Multi-scale and multi-physics numerical models of galaxy formation

M. Rieder and RT, 2016, MNRAS, 457, 1722

J. Rosdahl, J. Schaye, RT and O. Agertz, 2015, MNRAS, 451, 34

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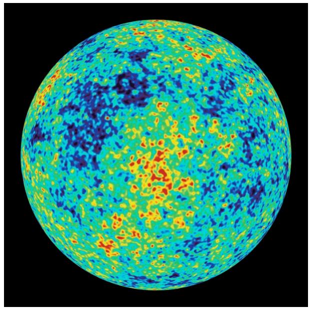
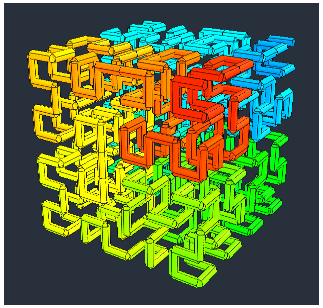
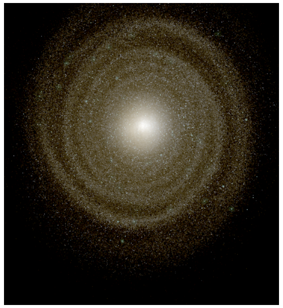
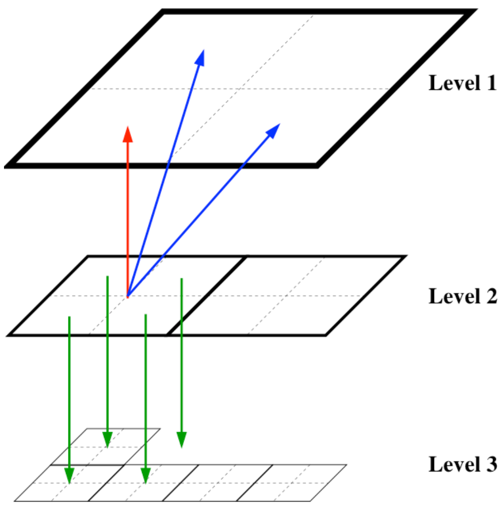






RAMSES: parallel Adaptive Mesh Refinement



- Graded octree structure: the cartesian mesh is refined on a cell by cell basis
- Full connectivity: each oct have direct access to neighbouring parent cells and to children octs (memory overhead 2 integers per cell).
- Optimise the mesh adaptivity to complex geometry but CPU overhead can be as large as 50%.

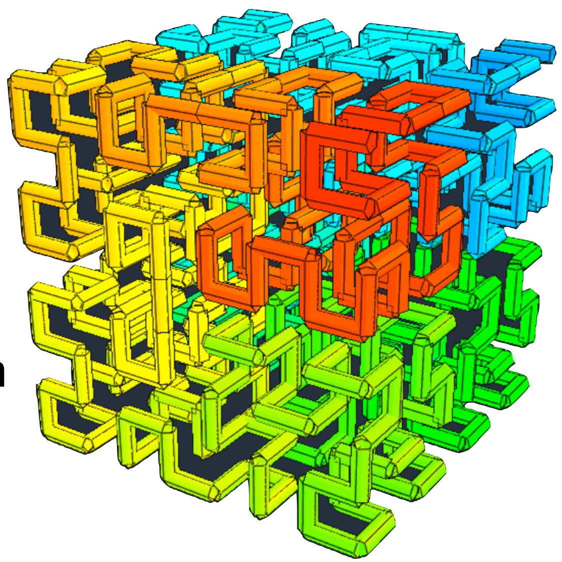
N body module: Particle-Mesh method on AMR grids. Poisson equation solved using a multigrid solver.

Hydro module: unsplit second order Godunov method (MUSCL) with various Riemann solvers and slope limiters. **MHD solver with Constrained Transport**.

Time integration: single time step or sub-cycling.

Other: **radiative transfer with moments method**, star formation, sink particles, stellar and AGN feedback

MPI-based parallel computing using time-dependent domain decomposition based on Peano-Hilbert cell ordering.

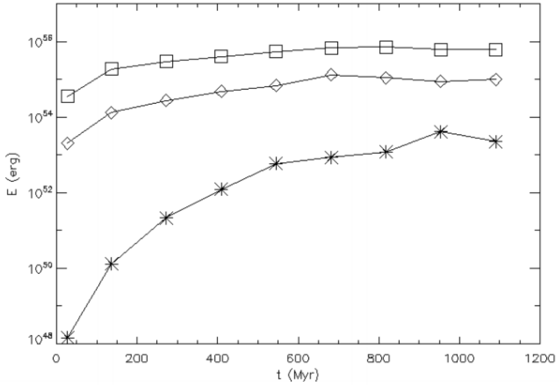


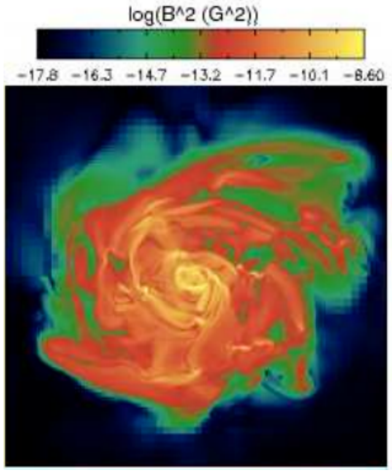
Download at **https://bitbucket.org/rteyssie/ramses**

Magneto-Hydrodynamics

The origin of cosmic magnetic fields

- Biermann battery sets the initial field at 10^{-20} G (Naoz & Narayan 2013).
- Current magnetic fields in local galaxies reaches several 10^{-6} G.
- High-redshift galaxies seems to have 10x larger fields, probably even increasing with increasing redshift (Bernet, Miniati & Lilly 2013)
- Successful large-scale dynamos are slow with growth rate $\simeq 0.1\Omega$ up to Ω Hanasz *et al.* (2004), Pariev et al. (2007), Gressel et al. (2008)
- Early galaxy formation MHD simulations with no or weak feedback show moderate field amplification: Wang & Abel (2009), Dubois & Teyssier (2010)



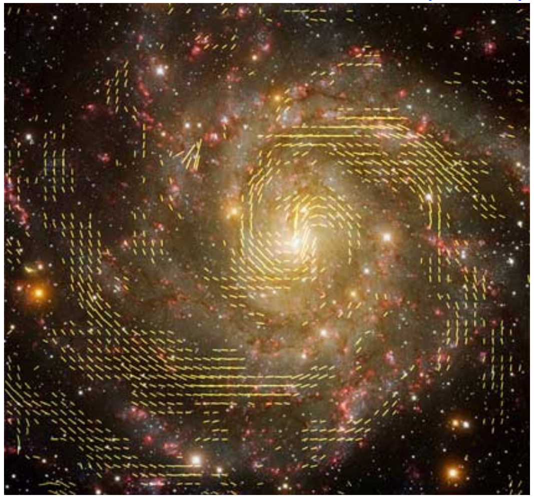


Wang & Abel (2009)

Recent simulations of magnetic fields in galaxy formation

- Beck et al. (2012): GADGET code, new MHD solver, small scale dynamo as a source of fast field amplification
- Pakmor and Springel (2013): AREPO code, new MHD solver, large scale field with fast amplification. See also Marinacci et al. (2015).
- Rodrigues et al. (2015): semi-analytical models of galaxy formation, small scale dynamo as a source of random fields, followed by mean field amplification for the large scale field

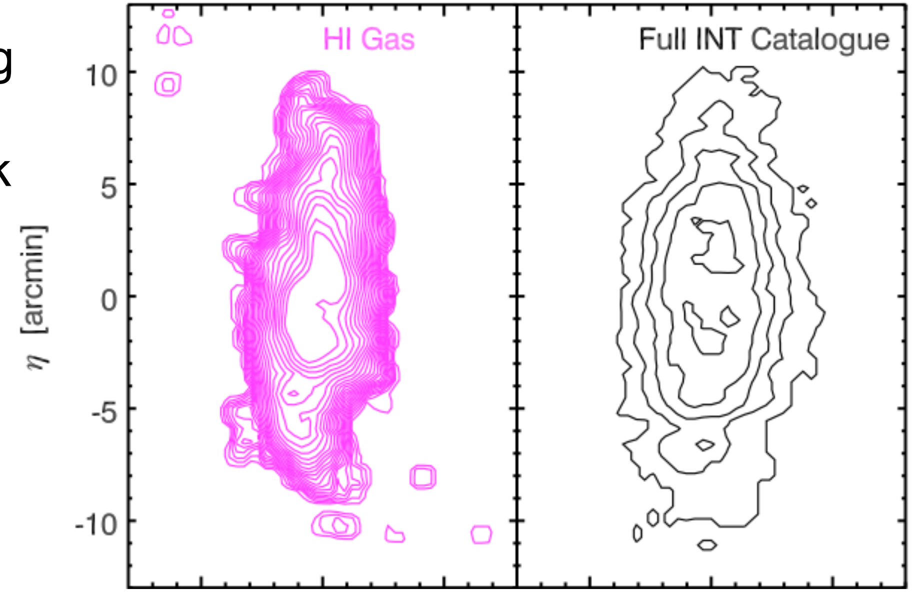
Beck (2015)

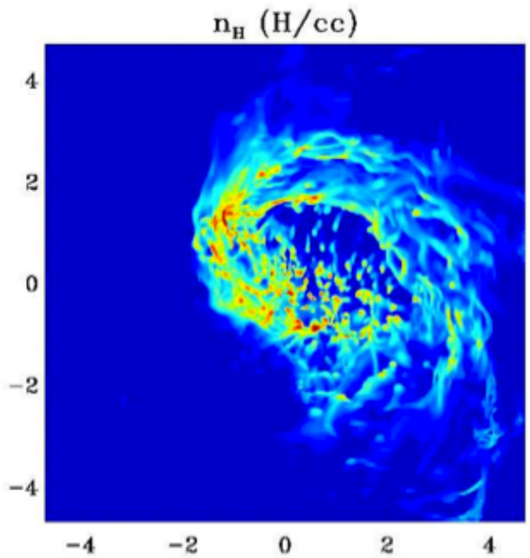


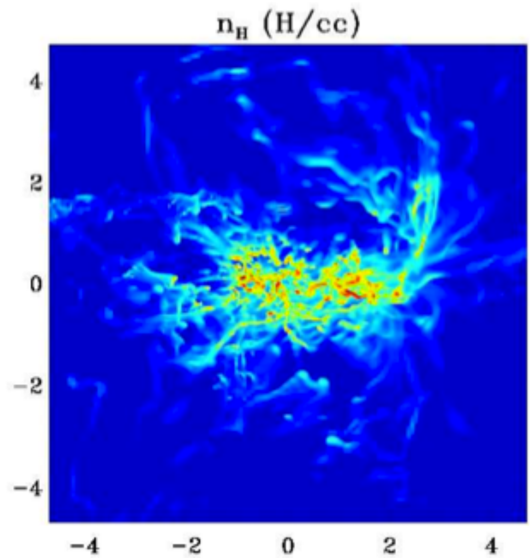
Supernovae feedback in dwarf galaxies

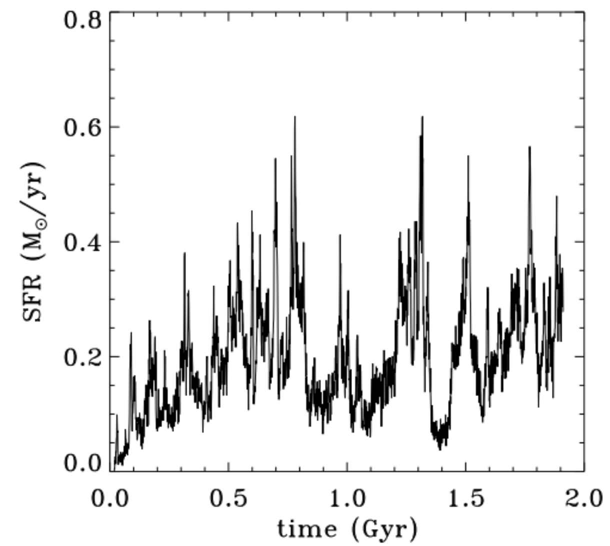
Supernovae feedback implemented using non-thermal energy dissipation (Teyssier et al. 2013) result in the formation of thick disks with V/sigma ~ 1, and a strongly reduced SF efficiency ($M_s/M_h \sim 0.01$).

This is in striking agreement with the nearby isolated dwarf WLM (Eastman et al. 2012) although $M_s/M_h \sim 0.001$.

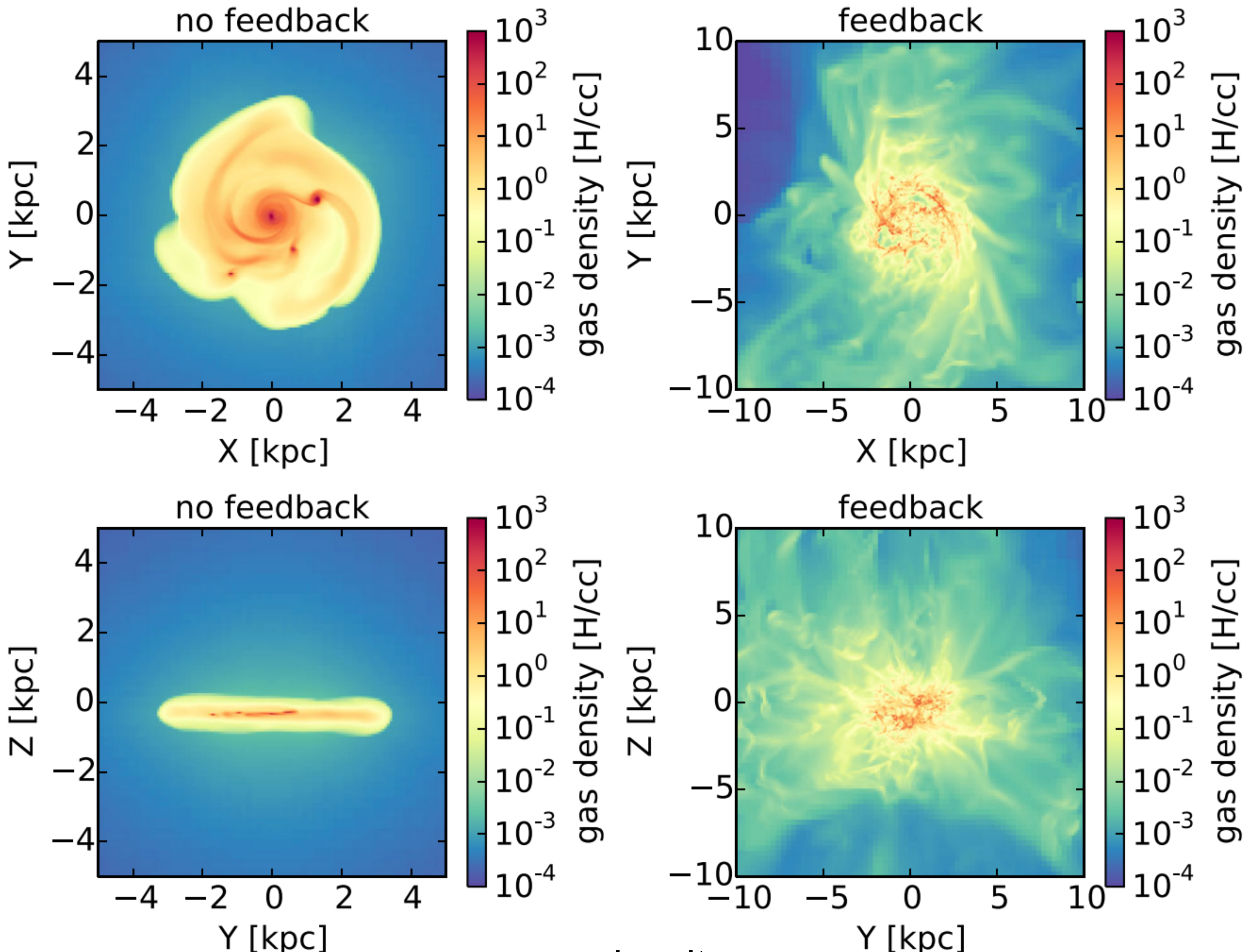






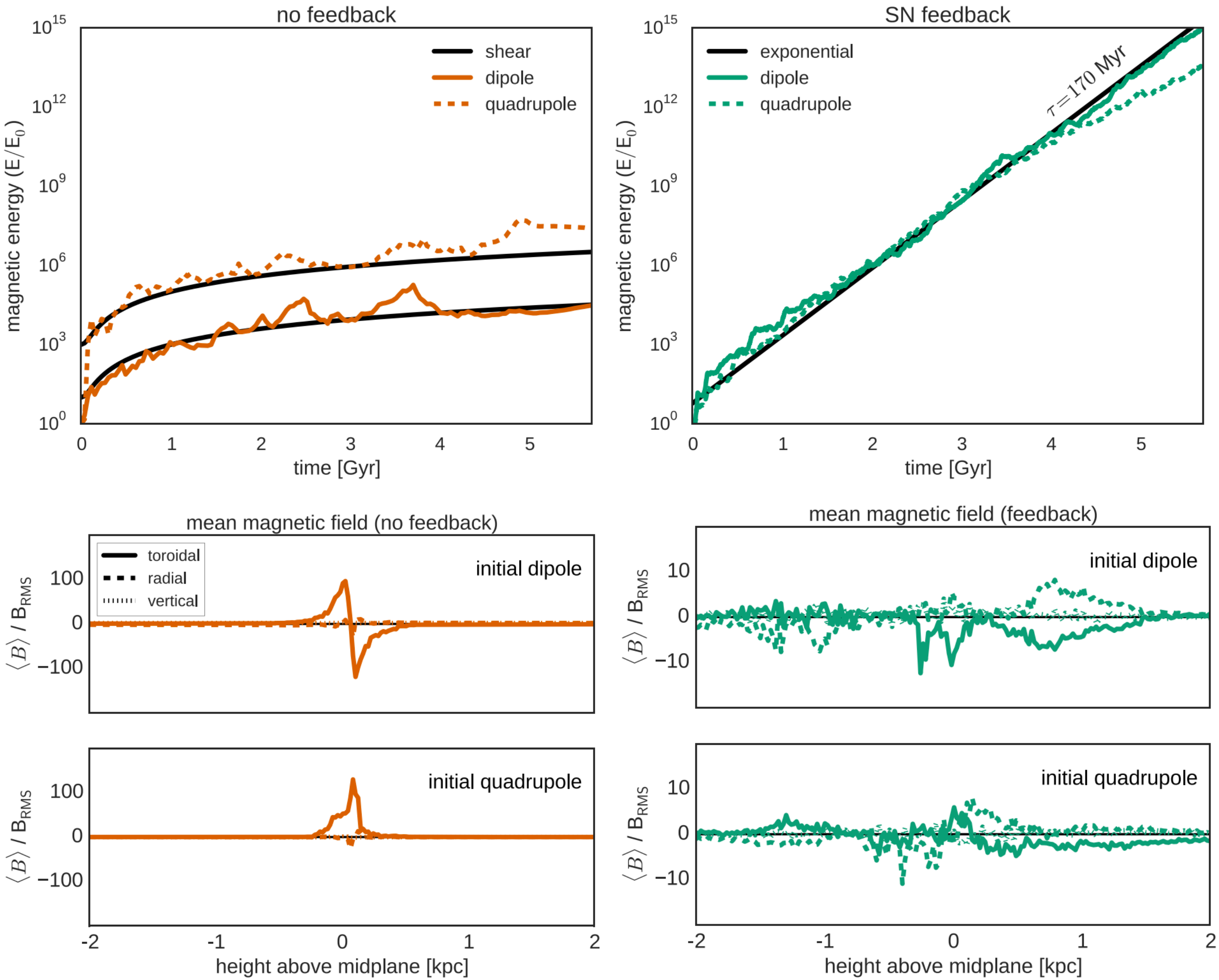


Turbulent dynamo in a dwarf galaxy

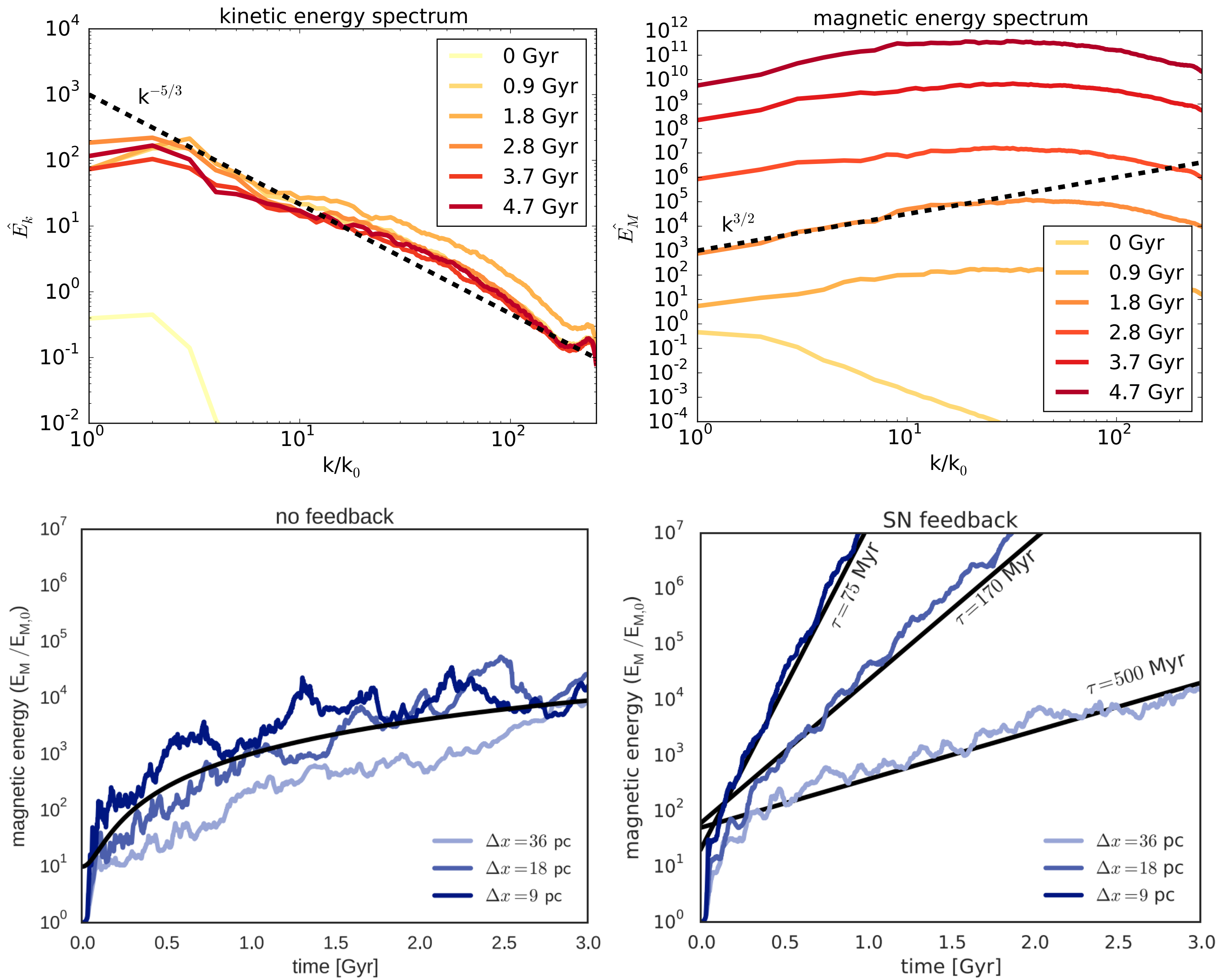


gas density

Magnetic field generation in dwarf galaxies



A small scale dynamo ?



Conclusions for the cosmic dynamo

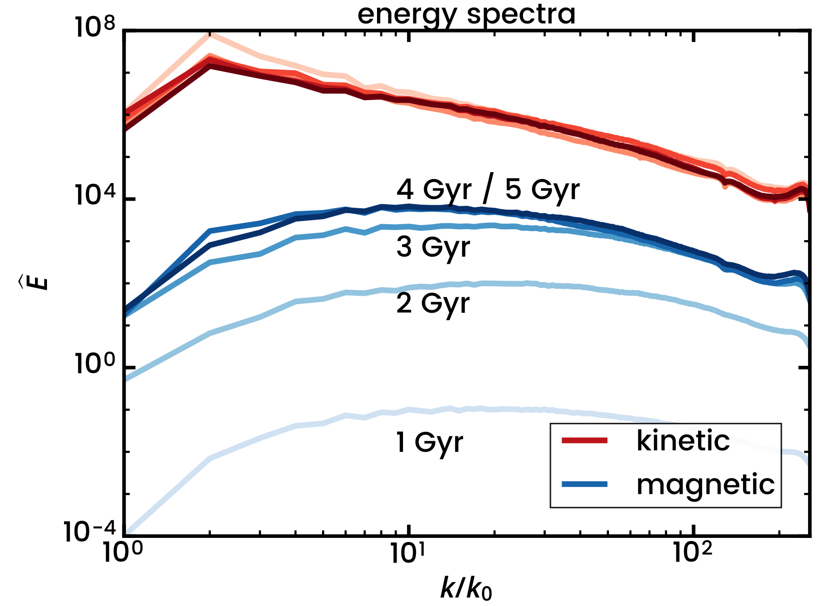
In high-redshift, feedback-dominated galaxies with $\sigma \simeq V_{\rm rot}$, we obtain a small scale magnetic dynamo with growth rate set by the smallest scale, and reaching saturation on larger and larger scales.

If field reaches equipartition $B_{\rm equ} \simeq \sqrt{8\pi\rho_{\rm gas}}\sigma \simeq 10\mu{\rm G}\,(1+z)^2 \left(\frac{M_{200}}{10^{10}M_\odot}\right)^{1/3}$

Saturation of the small scale dynamo is closer to 10% of equipartition.

Around redshift 2, for more massive galaxies, we have a transition from dispersion-dominated spheroids to rotation-dominated discs.

Formation of razor-thin discs, with competition between amplification through collapse and dissipation through reconnection. Final field strength ?

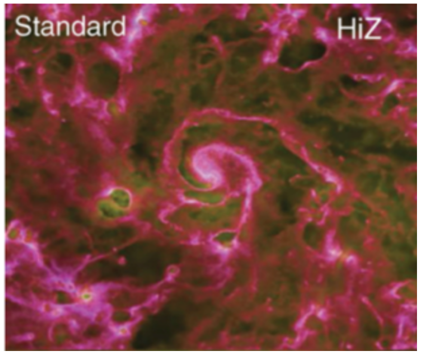


Later time evolution: magnetic energy is slowly decaying, or is slowly maintained by a large-scale dynamo.

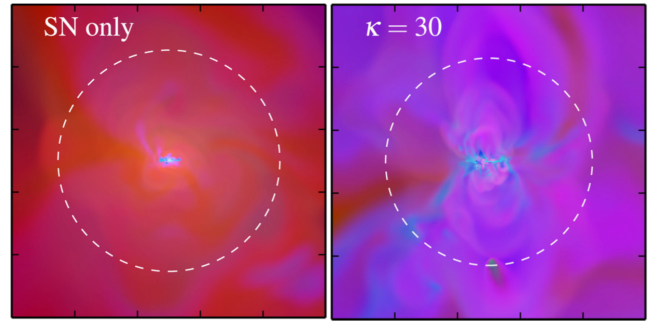
Radiation Hydrodynamics

Radiation plays a role in shaping galaxies

Radiation driven feedback is invoked to model stellar feedback in current galaxy formation simulations. Only implemented through sub-grid models.

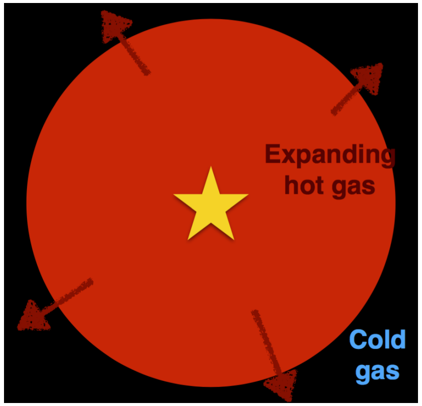


Hopkins et al. (FIRE)

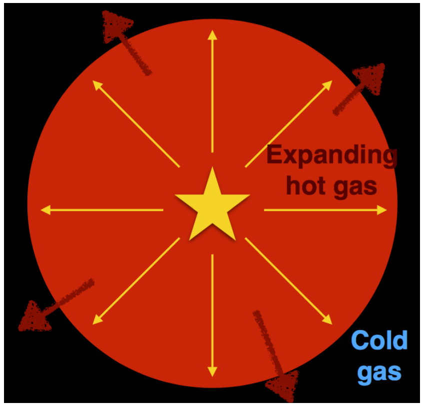


Roskar et al. (2014)

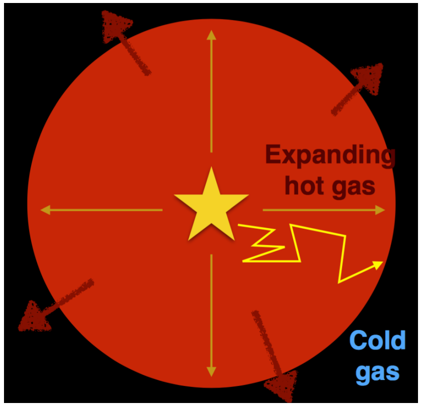
Different modes of radiation feedback, modelled self-consistently using radiation hydrodynamics in RAMSES-RT (Rosdahl et al. 2011, 2015)



1- UV radiation heats the gas



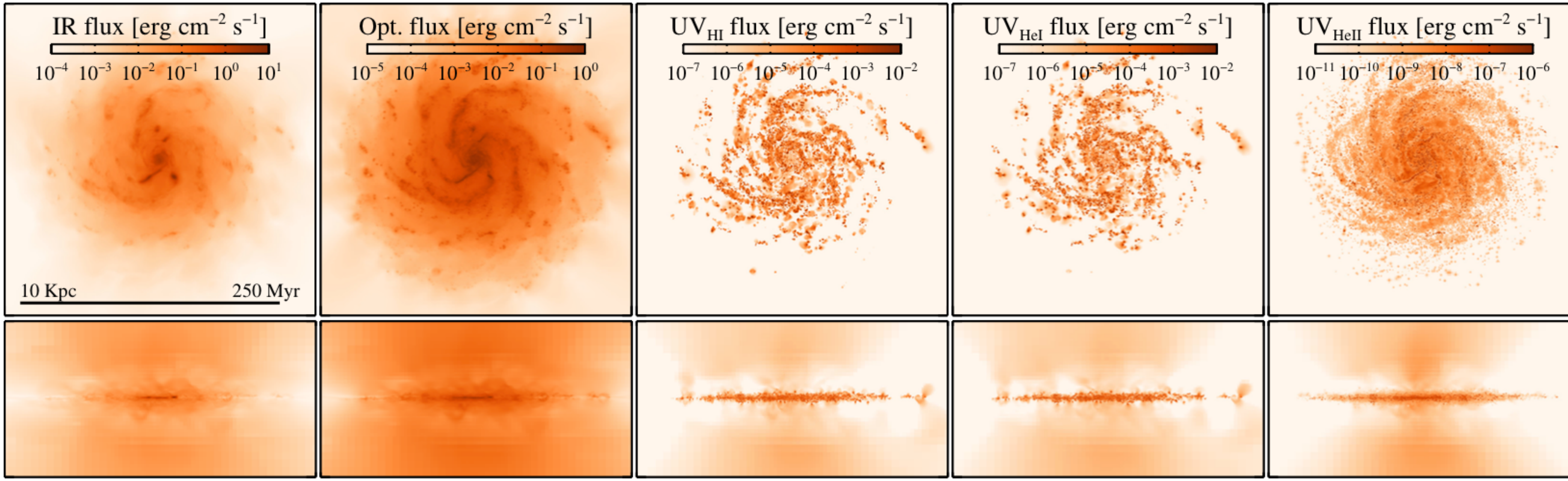
2- UV radiation gives momentum to the gas



3- IR radiation can multiply scatter and gives more momentum

Galaxies that shine

Isolated galaxy with 5 different photons groups, photo-ionisation and dust absorption.



Rosdahl *et al.* (2015)

- 10^{11} solar masses halo
- 3×10^{9} solar masses baryonic disk
- 50% gas fraction.

- 10^{6} stellar and DM particles
- 18 pc resolution
- 0.1 solar metallicity

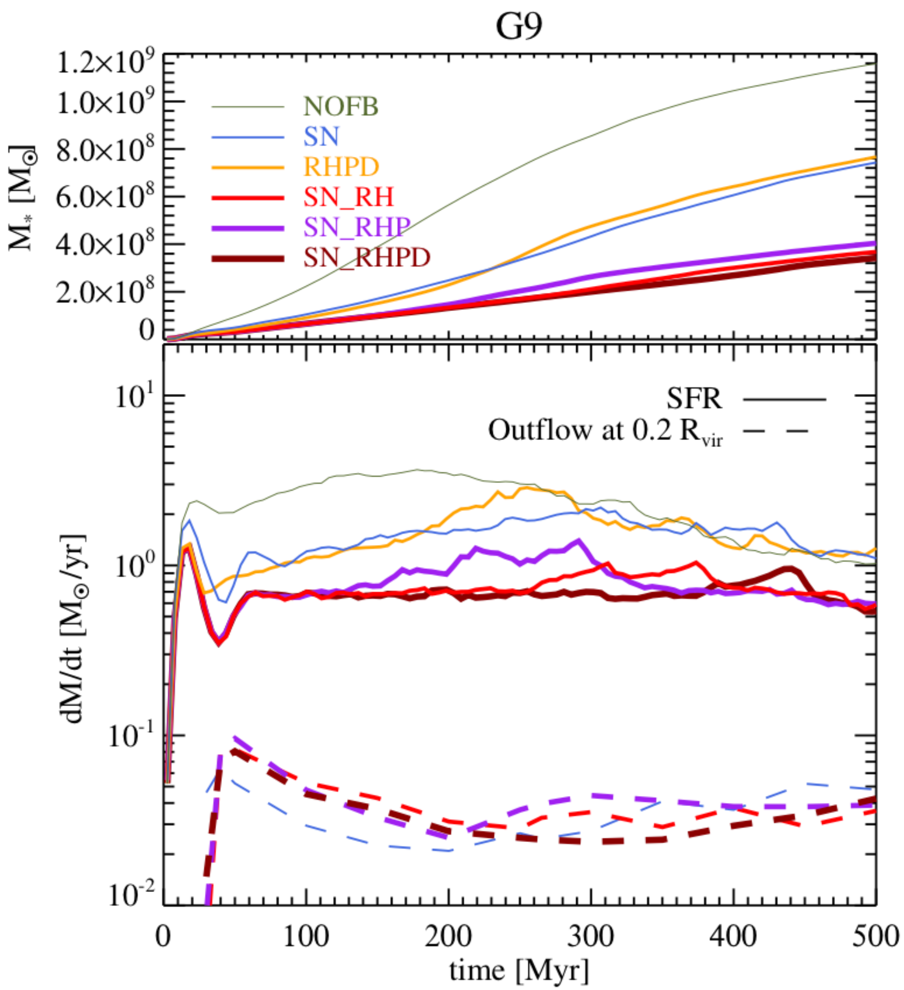
Feedback processes:

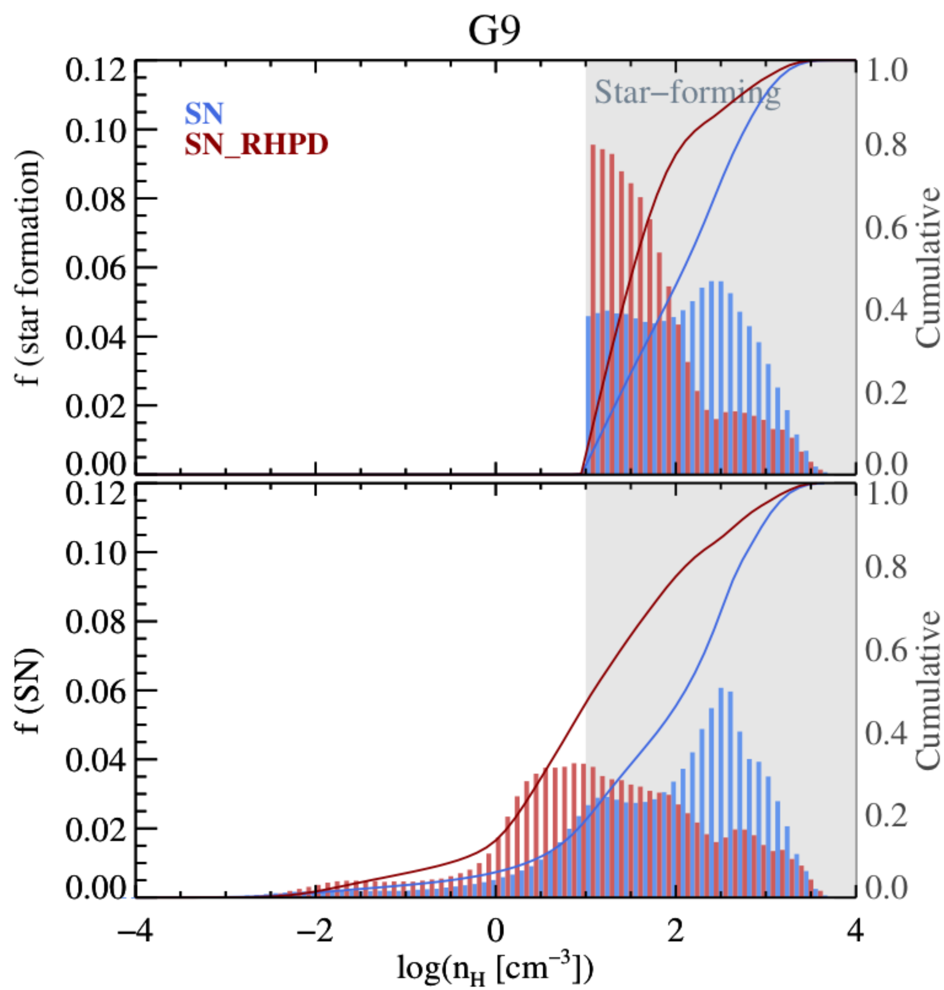
- thermal SN energy injection (no trick)
- radiation from the B&C (2003) SEDs.
- HI and dust opacities

Radiative processes:

- photo-ionisation heating
- direct pressure from UV
- IR pressure from dust scattering

The interplay between radiation and supernovae

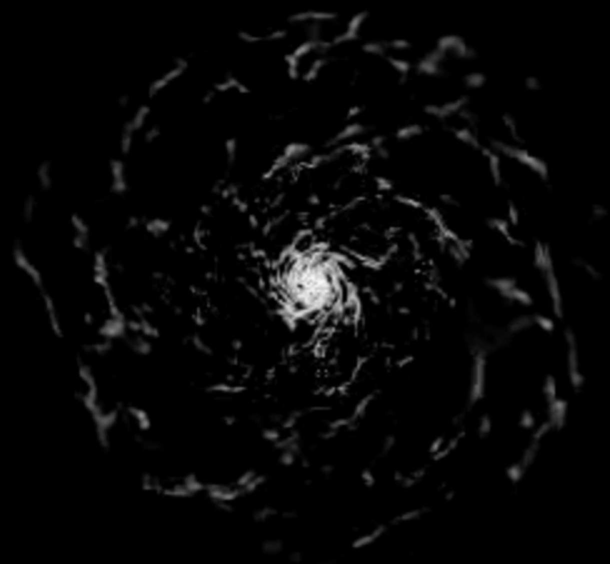




Rosdahl *et al.* (2015)

Photo-chemistry of Hydrogen

Total Hydrogen density



Molecular fraction

Conclusions

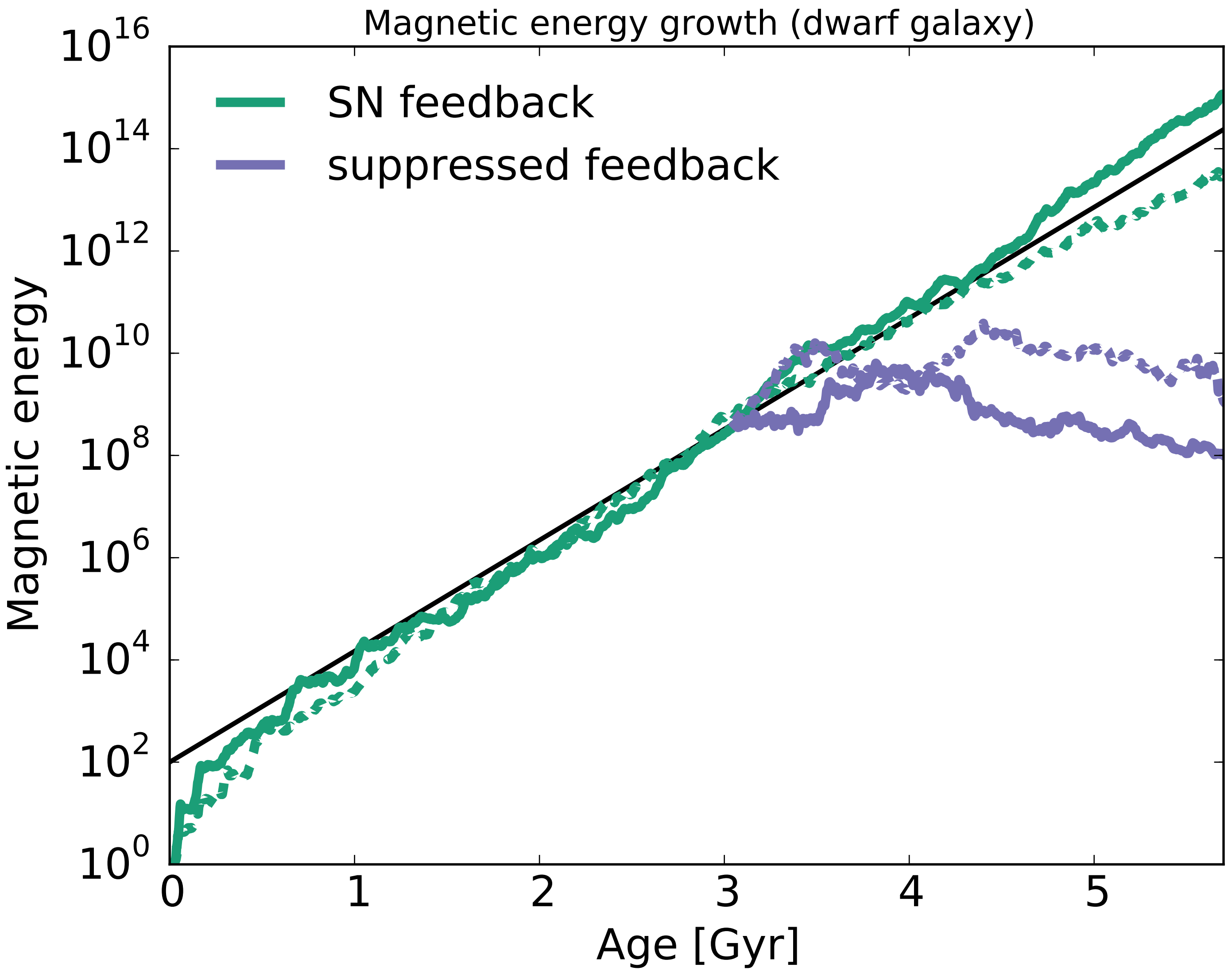
- Small-scale dynamos appear as a viable mechanism to amplify primordial fields in feedback dominated galaxies
- Saturation of the dynamo at 1/10 equipartition with turbulence
- Late time evolution: collapse back to razor-thin disks in which large scale dynamos shape the magnetic fields
- In the future : possible paradigm-shifting role of magnetic fields and cosmic rays?
- We are entering the era of radiation hydrodynamics of galaxy formation.
- Dynamical effect through photo-heating and radiation force.
- Current sub-grid models of radiation feedback are probably optimistic.
- Radiation hydrodynamics allows self-consistent chemistry (line excitation, molecular, neutral fraction…) and a detailed comparison to observations.

Photo-chemistry of Hydrogen

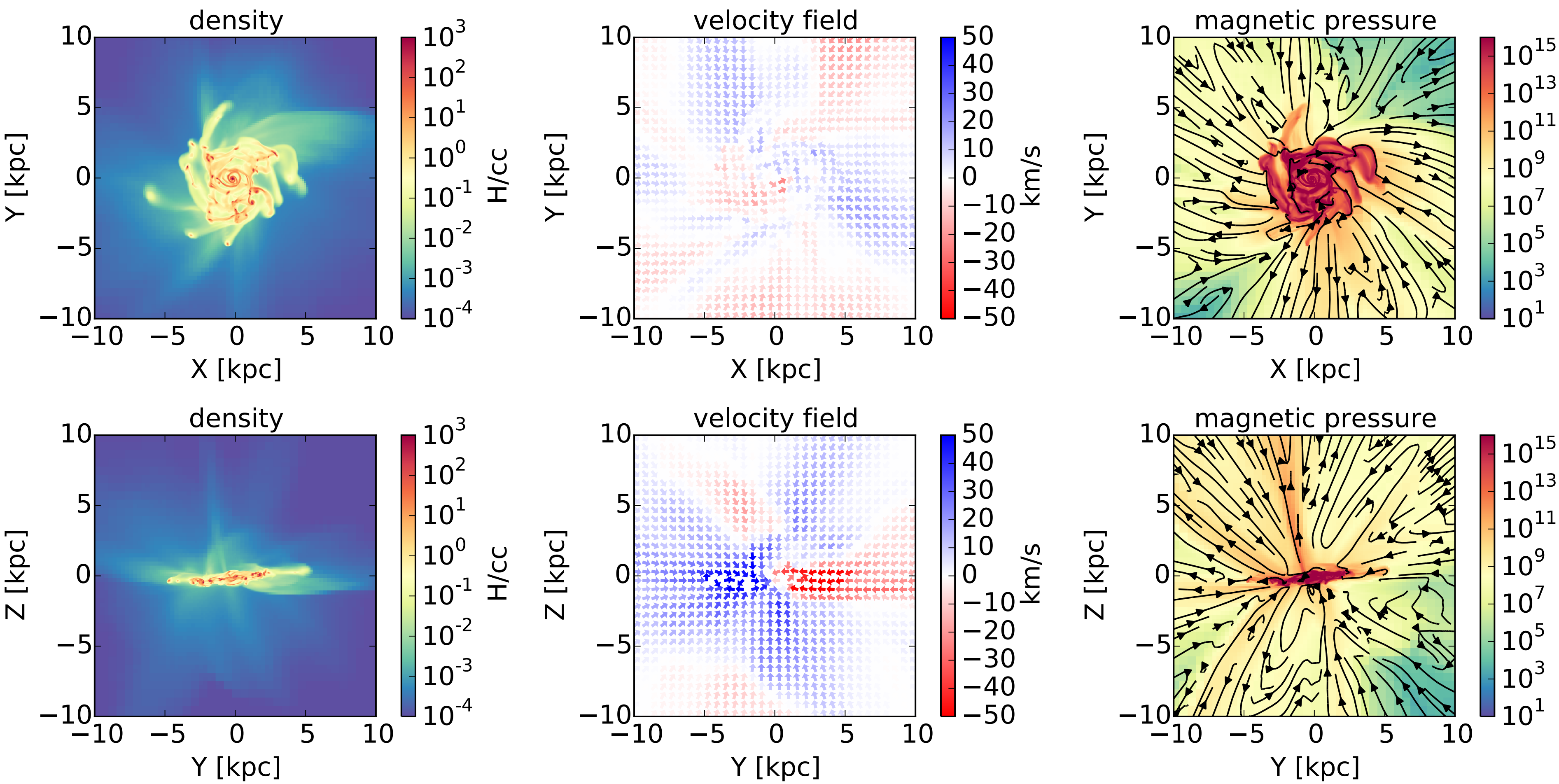
Total Hydrogen density

Molecular fraction

Suppressed feedback in dwarf galaxies



Suppressed feedback in dwarf galaxies



Suppressed feedback in dwarf galaxies