Magnetic Reconnection

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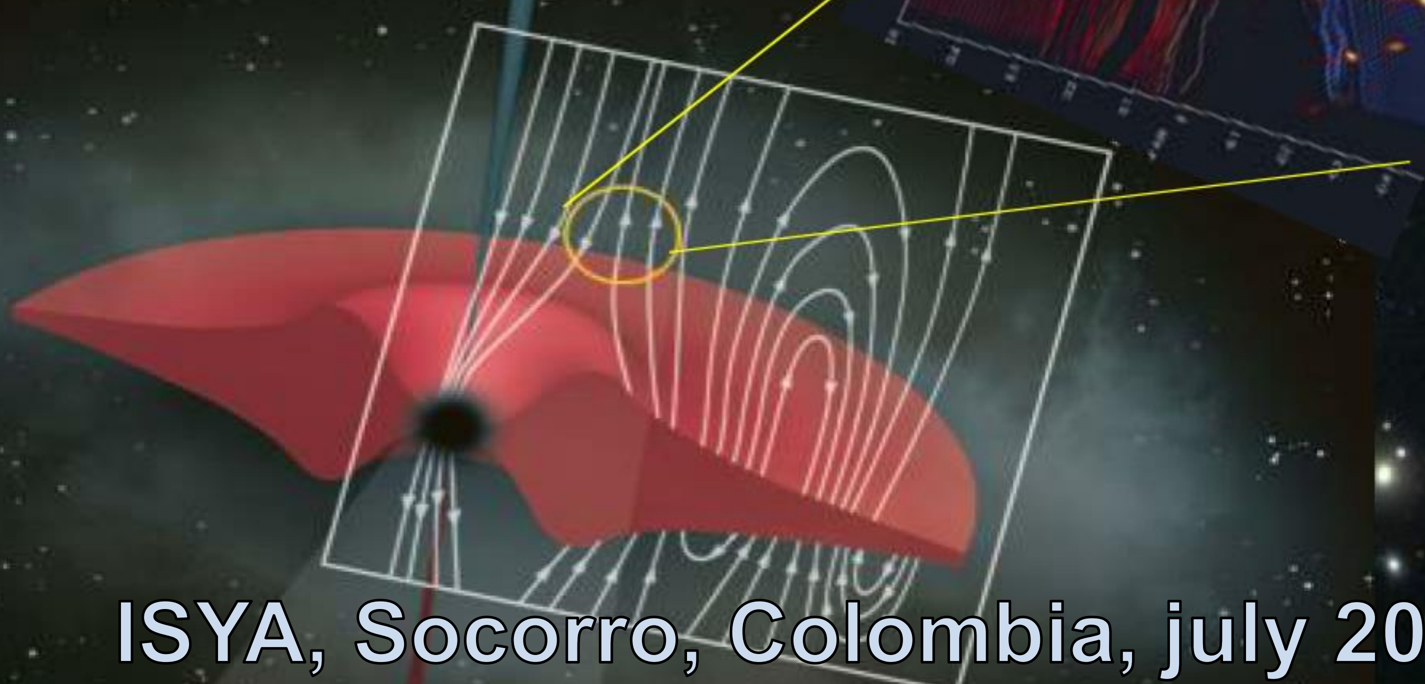


ISYA, Socorro, Colombia, july 2018

Class 4

Part I

Is B flux freezing always valid?

→ In astrophysical plasmas: **flux freezing (IDEAL MHD) valid in general because**

$$L, v \gg 1 \rightarrow \frac{L v_e}{\nu_M} = R_{eM} \gg 1$$

- **BUT there are exceptions:**

Ex. 1) **magnetic reconnection**: field dissipation (solar corona, earth magnetosphere)

Ex. 2) **MHD turbulence**: wandering of lines -> **reconnection**

In magnetic reconnection sites ideal MHD is not valid

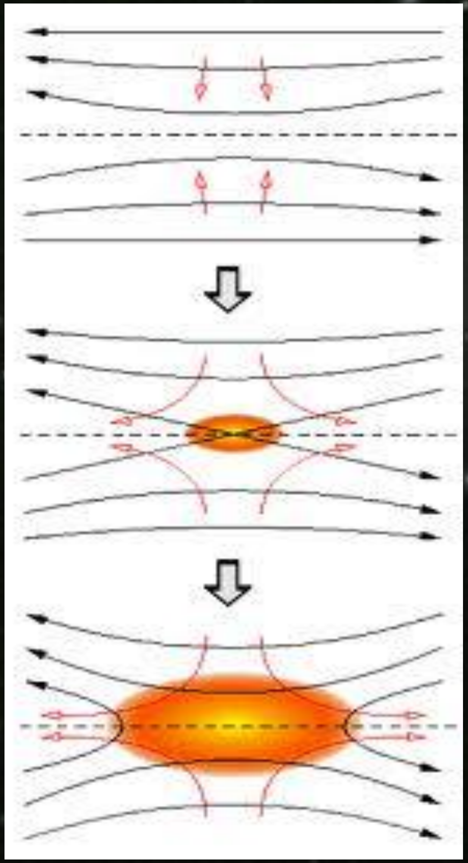
$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v}_e \times \vec{B}) + \nu_M \vec{\nabla}^2 \vec{B}$$

$$\nu_M = \eta c^2 / 4\pi$$

This term becomes important at reconnection site

WHAT IS MAGNETIC RECONNECTION ?

Approach of magnetic flux tubes of opposite polarity with finite resistivity (η ~1/conduction): **RECONNECT**



Earth magnetotail

Solar corona

Reconnection is *FAST* in these environments !

$$v_{rec} \rightarrow V_A = B/(4\pi\rho)^{1/2}$$

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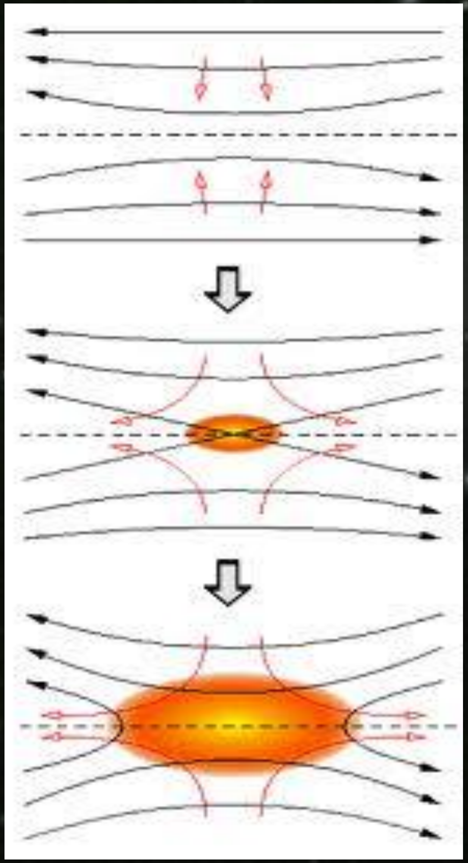


$$\vec{J} = \frac{c}{4\pi}\vec{\nabla} \times \vec{B}$$

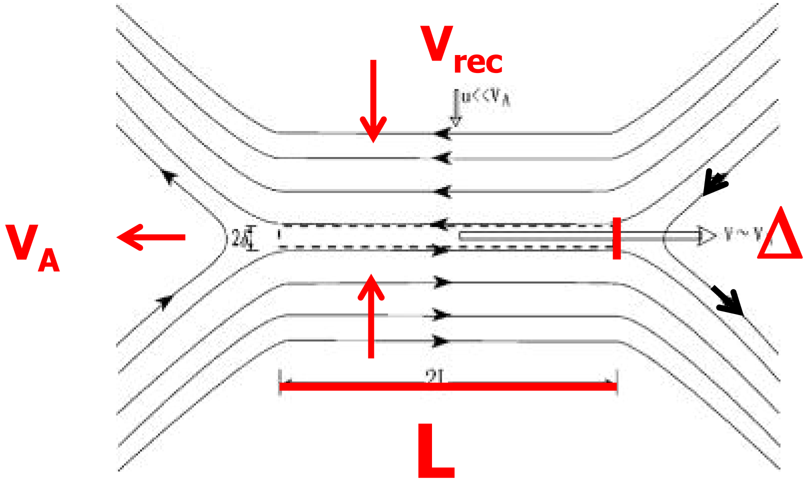
In the contact discontinuity the current density is:

$$J \sim \frac{2Bc}{4\,\pi\,\Delta} >> 1$$

Contact discontinuity is called *current sheet*

Magnetic Reconnection Models

- **Sweet-Parker (1957) reconnection model:**



From mass flux conservation in stationary flow:

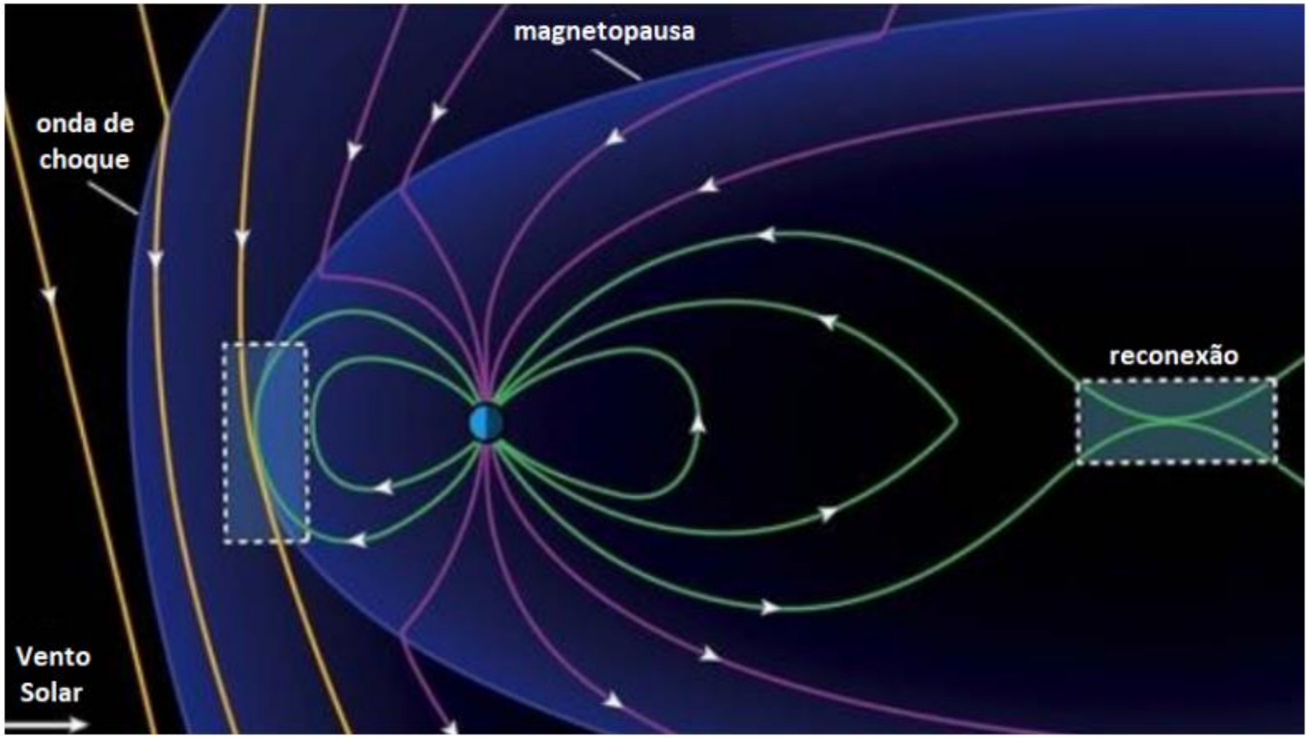
$$\cancel{\frac{\partial \rho}{\partial t}} + \nabla \cdot (\rho \mathbf{V}) = 0$$

$$V_{rec} \sim v_A\,(\Delta/L)$$

But $\Delta/L << 1$

$V_{rec} << v_A$ → *SLOW reconnection !*

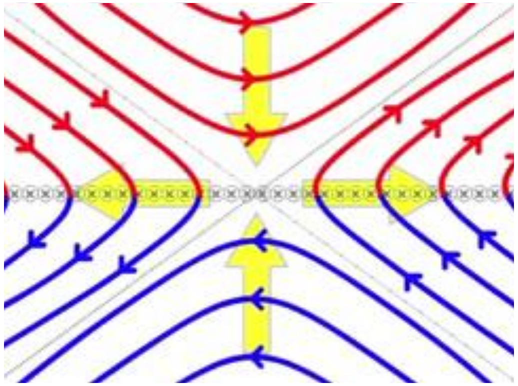
But what if reconnection is in a point rather than a line? (Petschek model, 1964)



Earth magnetotail

Magnetic Reconnection Models

Petschek (1964): X-point configuration ->



Lines encounter at a point, so that:

Δ → $\Delta \sim L$

L

Then reconnection rate is FASTER:

$$\mathbf{V_{rec} \sim \pi\, v_A / 4 \ln S}$$

Where $\mathbf{S = L\, v_A/\nu_M} \gg 1$

BUT*: unstable and evolves to Sweet-Parker** (Biskamp'96) ***unless:

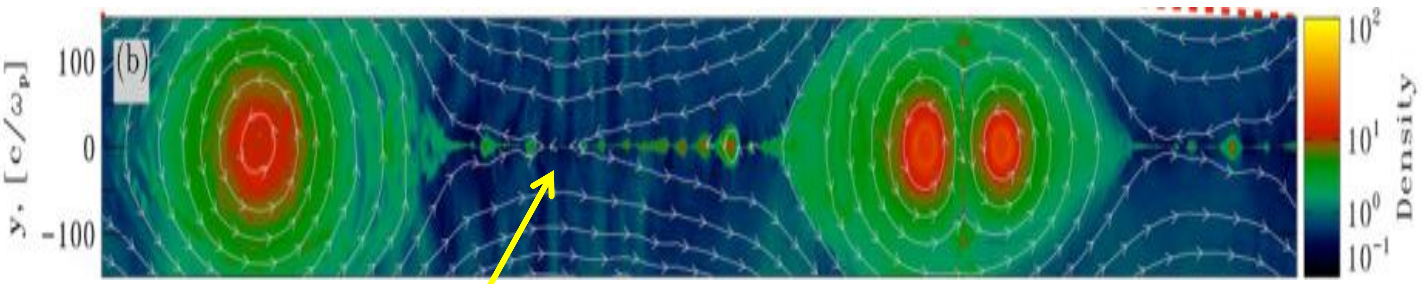
***pair* plasma at kinetic scales** with localized resistivity η $(\nu_M = \eta c^2/4\pi)$

Fast Reconnection Models in Kinetic Plasmas

Petschek X-point configuration -> arises naturally in **kinetic** ***(collisionless)*** ion-e$^-$ or e$^+$e$^-$ *pair* plasma with localized magnetic resistivity (η)

- **Kinetic simulations**: 2-dimensional (2D) Particle In Cell **(PIC)** simulations of e$^+$e$^-$ *pair* plasma :

few plasma inertial length ~ 100-1000 c/ω_p



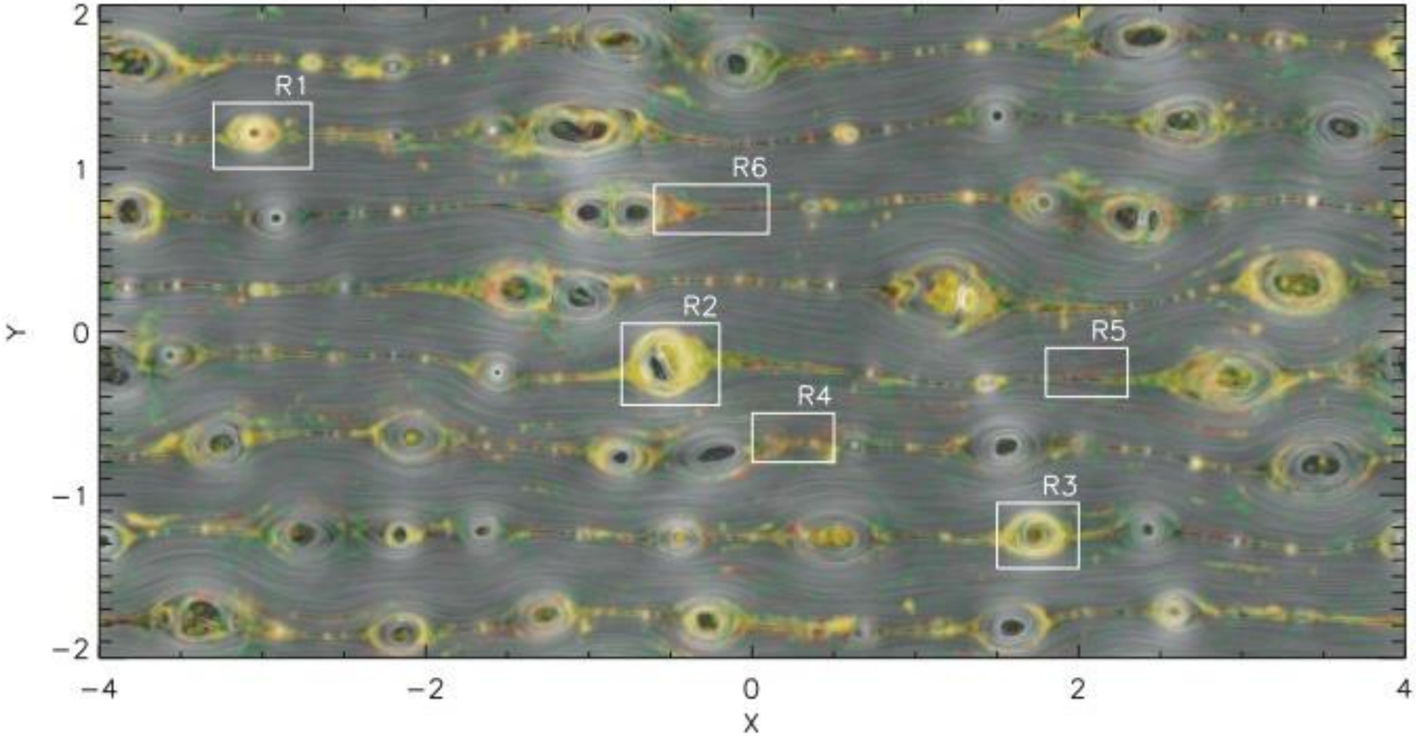
X-point

(Sironi & Spitkovsky 14)

Single Current sheet: unstable to **tearing mode** and breaks up into chain of **plasmoids** (or islands)

Fast Reconnection Models in MHD Plasmas

- **2D MHD (collisional) simulations:** in presence of numerical resistivity η

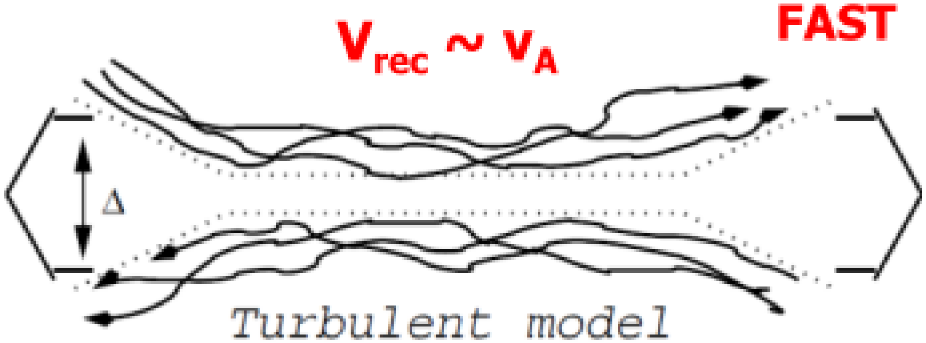


Current sheets: unstable to **tearing mode** and break up into chain of **plasmoids** (or islands)

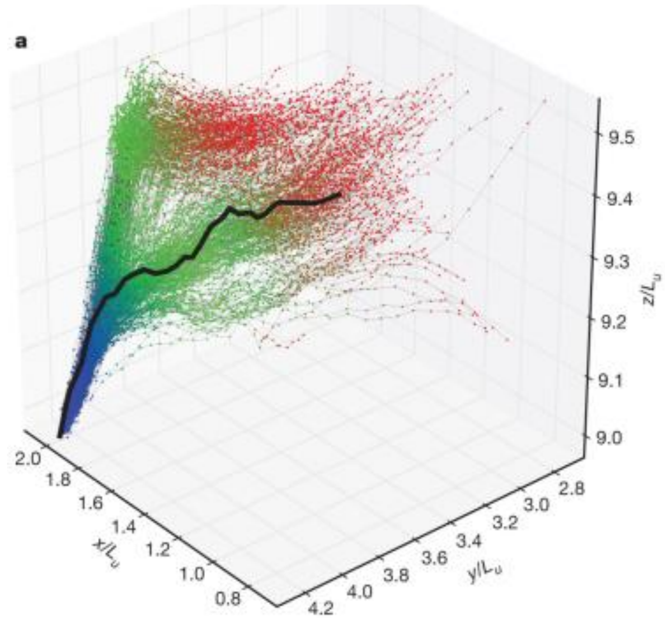
(Kowal, de Gouveia Dal Pino & Lazarian, ApJ 2011)

Ubiquitous Model of Fast Magnetic Reconnection in MHD flows

TURBULENT RECONNECTION (Lazarian & Vishniac 1999):



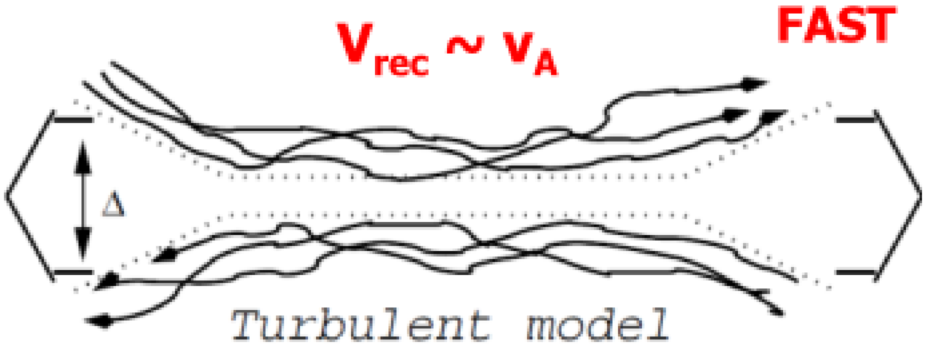
B dissipates on a small scale $\lambda_{||}$: many simultaneous reconnection events



Stochastic wandering of field lines in turbulence leads to Richardson diffusion that breaks the frozen in condition (Eyink et al. 2013)

Ubiquitous Model of Fast Magnetic Reconnection in MHD flows

TURBULENT RECONNECTION (Lazarian & Vishniac 1999):



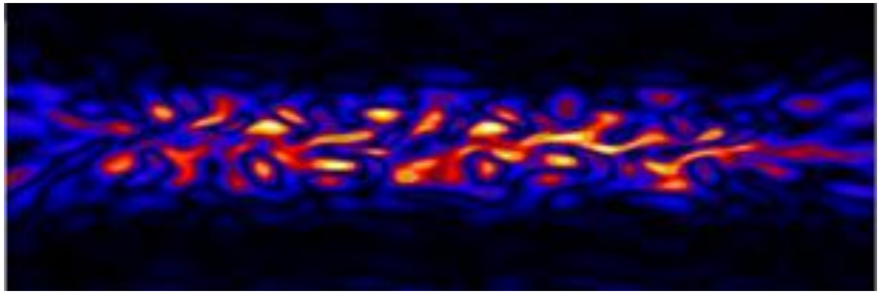
Using MHD turbulence theory (Goldreich-Striddar 1995), we can show that:

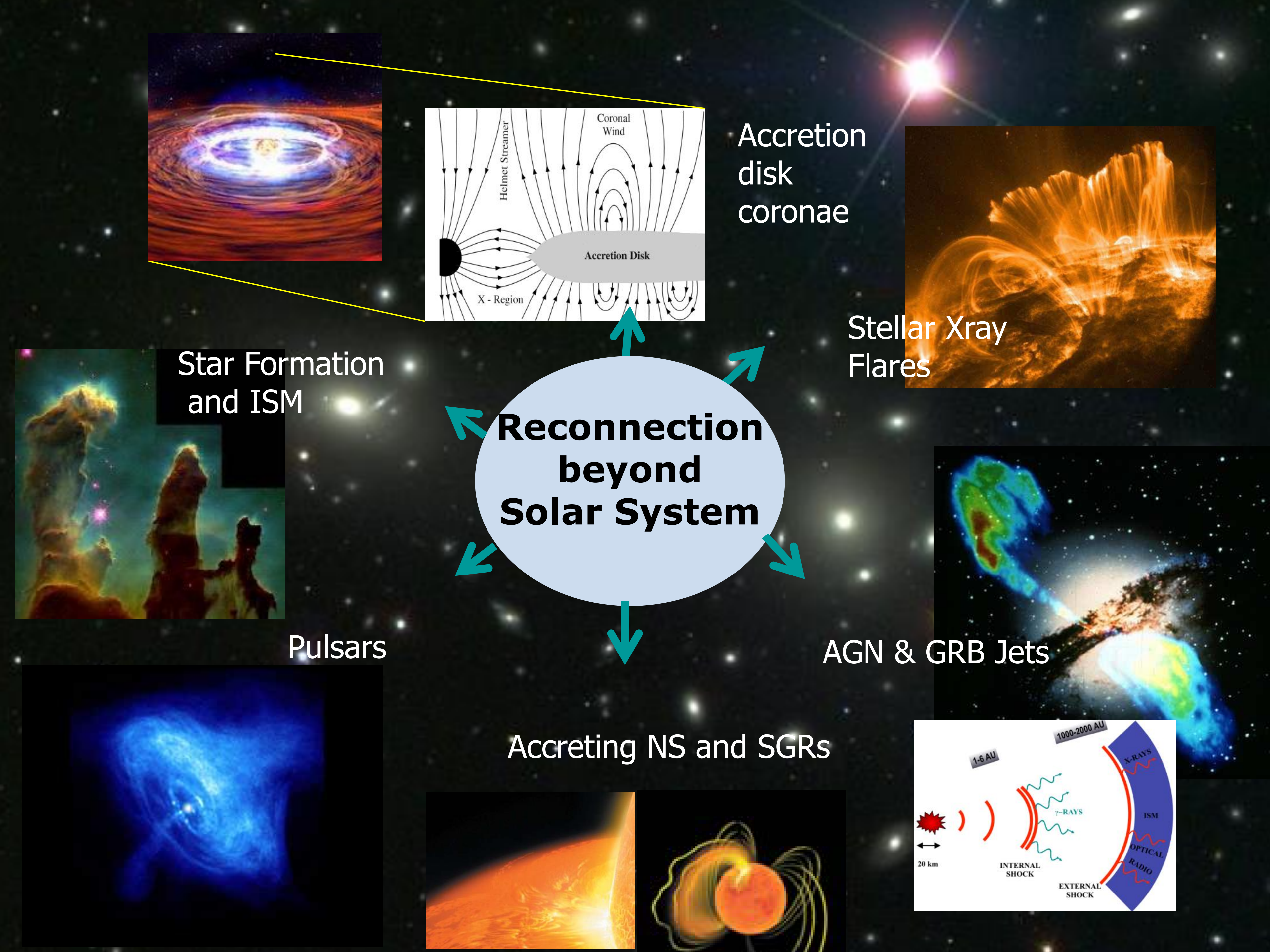
$$V_{\mathrm{rec}} = V_{\mathrm{A}} \left(\frac{l}{L}\right)^{1/2} \left(\frac{v_l}{V_{\mathrm{A}}}\right)^{2}$$

(does not depend on η)

- ✓ **Reconnection layer : THICKER**
- ✓ **THREE-DIMENSIONAL**

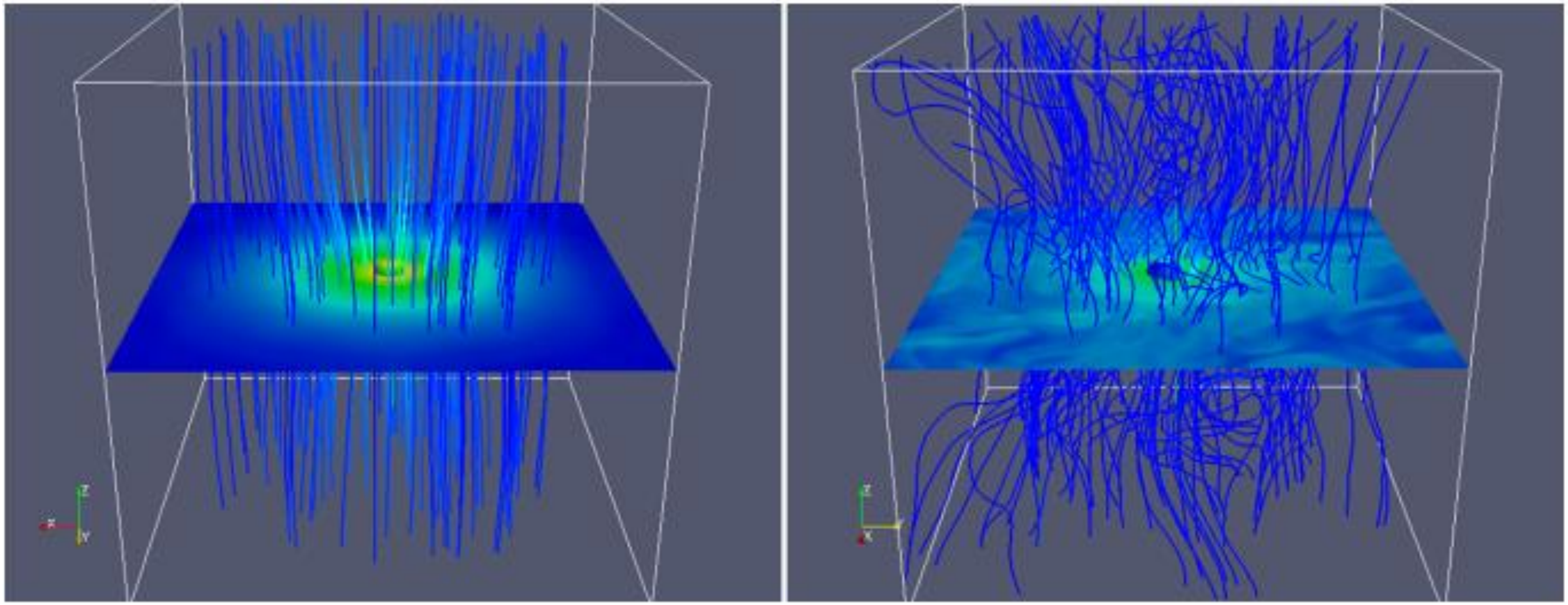
Successfully tested in numerical simulations (Kowal et al. 2009, 2012)




Reconnection beyond Solar System
Accretion disk coronae
Coronal Wind
Helmet Streamer
Accretion Disk
X - Region
Stellar Xray Flares
Star Formation and ISM
AGN & GRB Jets
Pulsars
Accreting NS and SGRs
1000-2000 AU
1-6 AU
X-RAYS
γ-RAYS
ISM
OPTICAL
RADIO
20 km
INTERNAL SHOCK
EXTERNAL SHOCK

MHD simulation of Self-Gravitating collapsing clouds

Non-turbulent t~ 40Myr Turbulent

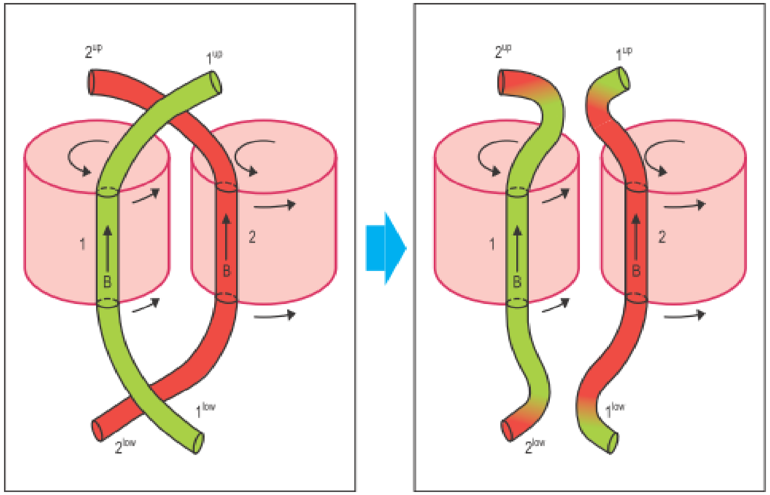


B does not allow core collapse **But with turbulence it collapses**

Leão, de Gouveia Dal Pino et al., ApJ 2013

MHD turbulent diffusion: new scenario

In presence of turbulence: field lines reconnect fast (Lazarian & Vishniac 1999) and magnetic flux transport becomes efficient --> there is magnetic flux removal in the collapse of the turbulent cloud!



$$\eta_t \sim l_{\rm inj} v_{\rm turb}$$

Lazarian 2005, 2012
Santos-Lima et al. 2010, 2012, 2013
de Gouveia Dal Pino et al. 2012

Reconnection Beyond the Solar System

Stellar X-ray flares (Cassak+08; Shibata+05)

Young stellar objects (van Ballegooijen94; Hayashi+1996; Goodson+1997; Feigelson & Montmerle’99; Uzdensky+’02; 04; de Gouveia Dal Pino+’10; D’Angelo & Spruit’10)

Interstellar medium and star formation (Zweibel89; Lesch & Reich92; Brandenburg & Zweibel95; Lazarian & Vishniac99; Heitsch & Zweibel03; Lazarian05; Santos-Lima+10, 12, 13; Leao+13)

Accreting neutron stars & white dwarfs (Aly & Kuijpers90; van Ballegooijen 1994; Warner & Woudt02)

Accretion disk coronae (Galeev+79; Haardt & Maraschi91; Tout & Pringle96; Romanova+98; Di Matteo+99; de Gouveia Dal Pino & Lazarian01, 05; Liu+03; Schopper et al. 1998; Uzdensky & Goodman08; Goodman & Uzdensky08; de Gouveia Dal Pino+10; Kadowaki et al. 2015; Singh et al. 2015; 2018; de Gouveia Dal Pino et al. 2016)

Pulsar magnetospheres and winds (Coroniti90; Michel94; de Gouveia Dal Pino & Lazarian01; Blasi+01; Lyubarsky & Kirk01; Lyubarsky03; Kirk & Skjæraasen03; Contopoulos07; Arons07; P´etri & Lyubarsky07; Spitkovsky08; Lyutikov10; Cerutti+13)

SGRs (Thompson & Duncan95, 01; Lyutikov 03, 06; Uzdensky08; Masada+10)

Relativisitc jets (microquasars/AGNs/GRBs) (Romanova & Lovelace92; Larrabee+03; Lyutikov+03; Jaroschek+04; Giannios10; Giannios+09, 10; Nalewajko et al. 2010); Spruit et al. 2001; Lyutikov & Blackman01; Lyutikov & Blandford02; Drenkhahn &Spruit02; Giannios & Spruit05, 06, 07; Rees & M´esz´aros 2005; Uzdensky & MacFadyen06; McKinney & Uzdensky10; 12; Uzdensky11; Zhang & Yan09; de Gouveia Dal Pino & Kowal 2015; Singh et a. 2016).

End of class4
part 1