Sympathetic flares and magnetohydrodynamical avalanches

Antoine Strugarek
AIM/CEA Paris-Saclay, France

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With **L.S. Guité, H. Lamarre**, P. Charbonneau, Q. Noraz, A. Blaise, A.S. Brun, M. Carlsson, B. Gudiksen

Outline

1) Statistics of sympathetic solar flares

   [Guité, Strugarek & Charbonneau A&A 2025]

2) Sandpile models of sympathetic flares

   [Guité, Charbonneau & Strugarek Sol Phys. 2025]

3) Unveiling avalanche behaviour in MHD simulations of the solar atmosphere

   [Lamarre et al., PRE 2025]

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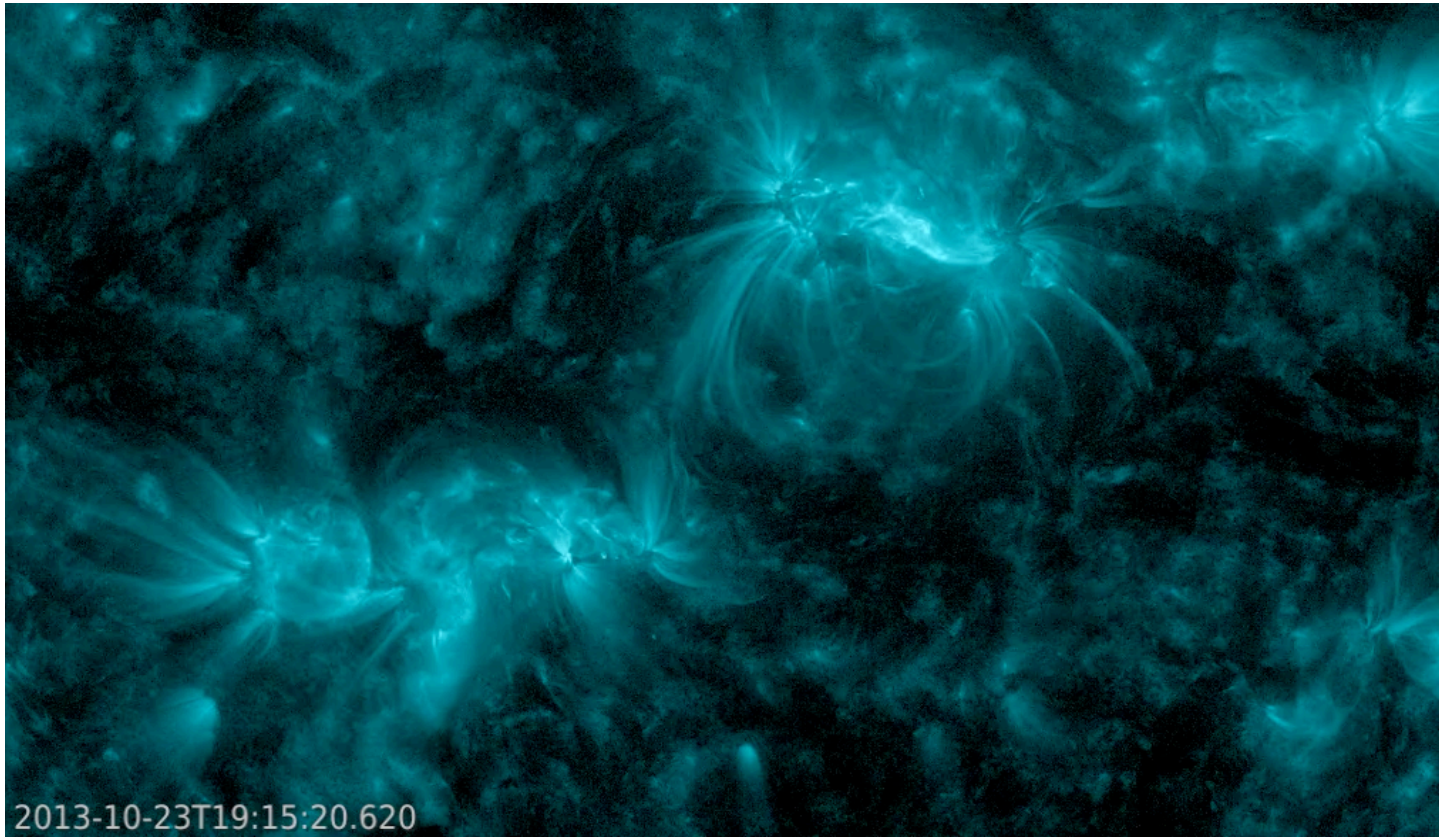
Candidate sympathetic flares & possible physical origin



Common magnetic field evolution from photospheric convective motion (Bumba & Klvaňa 1983)

Heat conduction along coronal loops (Changxi et al. 2000)

Mass transfer from a surge (Wang et al. 2001)

Magnetic reconnection of field lines joining nearby active regions (e.g., Cheng et al. 2005 ; Jiang et al. 2008 ; Török et al. 2011)

Need for robust identification and statistics!

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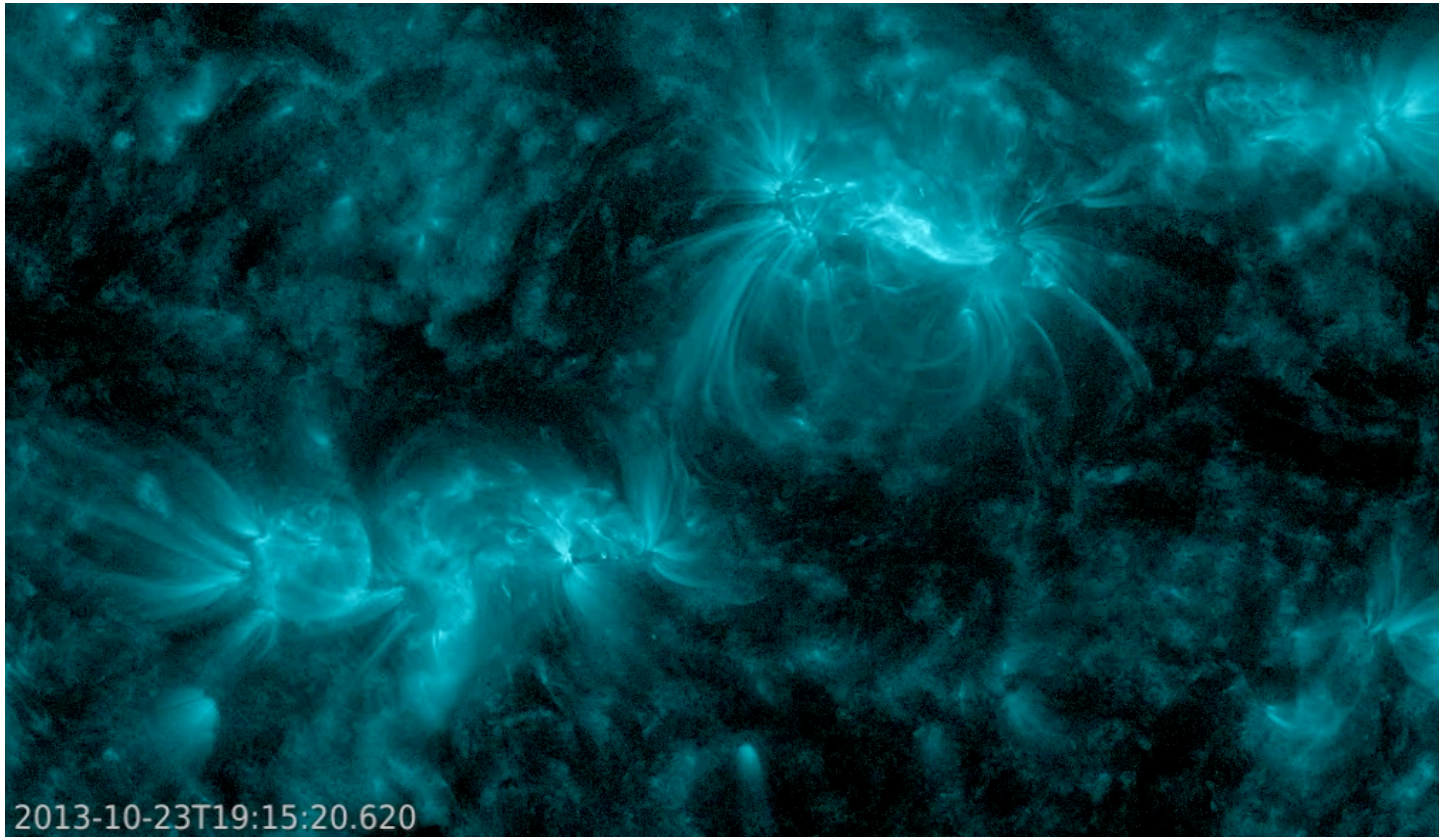

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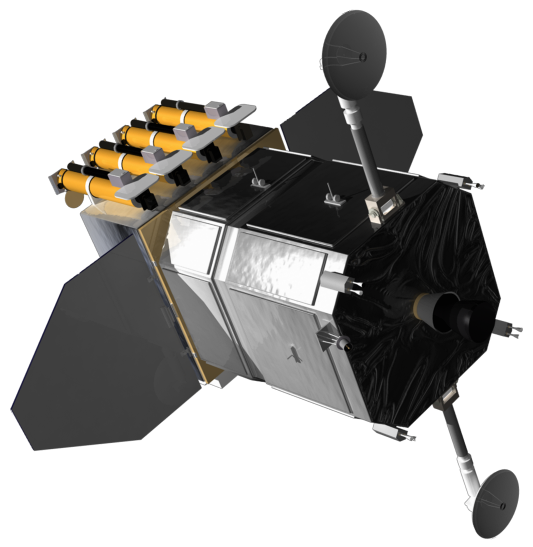
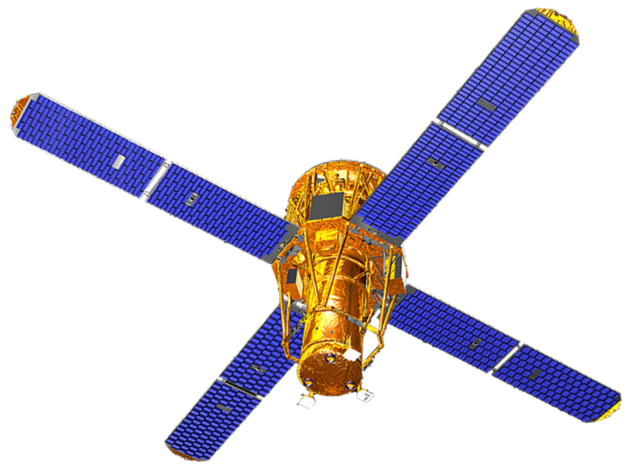
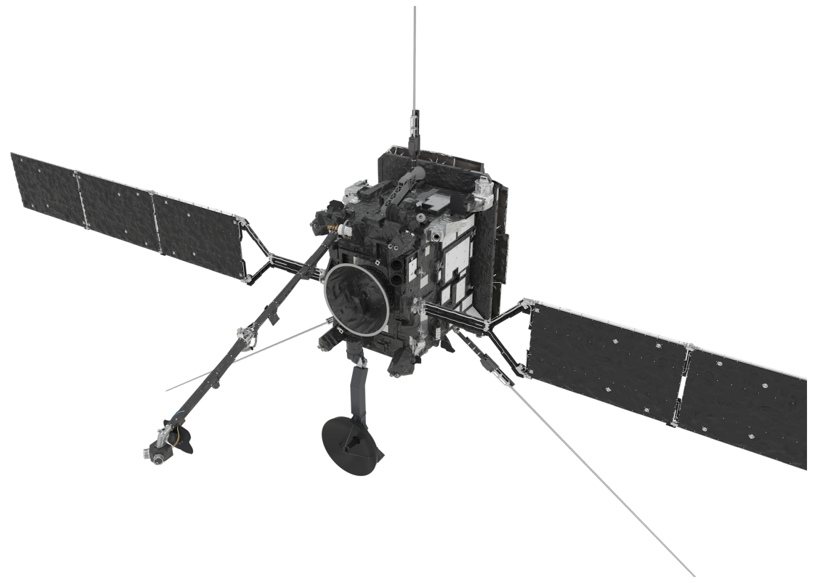
Flare Catalogs





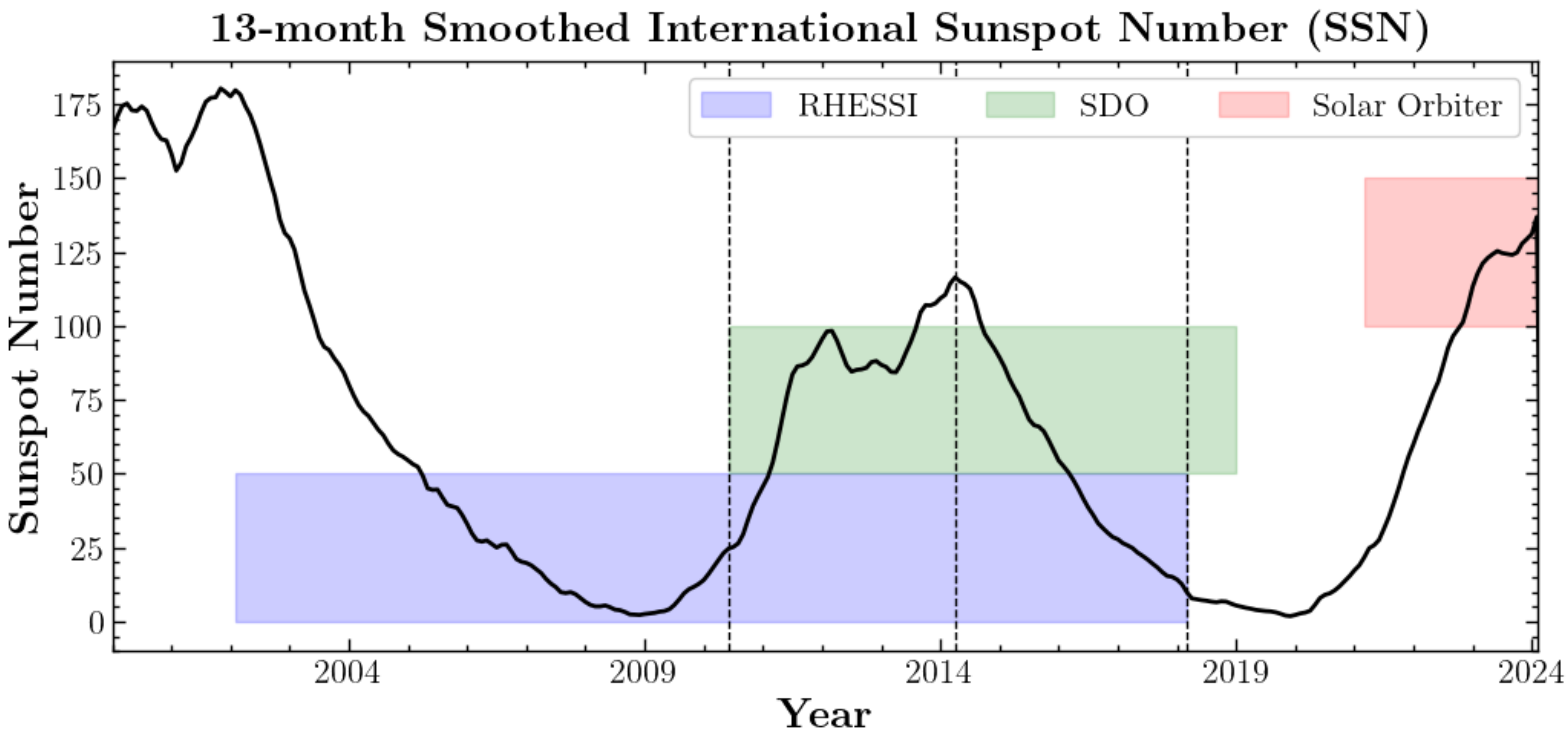


Mission	Number of flares (Original list)	Number of flares (Our analysis)
SDO / AIA (https://github.com/SWxTREC/aia-flare-catalog Van der Sande et al. 2022)	16 270	13 263
RHESSI (https://hesperia.gsfc.nasa.gov/rhessi3/data-access/rhessi-data/flare-list/index.html)	104 305	20 172
Solar Orbiter / STIX (https://github.com/hayesla/stix_flarelist_science)	17 031	8306

We keep flares with a GOES class > C1.0 (when available) and excluding within ± 30º from the limb.

Guité et al., A&A 2025

Flare Catalogs



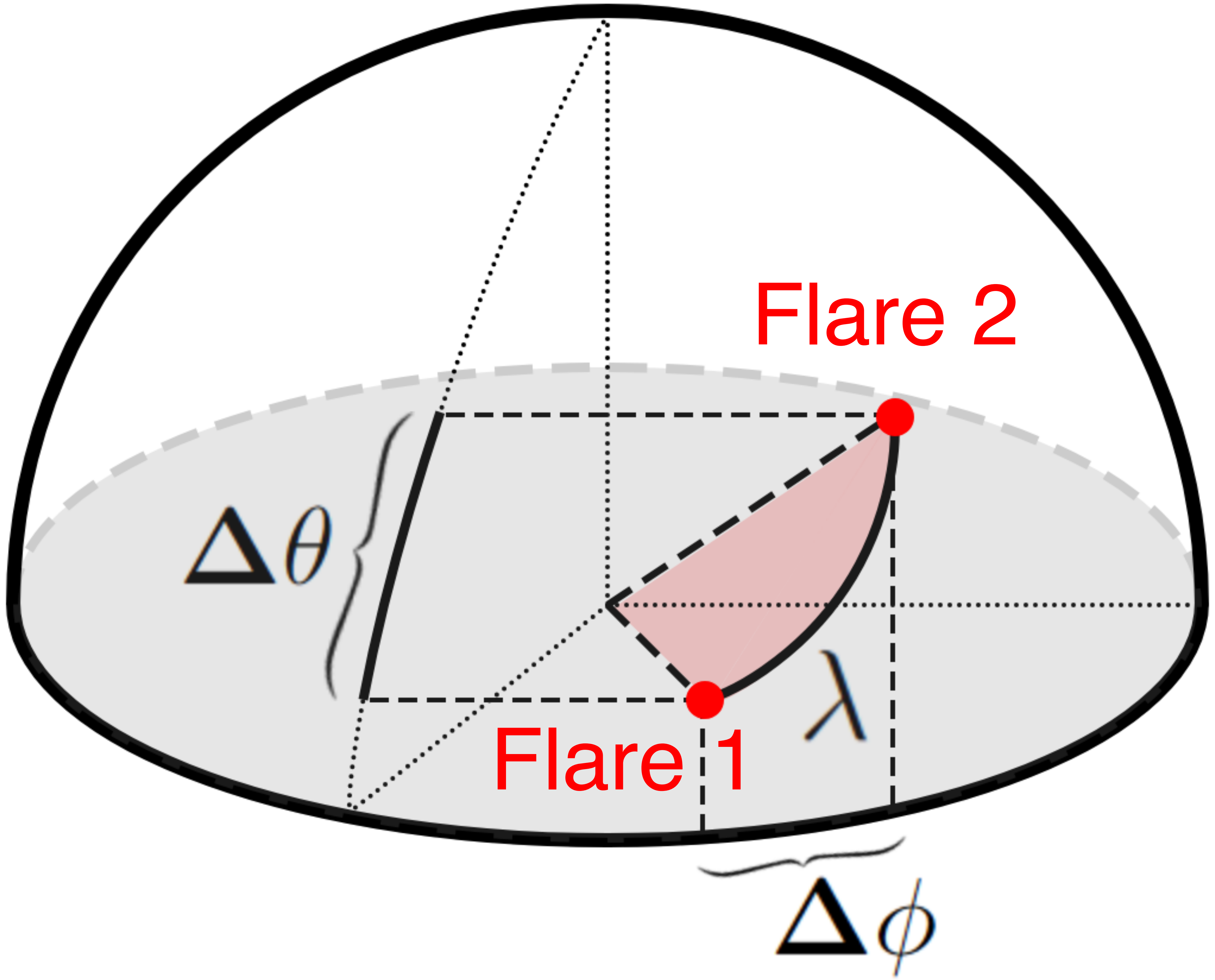
Sunspot Number reference: SILSO/Royal Observatory of Belgium

Guité et al., A&A 2025

Identification of sympathetic flares

We measure 4 parameters between each pair of consecutive flares:

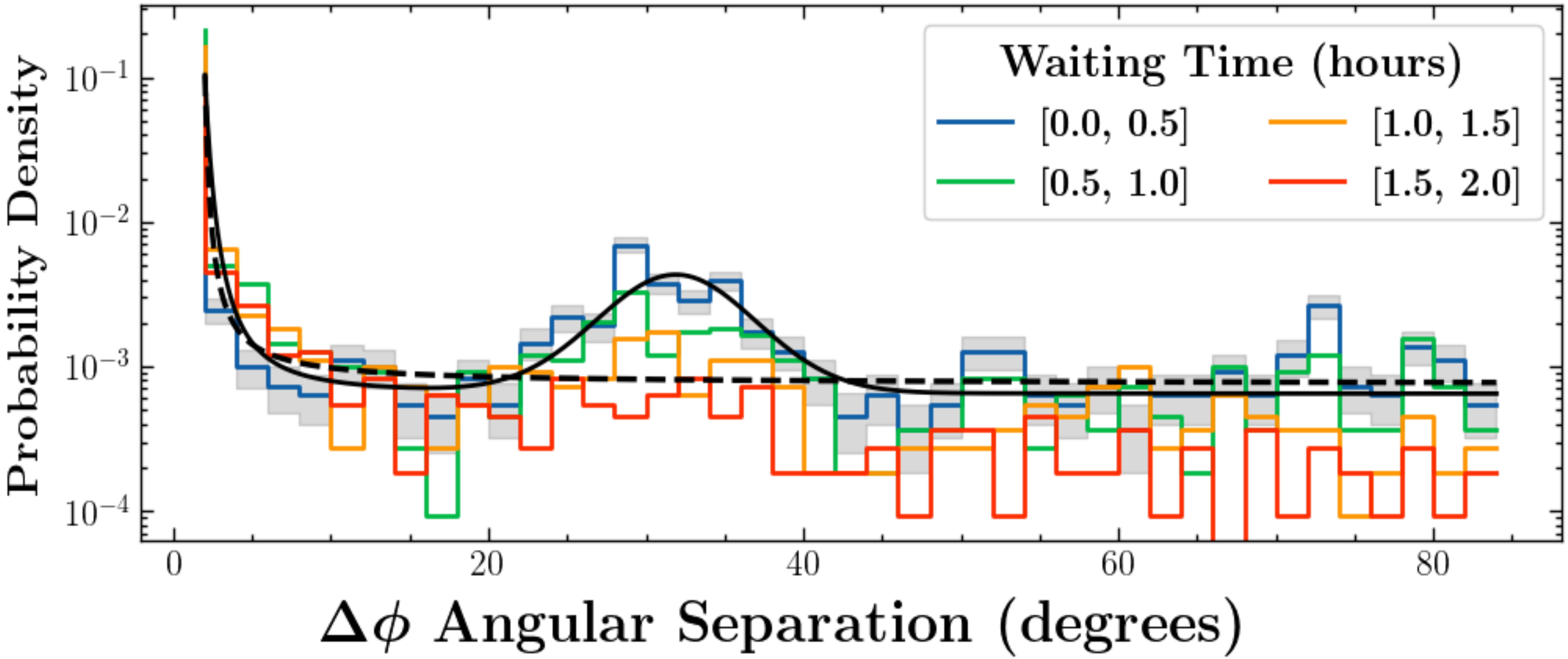
- Waiting time
- Angular separation (3 angles)



Guité et al., A&A 2025

Flares occurring within the same hemisphere

SDO Flarelist



Guité et al., A&A 2025

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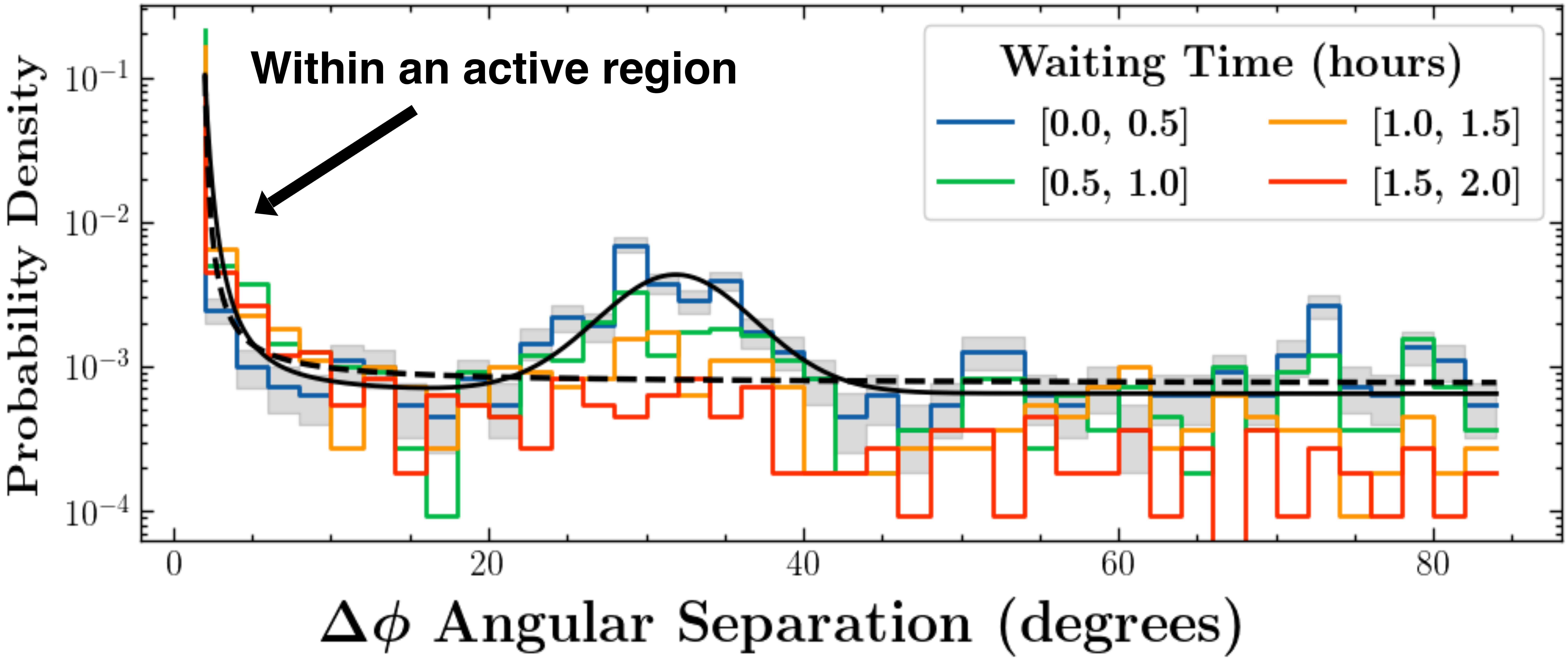

Guité et al., A&A 2025

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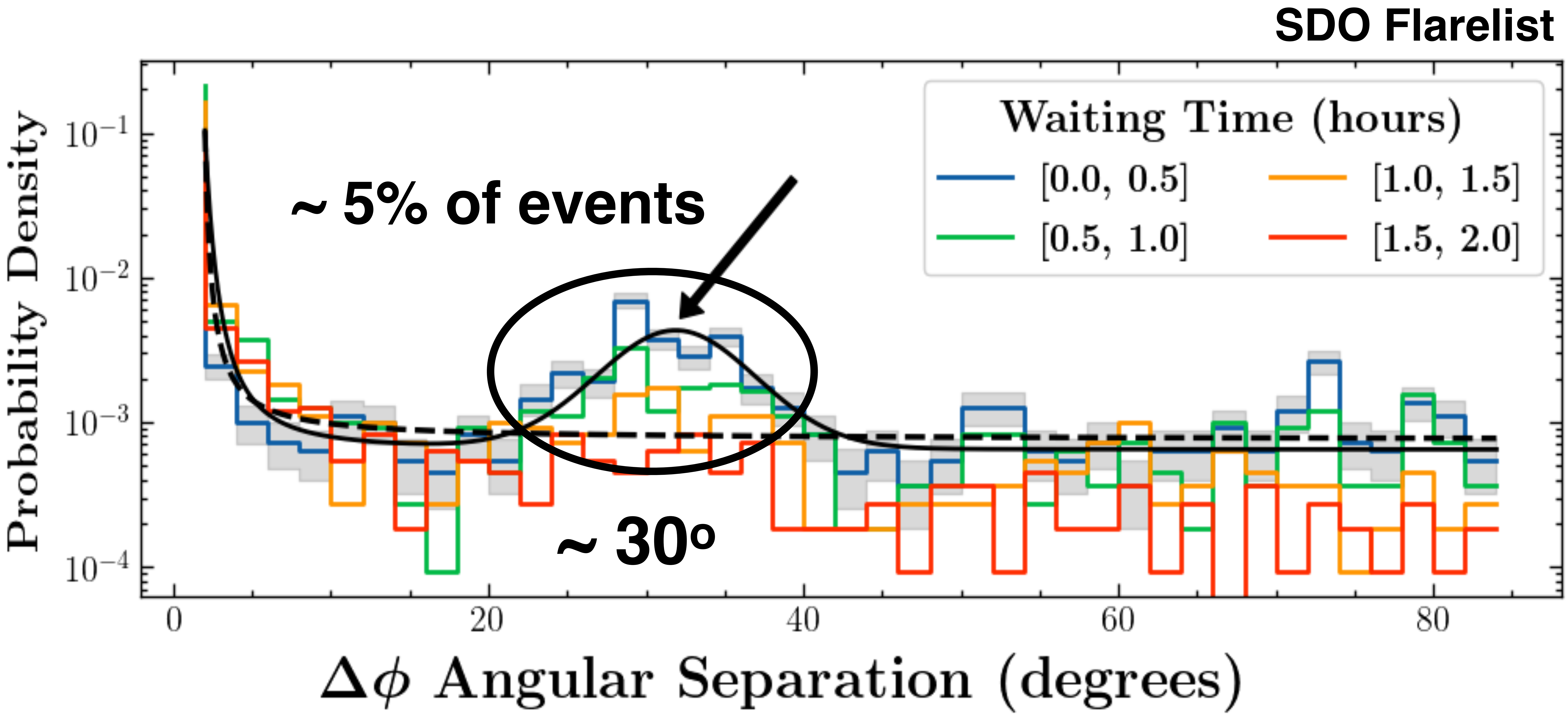
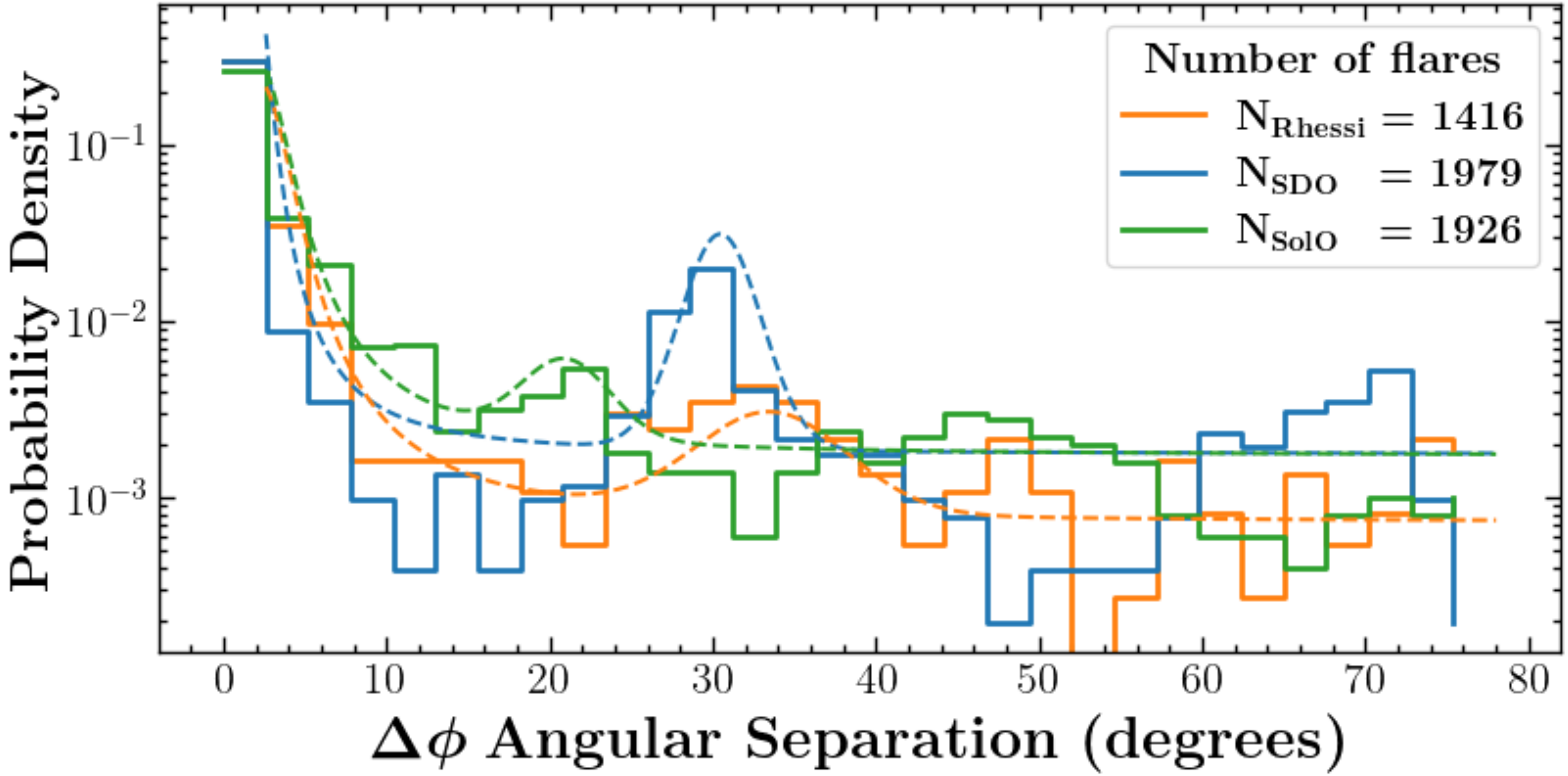


Guité et al., A&A 2025

Comparison between SDO, RHESSI and Solar Orbiter

Waiting time < 1.5h



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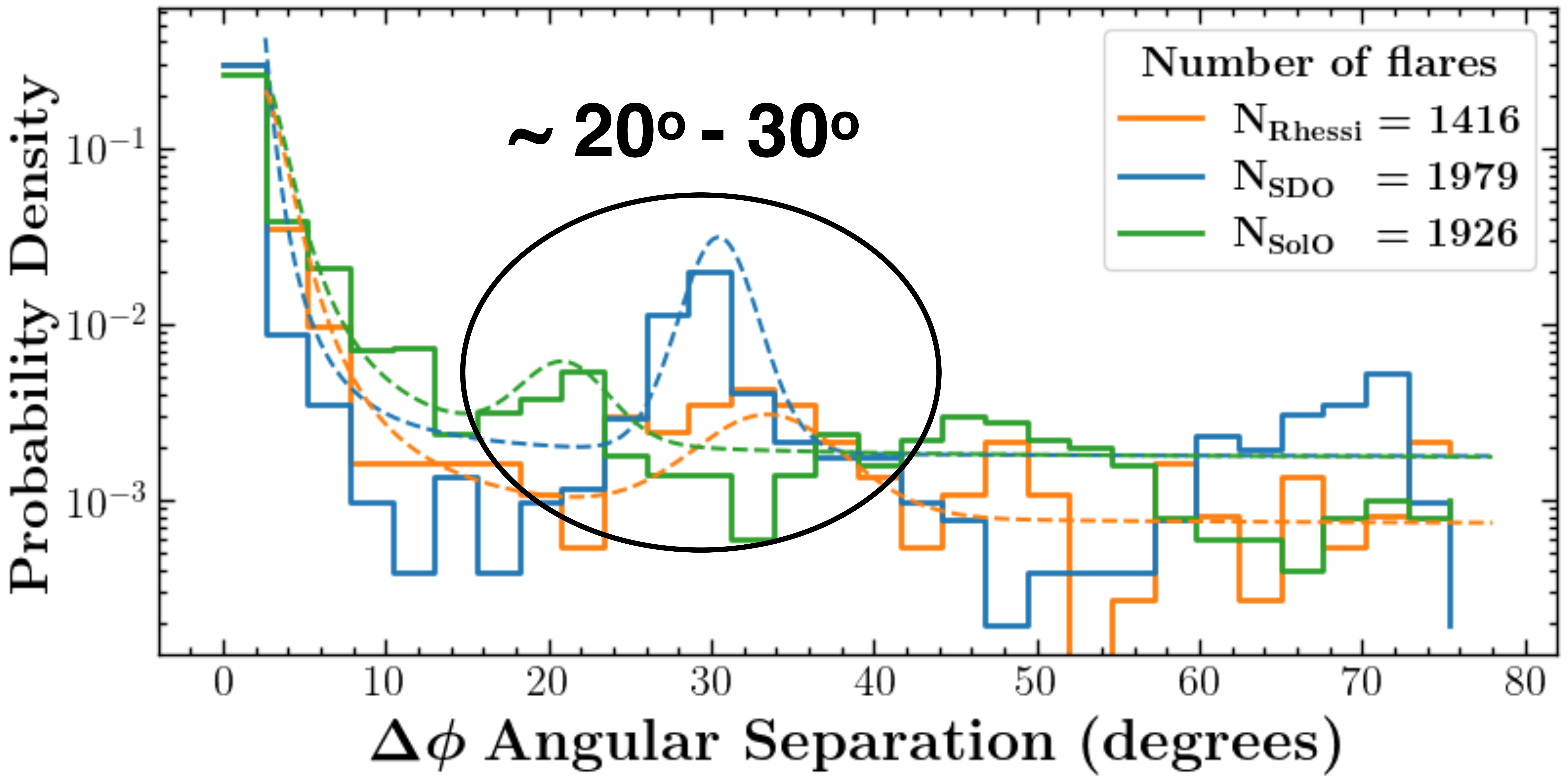

Guité et al., A&A 2025

Observed sympathetic flares summary

Guité, Strugarek & Charbonneau, A&A 2025, doi: 10.1051/0004-6361/202452381

Evidence of sympathy from excess of hemispheric events separated by approx. **30° in longitude** (5% of events)

Consistent with the peak angular separation between **footpoints of closed magnetic field lines**

Deficit of transequatorial events separated by approx. 30° in latitude: **Unsympathetic flares ? Longitude exclusion of activity nests ?**

Sympathetic flares list (candidates)

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[Guité, Strugarek & Charbonneau A&A 2025]

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3) Unveiling avalanche behaviour in MHD simulations of the solar atmosphere
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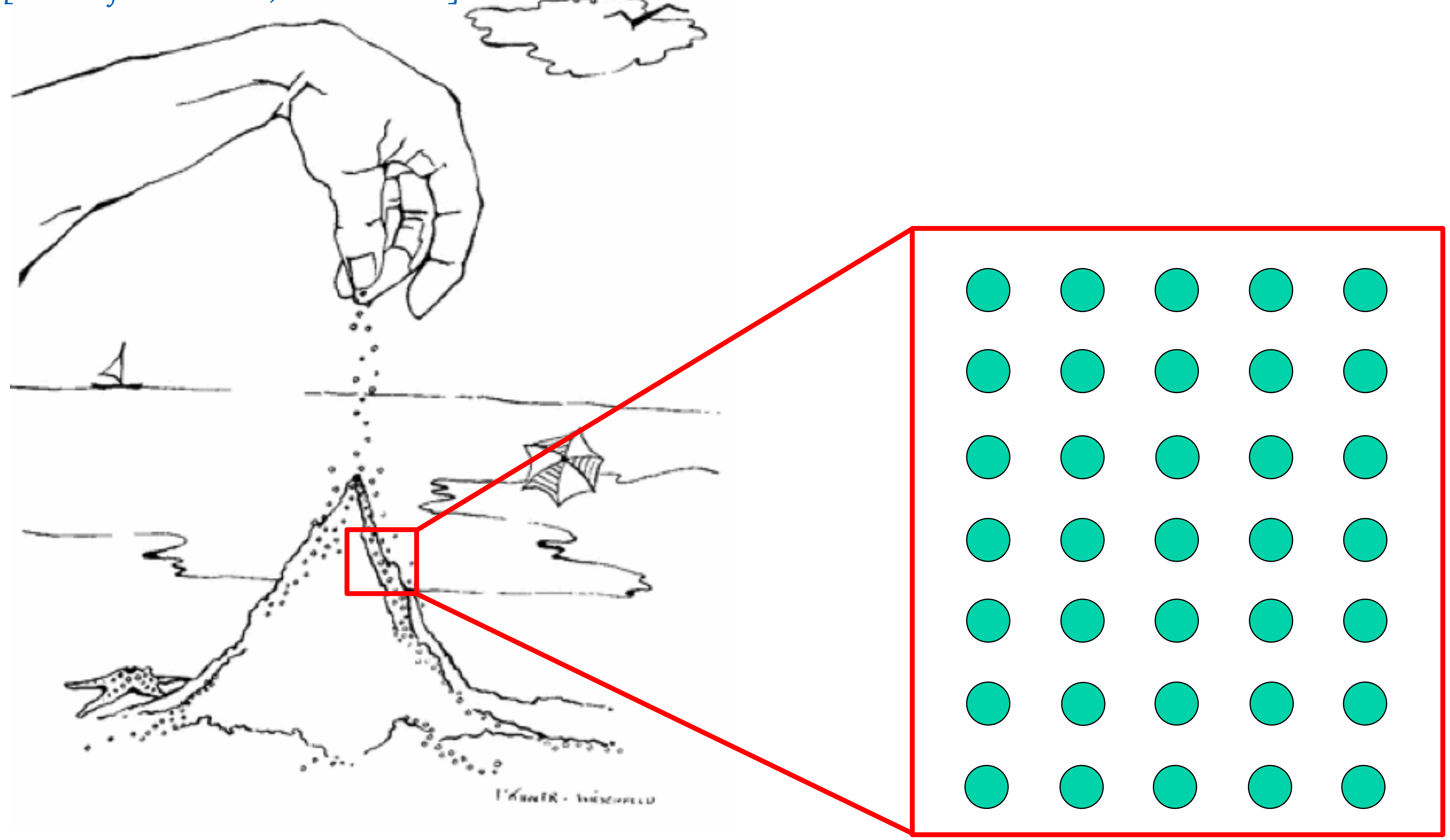
Sandpile model for solar flares

[Wiesenfeld+ 1989; Bak+ 1987]

Driver



‘Self-Organized Criticality’

[Lu & Hamilton 1993]

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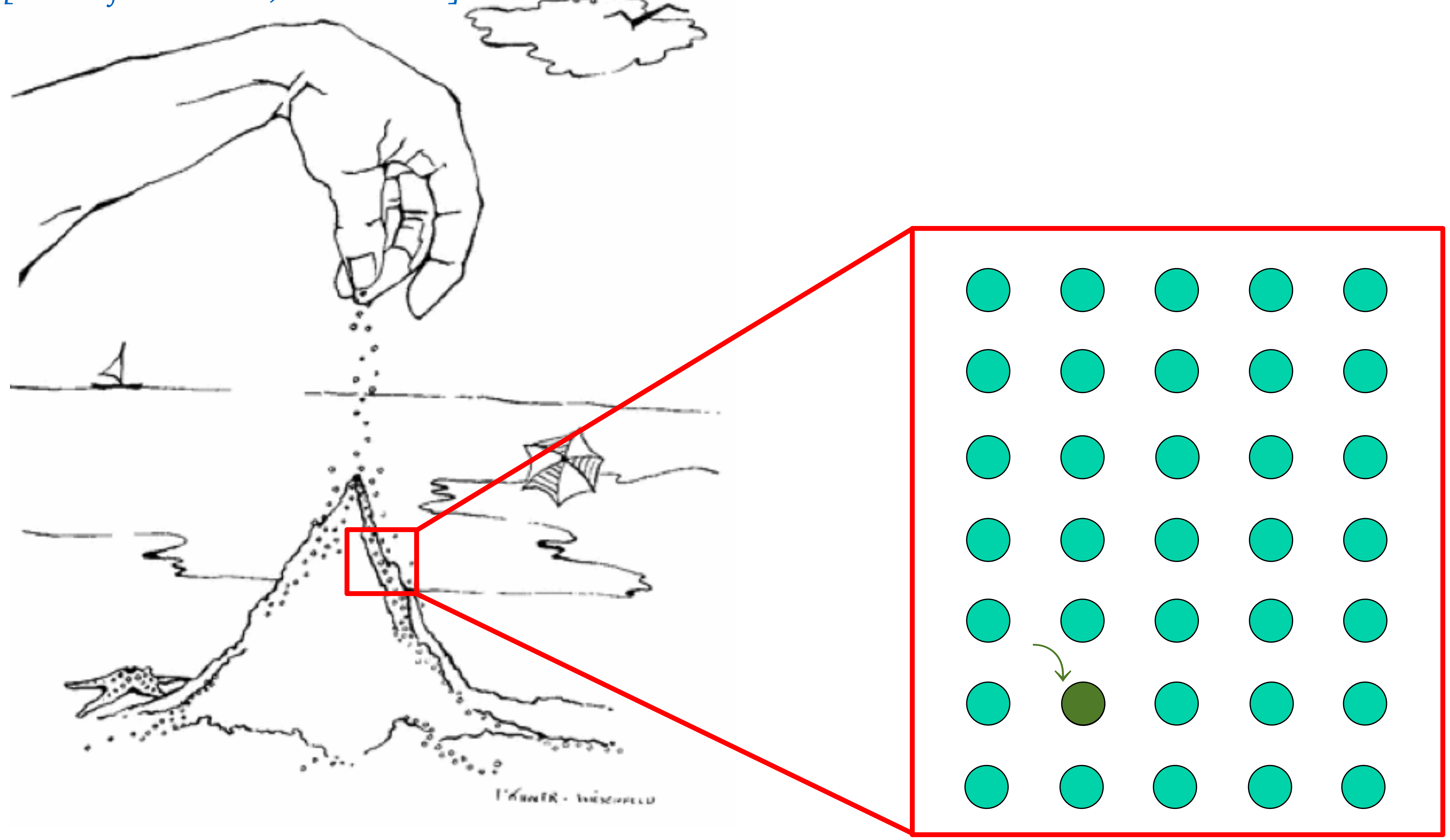

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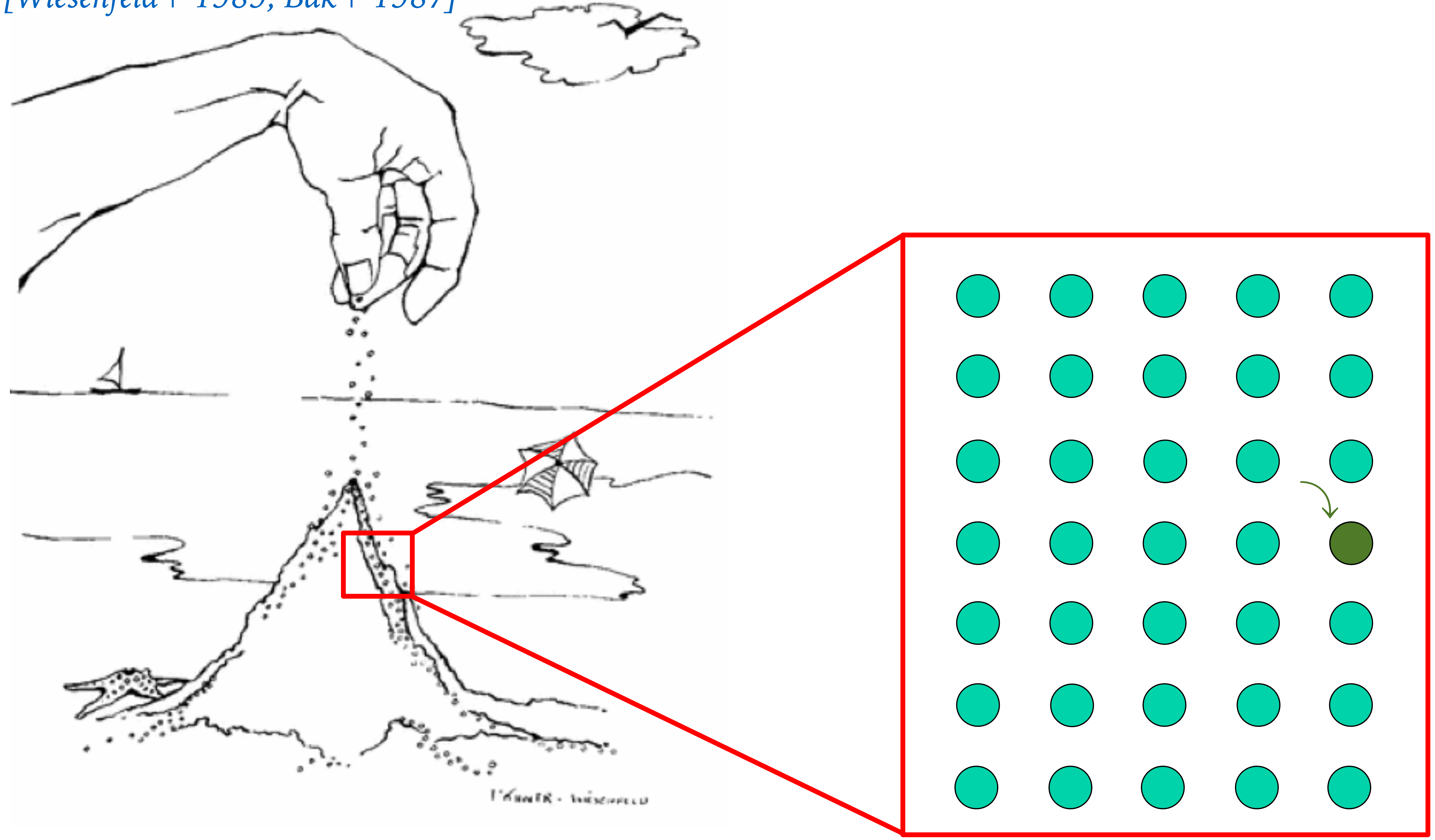

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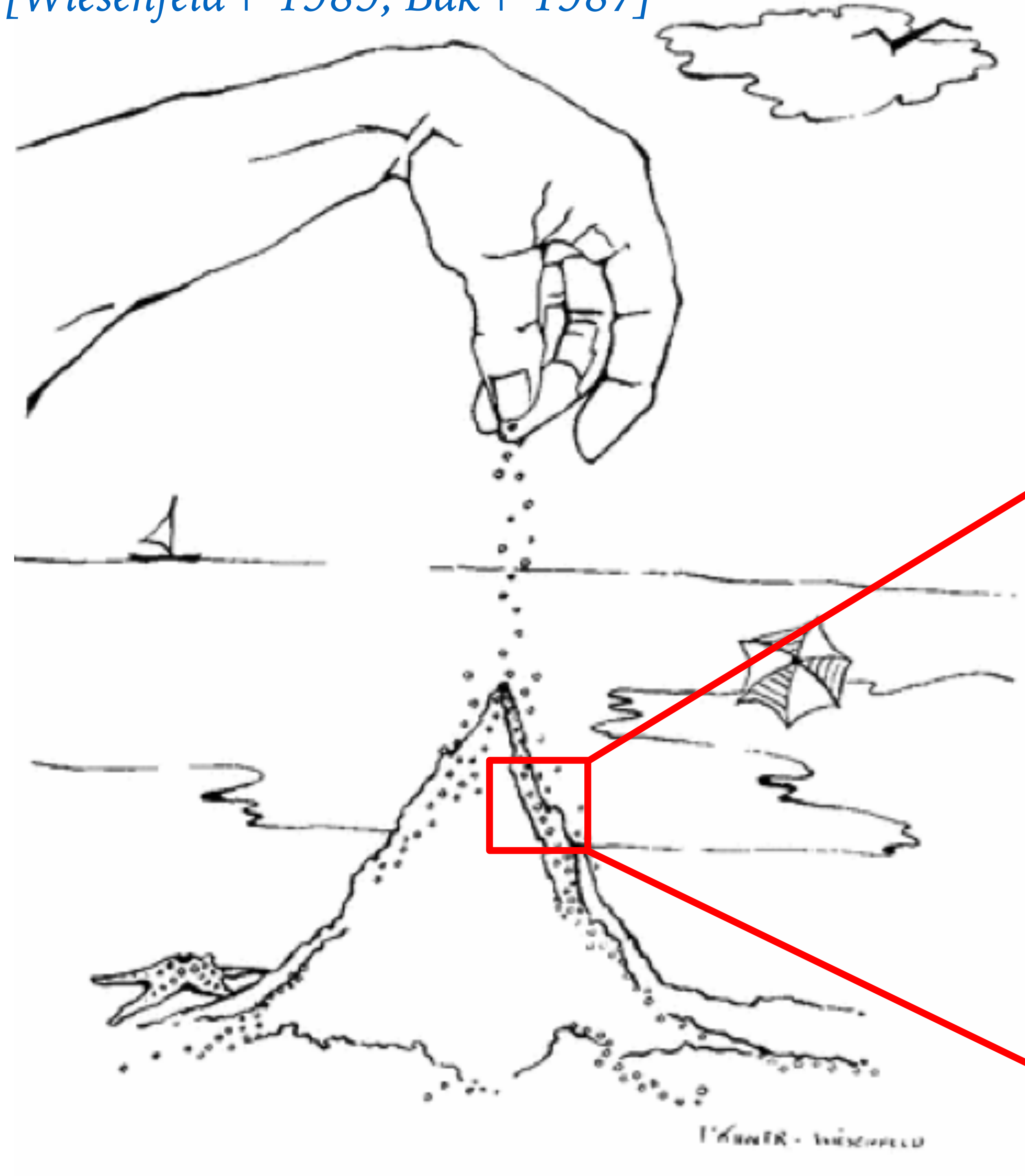

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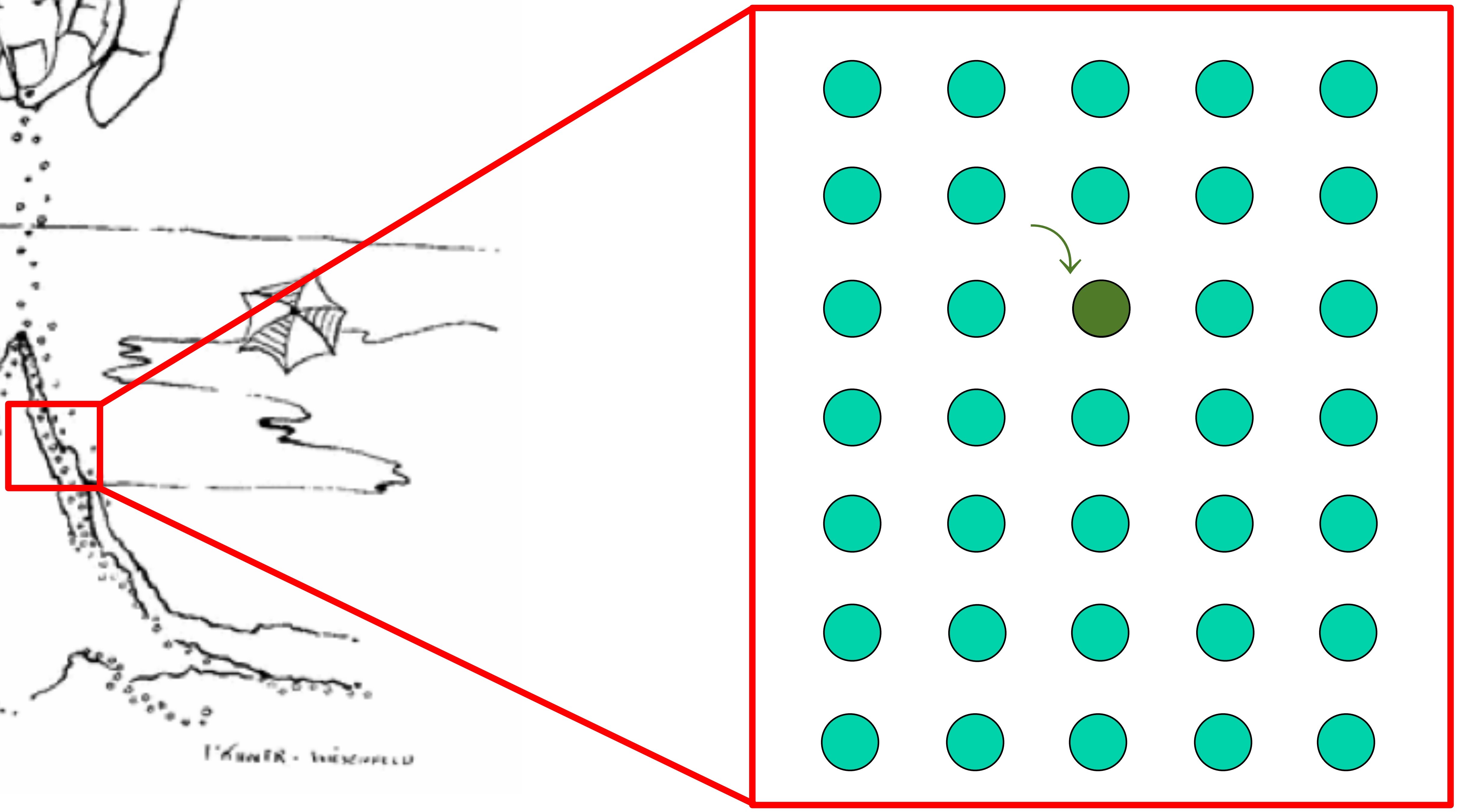

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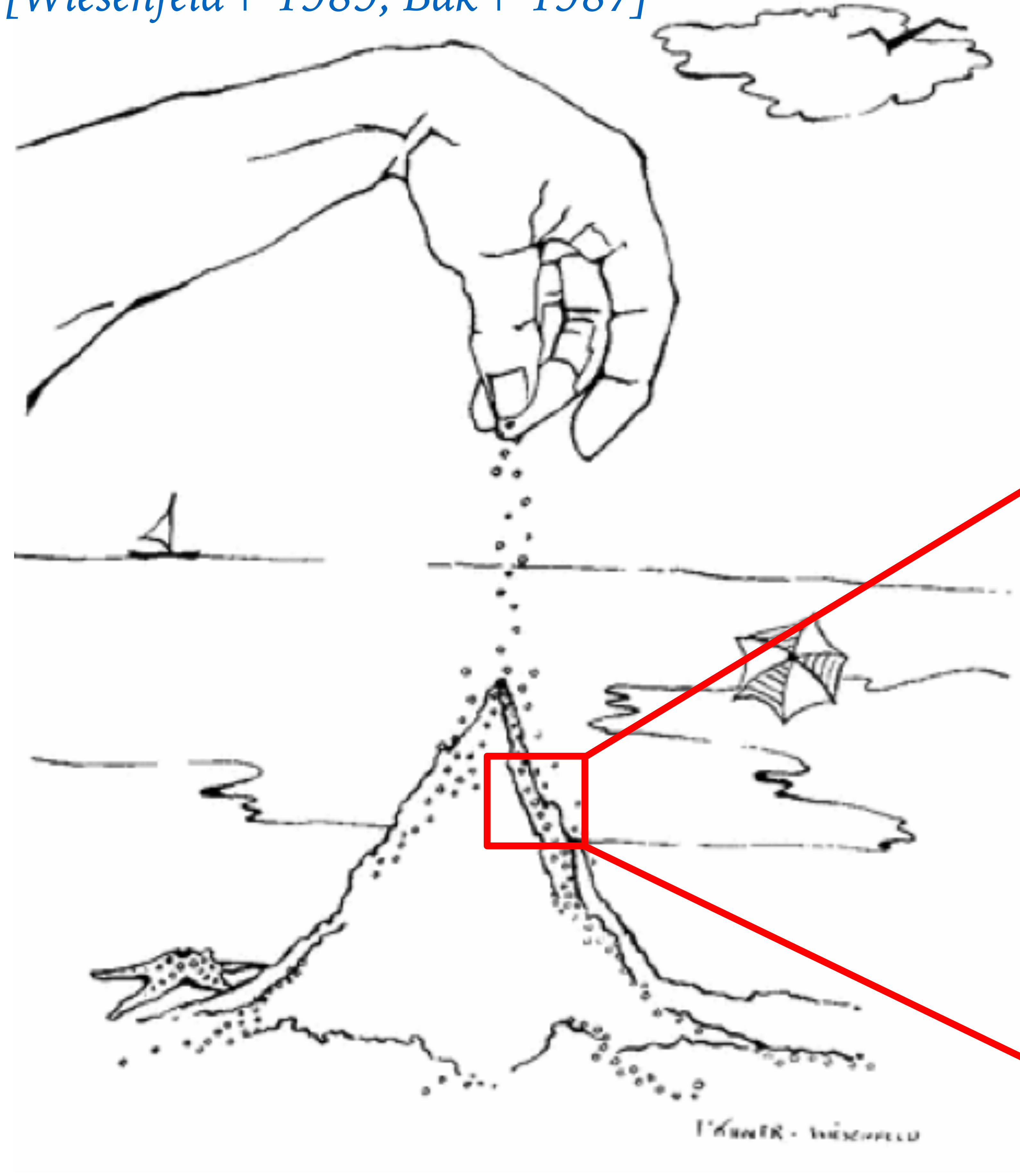

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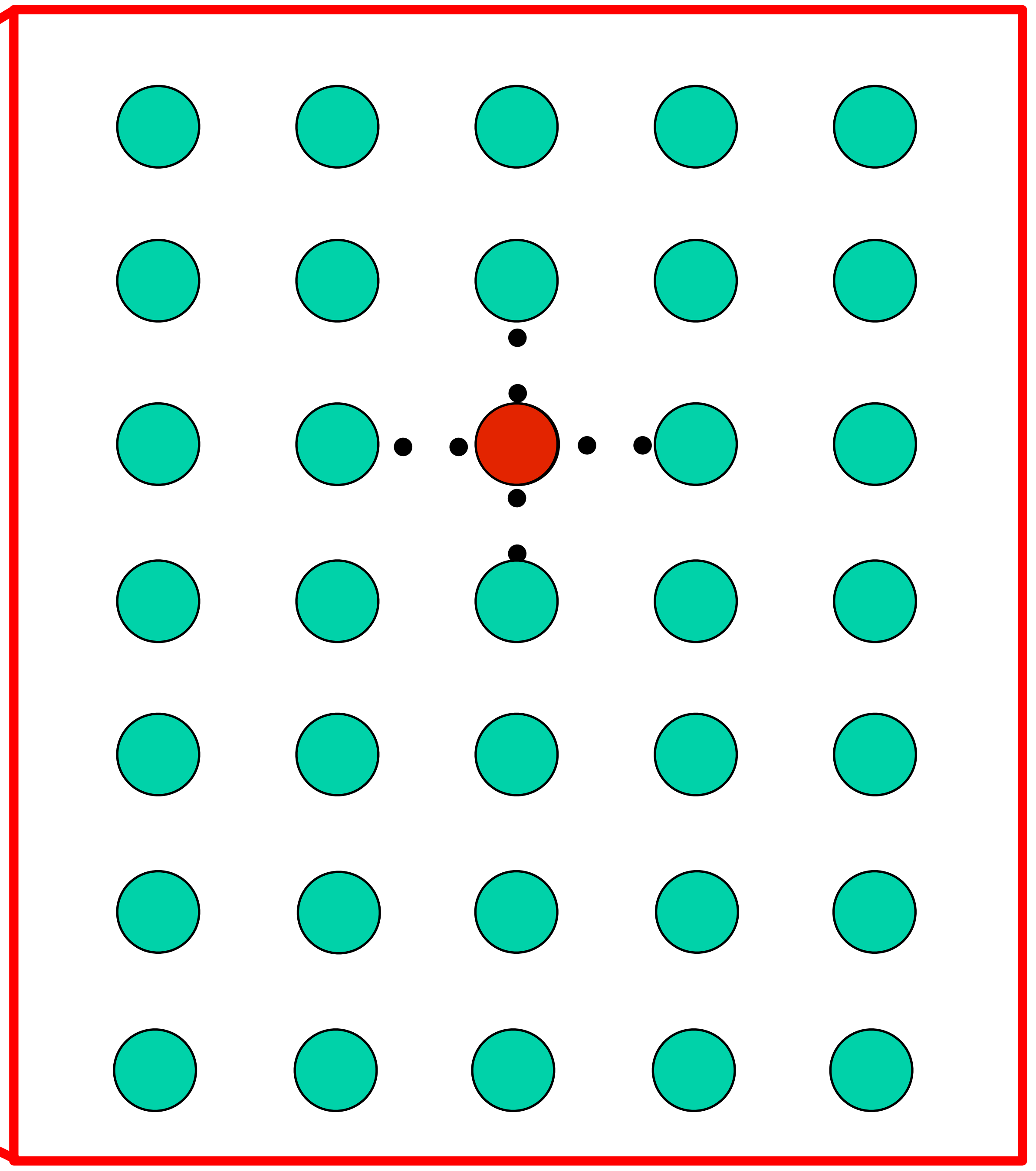
Driver

Threshold



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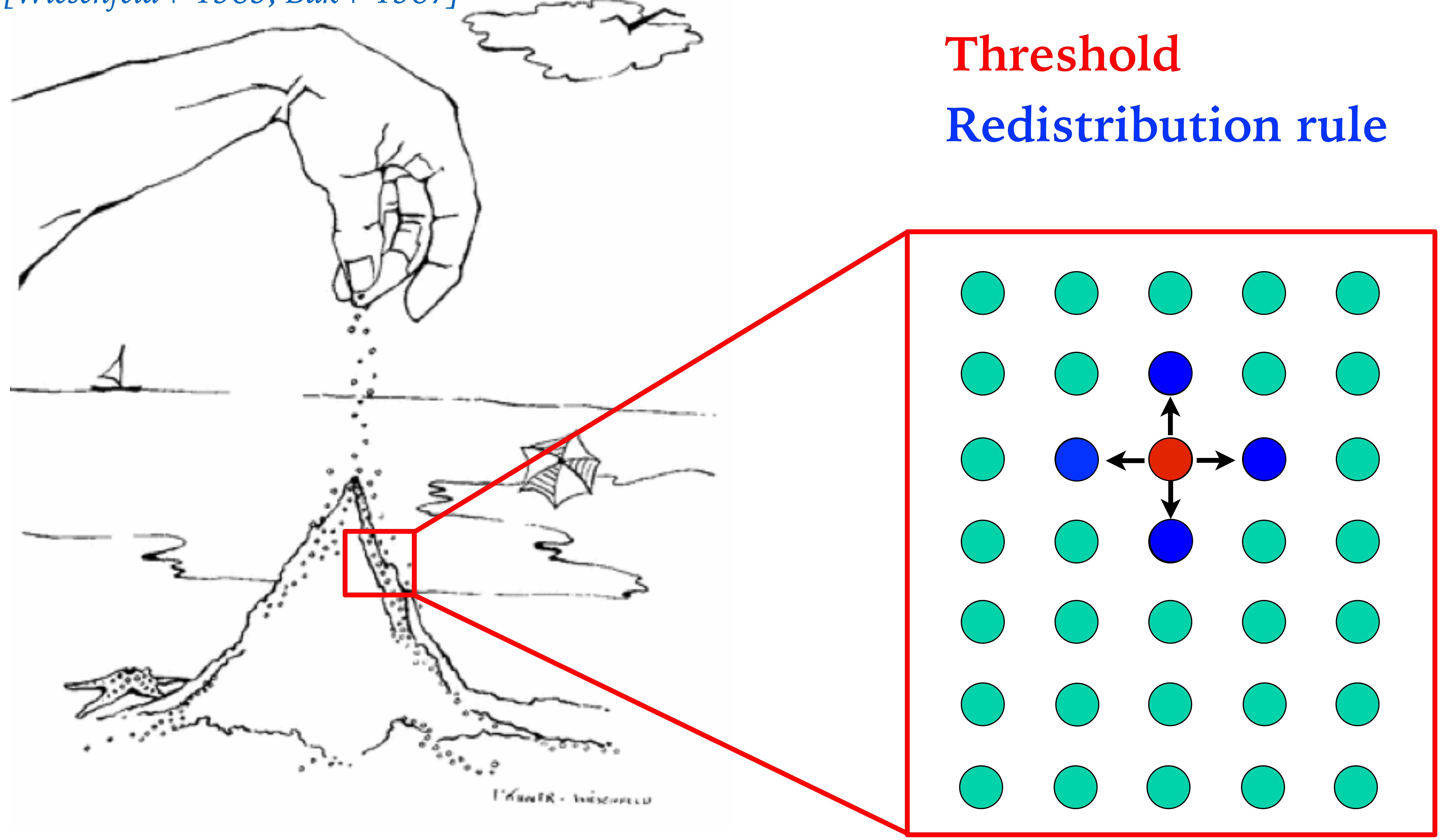
Threshold

Redistribution rule



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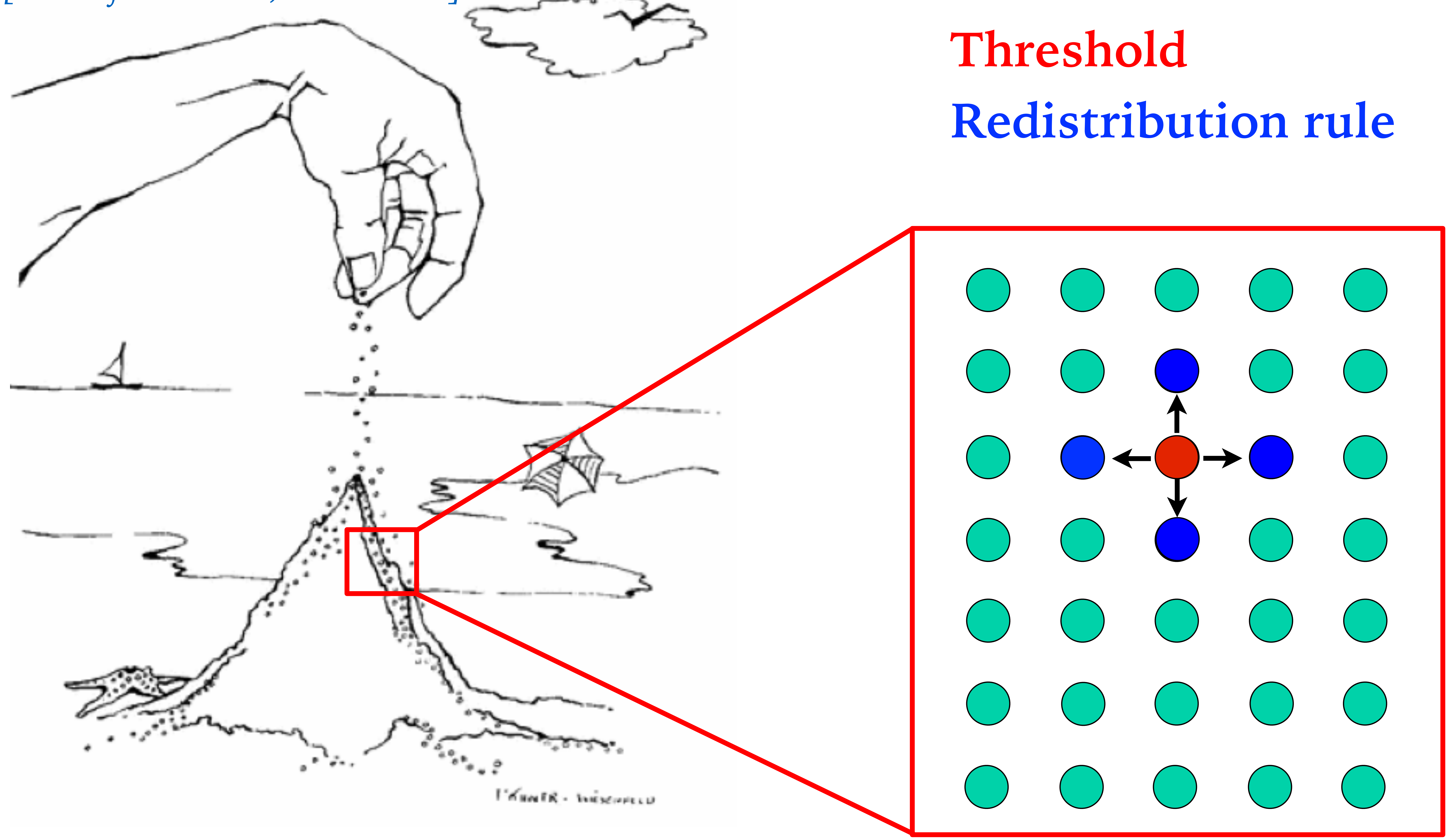

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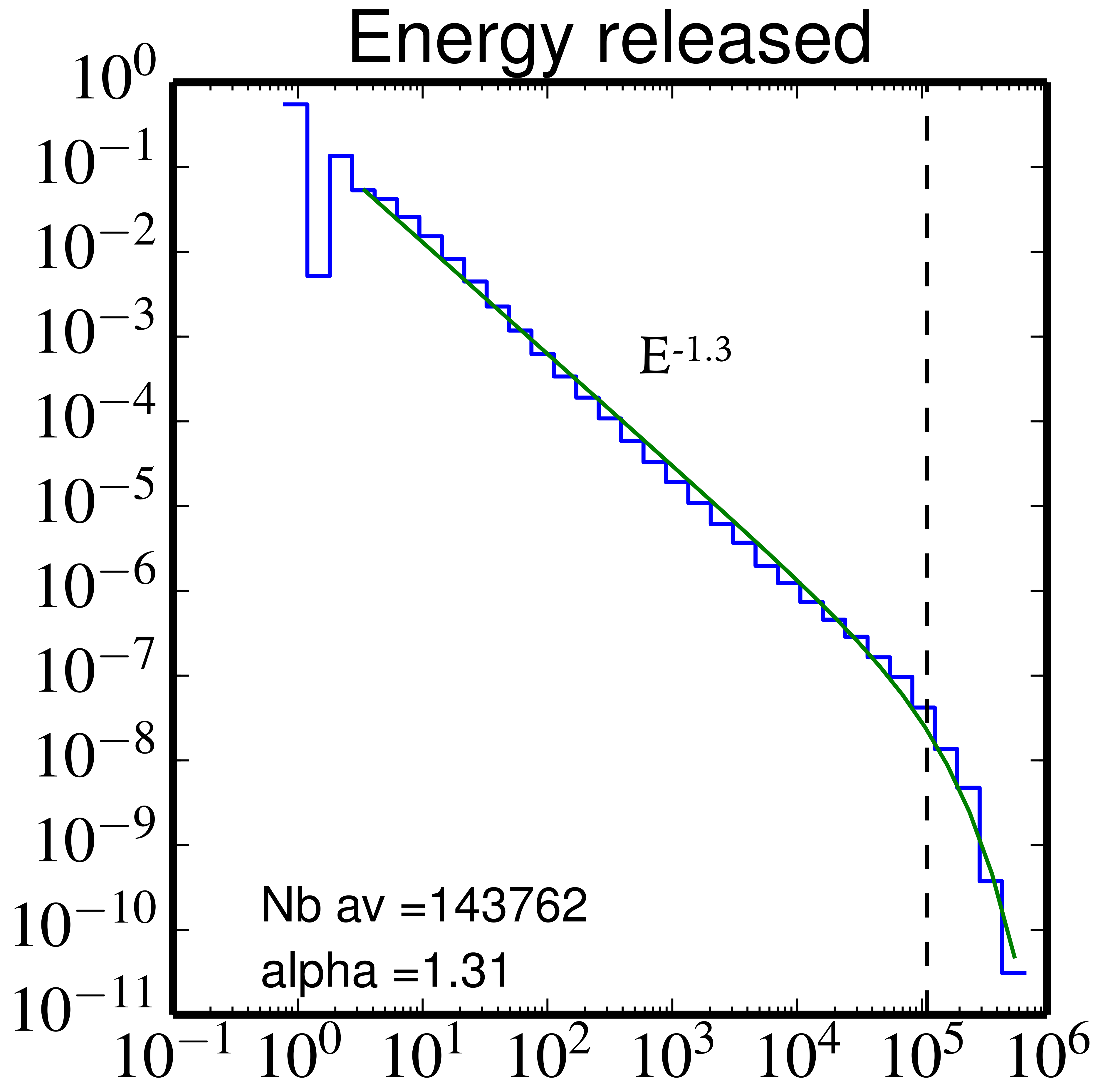
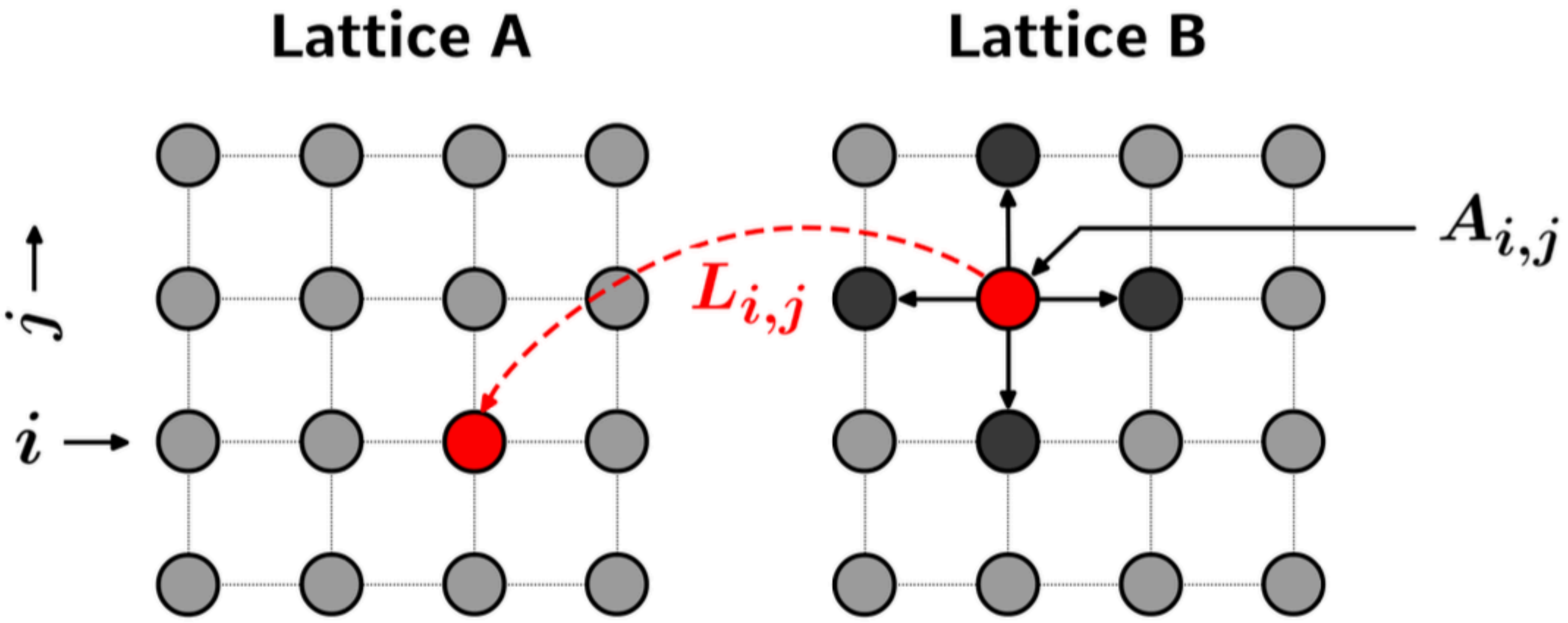


[Strugarek+ 2014a,b]

Coupled sandpile models to represent sympathetic flares



Two coupling parameters:

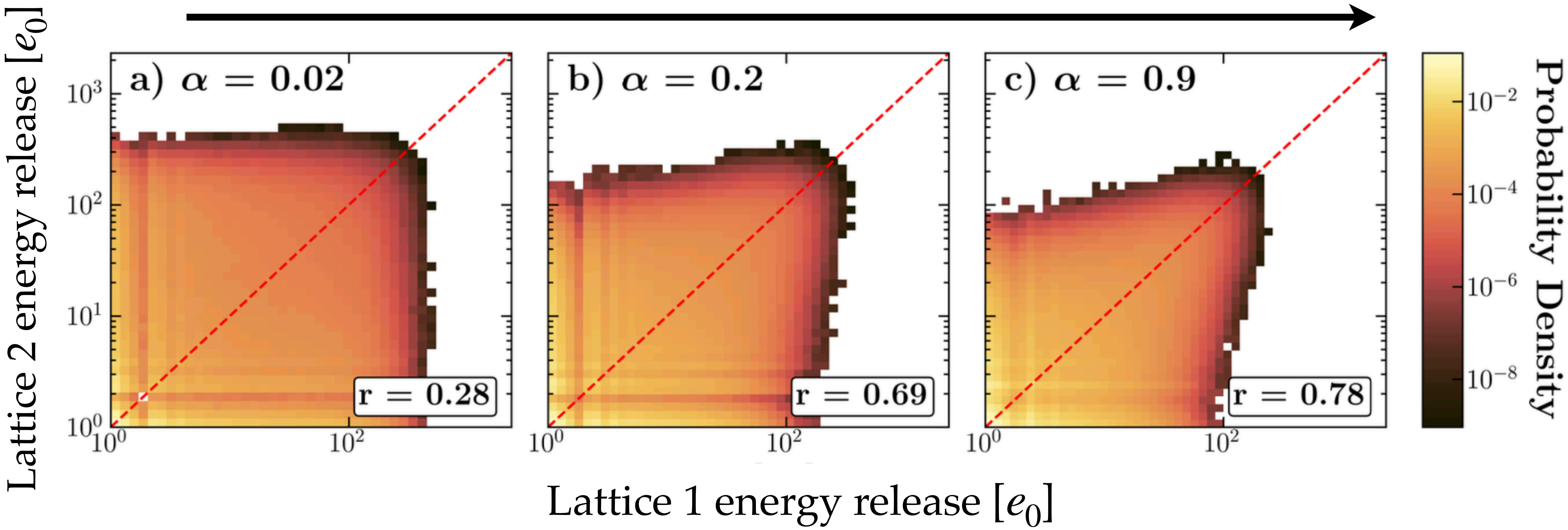
f → fraction of nodes in one lattice connected to the other lattice

α → Amount of transferred nodal variable drawn randomly in $[0,\alpha]$

Guité et al., Sol.Phys. 2025

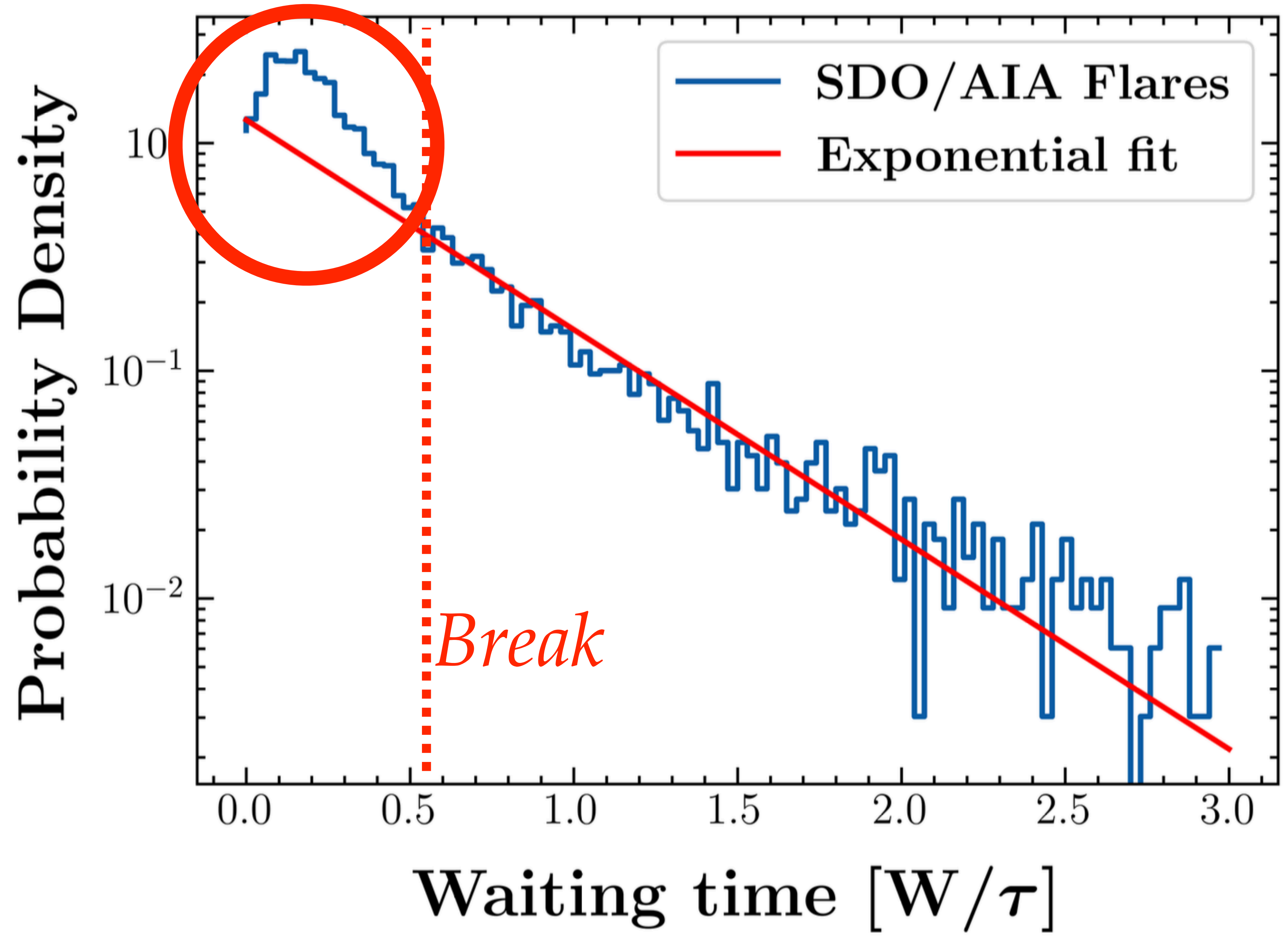
Realtionship between the energy of connected events

Amount of coupling increases: stronger energy correlation



Guité et al., Sol.Phys. 2025

The degree of connectivity impacts the departure from power-laws



Guité et al., Sol.Phys. 2025

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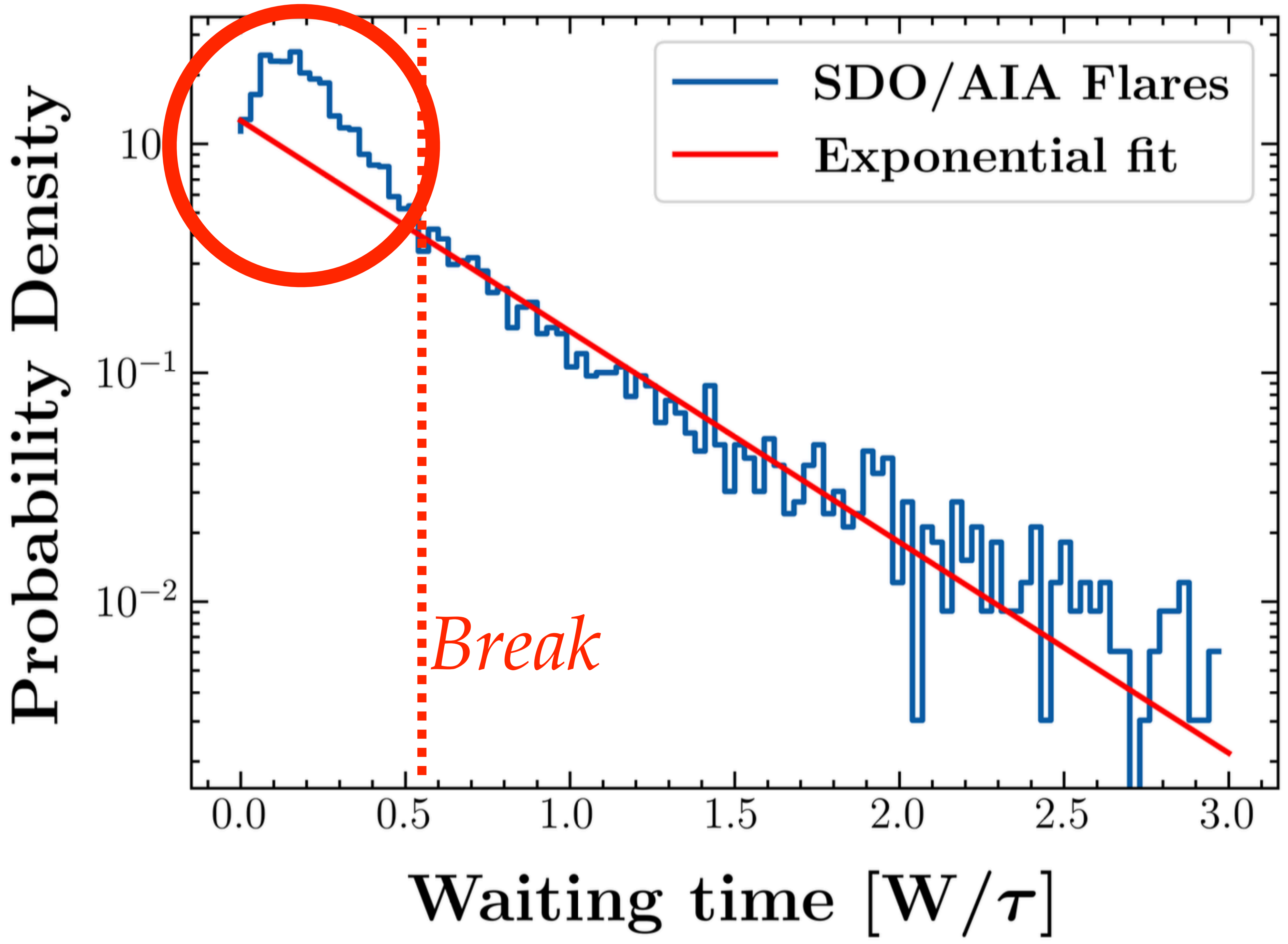
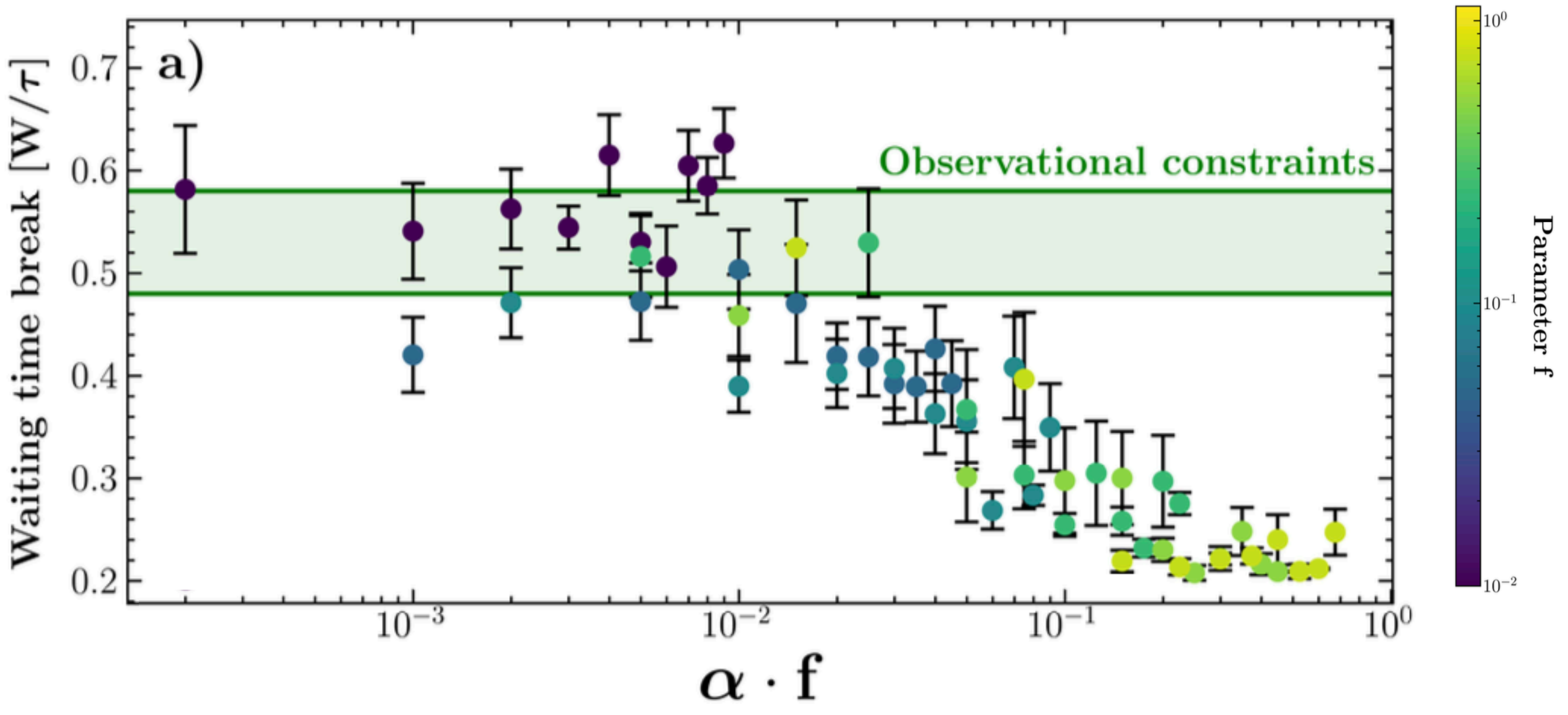


The value of waiting time break suggests a **weak coupling** in the solar case



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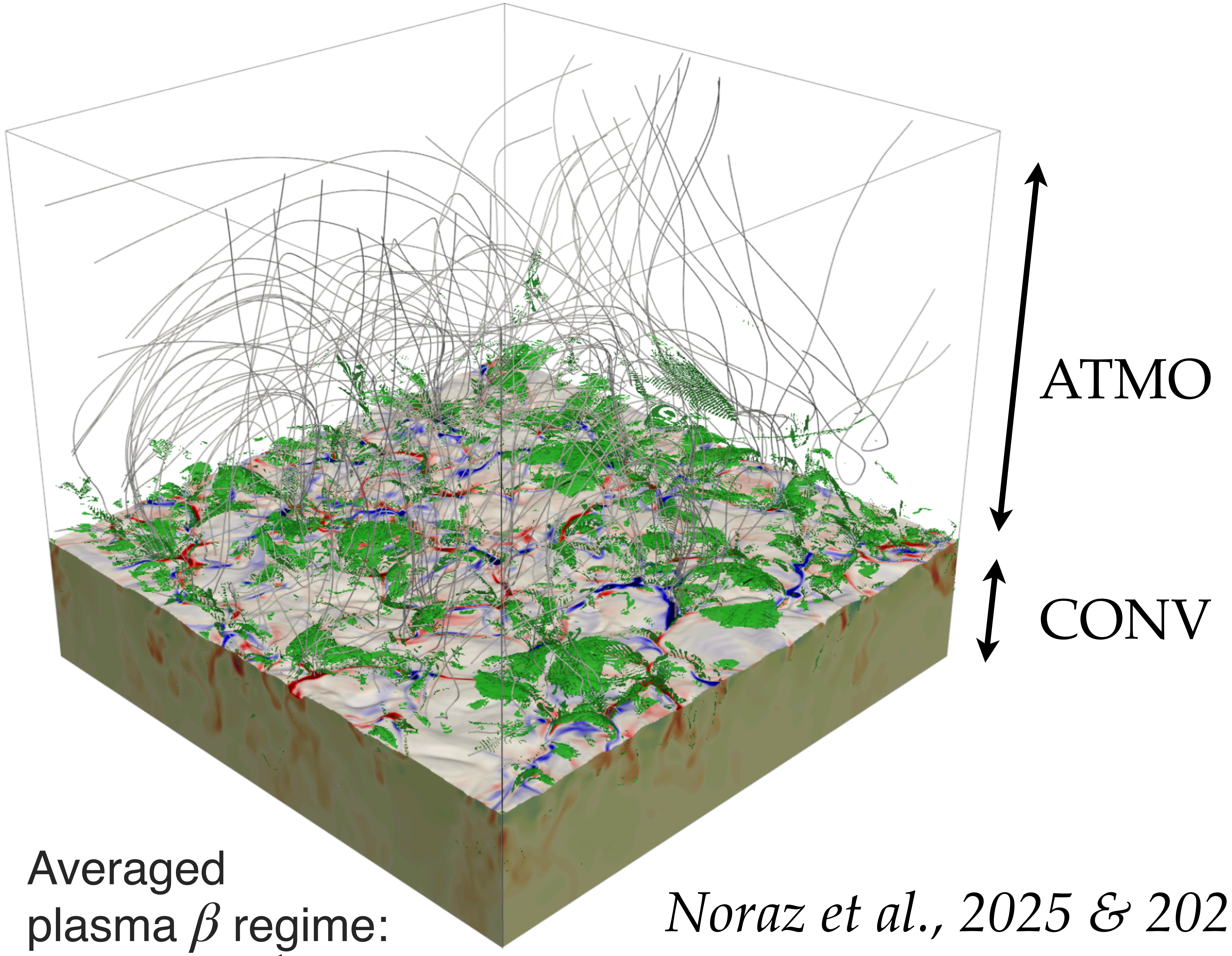
Hunting for avalanche-like behaviour in MHD simulations

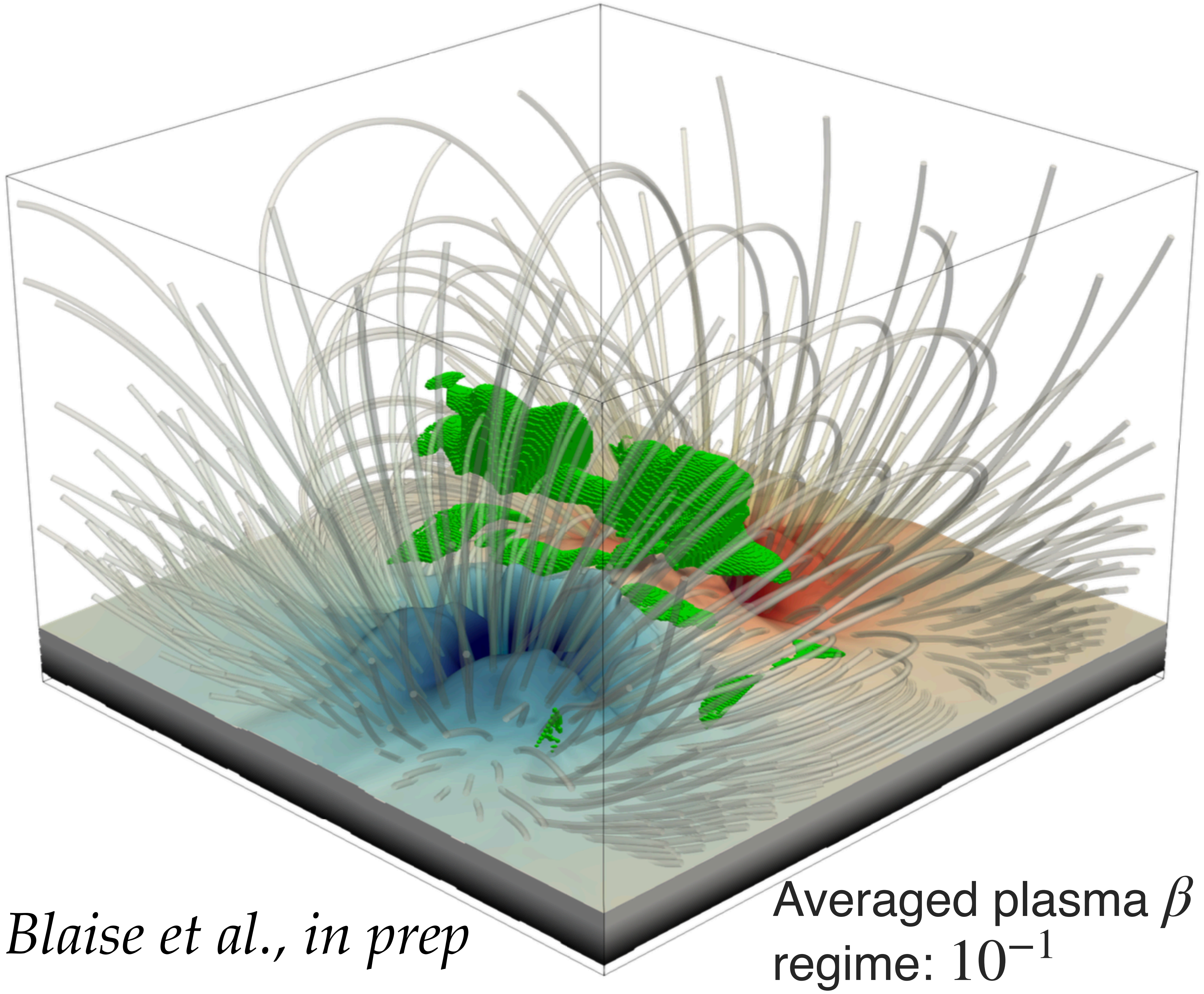
Bifrost - Quiet Sun



Averaged plasma β regime:
ATMO: 10^{-1}
CONV: 10^{3}

Noraz et al., 2025 & 2026

Pluto - twisted reconnecting loop



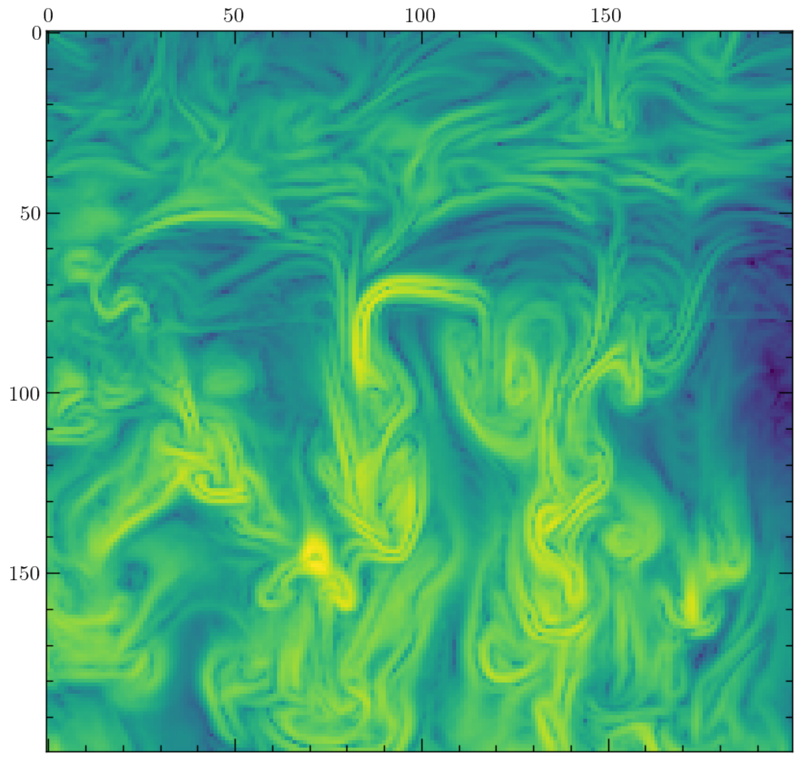
Blaise et al., in prep

Averaged plasma β regime: 10^{-1}

Lamarre et al., PRE 2025

Algorithm to identify dissipation regions (Bifrost example)

$$|\nabla \times \mathbf{B}|$$



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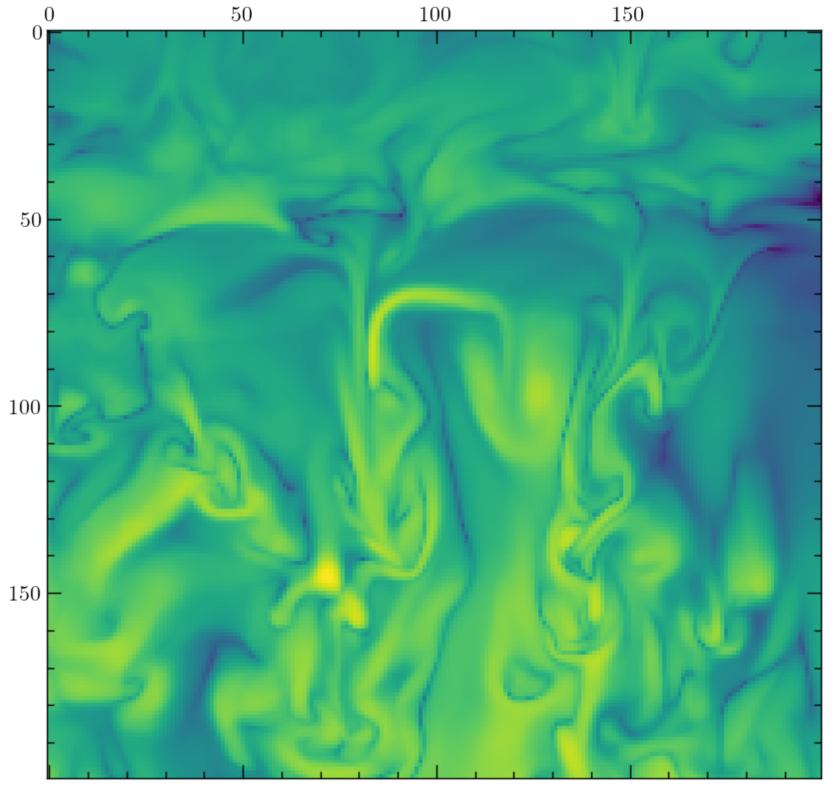
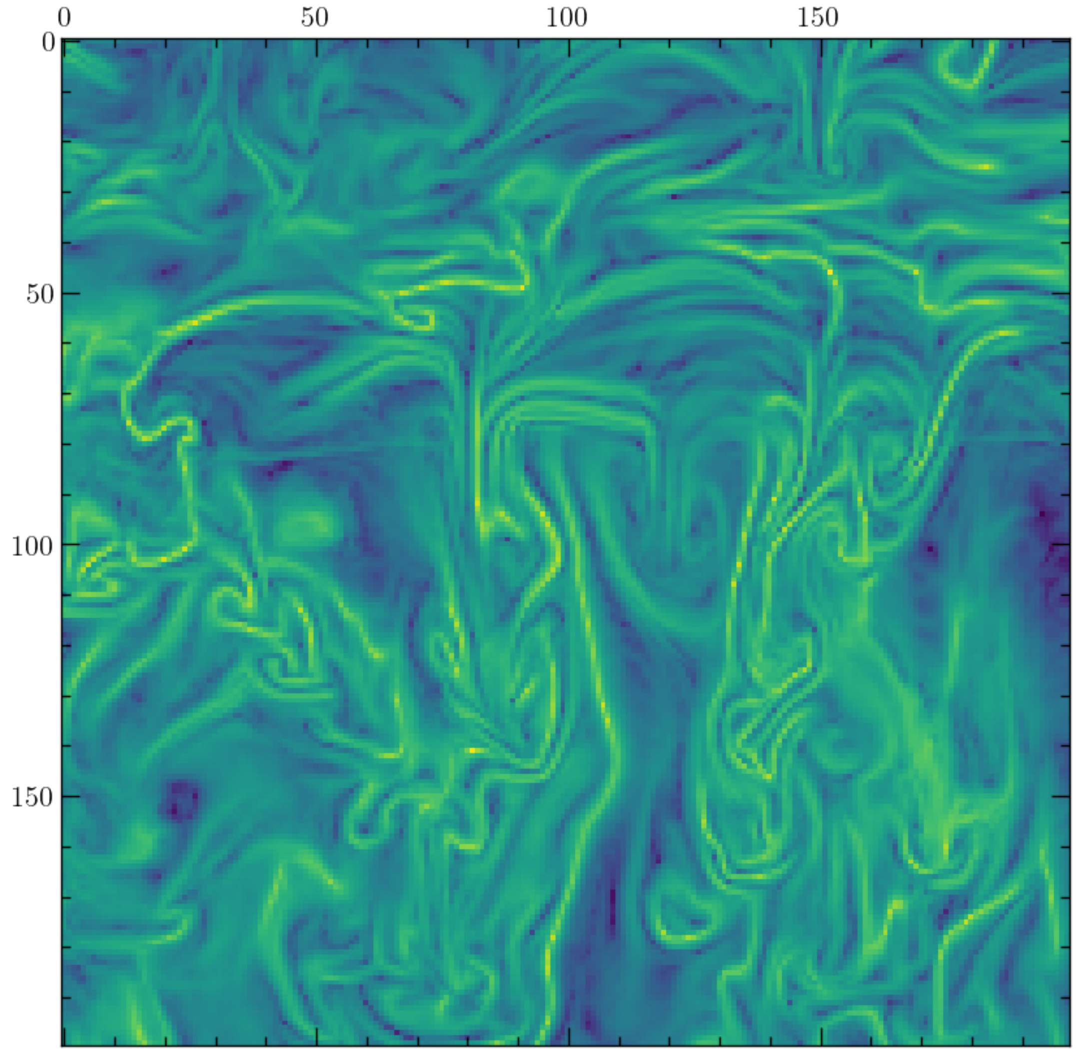
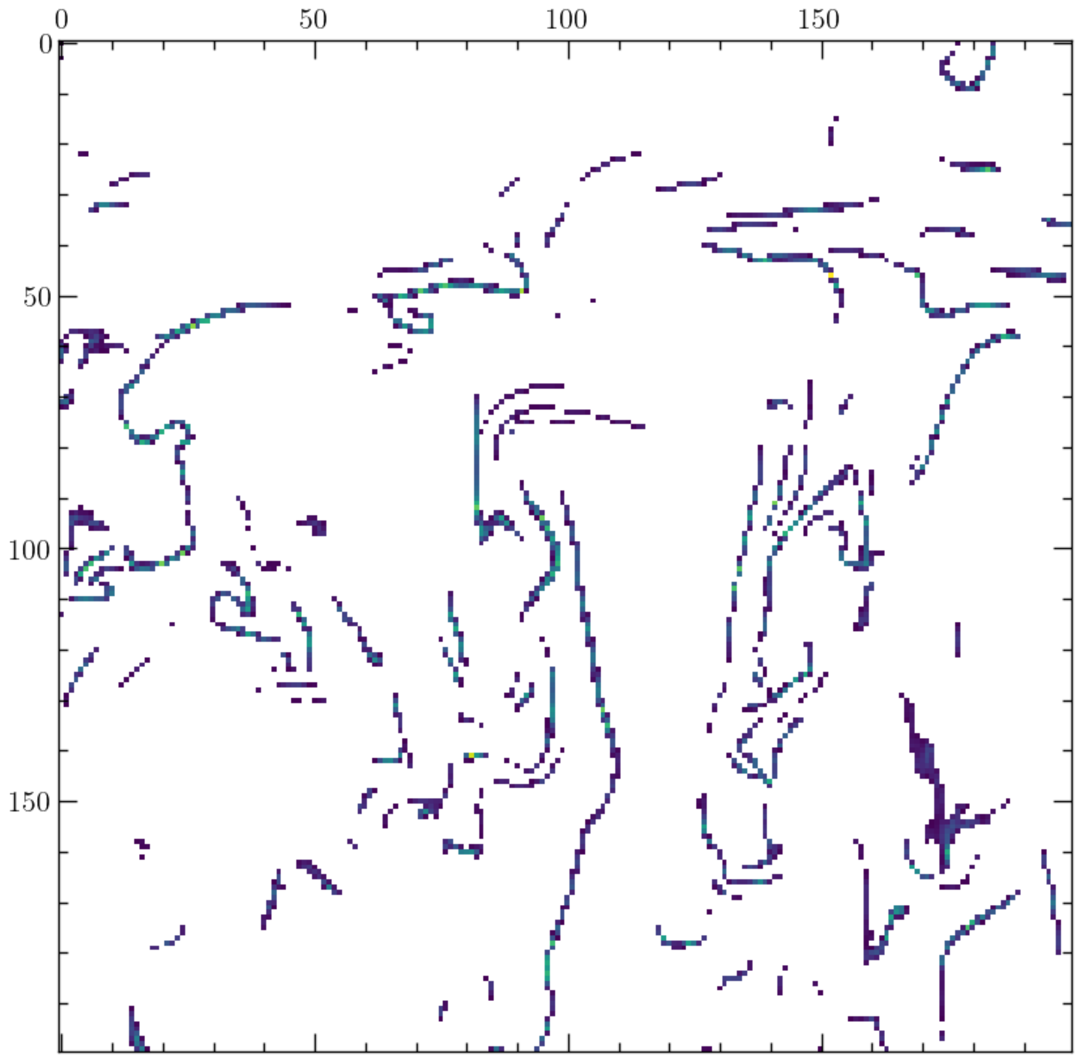


$$\frac{|\nabla \times \mathbf{B}|}{|\mathbf{B}|}$$





Labelling strategy: Hoshen-Kopelman algorithm
Time-tracking: ancestry as in *Zhdankin et al. (2015)*

Lamarre et al., PRE 2025

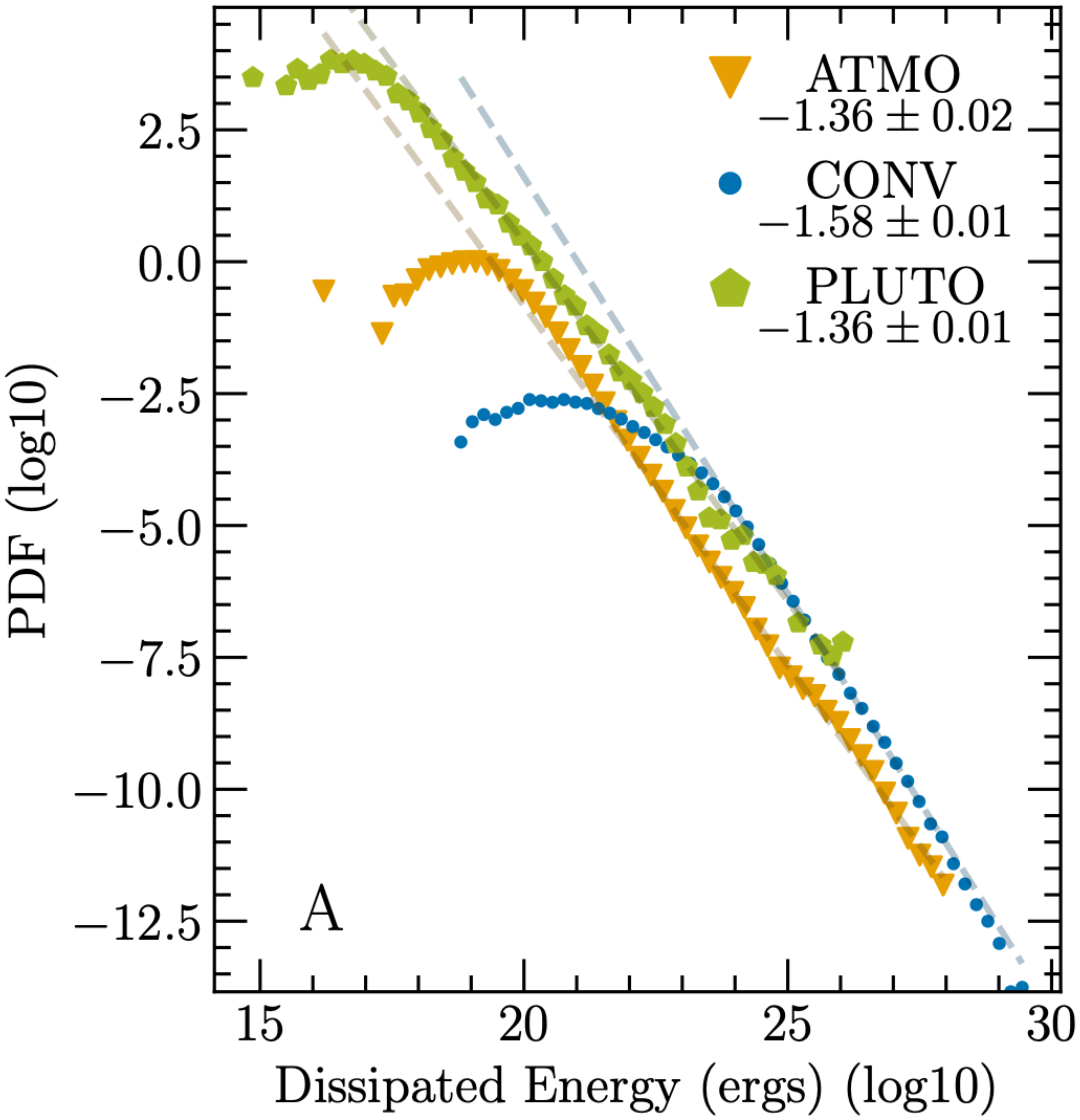
Statistics of the identified events

All identified regions lead to a distribution of dissipation events organised as power laws

ATMO (Bifrost) and **PLUTO** regions have a distribution $\propto E_{\rm diss}^{-1.36}$

CONV (Bifrost) have a distribution $\propto E_{\rm diss}^{-1.58}$

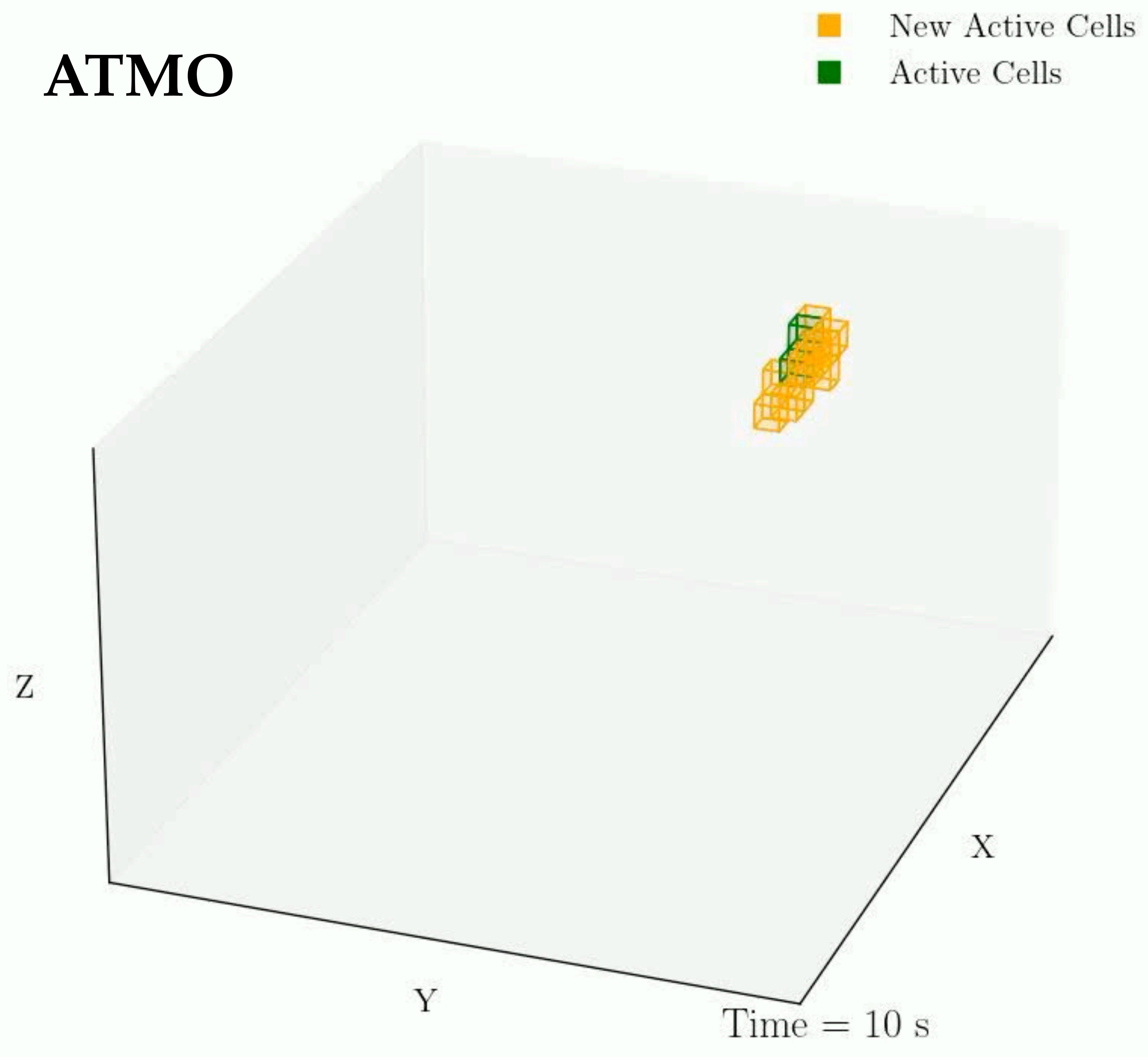
BUT different regions reach similar extrema of dissipated energy…
and **various physical processes can lead to a power-law distribution of events**



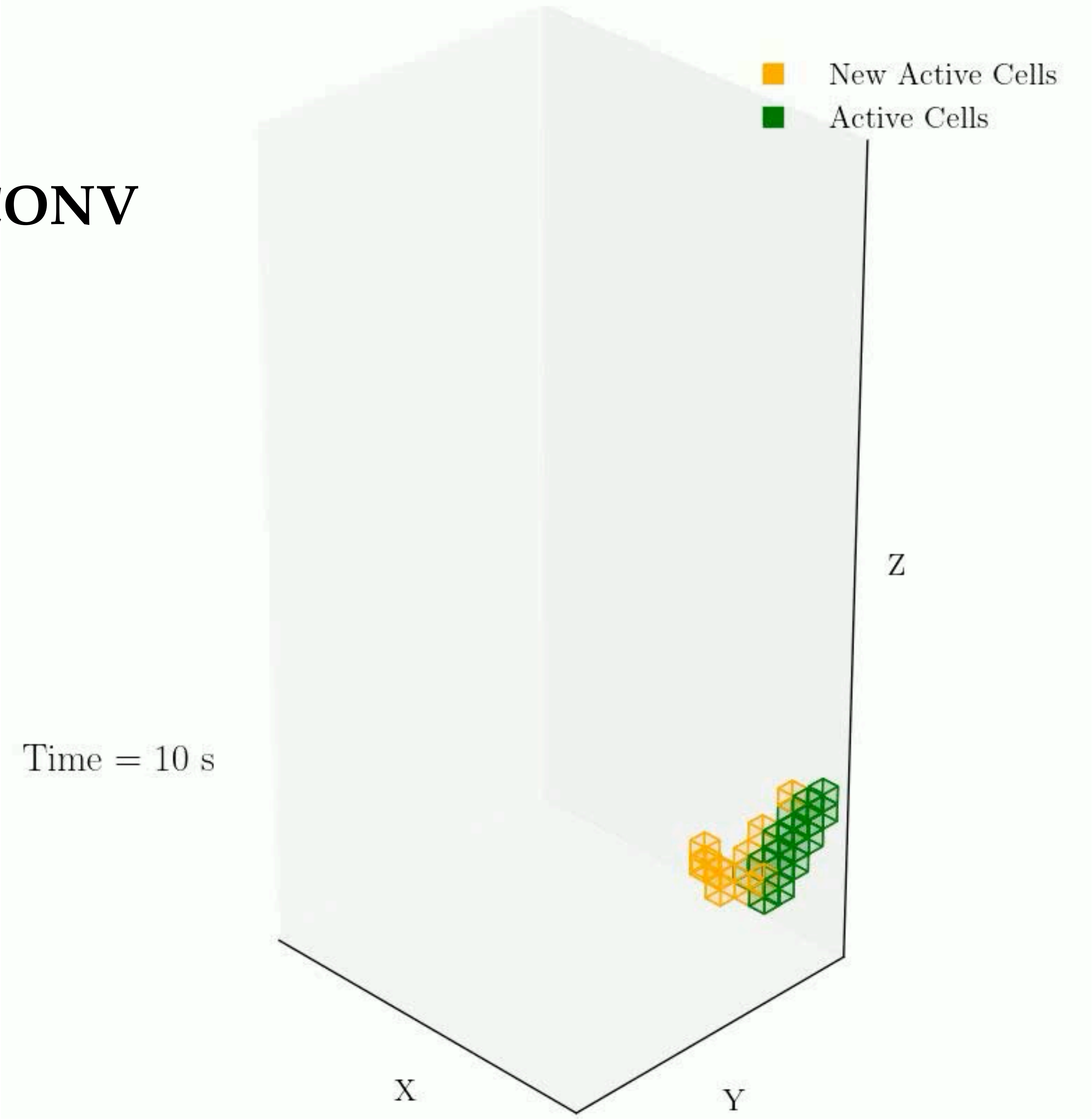
Lamarre et al., PRE 2025

Example of identified events in Bifrost simulation

ATMO



CONV



Lamarre et al., PRE 2025

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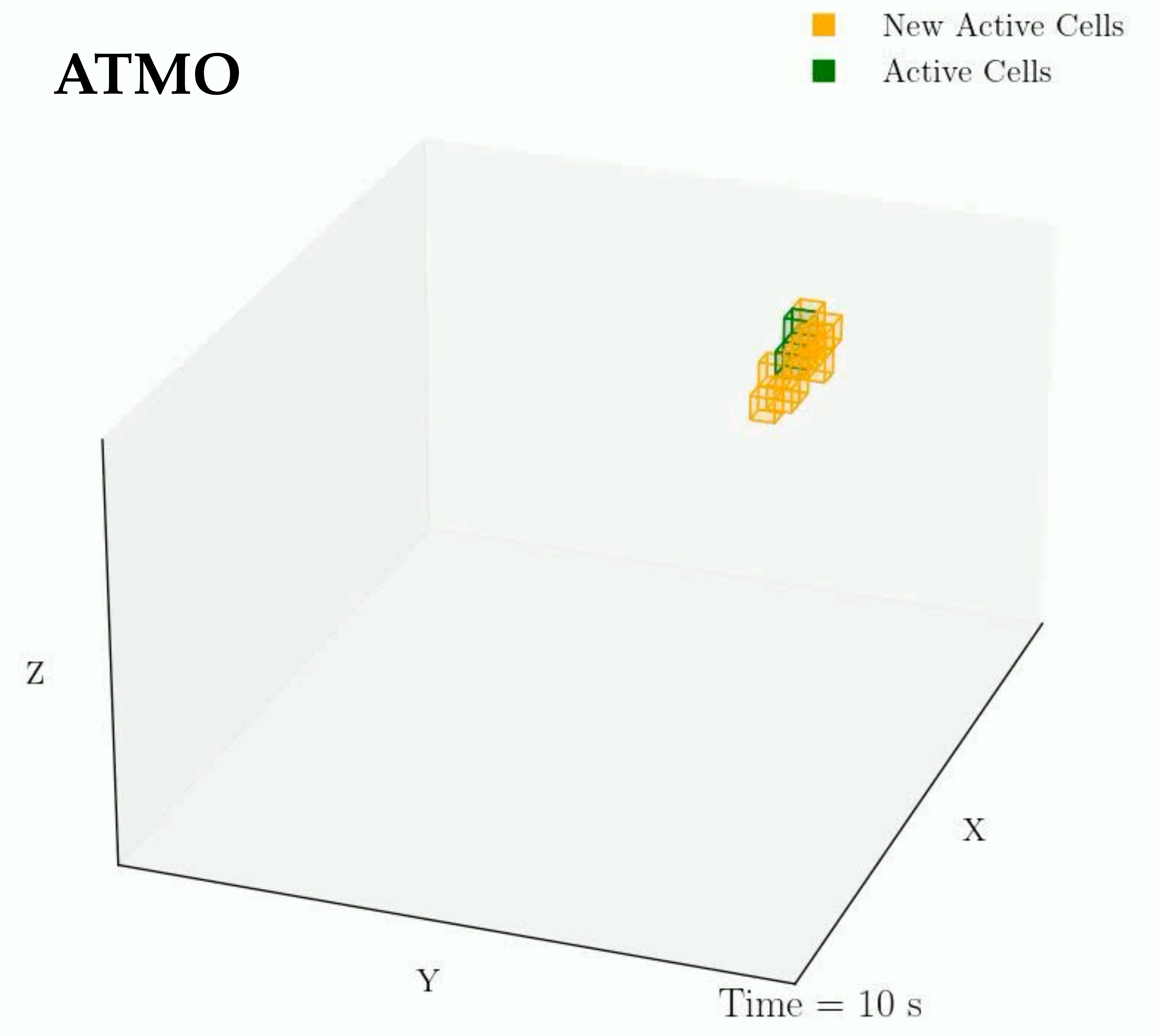

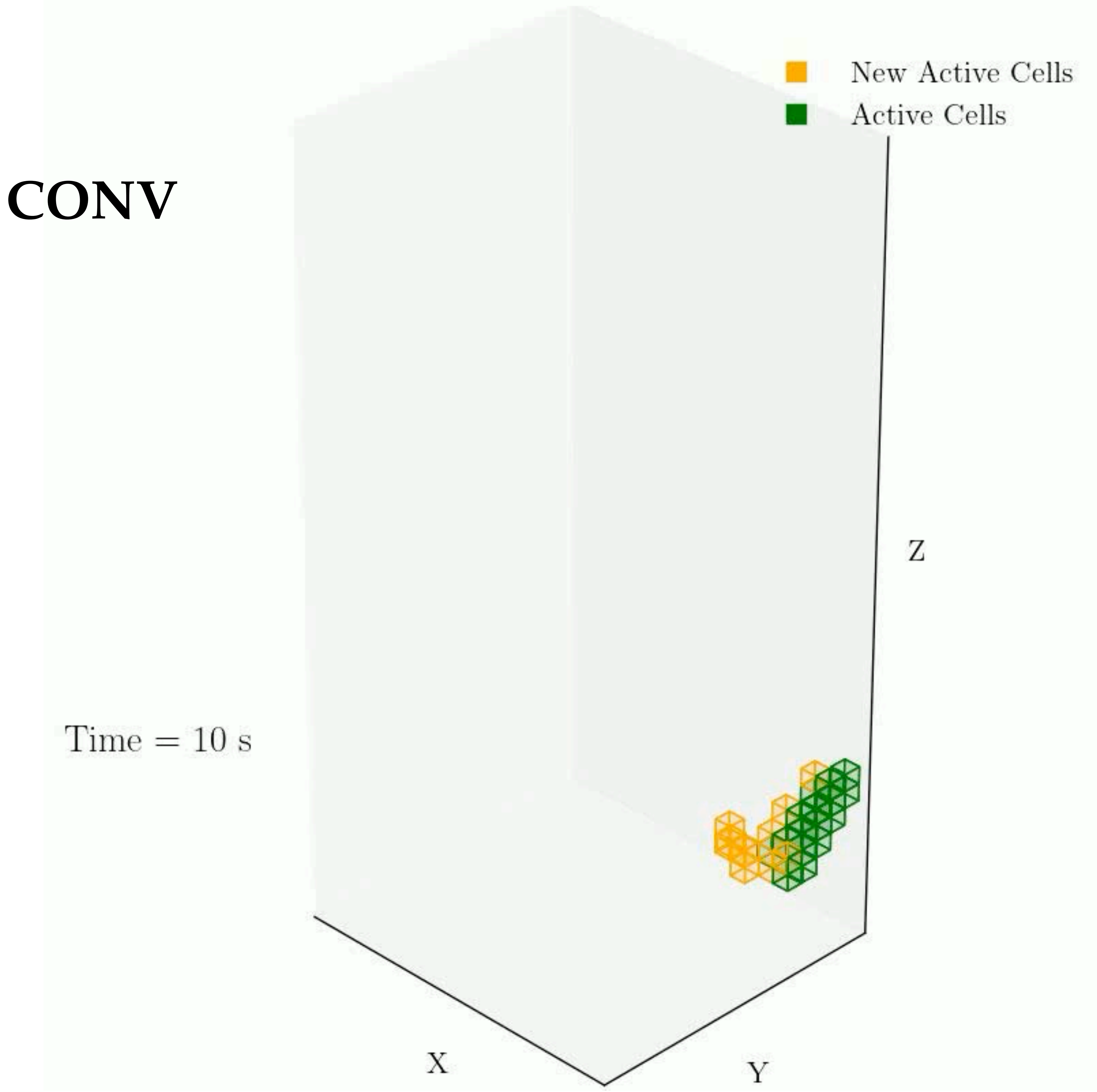

Lamarre et al., PRE 2025

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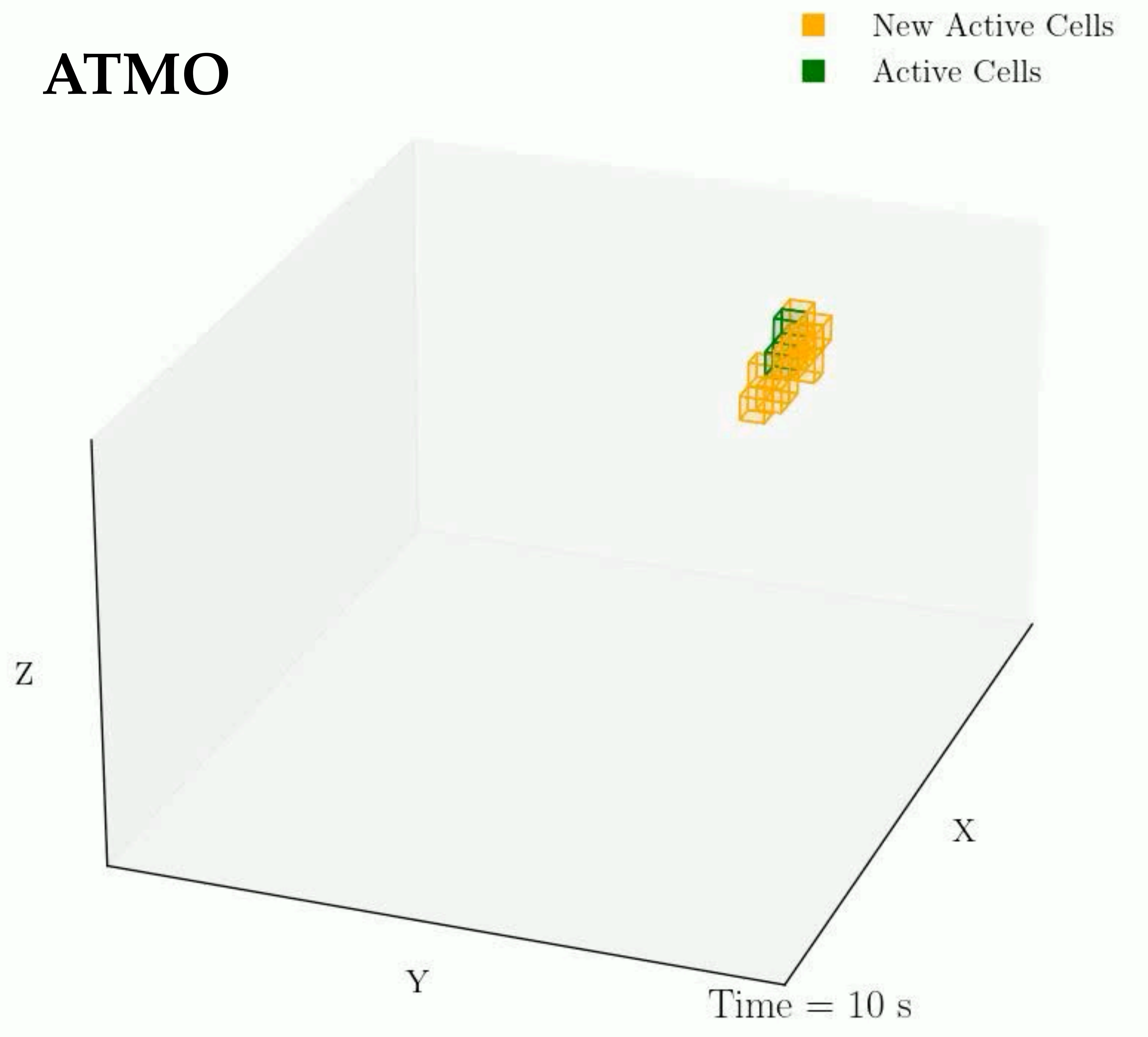

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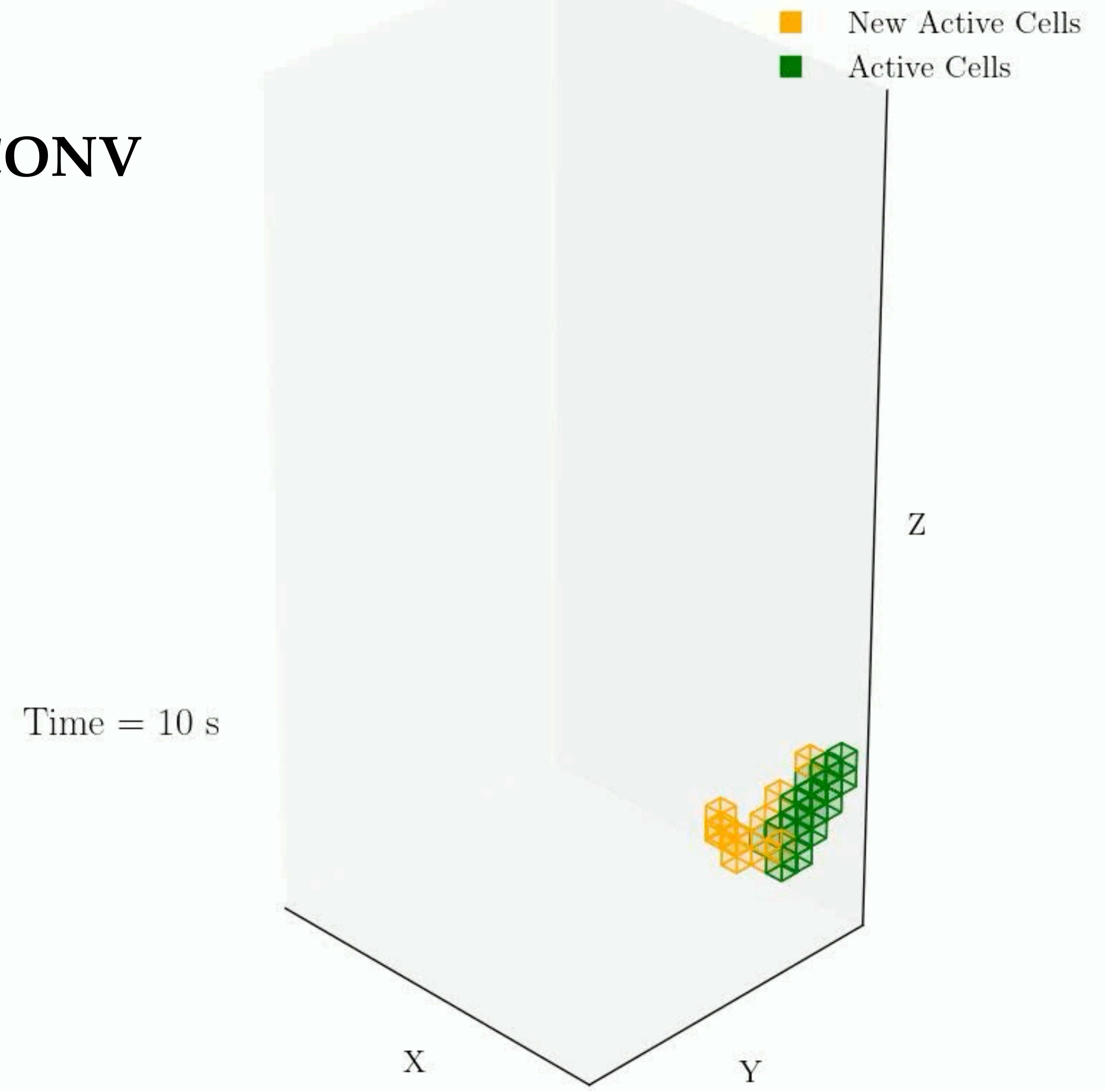


Lamarre et al., PRE 2025

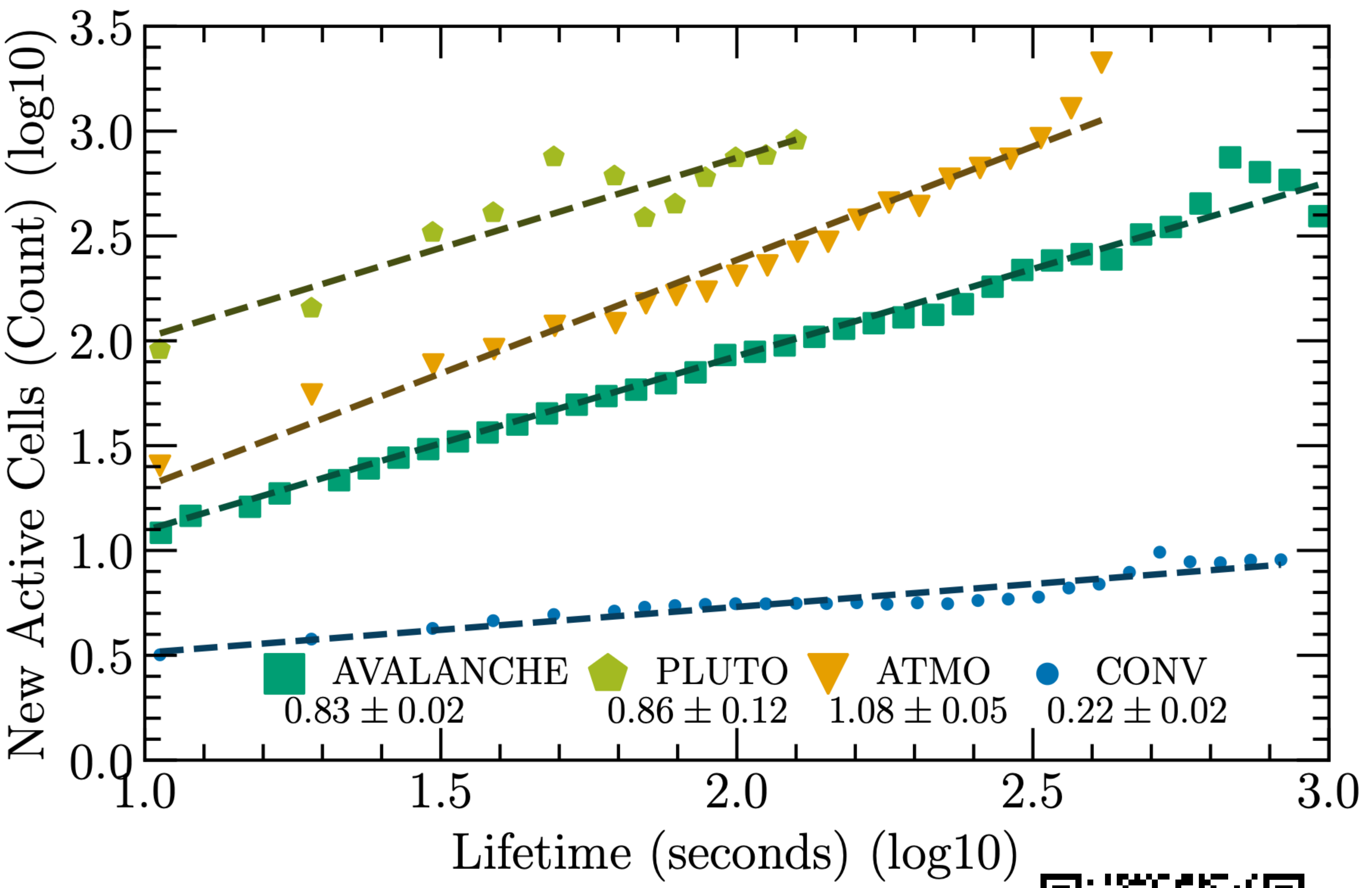
Unveiling an avalanche-like behaviour: the spreading exponent

The **spreading exponent characterises how the identified structures grow**. If the growth is scale-invariant, $S(t) \propto t^{\sigma}$

The **value of σ** allows to distinguish various classes of scale-invariant growth processes

Munoz et al., PRE (1999)

Aschwanden, ApJ (2012)



ATMO and PLUTO are very similar to classical avalanche models!

CONV is definitely not, as expected

Lamarre et al., PRE 2025

Conclusions

Statistics of sympathetic solar flares: a 30° separation and a list of candidates (including STIX flares!)

[Guité, Strugarek & Charbonneau A&A 2025]

Sandpile models of sympathetic flares: suggests quite a weak coupling in the solar case

[Guité, Charbonneau & Strugarek Sol Phys. 2025]

Dissipation events MHD simulations of the solar atmosphere (low-beta) behave as avalanches

[Lamarre et al., PRE 2025]