Simulating magnetic fields in structure formation

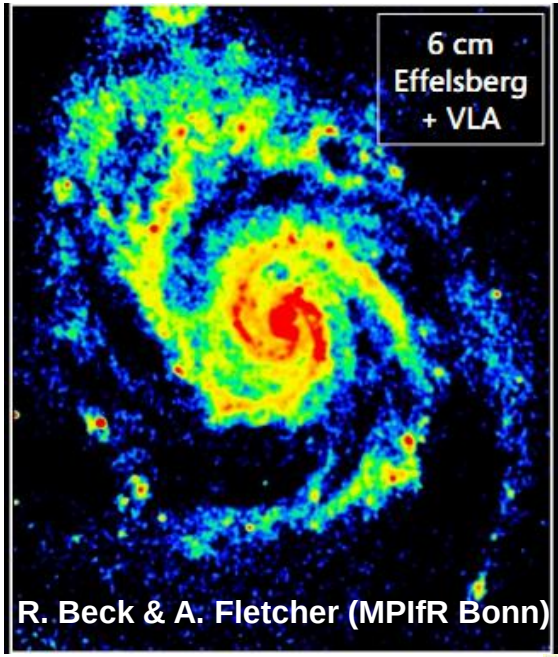
USM / MPE / MPA

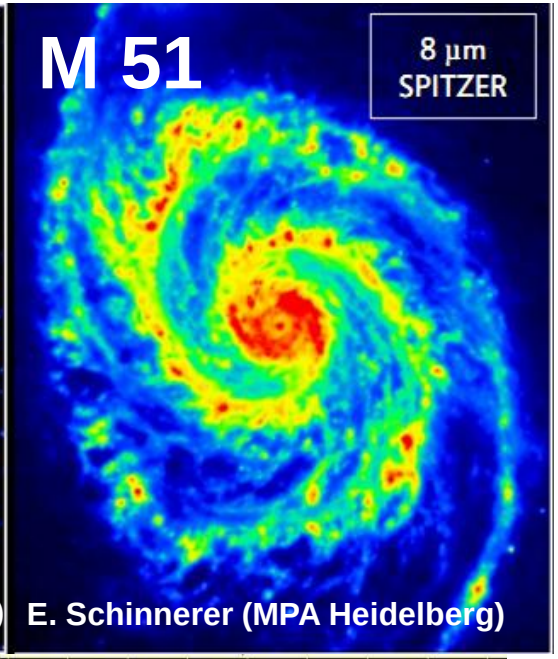
Harald Lesch & Klaus Dolag
Annette Geng, Federico Stasyszyn & Marcus Beck

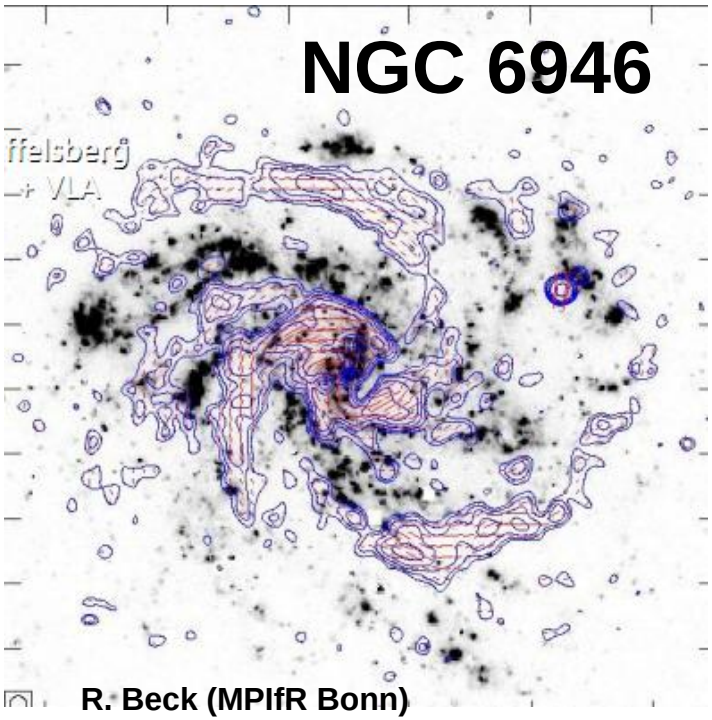
July, 2012 (Mainz)

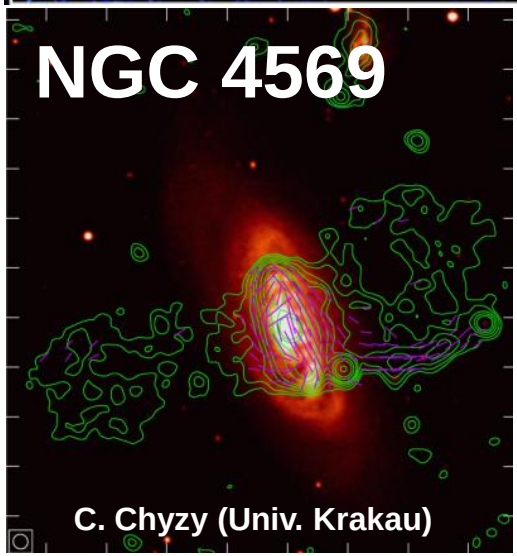
Alexander Beck

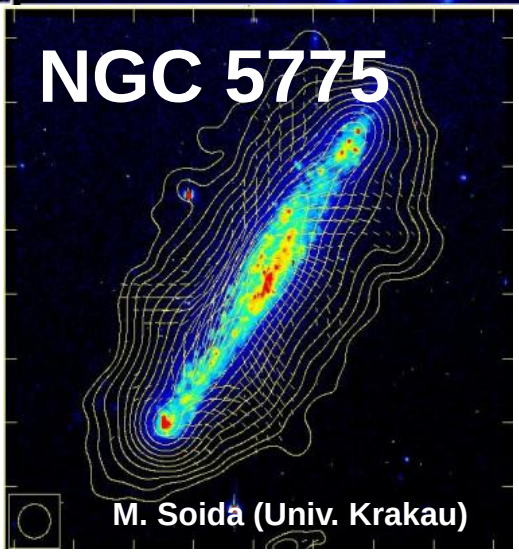
Magnetic fields in galaxies

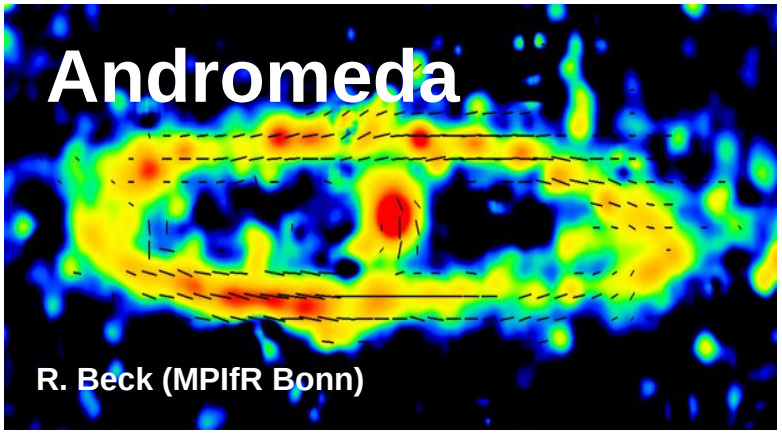










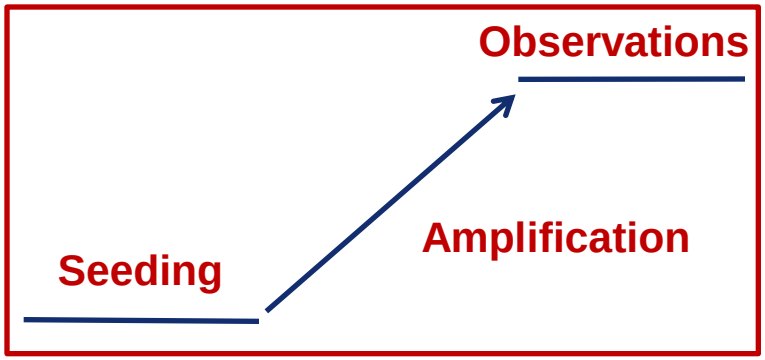


Numerical method

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

Astrophysics

Decay & topology changes

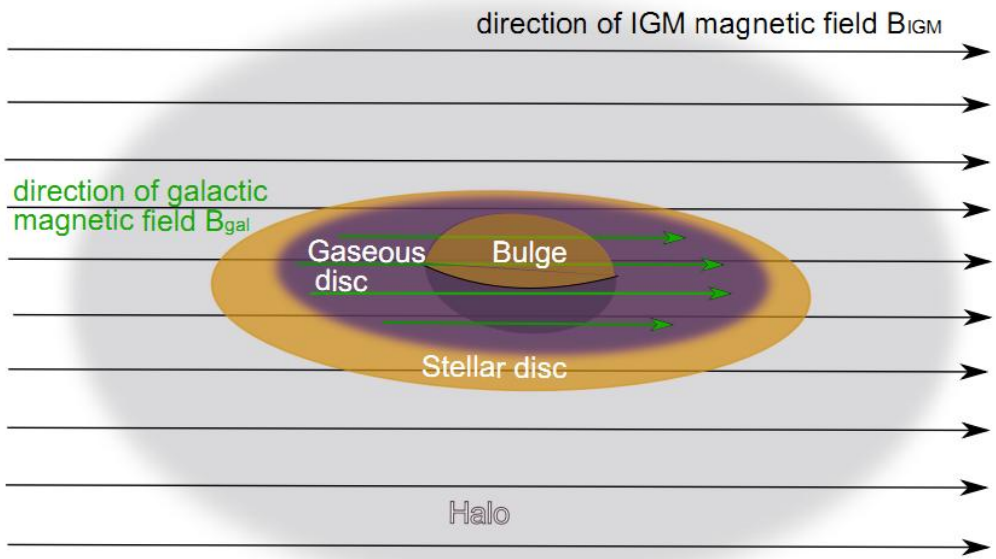


- Velocity field has to be modeled properly to described the evolution of the magnetic field

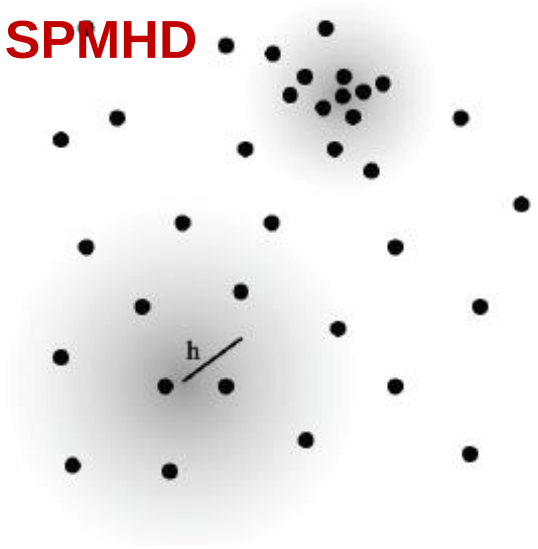
- Simulations with the N-body / SPH code Gadget3 (Springel et al., 2001)
- Multi-phase star formation model (Springel & Hernquist 2003)
- Standard SPMHD technique (Price 2012)
- SPMHD in Gadget3 (Dolag & Stasyszyn 2009)
- Dedner 2002 cleaning scheme (Stasyszyn, Dolag & Beck A., 2012, submitted)
- Spatial constant turbulent resistivity (Bonafede et al., 2011)

- Visualisation with P-Smac2 (Donnert et al., 2012, in preparation)

Setup of isolated galaxies



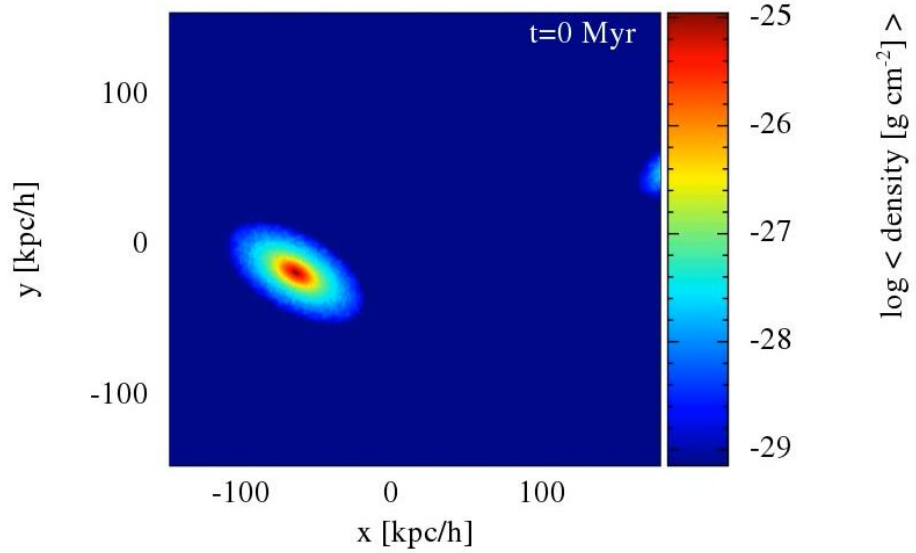
Geng, Beck A. et al., 2012 (b)

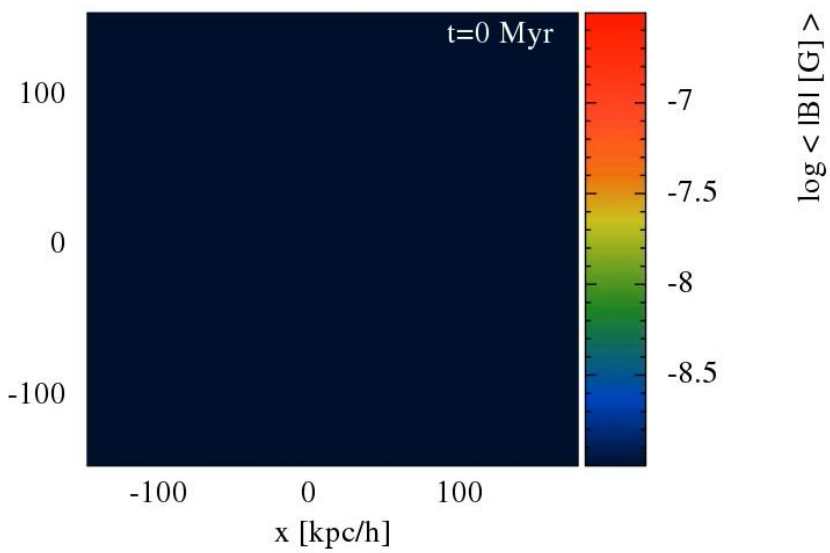


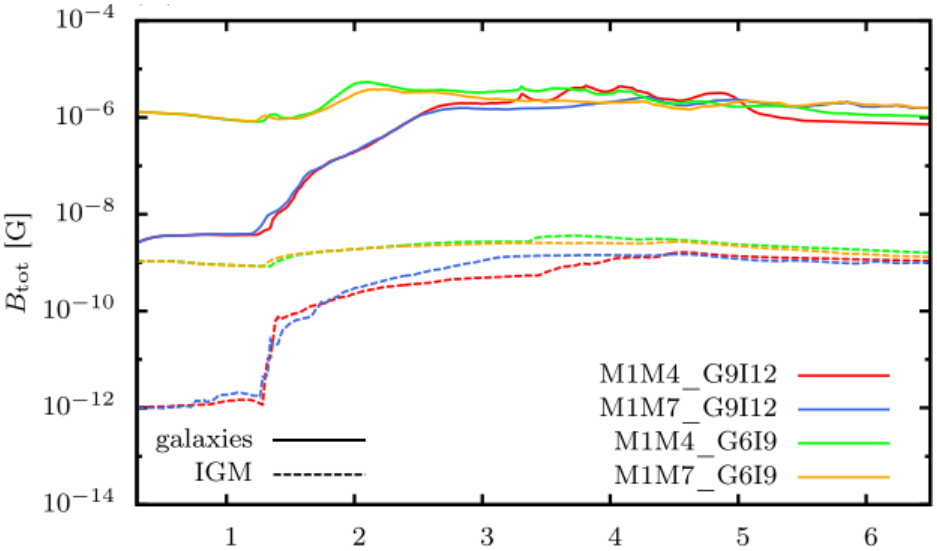
Price 2012

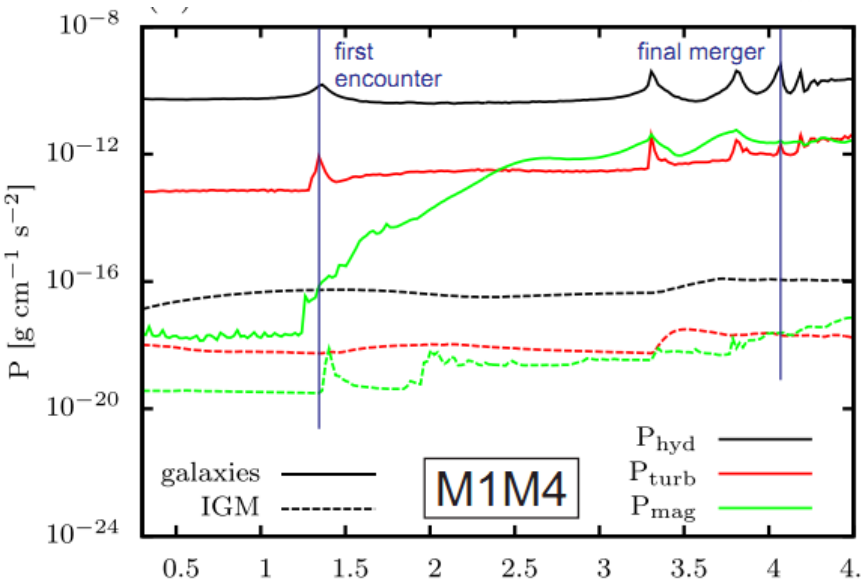
- Galaxies consist of a dark matter halo and a stellar bulge, a stellar disk and a gaseous disk (Setup program by Volker Springel (Springel et al., 2005))
- Embedded in a low density ambient IGM (hexagonal grid)
- Uniform initial magnetic field setup
- 10^{-6} Gauss in the galaxy, 10^{-9} Gauss in the ambient IGM
- Dynamical galaxy setup (Cooling, Rotation, Feedback)

Galaxy minor mergers



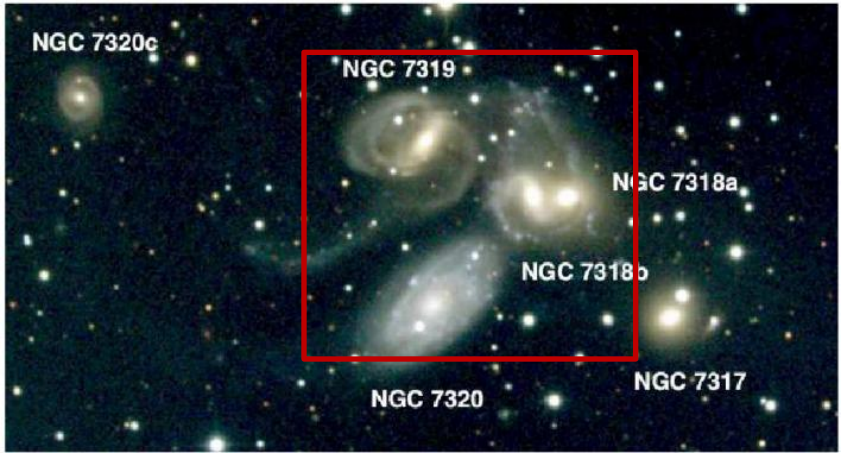




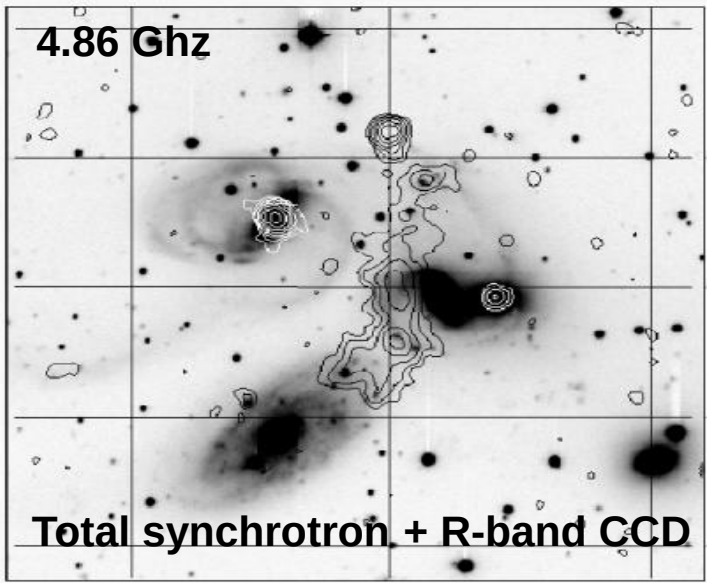


Geng, Beck A. et al., 2012 (a)

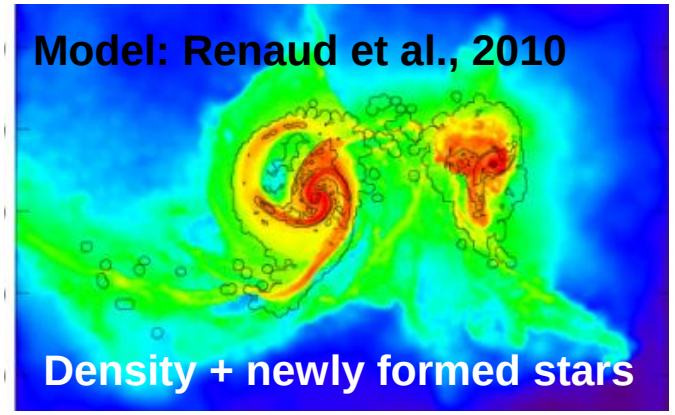
Stephan‘s Quintet

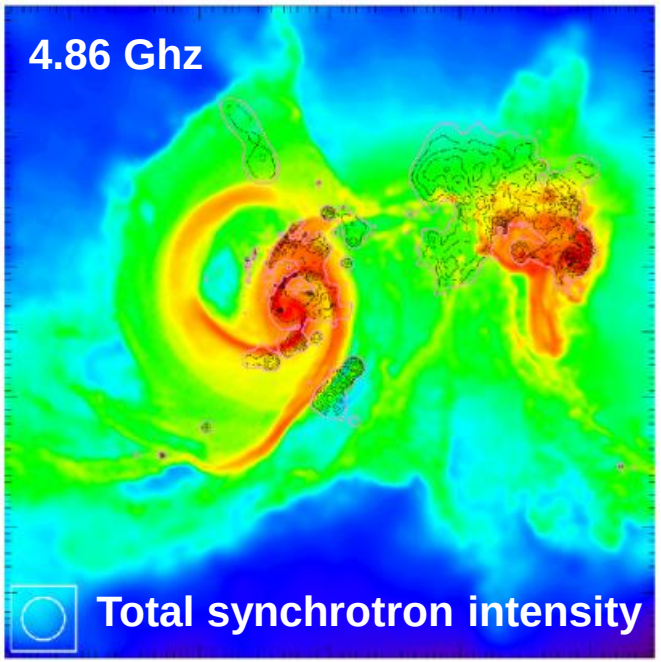


Hwang et al., 2010, Credit: NOAO/AURA/NSF



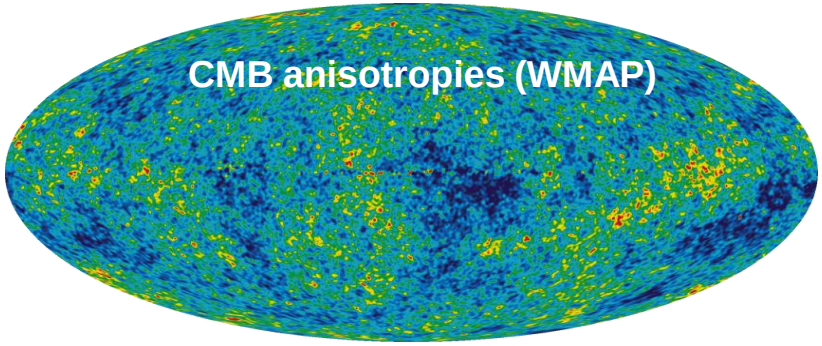
Xu et al., 2003

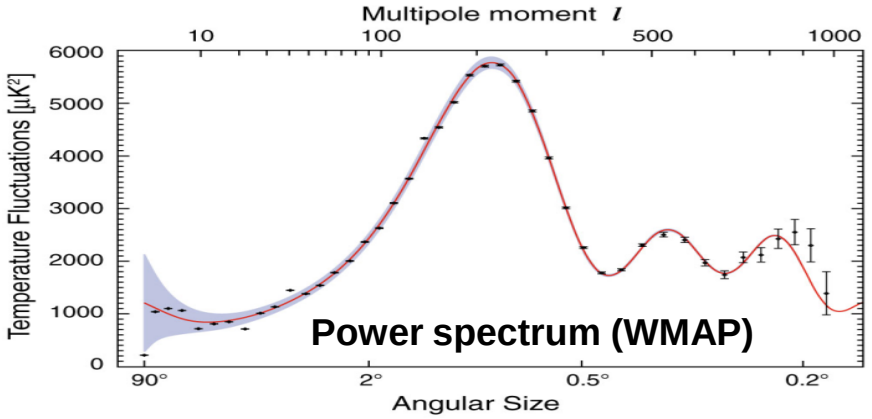


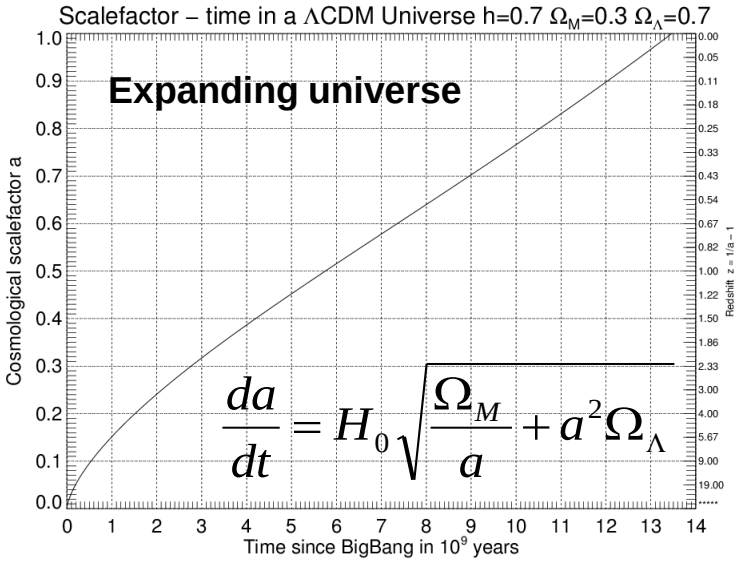


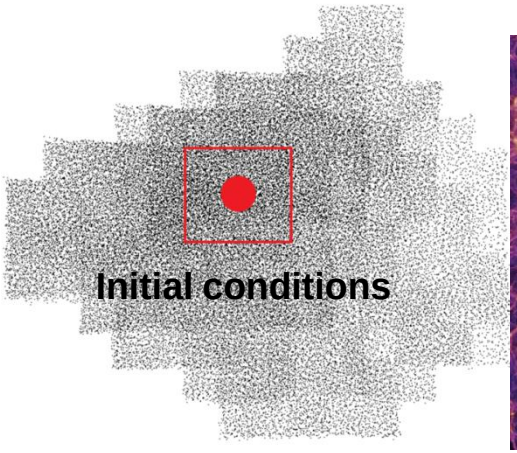
Geng, Beck A. et al., 2012 (b)

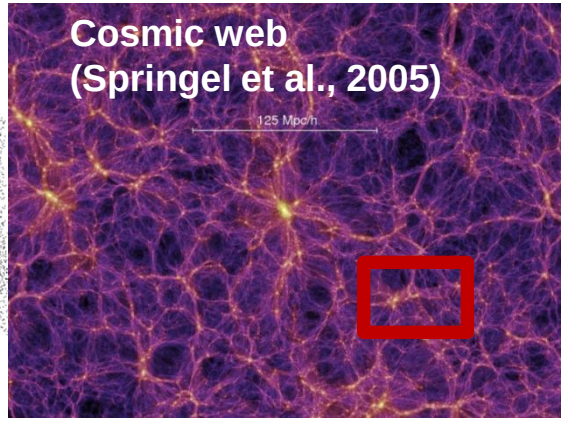
Cosmological initial conditions





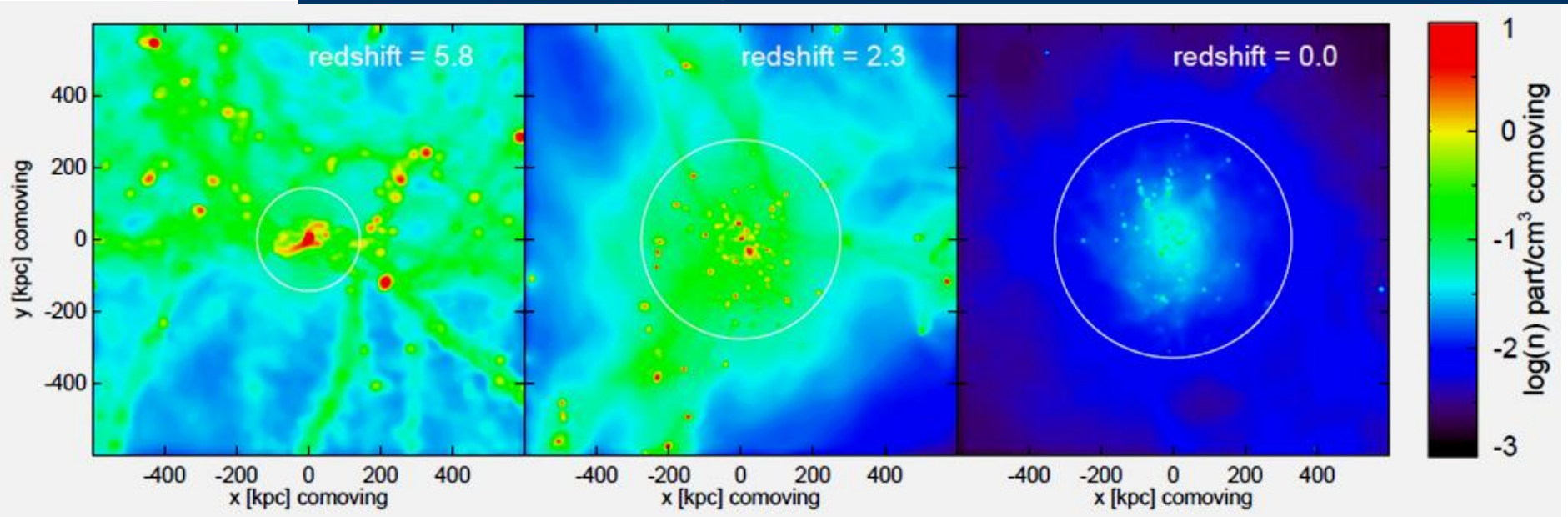






- Re-simulate a MW-like dark matter halo at different resolutions
- Velocity curve peaks at 220 km/s and virial radius is 270 kpc
- Initial conditions introduced by Stoehr et al. 2002, 2003, 2006

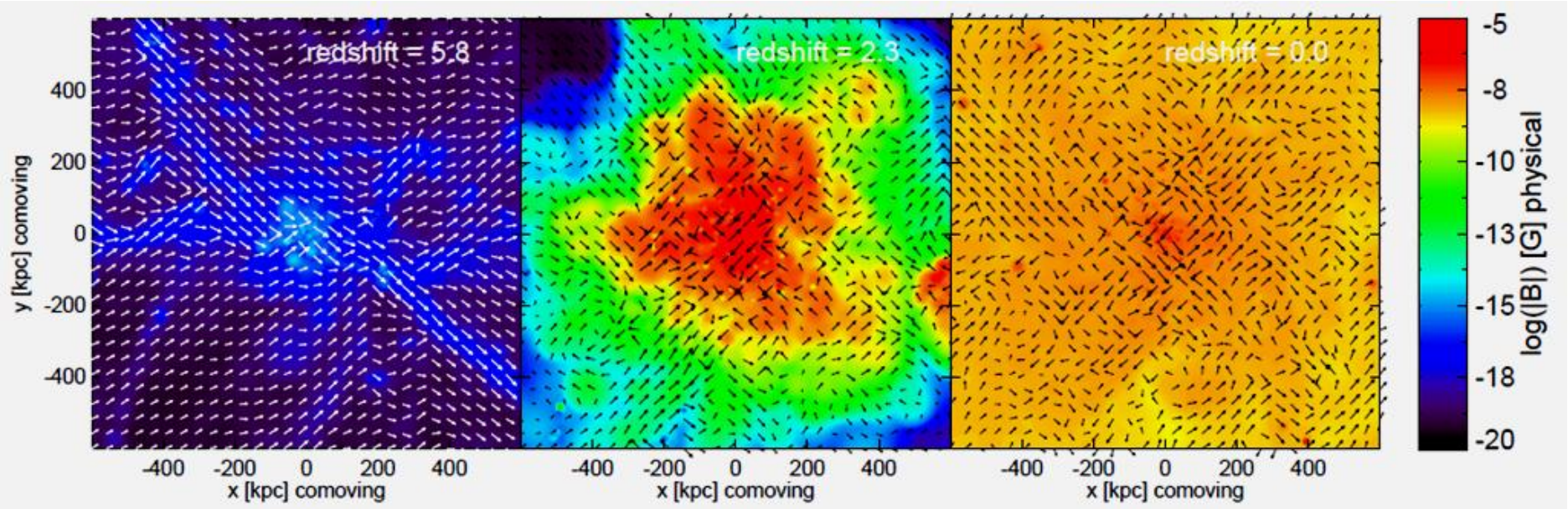
Gas density



- Milky-Way like dark matter halo is forming from redshift 40 to 0
- Gas cools and collapses into protohaloes and forms filaments
- Star formation is taking place inside dense structures
- Haloes undergo a series of major and minor mergers
- Main halo increases by accretion and mergers
- Gas structure in the halo forms no disk in MHD case

Beck A. et al., 2012 (a)

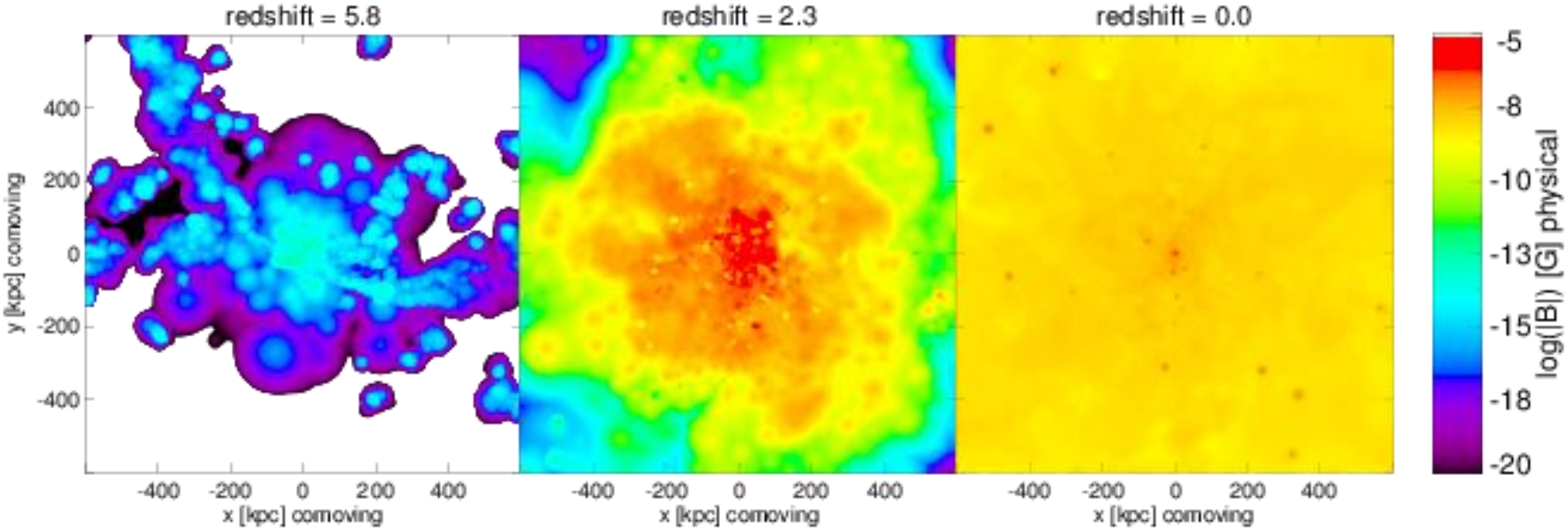
Primordial magnetic field



- Weak magnetic field follows the velocity field
- Agglomorates with the gas in filaments and protohaloes
- Turbulence is driven by mergers, gravitation and star formation
- Small-scale dynamo action inside the haloes
- Shock amplification into the IGM
- Equipartition reached with other energy densities
- Decaying turbulence and magnetic power-law decay

Beck A. et al., 2012 (a)

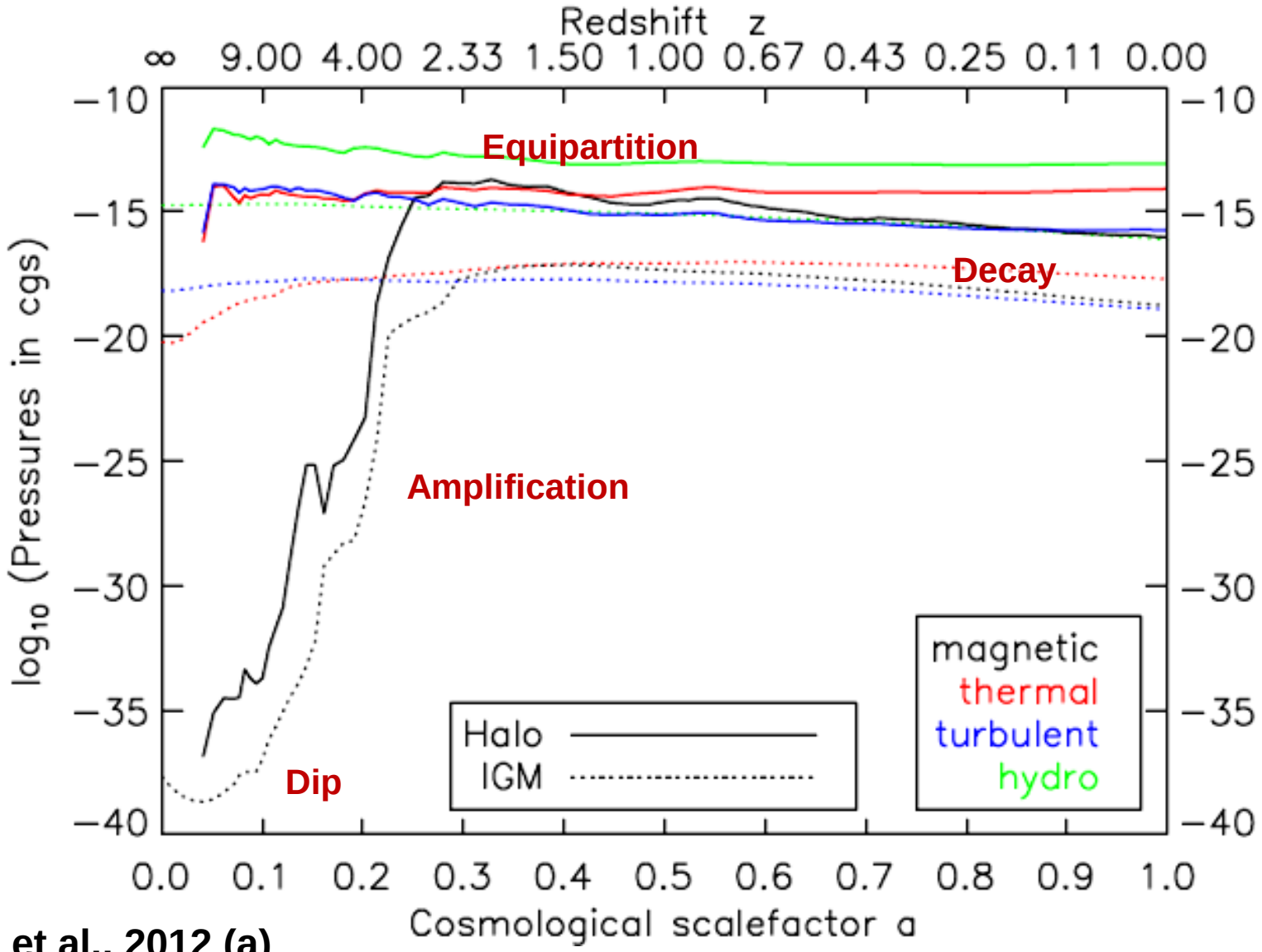
Supernova magnetic field



- Within star forming regions, magnetic dipols are injected based upon the supernova rate
- Small-scale dynamo action inside the haloes
- Shock amplification into the IGM
- Magnetic energy first has to be transported into the IGM before amplificaton can take place
- Entire galactic halo is magnetized

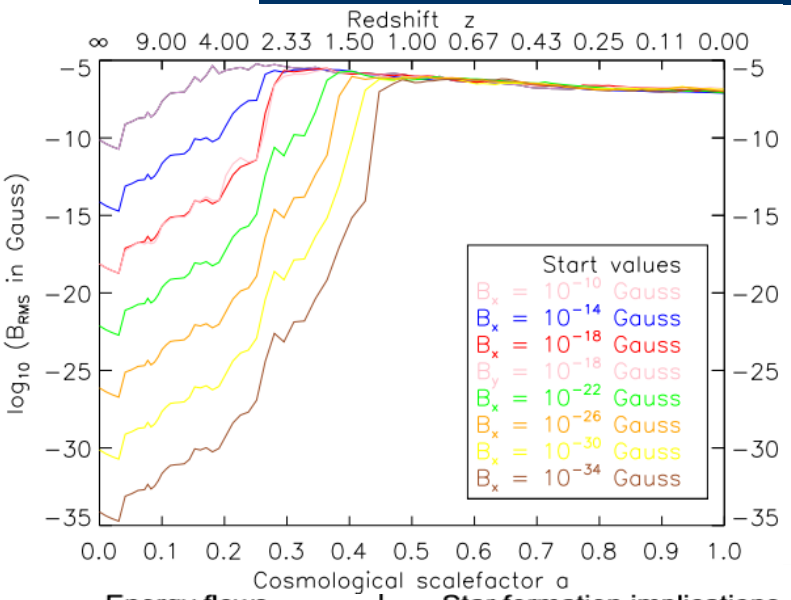
Beck A. et al., 2012 (b)

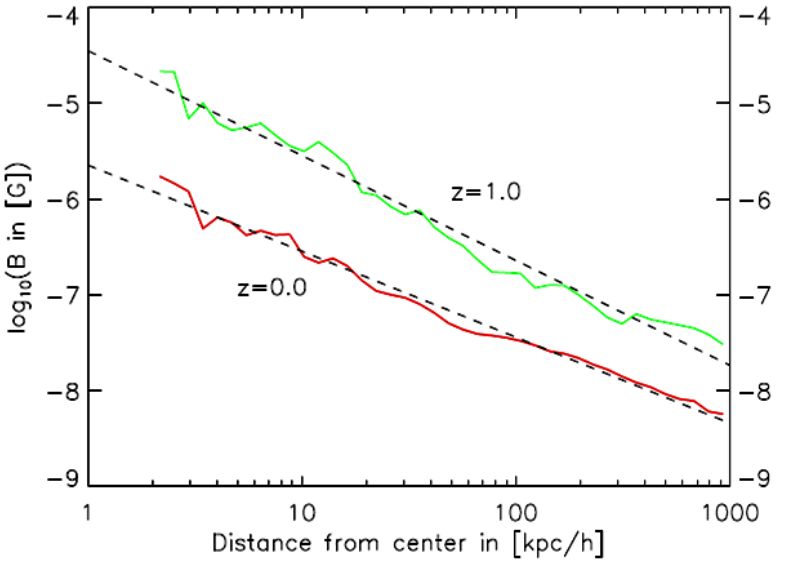
Energy densities (primordial)

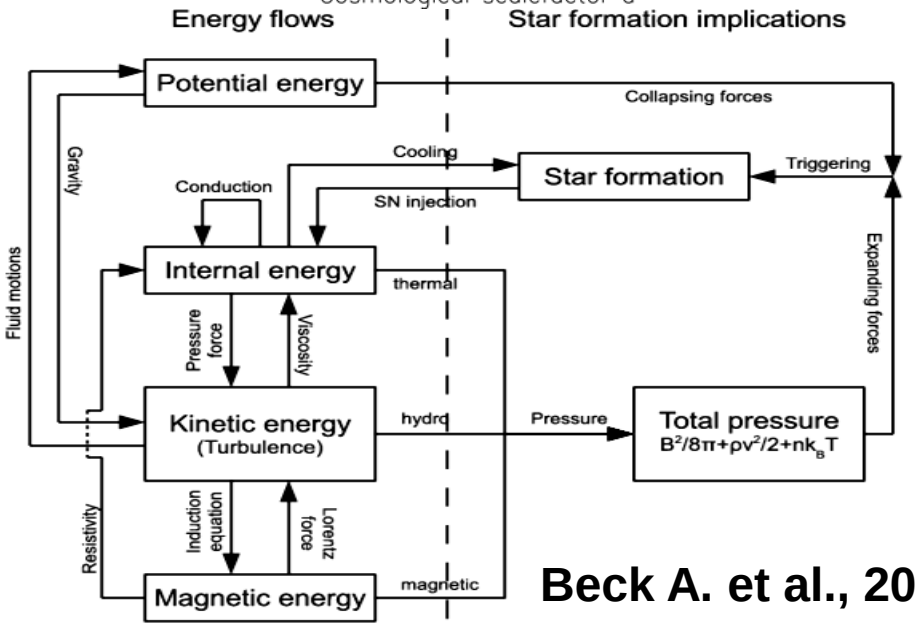


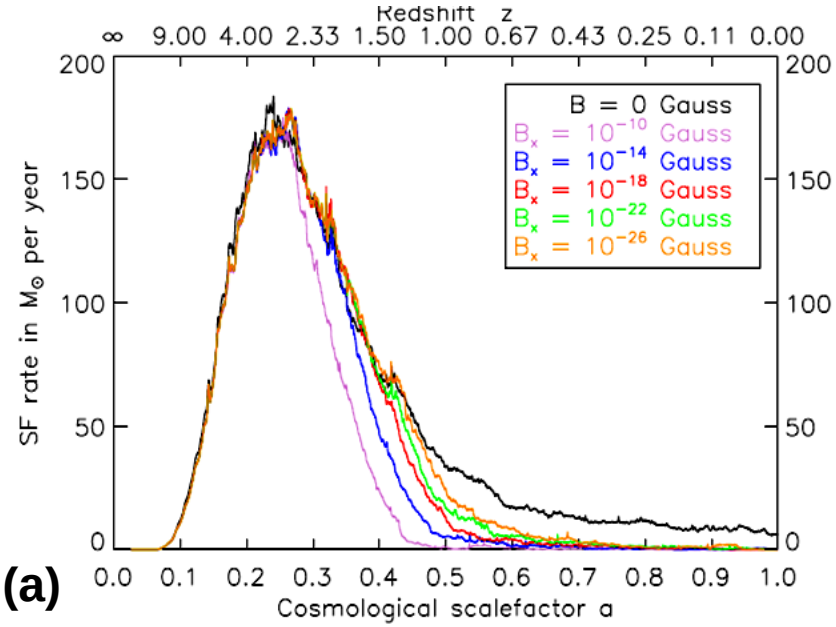
Beck A. et al., 2012 (a)

Further magnetic results



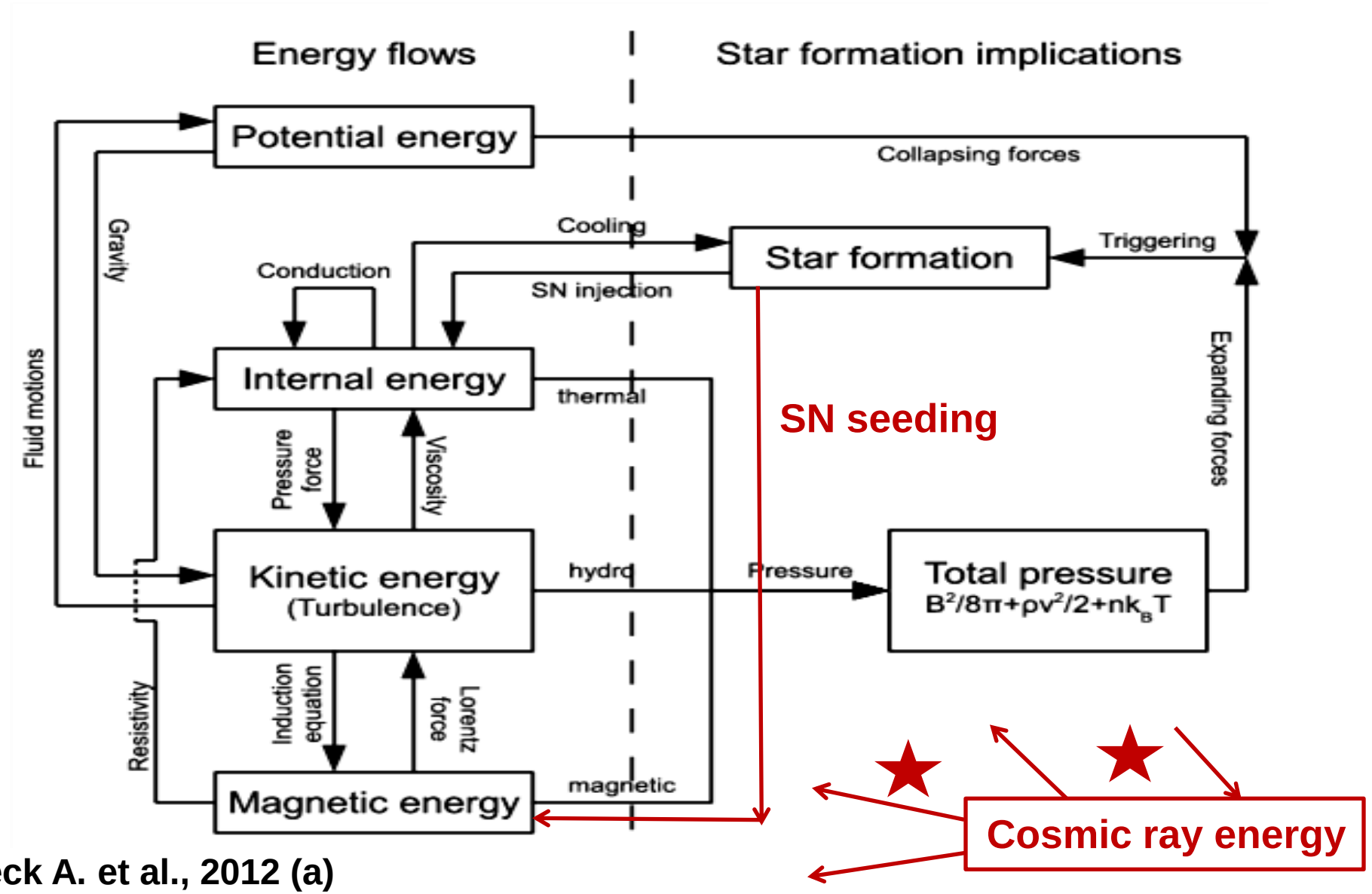






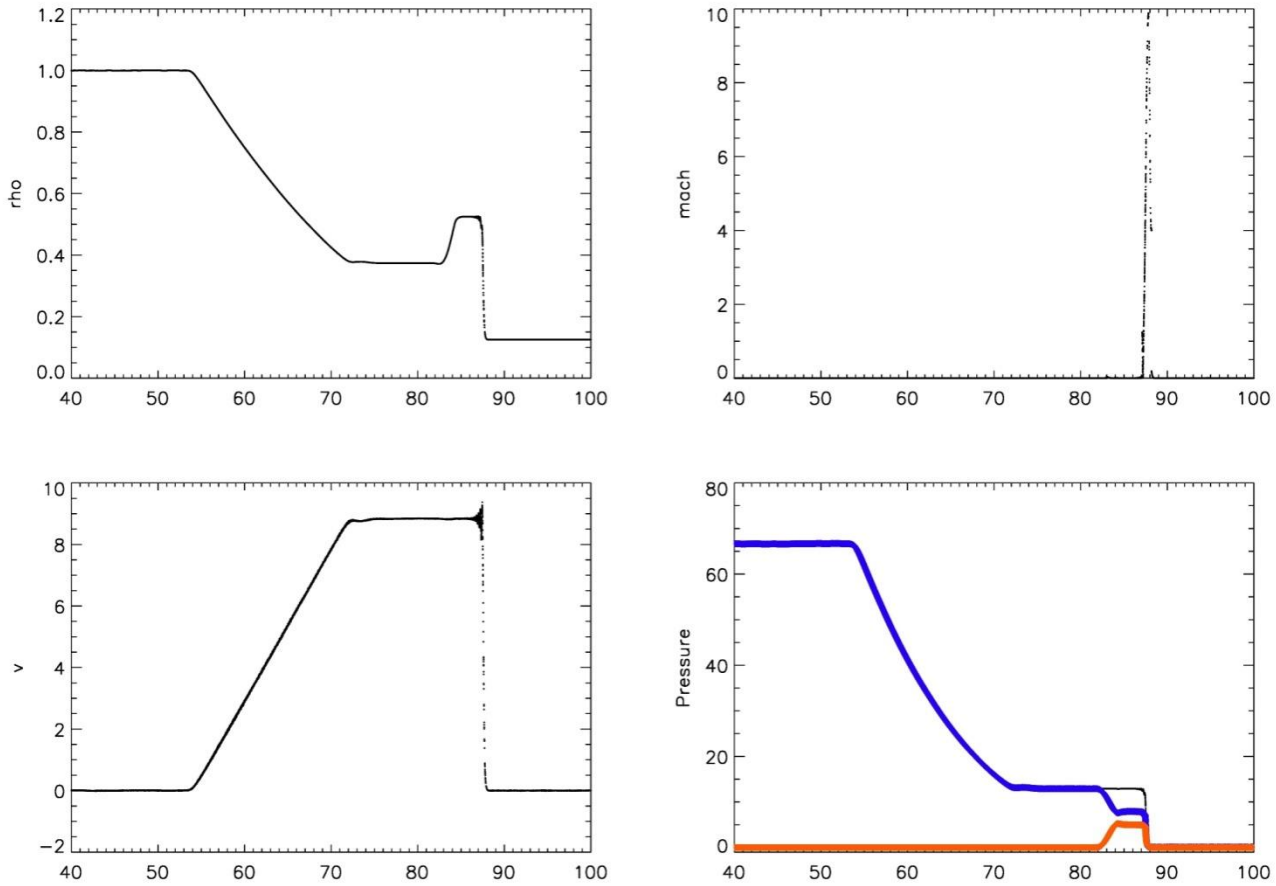
Beck A. et al., 2012 (a)

Cosmic ray dynamics



Beck A. et al., 2012 (a)

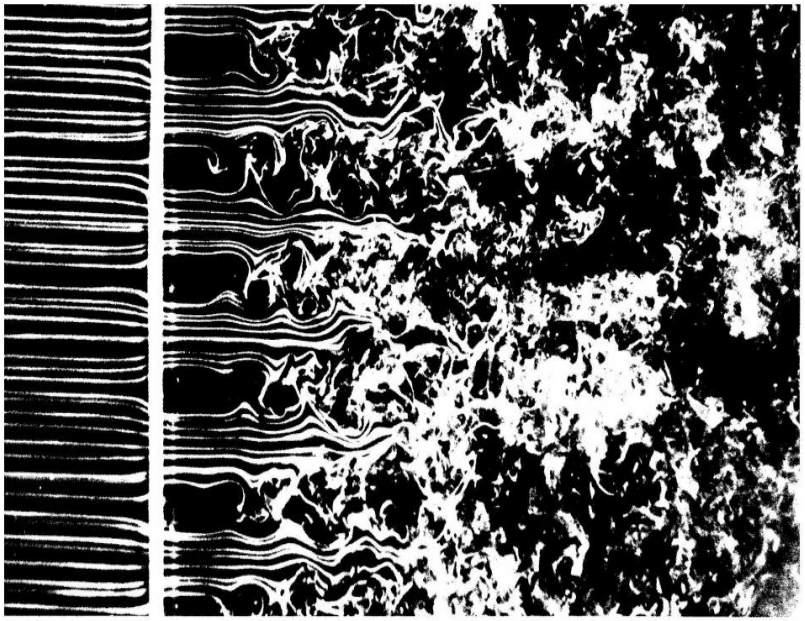
Beata‘s cosmic ray model



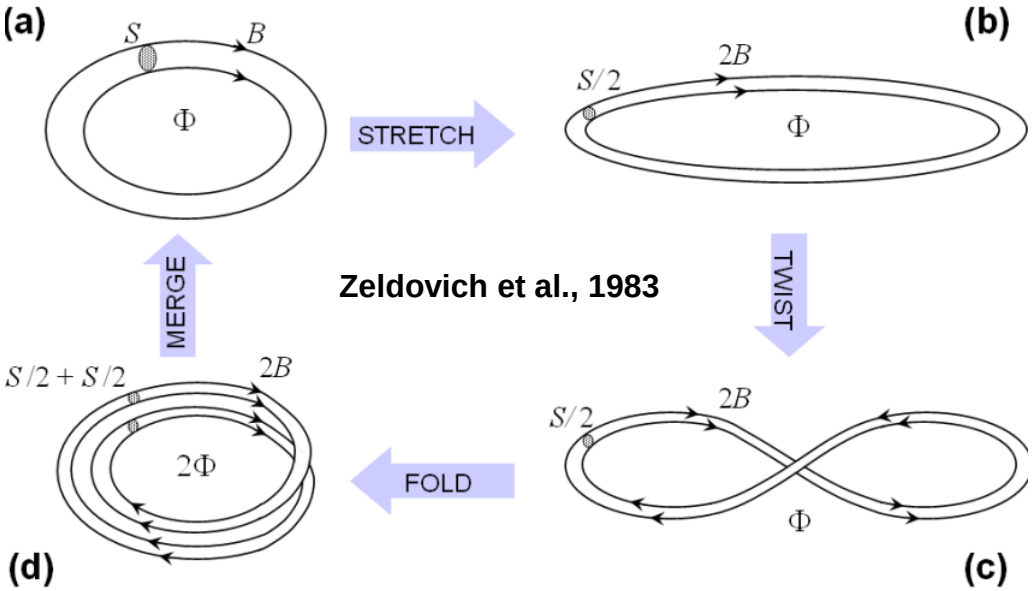
Pasternak et al., 2012, in preparation

- Developing a on-the-fly Machnumber calculation scheme
- Implementing full cosmic ray seeding, injection and evolution model
  -> Postprocessing will become much more easy

Small-scale dynamo



Van Dyke et al., 1982



Zeldovich et al., 1983

$$B \propto 2^n \quad \Rightarrow \quad B \propto e^{\gamma t}$$

Inertial forces >> Viscous forces ---- Very complex physical processes

- Turbulent and instable hydrodynamical flow with Re >> Re_{crit}
- Study small magnetic perturbations
- Magnetic field following the velocity field (weak-field / frozen in)

Analytical model

Ansatz $$B_t(t) = B_t(t_0) e^{\Gamma t} e^{-i\omega t}$$

Evolution equation $$\frac{\partial B_t^2(t)}{\partial t} = 2\Gamma B_t^2(t)$$

Beck at al., 2012 (a)
Kulsrud & Anderson, 1992
Malyshkin & Kulsrud, 2002

Truncation $$\Gamma = \gamma \left[1 - \frac{B_t^2(t)}{B_{\rm sat}^2} \right]$$

Belyanin, Sokoloff & Shukurov, 1993

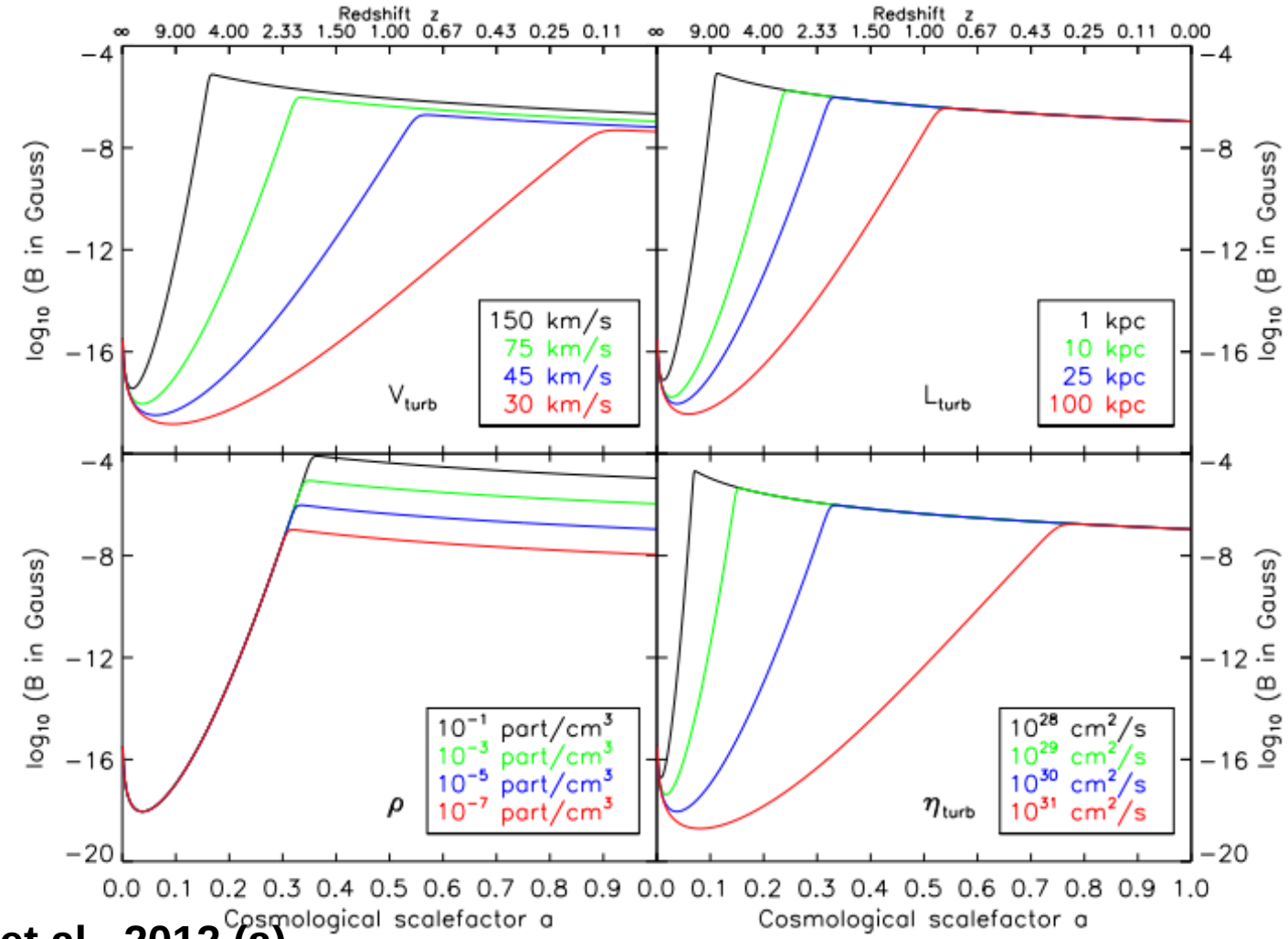
Growth rate $$\gamma = 2.050 \frac{v_{\rm turb}^{3/2} k_{\rm turb}^{1/2}}{\eta_{\rm turb}^{1/2}}$$

Kulsrud et al., 1997 (Kolmogorov turbulence)

$$B_t(a) = \frac{1}{a^2} \left[(4\pi\rho v_{\rm turb}^2)^{-1} + B_0^{-2} e^{-2\gamma t(a)} \right]^{-\frac{1}{2}}$$

Cosmological turbulent small-scale equipartition dynamo

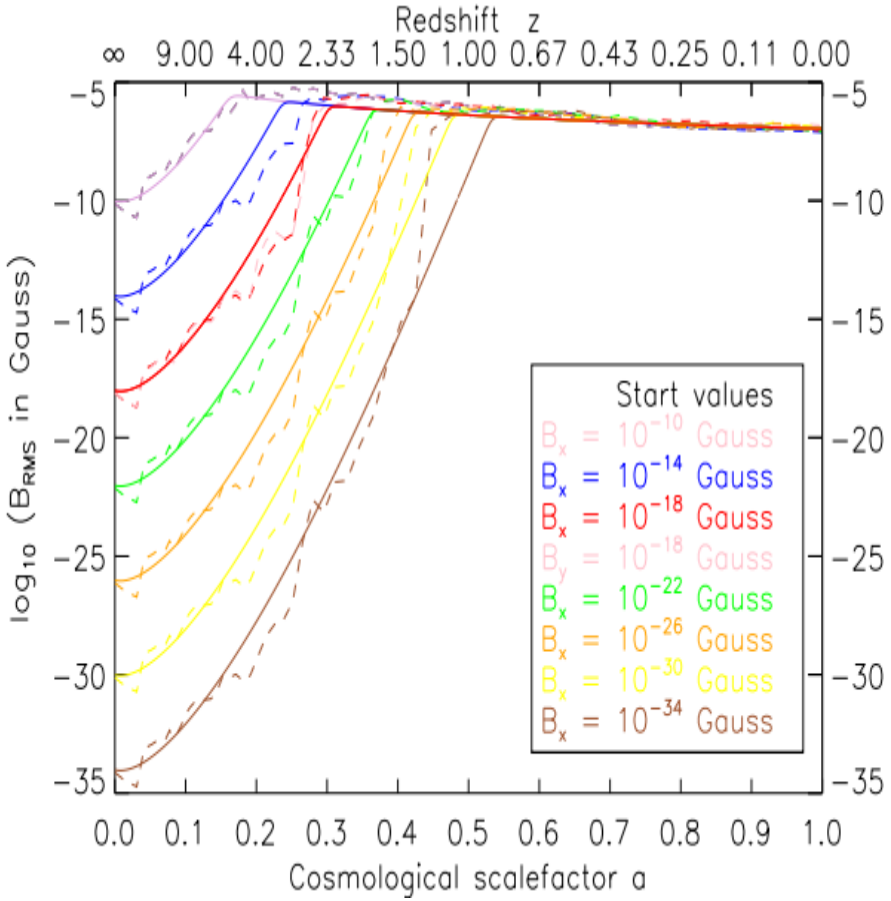
Discussion

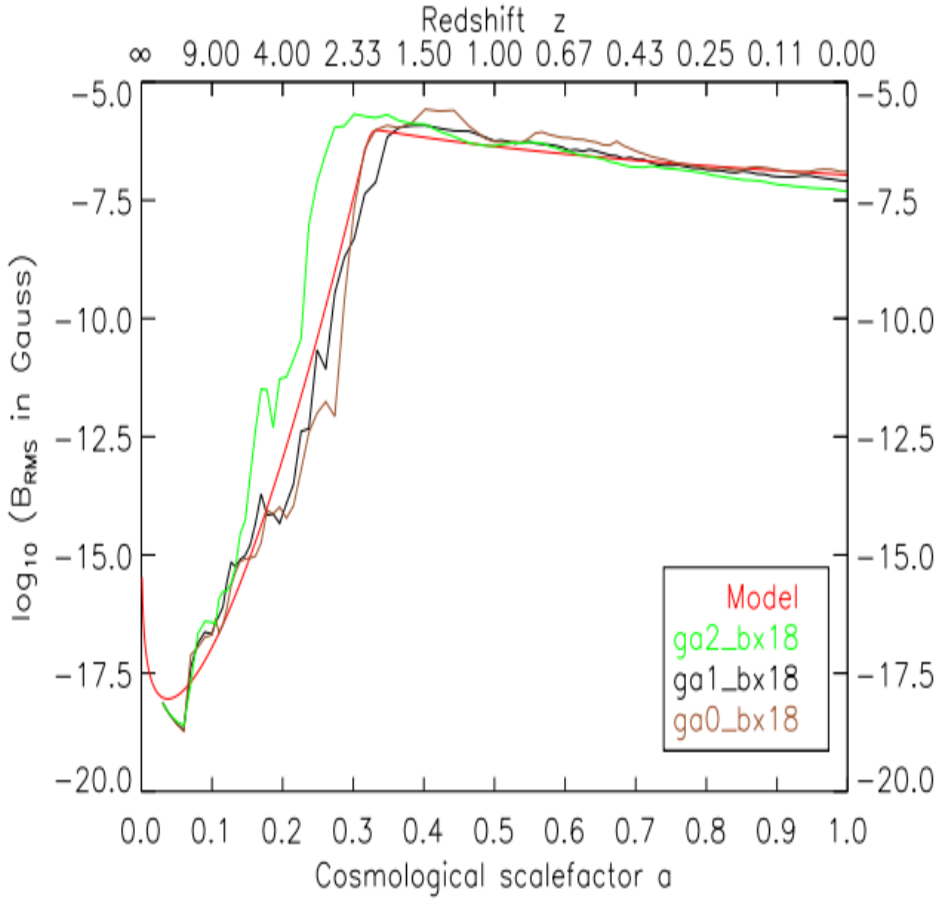


Beck A. et al., 2012 (a)

Growth curves for different astrophysical systems

Agreement with model





Beck A. et al., 2012 (a)

Length scale: 25 kpc
Turbulent velocity: 75 km/s

→ Excellent agreement !!!

Summary

Structure formation (ΛCDM)

Primordial universe	Energy fluctuations	Magnetic seeding	$B_{Seed} \sim 10^{-18}$ G
DM Potentials	Baryonic matter infall	Cosmological dip	$B \sim a(t)^{-2}$
Filaments Haloes	Compression	Isotrop compression	$B \sim \rho^{2/3}$
	Star formation	Turbulent dynamo Exponential amplification	$B \sim e^{\gamma \cdot t(a)}$
Haloes	Star formation Mergers		
IGM	Mergers Shocks Outflows		
Virialized systems	Equipartition	Power-law decay	$B_{Halo} \sim 10^{-7}$ G $B_{IGM} \sim 10^{-9}$ G
Galactic disks	Rotation	α-ω-dynamo CR-dynamo	$B_{Disk} \sim 10^{-5}$ G

Magnetic amplification

Beck A. et al., 2012 (a)

Summary

- Magnetic fields are amplified in galaxy mergers
- Hierarchical structure formation amplifies magnetic fields from seed fields to observed (equipartition) values
- Analytical model and numerical simulations agree very well

Main result papers:

Beck A., Lesch, Dolag, Kotarba, Geng & Stasyszyn
2012, MNRAS, 422, 2152, Primordial seeded cosmological simulation

Geng, Kotarba, Bürzle, Dolag, Stasyszyn, Beck A. & Nielaba
2012, MNRAS, 419, 3571, Galaxy minor mergers

Geng, Beck A., Dolag, Bürzle, Beck M., Kotarba & Nielaba
2012, ArXiv: 1206.1234, MNRAS minor revision, Stephan's Quintet

Beck A., Stasyszyn, Geng, Dolag & Lesch
2012, in preparation, Supernova seeded cosmological simulation

Pasternak, Dolag, Beck A., Siemieniec-Ozieblo
2012, in preparation, Cosmic ray evolution model

Thank you !