Universität Zürich UZH

• OMAR ATTIA •

GENERATING MAGNETIC FIELDS WITH THE BIERMANN BATTERY

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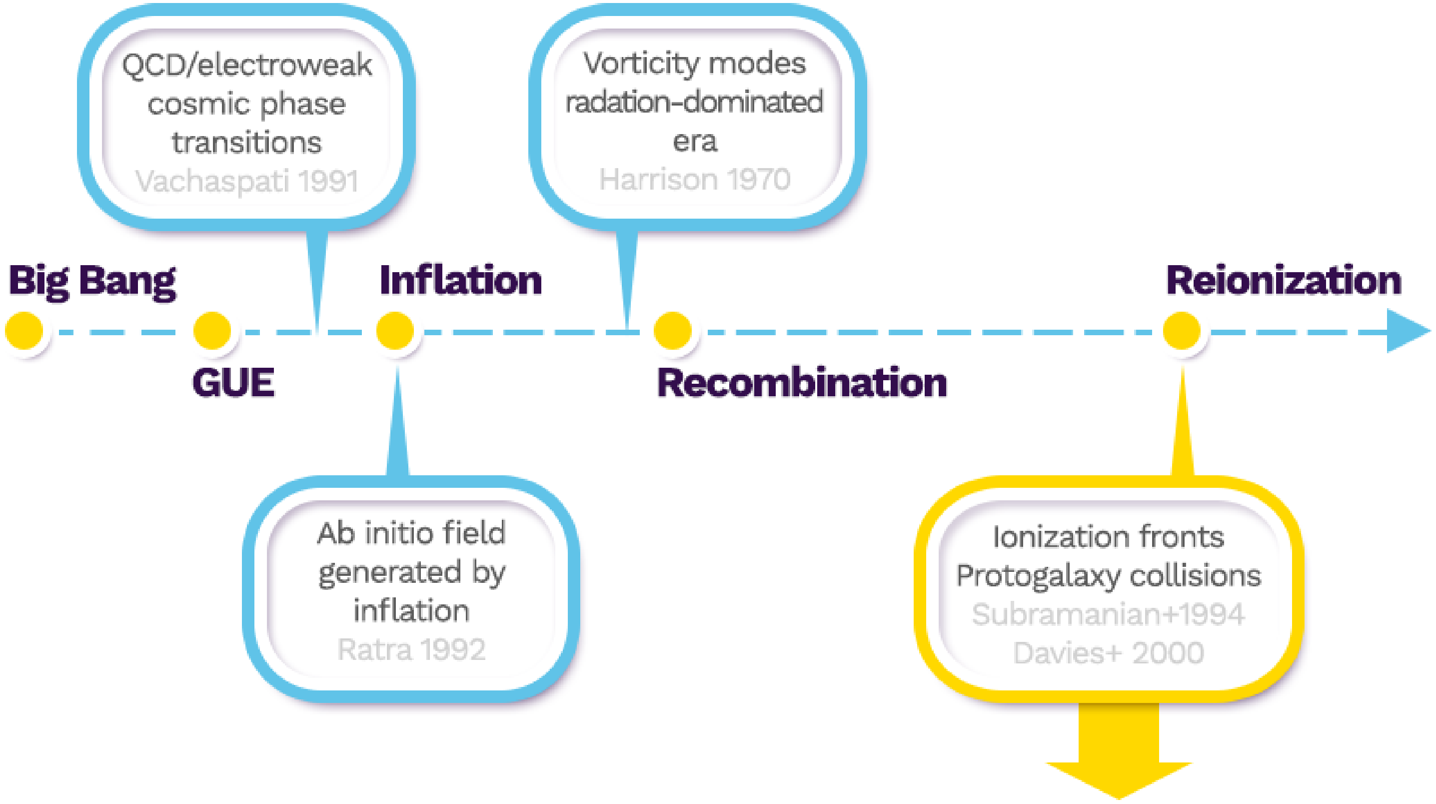
INTRODUCTION

PRIMORDIAL MAGNETOGENESIS

- Origin of cosmic magnetic fields?



underlying mechanism:
the **Biermann battery**

THE BIERMANN BATTERY

THEORETICAL BACKGROUND

- 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.

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.

THE RAMSES CODE

THE MHD INTEGRATOR

- 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

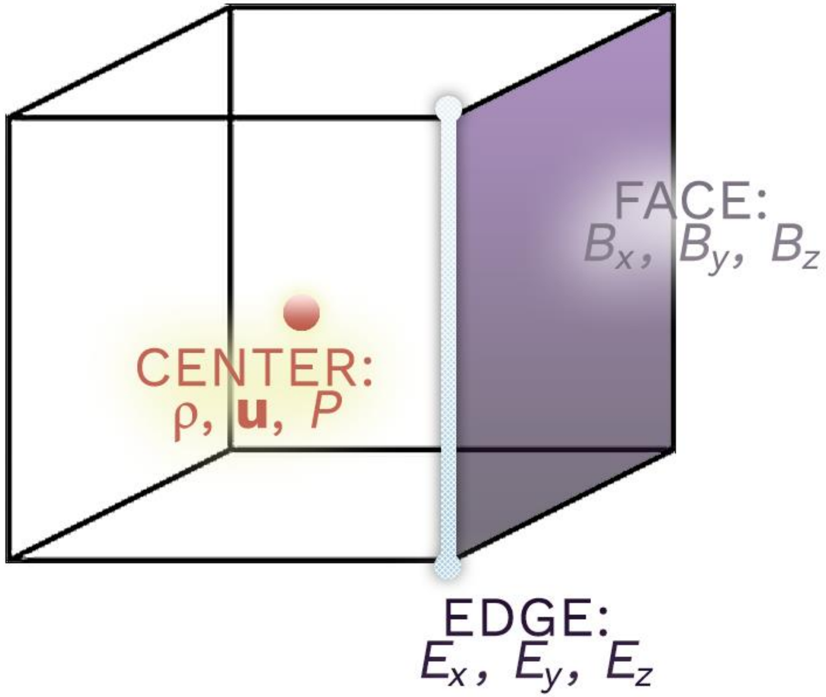


Illustration of where the quantities are defined with respect to the cell in the RAMSES code.

IMPLEMENTATION OF THE BIERMANN BATTERY

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

- 2 implementation methods:
  → *Naive* method – average of the adjacent cell-centred values.
  → *Stable* 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 $p_\mathrm{e} \equiv n_\mathrm{e} k_\mathrm{B} T_\mathrm{e}$

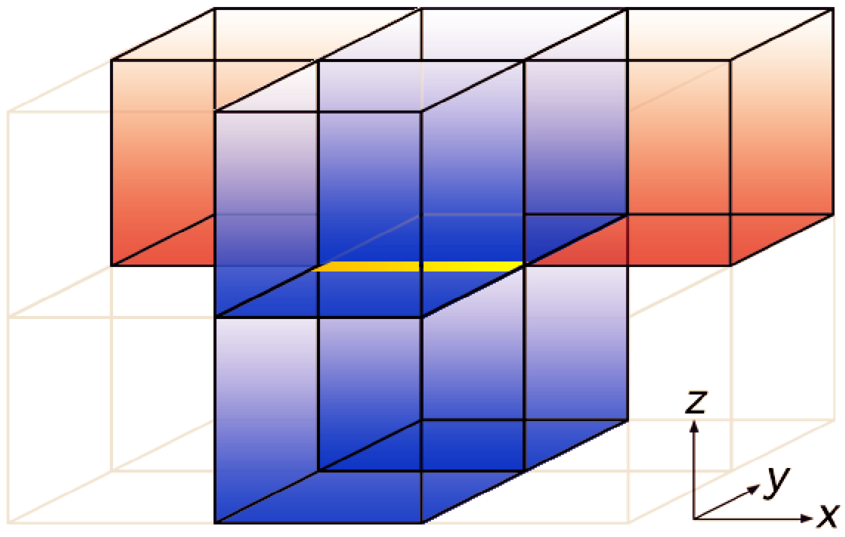
- The stable method avoids the **“Biermann catastrophe”** (Graziani+ 2016).

IMPLEMENTATION OF THE BIERMANN BATTERY

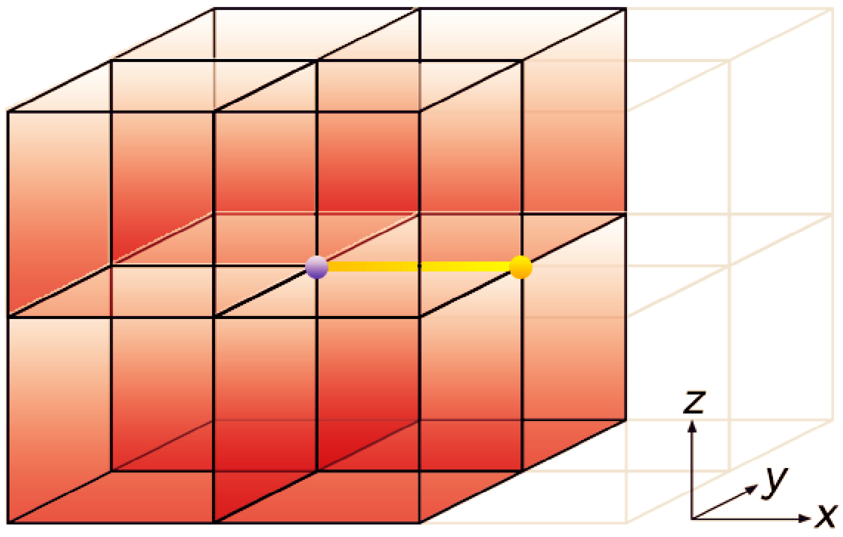
$$\mathbf{E}_\mathrm{B} \equiv c\,\frac{\nabla p_\mathrm{e}}{e n_\mathrm{e}}$$

$$\mathbf{E}_\mathrm{B} = \frac{c k_\mathrm{B}}{e}\left(T_\mathrm{e}\nabla \ln n_\mathrm{e} + \nabla T_\mathrm{e}\right)$$

naive



correct

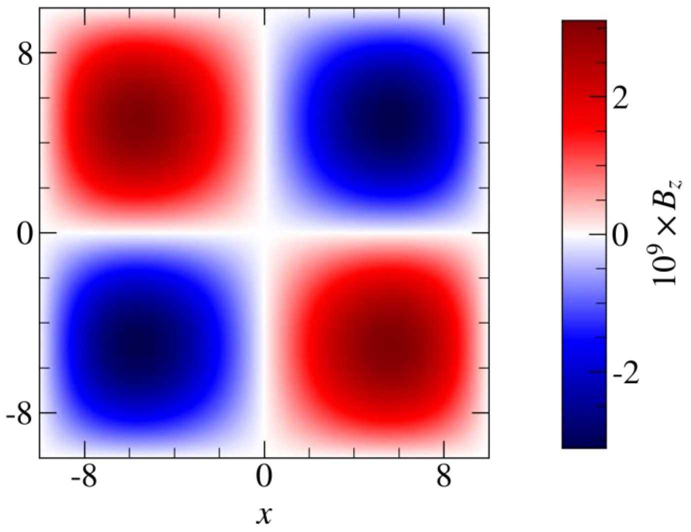


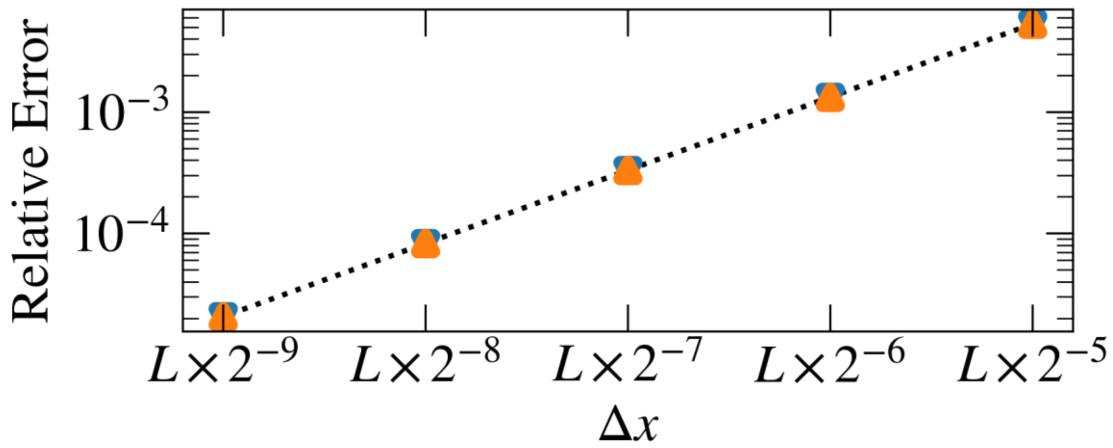
APPLICATIONS

SMOOTH TEST

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

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



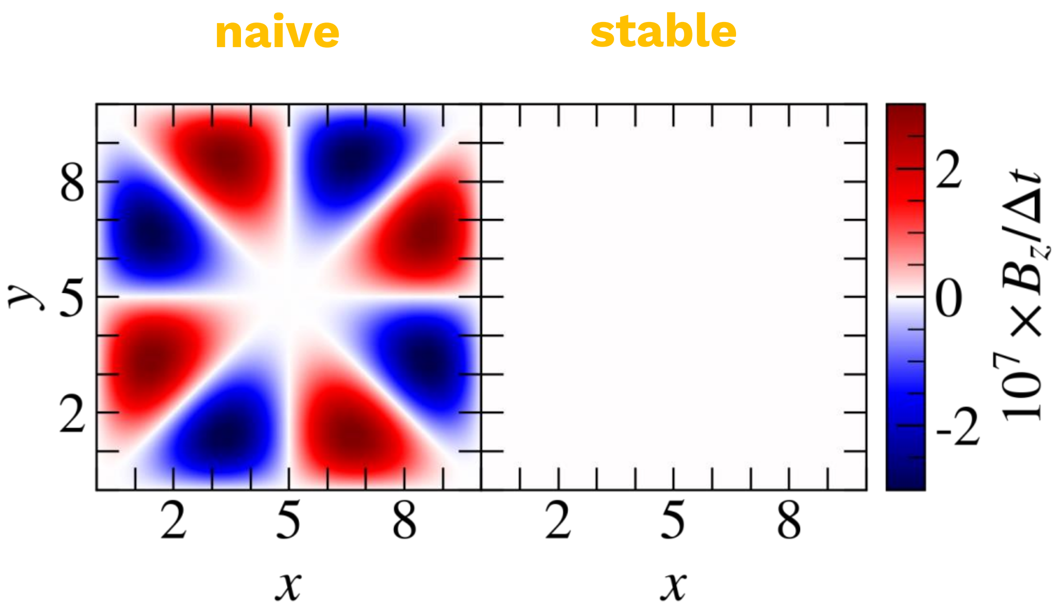


Magnetic field generated by the smooth test, where the conditions for the Biermann battery are met.

MODIFIED SMOOTH TEST

- Same test, but **aligned** density and pressure profiles.

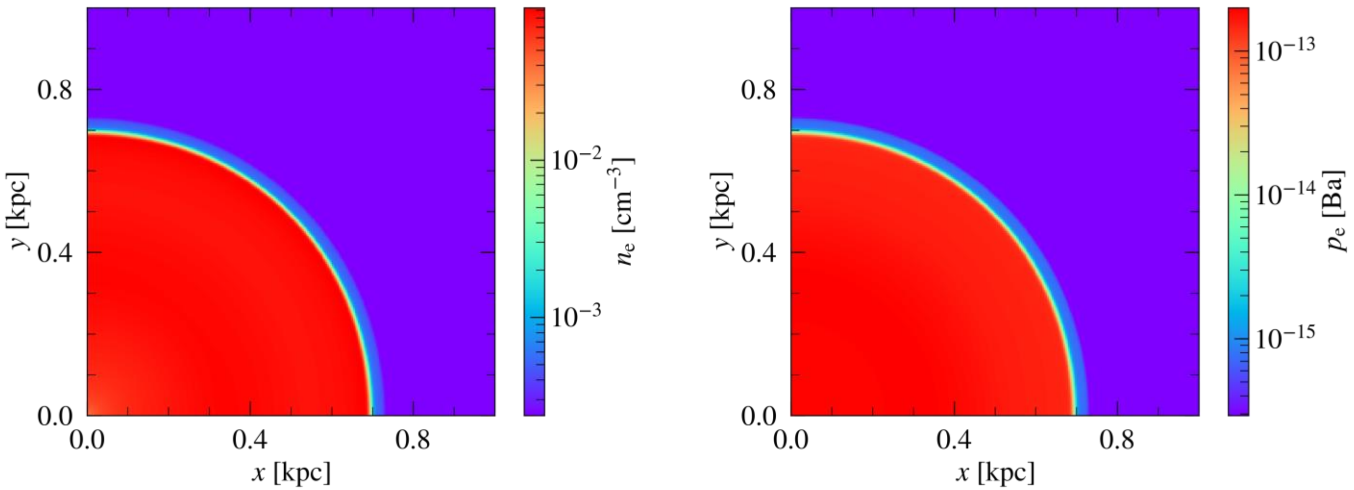
$$n_{\mathrm{e}} = n_0\left(\sin(k_x x)^2 + \sin\left(k_y y\right)^2\right)\ ;\ p_{\mathrm{e}} = p_0\left(\sin(k_x x)^2 + \sin\left(k_y y\right)^2\right)$$



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

STRÖMGREN SPHERE

- 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

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

$$n_\mathrm{e} = n_0 + n_1 \cos(k_x x) \ ; \ T_\mathrm{e} = T_0$$

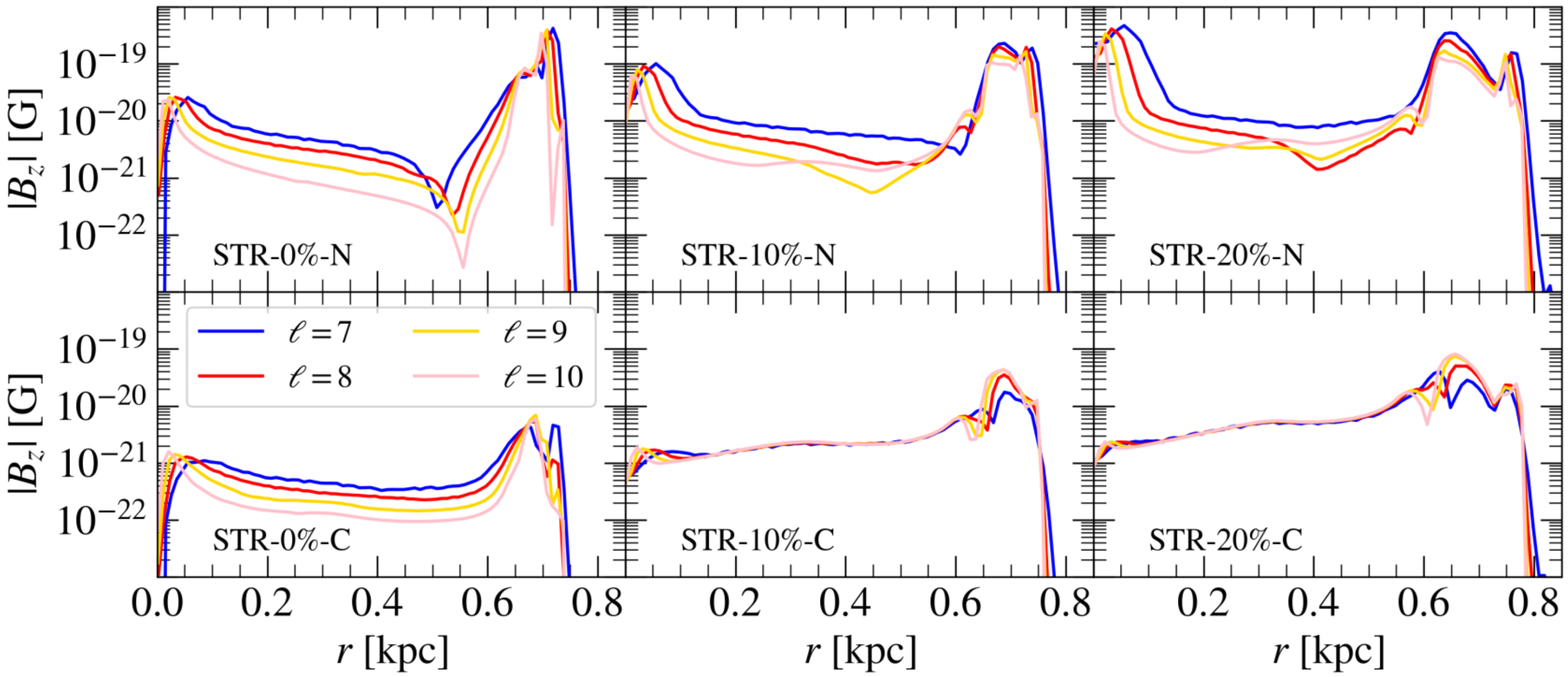
Simulation name	n_1	Method
STR-0%-N	$0.0 \times n_0$	Naive
STR-10%-N	$0.1 \times n_0$	Naive
STR-20%-N	$0.2 \times n_0$	Naive
STR-0%-C	$0.0 \times n_0$	Correct
STR-10%-C	$0.1 \times n_0$	Correct
STR-20%-C	$0.2 \times n_0$	Correct

MODULATED STRÖMGREN SPHERE

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

Naive method →

Correct method →



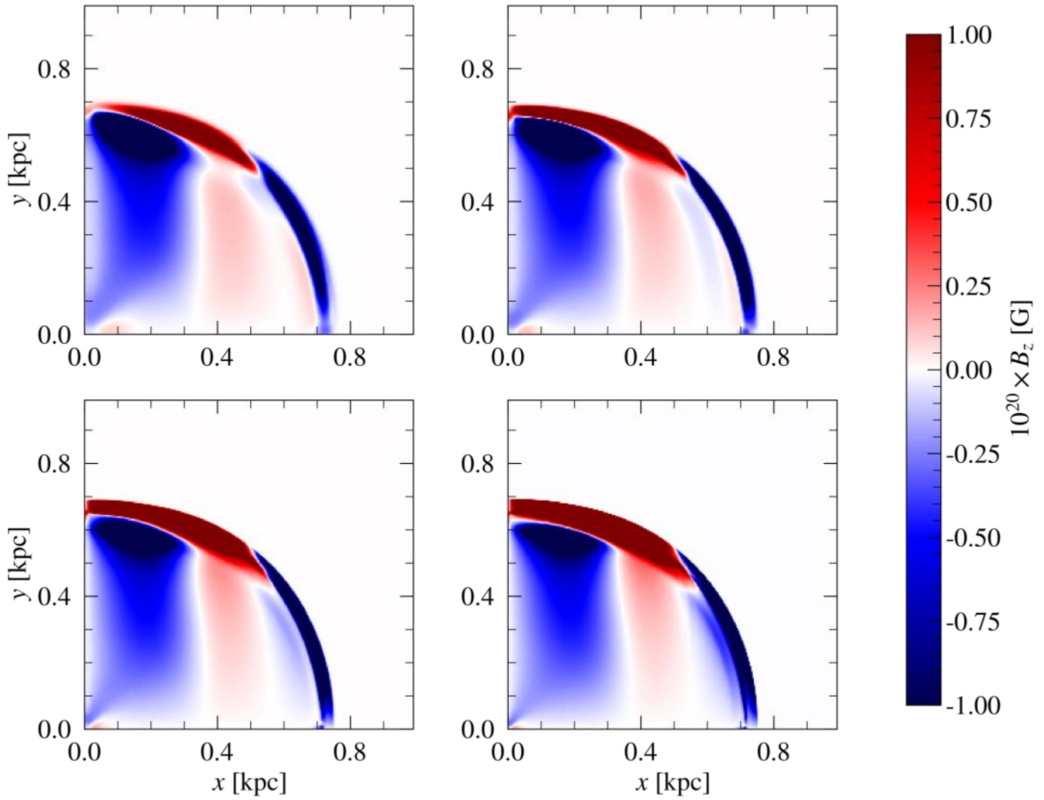
↑ 0% modulation (no expected Biermann battery)

↑ 10% modulation

↑ 20% modulation

MODULATED STRÖMGREN SPHERE

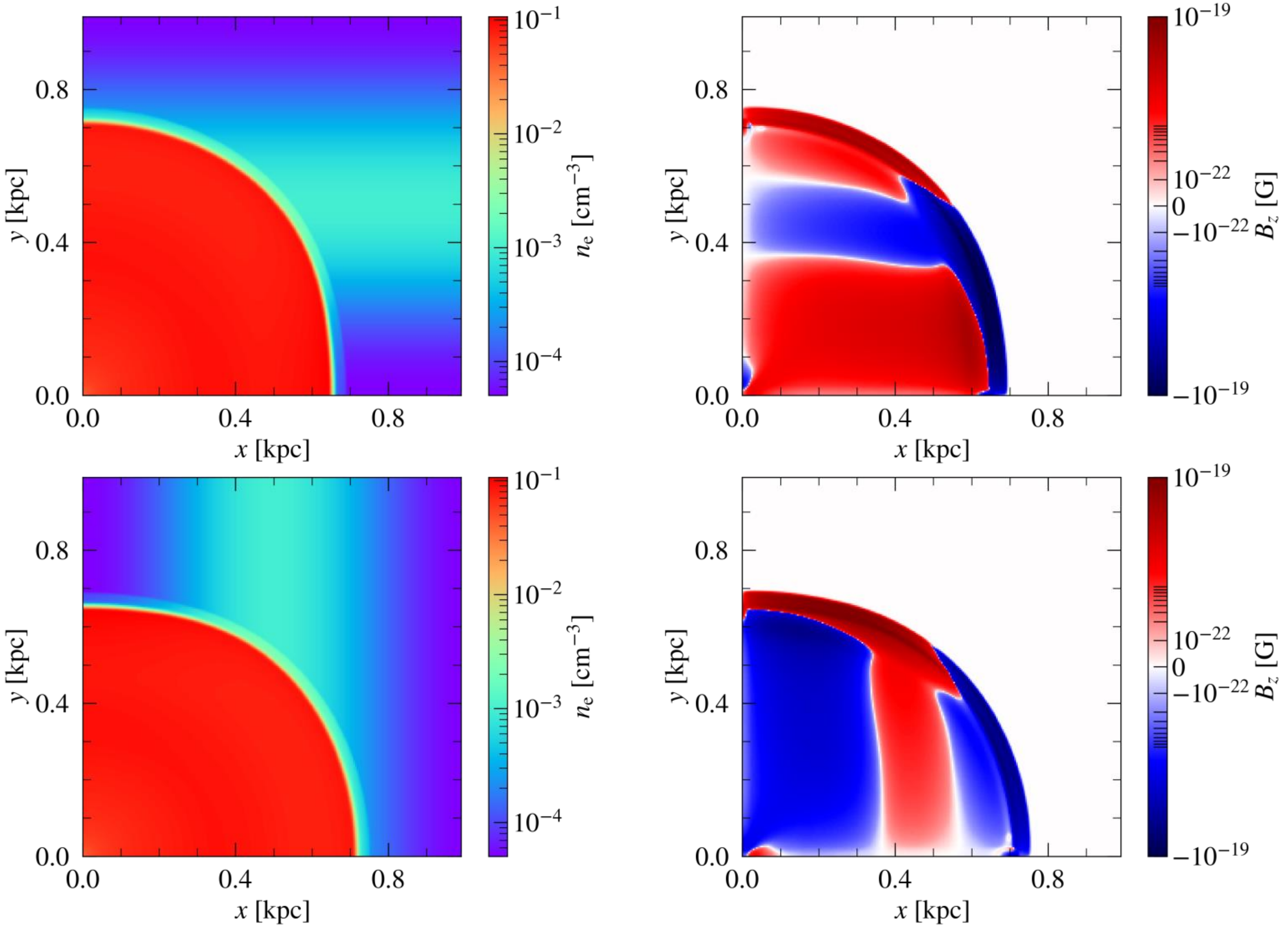
- The maximum of the field is located at the **ionization front**.



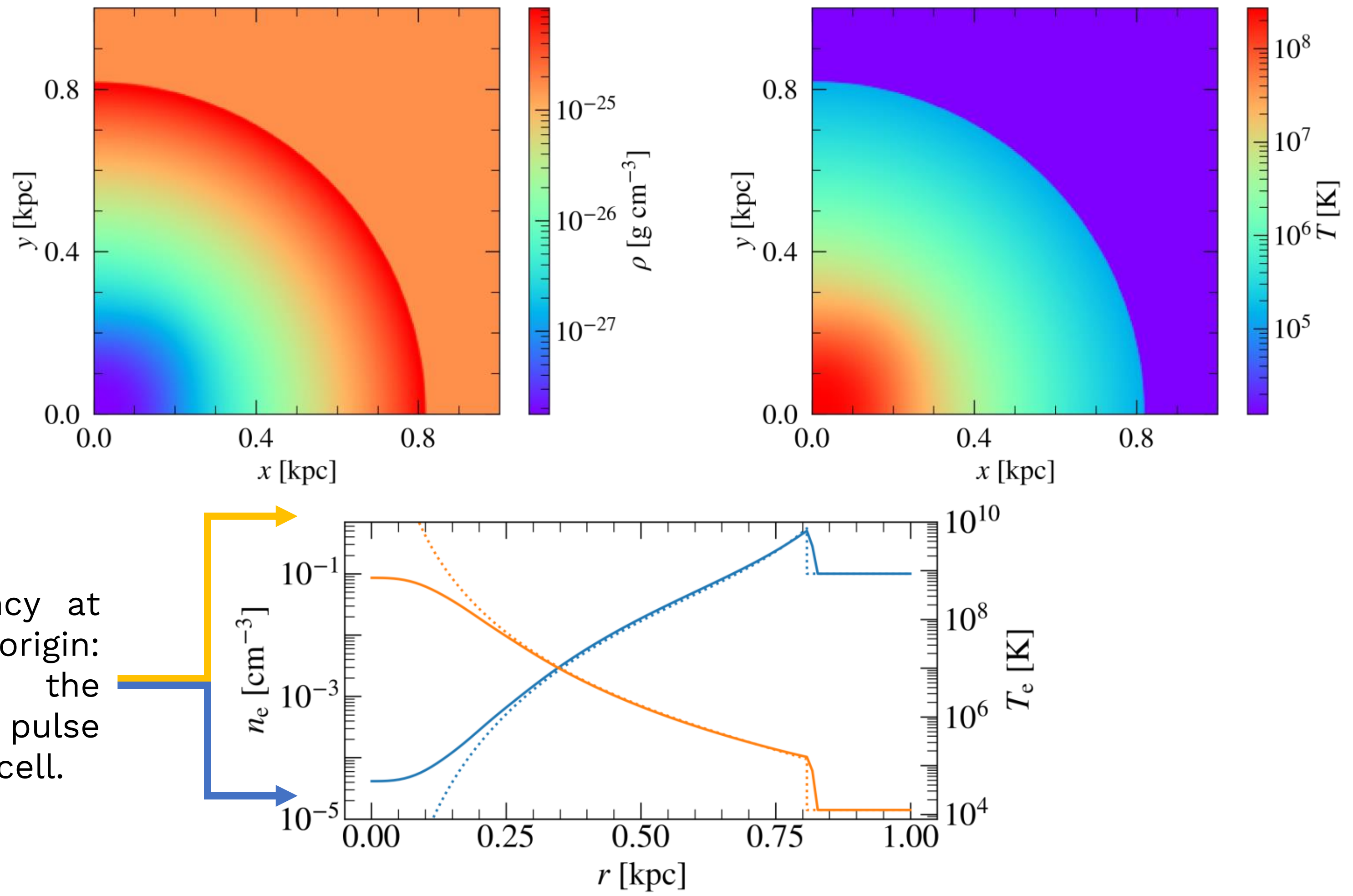
increasing resolution

Magnetic field generated by a sinusoidally-modulated Strömgren sphere.

MODULATED STRÖMGREN SPHERE



SEDOV BLAST WAVE

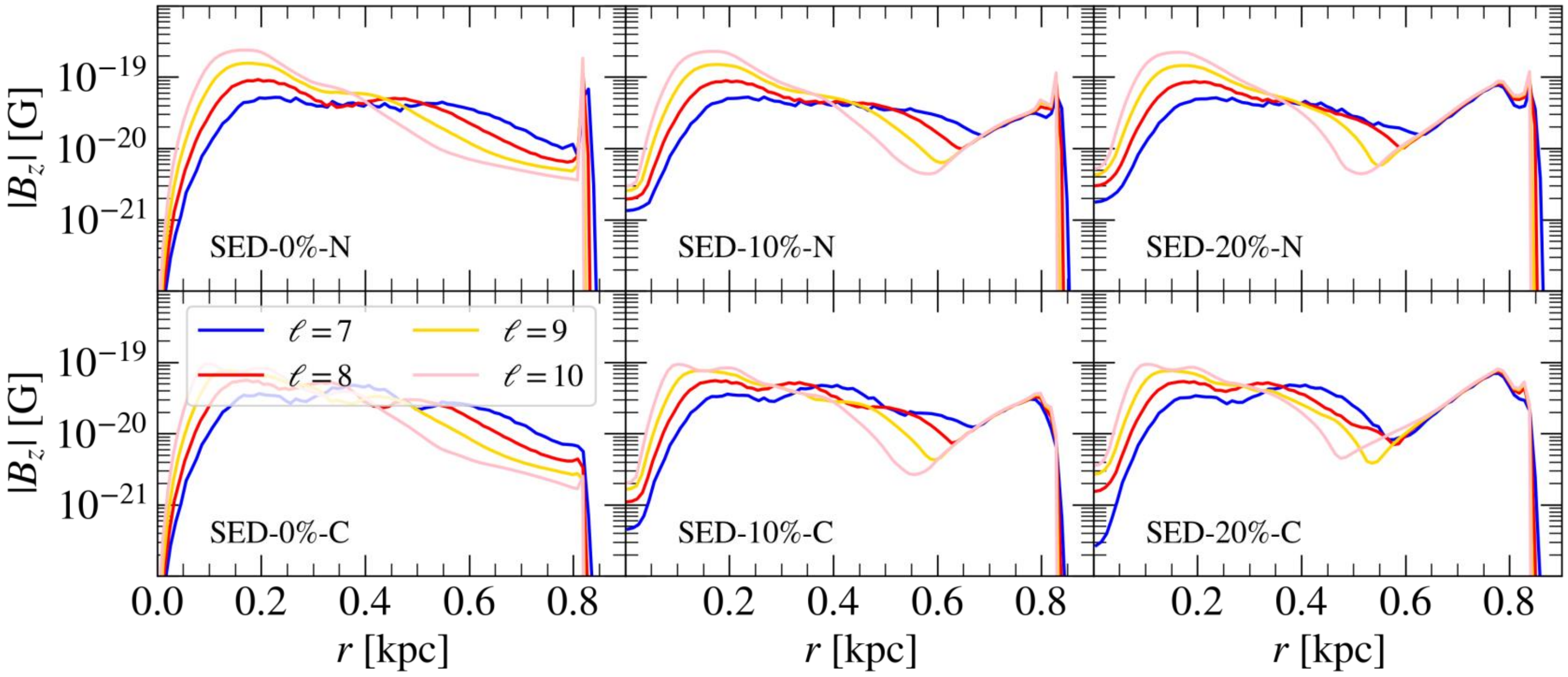


Discrepancy at the origin: sampling the punctual pulse with one cell.

MODULATED STRÖMGREN SPHERE

Naive method →

Correct method →



↑ 0% modulation

↑ 10% modulation

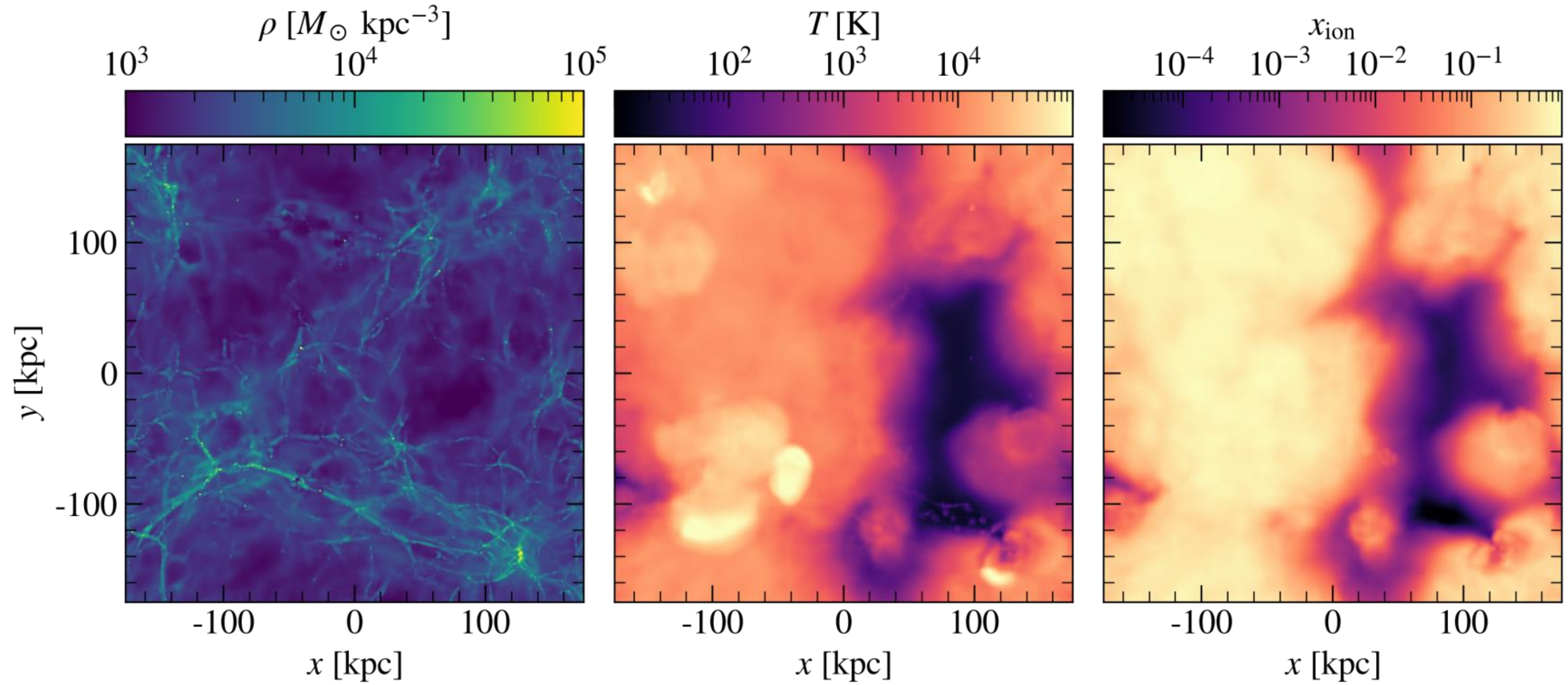
↑ 20% modulation

→ A bit less convincing than the Strömgren test,

but the **correct method** still behaves better at the **shock location**.

COSMOLOGICAL SIMULATIONS

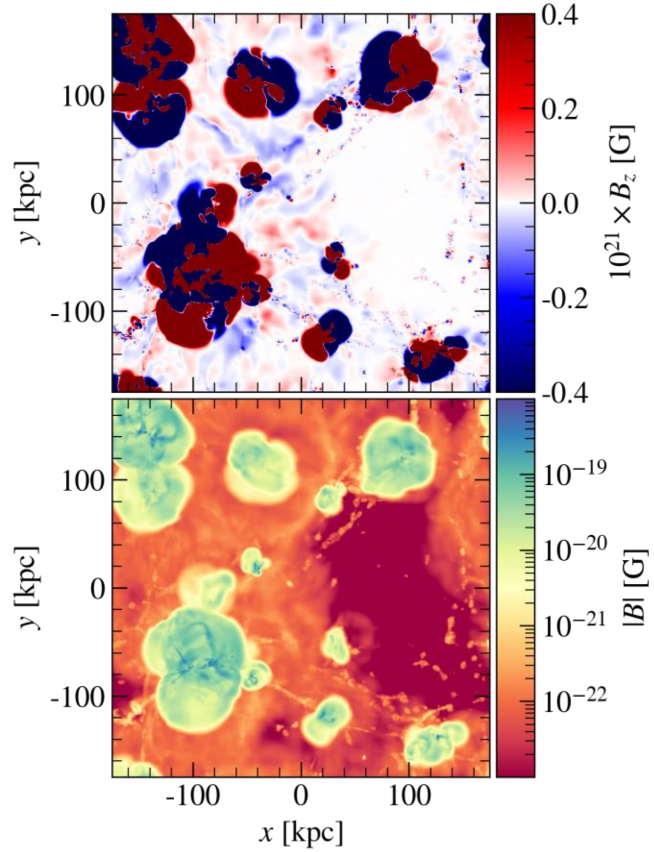
- Box of size $2.5\ \mathrm{cMpc}$ at $z = 6$: **EoR**.



COSMOLOGICAL SIMULATIONS

Signed B
(morphology)

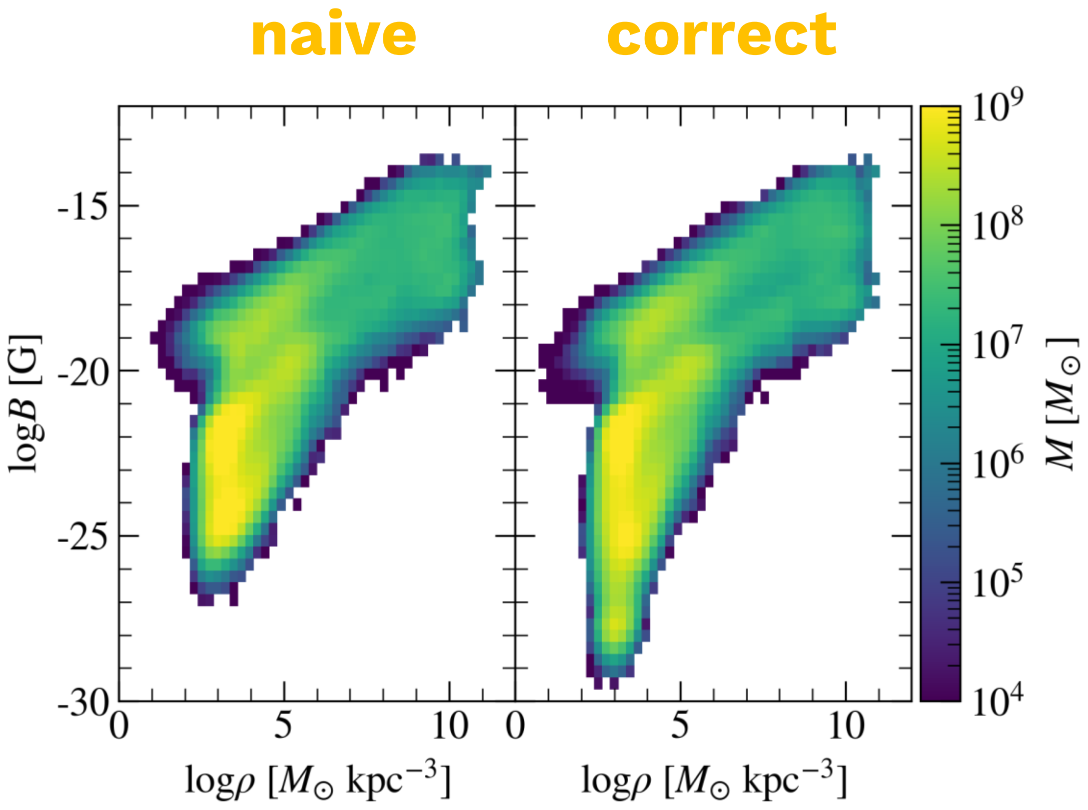
Unsigned B
(amplitude)



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

COSMOLOGICAL SIMULATIONS

- MW **2D histograms** of B vs ρ.



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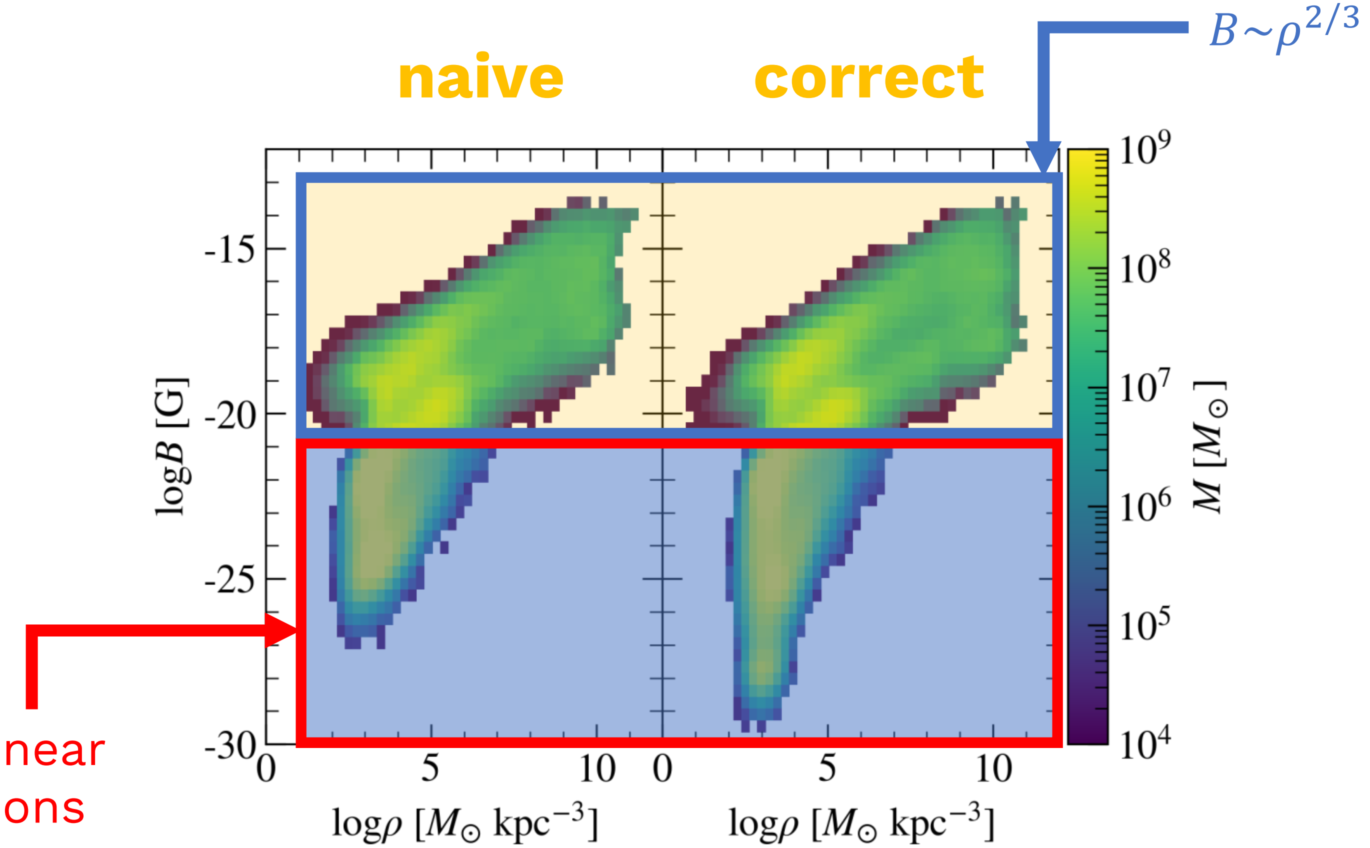
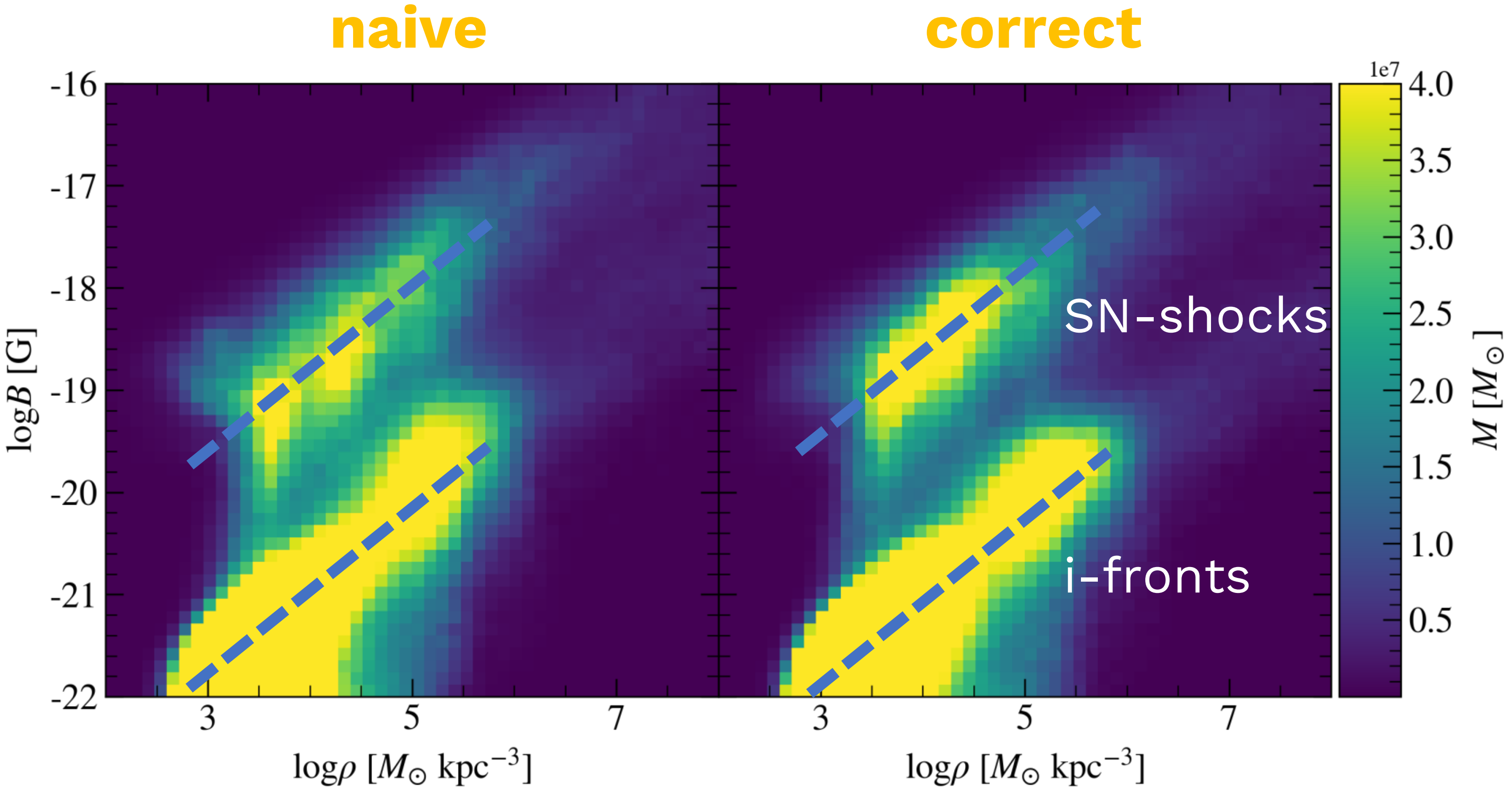


Naoz & Narayan 2013

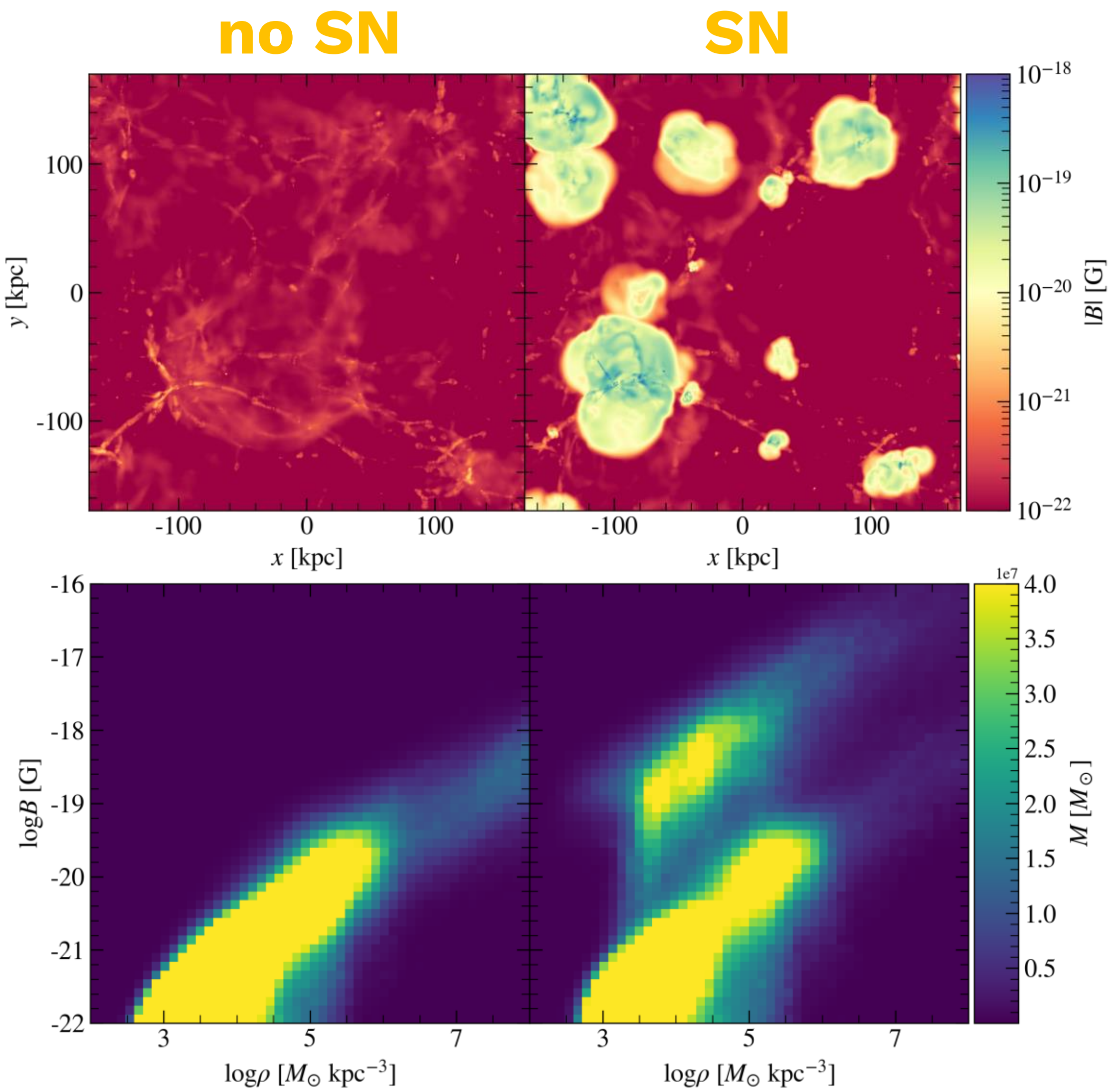
COSMOLOGICAL SIMULATIONS

- 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

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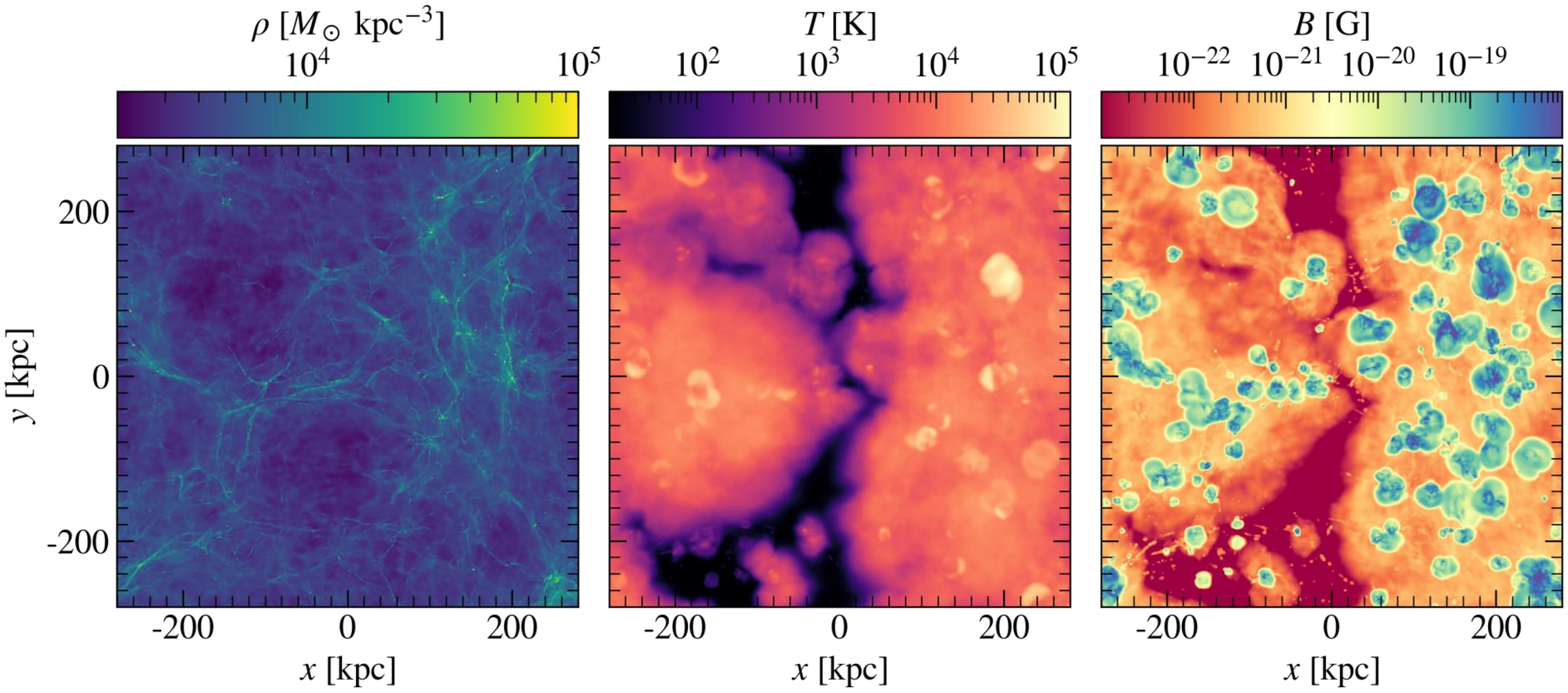
THE RAMSES CODE
APPLICATIONS
CONCLUSION

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



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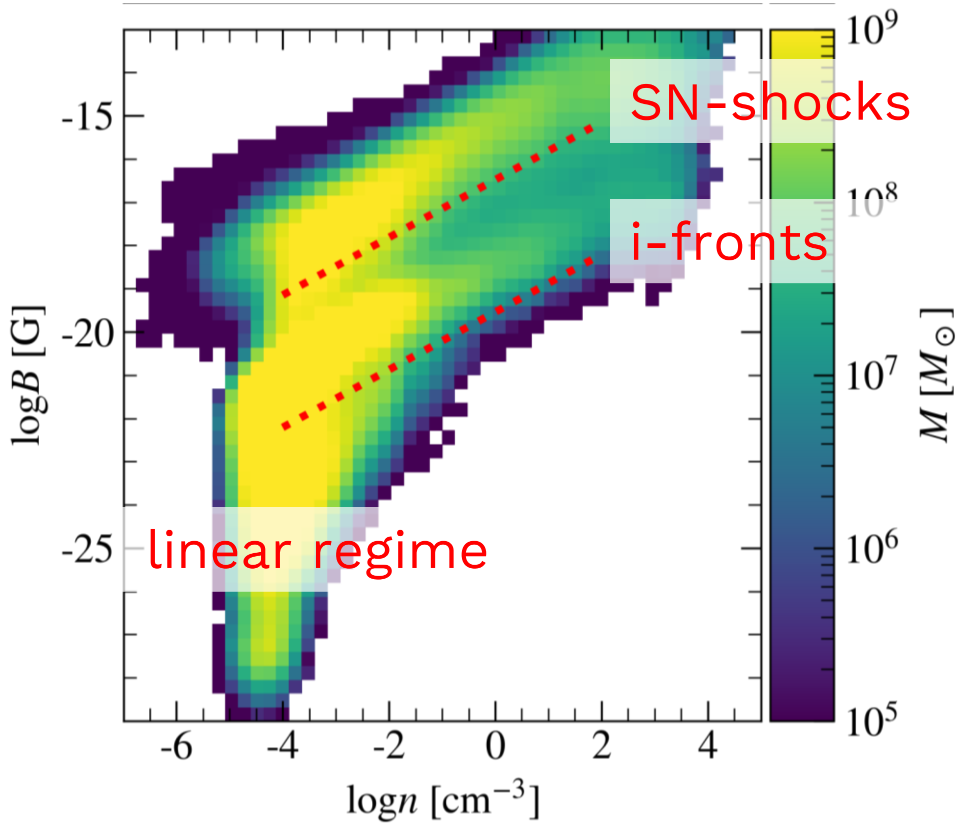
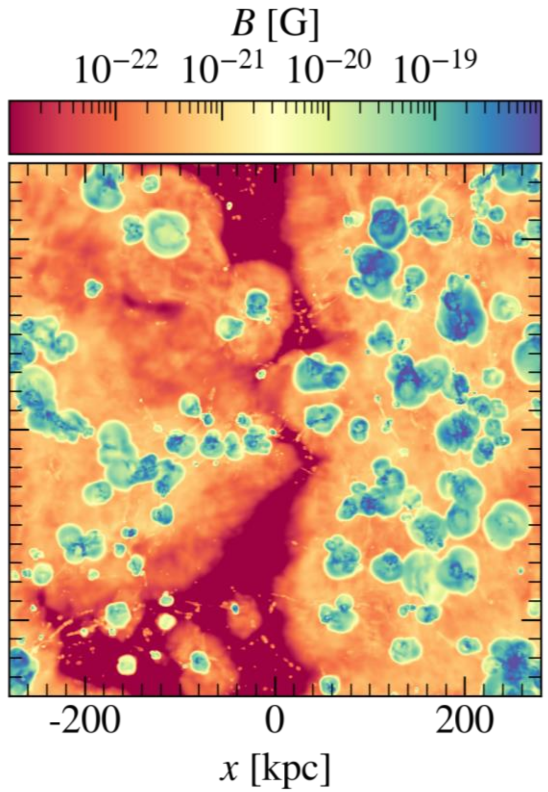
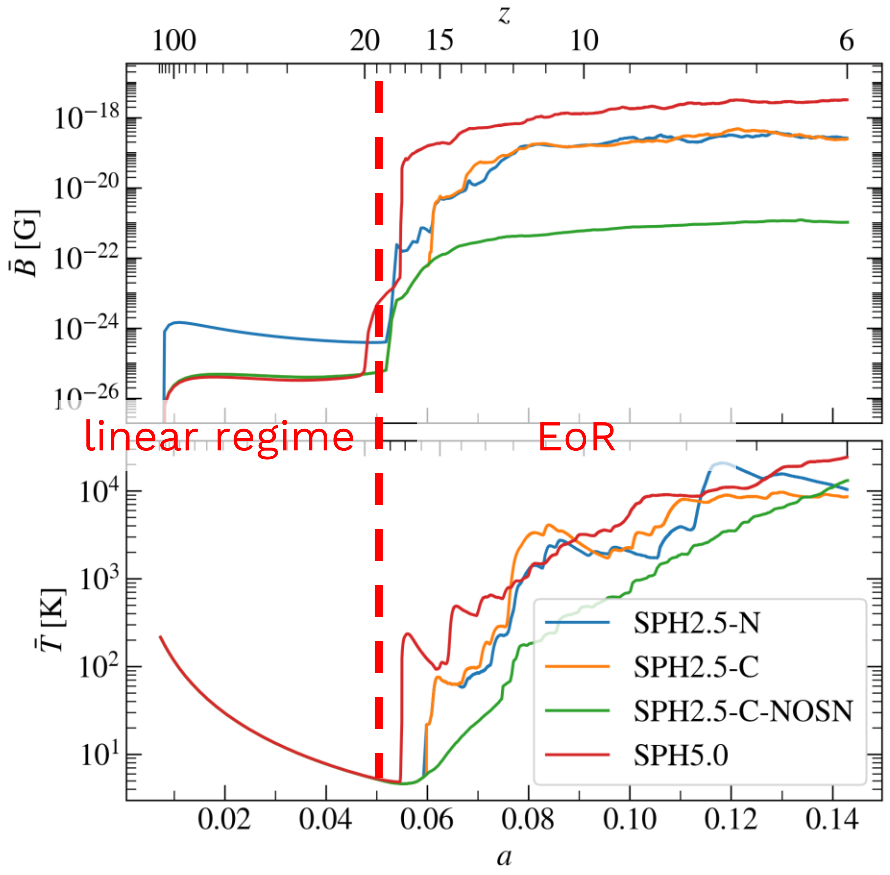




COSMOLOGICAL SIMULATIONS

- Temporal comparison: VW **magnetic field** and **temperature**.



CONCLUSION

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…