Galaxy simulation: more physics, more resolution, more sense ?

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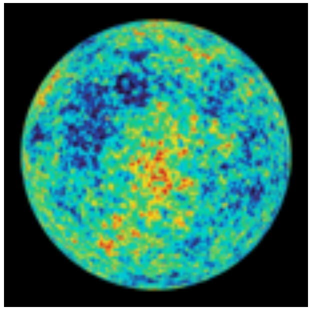
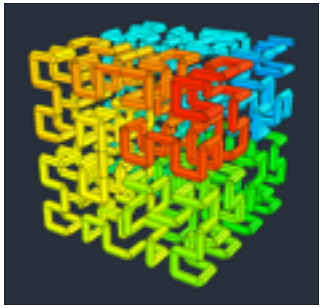
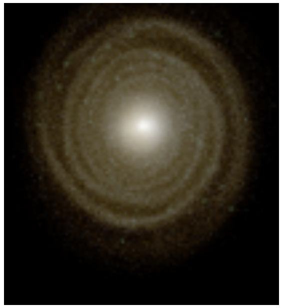
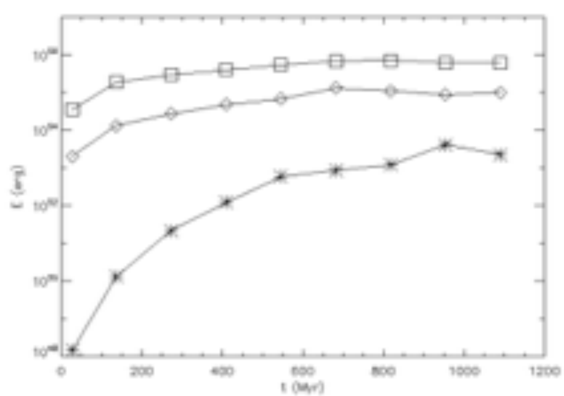




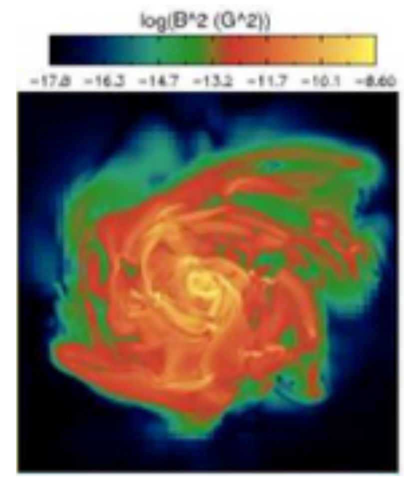
Outline

- The origin of magnetic fields in galaxies (Michael Rieder)
- Modelling galactic radiation fields (Joki Rosdahl)
- A new recipe for star formation (Valentin Perret)
- Modelling SMBH in clumpy galaxies (Pawel Biernacki)

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

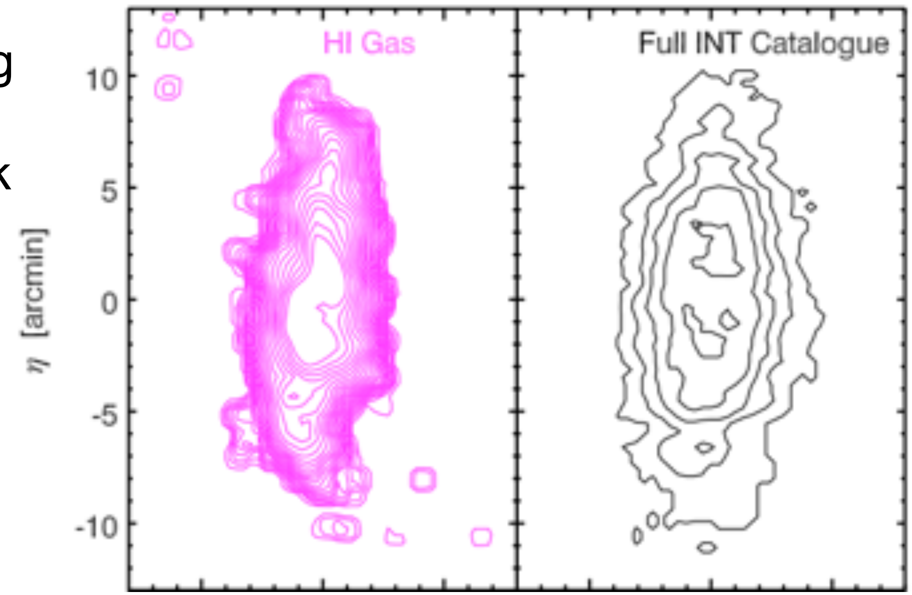
- Beck et al. (2012): GADGET code, new MHD solver, small scale dynamo as a source of fast field amplification
- Pakmor and Springel (2013): AREPO code, new MHD solver, large scale field with fast amplification. See also Marinacci et al. (2015).
- Rodrigues et al. (2015): semi-analytical models of galaxy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

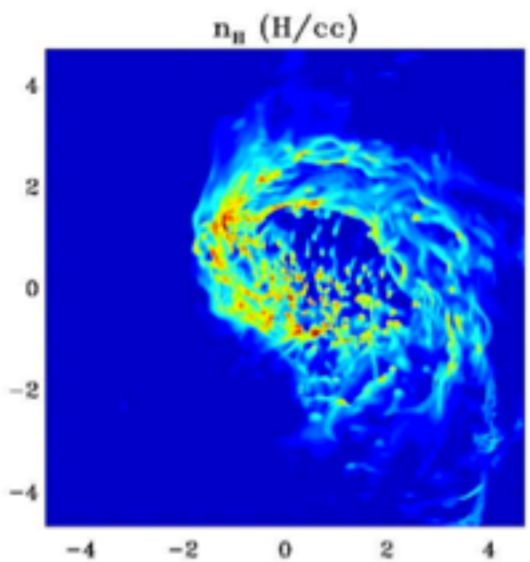
Beck (2015)

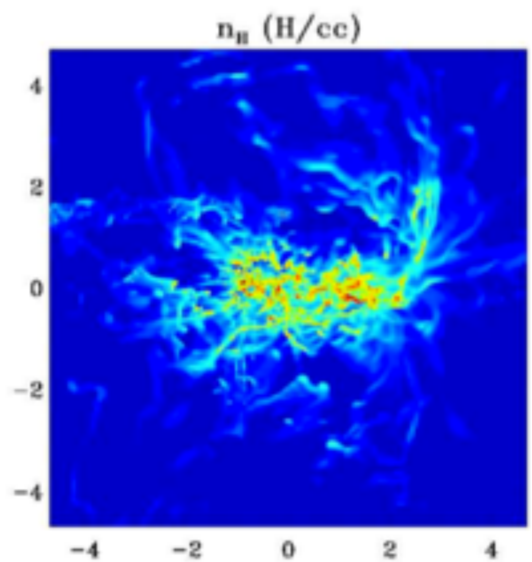
Supernovae feedback in dwarf galaxies

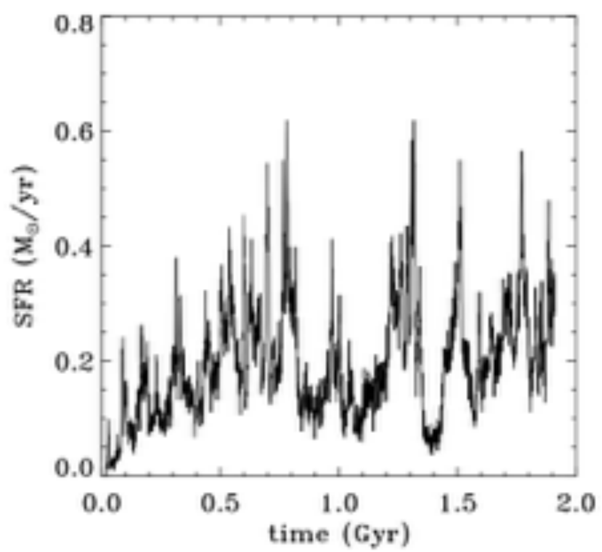
Supernovae feedback implemented using non-thermal energy dissipation (Teyssier et al. 2013) result in the formation of thick disks with V/sigma ~ 1, and a strongly reduced SF efficiency ($M_s/M_h \sim 0.01$).

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

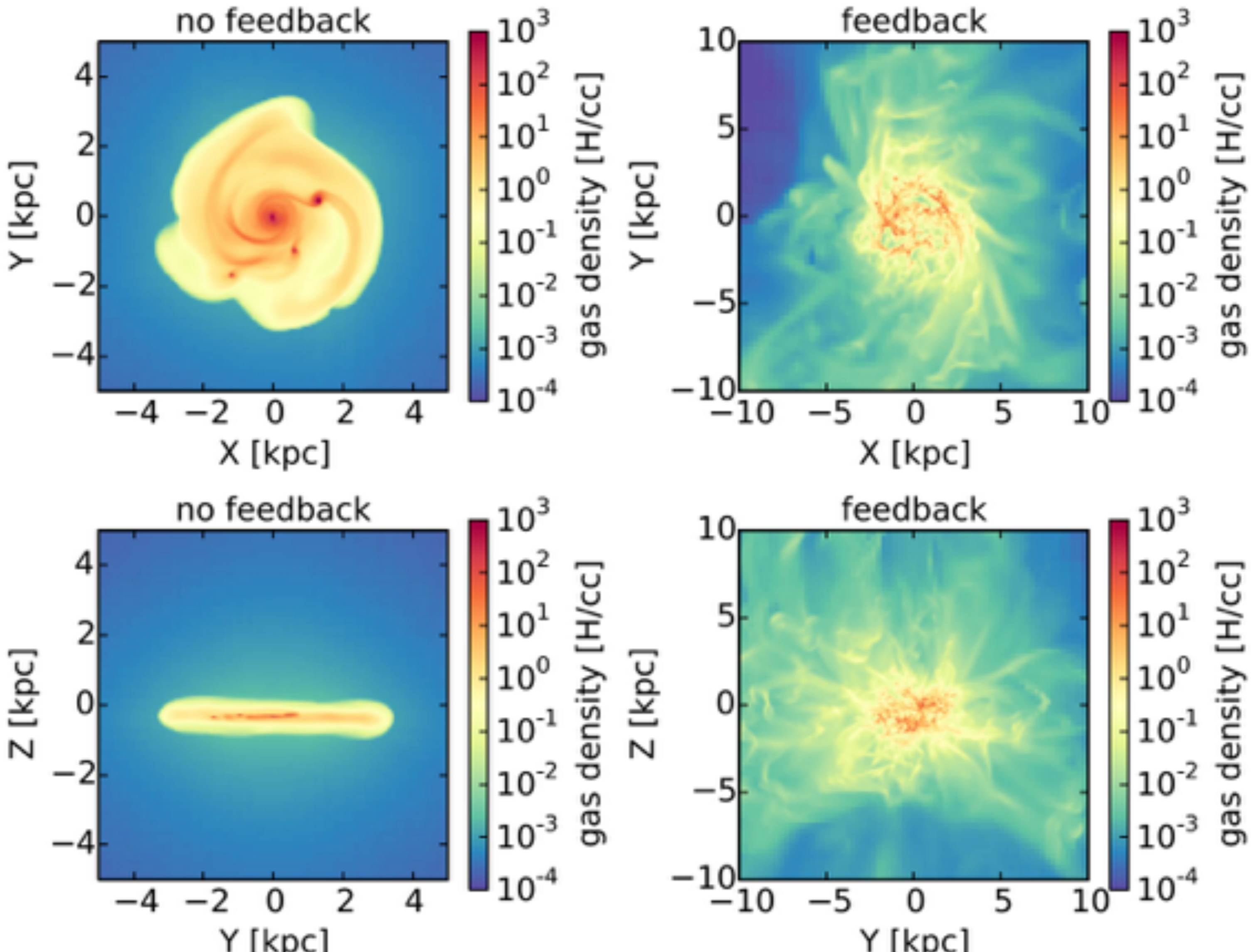






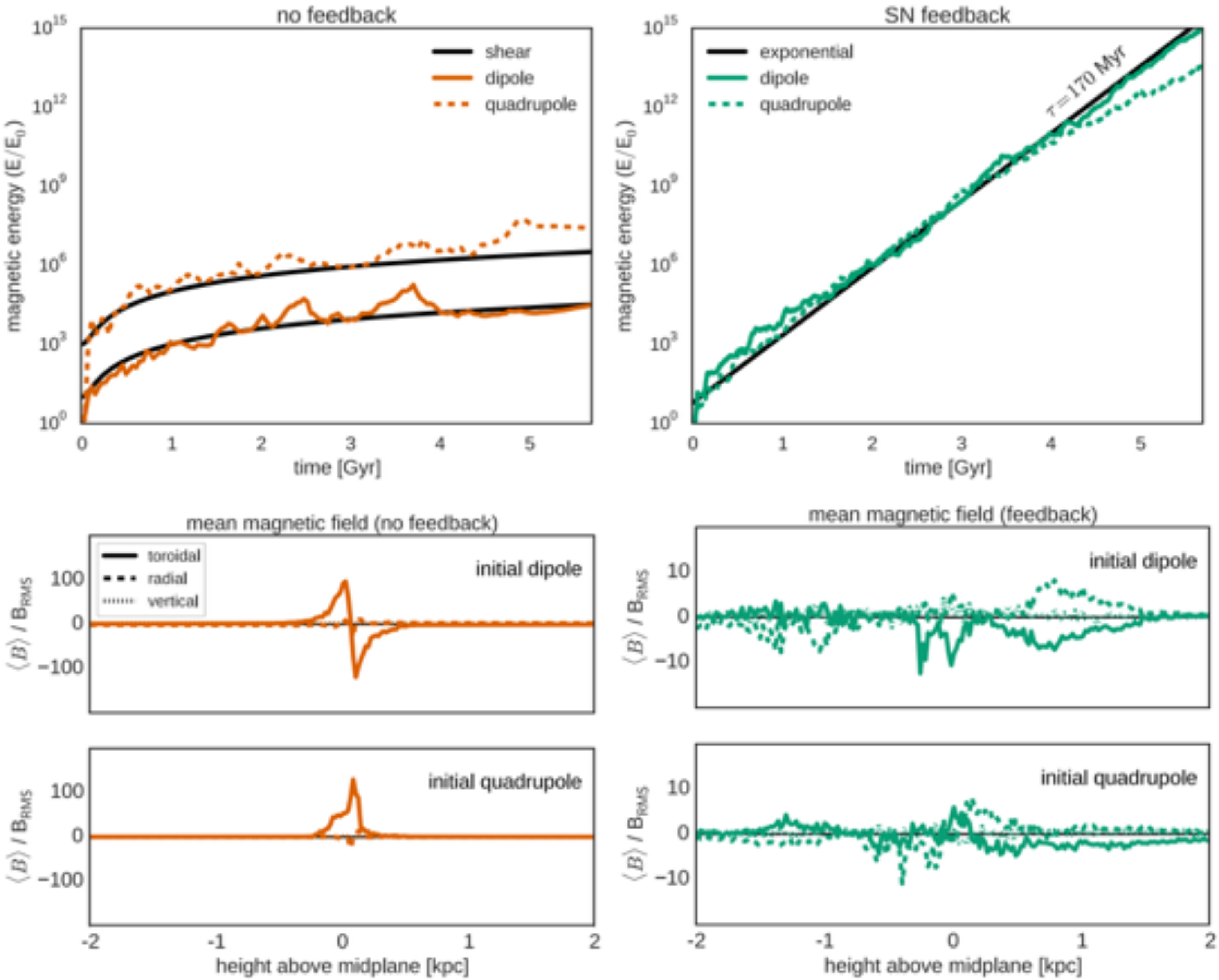


Turbulent dynamo in a dwarf galaxy

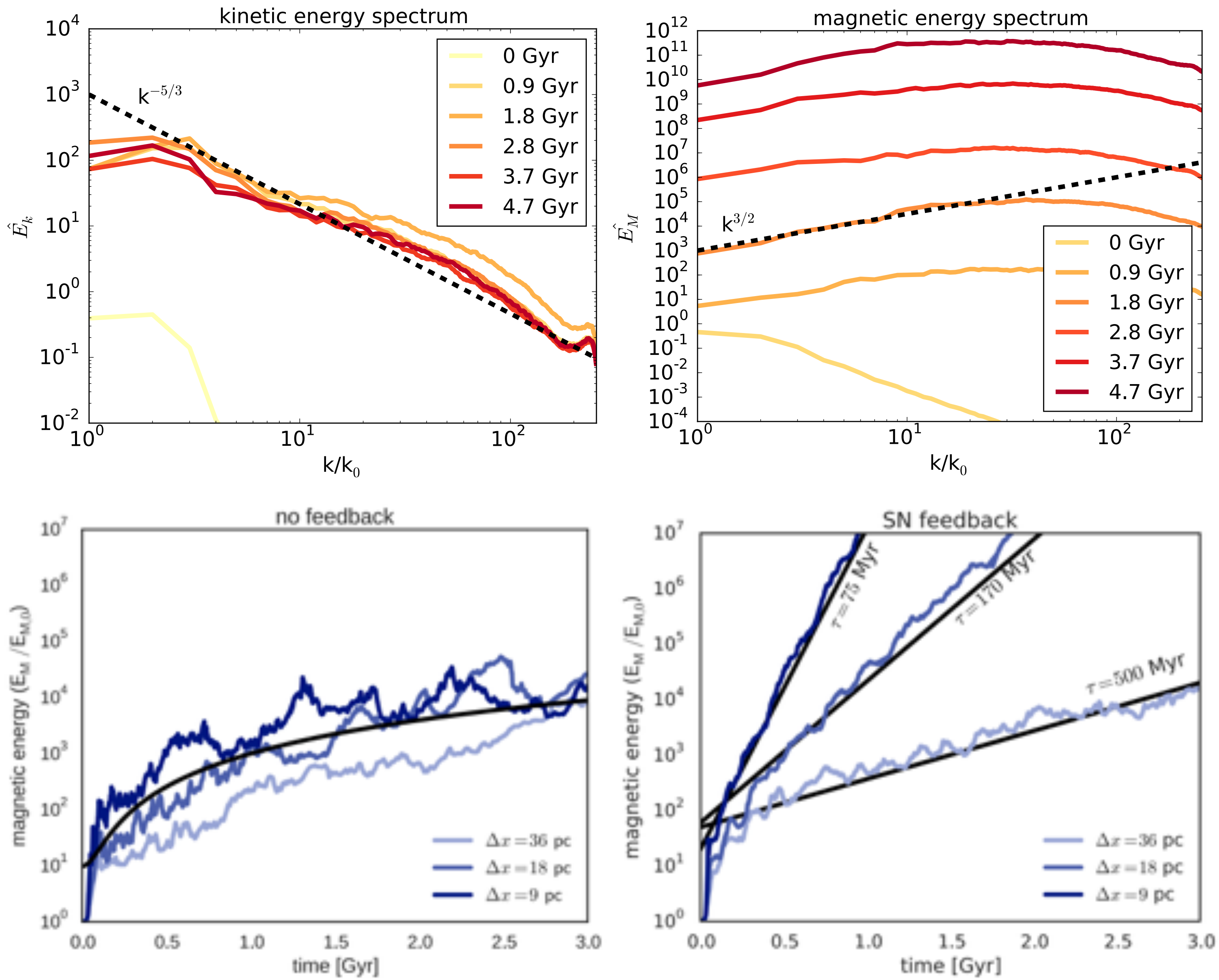


gas density

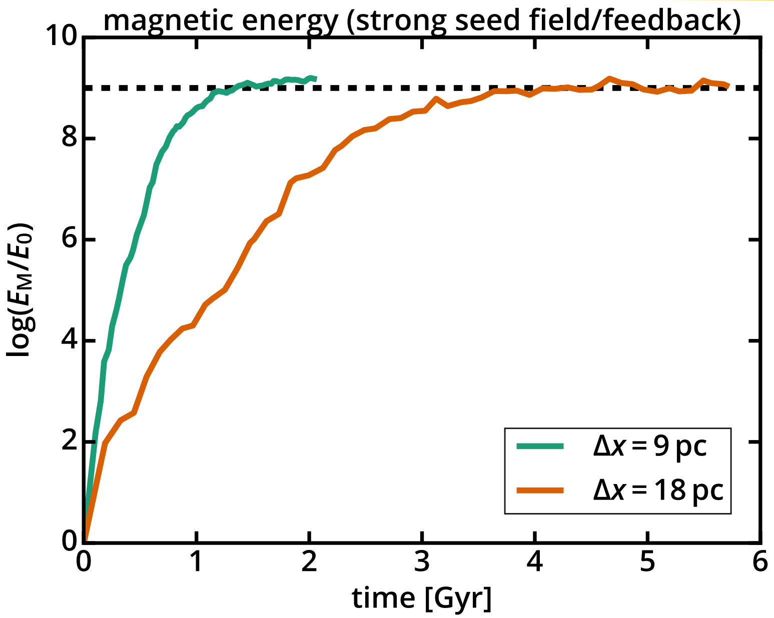
Magnetic field generation in dwarf galaxies

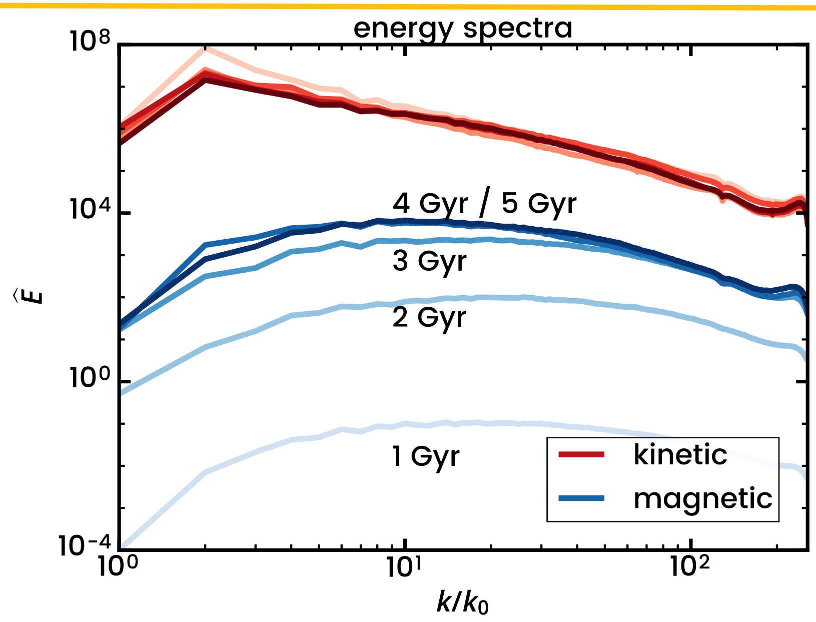


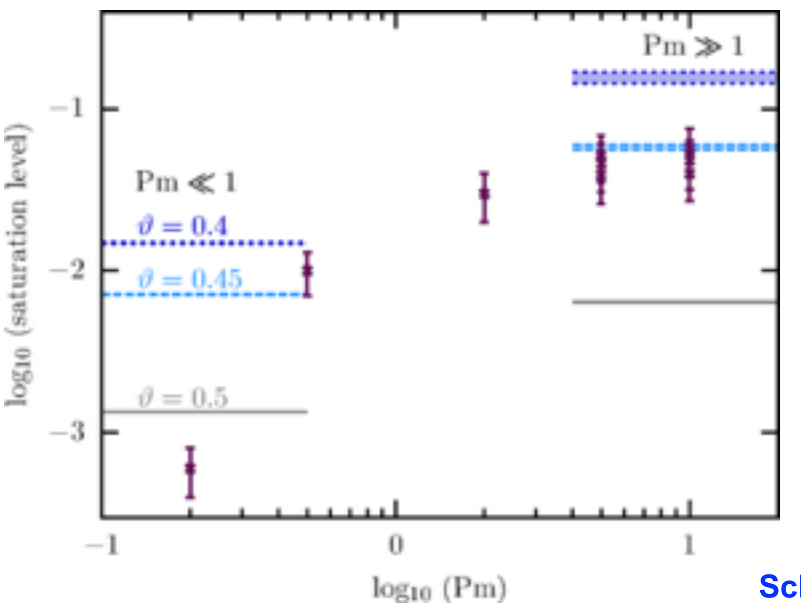
A small scale dynamo ?

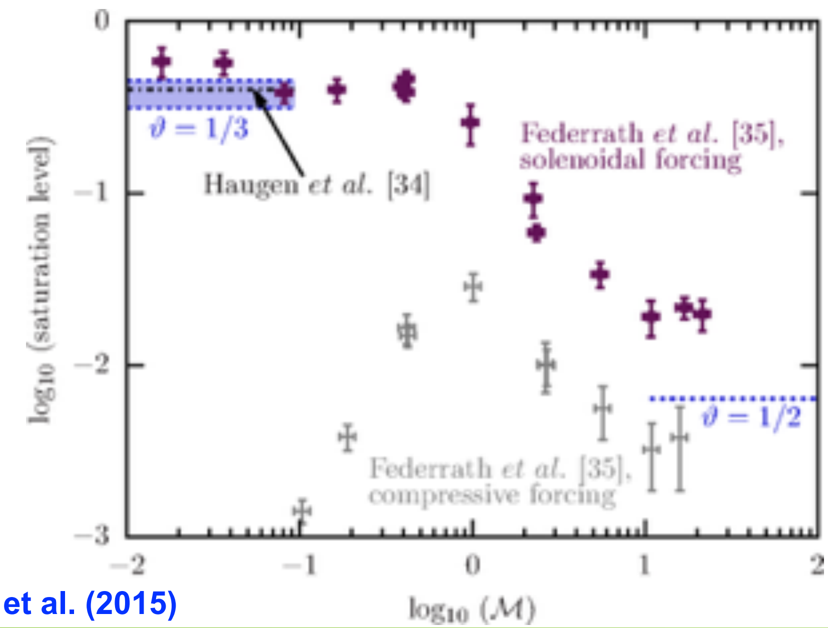


Saturation of the small scale dynamo



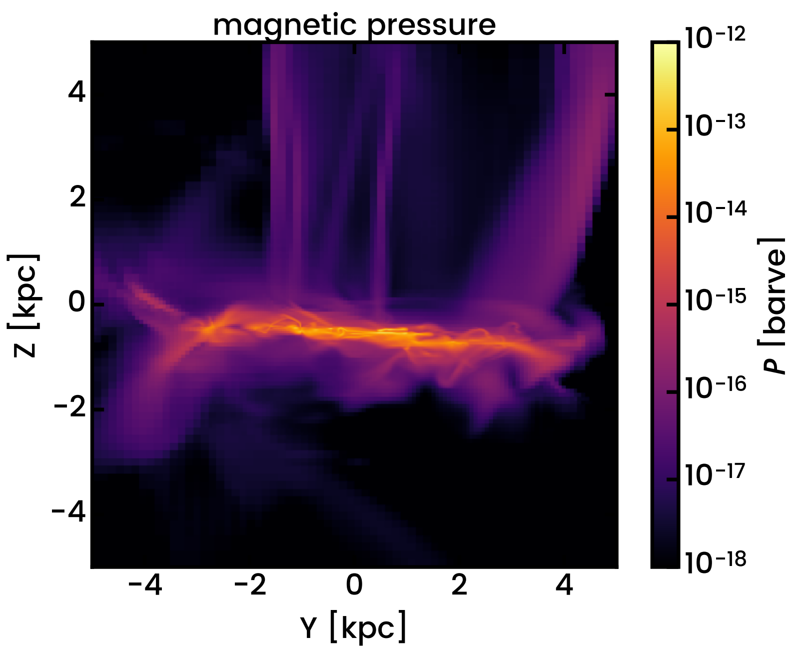


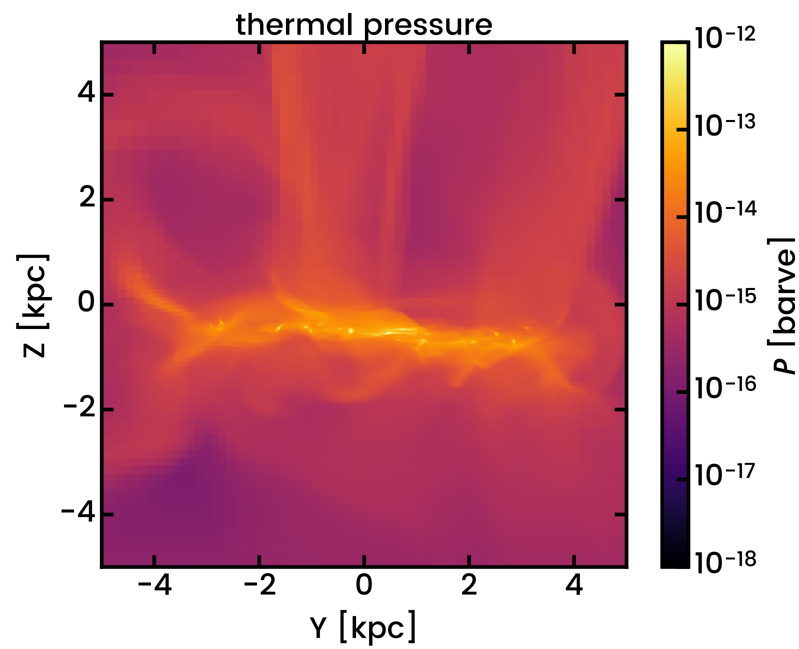


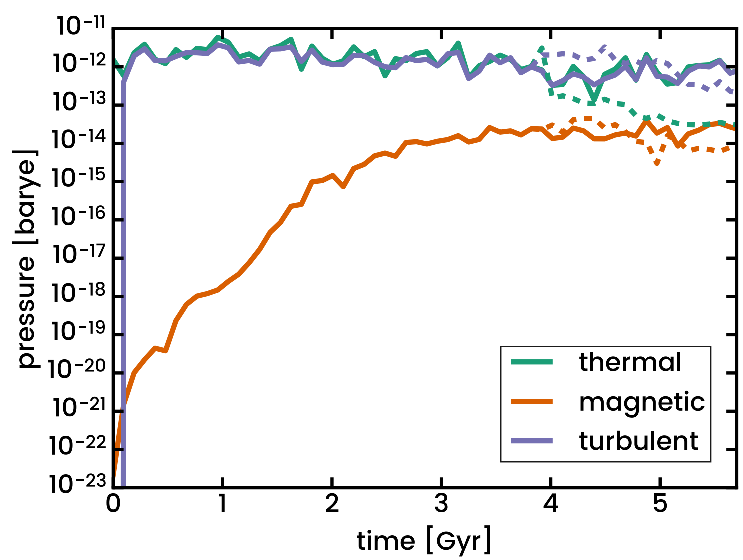


Schober et al. (2015)

Suppressing feedback after 4 Gyr







A theory 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 in the corona is only at 10% of equipartition. The field is highly turbulent with a flat power spectrum.

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

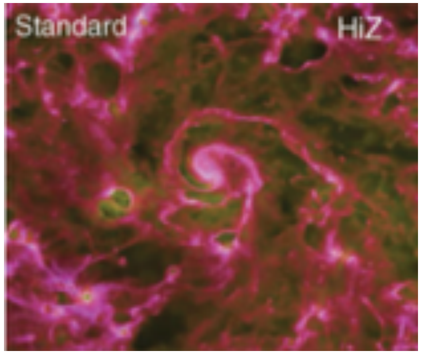
Formation of razor-thin discs, with competition between amplification through collapse and dissipation through reconnection.

Final magnetic field in the disc is toroidal and close to equipartition.

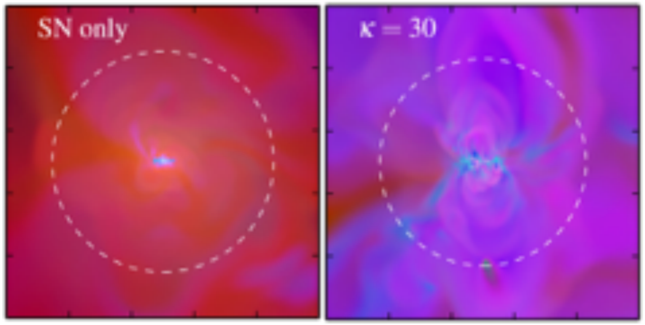
Later time evolution: magnetic energy is slowly decaying, or is slowly maintained by a large-scale dynamo. Observational characteristics set by the large scale dynamo.

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.

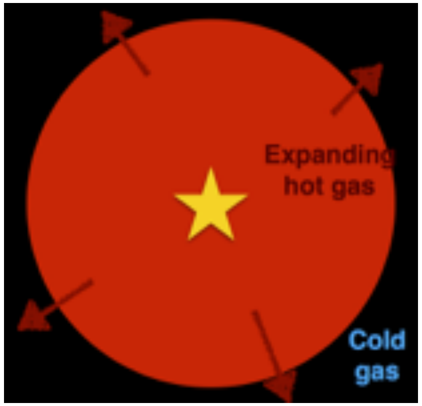


Hopkins et al. (FIRE)

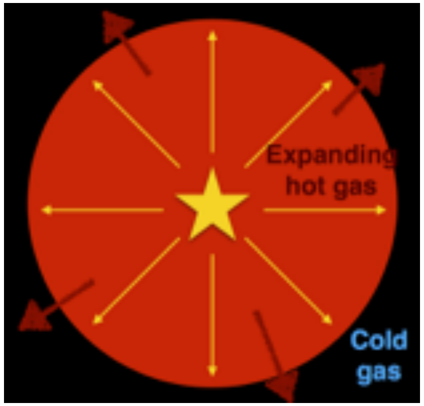


Roskar et al. (2014)

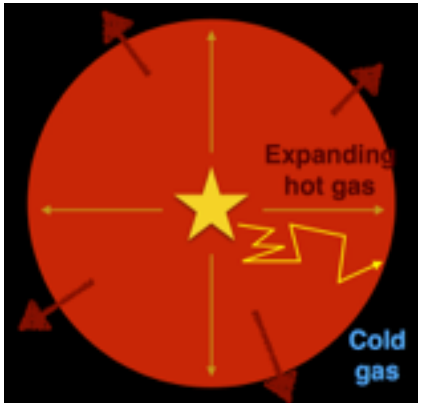
Different modes of radiation feedback, modelled self-consistently using radiation hydrodynamics in RAMSES-RT (Rosdahl et al. 2011, 2015)



1- UV radiation heats the gas



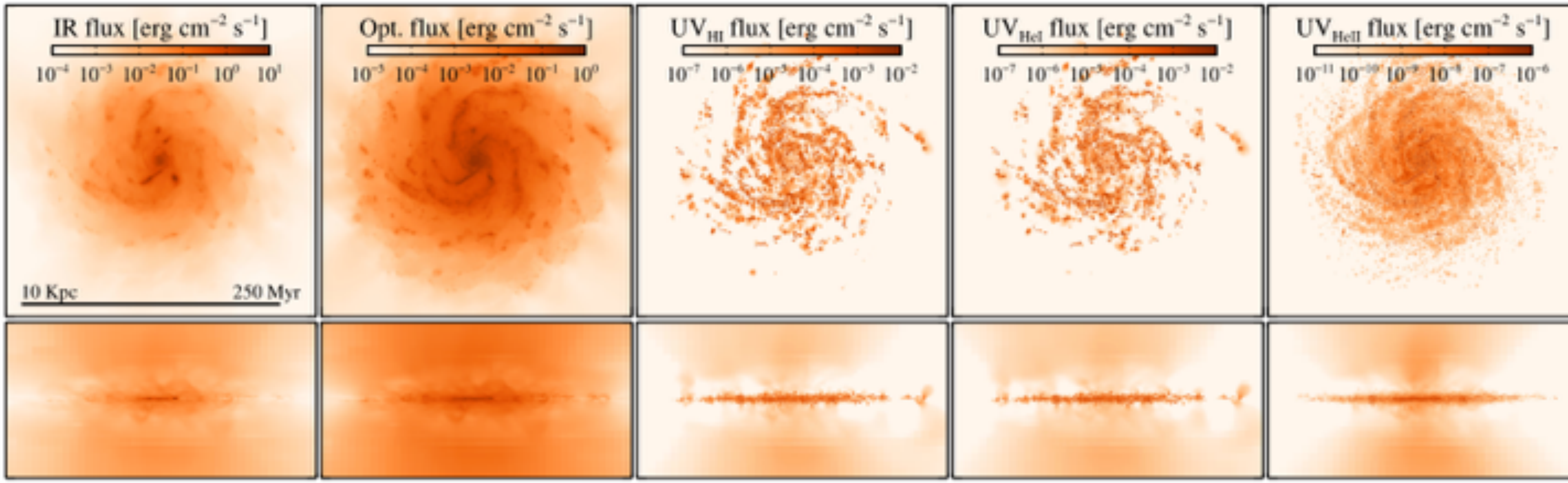
2- UV radiation gives momentum to the gas



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)

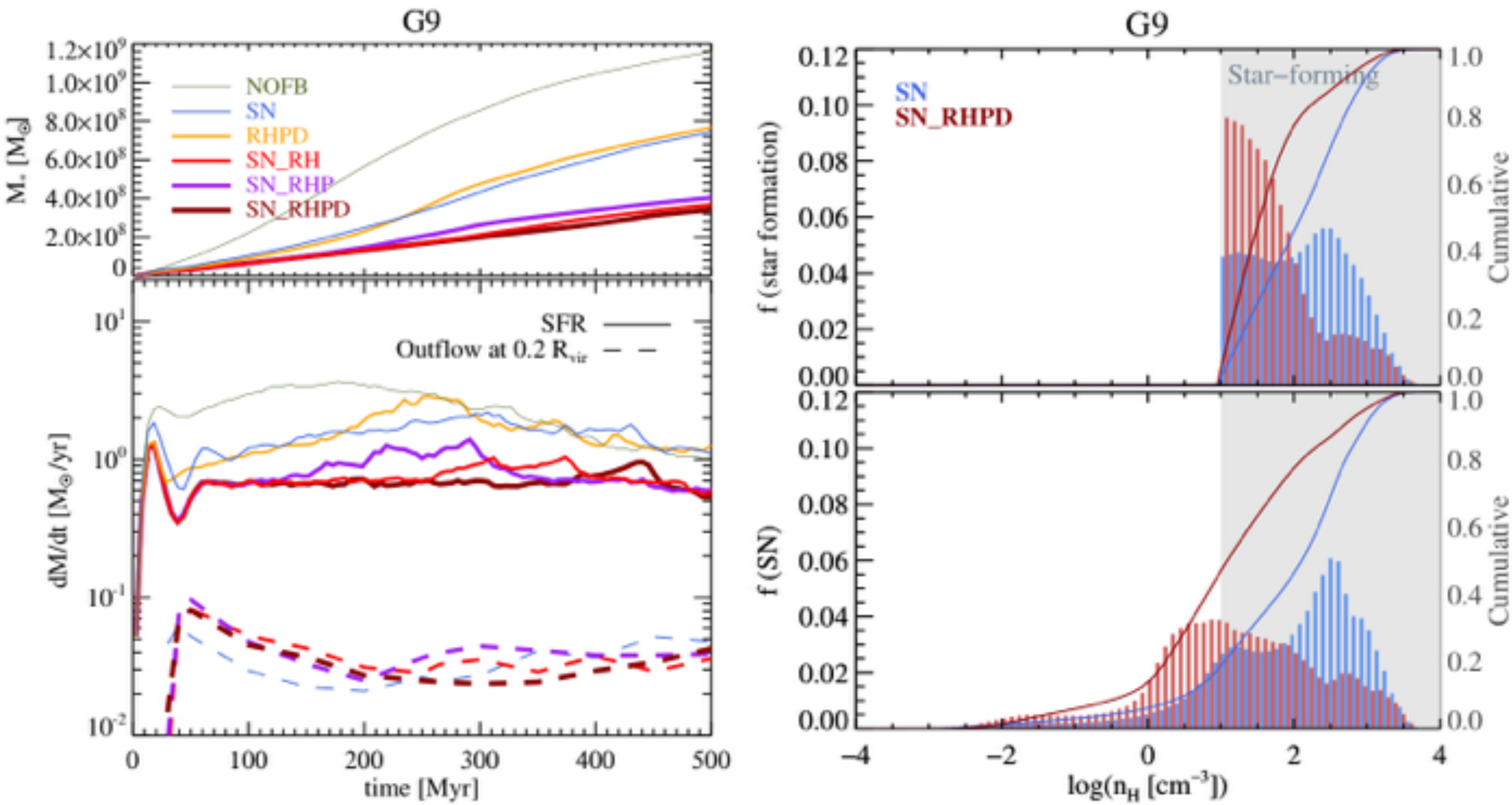
- 10^{11} solar masses halo
- 3×10^{9} solar masses baryonic disk
- 50% gas fraction.

- 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

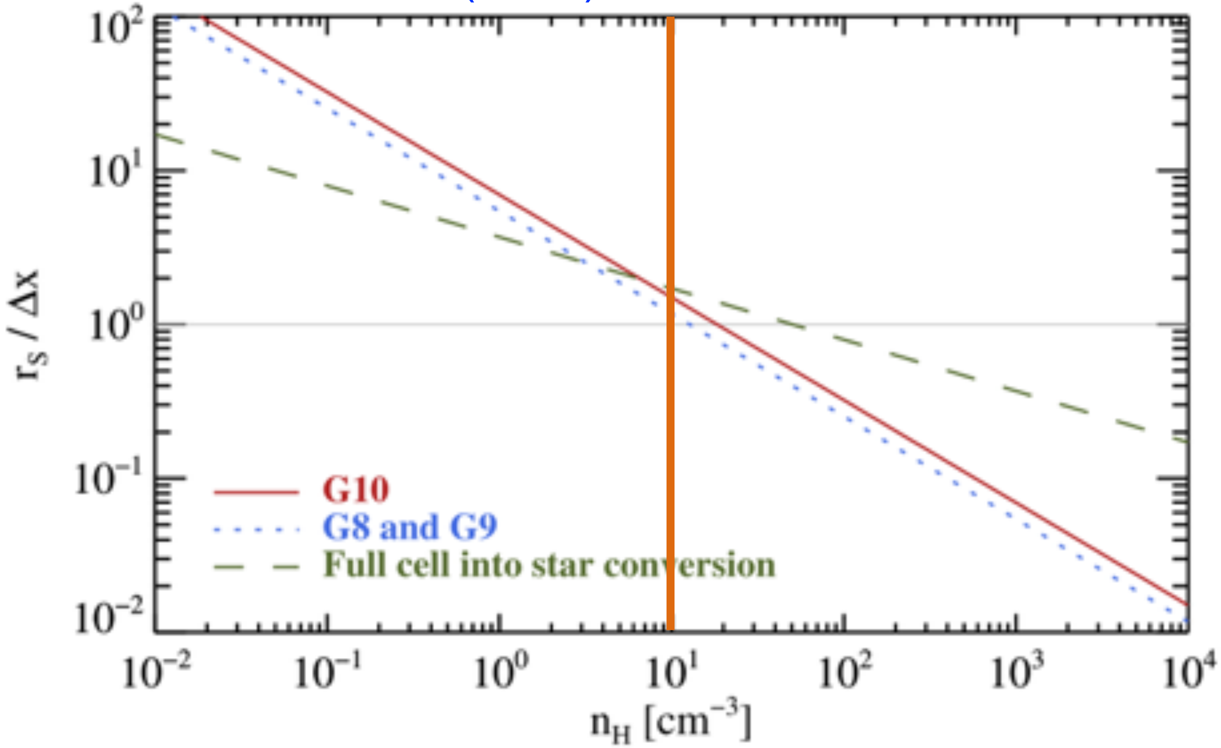


Rosdahl *et al.* (2015)

Problem: unresolved HII regions

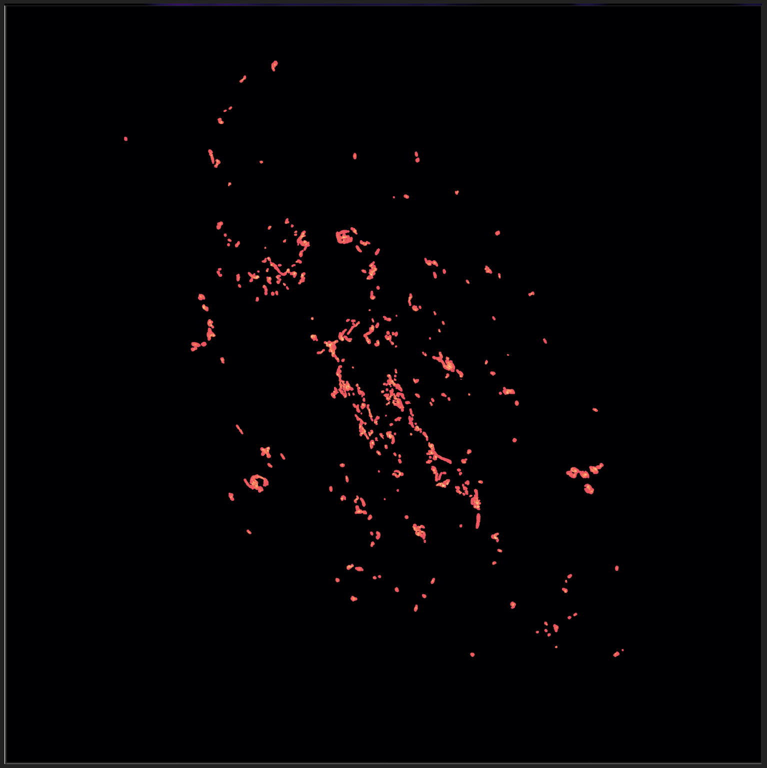
Stromgren sphere around one star particle is barely resolved at or above star formation density threshold. Need stochastic feedback or new star formation recipe.

Rosdahl *et al.* (2015)



CLASSICAL STAR FORMATION CRITERION

- Local Schmidt law: $t_{ff} \propto 1/\sqrt{G\rho}$ $\dot{\rho}_\star \propto \rho/t_{ff} \propto \rho^{1.5}$
- Density trigger $\rho > \rho_0$ and efficiency are free parameters
- $[\rho_0, \epsilon]$ are fine tuned to match the KS relation
- In high resolution hydro simulations, common values are:
    - ε~1%
    - ρ_0~100 cm^{-3}



PERRET ET AL. (IN PREP)

VIRIAL STAR FORMATION CRITERION

- Consider the local Virial theorem locally

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

$$\alpha = (\sigma_{eff}^2 + c_s^2)\delta r / \beta GM(< \delta r)$$

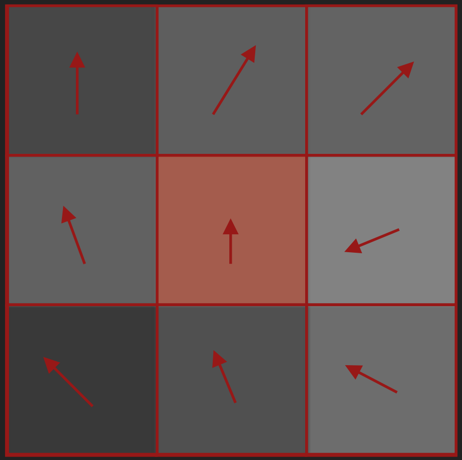
$$\alpha = \beta' \frac{|\nabla . v|^2 + |\Delta \times v|^2 + c_s^2}{G\rho} < 1$$

$$\beta' = 1/2 \qquad \epsilon = 1 \qquad \dot{\rho}_\star = \frac{\epsilon\rho}{t_{ff}}$$

Hopkins, Narayanan, Murray 2013

See also Semenov, Kravtsov, Gnedin 2015

- Benefit: this formulation does not depend on free parameters!
- Only depends on the ability to resolve the turbulent cascade

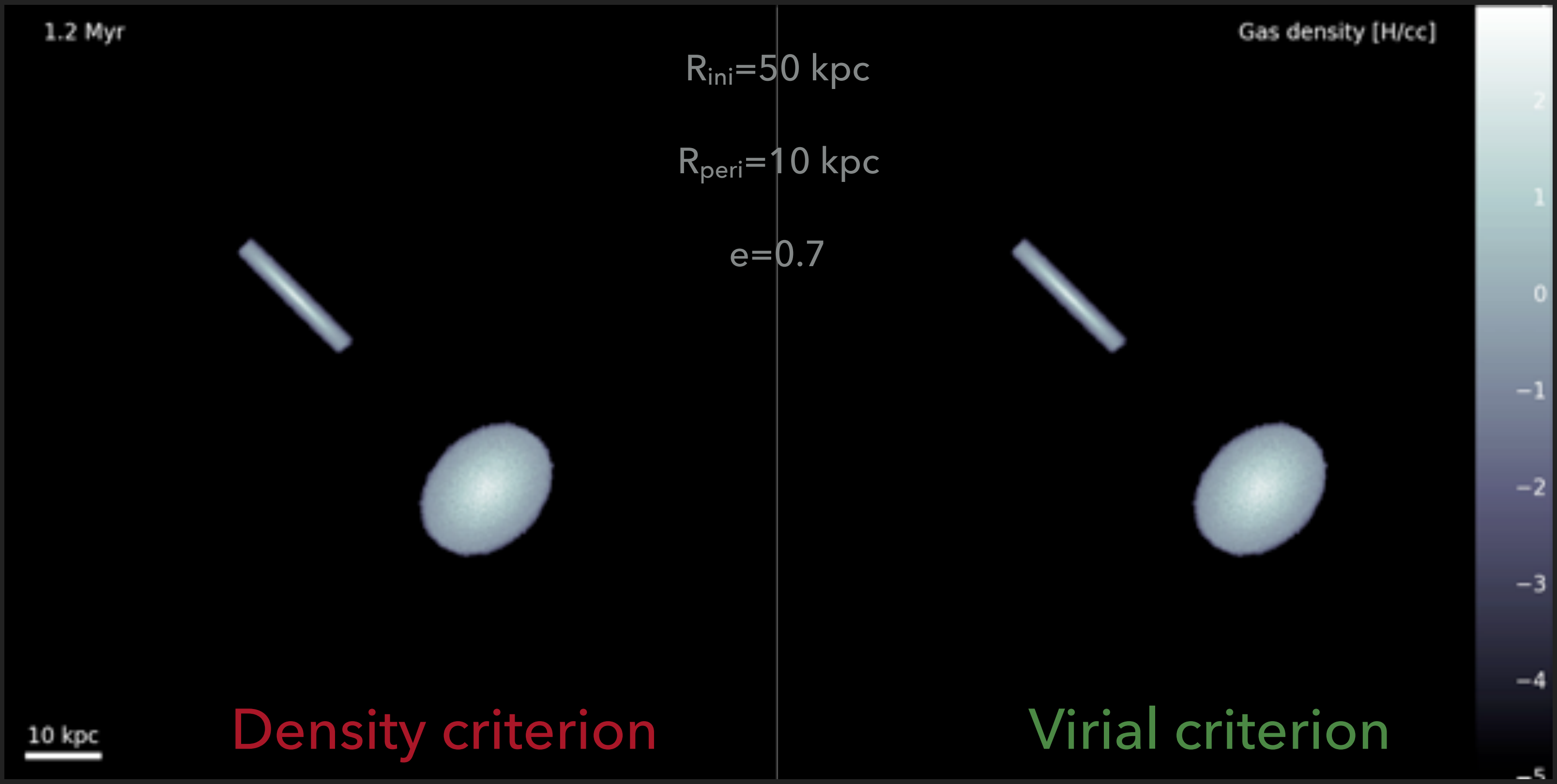


Density criterion
Virial criterion

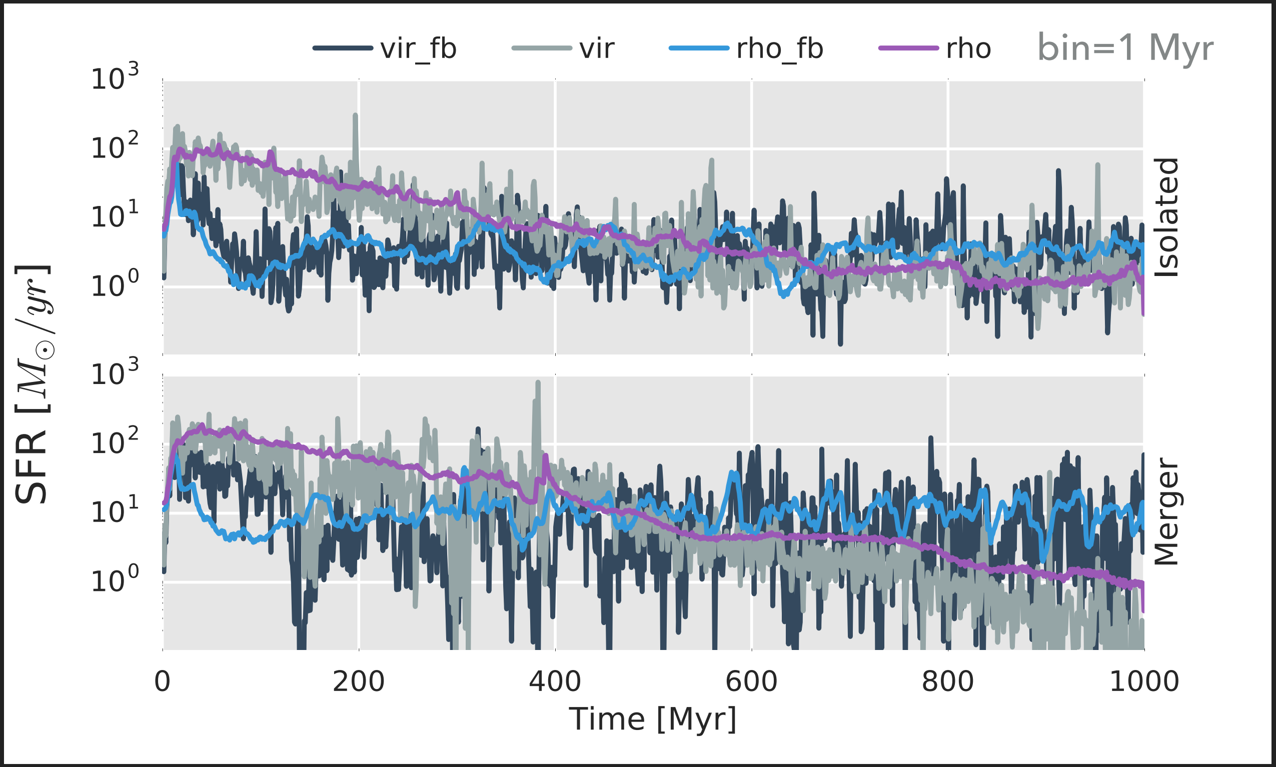
$$|\nabla . v| \qquad |\Delta \times v|$$

Devriendt et al. in prep.

MERGER STELLAR FEEDBACK SIMULATION



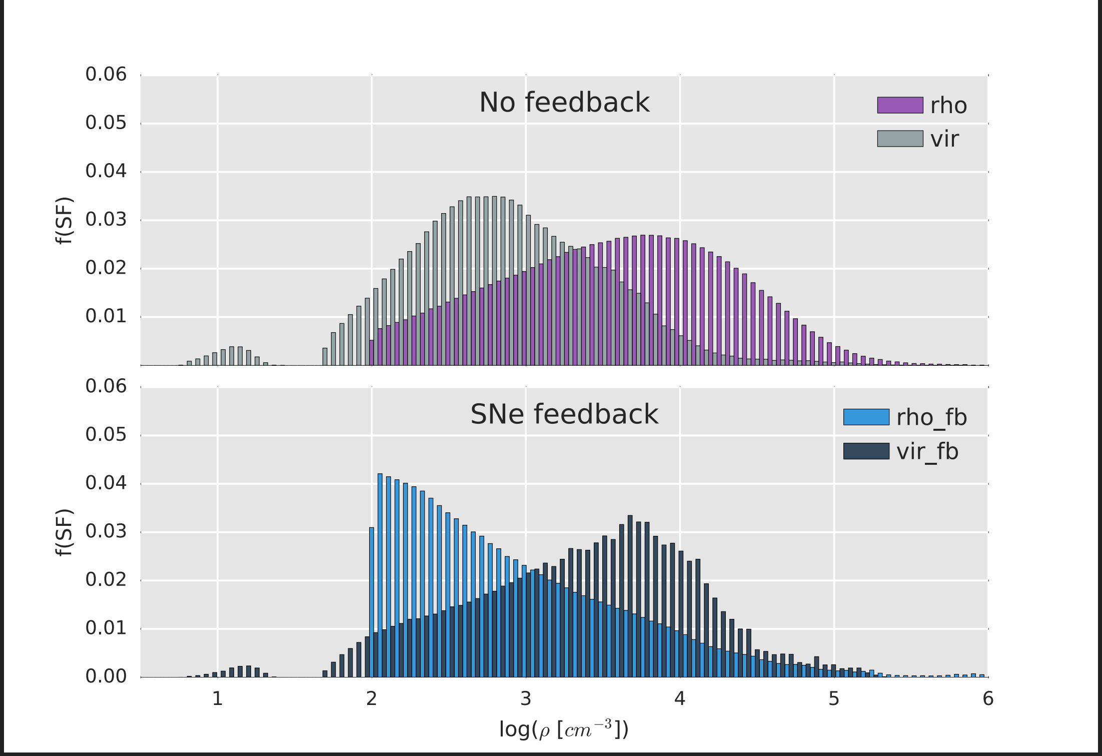
STAR FORMATION HISTORY



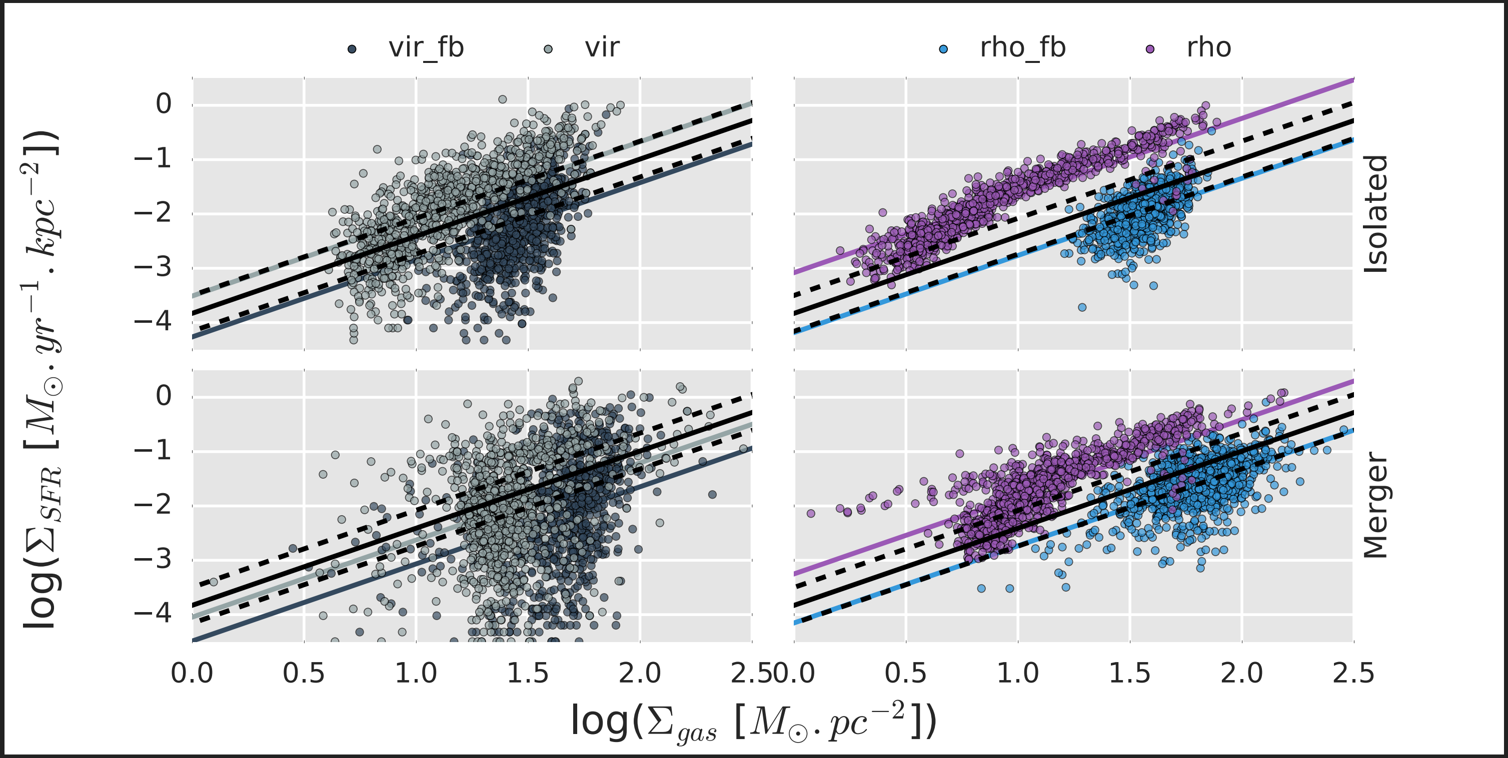
σ=0.09
σ=0.53

σ=0.13
σ=0.66

WHERE ARE BORN THE STARS?

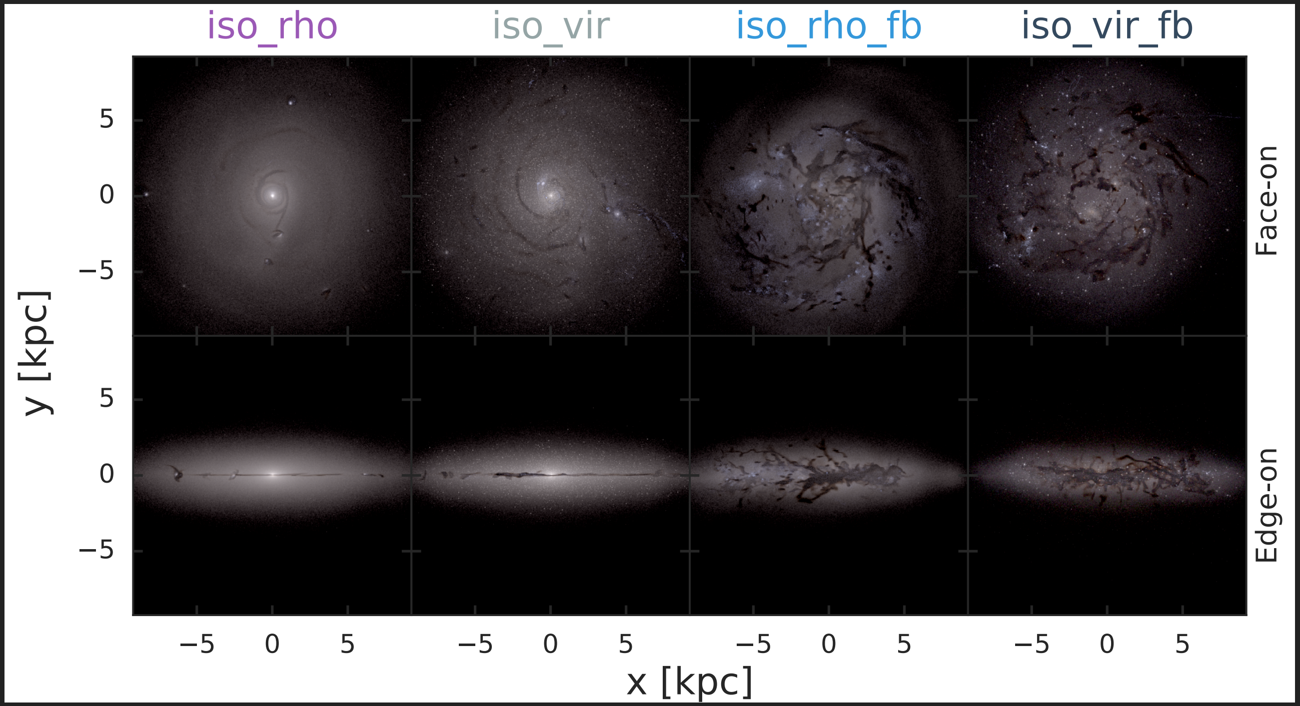


KENNICUTT-SCHMIDT RELATION



CLUSTERING OF SF FROM RESOLVED TURBULENCE

Mock SDSS ugr @ t=1 Gyr



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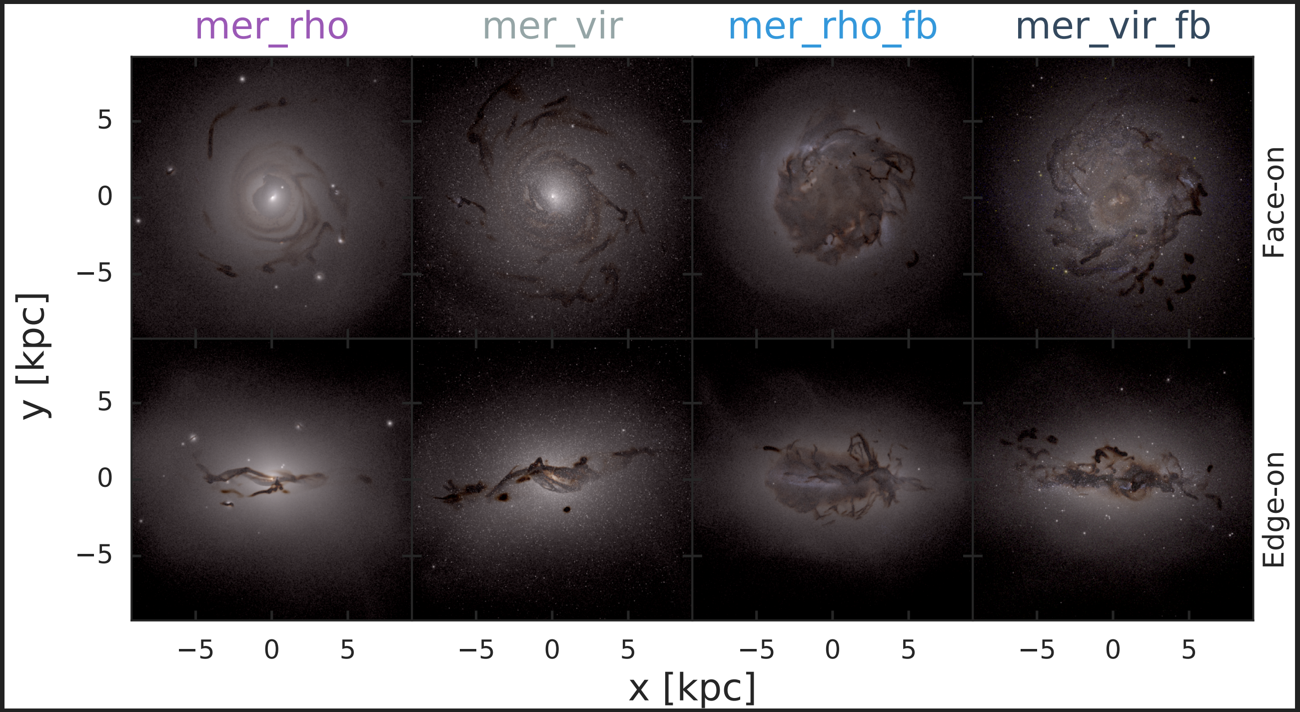

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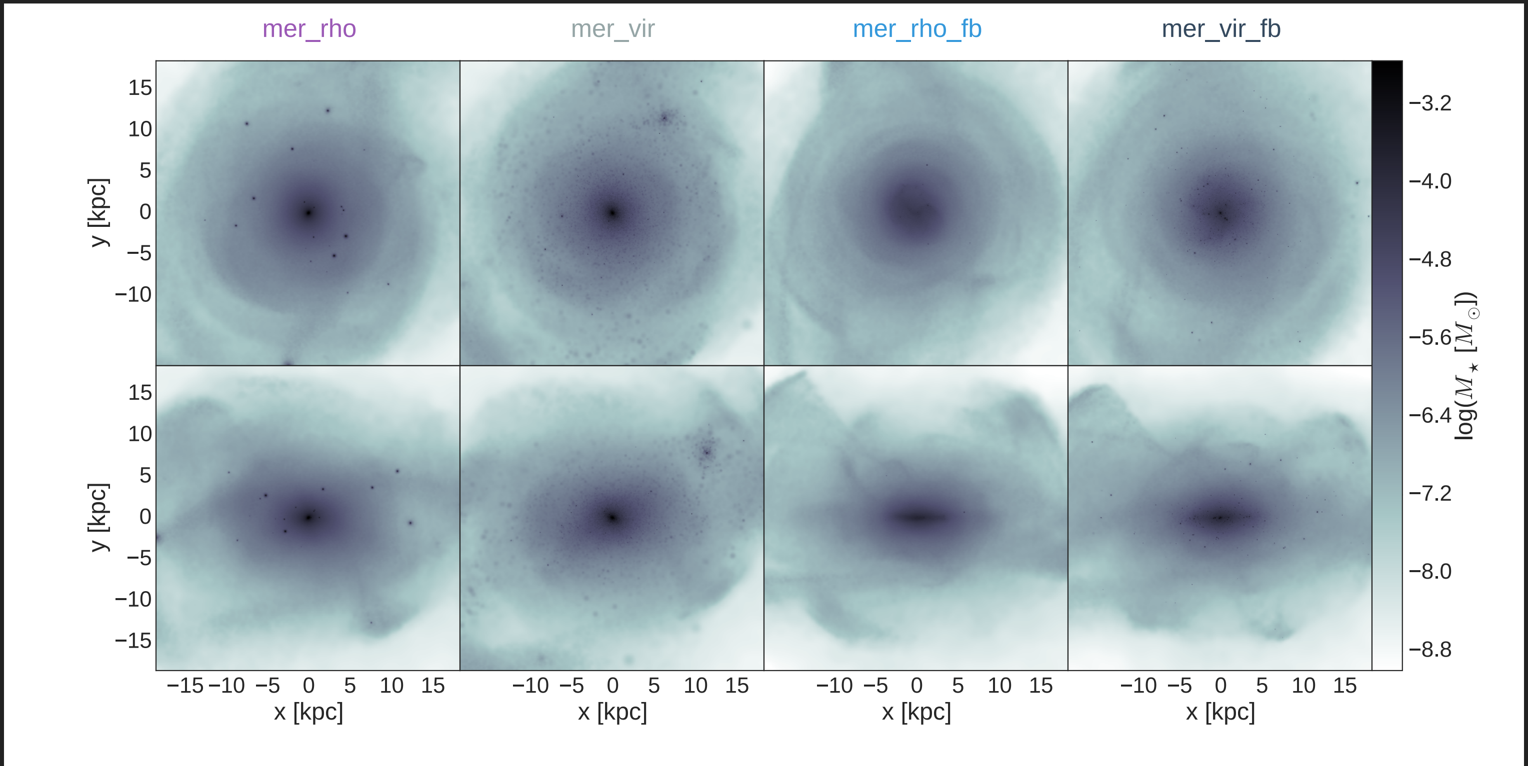
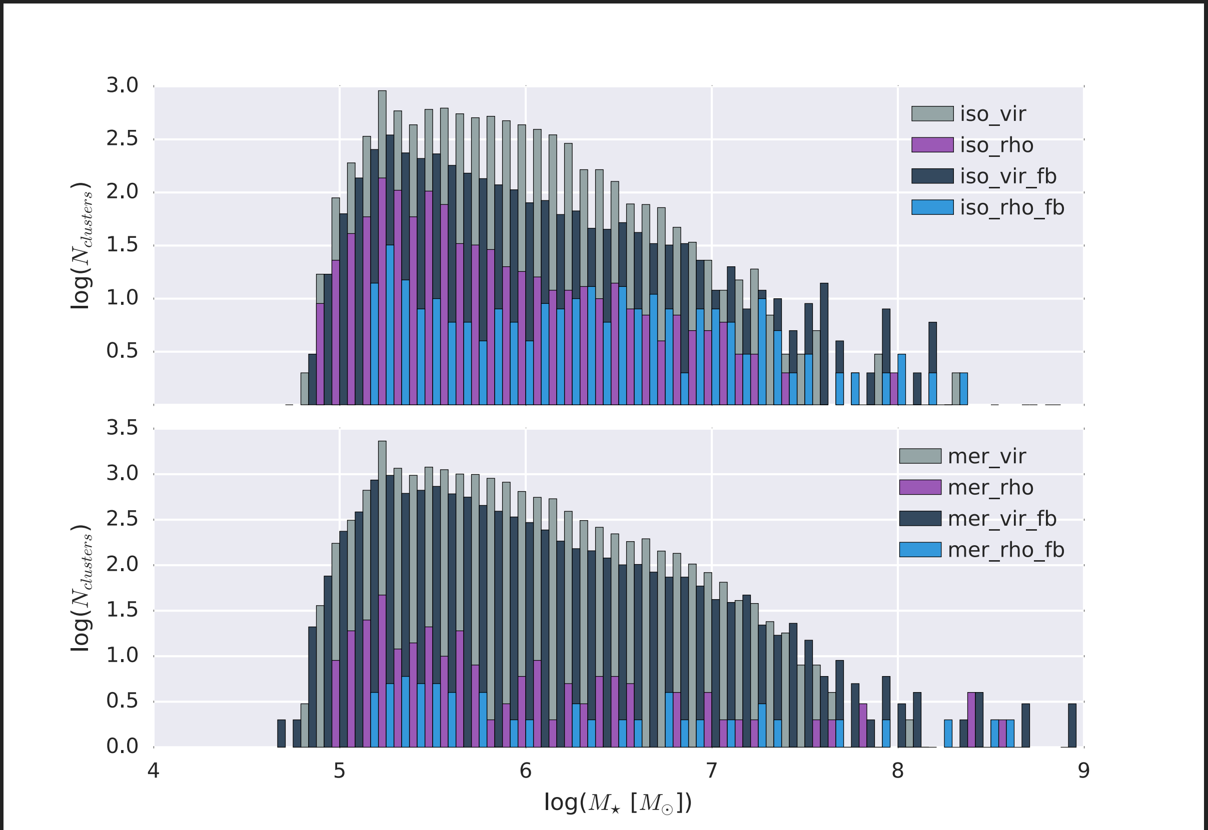
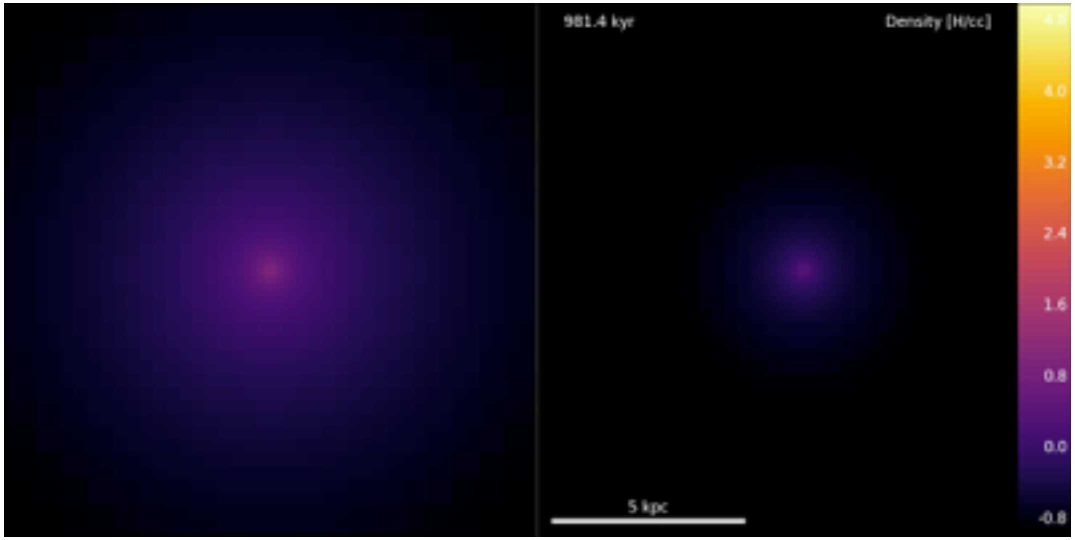


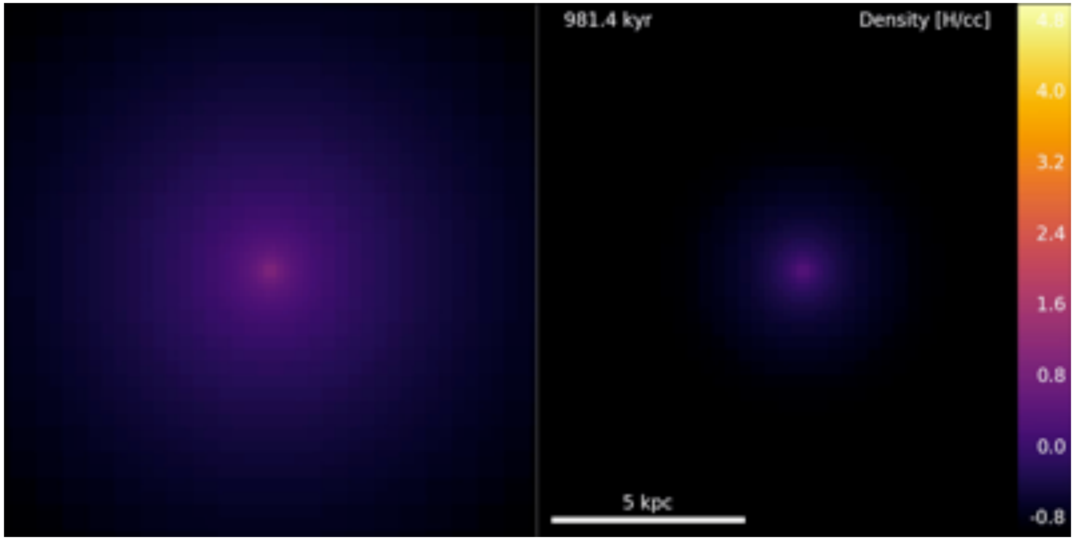
STAR CLUSTERS POPULATION



SMBH dynamics in clumpy galaxies

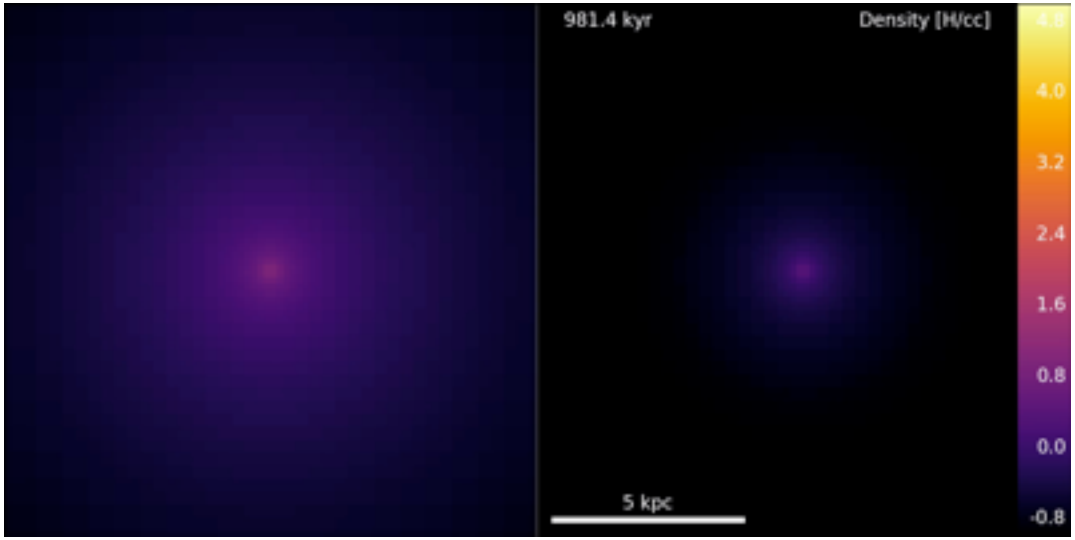


no feedback
SMBH growth only

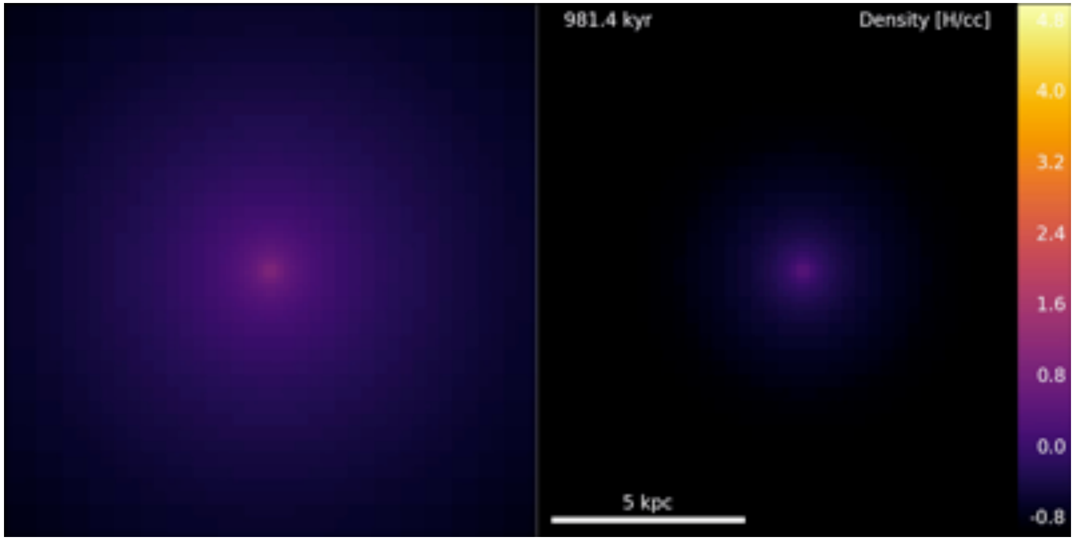


SN feedback only
SMBH growth only

SMBH dynamics in clumpy galaxies

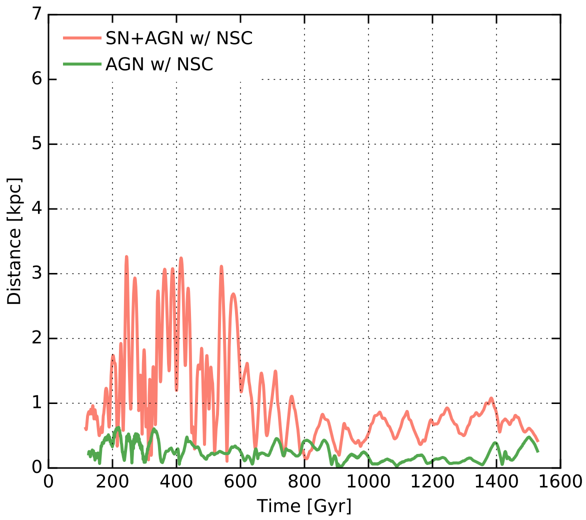


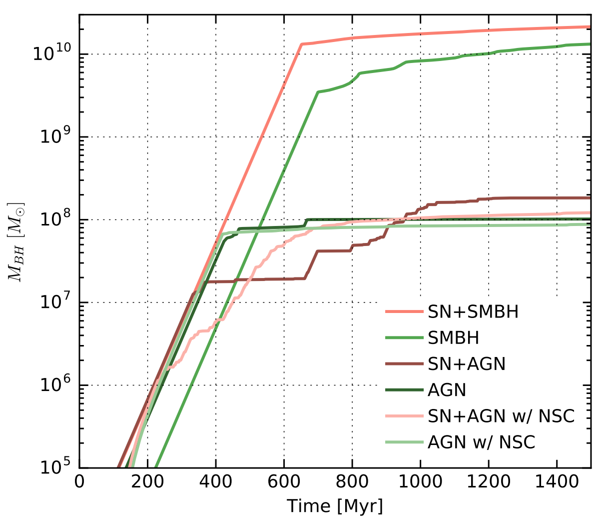
AGN feedback only

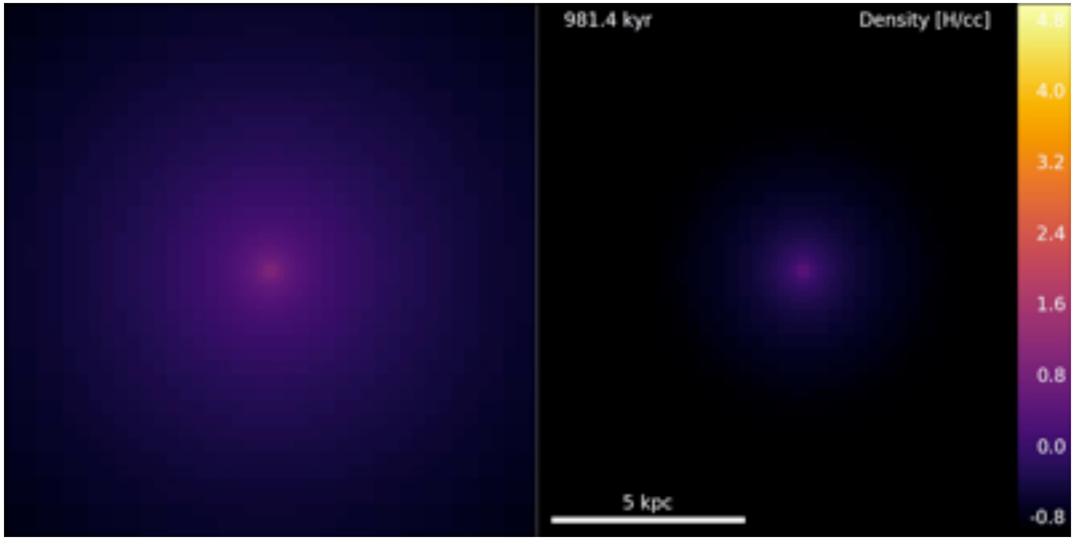


Both SN and AGN feedback

Nuclear star cluster and SMBH coevolution ?

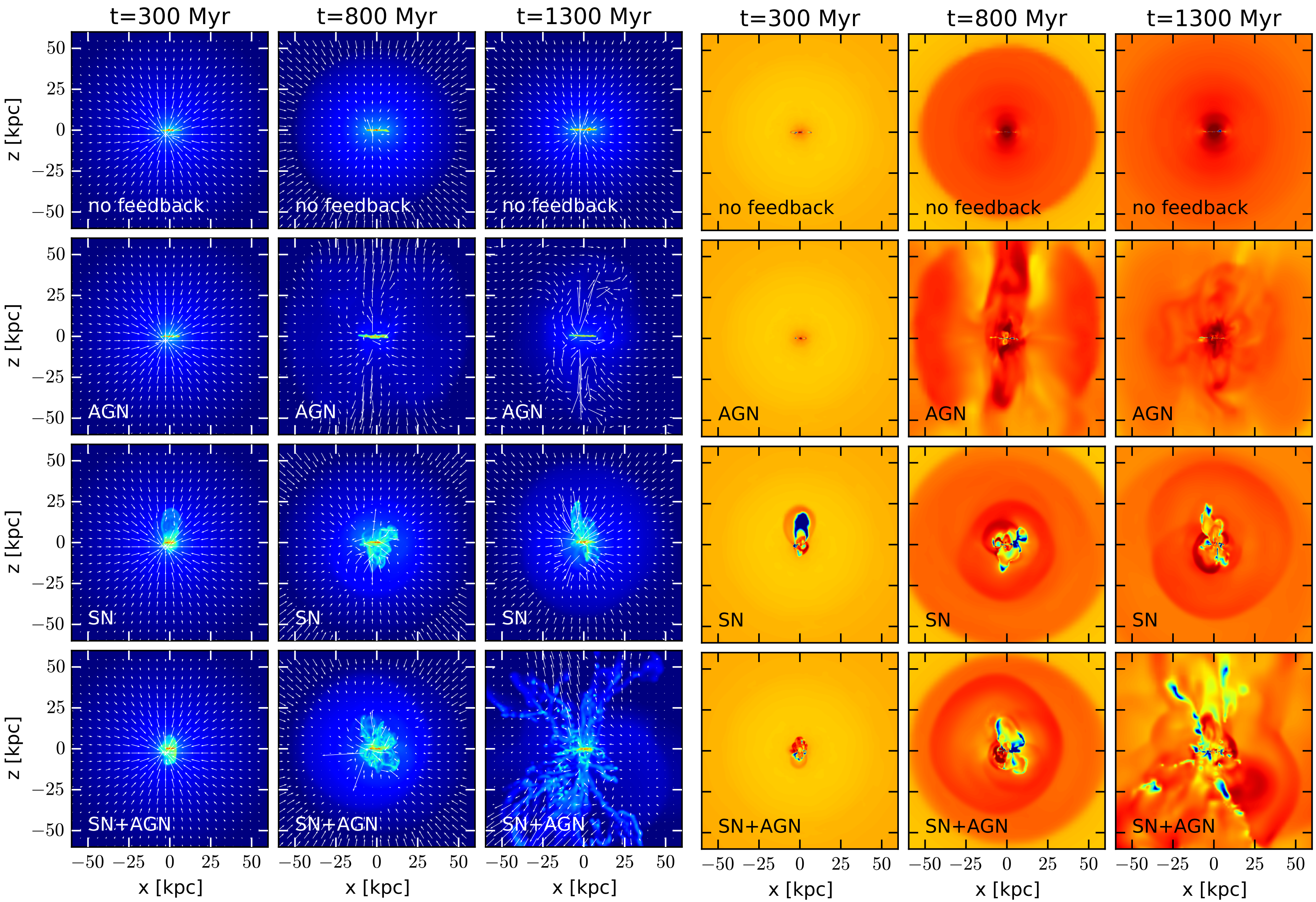






Both SN and AGN feedback with a nuclear star cluster 100x more massive than the SMBH

The interplay between SN and AGN feedback



Same effect as in Costa, Sijacki & Haehnelt (2015)

Conclusions

- Small-scale dynamos appear as a viable mechanism to amplify primordial fields in feedback dominated galaxies. Need a critical resolution to see the dynamo.
- Saturation of the dynamo at 1/10 of equipartition in the galactic corona.
- Late time evolution: collapse back to a thin disk and finally reach equipartition.
- New physics: radiation hydrodynamics of galaxy formation. Very sensitive to resolution and adopted star formation recipe.
- Current sub-grid models of radiation feedback are probably optimistic.
- New star formation recipe based on local turbulence. High resolution is required to resolve the supersonic turbulence. More realistic star clusters ?
- SMBH models at higher resolution are tricky to handle. Dynamics in clumpy galaxy seems to point towards the need for NSC and SMBH co-evolution.
- Resolved ISM and SMBH feedback as the origin of fast cold outflows ?