Jennifer Schober
Zentrum für Astronomie Heidelberg

"Magnetic Fields in Young Galaxies"

Collaborators:

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Robi Banerjee (Hamburg, Germany)

MFU IV, Playa del Carmen 2013

“ B-Fields in Young Galaxies”

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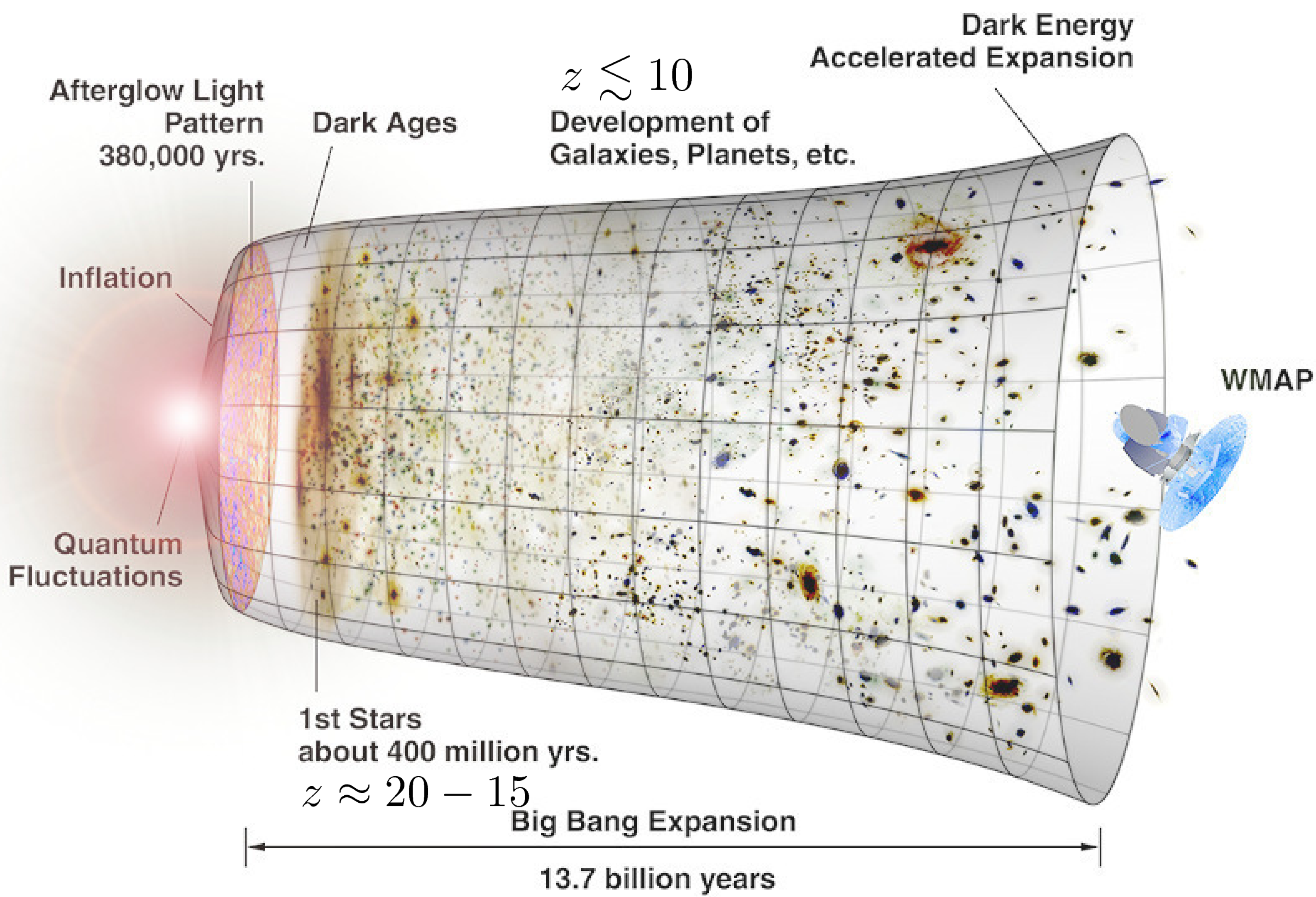
“ B-Fields in Young Galaxies”

The First Stars and Galaxies

1. **Introduction**
2. Small-Scale Dynamo - Theory
3. Magnetic Fields in Primordial Halos
4. Conclusion



[http://www.wpclipart.com/space/stars_universe/universe_timeline_light.jpg.html]

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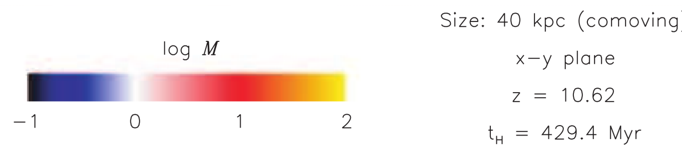
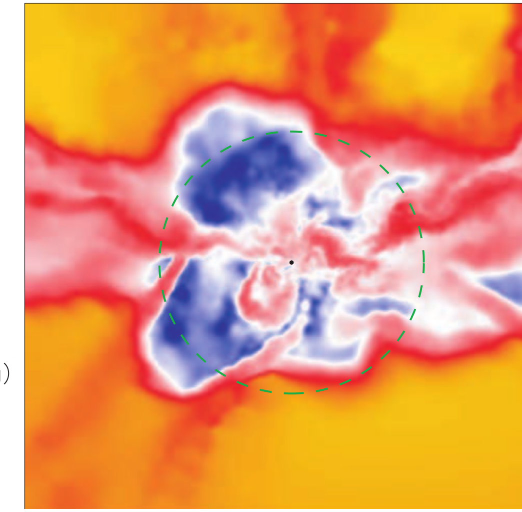
The First Stars and Galaxies

- **turbulence**
  driven by accretion
  and SN explosions

Fig.: Mach number in Primordial Halo
[Greif et al. 2008]





- **weak magnetic seed fields**

  - phase transitions in the early Universe:

    $$B \approx 10^{-20}\ \mathrm{G}$$

    [QCD phase transition, 10 Mpc comoving scale,e.g. Sigl et al. 1997]

  - battery processes:

    $$B \approx 10^{-18}\ \mathrm{G}$$

    [Biermann battery, kpc scale, e.g. Xu et al. 2008]

=> dynamo action is possible

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Small-Scale Dynamo

- definition: **“small-scale dynamo”**

  Mechanism that converts turbulent kinetic energy into magnetic energy.

- **depends strongly on environment:**

  - magnetic Prandtl number

$$\mathrm{Pm} = \frac{\nu}{\eta} = \frac{\mathrm{Rm}}{\mathrm{Re}}$$

  - type of turbulence

$$\delta v(\ell) \propto \ell^{\vartheta}$$ (in inertial range)

$$1/3 \leqslant \vartheta \leqslant 1/2$$

Kolmogorov (incompressible) → $1/3$; Burgers (highly compressible) → $1/2$

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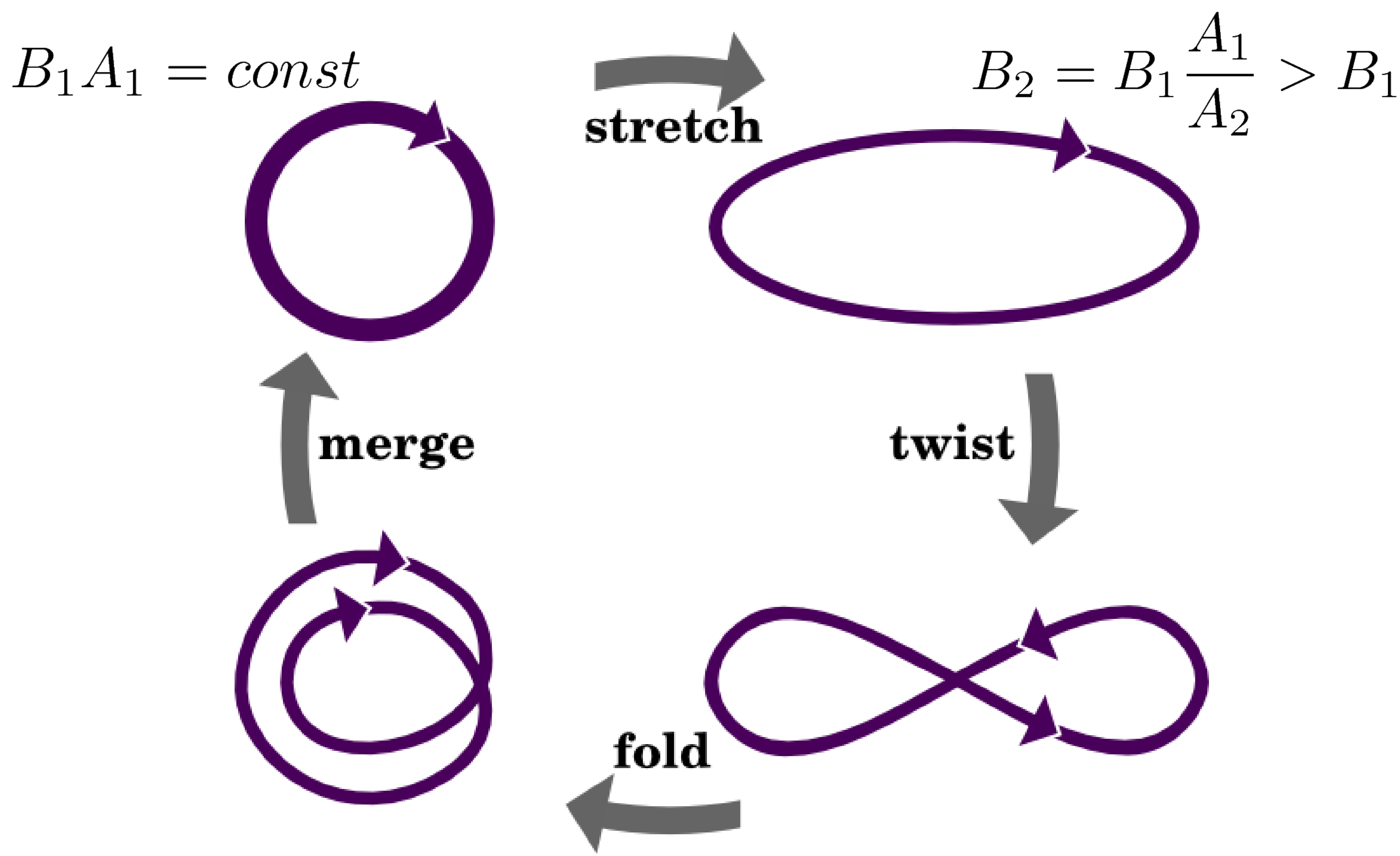
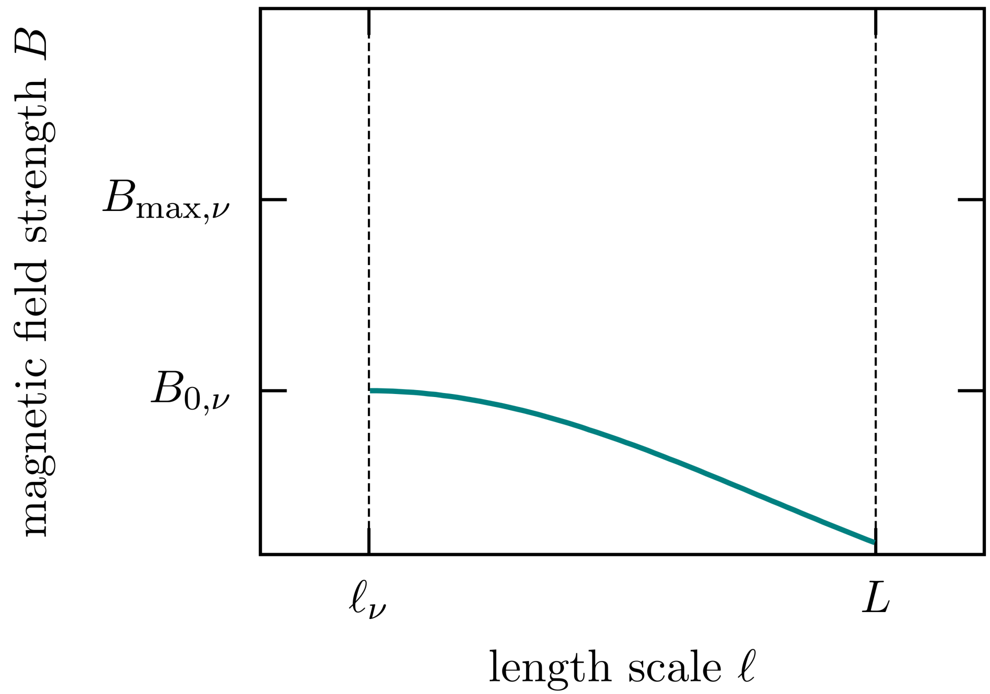
Stretch-Twist-Fold Dynamo



→ fastest on length scale with shortest eddy time scale = viscous scale (smallest scale of inertial range)

Kinematic Phase

- **evolution of the spectrum** (schematically):



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Kinematic Phase

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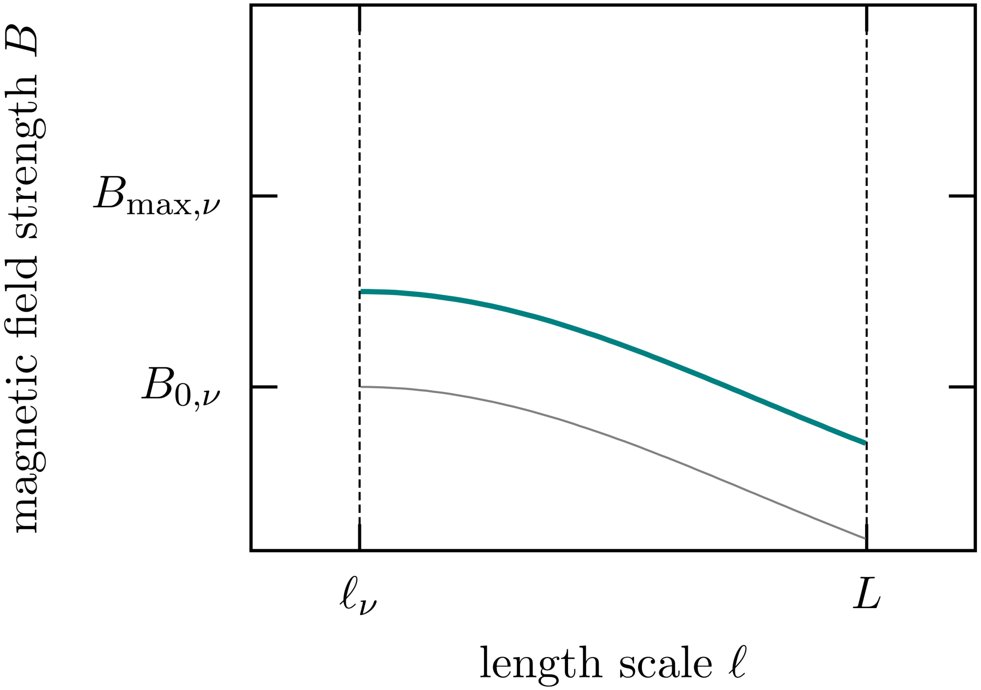

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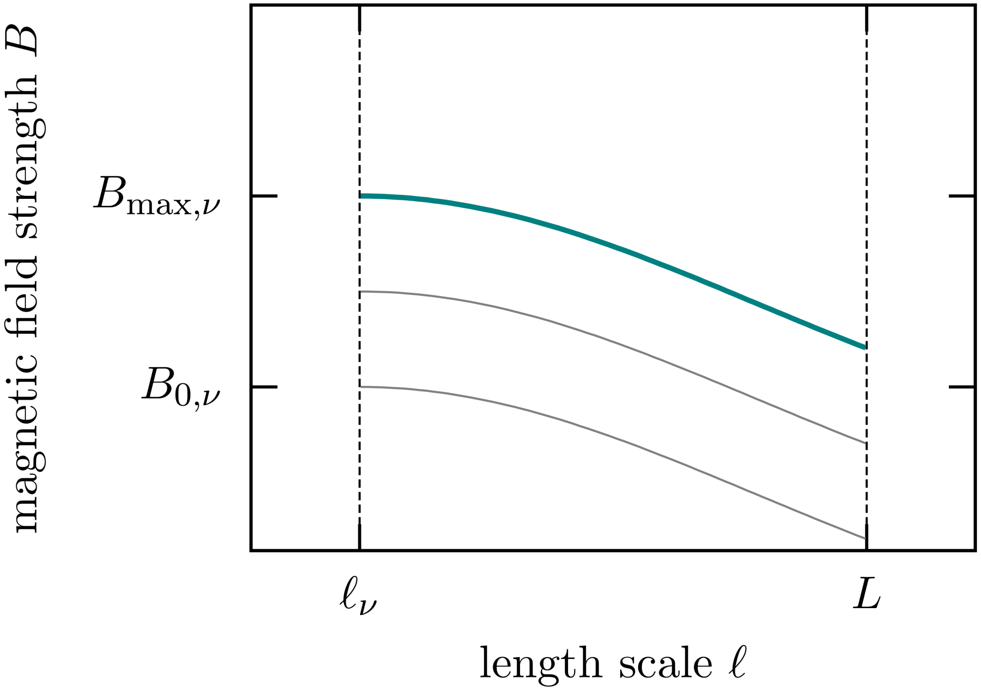

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Kinematic Phase

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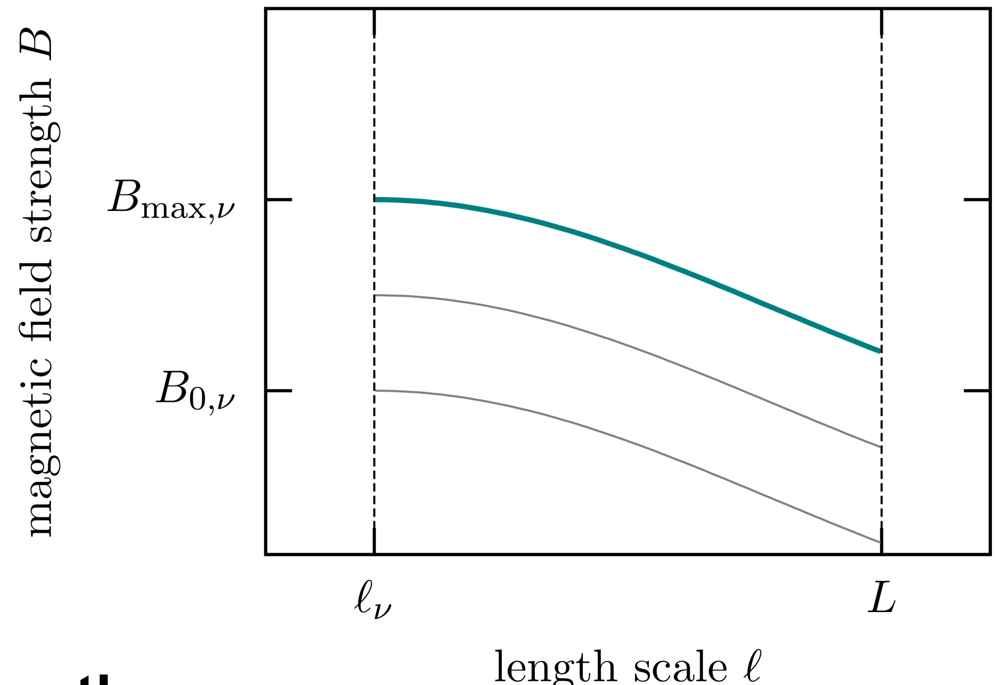

- **magnetic field growth:**

$$B(t) = B_0 \exp(\Gamma t)$$

(from Kazantsev theory)

- **growth rate** on ℓ_ν :

$$\Gamma \propto \begin{cases} \mathrm{Re}^{(1-\vartheta)/(1+\vartheta)} & , \mathrm{Pm} \gg 1 \\ \mathrm{Rm}^{(1-\vartheta)/(1+\vartheta)} & , \mathrm{Pm} \ll 1 \end{cases}$$

[Schober et al. 2012a] ($\mathrm{Pm} \gg 1$)
[Schober et al. 2012c] ($\mathrm{Pm} \ll 1$)

[see also: Bovino et al. 2013]

Non-Linear Phase

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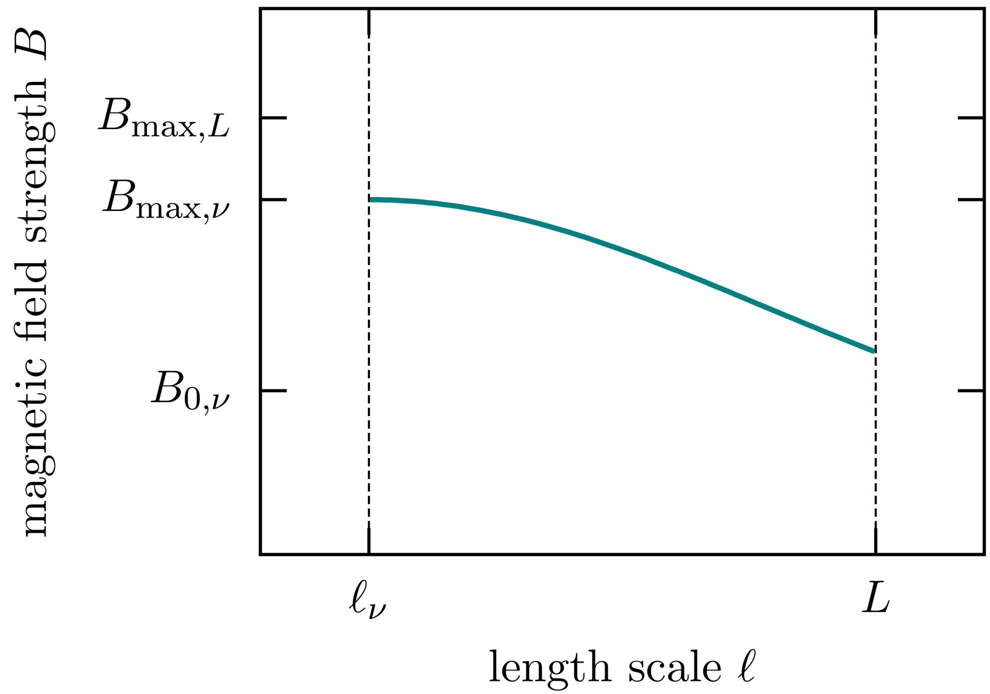

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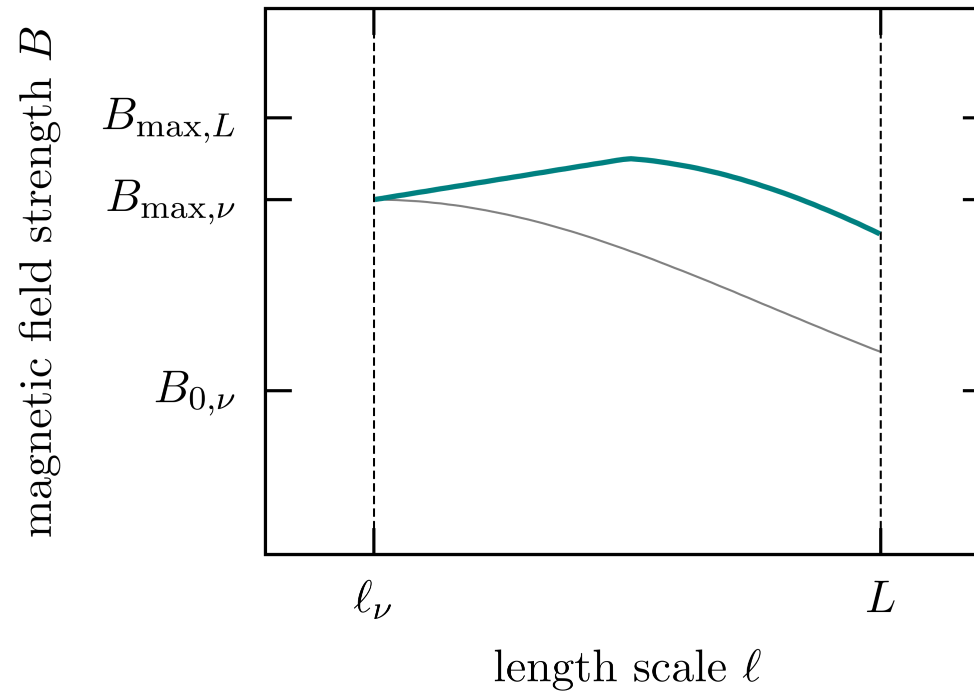

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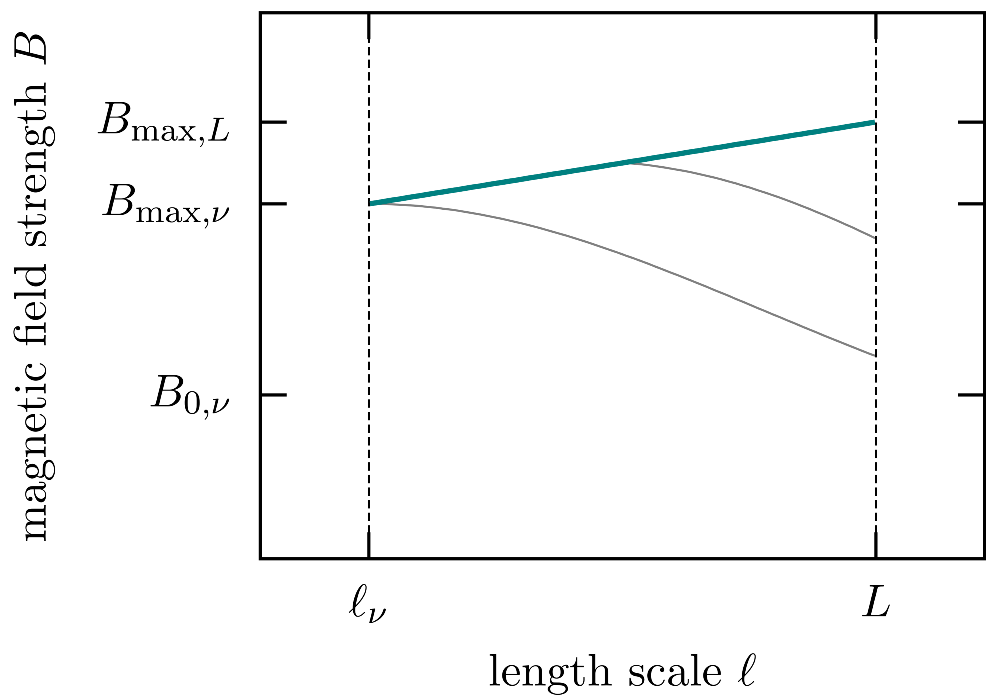

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Non-Linear Phase

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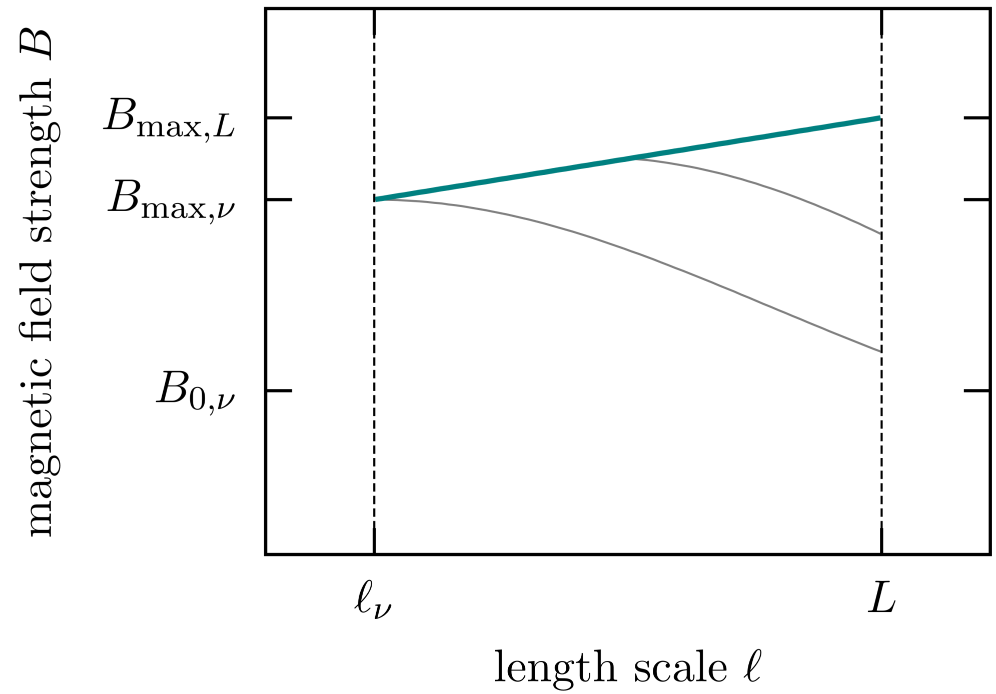

- Fokker-Planck model (see e.g. Schekochihin 2002) with assumption that peak scale shifts on eddy time scale
- no more dependence on $\mathrm{Pm}, \mathrm{Re}, \mathrm{Rm}$
- **magnetic field growth:**

$$B(t) \propto t^{\vartheta/(1-\vartheta)}$$

[Schleicher et al. 2013]

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3. Magnetic Fields in Young Galaxies

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Simple Model for Primordial Halo

- **spherical core**
- **radius:** $L = 10^{20}\ \text{cm} \approx 32\ \text{pc}$
- **density:** $\rho = 1.6 \times 10^{-22}\ \text{g cm}^{-3}$

$\Big\}\ M \approx 3.5 \times 10^{5}\ M_{\odot}$

- **temperature:** $T = 10^{4}\ \text{K}$

  $\rightarrow$ gas is ionised

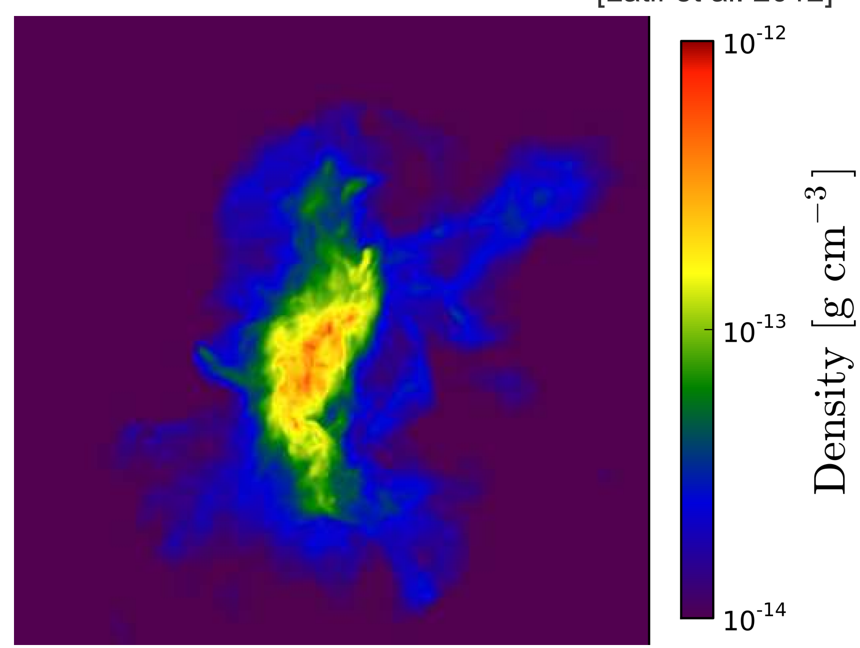
- **sources of turbulence:**

  - accretion

  - SNe (not in this talk)

  worst case assumption:
  compressive turbulence
  ($\vartheta = 1/2$)

Fig.: Density in the center of a protogalaxy. [Latif et al. 2012]



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Simple Model for Primordial Halo

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- **viscosity:** $\nu \approx 1.3 \times 10^{17}\ \mathrm{cm^2\ s^{-1}}$
- **resistivity:** $\eta \approx 4.1 \times 10^{2}\ \mathrm{cm^2\ s^{-1}}$

$$\mathrm{Pm} = \frac{\nu}{\eta} \approx 3.2 \times 10^{14}$$

- **sound speed:** $c_\mathrm{s} \approx 1.2 \times 10^{6}\ \mathrm{cm\ s^{-1}}$
- **turbulent velocity:**

$$V \approx 2\ c_\mathrm{s}\ 0.01^{1/2} \approx 2.4 \times 10^{5}\ \mathrm{cm\ s^{-1}}$$

Mach number; percentage that goes into turbulence

(motivated by simulation of protogalaxies by Latif et al. 2012)

- **Reynolds numbers:**

$$\mathrm{Re} = \frac{VL}{\nu} \approx 1.8 \times 10^{8} \quad \text{(hydrodynamic)}$$

$$\mathrm{Rm} = \frac{VL}{\eta} \approx 3.2 \times 10^{22} \quad \text{(magnetic)}$$

Kinematic Phase

- **kinematic growth of magnetic energy** (on viscous scale):

$$B_\nu(t) = B_{\nu,0}\, \exp\left(\Gamma t\right)$$

$$\Gamma = \frac{11}{60}\frac{V}{L}\mathrm{Re}^{1/3} = 2.5\times10^{-13}\ \mathrm{s}^{-1}$$

- **maximum field strength:**

$$B_{\nu,\max} \approx \underbrace{(4\pi\rho)^{1/2}\ V\ \left(\frac{\ell_\nu}{L}\right)^{\vartheta}}\ 0.12 \approx 2.3\times10^{-9}\ \mathrm{G}$$

from equipartition with kinetic energy

scaling velocity down to viscous scale

efficiency factor for Mach 2 and compressive forcing (Federrath et al. 2011)

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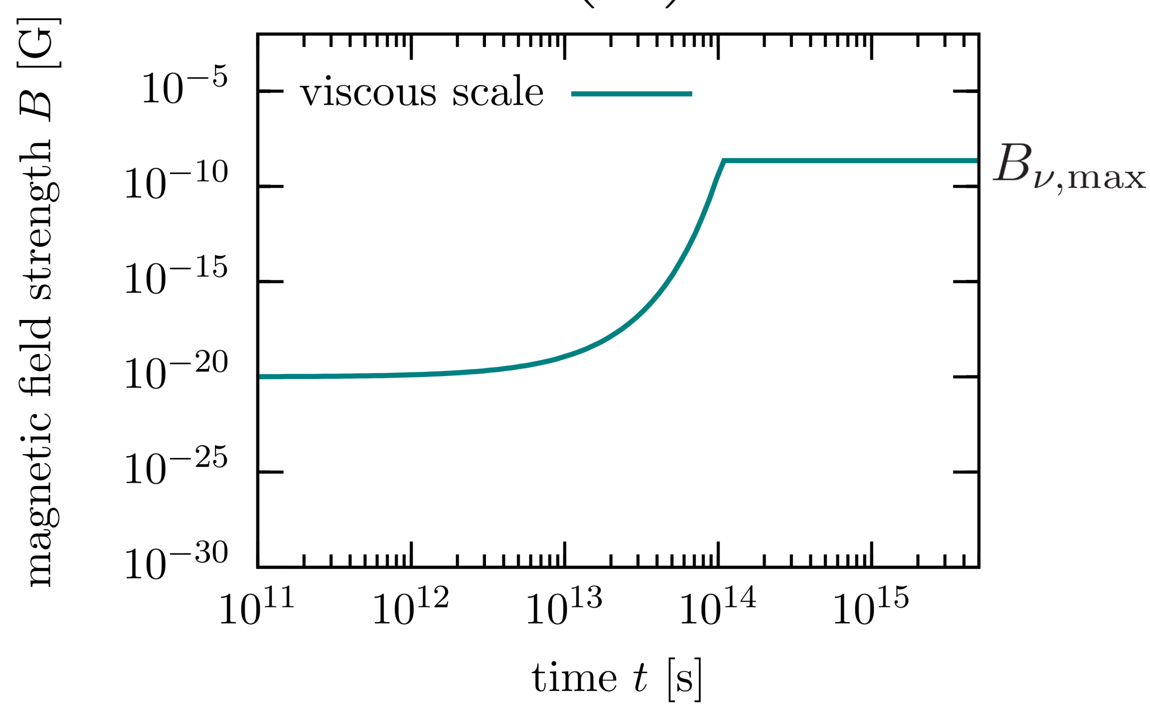

Non-Linear Phase

- **non-linear growth of magnetic energy :**

  $$B(t) \propto t$$

- **maximum field strength on forcing scale:**

  $$B_{L,\max} \approx \underbrace{(4\pi\rho)^{1/2} \; V}_{} \; 0.12 \approx 1.3 \times 10^{-6} \text{ G}$$

from equipartition with kinetic energy

efficiency factor for Mach 2 and compressive forcing (Federrath et al. 2011)

Non-Linear Phase

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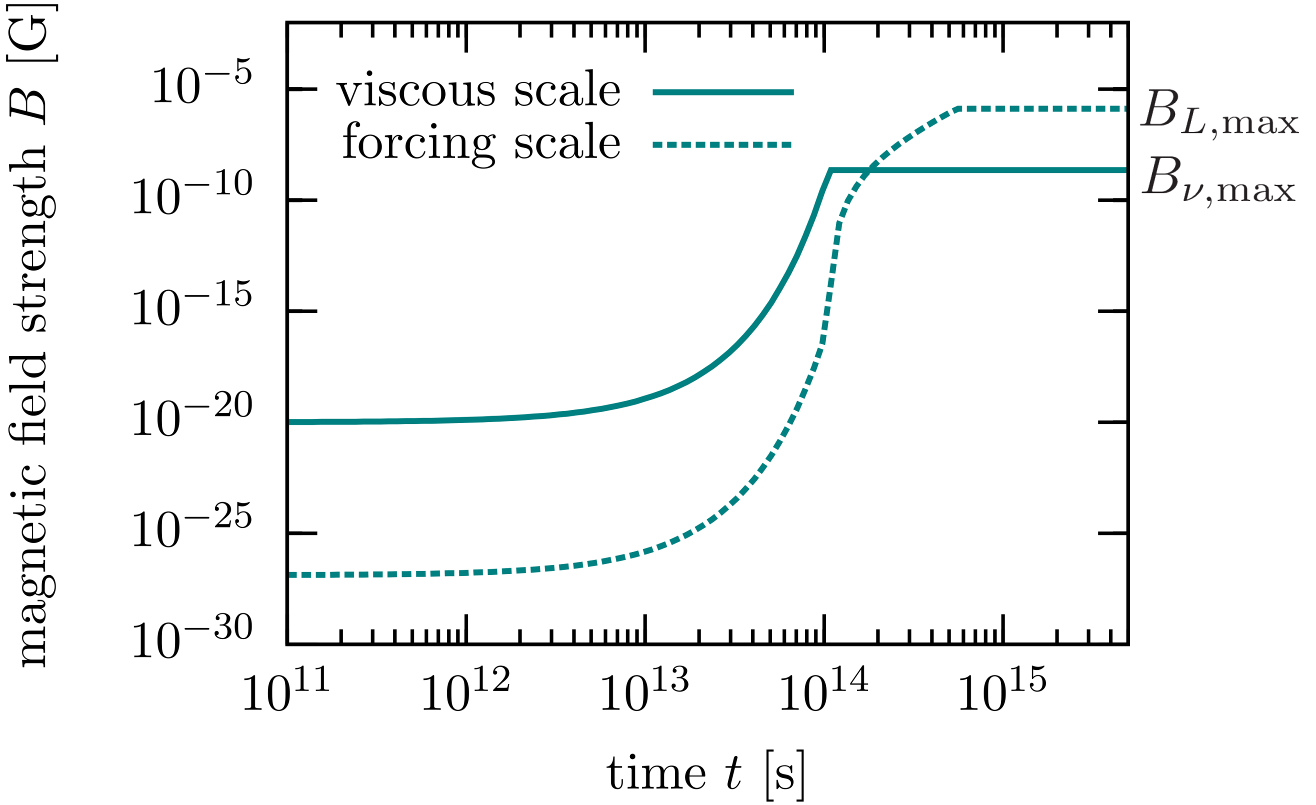

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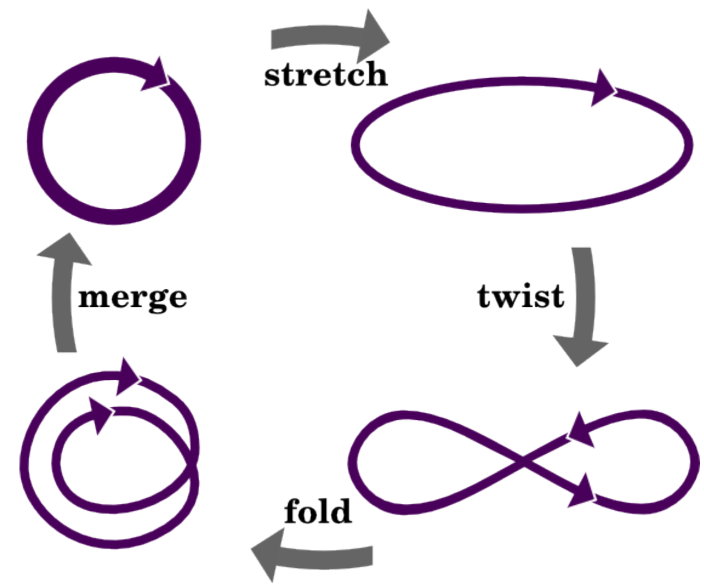
Conclusion

- dynamo amplification in **kinematic phase**:

$$B(t) = B_0 \exp(\Gamma t)$$

- dynamo amplification in **non-linear phase**:

$$B(t) \propto t^{\vartheta/(1-\vartheta)}$$



- small-scale dynamo in **formation of first stars & galaxies**:

Dynamical important magnetic fields can be generated on small time scales compared to free-fall time.

=> **magnetisation of the primordial ISM**

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Thanks for your attention!

Further questions/comments?
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