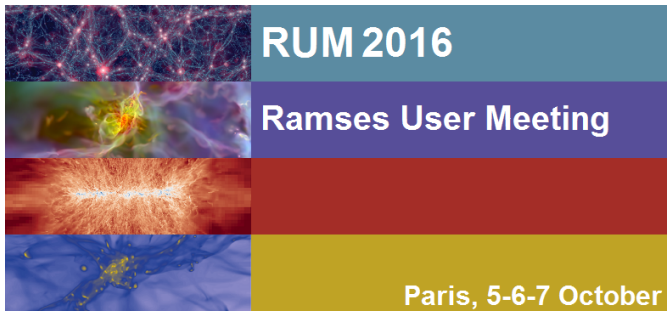

Magnetic fields in galaxies:

the small-scale dynamo in a cosmological context

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Magnetic fields in galaxies

Importance of galactic magnetic fields

- Equipartition with thermal energy
- Modify the dynamics of ISM
- Affect star formation
- May magnetize cosmic web
- Drive cosmic rays diffusion

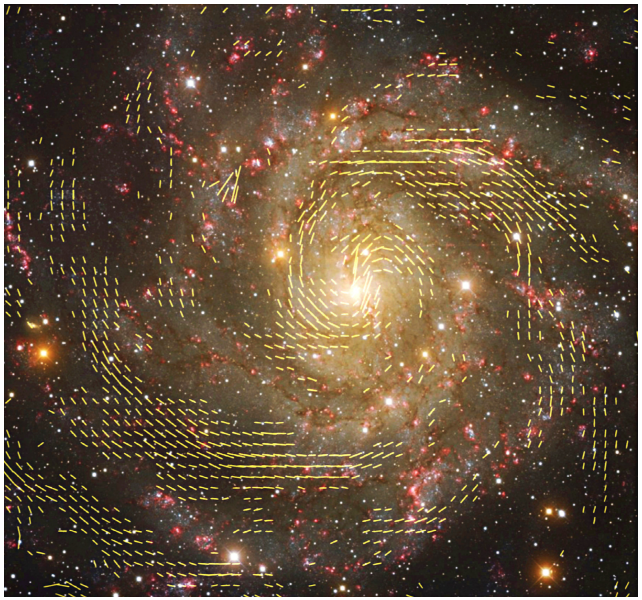


Figure: IC 342 polarized emission at $\lambda = 6.2$cm: yellow vectors indicate orientation of the magnetic field.

Image credit: R. Beck/MPIfR (radio emission, VLA+Effelsberg) and T. A. Rector, University of Alaska Anchorage, and H. Schweiker, WIYN and NOAO/AURA/NSF (optical, Kitt Peak Observatory)

The amplification problem

Initial magnetic field

Plasma spontaneous magnetization:	10^{-16}G
Biermann battery:	10^{-20}G
Inflation seed:	$\rightarrow 0$

Current day magnetic fields

Galactic fields:	$1 - 10\ \mu$G
Galaxy clusters:	< 10 nG
Voids:	$\ll 10^{-10}$ G

Evidence suggests that strong magnetic fields are already in place at high redshifts ($z \sim 2$). (Widrow 2002, Bernet et al. 2008, Beck & Wielebinski 2013)

The small-scale dynamo

Amplification mechanisms

- $\alpha - \Omega$ dynamo
- Astrophysical objects amplification
- Small-scale dynamo

Small-scale dynamo

Exponential amplification:

$$E_{mag} \propto e^{\Gamma t}$$

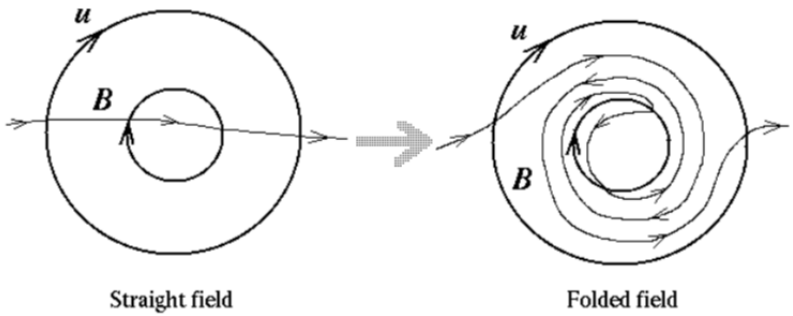


Figure: The small-scale dynamo amplifies the field by folding the lines in the small-scale eddies.

(Schekochihin et al. 2004)

MHD with RAMSES

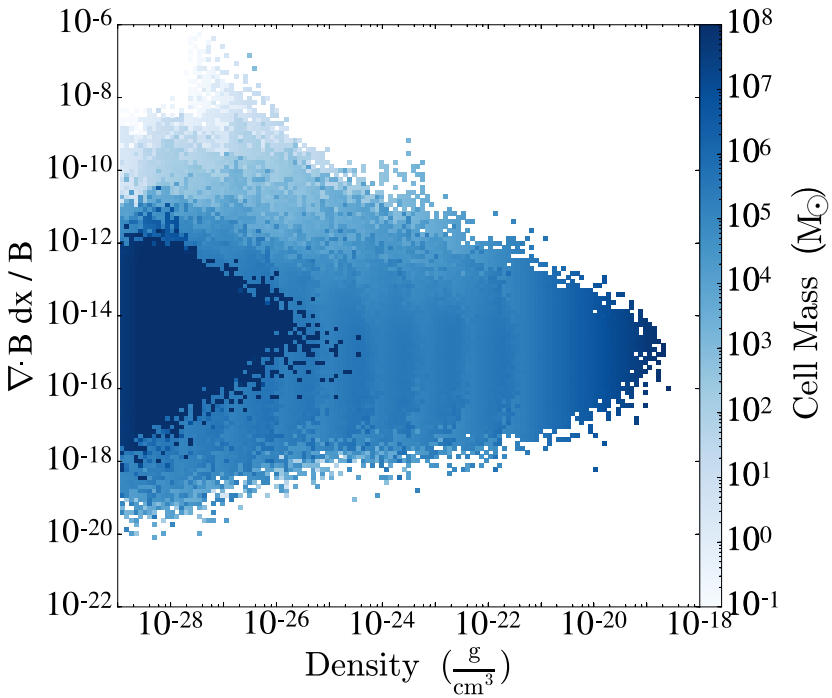


Figure: $\frac{|\vec{\nabla}\cdot\vec{B}|}{|\vec{B}|}\Delta x_{\text{cell}}$ vs gas density for the Biermann run full box at $z = 3$, with our modified MHD version of RAMSES.

Solenoidal constraint:

$$\vec{\nabla}\cdot\vec{B} = 0$$

Other codes either:

- Require divergence cleaning
- Feature $\frac{|\vec{\nabla}\cdot\vec{B}|}{|\vec{B}|}\Delta x_{\text{cell}} \sim 0.5$ values (especially SPH)

The NUT galaxy

We use our own modified MHD version of the AMR code RAMSES

(Teyssier 2002, Teyssier et al. 2006).

Simulation setup:

- $9\,h^{-1}$Mpc comoving side box
- High resolution $3\,h^{-1}$Mpc diameter sphere
  - 10 pc max. resolution
  - $M_{DM} \sim 5 \cdot 10^4 M_\odot$
  - $M_* \sim 5 \cdot 10^3 M_\odot$
  - $M_{vir} \sim 5 \cdot 10^{11} M_\odot$ halo at z = 0
- WMAP5 cosmology

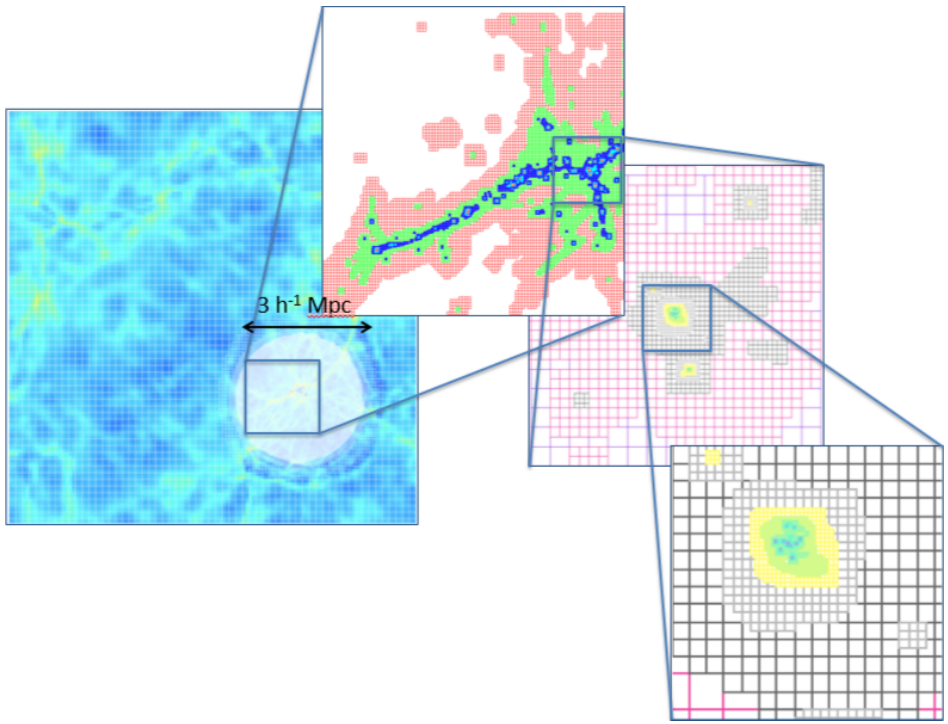
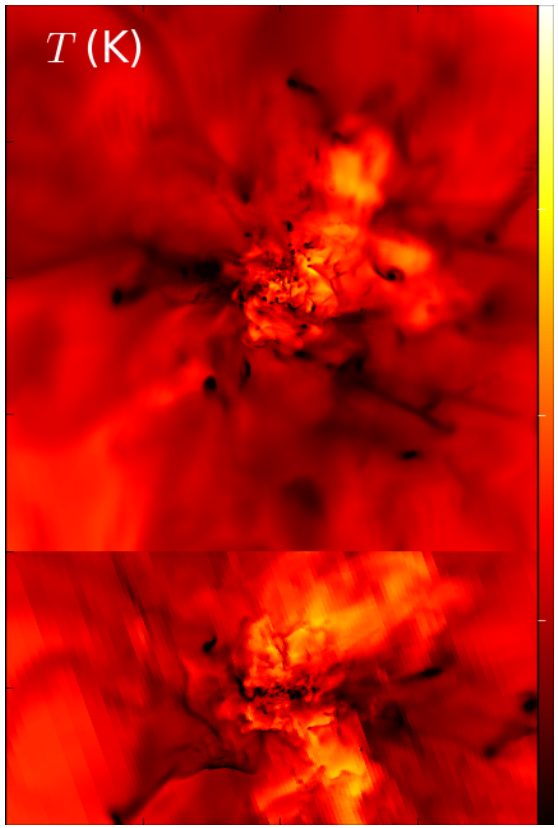


Table: Simulation setups employed on the different runs of NUT.

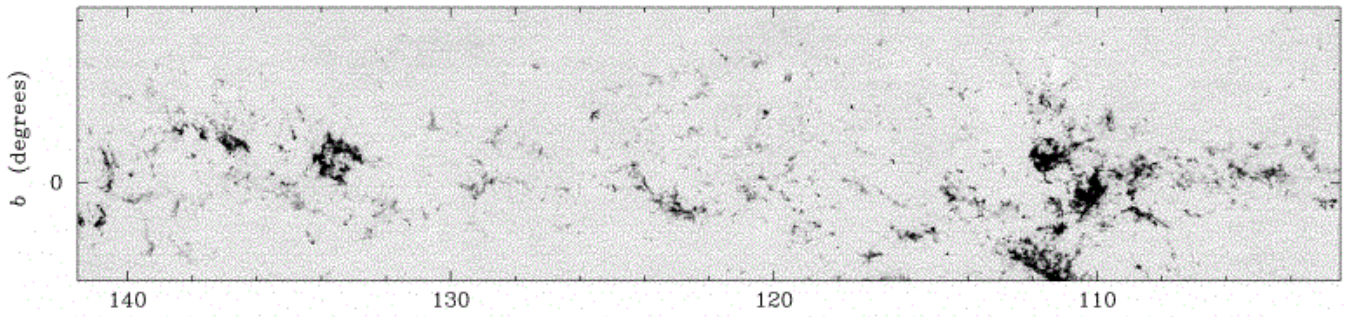
Simulation	B_0	Feedback	SF-P_{mag}
Biermann	10^{-20} G	✓	✗
Biermann-NoFB	10^{-20} G	✗	✗
Planck-Pmag	10^{-12} G	✓	✓
Planck	10^{-12} G	✓	✗



Subgrid physics in NUT-dynamos

- Mechanical SNe feedback
  - (Kimm et al. 2015)
- Turbulent star formation
  - (Kimm et al. 2016)
- Metal cooling
  - (Sutherland & Dopita, 1993)
  - (Rosen & Bregman, 1998)
- UV background
  - (Haardt & Madau, 1996)

Turbulent star formation



FCRAO CO Survey (Heyer et al. 1998)

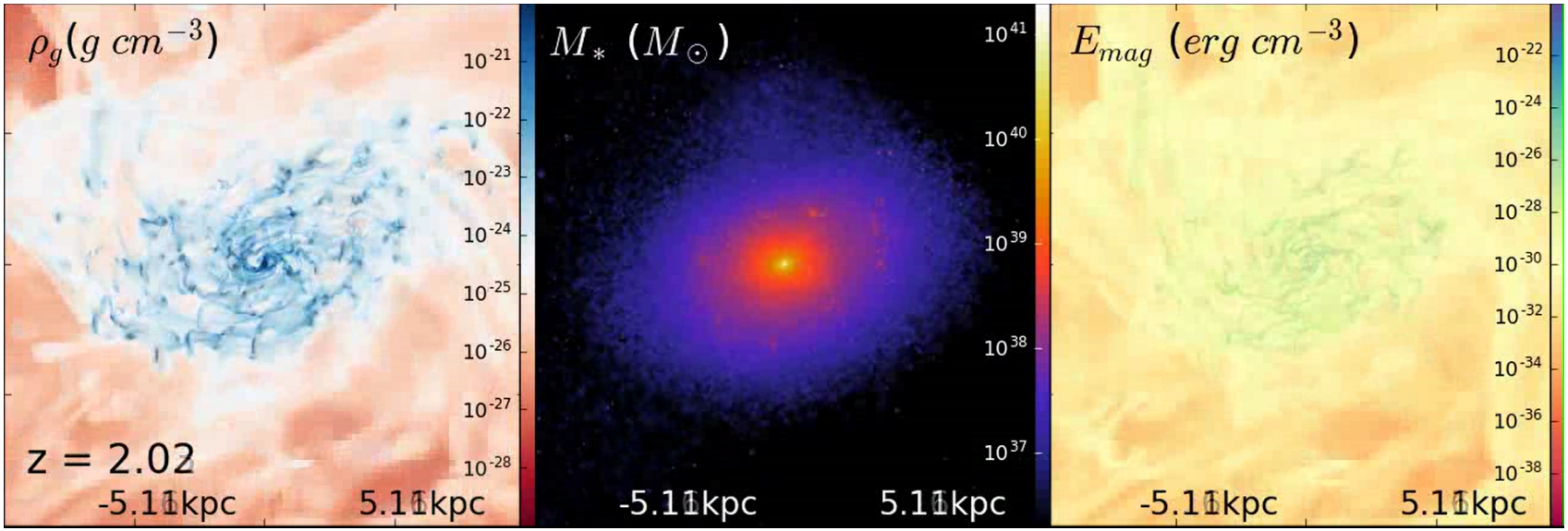
Kennicutt-Schmidt relation for star formation:

$$\dot{\rho}_* = \frac{\epsilon\rho}{t_{ff}},$$

but star formation occurs in collapsing regions (Kimm et al. 2016), with magnetic fields:

$$P_{mag} + \sigma_{eff}^2 + c_s^2 < \beta GM$$

Results


$\rho_g(g\ cm^{-3})$
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{-27}
10^{-28}
z = 2.02
-5.11kpc
5.11kpc
$M_*\ (M_\odot)$
10^{41}
10^{40}
10^{39}
10^{38}
10^{37}
-5.11kpc
5.11kpc
$E_{mag}\ (erg\ cm^{-3})$
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
-5.11kpc
5.11kpc

Amplification

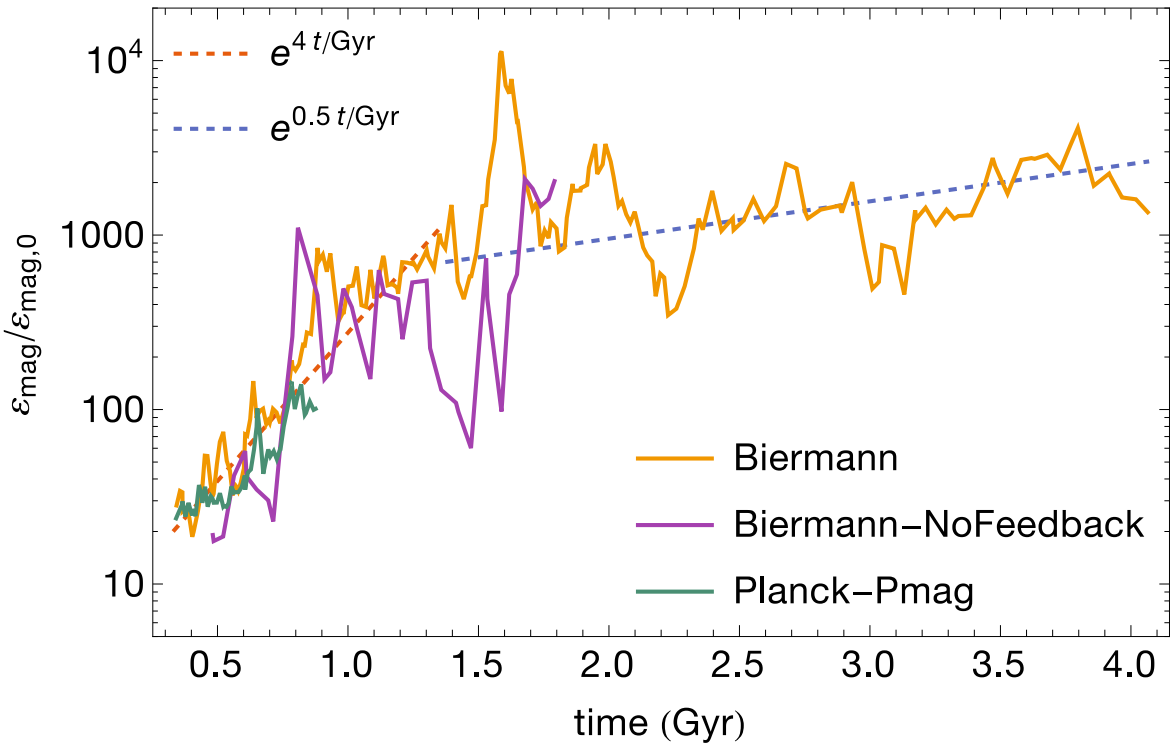


Figure: Specific magnetic energy growth over time for the ongoing simulations in a cylinder around the galaxy. Normalized to the initial value.

Amplification

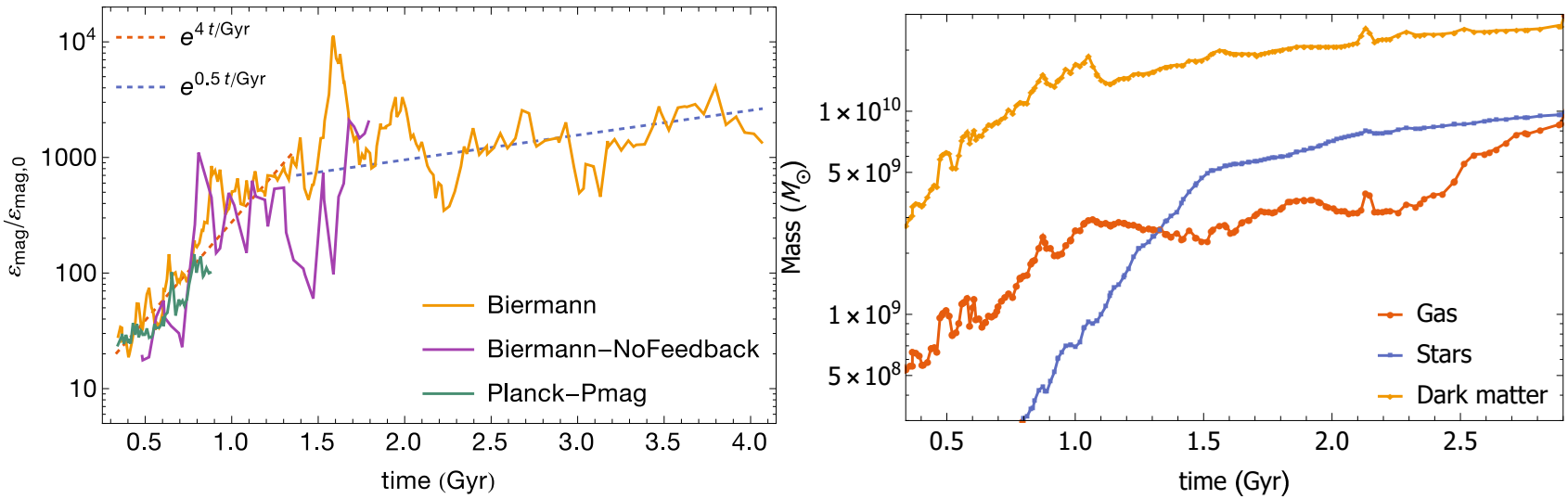


Figure: (Left) Specific magnetic energy growth over time for the ongoing simulations in a cylinder around the galaxy. (Right) Mass content for each of the components in the same region.

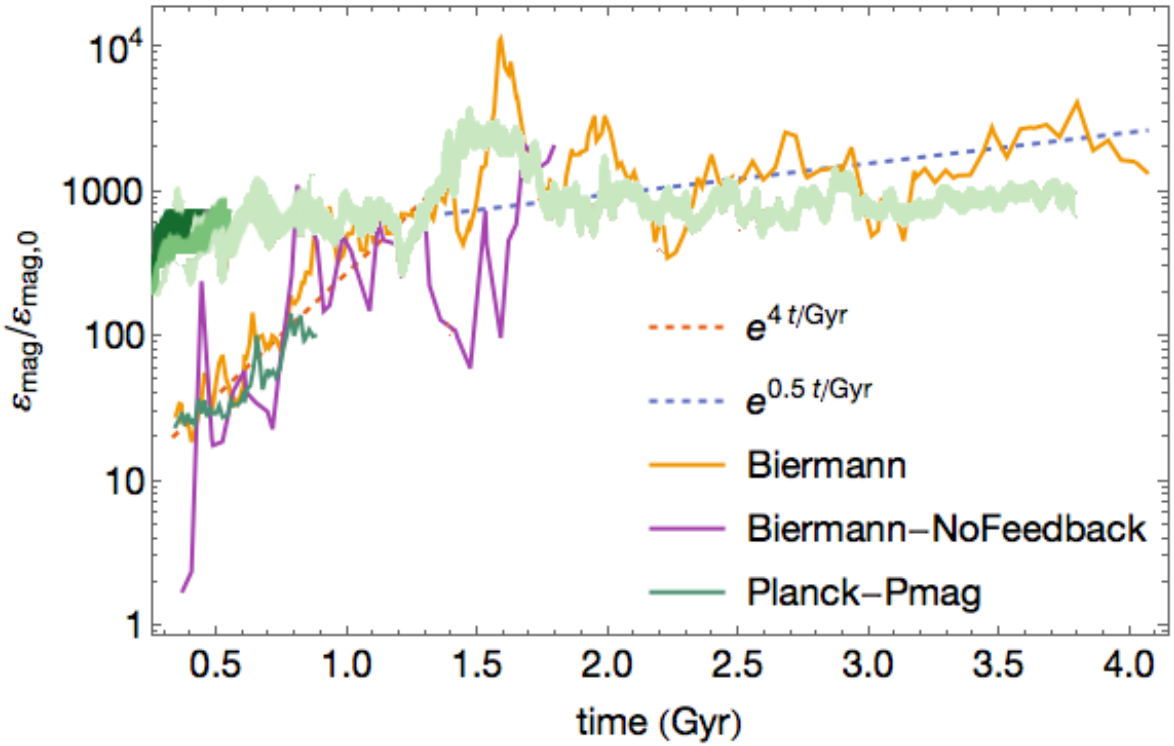


Figure: (Light green) overplot of the amplification in an isolated galaxy simulation with SNe feedback (Rieder and Teyssier, 2016).

The ISM

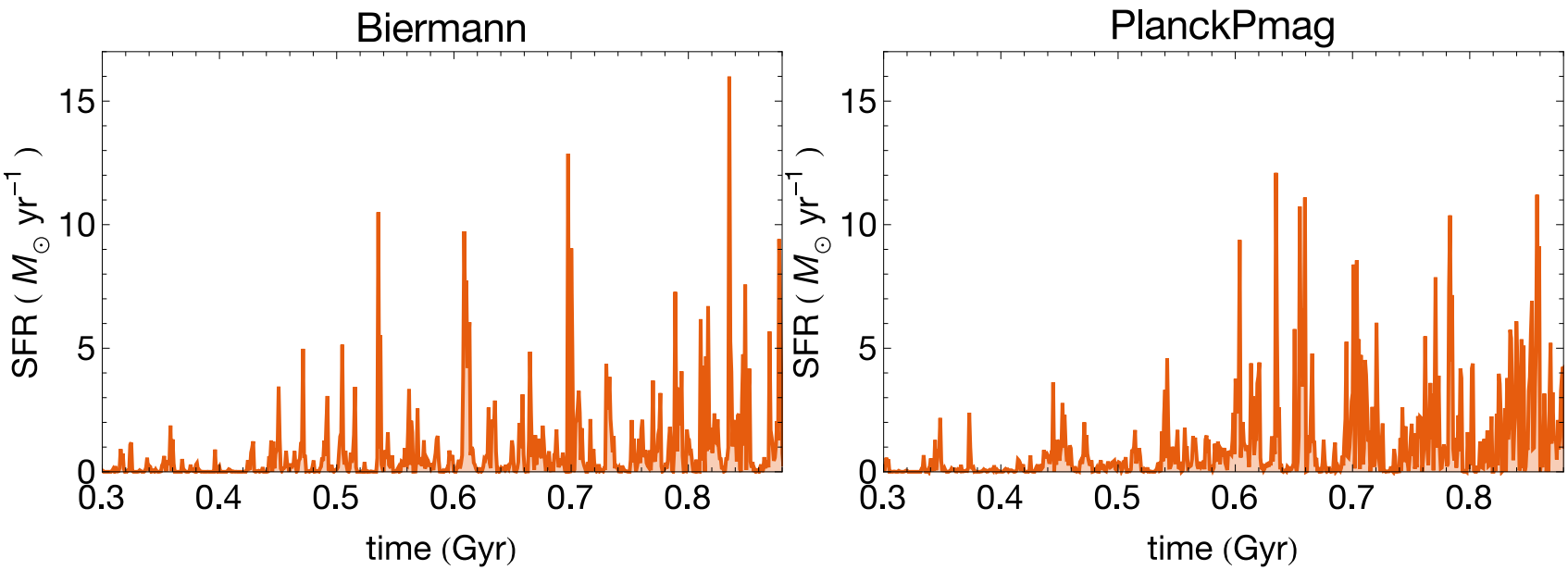


Figure: Early star formation histories for the Biermann (left) and the PlanckPmag (right) runs.

The small-scale dynamo

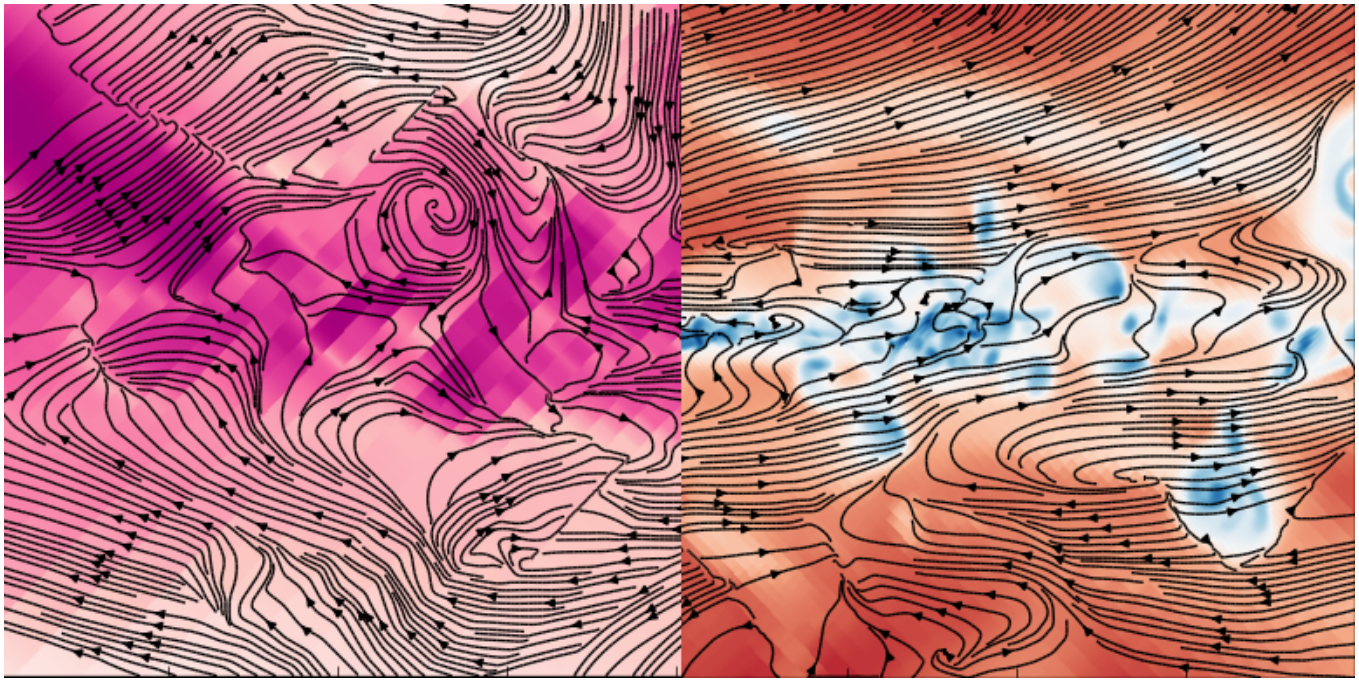


Figure: Edge-on view of the central region of the galaxy at z = 1.5. Magnetic field lines and magnetic field strength on the left and gas flow streamlines and gas density on the right show how the magnetic field is highly entangled.

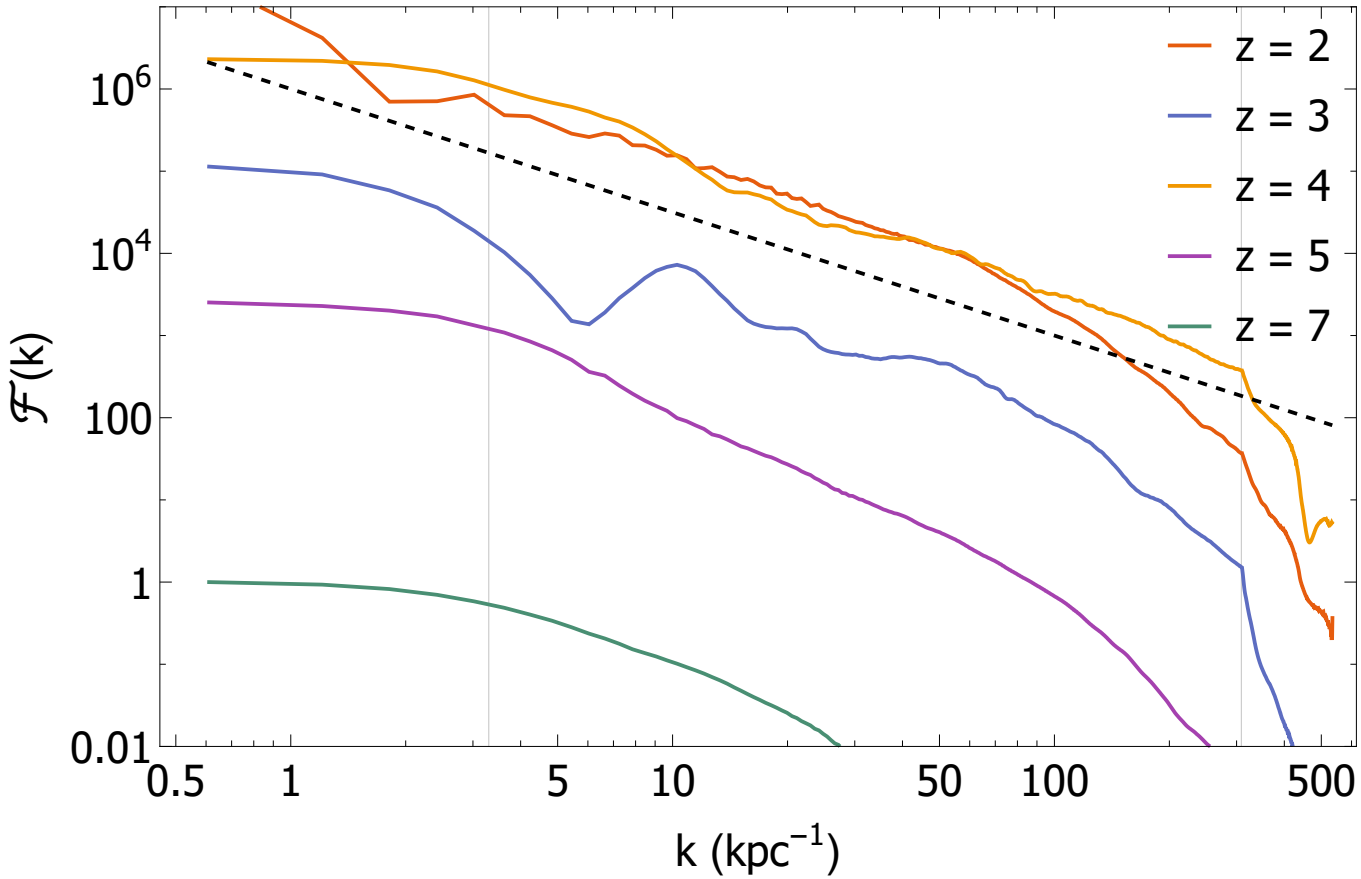


Figure: Power spectra $\mathcal{E}_{mag}(k)$ of the magnetic energy density in a 10kpc cubic box centred around the galaxy.

Conclusions and future work

So far:

- Amplification of the field occurs in our cosmological zoom-in simulation of a Milky-Way like galaxy.
- Small-scale dynamo amplification occurs at some moments during the simulation.
- Strong magnetic fields affect the star formation.

Incoming:

- Simulations still running.
- Turbulence analysis to understand small-scale dynamo.
- Field depletion during star formation and injection by supernova feedback.
- Study of the magnetic field impact on the ISM.

Thank you for your time!