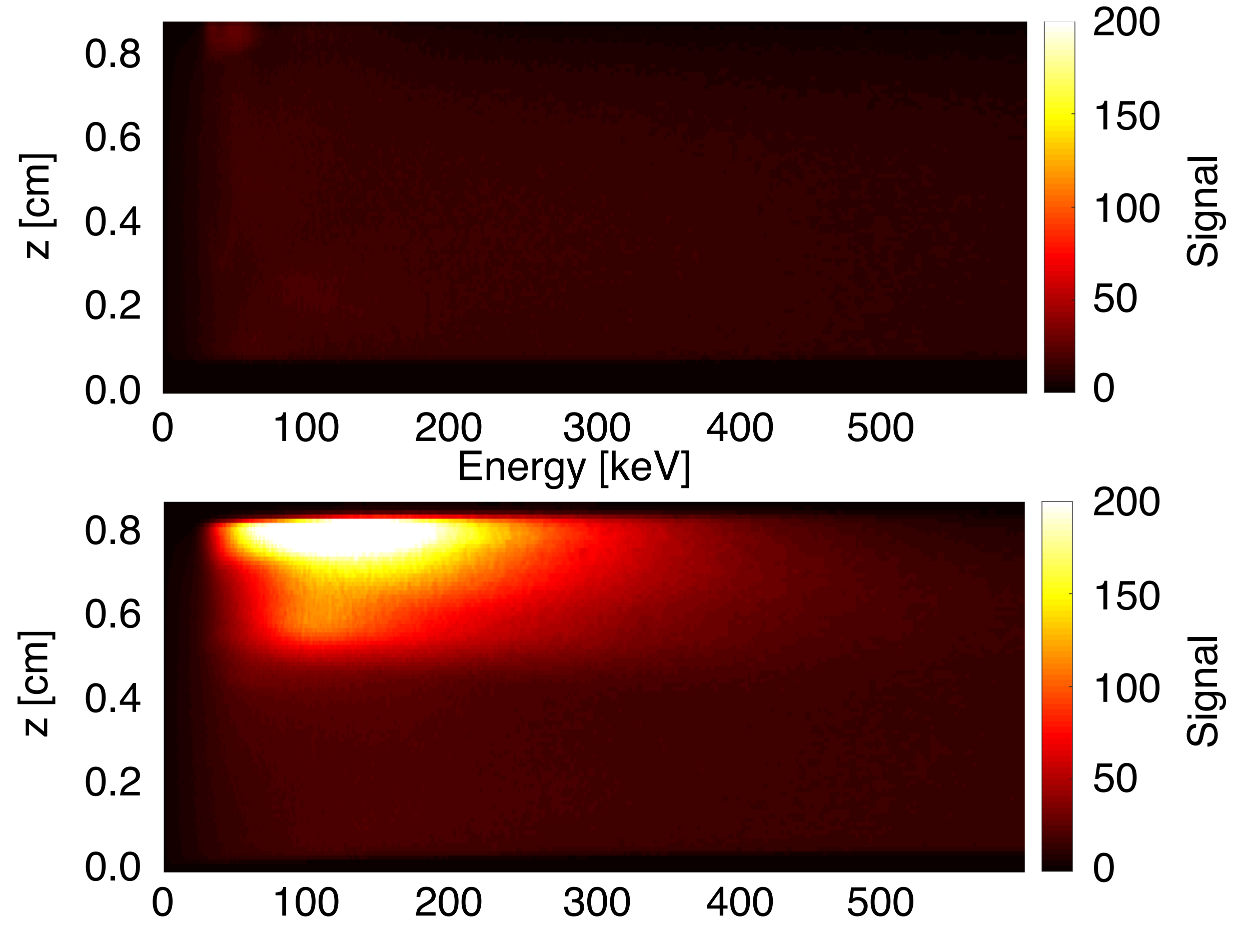
Thomson scattering



Plasma X-ray self emission

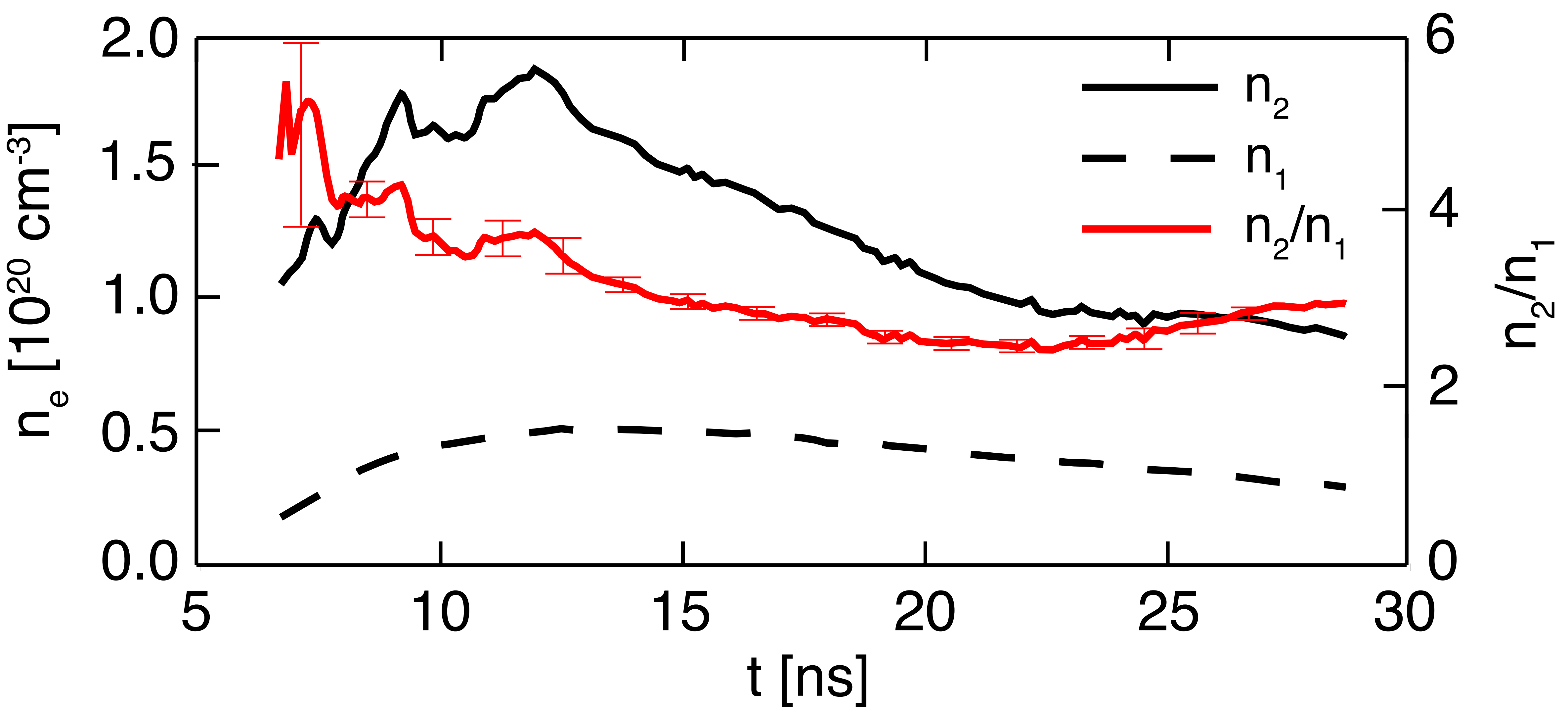


Electron magnetic spectrometer



Experimental observation of collisionless shock formation

Density evolution of shocked plasma



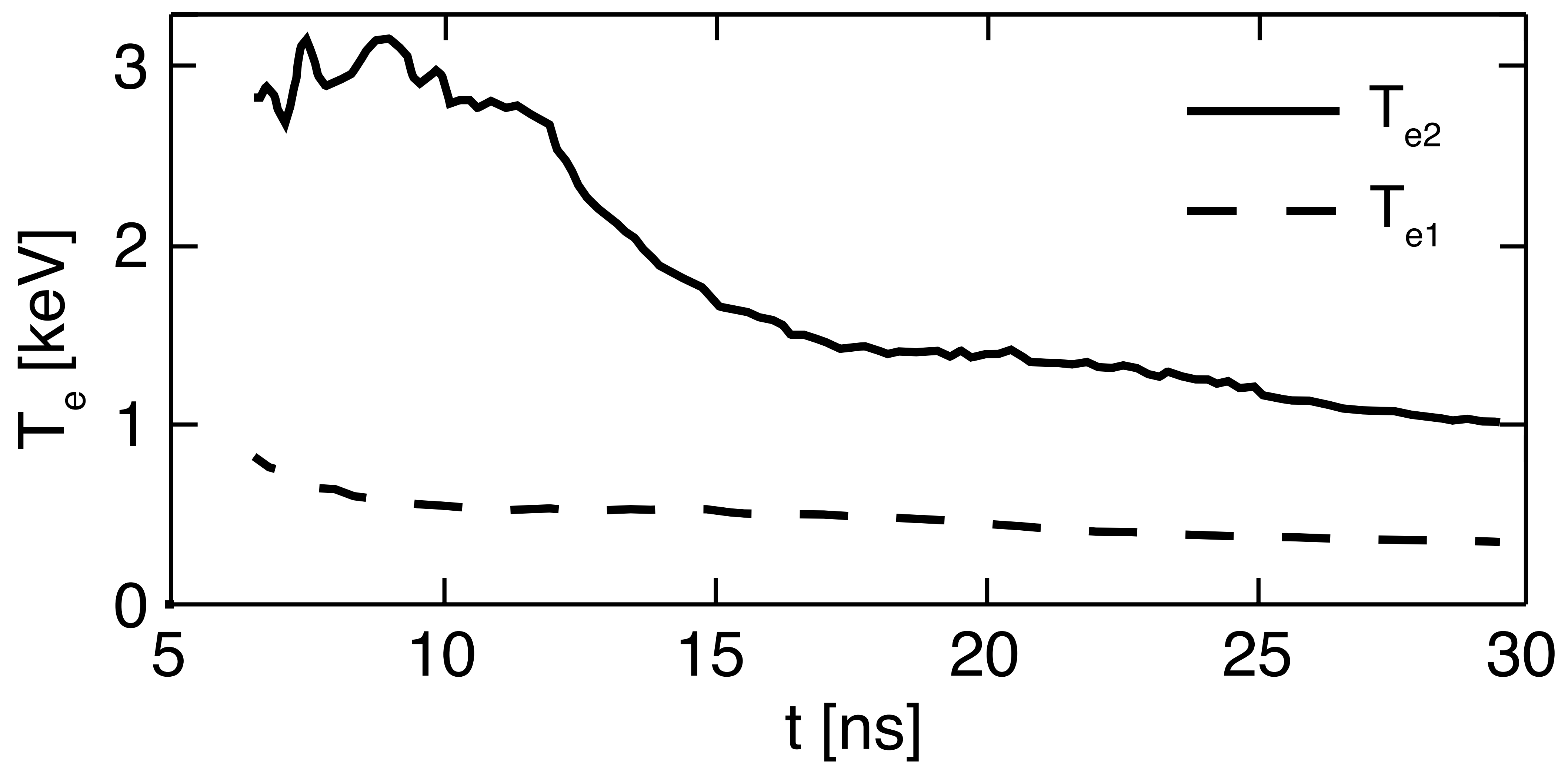
$$v_{\text{flow}} = c_{S1} + \frac{1}{2}\frac{L_{\text{system}}}{t} \simeq 1750\text{km/s}$$

$$\frac{n_2}{n_1} = \frac{(\gamma+1)M^2}{2+(\gamma-1)M^2} \sim 4 \qquad M_{sh} \sim 15$$

$$L_{m.f.p.} \simeq 10^{-12}\frac{A^2 v_{flow}^4}{Z^4 n_i} \simeq 21\text{cm} \gg L_{\text{system}}$$

Observed shock is collisionless!

Temperature evolution of shocked plasma



$$\frac{1}{2}m_i v_{\text{flow}}^2 \simeq \frac{3}{2}k_B(T_i + ZT_e)$$

$$\frac{T_e}{T_i} = \frac{0.34}{A}$$

Temperature ratio consistent with previous observations of SNR shocks (Rakowski 2003, 2006)

Simulations show consistent Weibel-mediated shock structure

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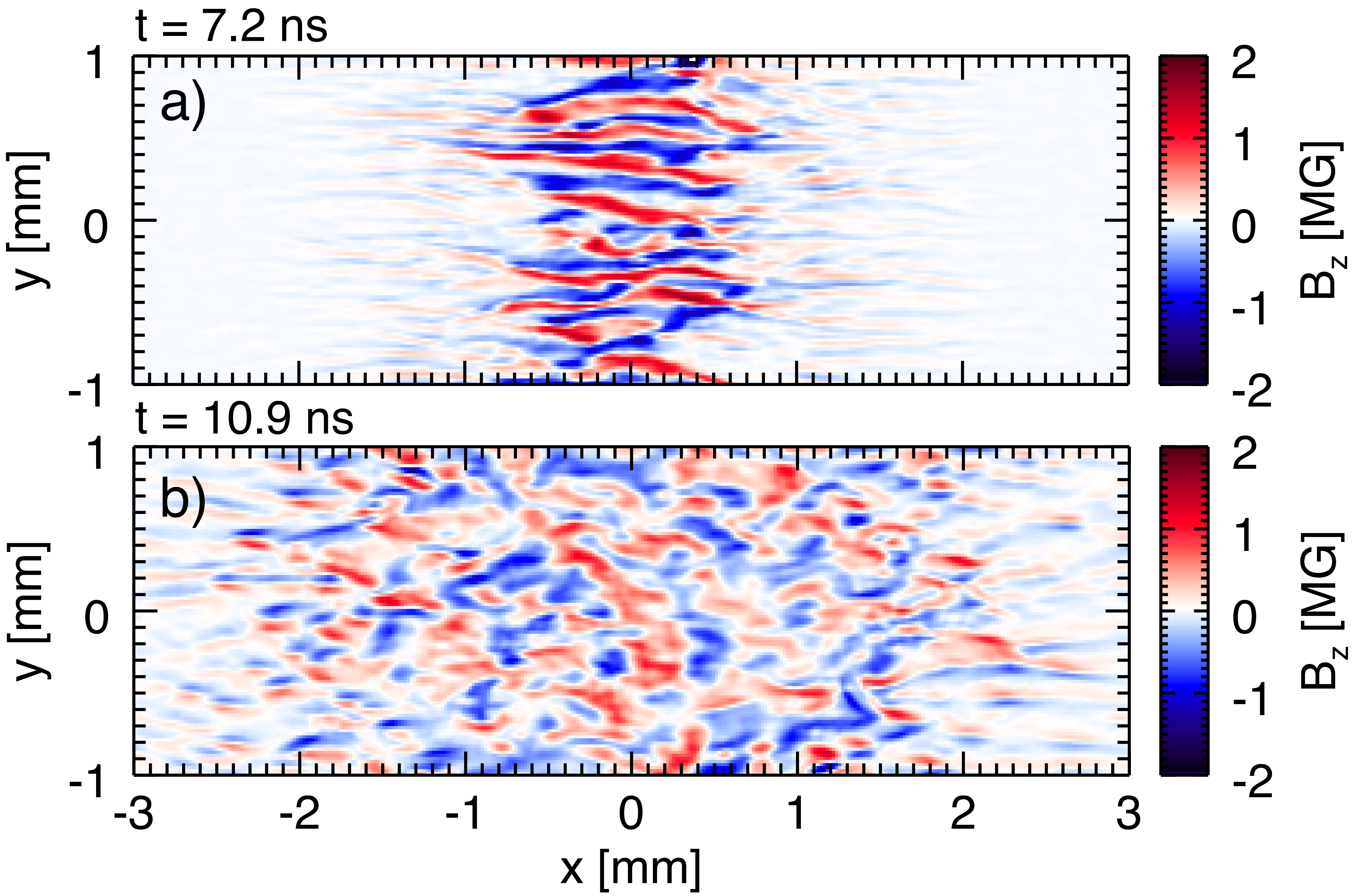
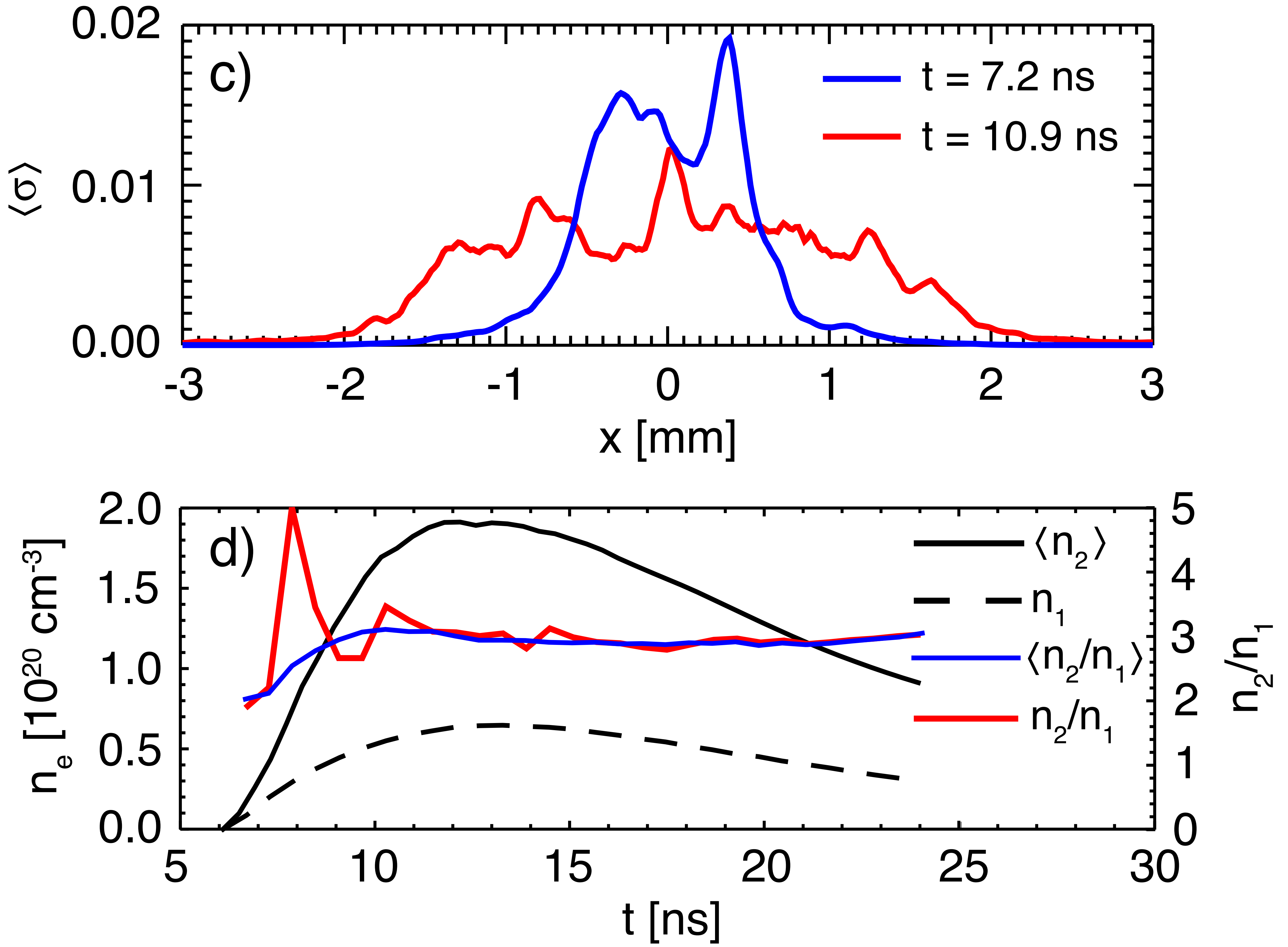
Onset of magnetic turbulence from Weibel instability



Turbulence scale $L_B \sim 200\mu\mathrm{m}$ comparable to ion gyroradius $r_i \sim 300\mu\mathrm{m}$*

Effective magnetization σ ~ 0.01

Density evolution consistent with experiments



Shock formation at ~9 ns consistent with experiments

* C. Ruyer and F. Fiuza, PRL (2018); A. Grassi et al., in preparation (2019)

Experiments show clear evidence of nonthermal electron acceleration

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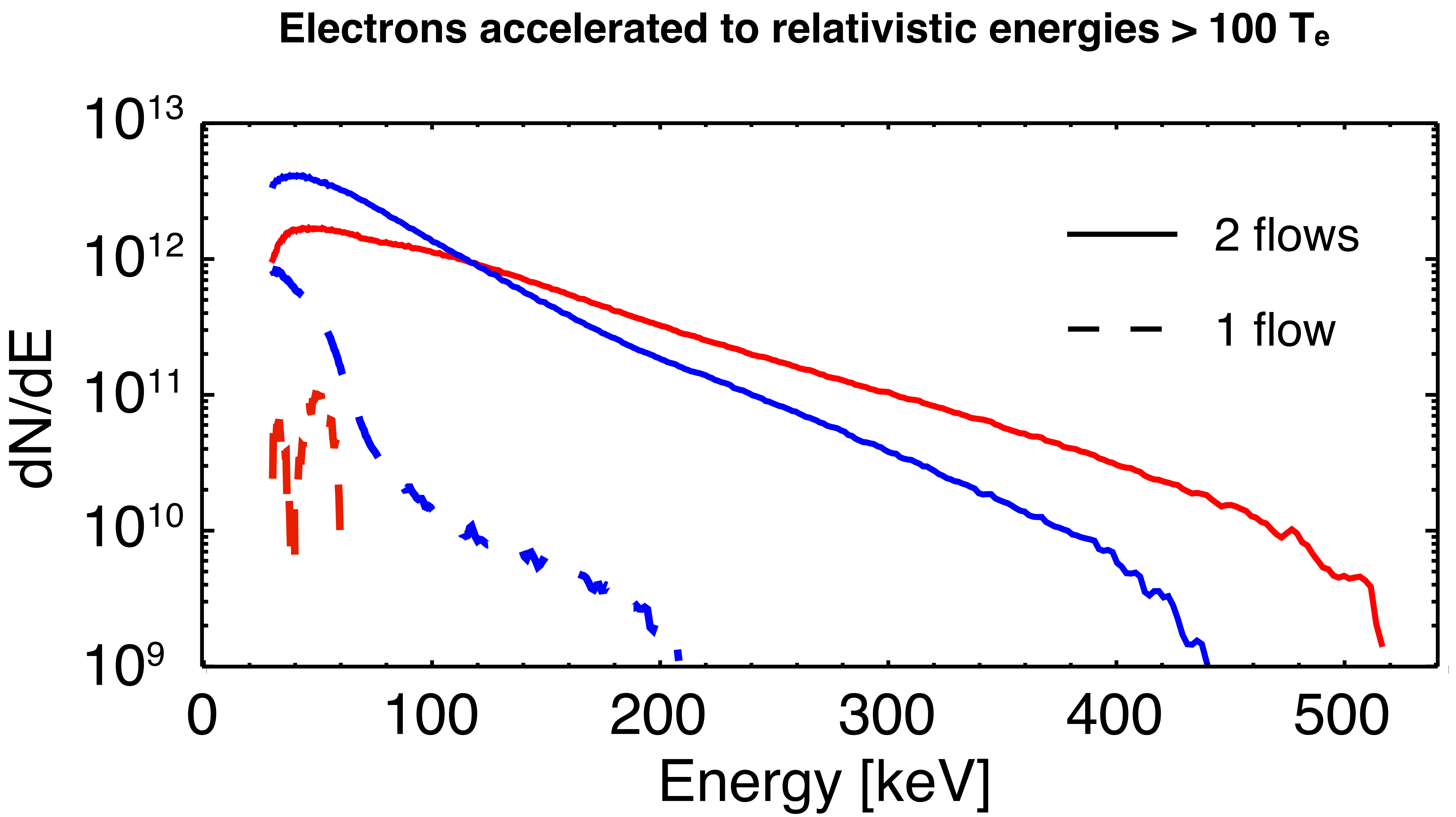
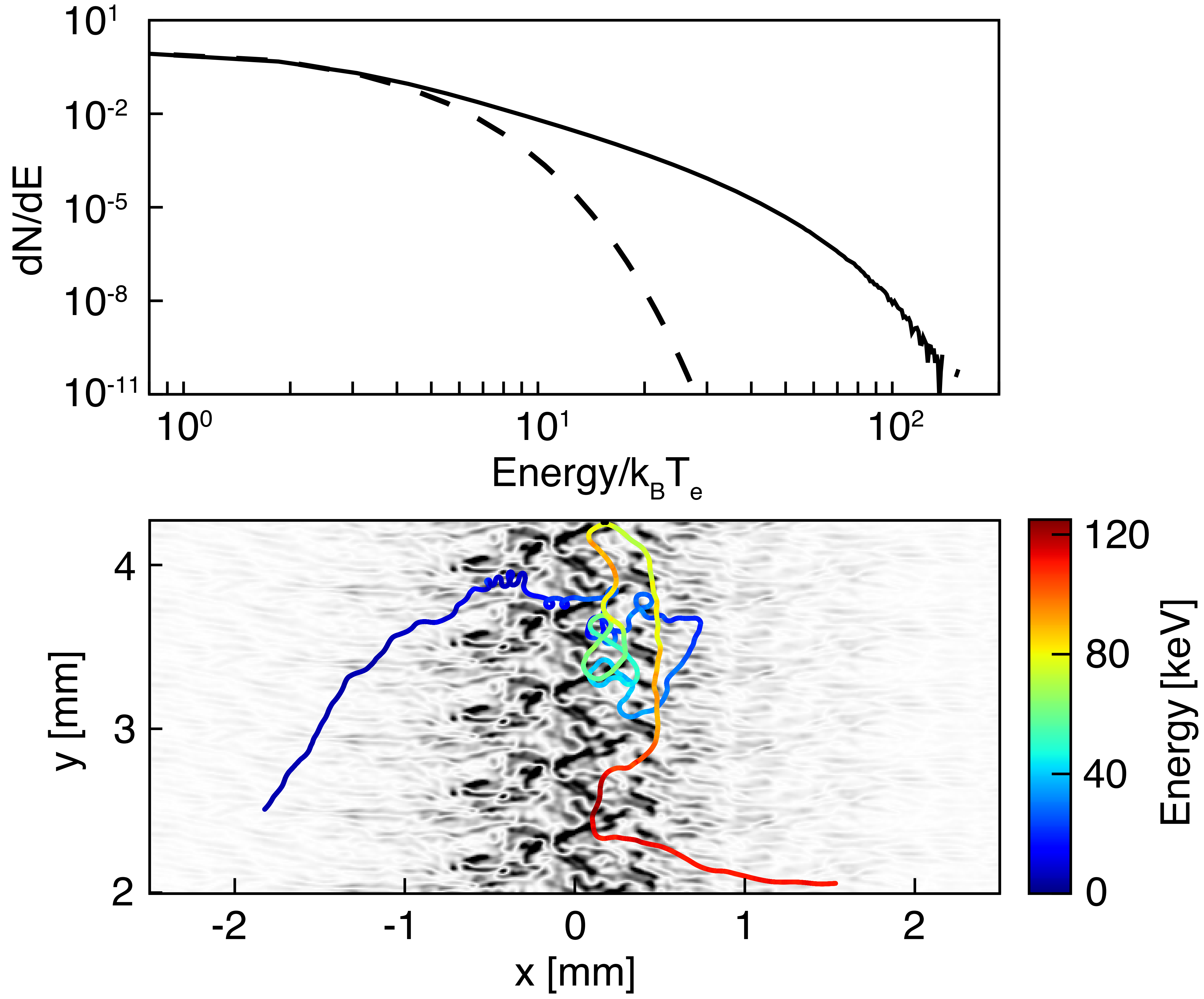
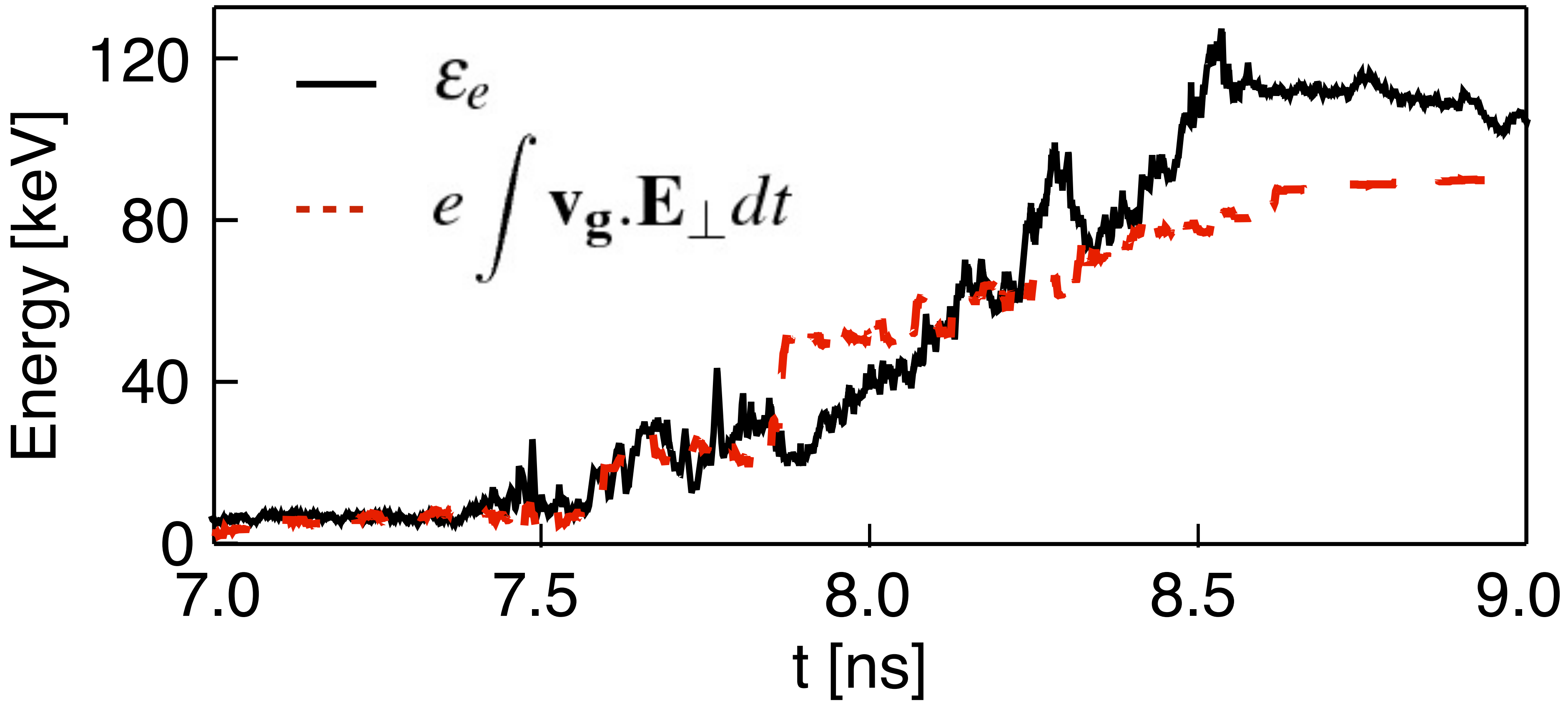


- Fast electrons from individual plasma flows are produced by the lasers and escape system before flow interaction (< 0.3 ns)
- **Electrons must then be injected from 3 keV shocked plasma!**
- **Nonthermal electrons exceed kinetic energy of the flow ions (~ 250 keV) and can access DSA!**
- $\varepsilon_e / \varepsilon_{flow} \sim 10^{-4}$ similar to Tycho observations (Morlino & Caprioli 2012)

F. Fiuza *et al.*, in preparation (2019)

Simulations reveal that injection is associated with scattering in magnetic turbulence





Stochastic interaction of electrons with magnetic turbulence allow for significant energization in ns time scale*:

$$t_{acc} \sim \frac{K(\varepsilon)}{v_{turb}^2} \sim \text{ns}$$

$$\varepsilon_{max} = |e|(u_{sh}/c)BR_{sh} \sim 500\text{keV}$$

F. Fiuza *et al.*, in preparation (2019); T. Katou and T. Amano arXiv:1903.02277

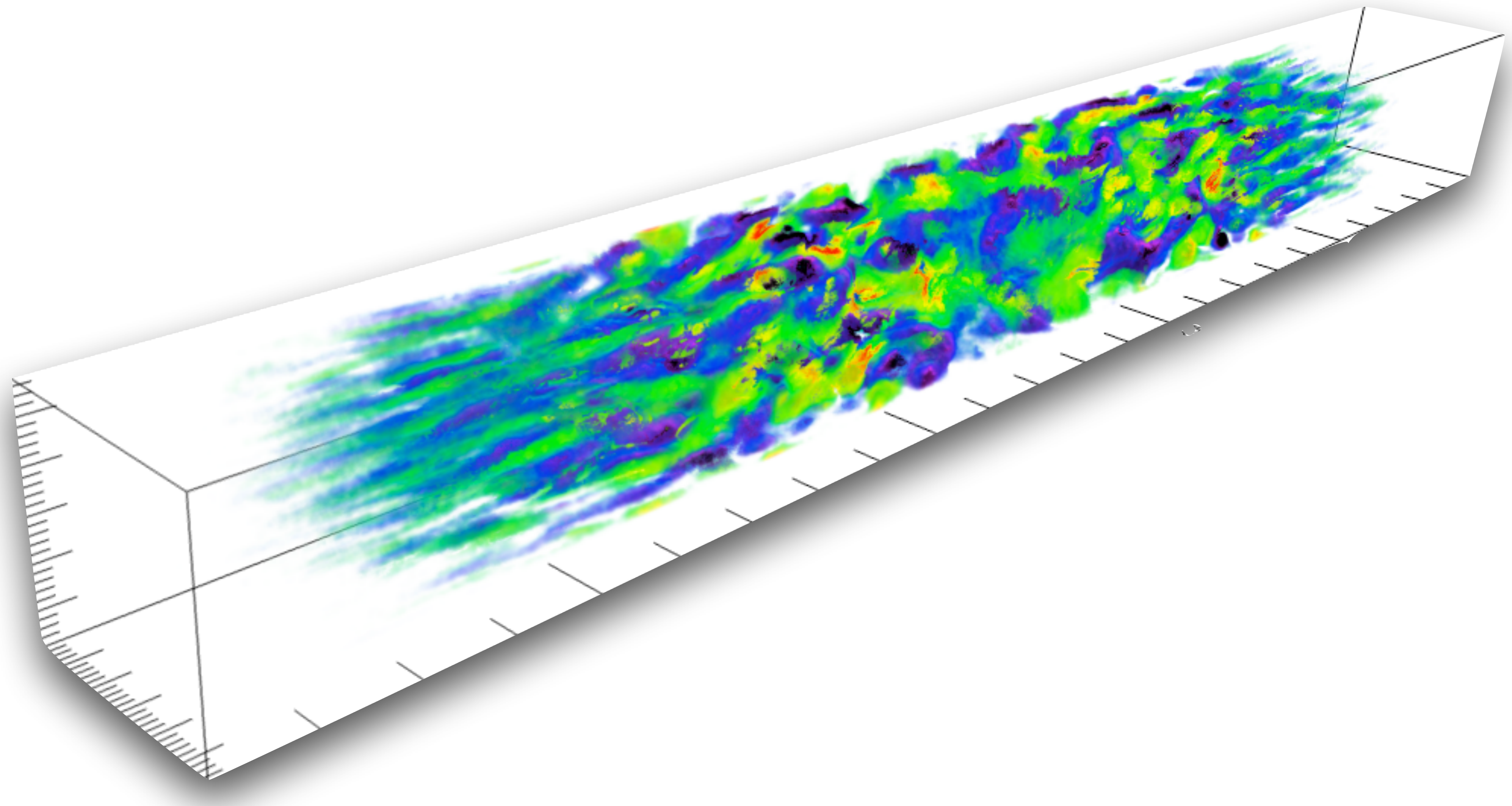
Conclusions and future perspectives

- Important progress in experiments of collisionless plasmas led to first laboratory measurements of:
  - **the amplification of magnetic fields by the ion Weibel instability**
  - **the formation of electromagnetic collisionless shocks**
  - **nonthermal electron acceleration in these shocks**

- Experiments provide important **benchmark of numerical codes and injection models** and can **complement spacecraft measurements and astrophysical observations**

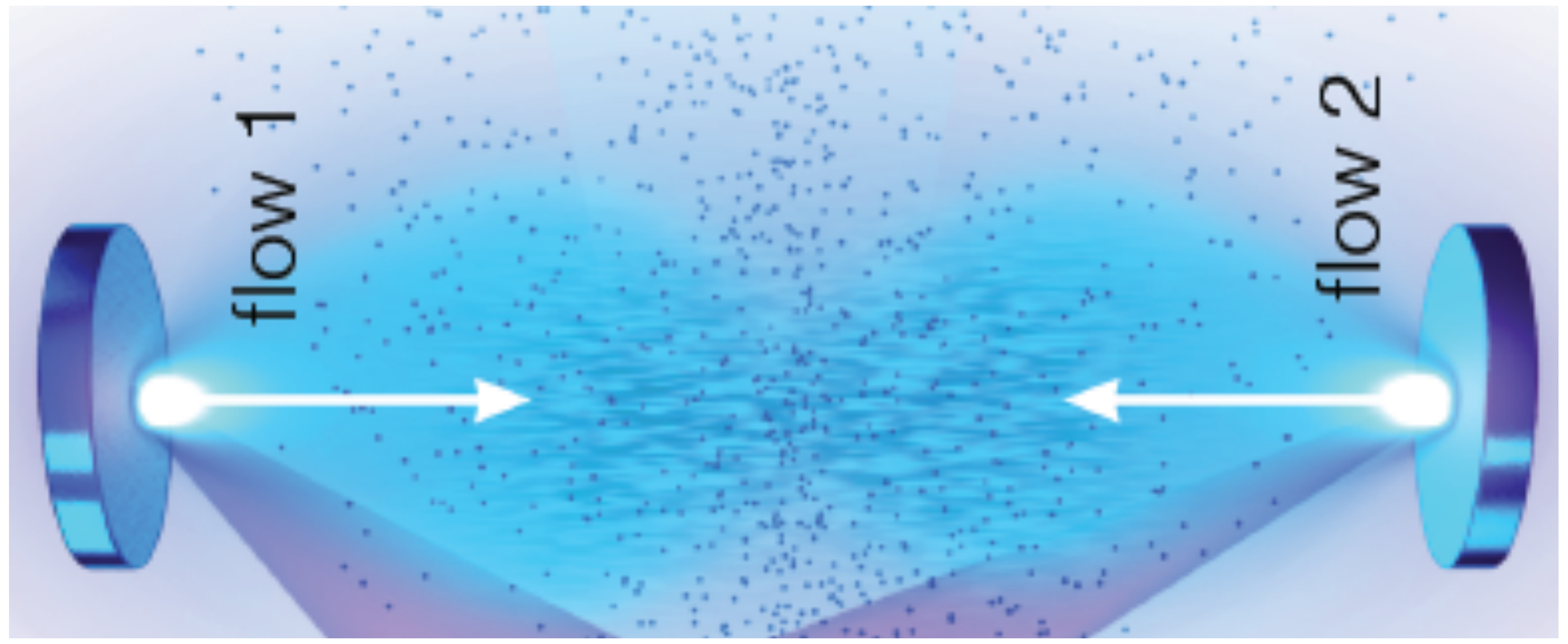
- Existing platforms can be extended to study relative acceleration efficiency of protons and electrons, magnetized shocks, different B-field amplification mechanisms (e.g. Bell instability). Stay tuned!

Extra slides

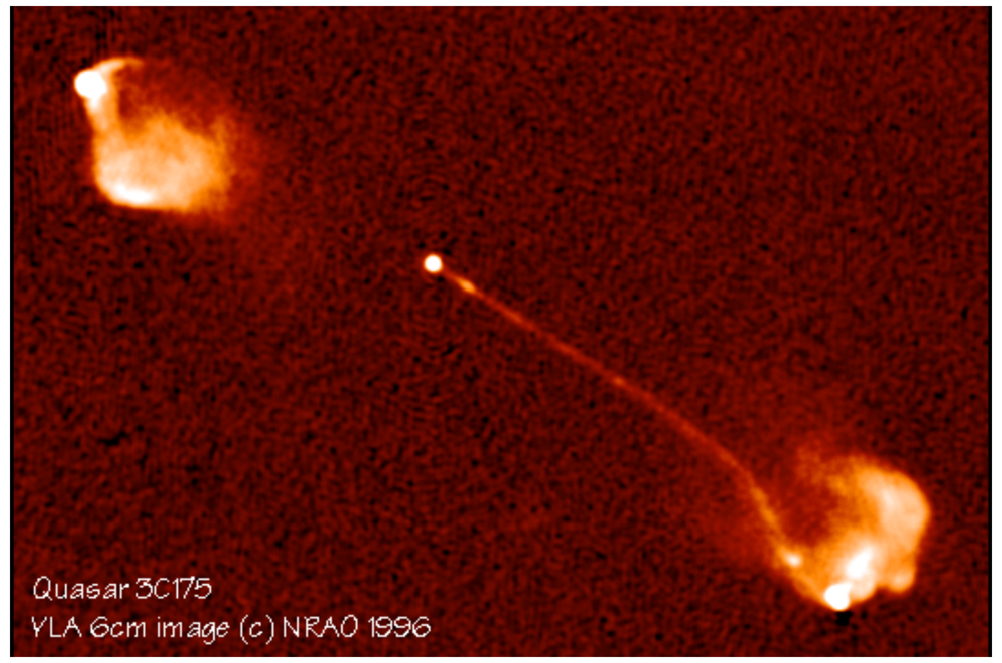


Shock microphysics can be scaled from lab to astrophysical plasmas

Laboratory system 1



Astrophysical system 2



Main assumptions: collisionless system ($\lambda_{mfp} >> L_{system}$), weakly magnetized ($\sigma << 1$), $v_{flow} >> v_{th}$, electromagnetic instabilities are dominant (Div. E ~ 0)

Normalized Vlasov-Maxwell equations:

$$\frac{\partial f_i'}{\partial t'} + \boldsymbol{v}' \cdot \frac{\partial f_i'}{\partial \boldsymbol{r}'} + \left(-\frac{\partial \boldsymbol{A}'}{\partial t'} + \boldsymbol{v}' \times \nabla' \times \boldsymbol{A}'\right) \cdot \frac{\partial f_i'}{\partial \boldsymbol{v}'} = 0,$$

$$\frac{\partial f_e'}{\partial t'} + \boldsymbol{v}' \cdot \frac{\partial f_e'}{\partial \boldsymbol{r}'} + \frac{1}{\mu}\left(-\frac{\partial \boldsymbol{A}'}{\partial t'} + \boldsymbol{v}' \times \nabla' \times \boldsymbol{A}'\right) \cdot \frac{\partial f_e'}{\partial \boldsymbol{v}'} = 0$$

$$\nabla'^2 \boldsymbol{A}' = \left(\int f_e' \boldsymbol{v}' \, d^3\boldsymbol{v}' - \int f_i' \boldsymbol{v}' \, d\boldsymbol{v}'^3\right). \qquad \mu \equiv \frac{Z m_e}{A m_p}$$

Scaling relations between both systems:

$$L_2 = L_1 \sqrt{\frac{n_1}{n_2}} \qquad t_2 = t_1 \frac{u_1}{u_2}\sqrt{\frac{n_1}{n_2}} \qquad T_{i2} = \frac{A_2 u_2^2}{A_1 u_1^2} T_{i1}$$

$$\tilde{E}_2 = \tilde{E}_1 \frac{u_2^2}{u_1^2}\sqrt{\frac{n_2}{n_1}} \qquad \tilde{B}_2 = \tilde{B}_1 \frac{u_2}{u_1}\sqrt{\frac{n_2}{n_1}}$$

D. D. Ryutov et al. Plasma Phys. Control. Fusion 54, 105021 (2012)

Weibel instability can amplify B-fields in weakly magnetized plasmas

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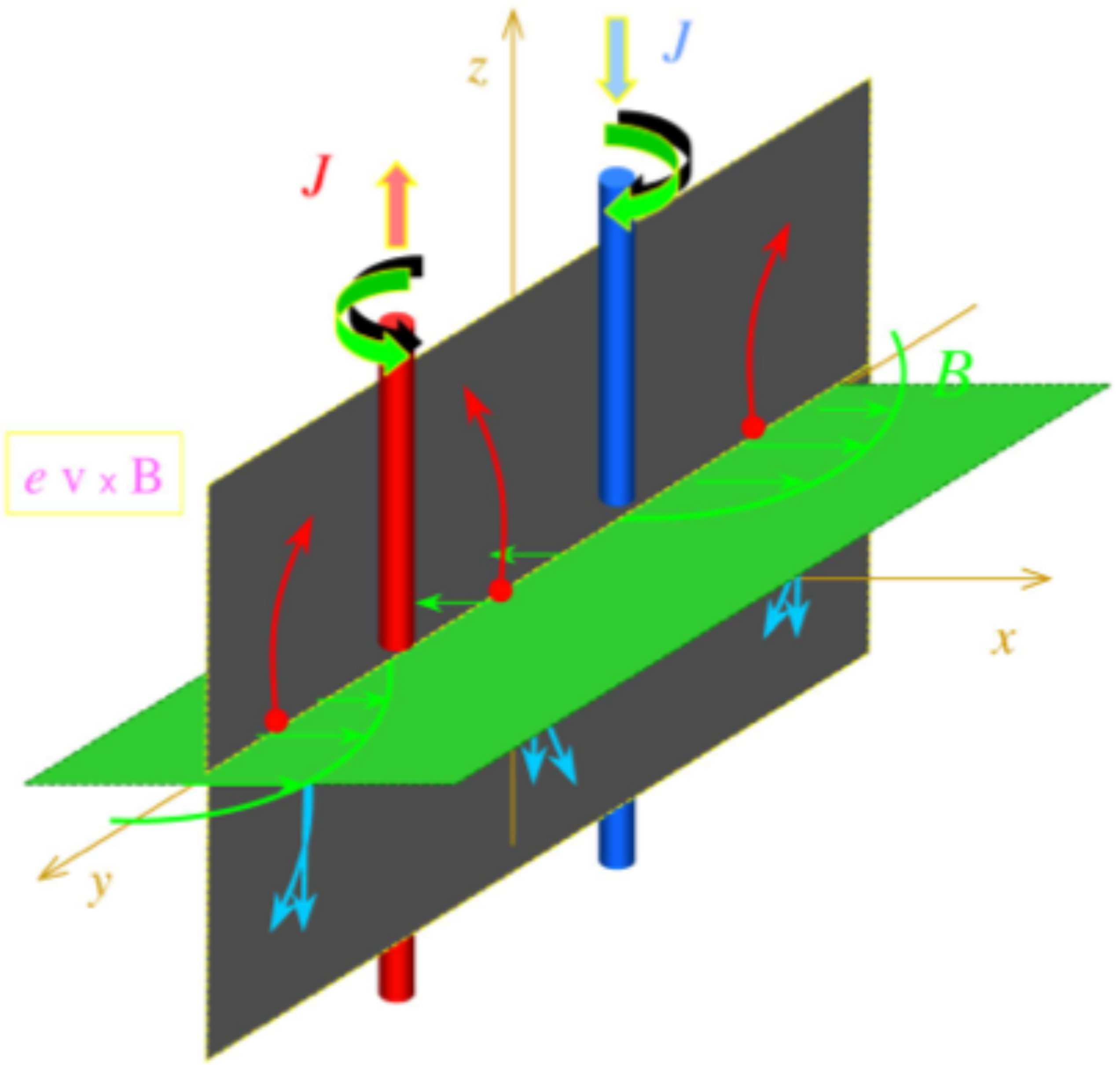
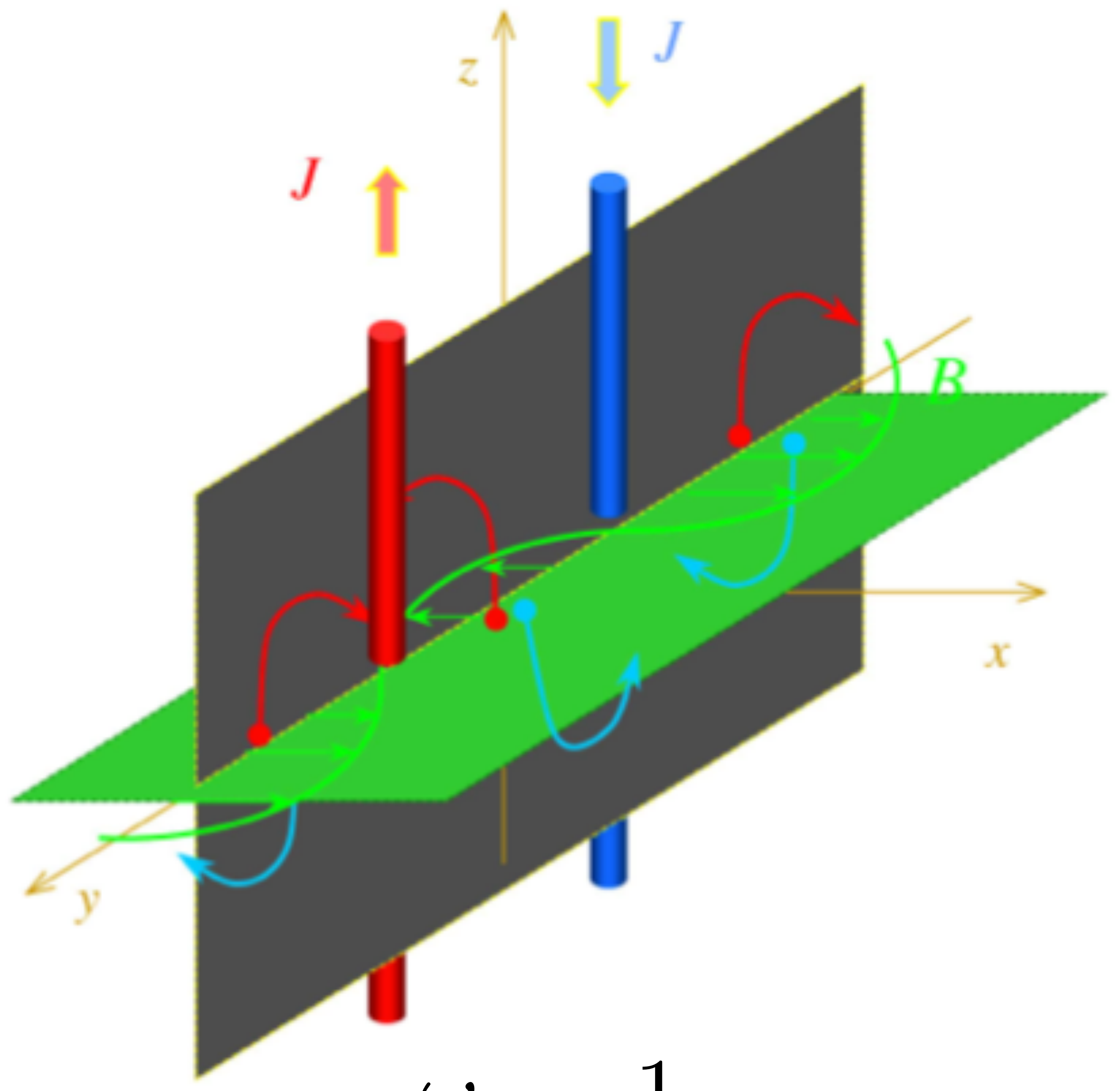
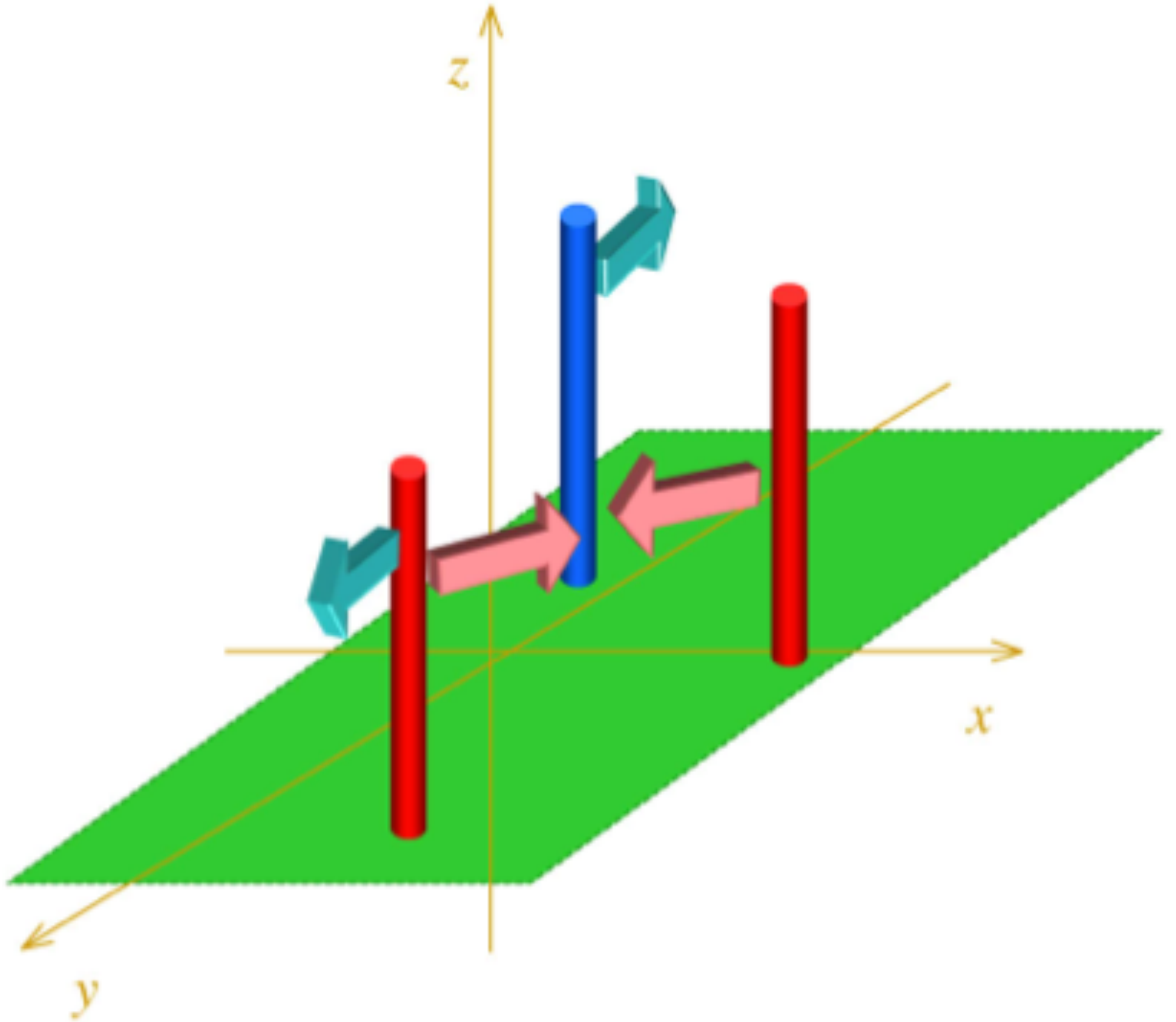
Linear regime	Saturation	Non-linear regime
		

$$\Gamma_W = \frac{v_0}{c}\frac{\omega_{pi}}{\gamma_0^{1/2}}$$

$$k_{max} = \frac{\omega_{pi}}{c}\frac{1}{\gamma_0^{1/2}}$$

Instability can transfer ~10% of kinetic energy of plasma flows into magnetic energy

E. S. Weibel, PRL 2, 83 (1959); B. D. Fried, Phys. Fluids 2, 337 (1959)
A. Gruzinov & E. Waxman, APJ 511, 852 (1999); M. Medvedev & A. Loeb, ApJ 526, 697 (1999)

Good agreement between linear theory, simulations, and experiments

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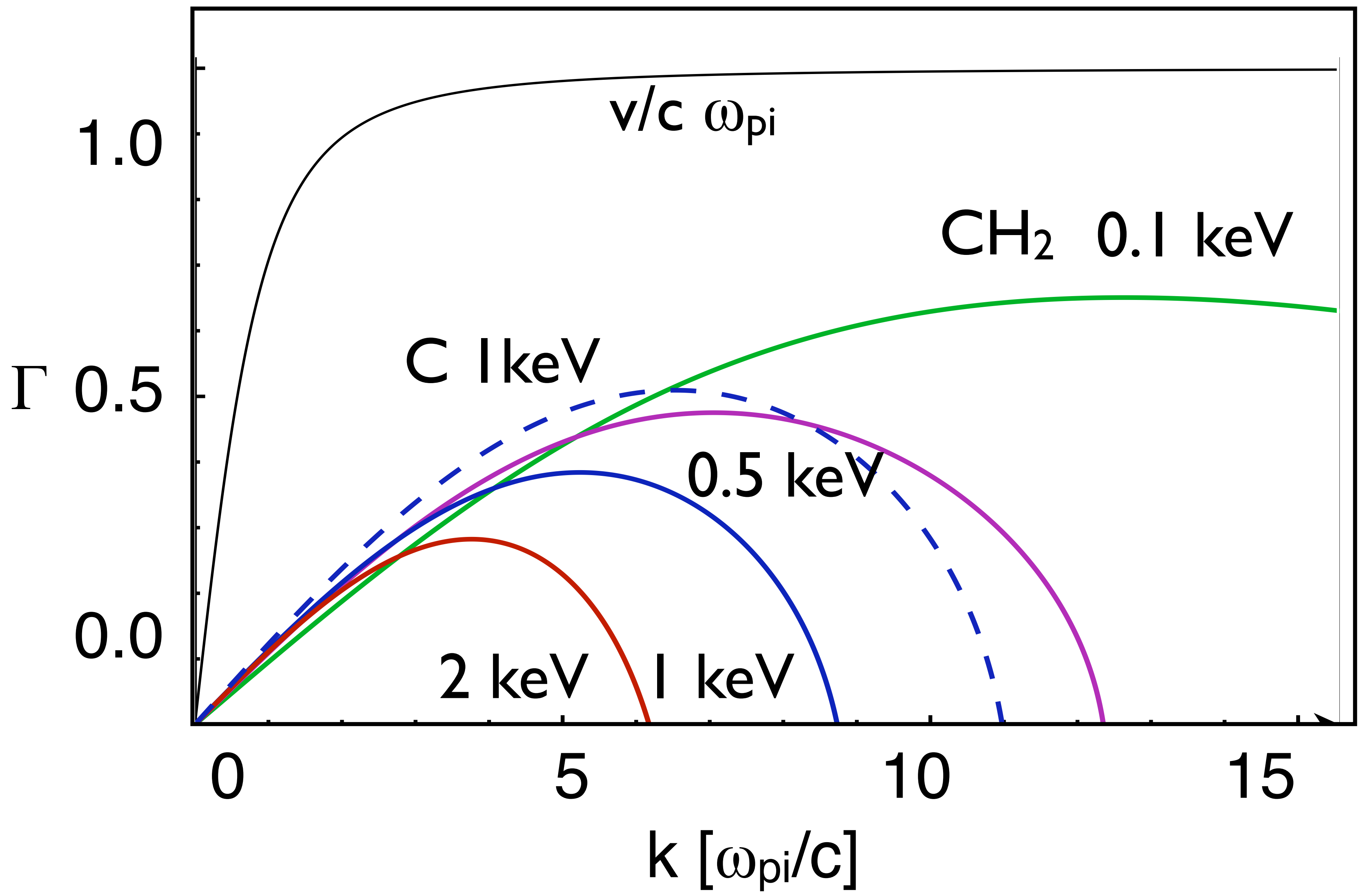
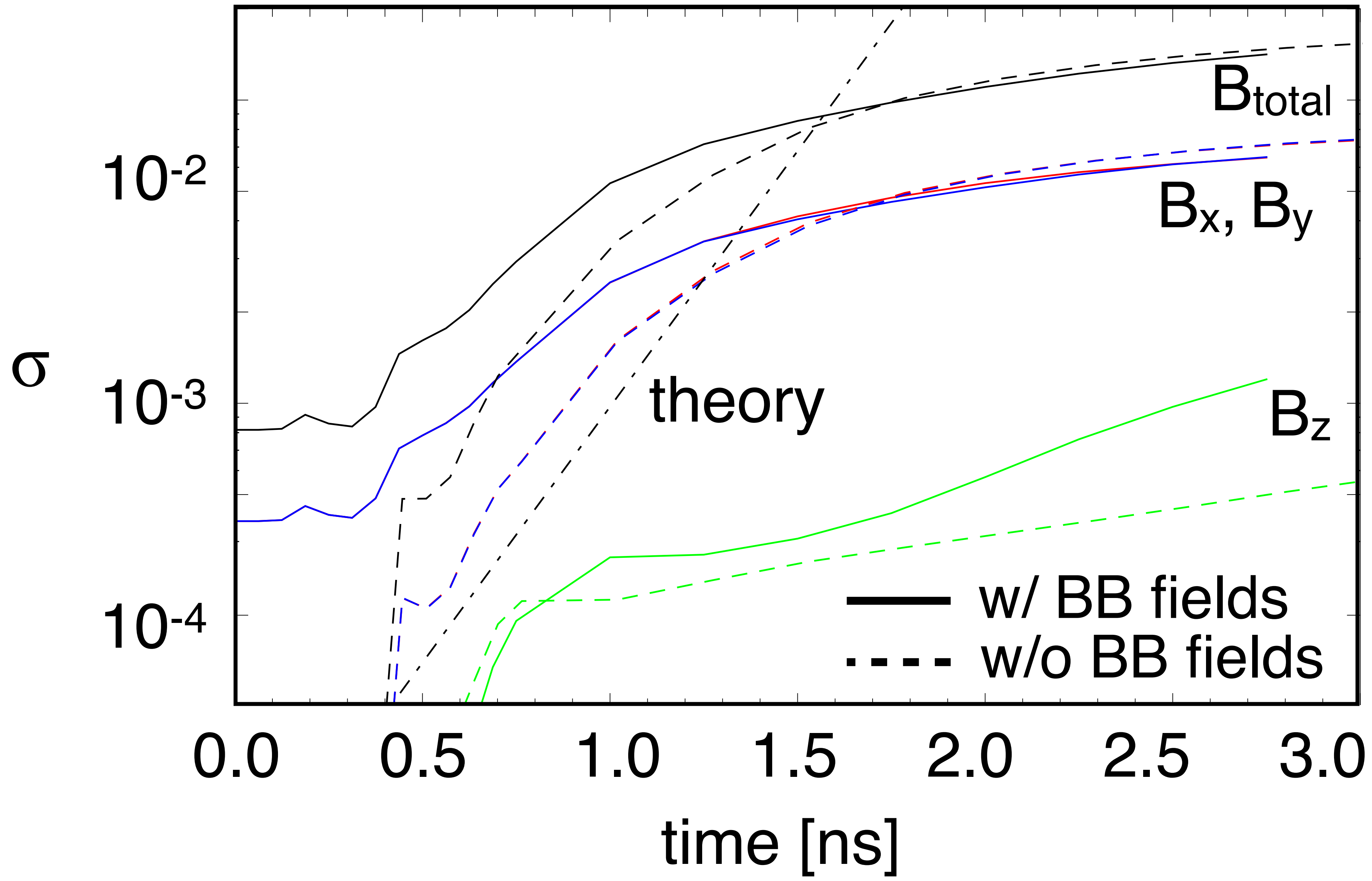
Dispersion relation for plasma with several ion components

$$\tilde{k}^2 + \frac{a_1}{1+\sqrt{\frac{a_2}{\pi}}\frac{|\tilde{k}|}{\tilde{\Gamma}}} + \sum C_Z \left[G_1\left(\frac{a_{3\alpha}\tilde{\Gamma}^2}{\tilde{k}^2}\right) - \frac{\tilde{k}^2}{\tilde{\Gamma}^2} G_2\left(\frac{a_{3\alpha}\tilde{\Gamma}^2}{\tilde{k}^2}\right)\right] = 0.$$

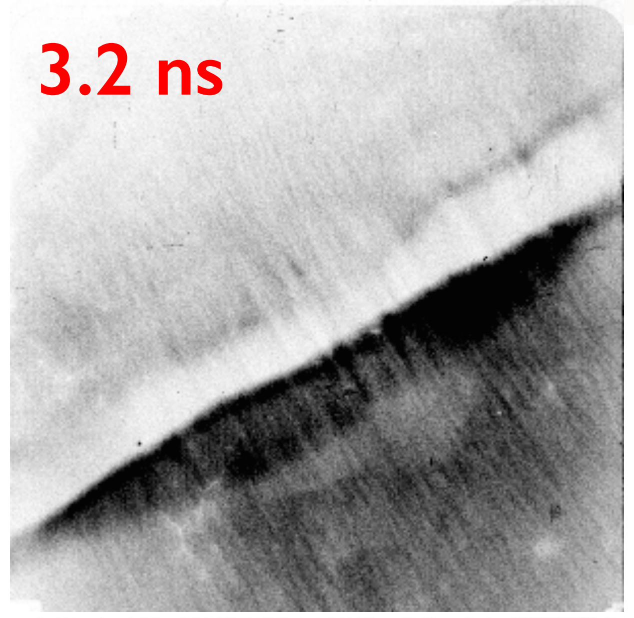
$$a_1 = \frac{\omega_{pe}^2}{\omega_{pi}^2} \quad a_2 = \frac{2T_e}{m_e v^2} \quad a_{3\alpha} = \frac{2T_\alpha}{A_\alpha m_p v^2} \quad G_1(y) = \frac{1}{\sqrt{\pi}}\int_{-\infty}^{+\infty} \frac{y e^{-x^2}}{x^2+y} dx \quad G_2(y) = \frac{2y}{\sqrt{\pi}}\int_{-\infty}^{+\infty} \frac{x^2 e^{-x^2}}{x^2+y} dx$$



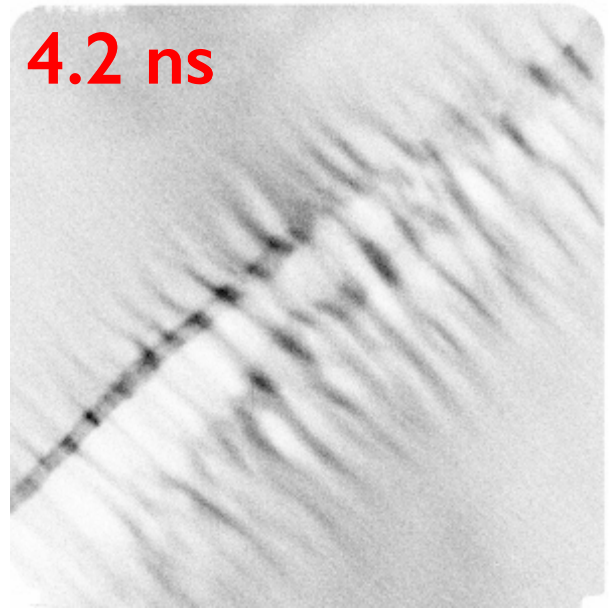


D. D. Ryutov *et al.*, Physics of Plasmas (2014)

Our measurements probe early non-linear development of instability

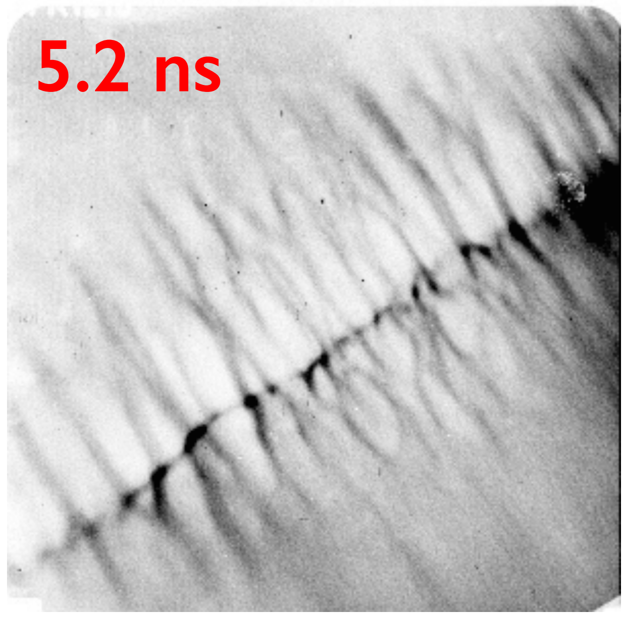


Early time interaction

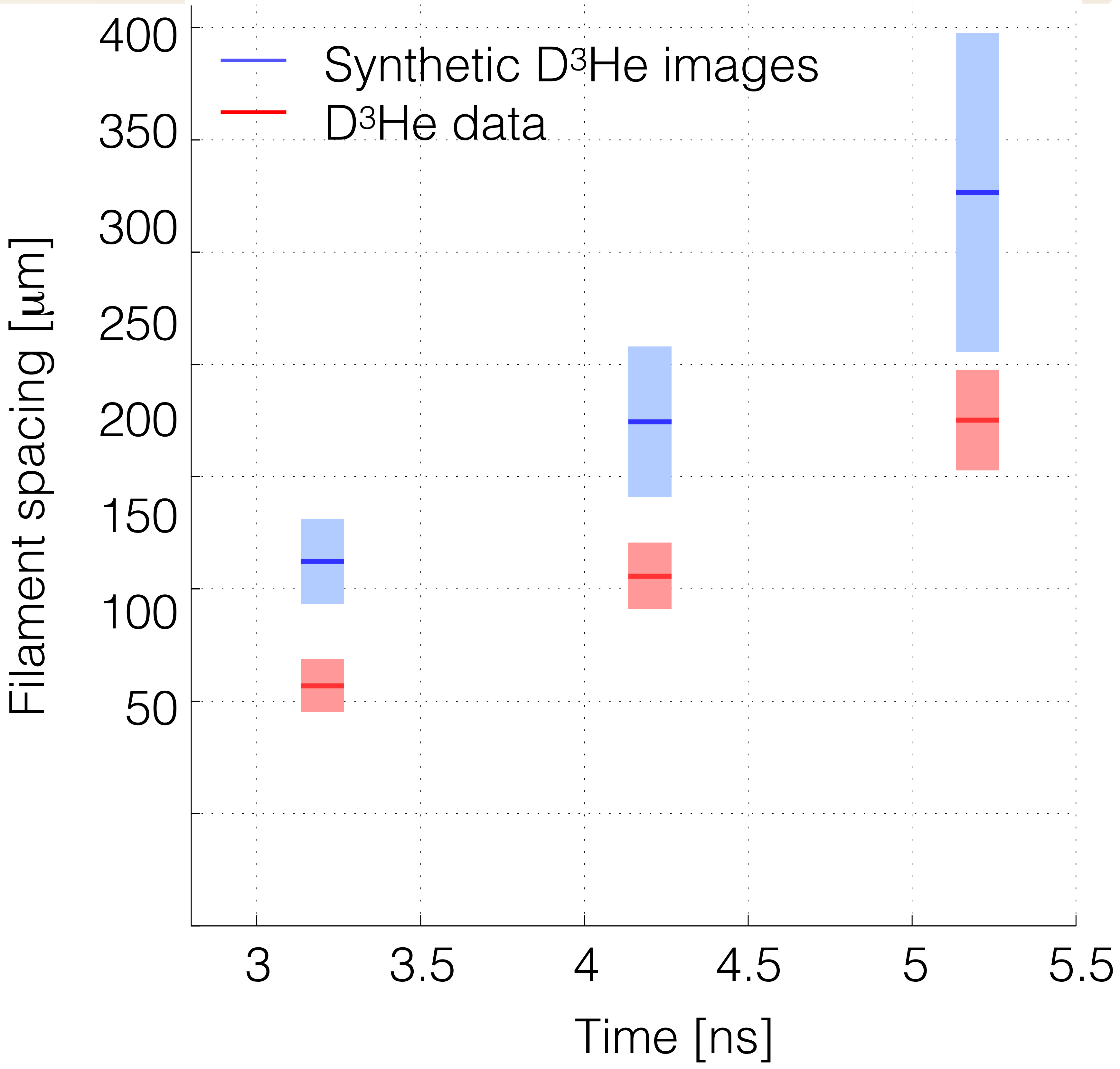


Bulk flow interpenetration

Development of Weibel instability



Non-linear development of Weibel instability

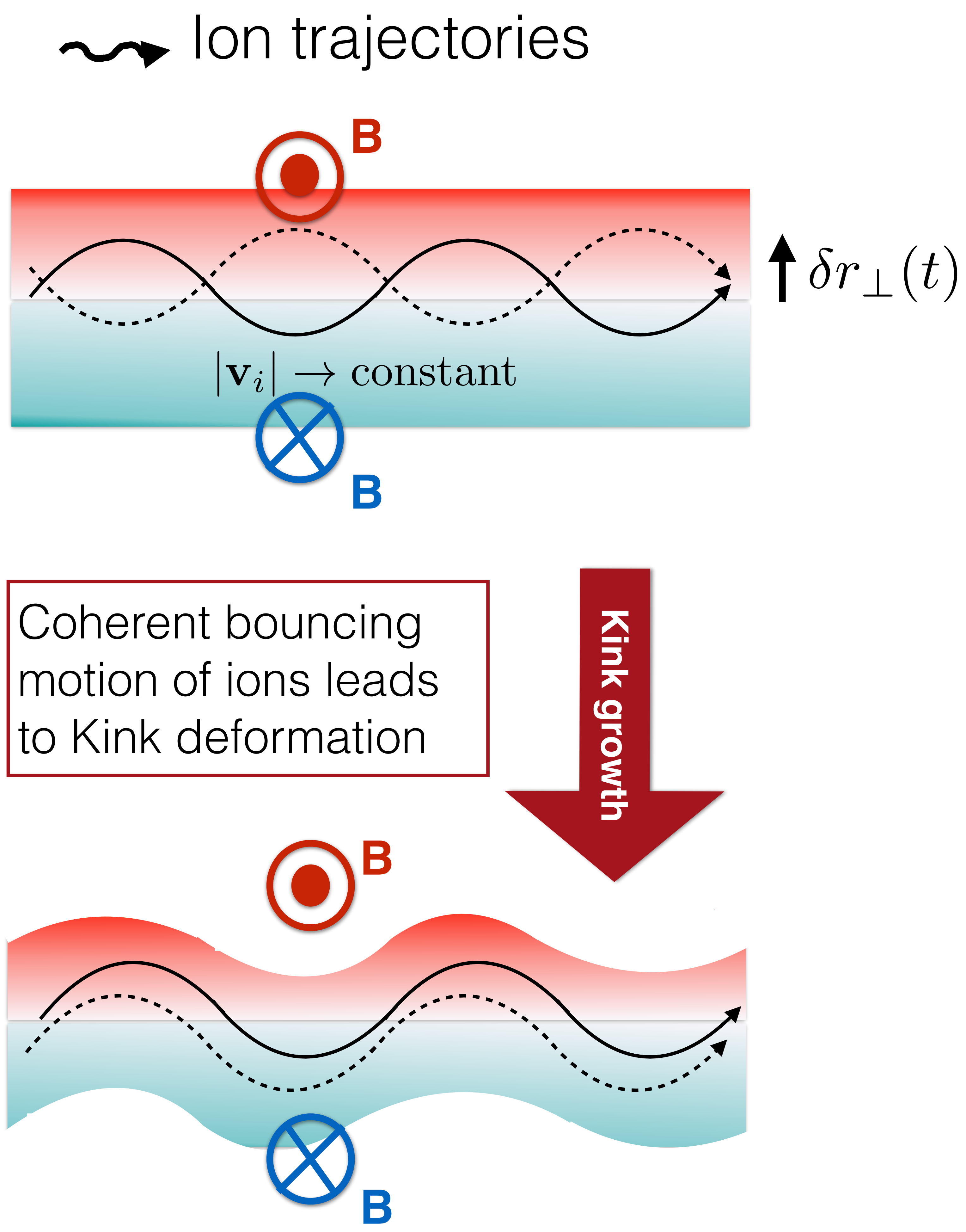


Simulations and experimental measurements indicate magnetization of 1%, consistent with astrophysical shocks

Shock formation requires larger interpenetration regions/higher density flows

C. Huntington, F. Fiuza *et al.* Nat. Physics (2015)

Kink deformation of filaments is due to resonant bouncing of ions



Proton trajectory to leading order in $\delta r_\perp / \lambda_B$

$$\frac{d^2 \delta r_\perp}{dt^2} + \omega_B^2 \delta r_\perp = 0$$

Bouncing frequency: $\omega_{\rm bounce}^2 \simeq \dfrac{eBv_i}{\gamma_i m_i (\lambda_{\rm sat}/2\pi)}$

- Most unstable $\lambda_{\rm kink}/2\pi \simeq v_i/\omega_B$
- Growth rate given by typical attraction-time between bouncing ions

$$\Gamma_{\rm kink} \simeq \frac{\omega_{pi}\lambda_B}{4c}\frac{v_i}{\lambda_{\rm kink}} \simeq \frac{\omega_{pi}\lambda_B}{4c}\omega_{\rm bounce}$$

- Saturation when transverse kinetic ion pressure exceed magnetic pressure

$$n_i m_i (\delta r_\perp^{\rm sat}\omega_{\rm bounce}/\pi)^2 \sim B^2/2\mu_0 \Rightarrow \delta r_\perp^{\rm sat} \simeq \pi\lambda_B/4$$

Davidson *et, al.*, Phys. Fluids **15**, 317 (1972); Milosavljevic *et, al.*, Astrophys. J. 641, 978 (2006)
W. Daughton, JGR 103, 29 (1998)

Proton radiography data is consistent with 3D PIC simulations

Initial analysis indicates isotropization of B-field energy at late times

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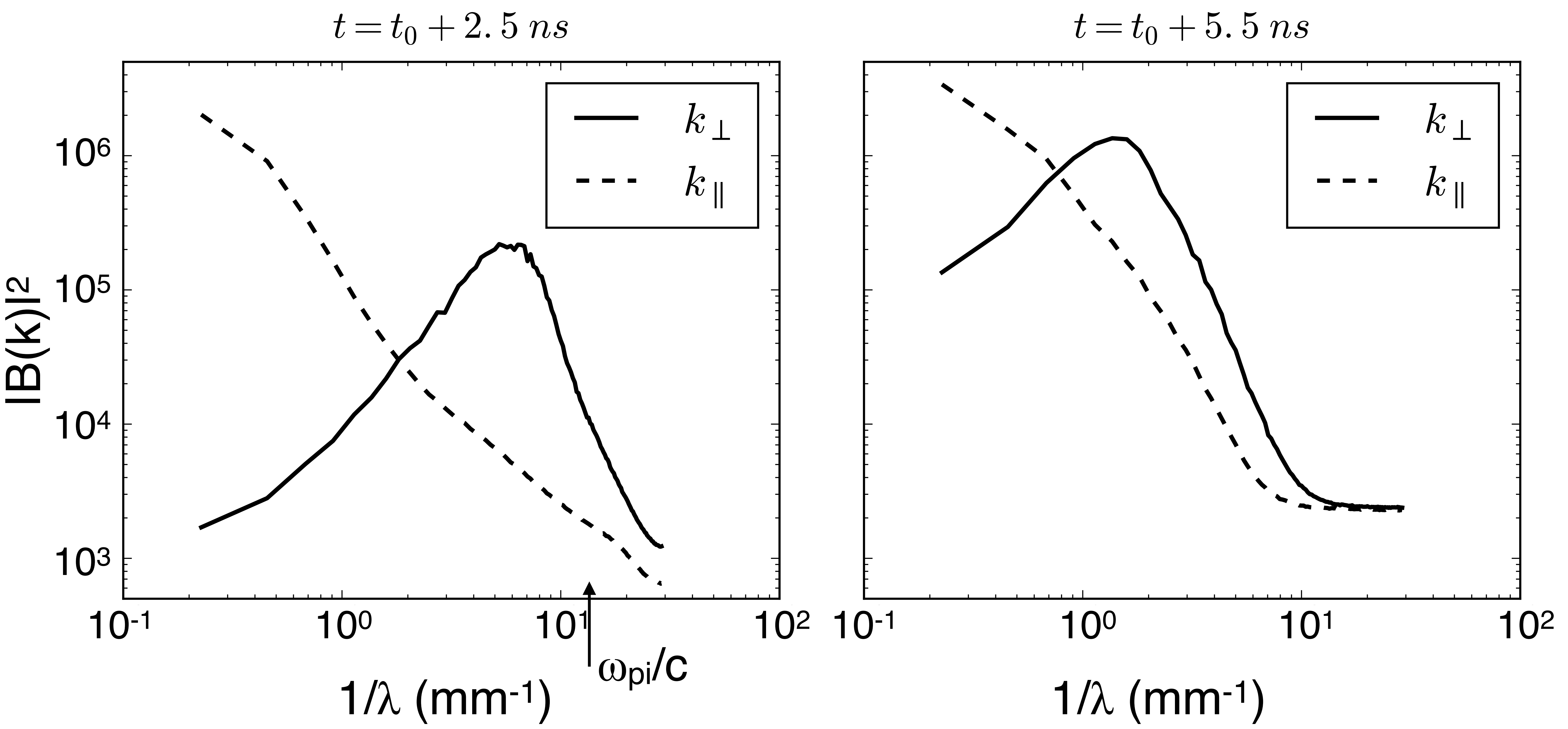
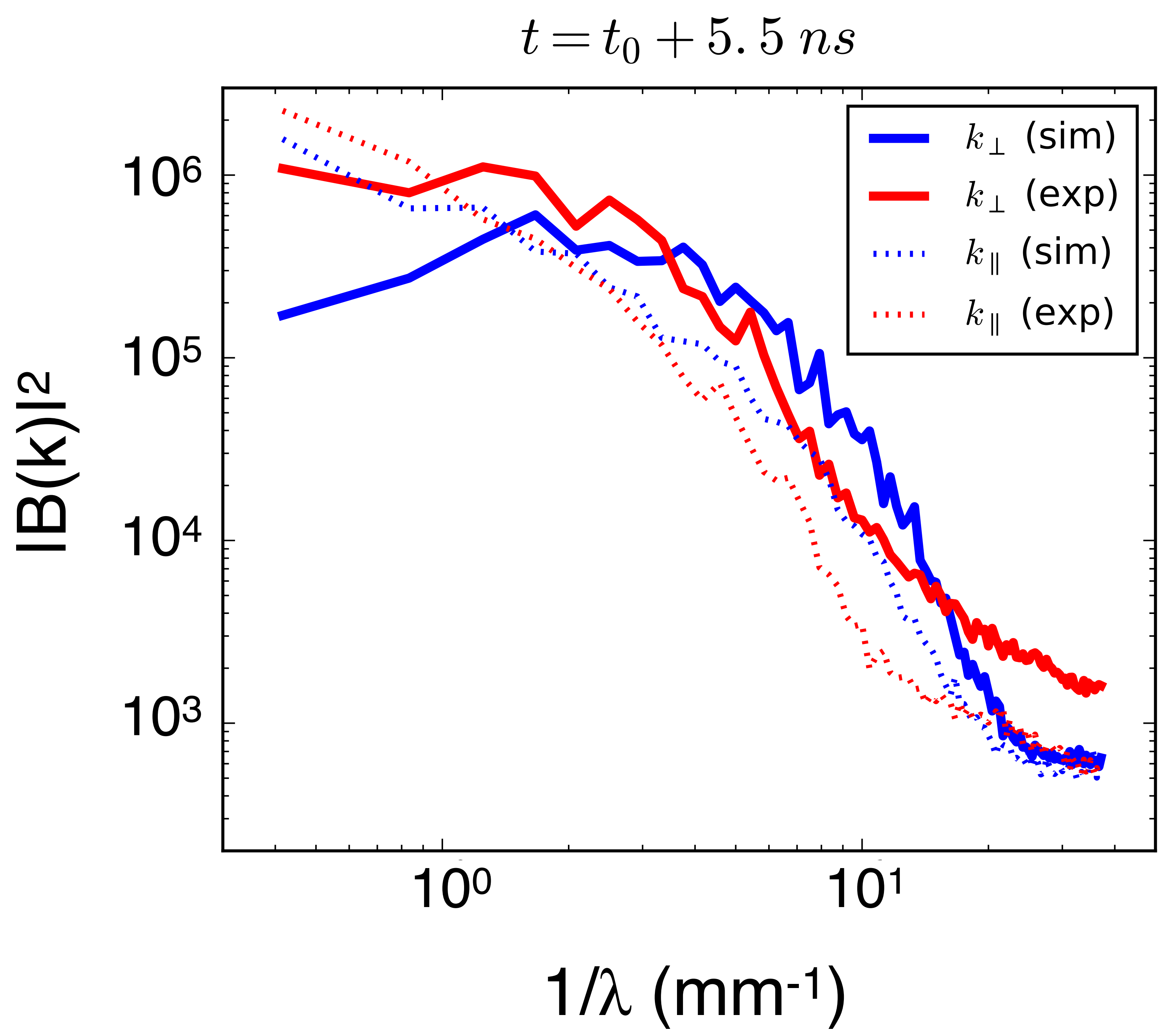
3D PIC simulation shows isotropization of B-field energy



Experiment vs 3D simulation



More detailed analysis is needed to benchmark ion resonance model with experiments

NIF experiments will study shock formation and particle acceleration

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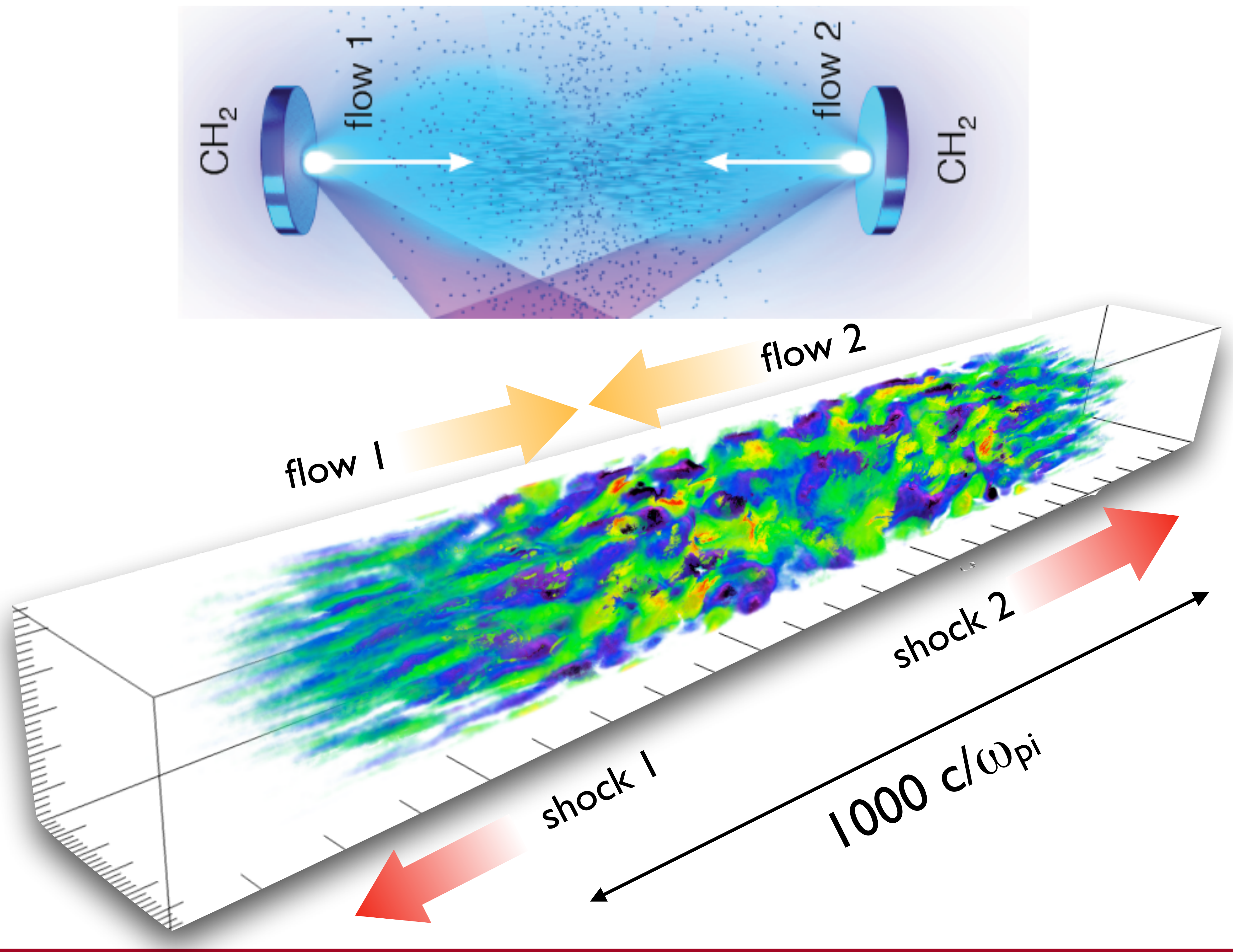
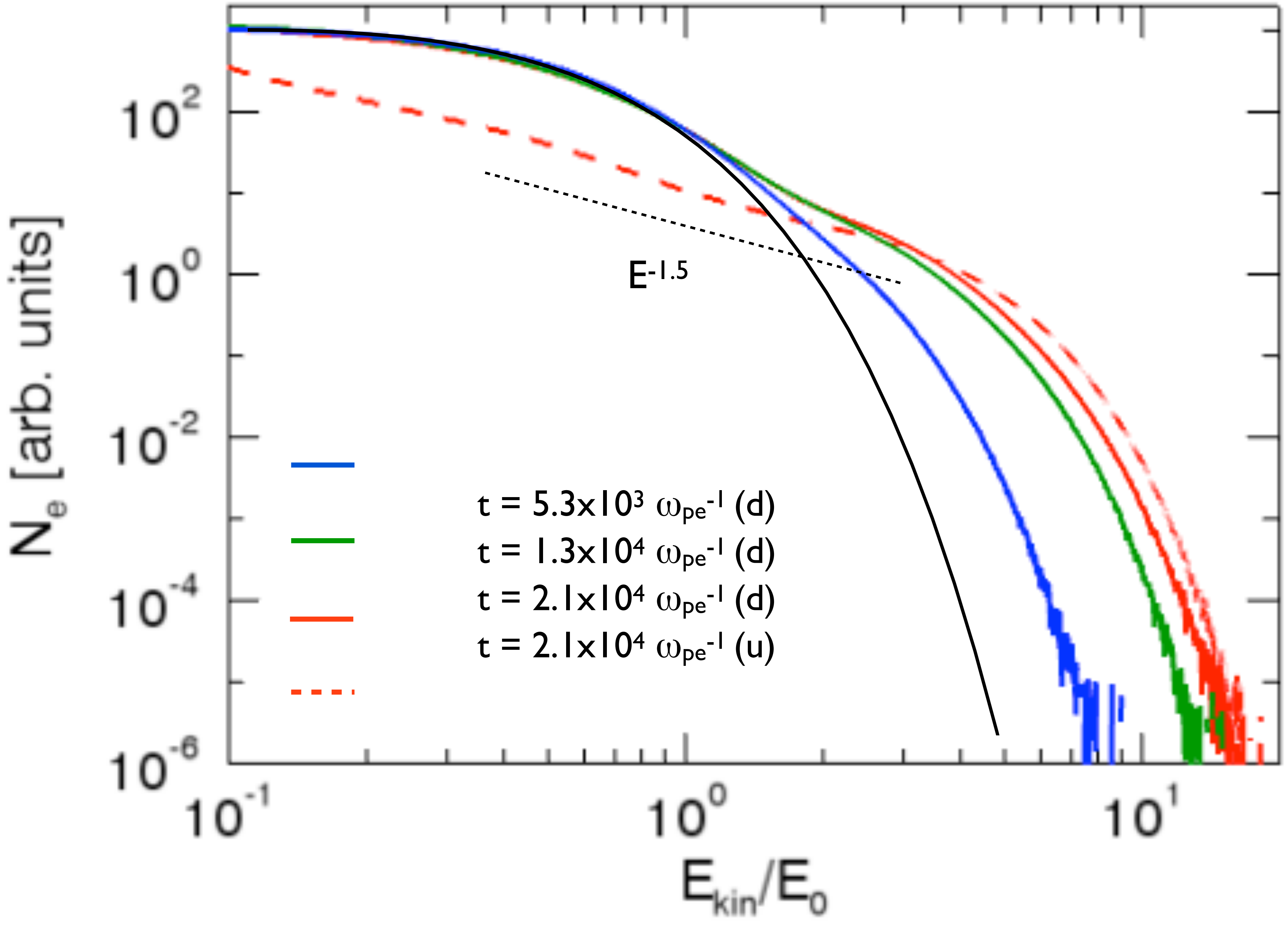
PI: F. Fiuza

500 kJ/target at NIF can generate large system size



Evidence of Fermi acceleration (cosmic rays)



These experiments can validate current models for shocks formation and particle injection

C. Huntington, F. Fiuza, et al, Nature Physics (2015); S. Ross et al, PRL in press (2017)