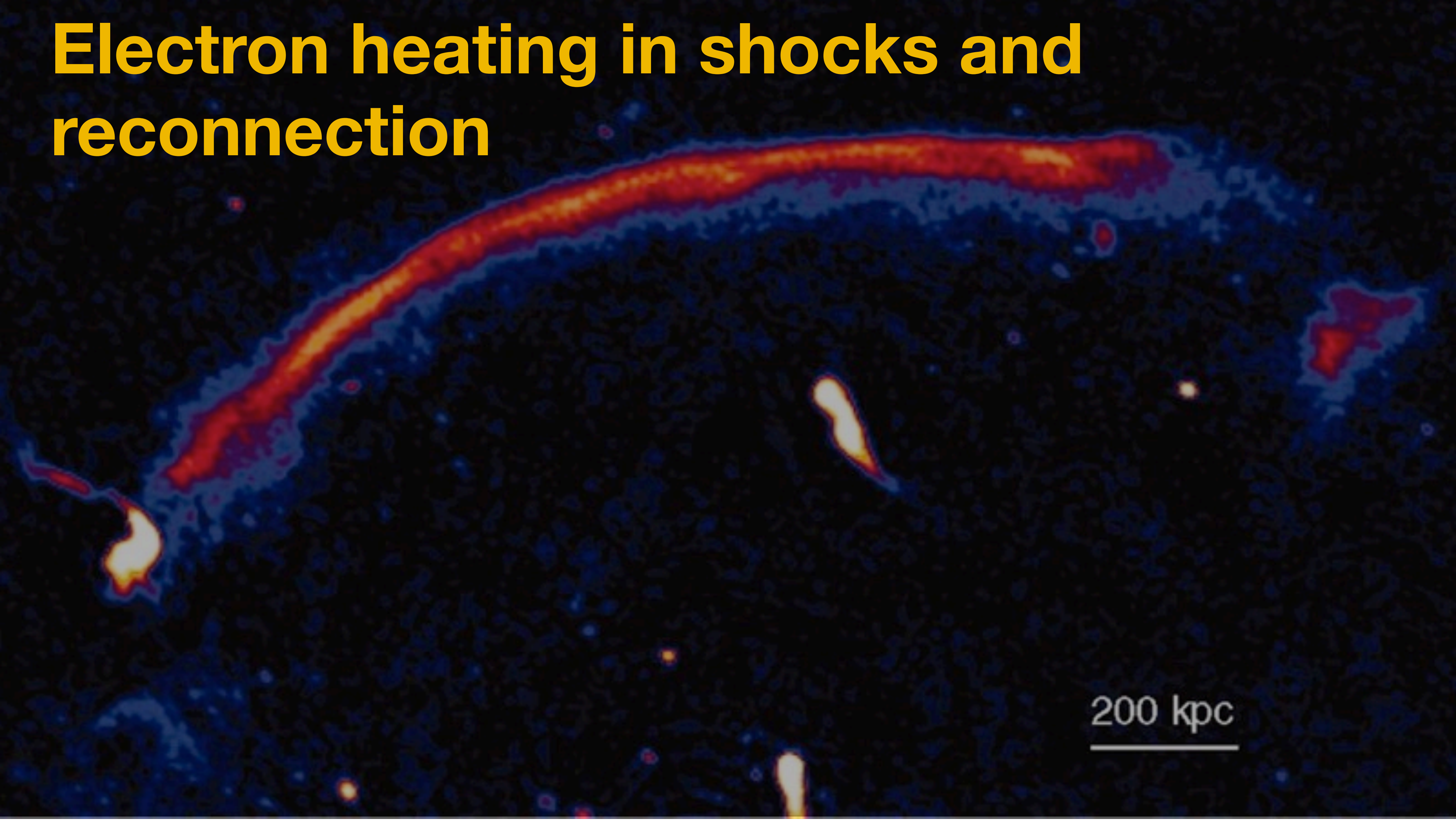
Electron heating in shocks and reconnection



11th Plasma Kinetics Working Meeting, **Vienna, July 23rd 2018**

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Electron Heating in Shocks

The physical motivation

- Rankine-Hugoniot relation only determines the mean post-shock temperature.
- How is the shock heating distributed between electrons and protons?
- More massive protons dominate energy flux. Naively, one would expect

$$T_{e2}/T_{i2} \simeq m_e/m_i \ll 1$$

- Electrons will be at least heated adiabatically through shock compression

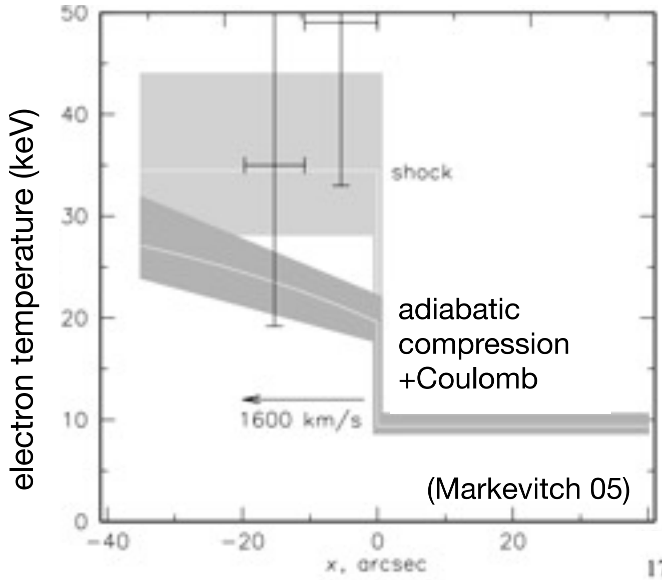
$$T_{e2,\mathrm{ad}} \leq T_{e2} \leq T_{i2}$$

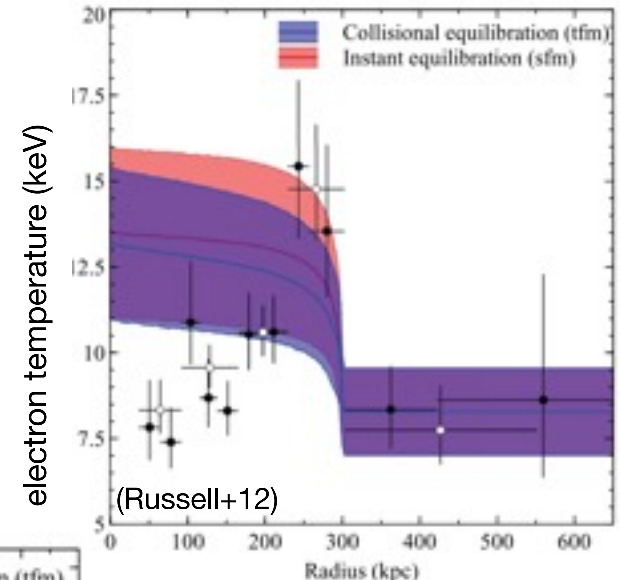
- Can *collisionless* processes heat electrons beyond adiabatic? What is the mechanism and how does it depend on flow conditions?

High-beta Shocks

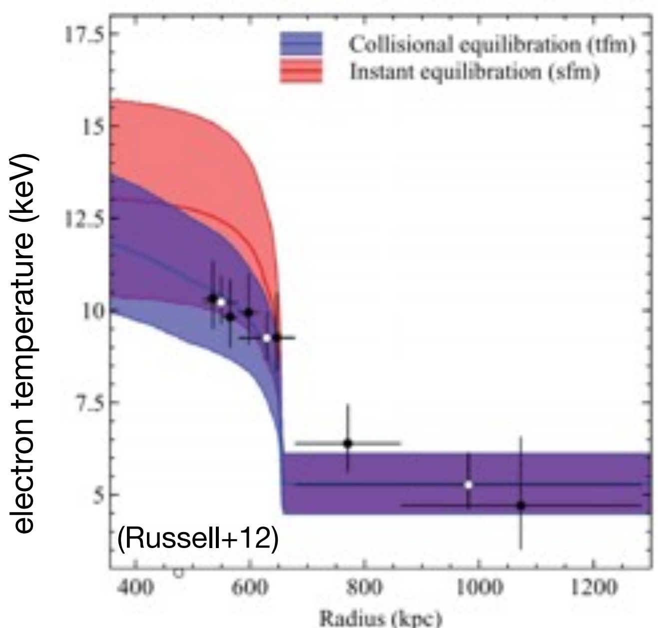
The observational motivation

In some merger shocks in galaxy clusters (high beta), electrons are heated to equipartition.





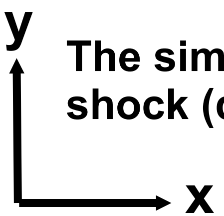
But not always!



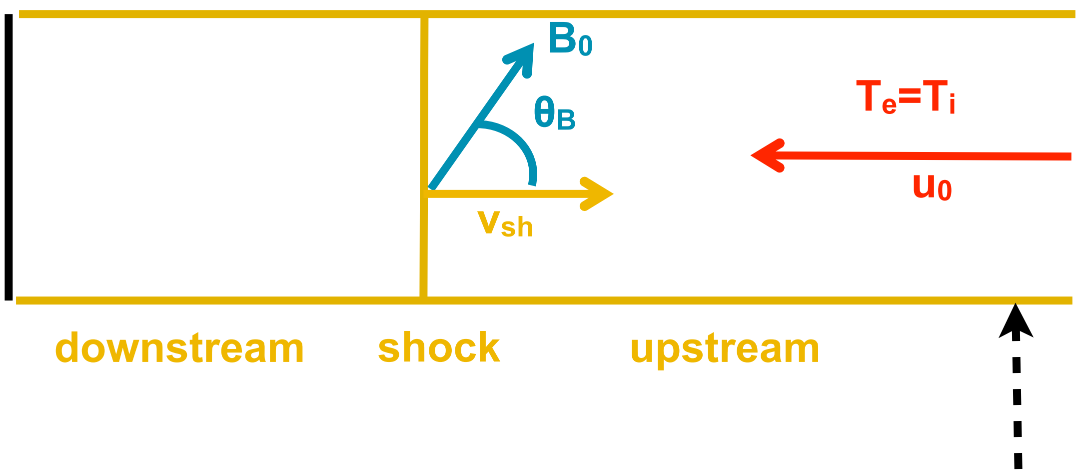
Simulation Setup

2D simulations of high beta, low Mach number shocks

Particle-in-Cell Code: TRISTAN-MP (Buneman 93, Spitkovsky 05)



The simulation is performed in the post-shock (downstream) rest frame



The electron and ion distributions are initialized as drifting Maxwellians

Mach number: $M_s = \dfrac{u_0 + v_{sh}}{c_s} = 3$

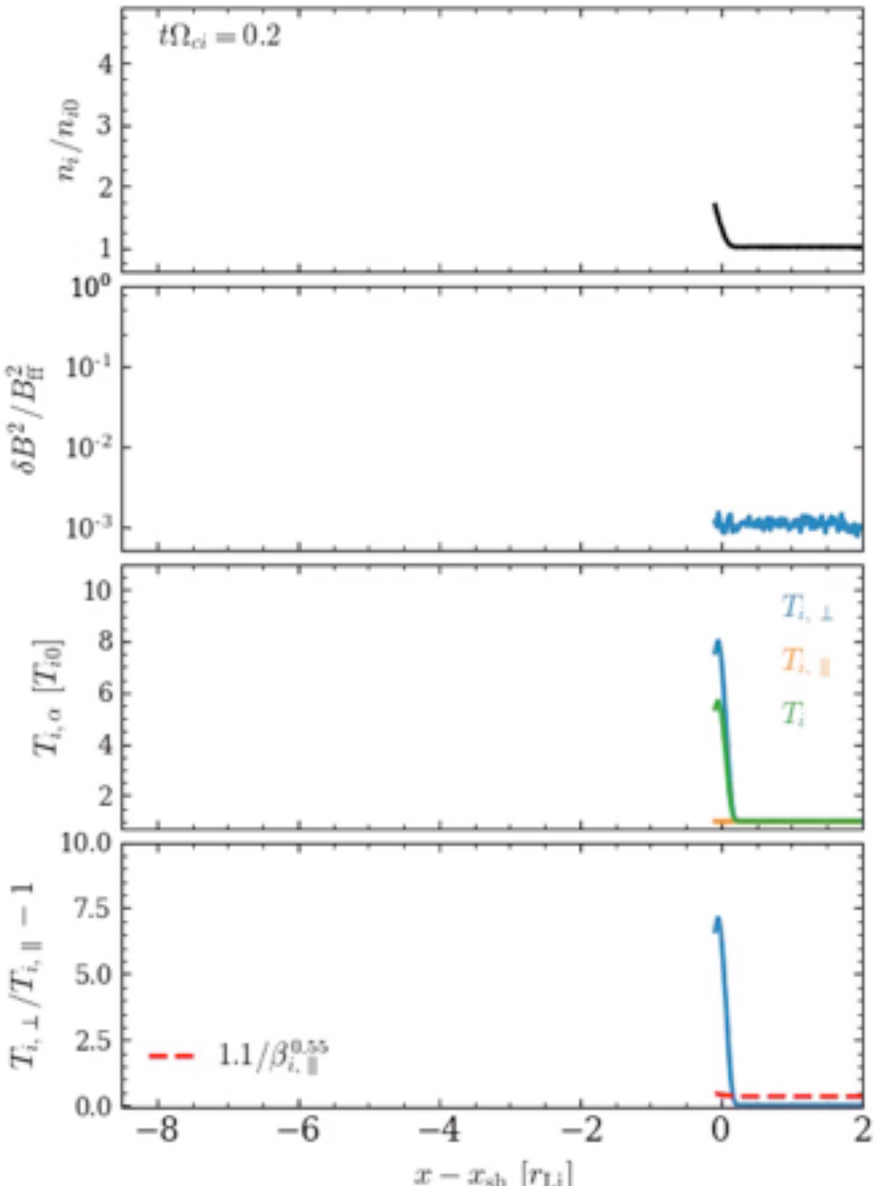
plasma beta : $\beta_p = \dfrac{n k_B (T_i + T_e)}{B_0^2/8\pi} = 16$

Magnetic obliquity θ_B =90 deg

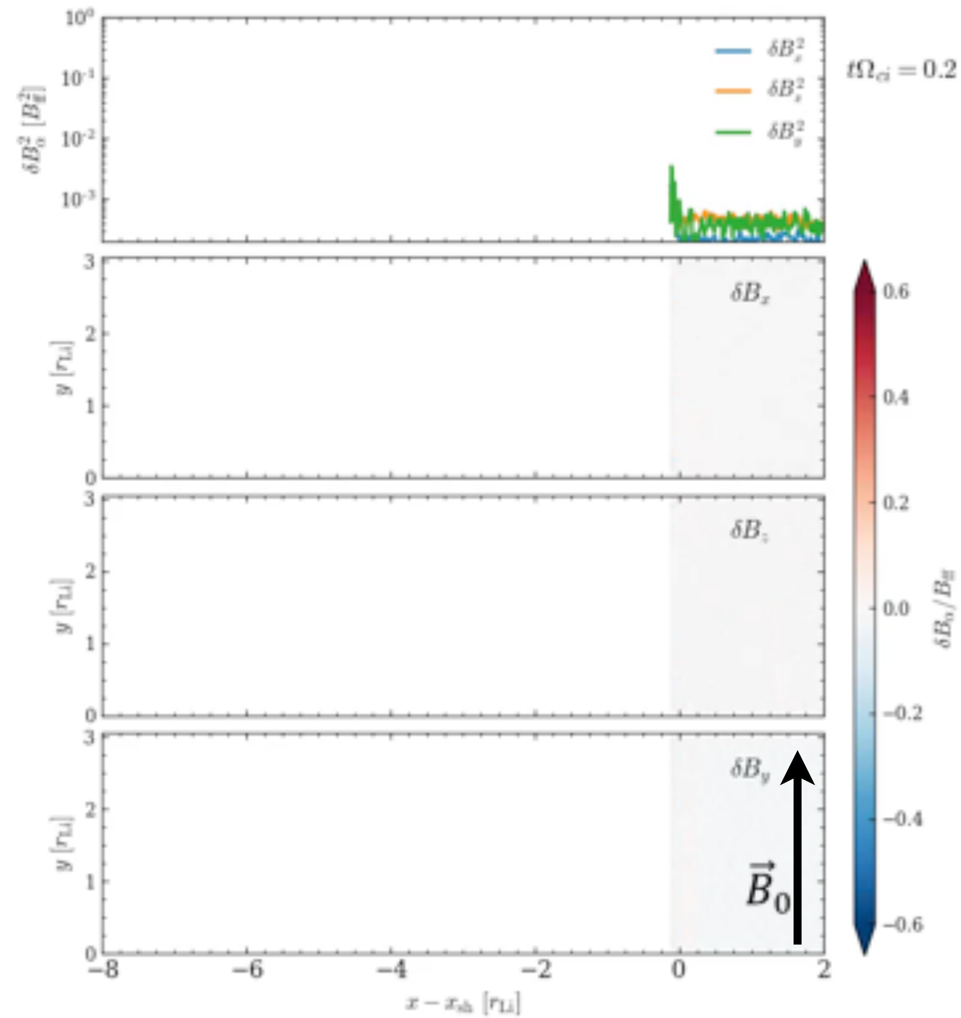
[mass ratio m_i/m_e]

Shock Structure (protons)

Reference run with M_s=3, β=16 and θ_B=90˚ (perp shock)



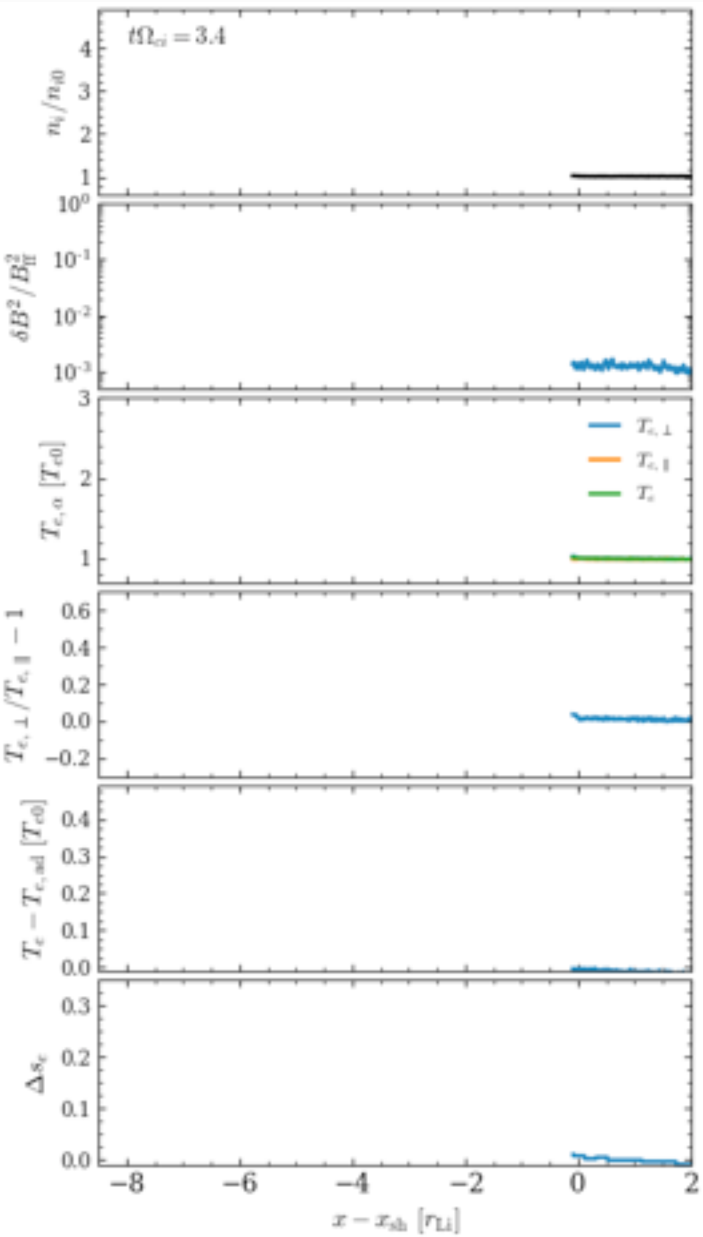
(Guo, Sironi, Narayan 2017a)

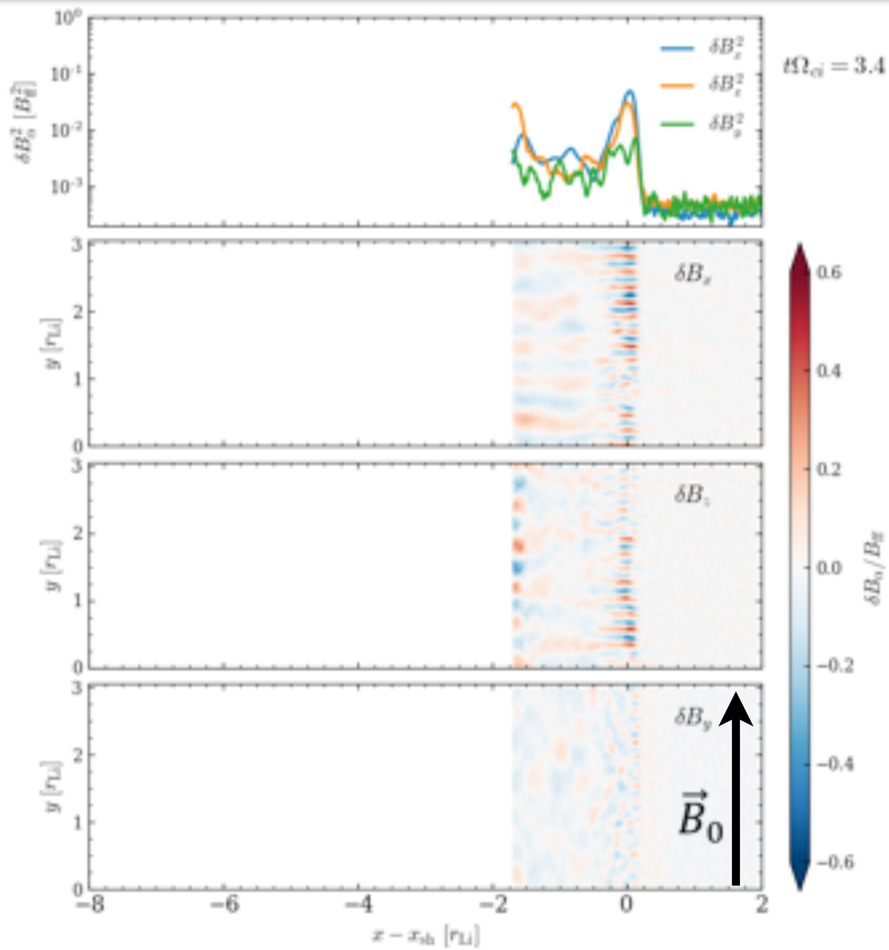


The proton temperature anisotropy drives strong long-wavelength magnetic waves (mirror and proton cyclotron modes) in the downstream.

Shock Structure (electrons)

Electron-driven waves and entropy increase





Flux freezing:

$$B \propto n$$

Double adiabatic:

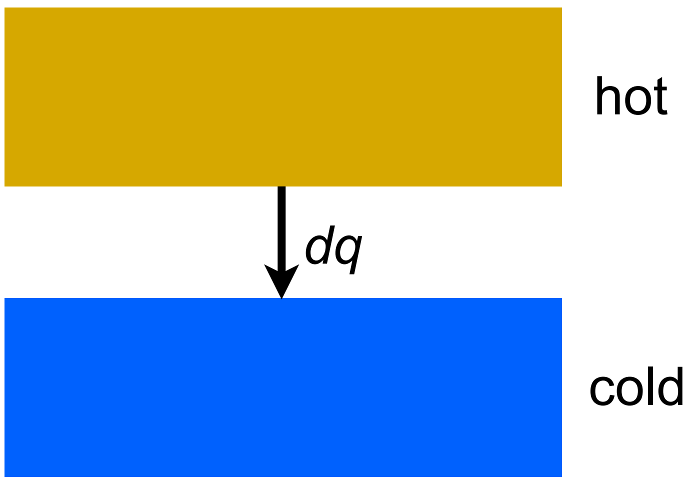
$$T_{e,\perp} \propto B$$

$$T_{e,\parallel} \propto (n/B)^2$$

- The electron temperature anisotropy at the shock drives short-wavelength (whistler) waves.
- Two preferential locations of entropy generation: (1) at the shock, and (2) where proton waves grow.

Electron heating

Two heat reservoirs, one transfer mechanism



What are the two heat reservoirs?

$\boxed{T_{e,\perp} \propto B}$ As a result of shock compression coupled with flux freezing, B increases → $T_{e,\perp}$ increases.

$\boxed{T_{e,\|} \propto (n/B)^2}$ From flux freezing, $T_{e,\|}$ stays the same.

What is the mediator of *dq*?

We need a mechanism to scatter electrons in pitch angle, so that $T_{e,\|}$ increases at the expense of $T_{e,\perp}$ (i.e., a mechanism to break adiabatic invariance).

Whistler waves! (self-consistently generated due to $T_{e,\perp} > T_{e\,\|}$**)**

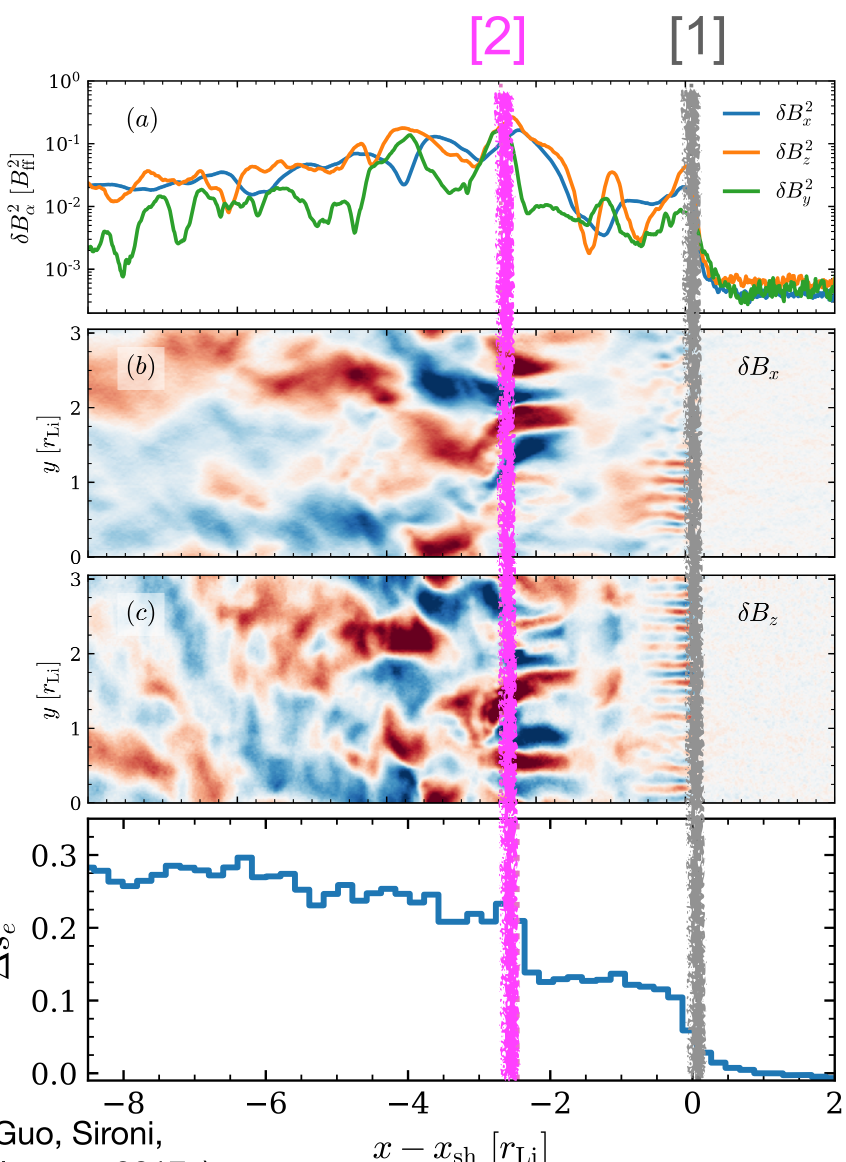
Model for entropy increase:

$$ds_e = \boxed{\left[\frac{1}{2} d\ln\left(\frac{T_{e,\|}}{(n/B)^2}\right)\right]} \boxed{\left(1 - \frac{T_{e,\|}}{T_{e,\perp}}\right)} - \frac{de_{w,e}}{T_{e,\perp}}$$

Two ingredients:
(a) temperature anisotropy
(b) breaking of adiabatic invariance

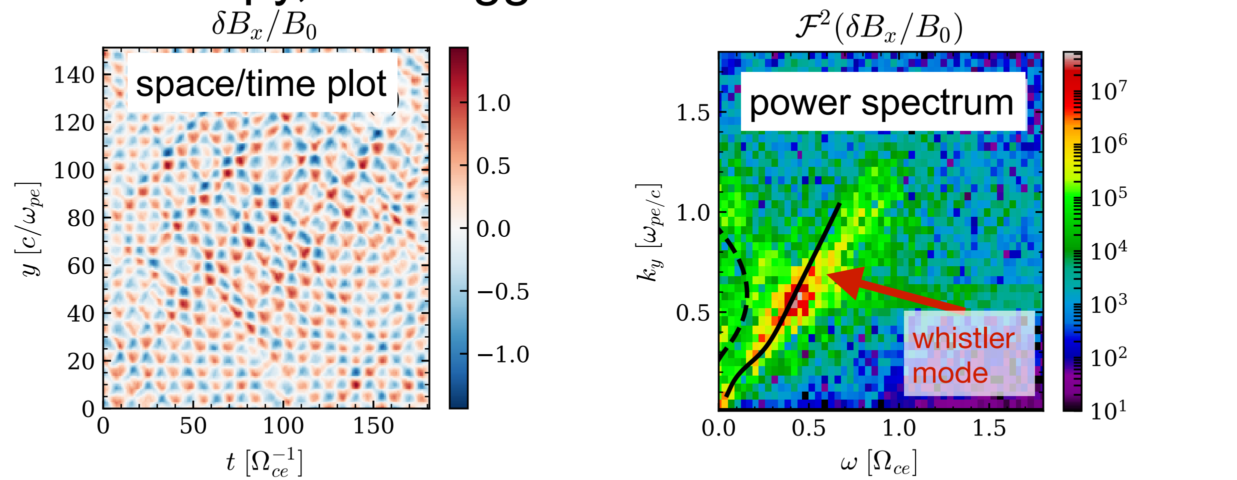
Whistler waves

Whistlers are present where entropy increases

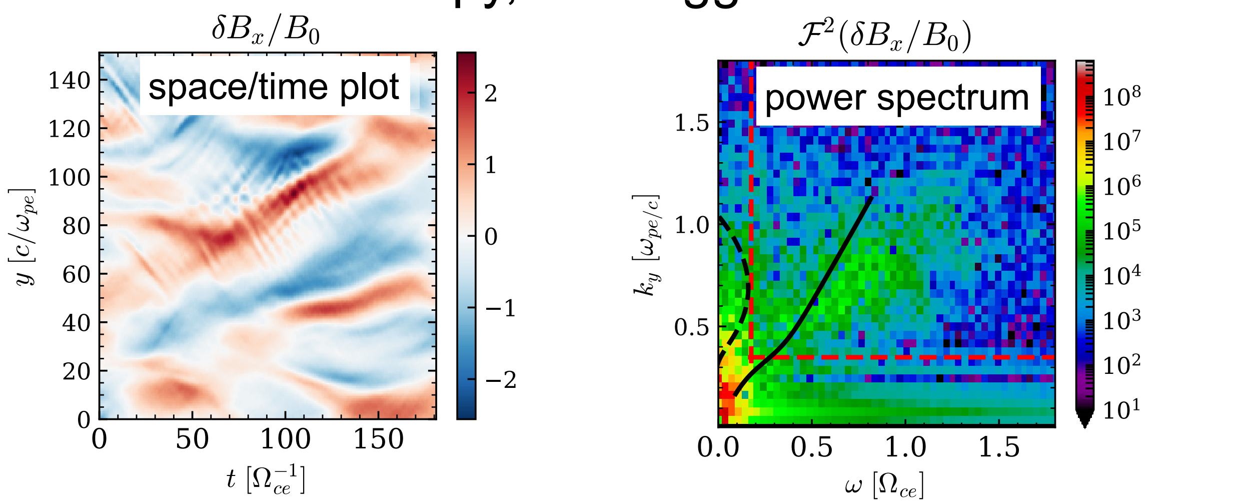


(Guo, Sironi, Narayan 2017a)

In [1], shock compression induces electron anisotropy, that triggers whistler waves.



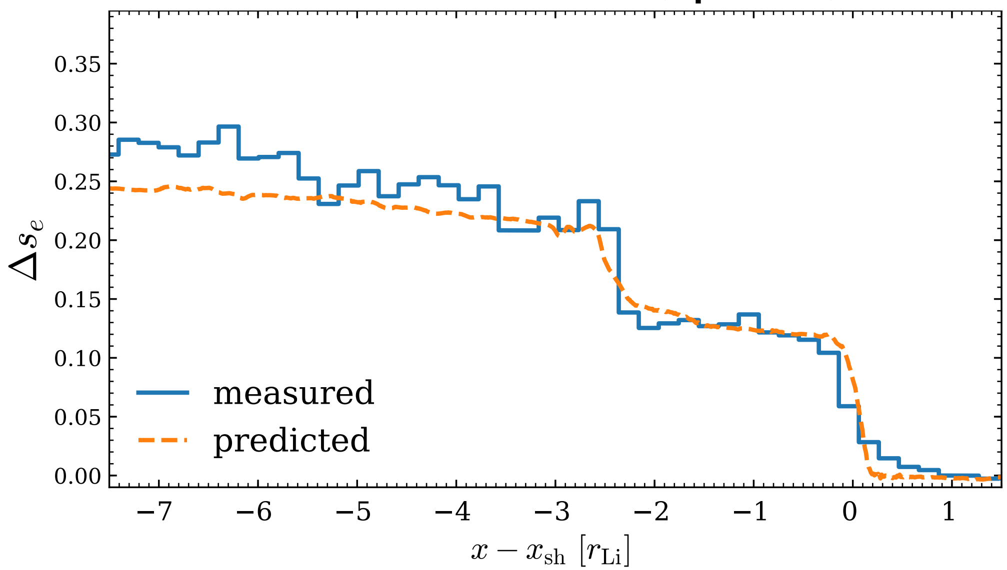
In [2], field amplification by proton modes induces electron anisotropy, that triggers whistlers.



Model vs simulation

The heating model agrees well with PIC results

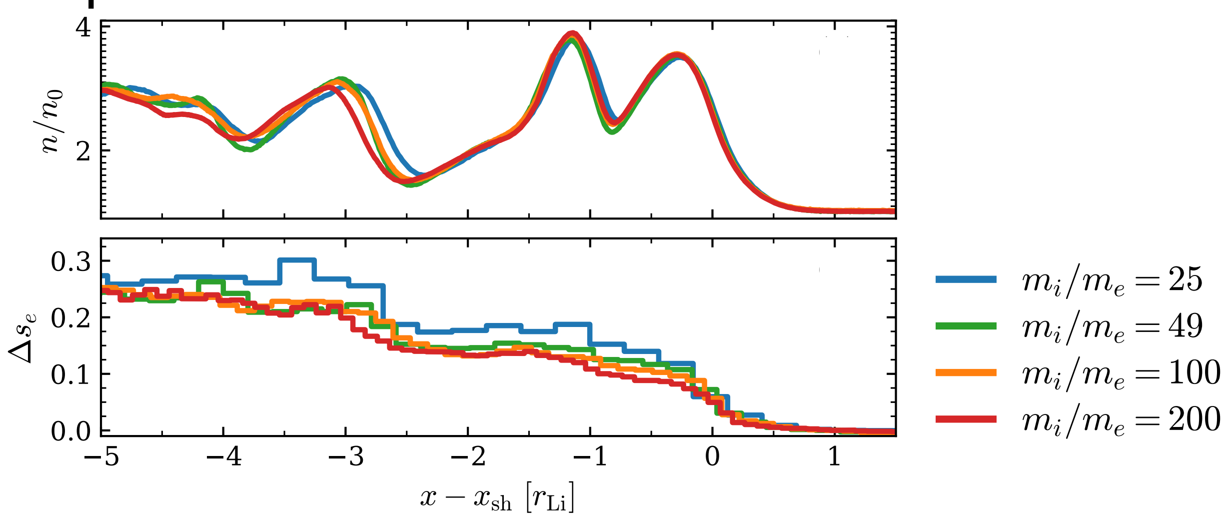
Reference run with M_s=3, β=16, θ_B=90˚ (perp shock) and m_i/m_e=49



(Guo, Sironi, Narayan 2017a)

Our model correctly predicts both the **location** and **magnitude** of electron entropy increase.

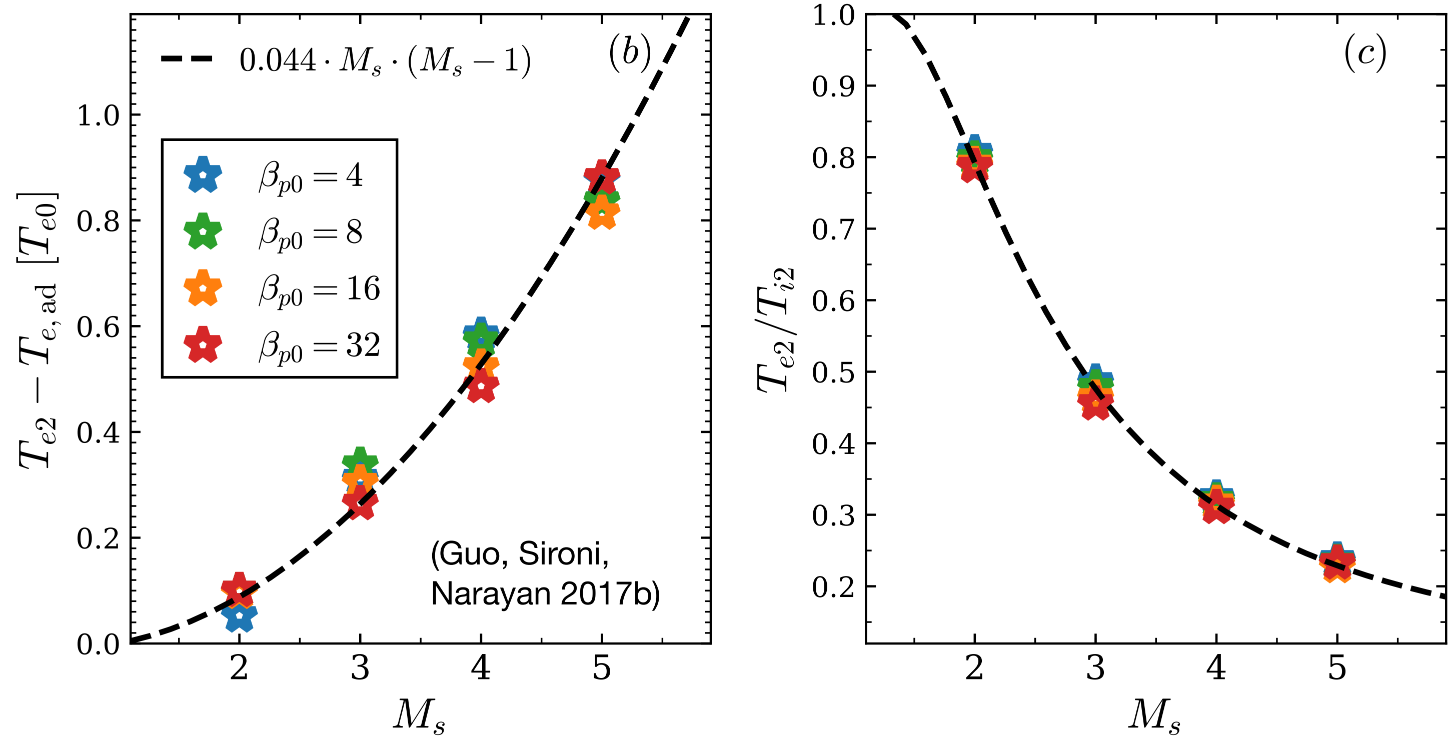
Dependence on mass ratio



The entropy increase is remarkably independent of mass ratio.

Dependence on beta and Mach

The efficiency of irreversible heating is higher at larger M_s



The post-shock temperature is above the 3D adiabatic expectation by

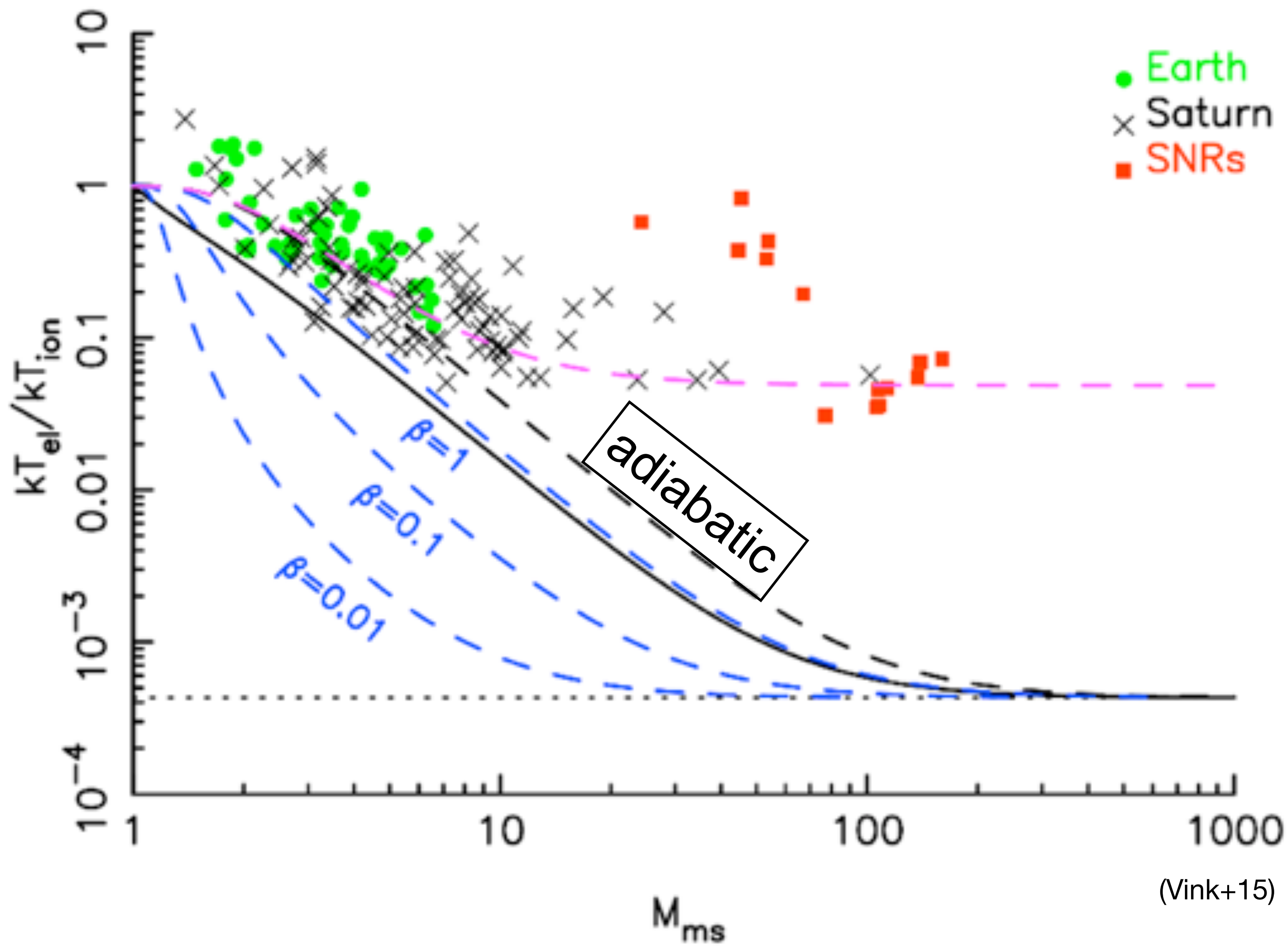
$$\frac{T_{e2} - T_{e,ad}}{T_{e0}} \simeq 0.044\, M_s\, (M_s - 1)$$

[caveat: we expect some dependence on the field obliquity, with θ_B=90˚ giving a lower limit in electron entropy increase]

Low-beta Shocks

The observational motivation

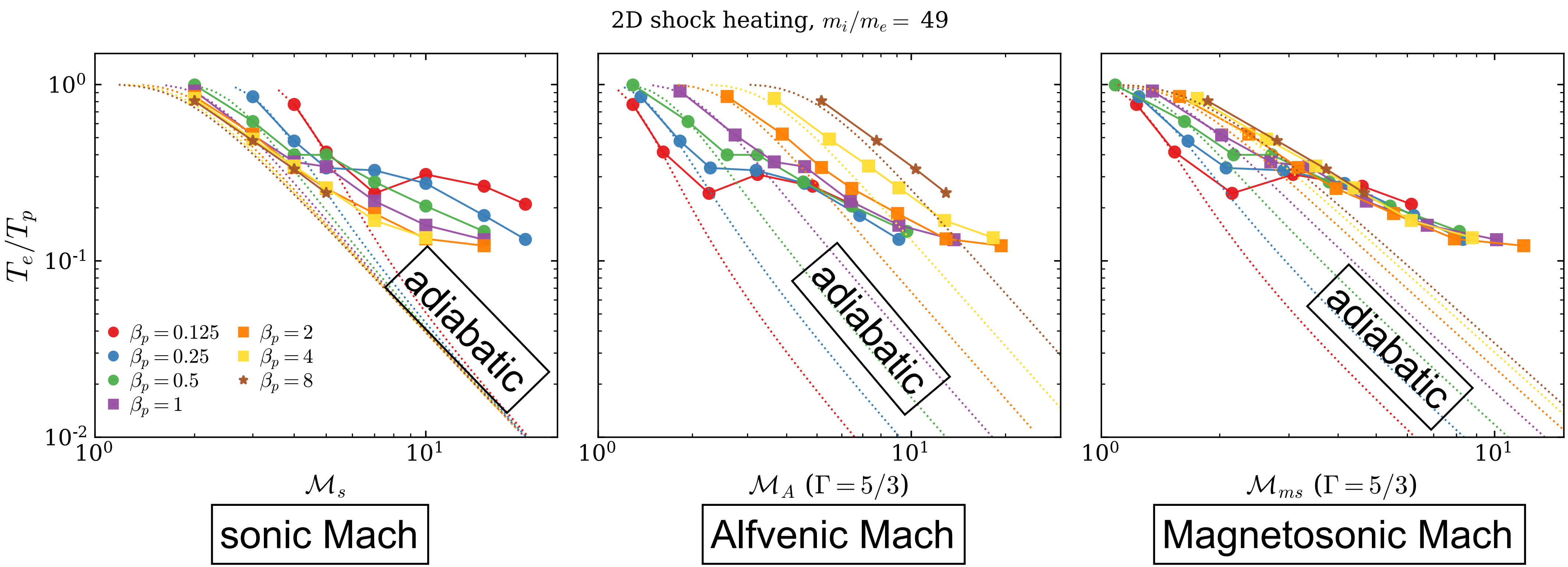
Evidence of non-adiabatic electron heating in Earth and Saturn bow shocks (beta~1).



(Vink+15)

Low-beta Shocks

Electron-proton temperature ratio

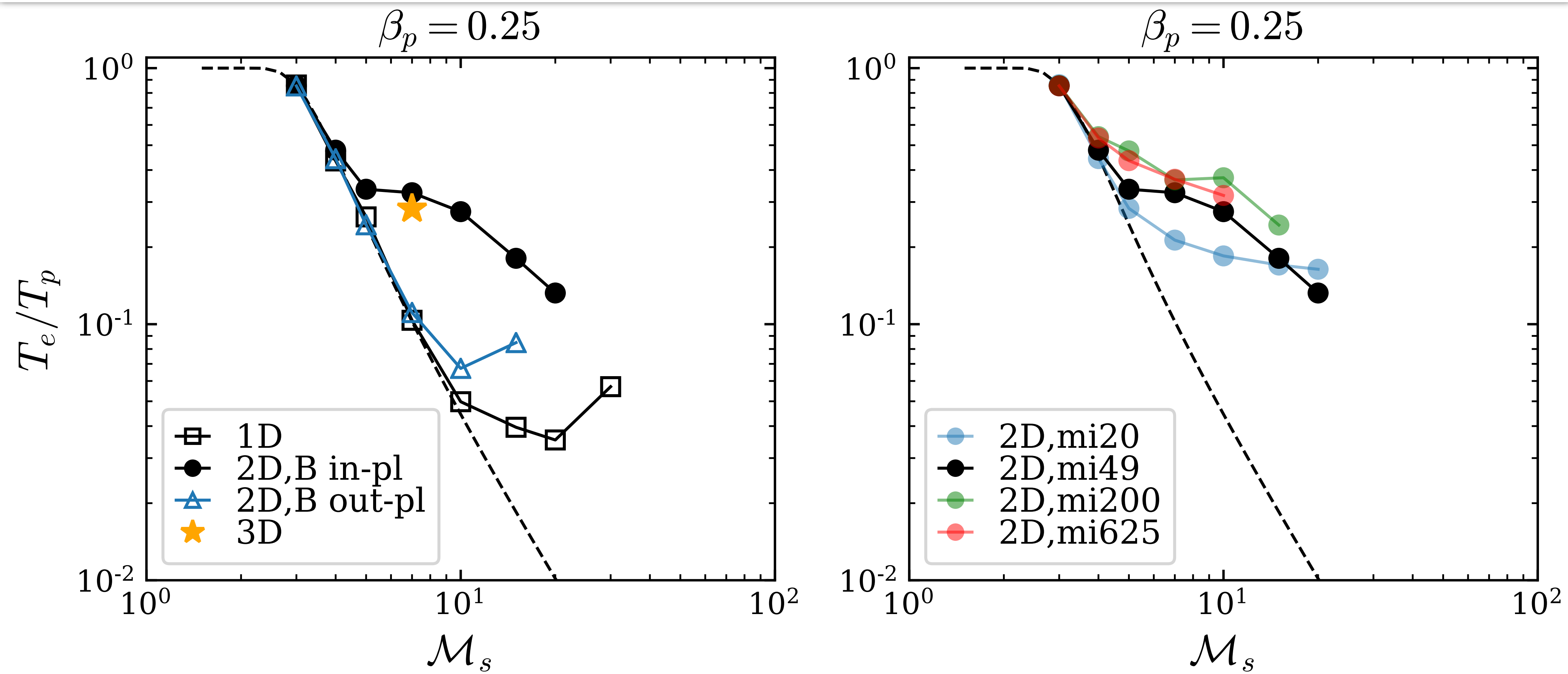


- Lower beta shocks show a larger deviation from the adiabatic expectation.

- Evidence for a “universal” electron-to-proton temperature ratio as a function of the magnetosonic Mach number.

Dimensionality and mass ratio

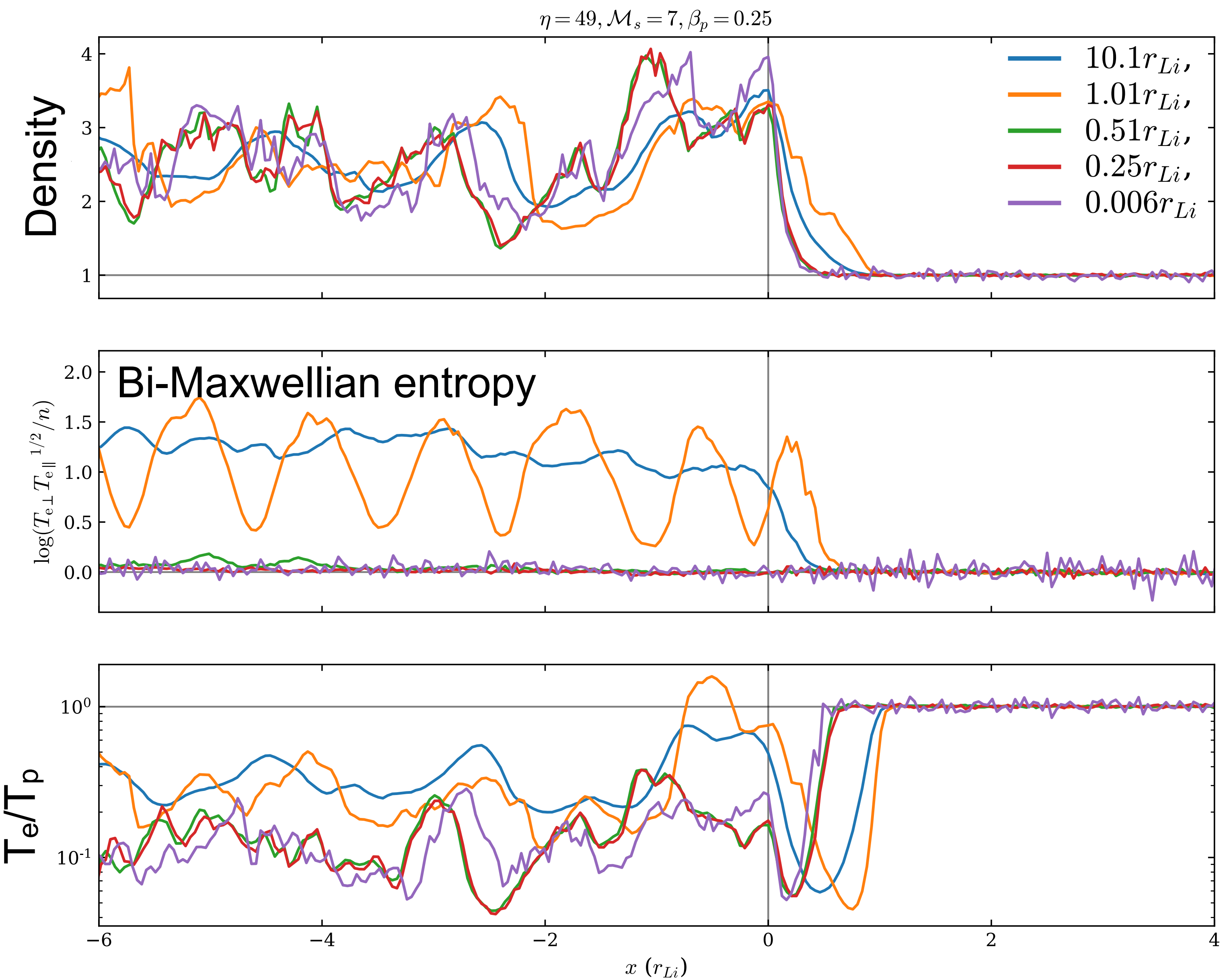
1D not sufficient; 2D ok, independently of the mass ratio



- 1D simulations are insufficient to capture the relevant physics, as well as 2D with out-of-plane field.
- 2D with in-plane background field is consistent with 3D.
- Electron-to-proton temperature ratio is nearly independent of mass ratio.

Hints on the heating physics

Width of the simulation box

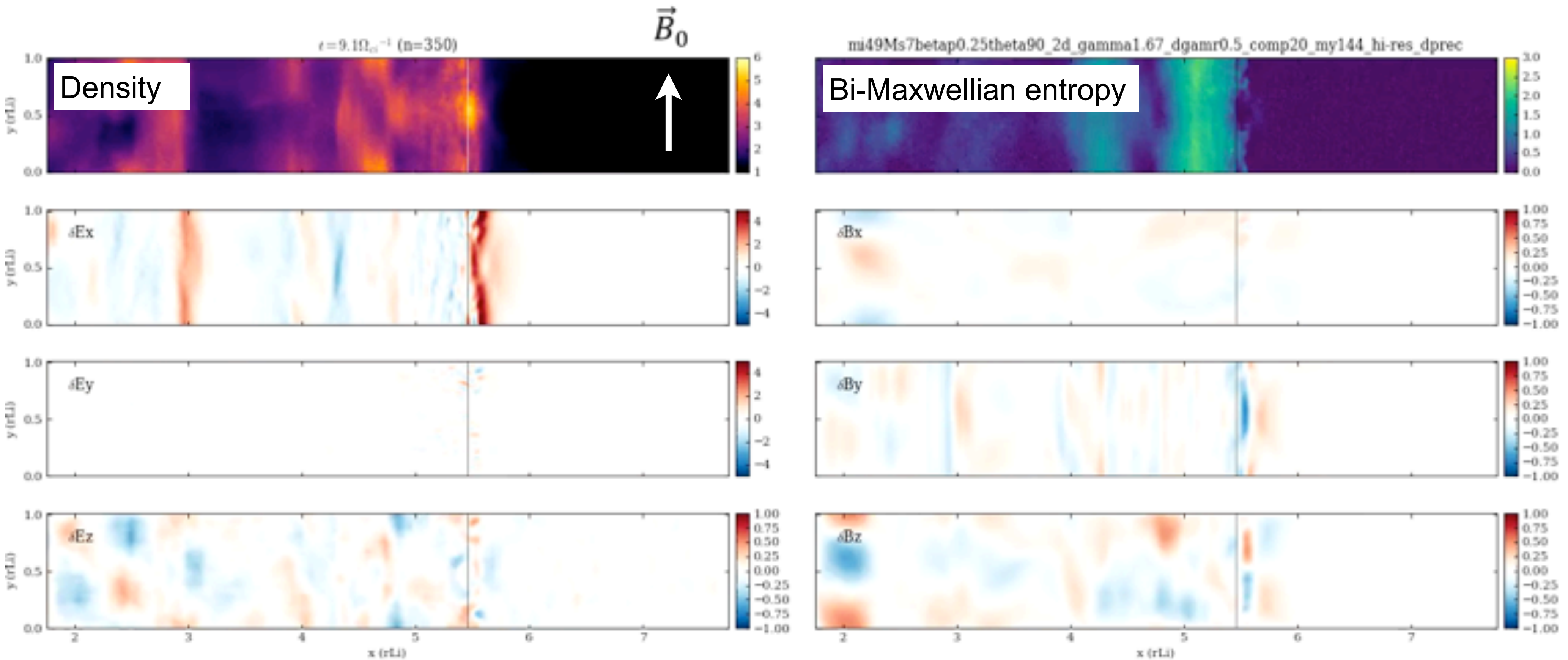


- Substantial electron heating only when the 2D simulation box is wider than ~ 1 proton Larmor radius.

- Electron heating happens in "cycles".

Hints on the heating physics

Shock reformation and rippling



• Electron heating cycles are correlated with the shock reformation and rippling.

• Evidence for electron-scale waves during heating episodes,
with component of E along the background B. No ID yet.

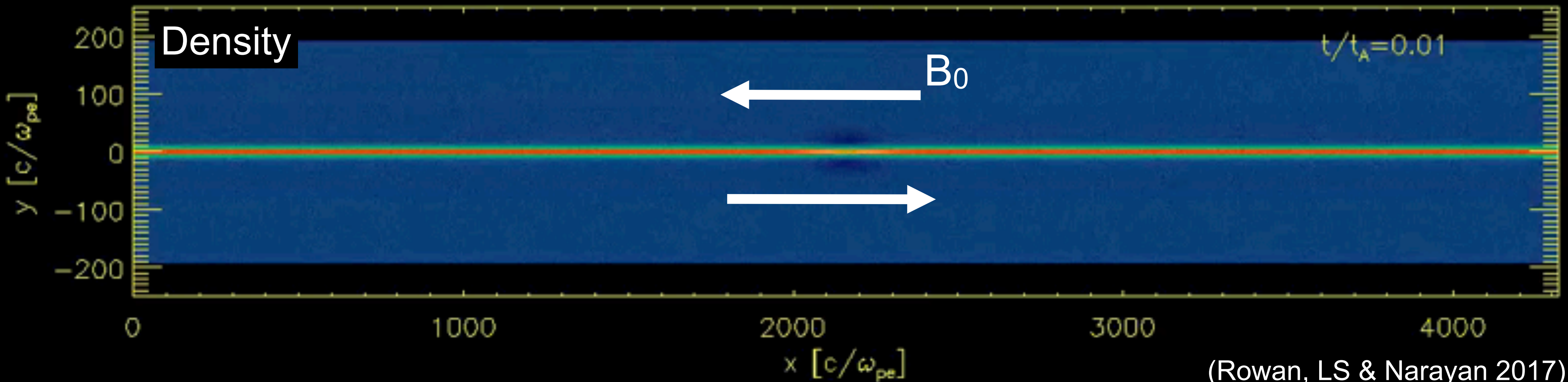
Electron and proton heating in trans-relativistic reconnection (sigma~1)

As a function of beta, sigma, and the guide field strength

$$\beta = \frac{8\pi n_0 k_B T}{B_0^2} \qquad \sigma = \frac{B_0^2}{4\pi w} \qquad B_g/B_0$$

Dependence on beta

σ=0.1 β=0.01, realistic mass ratio, ZERO guide field

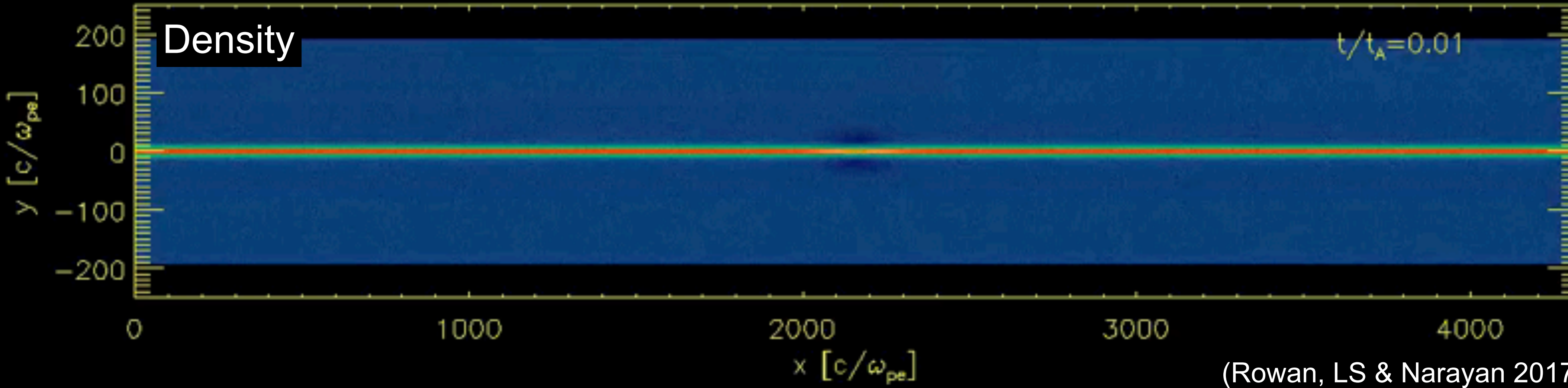


(Rowan, LS & Narayan 2017)

- Low beta: the outflow is fragmented into a number of secondary plasmoids.

Dependence on beta

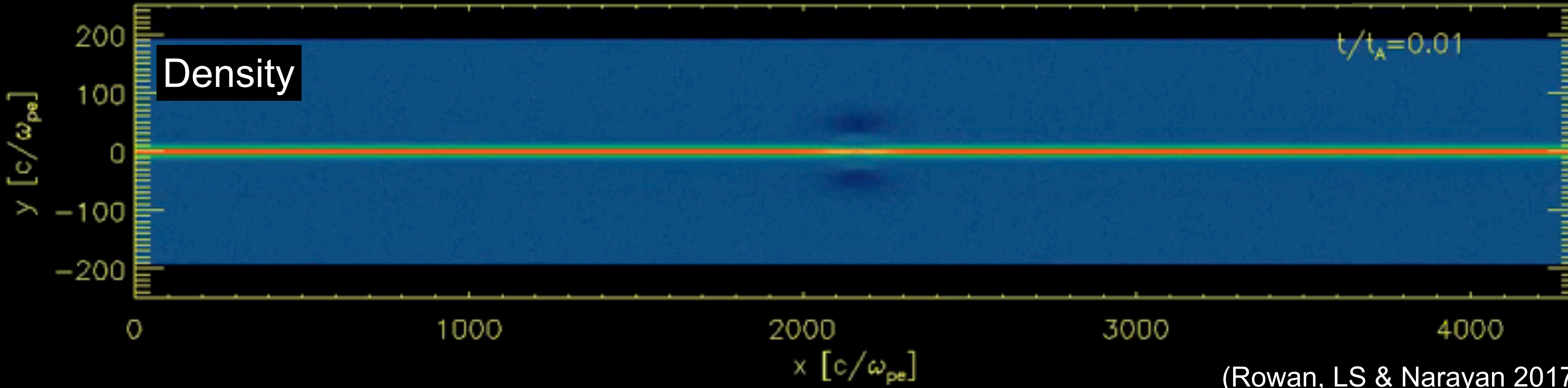
σ=0.1 β=0.01, realistic mass ratio, ZERO guide field



(Rowan, LS & Narayan 2017)

- Low beta: the outflow is fragmented into a number of secondary plasmoids.

σ=0.1 β=2, realistic mass ratio, ZERO guide field

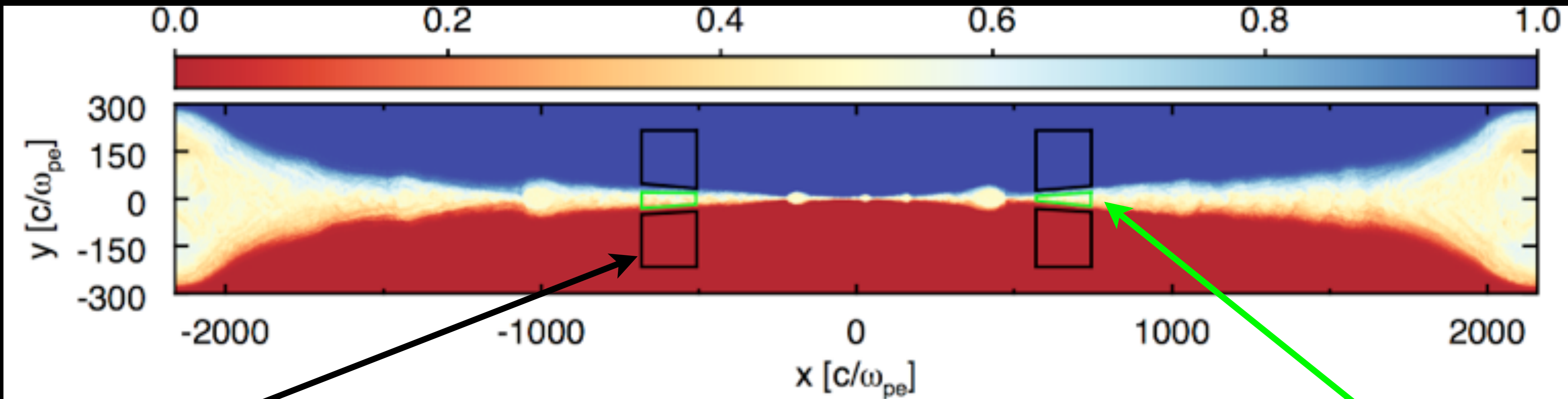


(Rowan, LS & Narayan 2017)

- High beta: smooth outflow, no secondary plasmoids.

Characterization of heating

- Blue: upstream region, starting above the current sheet.
- Red: upstream region, starting below the current sheet.
- White/yellow: mix of blue and red particles → downstream region.



Upstream

Downstream

Define total electron heating as $$M_{ue,\mathrm{tot}} \equiv \frac{\upsilon_{\mathrm{e,down}} - \upsilon_{\mathrm{e,up}}}{\sigma\, m_{\mathrm{i}}/m_{\mathrm{e}}}$$ υ=internal energy per unit rest mass.

alternatively, $$M_{Te,\mathrm{tot}} \equiv \frac{\theta_{\mathrm{e,down}} - \theta_{\mathrm{e,up}}}{\sigma\, m_{\mathrm{i}}/m_{\mathrm{e}}}$$ θ=dimensionless temperature.

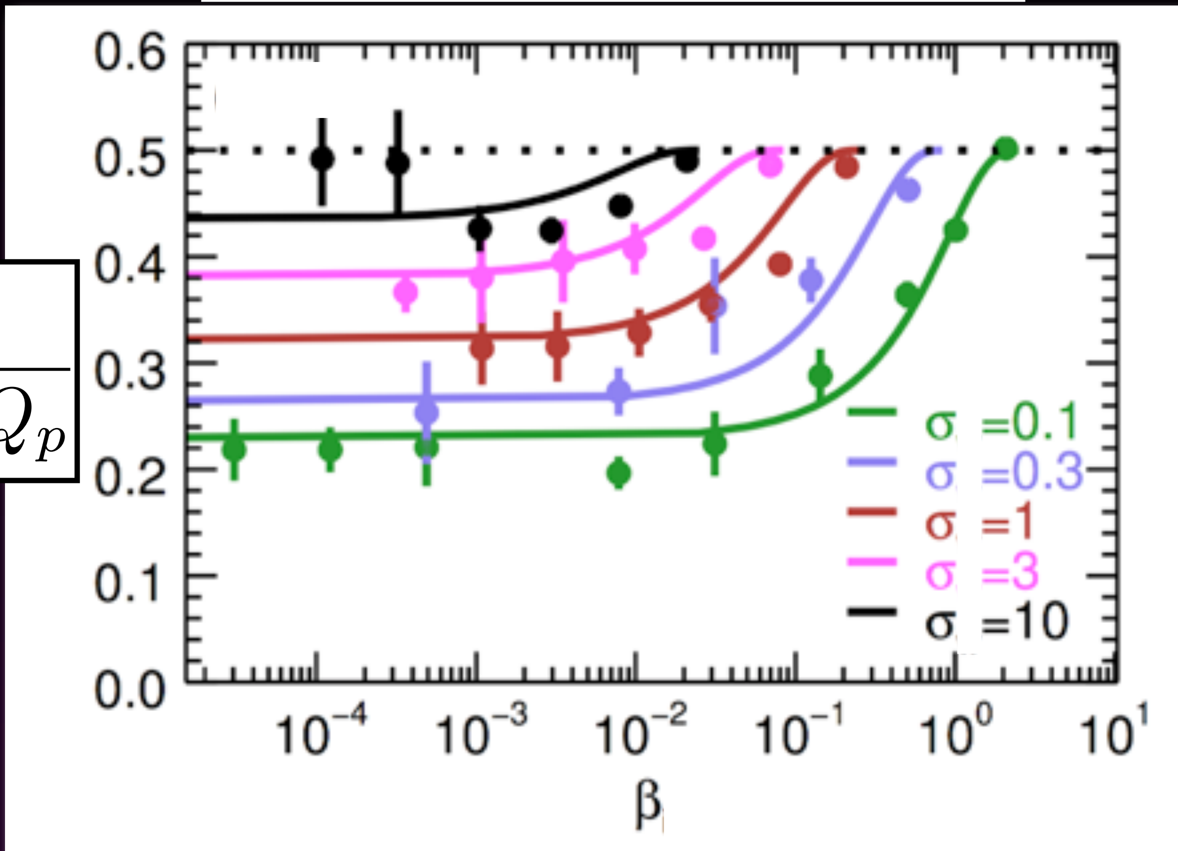
(Shay et al. 2014)

and then separate adiabatic and irreversible contributions.

Electron heating efficiency (B_g=0)

Electron-to-overall heating ratio

$$\frac{Q_e}{Q_e + Q_p}$$



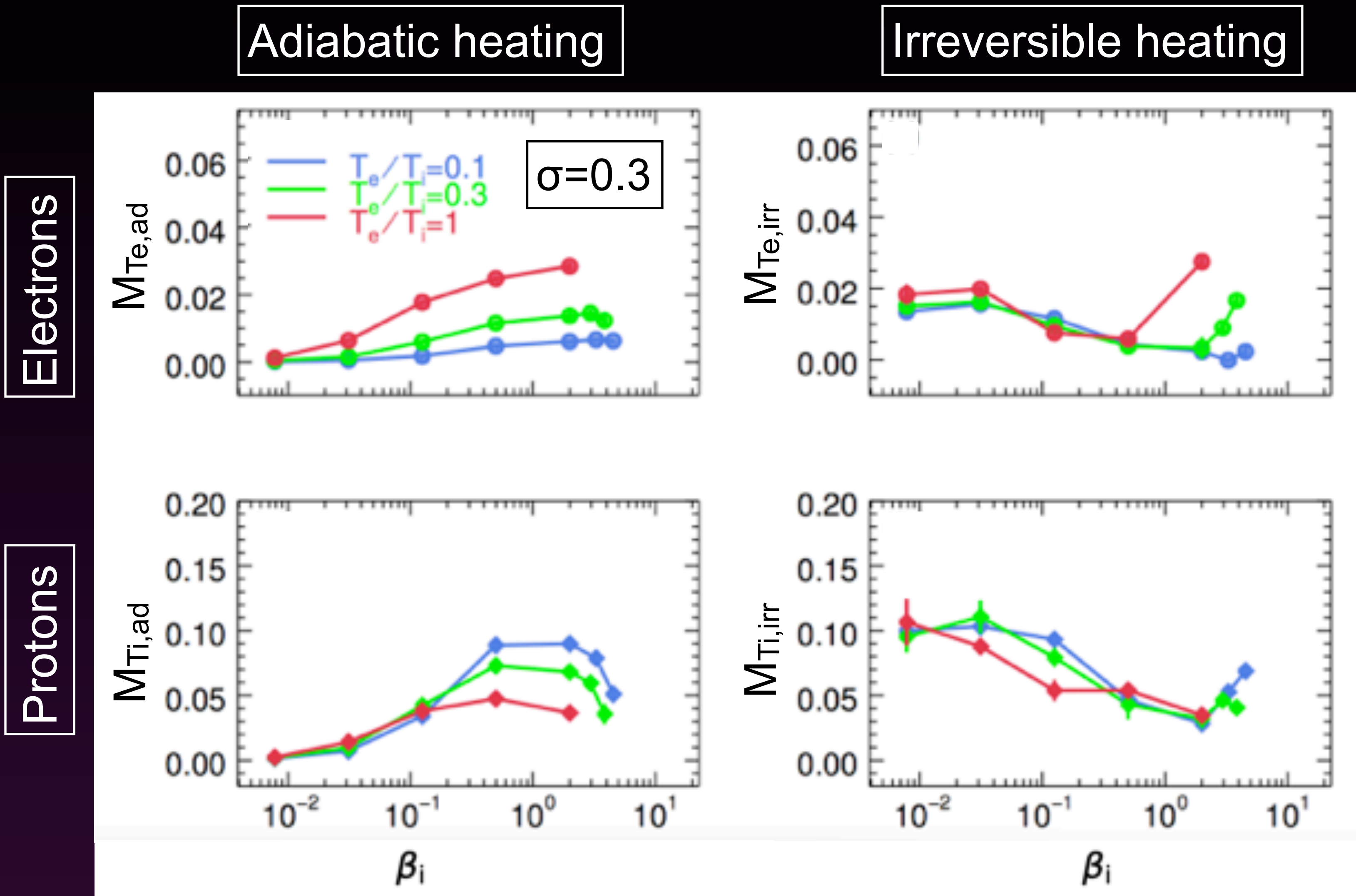
The curves extend up to β_{max}~1/(4σ)

(Rowan, LS & Narayan 2017)

- Electrons are heated less then protons (for σ≪1, the ratio is ~0.2). See also Werner+18.

- Comparable heating efficiencies:
  - at high beta, when both species already start relativistically hot.
  - in ultra-relativistic (σ≫1) reconnection.

No dependence on the upstream T_e/T_i



$$M_{Te} \equiv \frac{\theta_{\rm e,down} - \theta_{\rm e,up}}{\sigma\, m_{\rm i}/m_{\rm e}}$$

(Rowan, LS & Narayan 2017)

- Adiabatic heating (obviously) dependent on the temperature ratio.
- Irreversible heating nearly independent of the temperature ratio.

Dependence on B_g/B_0

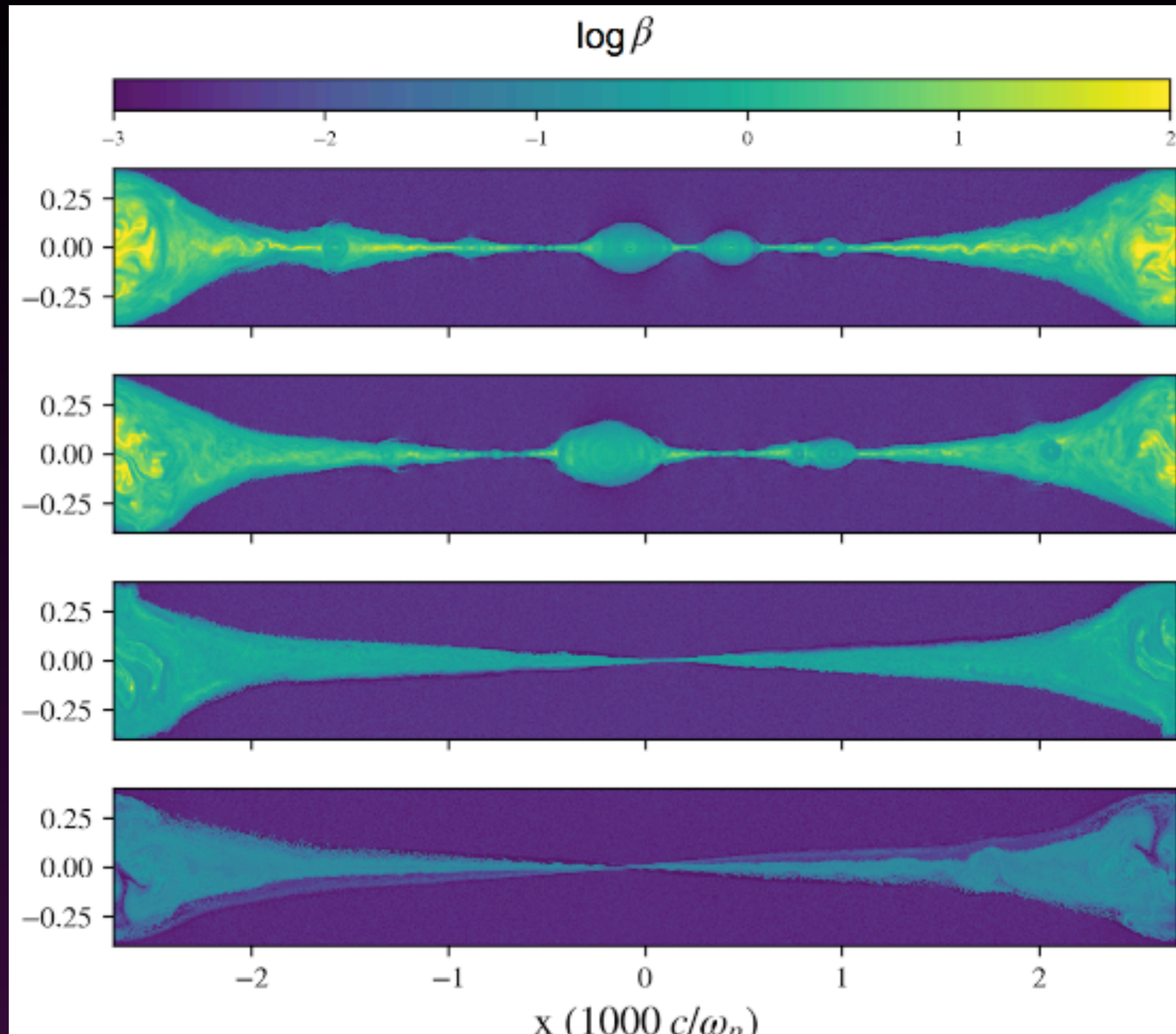
σ=0.3 β=0.003, realistic mass ratio

B_g/B_0=0.0

B_g/B_0=0.1

B_g/B_0=0.3

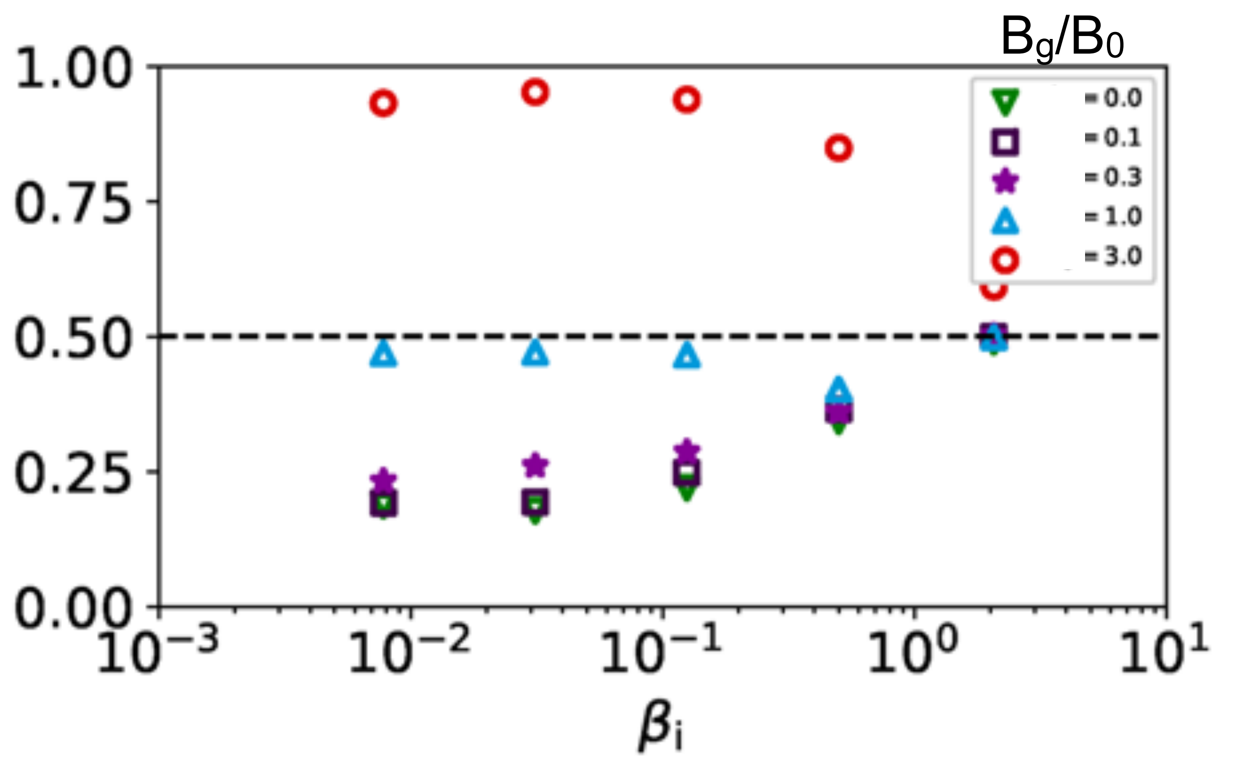
B_g/B_0=0.7



Dependence on B_g/B_0

Electron-to-overall heating ratio (σ=0.1)

$$\frac{Q_e}{Q_e + Q_p}$$



The curves extend up to β_{max}~1/(4σ)

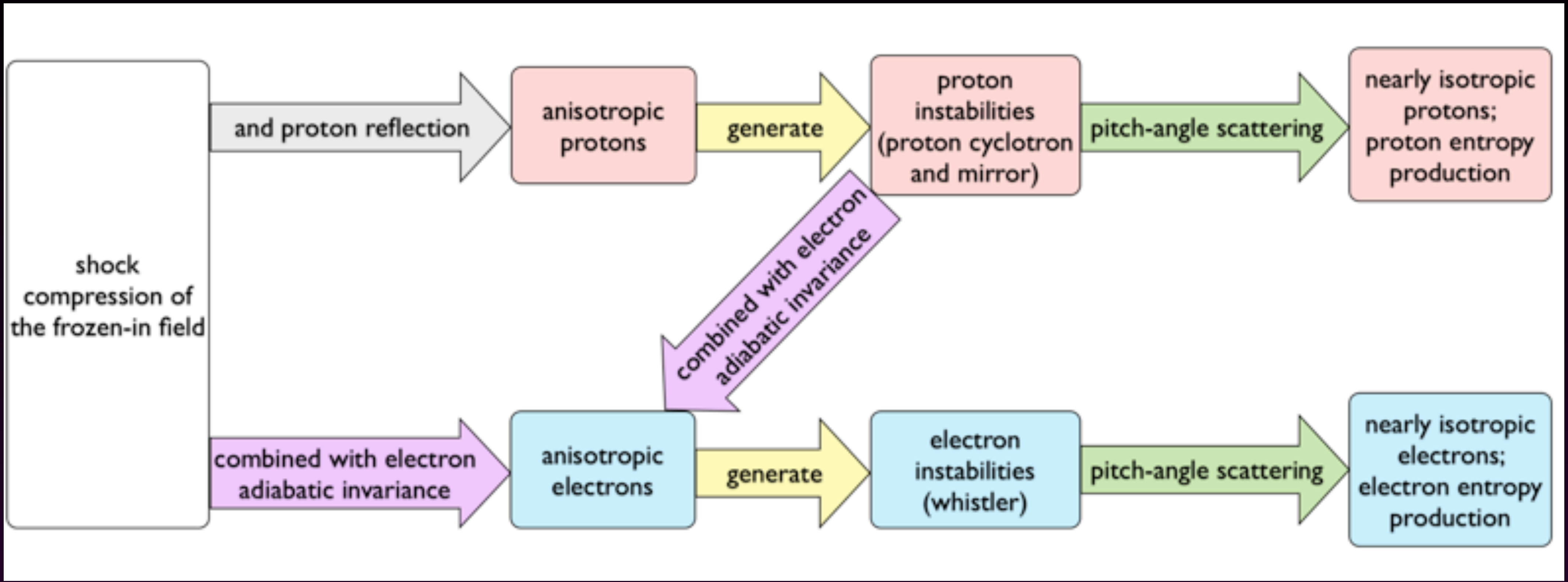
(Rowan, LS & Narayan, in prep)

- At low beta: electrons are heated less then protons for B_g/B_0<1, but most of the dissipated energy (~90-95%) goes into electrons for B_g/B_0>1.

- In agreement with non-relativistic PIC (Tenbarge+14) and GK calculations (Numata & Loureiro 15, Kawazura+ today).

Summary

Electron heating in high-beta low Mach number shocks:



Electron heating in trans-relativistic reconnection:

- For $B_g/B_0=0$, electrons are heated less then protons (for $\sigma \ll 1$, the ratio is ~0.2).

Comparable heating efficiencies at high beta, when both species already start relativistically hot.

- At low beta: electrons are heated less then protons for $B_g/B_0<1$, but most of the dissipated energy (~90-95%) goes into electrons for $B_g/B_0>1$.