SHOCKS, TURBULENCE, and PARTICLE ACCELERATION

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Outline

- Shocks
- Turbulence
- Particle acceleration

Outline

- Basic phenomenology

- Shocks
  - Basic physics (conservation laws etc)
  - Shocks in the solar corona and collisionless SW plasma
  - Fermi I particle acceleration

- Turbulence
  - Basic physics in different regimes (collisionless, HD)
  - Existing misconceptions and non-existent controversies
  - Turbulence in the corona and SW
  - Fermi II particle acceleration

- Particle acceleration
  - Mechanisms of particle acceleration
  - Outstanding problems

- Summary and open questions

T&Cs, basic phenomenology etc

Thermal

- **Collisional**
- Particle distribution quickly becomes Maxwellian
- Behaves like a fluid
- Magnetohydrodynamics
- Fluid lectures:
  - Philippa Browning: **MHD**;
  - Gunnar Hornig: **Magnetic reconnection**;
  - Valery Nakariakov: **Waves & instabilities**

Non-thermal

- **Collisionless**
- No reason for Maxwellian distribution
- Behaves like a N-body system
- Kinetics
- Kinetic lectures:
  - David Tsiklauri: **Plasma kinetics**;
  - Eduard Kontar**: High-energy solar/stellar atmospheres**

T&Cs, basic phenomenology etc

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- **Most interesting thing happen here**
- Events in the solar corona: **Non-thermal plasma (energetic particles) in thermal plasma**

Non-thermal

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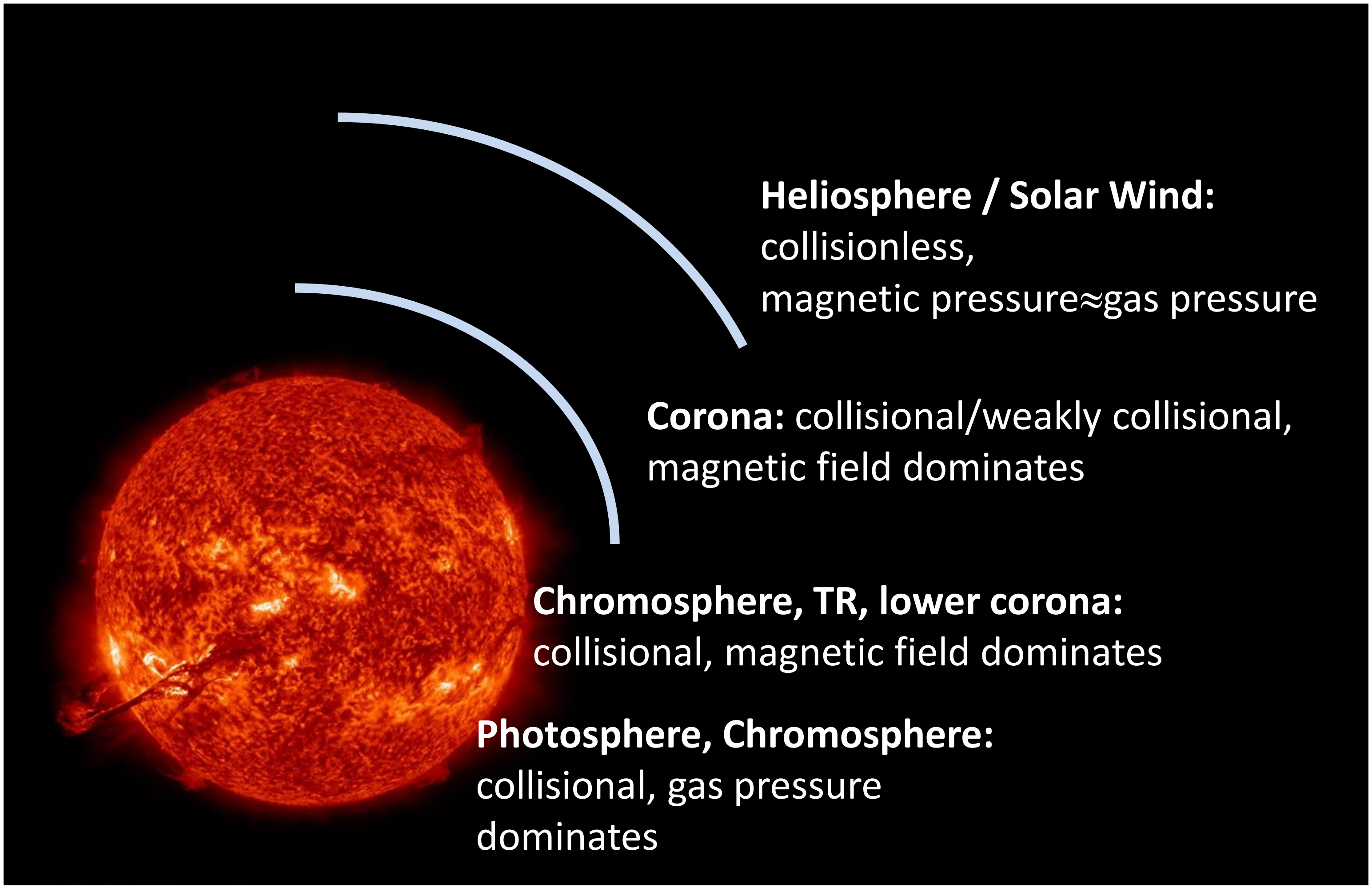
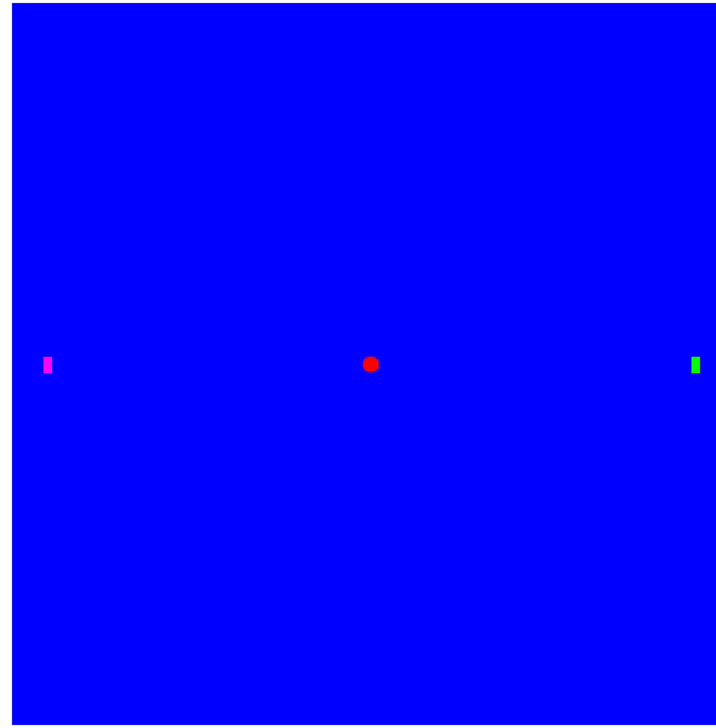
T&Cs, basic phenomenology etc



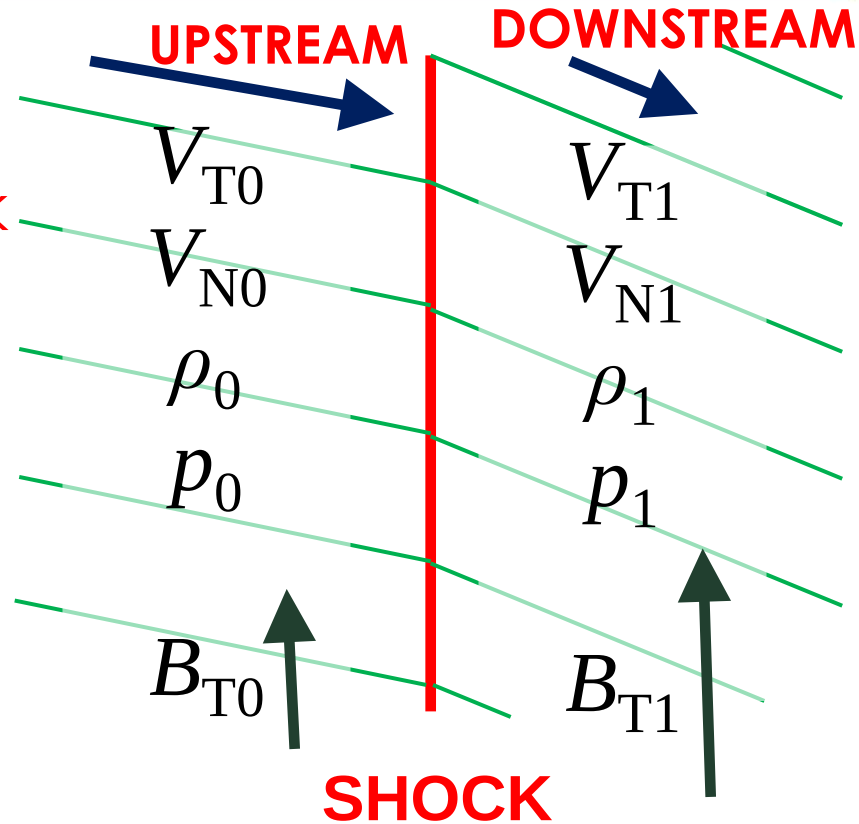
Shock: basic physics



- Perturbation travels faster than the local phase speed ⇒ wave is steepening, becomes non-linear

Simple 1D (M)HD shock model

- $B_{T0}=B_{T1}=0$ -> Parallel shock
- $B_{N0}=B_{N1}=0$ -> Perpendicular shock



- Normal component B_n does not change!! (div$\boldsymbol{B}$=0)
- Normal mass flux is conserved (mass conservation)
- Total energy density (I + K + M) is conserved
- Momenta (separately, N and T) are conserved
- E_T is conserved

$$\vec{\nabla} \times \vec{E} = \frac{\partial \vec{B}}{\partial t} = 0 \qquad \frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y} = 0$$

$$\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z} = 0$$

$$\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x} = 0$$

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho_E}{\varepsilon_0} = 0 \qquad \frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z} = 0$$

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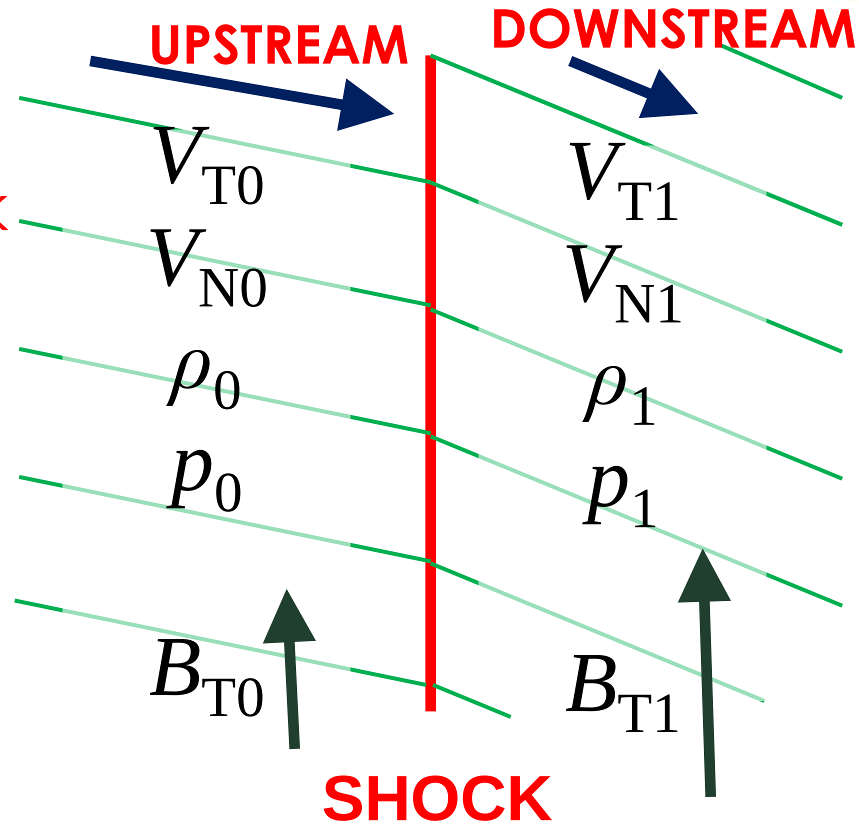

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Rankine-Hugeniot relations

- MHD equations in conservative form

$$\frac{\partial Й}{\partial t} = -\vec{\nabla} \cdot Flux_{Й} + Sources_{Й}$$

Conserved value	"Normal" form	Conservative form	Flux of value
Mass	$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{V}) = 0$	$\frac{\partial \rho}{\partial t} + \nabla(\rho \mathbf{V}) = 0$	$\rho \mathbf{V}$
Momentum	$\rho\left[\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\nabla)\mathbf{V}\right] = -\nabla p + \mathbf{j} \times \mathbf{B}$	$\frac{\partial(\rho \mathbf{V})}{\partial t} + \nabla \cdot \left((\rho \mathbf{V})\mathbf{V} + \left(p + \frac{B^2}{2\mu}\right)\mathbf{I} - \frac{\mathbf{BB}}{\mu}\right) = 0$	$(\rho \mathbf{V})\mathbf{V} + \left(p + \frac{B^2}{2\mu}\right)\mathbf{I} - \frac{\mathbf{BB}}{\mu}$
Energy	$\frac{\partial}{\partial t}\left(\frac{p}{\rho^{\gamma}}\right) + (\mathbf{V} \cdot \nabla)\left(\frac{p}{\rho^{\gamma}}\right) = s$	$\frac{\partial E}{\partial t} + \nabla \cdot \left(\left(E + p + \frac{B^2}{2\mu}\right)\mathbf{V} - \frac{\mathbf{B}(\mathbf{V} \cdot \mathbf{B})}{\mu}\right) = 0$	$\left(E + p + \frac{B^2}{2\mu}\right)\mathbf{V} - \frac{\mathbf{B}(\mathbf{V} \cdot \mathbf{B})}{\mu}$

$E = \frac{p}{\gamma - 1} + \frac{\rho V^2}{2} + \frac{B^2}{2\mu}$ is total energy density (Internal + Kinetic + Magnetic)

Rankine-Hugeniot relations

$[A] \equiv A_1 - A_0$

- Mass conservation

$$[\rho V_{\mathrm{N}}] = 0$$

- Parallel momentum conservation

$$\left[\rho {V_{\mathrm{N}}}^2 + p + \frac{B^2}{2\mu_0}\right] = 0$$

- Perpendicular momentum conservation

$$\left[\rho \vec{V}_{\mathrm{T}} V_{\mathrm{N}} + \frac{B_N}{\mu_0}\vec{B}_{\mathrm{T}}\right] = 0$$

- Total energy conservation

$$\left[V_{\mathrm{N}}\left(\frac{\rho V^2}{2} + \frac{\gamma p}{\gamma - 1}\right) + V_{\mathrm{N}}\frac{B^2}{\mu_0} - B_{\mathrm{N}}\frac{\vec{V}\cdot\vec{B}}{\mu_0}\right] = 0$$

- E_{T} conservation

$$\left[V_{\mathrm{N}}\vec{B}_{\mathrm{T}} - B_{\mathrm{N}}\vec{V}_{\mathrm{T}}\right] = 0$$

- divB =0

$$[B_{\mathrm{N}}] = 0$$

Simplest case: 1D parallel shock

- 1D case, only normal component of B and V

$$\rho_1 V_1 = \rho_0 V_0$$

$$\rho_1 {V_1}^2 + p_1 = \rho_0 {V_0}^2 + p_0$$

$$\frac{\rho_1 {V_1}^3}{2} + \frac{\gamma p_1 V_1}{\gamma - 1} = \frac{\rho_0 {V_0}^3}{2} + \frac{\gamma p_0 V_0}{\gamma - 1}$$

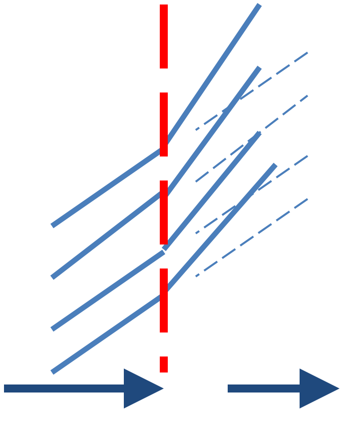
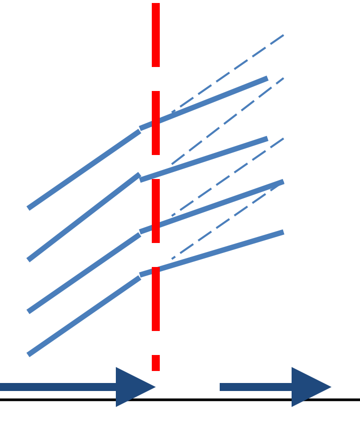
- Solution
  - Shock compression ratio

$$r = \frac{\rho_1}{\rho_0} = \frac{V_0}{V_1} = \frac{(\gamma+1)M^2}{(\gamma-1)M^2+2} \overset{M>>1}{\approx} \frac{(\gamma+1)}{(\gamma-1)} \overset{\gamma=5/3}{\approx} 4$$

where $M = \frac{V_0}{C_{s0}} = V_0\sqrt{\frac{\rho_0}{\gamma p_0}}$ is the Mach number

MHD shocks v. MHD waves

[Valery Nakariakov: Waves and instabilities]

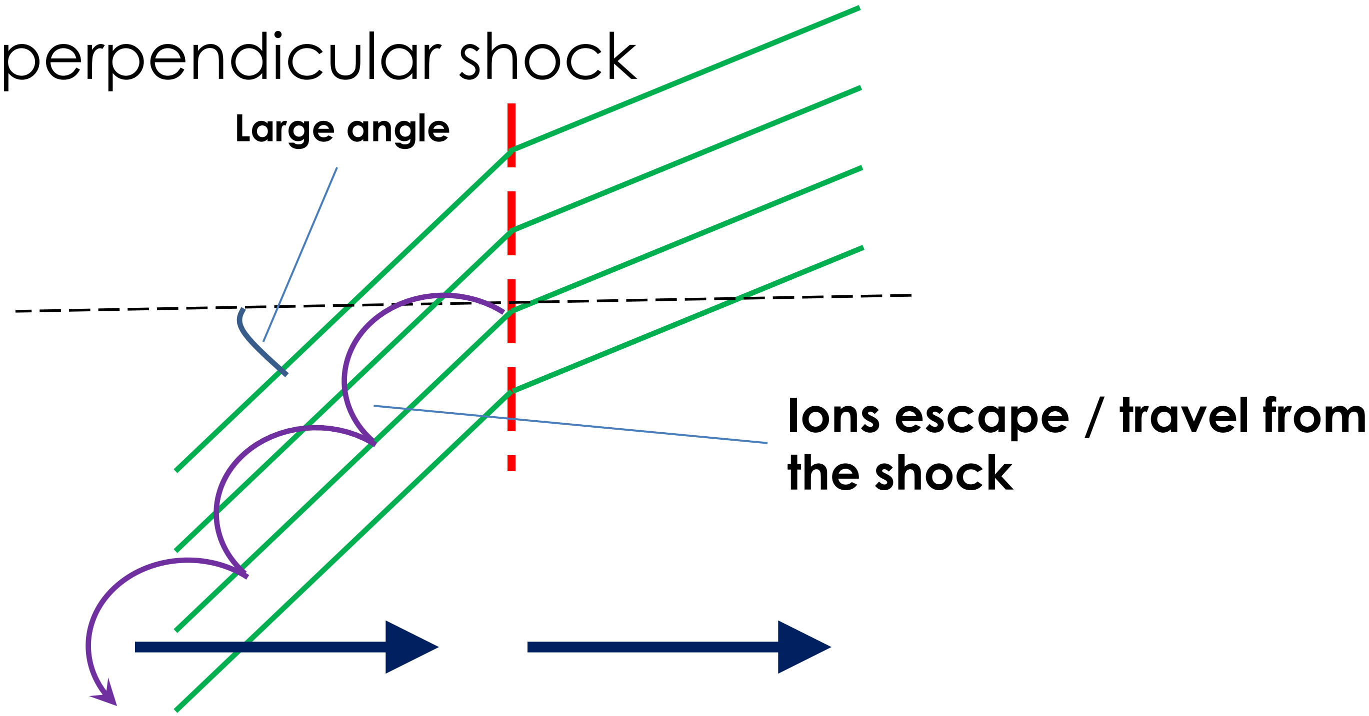
Alfven	Not compressive	No shock; $r=1$ discontinuity
Fast magneto-sonic	B correlates with ρ	
Slow magneto-sonic	B anti-correlates with ρ	

Collisionless shocks

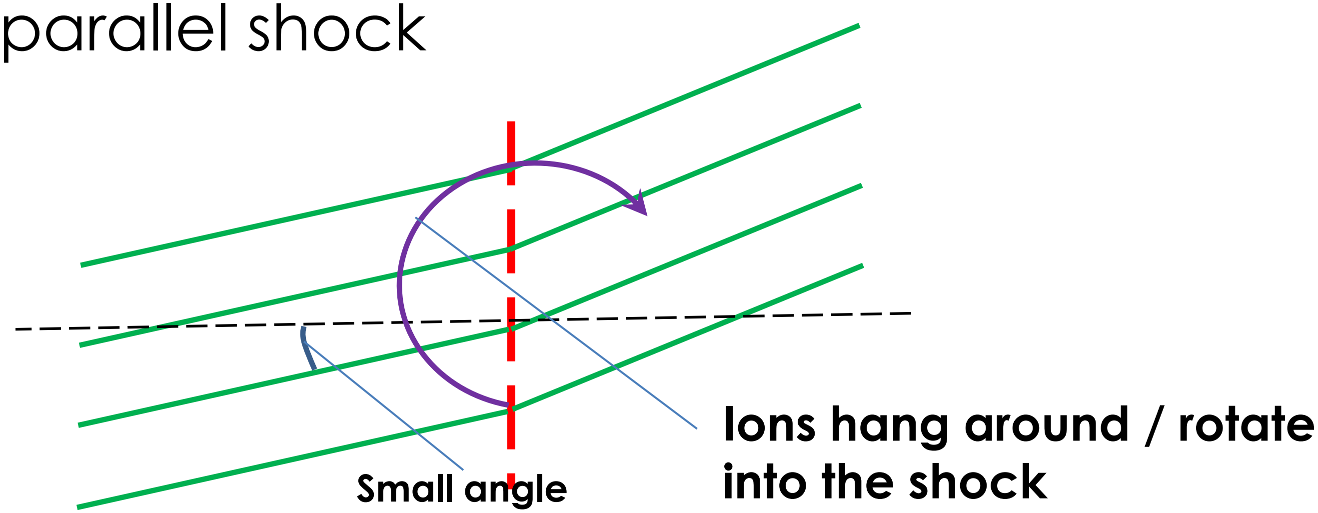
- Collisionless ≡ L_R > m.f.p.
- Particles don't thermalise due to collisions
- Particle scattering (velocity/pitch-angle change) is determined by magnetic field spatial scale (Turbulent magnetic field!!!)
- Collisionless shocks are more versatile and require more complicated math description

Collisionless shocks

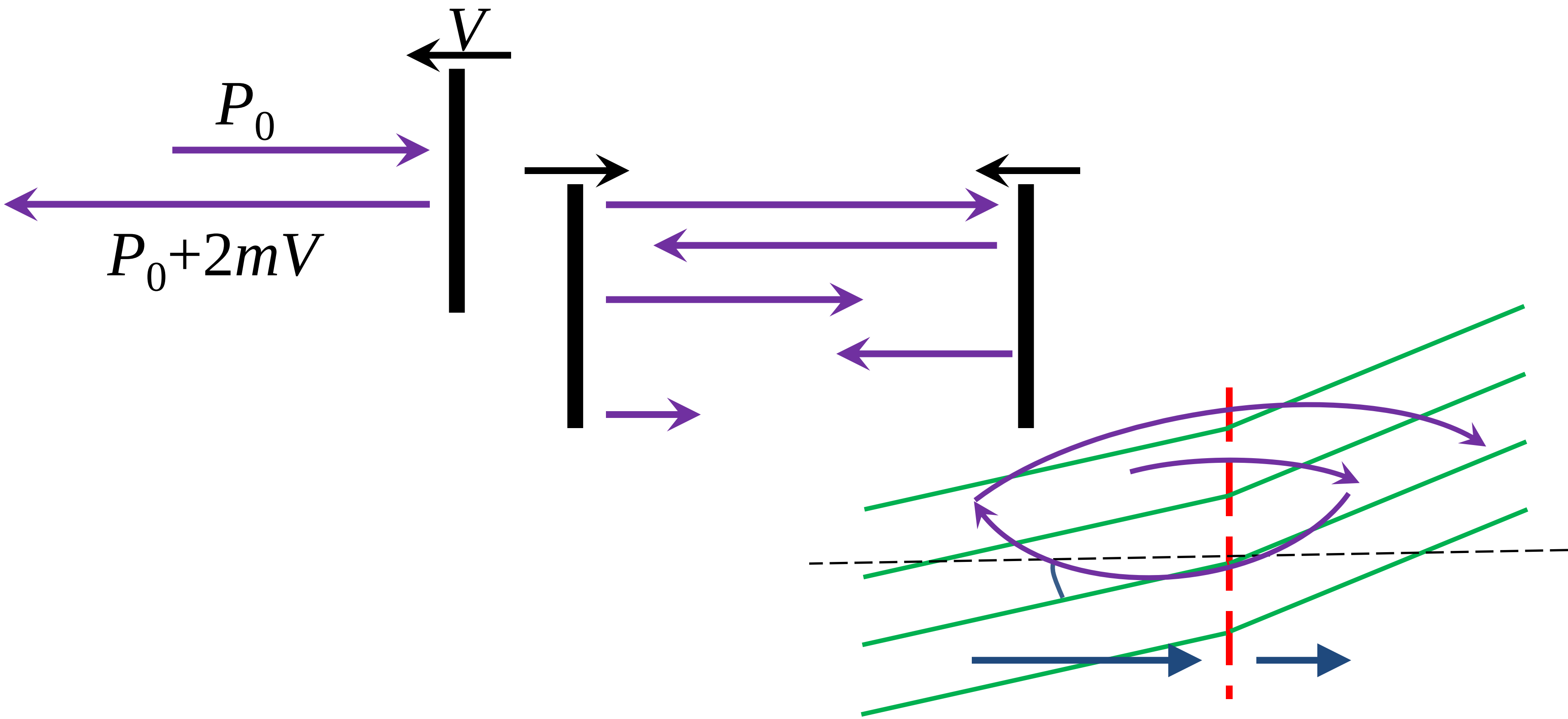
- Quasi-perpendicular shock



- Quasi-parallel shock



Collisionless shocks: particle acceleration



- Type I Fermi acceleration: particle repeatedly reflected by "mirrors" moving towards each other
- Guarantied energy gain!!

Collisionless shocks: particle acceleration

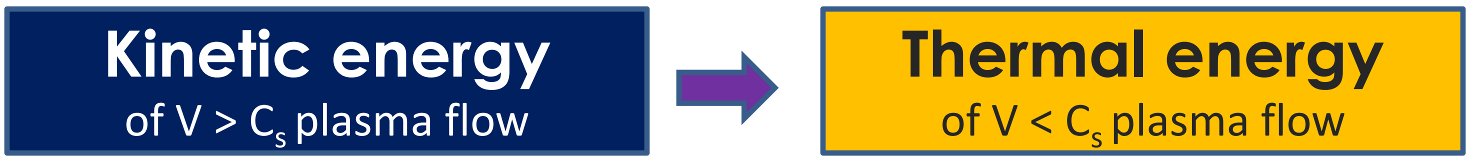
- Both HD and collisionless shocks accelerate particles but…

- …when m.f.p. is short, the energy gained by particles becomes "thermal" (particle distribution is Maxwellian)

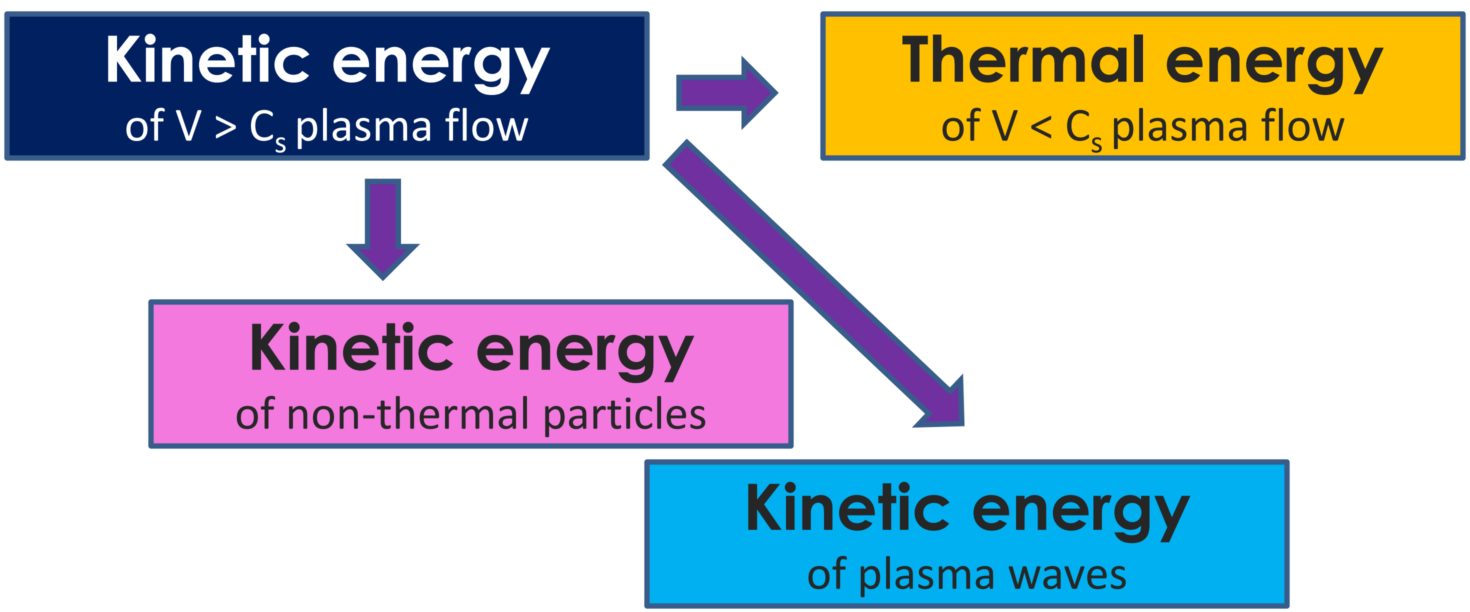
- Therefore, particle acceleration on collisionless shocks is unavoidable, as plasma heating on HD shocks

Energy conversion on shocks

- MHD shocks



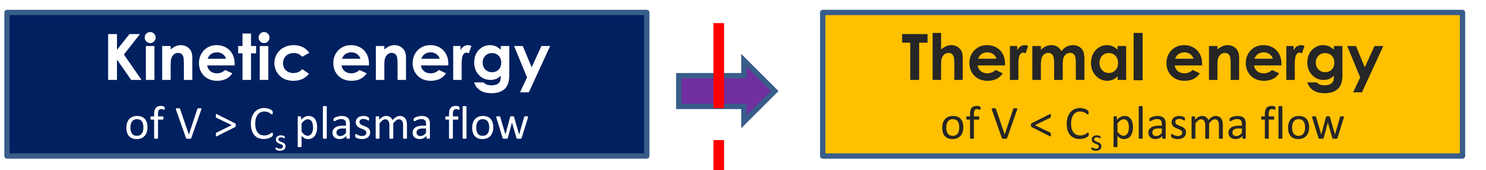
- Collisionless shocks



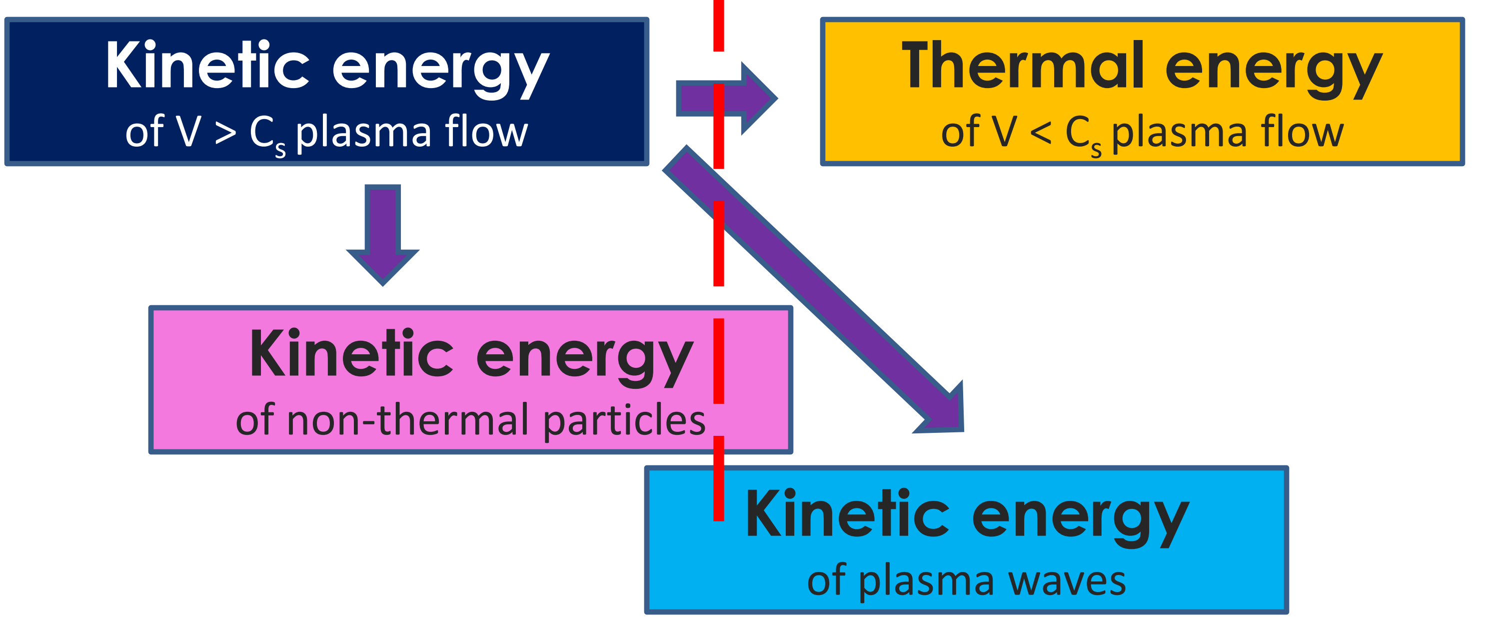
Energy conversion on shocks

UPSTREAM | DOWNSTREAM

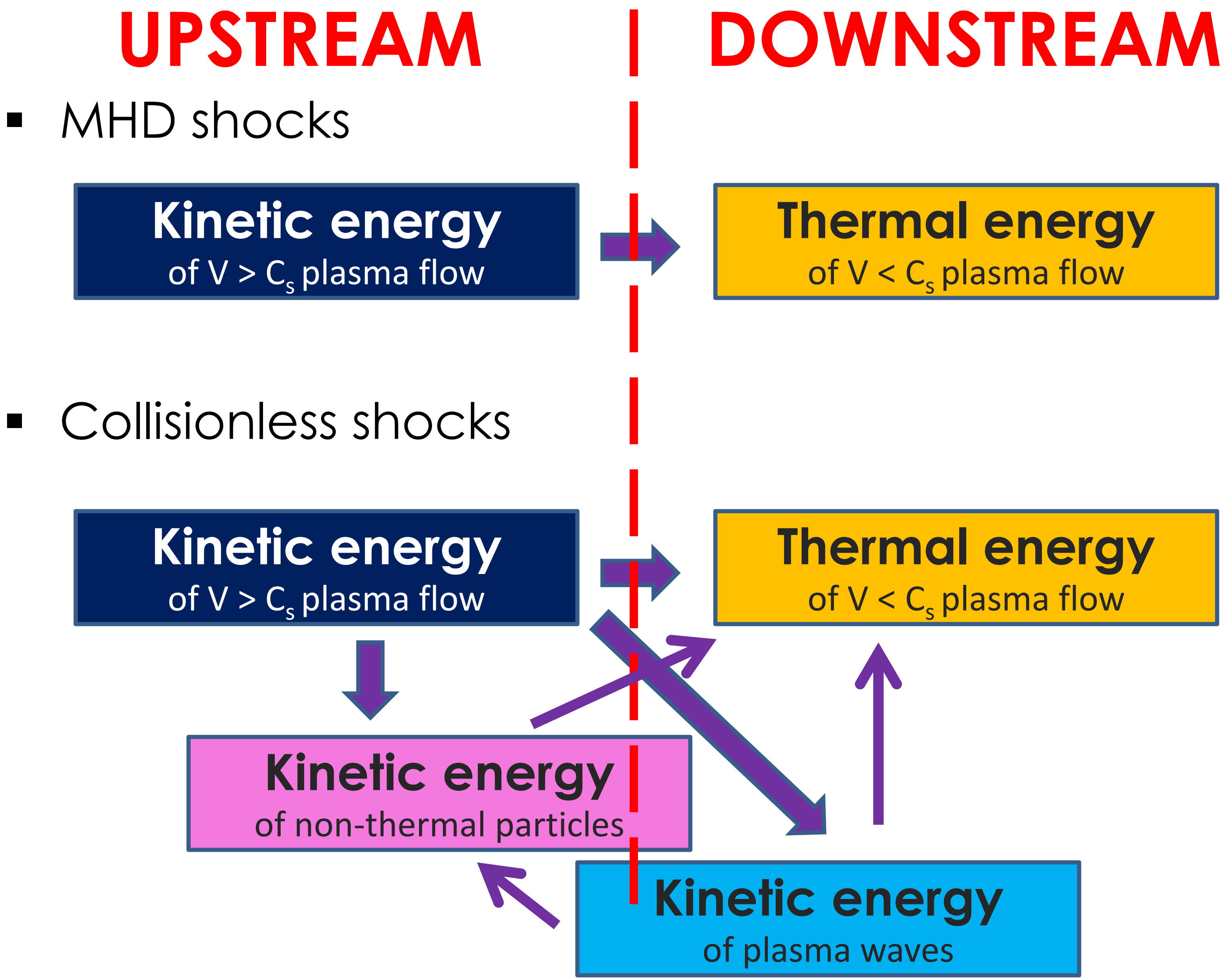
- MHD shocks



- Collisionless shocks



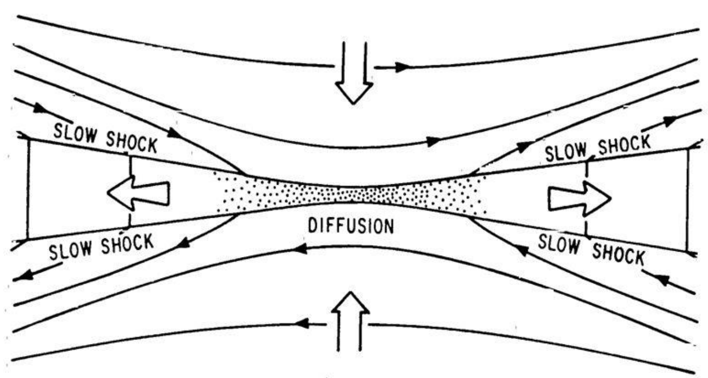
Energy conversion on shocks



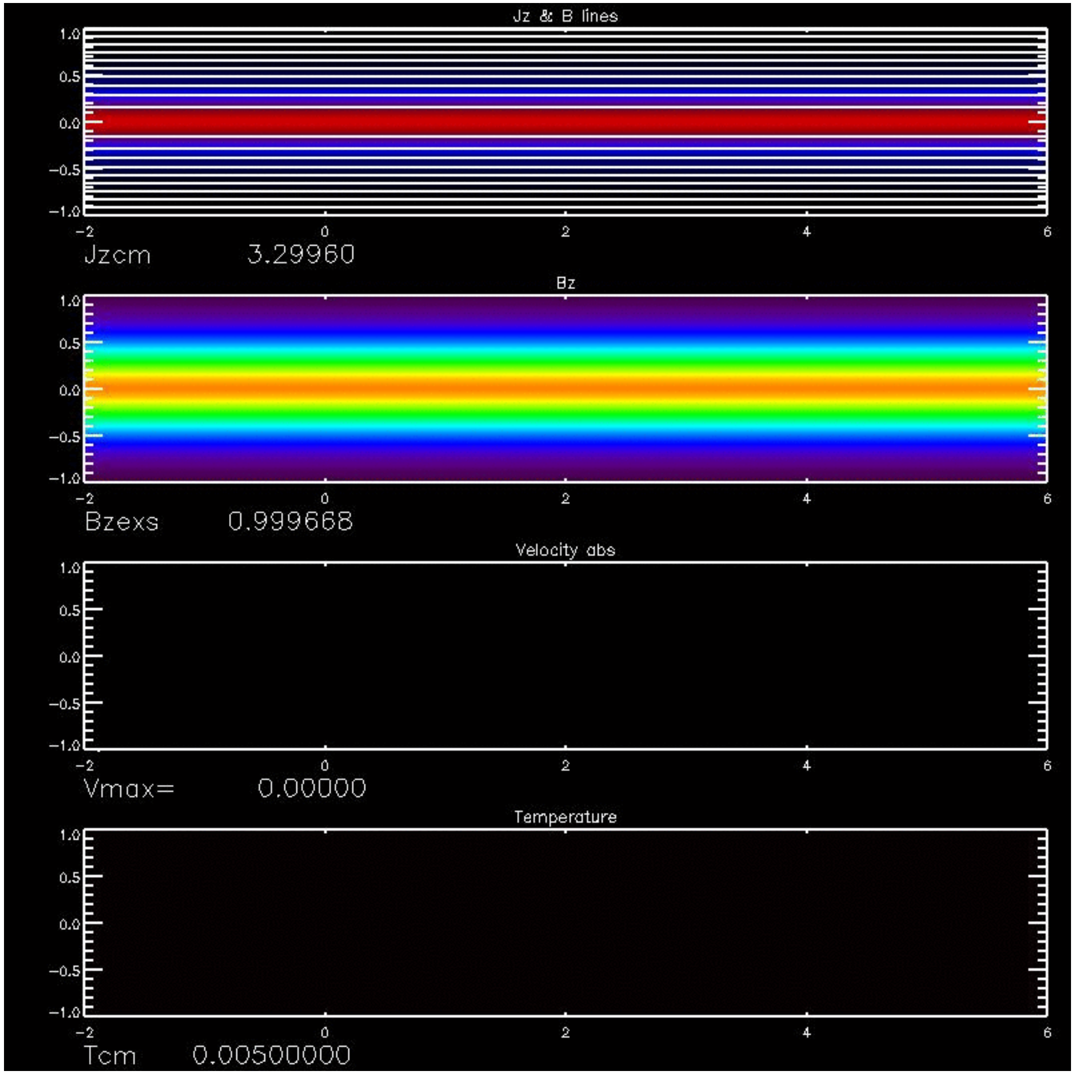
Shocks in the corona

- Shocks in the reconnection regions

Petschek Reconnection



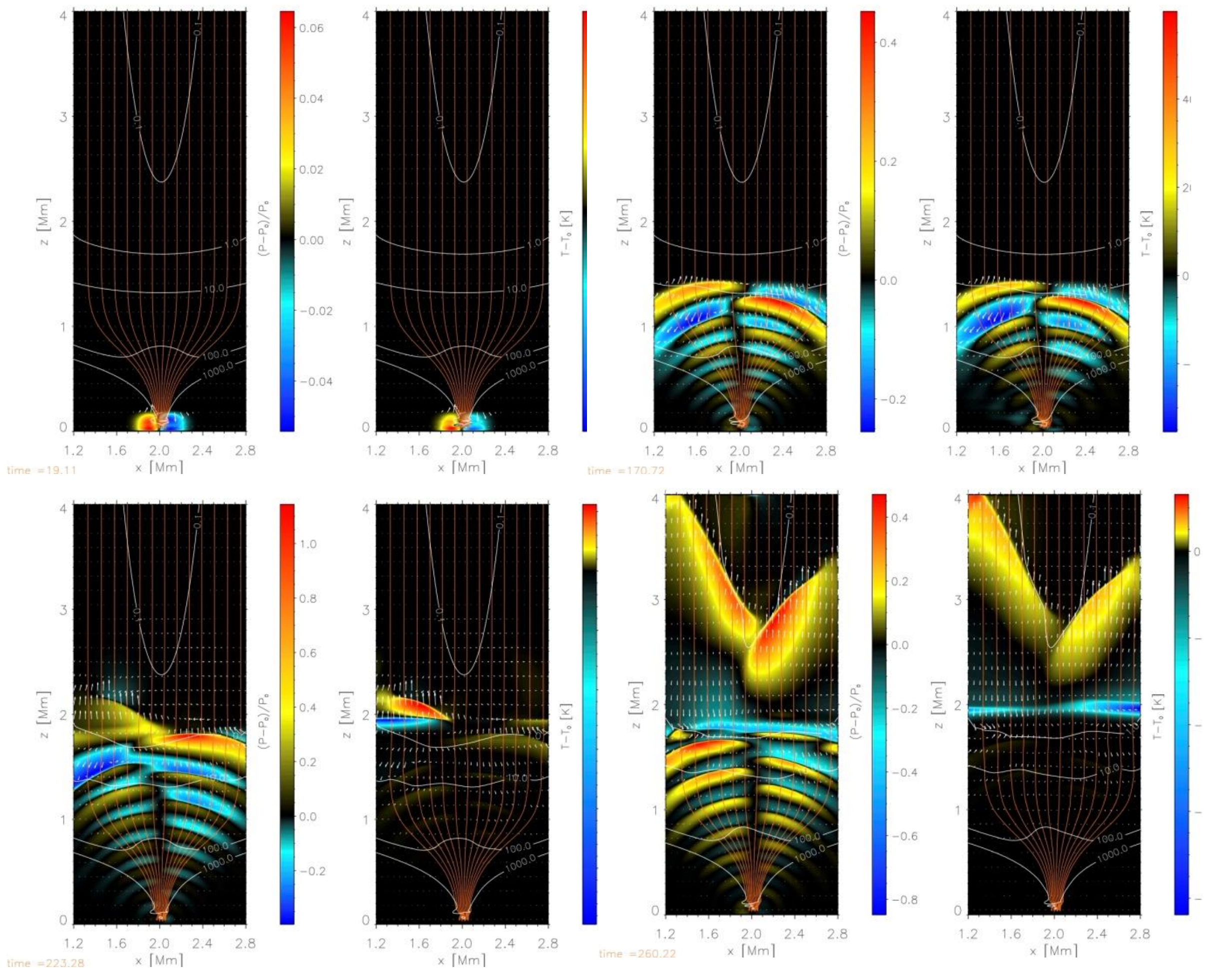
Petschek 1964



Forced reconnection in non-neutral Harris current sheet (Gordovskyy et al, 2011)

Shocks in the corona

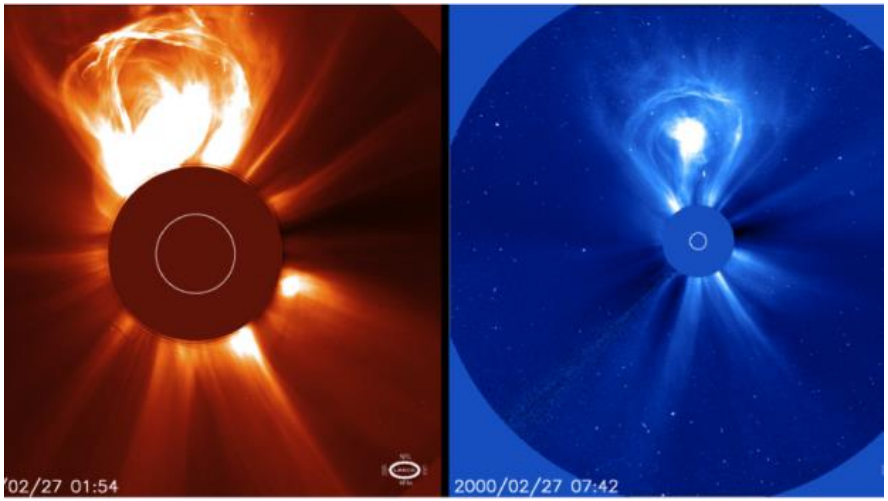
- Upward-propagating waves becoming non-linear (can contribute to the coronal heating)



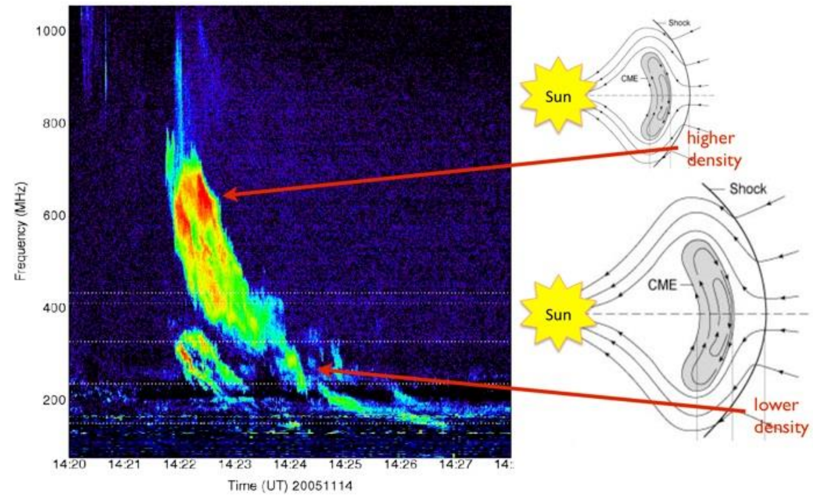
Footpoint-driven magneto-acoustic wave propagation in a localized solar flux tube
Fedun et al. 2011

Shocks in the SW / Heliosphere

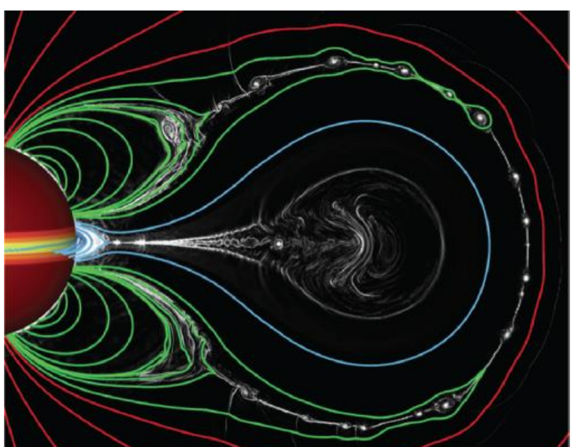
- Coronal Mass Ejections



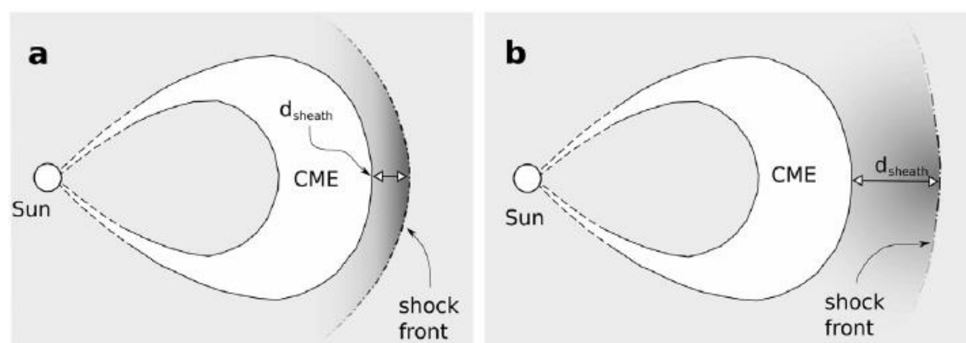
NASA / SOHO / LASCO



S White / U Mariland



Karpen et al. 2012

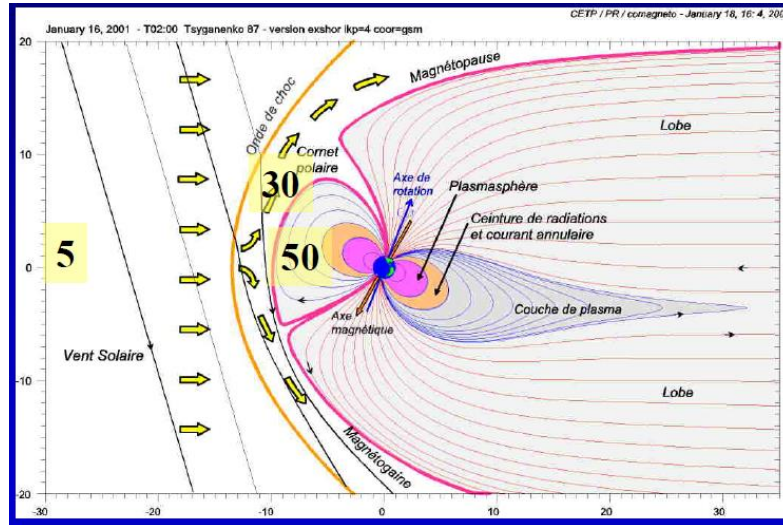


Corona-Romero & Gonzalez-Esparza 2012

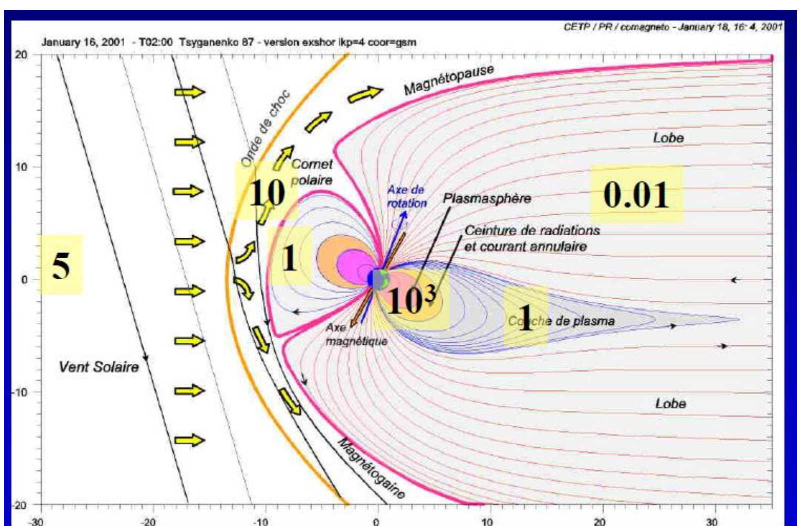
Shocks in the SW / Heliosphere

- Planetary magnetospheres

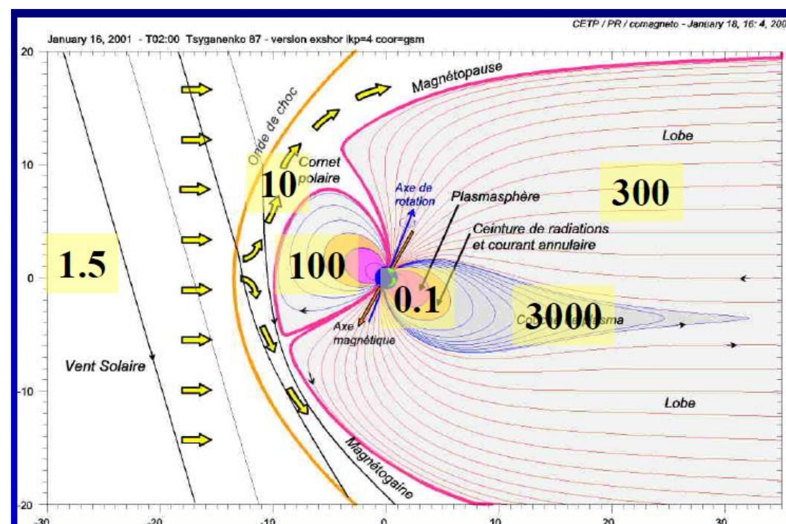
Belmont / Tsyganenko / 2008



Magnetic field, nT

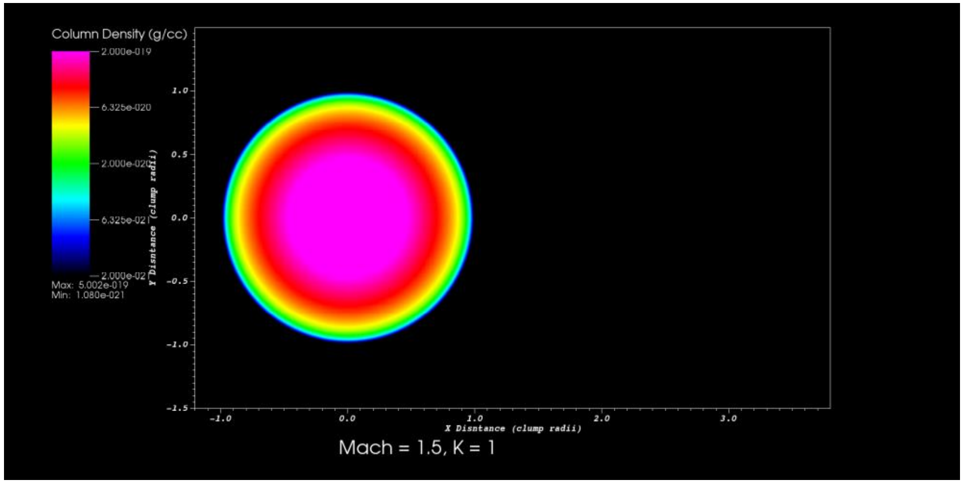


Density, 1/cm³

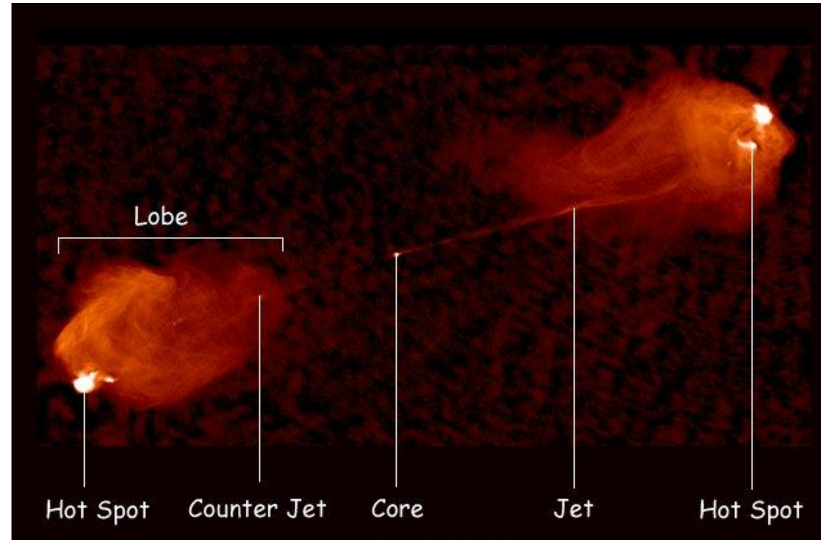


Temperature, eV

Shocks outside Solar System



Shock generated star formation / AstroBEAR code



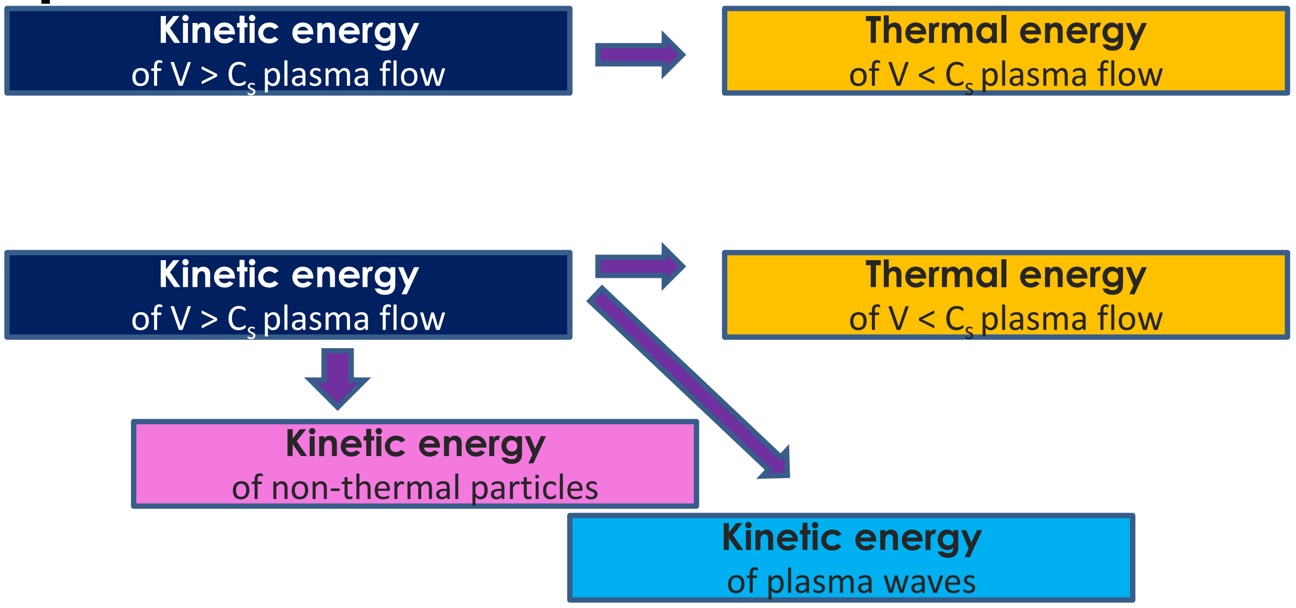
Cygnus A DRAGN

Tiho supernova remnant

Veil nebula supernova remnant

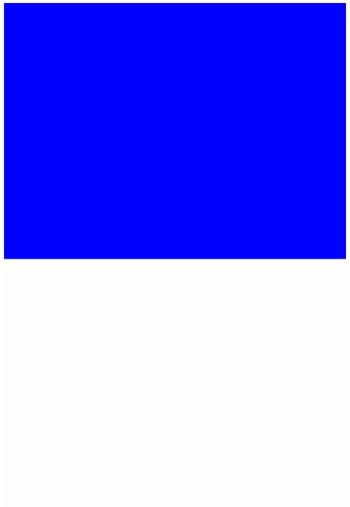
Summary: shocks

- **Creates structures in the solar/space plasmas**
- **Fast flow kinetic energy is converted into heat, non-thermal particles, waves**

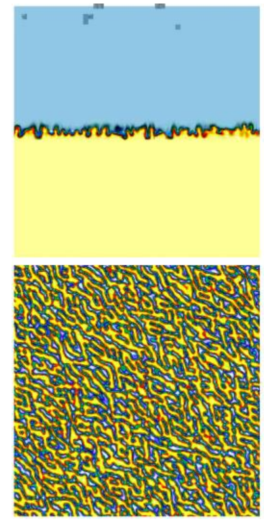


- Occurs during magnetic reconnection and eruptions in the corona, ubiquitous in the solar wind, Earth/planetary magnetospheres etc

What is turbulence?



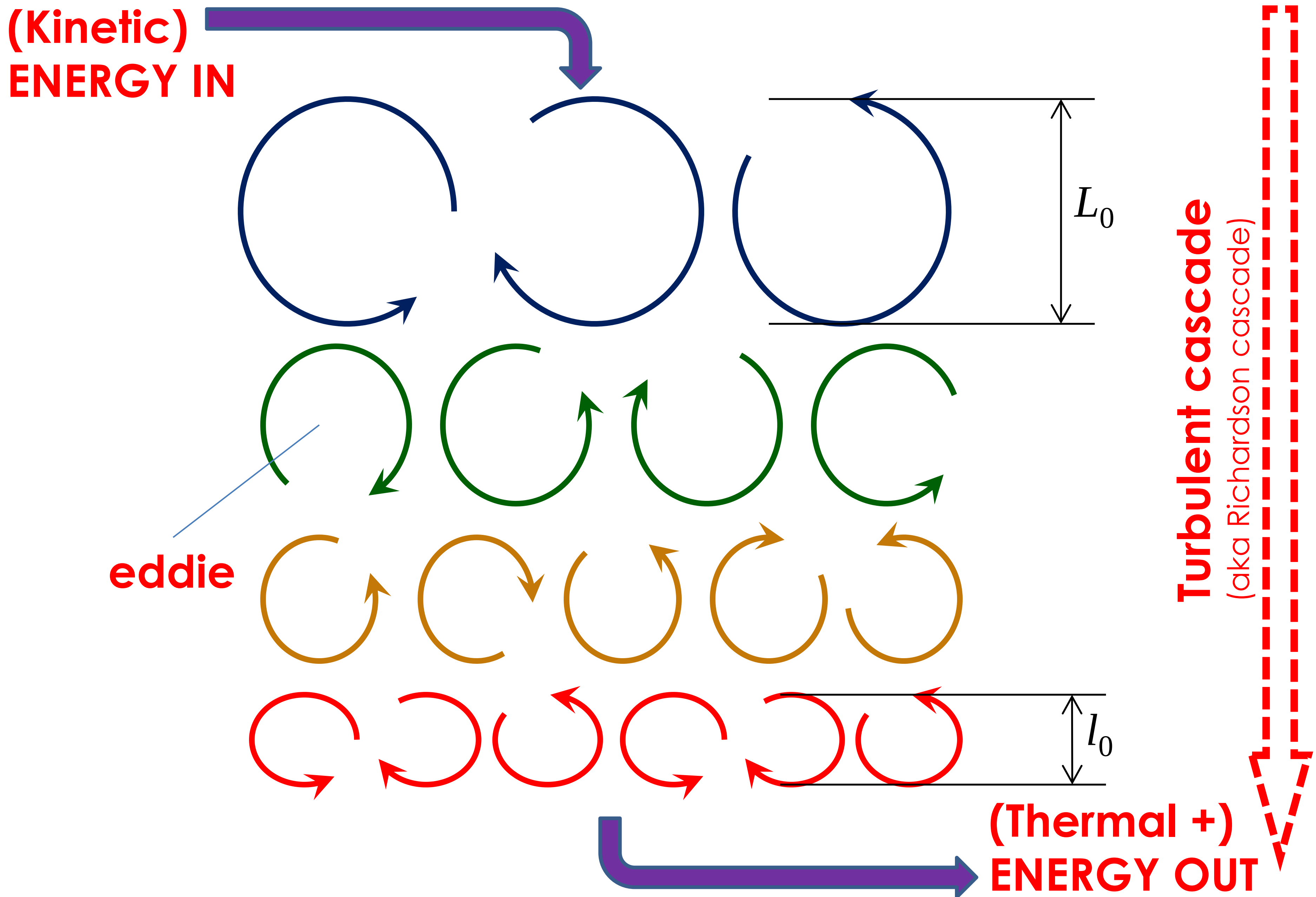
K Hayashi, Uni Stanford



N Vladimirova, Uni New Mexico

- Essentially non-linear, fluid phenomenon
- Occurs when inertial forces in fluid dominate over viscosity
- **Results in energy transfer from larger to smaller spatial scales**

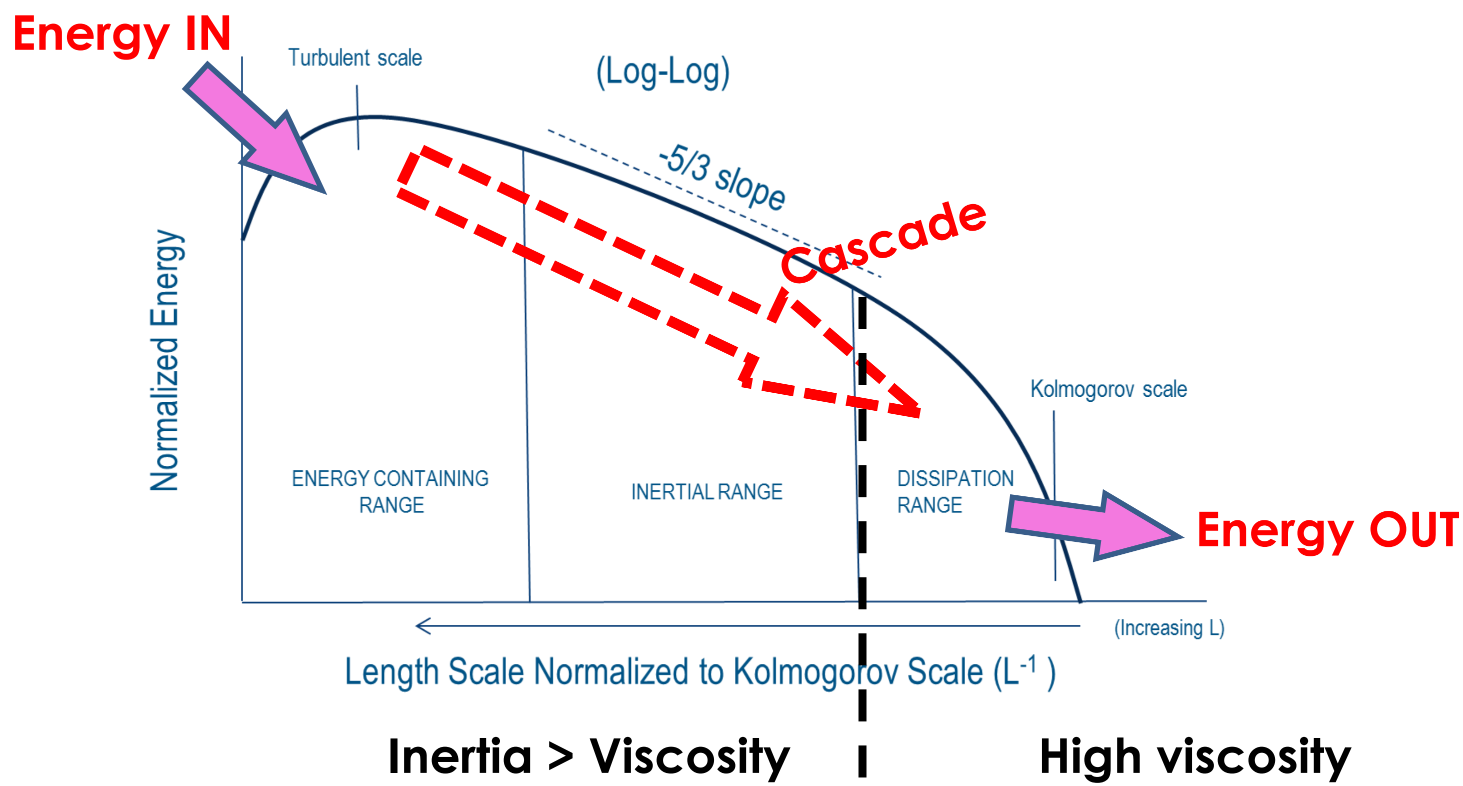
Turbulence: basic physics



Turbulence: theory

- **Results in energy transfer from larger to smaller spatial scales**

- Steady energy input results in a steady state solution: Kolmogorov spectrum with the inertial range

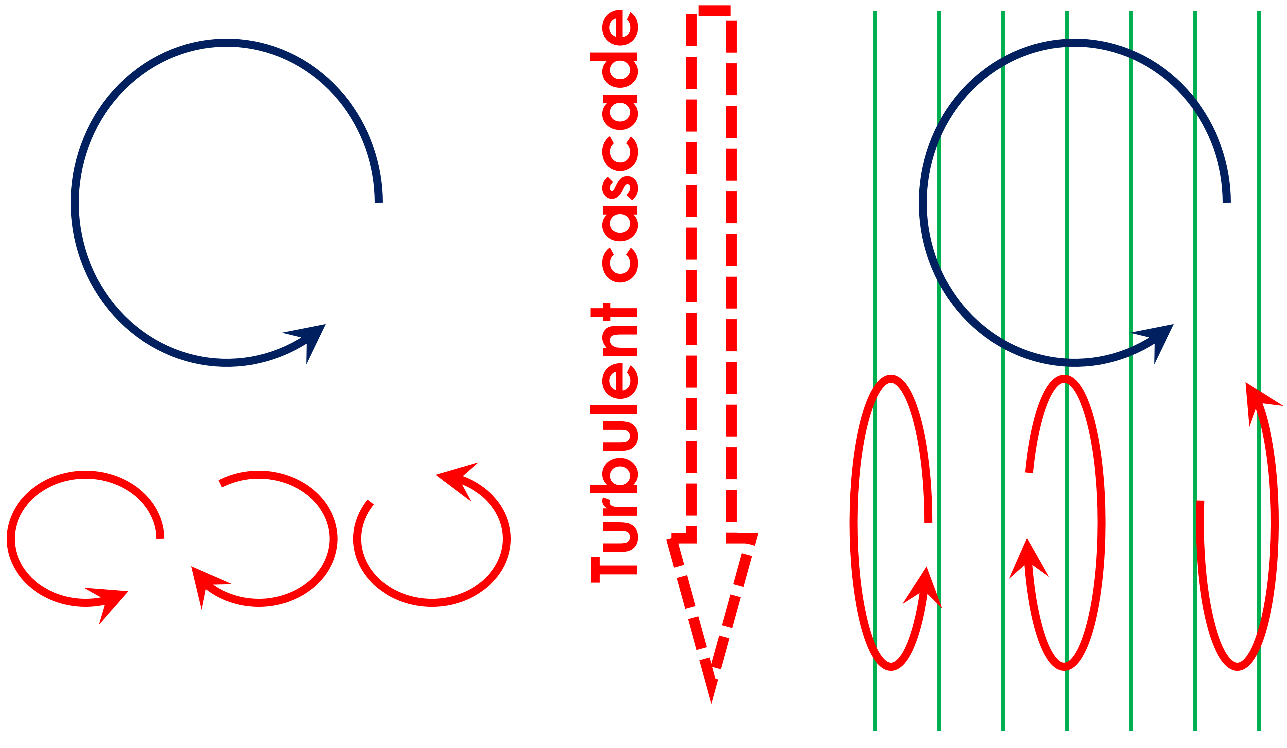


Waves v. Turbulence

- "Waves or turbulence?!" – Turbulence can always be represented by waves with a wide spectrum
- Therefore, Acoustic / Alfven / Magneto-sonic / etc turbulence

MHD v. HD Turbulence

- Magnetic field adds a preferred direction, making turbulence anisotropic, with more interesting effects

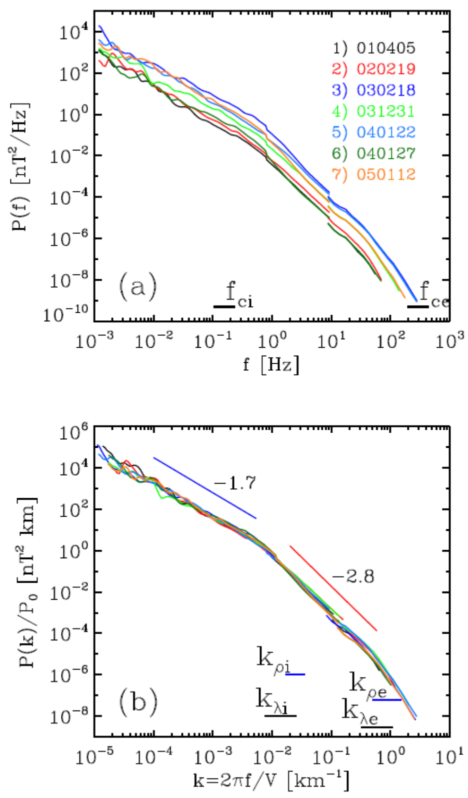


- Advection is stronger $\| B$, dissipation is stronger $\perp B$, - similar to other transport effects in plasma

Turbulence in collisionless plasma

- Its possible to have wide spectrum kinetic waves with the cascade and dissipation at high $\boldsymbol{k}$

- Collisionless plasma may have viscosity due to wave-particle interaction

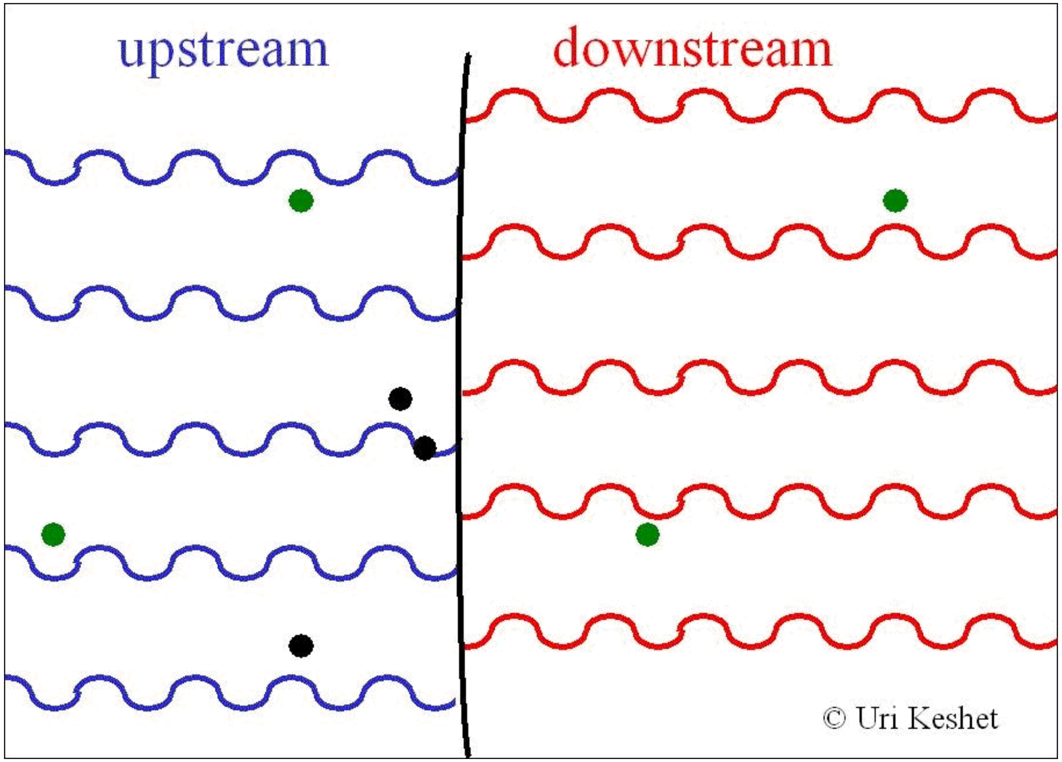


Alexandrova et al 2009 PRL

- Same 5/3 spectrum is observed in SW turbulence, the inertial range spanning 6 orders of magnitude – SW turbulent spectrum seems to be universal from MHD to electron scales

- Particle acceleration

Turbulence: particle acceleration



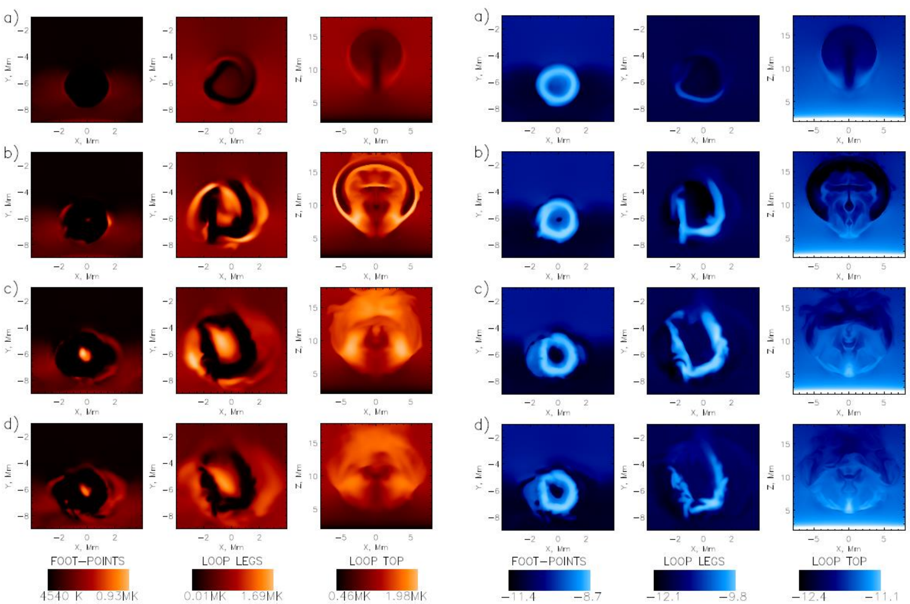
U Keshet / Uni Ben Gurion

- Type II Fermi acceleration: particle repeatedly scattered by moving waves, its momentum & energy changing stochastically

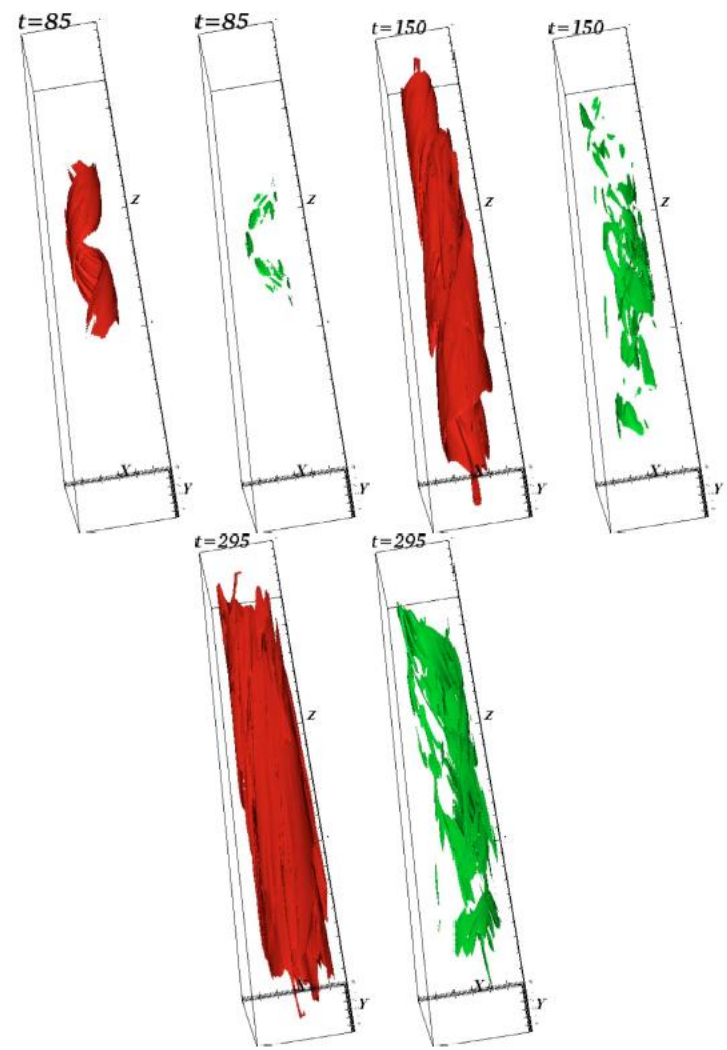
- May gain or lose energy depending on the wave spectrum

Turbulence in the solar corona

- Turbulisation of plasma during magnetic reconnection



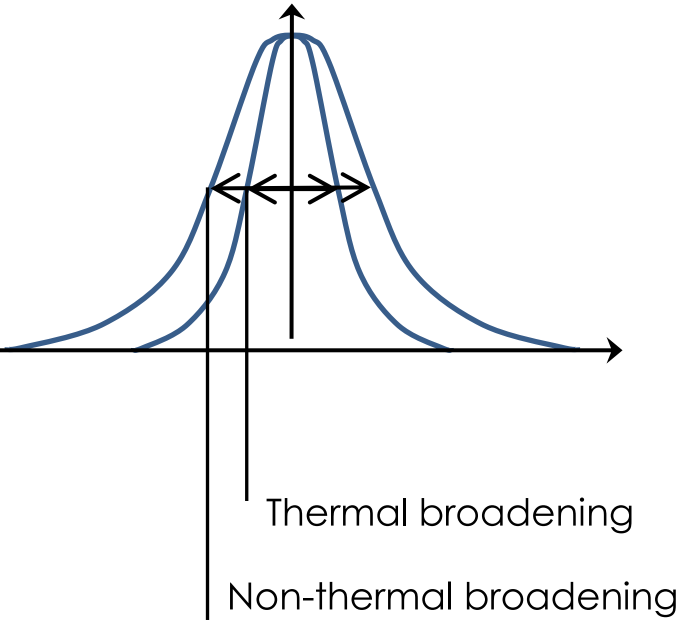
Temperature and density in twisted coronal loop (Pinto et a. 2016)

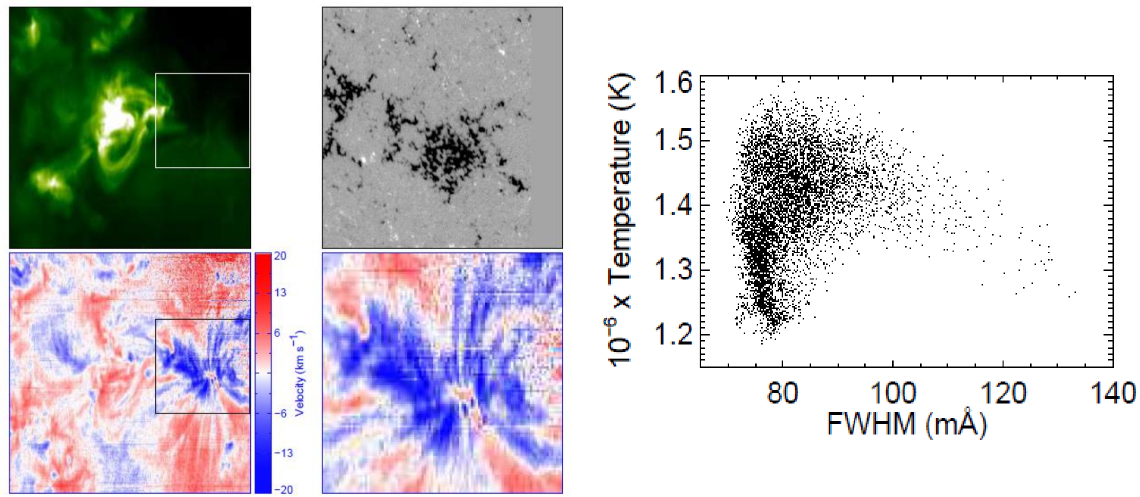


Temperature evolution in kink-unstable twisted magnetic fluxtube (Hood et al. 2009)

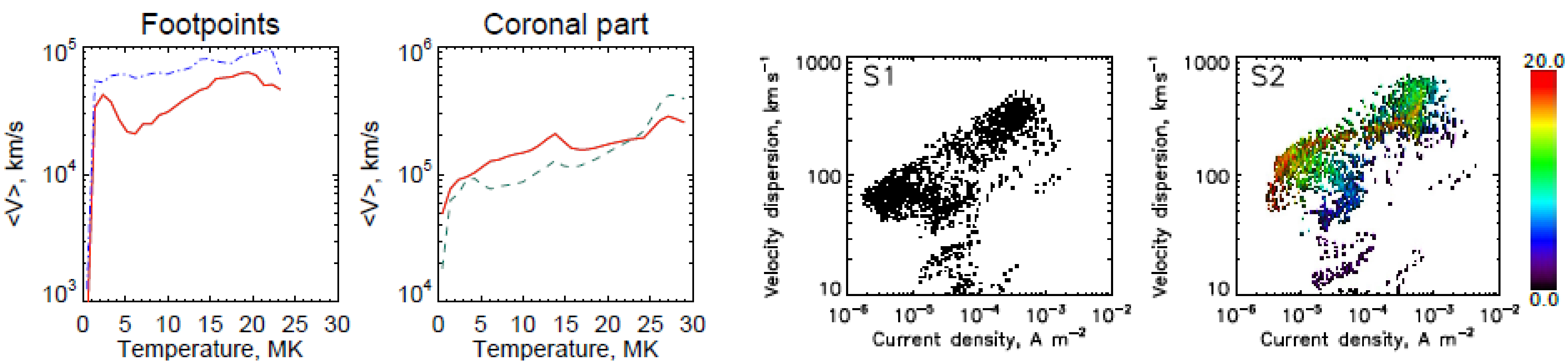
Turbulence in the solar corona

- Non-thermal line broadening indicates strong turbulence in flares





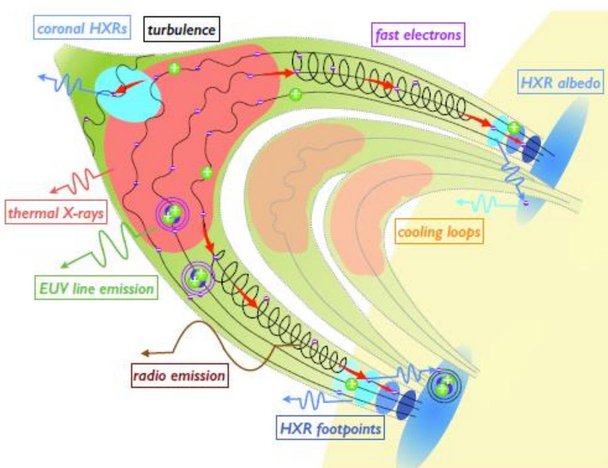
Turbulent line broadening in flares, correlates with the temperature (Doschek et al. 2008)

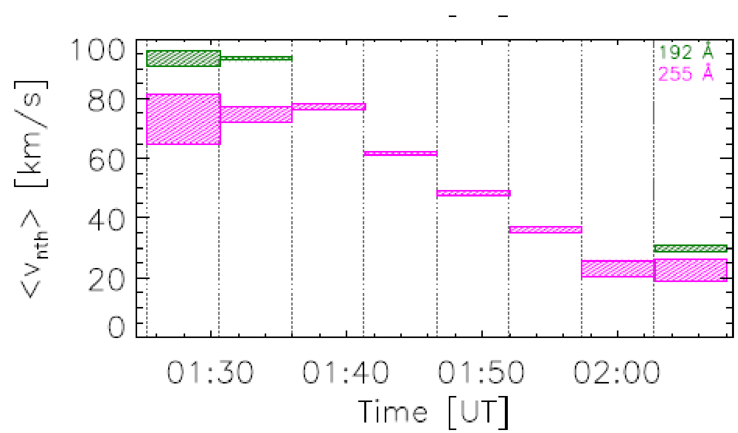


Turbulence spatially correlates with the temperature and energy release (Gordovskyy et al. 2016)

Turbulence in the solar corona

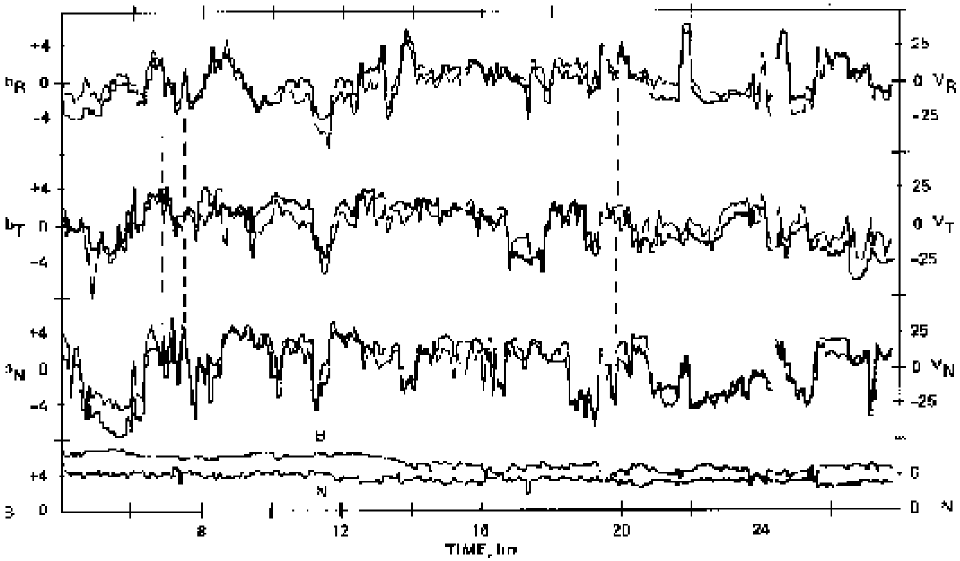
- Turbulence accounts for ~1% of the energy released in solar flares, but can be extremely important for non-thermal particle scattering



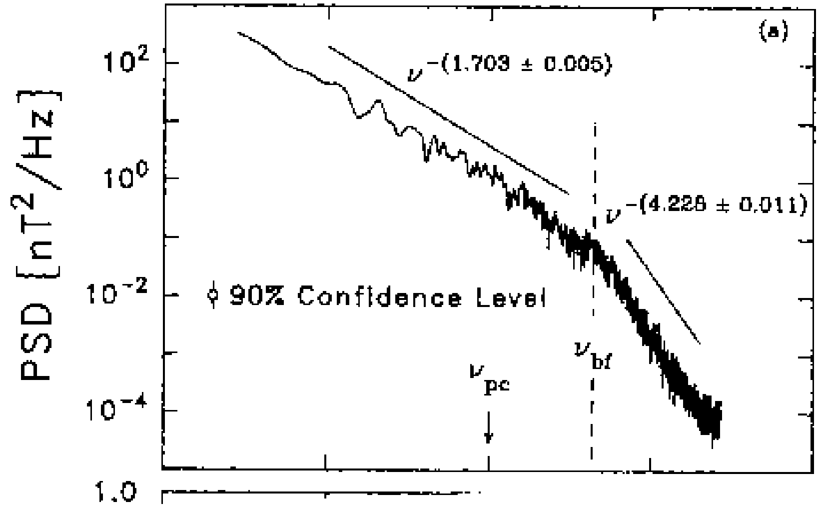


Kontar et al. 2016 PRL

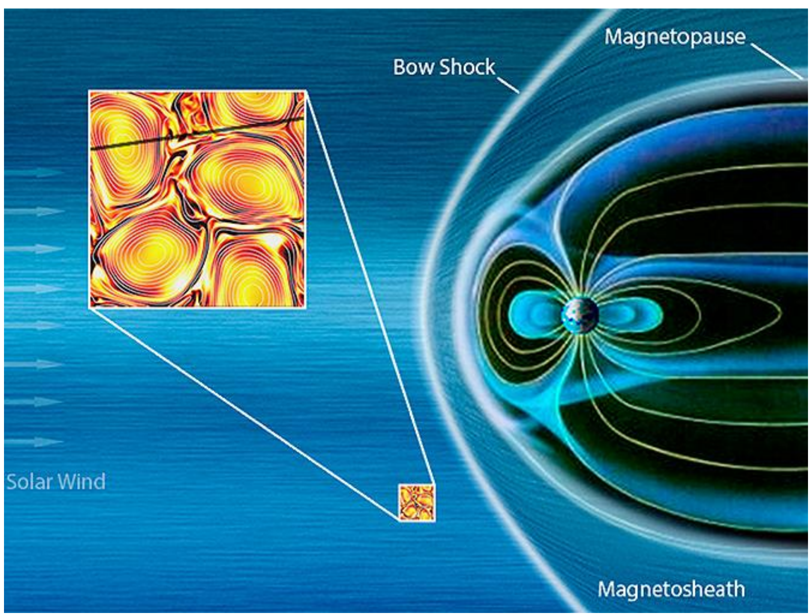
Turbulence in solar wind



Belcher & Davis 1971



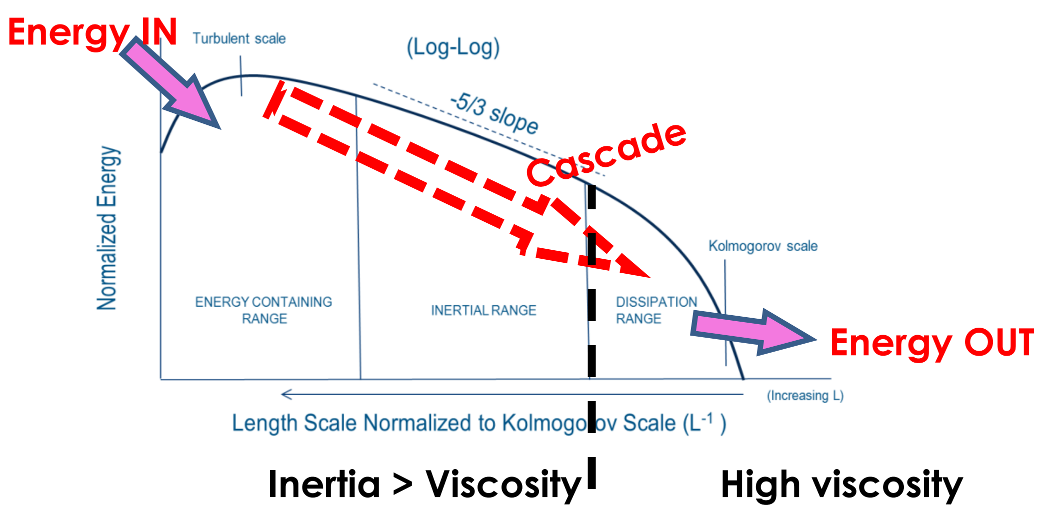
Leamon et al. 1996



Cluster mission observed the turbulent eddies in SW in-situ / NASA / Derelli 2013

Summary: turbulence

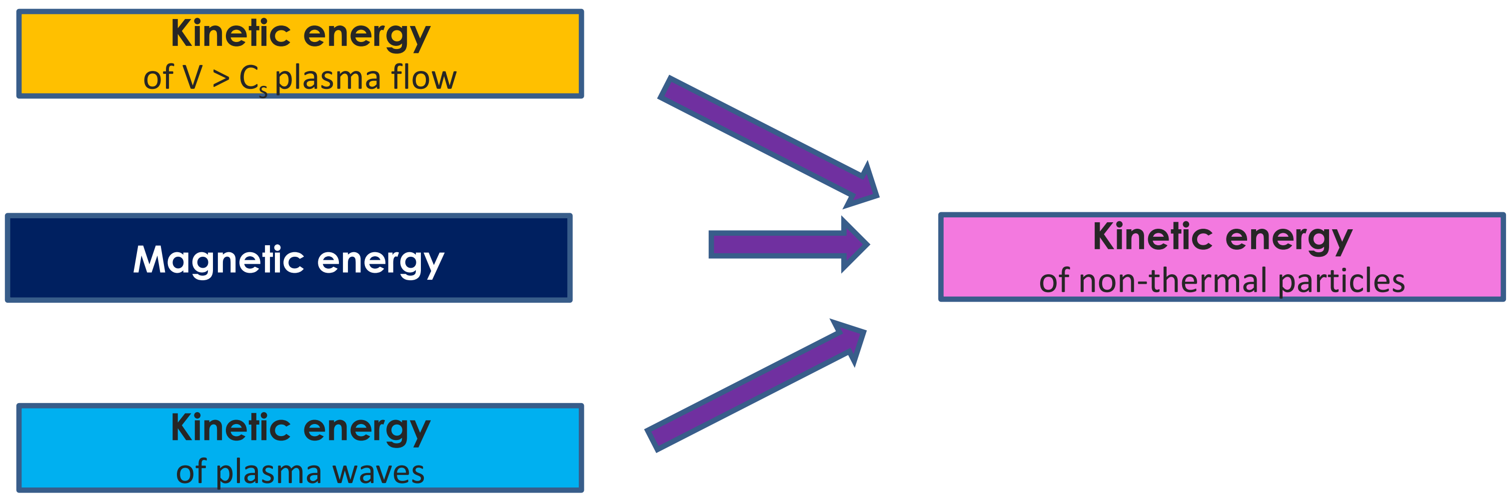
- Occurs when inertial forces dominate over collisions
- **Transfers energy from large-scale plasma flows to small-scale flows, then dissipates, converting energy into heat.**



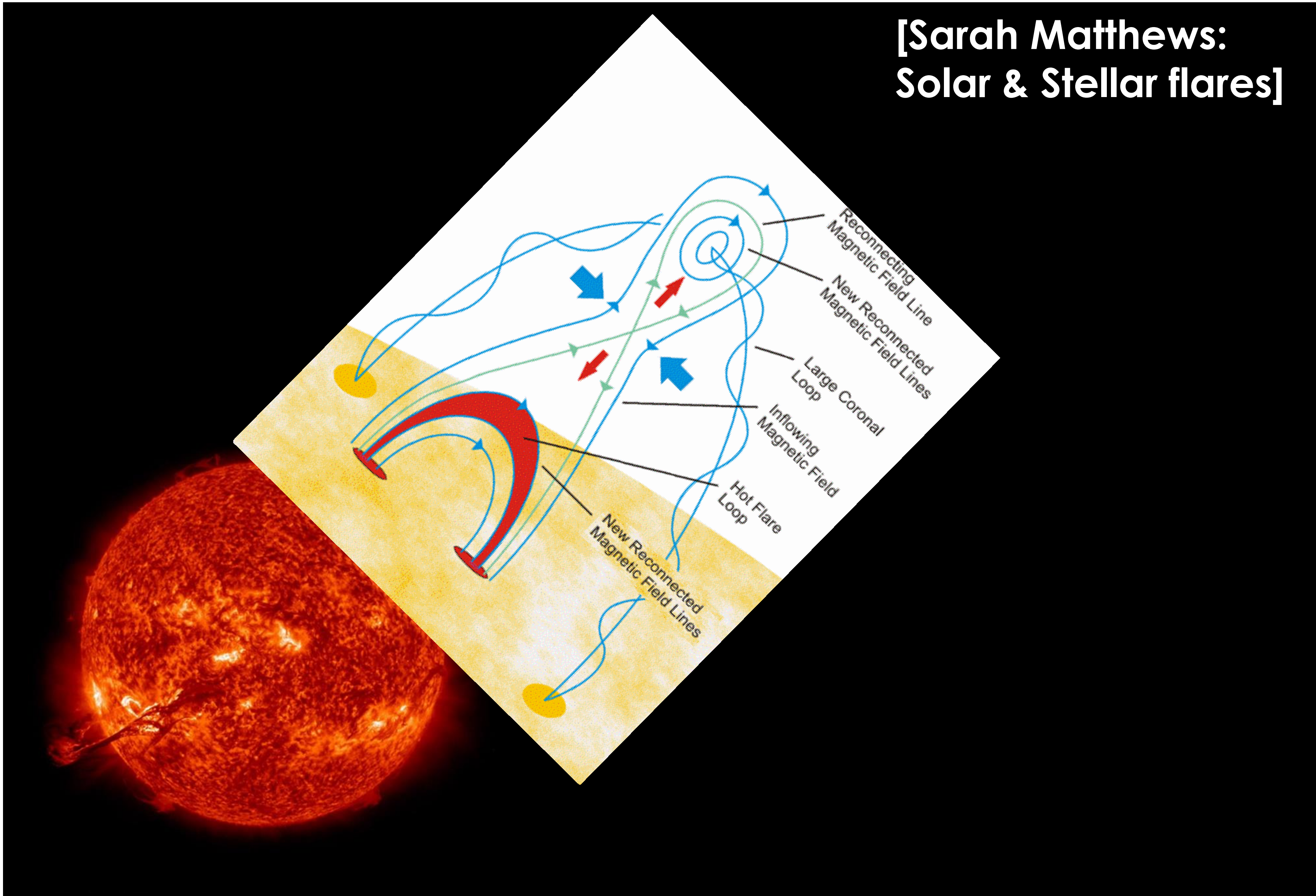
- **Destroys large-scale structures**

Particle acceleration and transport

- Different types of particle acceleration: stationary **electric field**, **waves & turbulence**, **shocks**, **betatron** (collapsing magnetic traps) [Eduard Kontar's lecture on Monday]



Particle acceleration in the corona and SW



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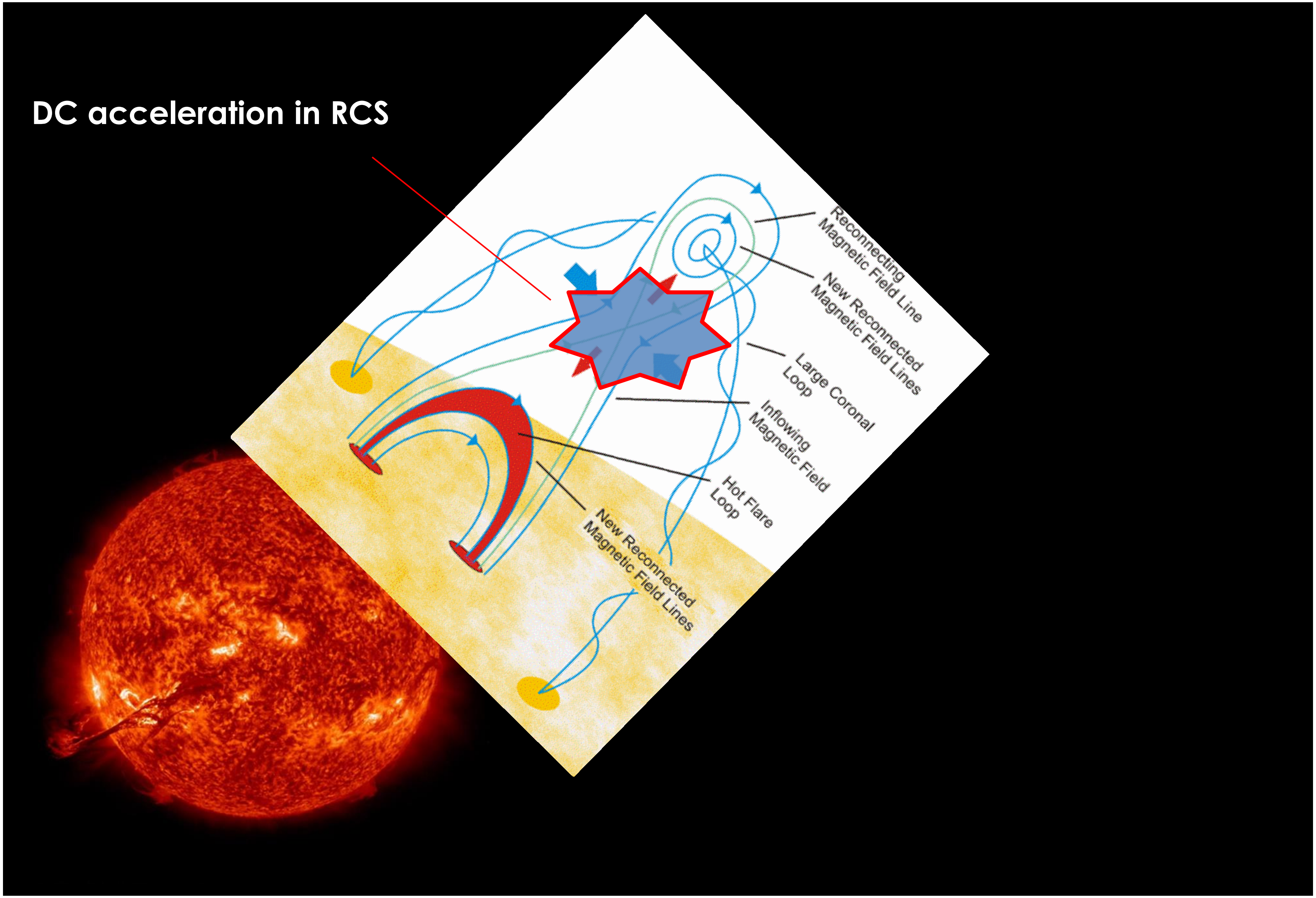

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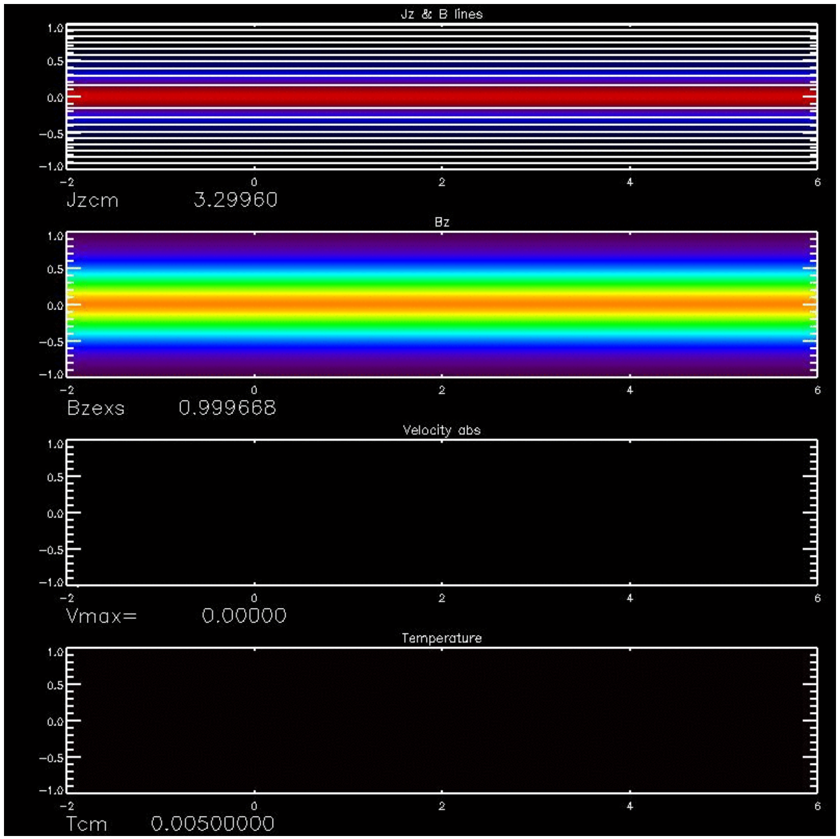
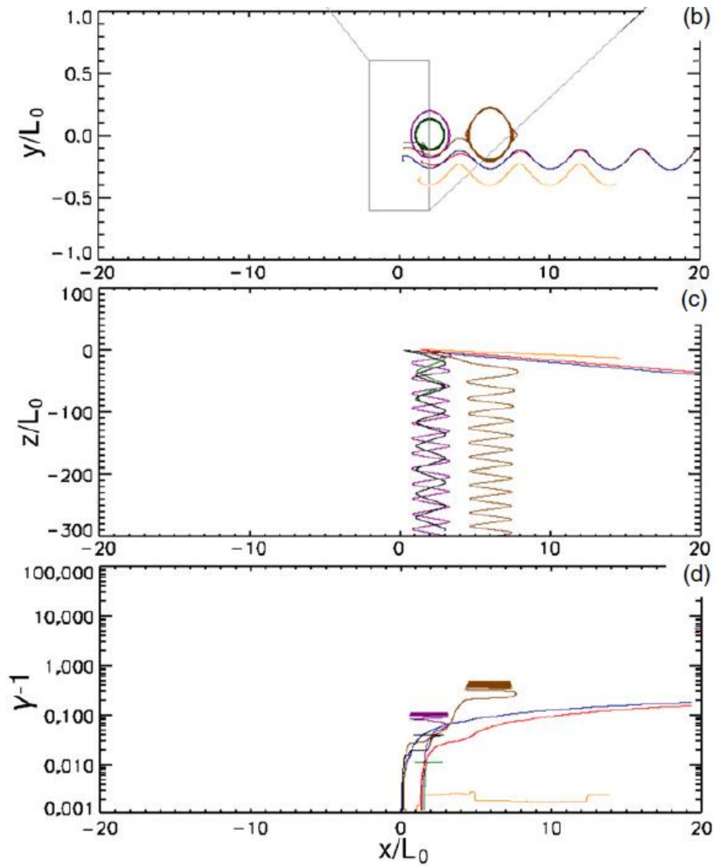
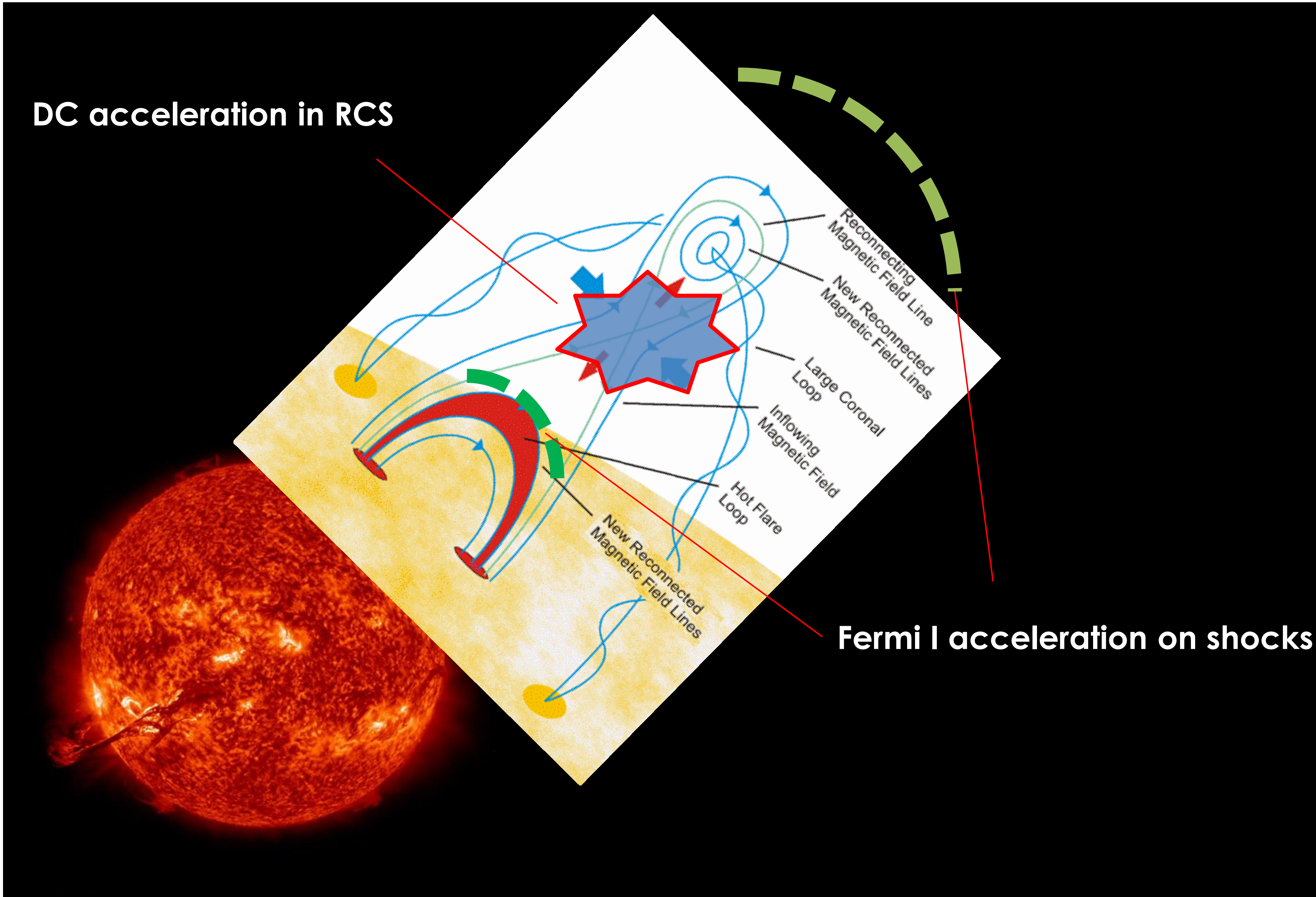




Gordovskyy et al. 2011

Particle acceleration in the corona and SW



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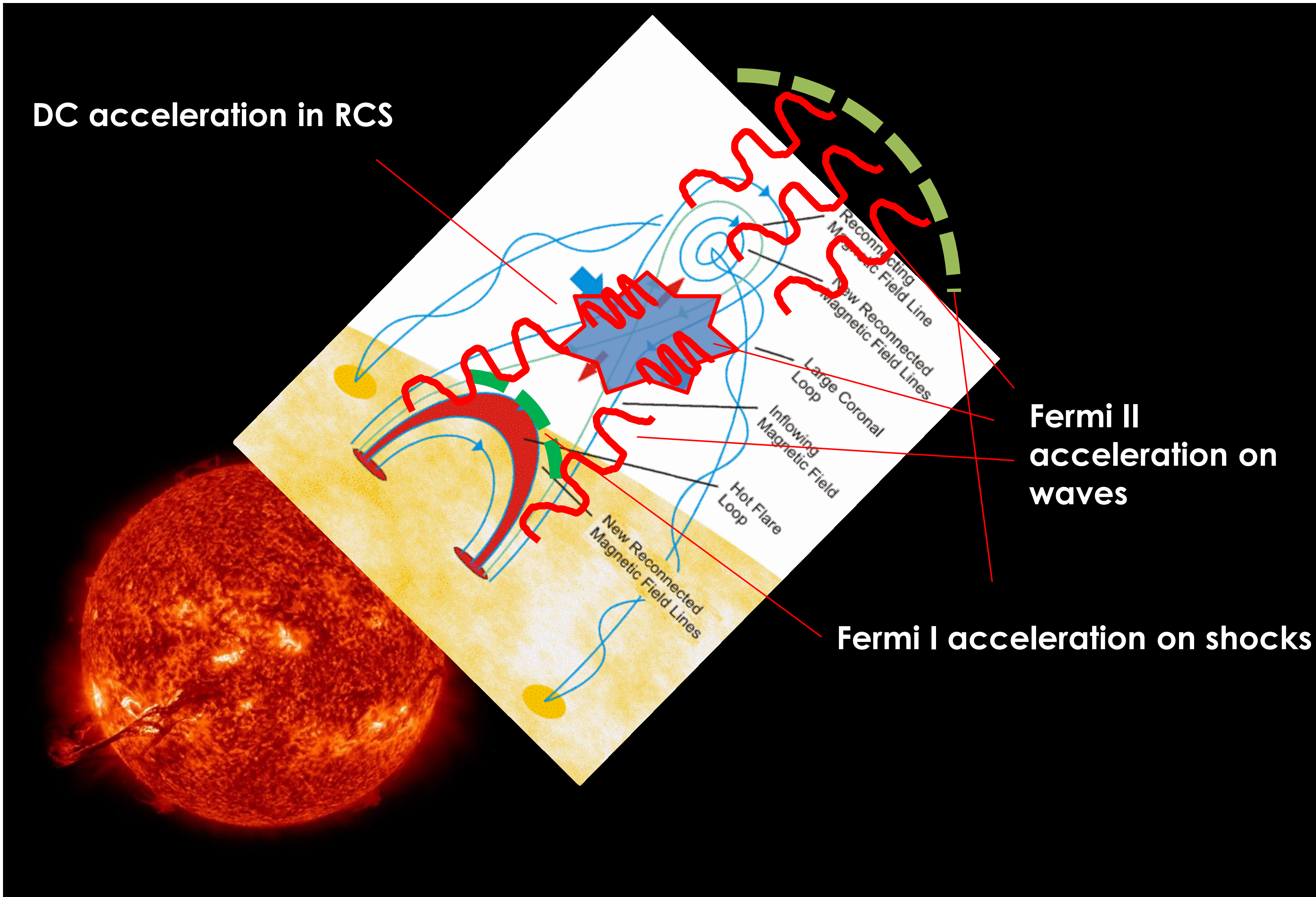

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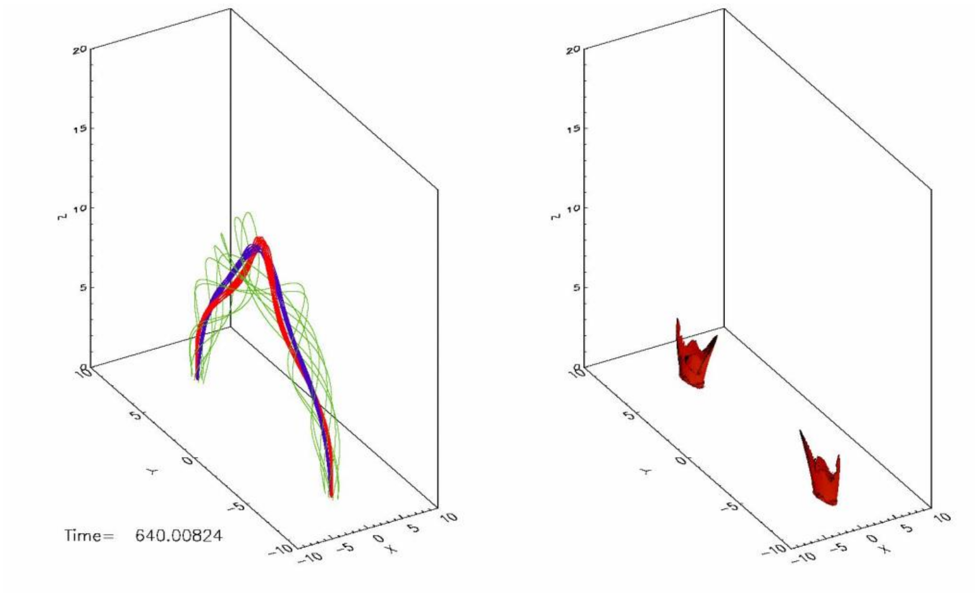
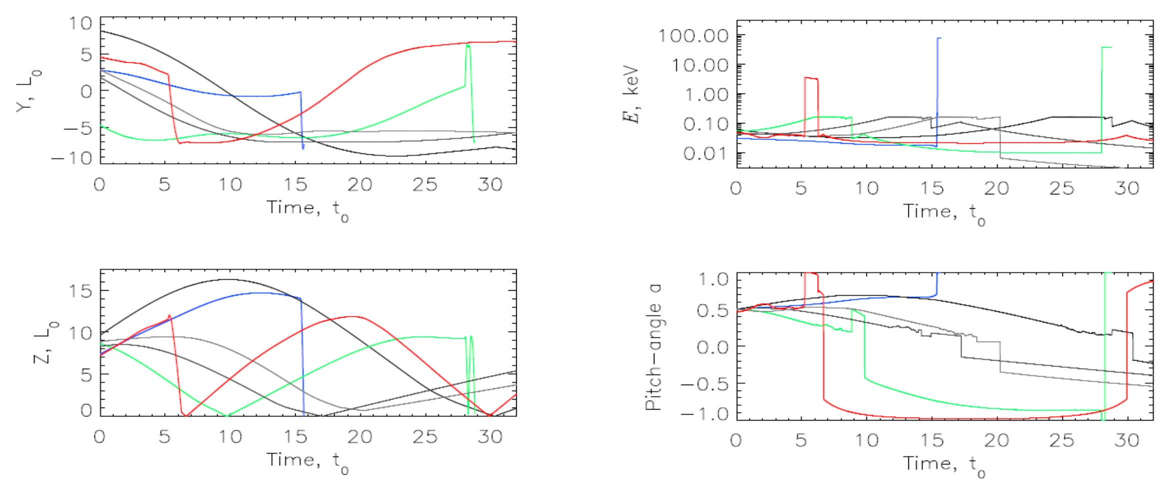




Gordovskyy et al. 2014

Outstanding problems

- How, where and when particles are accelerated?
- Do coronal and IPS particles come from the same source of acceleration?
- Are the same mechanisms responsible for electrons and ions?
- How ~~on Earth~~ you can transport a huge amount of charged particles from the upper corona to the chromosphere?

Precipitating electrons

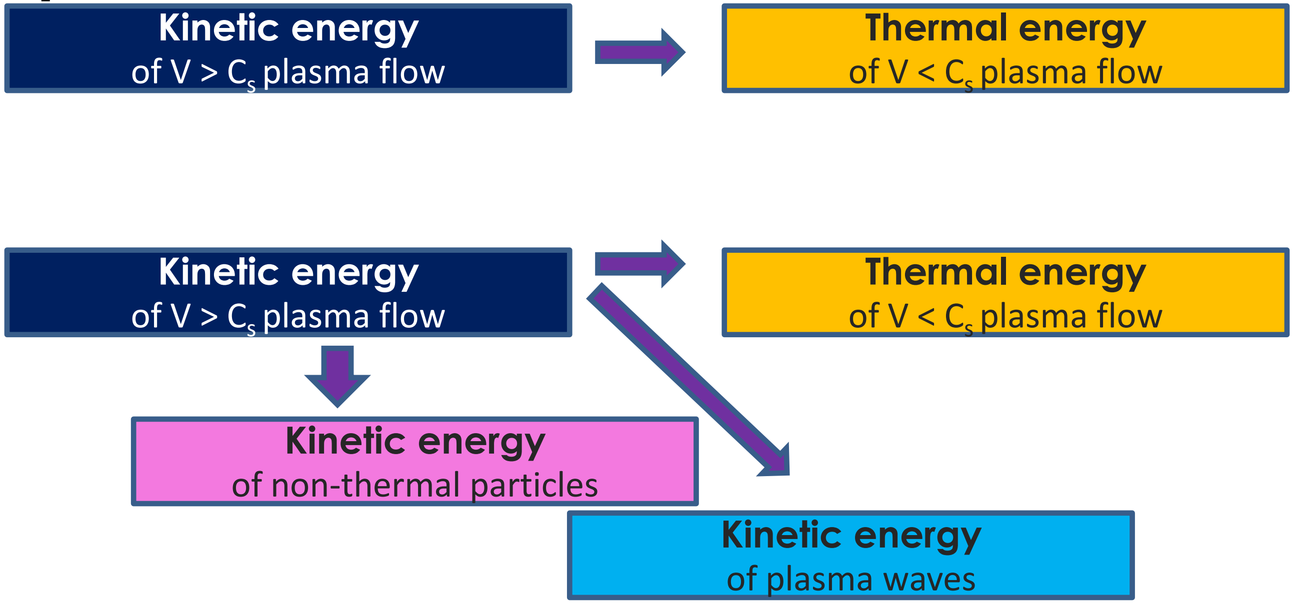
Footpoint area ~1-10 Mm^2
Electron flux density is about 10^{23-24} m^{-2} s^{-1}, current ~10^{4-5} A/m^2, corresponding to $B \sim 10^4 T$

Compensation in the corona

$f_{down} = f_{up} = 10^{23-24}$
for $n=10^{16} m^{-3}$, $\langle v \rangle = 10^{7-8} m/s$
Return current is not “thermal”

Summary: shocks

- **Creates structures in the solar/space plasmas**
- **Fast flow kinetic energy is converted into heat, non-thermal particles, waves**



- Occurs during magnetic reconnection and eruptions in the corona, ubiquitous in the solar wind, Earth/planetary magnetospheres etc

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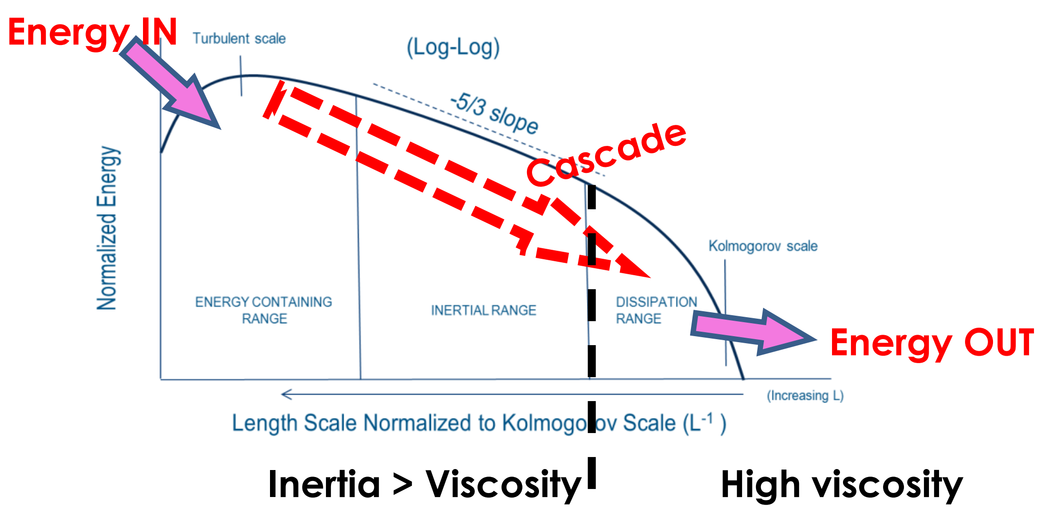

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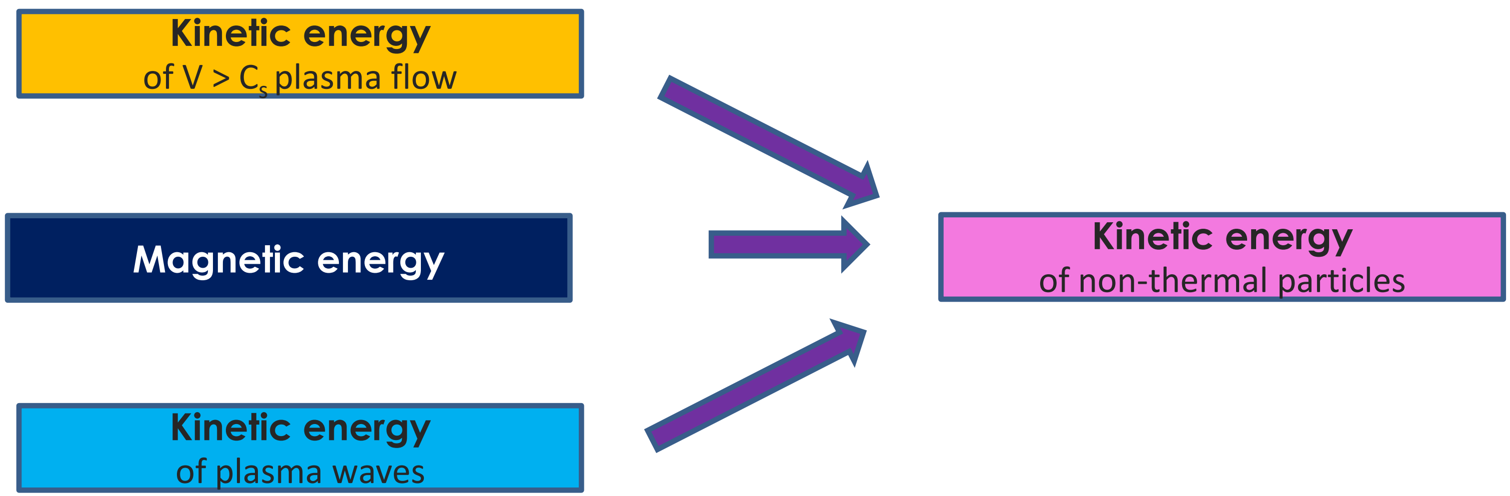

- Still no clear, comprehensive picture of particle acceleration and **transport** in the corona and heliosphere