Monday June 1st - IDM 2026

Tracking Dark Matter through Cosmic Magnetism: Can the Footprint of Dark Matter Survive Nonlinear Evolution?

16th International Workshop on the Identification of Dark Matter 2026

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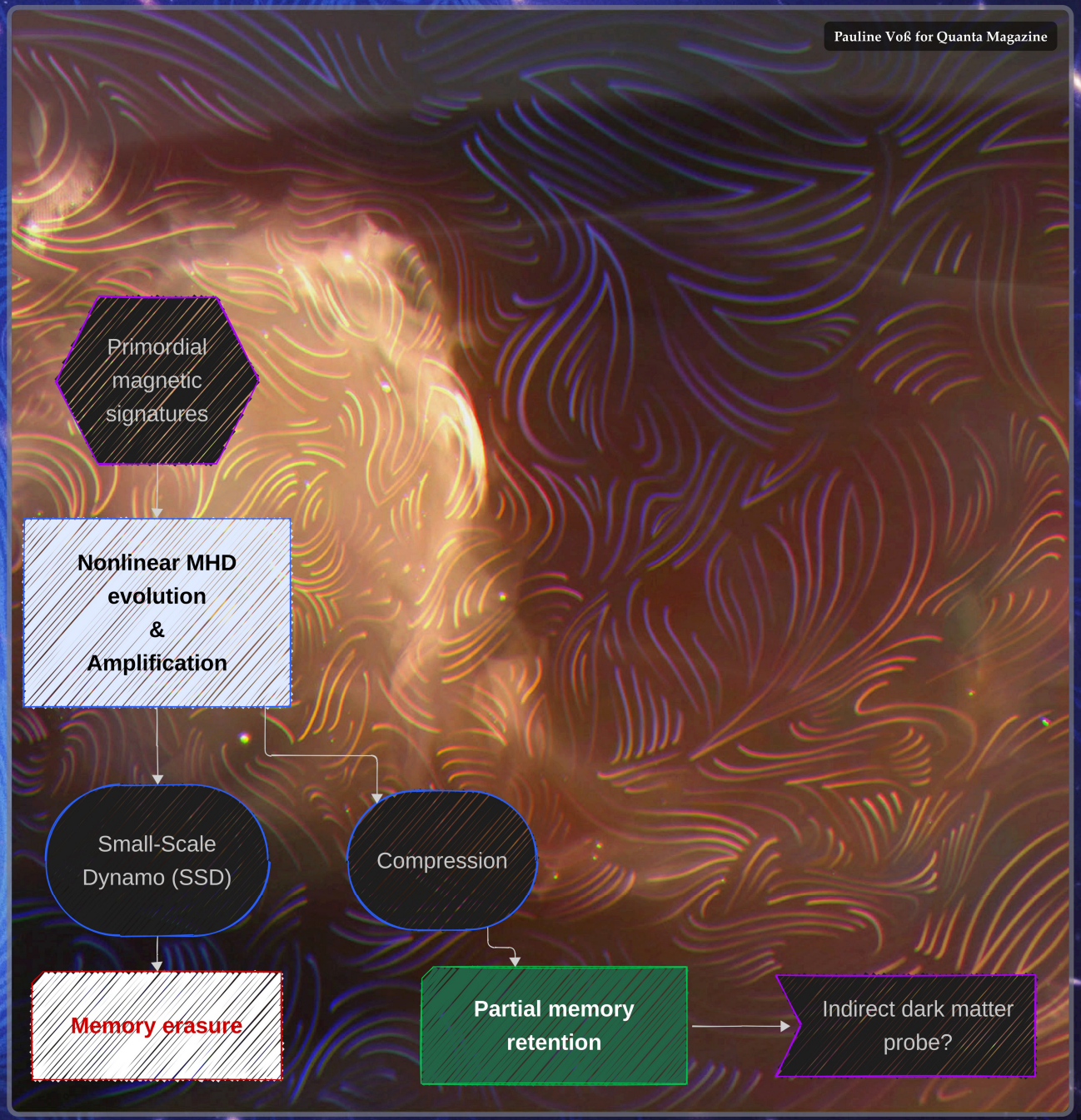
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Overview

The Primordial Question

- **Primordial magnetic signatures** may carry information about early-Universe dark matter physics

- Nonlinear structure formation reshapes that information through **compression**, **turbulence**, and **small-scale dynamo action**

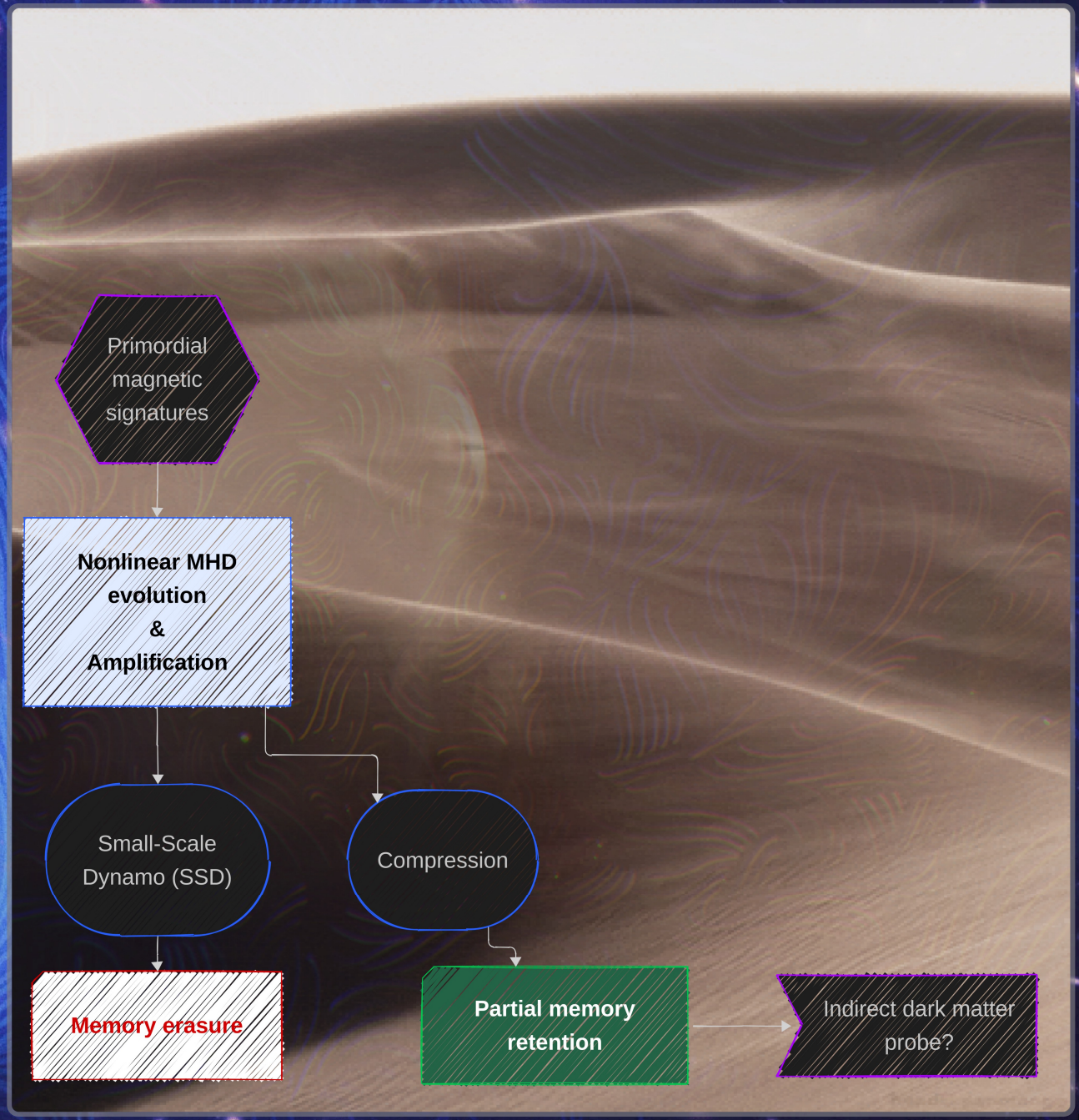


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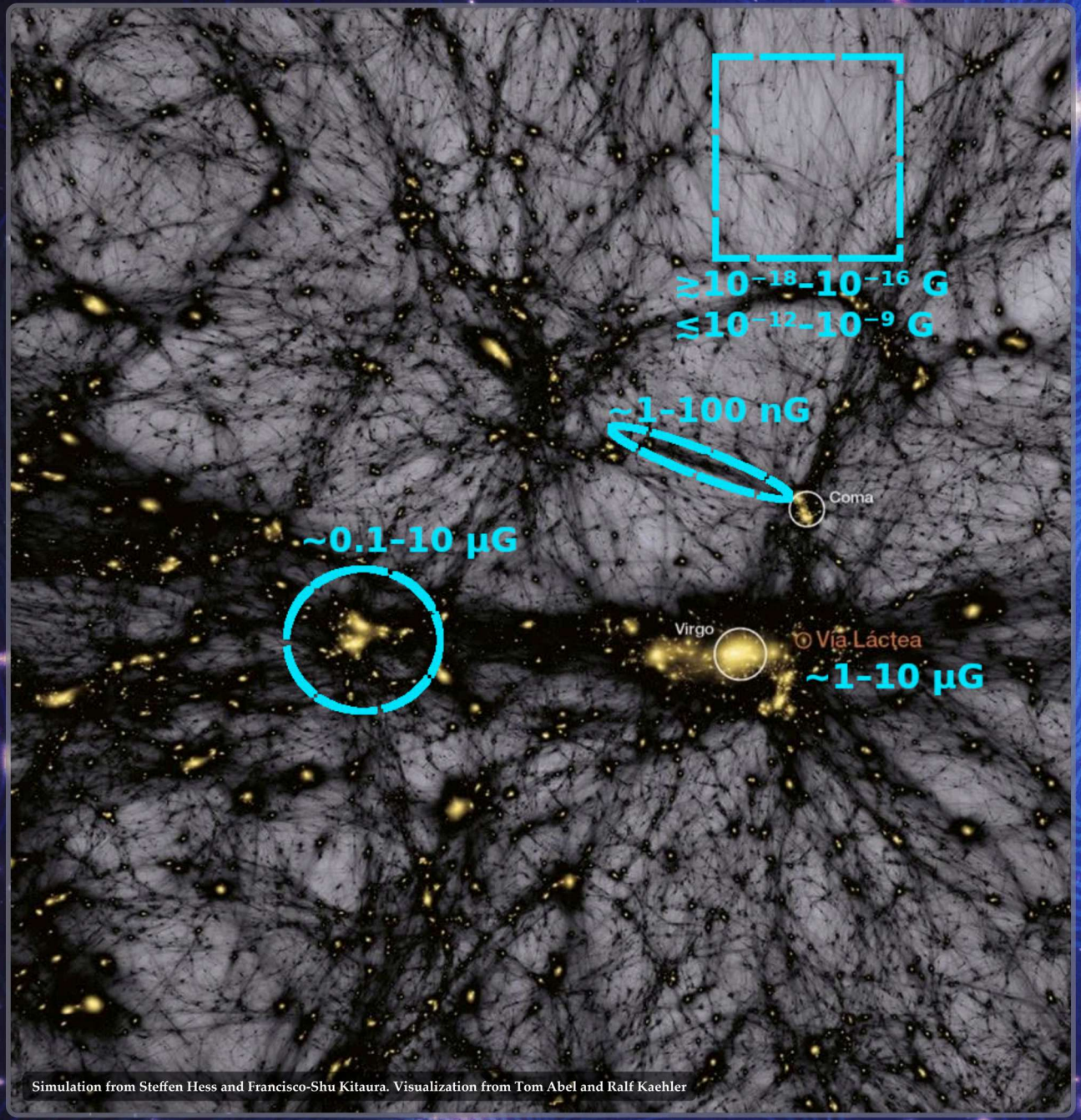
The Primordial Question

- **Primordial magnetic signatures** may carry information about early-Universe dark matter physics
- Nonlinear structure formation reshapes that information through **compression**, **turbulence**, and **small-scale dynamo action**
- The **key question** is whether the magnetic imprint can be amplified and still survive as an **indirect probe of dark matter**



What are Cosmological Magnetic Fields?

Definitions & Diagnostics

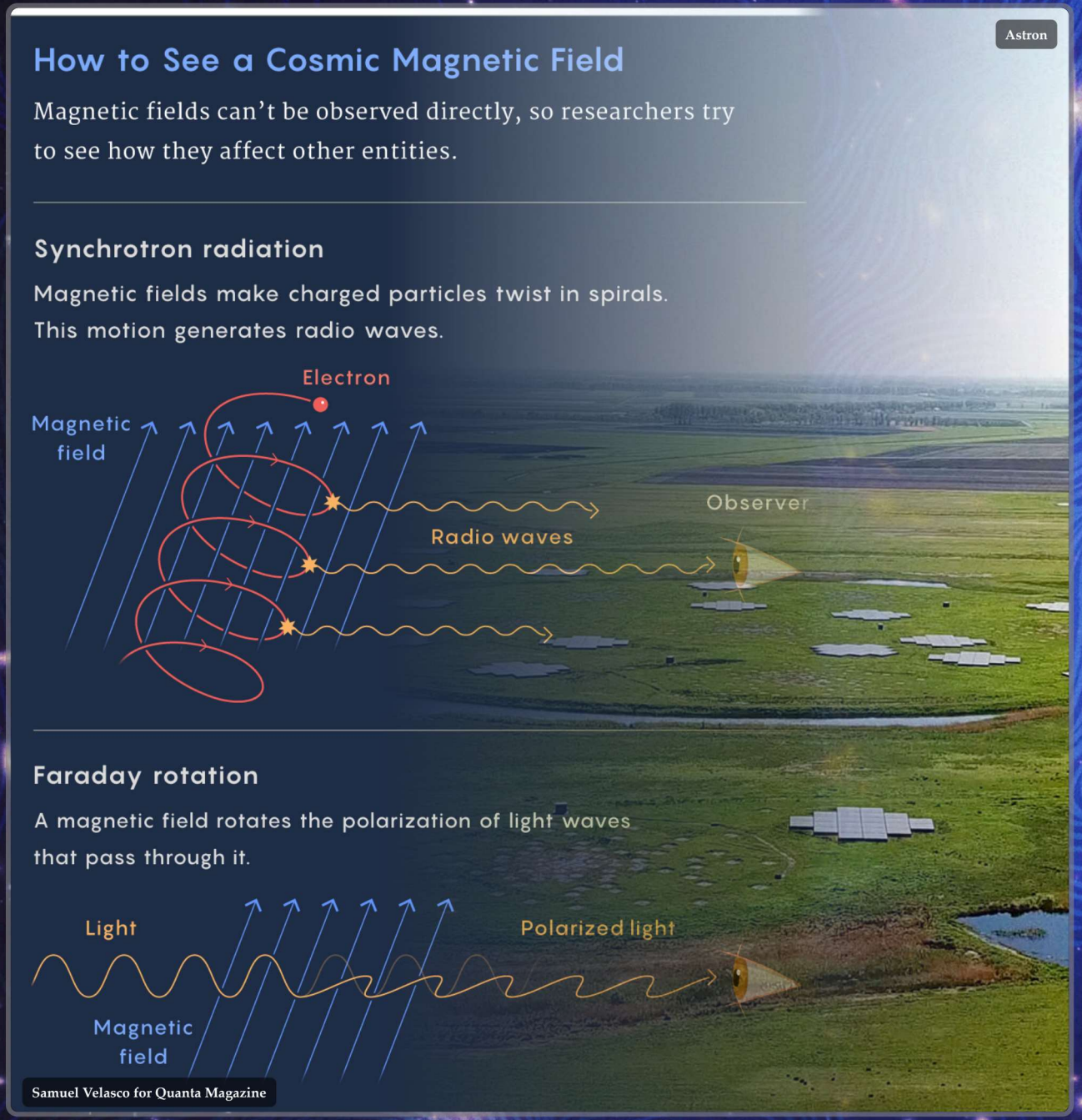


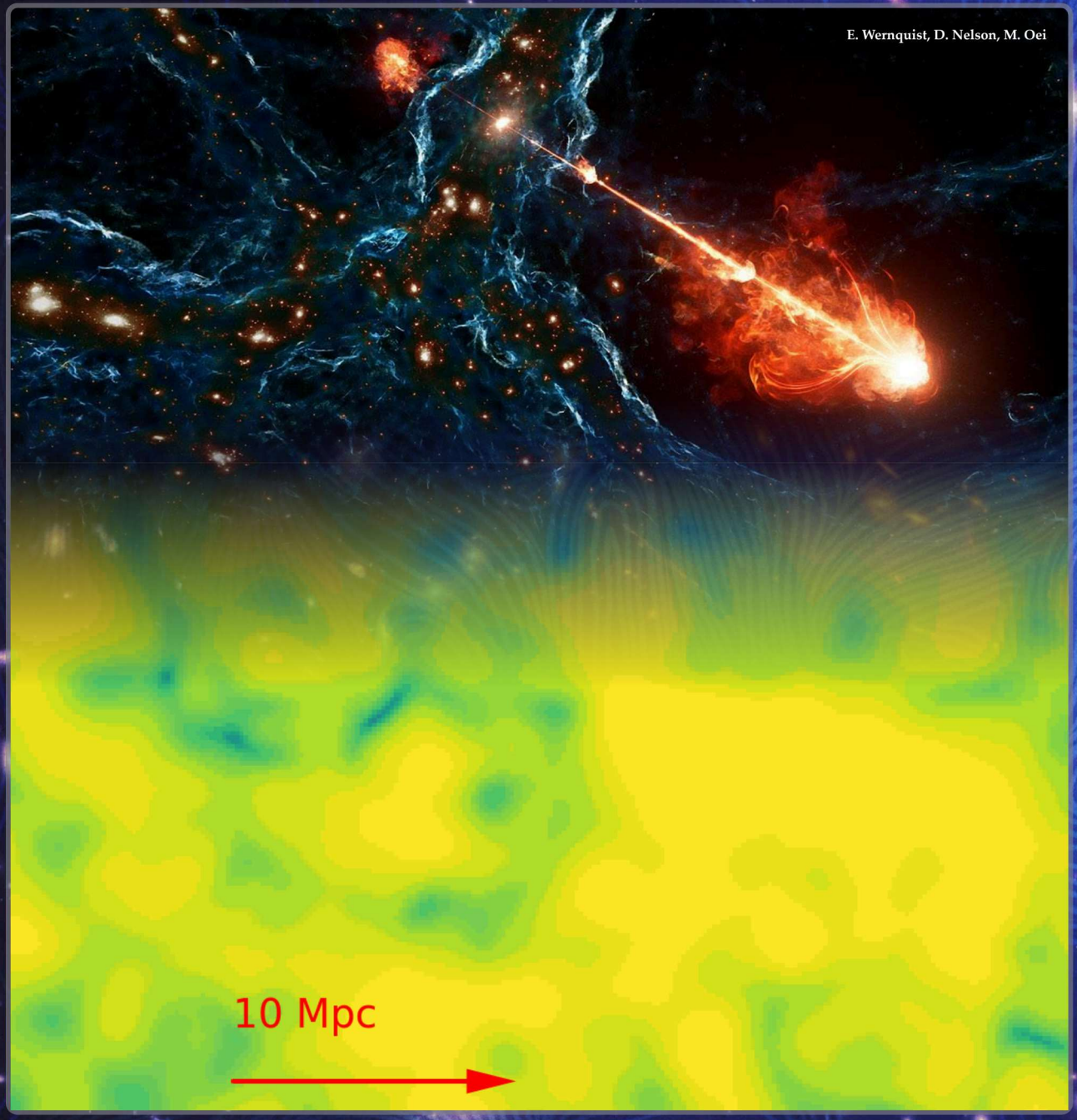
- **Observed across cosmic scales:** Galaxies → clusters → filaments → voids

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- **Diagnostics:** Faraday RM, Synchrotron, Blazar/CMB/21-cm bounds...



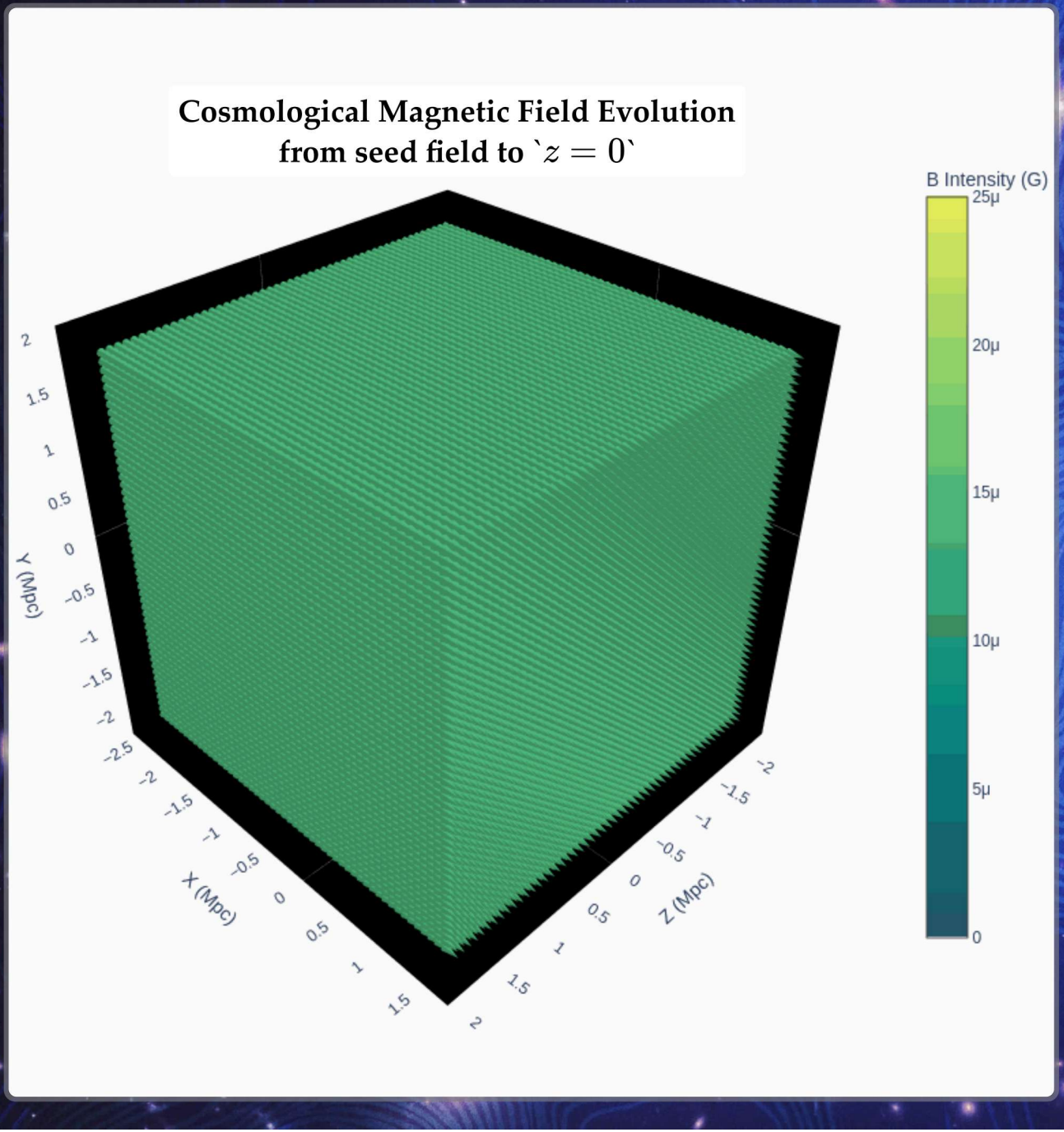


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- **Origins: Primordial Vs Astrophysical**

{Early-Universe} Vs {Outflows, AGN, Battery effects...}



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- Origins: Primordial Vs Astrophysical

{Early-Universe} Vs {Galactic outflows, AGN, battery effects...}

- **Tools: High-res MHD (MASCLET); Synthetic observables/constraints**

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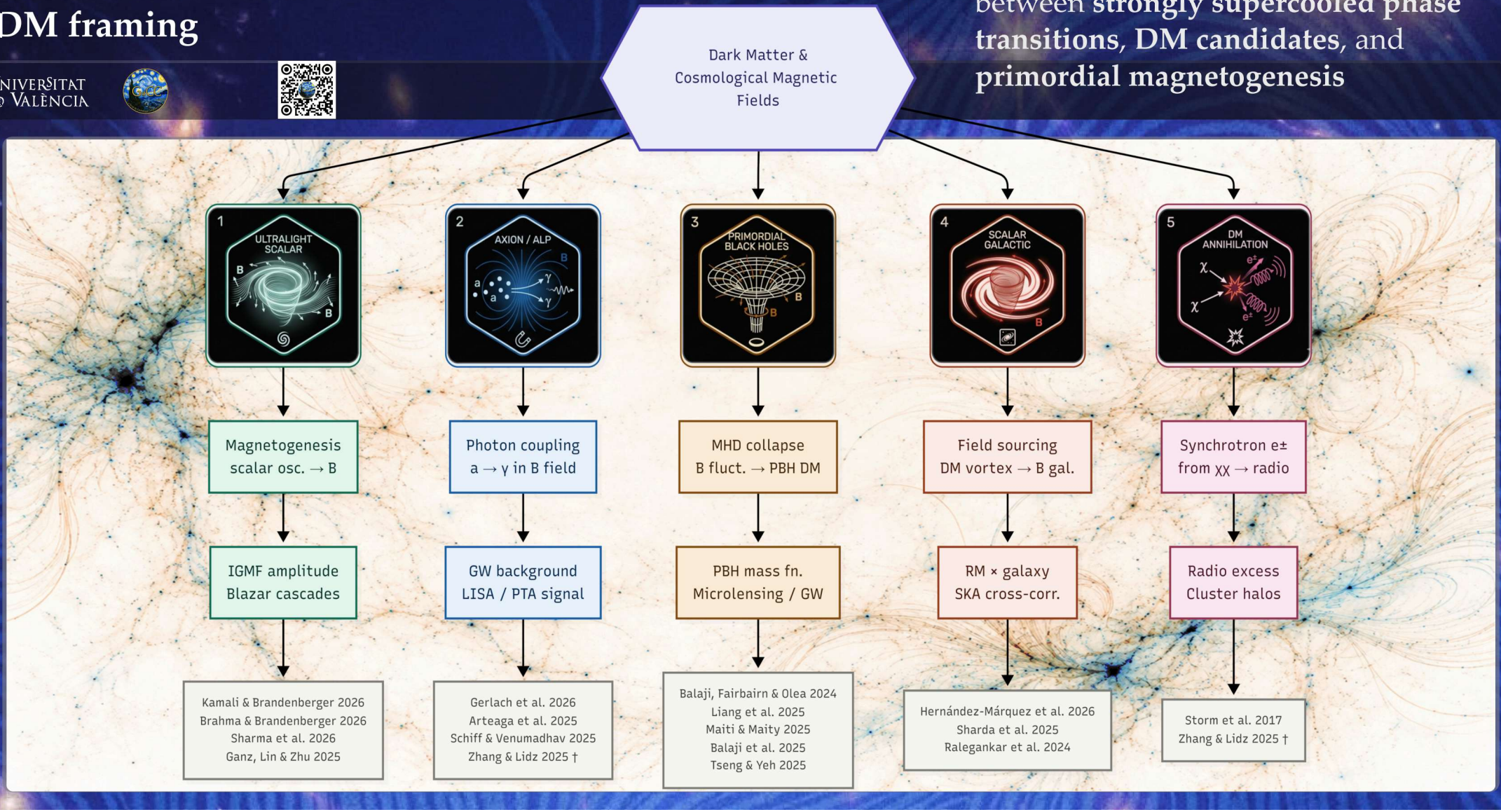
Why It Matters

IDM framing

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- The observational **question** is not only why magnetic fields exist, but **whether their initial imprint survives**

- Some dark matter scenarios can affect **primordial magnetic fields**
- A useful example is the cosmological link between **strongly supercooled phase transitions**, **DM candidates**, and **primordial magnetogenesis**



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Primordial Seeding

PRIMAL Seed Gen *(PRImordial MAgnetic fieLd Seed Generator)*

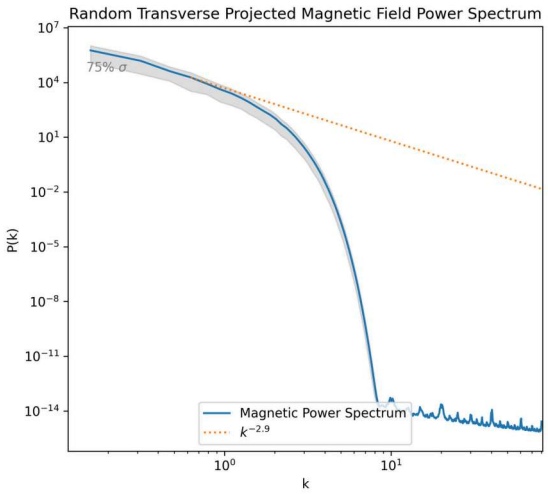


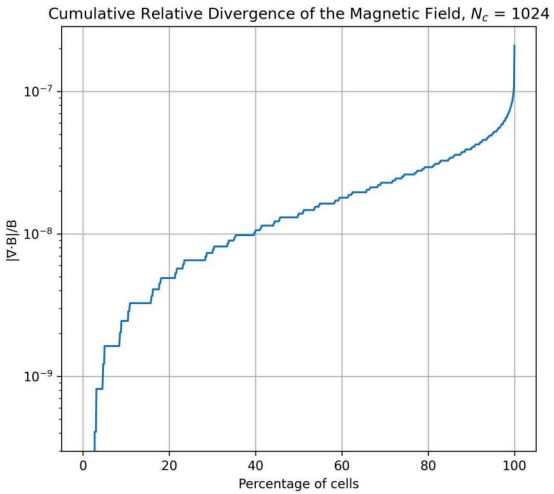
- Random seed realizations reflect the fact that **primordial magnetic structure is not homogeneous**
- The initial magnetic spectrum can be selected at will to **mimic different primordial scenarios** from the literature
- The goal is to test whether late-time MHD evolution can still **distinguish one seed class from another**

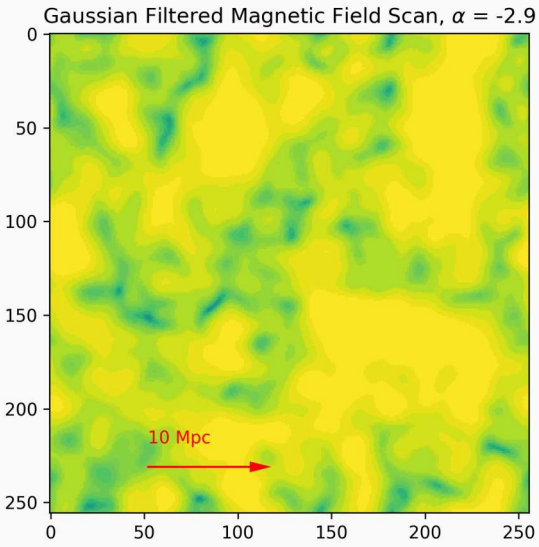
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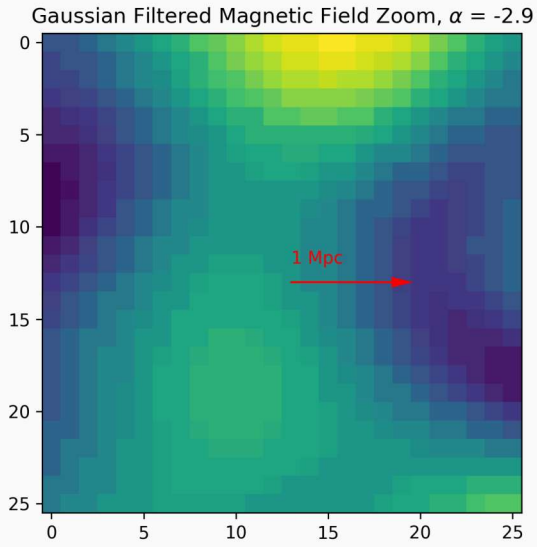
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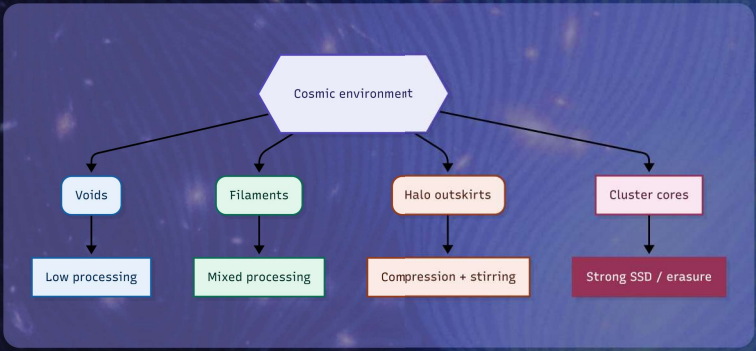
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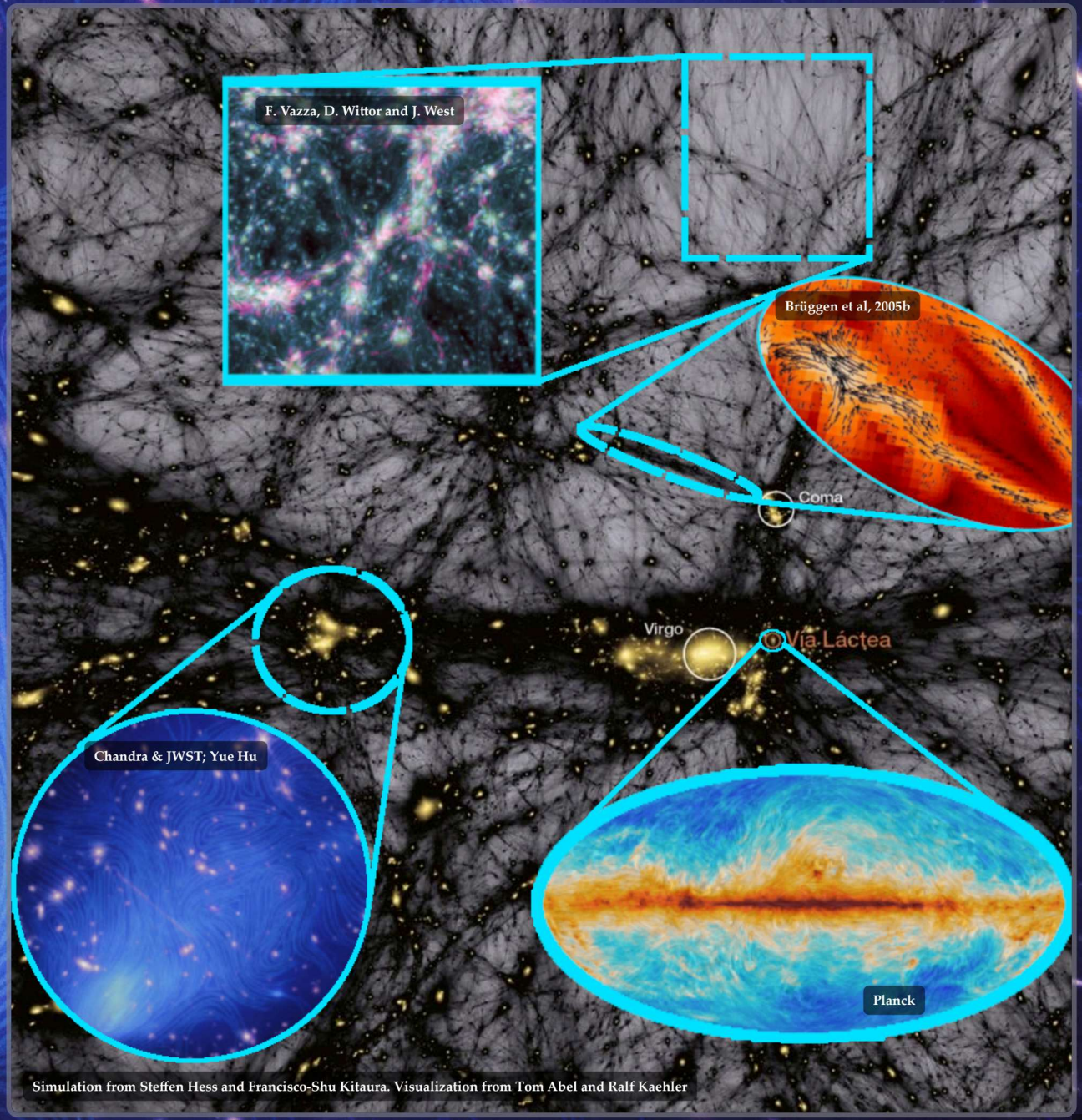
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Nonlinear Processing

Structure formation as an information filter

- Shocks, accretion, shear, and turbulence continuously reshape the field: it's not a simple fossil...
- **Different environments process magnetic memory differently**





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Induction Equation

Magnetic Induction in an Expanding Background

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- The induction equation can be decomposed into ⟶
- The goal is **physical interpretation**:
  - Which term is actually driving **amplification**?

- **Compression**
- **Stretching**
- Advection
- Cosmic Drag
- ~~Divergence~~

$$\frac{\partial \tilde{\vec{B}}}{\partial t} - \frac{1}{a}\vec{\nabla} \times (\vec{v} \times \tilde{\vec{B}}) = -\frac{H}{2}\tilde{\vec{B}}$$

$$\downarrow$$

$$\frac{\partial \tilde{\vec{B}}}{\partial t} = \frac{1}{a}[\vec{v}(\vec{\nabla} \cdot \tilde{\vec{B}}) - \tilde{\vec{B}}(\vec{\nabla} \cdot \vec{v}) + (\tilde{\vec{B}} \cdot \vec{\nabla})\vec{v} - (\vec{v} \cdot \vec{\nabla})\tilde{\vec{B}}] - \frac{H}{2}\tilde{\vec{B}}$$

$$\text{Compression}: \quad -\frac{1}{a}\tilde{\vec{B}}(\vec{\nabla} \cdot \vec{v}) \qquad \text{Stretching}: \quad \frac{1}{a}(\tilde{\vec{B}} \cdot \vec{\nabla})\vec{v}$$

$$\text{Advection}: \quad -\frac{1}{a}(\vec{v} \cdot \vec{\nabla})\tilde{\vec{B}} \qquad \text{Cosmic Drag}: \quad -\frac{H}{2}\tilde{\vec{B}}$$

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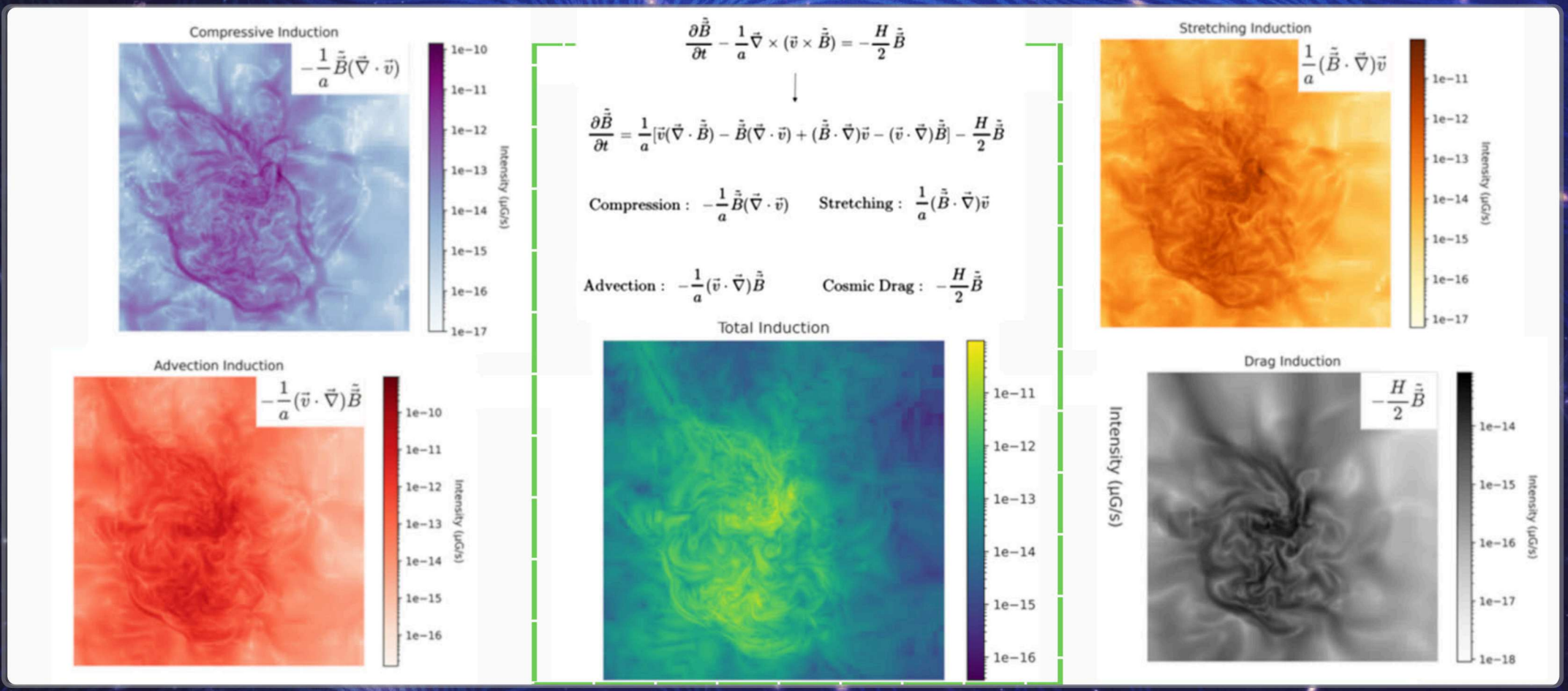
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Compression : $-\frac{1}{a}\vec{\tilde{B}}(\vec{\nabla} \cdot \vec{v})$ Stretching : $\frac{1}{a}(\vec{\tilde{B}} \cdot \vec{\nabla})\vec{v}$

Advection : $-\frac{1}{a}(\vec{v} \cdot \vec{\nabla})\vec{\tilde{B}}$ Cosmic Drag : $-\frac{H}{2}\vec{\tilde{B}}$



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Velocity Decomposition

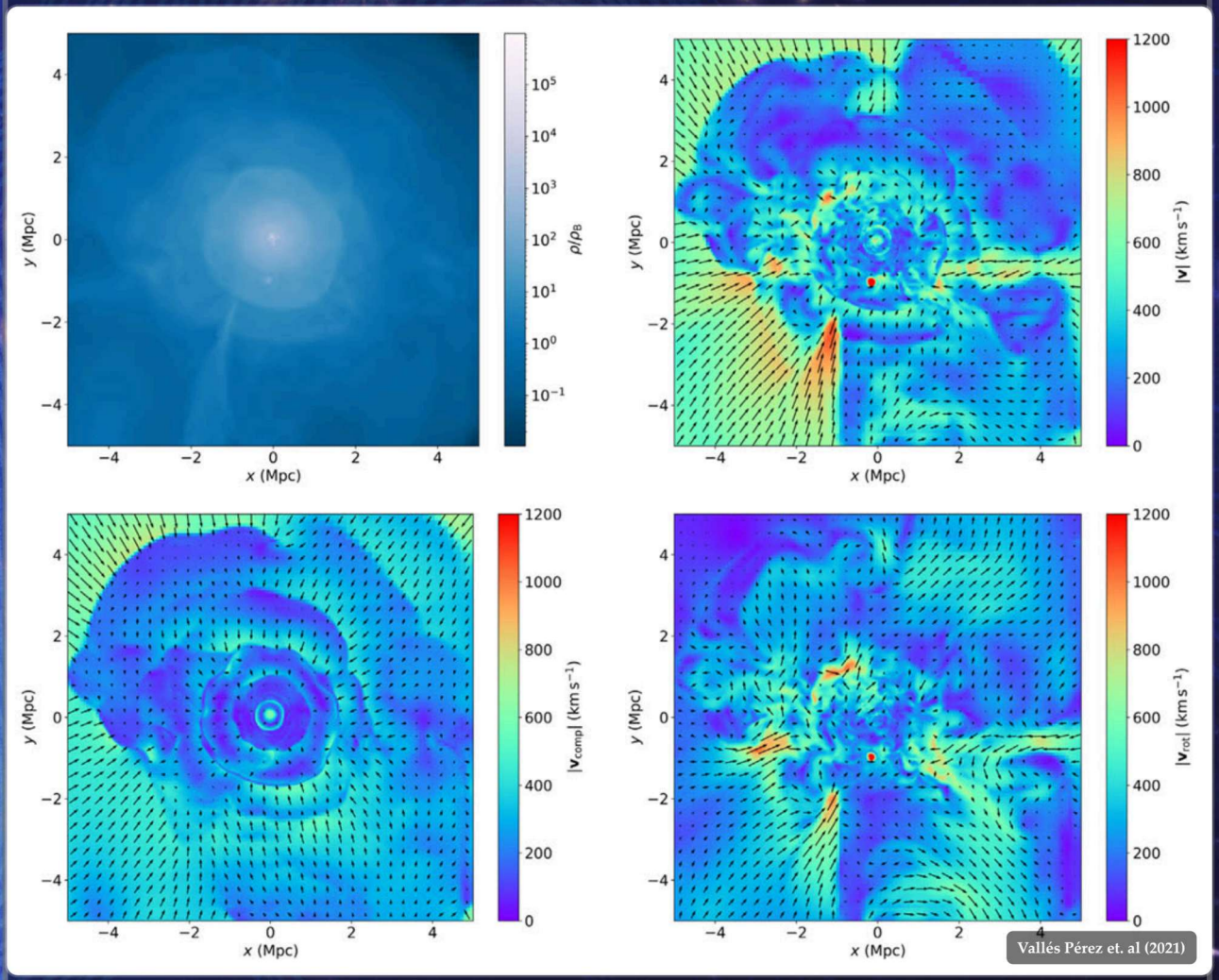
Finding the dynamo signature with VORTEX

- The induction equation alone does not tell us whether amplification is compressive or dynamo-driven

- A Helmholtz decomposition separates the flow into:
  - **solenoidal** rotational motions
  - **compressive** motions

- The **stretching-solenoidal component** in the is the cleanest physical signature of the SSD

$$\frac{\partial \tilde{\vec{B}}}{\partial t} = \frac{1}{a}[\vec{\mathbf{v}}(\vec{\nabla}\cdot\tilde{\vec{B}}) - \tilde{\vec{B}}(\vec{\nabla}\cdot\vec{\mathbf{v}}) + (\tilde{\vec{B}}\cdot\vec{\nabla})\vec{\mathbf{v}} - (\vec{\mathbf{v}}\cdot\vec{\nabla})\tilde{\vec{B}}] - \frac{H}{2}\tilde{\vec{B}}$$



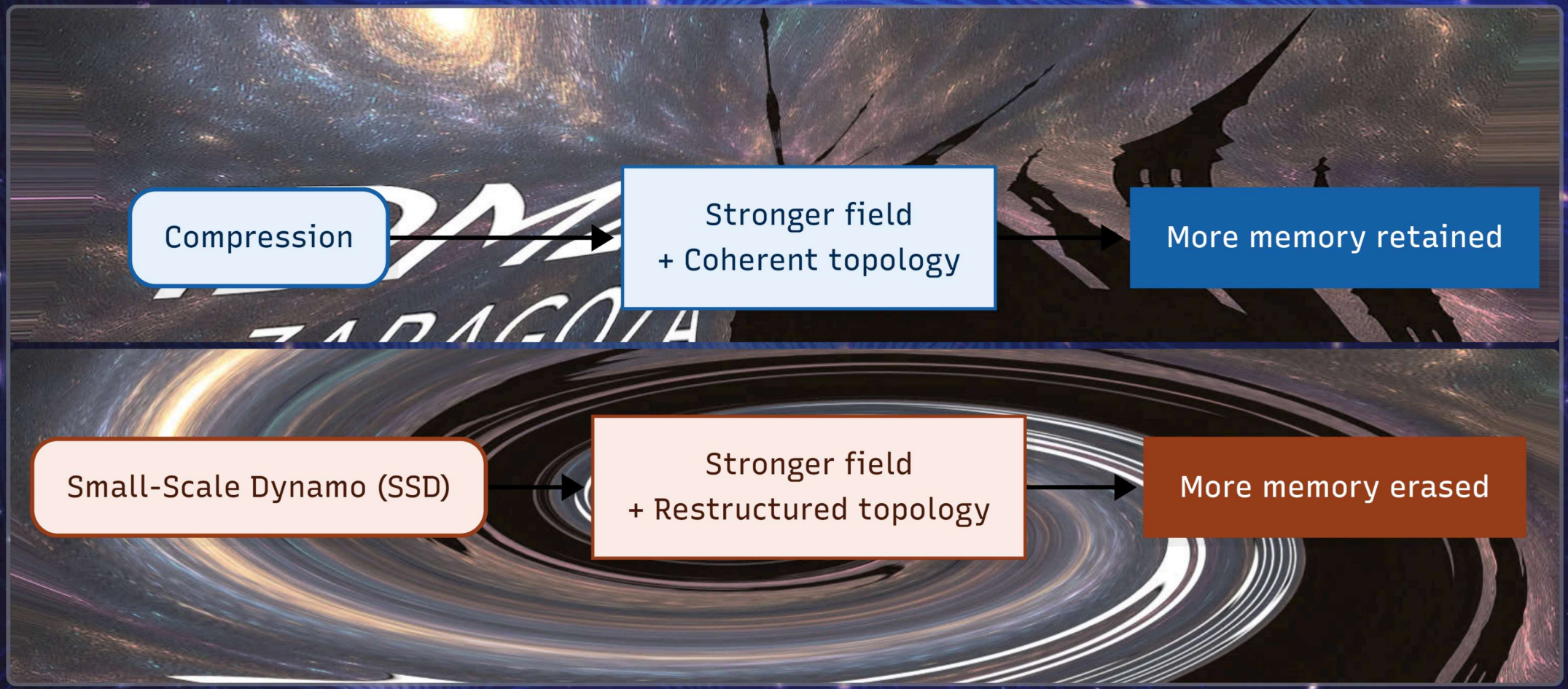
$$\vec{\mathbf{v}} = \vec{\mathbf{v}}_{\mathrm{sol}} + \vec{\mathbf{v}}_{\mathrm{comp}}$$

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Compression Vs. SSD

Two amplification channels, different memory outcomes

- **Compression** amplifies the field by flux freezing during collapse
  - Tends to **preserve** large-scale topology better
- **Stretching** leads to **Small-scale dynamo (SSD)** which, folds, and reorders the field
  - Strongest candidate for **erasing** primordial memory



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INTERACTIVE MODEL

Cosmic Web Magnetic Field at z=7 (MASCLET)

Interactive 3D visualization of a 40 Mpc comoving MASCLET simulation box at z=7.
Density contours trace the emerging cosmic web, while magnetic field lines highlight the dominant MHD amplification mechanisms.

🔵 Blue lines: Compression along infalling filaments. 🔴 Red lines: Stretching in turbulent cluster regions.



Cosmic Web Magnetic Field at z=7 (MASCLET) by Marco_Mol on Sketchfab

Environment Dependence

Where does information survive?

- Amplification is strongly **environment dependent**
- **Compression-dominated** regions are more favorable for **preserving magnetic memory**
  - Halo outskirts
  - Walls, Filaments
- Turbulent, solenoidal regions favor **SSD amplification** but also **memory loss**
  - Cluster cores

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Implications & Take-Home Message

What we've learned...

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1. Magnetic fields are only useful as dark matter probes if their imprint **survives nonlinear processing**

2. **Decomposing the induction equation** and the **velocity field** separates growth that preserves memory from growth that destroys it
   - In most environments, collapse, shear, and turbulence progressively erase the imprint

3. Both **compression and SSD** are driven by gravity through collapse, turbulence, and the formation of structures, and are therefore **closely linked to dark matter**
   - In compression-dominated regions, part of that memory can still survive

4. A single probe is not enough: We need **multimessenger constraints and observations** (21-cm, gravitational waves...), and **simulation-based diagnostics**
   - Mock images and synthetic observables help identify **where** primordial information may remain observable

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Bibliography & Acknowledgments

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- MASCLET: Quilis, Martí & Planelles (2020)
- Background image credit: Chandra X-ray (NASA/CXC/Rutgers); JWST infrared (NASA/ESA/CSA); Magnetic field lines (Yue Hu)
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- The magnetic field of our Milky Way galaxy as seen by the Planck satellite
- Simulations suggest cosmic webs, made of filaments of dark matter, stretch throughout the galaxy. (Image credit: F. Vazza, D. Wittor and J. West)