MHD Simulation of 3D Turbulent Magnetic Reconnection within Solar Flare Current Sheets

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Introduction

- **Questions:**
  (1) How does turbulent reconnection develop within the solar flare current sheet (CS)?
  (2) What is the relation between turbulent reconnection and observations?
  (3) How to unveil the fundamental laws of 3D turbulent reconnection?
- **Large-scale MHD simulation:**
  (1) High-resolution: 26 km uniform grid in the CS and loop top, 4 M+ core-hour, Athena++;
  (2) Coronal physics: full thermal dynamics, gravity, thermal conduction, radiation cooling, background heating;
  (3) Self-consistency: CSHKP model, a low background resistivity (Lundquist number $S = 2 \times 10^5$).
- **Novel quantitative analysis method of turbulent reconnection:**
  (1) Locating 3D reconnection sites within turbulent plasmas with high efficiency;
  (2) Fast classification of local magnetic field structure;
  (3) Recognizing fragmented reconnection patches (RPs) and their reconnection properties.

Publications

1, Y. Wang et al., Three-dimensional Turbulent Reconnection within the Solar Flare Current Sheet, ApJL 954, L36 (2023). **Featured in AAS NOVA.**

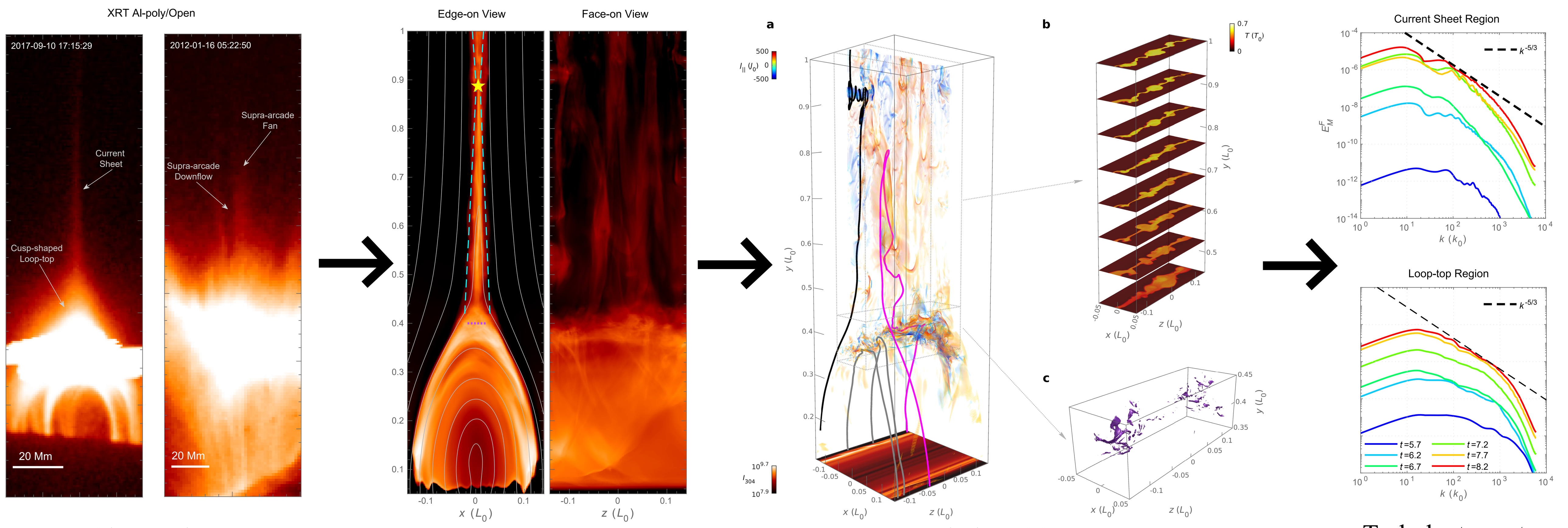
2. Y. Wang et al., A method for determining the locations and configurations of magnetic reconnection within three-dimensional turbulent plasmas, A&A 683, A224 (2024).

3. Z. Ren et al., Understanding Observational Characteristics of Solar Flare Current Sheets, Submitted.

4. Y. Wang et al., Basic pattern of 3D Turbulent Reconnection within Flare Current Sheets, in preparation.

5. The LoRD code: ascl.net/2401.014

Turbulent Reconnection behind the Observed Flare CS



Observation — Simulation — Turbulent CS & Loop top — Turbulent spectra

⇐ Key Messages

☼ Our simulation reproduces key observations from different view points;

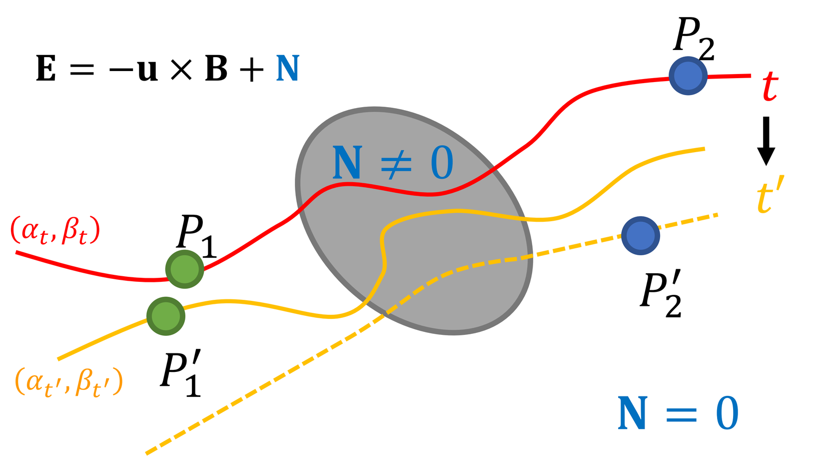
☼ Fragmented current patches of different scales are generated with a well-developed turbulence spectrum at both the CS and the loop-top regions;

☼ The development of turbulence results from the coupling of the kink, tearing-mode, and Kelvin-Helmholtz (KH) instabilities.

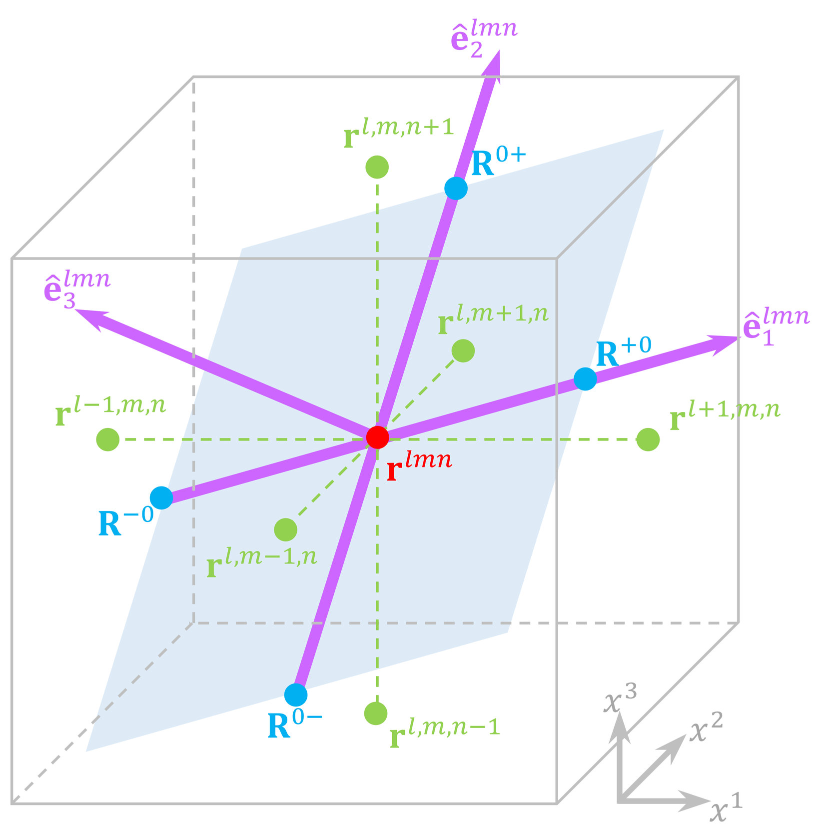
☼ The KH instability driven by z-direction shear flows in the CS forms the finger-like structures as viewed from the face-on view.

☼ The termination shock in the loop top is highly shattered.

$E_{\max}$ Grids

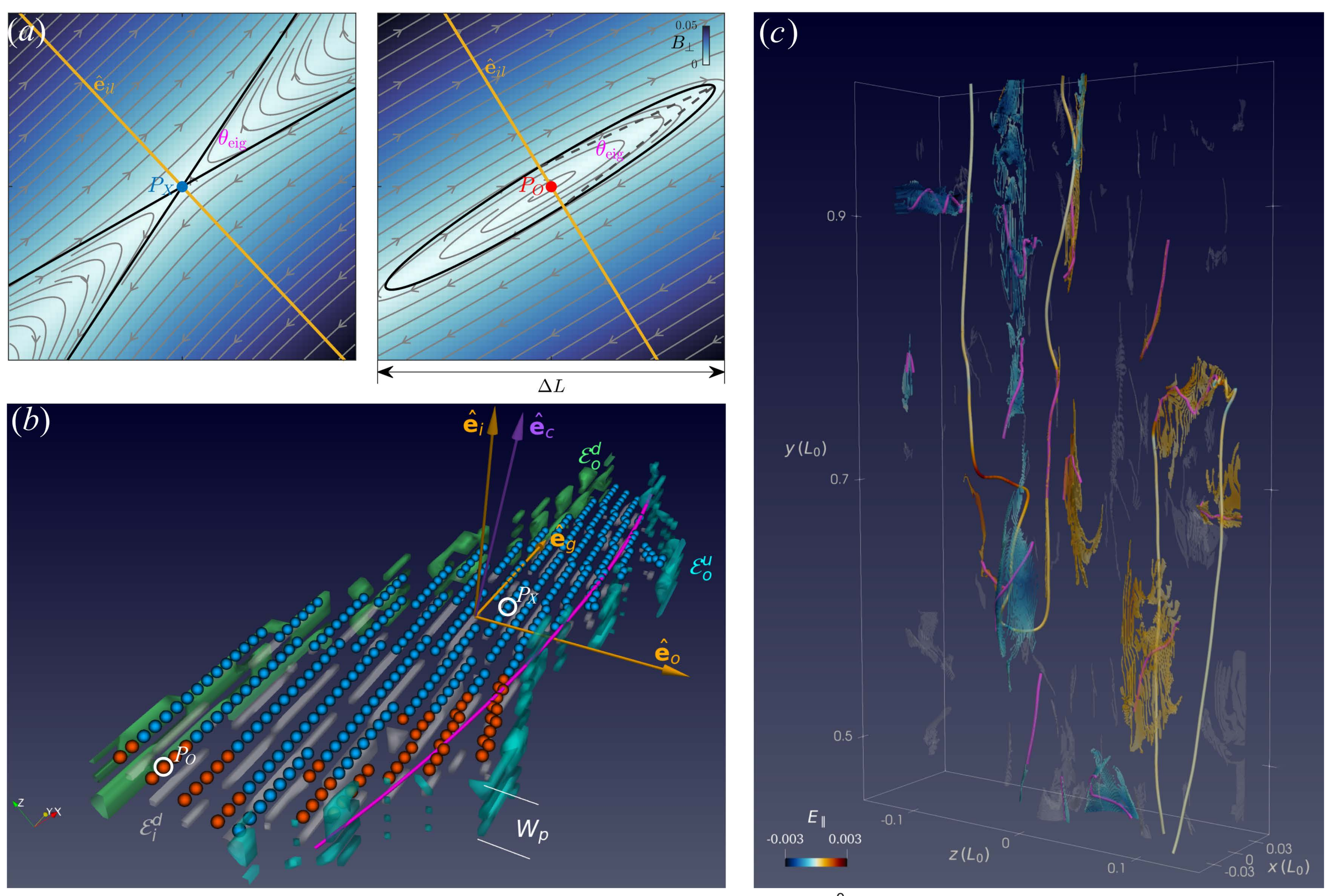


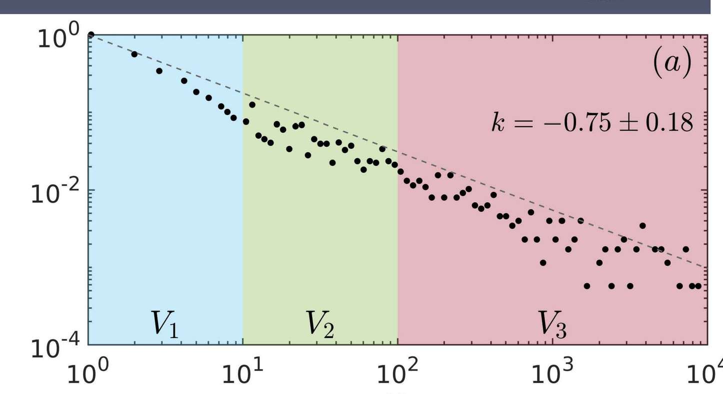
- **Reconnection condition:**
  $\Xi \equiv \int E_\parallel \mathrm{d}s \neq 0$.
- **$\Xi_{\max}$ line:**
  $\partial\Xi/\partial\alpha = \partial\Xi/\partial\beta = 0$;
  Extremal Ξ is equivalent to reconnection rate (Hesse et al. 2005).



- **$E_{\max}$ grids:**
  $|E_\parallel| > E_{\text{thres}}$ & $\nabla_\perp E_\parallel \sim 0$;
  Approximately reflect the distribution of $\Xi_{\max}$ lines (Wang et al. 2024).
- **The LoRD toolkit:**
  An open-source Matlab toolkit.
  github.com/RainthunderWYL/LoRD

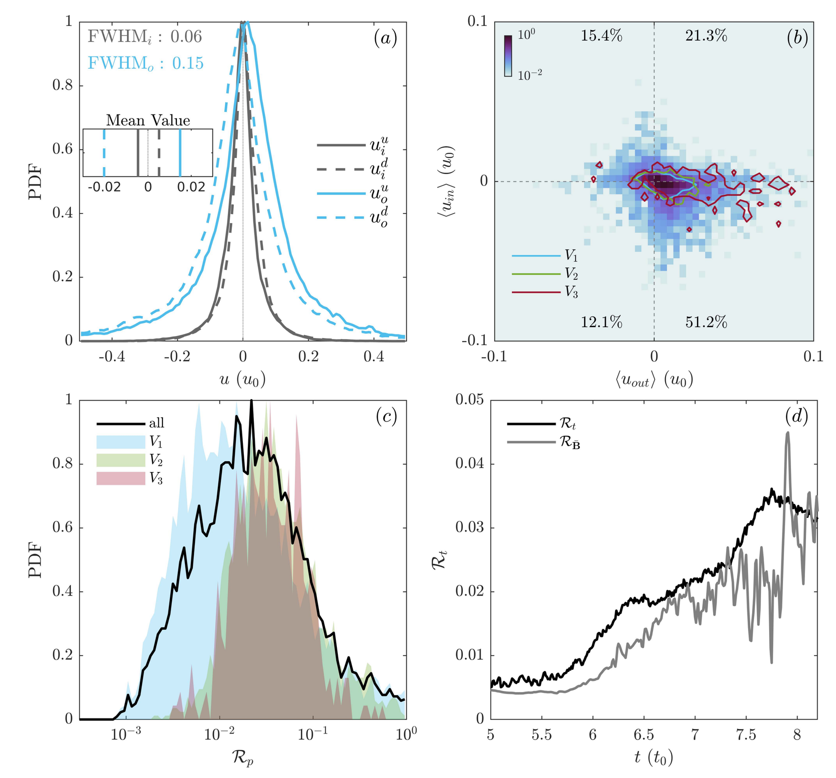
Reconnection Patches





- **Reconnection patch (RP):**
  Spatially connected $E_{\max}$ grids;
  One field line threads multiple RPs.
- **Intrinsic reconnection frame:**
  (1) Inflow: $\hat{\mathbf{e}}_i = \langle\hat{\mathbf{e}}_{il}\rangle/|\langle\hat{\mathbf{e}}_{il}\rangle|$;
  (2) Outflow: $\hat{\mathbf{e}}_o = \langle\hat{\mathbf{B}}_{lg}\rangle \times \hat{\mathbf{e}}_i/|\langle\hat{\mathbf{B}}_{lg}\rangle \times \hat{\mathbf{e}}_i|$;
  (3) Guide-field: $\hat{\mathbf{e}}_g = \hat{\mathbf{e}}_i \times \hat{\mathbf{e}}_o$.
  Definitions: $\hat{\mathbf{e}}_{il}$ (Orange lines in panel (a)); $\hat{\mathbf{B}}_{lg}$ (Local magnetic field at an $E_{\max}$ grid); $\langle\cdot\rangle$ (Average over RP).
- **Inflow and outflow edges:**
  Inflow edges: Nearest surfaces satisfying $|E_\parallel| < E_{\text{thres}}$ along $\hat{\mathbf{e}}_i$;
  Outflow edges: RP boundaries along $\hat{\mathbf{e}}_o$.
- **RP reconnection rate:**
  For each RP, we locate its $\Xi_{\max}$ line. The reconnection rate of a RP can be obtained by $\mathcal{R}_p = \Xi_{\max}/B_{in}V_{in}L_{in}$, where B_{in} and V_{in} are the average magnetic field and Alfvénic speed at the inflow edges, and L_{in} is the length scale of RP on the outflow direction;
- **Total reconnection rate:**
  $\mathcal{R}_t = \sum \Xi_{\max}/(B_0 V_{A0} L_0)$, where B_0, V_{A0} and L_0 are background parameters.

⇐ Key Messages



☼ **RP volumes:**
PDF of RP volumes show a power-law distribution.

☼ **RP shapes:**
Distributed along flux surfaces.

☼ **RP reconnection flows and rates:**
Uncertainty: reconnection flows and rates show strong statistical broadenings as affected by turbulence.
On average: Largest probability for "inflow"+"outflow" pattern and "0.01–0.1" rate.

☼ **Scale independency:**
The statistical laws are approximately independent with RP sizes.