# Fast Shocks in Magnetic Reconnection Outflows

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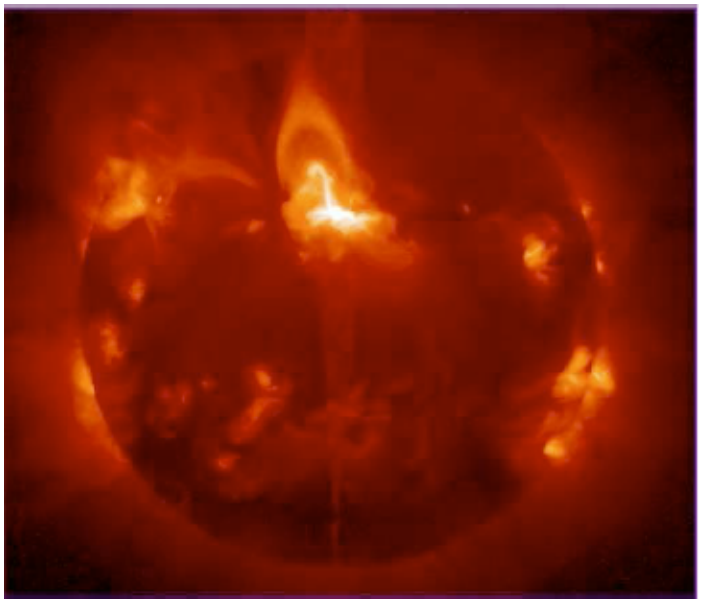
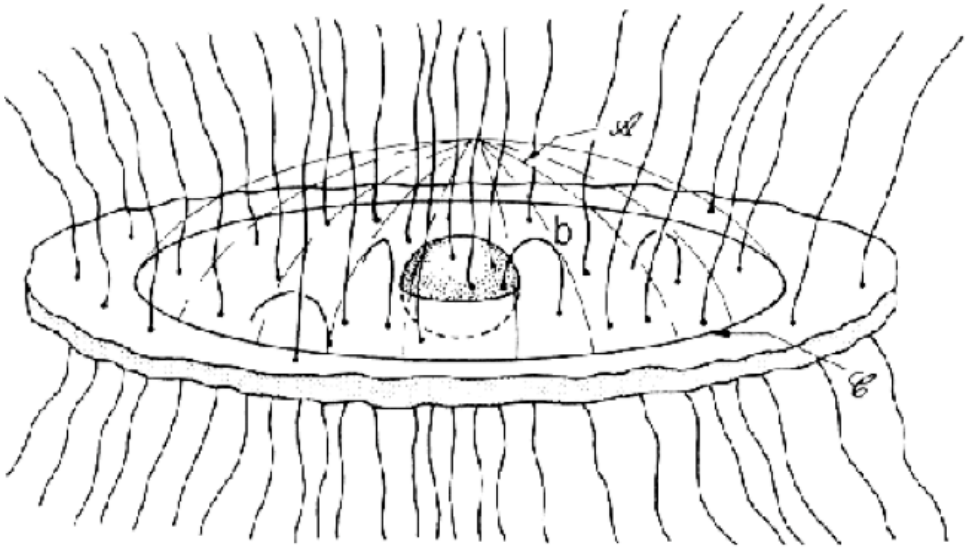
***Workman, Blackman, Ren (2011)***

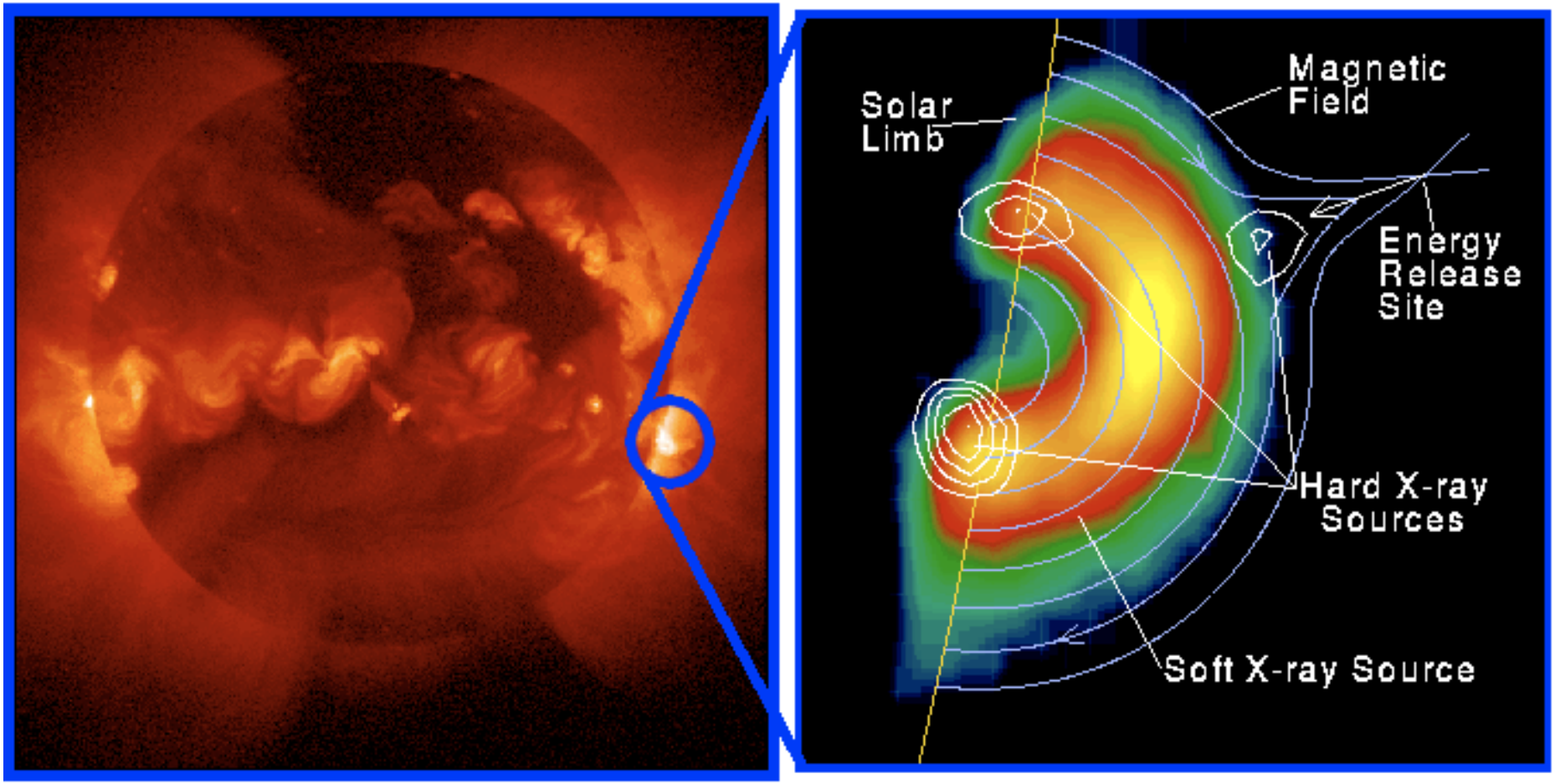
*Park et al. (2012,in prep).*





# Reconnection Rate vs. Particle Acceleration

- More recent progress in understanding reconnection rates and basic conditions when rates are fast vs. slow.
- Understanding the particle acceleration spectrum from magnetic reconnection is less understood, and more difficult to measure in lab.

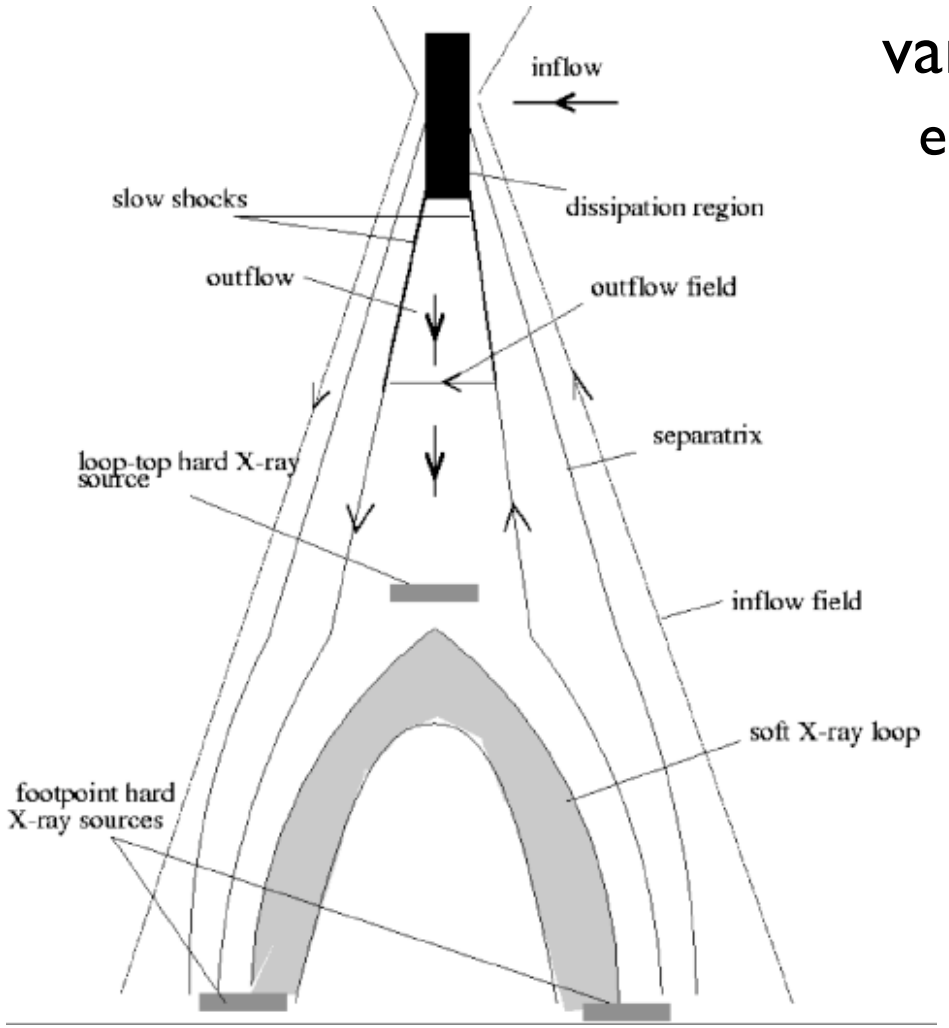



Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

# Solar Flares

- LDE Flares: hours, ~ $10^{28}$ erg/s, $10^{4\text{-}5}$km, ion dominated few nonth. e-;
- CI Flares: minutes, ~ $10^{28}$ erg/s, $10^{3\text{-}4}$km, ~50% energy in nonth. e-
- Yohkoh revealed that: LDE and CI are consistent with same inverse-Y structure (Tsuneta, Masuda et al. 94); RHESSI, Hinode..
- Foot point and loop top (e.g. Masuda flare) X-rays
- CI-Thermal to 20keV; power-laws 20-100keV and > 100keV
- Pulsed and smooth components of non-thermal electrons
  - Pulsed Component (0.1-1sec) Time delays: **Low** energies (E/2) lag **high** (E) by ~30-100ms
  - Smooth Component(4-20sec)Time delays: **High** energies (E) lag **Low** (E/2) by ~ few secs.
- Variety motivates thinking of inverse-Y **reconnection as an acceleration environment** not a single process
- review of electron acc. in flares (Holman et al. 11, Zharkov et al. 11))

# Reconnection as an "acceleration environment"




- different conditions likely give different relative importance for various processes

  e.g.

  -direct acceleration at X-point
  -slow shocks
  -shear+turbulence in downflows
  -stochastic Fermi
  -cooling (e.g. Uzdensky)
  -scattering inflows
  **-fast shocks**....

(e.g. Forbes 86, Chiueh & Zweibel 87, Romanova & Lovelace 92; Blackman & Field 94; Petrosian et al. 94; Larosa et al. 96;, Shibata 95; B97; Tsuneta 97; Blackman Selkowitz 07; Uzdensky & McKinney 2011; Kowal et al.11; Drury '12)

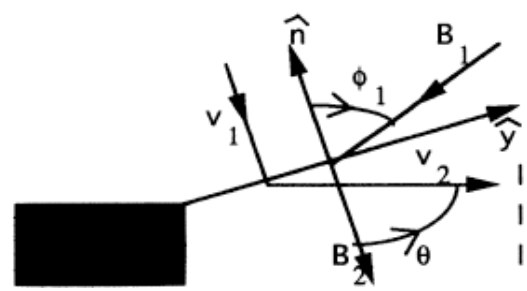
# Past Work on Reconnection Outflow Fast Shocks

- numerical: Forbes, 1986,1988: line tied configurations, using, SHASTA, configuration unstable without imposed perturbation; fast shocks, but reconnection rate faster than Petschek; warrants revisiting for more generic configuration

- Flare scenarios (Shibata 95; B97 ; Tsuneta et al 97; Tsuneta & Naito 98; Blackman & Selkowitz 07; Aurass et al. 02,04; Mann et al 06)

- analytic solutions for reconnection inflow, across slow shocks; outflow speed, function of inflow field angle (e.g. Blackman & Field 1994);

- Mach numbers ≤ 2 expected (adiabatic)




- Mann et al. (2006): Used relativistic drift acceleration at a termination shock to explain temporal coincidence of hard X-rays and γ-rays up to 10MeV (observed with RHESSI, and INTEGRAL) and radio burst emission (from 200-400MHz Warmouth et al. 07) via acceleration of relativistic particles at a fast shock in a 2003 LDE flare

- Flare acceleration reviews by Holman et al. (2011); Zharkova et al. (2011)

# OUR SIMULATION SETUP

- Used ATHENA (compressible MHD, 2nd order Godunov) Gardiner & Stone 05, public)
- solve 2-D resistive, non-viscous MHD; typical runs: 480 x 960 or 960x 1920; Lundquist numbers ~3000 ($v_A \sim 1.5$, $L_x \sim 13$, $L_y \sim 26$, $\nu \sim 0.01$)
- Initial Harris sheet configuration (1-D Equilib. soln of Vlasov-Maxwell eqn.) used in GEM studies (e.g. Birn et al. 2001); no line tying. Initial $\beta \sim 0.2$
- considered initial isothermal state subject to either isothermal or adiabatic state (solved energy equation for latter)
- outflow boundaries; mass/flux not resupplied
- units : $t \sim 10$ is Alfvén crossing time across inflow so $t \sim 50$ is time to lose about 1/2 inflow at recon rate $0.1V_A$
- dense, T=0, plasma wall inserted at $11 < y < 13$, at t=0, or 30, or, 44;
- compared adiabatic vs. isothermal (cooling) cases, and uniform resistivity vs. enhanced origin resistivity cases

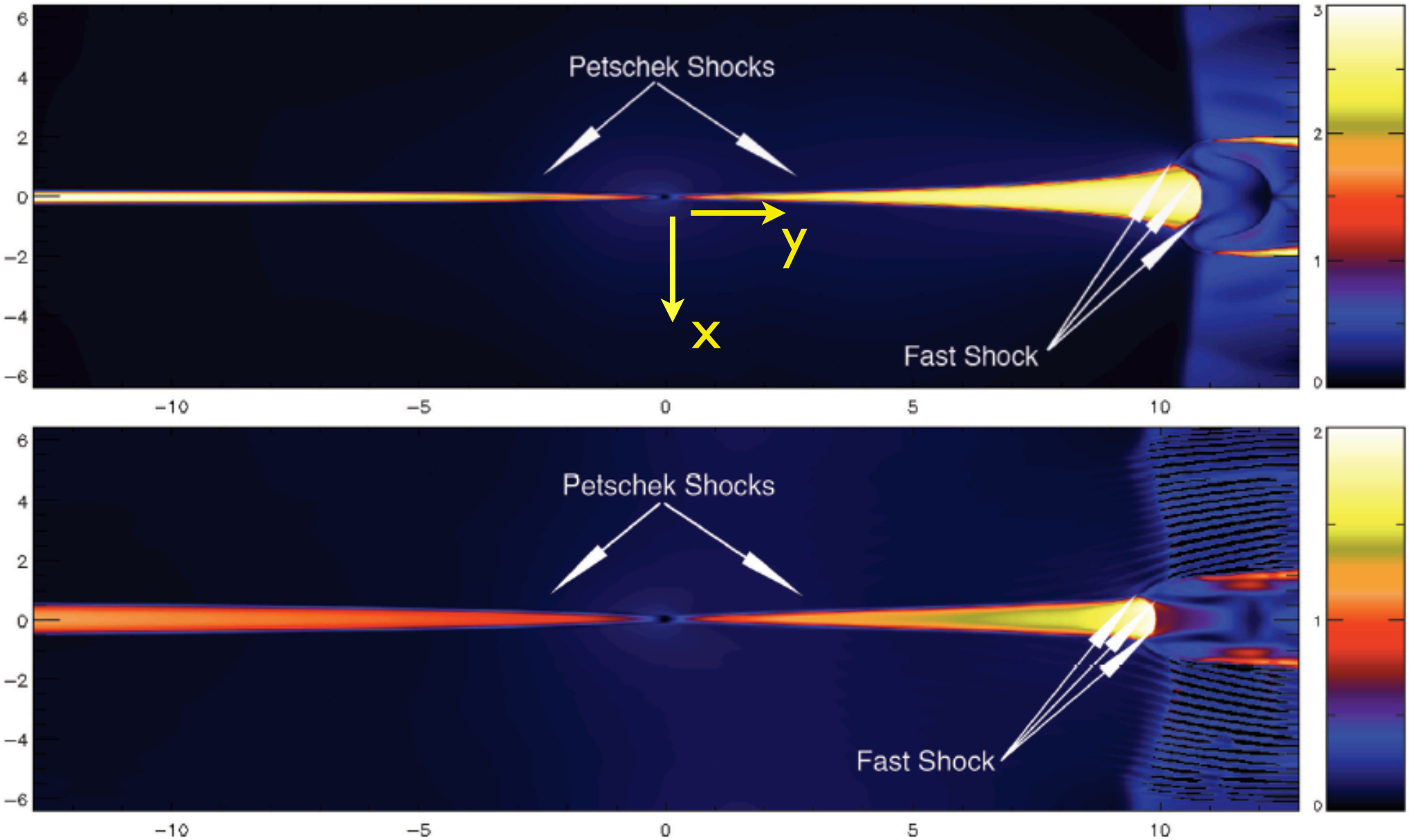
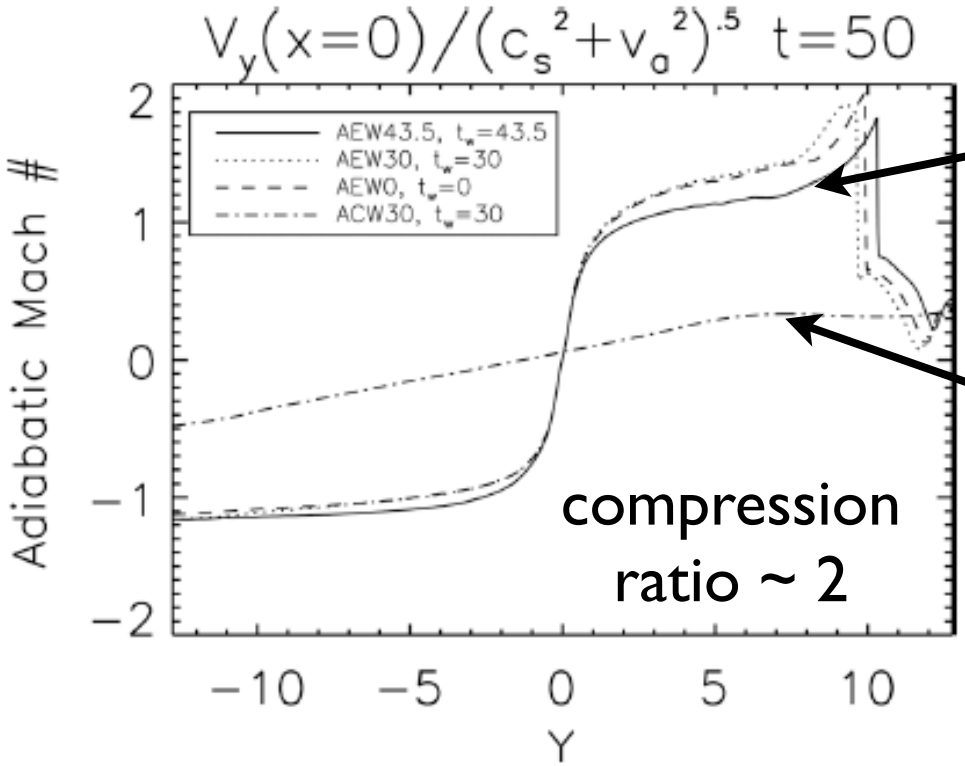



FIG. 6. (Color) Snapshot of the magnetosonic Mach number for IEW30 (top image) and AEW30 (bottom image) at t = 50. The color bars denote the magnitude of the Mach number. The location of the Petschek shocks and the fast shocks are labeled for the top figure only but occur at the same location for the bottom figure. We plot the results with the axis flipped from their definition in the text for ease of visualization.




cases with $\nu_0=10\nu_{amb}$ (Petschek)

case $\nu_0=\nu_{amb}$ (Sweet Parker)

FIG. 4. Mach number $M = V_y/\sqrt{(c_s^2+v_A^2)}$ at $x=0$ and $t=50$ for the adiabatic simulations of Table I with walls placed near $y\sim 11$ at times 0, 30, and 43.5. At negative $y$, there is no wall. The curve that remains subsonic at all $y$ is run ACW30 in Table I, the only case shown with $\nu_e=0$.

Cooling exacerbates compression ratio at the fast shocks

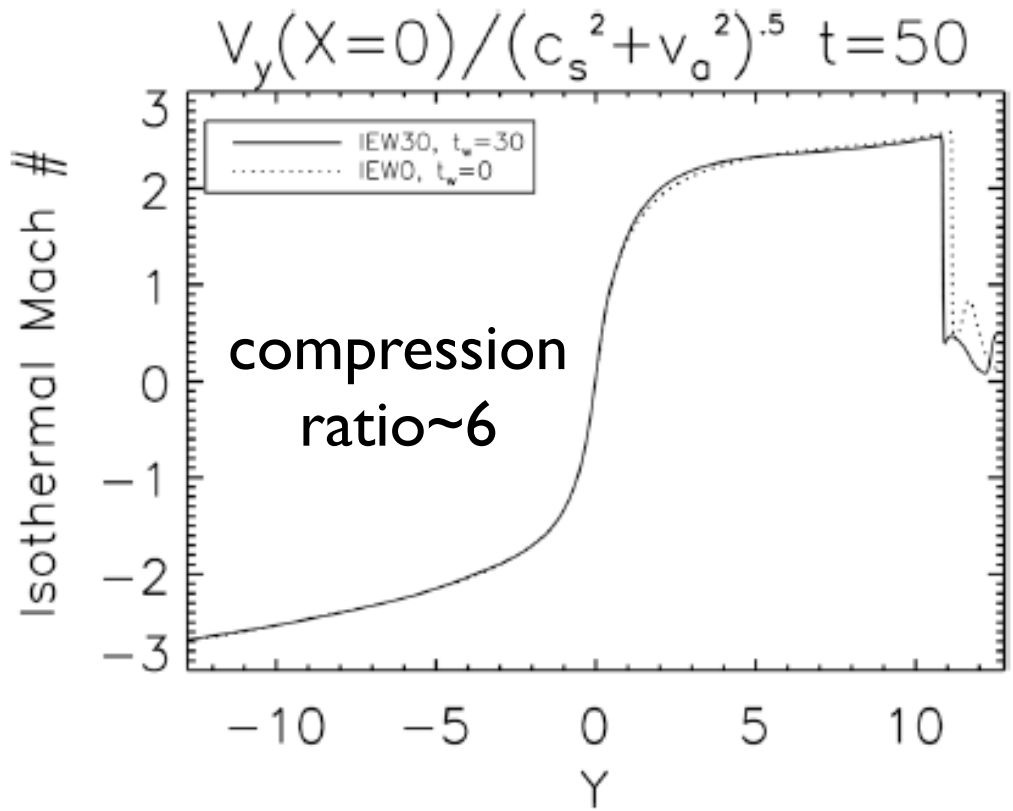
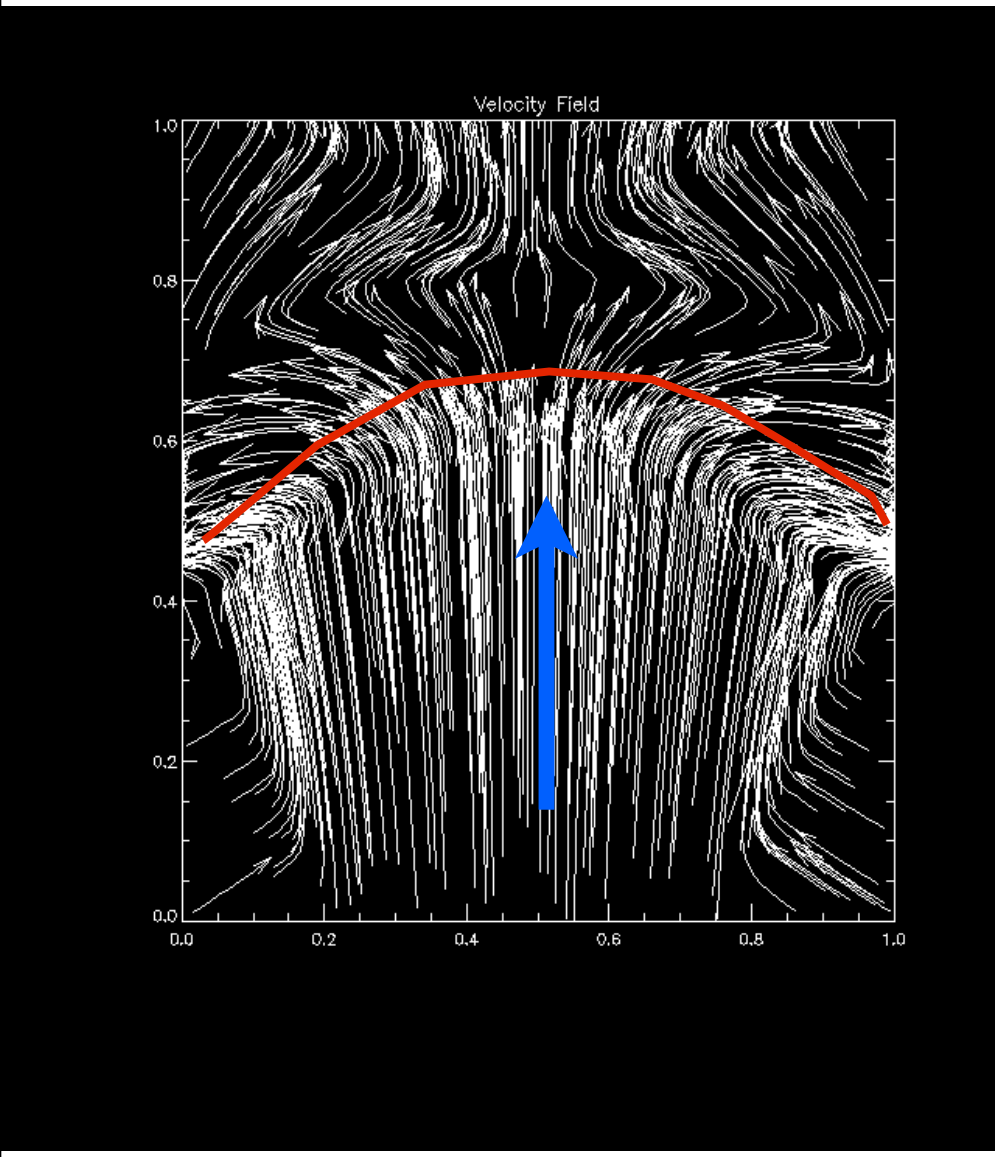
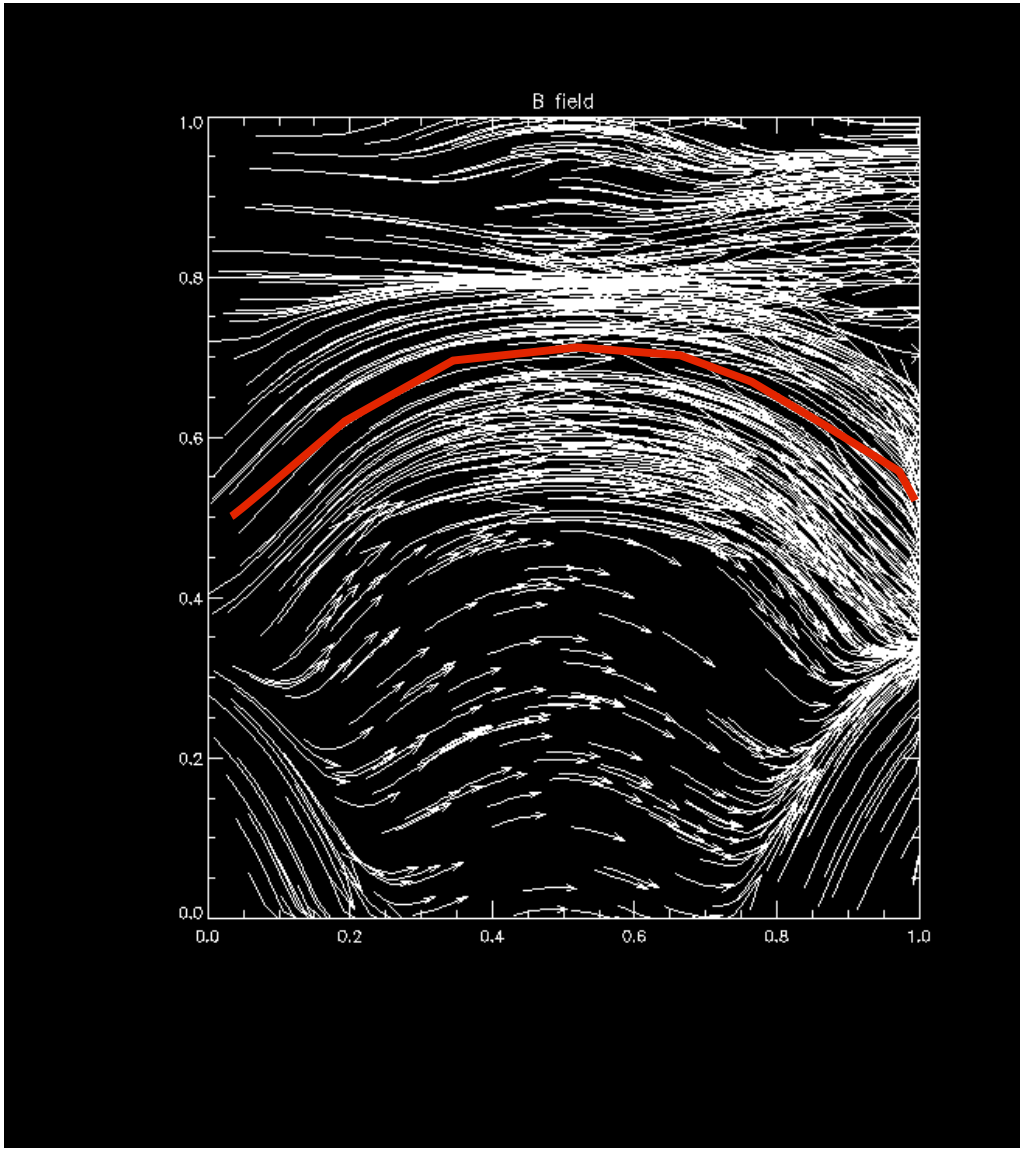



FIG. 5. Same as Fig. 2 for the isothermal simulations with walls in Table I

# Shock is a Perpendicular shock




Velocity Field

Magnetic Field

# Implications and Further Work

- Generic GEM challenge 2-D reconnecton configuration shows fast shocks with compress. ratio ~ 2; potentially ubiquitous feature of collisionless reconnection

- outflows only super-magnetosonic in MHD simulations for enhanced resistivity (see also Biskamp 00; Kulsrud 01) at origin; insensitive to the enhancement once above factor of 3

- Phenomenological evidence for fast shocks above loop tops in solar flares

  - fast pulsed component of solar flares shows non-relativistic Energy spectrum $N(E) \propto E^{-\delta}$ with $3 < \delta < 4.5$ (e.g. Bromund et al. 95) conisitent with **diffusive Fermi** shock acceleration (Bell 78) $\delta=(r+0.5)/(r-1)$ for weakly compressive $r <= 2$ outflow fast shocks. But Fermi likely better for oblique shocks (e.g. Jones & Ellison 1991; Park et al. in prep.)

  - Mann et al. (2006): **shock drift** relativistic particle acceleration at r=2 shock to explain hard x-rays, γ-rays and radio, using diffusive shock acceleration

- 2-D vs 3-D: (3-D: asymmetric shear of outflow, guide field, varying obliquity? Fermi vs. Drift accel.)

- We are studying the plasma physics of the particle acceleration and shock formation(***Ren talk next!***)

  - Park et al. (2012): PIC sims: Studying formation and particle acceleration at collisionless weak fast shocks. Importance of **two-stream instability** and **shock-drift** acceleration for strictly perpendicular shocks. Generalize to oblique shocks (?)

- **Evidence for shocks in reconnection experiments would be interesting**

- **General experimental study of magnetized collisionless shocks (fast and slow mode) at LOW and HIGH compression ratios; with and without cooling is of interest**

END