non-relativistic
strictly perpendicular
Mach ~ 1–10
$\beta \sim 0.25$

e^- heating in collisionless shocks

Aaron Tran, Lorenzo Sironi (Columbia University)
KITP Astroplasmas 2019

Work in prep/revision

Non-relativistic one-fluid limit: sound, Alfvén, shock speeds set behavior

B-field ⊥ shock normal (“perpendicular shock”), upstream $T_i = T_e = T_0$

$$\mathcal{M}_\mathrm{s} \equiv \frac{u_\mathrm{sh}}{c_s} \quad , \quad \beta_p \equiv \frac{8\pi(2n_i)k_B T_0}{B^2}$$

Rankine-Hugoniot gives total pressure (temperature) jump

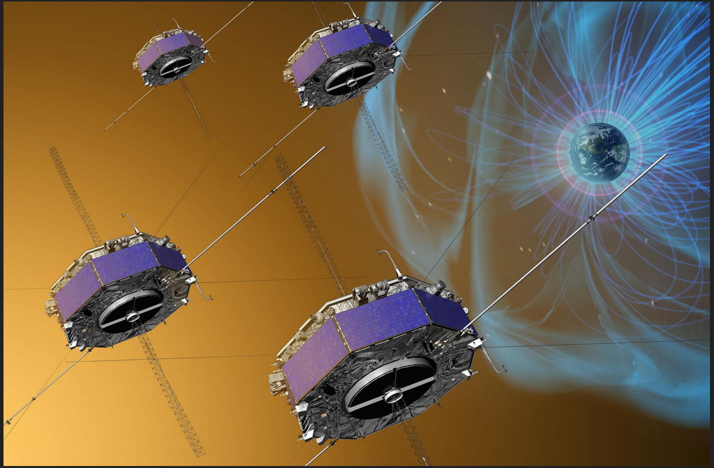
$$\frac{T_f}{T_0} = \frac{1}{r}\frac{2\Gamma{\mathcal{M}_\mathrm{s}}^2 - (\Gamma - 1)}{\Gamma + 1} \quad , \quad r = \frac{(\Gamma+1){\mathcal{M}_\mathrm{s}}^2}{{\mathcal{M}_\mathrm{s}}^2(\Gamma - 1) + 2} \quad (\beta_p \to \infty)$$

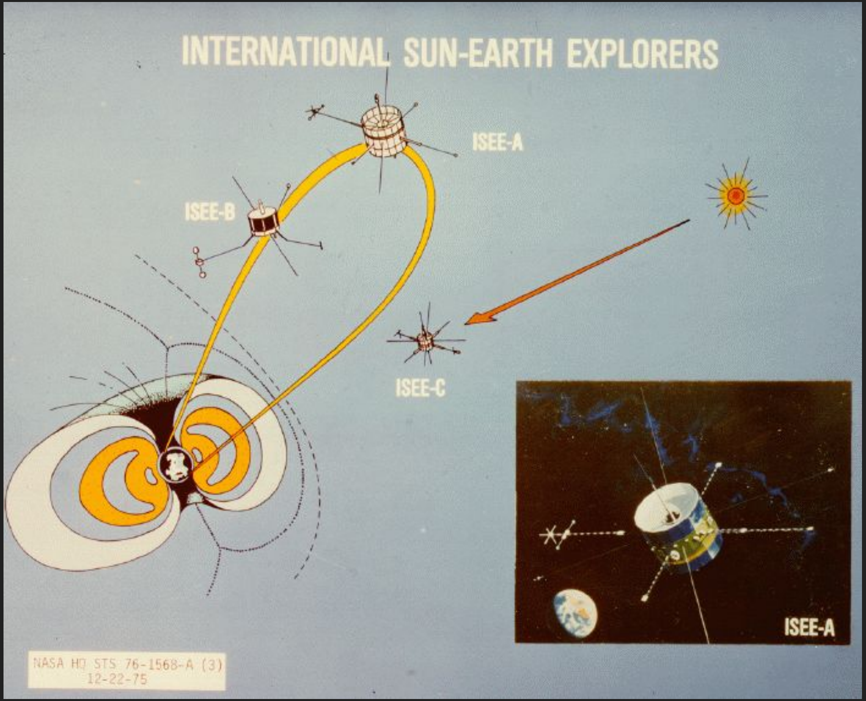
but e-, p+ partition unspecified. Observations show < 1.

$$\frac{T_e}{T_p} = ?$$

Why should we care?

Solar wind: Mach ~ 1–10, $\beta \sim 0.1$–1

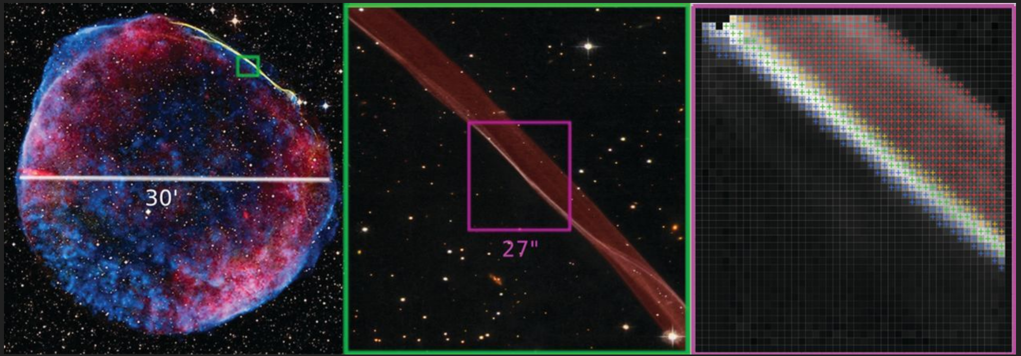




Why should we care?

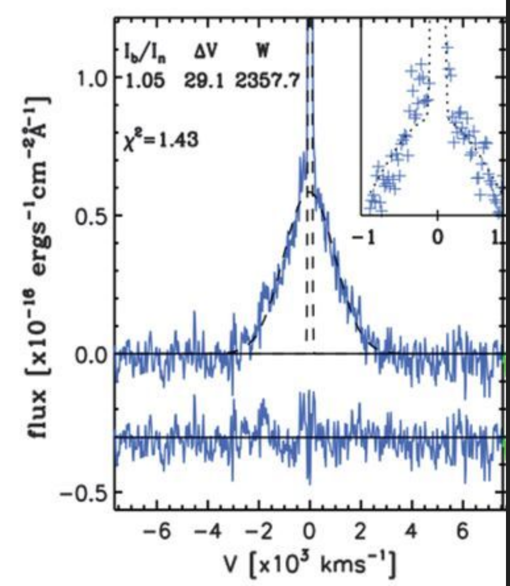
Solar wind: Mach ~ 1–10, β ~ 0.1–1

Young SNRs: Mach ~ 100, β ~ 1



Nikolić+ 2013. SN1006, Hα (yellow), X-ray (blue, red)

Two-component Hα line

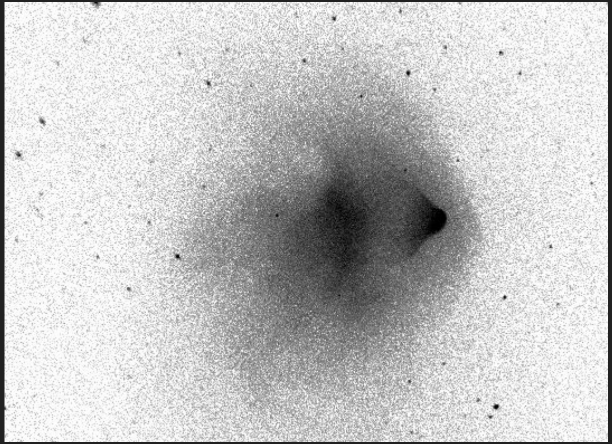


Why should we care?

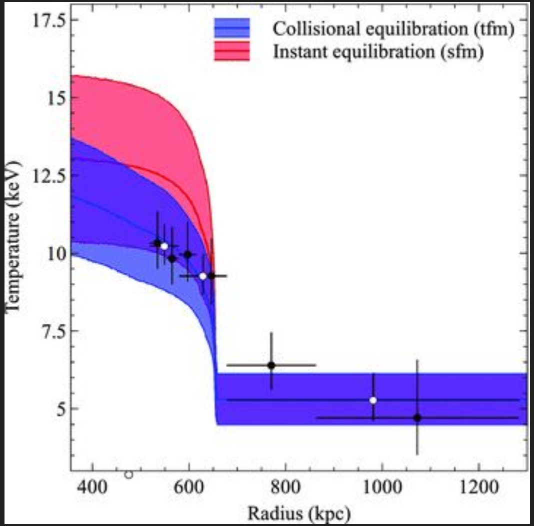
Solar wind: Mach ~ 1–10, β ~ 0.1–1

Young SNRs: Mach ~ 100, β ~ 1

Cluster mergers: Mach ~ 1–3, β >~ 10



Markevitch 2005. Bullet Cluster, X-ray



Russell+ 2012. Abell 2146, X-ray

Cf. Guo, Sironi, Narayan, 2017 & 2018

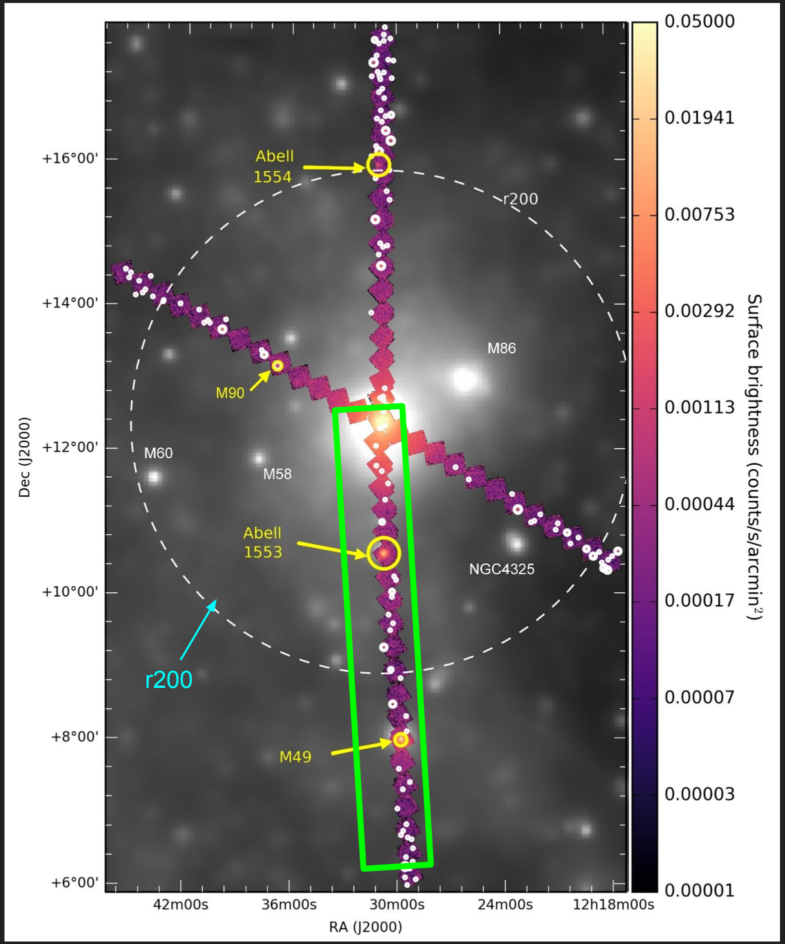
Why should we care?

Solar wind: Mach ~ 1–10, β ~ 0.1–1

Young SNRs: Mach ~ 100, β ~ 1

Cluster mergers: Mach ~ 1–3, β >~ 10

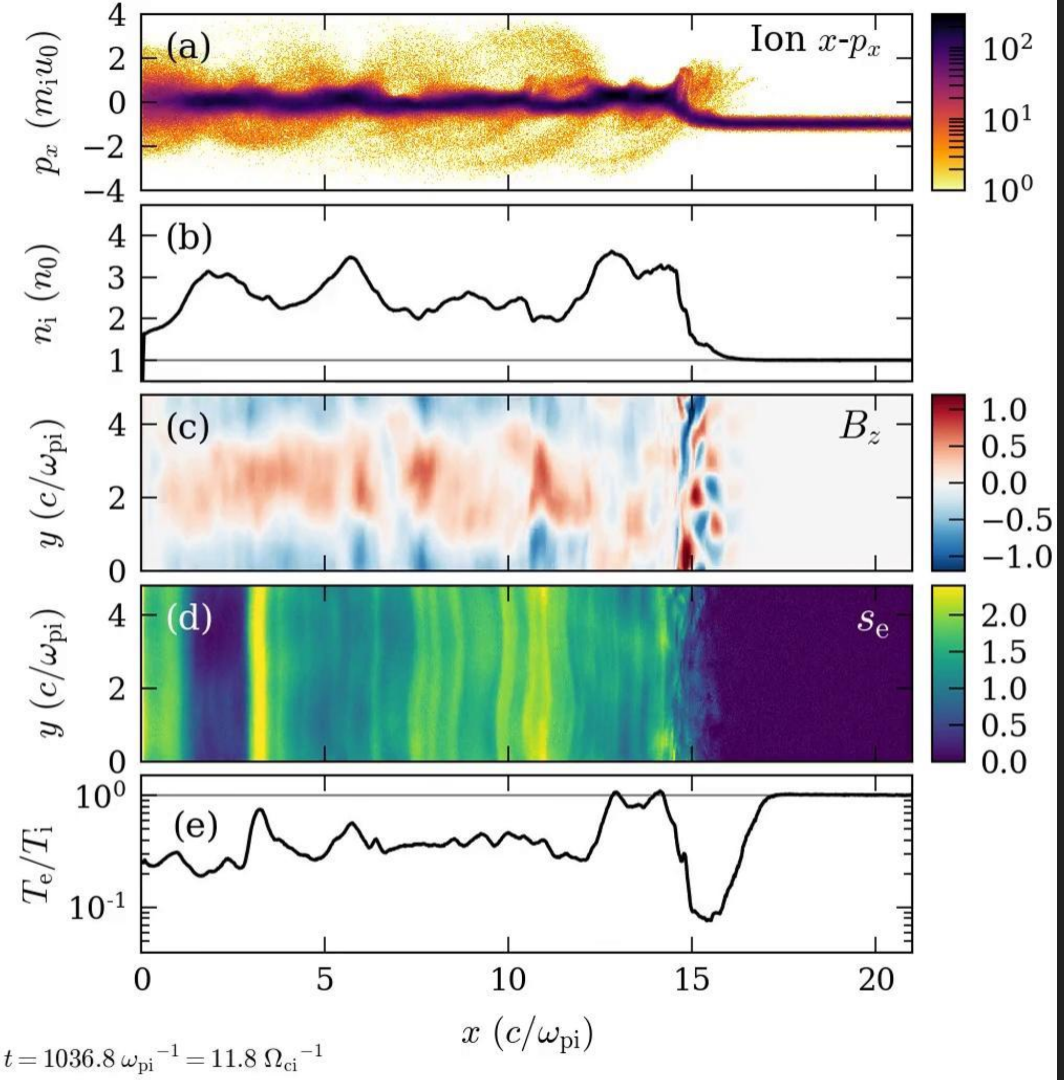
IGM accretion: Mach 1–100?, β ~ 1???



Simionescu+ 2017. Virgo Cluster, X-ray

What does PIC say?

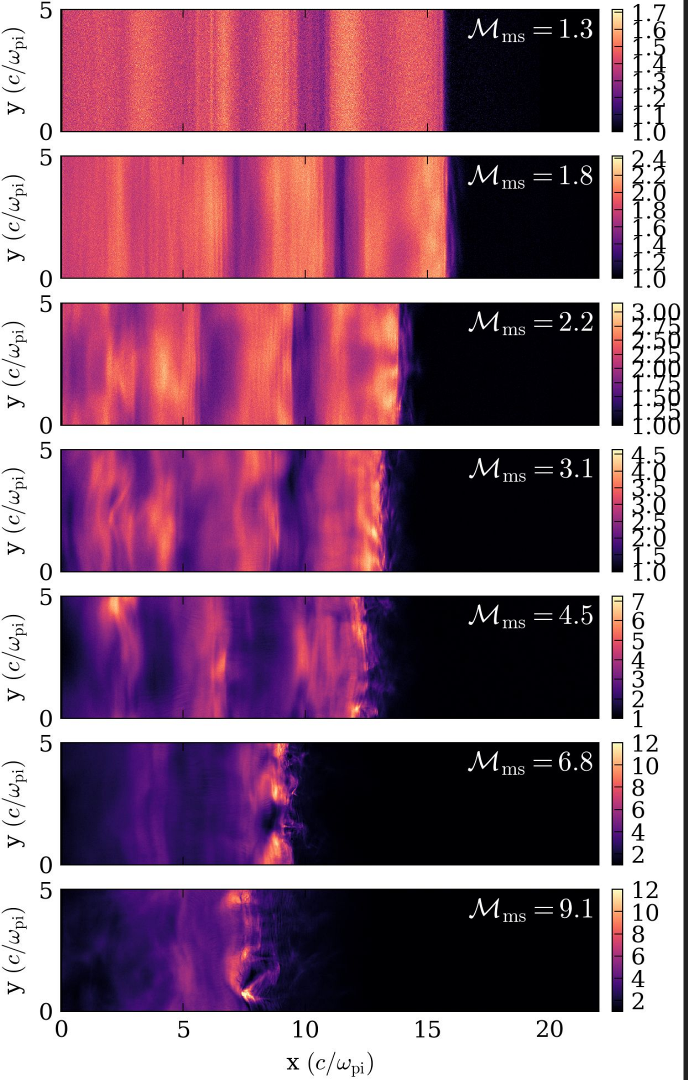
2-D shocks with B in plane.
Electrons marginally non-rel.
Strictly perpendicular B-field simplifies problem a lot.



What does PIC say?

$$m_\mathrm{i}/m_\mathrm{e} = 625$$
$$\beta_\mathrm{p} = 0.25$$
$$\beta_\mathrm{i} = \beta_\mathrm{e} = 0.125$$
$$\mathcal{M}_\mathrm{ms} = 1\text{–}10$$

Ion density →

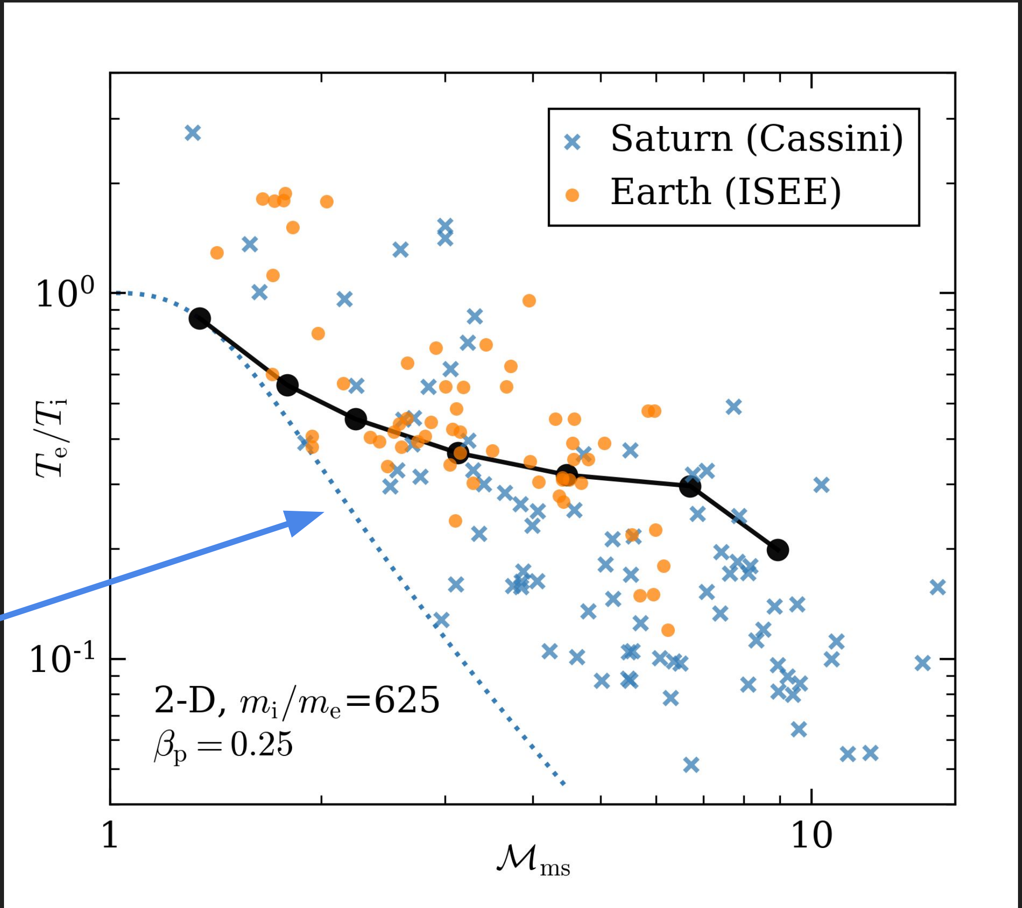


Higher Mach non-rel PIC:
see poster by Vassilis Tsiolis,
Crumley, Spitkovsky

What does PIC say?

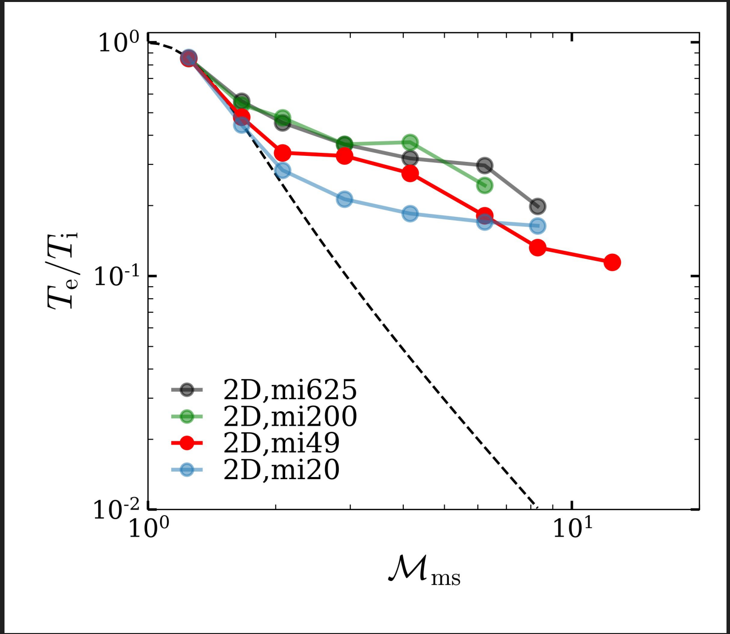
Data: quasi-perp
Sims: pure perp 2D

ISEE: Schwartz+ 1988 JGR
Cassini: Masters+ 2011 JGR
Compilation: Ghavamian+ 2013 SSRv

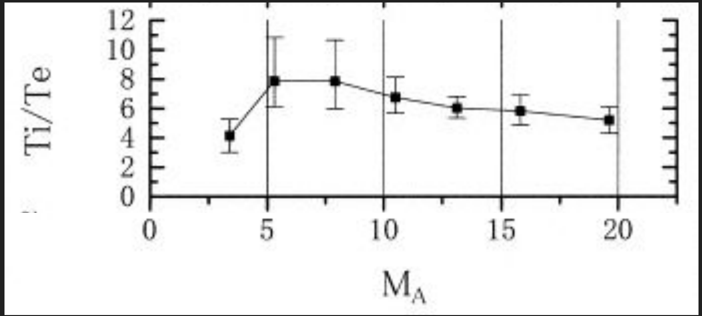


Baseline: e- compress as adiabatic fluid,
Ions get rest of shock heating

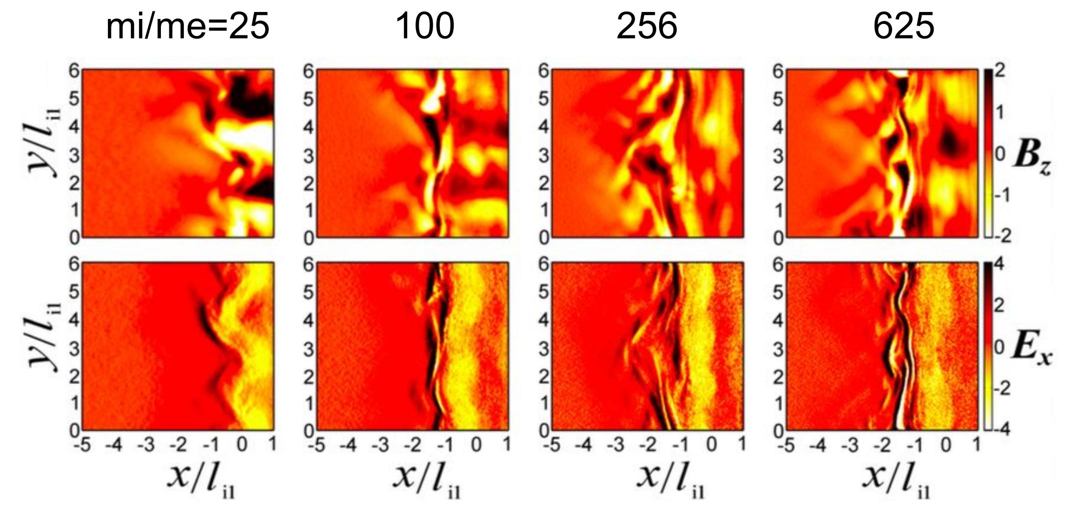
What mi/me is needed?



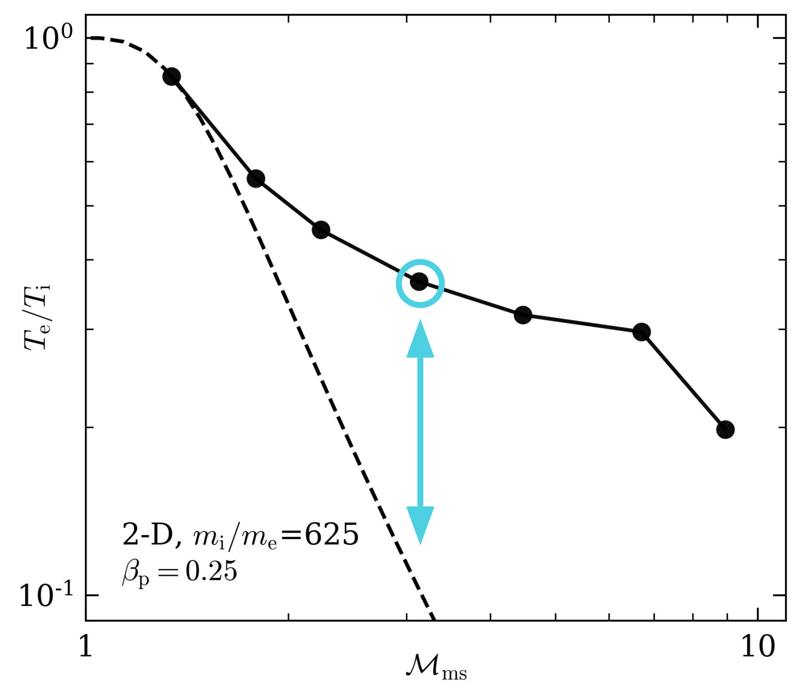
Shimada & Hoshino 2000; mi/me = 20



Umeda+ 2014 Phys Plasmas



How do e- heat?



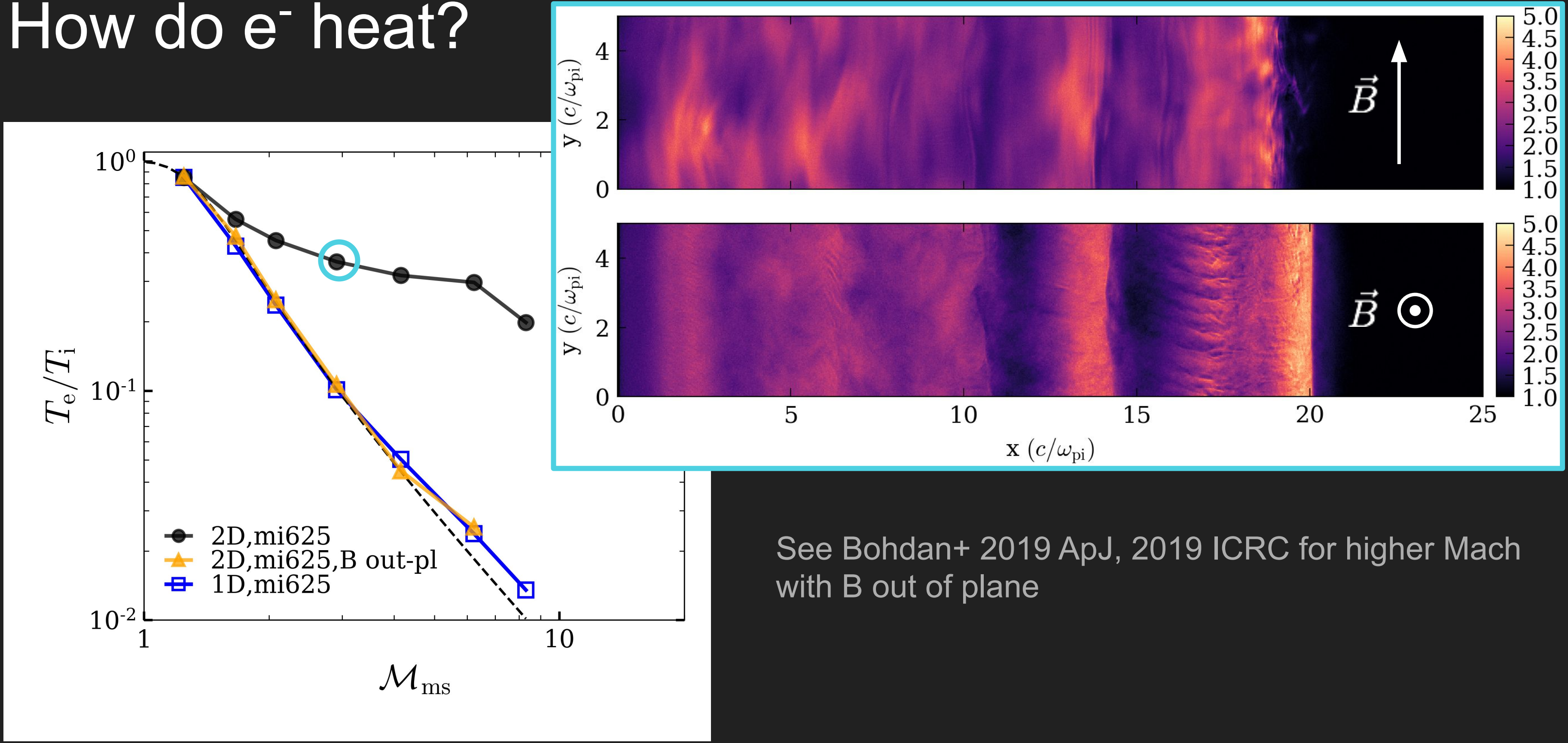
$$\mathcal{M}_{ms} = 3.1$$

$$\mathcal{M}_A = 3.4$$

$$\mathcal{M}_s = 7$$

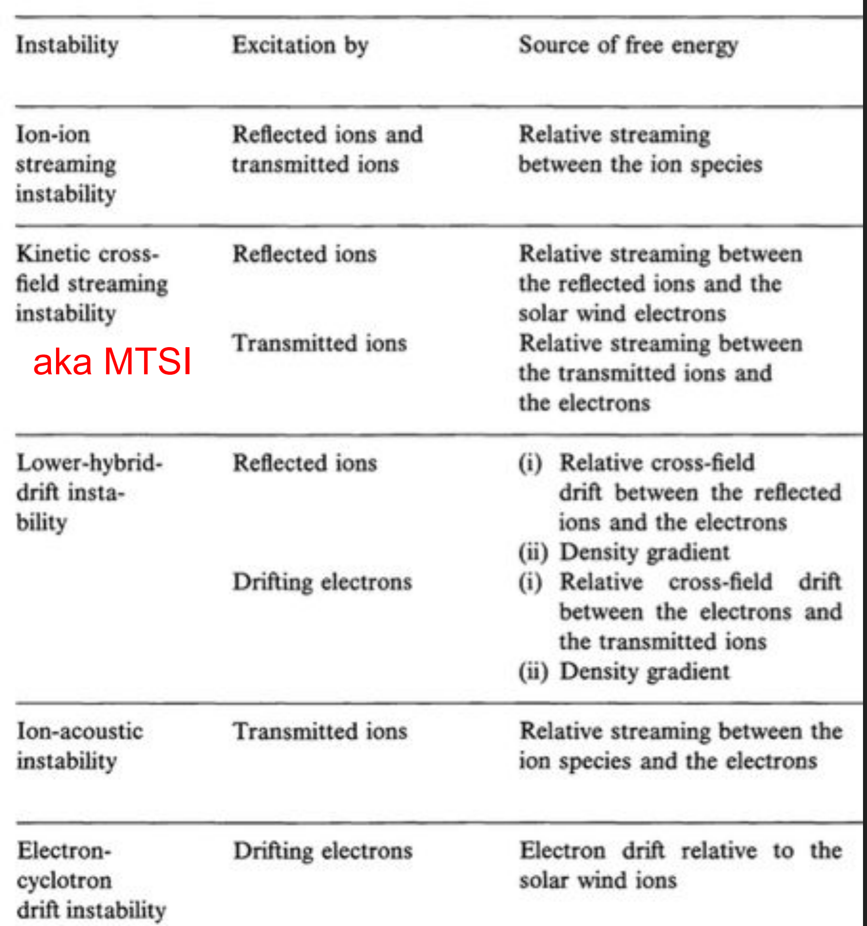
Supercritical: M_ms > 2.76

How do e⁻ heat?

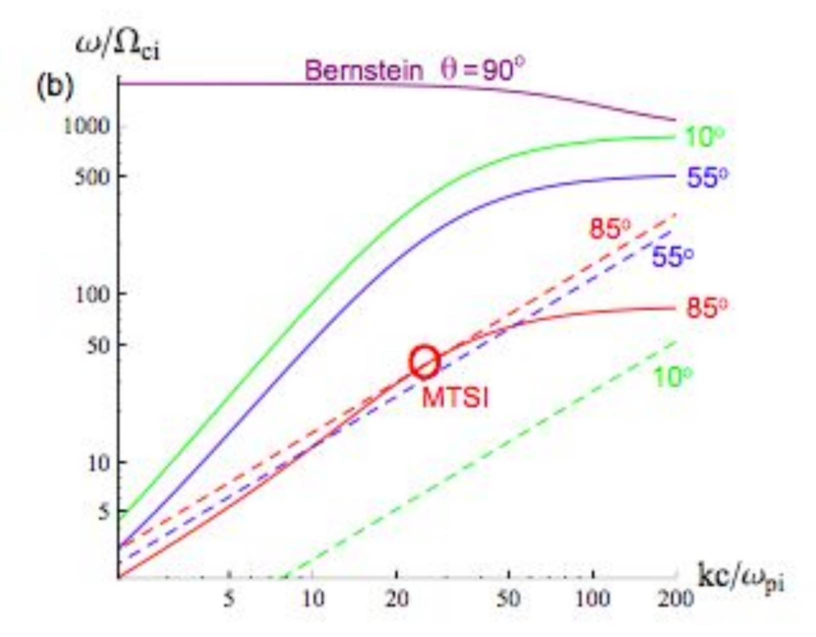


See Bohdan+ 2019 ApJ, 2019 ICRC for higher Mach with B out of plane

Ion reflection → beam instabilities → e$^-$ heating via LH-wave E_parallel?



Instability	Excitation by	Source of free energy
Ion-ion streaming instability	Reflected ions and transmitted ions	Relative streaming between the ion species
Kinetic cross-field streaming instability	Reflected ions	Relative streaming between the reflected ions and the solar wind electrons
aka MTSI	Transmitted ions	Relative streaming between the transmitted ions and the electrons
Lower-hybrid-drift instability	Reflected ions	(i) Relative cross-field drift between the reflected ions and the electrons (ii) Density gradient
	Drifting electrons	(i) Relative cross-field drift between the electrons and the transmitted ions (ii) Density gradient
Ion-acoustic instability	Transmitted ions	Relative streaming between the ion species and the electrons
Electron-cyclotron drift instability	Drifting electrons	Electron drift relative to the solar wind ions

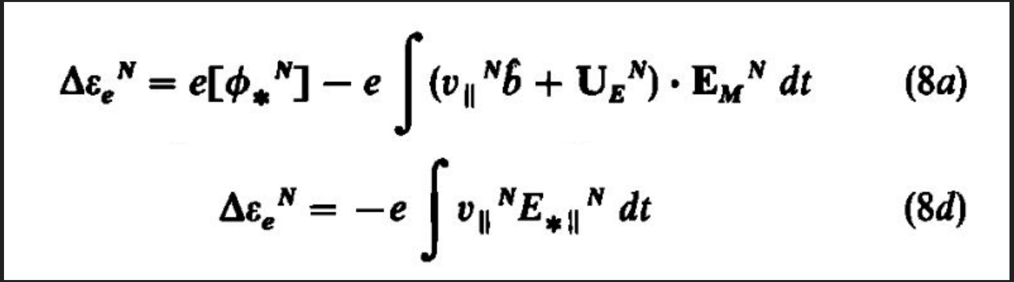


Slow reflected ion beam, v = 1.5 v_A
Muschietti & Lembege 2017 Ann Geophys

← Wu 1984; huge literature not well cited in this talk

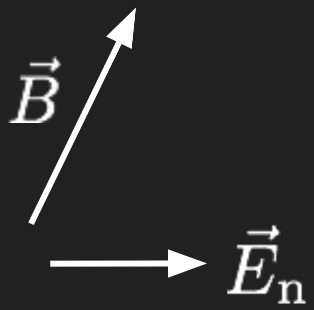
Cross-shock E_x in *quasi*-perp → DC e$^-$ heating via E_x-to-E_parallel?

Goodrich & Scudder 1984 (GS84); Scudder, Hull, etc.

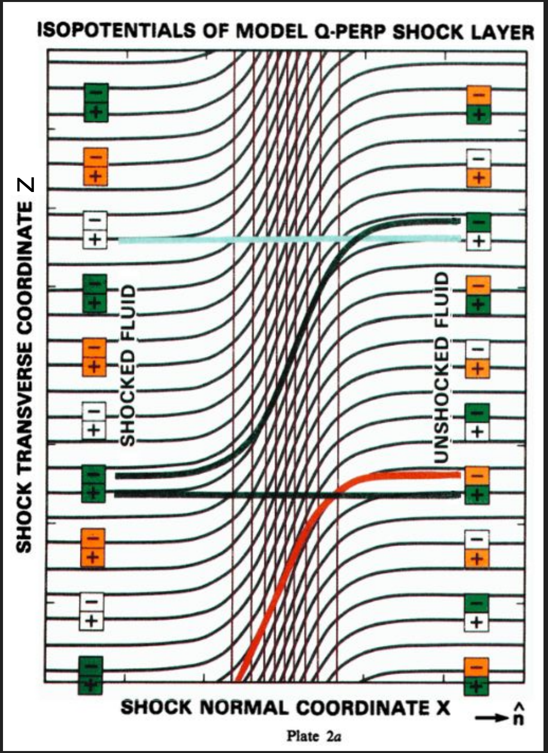


$$\Delta\varepsilon_e{}^N = e[\phi_*{}^N] - e\int (v_\parallel{}^N\hat{b} + \mathbf{U}_E{}^N)\cdot\mathbf{E}_M{}^N\,dt \qquad (8a)$$

$$\Delta\varepsilon_e{}^N = -e\int v_\parallel{}^N E_{*\parallel}{}^N\,dt \qquad (8d)$$



(= E_x in our geometry)

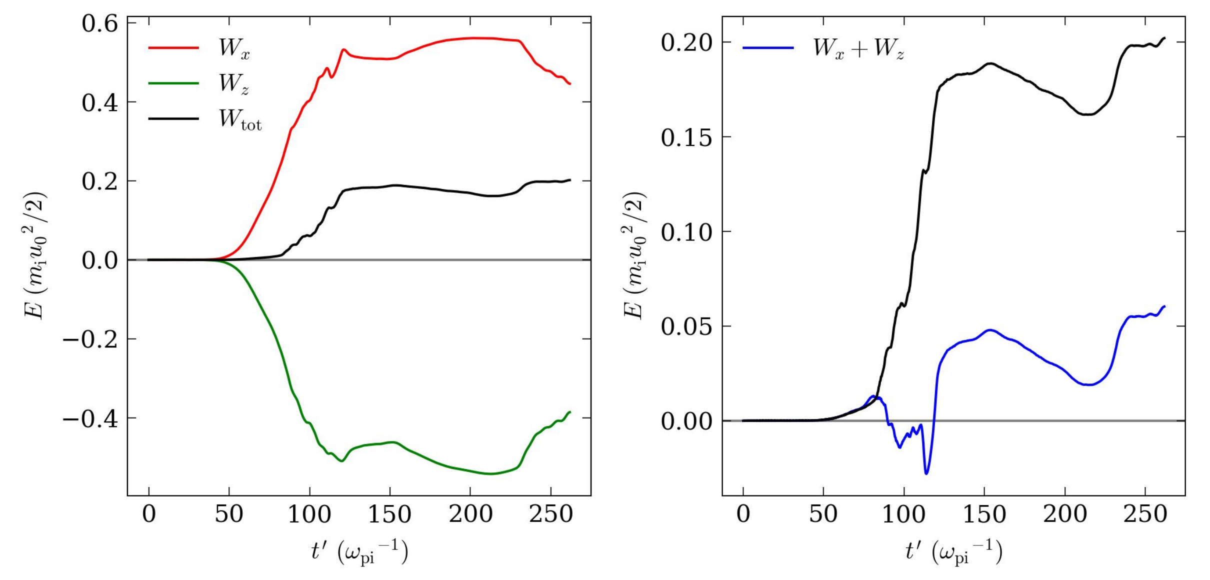


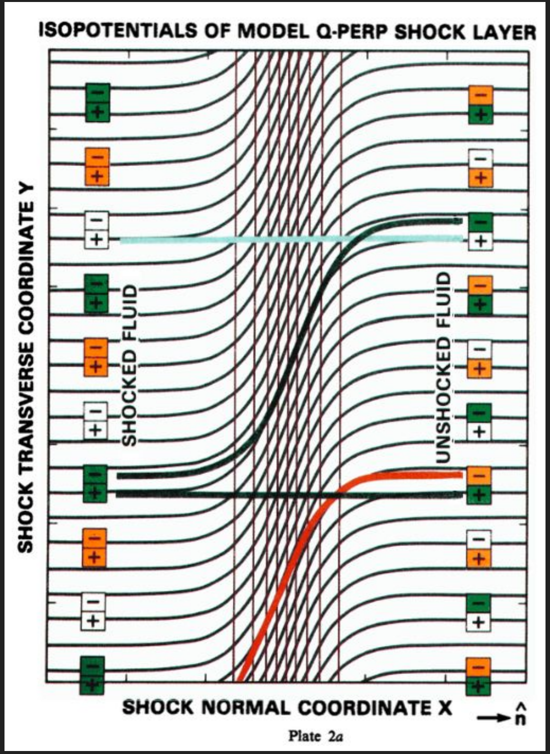
Modified from GS84

Cross-shock E_x in *quasi*-perp → DC e^- heating via E_x-to-E_parallel?

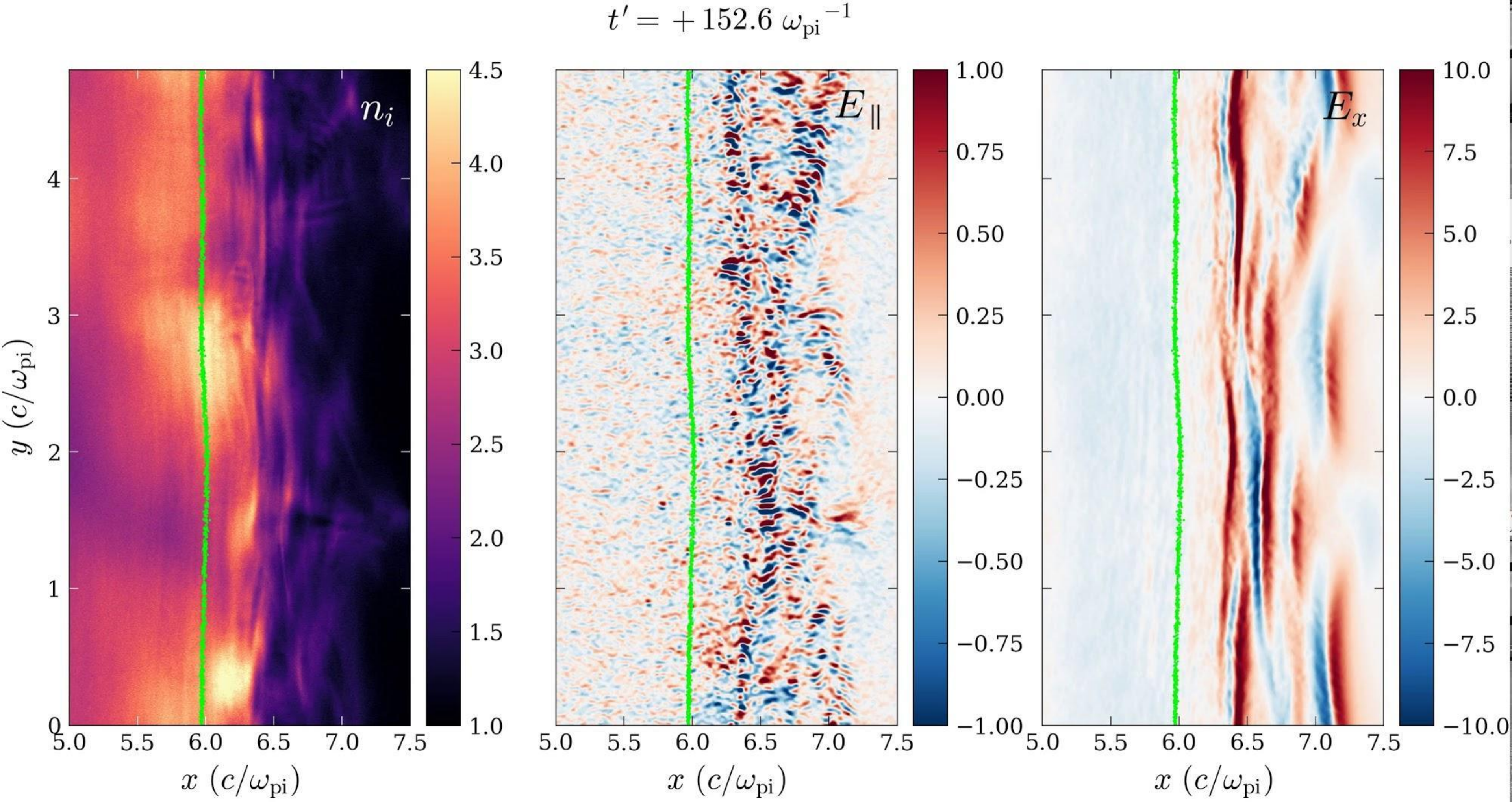
Goodrich & Scudder 1984 (GS84); Scudder, Hull, etc.

Electron Ex*vx work mostly cancelled by Ez*vz,
Ez = motional field, vz = En x B drift in shock layer

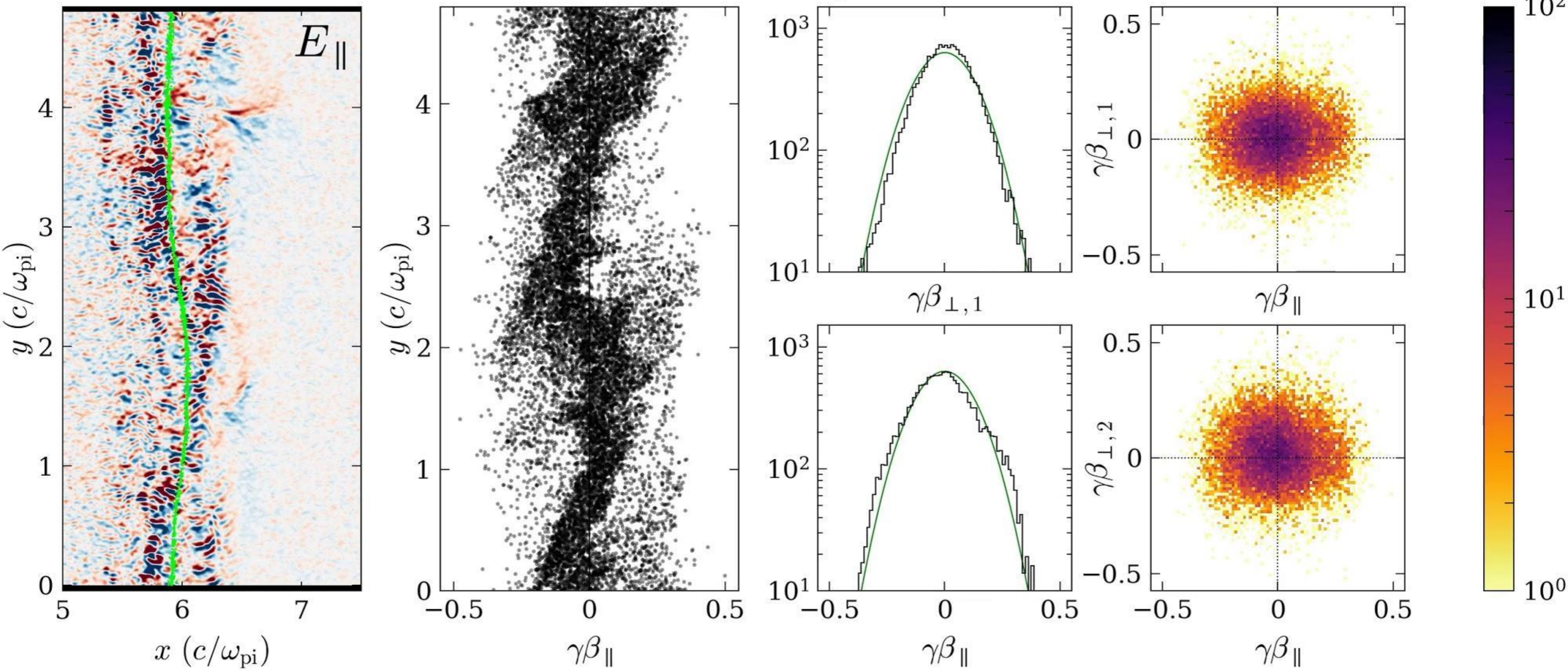




Modified from GS84


$t' = +152.6\ \omega_{\mathrm{pi}}{}^{-1}$
n_i
$E_\parallel$
E_x
$y\ (c/\omega_{\mathrm{pi}})$
0
1
2
3
4
$x\ (c/\omega_{\mathrm{pi}})$
5.0
5.5
6.0
6.5
7.0
7.5
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0

$t' = +107.6\ \omega_{\mathrm{pi}}{}^{-1}$



How do e^- heat?

$$W_{||} = -e \int E_{||} v_{||} \mathrm{d}t$$

$$W_{\perp} = -e \int E_{\perp} v_{\perp} \mathrm{d}t$$

How do e^- heat?

$$W_{\parallel} = -e \int E_{\parallel} v_{\parallel} \mathrm{d}t$$

$$W_{\perp} = -e \int E_{\perp} v_{\perp} \mathrm{d}t$$

$$W_{\perp,\mathrm{ad}} = \sum_{n} (\gamma_{n \to n+1,\mathrm{ad}} - \gamma_n) m_{\mathrm{e}} c^2$$

$$\gamma_{n \to n+1,\mathrm{ad}} = \sqrt{1 + (\gamma\beta_{\parallel})_n^2 + (\gamma\beta_{\perp})_n^2 \, (B_{n+1}/B_n)}$$

How do e^- heat?

$$W_\parallel = -e\int E_\parallel v_\parallel \mathrm{d}t$$

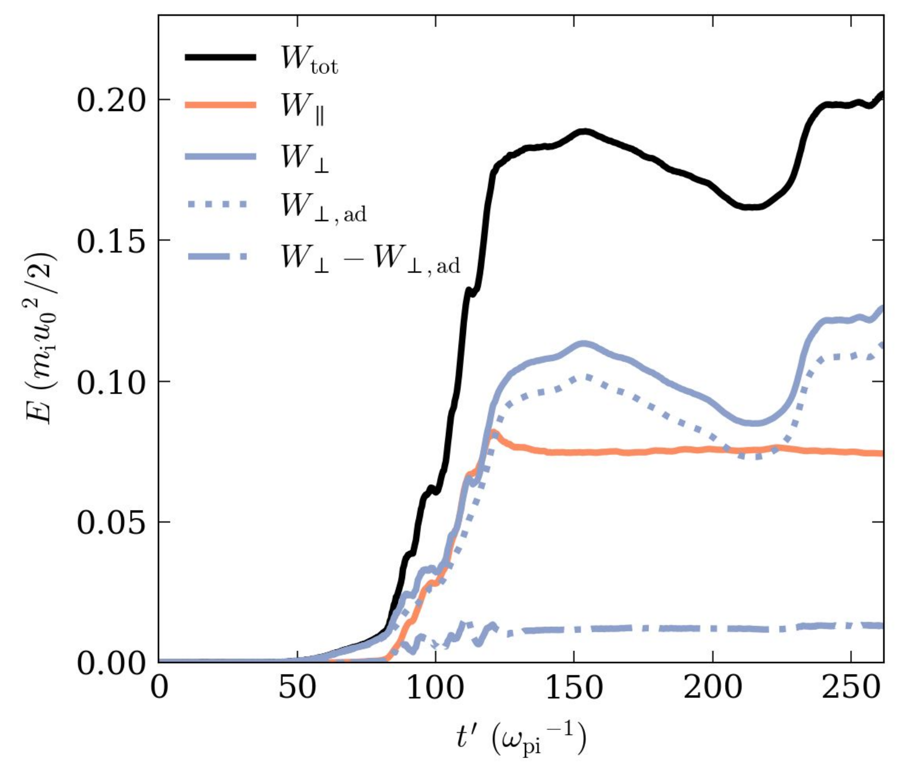
$$W_\perp = -e\int E_\perp v_\perp \mathrm{d}t$$

$$W_{\perp,\mathrm{ad}} = \sum_n (\gamma_{n\to n+1,\mathrm{ad}} - \gamma_n) m_\mathrm{e} c^2$$

$$\gamma_{n\to n+1,\mathrm{ad}} = \sqrt{1 + \underbrace{\left(\gamma\beta_\parallel\right)_n^2}_{\text{conserve } p_\parallel} + \underbrace{\left(\gamma\beta_\perp\right)_n^2 \left(B_{n+1}/B_n\right)}_{\text{conserve } \mu}}$$

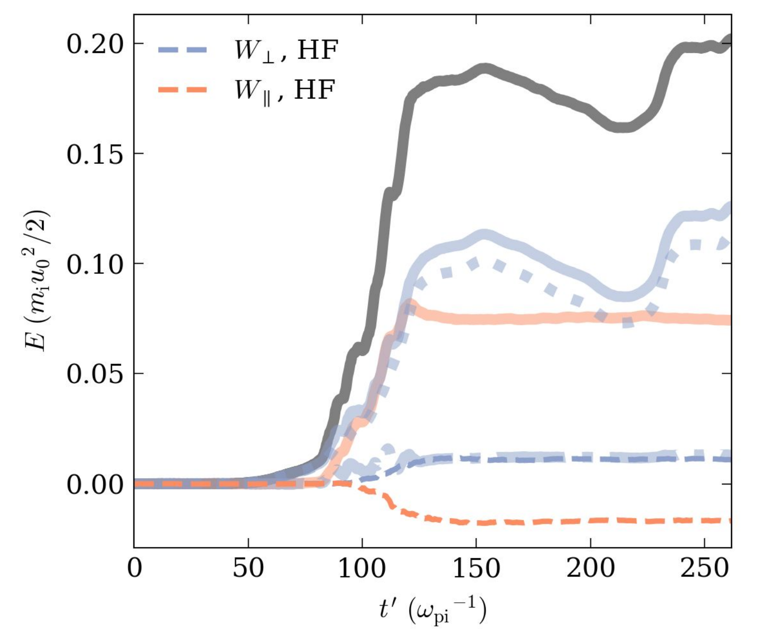
How do e⁻ heat?

E_parallel provides super-adiabatic work

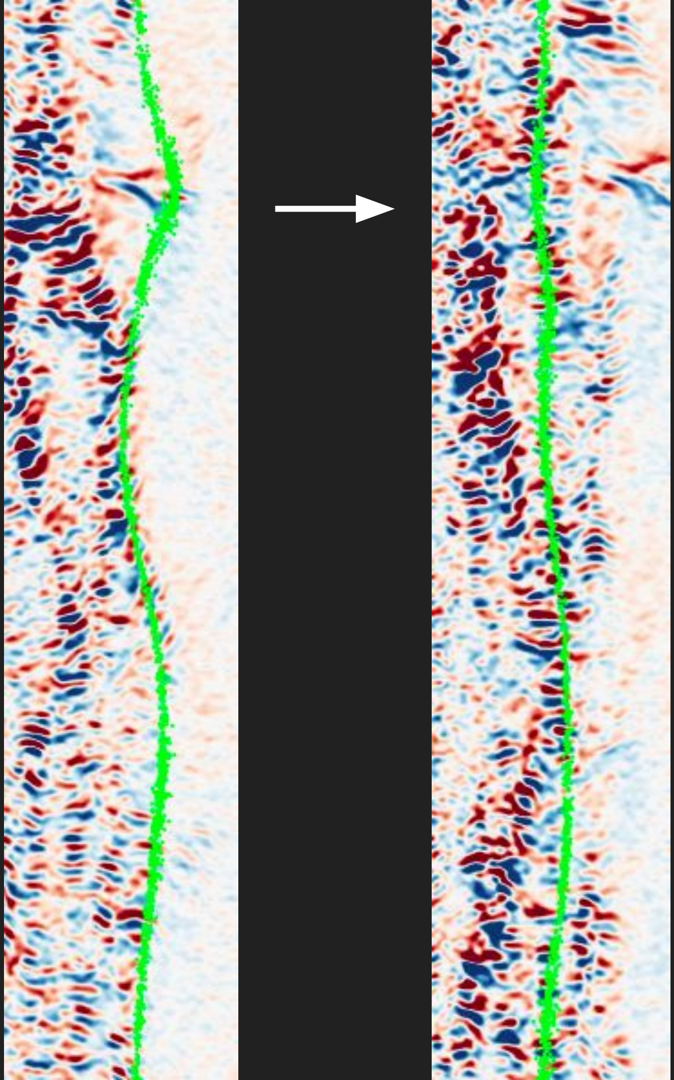


How do e⁻ heat?

E_parallel provides super-adiabatic work

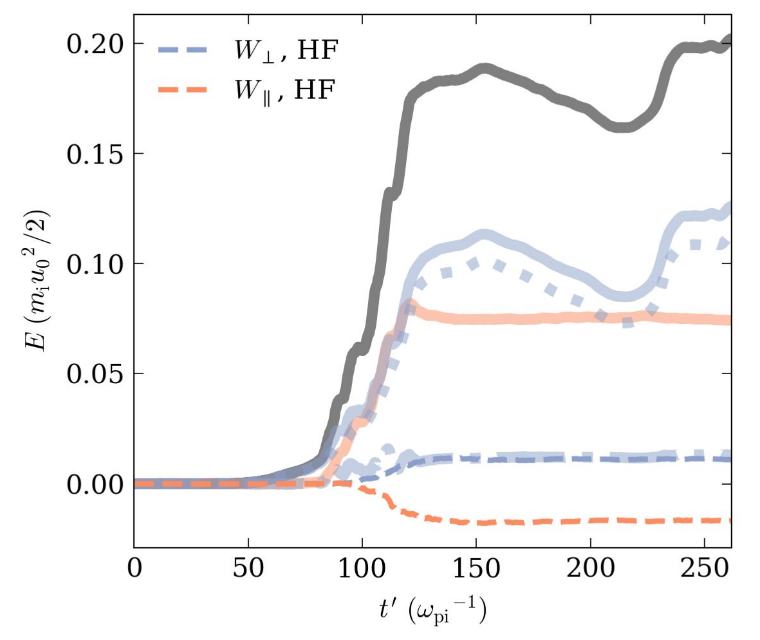


HF = high-pass filter, keep only $k_y > \omega_{\rm pe}/c$

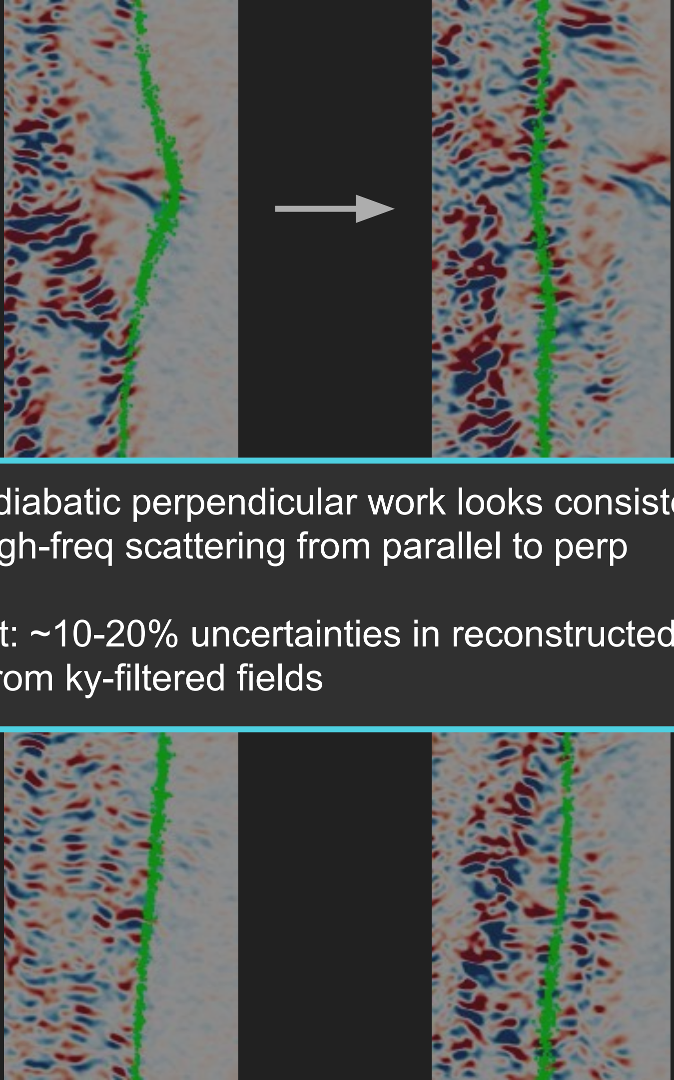


How do e^- heat?

E_parallel provides super-adiabatic work



HF = high-pass filter, keep only $k_y > \omega_{\mathrm{pe}}/c$

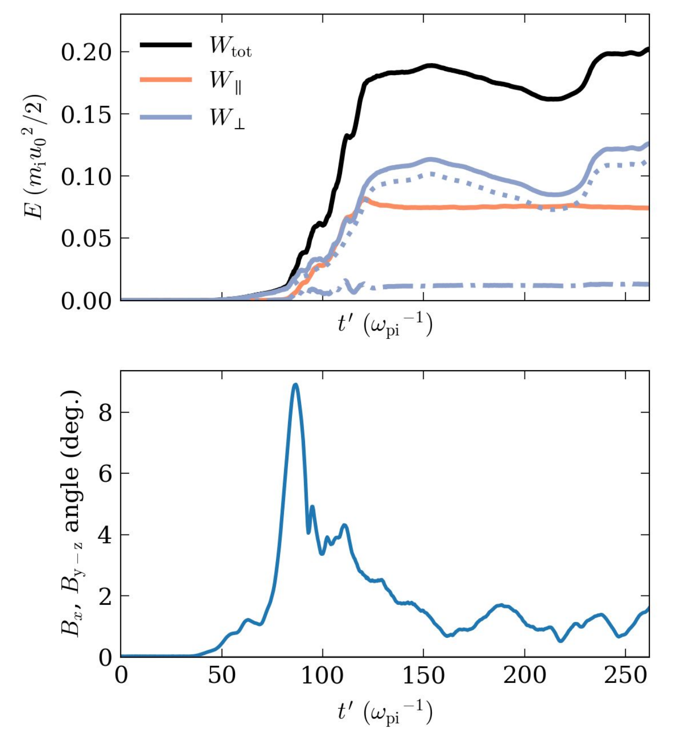


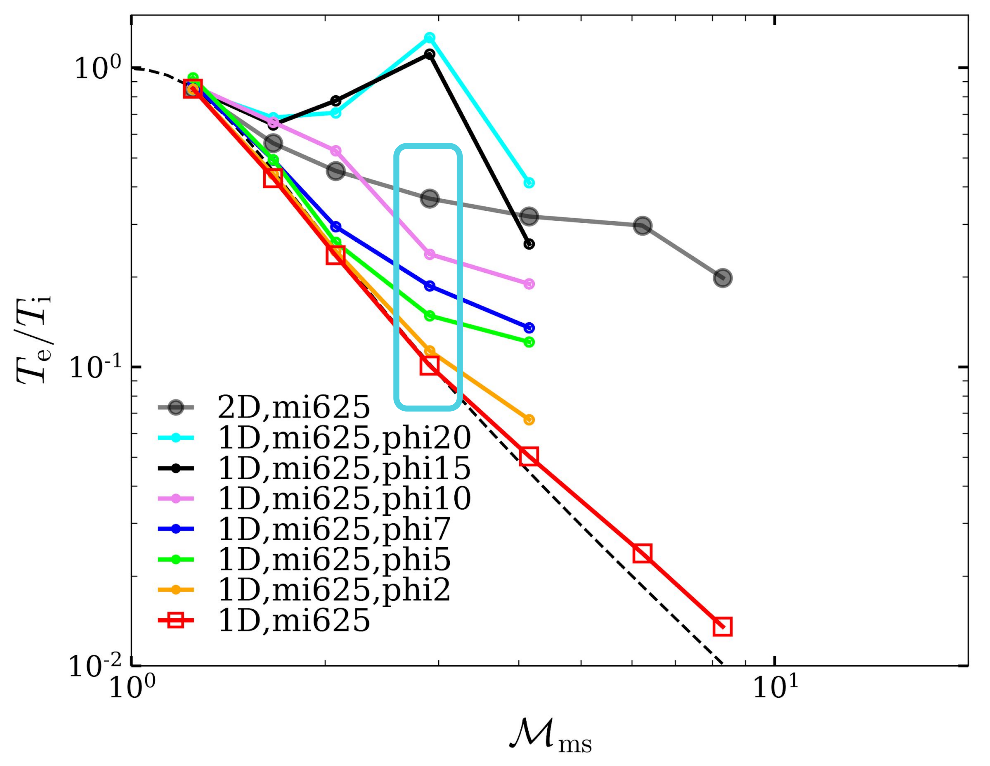
Non-adiabatic perpendicular work looks consistent with high-freq scattering from parallel to perp

Caveat: ~10-20% uncertainties in reconstructed work from ky-filtered fields

How do e⁻ heat?

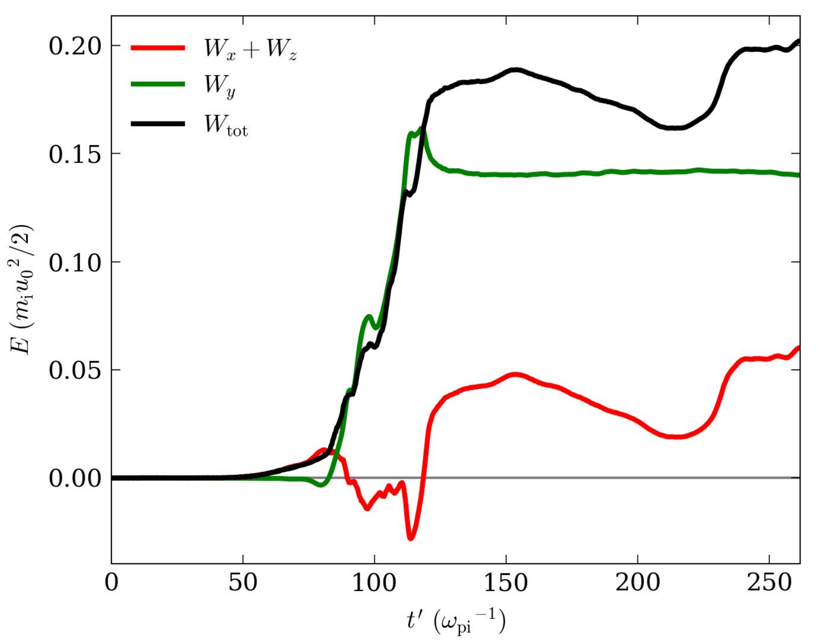
How much can DC heating contribute?





How do e$^-$ heat?

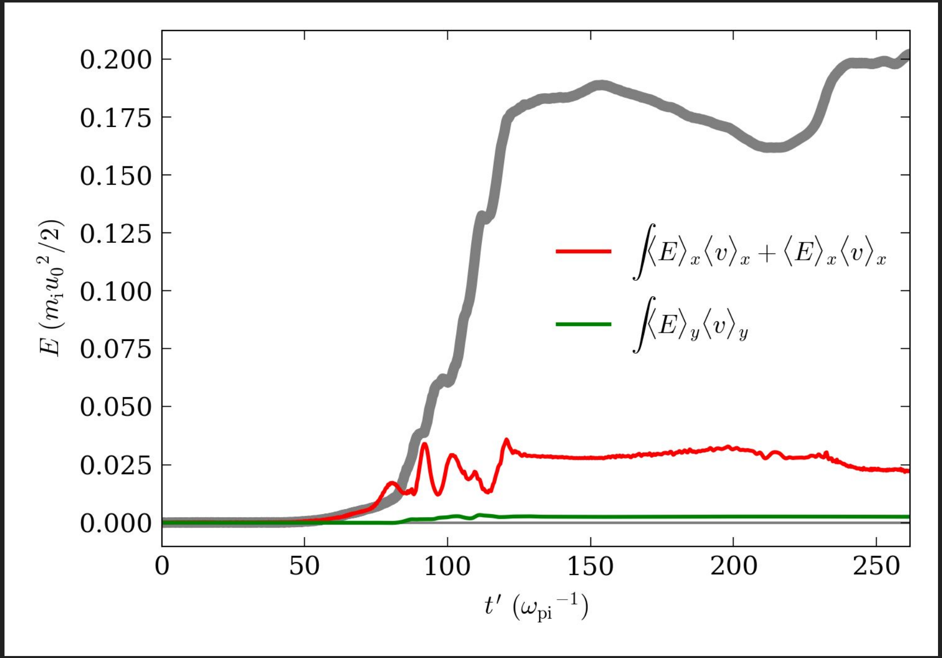
How much can DC heating contribute?



Preliminary - more work/vetting needed

Work in a “1-D average” shock

$$\int \langle \vec{E} \rangle \cdot \langle \vec{v} \rangle \, \mathrm{d}t$$



Conclusions

- Spatially varying, low-freq Eprll heats e^- above fluid adiabatic expectation in low Mach, low beta, strictly-perp shock.
- Rapid electrostatic waves scatter, isotropize
- Geometry and mass ratio are important.

Future work

- Quasi-perp regime? (Chen+ 2018 PRL)
    - Rapid electrostatic structure - maybe still similar to strict-perp case?
- Cross-shock drift heating in 3-D? (get all of shock n, kz, Eprll)
- Instability parameter regimes in simulations?
    - An old question: can instab develop even if growth time > reflected ion gyrotime?