Dynamo Lecture

Neco Kriel

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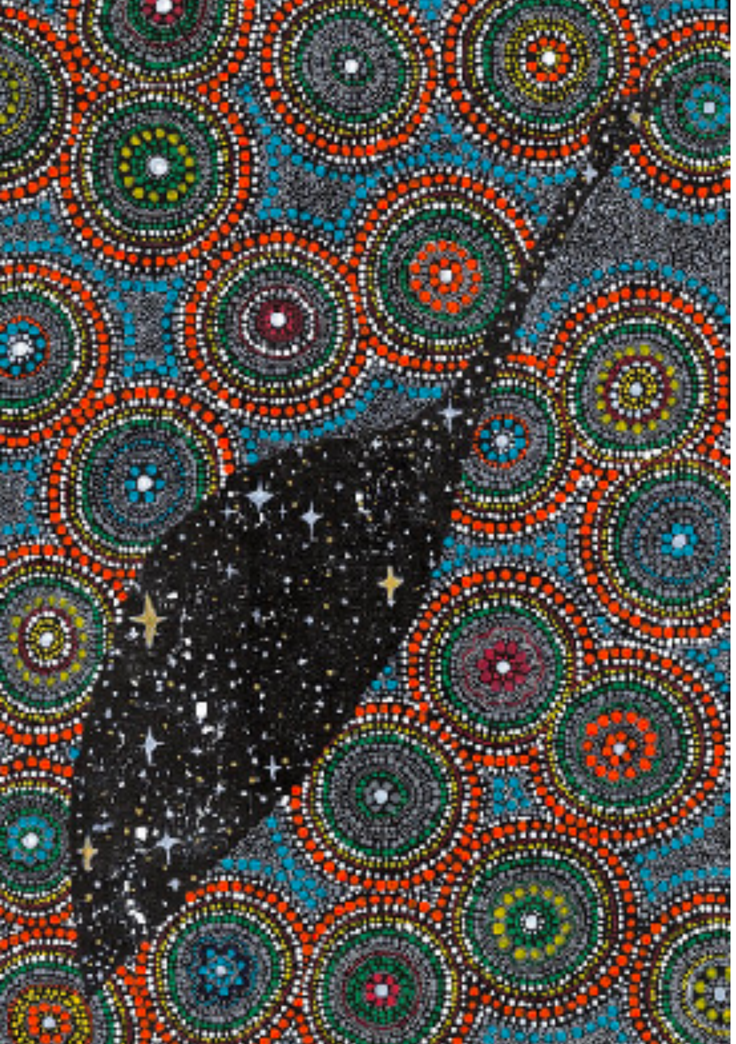
AstroKriel

1st year PhD student

ASTR4012/ASTR8002

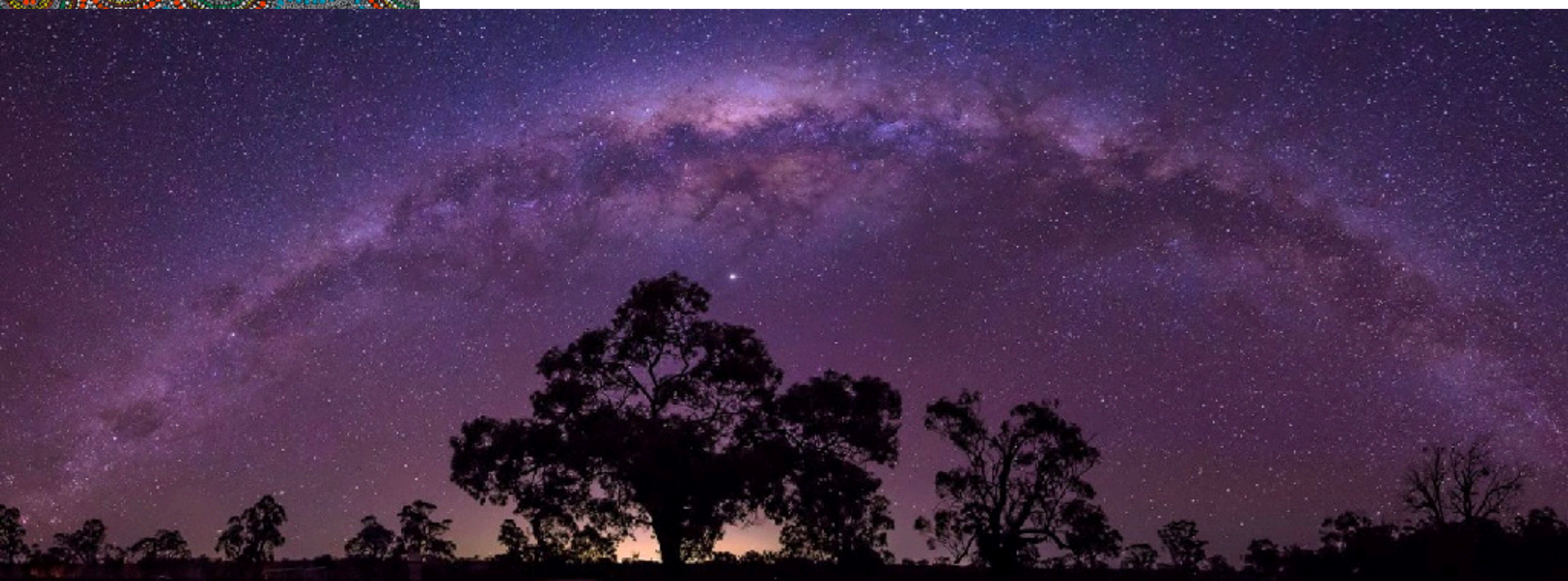
Neco Kriel, 29 September 2022

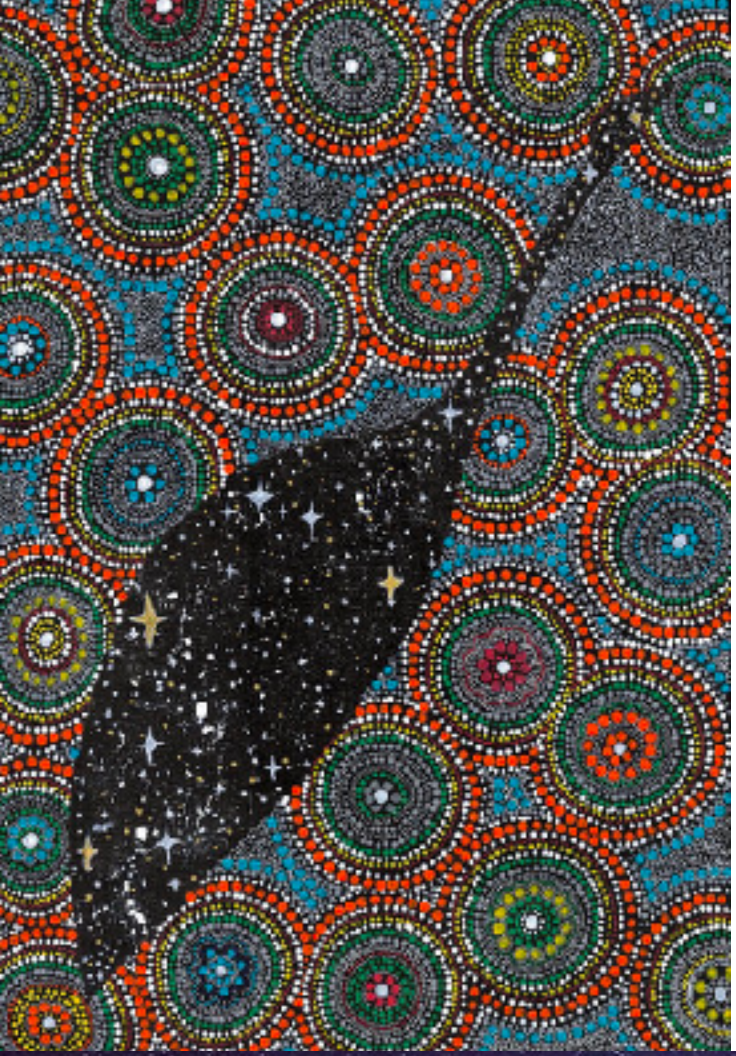


Acknowledgement of Country

"Inside the EMU the many many galaxies with the EMU looking out into deep space"

Image credit: Zachriah George





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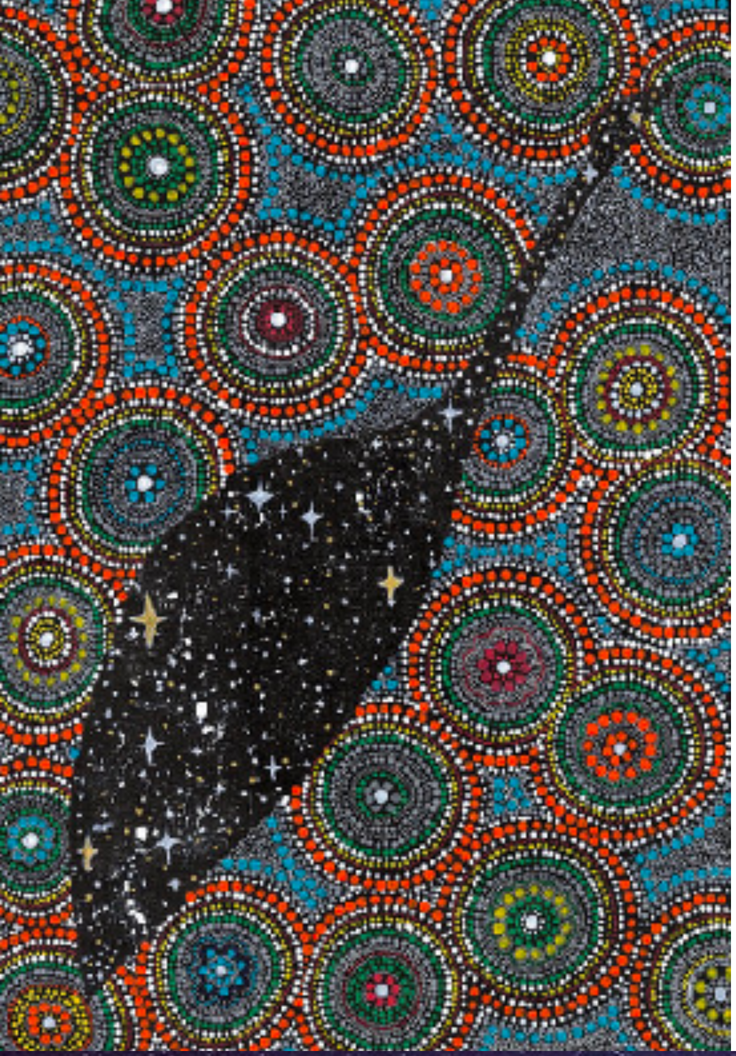

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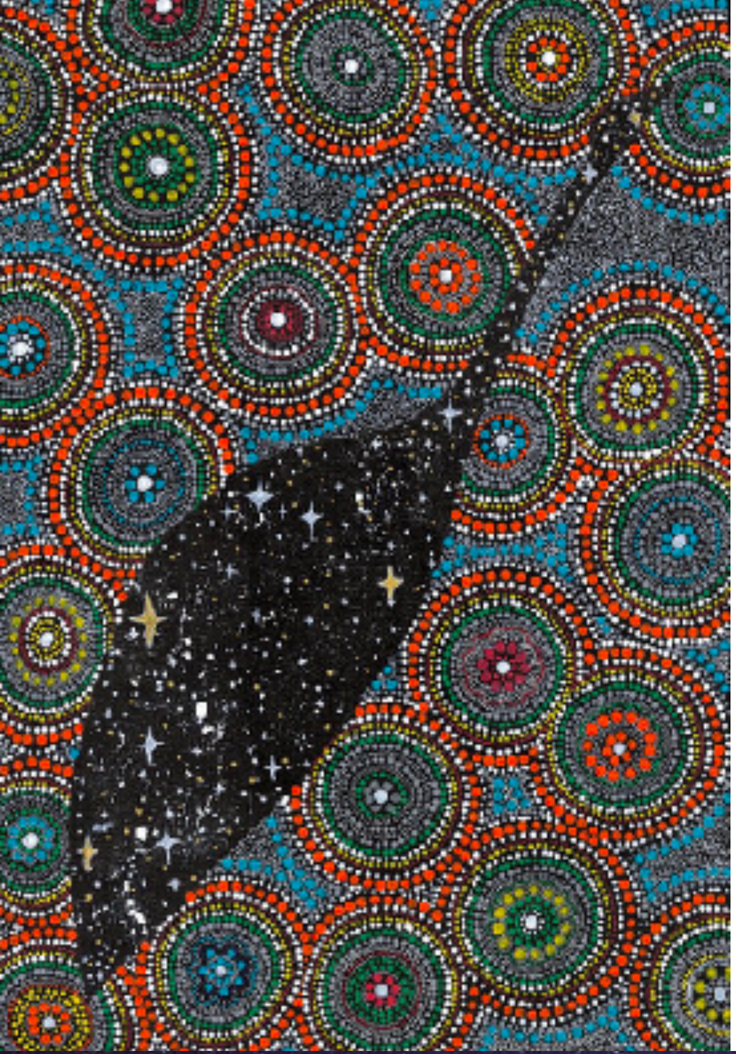
The emu in the sky is linked to the breeding cycle (seasons) of emus in Australia.

Image credit: Zachriah George



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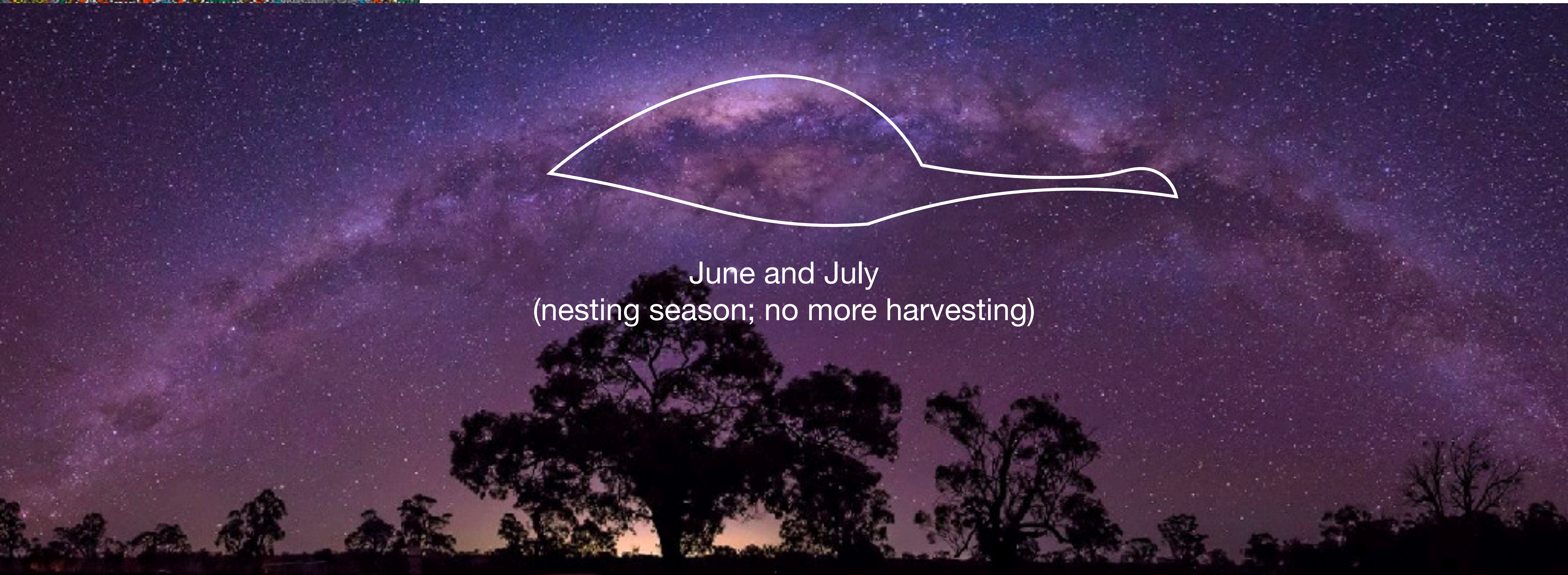

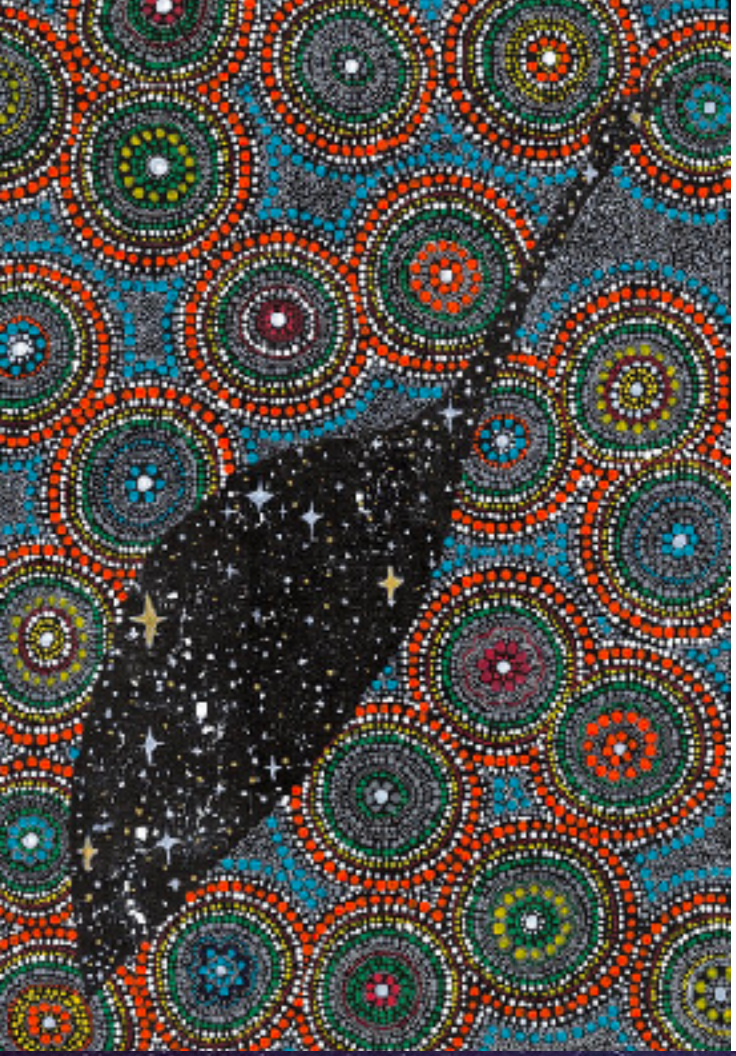

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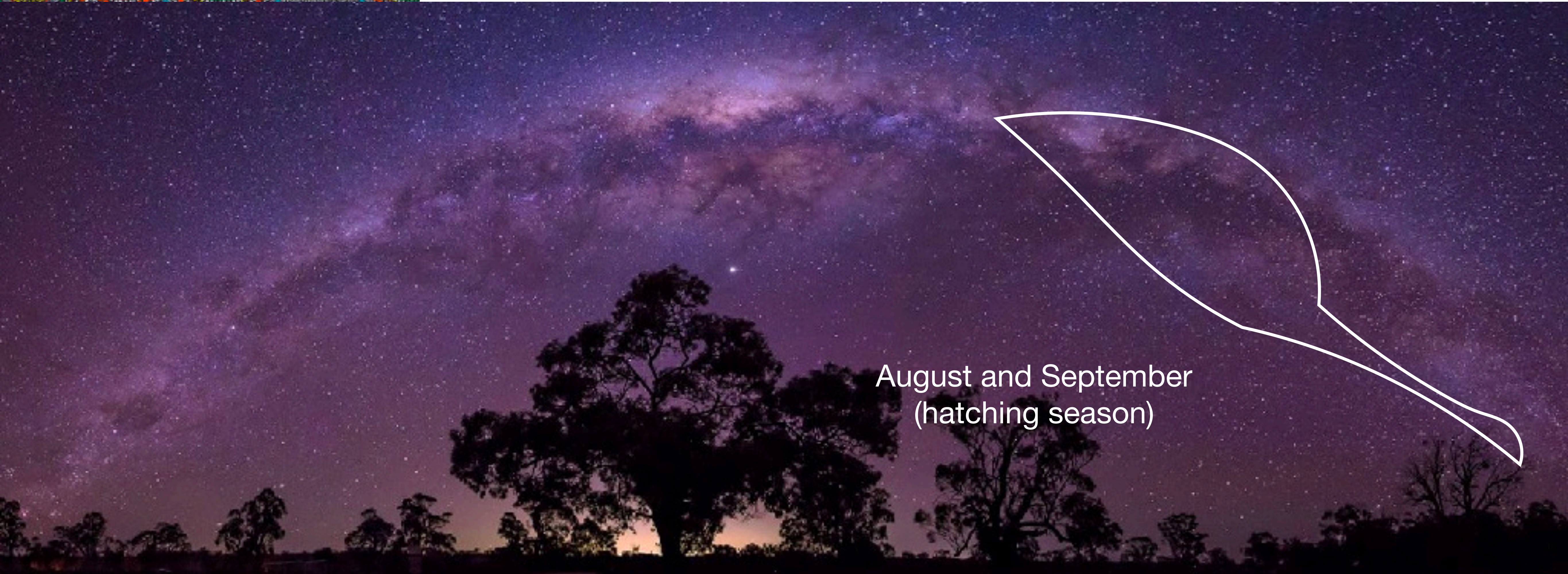

Brief outline

- We live in a Universe that has evolved to become strongly magnetised
- Magnetic amplification (dynamo) comes in many flavours
- My favourite flavour: the turbulent dynamo
  - A Markovian process
  - Characterised by a hierarchy of scales
- Wrap things up

Brief outline

This will be a success if…

- We live in a Universe that has evolved to become strongly magnetised
- Magnetic amplification (dynamo) comes in many flavours
- My favourite flavour: the turbulent dynamo
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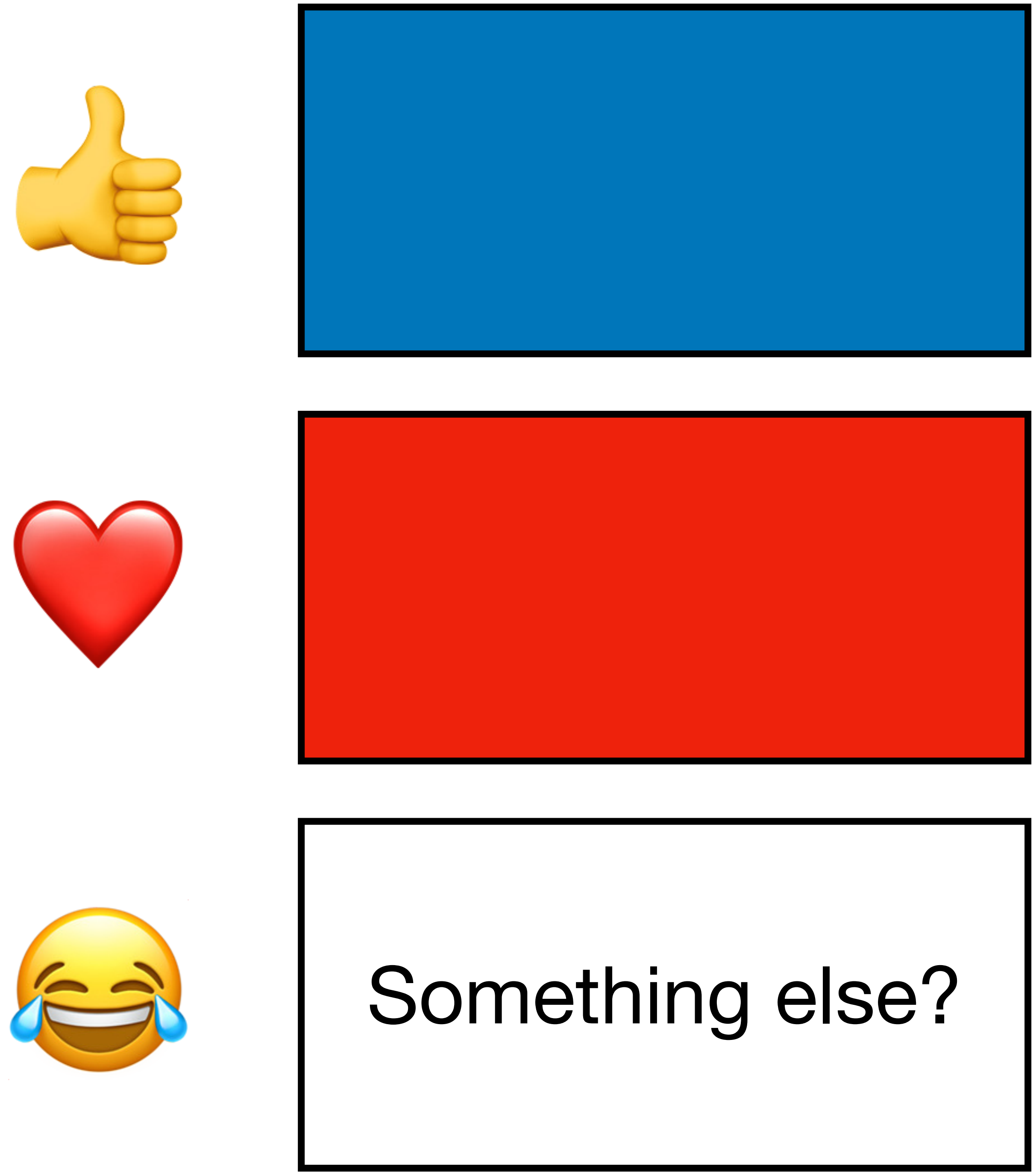
A quick survey

A quick survey

What colour are magnetic fields?



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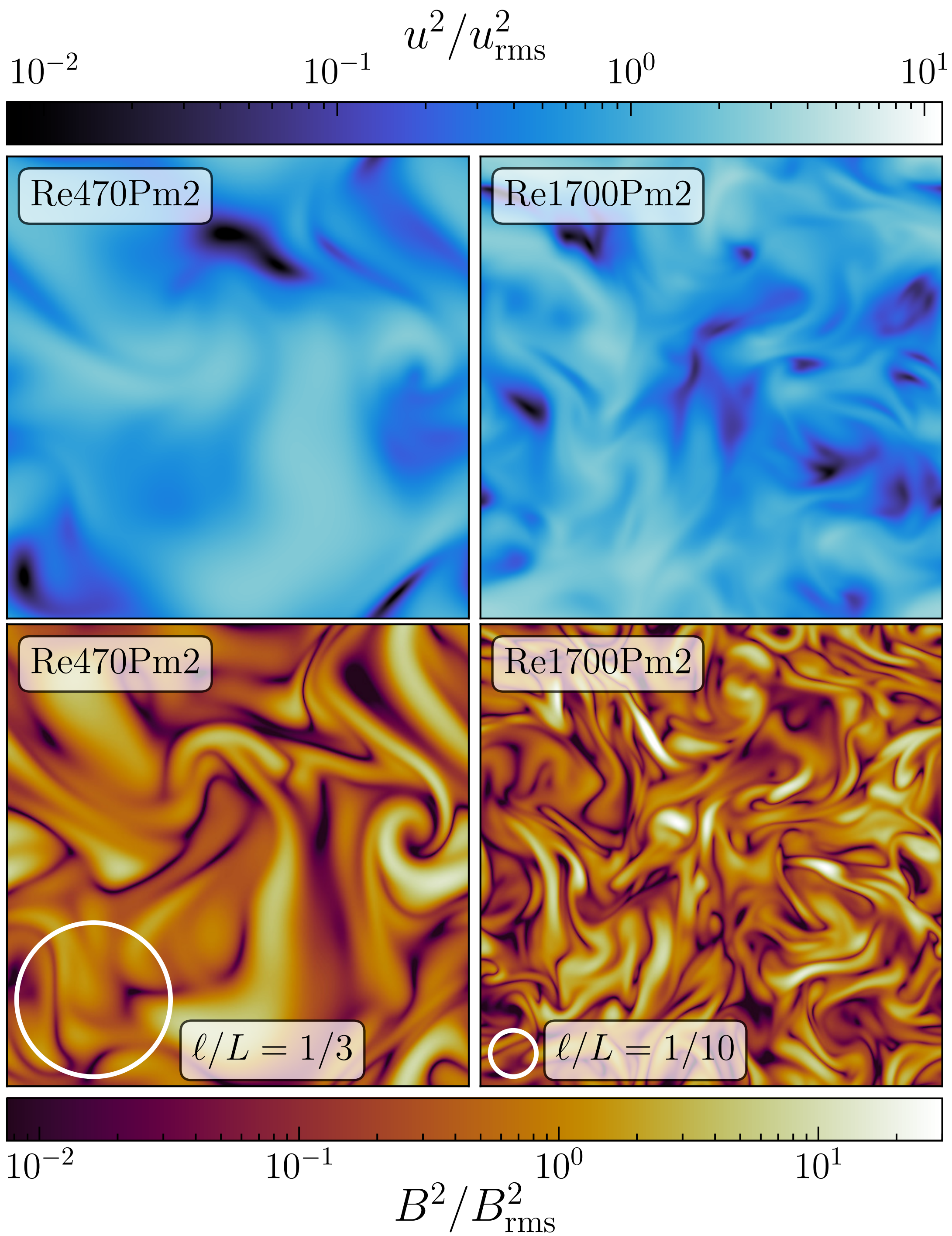
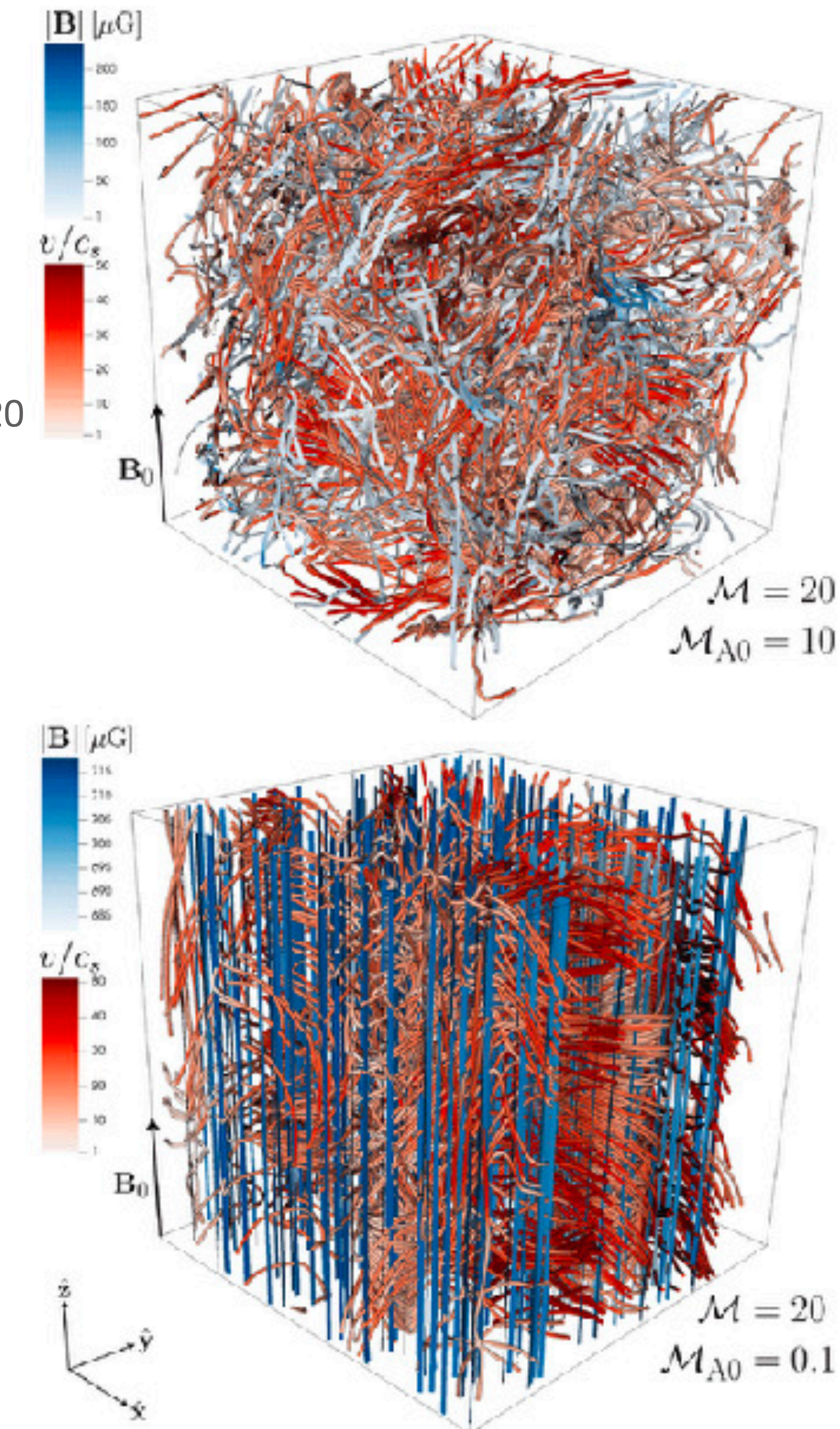


Kriel et al. 2022



Beattie et al. 2020

A magnetised Universe

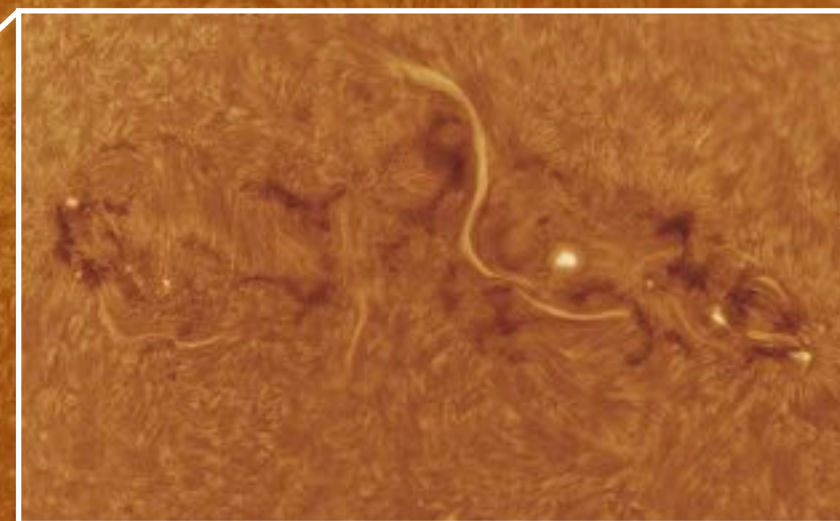
Today: a magnetised Universe

Our Sun

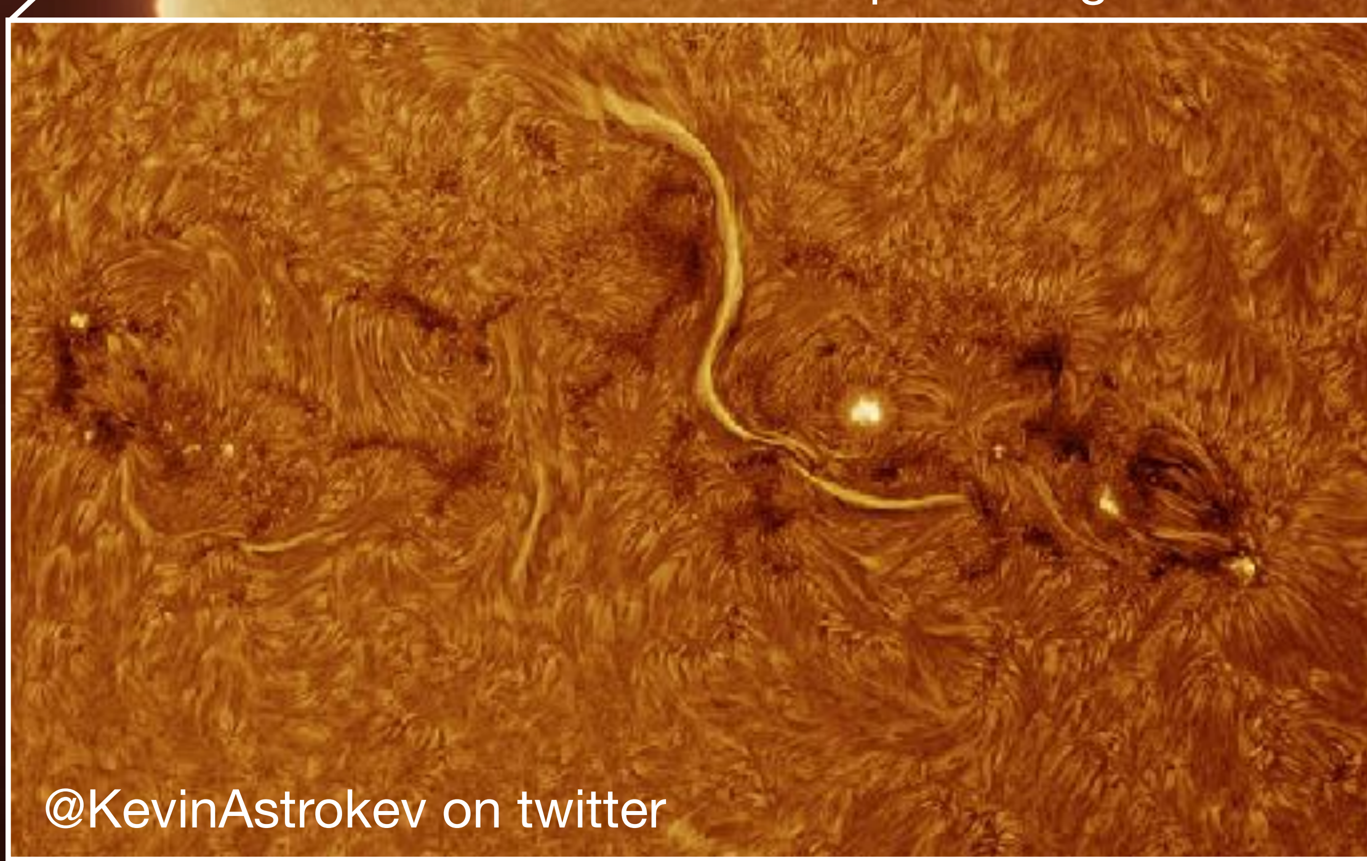
@KevinAstrokev on twitter

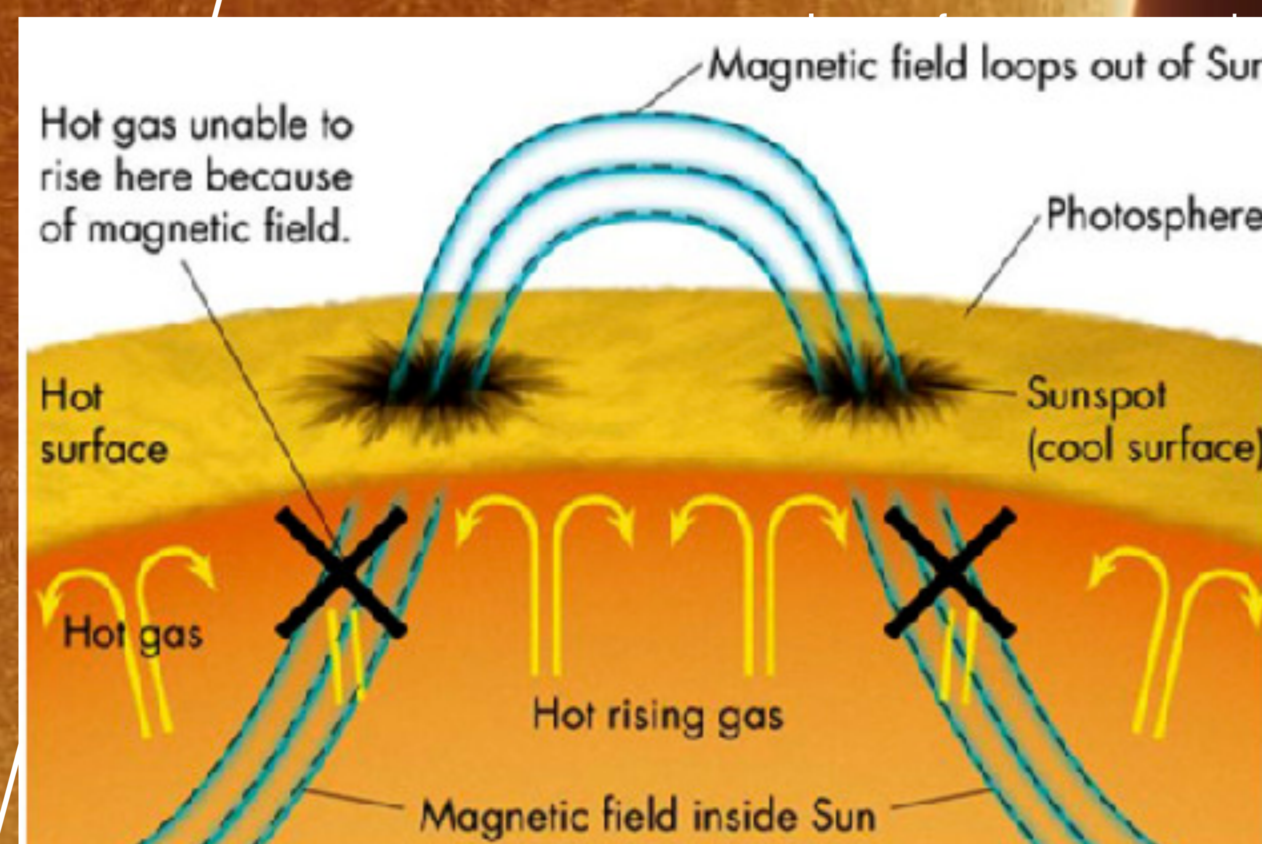
Today: a magnetised Universe

Our Sun



$\sim 10\,\mathrm{G}$ dipolar magnetic field

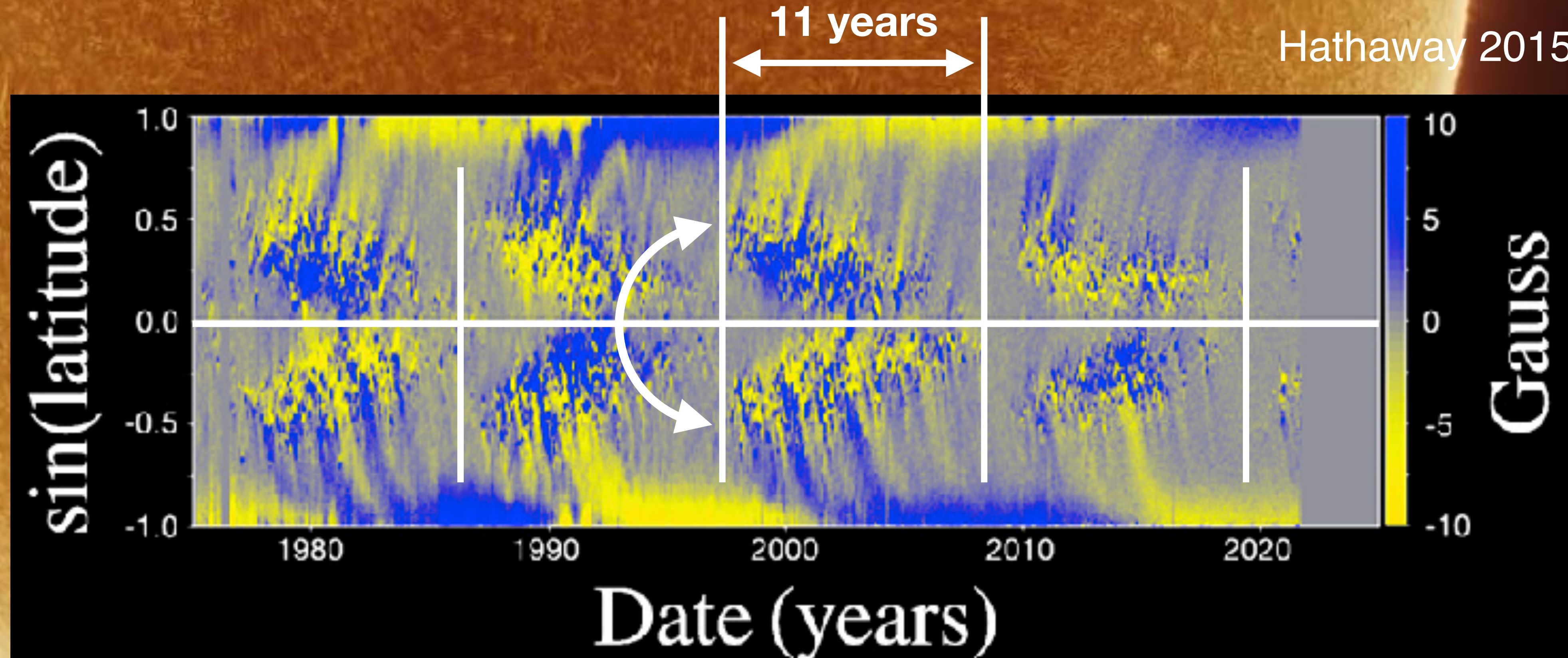




Today: a magnetised Universe

Our Sun

Hathaway 2015



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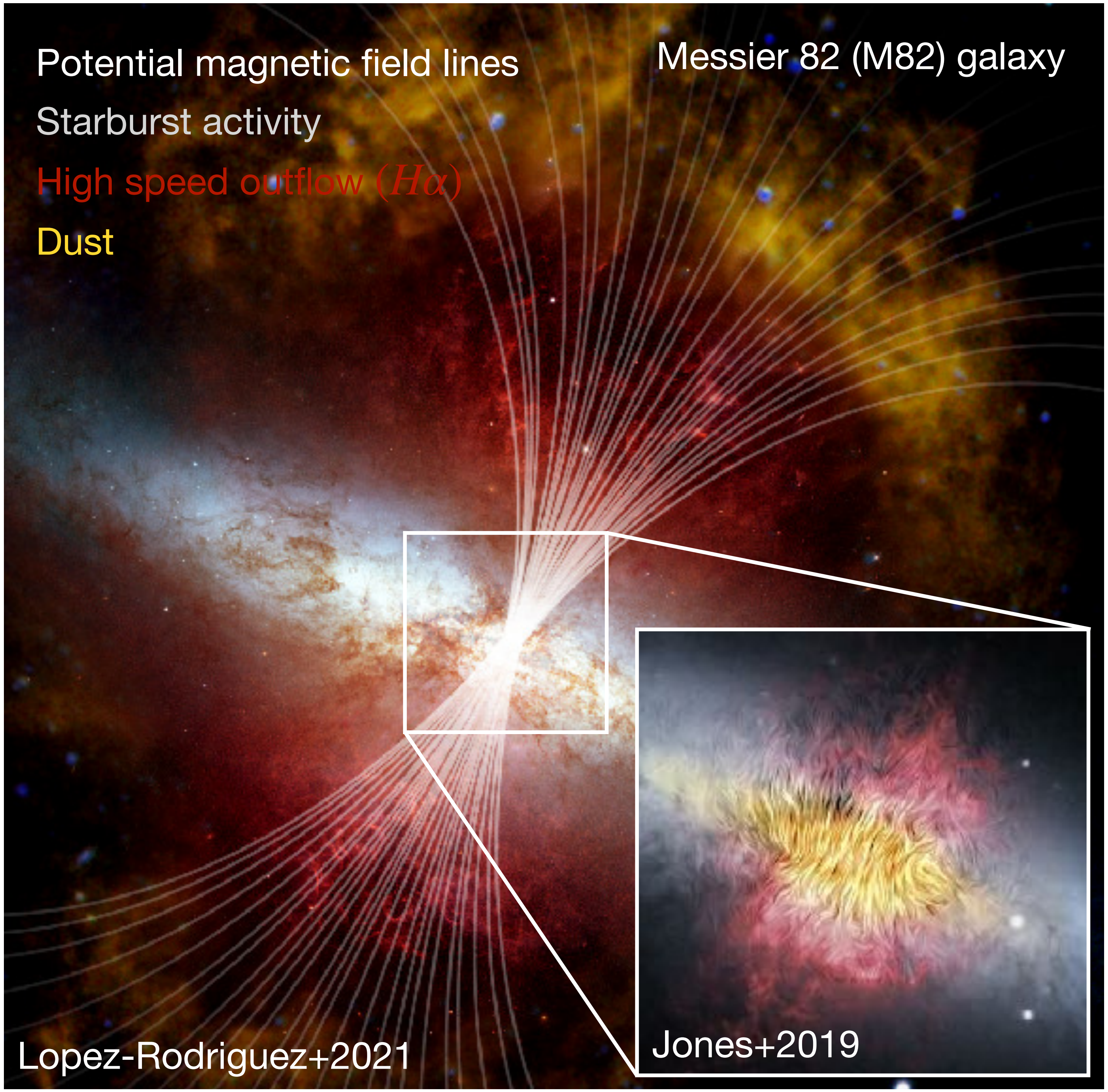
Today: a magnetised Universe



- Galaxies host magnetic fields of $\sim \mu\mathrm{G}$, coherent on scales up to $\sim 10\,\mathrm{kpc}$
- Outflows can drive magnetic fields $\sim 100\,\mu\mathrm{G}$ out of the galaxy
- Magnetic fields are in close energy equipartition with turbulent kinetic energy up to $\sim \mathrm{kpc}$

The MHD equations

How can we generate magnetic fields?

Continuity:

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

Momentum:

fluid mass | fluid acceleration | all the forces that act on the fluid

$$\rho \left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u} = \frac{1}{4\pi} (\mathbf{B} \cdot \nabla) \mathbf{B} - \nabla \left(p_{\text{th}} + \frac{B^2}{8\pi} \right) + \nabla \cdot \left(2 \nu \rho \mathcal{S} \right) + \rho \mathbf{F}$$

- $\frac{\partial}{\partial t}$: change in flow
- $\mathbf{u} \cdot \nabla$: inertial term (speed and direction of fluid flow)
- $\frac{1}{4\pi} (\mathbf{B} \cdot \nabla) \mathbf{B}$: magnetic force associated with the Lorentz force
- $\nabla \left(p_{\text{th}} + \frac{B^2}{8\pi} \right)$: pressure
- $\nabla \cdot \left(2 \nu \rho \mathcal{S} \right)$: stress (viscosity)
- $\rho \mathbf{F}$: external forces

Induction:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

- $\nabla \times (\mathbf{u} \times \mathbf{B})$: Lorentz forces
- $\eta \nabla^2 \mathbf{B}$: stress forces (resistivity)

Constitutive (no magnetic monopoles):

$$\nabla \cdot \mathbf{B} = 0$$

The MHD equations

The induction equation

Induction:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Lorentz forces   stress forces (resistivity)

Early Universe: Biermann battery

Is it possible to produce a seed magnetic field?

Induction: $$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Lorentz forces — stress forces (resistivity)

$$\propto \frac{\nabla n \cdot \nabla p}{q n^2}$$

- Galactic magnetism
  - Electron and protons interact with rotating medium
  - They have different masses, so electrons flow with medium, and protons lag behind
  - Misalignment between density and pressure induces/generates non-zero circular currents (magnetic fields)
  - See *Mikhailov and Andreasyan (2021)* for more

Early Universe

We have a seed magnetic field, now what?

- No magnetic monopoles $(\nabla \cdot B = 0)$, so magnetic fields can't be destroyed
- Magnetic fields decay
- Outflows remove magnetic fields from galaxies

Early Universe

We have a seed magnetic field, now what?

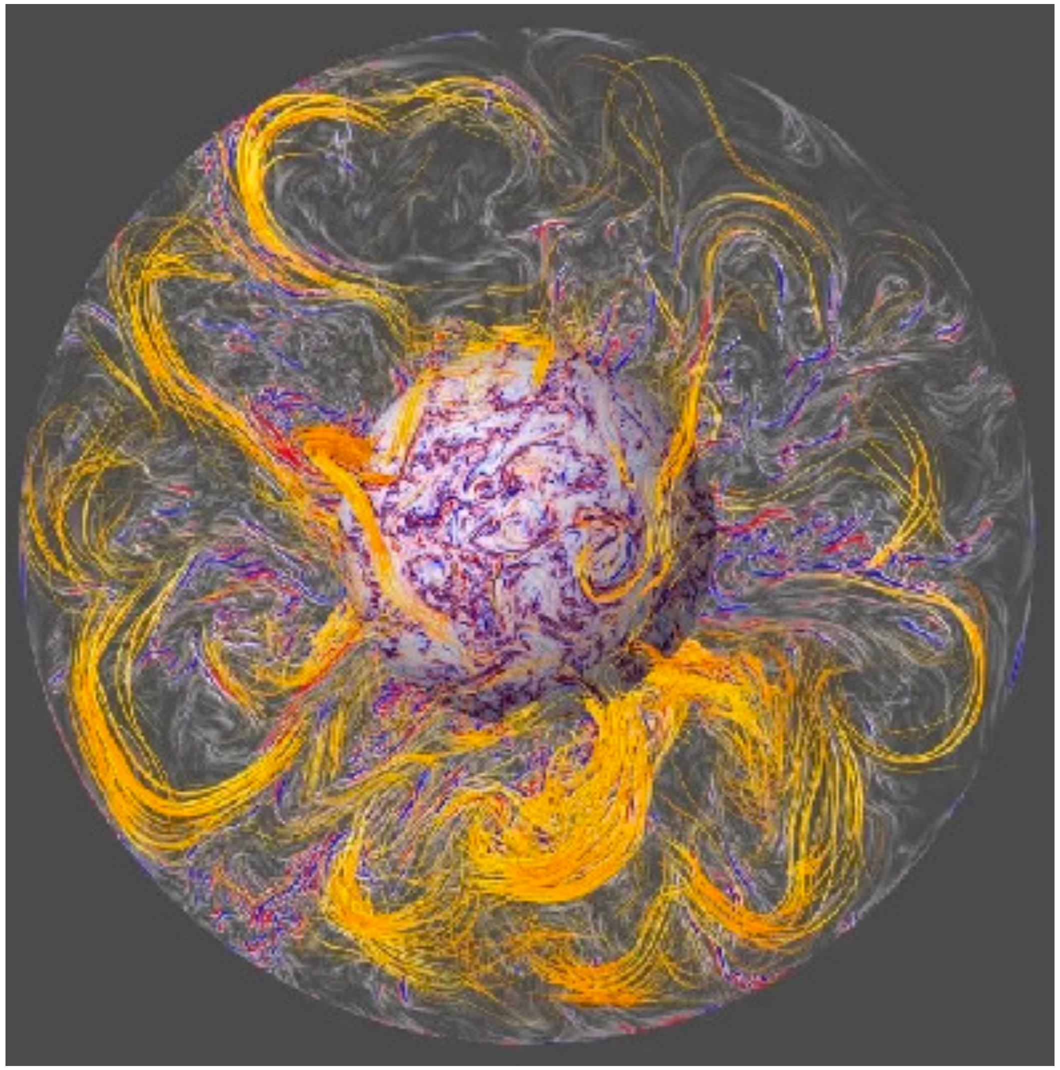
- No magnetic monopoles $(\nabla \cdot B = 0)$, so magnetic fields can't be destroyed
- Magnetic fields decay
- Outflows remove magnetic fields from galaxies
- **How did these fields become so strong?**

Dynamo!

(magnetic fields grew… quickly!)

Flavours of dynamo

Large scale



Aubert et al./IPGP/CNRS
Photo library

Flavours of dynamo

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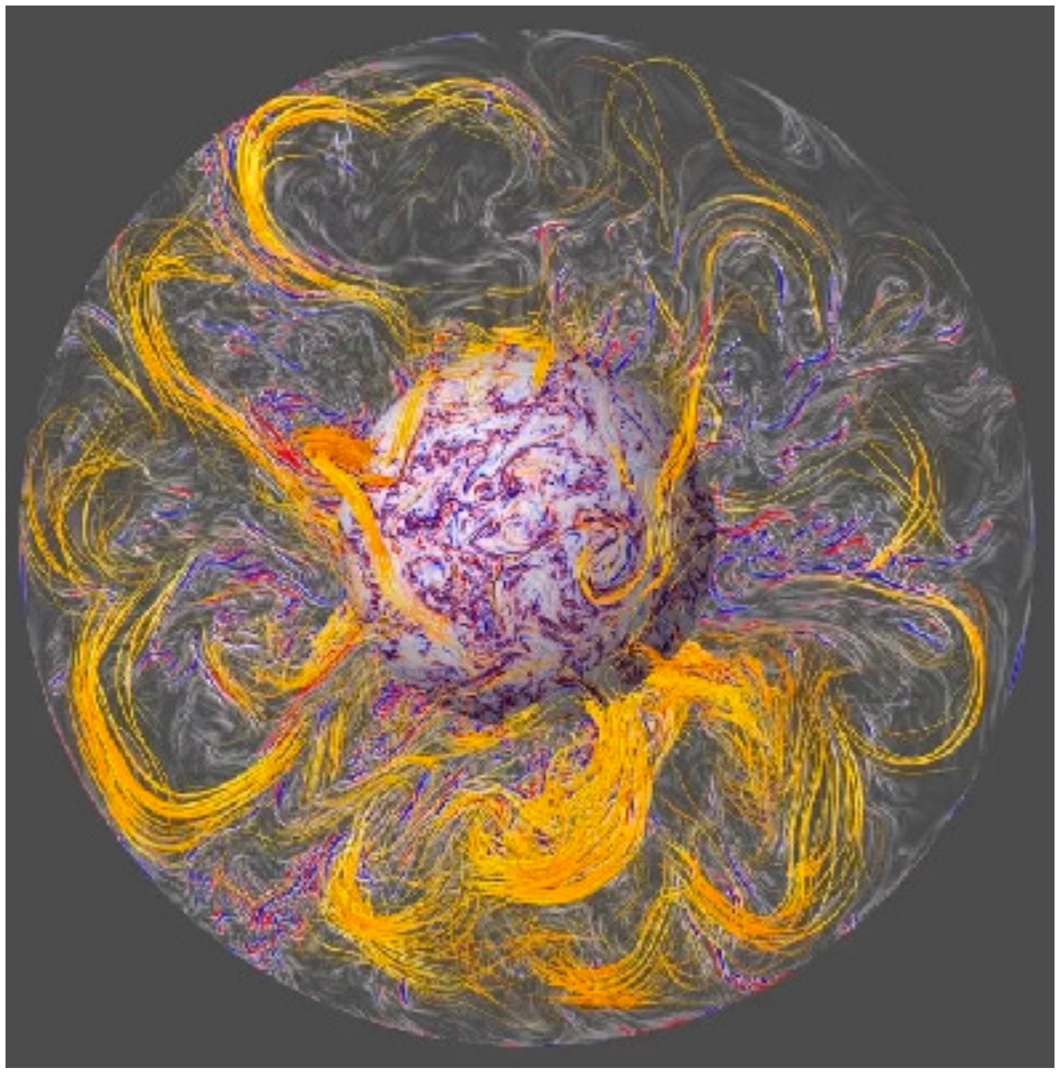


Aubert et al./IPGP/
CNRS Photo library

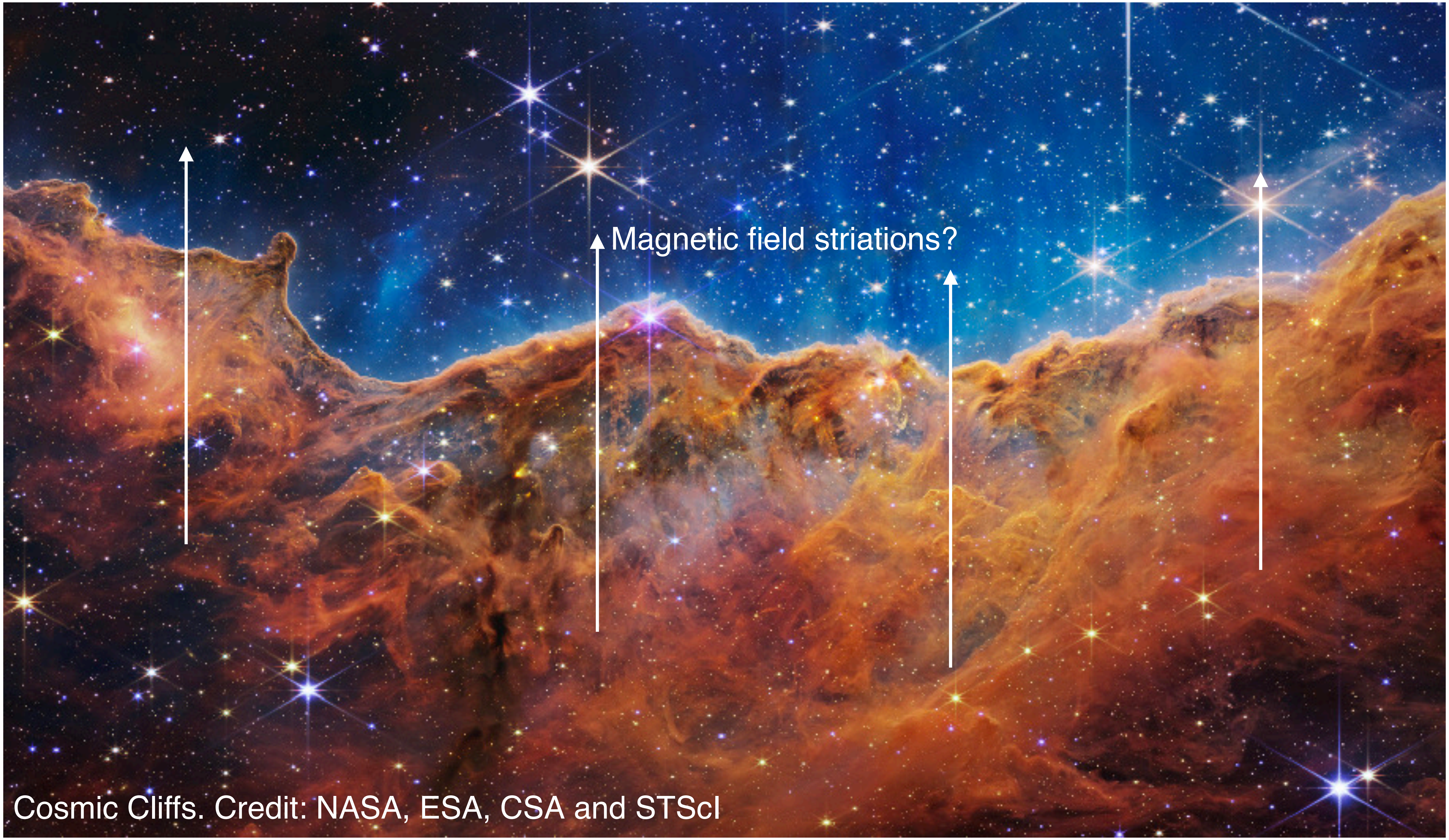
Planets, stars, galaxies

NASA/NOAA/GSFC/Suomi NPP/
VIIRS/Norman Kuring

Flavours of dynamo

Small scale (turbulent dynamo)

Interstellar medium (ISM)

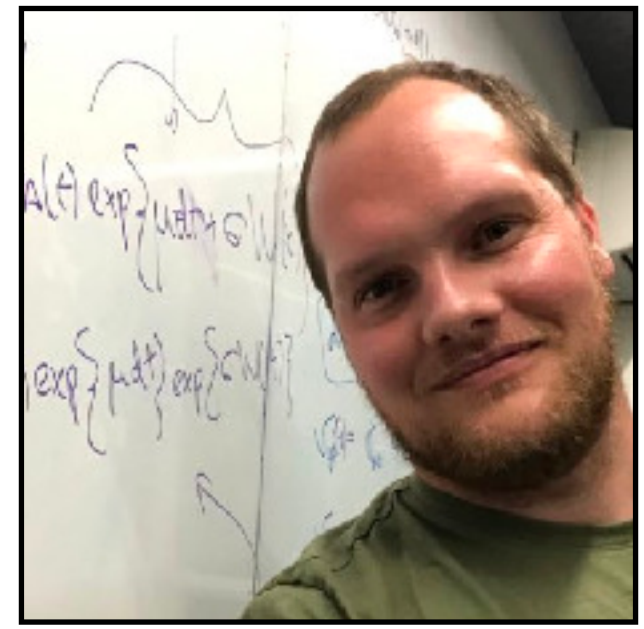


The dynamo family at the RSAA

Christoph Federrath

Amit Seta

James Beattie



Radhika Chirakkara

Neco Kriel (me)

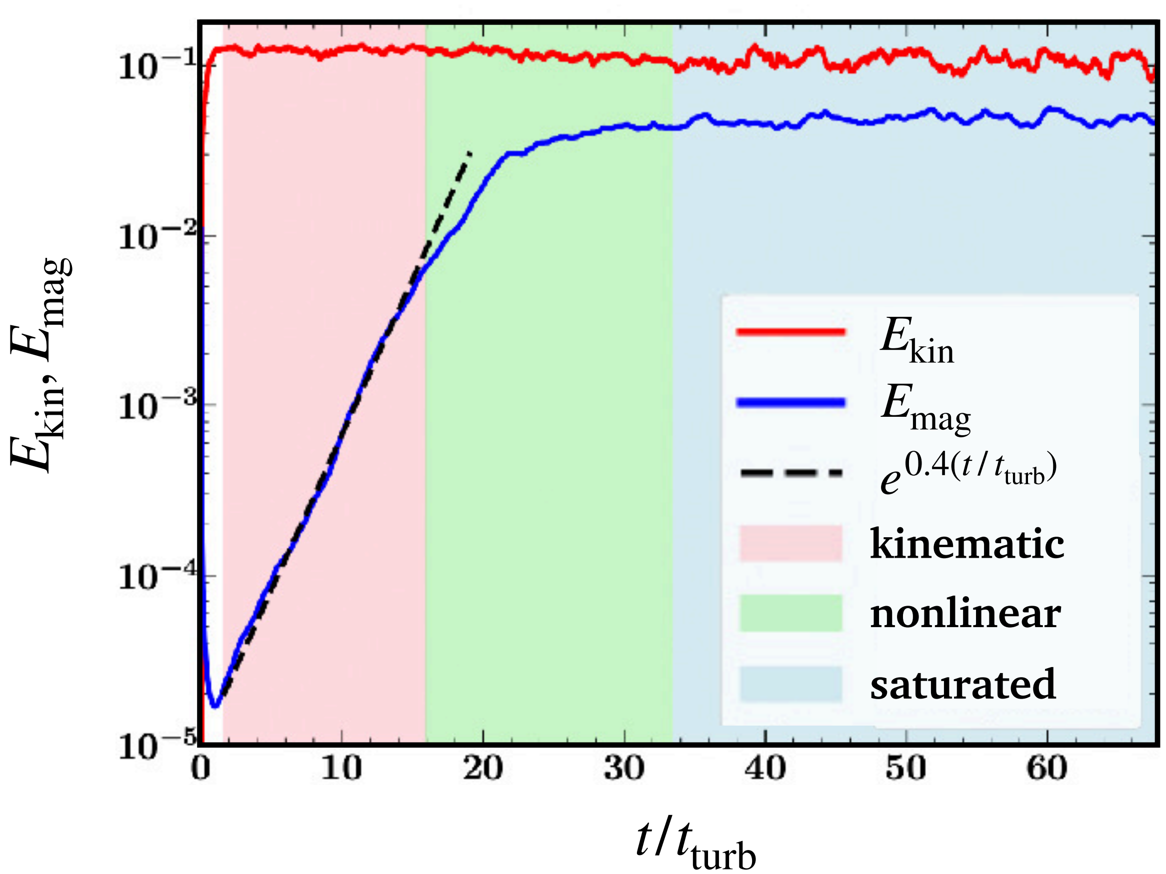
A simple theory

Turbulent dynamo

Volume integrated quantities

Kinetic and magnetic energy density

$$E_{\mathrm{kin}} = \frac{\rho u_{\mathrm{turb}}^2}{2} \qquad E_{\mathrm{mag}} = \frac{B^2}{8\pi}$$



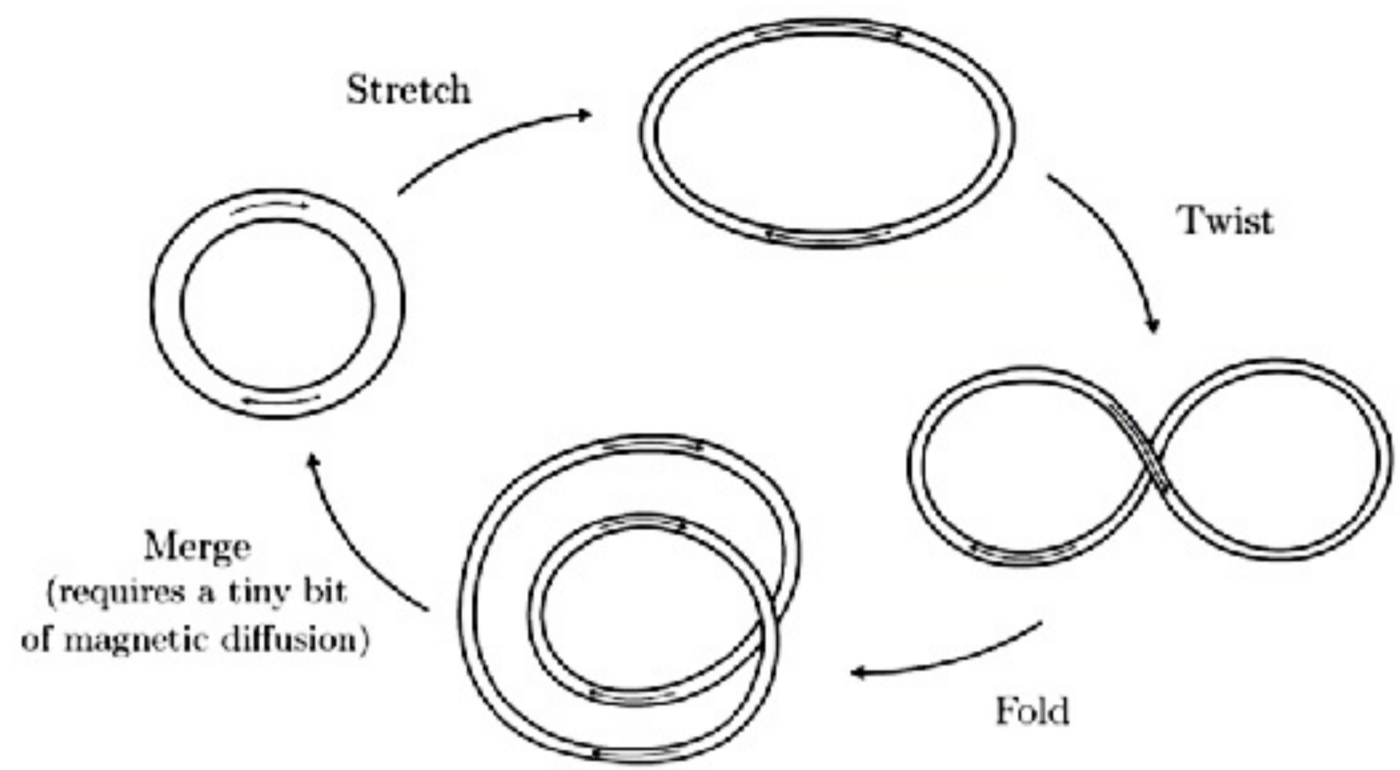
Seta and Federrath 2020

Phenomenological model

No magnetic monopoles

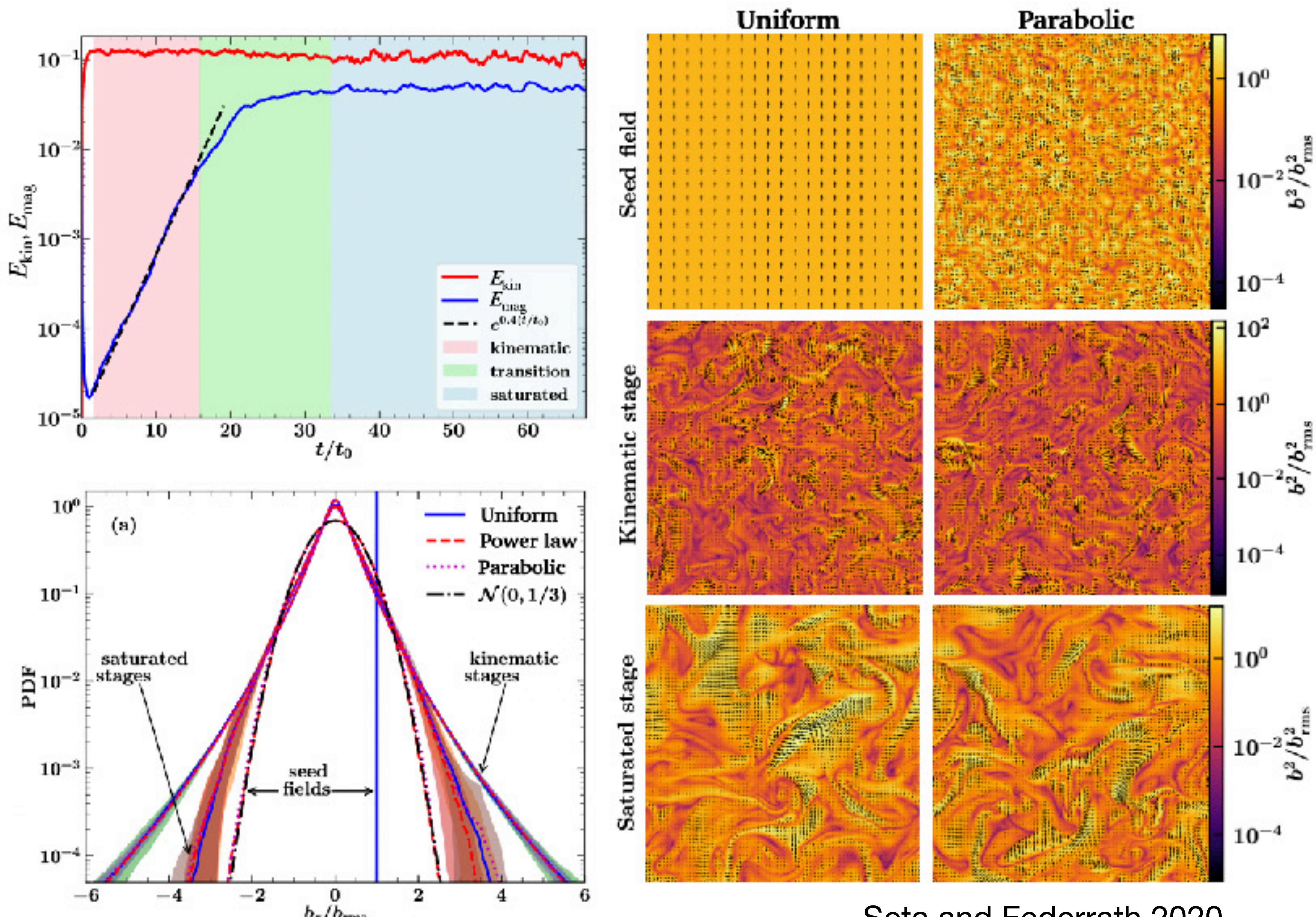
$$\nabla \cdot B = 0$$

Statistically this happens!



Vainshtein and Zeldovich 1972

Turbulent dynamo



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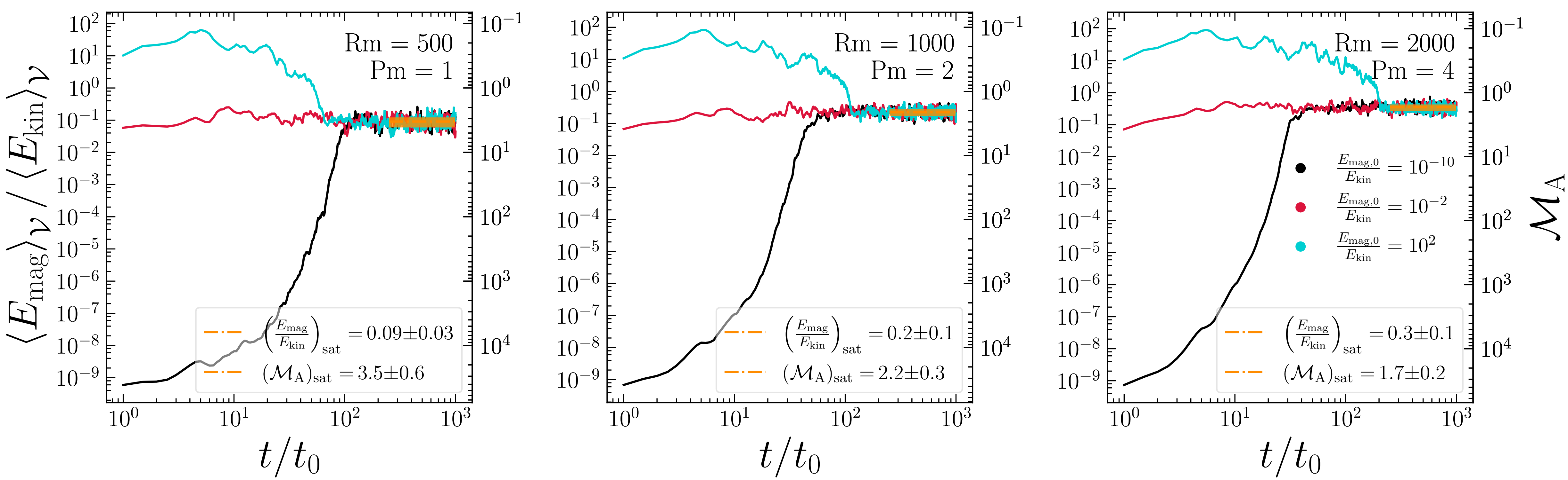
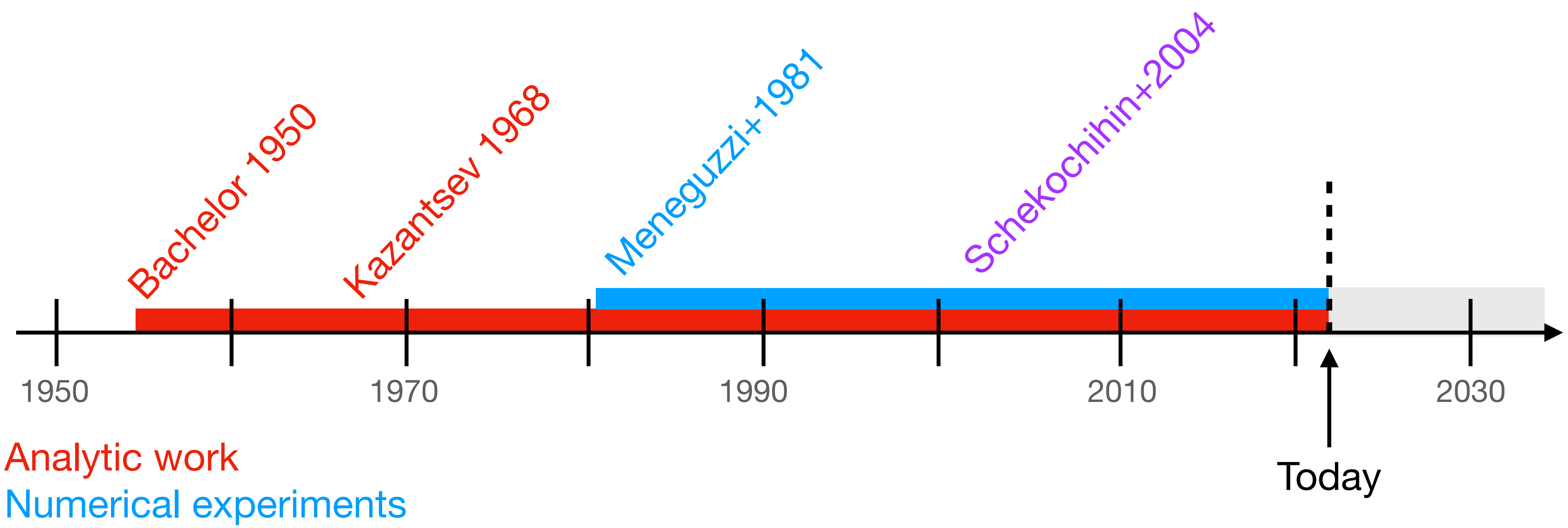


Beattie et al 2022b

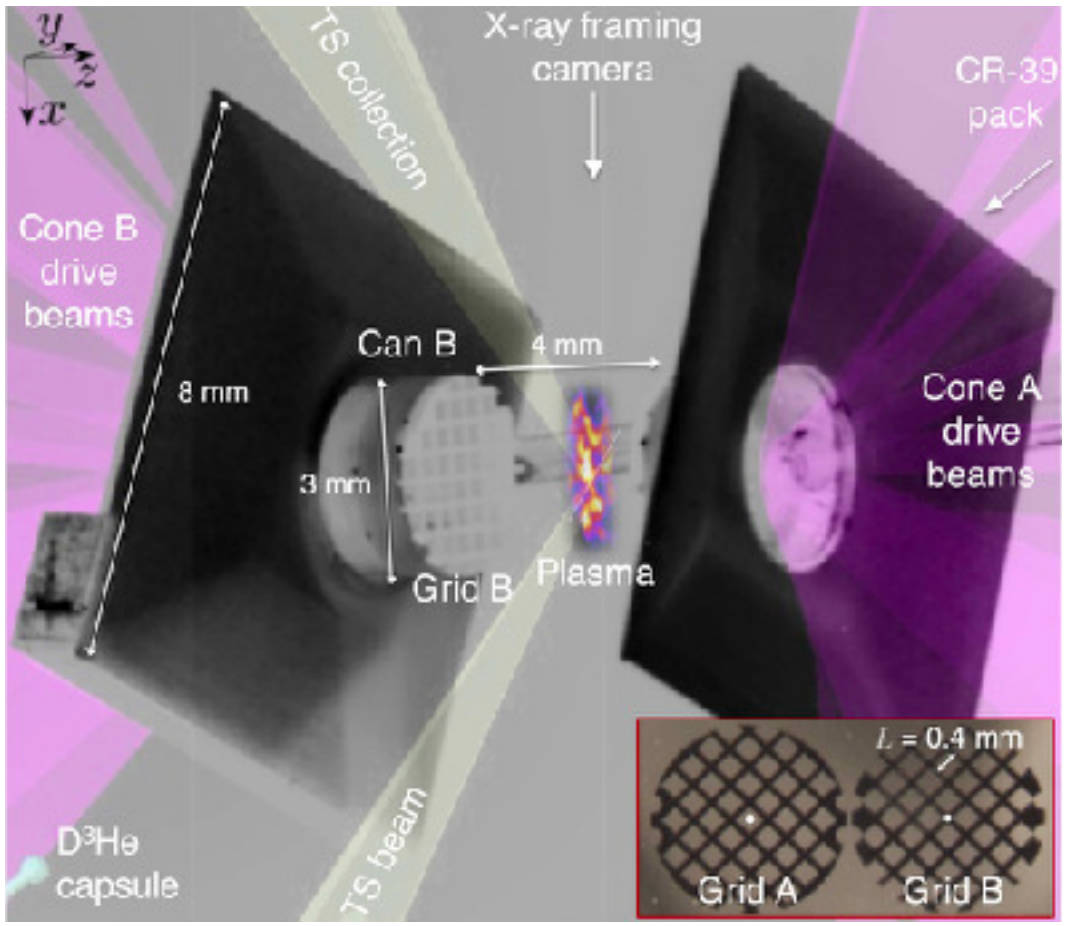
Turbulent dynamo

Is this just a theory?

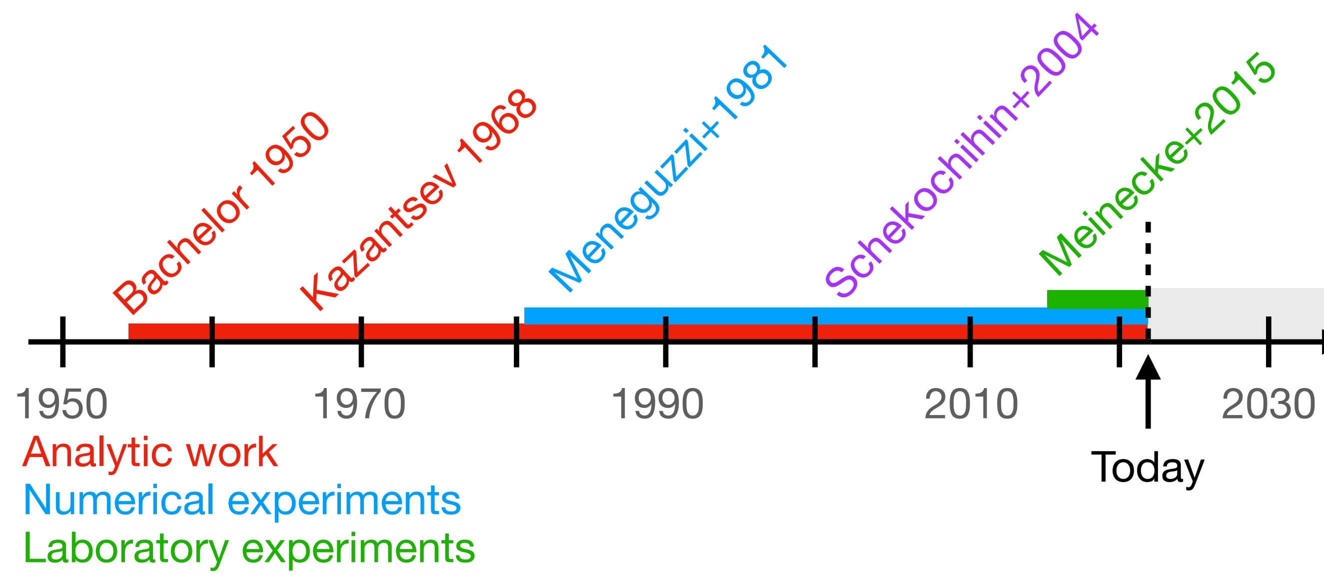


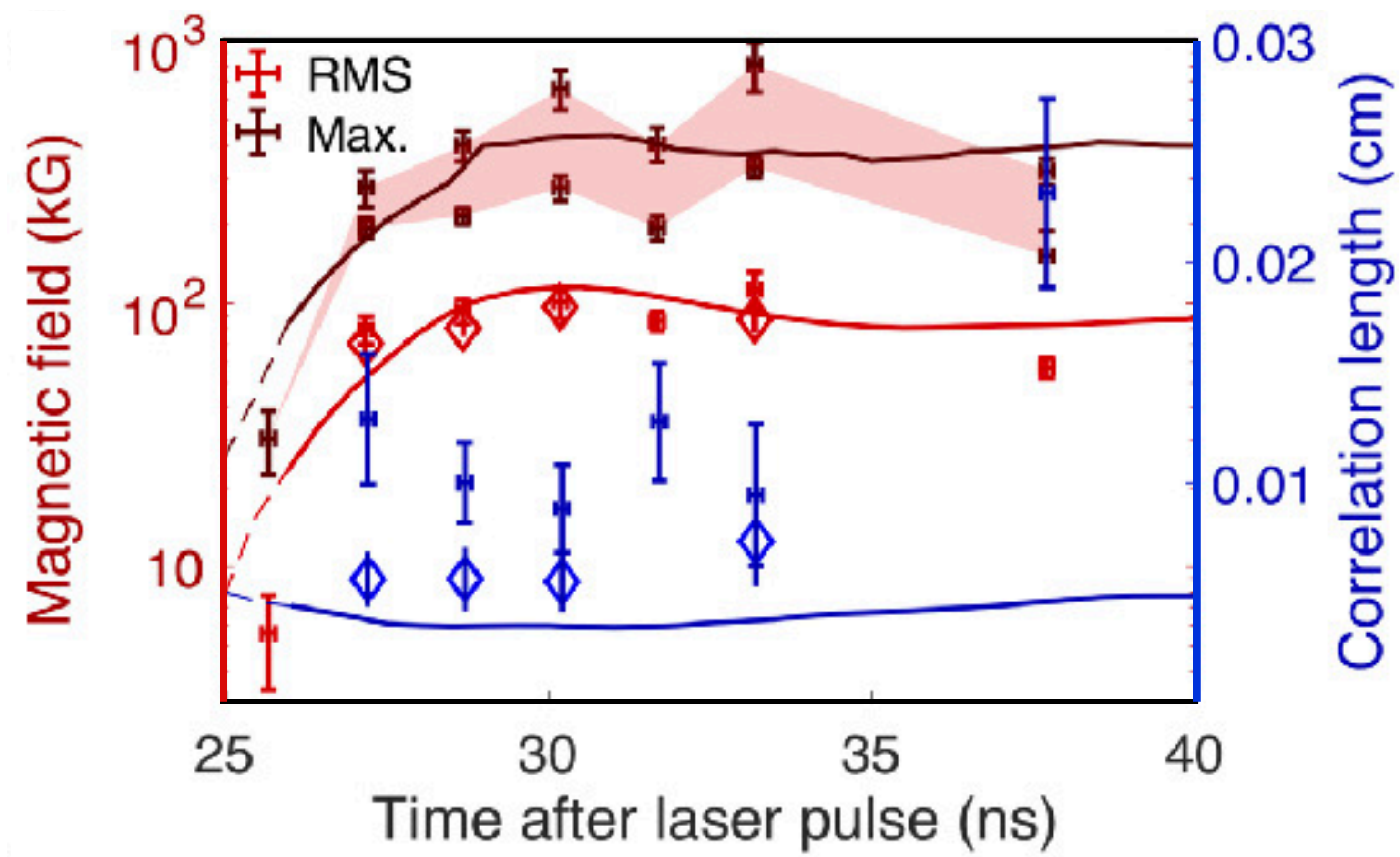
Turbulent dynamo

More than just a theory



Bott+2020

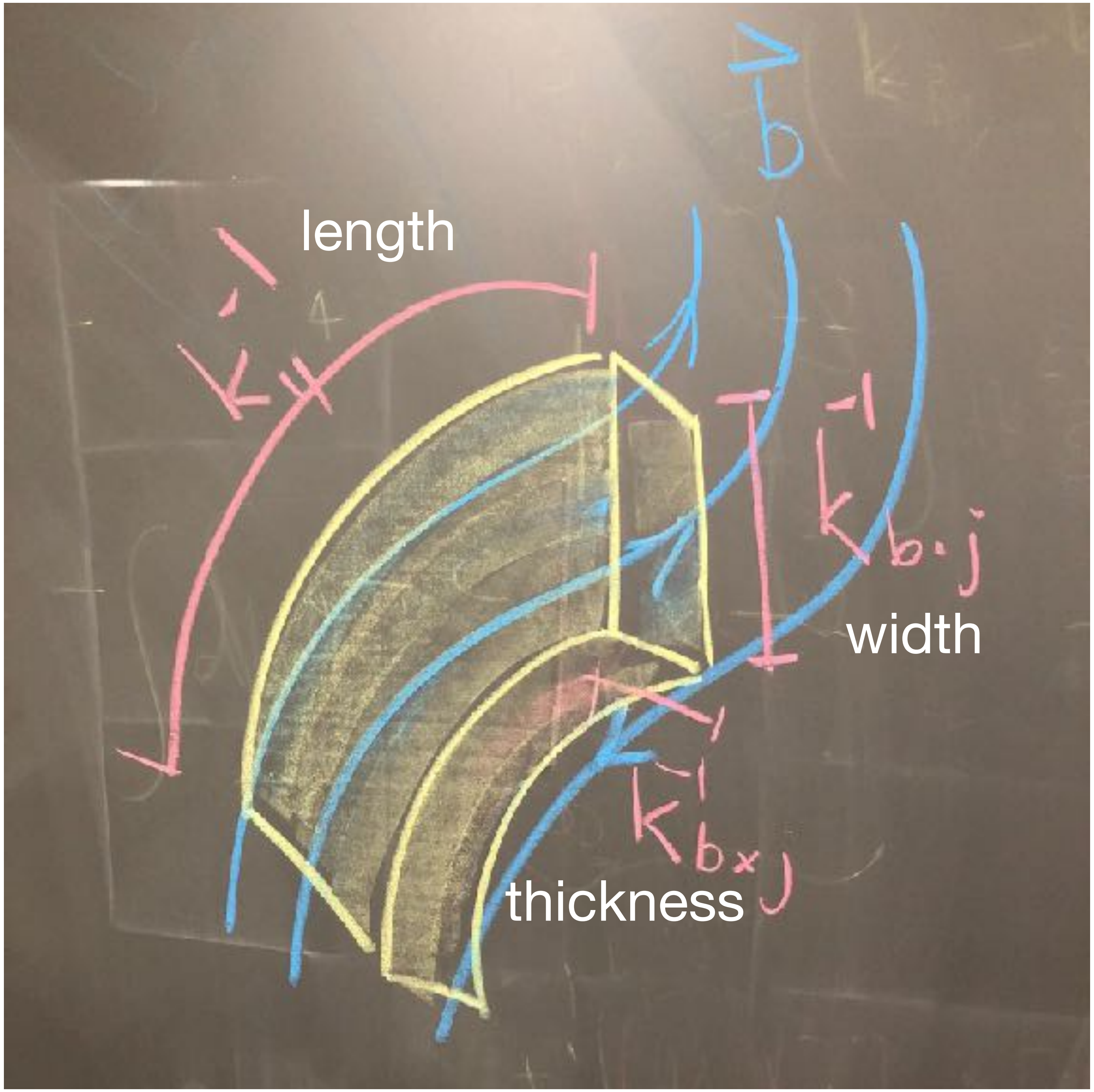




A hierarchy of scales

Morphology of magnetic fields

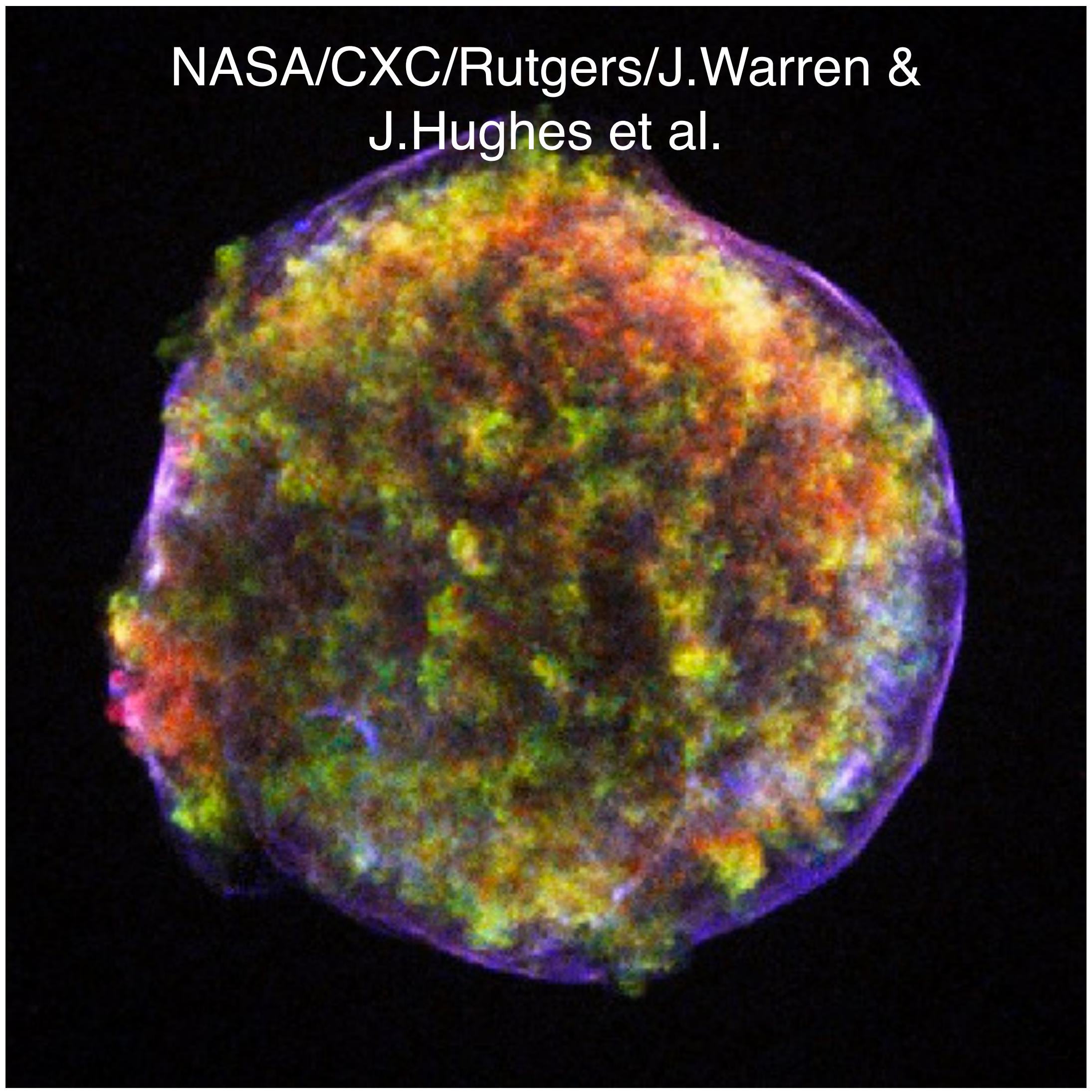
Characterising magnetic structures

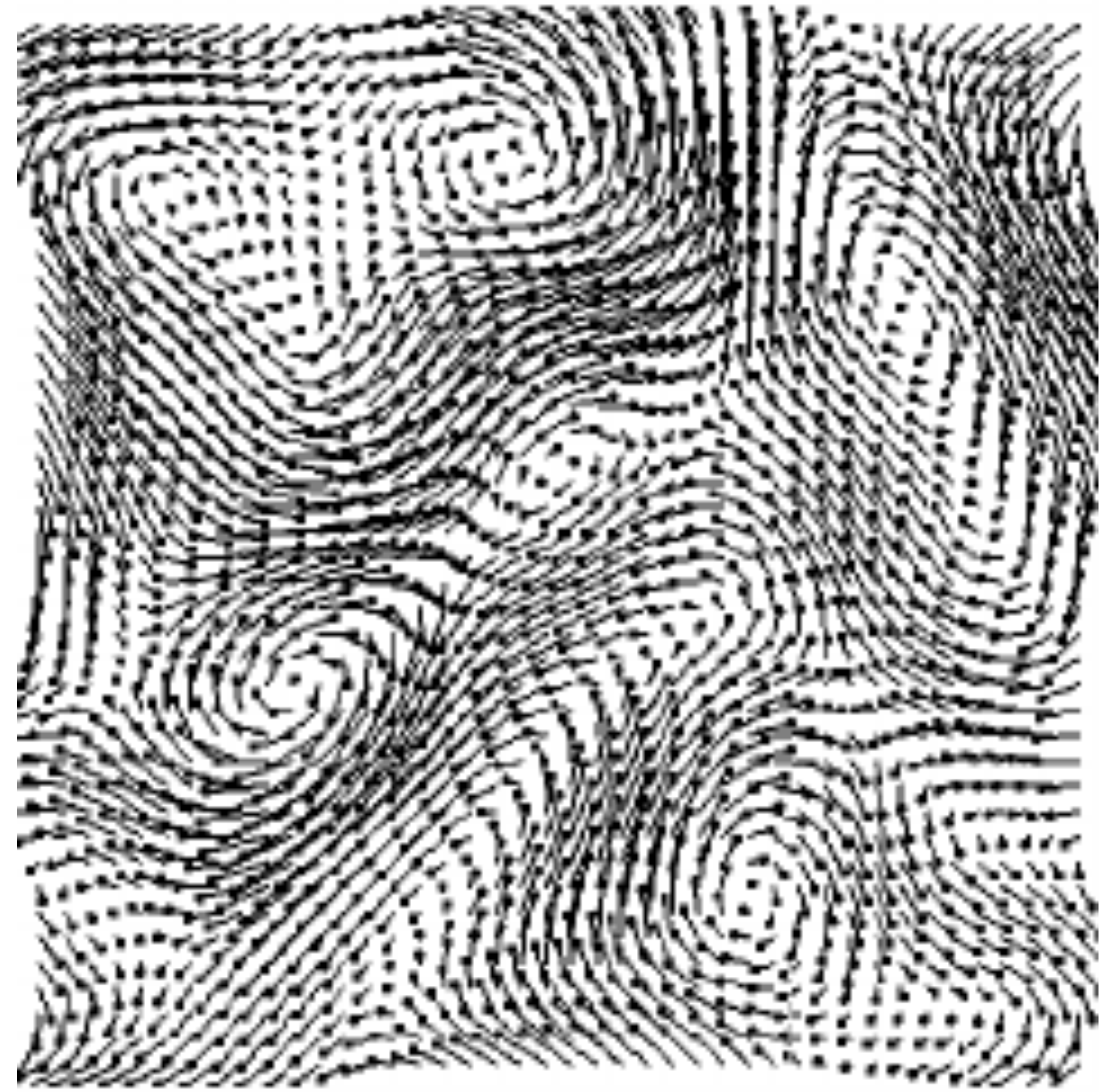


- We like to think in characteristic lengths
- The goal is to determine what parameters determine the sizes of these dimensions?

Schematic by James Beattie

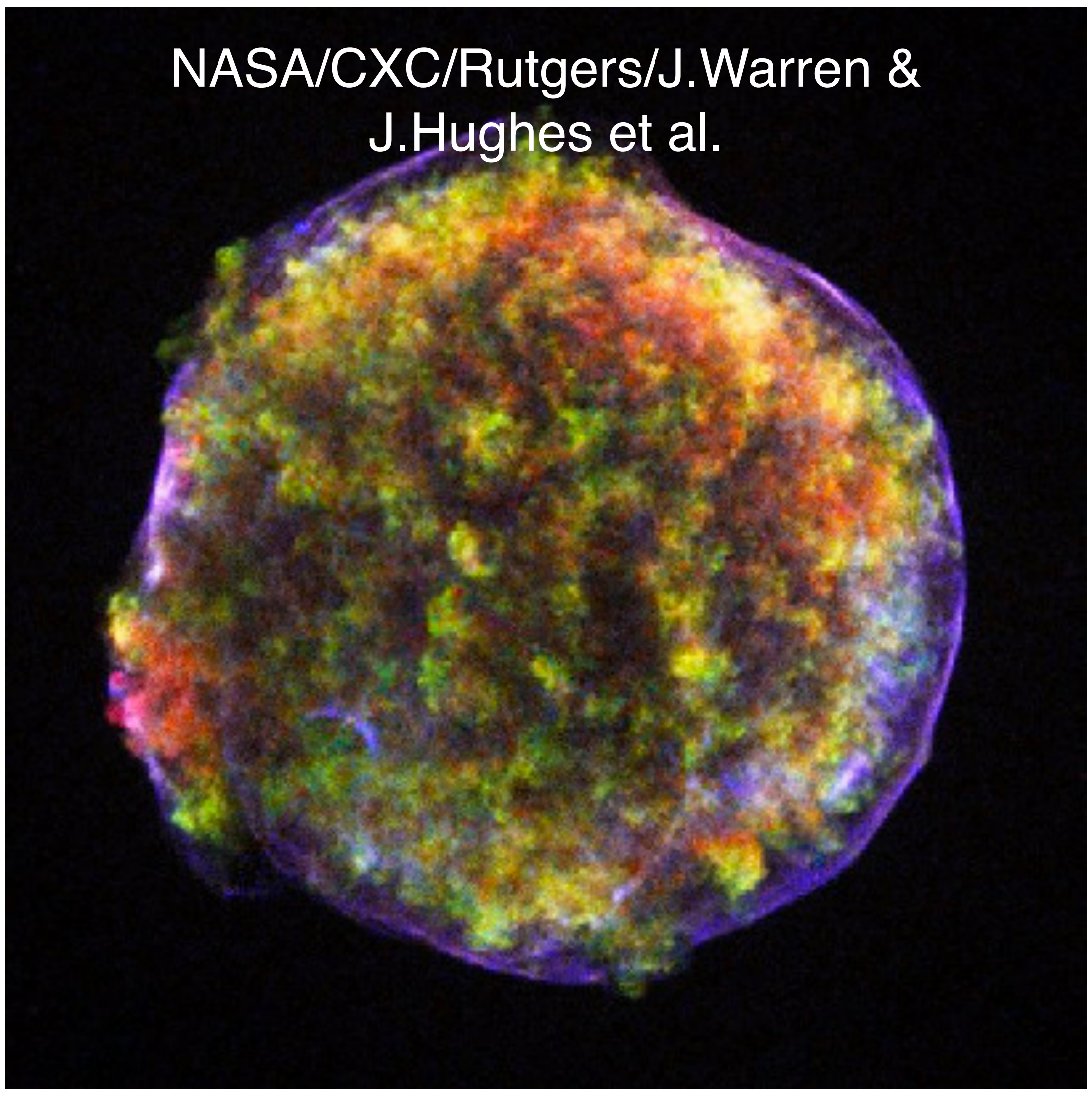
Characterising turbulent flows

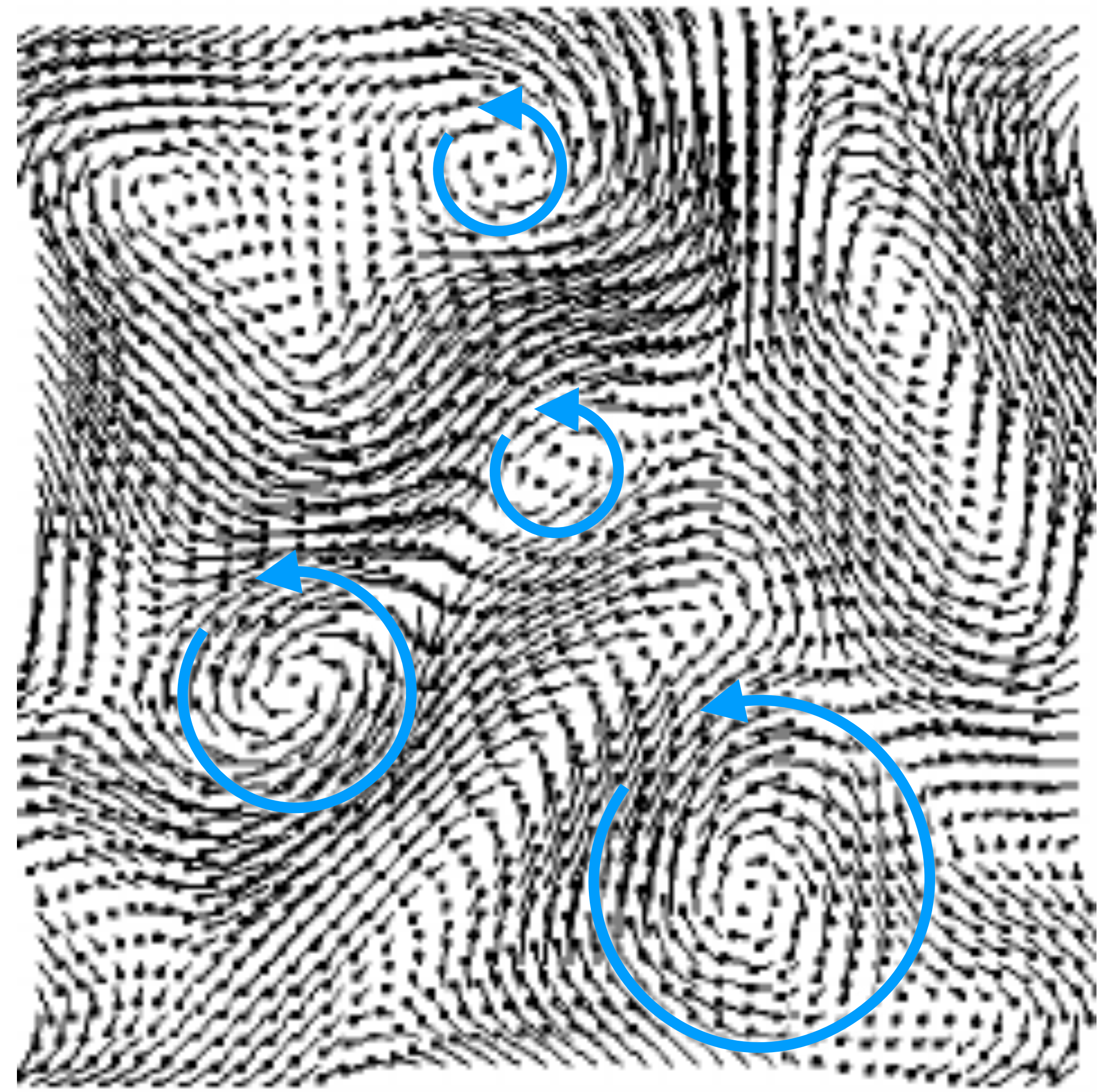




Cuzol and Mémin 2005

Characterising turbulent flows





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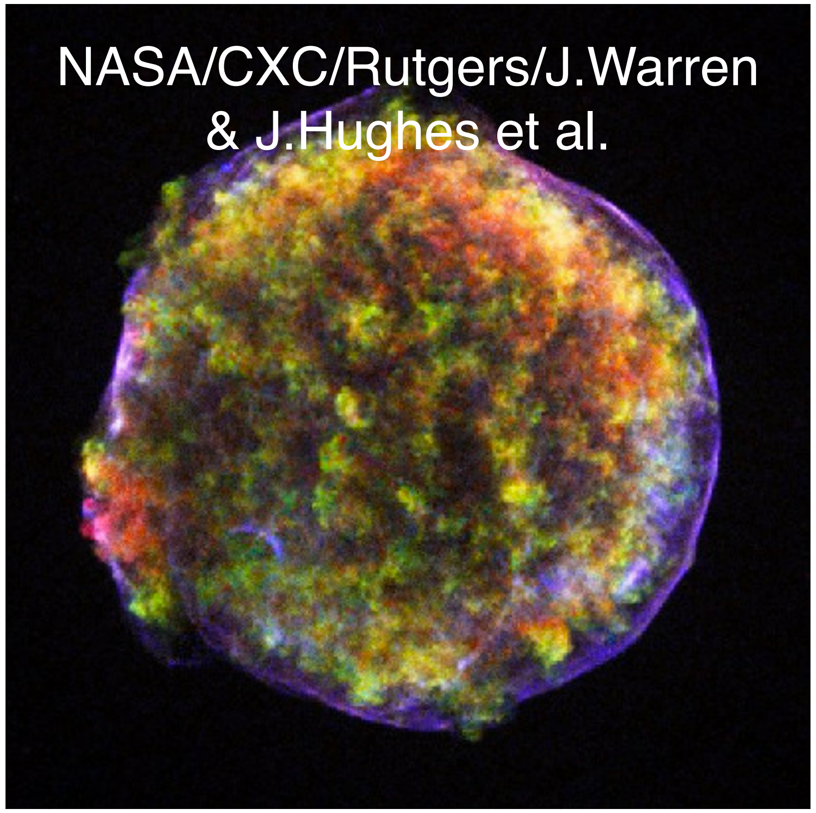
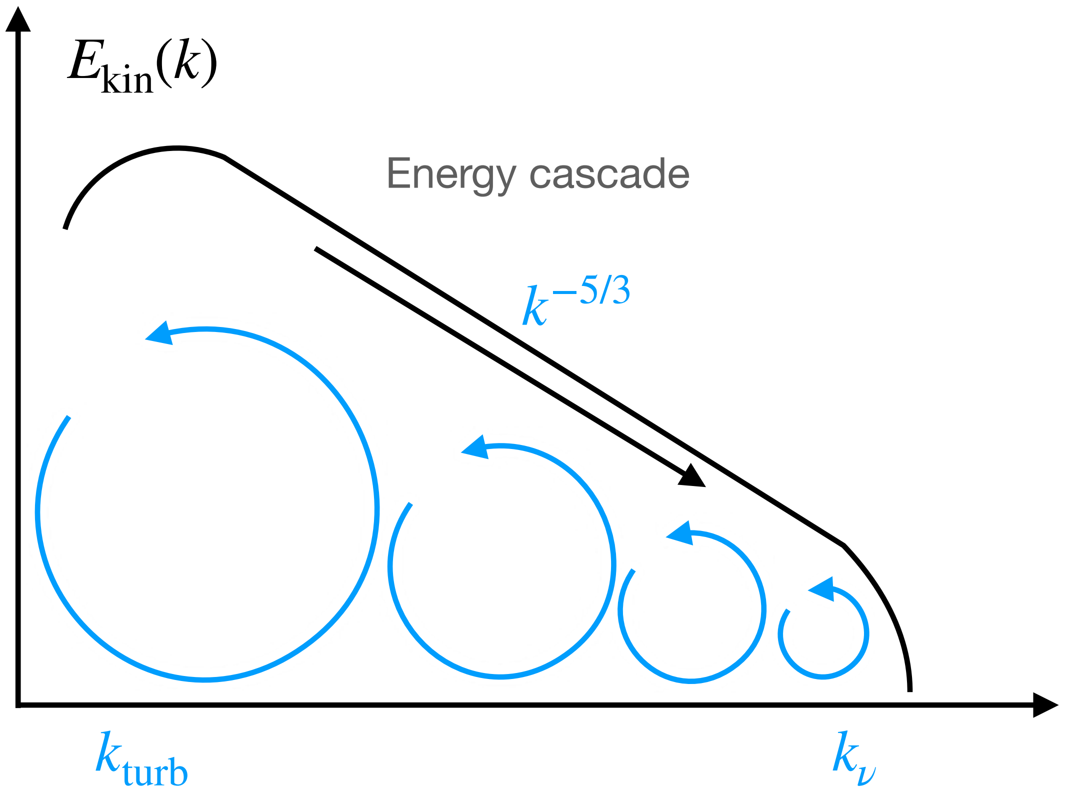
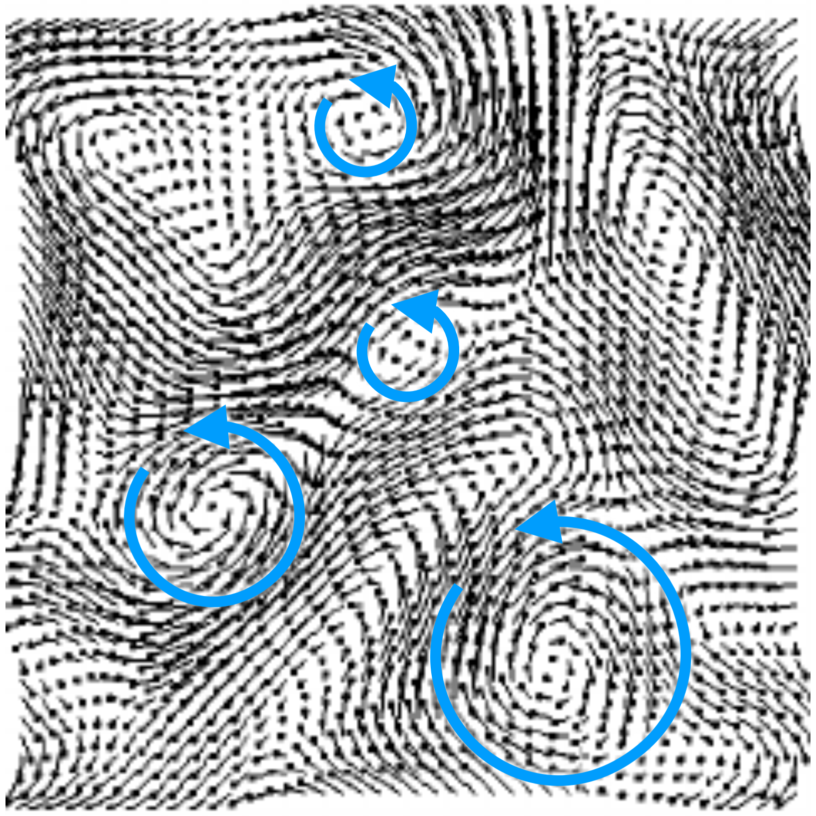


Distribution of energy across scales (spatial structures)

Wavenumber: $k = 2\pi/\ell$





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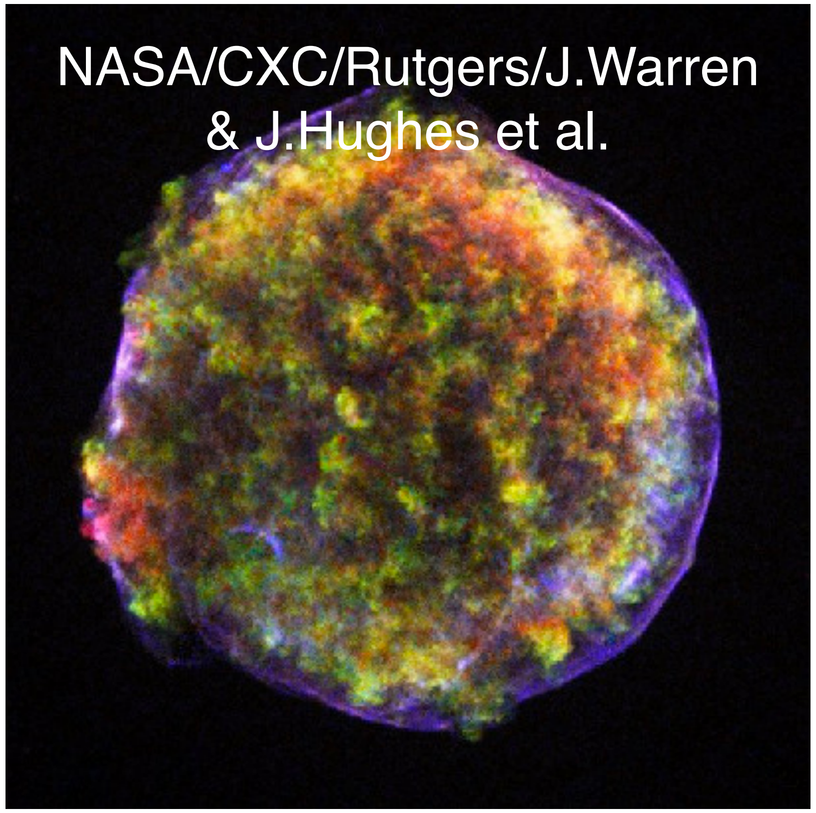
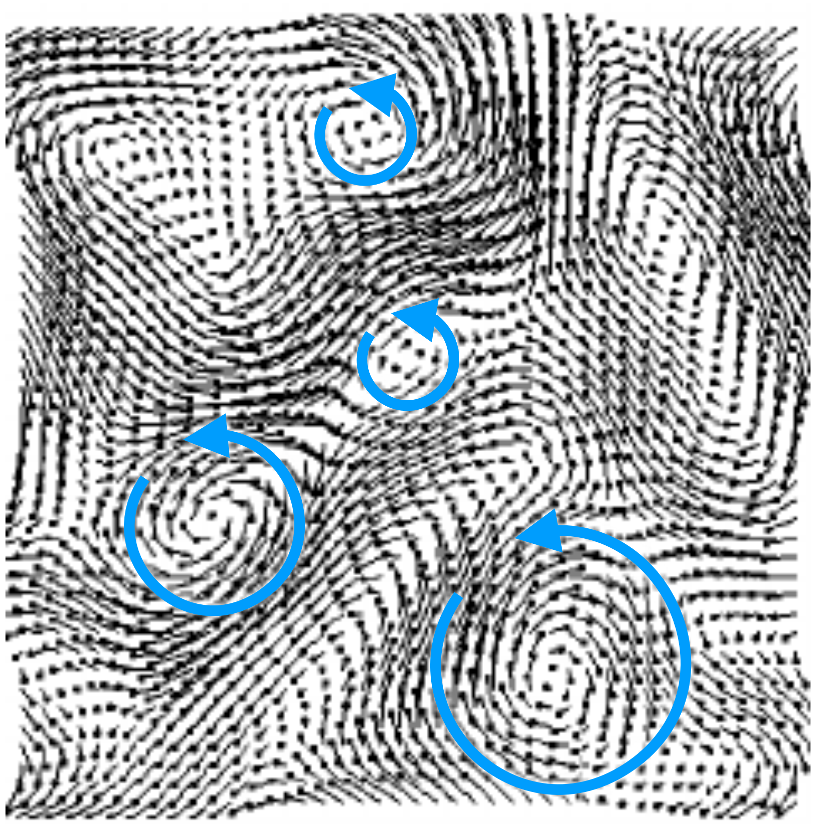
Characterising turbulent flows





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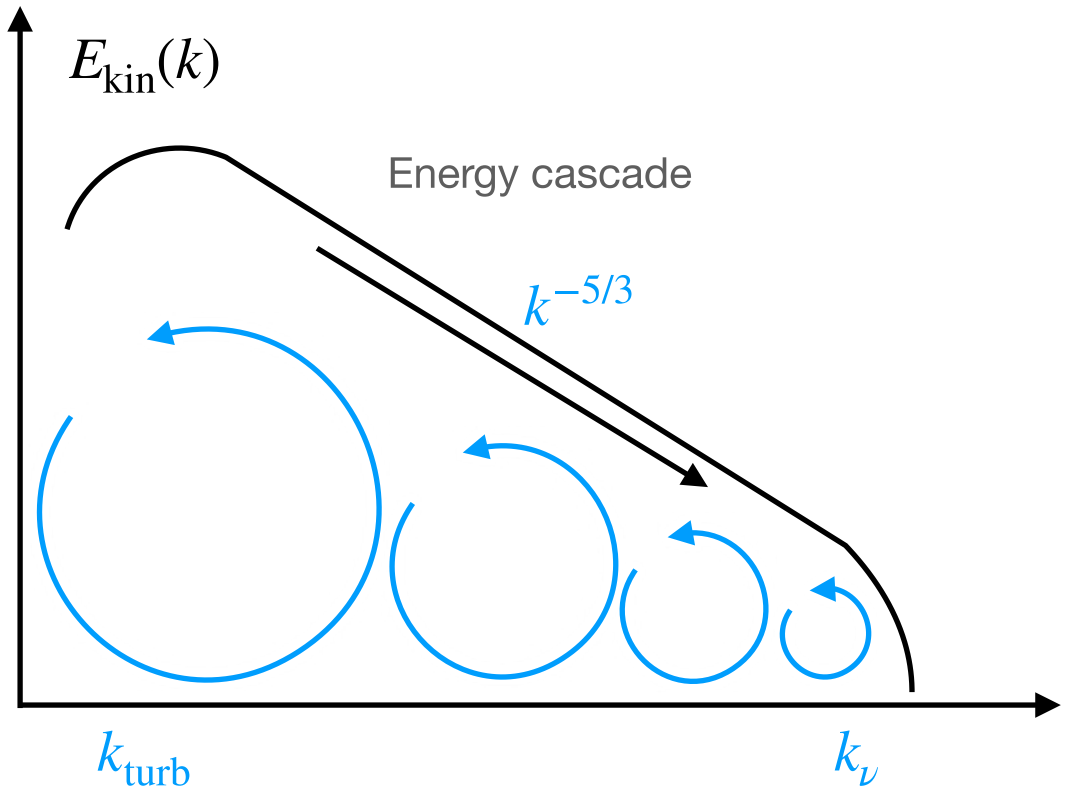

"Big whirls have little whirls,
That feed on their velocity;
And little whirls have lesser whirls,
And so on to viscosity."

— Lewis Fry Richardson

Characterising turbulent, magnetised flows

Magnetic Prandtl number: $$\mathrm{Pm} = \frac{\text{magnetic dissipation}}{\text{kinetic dissipation}}$$

Characterising turbulent, magnetised flows

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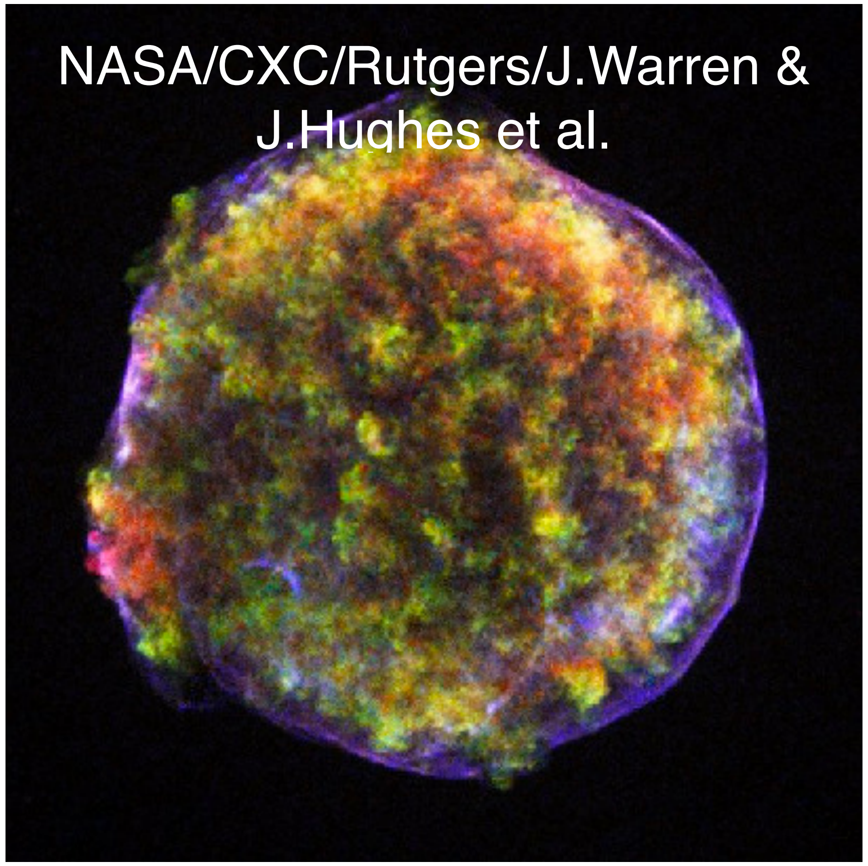
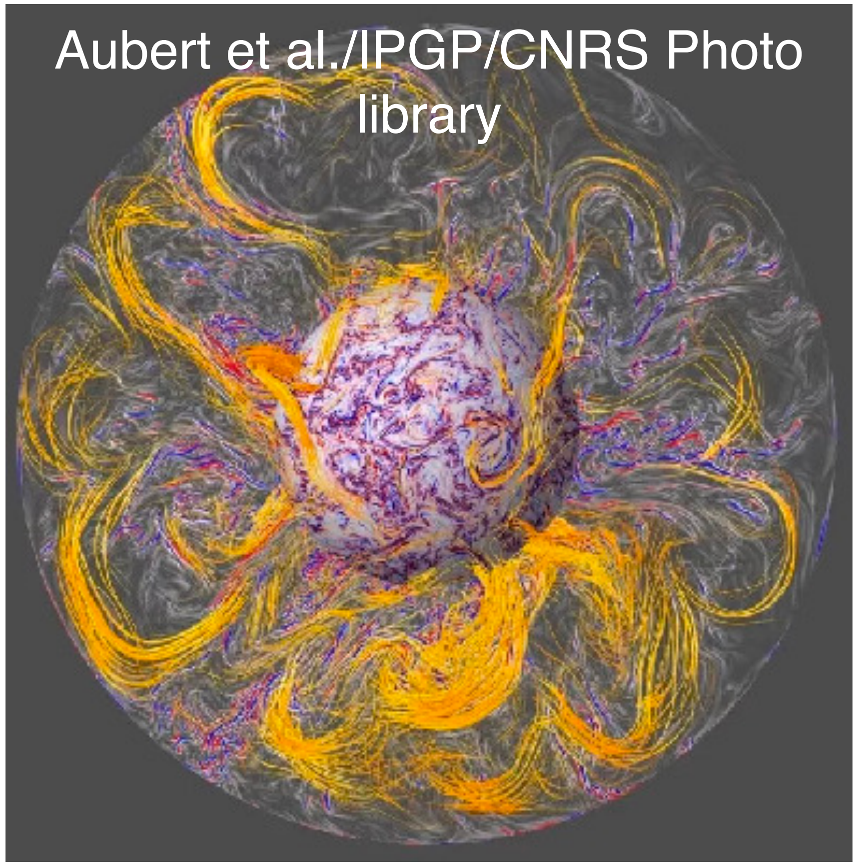
$\mathrm{Pm} \gg 1$



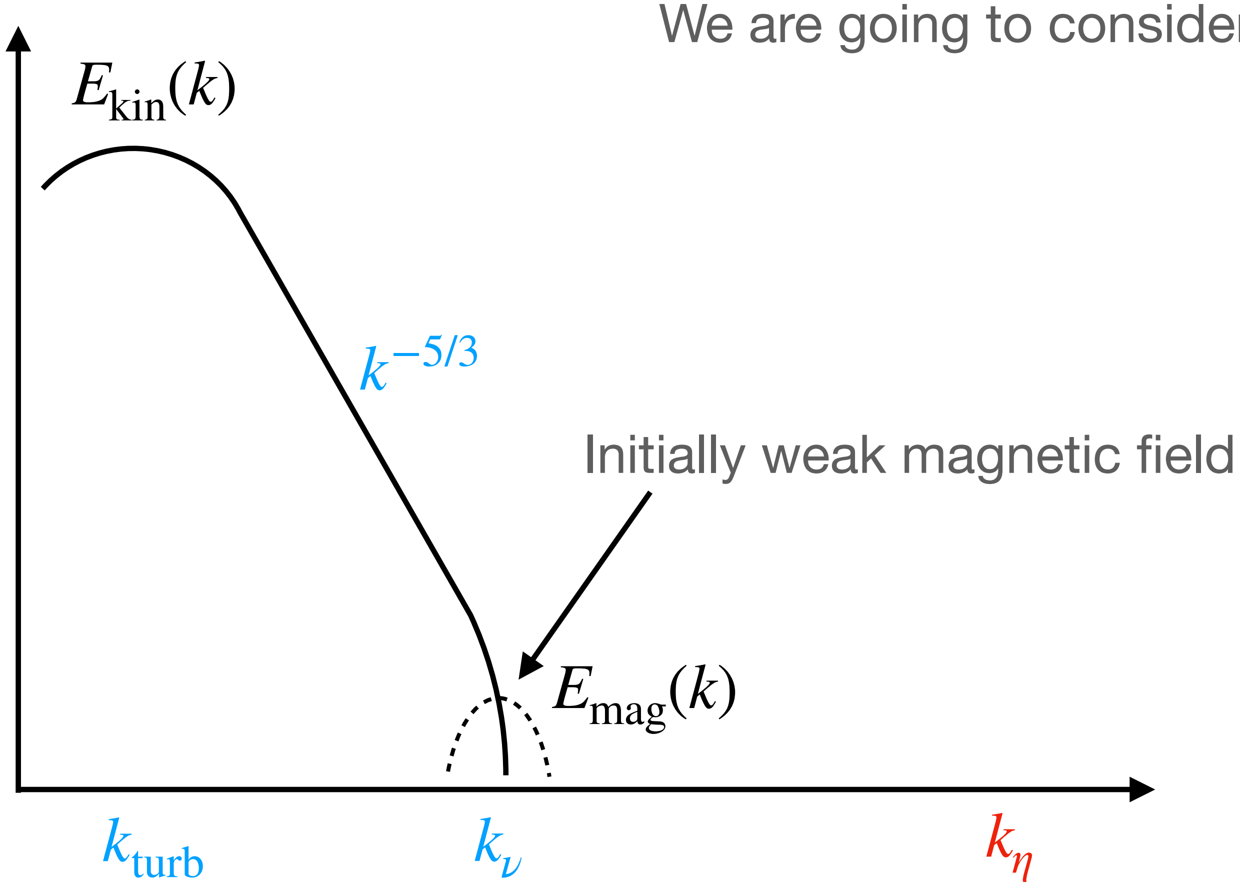
$\mathrm{Pm} \lesssim 1$



Characterising turbulent, magnetised flows

Where magnetic and kinetic energy dissipates $\frac{k_\eta}{k_\nu} = \mathrm{Pm}^{1/2}$

We are going to consider $\mathrm{Pm} \gg 1$.



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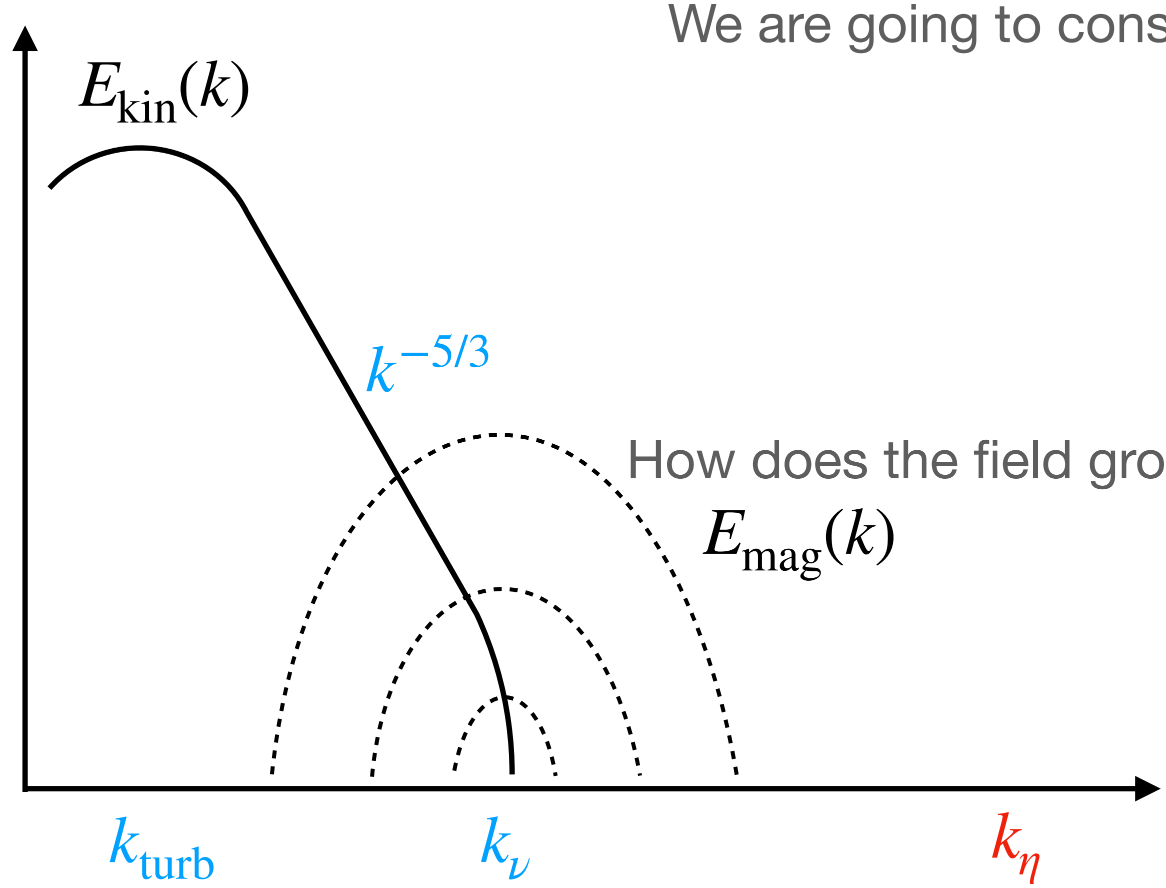
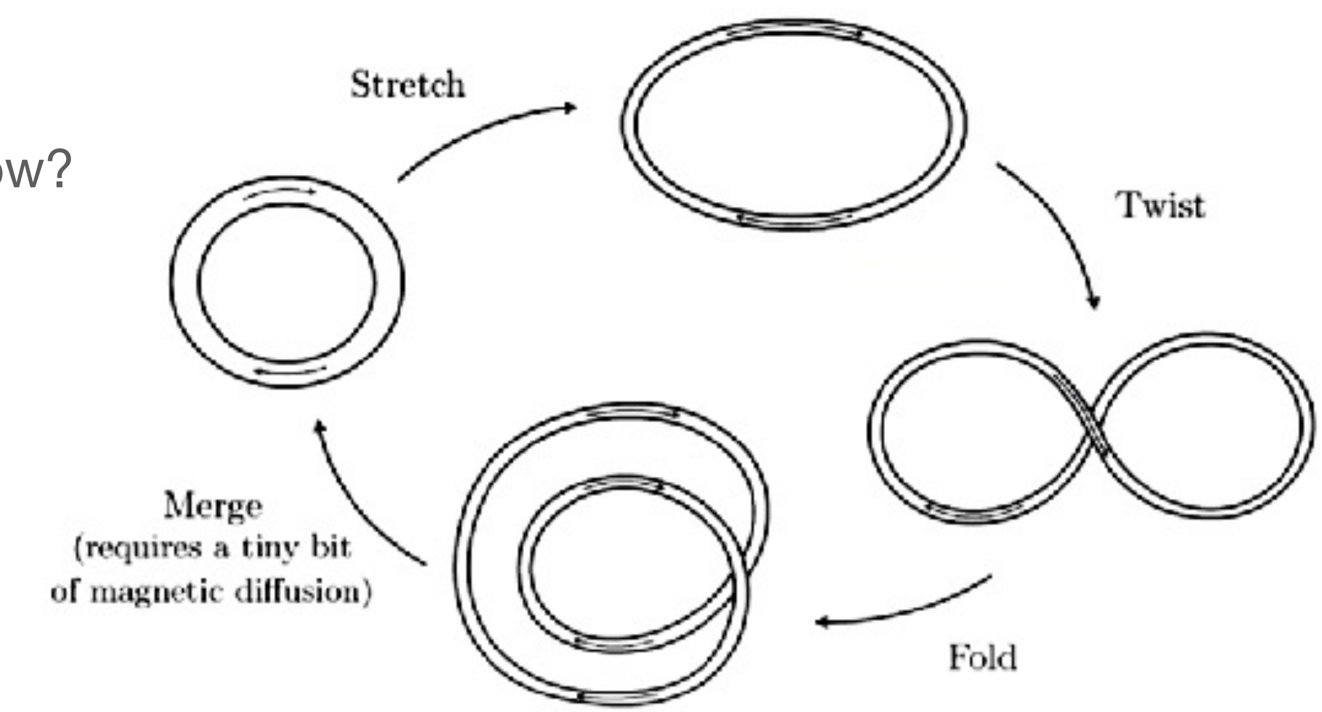
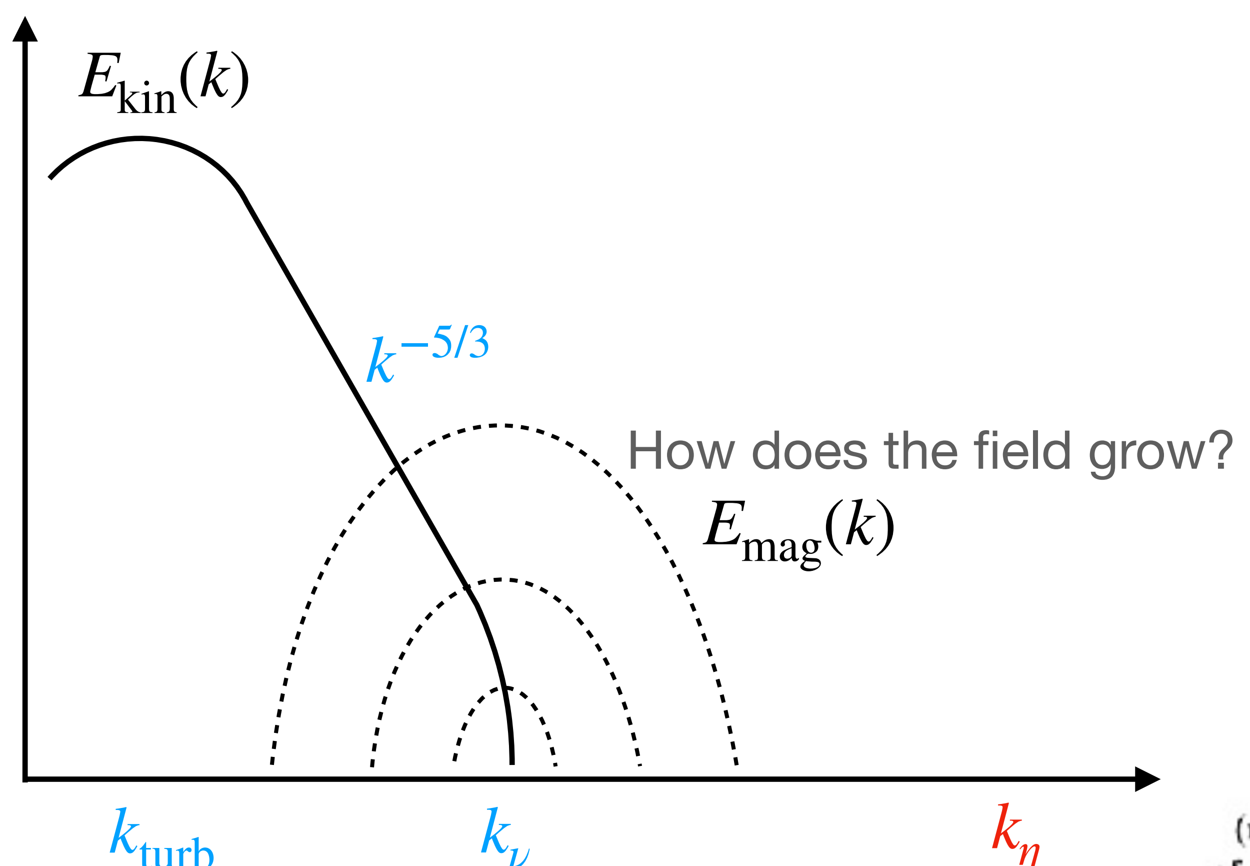
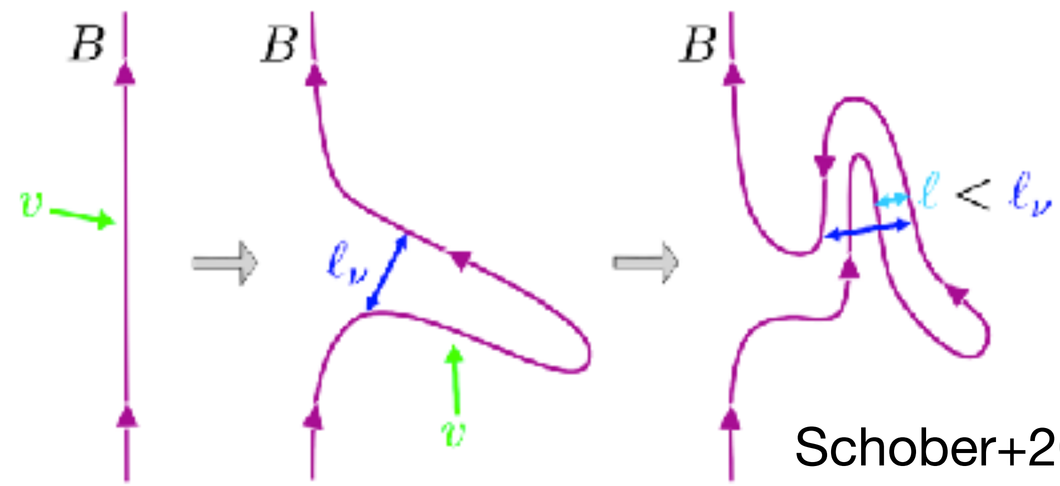




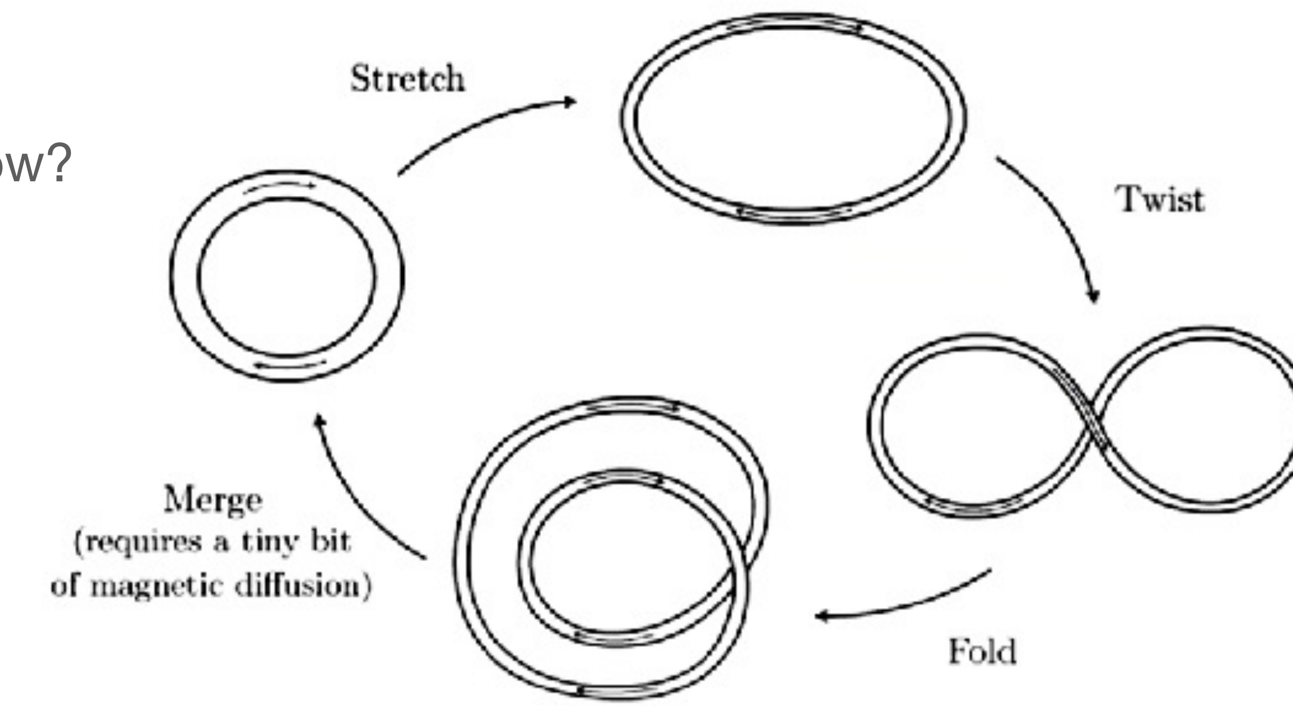
Vainshtein and Zeldovich 1972

Characterising turbulent, magnetised flows





Schober+2015



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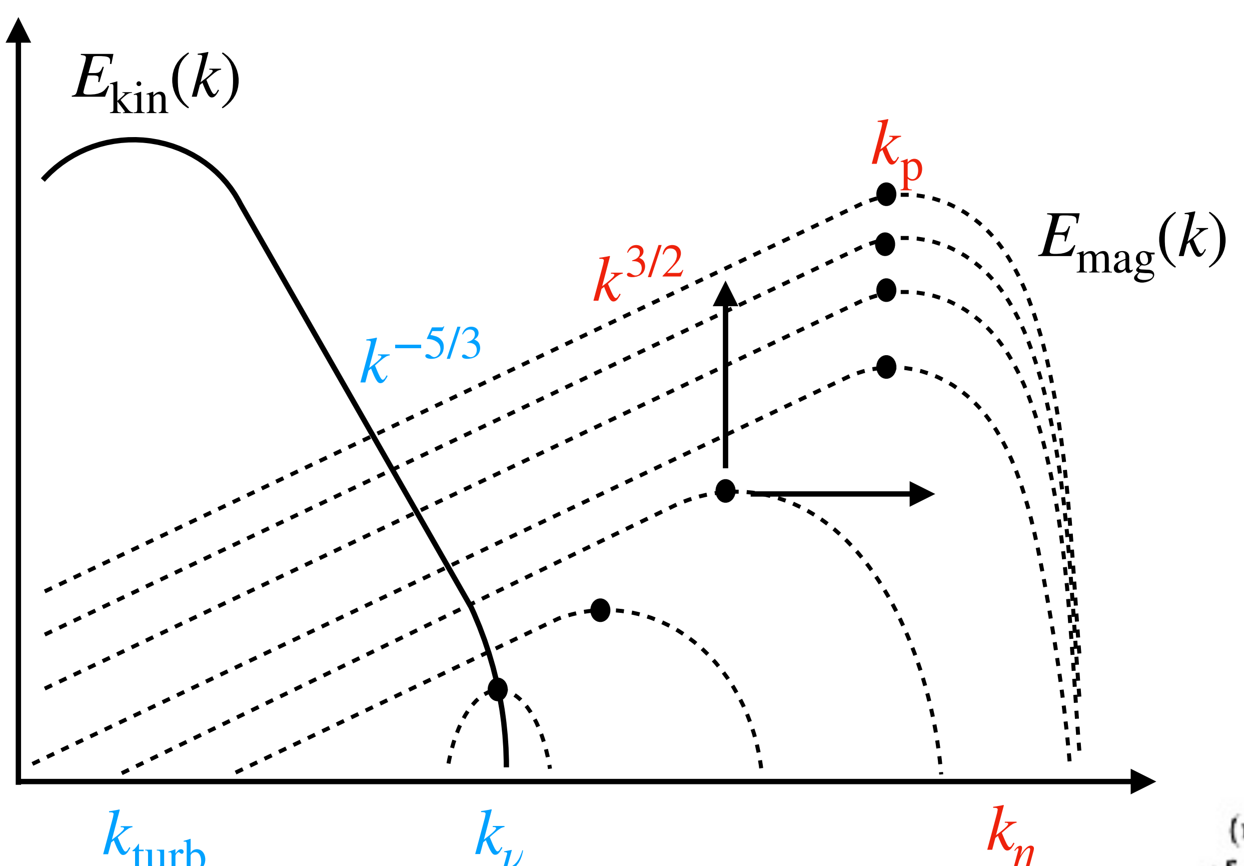

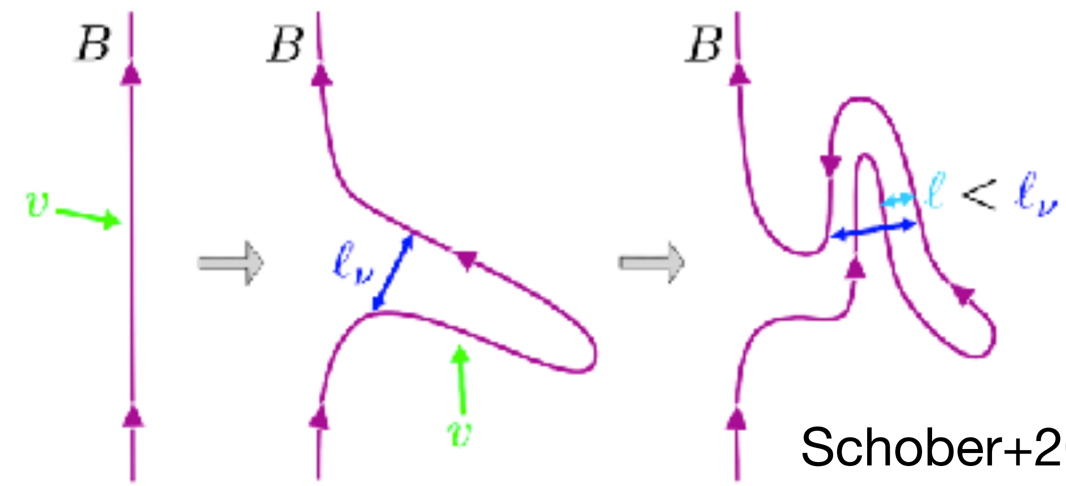

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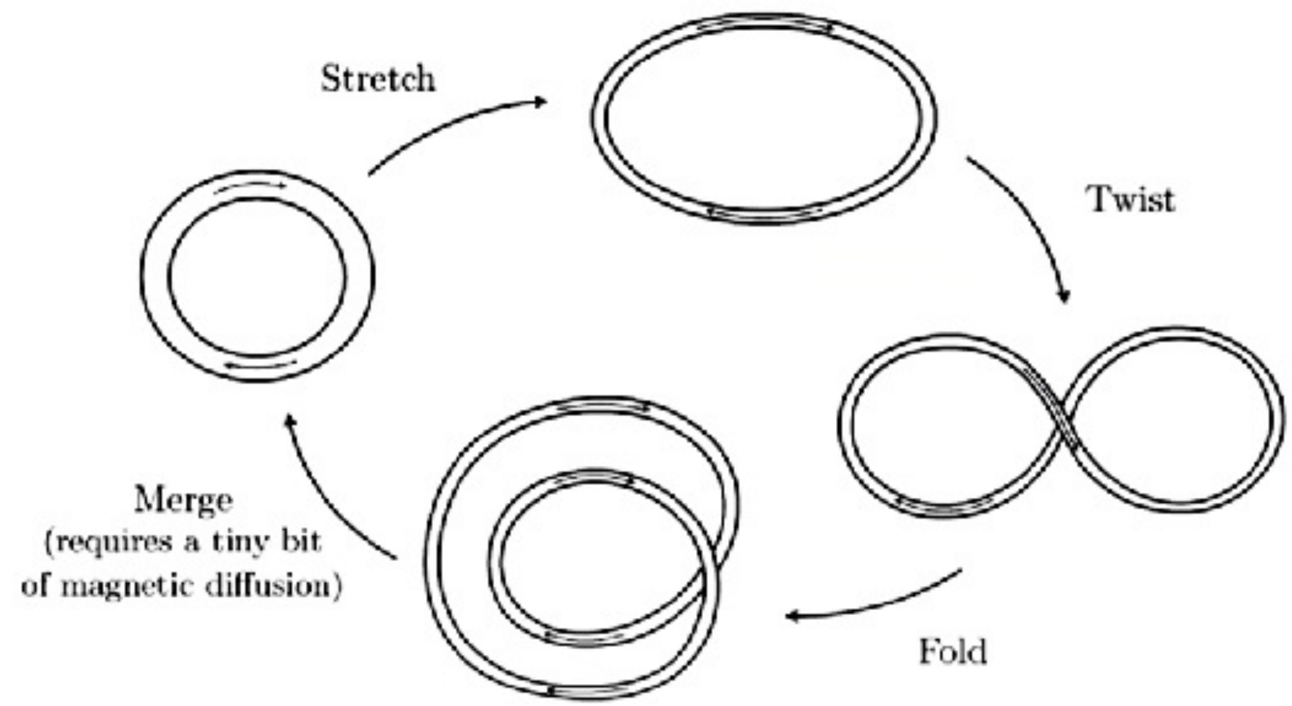

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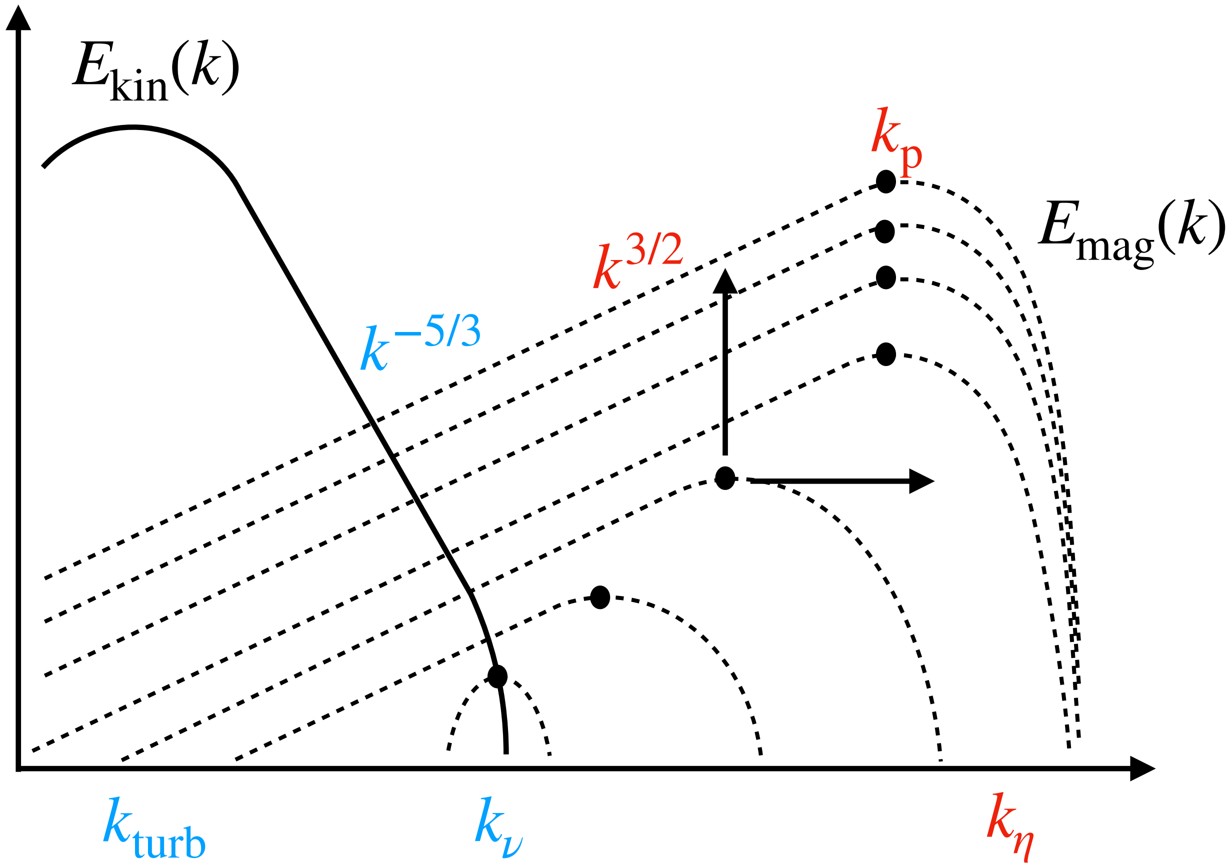
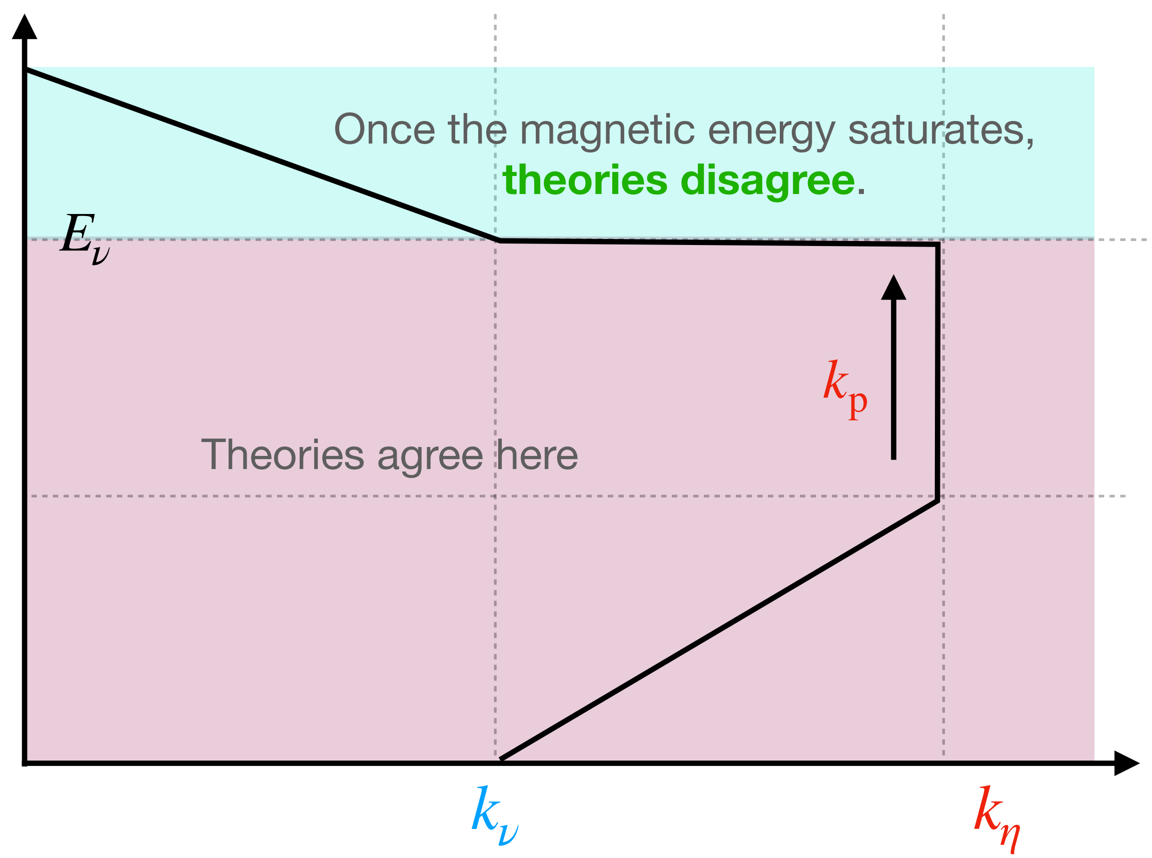
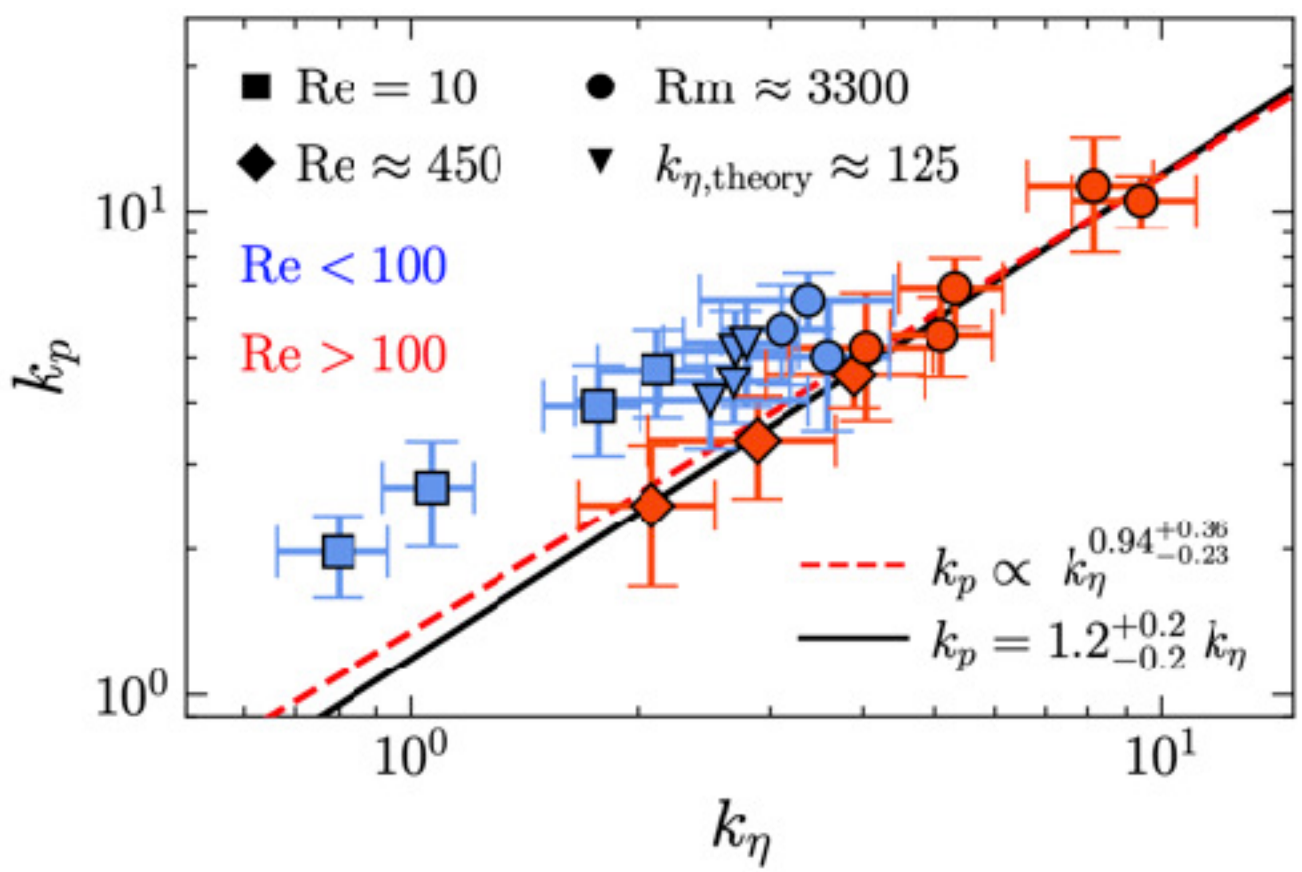
Characterising turbulent, magnetised flows

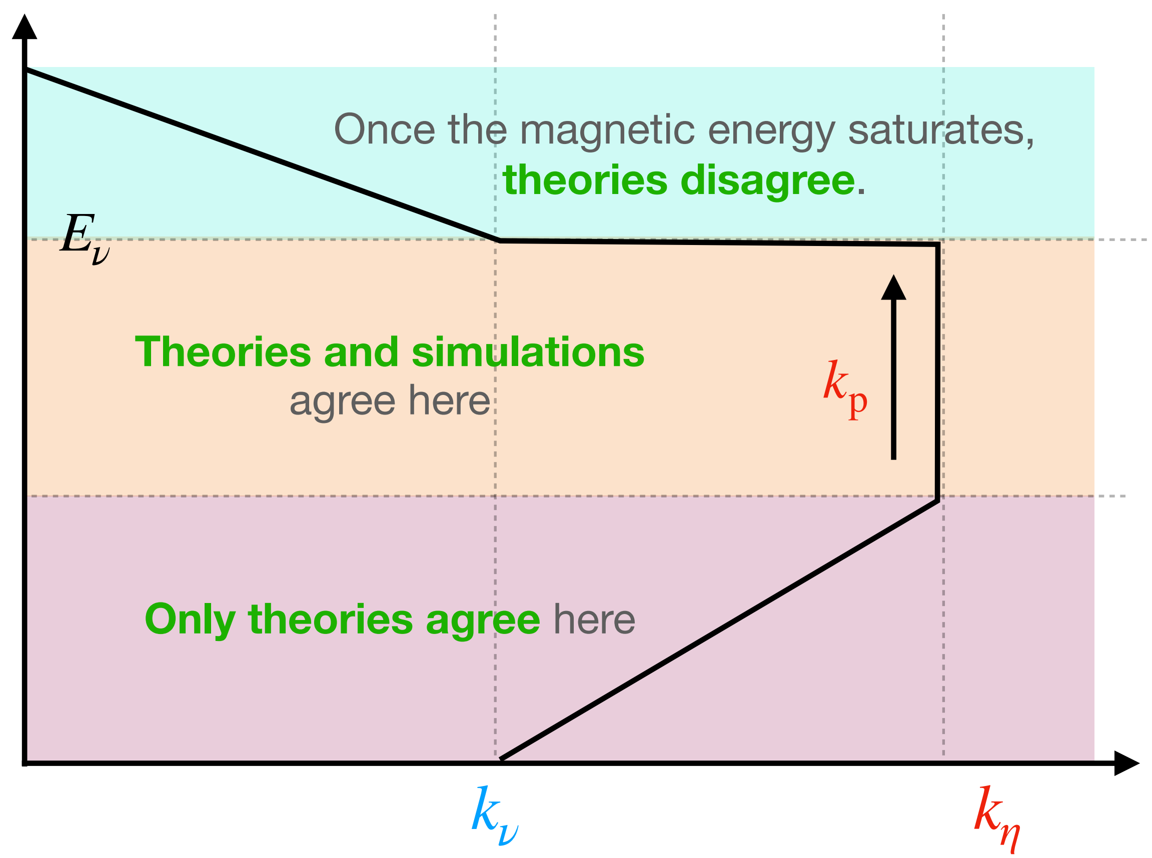




Characterising turbulent, magnetised flows

Kriel+2022



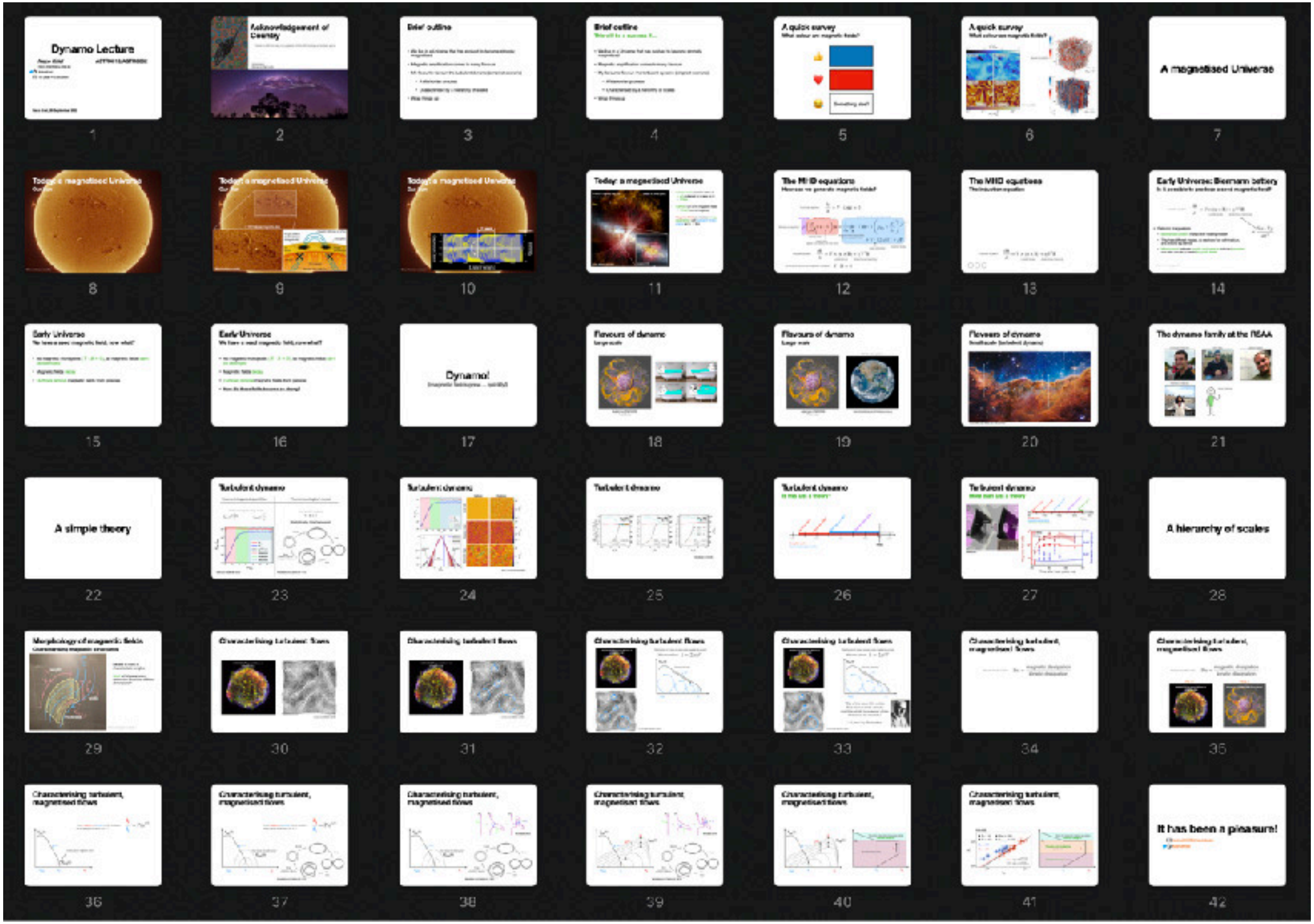


It has been a pleasure!

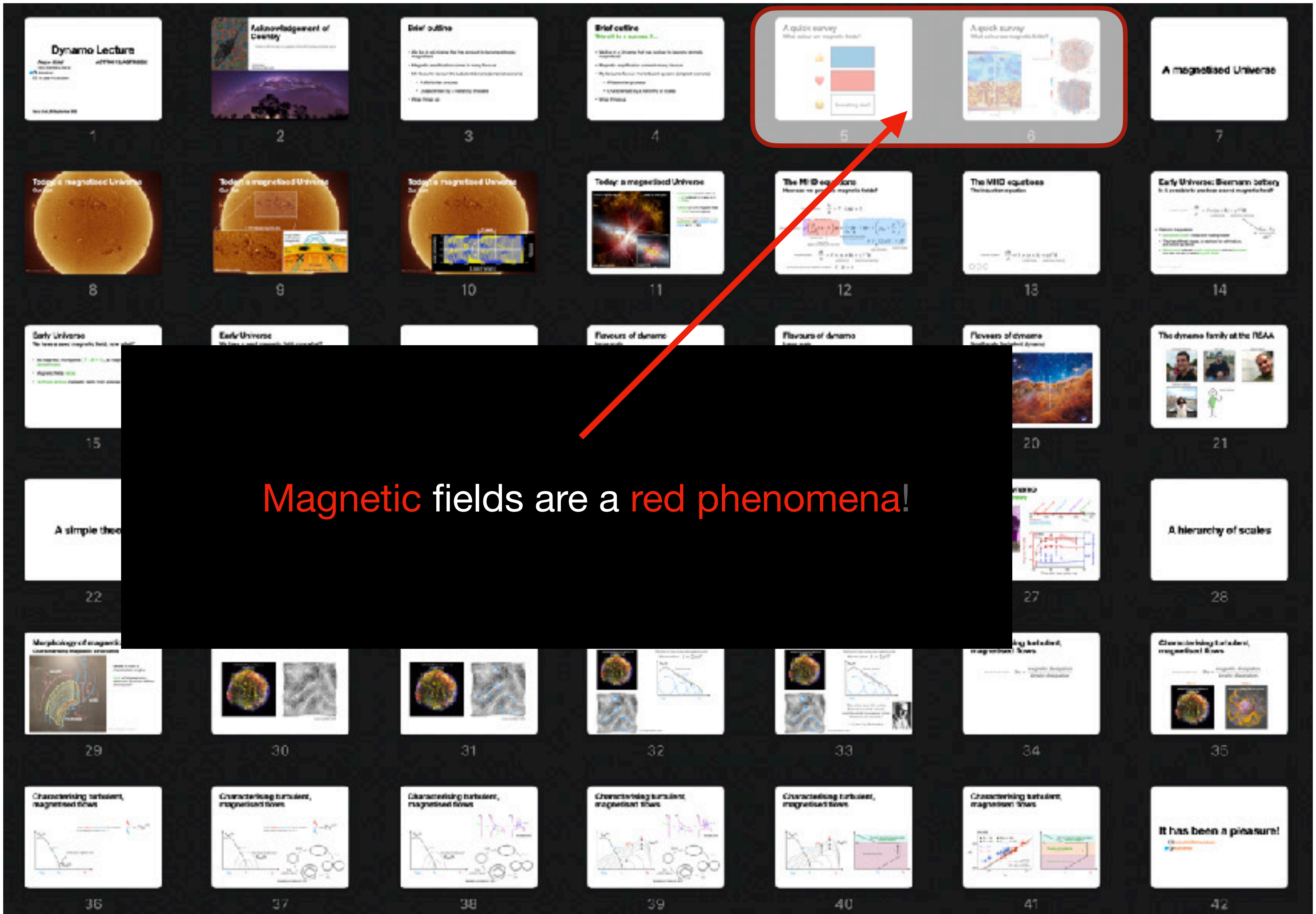
✉ neco.kriel@anu.edu.au

AstroKriel

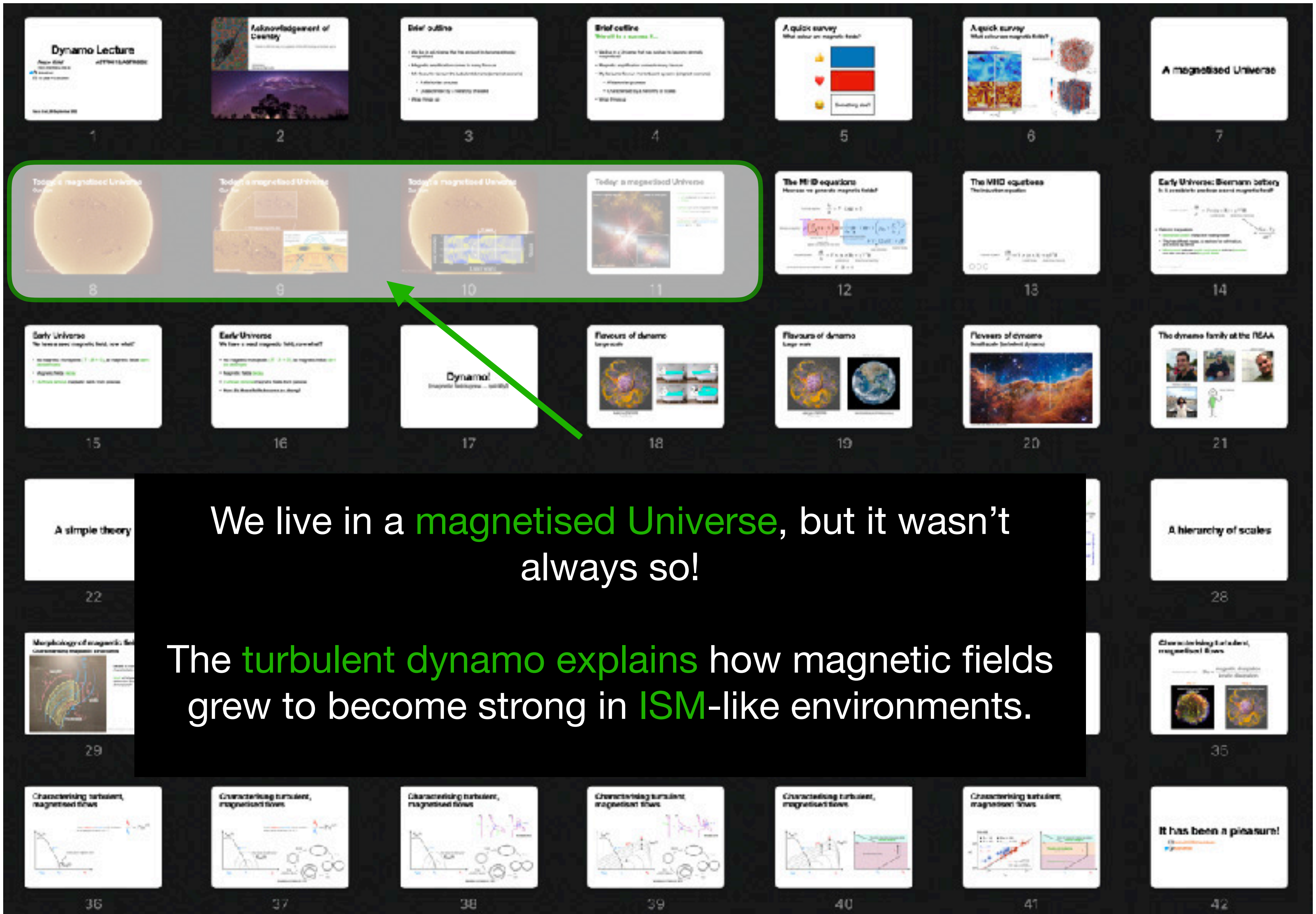
Let’s recap what we learned



Let’s recap what we learned



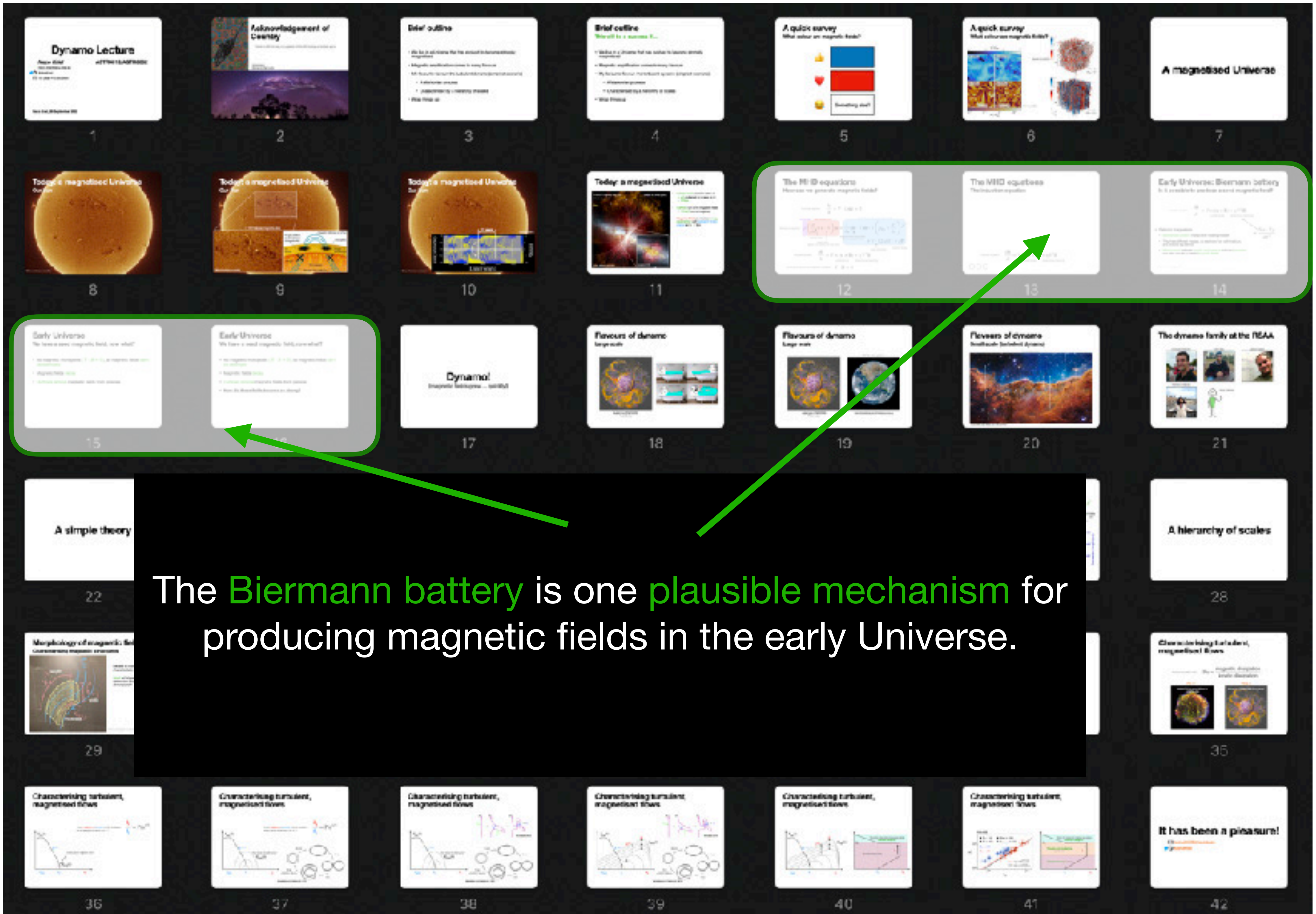
Let’s recap what we learned



We live in a magnetised Universe, but it wasn’t always so!

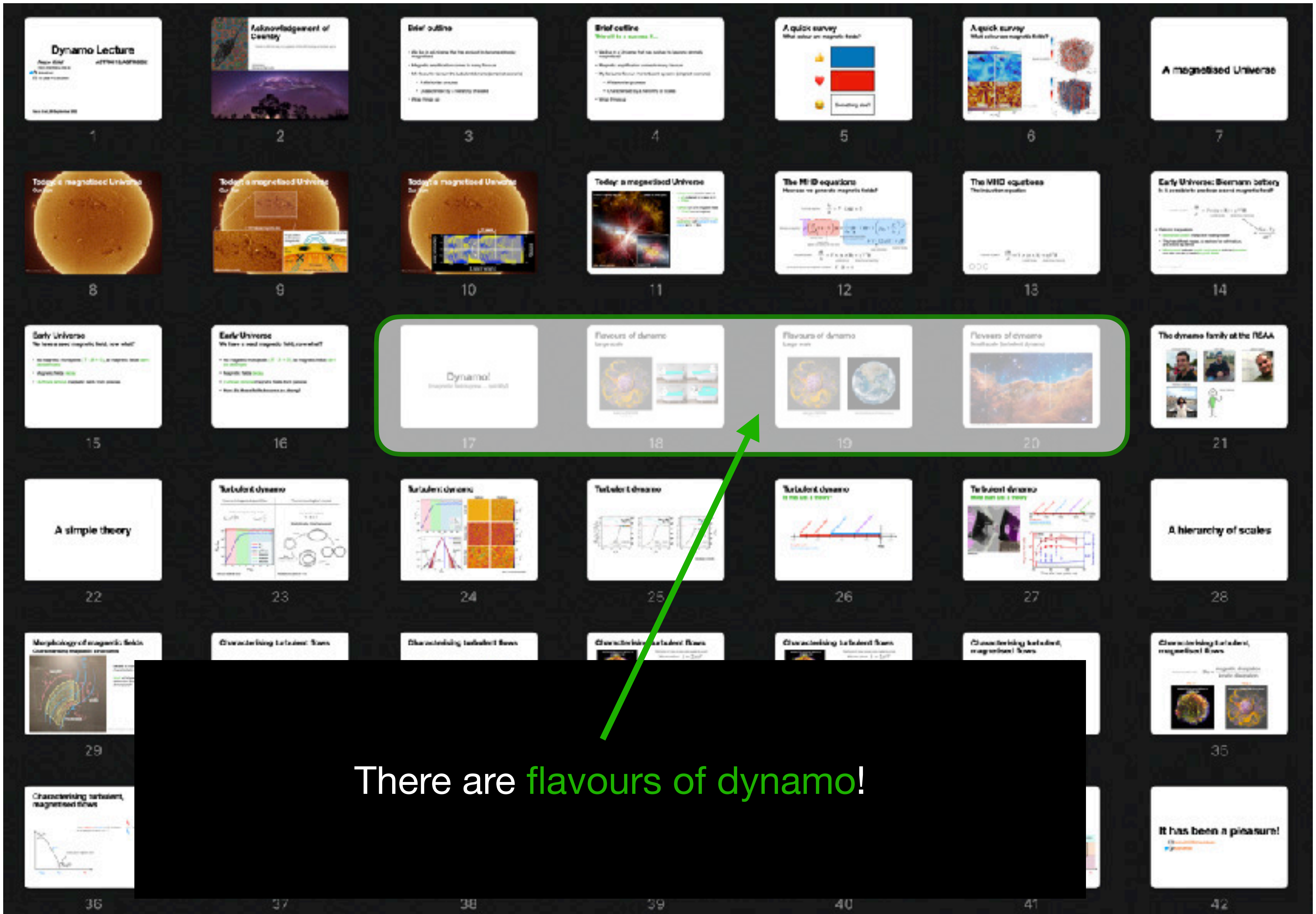
The turbulent dynamo explains how magnetic fields grew to become strong in ISM-like environments.

Let’s recap what we learned



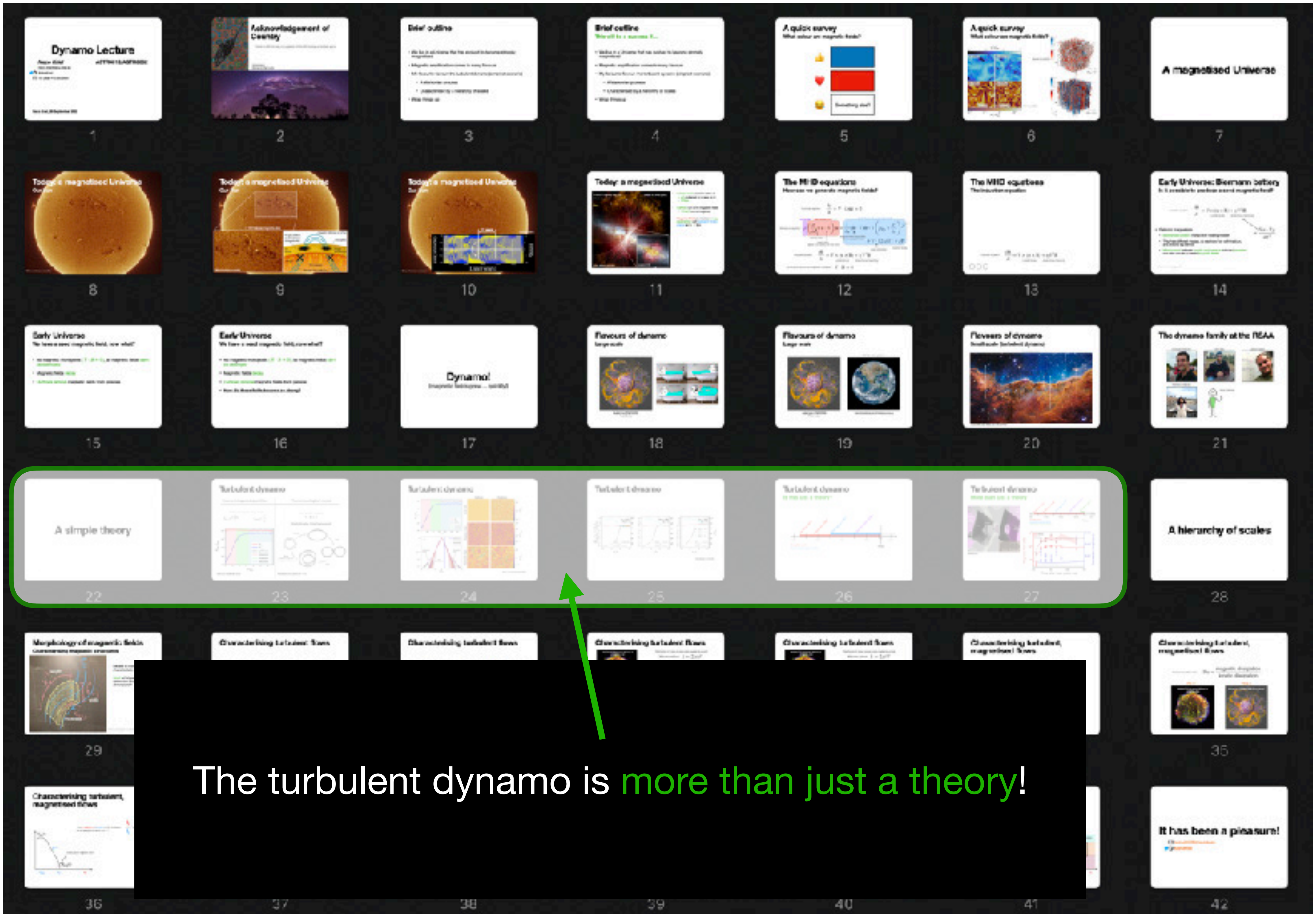
The Biermann battery is one plausible mechanism for producing magnetic fields in the early Universe.

Let's recap what we learned



There are flavours of dynamo!

Let’s recap what we learned



Let's recap what we learned

We characterise MHD flows by studying fundamental scales in the flow.