Non-thermal Electron Acceleration in Low Mach Number Collisionless Shocks

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In collaboration with
Lorenzo Sironi and Ramesh Narayan
ApJ 794 ,153, arXiv1406.5190
ApJ in presss, arXiv1409.7393

Outline

- Motivation
- Simulation setup
- Shock structure and energy spectra
- Acceleration mechanism
- Parameter dependence
- Astrophysical implications

Observational Evidence

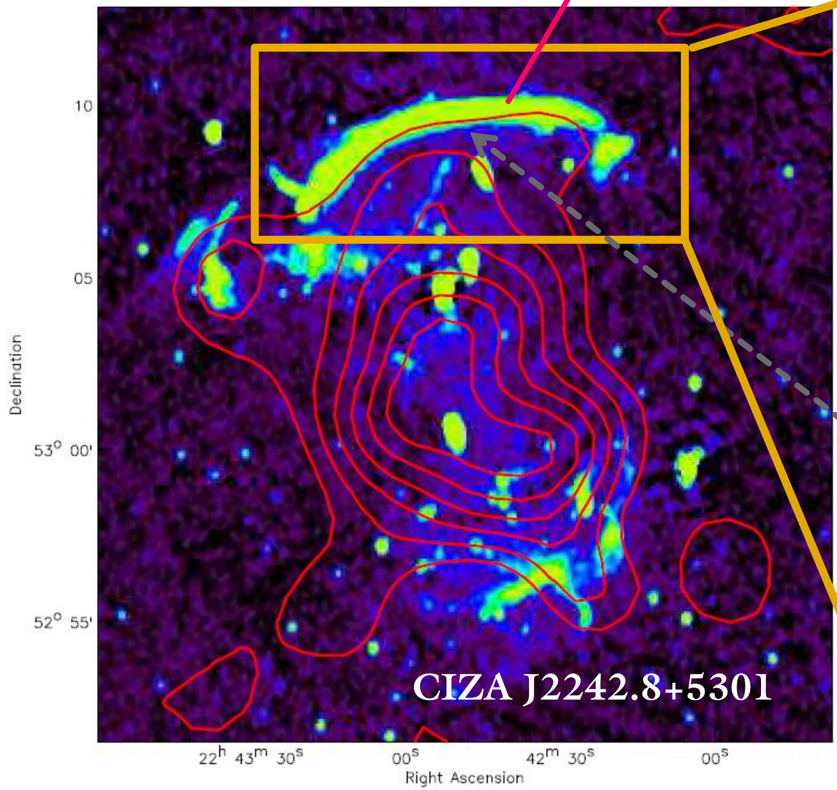
Radio relics at outskirts of galaxy clusters

accelerated electrons

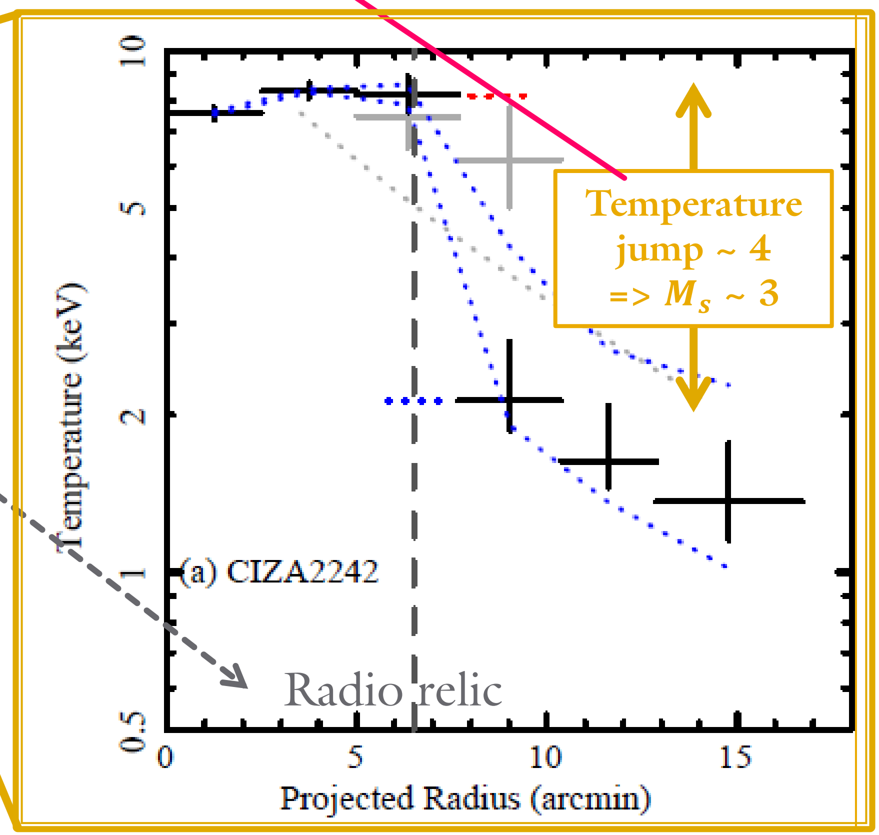
low Mach number shock

Radio (WSRT)

X-Ray (Suzaku)



van Weeren et al 2010



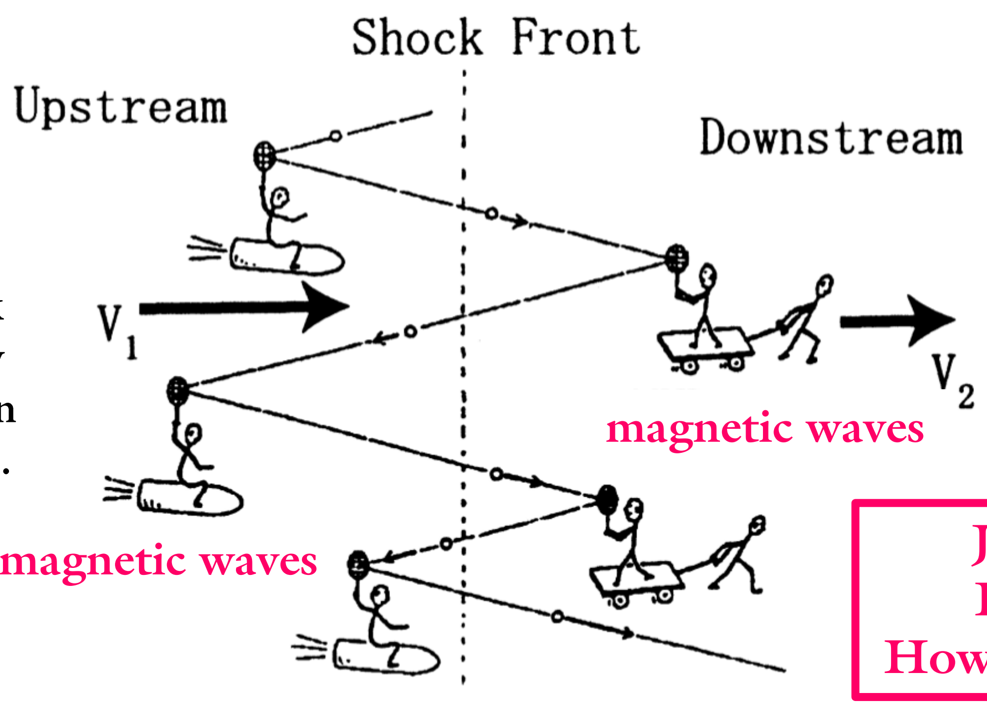
Akamatsu & Kawahara 2012

Particle acceleration at shocks

First-order Fermi acceleration

Particles gain energy after each shock crossing .

Particles cross shock due to scatterings by the magnetic waves in up- and downstream.



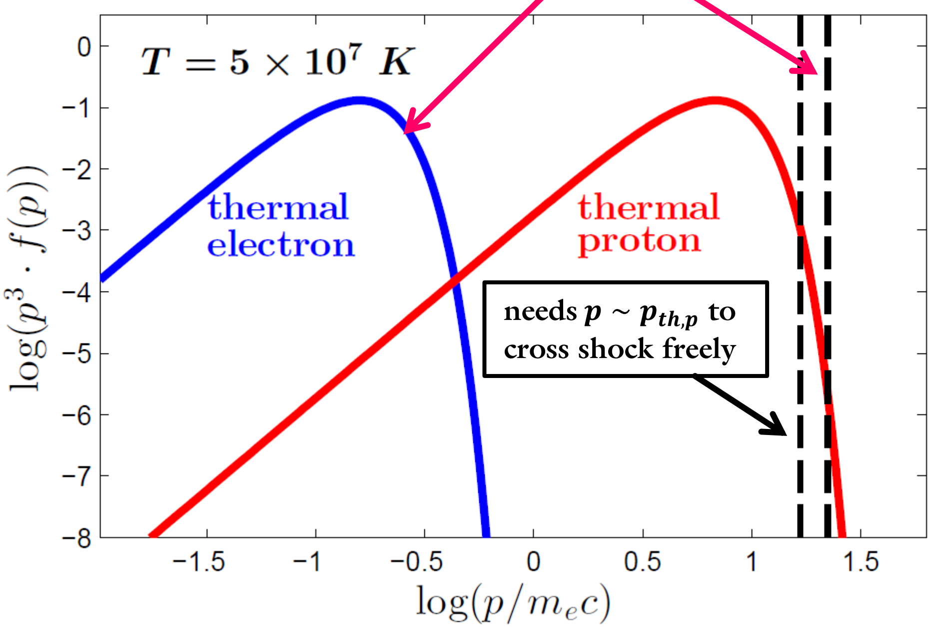
Just a paradigm.
Relies on waves.
How do the waves arise?

(original sketch by Scholer)
Credit: Hoshino 2001

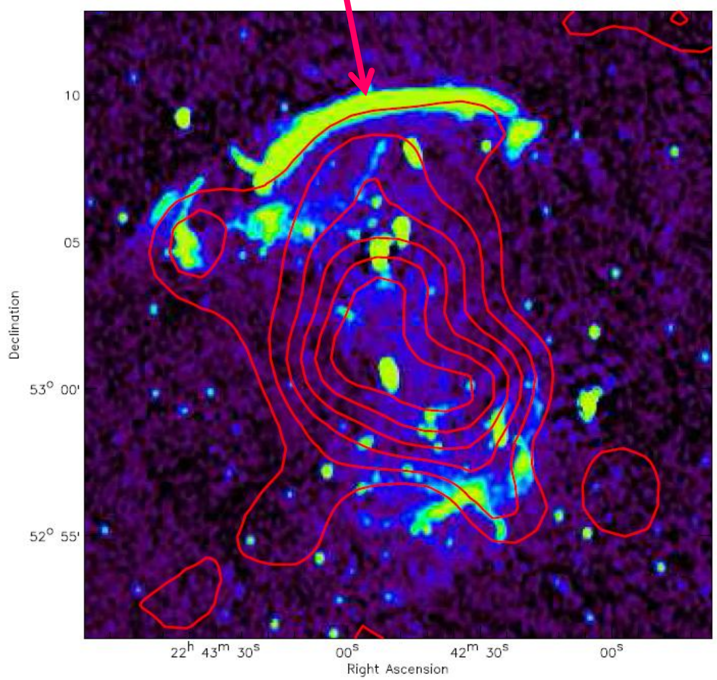
Theoretical Challenge
electron injection problem

Traditional injection model:
assumes particles need to cross shock from downstream

electron acceleration efficiency too poor.



In tension with observations!



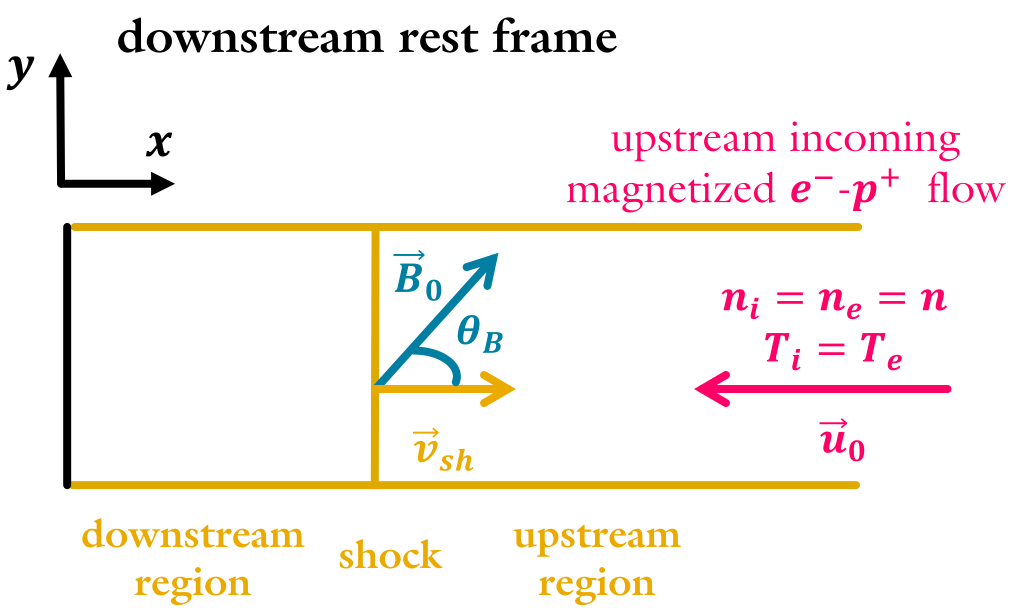
This work: studies electron acceleration in low Mach number shock from first principles, identifies an electron Fermi-type acceleration mechanism, which is mediated by electron self-generated waves and operates efficiently over a wide range of parameter space.

Simulation Setup

Self-consistent particle-in-cell plasma simulations

Method: Particle-in-cell (PIC) method, simulates collisionless plasma from first principles.

Code: TRISTAN-MP (Spitkovsky 2005)



Mach number: $M_s = \frac{u_0 + v_{sh}}{c_s}$

plasma beta : $\beta_p = \frac{n k_B (T_i + T_e)}{B_0^2/8\pi}$

Simulation runs:

$M_s = 3$ fixed

T_e varies from $10^{7.5}$K to 10^9K

β_p varies from 6 to 60

θ_B varies from 13° to 80°

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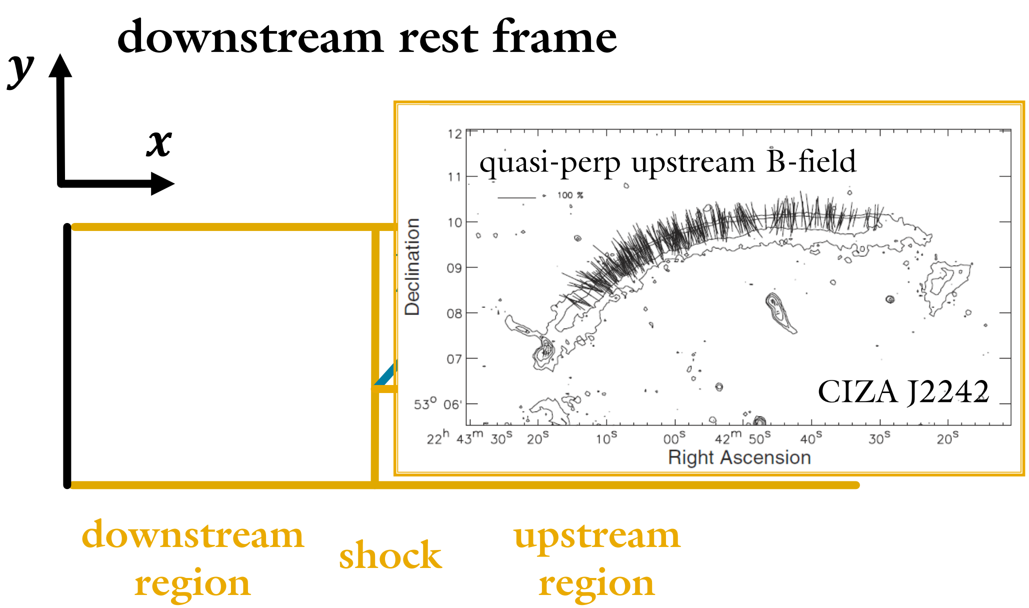

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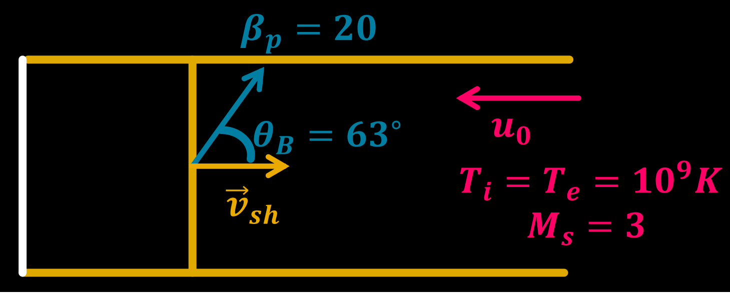
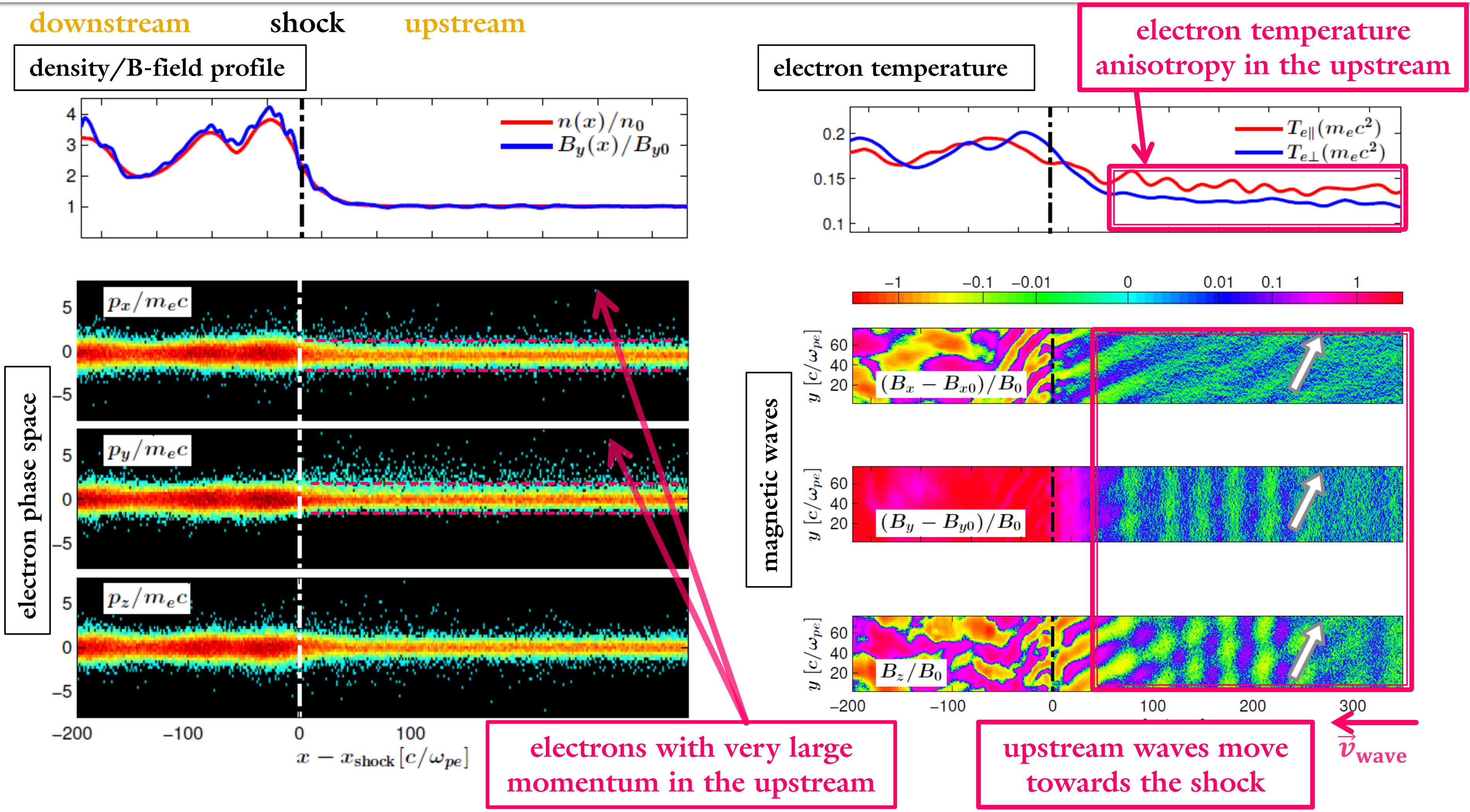
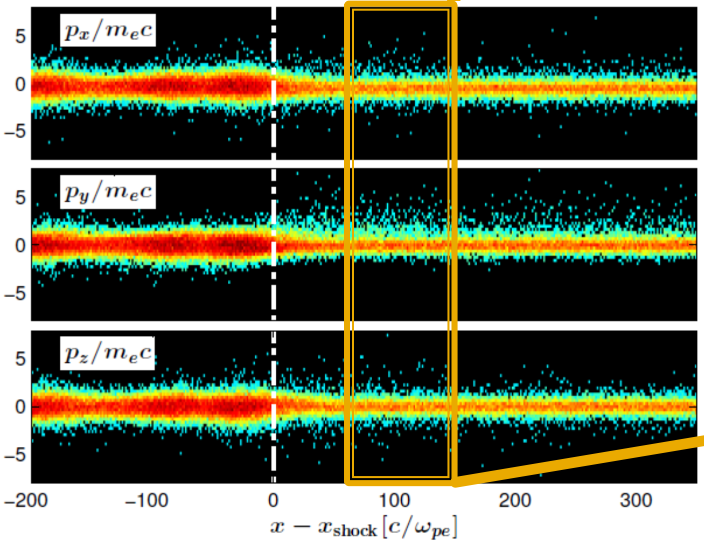
Shock Structure

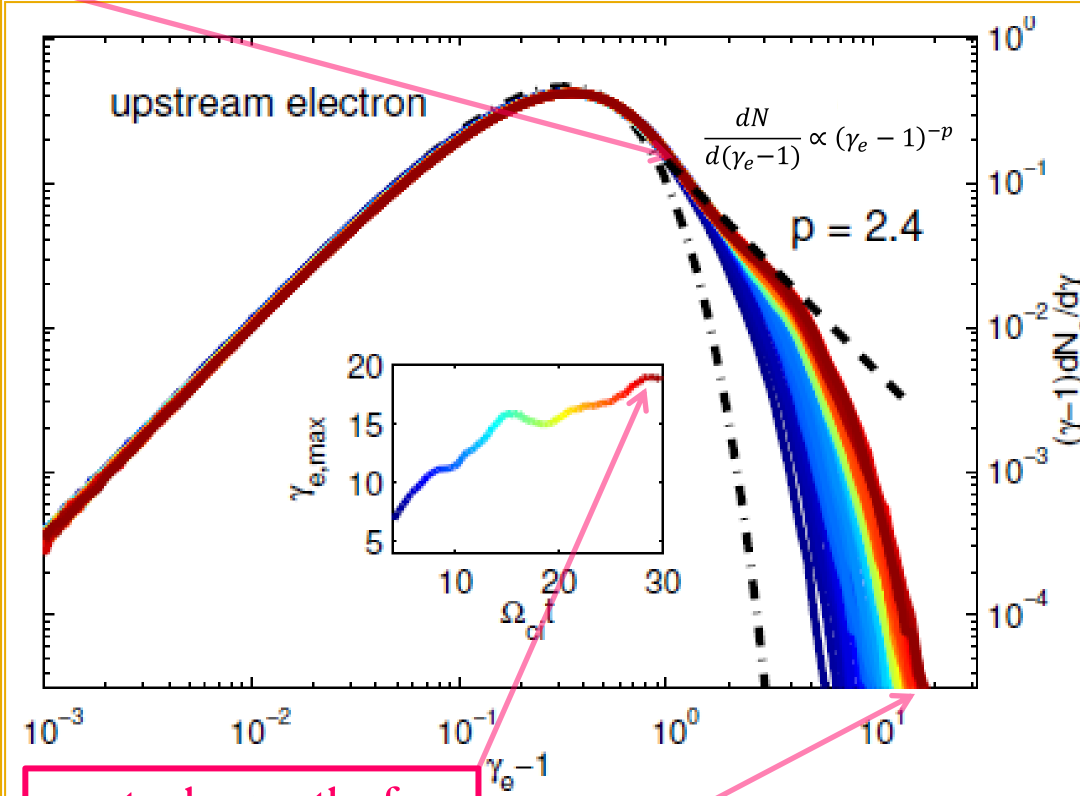




Electron Spectral Evolution

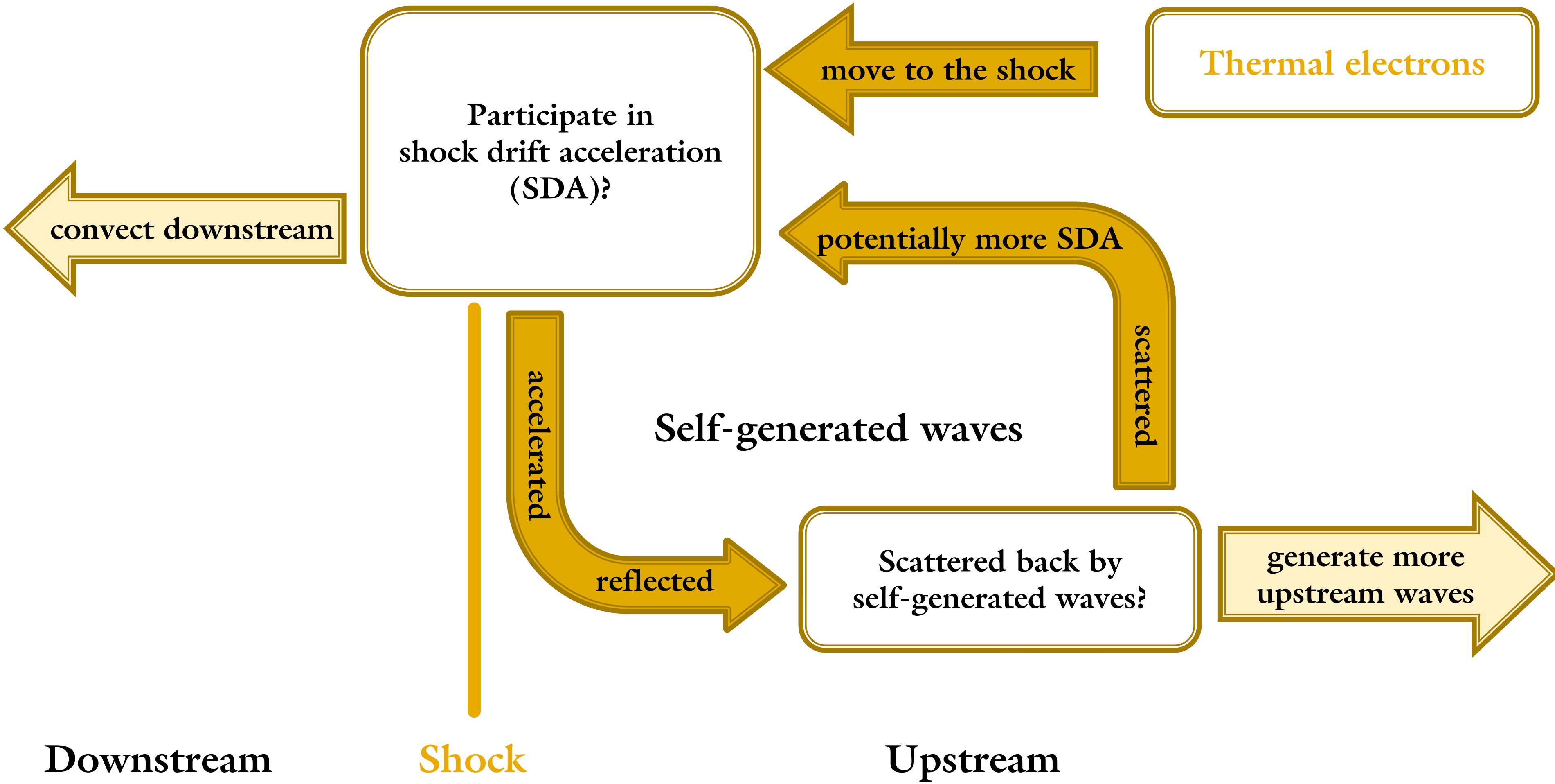
about 10% upstream electrons are accelerated to non-thermal energy





steady growth of maximum energy, efficient acceleration

The Big Picture



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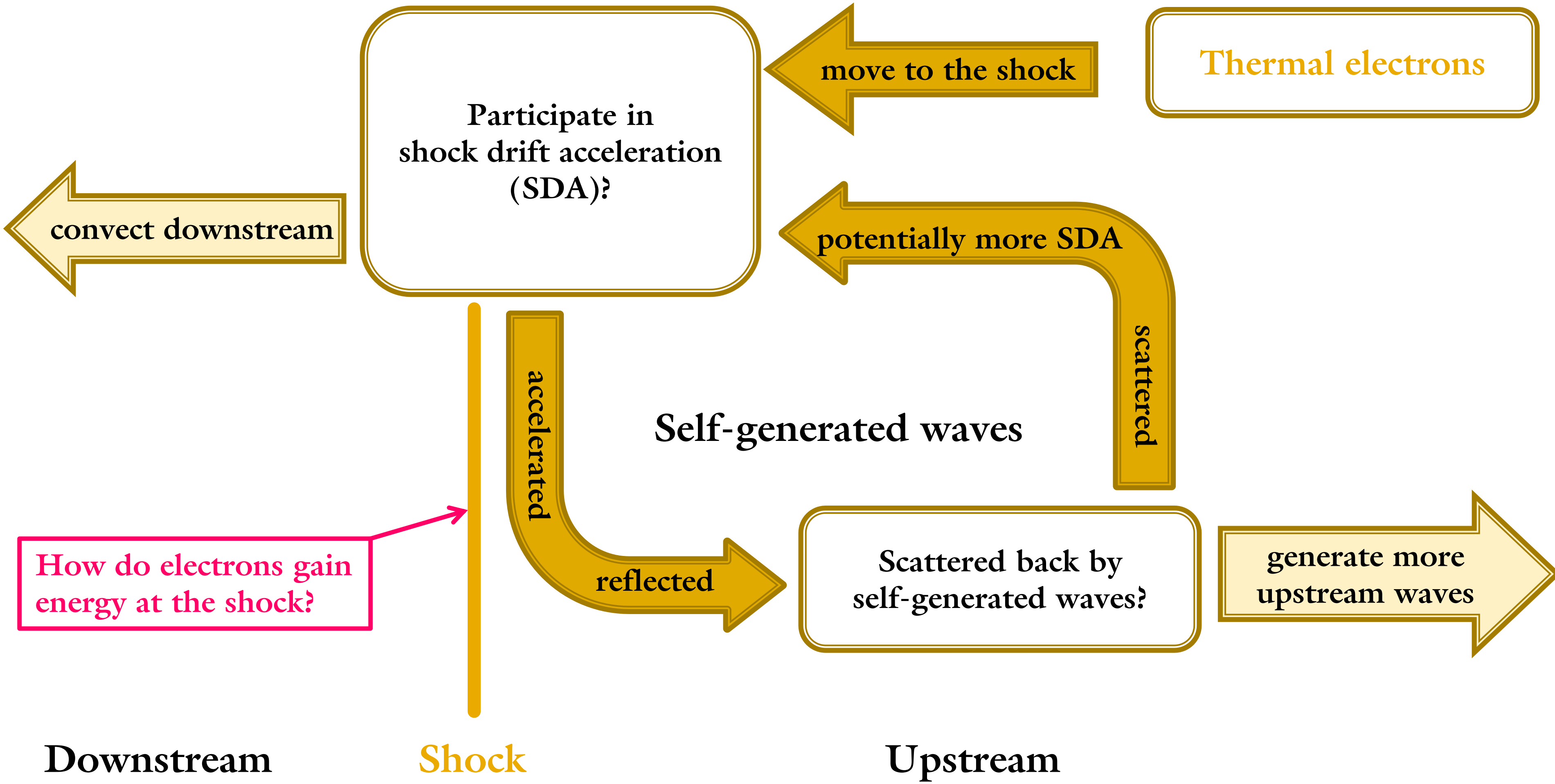
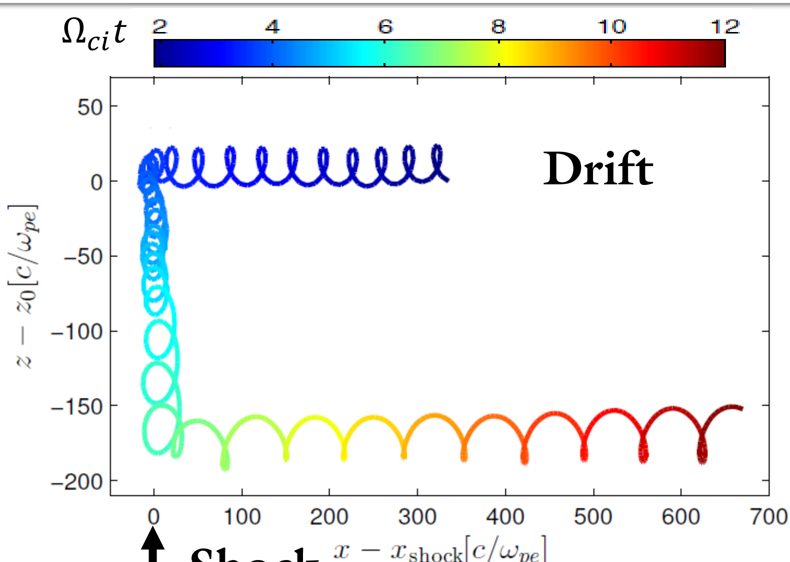
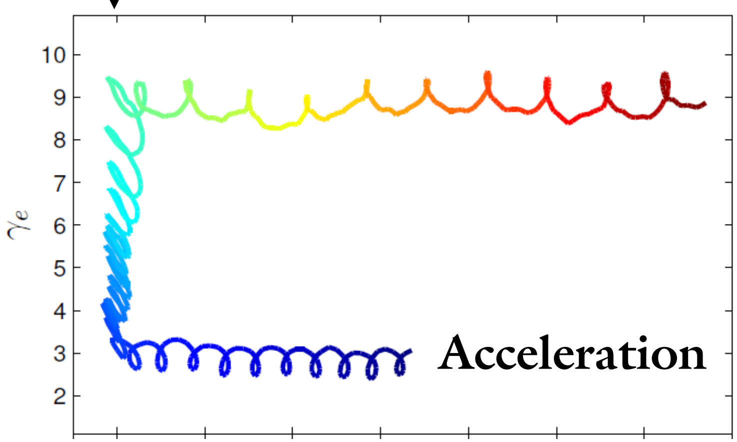


Shock Drift Acceleration

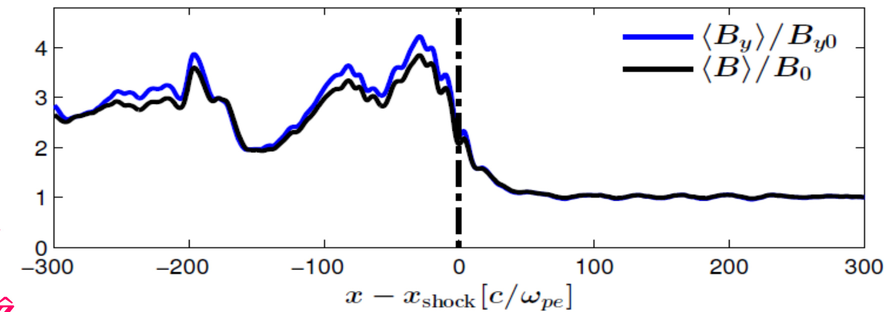


Shock



grad-B force

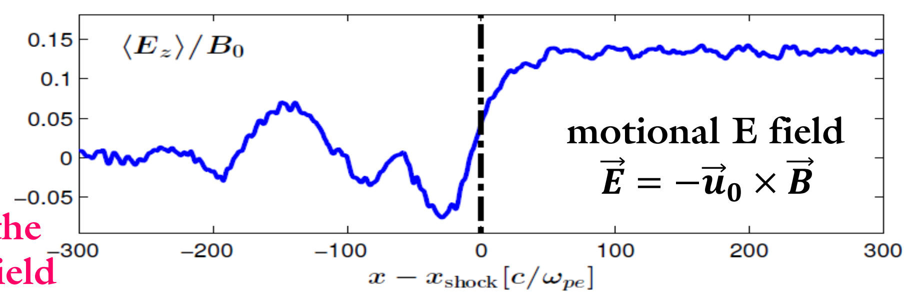
drift along $-\hat{z}$



$$\vec{v}_{\nabla B} = \mu/q(\vec{B} \times \vec{\nabla} B)/B^2$$

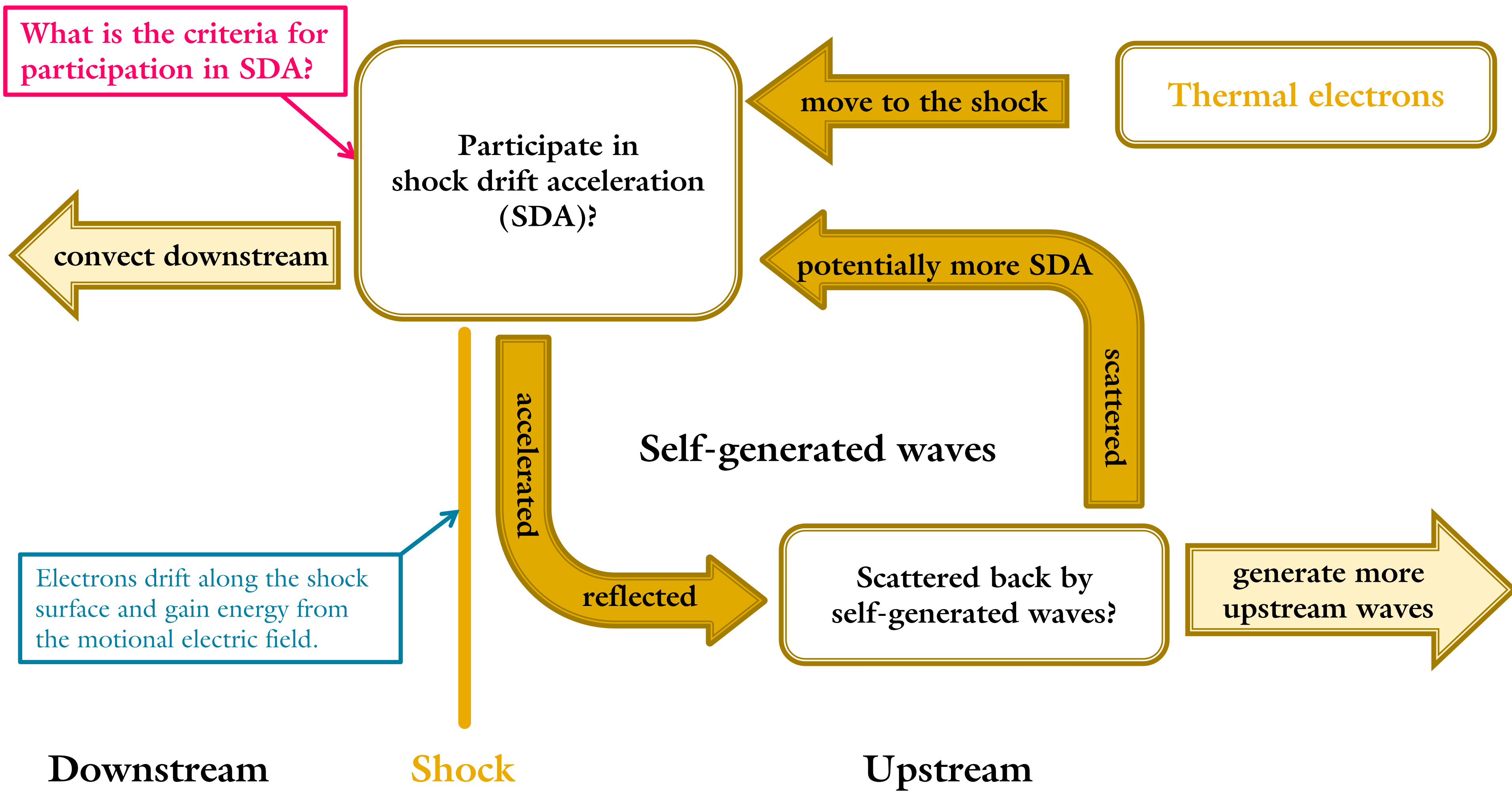
drift along the motional E field

energy gain



$$\Delta\gamma_e m_e c^2 = q\int E_z dz$$

The Big Picture



Frame Transformation

downstream rest frame

also the simulation frame, most straightforward!

$-u_1\hat{x}$

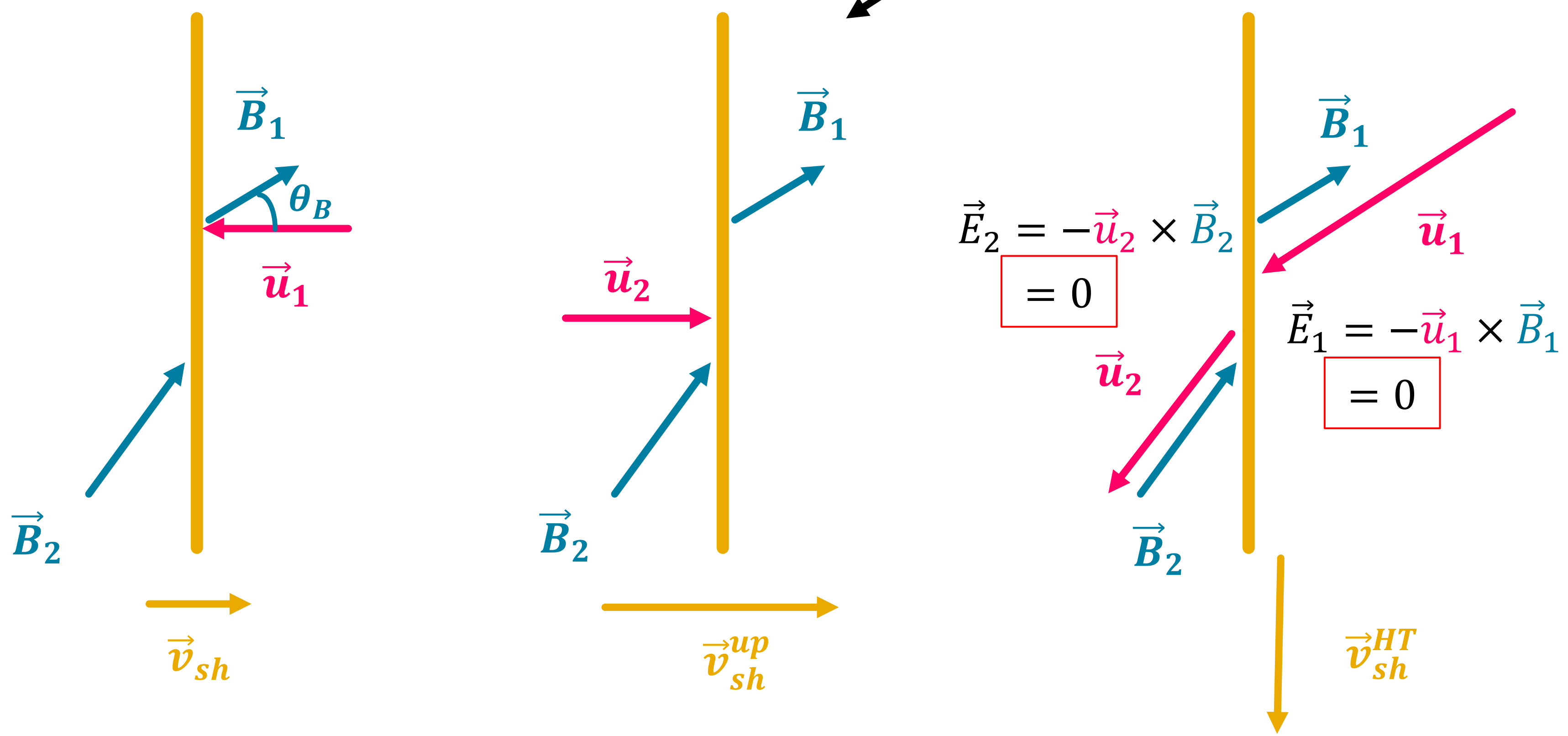
upstream rest frame

upstream plasma velocity space independent of bulk motion

de Hoffman-Teller frame

No motional electric field!

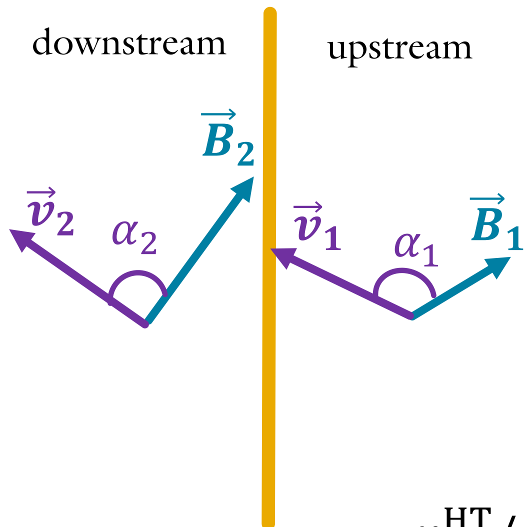
$-u_t c\hat{B}_1 = -v_{sh}^{up}/\cos\theta_B\,\hat{B}_1$



Injection into SDA

governed by mirror reflection at the shock

HT frame **No motional electric field**



Assumptions:
Energy conservation
Magnetic moment conservation

If transmitted

$$\sin\alpha_2{}^2 = \frac{B_2}{B_1}\sin\alpha_1^2 \leq 1$$

Reflection Criteria

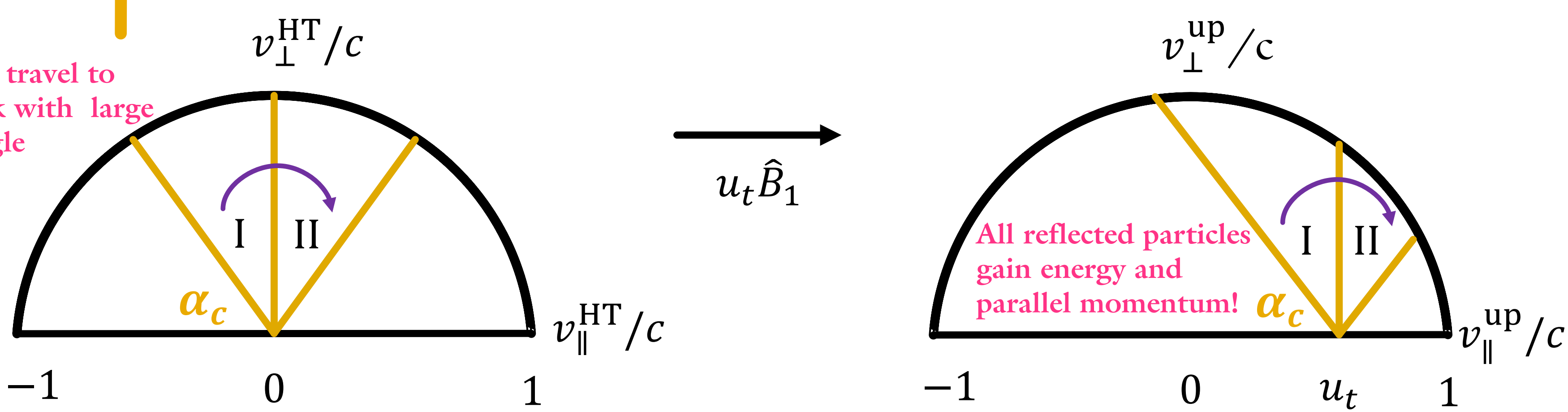
$$v_{1\parallel}^{\mathrm{HT}} < 0$$

$$\alpha_1^{\mathrm{HT}} > \alpha_c \equiv \sin^{-1}\sqrt{\frac{B_2}{B_1}}$$

After reflection

$$v_{1\parallel}^{\mathrm{HT}} \Rightarrow -v_{1\parallel}^{\mathrm{HT}}$$

Needs to travel to the shock with large pitch angle

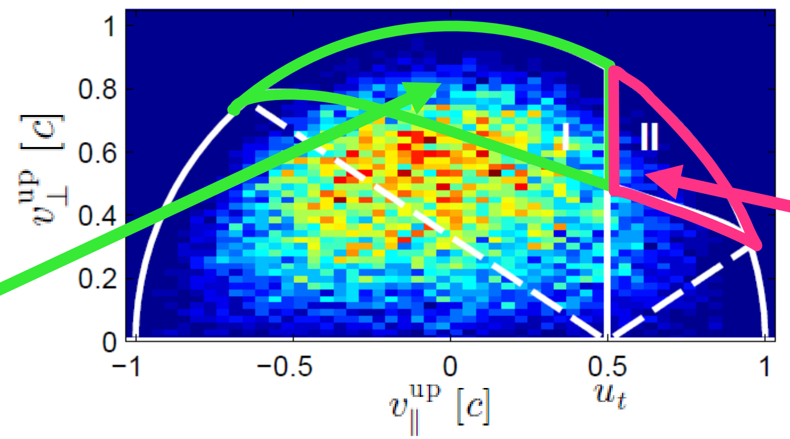


Injection into SDA

mirror reflection criteria verified by particle tracing

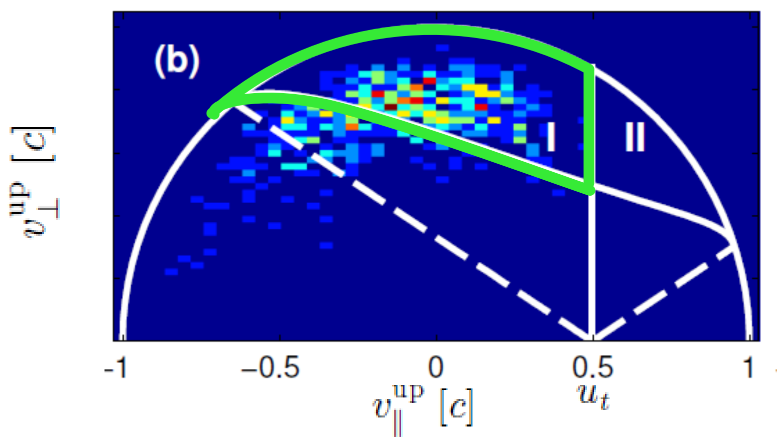
representative particles at initialization

region in velocity space allowed for reflection

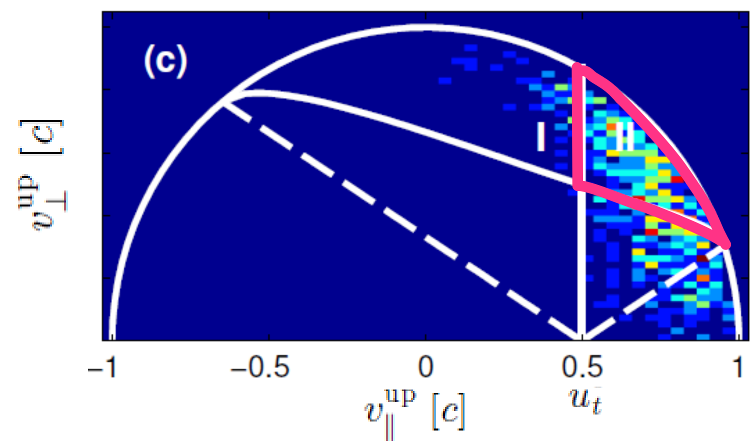


region in velocity space occupied by reflected particles

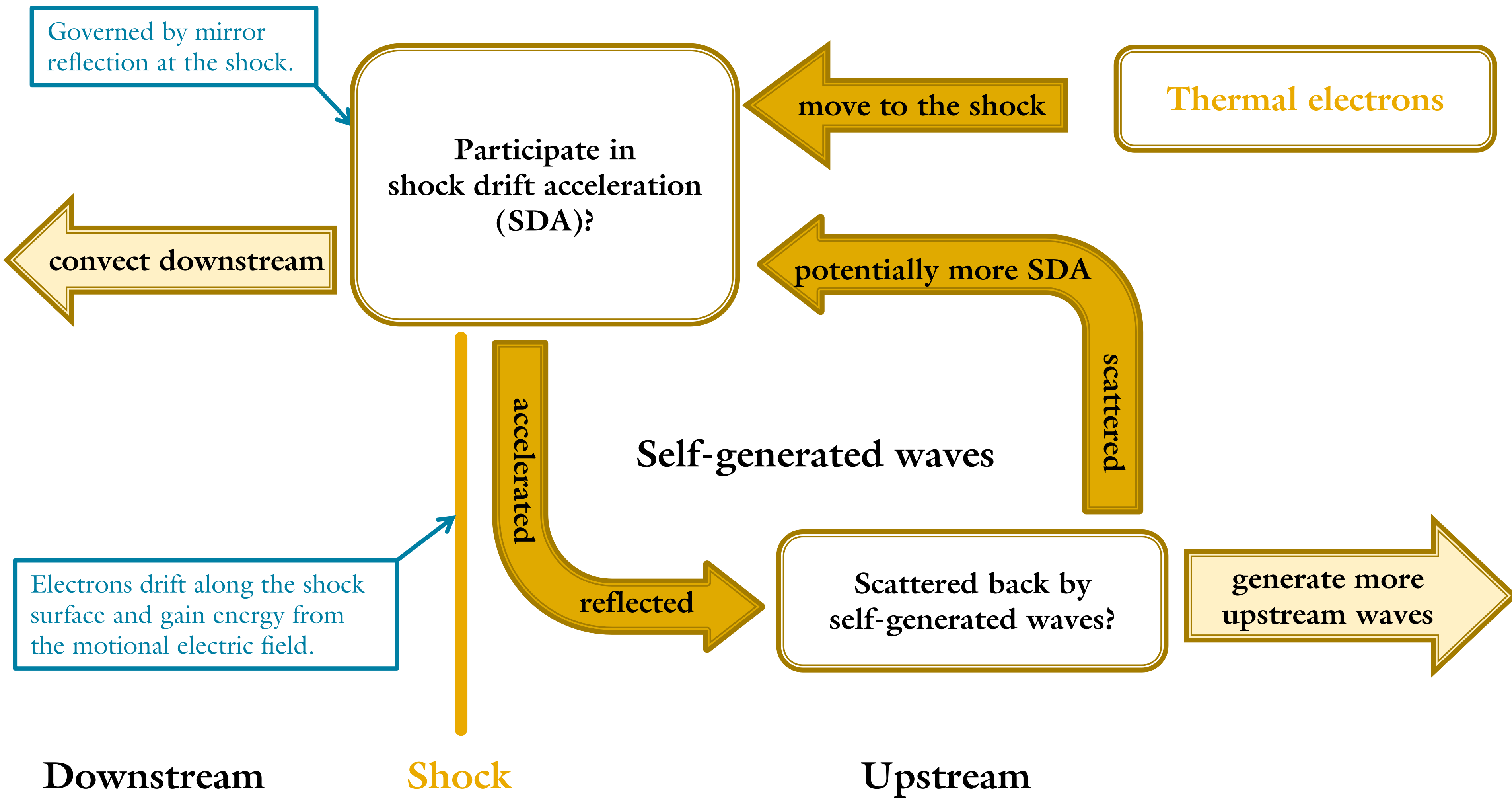
reflected particles before reflection



reflected particles after reflection



The Big Picture



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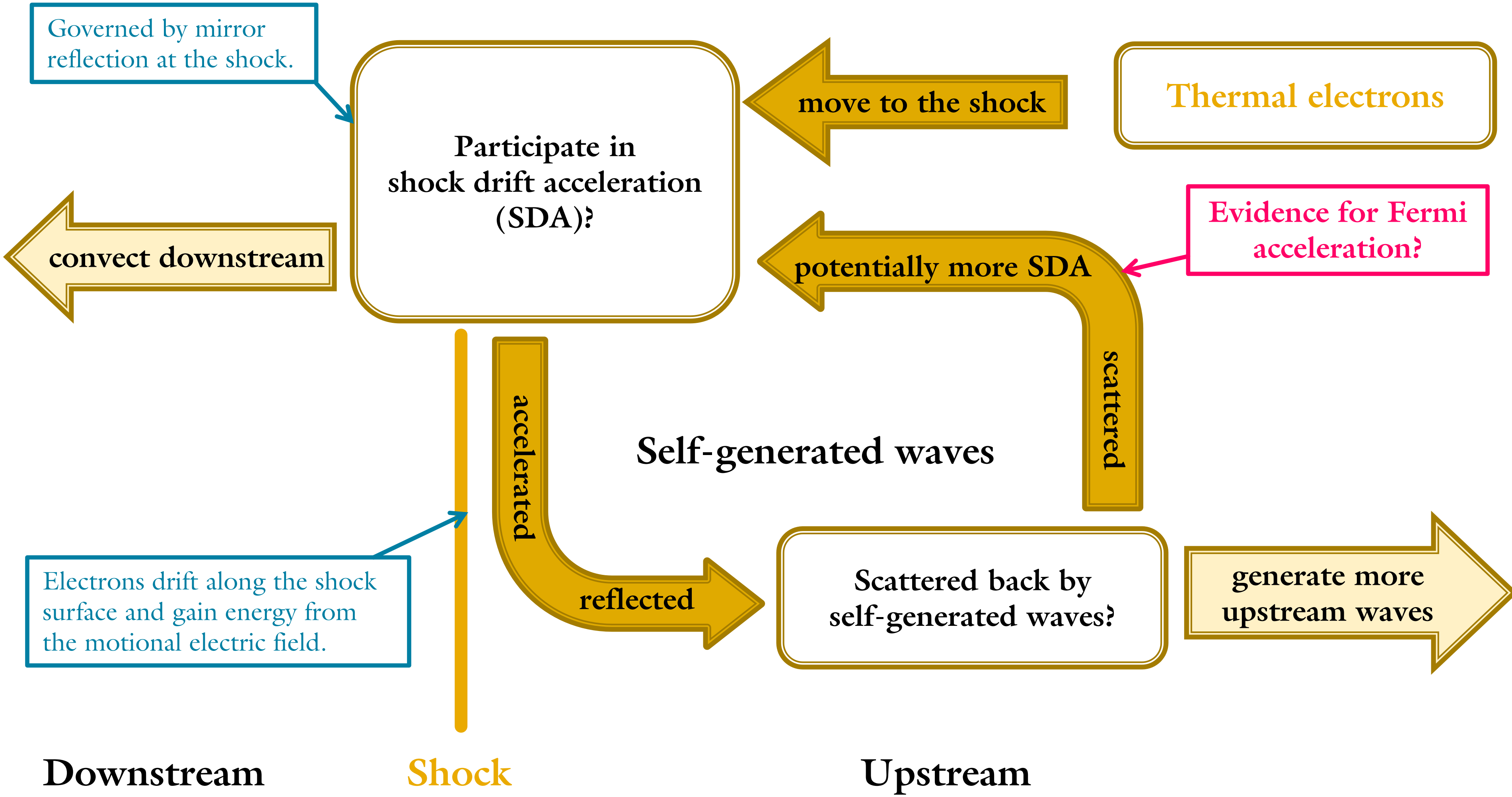
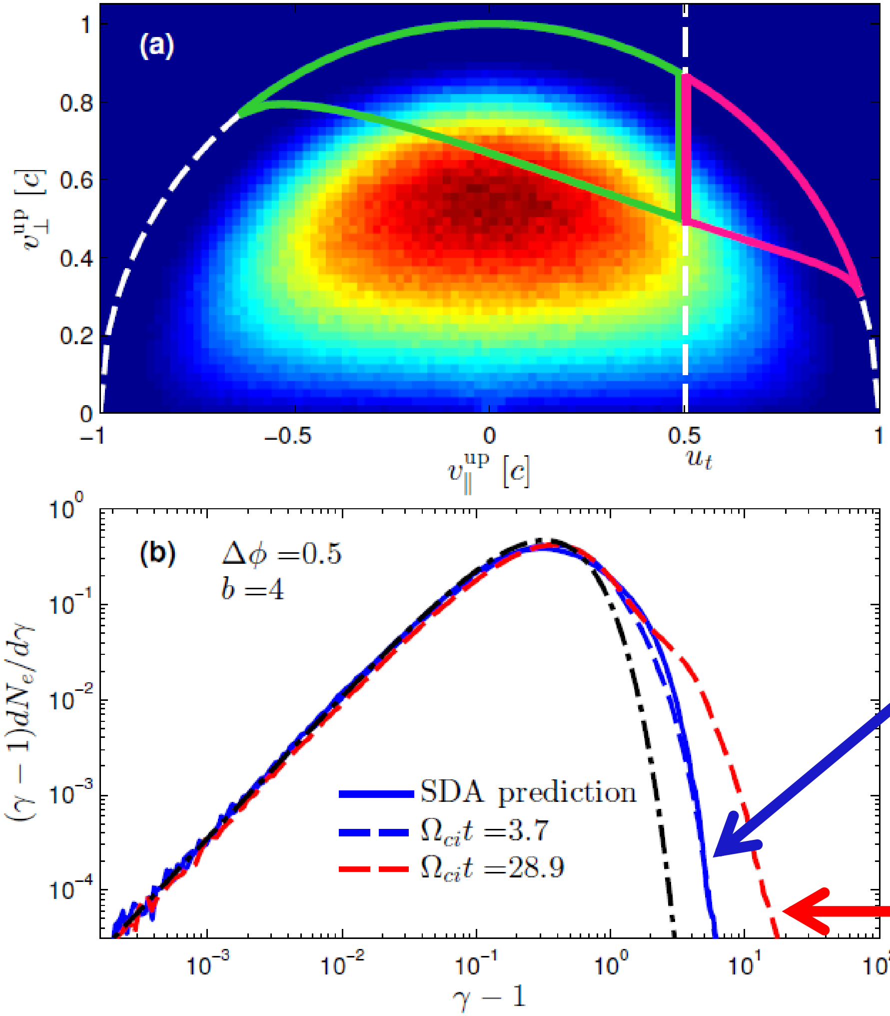


Beyond single-cycle SDA

single-cycle SDA cannot explain long-term spectral evolution

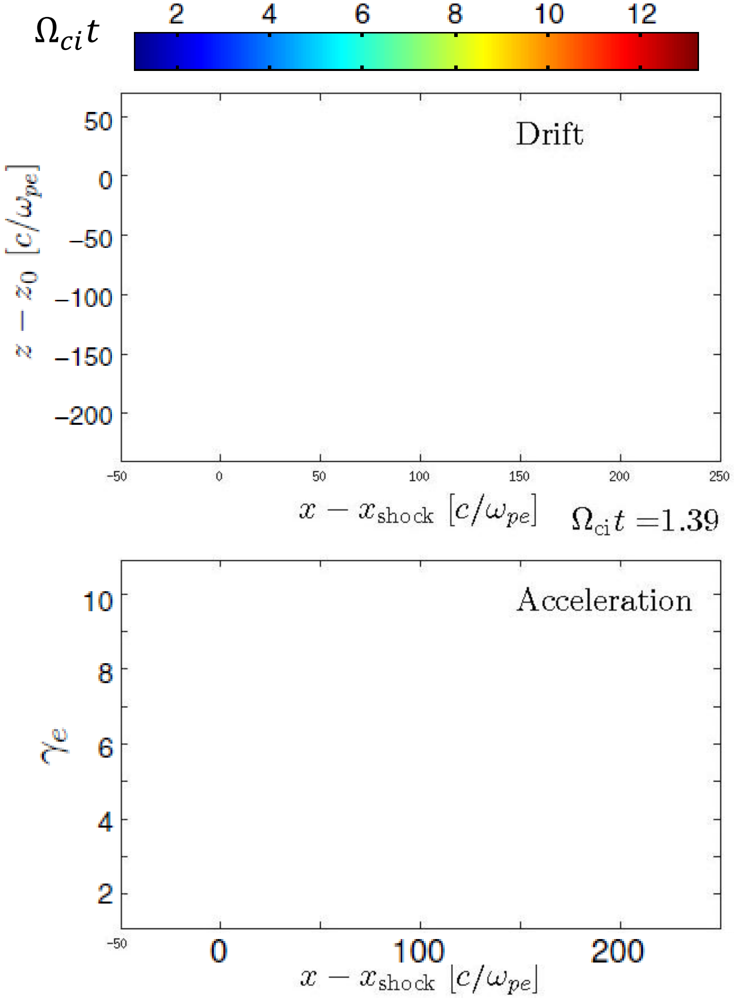


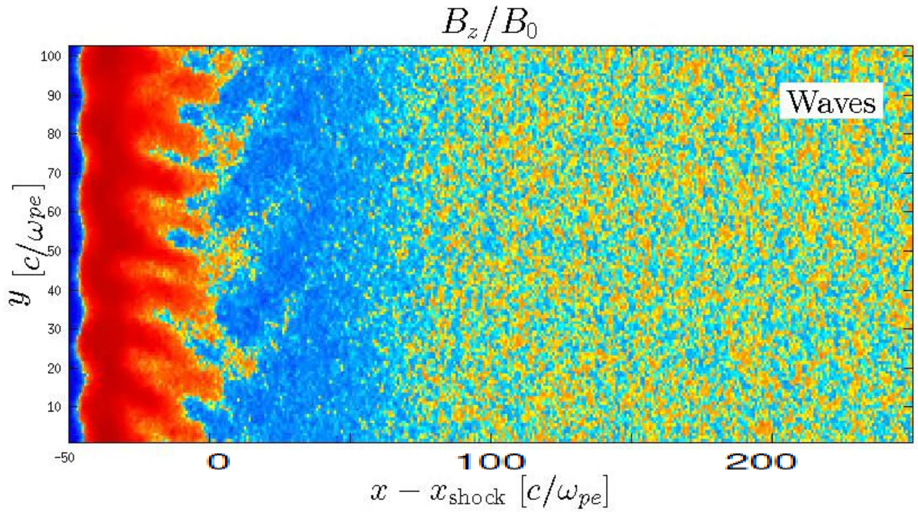
Single-cycle SDA agrees with spectrum at early times.

Single-cycle SDA is not enough to explain the long term spectral evolution.

Fermi-like Acceleration

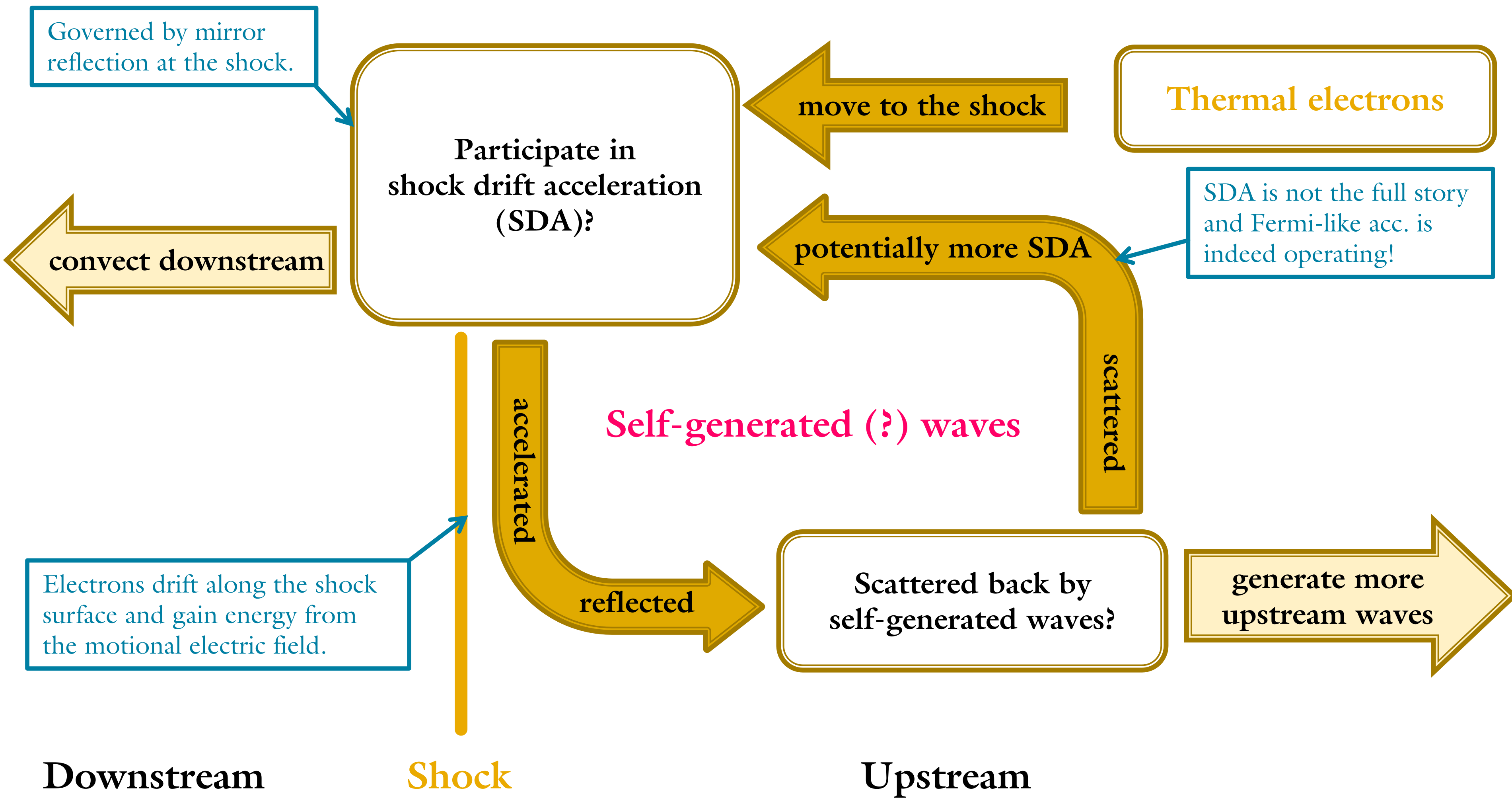
multiple cycles of SDA mediated by upstream waves





video link:
http://youtu.be/asXmDyNSL8s

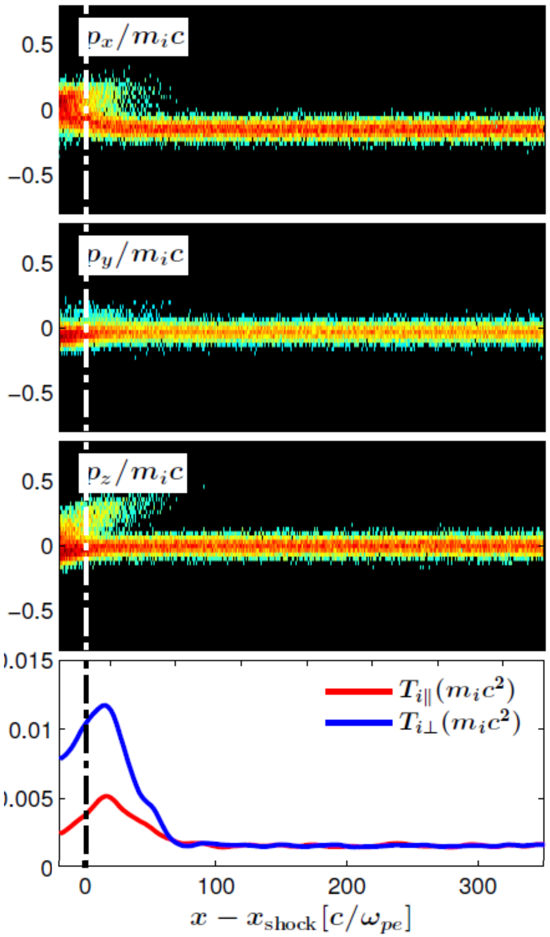
The Big Picture



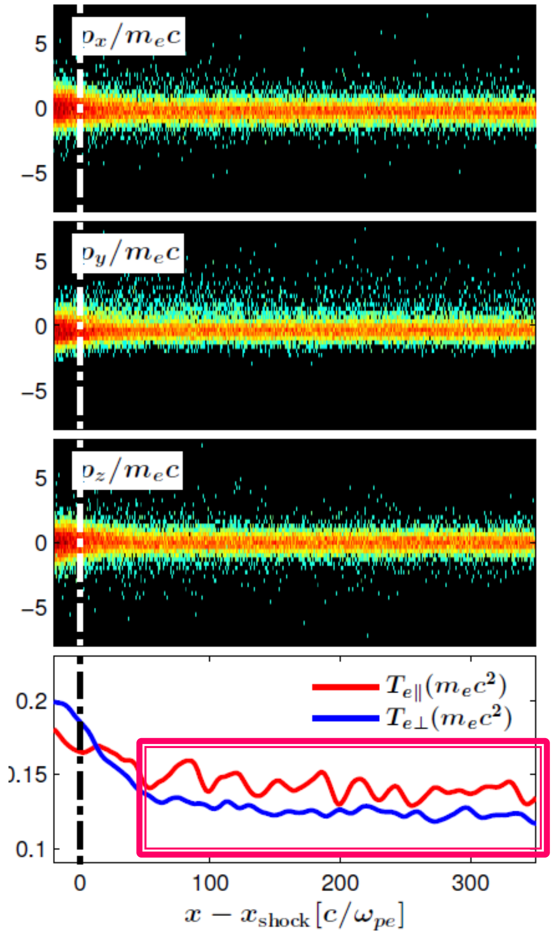
Waves generated by e^- or p^+ ?

p^+ isotropic vs. e^- temperature anisotropy provides source of free energy

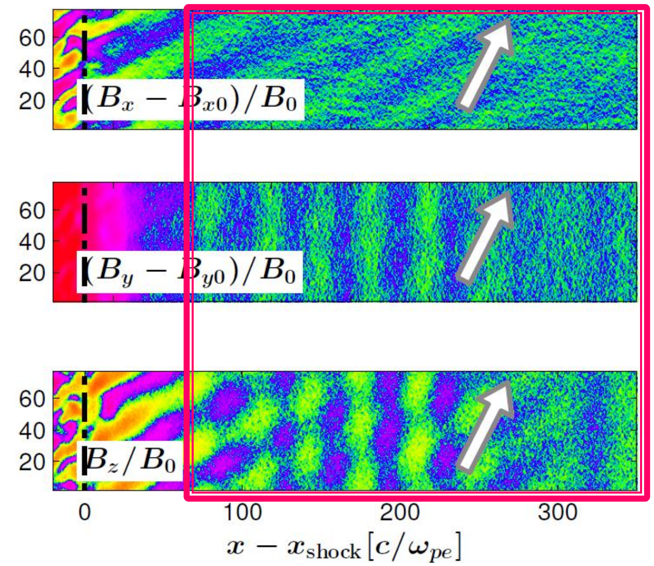
Ions



Electrons



Waves

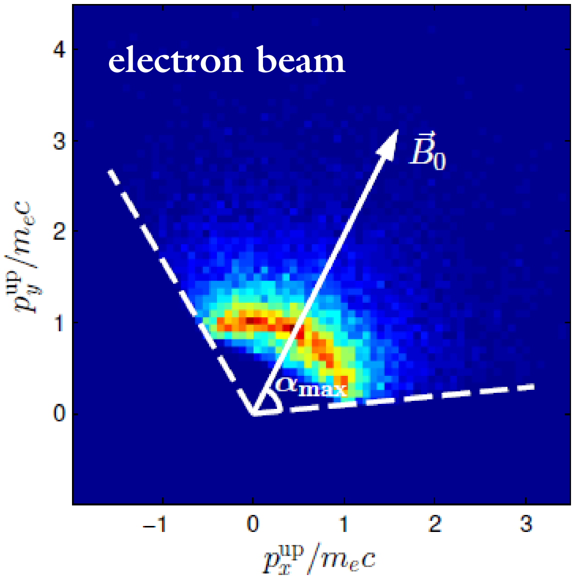


e^- self-generate the waves

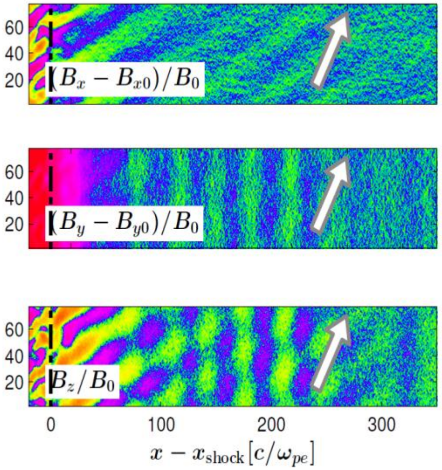
controlled beam-plasma instability experiment reproduces the wave patterns

Controlled Beam-Plasma Instability Experiment

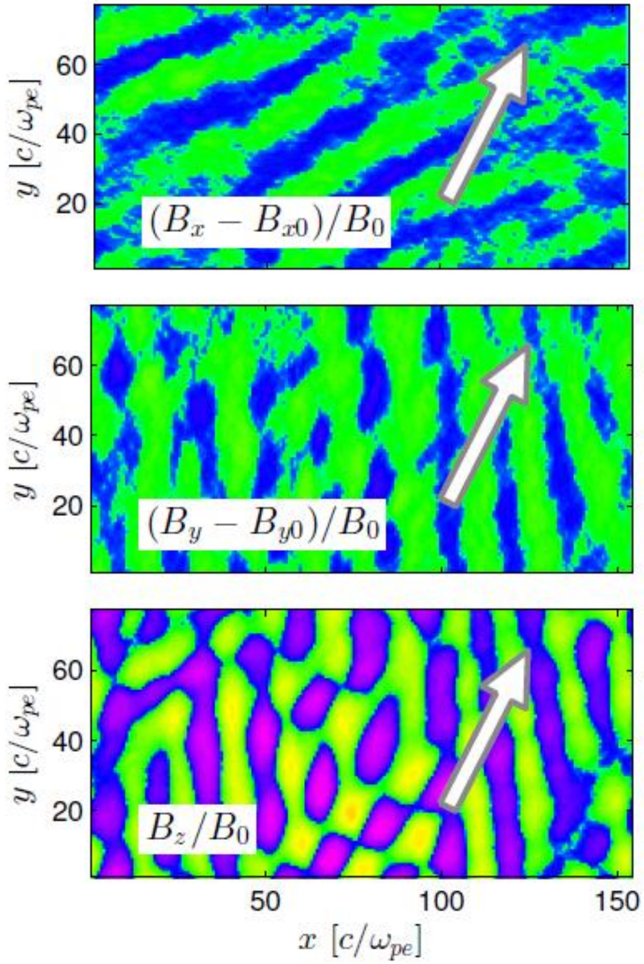
- Upstream rest frame
- Periodic boundary conditions
- Maxwellian magnetized background plasma
- Electron beam modeled by SDA injection theory



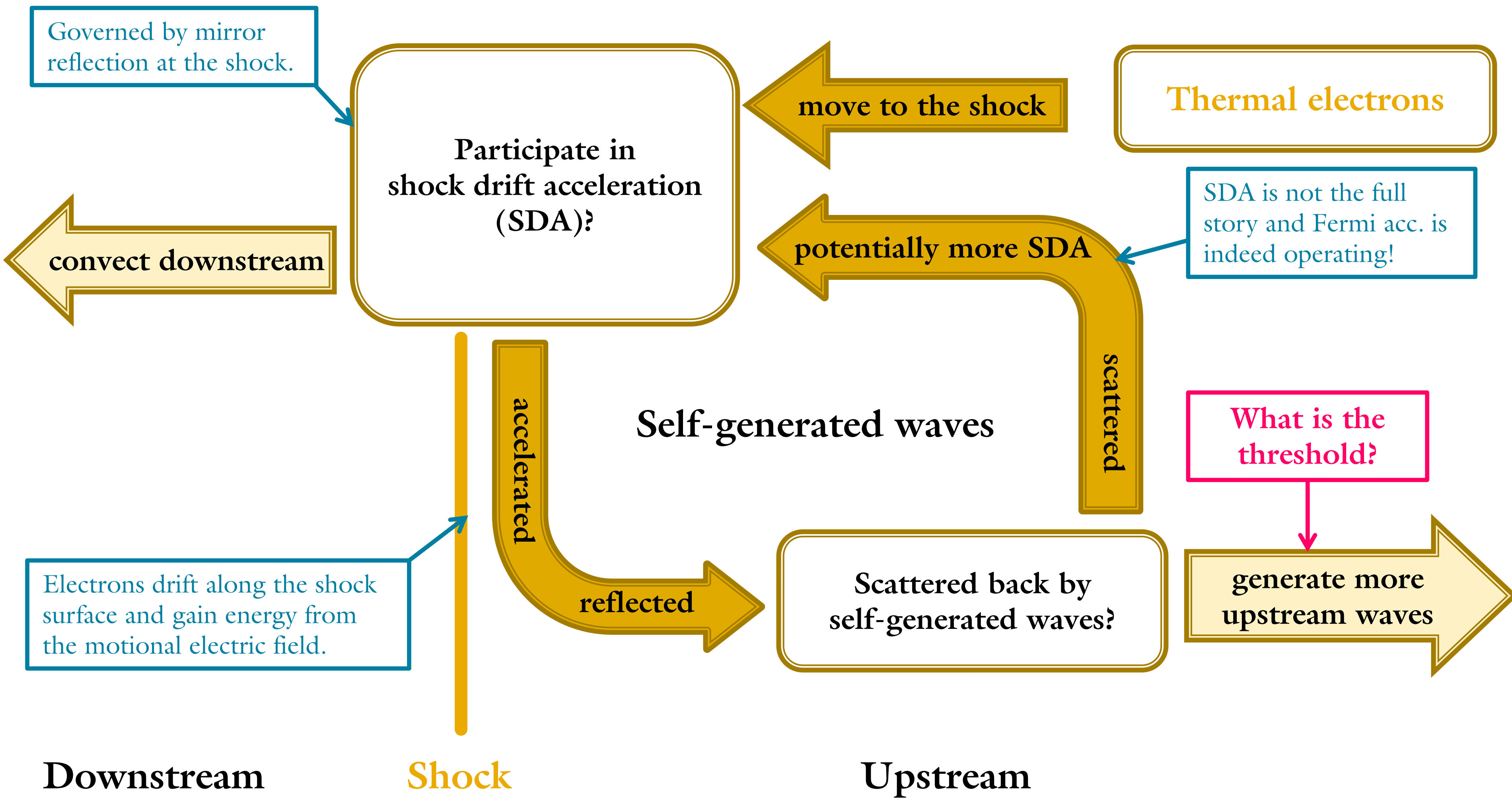
shock simulation



controlled experiment



The Big Picture



Threshold for the wave growth

e^- pressure anisotropy > background magnetic pressure

Electron firehose instability (oblique mode)

Pressure due to electron temperature anisotropy.

$$\frac{n_e k T_{e\parallel} - n_e k T_{e\perp}}{B_0^2/8\pi} > 1.3$$

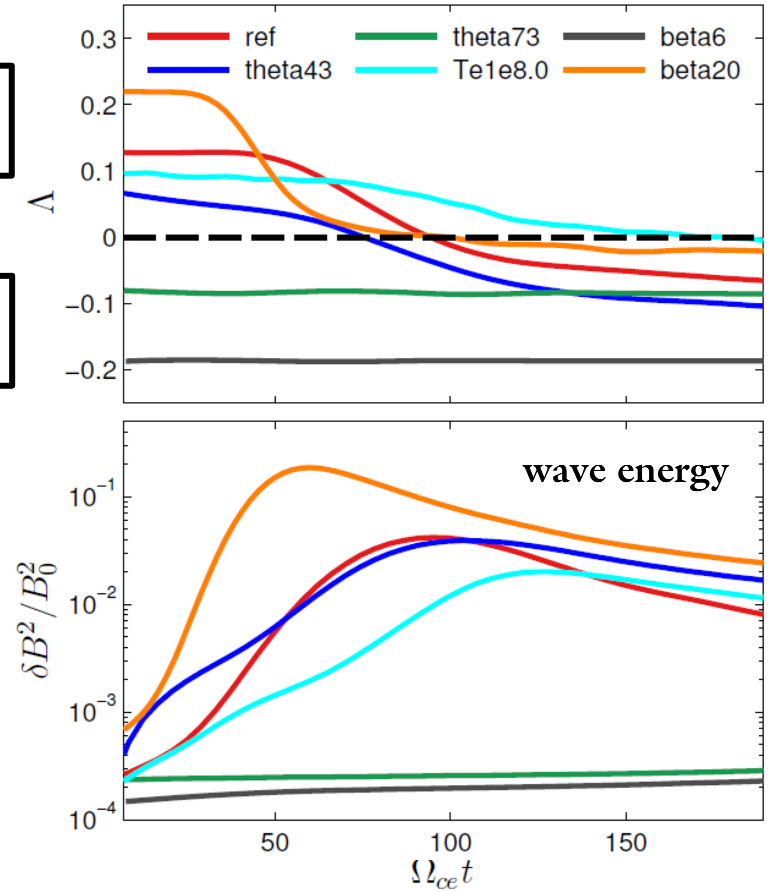
Background magnetic pressure

above threshold, waves grow

below threshold, no waves grow

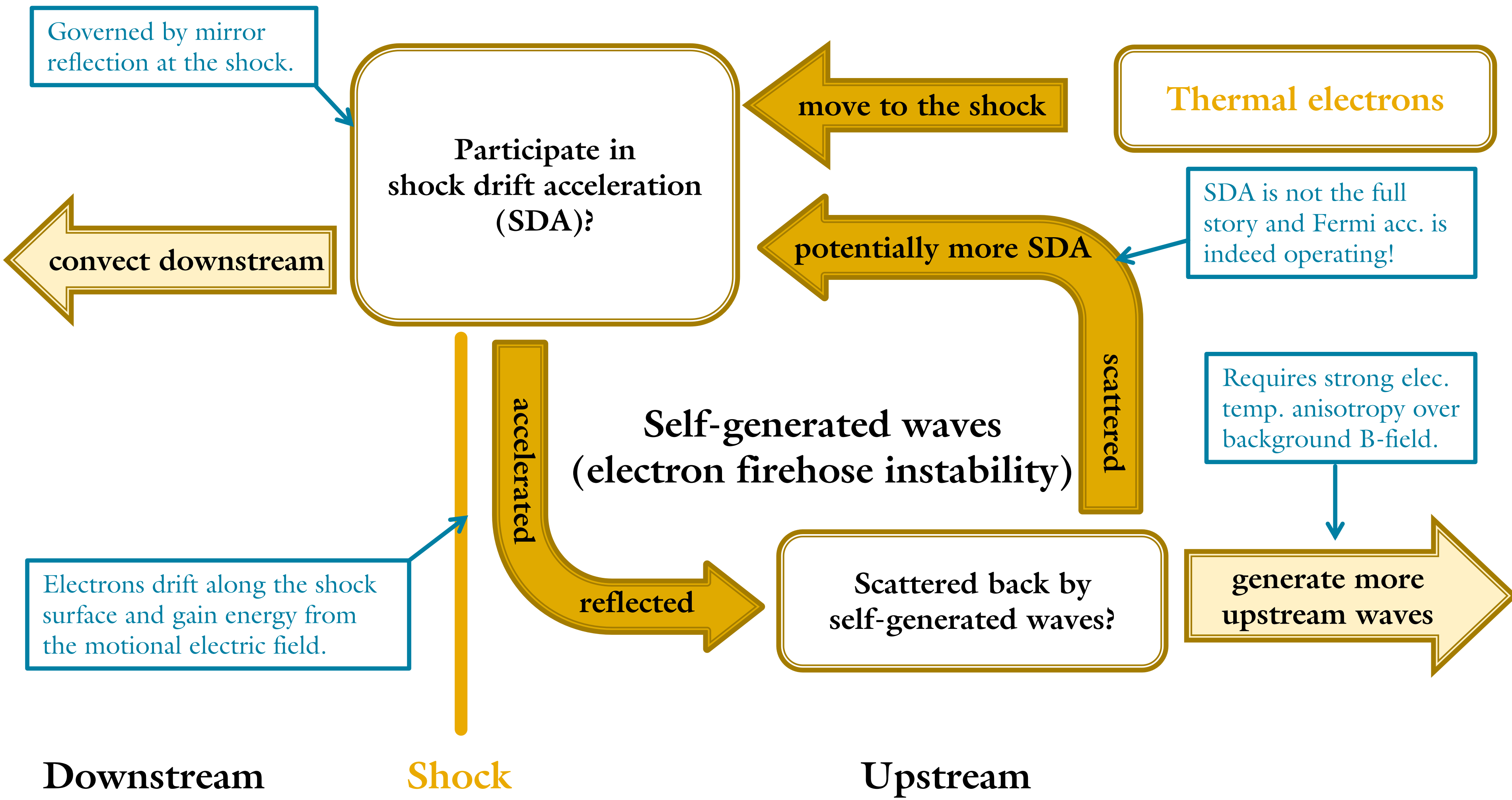
Threshold parameter

$$\Lambda \equiv 1 - \frac{T_{e\perp}}{T_{e\parallel}} - 1.3\frac{B_0^2/8\pi}{n_e k T_{e\parallel}} > 0$$

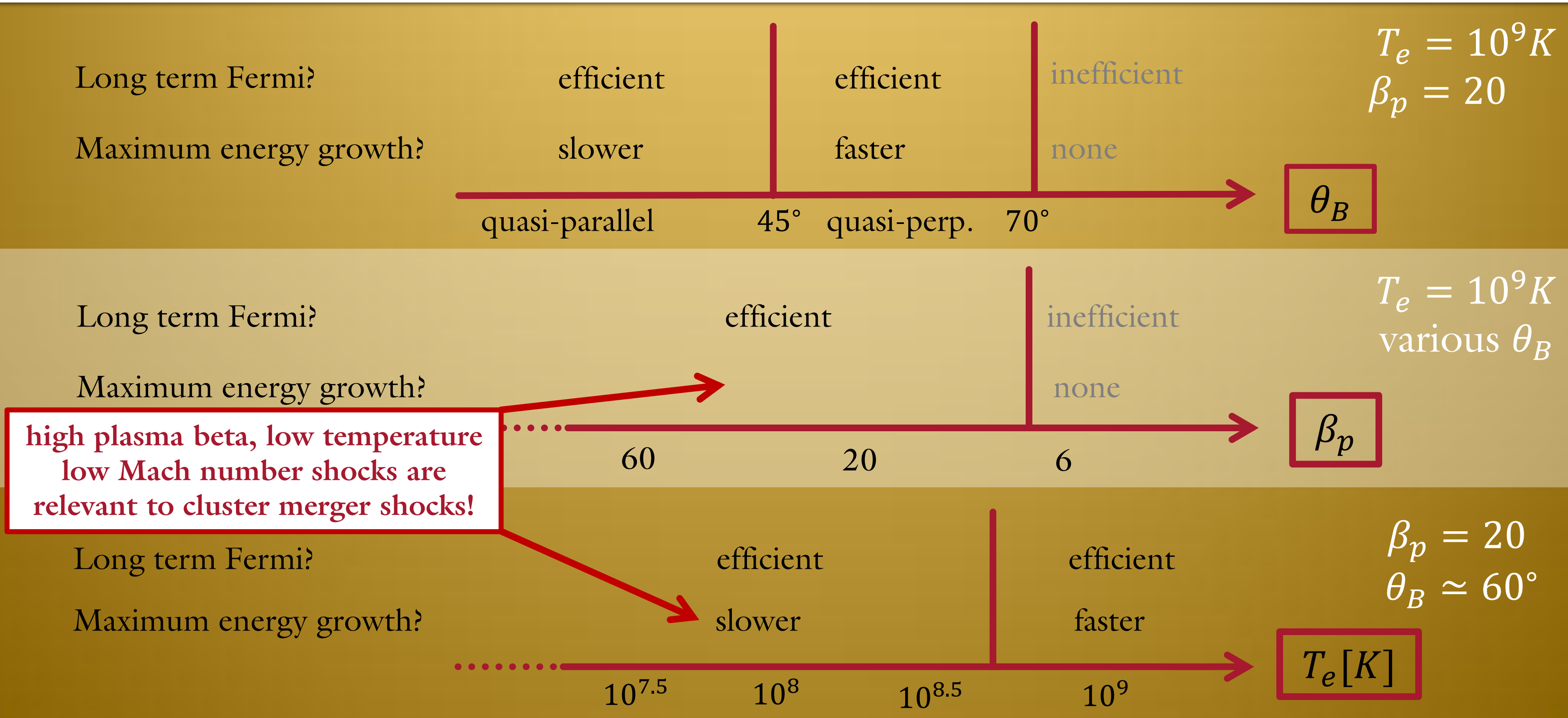


Gary & Nishimura 2003
Campoреale & Burgess 2008

The Big Picture

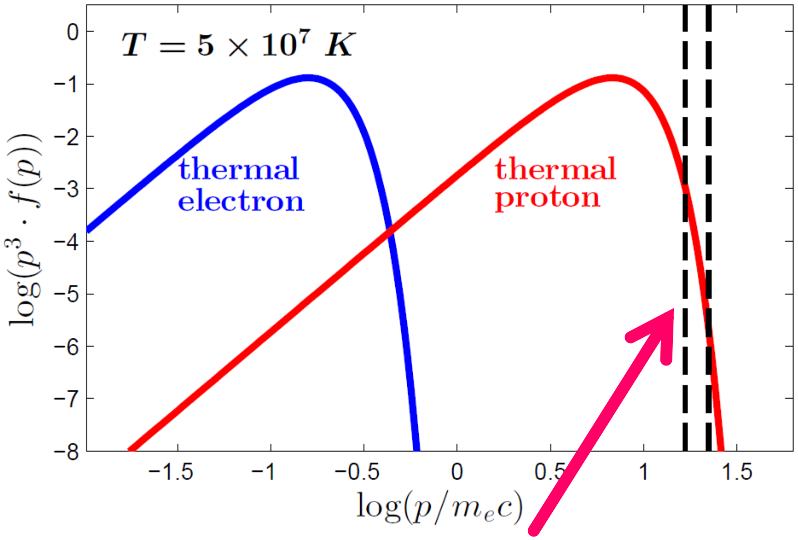


Parameter Dependence

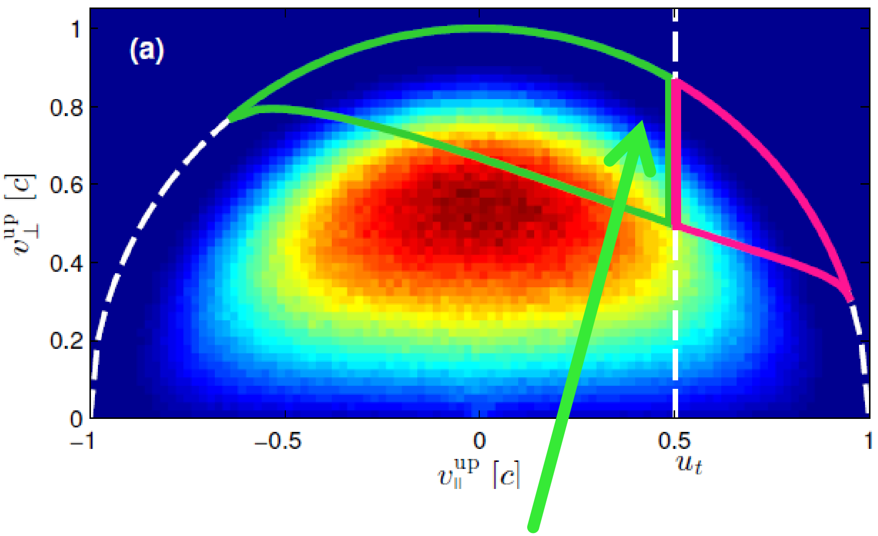


Electron injection problem

direct injection via thermal leakage



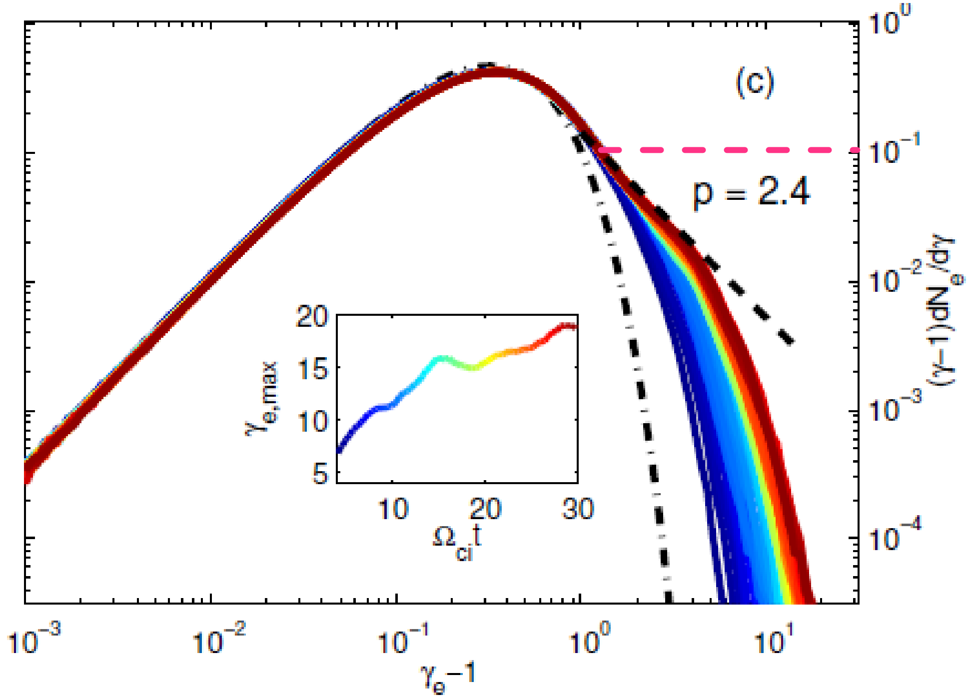
injection into SDA



- Relies on scattering by downstream waves.
- Needs $p_e > p_{th,p}$.
- Electron acceleration efficiency extremely poor.

- Shock itself reflects electrons.
- No need for $p_e > p_{th,p}$.
- Thermal electrons can be easily accelerated.

Electron injection problem



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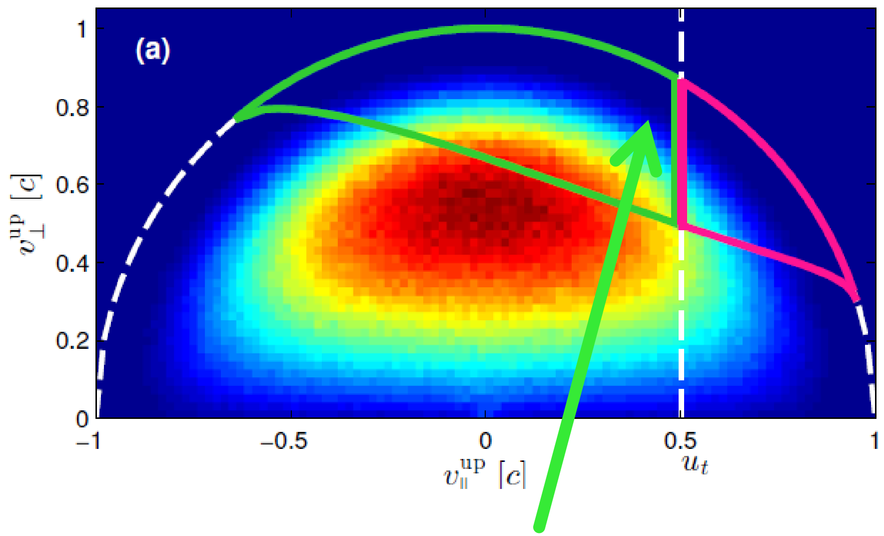

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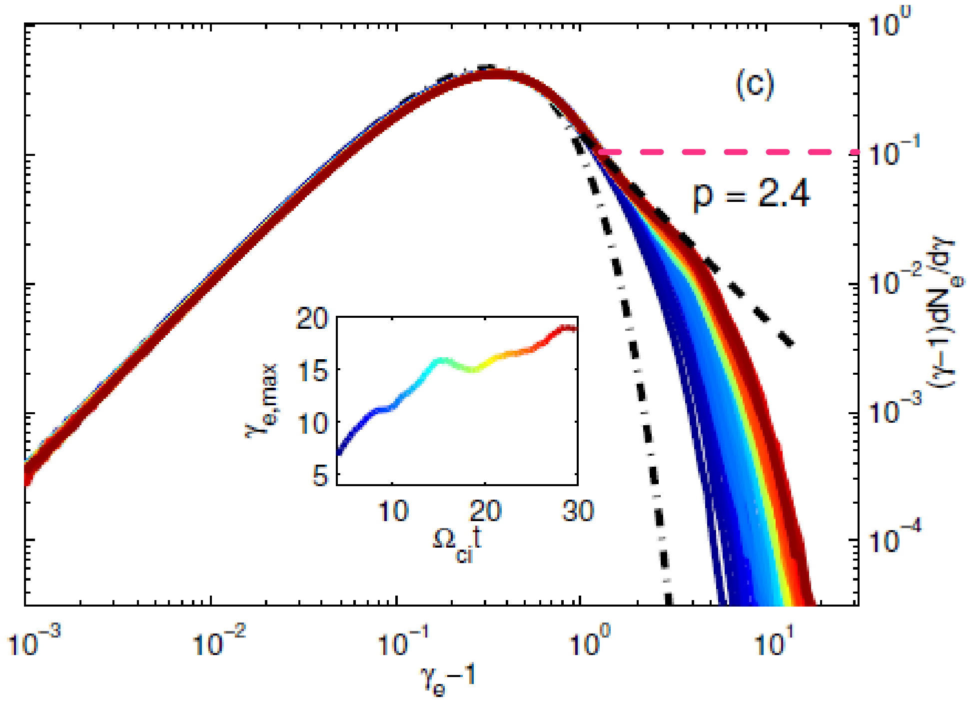
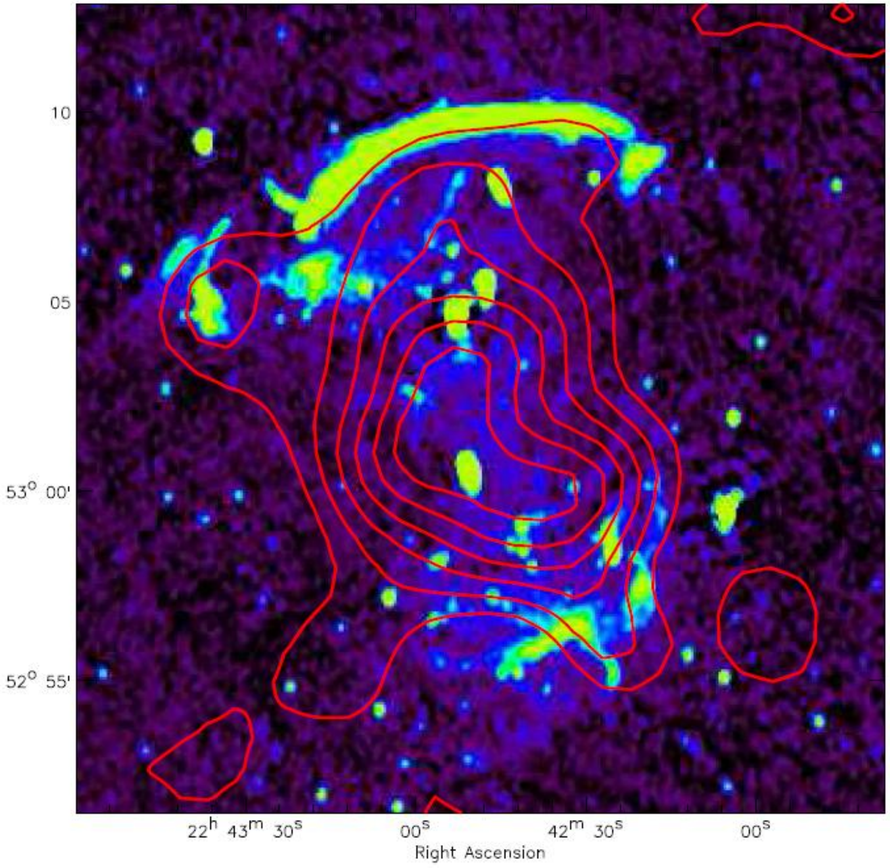


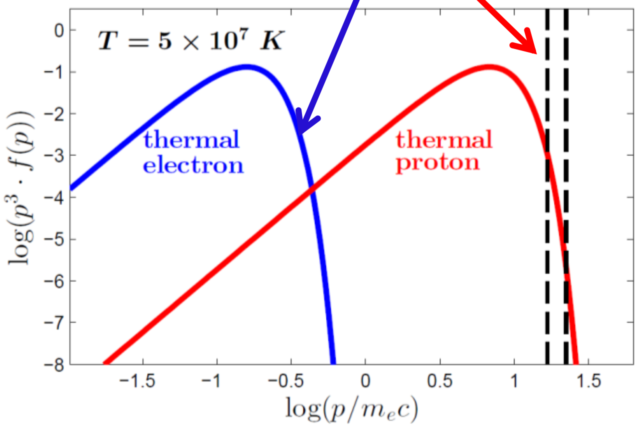


no more tension with observations!

Missing γ-ray from accelerated ions?

CRp/CRe ratio ≪ previously thought

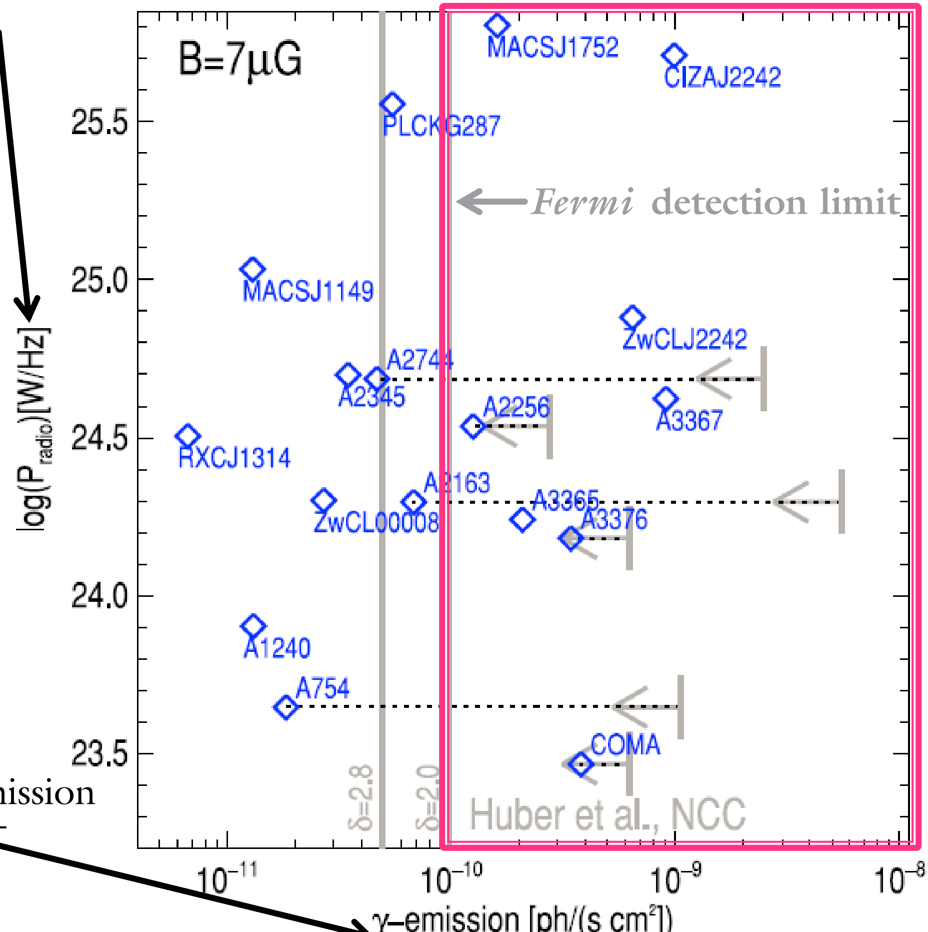
thermal leakage model: a lot more p^+ than e^- could be accelerated



observed radio emission from accelerated e^-

estimated γ-ray emission from accelerated p^+

Above *Fermi* limit, yet no detection!



Vazza & Brüggen 2014

Missing γ-ray from accelerated ions?

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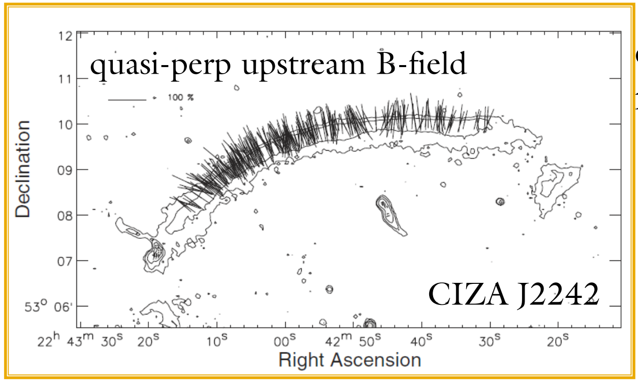

observed radio emission from accelerated e^-

- We find electrons are efficiently accelerated over a wide range of obliquities.
- Ion acceleration is poor in quasi-perp shocks. (Caprioli & Spitkovsky 2014)
- The ratio of ion- to electron-acceleration efficiency is much smaller than previously thought.

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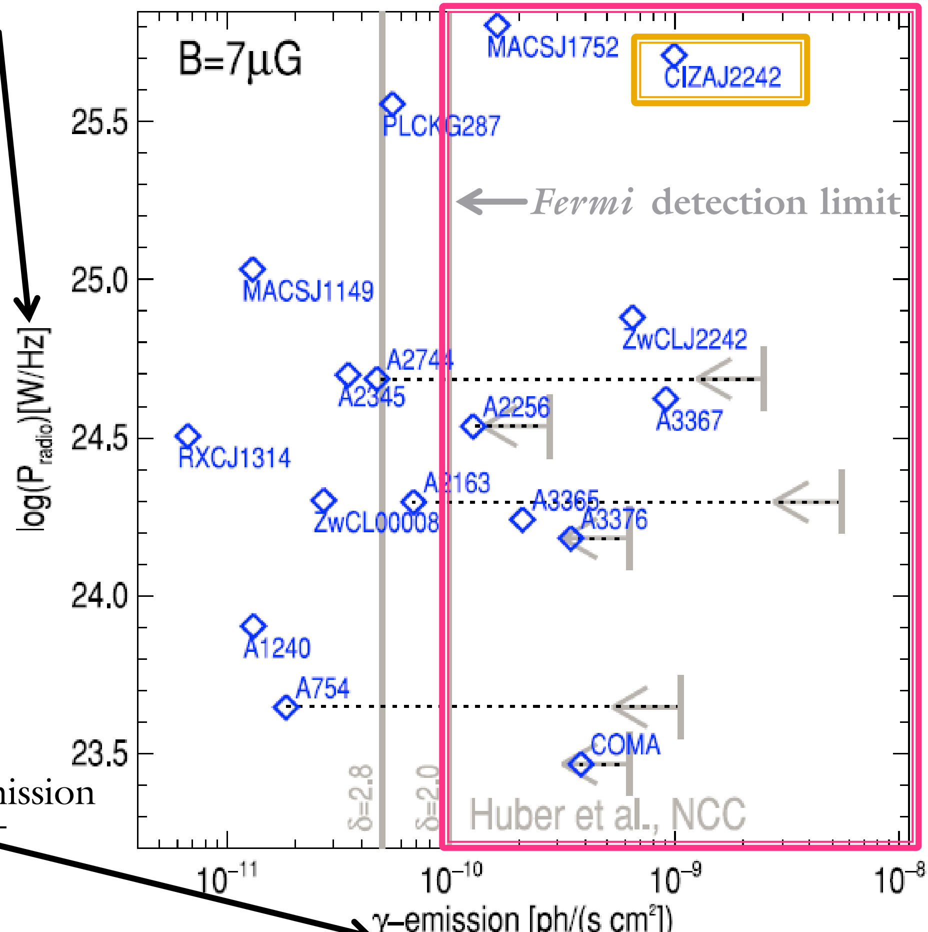

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Vazza & Brüggen 2014

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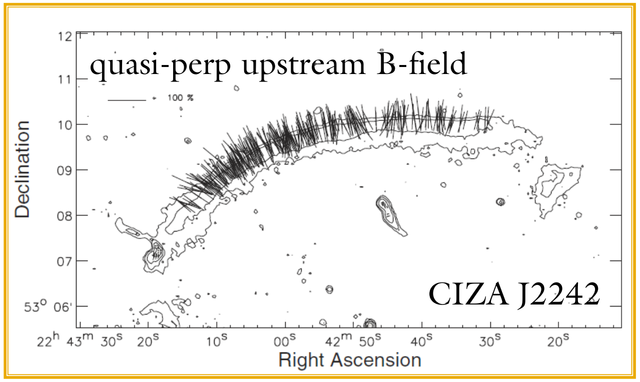

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The expected γ-ray emission from ions is actually lower, consistent with null detections of *Fermi*.

Summary

- Electron acceleration to non-thermal energies at low Mach number shocks are revealed through radio relics, but the mechanism has been poorly understood.
- We study electron acceleration in low Mach number shocks from first principles using the PIC method.
- We identify a Fermi-like electron acceleration mechanism.
- The electrons are efficiently injected into shock drift acceleration (SDA) by mirror reflection at the shock front, they gain energy by multiple cycles of SDA mediated by scattering with self-generated upstream waves associated with oblique electron firehose instability.
- We find that the mechanism can operate over a large range of parameter space, especially relevant for cluster merger shocks.
- Our mechanism naturally explains the bright radio emission from radio relics, and alleviates tension with null detection of gamma-ray from merger shocks through *Fermi*.

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2014arXiv1409.7393