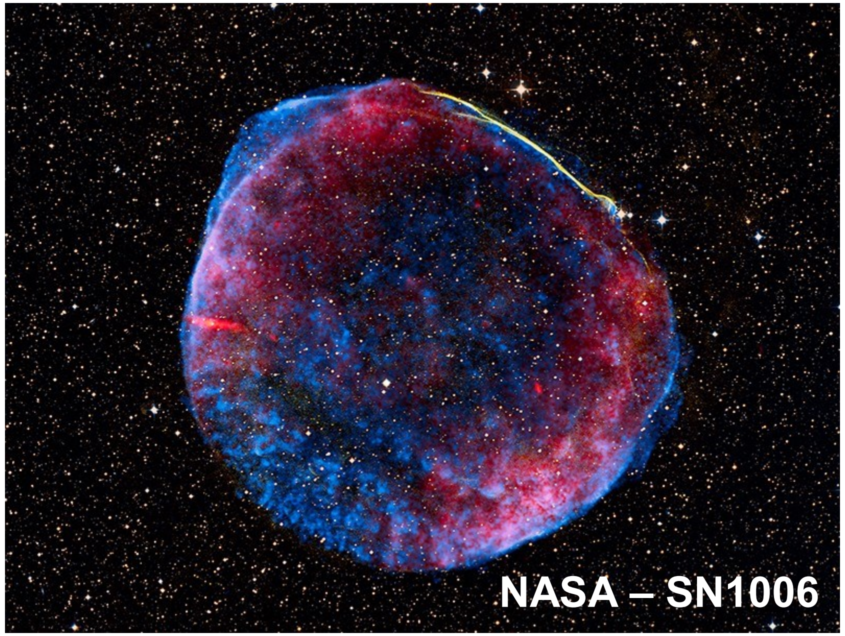
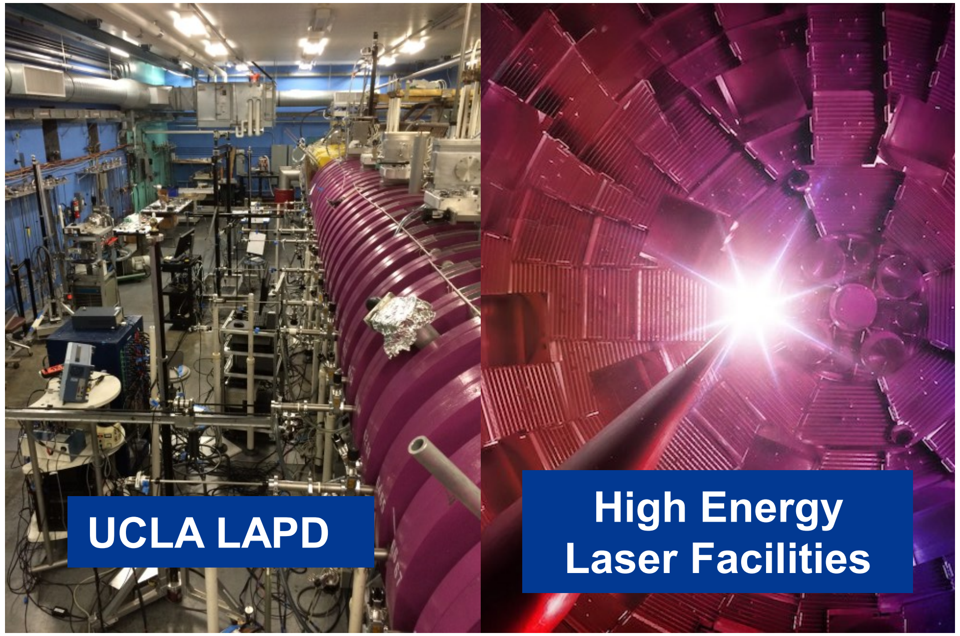
Studying Quasi-Parallel Collisionless Shocks in the Laboratory



Scaled Experiments



Peter V. Heuer
University of Rochester
Laboratory for Laser Energetics

63rd Annual Meeting of the American Physical Society Division of Plasma Physics
Pittsburgh, PA
11/8/21-11/12/21

Laboratory quasi-parallel shock experiments are an exciting and rapidly opening frontier

Quasi-parallel collisionless shocks are …

- **…complex, turbulent structures mediated by electromagnetic ion/ion beam instabilities**
- **…of great interest in space and astrophysics as accelerators of high energy particles (and may be a source of high energy cosmic rays)**
- **…difficult to create in a laboratory environment because of the extremely long length and time scales they require to form**

A quasi-parallel shock has never been created in a laboratory experiment.

We are currently pursuing approaches at both large and small scales.

Collaborators

Y. Zhang, C. Ren, J. R. Davies
University of Rochester Laboratory for Laser Energetics

D. B. Schaeffer
Princeton University

M. S. Weidl
Max-Planck-Institut fur Plasmaphysik

C. Niemann
University of California Los Angeles

W. Fox
Princeton Plasma Physics Laboratory

D. Caprioli
University of Chicago

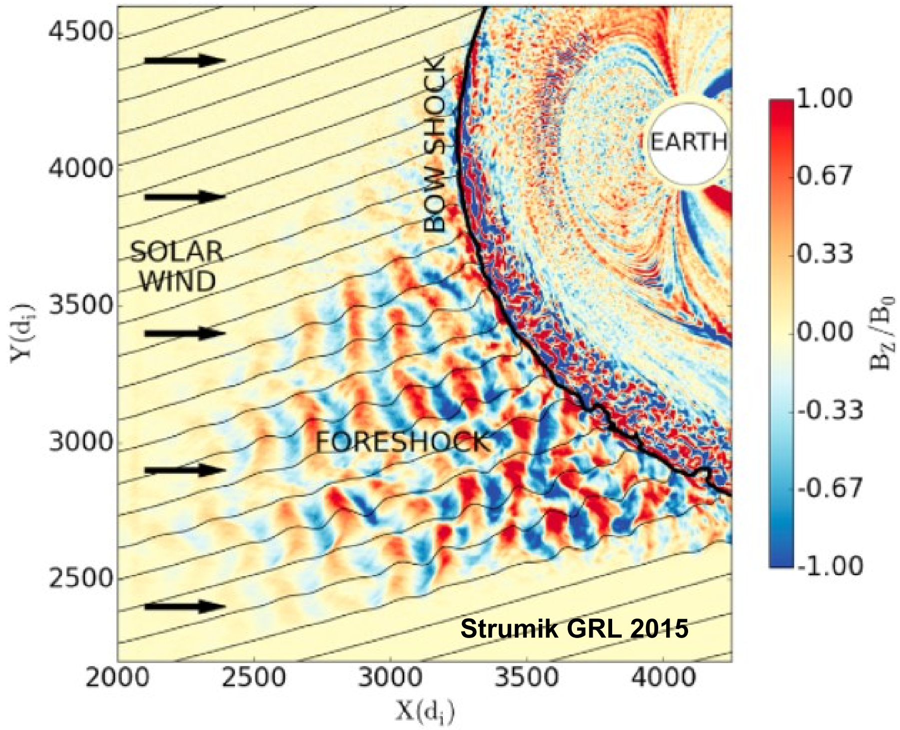
Collisionless quasi-parallel shocks are large-scale, turbulent structures that form when a supersonic “beam” plasma impinges on a second “core” plasma

Collisionless
Collisions between particles (especially ions) are dynamically unimportant.

Quasi-parallel
Magnetic field is parallel to the shock normal.

Large-scale
Quasi-parallel shocks have characteristic length scales of 100’s to 1000’s of δ_{di} (compared to a few δ_{di} for quasi-perpendicular shocks).

Turbulent structures
Upstream of quasi-parallel shocks is characterized by large amplitude magnetic turbulence (the “foreshock”)

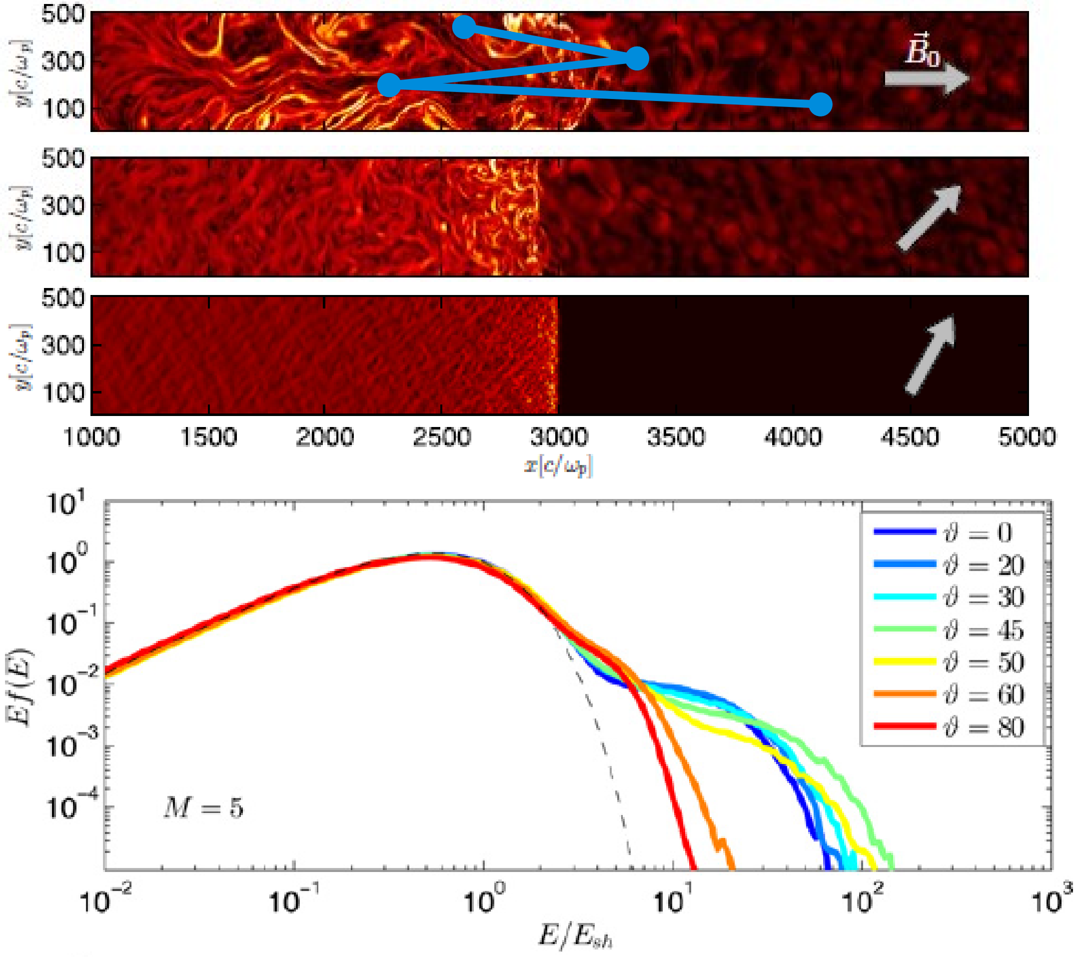


* Burgess & Scholer 2015 Cambridge University Press

Quasi-parallel collisionless shocks can energize particles to high energies

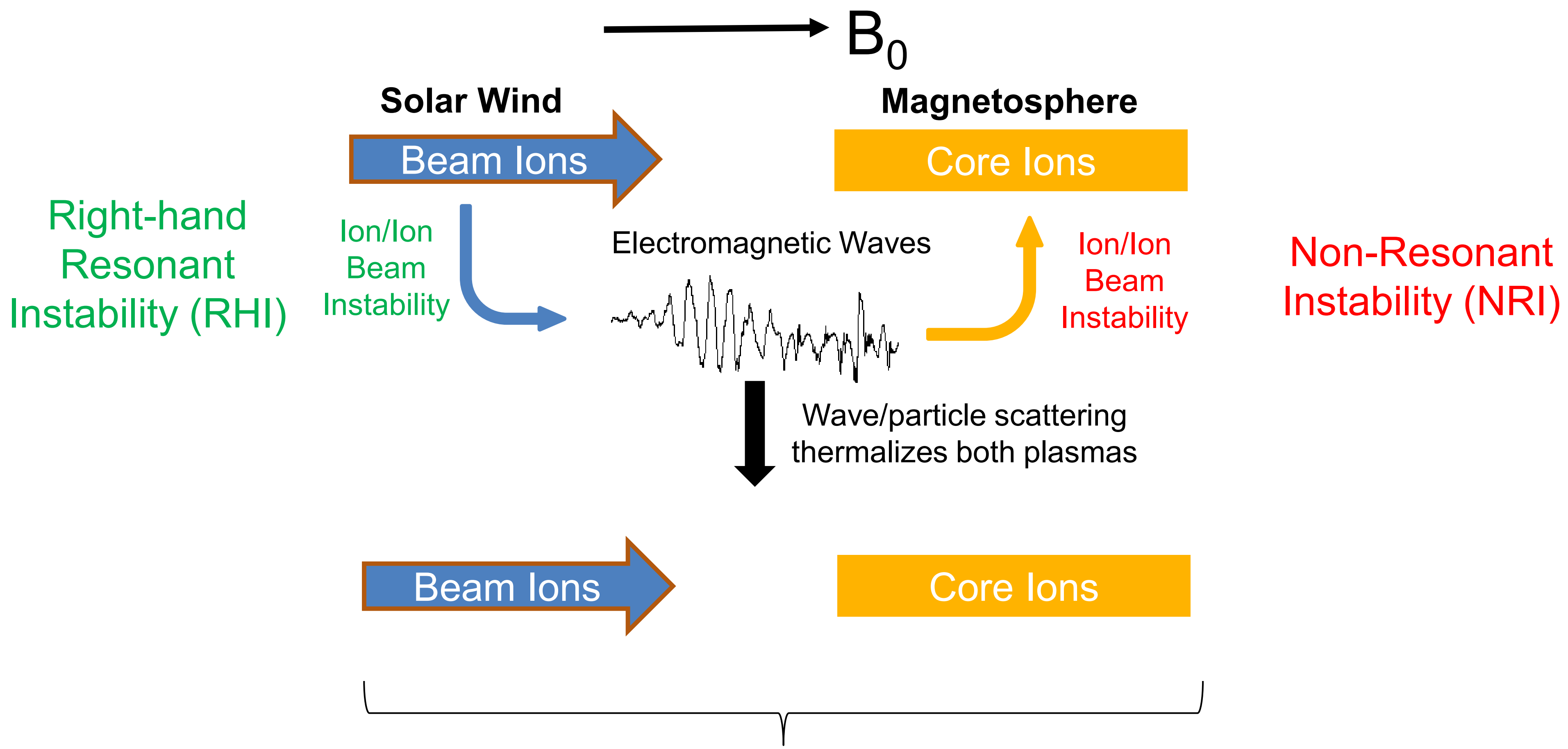
- **Fermi acceleration of particles to high energy requires large system sizes**
- **Large-scale magnetic turbulence at quasi-parallel shocks can fill this role, accelerating particles to higher energies than shocks of other orientations**

Quasi-parallel astrophysical shocks are a likely source of high energy cosmic rays.



Caprioli & Spitkovsky 2014 *ApJ*

Quasi-parallel shocks are mediated by electromagnetic ion-ion beam instabilities



Long instability growth times → shock width of L » 100 δ_{di}

* Weidl et al. 2019 APJ
** Burgess & Scholer 2015 Cambridge University Press

What parameters are required to form a quasi-parallel collisionless shock in the laboratory?

Theory outlines requirements for forming a space-relevant quasi-parallel collisionless shock in the laboratory:

- **$L << \lambda_{mfp}$ (Collisionless)**
- **$n_b/n_c >$ 5% (Sufficient density to excite both instabilities)**
- **$M_A > 3$ (Sufficient velocity to excite both instabilities)**
- **$L \geq 500\ \delta_i$ (Sufficient space to develop)***
- **$M_A < 10$ (Similarly magnetized to shocks in space)**

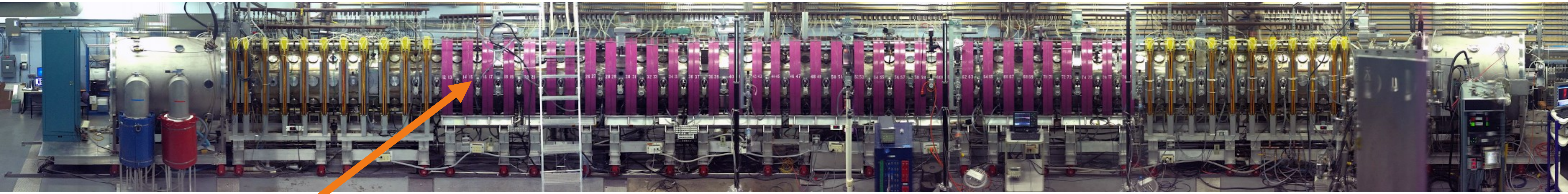
Large-Scale (UCLA LAPD)	=	Small-Scale (Large Laser)
▪ $L \sim 10^3$ cm ▪ $N_c \sim 10^{14}$ cm^{-3} ▪ $v_b \sim 200$ km/s ▪ $B_0 \sim 100$ G	Equivalent Dimensionless Parameters	▪ $L \sim 1$ cm ▪ $N_c \sim 10^{20}$ cm^{-3} ▪ $v_b \sim 1000$ km/s ▪ $B_0 \sim 10^6$ G

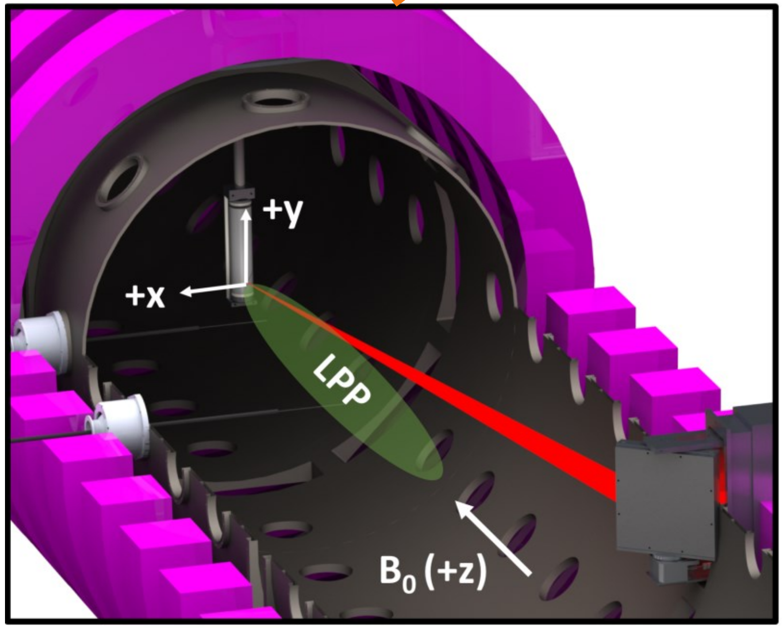
Heuer et al. PoP 2020

Observing even the early stages of quasi-parallel shock formation requires a very long experiment!

* Weidl et al. 2016 PoP

Large scale: parallel shock beam instabilities in the Large Plasma Device

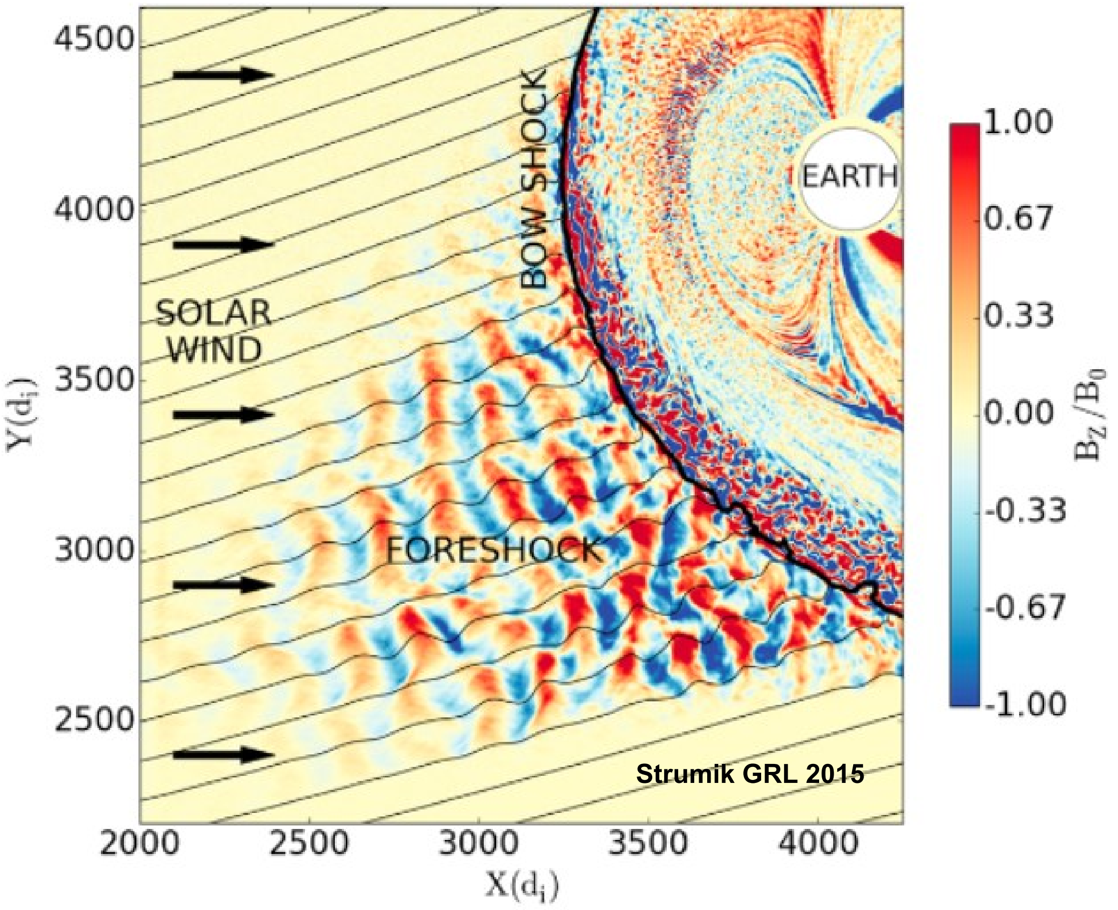


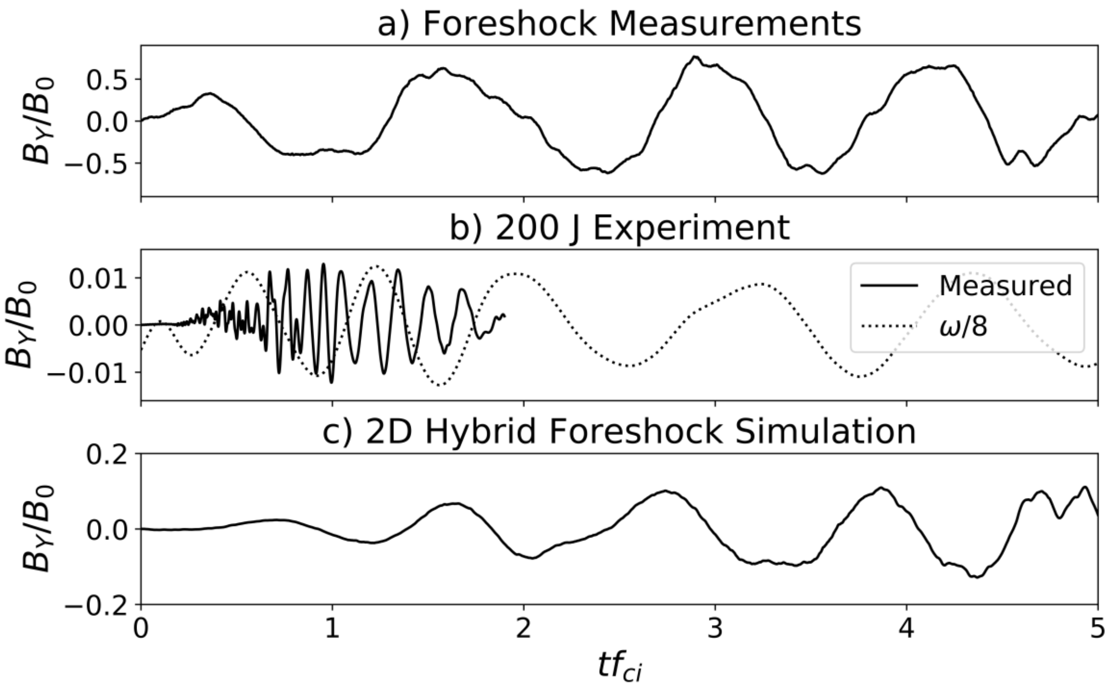


- **Experiment is nominally 12 m (85 ion inertial lengths)**
- **Beam plasma produced by a 200 J laser**
- **Diagnosed with an array of magnetic flux probes**

* Gekelman et al. 2016 RSI
** Heuer et al. 2018 PoP

The experiment observed waves like those in Earth's quasi-parallel foreshock





Frequency of waves in experiment are ~8x higher because different ions are present (C+4, He+) than in space (H+,H+).

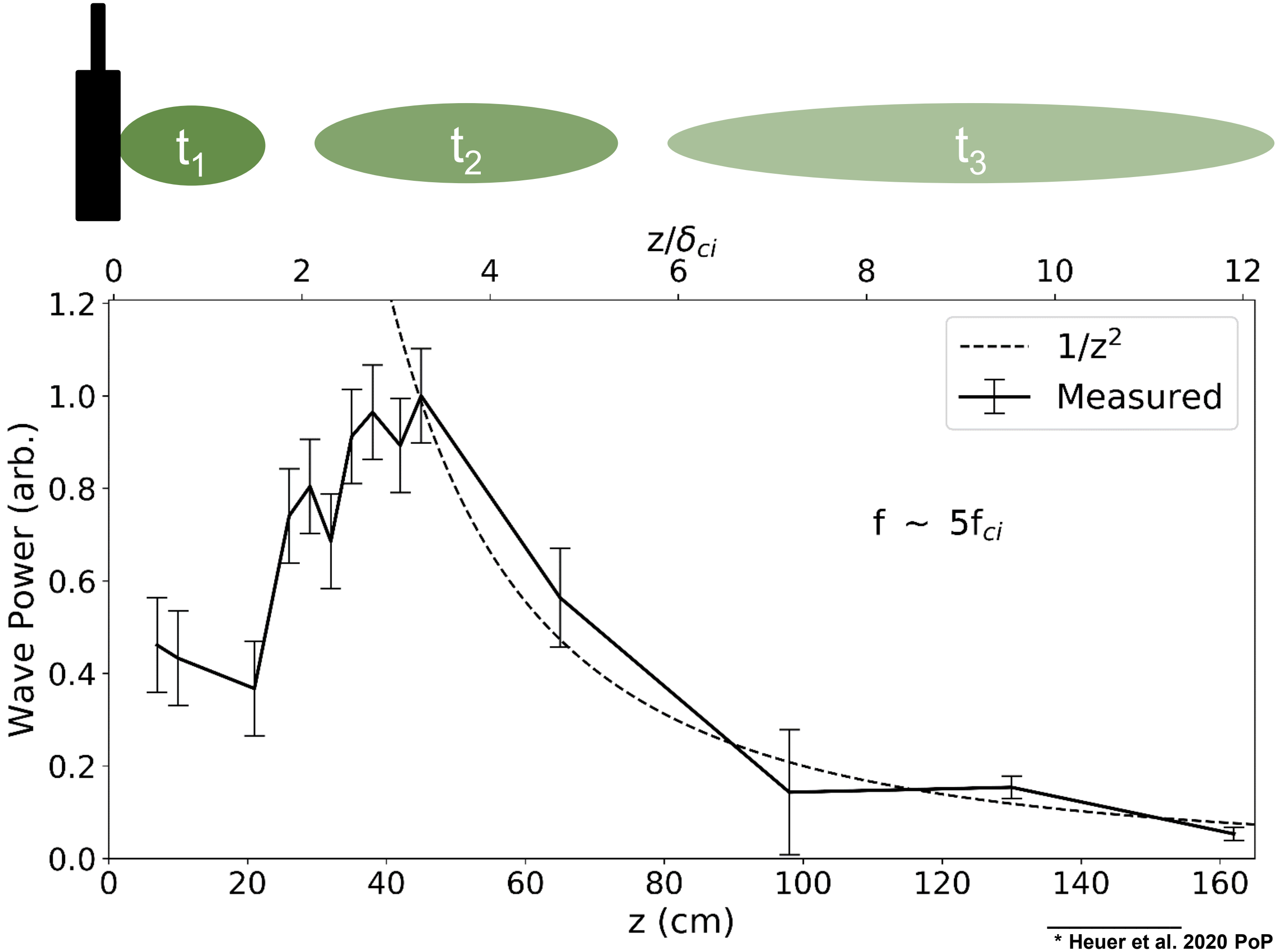
* Wilson III, 2016 AGU Press
**Heuer et al. 2018 PoP
† Heuer et al. 2020 ApJL

Velocity dispersion severely limits the effective length of large experiments

Density rapidly decrease with distance from the laser target, stopping instability growth.

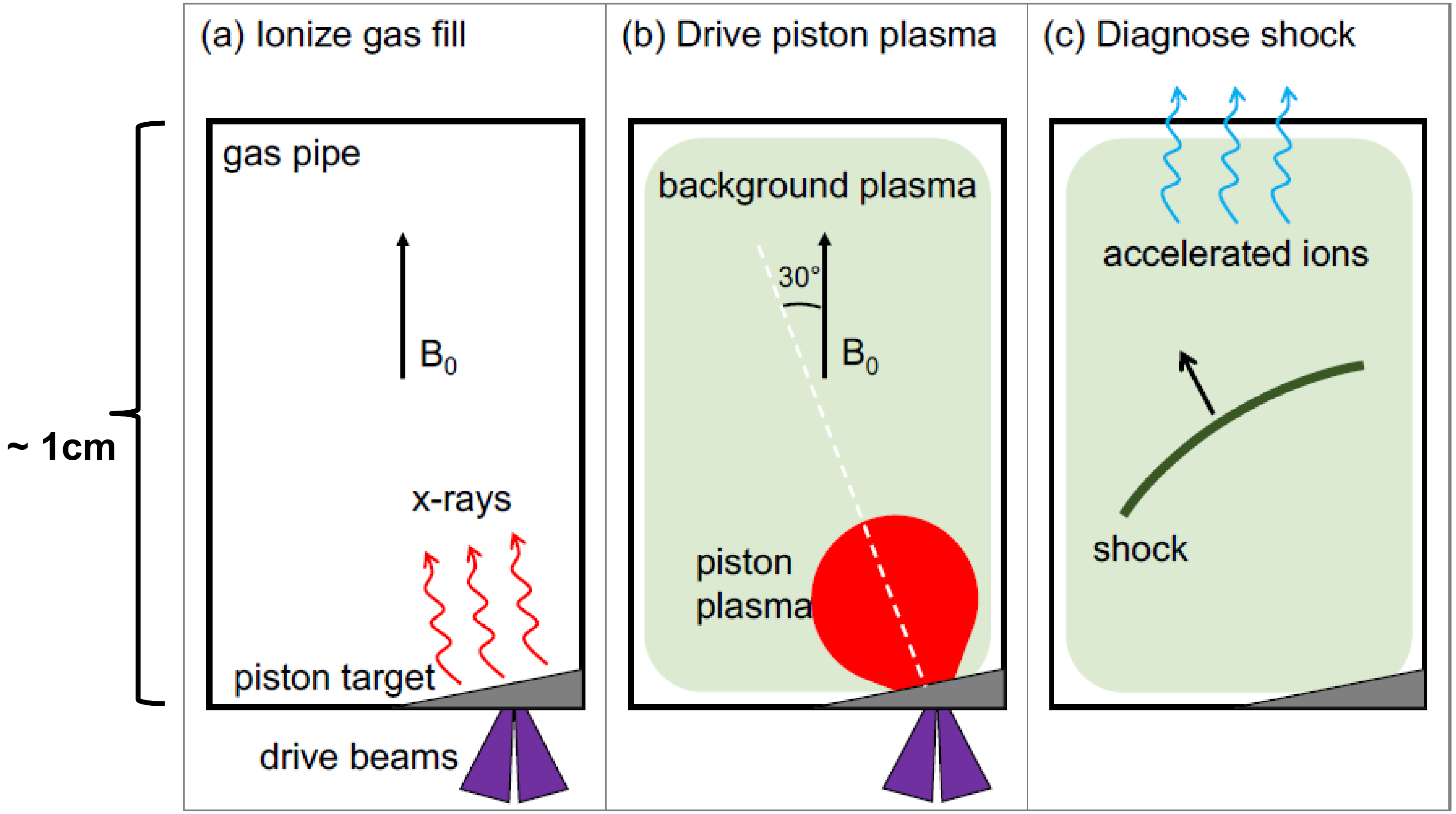
Two possible solutions moving forward

1. Combine a series of pulses to extend the LPP.
2. Scale the experiment down to be closer to the LPP scale (requires much higher laser energies).



* Heuer et al. 2020 PoP

Towards quasi-parallel shocks on large laser facilities (work in progress!)

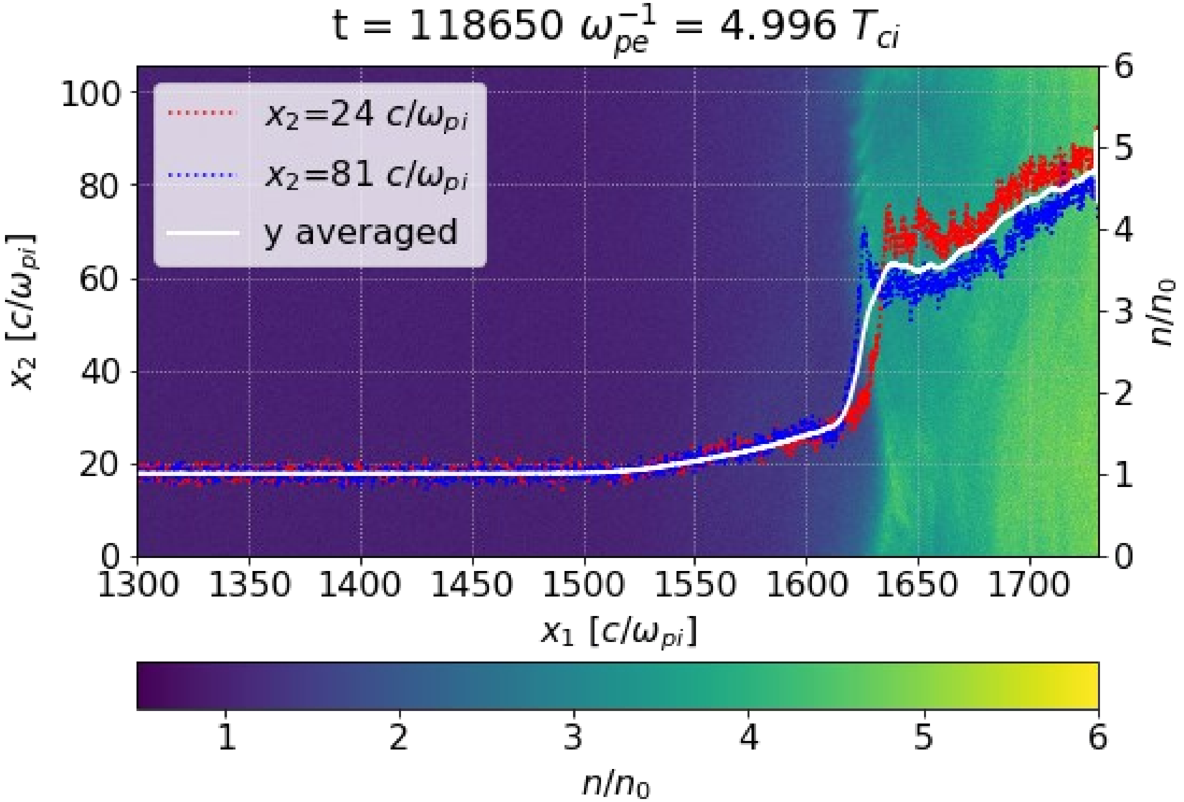


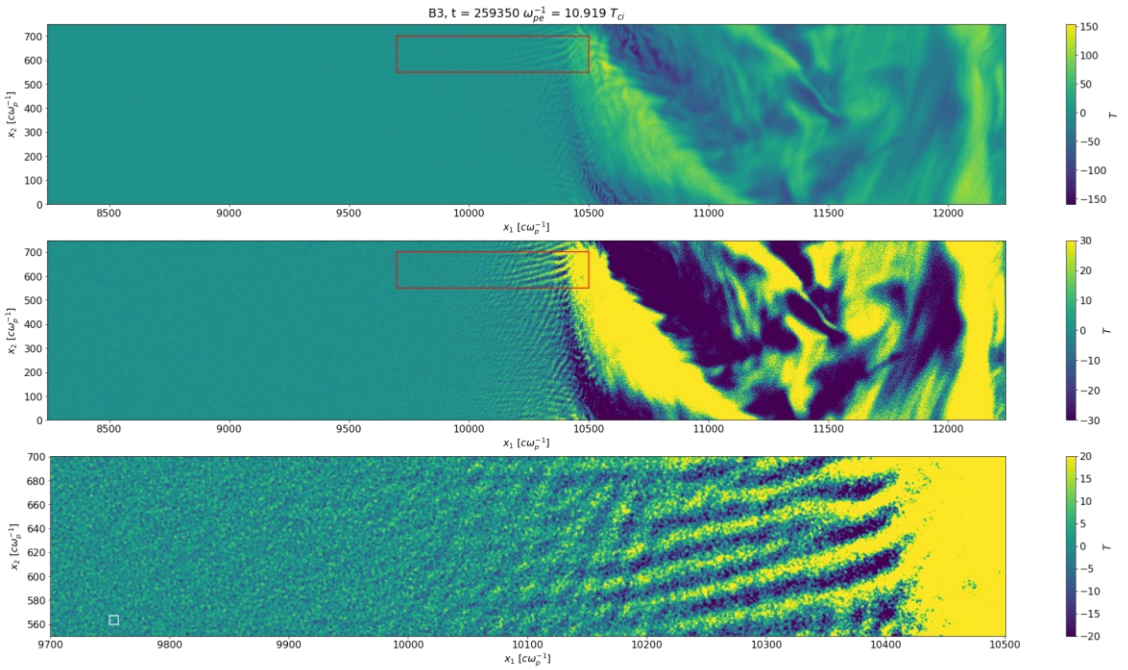
Parameter	Proposed Experiment
L/d_{i0}	620
(L/v_s) * ω_{ci}	46
M_A	14
L/λ_{ii}	2

Current generation laser facilities could create shock systems of unprecedented size.

* Image Credit: Derek Schaeffer

Exploring quasi-parallel shocks with PIC simulations





Simulations by Victor Zhang (graduate student)
Presentation (on perpendicular shocks): ZO06.00002
(Friday @ 9:40 am)

Laboratory quasi-parallel shock experiments are an exciting and rapidly opening frontier

Quasi-parallel collisionless shocks are …

…complex, turbulent structures mediated by electromagnetic ion/ion beam instabilities

…of great interest in space and astrophysics as accelerators of high energy particles (and may be a source of high energy cosmic rays)

…difficult to create in a laboratory environment because of the extremely long length and time scales they require to form

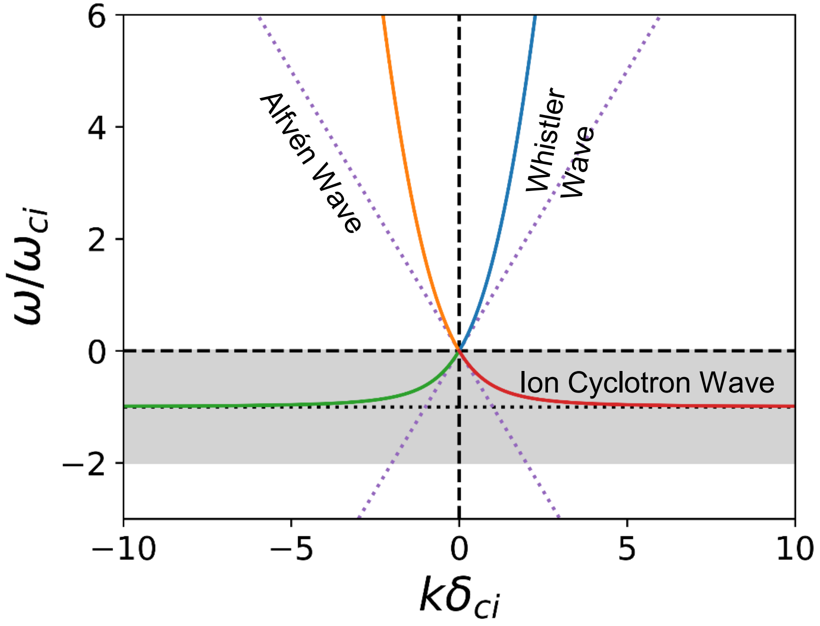
A quasi-parallel shock has never been created in a laboratory experiment.

We are currently pursuing approaches at both large and small scales.

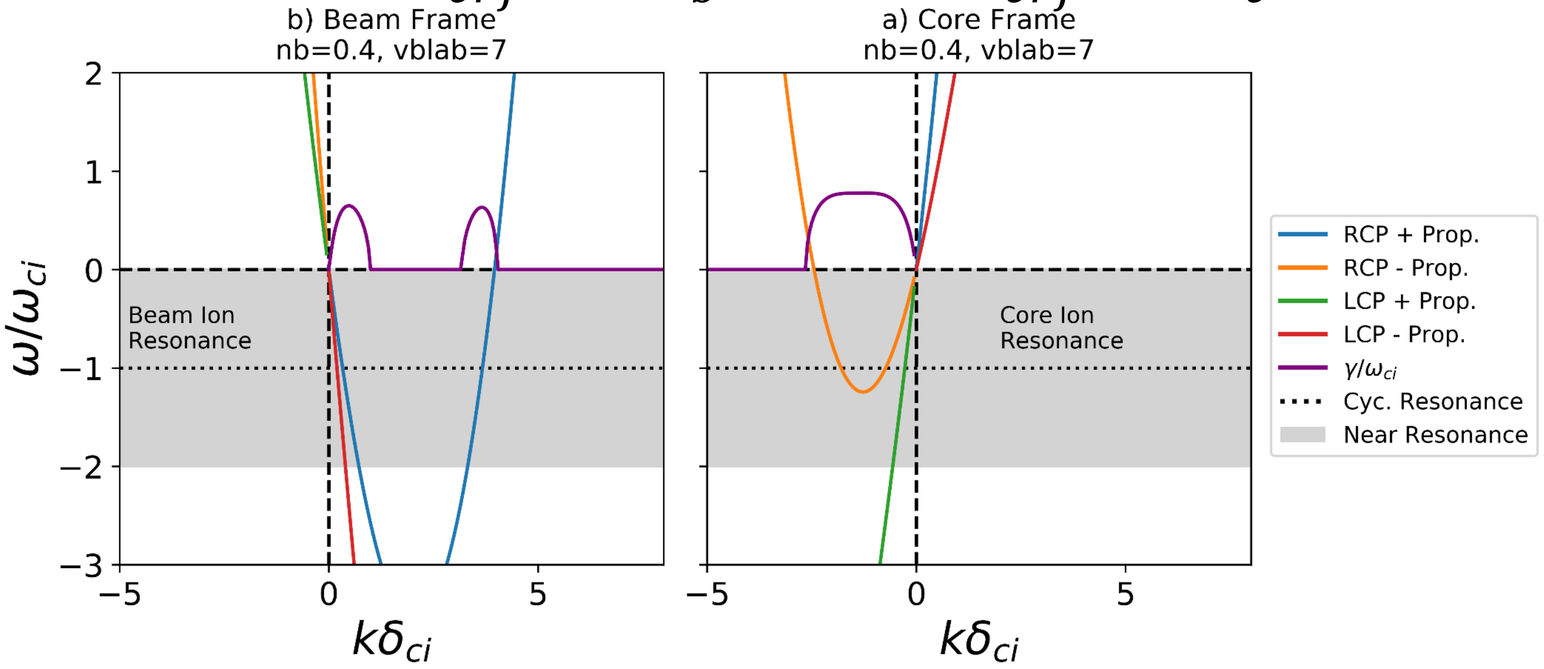
Backup Slides

Instability theory

Single Plasma Solutions



$\omega' = \omega_{erf} - k\, v_b$ $\omega' = \omega_{erf} - k\, v_c$



$s \in \{e, i\}$

$$\frac{\omega^2}{\omega_{p,c}^2} - k^2 - \sum_s \frac{n_s q_s^2}{m_s} \frac{\omega - k v_s}{\omega - k v_s \pm \Omega_s} = 0$$

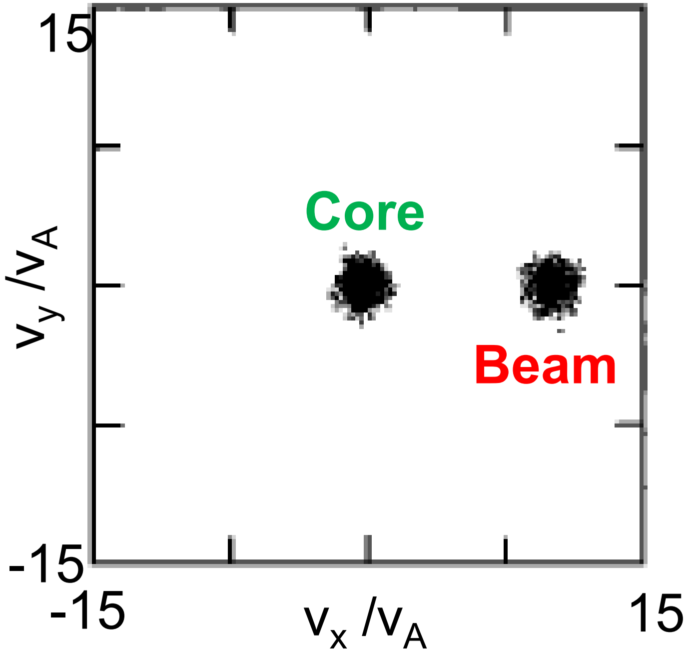
RHI = RCP Waves

NRI = LCP Waves

Weidl et al. 2019 ApJ “F,A,C,E”
Weidl et al. 2019 ApJ “Background”

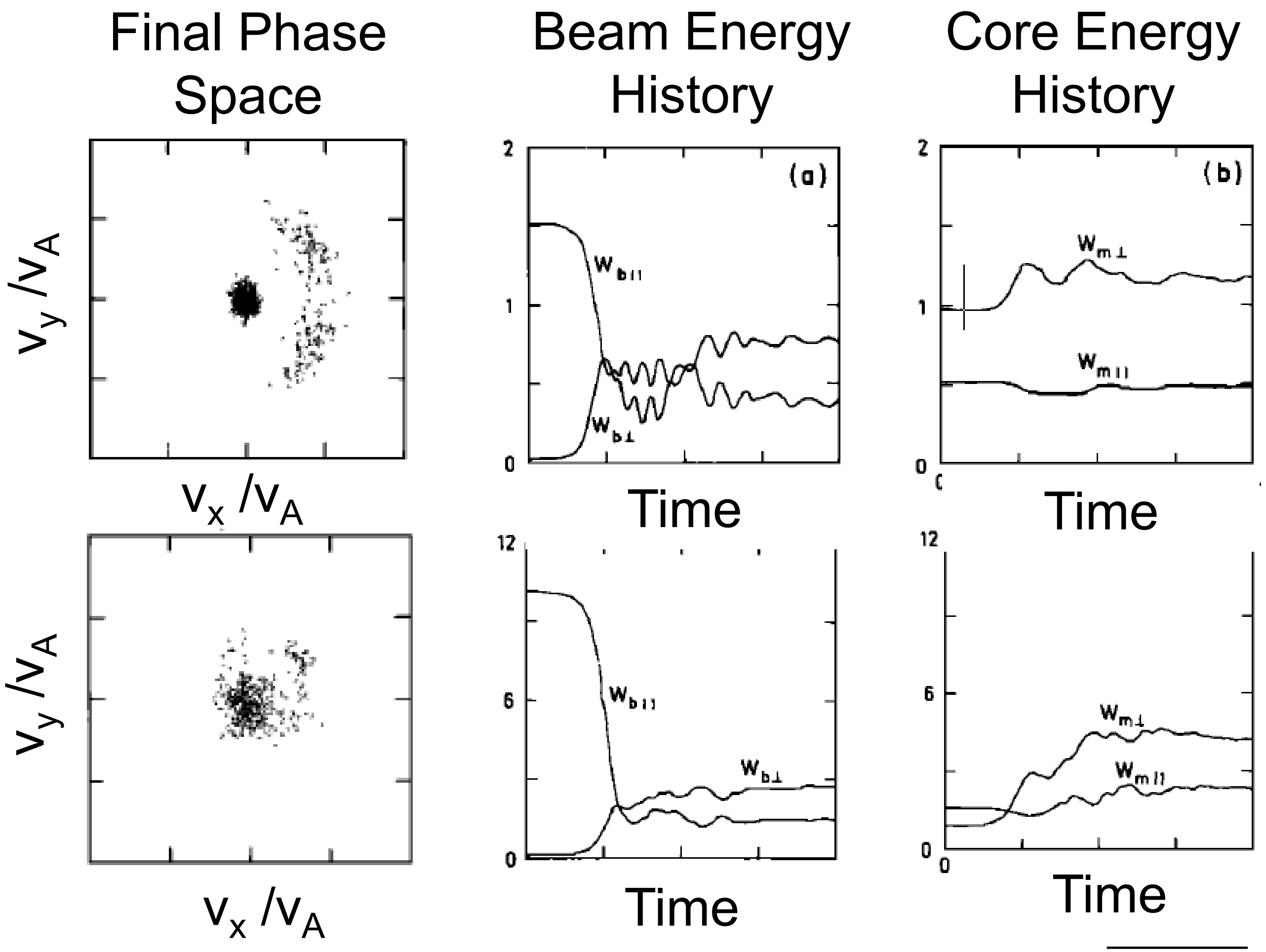
Different beam instabilities scatter particles in different ways

Initial Phase Space



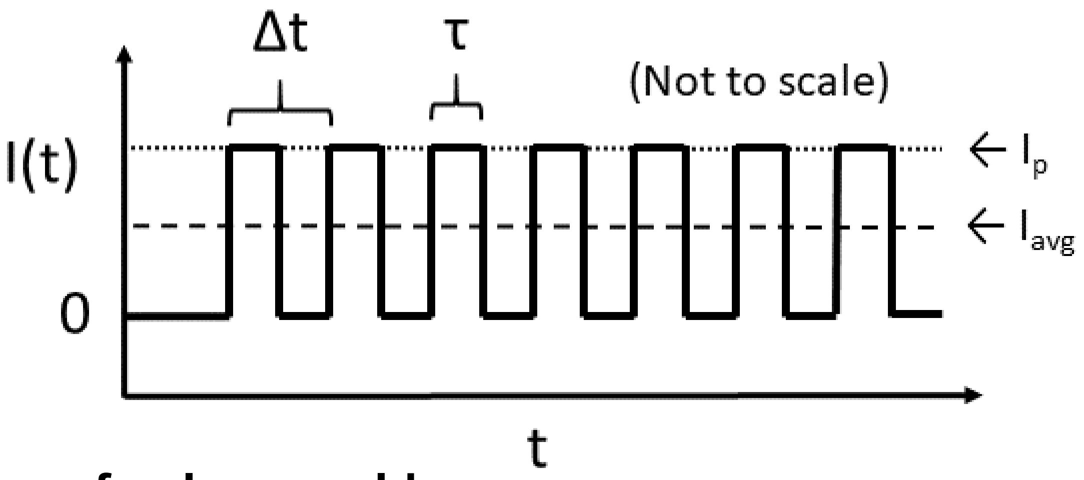
RHI

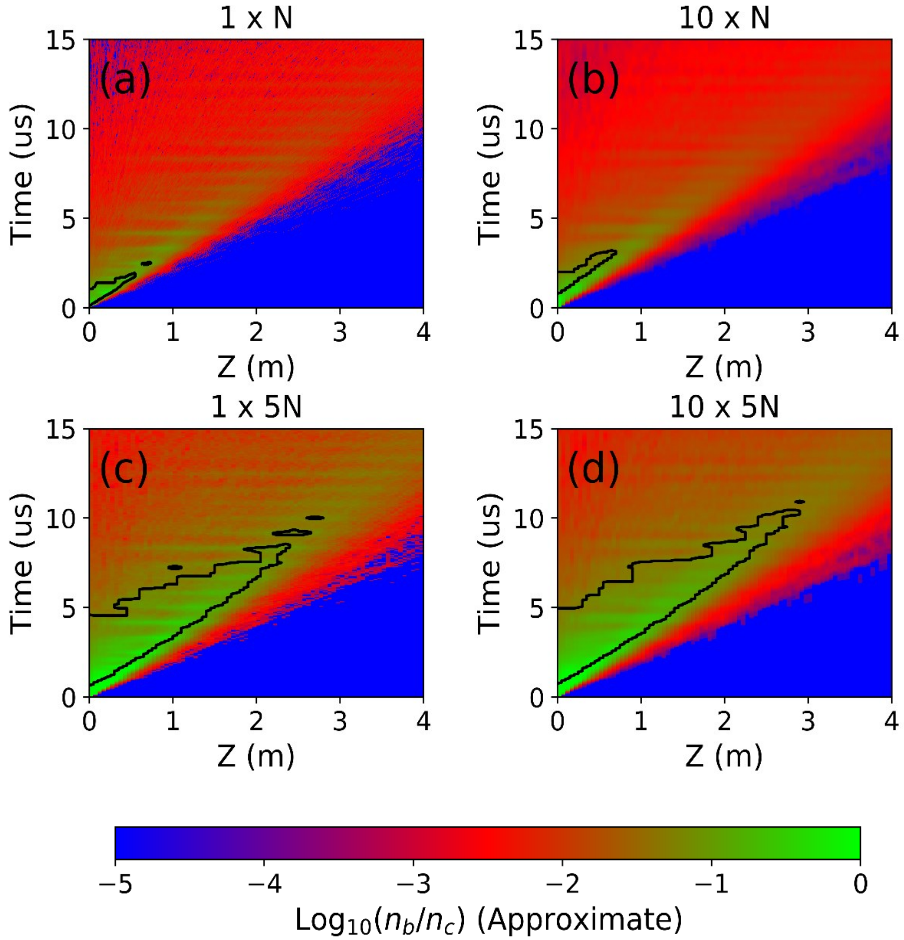
NRI (& RHI)



* Winske & Leroy JGR 1984

“Pulse trains” could push large-scale experiments further





Trains of pulses could:

- **Allow higher source energies to be used (by lowering average intensity)**
- **Maintain LPP velocity (by maintaining peak intensity).**
- **Produce a spatially extended plasma but quasi-uniform plasma**

Initial pulse train simulations showed the formation of non-linear waves.

* Heuer et al. 2020 PoP