Energy partition in high-Mach-number collisionless shocks

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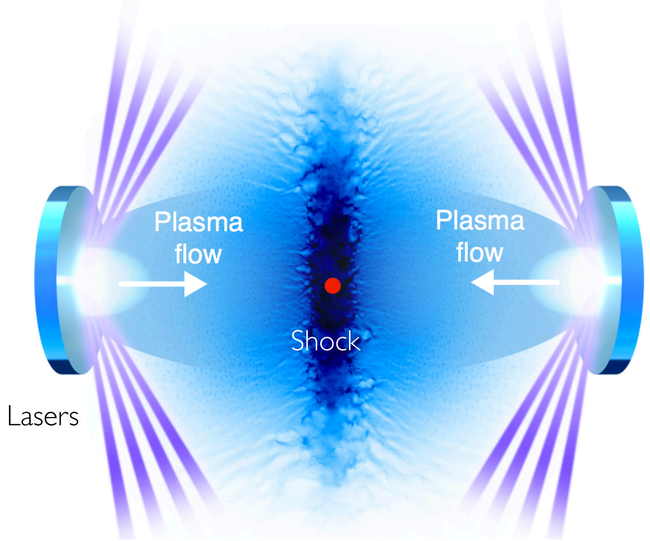

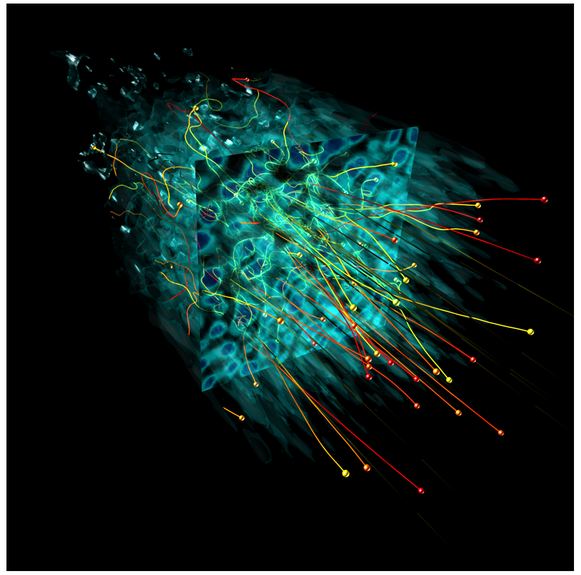

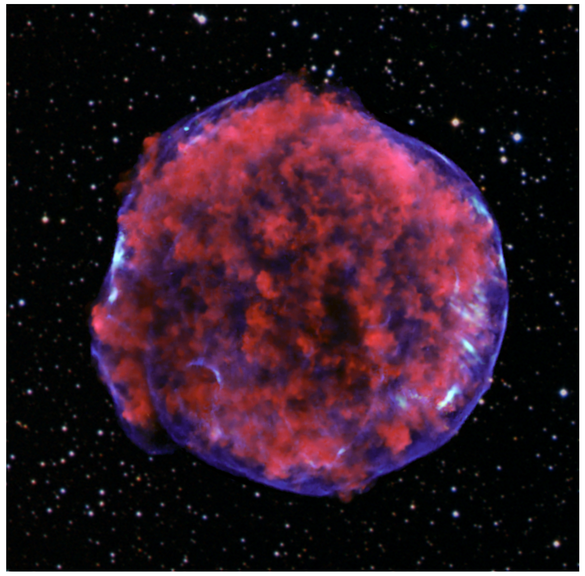

European Research Council

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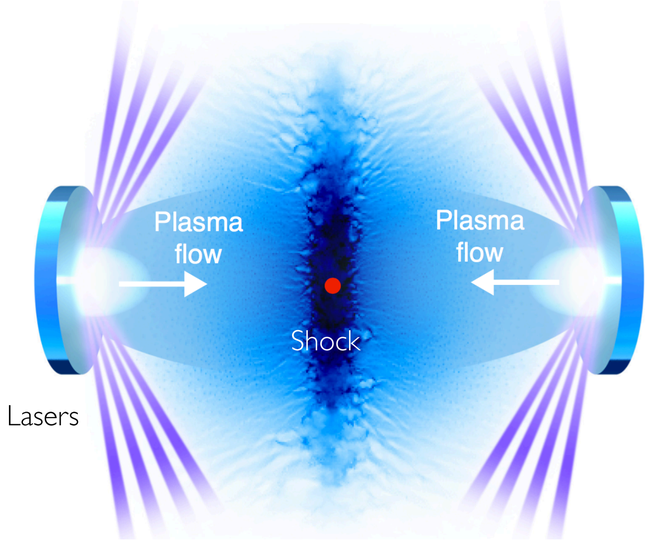
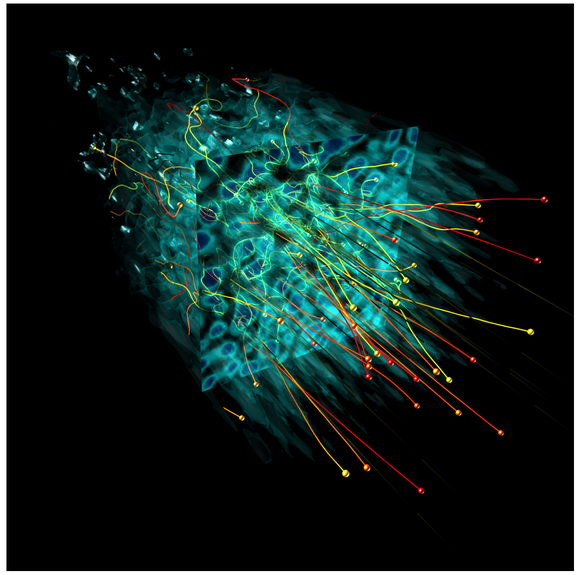
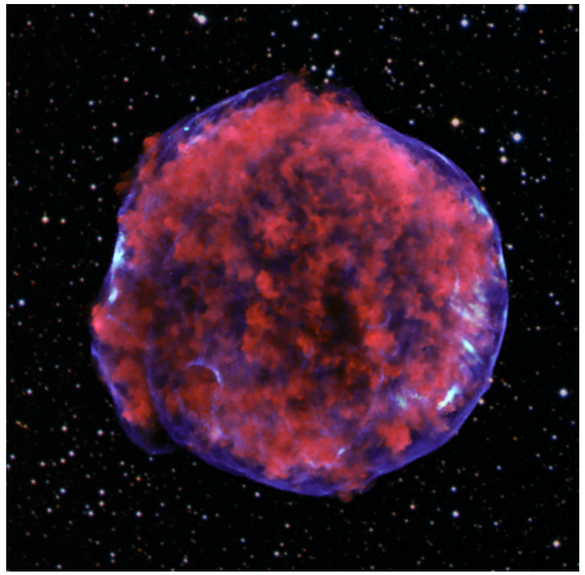
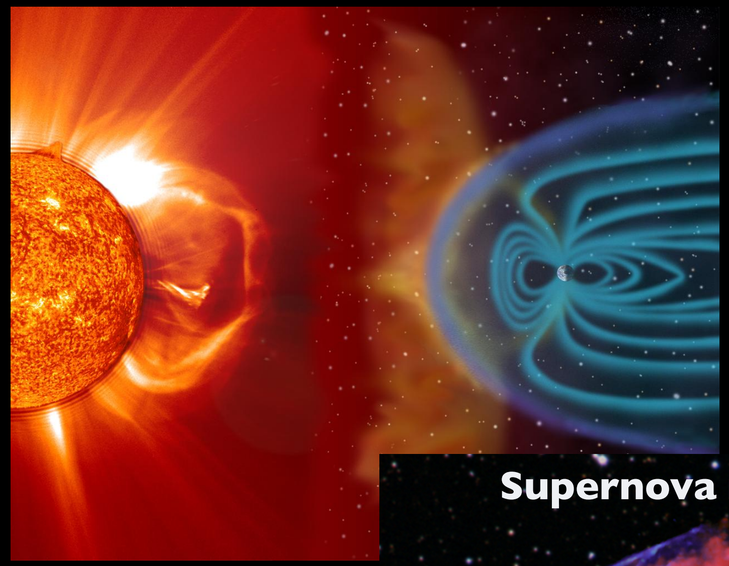




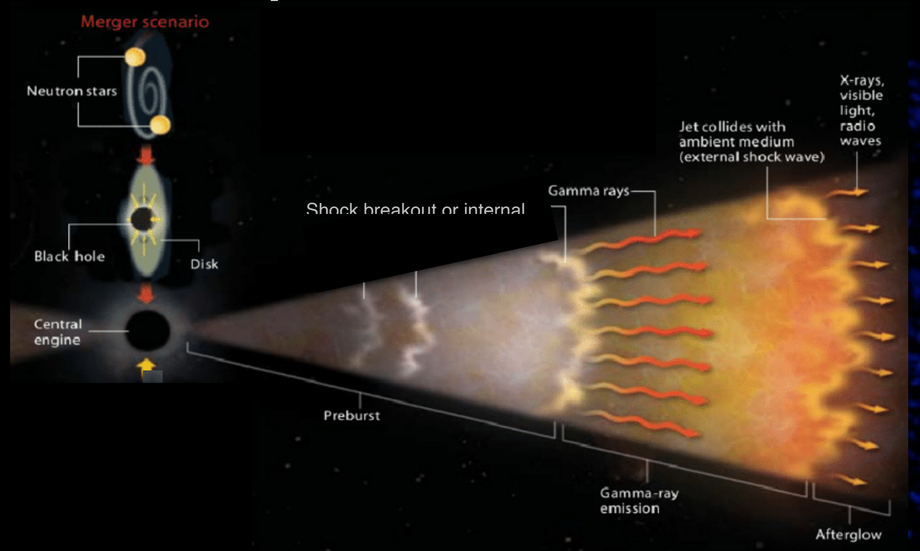


Collisionless shocks are ubiquitous in space and astrophysical plasmas

Earth's bow shock

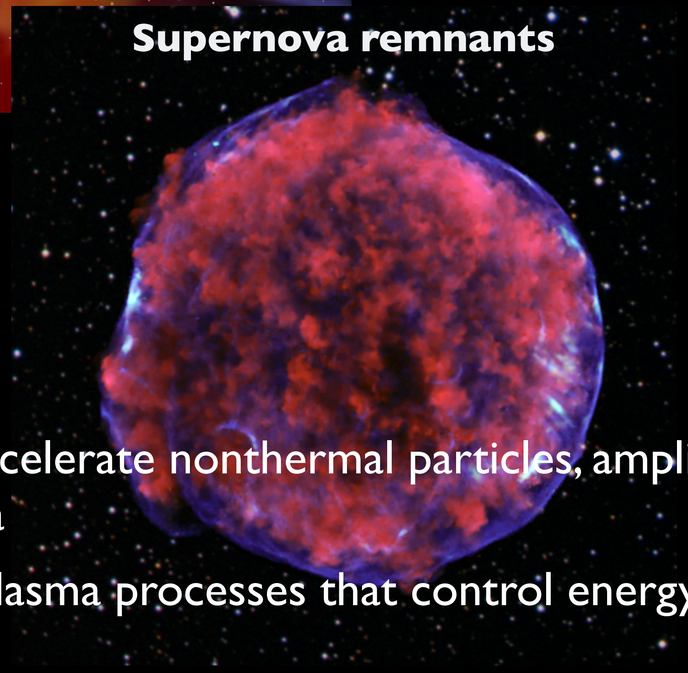


Gamma-Ray Bursts

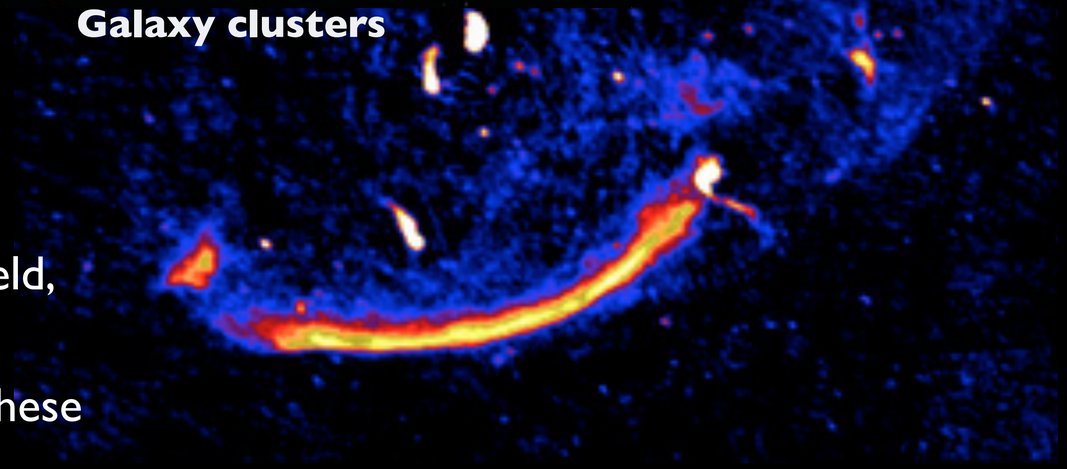


Adapted from Gehrels et al, Sci. Am.

Supernova remnants



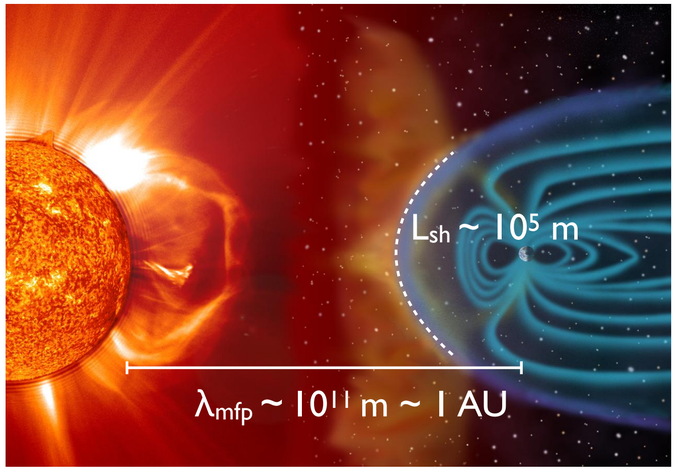
Galaxy clusters

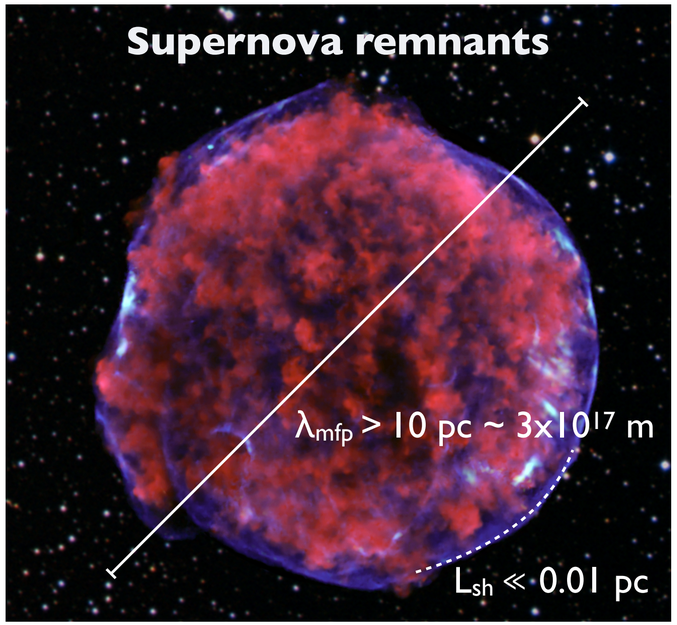


- Observed to accelerate nonthermal particles, amplify magnetic field, and heat plasma
- What are the plasma processes that control energy partition in these environments?

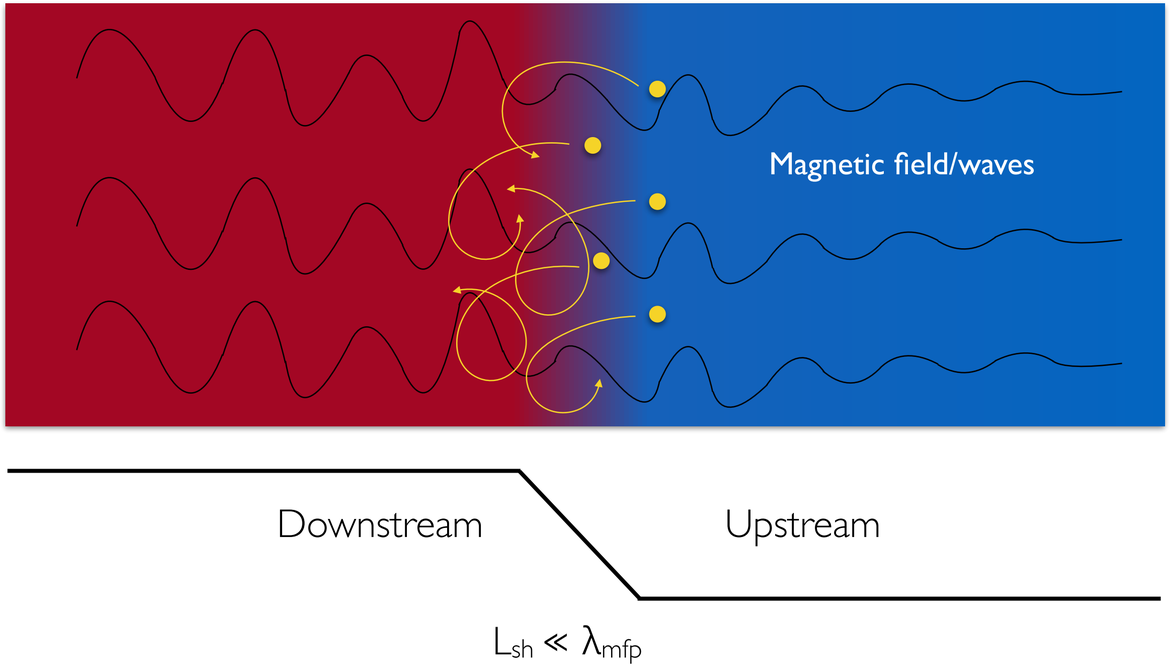
Energy partition is a fundamental open question in collisionless shocks

Earth's bow shock





Collisionless shock



- electron temperature T_e?
- ion temperature T_i? ← ion kinetic energy
- non-thermal particles?

Energy partition is a fundamental open question in collisionless shocks

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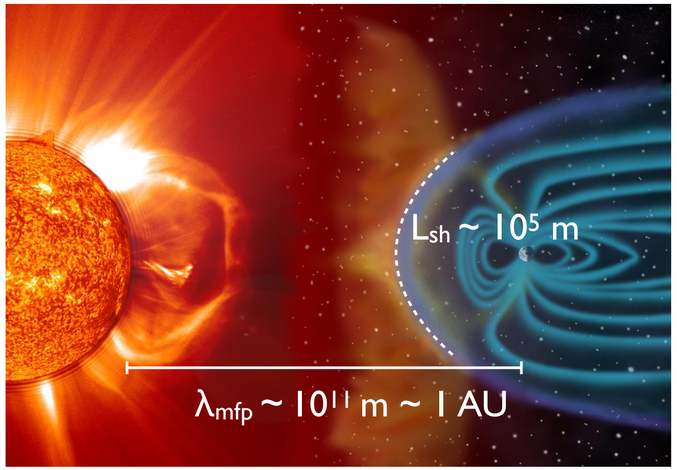
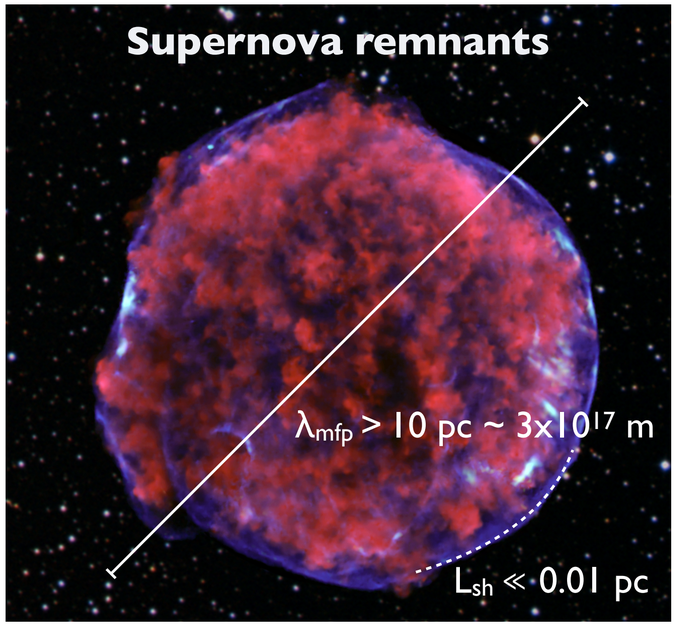
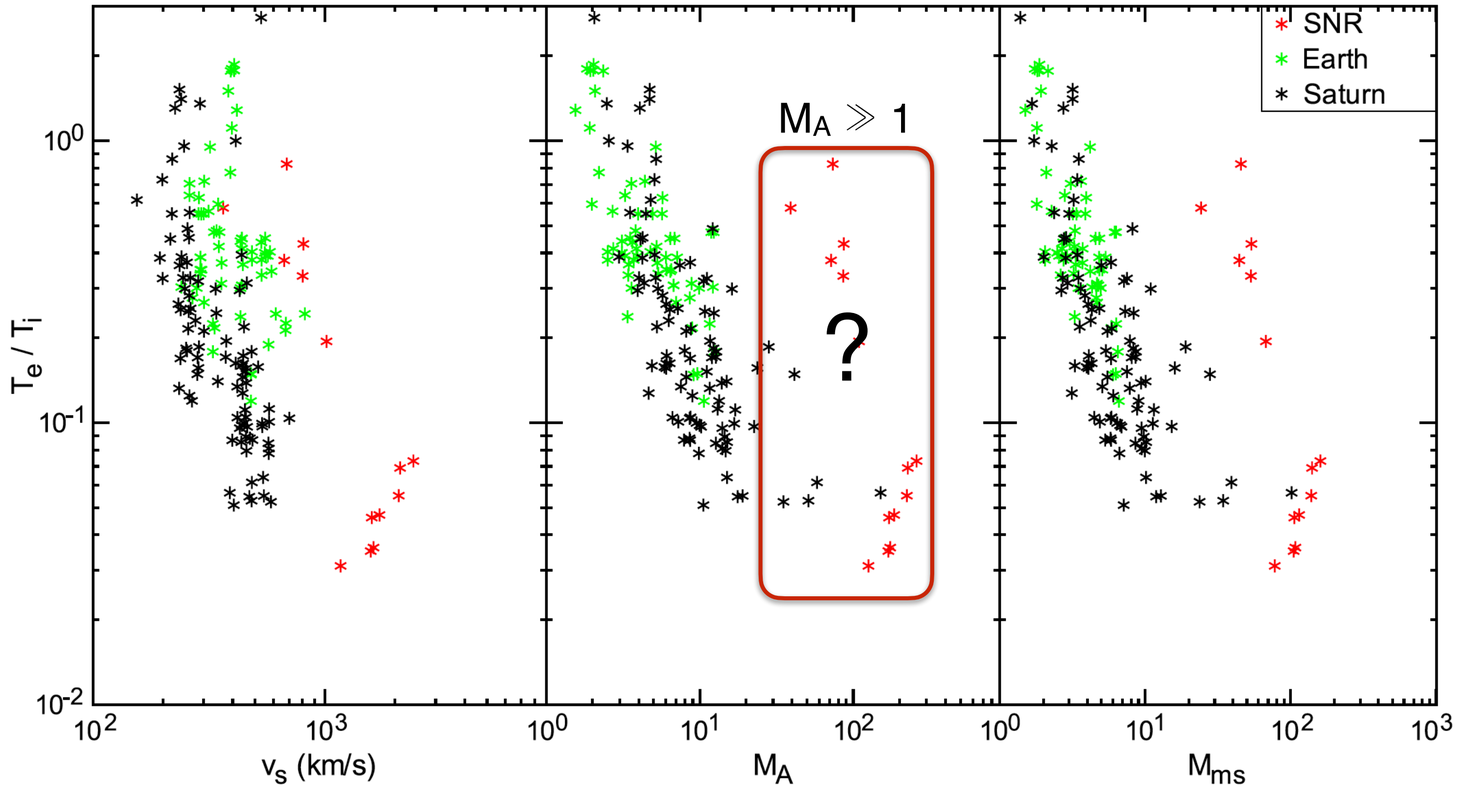
Earth's bow shock



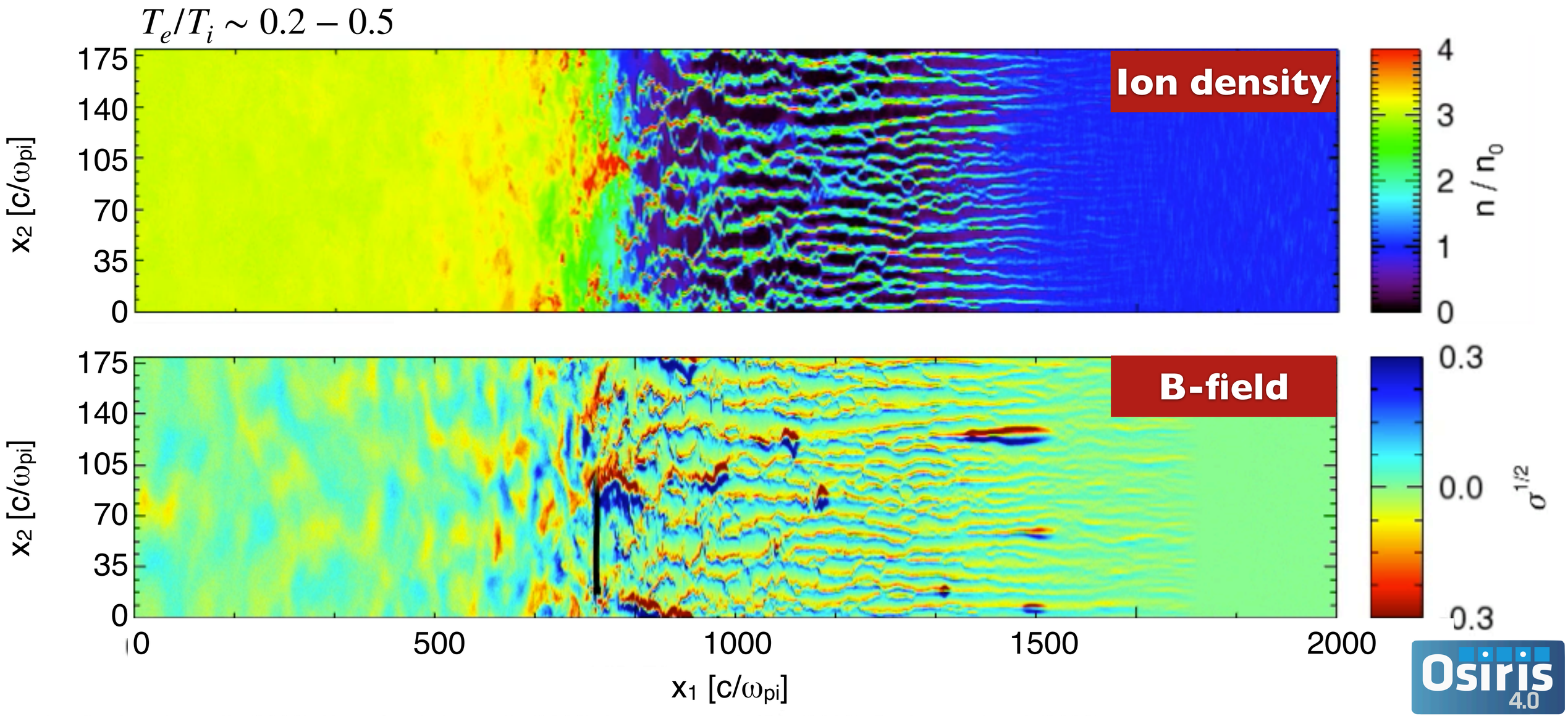


* P. Ghavamian et al Space Sci. Rev. 178, 633 (2013); J. C. Raymond et al, arXiv:2303.08849



- Observations indicate $T_e/T_i \sim 0.05$-1, which is much larger than m_e/m_i
- No well-established models for how wave-particle interactions control T_e/T_i
- **Can laboratory experiments help address this fundamental question?**

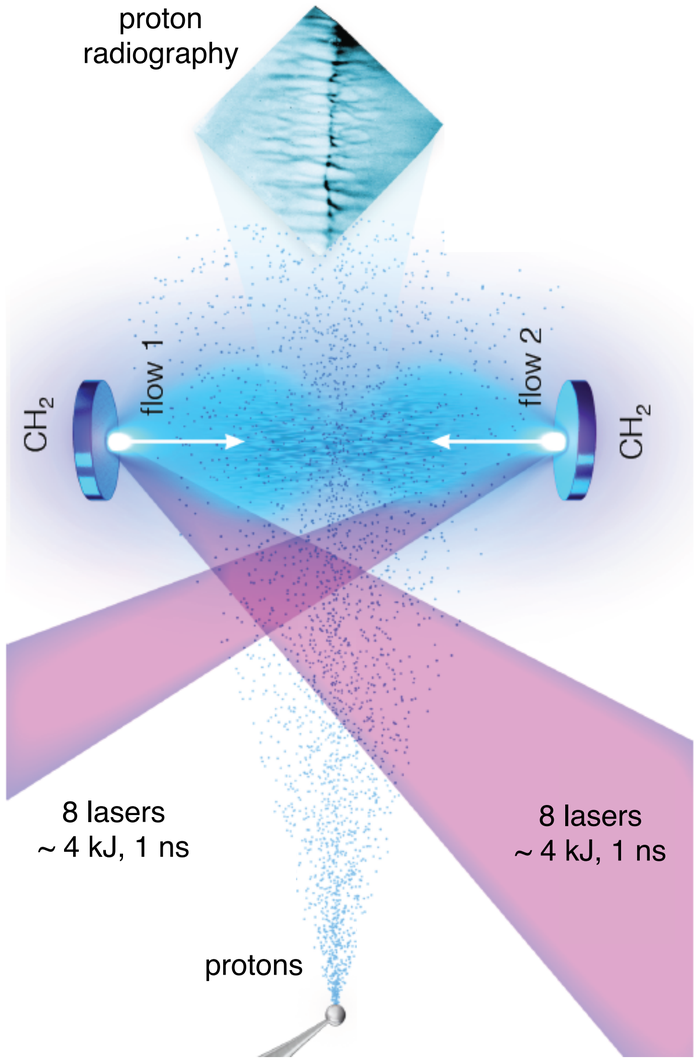
At high-M_A self-generated turbulence dominates shock structure

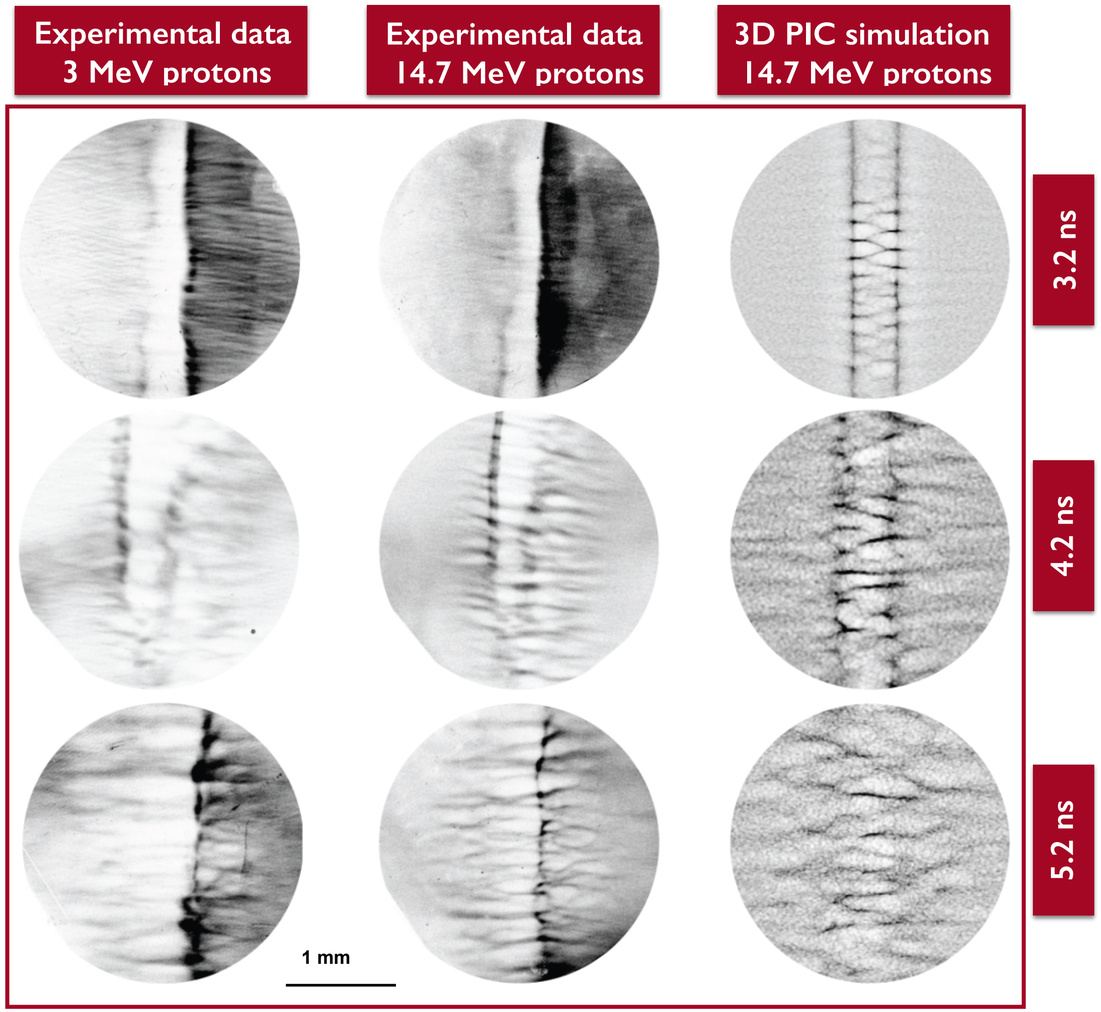


see also Spitkovsky ApJL (2008); Kato & Takabe, ApJL (2008); Lemoine et al, PRL (2019); Bodan et al, ApJ (2020)

B-field amplification by the Weibel instability observed experimentally

Experiments at the OMEGA laser facility (LLE, NY)



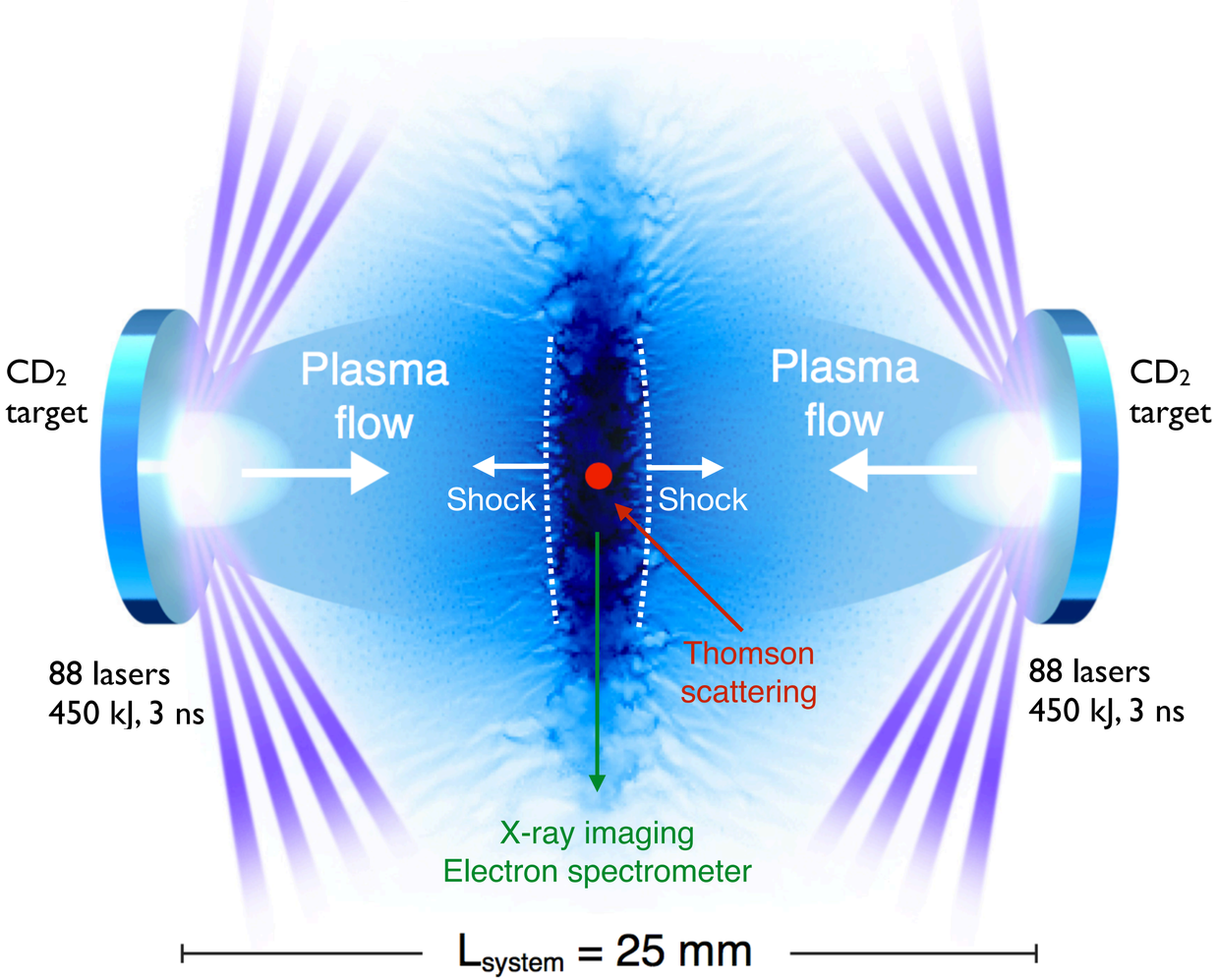


Proton deflection consistent with 1% conversion efficiency from kinetic to magnetic energy

C. Huntington, F. Fiuza *et al*. Nat. Physics 11, 173 (2015); G. Swadling et al., PRL 124, 215001 (2020)

Platform to study high-Mach number shocks on the National Ignition Facility (NIF)

NIF laser system delivers ~ 1MJ in 190 beams

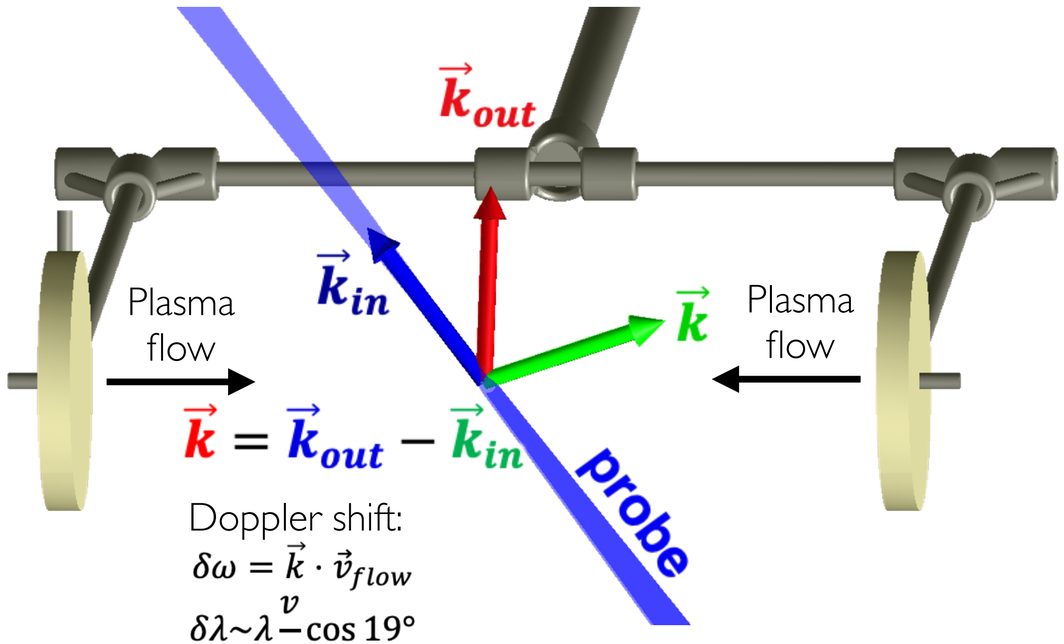


Exploring plasma regimes relevant to young SNR shocks

Parameter	NIF experiments	Typical young SNR (for example, SN 1006)
Shock velocity (km s^{-1})	1,000–2,000	3,000–5,000
Ambient magnetic field (G)	2×10^{4}	3×10^{-6}
Ambient plasma density (cm^{-3})	5×10^{19}	0.2
Ambient plasma temperature (eV)	500	1
System size (cm)	2.5	3×10^{19}
Collisionality ($L_{system}/L_{m.f.p.}$)	0.03	0.01
Sonic Mach number (v_{sh}/c_S)	12	400
Alfvén Mach number (v_{sh}/v_A)	400	400

F. Fiuza et al., Nature Physics 16, 916 (2020)

NIF experiments use Thomson scattering to measure n, v, T

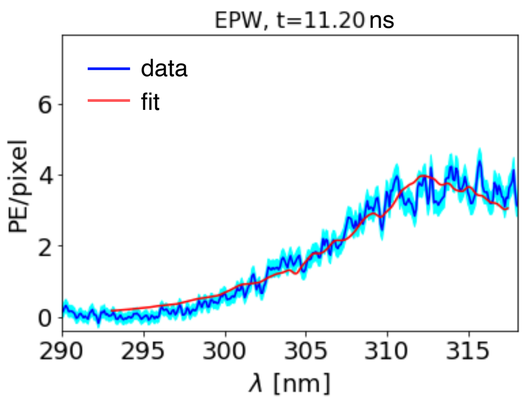


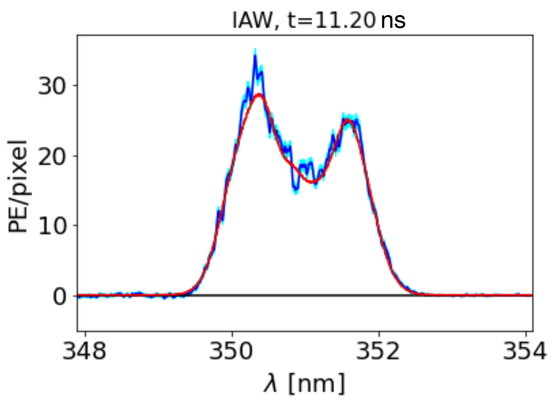
$$\vec{k} = \vec{k}_{out} - \vec{k}_{in}$$

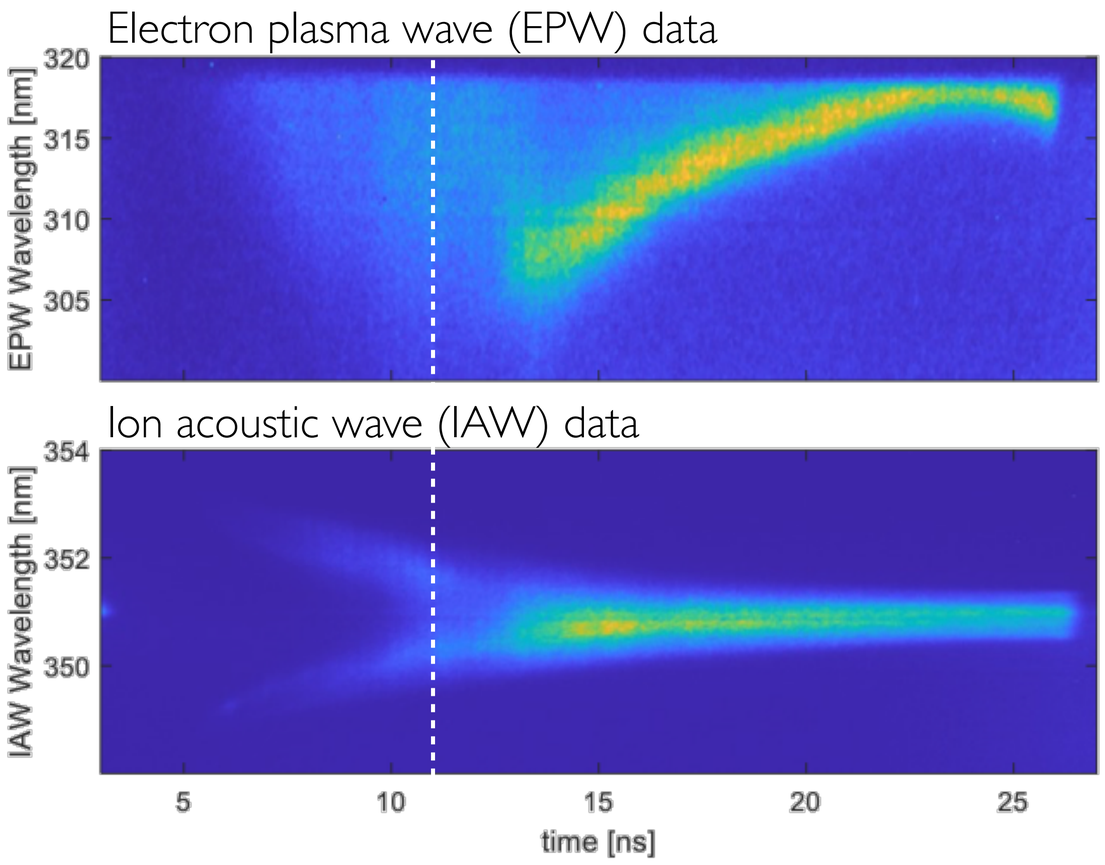
Doppler shift:

$$\delta\omega = \vec{k} \cdot \vec{v}_{flow}$$

$$\delta\lambda \sim \lambda \frac{v}{c} \cos 19°$$







Laser drive | Flows interact, slow down, and heat | Shock is formed | Shocked plasma expands and cools

Formation of high-Mach-number collisionless shock on NIF

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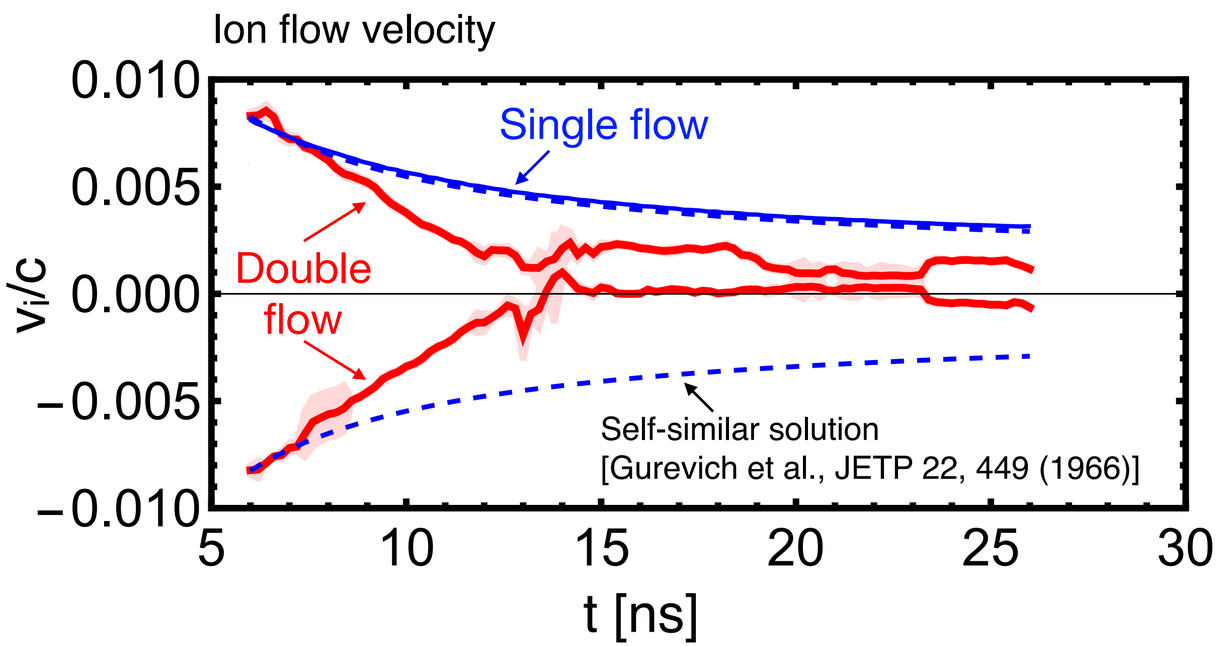
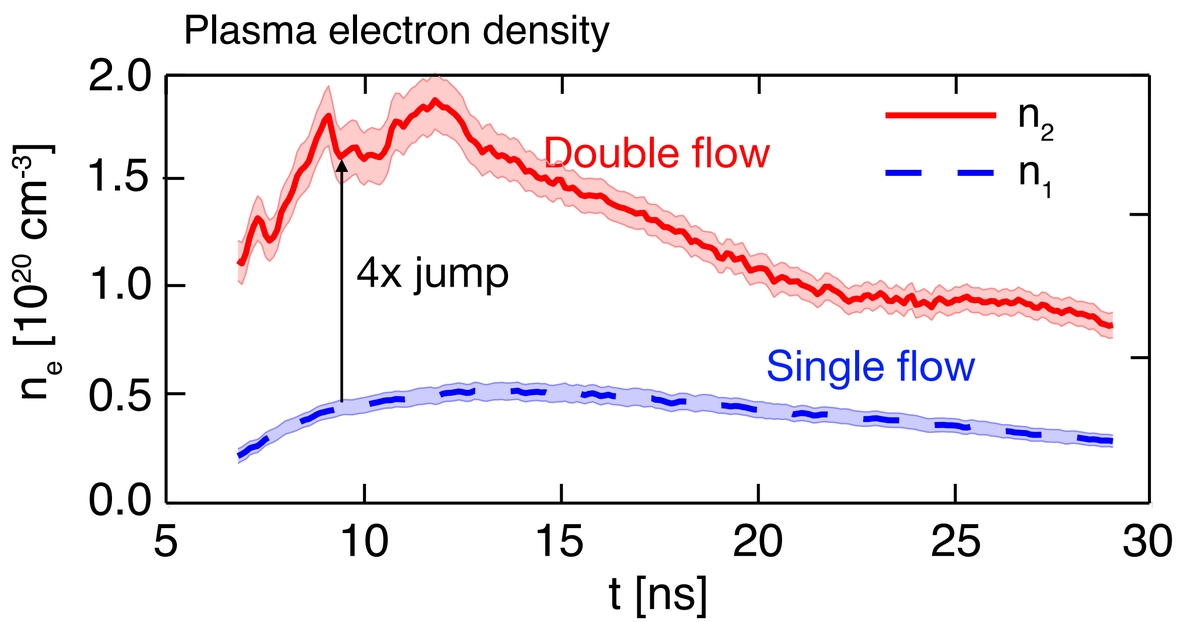
Evolution of plasma flow velocity



$v_{\rm flow} \simeq 1750 {\rm km/s}$ $\lambda_{\rm mfp} \simeq 80 {\rm cm} \gg L_{\rm system}$

Flows strongly slowed down by self-generated turbulence

Density evolution of shocked plasma

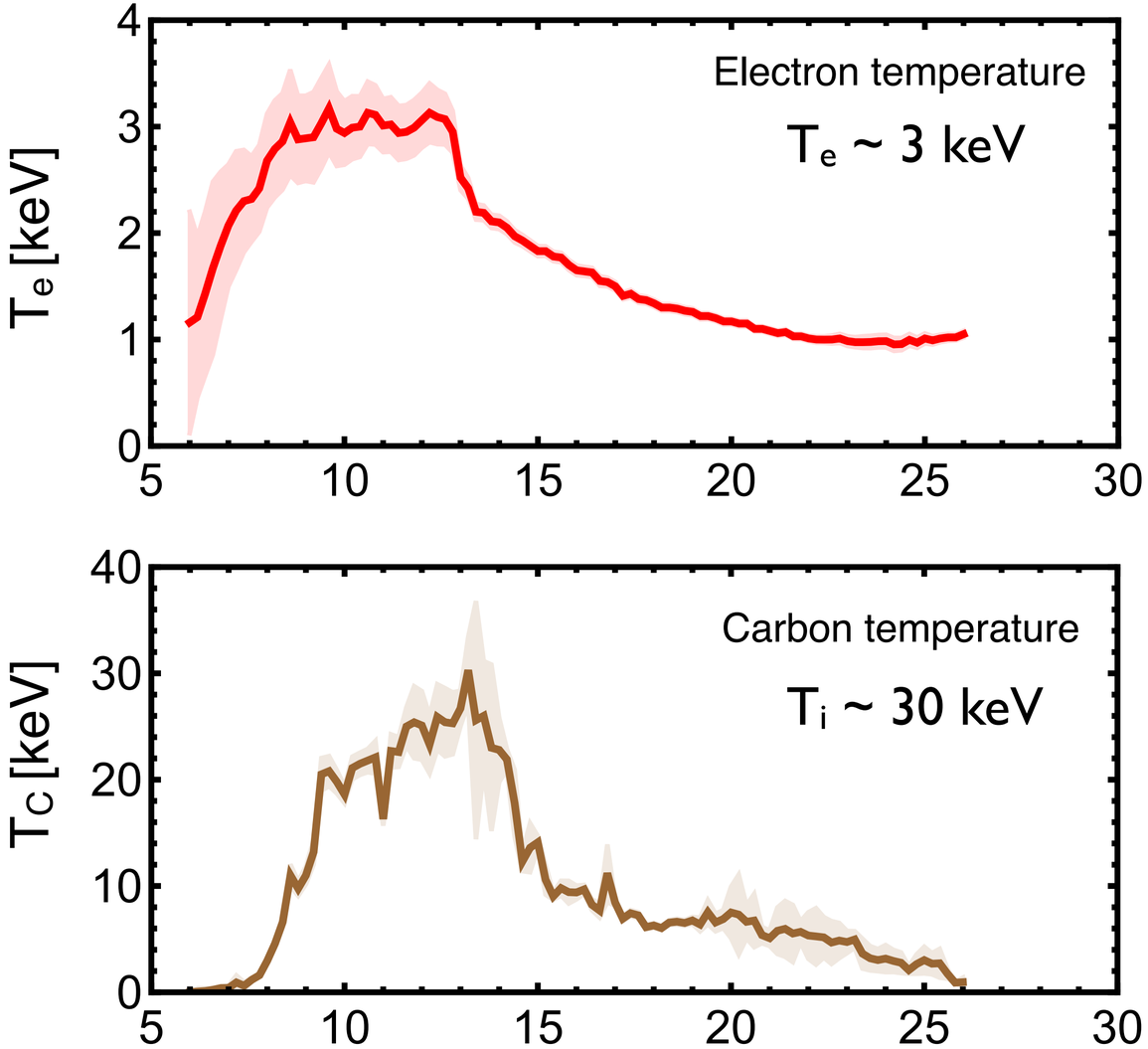


$$\frac{n_2}{n_1} = \frac{(\Gamma_{\rm ad}+1)M^2}{2+(\Gamma_{\rm ad}-1)M^2} \simeq 4$$

Strong collisionless shock observed!

F. Fiuza et al., Nature Physics 16, 916 (2020)

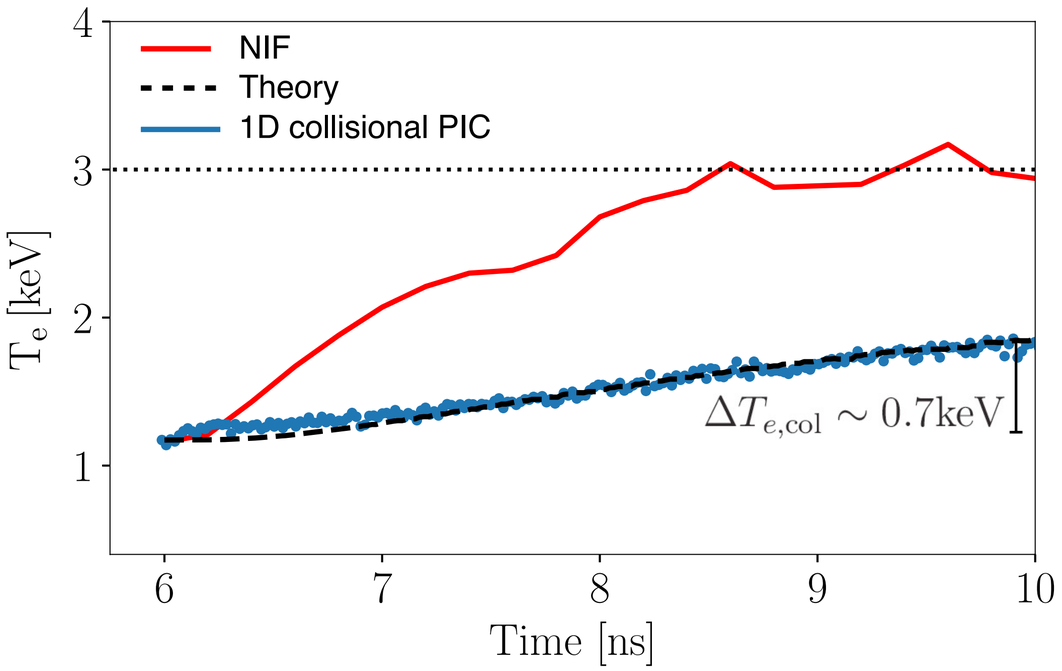
Electrons gain important fraction of total ion energy



G. Swadling et al, in preparation (2023)

Electron collisional heating is subdominant

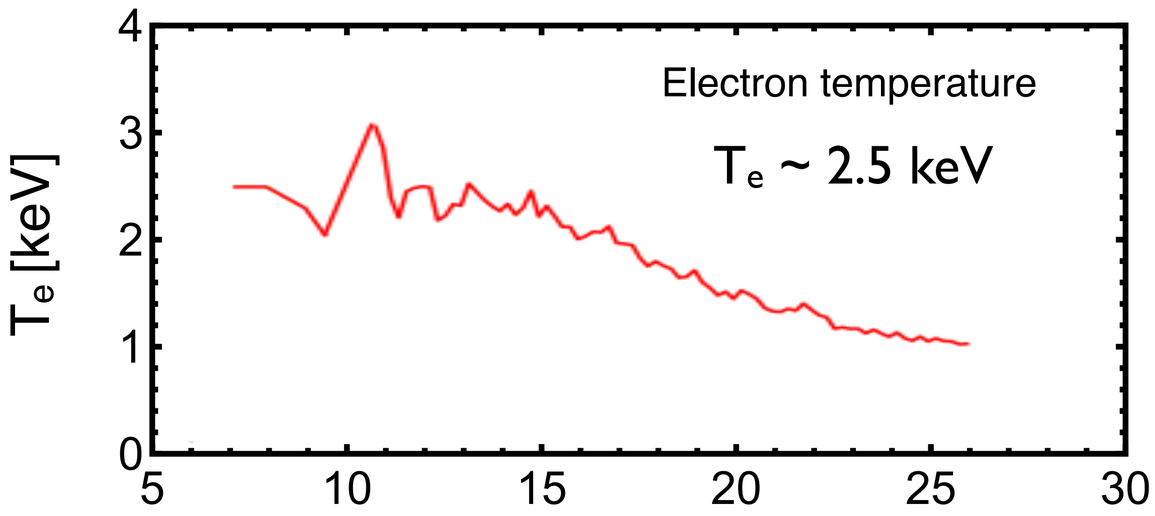
$$\frac{dT_e}{dt} = \frac{2}{3} m_e (\nu_{ei1} + \nu_{ei2}) \frac{n_{i1} n_{i2}}{(n_{i1} + n_{i2})^2} (v_{i1} - v_{i2})^2$$

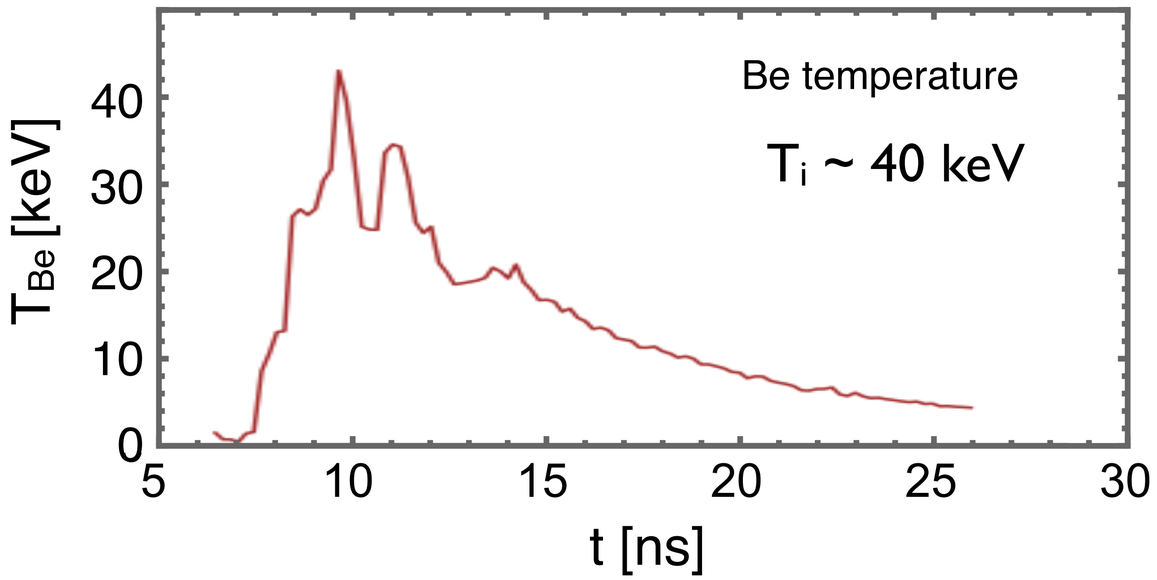


Collisionless temperature ratio: $\frac{ZT_e}{T_i} = 0.24 - 0.45$

Preliminary analysis from Be plasmas confirms collisionless heating ratio

NIF experiments for same conditions but Be targets instead of CH_2/CD_2



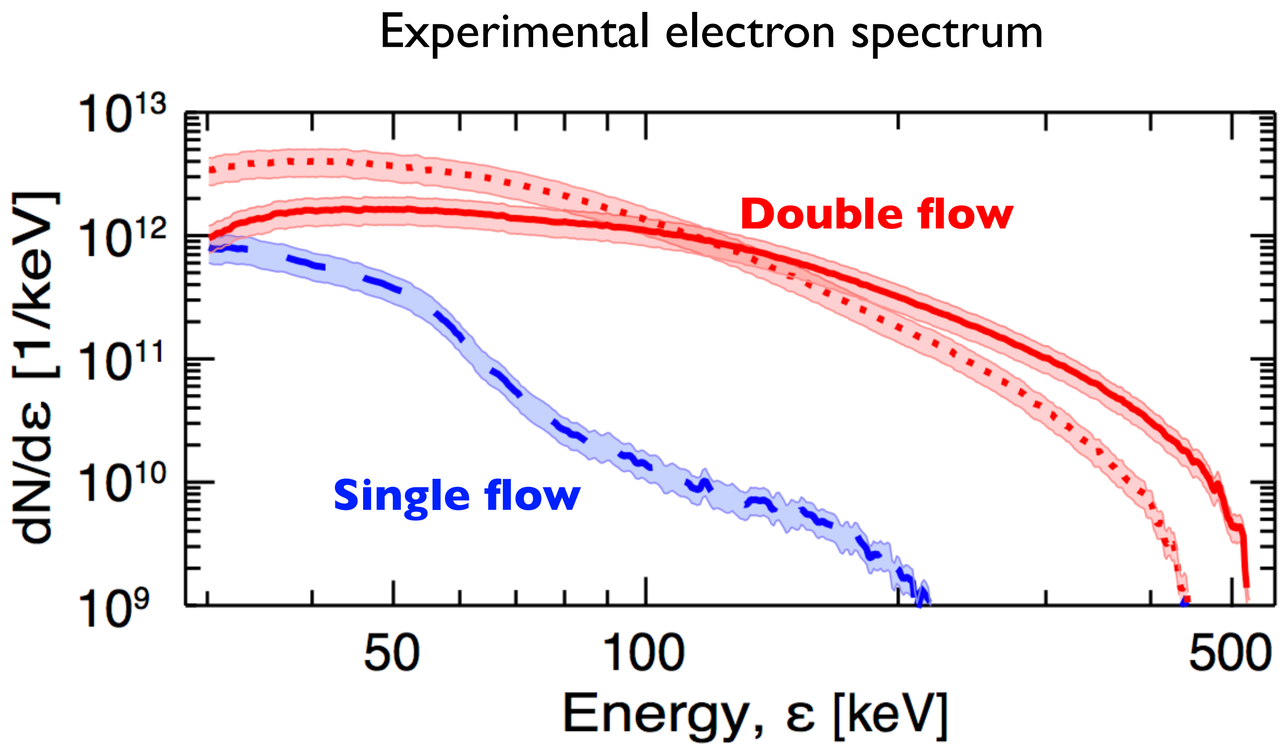


Collisionless temperature ratio: $\frac{ZT_e}{T_i} = 0.25$

Observed Te/Ti is consistent with electron transport model in self-generated magnetic turbulence: see A. Vanthieghem's talk

G. Swadling et al, in preparation (2023)

Experiments show clear evidence of nonthermal electron acceleration



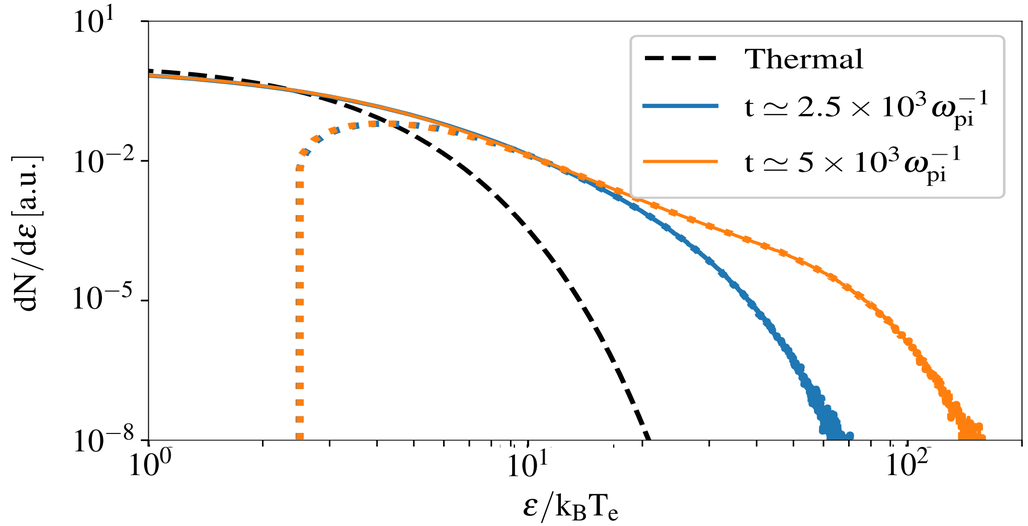
- Significantly larger (>10x) number and energy of electrons from flow interaction: **electrons must be injected from 3 keV shocked plasma**
- **Electrons are accelerated to > 100x Te in a few ns**
- 500 keV electrons are magnetized at the scale of the shock front: **particle escape is primarily transverse**
- **Maximum energy given by Hillas limit and consistent with experiment:**

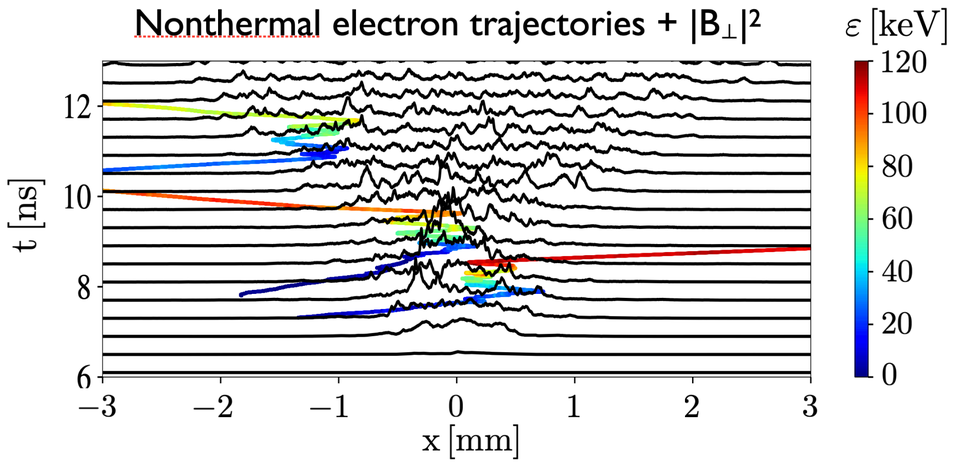
$$\varepsilon_{\max} = |e|(u_{sh}/c)BR_{sh} \sim 500\text{keV}$$

F. Fiuza et al., Nature Physics 16, 916 (2020)

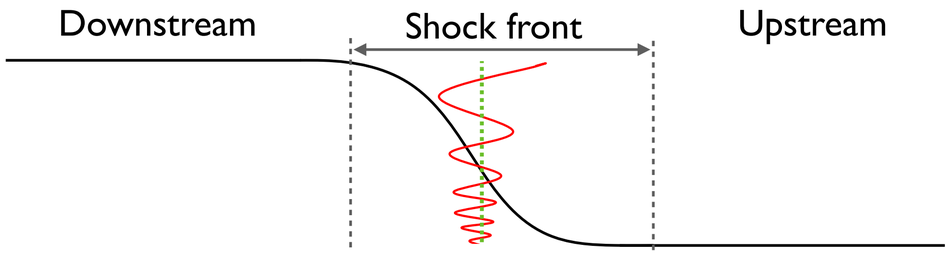
Electron injection via modified diffusive shock acceleration

PIC simulations show consistent nonthermal spectra

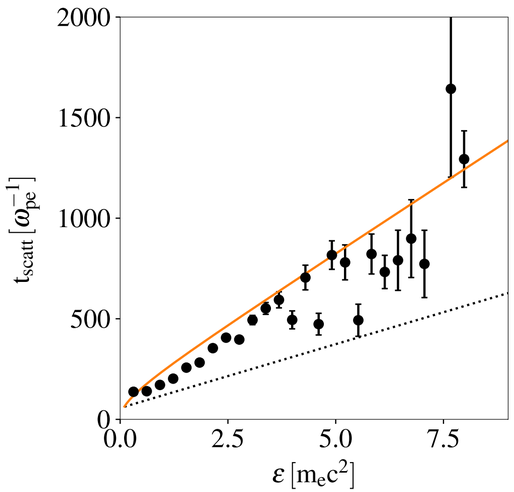


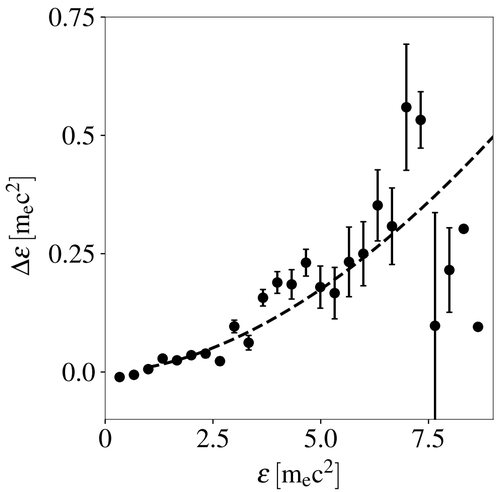


Modified diffusive shock acceleration within shock front



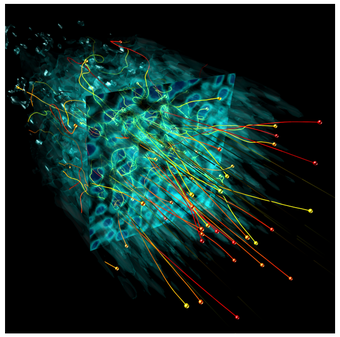
$$\left.\frac{d\varepsilon}{dt}\right|_{m-DSA} \simeq \frac{\Delta\varepsilon}{t_{scatt}^{m-DSA}} \simeq \frac{4}{3}\frac{\Delta u}{c}\frac{v_e}{c}\frac{\varepsilon}{t_{scatt}^{m-DSA}} \propto \frac{v_e}{c}\varepsilon$$



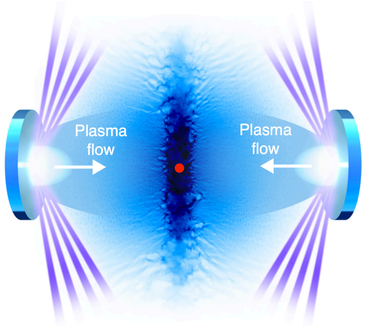


A. Grassi et al., ApJL 958, L32 (2023)

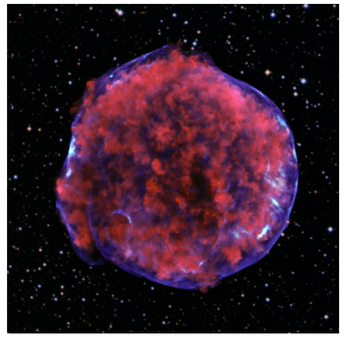
Opening new windows into the inner workings of collisionless shocks



Space and astrophysical observations indicate that electrons can be significantly heated and accelerated in collisionless shocks but **microphysics is still not well understood**



Laboratory experiments at NIF have resolved for the first time electron and ion energy partition in high-M_A shocks and indicate **Te/Ti ~ 0.25 - 0.45**



Observed nonthermal electron acceleration consistent with modified diffusive shock acceleration due to microturbulence **within shock transition**

Laboratory experiments are **opening unique windows** to probe relevant shock microphysics and **test numerical simulations and models**

Interested in working on this topic?

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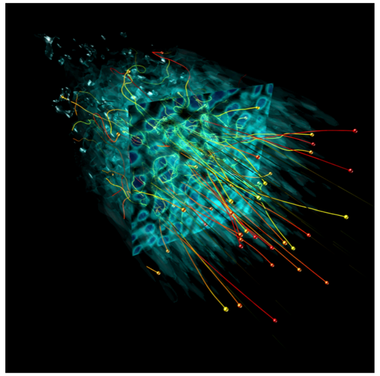
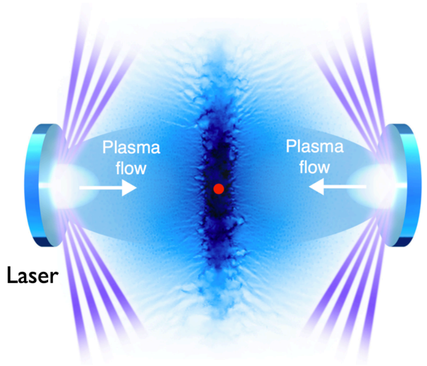
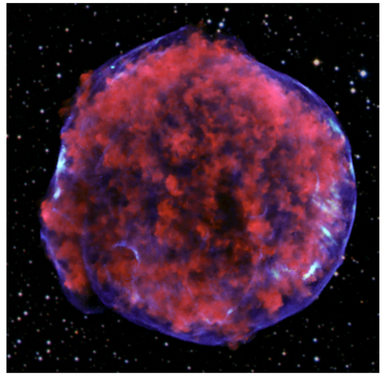
XPACE

Extreme **P**article **Acce**leration in Shocks:
from the laboratory to astrophysics







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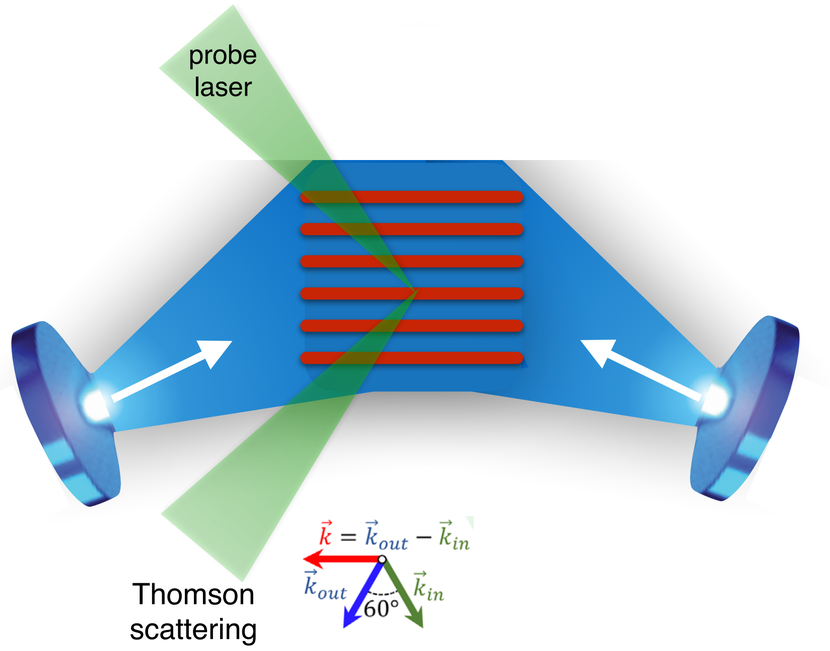
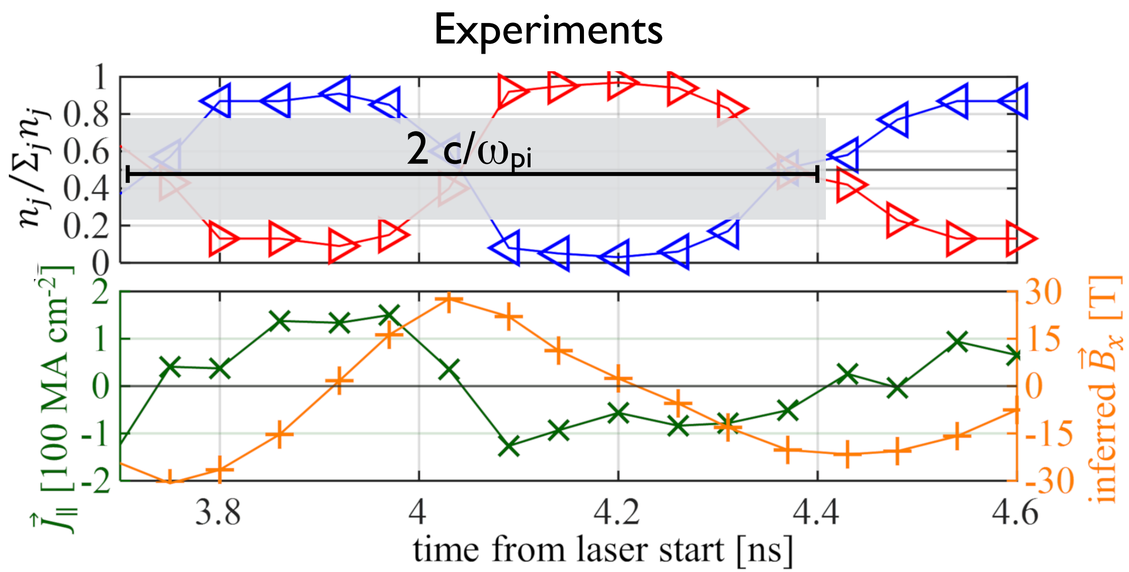
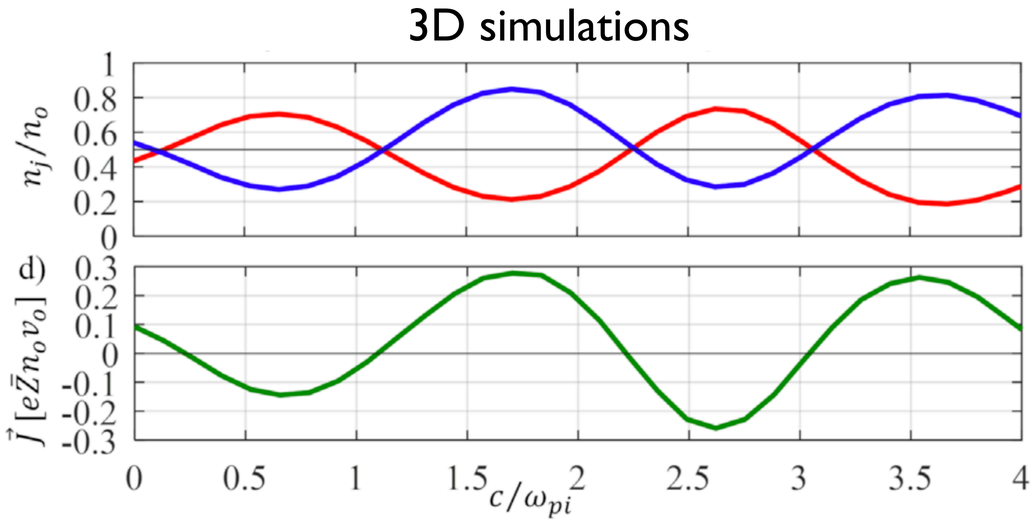
First measurements of local current structure and B-field







Measured B-field = 30 T corresponds to 1% of flow kinetic energy density

Saturation amplitude consistent with magnetic trapping mechanism [Davidson 1972]

G. Swadling, C. Bruulsema, F. Fiuza et al., PRL 124, 215001 (2020)