Laboratory Observation of High-Mach Number, Laser-Driven Magnetized Collisionless Shocks

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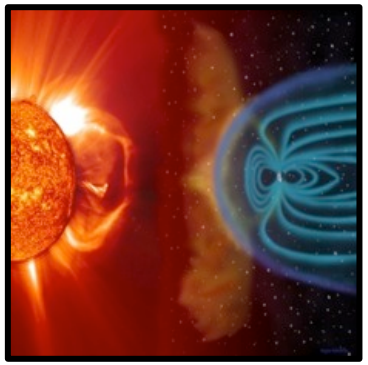
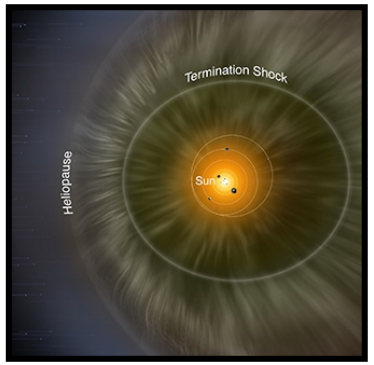
Collisionless Shocks are Prevalent in Many Space and Astrophysical Systems

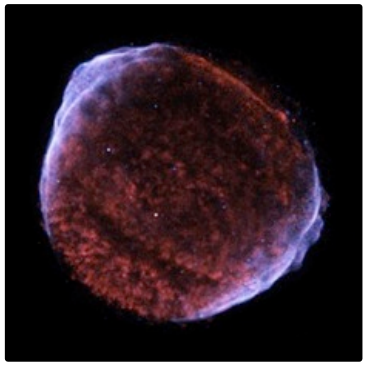
Solar Wind



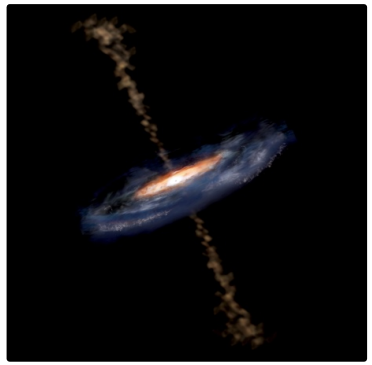
Heliopause



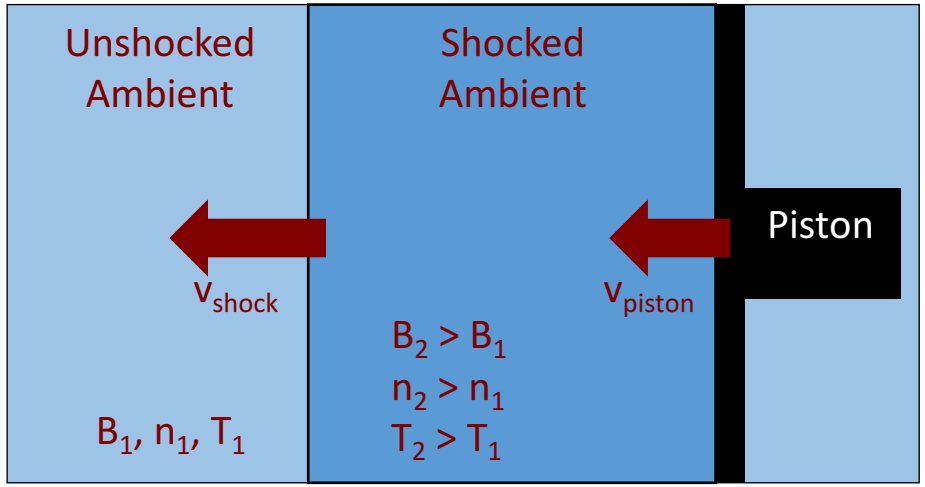
Supernovae Remnants



Active Galactic Nuclei



- Collisionless shocks convert the ram pressure of incoming supersonic flows to thermal pressure over length scales much shorter than the collisional mean free path



Drake, PoP, 2000

Collisionless Shock Studies Originated with Laboratory Experiments

- Pioneering experiments were carried out soon after the discovery of collisionless shocks
  - Successfully generated collisionless shocks
  - But limited diagnostics, magnetic geometries, and Mach numbers

Paul, *et al.*, Nature, 1965
Kurtmullaev, *et al.*, J. App. Mech. Tech. Phys., 1965
Goldenbaum, *et al.*, PoF, 1967
Stamper, *et al.*, PoF, 1969

- Laser-driven experiments appeared shortly thereafter
  - More flexible experimental parameters
  - But not enough laser energy to drive full shocks

Cheung, *et al.*, PRL, 1973
Borovsky, *et al.*, ApJ, 1984
Ripin, *et al.*, PRL, 1987

- Ultimately, experiments replaced with satellite missions
  - Very successful at measuring Earth's bow shock
  - But largely limited to 1D datasets, lower Mach numbers ($M<10$), and pre-formed conditions

Collisionless Shock Studies Originated with Laboratory Experiments

- Experiments in the 1960s-1970s pioneered laboratory shock experiments
  - Successfully generated collisionless shocks
  - But limited diagnostics, magnetic geometries, and Mach numbers

Paul, *et* al., Nature, 1965
Kurtmullaev, *et* al., J. App. Mech. Tech. Phys., 1965
Goldenbaum, *et al.*, PoF, 1967
Stamper, *et* al., PoF, 1969

Many questions still unanswered:

- How are particles injected into shock acceleration mechanisms?
- What are the characteristic scales of shock formation and reformation?
- What is the role of turbulence and reconnection in high-Mach number shocks?

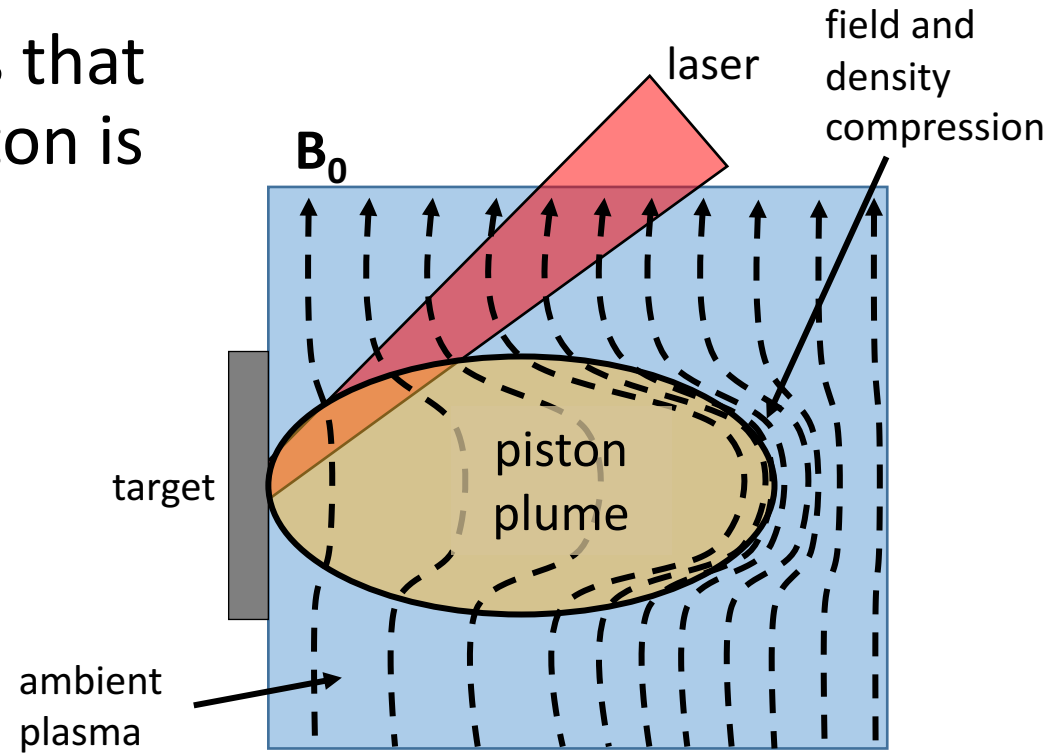
Laboratory experiments can thus complement spacecraft and remote sensing measurements.

Laboratory Experiments can Reproduce the Physics of Space and Astrophysical Collisionless Shocks in a Controlled Setting

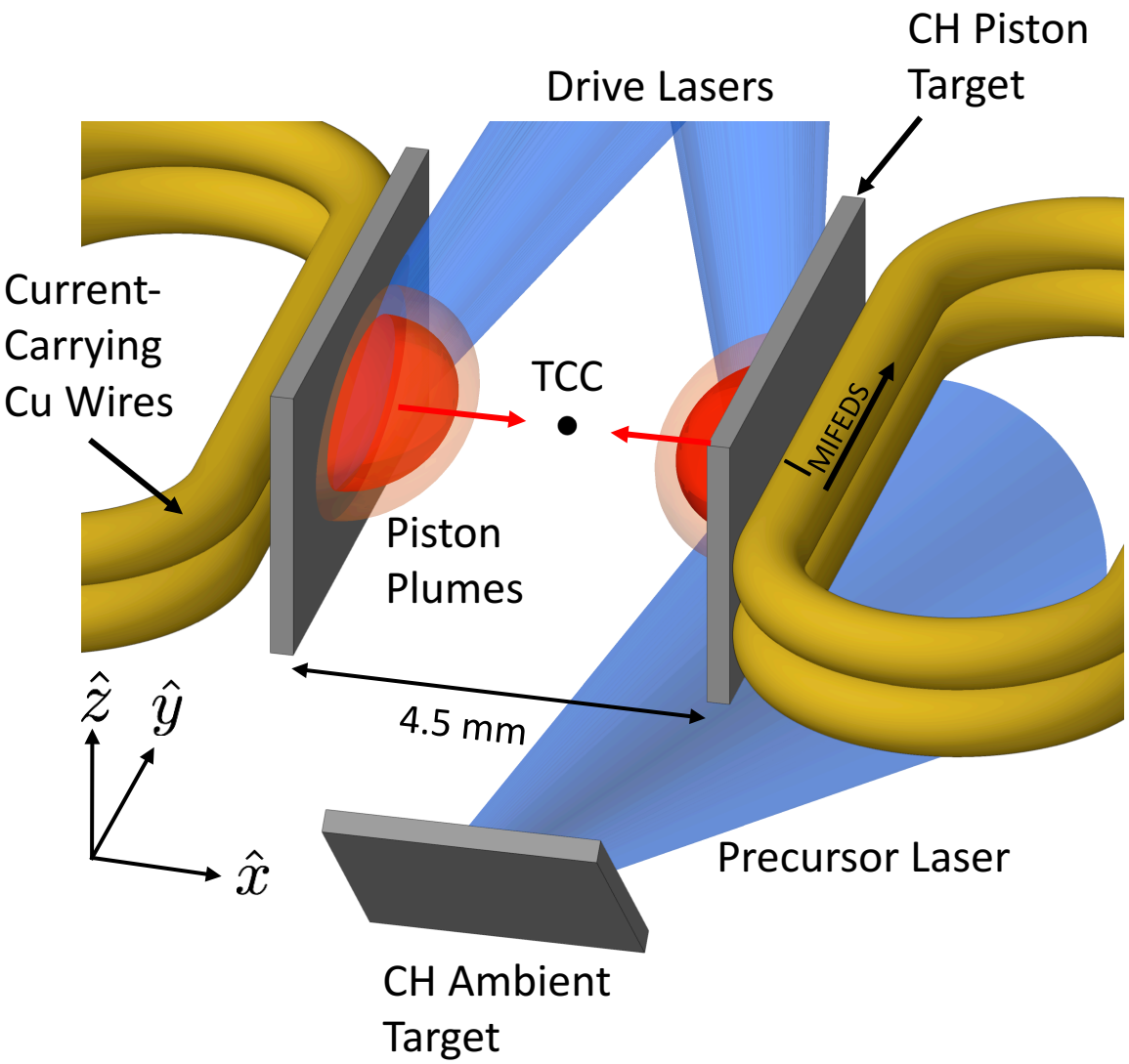
- Collisionless shocks are an active area of research
  - Electrostatic
  - Weibel-mediated
  - Magnetized

Romagnani, *et al.*, PRL, 2008
Kuramitsu, *et al.*, PRL, 2011
Haberberger, *et al.*, Nature, 2011
Fox, *et al.*, PRL, 2013
Huntington, *et al.*, Nature, 2015
Niemann, *et. al.*, GRL 2014

- A new class of collisionless shocks experiments that utilize a laser-driven, magnetically-coupled piston is now available
  - Wide range of Mach numbers (M<40)
  - 2D and 3D datasets
  - Quasi-perpendicular and quasi-parallel magnetic geometries

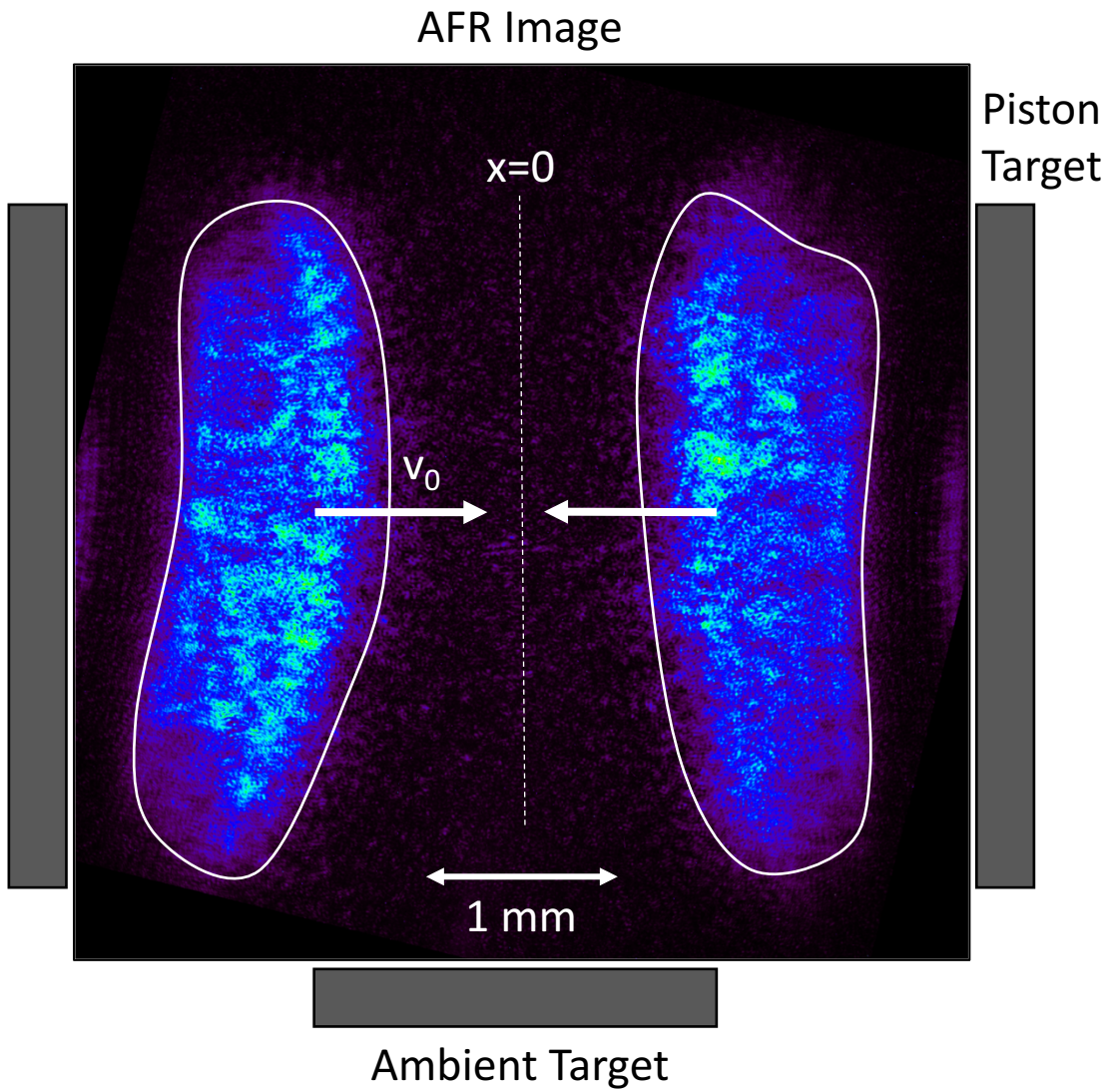


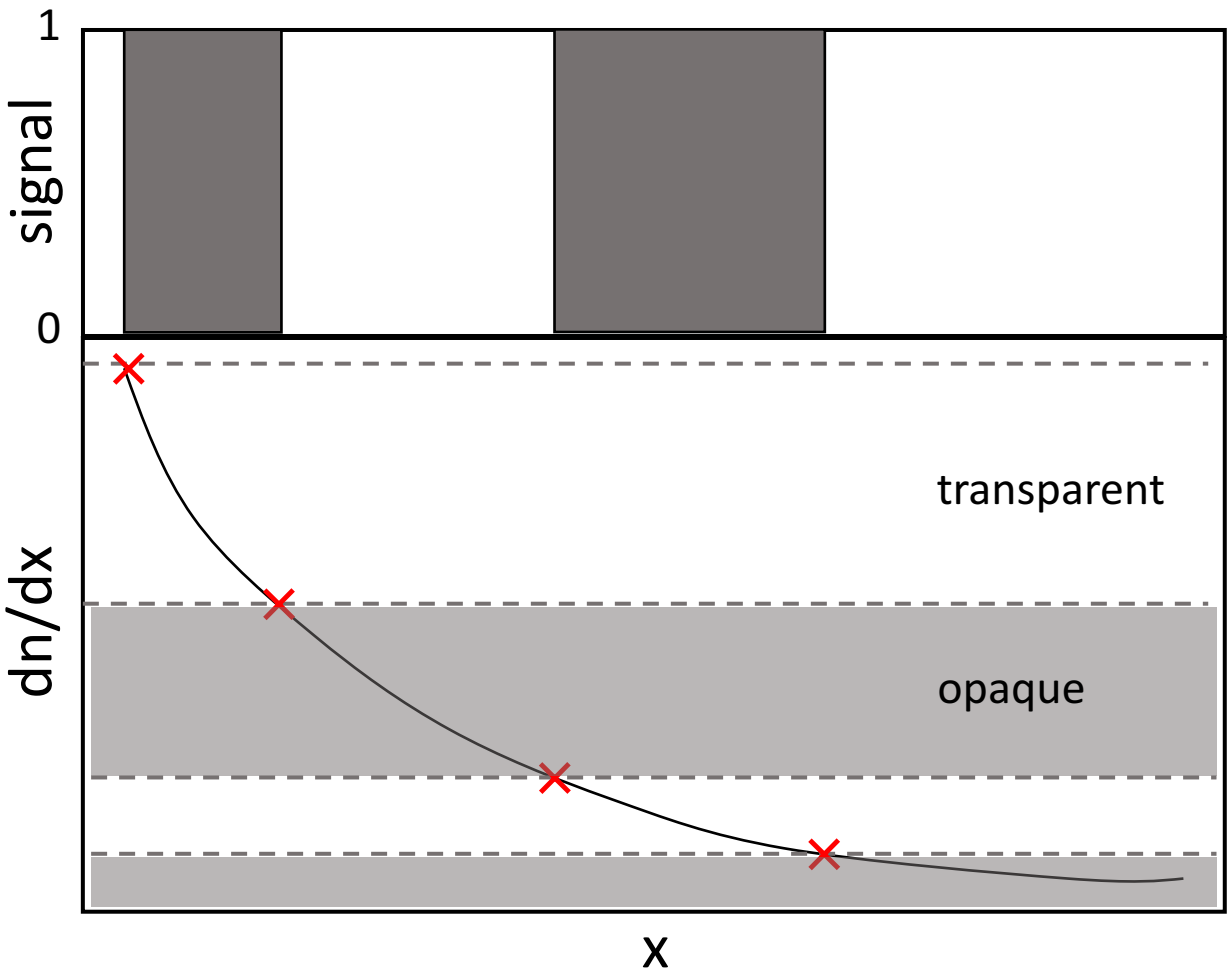
Experimental Setup for Quasi-Perpendicular Shocks on Omega EP



- MIFEDS coils provide background magnetic field ~ 8T
- Heater beam ablates ambient plasma ($n_{i,0} \approx 10^{18}$ cm^{-3}) 12 ns before drive beams
- Drive beams create supersonic piston plumes that expand into ambient plasma
- Diagnostics:
  - Angular Filter Refractometry (AFR)
  - Shadowgraphy
  - Proton radiography

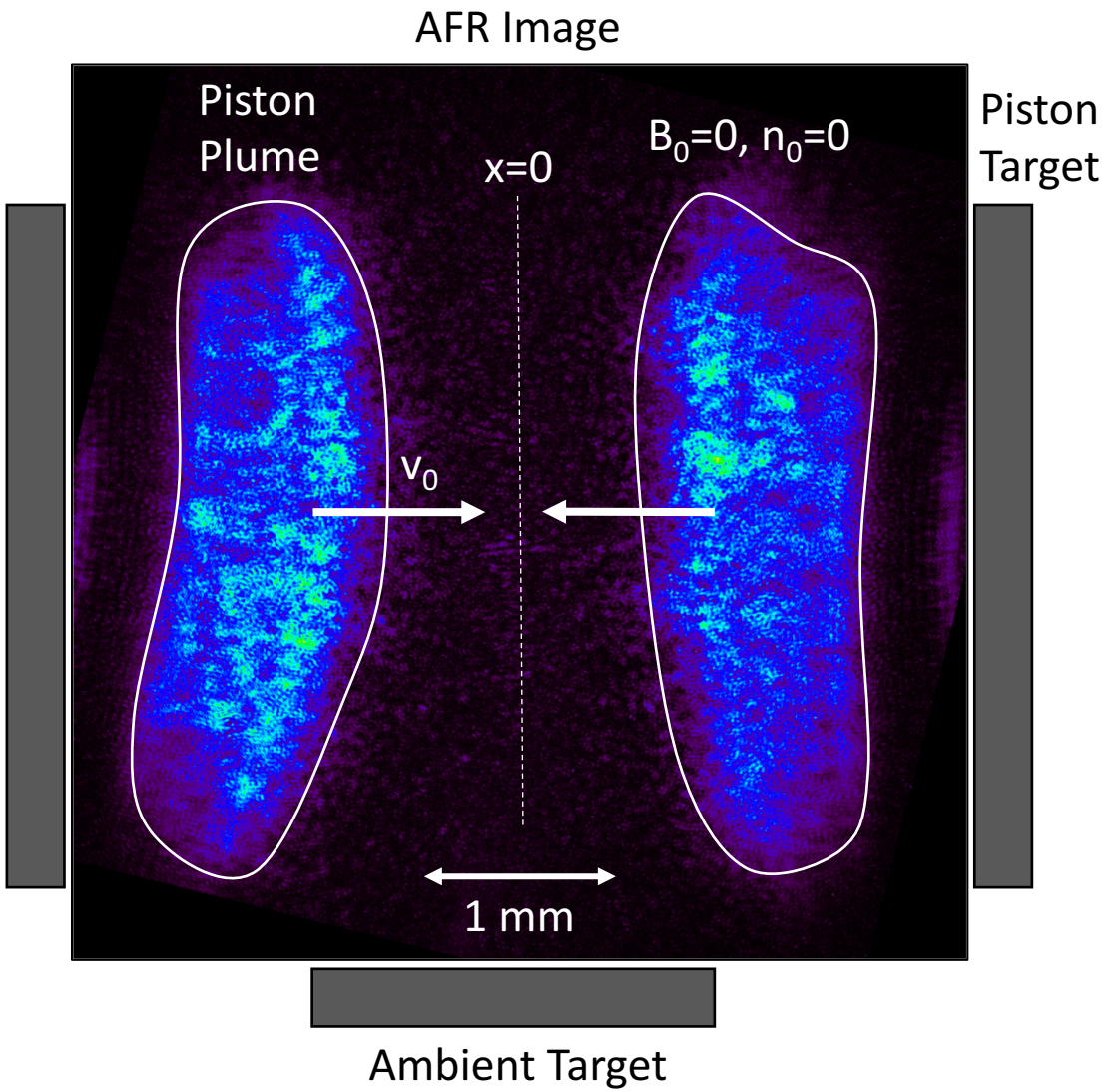
AFR Diagnostic Measures Density Gradients



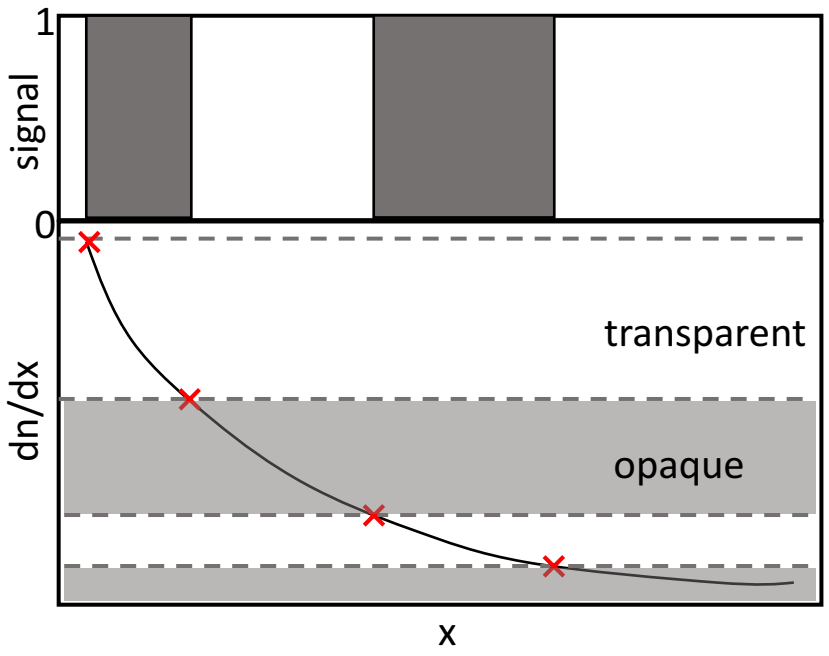


Haberberger, *et al.*, PoP, 2014

Null Shots Show No Shock Features

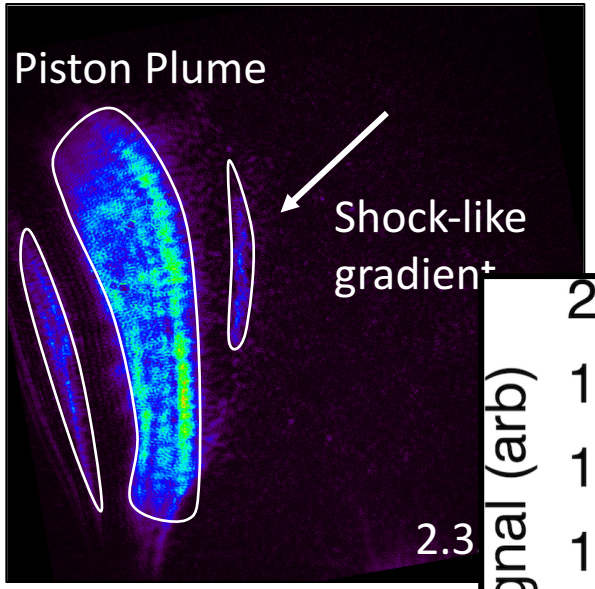


- Without background magnetic field or ambient plasma, only piston plumes observed



Propagating Density and Magnetic Compressions Observed with $B_0 \neq 0$ and $n_0 \neq 0$

AFR



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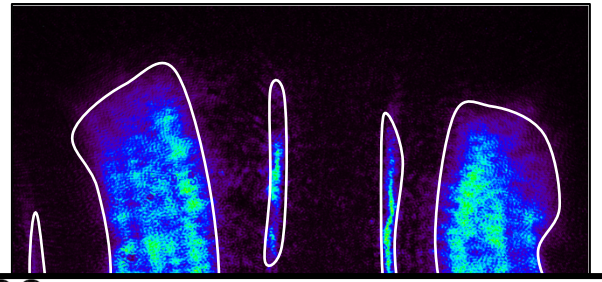

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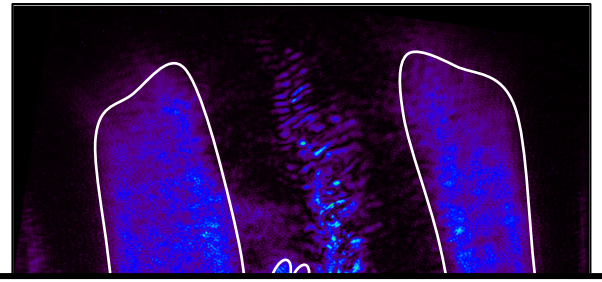
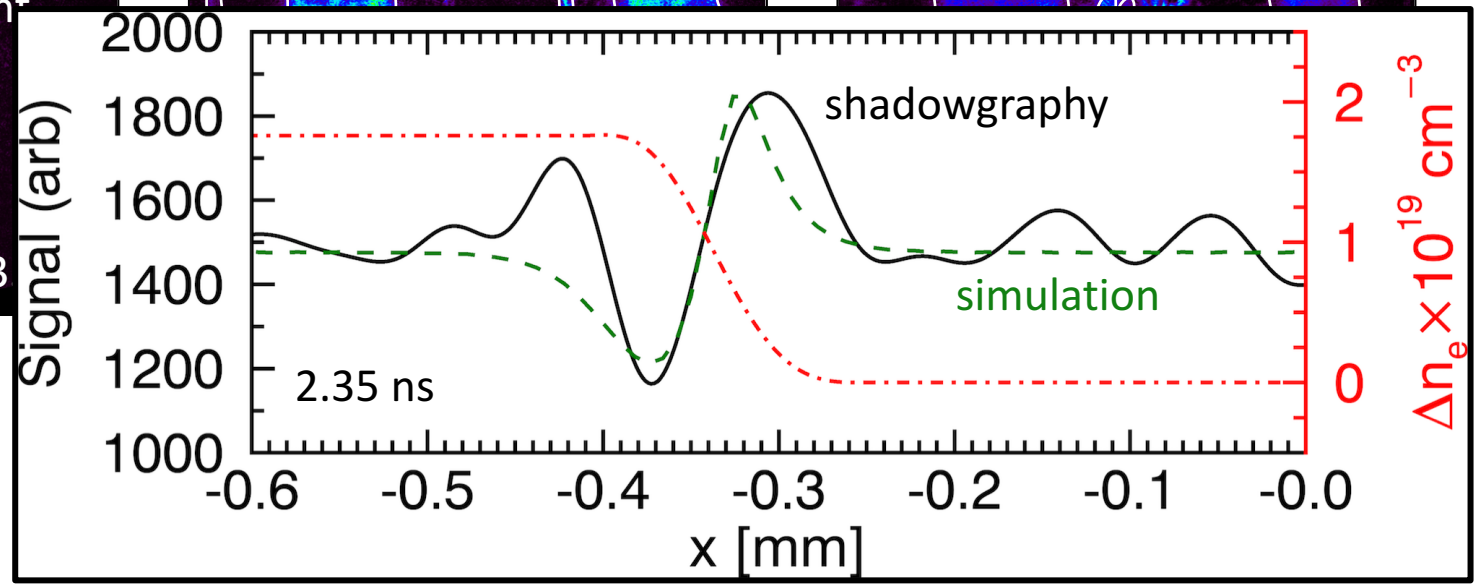
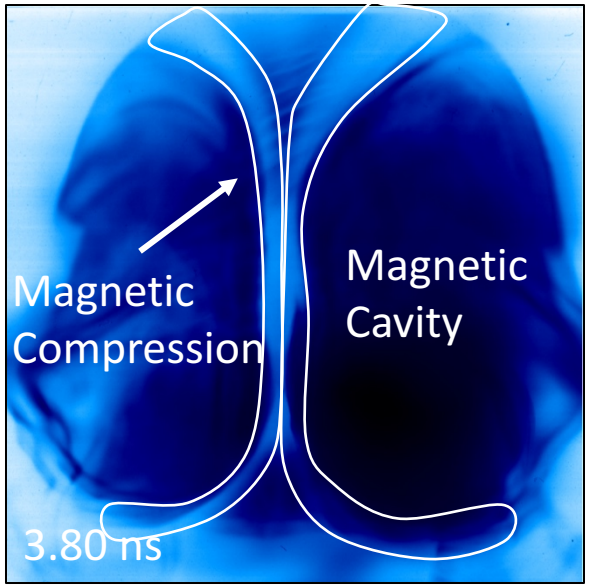




Proton Radiography



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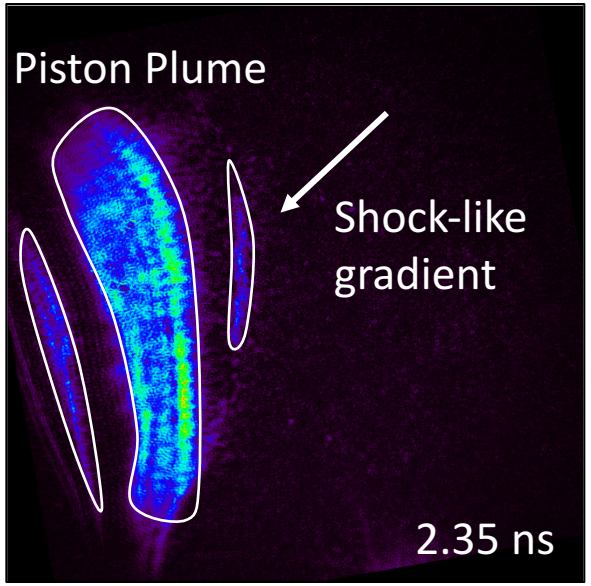

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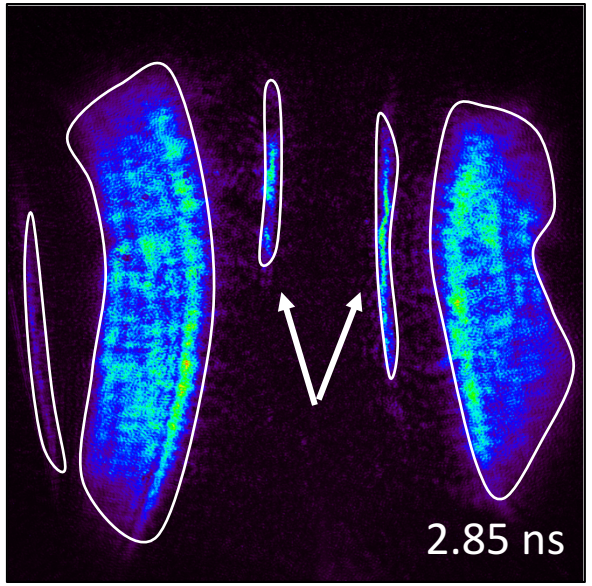
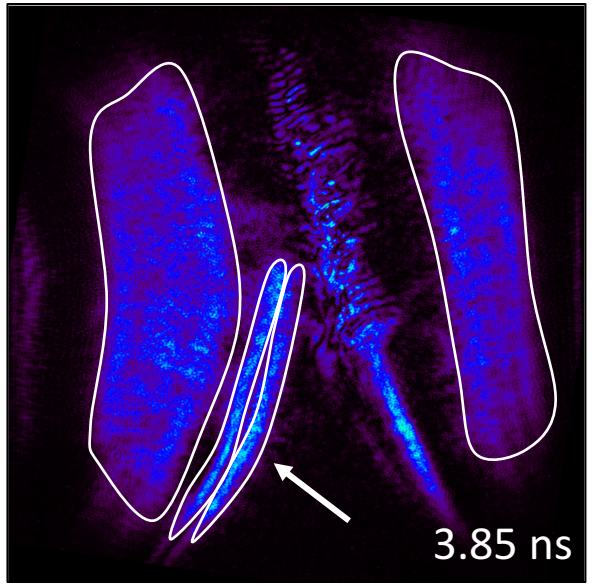
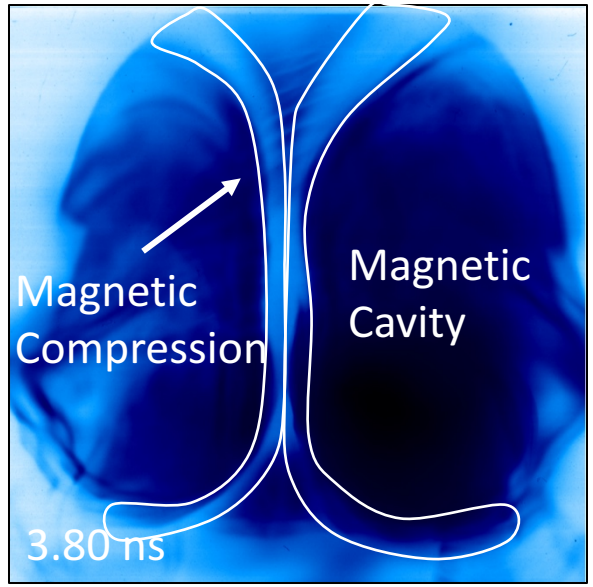


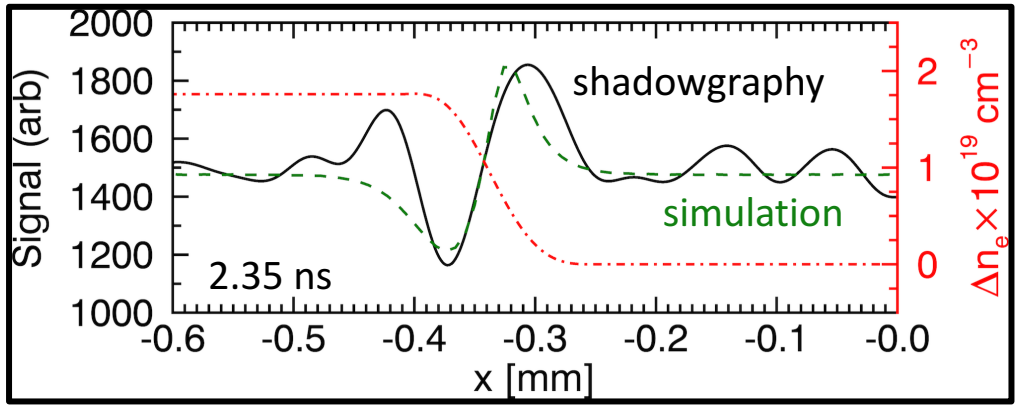
AFR



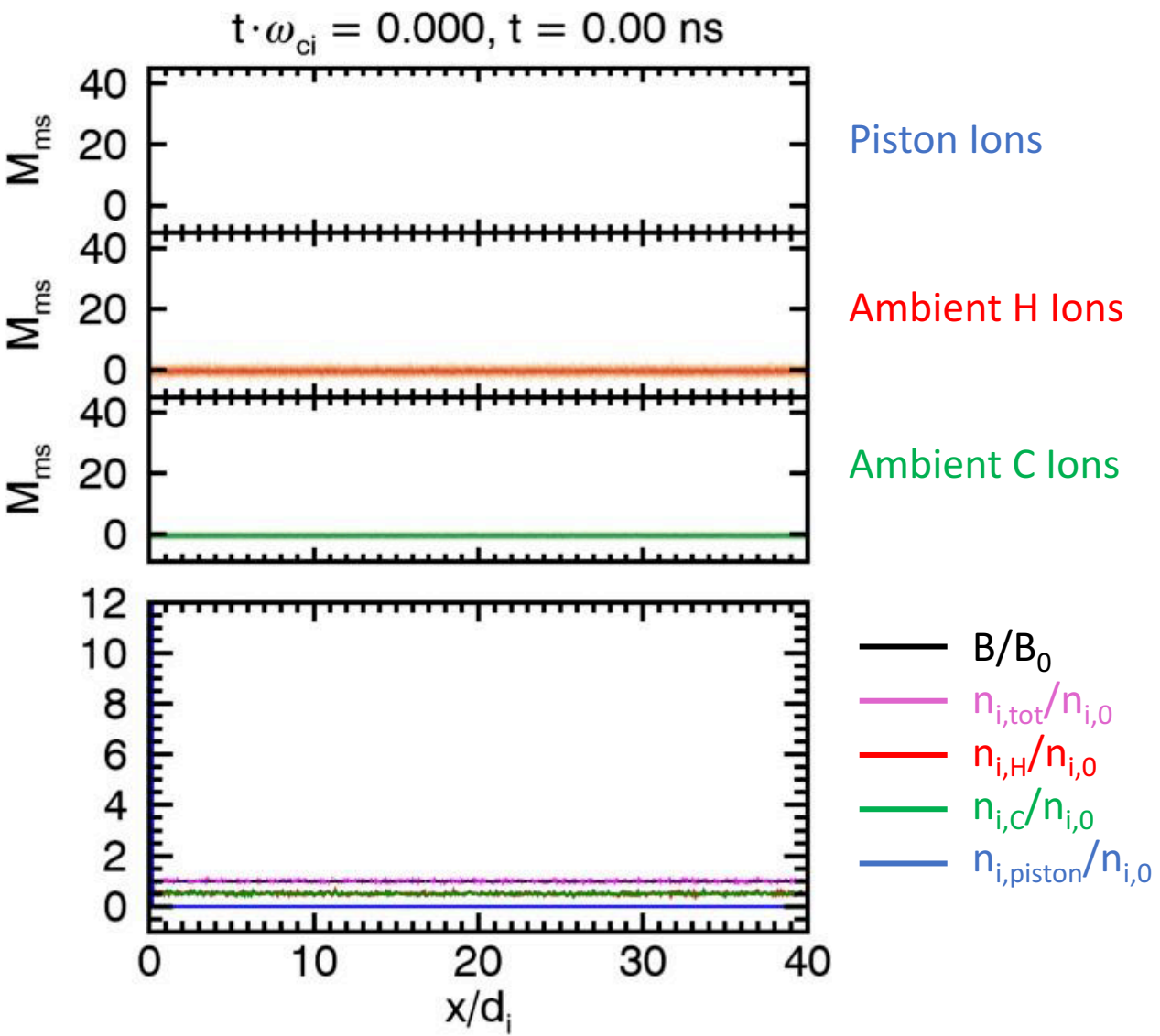
Proton Radiography



- Expanding at 700 km/s, yielding $\mathbf{M_{ms}} \approx 12$
- Density compression $\mathbf{n/n_0} \sim 3\text{-}4$
- Magnetic compression $\mathbf{B/B_0} \sim 2\text{-}4$
- Compression width $\boldsymbol{\Delta} > 1\ \mathbf{c}/\boldsymbol{\omega}_{\mathbf{pi}}$

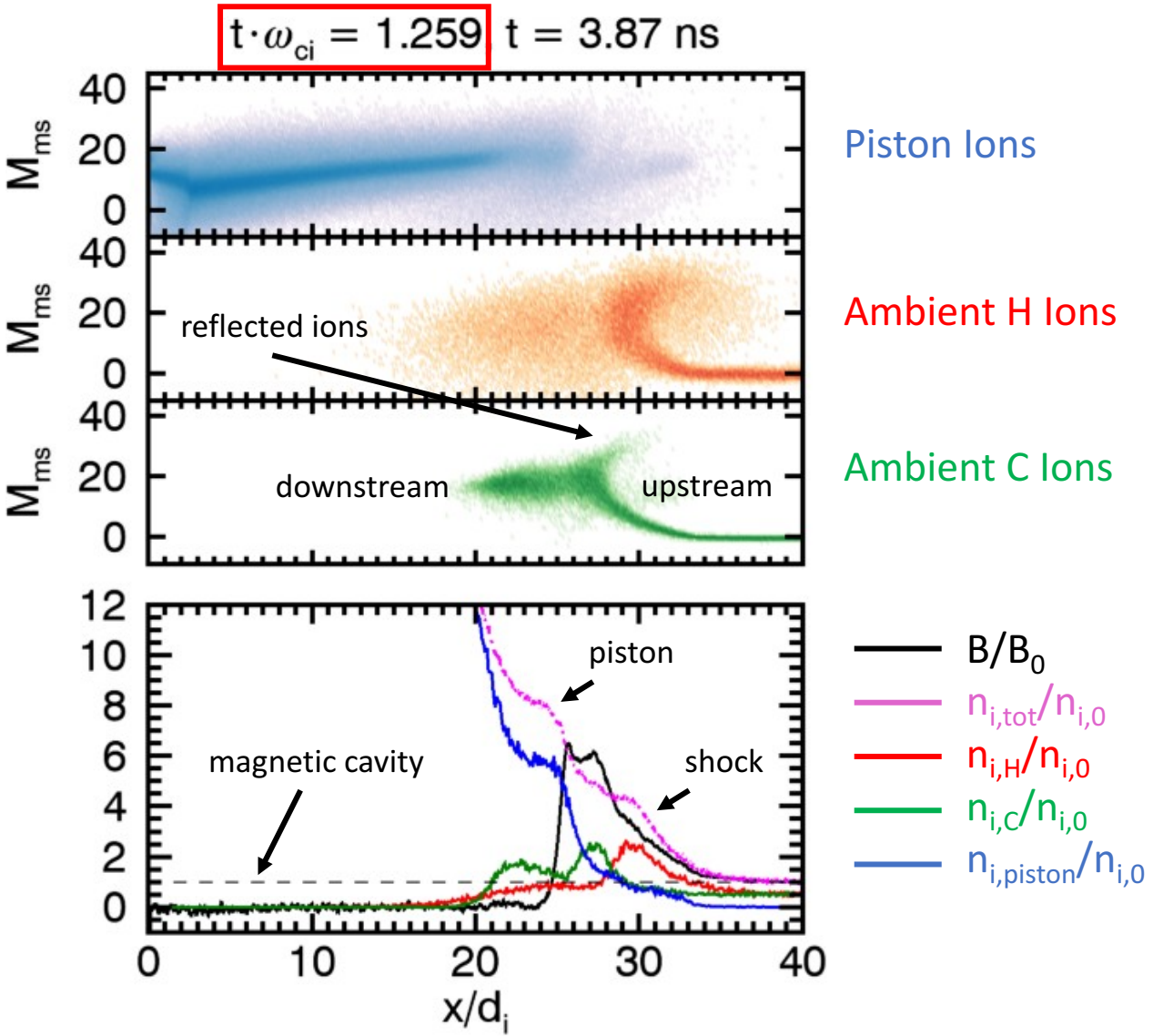


PIC Simulations Indicate Formation of High-M_A Shock



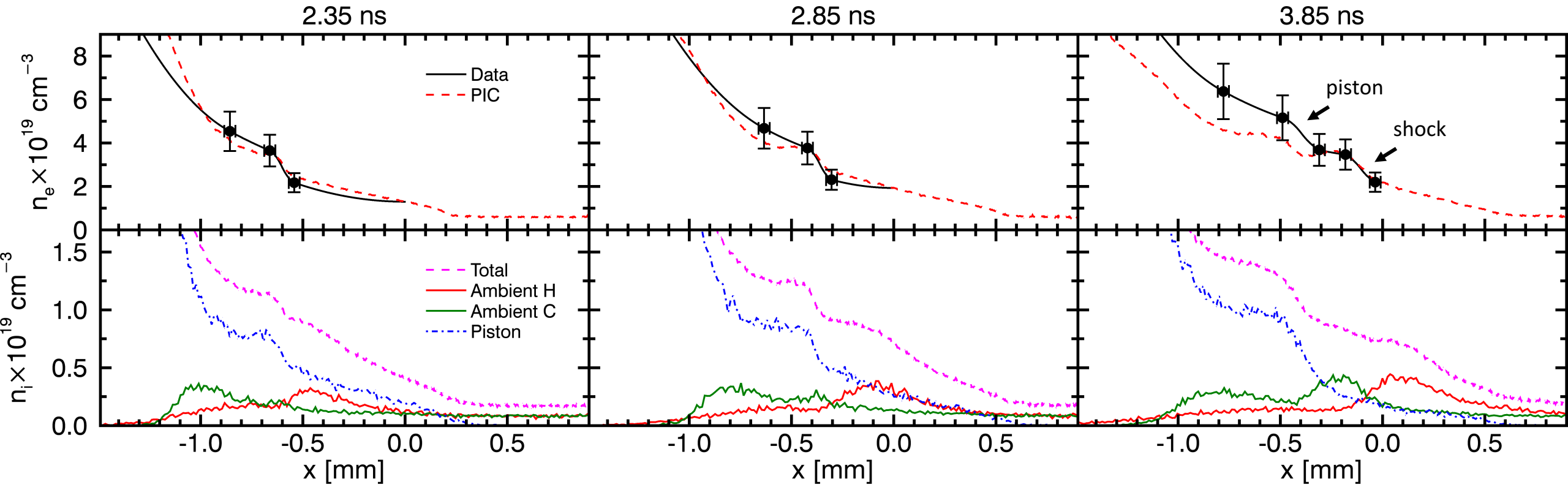
- CH piston plasma expanding into CH ambient plasma embedded in magnetic field
- Piston ions sweep out ambient ions and magnetic field
- At early times, this leads to the formation of a H shock, mixed with piston ions and the beginnings of a C shock
- At later times, a separate C shock forms behind the H shock, and the piston ions become trapped behind the C shock

PIC Simulations Indicate Formation of High-M_A Shock



- The formation of a shock leads to a double "bump" density profile, corresponding to the leading shock and the trapped piston ions
- The density compression associated with the shock is **n/n_0~4**
- The magnetic compression associated with the shock is **B/B_0>4**
- The width of the density compression **Δ ~ 1 ρ_i**

Data Profiles Show Density Evolution that is Consistent with High-M_A Shock Formation



- Early time density compression mostly associated with pile-up of piston ions
- At late time clear double bump feature associated with shock and trapped piston ions

Schaeffer, *et al.*, PRL, 2017

Summary and Outlook

- We have observed for the first time the formation and evolution of a laser-driven, high-M_A (supercritical) collisionless shock.
- The shocks are observed to form within 1 $\boldsymbol{\omega}_{ci}^{-1}$, which is also when the shock begins to separate from the piston.
- The results agree well with 2D PIC simulations.
- The development of this platform allows the study of high-Mach number shocks under a number of ambient plasma and magnetic conditions.
- Outstanding problems that can be addressed with laboratory shock experiments?