Hinode-15 / IRIS-12: 19-23/09/2022

MHD waves and instabilities in relation to oscillatory reconnection
(Waves and null points interaction in relation to oscillatory reconnection)

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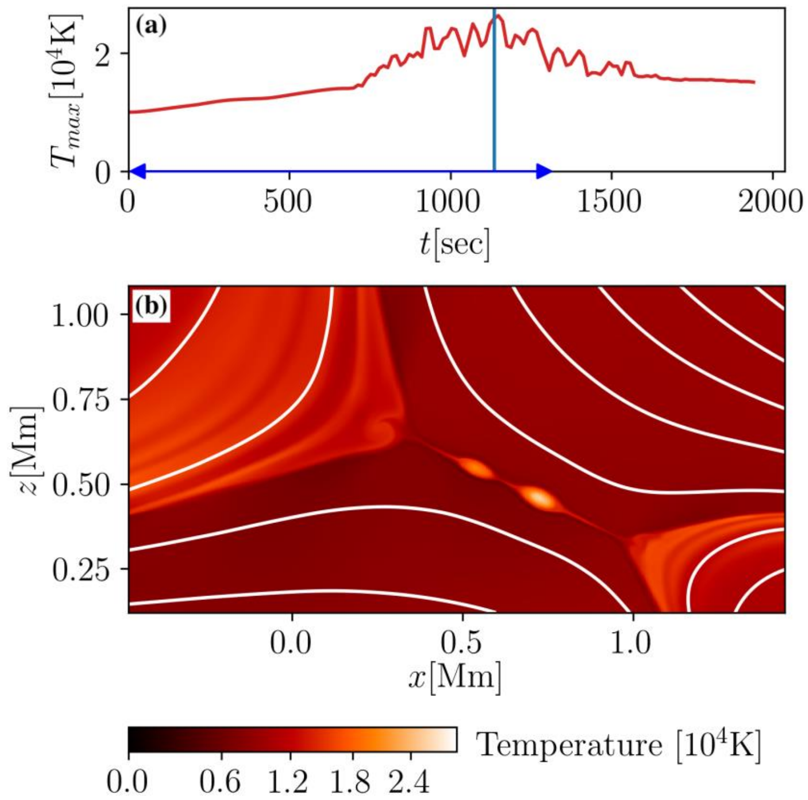
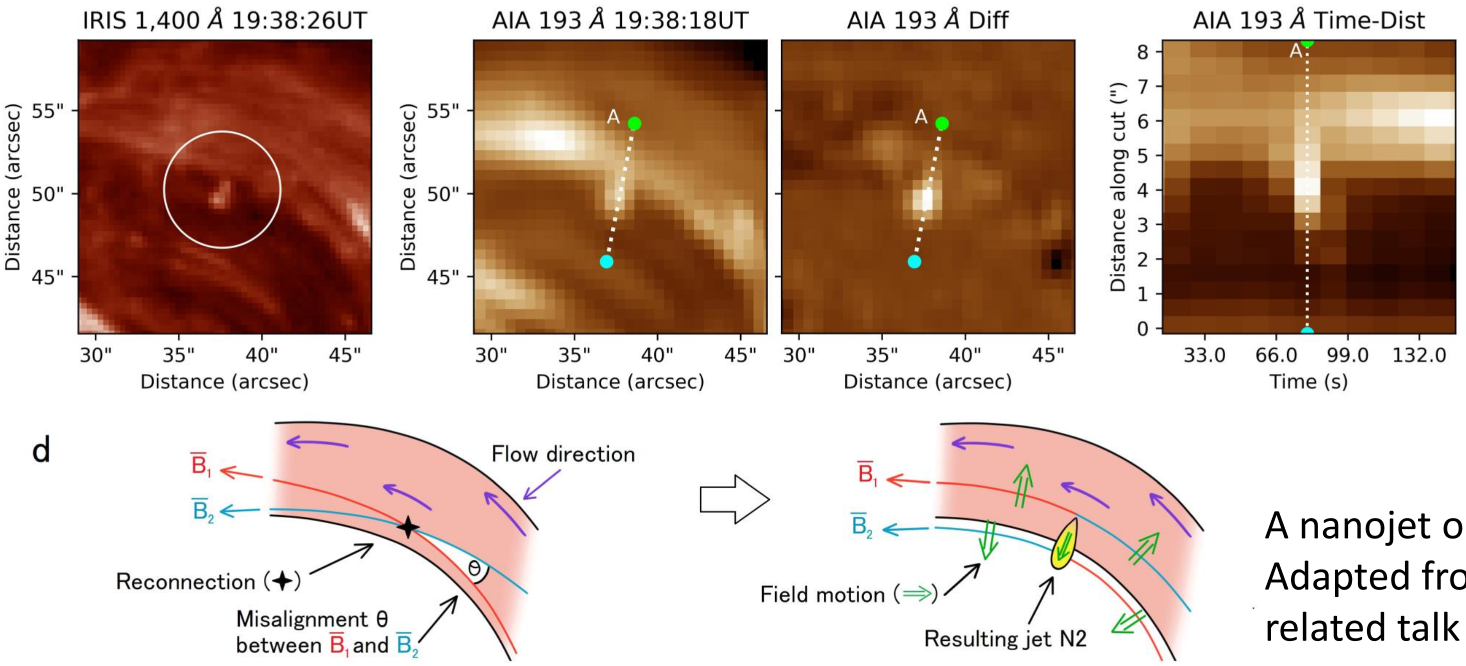
Reconnection in the solar atmosphere

- **Very Common** in the solar atmosphere.
- **Slow and fast reconnection** (Parker 1957; Sweet 1958; Petschek 1964)*.
- **Unsteady reconnection** Furth et al. (1963)*
- **Mechanism behind flares** (including micro/nano-flares).
- **Nanojets** (Antolin et al. 2021, Pagano et al. 2021, Sukamardji et al. (2022).
- **DC Heating (Reconnection based).**

*S2 Review talk by K. Reeves



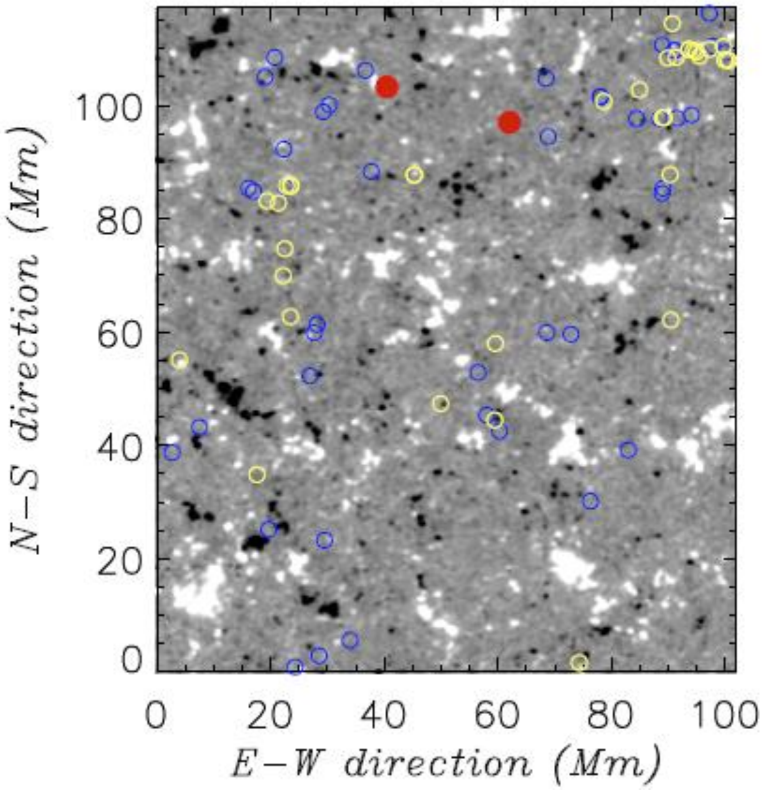
Plasmoids at a simulated reconnection region. From Peter et al. (2019).



A nanojet observation in a solar blowout jet. Adapted from Sukamardji et al. (2022). See also related talk on Friday. Also, Antolin et al. 2021.

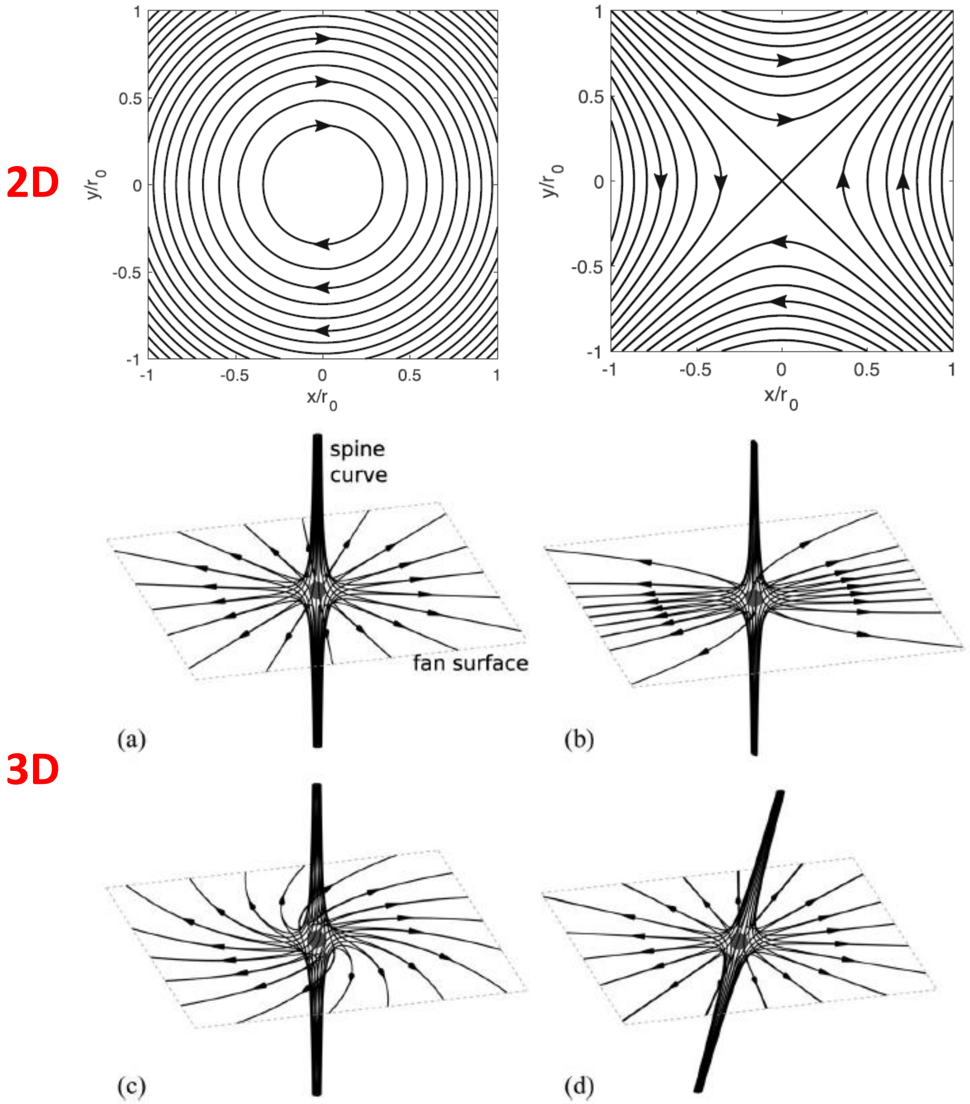
Null points in the solar atmosphere

- Magnetic field singularities in which the magnetic field strength strongly decreases in very small spatial scales.
- Omnipresent (e.g. Longcope 2005; Régnier et al. 2008).
- Sites of reconnection (e.g. Priest & Forbes 2000)



LOS photospheric magnetic field, by Hinode/SOT + location of the null points. From Régnier et al. (2008).

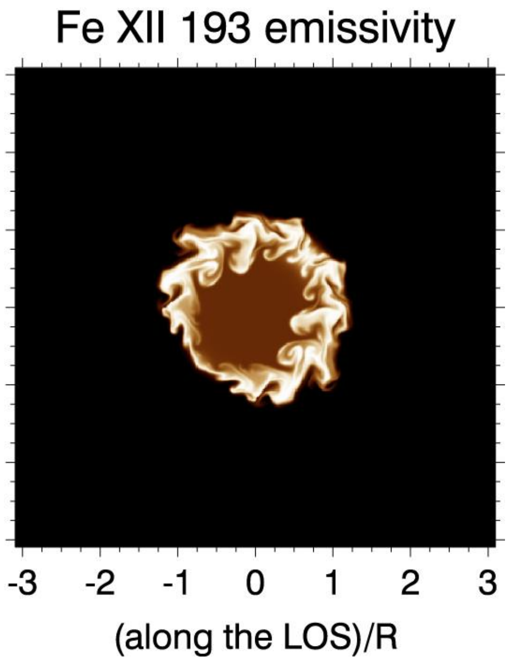
Pontin & Priest, 2022



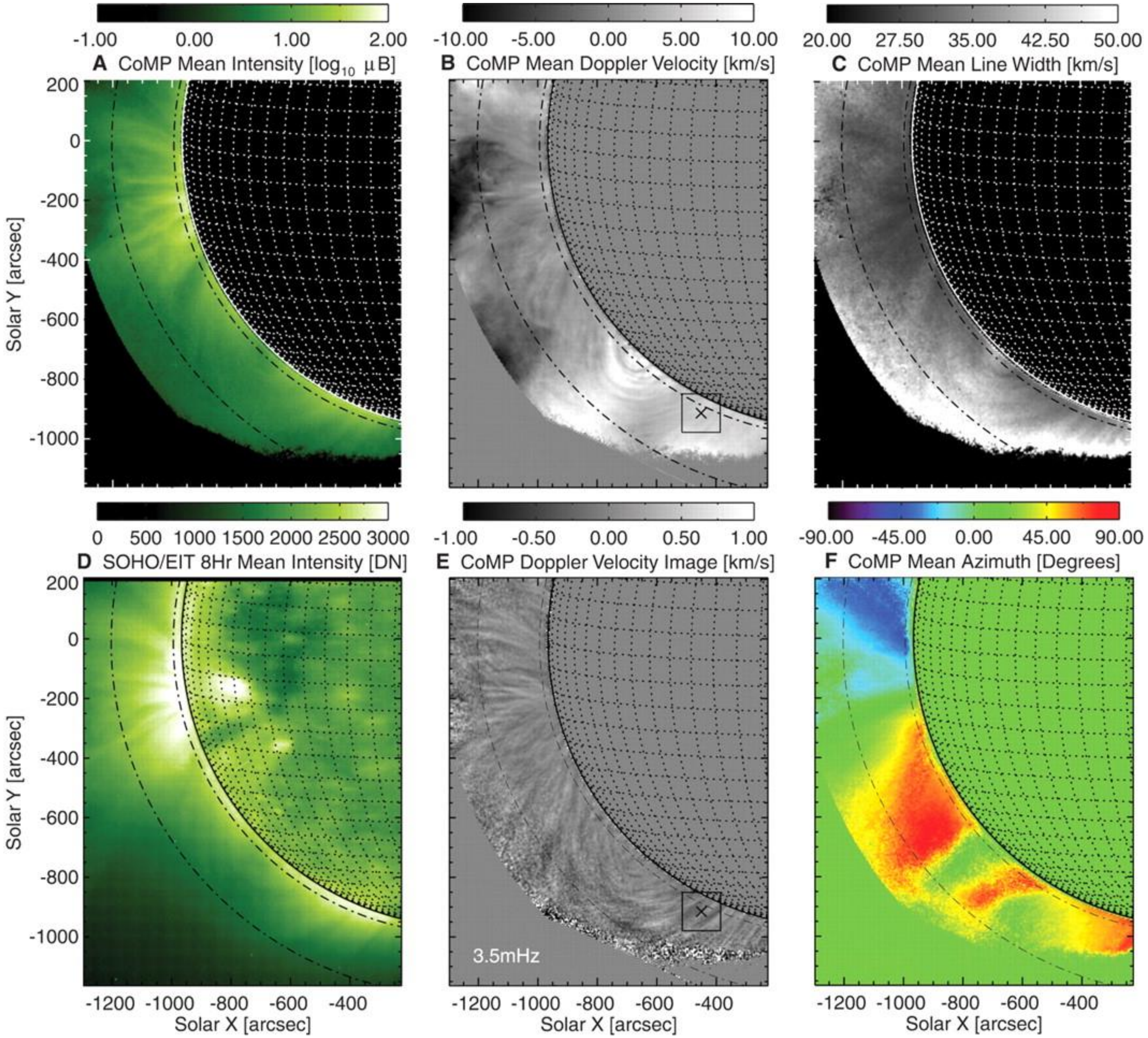
Hinode-15 / IRIS-12: 19-23/09/2022

Waves in the solar atmosphere

- **Ubiquitous** in the solar atmosphere (e.g. De Pontieu et al. 2007, Tomczyk et al. 2007, Morton et al. 2012, Anfinogentov et al. 2015, Prasad et al. 2015,…).
- **Compressible** and **incompressible** modes
- Can generate **instabilities** (i.e. KHI – TWIKH rolls).
- Can lead to **turbulence.**
- **Coronal Seismology.**
- **AC Heating (wave based).**



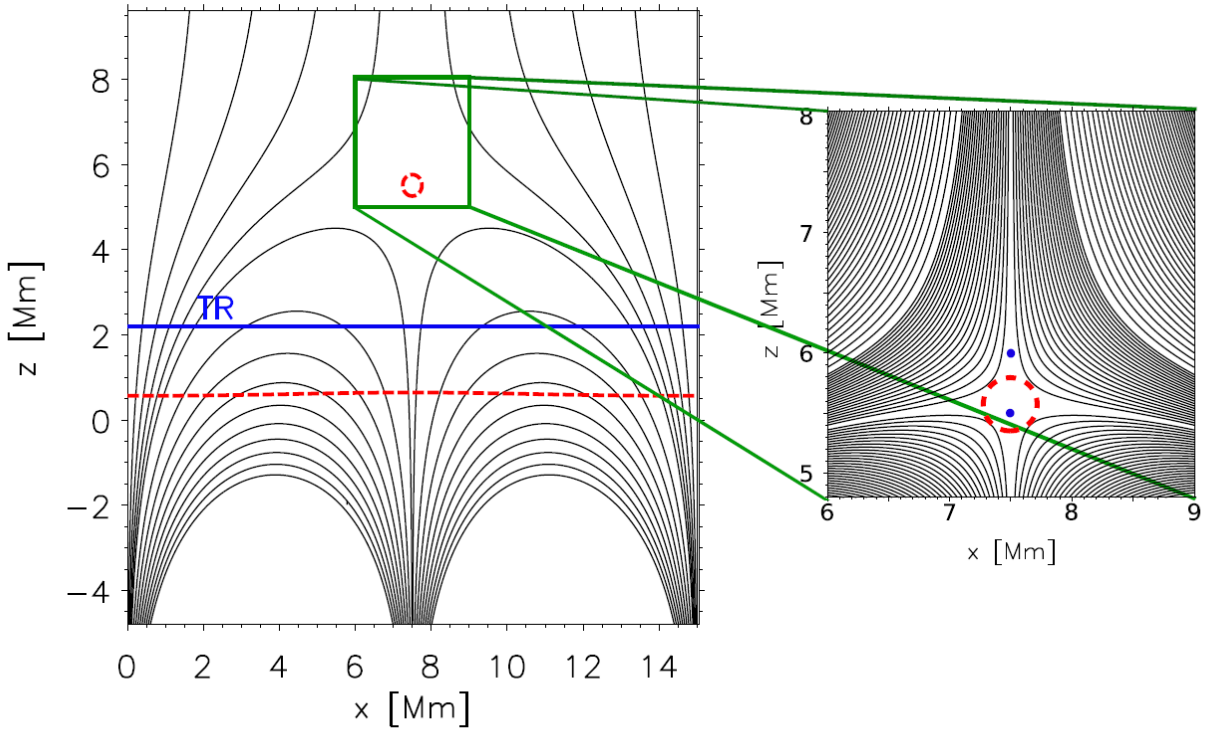
KH instability of a loop cross section (Antolin et al. 2016).

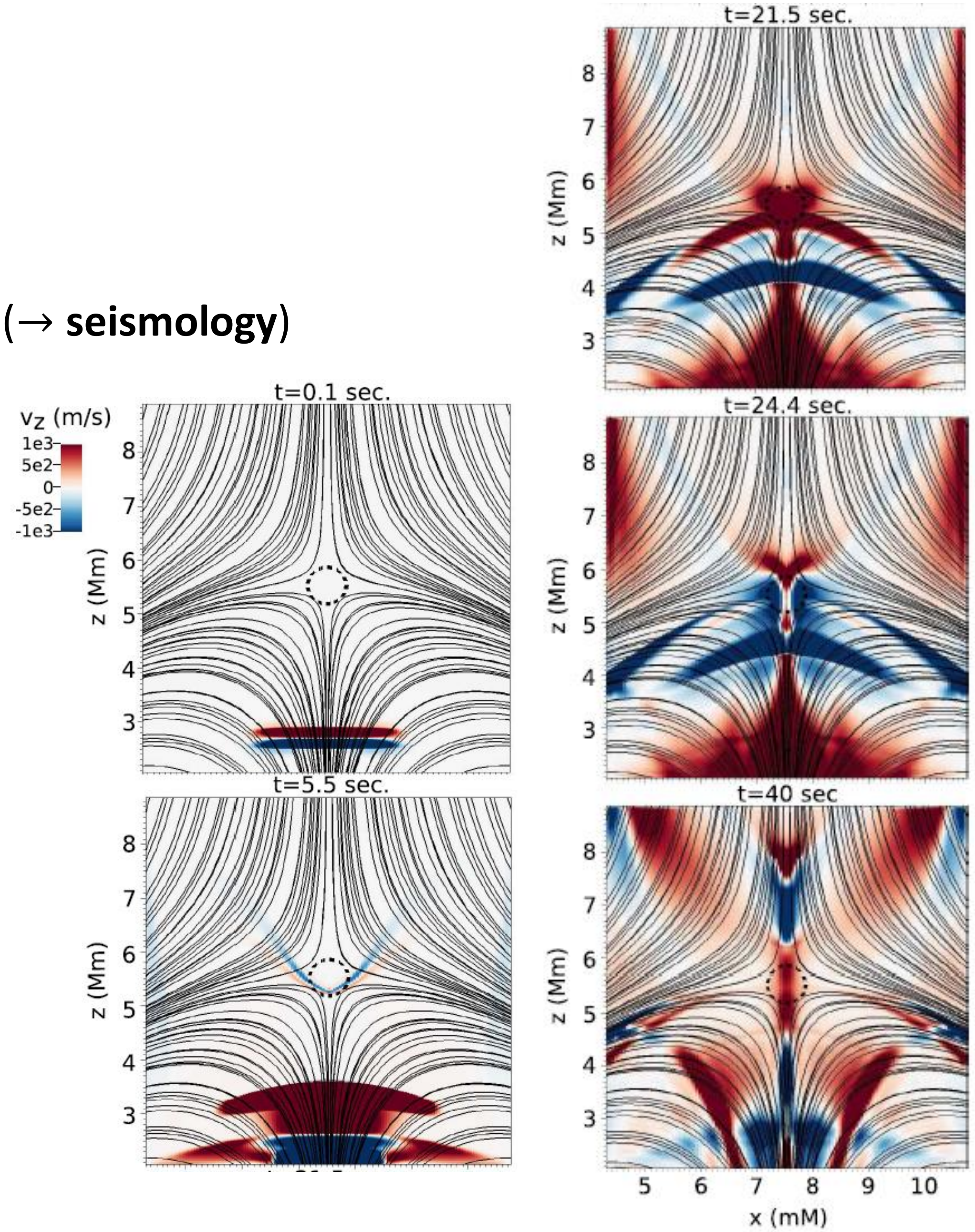


CoMP observations of propagating waves. Tomczyk et al. (2007).

Wave - null point interaction

1. Null points alter the behavior of waves around them.
2. Santamaria & Van Doorsselaere (2018):
    - Null points can act as **resonant cavities**, generating waves
    - Frequencies depend upon plasma conditions
    - Frequencies do not depend upon the strength of the driver (→ **seismology**)





Adapted from Santamaria & Van Doorsselaere (2018). **Left.** Magnetic field, including the null point. **Right.** Vertical velocity in the vicinity of a null point.

Wave - null point interaction

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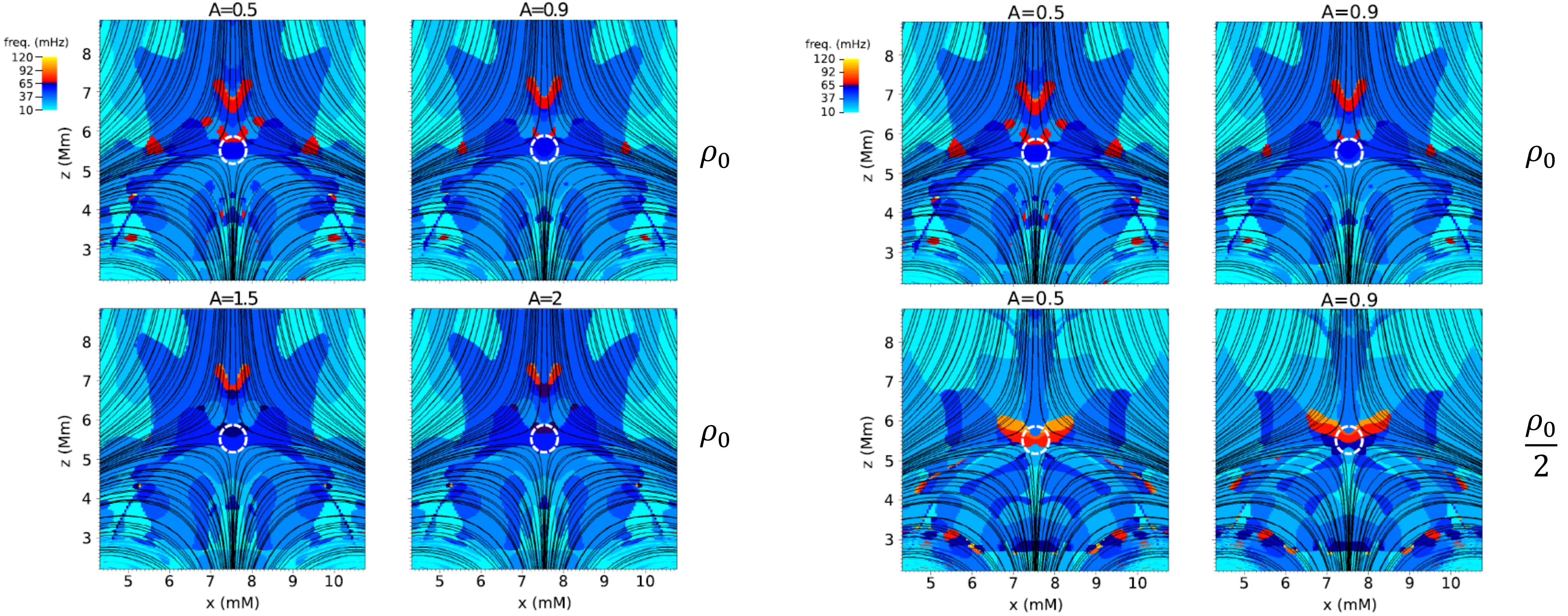

From S&VD (2018). Dominant frequencies for different driver amplitudes (A).

Wave - null point interaction

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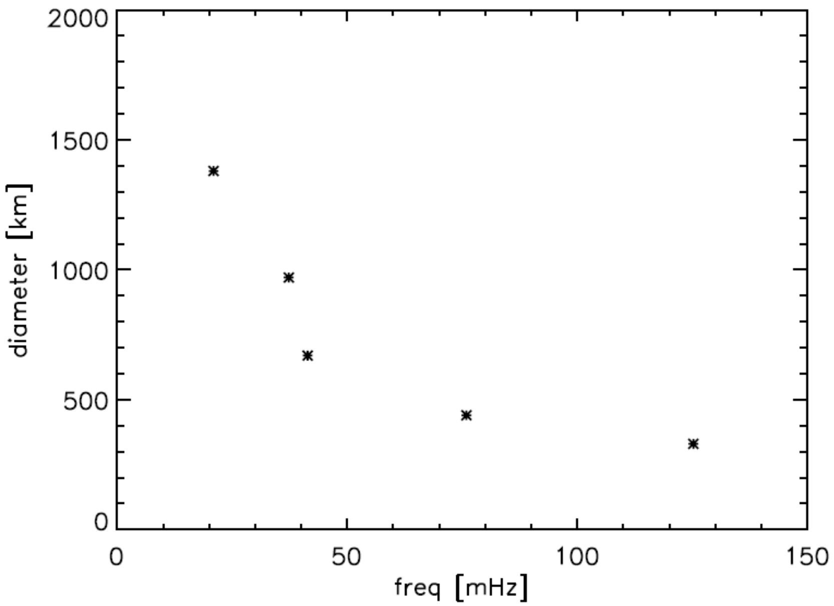
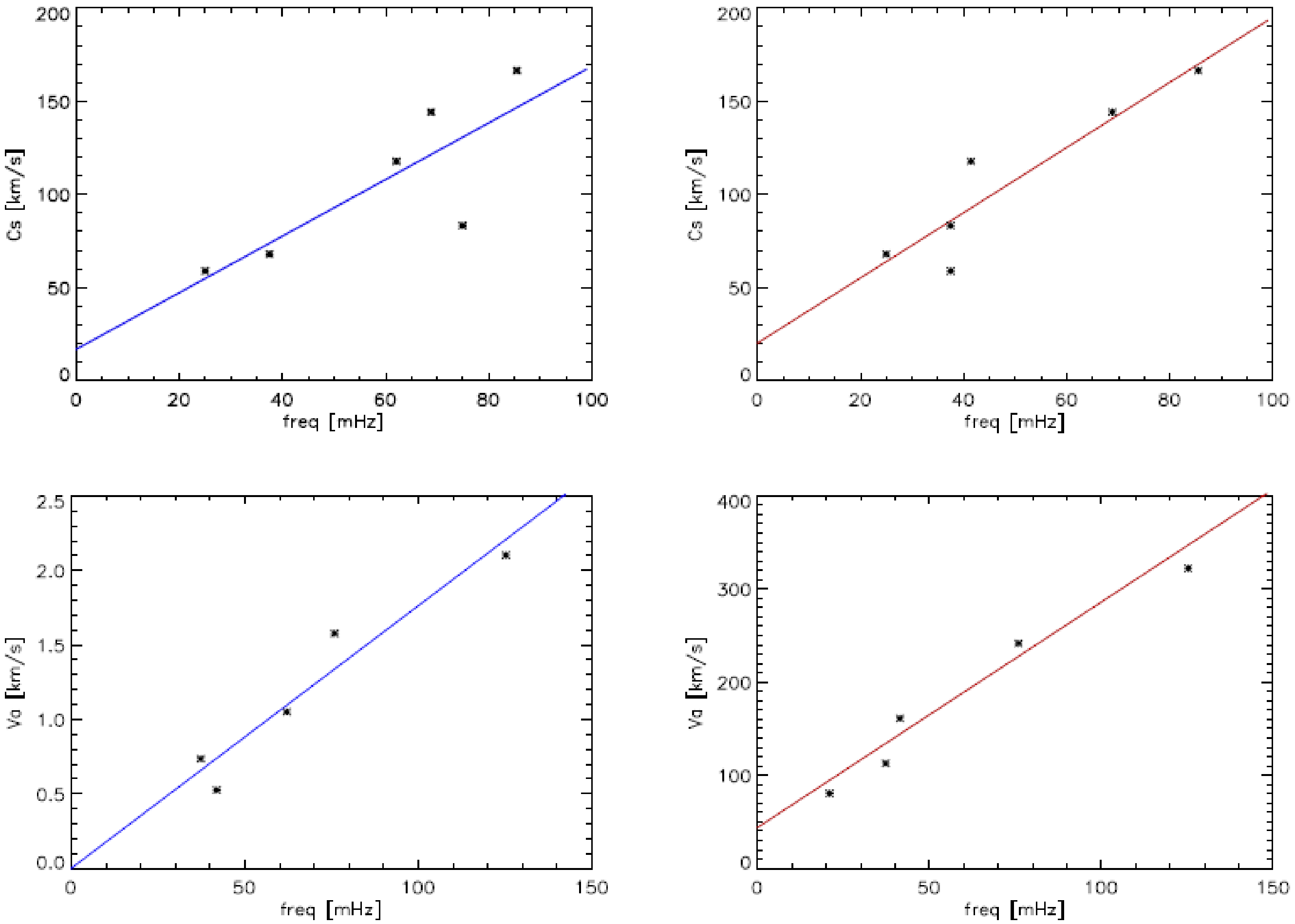
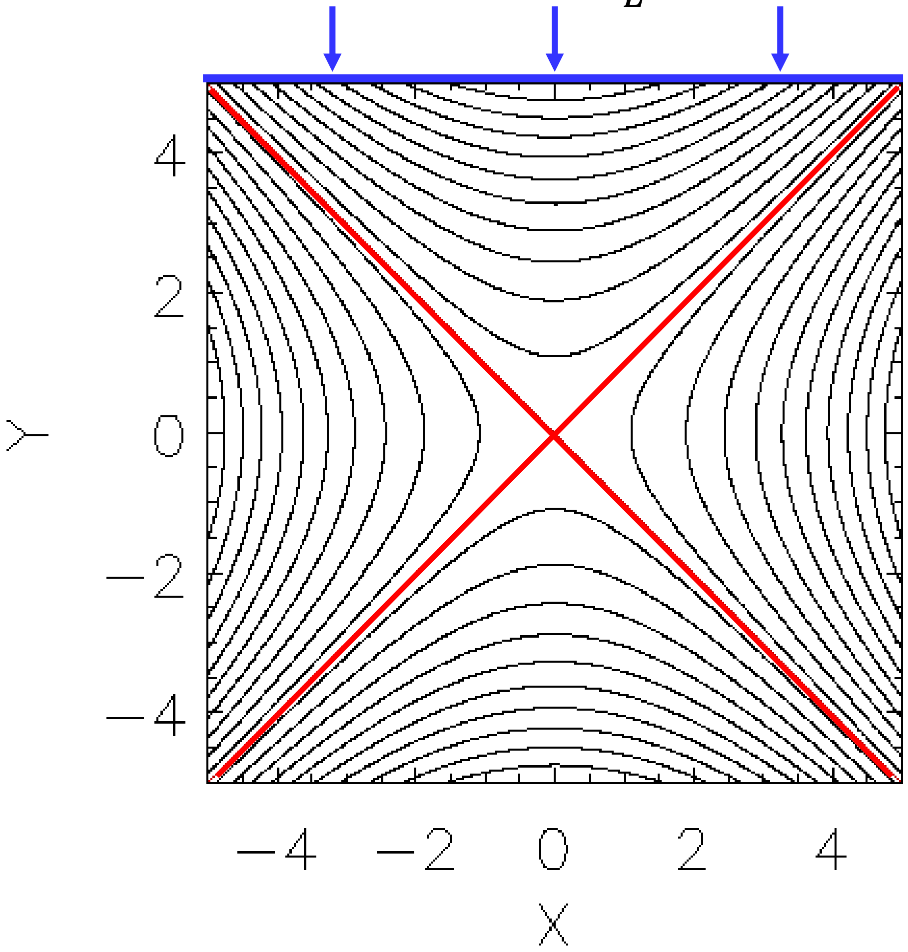
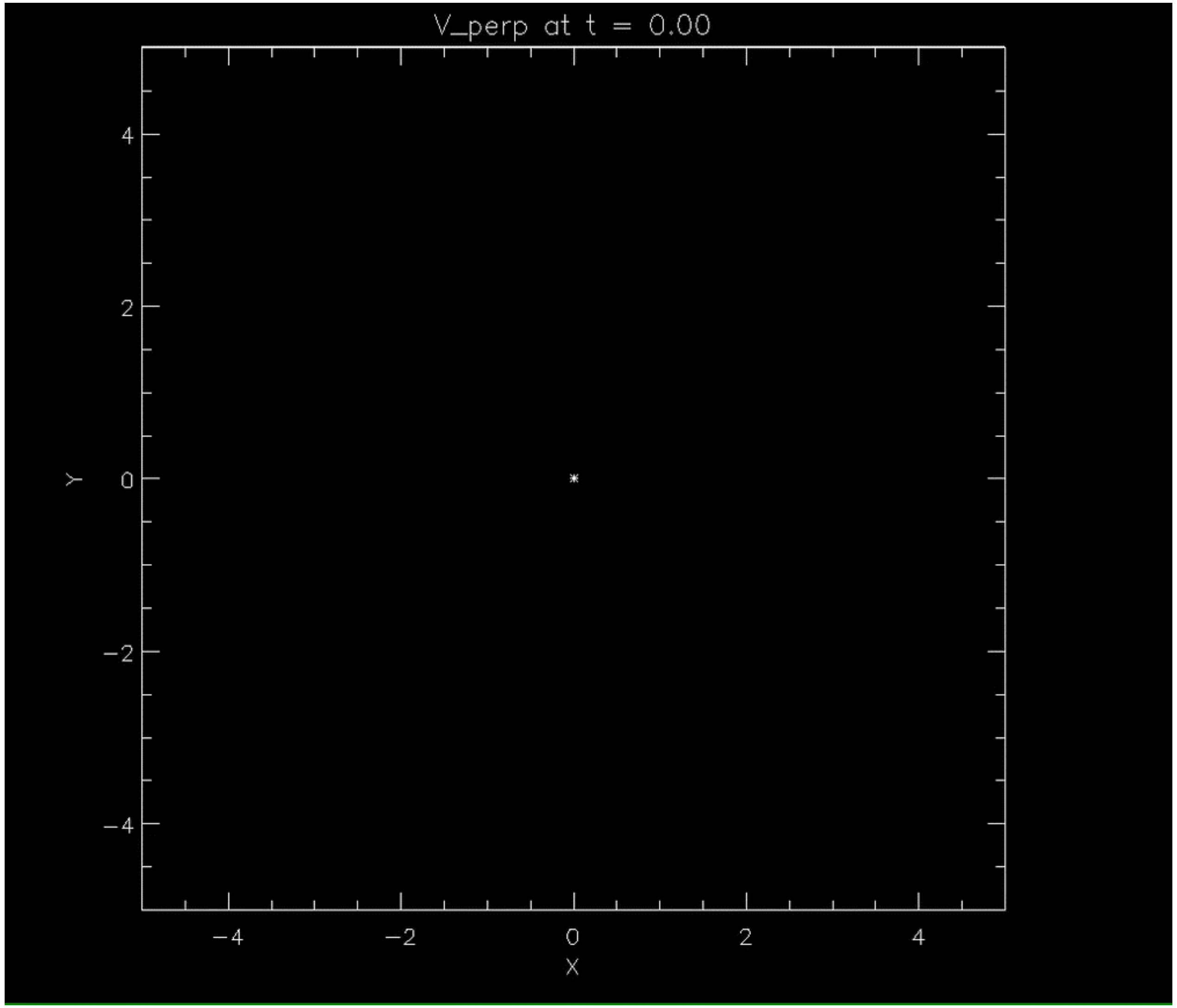




Linear fast wave in cold plasma (β=0) – straight wave pulse

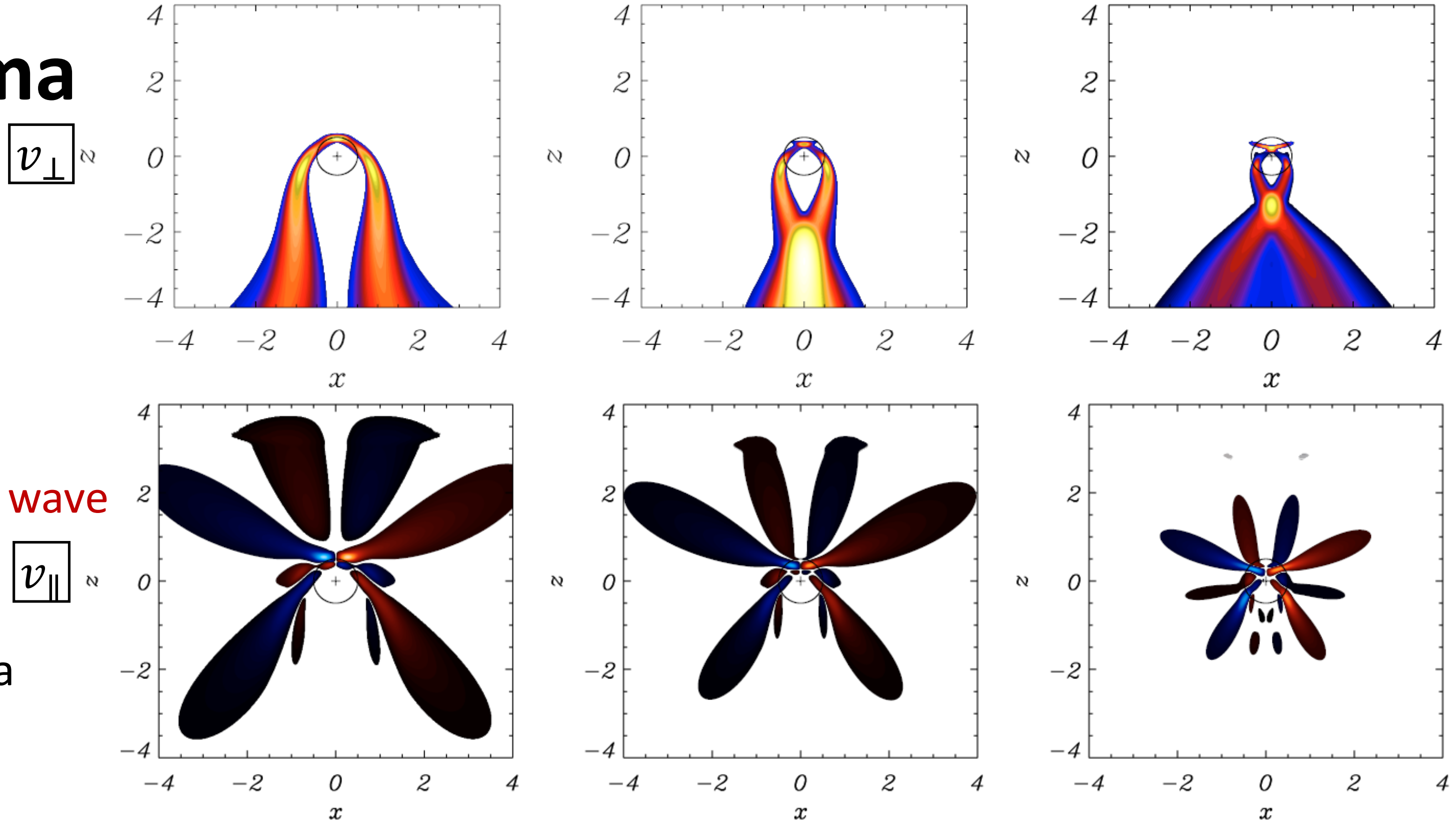
- McLaughlin & Hood (2004)
- Wave propagation near a simple 2D X-point.
- Magnetic field: $\boldsymbol{B_0} = \frac{B_0}{L}(y, x, 0)$

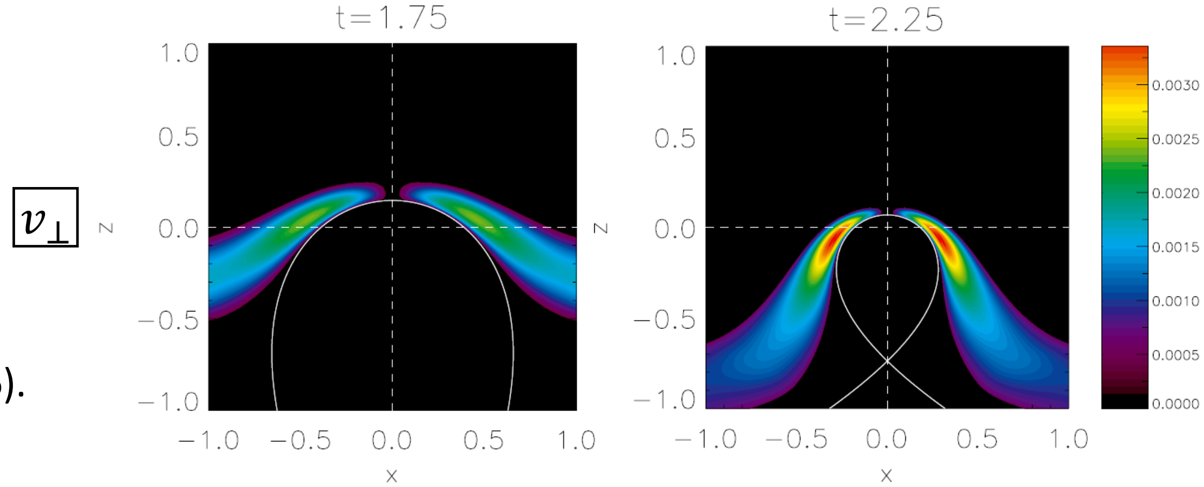




Linear fast wave in cold plasma

1. McLaughlin & Hood (2004):
   - **refraction** in **cold plasma.**
2. McLaughlin & Hood (2006):
   - linear wave in **finite-$\boldsymbol{\beta}$** plasma,
   - **crossing** the equipartition layer, a **low-$\boldsymbol{\beta}$** fast wave generates **high-$\boldsymbol{\beta}$** fast and slow waves.
3. Thurgood & McLaughlin (2012):
   - Expanding results for a 3D null in cold plasma



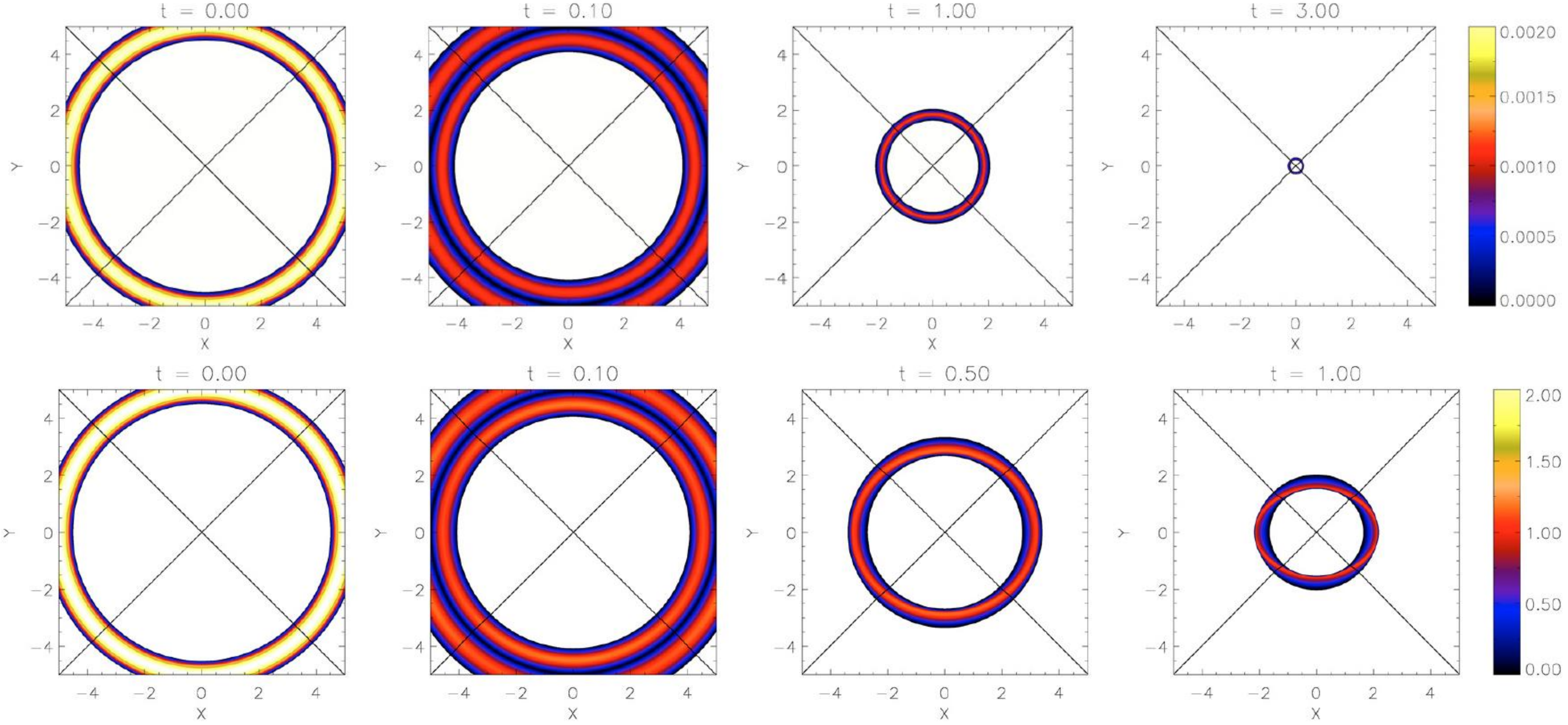


Top and middle panels: Adapted from McLaughlin & Hood (2006).
Bottom panel: Adapted from Thurgood & McLaughlin (2012)

Fast wave in cold plasma (β=0) – Circular wave pulse

- Linear wave: the pulse never reaches the null ($V_A = 0$)!
- Non-linear wave: formation of shocks!

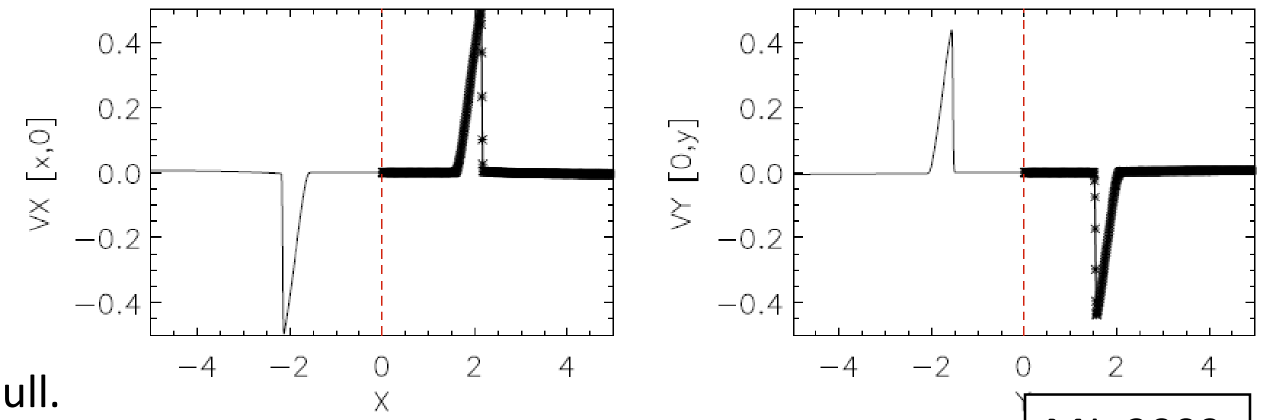
McLaughlin et al. 2009



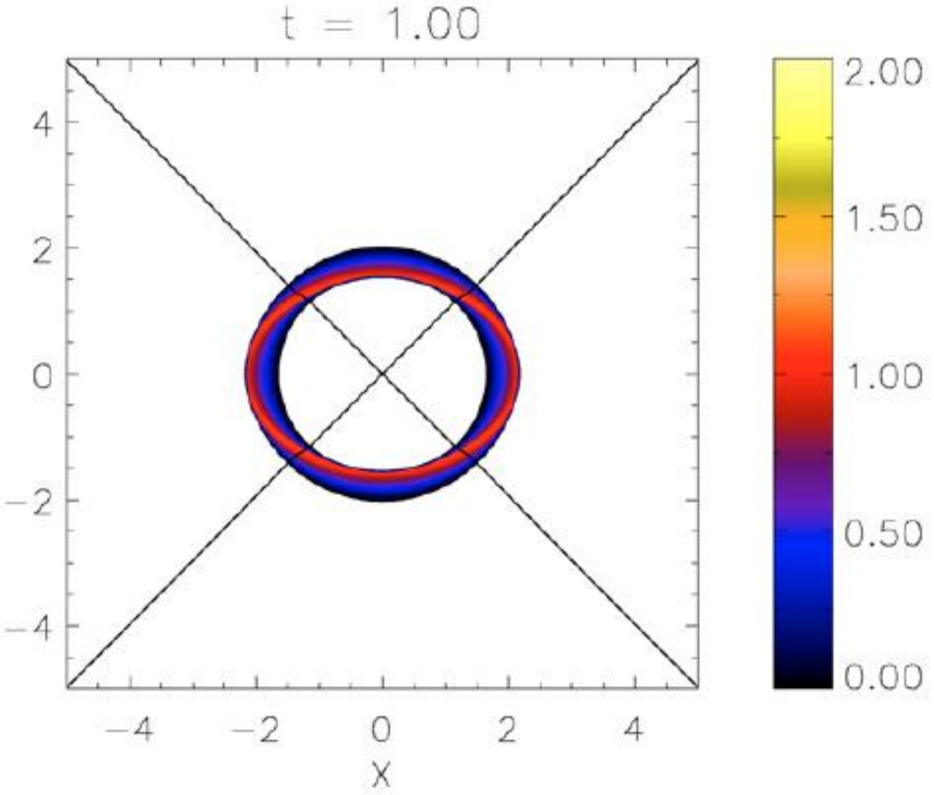
Circular fast wave in cold plasma

Gruszecki et al. (2011) – Non-linear waves

- Polar angle dependency for radial velocity
- Shock fronts: **compression** and **rarefaction** pulses
- Steeper, stronger pulses “overturn” before reaching the null.
- Stronger mother flares are not certain to trigger daughter flares!

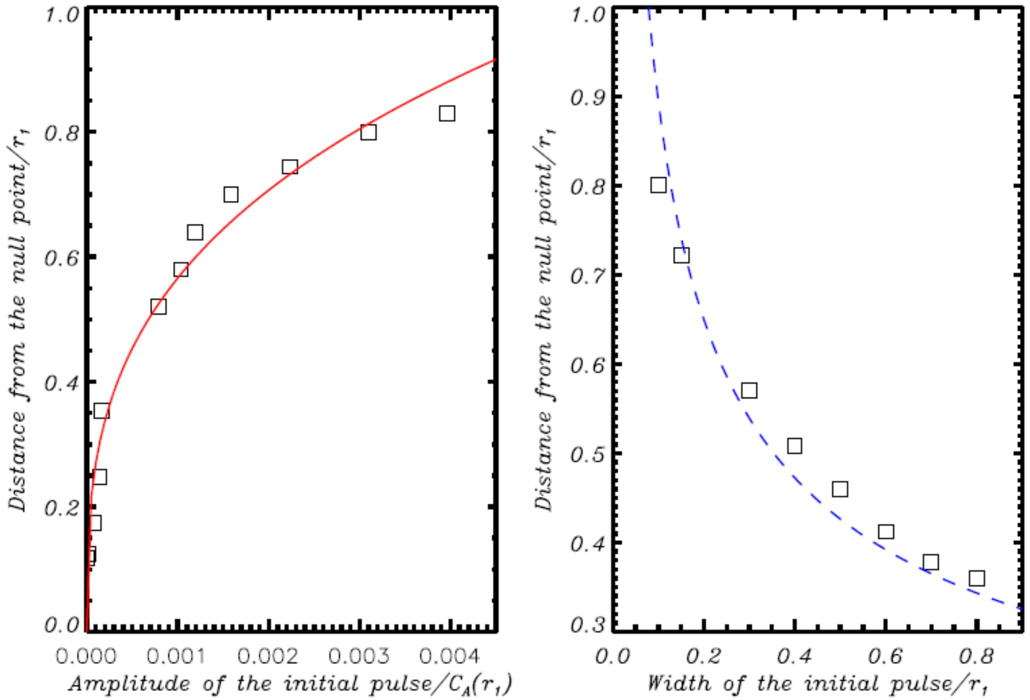


MJ+2009



MJ+2009

G+2011



Circular fast wave in cold plasma

Gruszecki et al. (2011) – Non-linear waves

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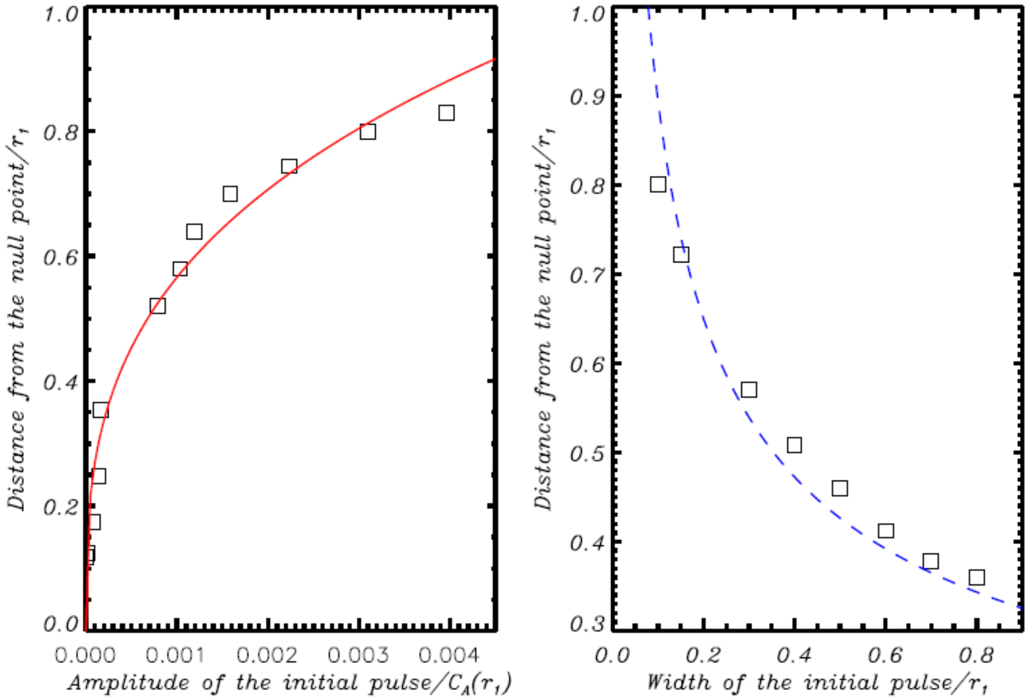
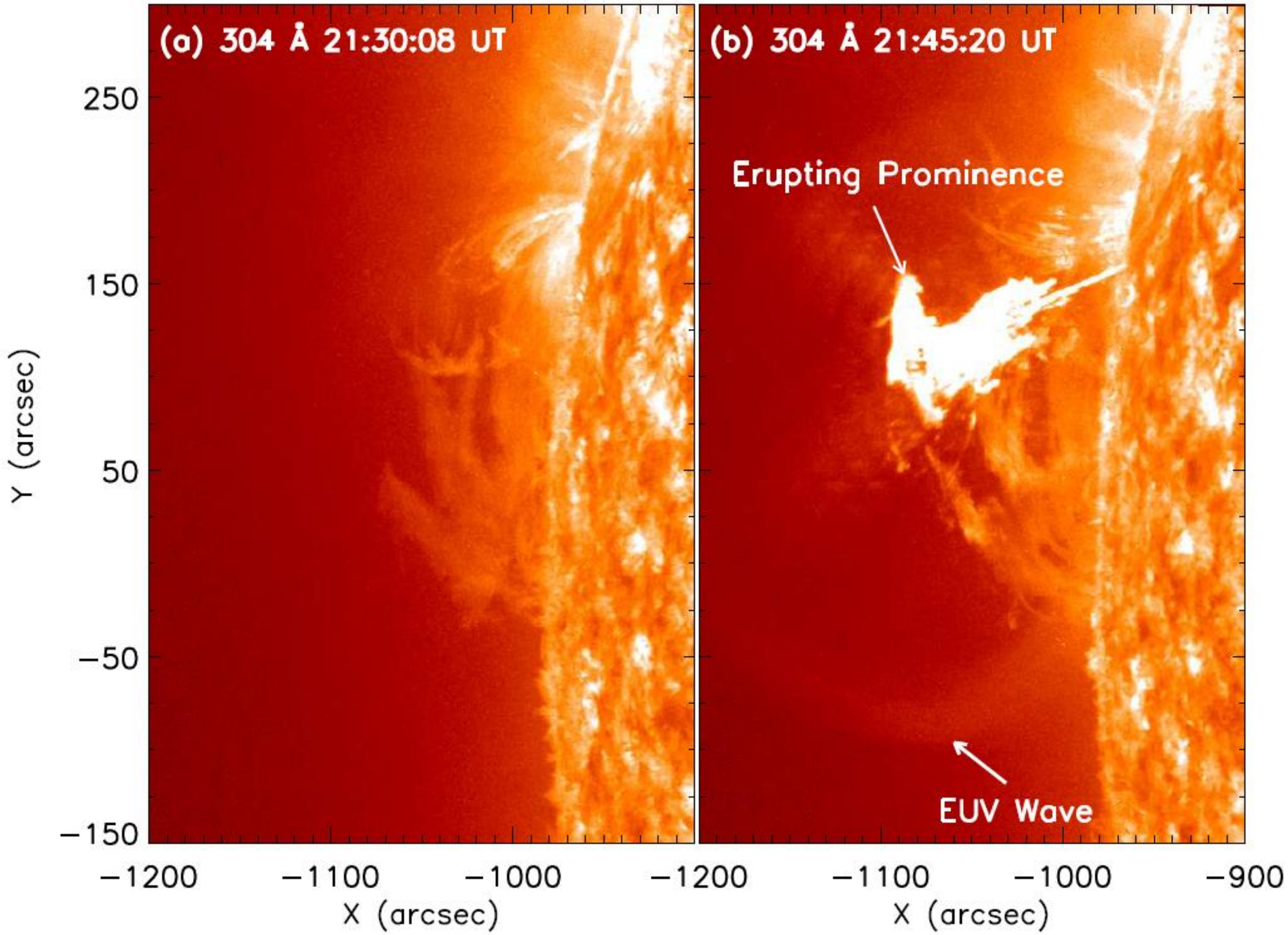


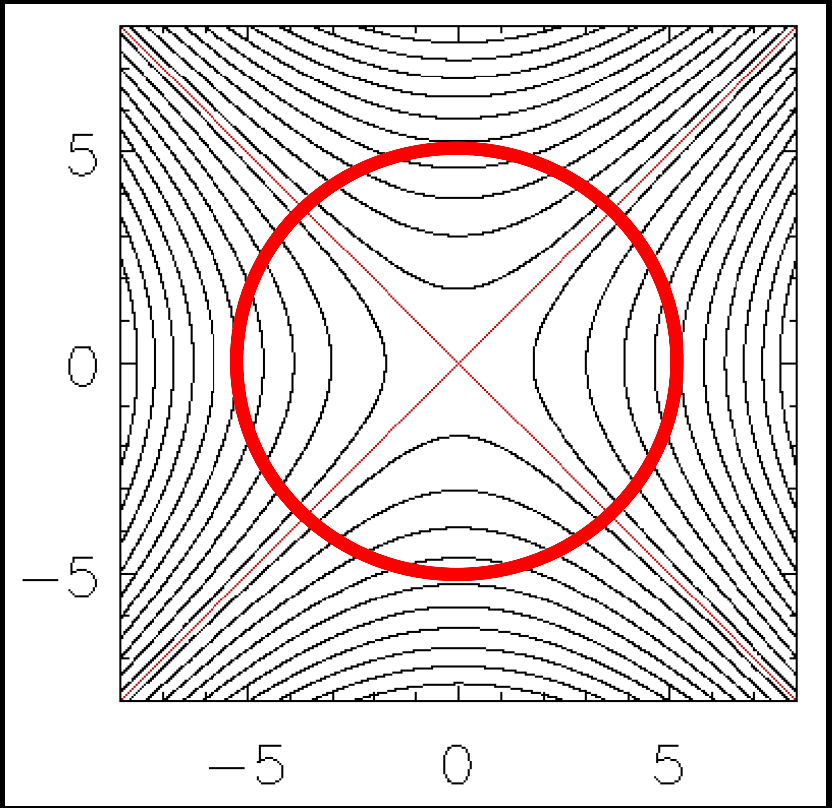


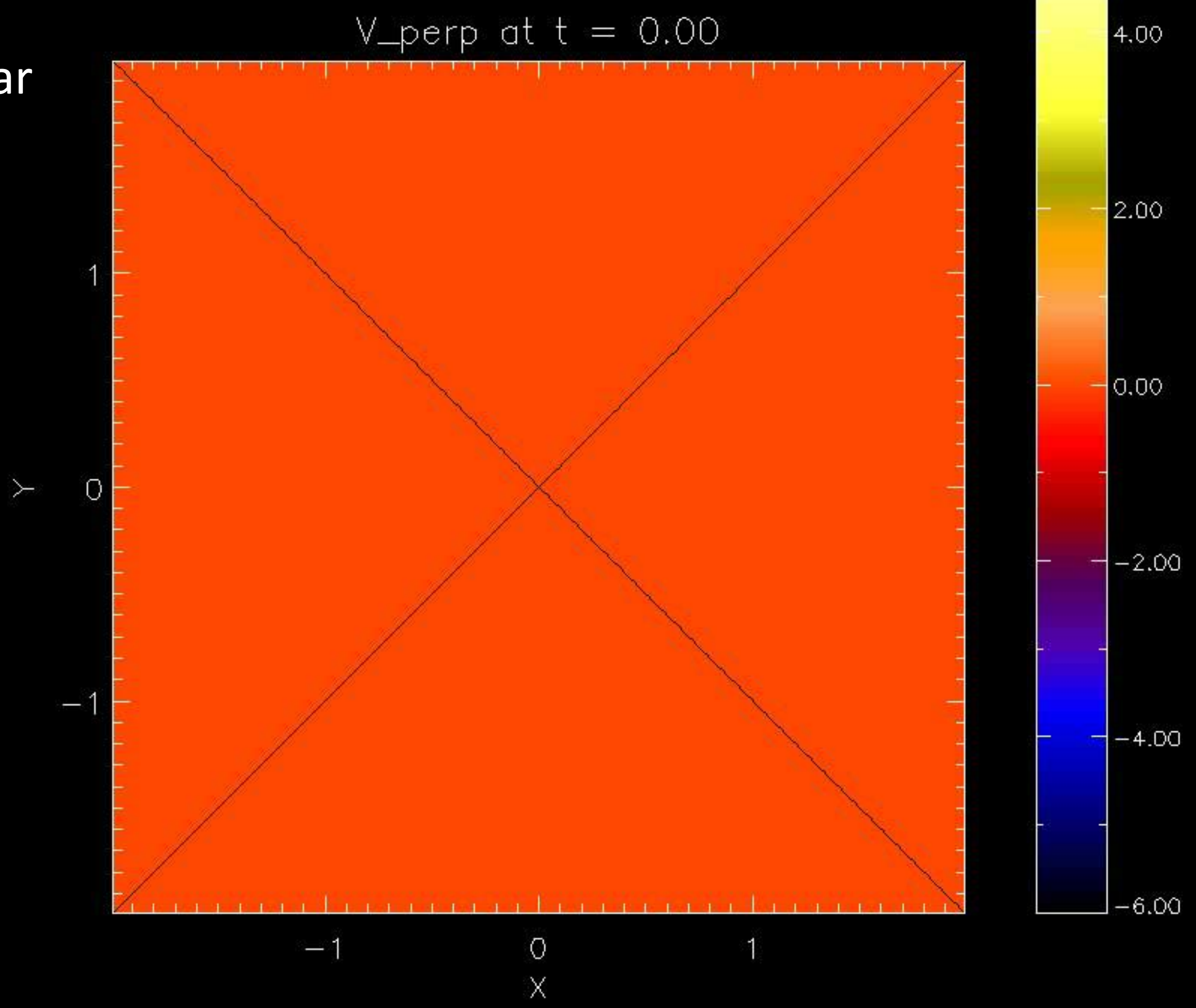
From Chandra, Chen, Devi et al. (2021). Prominence eruption and leading edge the EUV wave, as seen by SDO/AIA 304 A° .

Circular fast wave in cold plasma

McLaughlin et al. 2009

- 2D X-point magnetic field configuration
- Annulus velocity pulse, component perpendicular to the magnetic field – fast wave pulse.





Circular fast wave in cold plasma

McLaughlin et al. 2009

- 2D X-point magnetic field configuration
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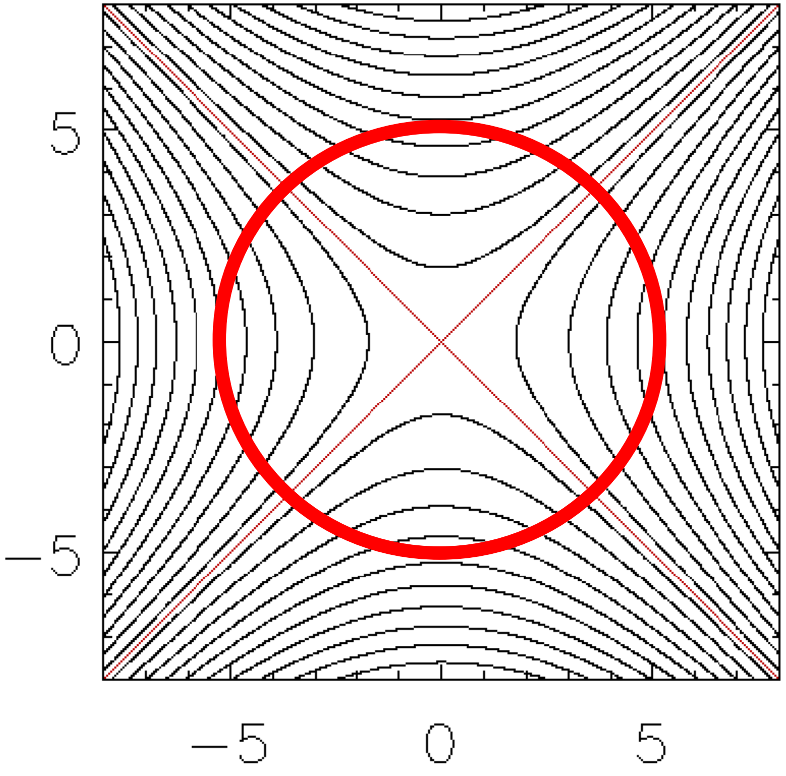
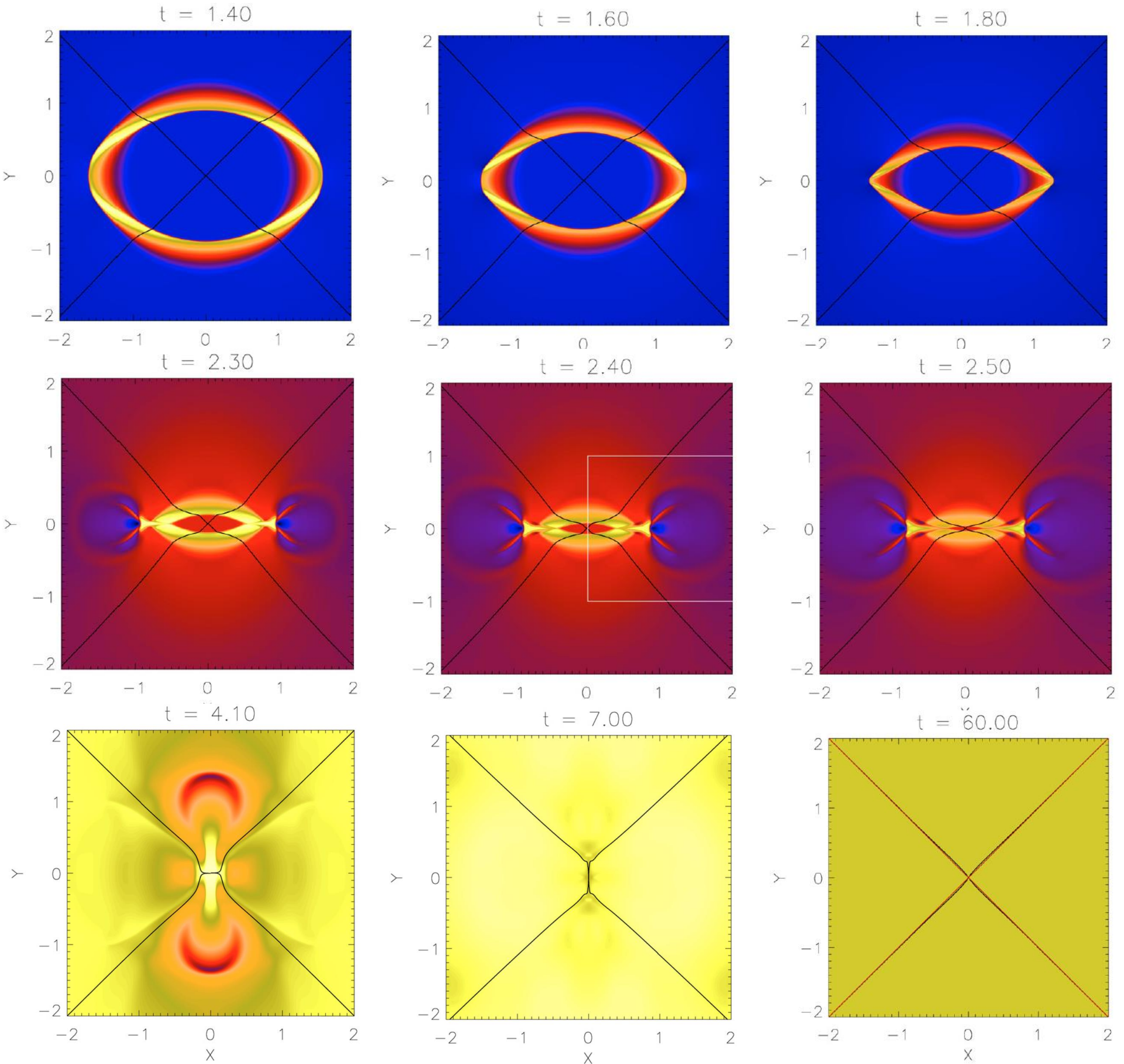




Oscillatory Reconnection (O.R.)

- Craig & McClymont (1991): free magnetic energy dissipated by **oscillatory reconnection** in a 2D X-point.
- Periodic changes in magnetic connectivity of 2D X-points/3D null points.
- The periodicity is not imposed by the driver.

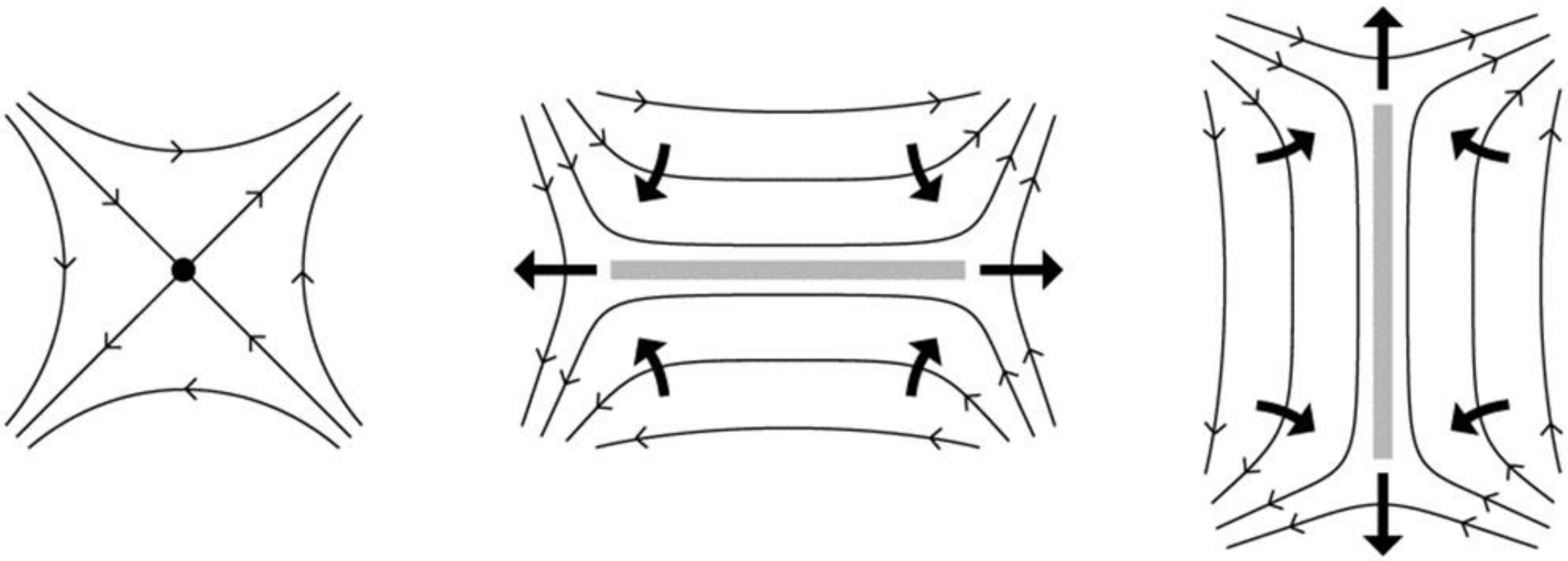
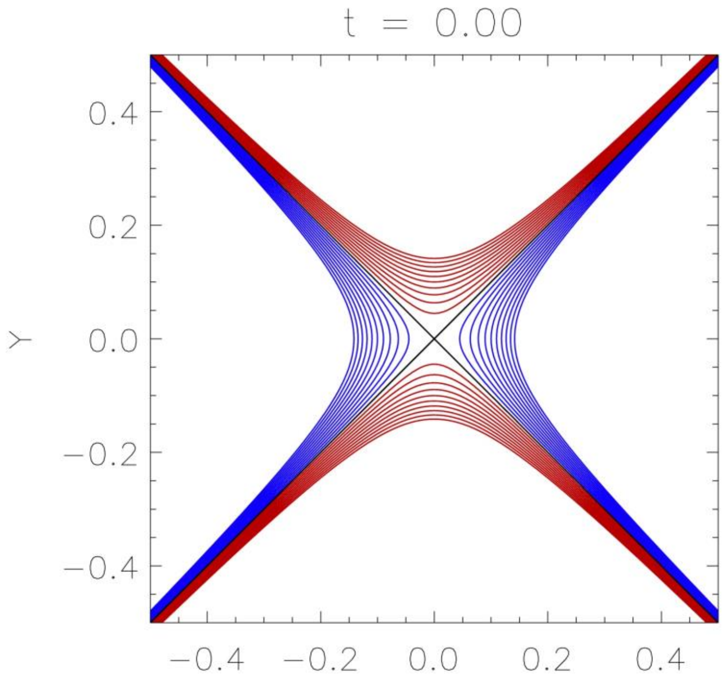


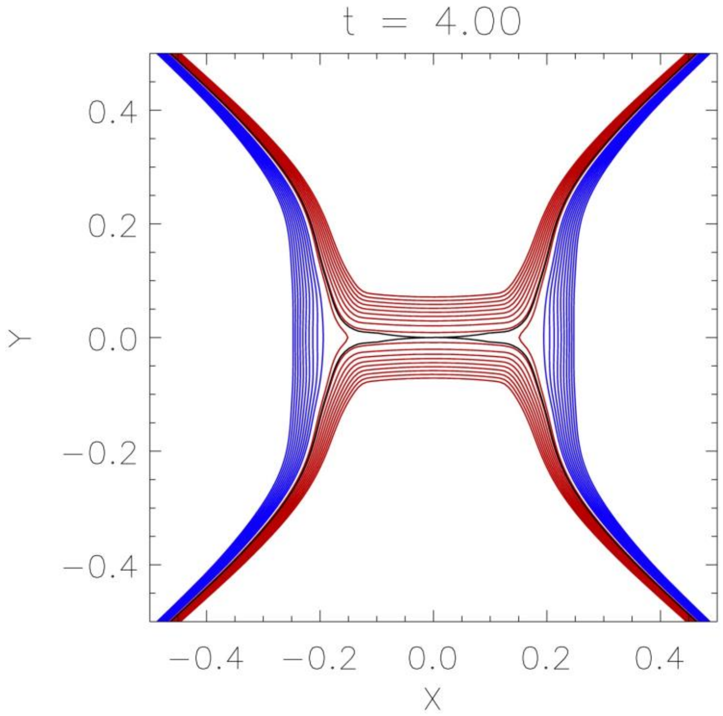
Figure. Schematic representation of the formation of the current sheet and the initiation of oscillatory reconnection.

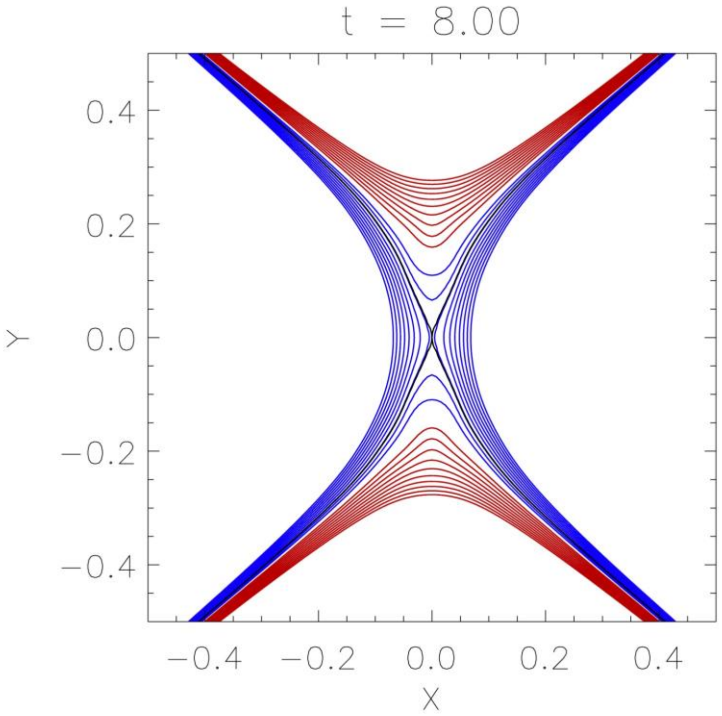
Oscillatory Reconnection (O.R.)

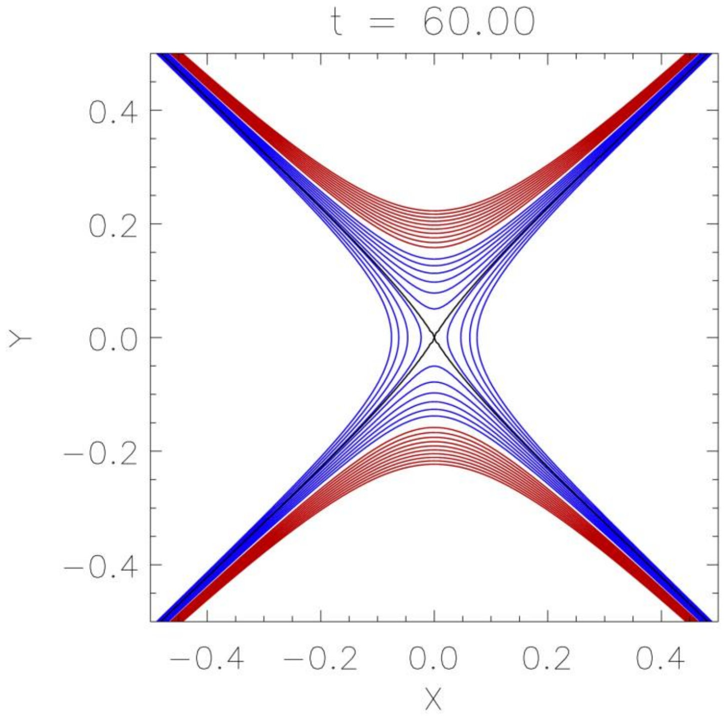
From McLaughlin et al. (2009).

- Field-lines of a perturbed X-point.
- Regions with opposite polarity are shown in red and blue.
- Separatrices are plotted in black.
- Clear signs of the changing magnetic topology. – **Reconnection!**





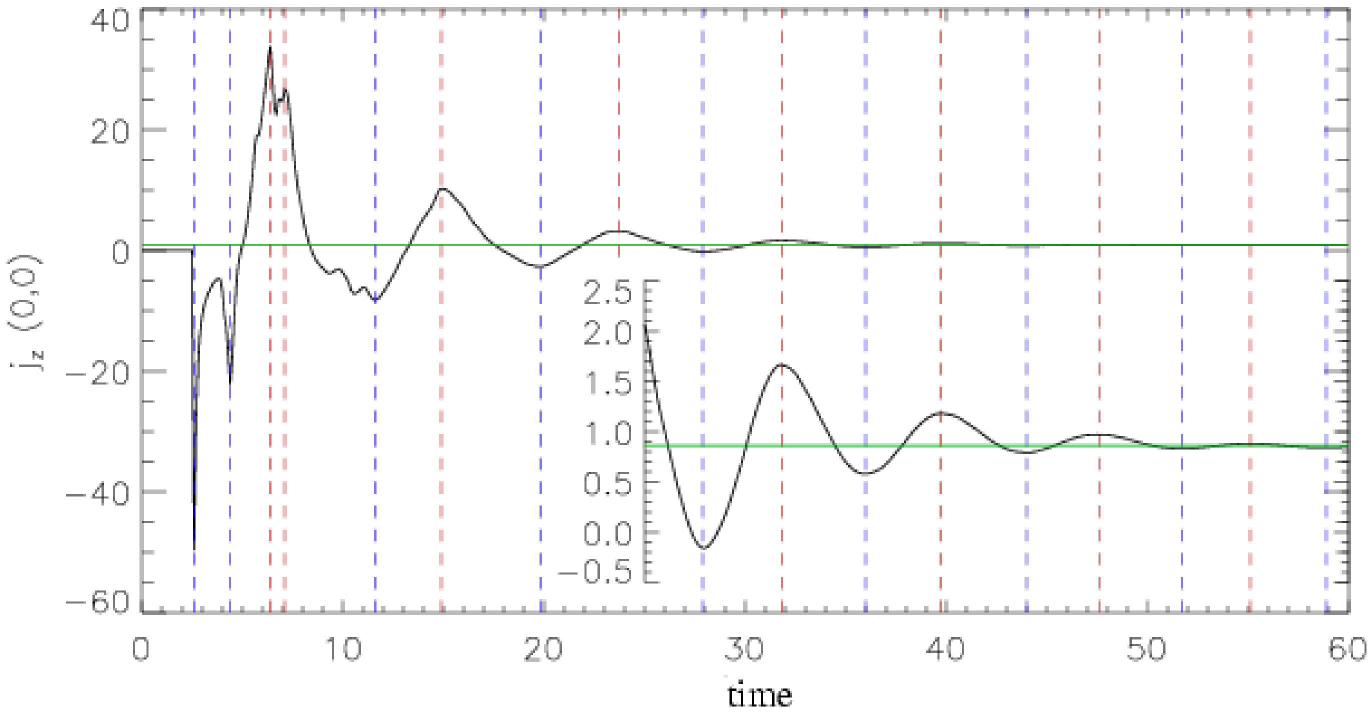


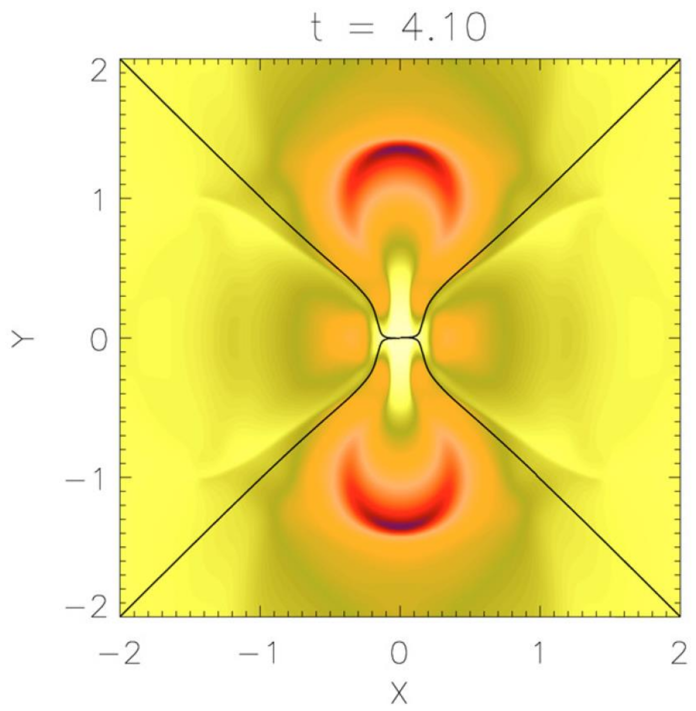


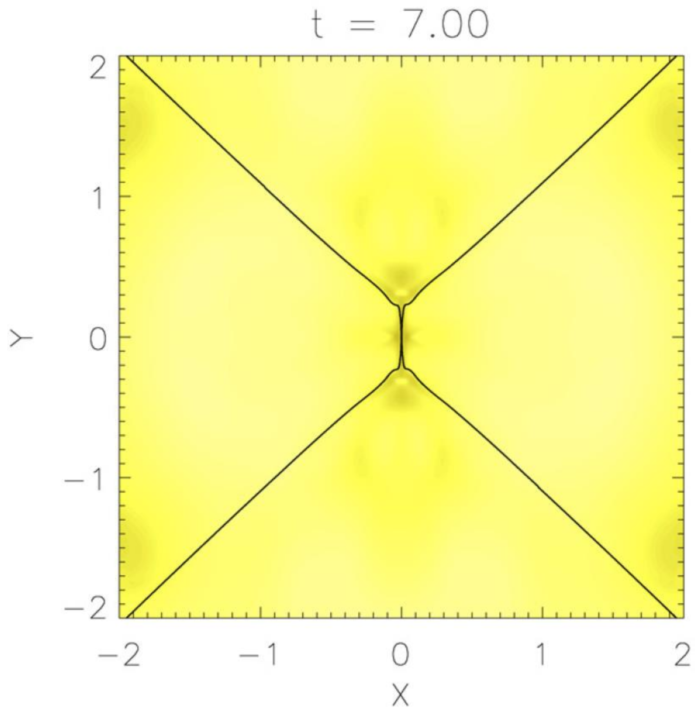
Oscillatory reconnection (O.R.)

McLaughlin et al. 2009

- Periodic changes in the magnetic field topology.
- Periodic signal for the J_z current density at the null
- J_z associated with horizontal and vertical current sheets.



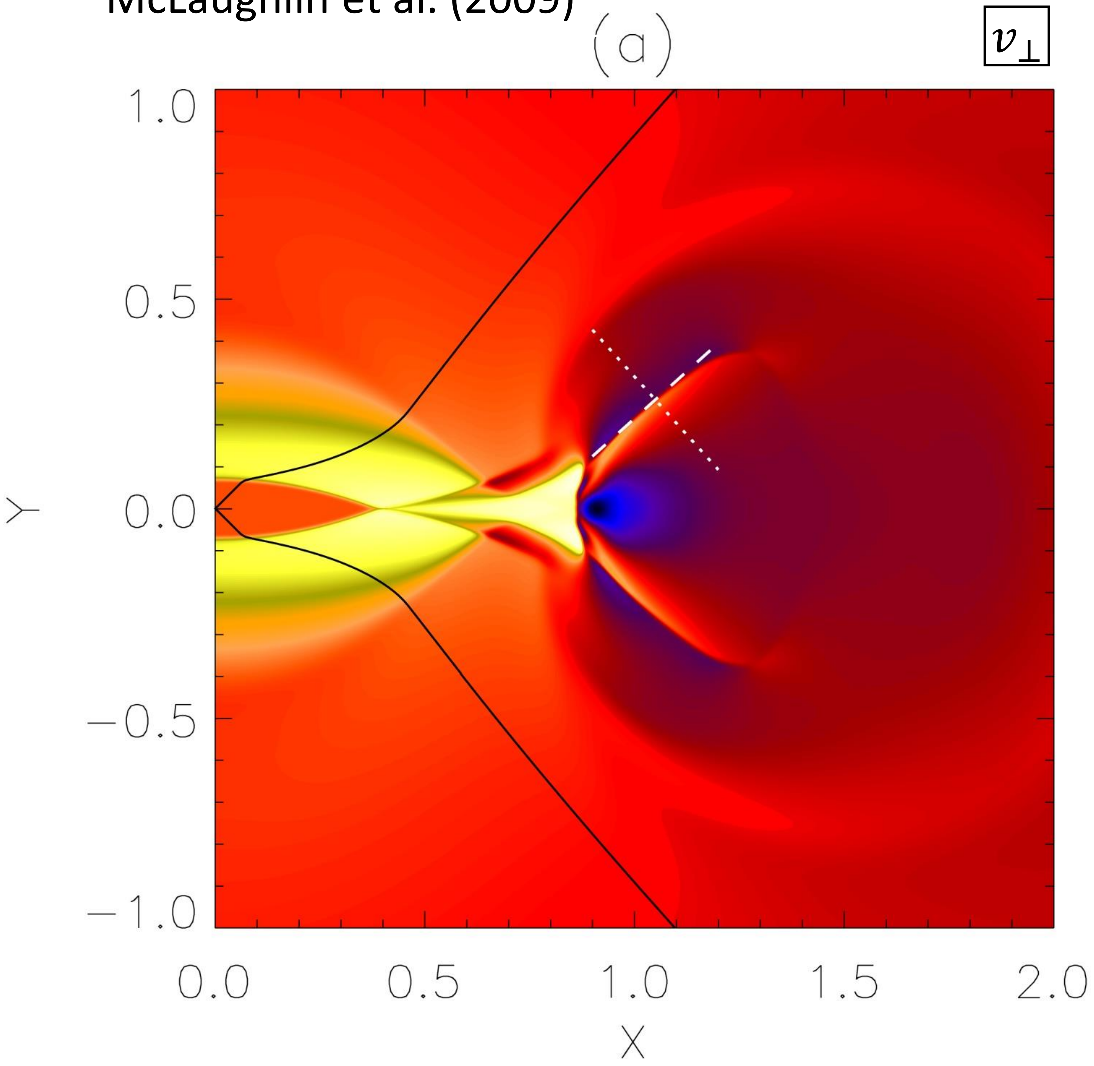




Credit: J. A. McLaughlin

Oscillatory Reconnection (O.R.)

McLaughlin et al. (2009)



Forbes, T. (1988, *Sol. Phys*, **117**, 97)

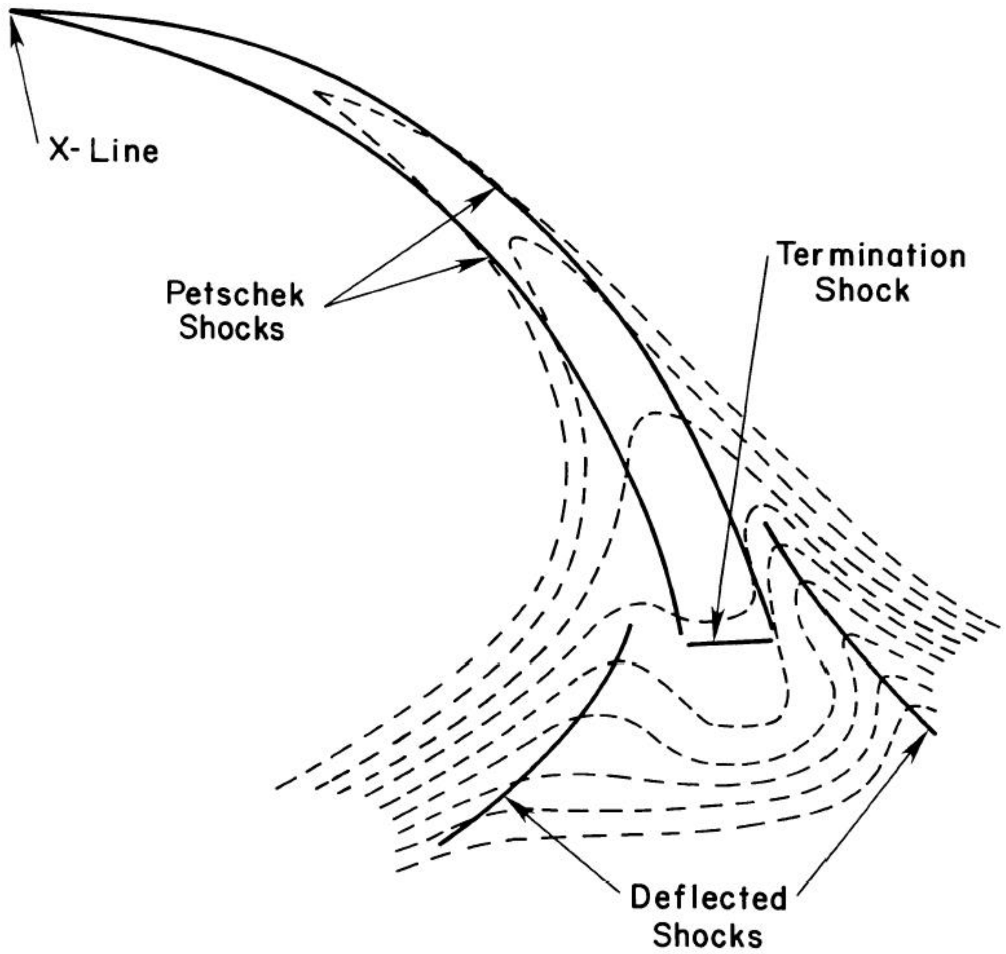
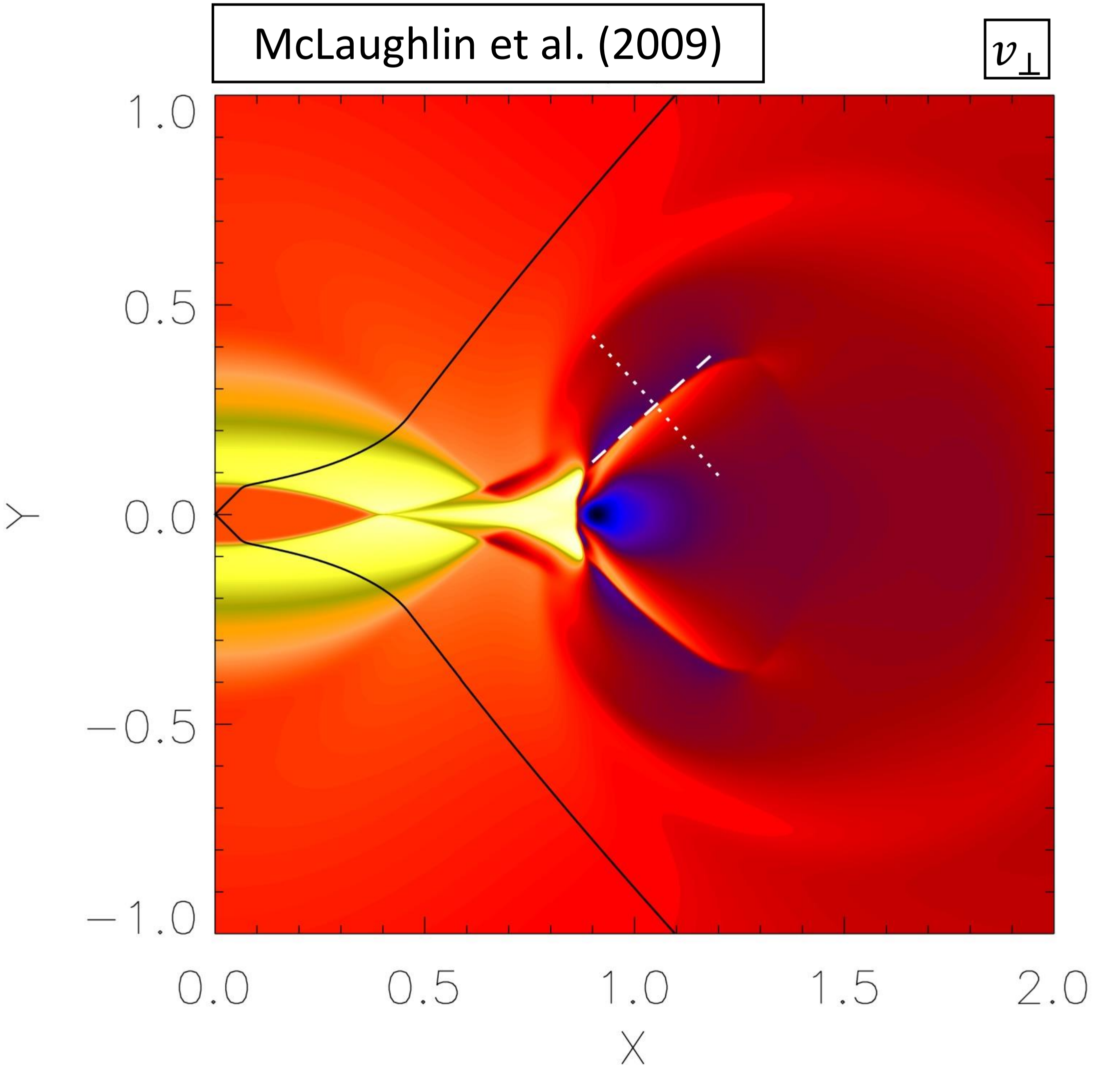
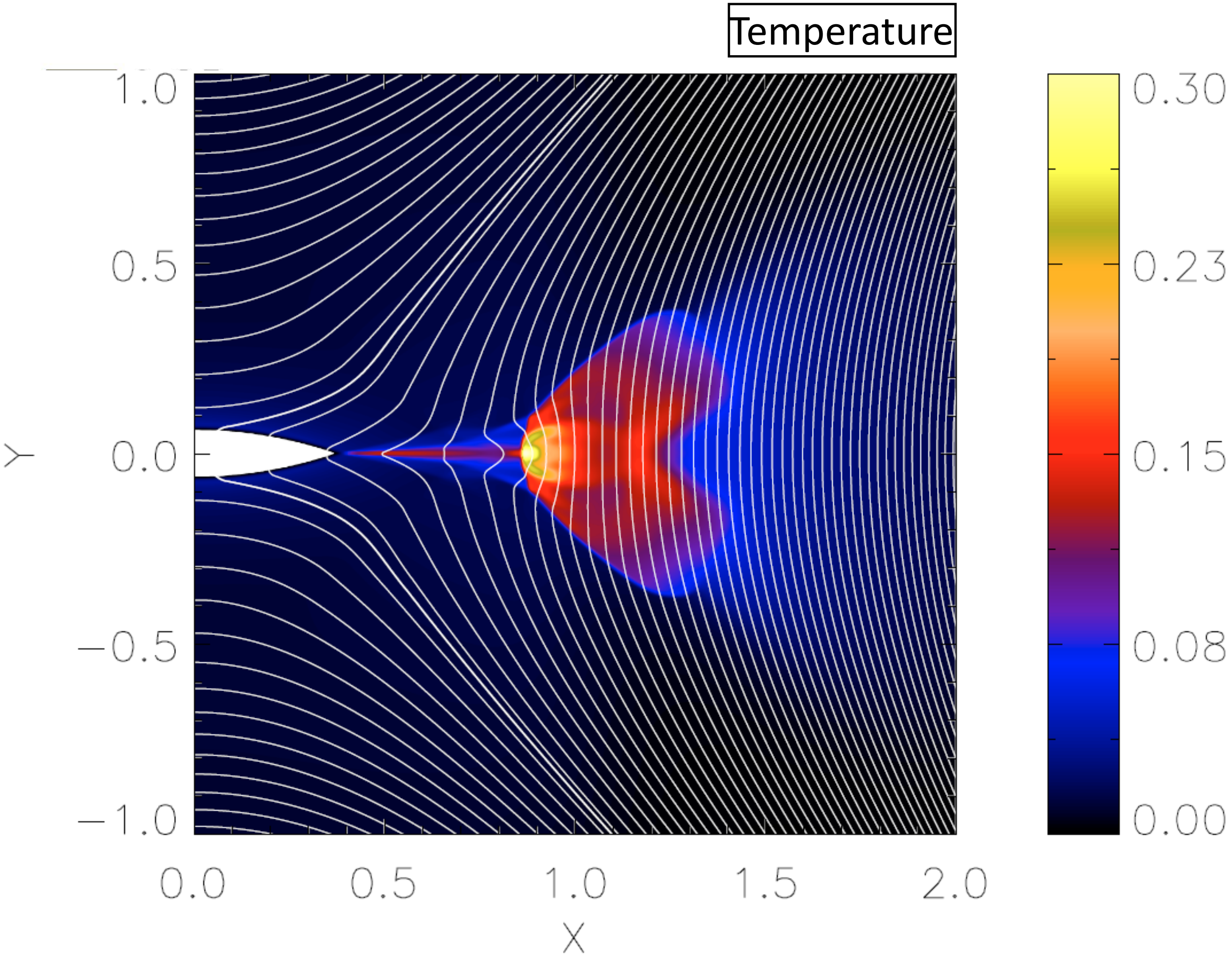


Fig. 15. Schematic diagram of shock structures surrounding the reconnection jet. 'Deflected shocks' are tentatively identified as slow-mode shocks.

Oscillatory Reconnection (O.R.)

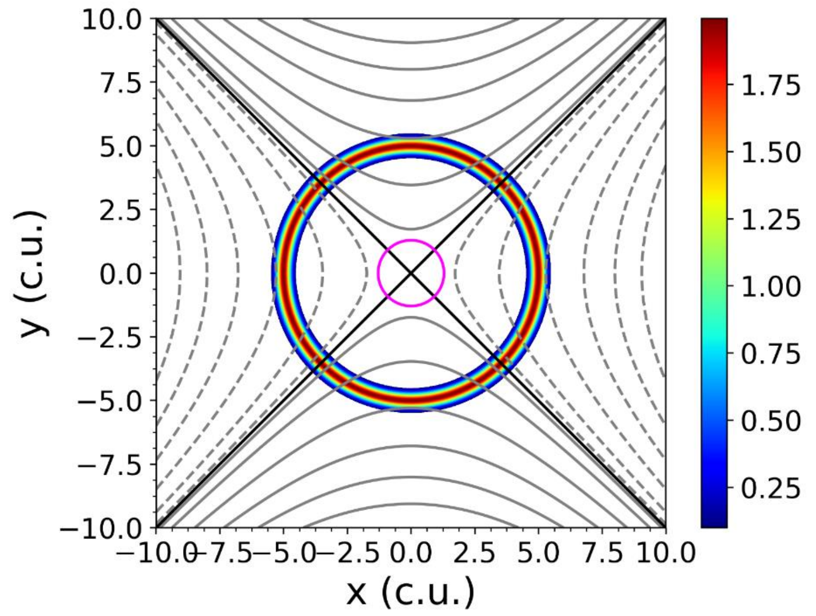


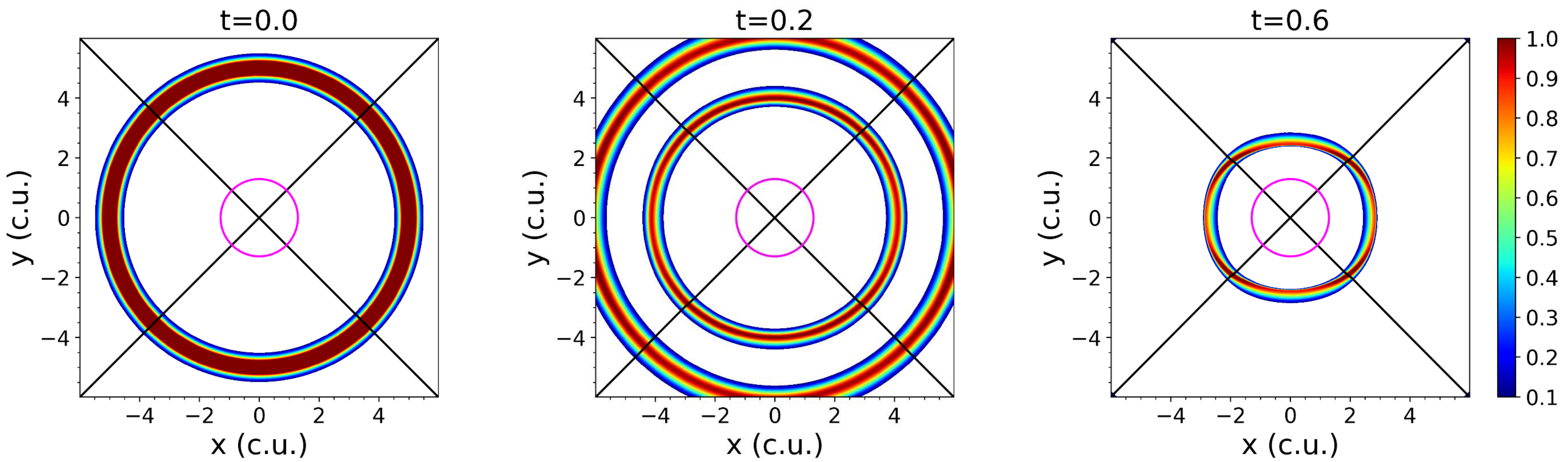


Circular fast wave in hot coronal plasma

Karampelas et al. (2022a)

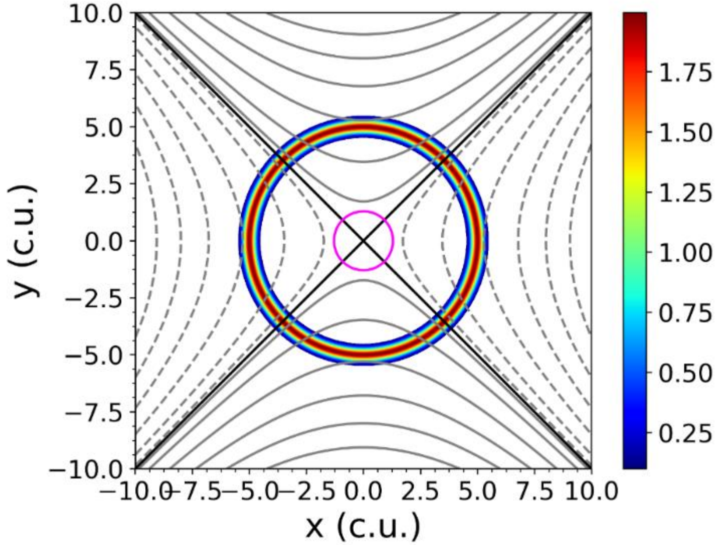
- Annulus velocity pulse – fast magnetoacoustic wave.
- 2D compressible and resistive MHD equations for $\beta \neq 0$.
- Hot coronal plasma (1 MK).
- The solution breaks away from the initial symmetry.
- Inward velocity pulse – compression and rarefaction pulses.





Circular fast wave in hot coronal plasma

1. McLaughlin & Hood (2006):
    - Linear wave in **finite-β** plasma.
    - **Crossing** the equipartition layer, a **low-β** fast wave generates **high-β** fast and slow waves.
2. Karampelas et al. 2022a
    - Non-linear, circular, fast wave in finite-β plasma.
    - Mode conversion at the equipartition layer.



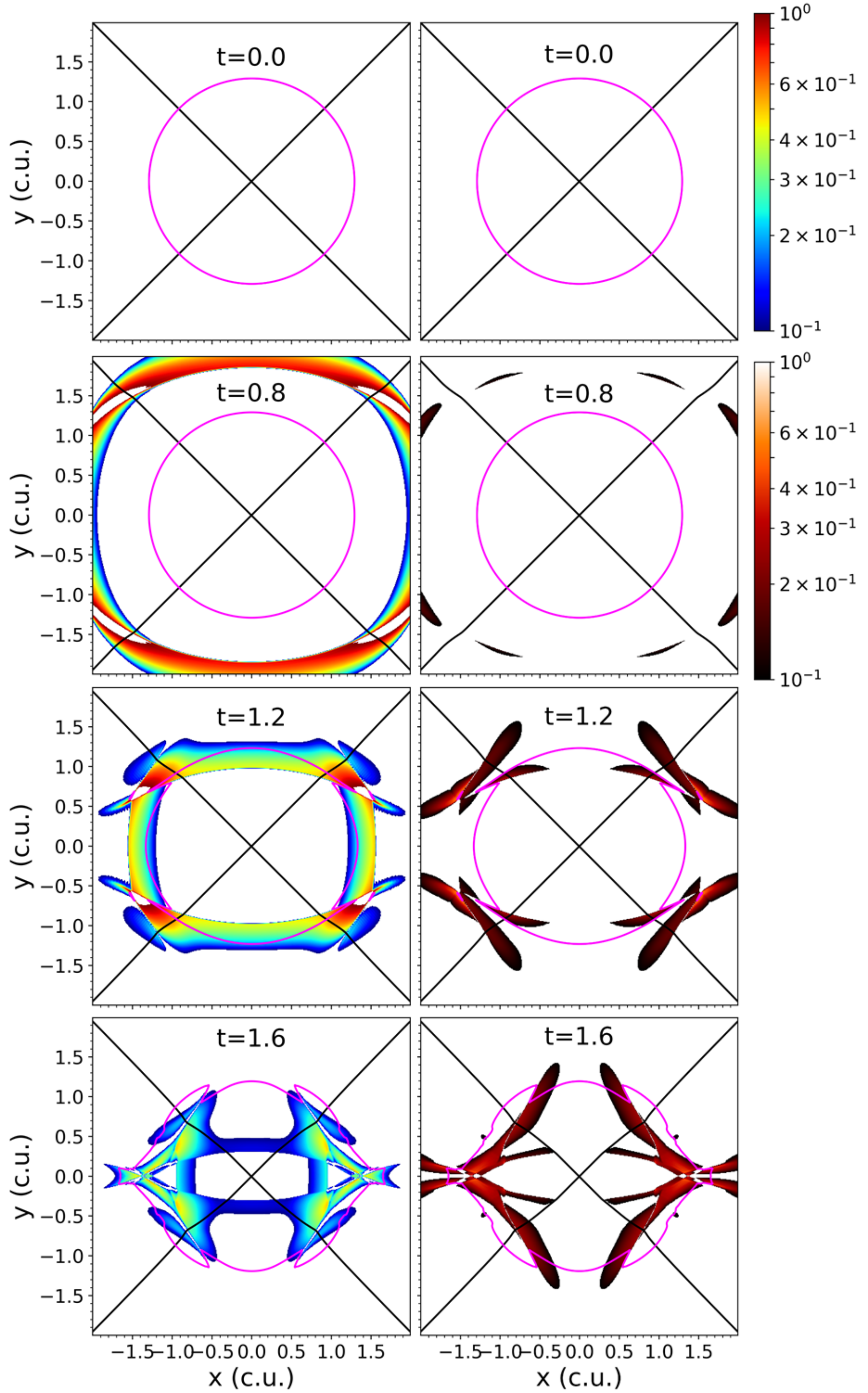


Figure. Profiles of the incoming pulse velocity **(left)** perpendicular to the magnetic field (fast wave) and **(right)** longitudinal to it (slow wave). The $V_A = C_S$ (magenta) layer is also shown.

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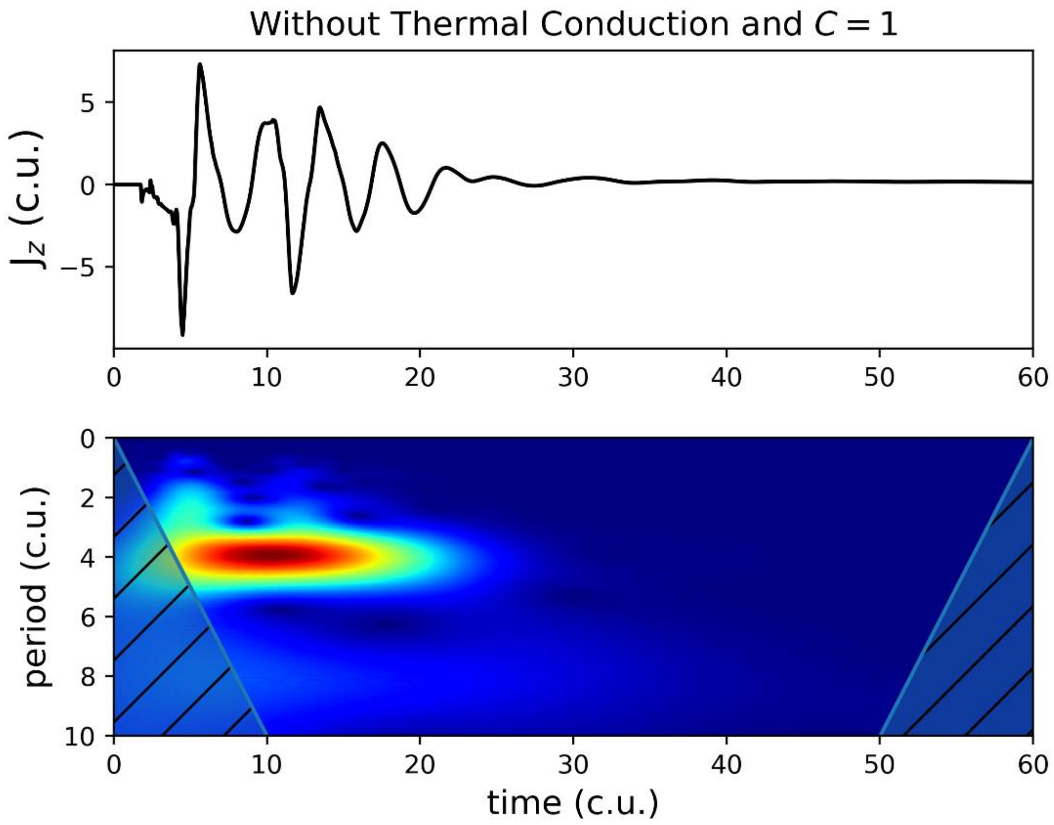
Oscillatory Reconnection in a hot plasma

Karampelas et al. (2022a):

- O.R. manifests in hot coronal plasma.
- First demonstration for a 2D X-point.
- Use of different code (PLUTO) – Not a numerical effect.
- Thermal conduction does not suppress the mechanism.
- Robust mechanism, that can be tailored to different periods.

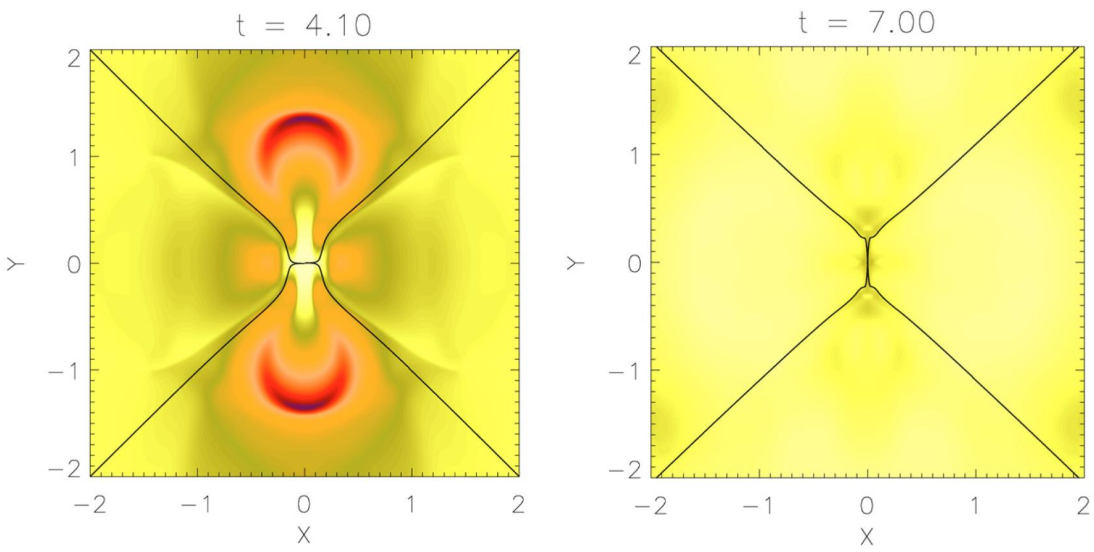


Karampelas et al. (2022b)

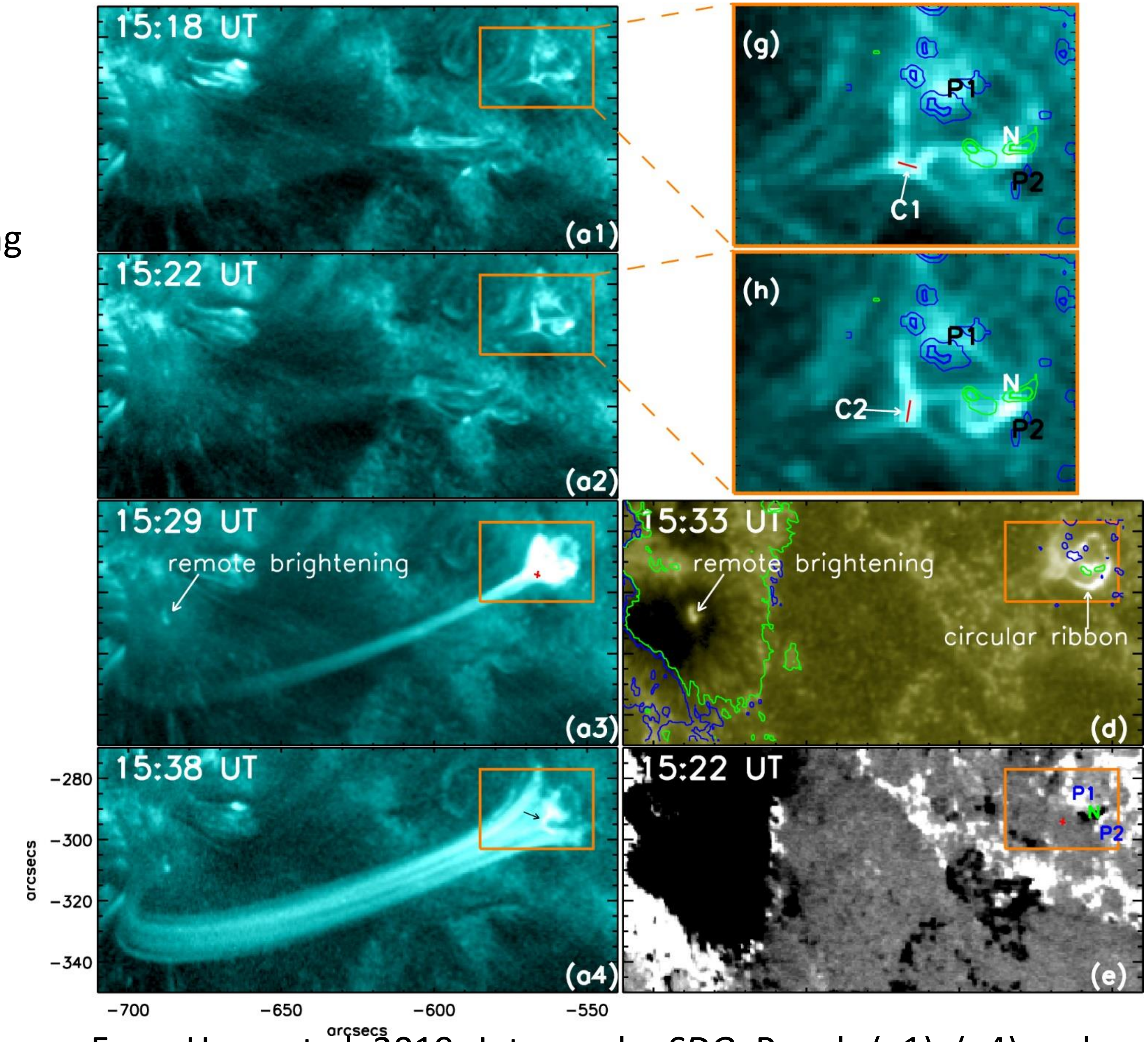
Oscillatory reconnection

Hong et al. 2019:

- jet produced by eruption of two minifilaments lying at the jet base



McLaughlin et al 2009



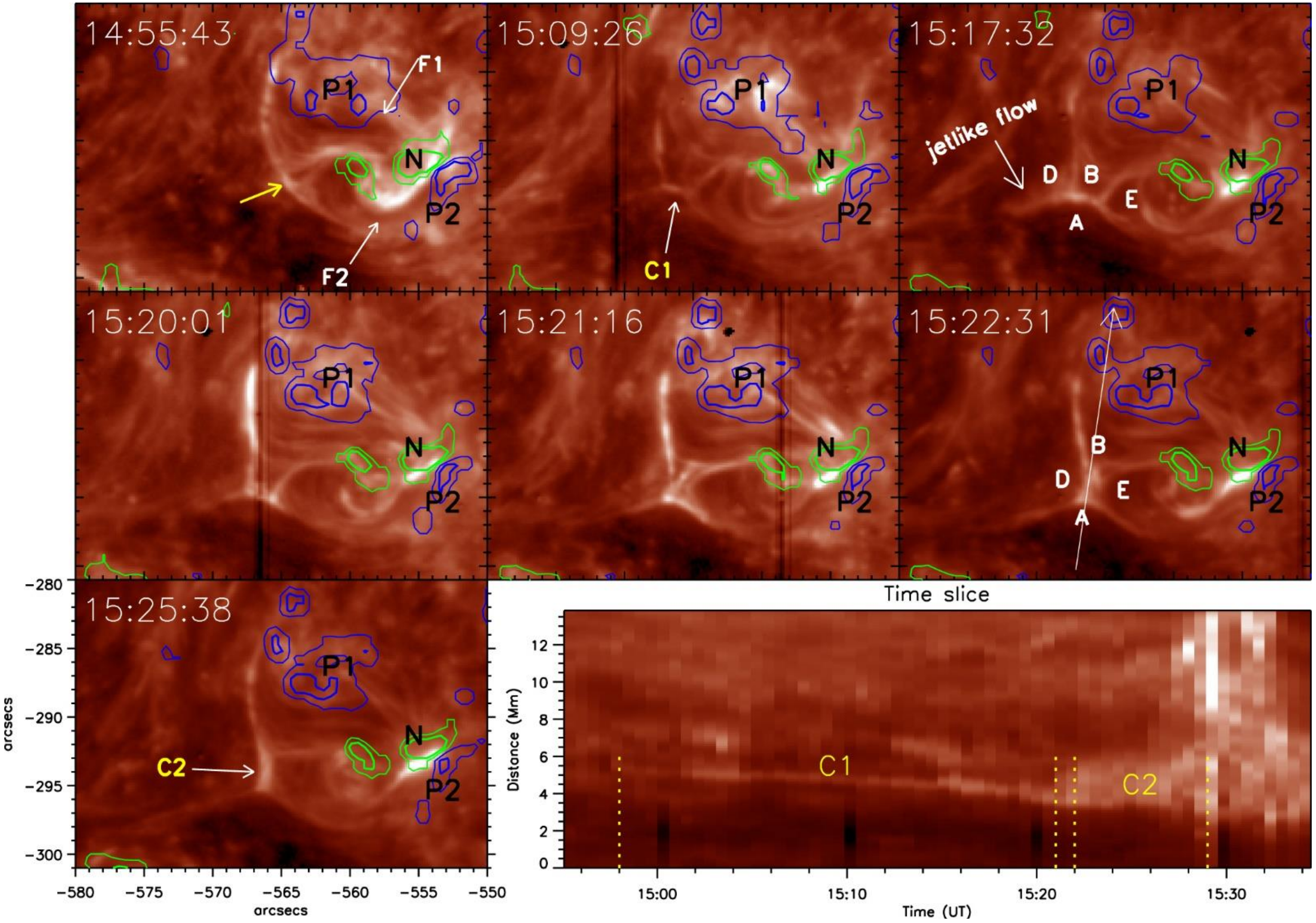
From Hong et al. 2019: Jet seen by *SDO*. Panels (a1)–(a4) and (g)-(h) are in AIA 131 Å. Panel (d) is in AIA 1600 Å. Photospheric magnetic field is shown in HMI magnetogram (e).

Oscillatory reconnection

Hong et al. 2019:

- Jet produced by eruption of two mini-filaments lying at the jet base.
- Interchange reconnection between open and closed field (Crooker et al. 2002).
- Breakout current sheets C1 and C2.
- Reversal of breakout reconnection.
- The inflow and outflow regions become the outflow and inflow regions after the transition.
- C2 erupts the second mini-filament, igniting the jet.

Proposed evidence for oscillatory reconnection

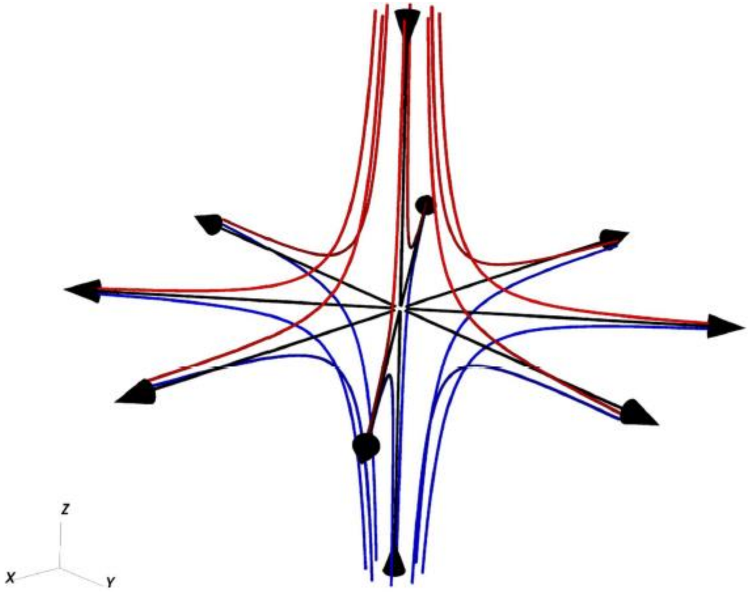


From Hong et al. 2019. C1 and C2 are possible current sheets showing reconnection reversal. IRIS/SJI 1400 °A images.

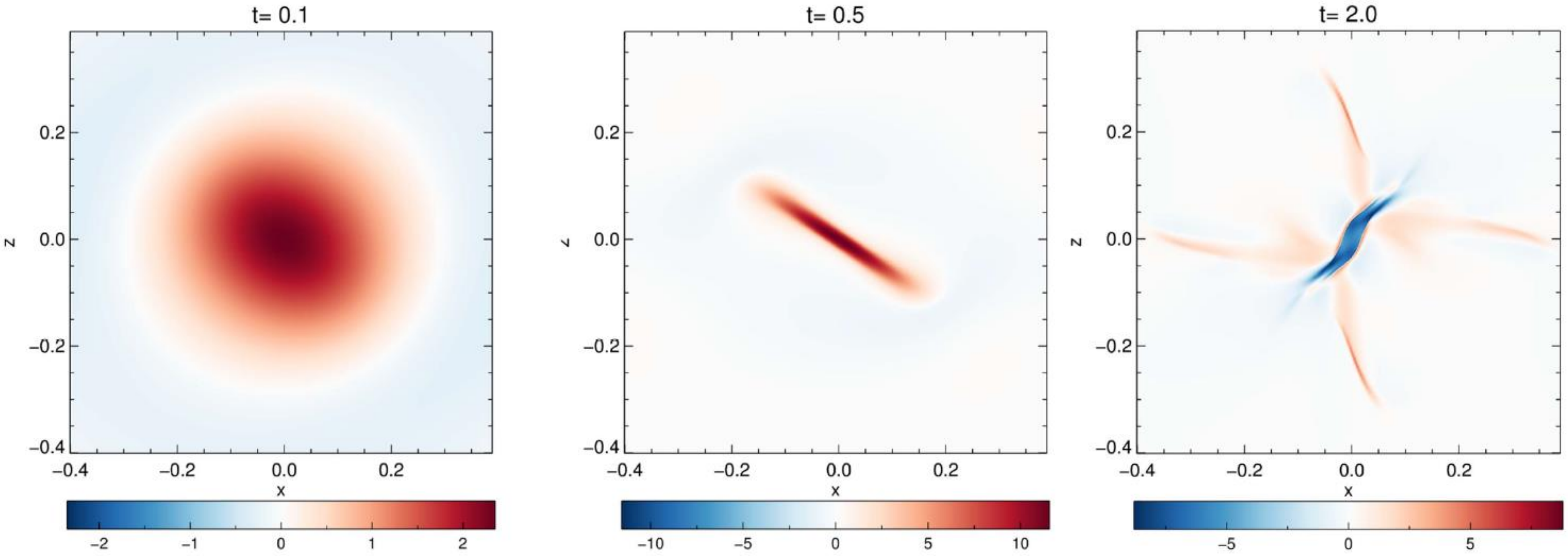
Oscillatory reconnection in 3D null points

Thurgood et al. (2017):

- 3D null point collapse due to ring current
- Oscillatory reconnection manifesting
- Wave generation due to the oscillatory process.



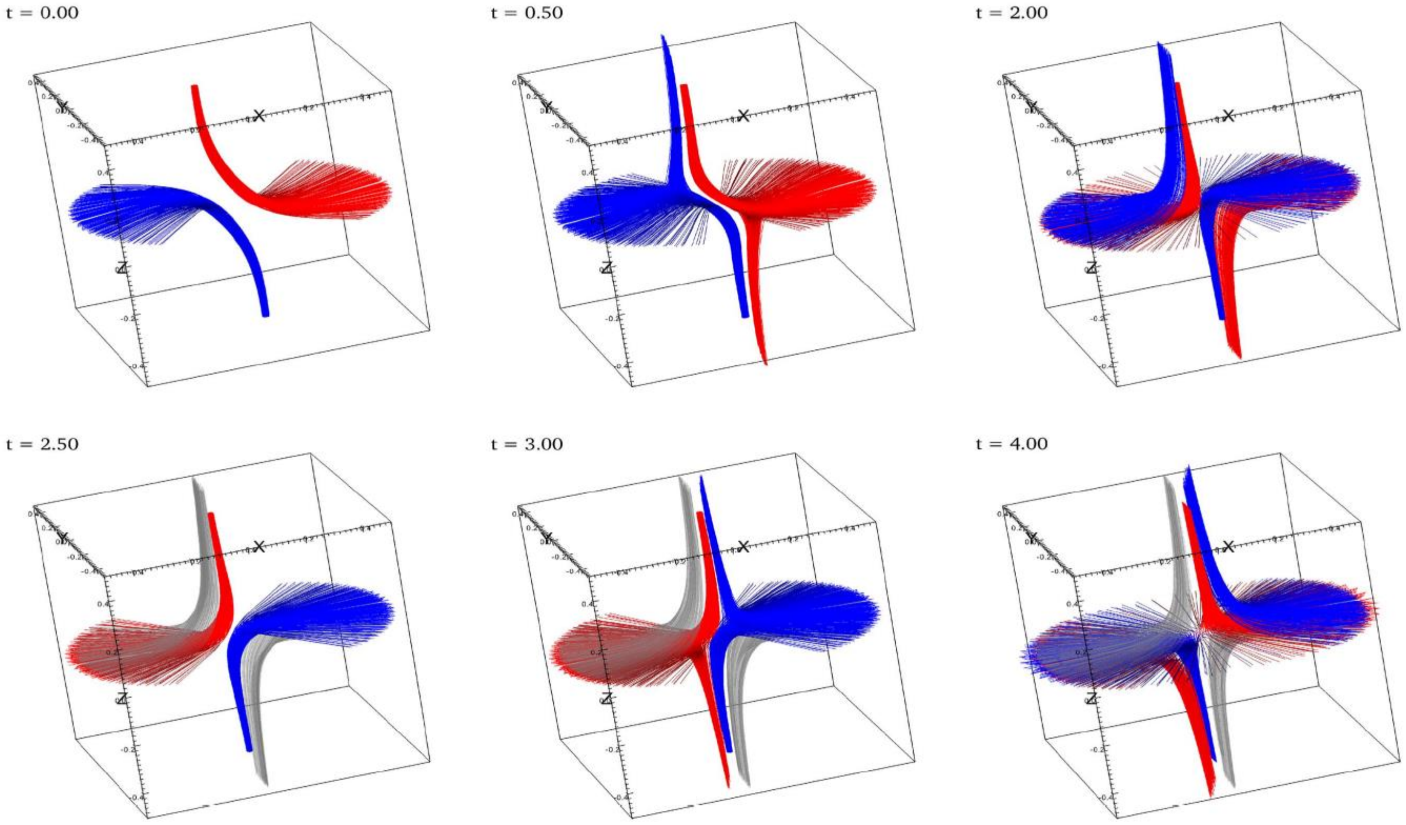
j_y current density



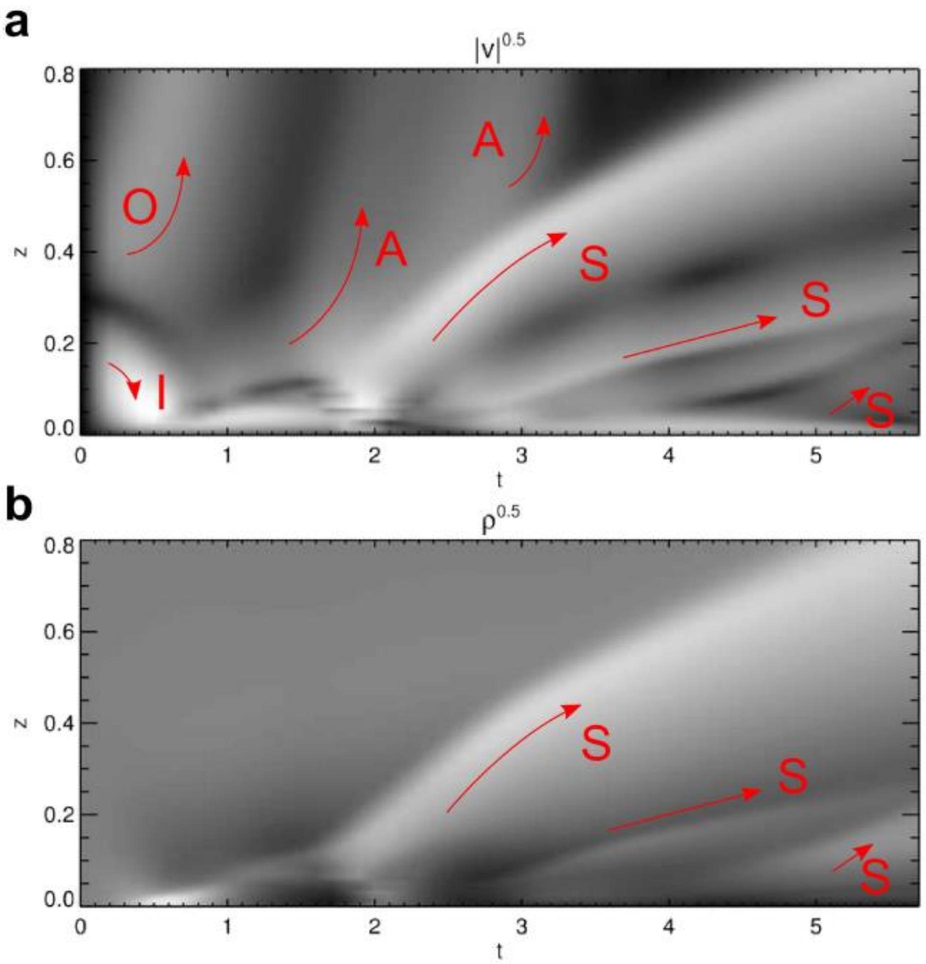
Oscillatory reconnection in 3D null points

Thurgood et al. (2017):

- Wave generation due to the oscillatory process.



Spine-fan reconnection

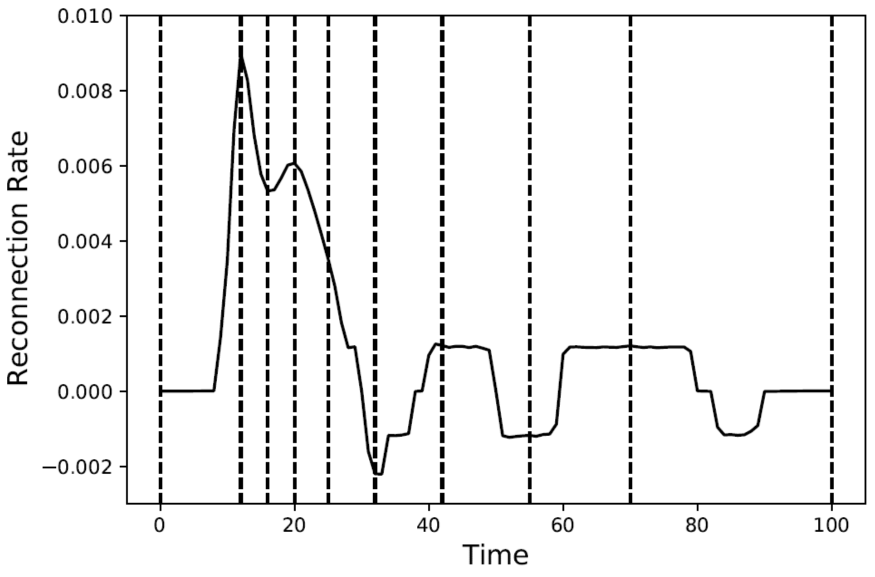


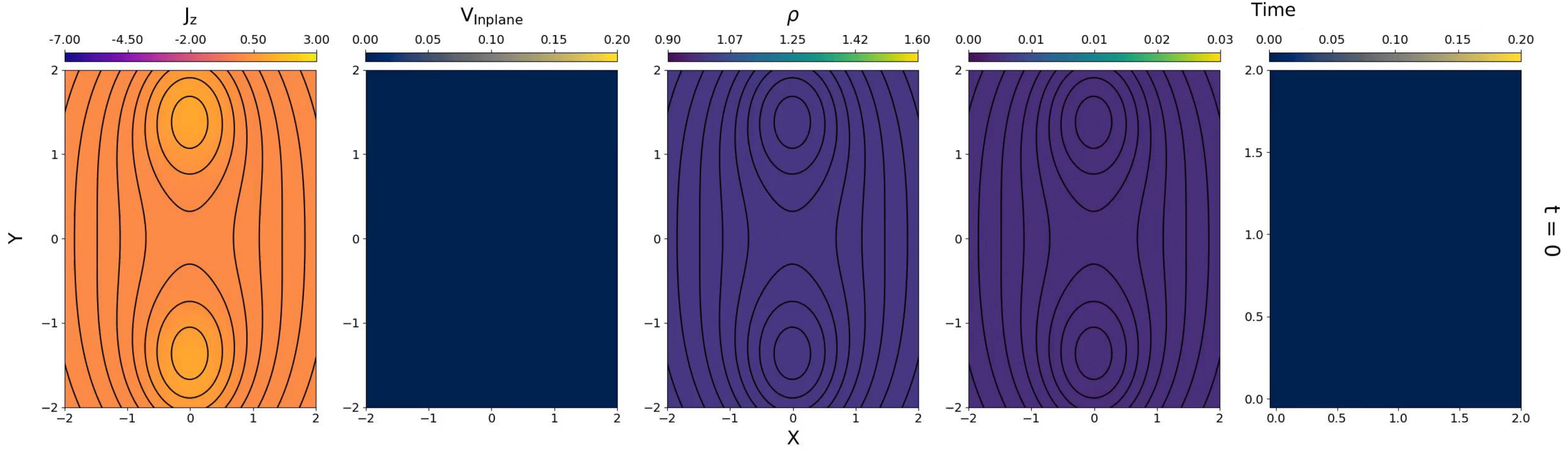
Velocity magnitude and density evolution.

Oscillatory reconnection in flux tubes

Stewart et al. (2022):

- Oscillatory reconnection from the merging of two flux tubes.
- No driver require to initiate nor sustain the process.
- The setup leads to the creation of outward-propagating waves.
- Period of waves = period of the driver (oscillatory reconnection).
- Wave periods can reveal the periodicity of O.R..





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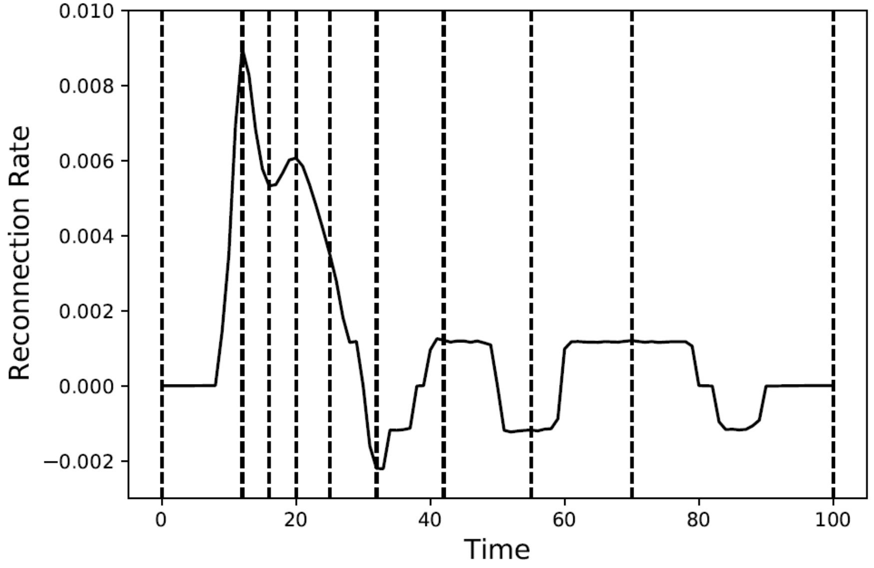
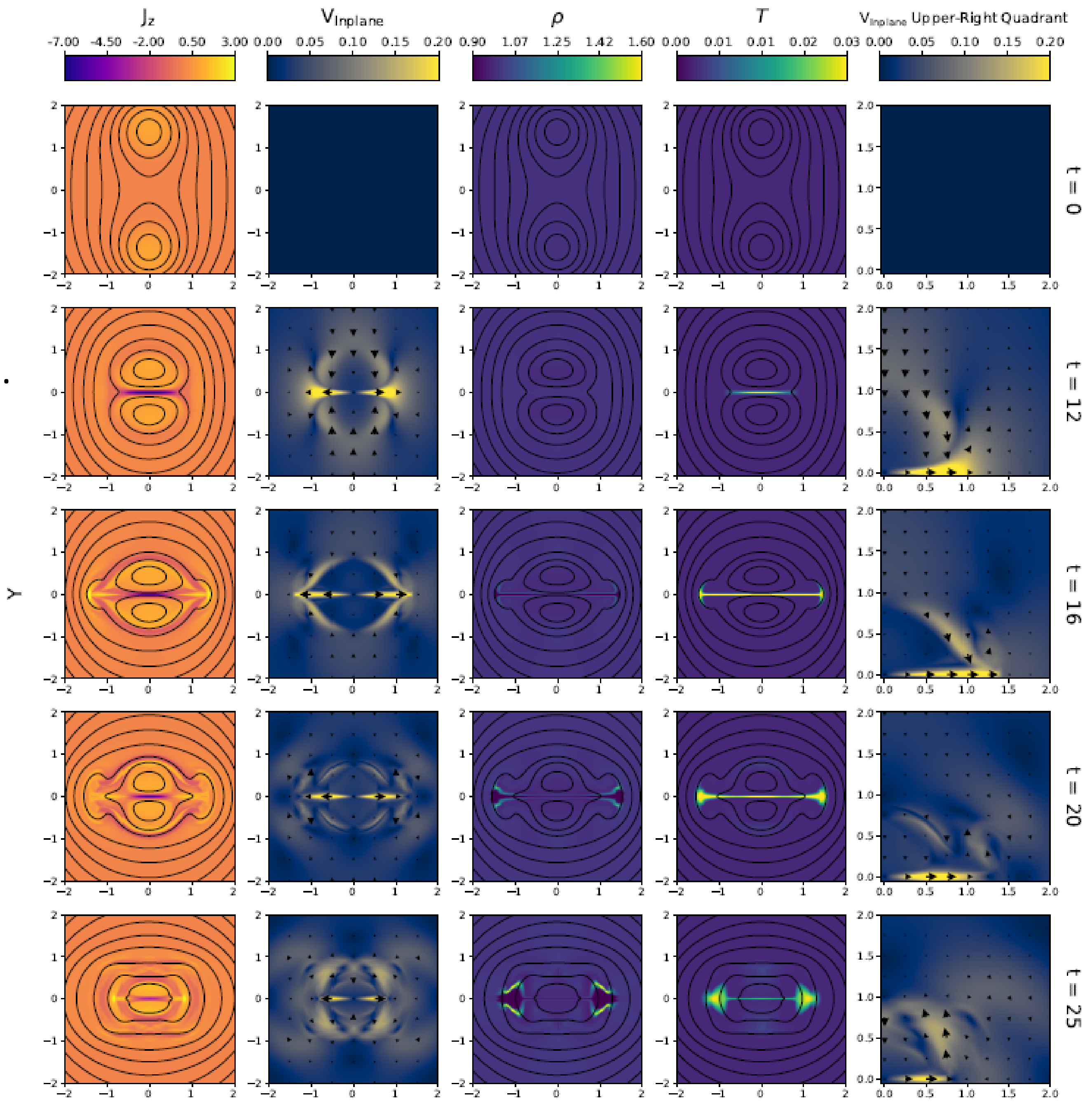
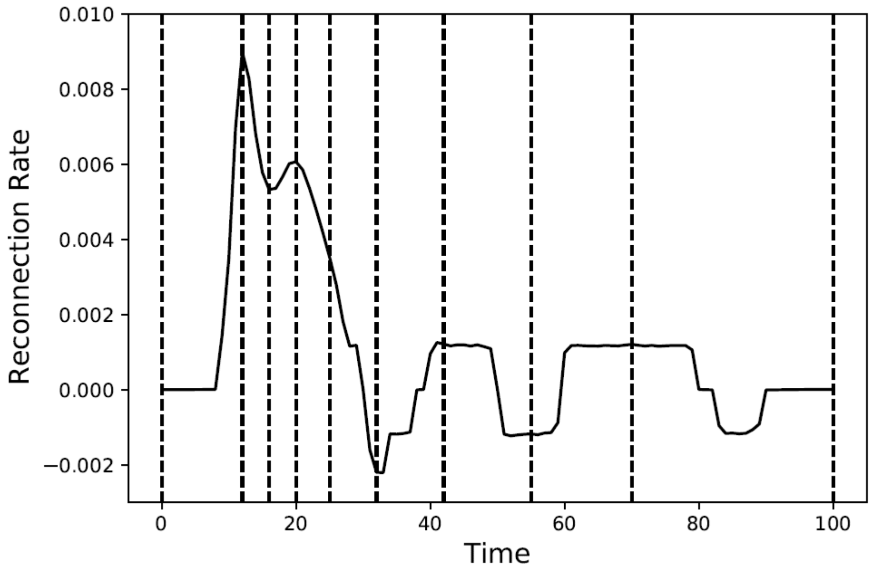




Oscillatory reconnection in flux tubes

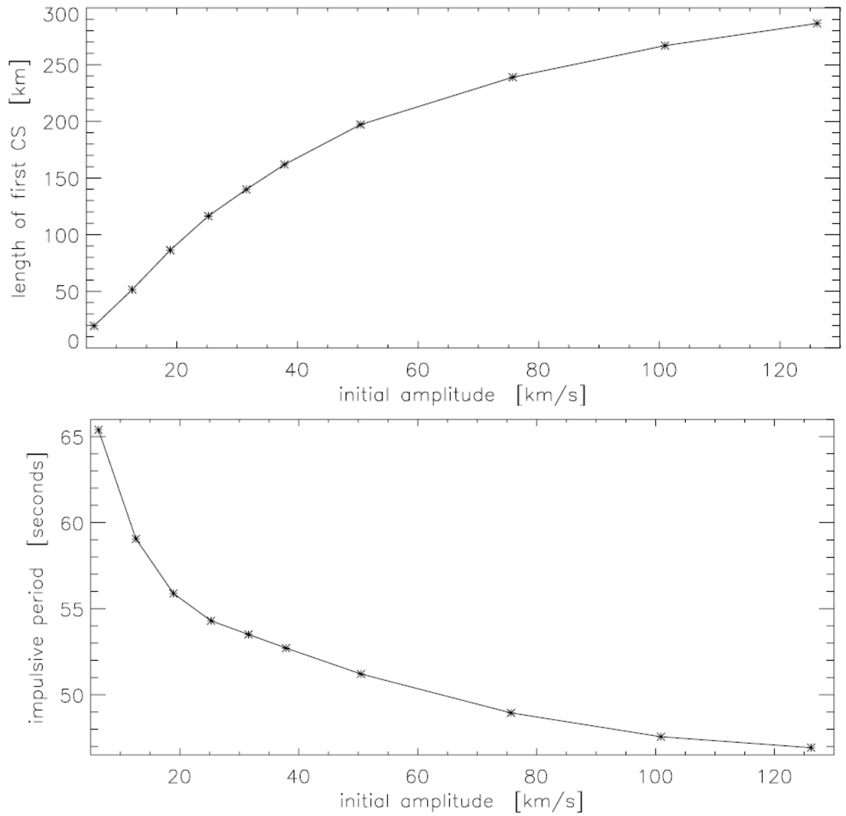
Stewart et al. (2022):

- Oscillatory reconnection from the merging of two flux tubes.
- No driver require to initiate nor sustain the process.
- The setup leads to the creation of outward-propagating waves.
- Period of waves = period of the driver (oscillatory reconnection).
- Wave periods can reveal the periodicity of O.R..

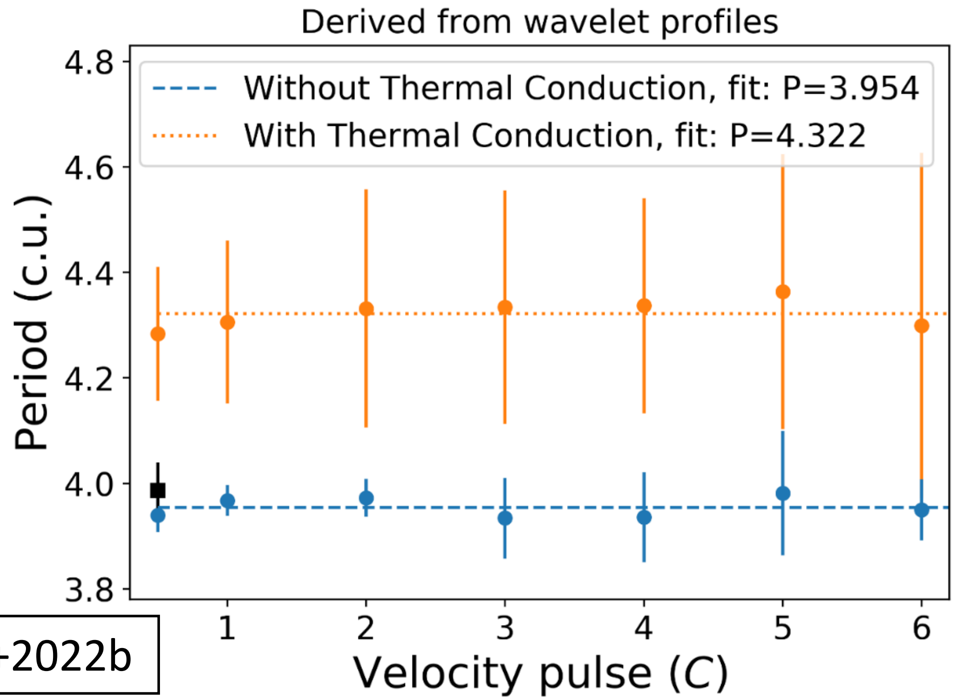


Periodicity of O.R. and the perturbing wave pulse

- McLaughlin et al. (2012b): The period of the oscillation depends on the length of the first current sheet.
- Thurgood et al. (2019): In coronal conditions, dependency upon the amplitude of J_z.
- Karampelas et al. (2022b): The period is independent from the amplitude or shape of the perturbing wave pulse!
- Useful traits for a seismological tool.



MJ+2012b



KK+2022b

Periodicity of O.R. and plasma conditions

1. McLaughlin et al (2012a):
    - Dependency upon the background magnetic field and density
2. Karampelas et al. (2022a + in prep):
    - $f(B_0) = \frac{a}{B_0} + b$, for the magnetic field
    - $f(\rho_0) = a\sqrt{\rho_0} + b$, for the density
    - $f(T) = \frac{a}{T} + b$, for the background temperature

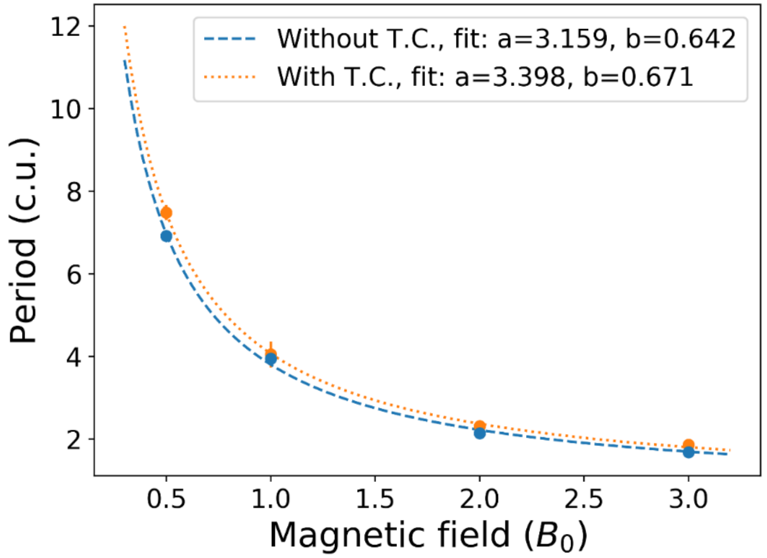
Empirical relation to be used as a seismological tool:

$$P(B_0, \rho_0, T_0) = \frac{a}{B_0} + b\sqrt{\rho_0} + \frac{c}{T_0} + D$$

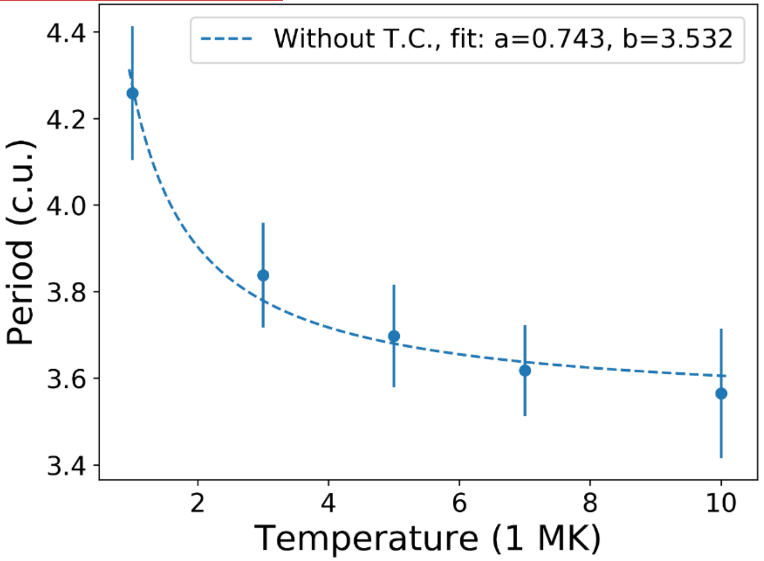
*In prep.

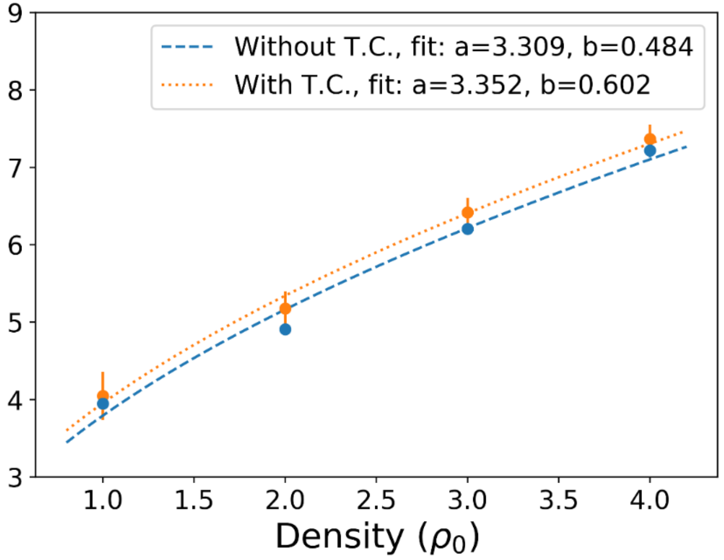
**See also, Santamaria & Van Doorsselaere. 2018

Opens up the tantalising possibility of utilising oscillatory reconnection as a seismological tool!



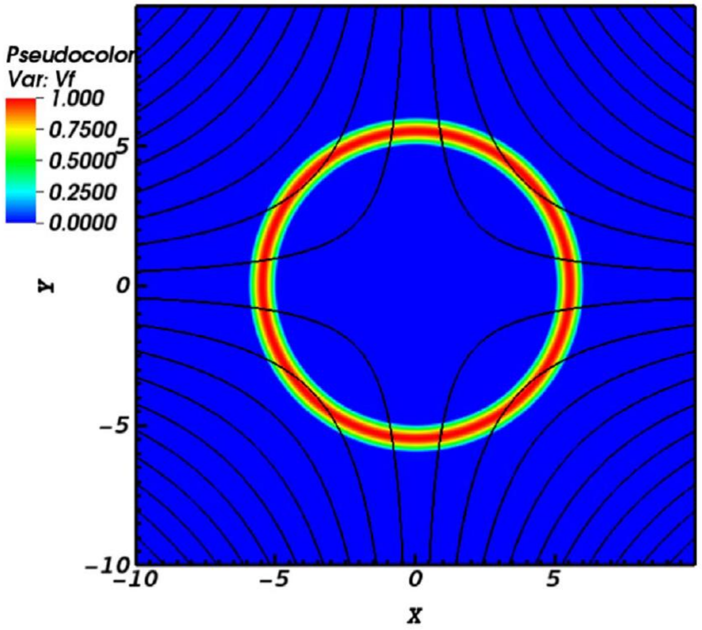
Karampelas et al. (2022, in prep.)

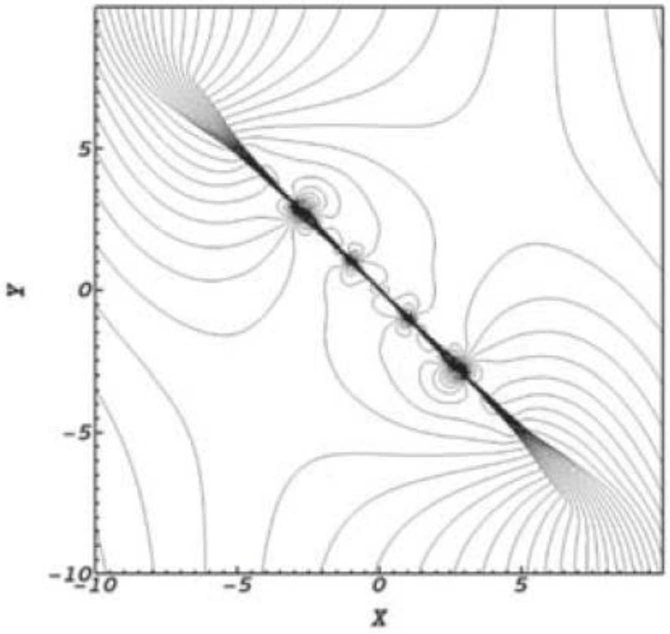




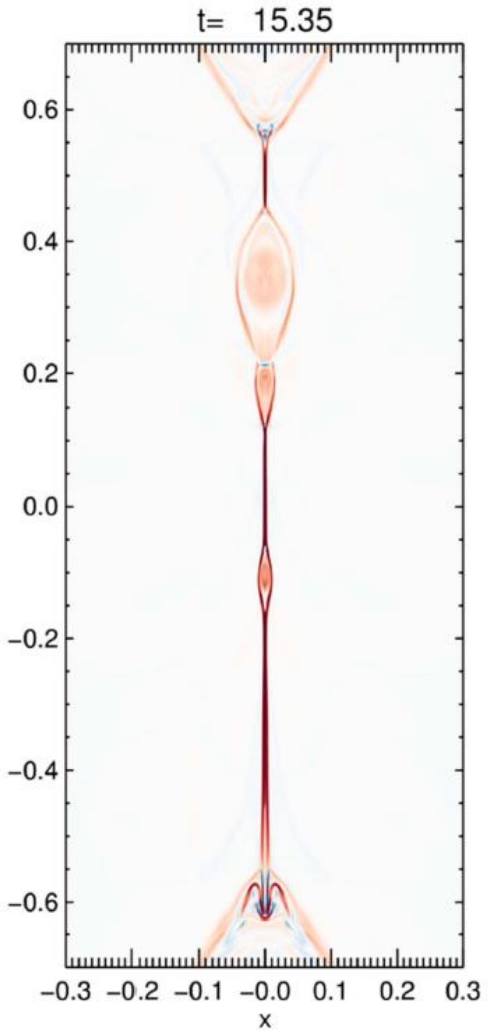
Tearing mode instability – breaking away from oscillatory reconnection

- Strong drivers can lead to very long current sheets with high J_z values.
- Thurgood et al. 2018: development of plasmoids in a high aspect ratio current sheet.
- Sabri et al. 2020: nonlinear tearing of a strong J_z current sheet.
- What are the limits of Oscillatory Reconnection in coronal conditions?





Left: Initial velocity pulse and magnetic field at t=0. Right: magnetic field at t=6. From Sabri et al. (2020).



Nonlinear tearing of the current sheet (Thurgood et al. 2018).

Oscillatory reconnection and QPPs

Quasi-periodic pulsations (QPPs) are quasi repetitive patterns in the signal of flares, which has at least three or four iterations — the QPP cycles.

Review papers:

- McLaughlin et al. (2018);
- Kupriyanova et al. (2020);
- Zimovets, McLaughlin, et al. (2021) – Latest review.

Many proposed mechanisms for generating QPPs:

- ...
- self-oscillations (like **oscillatory reconnection**)
- ...

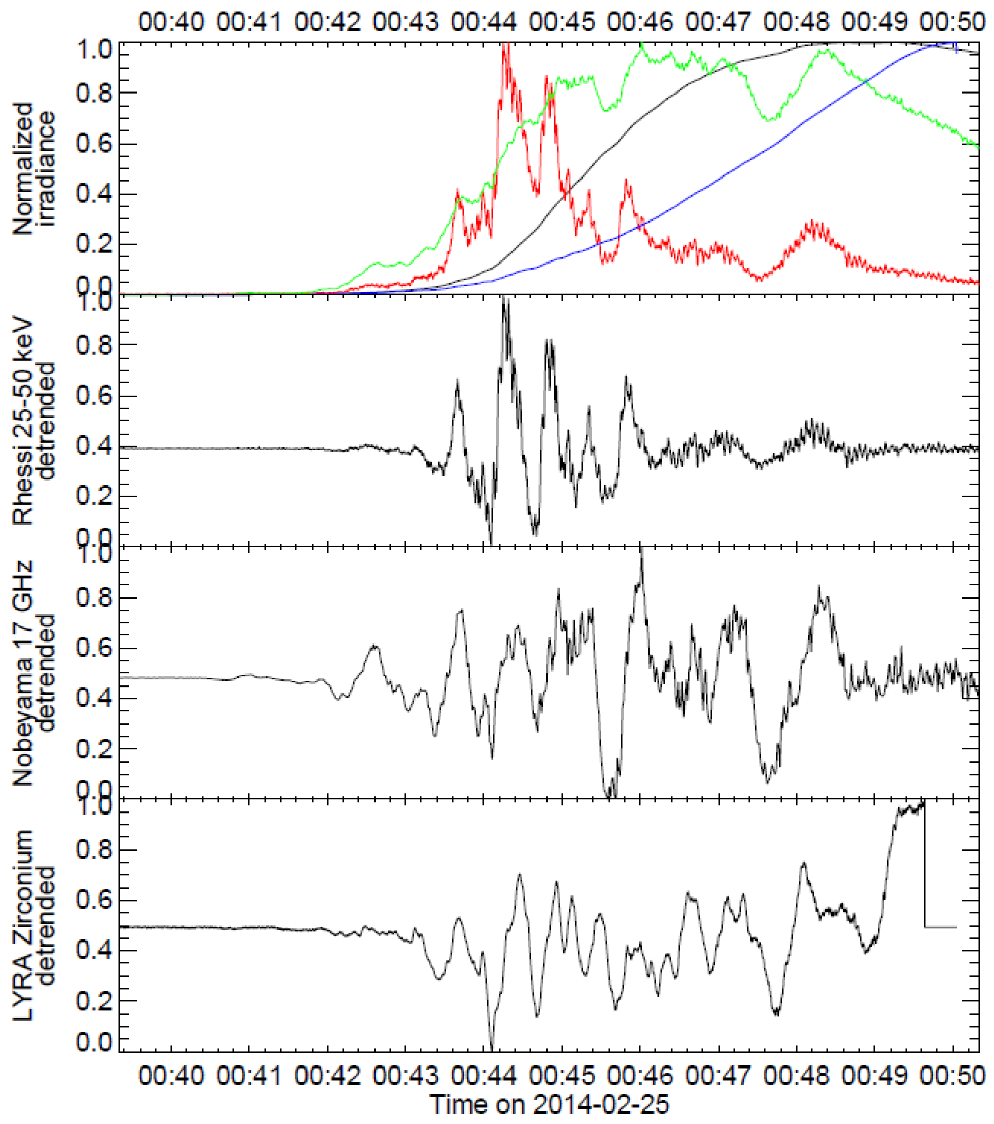


Figure. Example of QPPs for the X4.9 flare of 25 February 2014. Adapted from McLaughlin et al. (2018).

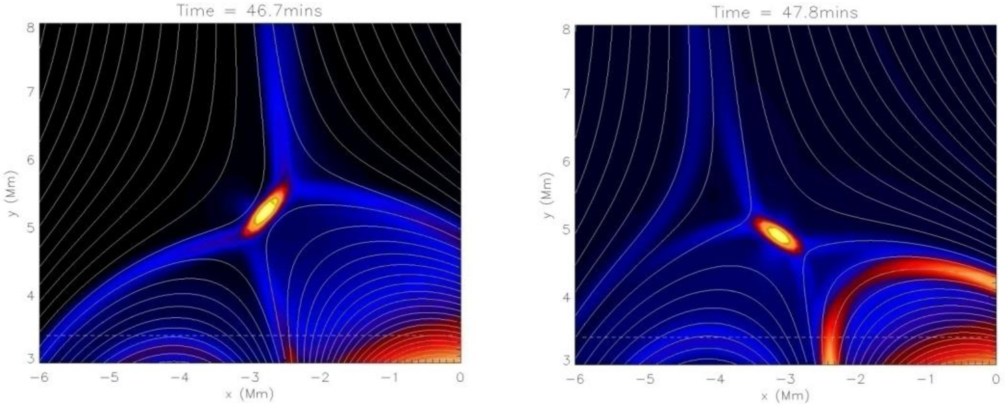
Oscillatory Reconnection and quasi-periodic flows

Mandal et al. 2022:

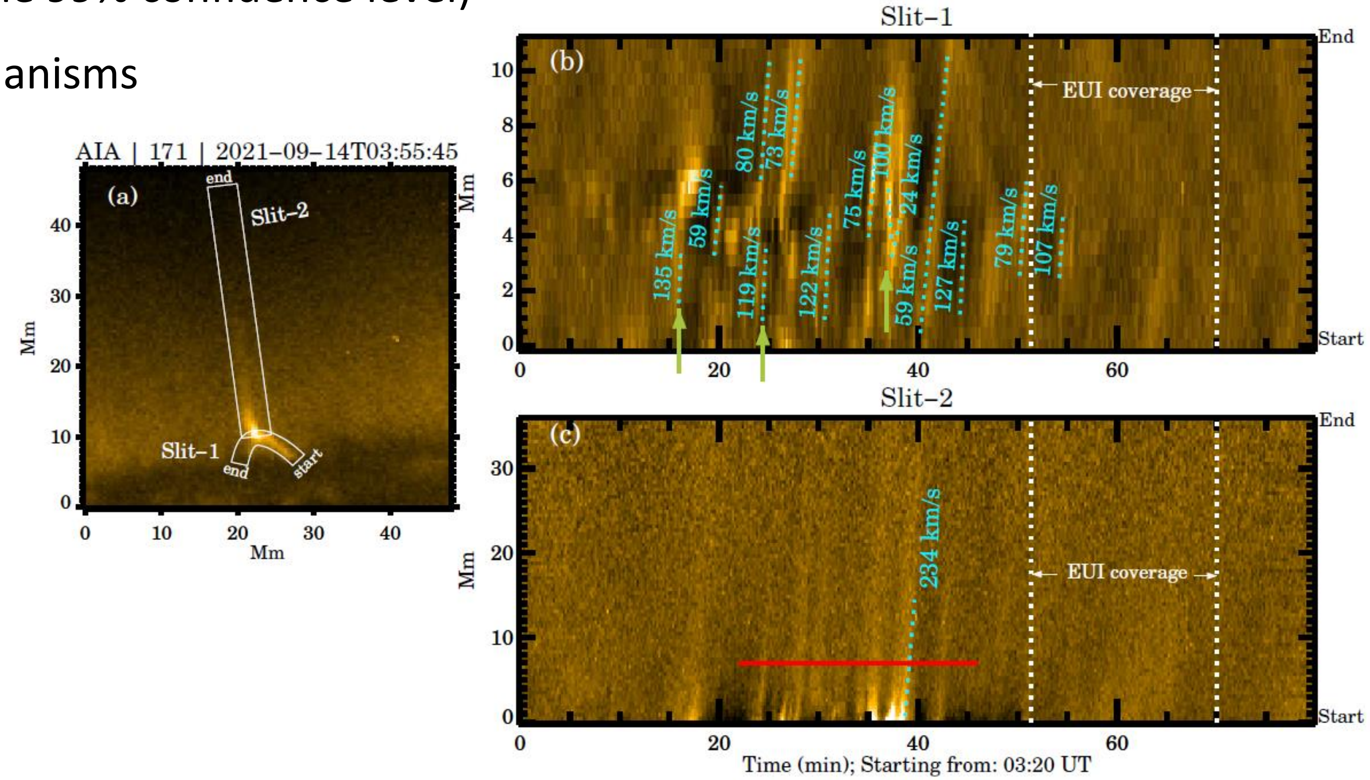
- Highly dynamic coronal hole jet (EUI and AIA).
- Flow speeds $\sim 230\ km\ s^{-1}$
- Periods $\sim$3.4 minutes* (no significant power at the 99% confidence level)
- Oscillatory Reconnection: one of suggested mechanisms

See also Murray et al. 2009 and McLaughlin et al. 2012a:

- Magnetic flux tube emergence into a stratified corona
- Oscillatory reconnection → quasi-periodic vertical outflows



McLaughlin et al. 2012a



Mandal et al. 2022

Credit: J. A. McLaughlin

Smoking gun?

Oscillatory Reconnection has been invoked as an explanation for several periodic phenomena, including:

- The periodicity of a highly dynamic coronal hole jet, observed with both EUI and AIA (Mandal et al. 2022A&A, 664A, 28M)
- Periodicities in an active region correlated with Type III radio bursts observed by Parker Solar Probe (Cattell et al. 2021, *A&A*, **650**, A6)
- A New Type of Jet in a Polar Limb of the Solar Coronal Hole (Cho, I.-H. et al. 2019, *ApJL*, **884**, L38)
- Oscillation of a Small Hα Surge in a Solar Polar Coronal Hole (Cho, K.-S. et al. 2019, *ApJL*, **877**, L1)
- Formation and Disappearance of a Solar Flux Rope with high-resolution data obtained by the New Vacuum Solar Telescope (Xue at al. 2019, *ApJL*, **874**, L27)
- Observation of a Reversal of Breakout Reconnection Preceding a Jet (Hong et al. 2019, *ApJ*, **874**, 146)
- Rotating network jets in the quiet Sun as observed by IRIS (Kayshap et al. 2018, *A&A*, **616**, A99)

- OR is explicitly mentioned in §6.5 of the Science Requirement Document for the European Solar Telescope (Schlichenmaier et al. 2019, 2nd edition).

Summary / Conclusions

Null points: omnipresent, sites of reconnection, affect the propagation of waves.
Non-linear waves can trigger the manifestation of oscillatory reconnection at null points.

- Overturn of steep, strong waves.
- Stronger mother flares are not certain to trigger daughter flares!
- How is O.R. related to the properties of null points as resonant cavities?

Oscillatory reconnection is found to produce waves.

- Wave periods can reveal the periodicity of Oscillatory Reconnection.

The period of oscillatory reconnection is:

- dependent on the length of the initial current sheet,
- independent on the amplitude of the perturbing velocity pulse, in coronal conditions,
- depending upon the background plasma state.

Tearing mode instability.

- What are the limits of oscillatory reconnection in solar atmospheric conditions?

Prospect of using oscillatory reconnection and the generated waves as seismological tools!