Particle Acceleration at Shocks

Dietmar Krauss-Varban

Space Sciences Laboratory
UC Berkeley

Collaborators:
J. G. Luhmann, Y. Li, A. Hull, *SSL/UC Berkeley;*
J. Raines and Th. Zurbuchen, *U Michigan;*
X. Blanco-Cano, E. Aguilar, *Instituto de Geofísica, UNAM/Mexico*
H. Karimabadi, *UCSD & SciberQuest*

CISM
CENTER FOR INTEGRATED SPACE WEATHER MODELLING

Contents

I. Shock Particle Acceleration: Overview

- bow shock and IP shocks as model laboratory
- types of shocks
- heating vs. acceleration: energy conversion
- electrons vs. ions
- acceleration mechanisms

II. Relevance to SEP Modeling

I. Shock Acceleration: Overview

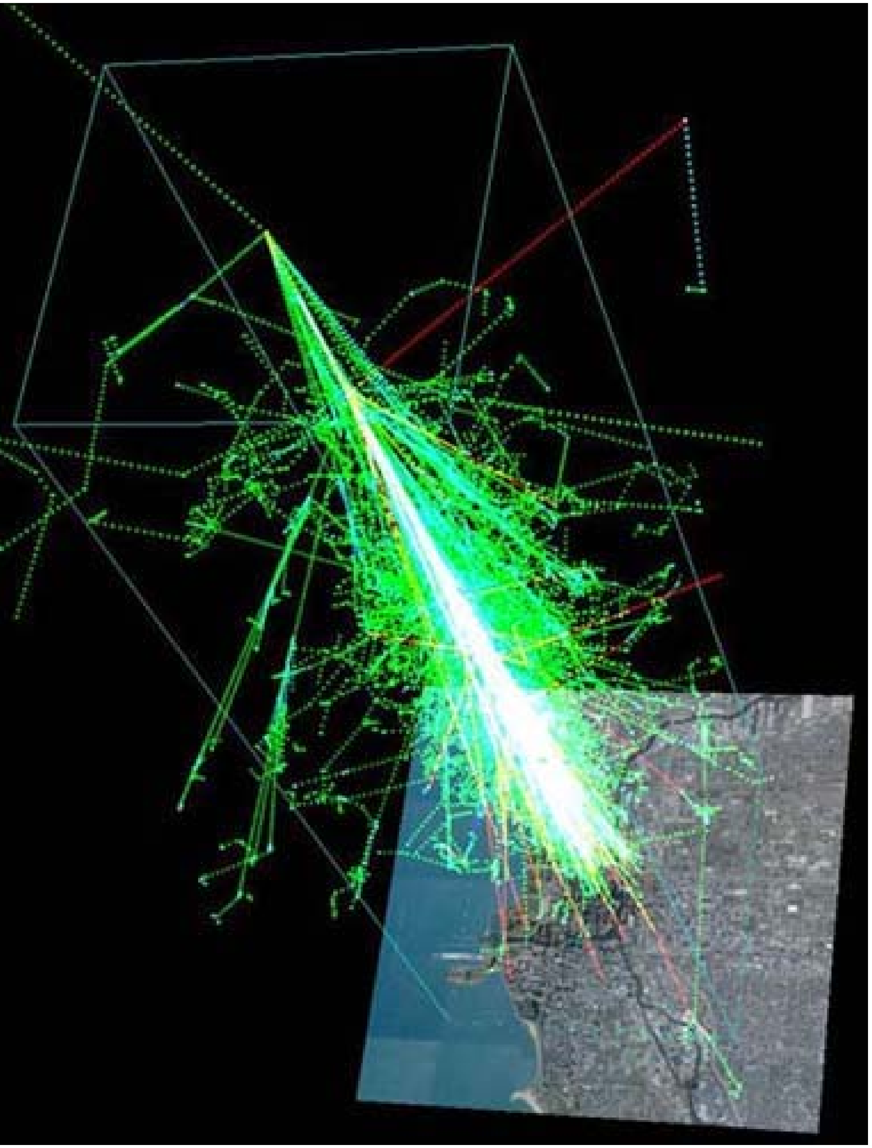
Planetary bow shocks and interplanetary shocks are great laboratories in which we can study collisionless shocks *in situ.*

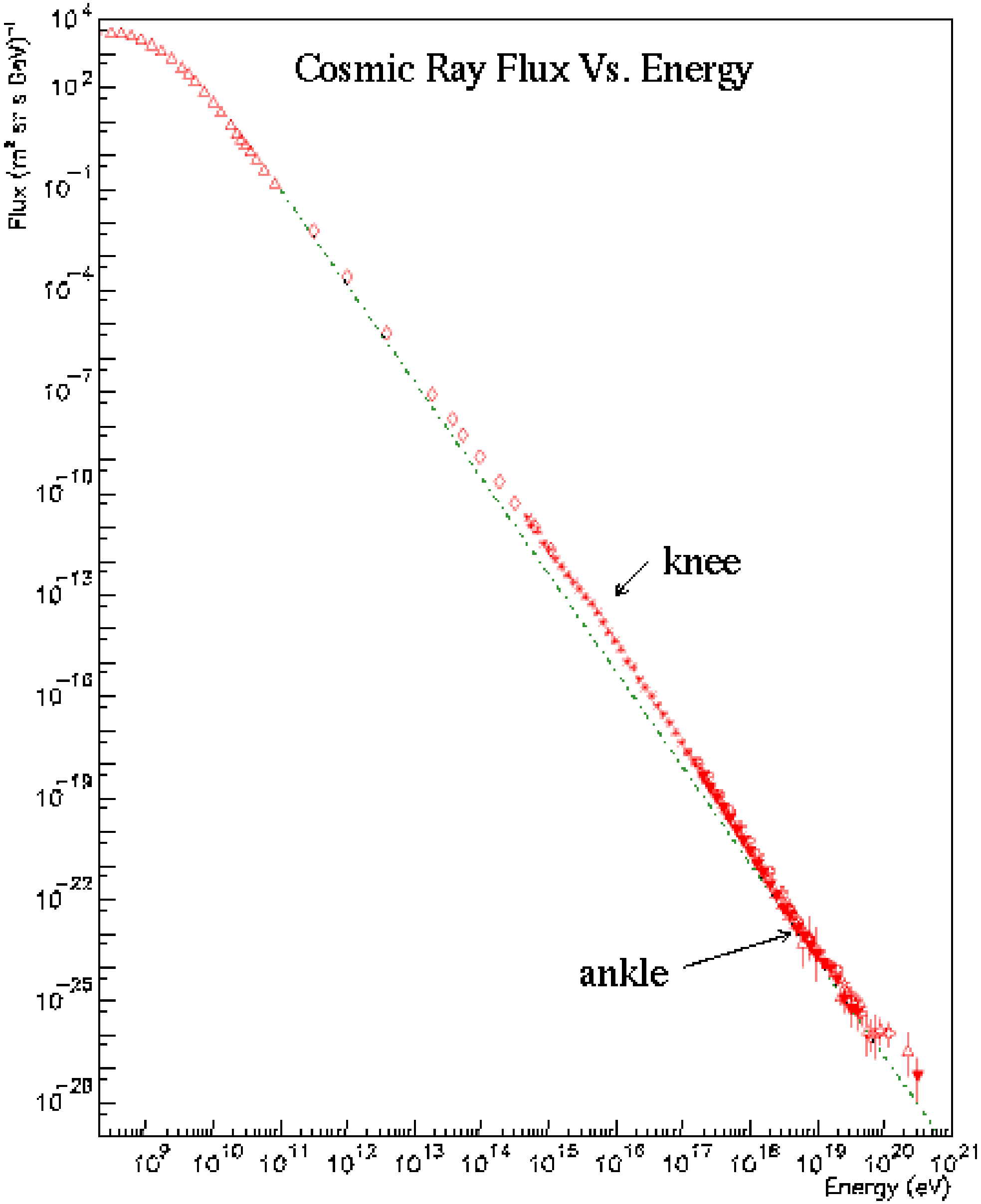
Processes are often similar to those occurring in astrophysical settings, for which we have only limited *remote sensing* data.

Astrophysical Settings

…shocks are omnipresent…

Cosmic Rays



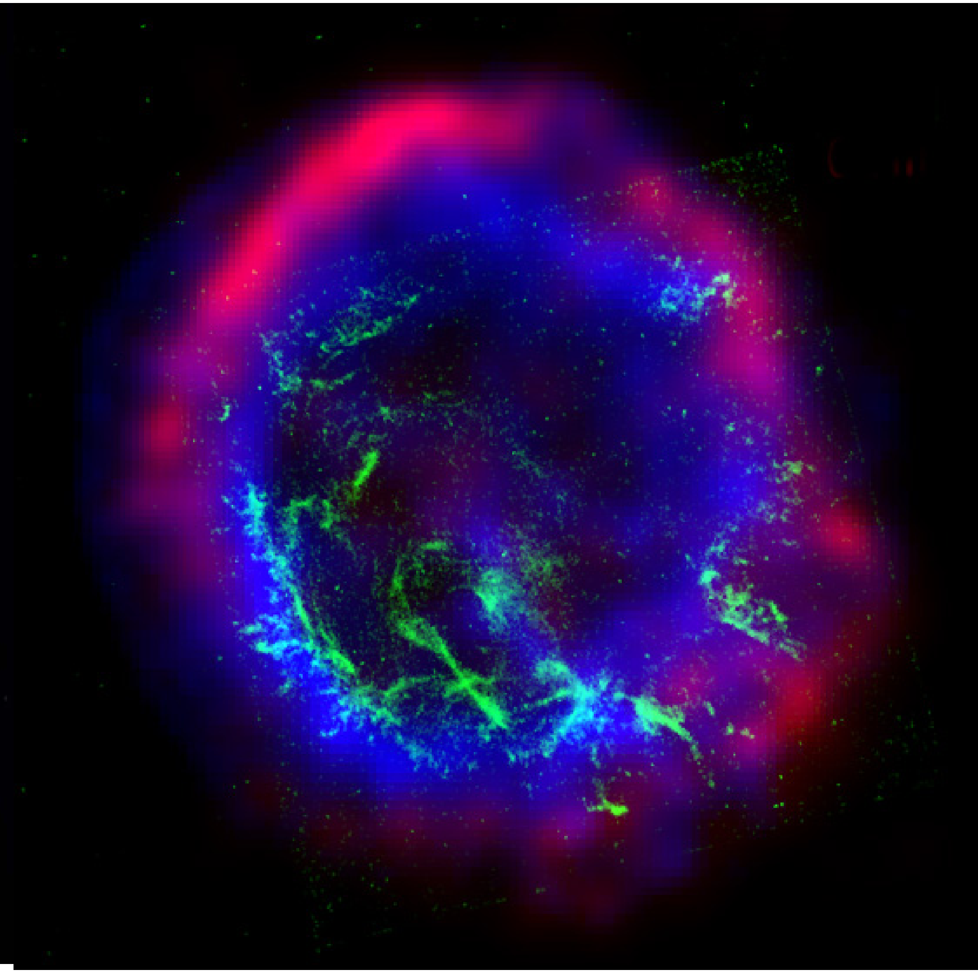


Cosmic Ray Flux Vs. Energy
knee
ankle
Flux (m² sr s GeV)⁻¹
Energy (eV)

Supernova Remnants

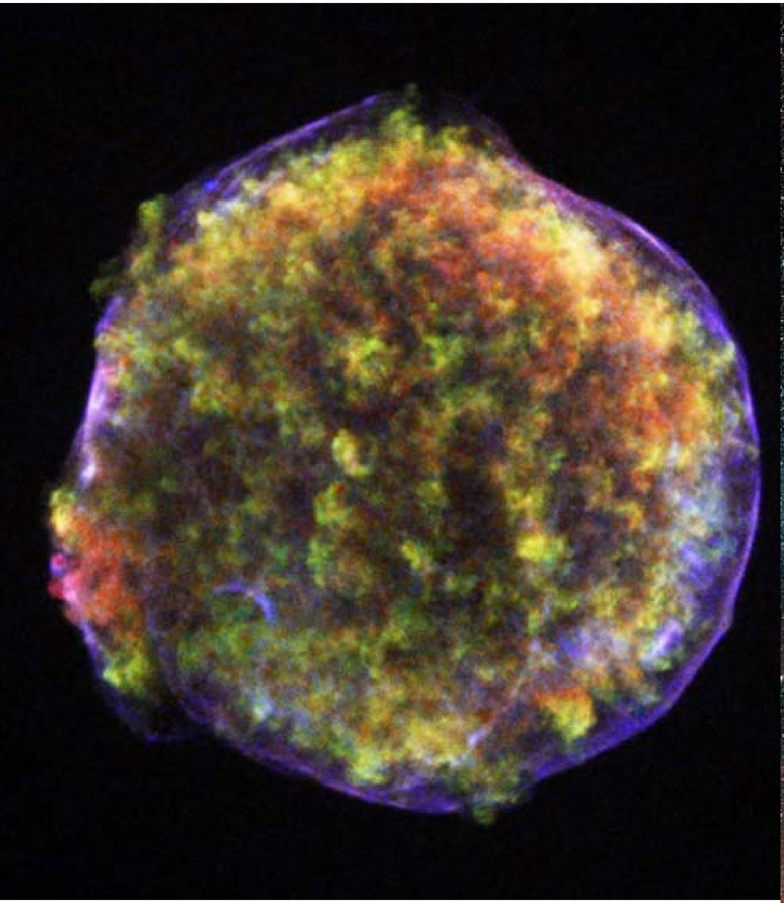
Kepler. Blue: highest energy

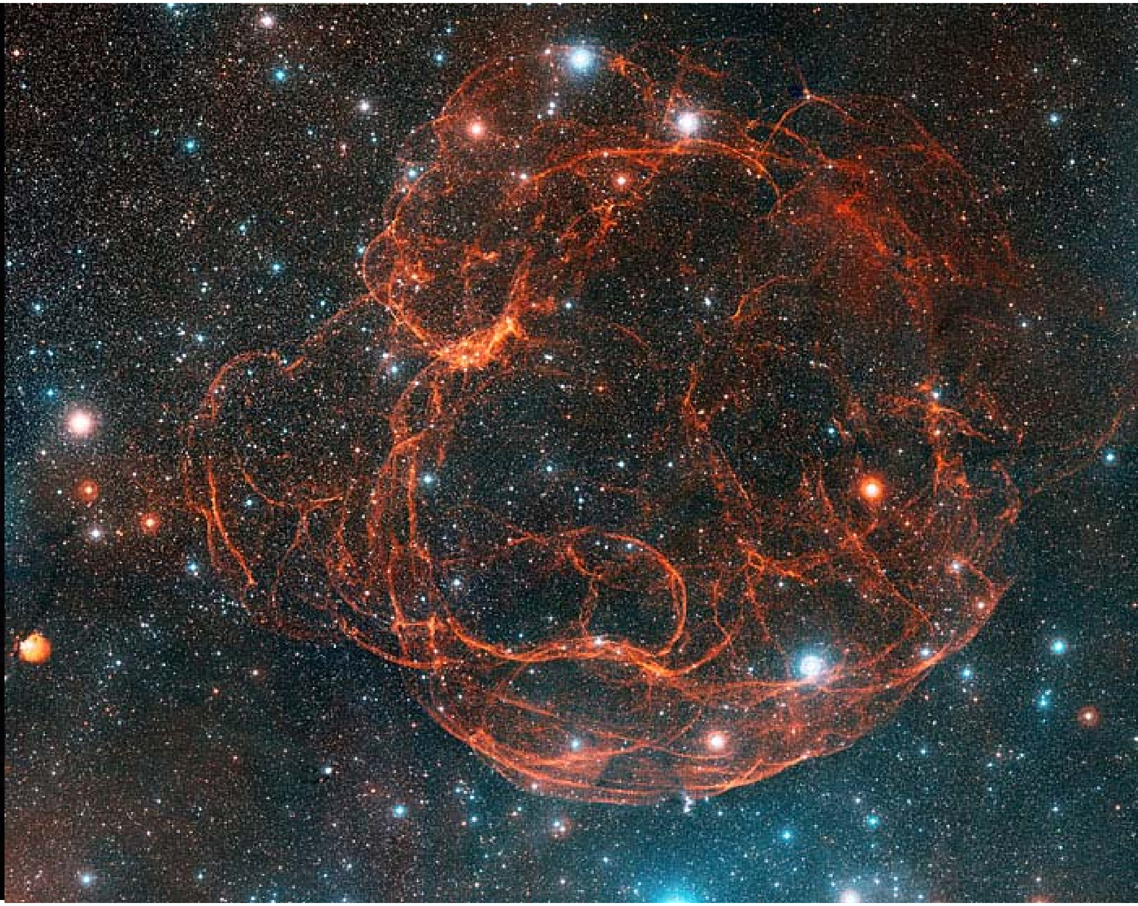
X-rays ←→ shock



e0102-723. blue: Chandra X-ray, million-K gas; red: radio, electrons. Green: “cool” oxygen gas.

Supernova Remnants





Tycho. Green, red: multimillion degree debris; blue: high-energy electrons. Nuclei energy ~100x electrons.

Simeis 147. 3º on the sky ←→ 160 light-years wide @ 3,000 light-years distance

Types of Shocks

- MHD (conservation equations) and Rankine-Hugoniot jump conditions.

Based on perturbation speed faster than characteristic fluid speed:

- slow shocks
- (time-dependent) intermediate shocks
- fast shocks

Slow shocks or *intermediate shock-like transitions* play an important role in reconnection. *Fast shocks* are prevalent elsewhere.

Electrons vs. Ions; Heating vs. Acceleration

- In most scenarios, both theoretical considerations and observations show that at first, primarily the ions get heated.
- This is due to the shock transition scale typically being on ion scales, and the electrons largely behaving adiabatically.
- Wave-particle interactions fill the downstream phase space and provide additional mechanisms for equi-partition of energy between species
- ***Acceleration to higher energies is secondary and typically relies on a combination of <u>kinematic</u> and <u>kinetic</u> processes*.**

General Acceleration Mechanisms

- **kinematic** (particles in macroscopic fields)
  - mirroring in propagating frame ("Fast Fermi")
  - betatron (collapsing magnetic field loops)
  - reflection between moving mirrors (first order Fermi; requires kinetic process to do so)
  - e-field acceleration, often when "unmagnetized"

- **kinetic** (particles in self-consistent wave fields)
  - second-order Fermi in resonant wave fields
  - pitch-angle scattering in conjunction with first-order Fermi

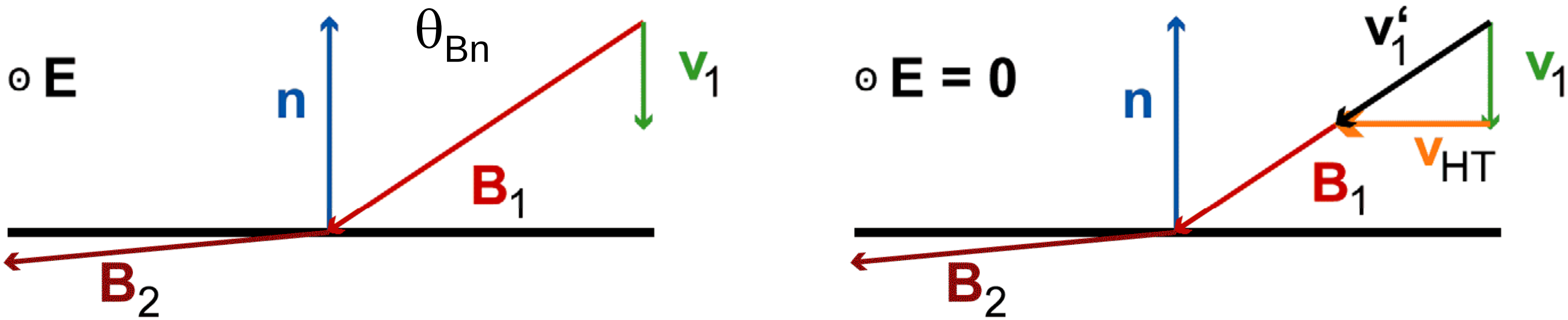
Note: the above processes are operative in many scenarios outside of shocks

Shock Acceleration Mechanisms

- **fast Fermi** (e$^-$ mirroring at highly-oblique shock)
- **shock drift** (phase-space subset that remains in E-field at shock for extended time)
- **first-order Fermi** (reflection of scattering centers *"pitch-angle scattering"* on both sides of moving discontinuity/shock)
- **second-order Fermi** (random pitch-angle scattering)
- **perpendicular diffusion** (in 3-D, charged particles are not strictly bound to field lines) *****
- **field-line meandering** (turbulent field lines transport particles back and forth across oblique shocks) *****

*** Note:** likely only applicable to the highest energies and largest structures.

NIF vs. HTF



normal incidence frame (NIF) de Hoffmann-Teller frame (HTF)

- Electron orbits are small compared to shock transition
- Ion orbits are comparable or larger, yet they may behave almost adiabatically initially
- SDA is gradient drift in E-field in NIF, or can be explained from slowing down and frame transformation in HTF
- Shock surfing affects subset of ions that are slowed down by cross-shock potential

Shock Acceleration Mechanisms

Relevance and configurations:

- **fast Fermi (e$^-$ or ions at reconnection discontinuities)**
- **shock drift/surfing (small phase-space subset, quasi-perpendicular or nearly perpendicular shocks)**
- **first-order Fermi (quasi-parallel shocks)**
- **second-order Fermi (quasi-parallel shocks, downstream?)**
- **perpendicular diffusion (extremely large scale/ high energies, almost perpendicular shocks)**
- **field-line meandering (very turbulent field lines, high beta, and large scale, almost perpendicular shocks)**

Expectation

- Major shock parameters are:

$$\theta_{Bn},\ \beta, \text{ and } M_A$$

- Naïve expectation is that acceleration should be strongest at fastest shocks, and at quasi-parallel shocks
- Observations at heliospheric shocks don't always confirm this, and typically don't show the expected ordering

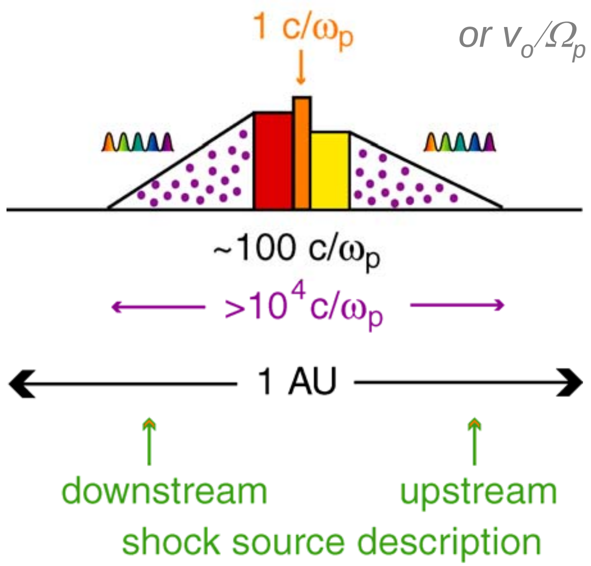
II. Relevance to SEP Modeling

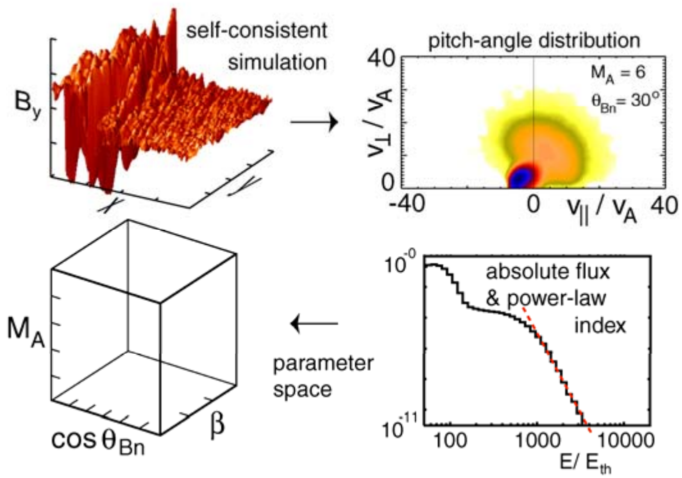
- non-relativistic, CME-driven IP shocks
- non-relativistic or semi-relativistic particles
- typically, not *“cosmic-ray-dominated”* shocks
- heating, shock transition, and acceleration dominated by ions
- ions (100keV to 100MeV) of highest interest
- hybrid code (kinetic ions, electron fluid) very appropriate

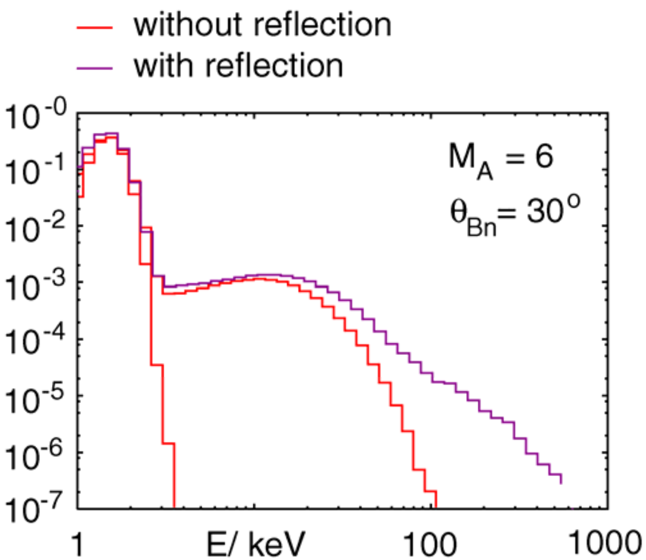
II. Relevance to SEP Modeling

- Other approaches use various mixtures of diffusion and transport theories
- this talk concentrates on particle (hybrid) simulations
- *Self-consistent* hybrid simulations have a long history in this context (*D. Burgess, J. Giacalone*)

Shock source description







<u>Important Considerations for Hybrid Code Approach:</u>

- Field line topology/ mirroring
- Seed particles
- Parameter dependence (M_A, β, θ_{Bn})

Example: Can observed energetic ion fluxes at CME-driven shocks be understood, quantified, and ultimately lead to Space Weather forecasts?

- Previous attempt of ordering fluxes **at ESP events** with θ_{Bn} and M_A not successful
- Here, optimistic approach: assume there are distinct reasons for observed variations
- Our approach: compare observed fluxes at ESP events to those obtained from self-consistent 2-D Hybrid simulations (kinetic ions, electron fluid)
- Can we learn something by comparing to the Earth's bow shock?

ESP event: *IP shock with energetic ions passing satellite*

Clean cases: *no additional shocks or major discontinuities 1 ½ to 2 days prior or past; undisturbed solar wind*

ACE Observations - Selected “clean” ESP Events:

Quasi-parallel cases:

CASE	M_A	θ_{Bn}	Peak Flux	Power Law Index		
				upstream	peak	downstream
P1 01-01-17	3.7	28	0.02 e06	1.9	1.9	1.9
P2 01-04-04	4.2	15	1.3 e06	1.2	2.2	1.9
P3 01-10-25	3.6	30	0.5 e06	1.5	2.4	2.1

P1: **No cloud:** peak only ½ to 1 order of magnitude above background. Far upstream index ~1.5.

P2: Peak is 2 ½ orders of magnitude above background. Far upstream index ~1.5.

P3: Peak is 1 ½ orders of magnitude above background. Far upstream index ~1.5.

Oblique cases:

CASE	M_A	θ_{Bn}	Peak Flux	Power Law Index		
				upstream	peak	downstream
O1 98-10-18	3.7	50	0.13 e06	3.0	3.0	3.0
O2 99-02-18	3.5	50	1.0 e06	1.9	2.7	2.9
O3 00-06-08	4.5	50	1.3 e06	1.1	1.7	1.4
O4 01-10-21	4.7	50	1.3 e06	1.4	2.1	2.2

O1: Peak is 2 ½ orders of magnitude above background. Far upstream index ~2.0.

O2: Peak is 4 orders of magnitude above background. Far upstream index ~2.0.

O3: Peak is 2 orders of magnitude above background. Far upstream index ~1 to 2.

O4: Peak is 3 orders of magnitude above background. Far upstream index ~1.5.

Highly Oblique Shocks

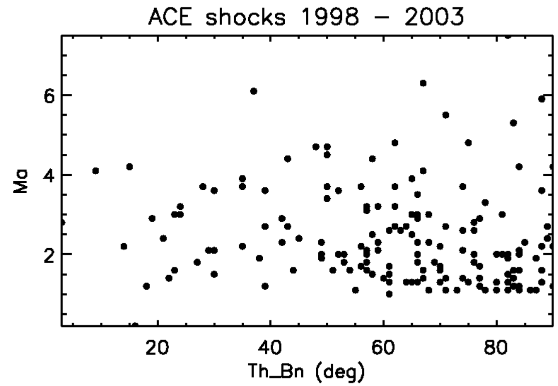
- What is the upper limit on θ_{Bn} for which shock undulation provides the main cause of acceleration?
- Are highly oblique IP shocks *that do accelerate ions* necessarily higher M_A?

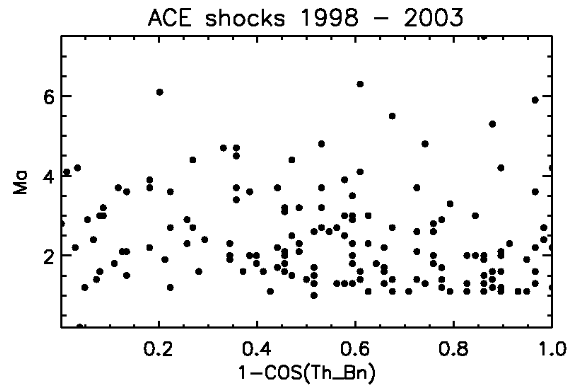
Case	Event	θ_{Bn}	M_A	P1 Peak	P8 Peak	comments
HO1	19980501t2122D121	77	2.9	0.90e06	0.97e02	
HO2	19990922t1145D265	64	2.7	0.98e06	0.79e02	
HO3	20000623t1227D175	66	3.5	0.83e06	1.40e02	broad energetic profile
HO4	20011011t1620D284	74	2.1?	1.10e06	2.70e02	listed M_A suspect

- selected cases, θ_{Bn} 60 to 80 degrees -

Case	Event	θ_{Bn}	M_A	P1 Peak	P8 Peak	comments
AP1	19980806t0644D218	82	1.5?	0.15e06	0.25e02	listed M_A suspect
AP2	19980826t0615D238	98	7.5	1.00e06	46.7e02	
AP3	20000719t1448D201	81	3.0	0.30e06	1.20e02	
AP4	20010428t0431D118	88	5.9	1.30e06	40.1e02	broad energetic profile

- selected cases, θ_{Bn} 80 to 90 degrees -





- all forward shocks -

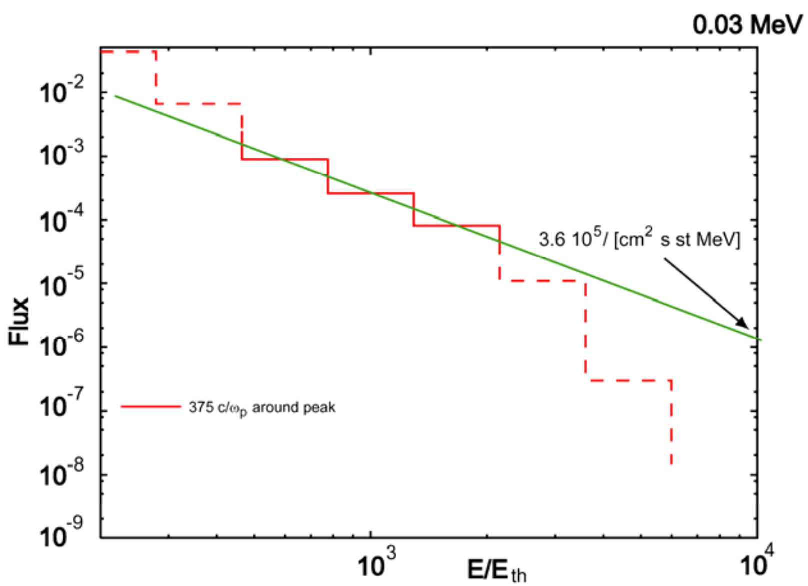
Hybrid Simulation Results

Selected *groups* of events (q-parallel vs. oblique); comparison with/without seed particles

q-parallel group

- Power law index ~ 2.2 in both simulations and observations

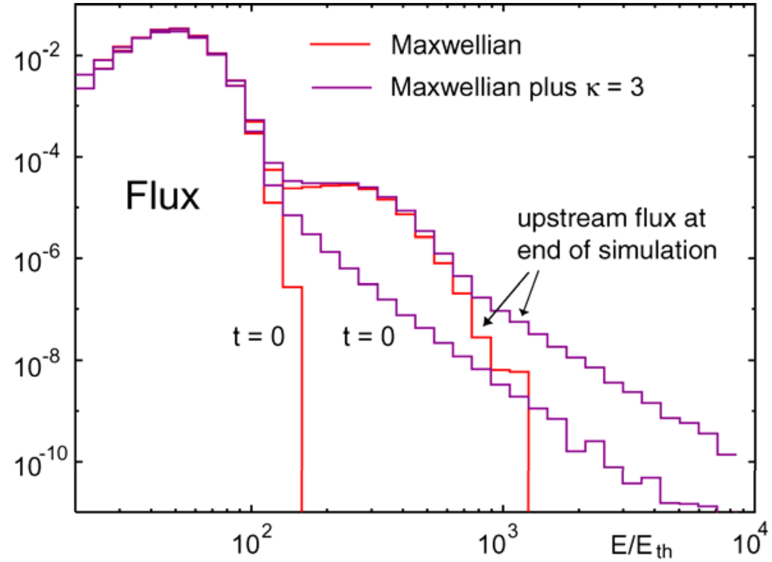
- seed particles *not* required for slope, nor for observed flux level



oblique group

- flux ~ 5 orders of magnitude too low w/o seed particles

- seed particles required for *both* absolute levels and slope?



What is the expectation from

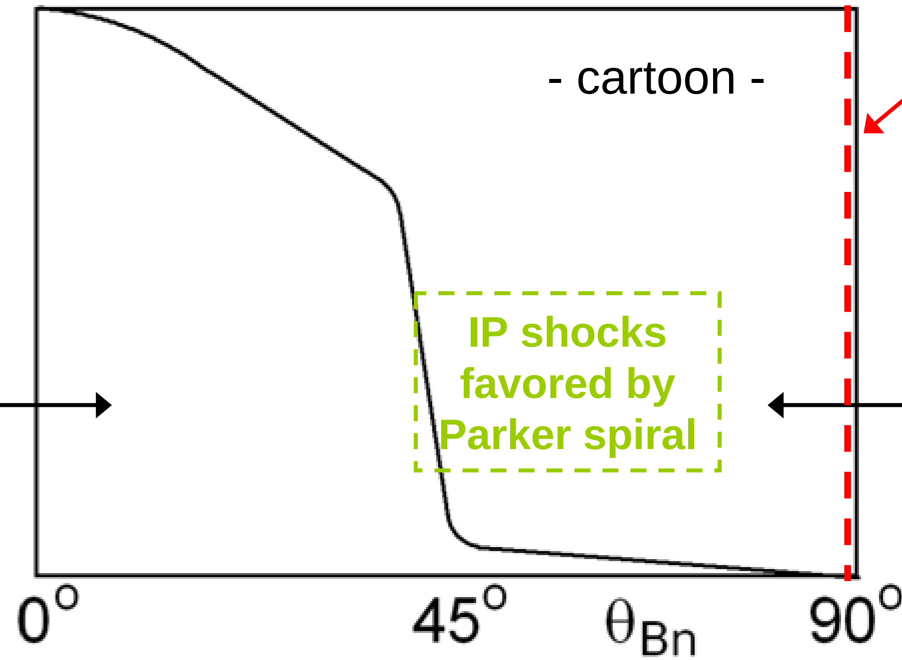
- the Earth's bow shock observations, and from
- typical particle simulations,

and what is different about IP shocks/ ESP events?

Transition from quasi-parallel to perpendicular:

Bow shock and 2-D simulations

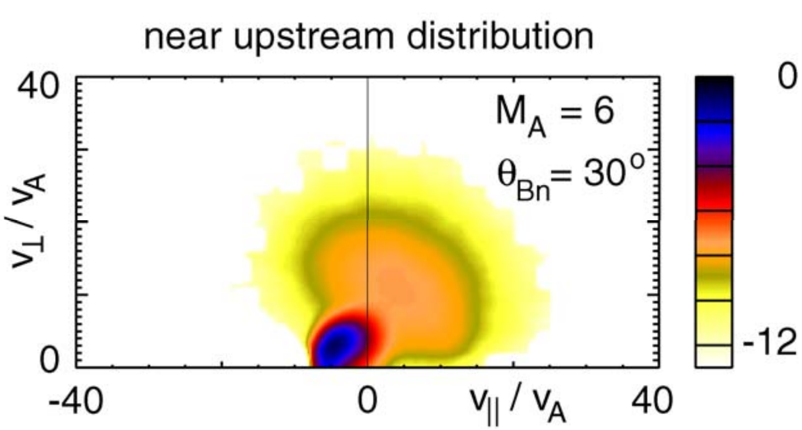
Self-consistently generated waves and ion acceleration

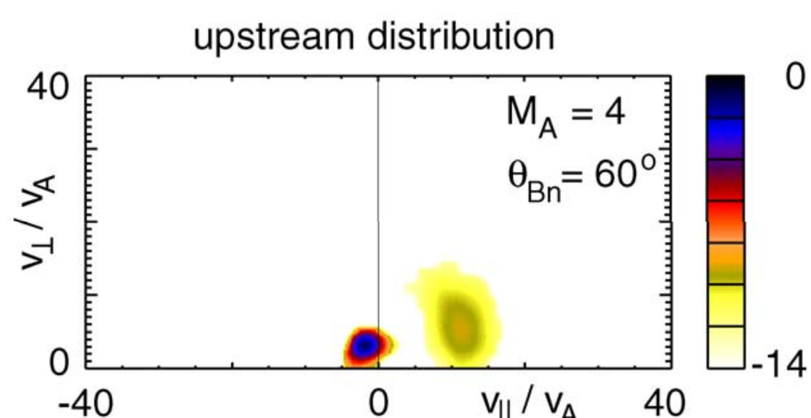


Fast Fermi e^- & radio emissions

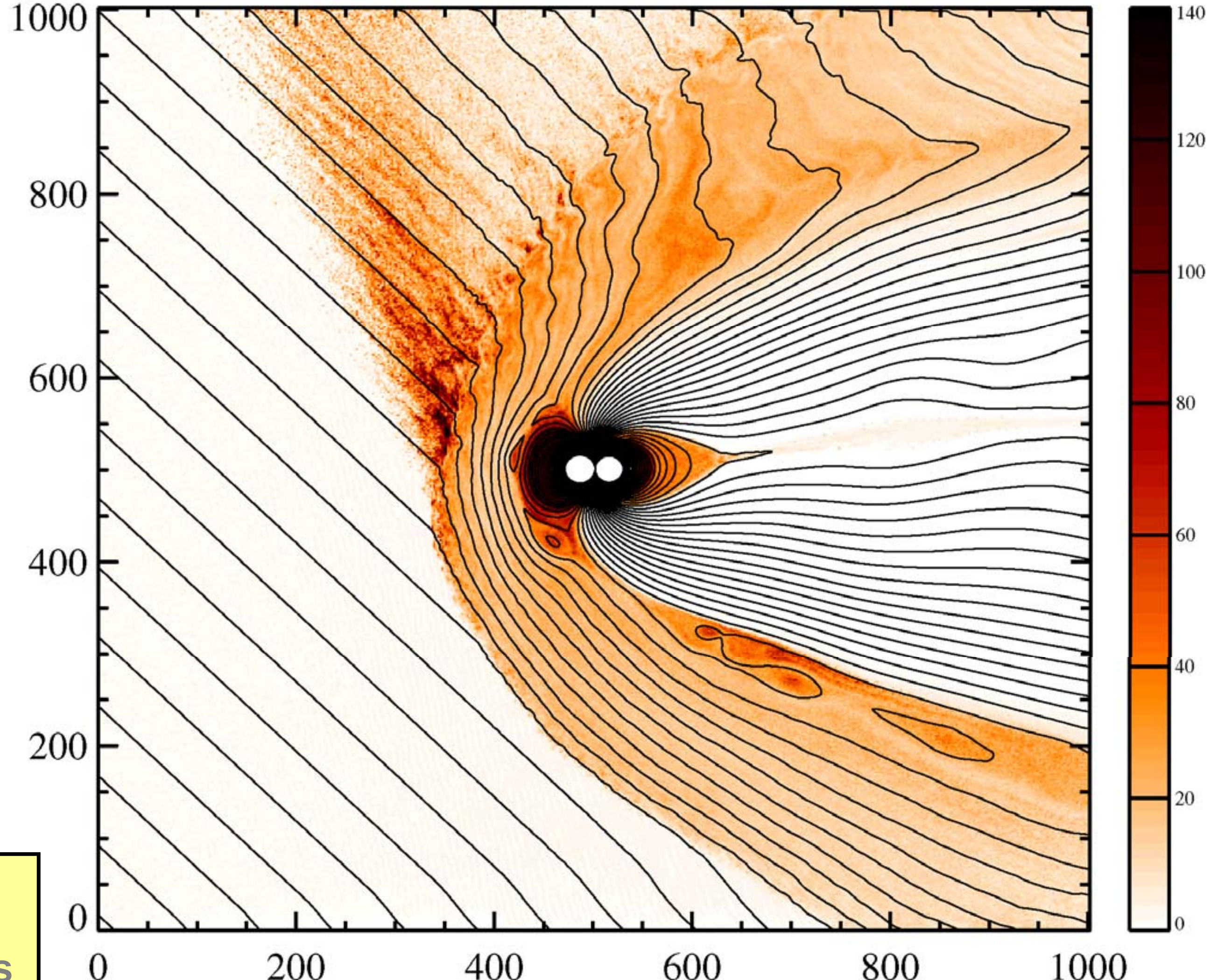
Adiabatic compression, drift/surfing acceleration; perpendicular transport

diffuse ions ←→ dilute beams





Example: Oblique Bow Shock



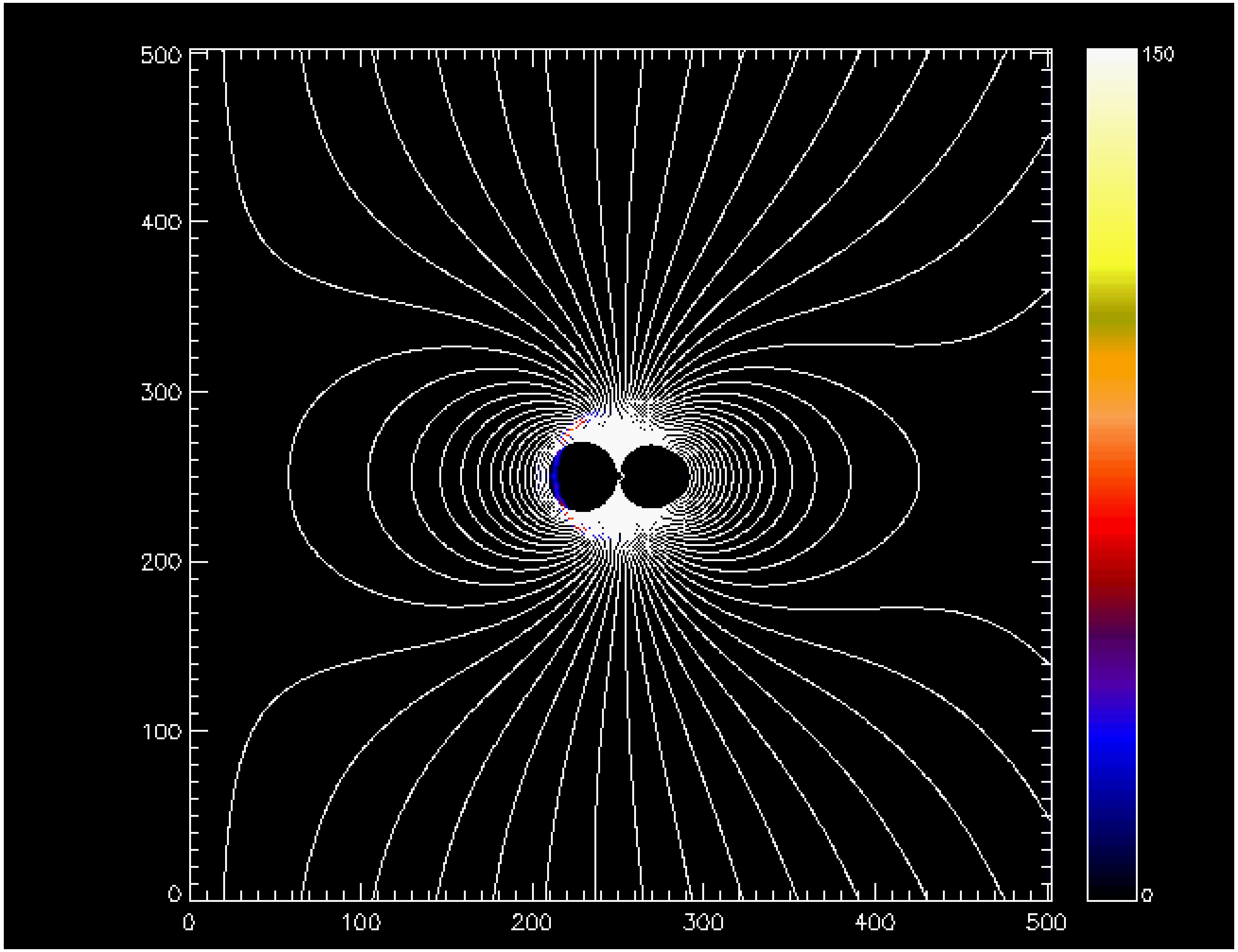
- parallel temperature -

Caveats:

1. **#particles /cell**
2. **scaling**

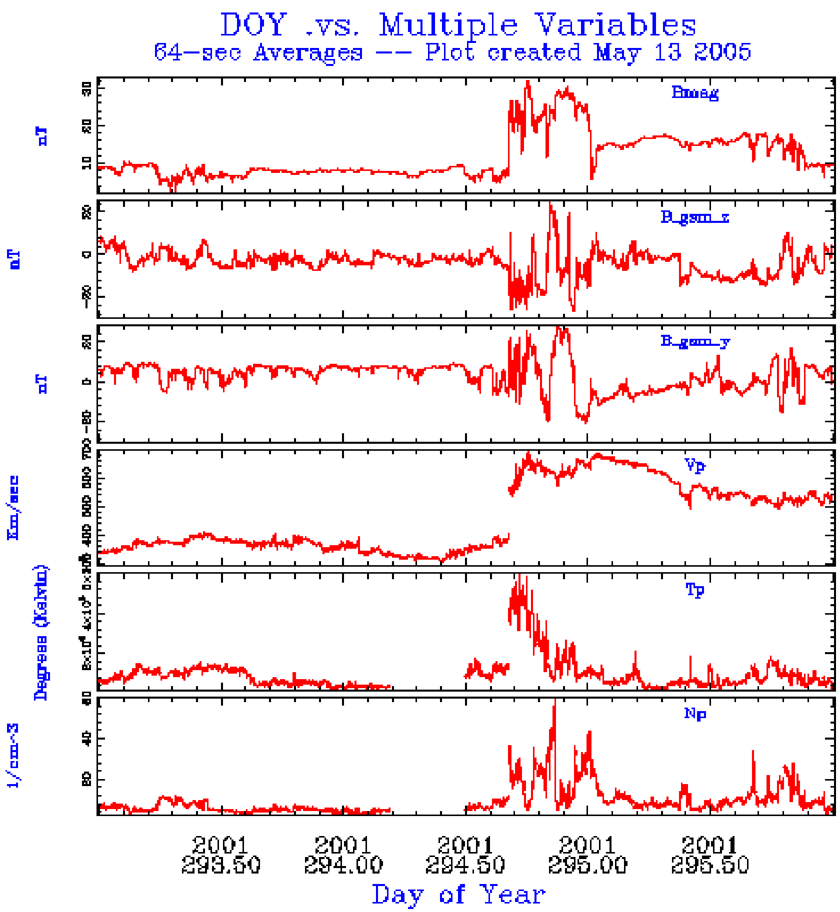
see also *Blanco-Cano et al.*, 2006

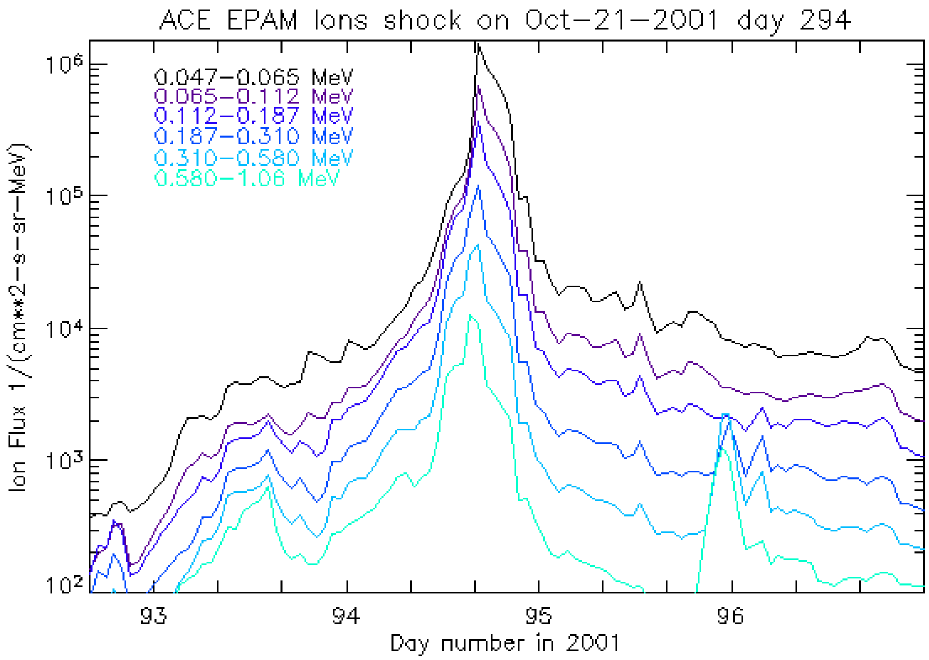
Example: Nearly Perpendicular Bow Shock



- temperature -

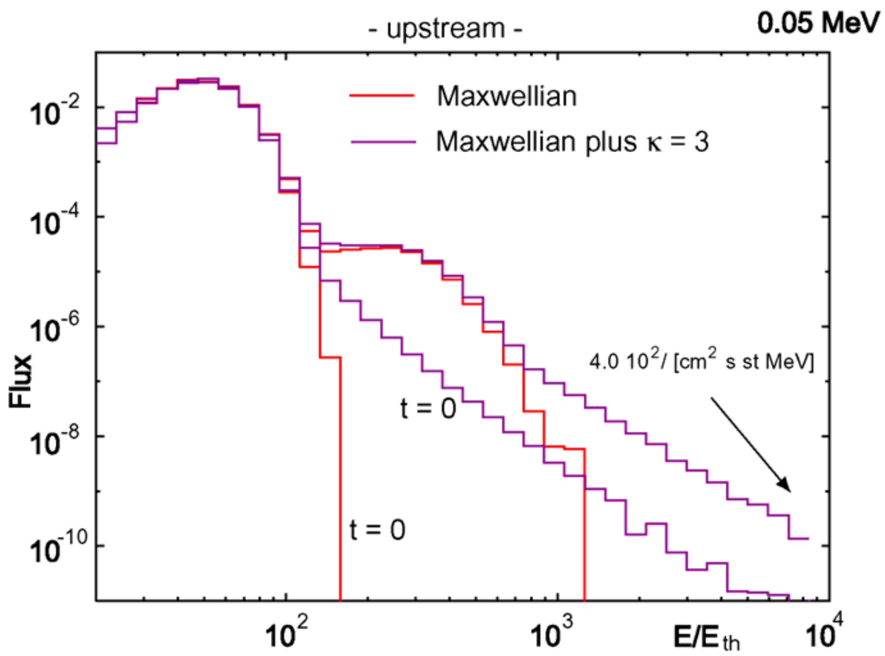
Event 10-21-01: $M_A = 4.7$, $\theta_{Bn} = 50^o$





Event 10-21-01:
"Standard" Simulation Results

- Example: Maxwellian plus κ with initial power law index ~ 3.0
- Slope is maintained in simulation
- Approximately 2 orders of magnitude larger flux than with Maxwellian, only, but still 3 orders lower than observed

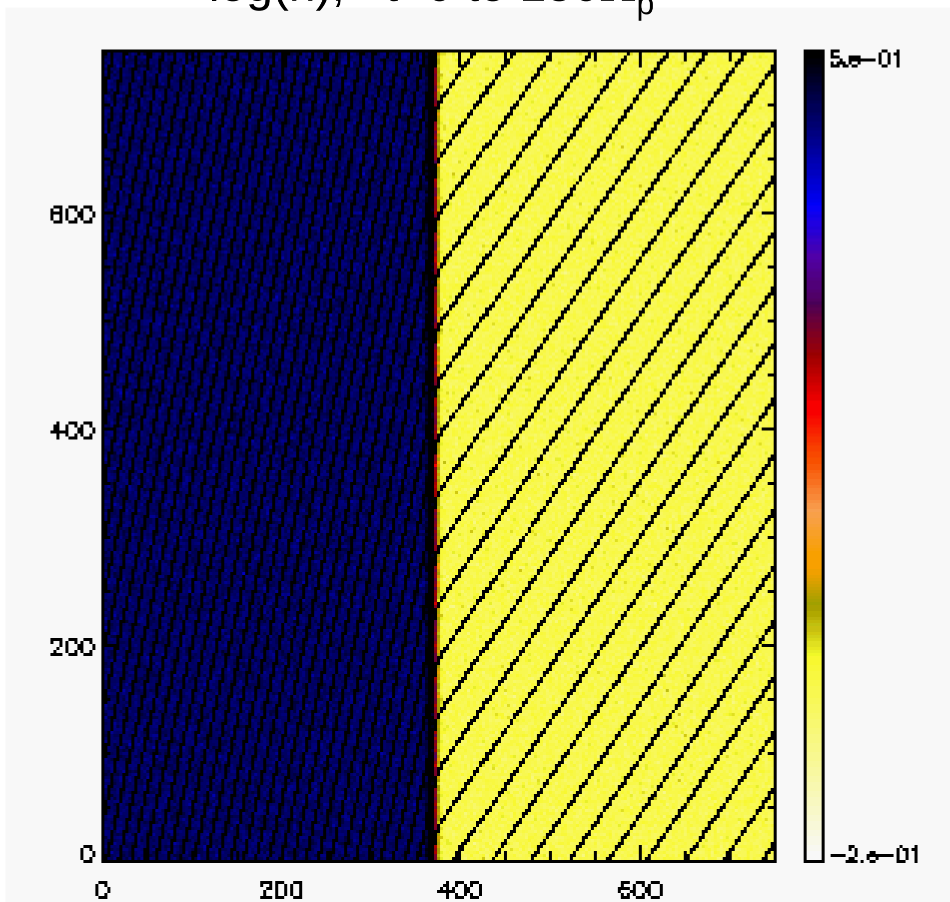


- Maxwellian plus kappa distribution -

***cf. Meziane et al.*, 2002 for qualitatively similar bow shock observations**

Quasi-periodic shock undulation

log(n), t=0 to 150Ω_p^{-1}

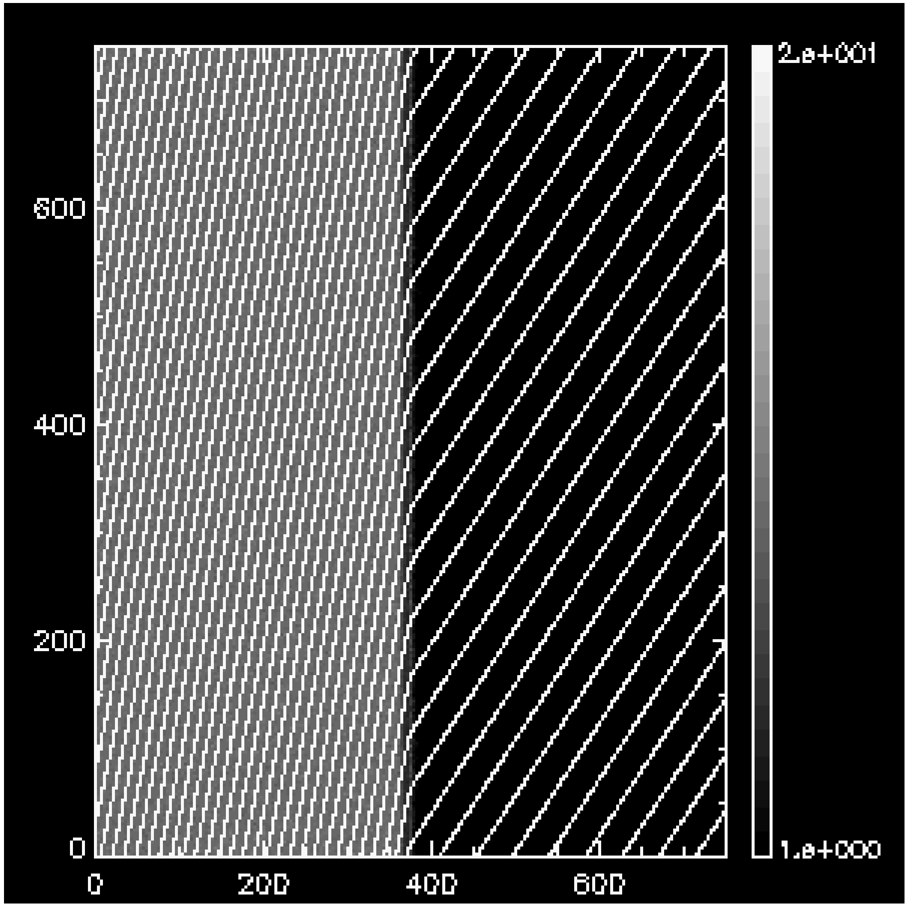


M_A = 4.7, θ_{BN} = 50^o, β_p=β_e=1.0, Δx=Δy=0.3, Δt=0.0025(/20);

60,000/1.2e6 time steps; 30 Million particles, no smoothing, η=0

(ACE 10/21/01)

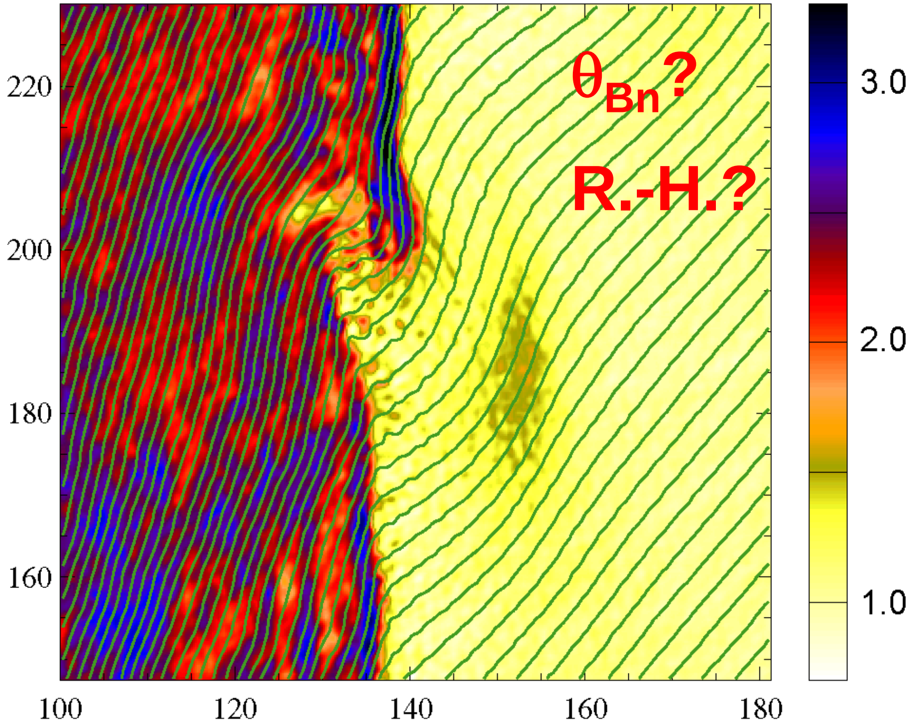
Quasi-periodic shock undulation



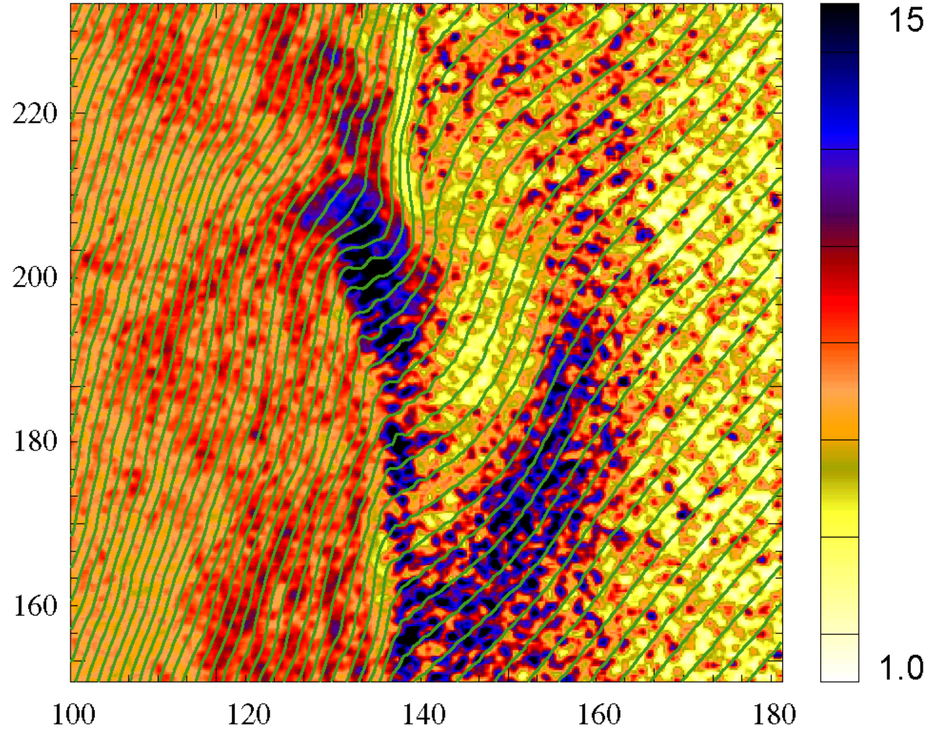
$T_{||}$, t=0 to 150Ω_p^{-1}

Quasi-periodic shock undulation (detail)

B/B_o at $t = 250\Omega_p^{-1}$

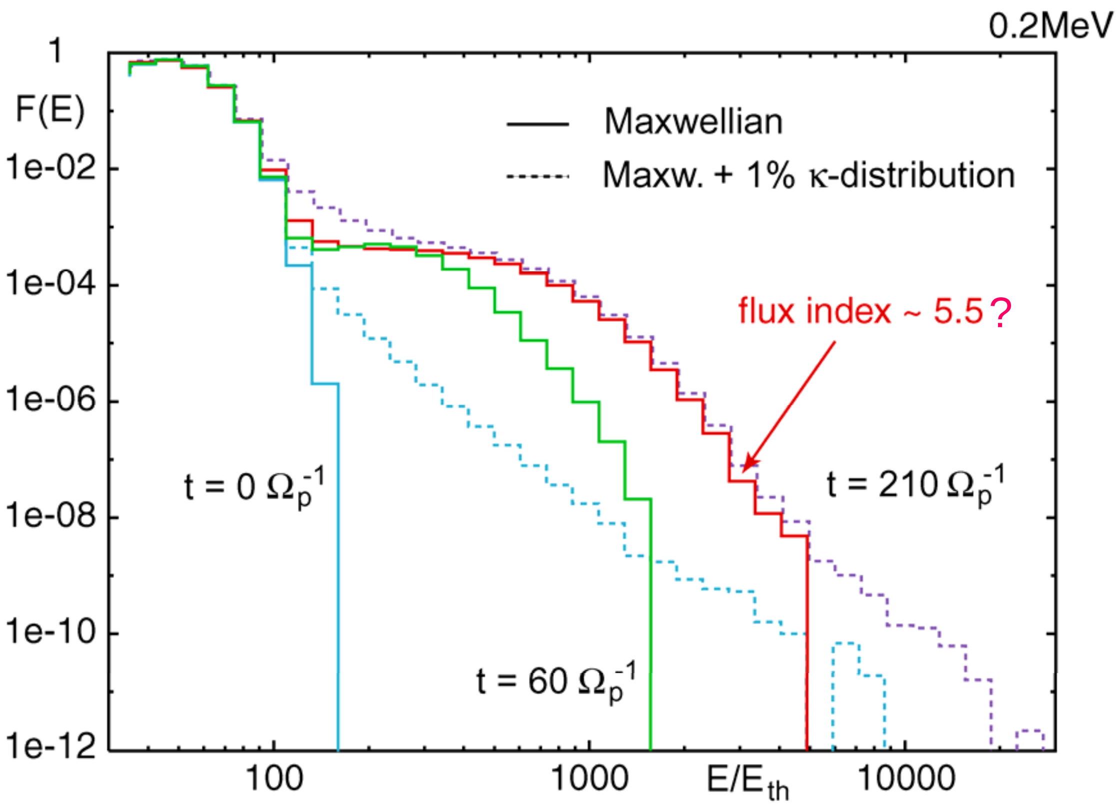


$T_{||}/T_o$ at $t = 250\Omega_p^{-1}$



Over sufficiently long times, even the relatively low-density upstream beams of oblique shocks generate sufficient-amplitude, compressional waves that impact the shock. Feedback leads to a quasi-periodic shock undulation with $\lambda \sim 100$ to $200\ c/\omega_p$ that travels along the shock.

Impact on ion acceleration

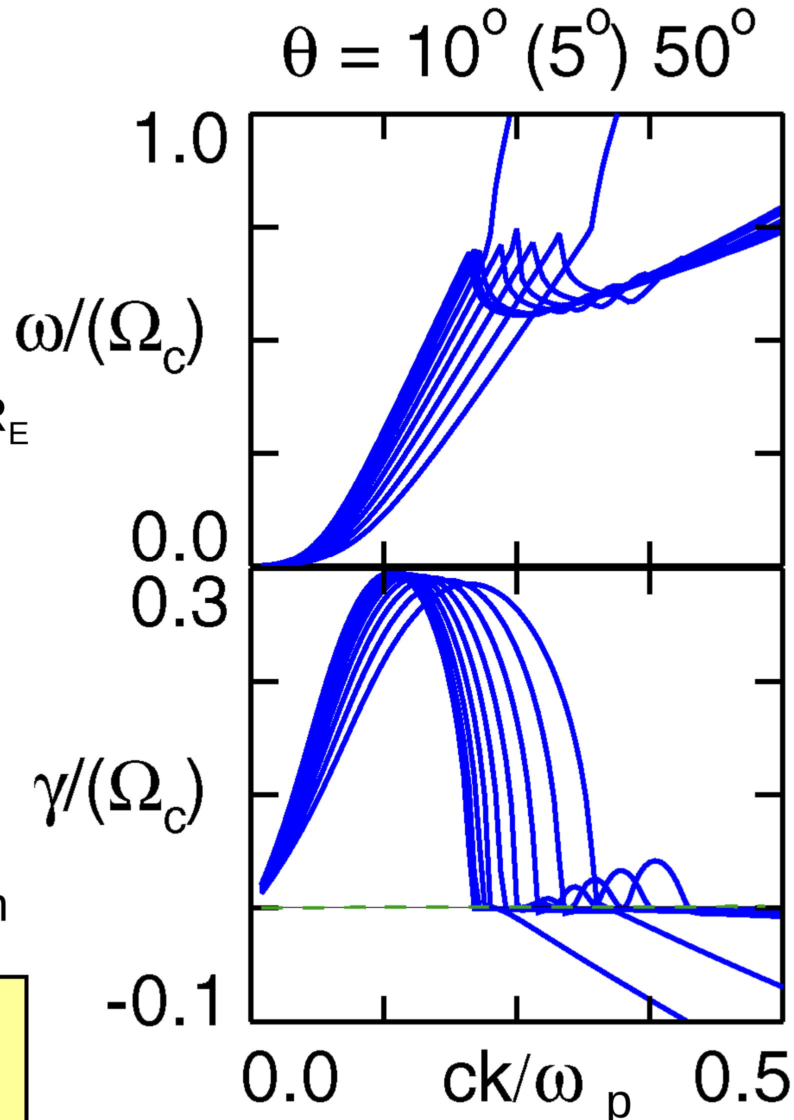


- Shock undulation enhances flux by more than 2 orders of magnitude.
- Index? ← sim. size
- Note that upper energy limit (of energized Maxwellian) is given by simulation dimensions.
- *Here,* a κ=3 seed population has little impact on results.

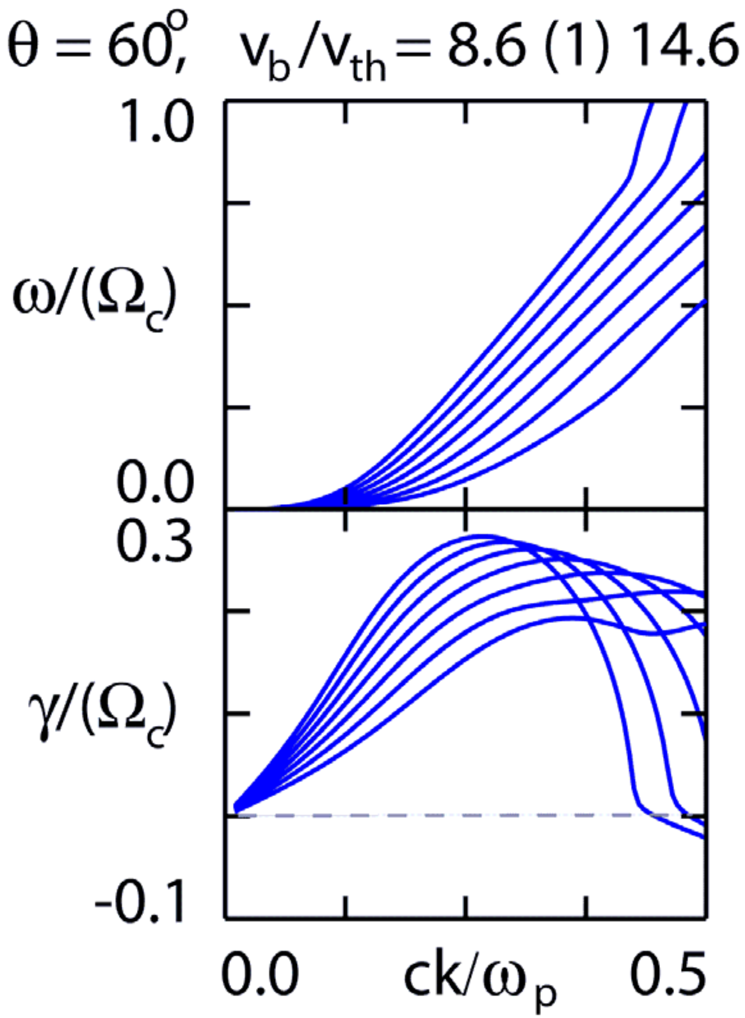
Linear Theory Results: Oblique ring-beam

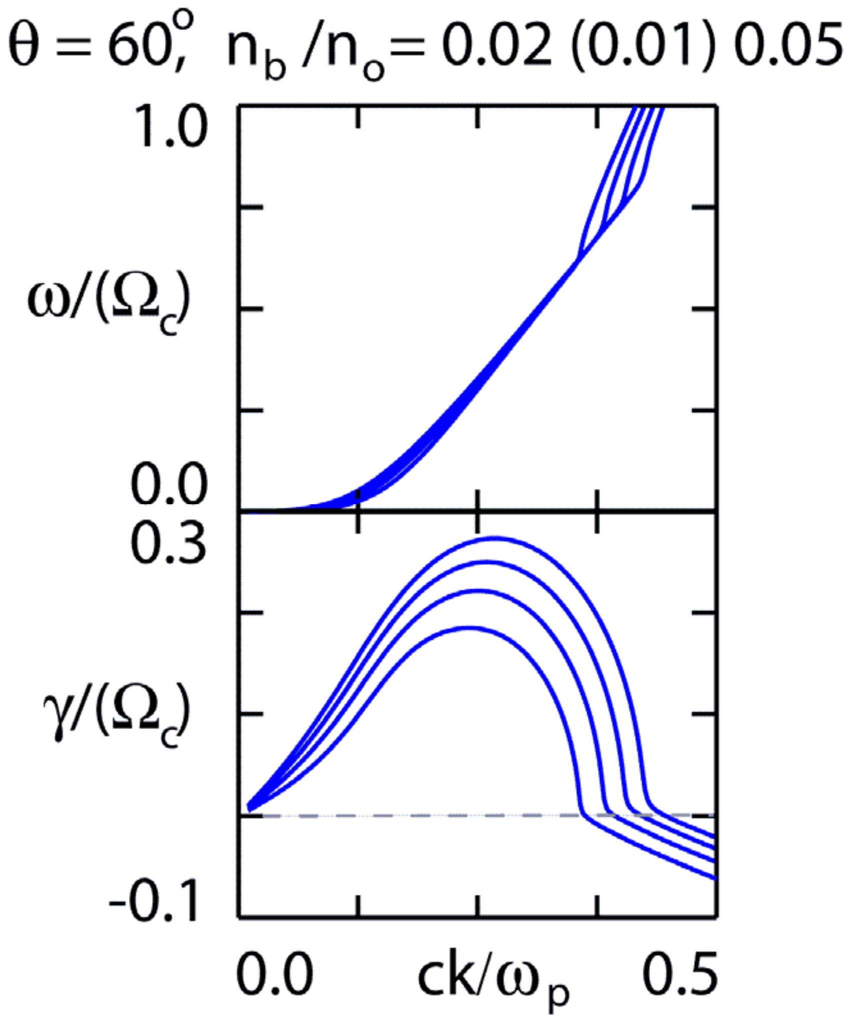
- reflected, dilute ring-beams generate oblique fast-magnetosonic waves
- growth almost independent of angle
- maximum growth at:
  $ck/\omega_p \sim 0.2$, or $\lambda \sim 30\ c/\omega_p \sim 1/2\ R_E$
- in agreement with simulations
- close to shock, stronger beam modifies dispersion; the much enhanced group velocity (of the order of the shock speed) leads to larger convective growth
- generally, modified dispersion close to resonance leads to large convective growth

Considerable detail known from prior bow shock and cometary studies (*Winske et al.*, 1985; *Killen et al.*, 1995)



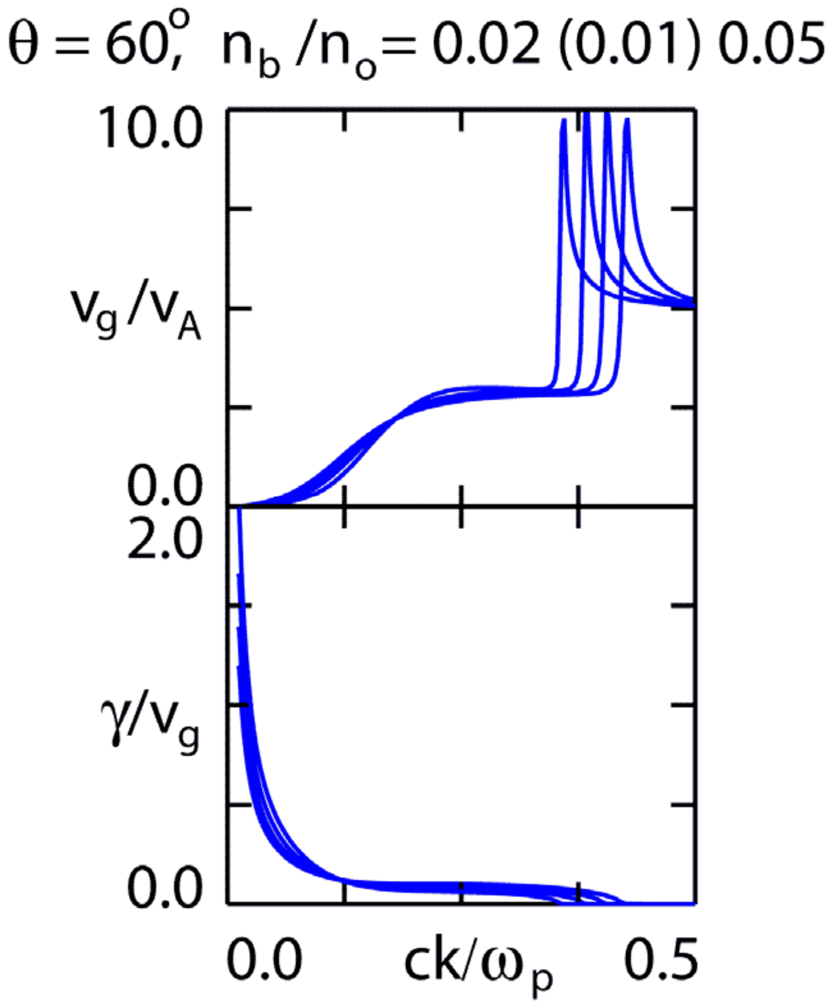
Linear Theory



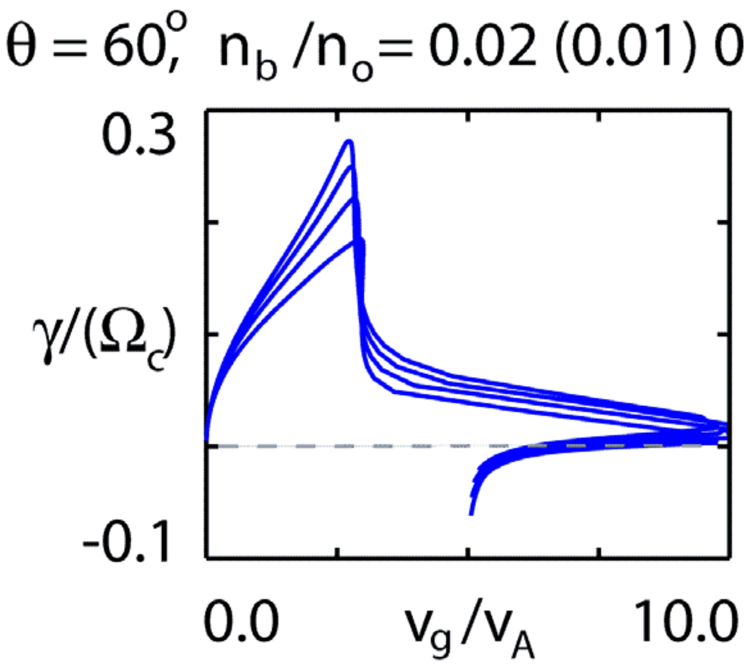


Instability is operational over wide range of Mach numbers and shock angles

Linear Theory



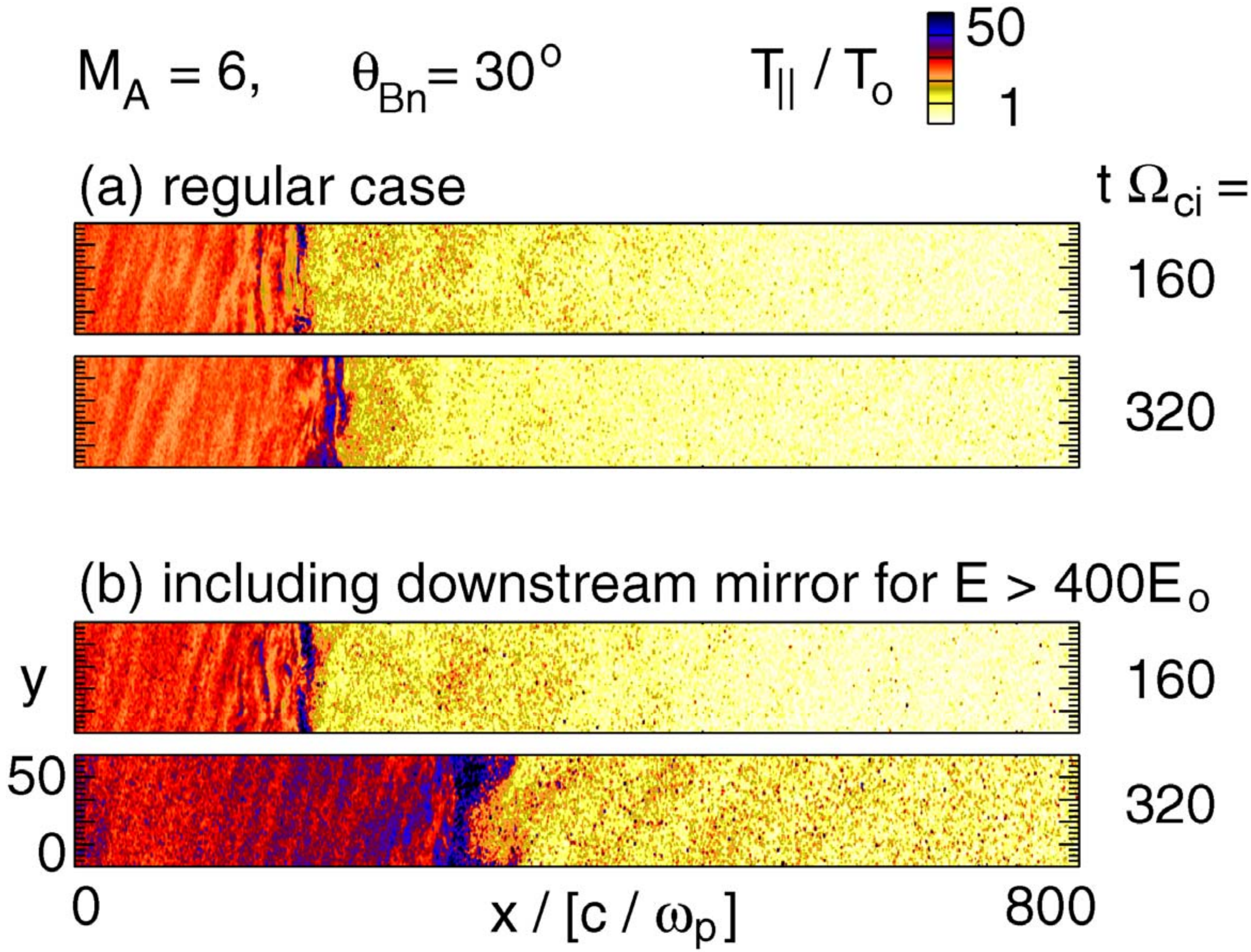
to simplify argument, these plots are for <u>one</u> beam speed…



While the convective growth maximizes around $M_A \sim 2.5$, it has positive growth in environments all the way to shocks with $M_A > 10$

What other process/mechanism has a truly significant impact on shock-generated energetic ion fluxes?

Mirroring in sunward converging field lines

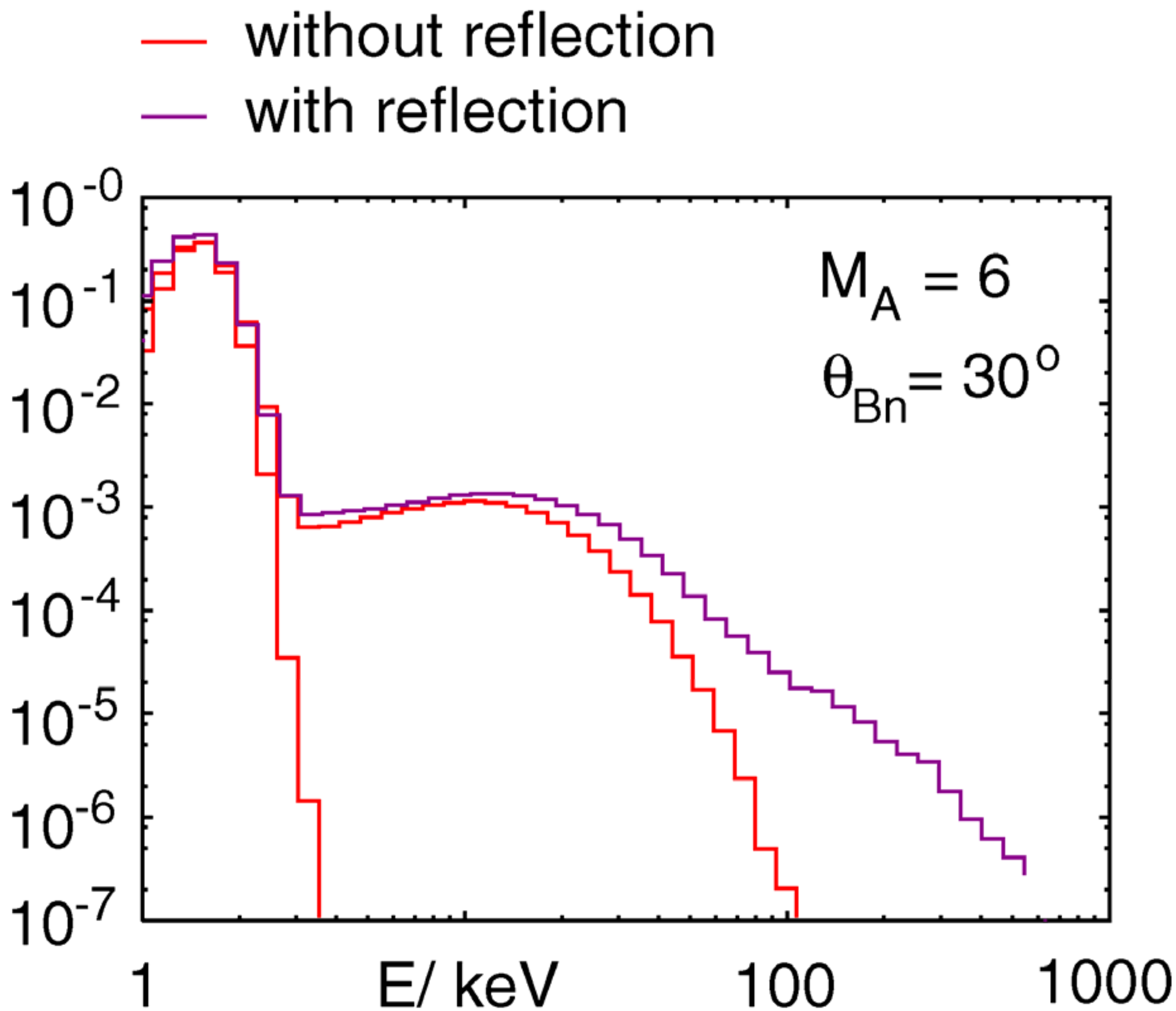


Mirroring in sunward converging field lines

$M_A = 6.0$, $\theta_{Bn} = 30^o$

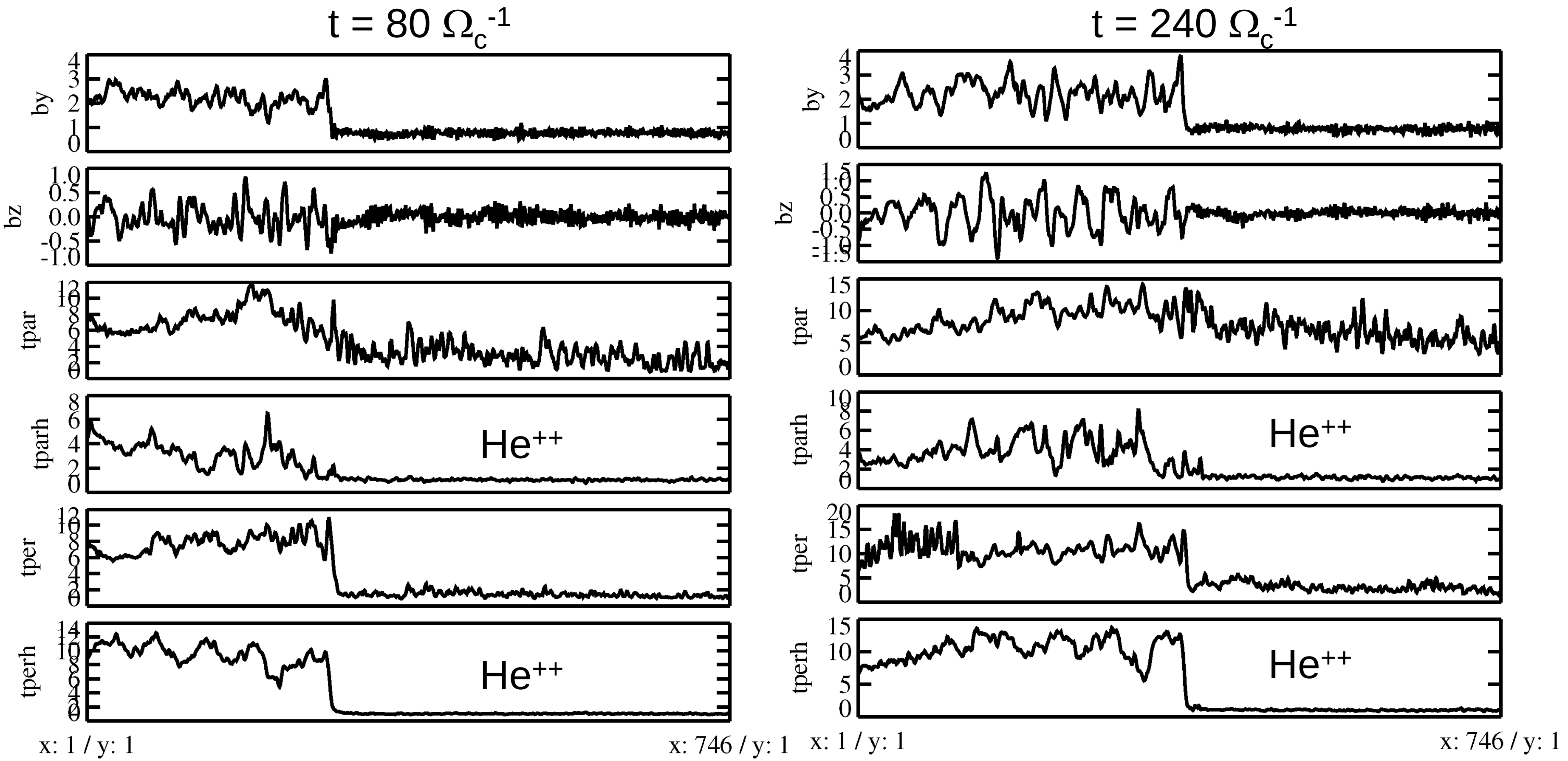
→ **much larger fluxes, much harder spectrum**

(similar effects have been shown previously in hybrid simulations)



Mirroring in sunward converging field lines

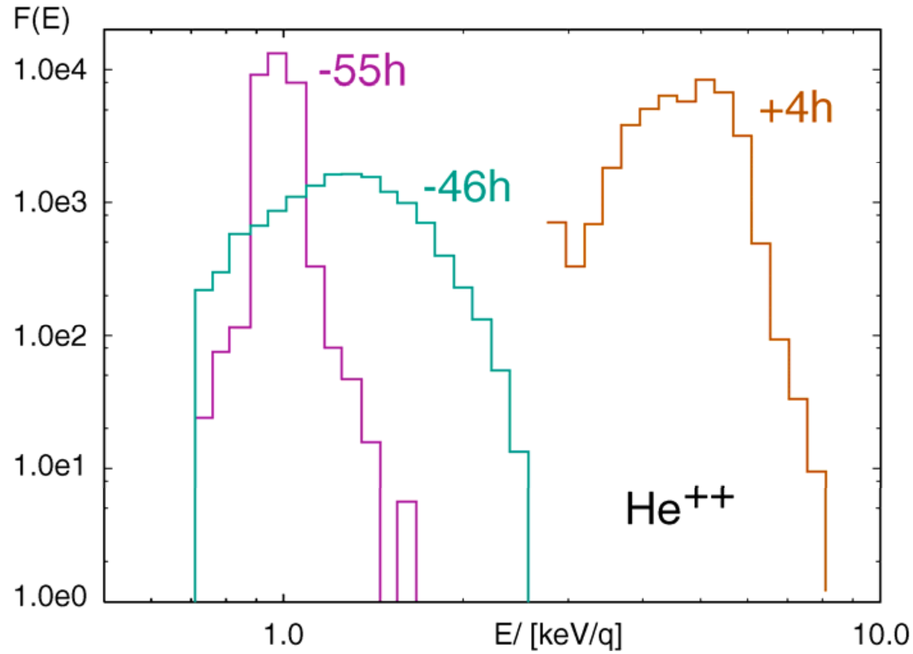
Oblique case, M_A = 4.7, θ_{Bn} = 50^o, Event 10-21-01



reflection of ions > 100E_o → order of magnitude larger downstream wave power; better coupling; >2 orders of magnitude larger fluxes

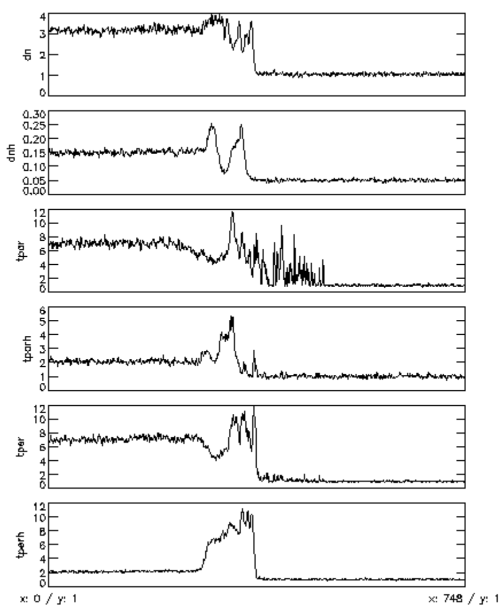
Minority Species

- with J. Raines and Th. Zurbuchen, U Michigan
- ACE SWICS instrument; currently have phase space density distribution functions for He2+, O6+ and C5+
- data averaged over several hours upstream covers transition to suprathermals



Example of He++ distributions before and after shock passage, 1-h data, Case O4

The upstream conditions can be highly variable, and need to be matched properly for the simulations



← Selective heating/acceleration of He++, case O4, t=160

Low β and Highly Oblique Shocks

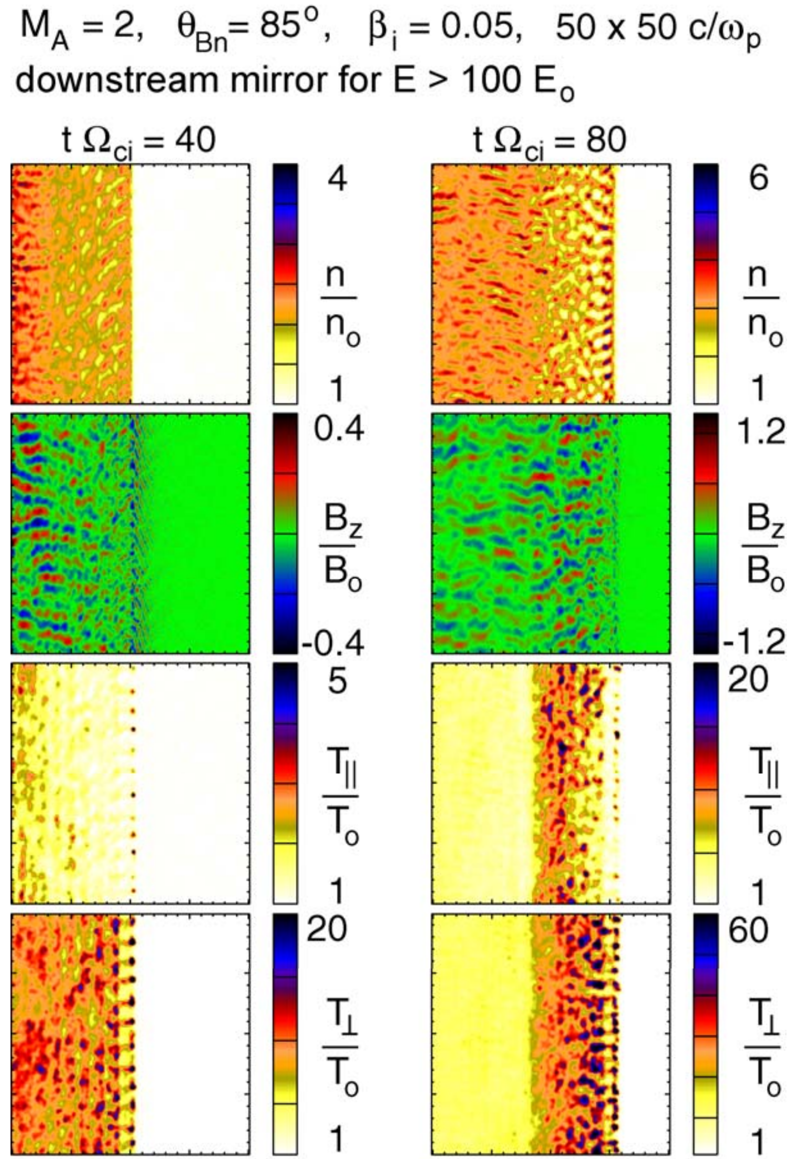
- In low beta plasma, many instabilities have slower growth rates and higher thresholds for growth

- Large anisotropies result, with relatively small fluctuation levels

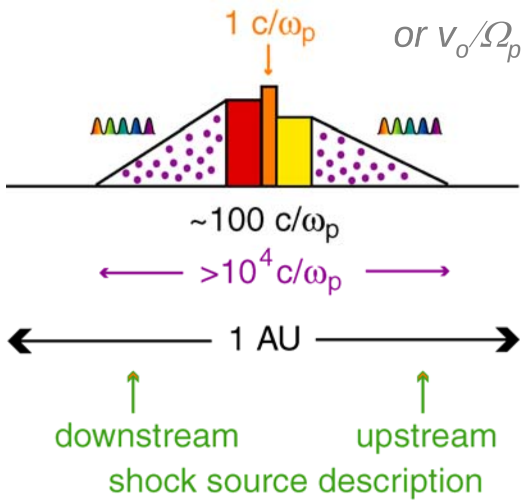
- In this case, reflected ions from a downstream (sunward) mirror magnetic field configuration have a huge impact on the turbulence level, thermalization, and generation of high-energy ions

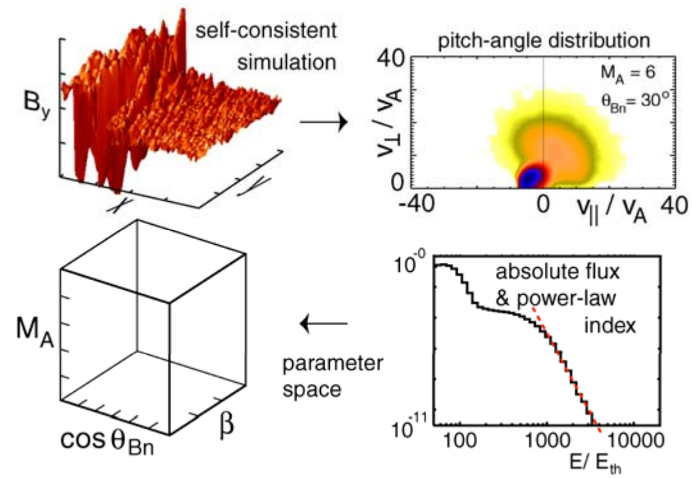
- *note change in scales →*

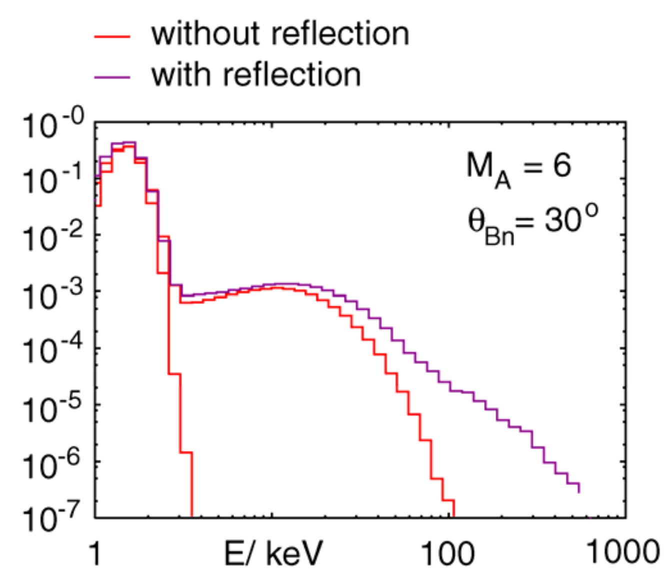
order of magnitude higher wave power, more isotropic heating, higher energy



Shock source description strategy







<u>Important Considerations for Hybrid Code Approach:</u>

- Field line topology/ mirroring
- Seed particles
- Parameter dependence (M_A, β, θ_{Bn})

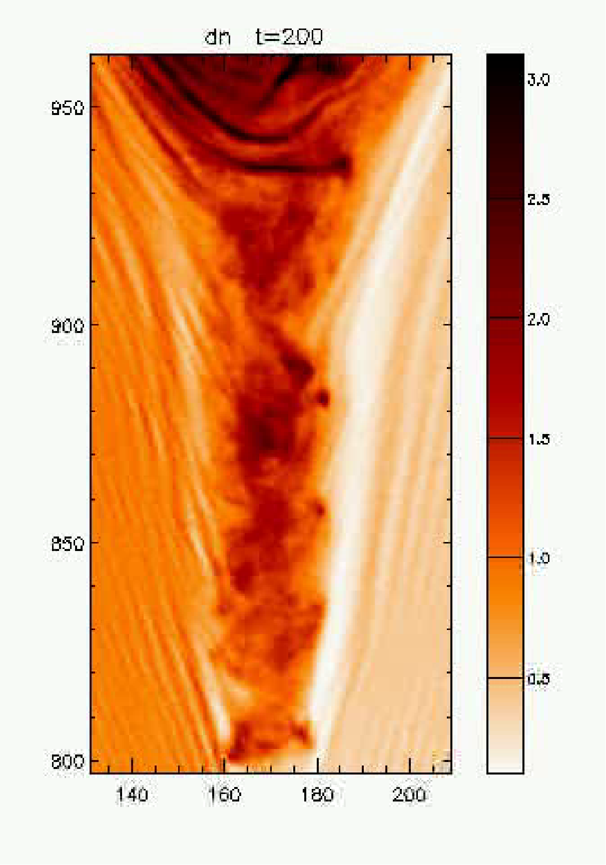
Shocks vs. Reconnection

Example: ion heating and acceleration at discontinuities attached to magnetic field line reconnection outflow

Conjecture: as in many (astrophysical) shocks, leads to secondary electron acceleration

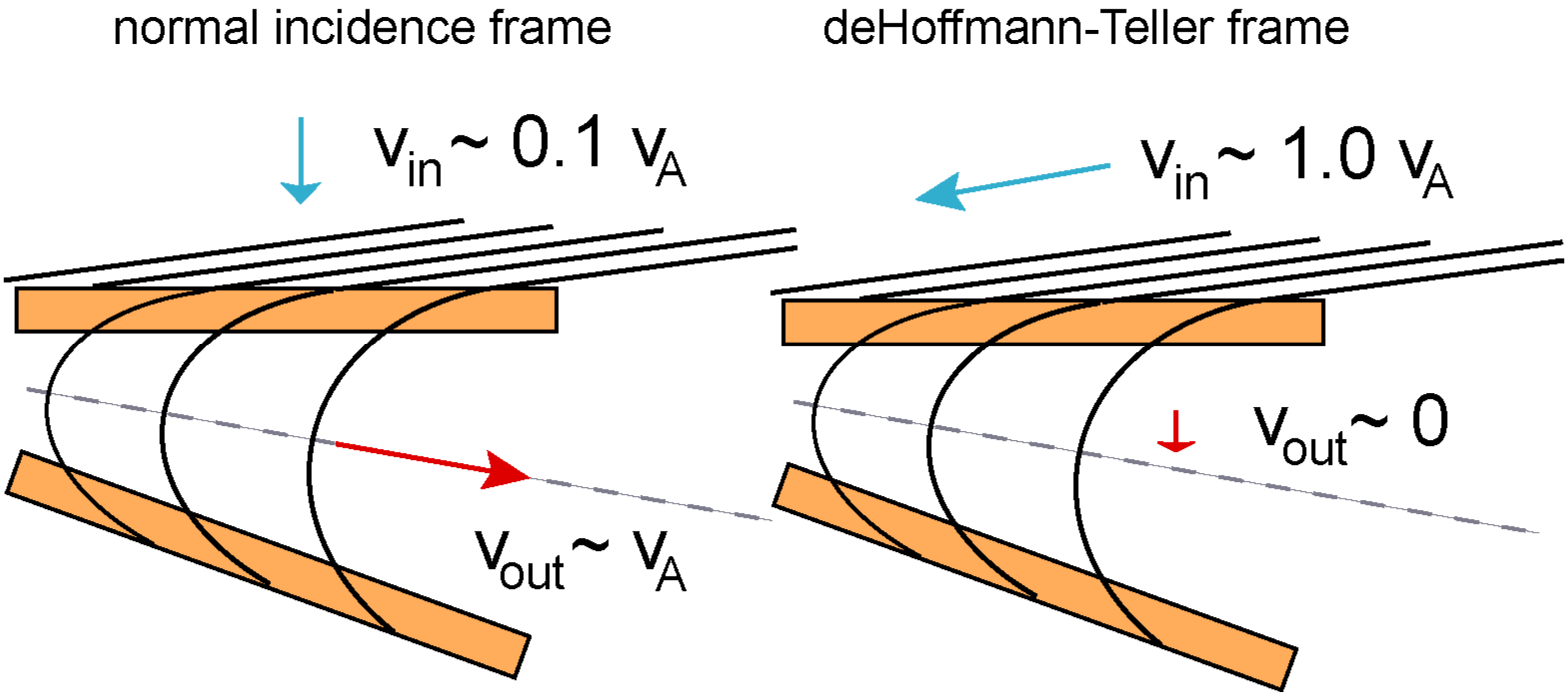
- stresses importance of low-beta scenarios (lower corona)…

Turbulent Outflow



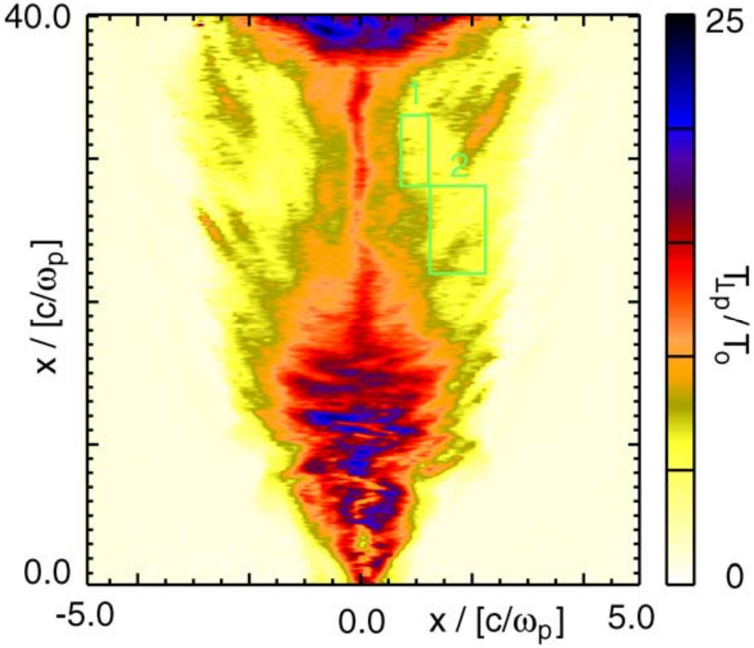
In addition, fast shocks may form where the outflow hits “obstacles” and slows down

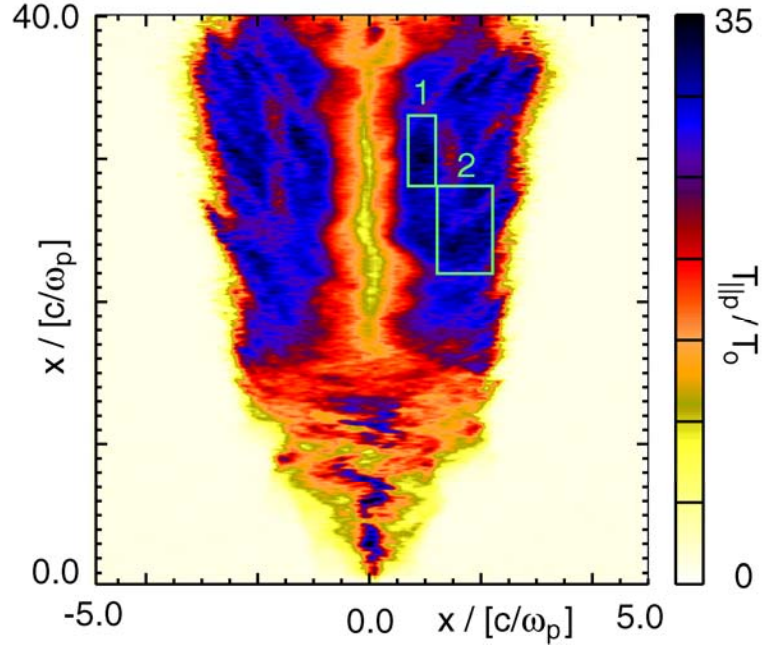
Ion Beam Generation

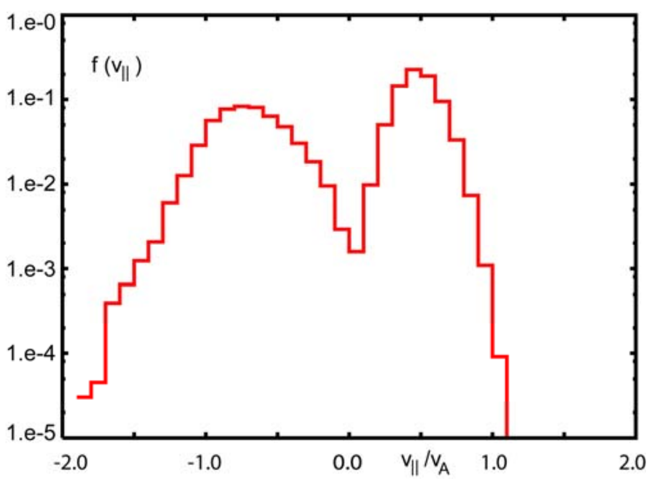


→ when $\beta << 1$ (I.e., $v_{th} << v_A$), result is interpenetrating ion beams with beam speed of $\sim v_A$

Ion Beam Generation in Flare Loops



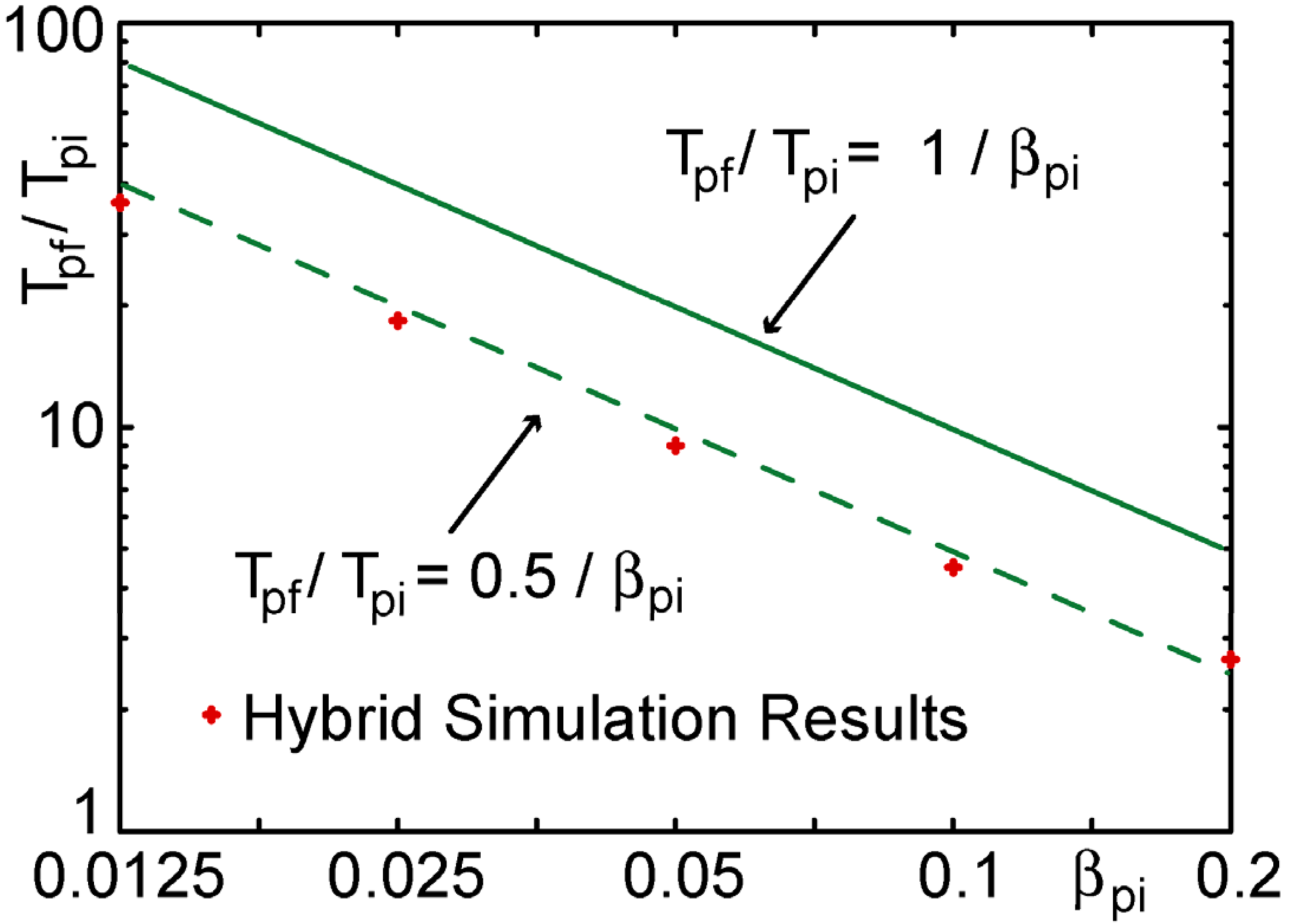




$\beta_i = \beta_e = 0.025$

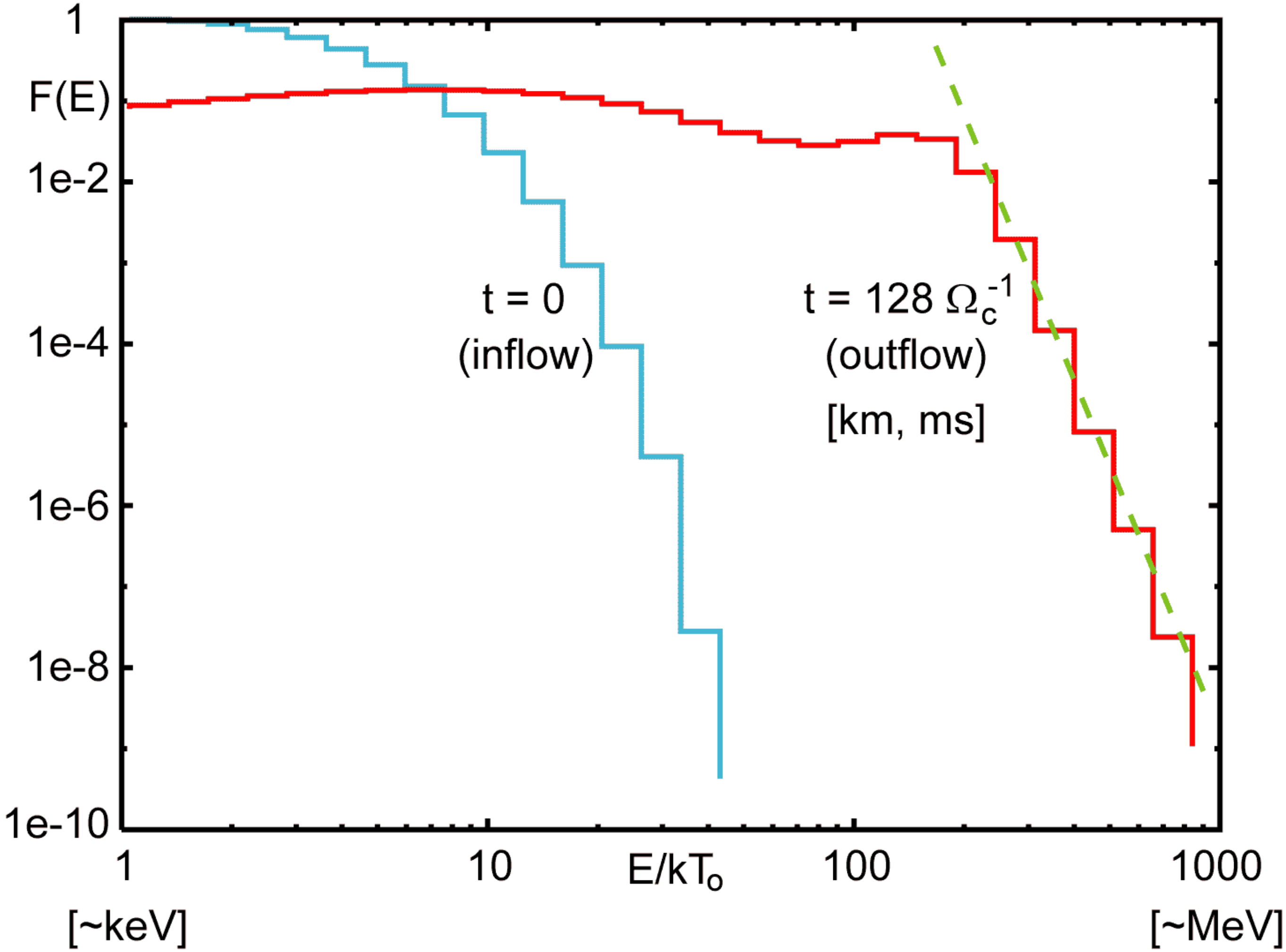
Ion beam generation is similar over wide range of betas: →

Scaling of Ion Heating with Upstream β_{pi}



…using effective temperature

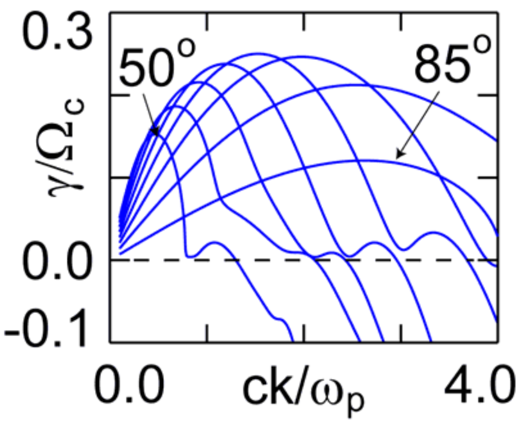
Ion Tail Generation



- bulk heating
- thermal pool, ~ 20keV seed particles
- energetic tail generation
- MeV protons within ms
- $E \propto m$

(energy in solar/upstream/inflow frame)

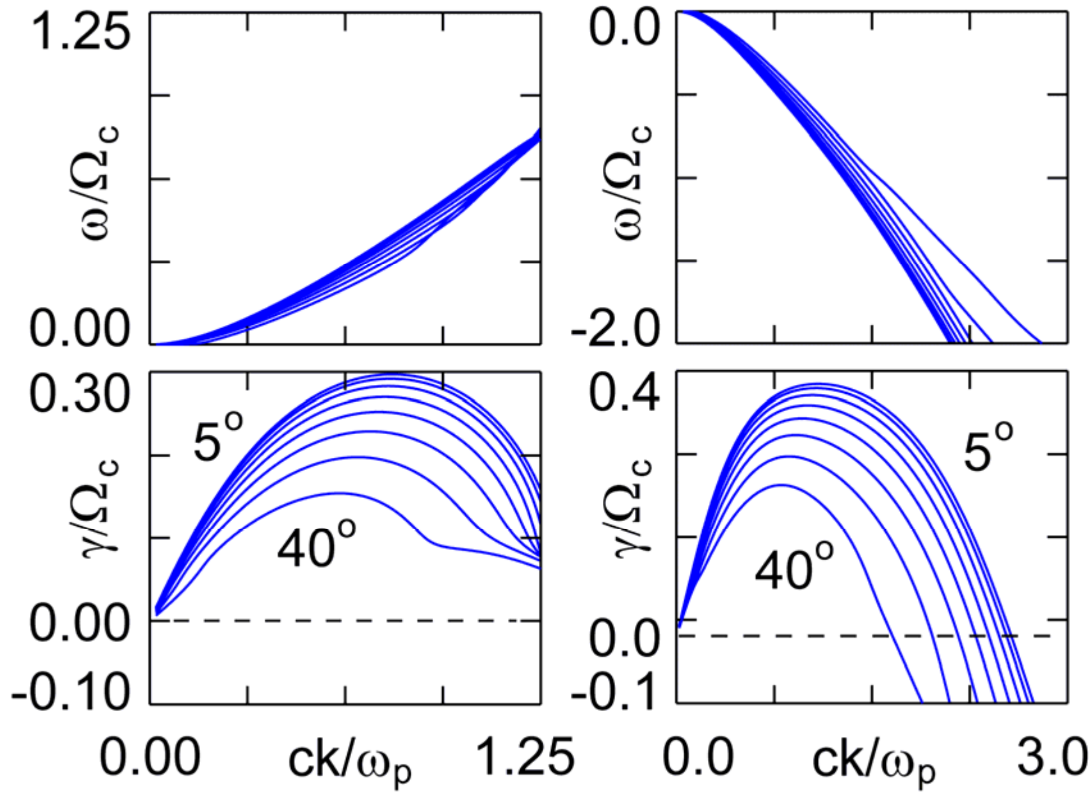
Linear Theory



EMIIC (slow shocks)

- e.s & e.m. A/IC -

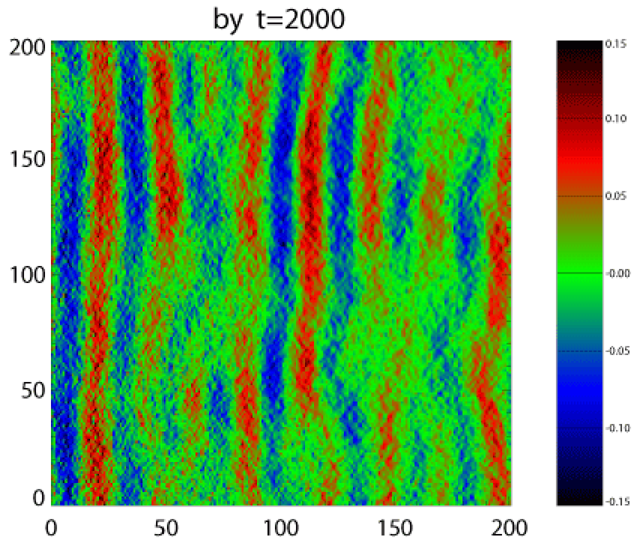
Winske & Omidi '92

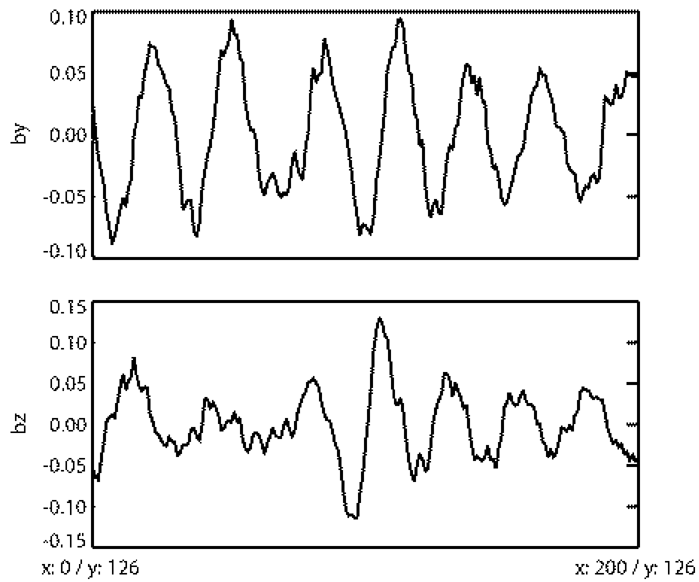


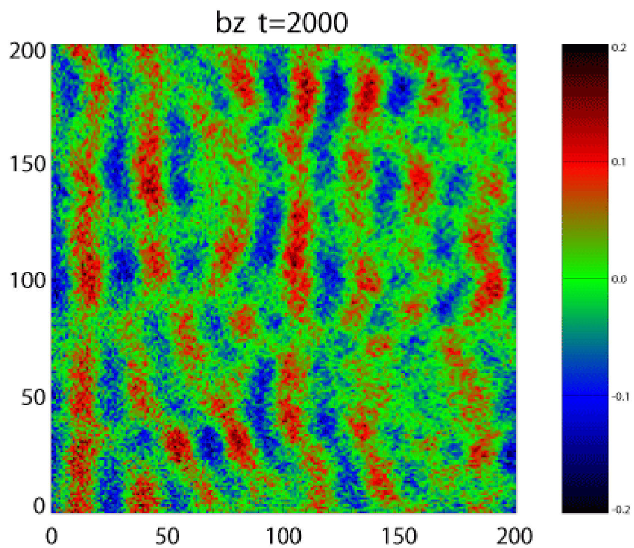
bi-directionally propagating
fast/magnetosonic waves

…using dual beam distributions from simulations

2-D periodic simulations





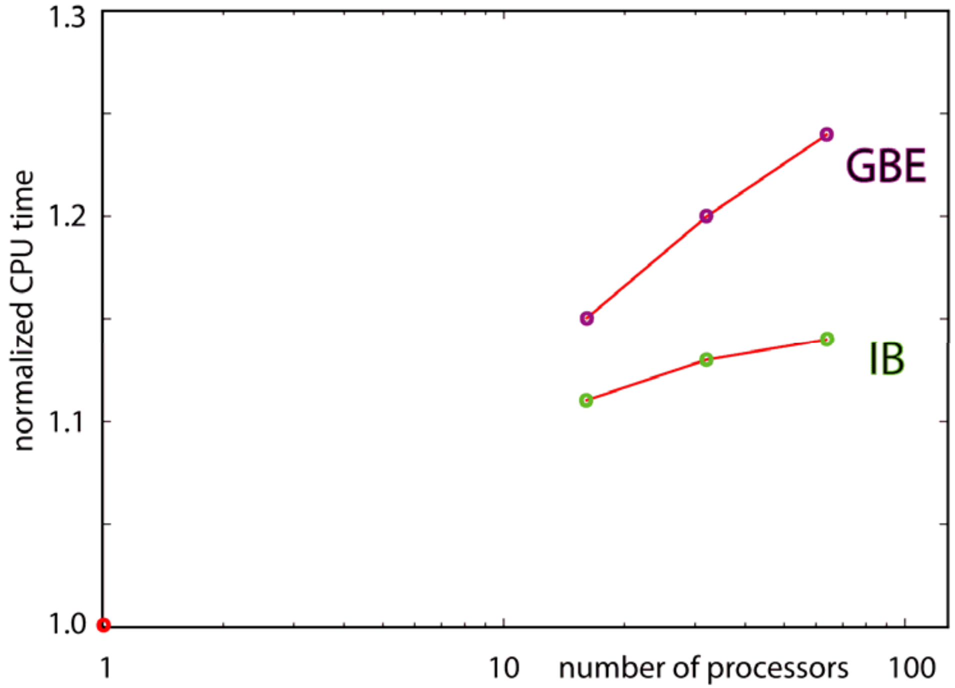


- both ~ parallel and oblique waves
- ck/ω_{pi} ~ 1 as in linear theory
- $\Delta B/B$ ~ 0.1

Higher Energies and Parallel Code

- Single-processor runs limited to ~1MeV (1 month or ~700 CPU h).
- Target energy of 10 MeV requires approximately factor 30 larger effort, ~20,000 CPU h.
- Quasi-parallel shocks are "cheaper" to run.
- Parallel version of code has progressed to point where it scales well with number of processors.

There is no "global solve" in the hybrid code, but care must be taken to have efficient particle communications



Example: 1000^2 cells, 100 M particles, 100,000 steps, 5 M pushes/second --> 555 hours