Universität Zürich[UZH]

· OMAR ATTIA ·

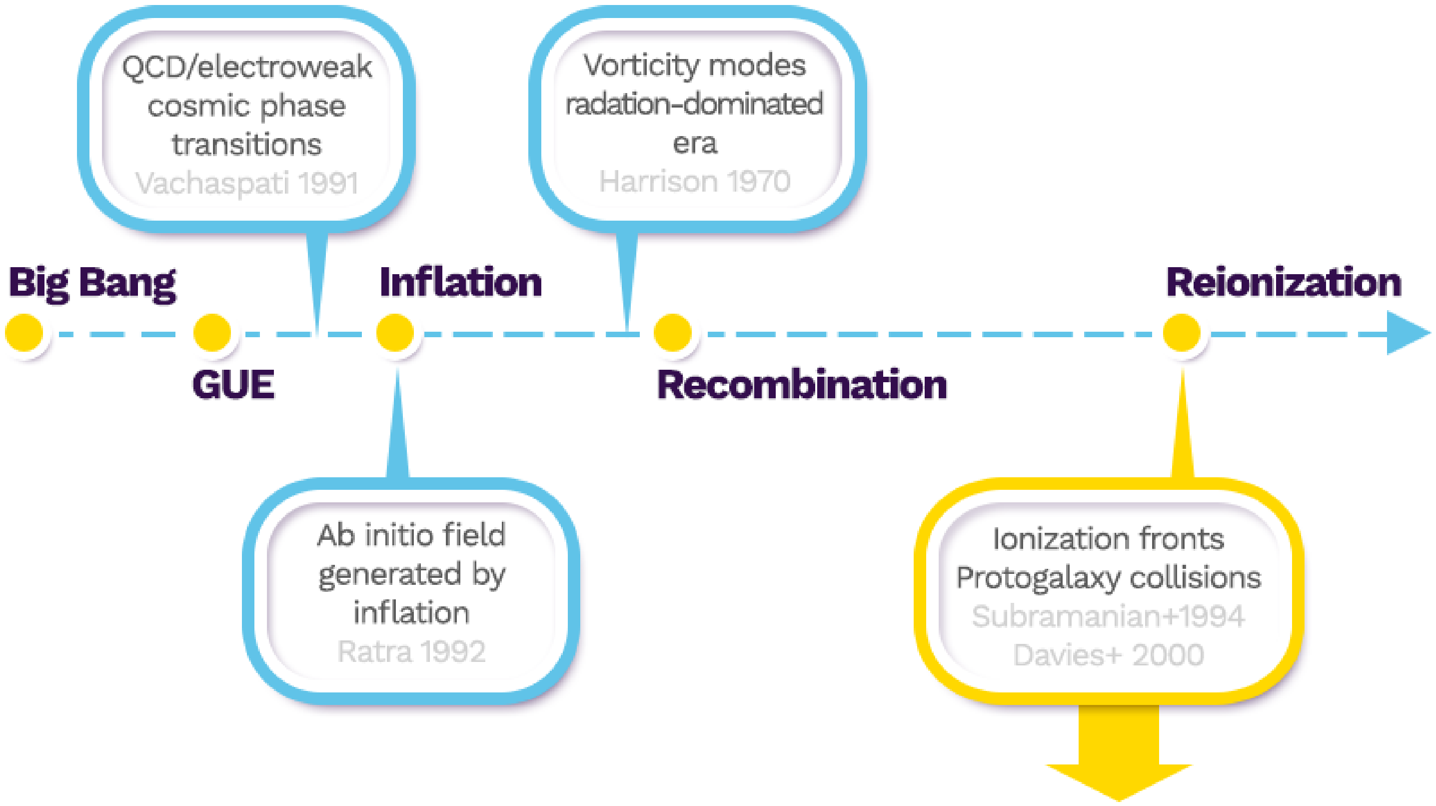
GENERATING MAGNETIC FIELDS WITH THE BIERMANN BATTERY

09/2021

INTRODUCTION

PRIMORDIAL MAGNETOGENESIS

- Origin of cosmic magnetic fields?



underlying mechanism:
the **Biermann battery**

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

THE BIERMANN BATTERY

THEORETICAL BACKGROUND

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) = \nabla \times \mathbf{E}_{\mathbf{EMF}}$$

- Fails to generate an *ab initio* magnetic field.

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

THEORETICAL BACKGROUND

- Using the conservation of electrons momentum:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}_{\mathbf{EMF}} + \nabla \times \underbrace{\left(c \frac{\nabla p_{\mathrm{e}}}{e n_{\mathrm{e}}} \right)}_{\mathbf{E}_{\mathbf{B}}}$$

PROPERTIES OF THE BATTERY

$$\mathbf{E_B} \equiv c\,\frac{\nabla p_{\mathrm{e}}}{e n_{\mathrm{e}}}$$

- Creates a magnetic field from zero initial conditions.
- Condition: misaligned ∇n_{e} and ∇p_{e}.

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

THE RAMSES CODE

THE MHD INTEGRATOR

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- Solves the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{E}_{\mathbf{EMF}} + \mathbf{E}_{\mathbf{B}}) = \nabla \times \mathbf{E}_{\mathbf{tot}}$$

- Satisfying the solenoidal constraint $\nabla \cdot \mathbf{B} = 0$

  → Constrained transport:

$$\frac{\partial}{\partial t} \iint \mathbf{B} \cdot \mathrm{d}\mathbf{S} = \oint \mathbf{E}_{\mathbf{tot}} \cdot \mathrm{d}\mathbf{l}$$

THE MHD INTEGRATOR

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

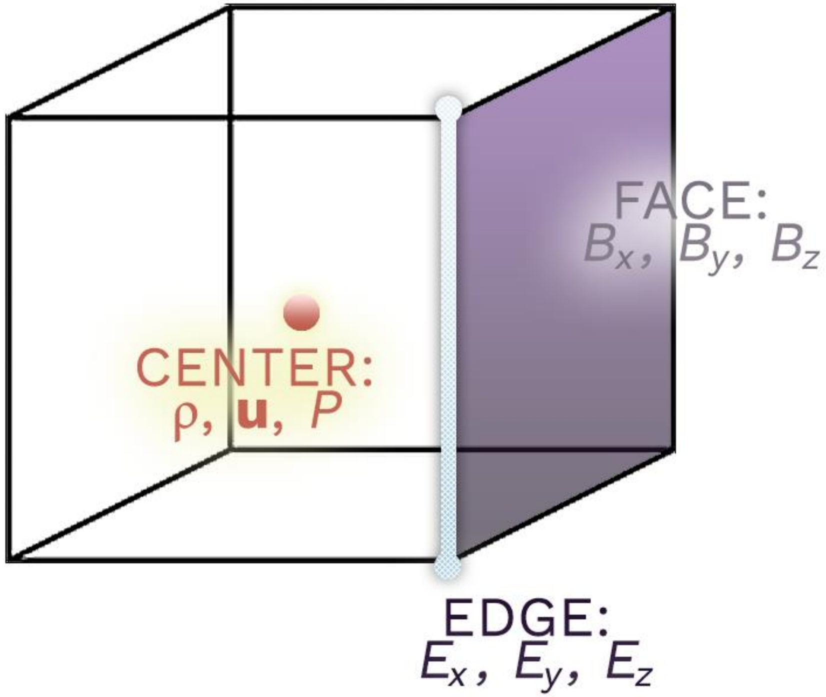


Illustration of where the quantities are defined with respect to the cell in the RAMSES code.

IMPLEMENTATION OF THE BIERMANN BATTERY

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- $\mathbf{E_B}$ needs to be defined at the cell edges.

- 2 implementation methods:
  → *Naive* method – average of the adjacent cell-centred values.
  → *Improved* method – average of the 2 adjacent vertices.

$$\mathbf{E_B} = \frac{ck_\mathrm{B}}{e}\left(T_\mathrm{e}\nabla\ln n_\mathrm{e} + \nabla T_\mathrm{e}\right)$$

with $p_\mathrm{e} \equiv n_\mathrm{e} k_\mathrm{B} T_\mathrm{e}$

- The stable method avoids the "Biermann catastrophe" (Graziani+ 2016).

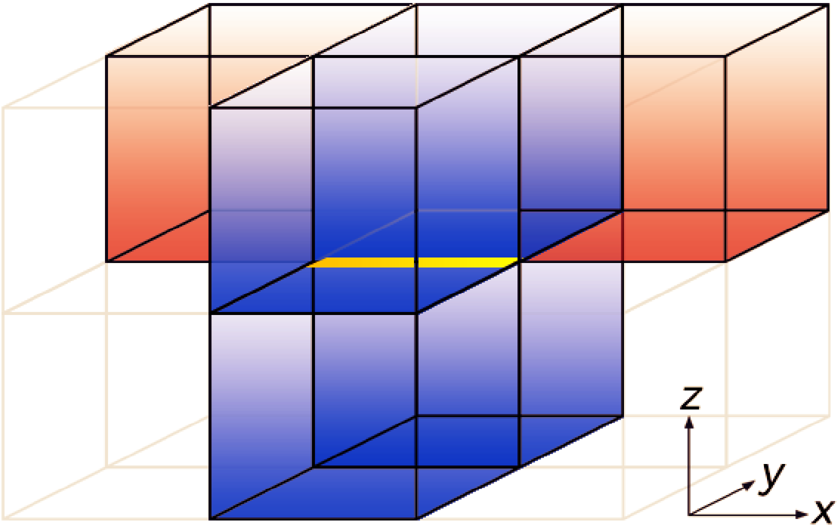
INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

IMPLEMENTATION OF THE BIERMANN BATTERY

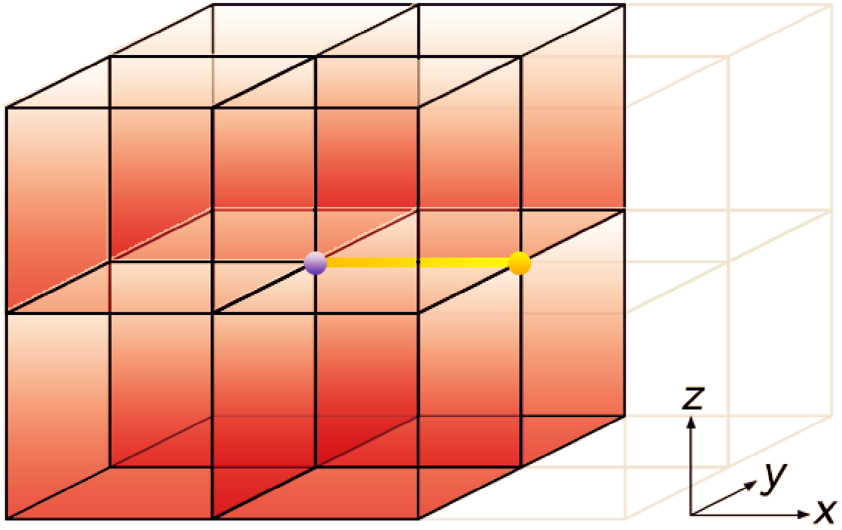
$$\mathbf{E_B} \equiv c\,\frac{\nabla p_e}{e n_e}$$

$$\mathbf{E_B} = \frac{c k_B}{e}\left(T_e \nabla \ln n_e + \nabla T_e\right)$$

naive



improved



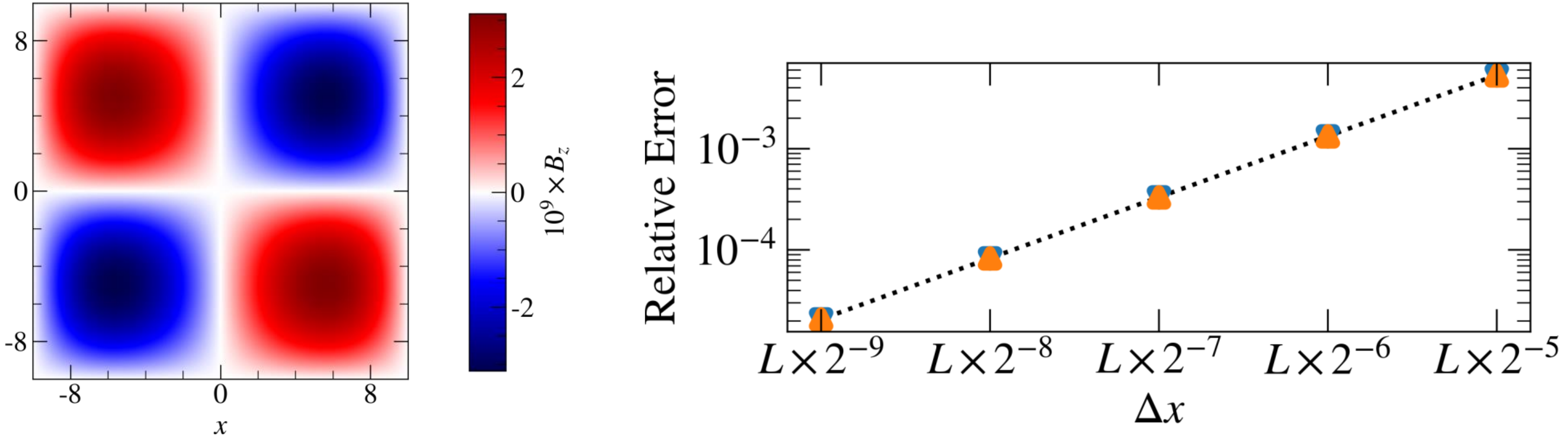
APPLICATIONS

SMOOTH TEST

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- Function test, where the analytic result is known in advance. Misaligned profiles:

$$n_e = n_0 + n_1 \cos(k_x x) \; ; \; p_e = p_0 + p_1 \cos(k_y y)$$



Magnetic field generated by the smooth test, where the conditions for the Biermann battery are met.

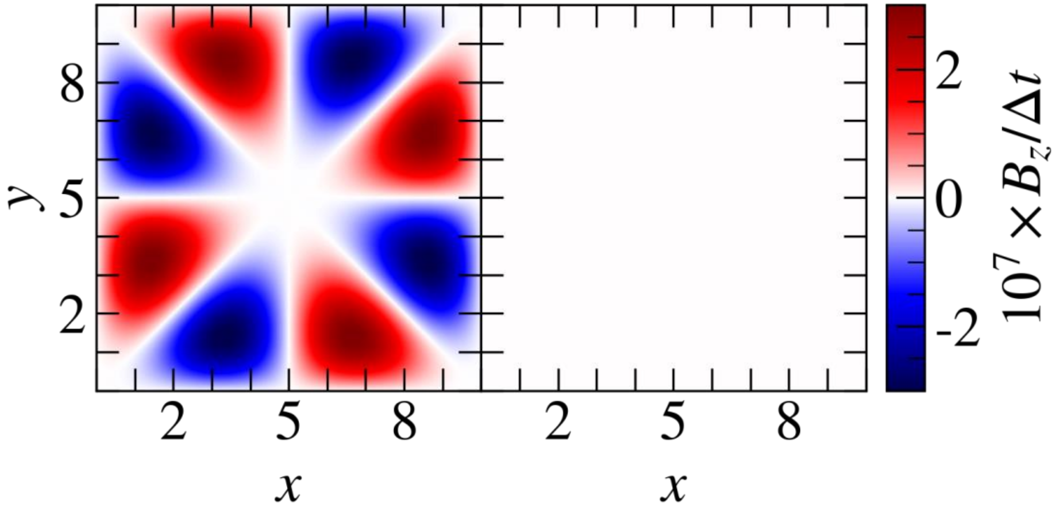
INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

MODIFIED SMOOTH TEST

- Same test, but aligned density and pressure profiles.

$$n_e = n_0\left(\sin(k_x x)^2 + \sin\left(k_y y\right)^2\right)\ ;\ p_e = p_0\left(\sin(k_x x)^2 + \sin\left(k_y y\right)^2\right)$$

naive improved

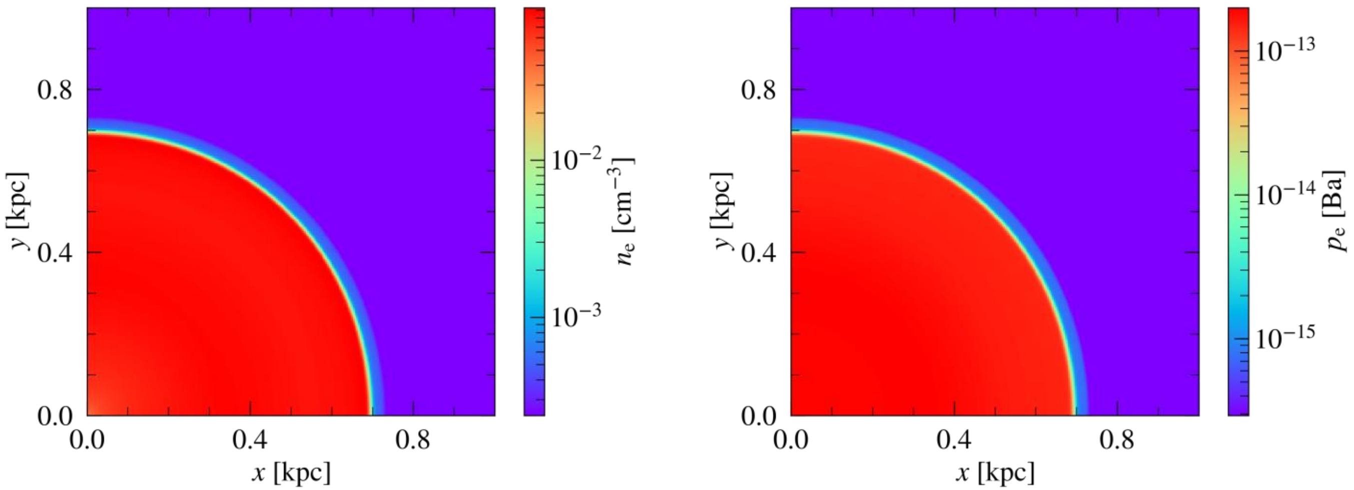


Magnetic field generated by the modified smooth test, where the conditions for the Biermann battery are not met.

STRÖMGREN SPHERE

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- Punctual source of ionizing photons propagating radially (e.g. forming star) → Strömgren sphere.
- Homogeneous ISM: $n_{\mathrm{e}} = n_0$, $p_{\mathrm{e}} = p_0$.



2D Strömgren sphere visible in the n_{e} and p_{e} maps.

- No Biermann battery is expected.

MODULATED STRÖMGREN SPHERE

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- Same punctual source but with a fluctuating density profile in the ISM:

$$n_e = n_0 + n_1 \cos(k_x x) \; ; \; T_e = T_0$$

Simulation name	n_1	Method
STR-0%-N	$0.0 \times n_0$	Naive
STR-10%-N	$0.1 \times n_0$	Naive
STR-20%-N	$0.2 \times n_0$	Naive
STR-0%-C	$0.0 \times n_0$	Correct
STR-10%-C	$0.1 \times n_0$	Correct
STR-20%-C	$0.2 \times n_0$	Correct

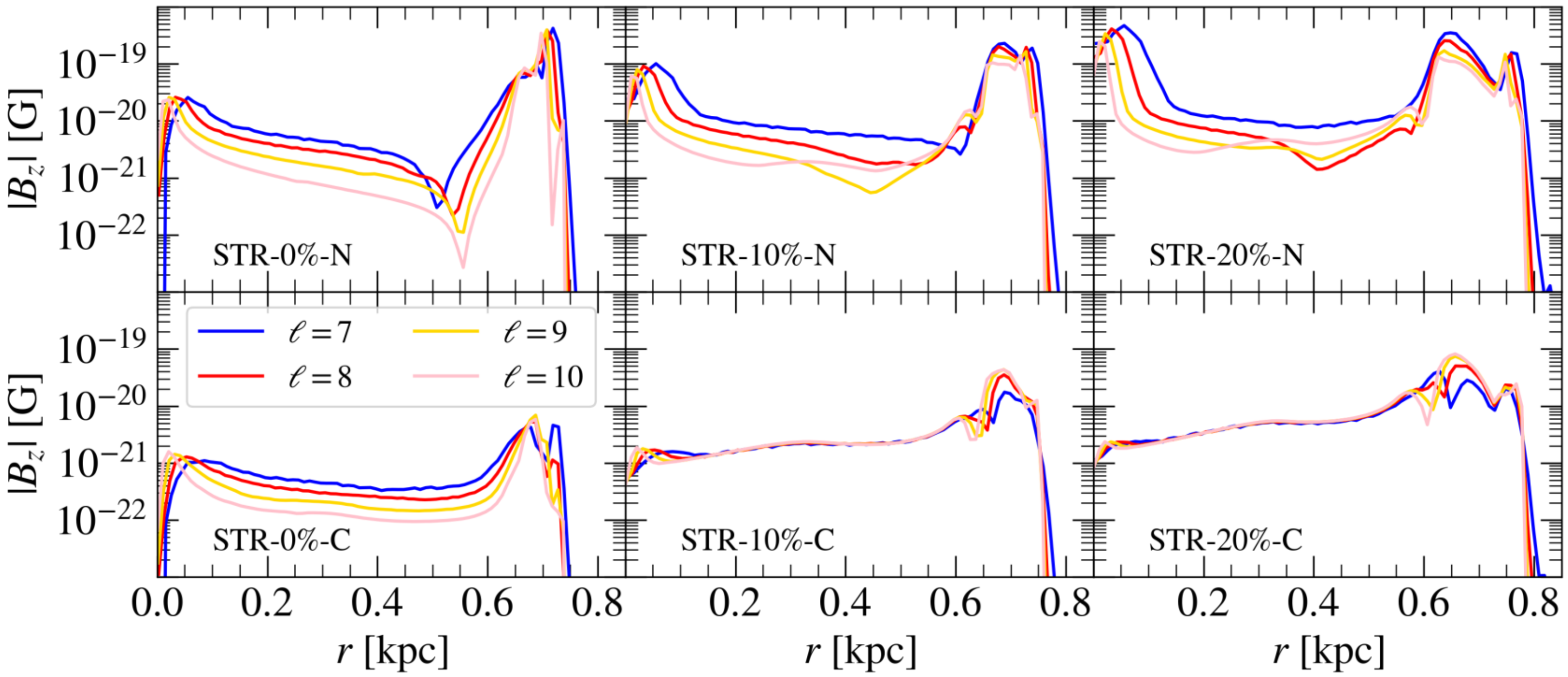
INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

MODULATED STRÖMGREN SPHERE

- The maximum of the field is located at the ionization front.

Naive method →

Correct method →



↑ 0% modulation (no expected Biermann battery)

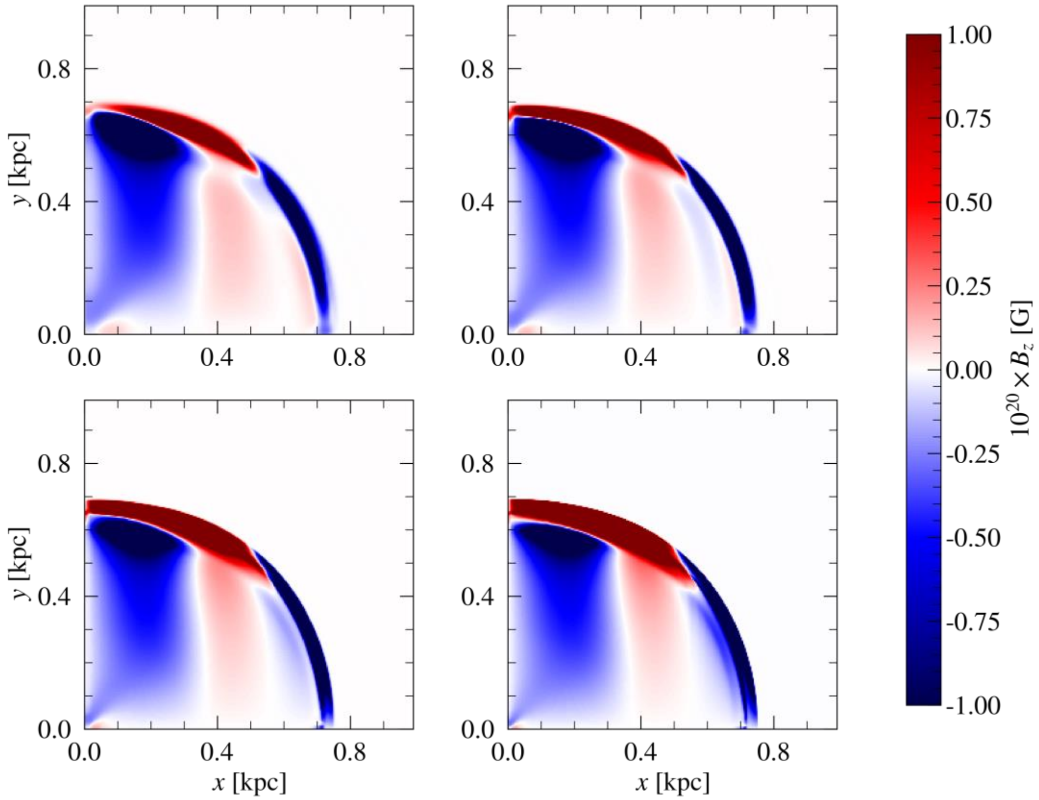
↑ 10% modulation

↑ 20% modulation

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

MODULATED STRÖMGREN SPHERE

- The maximum of the field is located at the ionization front.

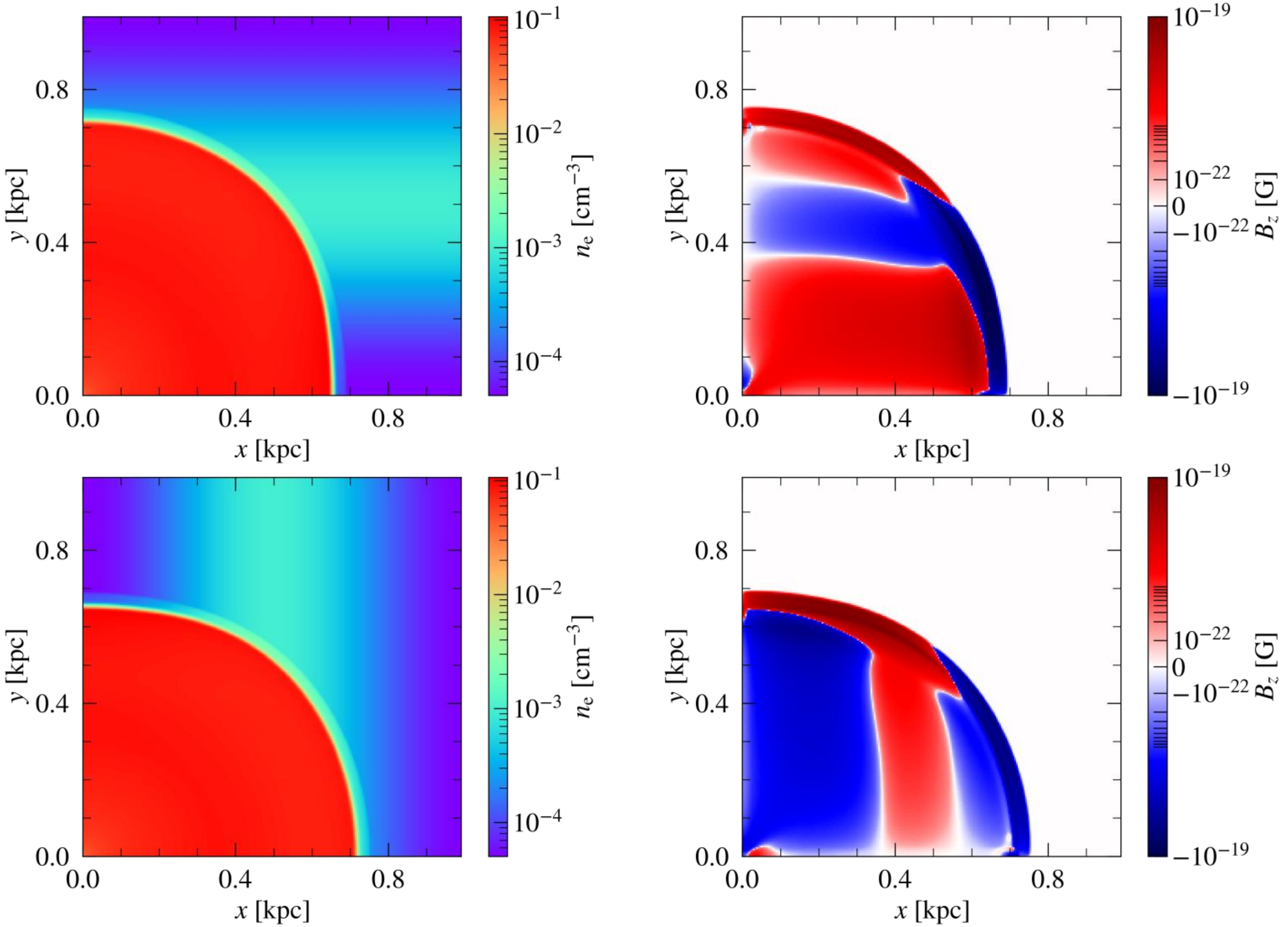


increasing resolution

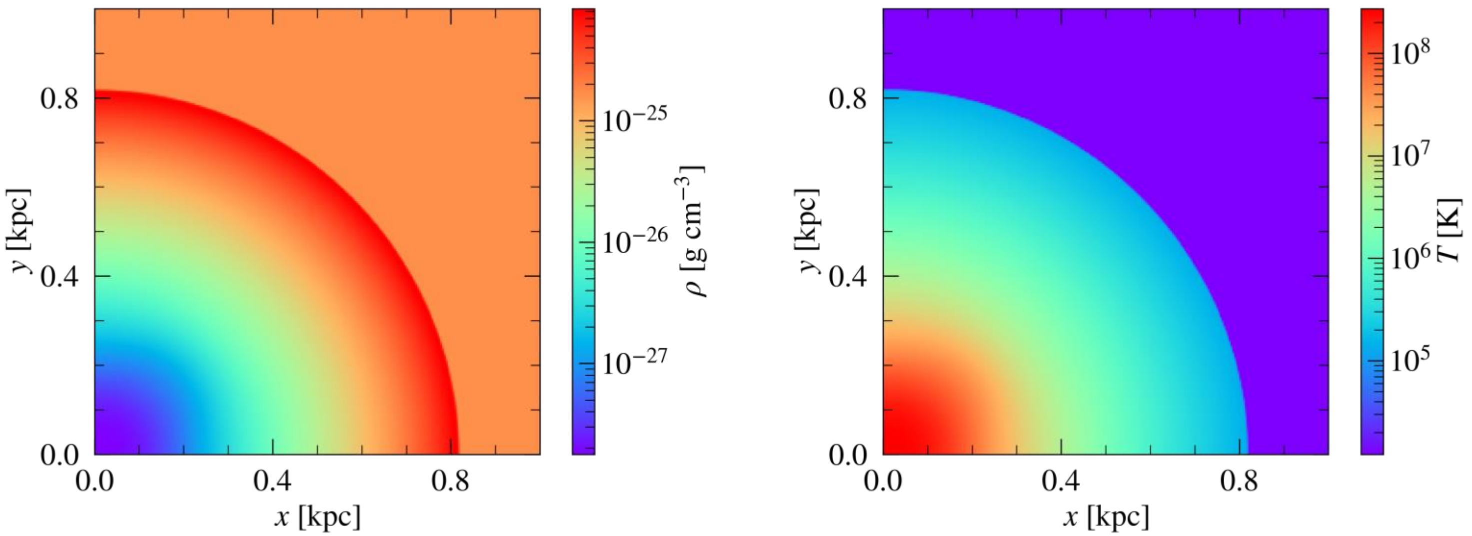
Magnetic field generated by a sinusoidally-modulated Strömgren sphere.

MODULATED STRÖMGREN SPHERE

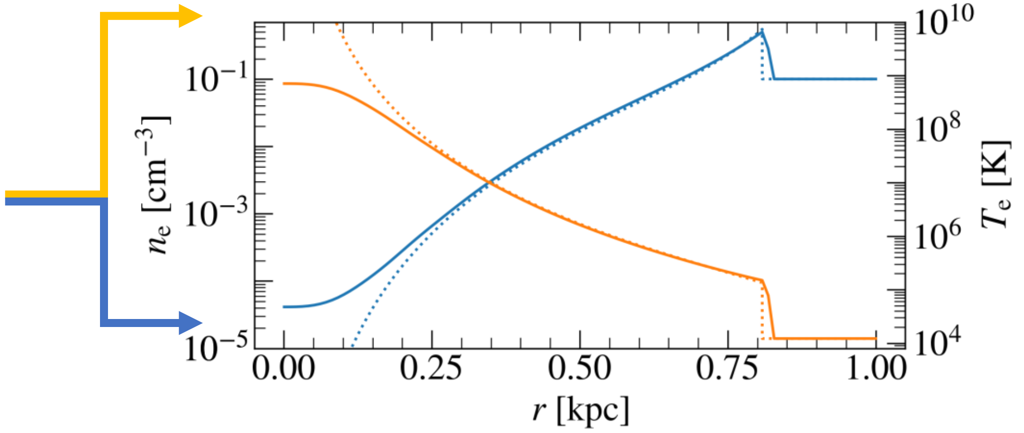
INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION



SEDOV BLAST WAVE



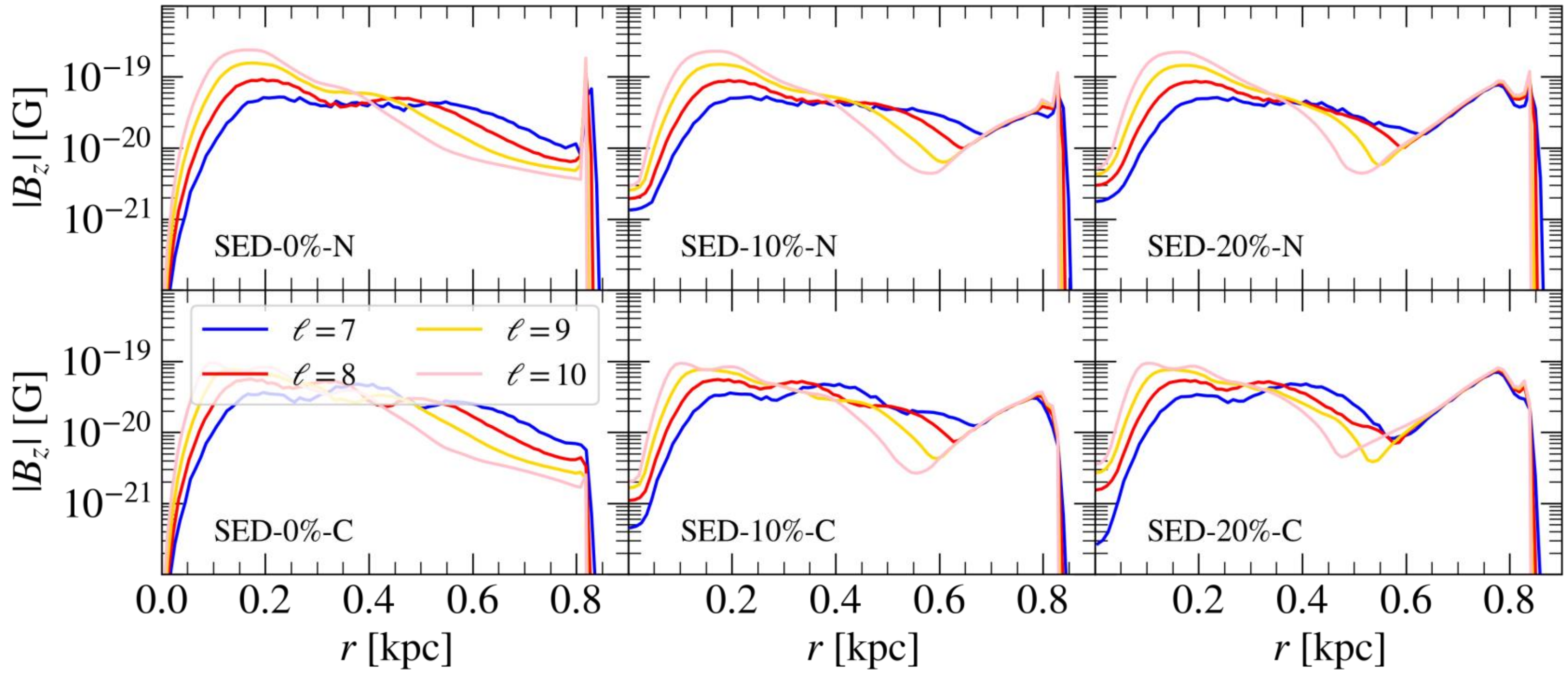
Discrepancy at the origin: sampling the punctual pulse with one cell.



MODULATED STRÖMGREN SPHERE

Naive method →

Improved method →



↑ 0% modulation

↑ 10% modulation

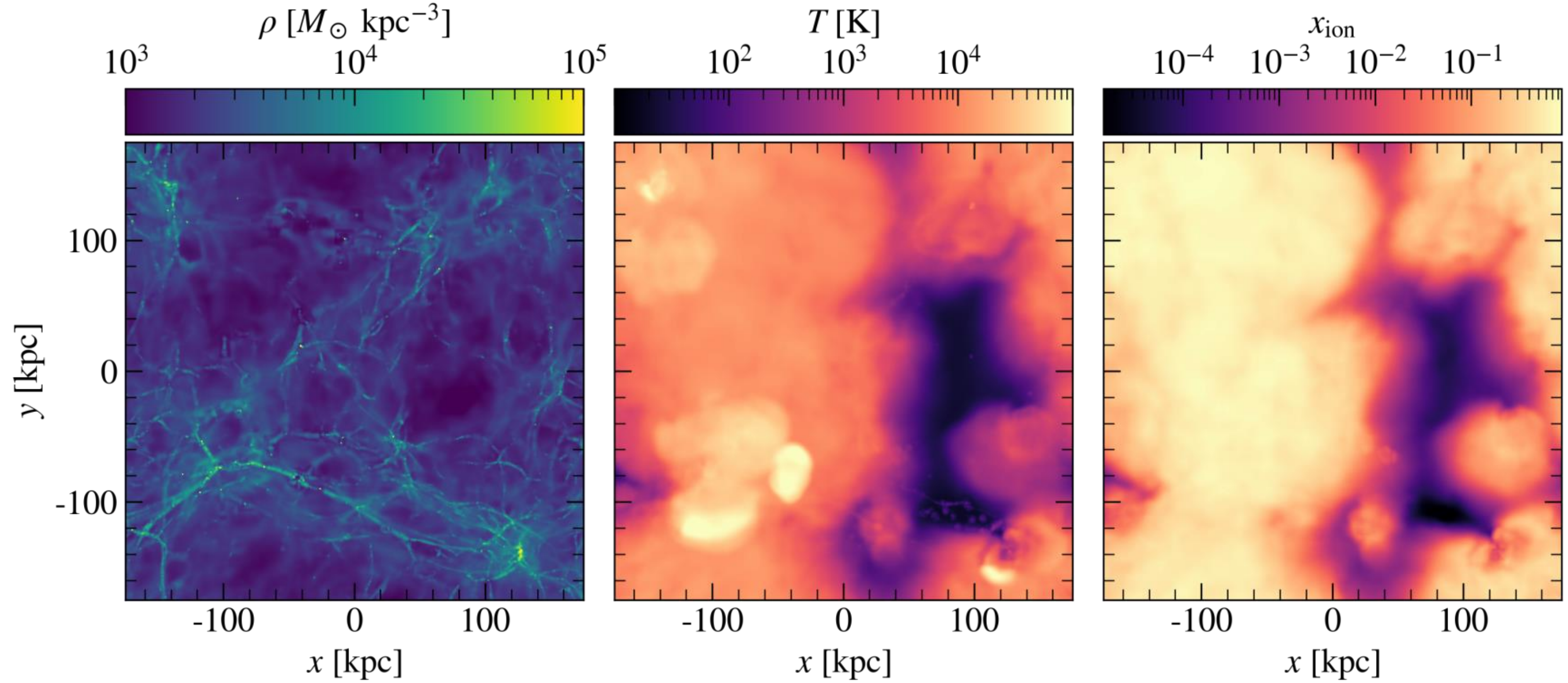
↑ 20% modulation

→ A bit less convincing than the Strömgren test,
but the improved method still behaves better at the shock location.

COSMOLOGICAL SIMULATIONS

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- Box of size 2.5 cMpc at $z = 6$: EoR.

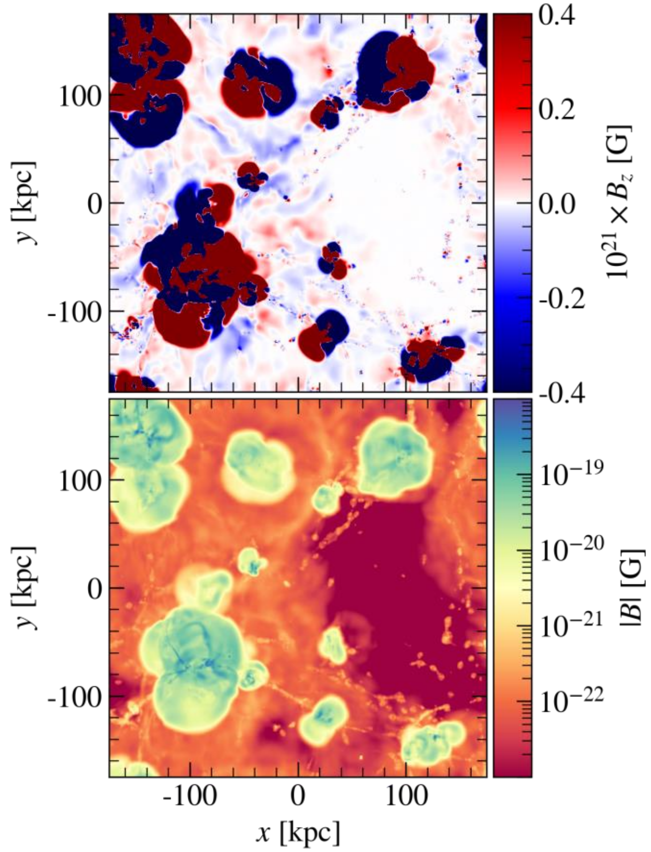


COSMOLOGICAL SIMULATIONS

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

Signed B
(morphology)

Unsigned B
(amplitude)

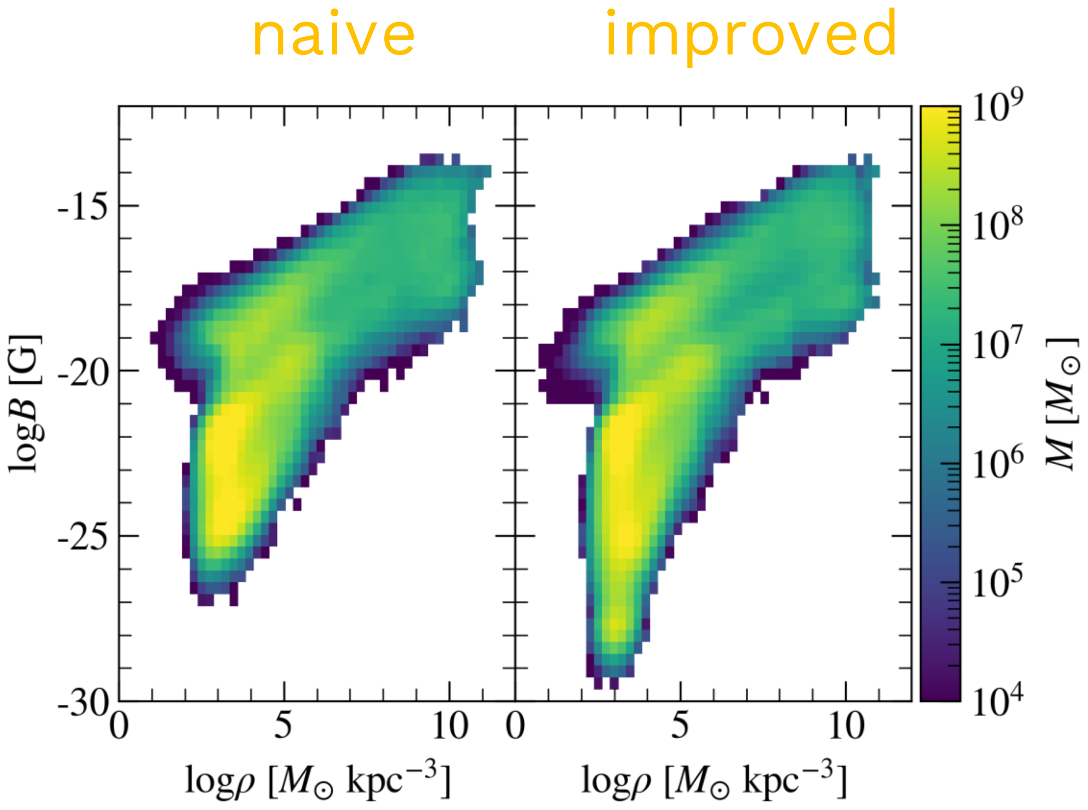


- Three battery channels: linear perturbations, i-fronts, shocks.

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

COSMOLOGICAL SIMULATIONS

- MW 2D histograms of B vs ρ.



INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

COSMOLOGICAL SIMULATIONS

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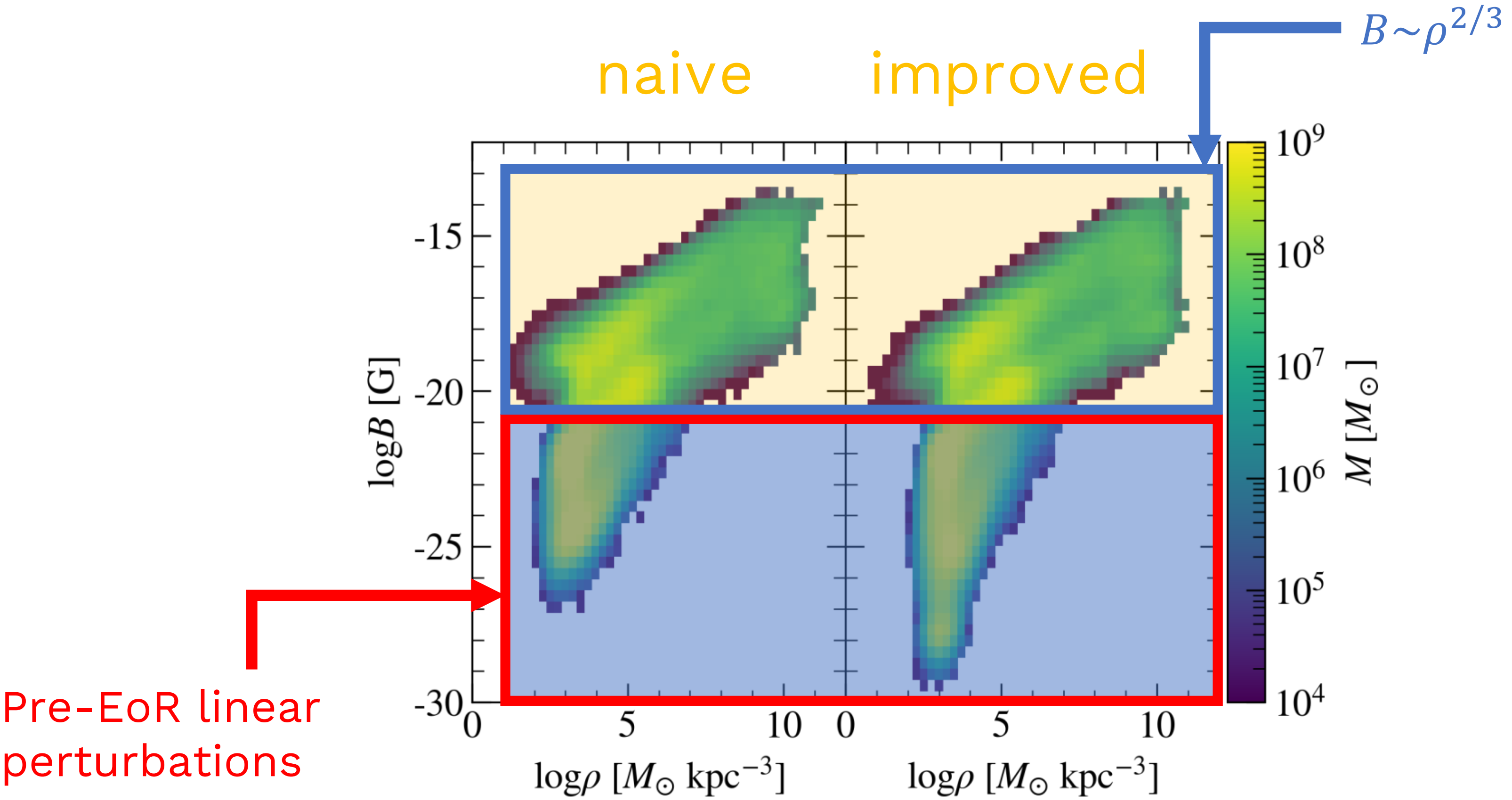
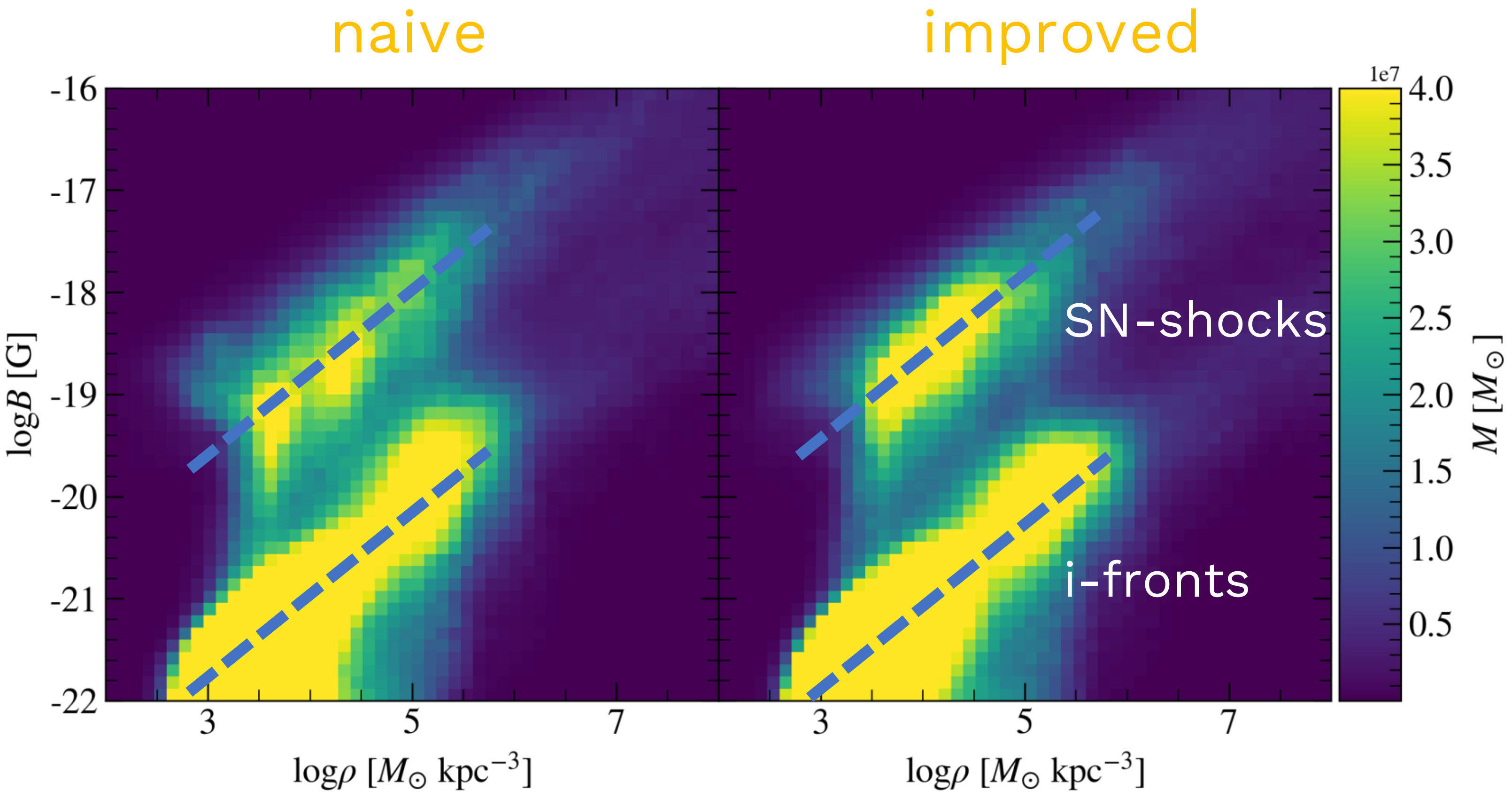


Naoz & Narayan 2013

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

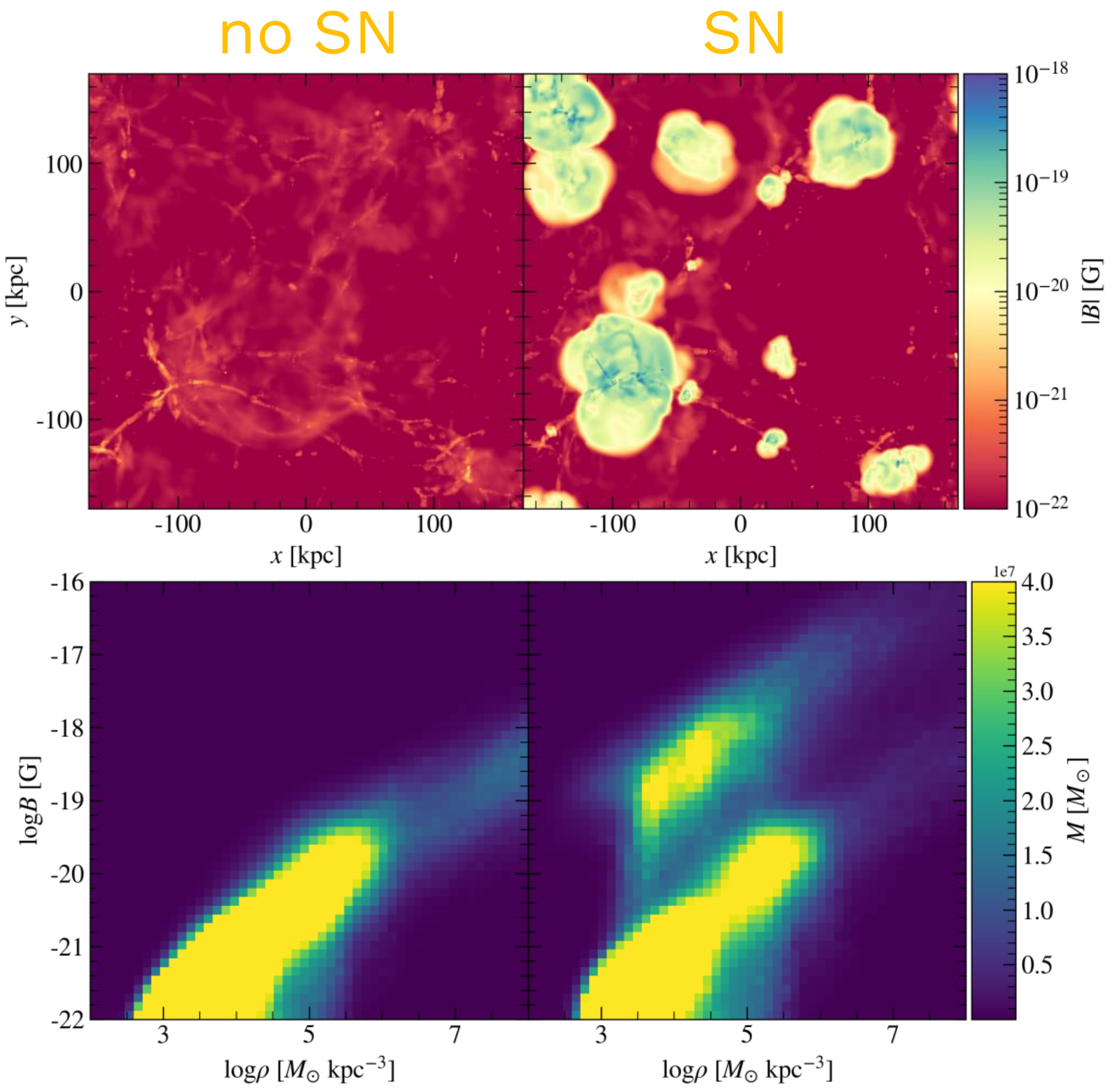
COSMOLOGICAL SIMULATIONS

- MW 2D histograms of B vs ρ: 2 branches, $B \sim \rho^{2/3}$



COSMOLOGICAL SIMULATIONS

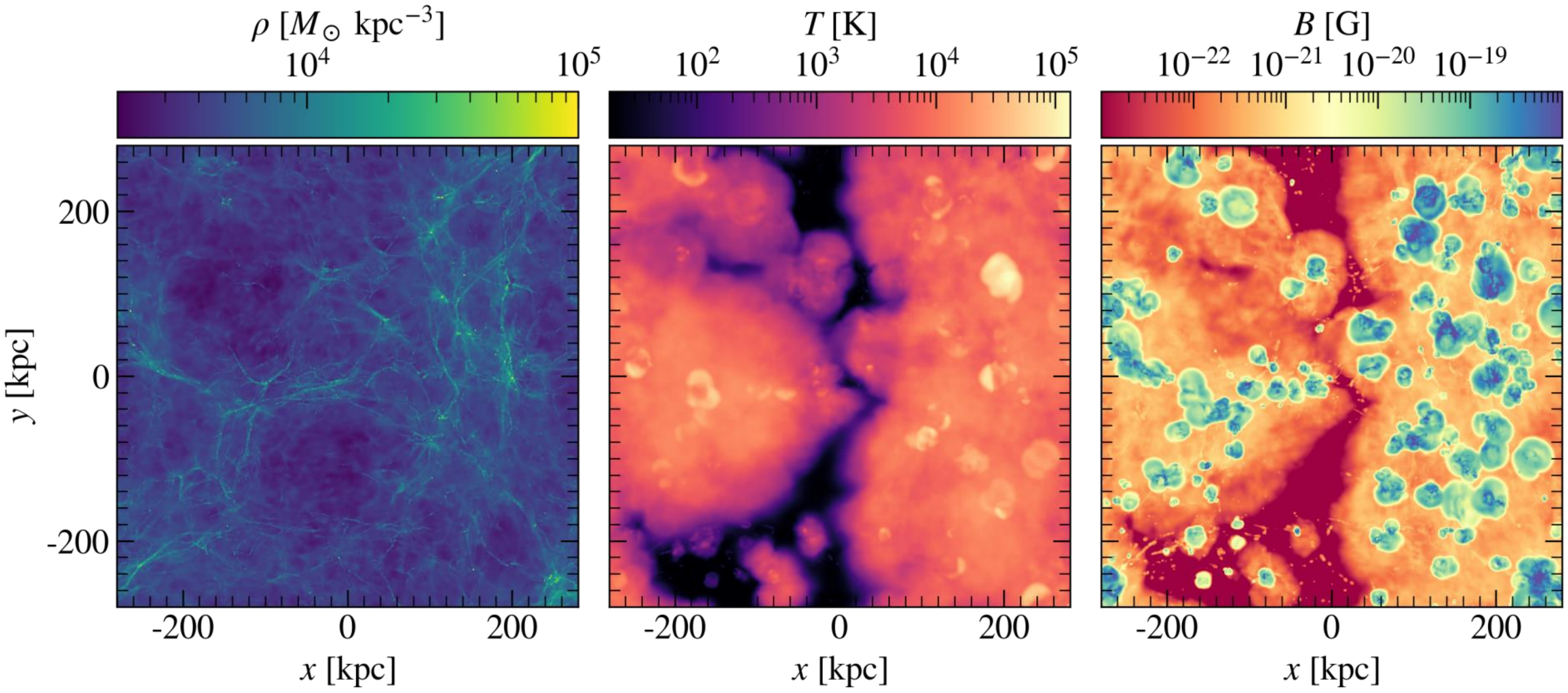
- Switching off SN feedback turns off the shock-driven channel.



COSMOLOGICAL SIMULATIONS

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- Box of size 5 cMpc at $z = 6$: same results.



INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

COSMOLOGICAL SIMULATIONS

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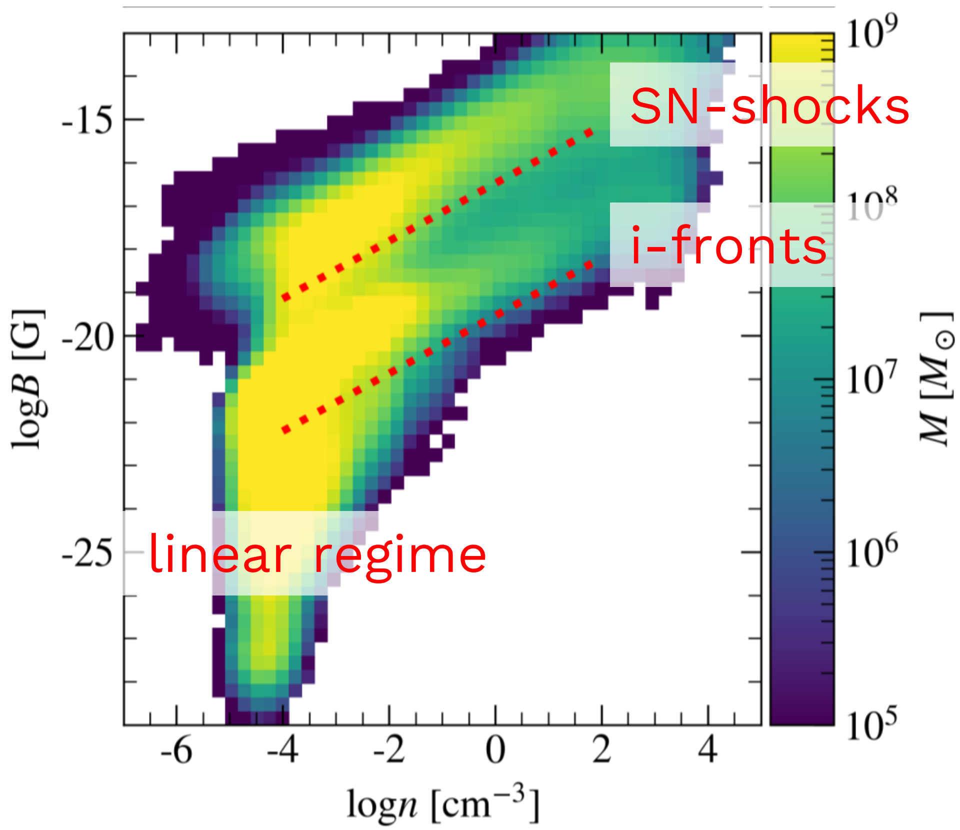
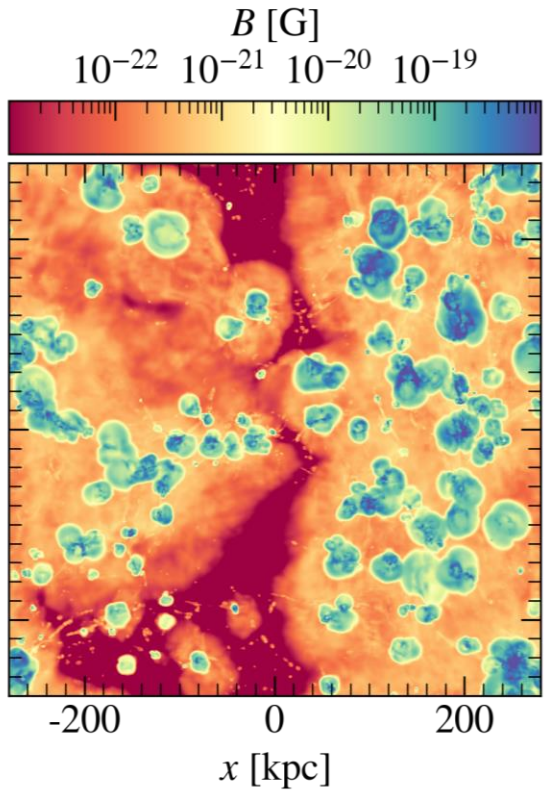
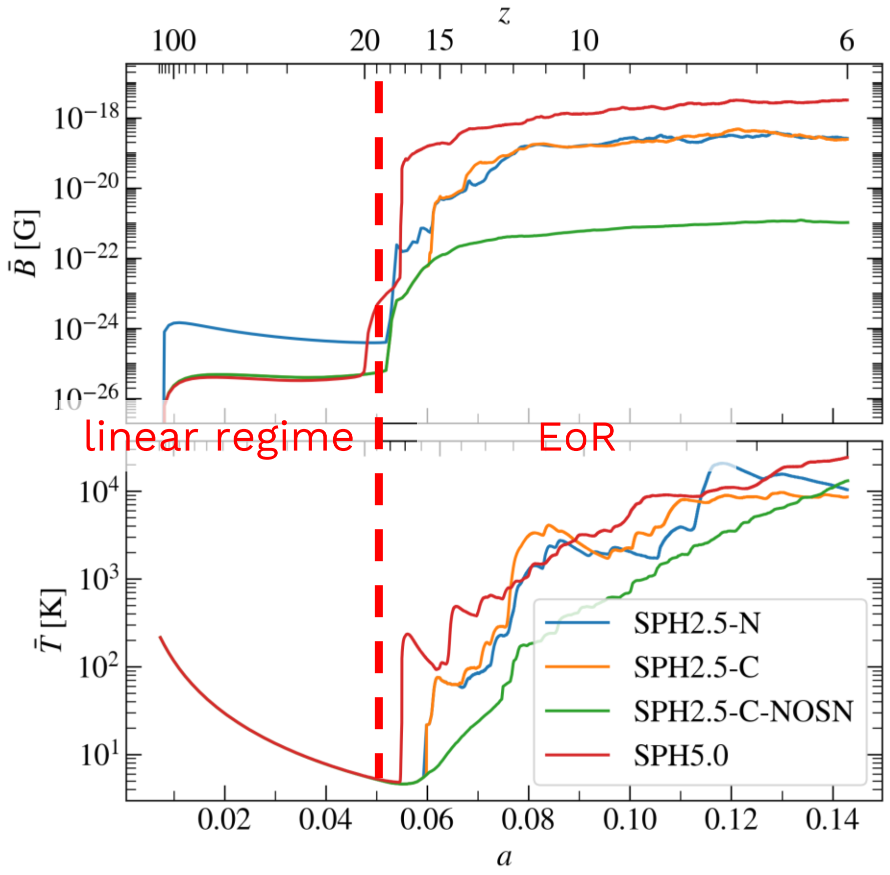




INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

COSMOLOGICAL SIMULATIONS

- Temporal comparison: VW magnetic field and temperature.



INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

CONCLUSION

CONCLUSION

INTRODUCTION
THE BIERMANN BATTERY
THE RAMSES CODE
APPLICATIONS
CONCLUSION

- Successfully implemented the Biermann battery in the RAMSES code. Requires caution (naive vs correct method).
- 3 channels of seed magnetic field:
  - linear perturbations → 10^{-25} G
  - i-fronts → 10^{-20} G
  - SN-driven galactic winds → 10^{-18} G
- What remains to be done: power-spectrum analysis, coupling to a sub-grid dynamo model...