On the origin of galactic magnetic fields

Magnetic field tracers

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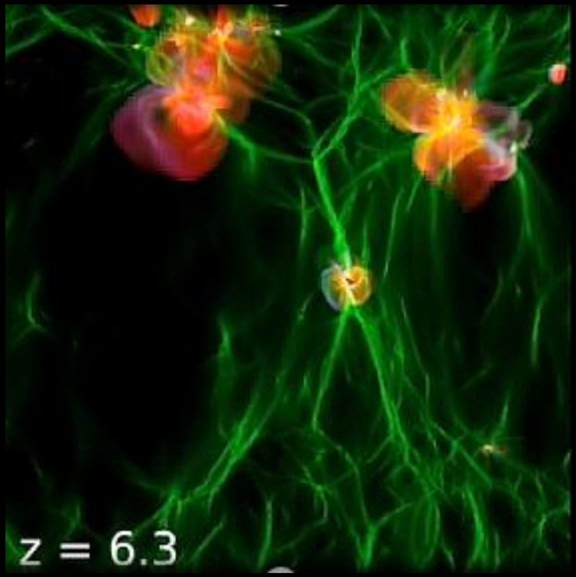
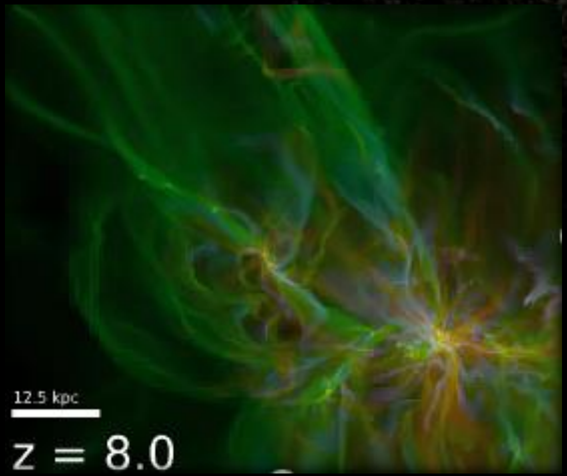
with Harley Katz, Julien Devriendt, and Adrianne Slyz





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Tracer fields to unveil the origin of present day galactic magnetic fields

Introduction

Magnetic fields in galaxies

Magnetic fields at equipartition with turbulent energy. They are a non-negligible component of the interstellar medium (ISM)

(Beck et al. 2015; Bernet et al. 2008; Beck & Wielebinski 2013).

Importance of galactic magnetic fields

- Equipartition with thermal energy
- Modify ISM dynamics
- Relevant in star formation
- Magnetize cosmic web? (outflows)
- Crucial for cosmic rays

IC 342, dashes display 6.2cm polarized emission (rotated 90 degrees)

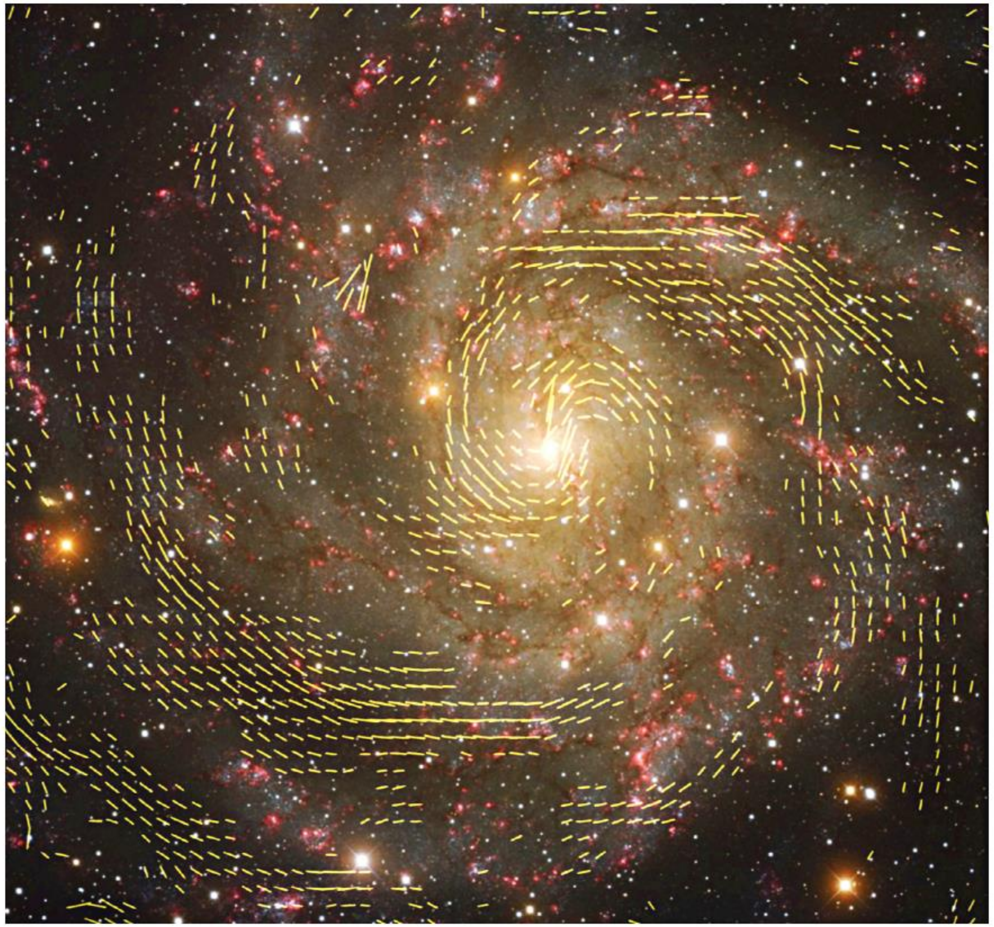


Image credit: R. Beck/MPIfR (radio emission, VLA+Effelsberg) and T. A. Rector, University of Alaska Anchorage, and H. Schweiker, WIYN and NOAO/AURA/NSF (optical, Kitt Peak Observatory)

Introduction

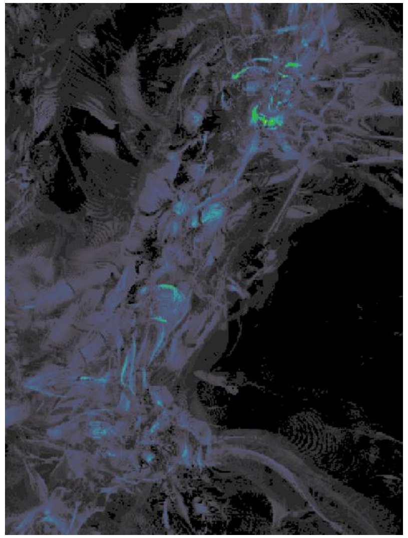
From theory to observations: the gap between primordial magnetism and galactic magnetic fields

From initial magnetic fields...

Inflation seeds $\lesssim 10^{-23}$ G
Biermann battery $\sim 10^{-21}$G
Plasma spontaneous mag. $\lesssim 10^{-16}$G

... to observational constrains...

Planck (+SPT): $B_{co} \lesssim 10^{-9}$ G (Planck collaboration XIX, 2015)
Fermi/HESS: $B_{co} \gtrsim 10^{-17}$ G (Neronov & Vovk, 2010; opposed by Broderick et al. 2012)



Simulated filament intrinsic radio emission. **Image credit:** Vazza et al. 2015.

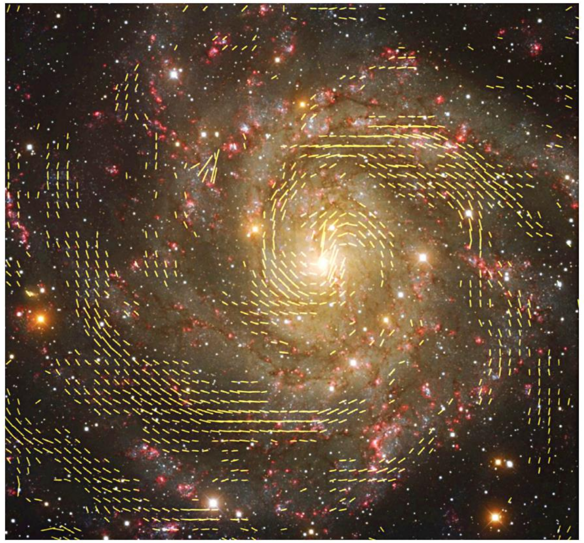


Image credit: R. Beck/MPIfR (radio emission, VLA+Effelsberg) and T. A. Rector, University of Alaska Anchorage, and H. Schweiker, WIYN and NOAO/AURA/NSF (optical, Kitt Peak Observatory)

... and magnetic fields in structure

Galaxies 1-10 μG (e.g. Mulcahy et al. 2014; Beck, 2015).
Clusters 1-100 nG (e.g. Clark, 2004; Ferrari et al. 2008).
Voids $\ll 10^{-10}$ G (???).

Origin of galactic magnetic fields

Dynamos

Turbulent dynamo

- Fast and efficient
- Ubiquitous
- Disorganised

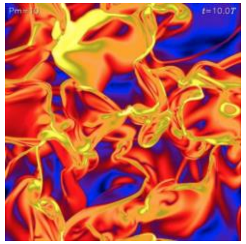


Image Credit: Federrath et al. 2014.

$\alpha - \Omega$ dynamo

- Slow
- Requires a disk
- Organised

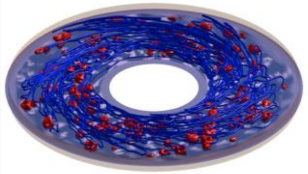


Image Credit: Gissinger et al. 2009

MRI dynamo

- Intermediate
- Stringent cond.
- Local

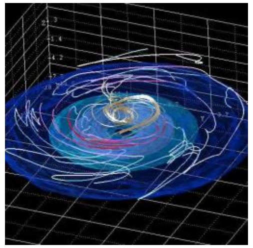


Image Credit: Machida et al. 2013

Primordial fields

A wide range of primordial fields that could lead to observed galactic magnetic fields are also **compatible with the observational constraints** for the cosmic magnetic field...

... to observational constrains...

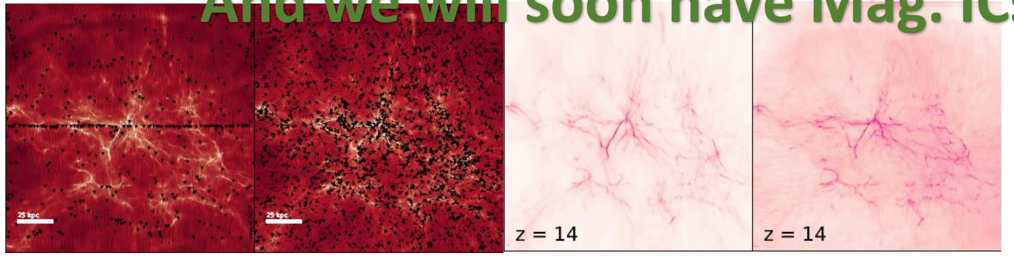
Planck (+SPT): $B_{co} \lesssim 10^{-9}$ G

Fermi/HESS: $B_{co} \gtrsim 10^{-17}$ G

Theoretical models exist for primordial magnetogenesis leading to $B_{co} > 10^{-14}$ G.

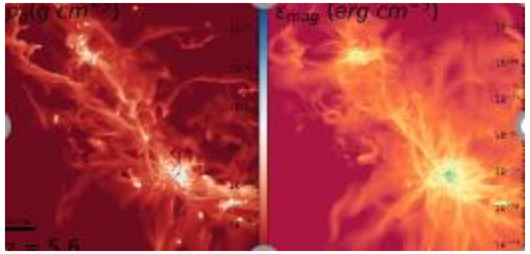
(e.g. Barrow & Tsagas, 2011; Sharma et al. 2018)

And we will soon have Mag. ICs!



Feedback sources

Supernovae feedback strong magnetic fields to the interstellar medium.



In the same manner, plasma **jets from AGN provide highly magnetised** gas to the intracluster medium.

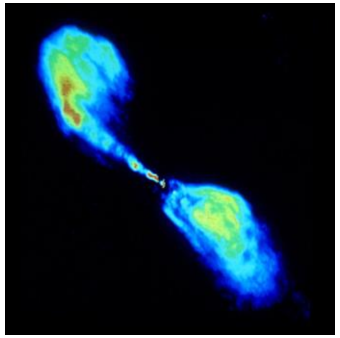


Image credit: J. O. Burns, University of Missouri/D. Clarke, St. Mary's University, Nova Scotia

Magnetic tracers

How do we separate the effects due to each source of ISM magnetic fields?

$$\vec{B} = \vec{B}_1 + \vec{B}_2 + \ldots$$

$$\partial_t \vec{B} = \vec{\nabla} \times (\vec{v} \times \vec{B}) + \eta \nabla^2 \vec{B} \left(+ \frac{\mathcal{H}}{2} \vec{B} \right)$$

$$\partial_t \vec{B} = \partial_t \vec{B}_1 + \partial_t \vec{B}_2 + \ldots = \left(\vec{\nabla} \times (\vec{v} \times \vec{B}_1) + \eta \nabla^2 \vec{B}_1 \right) + \left(\vec{\nabla} \times (\vec{v} \times \vec{B}_2) + \eta \nabla^2 \vec{B}_2 \right) + \ldots$$

$$\partial_t (\rho \vec{v}) = f_1 (\vec{B})$$

$$\partial_t E = f_2 (\vec{B})$$

$$\vec{\nabla} \cdot \vec{B} = 0 \Longrightarrow \vec{\nabla} \cdot \vec{B}_1 = 0, \quad \vec{\nabla} \cdot \vec{B}_2 = 0, \quad \ldots$$

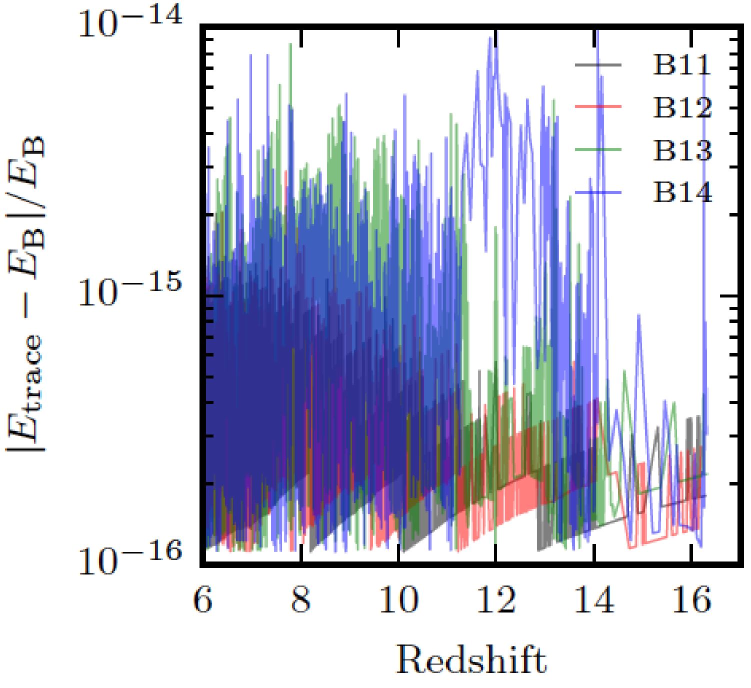
Magnetic tracers

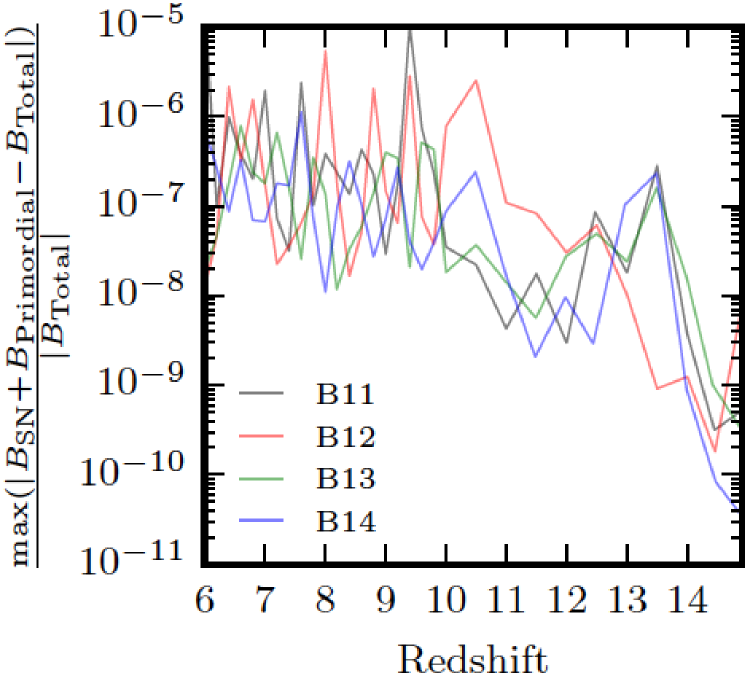
Numerical tests for the code

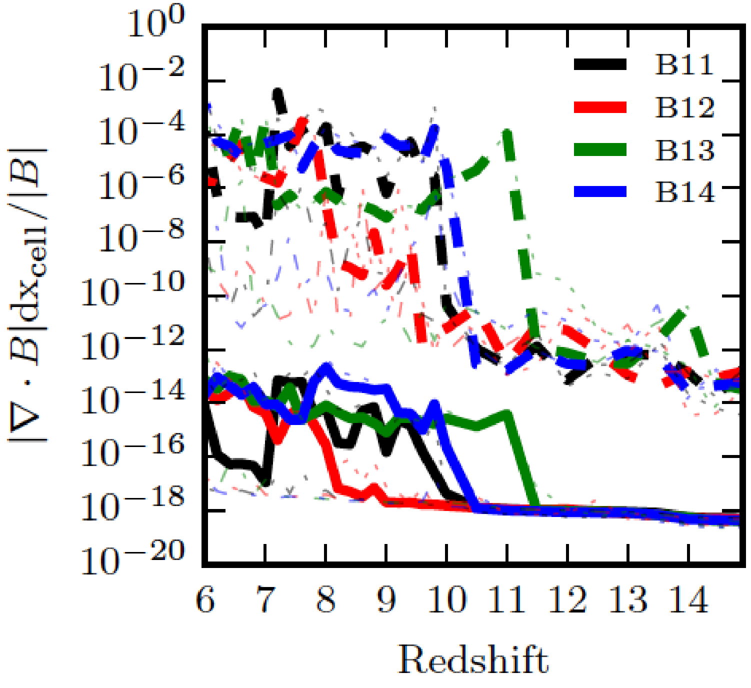
$$\int \frac{B^2}{2}\, dV = \int \frac{B_1^2}{2} + \frac{B_2^2}{2} \; ?$$

$$\vec{B} = \vec{B}_1 + \vec{B}_2 \; ?$$

$$\vec{\nabla} \cdot \vec{B}_1 = 0$$
$$\vec{\nabla} \cdot \vec{B}_2 = 0$$







Simulations

RAMSES MHD simulations

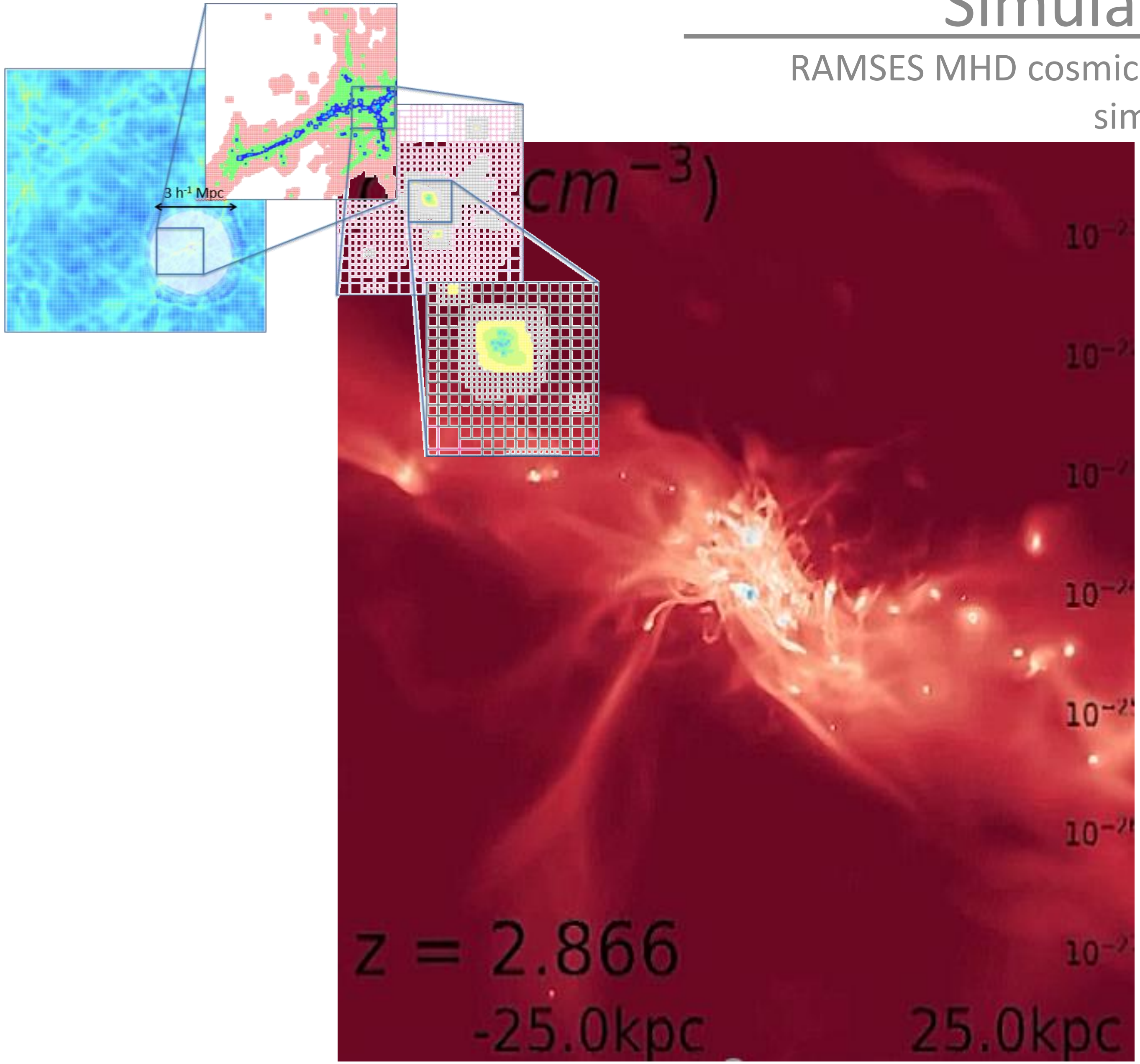
Cosmic MHD with RAMSES:

- Eulerian AMR gas treatment
- Lagrangian star and dark matter
- Constrained Transport magnetism

(Teyssier 2002, Teyssier et al. 2006, Fromang et al. 2006)

Simulation setup (NUT galaxy):

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



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- WMAP5 cosmology

Sub-grid physics

- Mechanical SNe feedback

(Kimm et al. 2015)

- Turbulent star formation

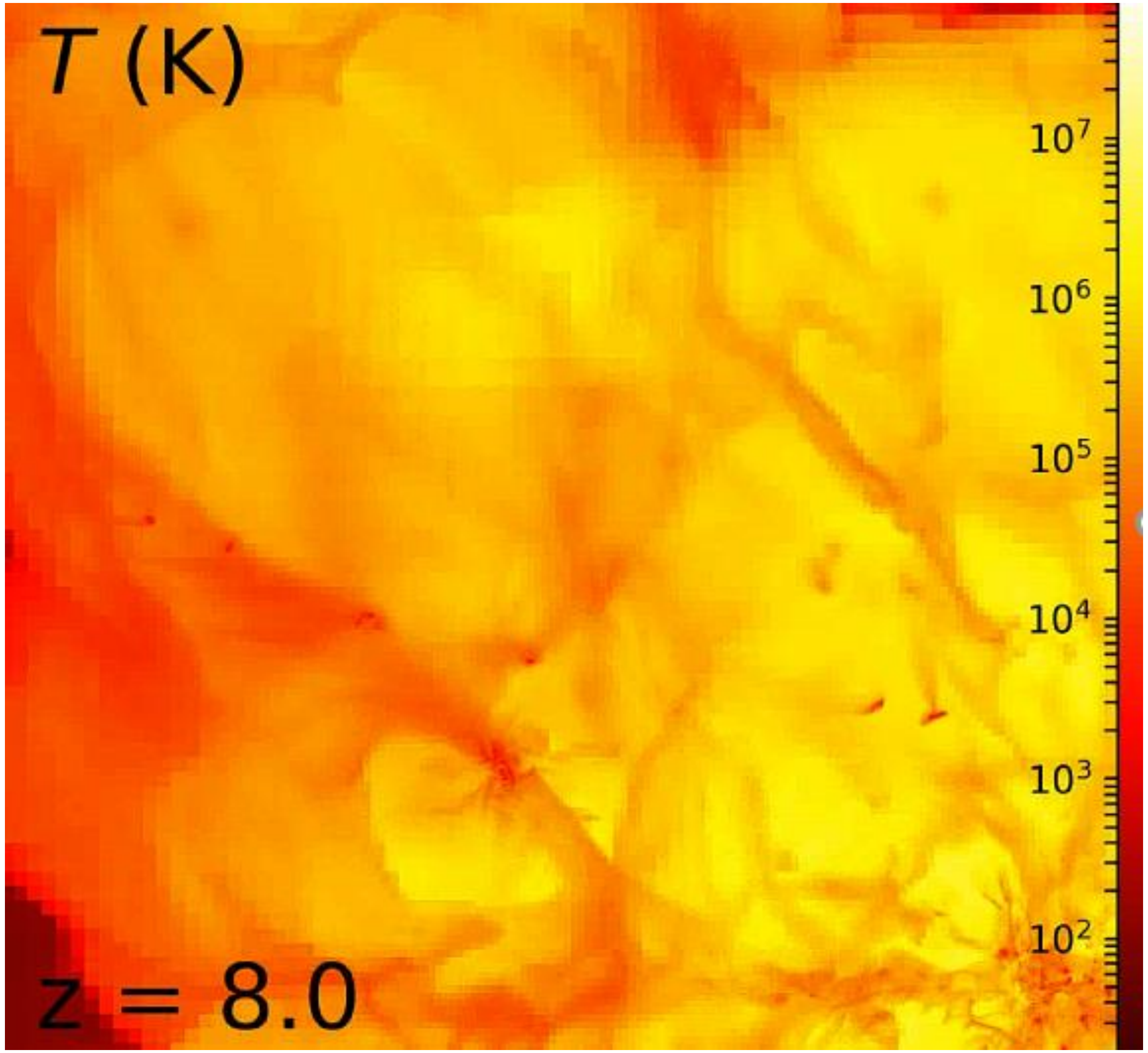
(Kimm et al. 2016; Devriendt et al. in prep)

- Metal cooling

(Sutherland & Dopita, 1993; Rosen & Bregman, 1998)

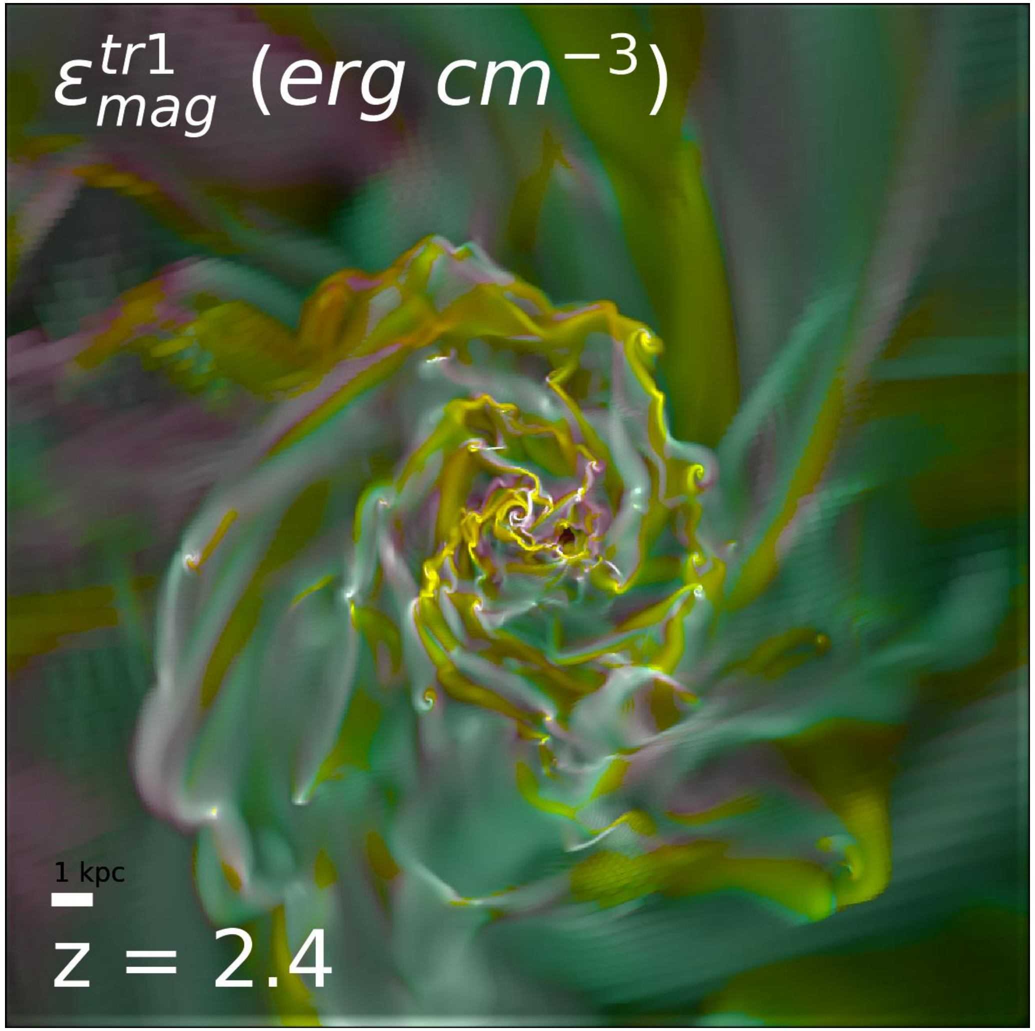
- UV background

(Haardt & Madau, 1996)



Results

Comparing primordial vs stellar magnetic fields



Injected by supernova

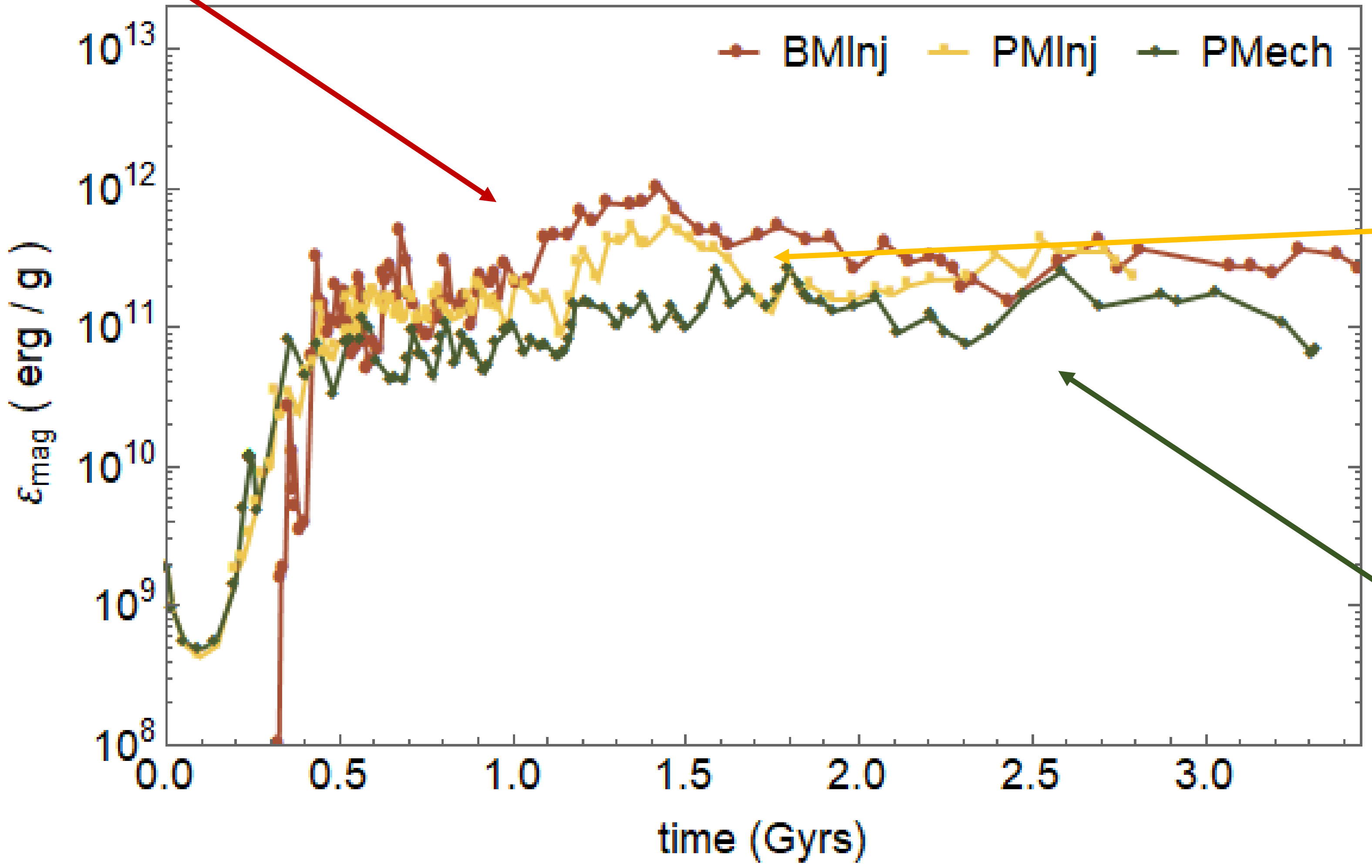
Interaction energy

Primordial

Injected + primordial

Specific magnetic energy in and close to the galaxy

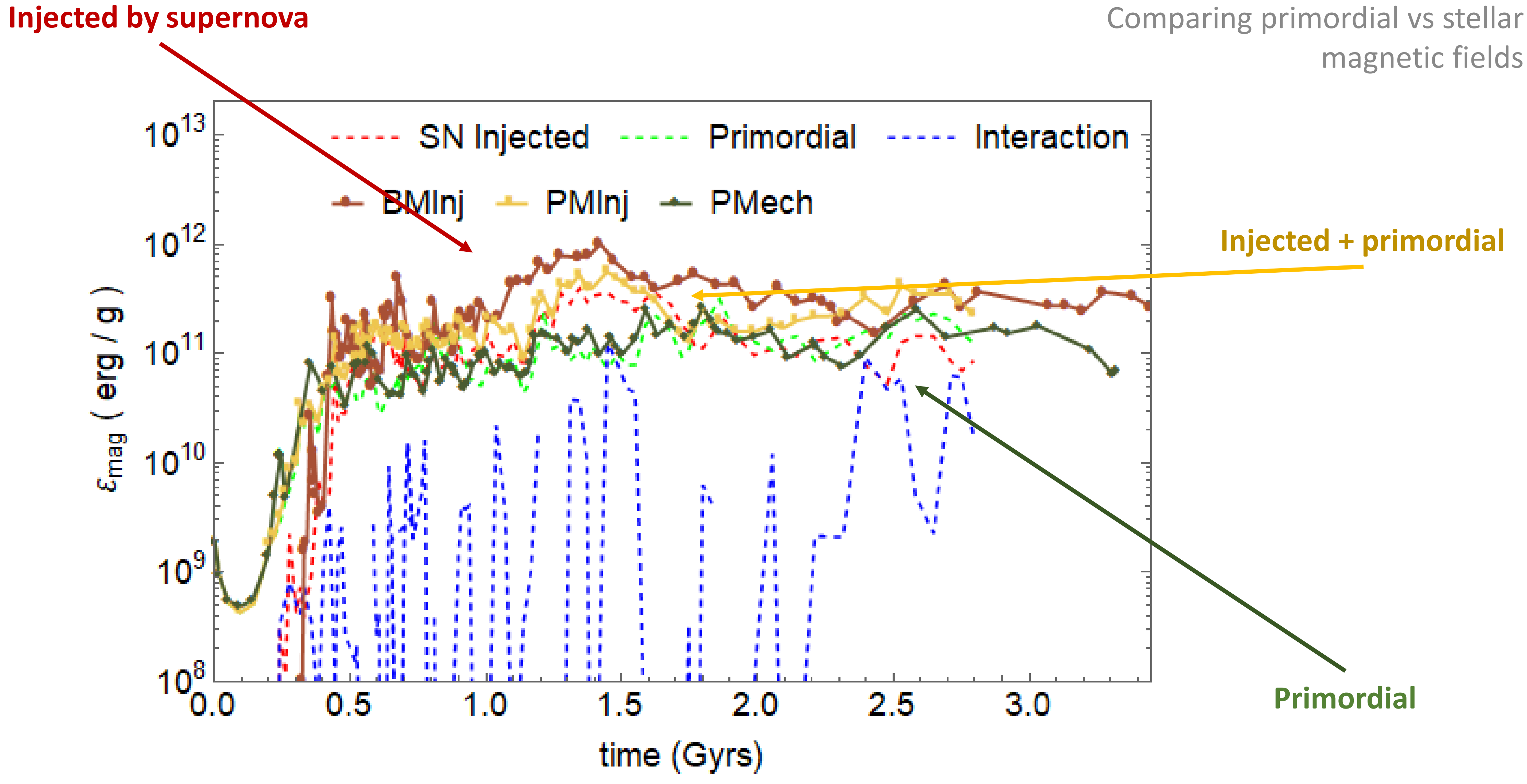
Injected by supernova



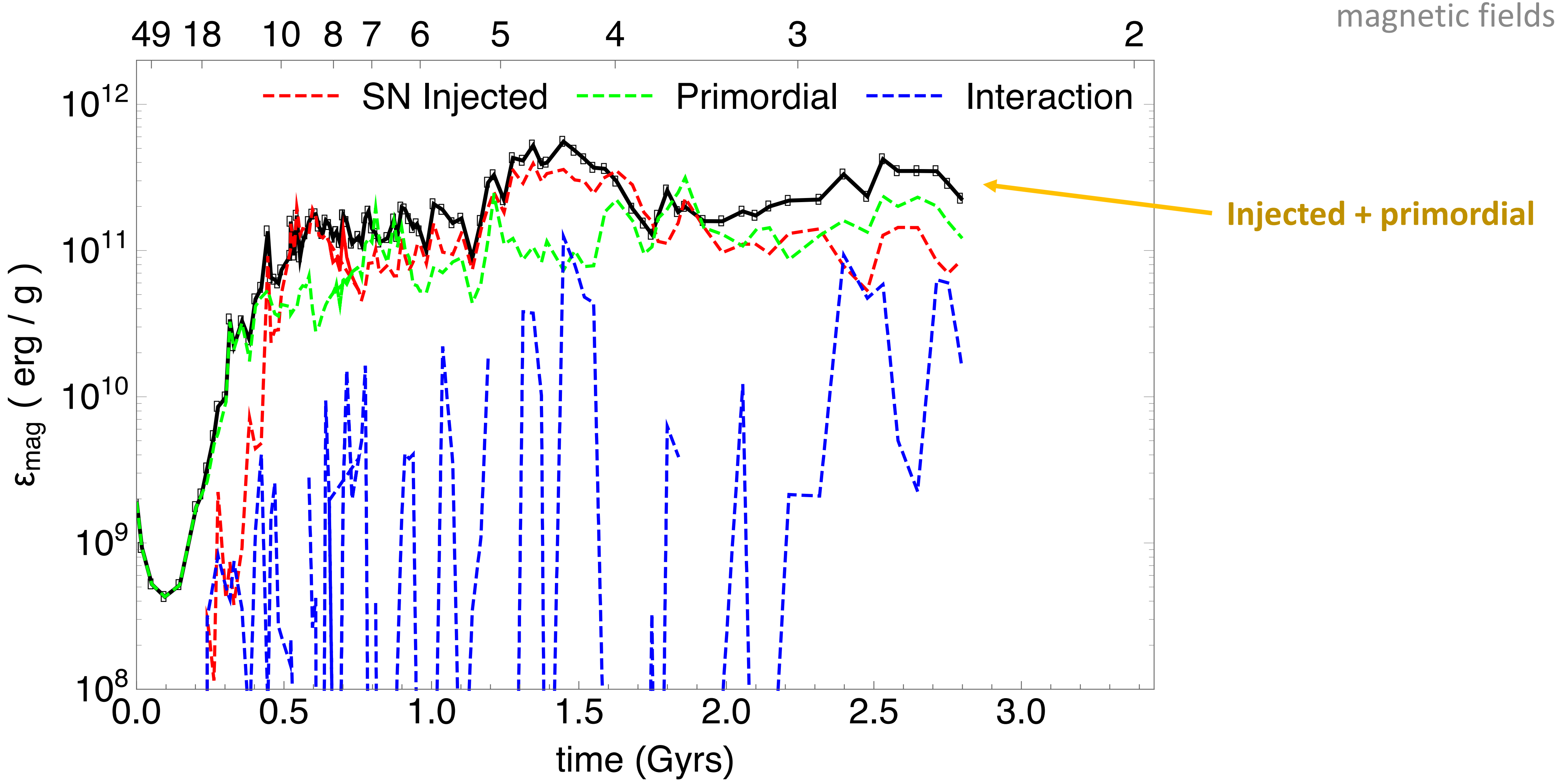
Injected + primordial

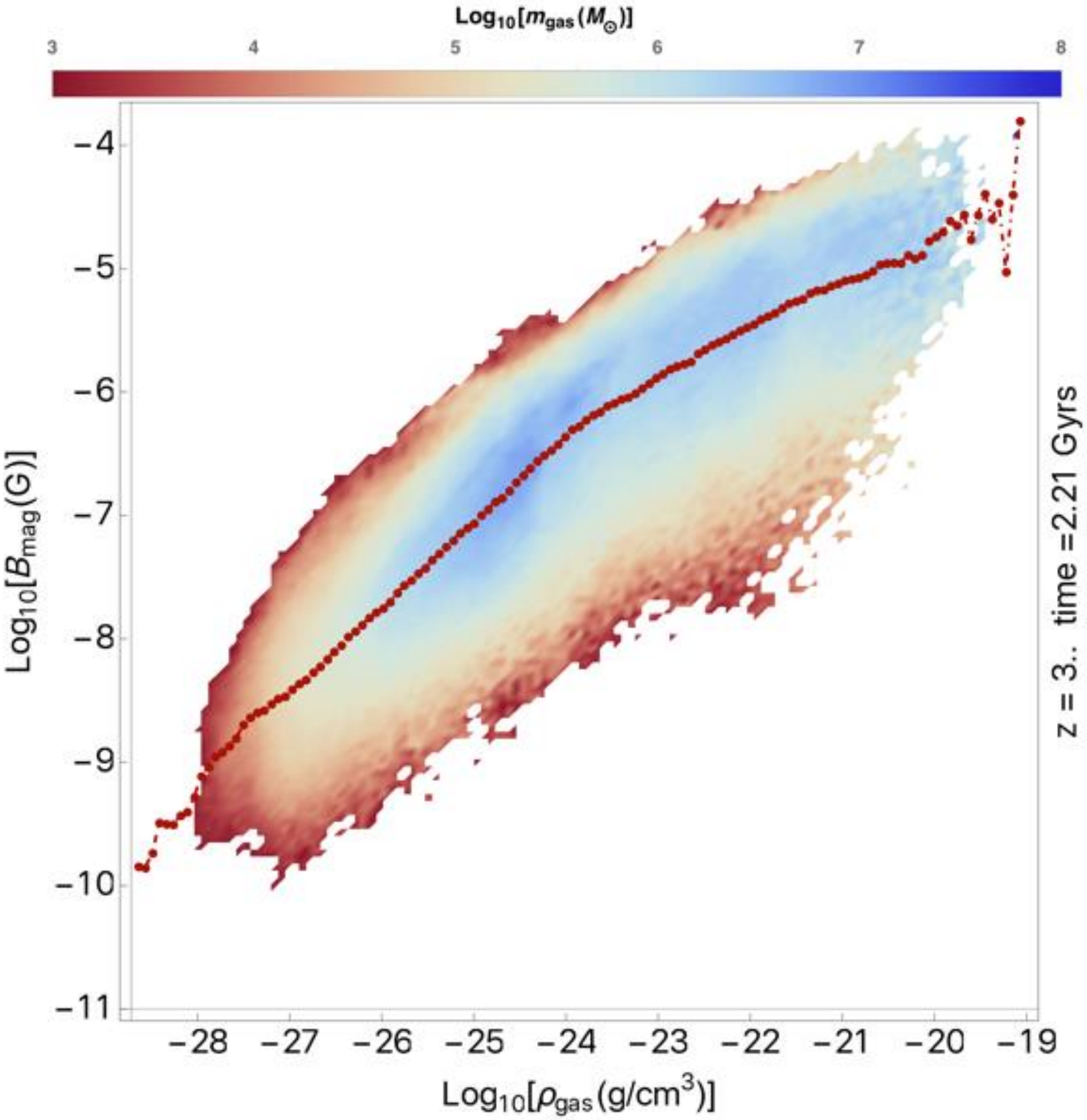
Primordial

Specific magnetic energy in and close to the galaxy



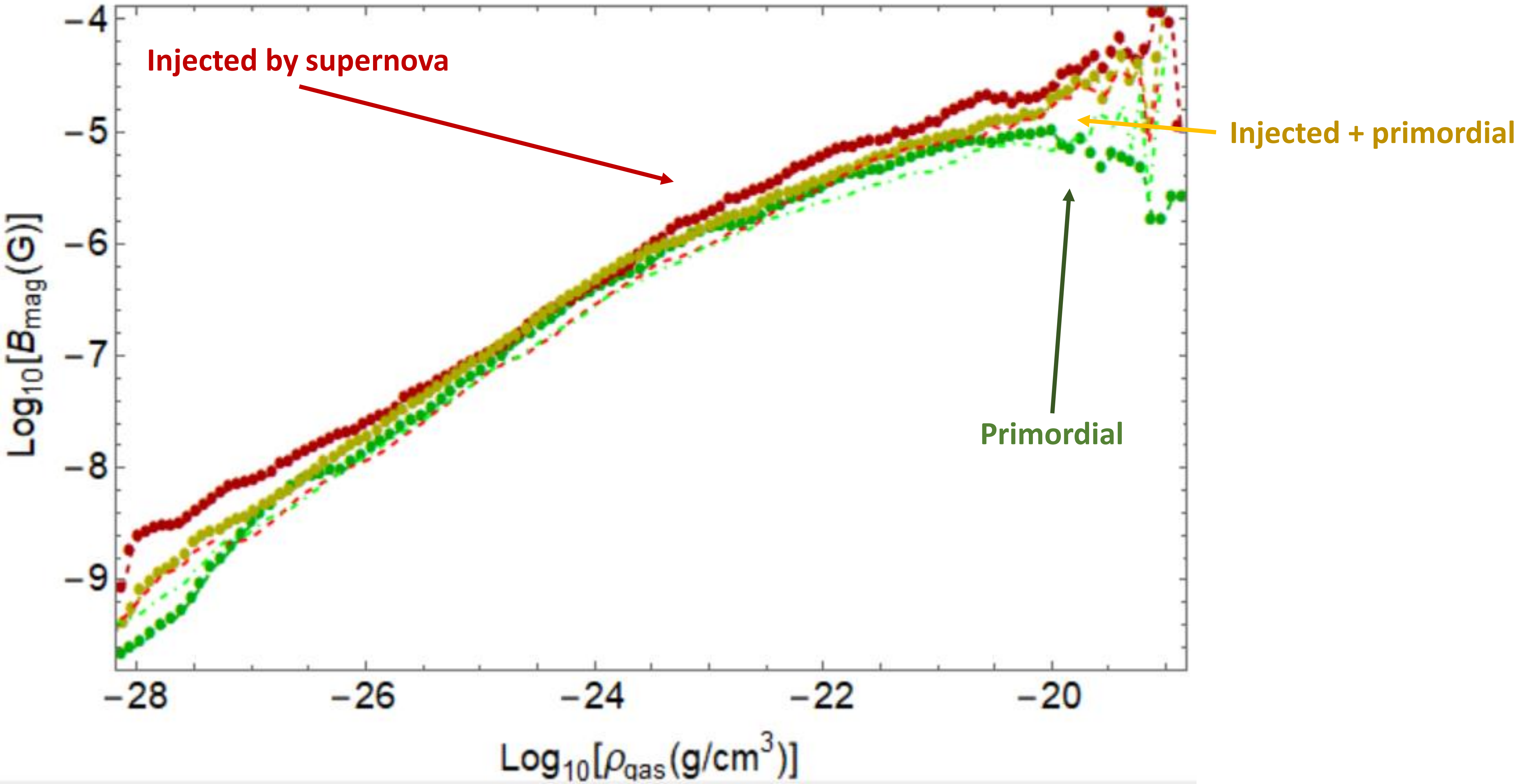
Specific magnetic energy in and close to the galaxy





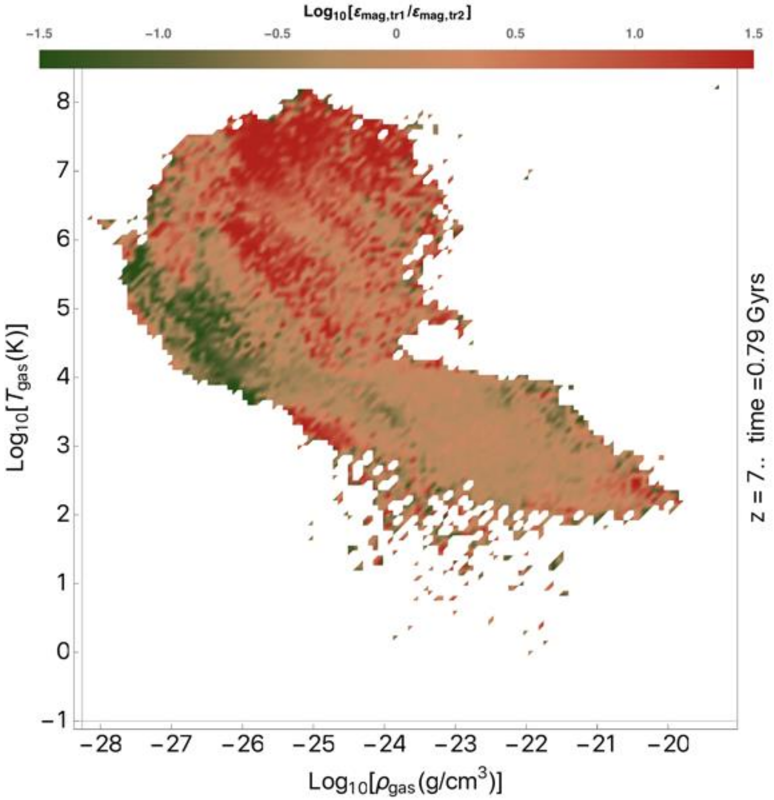
Log10[mgas (M⊙)]
3
4
5
6
7
8
Log10[Bmag(G)]
-4
-5
-6
-7
-8
-9
-10
-11
-28
-27
-26
-25
-24
-23
-22
-21
-20
-19
Log10[ρgas (g/cm3)]
z = 3.. time =2.21 Gyrs

Scaling of $B = B\,(\rho)$

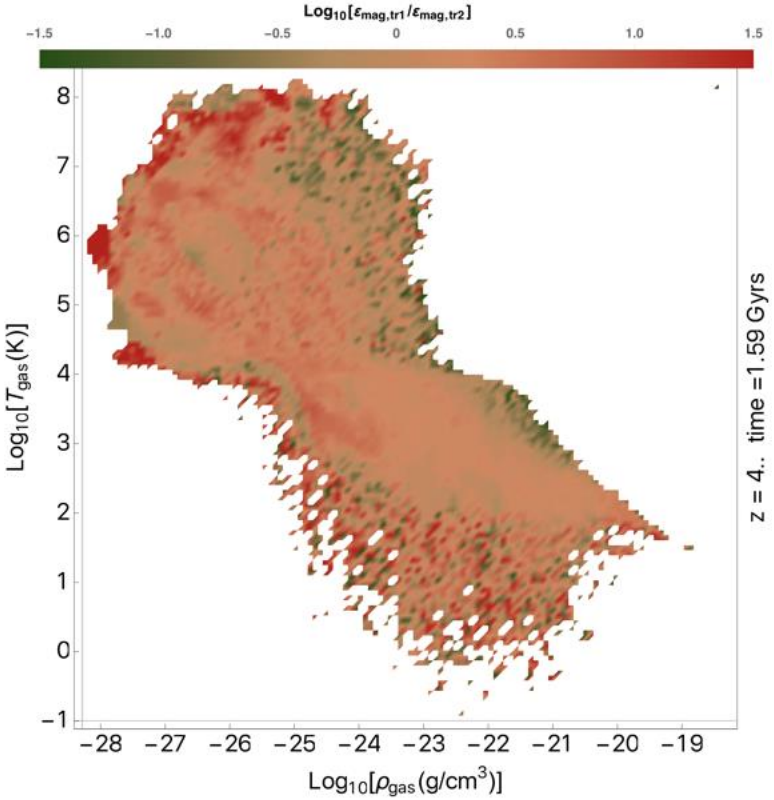


$\text{Log}_{10}[\varepsilon_{mag,tr1}/\varepsilon_{mag,tr2}]$

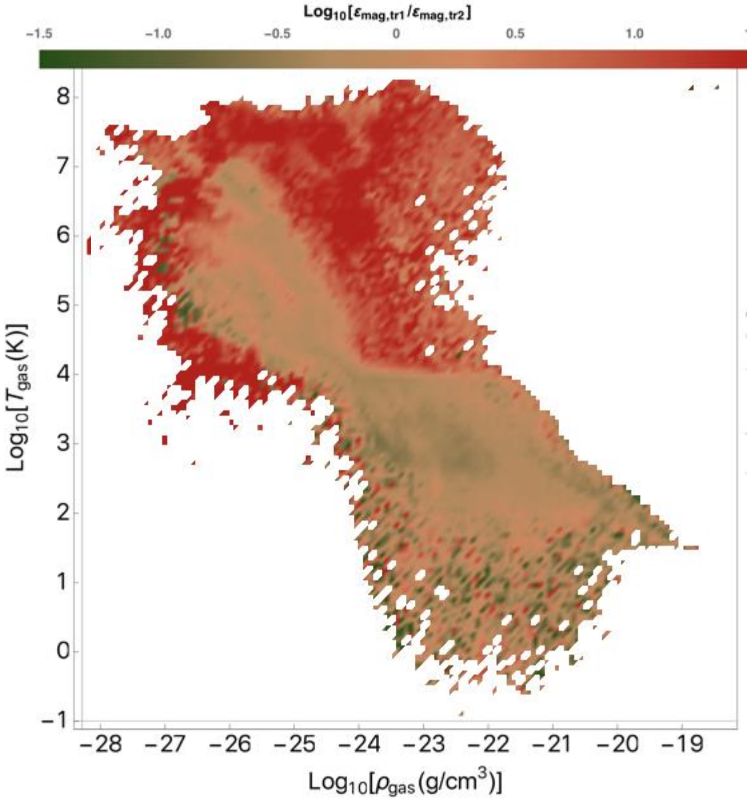
z = 7



z = 4



z = 2.5



Conclusions

and important remarks

The code works!

- Magnetic tracers are a useful method to better understand magnetism, unfolding its effects. And not only in galaxies.

So far:

- Magnetic fields of different nature distribute spatially differently in the ISM.
- The different scaling $B \propto \rho^{\alpha}$ advocated for different magnetic origins is more unclear when combined. Each tracer behaves differently.
- When combined, primordial and SN ejected magnetic fields dominate different parts of the density-temperature phase space.