

Swiss SKA Days

Bern ❖ June 2019

“Origin and evolution of cosmological magnetic fields”

Jennifer Schober

& collaborators:

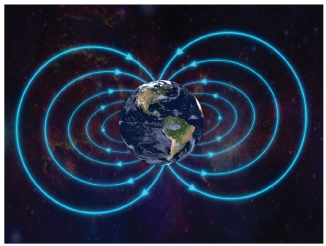
Axel Brandenburg, Alexey Boyarsky,
Ruth Durrer, Tomohiro Fujita, Jürg Fröhlich,
Tina Kahniashvili, Nathan Kleeorin,
Igor Rogachevskii, Oleg Ruchayskiy



The magnetic Universe

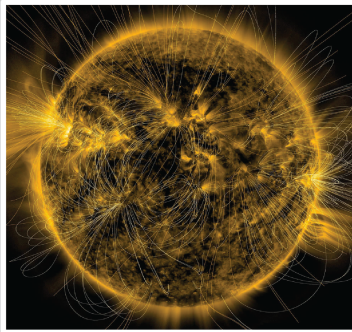
Planets

[here: Earth, credit: iStock]



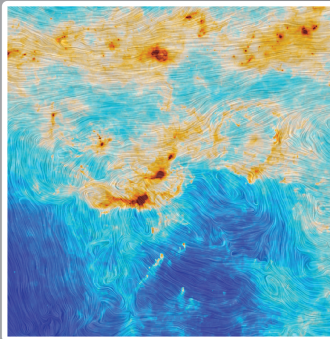
Stars

[here: Sun, credit: NASA/SDO/AIA/LMSAL]



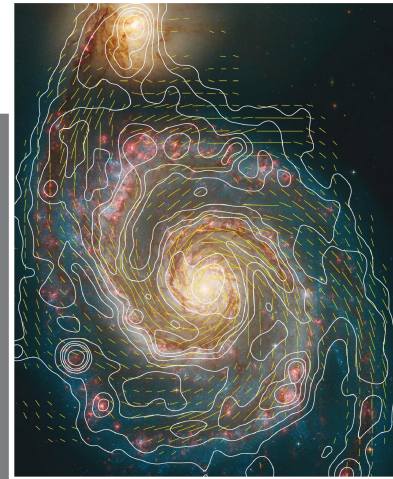
Interstellar medium

[here: Orion molecular cloud, credit: ESA and Planck Collaboration]



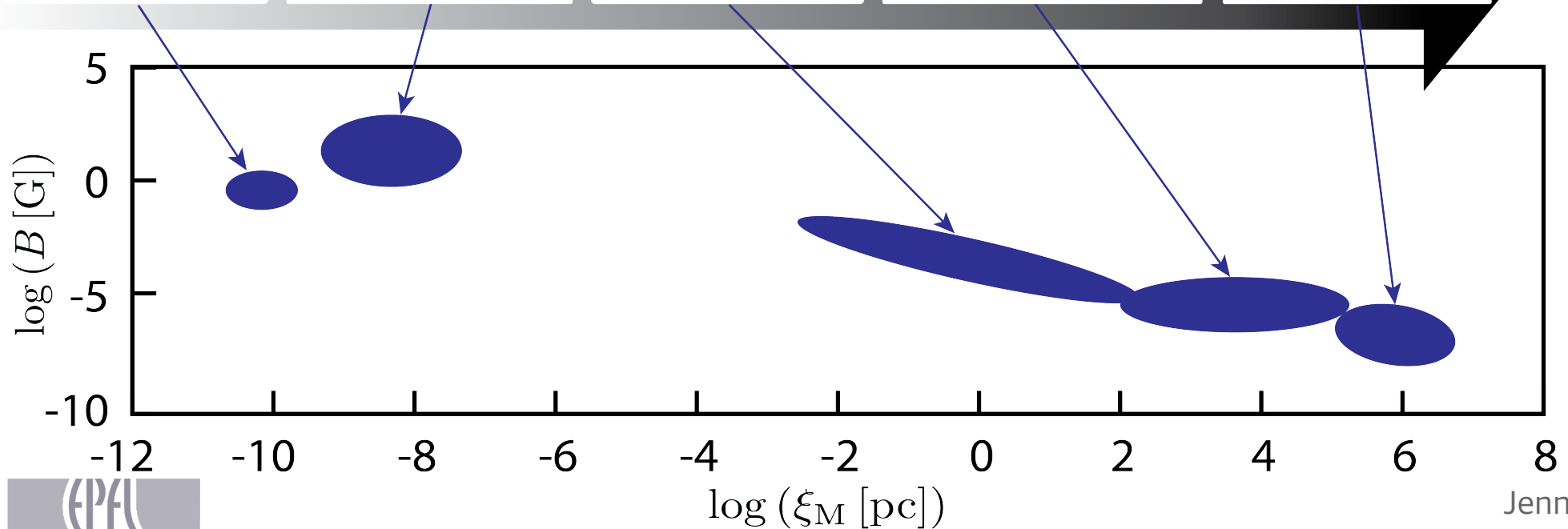
Galaxies

[here: M51, credit: Beck 2011]



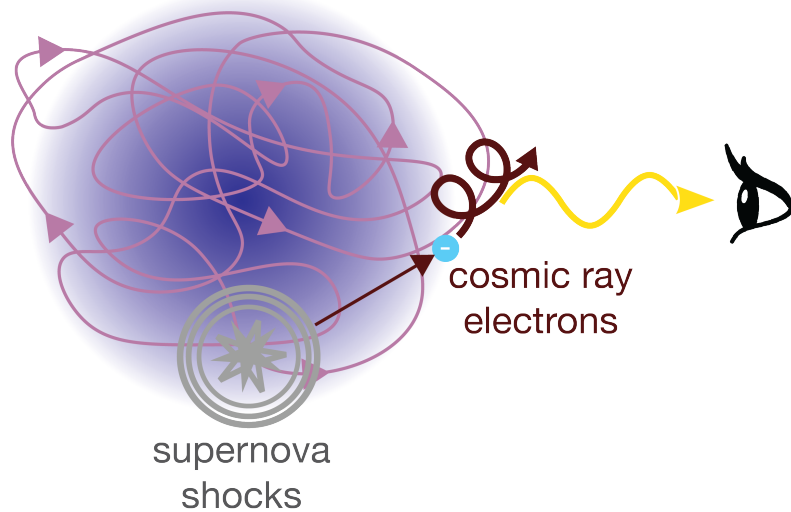
Galaxy clusters

[here: MACS J0717.5+3745, credit: NASA, ESA, CXC, NRAO/AUI/NSF, STScI]

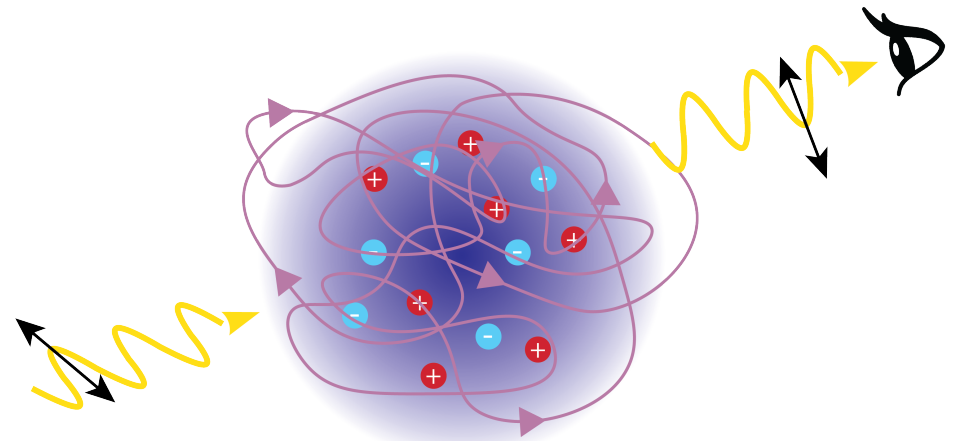


The role of SKA

Synchrotron emission



Faraday rotation

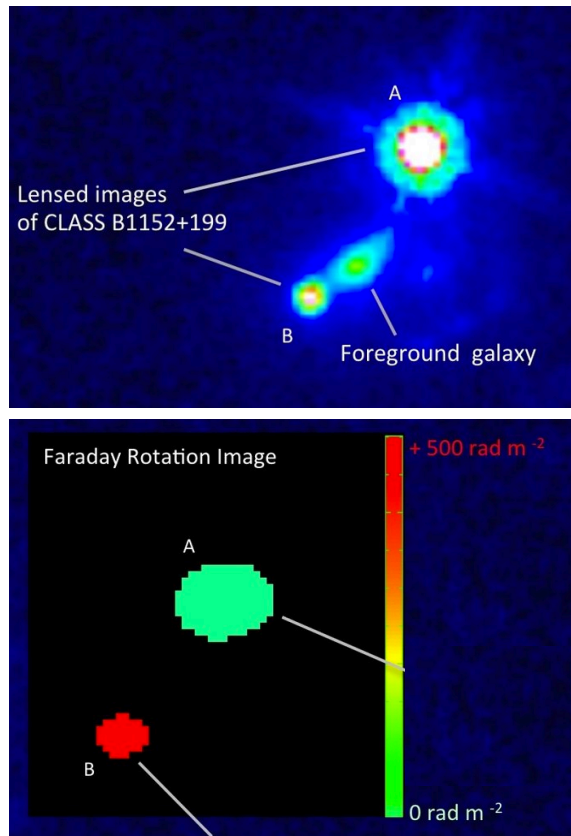


SKA will be a game changer in understanding the evolution of cosmic magnetic fields.

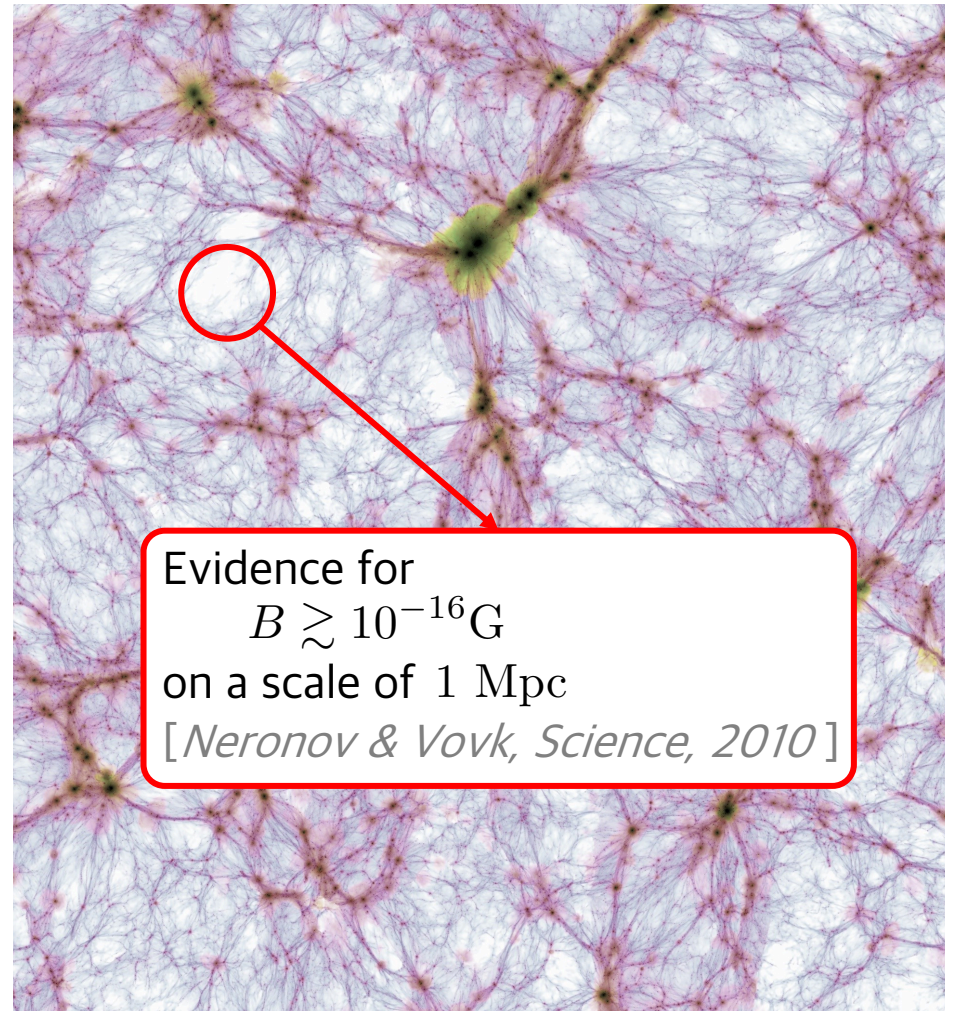
Glance at the observational status

Direct observations in high-redshift galaxies:

Detection of the most distant coherent galactic magnetic field ($1 \mu\text{G}$) at $z \approx 0.44$ [*Mao et al., Nature, 2017*]:



Relics of the oldest magnetic fields found in cosmic voids:



Magnetic history of the Universe

Magnetic seed fields:

❖ Inflation:

fluctuations of the electromagnetic field are increased

[*Turner & Widrow 1988, Ratra 1992*]

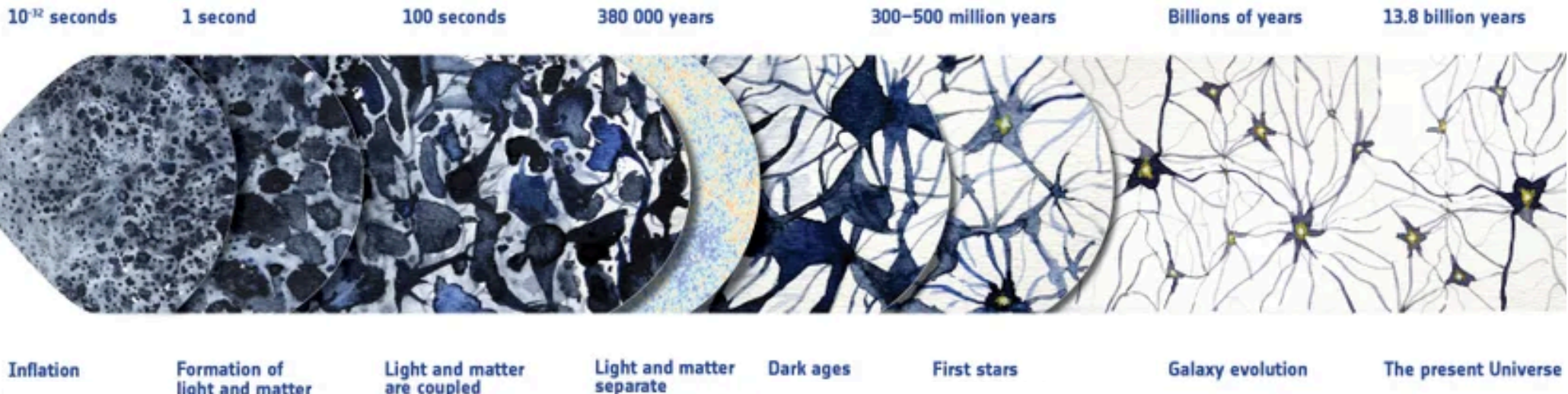
$$B_0 \approx 10^{-65} - 10^{-9} \text{ G}$$

❖ First-order phase transitions (QED and QCD):

non-equilibrium conditions allow for battery processes

[*Hogan 1983, Sigl et al. 1997*]

$$B_0 \approx 10^{-29} - 10^{-20} \text{ G}$$



Magnetic history of the Universe

Magnetic
seed fields

10^{-32} seconds

1 second

100 seconds

380 000 years

300–500 million years

Billions of years

13.8 billion years



Inflation

Formation of
light and matter

Light and matter
are coupled

Light and matter
separate

Dark ages

First stars

Galaxy evolution

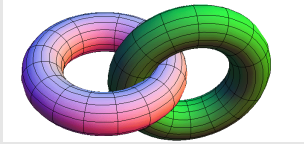
The present Universe

Magnetic history of the Universe

Decaying MHD turbulence:

- ❖ The evolution of magnetic fields depends strongly on the magnetic helicity:

$$\mathbf{A} \cdot \mathbf{B} \approx \xi B^2 \quad (\mathbf{B} = \nabla \times \mathbf{A})$$



- ❖ Magnetic helicity is a conserved quantity in ideal MHD ($\xi B^2 = \text{const}$), so if

$$B \searrow \rightarrow \xi \nearrow \quad (\text{"inverse cascade"})$$

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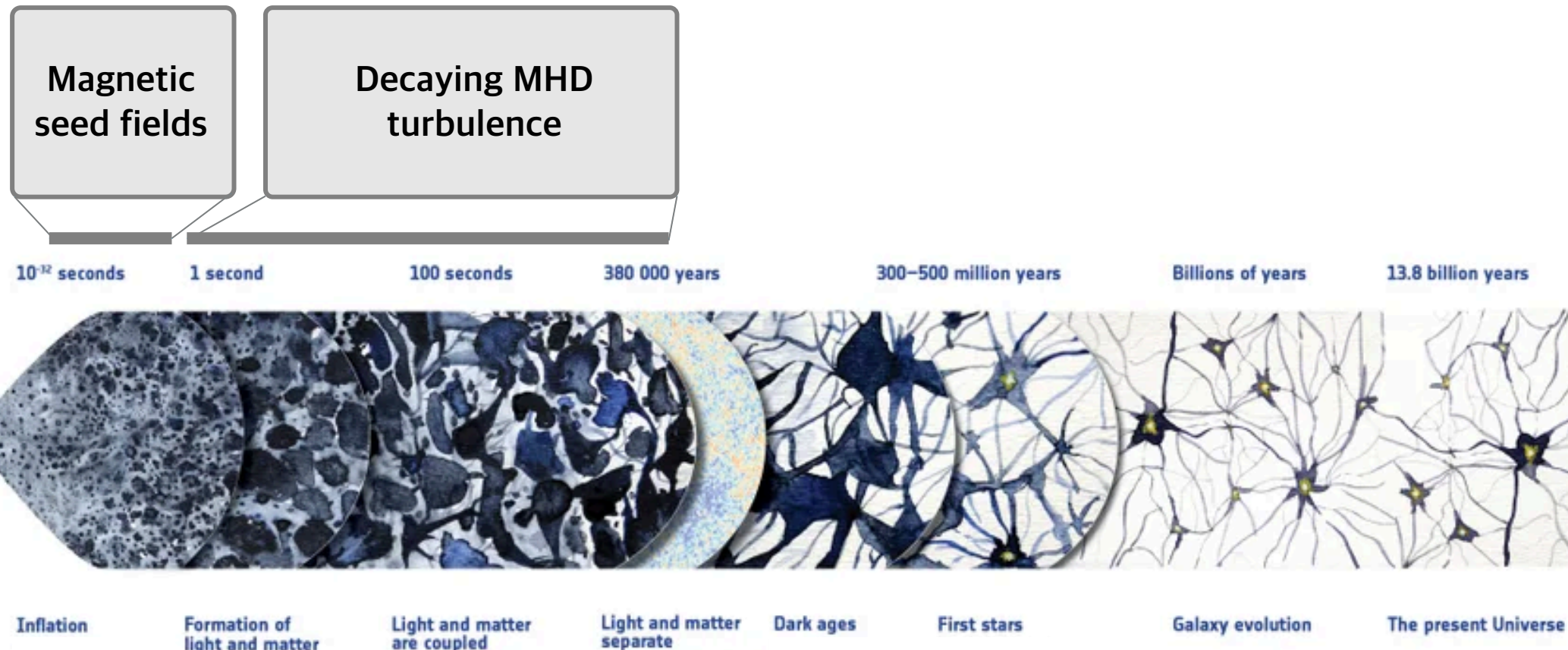
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Magnetic history of the Universe



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Magnetic history of the Universe

Passive evolution:

Magnetic field is frozen in Hubble expansion

[*Banerjee & Jedamzik 2004*]



Magnetic seed fields

Decaying MHD turbulence

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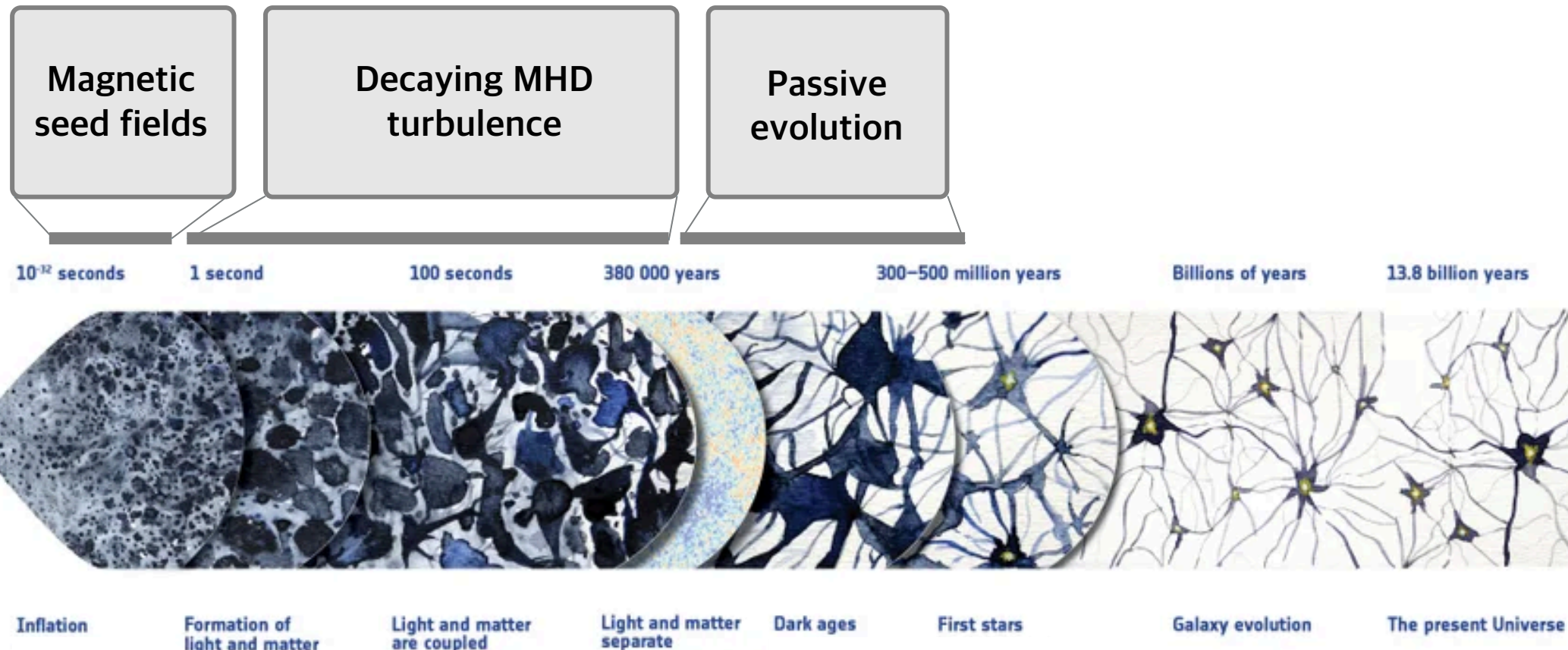
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Magnetic history of the Universe

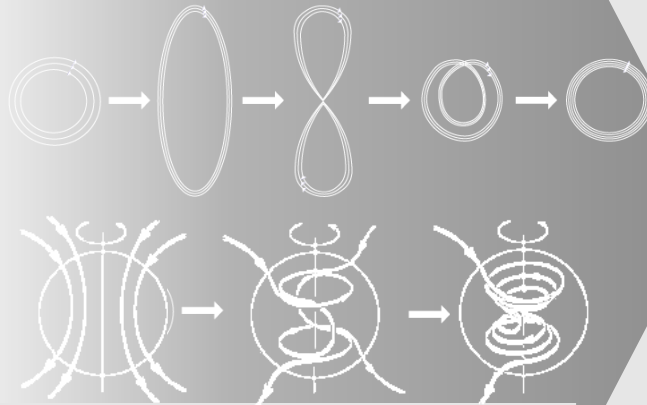


Magnetic history of the Universe

MHD dynamos [*Brandenburg & Subramanian 2005*]:

Kinetic energy:

- ❖ turbulence (accretion, supernovae)
- ❖ large-scale rotation



Magnetic energy

Magnetic seed fields

De

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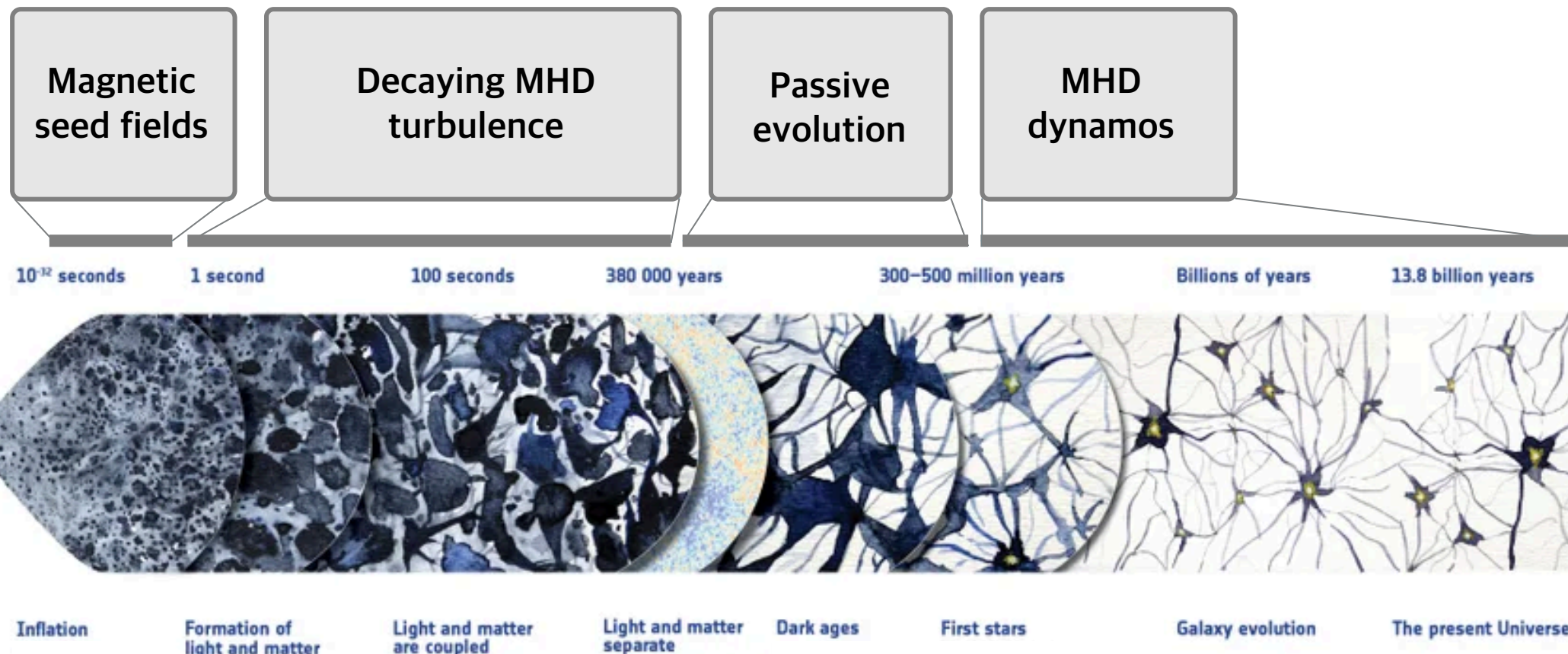
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Magnetic history of the Universe



Magnetic history of the Universe

[Fletcher et al. 2011]



**Magnetic
seed fields**

**Decaying MHD
turbulence**

**Passive
evolution**

**MHD
dynamos**

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Magnetic history of the Universe

[Fletcher et al. 2011]

A macroscopic quantum effect can lead to significant changes in this era.

Magnetic seed fields

Decaying MHD turbulence

Passive evolution

MHD dynamos



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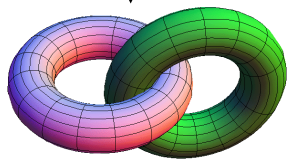
The present Universe

MHD at high energies

Magneto-hydro-dynamics (MHD)

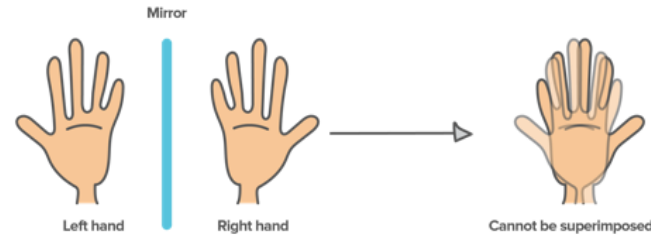
→ conservation of magnetic helicity:

$$\frac{\partial}{\partial t} (\mathbf{A} \cdot \mathbf{B}) = 0$$



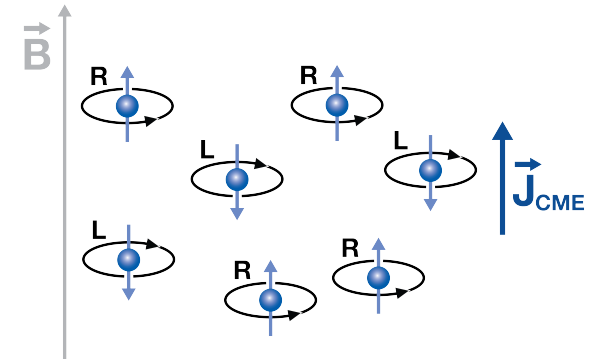
Transition at high temperature (> 10 MeV)
[Boyarsky, Froehlich, & Ruchayskiy 2012]

Chiral magnetohydrodynamics (Chiral MHD)



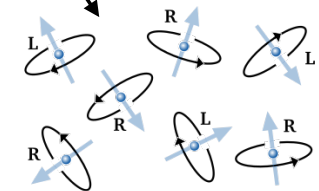
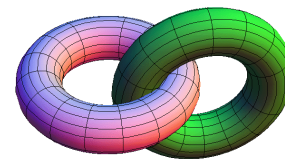
An asymmetry between left- and right handed fermions, μ_5 , leads to the “chiral magnetic effect” [Vilenkin 1980].

→ new current in the plasma:



→ conservation of total chirality:

$$\frac{\partial}{\partial t} \left(\mathbf{A} \cdot \mathbf{B} + \frac{2\mu_{5,0}}{\lambda} \right) = 0$$



Chiral dynamo instability

Full set of chiral MHD equations:

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

new
dynamo
term

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} - \eta (\nabla \times \mathbf{B} - \mu_5 \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

$$\frac{D\mu_5}{Dt} = D_5 \Delta \mu_5 + \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

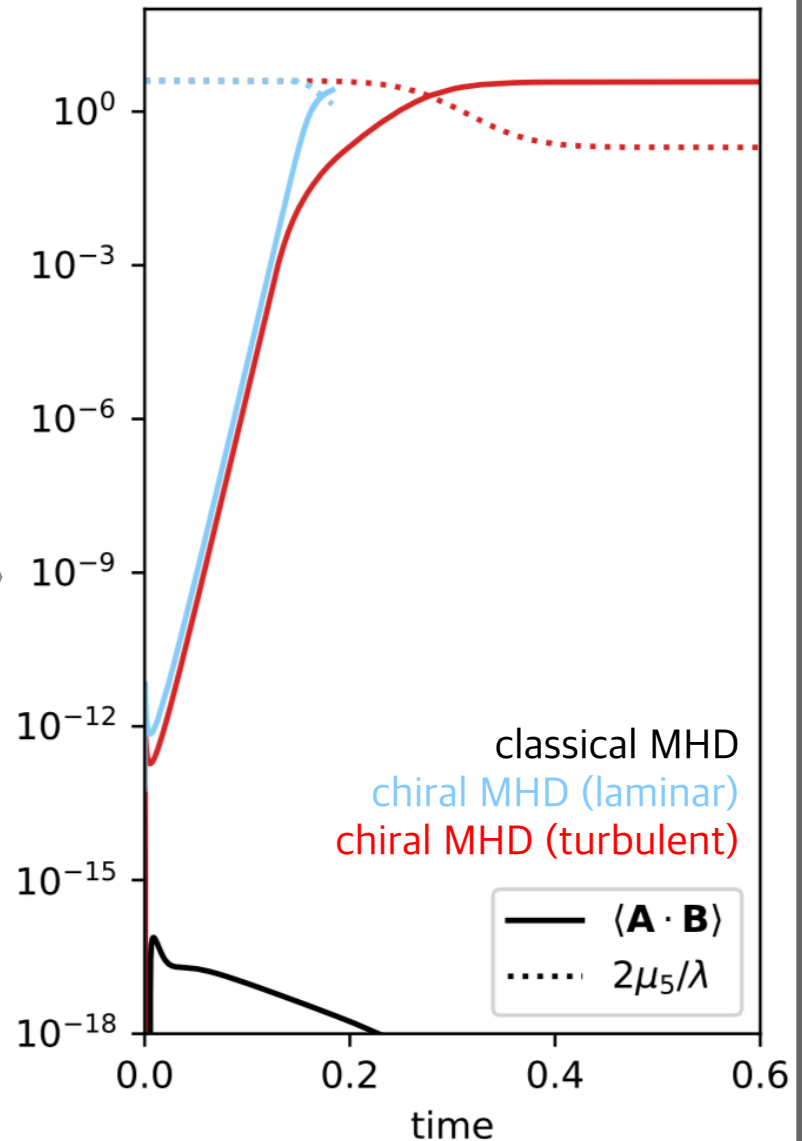
Initial conditions:

- ❖ large chiral asymmetry
(large $\mu_5(t=0)$)
- ❖ weak magnetic seed field
(very small $\langle \mathbf{A} \cdot \mathbf{B} \rangle(t=0)$)
- ❖ no velocity field

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CODE



[*pencil-
code.nordita.
org*]



Generation of chiral asymmetry

Full set of chiral MHD equations:

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} - \eta (\nabla \times \mathbf{B} - \mu \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

$$\frac{D\mu_5}{Dt} = D_5 \Delta \mu_5 + \underbrace{\lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]}_{\text{generation term}}$$

Initial conditions:

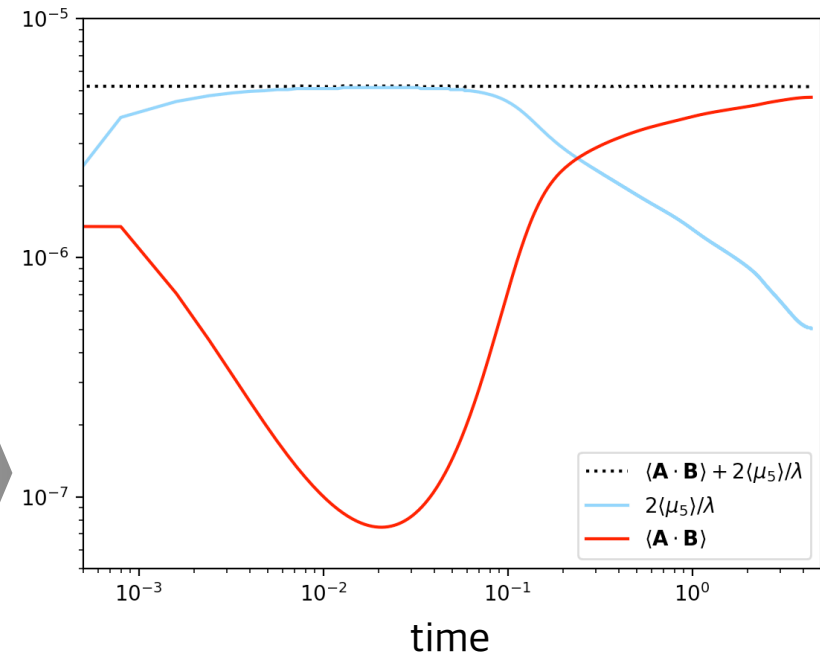
- ❖ strong magnetic seed field (very large $\langle \mathbf{A} \cdot \mathbf{B} \rangle(t=0)$)
- ❖ no initial chiral asymmetry ($\mu_5(t=0) = 0$)

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code.nordita.
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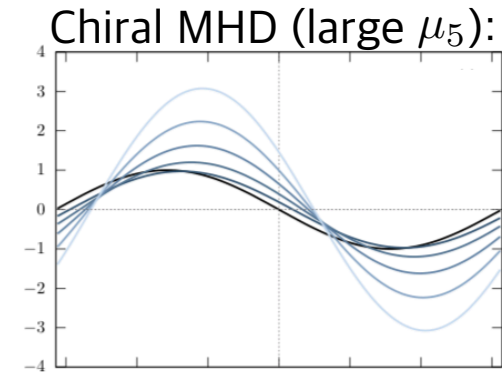
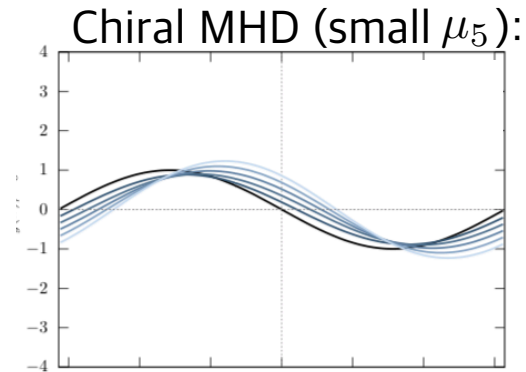
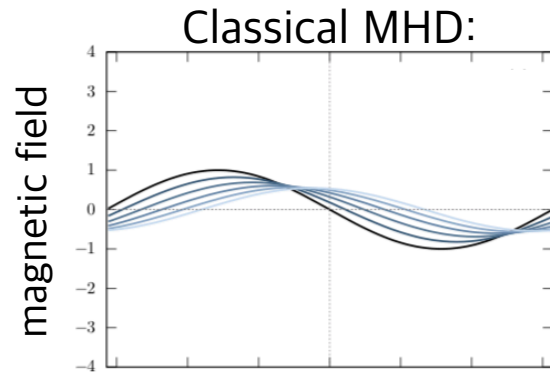
Preliminary results:



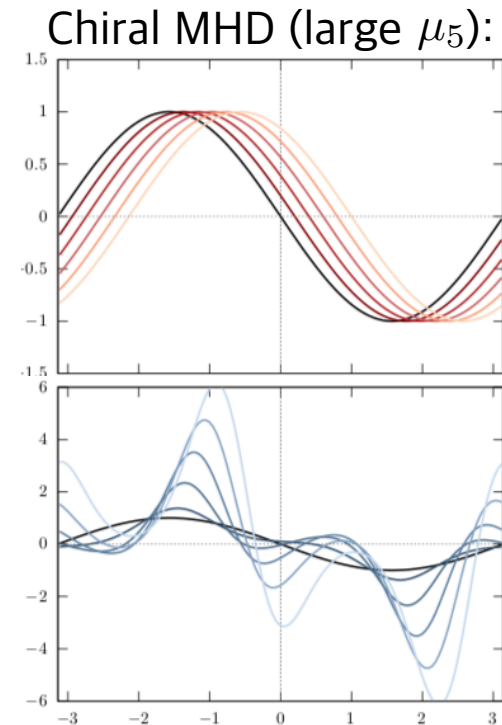
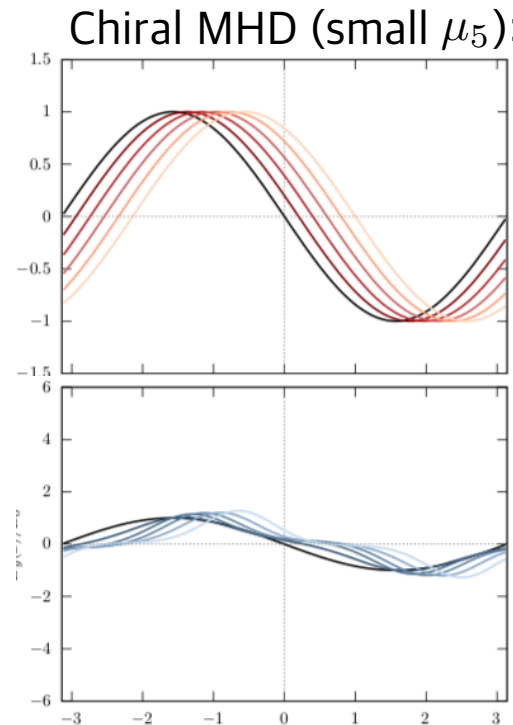
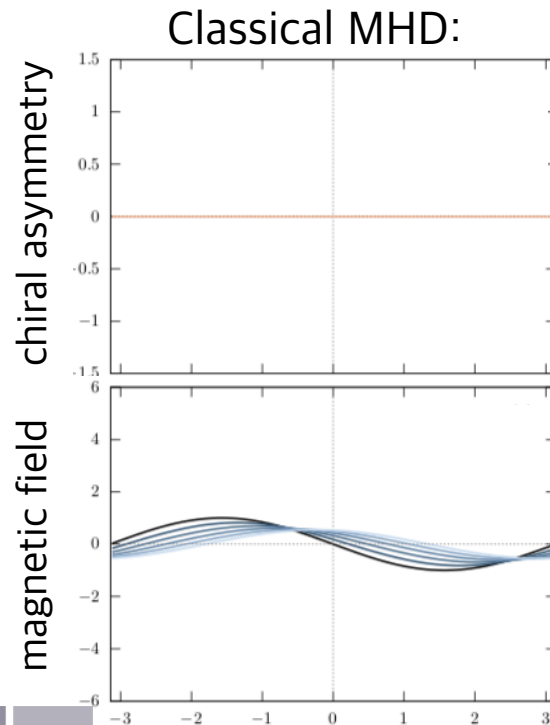
- Phase during which a significant amount of magnetic helicity is lost.
- What are the relevant timescales?
[Fujita, Durrer, & Schober, in prep.]

Chiral magnetic waves

Chirality affects MHD waves, e.g. Alfvén waves:



Inhomogeneities trigger chiral magnetic waves [Kharzeev & Yee 2011]:



Essence of the talk

**Magnetic fields
are everywhere**
(at present day).

**Cosmological
origin:**

Seed fields
shortly generated
after the Big Bang
+
Evolution via
chiral MHD

**Future radio
observations** of
cosmic magnetic
fields are a window
into the early
Universe and
thereby probe
**fundamental
physics.**

Key publications from this talk:

Rogachevskii et al. 2017 (ApJ, 846, 153)

Schober et al. 2018 (ApJ, 858, 124)

Schober, Brandenburg, & Rogachevskii 2019 (GAFD, in press)

→ mean-field theory of chiral MHD

→ numerical simulations of chiral dynamos

→ chiral magnetic waves