

# Dynamo Lecture

***Neco Kriel***

neco.kriel@anu.edu.au

  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: Zachariah George





# Acknowledgement of Country

“inside the EMU the many many galaxies with the EMU looking out into deep space”

Image credit: Zachariah George








# Acknowledgement of Country

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

Image credit: Zachariah George



April and May  
(mating season; harvesting)





# Acknowledgement of Country

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

Image credit: Zachariah George



June and July  
(nesting season; no more harvesting)

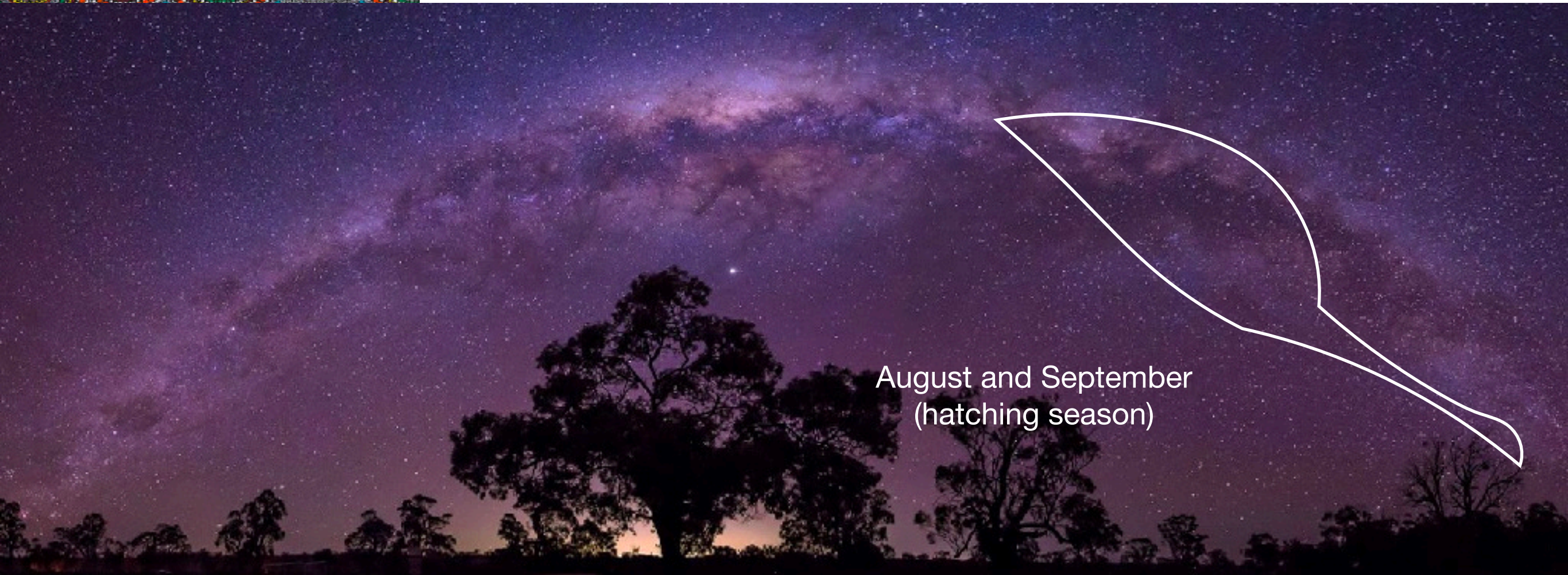




# Acknowledgement of Country

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

Image credit: Zachariah George





# 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
  - A Markovian process
  - Characterised by a hierarchy of scales
- Wrap things up



# **A quick survey**



# A quick survey

What colour are magnetic fields?



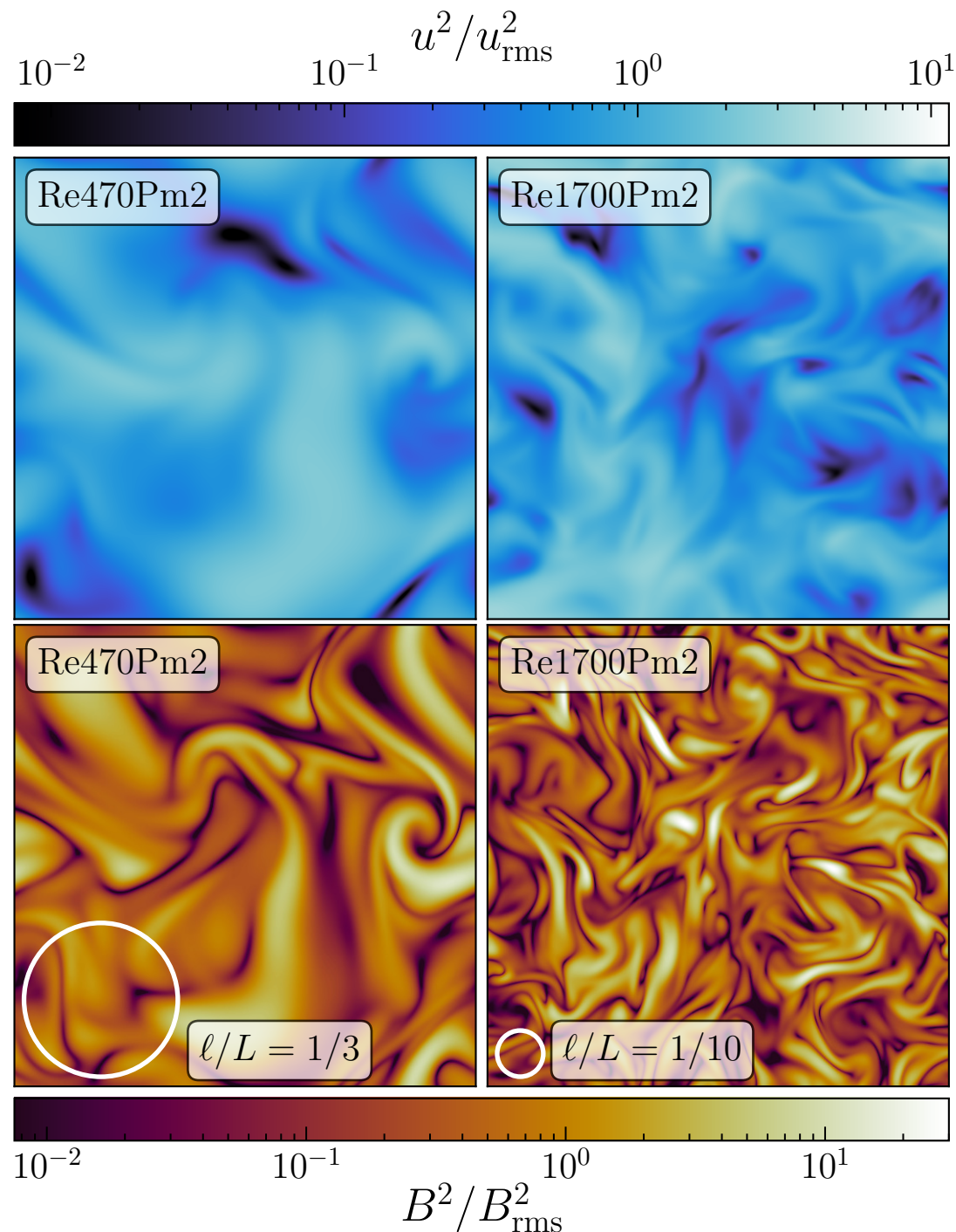
Something else?





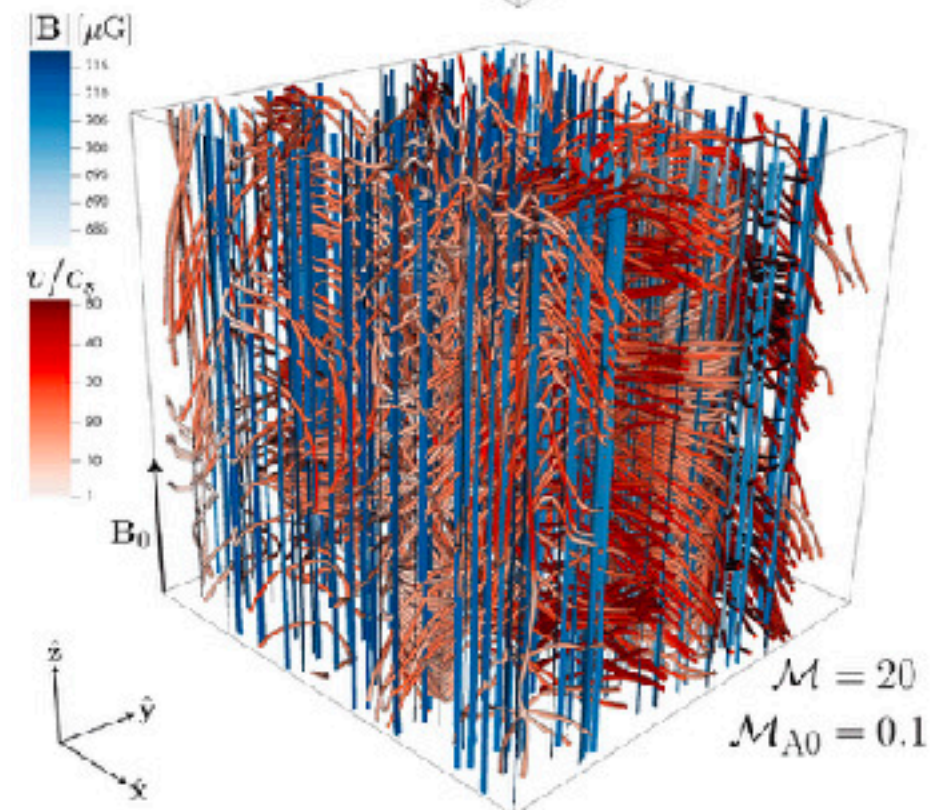
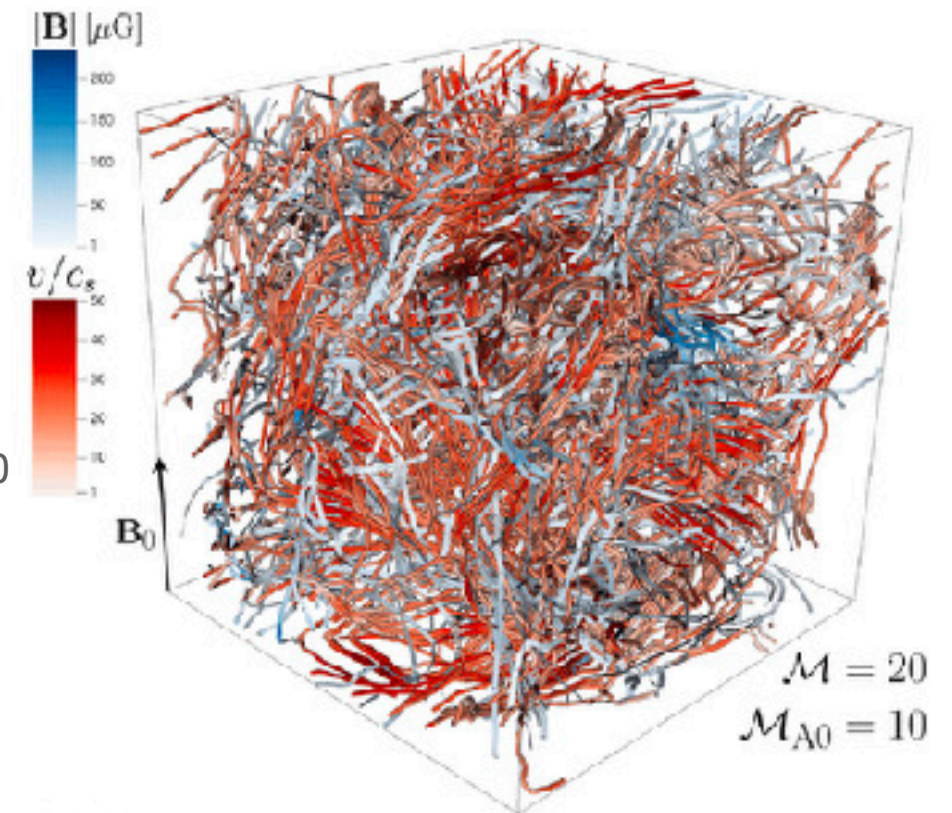
# A quick survey

## What colour are magnetic fields?



Kriel et al. 2022

Beattie et al. 2020



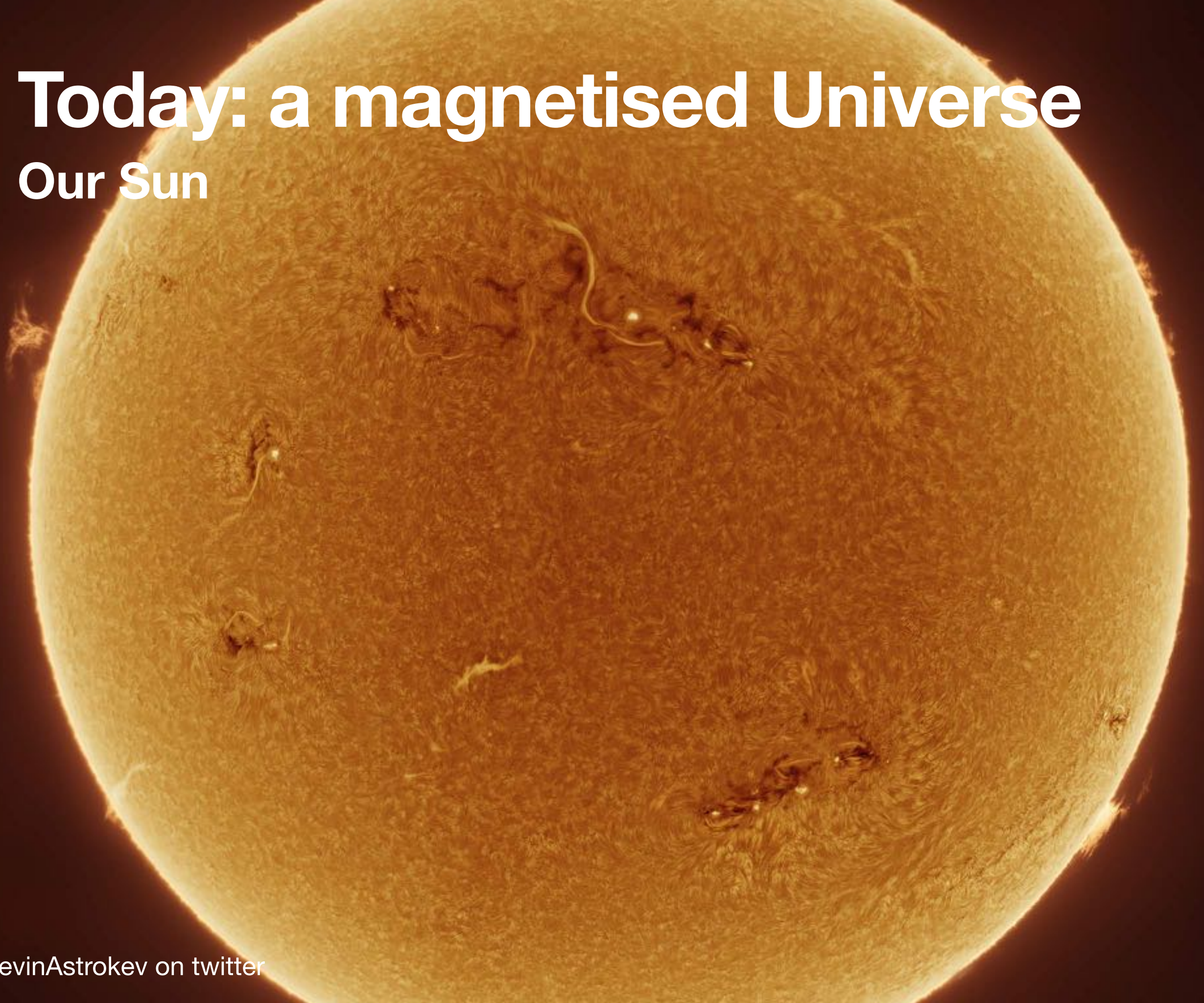


# **A magnetised Universe**



# Today: a magnetised Universe

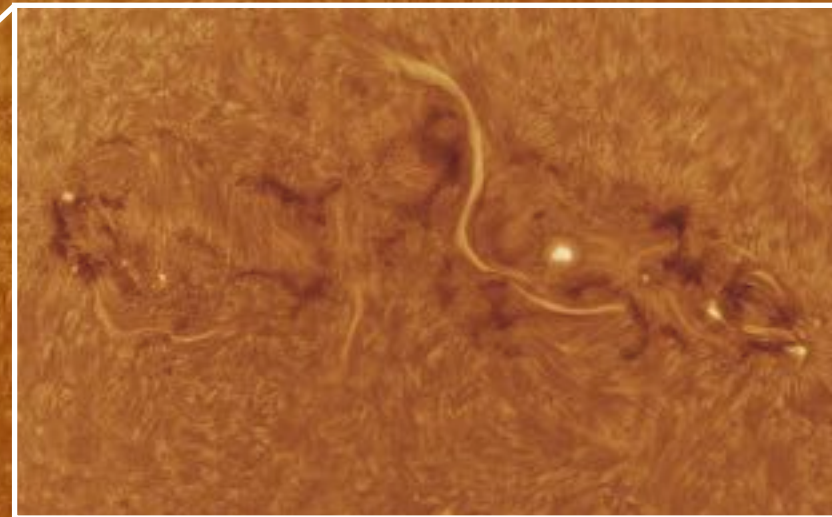
## Our Sun



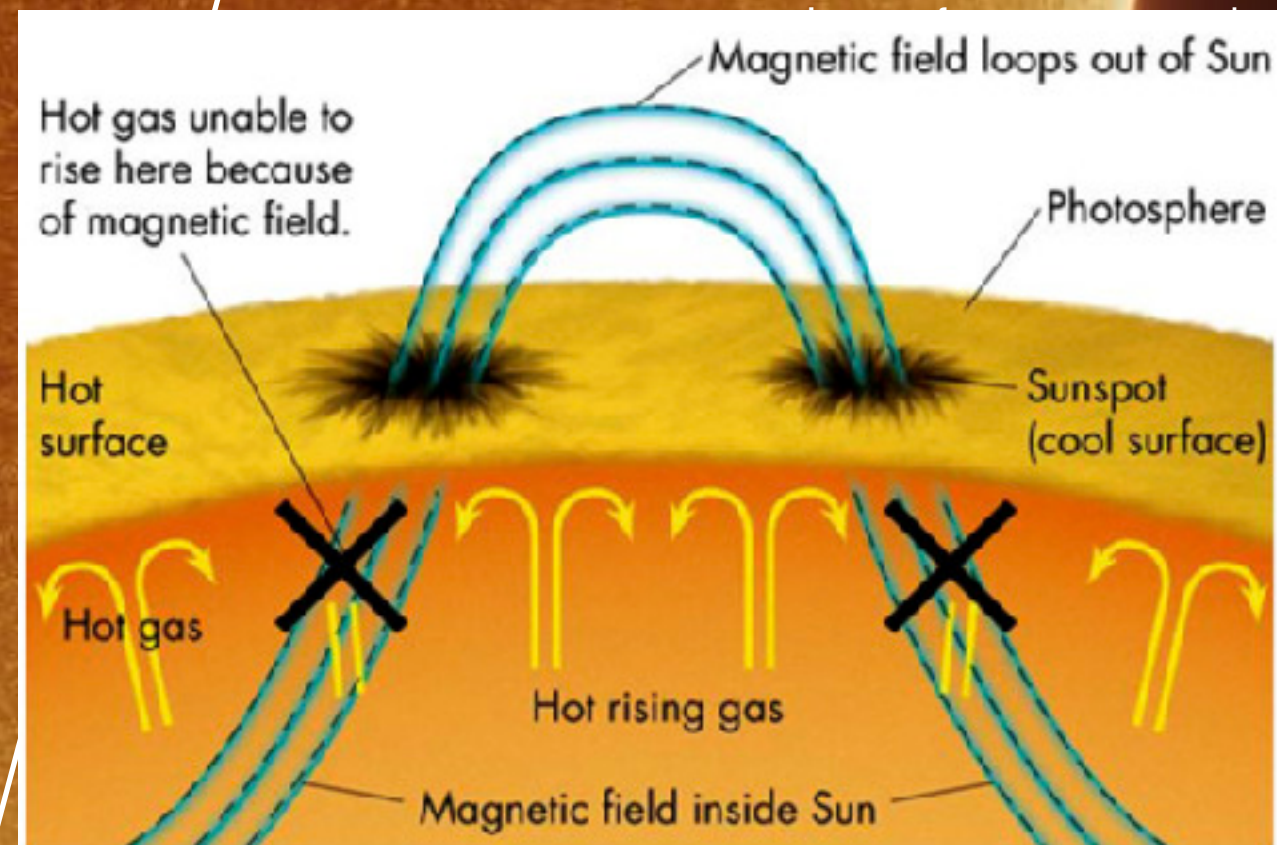
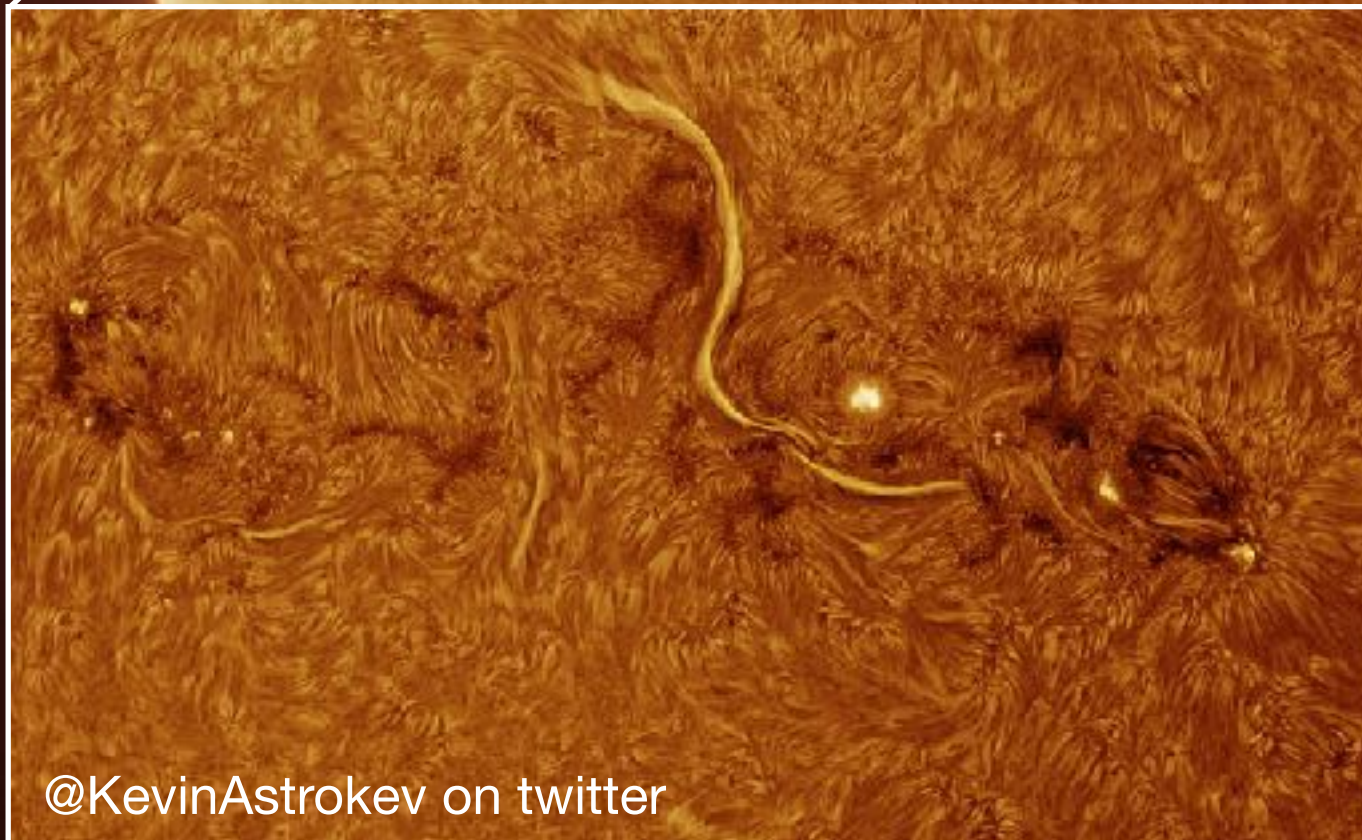


# Today: a magnetised Universe

## Our Sun



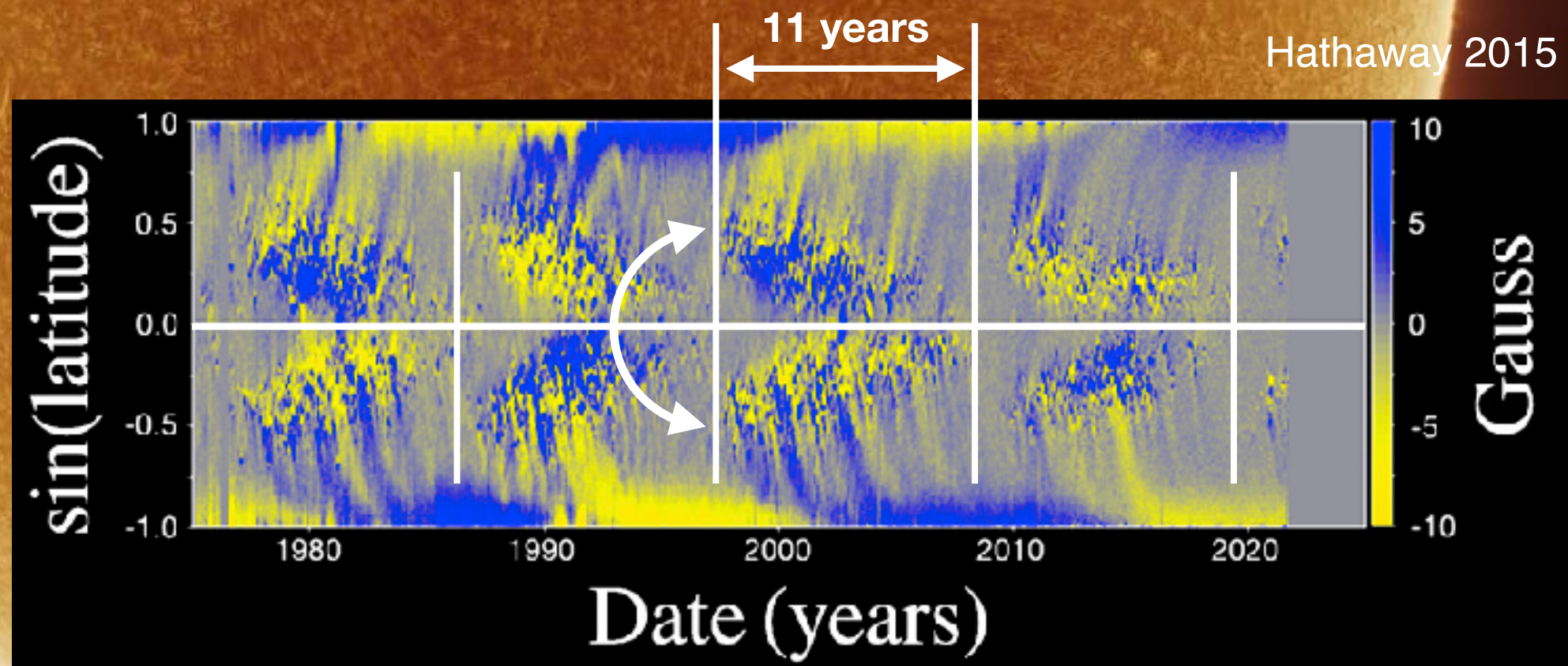
~ 10 G dipolar magnetic field





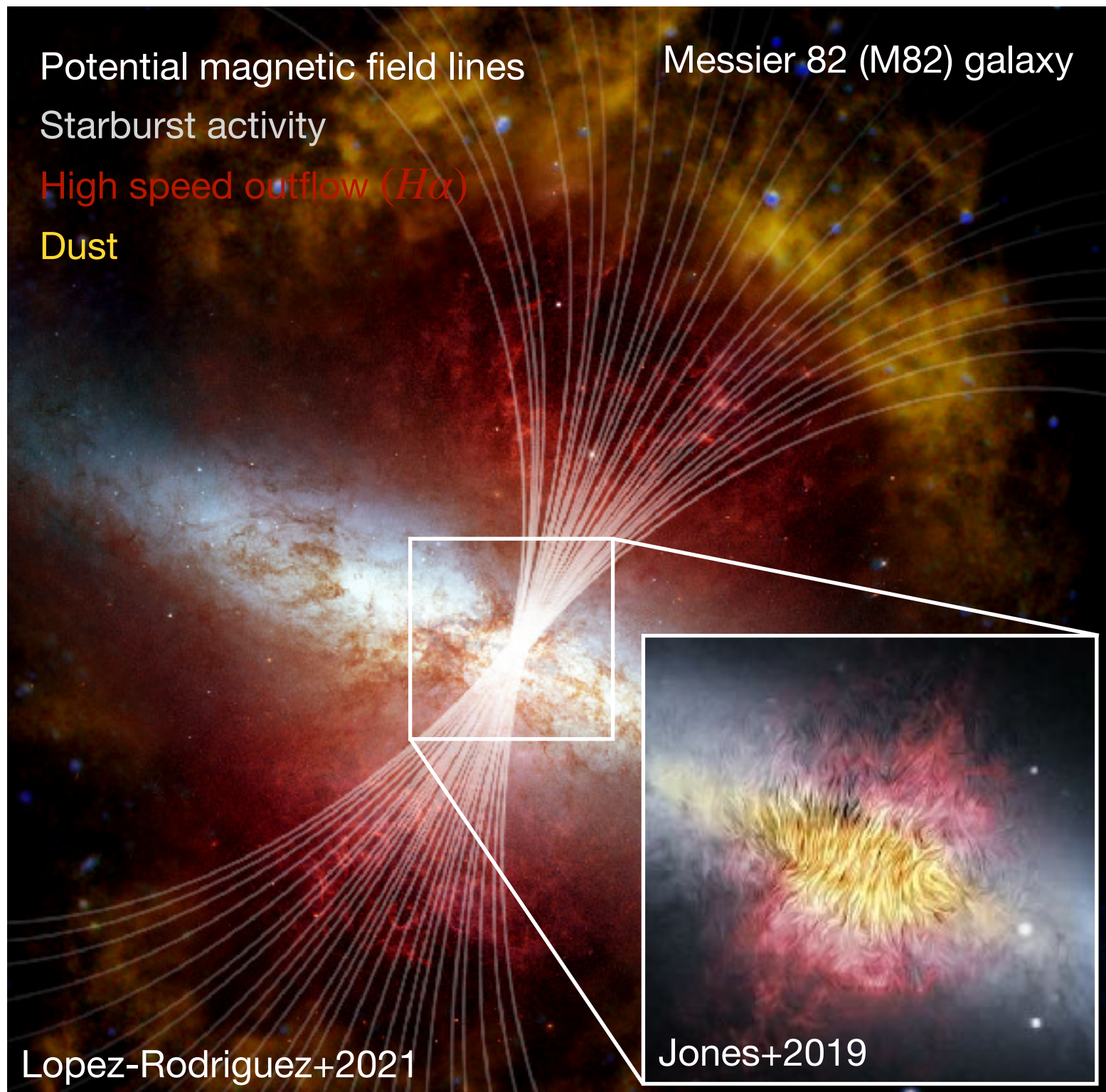
# Today: a magnetised Universe

Our Sun





# Today: a magnetised Universe



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



# The MHD equations

How can we generate magnetic fields?

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

Momentum:

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

Diagram annotations for the Momentum equation:

- fluid mass** (purple box):  $\rho$
- fluid acceleration** (red box):  $\left( \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla \right) \mathbf{u}$
- change in flow** (arrow to  $\frac{\partial}{\partial t}$ )
- inertial term** (arrow to  $\mathbf{u} \cdot \nabla$ )
- (speed and direction of fluid flow)** (text below inertial term)
- all the forces that act on the fluid** (blue box): Right-hand side of the equation
- magnetic force associated with the Lorentz force** (arrow to  $\frac{1}{4\pi} (\mathbf{B} \cdot \nabla) \mathbf{B}$ )
- pressure** (arrow to  $p_{\text{th}} + \frac{B^2}{8\pi}$ )
- stress (viscosity)** (arrow to  $\nabla \cdot (2\nu\rho\mathcal{S})$ )
- external forces** (arrow to  $\rho\mathbf{F}$ )

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

Diagram annotations for the Induction equation:

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

Constitutive  
(no magnetic monopoles):  $\nabla \cdot \mathbf{B} = 0$



# The MHD equations

## The induction equation

Induction: 
$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{u} \times \mathbf{B})}_{\text{Lorentz forces}} + \underbrace{\eta \nabla^2 \mathbf{B}}_{\text{stress forces (resistivity)}}$$



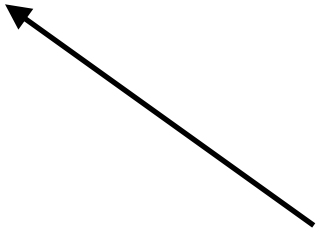
# Early Universe: Biermann battery

Is it possible to produce a seed magnetic field?

Induction: 
$$\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{u} \times \mathbf{B})}_{\text{Lorentz forces}} + \underbrace{\eta \nabla^2 \mathbf{B}}_{\text{stress forces (resistivity)}}$$

- 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 Andreyan (2021)* for more

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




# 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?**



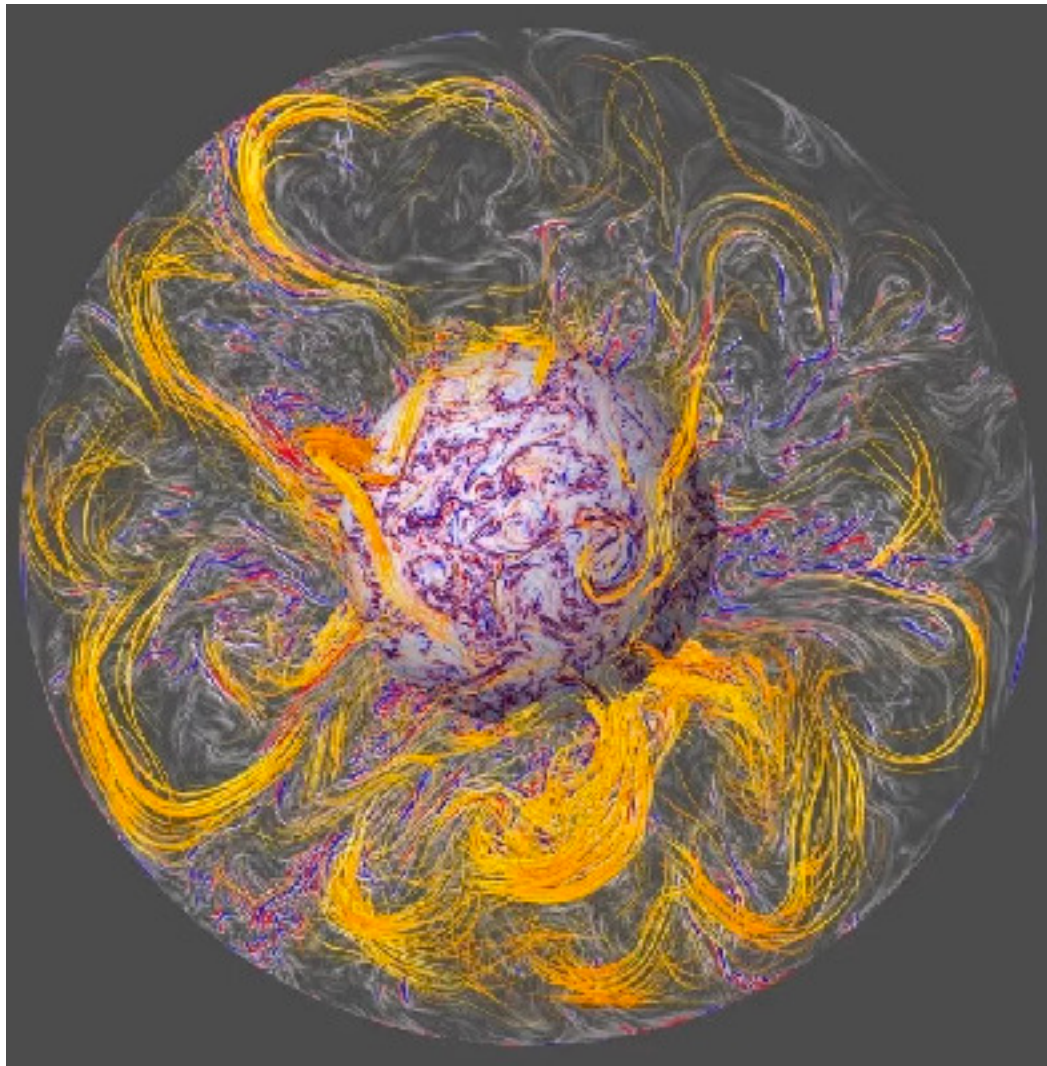
# **Dynamo!**

**(magnetic fields grew... quickly!)**



# Flavours of dynamo

## Large scale



Aubert et al./IPGP/CNRS  
Photo library

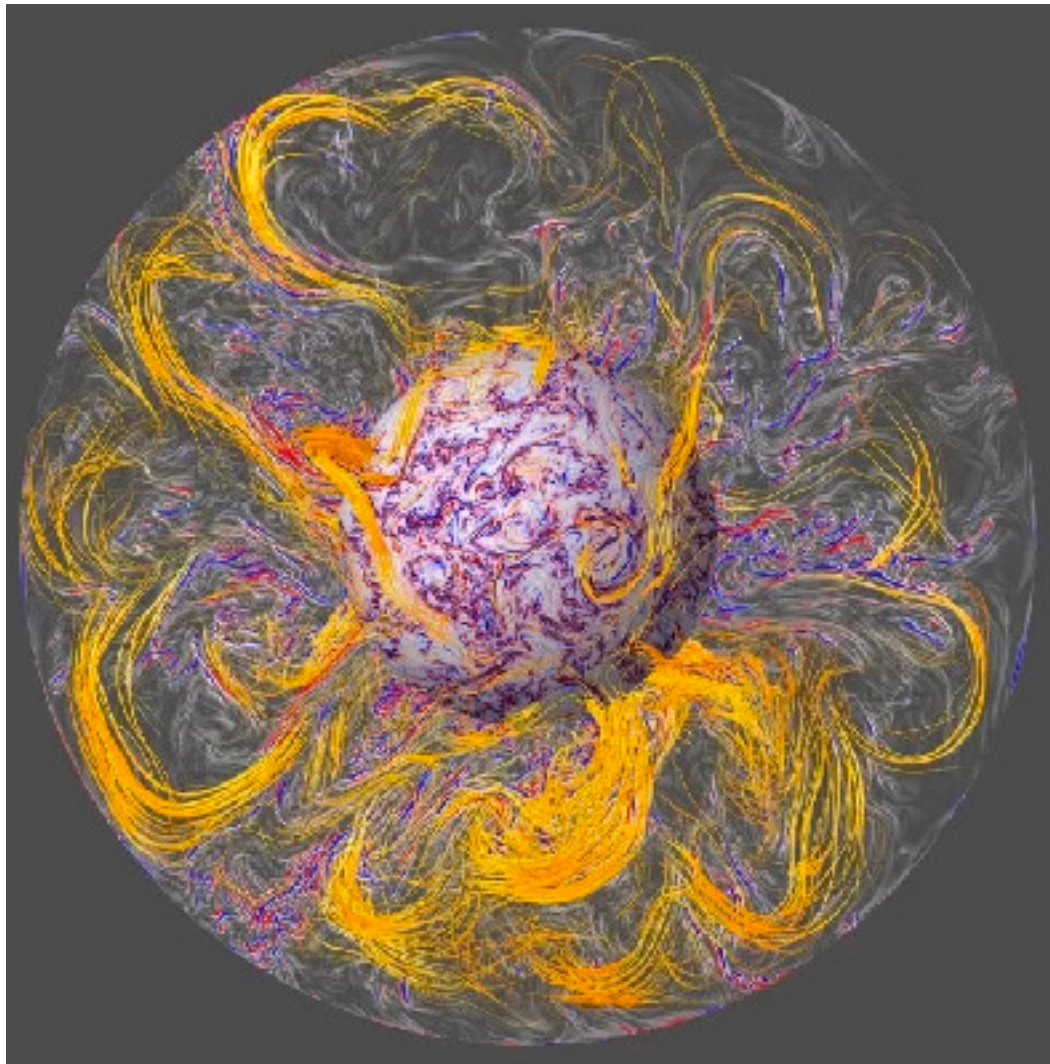




# Flavours of dynamo

## Large scale

Planets, stars, galaxies



Aubert et al./IPGP/  
CNRS Photo library



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



# Flavours of dynamo

## Small scale (turbulent dynamo)

Interstellar medium (ISM)



Cosmic Cliffs. Credit: NASA, ESA, CSA and STScI



# The dynamo family at the RSAA

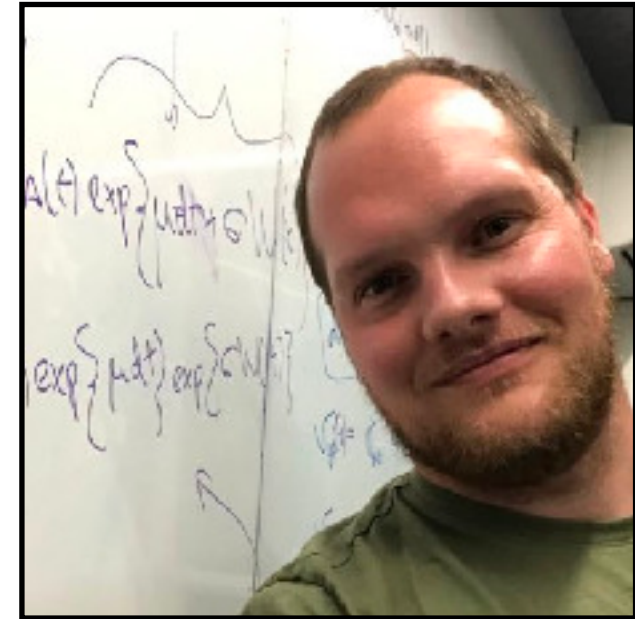
Christoph Federrath



Amit Seta



James Beattie



Radhika Chirakkara



Neco Kriel (me)





**A simple theory**



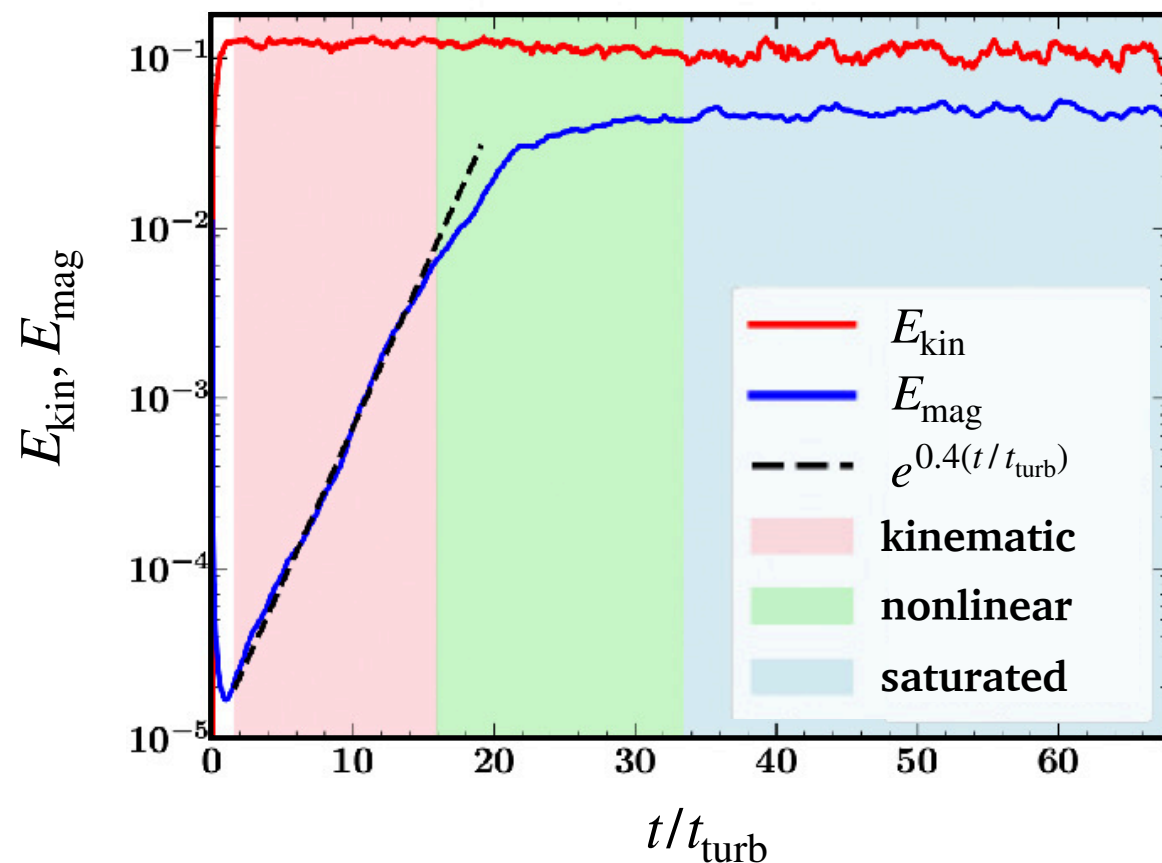
# Turbulent dynamo

## Volume integrated quantities

Kinetic and magnetic energy density

$$E_{\text{kin}} = \frac{\rho u_{\text{turb}}^2}{2}$$

$$E_{\text{mag}} = \frac{B^2}{8\pi}$$



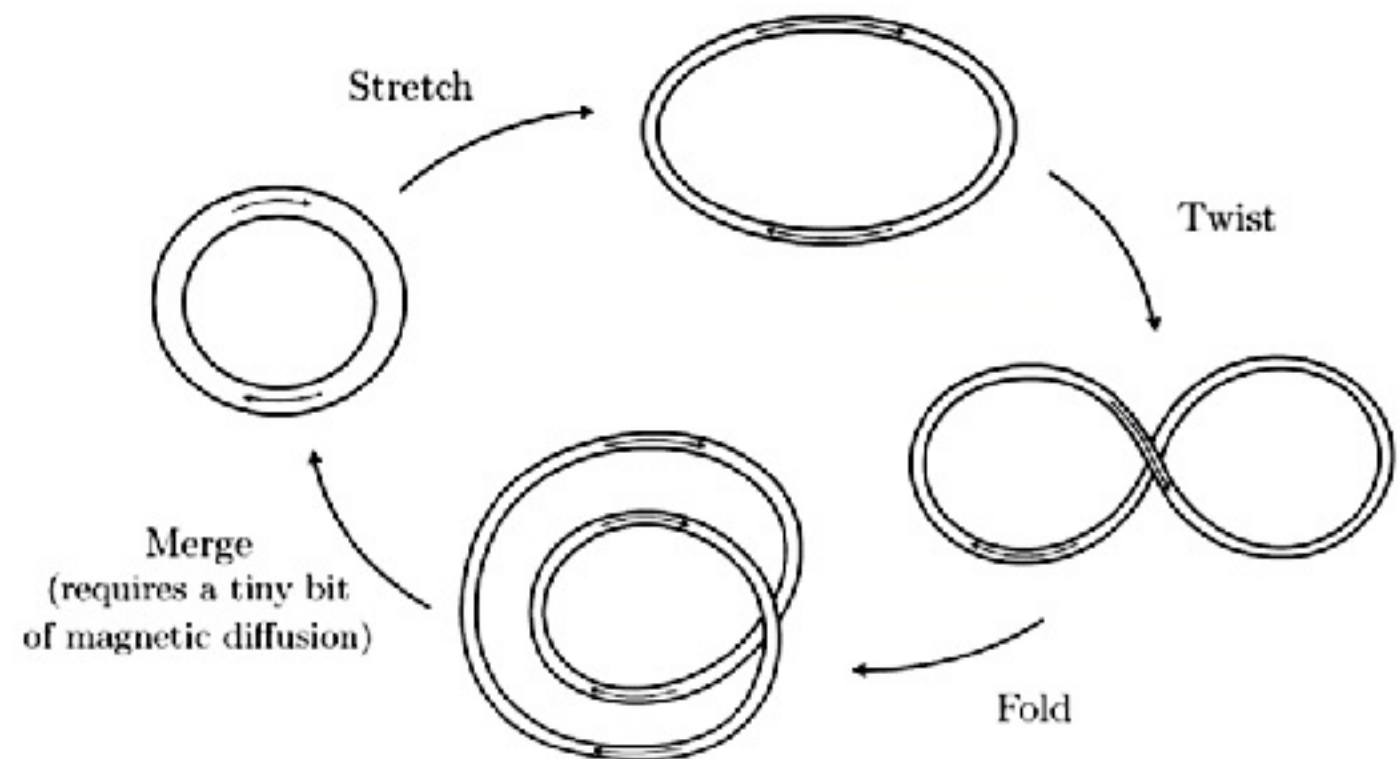
Seta and Federrath 2020

## Phenomenological model

No magnetic monopoles

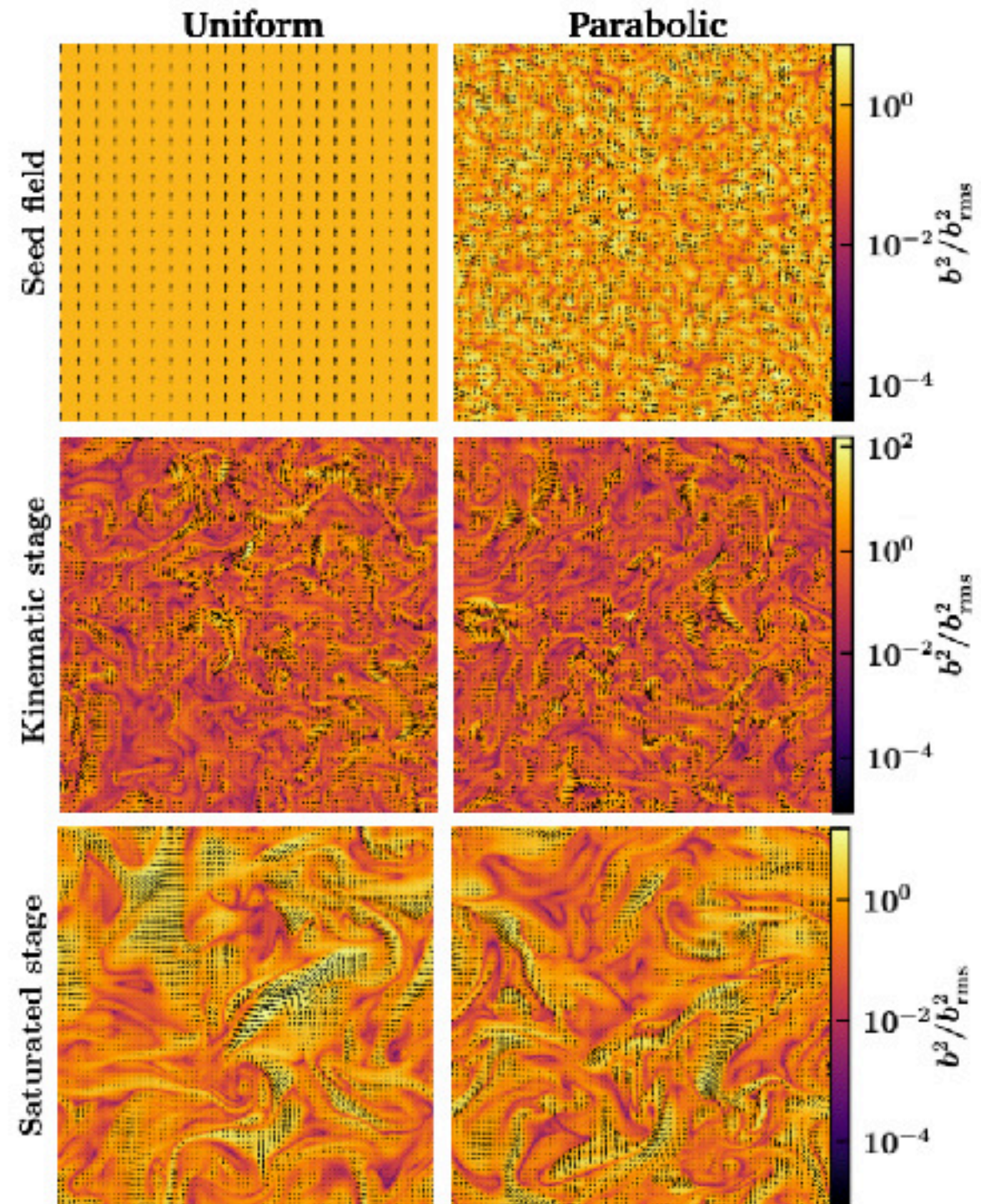
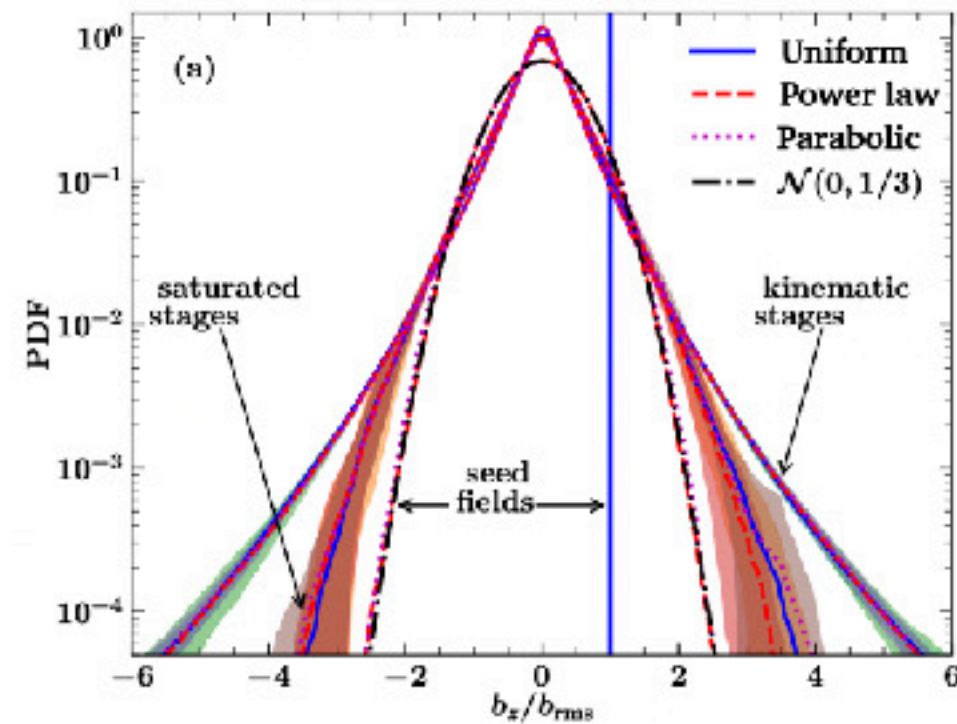
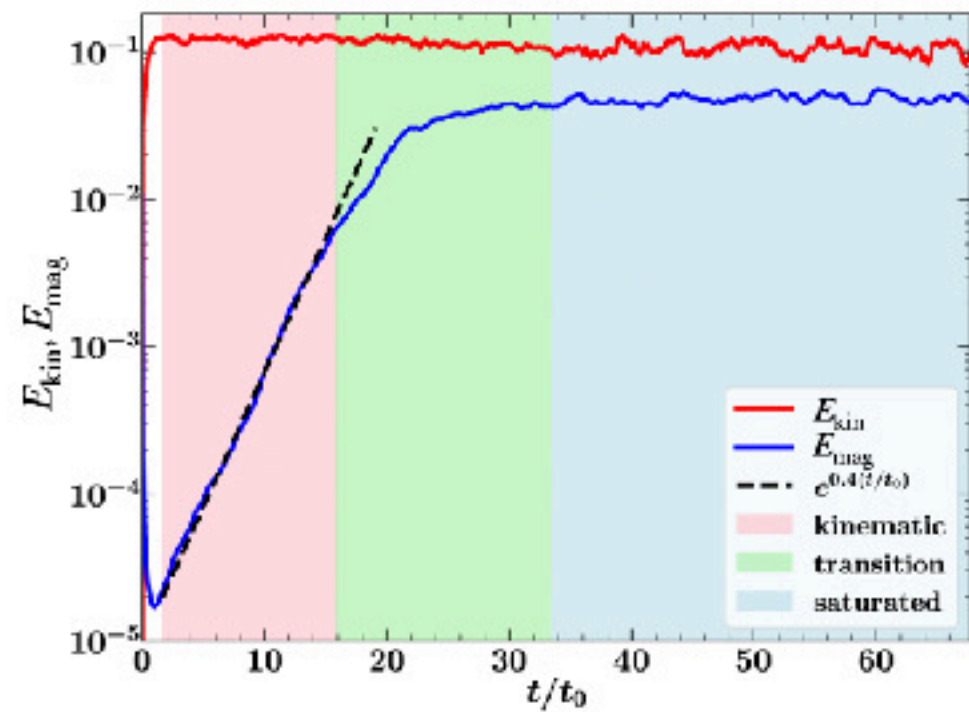
$$\nabla \cdot B = 0$$

Statistically this happens!



Vainshtein and Zeldovich 1972

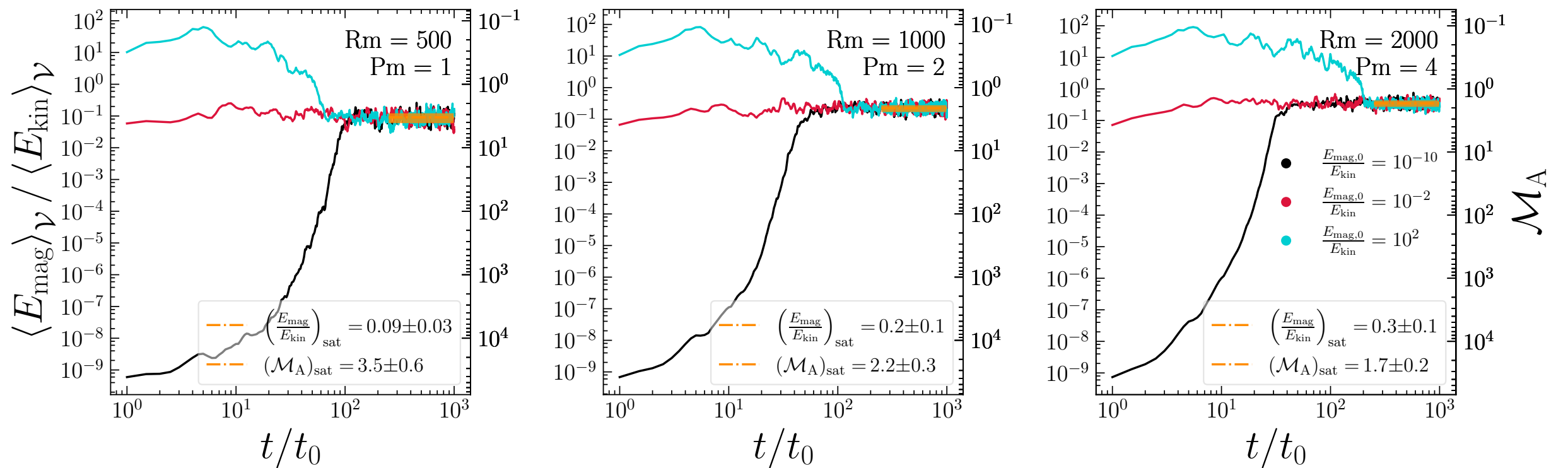
# Turbulent dynamo



Seta and Federrath 2020



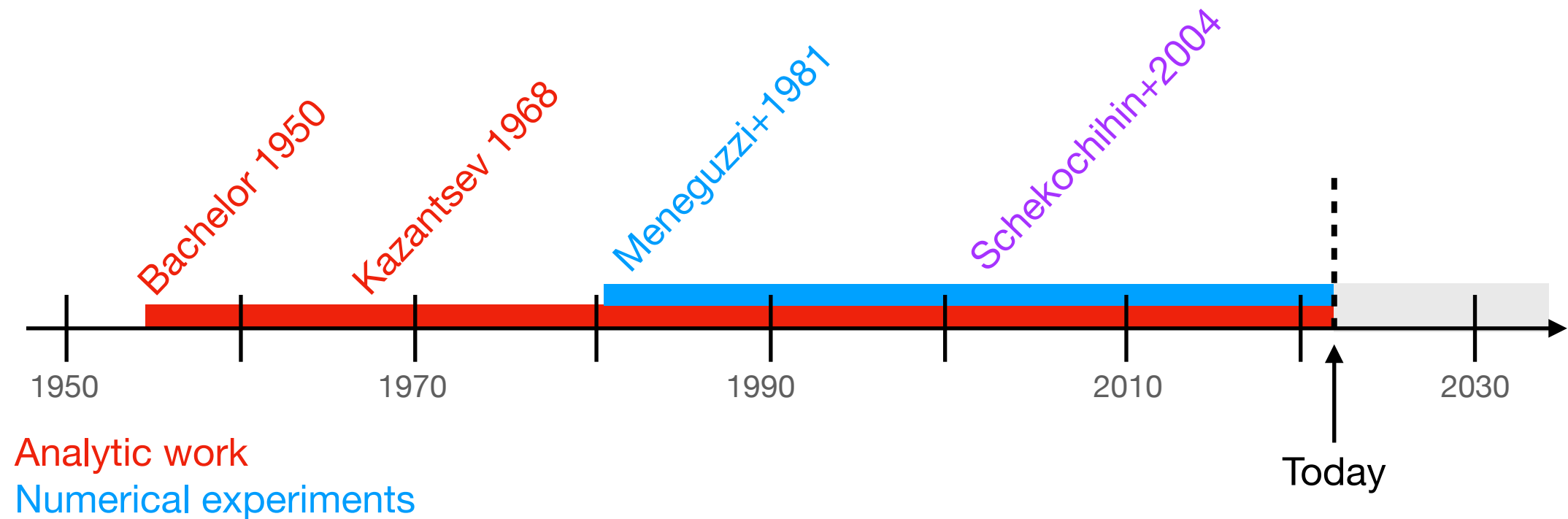
# Turbulent dynamo



Beattie et al 2022b

# Turbulent dynamo

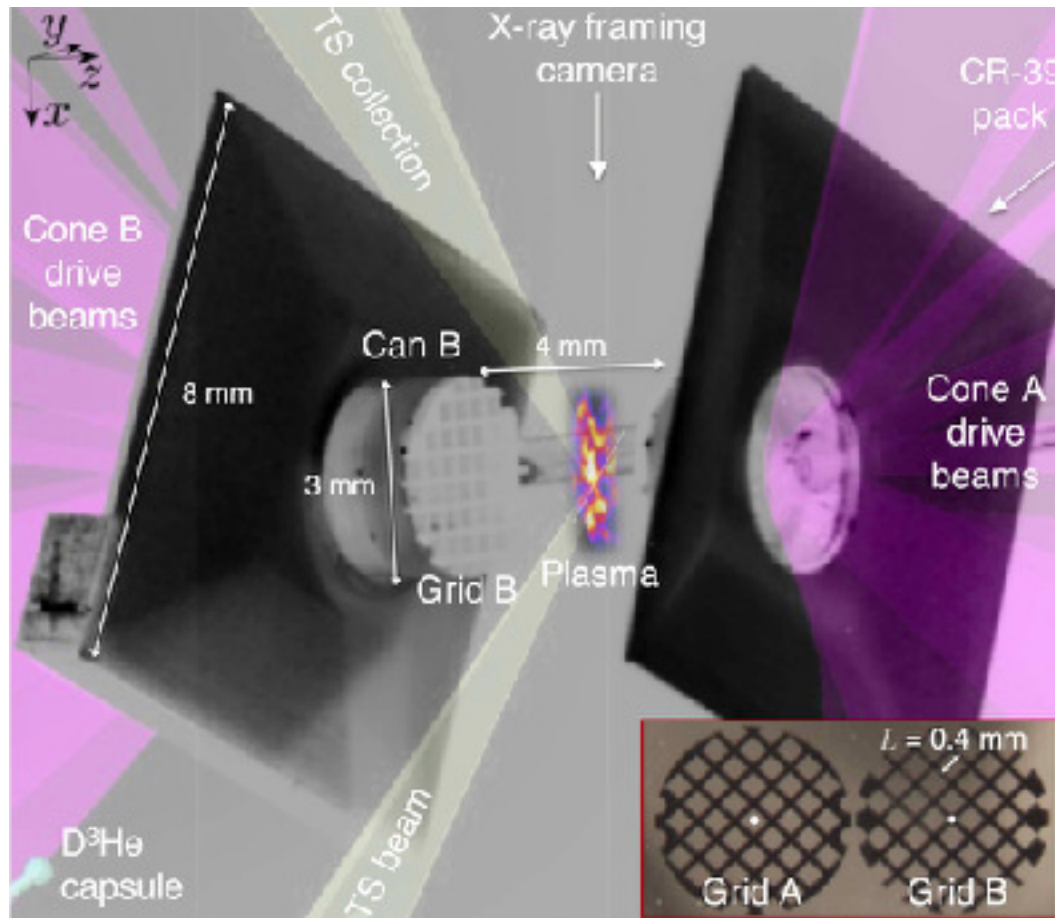
Is this just a theory?



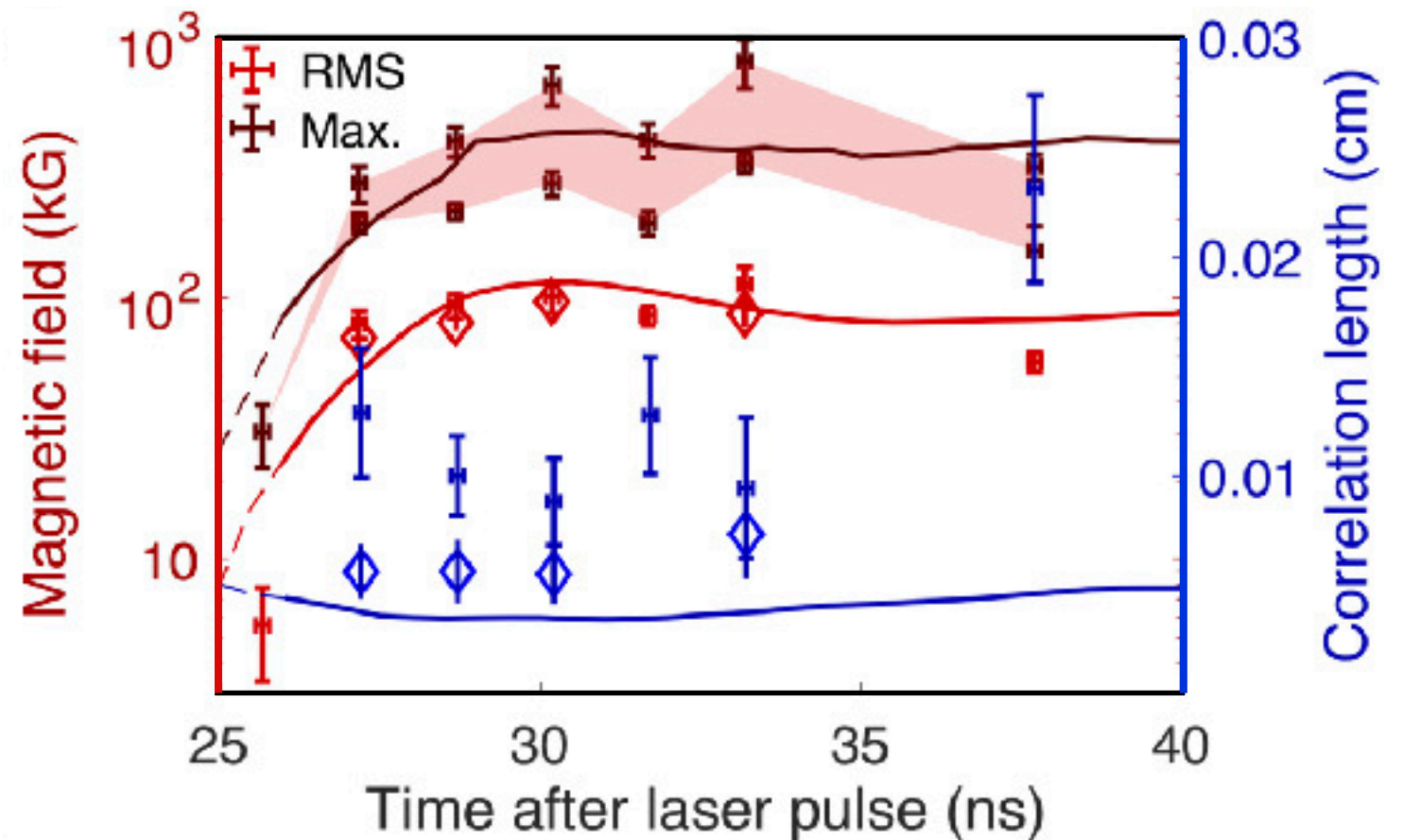
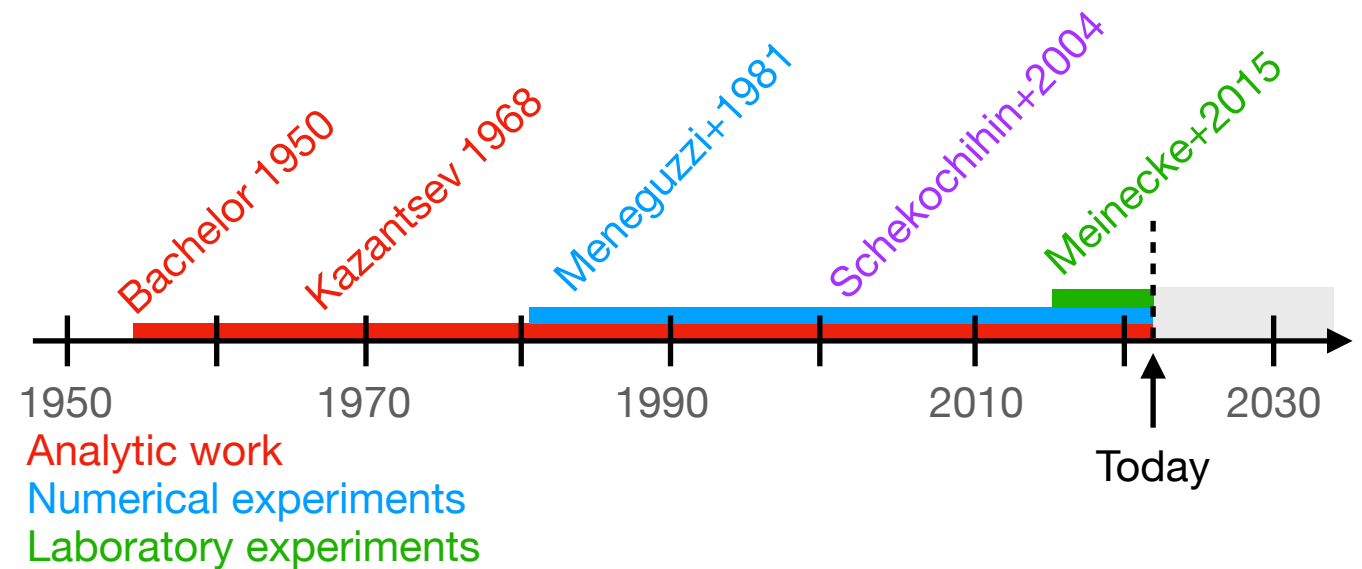


# Turbulent dynamo

More than just a theory



Bott+2020

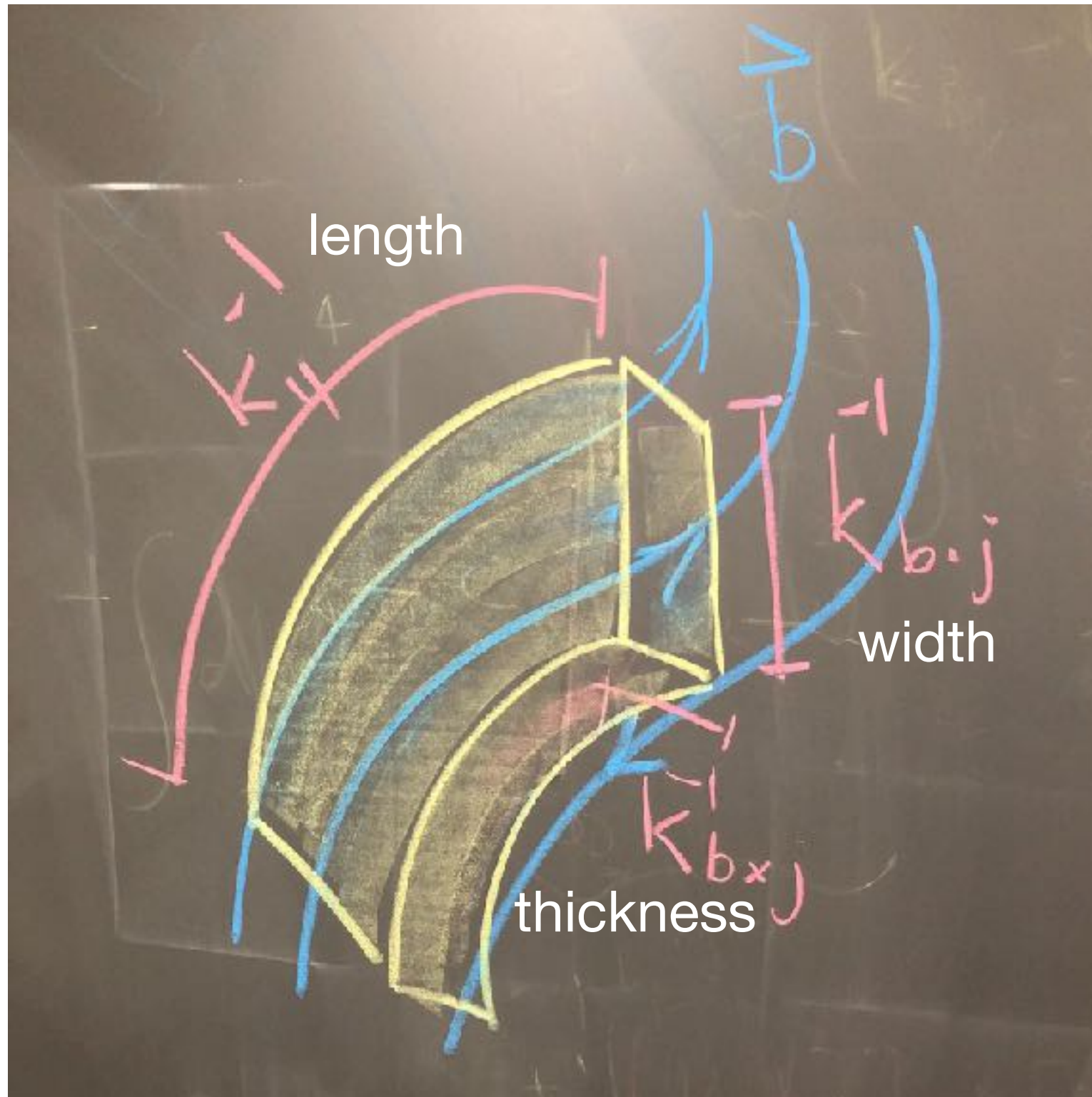


# **A hierarchy of scales**



# Morphology of magnetic fields

## Characterising magnetic structures

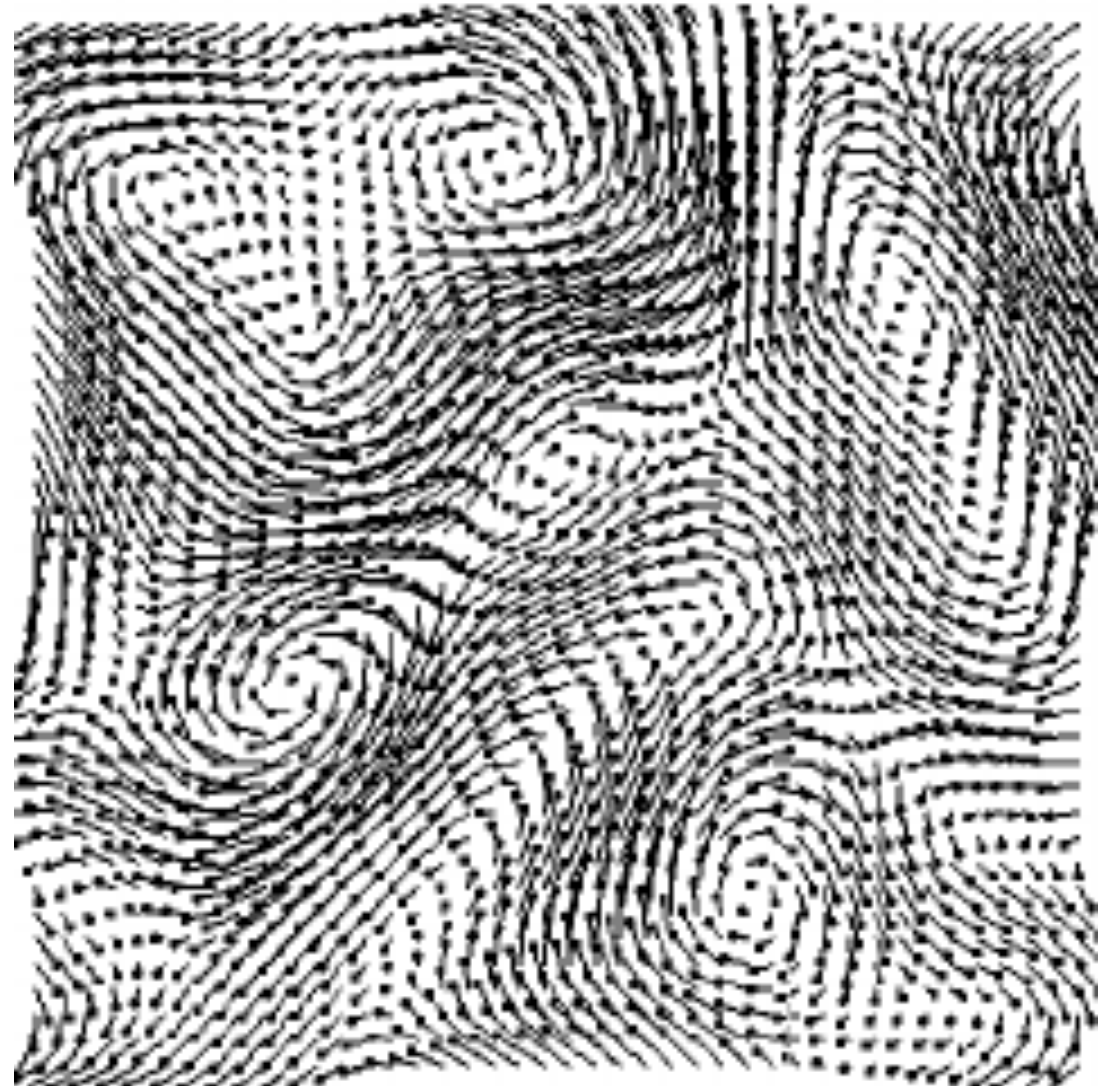
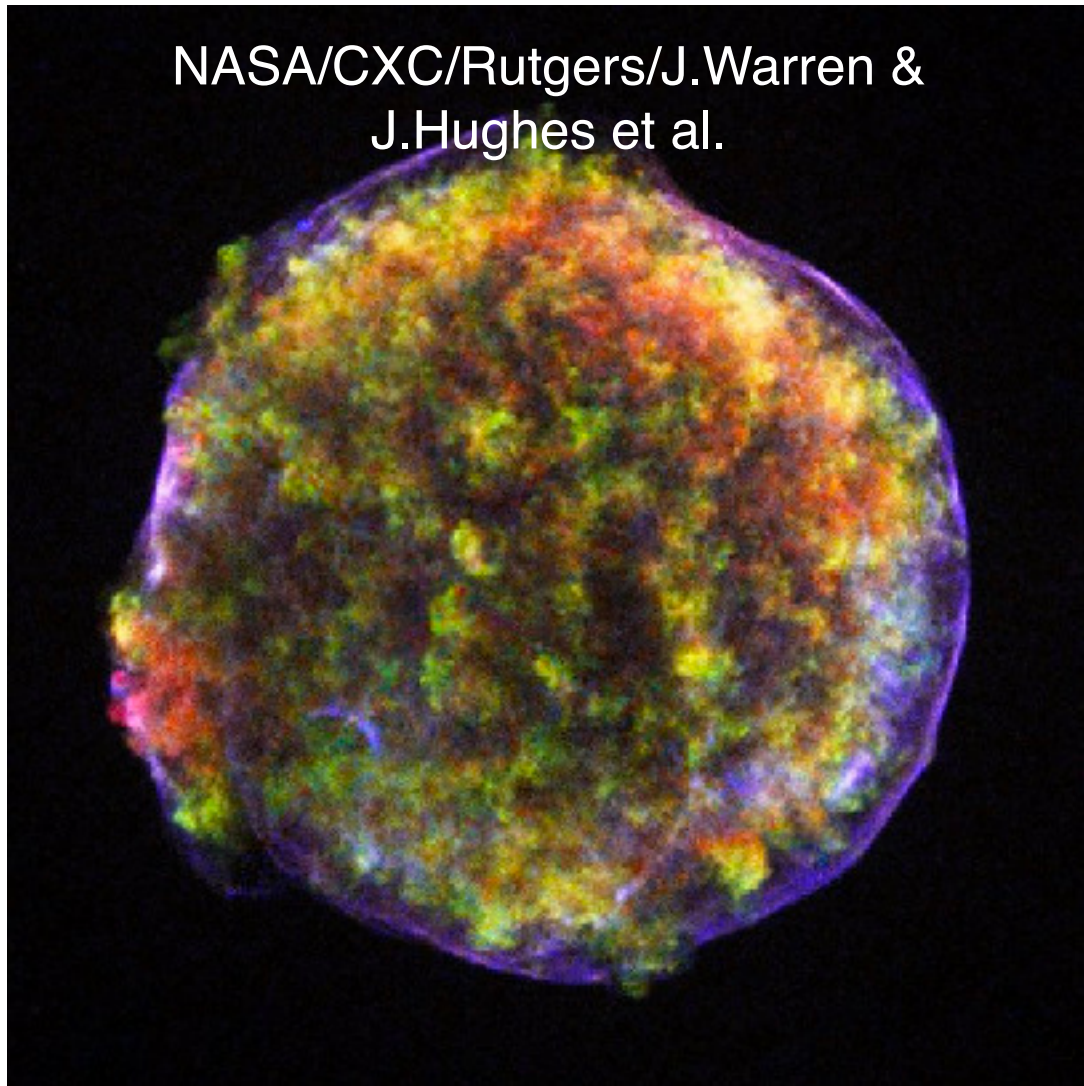


- We like to think in characteristic lengths
- The goal is to determine what parameters determine the sizes of these dimensions?

Schematic by James Beattie

# Characterising turbulent flows

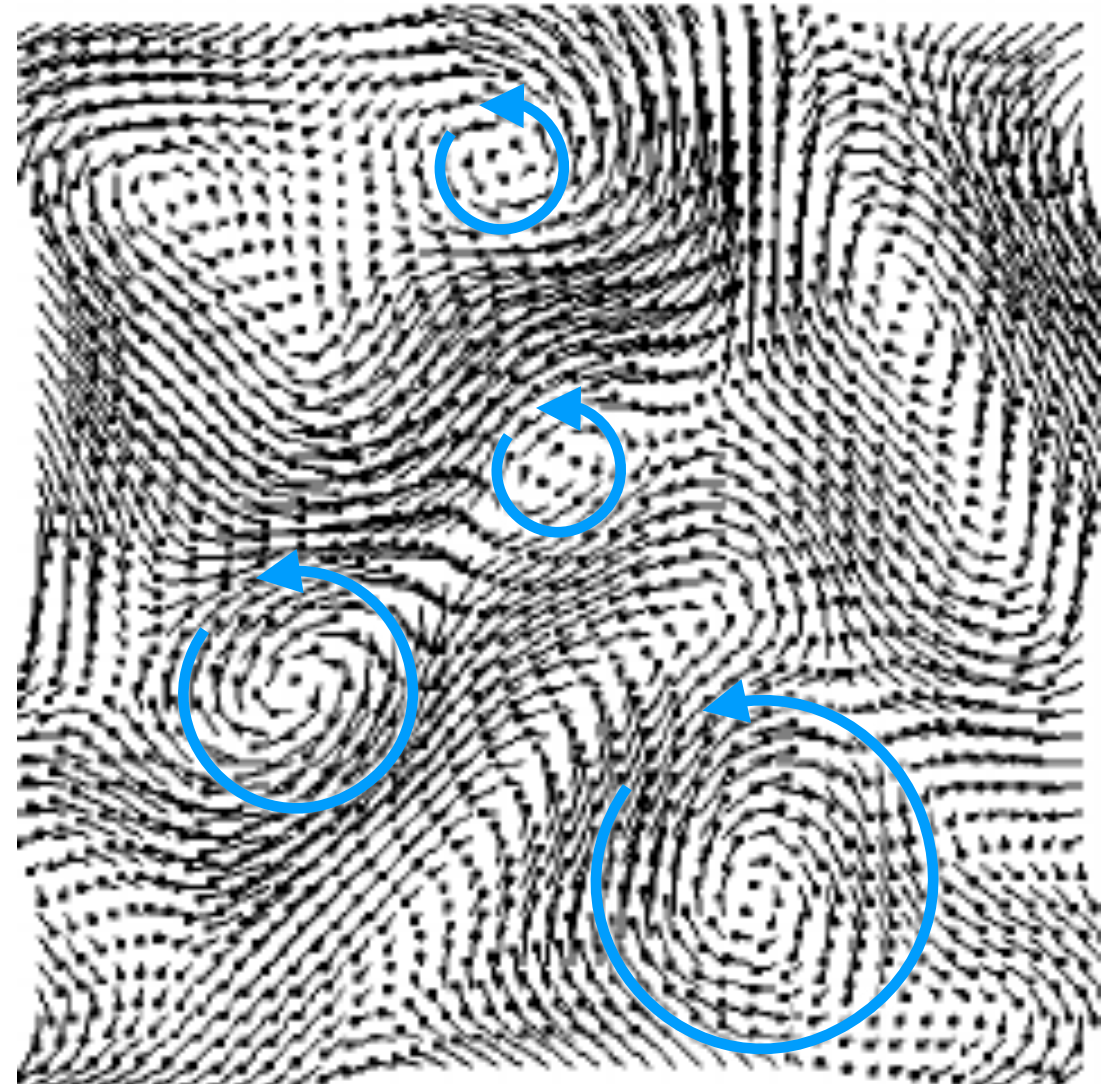
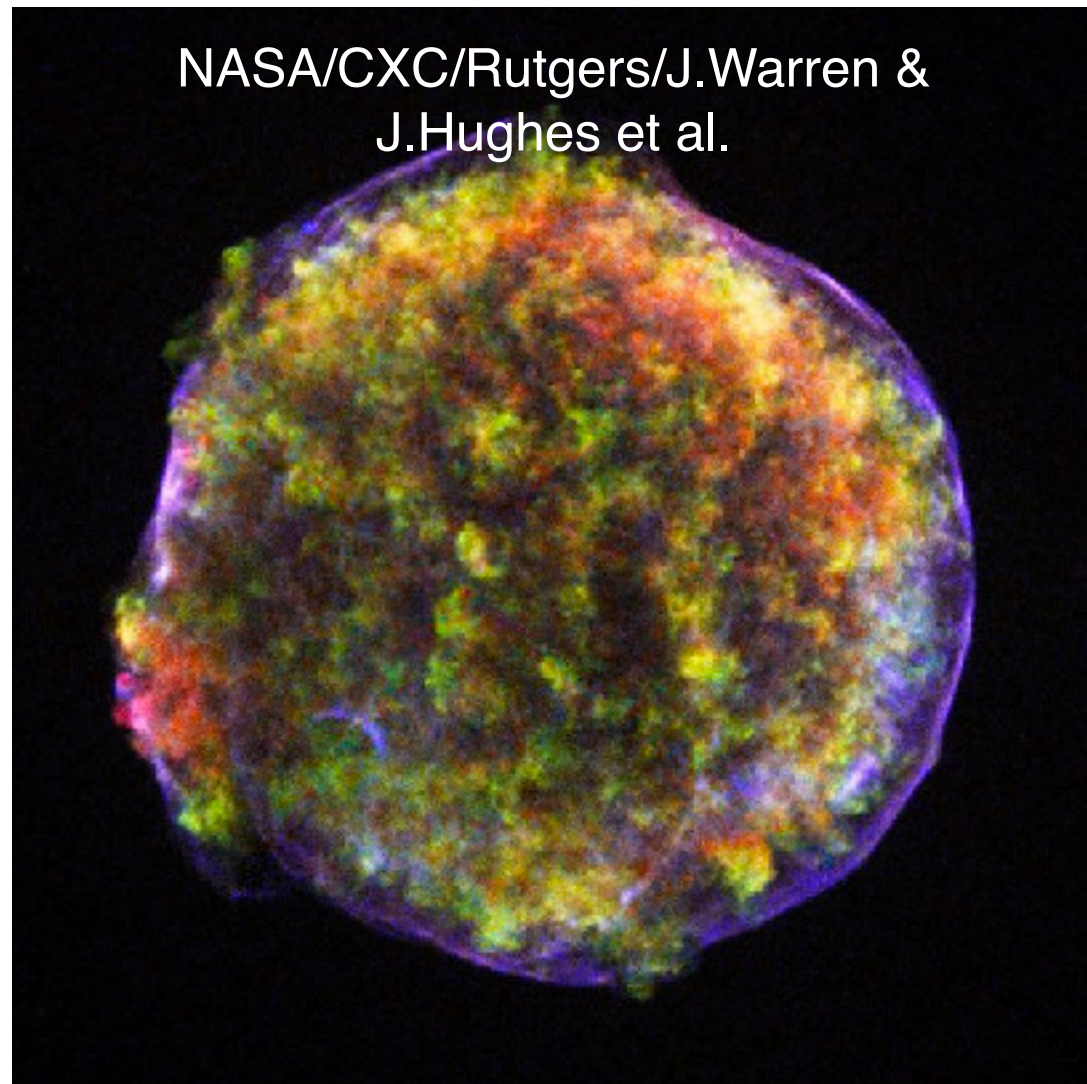
NASA/CXC/Rutgers/J.Warren &  
J.Hughes et al.



Cuzol and Mémin 2005



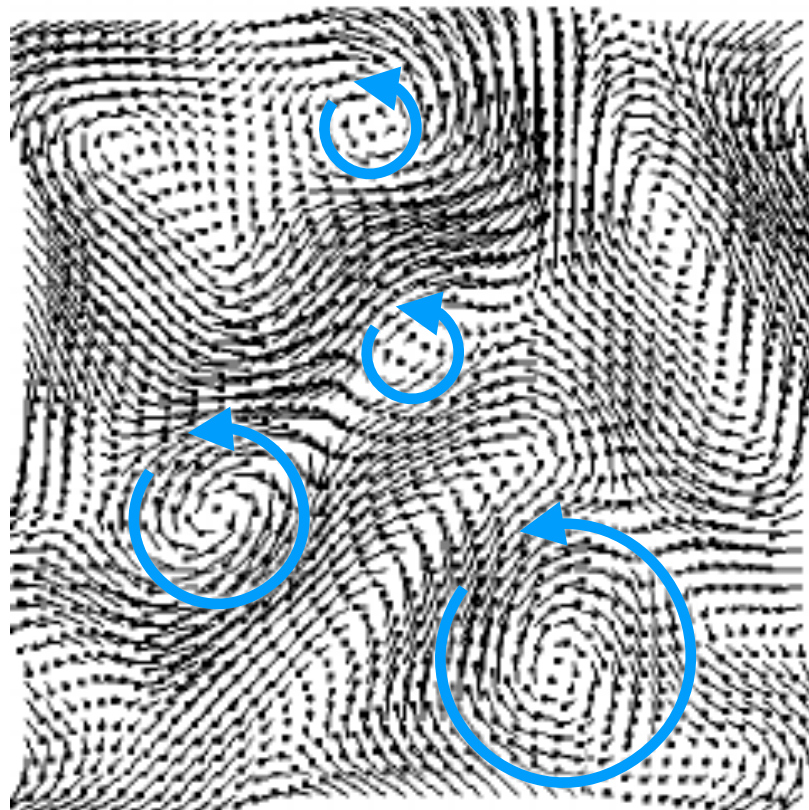
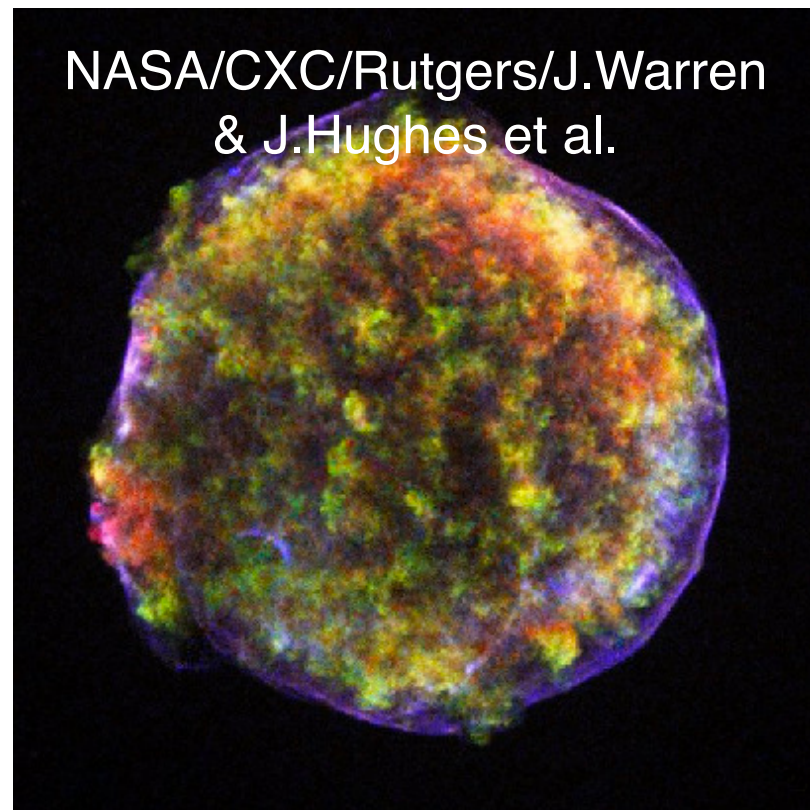
# Characterising turbulent flows



Cuzol and Mémin 2005

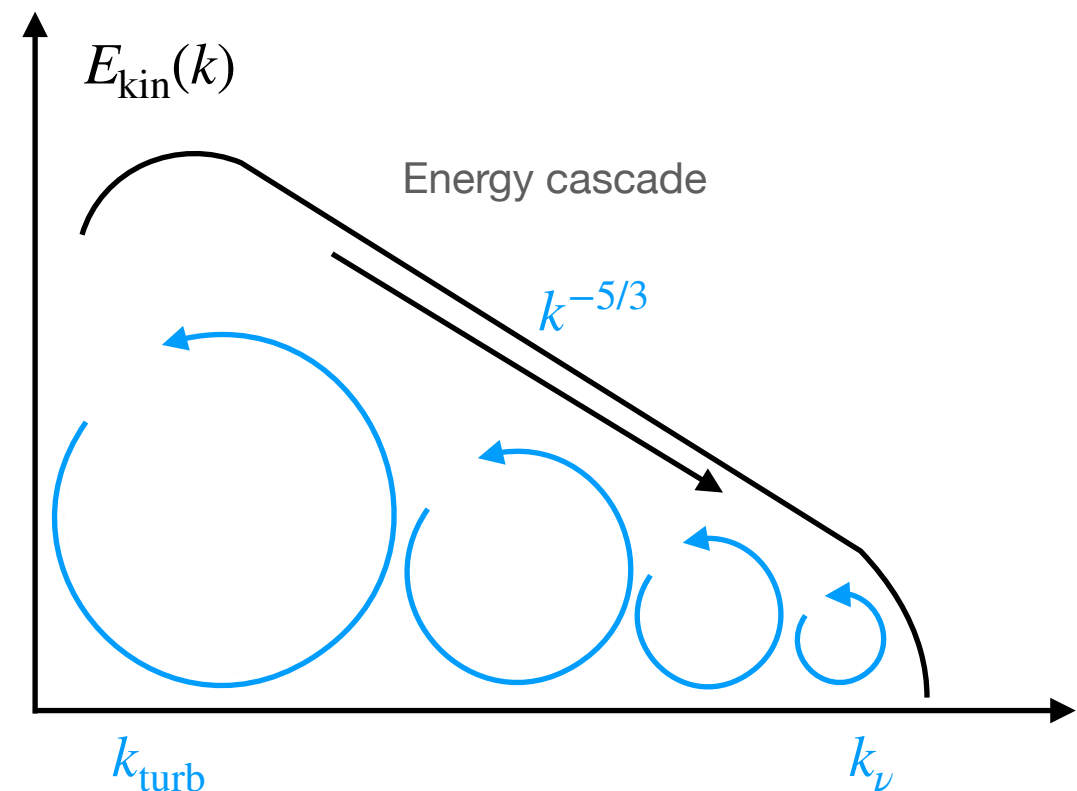


# Characterising turbulent flows



Distribution of energy across scales (spatial structures)

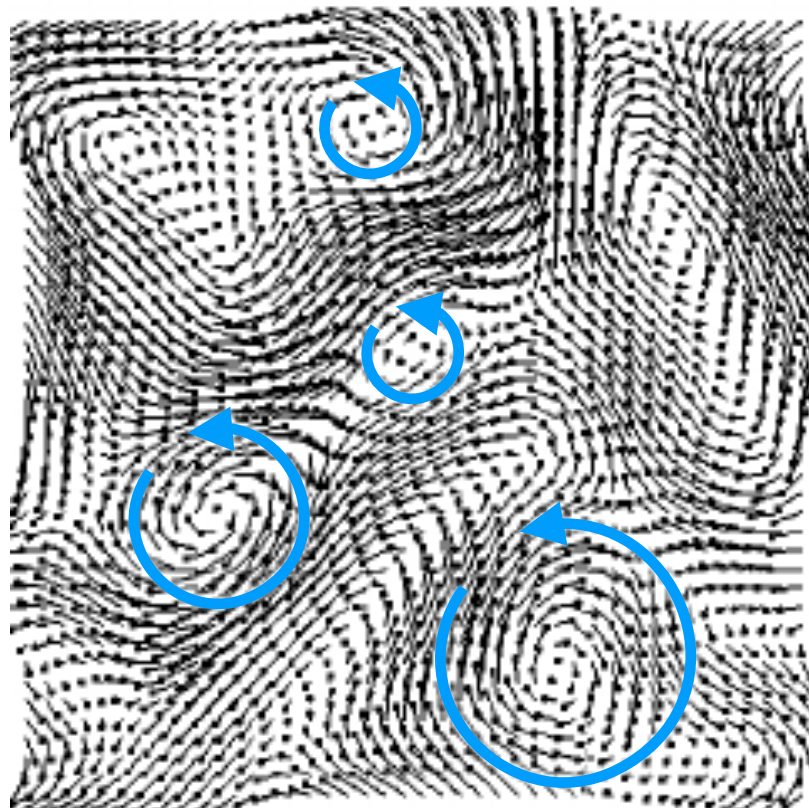
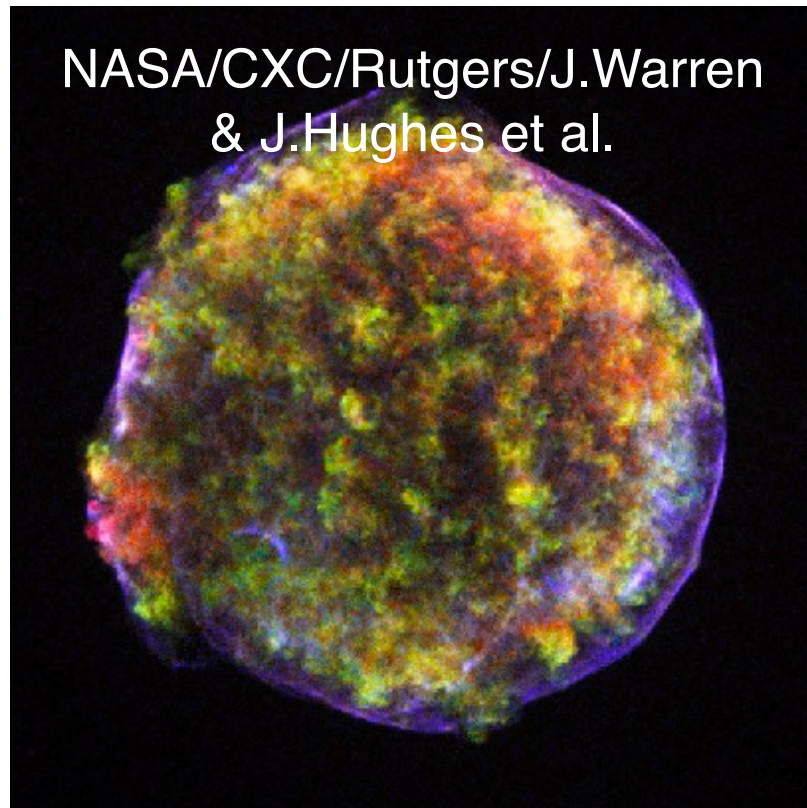
Wavenumber:  $k = 2\pi/\ell$



Cuzol and Mémin 2005

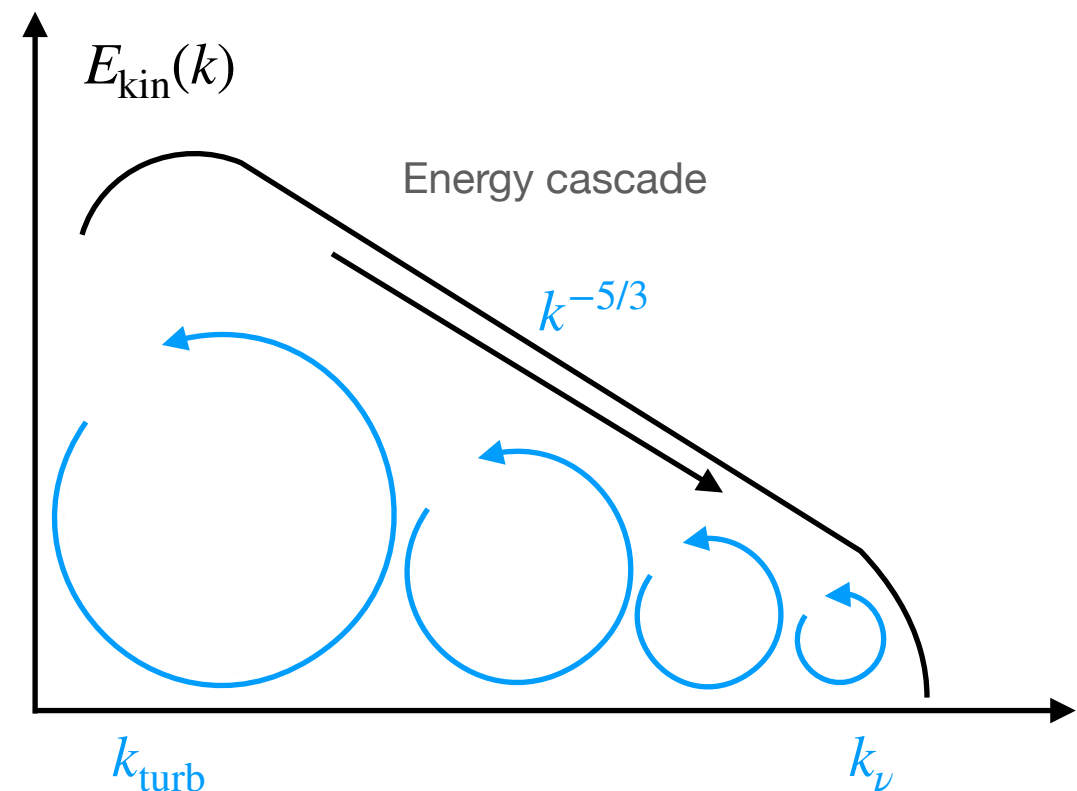


# Characterising turbulent flows



Distribution of energy across scales (spatial structures)

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



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

— Lewis Fry Richardson



Cuzol and Mémin 2005

# Characterising turbulent, magnetised flows

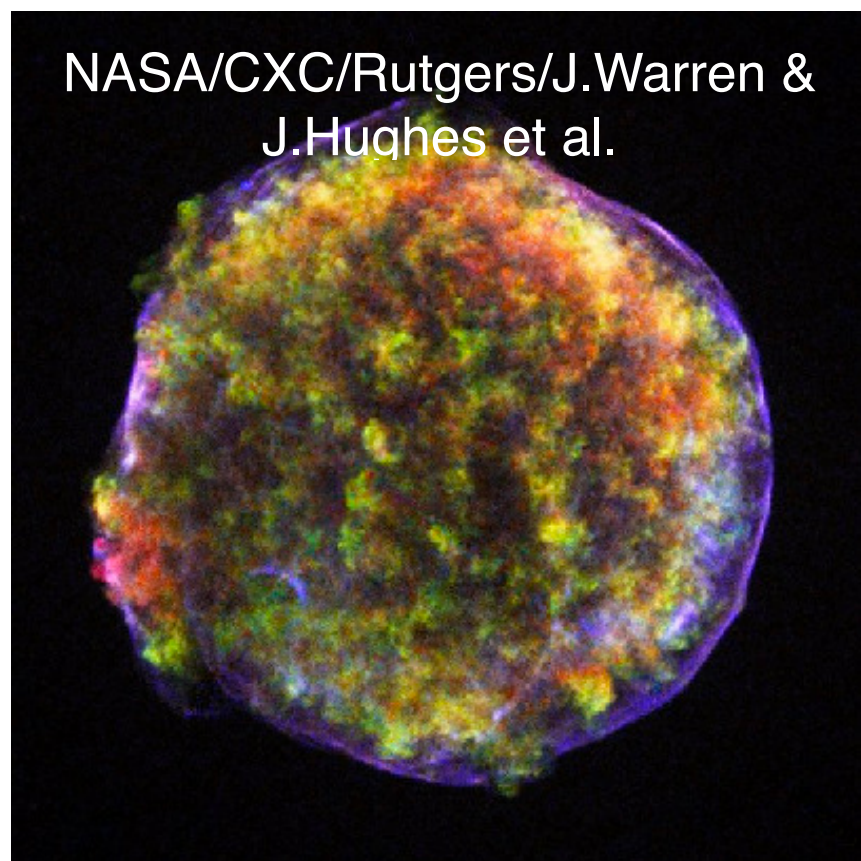
Magnetic Prandtl number:  $P_m = \frac{\text{magnetic dissipation}}{\text{kinetic dissipation}}$



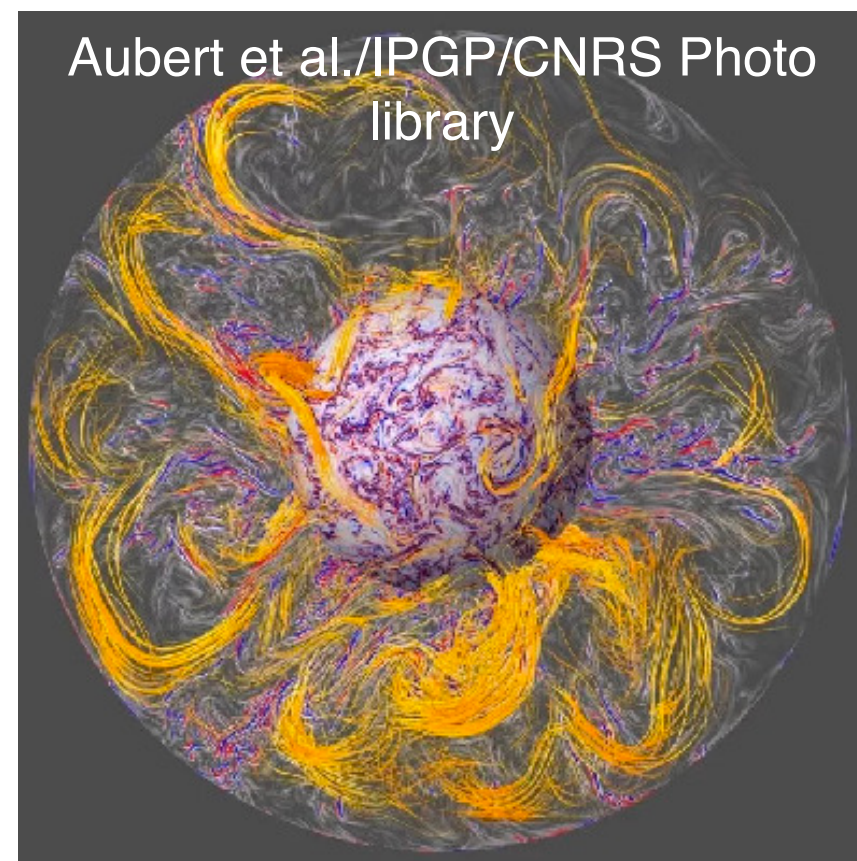
# Characterising turbulent, magnetised flows

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

$P_m \gg 1$



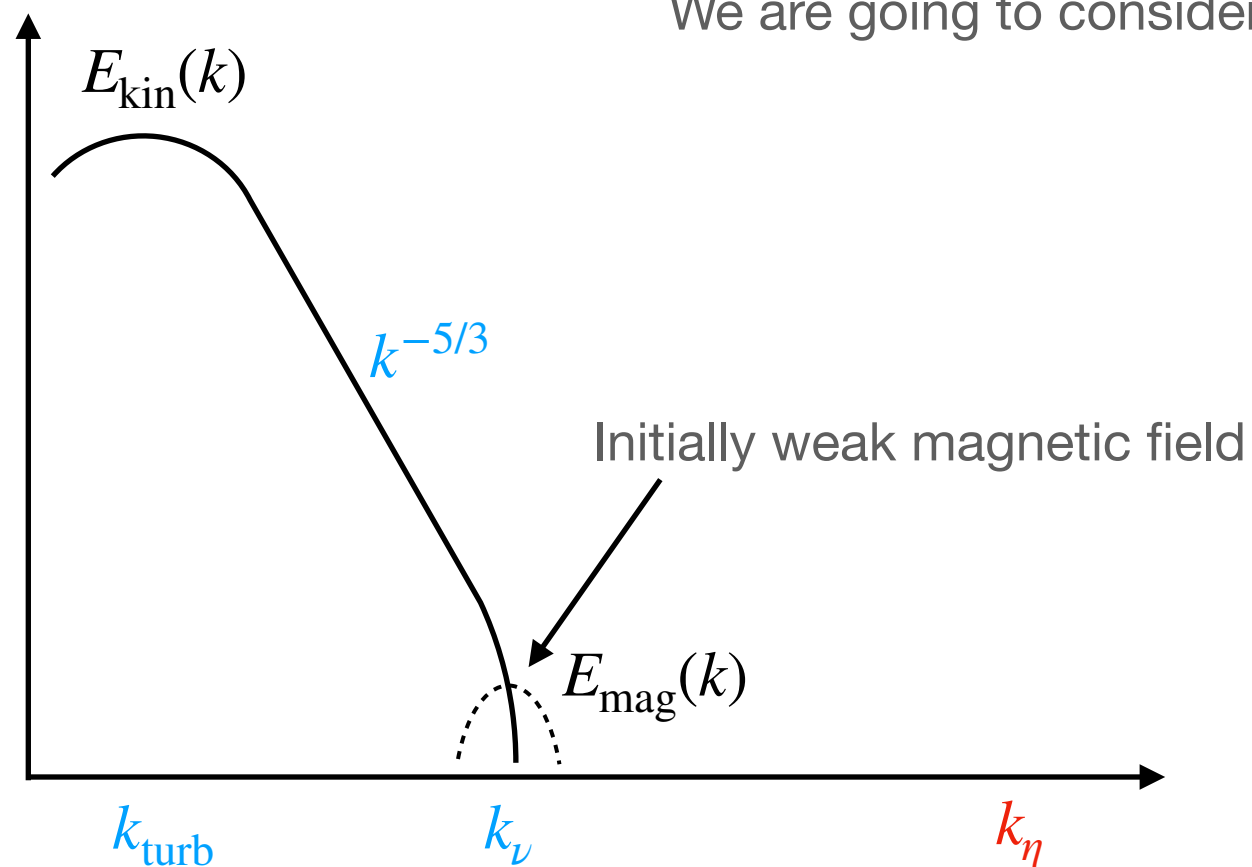
$P_m \lesssim 1$



# Characterising turbulent, magnetised flows

Where **magnetic** and **kinetic** energy dissipates  
We are going to consider  $\text{Pm} \gg 1$ .

$$\frac{k_\eta}{k_\nu} = \text{Pm}^{1/2}$$

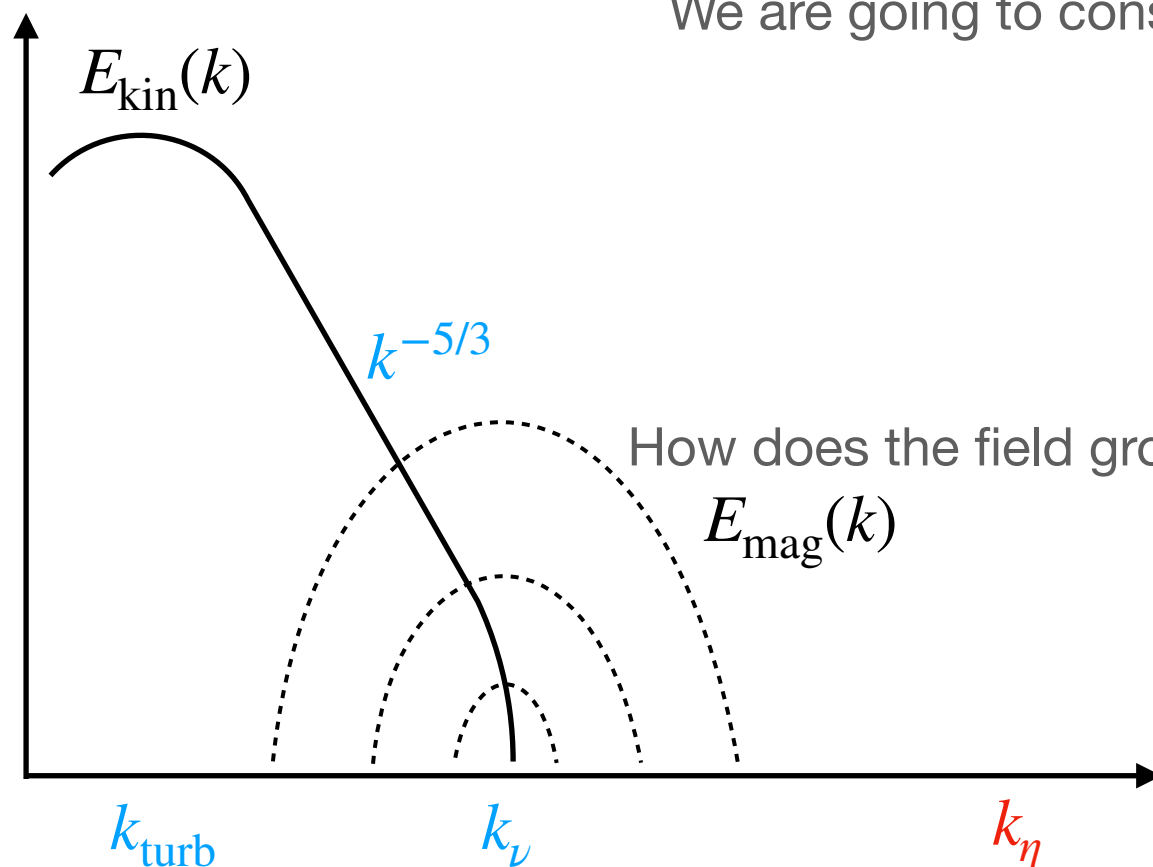




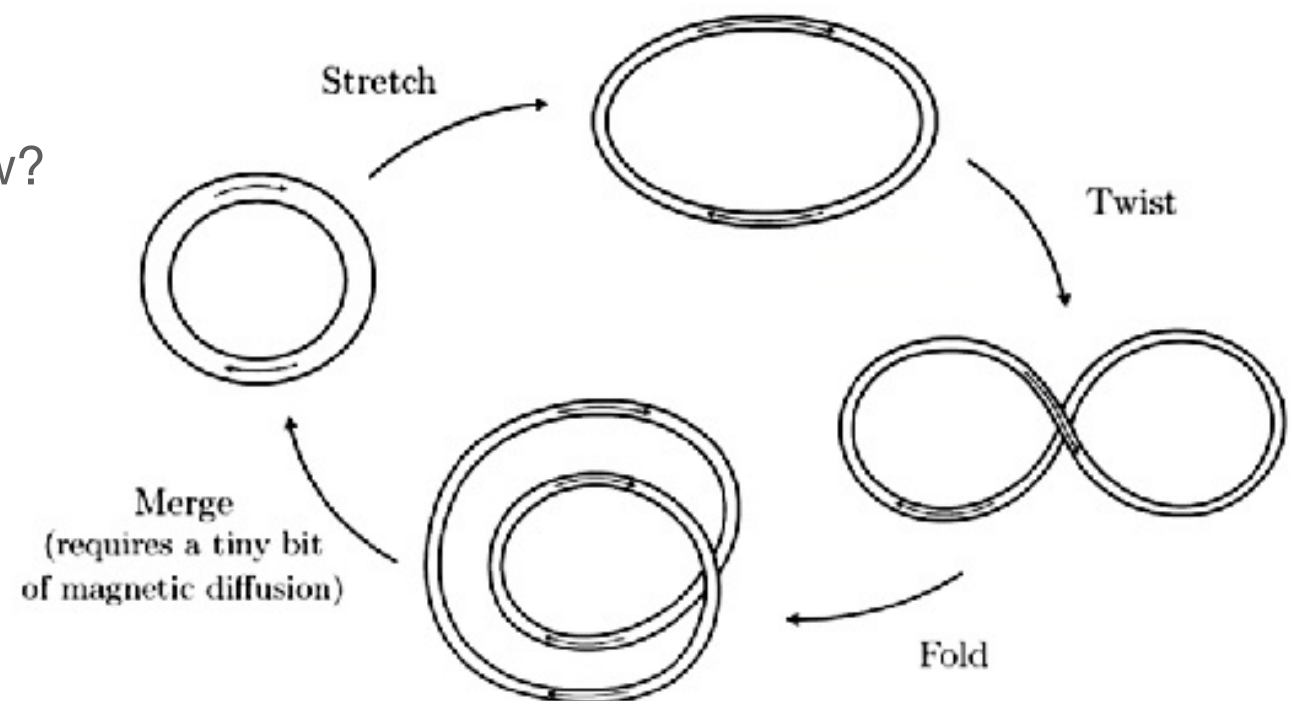
# Characterising turbulent, magnetised flows

Where **magnetic** and **kinetic** energy dissipates  
We are going to consider  $\text{Pm} \gg 1$ .

$$\frac{k_\eta}{k_\nu} = \text{Pm}^{1/2}$$

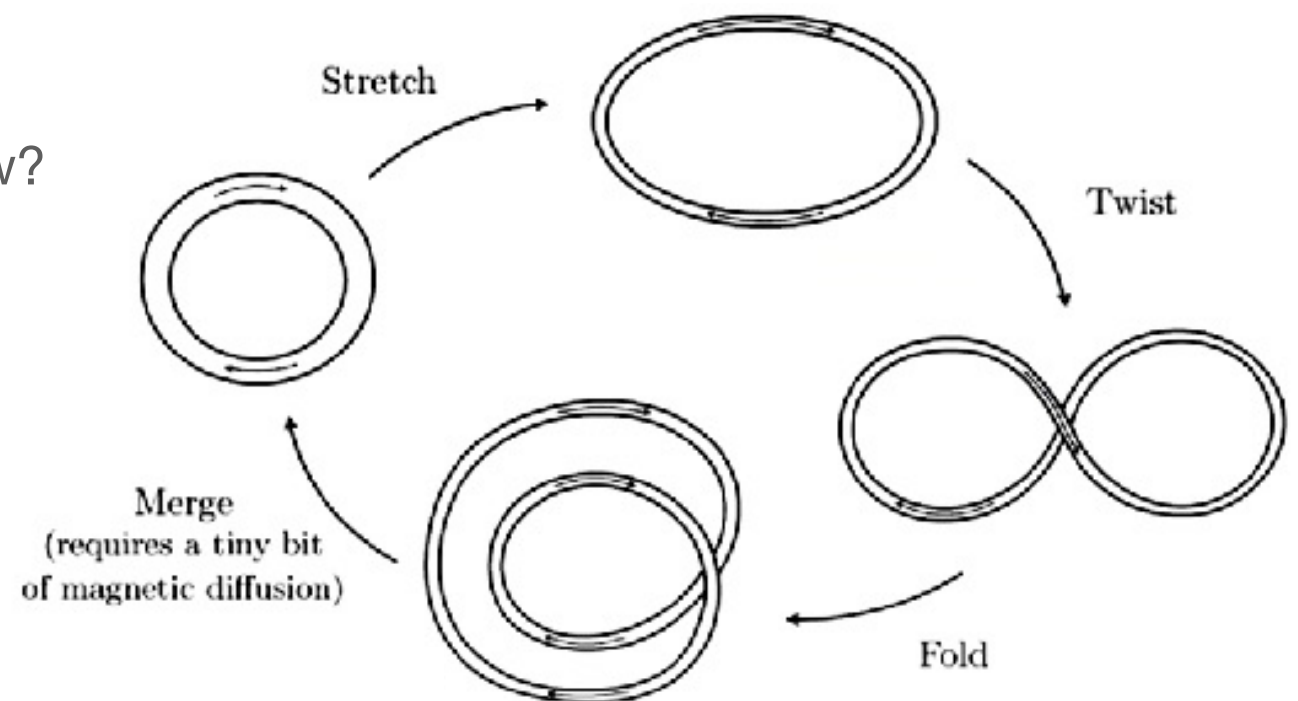
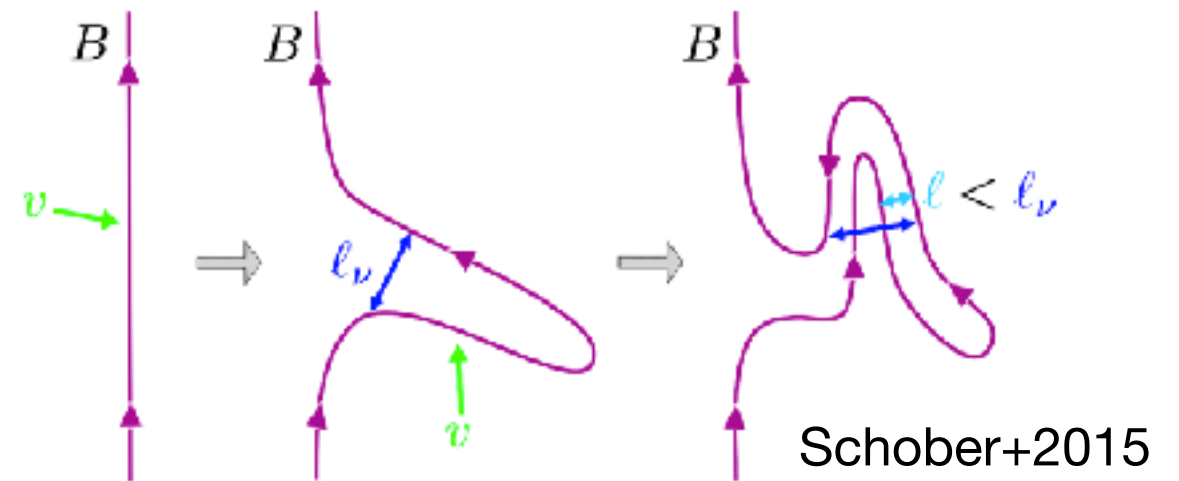
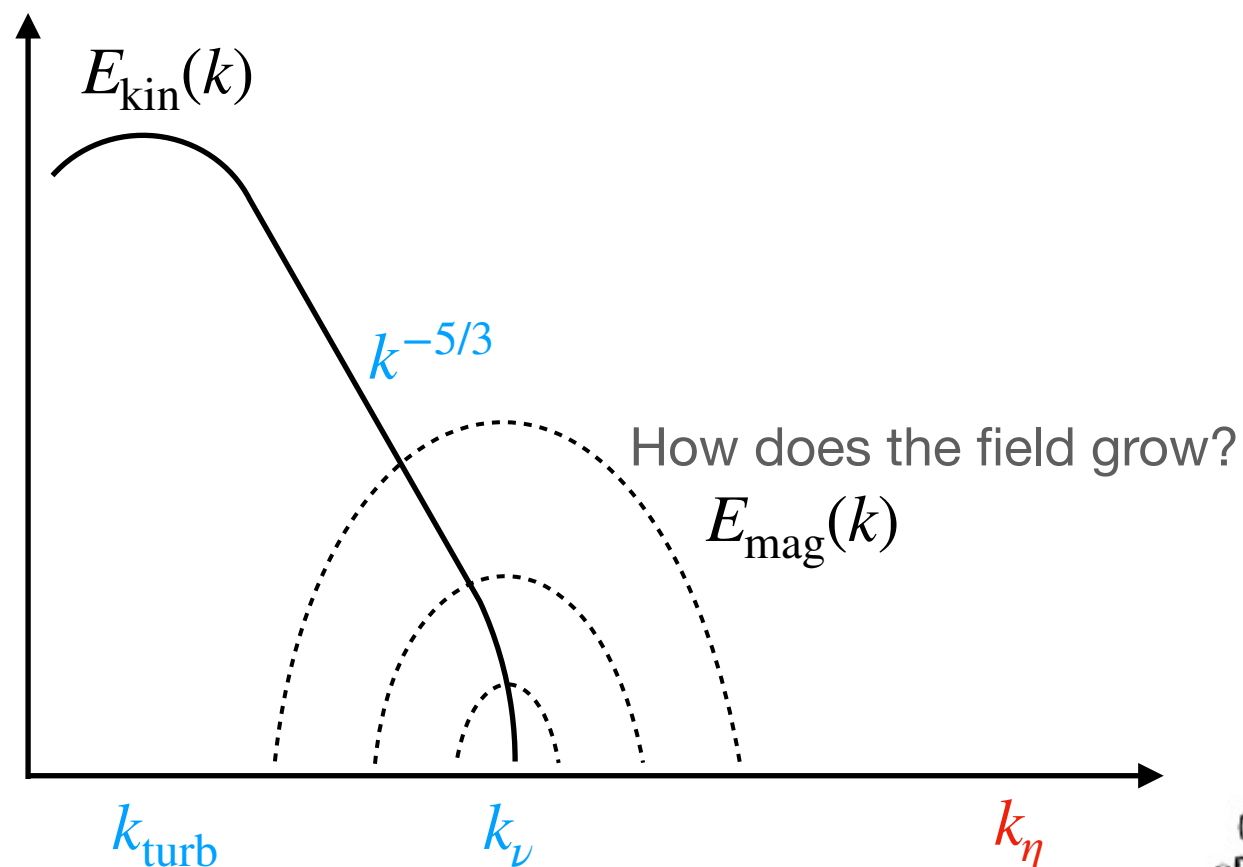


How does the field grow?



Vainshtein and Zeldovich 1972

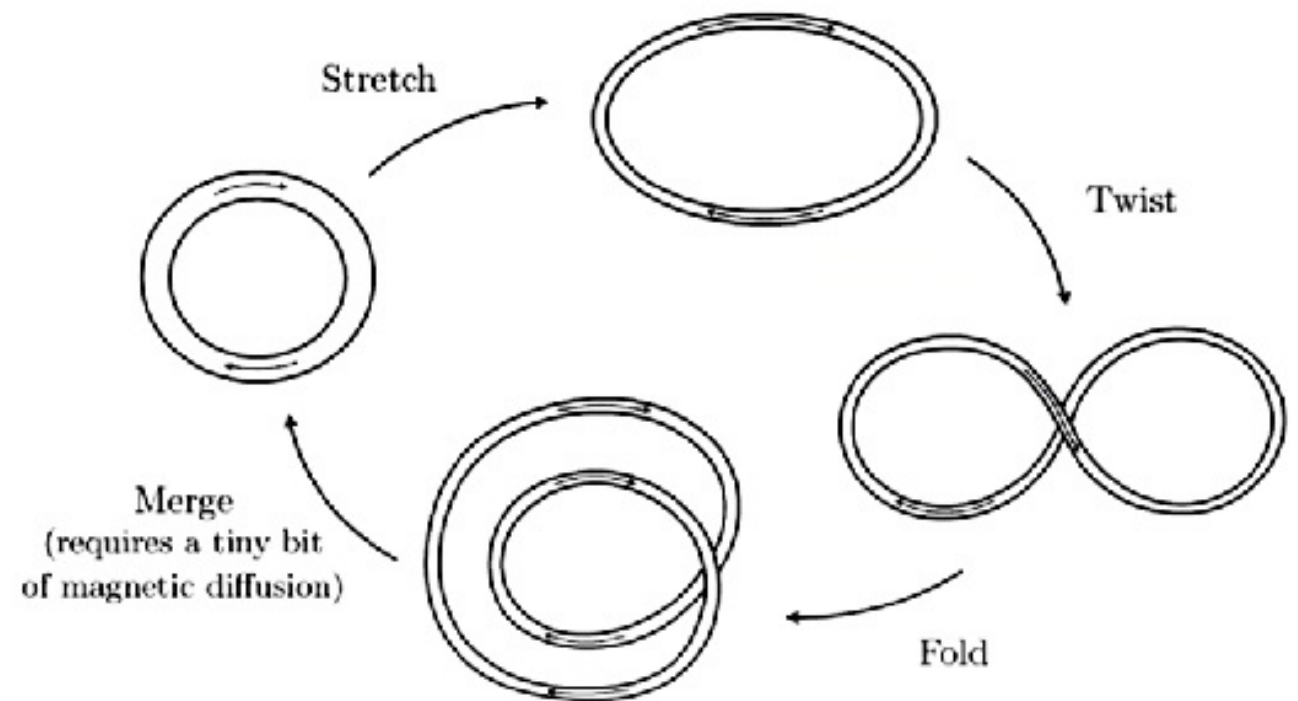
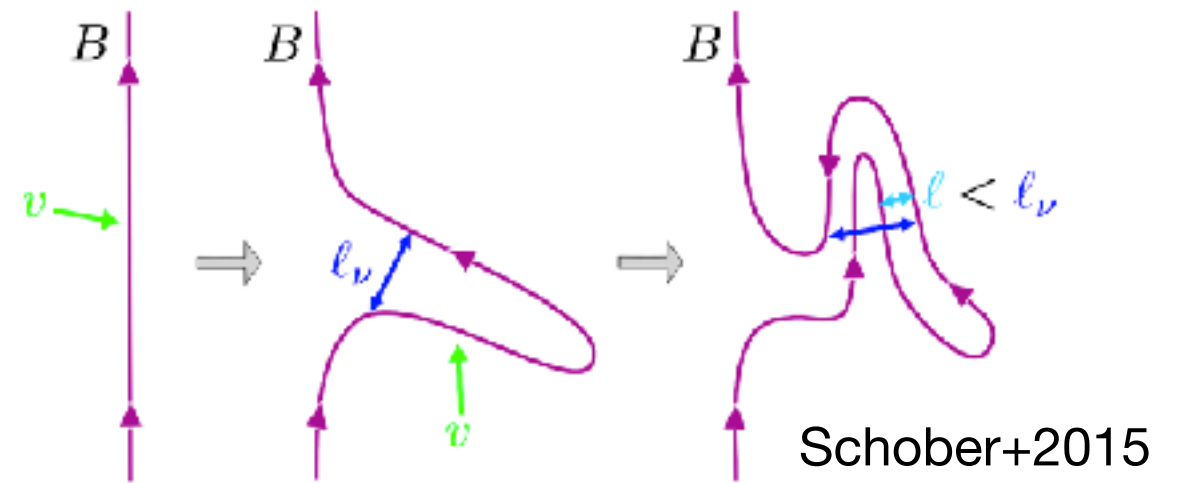
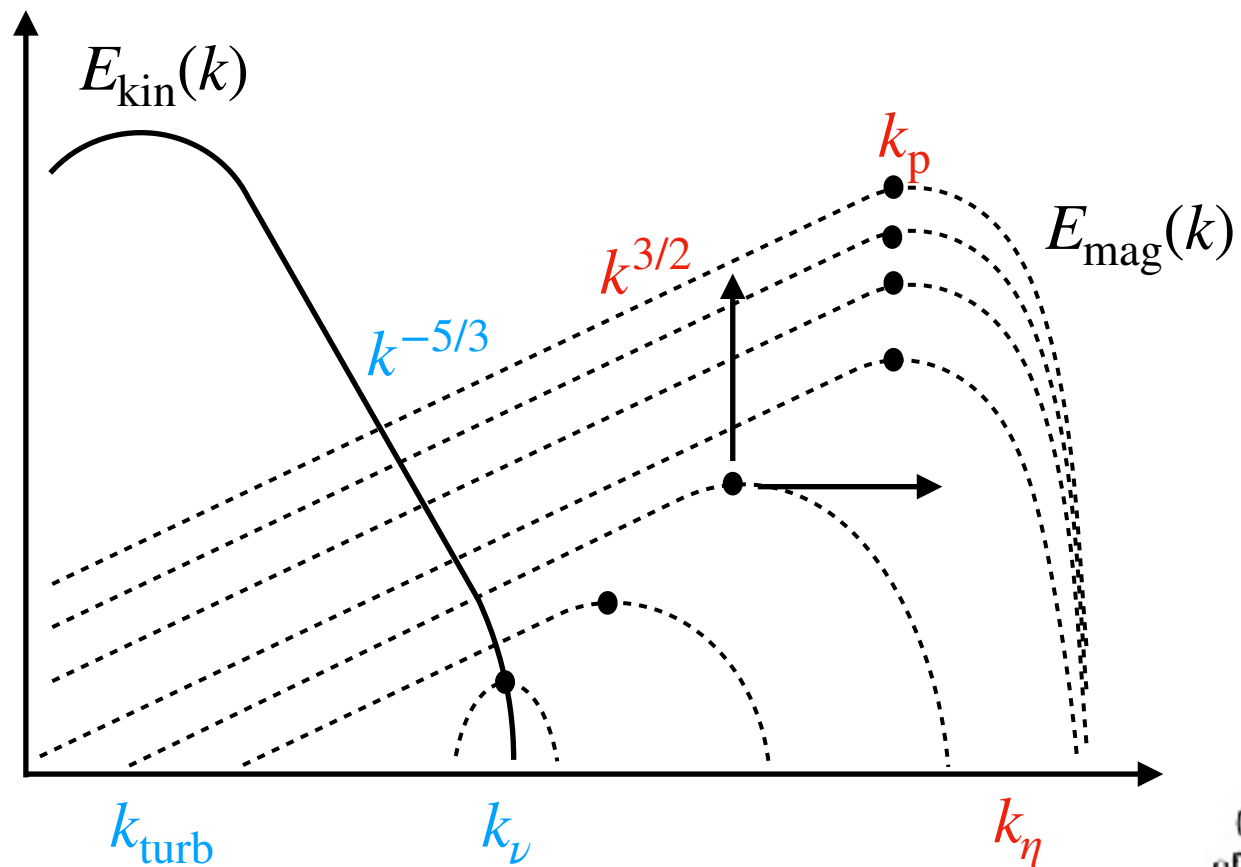
# Characterising turbulent, magnetised flows



Vainshtein and Zeldovich 1972

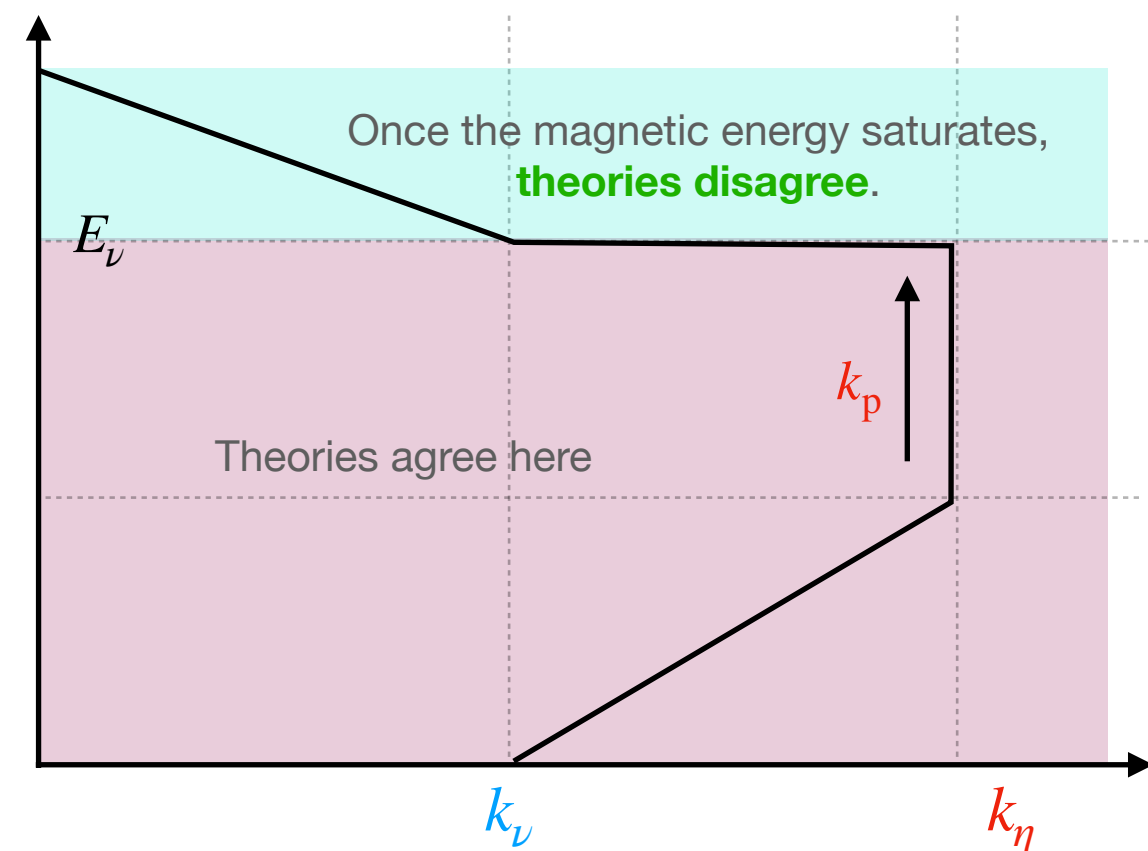
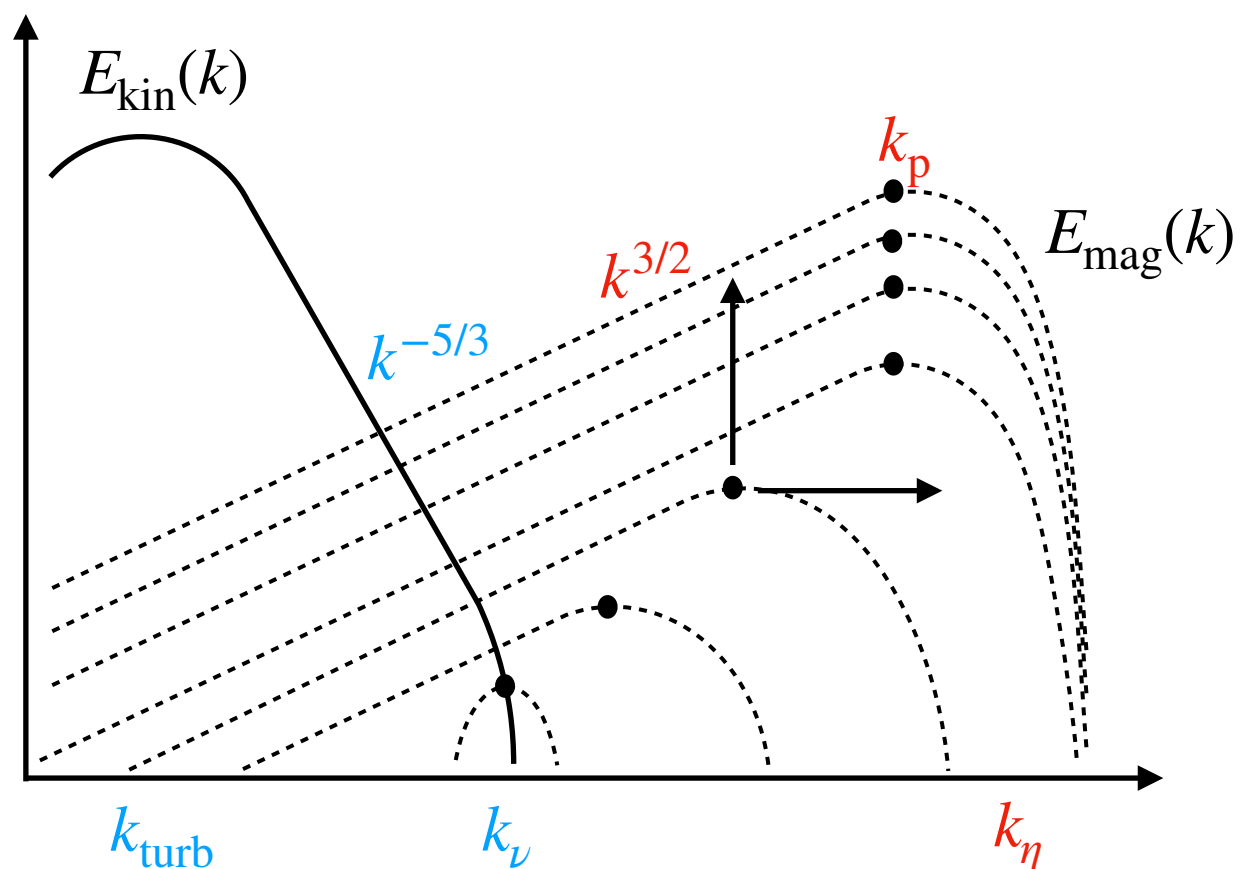


# Characterising turbulent, magnetised flows



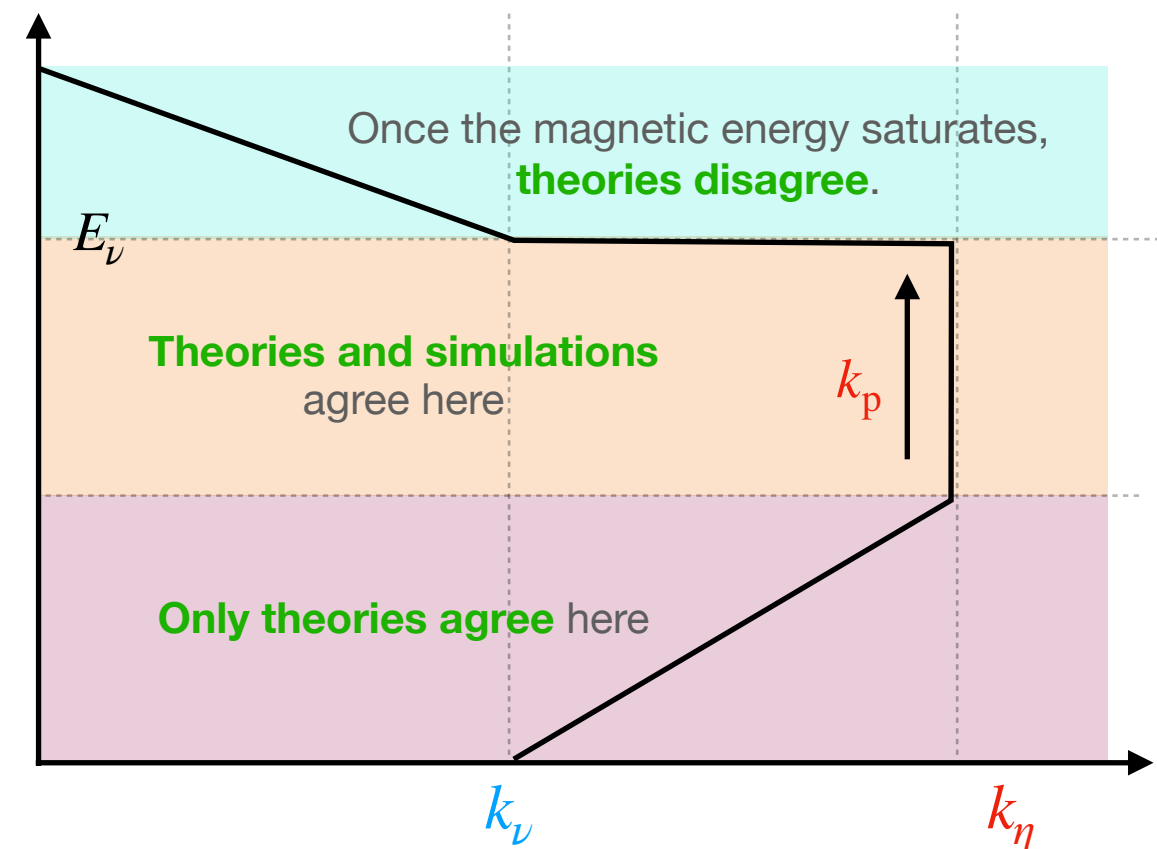
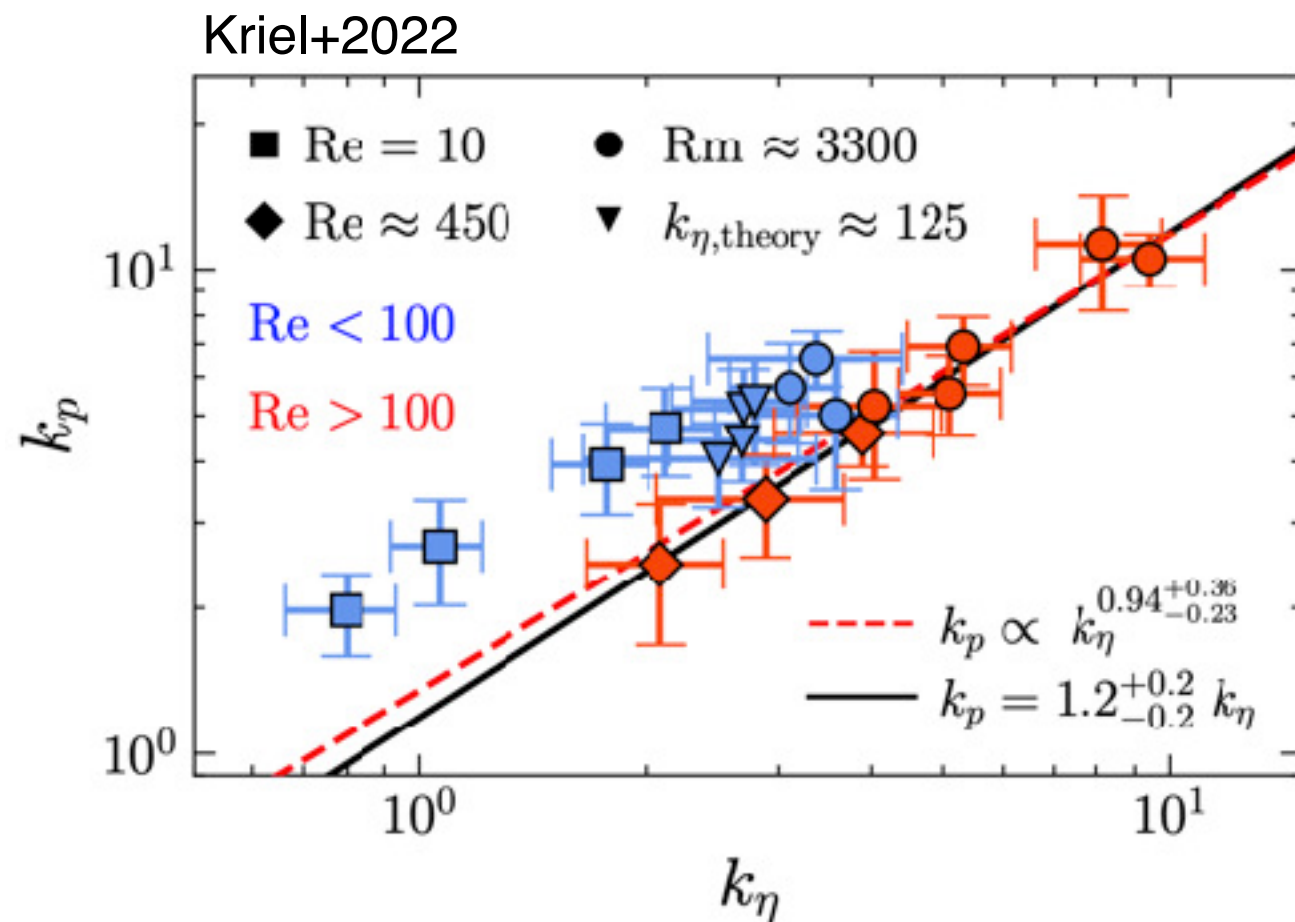
Vainshtein and Zeldovich 1972

# Characterising turbulent, magnetised flows





# Characterising turbulent, magnetised flows



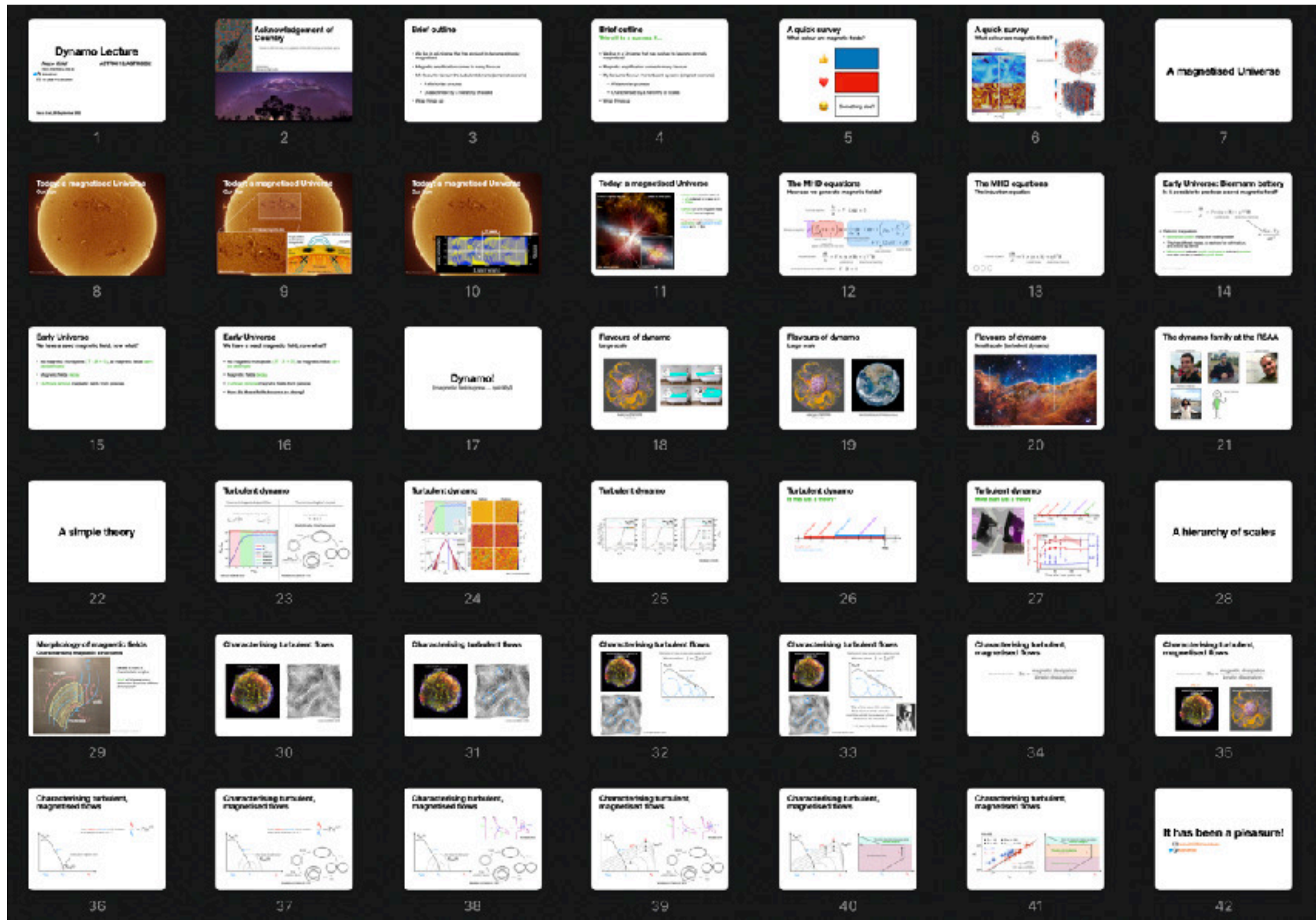
# It has been a pleasure!

 [neco.kriel@anu.edu.au](mailto:neco.kriel@anu.edu.au)

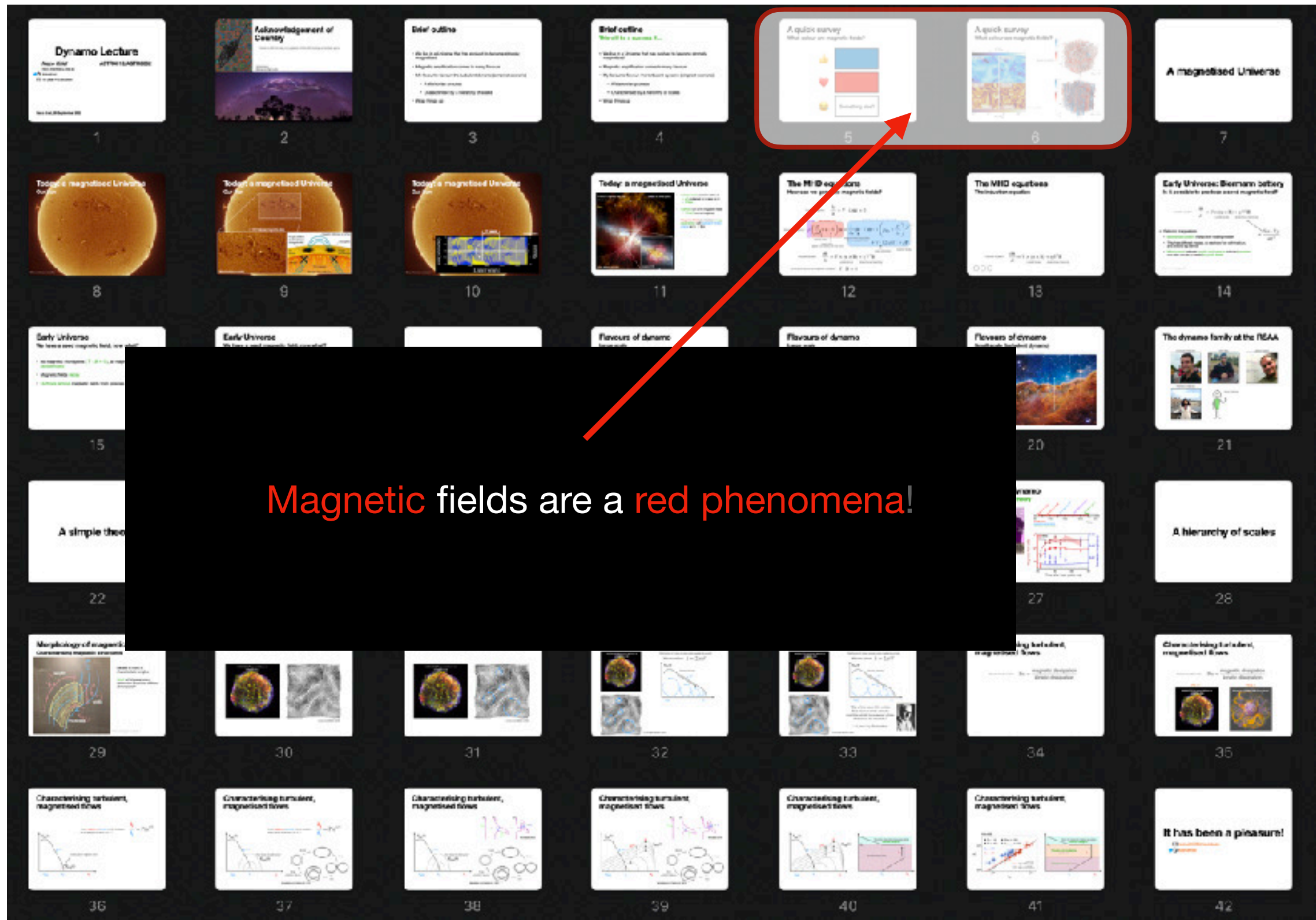
  [AstroKriel](#)



# Let's recap what we learned



# Let's recap what we learned





# Let's recap what we learned

**Dynamo Lecture**  
New York University  
1

**Future of magnetism**  
2

**Brief outline**  
3

**Brief outline**  
4

**A quick survey**  
What colour are magnetic fields?  
5

**A quick survey**  
What colour are magnetic fields?  
6

**A magnetised Universe**  
7

**Today's magnetised Universe**  
8

**Today's magnetised Universe**  
9

**Today's magnetised Universe**  
10

**Today's magnetised Universe**  
11

**The MHD equations**  
Magnetic field evolution  
12

**The MHD equations**  
Thermodynamic equation  
13

**Early Universe: Biermann battery**  
14

**Early Universe**  
The Biermann battery: how strong?  
15

**Early Universe**  
The Biermann battery: how strong?  
16

**Dynamo!**  
17

**Flavours of dynamo**  
Large scale  
18

**Flavours of dynamo**  
Large scale  
19

**Flavours of dynamo**  
Small scale (turbulent dynamo)  
20

**The dynamo family at the IAEA**  
21

**A simple theory**  
22

**Morphology of magnetic fields**  
29

**Characterising turbulent, magnetised flows**  
36

**Characterising turbulent, magnetised flows**  
37

**Characterising turbulent, magnetised flows**  
38

**Characterising turbulent, magnetised flows**  
39

**Characterising turbulent, magnetised flows**  
40

**Characterising turbulent, magnetised flows**  
41

**It has been a pleasure!**  
42

**A hierarchy of scales**  
28

**Characterising turbulent, magnetised flows**  
35

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

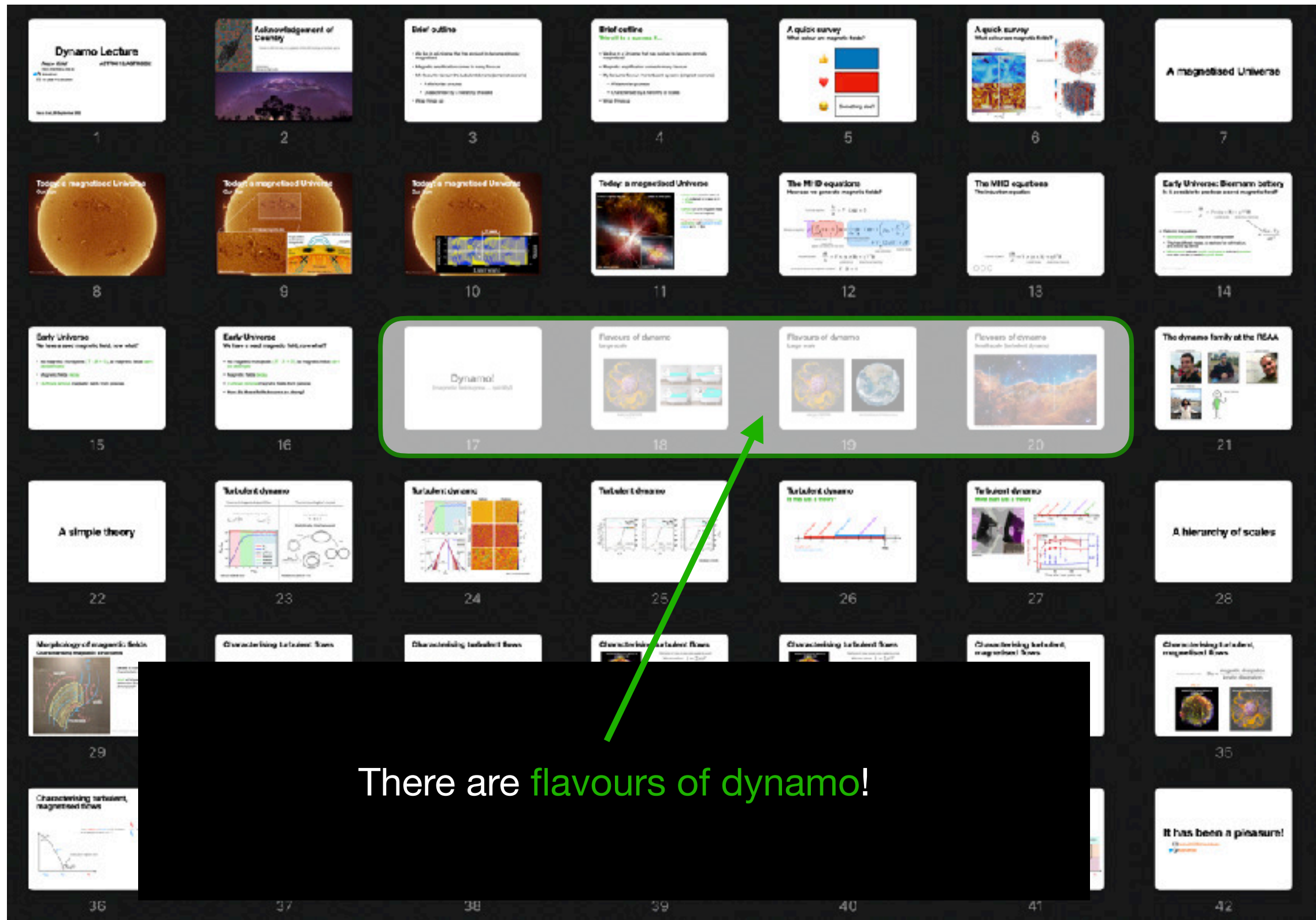
The grid of slides includes:

- Slide 1: Dynamo Lecture
- Slide 2: Acknowledgement of Country
- Slide 3: Brief outline
- Slide 4: Brief outline
- Slide 5: A quick survey
- Slide 6: A quick survey
- Slide 7: A magnetised Universe
- Slide 8: Today's magnetised Universe
- Slide 9: Today's magnetised Universe
- Slide 10: Today's magnetised Universe
- Slide 11: Today's magnetised Universe
- Slide 12: The MHD equations
- Slide 13: The MHD equations
- Slide 14: Early Universe: Biermann battery
- Slide 15: Early Universe
- Slide 16: Early Universe
- Slide 17: Dynamical
- Slide 18: Flavours of dynamo
- Slide 19: Flavours of dynamo
- Slide 20: Flavours of dynamo
- Slide 21: The dynamo family at the IAEA
- Slide 22: A simple theory
- Slide 23: Morphology of magnetic field
- Slide 24: A hierarchy of scales
- Slide 25: Characterising turbulent, magnetised flows
- Slide 26: Characterising turbulent, magnetised flows
- Slide 27: Characterising turbulent, magnetised flows
- Slide 28: Characterising turbulent, magnetised flows
- Slide 29: Characterising turbulent, magnetised flows
- Slide 30: Characterising turbulent, magnetised flows
- Slide 31: Characterising turbulent, magnetised flows
- Slide 32: Characterising turbulent, magnetised flows
- Slide 33: Characterising turbulent, magnetised flows
- Slide 34: Characterising turbulent, magnetised flows
- Slide 35: Characterising turbulent, magnetised flows
- Slide 36: Characterising turbulent, magnetised flows
- Slide 37: Characterising turbulent, magnetised flows
- Slide 38: Characterising turbulent, magnetised flows
- Slide 39: Characterising turbulent, magnetised flows
- Slide 40: Characterising turbulent, magnetised flows
- Slide 41: Characterising turbulent, magnetised flows
- Slide 42: It has been a pleasure!

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



# Let's recap what we learned



# Let's recap what we learned

The image displays a grid of 42 presentation slides, numbered 1 to 42, arranged in a 6x7 layout (with the last row having 6 slides). The slides are titled and numbered as follows:

- 1: Dynamo Lecture
- 2: Future development of Century
- 3: Brief outline
- 4: Brief outline
- 5: A quick survey
- 6: A quick survey
- 7: A magnetised Universe
- 8: Today's magnetised Universe
- 9: Today's magnetised Universe
- 10: Today's magnetised Universe
- 11: Today's magnetised Universe
- 12: The MHD equations
- 13: The MHD equations
- 14: Early Universe: Biermann battery
- 15: Early Universe
- 16: Early Universe
- 17: Dynamical
- 18: Flavours of dynamo
- 19: Flavours of dynamo
- 20: Flavours of dynamo
- 21: The dynamo family at the IAEA
- 22: A simple theory
- 23: Turbulent dynamo
- 24: Turbulent dynamo
- 25: Turbulent dynamo
- 26: Turbulent dynamo
- 27: Turbulent dynamo
- 28: A hierarchy of scales
- 29: Morphology of magnetic fields
- 30: Characterising turbulent flows
- 31: Characterising turbulent flows
- 32: Characterising turbulent flows
- 33: Characterising turbulent flows
- 34: Characterising turbulent flows
- 35: Characterising turbulent, magnetised flows
- 36: Characterising turbulent, magnetised flows
- 37: Characterising turbulent, magnetised flows
- 38: Characterising turbulent, magnetised flows
- 39: Characterising turbulent, magnetised flows
- 40: Characterising turbulent, magnetised flows
- 41: Characterising turbulent, magnetised flows
- 42: It has been a pleasure!

A green arrow points from slide 25 to a text box at the bottom of the grid.

The turbulent dynamo is more than just a theory!



# Let's recap what we learned

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

