Recent advances in simulation of magnetic fields in galaxies

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Magnetic field

Importance of magnetic field

- B is omnipresent in the universe and observed on vastly different scales
- In galaxies B is specially important
  - Magnetic pressure in the ISM is comparable to the thermal pressure
  - B determines the propagation of cosmic rays

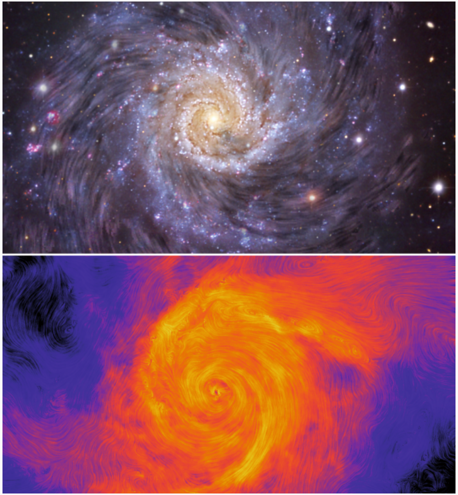


Figure 1: Galactic magnetic fields from observations (NGC 628) and simulations. Credit: top, Mulcahy et al. (2017); bottom, courtesy of Pakmor.

MHD

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{1}$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla) \mathbf{v} + \nabla p + \rho \nabla \psi - \frac{1}{4\pi} (\nabla \times \mathbf{B}) \times \mathbf{B} = 0, \tag{2}$$

$$\begin{aligned} \frac{\partial \mathbf{B}}{\partial t} &= \nabla \times (\mathbf{v} \times \mathbf{B}) && (3) \\ &= (\mathbf{B}.\nabla)\mathbf{v} - \mathbf{B}(\nabla.\mathbf{v}) + \mathbf{v}(\nabla.\mathbf{B}), && (4) \end{aligned}$$

$$\nabla^2 \psi = 4\pi G \rho. \tag{5}$$

Building up magnetic fields

- seeding
- amplifying and sustaining

Seeding

- Seed fields can be "primordial", i.e. generated in the early Universe (Durrer & Neronov 2013)
- May originate from later epochs, e.g. during cosmological structure formation by the Weibel instability (Lazar et al. 2009)
- Plasma fluctuations in protogalaxies (Schlickeiser 2012; Schlickeiser & Felten 2013)
- The Biermann mechanism in the first SN remnants (Hanayama et al. 2005)

Amplifying

- An efficient source of field amplification is the turbulence driven by SN explosions (Ferrière 1996) or by spiral shocks (Kim et al. 2006), called the **small-scale dynamo**.

In protogalaxies this mechanism can amplify weak seed fields to several μG strength (the energy level of turbulence) within less than 10^8 year (Kulsrud et al. 1997; Schleicher et al. 2010; Beck et al. 2012a; Rieder & Teyssier 2015). The resulting field is turbulent.

Sustaining

The most promising mechanism to *sustain* magnetic fields and generate large-scale regular fields from turbulent fields in the ISM of galaxies is the $\alpha - \Omega$ **dynamo** (Beck et al. 1996). It is based on

- differential rotation (Ω)
- α-effect, cyclonic motion of turbulent gas flows by Coriolis force which are driven by stellar winds and SN explosions (Ferrière 1996; Gressel et al. 2013) or cosmic rays (Hanasz et al. 2009)
- magnetic diffusivity (η)

The ”mean-field” dynamo equation

Remember induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B} \tag{6}$$

- Represent **B** and **V** each as a sum of a slowly-varying mean field and a weak small-scale fluctuation component

$$\mathbf{B} = \langle \mathbf{B} \rangle + \mathbf{B}' \tag{7}$$

$$\mathbf{V} = \langle \mathbf{V} \rangle + \mathbf{V}' \tag{8}$$

The "mean-field" dynamo equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{B}) + \nabla \times \alpha \mathbf{B} + (\beta + \eta) \nabla^2 \mathbf{B} \tag{9}$$

- **B** and **V** are the mean magnetic field and velocity (usually rotational)
- β can be interpreted as turbulent resistivity

Schematic view

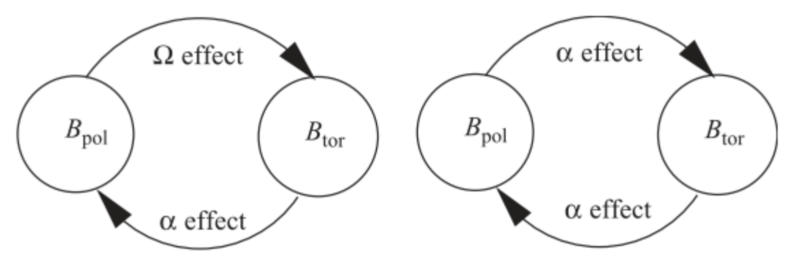


Figure 2: Mutual regeneration of poloidal and toroidal fields in the case of the $\alpha - \Omega$ dynamo (left) and the α^2 dynamo (right) (Brandenburg & Subramanian 2005).

Example works for isolated galaxies

Simulations of magnetic fields in isolated disc galaxies (Pakmor & Springel, 2013)

- AREPO code
- SN feedback with a modified equation of state
- Powel et al. (1999) scheme for divergence cleaning. In this approach, additional source terms are introduced into the momentum, induction and energy equations, without modifying MHD solver, to keep errors as small as possible.

Another method e.g.:

- constrained transport approach (Evans & Hawley 1988). This methods is existed just for Cartesian grids and tries to avoid divergence error by construction.

- Dedner et al. (2002) in which a local divergence error is both advected away from the place where it originates and damped at the same time.

Simulations of magnetic fields in isolated disc galaxies (PV13)

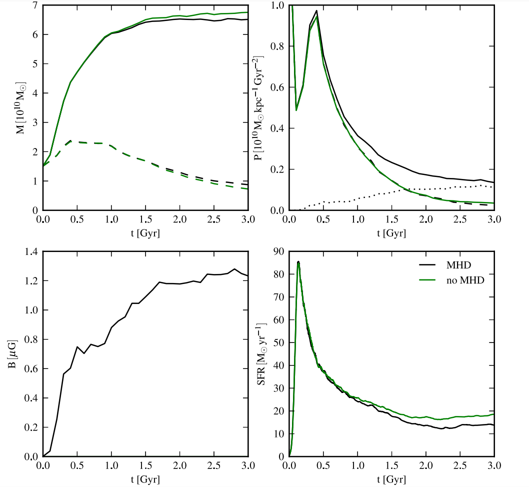


Figure 3: Time evolution of different quantities of a $10^{12}\ \mathrm{M}_\odot$ galaxy .

- TL: total baryonic mass in stars and gas (straight line) and the gas mass within a radius of $15\,\mathrm{kpc}$ (dashed line).
- TR: thermal pressure (dashed line), the magnetic pressure (dotted line) and the total pressure (straight line).
- BL: magnetic field within a radius of $15\,\mathrm{kpc}$.
- BR: total star formation rate in the whole simulation

Simulations of magnetic fields in isolated disc galaxies (PV13)

- B strength is **quickly amplified** in the initial central starburst and the differential rotation of the forming disc, eventually reaching a **saturation** value.
- At this point, the B pressure in the interstellar medium becomes comparable to the thermal pressure, and a further efficient growth of the B strength is prevented.
- B also leads to a **lower star formation rate** at late times compared to simulations without Bs, and induces changes in the spiral arm structures of the gas disc.
- They observed highly magnetized fountain-like outflows from the disc.
- They argue that their results are robust with numerical resolution and are largely independent of the initial magnetic seed field strength assumed, as the amplification process is rapid and self-regulated.

Ab Initio Simulations of a Supernova-driven Galactic Dynamo in an Isolated Disk Galaxy (Butsky et al., 2017)

- ENZO code
- Dedner et al. (2002) $\nabla \cdot B$ cleaning
- initially unmagnetized galactic disk
- novel prescription for MHD SN feedback
- supernova events occur in proportion to star formation activity and provide localized injections of thermal energy, metal-rich material, and a low level of toroidal B
- neglect the influence of CRs and focus on the role of turbulence driven by supernovae through their thermal feedback.

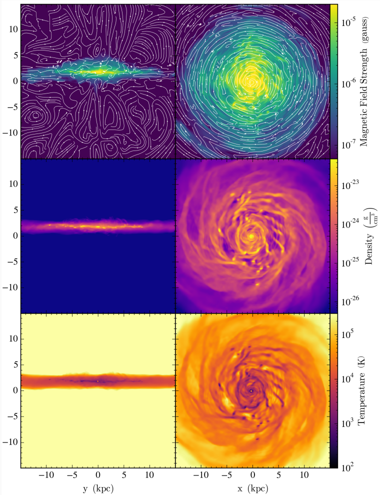


Figure 4: A model at t = 2.1 Gyr in 30 kpc boxes.

Ab Initio Simulations of a Supernova-driven Galactic Dynamo in an Isolated Disk Galaxy (Butsky et al., 2017)

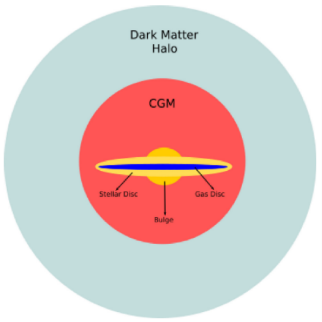
- The main result is that a galactic dynamo can be seeded and driven by SN explosions, resulting in magnetic fields whose strength and morphology are consistent with observations.
- seed fields that are supplied locally, in small volumes around supernovae, can be mixed efficiently $\rightarrow$ no dramatic difference from uniform seed
- B attains microgauss levels over gigayear timescales throughout the disk.
- B develops a large-scale structure, which appears to be correlated with the disk's spiral arm density structure
- seeding of the galactic dynamo by supernova ejecta predicts a persistent correlation between gas metallicity and magnetic field strength

Magnetic buoyancy in simulated galactic discs with a realistic circumgalactic medium (Steinwandel et al. 2019)

- GADGET-3 code
- a modern version of SPH + B (SPMHD) plus resistivity and artificial viscosity and conduction terms to overcome known problems of the SPH method in terms of shock-capturing and fluid mixing instabilities (Beck et al. 2016).
- Powell divergence cleaning
- Star formation, cooling, SN feedback, and metals (Springel & Hernquist 2003)
- Turbulence is driven on the scales of a few 100 pc due to SN-feedback and leads to small scale turbulent motion (similar to the α effect).

Magnetic buoyancy in simulated galactic discs with a realistic circumgalactic medium (Steinwandel et al. 2019)

- Addition of a spherical circumgalactic medium (CGM), motivated by observations and the results of cosmological simulations



Magnetic buoyancy in simulated galactic discs with a realistic circumgalactic medium (Steinwandel et al. 2019)

Two B implementation

- a primordial B of $10^{-9}\mu G$ in disk + $10^{-12}\mu G$ in CGM
- B is coupled to the SN explosions and seeds a magnetic dipole around an exploding star.

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \Delta \mathbf{B} + \left(\frac{\partial \mathbf{B}}{\partial t}\right)_{\rm seed} \tag{10}$$

Magnetic buoyancy in simulated galactic discs with a realistic circumgalactic medium (Steinwandel et al. 2019)

Strong evidence for three processes

- adiabatic compression
- $\alpha - \Omega$ dynamo
- small-scale turbulent dynamo

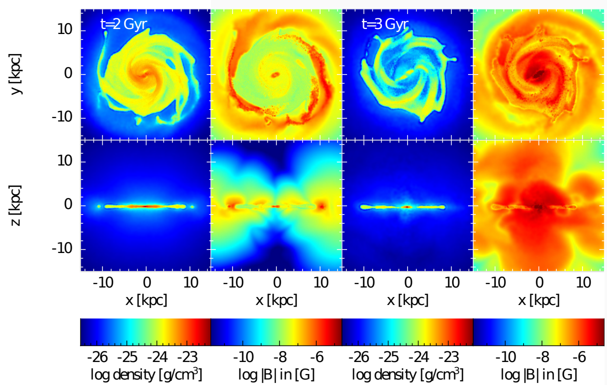


Figure 5: Slice through the gas density and the magnetic field strength for the simulation MW-snB for the face-on and edge-on view. The four panels on the left-hand-side are at t = 2 Gyr, while the four panels on the right-hand-side are at t = 3 Gyr.

Magnetic buoyancy in simulated galactic discs with a realistic circumgalactic medium (Steinwandel et al. 2019)

B amplification in the center of the disk leads to a biconical magnetic outflow of gas that magnetizes the CGM → 40% reduction in SFR

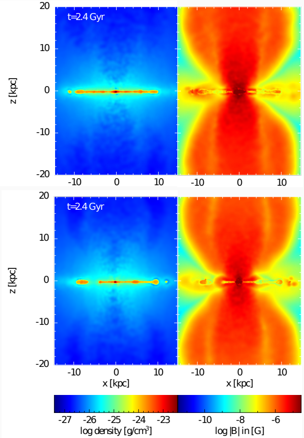


Figure 6: Cross-section slices for the MW–snB run (top panels) and the MW–primB run (bottom panels) at t = 2.4 Gyr.

Magnetic buoyancy in simulated galactic discs with a realistic circumgalactic medium (Steinwandel et al. 2019)

- In center, the gas density is driven by both adiabatic compression and small-scale turbulence.
- In spiral arms, B is lower compared to the interarm region and is amplified by adiabatic compression.
- In interarm regions, B is amplified by small-scale turbulence and not adiabatic compression.
- In outskirts of the galaxy, the amplification is not driven by adiabatic compression.

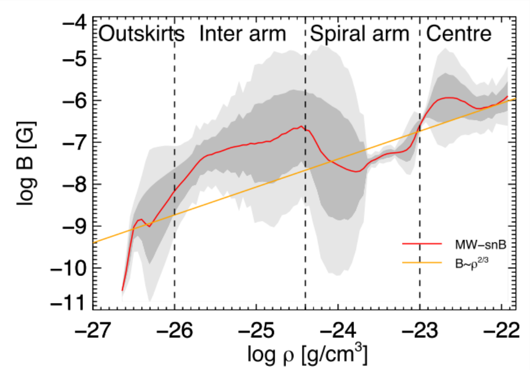


Figure 7: Median magneticfield strength for the model MW–snB

On the origin of magnetic driven winds and the structure of the galactic dynamo in isolated galaxies (Steinwandel et al., 2020)

$B \propto \Sigma_{SFR}^{1/3}$ (Schleicher & Beck; 2013)

- They showed that the star formation is following the Kennicutt relation in different time.

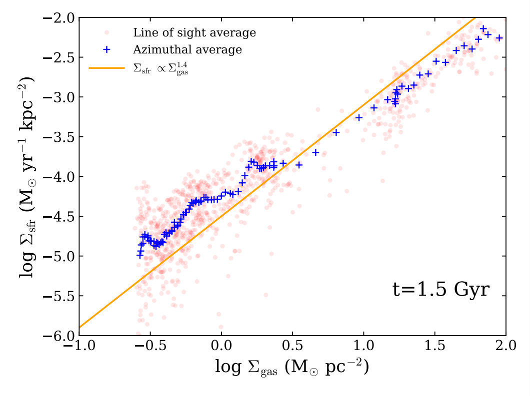


Figure 8: Star formation rate surface density as function of the gas surface density.

On the origin of magnetic driven winds and the structure of the galactic dynamo in isolated galaxies (Steinwandel et al., 2020)

- At early times they found that B is increasing with star formation rate. However, at later points B tends to be constant as a function of the local star formation rate or is even decreasing. At intermediate time they found that the B is oscillating with increasing star formation rate which indicates that there are regions in the galaxy where the local star formation rate is increasing but B is decreasing.

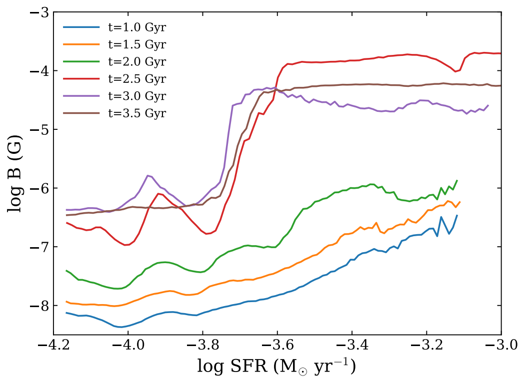


Figure 9: Magnetic field as a function of the local star formation rate for six different points in time, t=1 Gyr (blue), t=1.5 Gyr (orange), t=2 Gyr (green), t=2.5 Gyr (red), t=3 Gyr (purple) and t=3.5 Gyr (brown).

Discovery of massive star formation quenching by non-thermal effects in the centre of NGC 1097 (Tabatabaei et al., 2018)

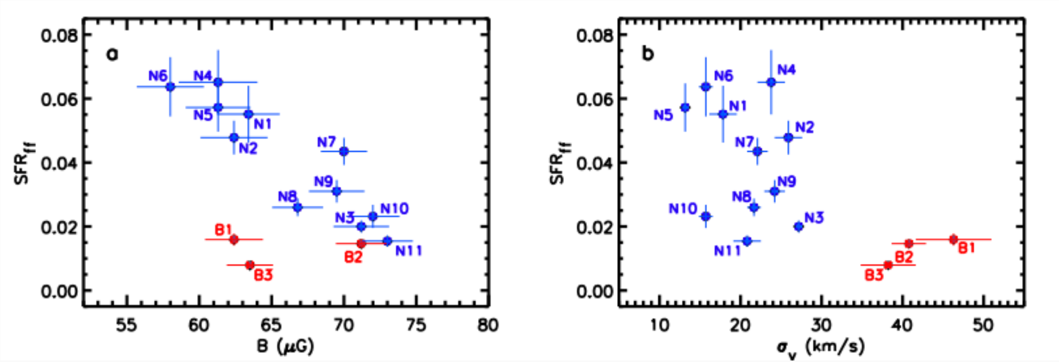


Figure 10: The massive SFR per free-fall, $\mathrm{SFR_{ff}}$, of the GMAs decreases with the magnetic field strength B (*a*) while it is uncorrelated with the turbulent velocity σ_v (*b*). The blue and red points show the narrow- and broad-line GMAs, respectively. Strong non-circular motions/shocks in the broad-line GMAs can act as additional cause of the low $\mathrm{SFR_{ff}}$ in these clouds.

Example works for zoom-in simulations

Magnetic fields in cosmological simulations of disk galaxies (Pakmor et al., 2014)

For the first time the formation and evolution of a Milky Way–like disk galaxy in its **full cosmological context** while taking into account B.

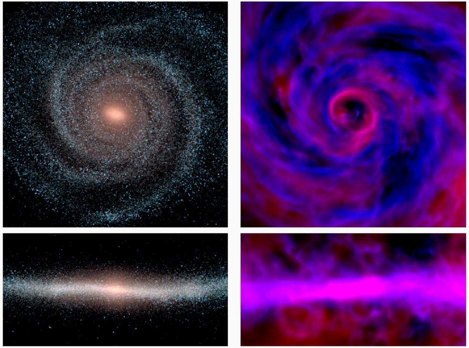


Figure 11: https://www.h-its.org/2014/03/10/a-milky-way-out-of-the-supercomputer

Magnetic fields in cosmological simulations of disk galaxies (PMS14)

Their Baryonic physics includes (Vogelsberger et al.)

- primordial and metal line cooling
- a subgrid model for the inter-stellar medium (ISM) and star formation (Springel &Hernquist 2003)
- a self-consistent treatment of stellar evolution and chemical enrichment
- galactic-scale winds (implemented with a kinetic scheme similar to Puchwein & Springel 2013)
- supermassive black hole growth and feedback

Magnetic fields in cosmological simulations of disk galaxies (PMS14)

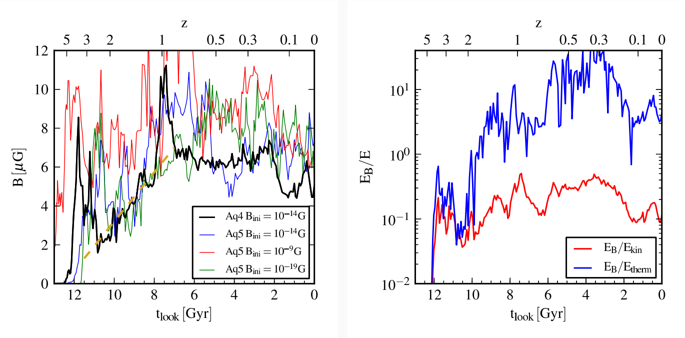


Figure 12: Evolution of the volume weighted average root mean square magnetic field strength (right), the ratio of magnetic energy to kinetic energy and thermal energy (left).

- They found that a prescribed tiny magnetic seed field **grows exponentially** by a small-scale dynamo until it saturates around $z = 4$ with a magnetic energy of about 10% of the kinetic energy in the center of the galaxy's main progenitor halo.

Magnetic fields in cosmological simulations of disk galaxies (PMS14)

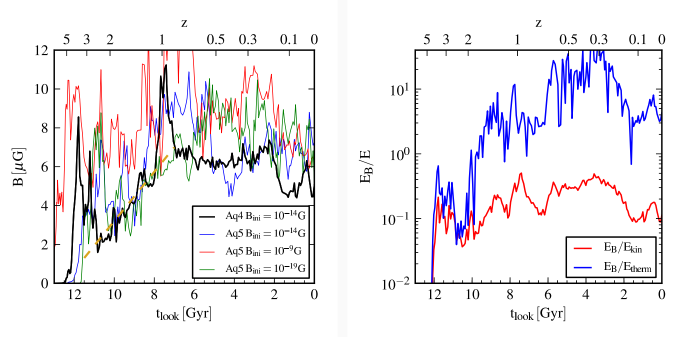


Figure 12: Evolution of the volume weighted average root mean square magnetic field strength (right), the ratio of magnetic energy to kinetic energy and thermal energy (left).

- By z=2, a well-defined gaseous disk forms in which B is further **amplified** by differential rotation, until it saturates at an average field strength of $\sim 6\mu G$ in the disk plane.

Magnetic fields in cosmological simulations of disk galaxies (PMS14)

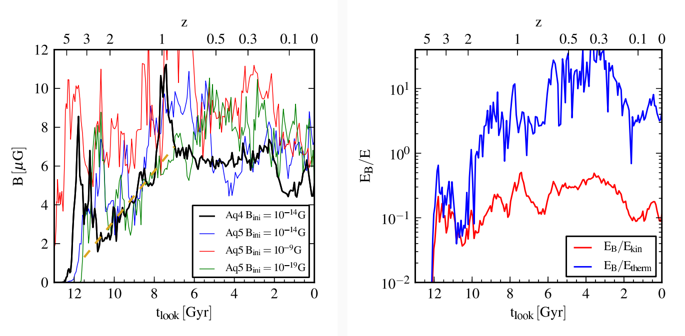
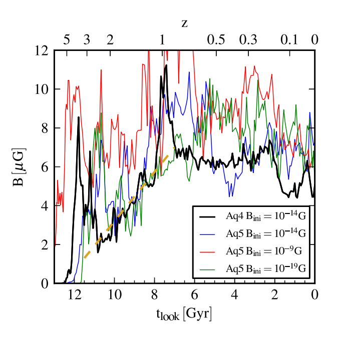


Figure 12: Evolution of the volume weighted average root mean square magnetic field strength (right), the ratio of magnetic energy to kinetic energy and thermal energy (left).

- In this phase, B is transformed from a chaotic small-scale field to an **ordered** large-scale field on scales comparable to the disk radius.

Magnetic fields in cosmological simulations of disk galaxies (PMS14)



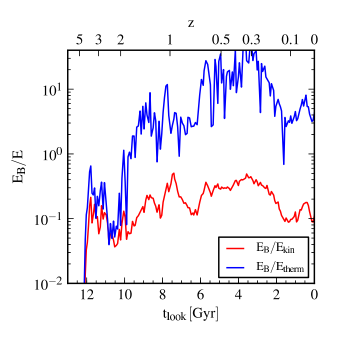


Figure 12: Evolution of the volume weighted average root mean square magnetic field strength (right), the ratio of magnetic energy to kinetic energy and thermal energy (left).

- They suggested that the **large-scale B in spiral galaxies** can be explained as a result of the **cosmic structure formation** process.

Effects of simulated cosmological magnetic fields on the galaxy population (Marinacci & Vogelsberger, 2016)

They examine

- how strong the effects of cosmological B fields (i.e. fields generated in the early Universe) on the global properties of the galaxy population are as a function of the field strength
- what is the critical intensity at which they become noticeable

Baryonic physics as Pakmor et al. (2014)

Effects of simulated cosmological magnetic fields on the galaxy population (MV16)

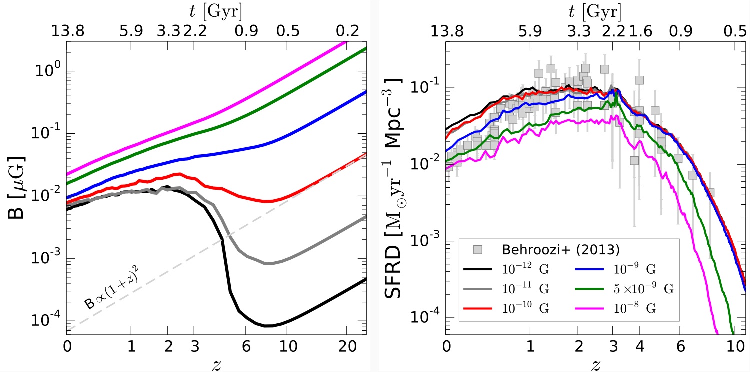


Figure 13: Evolution of the volume-weighted rms B field strength (left) and cosmic star formation rate density (SFRD) together with a compilation of observational data (right)

- Above the **critical B** field value of 10^{-9} G, the field intensity is **set by flux conservation** and little turbulent amplification is present

Effects of simulated cosmological magnetic fields on the galaxy population (MV16)

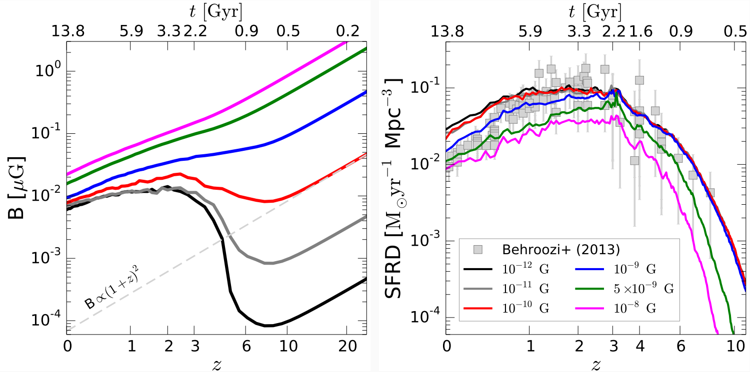


Figure 13: Evolution of the volume-weighted rms B field strength (left) and cosmic star formation rate density (SFRD) together with a compilation of observational data (right)

- For **larger seed** magnetic field strengths there is an **increasing suppression** of the SFRD, which is present at all times for seed fields $> 10^{-9}$ G.

References

Butsky, I., Zrake, J., Kim, J.-h., Yang, H.-I., & Abel, T. 2017, ApJ, 843, 113, doi: 10.3847/1538-4357/aa799f

Marinacci, F., & Vogelsberger, M. 2016, MNRAS, 456, L69, doi: 10.1093/mnrasl/slv176

Pakmor, R., Marinacci, F., & Springel, V. 2014, ApJl, 783, L20, doi: 10.1088/2041-8205/783/1/L20

Pakmor, R., & Springel, V. 2013, MNRAS, 432, 176, doi: 10.1093/mnras/stt428

Steinwandel, U. P., Dolag, K., Lesch, H., et al. 2020, MNRAS, 494, 4393, doi: 10.1093/mnras/staa817

Tabatabaei, F. S., Minguez, P., Prieto, M. A., & Fernández-Ontiveros, J. A. 2018, Nature Astronomy, 2, 83, doi: 10.1038/s41550-017-0298-7