Magnetic field amplification at planetary and astrophysical high Mach-number shocks.

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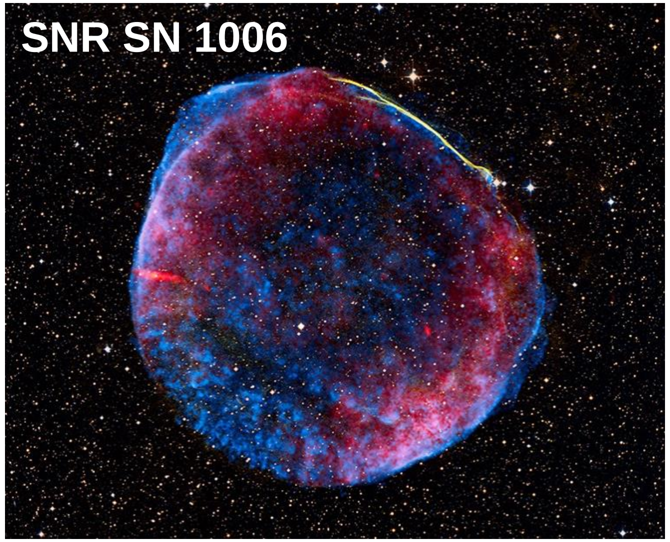
DESY.

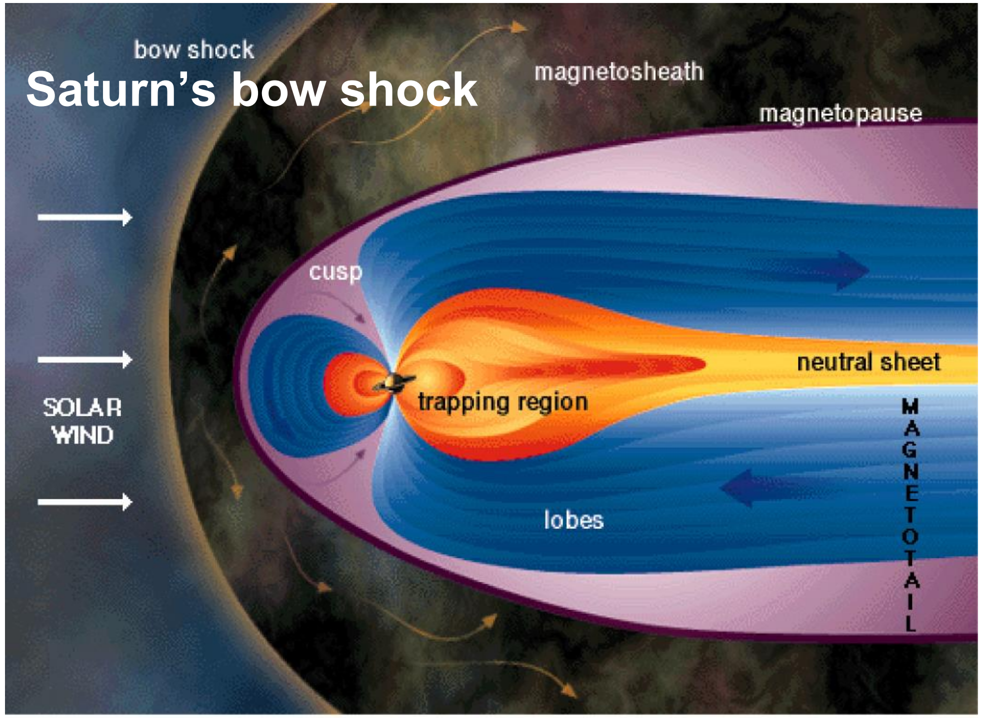
Nonrelativistic high Mach number shocks

$v_{sh} \ll c$; M_S , $M_A > 10$



Magnetic field plays a crucial role in the shock physics, particle acceleration mechanisms, X-ray radiation etc.

Magnetic field can be amplified at large scales (significantly larger than the shock width) via streaming instabilities (Bell 2004, 2005), fluid vorticity seeded by upstream density inhomogeneities (Giacalone 2007, Fraschetti 2013), cosmic ray pressure-driven magnetic field amplification (Downes 2012, 2014) etc.



However, magnetic field is also amplified at scales comparable with the shock width and mechanisms are rather unknown.

In-situ measurements of the Saturn's bow

In-situ measurements:

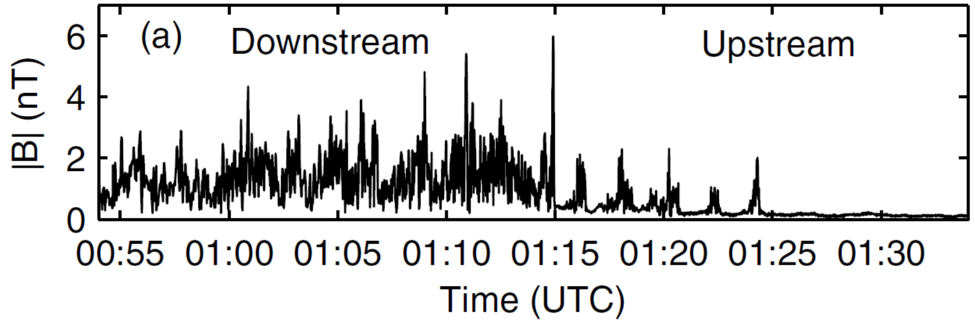
- Strong positive correlations between B_{max} / B_0 and M_A (Sulaiman 2016)
- Magnetic field is higher in reforming shocks by a factor of 1.4 (Sulaiman 2015)

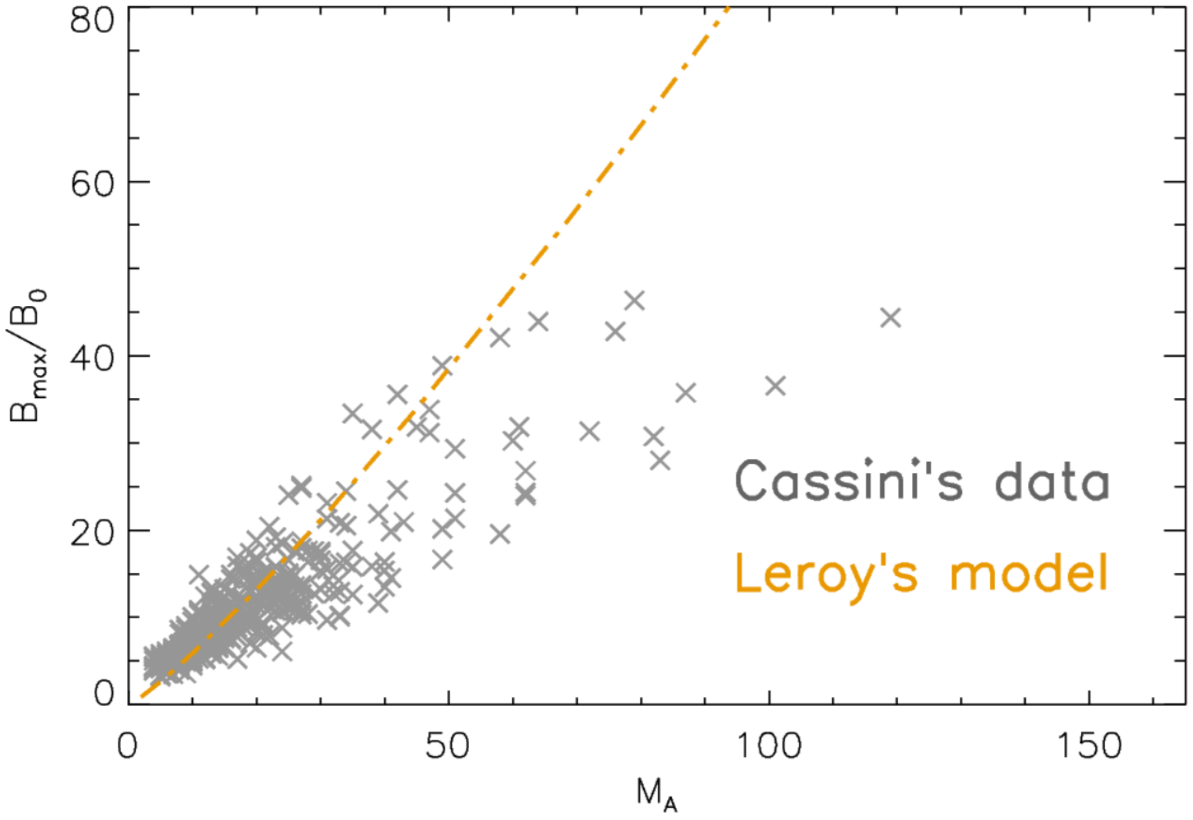
Leroy's model (Leroy 1983, Matsumoto 2012):

$$B_{\rm over} \approx 0.4 B_0 M_{\rm A}^{7/6}$$

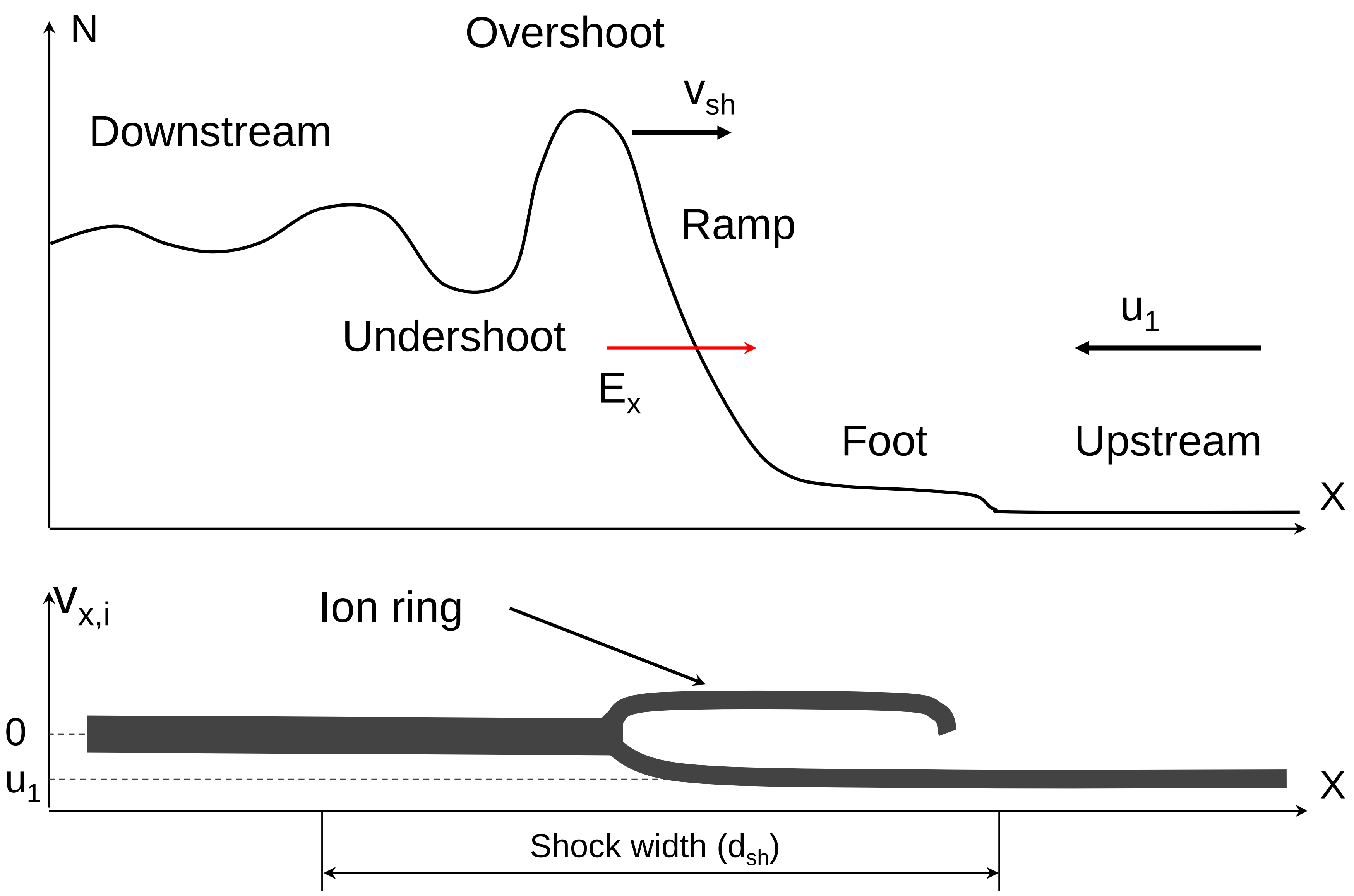
It is based on plasma compression and multidimensional effects are missed. However 3D PIC simulations (Matsumoto 2017), in-situ measurements (Sundberg 2017) and laboratory experiments (Fiuza 2020) suggest that high Mach number shocks are Weibel mediated.

(Sulaiman 2015)



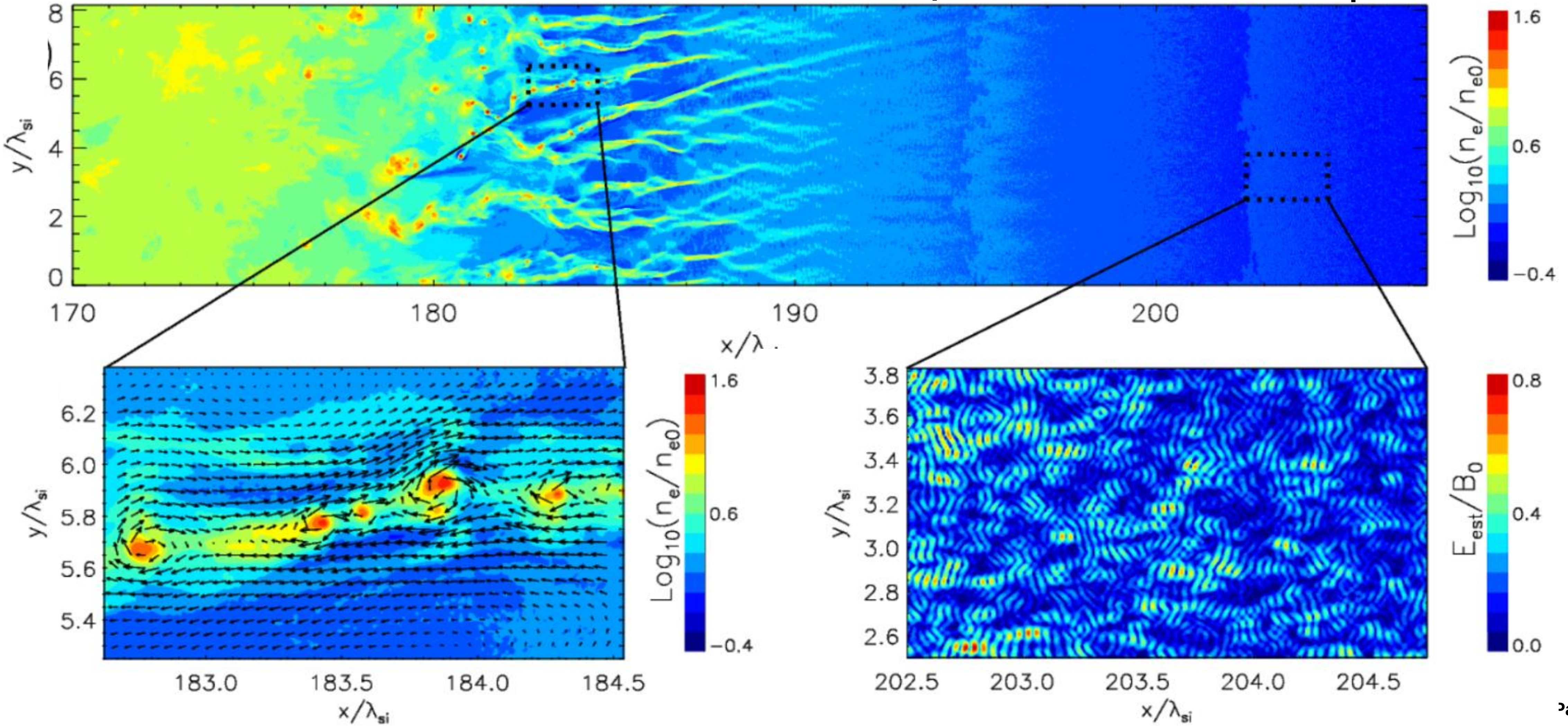


Microstructure of perpendicular supercritical shocks ($M_s \gtrsim 2.76$)



Microstructure of perpendicular shocks: 2D3V PIC simulations

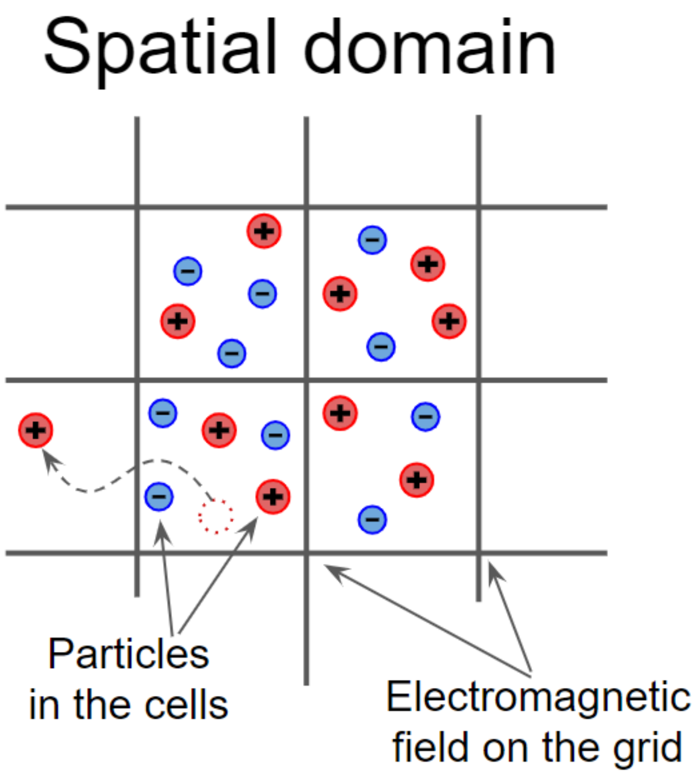
Downstream	Overshoot	Ramp	Foot	Upstream
		Weibel instability Magnetic reconnection	Buneman instability (shock surfing acc.)	

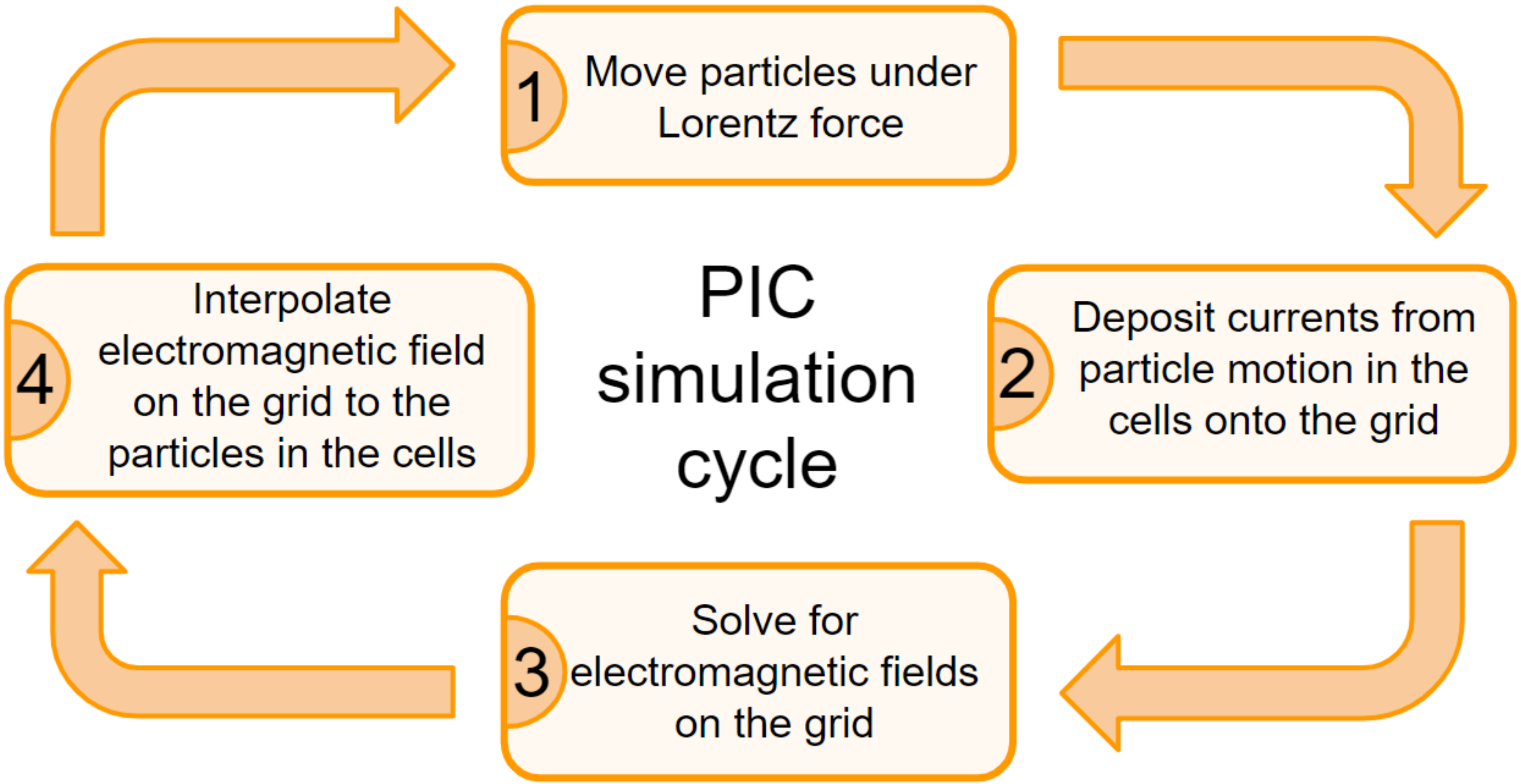


Particle-In-Cell (PIC) simulations

PIC modeling - an ab-initio method of Vlasov equation solution

PIC simulations are designed to explore cases when self-consistent treatment is needed, electron dynamic is important (electrostatic waves, instabilities generated by electrons), electron acceleration or heating processes are investigated

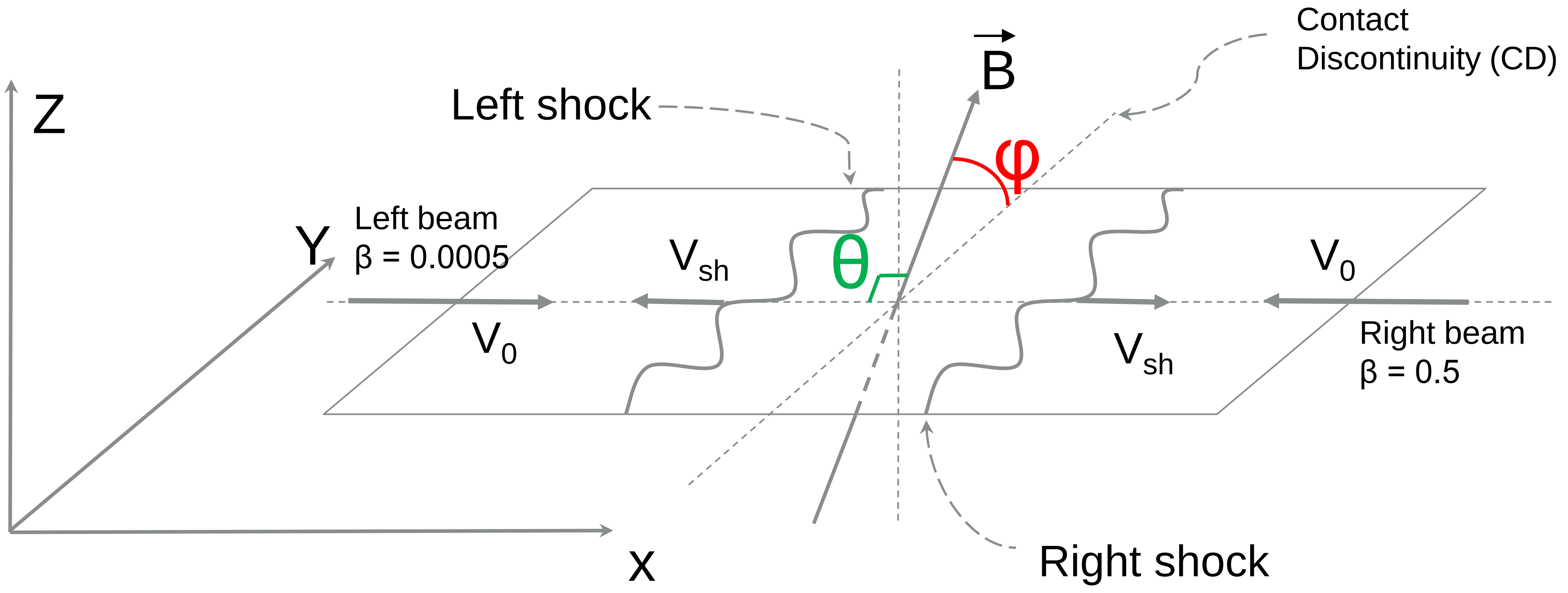




Simulation setup

Shock simulations are performed using an optimized fully-relativistic electromagnetic 2D code with MPI parallelization developed from TRISTAN (Buneman 1993, Niemiec 2008). Shocks are initialized with a **flow-flow method**. The collision of two counterstreaming electron-ion plasma flows spawns two independent shocks propagating in opposite directions. Shock are propagating in media which differs only by the electron plasma beta (the ratio of the electron plasma pressure to the magnetic pressure), which is $5*10^{-4}$ and 0.5 for the left and the right shocks, respectively.

Magnetic field configuration: **θ = 90º , φ = 0º**



Simulation parameters

M_A = 23 - 150
β_e = 0.0005 , 0.5

V_0 = 0.2c
m_i/m_e = 50 - 400

Runs	$m_{\mathrm{i}}/m_{\mathrm{e}}$	M_{A}	M_{s}	
			^{*1}	^{*2}
A1, A2	50	22.6	1104	35
B1, B2	100	31.8	1550	49
C1, C2	100	46	2242	71
D1, D2	200	32	1550	49
E1, E2	200	44.9	2191	69
F1, F2	400	68.7	3353	106
G1†, G2	50	100	4870	154
H1†, H2	50	150	7336	232

Saturn's bow shock

M_A ≈ 5 - 200
β_e ≈ 0.01 – 1

V_0 ≈ 500 km/s
m_i/m_e = 1836

Density and magnetic field profiles

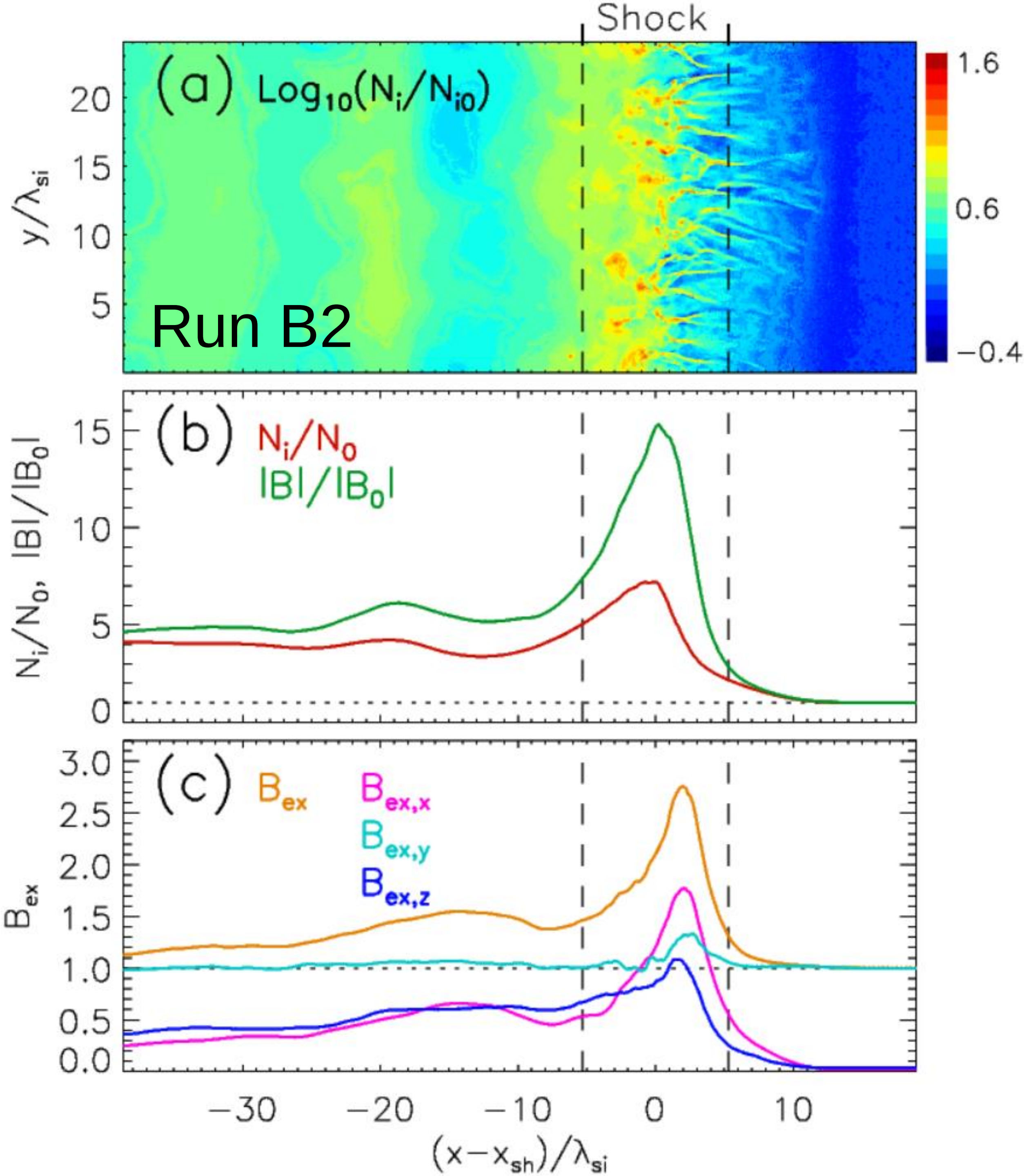
Density compression does not follow Leroy’s model.

The extra magnetic field:

$$B_{\mathrm{ex,a}} = \frac{|B_a|}{|B_0|}\frac{N_0}{N_i} \text{ where } a = x, y, z$$

If $\mathbf{B}_{\mathbf{ex}}$ is 1, magnetic field is amplified due to plasma compression.

$\mathbf{B}_{\mathbf{x}}$ and $\mathbf{B}_{\mathbf{z}}$ are amplified due to Weibel instability.



Magnetic field strength and energy

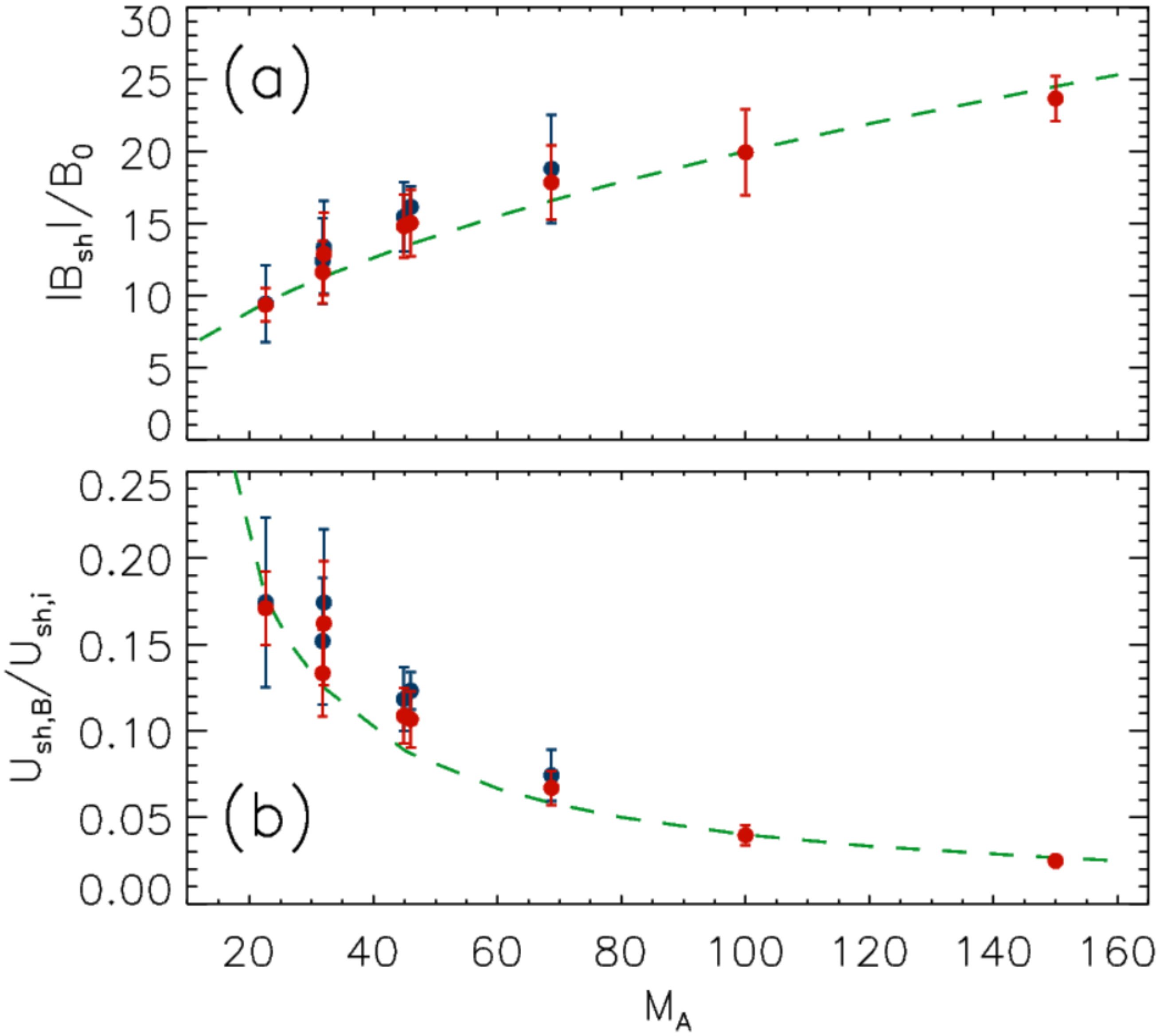
The magnetic field strength:

$$|B_{\rm sh}| \approx 2\sqrt{M_{\rm A}}\, B_0$$

The magnetic field energy:

$$\frac{U_{\rm sh,B}}{U_{\rm sh,i}} \approx \frac{4}{M_{\rm A}}$$

Does not depend on mass ratio and the upstream plasma beta.



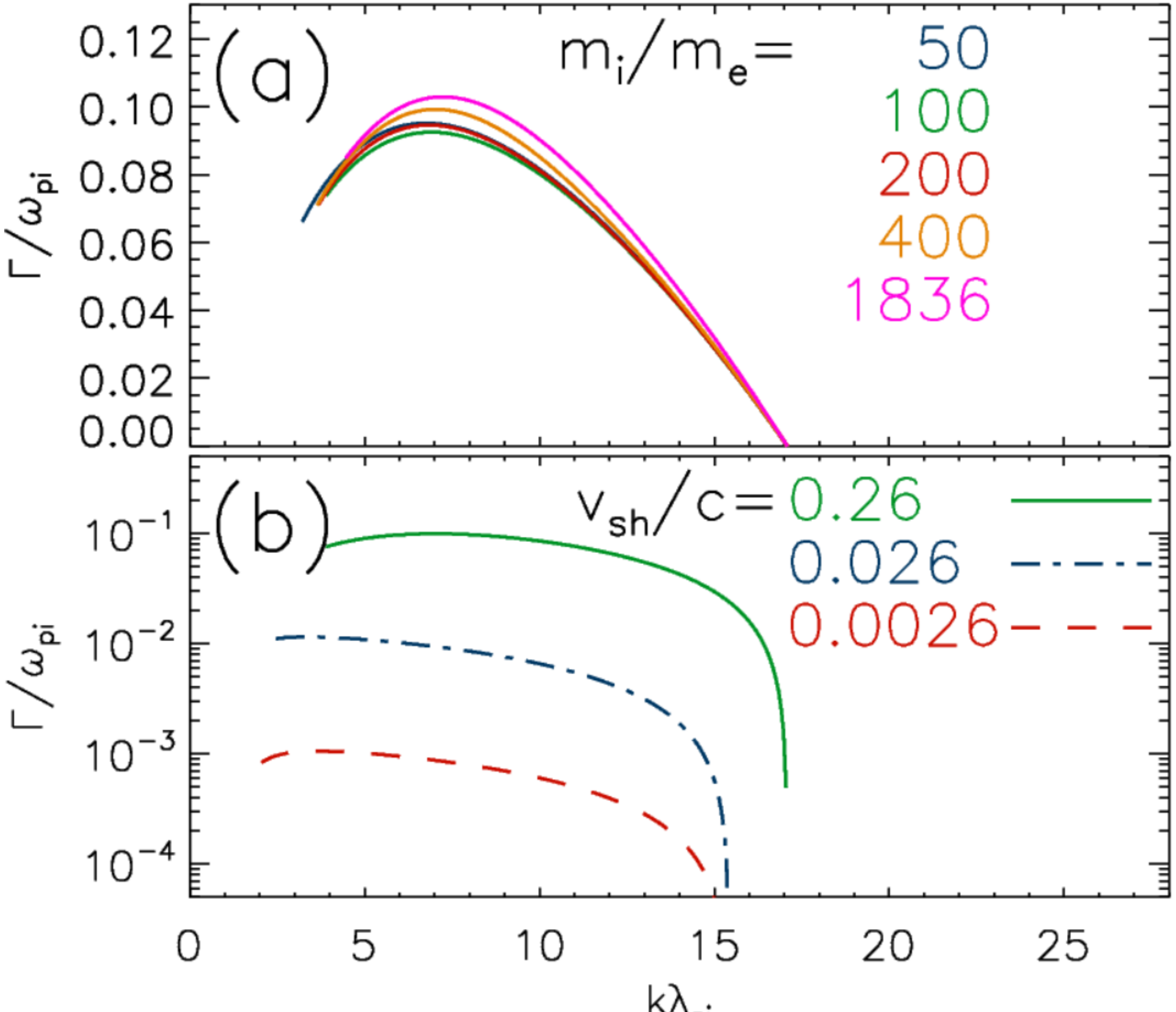
The Weibel instability growth rate

Solving numerically the dispersion relation for cases with different mass ratios and shock velocities using plasma parameters from the shock ramp we obtain that the normalized growth rate of the most unstable Weibel mode follow next rules:

(a) $\frac{\Gamma_{\max}}{\omega_{\rm pi}}$ does not depend on m_i/m_e

(b) $\frac{\Gamma_{\max}}{\omega_{\rm pi}} \propto v_{\rm sh}$ or $\frac{\Gamma_{\max}}{\Omega_{\rm i}} \propto M_{\rm A}$

Conclusion: magnetic field amplification is defined exclusively by ***M_A***



Magnetic field amplification: in-situ vs PIC

Cassini’s data

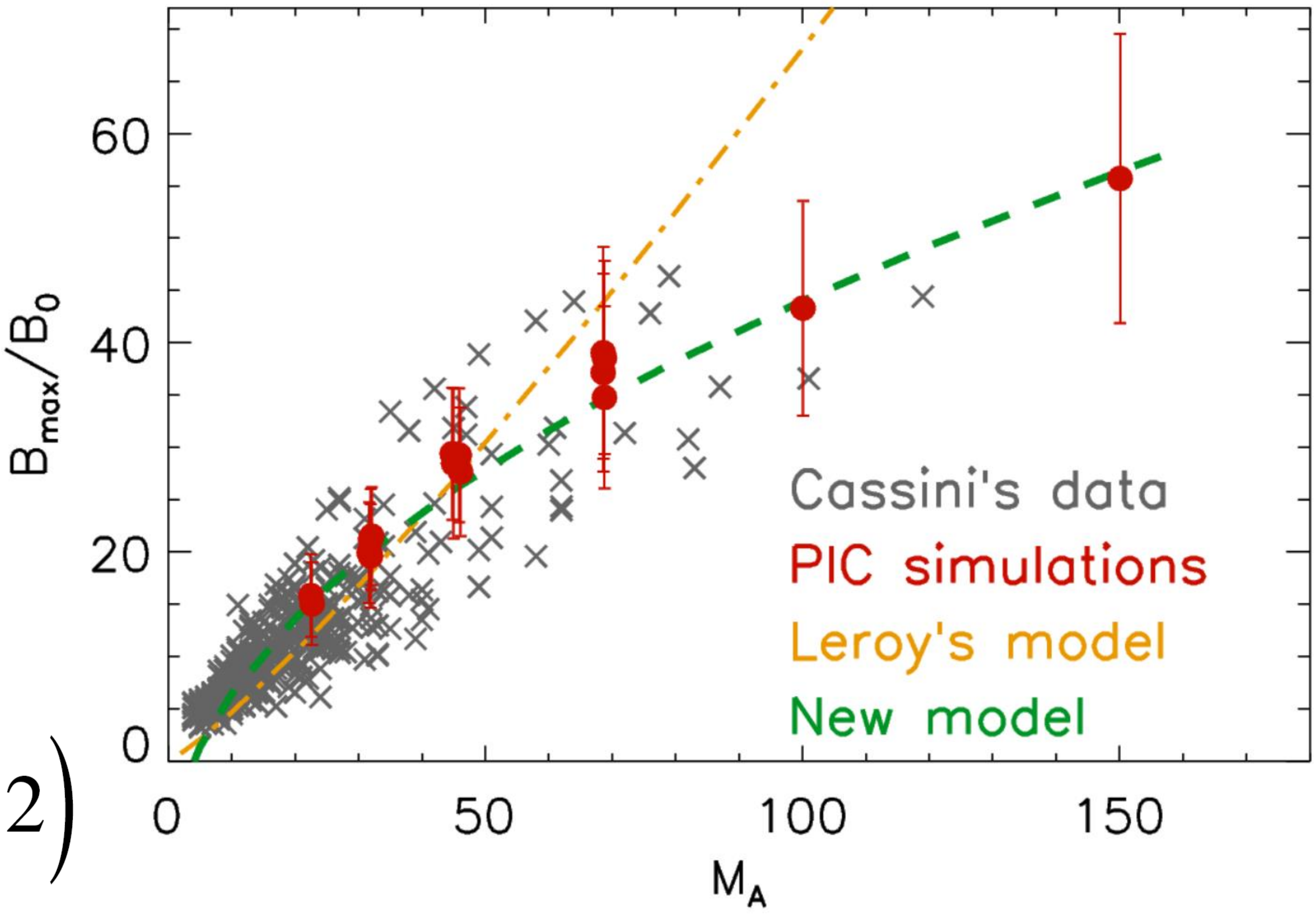
PIC simulation data

Leroy’s model*

$$B_{\text{over}} \approx 0.32 B_0 M_A^{7/6}$$

New model

$$\frac{B_{\max}}{B_0} = 5.5\left(\sqrt{M_A} - 2\right)$$



* Numerical coefficient is corrected due to the shock self-reformation

Influence of magnetic field on acceleration mechanisms

- Diffusive shock acceleration (DSA)

Due to the strong magnetic field at the shock transition particles require larger momenta for injection into classical DSA, where particles repeatedly cross the shock without significant deflection in the shock internal structure.

Therefore the injection momentum should depend on ***M***M_A: $p_{\rm inj} \propto r_{\rm sh} B_{\rm sh} \propto \sqrt{M_{\rm A}}$

- Stochastic shock drift acceleration (SSDA)

Shock drift acceleration combined with the pitch angle scattering at the shock transition results in so-called SSDA mechanisms which can efficiently accelerate electrons (Katou 2019, Amano 2020). Efficiency of SSDA depend on magnetic field $D_{\mu\mu}/\Omega_{\rm ce}$, which is define by magnetic field structure and strength. Also the cut-off energy is proportional to $B_{\rm sh}$

Conclusions

1. Weibel instability amplifies magnetic field at the shock transition up to values which far exceeds a plasma compression at the shock transition.

2. Magnetic field amplification level is defined by Alfvenic Mach number of the shock. The amplification level does not depend on the ion-to-electron mass ratio, the shock velocity and the upstream plasma beta.

3. Very good match between PIC simulation results and in-situ measurements done by the Cassini spacecraft. The average magnetic field strength at the shock transition can be estimated as $|B_{\rm sh}| \approx 2\sqrt{M_{\rm A}}\, B_0$

4. Amplified magnetic field strongly affects proton and electron acceleration mechanisms.

Thank you

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