Particle Acceleration at Nonrelativistic Astrophysical Shocks:

eligibility to participate in the diffusive shock acceleration

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with Damiano Caprioli (Chicago), Colby Haggerty (Hawaii), Anatoly Spitkovsky (Princeton)

based on Gupta, Caprioli, & Spitkovsky, in prep

PASTO 2022 @ Italy
September 5, 2022

Nonthermal sources: similar emission spectra

10 km ~ AU ~ 1 pc ~ 50 pc ~ kpc ~ Mpc

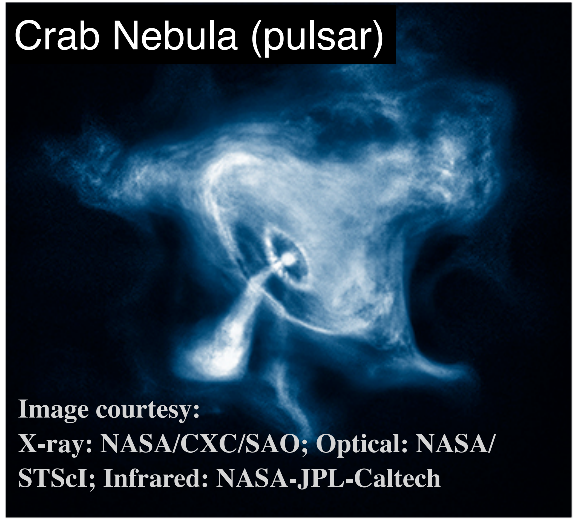

Crab Nebula (pulsar)

Image courtesy:
X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA-JPL-Caltech


LL Orionis bow shock

Courtesy: NASA/HST

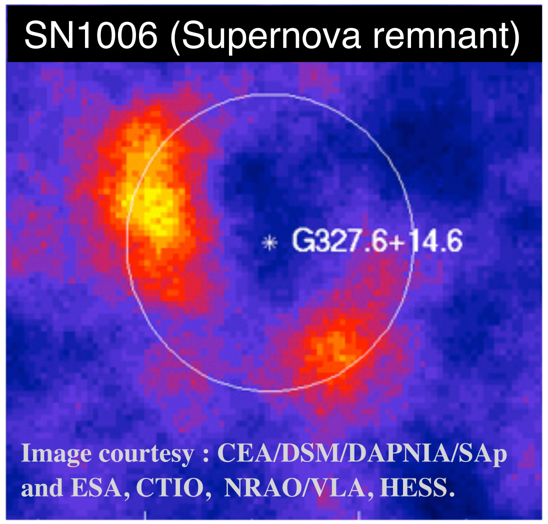
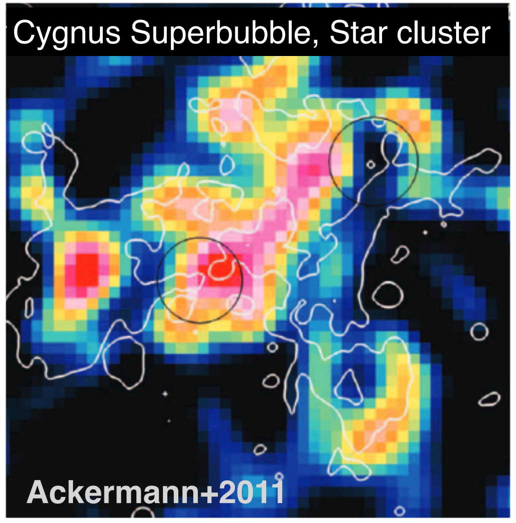
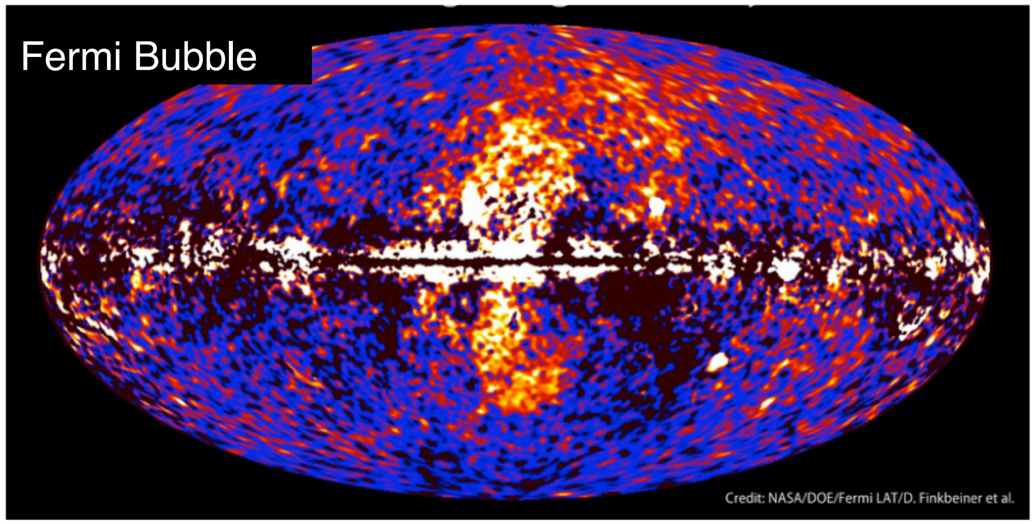

SN1006 (Supernova remnant)

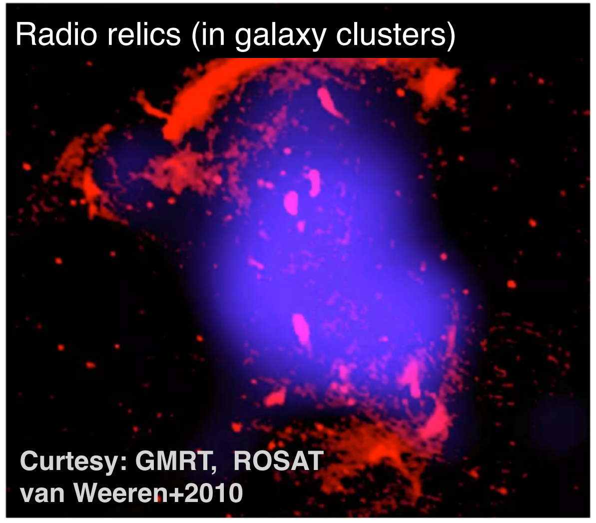
Image courtesy : CEA/DSM/DAPNIA/SAp and ESA, CTIO, NRAO/VLA, HESS.


Cygnus Superbubble, Star cluster

Ackermann+2011


Fermi Bubble

Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et al.


Radio relics (in galaxy clusters)

Curtesy: GMRT, ROSAT
van Weeren+2010

Nonthermal sources: acceleration mechanism

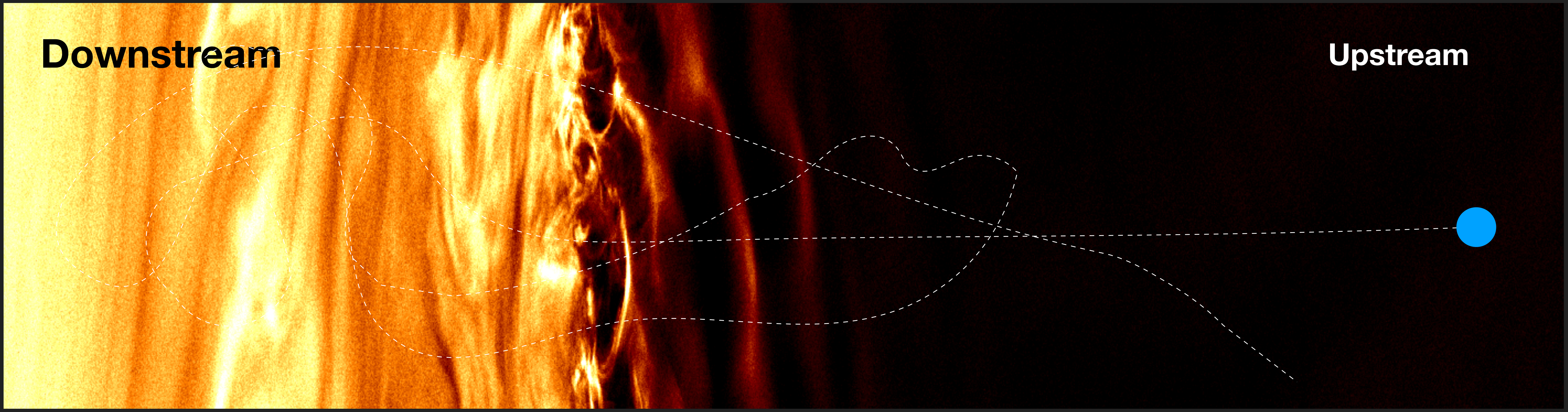
- Emission spectra follow power-law
- Thermal explanations do not work
- Highly energetic charged particles are required
- Possible mechanisms: Fermi Acceleration (Fermi, 1949)

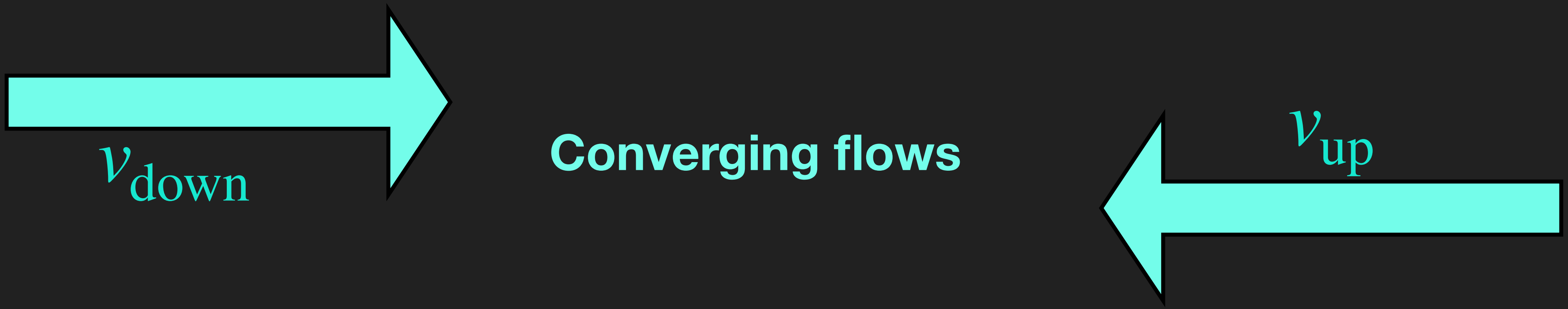
Diffusive shock Acceleration, Magnetic reconnection

Axford et al. 1977; Bell 1978; Blandford & Ostriker 1978;

Enrico Fermi

Diffusive Shock Acceleration





v_{down}

Converging flows

v_{up}

$$N(E) = N(E_0)\left(\frac{E}{E_0}\right)^{-q_{\mathrm{E}}} \iff N(p) = N(p_0)\left(\frac{p}{p_0}\right)^{-q_{\mathrm{p}}}$$

Challenges

$$N(E) = N(E_0)\left(\frac{E}{E_0}\right)^{-q_\mathrm{E}} \iff N(p) = N(p_0)\left(\frac{p}{p_0}\right)^{-q_\mathrm{p}}$$

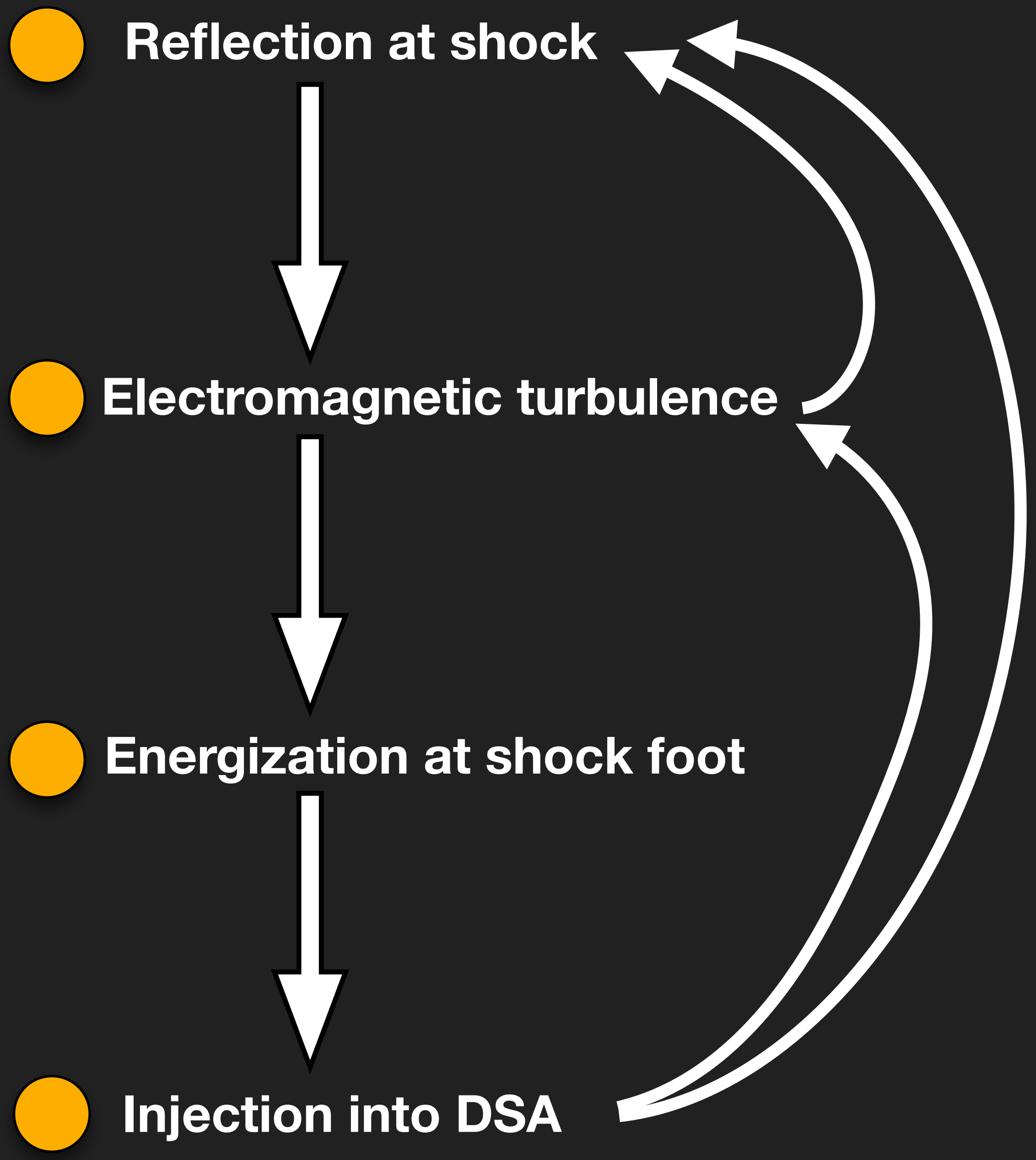
- Normalization
- Spectral index
- Maximum energy
- Different species (e.g. protons, electrons heavier ions)

$\}$ Observations

$\mathcal{M}_\mathrm{A},\ \mathcal{M}_\mathrm{s},\ v_\mathrm{sh},\ \theta_\mathrm{Bn}$

Recent studies: e.g., Guo+2014, Bell+2013, Caprioli+2014,2015, Park+2015, Bell+2019, Caprioli+2020, Bohdan+2020, Pohl 2021, Shalaby+2022,…

Outline



- Reflection at shock
- Electromagnetic turbulence
- Energization at shock foot
- Injection into DSA

Self-consistent investigation is necessary

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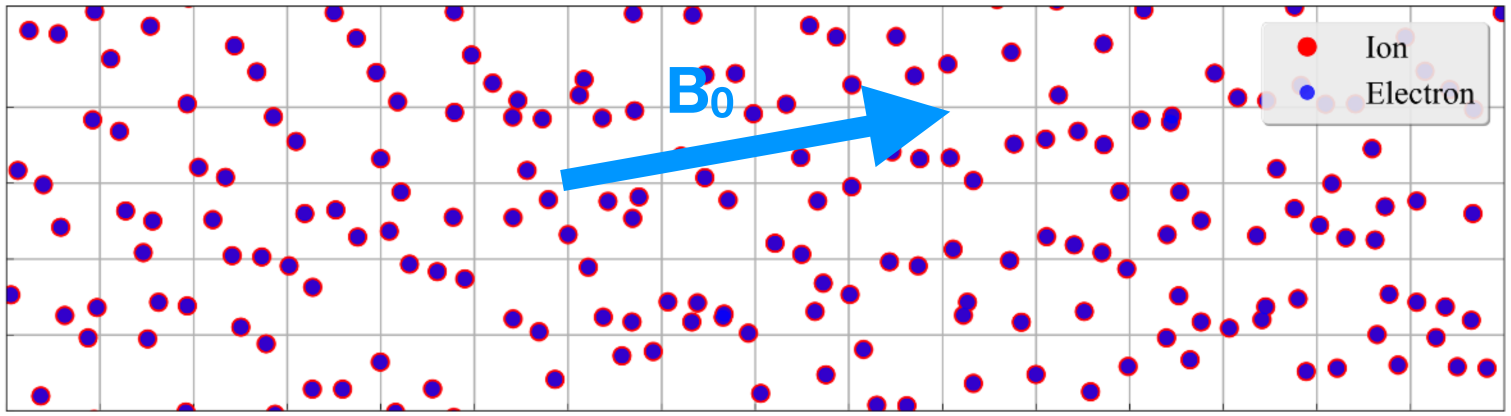
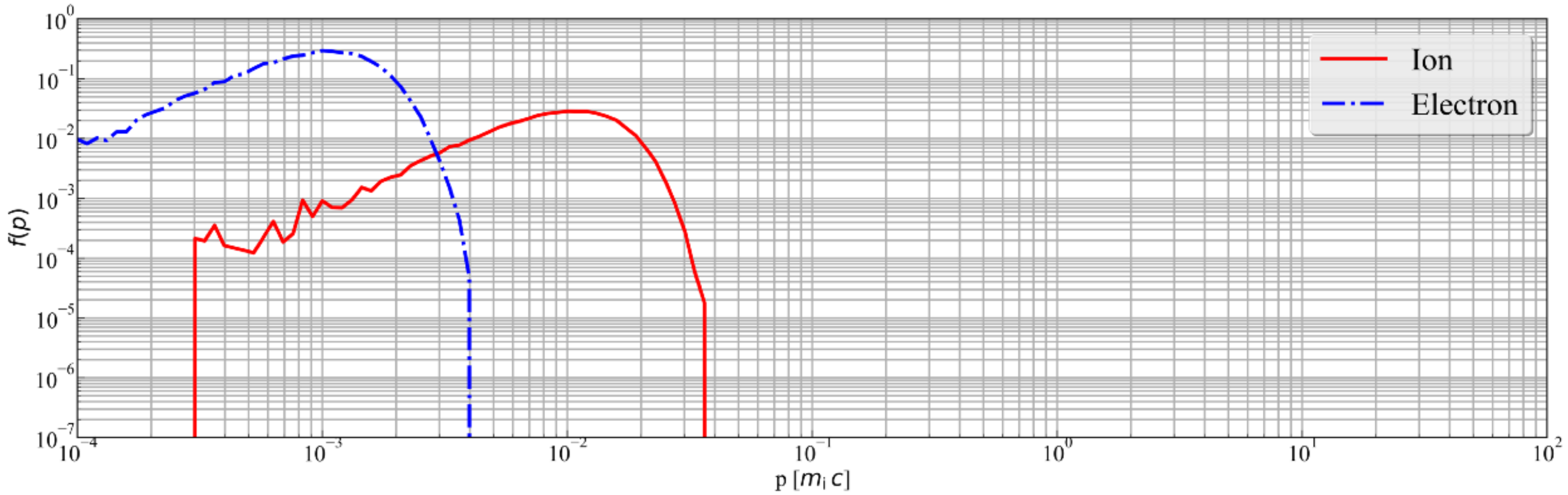
Fully Kinetic Simulation

Shocks from First Principles

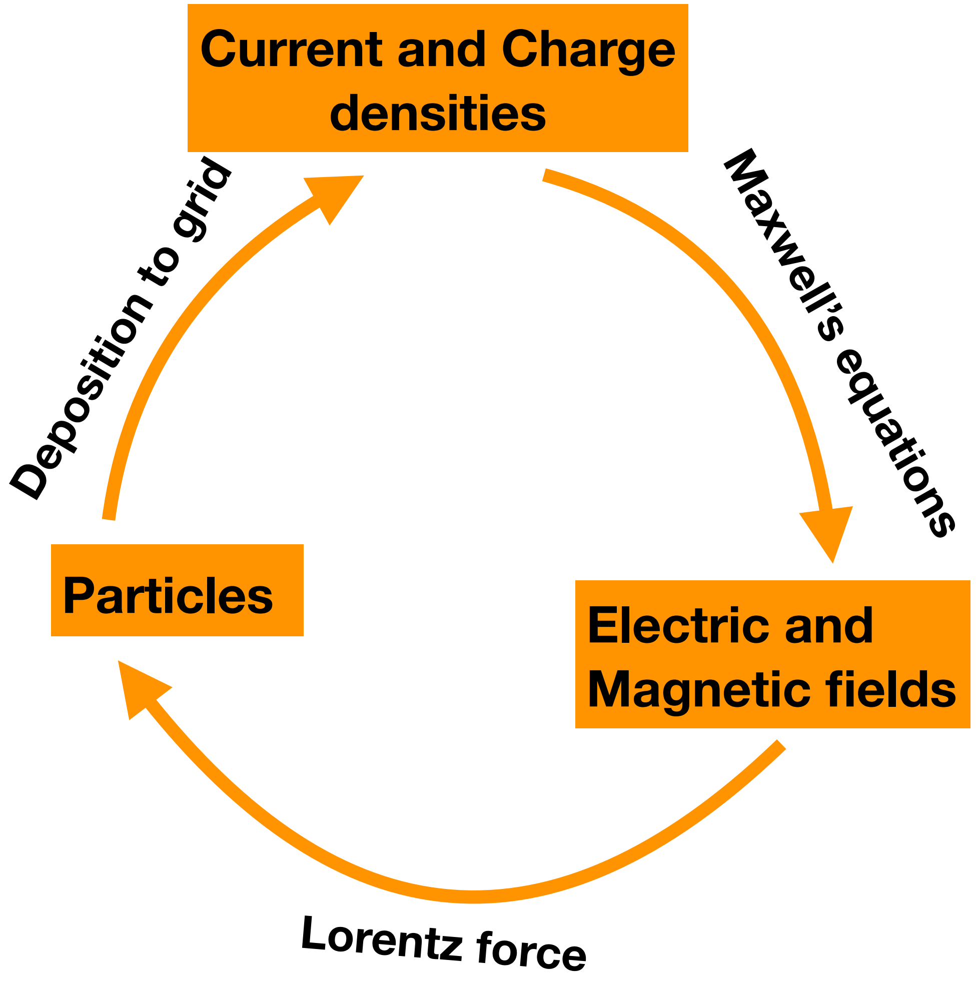


- Define E, B fields
- Populate cells with charged particles

$$T_\mathrm{i} = T_\mathrm{e} \qquad \beta = P_\mathrm{g}/P_\mathrm{B}$$



Shocks from First Principles

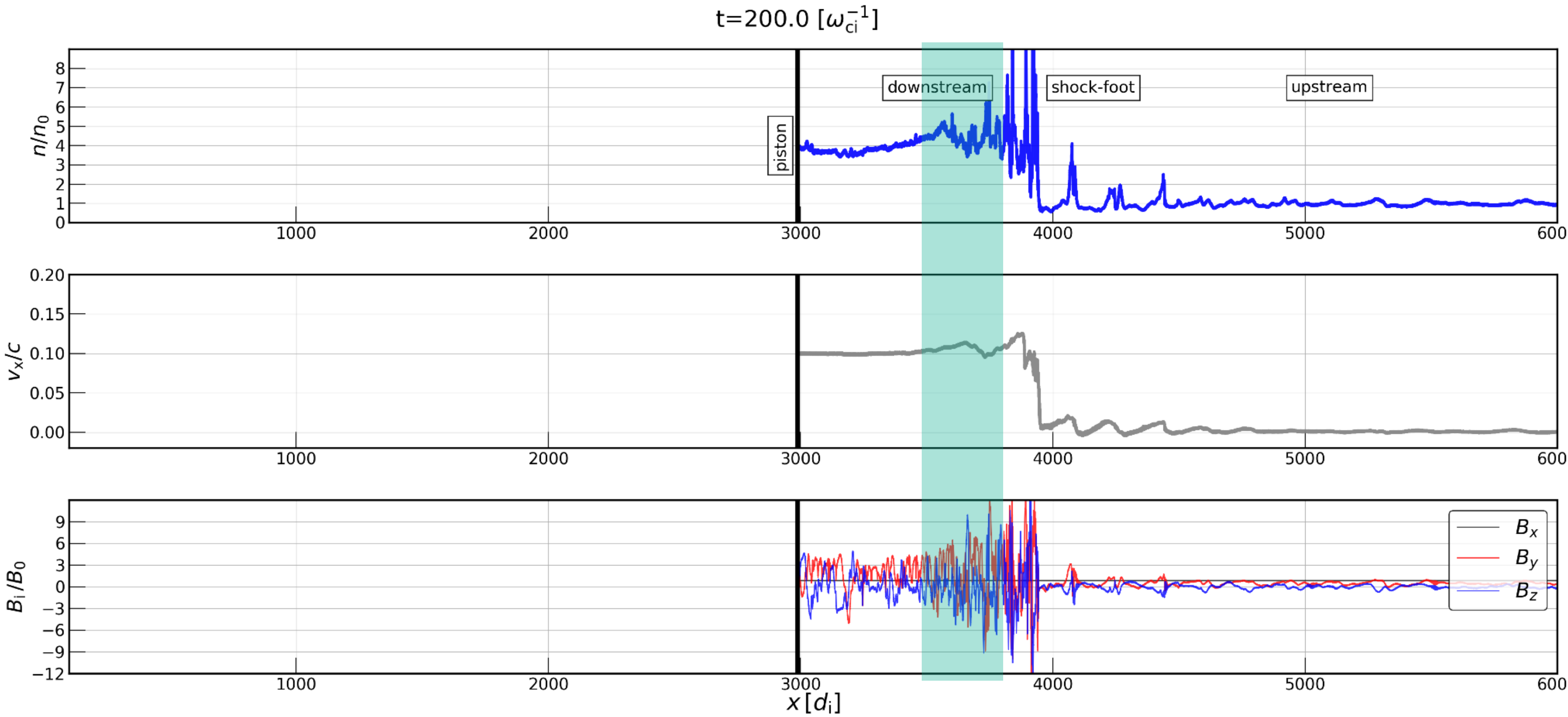


Tristan-MP (Spitkovsky 2008)

- Define E, B fields
- Populate cells with charged particles

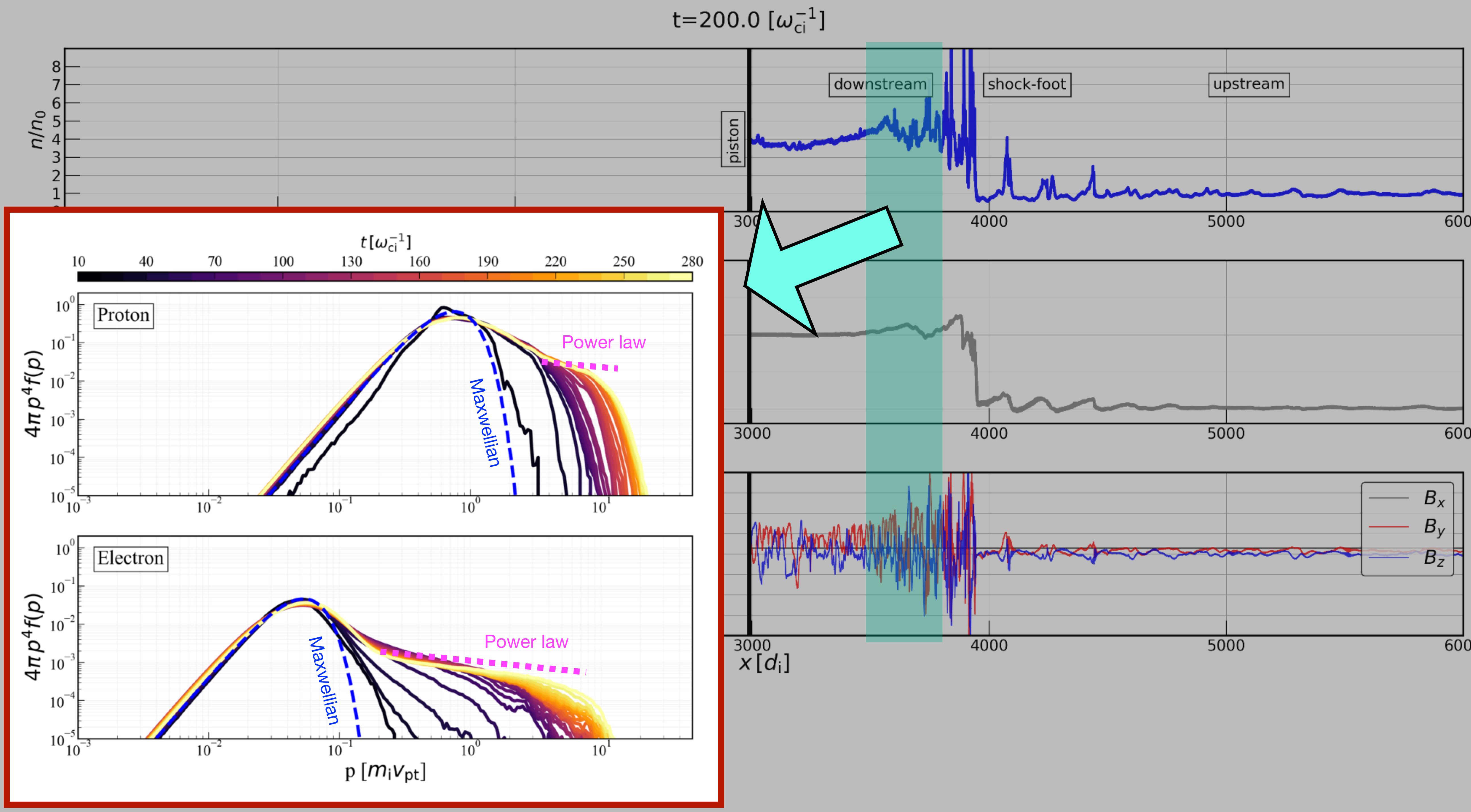
  $T_\mathrm{i} = T_\mathrm{e} \qquad \beta = P_\mathrm{g}/P_\mathrm{B}$
- Evolve particles based on Lorenz force
- Estimate current
- Solve Maxwell equations

Shocks from First Principles (1D)



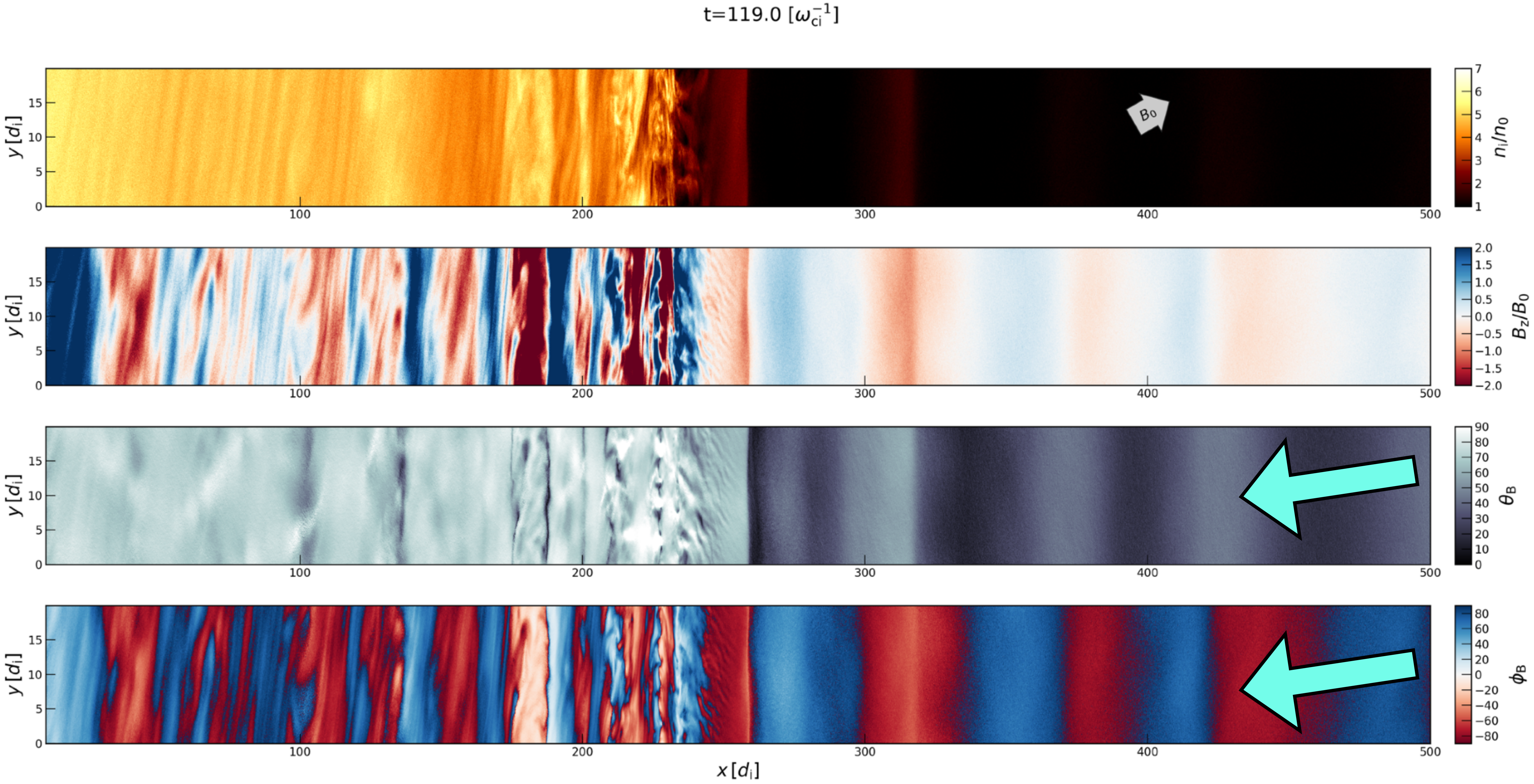
Gupta, Caprioli, Spitkovsky, in prep

Shocks from First Principles (1D)



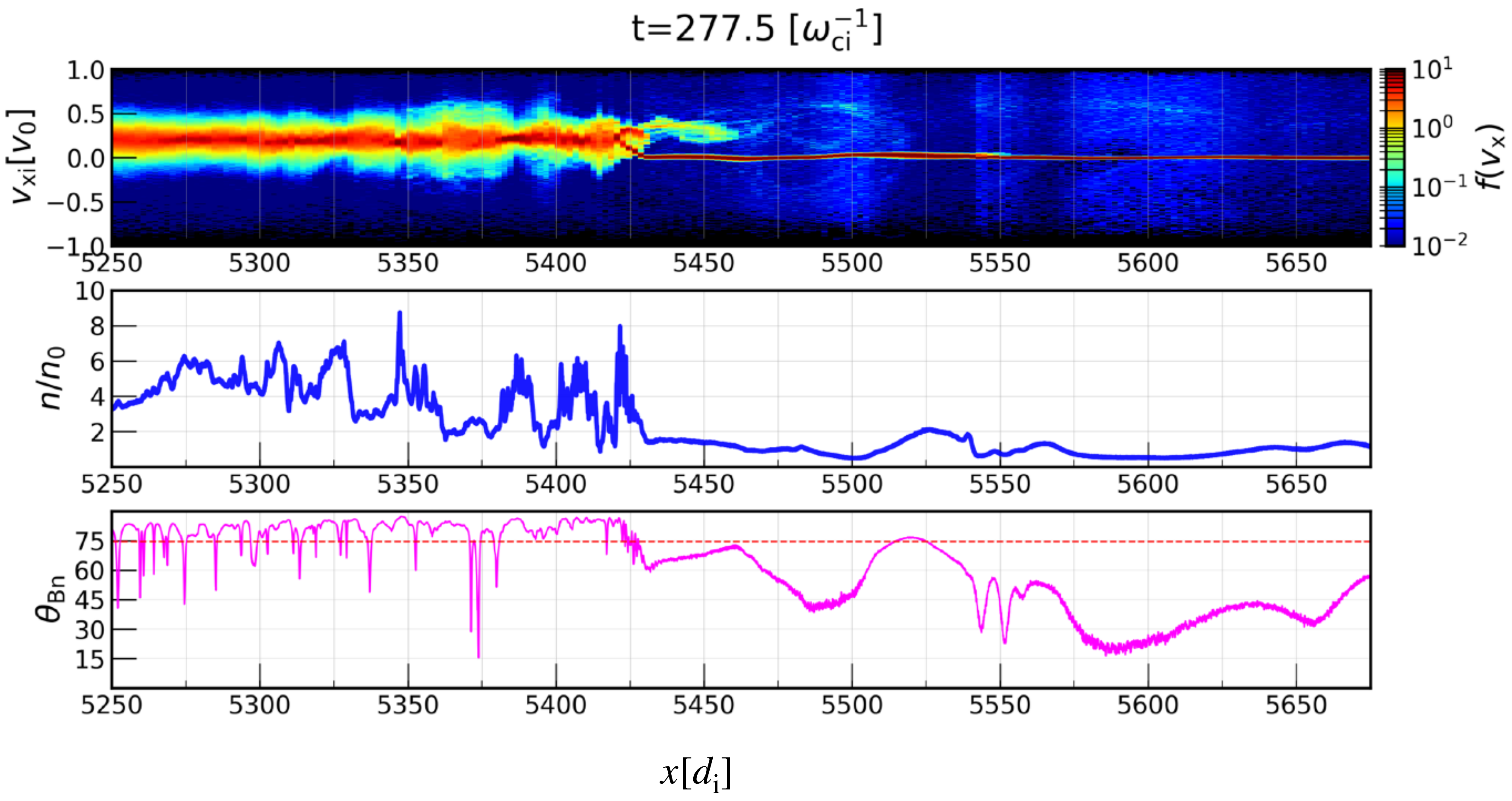
Gupta, Caprioli, Spitkovsky, in prep

Shocks from First Principles (2D)



- Shock modifies the initial magnetic orientation
- 1D quasi-parallel shock contains the key ingredients

Proton reflection



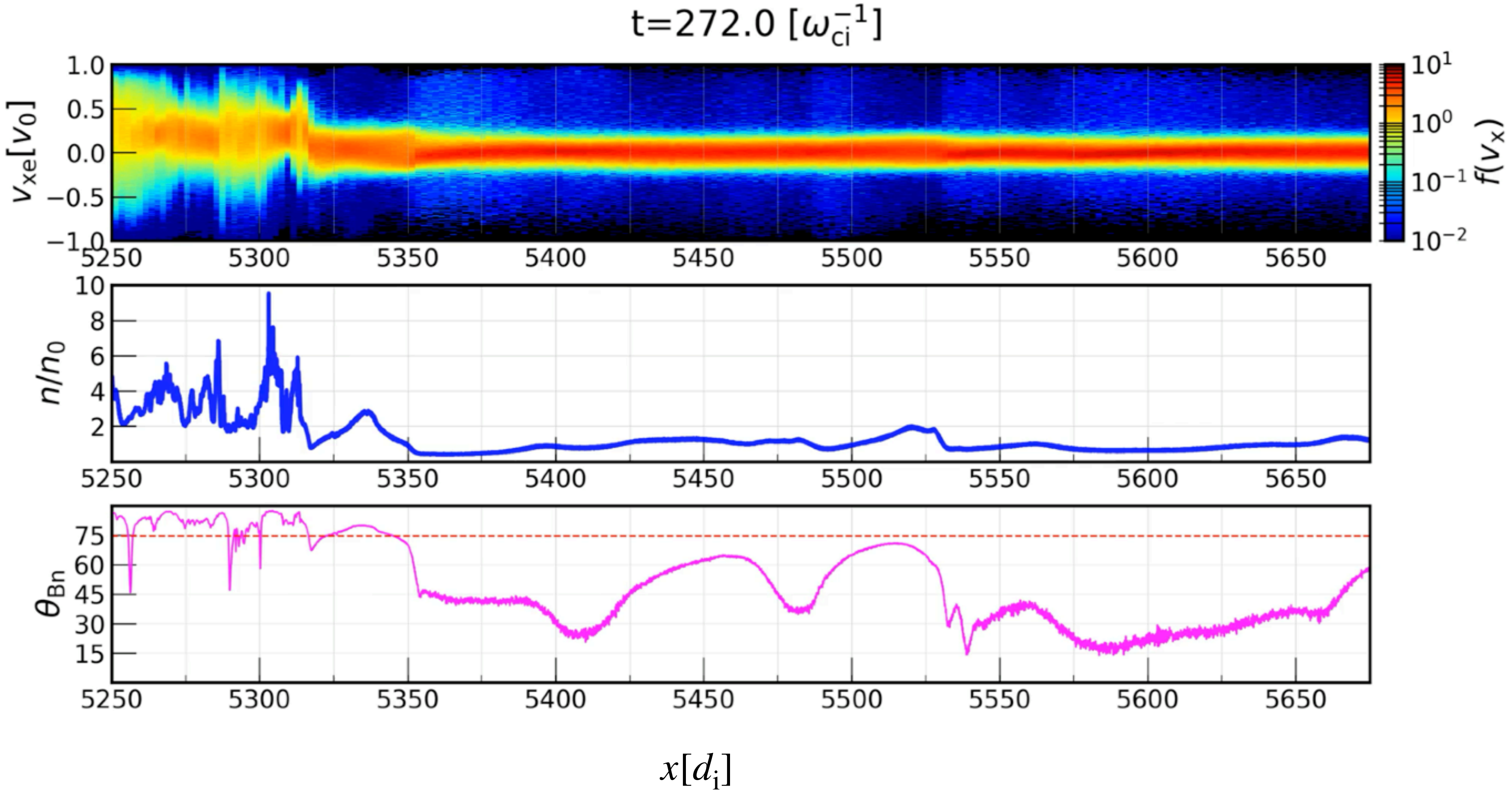
(Gupta, Caprioli, Spitkovsky, in prep)

- **Structure evolves in ~** $\frac{1}{\omega_{ci}}$
- **Specular reflection**
- **Density overshoot**
- **Upstream modification**

Extensively investigated using Hybrid PIC simulations (ion-particle+fluid electrons)

(e.g., Gargaté+12,Caprioli+14)

Electron reflection



(Gupta, Caprioli, Spitkovsky, in prep)

$$\frac{1}{\omega_{ce}} \ll \frac{1}{\omega_{ci}}$$

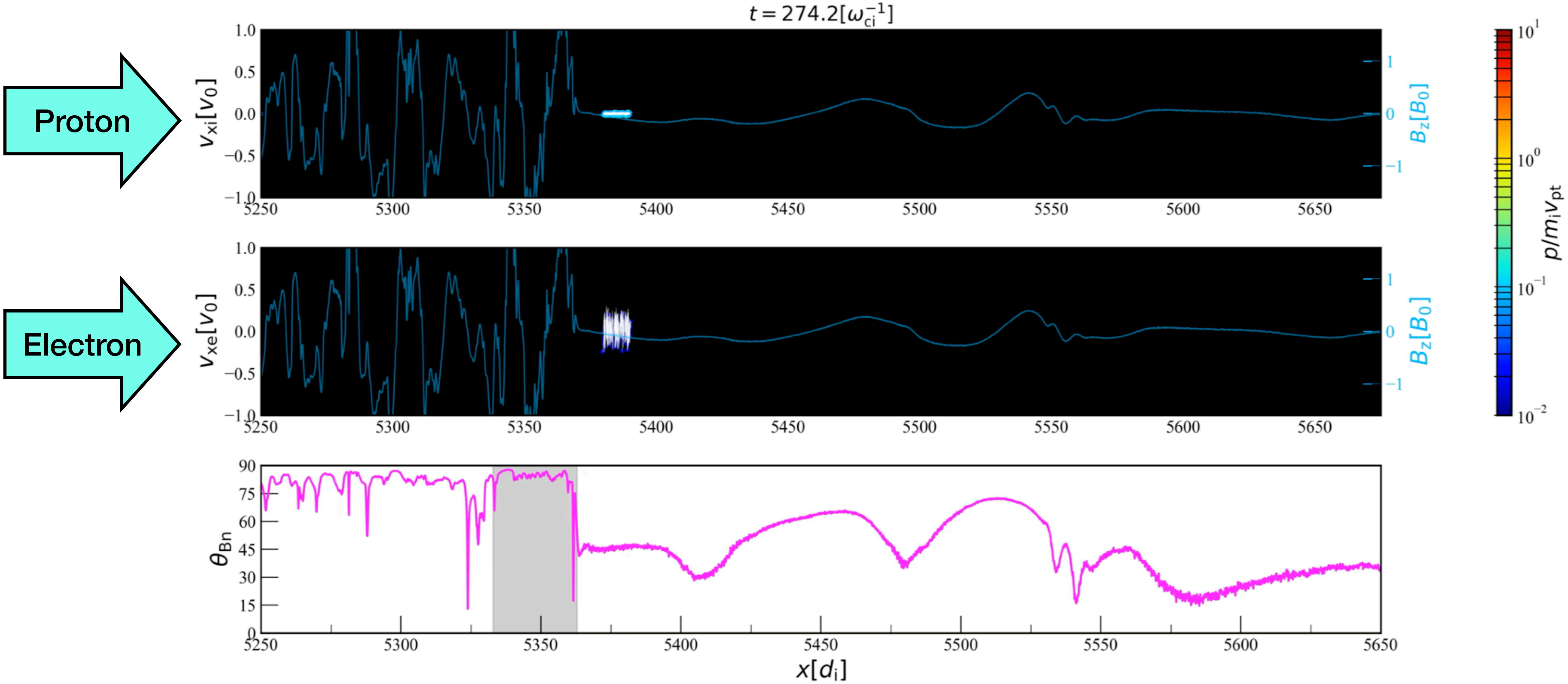
- **Shock is quasi-stationary**
- **Electron reflection is apparently messy**

Self-consistent PIC investigations started since past decade.

A conclusive answer is still missing

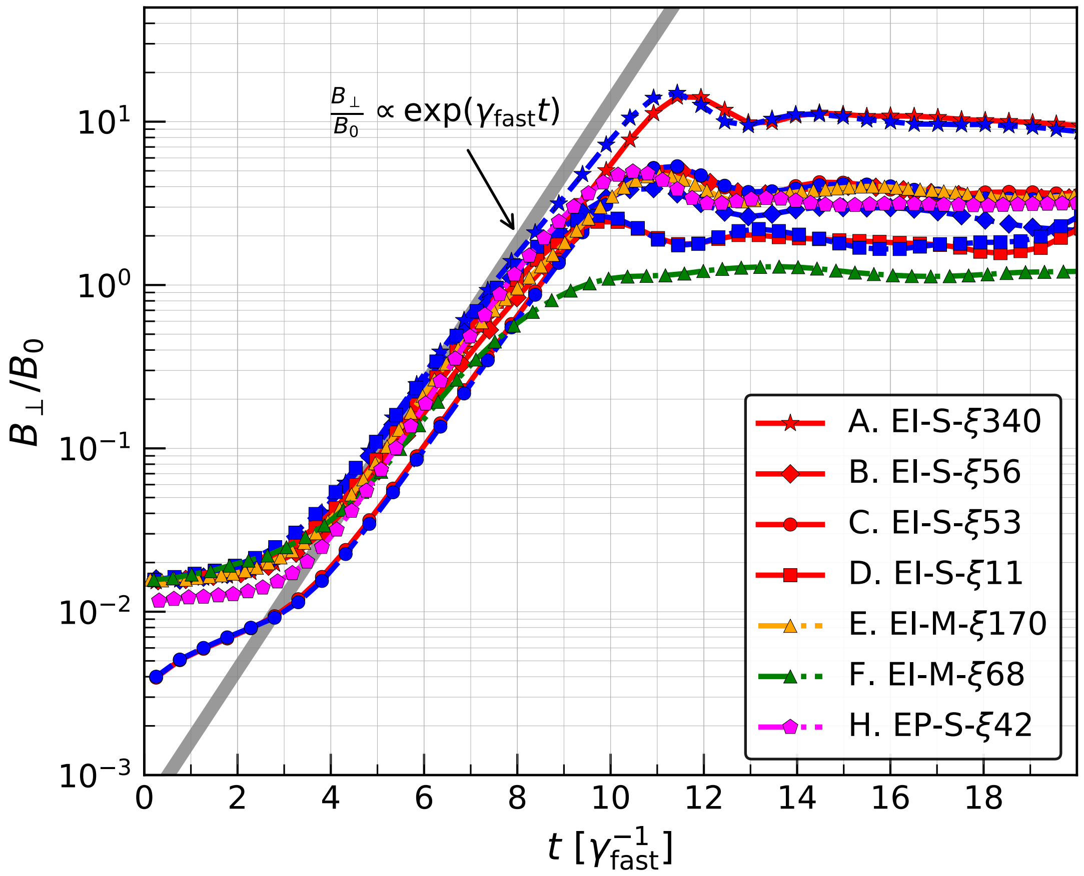
(e.g., Riquelme+2011, Guo+2014, Park+2015, Bohdan+2019, Xu+2020, Shalaby+2022, Morris+2022)

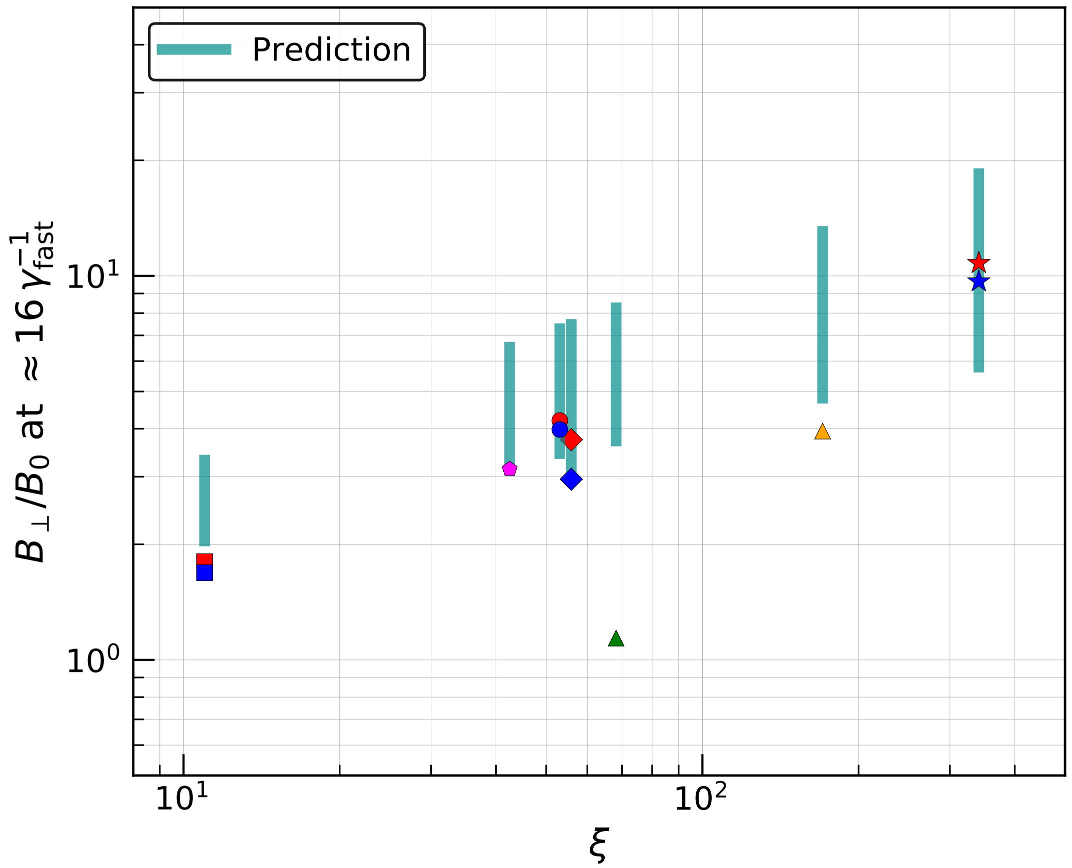
Reflection of test particle protons and electrons



- Shock is a not sharp surface
- Proton reflection: regulated by the strength of the shock barrier and inclination of B field (specular reflection — Caprioli, Pop, Spitkovsky 2015)
- Electron reflection: apparently messy. (Gupta, Caprioli, & Spitkovsky, in prep)

What can drive EM turbulence: $\frac{P_{CR}}{P_{B0}}$ is crucial





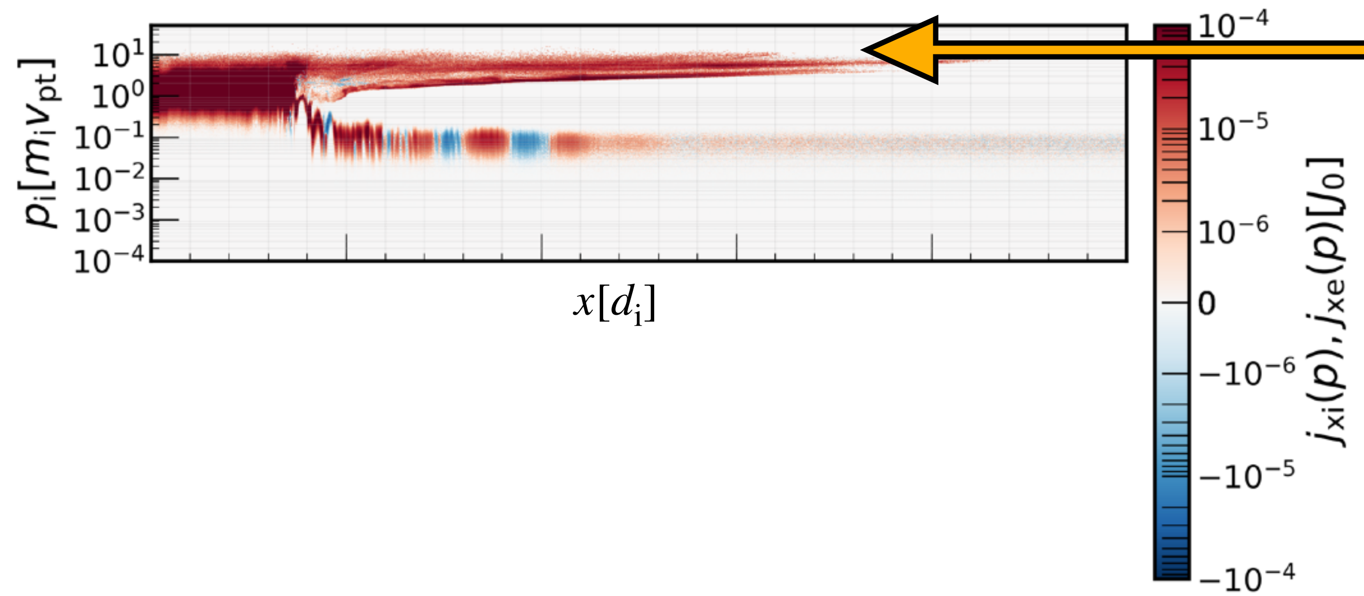
CR momentum flux in simulation frame

- Charge and mass do not matter
- Magnetic field at saturation depends on $\xi \propto \frac{P_{\rm CR}}{P_{\rm B0}}$

Results obtained from controlled periodic box simulations reported in

SG, Caprioli, Haggerty 2021 ApJ

What balances the ion current



Proton beam
(driving resonant/non-resonant instab.)

(e.g., Bell & Lucek 2001, Bell 2004, Amato & Blasi 2009)

(Gupta, Caprioli, Spitkovsky, in prep)

Electrons DO NOT become nonthermal easily

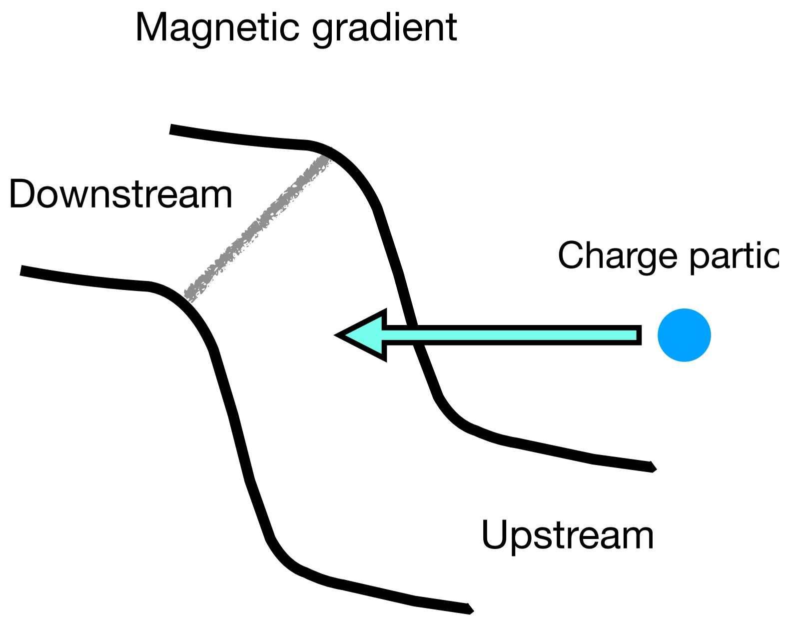
- Electrons are lighter than protons: more or less all plasma processes impact on dynamics

Not limited to

- **instabilities at the shock foot**
- **magnetic reconnection**
- **shock drift acceleration**
- **shock surfing acceleration**
- **…**

It is important to figure out which one is more effective

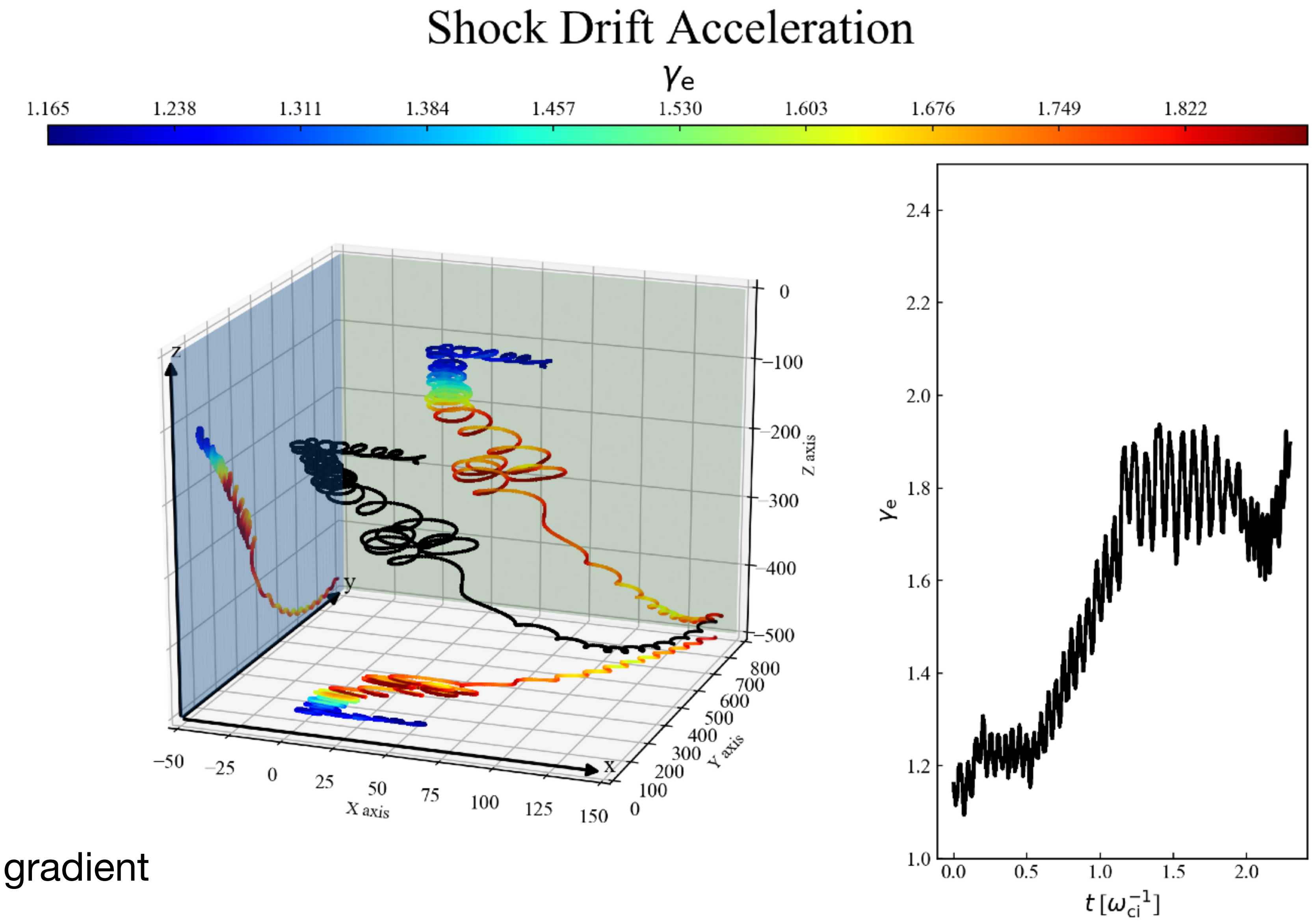
Shock Drift Acceleration: Revisited


Magnetic gradient

Downstream

Charge partic

Upstream

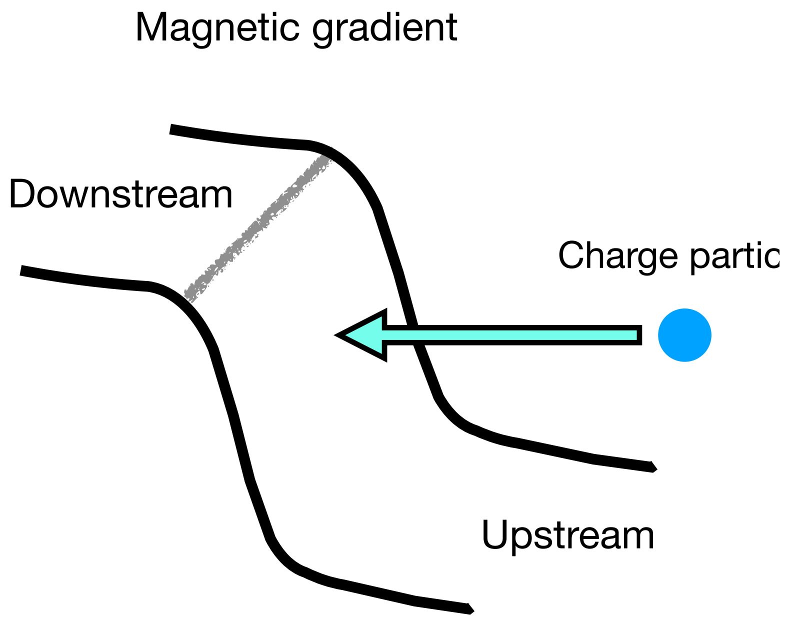

Shock Drift Acceleration

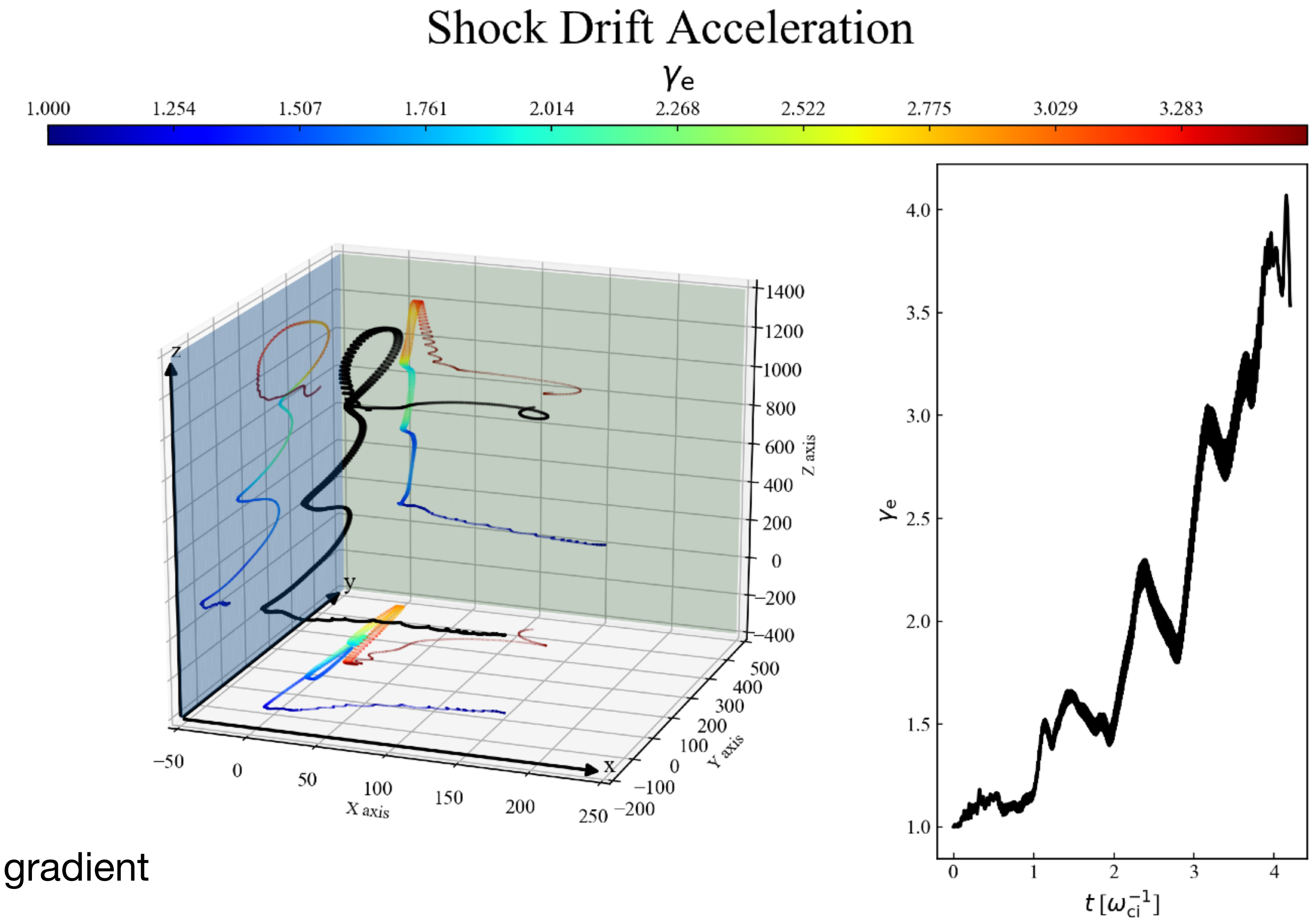
- Incoming particles see magnetic gradient
- Acceleration due to motional field

$$\mathbf{E}_s = -\frac{\mathbf{v}_{pt}}{c}\times \mathbf{B} = \hat{\mathbf{s}}\,\frac{\mathbf{v}_{pt}}{\mathbf{c}}\mathbf{B}$$

- Single SDA cycle is rare (Diffusive SDA Park+2015, Stochastic SDA Katou & Amino 2019)

Shock Drift Acceleration: Revisited





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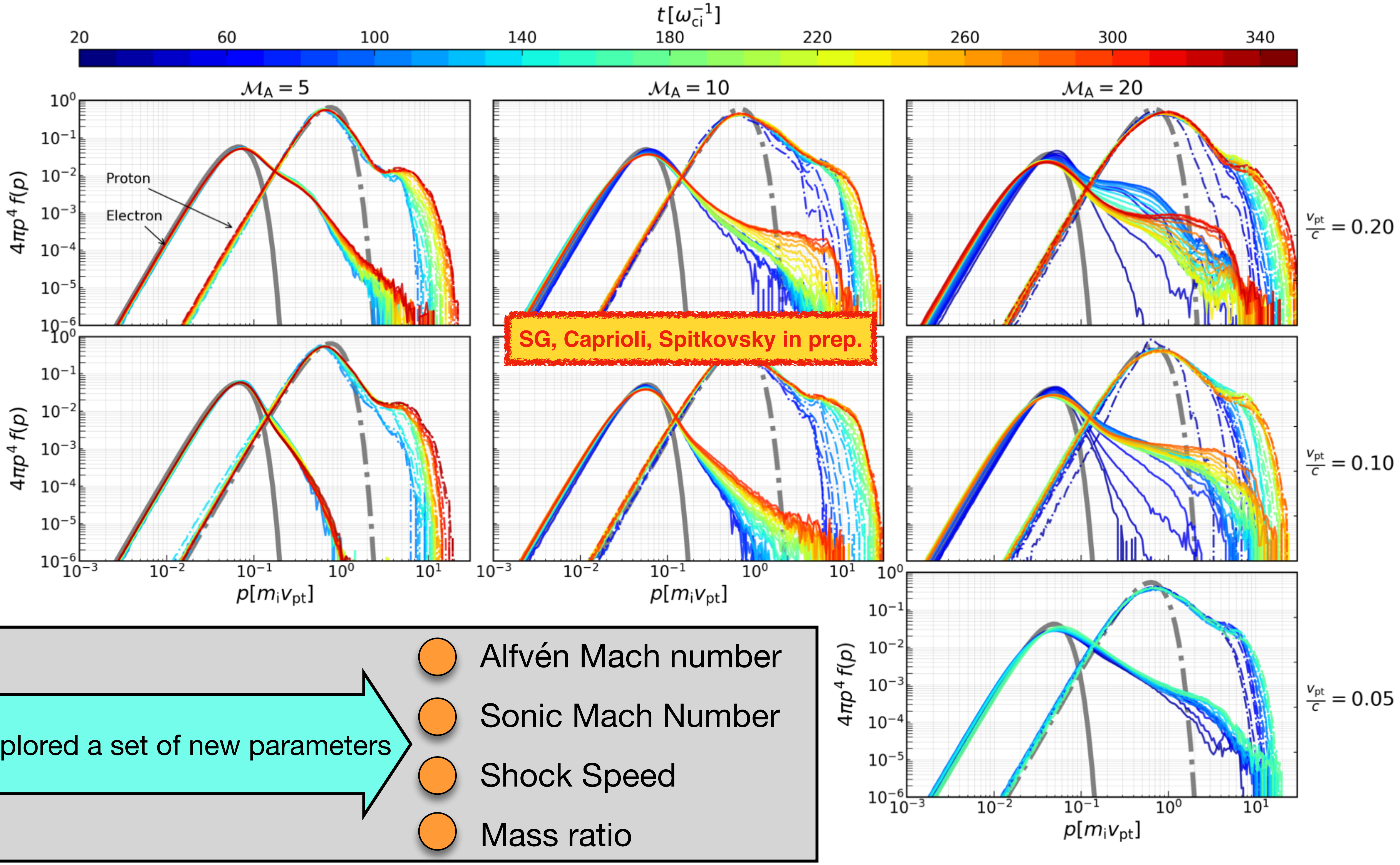
- Single SDA cycle is rare (Diffusive SDA Park+2015, Stochastic SDA Katou & Amino 2019)

- We develop analytic framework to quantify SDA gain **SG, Caprioli, Spitkovsky in prep.**

Survey of full PIC nonrelativistic quasi-parallel shocks

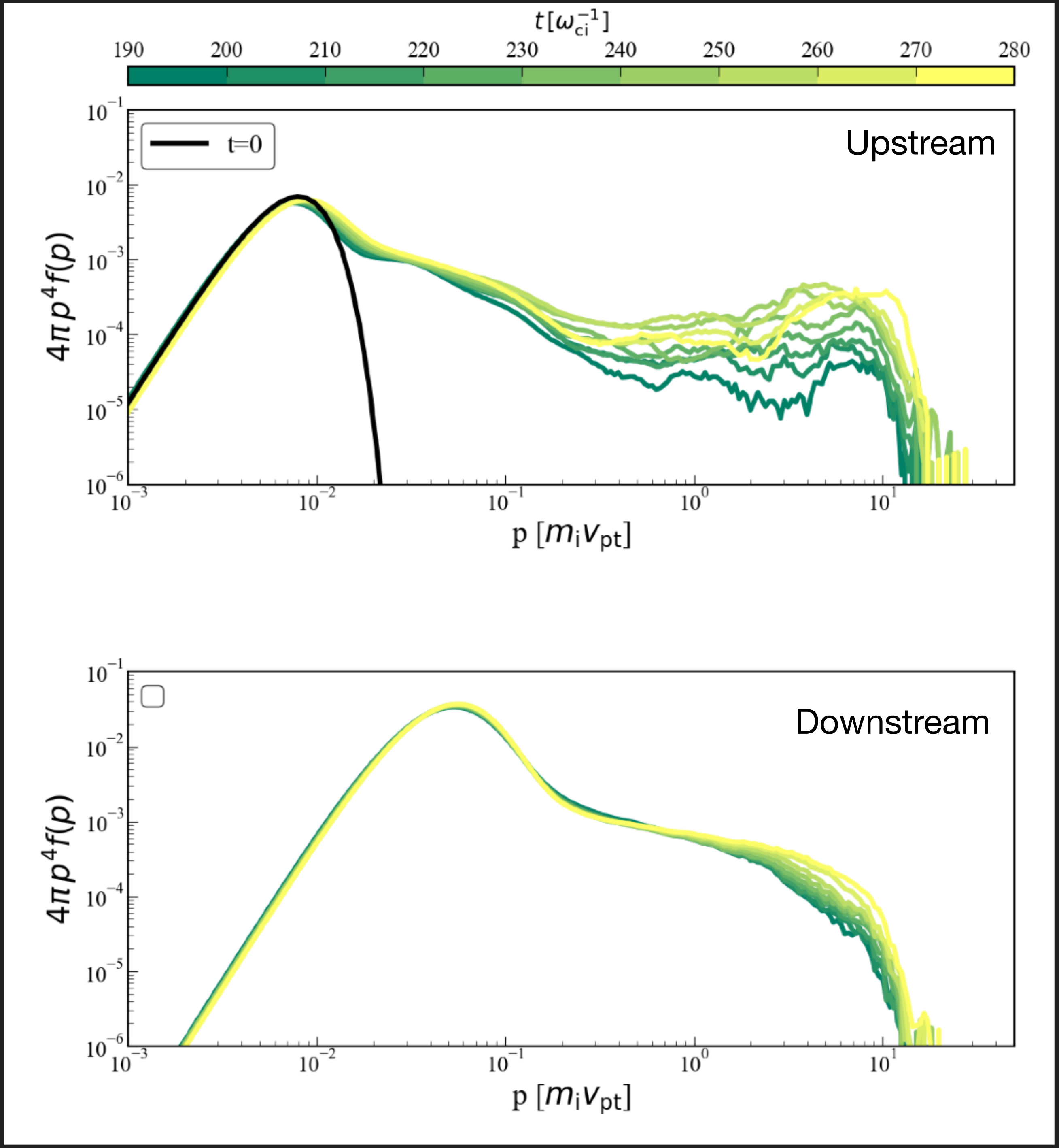


SG, Caprioli, Spitkovsky in prep.

Explored a set of new parameters

- Alfvén Mach number
- Sonic Mach Number
- Shock Speed
- Mass ratio

Synthetic spectra



Thermal Electrons

↓

Theoretical Ingredients (Including Reflection, SDA, DSA)

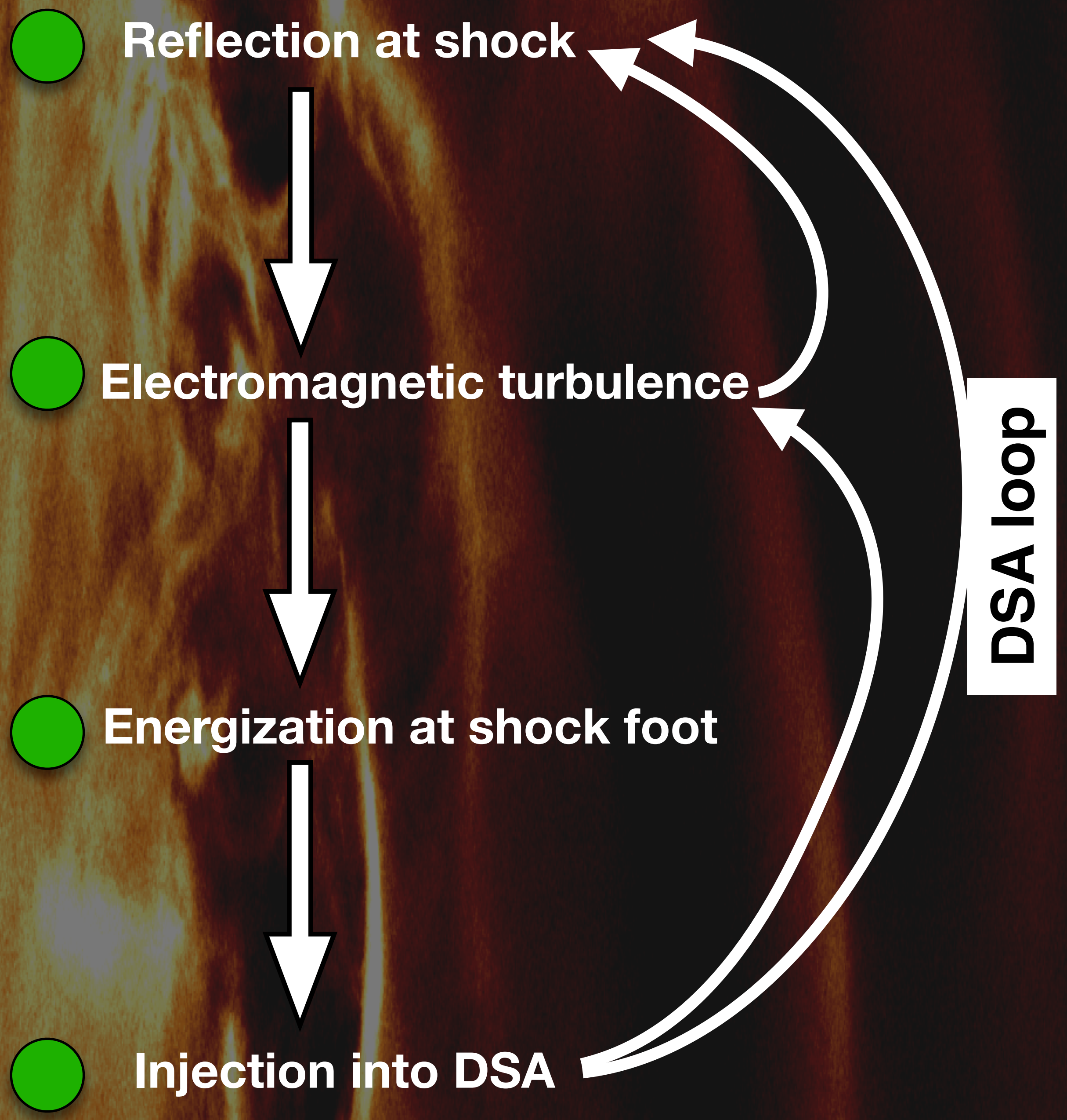
↓

Synthetic spectra

$\gtrsim$ 2 M CPU hr simulation →10 mins in 1 CPU

SG, Caprioli, Spitkovsky in prep.

Takehome messages



- Reflection at shock
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DSA loop

A survey of quasi-parallel nonrelativistic shock simulations: $v_{\rm sh}, \mathcal{M}_{\rm A}, \mathcal{M}_{\rm s}$ and $m_{\rm i}/m_{\rm e}$

Electron reflection:
apparently messy, but follows a pattern

What balances the ion current:
electrons?

Electron energization:
SDA is efficient, multiple cycles are required

Electron to proton ratio:
first time for different shock environments

Minimal model:
synthetic spectra agree with simulation

Gupta, Caprioli, & Spitkovsky a,b in prep

Thank you!