# Cosmological evolution of magnetic fields during halo formation

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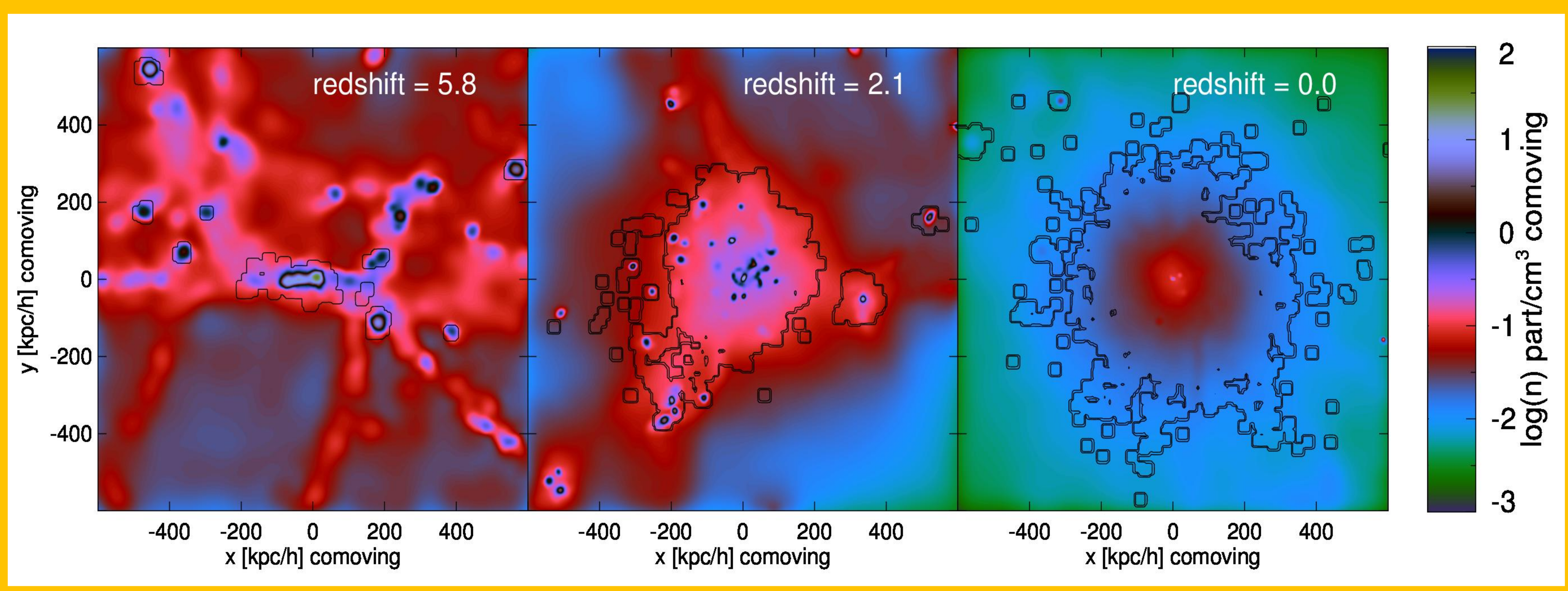
## Summary

We present cosmological simulations of galactic halo formation including the evolution of magnetic fields performed with the N-body / SPMHD code Gadget3. The simulations start at redshift 40 and support radiative cooling, star formation and supernova feedback. The magnetic seed field is assumed to be uniform and between $10^{-10}$ and $10^{-34}$ G in strength. The initial magnetic field agglomerates with the gas in filaments and gets amplified within a couple hundred million years up to equipartition with the turbulent energy corresponding to $10^{-6}$ G. Subsequently, a series of halo mergers leads to shocks and dynamo action magnetizing the surrounding gas within a few billion years up to $10^{-8}$ G. The magnetic energy grows on small scales first and is then spread to larger scales. The numerical results are compared to a simple analytical model of exponential amplification of a magnetic perturbation through turbulence. The model and our simulations agree well.

## Simulation:




Starting at redshift 40, we assumed a uniform **Biermann battery** (*ref: 1*) magnetic seed field of the strength $10^{-18}$ G (Sim A). To study the evolution of stars, a subgrid multi-phase model of **star formation** was used (*ref: 6*). The matter clumps into filaments and protohaloes, which undergo a series of mergers, to form bigger structures. At the end of the simulations, run with **Gadget3** (*ref: 5*), a MW-like halo with dark matter, gas and stars had formed.
Hubble constant $H_0$ and densities $\Omega$ connect physical time $t$ and scalefactor $a$:

$$\frac{da}{dt} = H_0 \sqrt{\frac{\Omega_M}{a} + a^2 \Omega_\Lambda} \qquad \text{(I)}$$

## Theory:

The evolution of a magnetic field $B$ is described by the **induction equation**:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left( \vec{v} \times \vec{B} \right) + \eta \Delta \vec{B}$$

To investigate how a velocity field $v$ can amplify a magnetic field $B$, one can do an ansatz, that splits the total magnetic field $B$ into a perturbated component $B_1$ and a non-perturbated component $B_0$. The **perturbated** component $B_1$ can be further split into a time-dependent part $B_{1,t}$ and a spatial component $B_{1,x}$:

$$\vec{B} = \vec{B}_0 + B_{1,t} \vec{B}_{1,x} \qquad B_{1,t}(t) = B_{1,t}(0) \cdot e^{\gamma t} e^{-i\omega t}$$

This leads to an evolution equation of the magnetic energy with time (*ref: 3, 4*):

$$\frac{\partial B_{1,t}^2}{\partial t} = 2\gamma \left( B_{1,t}^2 - \frac{B_{1,t}^4}{B_{\max}^2} \right) \qquad \text{(II)}$$

Within a **turbulent system**, the growth factor $\gamma$ can be estimated by some typical velocities and lengths of the system. Also, assuming **equipartition**, the maximum magnetic field value $B_{\max}$ is related to the turbulent energy density :

$$\gamma \approx \frac{v_{turb}}{l_{turb}} \qquad \frac{B_{\max}^2}{8\pi} = \frac{1}{2} \rho v_{turb}^2$$

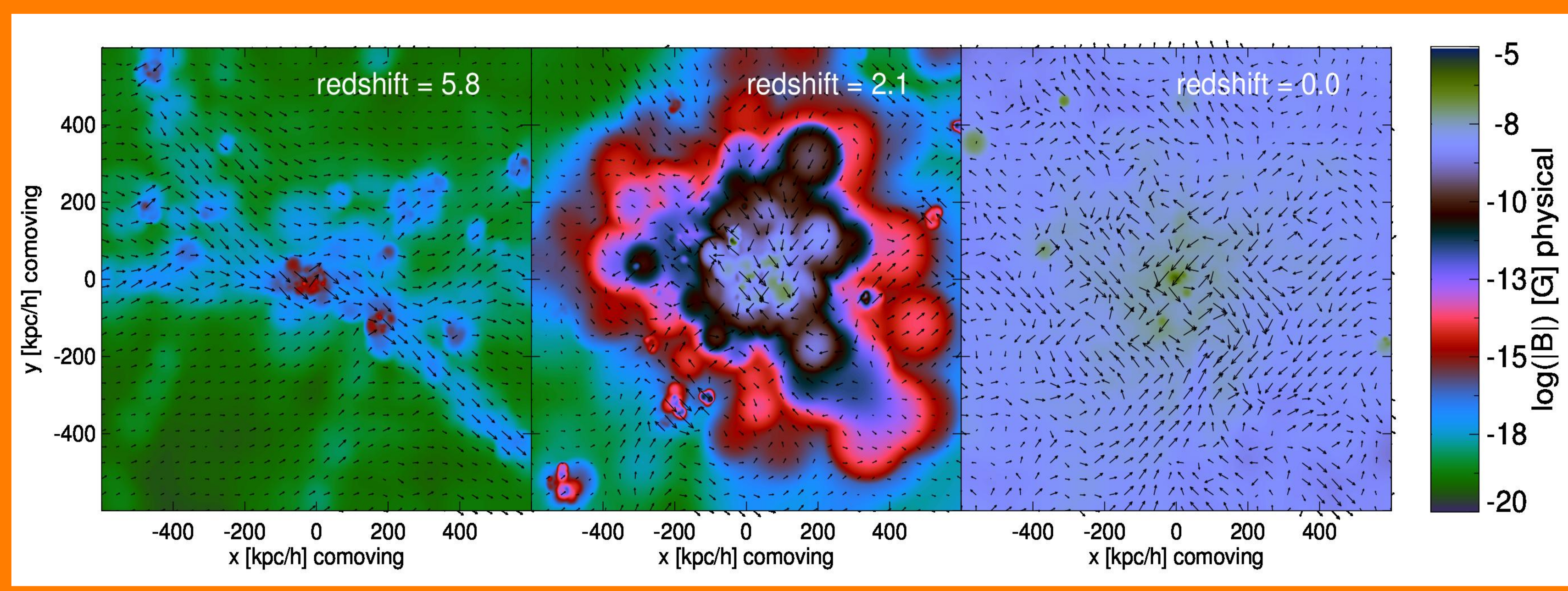
Furthermore, due to conservation of the magnetic flux in an expanding universe, a proportionality between magnetic field $B_{1,t}$ and **scalefactor** $a$ has also to be taken into account:

$$B_{1,t} \sim a^{-2} \qquad \text{(III)}$$

## References:

1) Biermann, 1950, Zeit. für Naturforsch., 5A, 65
2) Dolag & Stasyszyn, 2009, MNRAS, 398, 1678
3) Kulsrud et al., 1997, ApJ, 480, 481
4) Landau & Lifshitz, 1959, Fluid mechanics
5) Springel, 2005, MNRAS, 364, 1105
6) Springel & Hernquist, 2003, MNRAS, 339, 289
7) Widrow, 2002, Rev. Mod. Phys., 74, 775

## Results:




Figs 1 (left) and 2 (right) show the evolution of comov. gas density and phys. magnetic field strength for Sim A.

Using **SPMHD** to solve the induction equation (*ref. 2*), we find that the magnetic energy always gets amplified to an equipartition value with the turbulent energy, which is independent from the initial magnetic field. Note, the magnetic field strength increases first in filaments and protohaloes. This is due to the compression of the gas, but also because turbulent processes as gravitational collaps, star formation and supernovae are mainly taking place there. These mechanisms drive a **turbulent small-scale dynamo** (*ref 3*).

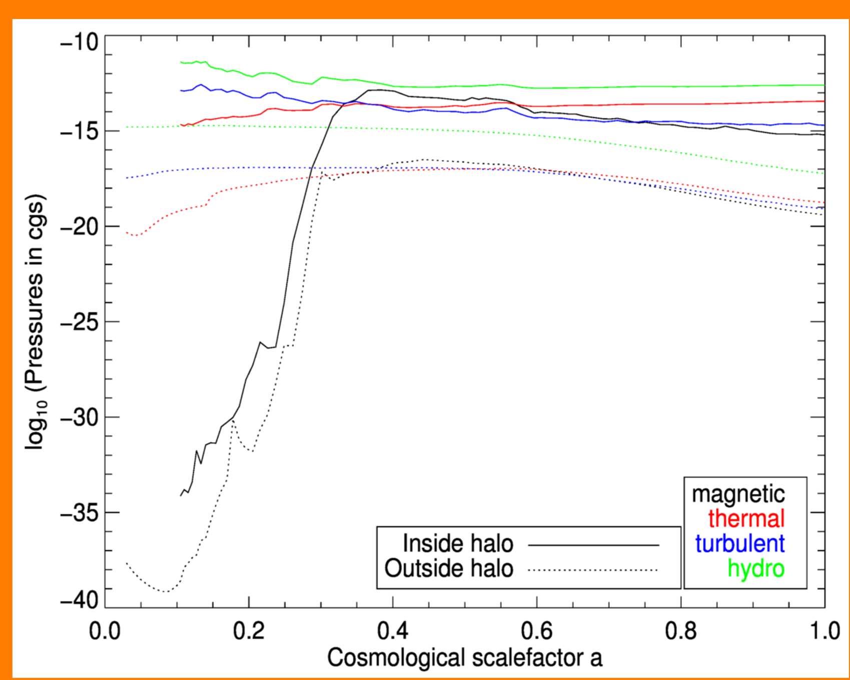



Fig. 3: Different energy densities in Sim A

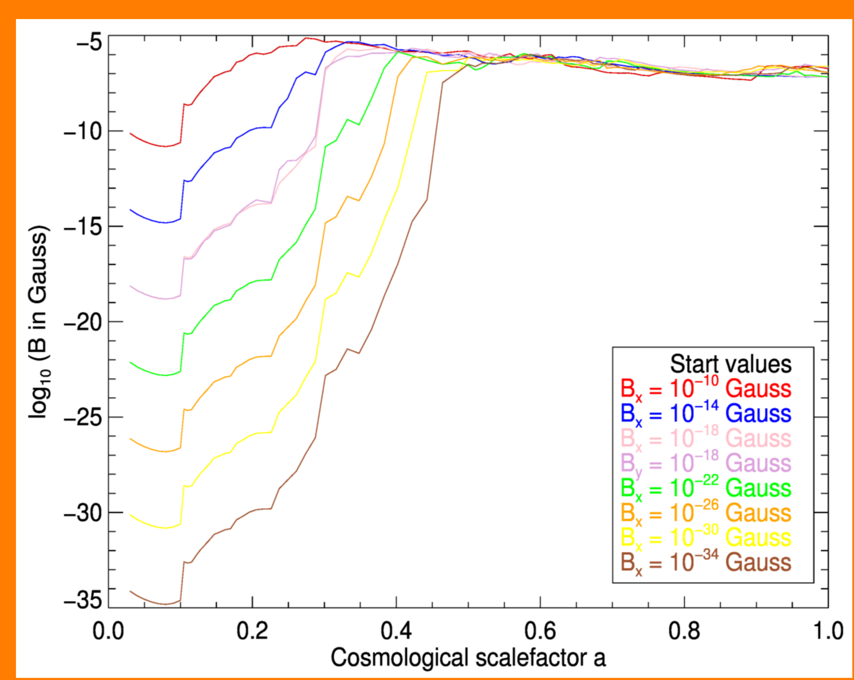



Fig. 4: Different initial magnetic fields

## Discussion:

To find an analytical description of the evolution of the magnetic field strength in an expanding universe, the relationship between time $t$ and scalefactor $a$ (I), the cosmological dependency of $B$ on $a^{-2}$ (III) and the solution to the differential equation II) have to be combined. This gives **growth curves** for the magnetic energy with a turbulent dynamo.

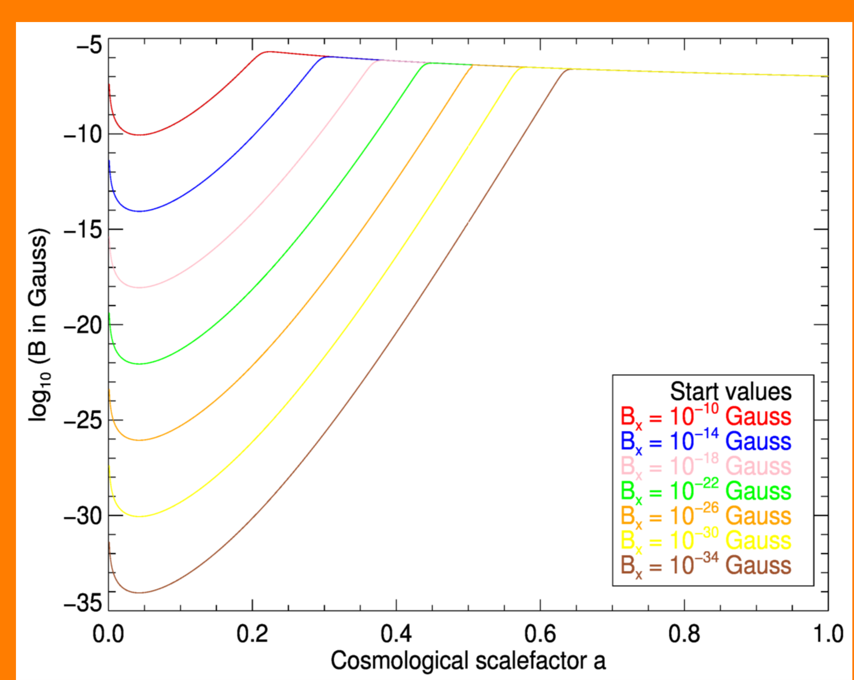



Fig 5: Analytically calculated growth curves

These results were derived assuming a turbulent length scale of 25 kpc, a turbulent velocity of 100 km/s and a number density of $10^{-1}$ particle/cm$^3$. An exact calculation which takes into account turbulent magnetic dissipation, leads to a **timescale** of 12 million years for this amplification mechanism. The time needed to get from a Biermann level of $10^{-18}$ G to present day values of $10^{-6}$ G is slightly higher than two billion years. Especially, we are able to **reproduce observed values** (*ref: 7*) for galaxies (μG) and the intergalactic medium (nG) with our simulations of halo formation. Furthermore, since the produced magnetic field is totally unordered, additional dynamo processes are needed.

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