MAGNETOGENESIS IN THE FIRST GALAXIES

- THE IMPACT OF SEEDING ON GALAXY FORMATION -

ENRICO GARALDI (MPA)

Rüdiger Pakmor (MPA)
Volker Springel (MPA)

Garaldi, Pakmor, Springel 2021
MNRAS 502, 5726

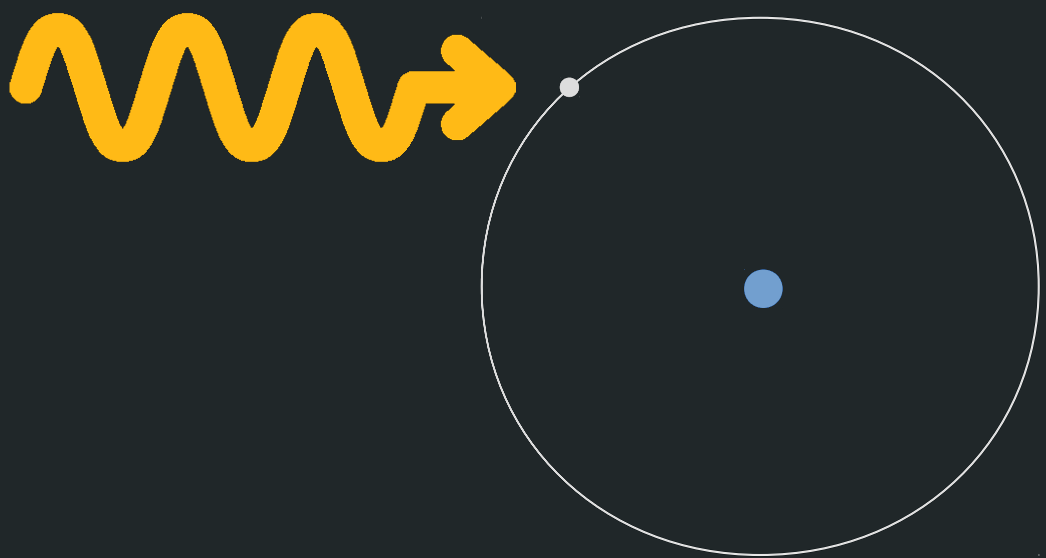
An initial disclaimer

For the purpose of this talk, I will crudely split the magnetic seeding processes into:

- “Cosmological” (anything at or before CMB time)
- Supernovae (and their remnants)
- Plasma physics (e.g. Biermann battery)
- Ionization fronts during Cosmic Reionization

Magnetic field seeding during Reionization

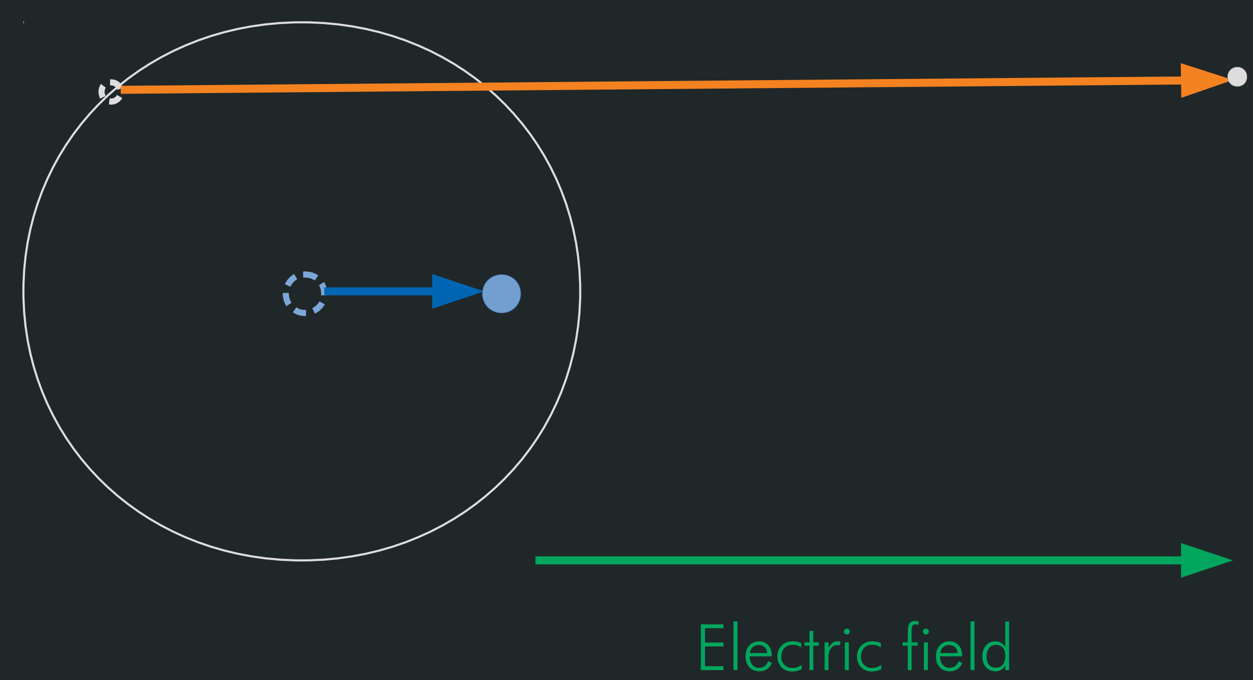
Photoionized electron are spatially segregated w.r.t. the proton because of mass difference, creating an E field ahead of the ionization front.



(Langer+03, Durrive & Langer+15)

Magnetic field seeding during Reionization

Photoionized electron are spatially segregated w.r.t. the proton because of mass difference, creating an E field ahead of the ionization front.

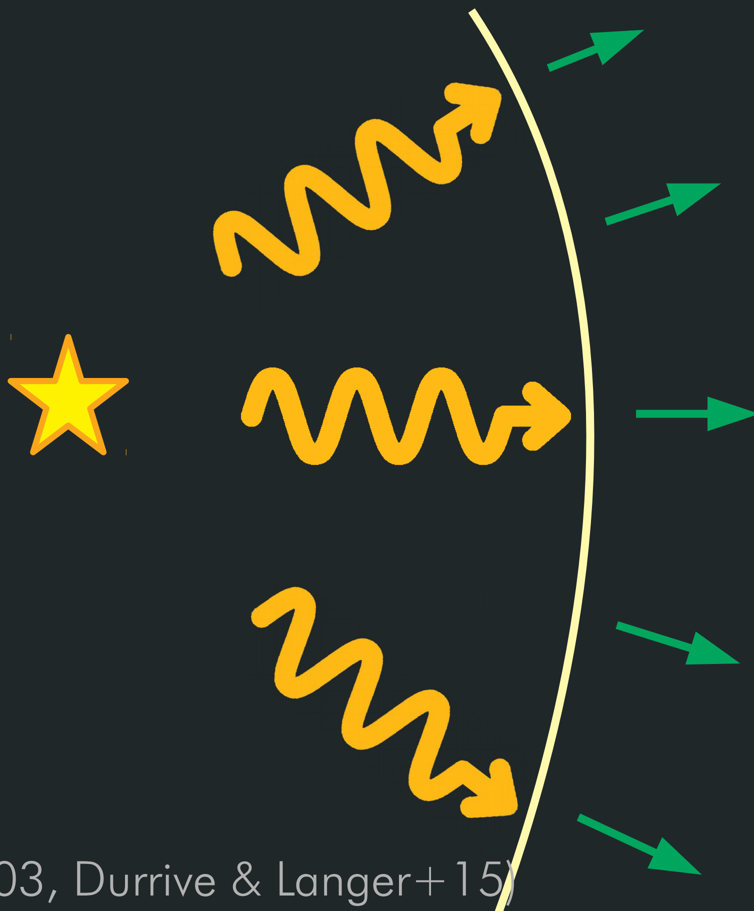


(Langer+03, Durrive & Langer+15)

Magnetic field seeding during Reionization

Enrico Garaldi

Photoionized electron are spatially segregated w.r.t. the proton because of mass difference, creating an E field ahead of the ionization front.

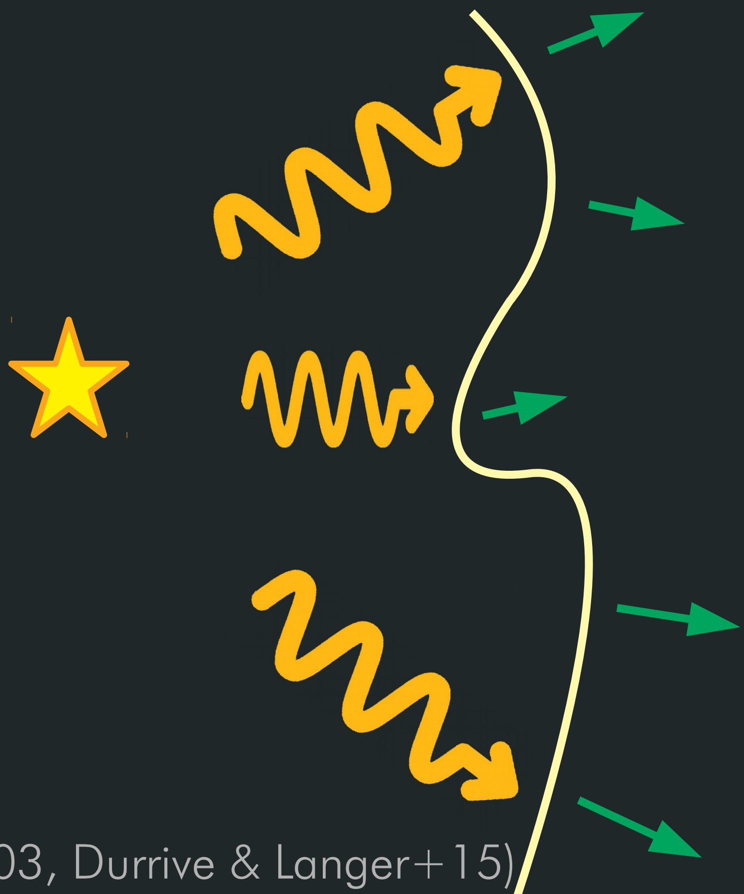


$$\vec{B} \sim \nabla \times \vec{E} = 0$$

(Langer+03, Durrive & Langer+15)

Magnetic field seeding during Reionization

Photoionized electron are spatially segregated w.r.t. the proton because of mass difference, creating an E field ahead of the ionization front.



$$\vec{B} \sim \nabla \times \vec{E} \neq 0$$

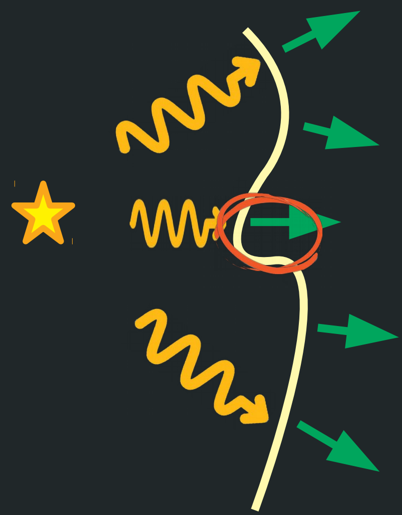
(Langer+03, Durrive & Langer+15)

Magnetic field seeding during Reionization

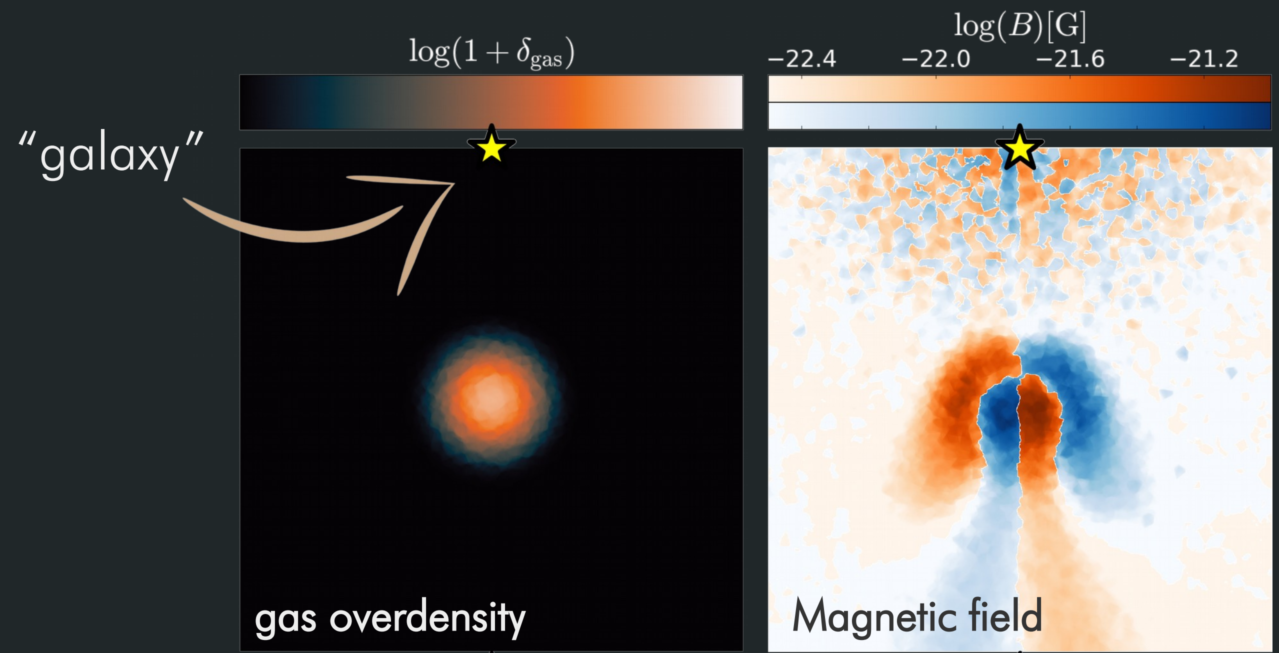
Enrico Garaldi

Photoionized electron are spatially segregated w.r.t. the proton because of mass difference, creating an E field ahead of the ionization front.

When the ionization front is not isotropic, a B field is generated.



(Langer+03, Durrive & Langer+15)



Garaldi et al. 2021

The riddle of cosmic magnetic fields

For the purpose of this talk, I will crudely split the magnetic seeding processes into:

- “Cosmological” (anything at or before CMB time)
- Compact objects (e.g. Supernovae and their remnants)
- Plasma physics (e.g. Biermann battery)
- Ionization fronts during Cosmic Reionization (Durrive battery)

For all seeding mechanisms, **galactic processes** are of key importance for amplification and ejection of magnetic fields.

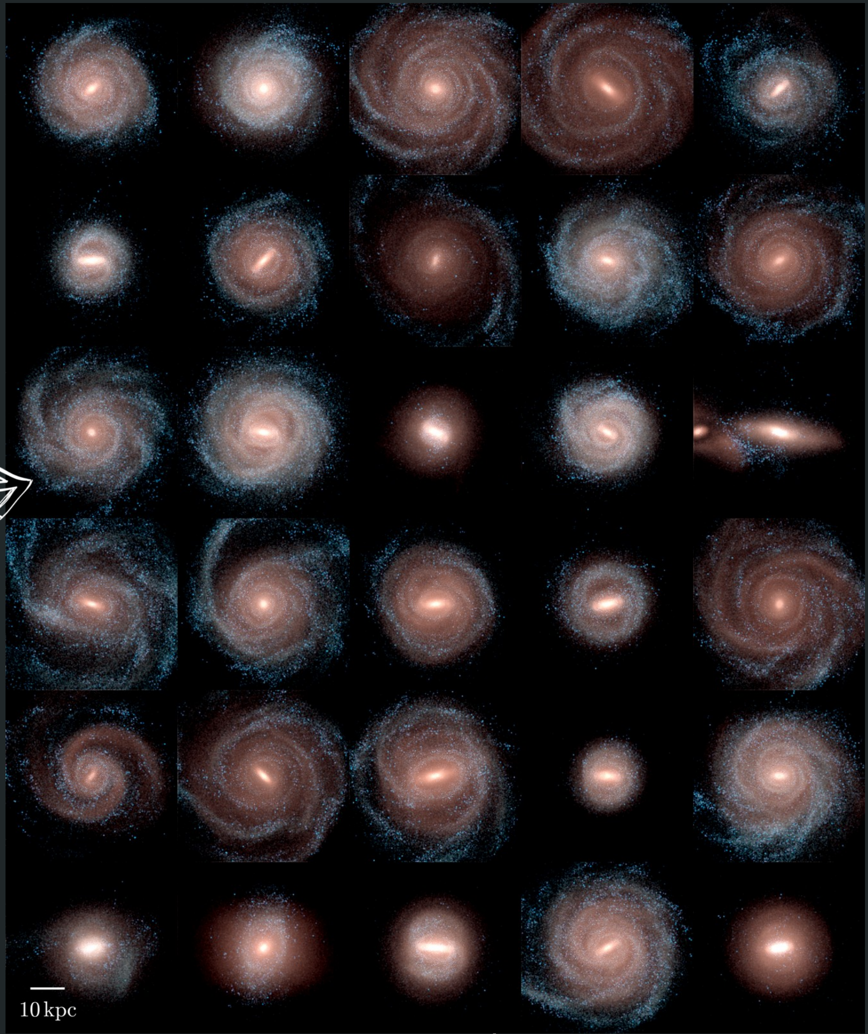
Testing seeding with state-of-the-art simulations

AREPO moving-mesh code

\+ Moment-based RT + ideal MHD (with Powell 8-wave cleaning scheme)

\+ the AURIGA galaxy formation model

- Stochastic star formation following KS relation
- Mass, energy, and metal return from SN and AGB stars
- Explicit tracking of 9 metal species (H, He, C, N, O, Ne, Mg, Si, Fe)
- Bimodal BH feedback: kinetic at low accretion rates
  thermal at high accretion rates
- Kinetic+thermal stellar winds



Credits: Auriga project

Testing seeding with state-of-the-art simulations

Enrico Garaldi

AREPO moving-mesh code

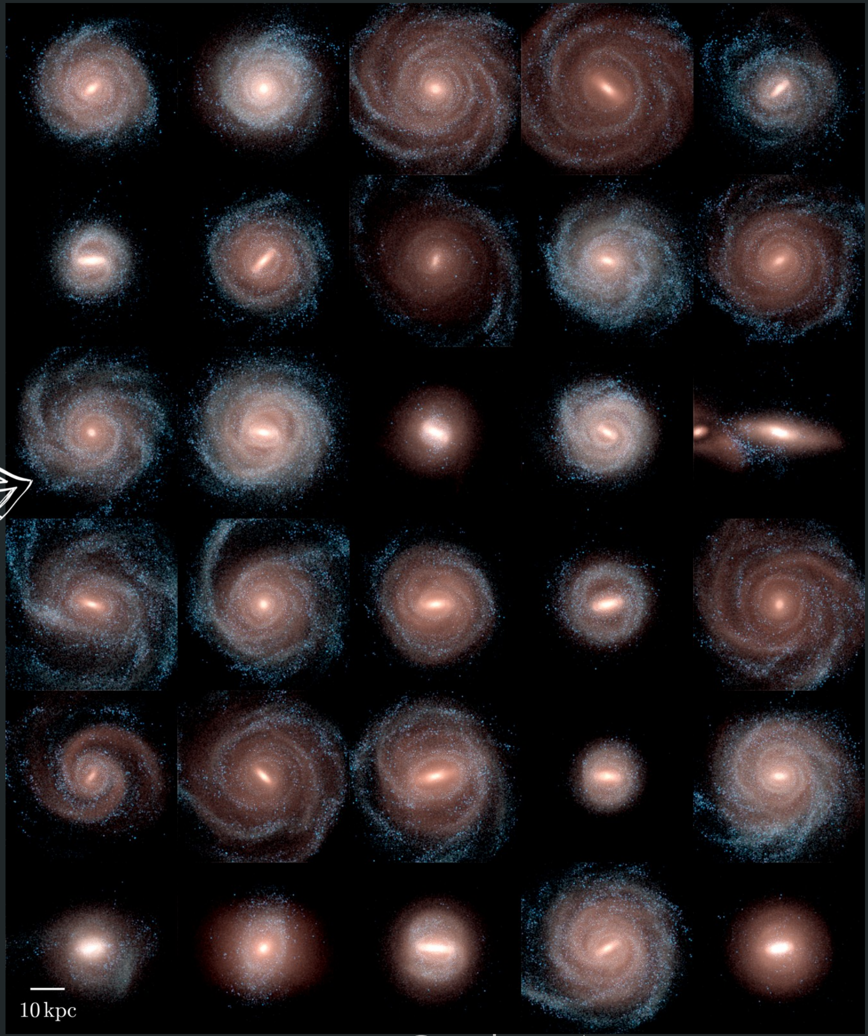
+ Moment-based RT + ideal MHD (with Powell 8-wave cleaning scheme)

+ the AURIGA galaxy formation model

+ Variable seeding mechanism:

- Cosmological (10^{-14} G in ICs)
- SN injection ($E_B = 0.01\%\ E_{SN}$)
- Biermann battery
- Durrive battery

zoom-in and cosmological runs

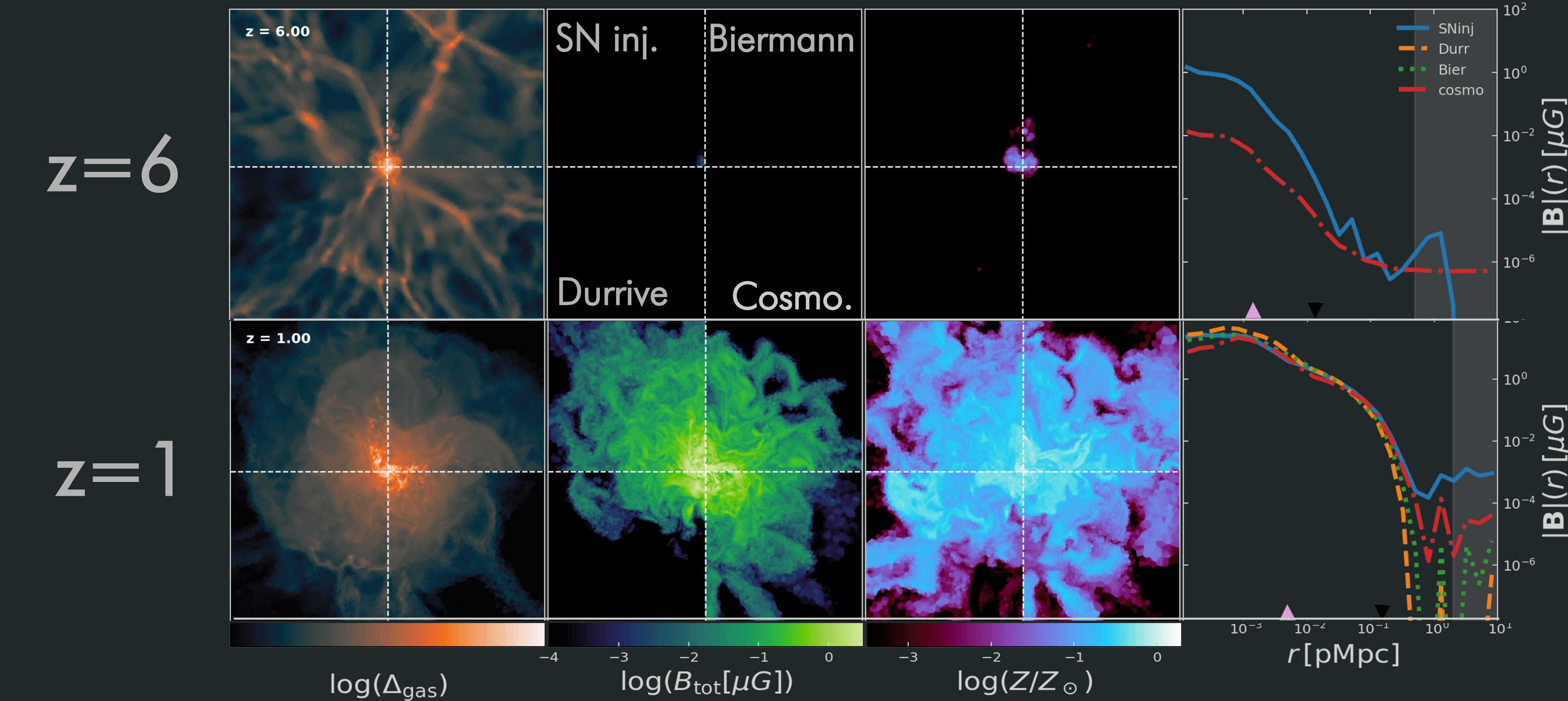


Credits: Auriga project

B fields on (sub-)galactic scales.

results from zoom-in simulations

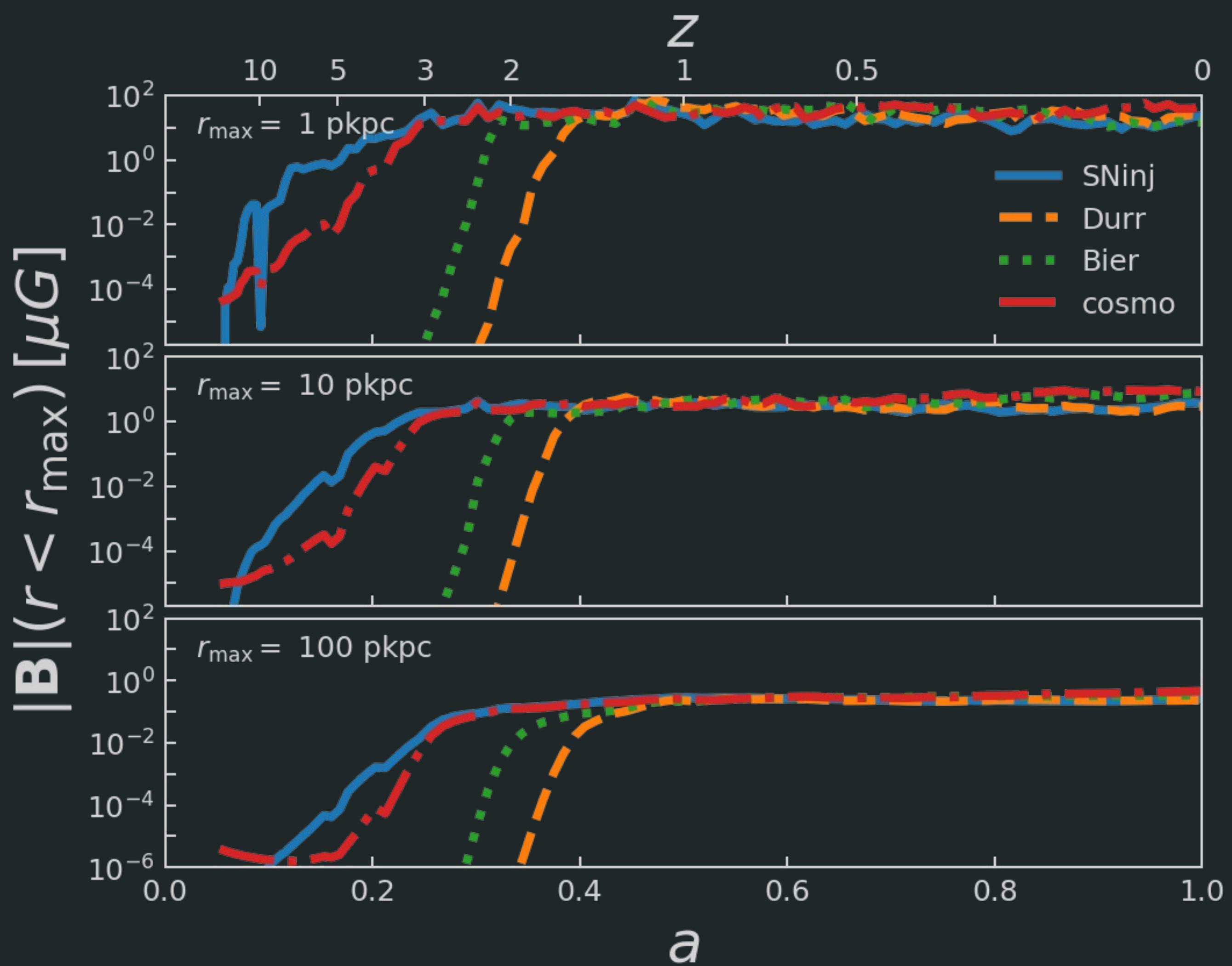
Indistinguishable B fields by z∼1



Garaldi et al. 2021

Seed process sets saturation time, but not strength

Enrico Garaldi

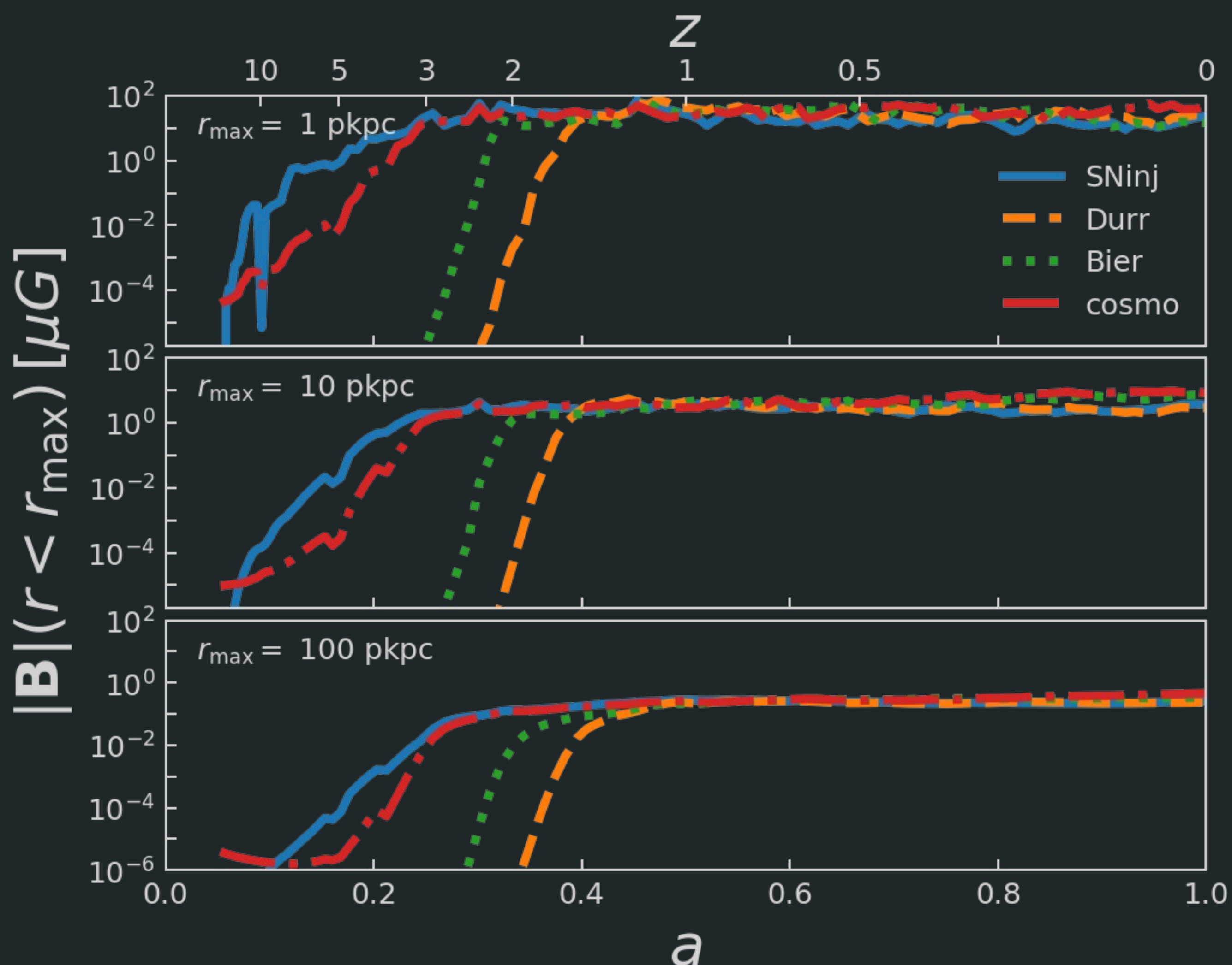


Caveat: the saturation time depends on numerical resolution

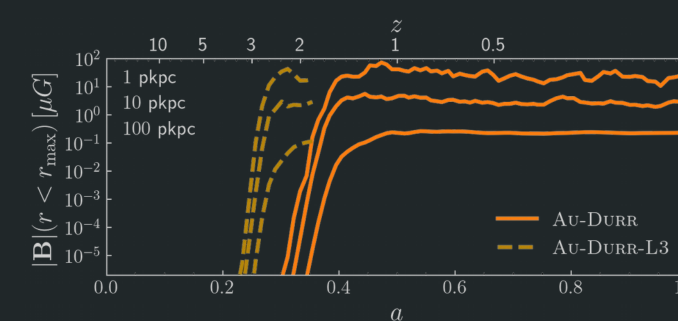
Garaldi et al. 2021

Seed process sets saturation time, but not strength

Enrico Garaldi



Caveat: the saturation time depends on numerical resolution



Garaldi et al. 2021

Galaxy properties are unaffected by the seeding

Simulation name	R_{200m} [kpc]	M_{200m} [10^{10} $M_\odot$]	$R_{hmr,*}$ [kpc]	$M_{hmr,*}$ [10^{10} $M_\odot$]
Au-none	332.71	129.60	4.29	1.31
Au-SNe	343.67	133.05	5.21	1.45
Au-SNe-H	343.89	133.29	6.04	1.47
Au-Durr	342.56	131.76	4.79	1.43
Au-Bier	343.82	133.22	4.49	1.63
Au-cosmo	344.41	133.91	3.64	1.65

Take-away message here: all magnetic seeds can be amplified in galaxies to observed strength.

Garaldi et al. 2021

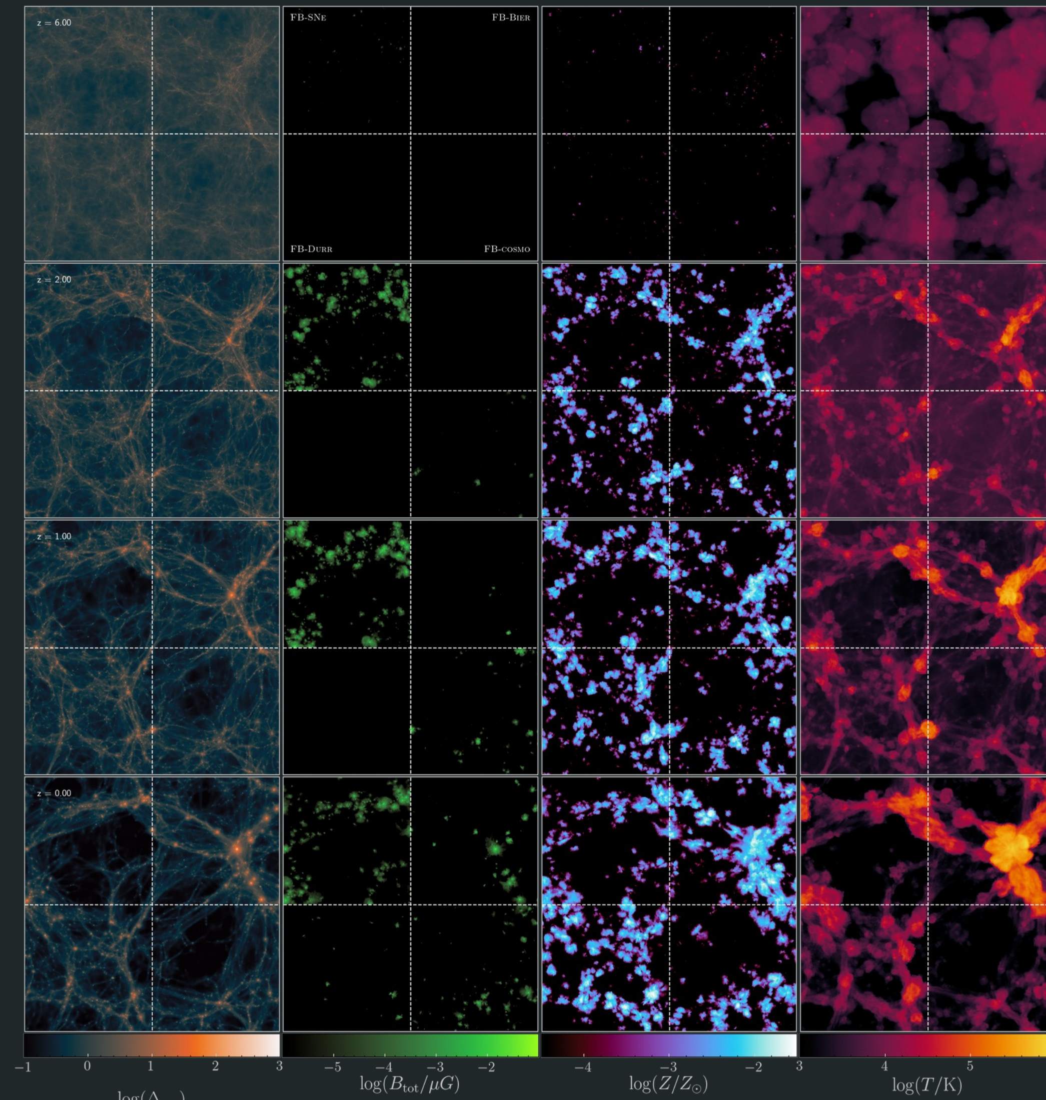
B fields on super-galactic scales.

results from cosmological simulations

Cosmological simulations

Same setup as the zoom-in for consistency.

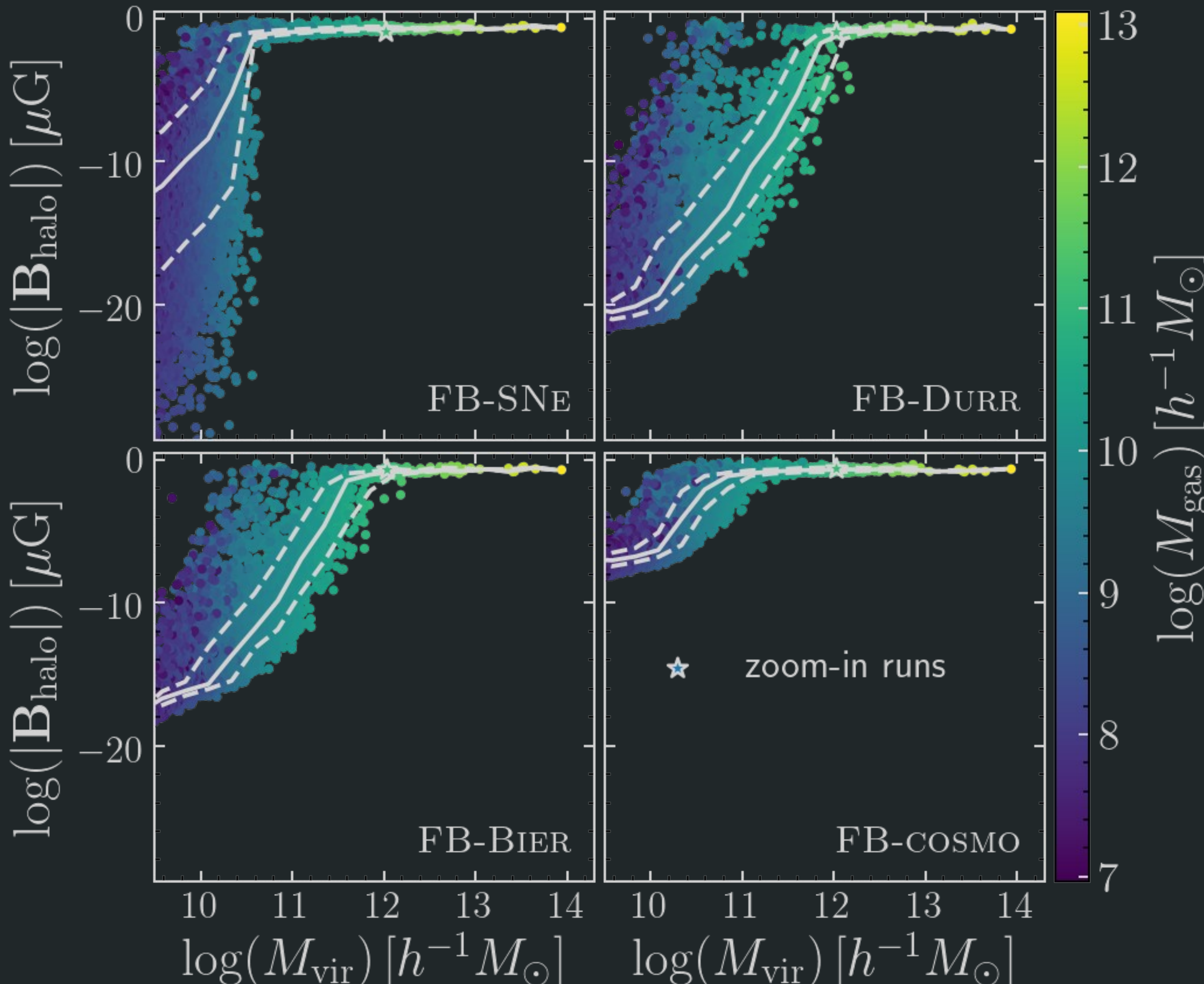
Note: the AURIGA model has been built and tested only on MW-like galaxies.



Garaldi et al. 2021

B fields as a function of halo mass

Enrico Garaldi

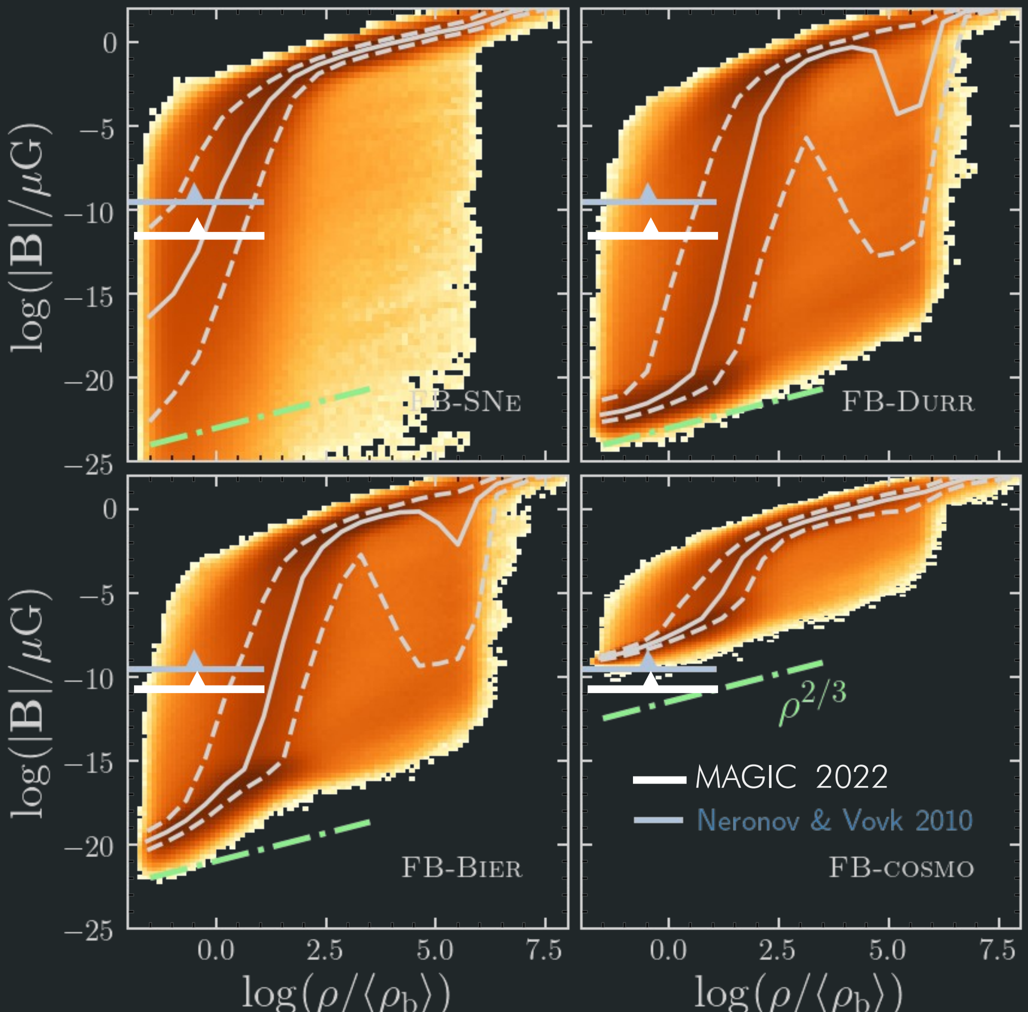


- Saturation strength does **not** dependent on M_{halo}
- Threshold M_{halo} for saturation depends on seed model
- SN inj. has different shape because the B seed is *strong and localised*

Garaldi et al. 2021

B fields in the IGM

ENRICO GARALDI



- Low-density gas retain traces of the seed field
- Biermann and Durrive batteries produce IGM fields lower than the (debated) Neronov&Vovk 2010 lower limit

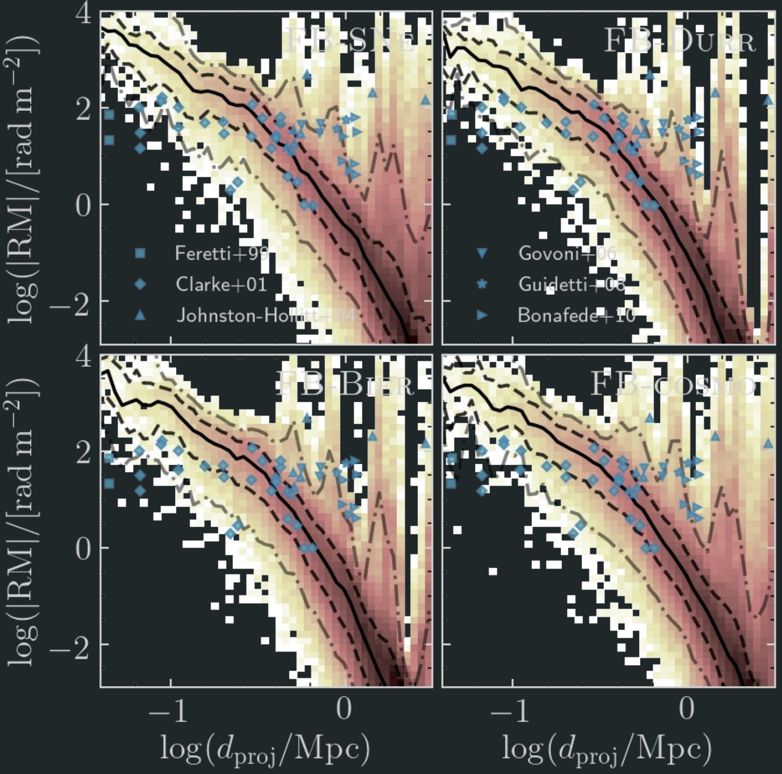
COHERENCE LENGTHS (at z=0)

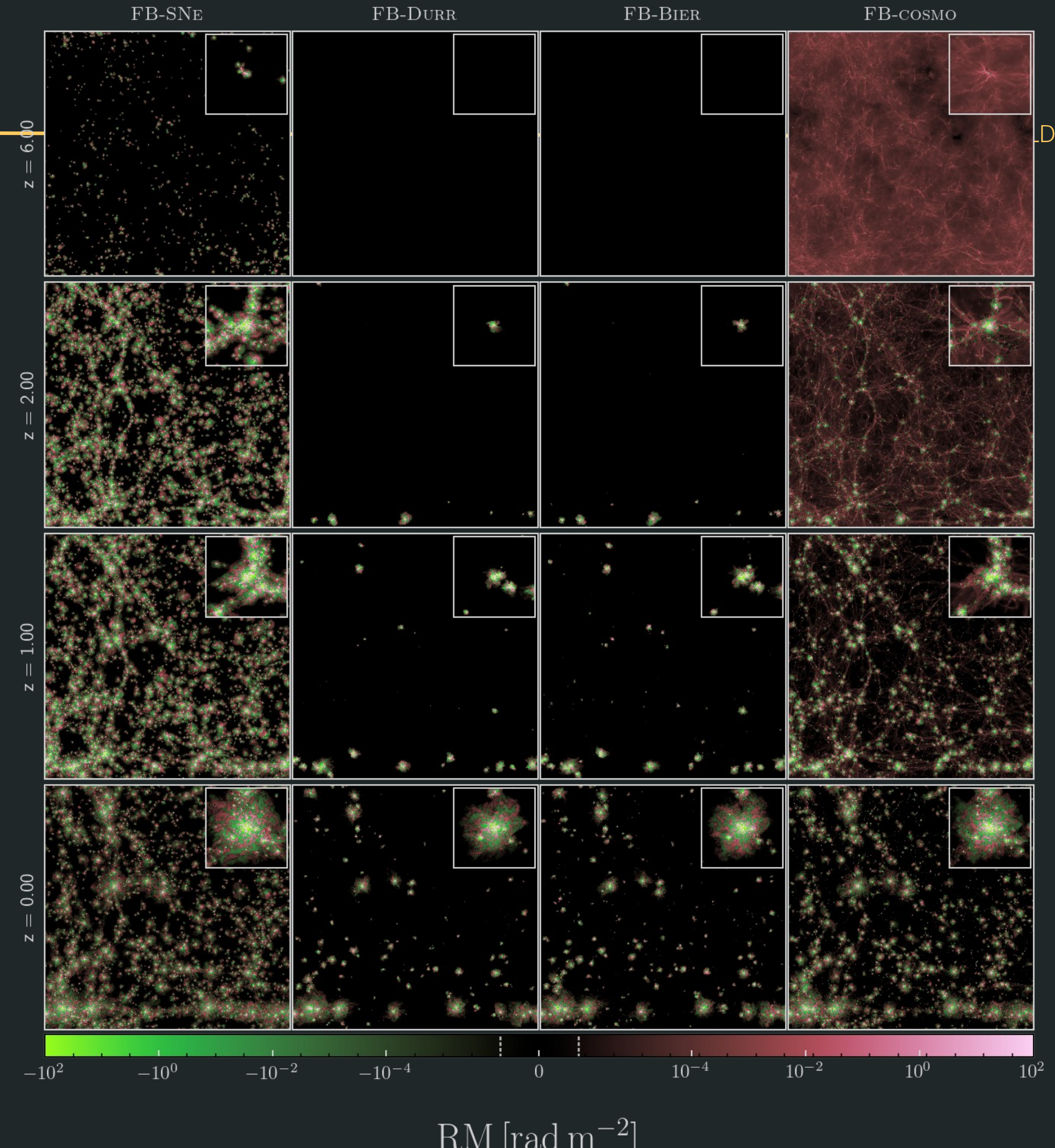
$L_C \approx 0.33$ Mpc/h for FB-BIER, FB-DURR, FB-SNE

$L_C \approx 0.49$ Mpc/h for FB-COSMO

Garaldi et al. 2021

RM prediction





Garaldi et al. 2021

Summary

Suite of **self-consistent** MHD+RT simulations, with state-of-the-art galaxy formation models and different magnetic field seeding.

- The Durrive battery is a viable candidate for magnetogenesis
- Observed galactic magnetic fields can be explained **without** a cosmological seeding mechanism
- The Durrive and Biermann battery behave similarly, but the latter is typically stronger
- The Durrive and Biermann battery are in tension with the (debated) Neronov & Vovk 2010 IGM lower limit

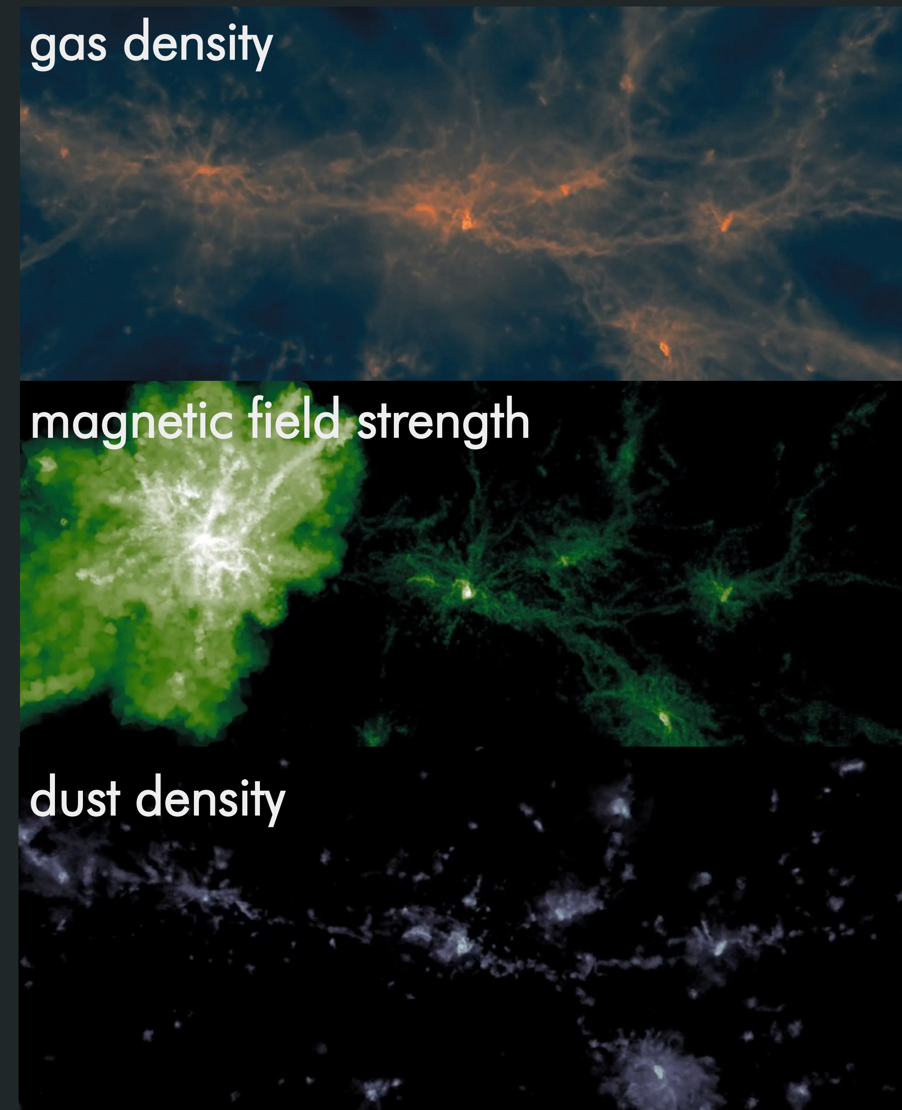
The THESAN simulation: self-consistent RMHD+dust

Enrico Garaldi

THESAN is a simulation suite developed to capture **simultaneously** galaxy formation and reionization.
(**Garaldi** et al. 2022, Kannan, **EG**, et al. 2022, Smith, **EG**, et al. 2022, ...)

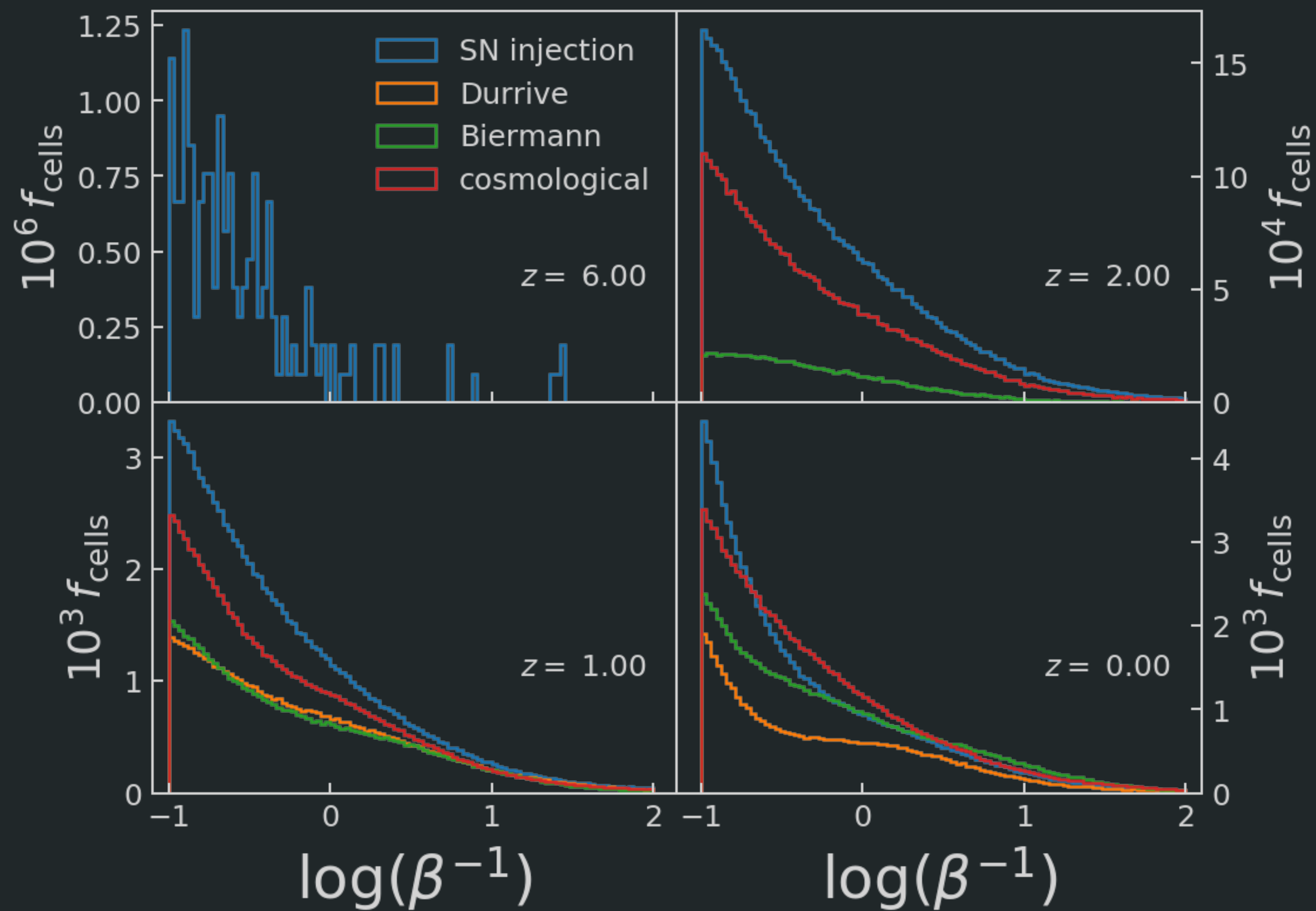
FEATURES: RMHD simulations (with the AREPO code)
+ **Illustris-TNG** galaxy formation model
+ self-consistent **radiation transport**
+ uniform initial ($z=50$) B field of 10^{-16} G.
+ **dust** creation & destruction
+ variance-suppressed initial conditions
+ cosmological volume $(100\ \mathrm{Mpc})^3$
+ **physical variations** (photon escape, DM)
+ main box stops at $z=5.5$, but some go to $z=0$

All data and data product will be freely available soon at www.thesan-project.com



The effect on galaxy evolution is mostly negligible

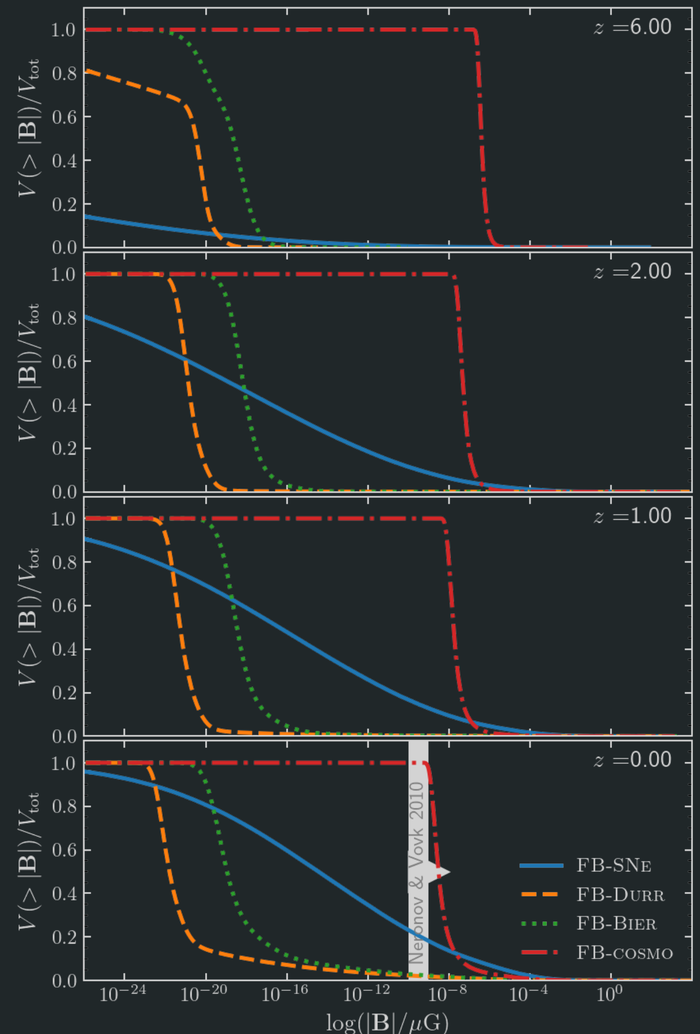
Enrico Garaldi



$$\beta \equiv \frac{P_{thermal}}{P_{magnetic}}$$

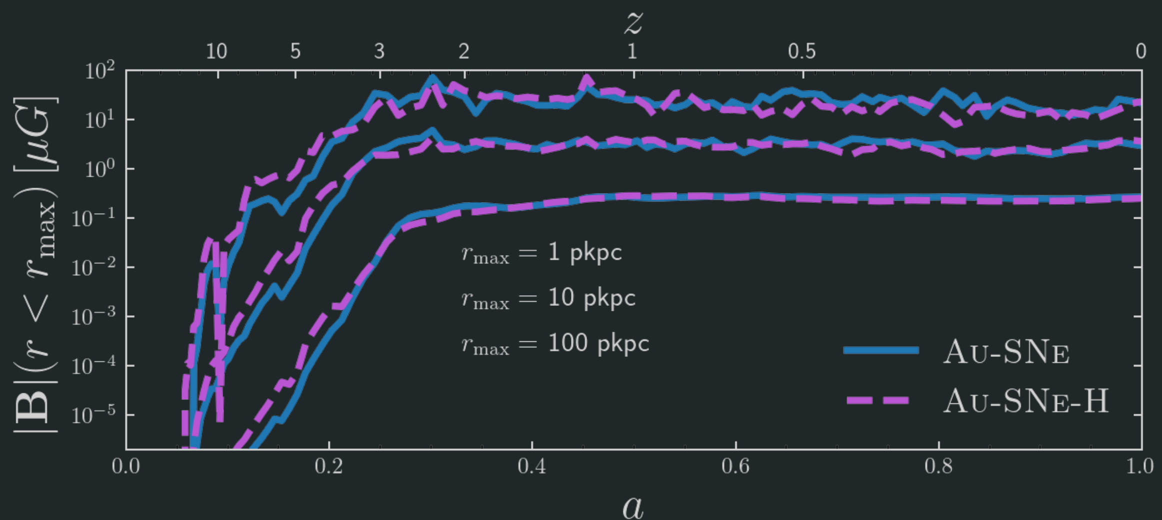
Garaldi et al. 2021

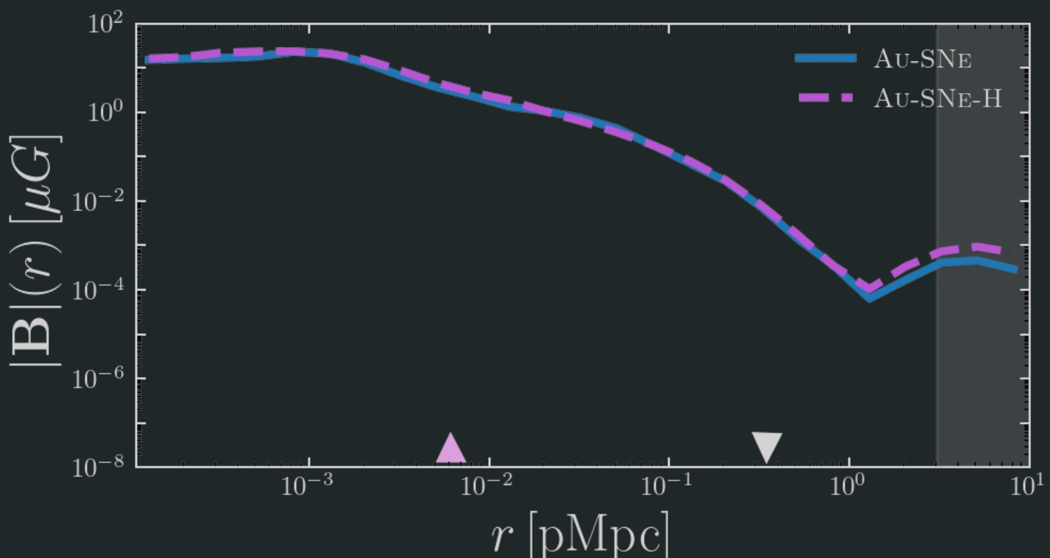
B fields filling factor



Garaldi et al. 2021

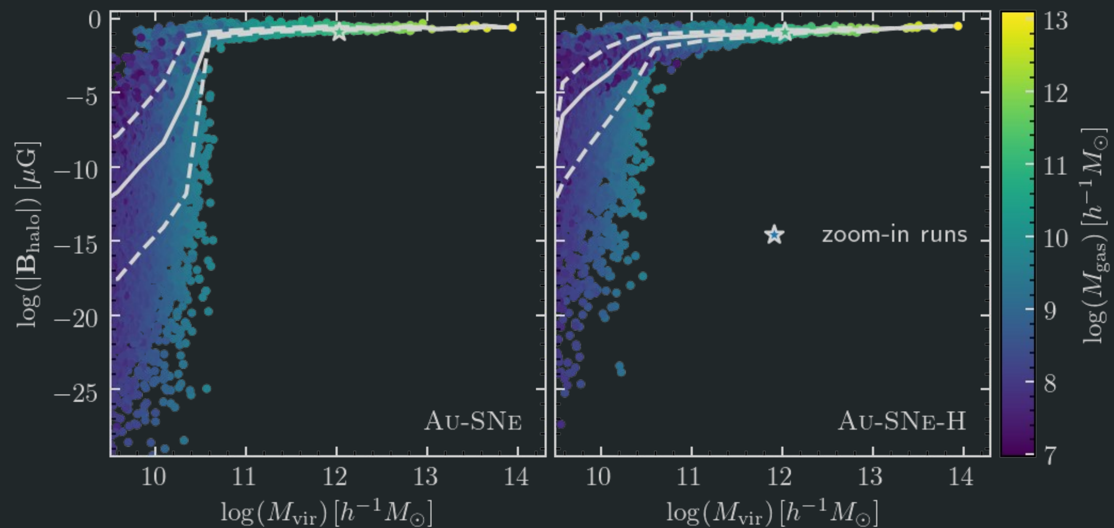
Effect of SN energy: zoom-in

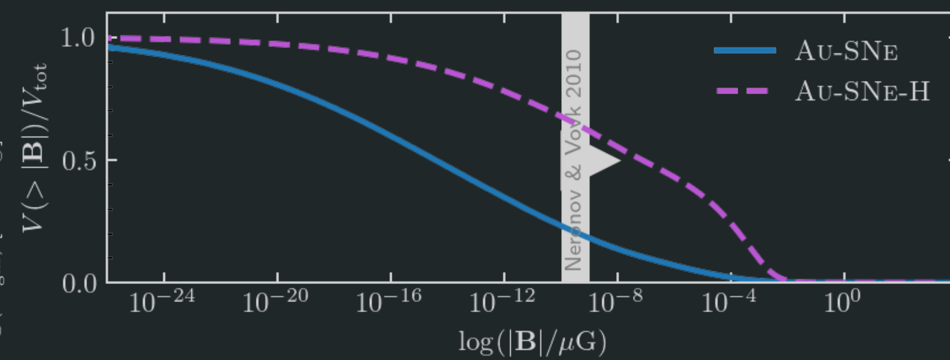


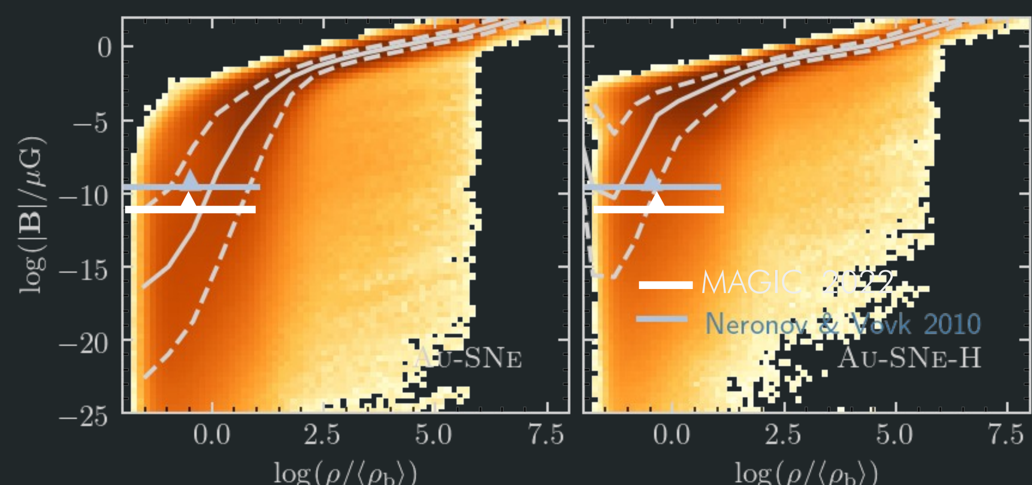


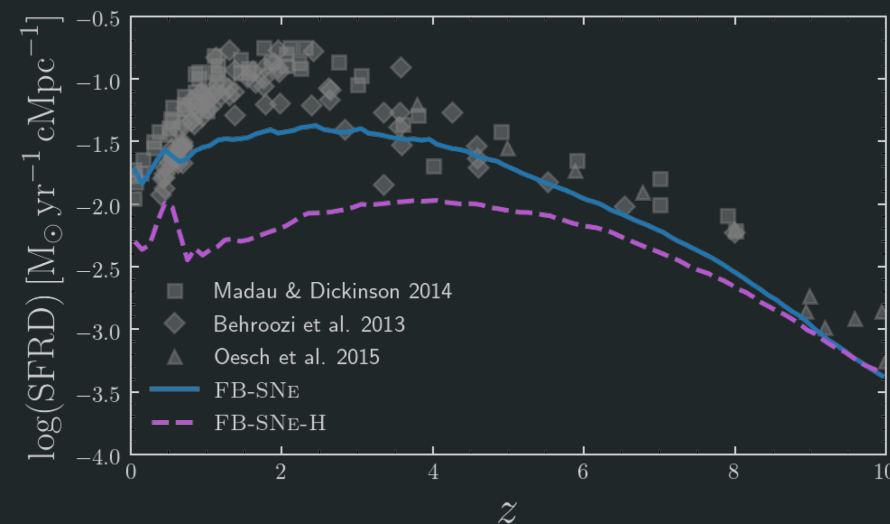
Garaldi et al. 2021

Effect of SN energy







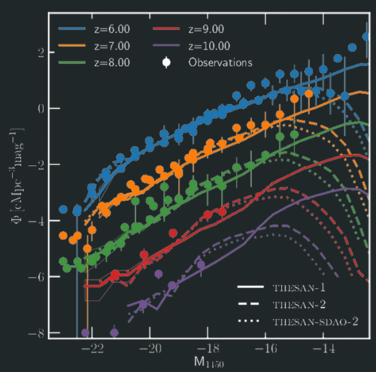


Garaldi et al. 2021

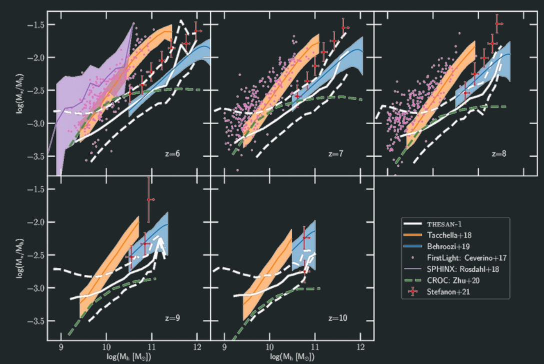
THESAN agrees with many high-z observables

Enrico Garaldi

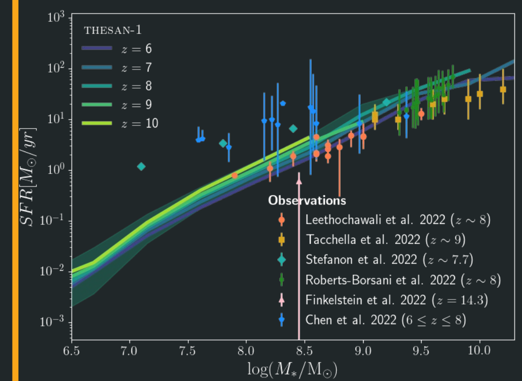
UV LUMINOSITY FUNCTION



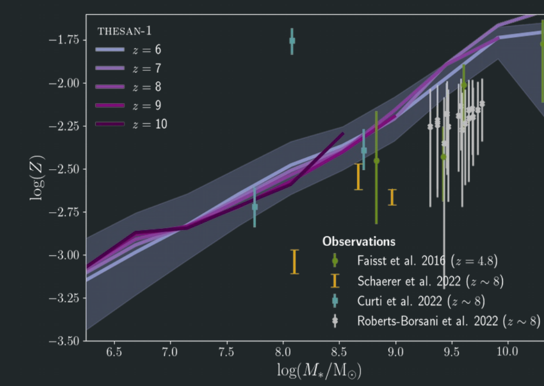
STELLAR-TO-HALO MASS RELATION



GALAXY MAIN SEQUENCE

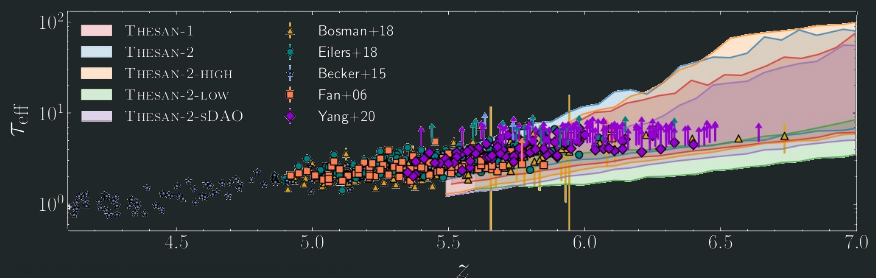


(STELLAR) MASS – (GAS) METALLICITY RELATION

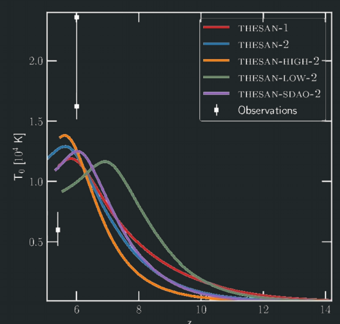


JWST OBSERVATIONS

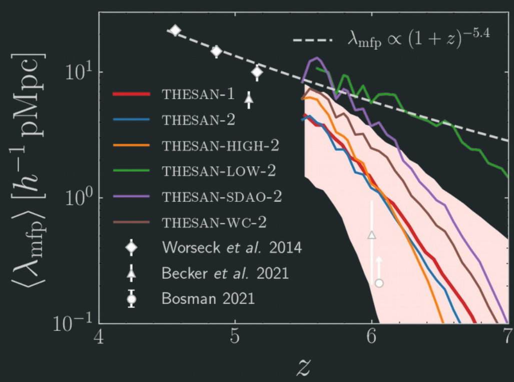
LYA OPTICAL DEPTH EVOLUTION



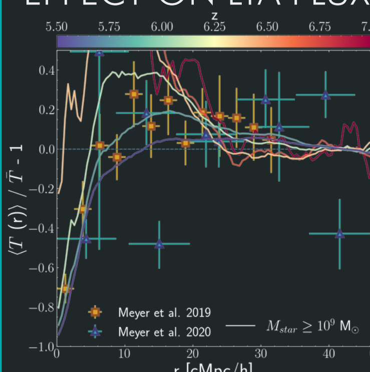
IGM MEAN TEMPERATURE



MEAN FREE PATH OF IONIZING PHOTONS



GALAXY PROXIMITY EFFECT ON LYA FLUX



FIRST TIME IN SIMULATIONS!

Garaldi et. al, 2022;
Kannan, EG et al., 2022;
Garaldi et. al, in prep.