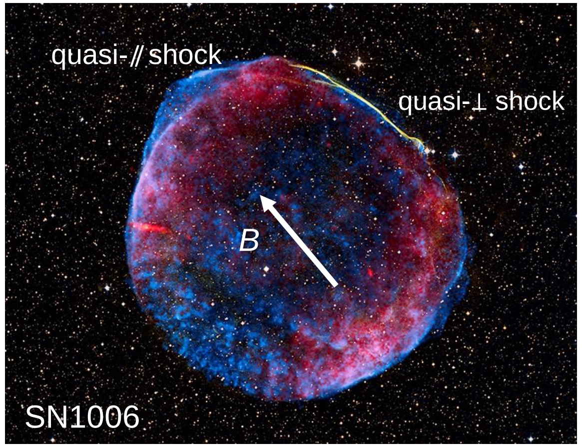
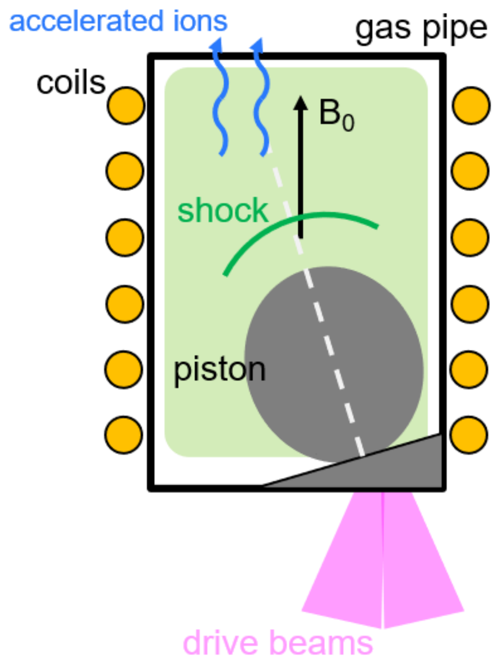
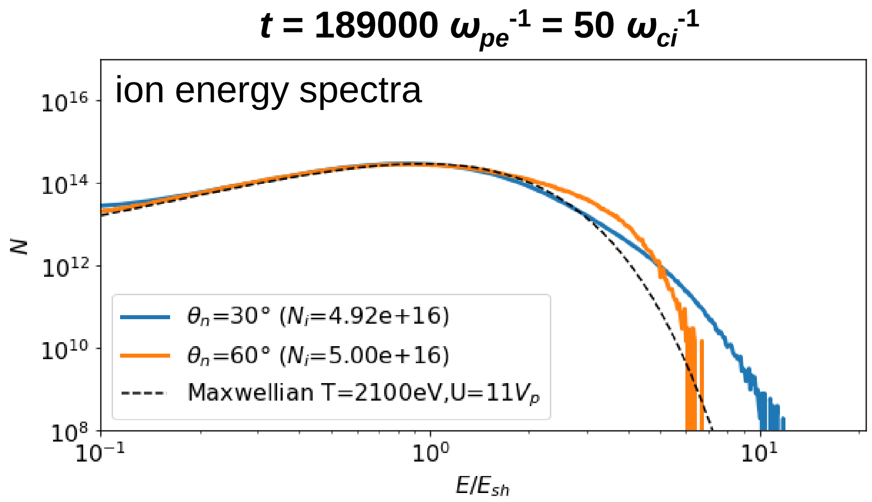
Kinetic Study of Quasi-Parallel Shock Formation and Particle Acceleration







Yu (Victor) Zhang
University of Rochester
Laboratory for Laser Energetics

64th Annual Meeting of the APS
Division of Plasma Physics
Spokane, Washington
17-21 October 2022

Summary

Kinetic study shows the early stage of quasi-parallel shock formation and particle acceleration are achievable at the National Ignition Facility (NIF)

UR LLE

- **Quasi-parallel collisionless shocks can accelerate ions to higher energies than quasi-perpendicular shocks**

- **Ion repetitive crossing of the shock front by scattering from waves and turbulence, and consequent ion acceleration are seen in the simulations**

- **The ion acceleration is expected to be experimentally observable at the NIF ($t > 50\ \omega_{ci}^{-1}$, $L > 500\ c/\omega_{pi}$)**

Collaborators

Peter V. Heuer, Jonathan R. Davies, Chuang Ren

University of Rochester
Laboratory for Laser Energetics

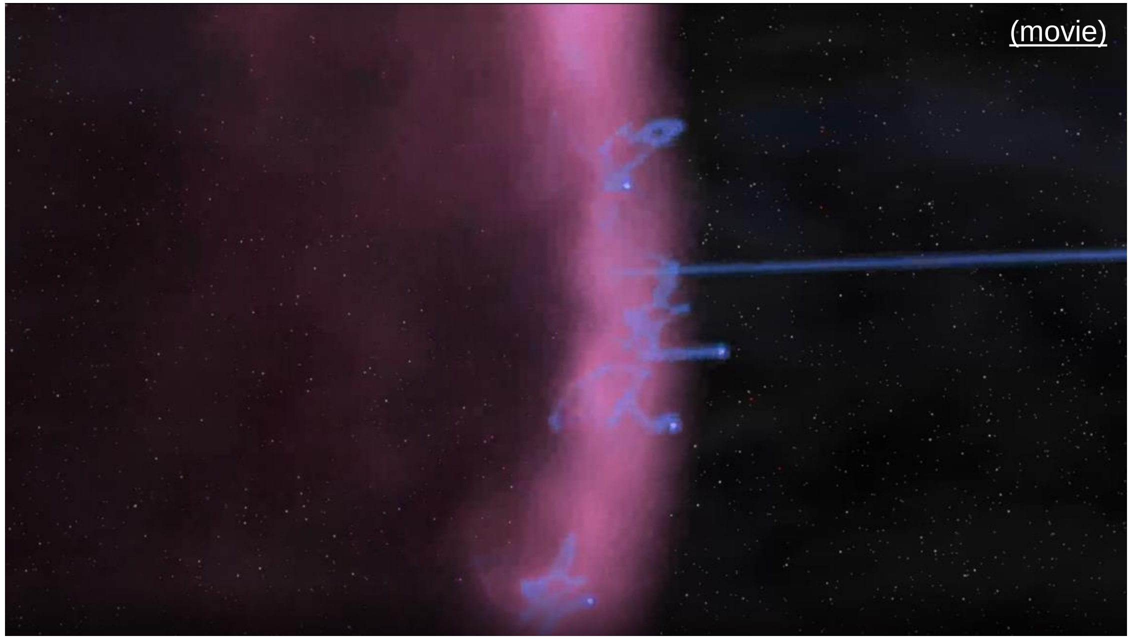
Derek B. Schaeffer

Princeton University

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, Department of Energy Award Number DE-SC0020431, and the resources of NERSC.
The authors thank *UCLA-IST OSIRIS consortium* for the use of *OSIRIS* code.

Quasi-parallel collisionless shocks are the most efficient accelerators in the universe

- **First-order Fermi acceleration*/Diffusive shock acceleration (DSA)****
  - **Cosmic particles interact with chaotic magnetic fields and gain energy from bouncing back and forth across the shock**
  - **Eventually result in a power-law energy spectrum**



Credit: NASA's Goddard Space Flight Center†

- **Energetic particles/cosmic rays**:**
  - **are accelerated in the vicinity of the shock**
  - **can re-cross the shock front many times**
  - **are scattered from downstream to upstream by the turbulent wake, and from upstream to downstream by the Alfven waves**

Quasi-parallel shocks are more capable of energizing ions than quasi-perpendicular shocks

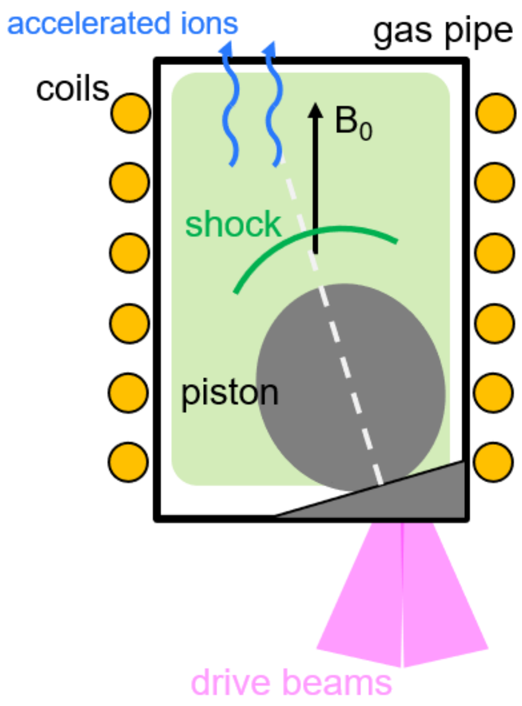
* Fermi, Phys. Rev. **75**, 1169 (1949);
** Bell, Mon. Not. R. Astr. Soc., **182**, 147 (1978); Blandford *et al.*, Astrophys. J. **221**, L29 (1978)
† NASA's Goddard Space Flight Center, https://svs.gsfc.nasa.gov/14170

Quasi-parallel shock experiments can only be done at the NIF

The NIF uniquely allows the simultaneous creation of :

- **a large axial magnetic field (~30 T)**
- **a large, uniform, magnetized plasma (~20 mm)**
- **a strongly-driven plasma flow (~ 1500 km/s)**

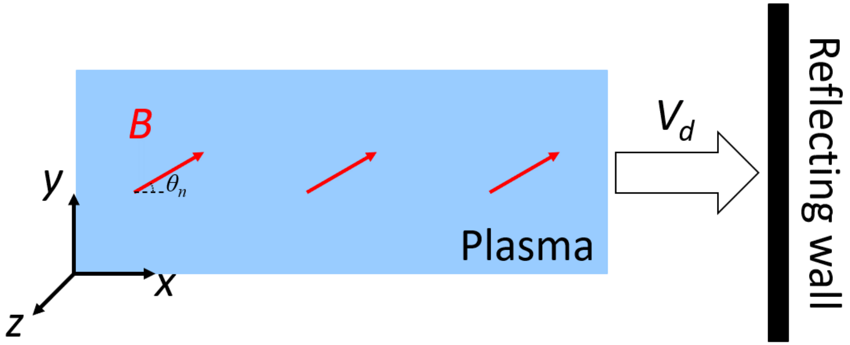
This platform can extend the shock evolution time up to ~50/Ω_{ci} (ion gyro-time) so the <u>early stage</u> of a quasi-parallel shock and particle energization by DSA is achievable.



This has never been experimentally observed before

Quasi-parallel shocks are studied using PIC simulations with a reduced ion mass and a reflecting wall

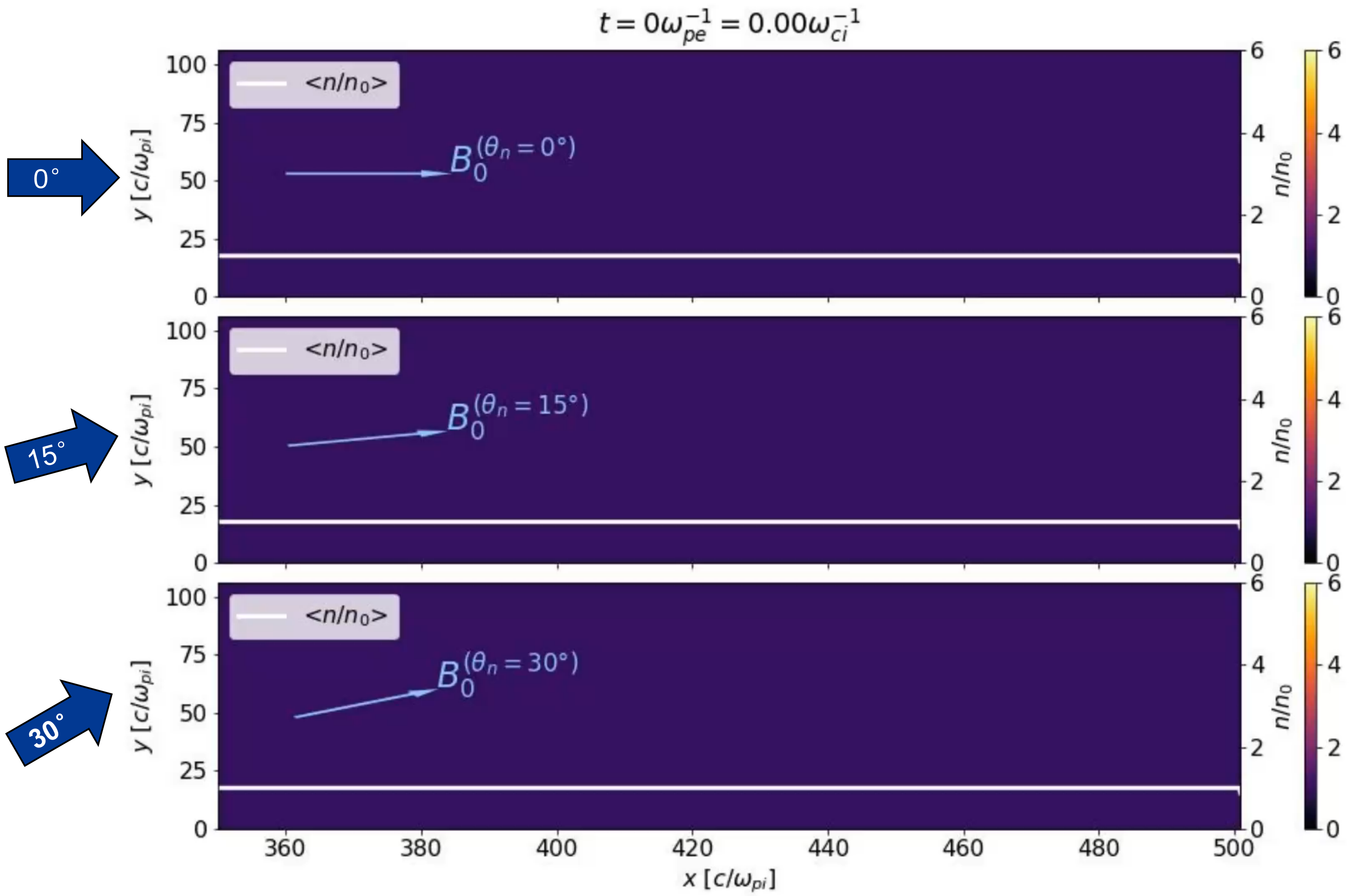
- **The instability candidates behind quasi-parallel shocks are ion-scale physics**
  - **right-handed resonant instability (RHI)****
  - **non-resonant instability (NRI)**/Bell instability†**
- **It is also not computationally feasible to perform realistic ion mass PIC simulations for quasi-parallel shocks**



A reduced ion specie with $m_i = 50m_e$ is used

* Zhang *et al.*, Phys. Plasmas **28**, 072111 (2021)
** Heuer *et al.*, Phys. Plasmas **27**, 042103 (2020), Weidl *et al.*, ApJ **873**, 57 (2019)
† Bell, Mon. Not. R. Astron. Soc. **353**, 550 (2004)

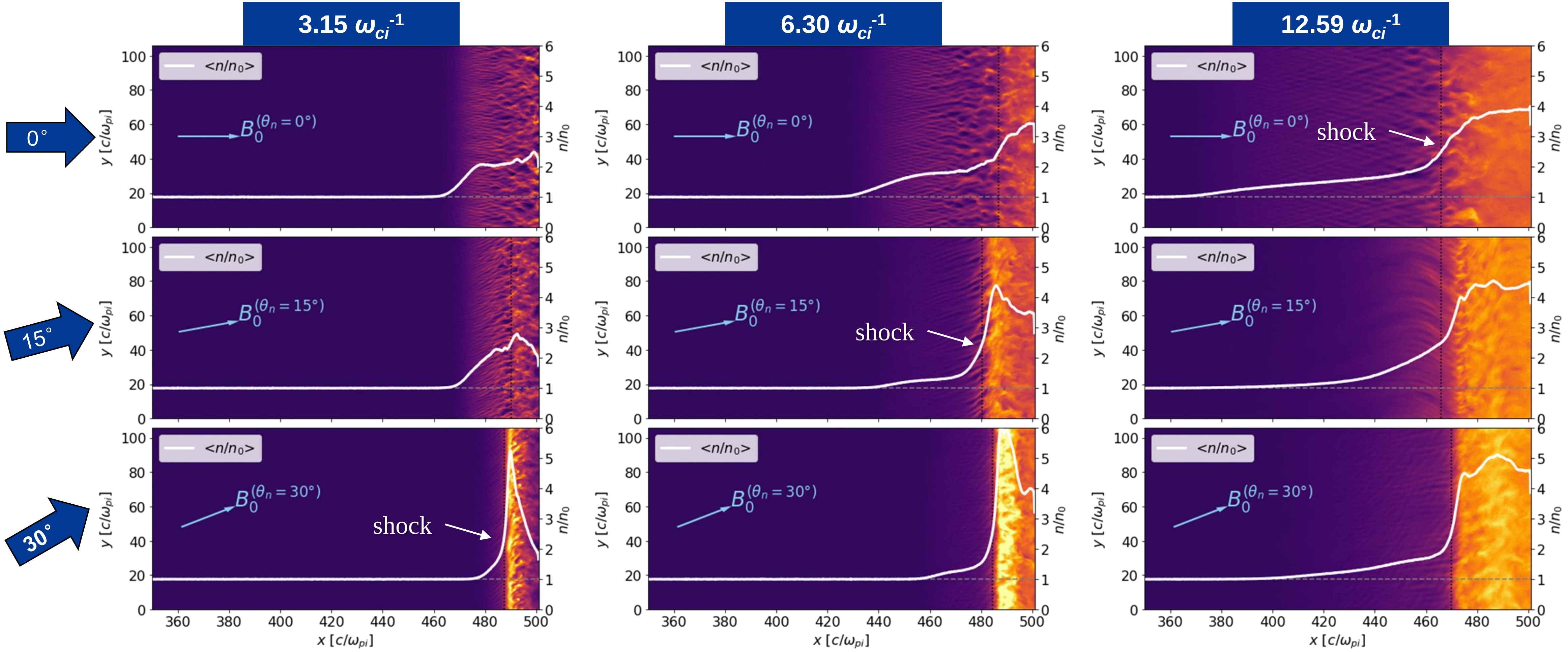
A quasi-parallel shock can be formed within the space and time given at the NIF



(movie)

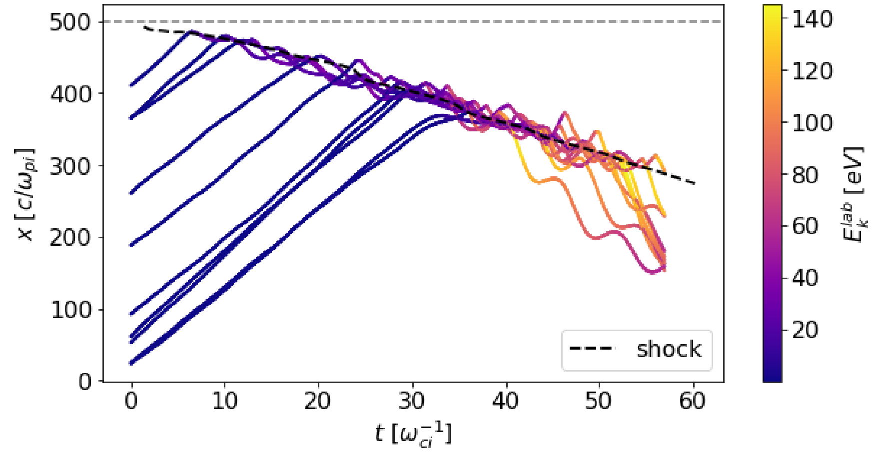
A quasi-parallel shock can be formed within the space and time given at the NIF

- **A smaller shock normal angle results in a longer formation time and a longer foot**

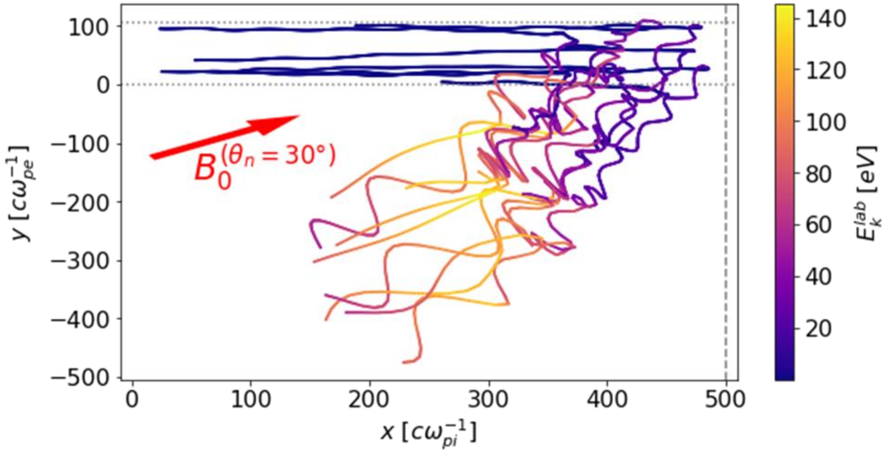


Repetitive acceleration by crossings of the shock front is seen in ion trajectories

- **Energetic ions in the vicinity of the shock are scattered repeatedly and thereby accelerated by the first-order Fermi process***
- **A maximum ion energy of ~145 keV (27x piston energy, 15x shock energy) is expected in the NIF experiments**



Ion tracks in *t*-*x*

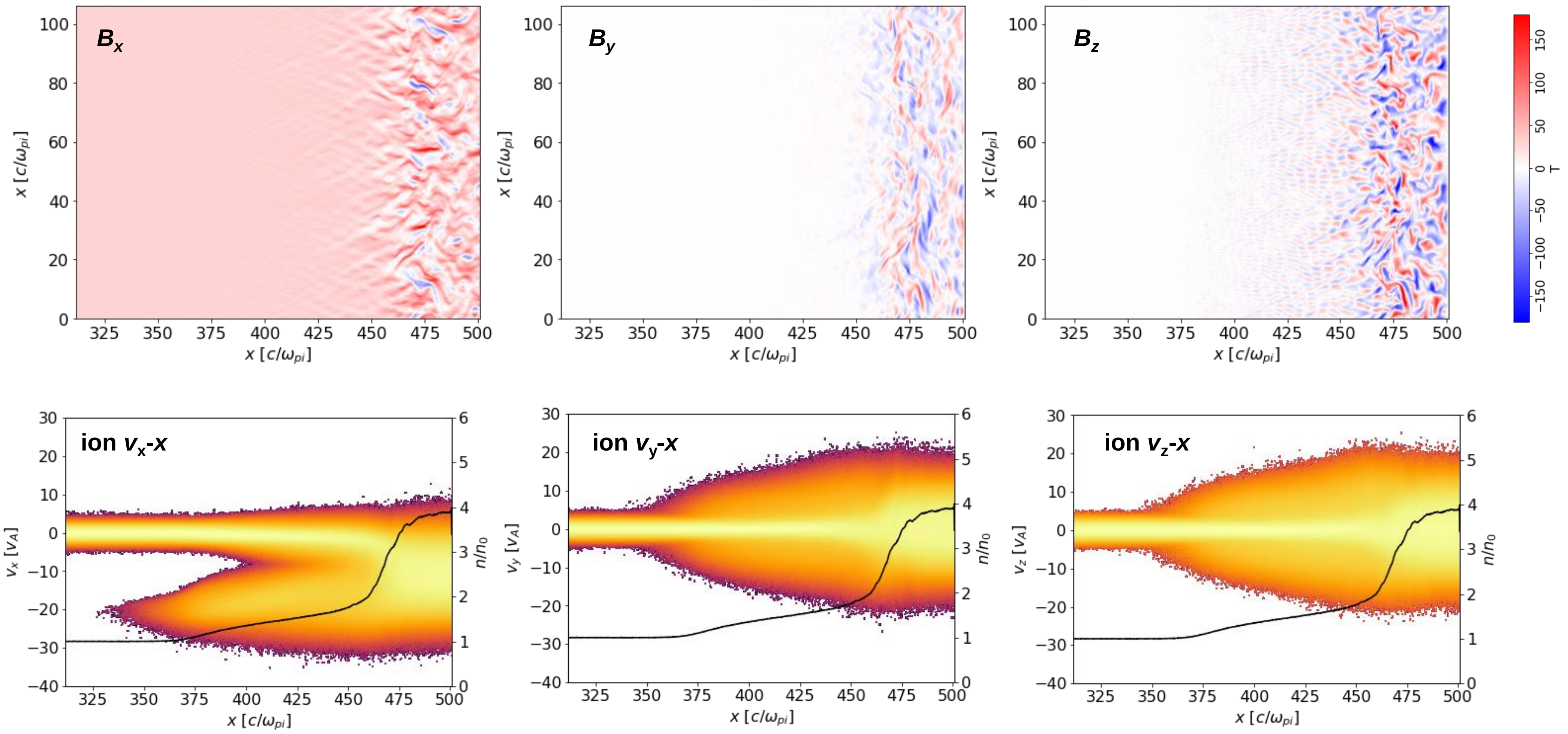


Ion tracks in *x*-*y* (periodic boundary condition in *y* is post-processed to show a continuous 2D space)

Piston energy $E_p = ½ m_i V_p^2 \approx 5.4$ keV
Shock energy $E_{sh} = ½ m_i V_{sh}^2 \approx 9.6$ keV

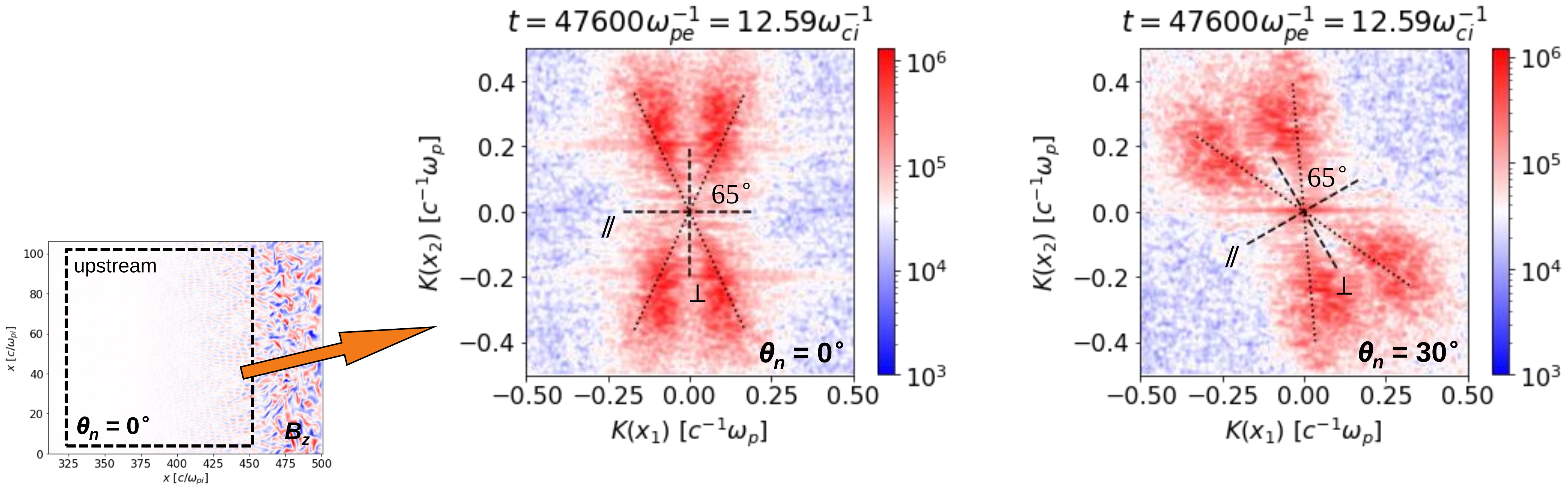
The distribution functions are strongly isotropized by the waves and turbulence

$t = 47600\ \omega_{pe}^{-1} = 12.59\ \omega_{ci}^{-1}$ [$\theta_n = 0°$]



Accelerated ions excite upstream Alfven and magnetosonic waves

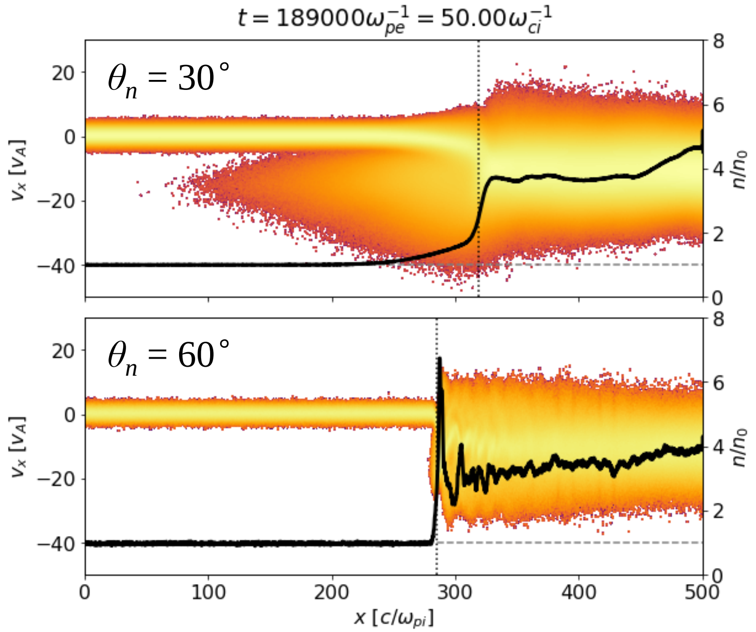
- Fourier spectra of upstream B_z field show an x-shaped mode ($\theta_n \neq 0$ results in a tilt angle)
- The mode indicates upstream parallel Alfven* wave and perpendicular magnetosonic waves

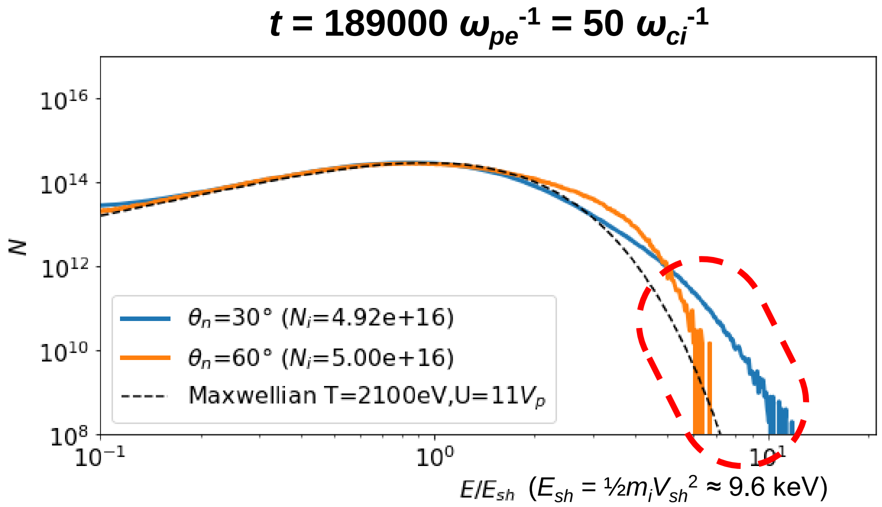


acrtan(v_{ms}/v_A) ≈ 65°

Quasi-parallel shocks are more difficult to form but more capable of energizing ions than quasi-perpendicular shocks

- **Compared to a quasi-perpendicular shock, a quasi-parallel shock:**
  - **requires much larger space and longer time**
  - **has a longer foot**
  - **results in an ion energy spectrum that extends further (early stage)**





- **Within the NIF achievable time (~50 /Ω_{ci}), the difference in particle acceleration between quasi-parallel and quasi-perpendicular shocks is experimentally observable**

Kinetic study shows the early stage of quasi-parallel shock formation and particle acceleration are achievable at the National Ignition Facility (NIF)

- **Quasi-parallel collisionless shocks can accelerate ions to higher energies than quasi-perpendicular shocks**
- **Ion repetitive crossing of the shock front by scattering from waves and turbulence, and consequent ion acceleration are seen in the simulations**
- **The ion acceleration is expected to be experimentally observable at the NIF ($t > 50\ \omega_{ci}^{-1}$, $L > 500\ c/\omega_{pi}$)**