WoRPA-Pu
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Particle acceleration efficiency in shocks: new insights from kinetic simulations

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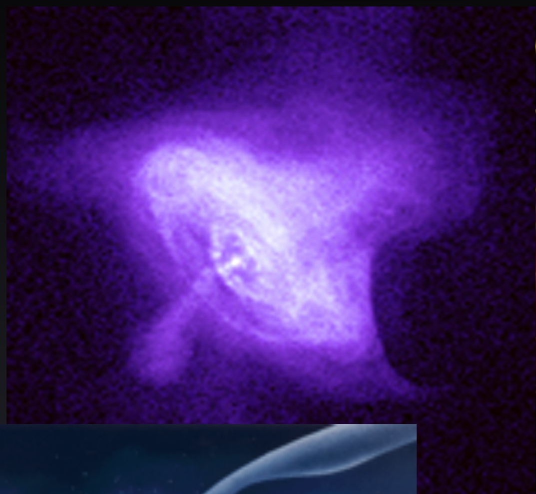
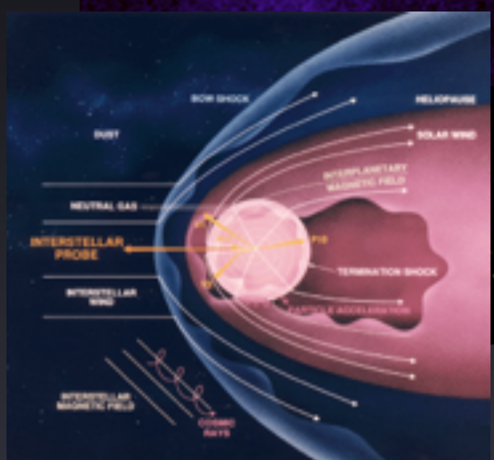
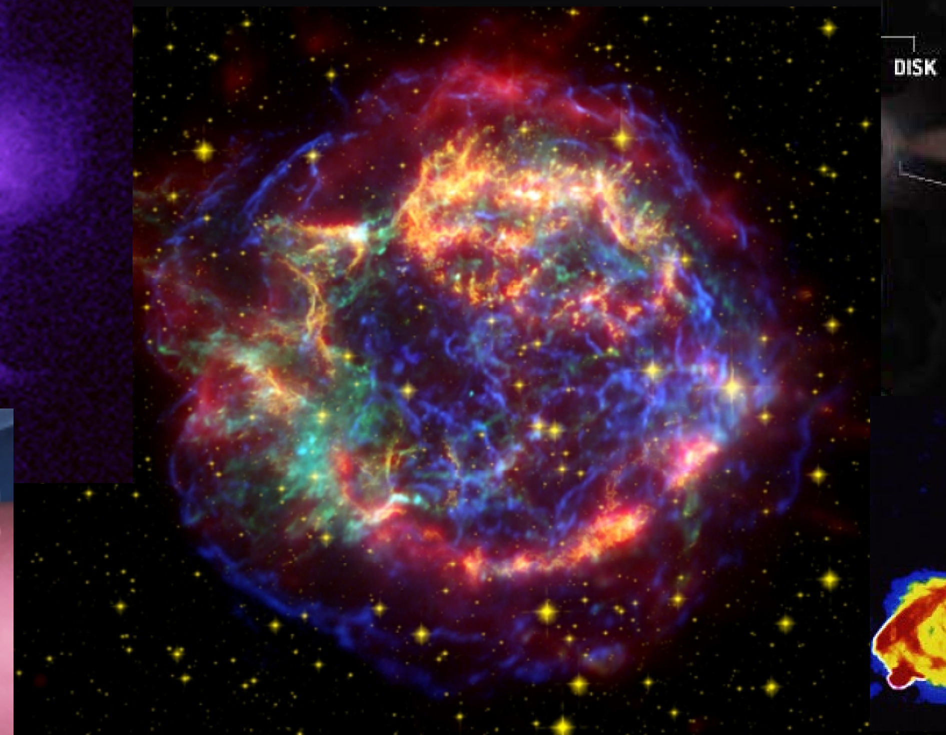
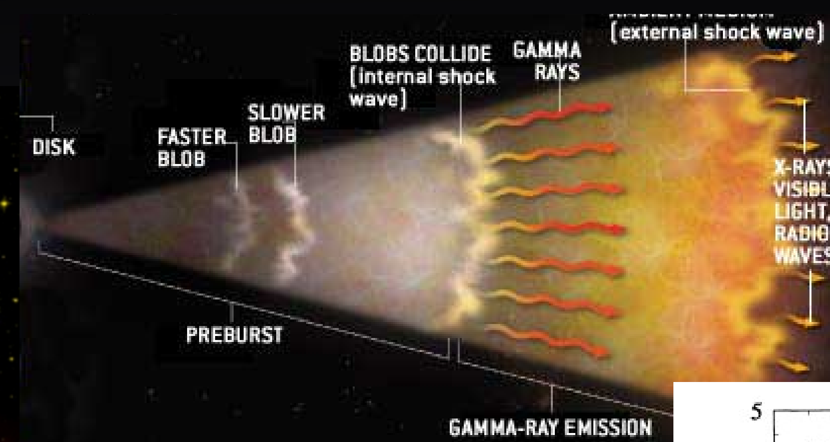
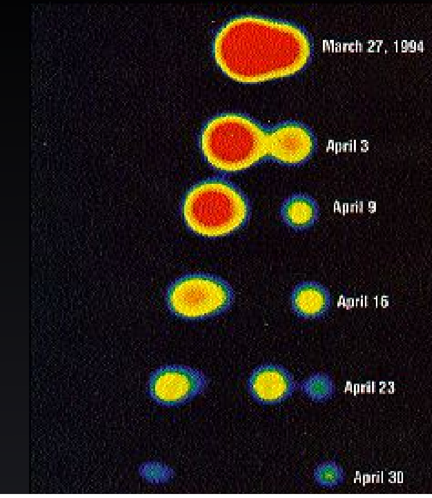
Shocks & power-laws in astrophysics

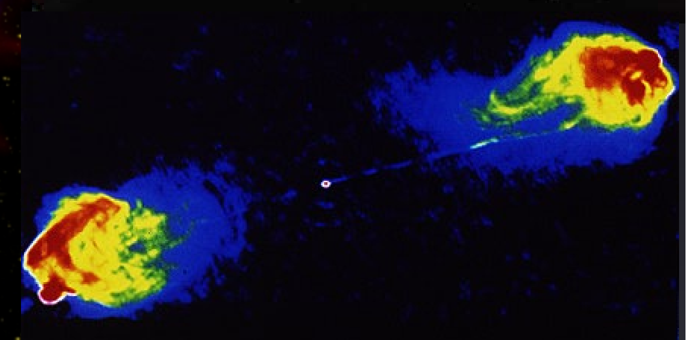


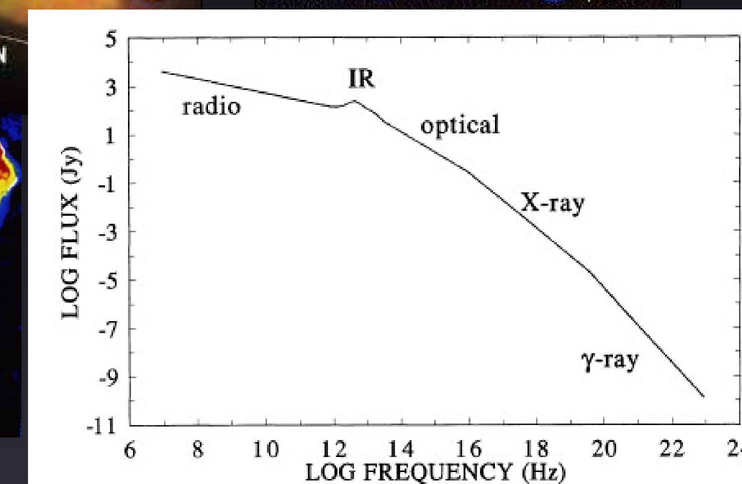












Power-laws are ubiquitous in astrophysics, most commonly associated with shocks.

“Injection problem: What determines if a particle joins the 1% or the 99%? Is it always 1%?”

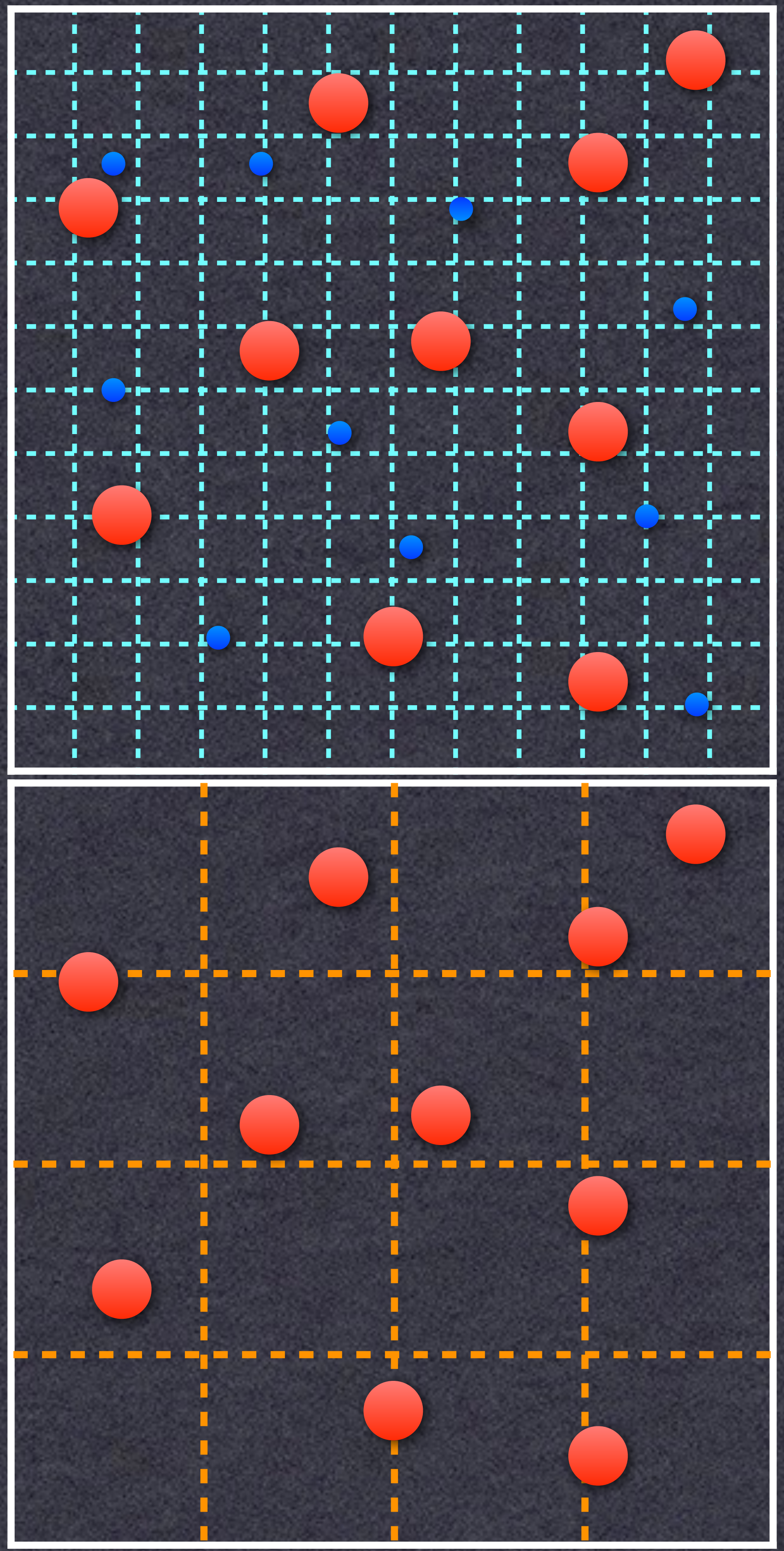
Is shock acceleration always there, or can only some shocks accelerate?

Can a shock become “self-made” accelerator (i.e., develop acceleration from unfavorable conditions by back-reaction)?

Collisionless shocks from first principles

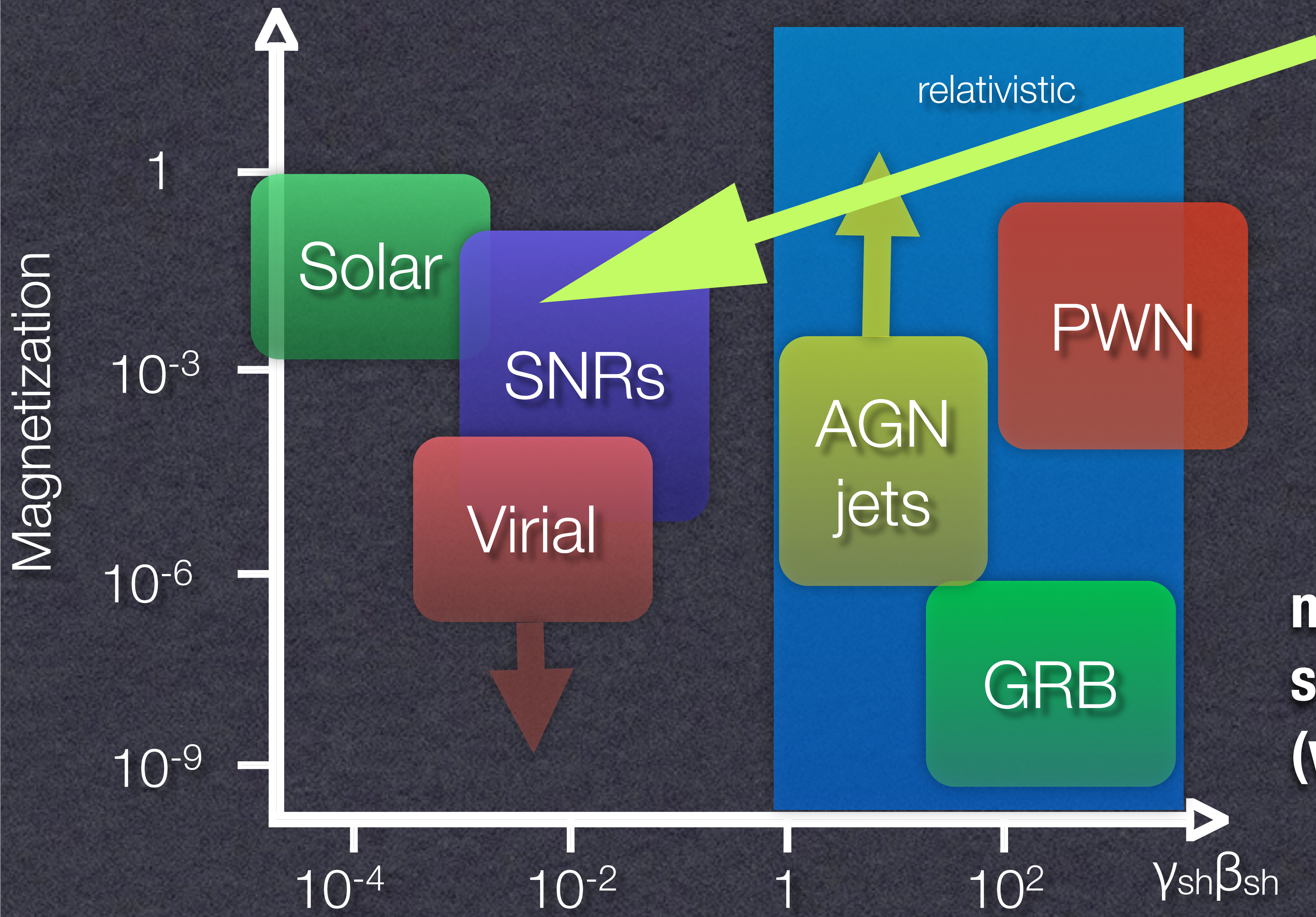
- **Full particle in cell**: TRISTAN-MP code
  (Spitkovsky 2008, Niemiec+2008, Stroman+2009, Amano & Hoshino 2007-2010, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park+2012, Niemiec+2012, Guo+14,...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally expensive!

- **Hybrid approach**: dHybrid code
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, DC & Spitkovsky 2013, 2014)
  - massless electrons for more macroscopic time/length scales



Parameter Space of shocks

$$\sigma \equiv \frac{B^2/4\pi}{(\gamma-1)nmc^2} = \frac{1}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2 \left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$



nonrelativistic shocks

e and ions are different in non-relativistic case

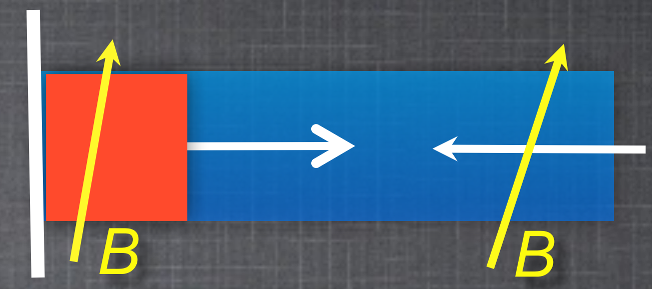
most of our PIC runs are still mildly relativistic (v/c~0.03-0.1c)

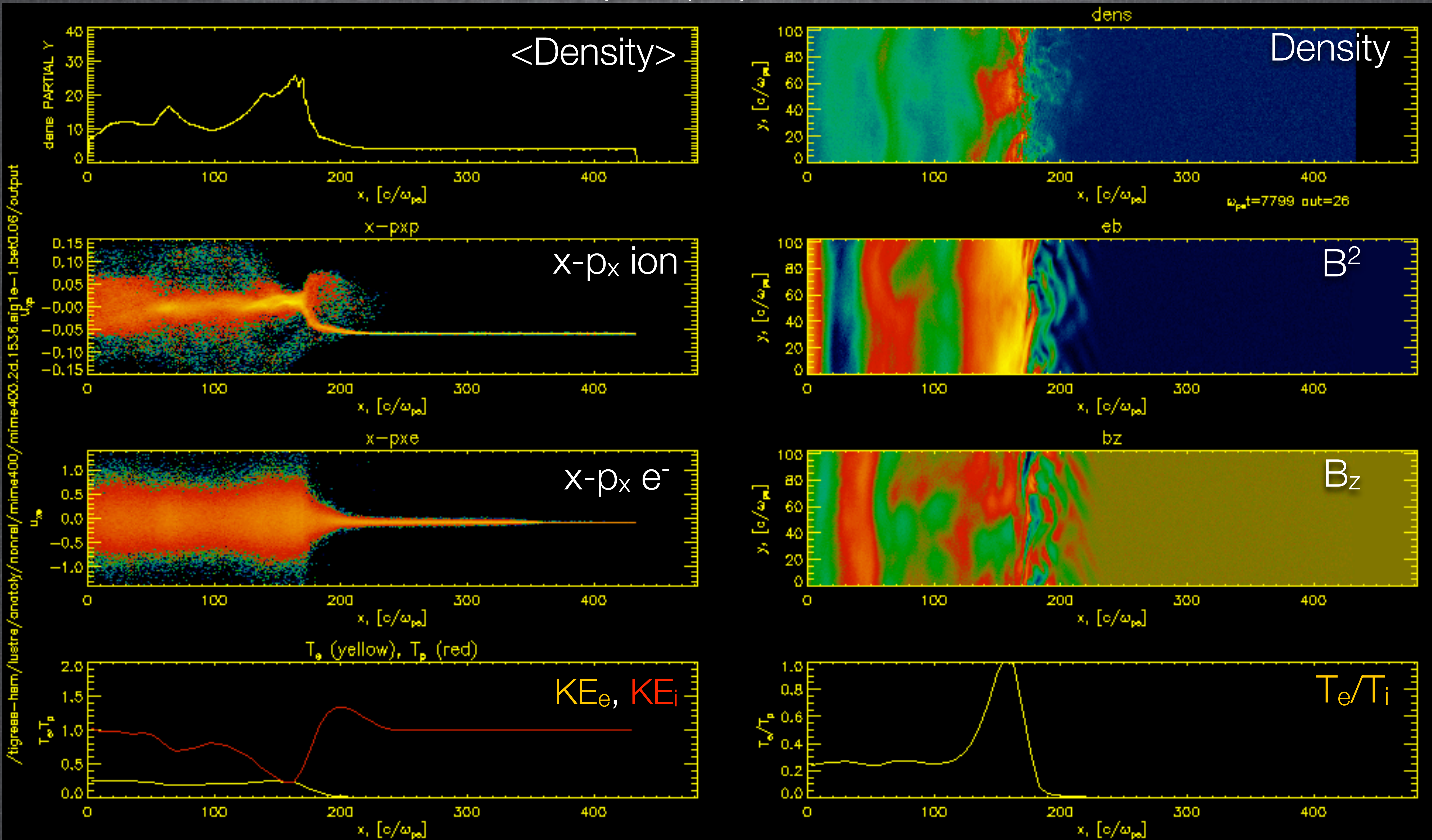
Outline

1) Proton injection physics
2) Electron injection physics and proton/electron ratio in CRs
3) Injection of heavy ions
4) Re-acceleration of cosmic rays

Nonrelativistic shocks: shock structure

mi/me=400, v=18,000km/s, Ma=5, quasi-perp 75° inclination

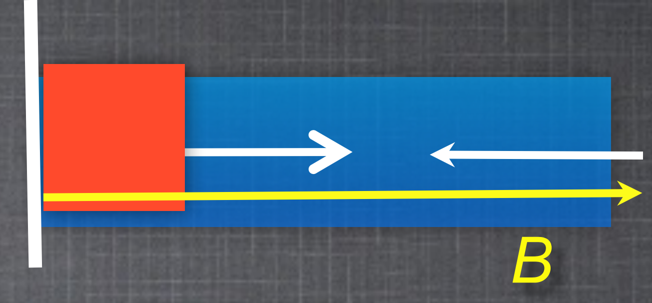


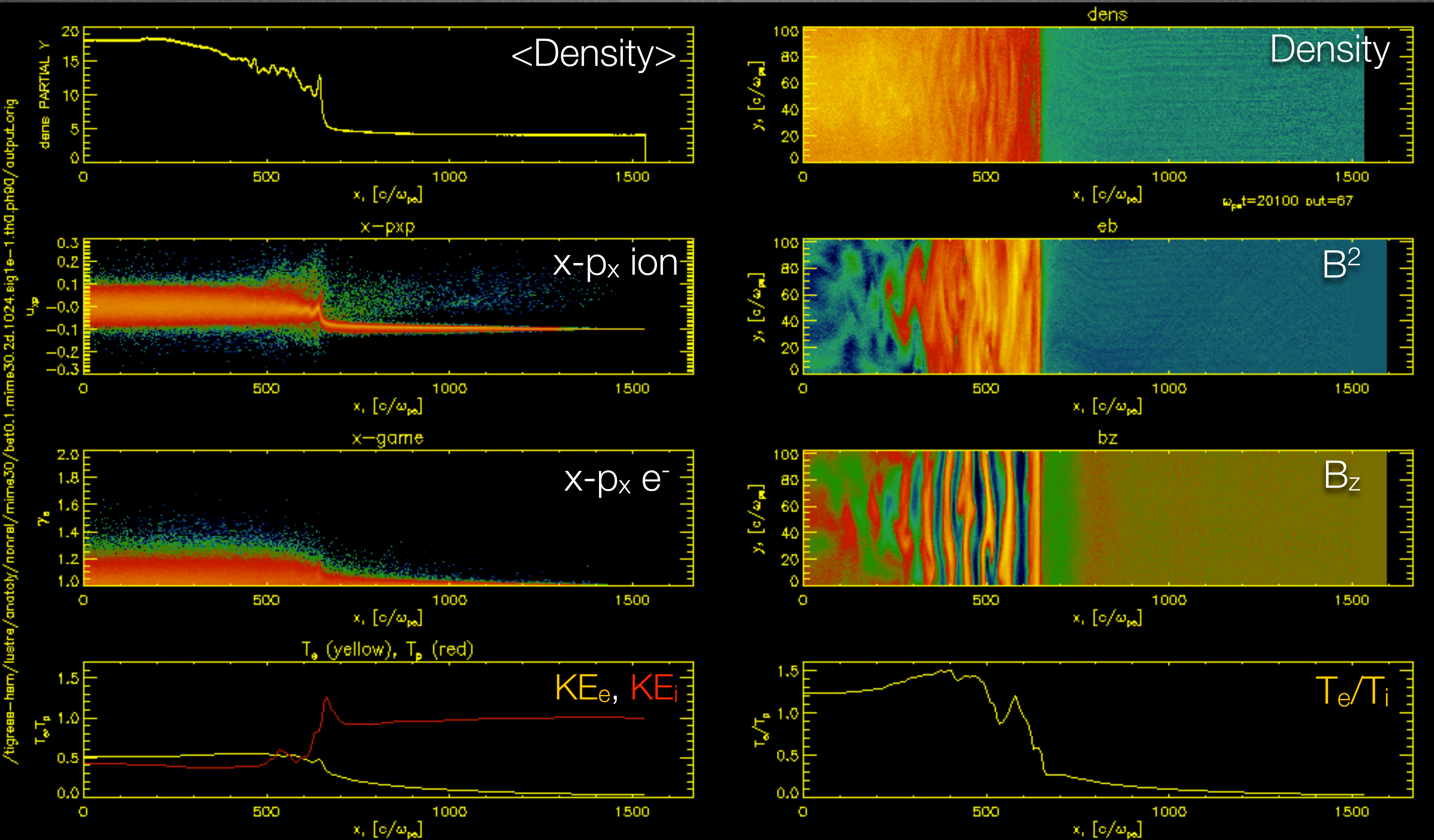


PIC simulation: Shock foot, ramp, overshoot, returning ions, electron heating, whistlers

Nonrelativistic shocks: quasiparallel shock

mi/me=30, v=30,000km/s, Ma=5 parallel 0° inclination





PIC simulation: returning ions, reorientation of B field, rotating B perp; shock reformations

Shock acceleration

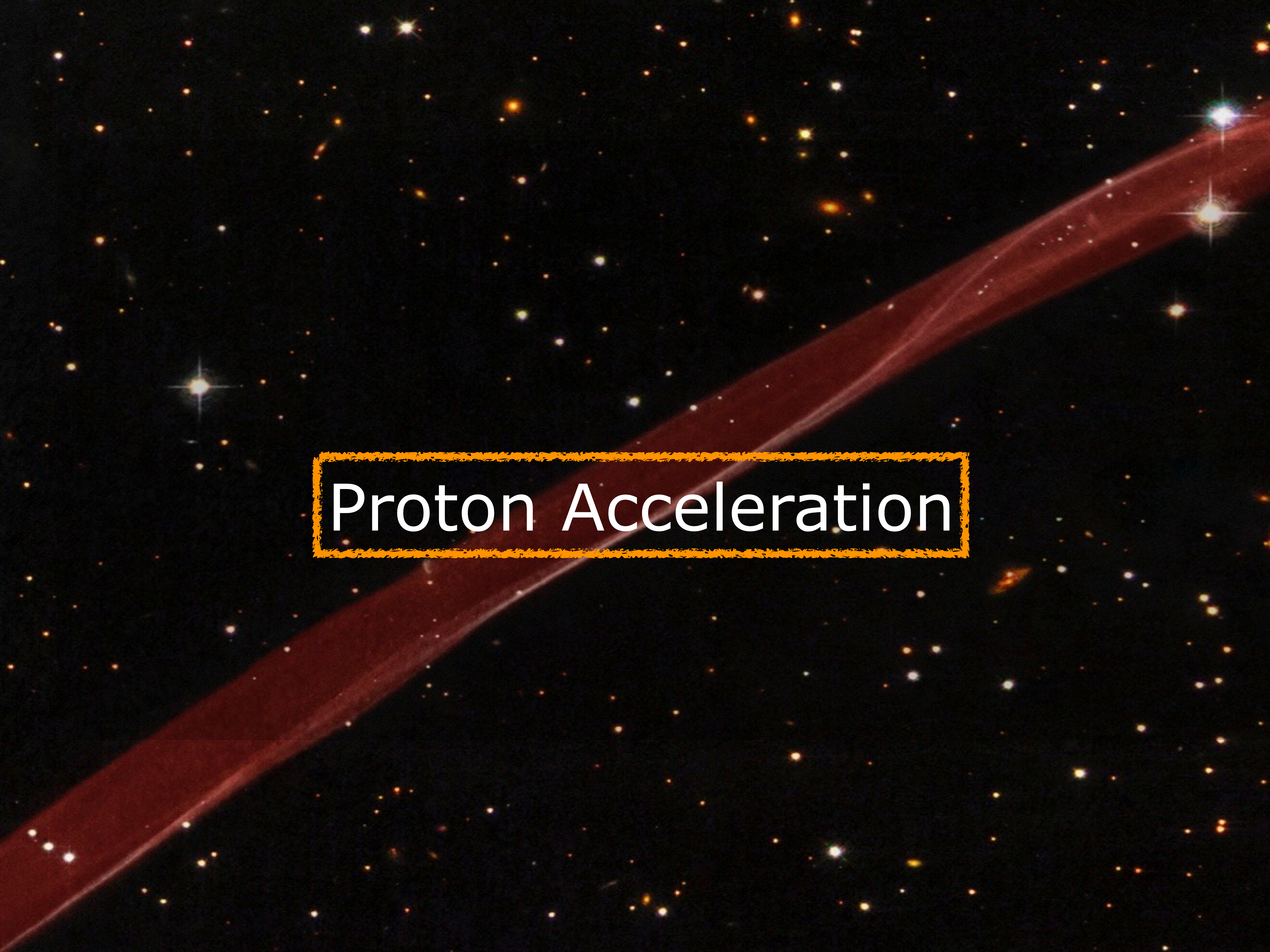
Two crucial ingredients:

1) ability of a shock to reflect particles back into the upstream (injection)

2) ability of these particles to scatter and return to the shock (pre-existing or generated turbulence)

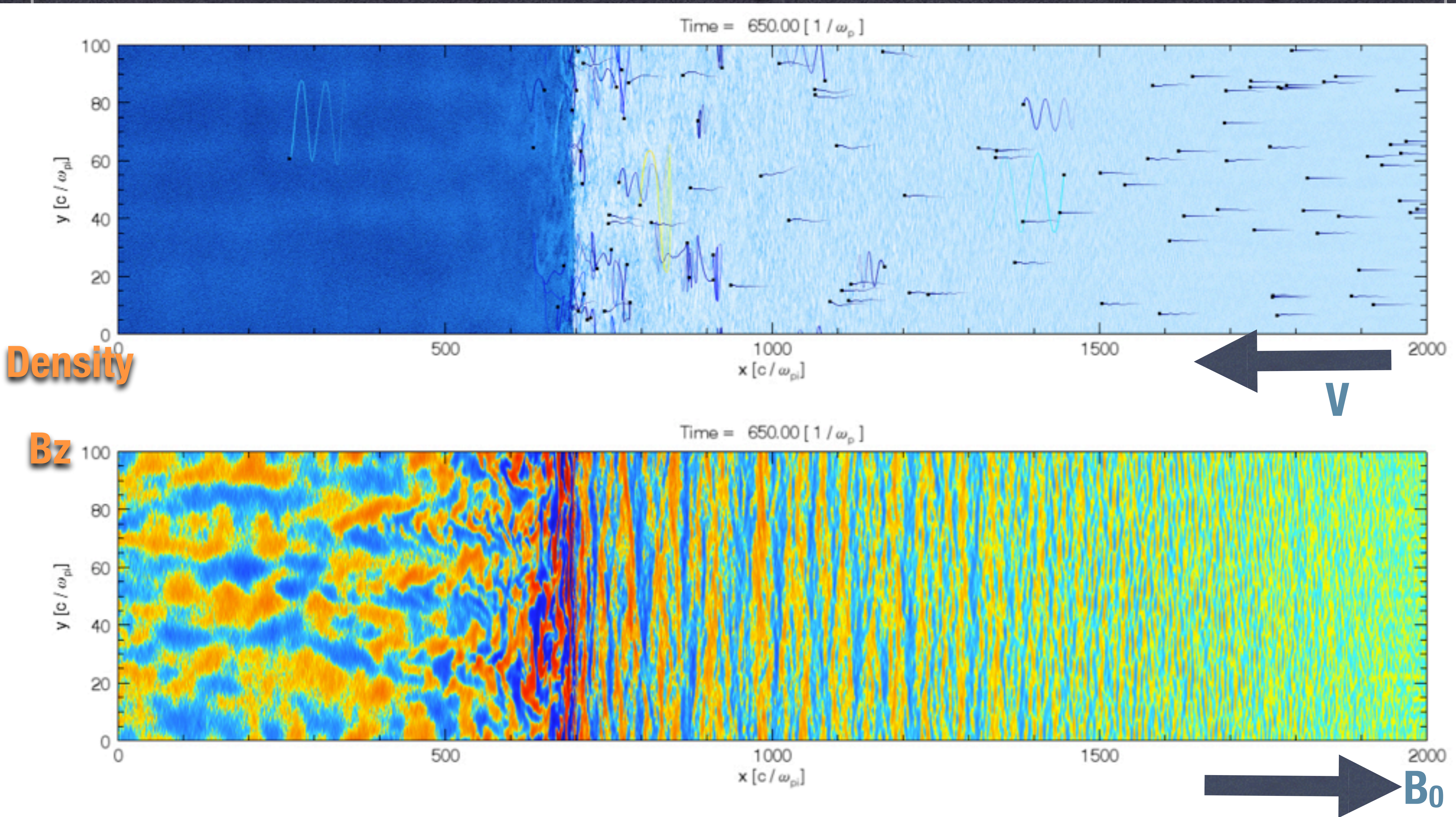
Generically, parallel shocks are good for ion and electron acceleration, while perpendicular shocks mainly accelerate electrons.

Proton Acceleration



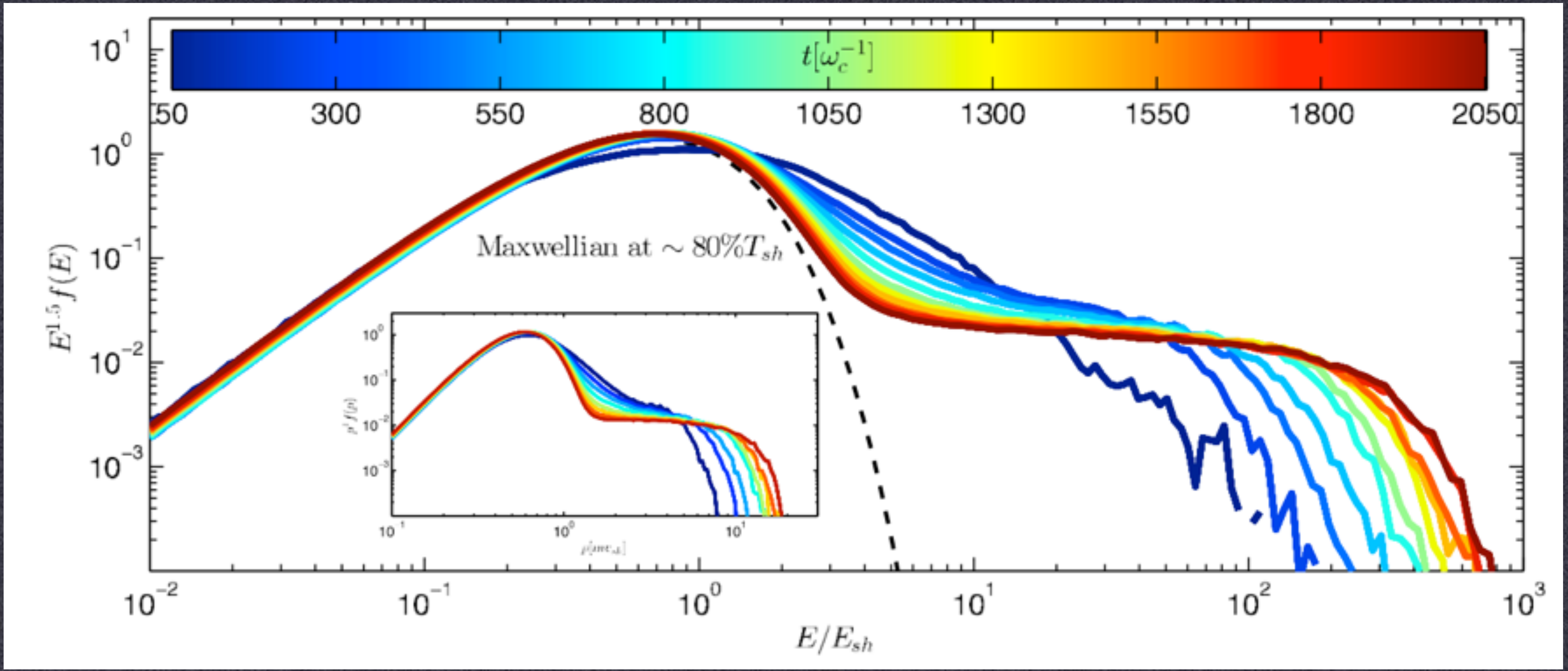
Proton acceleration

M_A=3, parallel shock; hybrid simulation. Quasi-parallel shocks accelerate ions and produce self-generated waves in the upstream.



Proton spectrum

Long term evolution: Diffusive Shock Acceleration spectrum recovered



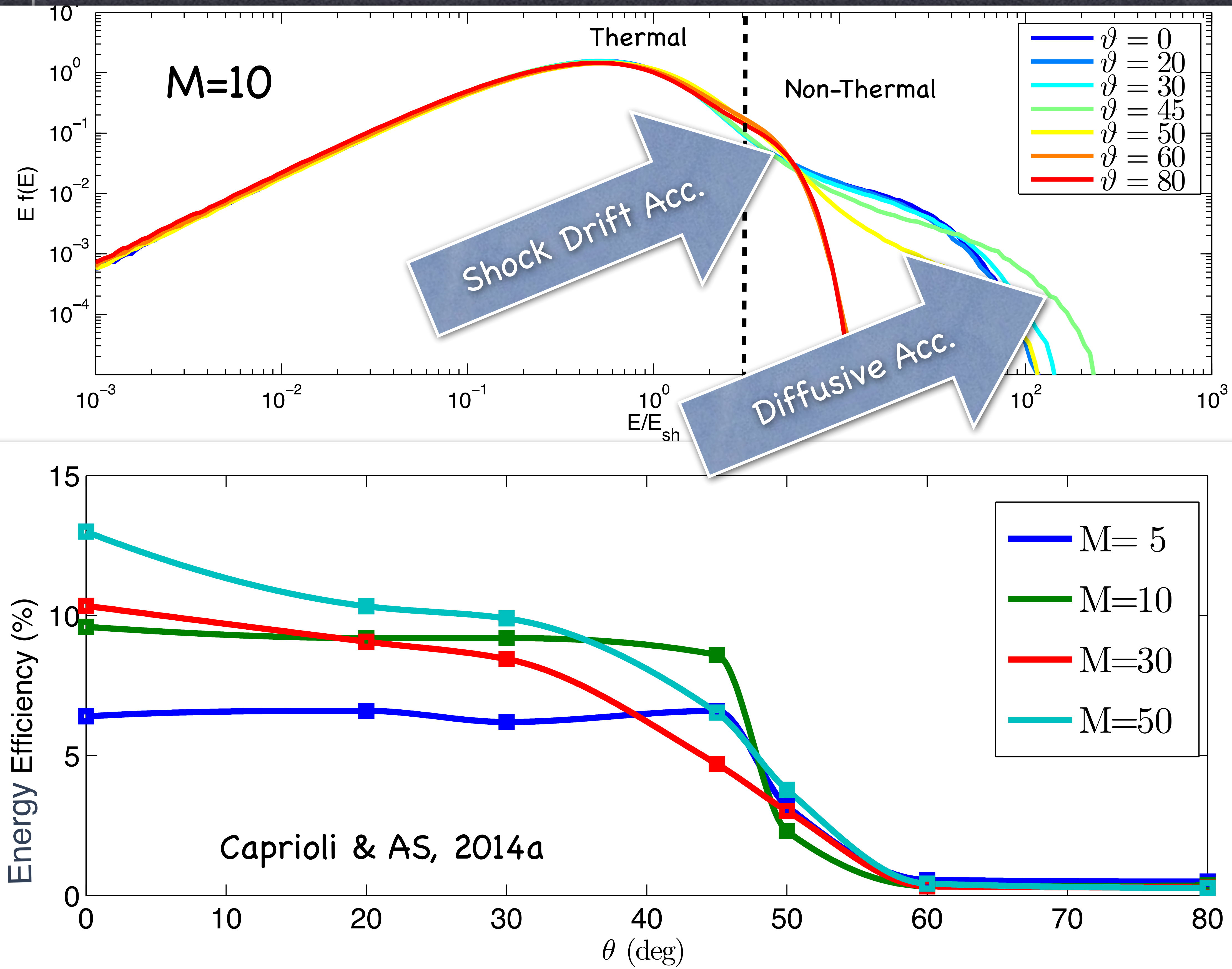
First-order Fermi acceleration: $f(p) \propto p^{-4}$ $4\pi p^2 f(p) dp = f(E) dE$

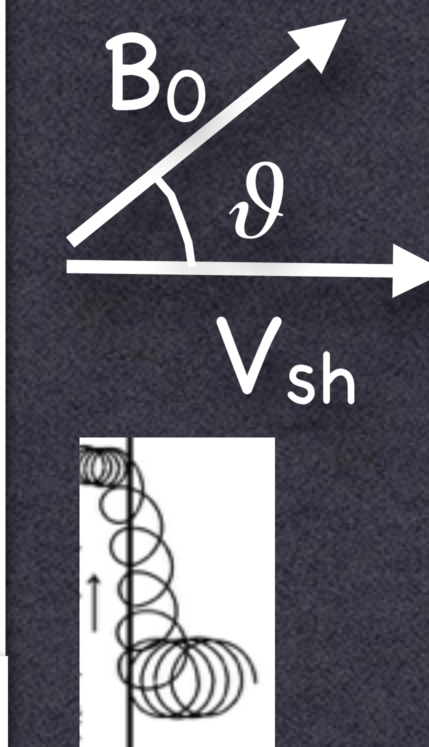
$f(E) \propto E^{-2}$ (relativistic) $f(E) \propto E^{-1.5}$ (non-relativistic)

CR backreaction is affecting downstream temperature

Caprioli & Spitkovsky 2014a

Acceleration in parallel vs oblique shocks

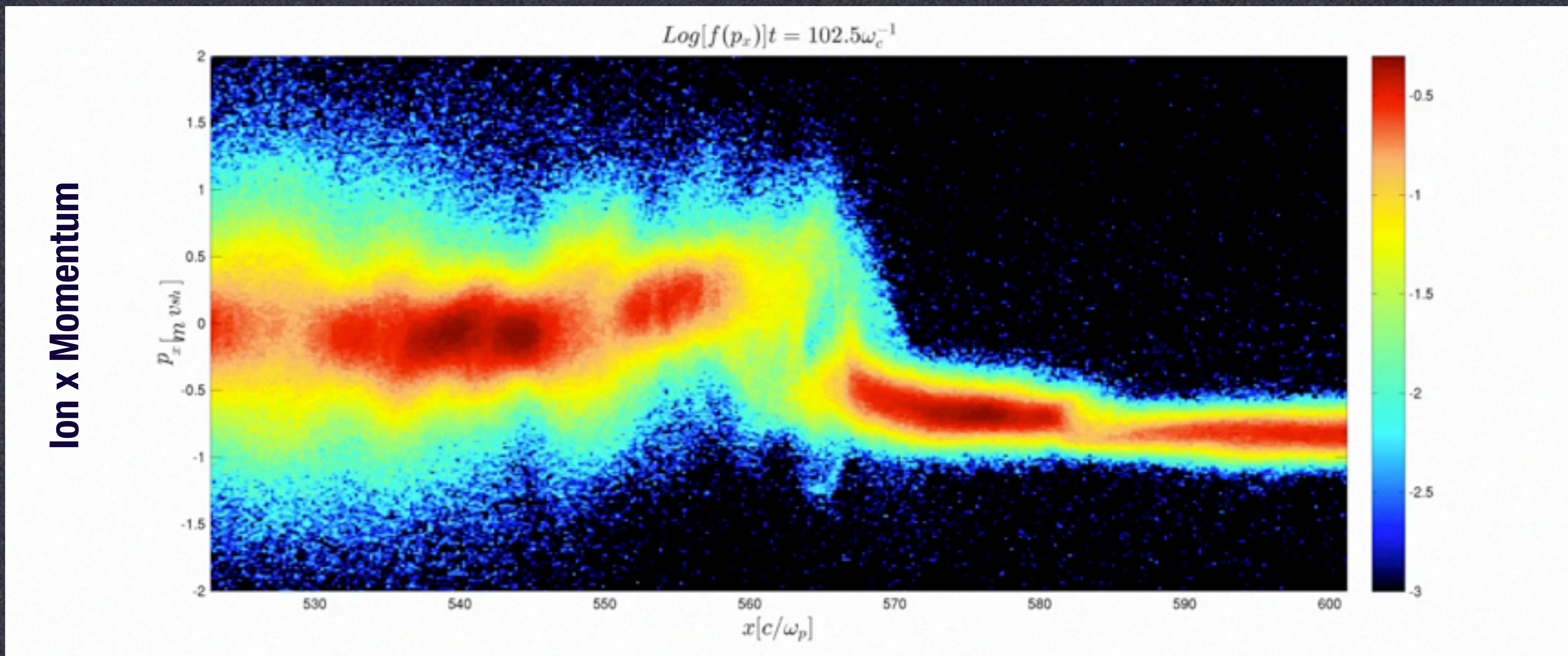




About 1% accelerated protons by number, what is causing that?

Shock structure & injection

Quasiparallel shocks look like intermittent quasiperp shocks

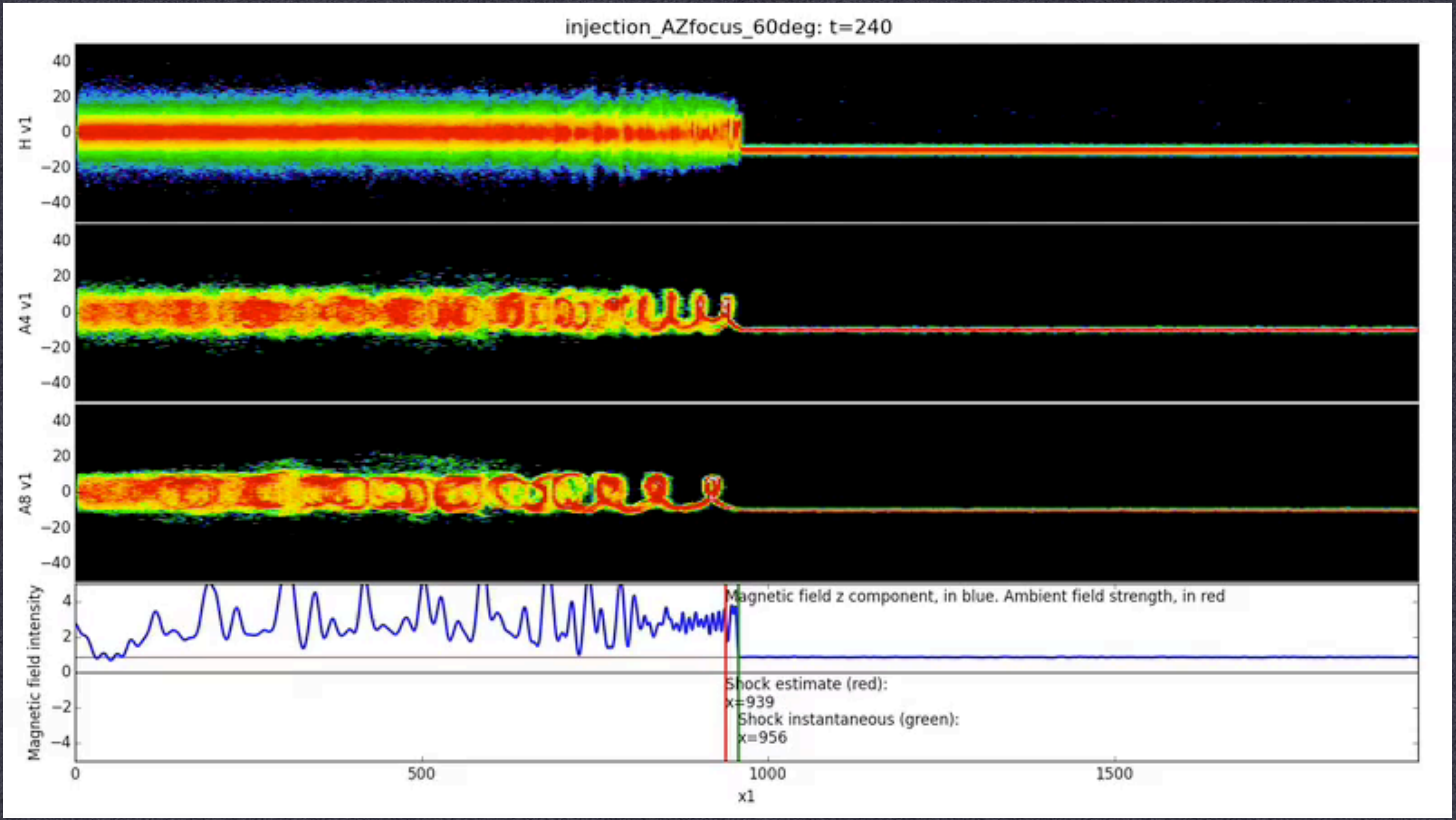


Injection of ions happens on first crossing due to specular reflection from reforming magnetic and electric barrier and shock-drift acceleration.

Multiple cycles in a time-dependent shock structure result in injection into DSA; no “thermal leakage” from downstream.

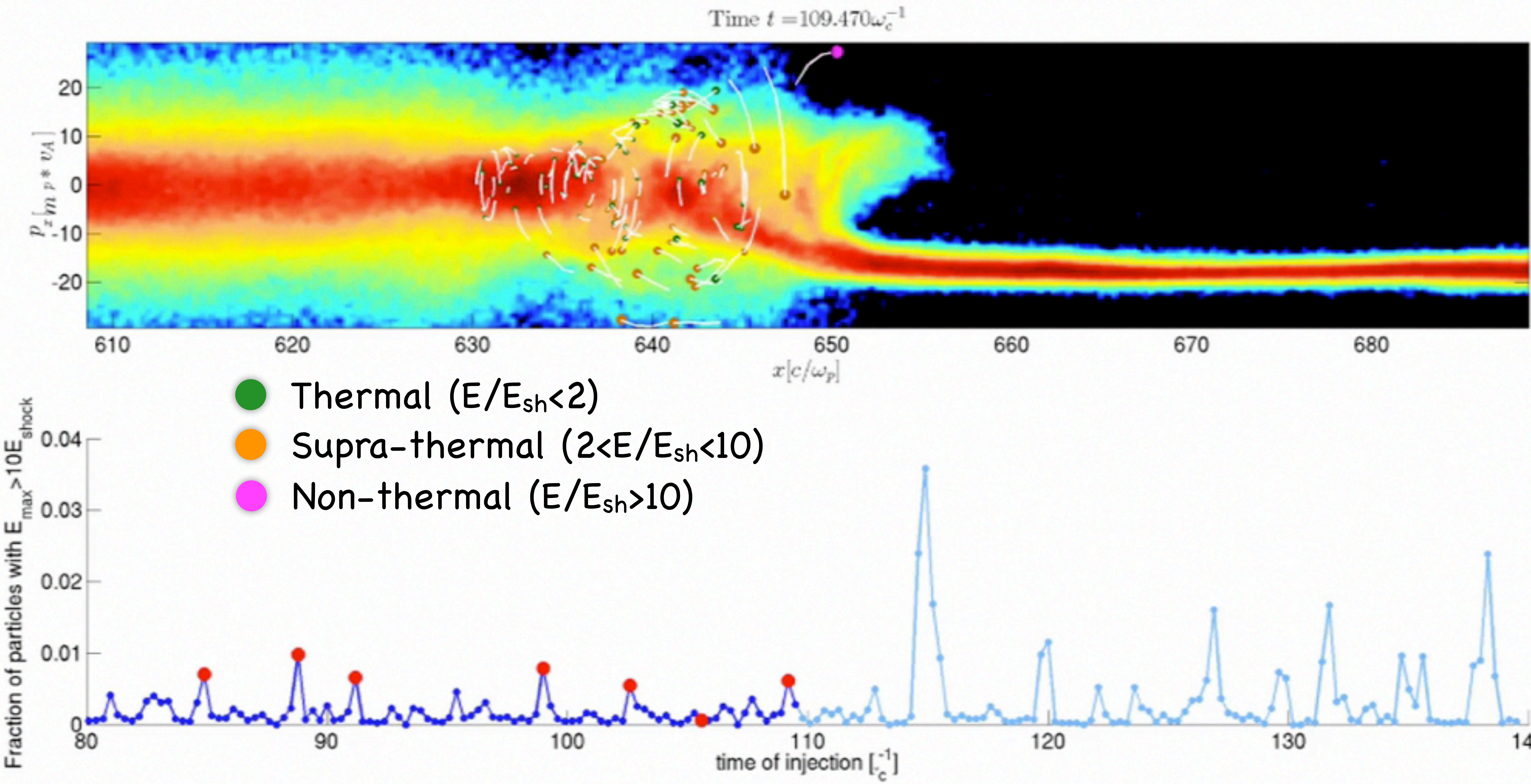
Quasi-perp shocks don't inject protons

- M=10, oblique (ϑ=60°) shock (Caprioli, Yi, AS ~subm.)



Injection mechanism: importance of timing

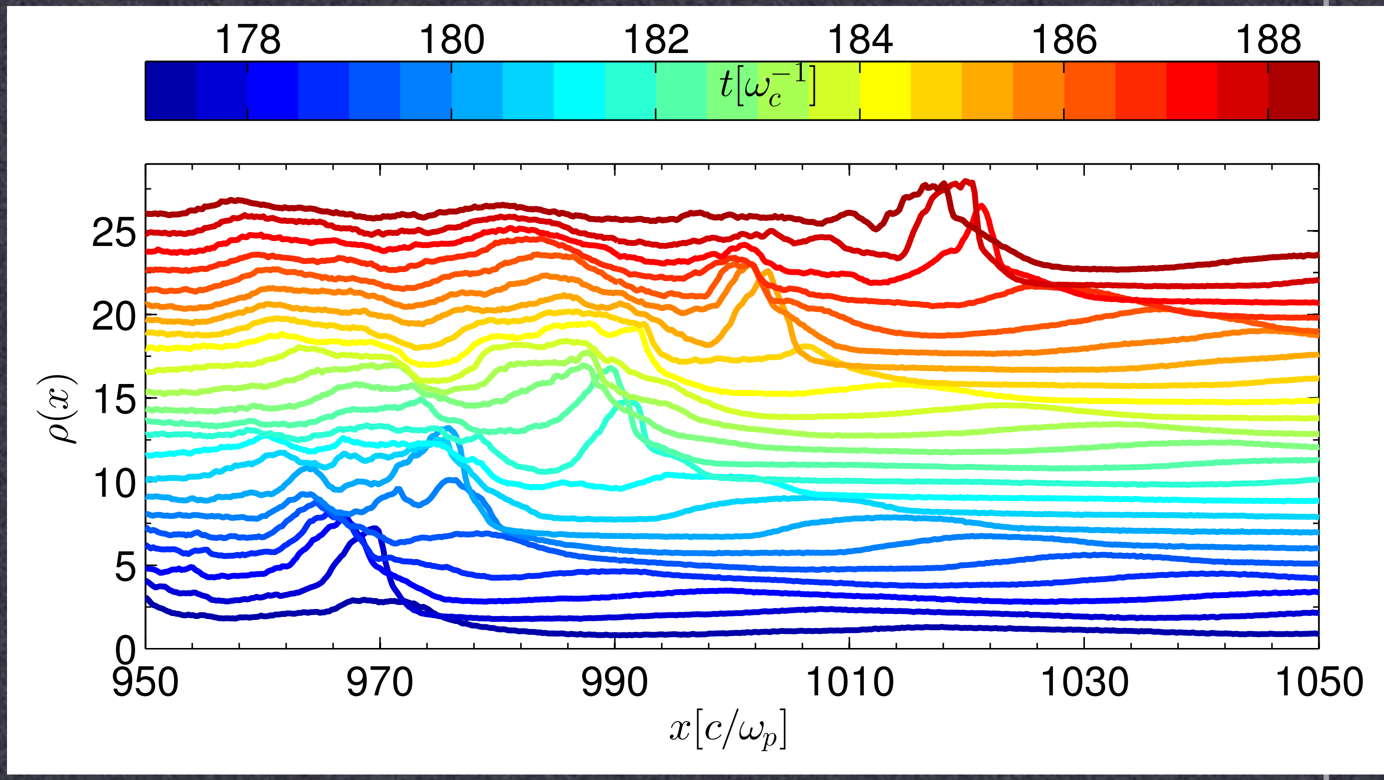
Caprioli, Pop & AS 2015



Proton injection: theory

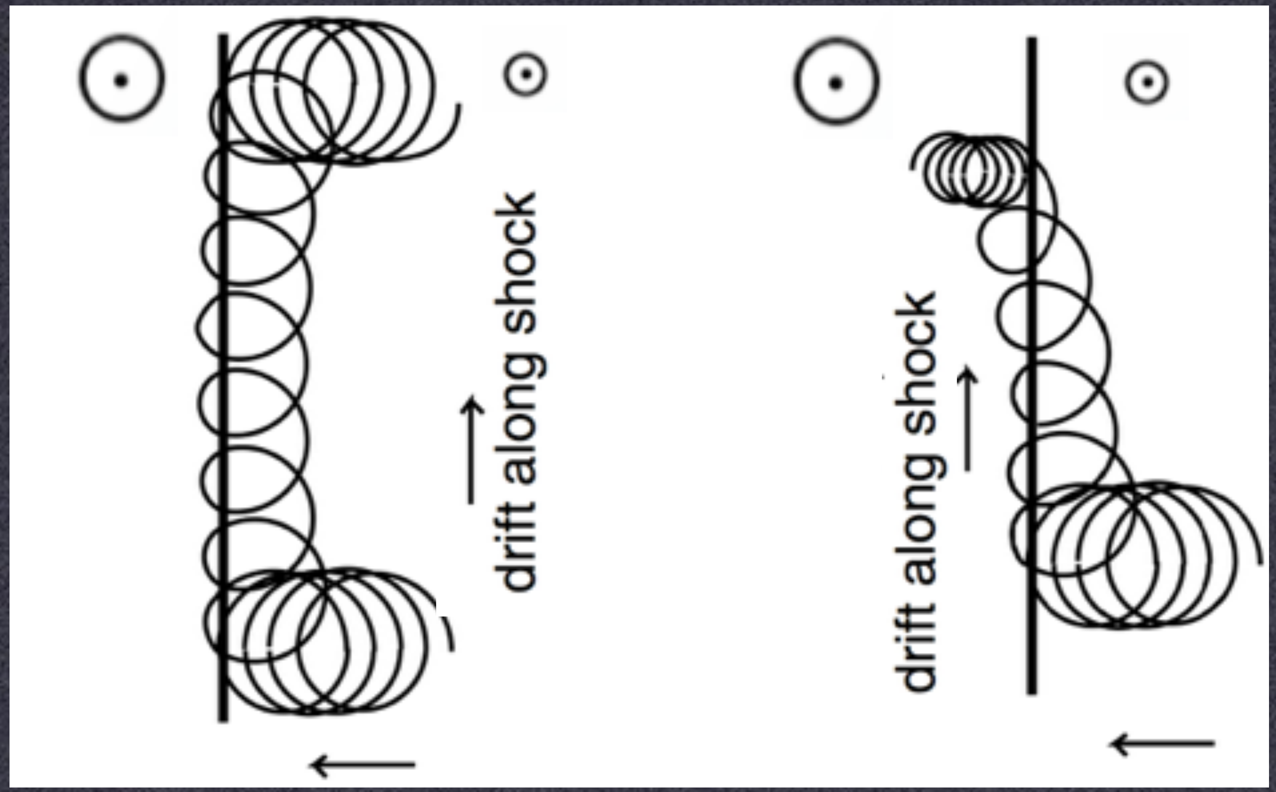
Caprioli, Pop & AS 2015

- Reflection off the shock potential barrier (stationary in the downstream frame)
- For reflection into upstream, particle needs certain minimal energy for given shock inclination;
- Particles first gain energy via shock-drift acceleration (SDA)
- Several cycles are required for higher shock obliquities
- Each cycle is "leaky", not everyone comes back for more
- Higher obliquities less likely to get injected



Shock-drift acceleration:

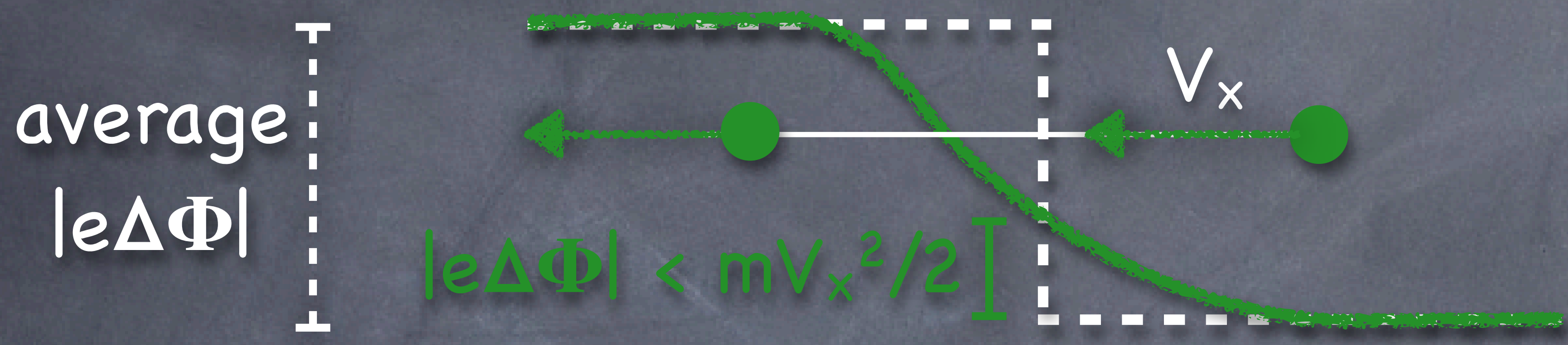
downstream upstream Larger B Smaller B



Path of incoming particle

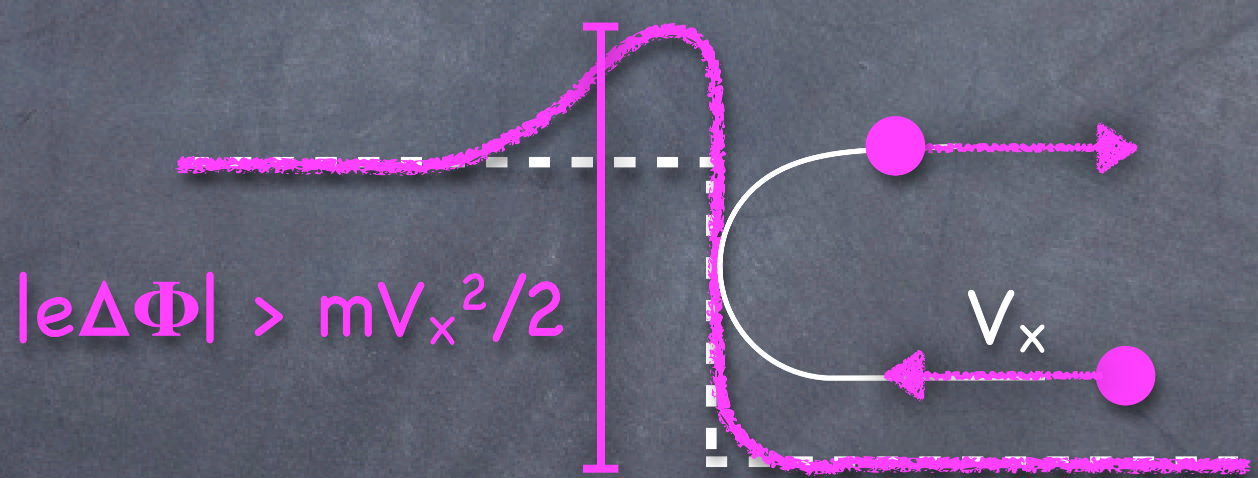
Encounter with the shock barrier

- Low barrier (shock reforming)



Particles are advected downstream, and thermalized

- High barrier (overshoot)



Particles are reflected upstream, and energized via Shock Drift Acc.

- To overrun the shock, proton need a minimum $E_{inj,}$ increasing with ϑ
- Particle fate determined by barrier duty cycle (~25%) and shock inclination
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta=45^\circ$, $E_{inj} \sim 10E_0$, which requires N~3 -> $\eta \sim 1\%$

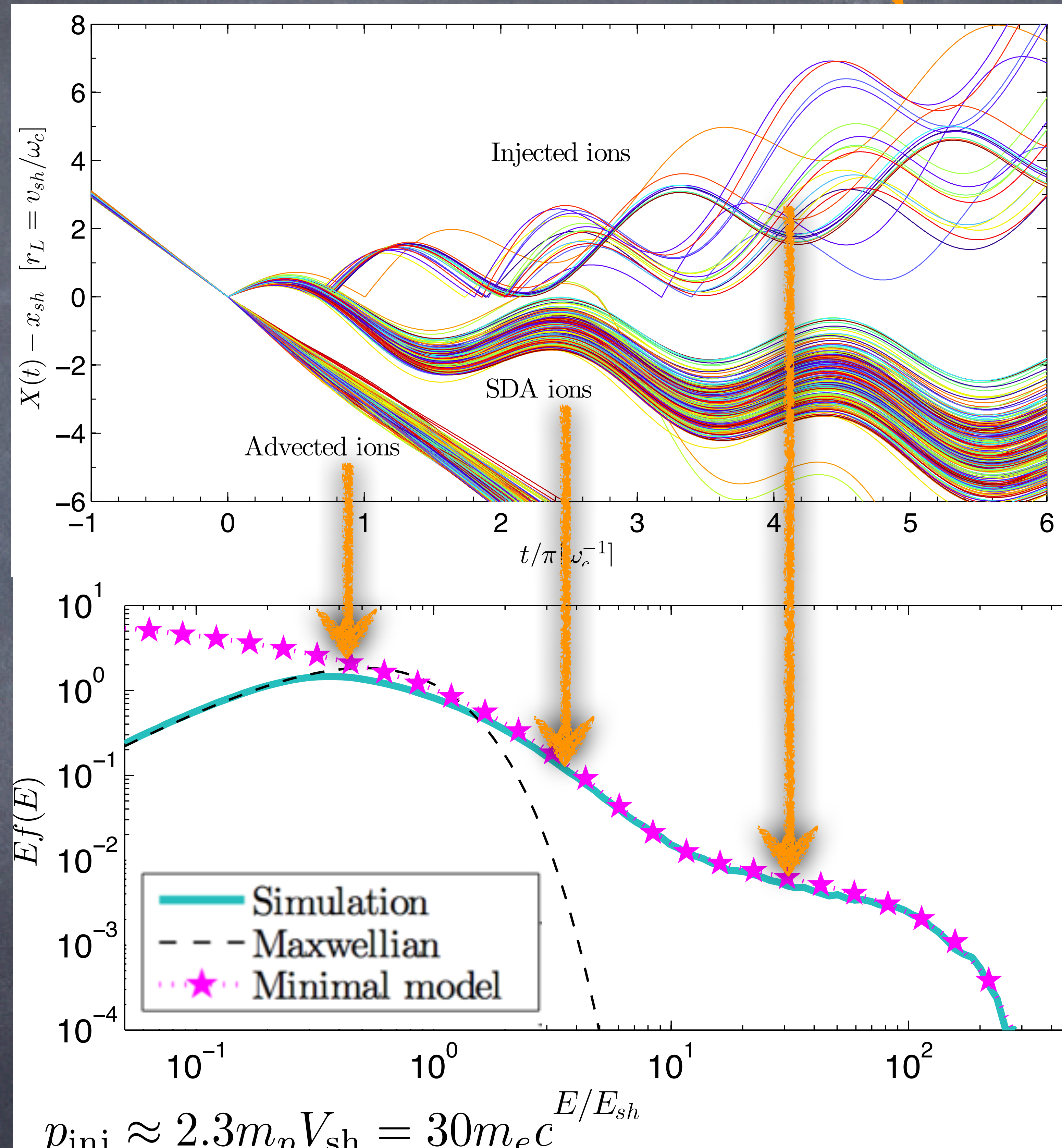
Minimal Model for Ion Injection

- Time-varying potential barrier
  - **High state** (duty cycle 25%)
    -> Reflection
    -> Shock Drift Acceleration
  - **Low-state** -> Thermalization

- Spectrum à la Bell (1978)

$$f(E) \propto E^{-1-\gamma}; \quad \gamma \equiv -\frac{\ln(1-\mathcal{P})}{\ln(1+\mathcal{E})}$$

- P=probability of being advected
- ε =fractional energy gain/cycle



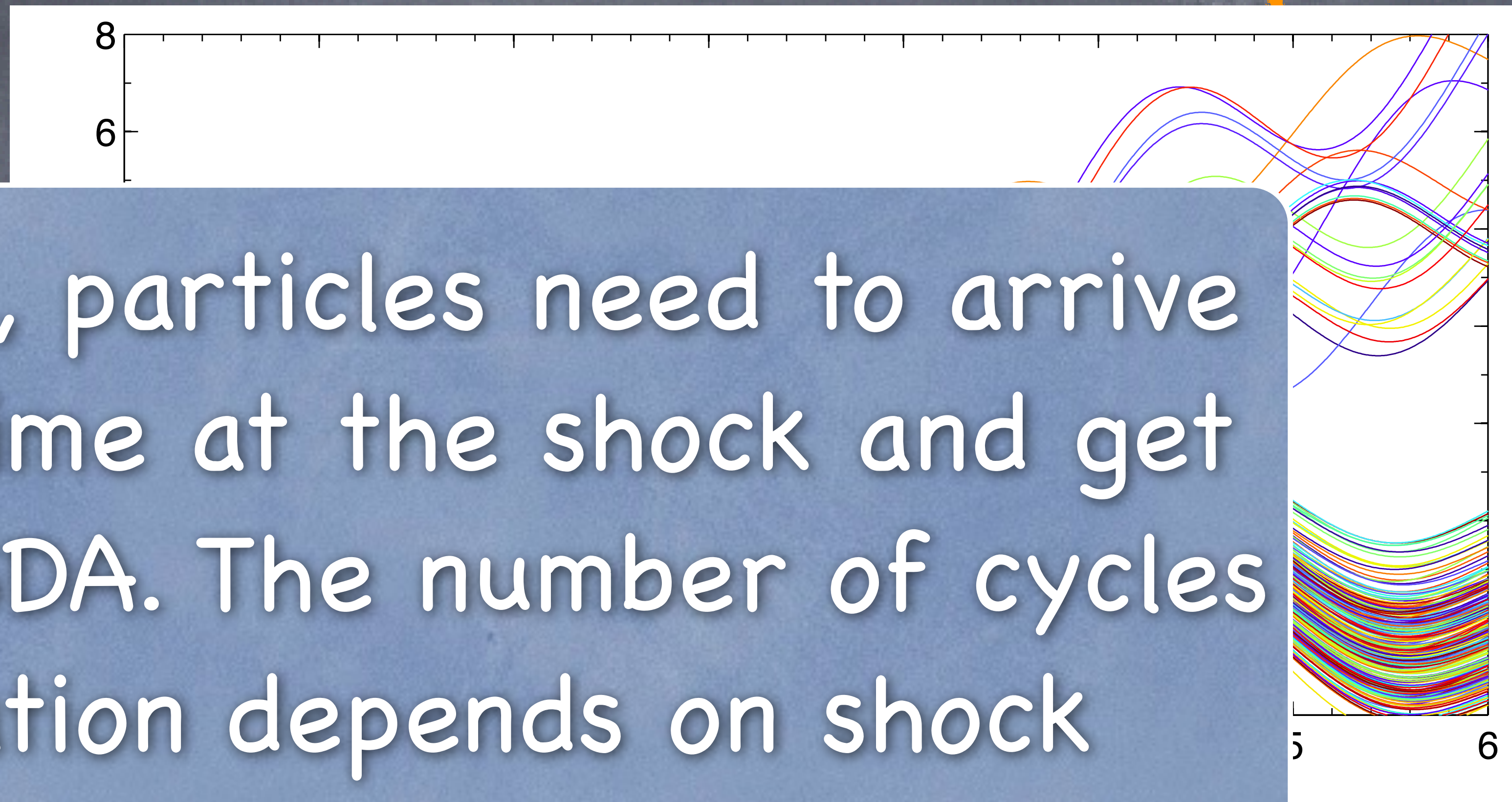
Caprioli, Pop & Spitkovsky, 2015

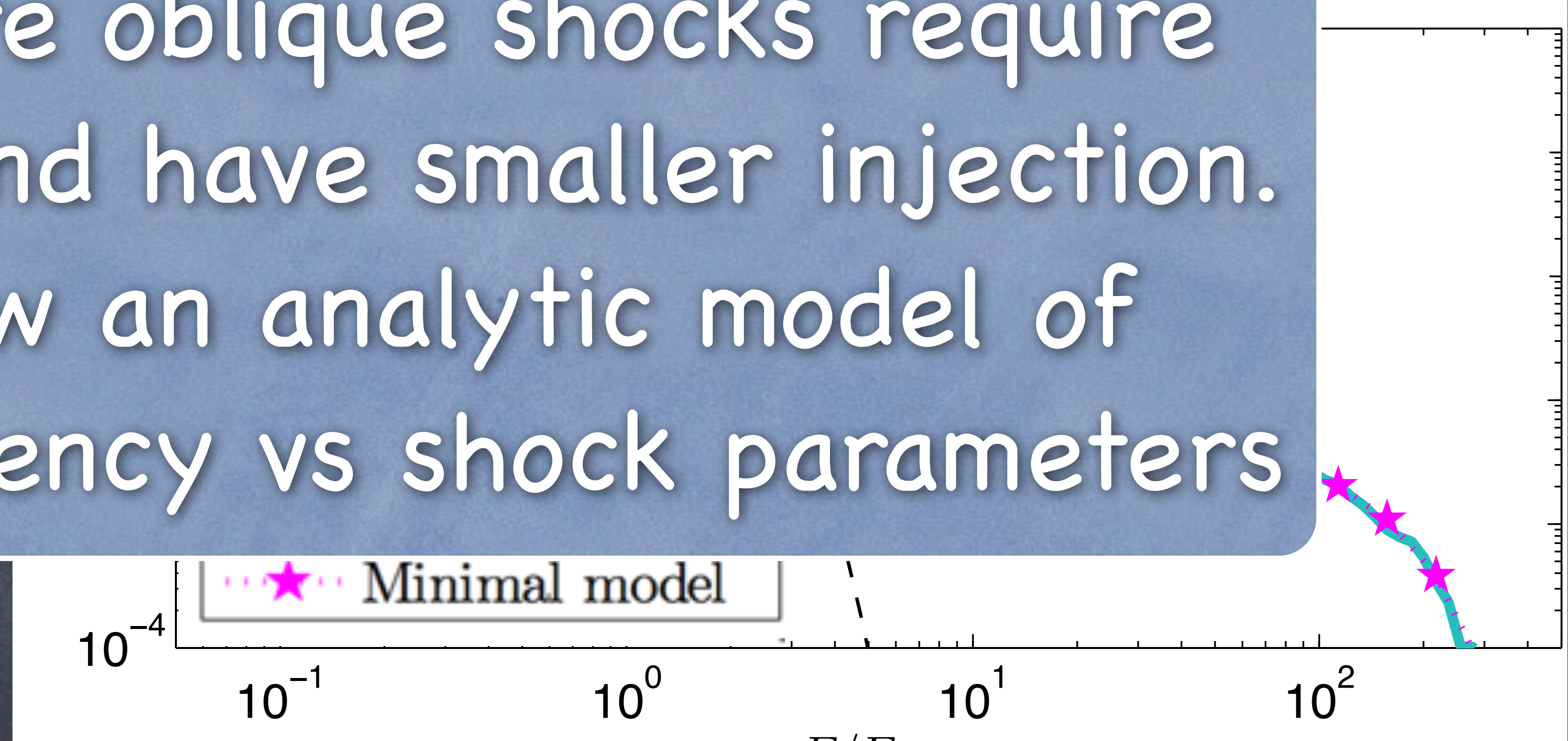
Minimal Model for Ion Injection

- Time-varying potential barrier
  - High
    - -> R
    - -> S
  - Low-
- Spectru

$f(E) \propto$

- P=proba
- ε =fractional energy gain/cycle

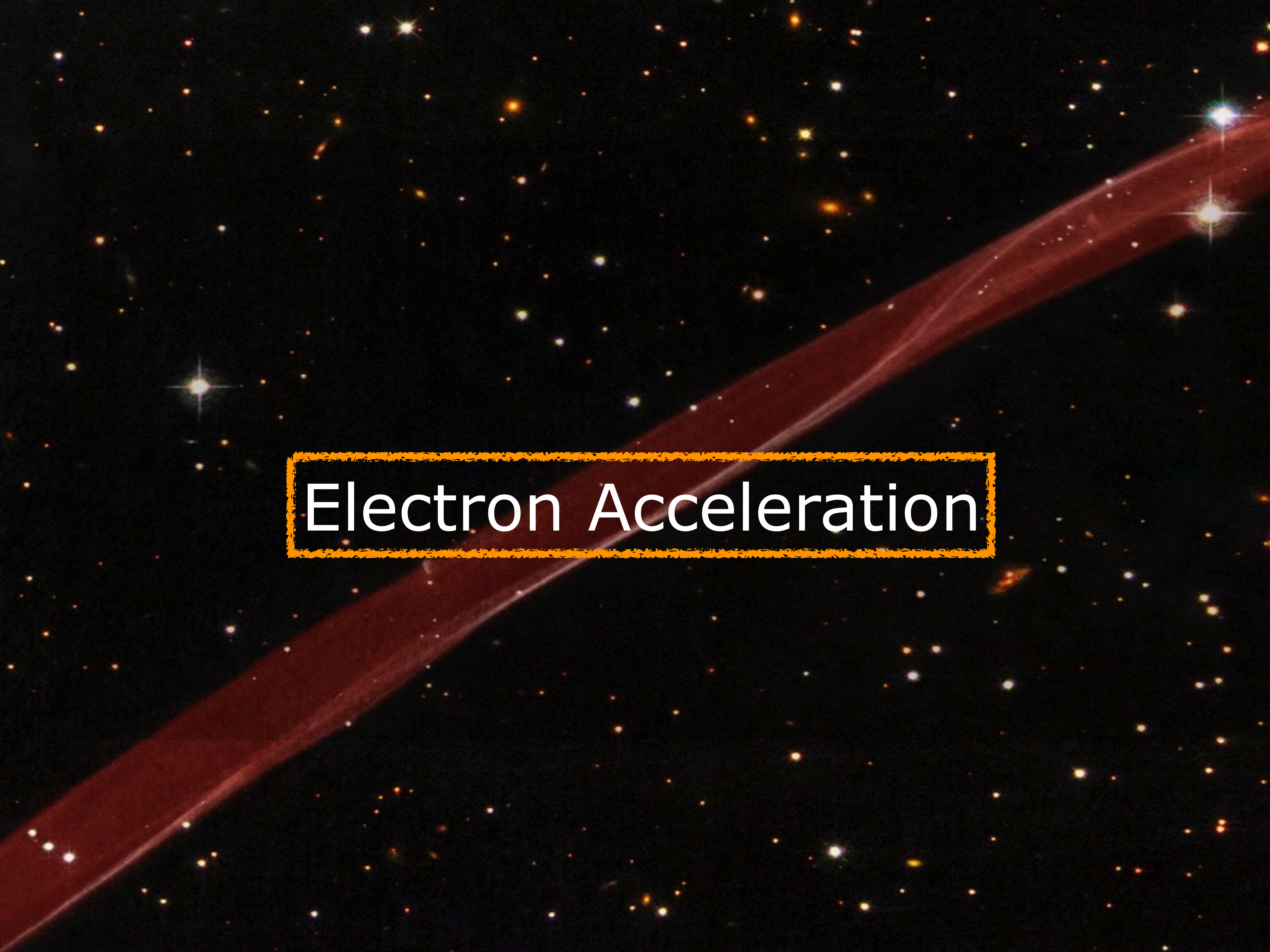




$p_{\rm inj} \approx 2.3 m_p V_{\rm sh} = 30 m_e c$

To be injected, particles need to arrive at the right time at the shock and get energized by SDA. The number of cycles of energization depends on shock obliquity. More oblique shocks require more cycles, and have smaller injection. There is now an analytic model of injection efficiency vs shock parameters

Caprioli, Pop & Spitkovsky, 2015


Electron Acceleration

Electron acceleration at parallel shocks

Recent evidence of electron acceleration in quasi parallel shocks.
PIC simulation of quasiparallel shock. Very long simulation in 1D.

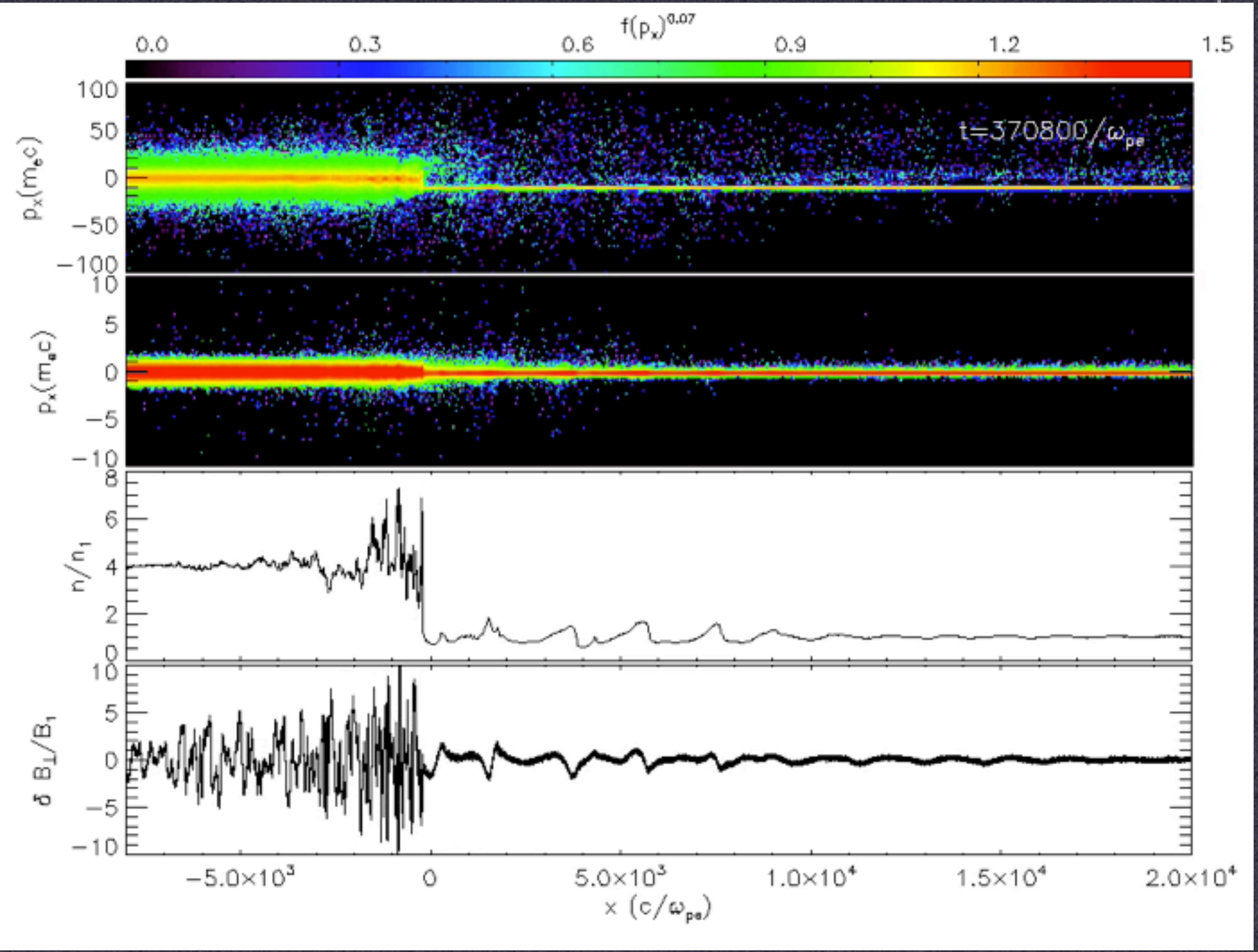
Ion-driven Bell waves drive electron acceleration: correct polarization

Ion phase space

Electron phase space

Density

Transverse Magnetic field



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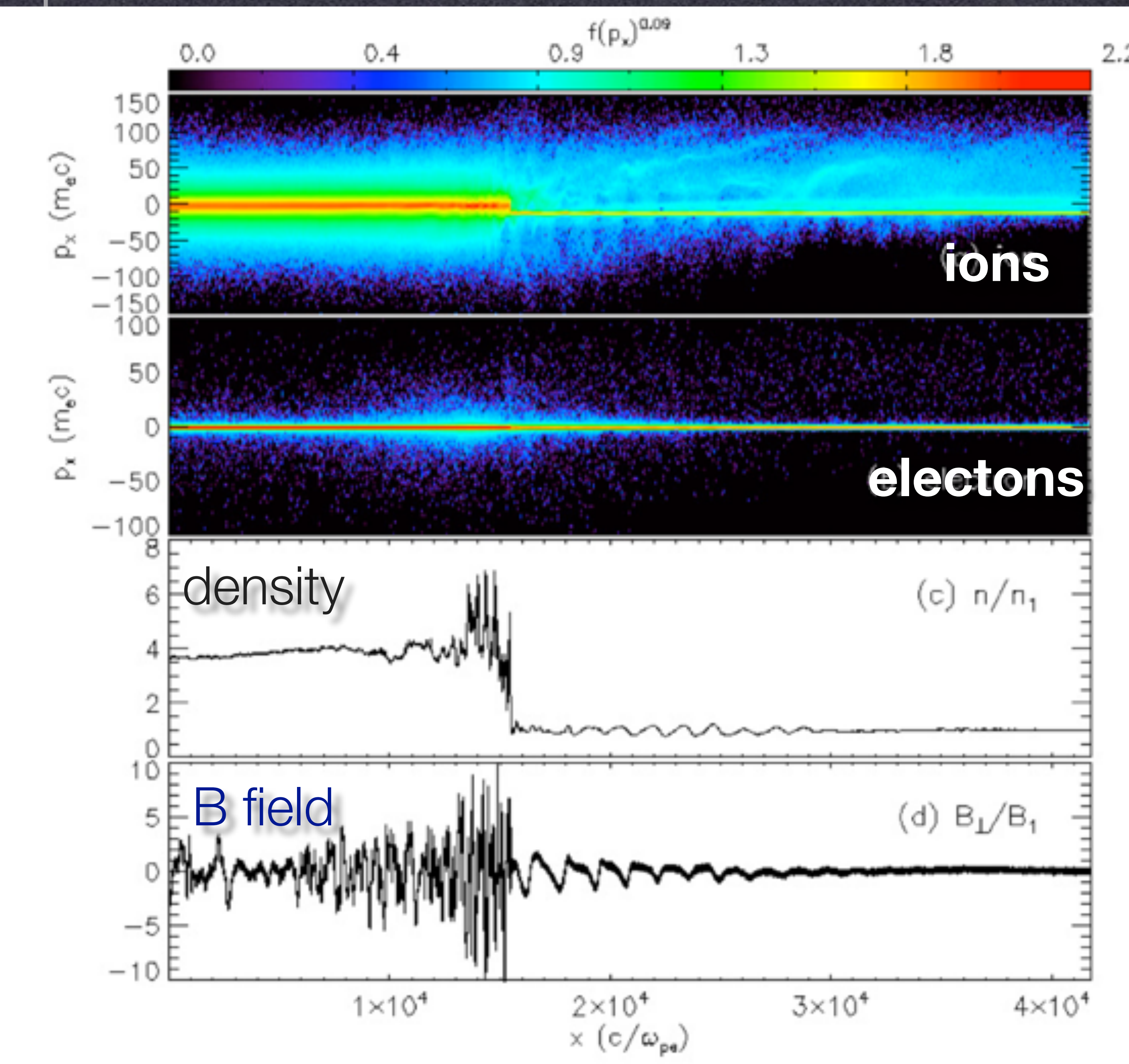
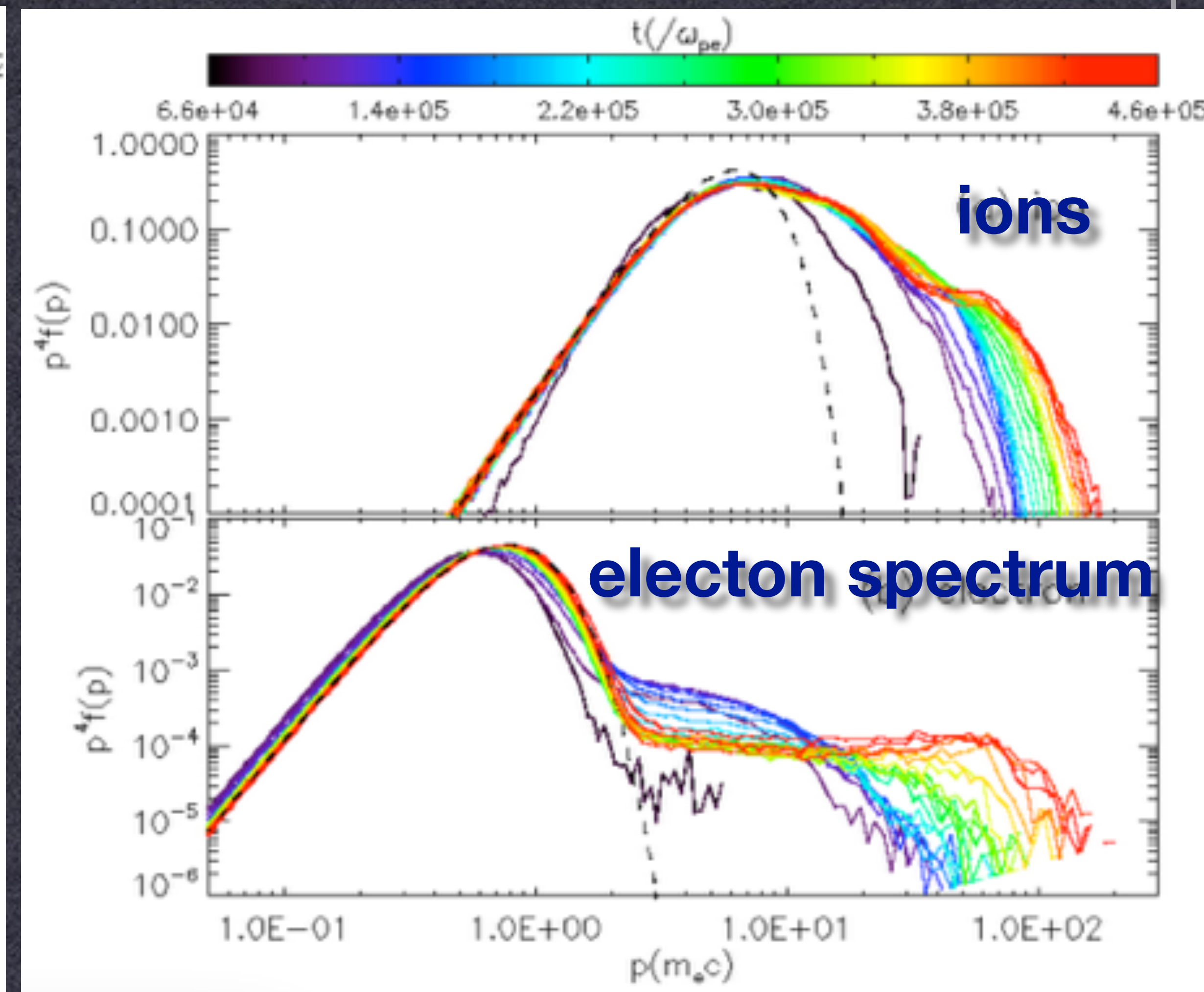


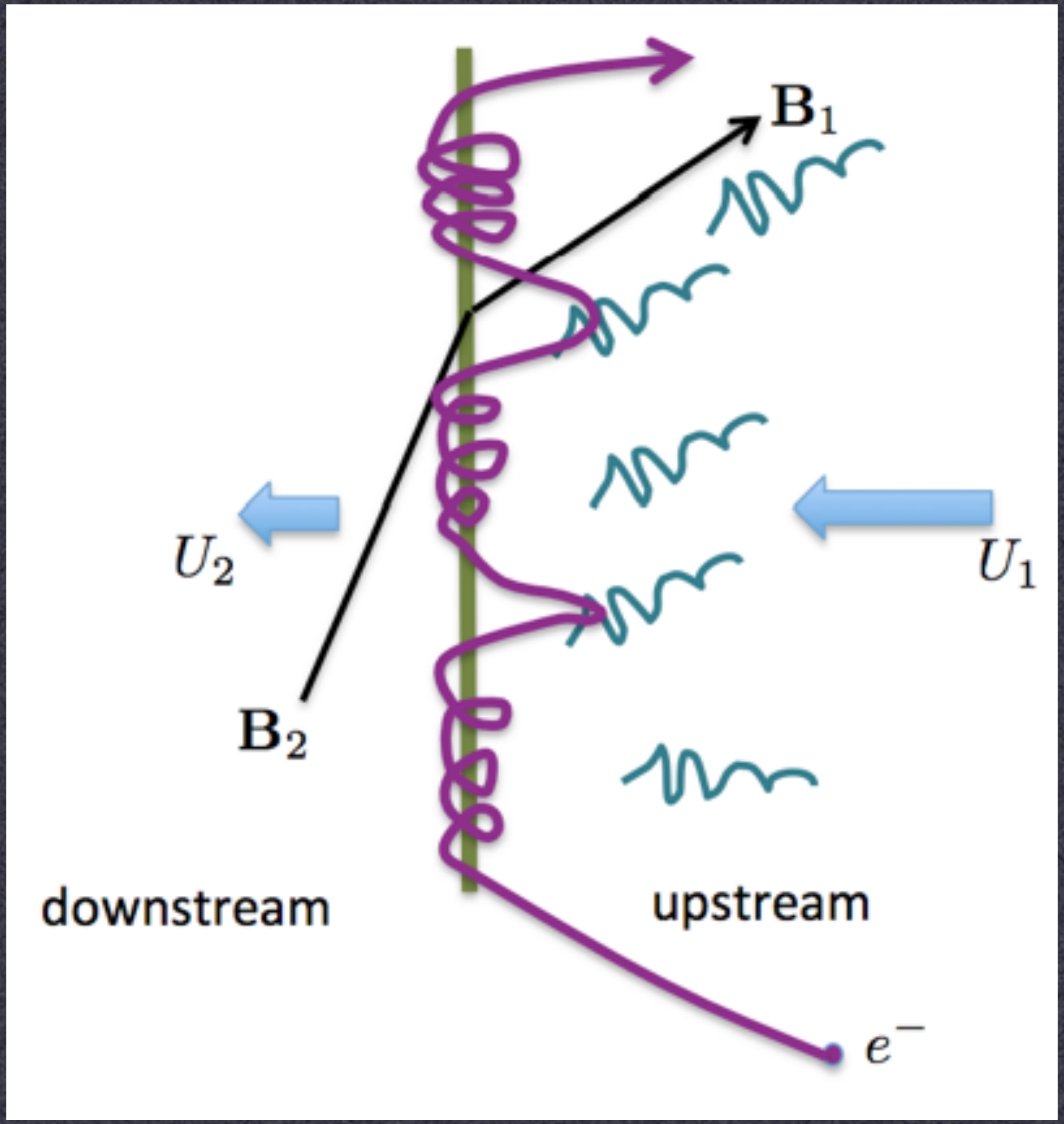


DSA spectrum recovered in _both_ electrons and ions
Electron-proton ratio can be measured!

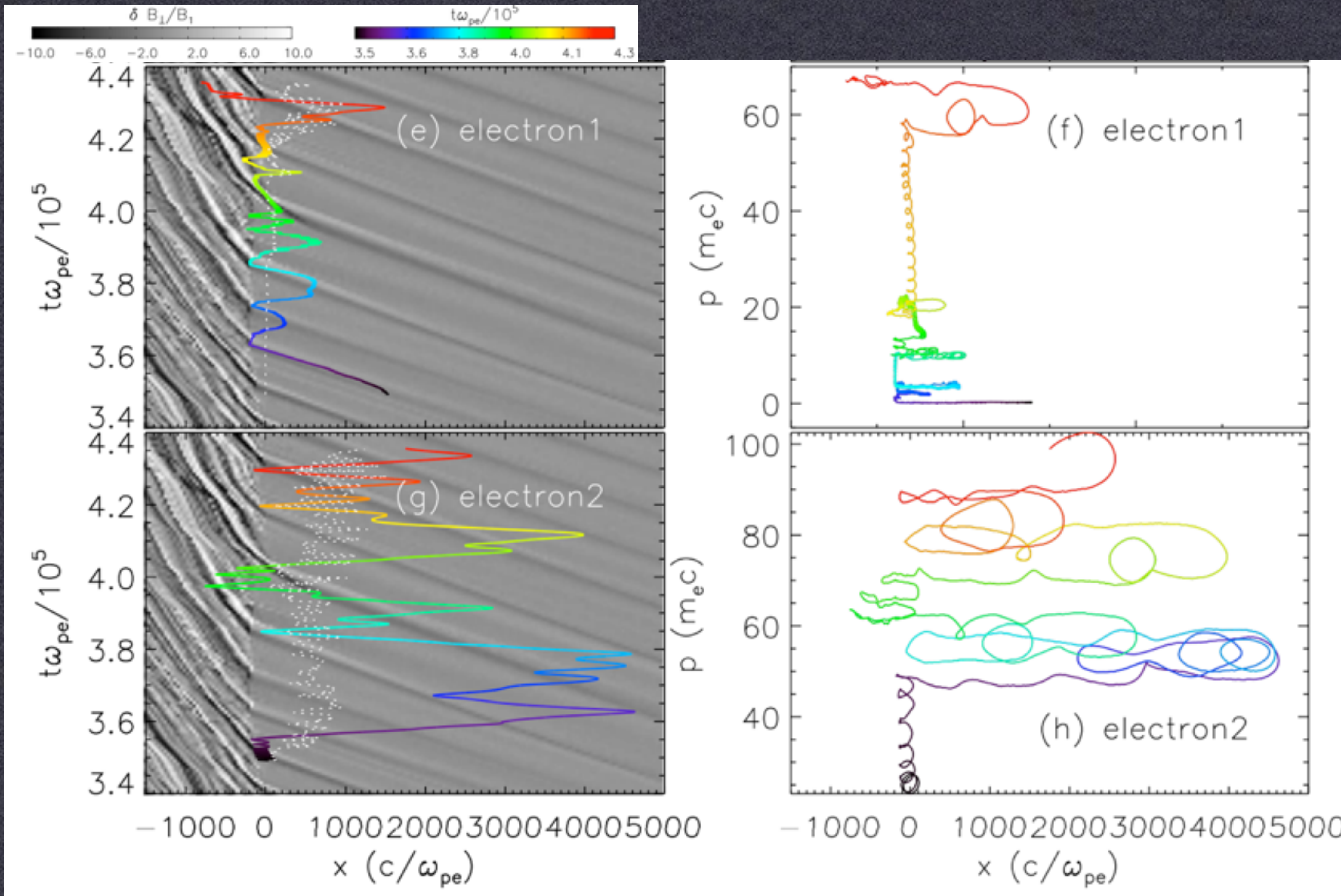
Park, Caprioli, AS (2015)

Electron acceleration at parallel shocks

Multi-cycle shock-drift acceleration, with electrons returning back due to upstream ion-generated waves.



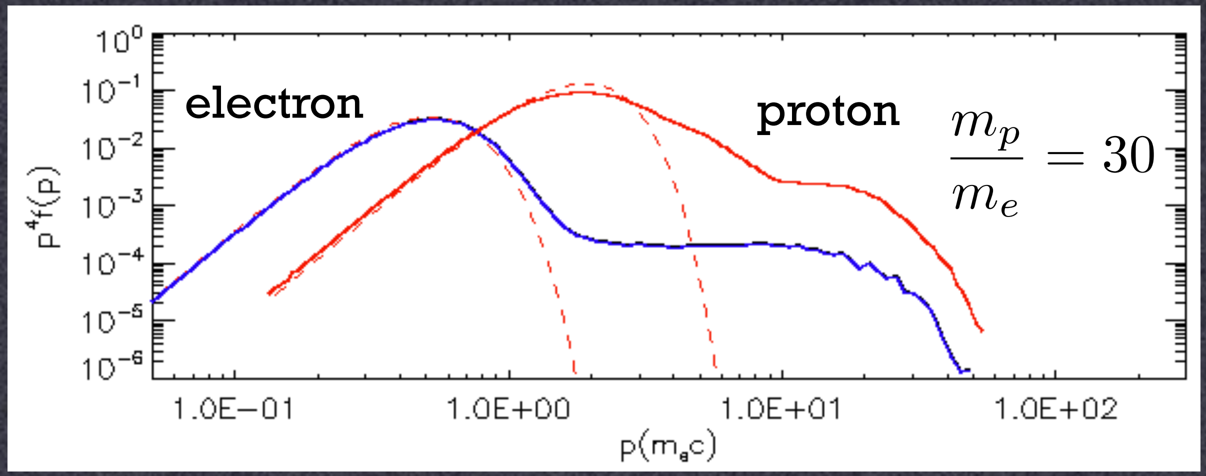
Electron acceleration mechanism: shock drift cycles

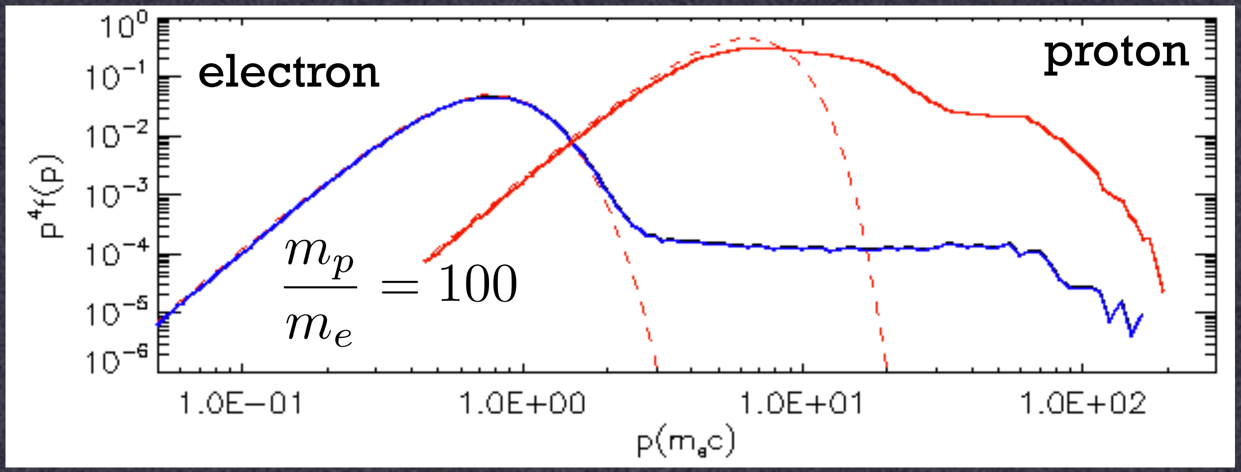


Electron track from PIC simulation.

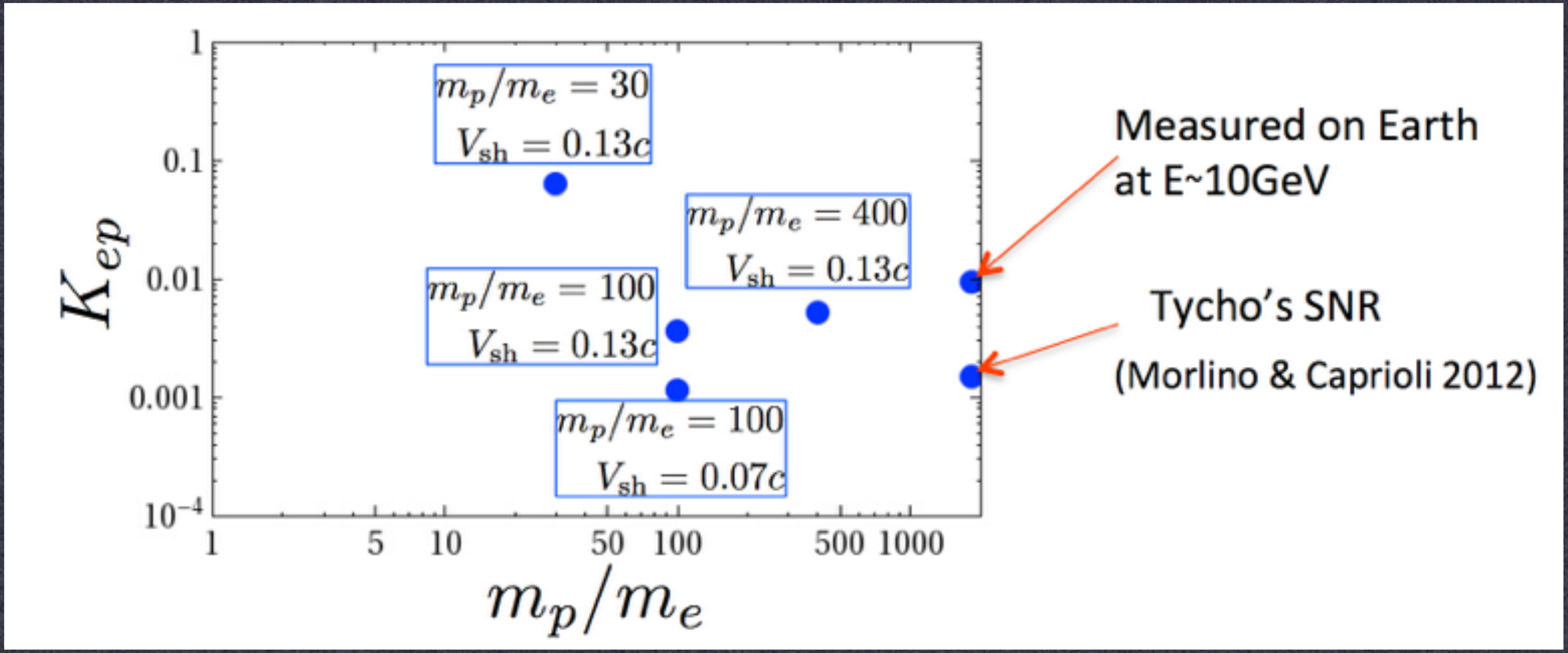
Electron-proton ratio K_{ep}:

Park, Caprioli, AS (2015)



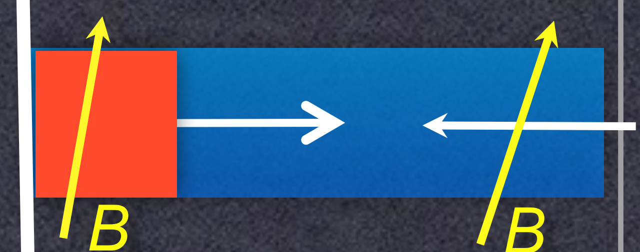


$$K_{\rm ep} \equiv \frac{f_e(p)}{f_p(p)} = \text{const for } p > p_{\rm inj} \quad K_{\rm ep} \approx 3.8 \times 10^{-3} \text{ for } \frac{m_p}{m_e} = 100$$

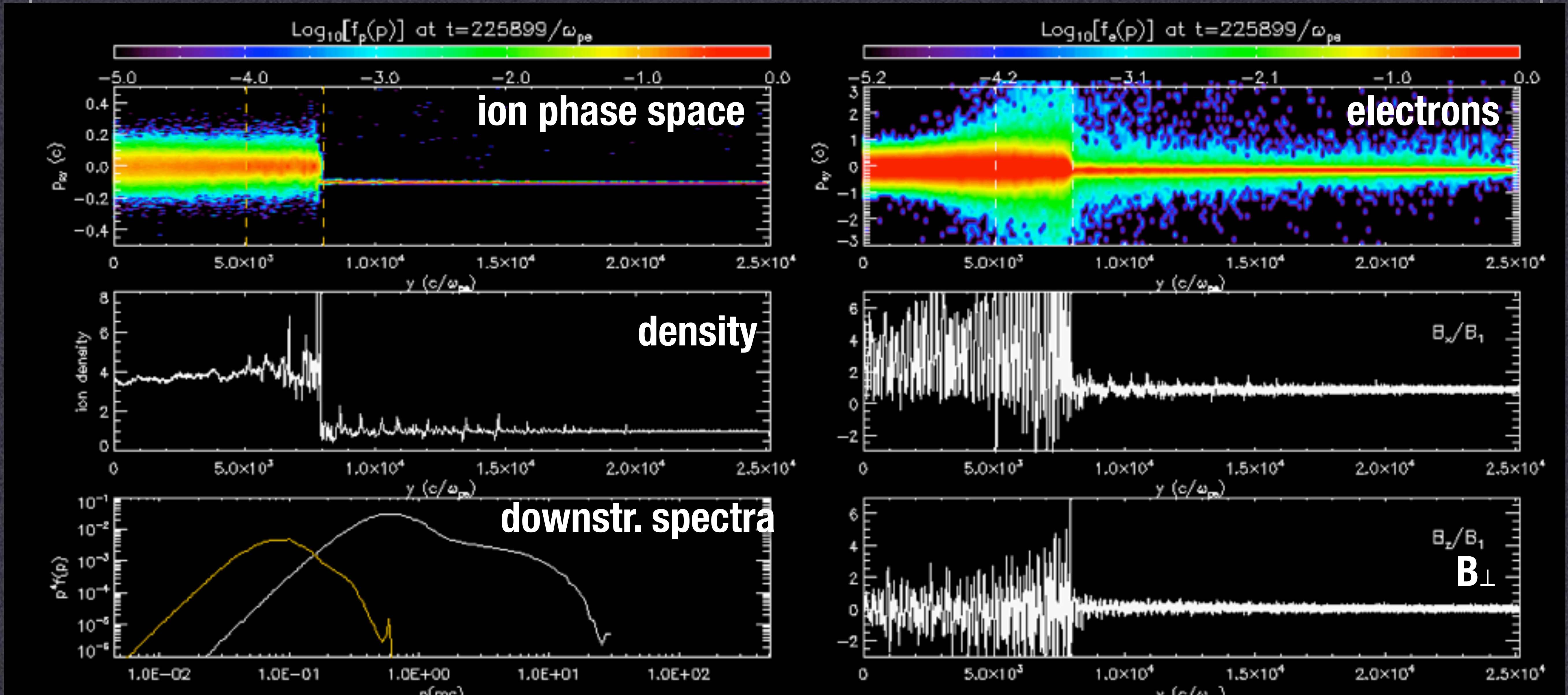


Electron acceleration at ⊥-shocks

60 degrees shock inclination, mi/me=100, M_A=20;
electron-driven waves upstream



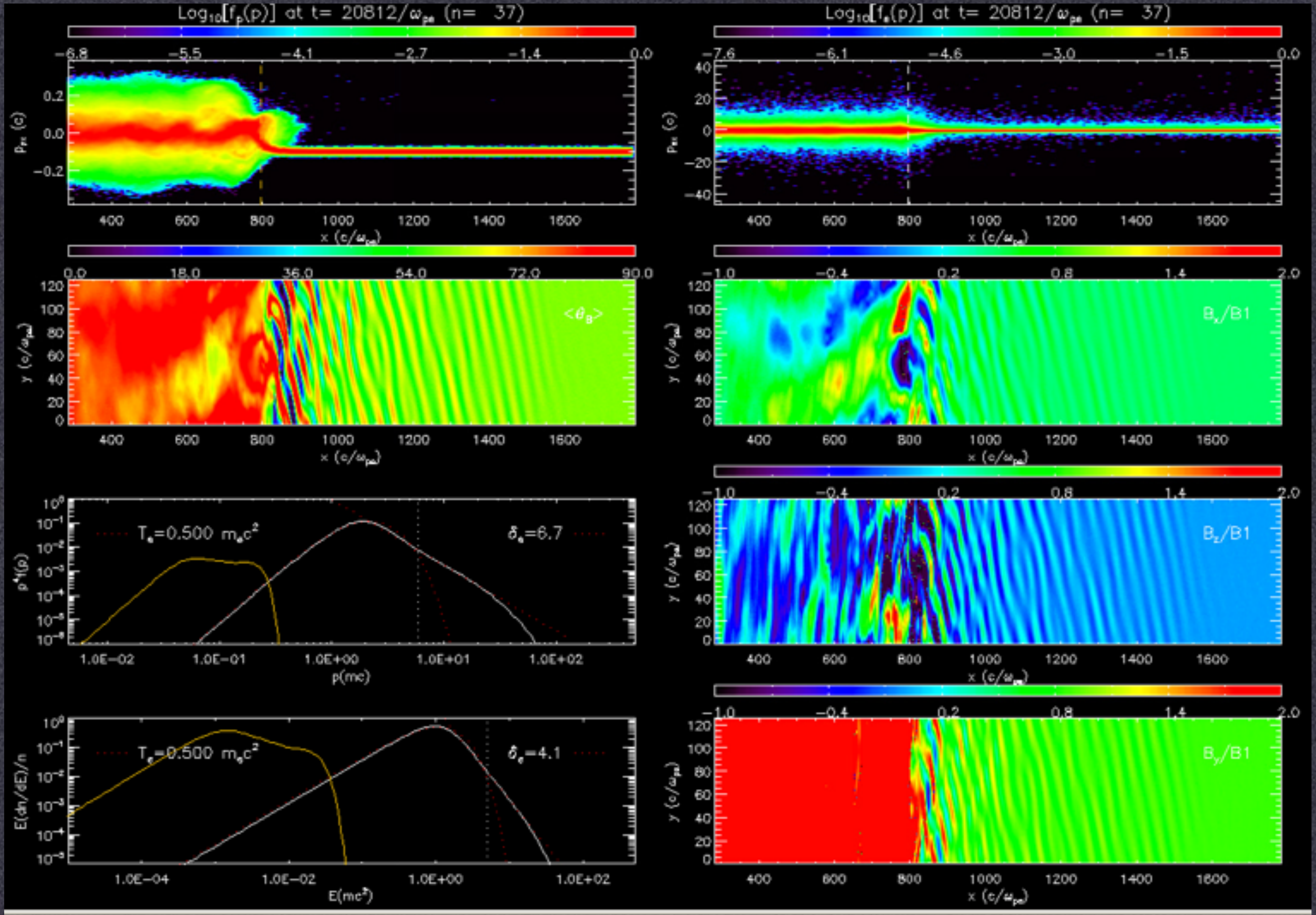
(Caprioli, Park, AS, in prep)



Ions are not injected or accelerated into DSA, while electrons drive their own Bell-type waves. Electrons are reflected from shock due to magnetic mirroring.

Recover DSA electron spectrum, 0.1-4% in energy, <1% by number.

Electron acceleration at ⊥-shocks: 2D



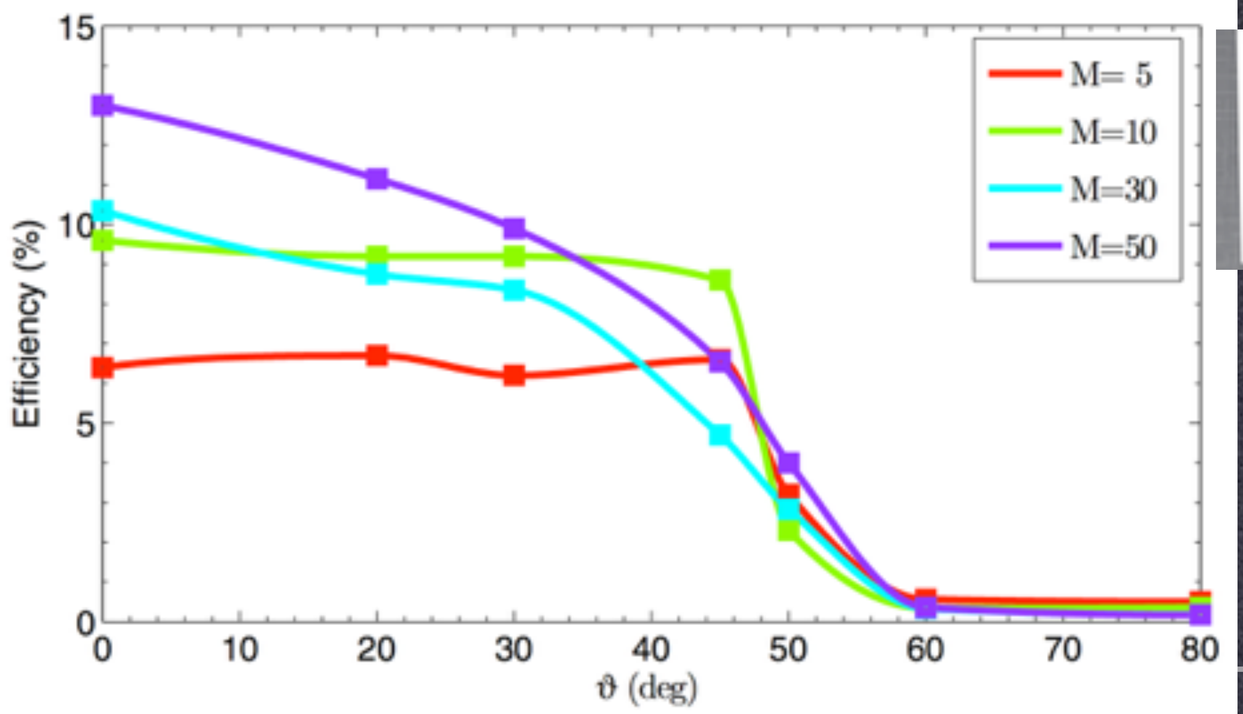
Low-M shocks; Whistler waves in the shock foot for $M_A<m_i/m_e$;

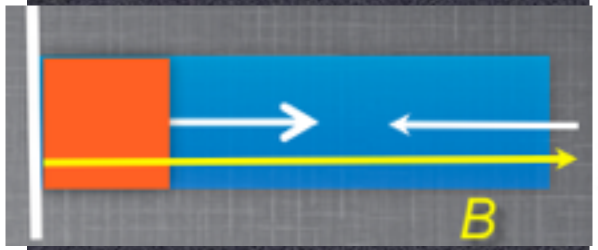
Electron DSA! Large-amplitude Electron-driven modes! Oblique firehose? (Guo 2014) Or whistlers?

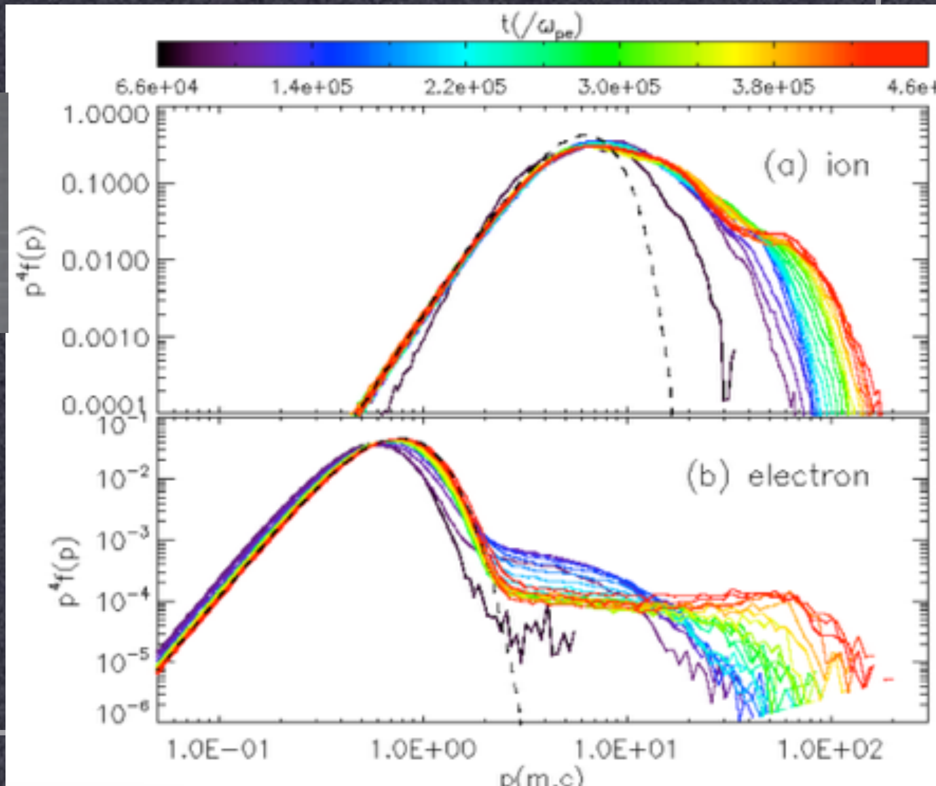
Shock acceleration: emerging picture

Acceleration in laminar field:

quasi-parallel -- accelerate both ions and electrons
(Caprioli & AS, 2014abc; Park, Caprioli, AS 2015)
quasi-perpendicular -- accelerate mostly electrons
(Guo, Sironi & Narayan 2014; Caprioli, Park, AS in prep)







Shock acceleration: emerging picture

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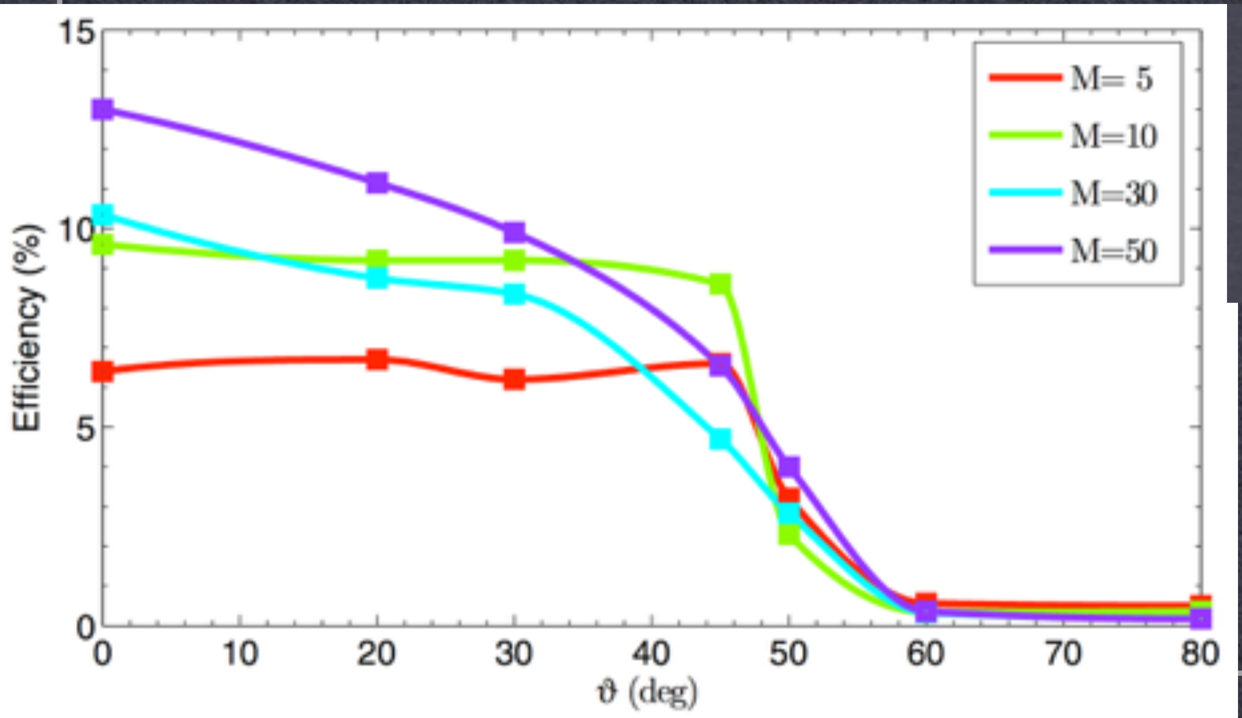
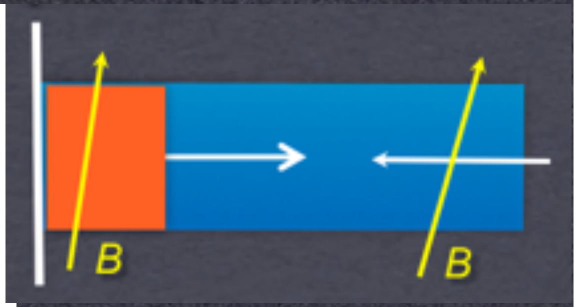
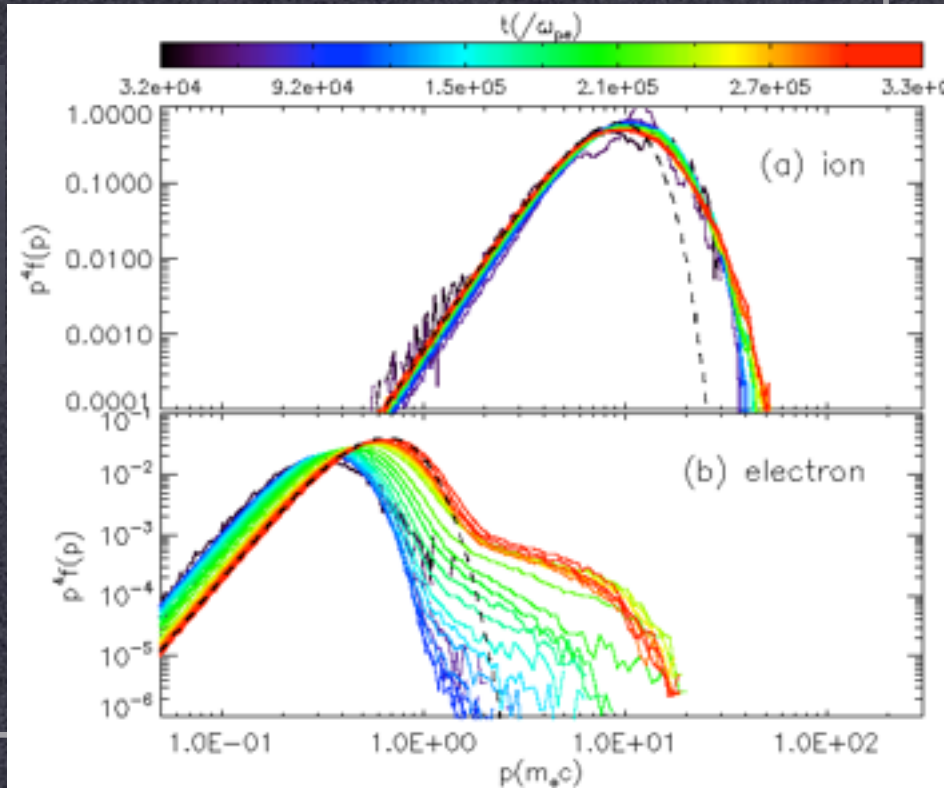
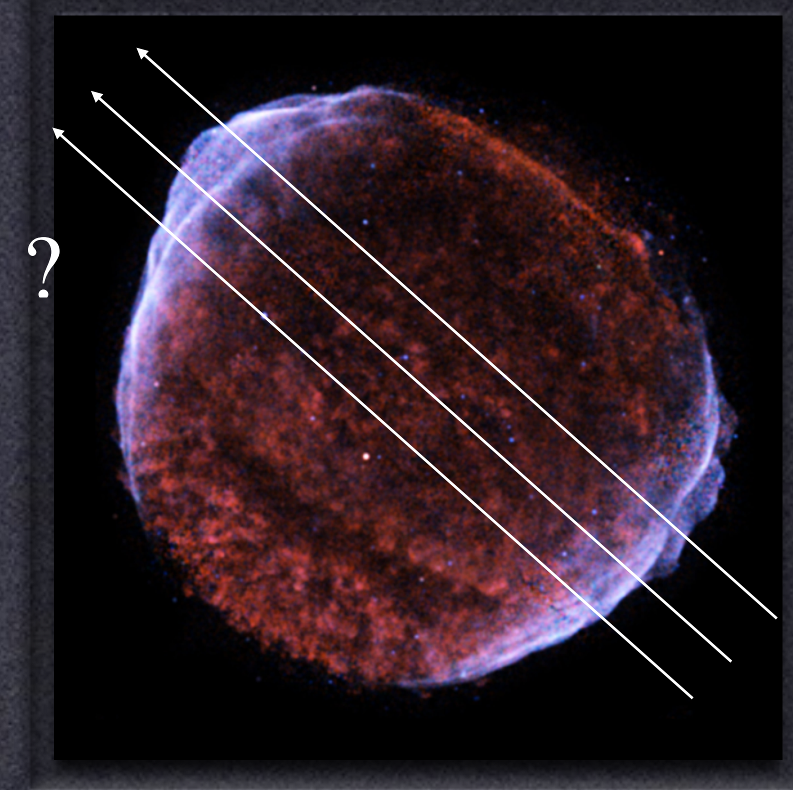






SNR story



Nonthermally-emitting SNRs likely have large scale parallel magnetic field (radial). This leads to CR acceleration and field amplification.

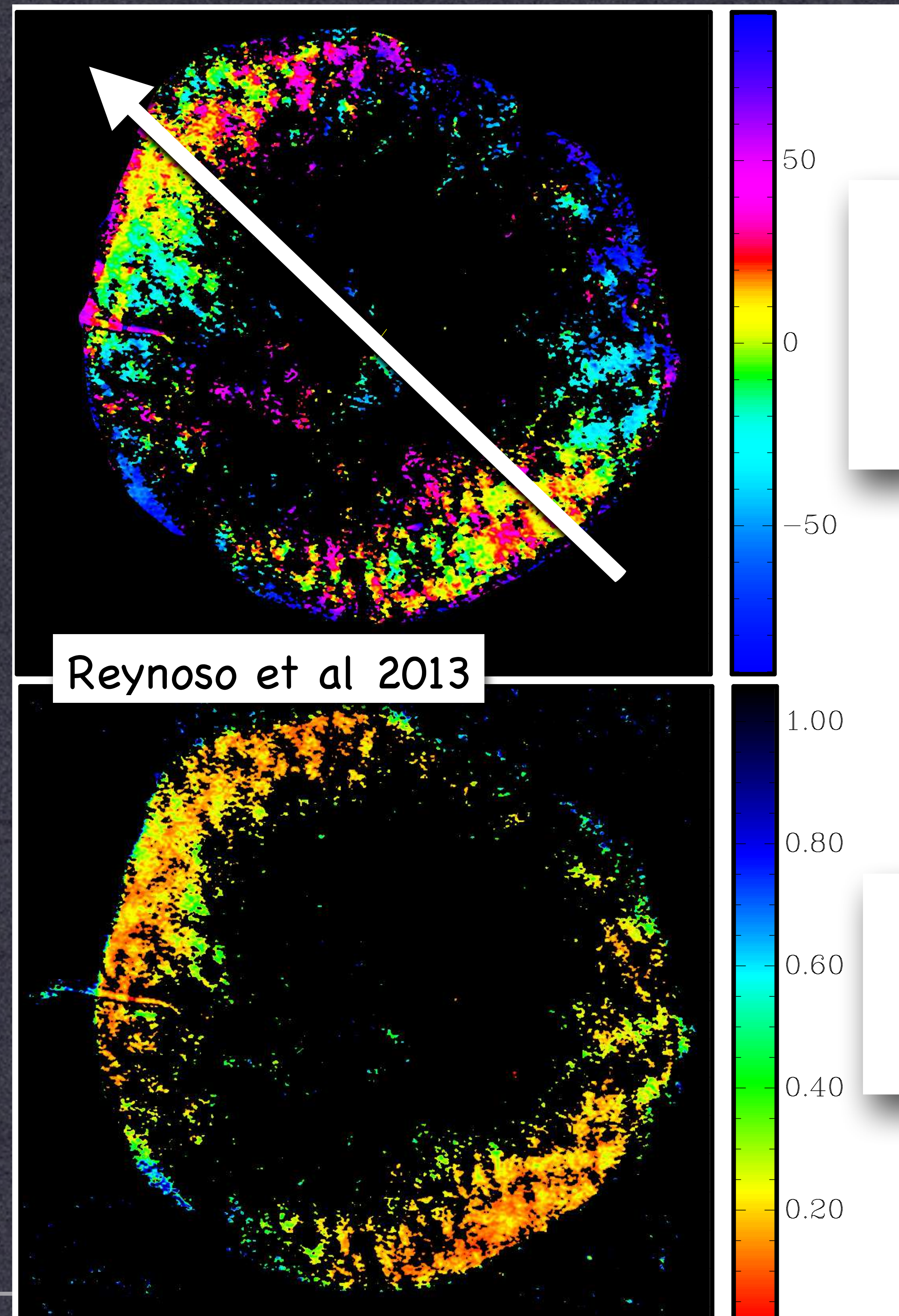
Locally-transverse field enters the shock, and causes electron injection and DSA.

This favors large-scale radial B fields in young SNRs. Polarization in “polar caps” should be small -- field is random

Ab-initio plasma results allow to put constraints on the large-scale picture!

SN1006: a parallel accelerator

X-ray emission (red=thermal white=synchrotron)



Inclination of the B field wrt to the shock normal

Polarization (low=turbulent high=ordered)

Magnetic field amplification and particle acceleration where the shock is parallel

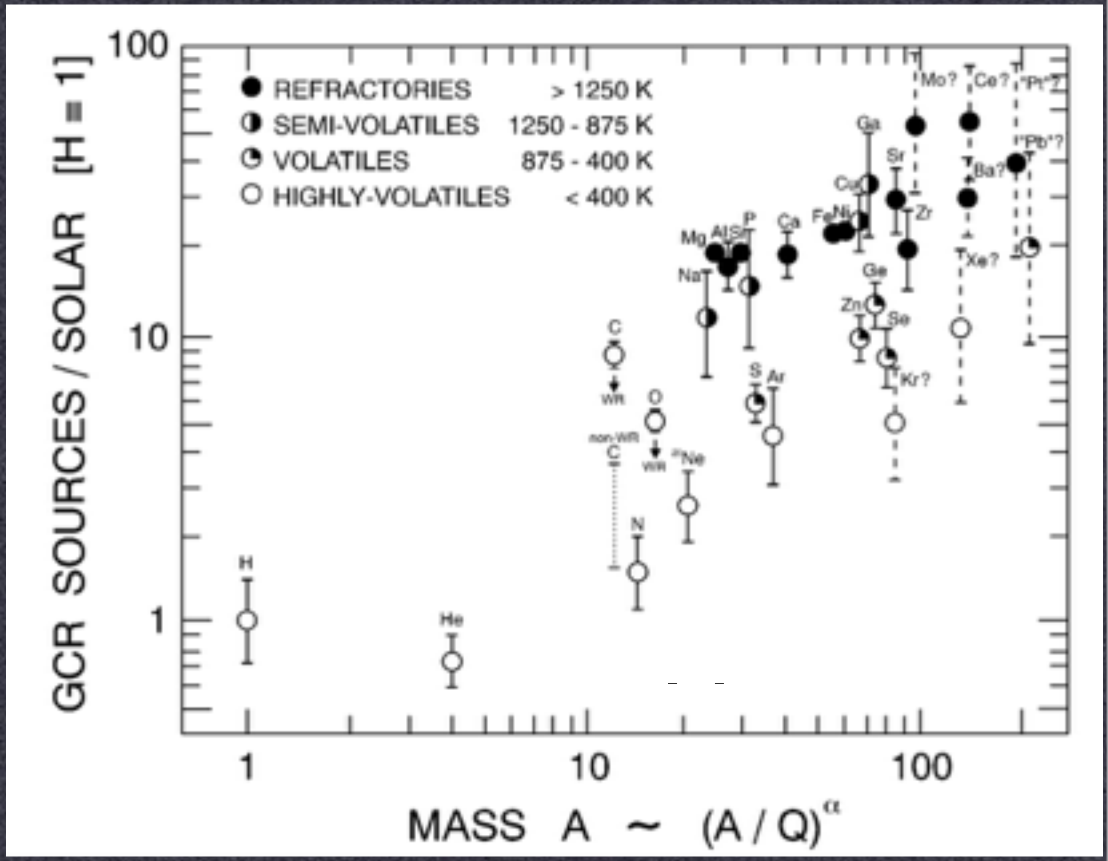
Acceleration of Nuclei Heavier than Hydrogen

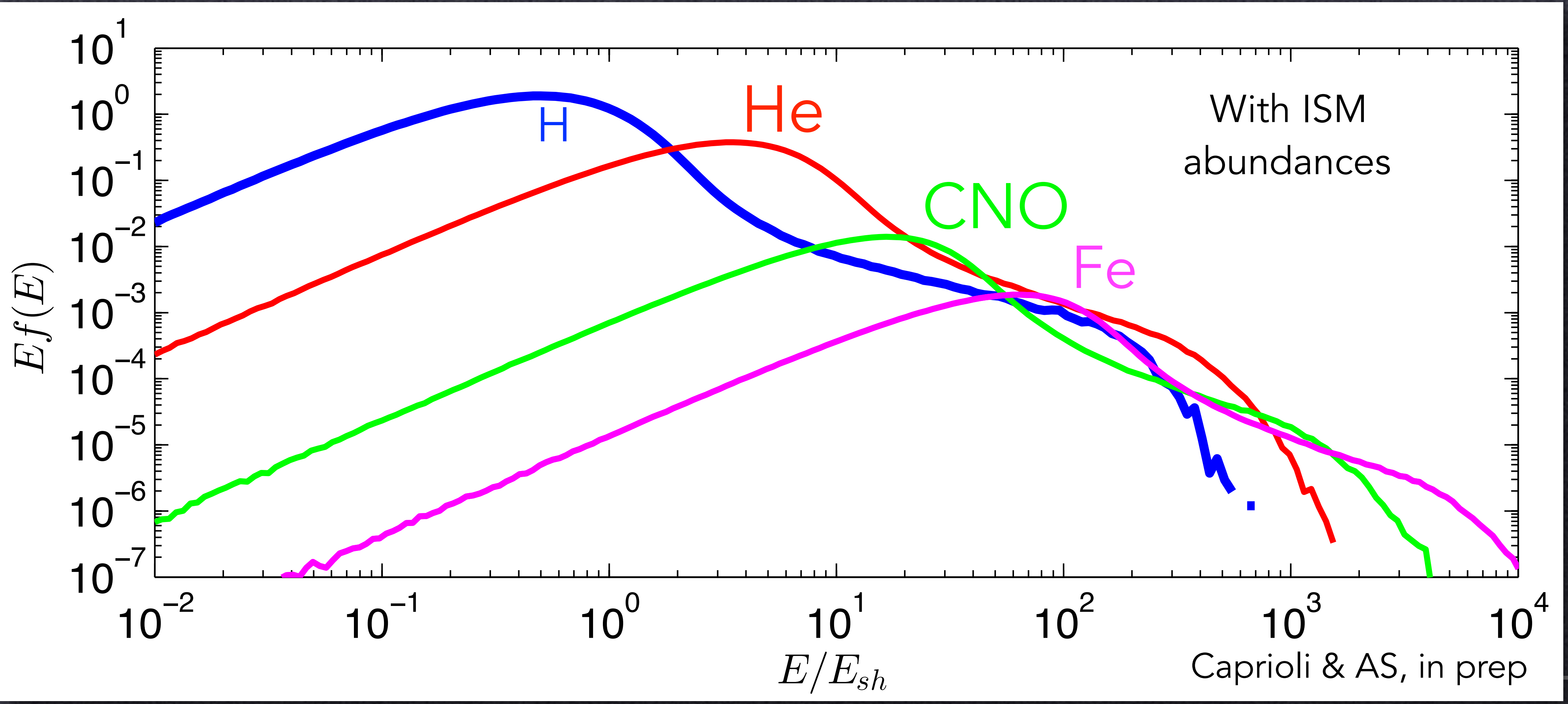
Acceleration of heavy nuclei

Nuclei heavier than H must be injected more efficiently (Meyer et al 97)

Multi-species hybrid simulations.
Max energy is proportional to charge Z;

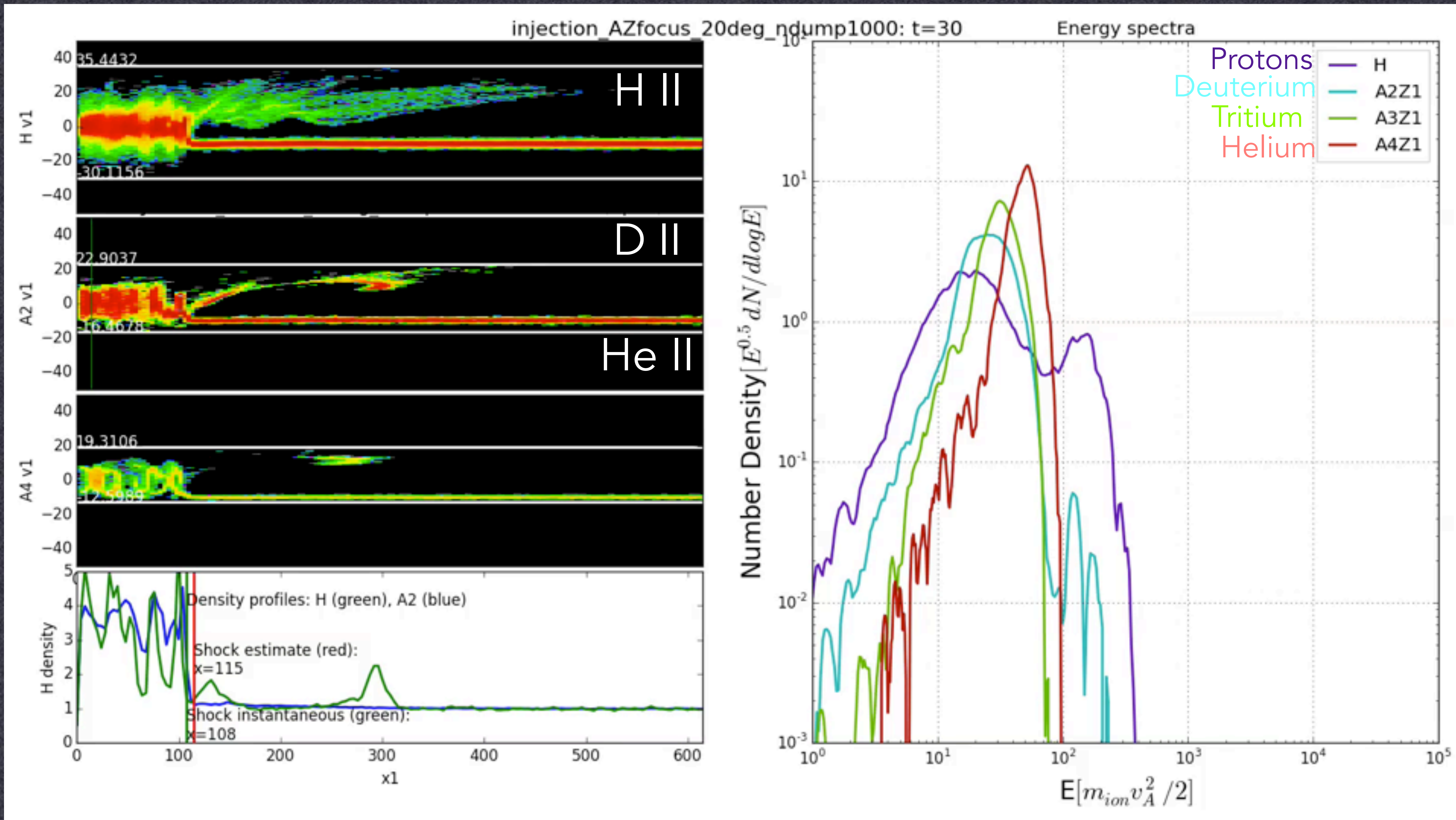
Most nuclei have A/Z ~ 2. Investigate also A/Z>2 for partially ionized nuclei.





Injection of singly-ionized nuclei

M=10, parallel shock (Caprioli, Yi, AS in prep)



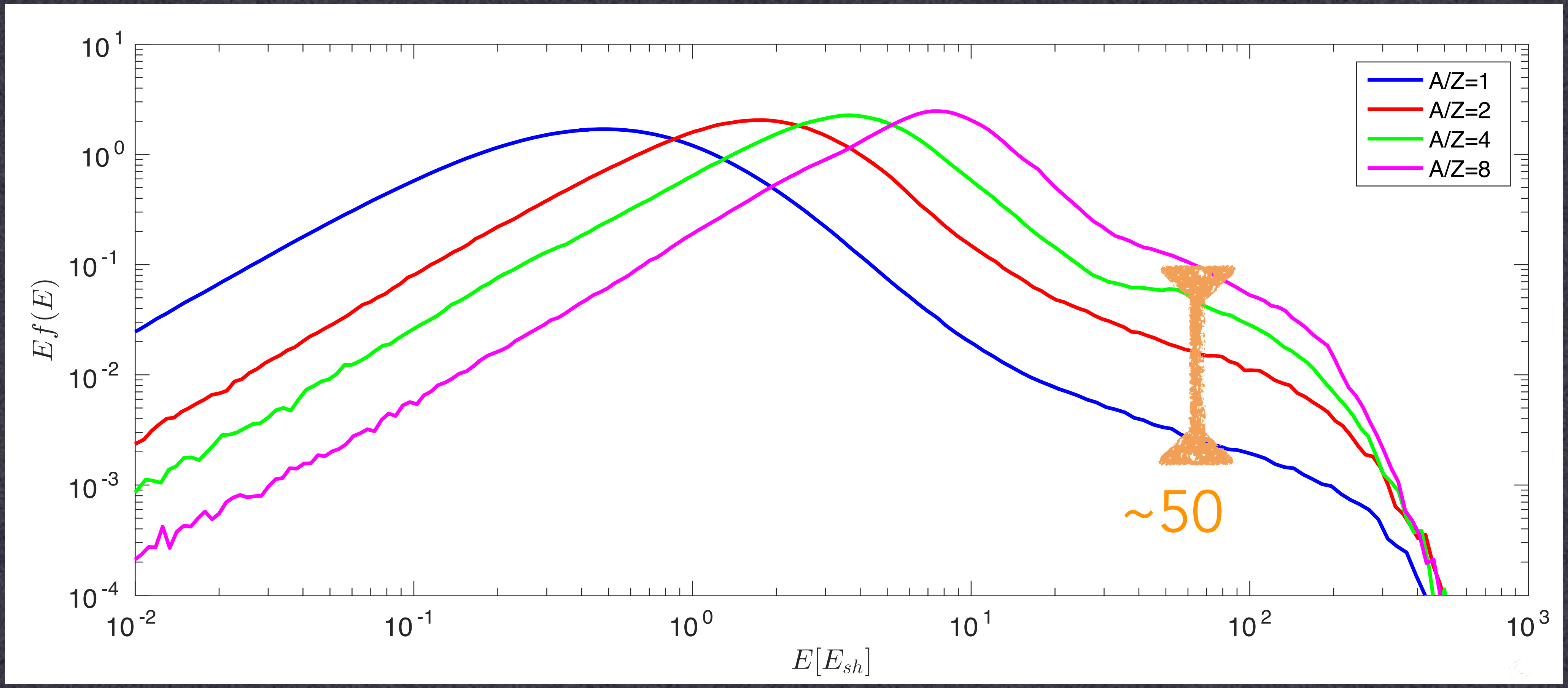
Injection fraction is larger for nuclei with larger A/Z!

Injection of singly-ionized nuclei

In the absence of H-driven turbulence, heavies are thermalized far downstream

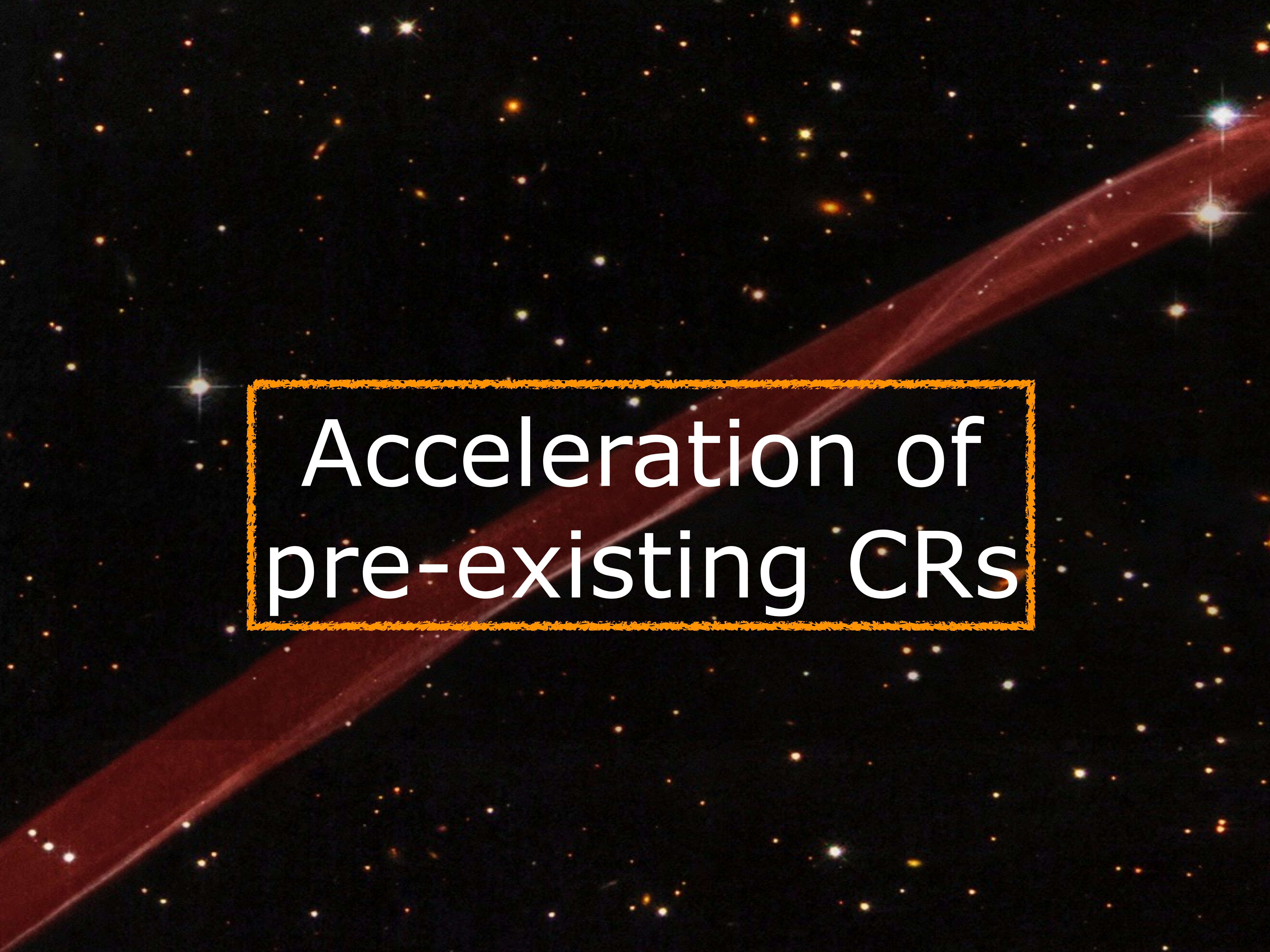
With B amplification from H, heavies are thermalized to $kT=A\,mv_{sh}^2/2$, and can recross the shock due to their large larmor radii. More chances to scatter on H fluctuations leads to higher "duty fraction" of the shock for larger A/Z.

Nuclei enhancement depends on A/Z and Mach number.



Caprioli, Yi, AS in prep

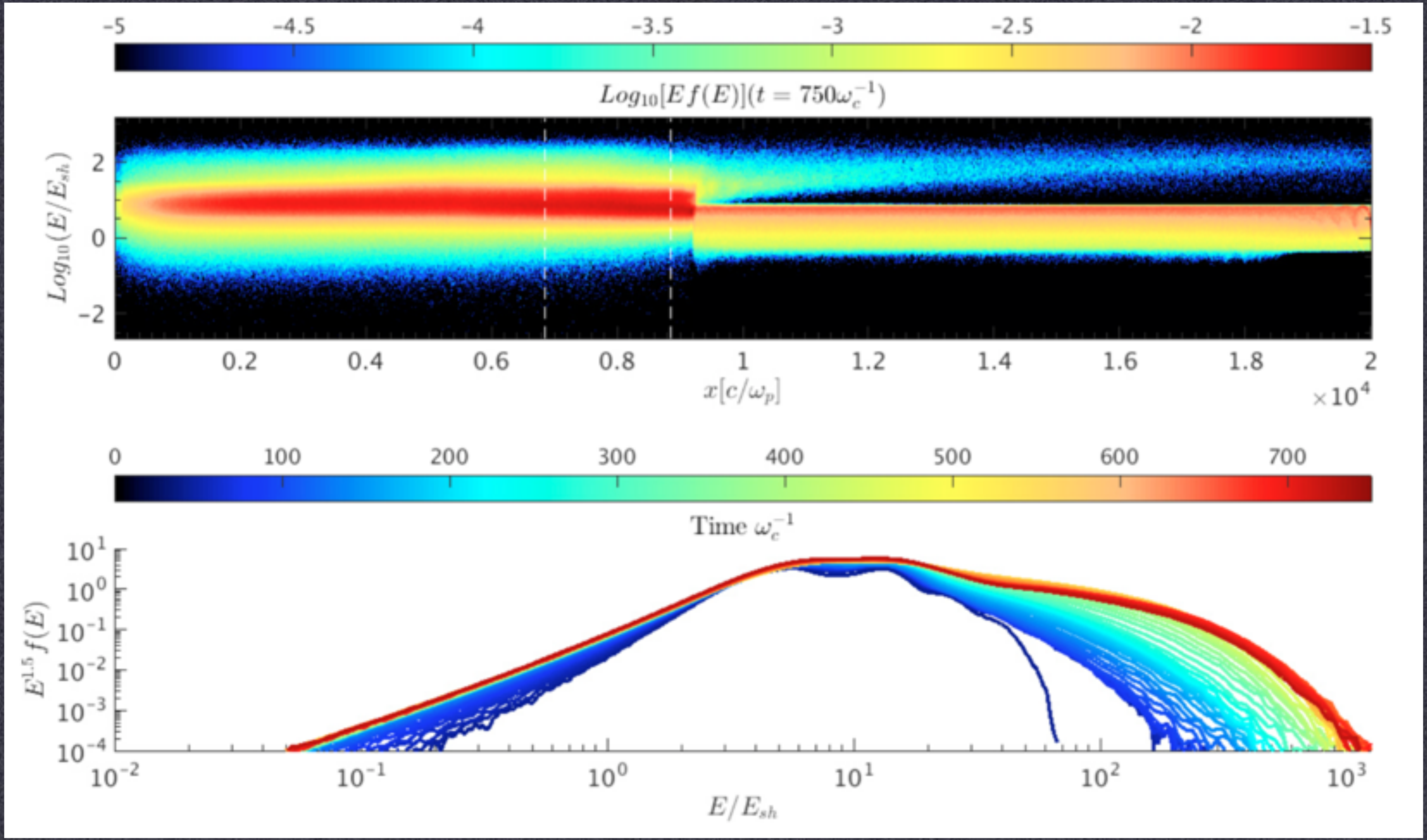
Injection fraction is larger for nuclei with larger A/Z!


Acceleration of
pre-existing CRs

Re-acceleration of pre-existing CRs

Add hot "CR" particles to upstream flow.

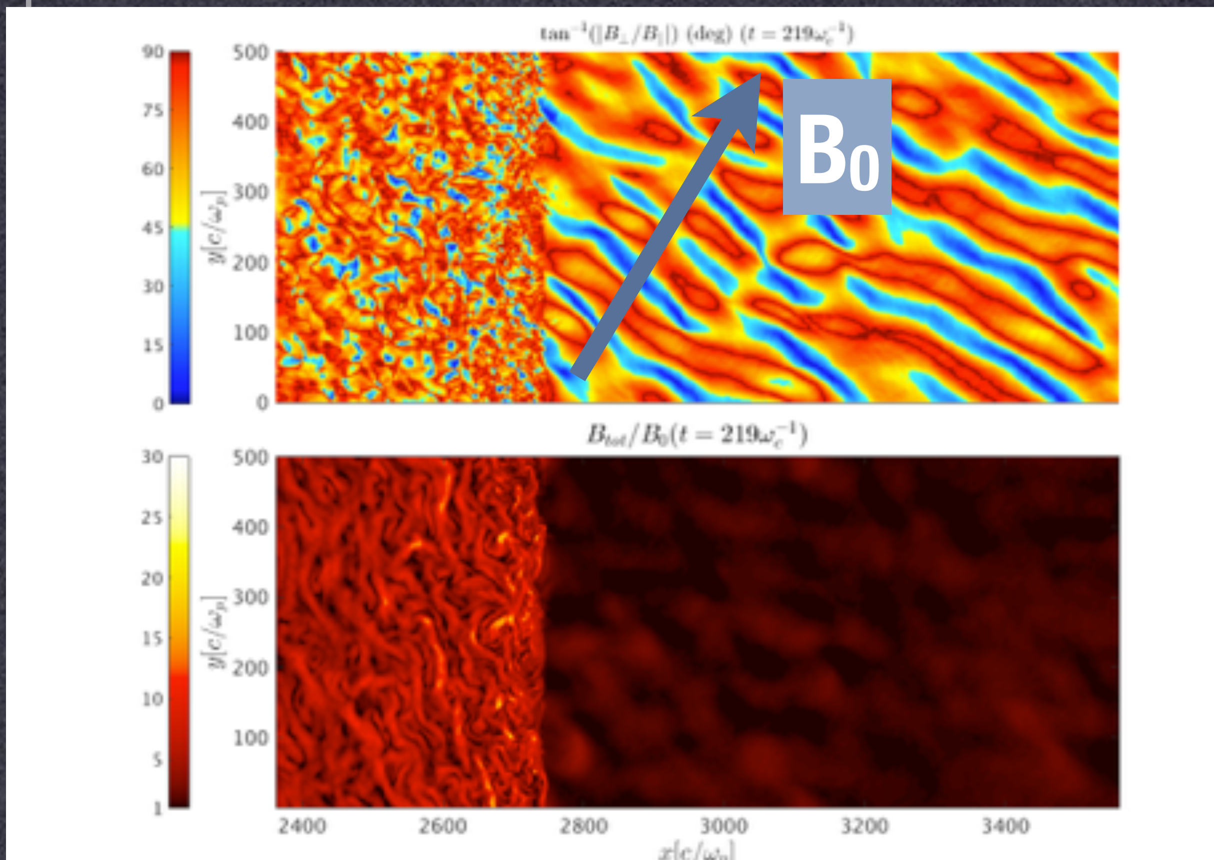
Quasi-perp shock: CRs have large Larmor radii and can recross the shock, accelerate, and be injected into diffusive acceleration process; 10



Turbulence driven by reaccelerated CRs

Escaping CRs drive turbulence

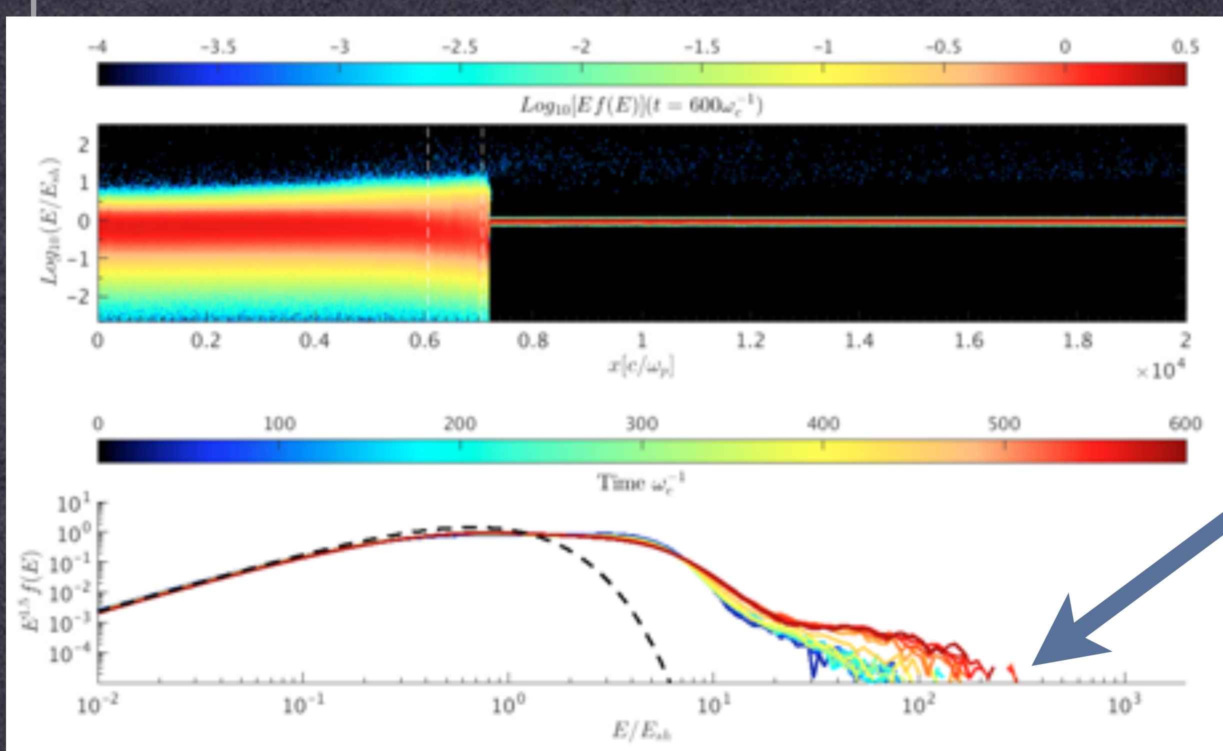
field inclination



Orientation of the field at the shock changes to regions of quasi-parallel, and efficiency of H acceleration increases.

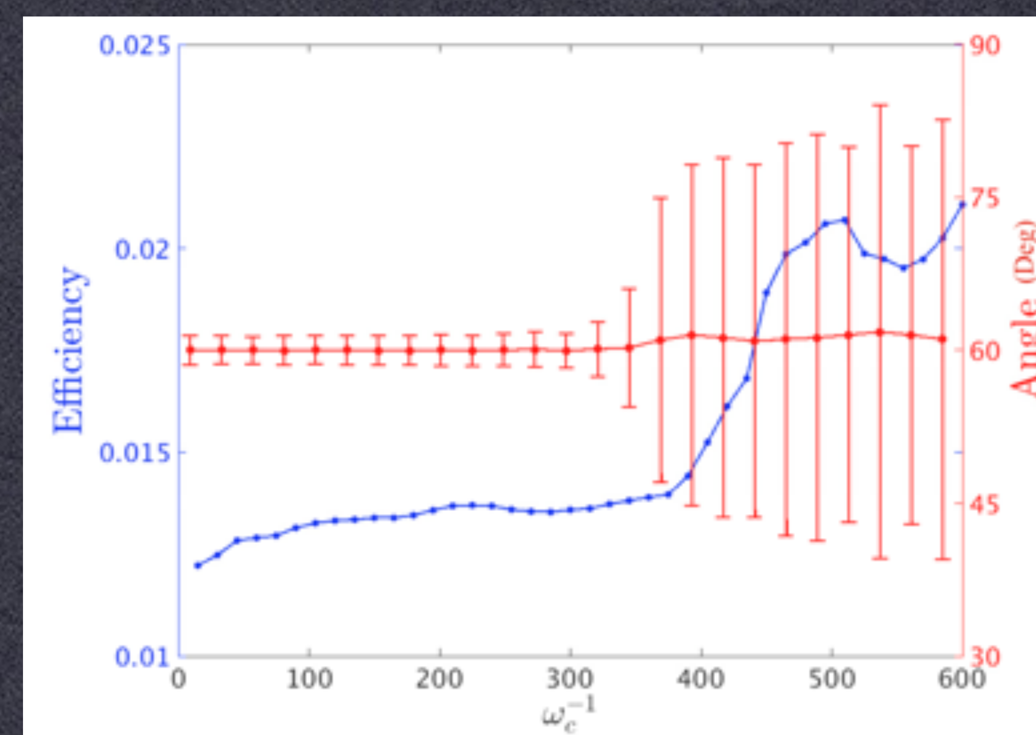
Pre-existing CRs improve local efficiency of the shock!

Growth time in SNR ~10yrs << age.

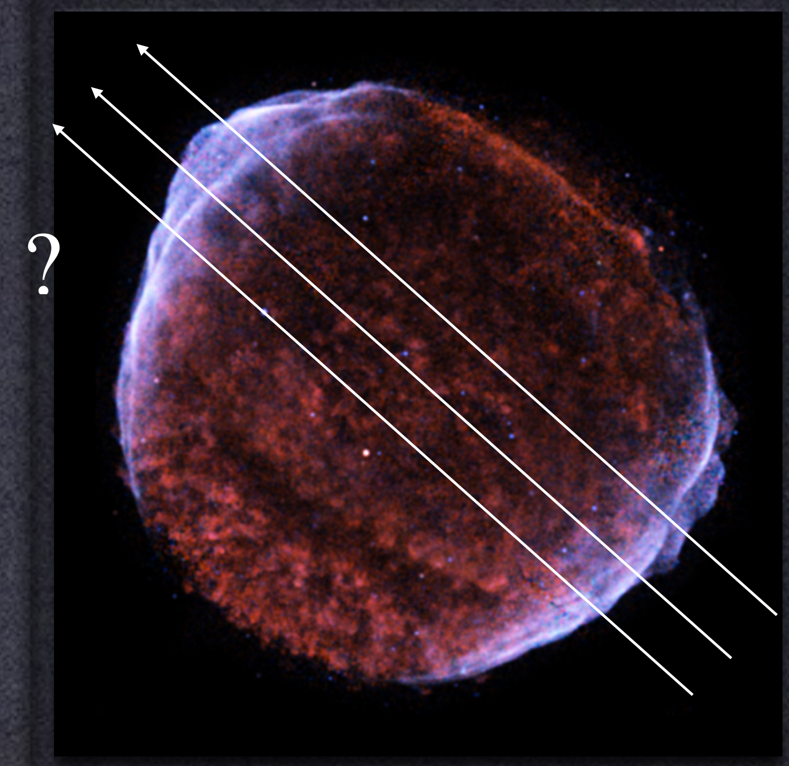


Proton spectrum

60˚ shock



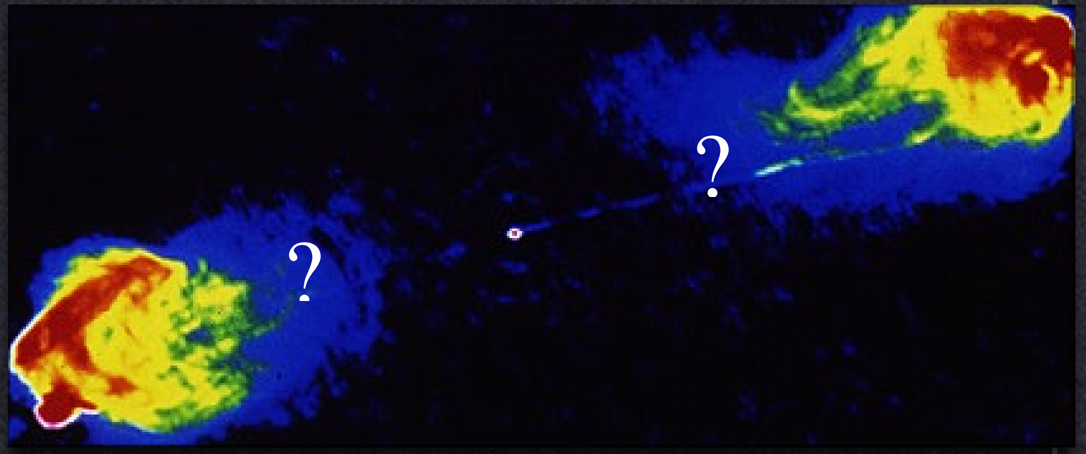
Conclusions



Kinetic simulations allow to calculate particle injection and acceleration from first principles, constraining injection fraction

Magnetization (Mach #) of the shock and B inclination controls the shock structure

Nonrelativistic shocks accelerate ions and electrons in quasi-par if B fields are amplified by CRs. Energy efficiency of ions 10-20%, number ~few percent; K_{ep}~10^{-3}; p^{-4} spectrum



Electrons are accelerated in quasi-perp shocks, energy several percent, number <1%. Fewer ions are accelerated at oblique shocks.

A/Z>2 species are injected more efficiently; CR re-acceleration may be important

Long-term evolution, turbulence & 3D effects need to be explored more: more advanced simulation methods are coming