Reconnected Astrophysical Plasma results from PIC code simulations

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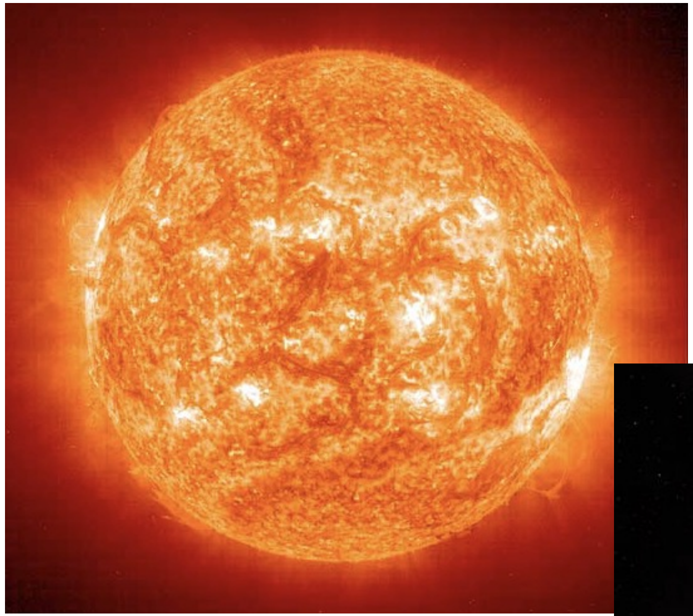
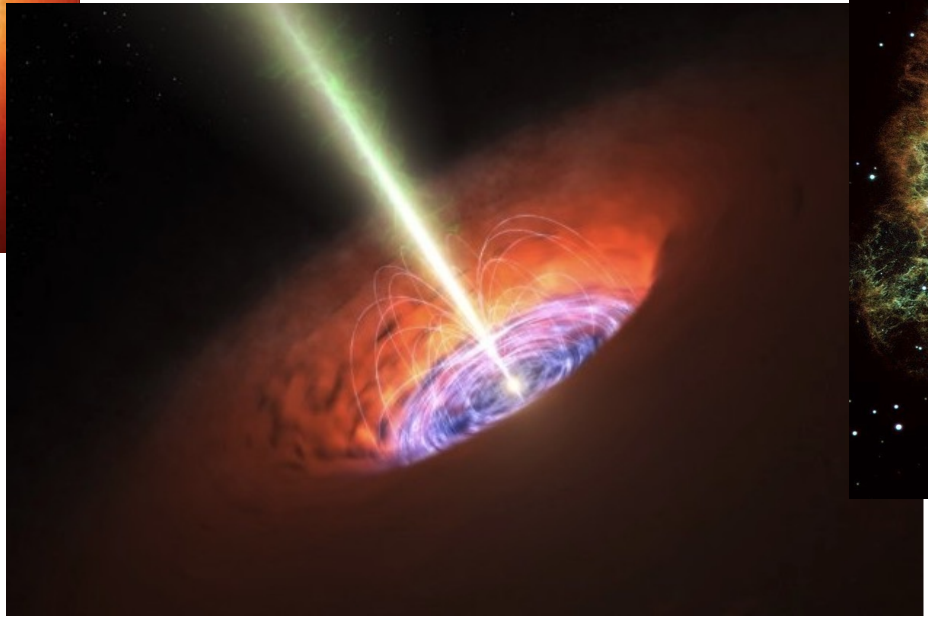
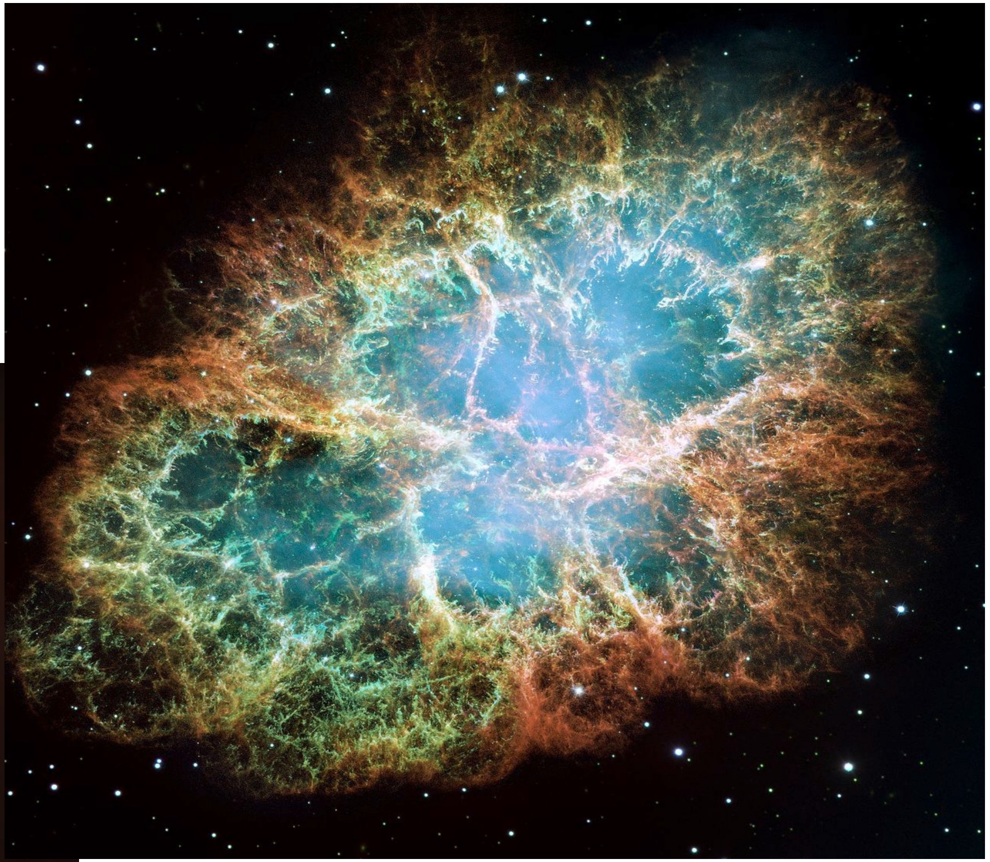
PASTO - Particle Acceleration in Astrophysical Objects (5-7 September 2022)

High Energy emissions from astrophysical sources







Credits NASA

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Magnetic Reconnection

The discovery of synchrotron **gamma-ray flares in the Crab Nebula**, well above the synchrotron burn-off limit, challenges the classical picture of particle acceleration. To overcome this limit, particles must accelerate in a region of high electric field and low magnetic field. This is possible only with a non-ideal magnetohydrodynamic process, like **Magnetic Reconnection***.

Magnetic Reconnection, especially in the relativistic regime, provides an efficient mechanism for accelerating relativistic particles and thus offers an attractive physical explanation for nonthermal high-energy emission from various astrophysical sources.

Magnetic Reconnection is a **topological rearrangement of magnetic field** that converts magnetic energy to plasma energy.

B. Cerutti, G. R. Werner, D. A. Uzdensky, & M. C. Begelman -2013*

Simulations with different ratio between Larmor radius & Box

The maximum energy reached by a charged particle in an astrophysical object is limited by the size of the acceleration region. If the relativistic Larmor radius is of order the system size L, the particle escapes and is no longer accelerated!!!

The maximum synchrotron photon energy emitted by an electron depends only on the ratio of the electric field (local) to magnetic field perpendicular to the particle's motion.

In MHD conditions where $E \leq B$, the energy of synchrotron radiation should not exceed the fundamental constant $\approx$ 160 MeV*.

B. Cerutti, G. R. Werner, D. A. Uzdensky, & M. C. Begelman - 2013*.

Vlasov equation

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- A necessary condition for non-thermal particle accelerati absence of Coulomb collision in the plasma of interest. The evolution of plasma is governed by the Vlasov equation:

$$\frac{\partial f}{\partial t} + \frac{\boldsymbol{p}}{\gamma \mathrm{m}} \frac{\partial f}{\partial \boldsymbol{r}} + \mathrm{q}\left(\boldsymbol{E} + \frac{\boldsymbol{v} \times \boldsymbol{B}}{\mathrm{c}}\right) \frac{\partial f}{\partial \boldsymbol{r}} = 0$$

Analytical solutions to the Vlasov equation are known for a few idealized situations only. In most cases, it must be solved numerically. They are at least two ways to solve this equation:

- Vlasov equation is solved directly using semi-Lagrangian or Eulerian methods;
- PIC (Particle-in-cells) technique (see: L. Sironi, B. Cerutti "Particle Acceleration in Pulsar Wind Nebulae: PIC Modelling" 10.1007/978-3-319-63031-1_11, 2017).

PIC (Particle-in-cells) model simulation

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Magnetization parameter

$$\sigma = B_0{}^2 / 4\pi n \gamma m c^2 \approx 16$$

Larmor radius

$$\rho = \gamma m c^2 / \mathrm{eB_0}$$ ⟷ L (box dimension)

Inverse Larmor frequency

$$\omega^{-1} = \rho / c \quad (seconds)$$

B. Cerutti, G. R. Werner, D. A. Uzdensky, & M. C. Begelman - 2013*

2D Simulation with Zeltron

Test Simulation:

PPC: 100 ← **Number of particles**

Pair jet/light jet: e-/e+

Boundary conditions: Periodic

σ= 16

ρ = 2 cm (Larmor radius)

L_x= 1000 cm

L_y= 1000 cm

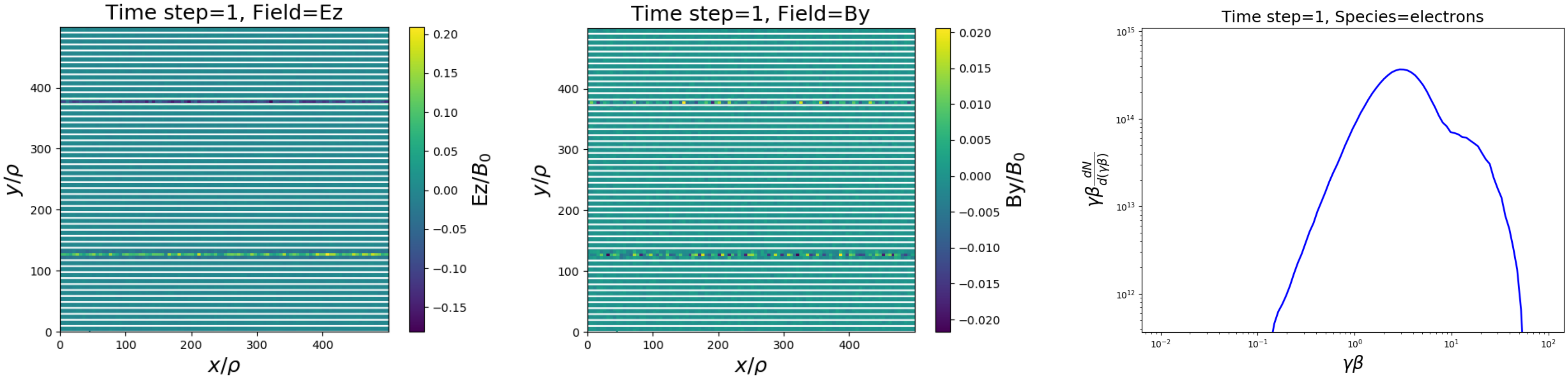
NCX=128

NCY=128

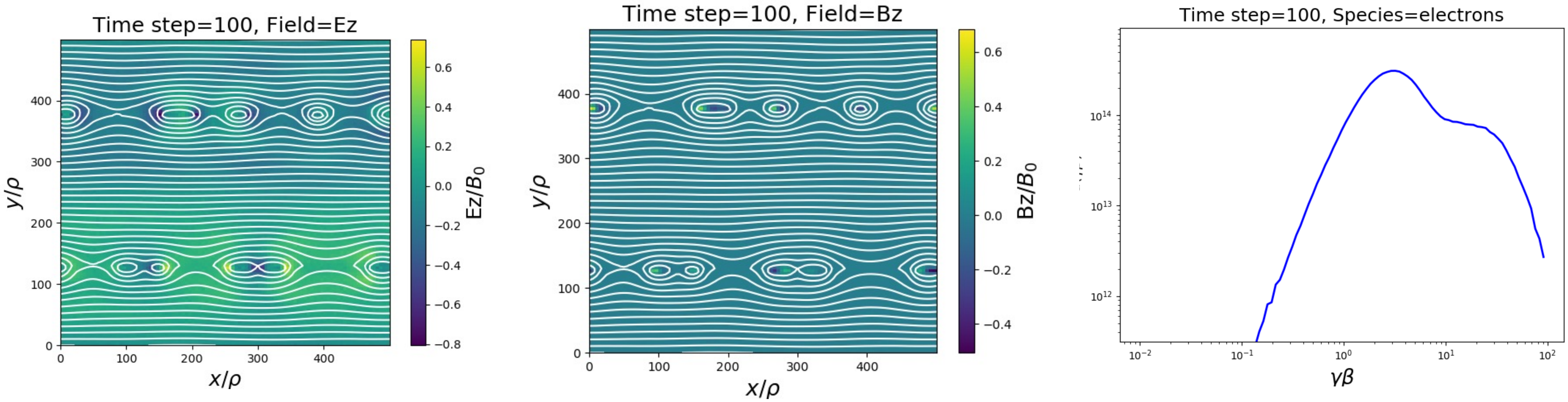
← **Cells number**

B_0=85 Gauss

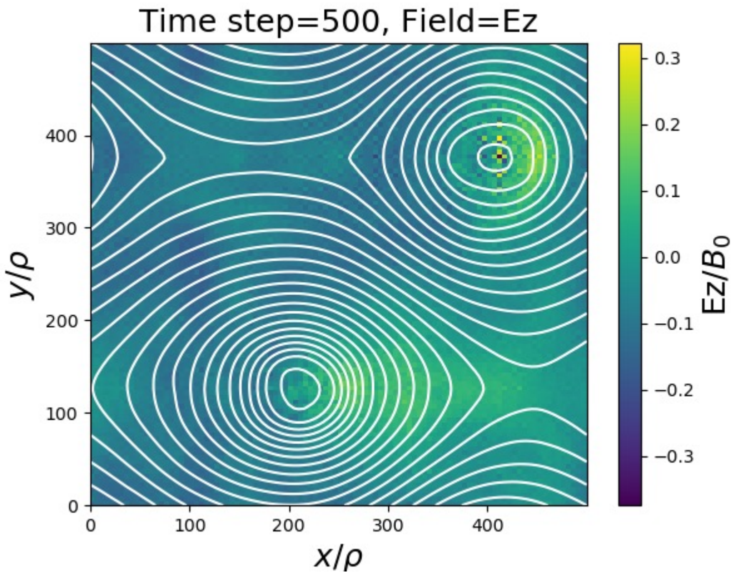
Simulation with Periodic Conditions

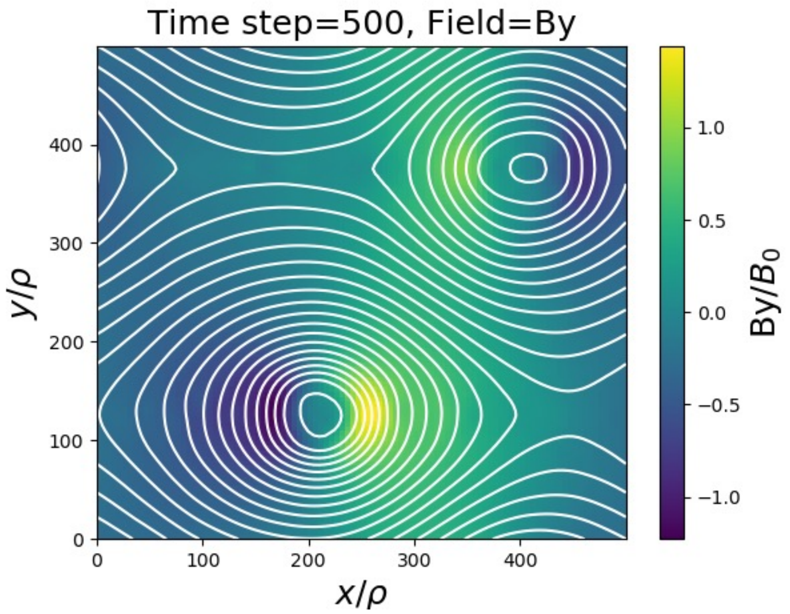


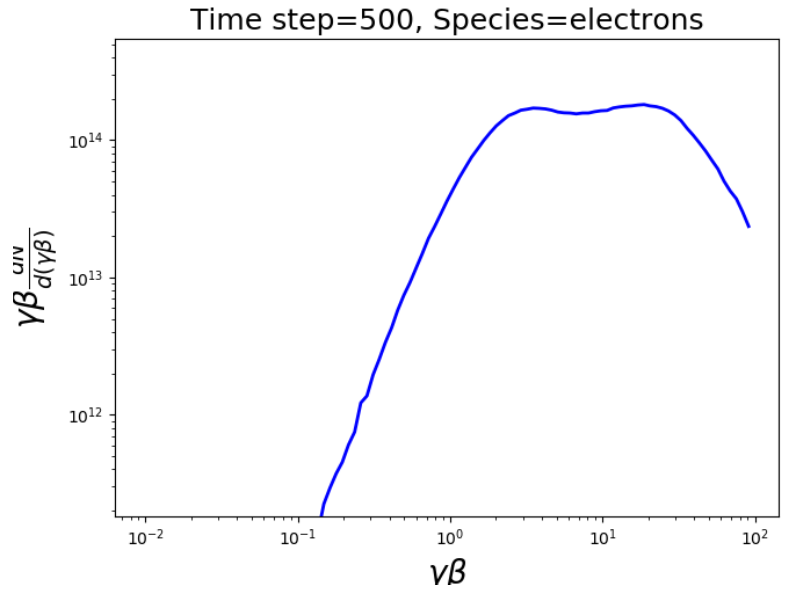
Simulation with Periodic Conditions



Simulation with Periodic Conditions







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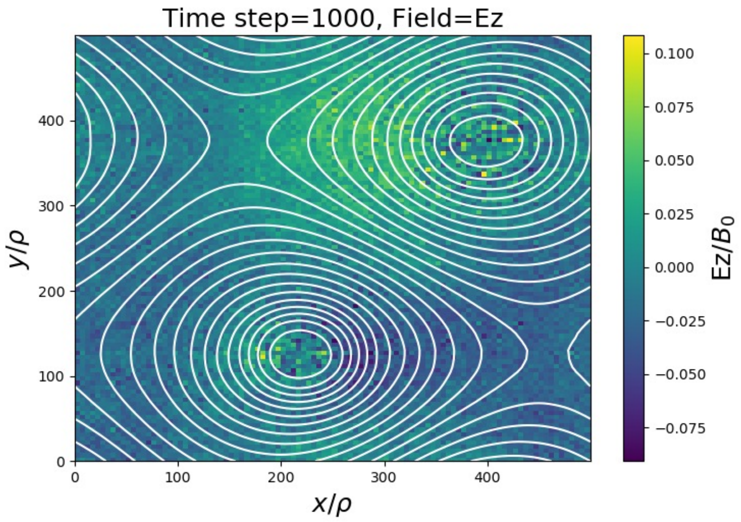

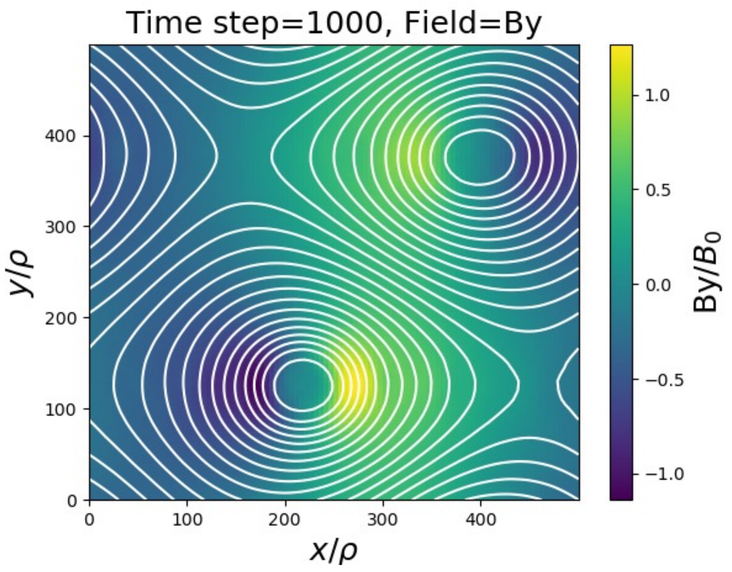

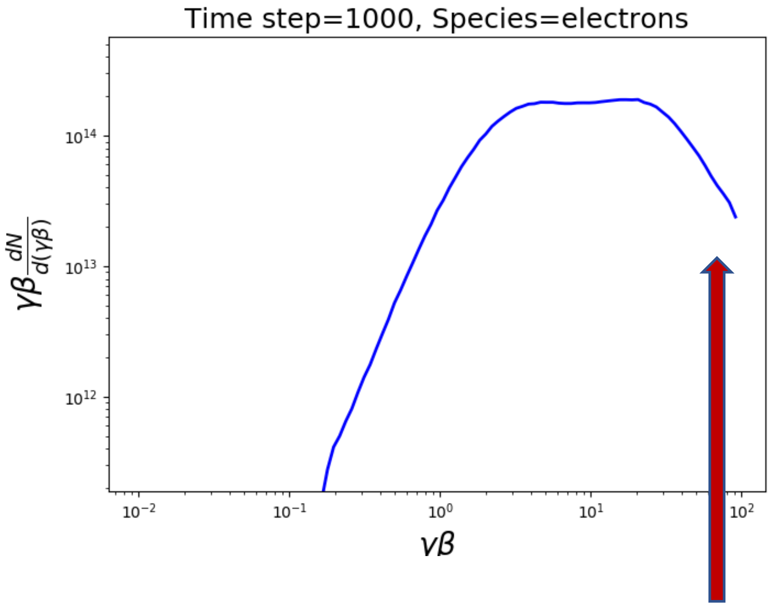

Numerical instability

Btw there is a caveat!!!

How we solve this problem?

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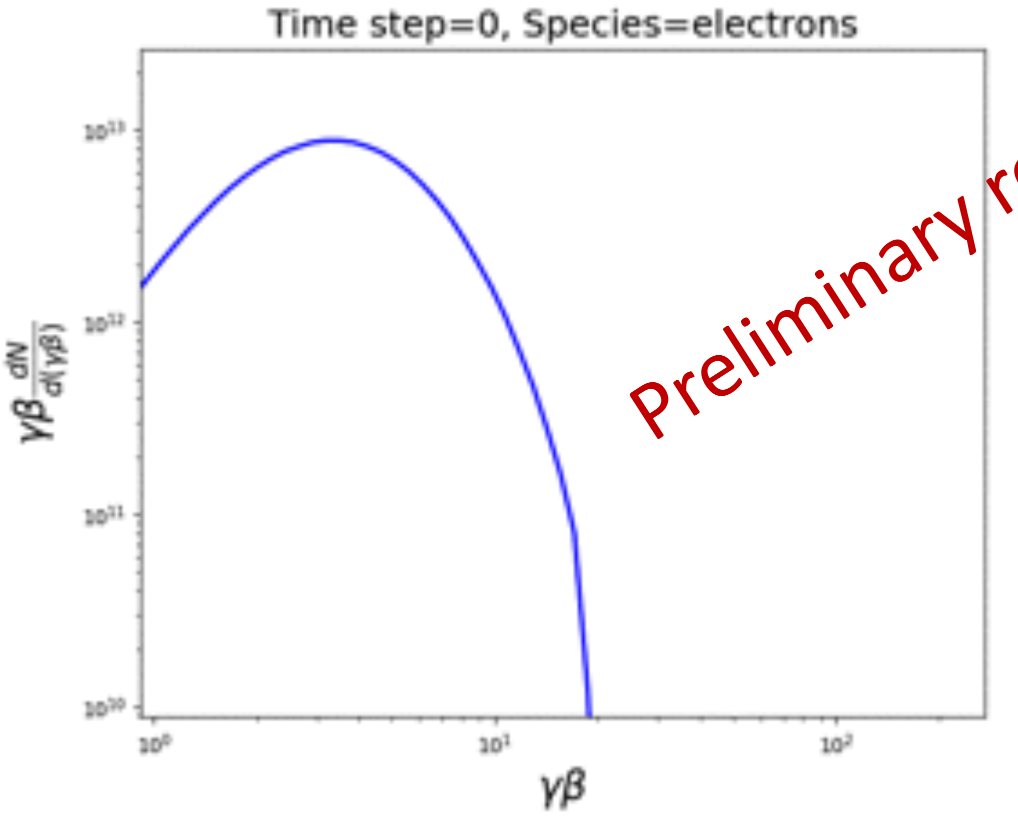
2D Simulation with density ratio=0.1

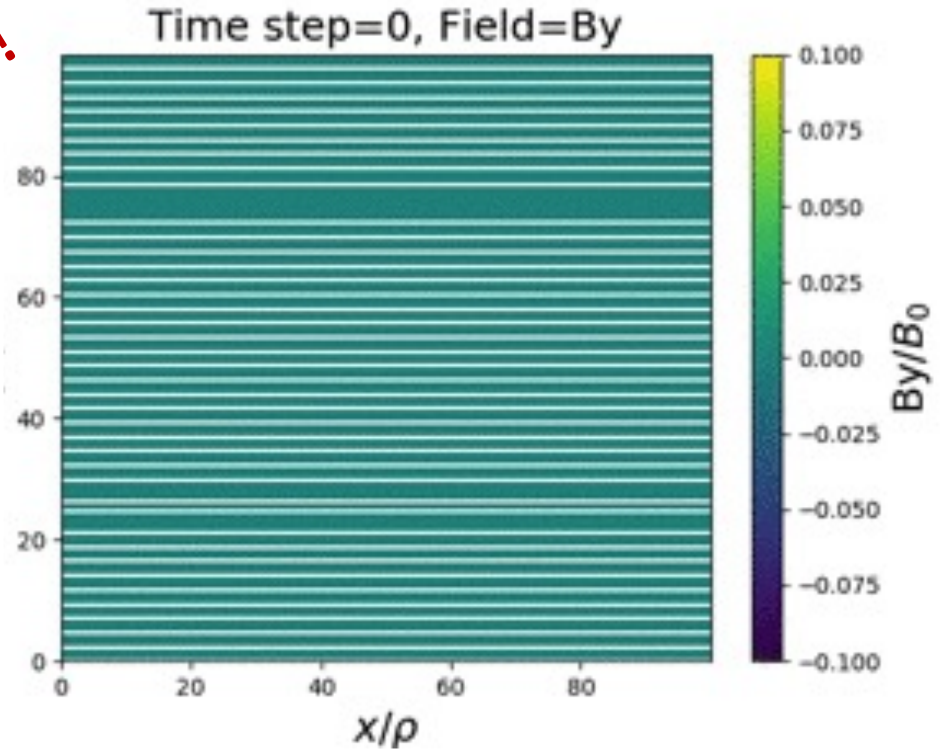
- Density ratio (n_{bg}/n_0): 0.1
- PPC: 100
- Pair jet/light jet: e-/e+
- Boundary conditions: Periodic
- σ= 16
- ρ = 100 cm (Larmor radius)
- L_x= 10000 cm
- L_y= 10000 cm
- NCX=300
- NCY=300
- B_0=85 Gauss

We can choose parameters in a smarter way, but we need extra computation power…!

Preliminary results from Periodic condition simulations $n_{bg}/n_0 = 0.1$



Preliminary results!



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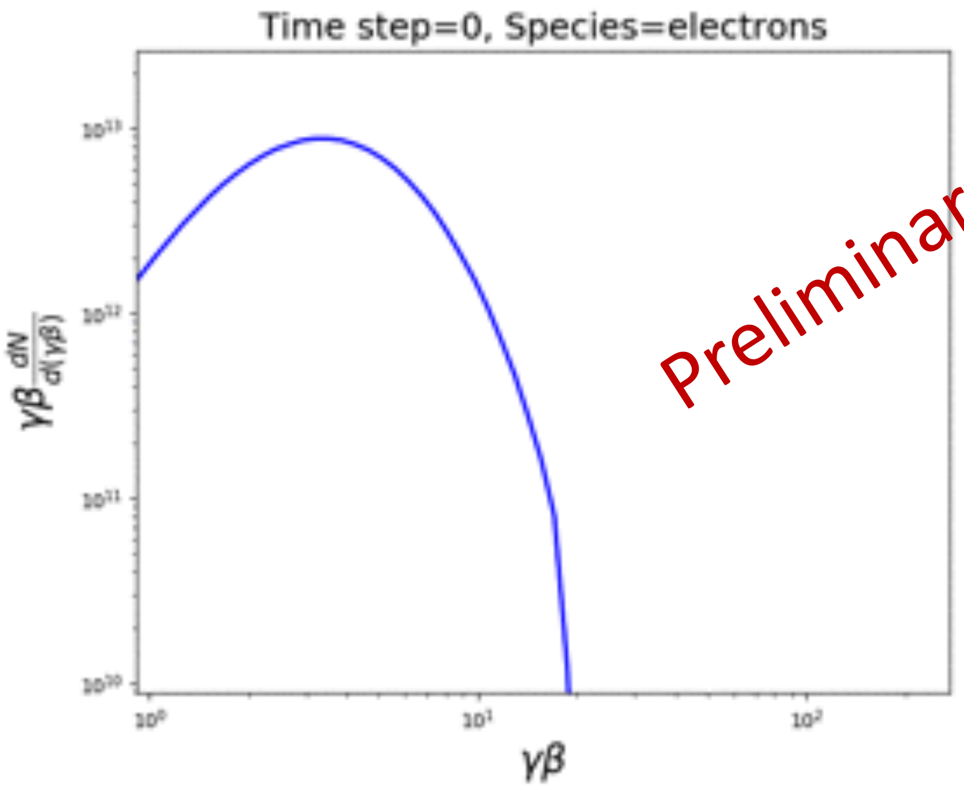
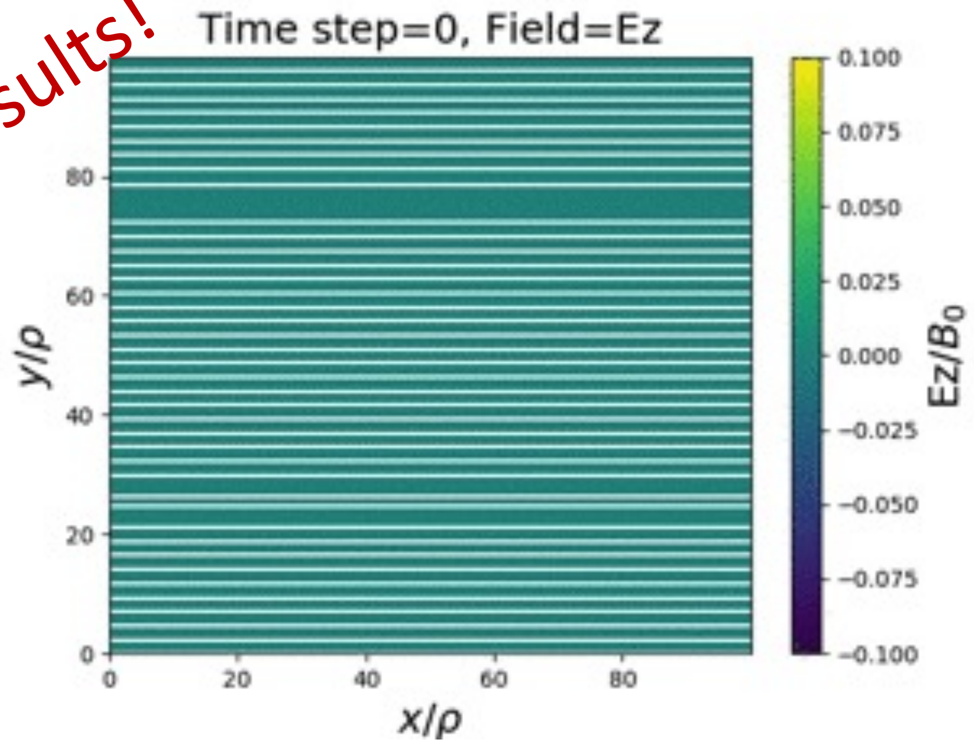


Preliminary results!



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2D Simulation with density ratio=0.01

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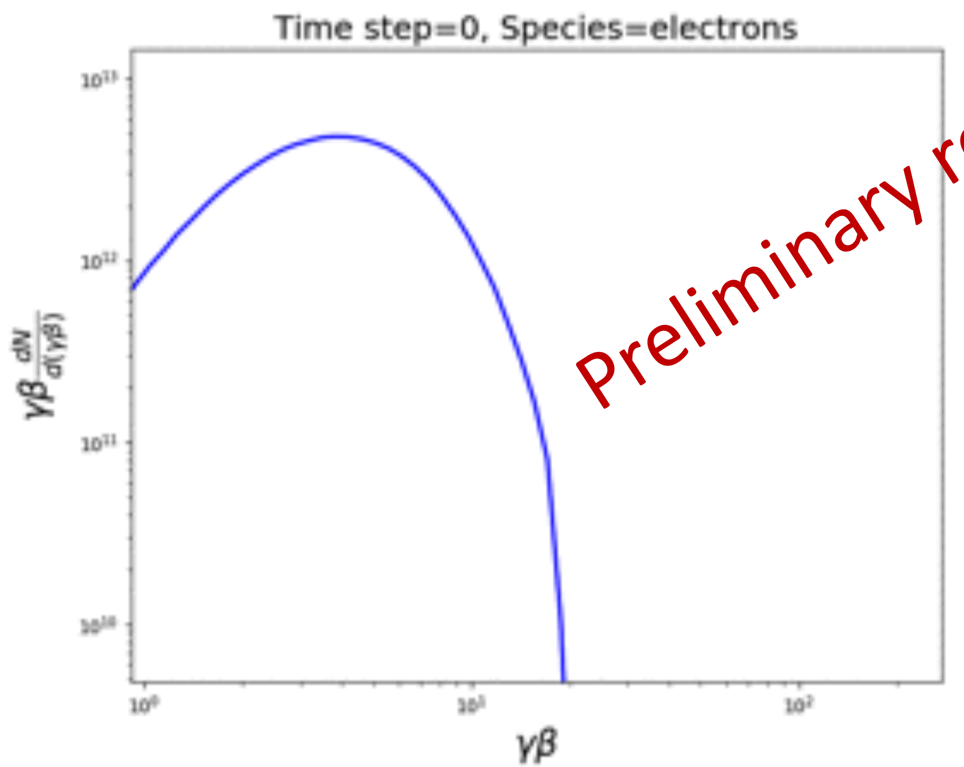
- Density ratio (n_{bg}/n_0): 0.01
- PPC: 100
- Pair jet/light jet: e-/e+
- Boundary conditions: Periodic
- σ= 16
- ρ = 100 cm (Larmor radius)
- L_x= 10000 cm
- L_y= 10000 cm
- NCX=300
- NCY=300
- B_0=85 Gauss

Preliminary results from Periodic condition simulations n_{bg}/n_0 =0.01



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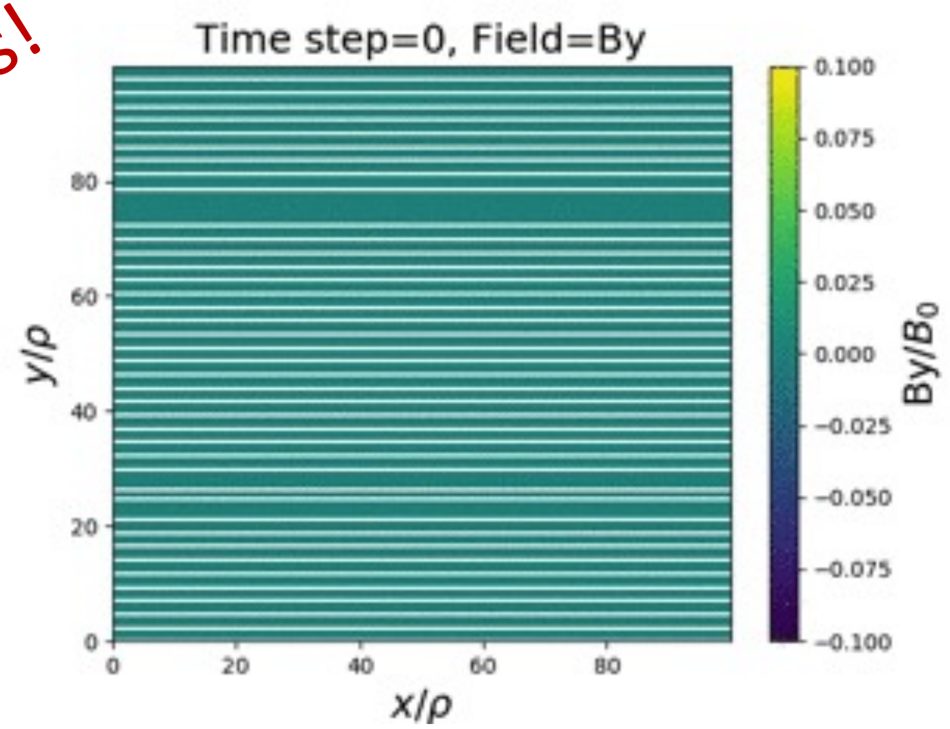
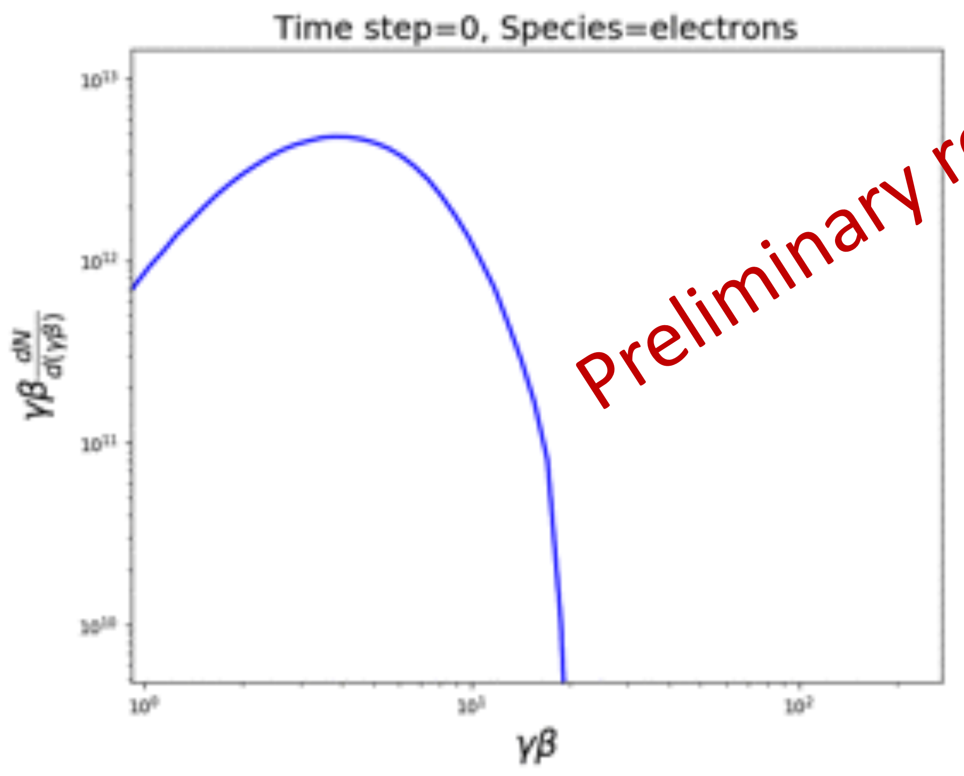
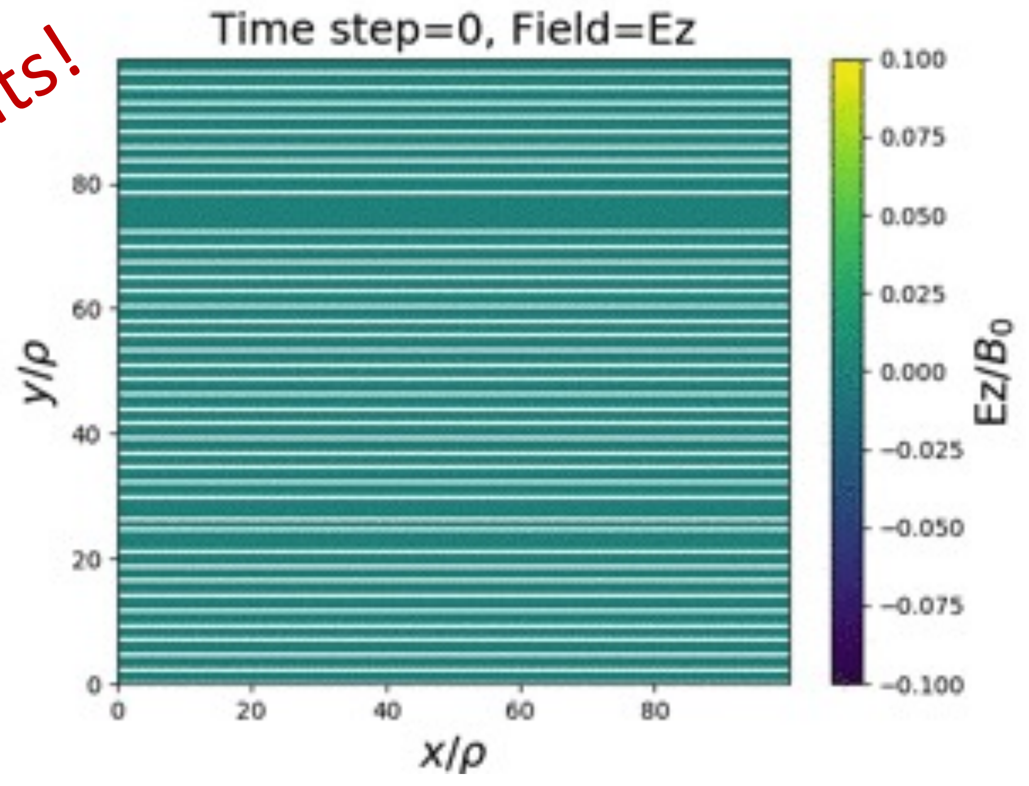


In prep. - E. Menegoni, V. Vittorini, P. Buratti, L. Foffano, M. Tavani.

Preliminary results from Periodic condition simulations $n_{bg}/n_0 = 0.01$



Preliminary results!



In prep. - E.Menegoni, V. Vittorini, P. Buratti, L. Foffano, M. Tavani.

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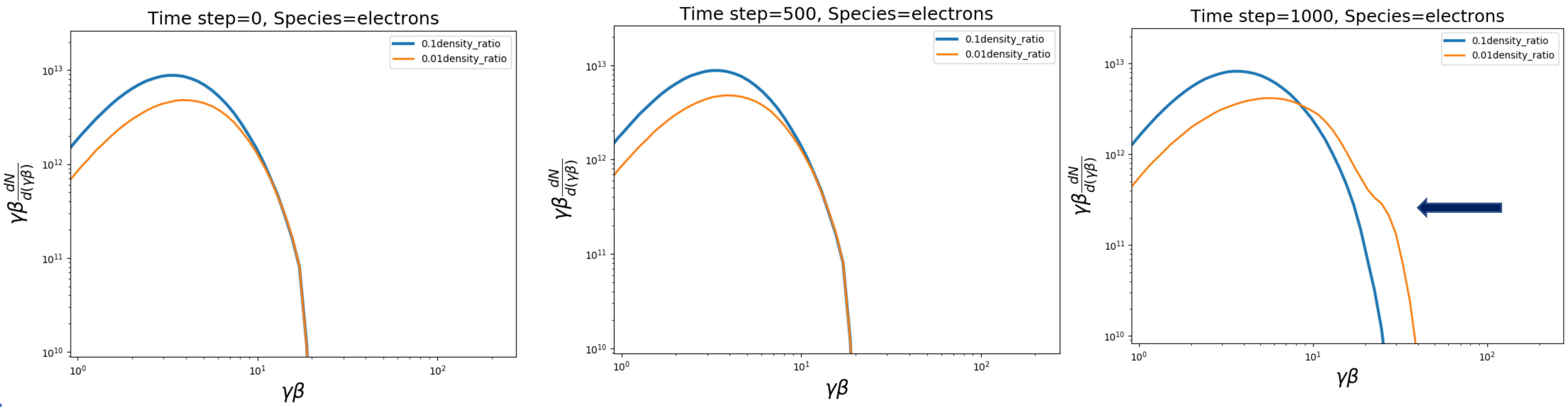
Comparison between 0.1- density and 0.01-density ratio simulations



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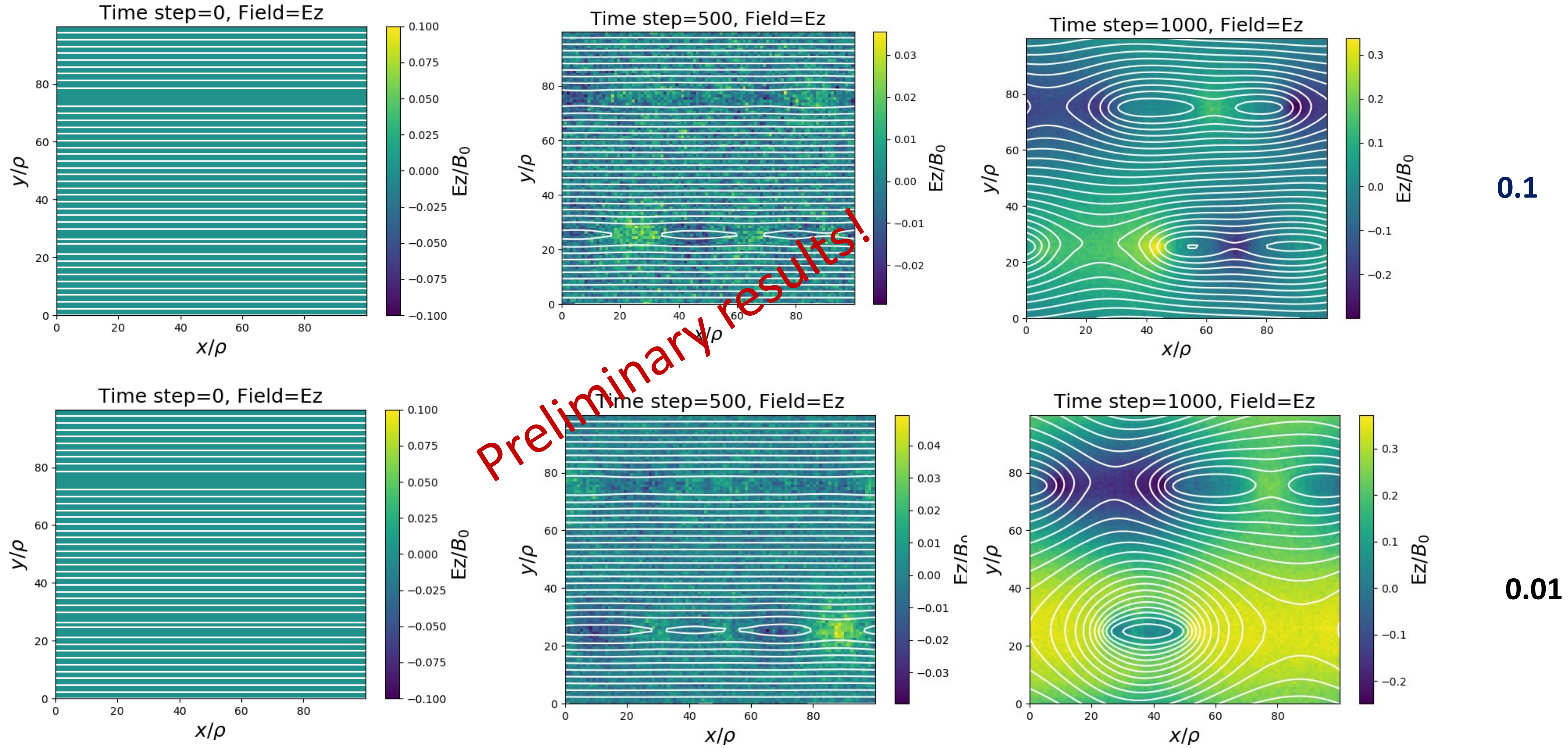
Ez comparison for the 2-values density



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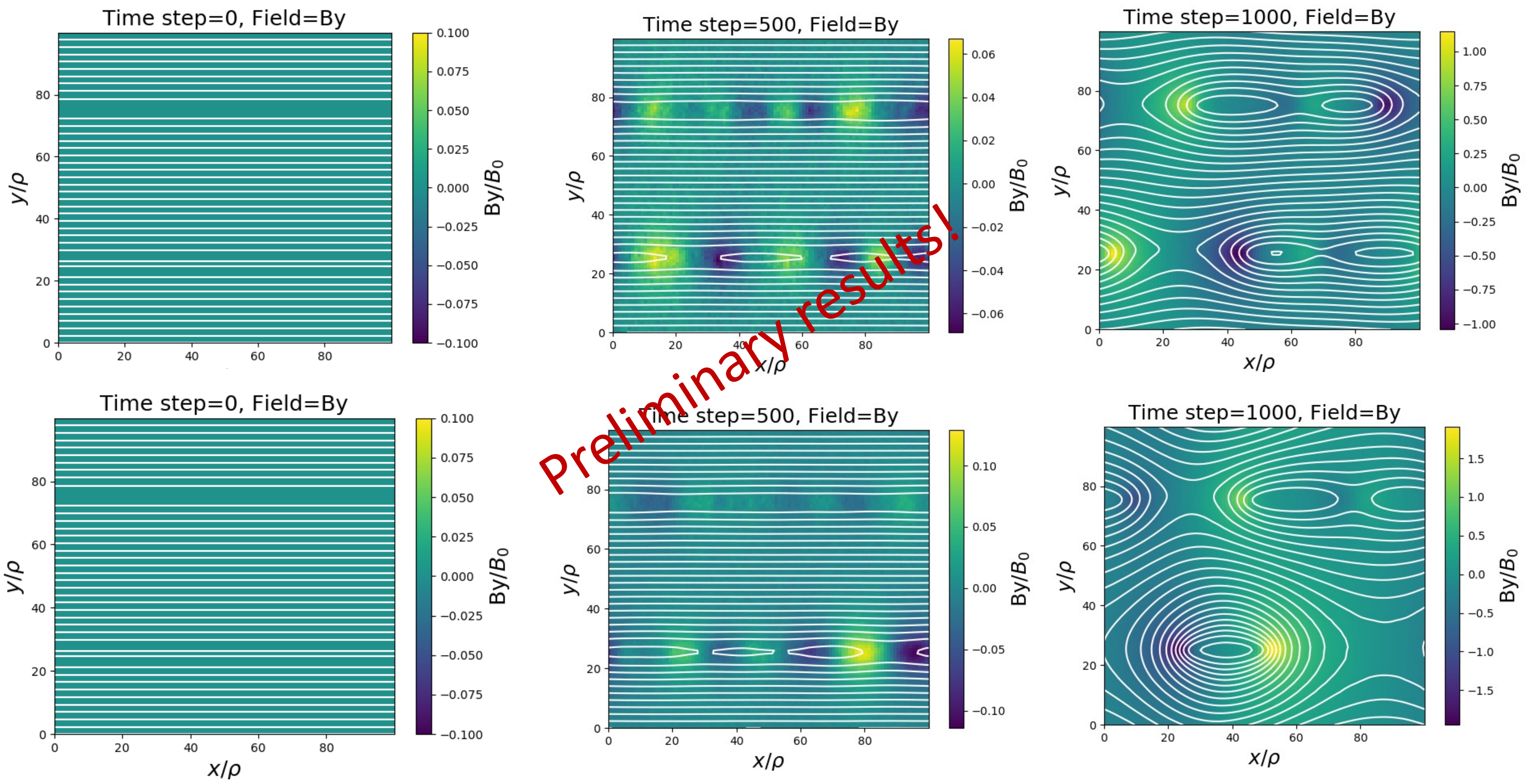
By comparison for the 2-values density



0.1

0.01

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What’s next?

- We are using also different temperature values of particles inside the plasma. Changing in temperatures cause changes in how the magnetic fields reconnect.. let’s see if we will achieve better results.

- We are performing several simulations changing the values of parameters, however, to achieve the desired value of acceleration and to see the formation of power-law we must have more computational power at least 300-400 cores. These calculus are very expensive!!!!! (see: Ji, H., Daughton, W., Jara-Almonte, J. *et al.* Magnetic reconnection in the era of exascale computing and multiscale experiments. *Nat Rev Phys* **4**, 263–282 (2022)).

- We need more calculus facilities to perform simulations with and to gain Cerutti’s results: in the last two weeks, we are starting to exploit the new **INAF computational infrastructure named PLEIADI.**

Conclusions

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- We are performing several simulations changing the values of parameters, however, to achieve the desired value of acceleration we must have a larger box (L very large…), but, most of all highly performing computers!!!! We are going to exploit the new **INAF computational infrastructure (PLEIADI).**

- In the 0.01 density model we start to see an hint of power-law formation, vice versa, in the 0.1 density model we don't see it because the formation of **magnetic islands** (or **plasmoids**) require more **time!!**

- We can apply different initial conditions, for example the ABC configuration (see Yuan, .., ,Blandford).

TEAM

- Supervisor: Marco Tavani
- Coordinator: Valerio Vittorini
- Members: Eloisa Menegoni, Luca Foffano, Samanta Macera.
- External Members (ENEA): Paolo Buratti, Alessandro Cardinali, Simone Mannori, Franco Alladio, Paolo Micozzi.
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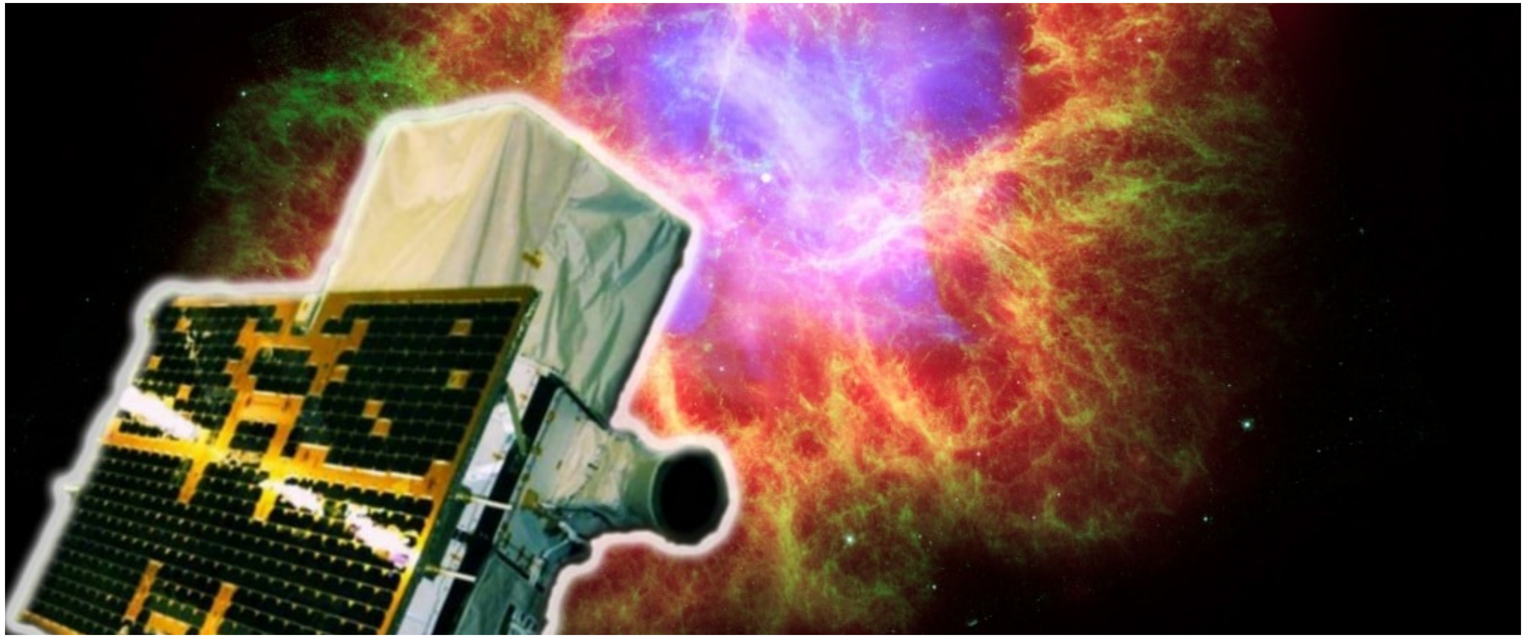

Thank you!!

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